DArT in ArDM

A Dedicated Detector for ^{39}Ar Characterization in Underground Argon

Sara Tullio
On behalf of the DarkSide-20k Collaboration

LIDINE 2025
Hong Kong, 23 October 2025

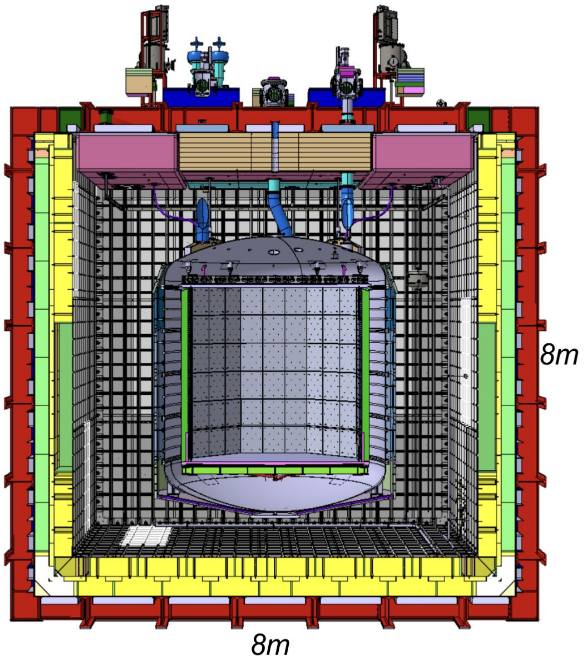
Overview

1. The **DarkSide-20k experiment**
2. The need of **Underground Argon**
3. Why **DArT in ArDM**
4. **DArT1 in test setup**
5. **DArT in ArDM status of the art**
6. Ongoing & Next steps

The DarkSide-20k experiment

Next-generation liquid argon TPC of the GADMC after DarkSide-50

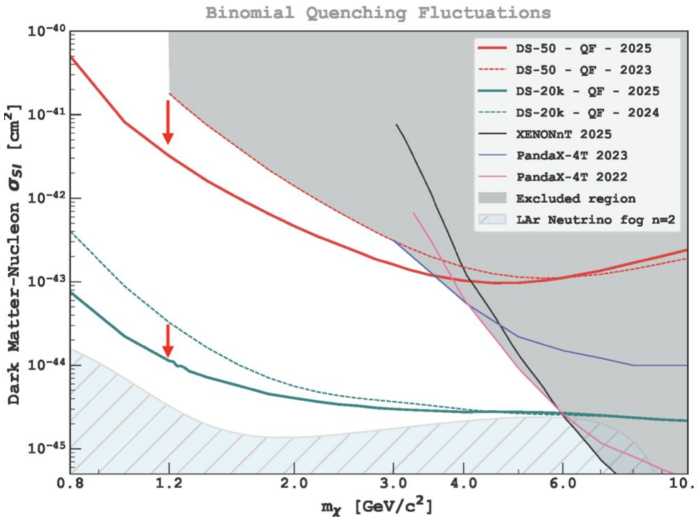
Under construction at LNGS Hall C
(3800 m w.e.)



Nested detectors structure

Outer Veto
650 tonnes of AAr, cosmogenic veto

Inner Detector:
- **TPC**
  49.7 tonnes of UAr
- **Inner Veto**
  32 tonnes of UAr, neutron veto



Good sensitivity also to low-mass WIMPs achieved through **S2-only analysis**

See A. Jamil's talk for more details on the DS-20k experiment overview

See D. Franco's talk for more details on the improved sensitivities

The need of Depleted Underground Argon

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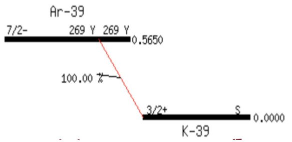
Atmospheric Argon (AAr)

→ rich in ^{39}**Ar**

$^{40}Ar + n \rightarrow 2n + {}^{39}Ar$

^{39}Ar β



half life: ~**269 y**

activity rate: ~ **1Bq/kg**

→ **100% dead time** in DS-20k
→ **limits S2-only analysis**
→ **lowers PSD reliability**

The need of Depleted Underground Argon

Atmospheric Argon (AAr) → rich in ^{39}**Ar**

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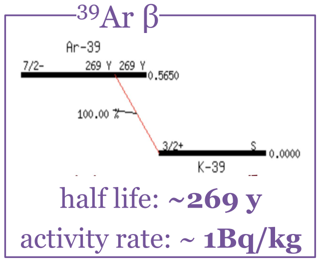

→ **100% dead time** in DS-20k
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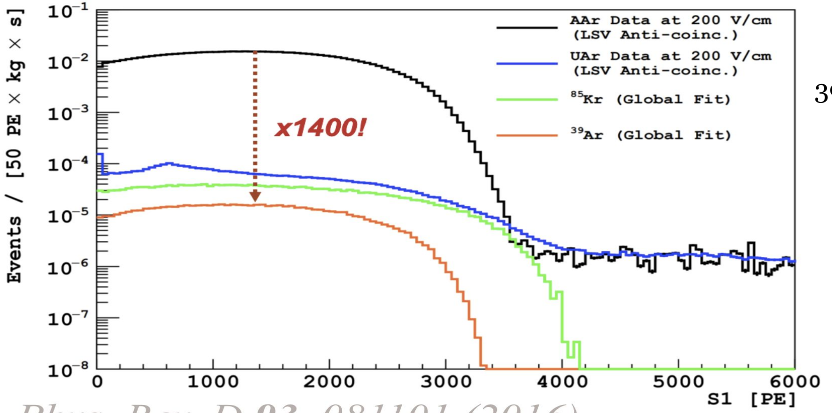
Underground Argon (UAr) → poor in ^{39}**Ar**

In DS-50 TPC:



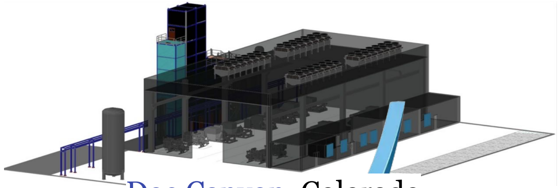
Phys. Rev. D 93, 081101 (2016)

^{39}Ar activity ~ **(1.4 ± 0.2) · 10^3 times lower than in AAr**

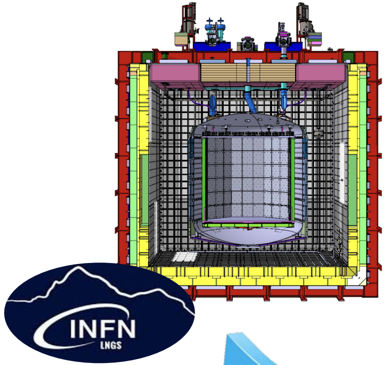
Upper limit!
The batch was probably affected by an air leak during extraction

Underground Argon procurement chain

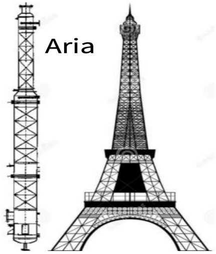
Urania facility
Industrial scale extraction plant

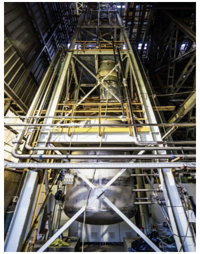


Doe Canyon, Colorado



Aria facility
Purification via chemical separation





Seruci mine, Cagliari, Sardinia, Italy

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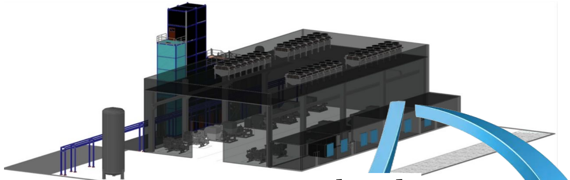

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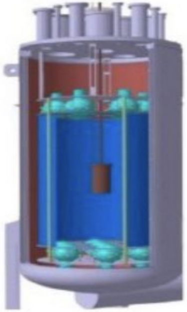
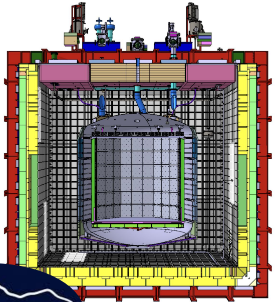
DarT in ArDM



UAr validation
Canfranc, Spain



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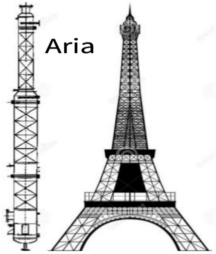

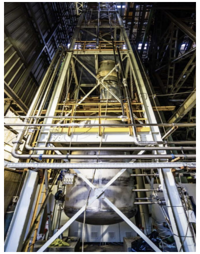

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Expected ^{39}Ar concentration ~ 10^{-19} g/g: **beyond reach of ICP-MS**

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@ Canfranc Underground Lab
2400 m.w.e

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Exploit the ArDM experiment (~ton-scale **dual-phase TPC)**
Turned into **single-phase detector → active veto for DArT**

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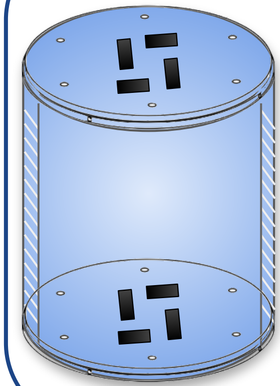
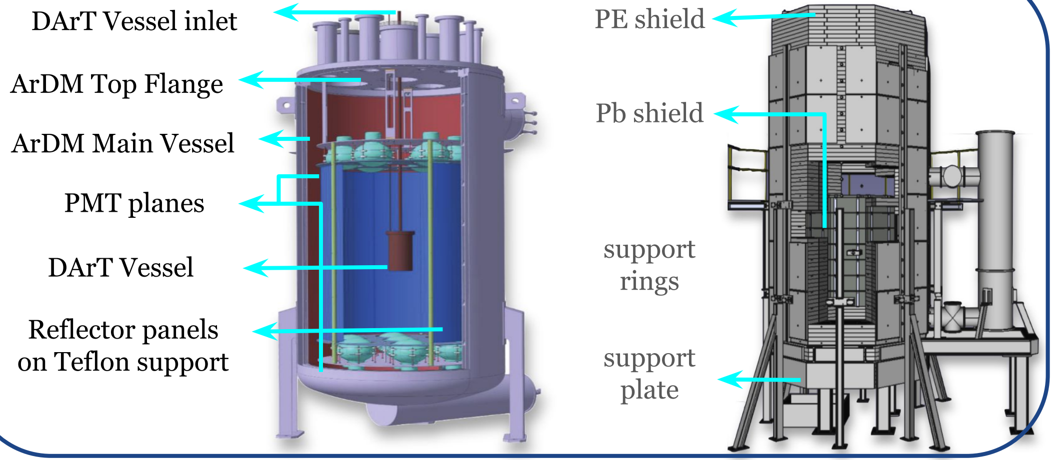
Depleted **Ar**gon **T**est **detector**



Single phase detector

- Photosensors: 8 × 1 cm² SiPMs
- 1.317 kg LAr active mass
- ESR reflectors
- TPB-coated acrylic

Argon **D**ark **M**atter active veto tank



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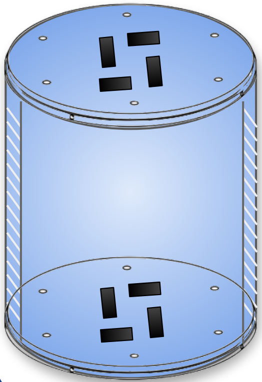

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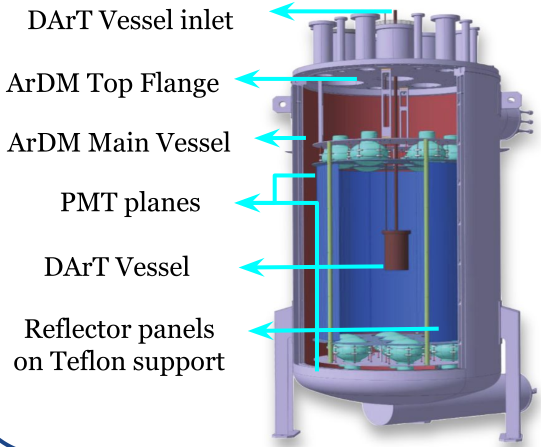

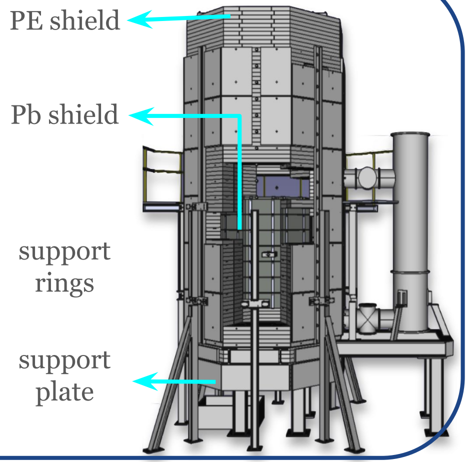

Projected Sensitivity: <1 mBq/kg , 10% statistical error in 1 week livetime

DArT1 in test setup

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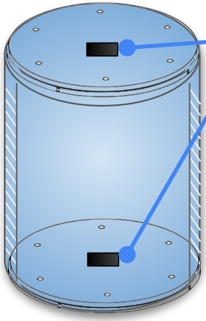
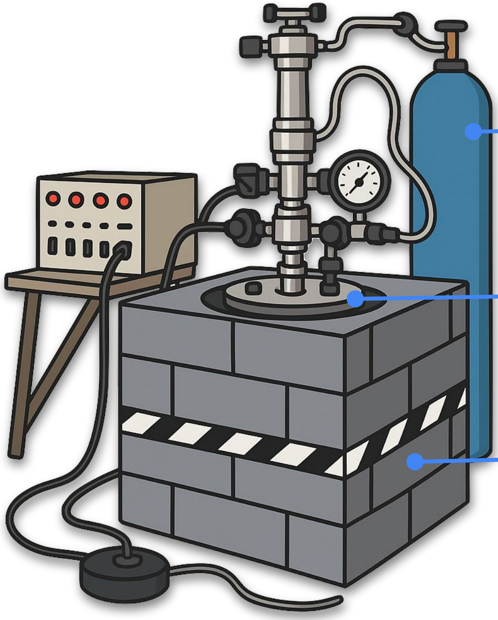
DArT1 detector



2 SiPMs only

1.317kg LAr active mass



Liquid Argon inside the chamber

Cryostat

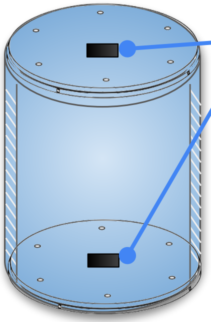
- Pressurized LN_2 (85K)

Pb shield

- flushed with Rn-free air

DArT1 in test setup

DArT1 detector



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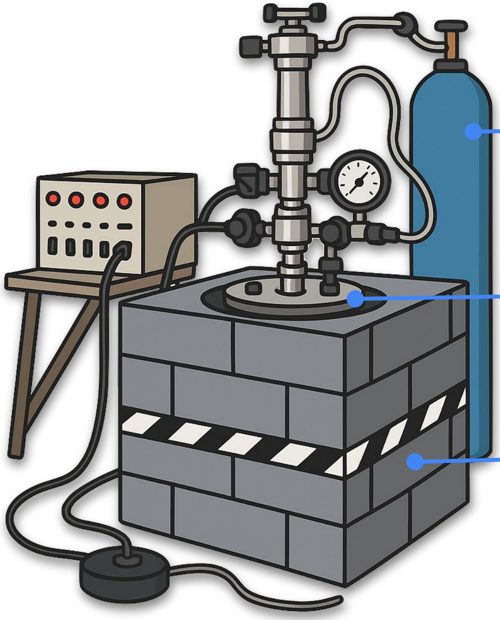

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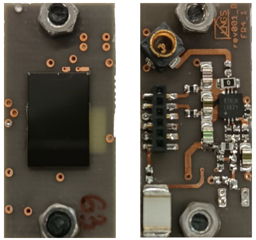
DArT SiPMs

- NUV-HD-Cryo SiPM of the DarkSide-20k batch
- Custom SiPM readout board (1 SiPM/board)
- Arlon 55NT substrate

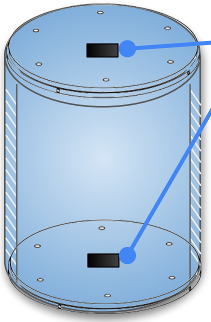


Goals of this setup

- **Continuous performance** over weeks
- **Operational conditions** for the DAQ and electronics
- **Measurement of ^{39}Ar** activity in atmospheric Ar

DArT1 in test setup

DArT1 detector



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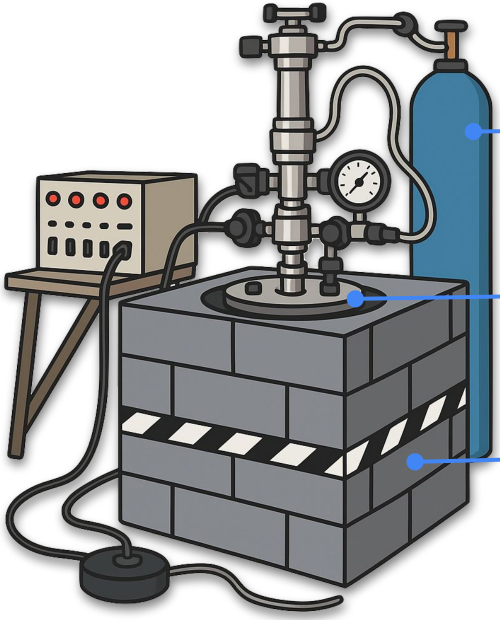

DArT1 in test setup will **operate in parallel** to the main detector DArTinArDM

Enabling **first UAr order 0 quality check** before the filling of the main detector

+

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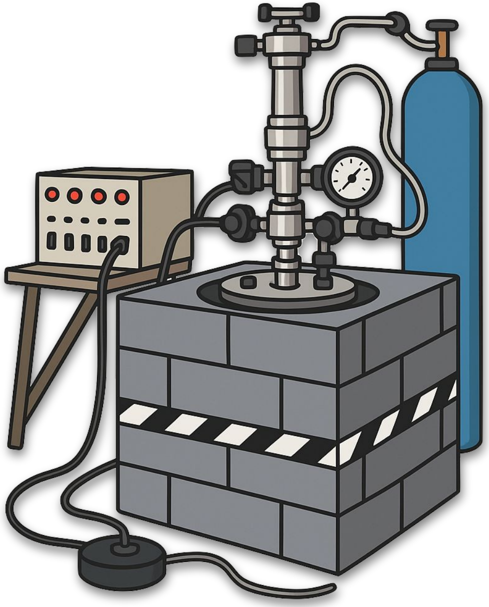
DArT1 in test setup - Run Overview



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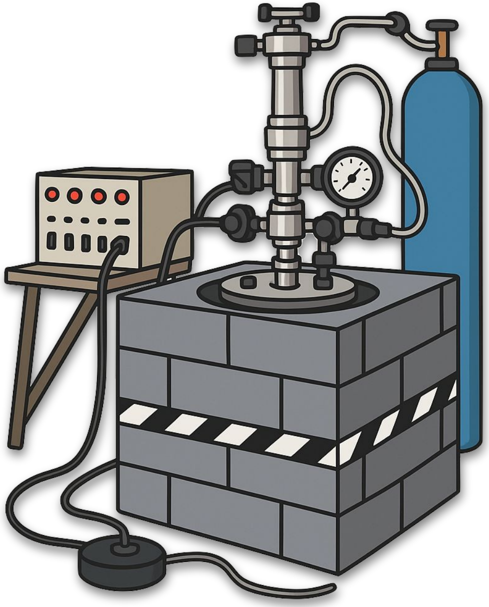

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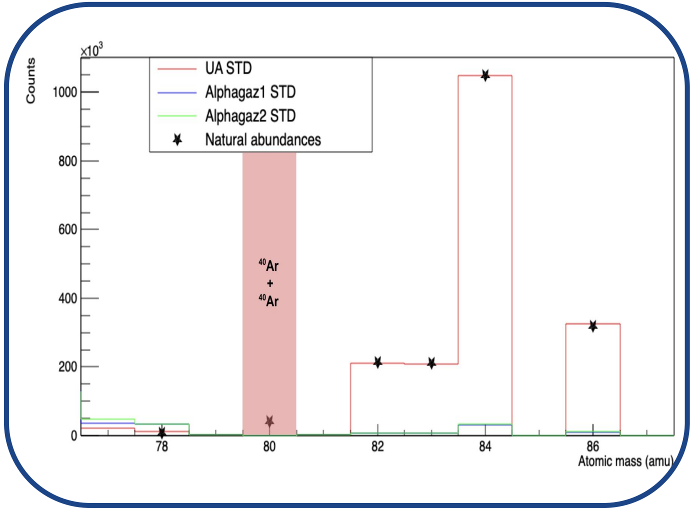
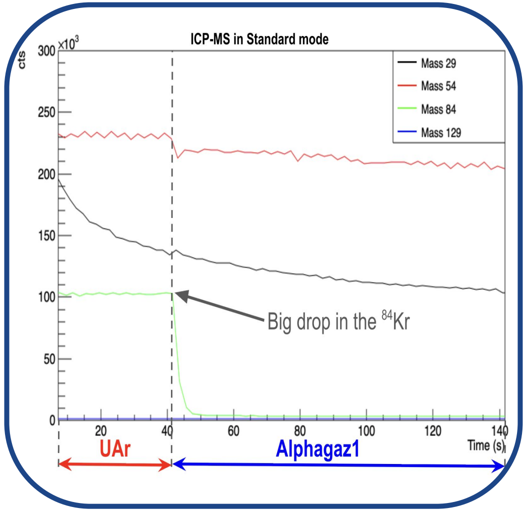
- **Atmospheric Argon runs** (**Argon 6.0**, 1ppm impurity level)

- **Underground Argon runs** (from DarkSide-50)

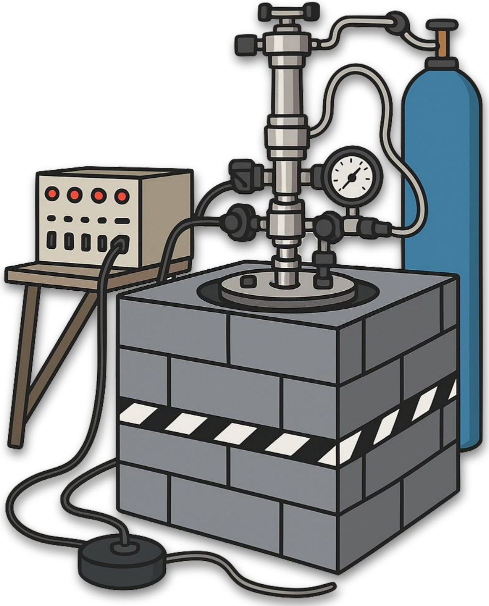
ICP-MS analysis, wrt AAr Argon 5.0/6.0 (10/1ppm impurity level):



^{85}Kr contamination confirmed
(all the isotopes at their natural abundances)



Only in the UAr batch!



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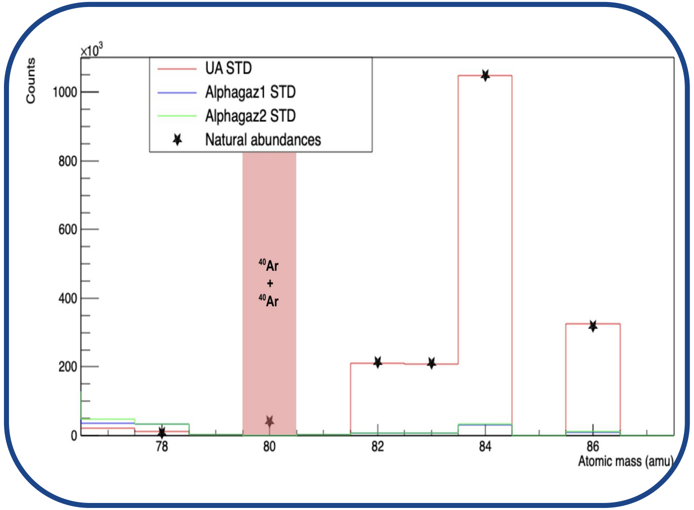

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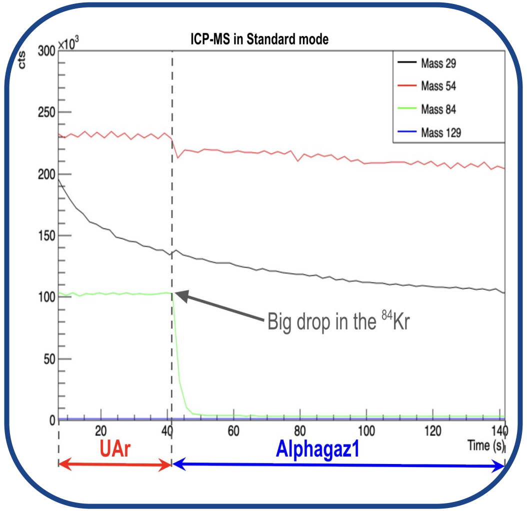

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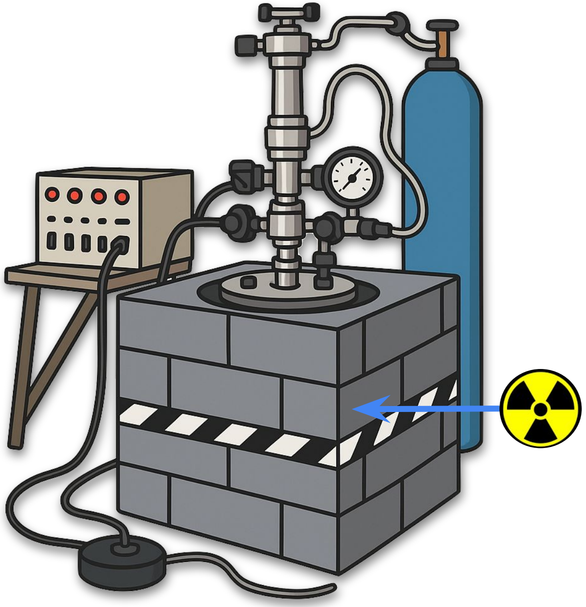

- **137-Cs runs** ^{137}**Cs** radioactive source (27kBq) **outside the cryostat**, at **mid-height**

DArT1 in test setup - full simulation chain

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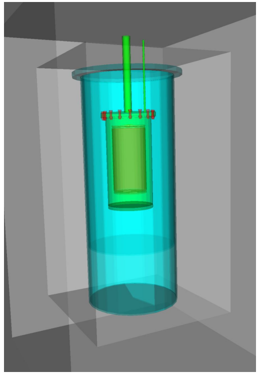
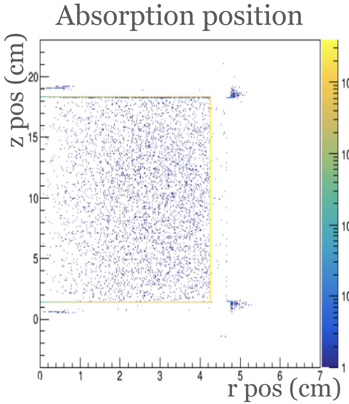
Optical Simulation

- **Energy deposition** in the active volume
- Argon scintillation
- Photon tracking till absorption





G4DS package
Agnes et al 2017 JINST 12 P10015

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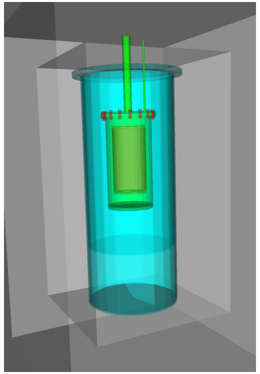
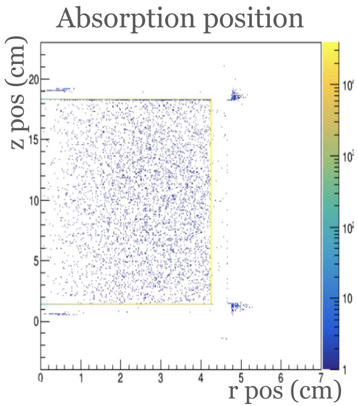
- Simulation of SiPMs **electronic response**
- Simulation of DAQ effect
- Waveform generation





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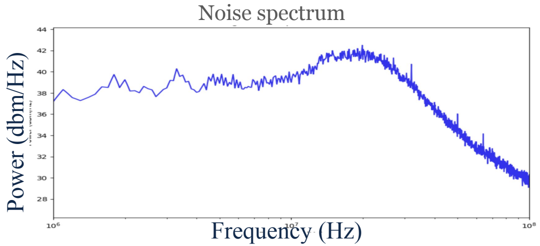

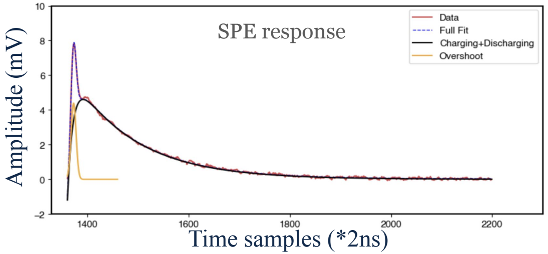

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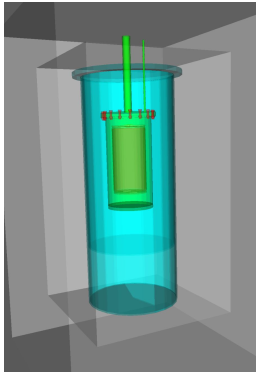
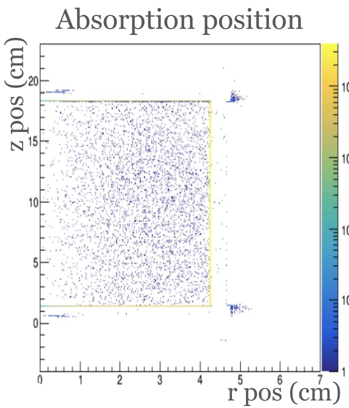
Reconstruction

- **Analysis** of the simulated **waveforms** as for the real ones





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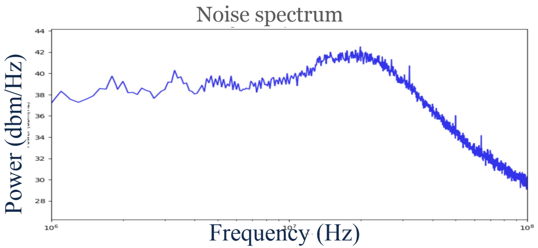
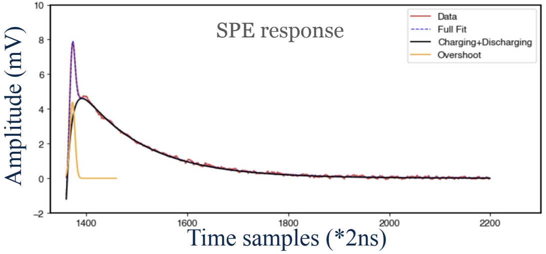
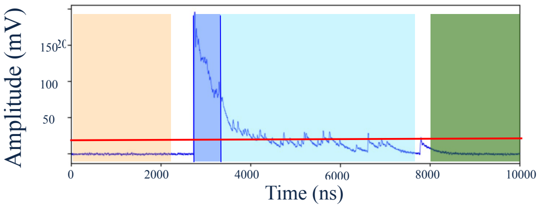
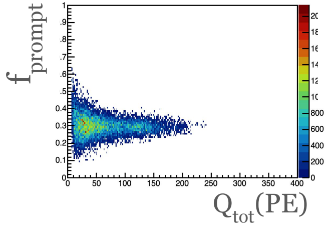
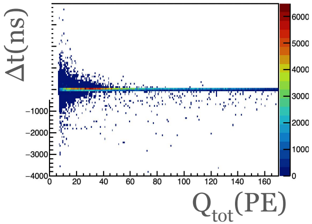






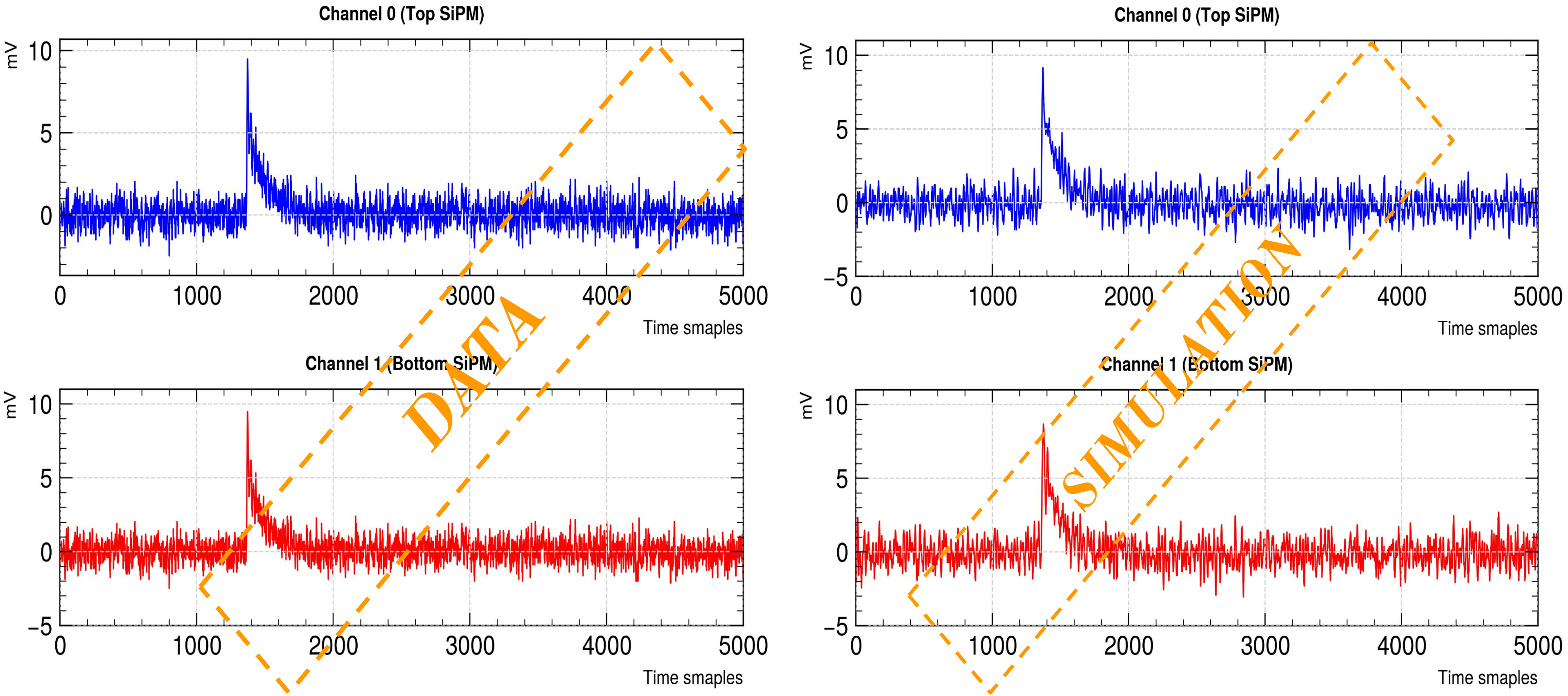




DArT1 in test setup - full simulation chain

Good agreement between data and simulations

- Waveform level



DArT1 in test setup - full simulation chain

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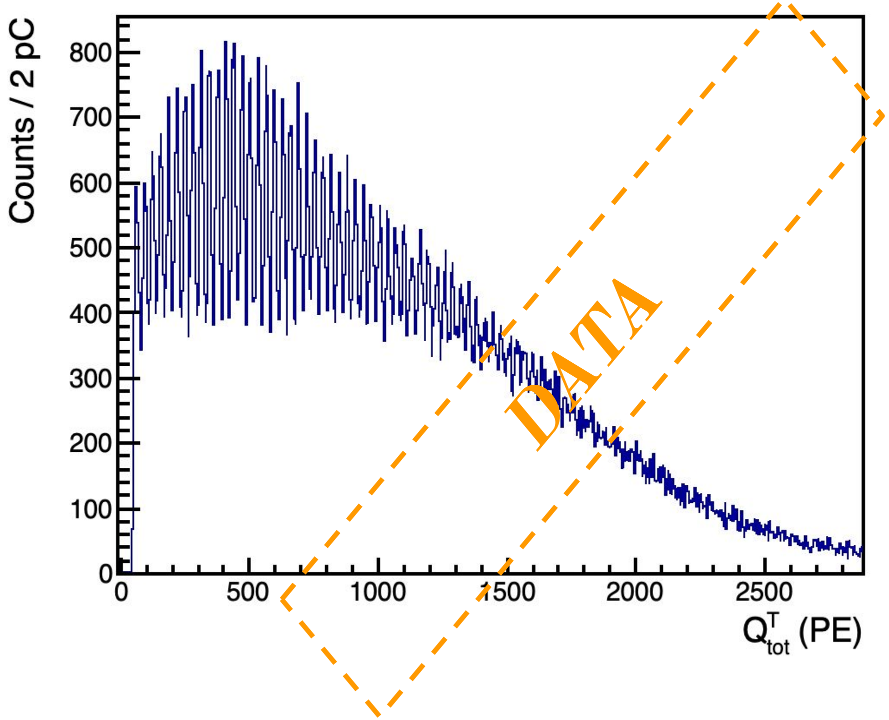
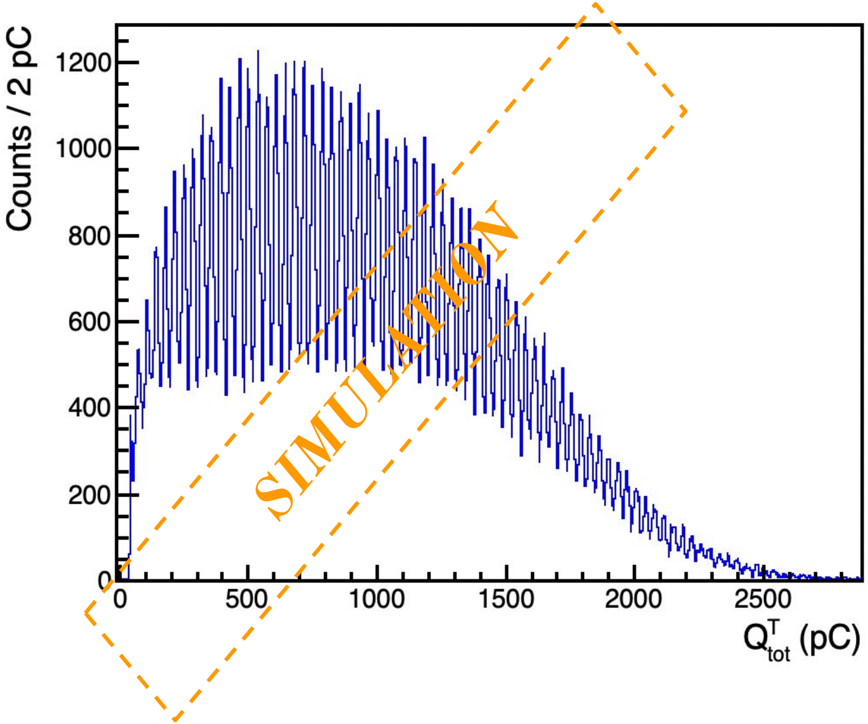
- Finger plots level



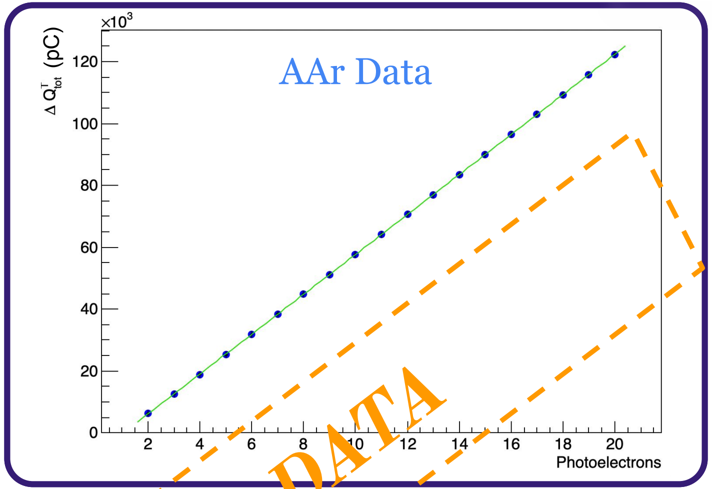


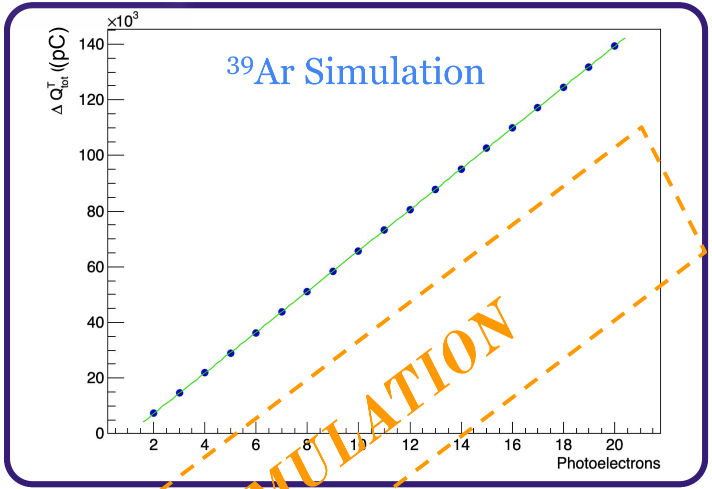
DArT1 in test setup - full simulation chain

Good agreement between data and simulations

- Calibration level

$$Q^{T,B}_{tot} = a + b \times N + c \times N^2$$





Ch.	a (pC)	b (pC/PE)	c (pC/PE²)	σ_2 (pC)
TOP	-31.88 ± 0.11	**31.34 ± 0.04**	0.009 ± 0.001	8.01 ± 0.01
BOT	-32.14 ± 0.14	**31.36 ± 0.03**	0.008 ± 0.001	7.9 ± 0.01

Ch.	a (pC)	b (pC/PE)	c (pC/PE²)	σ_2 (pC)
TOP	-34.70 ± 0.30	**33.20± 0.07**	0.002 ± 0.003	8.4 ± 0.11
BOT	-34.83 ± 0.33	**33.16 ± 0.06**	0.004 ±0.004	8.02 ±0.14

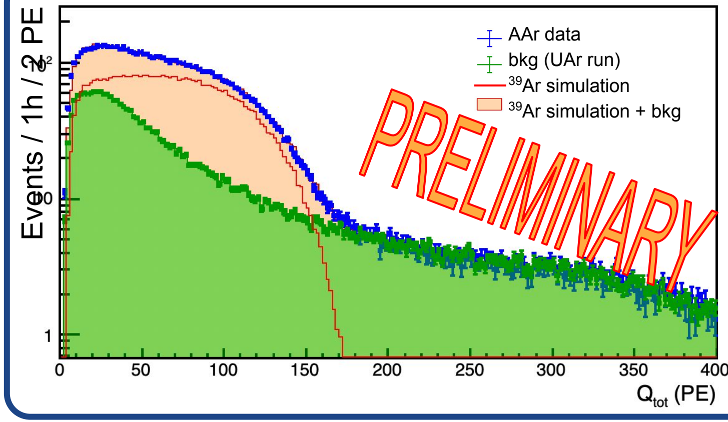
DArT1 in test setup - ^{39}Ar activity in AAr

Draft
in preparation

$$A_{AAr} = \frac{N(AAr_{run}) - N(UAr_{run}) \cdot f_{AAr/UAr}}{\varepsilon_{AAr} \cdot t_{AAr}} + a_{UAr} \cdot M_{LAr}$$

$$\mathbf{a_{AAr} = A_{AAr} / M_{LAr}}$$

- $N(AAr_{run})$: events after **cuts** of the AAr run
- $N(UAr_{run})$: events after **cuts** of the UAr run
- $f_{AAr/UAr}$: ratio of AAr and UAr time acquisition
- ε_{AAr}: total ^{39}Ar efficiency from simulation
- t_{AAr}: AAr run time
- a_{UAr}: UAr specific activity
- M_{LAr}: Liquid Argon Mass in DArT1 detector



DArT1 in test setup - ^{39}Ar activity in AAr

Draft
in preparation

$$A_{AAr} = \frac{N(AAr_{run}) - N(UAr_{run}) \cdot f_{AAr/UAr}}{\varepsilon_{AAr} \cdot t_{AAr}} + a_{UAr} \cdot M_{LAr}$$

$$\mathbf{a_{AAr} = A_{AAr} / M_{LAr}}$$

- $N(AAr_{run})$: events after **cuts** of the AAr run
- $N(UAr_{run})$: events after **cuts** of the UAr run
- $f_{AAr/UAr}$: ratio of AAr and UAr time acquisition
- ε_{AAr}: total ^{39}Ar efficiency from simulation
- t_{AAr}: AAr run time
- a_{UAr}: UAr specific activity
- M_{LAr}: Liquid Argon Mass in DArT1 detector

Other experiments outcomes

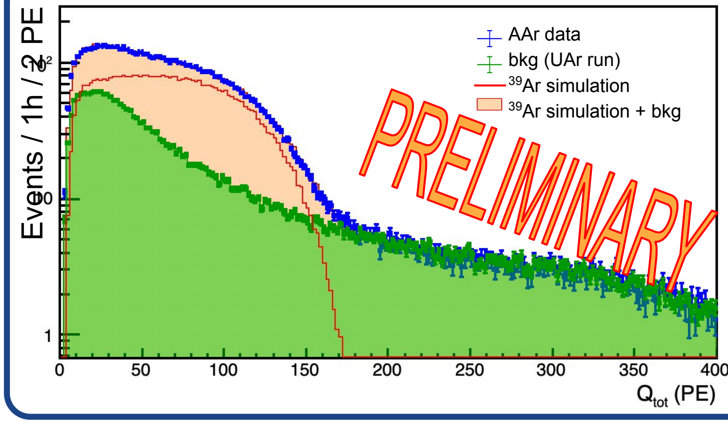
DEAP3600: aAAr= 0.96 ± 0.03 Bq/Kg
P. Adhikari et al., Eur. Phys. J. C 83, 642 (2023).

WARP: aAAr= 1.01 ± 0.04 Bq/Kg
P. Benetti et al., Nucl. Instrum. Meth. A 574, 83 620 (2007).

ArDM: aAAr= 0.96 ± 0.05 Bq/Kg
J. Calvo et al., JCAP 12, 011 (2018).

Systematic uncertainties

type	variation	uncertainty on a_{AAr}(%)
asymmetry factor f_B	±0.05	0.04
threshold cut in mV	±3mV	1.1
threshold cut in $Q_{tot}^{T,B}(PE)$	±0.1	0.02
cut in max $Q_{tot}(PE)$	±20	0.01
nuclear recoil background		
M_{LAr}		1.6
total		1.94

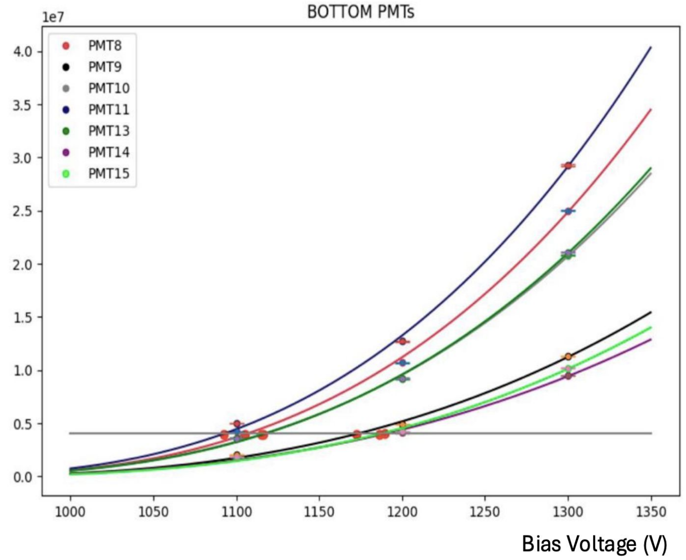


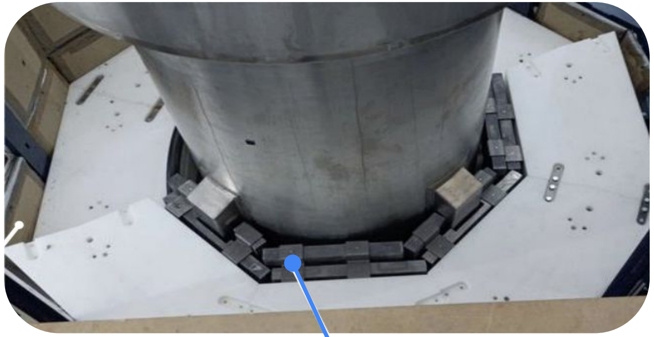
$$\mathbf{a_{AAr} = (xx \pm 0.025\ (stat.) \pm 0.019 (syst.))\ Bq/kg}$$

ArDM - refurbishment @LSC

Turned into a single-phase detector

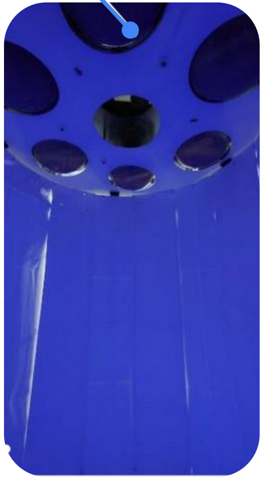
- New field cage
- New Lead shield (~6t)
- PMTs gain equalization





PMT Plane with reflector coated with TPB

Pb Shield

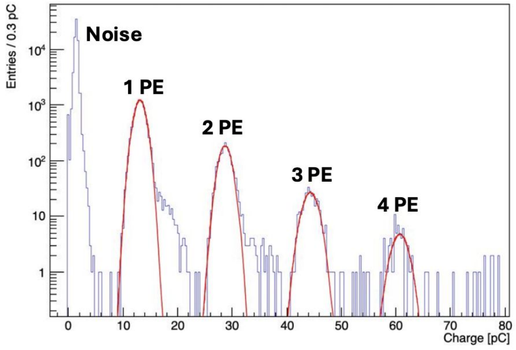


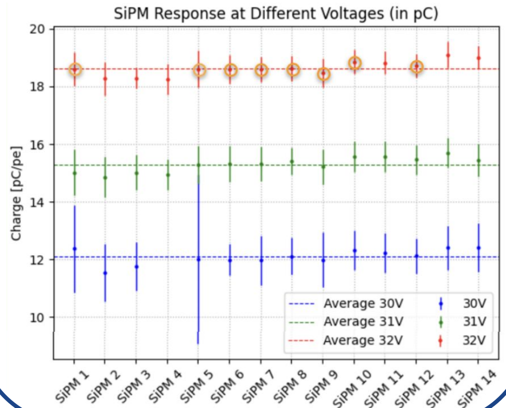
PE Shield

DArT2 - construction

DArT2 - construction

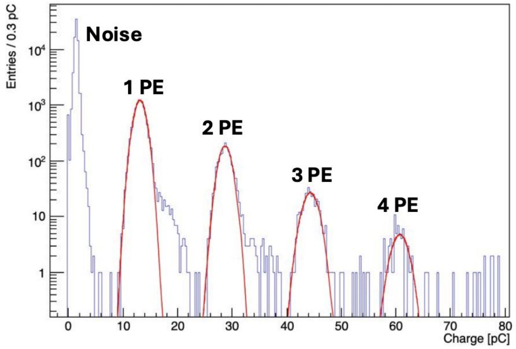
Characterization and selection of SiPMs

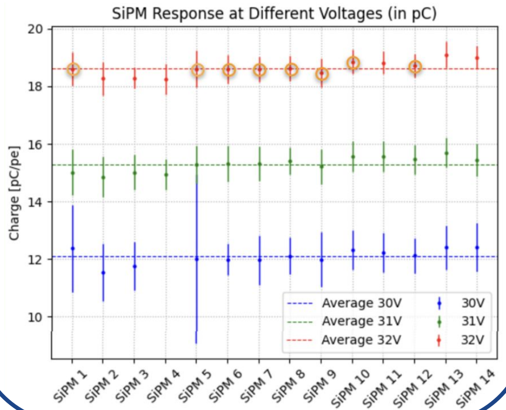




DArT2 - construction

Characterization and selection of SiPMs

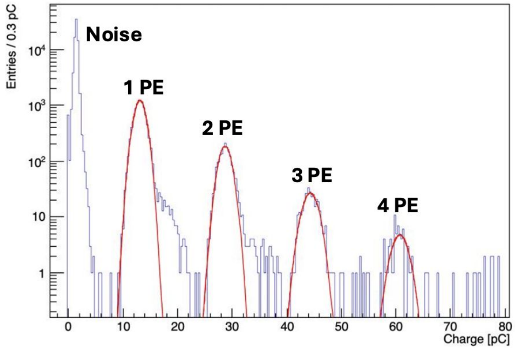


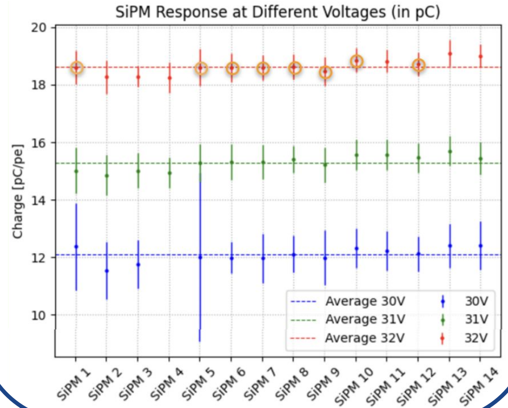


Cleaning

DArT2 - construction

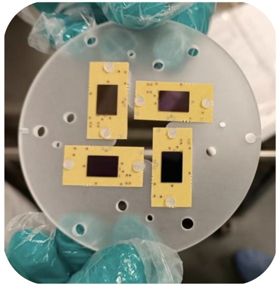
Characterization and selection of SiPMs

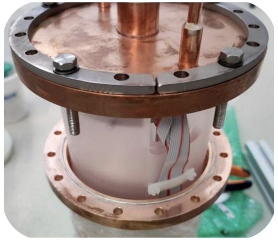




Cleaning

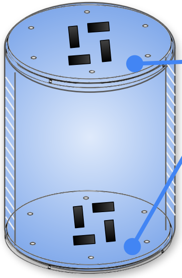
Assembly





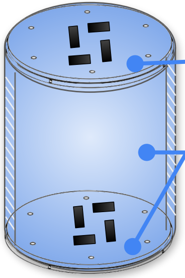
DArT2 - characterization in cold

DArT2 - characterization in cold



8 SiPMs

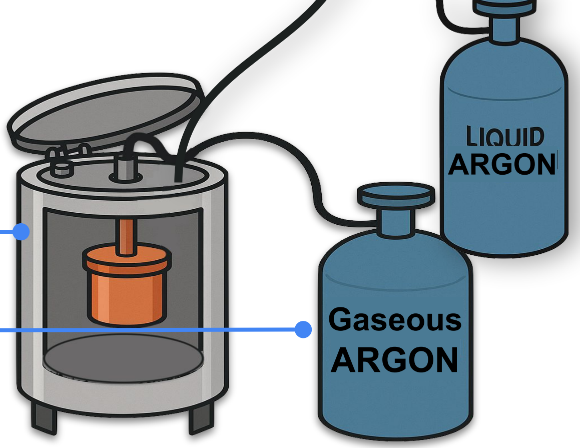
DArT2 - characterization in cold



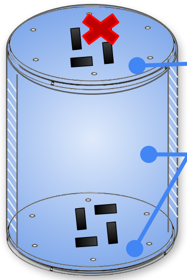
8 SiPMs

Opened cryostat
- LAr (87K)

GAr condensed inside the chamber



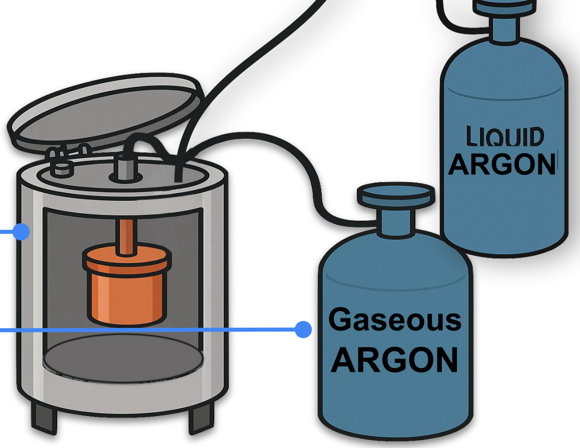
DArT2 - characterization in cold



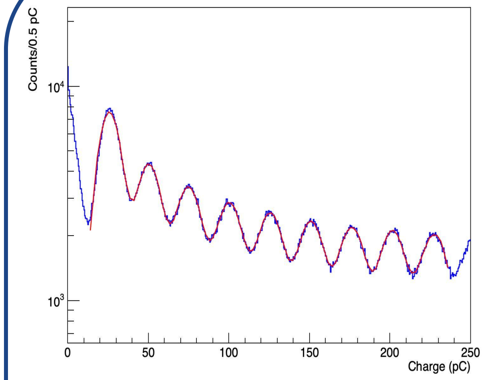
8 SiPMs,
1 broken

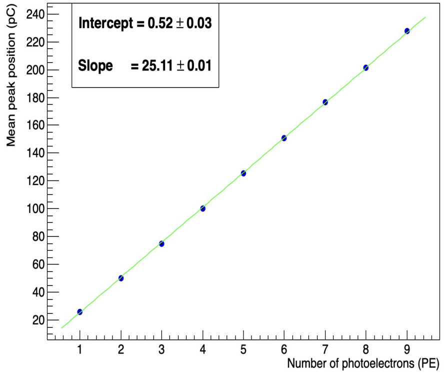
Opened cryostat
- LAr (87K)

GAr condensed inside the chamber



SiPMs Calibration and Gain measurement

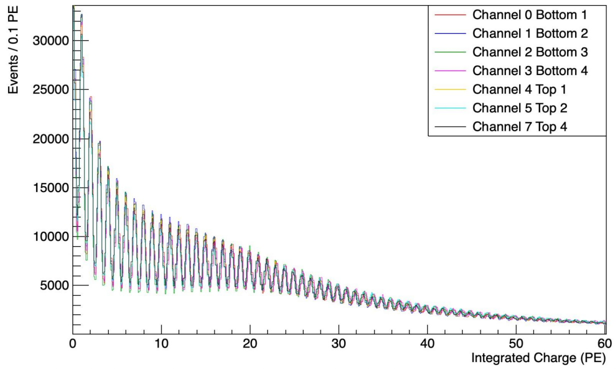




Gain at 3 VoV (ADCc/PE)
25.11 ± 0.01
24.6 ± 0.01
25.44 ± 0.01
25.18 ± 0.01
25.21 ± 0.01
25.55 ± 0.01
25.21 ± 0.01
25.43 ± 0.01

The gain variation among all SiPMs is less than 0.04%.

Channels equalization

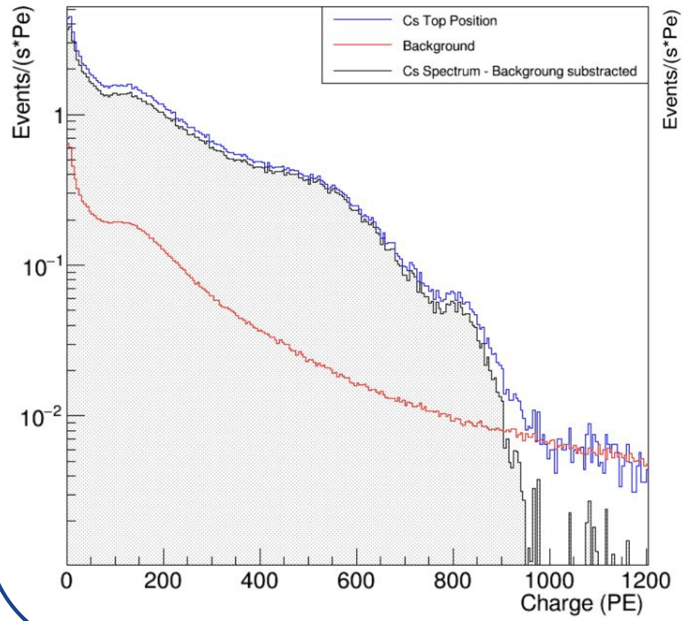


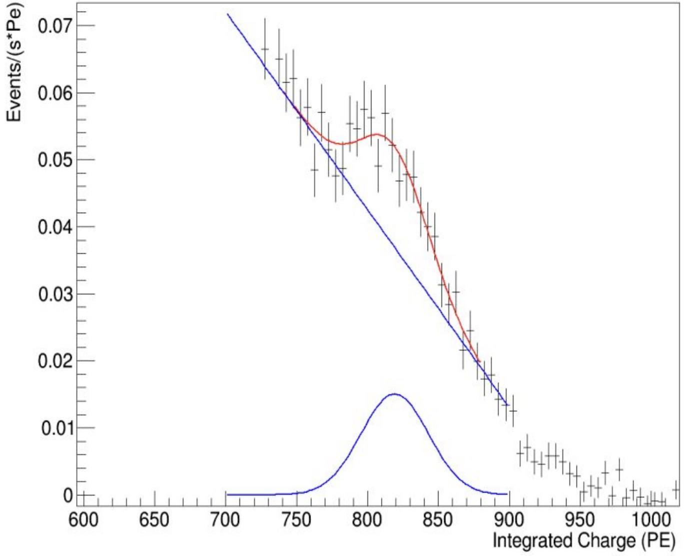
The photoelectron peaks are aligned for all the channels

DArT2 - characterization in cold

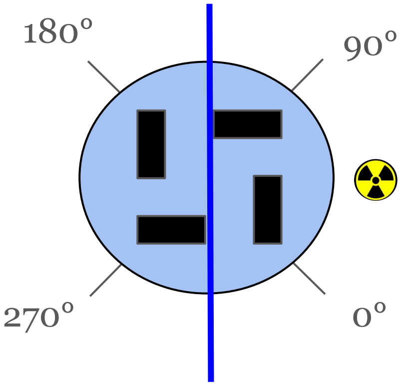
^{137}Cs source Data

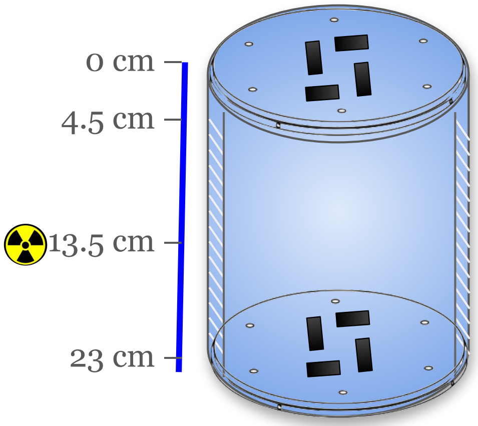
Light Yield evaluation





LY= 1.23 ± 0.01 PE/keV





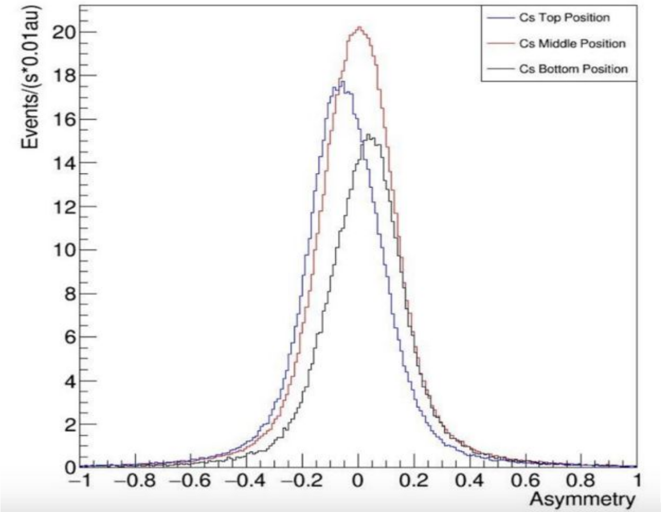
> 4× light yield increase achieved by quadrupling the number of photosensors (vs DArT1)

DArT2 - characterization in cold

^{137}Cs source Data

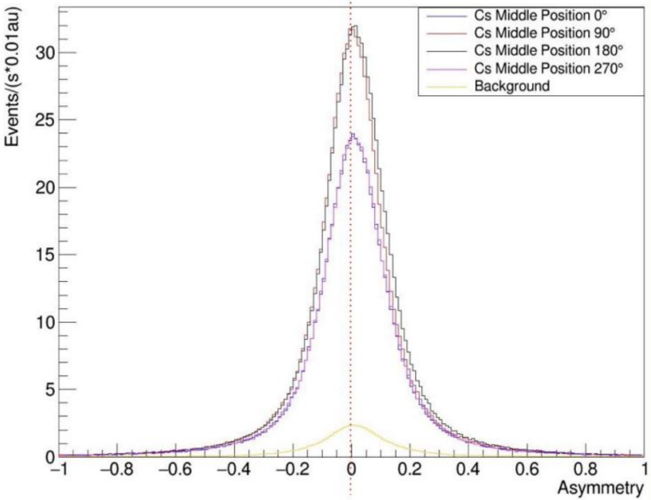
Position reconstruction evaluation

Top-Bottom Asymmetry

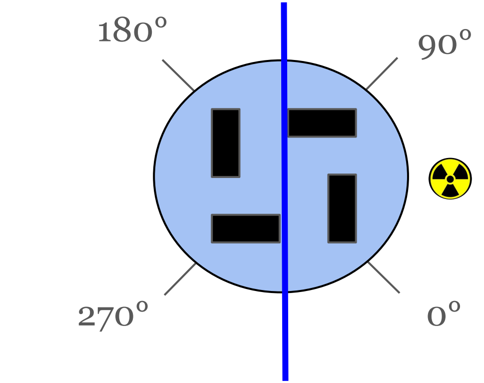


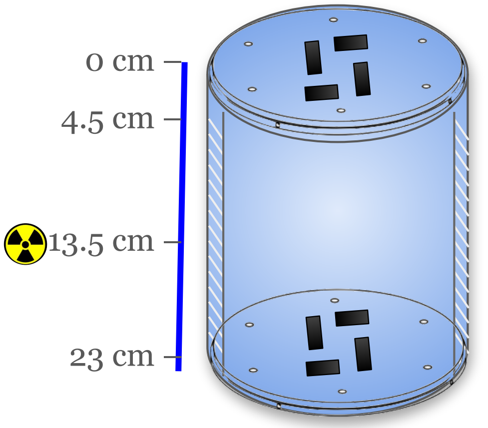
$$TBA=(Q^T_{tot} - Q^B_{tot})/(Q^T_{tot} + Q^B_{tot})$$

Left-Right Asymmetry



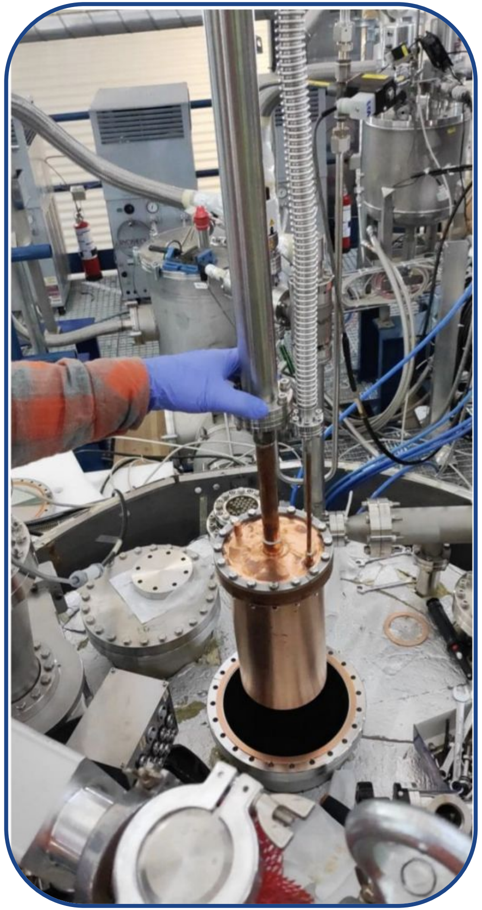
$$LRA=(Q^L_{tot} - Q^R_{tot})/(Q^L_{tot} + Q^R_{tot})$$





Good vertical (top–bottom) position discrimination,
but poor horizontal (right–left) resolution.

DArT2 - integration in the ArDM volume



DArT in ArDM is now **ready** to be filled and **take data**

Ongoing and next steps

DArT1 – Test Setup
- Finalizing the background simulation
- Finalizing the publication on **DArT1 in test setup**

DArT2 – Cold Test
- Define detector optical plane geometry and cold test setup in Geant4
- Develop calibration simulation (evaluate possible sources)
- Electronics simulation for 7 channels

DArT in ArDM
- Cool down and filling the ArDM main volume
- First UAr (from DarkSide-50) run of DArT in ArDM
- First batch of UAr from Urania expected by the beginning of 2026

Thank you for your attention!

LIDINE 2025
Hong Kong, 23 October 2025

Backup

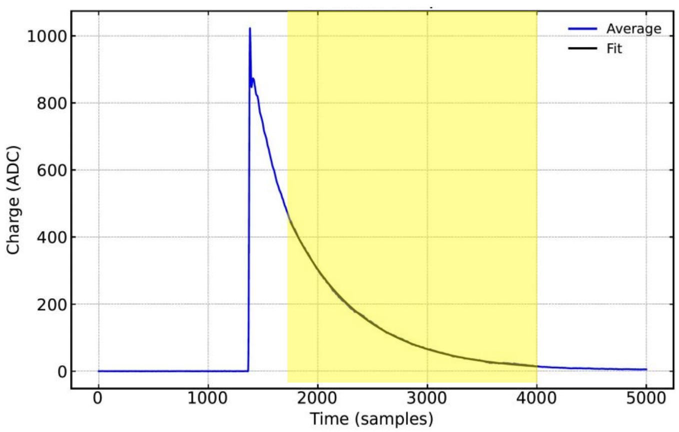
LIDINE 2025
Hong Kong, 23 October 2025

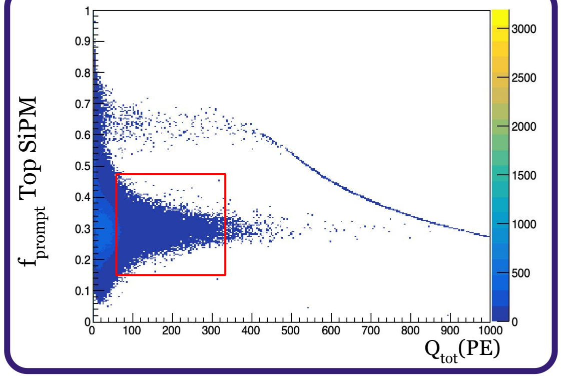
DArT1 in test setup - Purity monitoring

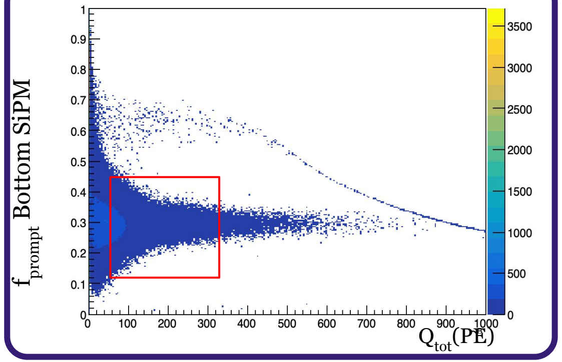
Triplet lifetime (τ_{slow}) → purity monitor
(any LN2 contamination shortens the slow component of argon scintillation)

Measuring τ_{slow} during a subrun:

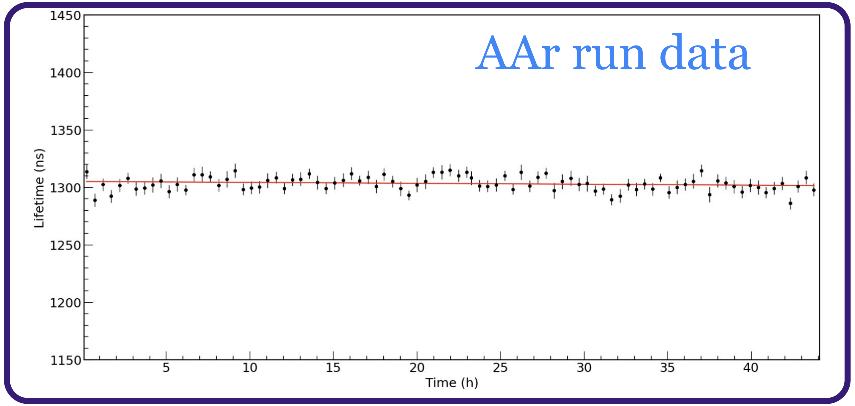
1. Select **beta events**.
2. Calculate the **average waveform**
3. **Fit the tail** (from 3.4 to 8 us) of the **waveform** with an **exponential decay**





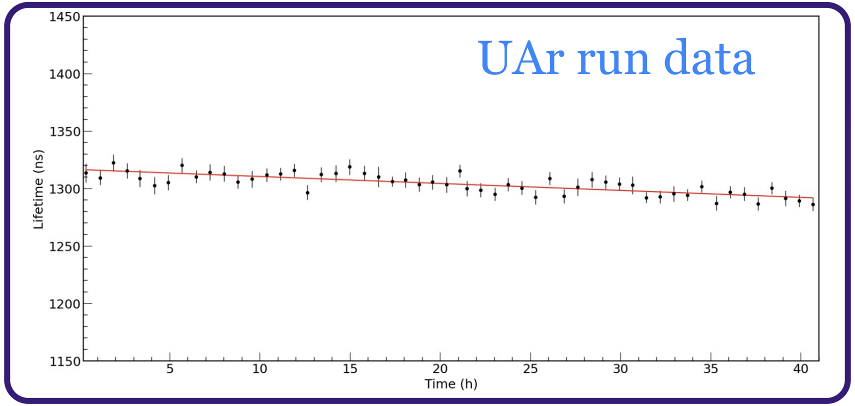


DArT1 in test setup - Purity monitoring



(1.31 ± 0.01) μs - t(h)· (0.08 ± 0.05) ns/h

$\Delta\tau_{slow}$ (AAr run) ~ 4.7 ns → (0.36%)

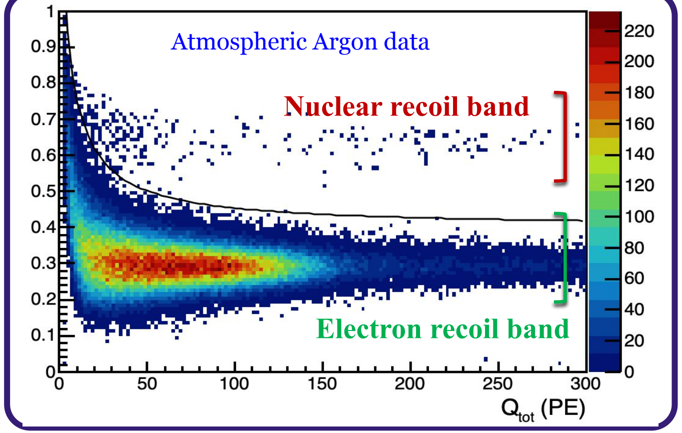


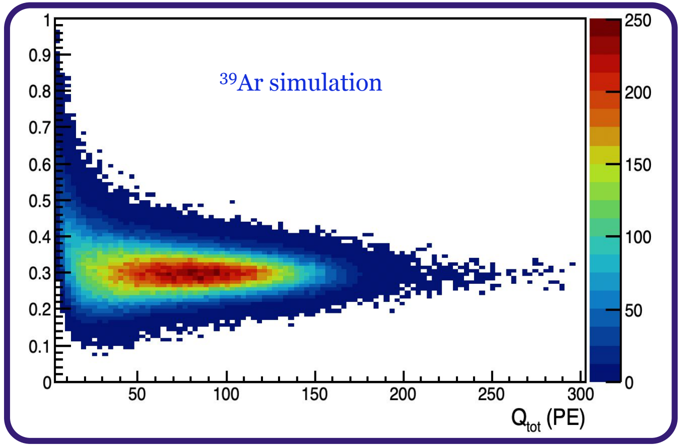
(1.32 ± 0.01) μs - t(h) · (0.60 ± 0.07) ns/h

$\Delta\tau_{slow}$ (UAr run) ~ 21.7 ns → (1.7%),

→ LN2 contamination below the ppm level

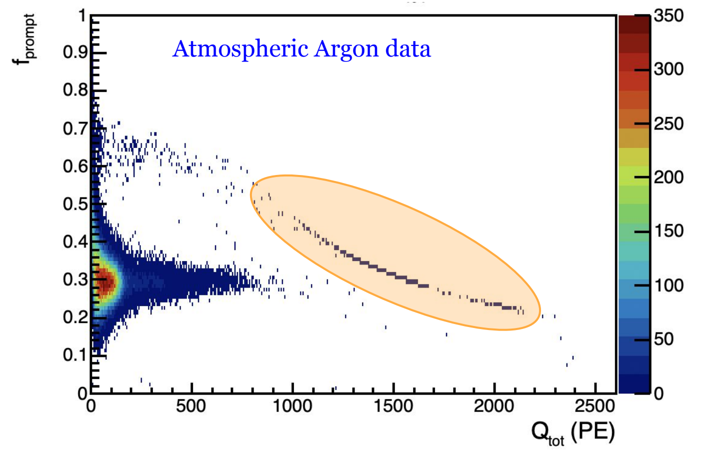
DArT1 in test setup - Pulse Shape Discrimination





Prompt window = 400 ns

Beta-events cut:
$f_{prompt} < (0.4 + 0.95 / (1 + Q_{tot}(PE)/6))$

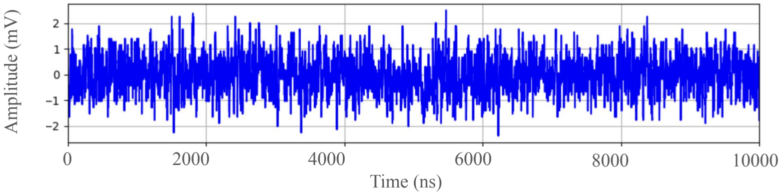


Q_{tot} > 400-500 PE in the NR band
The f_{prompt} distribution for nuclear recoils becomes **distorted** due to **electronic saturation** effects.

DArT1 in test setup - Noise spectrum

Selection of noise waveforms:

- set a **threshold below the RMS** of the noise
- waveforms Pulse Height < threshold selected as noise

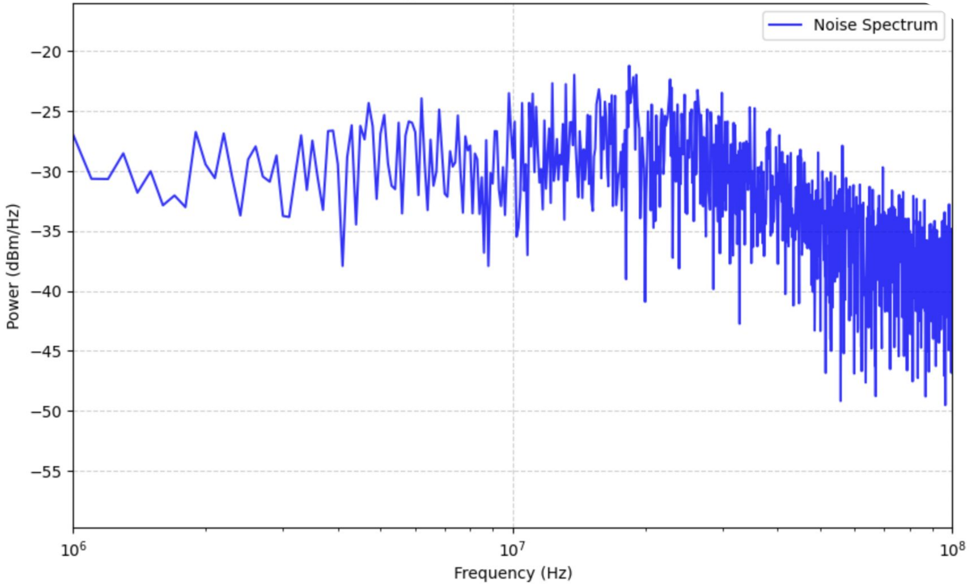


Noise power spectrum estimation:

- selection of a sample of noise waveforms
- calculation corresponding noise power spectra

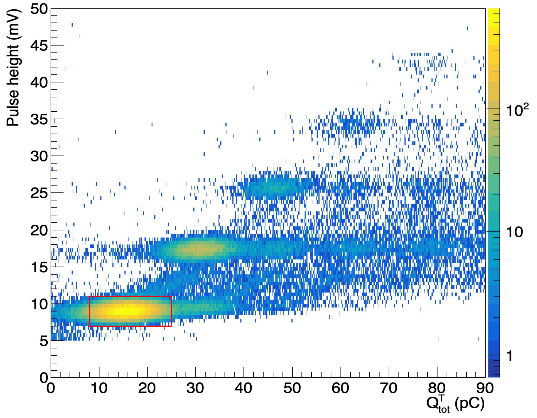
$$P(\nu)=\log_{10}(|FFT_{norm}(wf)|^2)$$

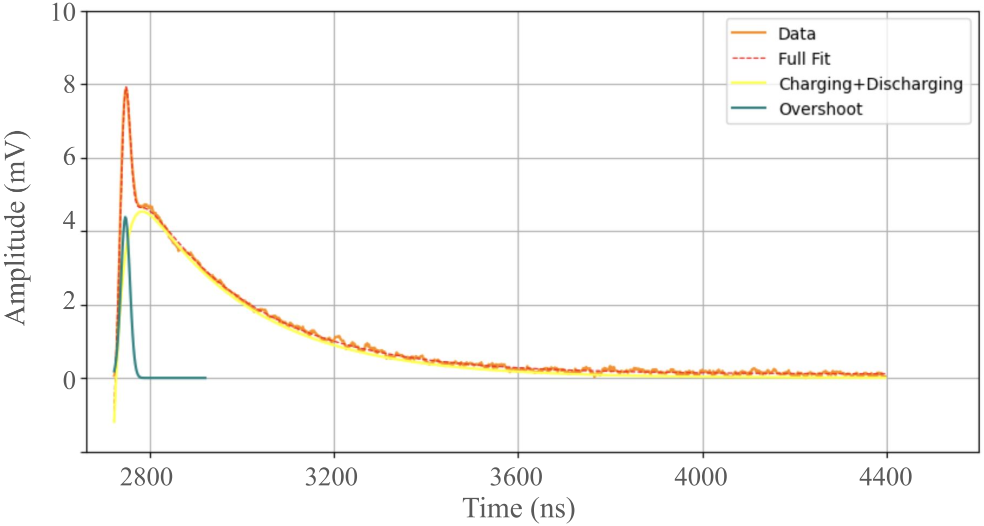
→ average noise power spectrum obtained



DArT1 in test setup - SinglePhotoElectron response

Selection of SPE waveforms:
- $Q_{tot}^{T,B} < 25$ pC
- 7 mV < Pulse Height < 10.5 mV





SinglePhotoElectron template estimation:
- Average of a sample of SPE wfs from data
- Fit of the SPE function:

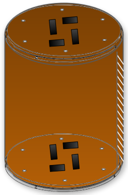
$$\mathrm{SPE}(t) = A_{\mathrm{SPE}}\left(\underbrace{e^{\frac{(t_0-t)}{t_2}}}_{\text{Discharging}} - \underbrace{e^{\frac{(t_0-t)}{t_1}}}_{\text{Charging}}\right) + \underbrace{A_1 e^{\frac{(t-m)^2}{2\sigma^2}}}_{\text{Gaussian overshoot}}$$

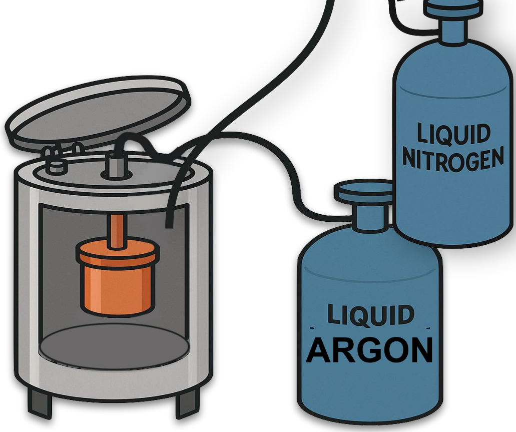
- start time of the pulse: t_0 = 2700 ns
- charging time of the SiPM: t_1 = (18 ± 4) ns
- discharging time of the SiPM: t_2 = (242 ± 10) ns
- position of the overshoot: m = (18 ± 4) ns
- width of the overshoot: σ = (4.780 ± 0.008) ns

DArT2 - characterization in cold

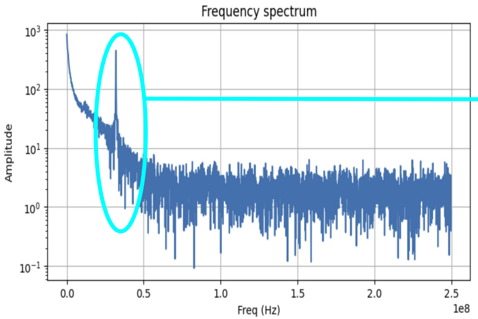
Experimental apparatus

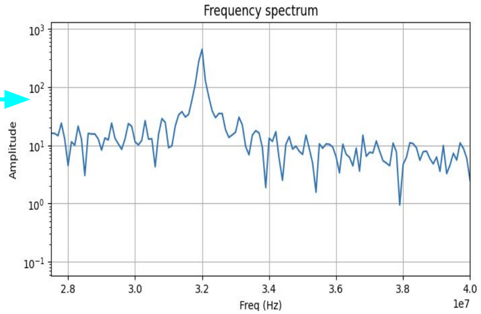
- DArT2 detector (**8 SiPMs**, 1 broken)
- Cryostat filled with LN_2 (87 K)
- No veto or shielding system

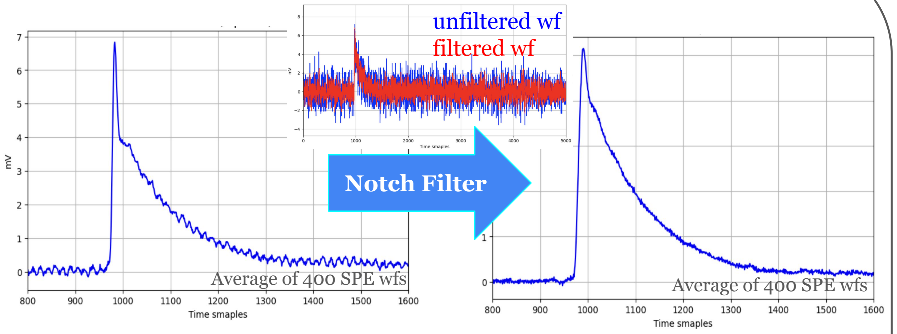




Noise studies and Single PhotoElectron response







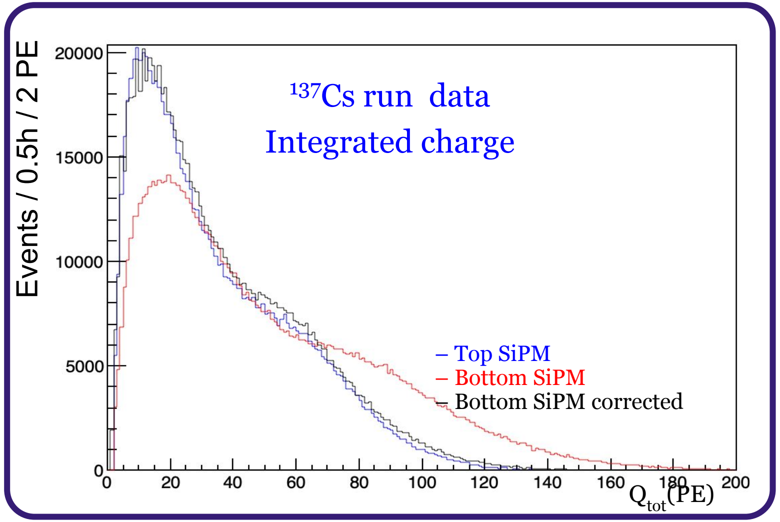
Significant peak in the noise spectrum of the 7 channels at ~ $3.2 \cdot 10^7$ (Hz)

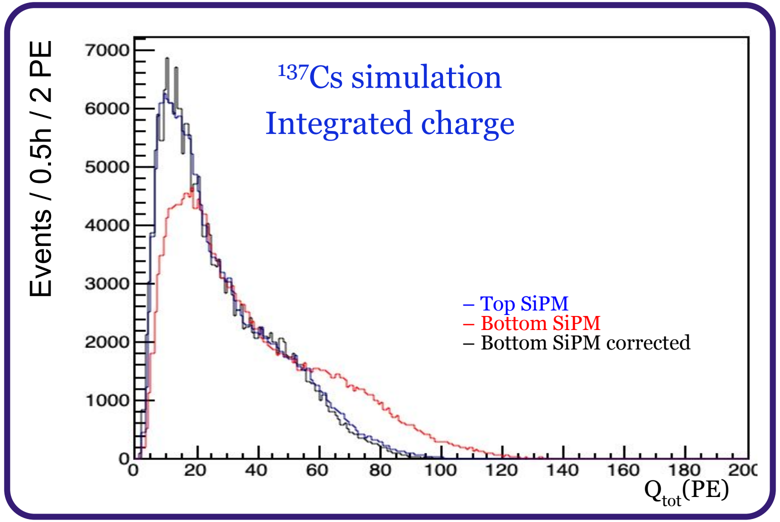
Notch Filter defined by:
f_0 → Frequency to remove (~32 MHz here)
Q → Controls the bandwidth ($\Delta f = f_0/Q$= 0.4 MHz here)

DArT1 in test setup - Top Bottom Asymmetry

Offline correction factor
- **applied to Q^B_{tot}** to equalize the 2 channels
- determined via **χ^2 minimization** over a range of correction factors

$\mathbf{f_B = 0.7}$





Total /prompt integrated charge

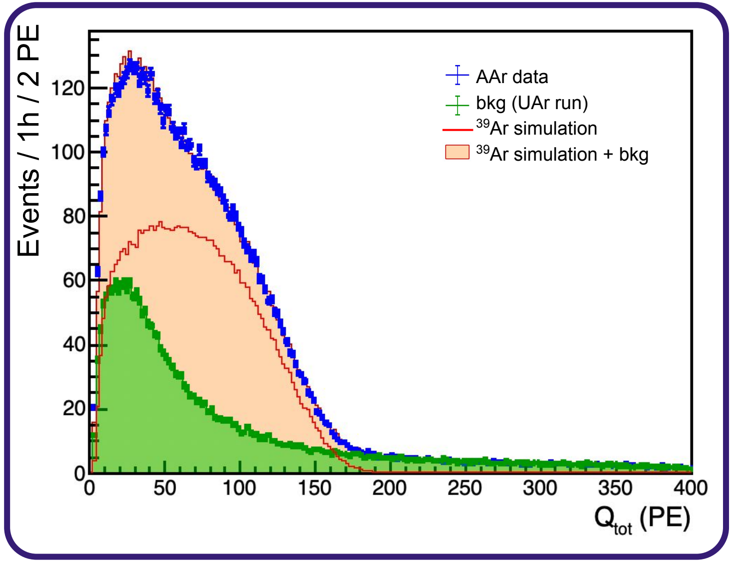
$$Q_{tot} = Q^T_{tot} + Q^B_{tot} \times \mathbf{f_B}$$

$$Q_{prompt} = Q^T_{prompt} + Q^B_{prompt} \times \mathbf{f_B}$$

DArT1 in test setup - ^{39}Ar Activity in AAr

$$A_{AAr} = \frac{N(AAr_{run}) - N(UAr_{run}) \cdot f_{AAr/UAr}}{\varepsilon_{AAr} \cdot t_{AAr}} + a_{UAr} \cdot M_{LAr}$$

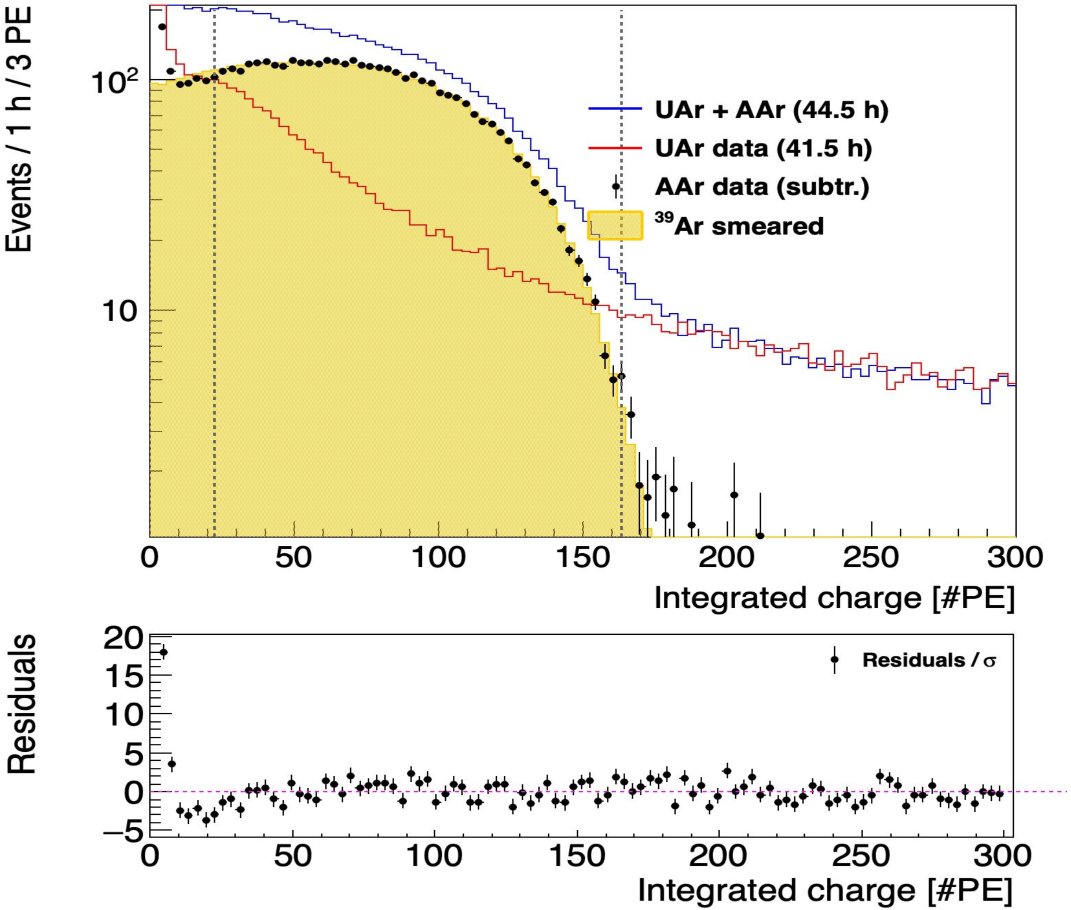
- **$N(AAr_{run})$:** events after **cuts** of the AAr run
- **$N(UAr_{run})$:** events after **cuts** of the UAr run
- **$f_{AAr/UAr}$:** ratio of AAr and UAr time acquisition
- **ε_{AAr}:** total ^{39}Ar efficiency from simulation
- **t_{AAr}:** AAr run time
- **a_{UAr}:** UAr specific activity
- **M_{LAr}:** Liquid Argon Mass in DArT1 detector



Analysis cuts

Beta events	$f_{prompt} < (0.4 + 0.95 / (1 + Q_{tot}(PE)/6))$
Signal Amplitude	$Max(wf^{T,B}) > 10mV$
Integrated charge	$Q^{T,B}_{tot} > 1.5$ PE
End point	$Q_{tot} < 250$

AAr run - 3 parameters smearing algorithm



$$\mathrm{GammaPDF}(x_i;\alpha,\beta) = \frac{x_i^{\alpha-1}e^{-x_i/\beta}}{\beta^\alpha\Gamma(\alpha)}$$

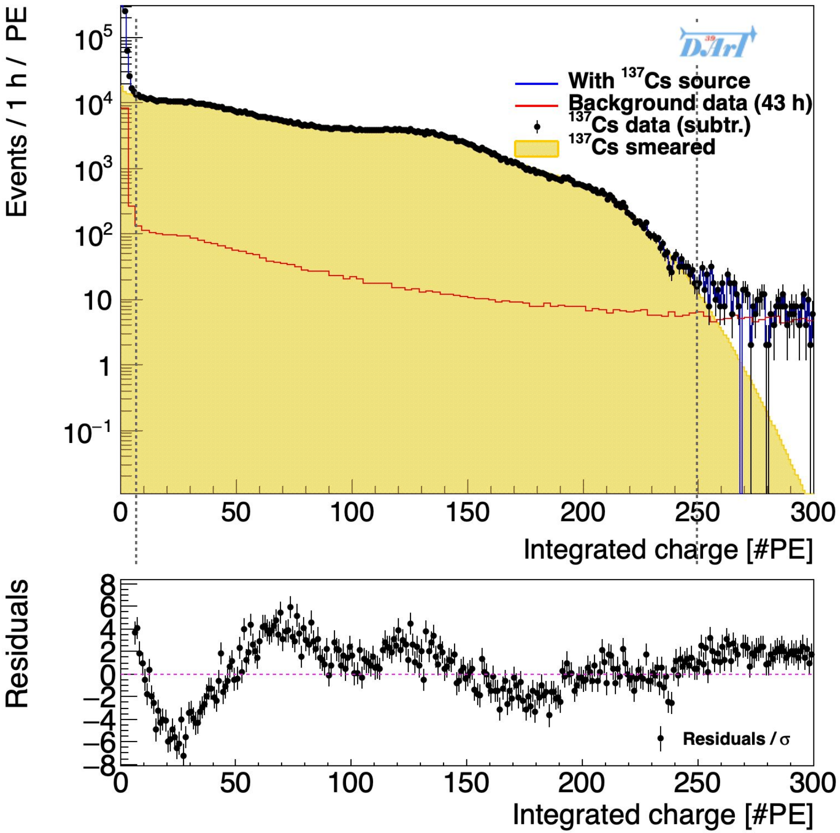
- $\beta = \mathrm{ResFactor}$
- $\alpha = \frac{x_j}{\mathrm{ResFactor}}$

Best fit parameters:

Light Yield = 0.291 +/- 0.007
Resolution Factor = 0.92 +/- 0.21
Activity = 1.275 +/- 0.002
fit range : (12PEs - 153PEs)
χ^2/ndf=1.68

Cs137 run - 5 parameters smearing algorithm

Cs - AAr run



$$\mathrm{GammaPDF}(x_i;\alpha,\beta) = \frac{x_i^{\alpha-1}e^{-x_i/\beta}}{\beta^{\alpha}\Gamma(\alpha)}$$

$$\mathrm{Var}(x_j) = RF1 \cdot x_j + RF2 + RF3 \cdot x_j^2$$

- $\alpha = \frac{x_j^2}{\mathrm{Var}}$
- $\beta = \frac{\mathrm{Var}}{x_j}$

Fit Range: (12PEs-240PEs)

Best fit parameters:

LY = 0.298 +/- 0.0022
RF1 = 1.81 +/- 0.04
RF2 = 0.04 +/- 1.26
RF3 = 6e-10 +/- 6e-10

χ^2/ndf=4.3