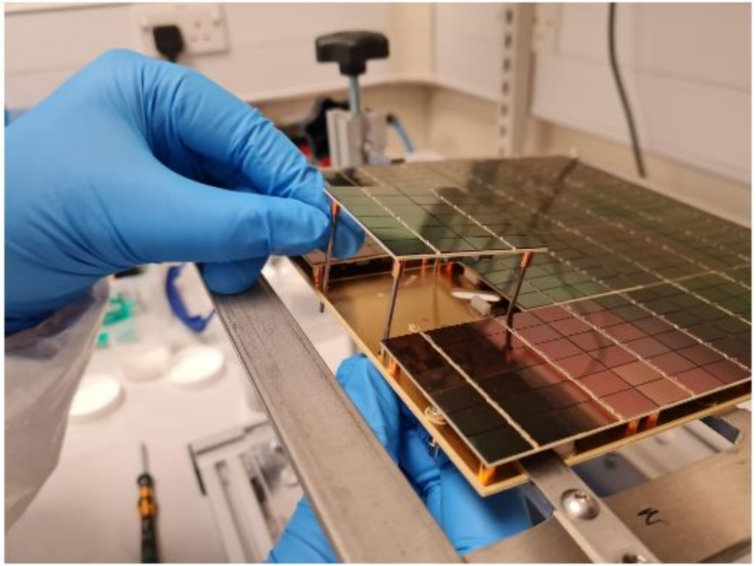
Physics potential of low-background experiments with Ar



Vicente Pesudo
(CIEMAT / LSC)

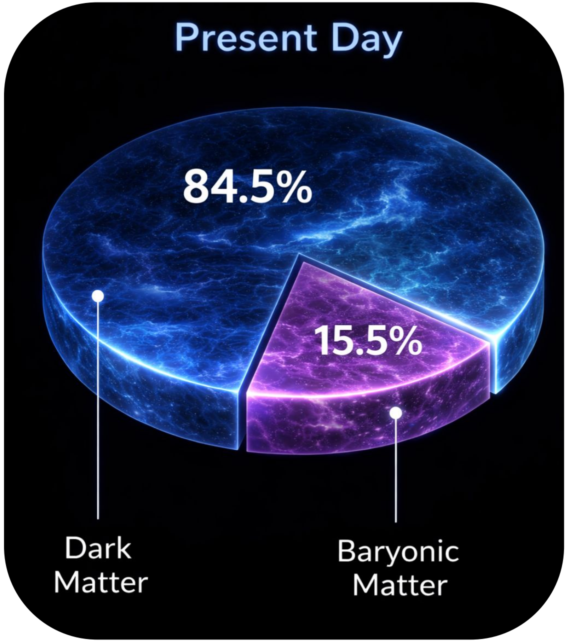
Marseille,
14th September 2026

Outline

- The dark matter problem
- Direct WIMP searches
- DEAP-3600 and DarkSide-20k
- the underground Ar program
- Current status
- Physics goals
- Final remarks

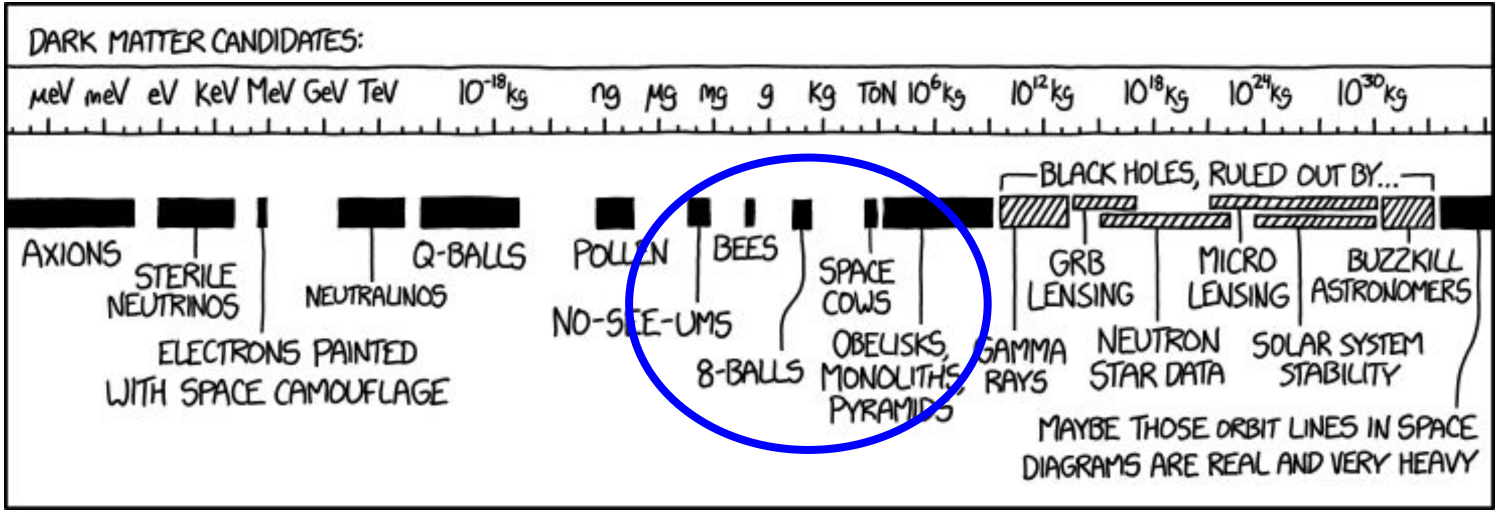
The Dark Matter Problem

The Dark Matter Problem



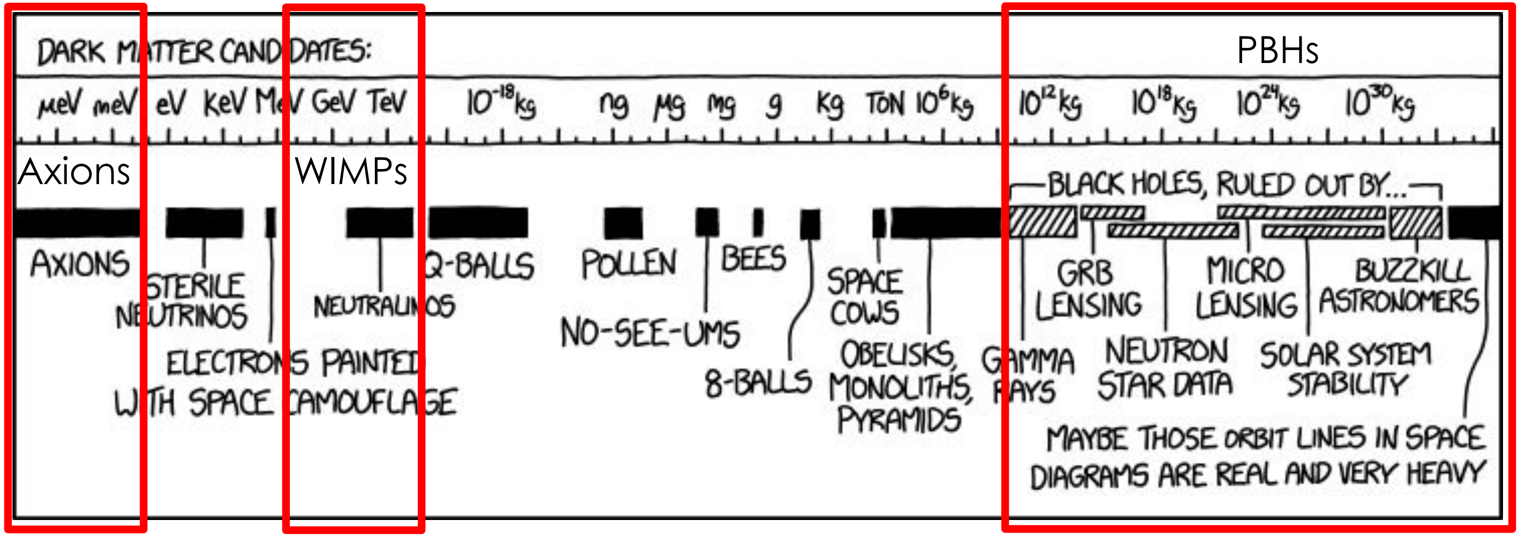
- **The dark matter problem in a nutshell: We have evidences at many different scales (cosmological, cluster, galactic and nuclear) of the existence of dark matter, but no direct observation.**

The Dark Matter Problem



- **Consequence: No candidate can be ruled out in advance, and all the possibilities must be explored. Having said that…**
- **not everything has the same degree of justification,**
- **we have many observables that put very strong constraints.**

The Dark Matter Problem



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The Dark Matter Problem

Particle DM:

- **Axions: particles postulated to solve the Strong CP problem in QCD, which fit nicely as dark matter candidates.**

CPPM MADMAX

- **Weakly Interacting Massive Particles: born as the most natural solution to a thermal relic scenario.**

Non-particle DM:

- **Modified Newtonian Dynamics: Gravity depends on acceleration**
- **Primordial Black Holes: BHs formed from initial fluctuations, only a viable candidate for small window of masses (asteroid window) and/or large clusterings.**

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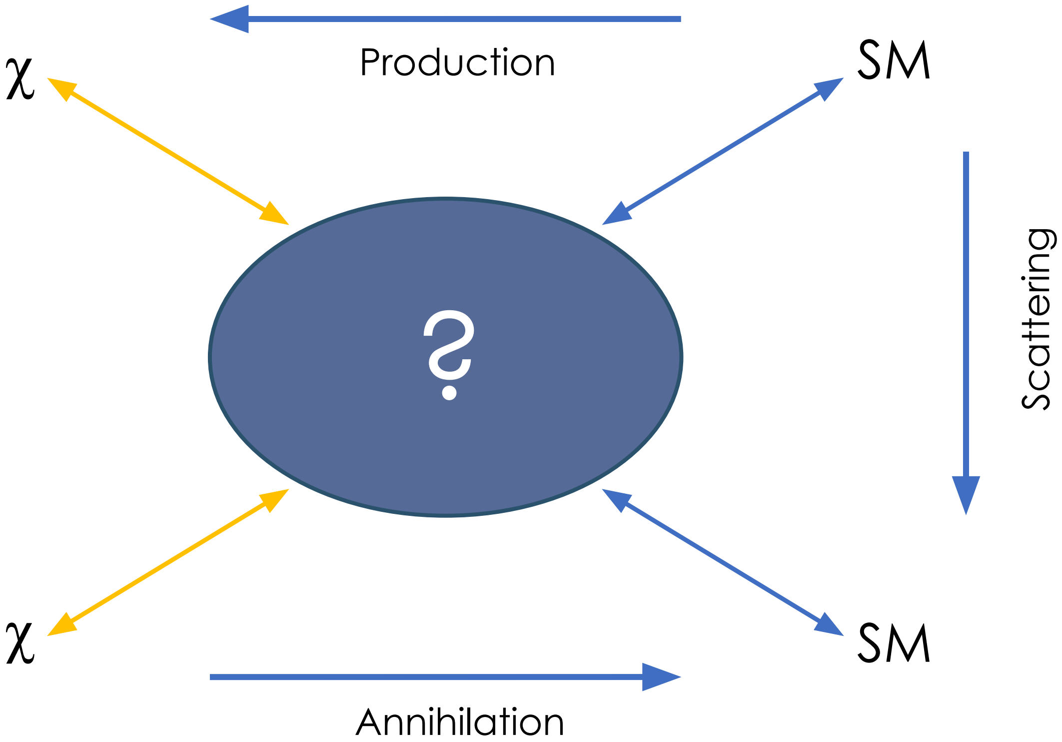
The Dark Matter Problem



The Dark Matter Problem

Production at colliders:

- When something decays to the dark sector it becomes undetectable
- Missing mass (missing transverse momentum) would evidence such couplings
- The connections of this to cosmological DM are model dependent

Indirect detection

- Annihilation might still be happening in regions with high DM density
- This annihilation can produce gamma rays or particles detectable in space
- Other sources could mimic similar signatures (the millisecond pulsar explanation to the Galactic center excess)

Direct WIMP searches

Direct detection:

- The local density of DM in the solar system should be 0.3-0.4 GeV/(c^2 cm^3)
- Particle DM should be going through Earth and we have chances to detect it if it does more things than just gravitating.
- We know Earth and low E physics better than the galactic center: if one is able to disentangle these interactions from background it is an undisputable way of determining we found DM.
- Caveat: We didn't yet (or did we?).

Direct WIMP searches

Direct WIMP searches

What do we aim for?

- We start with a minimal scenario in which WIMPs hit a nucleus in the detector, induces an elastic scattering and as a consequence a nuclear recoil.
- We ignore the details of the interaction and the structure of the DM candidate.

What do we search for, in addition to this?

- Other excess with distinctive spectral features
- Essentially anything incompatible with background.

Direct WIMP searches

What do we expect?

$$\frac{dR}{dE_R} = \boxed{\varepsilon(E_R)\, N_t} \boxed{\frac{\rho_0}{m_\chi} \int_{v \geq v_{\min}(E_R)} d^3v\ f_{\rm lab}(\mathbf{v})\ v} \boxed{\frac{d\sigma}{dE_R}(v, E_R)}$$

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Target dependence:

- Number of target nuclei
- Efficiency to detect events of a certain type and energy (acceptance, threshold, resolution...)

Direct WIMP searches

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$$\frac{dR}{dE_R} = \boxed{\varepsilon(E_R)\, N_t} \boxed{\frac{\rho_0}{m_\chi} \int_{v \geq v_{\min}(E_R)} d^3v\ f_{\text{lab}}(\mathbf{v})\ v} \boxed{\frac{d\sigma}{dE_R}(v, E_R)}$$

Halo term:

- Local DM number density: 0.3-0.4 GeV/(c^2 cm^3)
- Flux weighted by velocity distribution (which is Maxwell-Boltzmann within 10-30%)

Direct WIMP searches

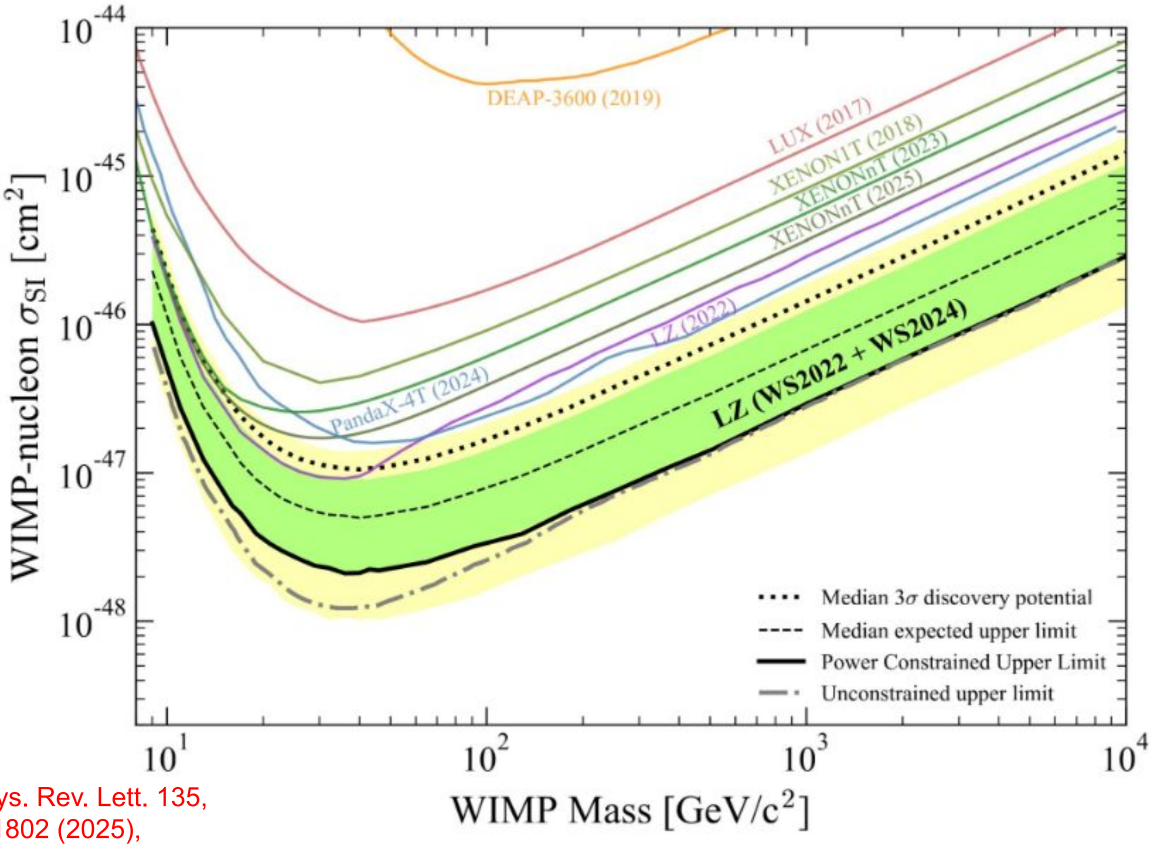
What do we expect?

$$\frac{dR}{dE_R} = \boxed{\varepsilon(E_R)\, N_t} \boxed{\frac{\rho_0}{m_\chi} \int_{v \geq v_{\min}(E_R)} d^3v \; f_{\rm lab}(\mathbf{v}) \; v} \boxed{\frac{d\sigma}{dE_R}(v, E_R)}$$

Cross section:

- Here one can plug whatever, but the general approach is starting with a spin independent cross section

Direct WIMP searches



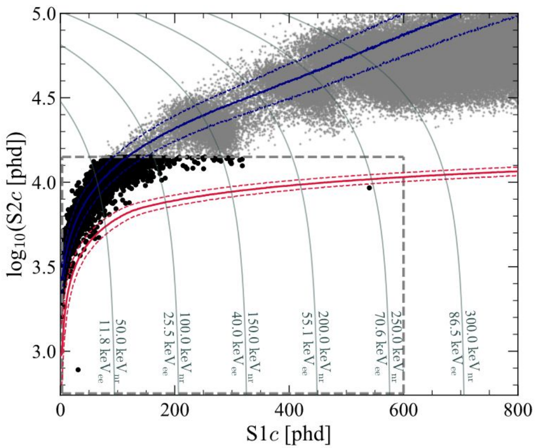
Phys. Rev. Lett. 135, 011802 (2025),

This is computed for all possible masses providing a sufficient:

- recoil E
- recoil rate (more massive means lower number)

Spoiler!
Potential DM-interaction published two weeks ago!!

arxiv:2609.02823

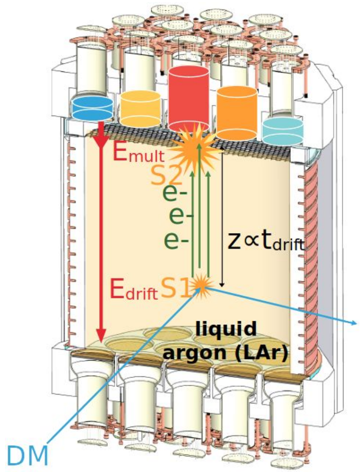


Dual-phase TPCs

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

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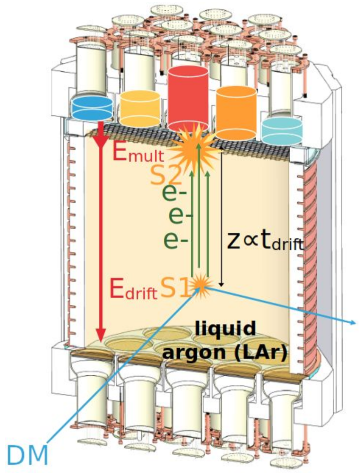

Bonus: another detector surrounding to veto external bkg.

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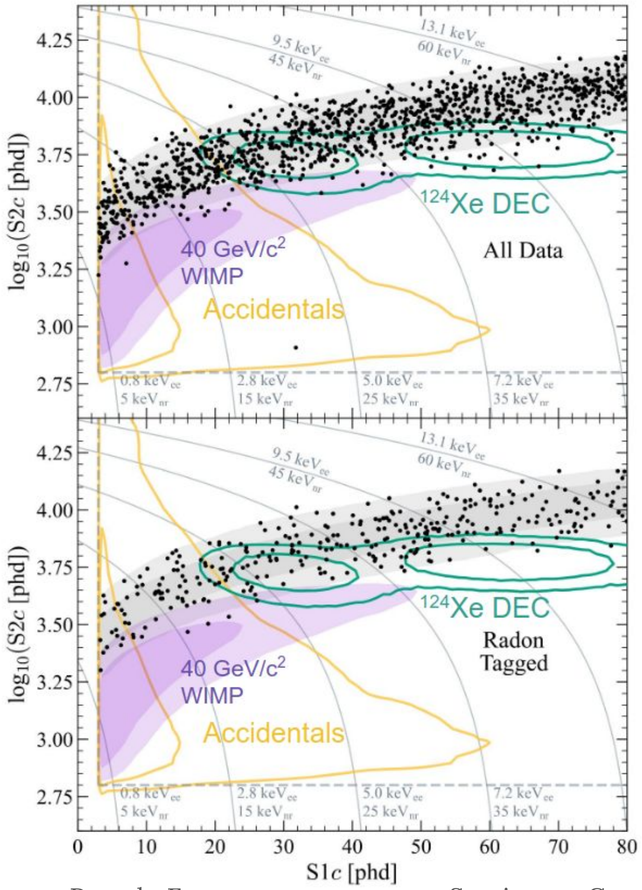
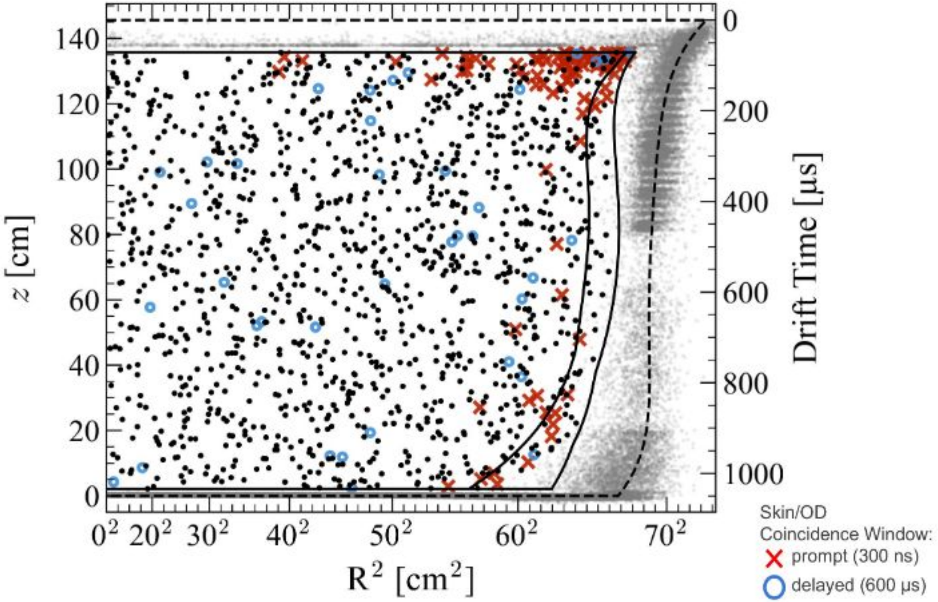
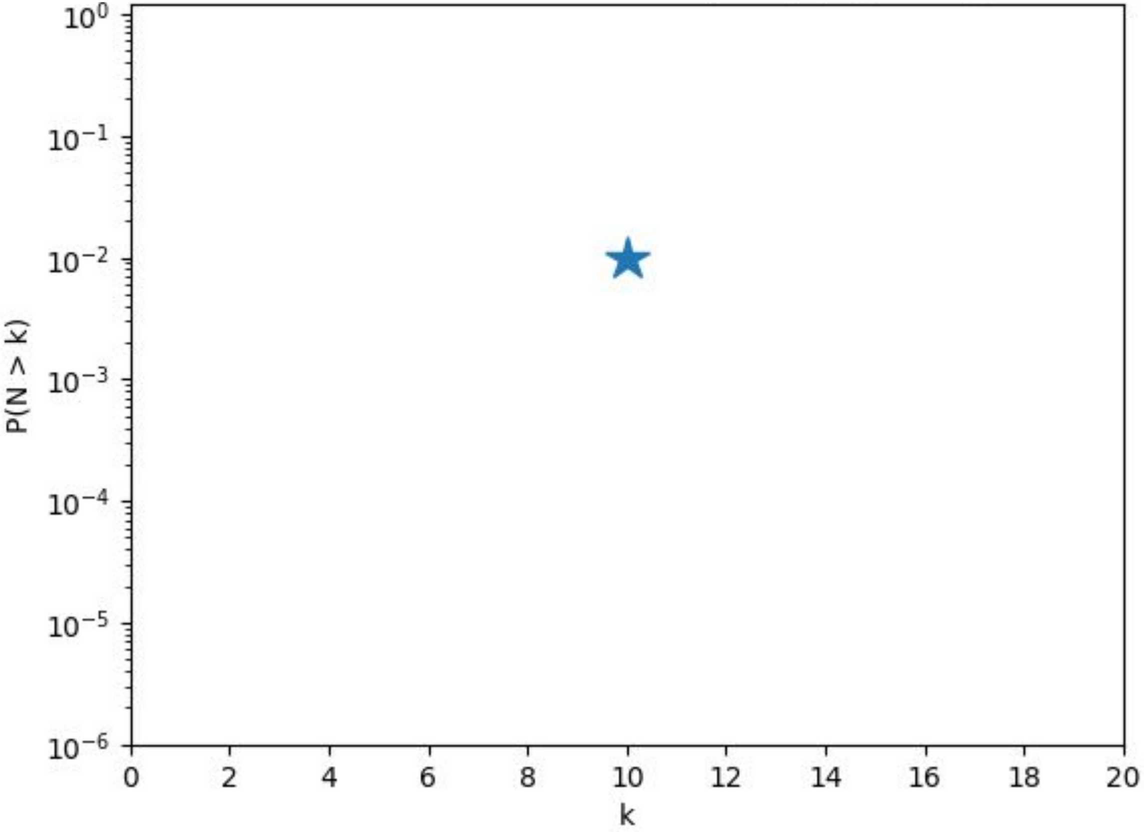
Xe TPCs

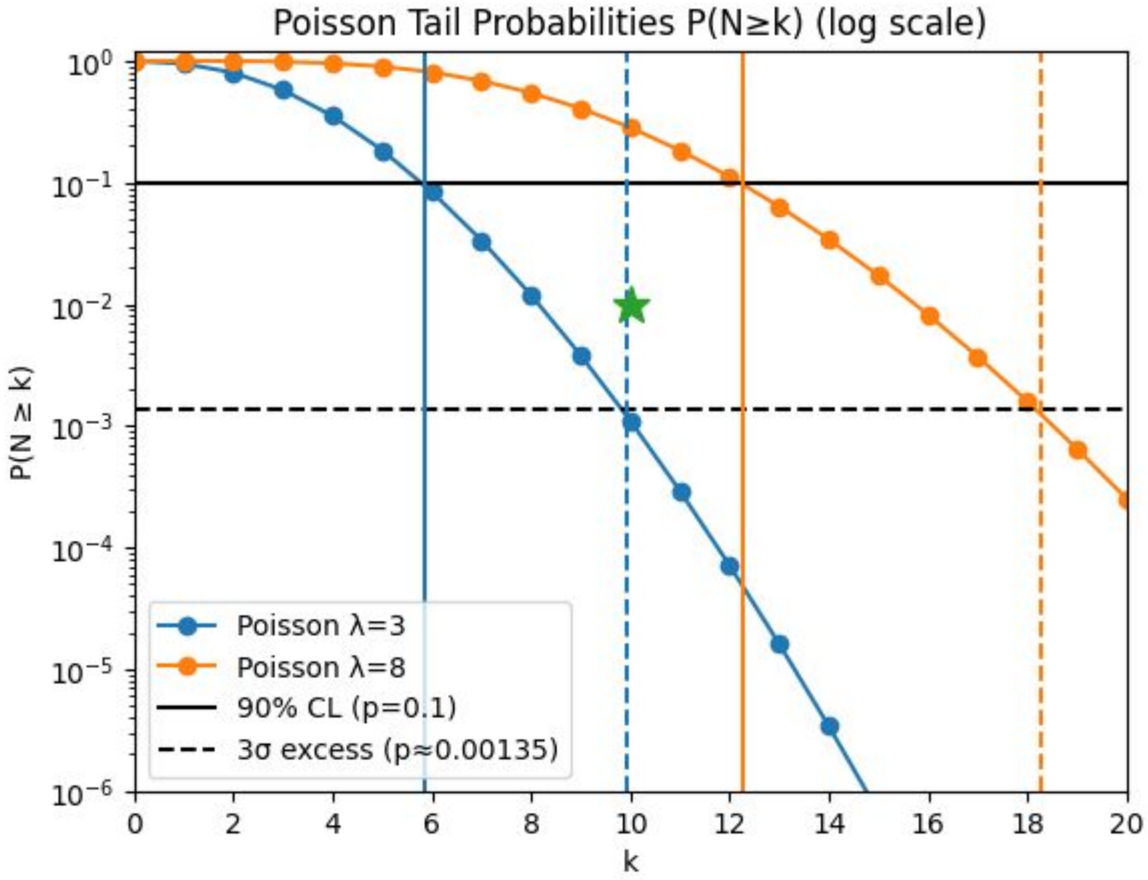


Example of position reconstruction and particle discrimination in the LUX-ZEPLIN experiment





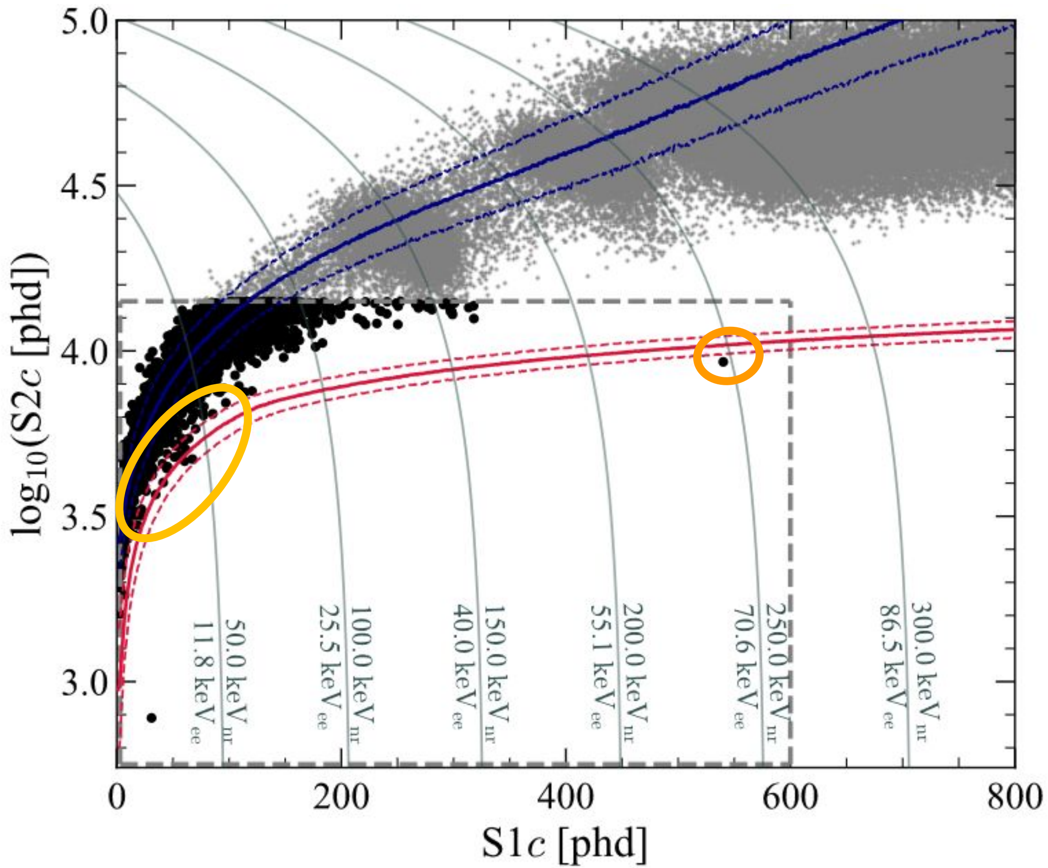
Is finding 10 WIMP-compatible events better than one?



Is finding 10 WIMP-compatible events better than one?

It depends on where

The rare-event business is (evidently) the background mitigation business. And background free regions are easier to exploit.



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What background sources do we expect?

- radiogenic activity
  - External (walls, rocks)
  - Surface contamination of materials
  - Bulk materials (themselves)
  - Radon emanation
  - Secondary (neutrons)
  - diluted dust
- Cosmogenic activity
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SHIELDS / Nested (onion) concept

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Monte Carlo simulation and Data analysis

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Underground labs

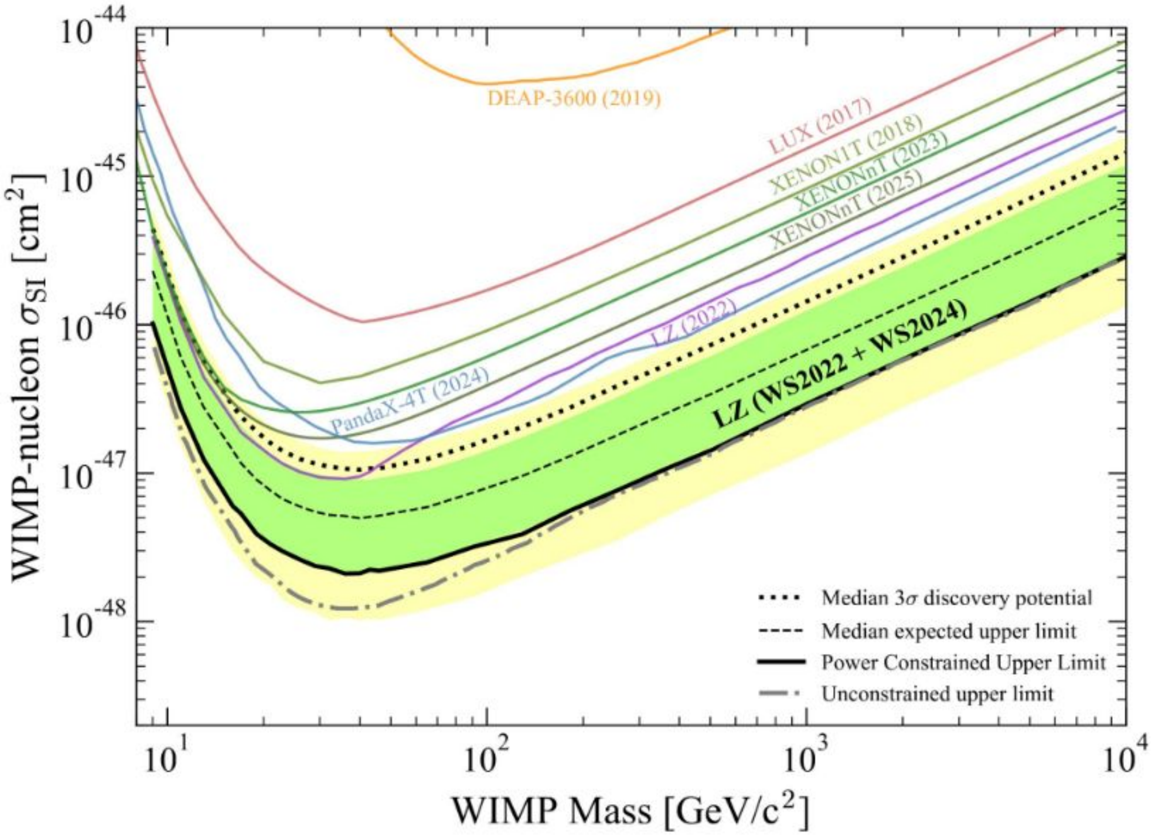
Rien à faire... except translating it into a new physics opportunity

- Instrumental artifacts

Monte Carlo simulation and Data analysis

Ar detectors

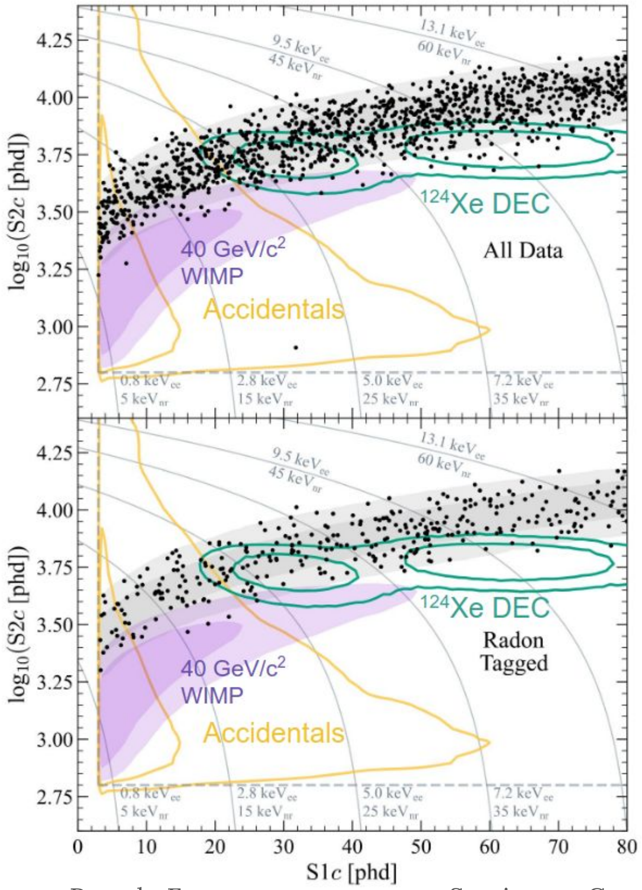
State of the art



If Xe has been so successful in the last decade…

Why Argon!?

Xe TPCs



Particle discrimination in Xe depends on S2-S1 correspondence.

The background to which more attention has been paid in LZ's recent paper is MSSI events: Multiple-scatter single-ionization events.

The main potential background culprits (at least that I have heard of) are:

- Dust from which an alpha is emitted. Some E is lost in the particulate and E is degraded.
- Accidental coincidence of actually uncorrelated S1 and S2

Ar, what's the point?

Lower mass than Xe (low-E recoils)

different nuclear properties: better in terms of keeping coherence, but no Spin Dependent sensitivity

Additional discrimination variable

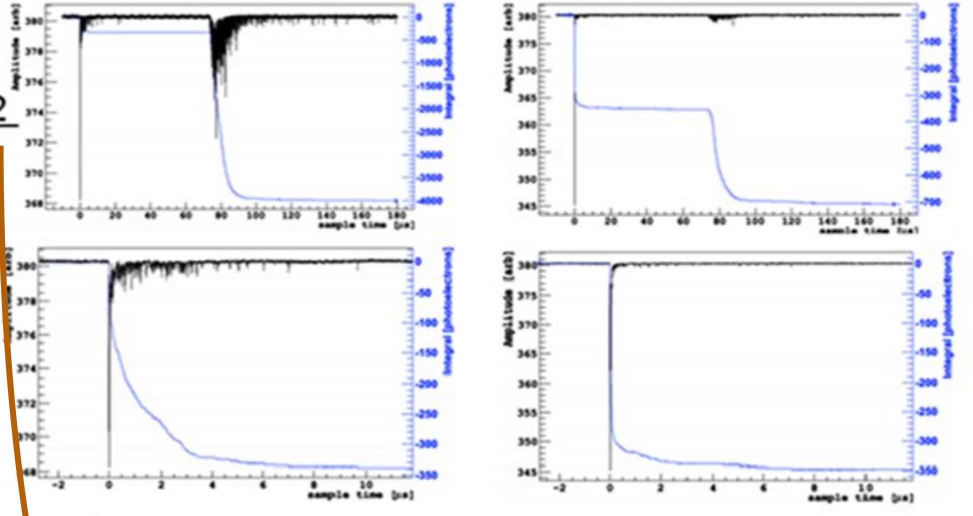
Pulse shape based on scintillation only: singlet vs triplet components

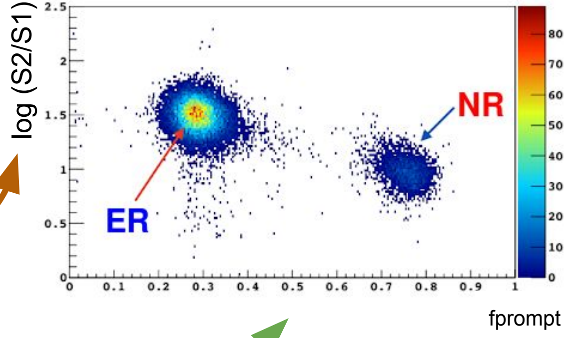
ER-like event

NR-like event

S1/S2

S1 only

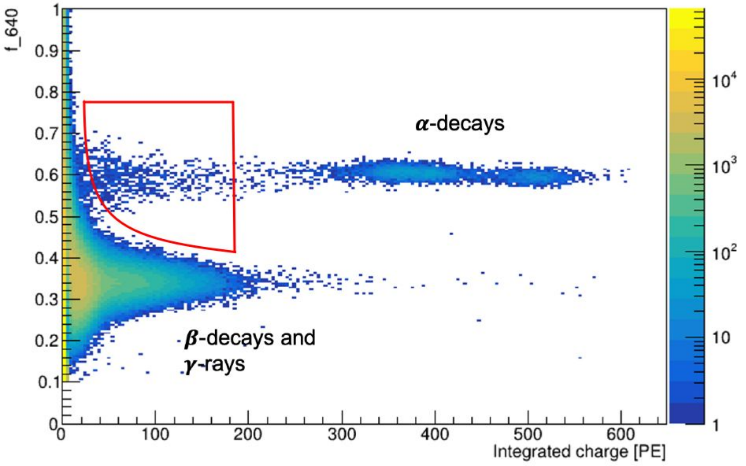


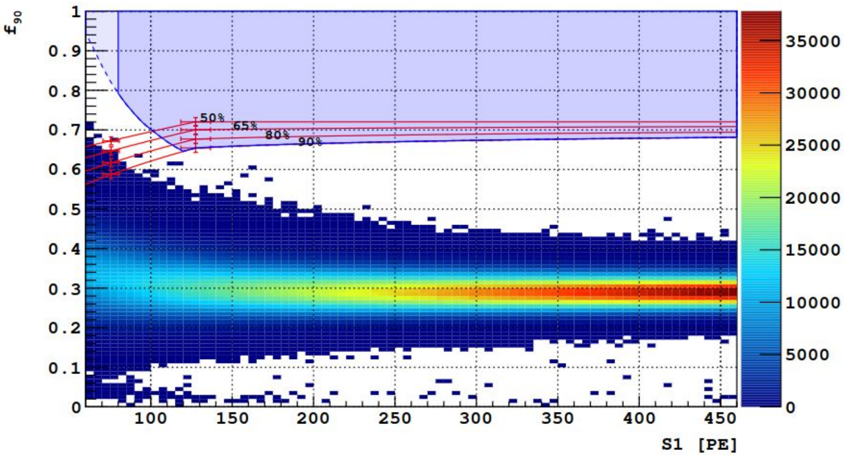


Ar, what's the point?

Electron recoils are further from region of interest at lower energies

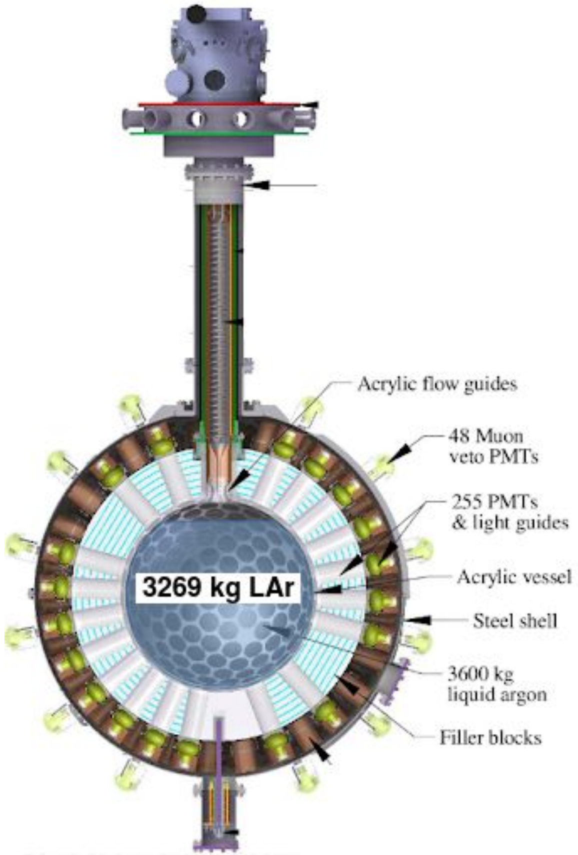
This discrimination does not depend on coincidences of any kind. Scintillation-light only.





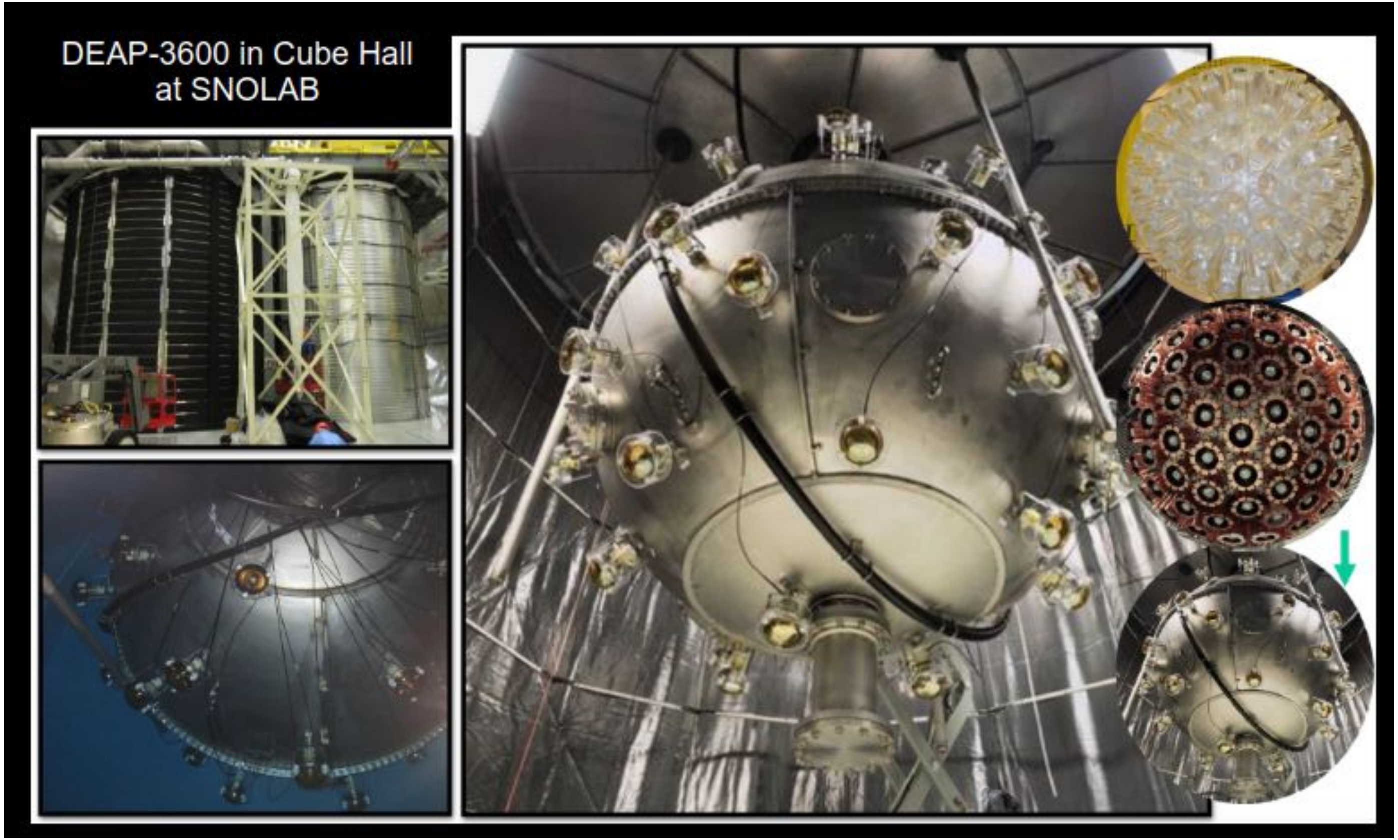
DEAP-3600

The DEAP-3600 detector



- 3.3 tonne LAr target in ultraclean acrylic vessel (R = 85 cm).
- In-situ vacuum evaporated TPB on inner 10 m^2 surface.
- 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/m2/day

The DEAP-3600 detector

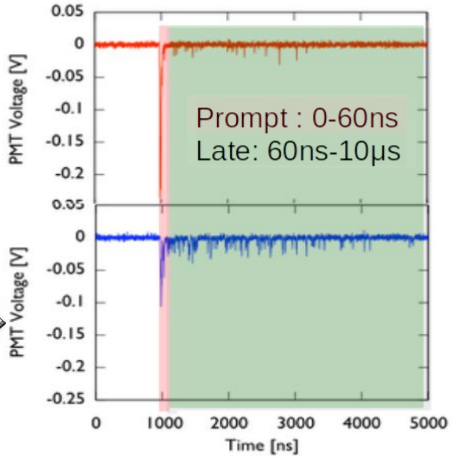


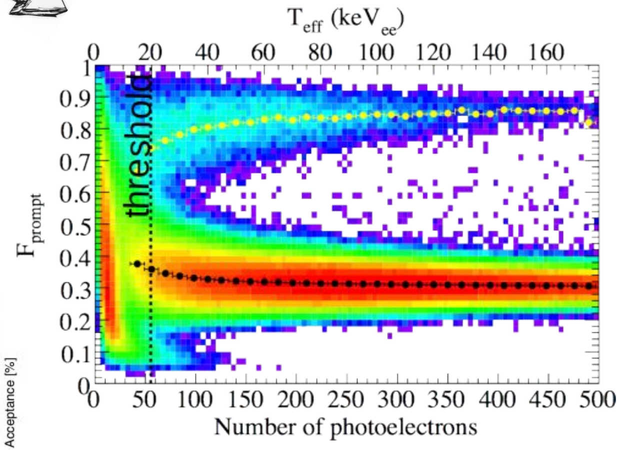
The DEAP-3600 detector

- **Pulse shape allows us to discriminate** against gamma and beta backgrounds.

Eur. Phys. J. C 80,303 (2020)

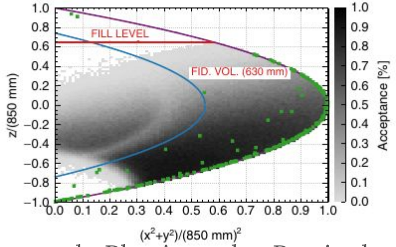
Eur. Phys. J. C 81,823 (2021)





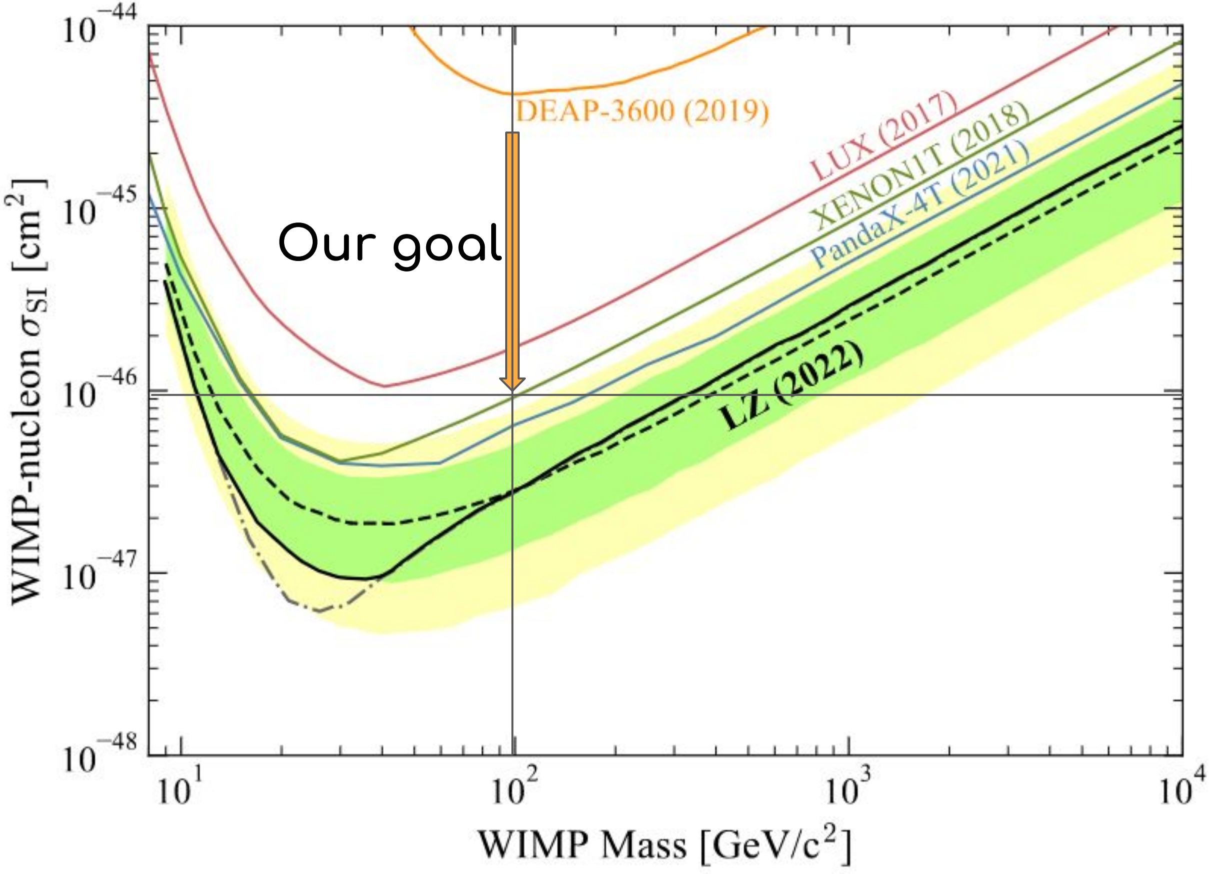
- Position reconstruction and fiducialization allow us to reduce surface and external backgrounds.

JINST 20 P07012 (2025)



- No electric field

The DEAP-3600 detector



The DEAP-3600 detector: goals

1. **Tackling limiting factors to WIMP sensitivity (hardware upgrades)**

2. **Continue improving DM analyses** (better detector model + Profile likelihood + machine learning + increase exposure without dust)

3. **Learning for DarkSide-20k, ARGO and LAr detectors**

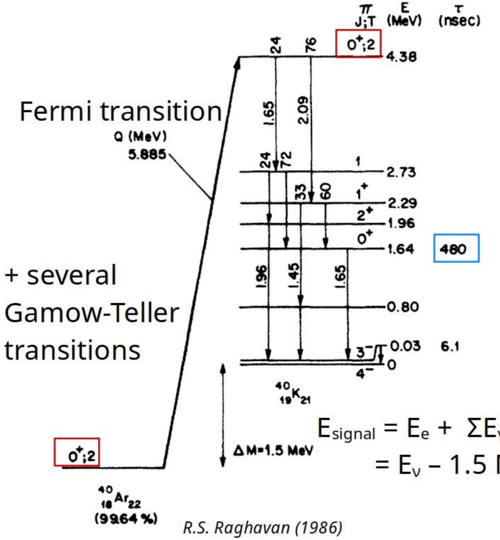
4. **Exploit science cases: exotic DM candidates, solar neutrino, axions…**

- ^{39}Ar half-life and specific activity in atmospheric Ar Eur. Phys. J. C 83, 642 (2023) Eur. Phys. J. C 85, 728 (2025)
- Alpha quenching in liquid Ar Eur.Phys.J.C 85 (2025) 1, 87
- Detection of ^{8}B solar neutrinos! arXiv:2605.12769
- Muon flux! arXiv:2608.20504
- new WIMP searches with profile likelihood method arXiv:2603.13965
- Search for solar axions
- Search for Inelastic boosted dark matter
- Neutrinoless double electron capture
- Search for neutrinos in coincidence with gravitational waves

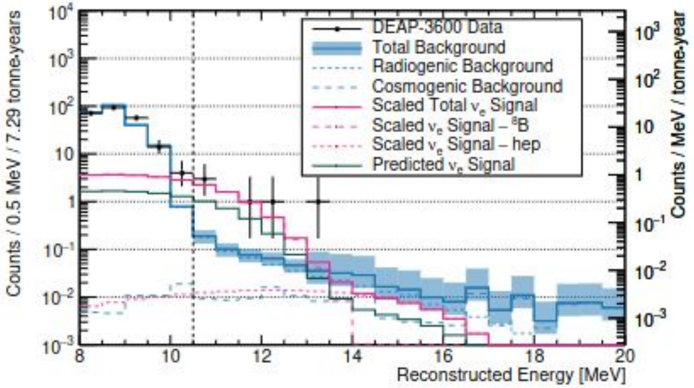
Detecting ^{8}B solar neutrinos

$$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$$

Enhanced cross section for populating the isobaric analog state (although not directly measured before!)



$E_{signal} = E_e + \Sigma E_\gamma$
$= E_\nu - 1.5$ MeV



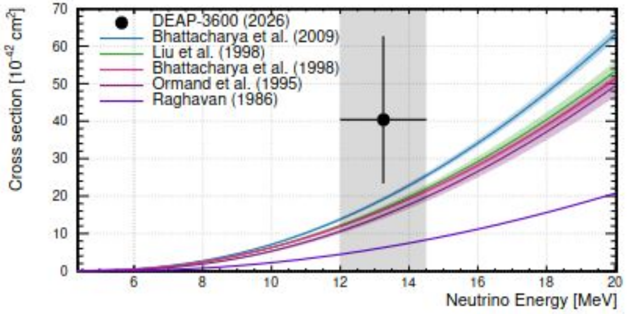


FIG. 2. Energy-averaged cross section result, compared with the energy-dependent cross section models Bhattacharya *et al.* [29][2], Liu *et al.* [30], Ormand *et al.* [31], and Raghavan [1].

Measured cross section larger than predicted.

Lessons learned:

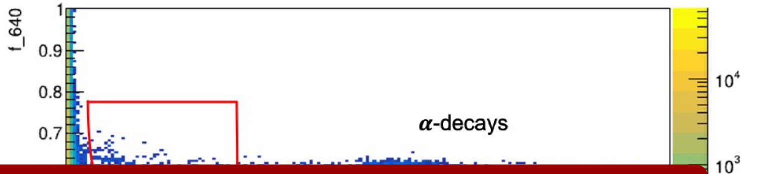
- Ar **pulse shape discrimination** is indeed much more **powerful** than ionization vs scintillation
  - 39Ar is not the leading background
- **Leading backgrounds** are
  - **topological backgrounds**: external events misreconstructed as WIMP-like by a series of accidental coincidences (light degradation + particular shading): better position reconstruction needed.
  - alpha decays from **suspended dust**: recirculation + filtering needed
- A LAr TPC with a purifying loop solves these problems.
- If we want sensitivity we need mass: DS-20k will scale up to 50 tonnes (20 fiducial)

Ar is great, nature is kind… but not so kind: ^{39}Ar

- **1Bq/kg** in atmospheric Ar: 50 tonnes means **50 kHz**.
- Makes the operation of a several-meter scale TPC too challenging: **5 ms drift vs 50 kHz.**
- At 50 kHz, low-E S1-S2 coincidence unfeasible (and certainly not a low background experiment).
- ^{39}Ar produced by cosmogenic activation.
    - Argon kept underground for centuries might solve this issue.

The Underground Argon program

Ar, what's the point?



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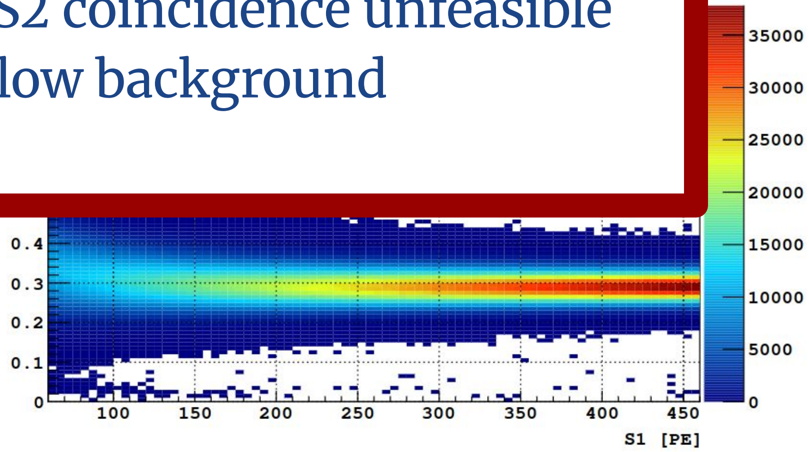
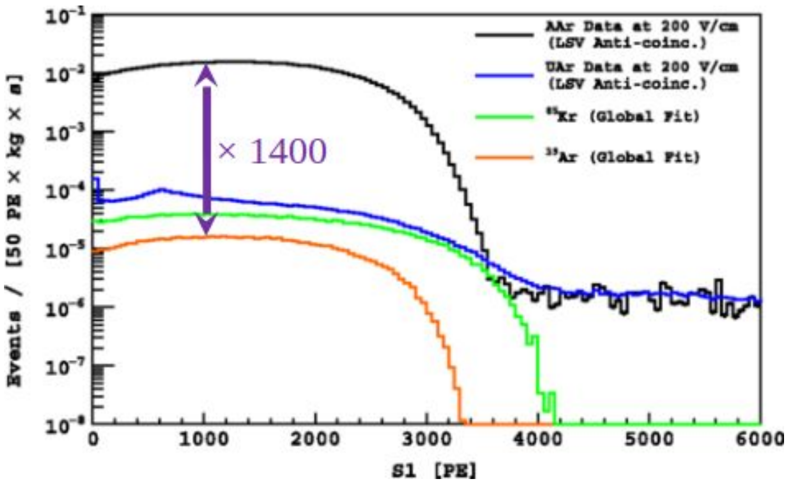


UAr in DarkSide-50 (history)



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... industrial extraction and purification are projects themselves

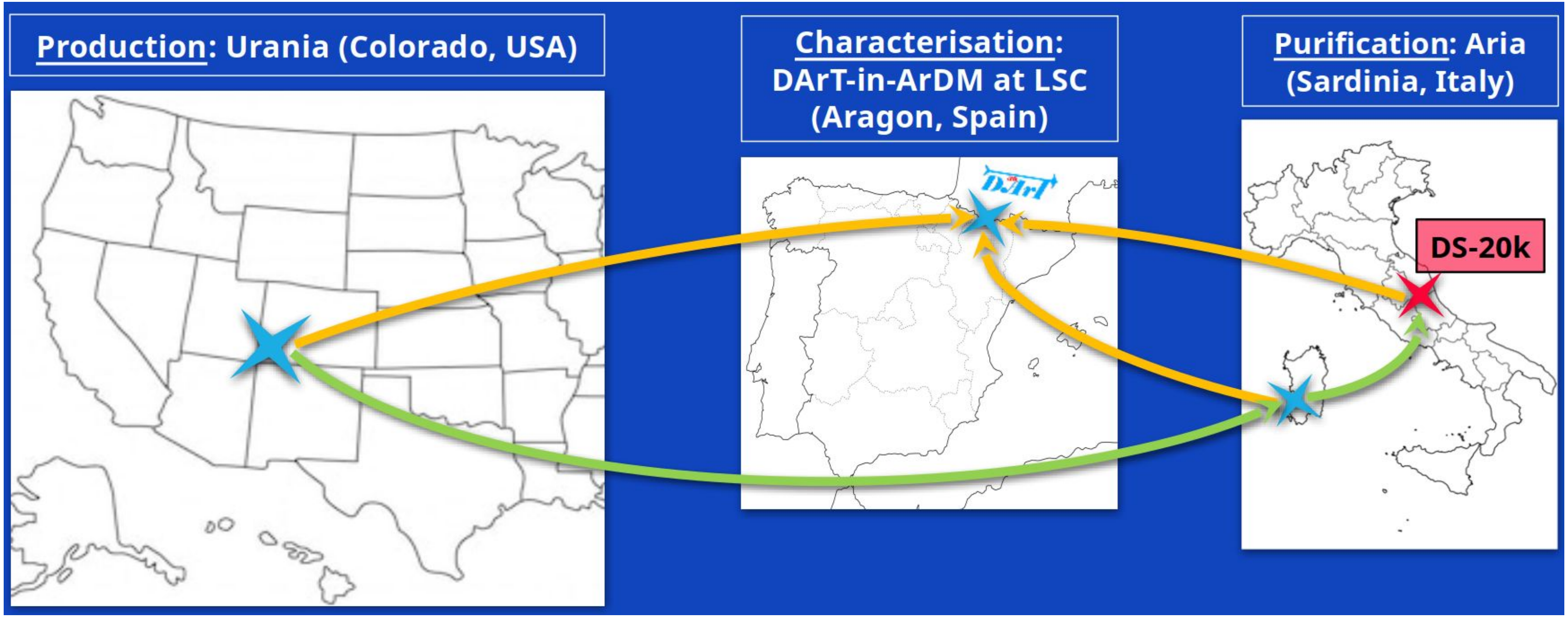
Presence of ^{85}Kr evidences **exposure to air** at some point...

Increasing ^{39}Ar activity.

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

Verification of UAr compliance is needed for each batch.

UAr program of DarkSide: Urania, Aria and DArT



Cosmogenic activation above ground, during storage and shipping, quantified and subdominant for sea freight (few % of DS-50 reference): **Astroparticle Physics 152, 102878 (2023)**

ARIA

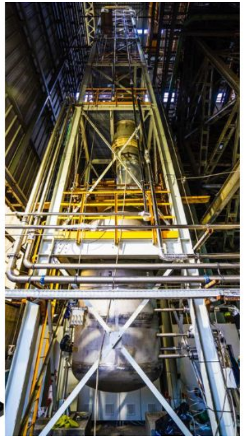
Cryogenic distillation column (total height ~350 m) in the shaft of a coal mine

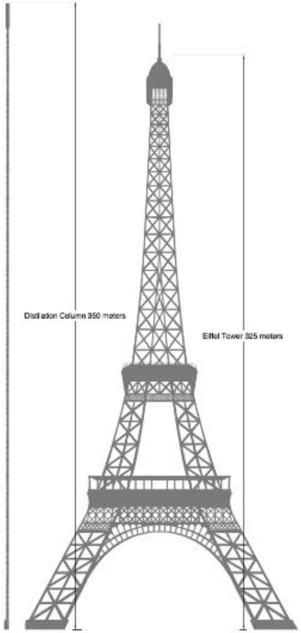
- 28 Central modules: 12 m each
- 1 Condenser (top) module: 7 m
- 1 Reboiler (bottom) module: 5m
- Outer Diameter of the column: 32.3 cm
- Outer Diameter of cold box: 71.2 cm

Process is based on the difference in volatility

Number of theoretical stages: ~2870

Chemical Purification rate: 1 t/d (or more)

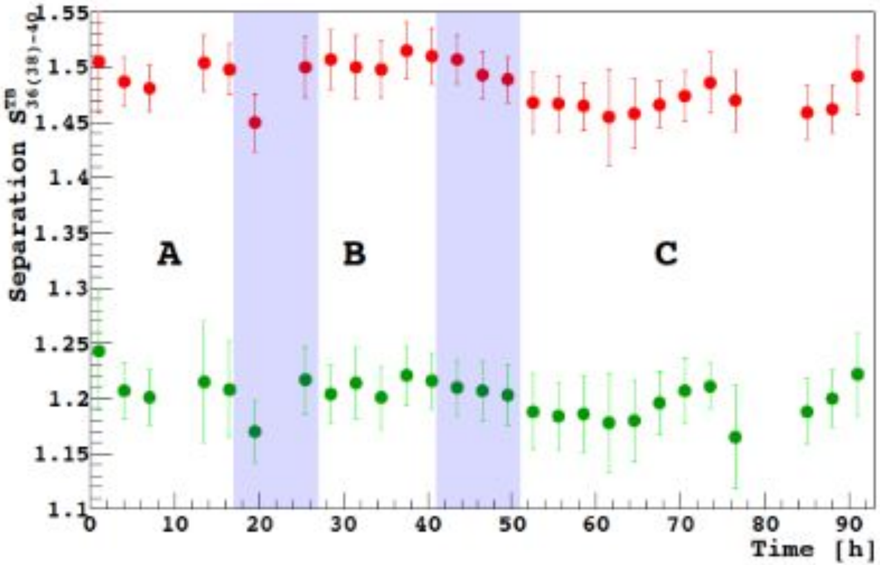




ARIA: Seruci-0

Measurement of **isotopic separation of nitrogen and argon** with the prototype of the cryogenic distillation plant Aria for dark matter searches

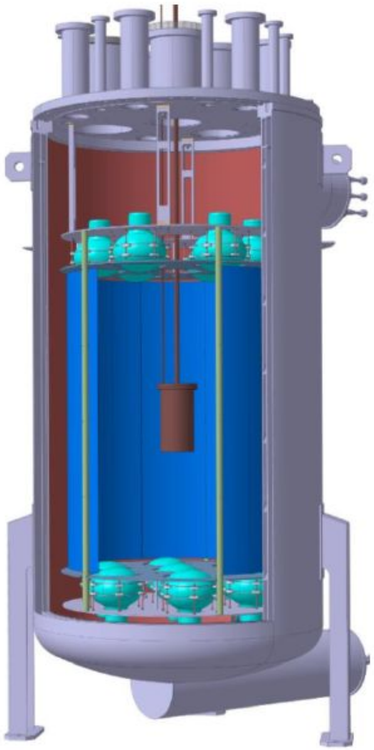
Eur. Phys. J. C (2023) 83:453



Separation $S^{TB}_{36\text{-}40}$ (red) and $S^{TB}_{38\text{-}40}$ as a function of time

$$S_{36-40} = S_{T-B} = \frac{\left(\frac{x_{36}}{x_{40}}\right)_T}{\left(\frac{x_{36}}{x_{40}}\right)_B}$$

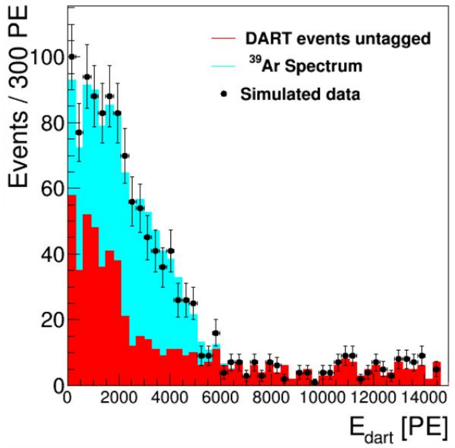
DArT-in-ArDM: the concept



JINST 15 (2020) 02, P02024

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

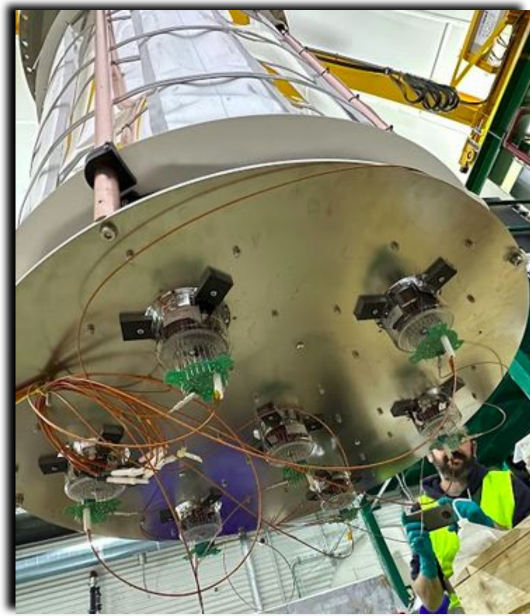
DS-50



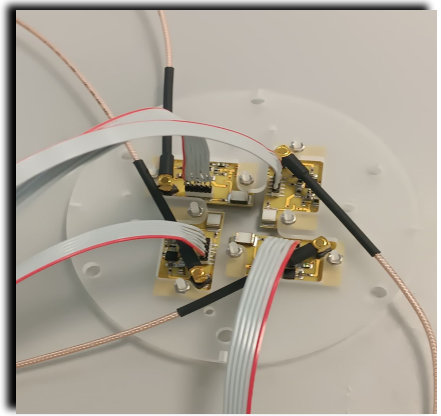
- 1 L active volume of UAr (DArT) seen by 8 SiPMs.
- ArDM full of atmospheric Ar as veto.
- Located at Laboratorio Subterráneo de Canfranc

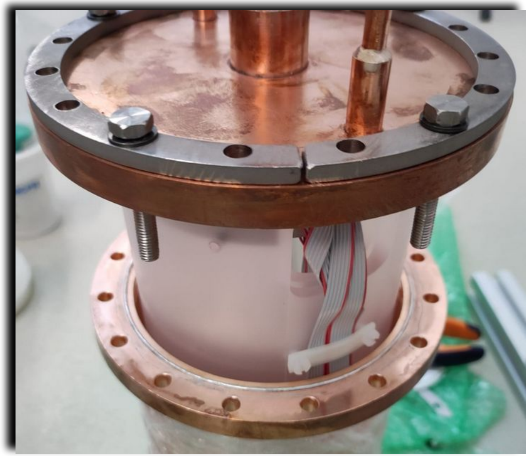
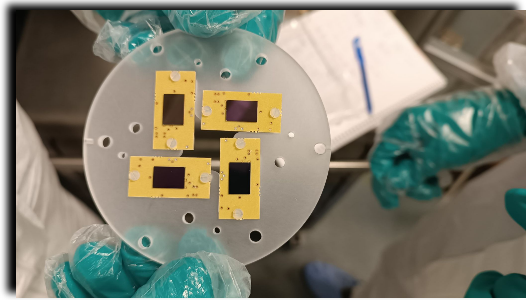
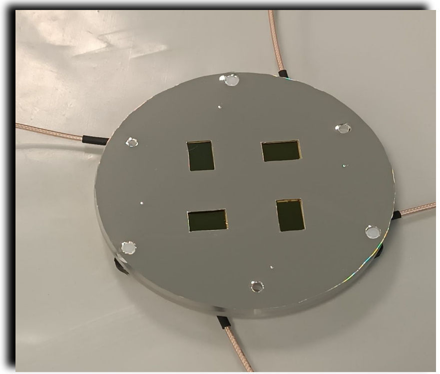
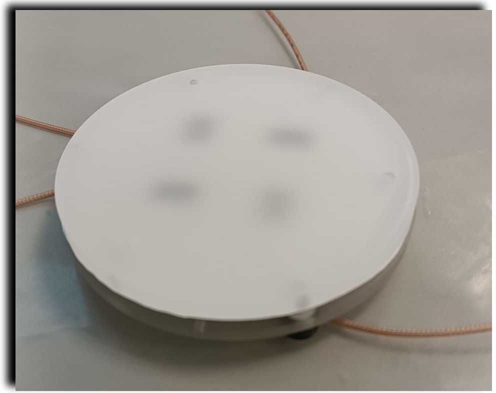
ArDM

ArDM fully refurbished and closed since Jan 2024.

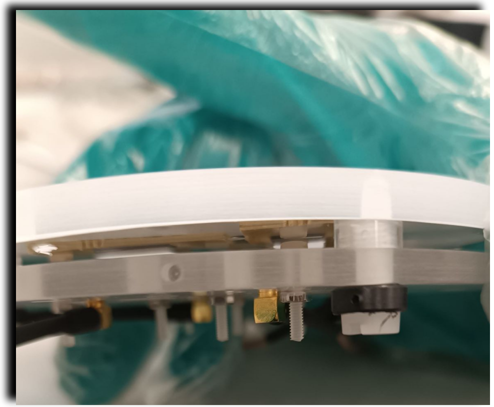


DArT-2



DArT-2

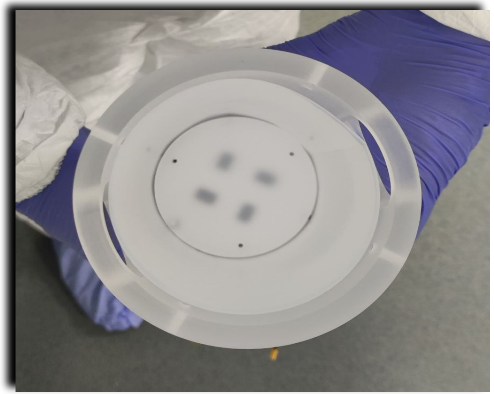


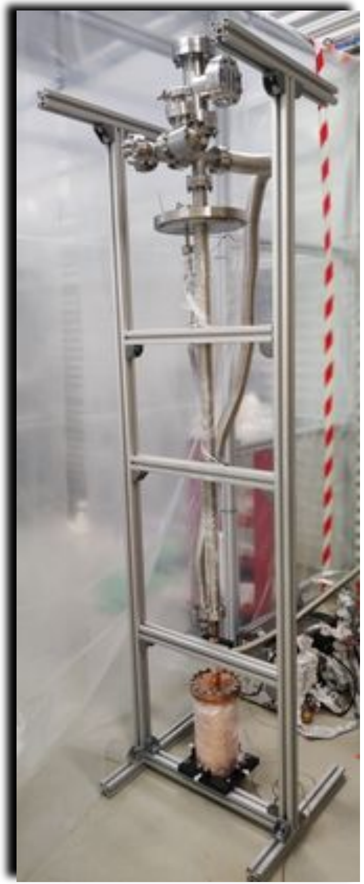
Assembled in September 2024

Integrated in ArDM in February.

Running since December 2025

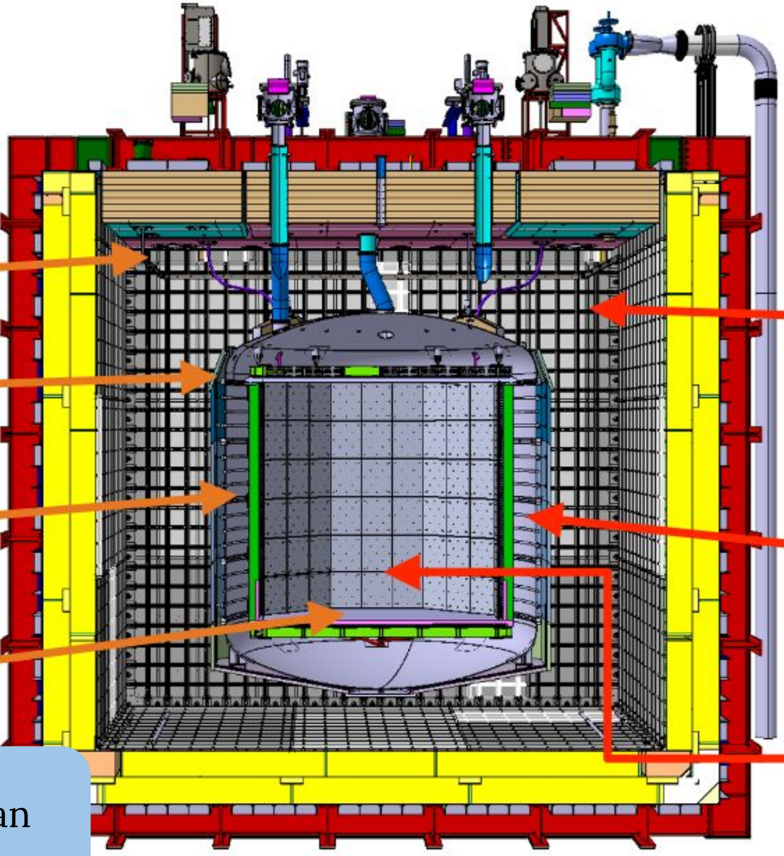
Waiting for first UAr batches soon





DarkSide-20k

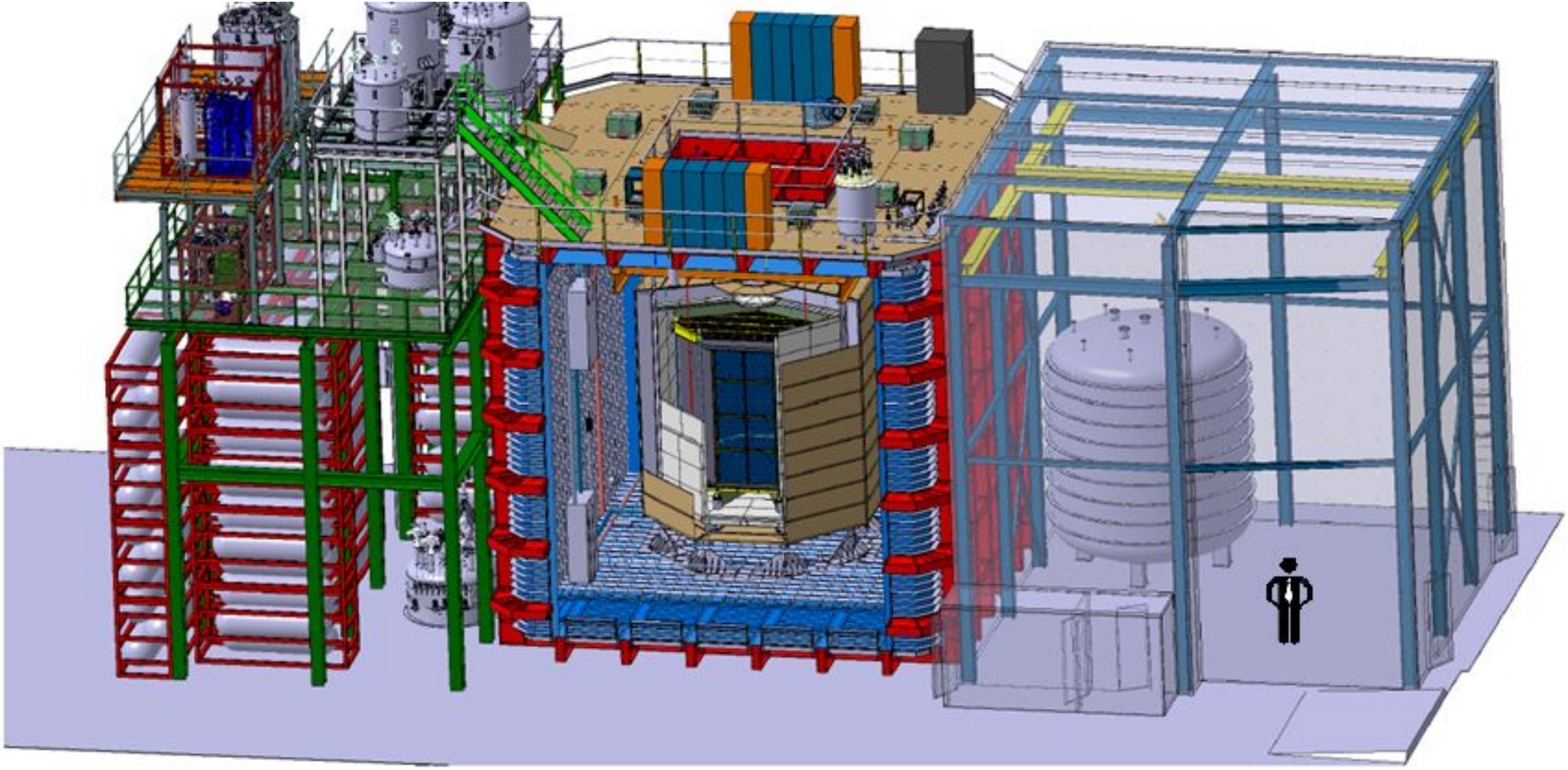
DarkSide-20k: what is it?



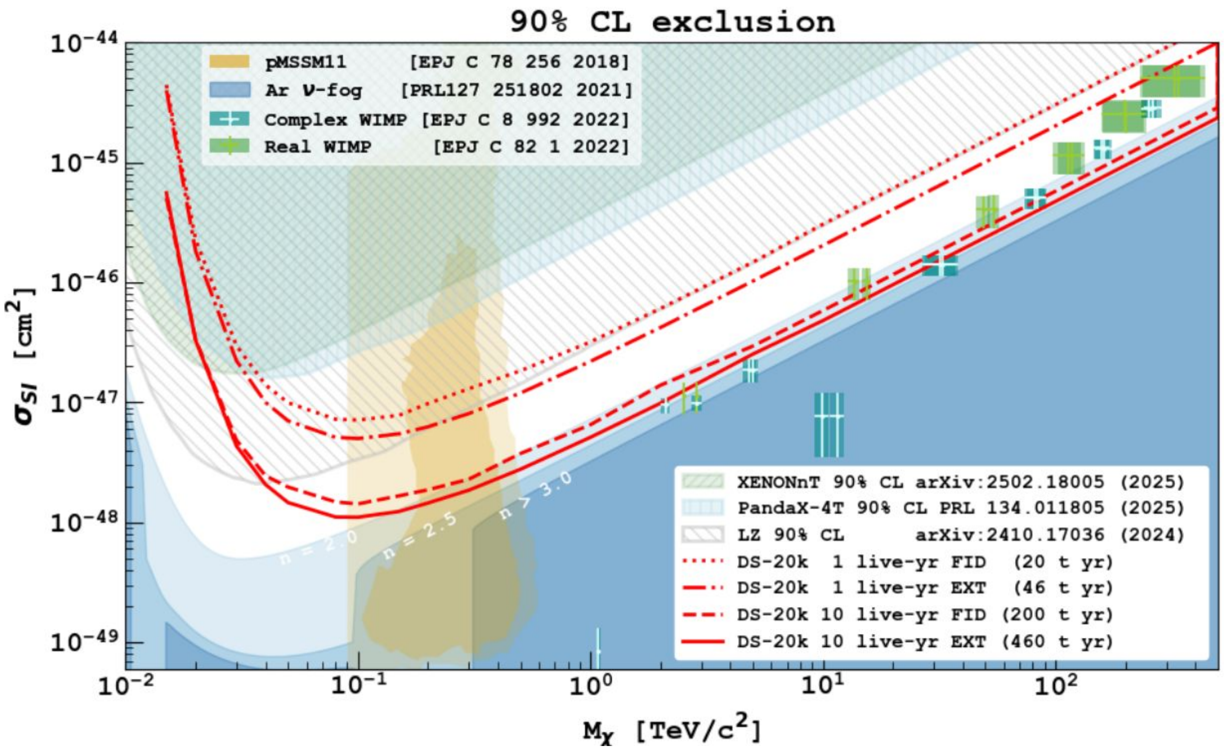
DarkSide-20k consists of three nested detectors:

- The **Outer Veto (OV)**, which is filled with AAr and designed to catch cosmogenic neutrons by detecting the primary muon
- The **Inner Veto (IV)**, which uses UAr to tag radiogenic neutrons by detecting gammas from their capture
- The **Dual-Phase UAr TPC**

Under construction at Laboratori Nazionali del Gran Sasso: 1.4 km of granite overburden



DarkSide-20k: main science cases



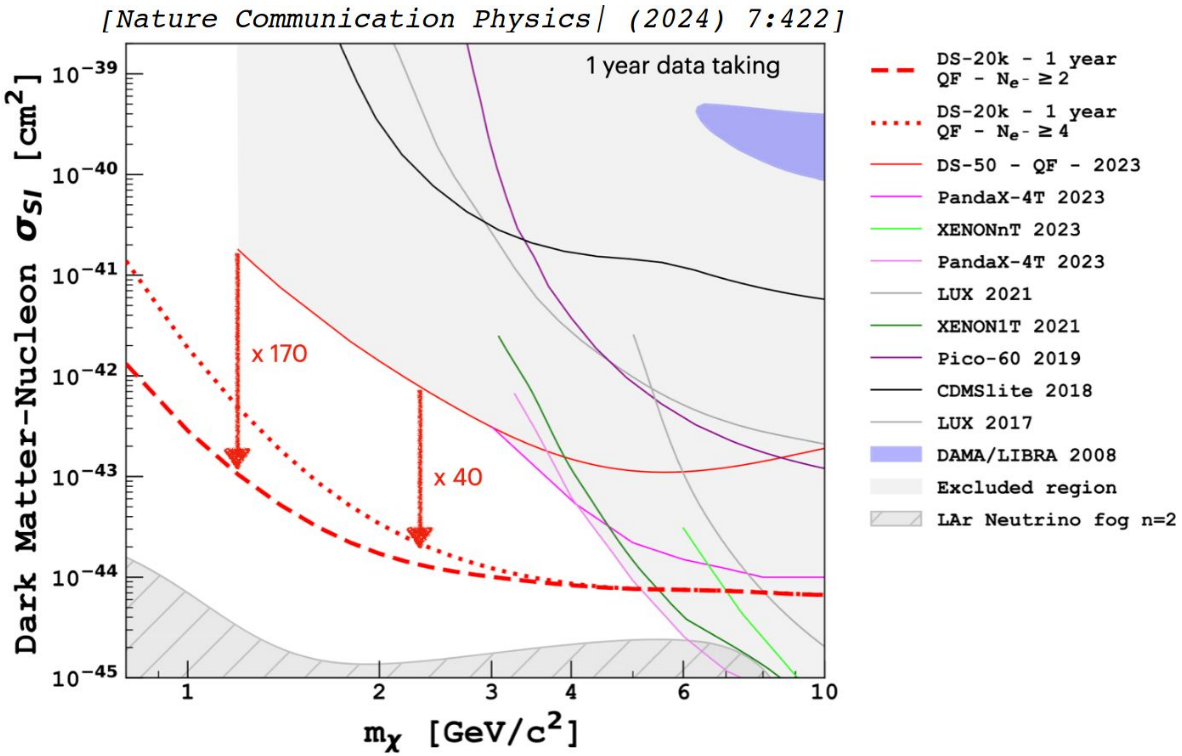
Prospects to lead the search for WIMPs in most of the “canonical” parameter space, particularly at high mass.

Best sensitivity to spin-independent wimp-nucleus interaction cross section:

$\sigma_{SI} = 10^{-48}$ cm^2 @ 100 GeV/c^2.

CPPM

DarkSide-20k: main science cases

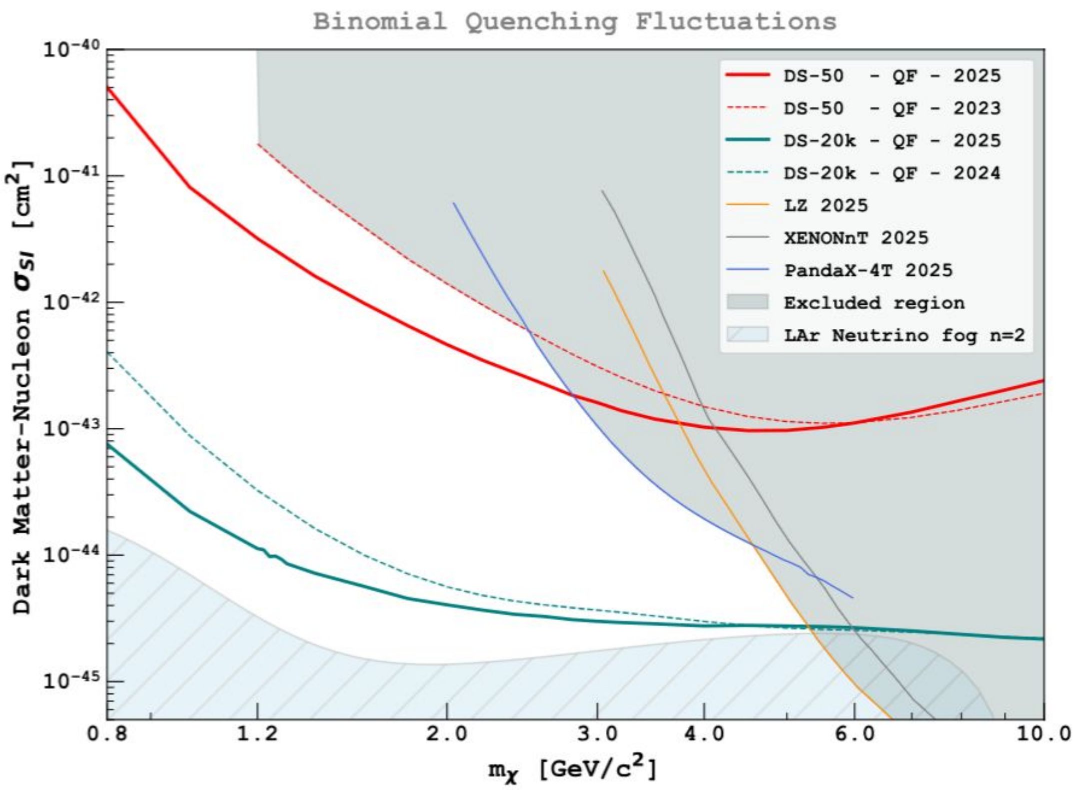


Prospects to dominate the search for light (~ GeV/c^2) WIMPs:

Improve current sensitivity by more than two orders of magnitude in some regions of the parameter space in 1 year of data taking.

Comm. Phys. 7, 422 (2024)

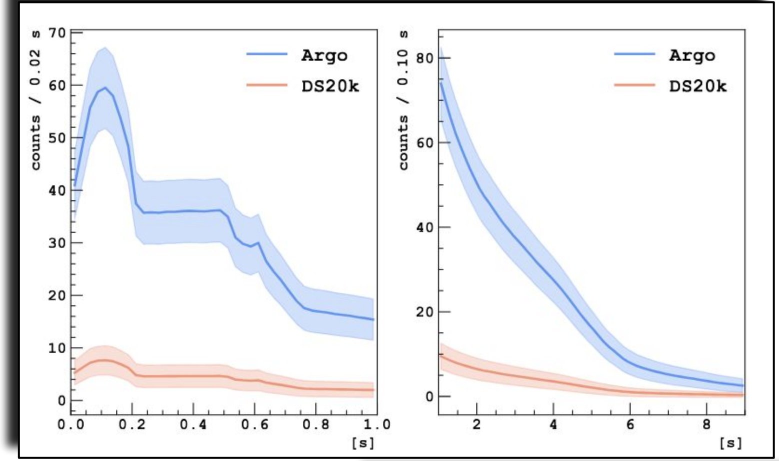
DarkSide-20k: main science cases

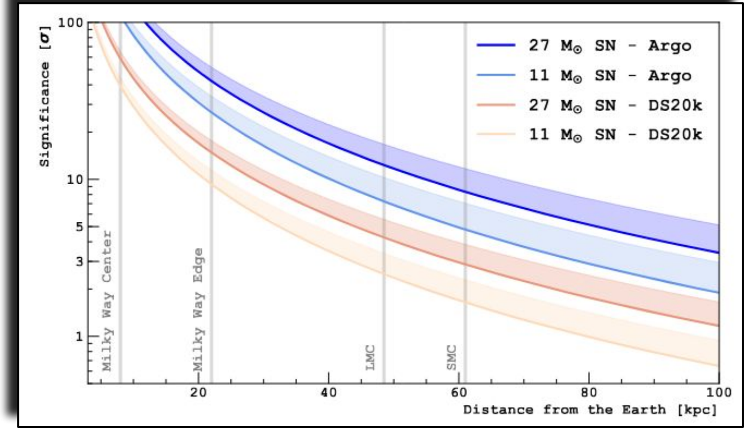


Prospects to dominate the search for light (~ GeV/c^2) WIMPs:

Prospects for 10 year exposure **[arXiv:2511.13629 approved by PRD]** with improved liquid argon ionization model **[Eur. Phys. J. C 86:220 (2026)]**

DarkSide-20k: main science cases





Best sensitivity to neutrinoless double electron capture in ^{36}Ar

Sensitivity to SuperNova neutrinos (~180 CEvNS events expected for a 11 $M_{\odot}$ Supernova in the galaxy) [JCAP03(2021)043]

Sensitivity to ^{8}B solar neutrinos via CC

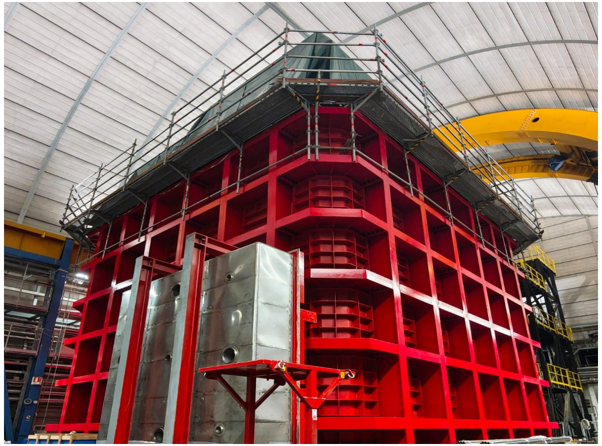
Other planned uses of UAr

Use as a veto for Legend-1000, mitigating the ^{42}Ar background problem

Use it doped with ^{136}Xe for neutrinoless double beta decay searches

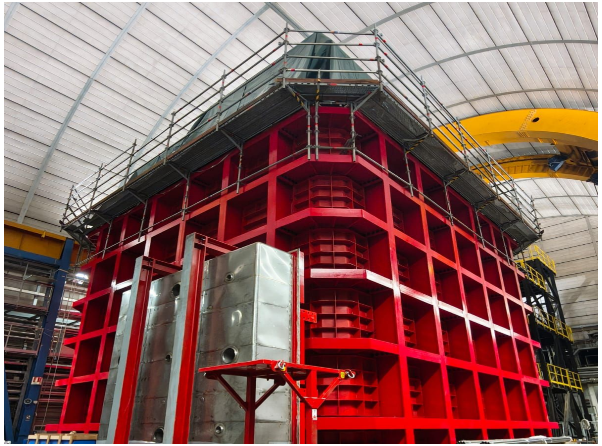
Construction of ARGO, the ultimate 300 t Ar detector to fully prospect the neutrino floor

DarkSide-20k: Current status



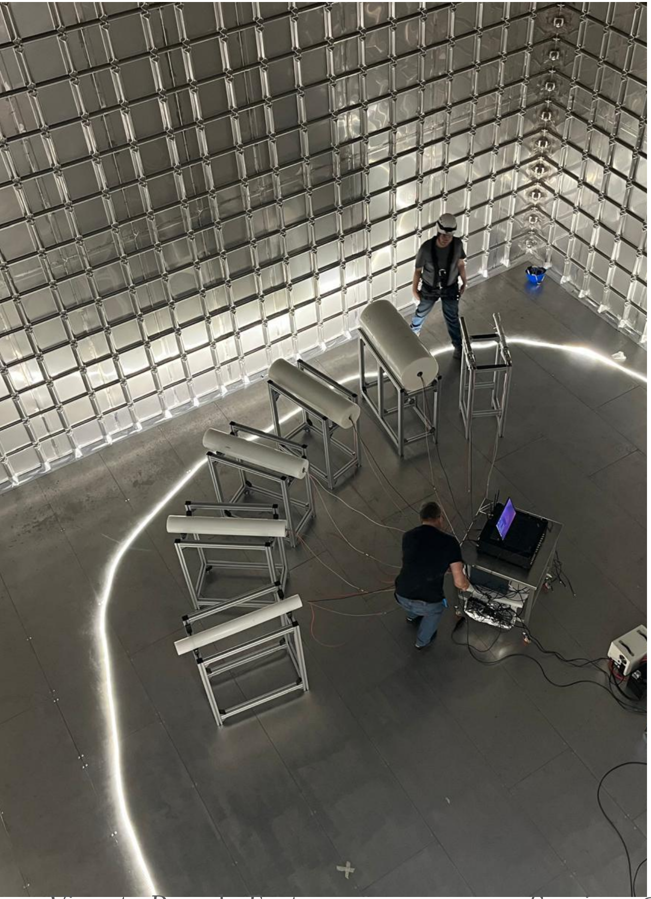
How far are we from seeing all this?

DarkSide-20k: Current status



- Cryostat and internal crane installed.
- Clean room panels and aeraulic plants design completed; contract being assigned right now.
- Design ongoing for electrical and safety plants.
- Cryogenics system atmospheric Ar 90%.
- Cryogenics system underground Ar to be upgraded by the end of the summer.
- Integration sequence defined.
  - Fine tuning going on.
- Gamma flux measurements performed outside and inside of the cryostat.
- Measurement of MeV-neutron flux inside the cryostat ongoing.

DarkSide-20k: Current status



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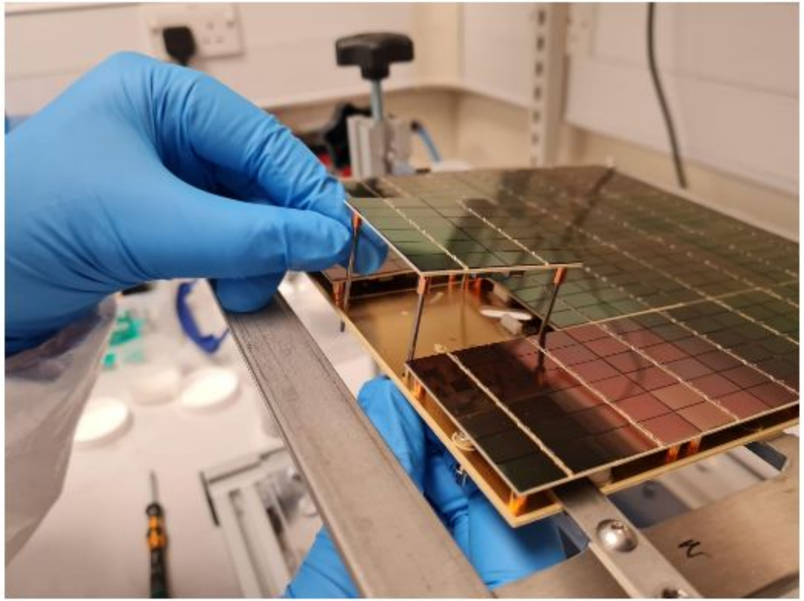
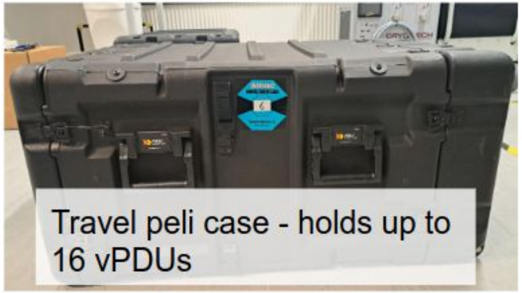
DarkSide-20k: Current status

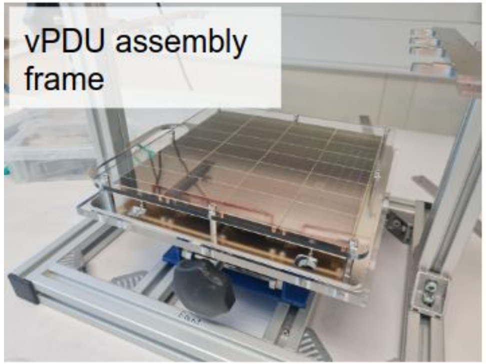


One of the main RnD outcomes of DarkSide-20k: production of radiopure cryogenic low-noise SiPMs-based photoelectronics within the collaboration.

- **24 x 1 cm^2 SiPMs integrated in 1 tile (5 x 5 cm^2). 96% occupancy in the optical planes.**
- **4 x 4 tiles in 1 PhotoDetection Unit (PDU)**
- **Read out implemented at the quadrant level:**
  - **2 x 2 tiles = 10 x 10 cm^2**
- **Slightly different solutions for the**
  - **TPC (21 m^2 - 528 PDUs) and**
  - **the veto (120 + 32 PDUs).**

DarkSide-20k: Current status





- veto PDUs: 119/120 past tests (detector-ready) More are being worked on for spares and outer veto.
  - Production and testing lead by UK groups + AstroCENT.
- TPC PDUs: 238/528 produced. The goal is achieving a production rate of 8 PDU/week.
  - Production in NOA (ISO6 CR @ LNGS)
  - Testing in PDU Test Facility (ISO7 CR @ Naples)
- Specific protocols in place for handling, transportation and storage.
- Dust level on SiPMs monitored with ad-hoc scanner.

DarkSide-20k: Current status

- Acrylic panels casted and being machined.
- Optical plane structures to be delivered this autumn.
- Integration of PDUs in Optical plane to be started upon reception.
- Cobot and CRAB for placing PDUs in Optical plane already @ LNGS being tested.
- Most of the structural material for TPC (SS) assayed, approved and procured.

Two octagon sides already machined

DarkSide-20k: Current status

Goal: keeping detector-induced background 1 order of magnitude below CEvNS (3.2 events in 200 ty).

Radiopurity and cleanliness at the core of all of it:

- **Conscious choice of technical solutions based on performance + potential background [(α,n)].**
- **Every component assayed (at the single capacitor level).**
- **Ambient Rn concentration, exposure time and potential impact is being factored in in the background estimates.**
- **Specific tests performed to approve bags and storage solutions in terms or Rn-tightness.**
- **Cleaning protocols to mitigate surface ^{210}Po activity defined on a component per component basis (not only material).**

Conclusions

- Liquid argon combines s**calability with exceptional recoil discrimination**. Its singlet-triplet scintillation timing provides powerful electronic-recoil rejection using the light signal alone.

- **Underground argon** changes what is experimentally possible. Suppressing cosmogenic ^{39}Ar enables large dual-phase detectors, lower thresholds, and long exposures with manageable event rates.

- A mature experimental ecosystem now exists. DEAP-3600 and DarkSide-50 demonstrated the key capabilities, while Urania, Aria, DArT, and DarkSide-20k are extending them toward much larger and cleaner exposures.

- **DS-20k** is deep into construction phase and transitioning to integration phase. The detector will be ready for filling by the end of 2028.

- Argon offers sensitivity to a remarkably **broad range of phenomena**: WIMPs across different mass regimes, nonstandard dark-matter interactions, solar neutrinos, Galactic-supernova neutrinos, and rare nuclear processes.

United States

Augustana University, University of Houston, Umass Amherst, Columbia University, Temple University, The University of Chicago, Princeton University, UC Riverside, UC Davis, Virginia Tech, Fort Lewis College, University of Hawai'i, PNNL, Williams College, University of Washington

United Kingdom

University of Oxford, The University of Manchester, University of Liverpool, University of Birmingham, University of Warwick, Royal Holloway Uni. of London, Rutherford Appleton Lab., University of Edinburgh, Lancaster University

Italy

INFN LNGS, INFN LNL, INFN LNS, Roma Tre University, Uni. of Naples Federico II, INFN Napoli, Fondazione Bruno Kessler, INFN Sezione di Roma, University of Genova, University of Cagliari, INFN Catania, Università of Catania, INFN Cagliari, University of Bologna, INFN Bologna, University of L'Aquila, INFN Roma Tre, INFN Genova, GSSI, INFN Pisa, University of Pisa, INFN Torino, INFN Milano, Sapienza Uni. of Rome, Kore University of Enna, Polytechnic Uni. of Turin, University of Milan, Polytechnic Uni. of Milan

Canada

University of Alberta, Carleton University, Queen's University, TRIUMF, Université de Sherbrooke, SNOLAB, Laurentian University, McDonald Institue

Germany

University of Hamburg, JGU Mainz

Brazil

Universidade de São Paulo

France

CPPM, AstroParticule et Cosmologie

Poland

AstroCeNT, Jagiellonian University, Warsaw Univ. of Technology

Spain

CIEMAT, Universidad de Zaragoza

China

IHEP, University of the CAS

The DarkSide-20k Collaboration

~400 scientists

~80 institutions

10 countries

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Merci!

GOBIERNO DE ESPAÑA — MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat — Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
cfp CIEMAT física de partículas

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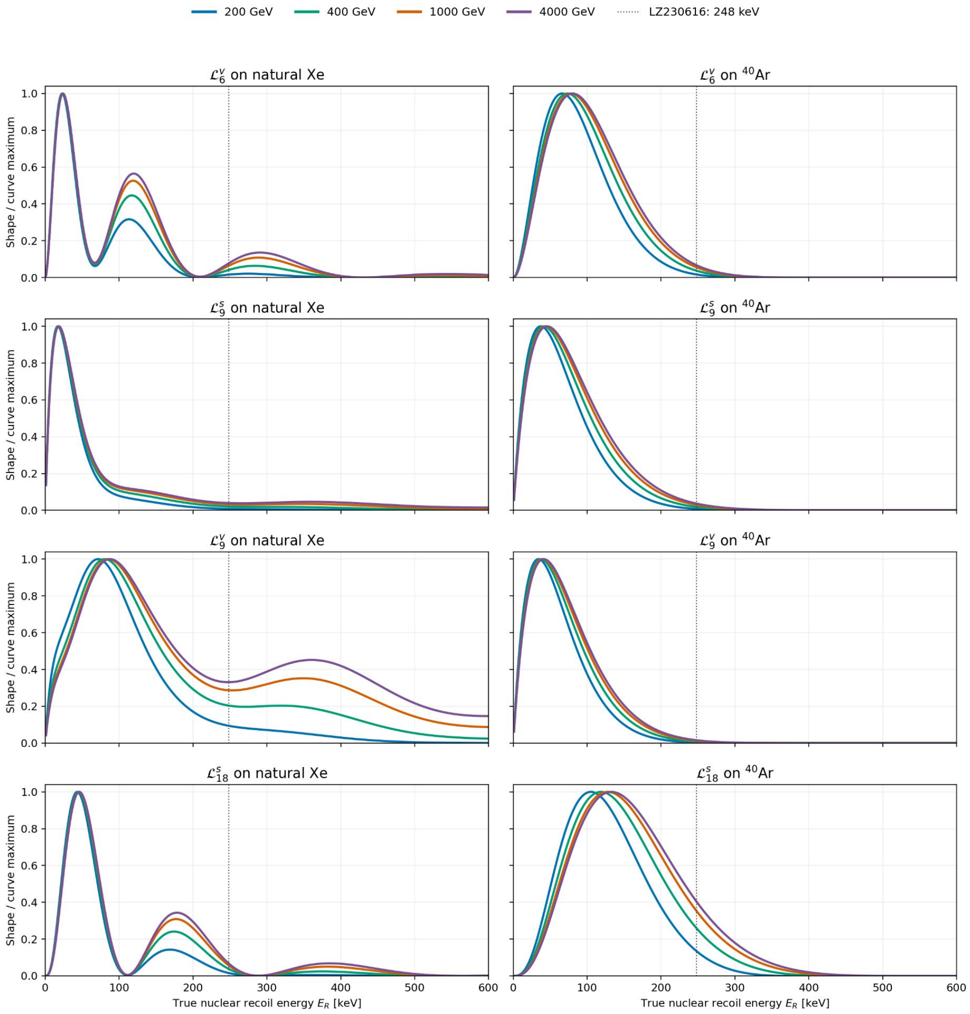
BACKUP

Mass dependence of argon-responsive elastic EFT spectra



Spin-1/2 WIMP, Standard Halo Model; no detector efficiency. Every mass-target curve is normalized independently.

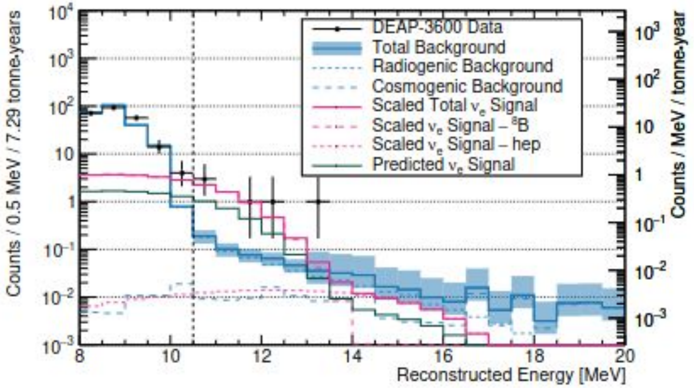
Detecting ^{8}B solar neutrinos

$$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$$

Enhanced cross section for populating the isobaric analog state (although not directly measured before!)

TABLE III. The dominant systematic uncertainties considered in this work and their impact on the background and signal estimates in the ROI, further described in the text. The energy resolution quoted here is at 10.5 MeV. $\langle\sigma_{\text{model}}\rangle$ is the energy-averaged cross section in the ROI based on Ref. [2].

Systematic Unc.	Value	Bkg	CC ν_e
Energy Scale Bias	$0 \pm 1.5\%$	10.1%	11.7%
Energy Resolution	96 keV $\pm$ 17 keV	0.5%	0.1%
Int./Ext.γ LY Bias	$0 \pm 1.3\%$	0.2%	12.6%
AmBe Bkg Scaling	0.8 ± 0.2	18.4%	–
AmBe Pile-up Est.	0.28 ± 0.09 events	21.9%	–
MV Cut Efficiency	$99.6\%^{+0.4\%}_{-1.0\%}$	$^{+14\%}_{-4.4\%}$	–
^{8}B solar ν_e flux	$(5.2\pm0.2)\times10^{6}$ cm^{-2} s^{-1}	–	3.9%
hep solar ν_e flux	$(0.8\pm0.2)\times10^{4}$ cm^{-2} s^{-1}	–	0.4%
Expected $\langle\sigma_{\text{model}}\rangle$	$(1.67\pm0.05)\times10^{-41}$ cm^{2}	–	3.0%
Total	–	$^{+33\%}_{-31\%}$	18%



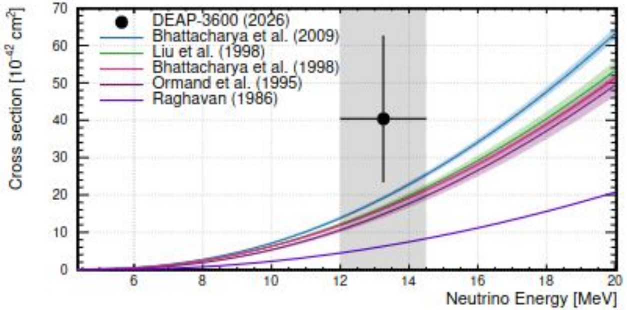
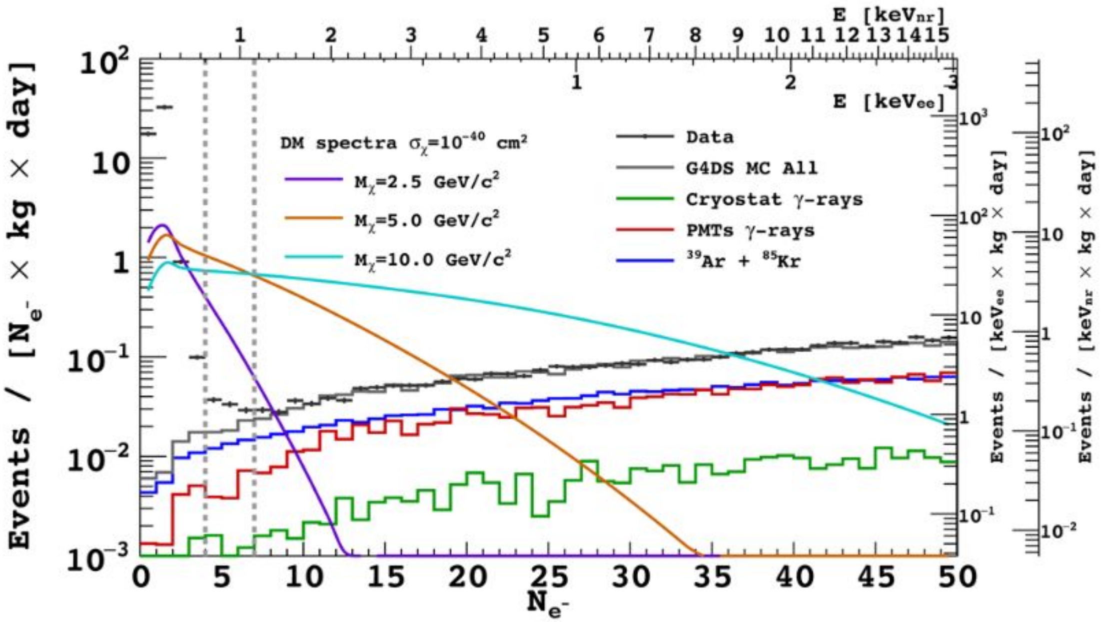


FIG. 2. Energy-averaged cross section result, compared with the energy-dependent cross section models Bhattacharya *et al.* [29][2], Liu *et al.* [30], Ormand *et al.* [31], and Raghavan [1].

Measured cross section larger than predicted.

Direct WIMP searches



All analysis cuts have an impact in WIMP acceptance

- The amount of background events without any cut is much higher than the expected rate for WIMPs. Most can be easily ruled out.
- Introducing these cuts always comes at a price, that needs to be factored in.

Threshold

Events with less than certain energy are just not detectable

Resolution

You never have direct access to energy. It's always
- number of photons,
- number of electrons or
- number of phonons.

The number of detections follows a distribution

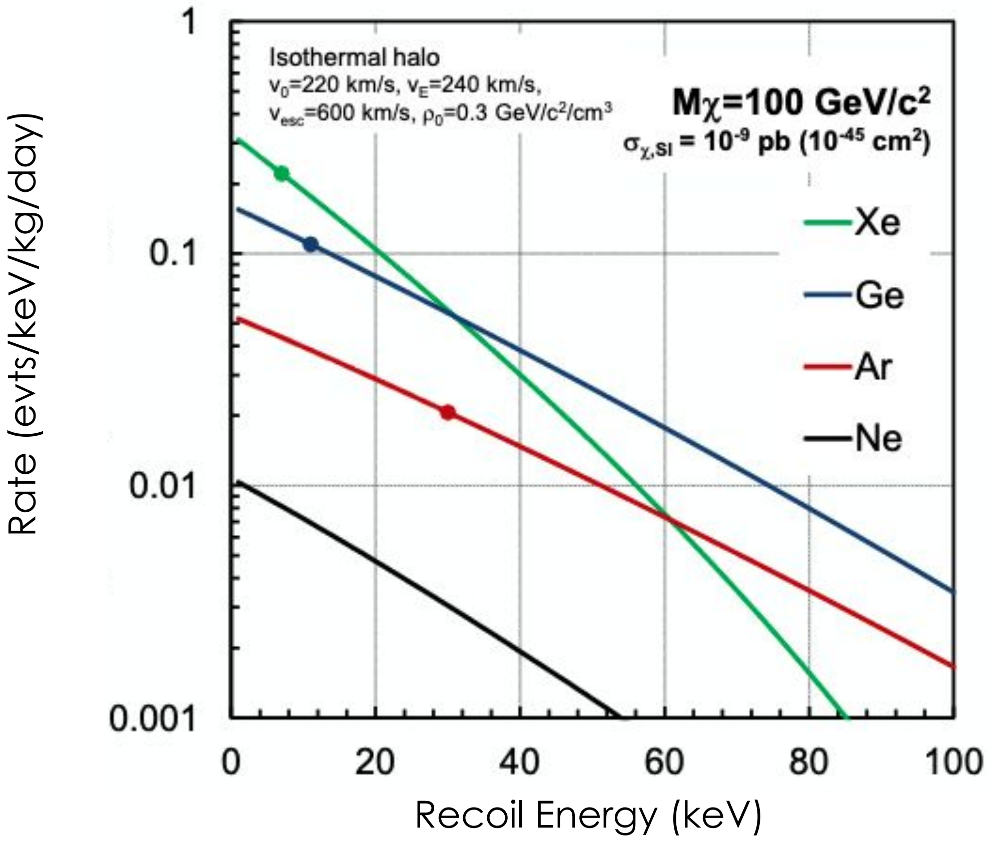
Direct WIMP searches

$$\sigma_T(E_R) = \sigma_T^0\, F^2(E_R)$$

The E dependence is due to the loss of coherence at non-zero momentum transfer and can be factorized

$$\sigma_T^0 = \sigma_{n,\chi}^0 A_T^2 \left(\frac{\mu_T}{\mu_n}\right)^2$$

To compare results of different experiments, we extract the WIMP-**nucleon** interaction cross section

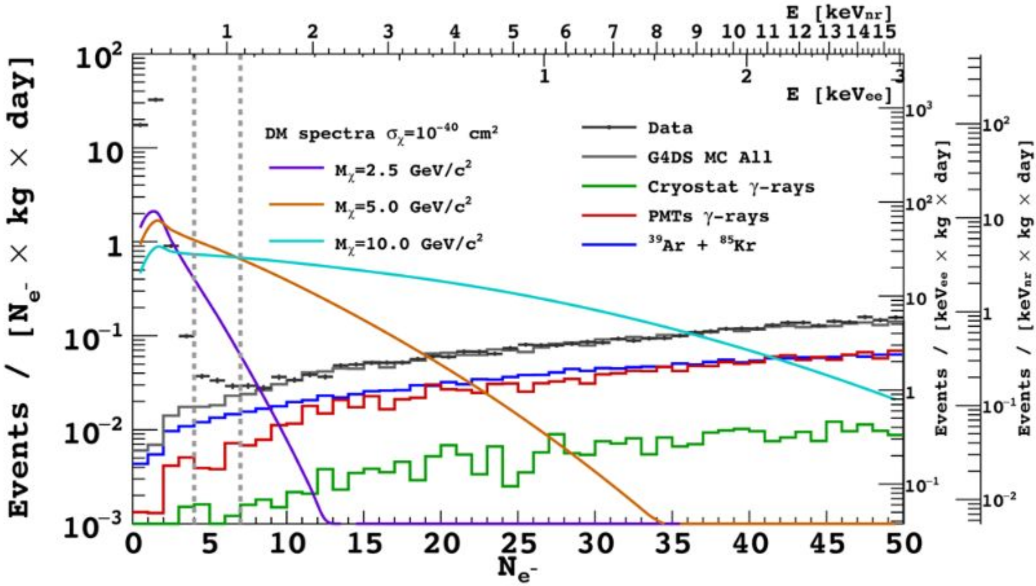


Direct WIMP searches

$$\frac{dR}{dE_R} = \varepsilon(E_R)\, N_t\, \frac{\rho_0}{m_\chi} \int_{v \geq v_{\min}(E_R)} d^3v\ f_{\text{lab}}(\mathbf{v})\ v\ \frac{d\sigma}{dE_R}(v, E_R)$$

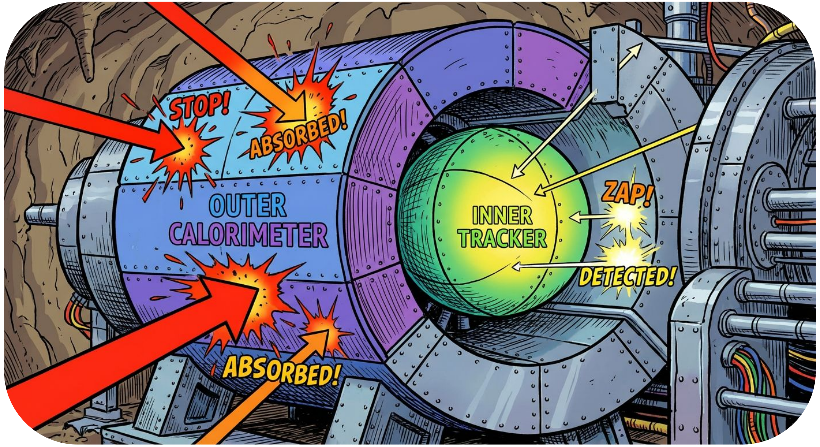
- With all the ingredients in hand we can have the expected spectral shape and rate in the detector

- Where do we sit in 2026 in the canonical WIMP searches?



Challenge: External background

- On the Earth's crust there are parts-per-million (ppms) of ^{40}K, ^{232}Th and ^{238}U.
  - Half-lives > 10^9 y.
  - These translate into 30 - 900 Bq/kg of material
- Our detector is built on Earth.



Mitigation

- Measuring external radiation onsite.
- Simulate particle transport through the detector materials.
- Nested detectors: vetoing anything leaving signal in the non-central one
- Fiducialization: rejecting even some events in the central detector if they are close to the wall.
- Installing shields to prevent external radiation to come in.

Challenge: Surface contamination of detector materials

- Rn is everywhere, particularly in suspension in air. Concentration depends on many parameters, but values range between 5-150 Bq/m^3.
- Rn itself or its decay products can diffuse and/or recoil into any material in contact with air.
- Rn decays away fast, but ^{210}Pb produced down the chain has a $T_{1/2}$ = 22 y.
- Any material exposed will accumulate Pb that will decay during the data taking time.
- **Not only that: most bags are Rn-transparent**

Mitigation

- Storage in Rn-depleted areas
- Specific studies of impact of bagging able to stop Rn.
- This is not always possible and most times you don't know the historical exposure of what you buy
  - You study the diffusion length for Rn in that material
  - You sand it down to remove the Pb-enriched crust

Challenge: Radiogenic activity (bulk)

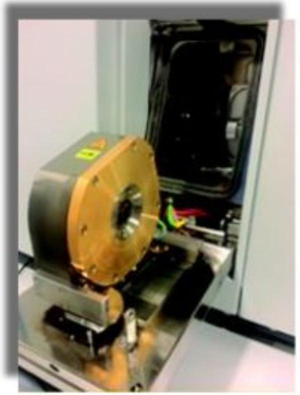
- On the Earth's crust there are parts-per-million (ppms) of ^{40}K, ^{232}Th and ^{238}U.
- Our detector materials come from Earth.
- Half-lives > 10^9 y.
  - These translate into 30 - 900 Bq/kg of material
  - Current experiments aim at mBq/kg level
  - Sometimes more stringent for materials close to the central detector.

Mitigation

- Simulate particle transport through the detector materials.
- Nested detectors: vetoing anything leaving signal in the non-central one
- Fiducialization: rejecting even some events in the central detector if they are close to the wall.
- Preselection: measuring the radioactivity of each detector component close to the sensitive target.

Inductively-Coupled-Plasma Mass Spectroscopy

- Fast technique.
- Sensitivity to **concentrations** down to ppts (10^{-12} g/g)
- Only sensitive to top part of the chains and K-41. One can assume the ratio in natural abundance (0.012%).
- Involves chemists for sample preparation.



Isotope	Half-life	Concentration (ppt)
^{238}U	4.468×10^{9} y	1.000×10^{3}
^{234}Th	24.10 d	1.45×10^{-8}
^{234m}Pa	1.17 min	4.89×10^{-13}
^{234}U	2.455×10^{5} y	5.40×10^{-2}
^{230}Th	7.54×10^{4} y	1.63×10^{-2}
^{226}Ra	1.60×10^{3} y	3.40×10^{-4}
^{222}Rn	3.8235 d	2.19×10^{-9}

High-Purity Germanium spectroscopy

- Measures gammas directly.
- Much slower (you need the isotope to decay and half-lives are long)
- Involves masses in the kg range, measurements in the month scale and sensitivities down to 0.1 mBq/kg in the best cases

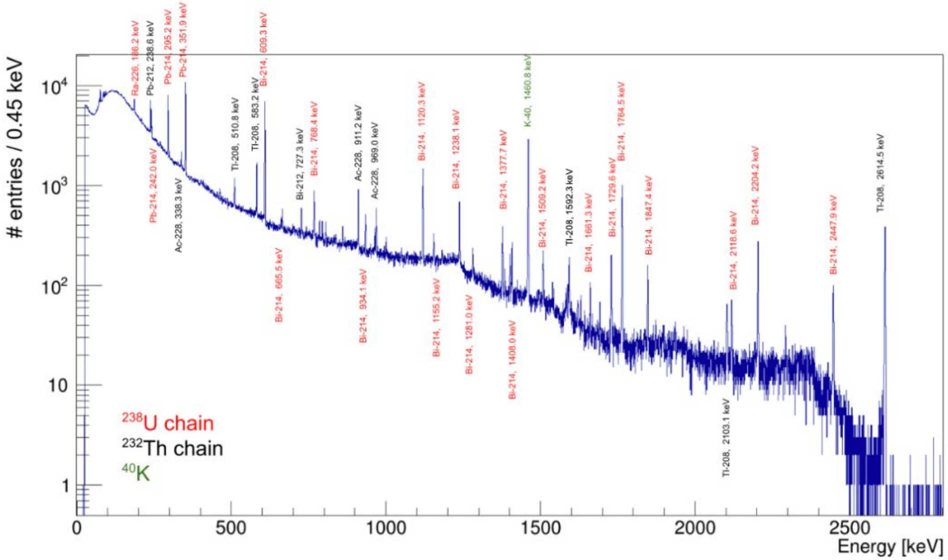
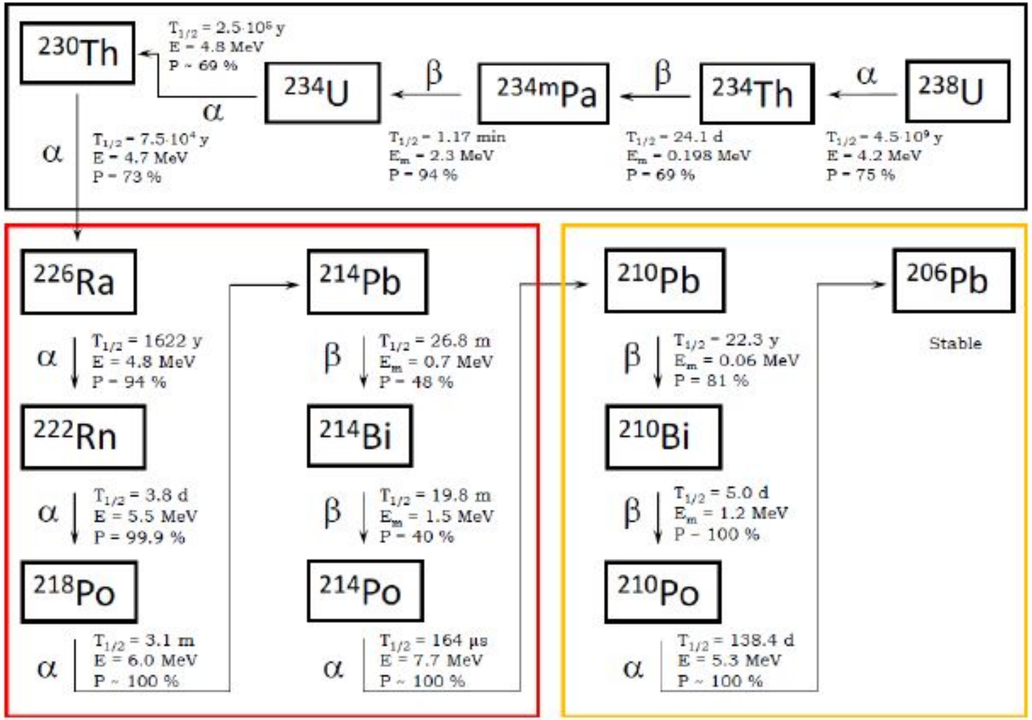


Fig. 4: Environmental energy-calibrated γ-ray spectrum with identified peaks from ^{238}U (red) and ^{232}Th (black) chains and from ^{40}K (green).

ICPMS

Secular equilibrium
Systematically broken

HPGe



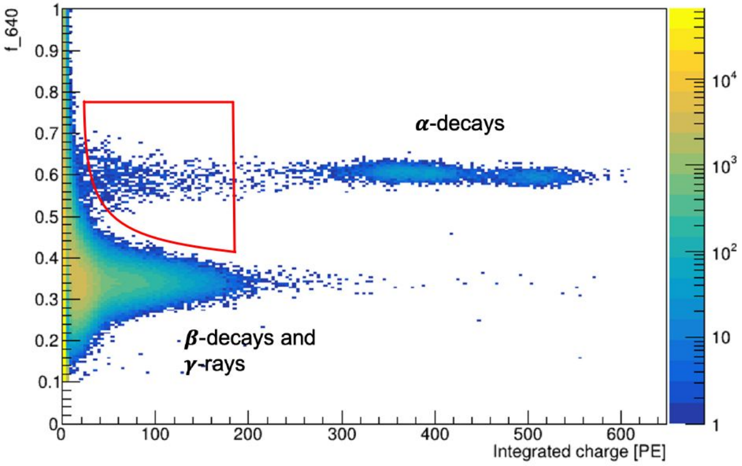
Po-extraction

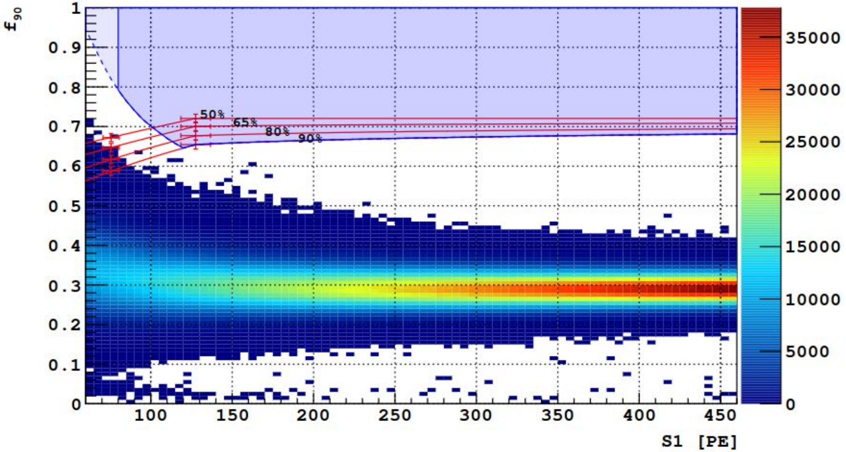
Not only we need to measure everything, but several times with different techniques

Ar, what's the point?

Electron recoils are further from region of interest from lower energies

This discrimination does not depend on coincidences of any kind. Scintillation-light only.





Challenges: Radon emanation

- ^{238}U chain passes through ^{222}Rn ($T_{1/2}$ = 3.8 d).
- Since it is a gas, it can escape the volume where it is produced.
- In liquid detectors, it will be diluted and carried everywhere, in particular to the sensitive volume

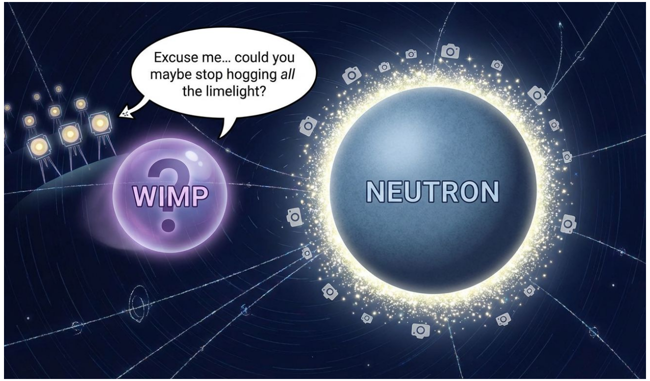
Mitigation

- Measuring emanation + Picking materials with low contamination in U and/or low diffusion coefficient.
- Controlling on the flow direction to
  - minimize the introduction of Rn in the active volume
  - carry the Rn present there somewhere else that does not bother.

Challenges: neutrons

- Low-E nuclear recoil, just as the expected WIMP signal.
- Produced via (a,n) reactions, the alpha coming from U, Th and interacting with the material.
  - Some isotopes of Li, Be, B, F and Al very high cross section.
- Produced via spontaneous fission of ^{238}U.
- Produced by muons

Draw a WIMP particle asking the neutron to stop gathering all the attention



Mitigation

- Simulations of billions of events
  - Neutrons thermalize via multiple scatterings
  - They are always captured once their momentum is low, which often produces visible gammas (2.2 MeV in H, 6 MeV in Ar).
- Measuring not only activity but also composition of materials.
- Larger vetos: if catch both the muon and the neutron, you can disregard the event, but showers can happen well above the detector and the distance in your detector be large.

Challenges: muons and muon-induced activity

- muons themselves are easy to tag, but at a rate of 1 cm^{-2} min^{-1} dead time would kill your experiment.
- high-E muons induce neutrons, beta delayed decays among other things.

Mitigation

- Deep underground labs (deep meaning hundreds of meters of overburden.
- Specific large vetos on which few muons inducing events in your central detector go unnoticed.

Challenges: neutrinos

- DS expects 3 CEvNS from atmospheric neutrinos
- Also solar and geo-neutrinos

Mitigation

- NONE

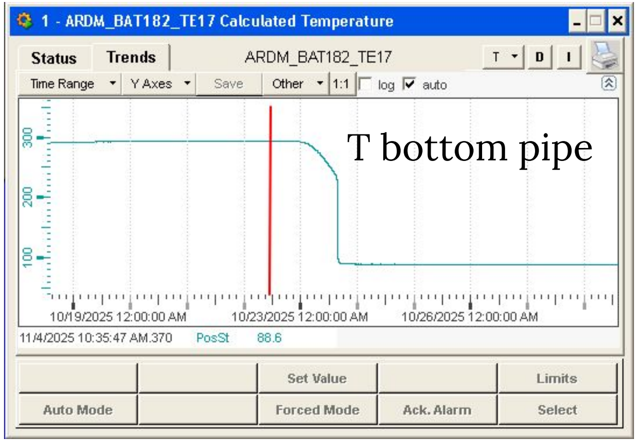
Alternative: if you can't beat them, join (or embrace) them

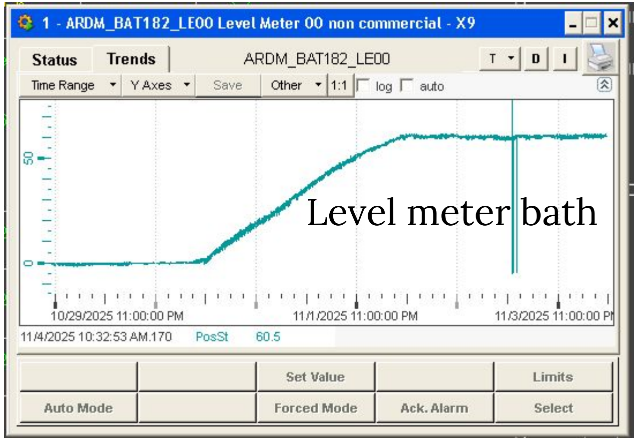
- Dark Matter detectors have specific physics goals involving neutrinos physics.

UAr measurement:
DArT

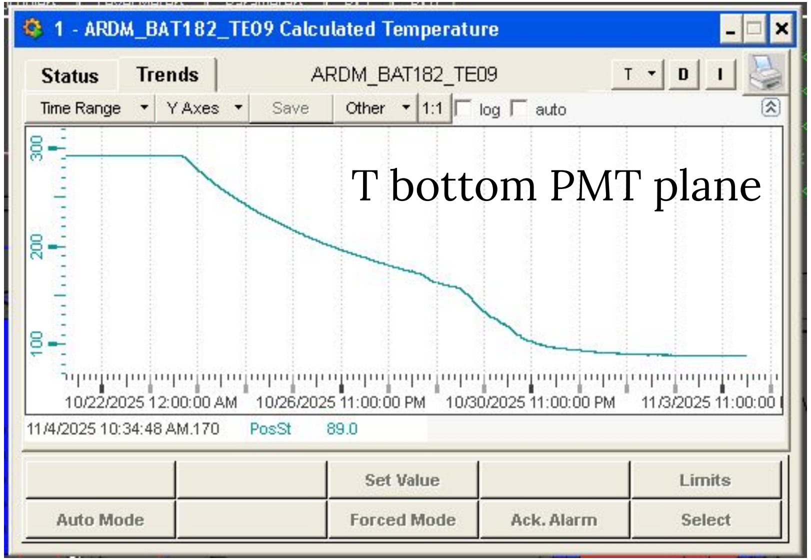
Canfranc, Aragon, Spain

ArDM

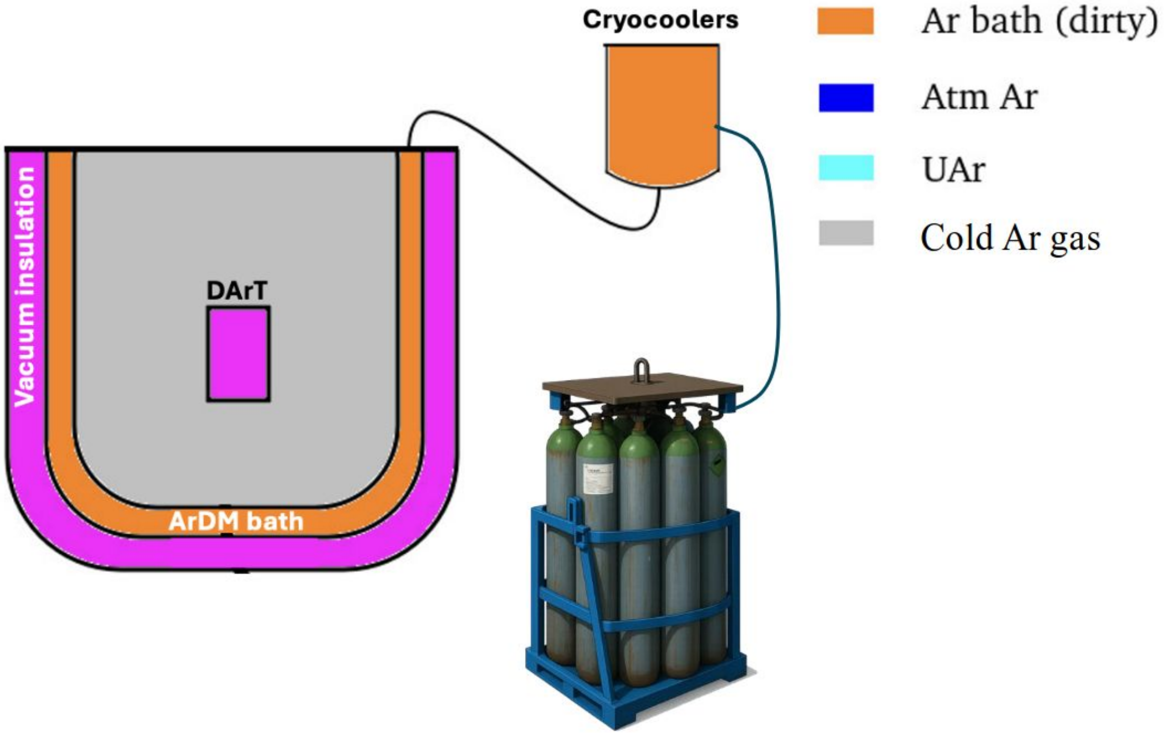




ArDM cool down started on October 22nd.
Filling with 2 tonnes of LAr finished in January.



ArDM

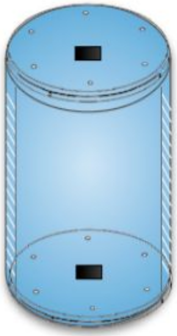


DArT taking data with atmospheric Ar during Christmas break

DArT taking data with UAr (DS-50) from January

UAr from Urania expected by Feb-March

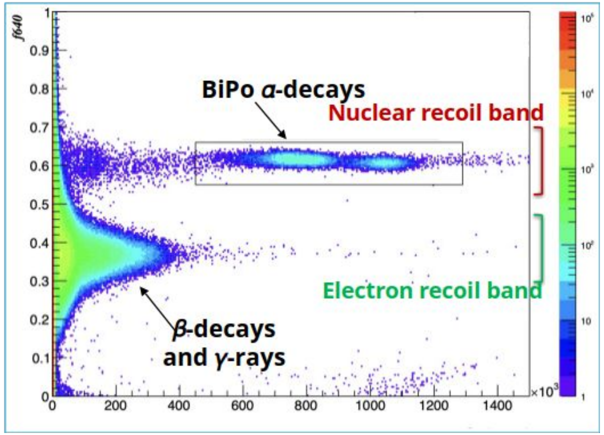
DArT-1 (2 SiPMs, external cryostat, Pb shield)

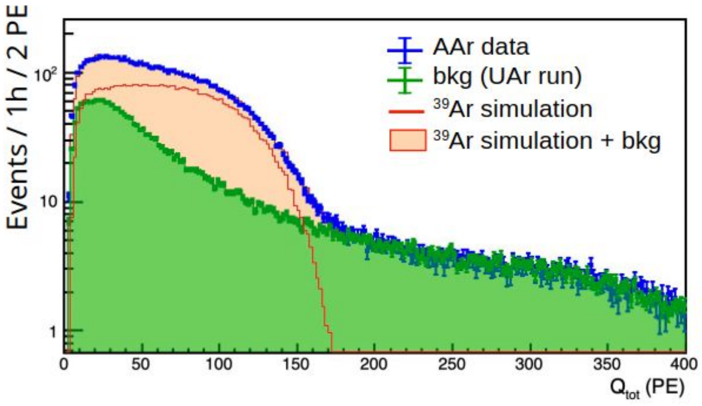


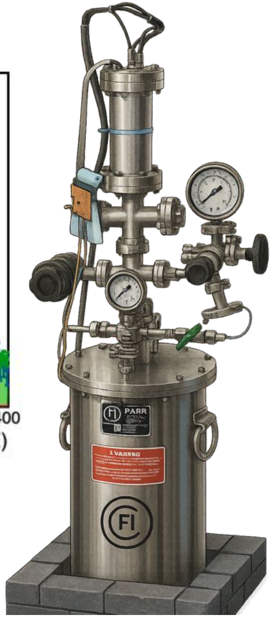
- Test of hardware operations, computing infrastructure, analysis.
- Test of slow control, gas system and UAr recovery procedure.
- Training

Data taken with AAr and UAr (DS-50):

+ **Competitive measurement of ^{39}Ar activity in AAr (analysis ongoing)**







UAr beyond DarkSide

White paper (+EOI) from

- ❑ COHERENT
- ❑ DUNE
- ❑ GADMC (DS-LowMass, ARGO)
- ❑ LEGEND

The infrastructures built for DarkSide-20k (URANIA, ARIA, DArT) can meet the UAr demand for most of the foreseen future experimental needs.

➔ **UAr fundamental for several low-background experiments beyond DM**

Snowmass2021 White Paper

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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Abstract/Executive summary

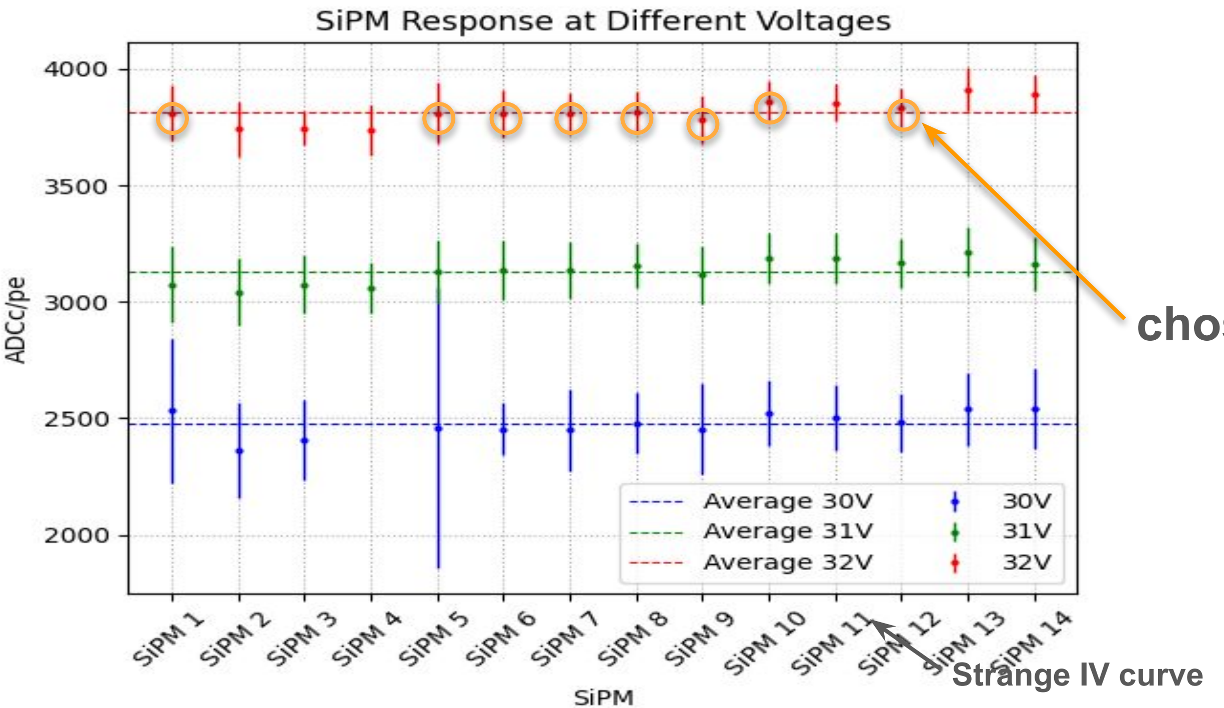
The DarkSide-50 experiment demonstrated the ability to extract and purify argon from deep underground sources and showed that the concentration of ^{39}Ar in that argon was greatly reduced from the level found in argon derived from the atmosphere. That discovery broadened the physics reach of

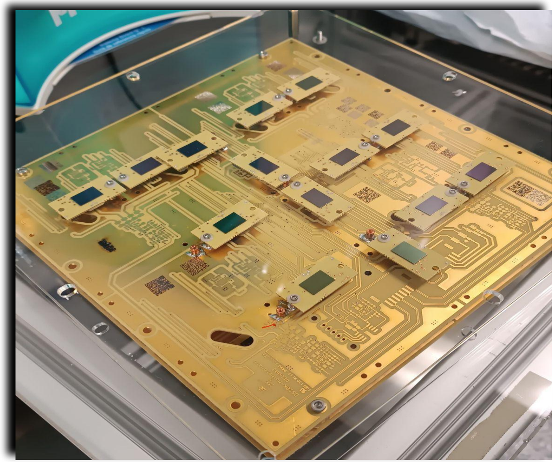
Formal request by the LEGEND coll. for 25 tonnes of UAr for LEGEND-1000

SiPM characterization and choice

DArTeyes assembled at LNGS.

Choice based on performance in cold:



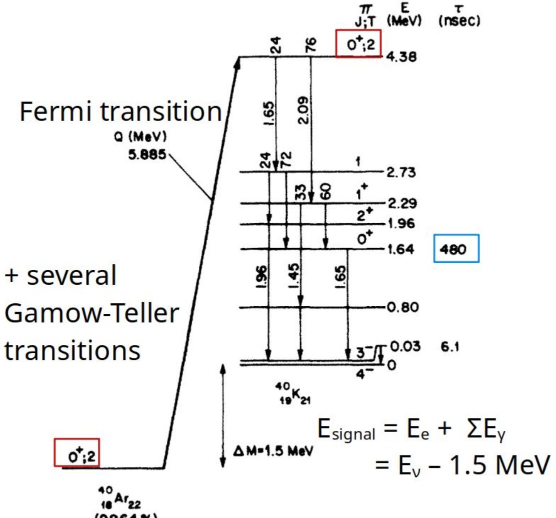


chosen SiPMs for DArT 2.0

Detecting ^{8}B solar neutrinos (coming soon)

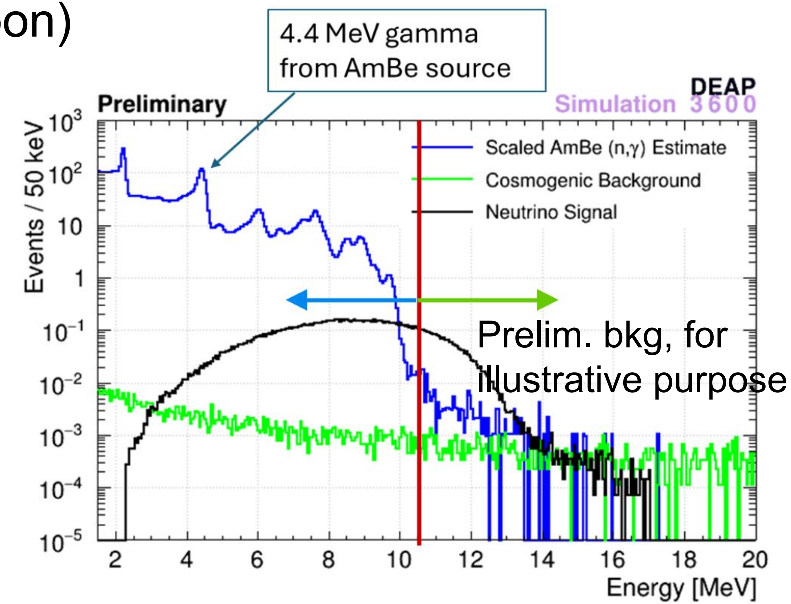
$$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$$

Enhanced cross section for populating the isobaric analog state (although not directly measured!)



$E_{signal} = E_e + \Sigma E_\gamma$
$= E_\nu - 1.5$ MeV

R.S. Raghavan (1986)



Two approaches towards radiogenic bkg estimation

Cosmogenic background from muon activation thoroughly studied