Large-Scale Production and Cryogenic Isotopic Separation of Special Gases for the DarkSide Experiment and Future Applications in Rare-Event Searches

Passage of Academic Year
October 16, 2025
Celín Hidalgo

Overview

1) Motivation for dark matter searches.
2) Direct detection of dark matter with noble liquids.

Report about some of my contributions to 3 projects within the DarkSide programme

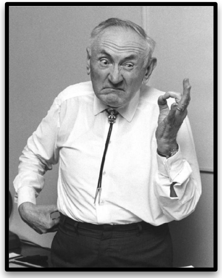
- **Aria**: purification of a liquid argon target for application in DM searches and beyond.
- **Proto-0**: developing analysis methods to assess the liquid argon purity and calibrate the detector.
- **X-Art**: studying the response of Xe-doped LAr to characterize particle detection.

Understanding and *Discovering* Dark Matter

Fritz Zwicky

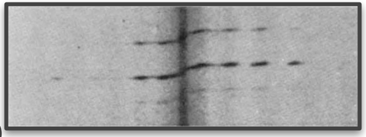
“If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.”

1933



1970

(Rubin, 1983)



Vera Rubin

“The conclusion is inescapable: mass, unlike luminosity, is not concentrated near the center of spiral galaxies. Thus the light distribution in a galaxy is not at all a guide to mass distribution.”

CMB

CMB anisotropies require dark matter to explain observed acoustic peaks and structure formation.

1964

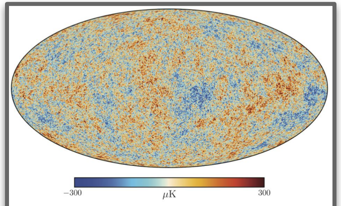
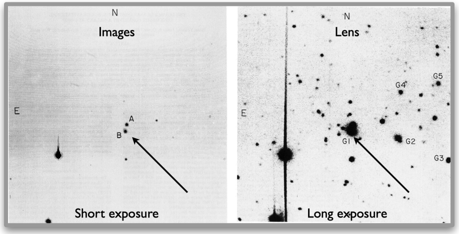


Figure 3: Planck measurement of the temperature variations in the CMB sky.

(Baumann, 2017)

1979

(Walsh, Carswell & Weymann 1979)



Gravitational Lensing Effect

The distribution of matter revealed by lensing does not match luminous matter.

Understanding and *Discovering* Dark Matter

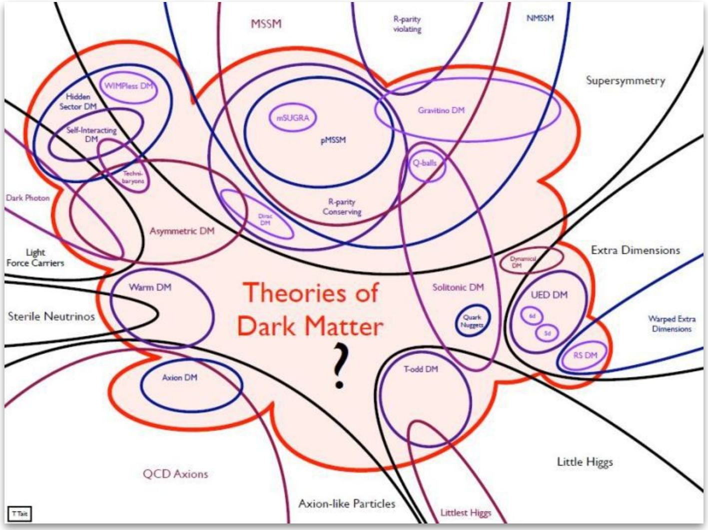
Many candidates proposed: axions, sterile neutrinos, dark photons, WIMPs, extra dimensions…

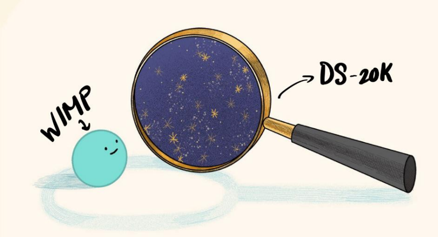
Dark matter properties remain unknown: mass, interaction type, production mechanism.

Weakly Interacting Massive Particles (WIMPs):

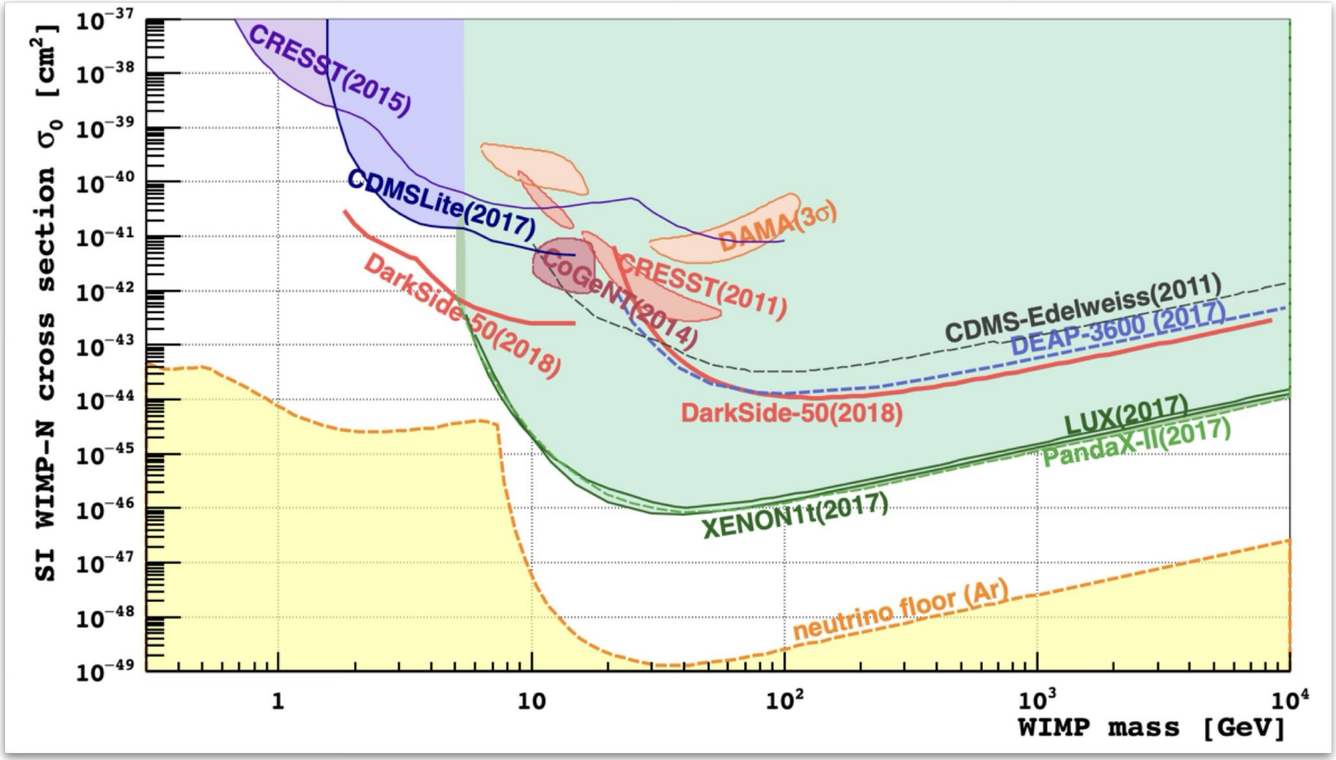
- Well-motivated in particle physics (supersymmetry, thermal relics).
- Predict interaction cross sections within reach of current detectors.

Direct detection experiments like DarkSide-20k focus on WIMP searches using liquid argon.





Current status of dark matter direct detection searches



Understanding and *Detecting* Dark Matter DarkSide-20k

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

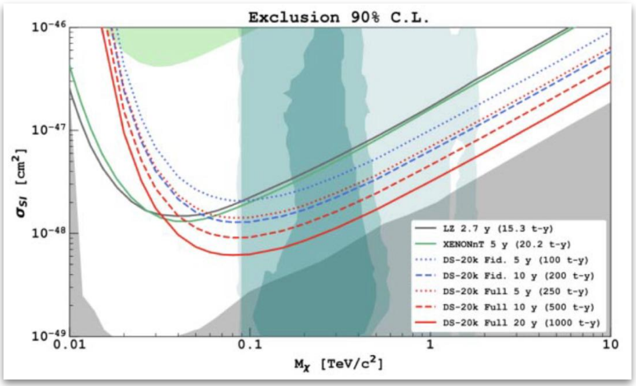
- 50-ton active mass of underground argon (UAr), depleted in 39Ar.

Key features:

- Exceptional pulse shape discrimination (PSD) to separate nuclear/electron recoils.
- Background-free design enabling exposures up to 100 t·yr.

Physics reach:

- Sensitivity to WIMP–nucleon cross section down to ~10–48 cm².
- <u>World-leading discovery potential</u> for multi-TeV WIMPs.



Inner veto (IV):

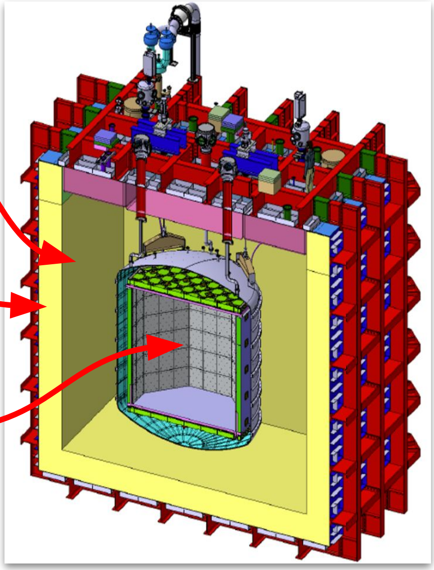
- ❏ Active UAr mass: 36 tonnes
- ❏ Neutron tagging

Outer Veto (OV):

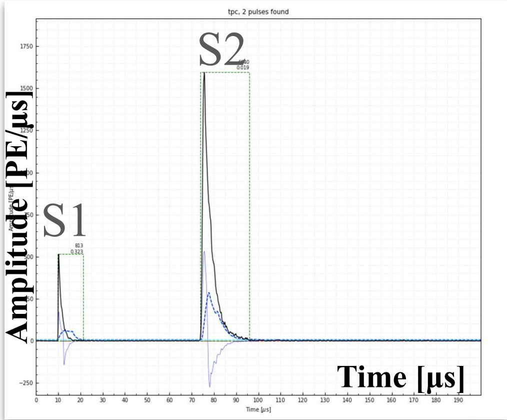
- ❏ 700 t of AAr

TPC:

- ❏ Active UAr mass: 49.7 tonnes
- ❏ Gas pocket thickness: 7.0 mm
- ❏ Light yield: 10 PE/keV
- ❏ Ionization yield: 20 PE/e$^-$

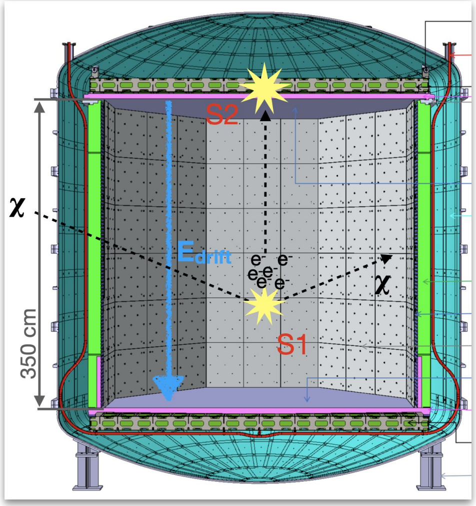


Working Principle of Dual-Phase TPCs



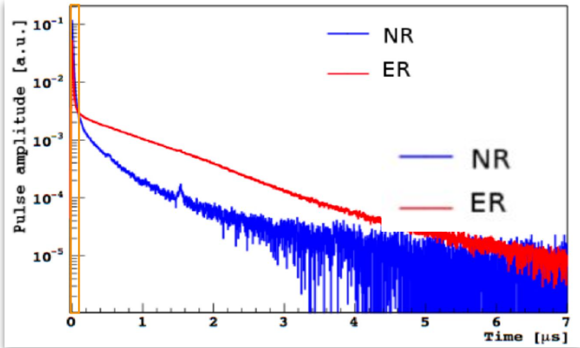
Dual-phase time projection chambers (**TPCs**), are used in rare-event searches for dark matter and neutrino physics.

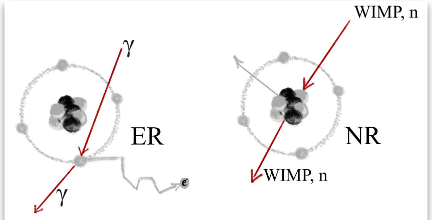
- These detectors operate with a noble gas (e.g. argon, xenon) in both liquid and gas phases.
- A particle interaction in the liquid generates:
  - S1: prompt scintillation light from excited atoms
  - Ionization electrons, which drift upward under an applied electric field.
- At the liquid-gas interface, electrons are extracted into the gas phase and accelerated
  - S2: a delayed signal from electroluminescence (light generated by accelerated electrons).
- The electroluminescence gain depends on the electric field and is key to signal reconstruction and detector calibration.



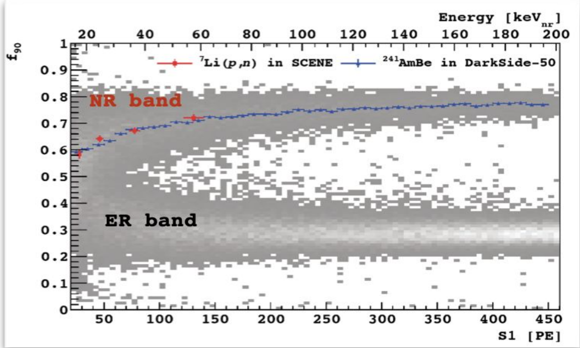
Understanding and *Detecting* Dark Matter

- ER vs NR differ in time profile and S2/S1 ratio, producing distinct bands in data.
- Clear separation of ER and NR bands demonstrates background rejection capability in LAr TPCs.
- The DEAP-3600 experiment demonstrated pulse shape discrimination (PSD) with a background rejection capability better than 10^9, effectively separating electron recoils from nuclear recoils using liquid argon scintillation timing.



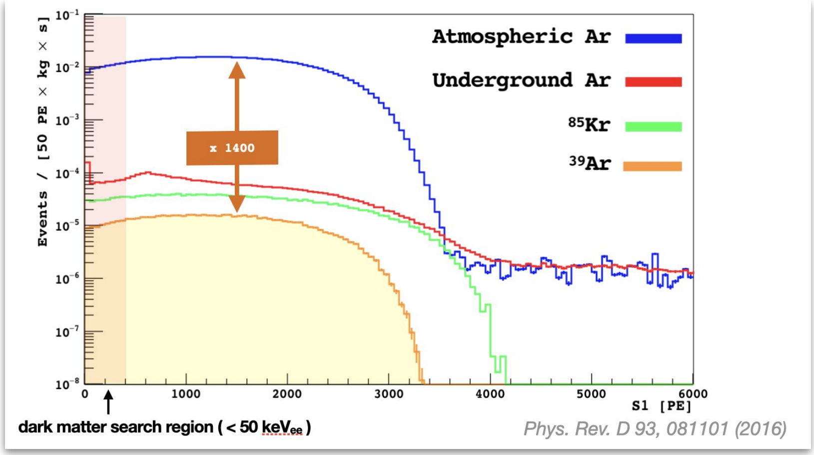


$$f_{90} = \frac{\text{S1 light in first 90 ns}}{\text{Total S1 light}}$$



Why Use Underground Argon?

Reducing Backgrounds for Dark Matter Searches



Argon is **ideal** for dark matter detection:

- Produces bright scintillation and ionization signals
- Enables excellent pulse shape discrimination (PSD) to separate nuclear from electronic recoils.

Challenge: Atmospheric argon contains radioactive 39Ar (activated in the atmosphere: β-emitter, 565 keV, half-life 269 years).

- Activity ≈ 1 Bq/kg, producing 3 x 10^8 of background events per ton-year.
- PSD can in principle ensure background-free operation, but such a high event rate makes large dual-phase TPCs impossible due to pile-up during the long charge-drift time (~1 ms/m).

Solution: Use underground argon (UAr), shielded from cosmic rays.

- 39Ar production suppressed by >3 orders of magnitude (DS50 demonstrated with 160 kg)
- Enables background-free searches for WIMPs and light dark matter.

DarkSide-20k requires ~120 tonnes of UAr, purified to detector-grade quality.

How We Obtain and Purify Underground Argon

The Aria Project

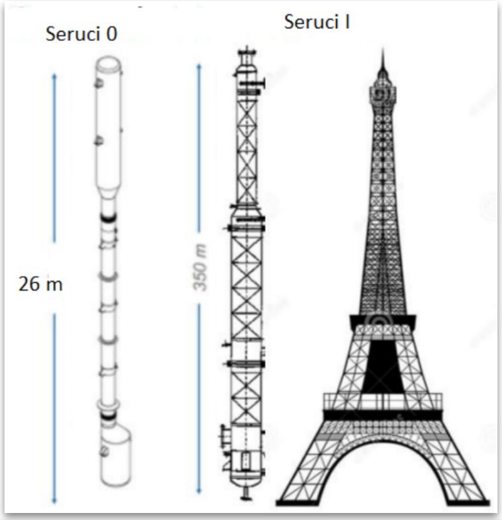
Source:

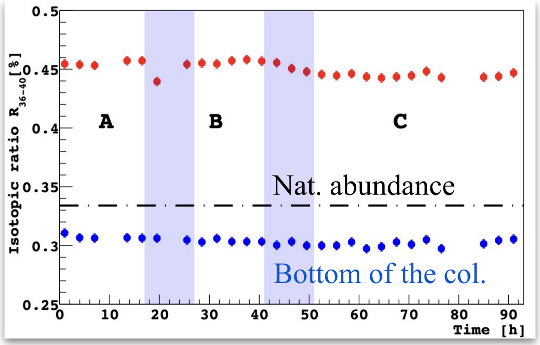
- Extracted from CO_2 wells in Colorado (Cortez site), where argon has been trapped underground for years.
- Collected and liquefied on-site in the Urania facility before shipment to Italy.

Purification: The **Aria** Plant (Sardinia, Italy)

- 350m cryogenic distillation column installed in a mine shaft at Carbosulcis.
- Designed to separate argon isotopes and further reduce 39Ar content.
- **Demonstrated isotopic separation of 36Ar, 38Ar, and 40Ar with the 26m prototype.**
- Operates with sub-ppb purity levels, using cryogenic distillation and hot getters.

Goal: Deliver ultra-pure, low-radioactivity argon for DarkSide-20k and future multi-ton detectors (e.g. DUNE, LEGEND).



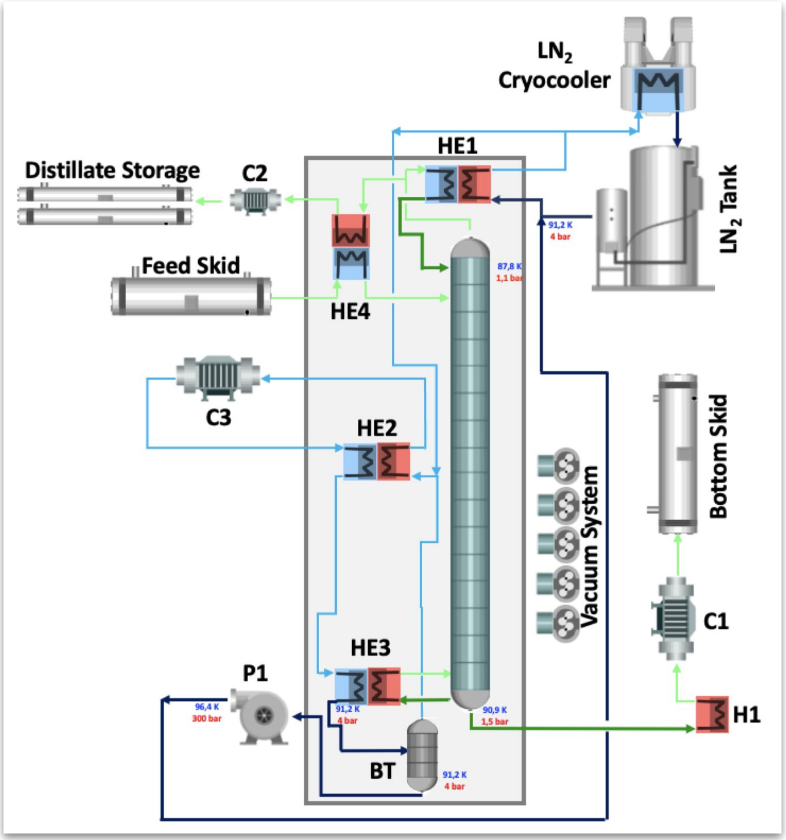


Proof of principle demonstration on a 26m section of the column

How We Obtain and Purify Underground Argon

The Aria Project

28 central modules;
height of each module = 10.28 m;
overall column D = 0.711 m;
internal column D = 0.3178 m;
total column height = 349 m;
2871 theoretical stages.



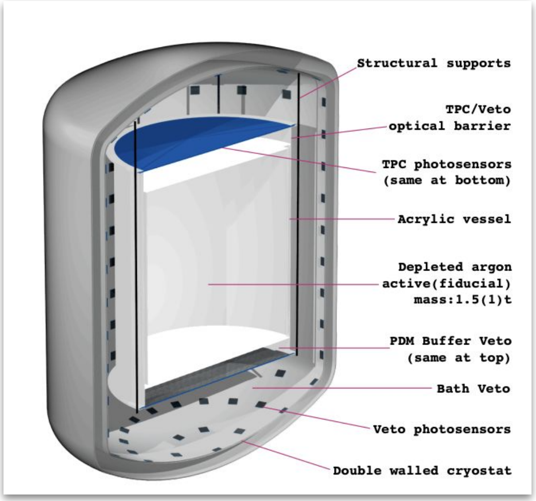
Future: production/applications of ultra-pure isotopes

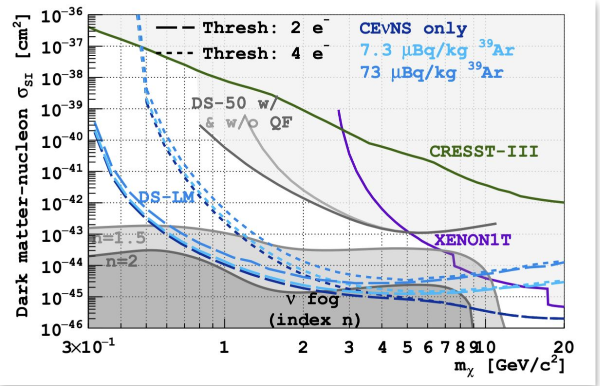
Cryogenic distillation enables isotopic separation at unprecedented scale, paving the way for new applications beyond DarkSide-20k.

- Further depletion of 39Ar 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.

Broader opportunities include target isotope enrichment for:

- **Rare-event searches**: 124Xe, 136Xe, 76Ge, 36Ar.
- **Medical** and **industrial** applications: 17O and 18O for diagnostics and imaging.





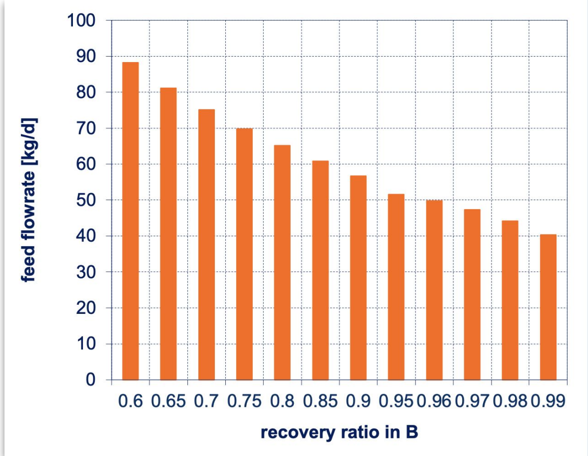
Future: production/applications of ultra-pure isotopes

Current status of the column:
Activities at Aria facility are currently on hold.

Current work:
- Training started with the Aspen Plus® software. Goal to reproduce previous simulation results.

Future work:
- Optimize distillation simulations and process parameters using Aspen Plus®.
- Investigate improved column geometries to enhance throughput and separation efficiency.
- Explore new isotopic production campaigns leveraging the Aria infrastructure.

- ASPEN Plus® V14.0
- addition of 16O 18O to the database
- recovery ratio of the heavy isotope of interest between 60% and 99%
- maximum feed to the unit determined on the basis of fluid dynamic performances.



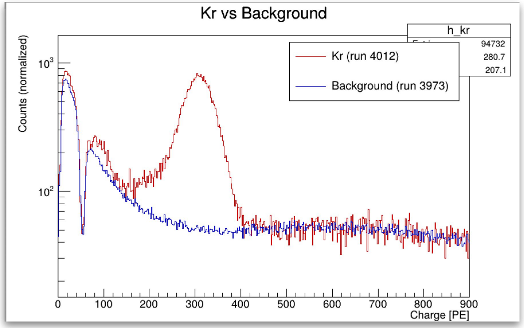
A DarkSide Prototype: Proto-0

Liquid argon TPC with top & bottom photodetector readout
Movable anode and bubbler

- Studies of S2 vs anode–grid distance
- Studies of S2 vs gas-pocket thickness/pressure

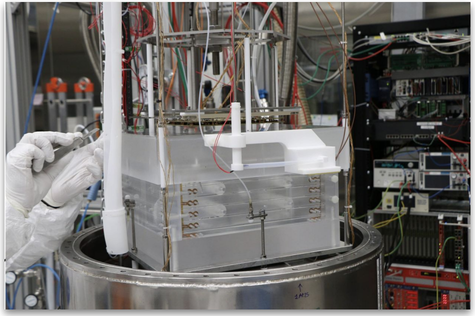
Dedicated cryogenic system

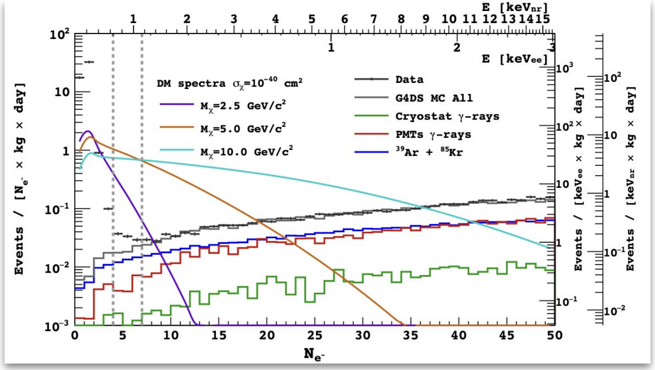
- ~200 kg of liquid argon (~7 kg active volume)
- 300 L cryostat with custom condenser & cryocooler
- Full recirculation, purification, and 83mKr calibration source



Current Activity: Optimizing Pulse Reconstruction in Proto-0

- Joined the experimental effort at INFN Naples and focussed on tuning the pulse reconstruction algorithms.
- The optimization effort improves detection and characterization of low-energy pulses, with particular attention to single-electron signals (SEs) from photoionization at the cathode.
- These SEs serve as a well-defined calibration source for measuring the electroluminescent gain, a detector's light response to drifting electrons as a function of electric field configurations.
- Incidentally, SE signals are a limiting background for low-energy searches with extremely low-thresholds (20 eV) – *arXiv:1802.06994*





Visualizing the Dynamic Threshold Mechanism in pySONAR

Threshold is not fixed but dynamically adapts:

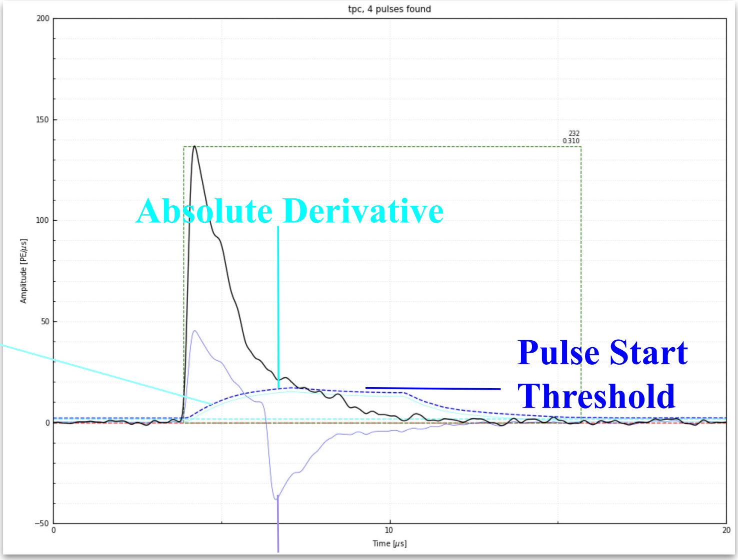
- Calculated as: Threshold = Base Value (constant) + Smoothed Absolute Derivative Threshold
- Allows pulses with any amplitude to be detected.

If the smoothed derivative exceeds the <u>threshold</u>
→ Start of Pulse Detected.

Two conditions define Pulse Ends:

1. Prolonged regions with absolute derivative below <u>threshold</u>
    - If the derivative remains below a threshold for at least <u>some duration</u>.
2. New Pulse Start Detected
    - If another rising derivative threshold is encountered.

Pulse Ends Are Identified & Paired with Pulse Starts.



Configuring the Pulse Finder Algorithm

The configuration file controls algorithm behavior without modifying the code.

Allows users to tune parameters for different experimental conditions.

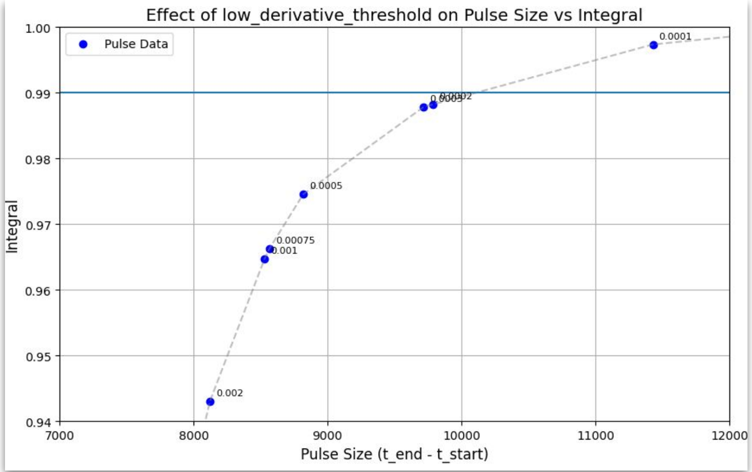
Adjusts pulse detection sensitivity, smoothing, and thresholding for optimal results.

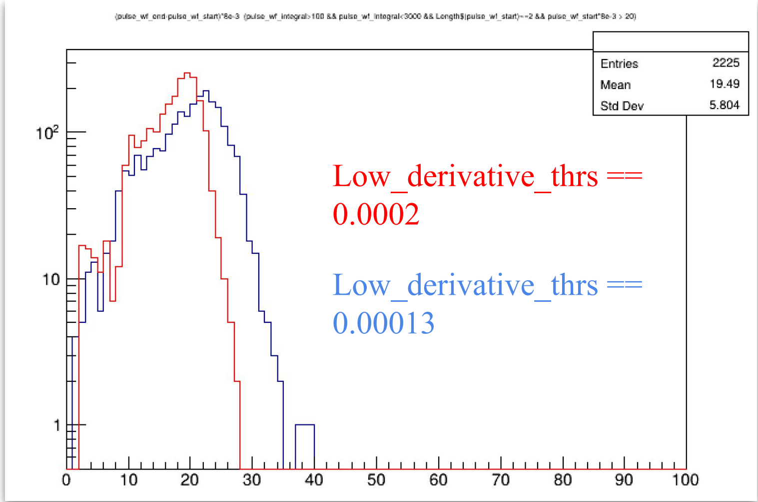
```
[pulse_finder] # Waveform summer must be enabled
  enable = true
  group = "tpc"
  algorithm = "derivative_dynamic"
  fprompt_gate = 88  # In samples. To convert in ns, multiply by 8
    [[charge_threshold]]    # Specific settings for "charge_threshold" algorithm
    amp_threshold = 0.03    # Valid for waveform in 1/S
    charge_threshold = 200  # Q/A threshold
    amp_certain = 0.1       # Amplitude above which Q/A check is skipped
    recluster_gate = 85     # In Samples
    [[derivative_dynamic]]
    minimum_pulse_time = 300      # Minimum duration (in samples) between rising and falling edges
    derivative_smoothing_gate = 100
    derivative_threshold = 0.001     # Threshold for detecting edges in the derivative
    abs_derivative_smoothing_gate = 400
    low_derivative_threshold = 0.0002 # Fraction of the derivative threshold used to define "low derivative"
    low_derivative_samples = 400      # Minimum number of consecutive samples with a low derivative
```

Repository Version of Source.config

Example Optimization: Tuning the Pulse End Threshold

- Pulse end detection depends on a threshold applied to the smoothed signal derivative.
- Lowering low_derivative_thrs from 2×10^{-4} to $\sim1.3\times10^{-4}$ improves charge recovery by extending the end time.

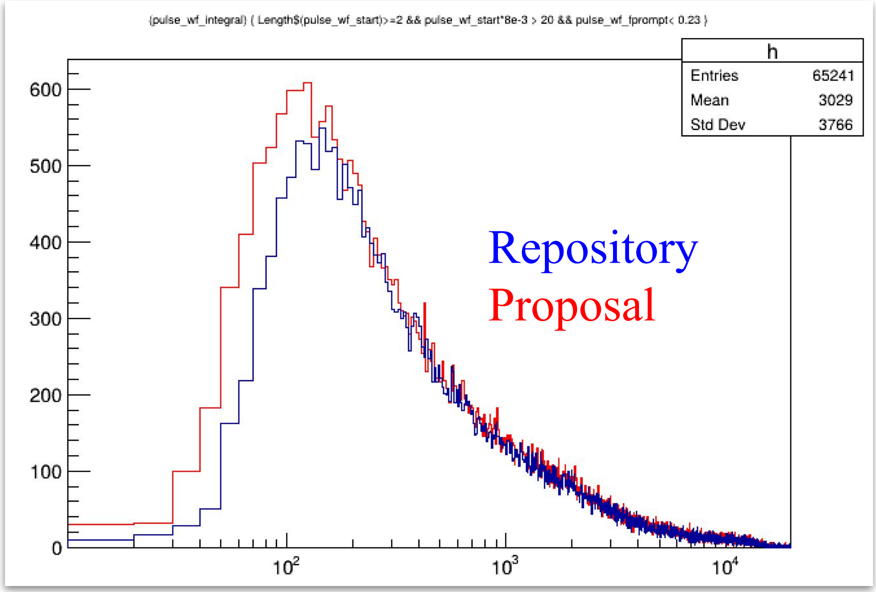




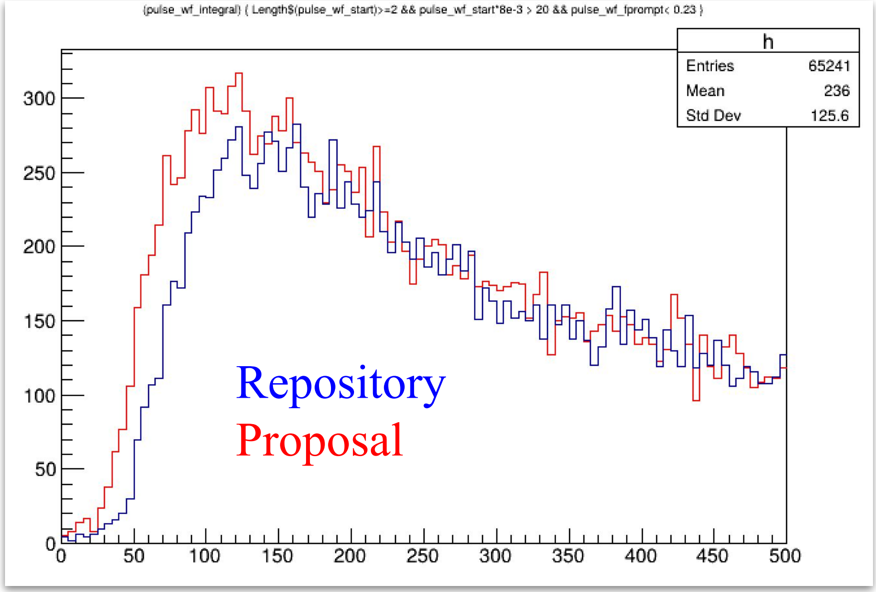
t_end - t_start [us]

Distribution of pulse lengths for S2 pulses in 2-pulse events still under control (no tails due to failing to find the pulse end)

New Parameters: Impact on S2 (more significant)



S2 integral [PE]



S2 integral [PE]

Work still ongoing as this might not be enough for SEs / echoes

Searching for Delayed Low-Energy Pulses in Proto-0: **Echoes**

Motivation:

- Investigate the presence of small, delayed pulses following a primary pulse, potentially linked to photoionization of the cathode or delayed extraction processes.
- These features can inform further our understanding of detector response and extraction dynamics.

Challenge: expected 4-15 PEs distributed over 10-20 μs for every extracted electron, to be compared with DCR and light leaks.

Approaches:

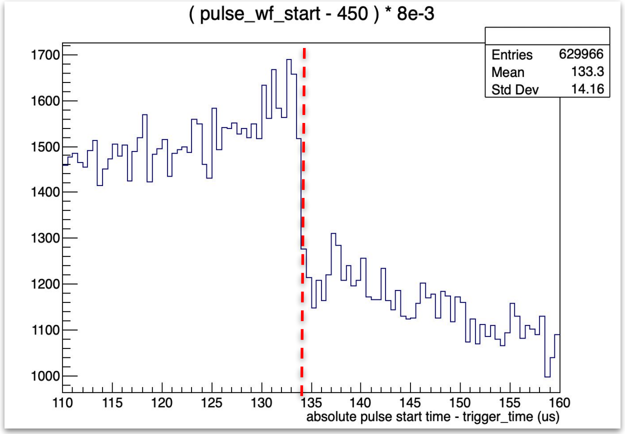
1. Implement ROI-based integration to capture charge near expected echo regions.
2. Tune the pulse finder to enhance sensitivity to low-charge signals.

Alternative strategy: pure ROI integration window

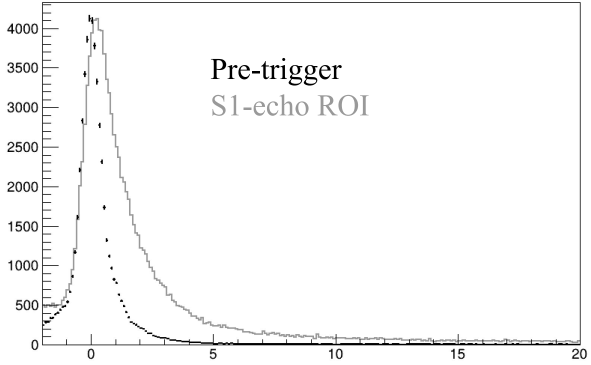
ROI-based approach, exploiting the time correlation between each pulse and the expected SE signal (separated by exactly one full drift length).

After precise measurement of the maximum drift length (134 µs):
→ for each pulse, define an echo ~20 µs integration window starting 134 µs sample after the start time of each pulse.
→ use a ~20 µs ROI at the end of the wf as control region for accidentals.

1) Evidence for excess of photoelectrons, compared to a random control region (pre-trigger), in the echo-ROI.
2) Work still ongoing to tune pulse finder to identify SEs.



Use distribution of successfully identified pulses to determine the max drift length.



Monitoring tools for the TPC operation

While on shift in Naples, and after returning, I have developed monitoring tools to help correlate the detector response to the operations on the system (refill, change of field configuration, purity)

Automated analysis and data selection using 83mKr calibration source (events with 1 S1 and 1 S2):

Select 2-pulse events. First pulse must:

– Start in trigger window (400–500 samples)

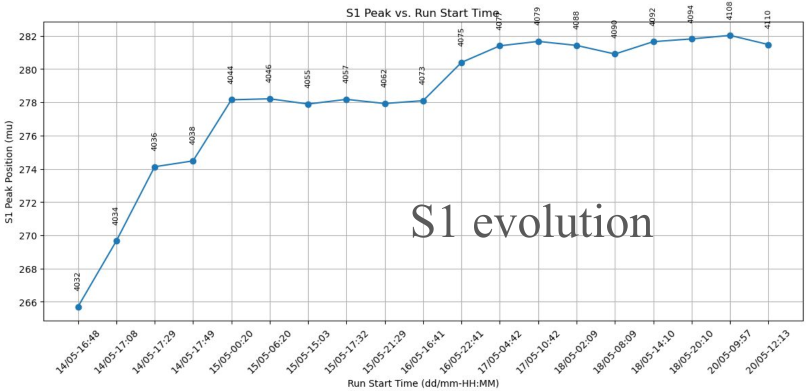
– Pass quality cuts: no saturation, low noise, wide RMS

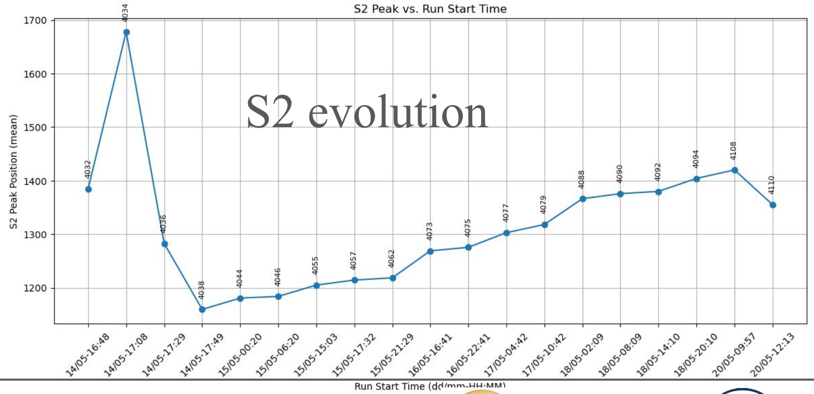
Select second pulses if first pulse (S1) in trigger window (400–500 samples)

– First pulse in range $\mu \pm 2\sigma$ from S1 fit

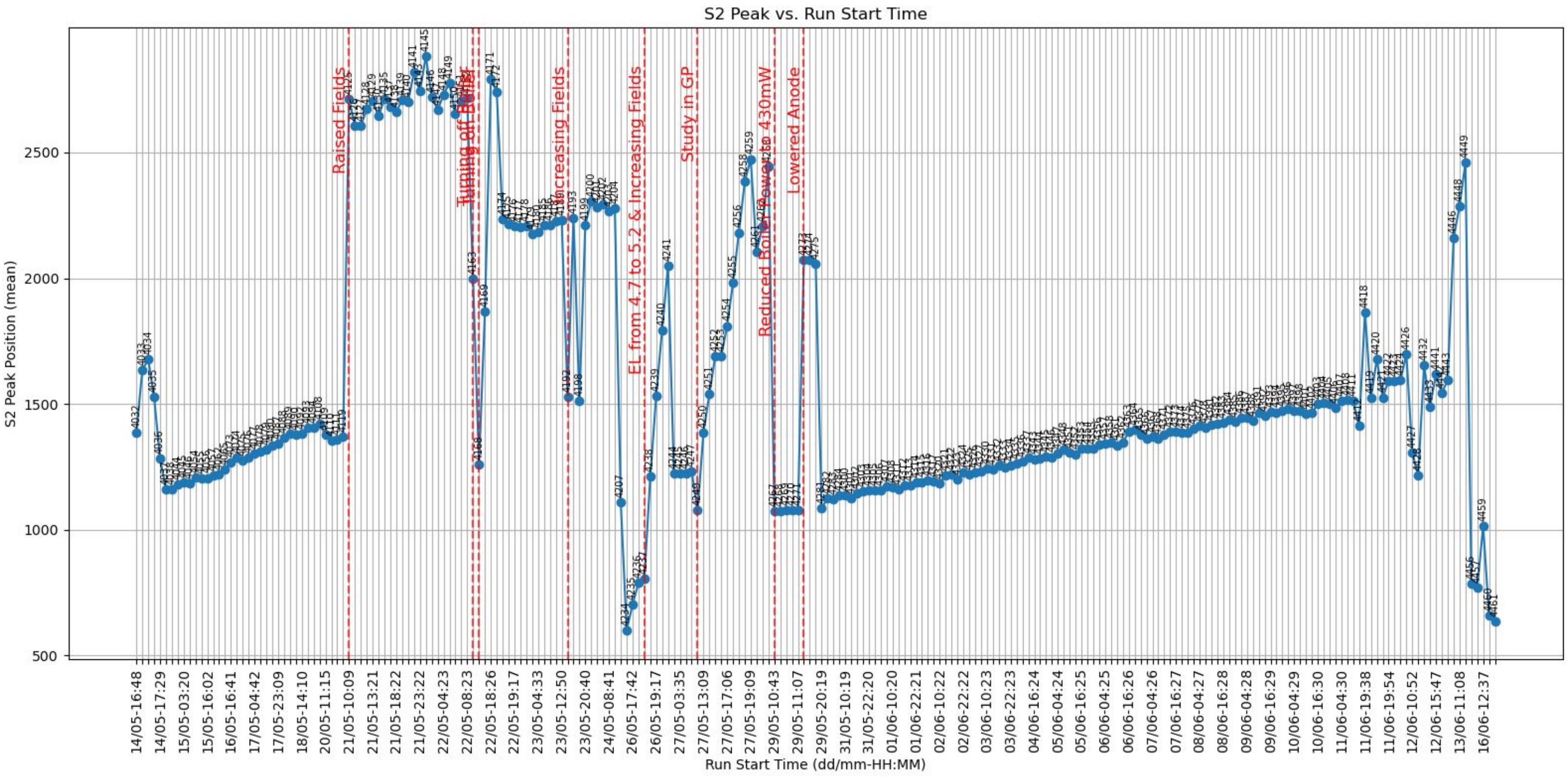
– Second pulse (S2) with fprompt < 0.1

– No saturated channels, low noise



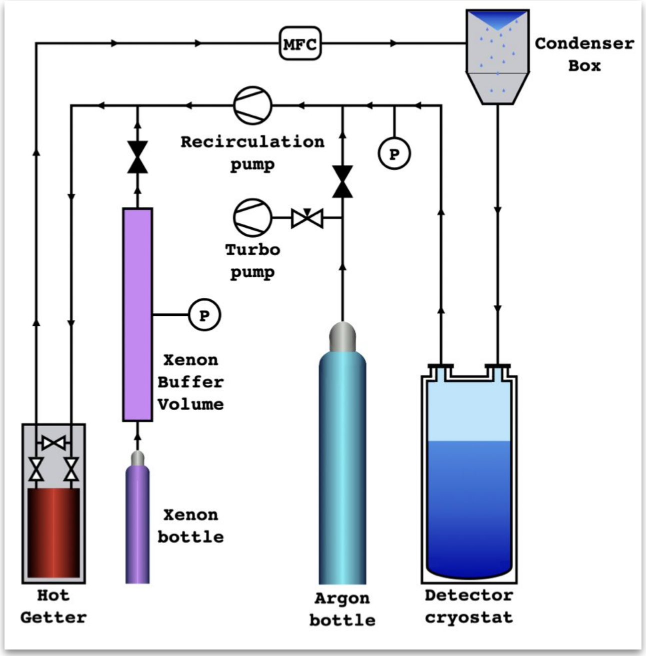


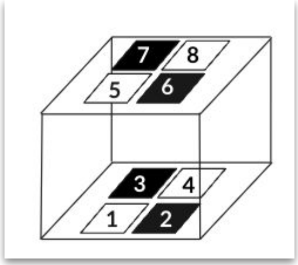
Monitoring tools for the TPC operation

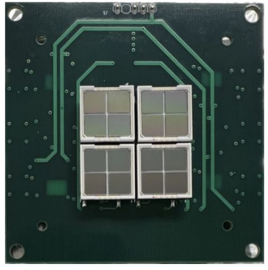


X-ArT Experimental Setup

- Single-phase liquid argon cylindrical chamber for studying scintillation in pure and Xe-doped LAr.
- 32 Hamamatsu VUV-sensitive SiPMs, arranged in top and bottom arrays:
  - *Windowless (WL)* SiPMs detect 128 nm Ar emission.
  - *With-window (WW)* SiPMs detect 175 nm Xe emission.
- The detector is housed in a custom cryogenic system that continuously purifies and re-liquefies the Ar–Xe mixture to maintain high purity.
- Controlled xenon injection enables precise tuning of the Xe concentration (from sub-ppm to tens of ppm).
- Calibration and monitoring systems ensure stable optical response and temperature control throughout data taking.





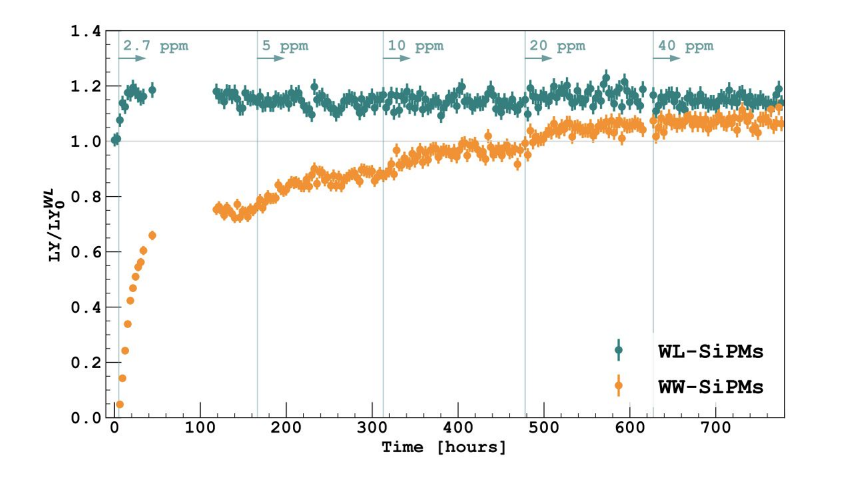


X-Art

Study the scintillation of pure and xenon-doped liquid argon

The capabilities of LAr can be extended by doping it with xenon, a technique that modifies the LAr response properties by making the scintillation process faster, increasing photon and ionization yields, and enhancing the photon attenuation length.

$\tau_{LXe} \sim 20\ ns$ *while* $\tau_{LAr} \sim 1.5\ \mu s$



Relative LY variation estimated with a 60Co calibration source

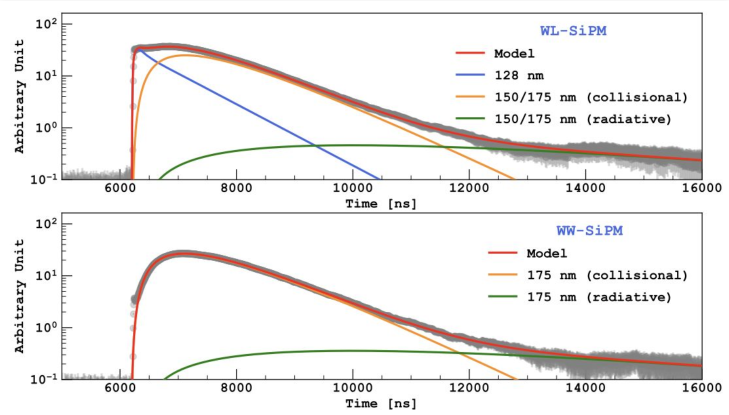
X-Art

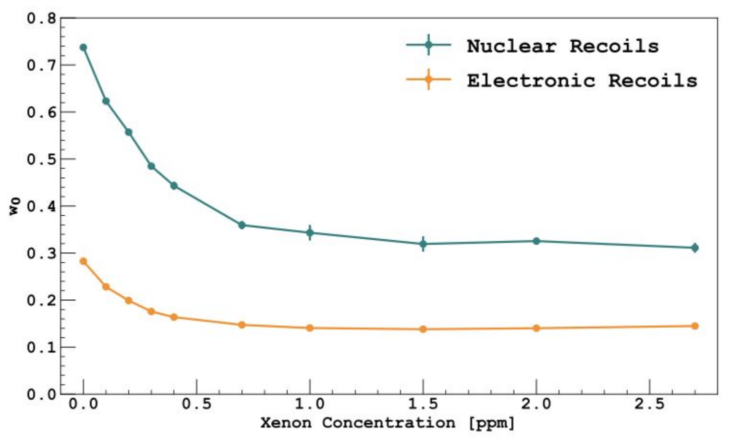
Study the scintillation of pure and xenon-doped liquid argon

- Evidence of a long-lived (>10 µs) extreme-UV (EUV) emission component in LAr scintillation.
  - → EUV photons may explain spurious electron production in noble liquid TPCs, a limiting background in light dark matter searches.

- Xe doping enhances light yield (up to +15%), but degrades pulse shape discrimination (PSD) at low energies.

(W0 is the PSD parameter)





Past activity and future plans with X-ArT

- I took part to the first data taking in the Princeton University and contributed to the data reconstruction software and data analysis

- I will participate to a new data taking starting in November at the Princeton University

- Goals:
  - Collect more statistics (LAr only)
  - Characterizing the EUV emission (longer acquisition gates - 1 ms)
  - Test hypothesis that part of this is explained by quartz fluorescence (modify the hardware setup)

1 year of PhD Activities

Conferences:
DarkSide Young Academy→ May, 2025
DarkSide Collaboration Meeting→ June, 2025
International Aeronautical Conference→ September, 2025

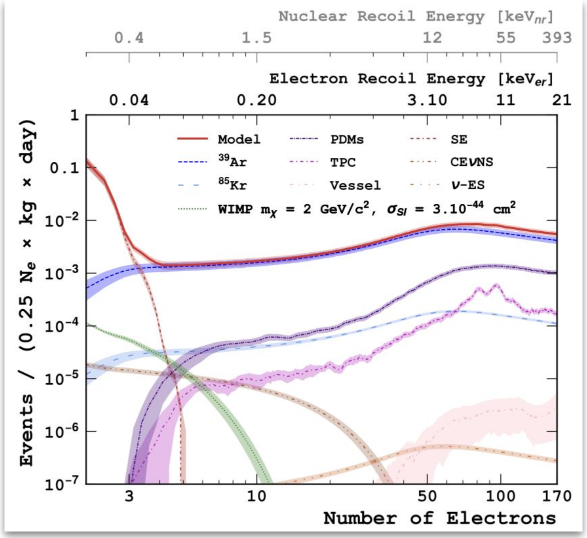
Schools:
IDPASC (Particle Physics, Astrophysics, and Cosmology)→ Paris, France (July, 2025)

Missions:
Proto-0 work related activities→ Naples (May, 2025)
Proto-0 work related activities→ Naples (August, 2025)
X-ArT related activities → Princeton University, NJ (Future 2025)

Papers:
X-ArT: *arXiv:2410.22863v2*
CUORE: *arXiv:2505.06129v2*
DarkSide: *arXiv:2507.07226v1*

Other Activities:
Outreach activity: Maker Faire Rome (Oct 16-20).
Innovative Tech Student Representative (2025-2026)

BackUp


Nuclear Recoil Energy [keV$_{nr}$]
0.4
1.5
12
55
393
Electron Recoil Energy [keV$_{er}$]
0.04
0.20
3.10
11
21
Model
^{39}Ar
^{85}Kr
WIMP m_χ = 2 GeV/c^2, σ_{SI} = 3.10^{-44} cm^2
PDMs
TPC
Vessel
SE
CEνNS
ν-ES
Events / (0.25 N_e × kg × day)
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
3
10
50
100
170
Number of Electrons