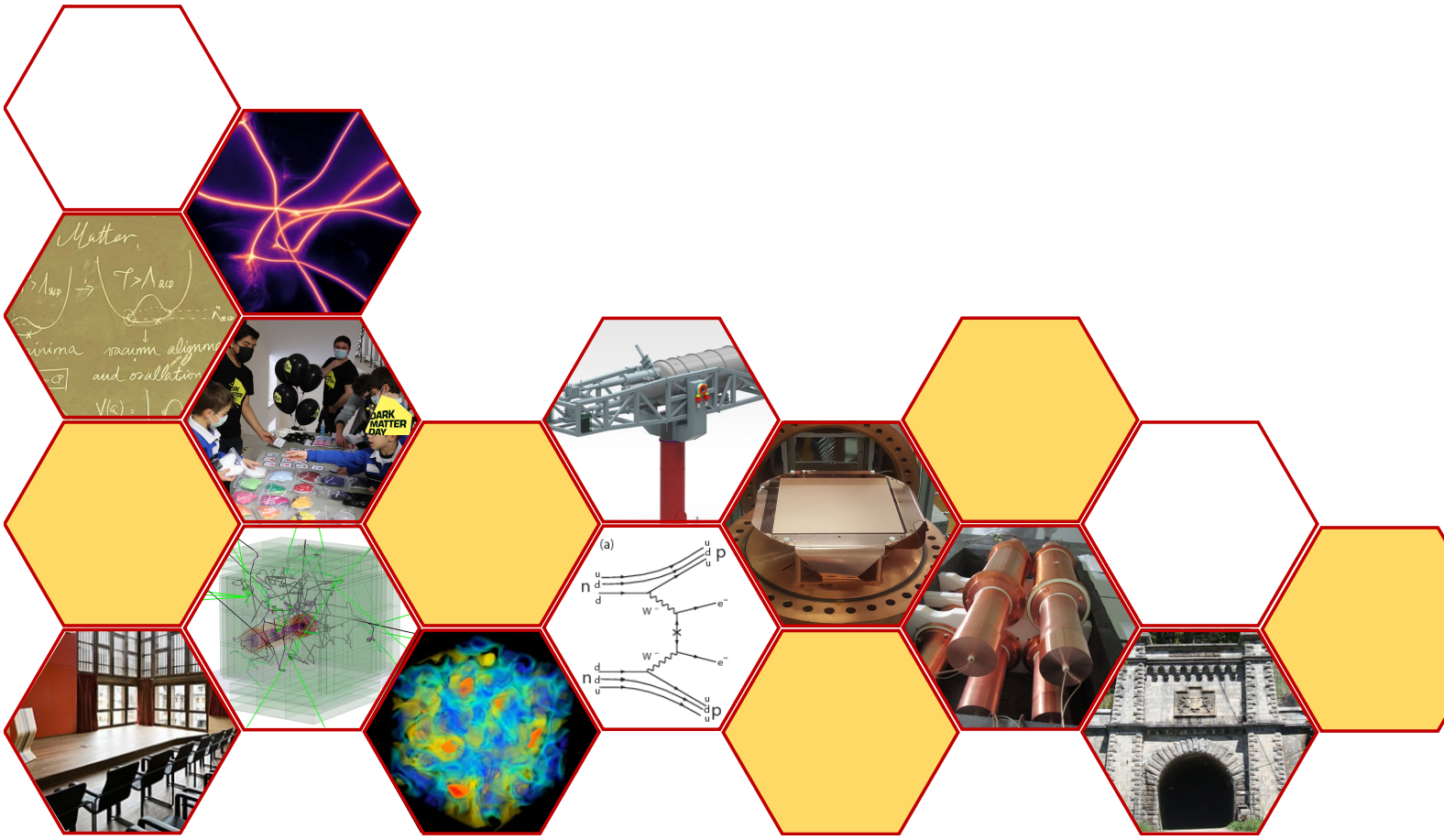
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Universidad Zaragoza
1542

Annual Report 2022

Centro de Astropartículas y Altas Energías (CAPA)



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Message from the Director

The *Centro de Astropartículas y Física de Altas Energías* (CAPA) is a research institute of Zaragoza University devoted to the study of particle physics, astrophysics and cosmology. We combine theory, simulations and experiments to deal with the major challenges at the frontier of those research areas in collaboration with a large family of partners and international collaborators.

In our fourth year we have continued the expansion of the institute. We incorporated four new members: two Maria Zambrano fellows, an engineer and a new research trainee, and two new external collaborators. In the same line we are running two substantial grants supported by the Recuperación, Transformación y Resiliencia Program of the European Union:

i) Program of *Planes Complementarios de I+D+I en Astrofísica y Física de Altas Energías en Aragón*

ii) *Quantum Spain project* of the Ministerio de Asuntos Económicos y Transformación Digital.

We continue to develop the *Master on Physics of the Universe: Cosmology, Astrophysics, Particles and Astroparticles*, which is attracting an increasing number of students from other Spanish universities as well as a substantial number of female and international students.

Members of CAPA have obtained substantial research grants from national and European Agencies to finance the basic research lines of the Center. CAPA members have a considerable presence in scientific boards and committees of conferences and funding agencies.

Our focus in outreach activities is expanding a lot with particular emphasis in the gender issues promoting the role of women and girls in science and technology. We also have led the organization of a great scientific and social event devoted to commemorate the centenary of the visit of Albert Einstein to Zaragoza in 1923. The event had a very impressive impact in the Aragonese community.

In summary, the Center keeps growing and gaining prestige in the HEP community. However, we did not make the expected fundamental progress in our goal of transforming CAPA into a Research Institute recognised by the Aragon Government. The main reason for the delay was the political instability of the involved institutions. We hope that, with new leadership in place at the institutions, we will be able to make up for lost time next year.

1

General description of CAPA

The *Centro de Astropartículas y Física de Altas Energías* (CAPA) of the University of Zaragoza, is a research center created in 2019 to foster the research in the fields of high energy physics, particle and nuclear physics, astrophysics, cosmology, astroparticle physics and theory, as well as in related technological developments. The center was built encompassing the research groups and lines already active in the University of Zaragoza in the aforementioned topics, some of them with a long and recognised trajectory.

1.1 | Main objectives

Apart from the general aim stated above, CAPA has the following specific objectives, as stated in its "memoria de creación":

1. Promote the presence of CAPA researchers in national and international scientific forums, increasing their specific weight in the mentioned fields of research.

2. Promote and support administratively new funding requests from the CAPA members, both in national programs (e.g. national R&D plans, María de Maeztu,...), as well as in international ones (European Research Council (ERC), European Innovation Council (EIC), European Cooperation in Science and Technology (COST), and others.)

3. Foster the creation of new synergies among the different research lines, especially between the theory and experimental areas.

4. Strengthen the participation of CAPA members in the Aragonese research centers related with the mentioned areas: the *Laboratorio Subterráneo de Canfranc* (LSC) and the *Centro de Ciencias de Benasque Pedro Pascual* (CCBPP), as well as to promote collaboration with the *Centro de Física del Cosmos de Aragón* (CEFCA).

5. Promote activites of specialized training and facilitate the incorporation of young scientist and technical manpower to the scientific community.

6. Ensure the corresponding transfer of the knowledge created in this field of research to the industrial sector.

7. Promote the scientific culture of the society through the realization of outreach activities addressed to the general public.

1.2 | Organizative structure

CAPA was created as a *center* of the University of Zaragoza and as such it is regulated by the University's statutes. The CAPA organizative structure includes the center's *Council*, which is composed by all the PhDs of the center plus representatives of the PhD students and technical personnel. The Council is the body that, among other things, elects the *Director* of the center, and approves (after the Director's proposal) its *deputy Director* and its *Secretary*. The Director represents the CAPA and, among other things, organizes and leads the actions needed to better achieve the center's objectives. The center also counts with an external scientific advisory board, chaired by the Director and including at least other five scientists of recognised prestige. This board is in charge of evaluating the annual report of CAPA, and advising its governing bodies on the activities of the center and strategical matters. The name of the persons currently holding the mentioned uni-personal positions at CAPA, as well as the members of the advisory board, are listed in the attached table.

Single-person governing positions:	
Director:	Manuel Asorey
Deputy Director:	Igor G. Irastorza
Secretary:	José Manuel Carmona
Scientific advisory board:	
Francisco del Aguila	U. Granada
Inés Gil-Botella	CIEMAT, Madrid
Axel Lindner	DESY, Hamburg
Teresa Marrodán	MPI, Heidelberg
Antonio Pich	IFIC, Valencia

1.3 | Areas of activity and research groups

The CAPA community encompasses several research groups active in the fields mentioned above, both in theoretical and experimental aspects. Regarding experimental research, CAPA inherits from the long-standing trajectory of the Nuclear and Astroparticle Physics groups, responsible of the pioneering research on low background techniques and underground experimentation that were the seed of the current Laboratorio Subterráneo de Canfranc (LSC). These groups are nowadays involved in several of the experiments at LSC and in particular are the leaders of WIMP dark matter experiments like ANAIS or TREX-DM, as well as in axion searches like BabyIAXO and RADES. The CAPA researchers are also active in more transversal developments of novel detector concepts and low background know-how in general. The center counts with the LABAC, a laboratory performing environmental radioactivity monitoring, as a node of a network funded by the "Consejo de Seguridad Nuclear" (CSN, Spanish Nuclear Regulatory Commission). Regarding the theoretical research, CAPA members also inherit a long standing trajectory in Theoretical and Particle Physics. At present they are active in a number of frontier aspects of particle and astroparticle physics. The most relevant are: axion theory, astrophysics and cosmology; the phenomenology of beyond-SM particle physics models; quantum gravity phenomenology and lattice field theory. CAPA is an institution represented in the EuCAPT Council and also leads the COST Action CA18108. Detailed information of the research lines performed at CAPA is given in section 3.

2

Human resources

In 2022, 4 new CAPA members and 2 external collaborators were admitted: the María Zambrano fellows Jaime Ruz and Julia Vogel, the research trainee Tamara Pardo, the engineer Javier Galindo, and the external collaborators Diego Blas (ICREA Professor) and Jacobo Asorey (María Zambrano fellow at UCM). The senior UZ collaborator, Rafael Núñez-Lagos, resigned as CAPA member. On the other hand, Juan Antonio García Pascual, previously Juan de la Cierva fellow, became Marie Curie fellow (MSCA) in 2022.

At the end of 2022, CAPA had a total of 76 members. Its gender gap is shown in Fig. 2.1. After the new incorporations, the gender gap is the same as in 2021. CAPA has been continuing carrying out specific activities addressed to female students to attract women to science, as described in Sec. 7.

CAPA members are distributed in the following personnel categories:

1. Teaching and research permanent staff

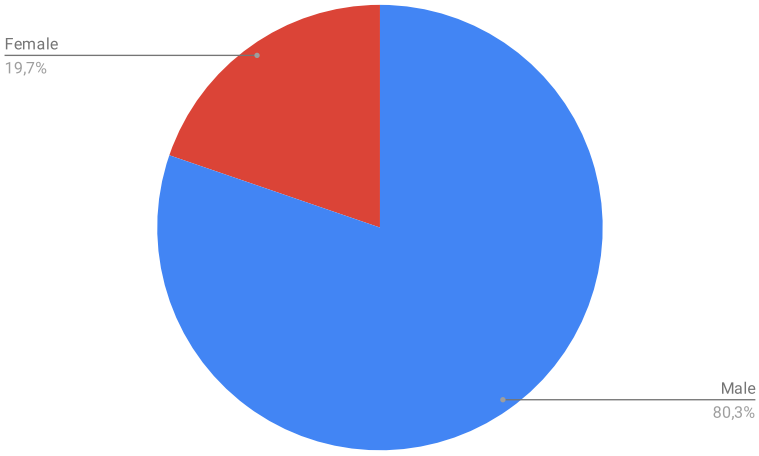

Figure 2.1: CAPA gender gap.

2. Teaching and research temporary staff
3. Collaborators from the University of Zaragoza (UZ)
4. Administration and technical staff
5. Research trainees (doctorate level)
6. Collaborators from external institutions

The distribution in percentages and in absolute numbers are shown in Fig. 2.2. The list of members as of end of 2022 is shown in Table 2.1.

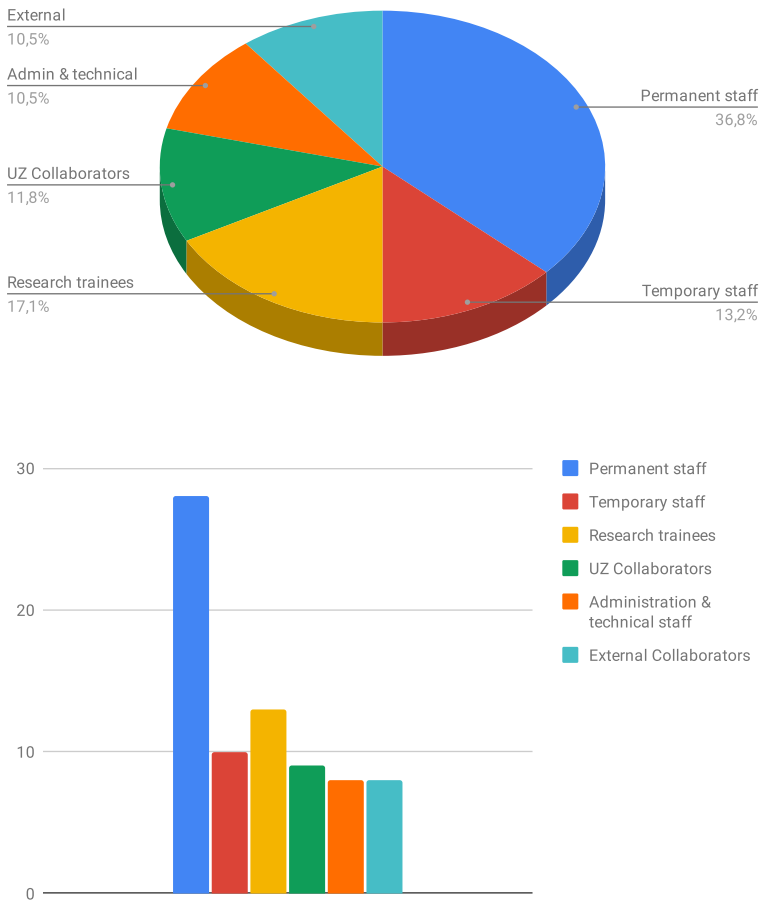

Figure 2.2: Distribution of CAPA members in categories of personnel, as percentage (upper plot) and in absolute numbers (bottom).

Table 2.1: List of CAPA members as of end of 2022.

Name	Personnel category
Agustín Camón Lasheras	Permanent staff
Alfonso Tarancon Lafita	Permanent staff
Ana Maria Salinas Baldellou	Permanent staff
Eduardo Follana Adin	Permanent staff
Eduardo García Abancéns	Permanent staff
Fernando Falceto Blecua	Permanent staff
Gloria Luzón	Permanent staff
Igor García Irastorza	Permanent staff
Inés Cavero Peláez	Permanent staff
Javier Redondo Martín	Permanent staff
Jesús Clemente Gallardo	Permanent staff
Jesús Gomez Gardeñes	Permanent staff
Jorge Puimedón Santolaria	Permanent staff
José Fernando Cariñena Marzo	Permanent staff
José Manuel Carmona Martínez	Permanent staff
José V. García Esteve	Permanent staff
Luis Fernando Velázquez Campoy	Permanent staff
Manuel Asorey Carballeira	Permanent staff
Manuel Clemente Membrado Ibáñez	Permanent staff
María Luisa Sarsa Sarsa	Permanent staff
María Martínez Pérez	Permanent staff
Pablo Díaz Benito	Permanent staff
Siannah Peñaranda Rivas	Permanent staff
Susana Cebrián Guajardo	Permanent staff
Theopisti Dafní	Permanent staff
Vicente Azcoiti Pérez	Permanent staff
Yamir Moreno Vega	Permanent staff
Ysrael Richard Ortigoza Paredes	Permanent staff
Alejandro Vaquero Avilés-Casco	Temporary staff
Bodo Georg Schwabe	Temporary staff
Carlos Pobes Aranda	Temporary staff
Cristina Margalejo Blasco	Temporary staff
Francisco Javier Jiménez Albericio	Temporary staff
Jaime Ruz Armendáriz	Temporary staff
Javier Galan Lacarra	Temporary staff
Juan Antonio García Pascual	Temporary staff
Julia Katharina Vogel	Temporary staff
Konrad Altenmüller	Temporary staff

Name	Personnel category
Carlos Bouthelier Madre	Research trainees
David Cintas González	Research trainees
David Díez Ibáñez	Research trainees
David Martínez Crespo	Research trainees
Eduardo Royo Amondarain	Research trainees
Fernando Ezquerro Sastre	Research trainees
Iván Coarasa Casas	Research trainees
Jorge Alda Gallo	Research trainees
Luis Antonio Obis Aparicio	Research trainees
Maykoll A. Reyes Hung	Research trainees
Óscar Pérez Lázaro	Research trainees
Tamara Pardo Yanguas	Research trainees
Yiseli Martínez Pérez	Research trainees
Amalio Fernández-Pacheco Pérez	UZ Collaborators
Antonio José Seguí Santonja	UZ Collaborators
César Asensio Chaves	UZ Collaborators
José Luis Alonso Buj	UZ Collaborators
José Luis Cortés Azcoiti	UZ Collaborators
José Mariano Gracia Bondía	UZ Collaborators
Julio César Amaré Tafalla	UZ Collaborators
Miguel Á. Pérez Torres	UZ Collaborators
Patricia Villar Gómez	UZ Collaborators
Alfonso Ortiz de Solórzano Aurusa	Admin & technical staff
Francisco Javier Mena Alastuey	Admin & technical staff
Héctor Mirallas Sánchez	Admin & technical staff
Javier Galindo	Admin & technical staff
Juan Francisco Castel Pablo	Admin & technical staff
María del Carmen Pérez Marín	Admin & technical staff
Pedro José Justes Aizpún	Admin & technical staff
Virginia Rodríguez Romeo	Admin & technical staff
Ciaran O'Hare	External Collaborators
Diego Blas Temiño	External Collaborators
Fernando Arteche González	External Collaborators
Héctor Gómez Maluenda	External Collaborators
Jacobo Asorey Barreiro	External Collaborators
José Javier Relancio Martínez	External Collaborators
Laura Seguí Iglesia	External Collaborators
Sven Heinemeyer	External Collaborators

3

Research lines achievements

This section describes the various core research lines being pursued at CAPA, in the fields of cosmology, astrophysics, astroparticle and particle physics, both in theoretical and experimental aspects, with an emphasis on the achievements in 2022. Several of these lines describe activities corresponding to well defined funded projects (see annexes A and B), while others correspond to more specific research lines framed within larger projects (but of sufficient entity as to deserve their own subsection here), research activity of more transversal character (e.g. R&D), or emerging activities or collaborations with external colleagues. Some CAPA members are also members of other "neighboring" research institutes like the BIFI (Biophysics and Complex Systems Institute) or the INMA (Nanotechnology and Materials Institute) and not all their research output can be adscribed to genuine CAPA research lines, something that can be seen in the automatically-produced list of publications in annex N. In addition, some of the newer members still enjoy scientific production from the previous projects in non-CAPA affiliations. In the following section we describe only the research lines fully considered within the CAPA scope. We divide them in experiment and theory research lines.

Experiment

The experimental research lines at CAPA largely inherit from the long-standing trajectory of the Nuclear and Astroparticle Physics group (GIFNA), responsible of the pioneering research on low background techniques and underground experimentation that were the seed of the current Laboratorio Subterráneo de Canfranc (LSC). Nowadays, GIFNA is an associated unit to the LSC, and its members participate actively in several of the approved experiment at the LSC. In particular they are the leaders of WIMP dark matter experiments like ANAIS (section 3.2) or TREX-DM (section 3.3), and participate in the DarkSide-20k project to be hosted at Gran Sasso Laboratory, but with a ancillary setup DART at the LSC (section 3.4). They play a leading role in axion experiments like BabyIAXO (section 3.1) and RADES (section 3.6), the former to be hosted at DESY, but with detector prototyping activity at the LSC, and funded by a prestigious ERC-AdG grant. The relation with LSC make CAPA a *de facto* gateway to LSC for many external collaborators that seek the collaboration of CAPA members when implementing their projects at LSC. In this respect there are more specific contributions to other current (or future) neutrino projects like NEXT, Hyper-Kamiokande or LiquidO (section 3.5), mostly on radiopurity and low background expertise. The CAPA researchers are also active

in more transversal developments of novel detector concepts and low background know-how in general (e.g. section 3.7). The LABAC laboratory (section 3.8), applies the expertise on low radioactivity techniques to the environmental radioactivity monitoring, contributing to the public health of the population within the net of the Spanish Nuclear Regulatory Commission.

3.1 | Search for solar axions with the International Axion Observatory (IAXO)

Responsible investigator(s) / coordinator(s):	
Igor G. Irastorza	staff
Gloria Luzón	staff
Researchers involved:	
Theopisti Dafni	staff
Susana Cebrián	staff
Javier Redondo	staff
Javier Galán	postdoc
Konrad Altenmueller	postdoc
Juan A. García Pascual	postdoc (MC)
Jaime Ruz	postdoc (MZ)
Julia Vogel	postdoc (MZ)
Yikun Gu	postdoc
Cristina Margalejo	predoc
Oscar Pérez	predoc
Luis Obis	predoc
David Díez Ibáñez	predoc
Ana Quintana	predoc
Alvaro Ezquerro	predoc
Technical support:	
Alfonso Ortiz de Solórzano	engineer
Hector Mirallas	engineer
Juan Castel	engineer
Javier Mena	technician
Javier Galindo	engineer

The International Axion Observatory (IAXO) is the largest international collaboration in search for axions, with more than 125 scientists from more than 20 institutions. Axions are hypothetical particles appearing in extensions of the Standard Model (SM) of particle physics featuring the Peccei-Quinn (PQ) mechanism. This mechanism was postulated in the 1970s to solve the *strong CP problem*, a somewhat technical but fundamental problem of the SM, that regards why the *strong interactions do not seem to violate the time-reversal symmetry*, as the electroweak interaction does. In addition, axions are an excellent candidate to compose the Dark Matter (DM) of the Universe, and that is the reason why they are now among the most important goals of experimental searches of new physics beyond the SM. Axions (as well as their relatives, axion-like particles or ALPs) are sought in various ways [1], depending on the *origin* of these axions: cosmological, laboratory or astrophysical axions.

IAXO belongs to the latter category, as it follows the concept of an *axion helioscope*, whose main goal is to search for axions emitted from the Sun, although it could additionally host other setups targeting different sources of axions. A generic property of axions is that they couple with photons in a way that axion–photon conversion (and vice versa) can occur in the presence of strong magnetic or electric fields. This phenomenon is the basis of axion production in stars, as well as of most strategies for detecting axions. Magnets are therefore at the core of any axion experiment, as is the case for axion helioscopes. In these experiments, solar axions crossing the magnet may convert into x-rays that can be subsequently detected in devices placed at the end of the magnetic field region. This is the strategy followed by the CERN Axion Solar Telescope (CAST) that, using a decommissioned LHC magnet, has been the most powerful axion helioscope built so far. After almost two decades of operation, CAST has put the strongest limits yet on the axion–photon coupling across a range of axion masses [2] (see Fig. 3.3), surpassing previous astrophysical limits for the first time and probing relevant axion models of sub-electron-volt mass. IAXO was conceived as a new generation axion helioscope that builds on the CAST experience [3], and aims to provide a substantially improved sensitivity to go deep into unexplored axion parameter space [4].

The central component of IAXO is a purpose-built large-scale superconducting magnet similar to those used in large HEP detectors. It follows a toroidal configuration, and includes eight large "user" bores in which the solar axions can convert into x-rays. All of them are equipped with optics that concentrate the signal x-rays into small very sensitive low-background detectors. These x-ray optics are based on the reflection of x-rays by mirrors at grazing incident angle, technologies used in x-ray astronomy. The detectors will image the signal photons at the focal spot with very low level of background, achieved by means of techniques similar to that used in underground experiments: the use of radiopure detector components, passive and active shielding of environmental and cosmic radiation, and offline event discrimination techniques. The whole infrastructure is installed on a movable platform that allows tracking the Sun for about half the time. The baseline design of IAXO, shown in figure 3.1, is endowed with a sensitivity to solar axions of about 5 orders of magnitude better in signal-to-noise-ratio than CAST.

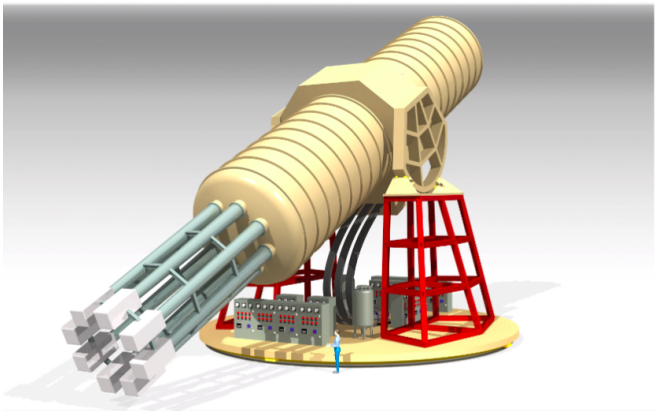

Figure 3.1: Sketch of the IAXO infrastructure as described in its conceptual design [3], showing the magnet and the eight detection lines including optics and detectors. The overall assembly is placed on a rotating platform to follow the Sun.

As a prior stage towards IAXO, the collaboration is planning the construction and operation of BabyIAXO, an intermediate scale version of IAXO. It is conceived to test all IAXO subsystems (magnet, optics and detectors) at a relevant scale for the final system and thus serve as a prototype for IAXO, but at the same time as a fully-fledged helioscope with relevant physics reach itself. The conceptual design of BabyIAXO [5] is shown in figure 3.2. The

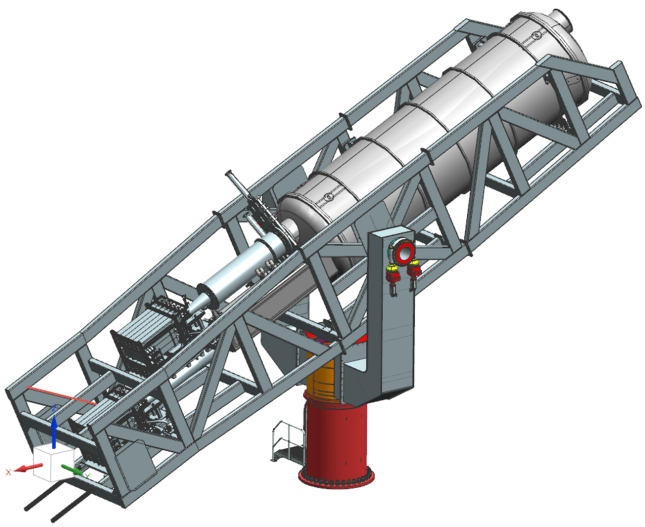

Figure 3.2: CAD design of the full BabyIAXO infrastructure, as described in its conceptual design [5], including the two-bore magnet, and the two detection lines, with x-ray telescopes and focal plane detectors, the latter surrounded by their shielding. All the assembly is placed on a support frame and positioner to keep the optical axis of the experiment pointing to the Sun. The overall system length is about 19 meters. The focal length is of 7.5 m for the line equipped with the XMM optics, and of 5 m for the custom-made optics.

BabyIAXO magnet will feature two 10 m long, 70 cm diameter bores, and will host two detection lines (optics and detector) of dimensions similar to the final ones foreseen for IAXO.

The project has been approved to be hosted by DESY, which offers an ideal environment to BabyIAXO as part of its emerging axion experimental program. The collaboration has been strengthened during the last years, and counts now 125 scientists, which make IAXO the largest collaboration in axion physics. In particular, the project relies on the superconducting magnet expertise from CERN. Indeed both the designs of the IAXO and BabyIAXO magnet have been carried out by CERN magnet experts, the latter with partial support form the CERN Physics Beyond Colliders (PBC) study group. Recently an agreement has been signed between DESY and CERN to frame such contribution, which will continue during the construction phase. One of the two x-ray optics to be used in BabyIAXO is a flight spare module of the XMM-Newton mission that has been kindly lent to the collaboration by the European Space Agency (ESA). The second one will be built by the collaboration, as a prototype for the future IAXO optics. It will be the first large-scale optics specifically designed and built for axion physics. The baseline detectors to be placed at the focal point of the optics are small time projection chambers read with Micromegas readout planes of microbulk type. These detectors have achieved record background levels after many years of development especially within the CAST experiment. However, a portfolio of additional x-ray detection technologies is being developed in the collaboration, especially in view of IAXO, including Ingrid detectors, Magnetic Metallic Calorimeters, Silicon Drift Detectors or Transition Edge Sensors. These technologies could provide improved performance (e.g. in terms of energy threshold and resolution) that could be particularly important e.g. in case of a positive detection, to extract additional information from the data, like the mass or other couplings of the axion.

BabyIAXO will detect or reject solar axions with axion-photon couplings down to $\sim 1.5 \times 10^{-11}$ GeV^{-1}, and masses up to $\sim$0.25 eV. BabyIAXO will offer additional opportunities for axion research in view of IAXO, like the tests of improved detectors such as the ones mentioned above, or the implementation of radiofrequency-cavity-based setups to search for dark matter axions (see section 3.6). The latter is being studied under the RADES project, already producing results in the CAST magnet, and also exploiting technological synergies with CERN expertise. Figure 3.3 shows the sensitivity prospects of both BabyIAXO and IAXO in their baseline configurations, within the current context of axion searches. BabyIAXO, and later on IAXO, will go well beyond current upper bounds on the axion-photon coupling from CAST and astrophysics, and venture deep into unexplored areas, in particular probing a large fraction of QCD axion models in the meV to eV mass band. This region encompasses the values invoked to solve the transparency anomaly, and the ones solving the stellar cooling anomalies, as well as

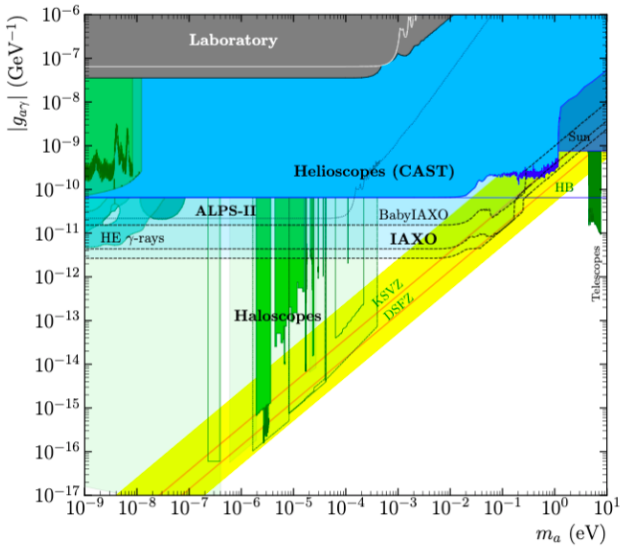

Figure 3.3: Sensitivity plot of IAXO and BabyIAXO in the primary axion-photon coupling versus axion mass parameter space, compared with the QCD axion (yellow) band and other current (solid) and future (dashed) experimental and observational limits

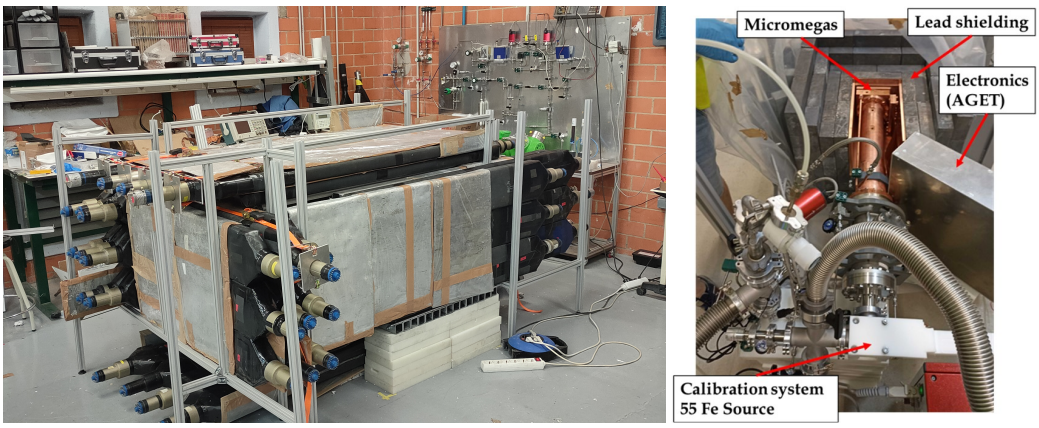

Figure 3.4: **Left:** Picture of the IAXO-D0 setup at CAPA, showing the outermost active shielding composed by three layer of plastic scintillators. **Right:** Picture of IAXO-D1 setup at the LSC with the lead shielding opened. The different components of the experimental setup are labeled.

a number of other possible hints. It also includes some of the axion models that can account to the totality of dark matter. Most of this region can only be reached realistically by using the helioscope technique, and therefore the BabyIAXO/IAXO program is unique in the wider landscape of experimental axion searches. In the case of a positive detection, (Baby)IAXO will permit high-precision measurements campaigns to determine axion parameters and getting further insight into the underlying axion models. In any case, IAXO is bound to play an important role in the future of axion and ALP research, with potential for a discovery, already at the BabyIAXO stage.

The CAPA group in IAXO plays a central role in the IAXO collaboration, as continuation of the long trajectory of research in the CAST experiment at CERN, that culminated with the IAXO pathfinder system that took data in CAST in the last data taking campaigns of the experiment. CAPA researcher and IAXO spokesperson Igor G. Irastorza is since 2019 recipient of a ERC-AdG to support the construction of BabyIAXO. The CAPA group leads the conception, design and construction of the low background Micromegas detectors for the two BabyIAXO focal points. In this respect, a first prototype called IAXO-D0, built on the successfull IAXO pathfinder of CAST, but with improved shielding, is already in operation at CAPA. Another prototype, IAXO-D1, already with form-factor fully compatible with the BabyIAXO geometry is was finalized in 2022 and is now also taking data underground at the LSC, with the goal to provide insight on the background components. CAPA members are also leading the software and radiopurity working groups of the collaboration.

3.1.1 | Achievements in 2022

In 2022 the collaboration has progressed substantially in preparing many of the experiment's subsystems for construction. However, a number of issues are threatening to delay the magnet construction timetable, most particularly the non-availability of aluminum-stabilized superconducting cable in industry. These are being studied in priority with experts from CERN and DESY. A modification of the construction schedule have been approved by the collaboration board in which all the experiment except the magnet will be built, commission and operated first, in order to better use the time while the magnet is being built, debug all systems in advance, and take data in search for dark photons. A more detailed schedule of this and the revised magnet construction is being determined now. An important milestone

for the collaboration will be a external review of the magnet design to be schedule for the fall of 2023. Other important achievements for 2022, particularly those involving work at CAPA, are the following.

1. The IAXO-D0 prototype at the CAPA IAXOlab has produced the first relevant measurement of the background with enhanced active shielding. It consist of three layers of 5-cm thick plastic scintillators read by photomultipliers, intercalated with cadmium sheets (as seen in Fig. 3.4, left). The data points to background at the $7-8\times10^{-7}$ nfu[1], the lowest level ever achieved with a detector at surface, although still above the BabyIAXO target of 10^{-7} nfu. This may be due to insufficient tagging efficiency of the veto system or to new unidentified background sources, e.g. related to Rn progeny. This issue is being actively investigated at present.

2. In 2022, the construction of IAXO-D1, the first prototype Micromegas detector for BabyIAXO, was concluded and installed underground in the Lab2500 of LSC (as seen in Fig. 3.4, right). First preliminary data points to background levels similar to those of IAXO-D0 at IAXOlab, but the data-taking campaign is still ongoing. IAXO-D1 is the first prototype fully compatible with the geometrical constraints of the final BabyIAXO environment. Its data will be precious, compared to that of IAXO-D0, to understand the effects of cosmics in the background of the detector, and to understand the intrinsic background limits of the detector.

3. The determination of the final sensitivity in BabyIAXO and future IAXO data taking programs requires an accurate calculation of the axion signal starting from the generation of the solar axion flux to the integration of the different helioscope components. This determination requires of MonteCarlo ray-tracing techniques in order to include the non-homogeneous magnetic field found in the axion-photon conversion volume combined with the x-rays optics system of the experiment. A ray tracer has been integrated in REST-for-Physics [6] allowing to produce an accurate final signal pattern and probability density function (PDF) expected in our detector. The combination with other helioscope components already integrated in the ray-tracer, such as windows transmission or detector response, will allow to build a final sensitivity plot of the experiment with statistical methods currently under construction in REST-for-Physics.

4. The CAPA team led and guided the optics development for the BabyIAXO optics in 2022. Significant advances have been made to recommission a flightspare telescope of ESA's XMM-Newton mission and CAPA members have been involved in planning the recalibration campaign for this optic. Good progress has also been made with further development of the custom BabyIAXO optics in collaboration with INAF Brera, Columbia University and DTU Space and, in collaboration with the University of Bonn, the optics have also been included in the CAPA-led REST software framework.

5. CAPA researches have been particularly active in the dissemination of results related to axion searches with IAXO in 2022, with the publication of a topical short review of IAXO in the Universe journal [7], as well as the publication of introductory Lecture Notes on axions [8] derived from the participation of Igor G. Irastorza as lecturer in the Les Houches dark matter school the year before. Moreover, CAPA researchers have participated in the work to define the potential sensitivity of IAXO to the axion-nucleon coupling, via the detection of 14.4 keV axions from the transition of ^{57}Fe nuclei in the Sun, that has been published in 2022 [9].

[1] nfu $\equiv$ normalized flux unit $\equiv$ c/keV/cm^2/s

3.1.2 | References

1. Irastorza, I. G. & Redondo, J. New experimental approaches in the search for axion-like particles. arXiv: 1801.08127 [hep-ph] (2018).
2. Anastassopoulos, V. *et al.* New CAST Limit on the Axion-Photon Interaction. *Nature Phys.* **13,** 584–590. arXiv: 1705.02290 [hep-ex] (2017).
3. Armengaud, E., Avignone, F., Betz, M., Brax, P., Brun, P., *et al.* Conceptual Design of the International Axion Observatory (IAXO). *JINST* **9,** T05002. arXiv: 1401.3233 [physics.ins-det] (2014).
4. Armengaud, E. *et al.* Physics potential of the International Axion Observatory (IAXO). *JCAP* **06,** 047. arXiv: 1904.09155 [hep-ph] (2019).
5. Abeln, A. *et al.* Conceptual design of BabyIAXO, the intermediate stage towards the International Axion Observatory. *JHEP* **05,** 137. arXiv: 2010.12076 [physics.ins-det] (2021).
6. Altenmüller, K. *et al.* REST-for-Physics, a ROOT-based framework for event oriented data analysis and combined Monte Carlo response. *Comput. Phys. Commun.* **273,** 108281. arXiv: 2109.05863 [physics.comp-ph] (2022).
7. Dafni, T. & Galán, J. Digging into Axion Physics with (Baby)IAXO. *Universe* **8,** 37. arXiv: 2112.02286 [astro-ph.IM] (2022).
8. Irastorza, I. G. An introduction to axions and their detection. *SciPost Phys. Lect. Notes* **45,** 1. arXiv: 2109.07376 [hep-ph] (2022).
9. Di Luzio, L. *et al.* Probing the axion–nucleon coupling with the next generation of axion helioscopes. *Eur. Phys. J. C* **82,** 120. arXiv: 2111.06407 [hep-ph] (2022).

3.2 | ANAIS Experiment

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Sodium Iodide Thallium doped (NaI(Tl)) scintillation detectors are a convenient choice for detecting radiation in many applications. In particular, they have been applied to the direct searches for dark matter since the 1990s and have produced one of the most challenging results in the field—the observation by DAMA/LIBRA collaboration of an annual modulation in the detection rate for more than twenty years.

After more than three decades of DM direct searches, most of the experimental results are compatible with the estimated backgrounds.

At present, there are a few event excesses pointing at the necessity of further understanding of the backgrounds at or below 1 keVee. However, one anomalous results survives in the field: the DAMA/LIBRA result, the observation of an annual modulation in the detection rate that cannot be explained by any known background, and that shares all the expected features with a dark matter signal.

The annual modulation effect in the DM interaction rate is the consequence of the orbital motion of the Earth around the Sun along the year. The corresponding variation in the relative velocity of the DM particles with respect to the target nuclei induces a modulation with a one-year period and a maximum at about the 2nd of June in the DM interaction rate, for the standard halo model. Backgrounds able to fake this signal have been proposed and discarded by the DAMA/LIBRA collaboration. However, the DAMA/LIBRA

result is very difficult to reconcile with the negative results derived from other experiments using a large variety of target materials and detection techniques. It is important to solve this experimental puzzle, which could be the door into new physics, and in order to do so a model independent test needs to be faced. Although the DAMA/LIBRA result is incompatible with the rest of the experiments searching for DM in most of the analyzed scenarios, it should be stressed that this comparison is model dependent and the DM nature is still fully unknown. Recent reviews of the present experimental situation of the direct dark matter detection searches and the testing of the DAMA/LIBRA puzzle can be found in Refs. [1-3].

A model-independent test of DAMA/LIBRA result requires an experiment using the same target material, a similar (or better) background and threshold energy to those of DAMA/LIBRA in the region of interest (ROI), large exposure (product of mass and measurement time) and stability, in order to analyze the annual modulation effect. This is the goal of the ANAIS-112 experiment, in data taking phase at the Canfranc Underground Laboratory, in Spain, since August 2017. The ANAIS-112 design and operation leans on the expertise acquired at the University of Zaragoza using NaI(Tl) scintillation detectors for about thirty years [4].

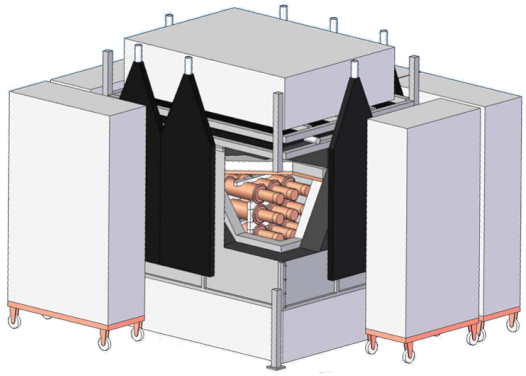

Figure 3.5: ANAIS-112 set-up at the Canfranc Underground Laboratory.

The ANAIS-112 experiment consists of 112.5 kg of NaI(Tl) , distributed in 9 modules, 12.5 kg each and built by Alpha Spectra Inc., arranged in a 3 x 3 configuration (see Figure 3.5). Among the most relevant features of ANAIS-112 modules we can mention a remarkable optical quality, which combined to using high quantum efficiency Hamamatsu photomultipliers (PMTs) results in a very high light collection, at the level of 15 photoelectrons (phe) per keV. That is by far larger and more homogeneous than that achieved by DAMA/LIBRA modules in the improved phase2 of the experiment. Another interesting feature is a Mylar window in the middle of one of the lateral faces of the detectors, which allows to calibrate the modules with external sources of energies just few keV above the ROI for testing the DAMA/LIBRA result ([1–6] keV). The ANAIS-112 experiment is installed inside a shielding consisting of an inner layer of 10 cm of archaeological lead and an outer layer of 20 cm of low activity lead. This lead shielding is encased into an anti-radon box, tightly closed and kept under overpressure with radon-free nitrogen gas. The external layer of the shielding (the neutron shielding) consists of 40 cm of a combination of water tanks and polyethylene bricks. An active veto made up of 16 plastic scintillators is placed between the anti-radon box and the neutron shielding, covering the top and sides of the set-up (see Figure 3.5) allowing to effectively tag the residual muon flux.

The signals from the two PMTs coupled to each module are digitized at 2 GS/s with high resolution. The trigger requires the coincidence of the two PMT trigger signals in a 200 ns window, while the PMT individual trigger is set at the single photo-electron level. The stability of the experiment is guaranteed by calibrating with ^{109}Cd sources every two weeks. This allows the correction of the small gain drifts. The energy calibration is performed with the ^{109}Cd lines plus the energy depositions at very low energy (3.2 and 0.87 keV) associated with the decay of ^{40}K and ^{22}Na crystal contaminations, respectively, that can be tagged by coincidences with high energy gammas in a different

module. This procedure allows to perform a reliable energy calibration of the ANAIS-112 data down to 1 keV, while the identification of the events from ^{22}Na allows to confirm the highly efficient triggering below 1 keV. The residuals of the energy associated to the ^{40}K and ^{22}Na peaks with respect to their nominal energy, gathering data every 90 days, are 0.01 keV at the 3.2 keV line and 0.04 keV at the 0.87 keV line.

The background in the ROI is dominated by non-bulk scintillation events, so strong filtering protocols based on the pulse shape and light sharing among the two PMTs have been developed. The efficiency of the event selection criteria is calculated with scintillation populations (^{109}Cd, ^{40}K, ^{22}Na) and is very close to 100% down to 2 keV, but then decreases steeply to about 15% at 1 keV, where we set the analysis threshold. A careful background model of the ANAIS-112 experiment has been developed over the years, by combining inputs from different analysis techniques: HPGe screening of different materials used in the set-up and in the detector building, measurements in coincidence of the modules before ANAIS-112 commissioning, determination of alpha rate by using PSD, estimates of cosmogenic activation rates in NaI, and so forth.

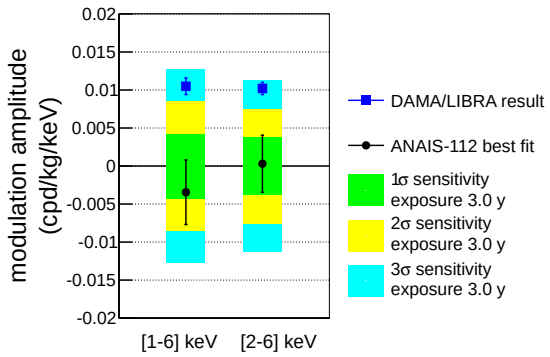

Figure 3.6: Comparison between ANAIS-112 results on annual modulation using three years of data and DAMA/LIBRA modulation best fit [5]. Estimated sensitivity is shown at different confidence levels as colored bands: green at 1σ, yellow at 2σ, and cyan at 3σ.

A full description of the experiment's performance after the first year, a detailed background model and the analysis of the corresponding sensitivity to the DAMA/LIBRA signal were published in 2019 and shortly after, preliminary annual modulation analysis corresponding to 1.5 years of data were released. These first results were fully compatible with the absence of modulation and in slight tension (2σ level) with the positive result of DAMA/LIBRA. In 2021, results of the data analysis searching for annual modulation in three-year exposure were published in Physical Review D [5]. They were highlighted as "Editors' suggestion" and the magazine "Physics" published a Synopsis of the paper. ANAIS-112 results are leading the worldwide efforts to test DAMA/LIBRA result. The published result (see figure 3.6) is compatible with the absence of modulation and incompatible with DAMA/LIBRA at 3.3 (2.6) σ C.L. in the two energy regions analysed, [1-6] keV and [2-6] keV, for a sensitivity of 2.5 (2.7) σ. This result fully confirmed the sensitivity projections.

The ANAIS-112 experiment was scheduled to operate for five years at the Canfranc Underground Laboratory, with the goal of reaching a sensitivity at 3σ level of the DAMA/LIBRA result. At present, and because no other experiment with larger sensitivity is in operation, the experiment operation has been granted until 2025, in order to approach 5σ sensitivity to DAMA/LIBRA result (See Fig. 3.7).

The operation of the experiment at the Canfranc Underground Laboratory is progressing smoothly and more than 95% of the total time is live time. Strong efforts to improve the analysis procedure in the last year have resulted in the development of a new machine-learning filtering for bulk scintillation events [6], which allowed to improve the ANAIS-112 sensitivity. Moreover, the consistency of the annual modulation analysis results has been significantly enhanced by further improvements in the data analysis. This analysis will be used along 2023 for a reanalysis of the three-year exposure and the unblinding of the five-year data. In parallel, work in R&D using SiPMs for the optical readout of NaI crystals cooled down to 100K is in progress. This project will be referred to as ANAIS+, being a

follow-up of the ANAIS-112 experiment.

3.2.1 | Achievements in 2022

1. Data taking progresses smoothly with same quality parameters as in previous years, accumulating more than five years of data.

2. In 2021 a new program of calibration of the experiment using neutrons produced by a ^{252}Cf source started. This program has been also ongoing in 2022. These calibrations are being very useful to provide a population of nuclear recoils in the NaI crystals at very low energy very similar to those DM particles should produce in the detectors and then, they are helping to improve our knowledge on the response function of the ANAIS-112 detectors.

3. Along 2022, we developed a specific machine learning based protocol for the filtering of non-bulk scintillation events. This protocol was based on the results obtained in the PhD dissertation from Iván Coarasa, but incorporated new features, as training the decision tree with neutron populations in the very low energy range, from 1 to 2 keV. A clear sensitivity improvement was achieved by using this new filtering with respect to the previous ANAIS-112 selection cuts (see Figure 3.7). This result was published in Ref. 6 and points at a 3σ sensitivity to DAMA/LIBRA result with tree-year exposure. A reanalysis of the data has already started and it will be released in 2023.

4. We have started to publish in open access ANAIS data. In collaboration with the Dark Matter Data Center, funded by the ORIGINS Excellence Cluster: https://www.origins-cluster.de/odsl/dark-matter-data-center. ANAIS data can be found at: https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais. At this moment, only data corresponding to the analysis of three years (published in Ref. 4) is available, but we plan to incorporate every data release in the future.

5. We started working on designing and getting funds for a cryogenic facility at the University of Zaragoza to test at about 100 K NaI crystals coupled to SiPM to evaluate the feasibility of a DM search, the ANAIS+ project. It will consist of a dedicated cryostat, a convenient test bench for the mounting of different size crystals and testing with SiPMs from different providers. In the longer term, underground testing could be of interest, because a good-performing prototype of only 1 kg has a competitive sensitivity for low mass Spin-Dependent interacting dark matter candidates if a threshold of 0.1 keVee is reached. Sensitivity projections for two different background level scenarios: 1 (0.1) counts/keV/kg/day are shown in Figure 3.8.

6. The PhD student, David Cintas, carried out a research stage at the LNGS under the supervision of Dr. Alessandro Razeto from March to June 2022. This stage allowed to test both, NaI and NaI(Tl) crystals at liquid argon temperature with the light readout done by SiPMs developed in the group from Dr. Razeto, specifically for measuring the scintillation of liquid argon. The results of these measurements allowed to conclude that NaI crystals are a much better option than NaI(Tl), as expected, to be used as targets in ANAIS+. Moreover, feasibility of the cooling down and recovery of the crystals without damage was demonstrated. This stage was the first step, starting a collaboration path with the LNGS (via Dr. A. Razeto) for the building of specifically designed SiPMs (integrating first steps of the readout front-end electronics) with outstanding performance

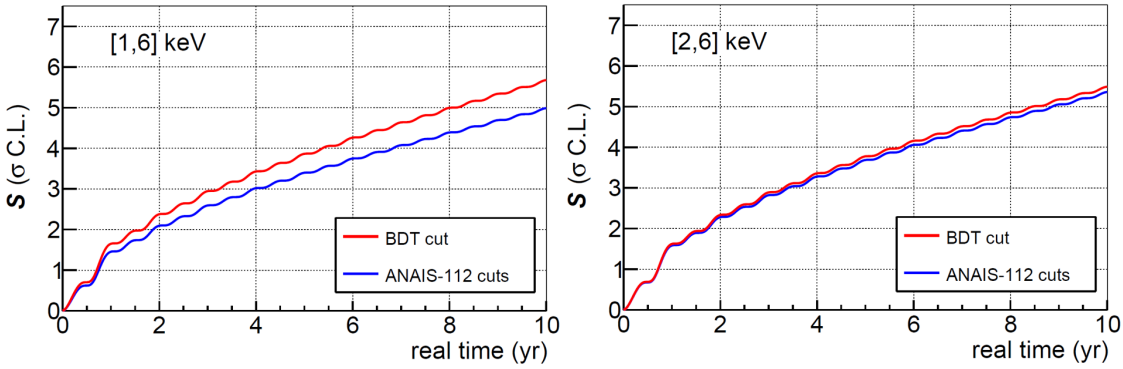

Figure 3.7: Sensitivity projections of ANAIS-112 experiment on the DAMA/LIBRA annual modulation signal after including the new filtering procedure (BDT cut) in the two energy regions, [1-6] and [2-6] keV [5].

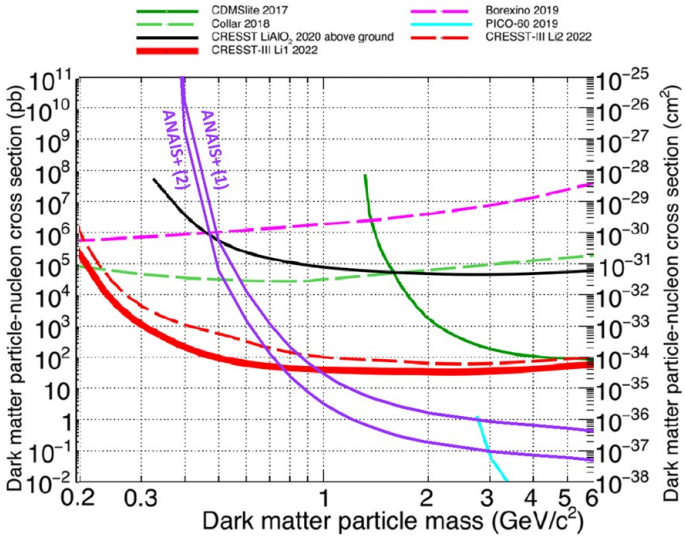

Figure 3.8: Sensitivity projections of ANAIS+ experiment for light WIMPs with Spin-Dependent coupling to nucleons for 1 kg of NaI crystal with a reduced energy threshold of 0.1 keV and 1 year of measurement for backgrounds of 1 counts/keV/kg/day [ANAIS+(1)] and 0.1 counts/keV/kg/day [ANAIS+(2)].

at low temperature. This collaboration is under development, and it could incorporate more international collaborators.

3.2.2 | References

[1] J. Billard et al., Direct detection of dark matter—APPEC committee report*, Rept. Prog. Phys. 85 (2022) 056201

[2] J. Cooley et al., Report of the Topical Group on Particle Dark Matter for Snowmass 2021, FERMILAB-PUB-22-718-PPD, arXiv: 2209.07426

[3] R.K. Leane et al., Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them, FERMILAB-CONF-22-191-PPD-T, arXiv: 2203.06859

[4] J. Amaré et al., Dark Matter Searches Using NaI(Tl) at the Canfranc Underground Laboratory: Past, Present and Future, Universe 8 (2022) 2, 75. https://doi.org/10.3390/universe8020075

[5] J. Amaré et al., Annual modulation results from three-year exposure of ANAIS-112, Phys. Rev. D 103 (2021) 10, 102005. https://doi.org/10.1103/PhysRevD.103.102005

[6] I. Coarasa et al., Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques, JCAP 11 (2022) 048. https://doi.org/10.1088/1475-7516/2022/11/048

3.3 | Search for low-mass WIMPs with the TREX-DM experiment

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The composition of the Dark Matter that dominates the Universe is currently a mystery, the resolution of which is one of the most important challenges in current cosmology and particle physics. One of the most attractive hypotheses to solve it is that Dark Matter is composed of massive particles of weak interaction, or WIMPs. Both the Large Hadron Collider at CERN, as well as a multitude of experiments in laboratories around the world are trying to detect these particles, and thus achieve what would be a revolutionary discovery, to date without success. The TREX-DM experiment at the Canfranc Underground Laboratory, led by CAPA researchers, targets the detection of WIMPs with particularly low masses (below $\sim$ 10 GeV), which would have gone unnoticed in mainstream WIMPs experiments. For this purpose, it follows a novel technology, based on temporal projection chambers (TPC) with gases composed by low-atomic-number species (e.g. neon plus isobutane) at high pressure [1], which promises operation with an energy threshold and background noise lower than that obtained by other detectors to date [2]. If these projections are confirmed, TREX-DM could enjoy highly competitive sensitivity to low-mass WIMPs, even with discovery potential.

The core of the TREX-DM TPC are the readout planes, based on novel Micromegas readouts of a particular type, known as *microbulk*, developed mostly at CAPA within the T-REX project [3, 4], and ERC-StG grant carried out from 2009 to 2015. Moreover, many of the technical advantages exploited in the development of the detectors for axion research (see section 3.1) are of direct application also in this case; namely, the possibility to build Micromegas readouts with very radiopure materials and with a signal extraction scheme of extreme radiopurity or the capability to use topological discrimination techniques based on the highly granular readout. In addition, the way event detection happens in gas (i.e. drift of charge and signal amplification confined in the Micromegas structure) allows, in principle, to reach very low energy threshold even in relatively large size detectors [5]. Another aspect, very important for application to WIMP searches, are the scaling-up prospects. Technical solutions for scaling-up via tessellation of identical microbulk detectors have been defined.

The TREX-DM TPC has been designed to host 0.3 kg of argon mass at 10 bar (or, alternatively, 0.16 kg of neon). It is composed of a cylindrical vessel made of radiopure copper, with an inner diameter of 0.5 m, a length of 0.5 m

and a wall thickness of 6 cm. These dimensions are set by the requirements that the vessel holds up to 10 bar of pressure, while at the same time constitutes the innermost part of the shielding. The vessel is divided into two active volumes by a central mylar cathode, which is connected to high voltage by a tailor-made feedthrough. At each side there is a 19 cm long field cage defined by a series of copper strips imprinted on a kapton substrate supported by four teflon walls.

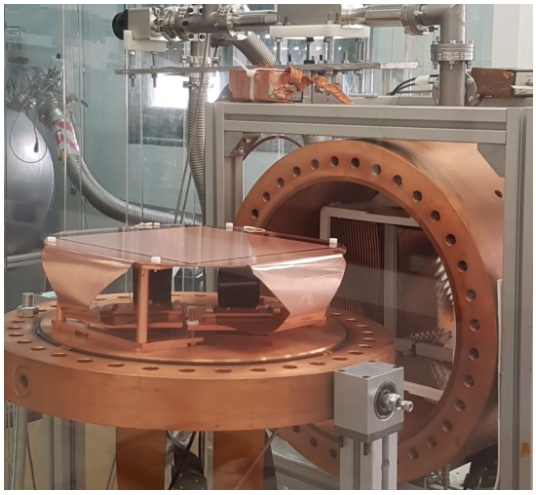

Figure 3.9: Picture of the TREX-DM detector with one of the endcaps open, showing the microbulk Micromegas readout plane, the largest ever built in this technology, and the flaps carrying out the signals via radiopure feedthroughs out of the vessel.

The installation of the TREX-DM detector at LSC was completed in 2018 (with the exception of the external neutron shielding) and the experiment went though its commissioning and first engineering runs in 2019. By then a full simulation-based background model of the experiment was finished and published. In 2020, the experiment started its first physics runs with Ne + Isobutane at a nominal pressure of 4 bar. The first data revealed an unanticipated background population at low energy, coming both from radon emanated into the detector gas, and decaying in the active volume, as well as from Rn progeny contamination of the inner surfaces of the detector. The 2021 runs wer focused into the study and mitigation of these populations. In 2022, the detector underwent a major upgrade with the replacement of both Micromegas readout planes and part of the associated mechanics, with several improvements implemented, in particular a new type of home-made radiopure contact connector. In october 2022, after a few weeks of operation with the upgraded detector, the experiment had to be dismantled from hall A as per request of LSC management, due to the assignment of a new site for the experiment in a different hall (Lab2500). Due to the unpreparedness of the new site, the recommissioning of the experiment is not expected before summer 2023.

3.3.1 | Achievements in 2022

As mentioned, in 2022 a major upgrade of the TREX-DM detector took place. Both readout planes of the TPC were replaced by new ones implementing several technical improvements, most relevantly a new system of signal connections, developed in the group, based on solder-less fact-to-face contact between two radiopure kapton-based footprints. The new readouts, fabricated at the Rui de Oliveira's PCB workshop at CERN, had been thoroughtly tested at the CAPA premises at IAXOlab, before installation. The replacement and recommissioning of the experiment took place in spring-summer 2022.

1. A new operation mode of the experiment, *semi-sealed* mode, was successfully implemented to mitigate the presence of Rn in the detector gas, which was a major background component identified in the 2021 campaign. It consists in working in open loop (i.e. new gas is continuously injected to the detector, and old gas go out through the exhaust) but with very low gas flow. Thanks to the very good leak-tightness and outgassing properties of the TREX-DM gas circuit and vessel, a flow <1 ln/h is sufficient, allowing for a reasonable gas

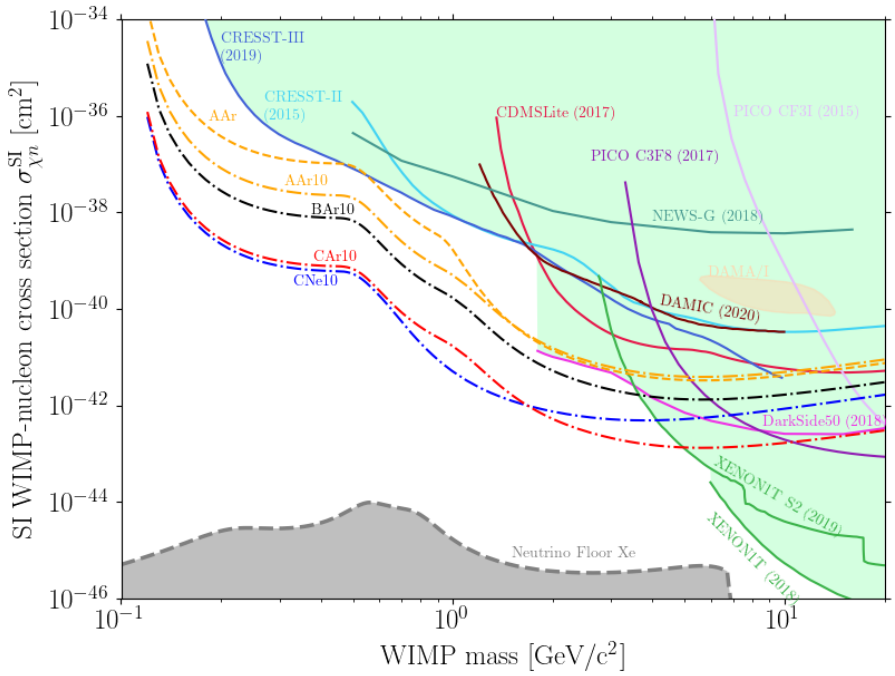

Figure 3.10: TREX-DM projected sensitivity in the WIMP-nucleon cross-section versus WIMP mass parameter space. Different TREX-DM scenarios, together with current bounds from leading light-WIMP DM experiments are shown. Scenario A represents nominal TREX-DM background and an improved threshold that can be reached with on-going developments, while AAr10 assume an enriched Hydrogen gas mixture. Scenario BAr10 assumes an improved background. Scenarios CAr10 and CNe10, assume a ten-fold improvement in background and exposure, that would require a larger sensitive volume.

consumption. In this mode the identified Rn emanators in the system are effectively bypassed, and the Rn concentrations in the gas dropped to negligible levels. As a result, a background improvement of one order of magnitude has been obtained, achieving a low-energy level of O(80) dru[2] This level is the best obtained so far by the experiment, but still an order of magnitude above the target suggested by our background model. Especial low-gain runs to study alpha contamination seem to point out to a contamination of the Rn progeny (basically Pb210 in the inner surfaces) as accounting for the remaining background. The run in september-october 2022 with the upgraded readouts confirmed this situation, and in addition suggested that most of such contamination is in the cathode of the TPC (made of aluminized mylar foil). Alternative materials and designs for the cathode are now being investigated, its replacement being a priority in a forthcoming intervention.

2. A first prototype of the AlphaCAMM detector was built and sucessfully operated as proof-of-concept, result that was published last year in JINST [6]. AlphaCAMM is a high-sensitivity alpha surface detector (see section 8.3) conceived to accurately screen ^{210}Po surface contamination, especially motivated by TREX-DM needs. The detection concept of AlphaCAMM replicates that of TREX-DM high energy runs. It is a Micromegas-read TPC with a cathode that is transparent to alphas. The sample to be measured is placed on top of the cathode,

[2] dru ≡ daily rate unit ≡ counts/keV/kg/day.

and the alphas emitted are detected and imaged by the Micromegas. After the result in [6], a more carefully designed, radiopure, version of AlphaCAMM has been built, and is currently under commissioning at the CAPA premises.

3. Echoing the R&D results described in 3.7, a preamplification GEM stage was successfully mounted onto a 25x25 cm^2 microbulk detector with the same design as the ones currently installed in TREX-DM. Tests at 1 bar using an Ar-1%isobutane mixture showed an extra amplification factor of the order of 100. This is a very important achievement, and reveals a very clear path towards lowering the energy threshold of the experiment. Plans are already underway to implement this upgrade in TREX-DM by the end of 2023-beginning of 2024 (as soon as the clean room to open the detector chamber is ready at Lab2500 of LSC).

4. Due to the current difficulty in acquiring Ne gas, the preferred gas mixtures in the detection volume are Ar based mixtures. In this context, the key point for the improvement of the sensitivity at low WIMP masses is the use of a mixture enriched with Hydrogen. Therefore, the baseline for TREX-DM is the use of an Ar mixture with 10% of Isobutane quencher. Taking these considerations, different TREX-DM sensitivity scenarios have been projected and are shown in Figure 3.10. Scenario A represents the sensitivity projection assuming a threshold (Eth = 50 eVee) as would be expected once the GEM preamplification is implemented in TREX-DM, a nominal background of 10 dru and 1 year of exposure. Scenario B assumes an improved background (b = 1dru) and the expected improved threshold (Eth = 50 eVee). To illustrate the effect of potential future experiment improvements, scenarios CAr10 and CNe10 are included, which represent a ten-fold improvement in background level beyond current nominal, as well as in exposure. However, this scenario would require a new detector design with a larger sensitive volume.

3.3.2 | References

1. Iguaz, F. J. *et al.* TREX-DM: a low-background Micromegas-based TPC for low-mass WIMP detection. *Eur. Phys. J.* **C76,** 529. arXiv: 1512.01455 [physics.ins-det] (2016).
2. Castel, J. *et al.* Background assessment for the TREX Dark Matter experiment. *Eur. Phys. J. C* **79,** 782. arXiv: 1812.04519 [astro-ph.IM] (2019).
3. Irastorza, I. G. *et al.* Gaseous time projection chambers for rare event detection: Results from the T-REX project. I. Double beta decay. *JCAP* **1601,** 033. arXiv: 1512.07926 [physics.ins-det] (2016).
4. Irastorza, I. G. *et al.* Gaseous time projection chambers for rare event detection: Results from the T-REX project. II. Dark matter. *JCAP* **1601.** [Erratum: JCAP1605,no.05,E01(2016)], 034. arXiv: 1512.06294 [physics.ins-det] (2016).
5. Iguaz, F. J. *et al.* Microbulk Micromegas in non-flammable mixtures of argon and neon at high pressure. *JINST* **17,** P07032. arXiv: 2204.08199 [physics.ins-det] (2022).
6. Altenmüller, K. *et al.* AlphaCAMM, a Micromegas-based camera for high-sensitivity screening of alpha surface contamination. *JINST* **17,** P08035. arXiv: 2201.01859 [physics.ins-det] (2022).

3.4 | The DarkSide-20k project

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Researchers involved:	
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David Cintas González	predoc
Technical support:	
Alfonso Ortiz de Solórzano Aurusa	engineer

The DarkSide-20k project is intended to directly detect galactic dark matter particles using a two-phase liquid argon (LAr) TPC (see Fig. 3.11) filled with 20.2 tonnes (fiducial mass) of Underground Argon (UAr) depleted in ^{39}Ar at the Laboratori Nazionali del Gran Sasso (LNGS). Liquid argon offers important advantages for radiation detection, like a high scintillation yield and easy purification for non-noble contaminants; in addition, very efficient discrimination between electron recoils (ER) and nuclear recoils (NR) typically expected from WIMPs can be implemented based on Pulse Shape Discrimination techniques and on the measurement of both the primary scintillation and the electroluminescence from electrons multiplied in a gaseous region above the liquid. DarkSide-20k is the successor of the successful DarkSide-50 experiment and the first project of the Global Argon Dark Matter Collaboration (GADMC) collecting all the community working on dark matter searches using liquid argon. Data taking is expected to start from 2026; the goal of DarkSide-20k is to explore regions of WIMPs down to the level where coherent scatters from atmospheric neutrinos becomes a limiting background.

One of the goals of GADMC is the procurement of large amounts of low-radioactivity UAr as detector target. The content of ^{39}Ar in atmospheric argon, at a level of 1 Bq/kg, is unacceptable; DarkSide-50 produced the first WIMP search results using UAr with a reduced content of ^{39}Ar by a factor 1400$\pm$200. The Urania plant, in Colorado (US), is being built to extract UAr from the same underground source. The Aria facility, in Sardinia (Italy), will chemically purify the UAr and could allow an additional 10-fold suppression of ^{39}Ar per pass based on cryogenic distillation.

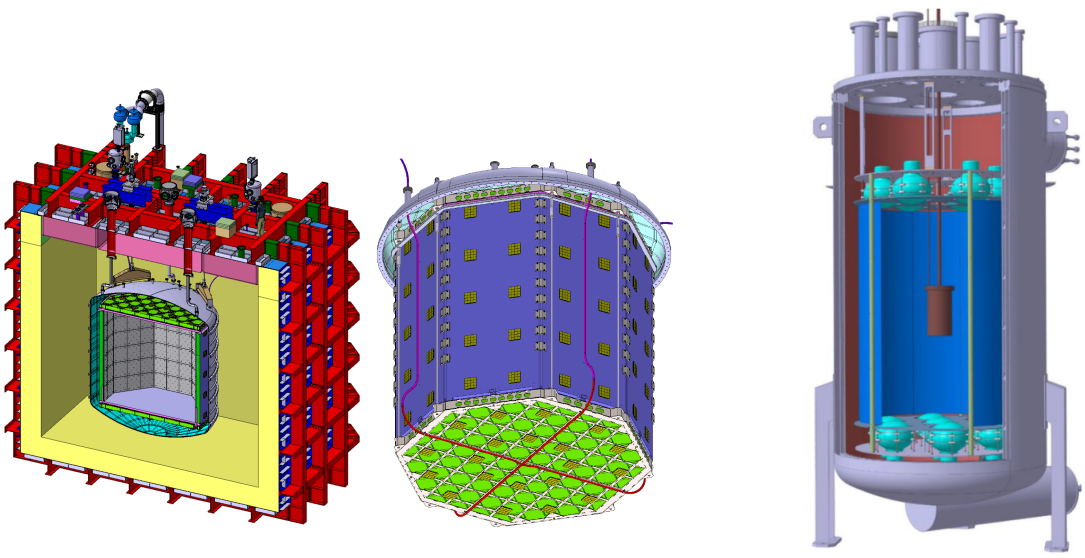

Figure 3.11: Left: cross section showing the detector system of the DarkSide-20k experiment to be installed in the Hall C of LNGS, with the TPC walls made of Gd-acrylic in green and the vessel in gray. Rigth: artistic view of the DArT chamber inside the LAr tank of the ArDM experiment at LSC.

The assessment of the ultra-low levels expected of ^{39}Ar is the goal of the DArT in ArDM experiment, in the Canfranc Underground Laboratory. The interest in obtaining radiopure Argon goes beyond GADMC (see the Letter of Intent signed by GADMC, COHERENT, DUNE, and LEGEND experiments, https://arxiv.org/abs/2203.09734).

DArT in ArDM consists on a small radiopure chamber with capacity for $\sim$1 liter of UAr (DArT) placed at the centre of the 1 ton LAr tank of the Argon Dark Matter (ArDM) detector, that was in operation at the LSC and recently decommissioned and that will act as active veto (see Fig.3.11). The scope of DArT is to measure ^{39}Ar depletion factors of the order of 1000 with a precision better than 10% in one week of running. The ^{39}Ar isotope decays via β emission with an end-point of 565 keV. The absence of other γ or X-ray emission makes this measurement very challenging and requires a powerful veto system, whose role will be played by the ArDM detector. The scintillation light of the DArT chamber is read by two 1 cm^2 SiPM of the same manufacturer as DarkSide-20K, while the veto readout is performed with 13 photomultipliers (PMTs) installed in the top and bottom flanges of the ArDM tank. While preparing the assembly of the final detector (DArTinArDM), tests are being carried out with a DArT detector in a test cryostat (DArTinTestCryo) installed in the hall A of LSC in order to tune some detectors parameters and characterize the radioactive background. CAPA is responsible for the data acquisition system for DArT and the veto (ArDM) and the design and construction of the provisional shielding underground and participates in the SiPM characterization. Operation of DArTinTestCryo is foreseen during all the year 2023, including a measurement of ^{39}Ar activity in the UAr used in the DarkSide-50 experiment, while commissioning of DArTinArDM is expected at the end of 2023.

DarkSide-20k is being designed to operate with all sources of instrumental background reduced to $<$0.1 events over a 200 tonnes$\cdot$year exposure, thanks to the powerful ER background discrimination and the neutron veto capabilities. This imposes the consideration and study of all possible background sources, including a very thorough control of the radioactivity in all the components of the set-up to minimize the effect of direct emissions as well as of the neutrons induced by (α,n) reactions. This effort for the selection of proper materials involves different laboratories all over the world applying a combination of different sensitive techniques for radioassays, like HPGe gamma spectroscopy, Inductively Coupled Plasma Mass Spectrometry (ICPMS) and alpha spectroscopy combined with chemical separation techniques. The University of Zaragoza is collaborating in the quantification of the cosmogenic activation of materials produced due to the exposure to cosmic rays above ground as well as in the radioassays performed in the Canfranc Underground Laboratory.

3.4.1 | Achievements in 2022

1. The DArT chamber installed at the LSC inside a test cryostat (DArTinTestCryo), with a lead shielding and including an anti-Rn system (plastic box) and a mechanism to calibrate the detector with different γ sources (see Fig. 3.12) has been operated along 2022 under different conditions to understand the detector response and background.

2. The cosmogenic activity of relevant long-lived radioisotopes induced in the argon and other massive components made of copper and stainless steel and the corresponding background rates have been estimated considering the expected exposure above ground and measured or calculated production rates. This allows to fix limitations

on the surface residency time of materials and requirements for storage and transportation during the detector building or operation. Production of ^{39}Ar in the UAr has been checked to be tolerable in the foreseen conditions for extraction, purification and transport on surface of the required argon. An article has been prepared and submitted to publication https://arxiv.org/abs/2301.12970.

3. Several samples of materials related mainly to the Gd-loaded acrylic for the TPC walls (acrylic, Gadolinium Oxide from different suppliers, surfactant IGEPAL) and the electronics (soldering paste) have been screened using germanium detectors at the Canfranc Underground Laboratory during 2022.

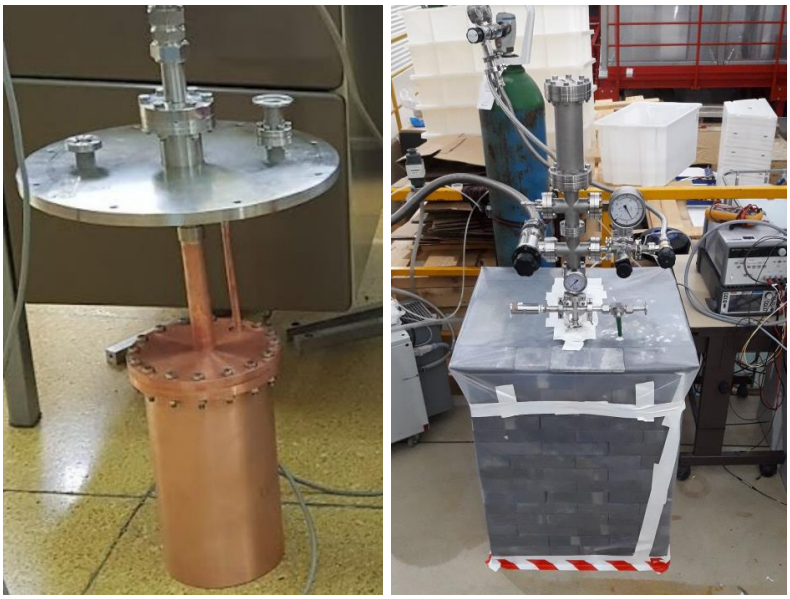

Figure 3.12: Left: copper OFHC vessel of the DArT chamber. Right: provisional lead shielding and cryogenic system for the experimental characterization underground.

3.5 | Radiopurity support to other projects

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The control of the radiopurity of materials and components used in detectors and the whole experimental set-up is a must for rare event experiments demanding ultra low background conditions, like those devoted to the direct detection of dark matter, the search for neutrinoless double beta decay or the study of neutrinos and axions. Extensive radioassay programs are defined based on HPGe gamma spectroscopy performed underground and other techniques like Inductively Coupled Plasma Mass Spectrometry (ICPMS) or Glow Discharge Mass Spectrometry (GDMS). Results from activity measurements are useful for the selection of materials as well as for inputs to background models based on Monte Carlo simulation to evaluate sensitivity. For the experiments where CAPA researchers are

involved, like ANAIS, IAXO and TREX-DM, material screening programs are underway using mainly detectors and facilities at the Canfranc Underground Laboratory; for DarkSide-20k this work is shared with other groups and underground laboratories like Laboratori Nazionali del Gran Sasso (LNGS) and SNOlab. The expertise in this field has been required by other projects and collaboration with the Canfranc Underground Laboratory for the radioactivity assessment is ongoing for years for the NEXT experiment and, more recently, also for the Hyper-Kamiokande and LiquidO projects.

The "Neutrino Experiment with a Xenon Time-Projection Chamber" (NEXT) is intended to study the nature of neutrinos searching for the neutrinoless double beta decay of ^{136}Xe using a TPC with electroluminescent amplification filled with high-pressure gaseous xenon in the Canfranc Underground Laboratory. NEXT has been highlighted as one of the most competitive projects, together with LEGEND and CUPID, by the Double Beta Decay APPEC Committee. It is an international collaboration with more than twenty institutions mainly from Spain and US. The first phase of the program included the construction and operation of various prototypes with masses of around 1 kg which demonstrated the technology. The NEXT-White demonstrator, deploying 5 kg of xenon and operated in Canfranc, confirmed the required energy resolution at the transition energy of ^{136}Xe and established the topological signature of electrons for background discrimination. NEXT-100, being a radiopure detector with 100 kg of xenon, is being constructed. In the longer term, different approaches are being considered for a tonne-scale detector, exploiting to the limit the distinctive capabilities of the NEXT technology (NEXT-HD) and also considering the daughter Barium ion detection (NEXT-BOLD); the goal is to explore half-lives for the neutrinoless channel larger than 10^{27} y.

Hyper-Kamiokande is to be the next generation of large-scale water Cherenkov detectors intended to attempt the determination of the ordering of neutrino masses and CP violation measurement, the observation of cosmic neutrinos from the Sun or supernova explosions and the verification of Grand Unified Theories by proton decay searches. The planned detector at the Kamioka underground laboratory will consist of an order of magnitude larger tank than the predecessor, Super-Kamiomakande, and will be equipped with ultra high sensitivity photosensors to measure the Cherenkov light. It aims to become operational in the second half of the 2020's. The Hyper-Kamiokande collaboration is composed of hundreds of members from institutes coming from 13 countries; Spanish institutions have joined the collaboration to work mainly on the design and production of photomultiplier covers, electronics and data analysis.

The international LiquidO consortium is intended to investigate neutrino physics by developing a novel detection concept based on an opaque scintillator and a dense array of optical fibres to confine and collect light near its creation point. This technique, preserving many advantages of conventional liquid scintillator detectors, can in addition provide high-resolution imaging to enable efficient identification of individual particles event-by-event. The load of suitable dopants at high concentrations is also possible.

3.5.1 | Achievements in 2022

1. The material screening program for the NEXT experiment, underway for several years, has been ongoing based on germanium spectrometry and ICPMS measurements at Canfranc, complemented by other GDMS assays in France and ICPMS analysis at Pacific Northwest National Laboratory (PNNL) in US. Although the facility of HPGe detectors at the hall C of LSC has been refurbished during 2022 and then temporarily unavailable, several samples important for the construction of the NEXT-100 detector were screened before, including the

final PMT bases, sapphire windows, High Density Polyethylene for field cage body, and teflon for the light tube and the masks of the Tracking Plane.

2. About ten samples of glass intended to be used in the photomultipliers of Hyper-Kamiokande sent from Japan were analyzed to quantify activity using HPGe detectors of the Canfranc Underground Laboratory.

3.6 | Development of new search strategies for relic axion detection (RADES)

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The most important strategy to search for axions that might compose our Dark Matter (DM) halo is the Sikivie's "axion haloscope", which uses a resonant microwave cavity inside a strong magnet to convert the DM axions into a small electromagnetic signal that can be amplified and detected. The signal is detectable only when the resonant frequency of the cavity matches the (unknown) axion mass, and therefore the haloscope must be tuned over a certain (limited) range of mass values. The concept has been implemented with sufficient sensitivity to reach viable axion models in the ballpark of few μeV by the pioneer ADMX collaboration. However, to push the sensitivity of axion haloscopes to other (higher or lower) axion masses is challenging. In particular, to go to higher frequencies, smaller cavities are required (to keep the resonance condition) which means also lower sensitivity. The RADES consortium, initiated by CAPA researchers but composed now also by researchers from other Spanish institutions like U. Politécnica de Cartagena, ICCUB (Barcelona) IFIC (Valencia) and LSC, as well as from CERN, MPP-Munich and Mainz, performs various developments to extend the haloscope concept to other axion mass ranges.

A first achievement of RADES has been the design of novel cavity geometries that allow to decouple the total cavity volume V (which enters the sensitivity expression) from the characteristic dimension that determines the resonant frequency. This is achieved e.g. by cavities composed by an array of unit cavities interconnected by irises [1]. The dimension of the small sub-cavity is what determines the resonant frequency, but the total volume of the cavity is 5 times that of a single sub-cavity. This cavity was fully implemented in the CAST magnet and took physics data in 2018 and 2019, without tuning, i.e., at a single axion mass point. Physics results were obtained and published with this data [2]. Successful tuning has been achieved with another prototype with movable parts, in a test bench. More recently, a larger prototype with 30 subcavities has also been successfully tested in the lab. The RADES group is also exploring novel inner coatings using high temperature superconductor (HTS) tape, in order to improve the quality factor of these cavities. This is done in collaboration with experts in HTS coatings, also of interest for accelerator physics, in particular CERN and ICMAB-Barcelona. Finally, more recently contacts with quantum technology experts (in particular, from Aalto U. and ENS-Paris) have been established to develop single-photon counters based on superconducting qubits. Such a system would be extremely promising to lower the effective noise figure of RADES, even beyond the standard quantum limit. The RADES groups are also promoting the concept of a large-size cavity system that could effectively use the volume available in the BabyIAXO magnet to search for DM axions at lower masses (around 1 μeV). In this task, most RADES colleagues form part of the IAXO collaboration.

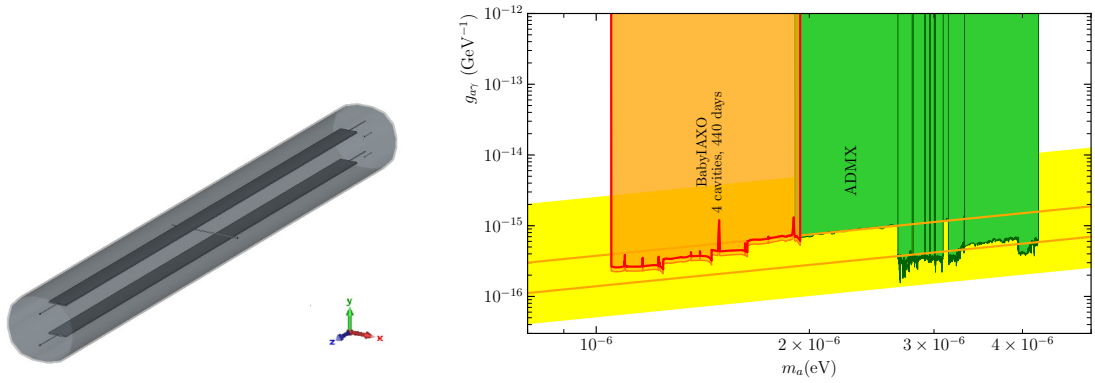

Figure 3.13: Left: sketch of a 5 m long cavity with movable slabs for BabyIAXO. Right: BabyIAXO sensitivity (defined as the average 90% CL upper limit obtained from a background-only data run) using the four 5-m cavities described in the text (orange region), for a total effective exposure time of 440 days. Two scenarios are plotted, one in which two similar cavities are coupled coherently (thin orange line), halving the acquisition time for each data taking configuration, and another one with parallel acquisition with different sized cavities (thick red line), yielding slightly less sensitivity. Also shown are the axion models band (yellow band and orange straigh lines) and the region explored by AMDX (green).

3.6.1 | Achievements in 2022

1. A realistic design of large-scale cavities optimized for the BabyIAXO magnet size have been realized. The dimensions are best adapted to axion masses in the $1 - 2\mu$eV range, which is currently not addressed by any experiment. The span in frequency is achieved by the use of four different cavity design, of 5 meter length, each of them tunable in about a 25% range, using movable slabs. Figure 3.13 shows the expected sensitivity of such a system, showing very competitive prospects the the mass region immediately below the one explored by ADMX. A publication with this result is being prepared.

2. Several microwave cavity which resonate at around 9 GHz, designed with a geometry optimized to facilitate superconducting coating (just one parallelepipedic shape with rounded corners), were built, coated and tested at a special magnet setup at the SM18 area at CERN. Several superconducting coatings and techniques were used to increase the quality factor and characterized in strong magnetic fields at 4.2 K. The cavity coated with HTS (REBCO tape) improved the quality factor over the copper coated one by a factor of 2 up to the highest magnetic field tested. This has given rise to a technical publication [3]. The data has also been analysed in search for axions and a physics paper is about to get finalised.

3. In collaboration with colleagues from ENS-Paris, we have performed a first test of a possible magnetic tuning of a RADES cavity. That is, a ferromagnetic crystal is placed inside a cavity and, by virtue of varying the external magnetic field, the cavity mode and frequency is modified. The concept is very appealing to tune cavities in haloscopes without the need of mechanical parts or feedthroughs. A first proof-of-concept is achieved but still work in needed to reach a realistic implementation.

4. A research stay of a CAPA PhD student (D. Díez) at ENS-Paris has started a program of tests to develop single-photon counters at 10 GHz, with superconducting qubits (transmons). This was a first step and more campaigns are planned for 2023.

5. A new computational method, lead by IFIC colleagues of RADES, has been developed to compute the expected signal in haloscopes, using state-of-the-art tools based on the Boundary Integral-Resonant Mode Expansion (BI-RME) 3D technique [4].

3.6.2 | References

1. Díaz-Morcillo, A. *et al.* Design of New Resonant Haloscopes in the Search for the Dark Matter Axion: A Review of the First Steps in the RADES Collaboration. *Universe* **8,** 5. arXiv: 2111.14510 [physics.ins-det] (2021).
2. Melcón, A. Á. *et al.* First results of the CAST-RADES haloscope search for axions at 34.67 μeV. *JHEP* **21,** 075. arXiv: 2104.13798 [hep-ex] (2020).
3. Golm, J. *et al.* Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter. arXiv: 2110.01296 [hep-ex] (Oct. 2021).
4. Navarro, P. *et al.* Wide-band full-wave electromagnetic modal analysis of the coupling between dark-matter axions and photons in microwave resonators. *Phys. Dark Univ.* **36,** 101001. arXiv: 2107.03137 [hep-ex] (2022).

3.7 | Generic R&D on novel low-background time projection chambers (TPC) concepts

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Óscar Pérez Lázaro	predoc
Technical support:	
Héctor Mirallas	engineer
Juan F. Castel Pablo	engineer

Some of the most active research lines at CAPA are largely based on the expertise and trajectory on the development of gaseous Time Projection Chambers (TPC) for low-background applications (see sections 3.1 and 3.3), a field in which CAPA is internationally recognised. This R&D was consolidated by the T-REX project funded by a StG-ERC in 2009-2015, which explored the applicability of Micromegas readouts, built following a particular manufacturing process, called *microbulk*. Micromegas are a very successful type of MPGD (micro-pattern gas detectors), that is, modern incarnations of the multiwire readout planes of traditional TPCs, but where the charge amplification is achieved in particular microstructures engraved in a substrate by standard lithography techniques similar to those of printed circuits [1, 2]. Micromegas of the microbulk type [3], a concept first proposed at CEA and CERN, and now mostly pushed by CAPA, are completely built out of very radiopure foils made of kapton and copper, and are therefore very promising as the core element of low-background TPCs. This R&D is done in part within the RD-51 collaboration, centered at CERN, which encompasses most of the worldwide community developing and using MPGDs. Since the end of the T-REX project, most of this activity is driven by the needs of the CAPA experiments using this technology, basically TREX-DM and IAXO. However, regularly the group performs developments of wider interest, also outside the mentioned experiments. An example is the full characterization of microbulk readout in gas mixtures of Ne and Ar with isobutane, at several pressures, a work motivated by TREX-DM, but that has given result to an technical publication in 2022 [4].

At the moment the research worth mentioning here is focused on two topics. On one side, the combined operation of a GEM preamplification foil placed just on top of the microbulk plane is being explored. The combined operation of GEM and Micromegas has been reported in the literature, but not in the context of low-background applications (i.e. using microbulks). The GEM would add an extra preamplification factor to the microbulk's gain, something very interesting in experiments requiring a very low energy threshold (like in TREX-DM). On the other hand, a new patterning layout for microbulk readouts, called *segmented mesh* microbulks, is being explored. It consists in segmenting the *mesh* electrode (or cathode) of the microbulk so that is it patterned in strips in one direction, while the anode is patterned with strips in the perpendicular direction. In standard microbulks, the mesh is common to all the readout area, while the anode is segmented in pixels, that need to be grouped and routed out in an underlying layer. Segmented-mesh microbulk would make the manufacturing process simpler (reducing material and potential process contamination) while adding reliability to the signal detection process (in the standard layout the charge is shared between the X and Y anode strips, in the new layout the X and Y signals would be exact mirrors of the charge cloud received on the readout). This development has received support from a RD-51 project led by CAPA (IP: J. Galan) with collaboration from CEA and Mainz.

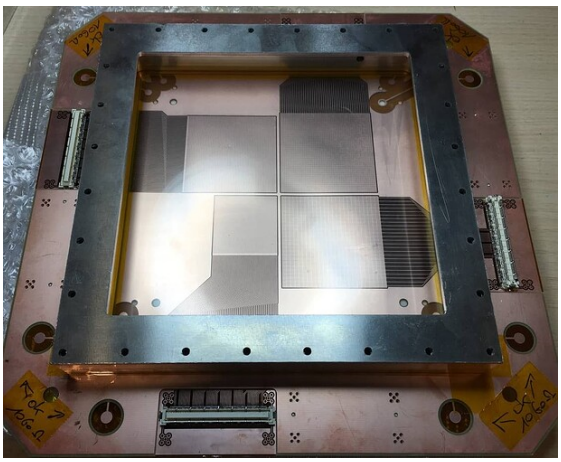

Figure 3.14: *On the left*, a picture of the segmented-mesh R&D prototype where the 4 different active areas can be distinguished, together with a metallic framework that will be mounted to define the chamber field cage.

3.7.1 | Achievements in 2022

1. GEM+MM setup: initial tests from Dec 2021 successfully demonstrated a significant improvement in the experiment's threshold when placing a GEM foil on top of a small unsegmented microbulk. During 2022, these tests have been extended to a finely segmented 25x25 cm^2 readout that has the same geometric characteristics as the current TREX-DM detectors. This setup was operated at 1 bar using an Ar-1%Isobutane mixture, and the amplification factor achieved was greater than 100. Currently, measurements are being carried out with the small GEM+microbulk setup (the chamber can reach pressures up to 10 bar). A preliminary analysis of data taken at 4bar (Ar-1%Isobutane) also suggests an improvement of the energy threshold by a factor of at least 100. The objective is to systematically continue these measurements and expand them to different gas mixtures and pressures.

2. Segmented-Mesh setup: The main objective of this RD51 research proposal consists on the characterization of different segmented mesh readouts using different pitch. The design and construction of this prototype has just been finalized and tests and data taking will be starting soon. The prototype implements *four* independent active regions with different pitch values (0.5 um, 0.75 um, 1 mm and 2 mm). For the readout, the mesh segmented channels are at high-voltage, thus the signals DC component need to be decoupled before connecting to the electronics. A dedicated card has been designed and produced (see Figure 3.14). The studies performed with this prototype will help to understand the relation of the low energy threshold as a function of the detector pitch, as well as to study different parameters that qualify the detector performance, such as the energy resolution. On top of that, these prototypes are intended to assess the robustness and stability of this technology to undesired effects, such as discharges damaging the detector.

3.7.2 | References

1. Irastorza, I. G. *et al.* Gaseous time projection chambers for rare event detection: Results from the T-REX project. I. Double beta decay. *JCAP* **1601,** 033. arXiv: 1512.07926 [physics.ins-det] (2016).
2. Irastorza, I. G. *et al.* Gaseous time projection chambers for rare event detection: Results from the T-REX project. II. Dark matter. *JCAP* **1601.** [Erratum: JCAP1605,no.05,E01(2016)], 034. arXiv: 1512.06294 [physics.ins-det] (2016).
3. Andriamonje, S. *et al.* Development and performance of Microbulk Micromegas detectors. *JINST* **5,** P02001 (2010).
4. Iguaz, F. J. *et al.* Microbulk Micromegas in non-flammable mixtures of argon and neon at high pressure. *JINST* **17,** P07032. arXiv: 2204.08199 [physics.ins-det] (2022).

3.8 | LABAC

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The main activity of the "Laboratorio de Bajas Actividades" (LABAC) of the University of Zaragoza[3] is the application of low radioactivity techniques to the environmental monitoring. LABAC measures the environmental parameters according to its agreement with the "Consejo de Seguridad Nuclear" (CSN, Spanish Nuclear Regulatory Commission). It is member of the REVIRA dense net ("Red de Vigilancia Radiológica Ambiental") of the CSN for more than 20 years. REVIRA is composed presently by 21 Spanish laboratories taking continuously data on environmental radioactivity; LABAC has assigned a program of sampling and analysis that controls the evolution of the quality radiological environmental in air, drinking water, diet and soil. LABAC is registered in the national control system for drinking water ("Sistema de Información Nacional de Agua de Consumo", SINAC) and makes regular analyses of water and food for the Government of Aragón since 2010. For the "Laboratorio Subterráneo de Canfranc" (LSC), LABAC performs periodic radiological controls of water and air, radon monitoring and dosimetry. Additionally, LABAC works also for research groups and public or private companies in order to quantify the concentrations of radioisotopes in environmental, industrial or suitable samples for human consumption (water, vegetables, food); in particular, the services currently offered include the determination of gross alpha and beta activity indexes, beta activity of ^{90}Sr, activity of gamma emitters like ^{131}I, ^{137}Cs, ^{60}Co and naturally occurring radioactive material (NORM).

The LABAC facilities are briefly described at Sec. 8.7. Since February 2019, LABAC has ENAC certification (number 1324/LE2490) for total alpha and beta activity assessment in drinking and continental water under rule UNE-EN ISO/IEC 17025. The laboratory takes part regularly in interlaboratory proficiency tests promoted by national (CSN) and international organizations (IAEA, International Atomic Energy Agency).

3.8.1 | Achievements in 2022

1. The different types of assessments on different samples required by the REVIRA dense net of CSN, the Government of Aragón ("Servicio de Seguridad Alimentaria y Salud Ambiental") and LSC have been successfully performed, as in previous years. We made other radioassays for new clients.

[3] https://gifna.unizar.es/labac/

2. Members of LABAC have collaborated with the Chemistry and Environment group of the University of Zaragoza in a study of the natural and anthropogenic radionuclides in soil, water and air in samples from Antarctica (Spanish Research Station “Gabriel de Castilla”, Deception Island). Our gamma spectrometry, together with mass spectrometry, provided useful information on the current radioactive contamination of the analyzed area.

Theory

The Standard Model (SM) of particle physics is one of the great achievements of twentieth century physics. It describes all known particles and their interactions with the exception of gravity, and allows us to calculate many processes that have been tested in accelerators to unprecedented precision. The discovery in 2012 of the Higgs Boson completed the last missing piece of the model.

It seems however unlikely that the SM is the final description of fundamental physics. It does not describe the hypothetical quantum effects of gravity, which are expected to appear at high enough energies. But also as a theory it leaves many unanswered questions: it does not account for neutrino masses, does not explain the replication of families and the patterns of masses and mixings, or the absence of CP violation in the strong interactions. From the experimental side, the strong evidence for the existence of non-baryonic dark matter and dark energy points to a gap in our understanding of the fundamental building blocks of nature.

The various research lines of the theory side of CAPA aim to shed light on some of the unexplained features of the SM, as well as trying to go beyond. This is achieved both by building and testing other possibilities, by testing the SM itself by high precision calculations, as well as by obtaining a better understanding of the intricate features of the SM.

3.9 | Axion Physics

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The QCD axion is a hypothetical 0^- boson, extremely light and weakly interacting, predicted by the Peccei-Quinn-Weinberg-Wilzcek mechanism that could explain the absence of CP violation in quantum chromodynamics. Axions produced in the early Universe can easily account for all the cold dark matter (CDM) observed in the Universe by non-thermal production mechanisms as the vacuum realignment and the decay of topological defects of the axion field, cosmic strings and domain walls. Axion CDM in our halo can be sought after by haloscope experiments, and axions in general by their impact on stellar evolution or by directly detecting the solar axion flux with helioscopes. In this landscape, our group works on the key issues required for a discovery of the axion (or eventual refutation). As primary concern, we focus on understanding axion CDM in the Post-Inflationary scenario (POSI). Here the axion Dark Matter yield is calculable for a cosmology, only depending on the axion mass. Knowing this yield with precision and assuming axions are all the dark matter, we could calculate the axion mass, which could accelerate enormously its discovery.

To do that we developed highly sophisticated large-scale numerical simulations of global cosmic strings and study radiation from them. We maintain an open-source massively parallel code *jaxions* and develop a dedicated adaptive-mesh-refinement code with the aim of reaching sufficient precision in our simulations to solve the long-standing controversy on the spectrum of Goldstone bosons radiated from cosmic strings. On the other hand, in the POSI, axion CDM is highly inhomogeneous and forms an early generation of low mass and compact halos, axion miniclusters. We study the formation, evolution and characteristics of these halos, the possibility of detecting them with astronomical probes such as gravitational lensing and how they affect the direct detection of axion CDM in lab

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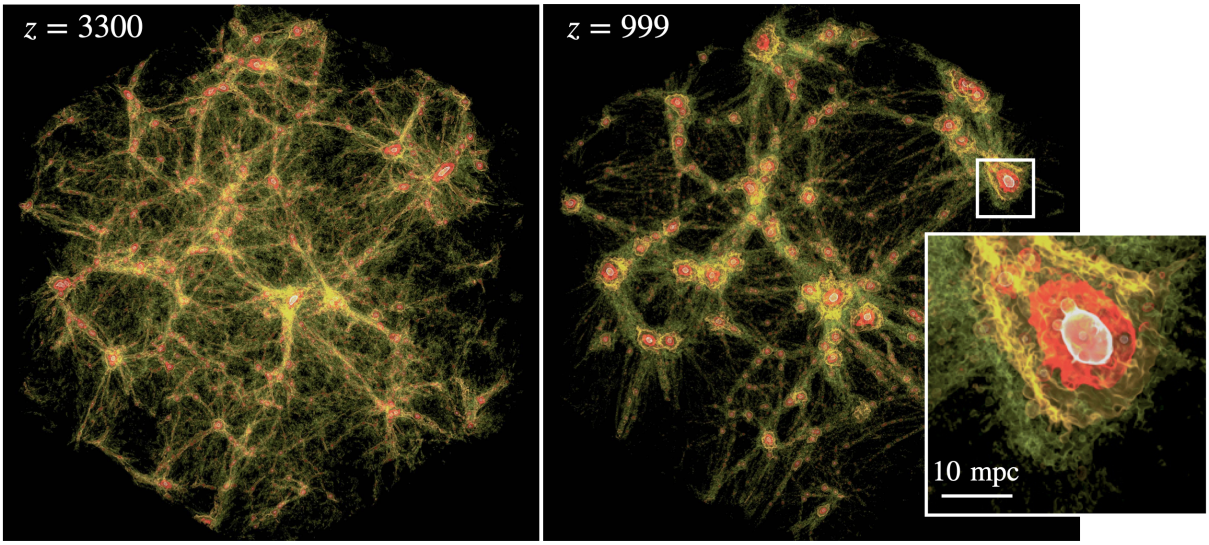

Figure 3.15: Snapshot of one of our simulations showing axionic strings, walls and axitons.

experiments. Beyond the POSI, we plan to extend our simulations to other scenarios, such as large-angle, kinetic misalignment, etc.

The direct detection of axion dark matter is the ultimate goal of this program. We work by giving theoretical support and analysing data for optimising detection schemes for DM axions as well as for solar axions (IAXO, babyIAXO). In particular we participate in the MADMAX collaboration to build a dielectric haloscope in DESY, Hamburg (MADMAX collaboration), the RADES initiative to build haloscopes in accelerator dipole magnets (with the hope of using these techniques in IAXO) and in FUNK, the dish-antenna experiment.

3.9.1 | Achievements in 2022

1. We have completed a study of the radiation of axions from cosmic strings from *jaxions* simulations with K. Saikawa. We have presented our results in conferences. The paper is expected along 2023.

2. We have used axion NYX and *jaxions* codes to simulate cosmic string loop decay. We have developed a module to input Nambu-Goto strings and generate Kalb-Rammond initial conditions that then integrate into the axion field. We have used this to study circular and non-circular loops and reported our results in conferences. We are preparing a paper.

3. We have studied the axion emission spectrum from the high-tension strings of Moore and Klaer in collaboration with G. Moore by adapting his codes. We are preparing a publication.

4. We have studied the axion minivoids, the space in between miniclusters. The POSI seems like it ought to spell doom for haloscopes, but while these minivoids might be underdense, they are not totally devoid of axions.

Using Schroedinger-Poisson and N-body simulations to evolve from realistic initial field configurations, we quantify the extent to which the local ambient dark matter density is suppressed in the post-inflationary scenario. We find that a typical experimental measurement will sample an axion density that is only around 10% of the expected galactic CDM density. Our results are taken as conservative estimates and have implications for experimental campaigns lasting longer than a few years, as well as broadband haloscopes that have sensitivity to transient signatures. We show that for a O(year)-long integration times, the measured dark matter density should be expected to vary by 20-30%.

5. We have used the Peak-Patch algorithm to identify the densest minicluster seeds in the initial axion density field simulated from string decay. The fate of these dense seeds is found by tracking the subsequent gravitational collapse in cosmological N-body simulations. We find that miniclusters at late times are well described by NFW profiles, although for around 80% of simulated miniclusters a single power-law density profile of $r^{-2.9}$ is an equally good fit due to the unresolved scale radius. Under the assumption that all miniclusters with an unresolved scale radius are described by a power-law plus axion star density profile, we identify a significant number of miniclusters that might be dense enough to give rise to gravitational microlensing if the axion mass is $\sim 0.2meV$.

6. We have calculated the spectrum of hidden photons (HPs) emitted from the Sun and the sensitivity of BabyIAXO and IAXO to them. We have found that they improve enormously compared with the previous helioscope CAST and they can compete with the exclusion results from XENON, having sensitivity to discover HPs with masses around the eV. A paper is in preparation.

3.10 | Quantum gravity phenomenology

The aim of this line of research is the exploration of deviations from special relativity (SR) both from theoretical and phenomenological perspectives. This is a central issue in the research program of the rather young field of quantum gravity phenomenology, whose development finds presently a driving force at the international level in the COST Action CA18108 “Quantum gravity phenomenology in the multi-messenger approach”, a project which is coordinated by the Zaragoza group (JMC is Action Chair of this COST Action).

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From a theoretical perspective, one main motivation in the consideration of possible departures from SR comes from the difficulties to incorporate the quantum effects of the gravitational interaction in the framework of relativistic quantum field theory (RQFT), which is probably due to the relation at the classical level between the gravitational interaction and the structure of space-time. More generically, the understanding of the origin of the matter-antimatter asymmetry, of the different flavors of elementary particles, of dark matter and dark energy might require to go beyond the RQFT framework.

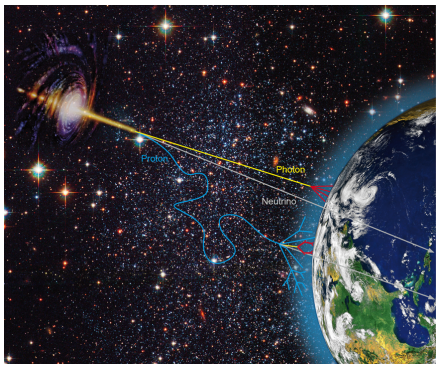

Figure 3.16: Multi-messenger astronomy involves the detection of different cosmic messengers: photons, neutrinos, cosmic rays and gravitational waves.

From a phenomenological perspective, there are new windows of observations in very high energy astroparticle physics which could show us the first signals of a deviation from SR if we find the appropriate ways to look for them. This is the main objective of the COST Action CA18108, joining together theorists with experimental physicists which are experts in the detection of the so-called "cosmic messengers": gamma rays, neutrinos, cosmic rays and gravitational waves. Our position in this network allows the Zaragoza group to be in close contact with the main ideas and results in the field, as well as to quickly and effectively disseminate our results in the relevant scientific community.

3.10.1 | Achievements in 2022

1. We have continued playing a prominent role in the organization and development of the COST Action CA18108 "Quantum gravity phenomenology in the multi-messenger approach". In particular, we have co-organized a number of international events that took place in 2022: the Annual Conference of the Action in Naples, a "Workshop on future challenges and opportunities in QGMM", also in Naples, a "Workshop on theoretical and experimental advances in quantum gravity" in Belgrade, and the "Second COST CA18108 Training School", also in Belgrade. Members of our group also presented our research in all these events. The review [1] was published with J.M. Carmona as corresponding author.

2. We have completed [2] the study of possible effects of a relativistic deformation of special relativity in the recent observations of very high-energy gamma rays by the LHAASO experiment, presenting prospects for the detection of such effects in future experiments. In this context, we started a collaboration with Tomislav Terzić, from Rijeka University (Croatia), who is an experimental physicist expert on detection of gamma rays with Cherenkov telescopes (CTA), member of the MAGIC collaboration, and coordinator of the gamma-ray Lorentz invariance violation (LIV) working group, which joins experimentalists of the largest CTAs in the world (H.E.S.S., MAGIC, VERITAS).

3. We gave an operative definition of time delays for the propagation of massless particles in the framework of doubly special relativity theories (DSR), which was shown, for the first time, to be compatible with the relative locality paradigm (a well-known feature of DSR), clarifying long-standing questions in the literature about

the arbitrariness in the choice of the energy-momentum labels and the independence of the time delay on this choice [3].

4. We produced a review paper on the challenges and the future prospects of using cosmic neutrinos as a window to possible departures of special relativity, both in the DSR and the LIV scenarios [4].

5. We started a collaboration with Denise Boncioli, from the University of L'Aquila, to study LIV propagation effects in cosmogenic neutrinos (neutrinos produced in the interaction of the highest energy cosmic rays with the cosmic microwave background), using the latest results from the AUGER collaboration (where Dr Boncioli leads the Cosmic-Ray Phenomenology task force). Maykoll Reyes made a first preparatory stage in Italy during September 2022.

3.10.2 | References

[1] A. Addazi et al., *Quantum Gravity Phenomenology at the Dawn of the Multi-Messenger Era—A Review*, Progress in Particle and Nuclear Physics **125**, 103948 (2022).
[2] J. M. Carmona, J. L. Cortés, J. J. Relancio, M. A. Reyes, and A. Vincueria, *Modification of the Mean Free Path of Very High-Energy Photons Due to a Relativistic Deformed Kinematics*, Eur. Phys. J. Plus **137**, 768 (2022).
[3] J. M. Carmona, J. L. Cortés, J. J. Relancio, and M. A. Reyes, *Time Delays, Choice of Energy-Momentum Variables, and Relative Locality in Doubly Special Relativity*, Phys. Rev. D **106**, 064045 (2022).
[4] J. M. Carmona, J. L. Cortés, J. J. Relancio, and M. A. Reyes, *Cosmic Neutrinos as a Window to Departures from Special Relativity*, Symmetry **14**, 7 (2022).

3.11 | Beyond the Standard Model

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The Standard Model (SM) of particle physics, with the prediction and discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC), is perhaps the crowning achievement of 20th century physics in its accurate description of all known particles and their interactions.

However, in spite of their enormous successes, there are some reasons to believe that the SM is incomplete as fundamental theory of nature. From the theoretical point of view, the SM does not describe quantum gravity, does not account for neutrino masses and does not offer satisfactory explanations for some of its ingredients and parameters: the replication of families and the patterns of masses and mixings (flavour problem), the hierarchy of the Higgs and Planck masses (hierarchy problem) and the absence of CP-violation in the strong interactions and the strong CP problem. On the other side, there are experimental measurements of flavor violating processes at LHCb, Babar and Belle that show interesting deviations from the SM predictions, making them excellent probes of New Physics (NP) beyond the SM. Some of the flavor transition processes relevant to constrain NP at the LHC are the leptonic, semileptonic, baryon and radiative exclusive decays.

In this context, both Effective Field Theory analysis and specific NP models (leptoquarks, W' and Z' bosons, axion-like particles, etc.) are mandatory to attack the flavour problem and the recent flavour anomalies. Naturally, it is necessary to follow the updates of any of the new experimental results from LHCb, Belle-II and others high energy colliders. The framework of Effective Field Theories allow to obtain constraints on New Physics contributions to the Wilson coefficients of the effective Lagrangian from the experimental results.

Particle physics phenomenology and, more concretely, flavor physics requires the analysis of a large number of experimental data and parameter spaces of high dimensionality. In addition, the number of competing NP theories poses a problem of model classification and selection. Traditional computational approaches may fall short in these kinds of settings. It is precisely in these conditions where Machine Learning and Deep Learning techniques are most useful. The history of Machine Learning in particle physics is very long and fruitful, specially in experimental settings, where these algorithms are used for tasks such as event selection, tracking, jet classification and substructure, and simulation. However, only very few works have tried to use neural networks to model selection in the context of the B-meson anomalies. This is a pioneering approach and a very fruitful field of research.

3.11.1 | Achievements in 2022

Different physical processes related to the phenomenology of Flavour Physics for quarks and leptons have been studied. Mainly, the works have been focused on the anomalies observed in the semileptonic decays of B mesons. A global fit including observables from all affected sectors have been performed. The sheer number of observables involved makes mandatory the use of numerical calculations, and in the most extreme cases, even using Machine Learning tools such as regression trees and SHAP (SHAPley Additive exPlanation) values. Besides, the leptonic decays of several mesons and their compatibility with Axion-Like Particles (ALPs) have been also analyzed.

1. The SM offers an excellent prediction for most of the phenomena that are observed in the high energy experiments, and these predictions must not be spoilt just to find an explanation for a few puzzling observables. Therefore, it is mandatory to perform global studies comparing all available experimental data from diverse physical sectors. A discussion on how the obtained results were limited by observables coming from superallowed nuclear β decays, electroweak precision tests and Leptonic Flavour Violation have been included in the analysis. In fact, our previous results of the global fits have been updated by taking into account experimental measurements with improved precision. A novel result is that the value of the best fit can be understood as the interplay between three different sectors: the B anomalies are sensitive to violations of lepton flavour universality, electroweak observables that are sensitive to universal NP contributions, and the superallowed nuclear β decays that are sensitive to physics in the muonic part. From our results, it is clearly established the relevance of the inclusion of all physical sectors in a phenomenological analysis.

2. A mechanism for the simultaneous generation of the $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies has been initially proposed, where the Effective Theory reflects an interaction that, at the high scale, affects only the third generation fermions before the corresponding rotation to the mass basis of the physical quarks and leptons. In this picture, the $R_{D^{(*)}}$ ratios are tree level phenomena, while the $R_{K^{(*)}}$ ratios are the result of the interplay between tree level affecting only the $B \to K^{(*)}e^+e^-$ decays, and loop level affecting universally the electron and muon decay modes. Tree level contributions to the muon decay modes are severly limited by Lepton Flavour-violating

observables. An interesting prediction of our proposal is the correlation between the $R_{D^{(*)}}$ anomalies and an excess in the $B \to K^{(*)}\nu\bar{\nu}$ decays. A similar excess has been independently reported by the Belle II experiment. Besides, a possible realization of this mechanism has been proposed in the form of a vector leptoquark U_1 that interacts with the second and third generations of quarks and the first and third generations of leptons. This leptoquark model extends a previous proposal to explain only the $R_{D^{(*)}}$ anomalies.

3. A relevant point of the work done is that, as we study more complete theories or models and include more observables, the required calculations become more involved. At first this means the jump from analytical to numerical calculations, and when even the traditional numerical approaches become too complicated and slow, as is the case of our global fit, alternative methods are need: A Machine Learning algorithm based on decision trees in order to approximate the likelihood function and speed up the calculations. Our work marks a novel approach to the study of the flavour anomalies, with a Machine Learning analysis being used to extract confidence intervals and correlations between observables.

4. Additionally, the possible impact on the analysis of the future measurements of the electroweak precision tests in the next generation of linear electron colliders have been investigated, showing that those future measurements improve the constrains to lepton-universal NP contributions.

5. Finally, in the case of the invisible ALP production, the importance of different leptonic meson decay channels in the analysis has been discussed, and their comparison with other decays analyzed previously included. Concretely, a detailed analysis of leptonic decays of mesons that could produce pseudoescalar ALPs, $M \to \ell\,\nu_\ell\,a$ have been presented. Some novel results are: the leptonic kaon decays can impose bounds to the couplings of invisible ALPs to quarks which are comparable, although not competitive, with bounds coming from hadronic decays and also the bounds on ALP-leptons couplings coming from leptonic meson decays, and specially from $K \to e\nu_e a$, are the most stringent in the GeV and sub-GeV range. The new experimental measurements in the leptonic decays of several mesons have been an important factor in the obtained results.

   Phenomenology is an area of physics that lives in the balance between theory and experiment, and therefore, any new development in either can have a large impact in our results. This is specially true in the phenomenology of Flavour Physics, which is in rapid evolution caused by the plethora of experimental measurements and the renewed theoretical interest. We have experienced this evolution during the elaboration of our works, then redoing some of our analyses and even re-evaluating previous conclusions. We have updated our global fits taking into account experimental measurements with improved precision which have been published after the completion of some of our works.

3.12 | Lattice field theory

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The lattice group in CAPA pursues two main lines of research: the calculation of quantities of phenomenological relevance, in particular in the search for physics beyond the Standard Model, and the study of systems with a strong sign problem.

The Standard Model (SM) is currently the best theory we have to describe nature, but it is not complete and it is currently regarded as an Effective Field Theory (EFT). We expect to find physics Beyond the SM (BSM) at some large energy scale. BSM physics can be accommodated in the SM by the addition of new operators in our EFT description. Experiments are of paramount importance to find constraints for the coefficients of these new operators, but experimental results must be matched with theory to find discrepancies indicative of BSM physics. This research line is devoted to the high precision testing of the SM, looking for small deviations between theory and experiment that can lead to new physics. Most of this high precision physics is done in the intensity frontier. By calculating to very high precision observables that can be influenced by the addition of new operators to the SM, one can test whether the experimental results match the current theory or not. In particular, A. Vaquero collaborates in a calculation of the hadronic contributions to observables and processes using Lattice QCD and supercomputers, and there is a close communication with experimentalist to decide which new quantities to calculate and how to orient future experiments. The weak sector of the SM is rich in phenomena that can potentially show signs of new physics. More precisely, we are currently calculating the CKM matrix elements Vxb, where there is a 2sigma tension between inclusive and exclusive determinations, using the semileptonic processes $B_{(s)} \to D^{(*)}_{(s)}$, $B \to \pi$, $B_s \to K$ and the rare process $B \to K$, but there is a very well established roadmap to determine other CKM matrix elements and decay constants with smaller errors. In fact, first-principle calculations of the parameters governing rare processes like $B_{(s)}$-mixing are being currently planned to start during the following months. There are many tensions in the flavor sector of the SM that could be confirmed or eliminated with an increased precision in our determinations, hence it is of foremost important that we carry out this plan in order to pinpoint the sources of new physics and establish new bounds for the coefficients of the new operators to be included in the SM. Of course this effort is accompanied with an increased precision in experimental measurements. As forthcoming experiments (Belle-II) reduce the uncertainty in their measurements, so must we.

But there are more places in the SM to look for new physics. A hot topic right now is the muon anomalous magnetic moment (a_μ), which can be calculated in theory or measured in experiment up to very high precision. Currently, there is a 3 σ difference between experiment and theory. Forthcoming experiments will reduce the current uncertainty by a factor of four (Fermilab Muon g-2 at BNL) or even more (J-PARC E34), therefore we need to increase the precision of the theoretical prediction. By using state-of-the-art techniques in LQCD we calculate the hadronic and the disconnected light-by-light contributions to a_μ. These two contributions currently lead the errors coming from theory. Another related topic is the calculation of hadronic form factors, in particular, the scalar, axial, tensor and electromagnetic form factors of the nucleon and other baryons using LQCD. The different contributions can be used to test the nucleon spin, axial charge or radius, to give a few examples. But some other quantities can only be computed in theory, like the scalar content of the nucleon, an essential input parameter in Dark Matter (DM)

detection experiments.

The second main research line of our group is the study of systems with a strong sign problem. Such systems have an euclidean action that cannot be interpreted as the Boltzmann weight of a partition function, and therefore cannot be simulated using standard Montecarlo algorithms. Several models of great physical interest fall into this category, for example QCD at finite density, QCD with a θ term, or the Hubbard model. Our group has been working for a long time developing new algorithms that can, at least in some cases, evade the sign problem. After testing the algorithms on some simpler models, we are studying now the case of QCD with a theta term in the action, with our main goal the calculation of the entire dependence of the order parameter on the θ angle.

3.12.1 | Achievements in 2022

1. Using our implementation of the geometric definition of the topological charge in lattice QCD, we are continuing our simulations to compare the results with other discretizations, in order to check finite-lattice spacing errors, the effect of dislocations, etc.

2. We have continued the work on the calculation of the muon anomalous magnetic moment, in particular the leading-order hadronic vacuum polarization (HVP) contribution. This quantity has been very difficult to calculate accurately due to the growth of statistical and systematic errors in the u/d quark correlation functions at large Euclidean time. We have shown that restricting the lattice contributions to a one-sided window 0<t<t1 can greatly improve lattice results while still capturing a large fraction of the total HVP [1].

3.12.2 | References

[1] C.T.H. Davies, C. DeTar, A.X. El-Khadra, Steven Gottlieb, D. Hatton, A.S. Kronfeld, S. Lahert, G.P. Lepage, C. McNeile, E.T. Neil, C.T. Peterson, G.S. Ray, R.S. Van de Water, and A. Vaquero, *Windows on the hadronic vacuum polarization contribution to the muon anomalous magnetic moment*, Phys. Rev. D **106**, 074509 (2022).

3.13 | Beyond General Relativity

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A fundamental component of the physical universe which is beyond the Standard Model is the gravitational interaction which in fact was the first discovered interaction. So far Einstein's theory of General Relativity describes quite successfully the gravitational interactions in a wide range of physical scales from the millimeter to intergalactic scales.

However, there are few reasons to expect a modification of the theory at shorter and larger scales. At larger scales the apparent failure in the explanation of the rotating curves of galactic halos is actually solved by adding a dark matter component which also helps in fitting the current cosmological data.

The inflationary model which best fits the observational data is the Starobinsky model which involves a modification of Einstein theory by means of an R^2 term (see Figure 3.17 where the dependence of the ratio of the tensor-scalar fluctuations on the primordial tilt n_s is analyzed according to Planck results).

On the other hand the emergence of infrared quantum effects due to long-range quantum correlations dues the conformal anomaly amounts to a well-defined modification of Einstein's theory of gravitation (GR). These effects can be encoded in an Effective Field Theory (EFT) and their role can be especially relevant in two research fields: near-horizon physics of Black Holes (BHs) and standard ΛCDM cosmology.

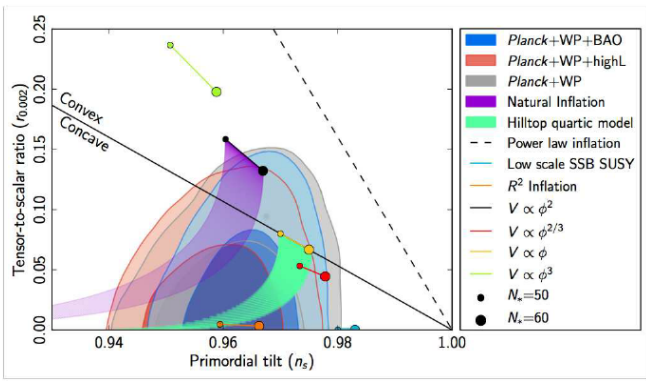

Figure 3.17: Ratio of the tensor-scalar fluctuations versus the primordial tilt, according to Planck results and predictions of different cosmological models.

The increasing amount of data coming from cosmological observations and multi-messenger astrophysics of black hole (BH) mergers provide new sources of information that make possible tests of the relevance of these quantum effects in gravity.

Another argument that leads to consider Einstein's theory as an effective theory of a more fundamental one is its non-renormalizability as a quantum field theory.

This problem can be cured by introducing high derivative terms generalizing Starobinsky model or even non-local terms. All these theories theories are renormalizable but most of them present consistency problems related to violations of causality and unitarity. Another effect of these theories is that in spite of the fact that they do not have ultraviolet divergences they present Black Hole solutions with peculiar properties and a dynamics quite different from Einstein theory Black Holes.

The research line of CAPA to approach this problem has the following fundamental goals:

- Complete Einstein's theory with higher derivative terms to achieve a consistent theory of quantum gravity.
- Explore the behaviour of the different theories of gravity at scales below the millimeter scale to find possible deviations from General Relativity.
- Analyse the black hole physics of higher derivative theories of gravitation and its implications for binary black hole mergers.

3.13.1 | Achievements in 2022

1. In order to understand the physical effects of higher derivative gravity we continue our exploration of the physical effects of UV completions of gauge theories and gravitation by means higher derivative terms. We have shown that high derivatives can dramatically change the behaviour of those theories at high energies [1]. The requirement of asymptotic freedom imposes very stringent constraints that are only satisfied by a small family of higher derivative theories. If the number of derivatives is large enough (n> 4) the theory is strongly interacting both at extreme infrared and ultraviolet regimes whereas it remains asymptotically free for a low number of extra derivatives ($n \leq 4$). In all cases the theory improves its ultraviolet behavior leading in some cases to ultraviolet finite theories with vanishing β-function. The usual consistency problems associated to the presence of extra ghosts in higher derivative theories may not harm asymptotically free theories because in that case the effective masses of such ghosts are running to infinity in the ultraviolet limit.

2. We have analysed the effective action induced by the conformal anomaly in the presence metric and scalar background fields [3]. Since the discovery of the Higgs boson the only fields of the Standard Model with non-vanishing background fields are the Higgs field and the gravitation field. We have solved the long standing problem of the ambiguities in the total derivative terms of the one loop effective action by using Pauli-Villars regularization.

3. Lorentz symmetry forbids decays of massive spin-1 particle like the into two massless photons, a result known as the Landau-Yang theorem. But it is known that infrared effects can break Lorentz invariance. Using the breaking of Lorentz symmetry, we propose an interaction leading to the decay and study the dependence of the decay on the parameter of this Lorentz violation [2].

4. We have developed a general theory of boundary conditions for field theories which preserve energy. We extended considerable the number of compatible boundary conditions [4]. The goal is to understand the appearance of a mysterious mass, lower than the glueball mass, in the calculations of Casimir energy of non-abelian gauge theories.

5. In the last years we have seen an intense development of extensions of the Einstein–Hilbert action containing non-local terms claiming to overcome inconsistencies (unitarity, absence of ghosts and conservation of probability) and at the same time removing all classical singularities of General Relativity. We have shown that most of these theories fail to admit a Källen-Lehmann decomposition, which raises a serious problem leading to inconsistency of the theories.

3.13.2 | References

[1] M. Asorey, F, Falceto and L. Rachwal, Asymptotic freedom and higher derivative gauge theories, JHEP **05** (2021) 075.

[2] A. Addazi *et al*, Quantum gravity phenomenology at the dawn of the multi-messenger era – A review Progress in Particle and Nuclear Physics (2022) 103948

[3] M. Asorey, W. Cesar e Silva, I. L. Shapiro and P. R. B. do Vale, Trace anomaly and induced action for a metric-scalar background arXiv preprint arXiv:2202.00154

[4] M. Asorey G Angelone, P Facchi, D Lonigro and Y Martinez, Boundary conditions for the quantum Hall effect J. Phys. A: Math. Theor. 56 (2022) 025301

3.14 | From Exoplanets to supermAssive black holes: exploring The cosmic frontiers at the HighEst angular Resolution and Sensitivity with the EHT and SKA pathfinders (FEATHERS)

Responsible investigator(s) / coordinator(s):	
Miguel Pérez Torres	IAA-CSIC
Researchers involved:	
Antonio Alberdi Odriozola	Full Professor (CSIC)
Manuel Membrado Ibañez	staff
Jacobo Asorey Barreiro	Maria Zambrano Fellow (UCM)
Luis Peña Moñino	predoc (CSIC)

The main goal of this research line is to make significant advances in our understanding of a number of relevant astrophysical areas of research thanks to the unmatched combination of angular resolution and sensitivity provided by world-leading interferometer facilities (EVN, VLBA, GMVA, eMERLIN, JVLA, EHT, GMVA, ALMA, VLTI and the SKA precursors, such as LOFAR, MeerKAT, and ASKAP). We carry out forefront research mainly in three broad areas: (i) Exoplanetary and Stellar studies, ranging from the study of star-planet interaction as a novel way of discovering exoplanets and studying the magnetosphere of low-mass stars to the formation of massive stars; (ii) Supermassive Black Holes and Active Galactic Nuclei, ranging from the imaging of the shadows of supermassive black holes-directly testing Einstein's theory of relativity to the study of the AGN phenomenon at galaxy-wide scales, aimed at understanding the AGN-host phenomenon; (iii) the study of the explosive transient radio sky, from the detection of SN type Ia progenitors and the study of core-collapse supernovae to the characterization of the population of extragalactic nuclear transients, including tidal disruption events (TDEs) and unveiling the nature of the elusive IceCube neutrinos.

3.14.1 | Achievements in 2022

1. **SMBHs and AGNs**

   We found that significant differences in specific SFR of the AGN host galaxies as compared with the larger galaxy population disappear once cold gas mass, in addition to stellar mass, is used to predict the star-formation rate for a specific AGN host. We conclude that AGN can be present in various stages of galaxy evolution, which makes it difficult to relate the SFR solely to the impact of the AGN. Our study shows that stellar mass alone is an insufficient parameter to estimate the expected SFR of an AGN host galaxy compared to the underlying

non-AGN galaxy population. We did not find any strong evidence for a global positive or negative AGN feedback in the CARS sample.

We found that the presence of spatially extended and compact [O III] wing emission is unrelated to the AGN bolometric luminosity and to inclination effects, which means other features such as time delays, or mechanical feedback (radio jets) may shape the ionized gas outflow properties in AGNs.

Arp 299 is the brightest luminous infrared galaxy (LIRG) within 50 Mpc. It provides a unique laboratory for testing physical processes in merging galaxies. We studied for the first time the low-frequency ($\sim$150 MHz) radio brightness distribution of Arp 299 at subarcsecond resolution, tracing in both compact and extended emission regions the local spectral energy distribution (SED) in order to characterize the dominant emission and absorption processes. We present the first subarcsecond image of the whole Arp 299 system at 150 MHz. The high surface brightness sensitivity of our LOFAR observations allowed us to detect all of the nuclear components detected at higher frequencies, as well as the extended steep-spectrum emission surrounding the nuclei. We obtained spatially resolved, two-point spectral index maps for the whole galaxy: the compact nuclei show relatively flat spectra, while the extended, diffuse component shows a steep spectrum. We fitted the radio SED of the nuclear regions using two different models: a continuous free-free medium model and a clumpy model. The continuous model can explain the SED of the nuclei assuming a population of relativistic electrons subjected to synchrotron, bremsstrahlung, and ionization losses. The clumpy model fits assuming relativistic electrons with negligible energy losses, and thermal fractions that are more typical of star-forming galaxies than those required for the continuous model.

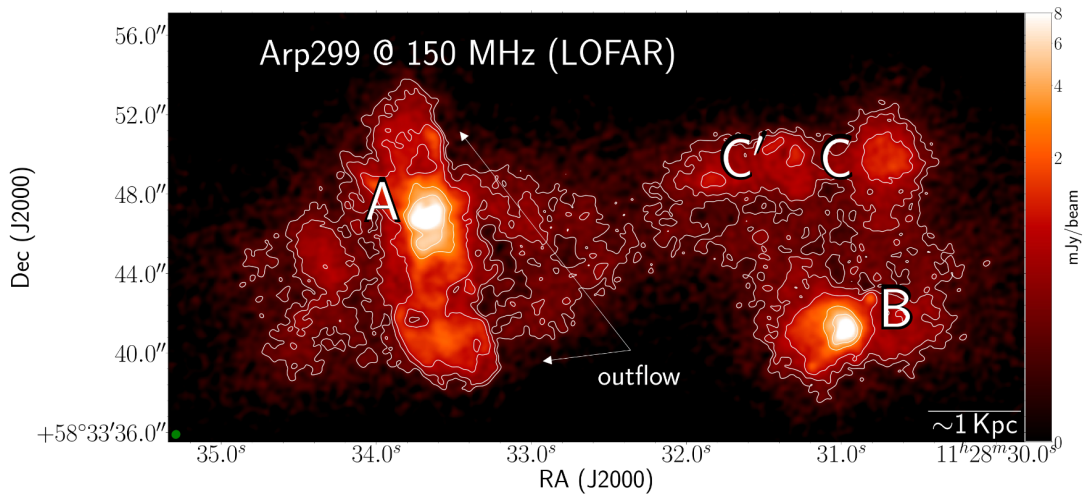

Figure 3.18: LOFAR VLBI images of the Luminous Infrared Galaxy Arp 299, obtained by Ramírez-Olivencia et al. (2022)

2. **Exoplanets, ultra-cool dwarfs and star-planet interaction**

The substellar triple system VHS J125601.92-125723.9 (hereafter VHS 1256-1257) is composed of an equal-mass M7.5 brown dwarf binary and an L7 low-mass substellar object. We aimed to identify the origin of the

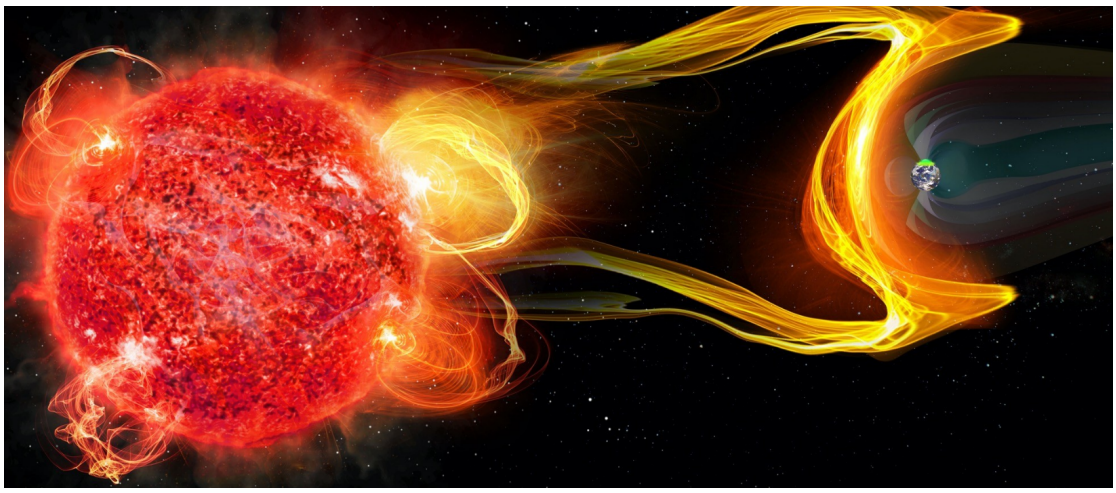

Figure 3.19: Artistic image of star-planet interaction (credits Karter, Caltech).

radio emission occurring in the central binary of VHS 1256-1257 while discussing the expected mechanisms involved in the radio emission of ultra-cool dwarfs. We found radio emission at 6 GHz and 33 GHz coincident with the expected position of the central binary of VHS 1256-1257. The Stokes I density fluxes detected were 73 and 83 microJy, respectively, with no detectable circular polarisation or pulses. No emission was detected at higher frequencies (230 GHz and 345 GHz), nor at 5 GHz with VLBI arrays. The emission appears to be stable over almost three years at 6 GHz. To explain the constraints obtained both from the detections and non-detections, we considered multiple scenarios including thermal and nonthermal emission, and different contributions from each component of the binary. Our results can be well explained by nonthermal gyrosynchrotron emission originating at radiation belts with a low plasma density, a moderate magnetic field strength (B =140 G), and an energy distribution of electrons following a power-law.

The HD 260655 system. We discovered two rocky worlds transiting a bright M dwarf at 10 pc. The planets have been detected in transit by the Transiting Exoplanet Survey Satellite (TESS) mission and confirmed independently with archival and new precise radial velocities obtained with the HIRES and CARMENES instruments since 1998 and 2016, respectively. At a distance of 10 pc, HD 260655 has become the fourth closest known multitransiting planet system after HD 219134, LTT 1445 A, and AU Mic. Due to the apparent brightness of the host star (J = 6.7 mag), both planets are among the most suitable rocky worlds known today for atmospheric studies with the James Webb Space Telescope, both in transmission and emission.

4

Scientific Publications in 2022

The publications of CAPA members during 2022 are listed in annex N[1]. The present section contains some plots which try to give an overview of the scientific production of CAPA in 2022.

Fig. 4.1 shows how the number of publications per year from present CAPA members have evolved in the last ten years. Fig. 4.2 indicates the evolution of the number of citations per year of these publications. Finally, Fig. 4.3 gives a graphical picture of how the 2022 CAPA publications are distributed in the different journals.

Figure 4.1: Evolution of the number of publications per year.

[1]One of CAPA's researchers, Juan Antonio García Pascual, is a member of the ATLAS collaboration; however, we do not list more than 30 publications from ATLAS since they are not representative of the activity of the center.

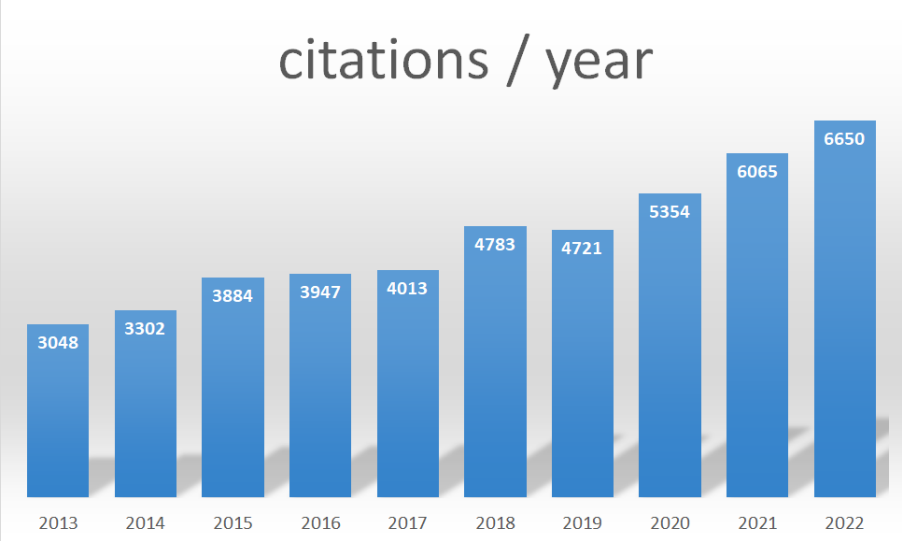

Figure 4.2: Evolution of the number of citations per year.

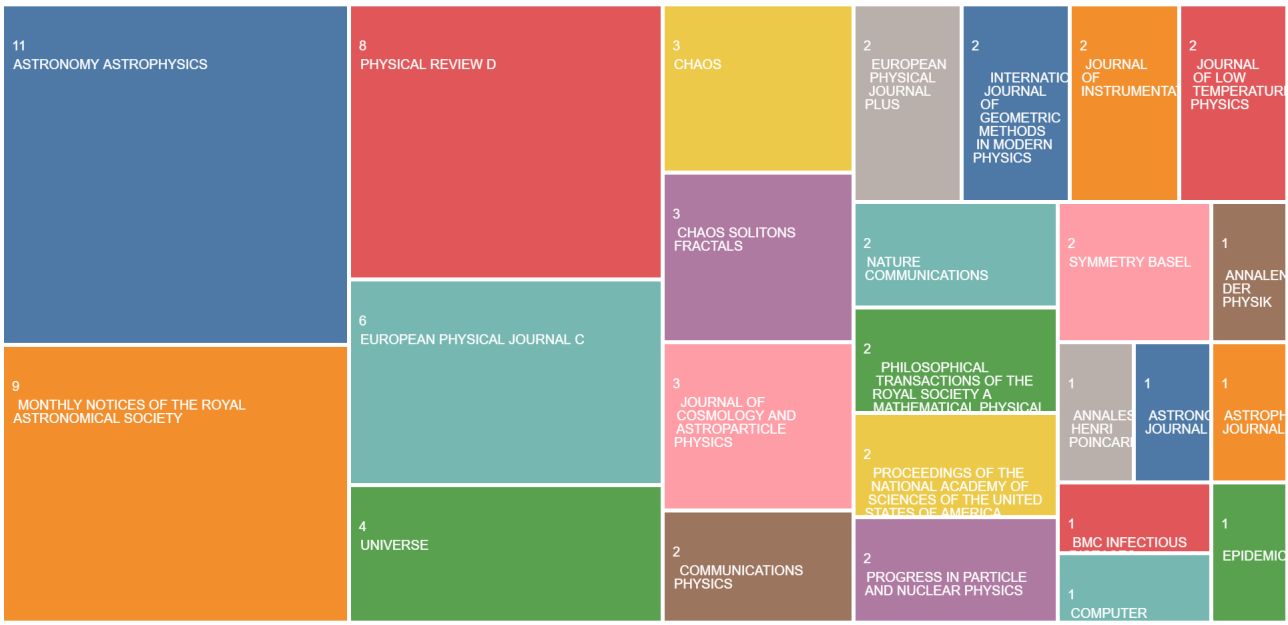

Figure 4.3: Journal distribution of CAPA publications in 2022.

5

Organization of conferences and seminars

5.1 | Conferences

CAPA members organized the *First LatticeNET workshop on challenges in Lattice field theory* which took place in the Centro de Ciencias Pedro Pascual in Benasque, which is a center closely related to CAPA.

The organization of the *Third Annual Conference of the COST Action CA18108*, held in Naples (Italy) was also led by CAPA; the website of the conference is indeed in the CAPA indico page (https://indico.capa.unizar.es/event/21/). The conference joined theoretical physicists and experimental physicists working in the search of quantum gravity signatures with the detection of the cosmic messengers. The meeting included review talks and contributions on quantum gravity models, cosmology and modified gravity models, as well as experimental analysis techniques and detection results of high-energy photons, neutrinos, ultra high-energy cosmic rays and gravitational waves. More than 80 participants attended the conference.

Finally, CAPA organizes yearly in December, in collaboration with the Department of Theoretical Physics of the University of Zaragoza, the *Saturnalia* meeting (https://indico.capa.unizar.es/event/32/), where different ex-members of the department and other invited researchers present their works in a rather informal atmosphere. This year's meeting was also celebrated in a hybrid mode, with a few talks delivered online.

We list these events in annex C. We also include there the organization of other conferences and workshops where, although not directly organized by CAPA, several CAPA members were involved.

5.2 | Seminars

CAPA organized different a number of research seminars. They are always announced at CAPA's website, https://capa.unizar.es/ and some of them are connected to activities of the Master on Physics of the Universe. Last year CAPA also started the organization of 'colloquia', which are addressed to a less specialized audience and have a larger outreach component on topics of broad interest related to the fields of research of the center. These colloquia are broadcasted live and stored in the CAPA YouTube channel, https://www.youtube.com/channel/UC8gheC8DEgTmiwyA1kqs8_Q

Seminars and colloquia are listed in annex D.

6

Training and teaching activities

6.1 | Master on Physics of the Universe at UNIZAR

The 2022-23 academic year has been the second academic year of the **Master on Physics of the Universe: Cosmology, Astrophysics, Particles and Astroparticles** (whose web page is here). This Master offers a theoretical-phenomenological or/and experimental-technological formation learning in leading research centers and in an international research environment. The training offered by the Master's degree is framed in a privileged area of unique and excellent research. In the national and international context, Aragon stands out for this line of research: the Centre of Astroparticles and High Energy Physics (CAPA), the Canfranc Underground Laboratory (LSC), and the Centre of Physics of the Cosmos of Aragon (CEFCA) have researchers and leading technologists in the lines of study of the title. A high-quality knowledge is offered, distinct from other national and international master titles. The University of Zaragoza, and CAPA as the Center coordinator of the Master could be a reference center for training in high-energy physics, cosmology, astronomy, astrophysics and astroparticles.

The Master also offers a blended learning, which combines a face-to-face traditional training with on line resources, to adapt the courses to the needs of the students anytime. For the same reasons, all the courses have an English/Spanish bilingual format.

The profile of the students are very varied: physicists, mathematicians, engineers; from the University of Zaragoza, from other universities, Erasmus; full time, part time; ... The teachers need to be able to adapt their classes to this diversity. After a first year, the degree of satisfaction of the students is very high.

Many of the CAPA researchers are involved in teaching activities of the Master, which implies a great effort, as well as coordination with researchers from the LSC and CEFCA. Courses have been taught on topics such as Cosmology, Particle Physics, Astroparticles and Astrophysics; leading researchers have given lectures; and visits to the LSC and CEFCA have involved some days of training in astroparticle physics, cosmology and astrophysics.

6.2 | Participation in schools

CAPA was the responsible of the organization of one of the most successful *Cursos extraordinarios de la Universidad de Zaragoza* (page 83 of the 2022 report). The objective of the course was to give a short introduction to topics

Figure 6.1: Master students visit the Laboratorio Subterráneo de Canfranc (left) and the Observatorio Astrofísico de Javalambre (right).

related to the Physics of the Universe, for a diverse audience (students of different levels, secondary school teachers and other interested people).

Researchers of CAPA were the organizers of the LatticeNET School on Computing in HEP. The school aimed to develop a broad interest program, oriented to generate synergies across the community, specially among Master students, PhD students and early career postdocs.

CAPA also participated in the organization of the COST Action CA18108 Second Training School (https://indico.capa.unizar.es/event/23/) that took place in Belgrade, Serbia, in September 2022. Its main objective was the training of PhD students and young postdoctoral researchers in advanced topics of the quantum gravity problem and the physics of the cosmic messengers. It consisted of seven courses which combined lectures and tutorial sessions. More than thirty students attended the training school.

These and other schools are listed together with other conferences and workshops organized or co-organized by CAPA in Annex C.

7

Outreach activities

7.1 | Dark Matter Day

Dark Matter Day is a globally recognized celebration sponsored by the Interactions Collaboration, an international community of particle physics communication specialists. CAPA has joined this celebration since its apparition in 2017.

This year, the activity "Hands on Dark Matter" was carried out on October 28. This day high school students attended different talks on the subject and participate in activities in GIFNA laboratories. Some pictures of the event are shown in Fig. 7.1.

Coinciding with Halloween, October 31, CAPA researchers organized, as every year, a gymkhana at the Faculty of Sciences. Stalls with activities around particle physics, astroparticles and astrophysics are set up. Families with children, and other interested people, willing to learn and have fun, attend the activity.

7.2 | Hands on Particle Physics

This activity has been organized by researchers of CAPA for more than a decade in the framework of the International Particle Physics Outreach Group. In the morning, high school students attend lectures on particle physics, accelerators, detectors and methods of basic research at the foundariona of matter and forces. That enables the students to perform measurements on real data from particle physics experiments themselves. After Higgs discovery in LHC, Zaragoza and Huesca students analyze ATLAS data regarding the *Z-path*. In the afternoon, as any international research collaboration does, the participants join students from other institutions in a video conference lead by CERN researchers for discussion and combination of their results.

7.3 | Faculty open days and Science immersion week (physics)

Members of CAPA once again welcomed high school students to talk to them about astroparticles and show them the activities carried out in the GIFNA laboratories.

Figure 7.1: Some pictures of the "Hands on Dark Matter" activity

A group of CAPA researchers were also involved in the Science immersion week aimed to high school students interested in Physics. In this context CAPA offers activities on cosmology ans astrophysics, particle physics, astroparticles and cosmic rays.

7.4 | European researchers' night

The University of Zaragoza held the European Night of Researchers on September 30, 2022. CAPA researchers collaborated with two "experiments" ("Bajo los rayos cósmicos" and "Un mundo radioactivo"), offering activities for all audiences in the *Paraninfo* building (figure 7.3), and two talks "Desarrollo de técnicas de bajo fondo para búsqueda de materia oscura" and "Un Universo de radiaciones".

Connected to this international celebration, and as an pre-event, some activities were offered to primary school students in the *Rincón de la Ciencia* of the *Mercado agroalimentario* of the Campus.

Figure 7.2: Pictures of the 2022 Dark Matter Day gymkhana

Figure 7.3: European researchers' night activities. Participants, soft toys of the *Particle Zoo*, radioactivity cards, and a muon detector, can be seen on the table.

7.5 | Other activities

Further activities, mainly talks, have been collected in the annex I.

8

Equipment and facilities

As it is typical from frontier particle physics research, the activity at CAPA is performed using very specialized infrastructure available in international research facilities and centers like CERN, DESY or LSC. The latter is particularly relevant to the research trajectory of CAPA, as it hosts unique infrastructure associated with underground physics and low-background techniques that are central in CAPA expertise and activity. In the following we describe only the particular equipment or facilities that have been developed mostly by CAPA researchers (or acquired as part of CAPA projects) and are currently being used for particular project or more transversally to provide service to more than one project. Some of the described infrastructure is at the CAPA premises at the University of Zaragoza, but other is physically at the LSC.

8.1 | Ge detectors

Several close-end, coaxial, High Purity germanium detectors owned by the University of Zaragoza are operated at the Canfranc Underground Laboratory to carry out gamma spectroscopy measurements to quantify the radioactivity of materials used in experiments with participation of members of GIFNA ("Grupo de Investigación en Física Nuclear y Astropartículas") like ANAIS, IAXO and TREX-DM. Sensitivities at the level of mBq/kg for ^{232}U and ^{238}Th natural chains and ^{40}K are typically obtained with these detectors. All of them have copper cryostats, shieldings made of copper and/or low activity lead from 20 to 30 cm and are enclosed in a plastic bag or box continuously flushed with boil-off nitrogen or radon-free air to avoid radon intrusion. The electronic chains for the data acquisition include linear amplifiers and Analog-to-Digital-Converter modules to get energy spectra.

The detectors named Paco and Paquito were produced in the US and have a mass of about 1 kg and 40% relative efficiency. They are operated at the LAB2500 of LSC (see Fig. 8.1); Paco is underground in Canfranc for more than thirty years. Other two detectors, having a mass of about 2 kg and 100% relative efficiency, were acquired to Canberra (model GC9571, serial numbers b 07074 and b 07084) in 2006. They are operated together with the germanium detectors of the Ultra Low Background Service of LSC at the LAB2400. The use and maintenance of these two detectors, named Asterix and Obelix, and their shieldings have been transferred to LSC as a part of the collaboration agreement between LSC and GIFNA, guaranteeing the preferential access to GIFNA for radiopurity measurements using these or equivalent detectors.

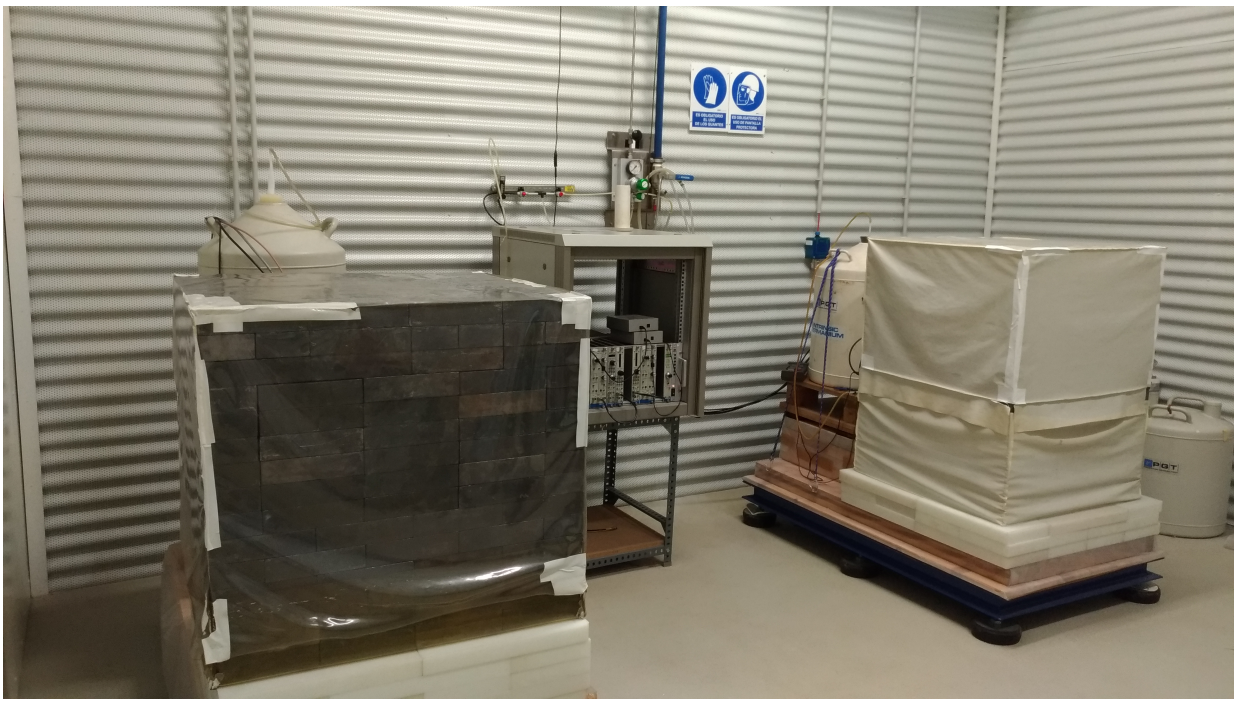

Figure 8.1: LAB2500 at the Canfranc Underground Laboratory where Paco and Paquito detectors are operated.

8.2 | IAXOlab

The new IAXOlab is a 140 m^2 laboratory space in the CIRCE building of the Rio Ebro campus of the Universidad de Zaragoza. It was set up mainly to host the activities of the IAXO project (see section 3.1), just after the AdG-ERC was granted in 2019. However it inherits from, and expands on, the previous TREX laboratory space that was previously set up by the group, for the development, construction and characterization of novel particle detectors based on time projection chambers (TPCs) and micro-pattern gas detectors (MPGDs), with a special focus on low background applications. As such, the laboratory counts with various gas working points and the needed circuitry from the outdoor gas storage space. It also includes equipment associated with high purity gas systems and ultrahigh vacuum vessels, like pressure sensors, flowmeters, back-pressure controllers, filters gas mixers, turbo molecular and primary pumps, leak detectors and a mass spectrometer, as well as different vacuum and high-pressure vessels. In addition, it includes two laminar flow cabinets, various oscilloscopes, a set of nuclear electronics modules and racks. A very important asset to equip TPC-like setups are the specific electronic TPC DAQ cards based on specialized chips like AFTER, AGET and more recently, the newest STAGE.

8.3 | AlphaCAMM

A new detection concept, AlphaCAMM (Alpha CAMera Micromegas), for a high-sensitivity screening of ^{210}Po surface contamination has been developmed at CAPA. AlphaCAMM exploits the Micromegas readout capabilities to

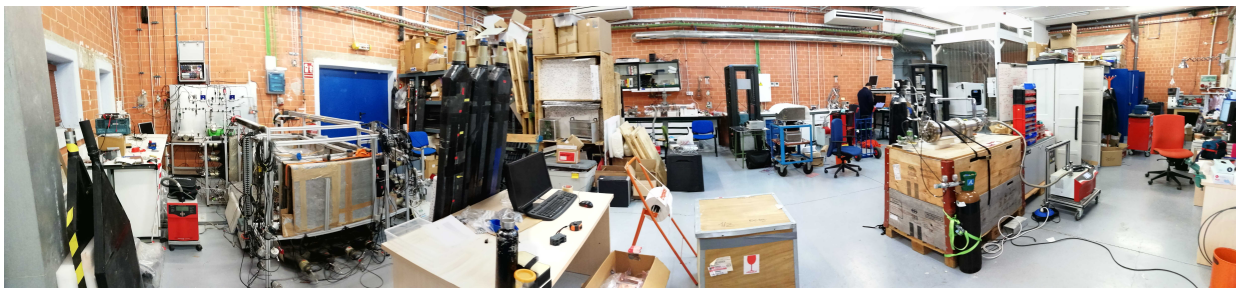

Figure 8.2: Picture of the IAXOlab at the CIRCE building in Rio Ebro Campus of the University of Zaragoza

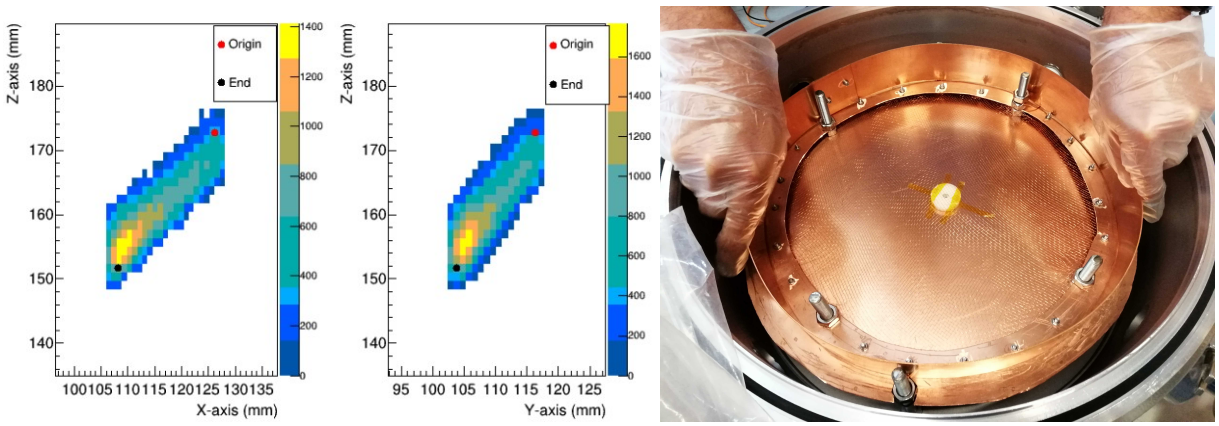

Figure 8.3: **Left:** Projection of a single ^{241}Am alpha event in the XZ and the YZ planes for the new AlphaCAMM radiopure prototype. The red dots represent the reconstructed origin of the track while the black dots correspond to the reconstructed end in the different projections. **Right:** New radiopure AlphaCAMM vessel, the ^{241}Am alpha source can be seen sitting on below of the cathode.

image and identify alpha particle tracks, therefore increasing the signal to background ratio. The detection concept of AlphaCAMM was proven in a non-radiopure prototype [1] by the development of a new reconstruction method for the determination of the origin and the end of alpha tracks with high precision (see Figure 8.3 left). A new radiopure AlphaCAMM prototype with high standards of radiopurity has been built at CAPA and is shown in the right hand side of Figure 8.3 and is currently under commissioning. A 256×256 mm^{-2} microbulk Micromegas readout has been installed, and the vessel's leak tightness has been evaluated. Initial measurements using a ^{241}Am source have been performed, demonstrating excellent spatial and energy resolutions of the Micromegas plane. AlphaCAMM is currently assessing its intrinsic background. Once the background level is determined, the ^{210}Po surface contamination of different samples will be measured.

[1] K. Altenmuller,et al. AlphaCAMM, a Micromegas-based camera for high-sensitivity screening of alpha surface contamination. *JOURNAL OF INSTRUMENTATION* **17** (2022).

8.4 | ANAIS

8.4.1 | ANAIS-112 experiment at LSC

The ANAIS-112 experiment consists of 112.5 kg of NaI(Tl), distributed in 9 modules, 12.5 kg each and built by Alpha Spectra Inc. Among the most relevant features of ANAIS-112 modules we can mention a remarkable optical quality, which combined to using high quantum efficiency Hamamatsu photomultipliers (PMTs) results in a very high light collection, at the level of 15 photoelectrons (phe) per keV in all the nine modules. Another interesting feature is a Mylar window in the middle of one of the lateral faces of the detectors, which allows to calibrate the modules with external sources at low energies.

The ANAIS-112 experiment is installed at the Canfranc Underground Laboratory, inside a shielding consisting of an inner layer of 10 cm of archaeological lead and an outer layer of 20 cm of low activity lead. This lead shielding is encased into an anti-radon box, tightly closed and kept under overpressure with radon-free nitrogen gas. The external layer of the shielding (the neutron shielding) consists of 40 cm of a combination of water tanks and polyethylene bricks. An active veto made up of 16 plastic scintillators is placed between the anti-radon box and the neutron shielding, covering the top and sides of the set-up (see Figure 3.5) allowing to effectively tag the residual muon flux.

Concerning radioactive backgrounds, a careful background model of the whole ANAIS-112 experiment has been developed, by combining inputs from different analysis techniques: HPGe screening of different materials used in the set-up and in the detector building, measurements in coincidence of the modules before ANAIS-112 commissioning, determination of alpha rate by using PSD, estimates of cosmogenic activation rates in NaI, etc. Considering altogether the nine ANAIS-112 modules the average background in the ROI (from 1 to 6 keV) is 3.6 cpd/kg/keV after three years of data taking, while DAMA/LIBRAphase2 background is below 0.80 cpd/kg/keV in the [1–2] keV energy interval, below 0.24 cpd/kg/keV in the [2–3] keV energy interval, and below 0.12 cpd/kg/keV in the [3–4] keV energy interval.

ANAIS-112 experiment operation at the LSC facilities has been granted until 2025. This will allow to accumulate enough statistics to test the DAMA/LIBRA result at about 5 sigma level.

8.4.2 | ANAIS laboratory at UNIZAR

At Zaragoza University there is a laboratory equipped to mount and test scintillating detectors. A large size glove box keeping a very low humidity atmosphere, shown in Figure 8.4, allows handling bare highly hygroscopic materials, as NaI and NaI(Tl) crystals, and coupling them to different light sensors, as PMTs or SiPMs.

Figure 8.4: Picture of the ANAIS glove box, continuously keeping a dry atmosphere to preserve and work with sodium iodide crystals.

Along 2022, a new test bench has been developed to allow cooling scintillation detector prototypes using SiPMs as light sensors down to -40ºC, and it has been initiated a tender process to acquire a cryocooler enabling to extend these tests under temperature controlled conditions below 100 K. In addition, the laboratory disposes of all the hardware and software components required for implementing the corresponding electronic chain and data acquisition system. Figure 8.5 shows a general view of the ANAIS laboratory at the Zaragoza University facilities.

Figure 8.5: General view of the ANAIS laboratory at Zaragoza University facilities.

8.5 | IAXO-D0 and IAXO-D1

IAXO-D0 and IAXO-D1 are two different Micromegas demonstrator set-ups for the R&D on ultra-low background detectors for BabyIAXO and IAXO. The Micromegas detector for both set-ups consists of a small gaseous time projection chamber of 3 cm drift distance, and a microbulk readout plane of about 6×6 cm^2 area, with a pixelated anode readout of 0.5 mm pitch. The detector chamber is built with the highest radiopurity standards (electroformed copper for the detector body, copper and teflon for the field cage, kapton and copper for the microbulk readout and the routing of the signals out of the detector). The cathode is provided by a small thin mylar window facing the vacuum of the beam line. The experimental set-up reproduces realistic data taking conditions, in which the signal x-rays that are focused into a few-mm-wide signal spot, enter the detector through this window.

The IAXO-D0 set-up was conceived as a replica of the most sensitive detector operated at CAST, known as the "IAXO pathfinder" system. However, different upgrades have been carried out taking into account the mechanical and space considerations for BabyIAXO. The detector is surrounded by an enhanced passive (lead) and active shielding with respect to the former CAST set-up. The active shielding is formed by three layers of plastic scintillators intercalated by cadmium foils, with the aim of tagging cosmic muons and neutrons (see figure 3.4 left).

The IAXO-D1 set-up introduces a new design in which new Micromegas detectors have been built with higher standards of radiopurity. They incorporate important technical improvements like a more robust and radiopure connectors and a better layout to extract the signals out of the detector to the front-end electronics. IAXO-D1 has been installed and commissioned at the LSC as shown in the right hand side of 3.4. The main objective is to measure the intrinsic background level of the Micromegas detector underground, in which the cosmic background is highly suppressed. The short-term plans include the assessment of the intrinsic background using different gas mixtures such as Xe-Ne-iC4H10 and Ar-iC4H10. Long-term plans foresee the installation of new radiopure electronics, currently under construction, in order to understand their effect on the background and a possible improvement in the signal to noise ratio.

8.6 | TREX-DM

TREX-DM is a high pressure time projection chamber conceived for the search of low-mass WIMPs (see section 3.3). The detector (Fig. 8.6) has been designed to host 0.3 kg of argon mass at 10 bar (or, alternatively, 0.16 kg of neon). In some aspects, it is a scaled-up version of CAST Micromegas x-ray detectors but with a 10^3 larger active mass. It is composed of a copper vessel, with an inner diameter of 0.5 m, a length of 0.5 m and a wall thickness of 6 cm. The vessel is divided in two active volumes by a central aluminized mylar cathode, which is connected to high voltage by a tailor-made feedthrough. At each side there is a 19 cm long field cage, composed of a copper-kapton printed circuit screwed to four teflon walls. At each vessel endcap, one Micromegas readout plane (Fig. 3.9) is screwed to a copper base, which is then attached to the endcap. The readout has an active surface of 25×25 cm^2 and has been built with the microbulk technology, out of kapton and copper. It is patterned with ~ 1 mm side pixels, which are linked together in x and y directions, amounting to a total of 250 x and 250 y channels each of the 2 planes. The signals are extracted from the vessel by flat cables coming out through a slit at the endcap and a feedthrough screwed at the external side. The outer end of the cable is connected to the front-end electronics, an auto-triggering multichannel digitized board based on the AGET chip developed at CEA/Saclay.

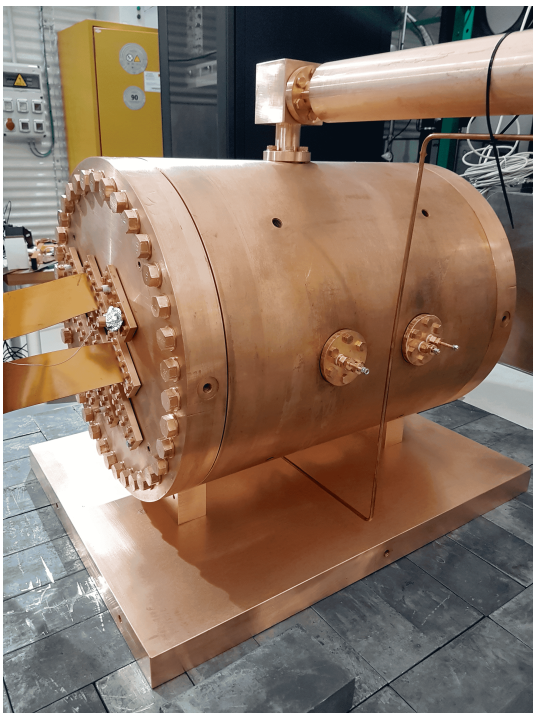

Figure 8.6: Picture of the TREX-DM detector, during its installation at the LSC, previous to the installation of the shielding.

The detector is surrounded by a 20 cm thick passive shielding against environmental gammas, made of low-radiactivity lead. The 6-cm thickness of the copper vessel serves, in addition to hold the high pressure gas, as the innermost layer of passive shielding to stop the emissions of the innermost lead layers (e.g. Pb^{210}). The lead shielding is further surrounded by an additional 40 cm of polyethylene (at the top and bottom) or water tanks (at the sides) as neutron shielding (the water tanks are foreseen but not yet installed). Finally, the inside of the shielding is flushed with radon-free air to remove the radon from the space close to the detector.

In october 2022, the setup was dismantled from its location at the hall A of LSC, and is expected to be recommissioned at its new site at the LAB2500, by summer 2023.

8.7 | LABAC

The LABAC facilities, located at the Faculty of Science (see Fig. 8.7), include a radiochemistry laboratory fully equipped for the preparation of samples. In some cases physical-chemical treatments are required to set up the original samples in shape and size according to the different requirements of the equipment. In other cases, as in the determination of certain radioisotopes, it is necessary to perform a radiochemical separation of a specific element.

There is also appropriate equipment for sampling (aerosols and radioiodine, tap or rain water, soil, food) in accordance with standard operating procedures. In the radiophysics laboratory the determination of ambient equivalent doses or alpha, beta and gamma activities is performed using different detection systems, which include two low background germanium detectors (GR3520 and GX4018 Canberra), two gas flow proportional counters (HT-1000 Canberra and Berthold 770-2), a solid scintillation counter, an integrated alpha spectrometer (Alpha Analyst 7401 VR Canberra) and a thermoluminescent dosimeter reader (Panasonic UD-716AGL).

Figure 8.7: Pictures of some LABAC facilities: radiochemistry laboratory (left) and one germanium detector inside a shielding (right)

A

Research grants

Current research grants (remarking which ones where obtained in 2022)

1. TITLE: **From Exoplanets to supermAssive black holes: exploring The cosmic frontiers at the HighEst angular Resolution and Sensitivity with the EHT and SKA pathfinders (FEATHERS) (MICIUN PID2020-117404GB-C21)**
   MAIN RESEARCHER(S): Miguel Pérez Torres, Antonio Alberdi Odriozola
   BUDGET: 138.545 EUR €
   AGENCY: Spanish MICIN
   YEARS: 2021-2023

2. TITLE: **Low background techniques on particle detectors for Rare Event Searches (LOBRES) (MSCA 101026819)**
   MAIN RESEARCHER(S): Theopisti Dafni, Juan Antonio García
   BUDGET: 160 000 €
   AGENCY: European Union (MSCA Horizon 2020)
   YEARS: 2022-2024

3. TITLE: **IAXO+: Towards the detection of the axion with the International Axion Observatory (ERC-AdG 788781)**
   MAIN RESEARCHER(S): Igor G. Irastorza
   BUDGET: 3 106 875 €
   AGENCY: European Research Council
   YEARS: 2018-2023

4. TITLE: **ANAIS-112 experiment and new research lines for rare events detection at Canfranc Underground Laboratory (PID2019-104374GB-I00)**
   MAIN RESEARCHER(S): María Luisa Sarsa Sarsa and María Martínez Pérez
   BUDGET: 219 010 €

AGENCY: Agencia Estatal de Investigación
YEARS: 2020-2023

5. TITLE: **Actividades de coordinación de la construcción de BabyIAXO, construcción de los detectores de rayos-X del experimento, y otras contribuciones relacionadas. (PID2019-108122GB-C31)**
MAIN RESEARCHER(S): Igor G. Irastorza and Gloria Luzón
BUDGET: 340 736 €
AGENCY: Agencia Estatal de Investigación
YEARS: 2020-2024

6. TITLE: **Further beyond the standard models in dark matter, gravity and symmetry (PGC2021-126078NB-C2)**
MAIN RESEARCHER(S): Javier Redondo, Siannah Peñaranda
BUDGET: 387.200 €
AGENCY: Ministerio de Ciencia e Innovación
YEARS: 2022-2025

7. TITLE: **Beyond the standard models: symmetry, gravity and dark matter (PGC2018-095328-B-100)**
MAIN RESEARCHER(S): Eduardo Follana, Javier Redondo
BUDGET: 326.700 €
AGENCY: Ministerio de Ciencia, Innovación y Universidades
YEARS: 2019-2022

8. TITLE: **Quantum ENIA: creación de un ecosistema de computación cuántica para la Inteligencia Artificial (IA) (605851-C16.R1)**
MAIN RESEARCHER(S): Manuel Asorey
BUDGET: 250.000 €
AGENCY: Ministerio de Asuntos Económicos y Transformación Digital
YEARS: 2022-2025

9. TITLE: **Large area high-granularity segmented-mesh microbulk for future rare event searches (RD51-2021)**
MAIN RESEARCHER(S): Javier Galan
BUDGET: 20.000 €
AGENCY: RD51 Collaboration, CERN
YEARS: 2021-2022

10. TITLE: **Búsquedas directas de materia oscura (ANAIS+: mejoras en la sensibilidad de ANAIS-112 usando aprendizaje automático y una nueva aproximación experimental), en el marco del Convenio de Colaboración entre el Gobierno de Aragón, la Fundación Centro de Estudios de Físicas del Cosmos de Aragón, la Universidad de Zaragoza y el Instituto Tecnológico de Aragón para la ejecución de líneas de actuación de I+D+i en el marco de los planes complementarios previstos en el Plan de Recuperación, transformación y Resiliencia-MRR (LA5.A3.)**

MAIN RESEARCHER(S): María Martínez
BUDGET: 185.000 €
AGENCY: Ministerio de Ciencia e Innovación / Gobierno de Aragón
YEARS: 2022-2025

11. TITLE: **Búsquedas directas de materia oscura (Integración de la línea de detección de ultra-bajo fondo del heliscopio de axiones BabyIAXO, y estudio de la ampliación del caso de física a la detección de axiones de Materia Oscura), en el marco del Convenio de Colaboración entre el Gobierno de Aragón, la Fundación Centro de Estudios de Físicas del Cosmos de Aragón, la Universidad de Zaragoza y el Instituto Tecnológico de Aragón para la ejecución de líneas de actuación de I+D+i en el marco de los planes complementarios previstos en el Plan de Recuperación, transformación y Resiliencia-MRR (LA5.A1.)**
MAIN RESEARCHER(S): Igor G. Irastorza and Gloria Luzón
BUDGET: 725.000 €
AGENCY: Ministerio de Ciencia e Innovación / Gobierno de Aragón
YEARS: 2022-2025

12. TITLE: **Búsquedas directas de materia oscura (Implementación de mejoras en umbral energético y ruido de fondo del experimento TREX-DM de búsqueda de WIMPs de baja masa en el LSC), en el marco del Convenio de Colaboración entre el Gobierno de Aragón, la Fundación Centro de Estudios de Físicas del Cosmos de Aragón, la Universidad de Zaragoza y el Instituto Tecnológico de Aragón para la ejecución de líneas de actuación de I+D+i en el marco de los planes complementarios previstos en el Plan de Recuperación, transformación y Resiliencia-MRR (LA5.A2.)**
MAIN RESEARCHER(S): Theopisti Dafni
BUDGET: 196.075 €
AGENCY: Ministerio de Ciencia e Innovación / Gobierno de Aragón
YEARS: 2022-2025

B

Networking grants

1. TITLE: **Quantum gravity phenomenology in the multi-messenger approach (COST Action CA18108)**
   MAIN RESEARCHER(S): José Manuel Carmona (Action Chair)
   LOCAL NODE MAIN RESEARCHER(S): José Manuel Carmona, José Luis Cortés
   BUDGET: 3rd Grant Period (2021-22): 151 800 €
   AGENCY: COST (European Cooperation in Science and Technology)
   YEARS: 2019-2023

2. TITLE: **Red de Física de Partículas (RED2022-134487-T)**
   MAIN RESEARCHER(S): Igor G. Irastorza (resolución provisional)
   BUDGET: 20 300 €
   AGENCY: Agencia Estatal de Investigación
   YEARS: 2023-2025

3. TITLE: **Red española de Lattice Gauge Theory LATTICENET (RED2018-102504-T)**
   MAIN RESEARCHER(S): Vicente Azcoiti
   BUDGET: 12 000 €
   AGENCY: Agencia Estatal de Investigación
   YEARS: 2020-2022

4. TITLE: **COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments (COST Action CA21106)**
   MAIN RESEARCHER(S): Alessandro Mirizzi (Bari University), Action chair
   LOCAL NODE MAIN RESEARCHER(S): Igor G. Irastorza (Spanish representative in Managing Committee), Javier Redondo, Julia Vogel
   AGENCY: COST (European Cooperation in Science and Technology)
   YEARS: 2022-2026

C

Organization of conferences, workshops and schools

1. EVENT: **COST CA18108 Third Annual Conference and Workshop on future challenges and opportunities in quantum gravity phenomenology**
   PARTICIPANT(S): José Manuel Carmona
   TYPE OF PARTICIPATION: Member of the Organizing Committee
   VENUE: Naples, Italy
   DATE: 11/07/22-15/07/22
   URL: https://indico.capa.unizar.es/event/21/
   URL: https://indico.capa.unizar.es/event/22/

2. EVENT: **Workshop on New Trends in Quantum Physics**
   PARTICIPANT(S): Manuel Asorey, F. Falceto
   TYPE OF PARTICIPATION: Members of the Organizing Committee
   VENUE: CAPA, Zaragoza, Spain
   DATE: 5/05/22-6/05/22

3. EVENT: **Saturnalia 2022**
   PARTICIPANT(S): Javier Redondo, Siannah Peñaranda, Jorge Alda, Mathieu Kaltschmidt
   TYPE OF PARTICIPATION: Local Organizing Committee
   VENUE: Zaragoza, Spain
   DATE: 16/12/22-22/12/22
   URL: https://indico.capa.unizar.es/event/32/

4. EVENT: **COST CA18108 Second Training School**
   PARTICIPANT(S): José Manuel Carmona

TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Belgrade, Serbia
DATE: 03/09/22-10/09/22
URL: https://indico.capa.unizar.es/event/23/

5. EVENT: **Workshop on theoretical and experimental advances in quantum gravity**
PARTICIPANT(S): José Manuel Carmona
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Belgrade, Serbia
DATE: 01/09/22-03/09/22
URL: https://indico.capa.unizar.es/event/24/

6. EVENT: **Primer encuentro de la red temática española de lattice gauge theory, LatticeNET**
PARTICIPANT(S): Vicente Azcoiti, Eduardo Follana
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Zaragoza
DATE: 24/01/22-25/01/22

7. EVENT: **@FlipPhysics**
PARTICIPANT(S): Susana Cebrián
TYPE OF PARTICIPATION: Member of the Scientific Advisory Committee
VENUE: Zaragoza
DATE: 21/03/22-25/03/22
URL: https://indico.ific.uv.es/event/6372/

8. EVENT: **Curso extraordinario UNIZAR: Física del Universo**
PARTICIPANT(S): Theopisti Dafni and Eduardo Follana
TYPE OF PARTICIPATION: Organizers
PARTICIPANT(S): Manuel Asorey, Susana Cebrián,Javier Galán, Gloria Luzón, María Martínez and Siannah Peñaranda
TYPE OF PARTICIPATION: Lecturers
VENUE: Jaca
DATE: 18/07/22-20/07/22

9. EVENT: **First LatticeNET workshop on challenges in Lattice field theory**
PARTICIPANT(S): Vicente Azcoiti and Eduardo Follana
TYPE OF PARTICIPATION: Member of the Organizing Committee

VENUE: Benasque, Spain
DATE: 11/09/22-17/09/22
URL: https://www.benasque.org/2022lattice_workshop/

10. EVENT: **LatticeNET School on Computing in HEP**
PARTICIPANT(S): Vicente Azcoiti and Eduardo Follana
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Benasque, Spain
DATE: 18/09/22-24/09/22
URL: https://www.benasque.org/2022lattice/

11. EVENT: **10ª Jornada de Jóvenes Investigadores de Química y Física de Aragón**
PARTICIPANT(S): Susana Cebrián
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Valencia
DATE: 14/12/22-14/12/22
URL: https://eventos.unizar.es/89124/detail/10o-jornada-de-jovenes-investigadores-de-quimica-y-fisica-de-aragon.html

12. EVENT: **10ª Summer School on Geometry, Mechanics and Control**
PARTICIPANT(S): José Javier Relancio Martínez
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: Burgos
DATE: 04/07/22-08/07/22
URL: https://sites.google.com/view/14summerschoolgmcnetwork

13. EVENT: **Quantum Effective Field Theory and Black Hole Tests of Einstein Gravity**
PARTICIPANT(S): Manuel Asorey
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: IFPU, SISSA, Trieste, Italy
DATE: 12/09/22-16/09/22
URL: https://grams-815673.wixsite.com/september12-16

14. EVENT: **Workshop on Feebly-Interacting Particles FIPs2022**
PARTICIPANT(S): Igor G. Irastorza
TYPE OF PARTICIPATION: Member of the Organizing Committee
VENUE: CERN, Geneva, Switzerland

DATE: 17/10/22-21/10/22
URL: https://indico.cern.ch/event/1119695/

D

Seminars and Colloquia at CAPA

1. TITLE: **Soundscape of gravitational waves: a new tool to access the fundamental blocks of the Universe**
   SPEAKER: Diego Blas
   INSTITUTION: UAB and IFAE, Barcelona
   DATE: 21-02-2022

2. TITLE: **Spectral evolution of white dwarfs with J-PLUS**
   SPEAKER: Carlos López San Juan
   INSTITUTION: CEFCA(Centro de Estudios de Física del Cosmos de Aragón)
   DATE: 10-03-2022

3. TITLE: **Effective quantum gravity, cosmological constant and the Standard Model of particle physics**
   SPEAKER: Ilya L. Shapiro
   INSTITUTION: Universidade Federal de Juiz de Fora, Minas Gerais, Brazil)
   DATE: 29-03-2022

4. TITLE: **Quantum Gravity and Hamilton-Jacobi theory**
   SPEAKER: Jorge Gamboa
   INSTITUTION: Universidad de Santiago de Chile
   DATE: 28-04-2022

5. TITLE: **Primordial black holes as dark matter candidates**
   SPEAKER: Juan Garcia-Bellido
   INSTITUTION: UAM / IFT, Madrid
   DATE: 16-05-2022

6. TITLE: **How fundamental is entropy: on the way to unique universal entropy construct**
   SPEAKER: S.D. Odintsov
   INSTITUTION: ICE, CSIC/IEEC and ICREA Barcelona
   DATE: 18-05-2022

7. TITLE: **Muography and Nuclear Safety: Reactors surveillance, and monitoring and waste qualification**
   SPEAKER: Héctor Gómez-Maluenda
   INSTITUTION: Commissariat à l'énergie atomique et aux énergies alternatives» (CEA – France)
   DATE: 5-05-2022

8. TITLE: **Synergies in plasma physics: exoplanet habitability and radio emission**
   SPEAKER: Jacobo Varela Rodríguez
   INSTITUTION: Universidad Carlos III, Madrid
   DATE: 19-05-2022

9. TITLE: **Sterile neutrinos as dark matter candidates**
   SPEAKER: Susanne Mertens
   INSTITUTION: Technical University Munich (TUM)
   DATE: 19-05-2022

10. TITLE: **Dark matter searches at LHC**
    SPEAKER: Sven Heinemeyer
    INSTITUTION: Instituto de Física de Cantabria
    DATE: 26-05-2022

11. TITLE: **Stars as Particle-Physics Laboratories: Old Ideas and New Developments**
    SPEAKER: Georg G. Raffelt
    INSTITUTION: Max-Planck-Institut für Physik
    DATE: 27-10-2022

12. TITLE: **Indirect searches for dark matter with ANTARES and KM3NeT neutrino data**
    SPEAKER: Rebecca Gozzini
    INSTITUTION: Instituto de Física Corpuscular, Valencia
    DATE: 24-11-2022

13. TITLE: **Saturnalia 2022: ALP production in weak mesonic decays**
    SPEAKER: Alfredo Walter Mario Guerrera

INSTITUTION: INFN, Padua
DATE: 19-12-2022

14. TITLE: **Saturnalia 2022: Parametric resonances in domain walls and cosmic strings**
    SPEAKER: Daniel Jiménez-Aguilar
    INSTITUTION: Tufts U., Inst. of Cosmology, USA
    DATE: 20-12-2022

15. TITLE: **Saturnalia 2022: Cosmology from SKA Observatory pathfinders**
    SPEAKER: Jacobo Asorey
    INSTITUTION: UCM, Madrid
    DATE: 21-12-2022

16. TITLE: **Saturnalia 2022: Formation of shadows around compact objects as observational proofs of new gravitational physics**
    SPEAKER: Diego Saez
    INSTITUTION: UV, Valencia
    DATE: 20-12-2022

17. TITLE: **Saturnalia 2022: Machine-learned exclusion limits without binning**
    SPEAKER: Rosa María Sandá Seoane
    INSTITUTION: IFT, Madrid
    DATE: 21-12-2022

18. TITLE: **Saturnalia 2022: Automatic Nelson-Barr from Gauged Flavor and ALP searches at FASER**
    SPEAKER: Pablo Quílez
    INSTITUTION: UC, San Diego, USA
    DATE: 21-12-2022

19. TITLE: **Saturnalia 2022: Over the Rainbow ... of Gravitational Waves**
    SPEAKER: Diego Blas
    INSTITUTION: UAB and IFAE, Barcelona
    DATE: 22-12-2022

E

PhD Theses

E.1 | Theses defended in 2022

1. TITLE: **A Glance into Flavour Physics with Effective Field Theories and Machine Learning**
   STUDENT: Jorge Alda Gallo
   SUPERVISOR: Siannah Peñaranda
   DATE: 2017-2022

E.2 | Theses ongoing in 2022

1. TITLE: **Development of new strategies for the improvement of the sensitivity of the ANAIS-112 experiment.**
   STUDENT: David Cintas González
   SUPERVISOR: María Martínez Pérez and María Luisa Sarsa Sarsa
   DATE: 2019-2023

2. TITLE: **Exploración en física de astropartículas de alta energía de posibles señales de una deformación de la relatividad especial**
   STUDENT: Maykoll A. Reyes Hung
   SUPERVISOR: José Manuel Carmona and José Luis Cortés
   DATE: 2020-2023

3. TITLE: **Annual modulation and other rare processes searches using five-year exposure of ANAIS-112 and prospects of an upgraded experiment, ANAIS+.**
   STUDENT: Tamara Pardo Yanguas
   SUPERVISOR: María Martínez Pérez and María Luisa Sarsa Sarsa

DATE: 2021-2025

4. TITLE: **Diseño y prueba de un detector Micromegas para BabyIAXO**
   STUDENT: Cristina Margalejo Blasco
   SUPERVISOR: Gloria Luzón and Theopisti Dafni
   DATE: 2019-2024

5. TITLE: **Búsqueda de Axiones solares con BabyIAXO**
   STUDENT: Luis Antonio Obis Aparicio
   SUPERVISOR: Gloria Luzón
   DATE: 2020-2024

6. TITLE: **El experimento TREX-DM: fenomenología y búsqueda de WIMPs de baja masa.**
   STUDENT: David Díez Ibáñez
   SUPERVISOR: Theopisti Dafni
   DATE: 2020-2024

7. TITLE: **Looking for low-mass WIMPs with the TREX-DM detector**
   STUDENT: Óscar Pérez Lázaro
   SUPERVISOR: Igor G. Irastorza
   DATE: 2020-2024

8. TITLE: **Estados de borde en materiales topológicos**
   STUDENT: Yisely Martinez Pérez
   SUPERVISOR: Manuel Asorey
   DATE: 2020-2023

9. TITLE: **Energía de Casimir en Teorías Gauge no Abelianas**
   STUDENT: Fernando Ezquerro Sastre
   SUPERVISOR: Manuel Asorey and Eduardo Follana
   DATE: 2021-2024

10. TITLE: **Desarrollos de cámaras de proyección temporal con planos de lectura Micromegas para experimentos de búsqueda de sucesos poco probables.**
    STUDENT: Hector Mirallas
    SUPERVISOR: Theopisti Dafni and Igor G. Irastorza

DATE: 2015-2023

11. TITLE: **Design of advanced scintillators for rare event searches at the Canfranc Underground Laboratory.**
    STUDENT: Jaime Apilluelo Allué
    SUPERVISOR: María Martínez Pérez and María Luisa Sarsa Sarsa
    DATE: 2022-2026

12. TITLE: **Nuevos desarrollos de bajo fondo para la detección de axiones solares en BabyIAXO.**
    STUDENT: Ana Quintana García
    SUPERVISOR: Susana Cebrián and Igor G. Irastorza
    DATE: 2022-2026

13. TITLE: **Nuevas estrategias de reducción de fondo en experimentos para la búsqueda de Materia Oscura**
    STUDENT: Álvaro Ezquerro Sastre
    SUPERVISOR: Theopisti Dafni y Juan Antonio García Pascual
    DATE: 2022-2026

F

Bachelor and Master Theses

F.1 | Bachelor Theses presented in 2022

1. TITLE: **Soluciones de colapso en relatividad general**
   STUDENT: Juan Arnaudas Navalpotro
   SUPERVISOR: Eduardo Follana
   ACADEMIC YEAR: 2021-2022

2. TITLE: **Geodésicas tipo tiempo en agujeros negros de Schwarzchild y Kerr**
   STUDENT: Alejandro Cano Jones
   SUPERVISOR: Eduardo Follana
   ACADEMIC YEAR: 2021-2022

3. TITLE: **El zoo de las partículas: De la relatividad a la teoría de campos clásica y cuántica**
   STUDENT: Ignacio Ojer García
   SUPERVISOR: Siannah Peñaranda
   ACADEMIC YEAR: 2021-2022

4. TITLE: **Modelo Estándar: física del sabor**
   STUDENT: Alejandro Mir Ramos
   SUPERVISOR: Siannah Peñaranda and Jorge Alda
   ACADEMIC YEAR: 2021-2022

5. TITLE: **Estudio por Monte Carlo de la respuesta de los detectores de ANAIS-112 a distintas fuentes de neutrones.**
   STUDENT: Ainara Sola Jiménez
   SUPERVISOR: María Luisa Sarsa and María Martínez
   ACADEMIC YEAR: 2021-2022

6. TITLE: **Estudio del efecto de los fondos ambientales en la sensibilidad del experimento BabyIAXO a axiones solares.**

STUDENT: Daniel Mangirón Sisamón
SUPERVISOR: Igor G. Irastorza and Luis Obis
ACADEMIC YEAR: 2021-2022

7. TITLE: **Detección de alfas para medidas de radiopureza con detectores de Micromegas.**
   STUDENT: Lidia Escanciano Fernández
   SUPERVISOR: Juan Antonio García Pascual and Óscar Pérez Lázaro
   ACADEMIC YEAR: 2021-2022

8. TITLE: **Cosmología en Teorías de Gravitación con altas derivadas**
   STUDENT: Diego Bazo Sánchez
   SUPERVISOR: Manuel Asorey
   ACADEMIC YEAR: 2021-2022

9. TITLE: **Singularidades cosmológicas en teorías gravitacionales con altas derivadas**
   STUDENT: Juan Carlos Pardos Muñoz
   SUPERVISOR: Manuel Asorey
   ACADEMIC YEAR: 2021-2022

10. TITLE: **Rayos Cósmicos sobre la superficie terrestre**
    STUDENT: Leire Moreno Alzate
    SUPERVISOR: Gloria Luzón and Theopisti Dafni
    ACADEMIC YEAR: 2021-2022

G

Presentations in conferences, workshops and schools

1. TITLE: **Direct searches with Argon and study on cosmogenic activation above ground for the DarkSide-20k project**
   SPEAKER: Susana Cebrián
   EVENT: **19th MultiDark Consolider Workshop**
   VENUE: Miraflores de la Sierra, Madrid
   DATE: 23/05/2022-25/05/2022
   URL: http://workshops.ift.uam-csic.es/files/294/Susana_Cebrian.pdf

2. TITLE: **The direct detection of Dark Matter**
   SPEAKER: Susana Cebrián
   EVENT: **Annual Meeting of the European Astronomical Society (EAS2022), S3 Symposium "The dark matter multi-messenger challenge"**
   VENUE: Valencia
   DATE: 27/06/2022-01/07/2022
   URL: https://eas.unige.ch/EAS2022/session.jsp?id=S3

3. TITLE: **Dark Matter Direct Detection experiments**
   SPEAKER: Susana Cebrián
   EVENT: **Second MODE Workshop on Differentiable Programming for Experiment Design**
   VENUE: Kolymbari, Creta, Grecia
   DATE: 12/09/2022-16/09/2022
   URL: https://indico.cern.ch/event/1145124/timetable

4. TITLE: **Theoretical and experimental challenges in quantum gravity phenomenology**
   SPEAKER: José Manuel Carmona
   EVENT: **11th Conference of the Balkan Physical Union (BPU11 Congress)**
   VENUE: Belgrado (Serbia)
   DATE: 28/08/22-01/09/22
   URL: https://bpu11.info/

5. TITLE: **Experimental status and perspectives on dark matter direct detection and latest ANAIS results**
   SPEAKER: María Luisa Sarsa
   EVENT: **@FlipPhysics Workshop**
   VENUE: IFIC, Valencia, Spain
   DATE: 21/03/2022-25/03/2022
   URL: https://indico.ific.uv.es/event/6372/contributions/17346/attachments/10036/13418/ANAIS112_FlipPhysics.pdf

6. TITLE: **Calibrating the ANAIS-112 dark matter experiment with neutrons**
   SPEAKER: poster presenter: Tamara Pardo
   EVENT: **@FlipPhysics Workshop**
   VENUE: IFIC, Valencia, Spain
   DATE: 21/03/2022-25/03/2022
   URL: https://indico.ific.uv.es/event/6372/contributions/17885/attachments/10028/13409/Poster_TamaraPardo_FlipPhysics22.pdf

7. TITLE: **Testing DAMA/LIBRA at three-sigma with ANAIS-112 experiment**
   SPEAKER: María Luisa Sarsa
   EVENT: **2022 Korean Physical Society Spring Meeting, Pioneer Symposium Dark Matter and Neutrino Searches with scintillating detectors**
   VENUE: Seoul, Online
   DATE: 22/04/2022-
   URL: https://indico.ibs.re.kr/event/499/contributions/3562/attachments/3200/3559/KPS2022_MLSarsa.pdf

8. TITLE: **ANAIS-112 annual modulation results and prospects to test DAMA/LIBRA beyond three sigma**
   SPEAKER: María Luisa Sarsa
   EVENT: **14th International Conference on Identification of Dark Matter, IDM2022**
   VENUE: Vienna, Austria
   DATE: 18/07/2022-22/07/2022
   URL: https://indico.cern.ch/event/922783/contributions/4892762/attachments/2482431/4261919/ANAIS_IDM2022.

pdf

9. TITLE: **Calibraciones de neutrones en ANAIS-112**
   SPEAKER: Tamara Pardo
   EVENT: **X Jornada de Jóvenes Investigadores en Física y Química de Aragón**
   VENUE: Zaragoza, Spain
   DATE: 14/12/2022-

10. TITLE: **ANAIS-112: testing the DAMA/LIBRA signal beyond three sigma**
    SPEAKER: María Martínez
    EVENT: **The Dark Side of the Universe, DSU2022**
    VENUE: Sydney, Australia
    DATE: 05/12/2022-09/12/2022
    URL: https://indico.cern.ch/event/1107937/contributions/5100411/attachments/2559990/4412288/DSU_22_MMartinez.pdf

11. TITLE: **ANAIS-112: testing DAMA/LIBRA signal beyond three sigma**
    SPEAKER: María Martínez
    EVENT: **The 7th IBS-ICTP-MultiDark Workshop**
    VENUE: Daejeon, Korea
    DATE: 28/11/2022-02/12/2022
    URL: https://indico.ibs.re.kr/event/542/contributions/4077/

12. TITLE: **ANAIS-112: first direct test of DAMA/LIBRA beyond three sigma**
    SPEAKER: María Martínez
    EVENT: **XIV CPAN days**
    VENUE: Bilbao, Spain
    DATE: 23/11/2022-25/11/2022
    URL: https://indico.ific.uv.es/event/6735/contributions/19443/attachments/10600/14367/CPANDaysBilbao22_MMartinez.pdf

13. TITLE: **Direct search for dark matter: Status and perspectives**
    SPEAKER: María Martínez
    EVENT: **VIII Meeting on Fundamental Cosmology**
    VENUE: Granada, Spain
    DATE: 2/11/2022-4/11/2022
    URL: https://home.iaa.csic.es/fundcosmo22/resources/MFC2002-Program.pdf

14. TITLE: **Direct searches of dark matter**
    SPEAKER: María Martínez
    EVENT: **3rd GNN Workshop on Indirect Dark Matter searches with neutrino telescopes**
    VENUE: Granada, Spain
    DATE: 31/03/2022-1/04/2022
    URL: https://indico.cern.ch/event/1075227/contributions/4785688/attachments/2419225/4140599/DarkGhost22_MMartinez.pdf

15. TITLE: **Neutron calibrations in ANAIS-112**
    SPEAKER: Tamara Pardo
    EVENT: **19th MultiDark Consolider Workshop**
    VENUE: La Cristalera, UAM, Miraflores de la Sierra, Madrid, Spain
    DATE: 23/05/2022-25/05/2022
    URL: https://workshops.ift.uam-csic.es/multidark19/program

16. TITLE: **Deformed relativistic kinematics on curved spacetime: a geometric approach**
    SPEAKER: José Javier Relancio Martínez
    EVENT: **VII Iberoamerican Meeting on Geometry, Mechanics and Control**
    VENUE: Universidad Nacional del Sur
    DATE: 07/03/2022-11/03/2022
    URL: https://sites.google.com/view/iberogmc2022/home

17. TITLE: **Doubly special relativity as a road to quantum gravity**
    SPEAKER: José Javier Relancio Martínez
    EVENT: **Saturnalia 2022 Workshop Zaragoza**
    VENUE: Universidad de Zaragoza
    DATE: 16/12/2022-22/12/2022
    URL: https://indico.capa.unizar.es/event/32/

18. TITLE: **Geometrize and conquer: the Klein-Gordon and Dirac equations in Doubly Special Relativity**
    SPEAKER: José Javier Relancio Martínez
    EVENT: **Third Annual Conference of COST Action CA18108**
    VENUE: University of Naples
    DATE: 13/07/2022-15/07/2022
    URL: https://indico.capa.unizar.es/event/21/

19. TITLE: **TREX-DM experiment at Canfranc Underground Laboratory**
    SPEAKER: Óscar Pérez Lázaro

EVENT: **XIII CPAN days**
VENUE: Huelva, Spain
DATE: 21/03/2022-23/03/2022
URL: https://indico.ific.uv.es/event/6457/contributions/17704/

20. TITLE: **Experimental Searches for Axions**
SPEAKER: Igor G. Irastorza
EVENT: **Neutrino Oscillation Workshop (NOW2022), plenary talk.**
VENUE: Ostuni, Italy
DATE: 5/09/2022-11/09/2022
URL: https://web2.ba.infn.it/now/now2022/

21. TITLE: **Experimental Searches for Axions**
SPEAKER: Igor G. Irastorza
EVENT: **Feebly interacting Sectors Impact in Cosmology and Astrophysics (FISICA2022)**
VENUE: Mainz, Germany
DATE: 1/03/2022-4/03/2022
URL: https://indico.mitp.uni-mainz.de/event/288/

TITLE: **Design of an alpha contamination detector with high sensitivity**
SPEAKER: Ana Quintana García
EVENT: **@FlipPhysics Workshop**
VENUE: IFIC, Valencia, Spain
DATE: 21/03/2022-25/03/2022
URL: https://indico.ific.uv.es/event/6372/contributions/17572/attachments/10067/13459/AlphaCAMM_presentation.pptx

22. TITLE: **X-ray detectors for the BabyIAXO solar axion search**
SPEAKER: Konrad Altenmüller
EVENT: **9th Conference on new Developments in Photodetection (NDIP20)**
VENUE: Troyes, France
DATE: 04/07/2022-08/07/2022
URL: https://www.ndip.fr/

23. TITLE: **Axion search with the BabyIAXO helioscope: status and prospects**
SPEAKER: Konrad Altenmüller
EVENT: **XIII CPAN days**

VENUE: Huelva, Spain
DATE: 21/03/2022-23/03/2022
URL: https://indico.ific.uv.es/event/6457/contributions/17703/

24. TITLE: **New Aspects of Higher Derivative Theories**
SPEAKER: Manuel Asorey
EVENT: **Conference on Quantum Gravity, Cosmology and Black Holes**
VENUE: Universidade Beira Interior, Covilha, Portugal
DATE: 14/03/2022-18/03/2022
URL: https://inspirehep.net/conferences/2039122?ui-citation-summary=true

25. TITLE: **Aspects of Quantum Field Theory**
SPEAKER: Manuel Asorey
EVENT: **International School on Gravity, Cosmology and Mathematical Physics**
VENUE: Scalea, Italy
DATE: 13/06/2022-17/06/2022
URL: https://monge.u-bourgogne.fr/gdito/EQ2022/

26. TITLE: **Overview: Euclidean approach to Quantum Field Theories**
SPEAKER: Manuel Asorey
EVENT: **Quantum Theory and Applications**
VENUE: Policeta, San Rufo, Italy
DATE: 17/06/2022-24/06/2022
URL: https://agenda.infn.it/event/31556/

27. TITLE: **New aspects of higher derivative theories**
SPEAKER: Manuel Asorey
EVENT: **Workshop on Standard Model and Beyond**
VENUE: Corfu,Greece
DATE: 28/08/2022-08/09/2022
URL: http://www.physics.ntua.gr/corfu2022/sm.html

28. TITLE: **Trace anomaly and induced action for a metric-scalar background**
SPEAKER: Manuel Asorey
EVENT: **Quantum Effective Field Theory and Black Hole Tests of Einstein Gravity**
VENUE: SISSA, Trieste, Italy
DATE: 12/09/2022-16/09/2022

URL: https://grams-815673.wixsite.com/september12-16

29. TITLE: **Using Machine Learning techniques in phenomenological studies in flavour physics**
    SPEAKER: Jorge Alda Gallo
    EVENT: **XIII CPAN Days.**
    VENUE: Huelva, Spain
    DATE: 21/03/2022-23/03/2022
    URL: https://indico.ific.uv.es/event/6457/contributions/17809/attachments/9886/13210/Alda_XIII_CPAN.pdf

30. TITLE: **Using Machine Learning techniques in phenomenological studies in flavour physics**
    SPEAKER: Jorge Alda Gallo
    EVENT: **5th Inter-experiment Machine Learning Workshop.**
    VENUE: CERN, Switzerland
    DATE: 08/05/2022-13/05/2022
    URL: https://indico.cern.ch/event/1078970/contributions/

H

Seminars by CAPA members

1. TITLE: **Using Machine Learning techniques in phenomenological studies in flavour physics**
   SPEAKER: Jorge Alda Gallo
   VENUE: Instituto de Física Teórica (UAM-CSIC), Madrid
   DATE: 27/01/2022

2. TITLE: **Relativistic deformed kinematics: from flat to curved spacetime**
   SPEAKER: José Javier Relancio Martínez
   VENUE: Burgos
   DATE: 09/02/2022

3. TITLE: **Dark Matter annual modulation with ANAIS-112: testing the DAMA/LIBRA signal**
   SPEAKER: María Martínez
   VENUE: Dark Collaboration Meeting, Instituto de Física de Cantabria
   DATE: 23/02/2022

4. TITLE: **A la caza de la materia oscura**
   SPEAKER: María Martínez
   VENUE: Ciclo de Conferencias de la Facultad de Física, Universitat De València
   DATE: 10/02/2022

5. TITLE: **Aplicación de técnicas de aprendizaje automático a los datos de ANAIS-112**
   SPEAKER: Iván Coarasa
   VENUE: Café con ciencia, Laboratorio Subterráneo de Canfranc
   DATE: 02/03/2022

6. TITLE: **Using X-ray optics for nuclear physics applications**
   SPEAKER: Jaime Ruz Armendáriz
   VENUE: CAPA, Zaragoza
   DATE: 31/03/2022

7. TITLE: **Testing DAMA/LIBRA annual modulation result beyond three-sigma with ANAIS-112 experiment**
   SPEAKER: María Luisa Sarsa
   VENUE: HEP Seminar, Department of Physics and Astronomy, Northwestern University, Chicago, Illinois (US), online
   DATE: 02/05/2022

8. TITLE: **Edge States in Quantum Hall effect**
   SPEAKER: Manuel Asorey
   VENUE: Instituto de Física Teórica (UAM-CSIC), Madrid
   DATE: 13/05/2022

9. TITLE: **ANAIS and the dark matter wind**
   SPEAKER: María Luisa Sarsa
   VENUE: Commemoration of the 12º anniversary of the Canfranc Underground Laboratory, Canfranc Estación, Huesca, Spain
   DATE: 30/06/2022

10. TITLE: **Observando el universo invisible desde el túnel de Canfranc**
    SPEAKER: María Luisa Sarsa
    VENUE: XXVIII Ciclo de conferencias de Astronomía y Cosmología Carlos Sánchez Almagro. Aula Magna, Facultad de Ciencias, Universidad de Valladolid, Spain
    DATE: 06/10/2022

11. TITLE: **Searches for axions and other particles at the low mass frontier with (Baby)IAXO and beyond**
    SPEAKER: Igor G. Irastorza
    VENUE: Max Planck Institute for Physics, Munich, Germany
    DATE: 11/10/2022

12. TITLE: **Cotangent bundle geometries as a road to quantum gravity**
    SPEAKER: José Javier Relancio Martínez
    VENUE: CINESTAV, México (online)

DATE: 13/10/2022

13. TITLE: **Tools for background studies in rare event searches**
    SPEAKER: Susana Cebrián
    VENUE: HEPHY, Viena, Austria
    DATE: 17/11/2022

14. TITLE: **Bulk-Edge dualities in Topological Matter**
    SPEAKER: Manuel Asorey
    VENUE: Universidad del Pais Vasco, UPV-EHU, Leioa
    DATE: 23/11/2022

15. TITLE: **SKA: the mother of all radio telescopes**
    SPEAKER: Miguel Ágel Pérez Torres
    VENUE: CAPA, Zaragoza
    DATE: 25/11/2022

16. TITLE: **Searching for Dark Photons with IAXO**
    SPEAKER: Tomás Gerard O Shea
    VENUE: Saturnalia 2022, CAPA, Zaragoza
    DATE: 16/12/2022

17. TITLE: **Using X-ray optics for nuclear physics applications**
    SPEAKER: Jaime Ruz Armendáriz
    VENUE: Saturnalia 2022, CAPA, Zaragoza
    DATE: 19/12/2022

18. TITLE: **Searching for ALPs-photon conversion on fiber interferometer**
    SPEAKER: Yikun Gu
    VENUE: Saturnalia 2022, CAPA, Zaragoza
    DATE: 20/12/2022

19. TITLE: **Using Machine Learning techniques in phenomenological studies in flavour physics**
    SPEAKER: Jorge Alda
    VENUE: Saturnalia 2022, CAPA, Zaragoza
    DATE: 21/12/2022

20. TITLE: **Doubly special relativity as a road to quantum gravity**
    SPEAKER: Javier Relancio Martínez
    VENUE: Saturnalia 2022, CAPA, Zaragoza
    DATE: 22/12/2022

I

Outreach activities

1. NAME OF ACTIVITY: **Jornadas de puertas abiertas de la Facultad de Ciencias**
   PARTICIPANTS: Susana Cebrián, David Cintas, Iván Coarasa, Theopisti Dafni, David Díez, Gloria Luzón, María Martínez, Luis Obis, María Luisa Sarsa
   DATE: 2022
   PLACE: Facultad de Ciencias, Zaragoza

2. NAME OF ACTIVITY: **Visita virtual al Laboratorio Subterráneo de Canfranc (Avenida de la Física, CIEMAT)**
   PARTICIPANTS: Susana Cebrián, María Martínez
   DATE: 03/02/2022
   PLACE: Online

3. NAME OF ACTIVITY: **Hands on particle physics**
   PARTICIPANTS: Manuel Asorey, José García-Esteve, Fernando Ezquerro, Fernando Falceto, Gloria Luzón, Yisely Martinez, Siannah Peñaranda
   DATE: 23/03/2022
   PLACE: Facultad de Ciencias, Zaragoza

4. NAME OF ACTIVITY: **Hands on particle physics**
   PARTICIPANTS: Manuel Asorey, José García-Esteve, Fernando Ezquerro, Fernando Falceto, Gloria Luzón
   DATE: 31/03/2022
   PLACE: Centro de de Ciencias de Benasque Pedro Pascual

5. NAME OF ACTIVITY: **Aplicación de técnicas de aprendizaje automático a los datos de ANAIS–112**
   PARTICIPANTS: Iván Coarasa

DATE: 02/03/2022
PLACE: Café y Ciencia 2022, Laboratorio Subterráneo de Canfranc

6. NAME OF ACTIVITY: **16º Maratón de las Astropartículas en Zaragoza**
PARTICIPANTS: Susana Cebrián, Iván Coarasa, José Manuel Carmona, Tamara Pardo, María Martínez, María Luisa Sarsa, David Cintas
DATE: 1-3/06/2022
PLACE: IES Miguel Catalán, Colegio Cristo Rey, IES Ítaca, IES Pablo Gargallo, Facultad de Ciencias, Zaragoza

7. NAME OF ACTIVITY: **Semana de Inmersión en Ciencias 2022**
PARTICIPANTS: Susana Cebrián, Iván Coarasa, María Martínez, María Luisa Sarsa, Tamara Pardo, Theopisit Dafni, Cristina Margalejo, Manuel Membrado, Luis Obis, David Díez, Gloria Luzón, Siannah Peñaranda, Fernando Falceto, José García-Esteve, Jorge Alda, Maykoll Reyes
DATE: 13-17/06/2022
PLACE: Facultad de Ciencias, Zaragoza

8. NAME OF ACTIVITY: **Rincón de la Ciencia del Mercado Agroalimentario**
PARTICIPANTS: Susana Cebrián, Iván Coarasa, María Martínez, María Luisa Sarsa, Tamara Pardo, Theopisti Dafni, Cristina Margalejo, Luis Obis, David Díez, Gloria Luzón
DATE: 18/03/2022 and 01/06/2022
PLACE: Facultad de Ciencias, Zaragoza

9. NAME OF ACTIVITY: **Jornada de Puertas Abiertas del Laboratorio Subterráneo de Canfranc**
PARTICIPANTS: Susana Cebrián, María Luisa Sarsa, Tamara Pardo, Theopisit Dafni, Cristina Margalejo, Gloria Luzón
DATE: 25/09/2022
PLACE: Laboratorio Subterráneo de Canfranc, Canfranc, Huesca

10. NAME OF ACTIVITY: **Noche de los Investigadores**
PARTICIPANTS: José Manuel Carmona, Susana Cebrián, Iván Coarasa, Theopisti Dafni, David Díez, Gloria Luzón, Luis Obis, Maykoll Reyes
DATE: 30/09/2022
PLACE: Paraninfo de la Universidad de Zaragoza, Zaragoza

11. NAME OF ACTIVITY: **Día de la materia oscura: Taller Hands on Dark Matter**
PARTICIPANTS: Susana Cebrián, Theopisti Dafni, Gloria Luzón, Manuel Membrado, María Luisa Sarsa
DATE: 28/10/2022

PLACE: Facultad de Ciencias, Zaragoza

12. NAME OF ACTIVITY: **Día de la materia oscura: yincana Descubre la materia oscura**
    PARTICIPANTS: Konrad Altenmüller, Susana Cebrián, Iván Coarasa, Theopisti Dafni, David Díez, Fernando Ezquerro, Eduardo Follana, Javier Galán, Javier Galindo, Juan Antonio García, Gloria Luzón, Cristina Margalejo, María Martínez, Manuel Membrado, Luis Obis, Tamara Pardo, Carmen Pérez, Maykoll Reyes, María Luisa Sarsa, Jaime Apilluelo, Siannah Peñaranda, Jorge Alda, Yisely Martinez
    DATE: 31/10/2022
    PLACE: Facultad de Ciencias, Zaragoza

13. NAME OF ACTIVITY: **Conferencia — El telescopio espacial James Webb: buscando las primeras luces del cosmos, exoplanetas y vida extraterrestre**
    PARTICIPANTS: José Manuel Carmona
    DATE: 07/04/2022
    PLACE: IES Pablo Gargallo, Zaragoza

14. NAME OF ACTIVITY: **Hola! somos científicas**
    PARTICIPANTS: Tamara Pardo, María Luisa Sarsa
    DATE: 11/02/2022
    PLACE: Actividad organizada con motivo del 11F en el Hall de la Facultad de Ciencias, Universidad de Zaragoza.

15. NAME OF ACTIVITY: **El Universo invisible**
    PARTICIPANTS: María Luisa Sarsa
    DATE: 20/08/2022
    PLACE: XVII Maratón de Astropartículas: "El Cielo sobre el Cerro del Berrueco". Puente del Congosto, Ávila, Spain.

16. NAME OF ACTIVITY: **Metodologías para descubrir lo desconocido**
    PARTICIPANTS: María Luisa Sarsa
    DATE: 30/09/2022
    PLACE: Tercera parte del seminario interdiciplinar "Parámetros para comprender la incertidumbre", Instituto de Física Teórica, UAM-CSIC Excellence Campus, Madrid, Spain.

17. NAME OF ACTIVITY: **Astronomía Subterránea**
    PARTICIPANTS: María Luisa Sarsa
    DATE: enero-febrero 2022

PLACE: Revista Muy Interesante, edición coleccionista COSMOS, nº 13.

18. NAME OF ACTIVITY: **Desarrollo de técnicas de bajo fondo para búsquedas de materia oscura, proyecto MSCA LOBRES**
    PARTICIPANTS: Juan Antonio García Pascual
    DATE: 30/09/2022
    PLACE: European Researchers´ Night, Paraninfo, University of Zaragoza

19. NAME OF ACTIVITY: **Un universo de radiaciones**
    PARTICIPANTS: Gloria Luzón Marco
    DATE: 30/09/2022
    PLACE: European Researchers´ Night, Paraninfo, University of Zaragoza

20. NAME OF ACTIVITY: **Empacho cósmico**
    PARTICIPANTS: Miguel Pérez Torres
    DATE: 30/09/2022
    PLACE: European Researchers´ Night, Casino de Huesca

21. NAME OF ACTIVITY: **Outreach article — *Técnicas de bajo fondo en busca de materia oscura* about the MSCA LOBRES project**
    PARTICIPANTS: Juan Antonio García Pascual
    DATE: 28/11/2022
    PLACE: Tercer Milenio magazine from Heraldo de Aragon link

22. NAME OF ACTIVITY: **Radio interview in the podcast "Ciencia para escuchar" (Spanish) — *El violento estertor de una estrella devorada por un agujero negro.***
    PARTICIPANTS: Miguel Pérez Torres
    DATE: 11/12/2022
    PLACE: Tercer Milenio magazine from Heraldo de Aragon link

J

Research stays by CAPA members

1. INSTITUTION: **Laboratori Nazionali del Gran Sasso (INFN), Italy**
   PERIOD: 21/03/2022-20/06/2022
   RESEARCHER: David Cintas González
   REASON OF STAY: Investigación predoctoral

2. INSTITUTION: **Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Paris-Saclay, France**
   PERIOD: 21/09/2022-23/12/2022
   RESEARCHER: Óscar Pérez Lázaro
   REASON OF STAY: Investigación predoctoral

3. INSTITUTION: **Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Paris-Saclay, France**
   PERIOD: 21/09/2022-23/12/2022
   RESEARCHER: Luis Antonio Obis Aparicio
   REASON OF STAY: Investigación predoctoral

4. INSTITUTION: **Instituto de Física Teórica UAM–CSIC, Madrid**
   PERIOD: Sept 2022 – Oct 2022
   RESEARCHER: José M. Gracia Bondía
   REASON OF STAY: Investigador Severo Ochoa

5. INSTITUTION: **Zentrum für interdisziplinäre Forschung, Universität Bielefeld, Bielefeld, Germany**
   PERIOD: Nov 2022 – Dec 2022
   RESEARCHER: José M. Gracia Bondía

REASON OF STAY: Investigación interdisciplinaria

K

Guest researchers visiting CAPA

1. RESEARCHER: Ilya L. Shapiro
   INSTITUTION: **Universidade Federal de Juiz de Fora, Brasil**
   PERIOD: March 2022

2. RESEARCHER: Jorge Gamboa
   INSTITUTION: **Universidad de Santiago de Chile, Chile**
   PERIOD: April 2022

3. RESEARCHER: A. P. Balachandran
   INSTITUTION: **Siracuse University, USA**
   PERIOD: May 2022

4. RESEARCHER: Tomislav Terzić
   INSTITUTION: **University of Rijeka, Croacia**
   PERIOD: May 2022

5. RESEARCHER: Luis Peña Moñino
   INSTITUTION: **Instituto de Astrofísica de Andalucía. IAA-CSIC**
   PERIOD: November 2022

L

Memberships of editorial boards

1. JOURNAL: **Frontiers of Mathematical Physics, Frontiers in Physics**
   MEMBER: Manuel Asorey
   PERIOD: 2010-,
   https://www.frontiersin.org/journals/physics/sections/statistical-and-computational-physics

2. JOURNAL: **Symmetry, MDPI**
   MEMBER: Manuel Asorey
   PERIOD: Special Issue "Second International Conference on Symmetry ",
   https://www.mdpi.com/journal/symmetry/special[]issues/second[]int[]conference[]symmetry

3. JOURNAL: **International Journal of Modern Physics A, World Scientific Co.**
   MEMBER: Manuel Asorey
   PERIOD: 2019- ,
   https://www.worldscientific.com/page/ijmpa/editorial-board

4. JOURNAL: **Modern Physics Letters A, World Scientific Co.**
   MEMBER: Manuel Asorey
   PERIOD: 2019- ,
   https://www.worldscientific.com/page/mpla/editorial-board

M

Scientific evaluation and committees

1. NAME OF COMMITTEE: **Management Committee of COST Action CA18108**
   TASK: Coordination and organization of the activities of the COST Action CA18108
   MEMBER: José Manuel Carmona
   PERIOD: 2019-2023

2. NAME OF COMMITTEE: **International Scientific Advisory Committee of S. Korean's IBS Center for Axion and Precision Physics (CAPP)**
   TASK: Providing scientific guidance to the center, periodic evaluations, reports
   MEMBER: Javier Redondo
   PERIOD: 2017-

3. NAME OF COMMITTEE: **IAXO Collaboration Board**
   TASK: Institutional representation of the Zaragoza node in the board
   MEMBER: Igor G. Irastorza and Gloria Luzón
   PERIOD: indefinite

4. NAME OF COMMITTEE: **IAXO Steering Committee**
   TASK: Chair of committee
   MEMBER: Igor G. Irastorza
   PERIOD: indefinite

5. NAME OF COMMITTEE: **RD51 Institutional Board**
   TASK: Institutional representation of the Zaragoza node in the board
   MEMBER: Igor G. Irastorza

PERIOD: indefinite

6. NAME OF COMMITTEE: **FIP (Feebly Interacting Particle) Physics Center Steering Group - CERN**
   TASK: Member of the committee
   MEMBER: Igor G. Irastorza
   PERIOD: since 2021

7. NAME OF COMMITTEE: **European Innovation Council and SMEs Executive Agency (EISMEA) - Evaluation panel of FET-OPEN Action**
   TASK: External expert acting as "monitor"
   MEMBER: Igor G. Irastorza
   PERIOD: December 2022 - March 2023

8. NAME OF COMMITTEE: **Agencia para la Calidad del Sistema Universitario de Galicia (ACSUG) - Panel evaluador European de las ayudas del programa de consolidación y estructuración de unidades de investigación competitivas**
   TASK: External expert evaluator
   MEMBER: Igor G. Irastorza
   PERIOD: Jan-Feb 2022

9. NAME OF COMMITTEE: **European Research Council - Evaluation panel of "ERC Starting Grant - 2022" call**
   TASK: External expert evaluator
   MEMBER: Igor G. Irastorza
   PERIOD: July 2022

10. NAME OF COMMITTEE: **Agencia Nacional de Evaluación de la Calidad y Acreditación (ANECA). Programa ACADEMIA**
    TASK: Evaluator
    MEMBER: Gloria Luzón
    PERIOD: Since January 2021

11. NAME OF COMMITTEE: **Patronato del Centro de Estudios de Física del Cosmos de Aragón**
    TASK: Member of the Comitée
    MEMBER: Gloria Luzón
    PERIOD: May 2021-January 2022

12. NAME OF COMMITTEE: **State Research Agency (AEI)/Agencia Estatal de Investigación (AEI).**
    TASK: Evaluator// G Valenciana Plan GenT Doctores Excelencia 2021 (Modalidad 1-CIDEGENT)
    MEMBER: Siannah Peñaranda
    PERIOD: 2020-2022

13. NAME OF COMMITTEE: **Agencia Nacional de Evaluación y Prospectiva (ANEP)**
    TASK: Evaluator of research projects
    MEMBER: Siannah Peñaranda
    PERIOD: 2020-2022

14. NAME OF COMMITTEE: **CUPID Collaboration Institutional Board**
    TASK: Institutional representation of Zaragoza University group in the board
    MEMBER: María Martínez
    PERIOD: Since June 2020

15. NAME OF COMMITTEE: **ASEVA (Spanish Vacuum Society) Scientific Committee**
    TASK: Member of the Committee
    MEMBER: María Martínez
    PERIOD: Since July 2021

16. NAME OF COMMITTEE: **Comité Ejecutivo del Centro Nacional de física de Partículas, Astropartículas y Nuclear (CPAN)**
    TASK: Member
    MEMBER: Theopisti Dafni
    PERIOD: May 2017 to March 2022

17. NAME OF COMMITTEE: **COST Actions Program**
    TASK: Evaluator and Repporteur
    MEMBER: Manuel Asorey
    PERIOD: 2022-2023

18. NAME OF COMMITTEE: **Agencia Nacional de Evaluación y Prospectiva (ANEP)**
    TASK: Evaluator of research projects
    MEMBER: Manuel Asorey
    PERIOD: 2020-2022

19. NAME OF COMMITTEE: **Universidad de Valladolid**
    TASK: External Evaluator of Margarita Salas program
    MEMBER: Manuel Asorey
    PERIOD: 2020-2022

20. NAME OF COMMITTEE: **Ministero dell'Università e della Ricerca (MUR)**
    TASK: External Evaluator of PRIN (Progetti di ricerca di Rilevante Interesse Nazionale)
    MEMBER: Manuel Asorey
    PERIOD: 2020-2022

21. NAME OF COMMITTEE: **Fondo para la Investigación Científica y Tecnológica (FONCYT) Argentina**
    TASK: Evaluador Externo
    MEMBER: Manuel Asorey
    PERIOD: indefinite

22. NAME OF COMMITTEE: **UNIBASQ**
    TASK: External Evaluator of Research Groups in the Basque University System
    MEMBER: Manuel Asorey
    PERIOD: 2020-2022

23. NAME OF COMMITTEE: **DarkSide-20k Collaboration Institutional Board**
    TASK: Institutional representation of Zaragoza University group in the board
    MEMBER: Susana Cebrián
    PERIOD: Since September 2018

24. NAME OF COMMITTEE: **Sección Local de Aragón de la Real Sociedad Española de Física**
    TASK: Vicepresident
    MEMBER: Susana Cebrián
    PERIOD: Since November 2020

25. NAME OF COMMITTEE: **SPS and PS Experiments Committee (SPSC), CERN**
    TASK: Member of the committee, to referee the requests from the experimental teams
    MEMBER: Susana Cebrián
    PERIOD: Since January 2021

26. NAME OF COMMITTEE: **Banco de evaluadores del FONCYT (Fondo para la Investigación Científica y Tecnológica) de la Agencia de I+D+i de Argentina**

TASK: Evaluator of research projects
MEMBER: Susana Cebrián
PERIOD: 2022

27. NAME OF COMMITTEE: **Agencia para la Calidad del Sistema Universitario de Castilla y León**
TASK: Evaluator of research projects
MEMBER: Susana Cebrián
PERIOD: 2022

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List of publications in 2022

Here we list all the publications with CAPA authors appeared in 2022. Most of them have also been referenced in the corresponding sections in chapter 3.

1. Abareshi, B. *et al.* Overview of the Instrumentation for the Dark Energy Spectroscopic Instrument. *ASTRONOMICAL JOURNAL* **164** (Nov. 2022).
2. Abbott, T. M. C. *et al.* Dark Energy Survey Year 3 results: A 2.7% measurement of baryon acoustic oscillation distance scale at redshift 0.835. *PHYSICAL REVIEW D* **105** (Feb. 2022).
3. Adair, C. M. *et al.* Search for Dark Matter Axions with CAST-CAPP. *NATURE COMMUNICATIONS* **13** (Oct. 2022).
4. Adams, D. Q. *et al.* CUORE opens the door to tonne-scale cryogenics experiments. *PROGRESS IN PARTICLE AND NUCLEAR PHYSICS* **122** (Jan. 2022).
5. Addazi, A. *et al.* Quantum gravity phenomenology at the dawn of the multi-messenger era-A review. *PROGRESS IN PARTICLE AND NUCLEAR PHYSICS* **125** (July 2022).
6. Alda, J., Guasch, J. & Penaranda, S. Anomalies in B mesons decays: a phenomenological approach. *EUROPEAN PHYSICAL JOURNAL PLUS* **137** (Feb. 2022).
7. Alda, J., Guasch, J. & Penaranda, S. Using Machine Learning techniques in phenomenological studies on flavour physics. *JOURNAL OF HIGH ENERGY PHYSICS* (July 2022).
8. Aleta, A. *et al.* A Need for a Paradigm Shift in Healthy Nutrition Research. *FRONTIERS IN NUTRITION* **9** (Apr. 2022).
9. Aleta, A. *et al.* Quantifying the importance and location of SARS-CoV-2 transmission events in large metropolitan areas. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* **119** (June 2022).
10. Alexandrou, C. *et al.* Scalar, vector, and tensor form factors for the pion and kaon from lattice QCD. *PHYSICAL REVIEW D* **105** (Mar. 2022).
11. Alfonso, K. *et al.* CUPID: The Next-Generation Neutrinoless Double Beta Decay Experiment. *JOURNAL OF LOW TEMPERATURE PHYSICS* (2022 NOV 29 2022).
12. Alfonso, K. *et al.* Optimization of the first CUPID detector module. *EUROPEAN PHYSICAL JOURNAL C* **82** (Sept. 2022).
13. Altenmuller, K. *et al.* AlphaCAMM, a Micromegas-based camera for high-sensitivity screening of alpha surface contamination. *JOURNAL OF INSTRUMENTATION* **17** (Aug. 2022).
14. Altenmuller, K. *et al.* REST-for-Physics, a ROOT-based framework for event oriented data analysis and combined Monte Carlo response. *COMPUTER PHYSICS COMMUNICATIONS* **273** (Apr. 2022).
15. Alves, L. G. A., Mangioni, G., Rodrigues, F. A., Panzarasa, P. & Moreno, Y. The rise and fall of countries in the global value chains. *SCIENTIFIC REPORTS* **12** (May 2022).

16. Amare, J. *et al.* Dark Matter Annual Modulation with ANAIS-112: Three Years Results. *MOSCOW UNIVERSITY PHYSICS BULLETIN* **77,** 322–326 (Apr. 2022).
17. Amare, J. *et al.* Long term measurement of the Rn-222 concentration in the Canfranc Underground Laboratory. *EUROPEAN PHYSICAL JOURNAL C* **82** (Oct. 2022).
18. Amare, J. *et al.* Dark Matter Searches Using NaI(Tl) at the Canfranc Underground Laboratory: Past, Present and Future. *UNIVERSE* **8** (Feb. 2022).
19. Angelone, G., Asorey, M., Facchi, P., Lonigro, D. & Martinez, Y. Boundary conditions for the quantum Hall effect. *JOURNAL OF PHYSICS A-MATHEMATICAL AND THEORETICAL* (2022 DEC 28 2022).
20. Arola-Fernandez, L. *et al.* Emergence of explosive synchronization bombs in networks of oscillators. *COMMUNICATIONS PHYSICS* **5** (Oct. 2022).
21. Azzolini, O. *et al.* Final Result on the Neutrinoless Double Beta Decay of 82Se with CUPID-0. *PHYSICAL REVIEW LETTERS* **129** (Sept. 2022).
22. Bahr-Kalus, B. *et al.* A measurement of the integrated Sachs-Wolfe effect with the Rapid ASKAP Continuum Survey. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **517,** 3785–3803 (Oct. 2022).
23. Bazavov, A. *et al.* Semileptonic form factors for B ? D*l? at nonzero recoil from2+1-flavor lattice QCD. *EUROPEAN PHYSICAL JOURNAL C* **82** (Dec. 2022).
24. Billard, J. *et al.* Direct detection of dark matter-APPEC committee report*. *REPORTS ON PROGRESS IN PHYSICS* **85** (May 2022).
25. Calleja-Solanas, V., Khalil, N., Gomez-Gardenes, J., Hernandez-Garcia, E. & Meloni, S. Structured interactions as a stabilizing mechanism for competitive ecological communities. *PHYSICAL REVIEW E* **106** (Dec. 2022).
26. Carinena, J. F., de Lucas, J. & Wysocki, D. Stratified Lie systems: theory and applications. *JOURNAL OF PHYSICS A-MATHEMATICAL AND THEORETICAL* **55,** 385206 (Sept. 2022).
27. Carinena, J. F. & Fernandez-Nunez, J. Some Applications of Affine in Velocities Lagrangians in Two-Dimensional Systems. *SYMMETRY-BASEL* **14,** 2520 (Dec. 2022).
28. Carinena, J. F., Martinez, E. & Munoz-Lecanda, M. C. Infinitesimal Time Reparametrisation and Its Applications. *JOURNAL OF NONLINEAR MATHEMATICAL PHYSICS* **29,** 523–555 (Sept. 2022).
29. Carmona, J. M., Cortes, J. L., Relancio, J. J. & Reyes, M. A. Time delays, choice of energy-momentum variables, and relative locality in doubly special relativity. *PHYSICAL REVIEW D* **106** (Sept. 2022).
30. Carmona, J. M., Cortes, J. L., Relancio, J. J., Reyes, M. A. & Vincueria, A. Modification of the mean free path of very high-energy photons due to a relativistic deformed kinematics. *EUROPEAN PHYSICAL JOURNAL PLUS* **137** (July 2022).
31. Carmona, J. M., Cortes, J. L., Relancio, J. J. & Reyes, M. A. Cosmic Neutrinos as a Window to Departures from Special Relativity. *SYMMETRY-BASEL* **14** (July 2022).
32. Chen, R. *et al.* Measuring Cosmological Parameters with Type Ia Supernovae in redMaGiC Galaxies. *ASTROPHYSICAL JOURNAL* **938** (Oct. 2022).
33. Chirco, G., Liberati, S. & Relancio, J. J. Spacetime thermodynamics in momentum-dependent geometries. *PHYSICAL REVIEW D* **106** (Sept. 2022).
34. Climent, J. B. *et al.* Radio emission in a nearby, ultra-cool dwarf binary: A multifrequency study. *ASTRONOMY & ASTROPHYSICS* **660** (Apr. 2022).
35. Coarasa, I. *et al.* Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques. *JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS* (Nov. 2022).
36. Dafni, T. & Galan, J. Digging into Axion Physics with (Baby)IAXO. *UNIVERSE* **8** (Jan. 2022).
37. Damasso, M. *et al.* A quarter century of spectroscopic monitoring of the nearby M dwarf Gl 514. A super-Earth on an eccentric orbit moving in and out of the habitable zone. *ASTRONOMY & ASTROPHYSICS* **666,** A187. arXiv: 2204.06376 [astro-ph.EP] (Oct. 2022).
38. Davies, C. T. H. *et al.* Windows on the hadronic vacuum polarization contribution to the muon anomalous magnetic moment. *PHYSICAL REVIEW D* **106** (Oct. 2022).

39. De Miguel-Arribas, A., Aleta, A. & Moreno, Y. Impact of vaccine hesitancy on secondary COVID-19 outbreaks in the US: an age-structured SIR model. *BMC INFECTIOUS DISEASES* **22** (June 2022).

40. De Arruda, G. F., Jeub, L. G. S., Mata, A. S., Rodrigues, F. A. & Moreno, Y. From subcritical behavior to a correlation-induced transition in rumor models. *NATURE COMMUNICATIONS* **13** (June 2022).

41. De Arruda, H. F. R. *et al.* Modelling how social network algorithms can influence opinion polarization. *INFORMATION SCIENCES* **588,** 265–278 (Apr. 2022).

42. Del Genio, C. I., Faci-Lazaro, S., Gomez-Gardenes, J. & Boccaletti, S. Mean-field nature of synchronization stability in networks with multiple interaction layers. *COMMUNICATIONS PHYSICS* **5** (May 2022).

43. Di Luzio, L. *et al.* Probing the axion-nucleon coupling with the next generation of axion helioscopes. *EUROPEAN PHYSICAL JOURNAL C* **82** (Feb. 2022).

44. Diaz-Morcillo, A. *et al.* Design of New Resonant Haloscopes in the Search for the Dark Matter Axion: A Review of the First Steps in the RADES Collaboration. *UNIVERSE* **8** (Jan. 2022).

45. Dixon, M. *et al.* Using host galaxy spectroscopy to explore systematics in the standardization of Type Ia supernovae. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **517,** 4291–4304 (Nov. 2022).

46. Ellis, D. *et al.* Structure of axion miniclusters. *PHYSICAL REVIEW D* **106** (Nov. 2022).

47. Engsig, M., Tejedor, A. & Moreno, Y. Robustness assessment of complex networks using the idle network. *PHYSICAL REVIEW RESEARCH* **4** (Dec. 2022).

48. Faci-Lazaro, S. *et al.* Dynamical robustness of collective neuronal activity upon targeted damage in interdependent networks. *EUROPEAN PHYSICAL JOURNAL-SPECIAL TOPICS* **231,** 195–201 (Apr. 2022).

49. Falceto, F. Canonical Quantization of the Electromagnetic Field in Arbitrary ?-Gauge. *ANNALES HENRI POINCARE* (2022 DEC 28 2022).

50. Fantini, G. *et al.* Machine Learning Techniques for Pile-Up Rejection in Cryogenic Calorimeters. *JOURNAL OF LOW TEMPERATURE PHYSICS* **209,** 1024–1031 (Dec. 2022).

51. Gallo, J. A., Guerrera, A. W. M., Penaranda, S. & Rigolin, S. Leptonic meson decays into invisible ALP. *NUCLEAR PHYSICS B* **979** (June 2022).

52. Golm, J. *et al.* Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter. *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY* **32** (June 2022).

53. Gracia-Lazaro, C., Dercole, F. & Moreno, Y. Dynamics of economic unions: An agent-based model to investigate the economic and social drivers of withdrawals. *CHAOS SOLITONS & FRACTALS* **160** (July 2022).

54. Gubitosi, G., Lizzi, F., Relancio, J. J. & Vitale, P. Double quantization. *PHYSICAL REVIEW D* **105** (June 2022).

55. Guise, E. *et al.* Multiwavelength optical and NIR variability analysis of the Blazar PKS 0027-426. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **510,** 3145–3177 (Mar. 2022).

56. H. Figueroa, J. M., Gracia-Bondía & Várilly, J. Faà di Bruno Hopf Algebras. *REVISTA COLOMBIANA DE MATEMATICAS* **56** (2022).

57. Henriques, C. A. O. *et al.* Neutral Bremsstrahlung Emission in Xenon Unveiled. *PHYSICAL REVIEW X* **12** (Apr. 2022).

58. Herrero-Gómez, P. *et al.* Ba+2 ion trapping using organic submonolayer for ultra-low background neutrinoless double beta detector. *NATURE COMMUNICATIONS* **13** (2022).

59. Husemann, B. *et al.* The Close AGN Reference Survey (CARS). IFU survey data and the BH mass dependence of long-term AGN variability. *ASTRONOMY & ASTROPHYSICS* **659,** A124. arXiv: 2111.10417 [astro-ph.GA] (Mar. 2022).

60. Iguaz, F. J. *et al.* Microbulk Micromegas in non-flammable mixtures of argon and neon at high pressure. *JOURNAL OF INSTRUMENTATION* **17** (July 2022).

61. Irastorza, I. G. An introduction to axions and their detection. *SciPost Phys. Lect. Notes,* 45 (2022).

62. Jones, B. J. P. *et al.* The dynamics of ions on phased radio-frequency carpets in high pressure gases and application for barium tagging in xenon gas time projection chambers. *NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT* **1039** (Sept. 2022).

63. Khanjanianpak, M., Azimi-Tafreshi, N., Arenas, A. & Gomez-Gardenes, J. Emergence of protective behaviour under different risk perceptions to disease spreading. *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL PHYSICAL AND ENGINEERING SCIENCES* **380** (July 2022).

64. Kossakowski, D. *et al.* The CARMENES search for exoplanets around M dwarfs. Stable radial-velocity variations at the rotation period of AD Leonis: A test case study of current limitations to treating stellar activity. *ASTRONOMY & ASTROPHYSICS* **666,** A143. arXiv: 2209.05814 [astro-ph.EP] (Oct. 2022).

65. Liberati, S., Pfeifer, C. & Relancio, J. Exploring black holes as particle accelerators: hoop-radius, target particles and escaping conditions. *JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS* (May 2022).

66. Lu, D., Aleta, A. & Moreno, Y. Assessing the Risk of Spatial Spreading of Diseases in Hospitals. *FRONTIERS IN PHYSICS* **10** (June 2022).

67. Luque, R. *et al.* The HD 260655 system: Two rocky worlds transiting a bright M dwarf at 10 pc. *ASTRONOMY & ASTROPHYSICS* **664,** A199. arXiv: 2204.10261 [astro-ph.EP] (Aug. 2022).

68. McColl, K. *et al.* Are People Optimistically Biased about the Risk of COVID-19 Infection? Lessons from the First Wave of the Pandemic in Europe. *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH* **19** (Jan. 2022).

69. Moller, A. *et al.* The dark energy survey 5-yr photometrically identified type Ia supernovae. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **514,** 5159–5177 (July 2022).

70. Nanci, C. *et al.* Observing the inner parsec-scale region of candidate neutrino-emitting blazars. *ASTRONOMY & ASTROPHYSICS* **663,** A129. arXiv: 2203.13268 [astro-ph.HE] (July 2022).

71. Navarro, P. *et al.* Wide-band full-wave electromagnetic modal analysis of the coupling between dark-matter axions and photons in microwave resonators. *PHYSICS OF THE DARK UNIVERSE* **36** (June 2022).

72. Norris, R. P. *et al.* The Evolutionary Map of the Universe Pilot Survey (vol 38, E016, 2021). *PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF AUSTRALIA* **39** (Nov. 2022).

73. Novella, P. *et al.* Measurement of the Xe-136 two-neutrino double-beta-decay half-life via direct background subtraction in NEXT. *PHYSICAL REVIEW C* **105** (May 2022).

74. O'Hare, C. A. J., Pierobon, G., Redondo, J. & Wong, Y. Y. Y. Simulations of axionlike particles in the postinflationary scenario. *PHYSICAL REVIEW D* **105** (Mar. 2022).

75. Orejudo, S. *et al.* Evolutionary emergence of collective intelligence in large groups of students. *FRONTIERS IN PSYCHOLOGY* **13** (Nov. 2022).

76. Panessa, F. *et al.* Daily variability at milli-arcsecond scales in the radio-quiet NLSy1 Mrk 110. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **510,** 718–724. arXiv: 2111.12595 [astro-ph.GA] (Feb. 2022).

77. Penton, A. *et al.* OzDES reverberation mapping program: Lag recovery reliability for 6-yr C iv analysis. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **509,** 4008–4023 (Jan. 2022).

78. Perez-Martinez, H., Bauza, F. J., Soriano-Panos, D., Gomez-Gardenes, J. & Floria, L. M. Emergence, survival, and segregation of competing gangs. *CHAOS* **32** (Aug. 2022).

79. Perez-Martinez, H., Gracia-Lazaro, C., Dercole, F. & Moreno, Y. Cooperation in costly-access environments. *NEW JOURNAL OF PHYSICS* **24** (Aug. 2022).

80. Pfeifer, C. & Javier Relancio, J. Deformed relativistic kinematics on curved spacetime: a geometric approach. *EUROPEAN PHYSICAL JOURNAL C* **82** (Feb. 2022).

81. Ramírez-Olivencia, N. *et al.* Sub-arcsecond LOFAR imaging of Arp 299 at 150 MHz. Tracing the nuclear and diffuse extended emission of a bright LIRG. *ASTRONOMY & ASTROPHYSICS* **658,** A4. arXiv: 2108.07291 [astro-ph.GA] (Feb. 2022).

82. Relancio, J. J. Relativistic deformed kinematics: From flat to curved spacetimes. *INTERNATIONAL JOURNAL OF GEOMETRIC METHODS IN MODERN PHYSICS* **19** (Aug. 2022).

83. Relancio, J. J. & Liberati, S. Black Hole Surface Gravity in Doubly Special Relativity Geometries. *UNIVERSE* **8** (Feb. 2022).

84. Relancio, J. J. & Liberati, S. Exploring black hole mechanics in cotangent bundle geometries. *INTERNATIONAL JOURNAL OF GEOMETRIC METHODS IN MODERN PHYSICS* **19** (May 2022).

85. Reyna-Lara, A., Soriano-Panos, D., Arias-Castro, J. H., Martinez, H. J. & Gomez-Gardenes, J. A metapopulation approach to identify targets for Wolbachia-based dengue control. *CHAOS* **32** (Apr. 2022).

86. Reyna-Lara, A., Soriano-Panos, D., Arenas, A. & Gomez-Gardenes, J. The interconnection between independent reactive control policies drives the stringency of local containment. *CHAOS SOLITONS & FRACTALS* **158** (May 2022).

87. Reynolds, T. M. *et al.* Energetic nuclear transients in luminous and ultraluminous infrared galaxies. *ASTRONOMY & ASTROPHYSICS* **664,** A158. arXiv: 2202.04019 [astro-ph.GA] (Aug. 2022).

88. Rodrigo, S. G., Pobes, C., Sanchez Casi, M., Martin-Moreno, L. & Camon Lasheras, A. Neural network assisted design of plasmonic nanostructures on superconducting transition-edge-sensors for single photon detectors. *OPTICS EXPRESS* **30,** 12368–12377 (Apr. 2022).

89. Rosell, A. C. *et al.* Dark Energy Survey Year 3 results: galaxy sample for BAO measurement. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **509,** 778–799 (Jan. 2022).

90. Sabiu, C. G., Kadota, K., Asorey, J. & Park, I. Probing ultra-light axion dark matter from 21 cm tomography using Convolutional Neural Networks. *JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS* (Jan. 2022).

91. Singha, M. *et al.* The Close AGN Reference Survey (CARS) Locating the [O III] wing component in luminous local Type 1 AGN. *ASTRONOMY & ASTROPHYSICS* **659** (Mar. 2022).

92. Smirnova-Pinchukova, I. *et al.* The Close AGN Reference Survey (CARS). No obvious signature of AGN feedback on star formation, but subtle trends. *ASTRONOMY & ASTROPHYSICS* **659,** A125. arXiv: 2111.10419 [astro-ph.GA] (Mar. 2022).

93. Soriano-Panos, D. *et al.* Modeling Communicable Diseases, Human Mobility, and Epidemics: A Review. *ANNALEN DER PHYSIK* **534** (June 2022).

94. Steinegger, B., Arola-Fernandez, L., Granell, C., Gomez-Gardenes, J. & Arenas, A. Behavioural response to heterogeneous severity of COVID-19 explains temporal variation of cases among different age groups. *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL PHYSICAL AND ENGINEERING SCIENCES* **380** (Jan. 2022).

95. Valganon, P., Soriano-Panos, D., Arenas, A. & Gomez-Gardenes, J. Contagion-diffusion processes with recurrent mobility patterns of distinguishable agents. *CHAOS* **32** (Apr. 2022).

96. Ventura, P. C., Aleta, A., Rodrigues, F. A. & Moreno, Y. Epidemic spreading in populations of mobile agents with adaptive behavioral response. *CHAOS SOLITONS & FRACTALS* **156** (Mar. 2022).

97. Ventura, P. C., Aleta, A., Rodrigues, F. A. & Moreno, Y. Modeling the effects of social distancing on the large-scale spreading of diseases. *EPIDEMICS* **38** (Mar. 2022).

98. Wetzell, V. *et al.* Velocity dispersions of clusters in the Dark Energy Survey Y3 redMaPPer catalogue. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **514,** 4696–4717 (July 2022).

99. Williams, D. R. A. *et al.* LeMMINGs - IV. The X-ray properties of a statistically complete sample of the nuclei in active and inactive galaxies from the Palomar sample. *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY* **510,** 4909–4928. arXiv: 2111.09077 [astro-ph.HE] (Mar. 2022).

100. Winkel, N. *et al.* The Close AGN Reference Survey (CARS) Tracing the circumnuclear star formation in the super-Eddington NLS1 Mrk 1044. *ASTRONOMY & ASTROPHYSICS* **663** (July 2022).

101. Xie, J. *et al.* Indirect influence in social networks as an induced percolation phenomenon. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* **119** (Mar. 2022).