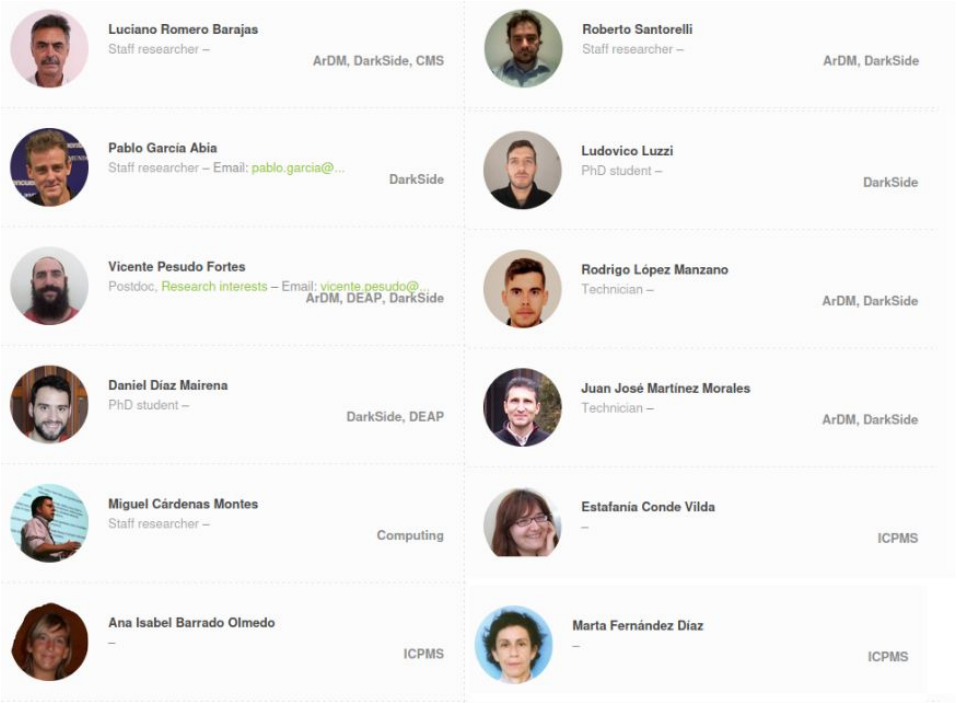
Direct detection of Dark Matter

R. Santorelli

on behalf of the
CIEMAT-DM group

Members



- 3 full time staff researchers (physicists)
- 2 Staff researchers (physicists) contributing to another CFP-research area
- 2 PhD students
- 1.5 technicians
- 3 Staff researchers (chemists) from the ionizing radiation laboratory (Env. Dep)
- + local support (... machine shop)

Expertise, Current Activities, and Short-Term Goals

The CIEMAT-DM team has extensive experience in **rare event research** with **noble element detectors**.

- *ICARUS*
  - *WARP-2.3L → WARP-100L*
    - *XENON10 → XENON100*
      - *ArDM, DEAP-3600, DarkSide-50*
        - *GADMC : DarkSide-20k → ARGO*

***Expertise*:**

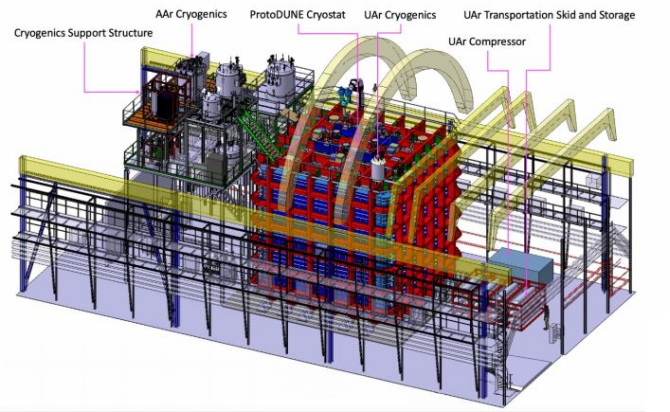
- ***Low background techniques***
- ***Background calculation, materials radiopurity***
- ***Noble element detectors***
- ***… Monte Carlo, analysis, ML techniques***

Expertise, Current Activities, and Short-Term Goals

The CIEMAT-DM team has extensive experience in **rare event research** with **noble element detectors**.

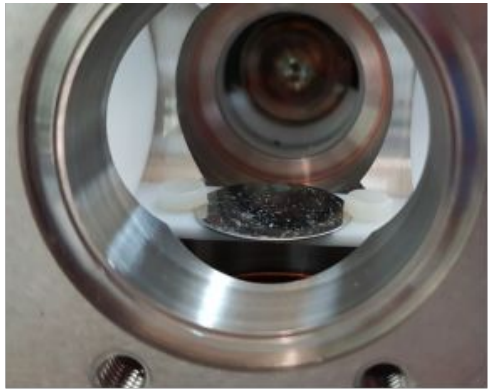
- *ICARUS*
  - *WARP-2.3L → WARP-100L*
    - *XENON10 → XENON100*
      - *ArDM,* ***DEAP-3600****, DarkSide-50*
        - ***GADMC → DarkSide-20k → ARGO***

DarkSide-20k



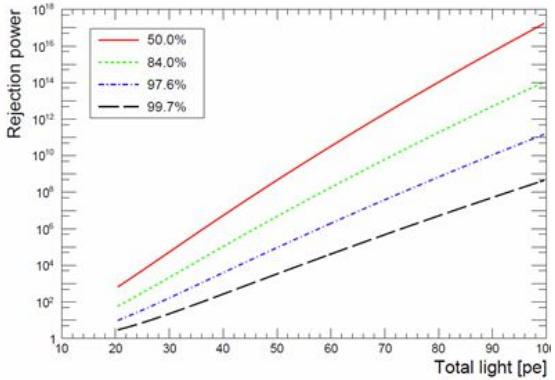
DEAP-3600

R&D on noble elements detectors



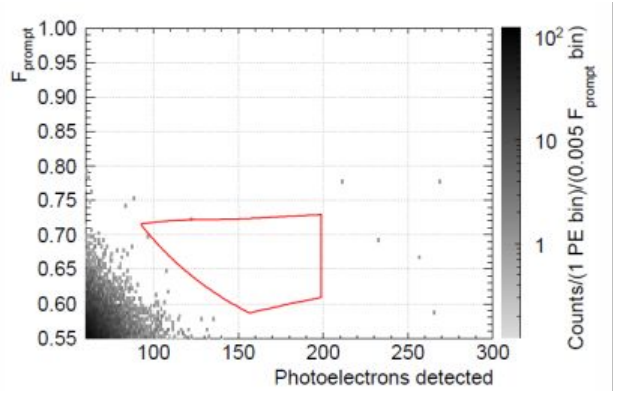
LAr for direct WIMP searches and the GADMC

- **ER background rejection Single-phase**



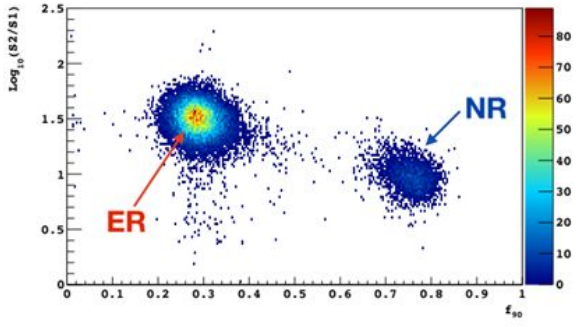
ArDM @ LSC
JCAP 12 (2018) 011

- **Background free mode WIMP-search**



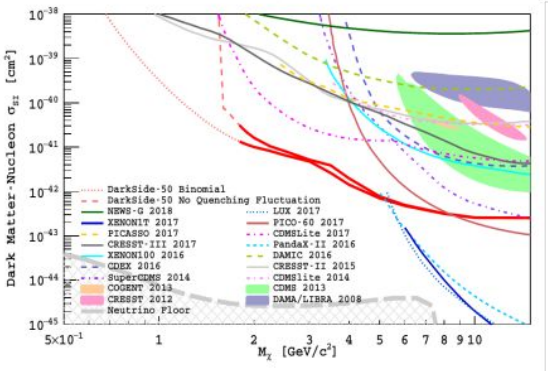
DEAP-3600@SNOLAB

- **ER background rejection Dual-phase**



- **World-best limit below 3 GeV/c²**

S2-only events
Eth<0.6 keV nr

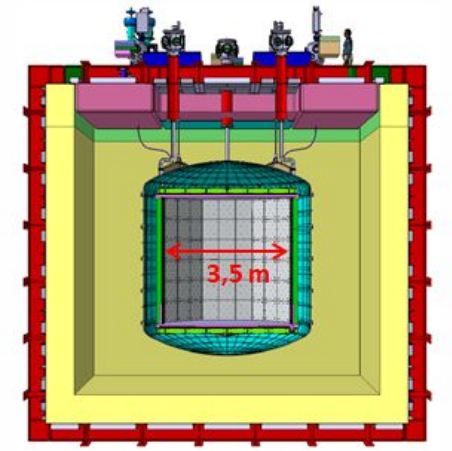


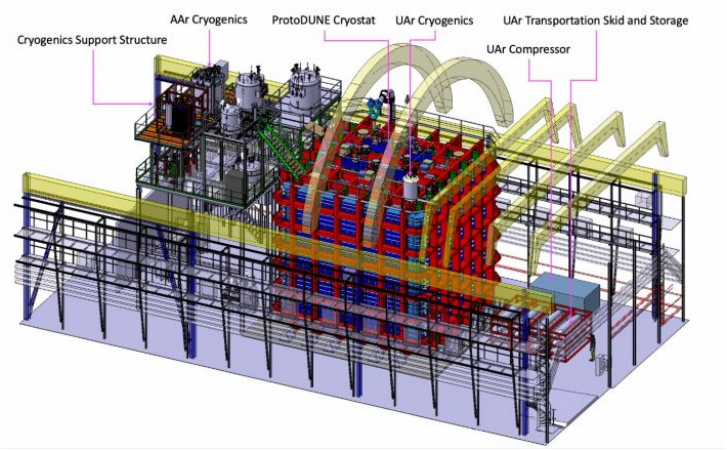
DarkSide-50@LNGS
Phys.Rev.Lett. 121 (2018)

- Remarkable and unique opportunity of having large exposures (~200 t×yr) **in background free mode**
- ***GADMC***: Collaboration with groups from DS-50, ArDM, DEAP-3600 and MiniCLEAN

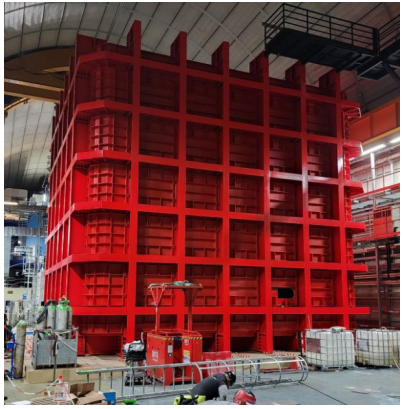
CIEMAT-DM one of the founding members of GADMC

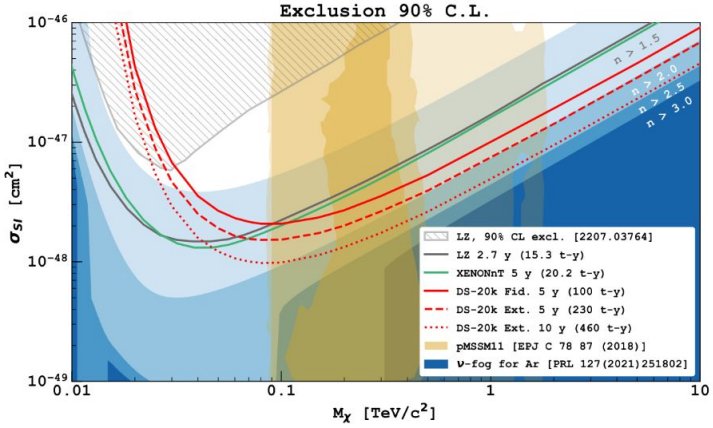
LAr for direct WIMP searches: DarkSide-20k





- ≈650 t Ar in a membrane cryostat (muon veto)
- 40 t (neutron veto)
- 50 t (20 t FV) Ar target
- 21 m^2 cryogenic SiPMs
- >**10 phe/keV** in the TPC (S1)
- Gd loaded (1%) acrylic (n-thermalization/capture)





➢ 200 t×y: **6.3×10^{-48}cm^2** (90% C.L., 1 TeV/c^2)

➢ < 0.1 bkg in (10×20) t×y
~Background free

CIEMAT-DM @ DarkSide-20k: background assessment /mitigation

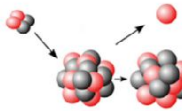
DS-20k: Very demanding background requirements (< 0.1 in 10 yr exposure) PSD alone is not sufficient

- CIEMAT-DM leading the material assay campaign - worldwide effort (Canada, Italy, France, Poland, Russia, Spain, UK, US…)
- Counting facilities in four Underground laboratories involved (Boulby, LNGS, LSC, SNOLAB)
- 3 different techniques employed: ICPMS, HPGe, Po extraction for Upper, Middle and Lower ^{238}U chain

➢ **Full characterization / control of the materials background**

- Control of the **cosmogenic activation** of materials
- Control of the **surface contamination**
- Evaluation of the **radioactive budget** of the experiment including activation UG
- Evaluation of the **systematic uncertainty** from the material composition
- New MC tools for (α, n) calculations

CIEMAT-DM background studies: highlights



(α,n)

- SaG4n@CIEMAT: code fully based on Geant4 to calculate neutron yields
- DarkSide is the first experiment with the (α,n) neutron background fully calculated with Geant4

Coll. with the CIEMAT Nucl. Innovation Unit

White paper on (α,n) neutron yields calculation

White paper on (α, n) neutron yields calculation

D. Cano,[1] S. Cebrián,[2] M. Haranczyk,[3] I. Lazanu,[4] G. Luzón,[2] H. Kluck,[5] A. Kish,[6] V. A. Kudryavtsev,[7] M. Gromov,[8,9] V. Lozza,[10,11] M. Parvu,[4] V. Pesudo,[1] A. Pocar,[12] R. Santorelli,[1,a] M. Selvi,[13] S. Westerdale,[14] and J. Zuzel[3]

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[4]Faculty of Physics, University of Bucharest, POBox 11, 077125, Magurele, Romania
[5]Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, 1050 Wien, Austria
[6]Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A
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[11]Universidade de Lisboa, Faculdade de Ciências (FCUL), Departamento de Física, 1749-016 Lisboa, Portugal
[12]Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA
[13]INFN - Sezione di Bologna, Bologna 40126, Italy
[14]Department of Physics and Astronomy, University of California, Riverside, CA 92507, USA

(Dated: Wednesday 10th January, 2024- 16:13, Version: F1.0)

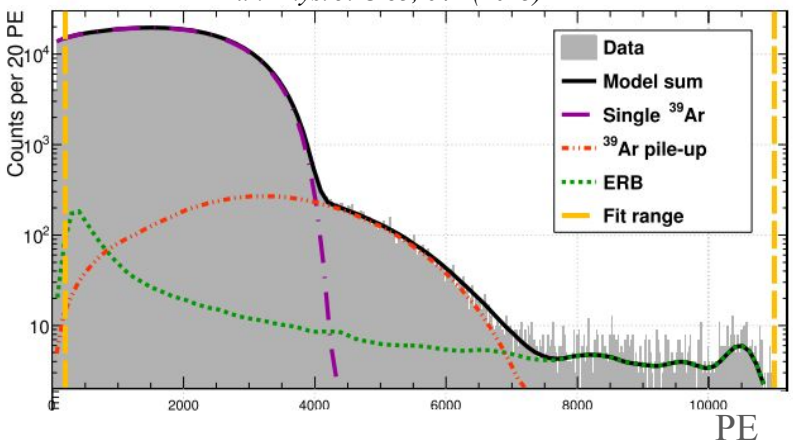
Understanding the radiogenic neutron production rate through the (α, n) reaction is essential in many fields of physics like dark matter searches, neutrino studies, nuclear astrophysics and medical physics. This white paper provides a review of the current landscape of (α, n) yields, neutron spectra, and correlated γ-rays calculations, and describes the existing tools and the available cross sections. The uncertainties that contribute to (α, n) yield calculations are also discussed with the plans for a program to improve the accuracy of the estimates. Novel ideas to measure (α, n) cross sections for a variety of materials of interest are presented. The goal of this study is to reduce the uncertainty in the expected sensitivity of next-generation physics experiments with keV–MeV measurements.

CONTENTS

~ 20 members from several low-background experiments

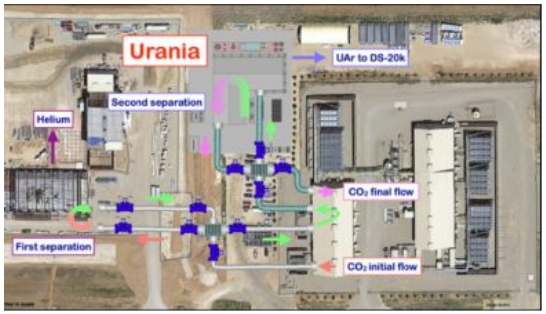
CIEMAT-DM @ DarkSide-20k: Worldwide effort for the UAr

Eur. Phys. J. C 83, 642 (2023)

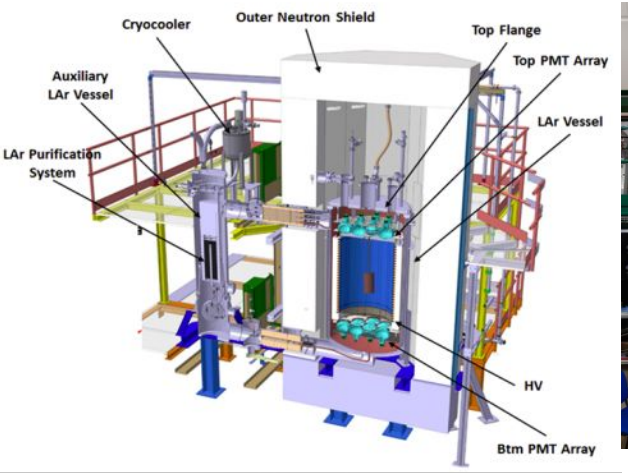


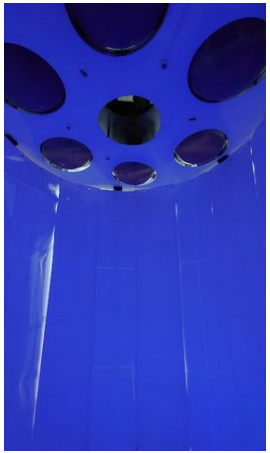
$S_{Ar\text{-}39} = (0.964 \pm 0.001_{stat} \pm 0.024_{sys})\ Bq/kg\ ^{atm}Ar$

- β-emitter with 565 keV endpoint, $T_{1/2}$=269 y (cosmogenic)
- Pure beta emitter, no accompanying gamma radiation
- ~17 mBq/m^3 in atmosphere
- Present in AAr due to the production process **(I.A. ~ 8×10^{-16}g(^{39}Ar)/g(^{Nat}Ar))**



CIEMAT-DM Ar-39 in UAr: DArT@LSC





- **Technical coordination** of the Ar-39 measurement @LSC
- **Leading the DArT experiment on multiple fronts**
  - Construction
  - Operations
  - Data analysis
  - Simulation

Collaboration with INFN-Ca, Univ. of Zaragoza, APC, Astrocent, Carleton

A Facility for Low-Radioactivity Underground Argon

Henning O. Back[1,*,†,‡] , Walter Bonivento[2,§] , Mark Boulay[3,‡,**], Eric Church[1,††], Steven R. Elliott[4,‡‡], Federico Gabriele[5,§] , Cristiano Galbiati[6,7,§§], Graham K. Giovanetti[8,§§] , Christopher Jackson[1,††], Art McDonald[9,§§,**], Andrew Renshaw[10,‡], Roberto Santorelli[11,***], Kate Scholberg[12,††,†††], Marino Simeone[13,‡] , Rex Tayloe[14,†††], Richard Van de Water[4,‡‡‡]

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7. Gran Sasso Science Institute, L'Aquila 67100, Italy
8. Williams College, Williamstown, MA 01267 USA
9. Queen's University, Kingston, ON K7L 3N6, Canada
10. University of Houston, Houston, Texas 77204, USA
11. CIEMAT, Madrid 28040, Spain
12. Duke University, Durham, North Carolina 27708, USA
13. Università degli Studi di Napoli "Federico II", Napoli 80125, Italy
14. Indiana University, Bloomington, Indiana 47405, USA

Abstract/Executive summary

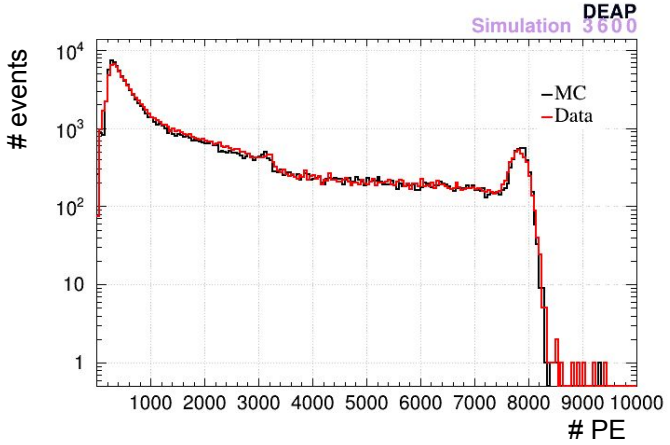
The DarkSide-50 experiment demonstrated the ability to extract and purify argon from deep underground sources and showed that the concentration of ^{39}Ar in that argon was greatly reduced from the level found in argon derived from the atmosphere. That discovery broadened the physics reach of argon-based detector and created a demand for low-radioactivity underground argon (UAr) in high-energy physics, nuclear physics, and in environmental and allied sciences. The Global Argon Dark Matter Collaboration (GADMC) is preparing to produce UAr for DarkSide-20k, but a general UAr supply for the community does not exist. With the proper resources, those plants could be operated as a facility to supply UAr for most of the experiments after the DarkSide-20k production. However, if the current source becomes unavailable, or UAr masses greater than what is available from the current source is needed, then a new source must be found. To find a new source will require understanding the production of the radioactive argon isotopes underground in a gas field, and the ability to measure ^{37}Ar, ^{39}Ar, and ^{42}Ar to ultra-low levels. The operation of a facility creates a need for ancillary systems to monitor for ^{37}Ar, ^{39}Ar, or ^{42}Ar infiltration either directly or indirectly, which can also be used to vet the ^{37}Ar, ^{39}Ar, and ^{42}Ar levels in a new UAr source, but requires the ability to separate UAr from the matrix well gas. Finding methods to work with industry to find gas streams enriched in UAr, or to commercialize a UAr facility, are highly desirable.

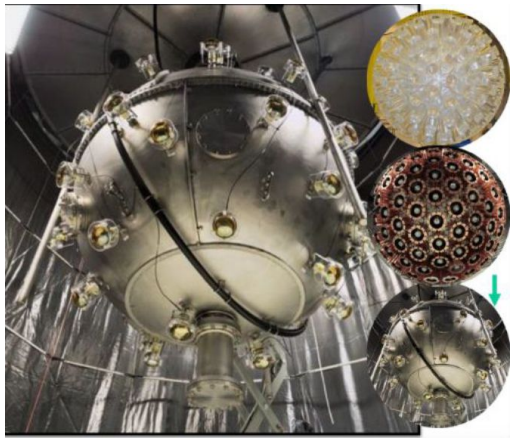
* *Corresponding author. PNNL, 902 Battelle blvd., P.O. Box 999, MSIN J4-65, Richland, WA 99352 Email:henning.back@pnnl.gov*
† Representing environment and applied sciences
‡ Representing the Urania portion of GADMC/Darkside-20k
§ Representing the Aria portion of GADMC/Darkside-20k
** Representing the DEAP-3600 collaboration
†† Representing the DUNE-like detector
‡‡ Representing the LEGEND collaboration
§§ Representing the GADMC/Darkside-20k collaboration
*** Representing the DART portion of GADMC/Darkside-20k
††† Representing the COHERENT collaboration
‡‡‡ Representing the Coherent Captain-Mills (CCM) collaboration

The relevance of the search for radiopure argon extends beyond the scope of the DarkSide-20k experiment

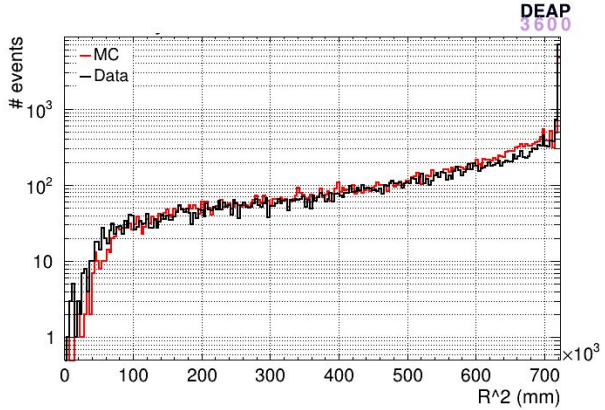
- GADMC (⇨ DS-20k, ARGO)
- LEGEND (LEGEND-1000)
- DUNE (Phase -II)
- COHERENT
- + ENVIRONMENTAL ASSAY…

CIEMAT-DM @ DEAP-3600: analysis, calibration, simulation, ML…

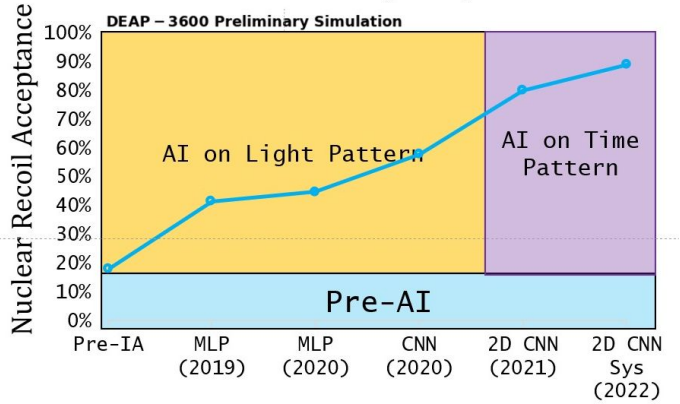




3.3 tonne LAr target in ultraclean acrylic vessel (R = 85 cm).



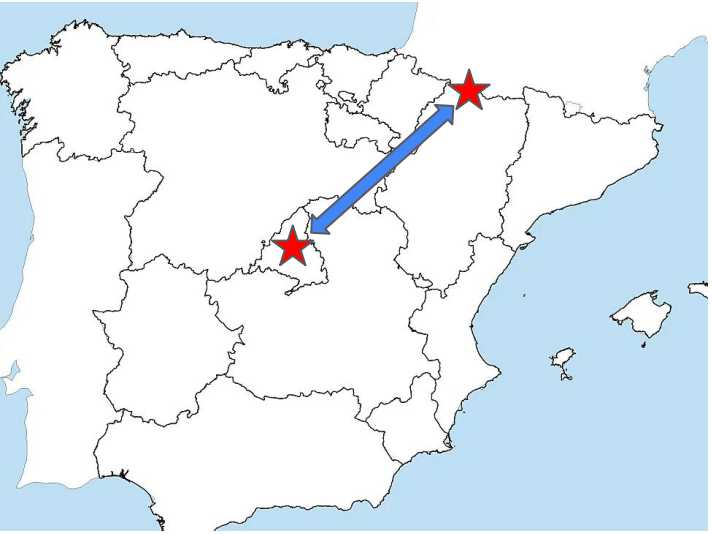
Neural network performance evolution for 99.9% neck alpha rejection

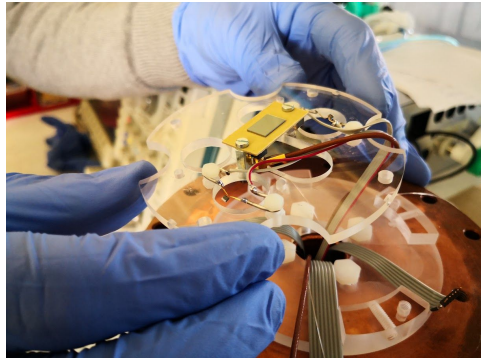


XIA (Explainable artificial intelligence): improvement in the background rejection algorithms and recovery of the NR acceptance

CIEMAT-DM and LSC

LSC
Laboratorio Subterráneo Canfranc





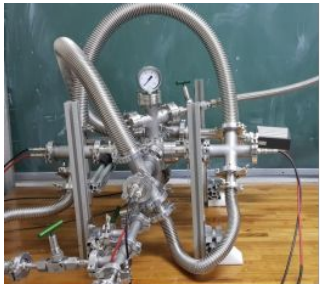
- ***CIEMAT-DM personnel permanently on-site at LSC***

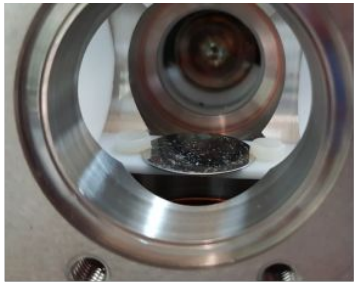
R&D: relevant papers

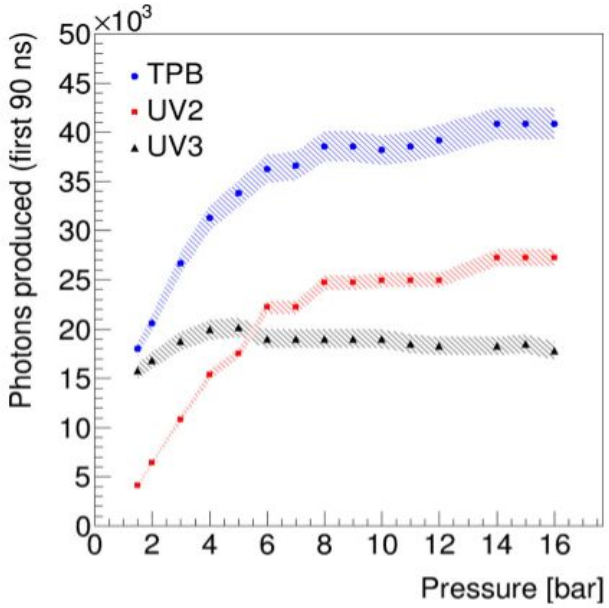
- "*Measurement of the Argon Purity by ICP-MS and Results of the Analysis of the Gas Used for the MicroBooNE Experiment*", arXiv:2303.00816
- "*Experimental Study of the Positive Ion Feedback from Gas to Liquid in a Dual-Phase Argon Chamber and Measurement of the Ion Mobility in Argon Gas*", **Universe** 8 (2022) 2, 134
- "*Time and band-resolved scintillation in time projection chambers based on gaseous xenon*", **Eur.Phys.J.C** 82 (2022) 5, 425
- "*Spectroscopic analysis of the gaseous argon scintillation with a wavelength sensitive particle detector*", **Eur.Phys.J.C** 81 (2021) 7, 622
- "*Design and Construction of a New Detector to Measure Ultra-Low Radioactive-Isotope Contamination of Argon*", **JINST** 15 (2020) 02, P02024
- "*Impact of the positive ion current on large size neutrino detectors and delayed photon emission*", **JINST** 13 (2018) 04, C04015
- "*Characterization of a CLYC detector for underground experiments*", **Nucl.Instrum.Meth.A** 906 (2018) 150-158
- "Dynamics of the ions in Liquid Argon Detectors and electron signal quenching", **Astropart.Phys.** 92 (2017) 11-20

- 1 PhD thesis, 2 Master thesis

CIEMAT-DM: *R&D on LAr technology →Light*







The fast component of the scintillation in GAr is not from the 2nd contiunuum

ArDis : spectroscopic analysis of the argon scintillation

- **Subprograma Estatal de Generación del Conocimiento/EXPLORA**.
  Title: *Discriminación de partículas con un detector de argón a alta presión para el estudio de materia oscura*.

PILSNER: Can we implement a new discrimination channel based on the scintillation wavelength?

- **Europa Excelencia 2023**
  Title "Particle Identifier based on Light Spectroscopy in Noble Elements for Rare event searches"

- "*Spectroscopic analysis of the gaseous argon scintillation with a wavelength sensitive particle detector*", Eur.Phys.J.C 81 (2021) 7, 622
- "Dynamics of the ions in Liquid Argon Detectors and electron signal quenching", Astropart.Phys. 92 (2017) 11-20

Recent scientific production

- *"First Direct Detection Constraints on Planck-Scale Mass Dark Matter with Multiple-Scatter Signatures Using the DEAP-3600 Detector"*, ***Phys.Rev.Lett.*** 128 (2022) 1, 011801
- "*Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector"*, ***Phys.Rev.D*** 102 (2020) 8, 082001
- "*Separating 39Ar39Ar from 40Ar40Ar by cryogenic distillation with Aria for dark-matter searches*",***Eur.Phys.J.C*** 81 (2021) 4, 359
- "*Sensitivity of future liquid argon dark matter search experiments to core-collapse supernova neutrinos*",***JCAP*** 03 (2021) 043
- "*The liquid-argon scintillation pulseshape in DEAP-3600*", ***Eur.Phys.J.C*** 80 (2020)
- "*Design and Construction of a New Detector to Measure Ultra-Low Radioactive-Isotope Contamination of Argon*", ***JINST*** 15 (2020) 02, P02024
- "*Pulse-shape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data*", ***Eur.Phys.J.C*** 81 (2021) 823
- "*Sensitivity projections for a dual-phase argon TPC optimized for light dark matter searches through the ionization channel*", ***Phys.Rev.D*** 107 (2023) 11, 112006
- "*Neutron production induced by α-decay with Geant4*", *Nucl.Instrum.Meth.A* 960 (2020) 163659

CIEMAT-DM: Leadership roles and positions held in international panels

- DS-20k: Level 1 Manager for Materials, Radio Purity (since 2017)
- DS-20k: Reference group for the background calculation - Coordination of the assay campaign - DArT technical coordination (since 2020)
- GADMC: Several managing positions held by the group (Management Board, Technical Board, Speakers bureau, advisory board)
- GADMC: Chair of the Advisory board (elected position, 2020-2021)
- DEAP-3600: RUN-coordination (2019-2020)
- Chair of the international group for the study of the (α,n) process in low background experiments (since 2021)
- Member of the CERN SPSC-committee (2019-2021)
- Chair of of the International Scientific Committee of the ”LIght Detection In Noble Elements” (LIDINE) conference (2022-2023)

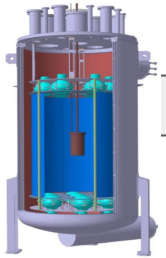
CIEMAT-DM: Funding

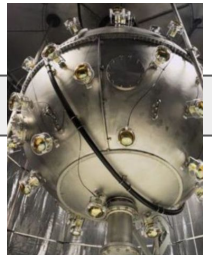
- 2023-2026 — **PID2022-138357NB-C22** (MICINN)
  Title: *Dark Matter Investigation at LSC: Spanish contribution to GADMC and advanced NaI detectors beyond ANAIS*
- 2024-2025 — **EUR2023-143480 (Europa Excelencia 2023)**
  Title "Particle Identifier based on Light Spectroscopy in Noble Elements for Rare event searches"
- 2020-2022 — **PID2019-109374GB-I00** (MICINN)
  Title: *Direct WIMP search with the Global Argon Dark Matter Collaboration*.
- 2019-2020 — **FPA2017-92505-EXP (Subprograma Estatal de Generación del Conocimiento/EXPLORA)**.
  Title: *Discriminación de partículas con un detector de argón a alta presión para el estudio de materia oscura*.
- 2018-2020 — **FPA2017-82647-P** (MINECO)
  Title: *Dark matter direct search with the ArDM/DarkSide-20k experiments and R&D on argon detector technology*.

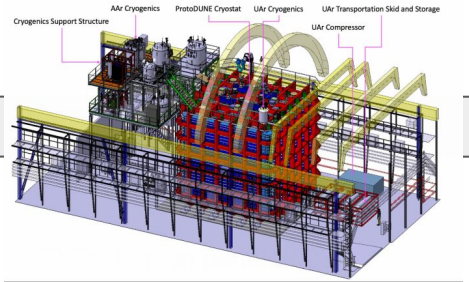
\+ other grants research assistant (CM), Students (PEJ), technicians…

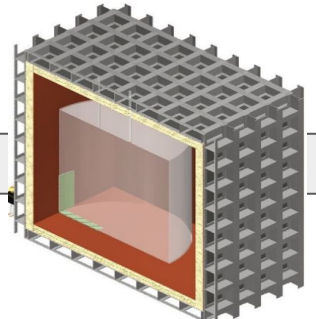
Goals:

2024	2025	2026	2027	2028		2030	2035	2040
DArTinArDM commissioning								
DArT data taking / analysis with UAr								
		DArT UAr publication						
DEAP-3600 analysis								
DEAP-3600 WIMP search publication			DEAP-3600 final publication					
DS-20k construction		DS-20k filling	DarkSide-20k commissioning/ data taking / analysis					
							ARGO construction	ARGO data-taking / analysis







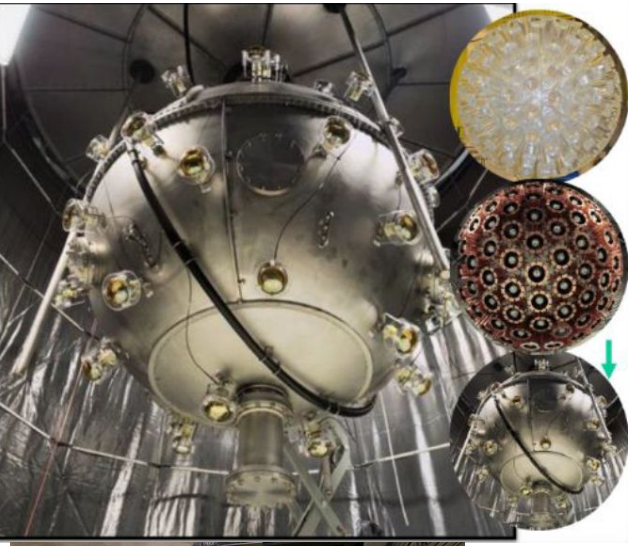


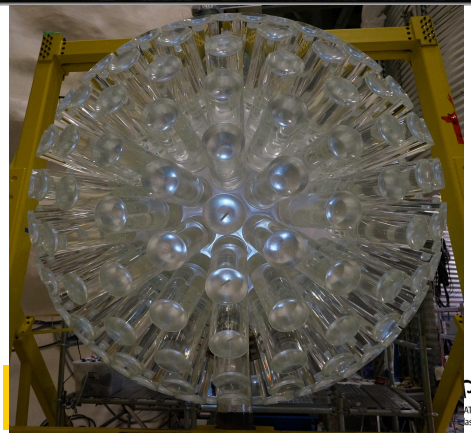
Conclusions:

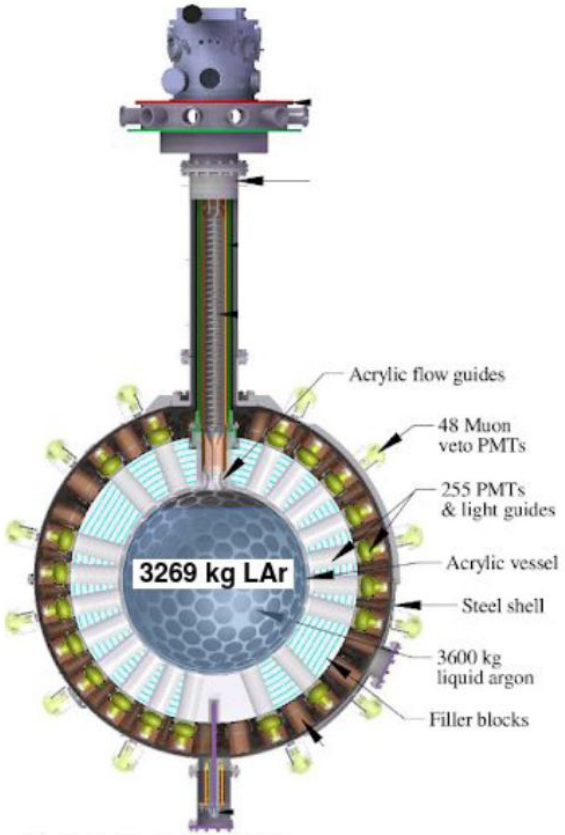
- CIEMAT-DM: a group with a clear focus on rare events search / underground physics, coupled with solid expertise in low-background techniques / Ar detectors.
- We have gained significant recognition in a competitive environment.
- Our short-to-medium-term endeavors are focused on a flagship project in the field of dark matter direct searches, and we play a central role in this project!
- There is a first-class ongoing R&D program.

Bonus slides!

LAr for direct WIMP searches: DEAP-3600



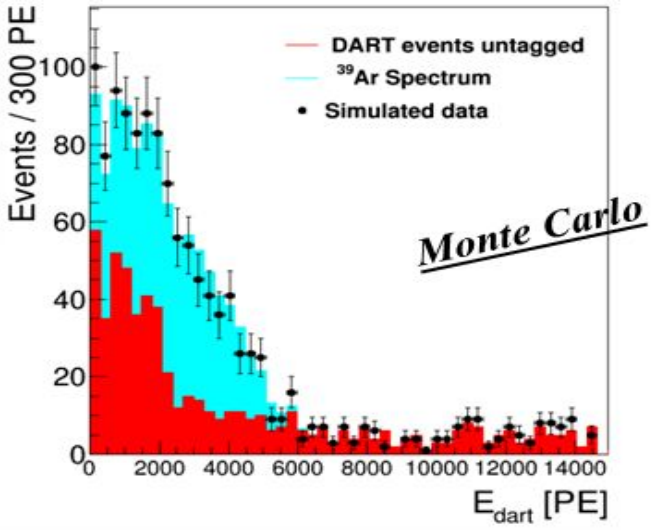




- 3.3 tonne LAr target in ultraclean acrylic vessel (R = 85 cm).
- Bonded 50-cm-long light guides: distance to PMTs
- 255 PMTs: Hamamatsu R5912 HQE. 8” - 32 % QE - 75% coverage.
- Immersed in water tank with PMTs to veto muons (Cherenkov light).
- Located 2 km underground @ SNOLAB: 6000 m.w.e -> 0.03 (muon/m^2/day)

CIEMAT-DM @ DarkSide-20k:

- **Signal**: β decays of ^{39}Ar (ROI $\in$ [0,600] keV) with < 10 keV deposited in the veto (minimal veto threshold)
- **Background**: untagged γ particles mainly from the radioactive decays in the detector materials (+ external)



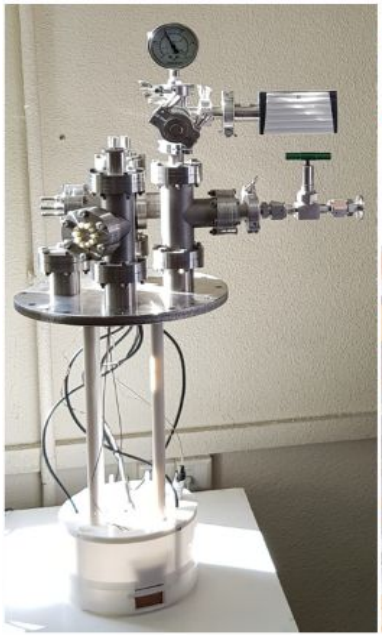
Bkg model

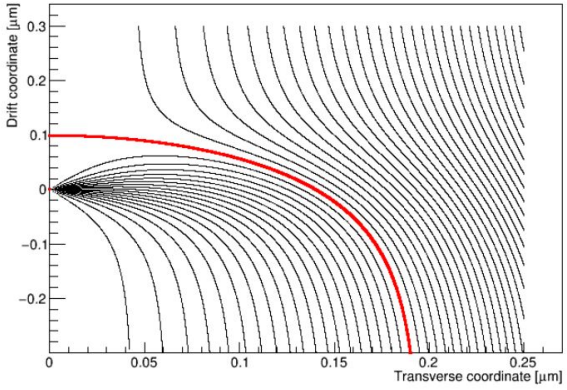
Background source	Evts/week ROI	Untagged Evts/week ROI
ArDM Cryostat	3164.4	218.3
ArDM PMTs	1053.0	42.8
ArDM supp. structure	28.5	0.6
Lead Belt	150.5	16.2
DArT vessel	16.6	5.4
Arlon SiPM	40.9	23.5
Acrylic	9.1	4.1
External without Pb	117623.0	10020.5
Total without Pb	122098.9	10301.7
External with Pb	2596.2	155.7
Total with lead	7209.9	465.5

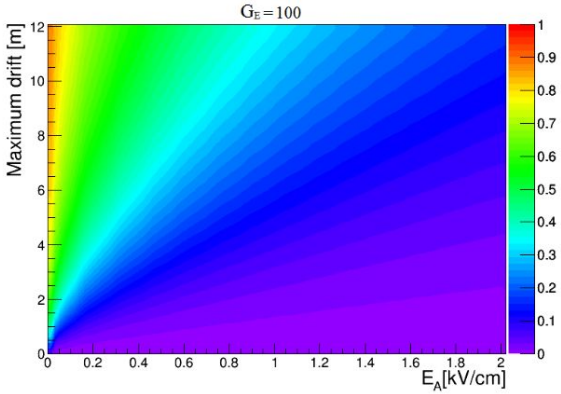
Signal 620 evt/week (D.F. 1400)
→ S/B > 1 for UAr

"Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon"
JINST 15 (2020) 02, P02024.

CIEMAT-DM: *R&D on LAr technology →Charge recombination*



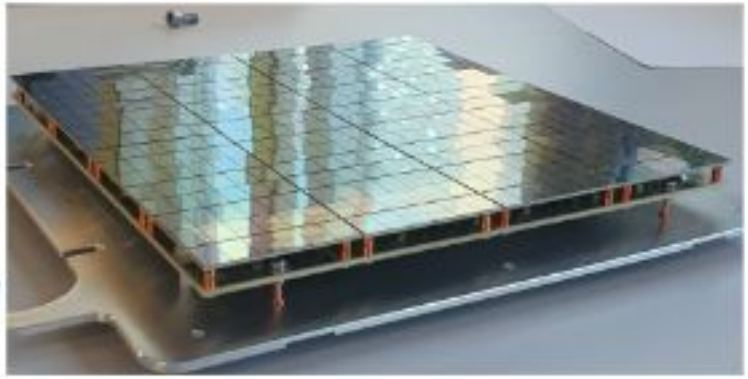




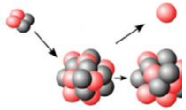
Arion project:

Intrinsic limit of the maximum electron drift given by the positive space charge

CIEMAT-DM @ DarkSide-20k: background assessment /mitigation



CIEMAT-DM @ DarkSide-20k: background assessment /mitigation



(α,n) *Coll. with the CIEMAT Nucl. Innovation Unit*

SaG4n@CIEMAT: code fully based on Geant4 to calculate neutron yields

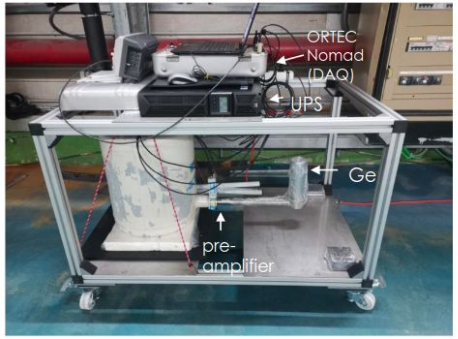
DarkSide is the first experiment with the (α,n) neutron background fully calculated with Geant4

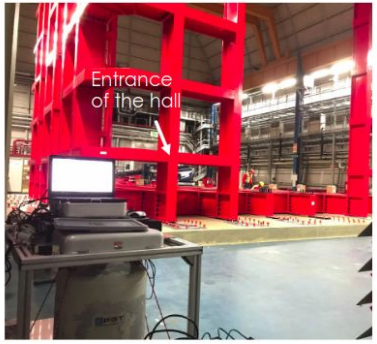
(α,n) yield in low background experiments WG: WP in preparation

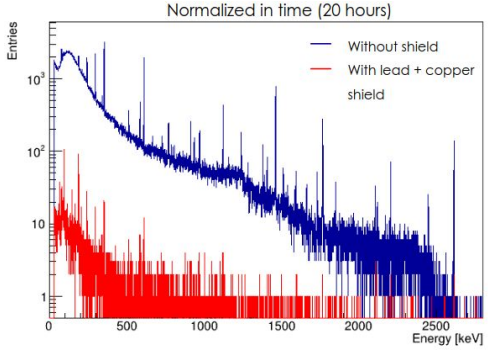
(~ **25 members from several low-background experiments**)

CONTENTS

Environmental radiation in the Hall-C@LNGS

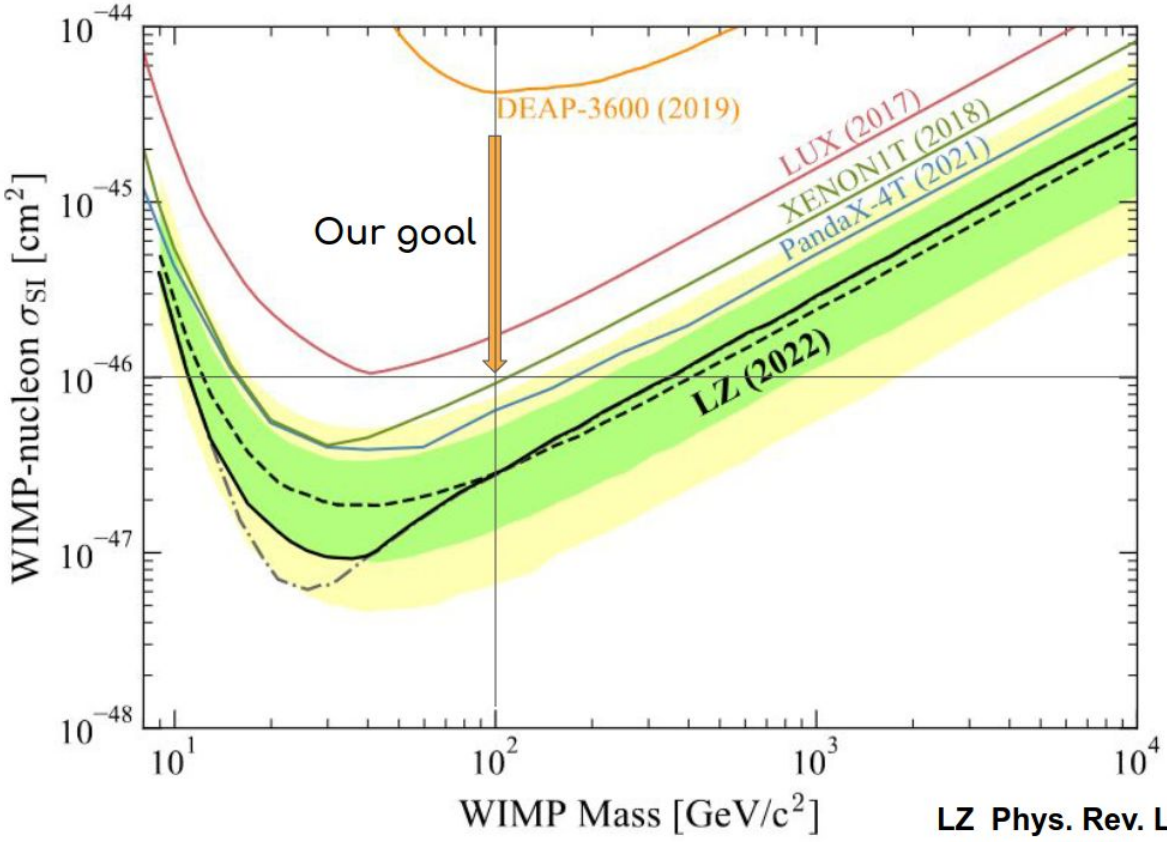




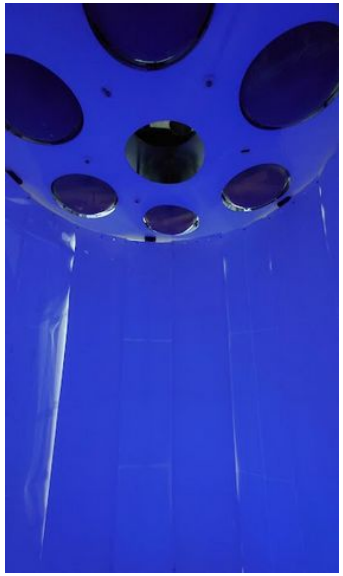


γ, n, Rn @ LNGS

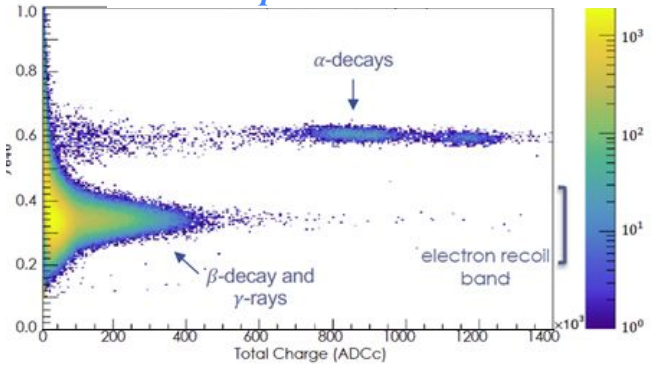
Coll. CIEMAT, LNGS, GSSI, Krakow Univ.



LZ Phys. Rev. Lett. 131, 041002 (2023)

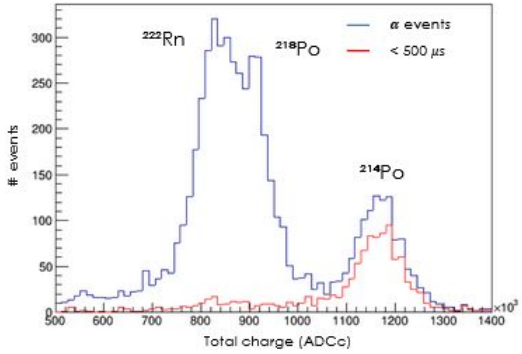


Pulse shape discrimination



Data

Internal bkg study



Measured $t_{1/2}$ (^{214}Po) = 158.3 ± 6.1 (stat) μs