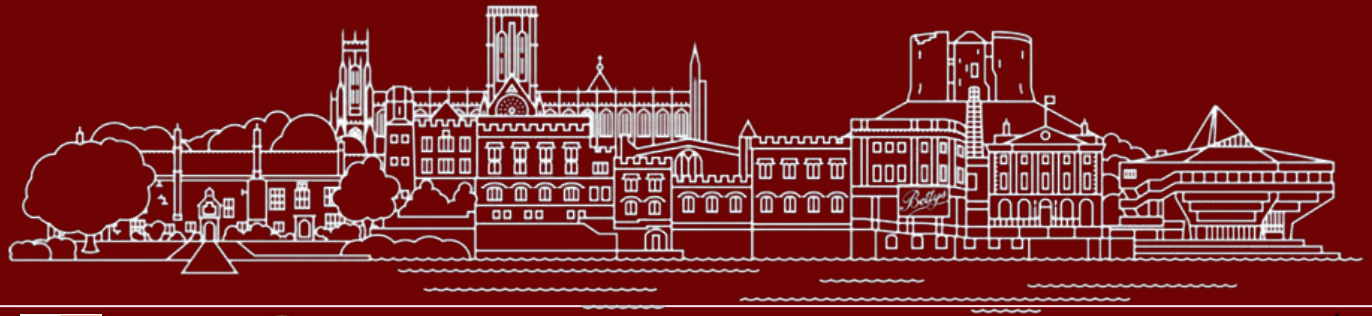
The Aria and Urania Projects

Industrial-Scale Production of Radiopure Argon for the DarkSide-20k Dark Matter Experiment

Celín Hidalgo on behalf of the DarkSide Collaboration

Low **R**adioactivity **T**echniques (LRT)

September 21, 2026



DarkSide-20k Overview

Next-generation liquid argon TPC hosted at LNGS (Gran Sasso, Italy).

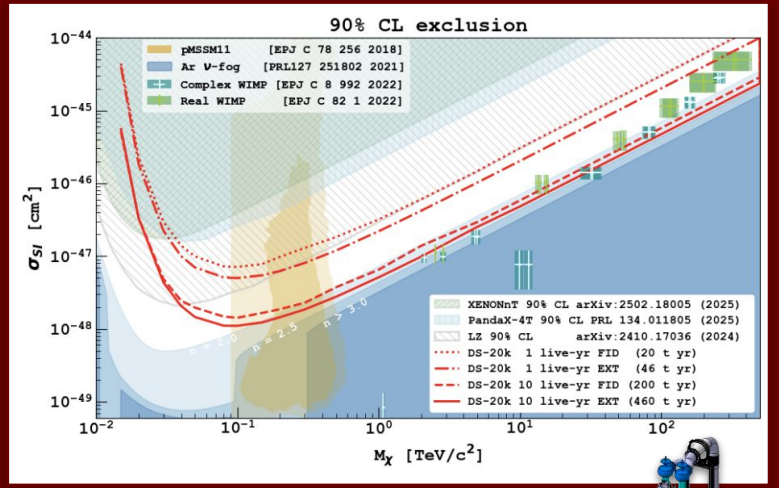
- 50-tonnes active mass (20-tonnes fiducial volume) of underground argon (UAr), depleted in ^{39}Ar.

Key features:

- Background-free design enabling exposures up to 200 t·yr.

Physics reach:

- Sensitivity to WIMP–nucleon cross section down to ~10^{-48} cm².
- World-leading discovery potential for multi-TeV WIMPs.



Inner veto (IV):

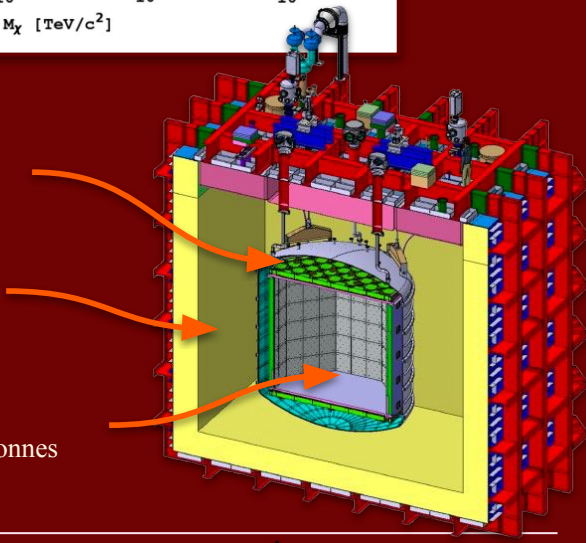
- ❑ Active UAr mass: 36 tonnes

Outer Veto (OV):

- ❑ 650 tonnes of AAr

TPC:

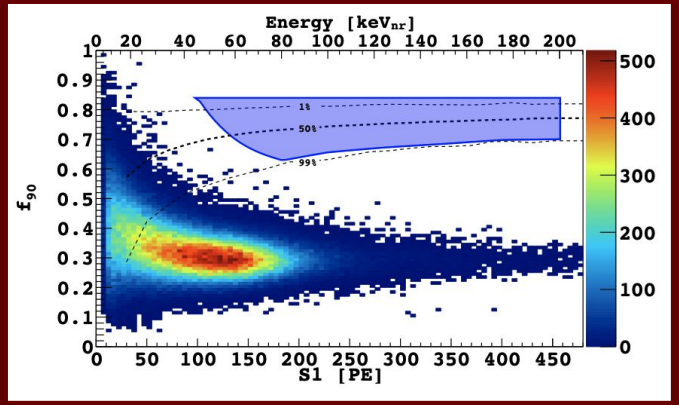
- ❑ Active UAr mass: 50 tonnes



DarkSide-50 Highlights

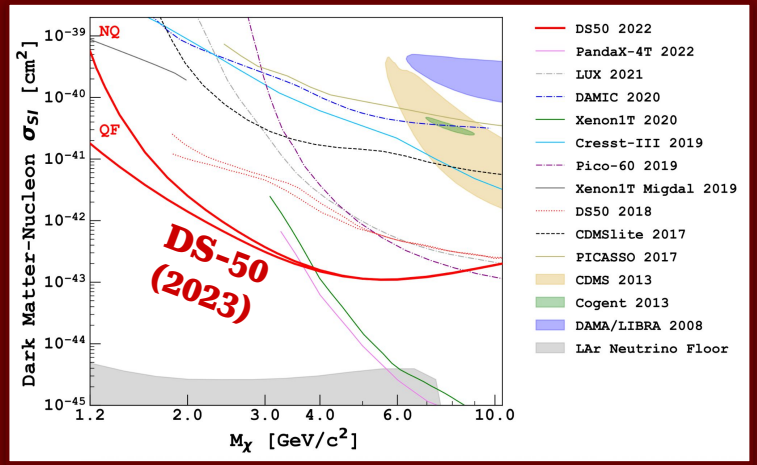
High-mass WIMPs

- **Blind analysis, 524 live-days** with UAr → first 70 days used to tune cuts, rest kept blind to avoid bias.
- **Total expected background in ROI: 0.09 ± 0.04 events** → ER leakage dominates over neutron backgrounds, demonstrated bg-free operation with UAr fill.



Low-mass WIMPs

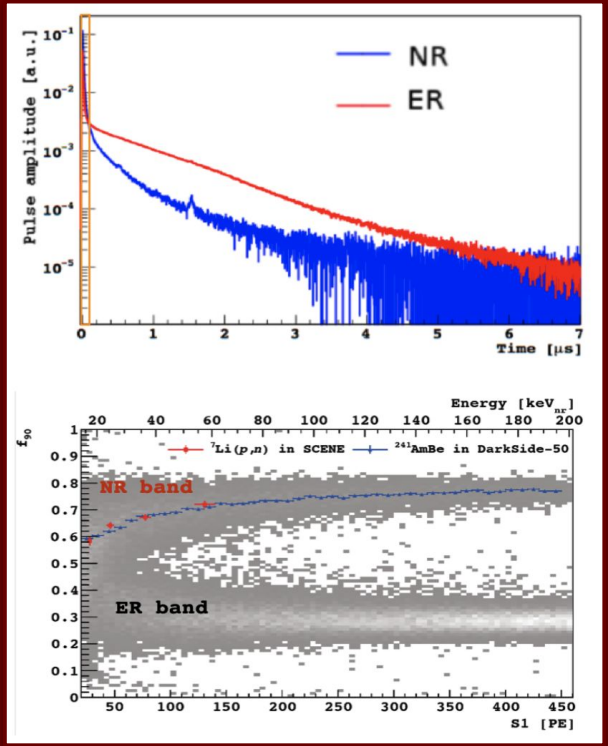
- **S2-only search,** bg limited (no S1 ⇒ no PSD).
- Analysis threshold at 4 electrons (~0.4 keV$_{NR}$).
- World leading constraints at ~1 GeV.



Pulse Shape Discrimination in LAr

Fast (singlet, ~6 ns) vs. slow (triplet, ~1.3–1.5 µs) scintillation components in LAr.

- **Discrimination parameter: prompt fraction** (f_{prompt}) — ratio of light collected in an early window (~60–200 ns) to total S1; NR and ER populate well-separated bands in f_{prompt} vs. energy.
- **DEAP-3600** achieves rejection > 10^9 in the energy ROI for WIMPs [arXiv:2302.14484v1].



Underground Argon

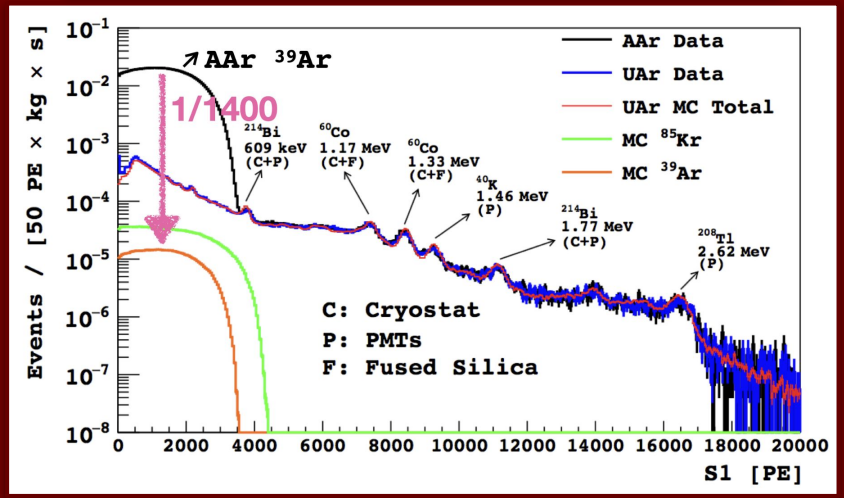
Intrinsic ^{39}Ar (Q=565 keV) is the dominant background in argon-based detectors:

~1 Bq/kg in atmospheric argon (AAr)

Sets the low-energy detection threshold, where PSD is least effective, and causes event pile-up in multi-tonne detectors.

^{39}Ar is produced by cosmic rays in the atmosphere → argon from underground wells, shielded from cosmic rays, is strongly depleted.

Reaction	Estimated ^{39}Ar Production rate [atoms/(kg_{Ar} day)]	Fraction of total AAr [%]
^{40}Ar(n, 2n)^{39}Ar + ^{40}Ar(n, d)^{39}Cl	759 ± 128	72.3
^{40}Ar(μ, n)^{39}Cl	172 ± 26	16.4
^{40}Ar(γ, n)^{39}Ar	89 ± 19	8.5
^{40}Ar(γ, p)^{39}Cl	23.8 ± 8.7	2.3
^{40}Ar(p, 2p)^{39}Cl	<0.1	< 0.01
^{40}Ar(p, pn)^{39}Ar	3.6 ± 2.2	0.3
^{38}Ar(n, γ)^{39}Ar	$\ll 0.1$ (UAr) 1.1 ± 0.3 (AAr)	- 0.1
Total	1048 ± 133	100



The Argon Purity Requirements for DarkSide

1) Isotopic purity — remove ^{39}Ar:

- Atmospheric argon contains **1 Bq/kg** of ^{39}Ar β-decays (endpoint 565 keV, $\tau_{1/2}$ = 268 yr) — a major source of background and pile-up.
- Reduced **x1400 (potentially more)** by sourcing **UAr (Urania)**, and could potentially be further suppressed via **isotopic distillation (Aria)** by a factor of 10.

2) Chemical purity — remove impurities (N_2, O_2, CH_4, etc.):

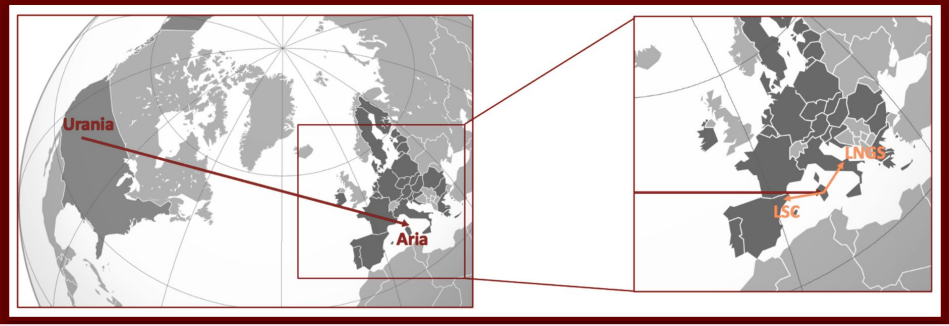
- Achieved in-situ with a **getter system**, continuously removing contaminants down to the **ppt–ppb** level.
- Getters only work effectively if the input argon is already very pure — so **chemical distillation (Aria)** is performed upstream.
- Contaminants would **quench scintillation light** and degrade pulse-shape discrimination.

The DarkSide Argon Procurement

Step 1 — Urania (Cortez, CO): extraction and purification of 120-t of UAr from CO_2 well gas, achieving ~99.9% purity (nitrogen $\lesssim$ **10^{-4}**, other contaminants $\lesssim$ **10^{-6}**).

Step 2 — Aria (Sardinia): further chemical purification + possible **isotopic depletion** of ^{39}Ar via cryogenic distillation, exploiting small differences in relative volatility between argon isotopes.

Step 3 — DArT (LSC, Spain): detector that measures the **^{39}Ar depletion factor** of UAr batches.



Urania

- Urania plant productivity: ~250-300 kg/day of UAr from CO_2.
- Kinder Morgan's Doe Canyon facility, pulling CO_2 from the Earth's mantle as part of its natural gas mining.
- Contained within this CO_2 stream coming from those deep underground wells is a small amount of low-radioactivity argon.

Our low-radioactivity argon is a byproduct in their production of natural gas.

Aria: Cryogenic Distillation Plant

Cryogenic distillation column (total height ~350 m):

28 Central modules: 12 m each

Outer Diameter of the column: 32.3 cm

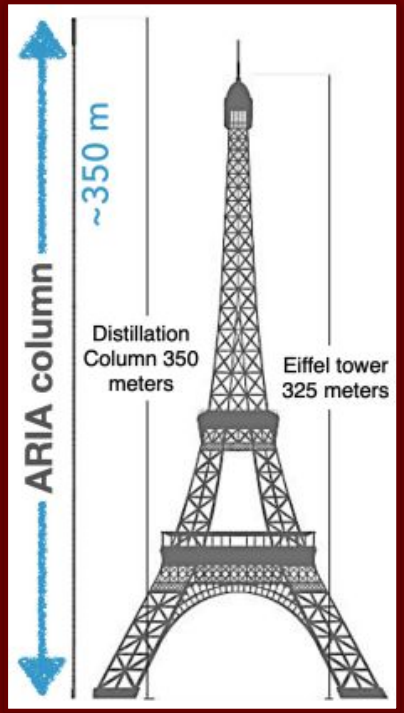
Inner Diameter of the column: 31.8 cm

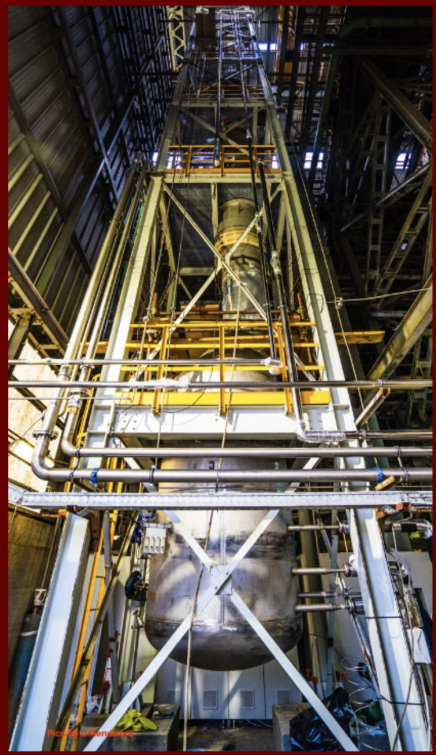
Outer Diameter of cold box: 71.2 cm

Number of theoretical stages: ~2870

Total column active height: ~ 287 m

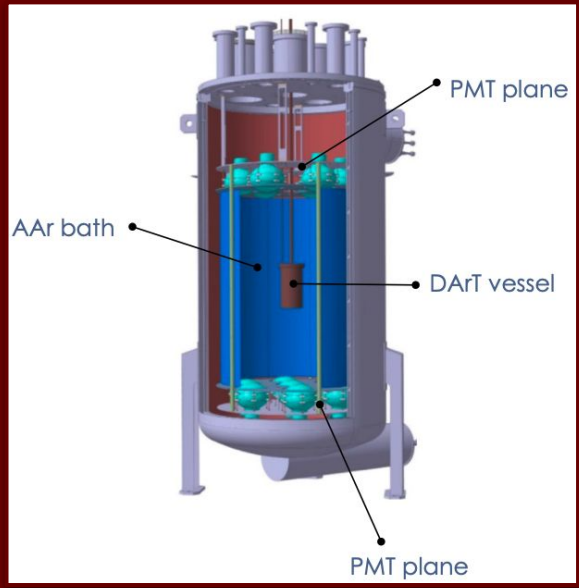
Structured packing





DArT–Measuring the ^{39}Ar Depletion Factor

- **DArT**: Single phase 1.35 kg of UAr detector that measures the **^{39}Ar depletion factor** of UAr batches from Urania and Aria.
- **Located inside ArDM** at the **Canfranc Underground Laboratory (LSC, Spain)** — ArDM's argon volume serves as an active veto.
- **Method**: **^{39}Ar** β-decays in DArT are the signal; events also seen in ArDM are tagged and removed as background.
- DArT will be sensitive to very high depletion factors of ^{39}Ar, which is of the order of 1000, reaching 10% statistical uncertainty in 1 week of data-taking.



Transport of argon from Urania to Aria

~15-20 tonne shipping and storage vessels will be used to transport liquid argon from Urania to Aria.

- repeating the whole shipment procedure for arrays of 8 skids.

The activity of ^{39}Ar induced during extraction, purification and transport on surface, in baseline conditions, is evaluated to be <5% of the UAr activity measured in DarkSide-50, and thus considered acceptable.

ISOVAC 20 - SCHEMATIC DIAGRAM

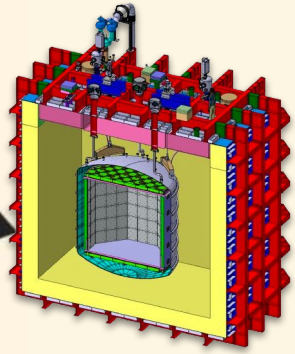
Chemical Purification of Argon

10^{-4} Presence of contaminants
(N_2, O_2, CH_4, Kr)

10^{-10} Optional secondary distillation
in Seruci-1
Suppression of other elements

10^{-10} Distillation in Seruci-1
Suppression of N_2

High Purity Argon
ready for DarkSide
1 tonne/day



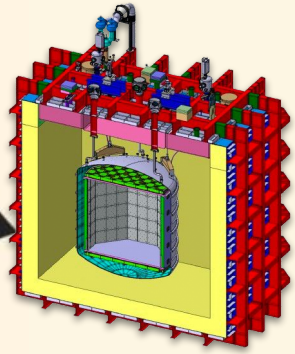
Isotopic Purification of Argon *(from Simulations)*

10^{-15} Natural abundance of ^{39}Ar in atmospheric argon

10^{-18} Underground Argon extracted in Urania

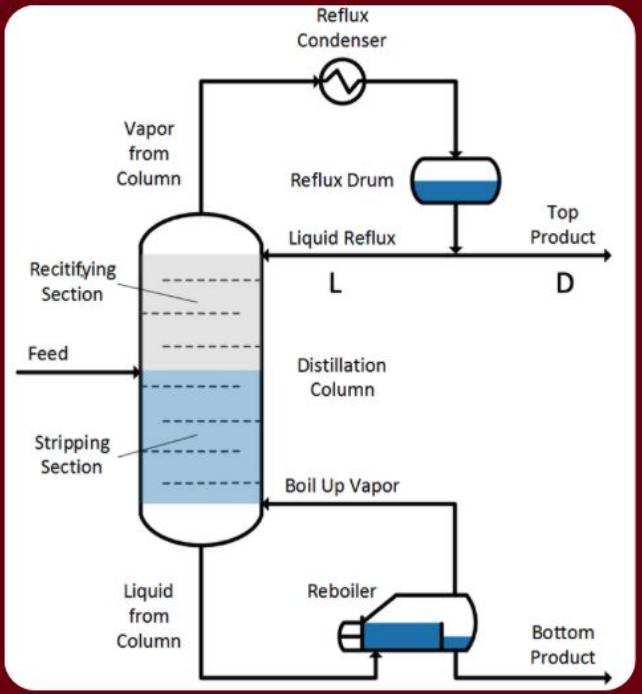
10^{-19} Argon Extracted in Aria

High Purity Argon ready for DarkSide **10 kg/day**



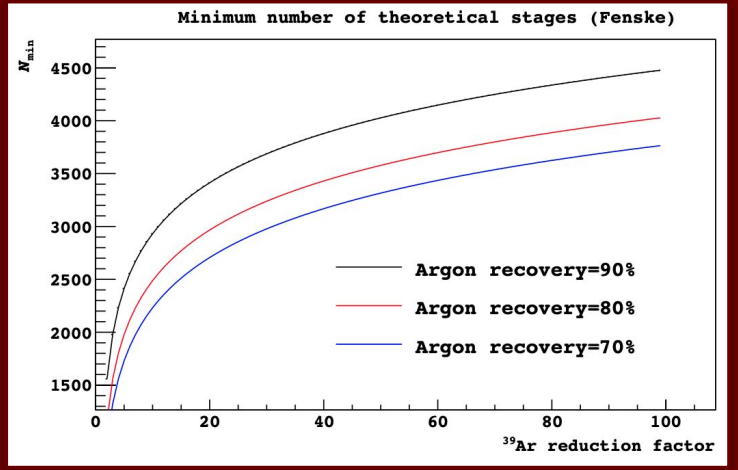
Cryogenic Distillation

- Isotopes separated by tiny boiling point differences in countercurrent exchange.
- Mass and heat transfer between descending liquid and ascending vapour drives enrichment.
- Structured packing maximises equilibrium stages.



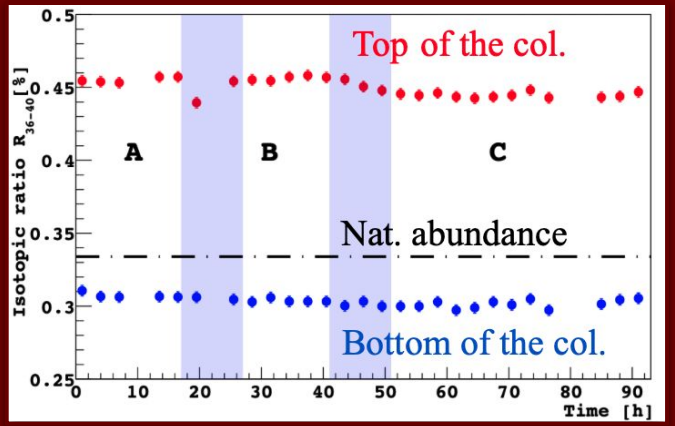
Relative Volatility $^{39}Ar/^{40}Ar$

- **Fieschi–Terzi model**: predicts relative vapor pressure between argon isotopes → separation factor α.
- **Validated on $^{36}Ar/^{40}Ar$** (Boato–Scoles data), then extrapolated to **$^{39}Ar/^{40}Ar$**.
- **α ≈ 1.0015**, consistent across 84.4–91.8 K.
- **Fenske equation** → thousands of theoretical stages required.



Proof of Concept–Seruci-0 Prototype

- 26 m prototype: one module of the full 350 m column.
- First demonstration of argon isotopic separation — all three stable isotopes (^{36}Ar, ^{38}Ar, ^{40}Ar) separated simultaneously.
- Column performance matches design and simulation, validating the full-scale plant.



Beyond DarkSide-20k with Aria

Isotopic separation for medical applications

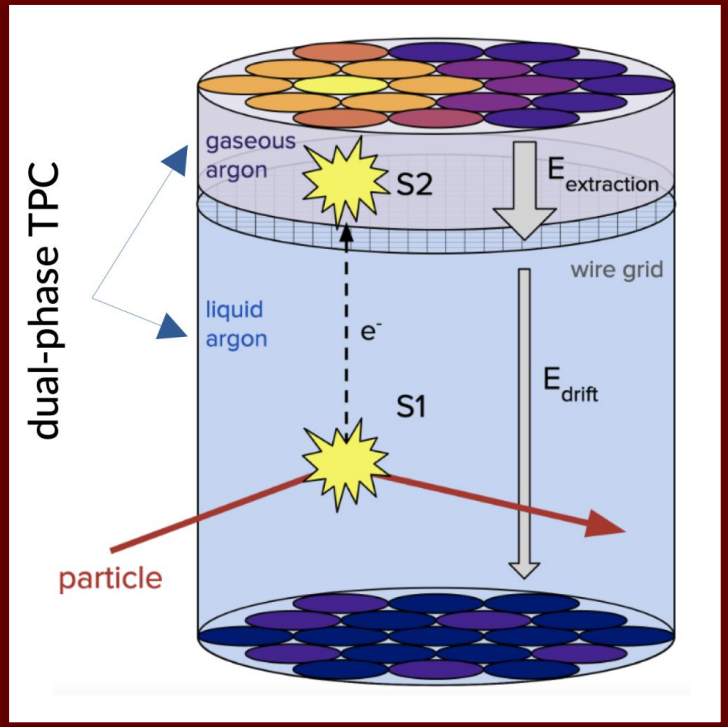
Production of high-purity stable oxygen isotopes as precursors for Positron Emission Tomography (PET).

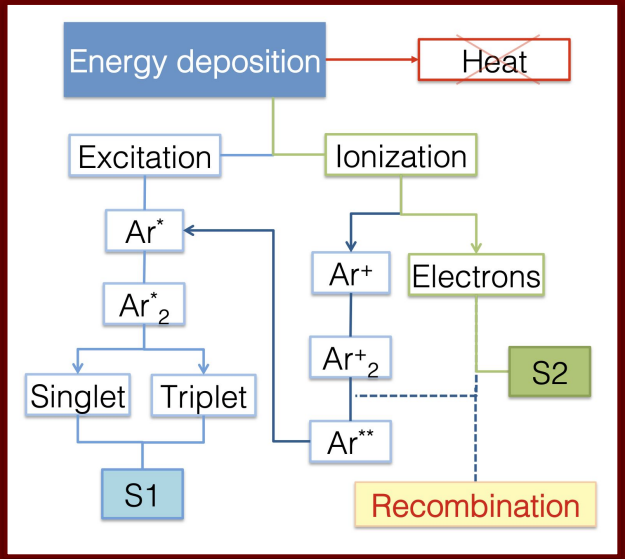
Fractionation of the $^{16}O_2$ / $^{16}O^{18}O$ binary mixture, overcoming the low natural abundance of ^{18}O (0.205%) and a relative volatility of only $\alpha \approx 1.006$.

Direct transfer of capability from fundamental physics to medicine.

BackUp

Dual Phase Time Projection Chamber

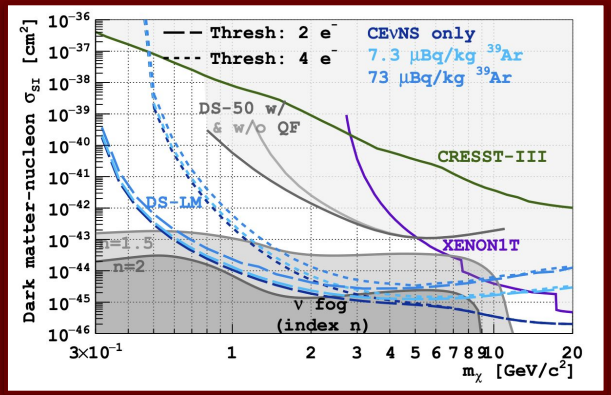


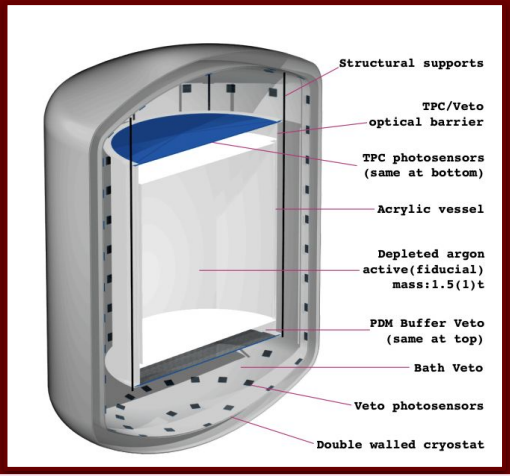


DarkSide-LowMass →Possible Future Project

Cryogenic distillation enables isotopic separation at unprecedented scale, paving the way for new applications beyond DarkSide-20k.

- Further depletion of ^{39}Ar by up to an additional factor of 10 per pass (≈7 kg/day throughput) could support **DarkSide-LowMass**, a 1.5-ton detector optimized for GeV-scale dark matter searches.





The Global Argon Dark Matter Collaboration

GADMC unites predecessors → DarkSide, DEAP, MiniCLEAN, ArDM into one staged argon program.

Argon: dense, scalable, high ionization, strong scintillation, excellent ER/NR discrimination.

DarkSide-20k, background-free via ultra-low backgrounds + active rejection (neutron veto + PSD).

Future: ARGO (SNOLAB, ~300 t fiducial).