Spanish contributions to direct dark matter searches: status and prospects

Vicente Pesudo
(CIEMAT / LSC)

2025 RENATA Meeting

Zaragoza,
22nd Sep 2025

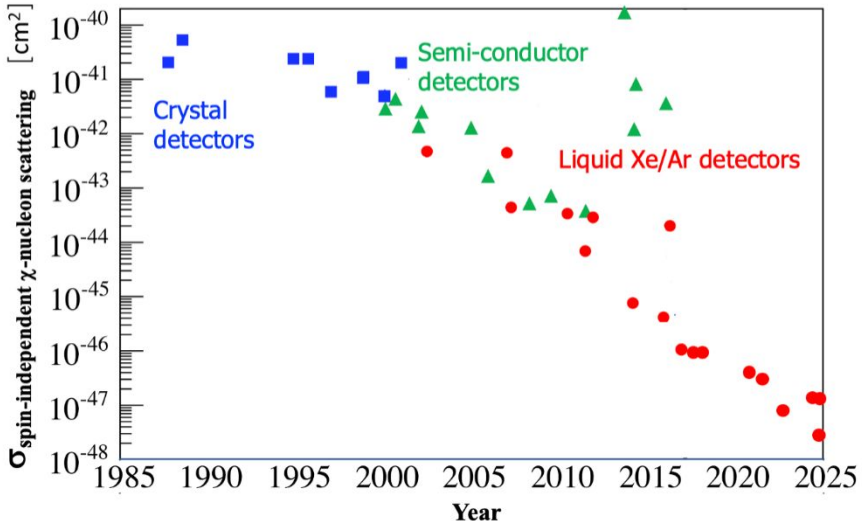
Overall context

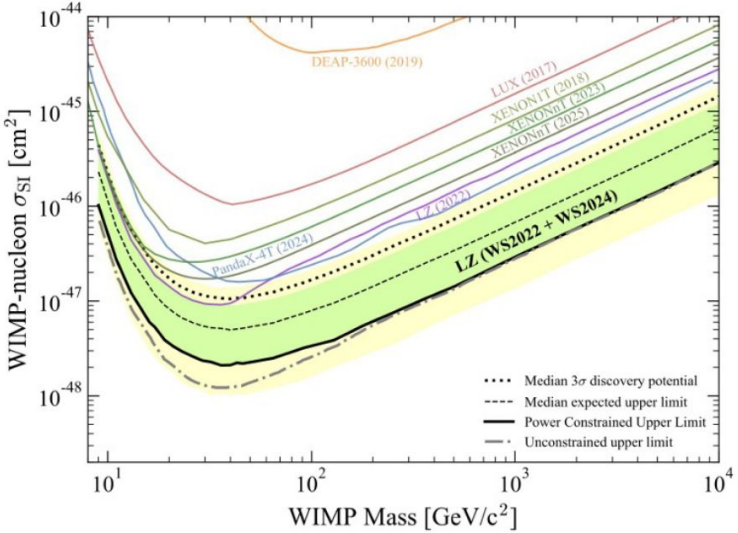
- Status of the field
- Contributions to low mass searches:
  - TREX-DM
  - SuperCDMS
  - DAMIC
- Contributions to high mass searches
  - DEAP-3600 / DarkSide-20k (GADMC)
  - ANAIS
- Wrap up

Status of the field

"Canonic" WIMPs (10 GeV- 10 TeV)

- **Signature**: low E nuclear recoils of WIMPs with target material.
- **Challenge**: Background mitigation + scaling size [actually, scaling size while not scaling bkg]
- Field utterly dominated by dual-phase TPCs with noble elements
- ~1-2 orders of magnitude away from the limit of the neutrino fog
  - It will take in the order of 20 years to dip into the fog.
- **Modulation**: DAMA-LIBRA Modulation essentially excluded by ANAIS and COSINE

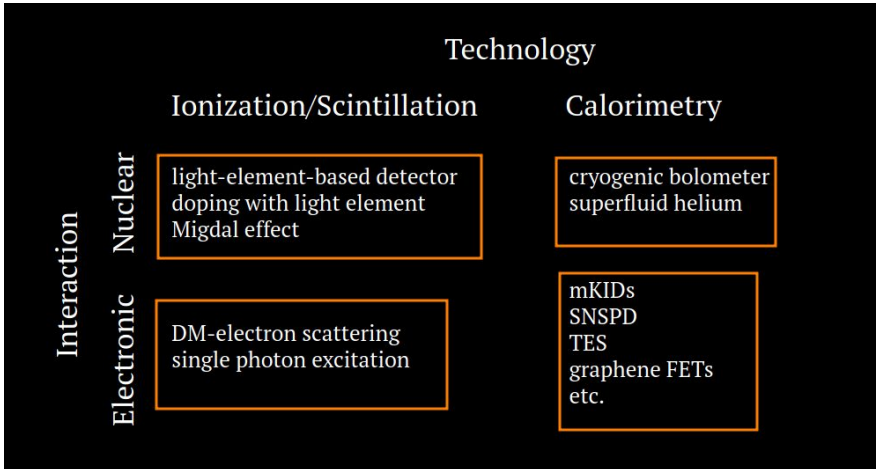




Status of the field

Light WIMPs and sub-GeV DM (axions not included)

- **Signature**:
  - light WIMPs: low**er** E nuclear recoils of target material,
  - lighter candidates: low E electronic recoils
- **Challenge**: same (+ the lower the E of the background, the more difficult to identify).
- Very lively field: Many different technologies for different candidates.



Low energy excess: All cryogenic calorimeter experiments have encountered an instrumental background extremely difficult to mitigate.

Joint effort towards understanding and mitigation.

Spanish contributions

Spain is making contributions of high impact in all these fronts

	FTEs					
Institution	Staff	Postdoc	PhDs	Tech	Experiments	
U. Zaragoza – CAPA	4.5 + 3	1.5	2.5 + 2.5	0.5 + 1.5	**ANAIS**	ANAIS+
					DarkSide-20k	**DArT**
					TREX-DM	
IFCA	3	2	2	2.5	DAMIC-M	**HULK**
UAM- IFT	2		2		SuperCDMS	MIGDAL
CIEMAT	5		3	1	DarkSide-20k	**DArT**
					DEAP-3600	ANAIS+

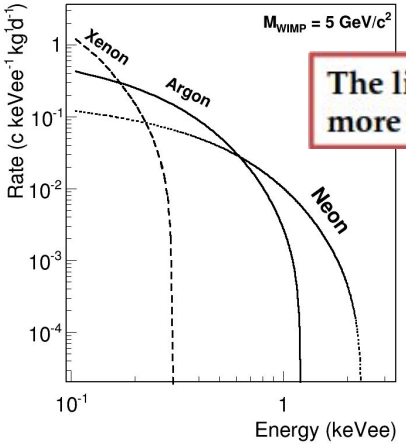
The Canfranc Underground Lab (**LSC**) is a key facility:

- the Spanish contributions in the field are to a large extent articulated around experimental efforts at LSC.
- In particular the results of ANAIS are having a large impact in the field and new efforts are being developed to follow the path.

TREX-DM

TPC for Rare Event eXperiments-Dark Matter

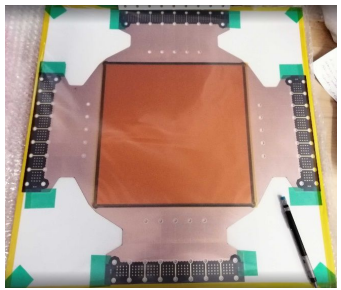
- **A Micromegas TPC for light-WIMPs at LSC**
- ~20 L of pressurized gas (~0.16 kg Ne at 10 b)
- microbulk Micromegas and AGET-based electronics.

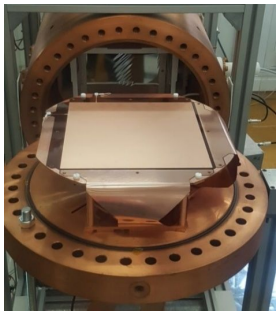


The lighter the target, the more sensitive to low mass

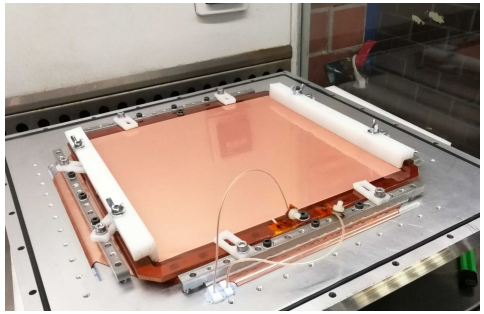
Goals:

- low energy threshold (< 1 keV) and low background level [~1 count/(keV kg day)].
- NOT focused on directionality ⟶ operation at high P



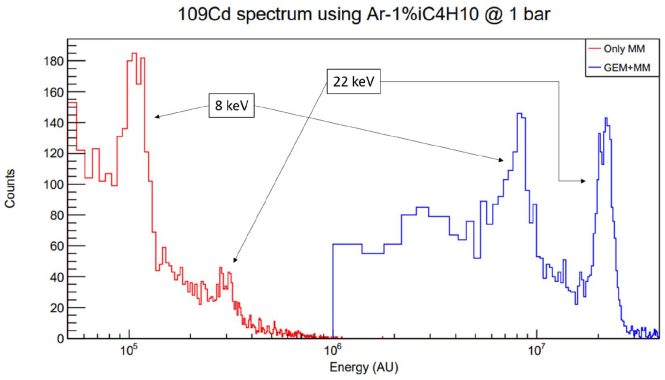


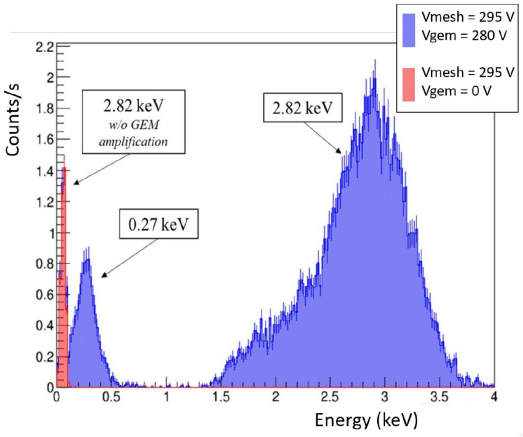
TREX-DM

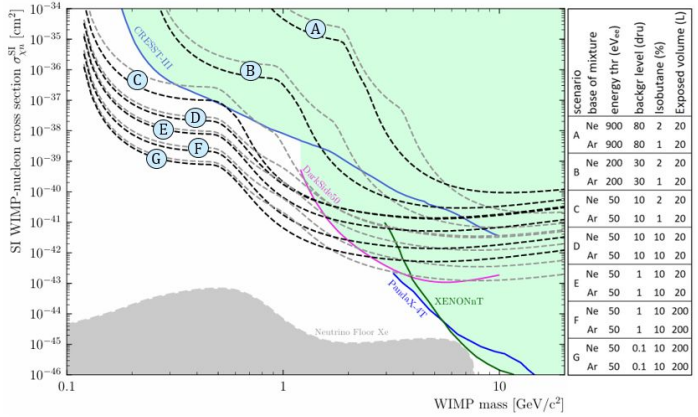


Goals

- Low Threshold Physics runs
  - Energy thresholds well below 1 keV achieved with GEM + mM
  - window to uncharted territory for this kind of detectors
- Progress in background studies and background mitigation
- Increase isobutane content
  - Would increase detector stability and physics sensitivity (lighter nuclei)







SuperCDMS SNOLAB

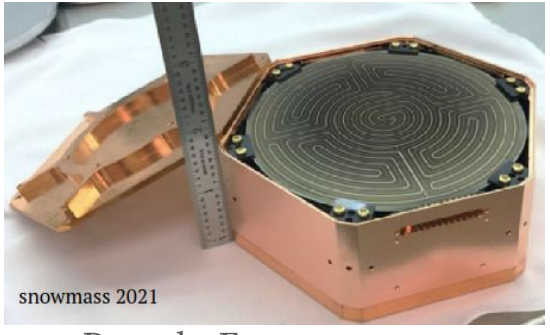
Detection of phonons + ionization in Si and Ge crystals. Starts commissioning in November 2025

IFT group (2 PI + 2 PhDs) contributions:

- Event reconstruction
- Software (ELA: Chair of SuperCDMS Software Working Group)

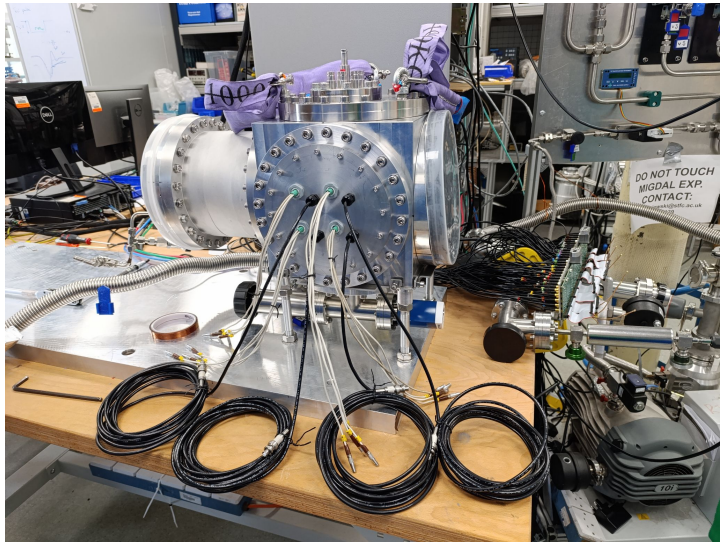
Planning to contribute to commissioning and data analysis:

- DM search via Migdal effect
- Search for freeze-in DM



MIGDAL

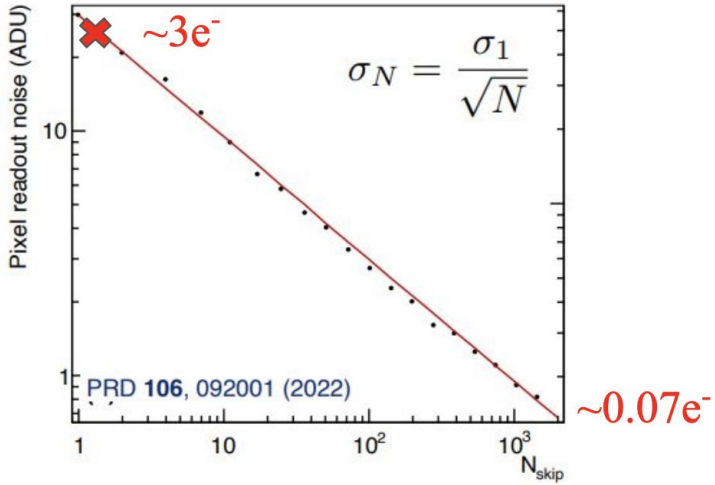
- MIGDAL plans to start 3rd science run in October 2025.
- IFT group built new PMT array for detection of primary scintillation:
  - Required for trigger and background rejection
  - Delivered to main experiment in August 2025, all 16 channels operative.
- Planning to contribute to data analysis of 3rd MIGDAL science run: **expecting first unambiguous observation of Migdal effect.**

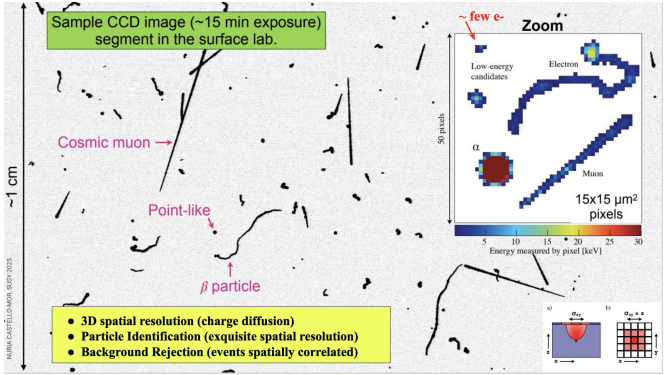


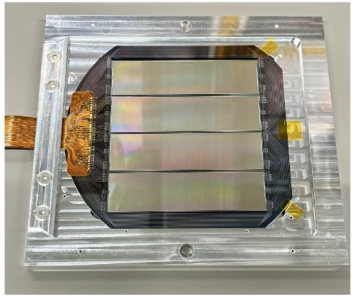
DAMIC-M

- Skipper CCDs: single electron detectors
- Conventional CCDs read out each pixel once, best achieved RMS noise of ~2e- (~10eV). They want single-electron resolutions for eV-scale thresholds.
- CCDs with “skipper” amplifiers. Move charge on and off sense node to make multiple non-destructive charge measurements (PRL 119, 131802 (2017))
    - Sub-electron resolution via NDCMs.

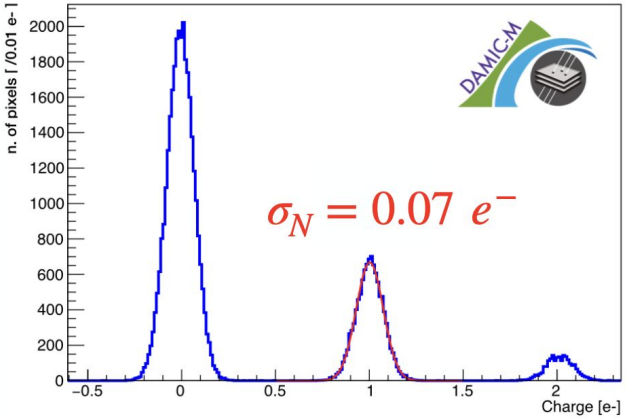
Reduces readout noise by 1/sqrt(Nskips)





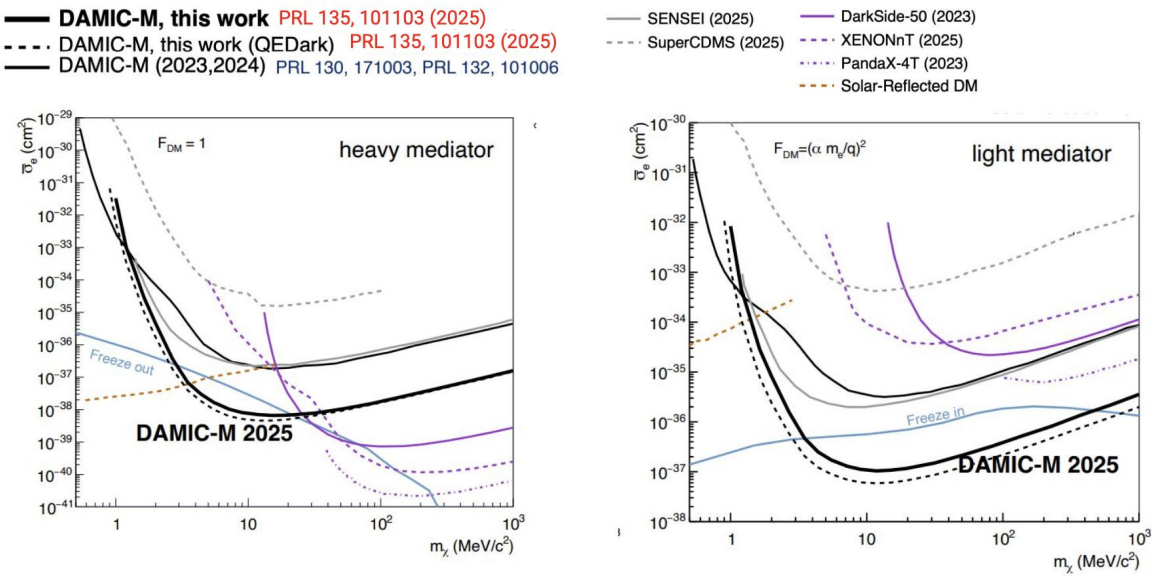


DAMIC-M CCD module



DAMIC-M

PRL 135 (2025) 071002



- Results with 4% of target mass
- exclude for the first time benchmark models of hidden-sector DM over wide range of sub-GeV masses

IFCA contributions

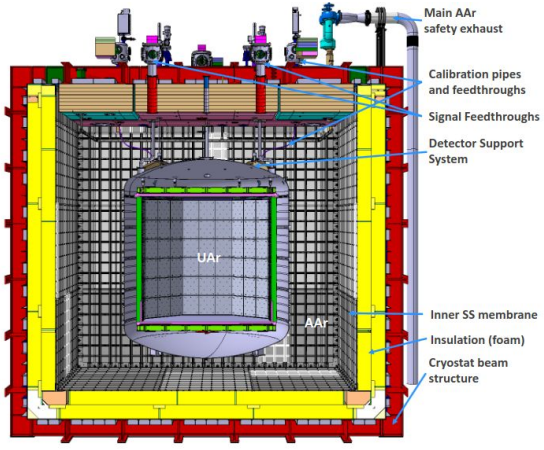
- Lids from EF Cu
- Characterization and mounting at Modane
- Management, analysis and software tasks

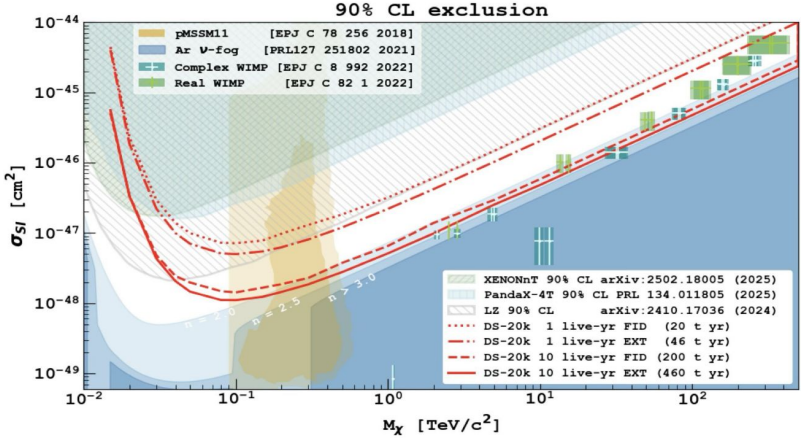
Towards full DAMIC-M (Online by 2026!)

- low background assays, cosmogenic mitigation procedures for transport/production in place
- 120 CCD modules sent to LSM, and being tested there (tested first at UW)
- low-noise electronics designed, tested, and being produced for full-scale experiment

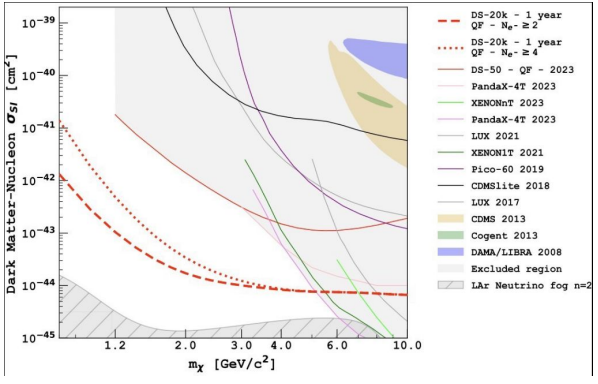
Global Argon Dark Matter Collaboration

Joint collaboration of all experiments that used liquid Ar for WIMP searches [ArDM + DarkSide-50 + DEAP-3600 + MiniCLEAN] towards **DarkSide-20k and ARGO**.

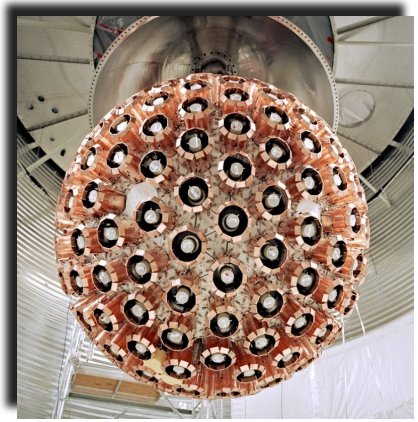


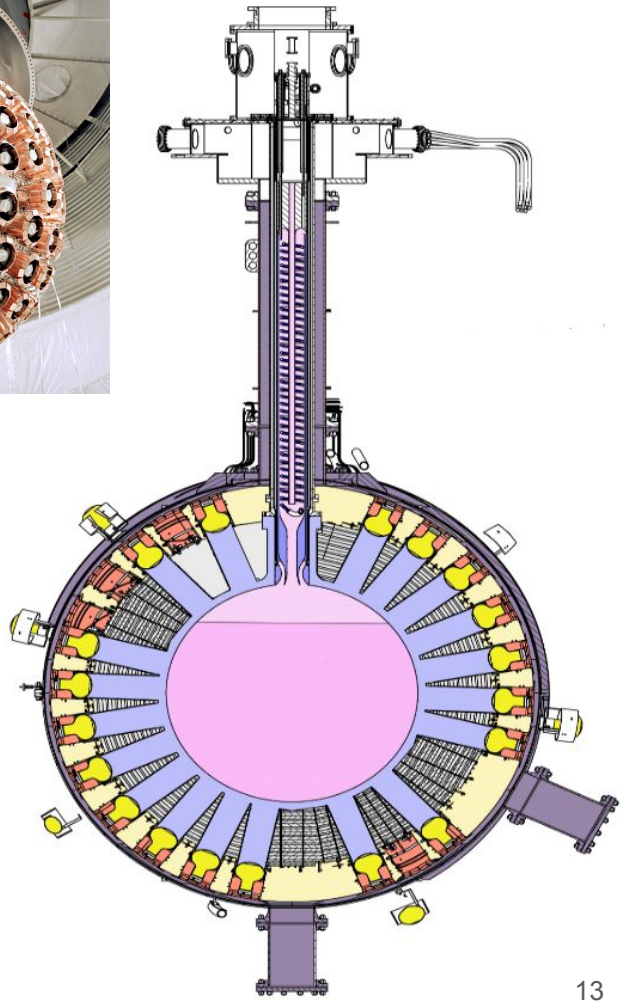


- Dual-phase Time projection Chamber with underground Ar
- Designed to lead WIMP searches [~100 M€ (2% Spanish)]
- Construction started at LNGS
- Production of SiPM-based photodetection units at > 20%.
- PMMA for TPC structure casted. Currently being machined
- Underground Ar extraction plant started precommissioning.



DEAP-3600

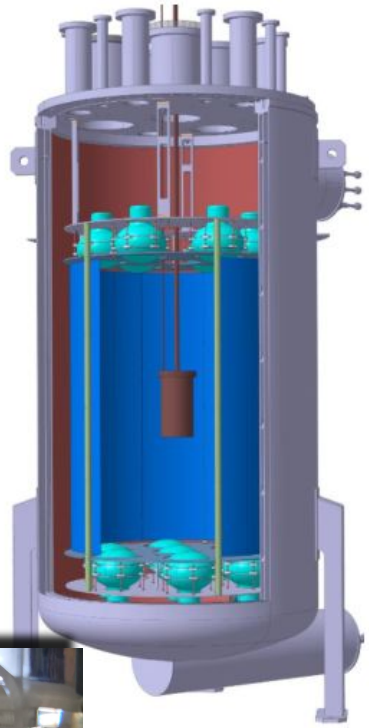


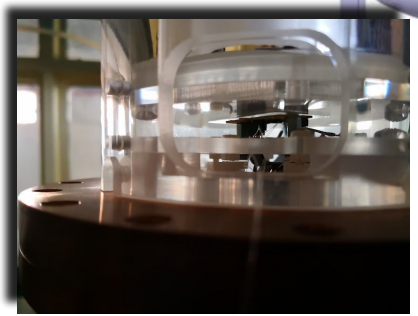


- Liquid-Ar Scintillation-only detector
- Taking data with 3.3 tonnes of Ar @ SNOLAB
- Fundamental to understand long term operation of large Ar detectors.
- WIMP results and solar neutrino measurements coming out soon
    - fundamental CIEMAT contributions in background rejection based on CNNs + event reconstruction.
- Competitive in several exotic DM searches. PRL 128 (1), 011801
- Proved unparalleled pulse shape discrimination in large detectors. Better prospects than Xe detectors. EPJ C 81 (9), 1 (2021)
- The only caveat to Ar detectors is ^{39}Ar intrinsic activity
    - Argon from underground sources brings this down from 1 Bq/kg to 700 μBq/kg.

DArT

- Experiment located at LSC JINST 15 (02), P02024 (2020)
- 1 L of underground Ar in target + 1 tonne of atmospheric Ar in the veto (ArDM) + Pb and PE shields.
- 8 large-surface SiPMs from DarkSide with specific electronics
- Only detector able to perform a batch-to-batch measurement of the ^{39}Ar activity in underground Ar
    - 8 measurements of Ar from extraction plant (URANIA)
    - 8 measurements of Ar from purification plant (ARIA)
    - N samples from DarkSide-20k during filling
    - N samples of Ar for LEGEND and other
- Prototype running since 2021. Results published soon
- DArT-in-ArDM Ready to start data taking.
- Mainly CAPA + CIEMAT + INFN Cagliari (+ GADMC).

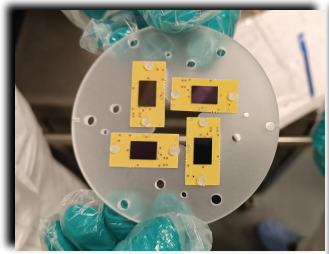


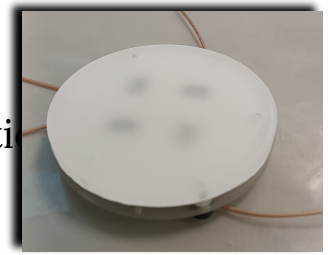


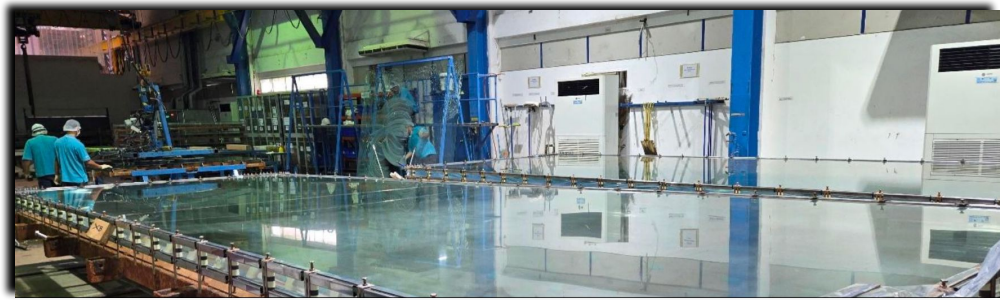
Global Argon Dark Matter Collaboration

Spanish contributions

- Underground Ar production chain: DArT experiment at LSC
- Analysis for DEAP-3600
- DarkSide-20k
  - Detector construction: neutron shield.
  - Development of neural networks for background rejecti and event reconstruction.
  - Management of the Materials & radiopurity group and associated analysis and developments.

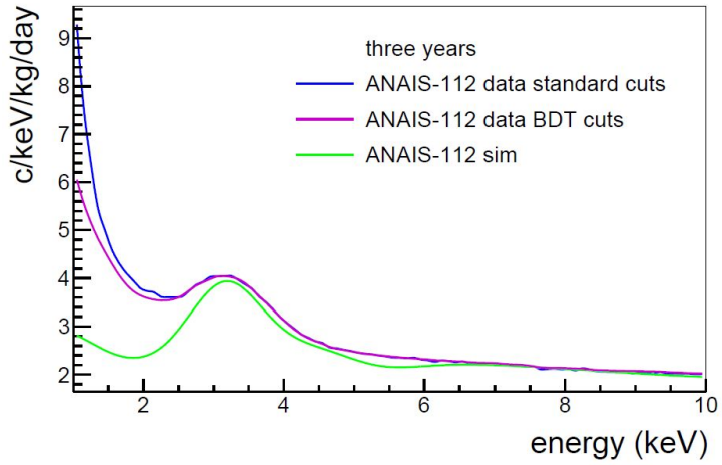






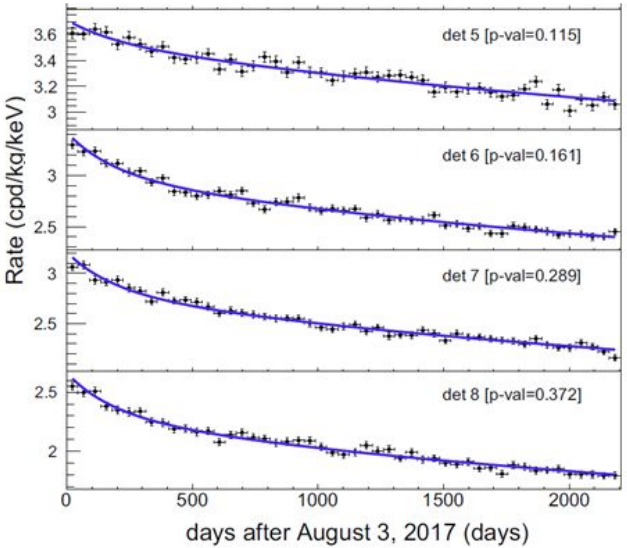
ANAIS-112

- 9 detectors, 112.5 kg NaI(Tl) + blank module
- Taking data smoothly since 2017 to have a definitive, independent test of the DAMA/LIBRA annual modulation result at LSC.
- Excellent light collection: energy threshold at 1 keVee in all modules.
- Robust energy calibration combining bkg / external sources.
- Thorough determination of QF (using 252Cf onsite).
- Background model reproducing remarkably data down to 2 keV, excess over background in 1-2 keV.
- Machine-learning techniques to improve noise rejection.

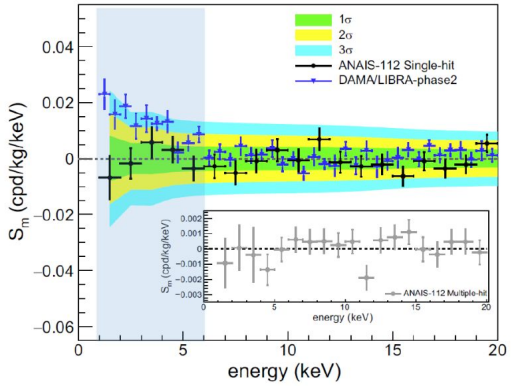


ANAIS-112

No modulation observed: 6-y results incompatible with DAMA/LIBRA signal at 4.0 (3.5) σ at [1-6] ([2-6]) keV Phys. Rev. Lett. 135 (2025) 051001.

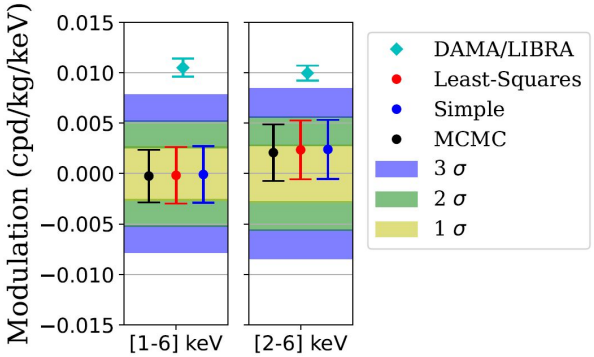


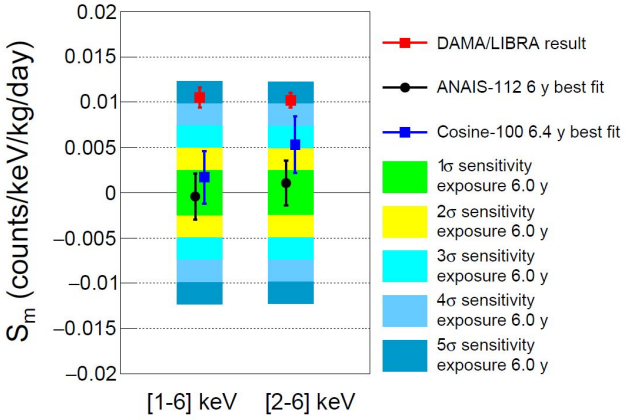
DAMA-LIBRA was already incompatible with Ar and Xe results, but this is completely model independent.



Combined with COSINE-100

Phys. Rev. Lett. 135 (2025) 121002 *





· Data taking going on to reach **5σ** sensitivity (late 2025)

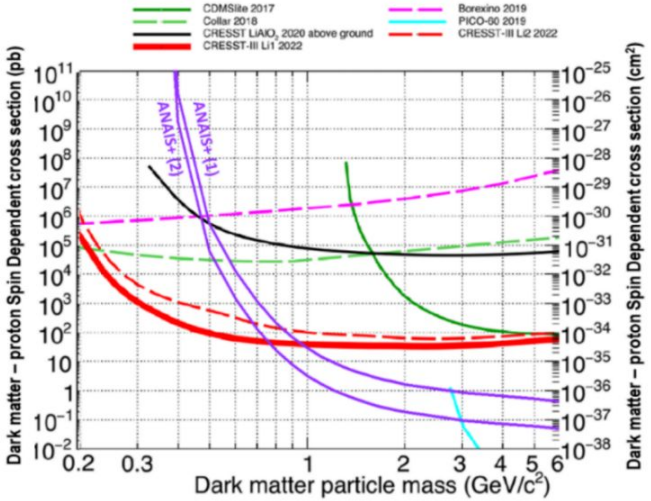
· Further improvements on analysis ongoing to be applied to final dataset

· Proposal by ANAIS team to characterize some DAMA/LIBRA crystals at LSC.

ANAIS+

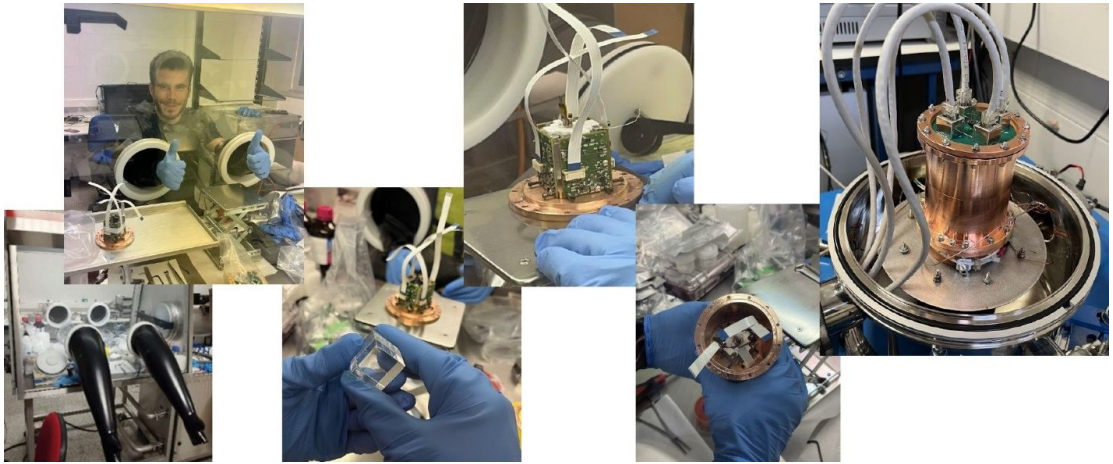
Replacing PMTs by SiPMs (at 100 K) could allow a reduction in energy threshold <0.5 keVee

Better sensitivity, specially to light WIMPs and SD interaction.



ANAIS+ prototypes

- With CsI and NaI cubic crystals (1” x 1” x 1”).
- Prepared in collaboration with LNGS.
- Test set-up at Zaragoza.
- Medium / long term: test in LAr at Canfranc in collaboration with CIEMAT.



Wrap up

- **Spain** is having contributions of **high impact** in many fronts, in large part thanks to the
  - **existence of LSC** and
  - a **scientific community with strong expertise** in low background techniques.
- Many international collaborations, aiming at **leading the prospection** of different zones of the parameter space, are having **visible contributions from our community**.
- **ANAIS** has provided ground-breaking results, with the largest exposure of NaI detectors out of LNGS and being **incompatible with DAMA-LIBRA at 4.0 σ**.
- Potential messages for the APPEC roadmap
  - Importance of the deep underground laboratories, even those at moderate depth, to perform competitive measurements and to generate know-how (5 ERCs + 2 Europa Excelencia thanks to low-background expertise in the last years).
  - The parallel development of different technologies for WIMP detection is fundamental
    - Different detector responses would help characterizing any positive signal
    - Different technologies will have to face different challenges, and what is the fastest path is still to be seen.
  - Add your request here

Gracias

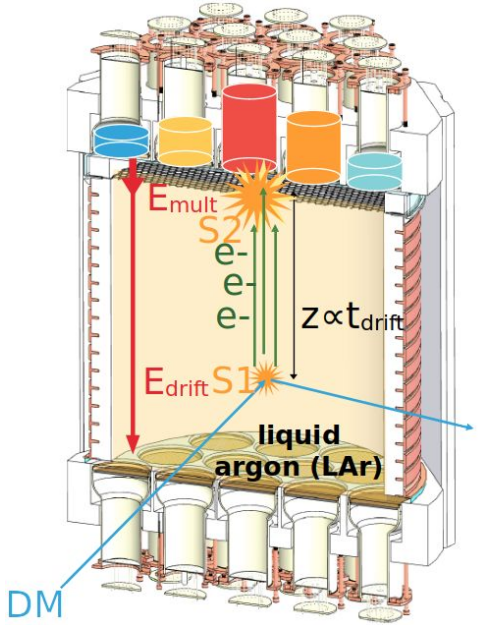
Material de las diapositivas proporcionado por Elías Lopez (UAM-IFT), Susana Cebrián (UNIZAR), Theopisti Dafni (UNIZAR) y Rocío Vilar (IFCA).

Dual-phase TPCs

Massive targets

Scintillation detected promptly (S1)

Uniform E field to measure ionization: prevents recombination + drifts e- to anode



e- extracted to gas phase in stronger field to induce electroluminescence (S2)

light pattern in detection plane provides XY information

Time difference between S1 and S2 provides Z info (mm resolution)

S2/S1 provides particle discrimination

At low Energies, S1 and S2 almost featureless: Unambiguous identification of S1-S2 necessary

DarkSide-20k

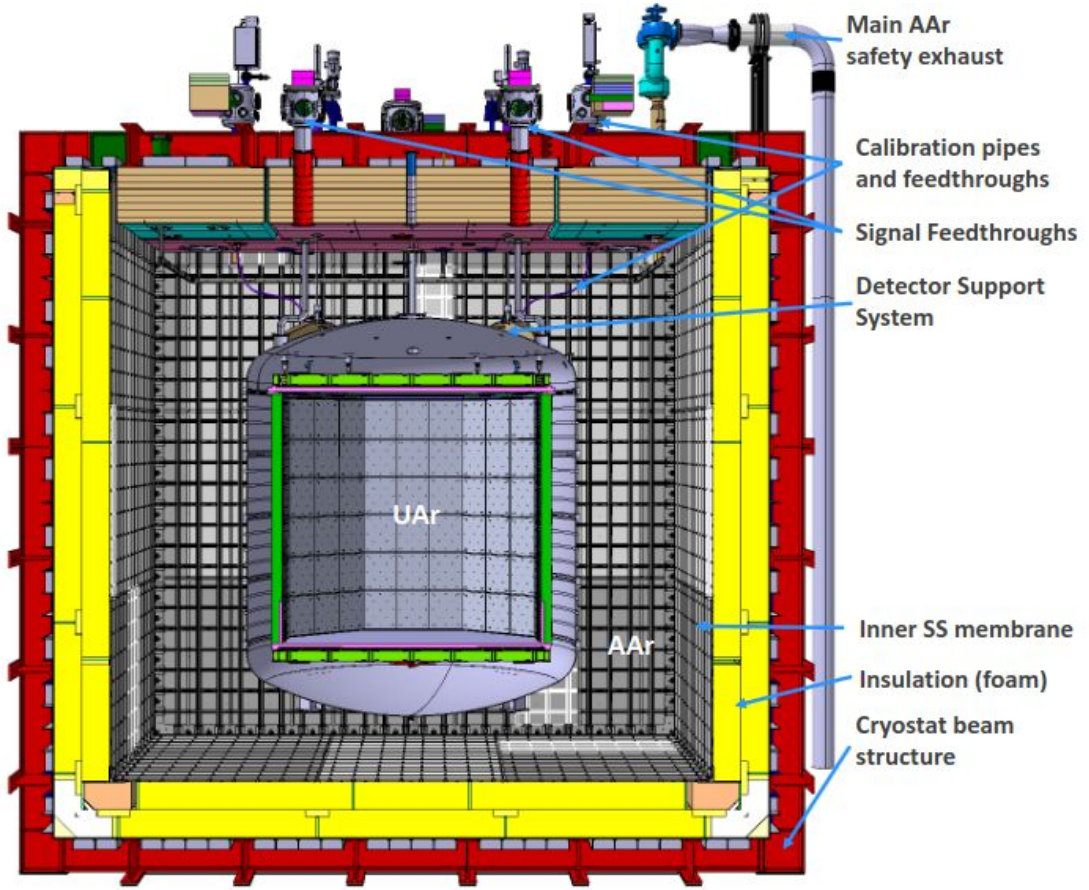
90 tonnes of UAr

50 TPC (20 fiducial) + 40 Veto

650 tonnes or AAr as buffer and muon veto

ProtoDune-like cryostat

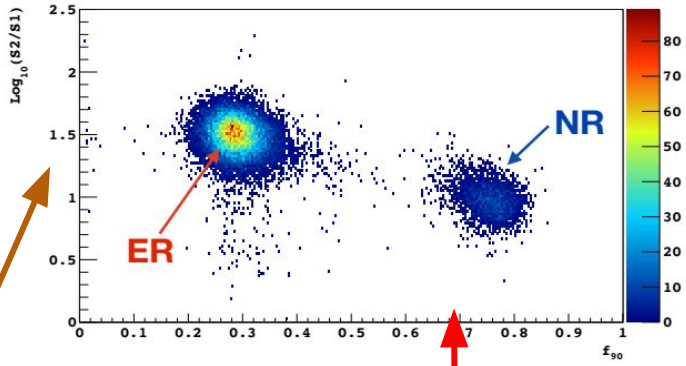
21 m^2 of cryogenic & high QE & radiopure SiPM + electronics



First detector of the Global Argon Dark Matter Collaboration

Ar, what's the point?

Additional discrimination variable: Pulse shape discrimination

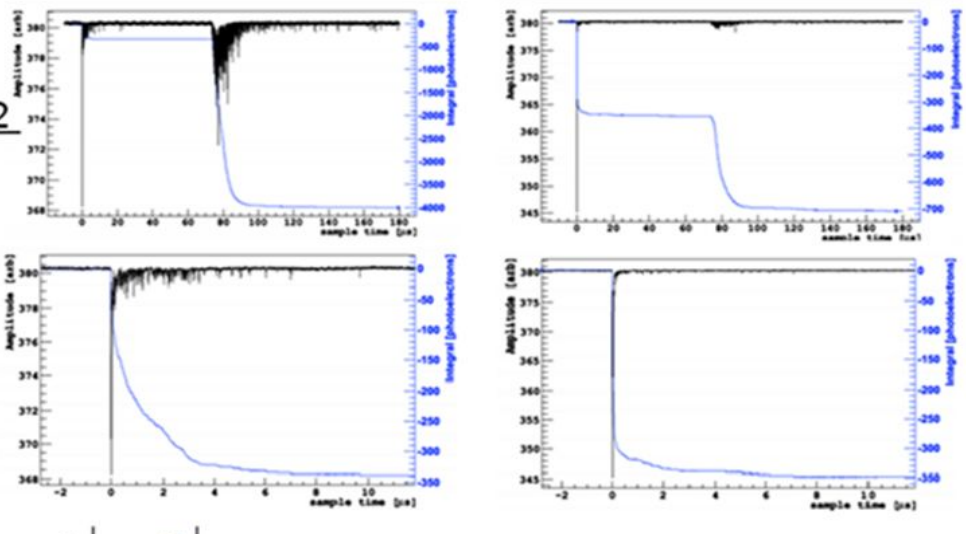


ER-like event

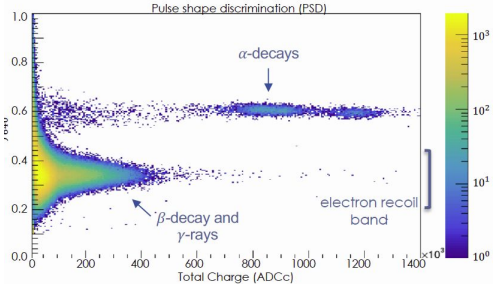
NR-like event

S1/S2

S1 only

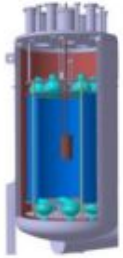


ER contributes as bkg to WIMP searches only at very low E

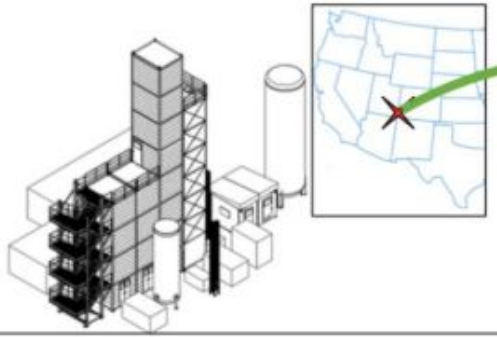


UAr program of DarkSide: Urania, Aria and DArT

The UAr program described in previous talk by R. Stefanizzi



Characterisation: DArT
Measurement of the ^{39}Ar depletion factor



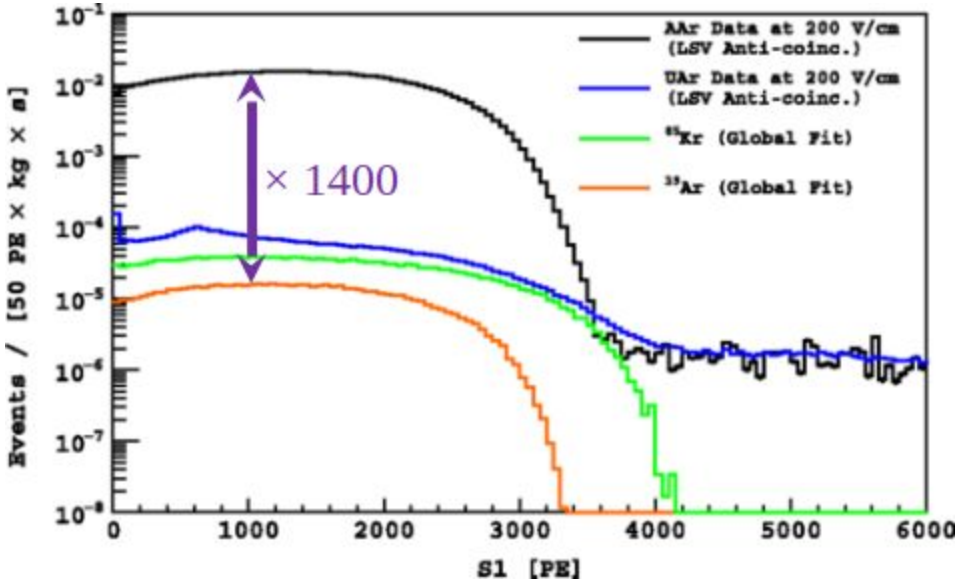
UAr transported via boat for final purification at Aria

Production: Urania
- Commercial-scale plant to extract UAr
- Located in Southwestern Colorado
- UAr extracted from CO_2 well gas at the tonne scale

330 kg/day → 90 tonne/year

Purification: Aria
- 350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements
- Located in refurbished carbon mine shaft in Sardinia, Italy
- Will chemically purify the UAr for DS-20k to detector grade

Underground Ar in DarkSide-50



DarkSide-50 showed a depletion factor of 1400 in UAr with respect to atmospheric Ar activity:
A (UAr) = 0.73 ± 0.11 mBq/kg.

Extraction and purification of UAr is a proven technology.

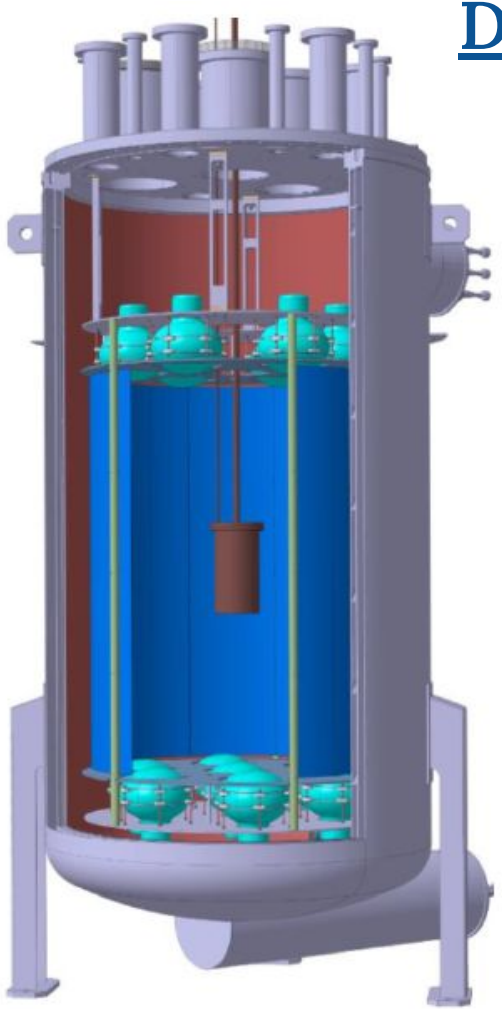
Presence of ^{85}Kr evidences **exposure to air** at some point...

Increasing ^{39}Ar activity.

Verification of UAr compliance is needed for each batch.

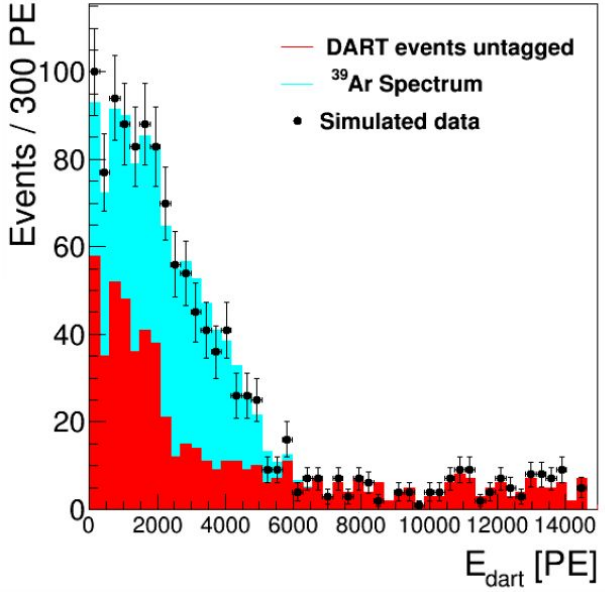
UAr intrinsic activity should be lower than in DarkSide-50.

DArT-in-ArDM: the concept



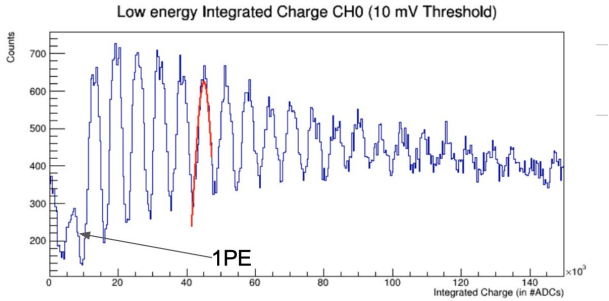
JINST 15 (2020) 02, P02024

Depletion factor with respect to AAr	Statistical uncertainty [%]
10	0.4
100	1.3
1400	**6.7** DS-50
14000	41.1



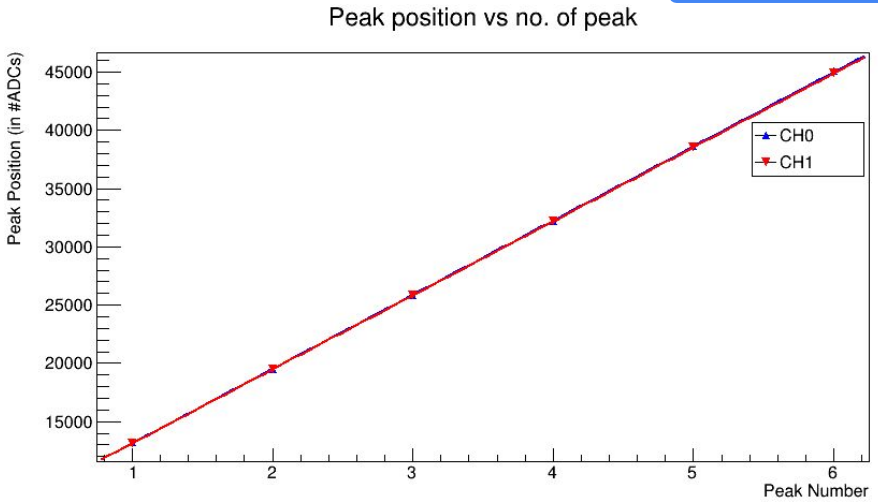
- 1 L chamber full of UAr (DArT) seen by 8 SiPMs.
- ArDM full of atmospheric Ar as veto

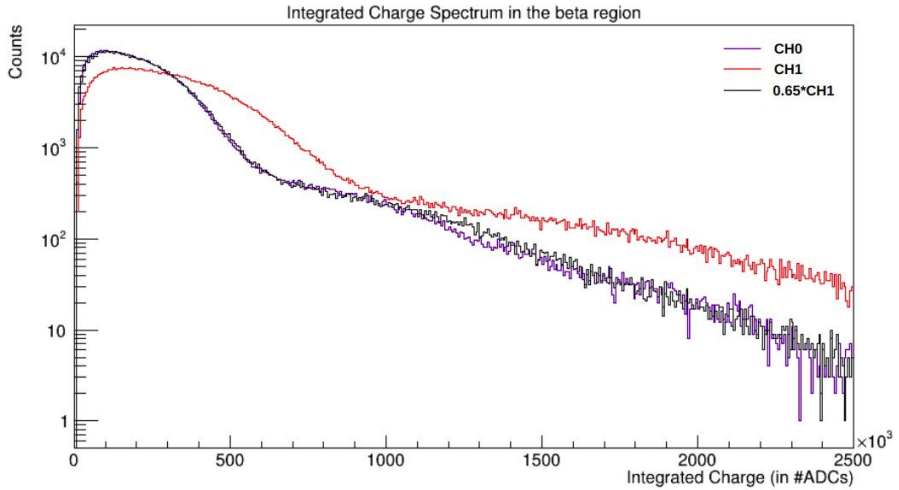
Data analysis



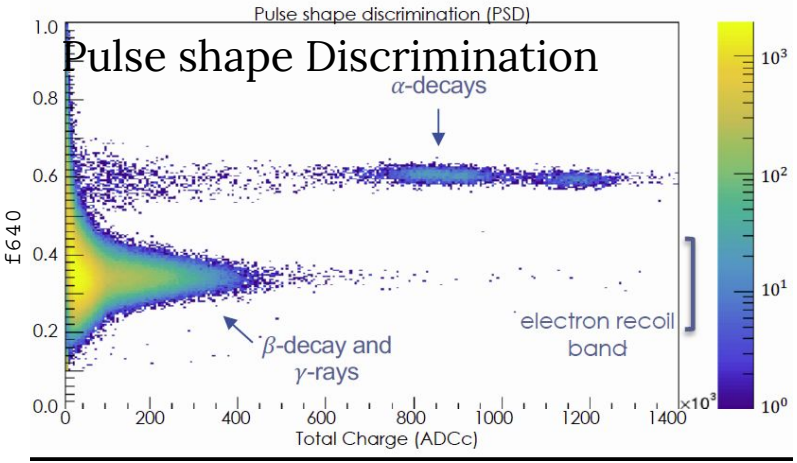
Single Photoelectron (SPE) calibration:

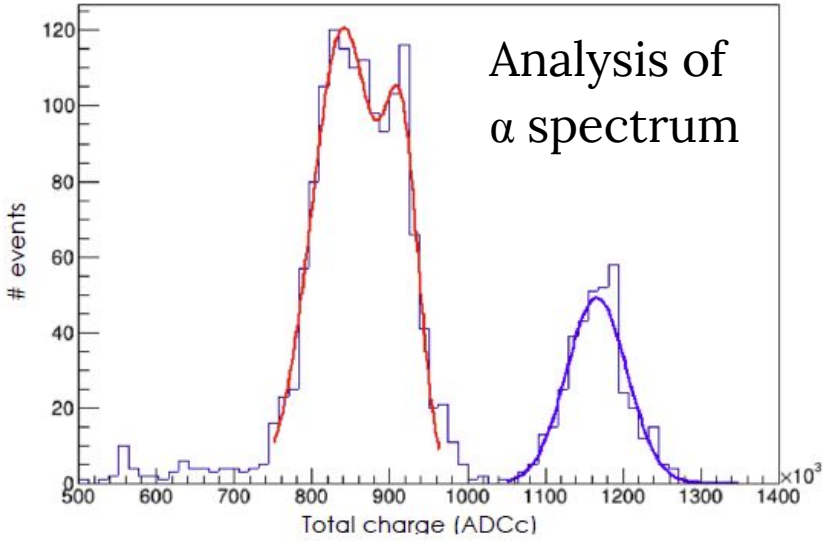
- Same gain in both SiPMs but light yield different.
- Lots of progress in optical simulation:
  - Compatible with 2 mm shift of the top SiPM position.
- Corrected offline.

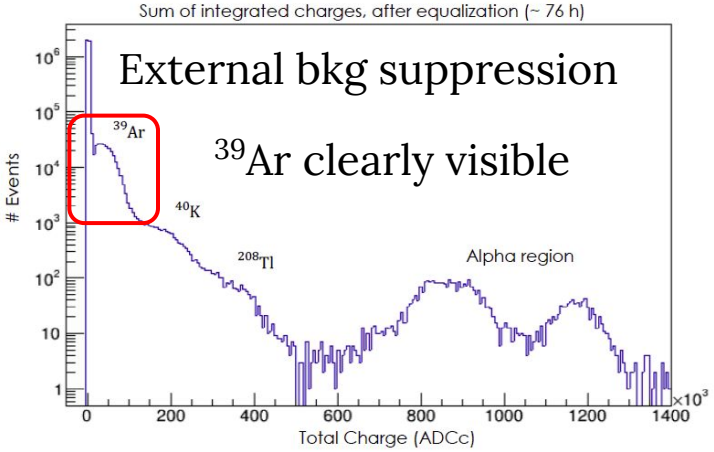


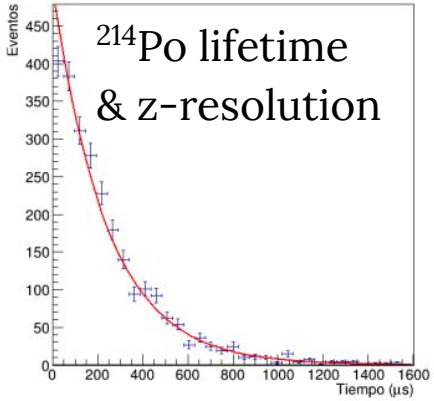


Data analysis









Integration test