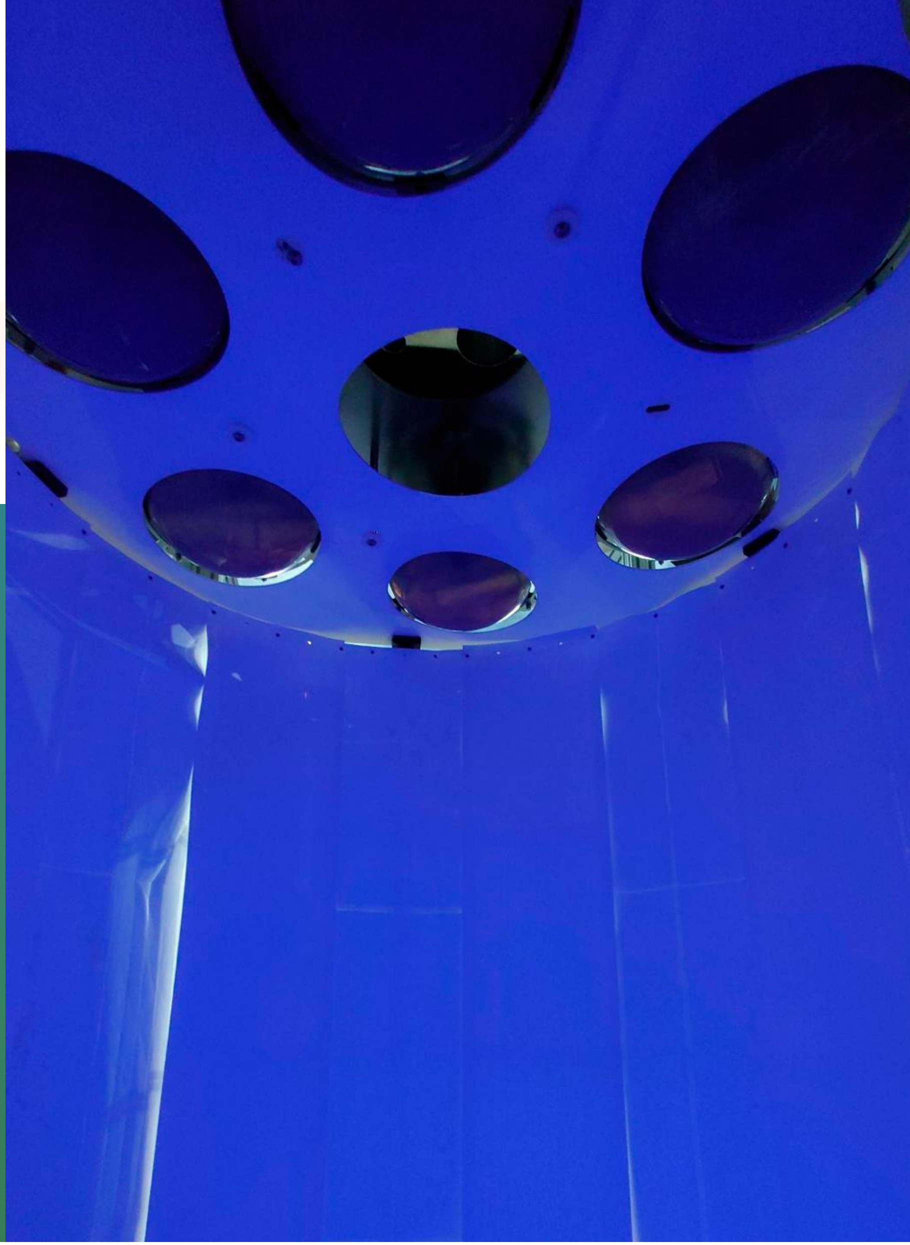
TeV Particle Astrophysics
TeVPA
Valencia 2025

The Underground Argon program of the Global Argon Dark Matter Collaboration

Daniel Díaz Mairena CIEMAT – Madrid
for the Global Ar Dark Matter collaboration



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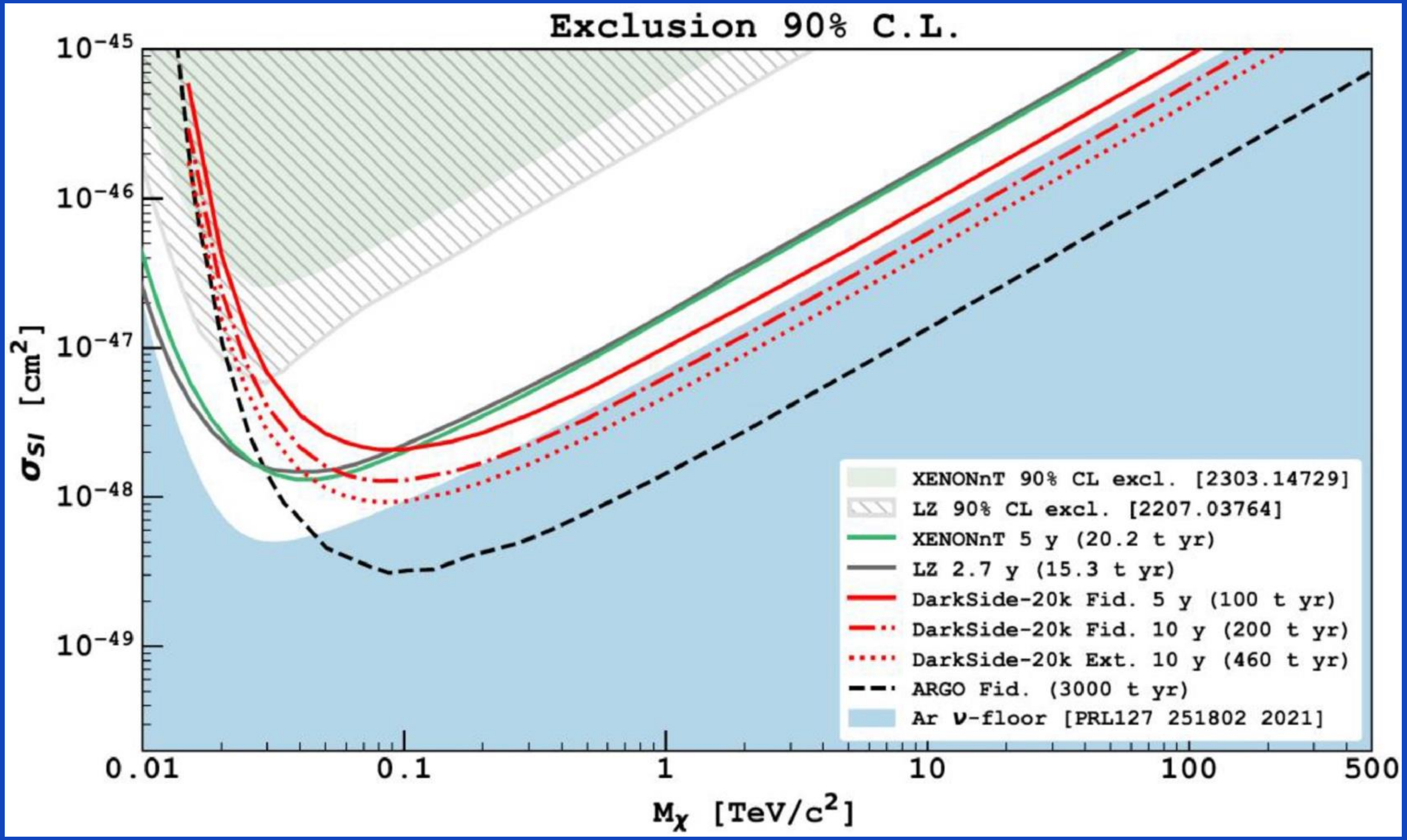
cfp CIEMAT física de partículas
DArT 39
DARKSIDE

Overall context: DarkSide-20k and the GADMC

The evidence for the existence of dark matter is abundant and diverse. One of the preferred candidates is the WIMP, and the DarkSide-20k experiment is designed to lead the wimp search in the coming years.

Expected Background:
<0.3 neutrons in ROI (20-200 keV) with 200 t-y exposure

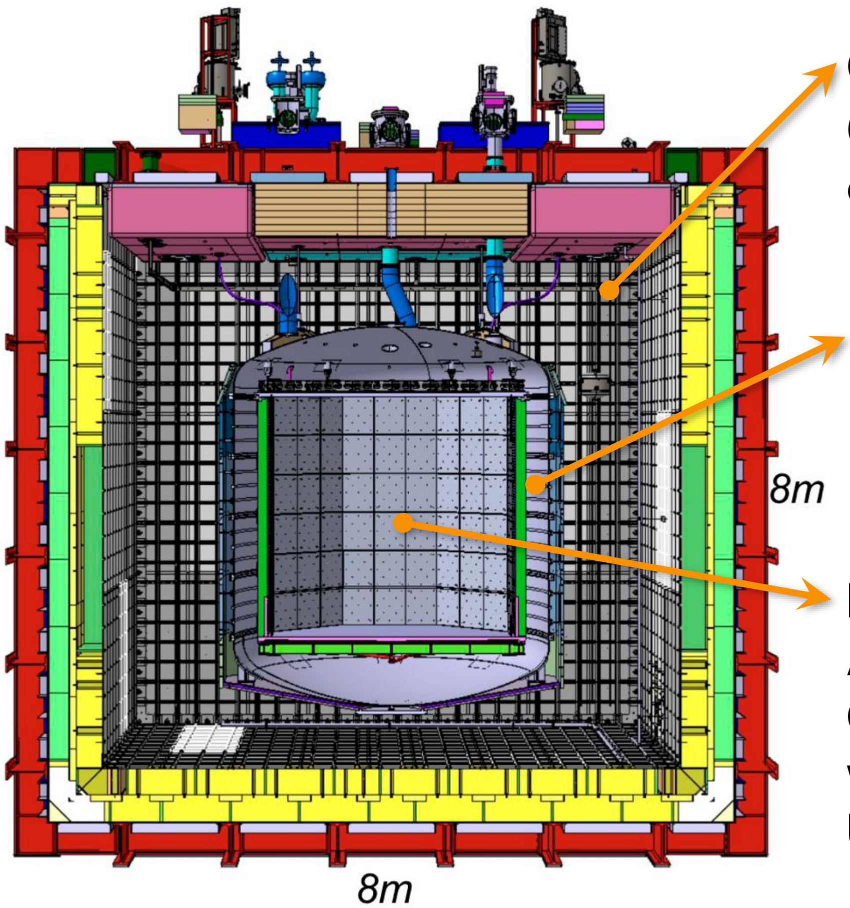


Nucl. Phys. B, vol. 1003 (2024)

Overall context: DarkSide-20k and the GADMC

@ LNGS, (Italy)

3800 m.w.e



Outer Veto:
650 tonnes of AAr, cosmogenic veto

Inner Veto:
32 tonnes of UAr, neutron veto

Inner Detector:
A Time Projection Chamber filled with 49.7 tonnes of UAr

Argon in Dark Matter Direct Detection

An ideal target?

- ✓ Negligible self-absorption of scintillation photons → Efficient collection of scintillation light
- ✓ Almost null attachment probability for electrons in pure Ar → Excellent ionization detector
- ✓ Pulse Shape Discrimination (PSD) of scintillation signal allow separate nuclear and electron recoils → Excellent background rejection
- ✓ Quite abundant in atmosphere (~ 1%) → Affordable large multi-ton detectors

^{39}Ar

Intrinsic activity of ^{39}Ar in atmospheric argon (AAr) → The high trigger rate, in multi-ton TPCs focus on low E, results in pile up problems

Cosmogenic: $^{40}Ar(n,2n)^{39}Ar$

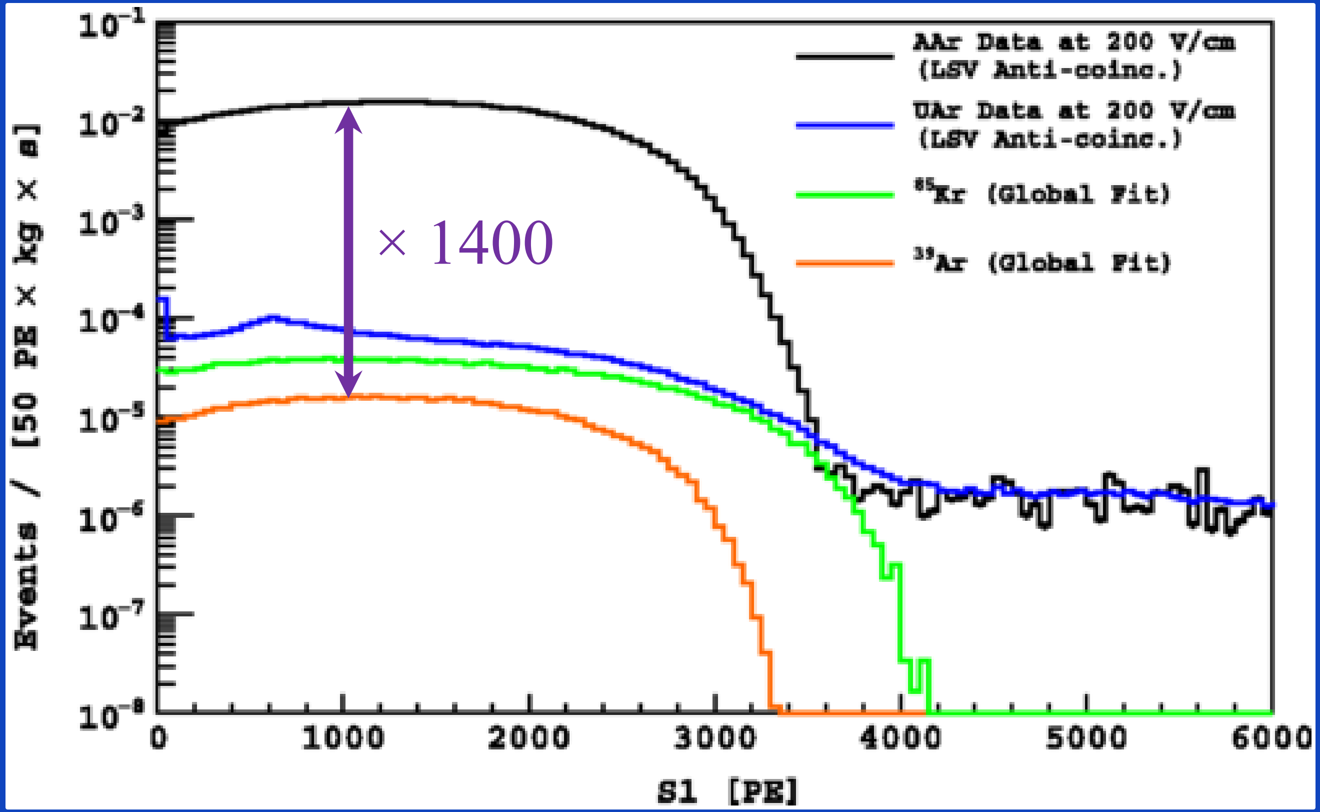
- β^- decay with Q_β = **565 keV**
- **Pure β** emitter
- $t_{1/2}$ = 269 y
- ~1 Bq/kg

Use of underground argon (**UAr**), with significant reduction of **^{39}Ar**

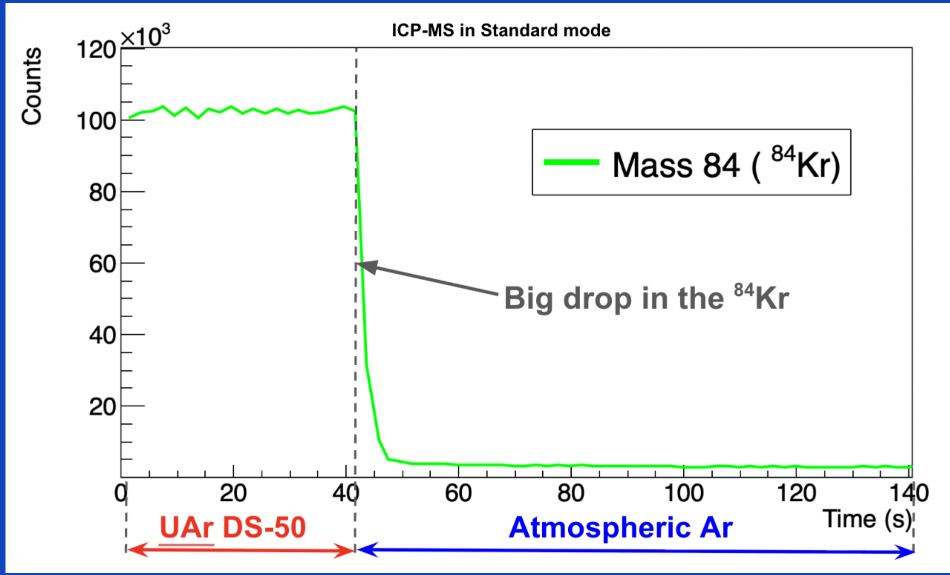
UAr for DarkSide-20k

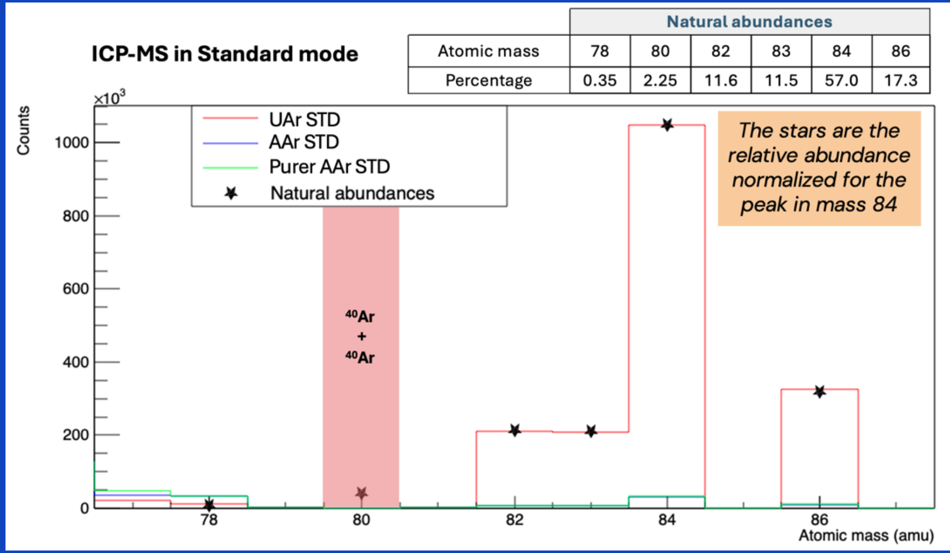
DarkSide-50 measured a ^{39}**Ar depletion factor of 1400** in UAr with respect to AAr, i.e. a ^{39}Ar activity of **0.73 ± 0.11 mBq/kg**:

This UAr batch was probably **affected by an air leak** during extraction. *Presence of Kr confirmed with ICP-MS*



Phys. Rev. D **93**, *081101 (2016)*





	Natural abundances					
Atomic mass	78	80	82	83	84	86
Percentage	0.35	2.25	11.6	11.5	57.0	17.3

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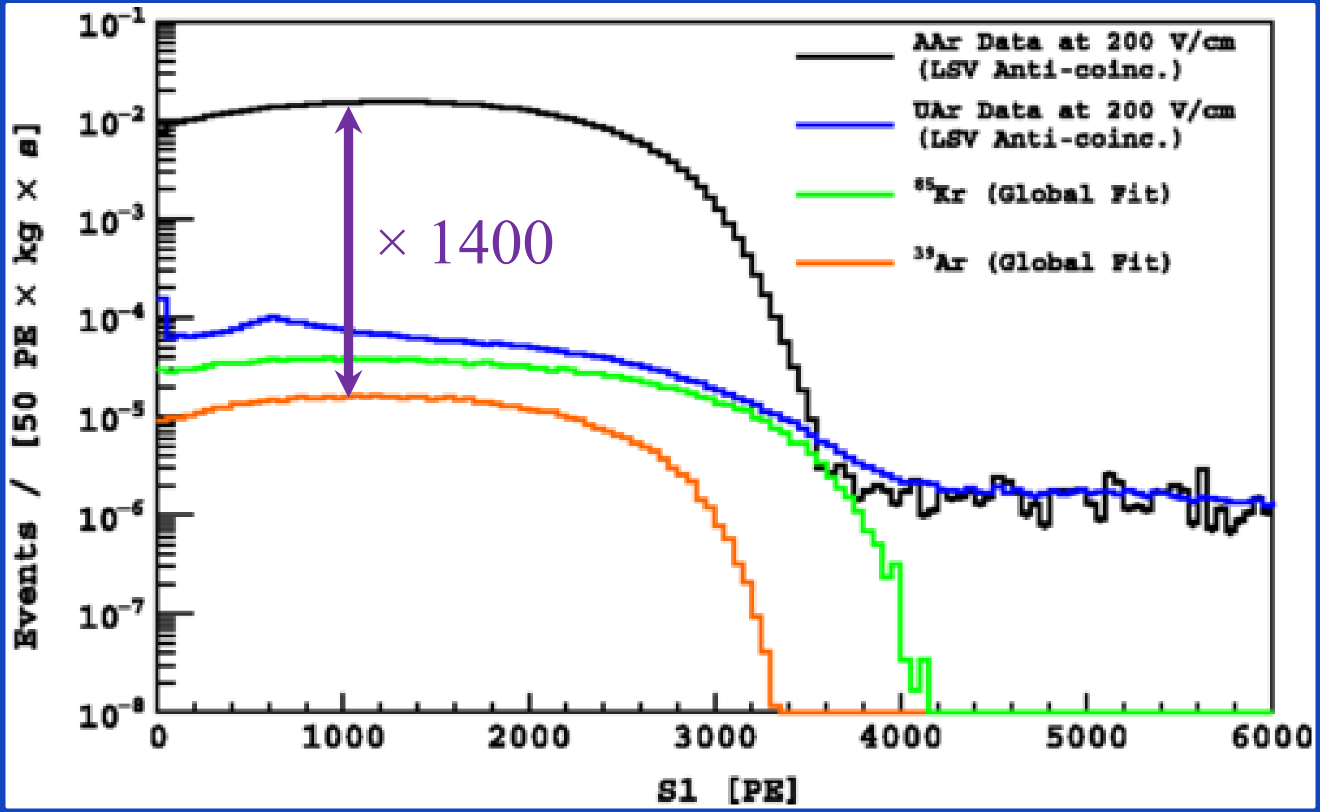


Phys. Rev. D **93**, *081101 (2016)*

This UAr batch was probably **affected by an air leak** during extraction. *Presence of Kr confirmed with ICP-MS*

Upper limit

A higher depletion factor can be expected in the UAr of DarkSide-20k

An infiltration could happen again

We will measure the ^{39}Ar levels of every batch for Darkside-20k

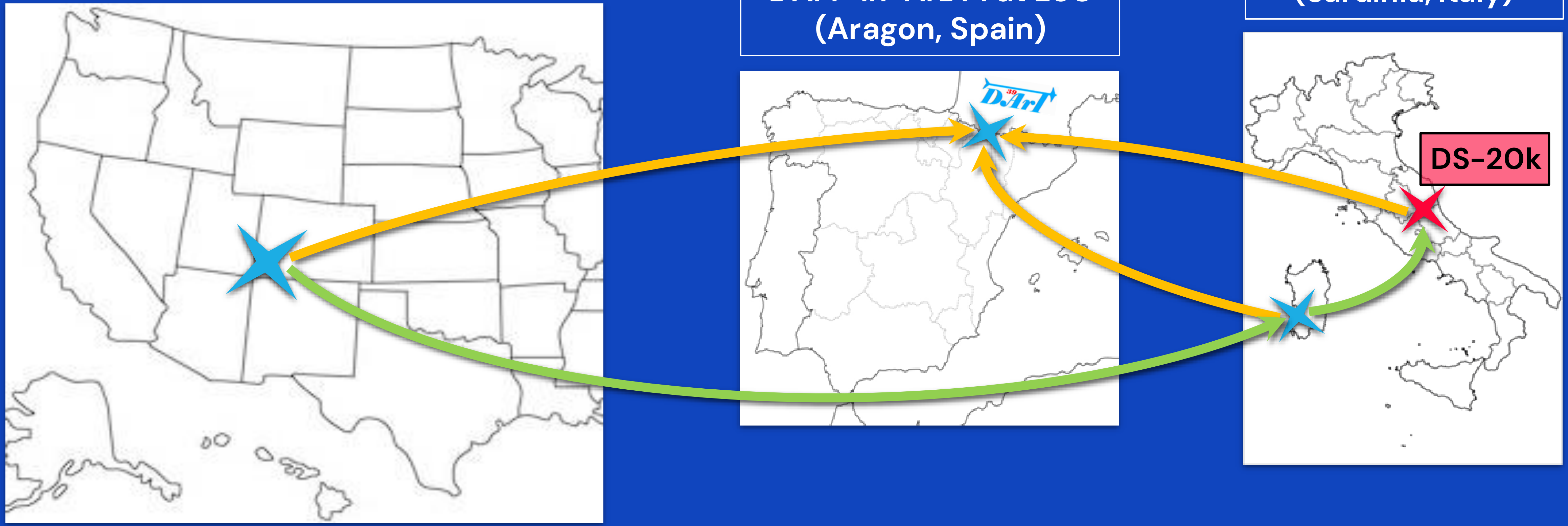
DS-20k: Going to industrial scale to extract and purify the ~120 tonnes of UAr

Extraction-Purification-Measurement

Production: Urania (Colorado, USA)

Characterisation: DArT-in-ArDM at LSC (Aragon, Spain)

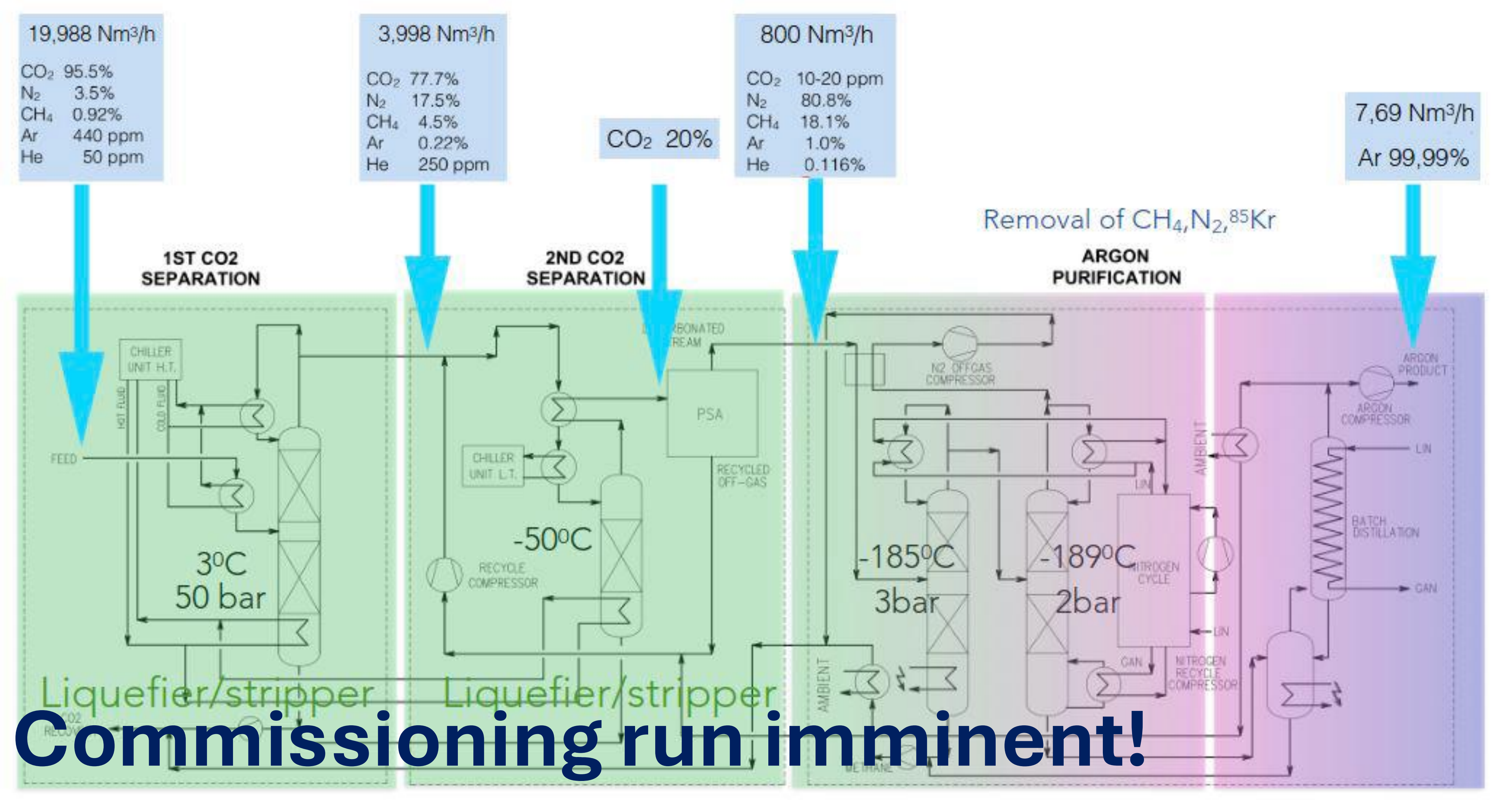
Purification: Aria (Sardinia, Italy)



Cosmogenic activation above ground, during storage and shipping, quantified and subdominant for sea freight (few % of DS-50 reference): *Astroparticle Physics 152, 102878 (2023)*
This program will be valuable for several future low-background experiments, such as LEGEND-1000, ARGO, COHERENT, and others.

Urania ➡ From 440 ppm to 99.99% Ar

@ Cortez, Colorado (US)



Commissioning run imminent!

➤ Extraction rate: **330 kg/day** ➤ Full amount for Darkside-20k (**120 tonne**) produced in **1.3 y**

Aria ➡ 10^3-fold reduction in chemical impurities

@ Carbosulcis, Sardinia (Italy)

A cryogenic distillation column (height ~350 m) under construction:

- 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**

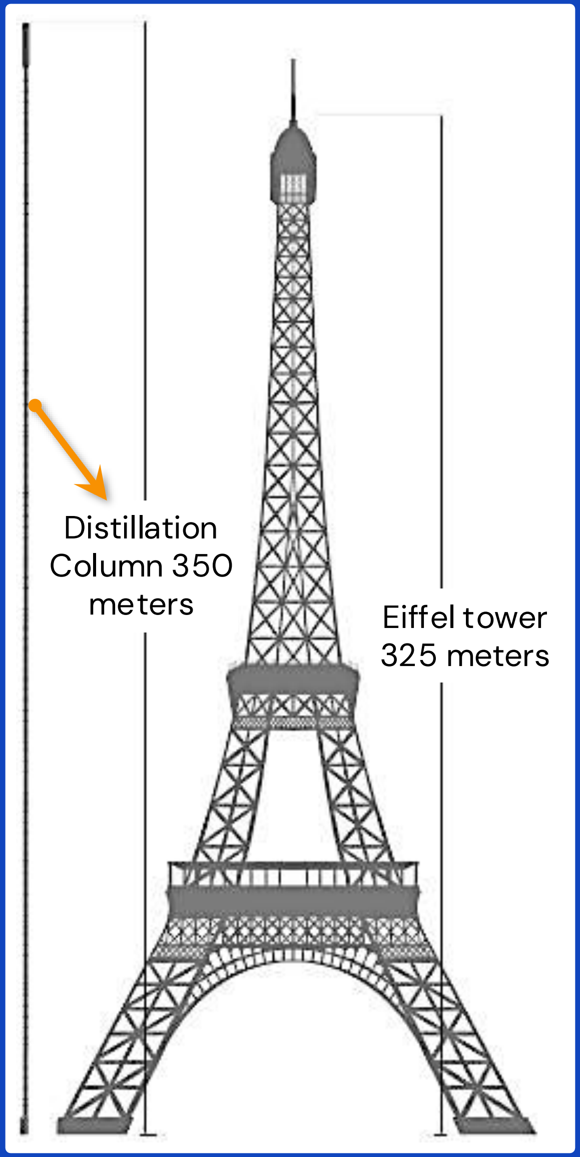
Number of theoretical distillation stages: ~2870

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

The process was already tested with a prototype, called **Seruci-0:**

1st operation with N_2: *2019 Eur. Phys. J. C (2021) 81:359*

2nd operation with Ar: *2021 Eur. Phys. J. C (2023) 83:453*

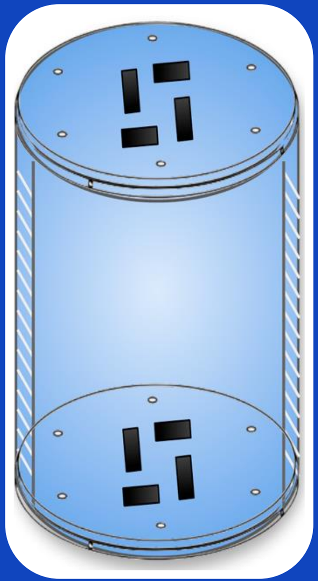


DArT-in-ArDM ➡ Characterization of the UAr

@ Canfranc Underground Lab (LSC), Aragón (Spain)

2400 m.w.e

Depleted Argon Test detector

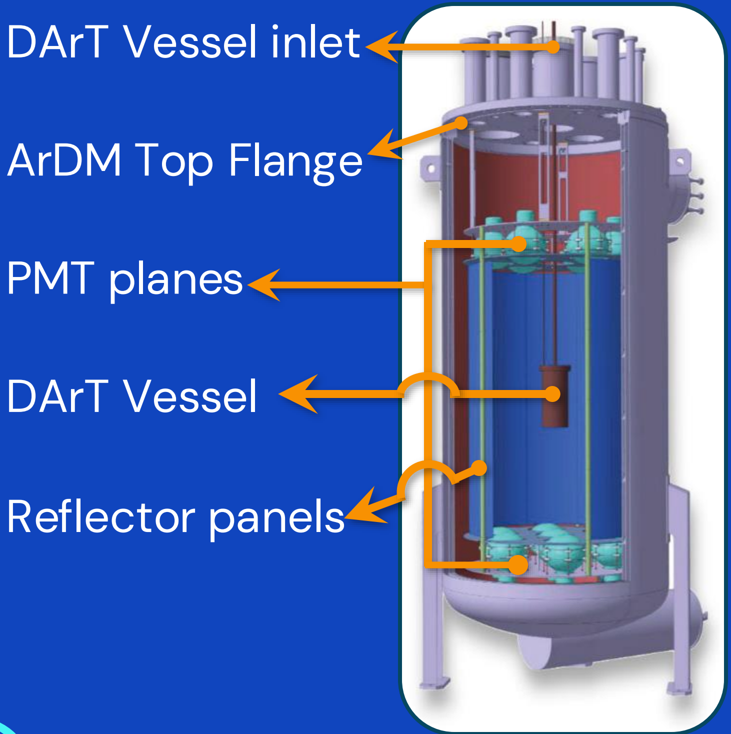


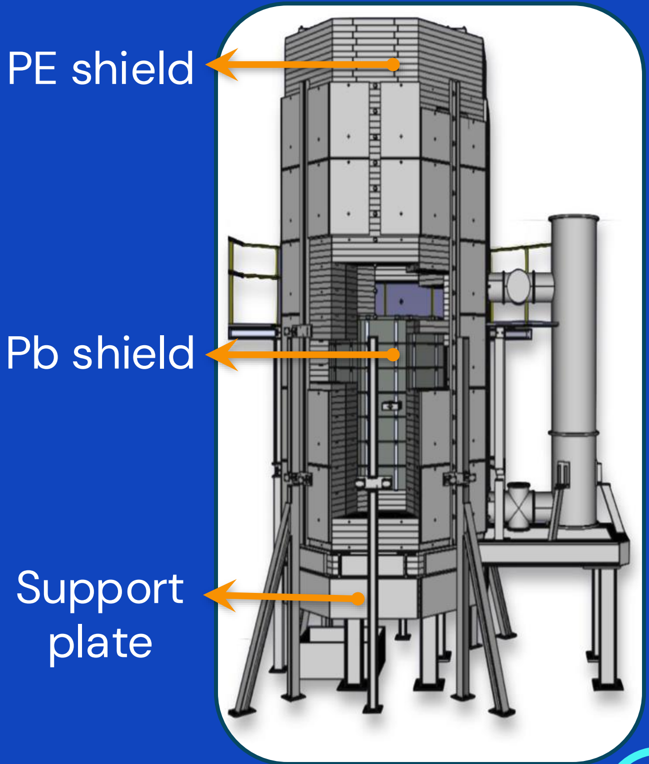
Single phase detector

- Photosensors: 8 x 1 cm^2 SiPMs
- 1.317 kg LAr active mass
- ESR reflectors
- TPB-coated acrylic

Argon Dark Matter active veto

ArDM Main Vessel



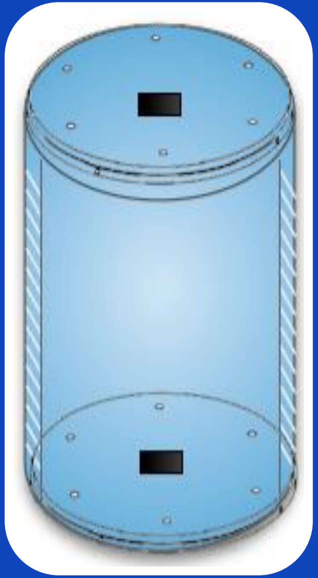


Projected Sensitivity: For the activity measured by DS-50, ~70 μBq/kg, less than 10% statistical error in 1-week livetime. *JINST 15 (2020) 02, P02024*

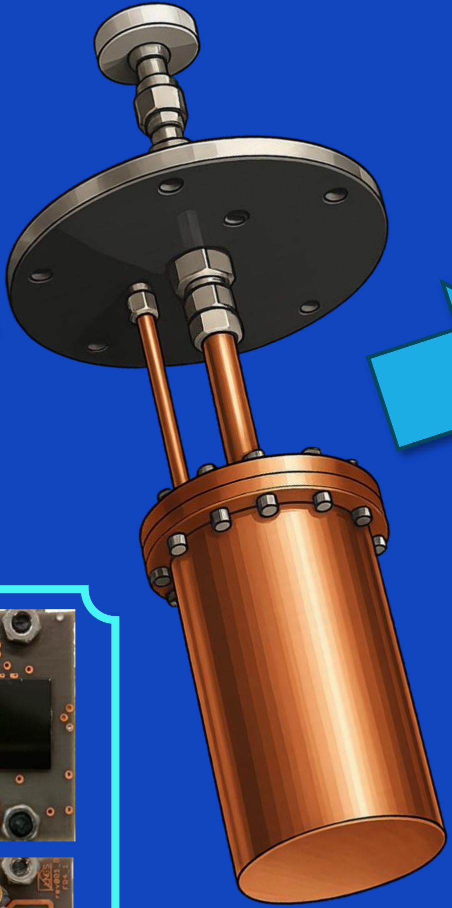
DArT-1 (in test cryostat)

DArT-1 (in test cryostat)

Acrylic structure

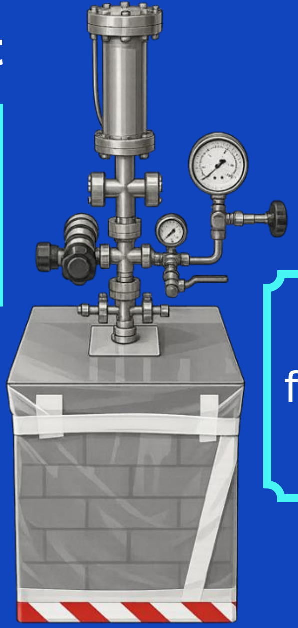


Inside a **copper vessel**



Stainless Steel Cryostat

Filling with LN_2 at overpressure (2.2 bar) keeps the liquid Ar (85 K)



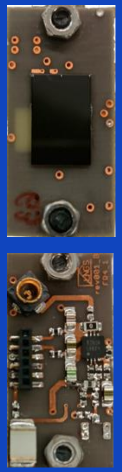
Pb shield flushed with Rn-free air

Goals of the setup

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

DArT SiPMS

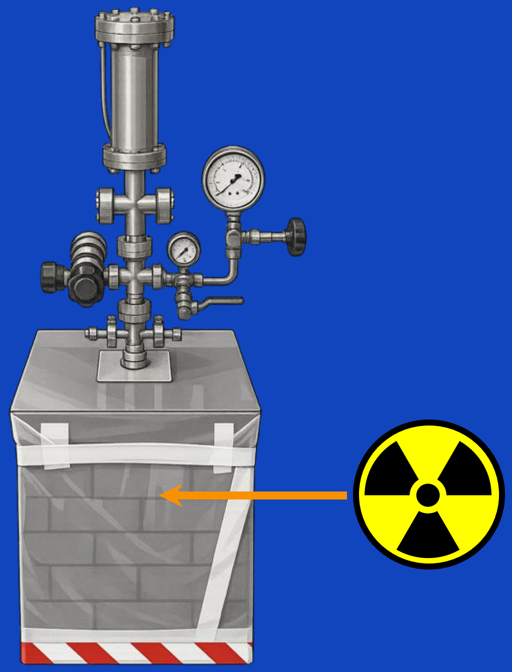
- NUV-HD-Cryo SiPM of the DarkSide-20k batch
- **Custom SiPM readout board (1 SiPM/board)**
- **Arlon 55NT substrate**



DArT-1 (in test cryostat): Run Overview

Data Taking

- **Atmospheric Argon runs**: With **Argon 6.0**, 1 ppm impurity level
- **Underground Argon runs**: With **UAr** from **DrakSide-50**
- ^{137}**Cs runs**: Adding a ^{137}Cs source (27 kBq) outside the cryostat inside the lead shield



Prospect

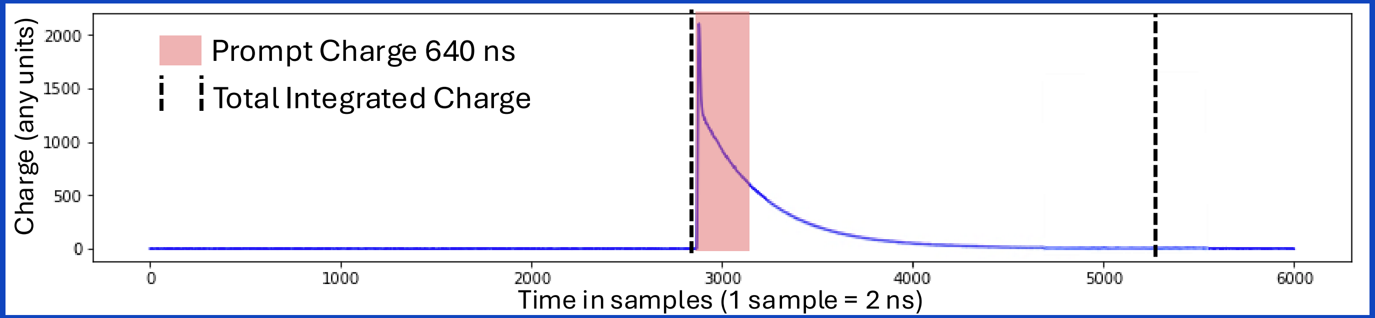
- **DArT-1 (in test cryostat) will operate in parallel to DArT-in-ArDM**

↓

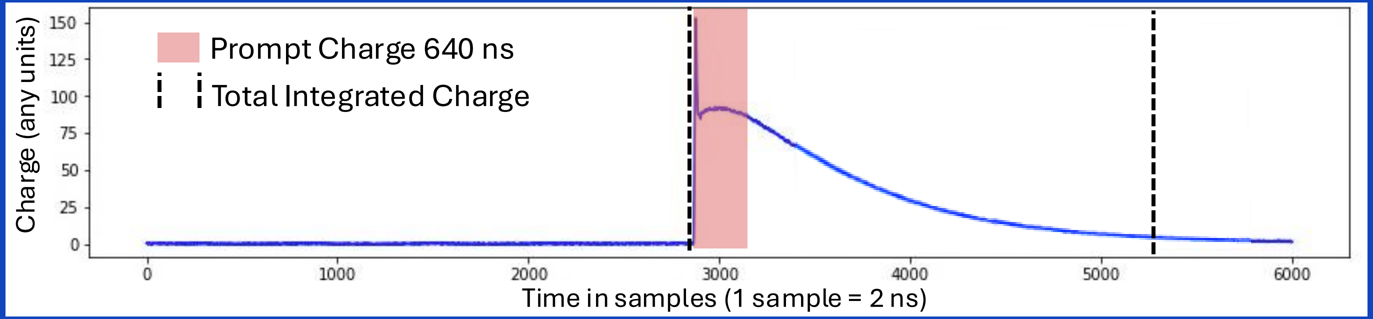
- Enabling **first UAr order 0 quality check** before the filling of the main detector

Demonstration of the Pulse shape discrimination with DS-20k SiPMs

α decay



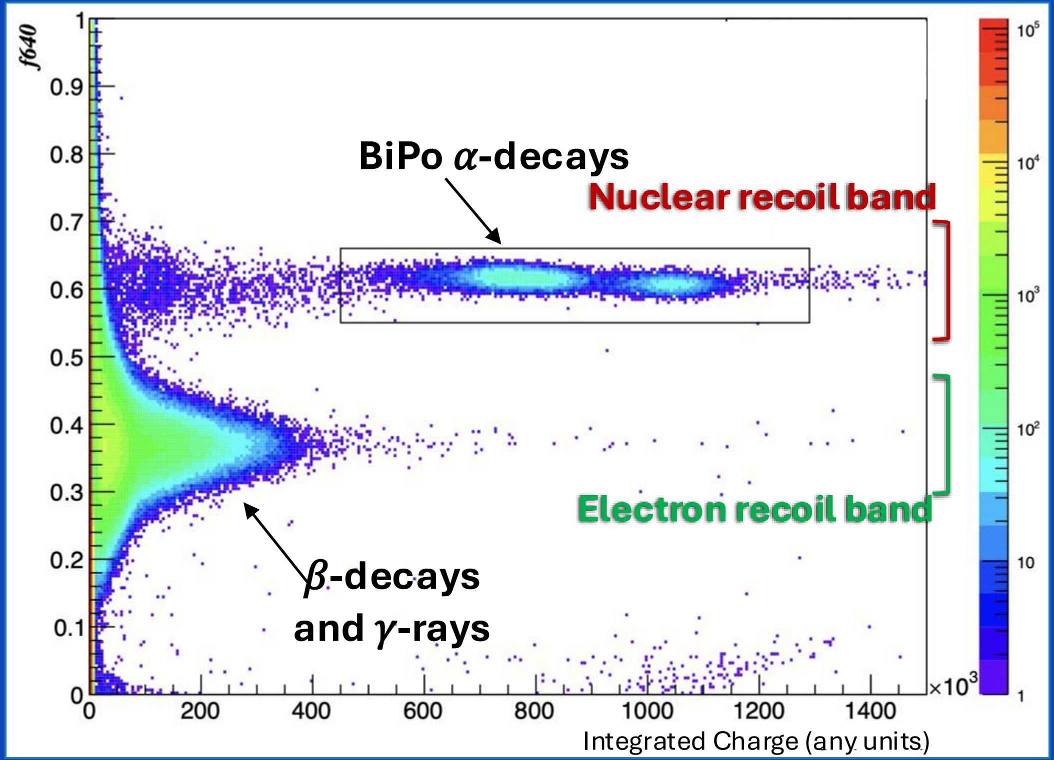
β or γ particle



To use this PSD tool of the Ar we define the following variable:

$$f_{640} = \frac{q_p}{q_T} ,$$

where q_p is the integrated charge in the first 640 ns and q_T is the total integrated charge.

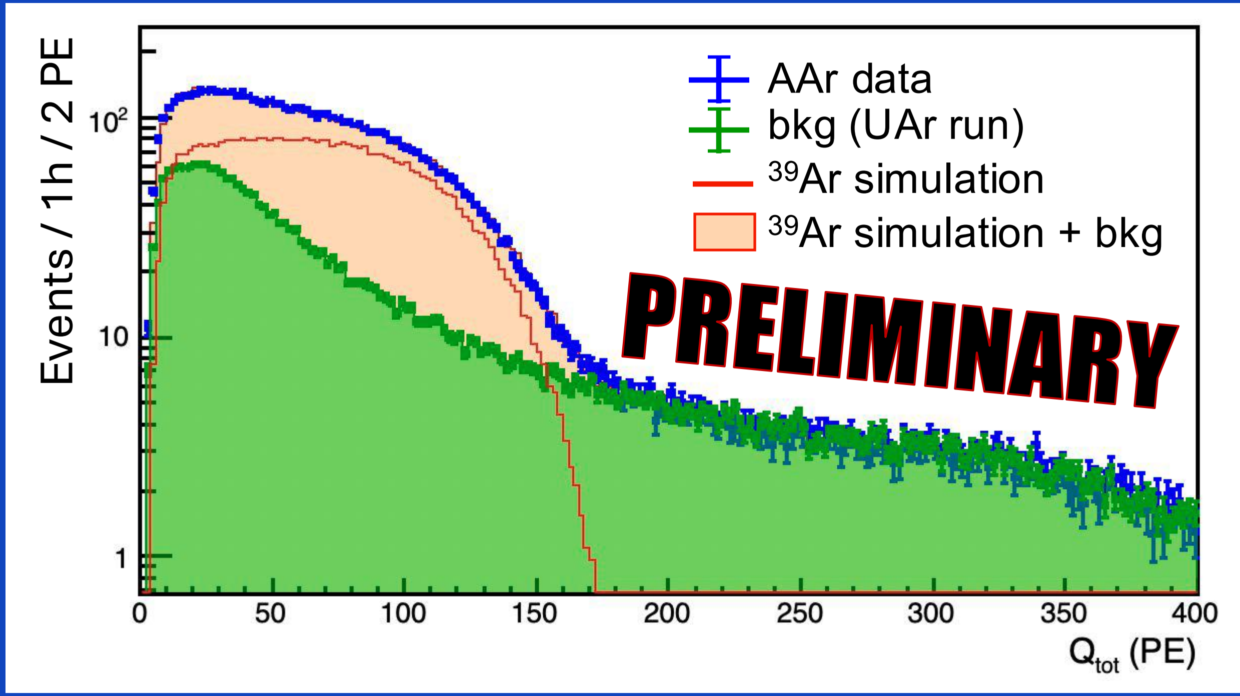


DArT-1: ^{39}Ar activity in atmospheric Ar

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

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

- $N(AAr_{run})$: Events **after** cuts of the UAr 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



Systematic Uncertainties

Type	Variation	Uncertainty on a_{AAr} (%)
Asymmetry factor for f_B	$\pm$ 0.05	0.04
Threshold cut in mV	$\pm$ 3 mV	1.1
Threshold cut in $Q^{T,B}_{tot}(PE)$	$\pm$ 0.1	0.02
Cut in max Q_{tot} (PE)	$\pm$ 20	0.01
Nuclear recoil background		
M_{LAr}		1.6
Total		1.94

a_{AAr} = (xx ±0.025 stat. ± 0.019 syst.) Bq/kg

Others experiments

- ***DEAP – 3600***: a_{AAr} = 0.96 ± 0.001 stat ± 0.024 sys Bq/kg *P. Adhikari et al., Eur. Phys. J. C 83, 642 (2023).*
- ***WARP***: a_{AAr} = 1.01 ± 0.02 stat ± 0.08 sys Bq/kg *P. Benetti et al., Nucl. Instrum. Meth. A 574, 83 620 (2007).*
- ***ArDM***: a_{AAr} = 0.96 ± 0.05 Bq/kg *J. Calvo et al., JCAP 12, 011 (2018).*

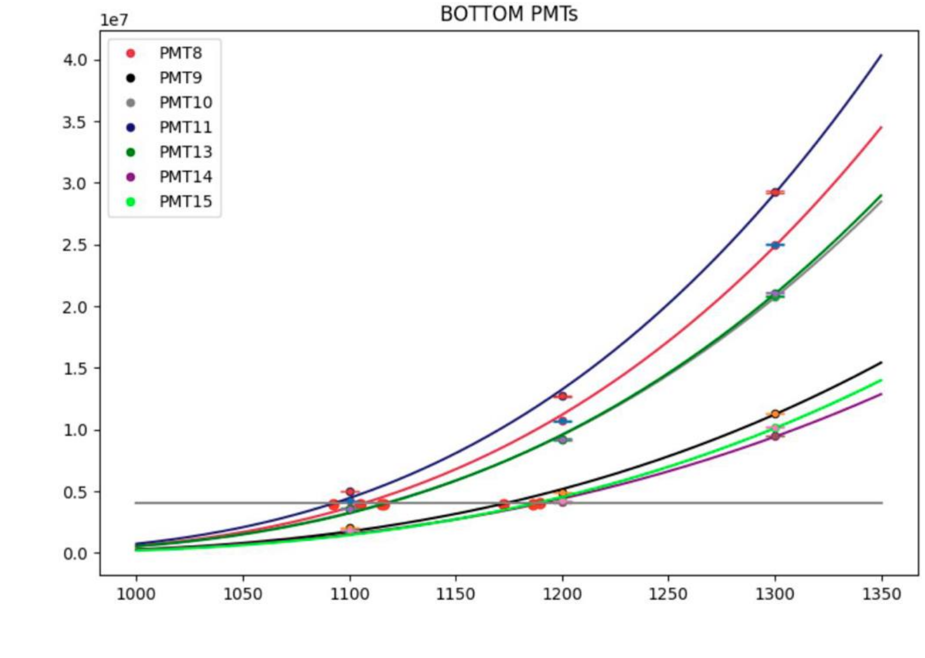
DArT in ArDM

Refurbishment of ArDM

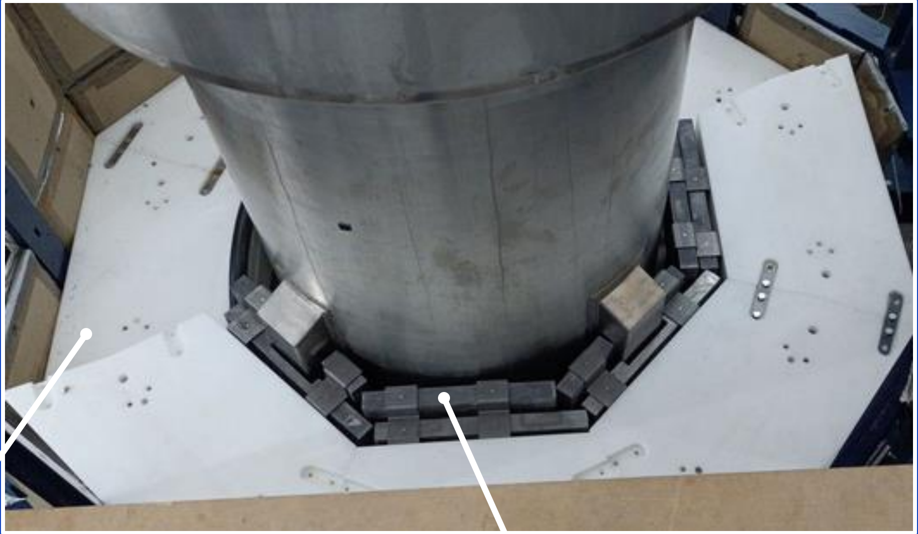
The refurbishment of ArDM was done at LSC:

- 6 tonnes of lead belt attached to the polyethylene shield
- New PMT planes mounted
- Reflectors installed inside

Characterization of the new PMTs:



PMT Plane with reflector coated with TPB



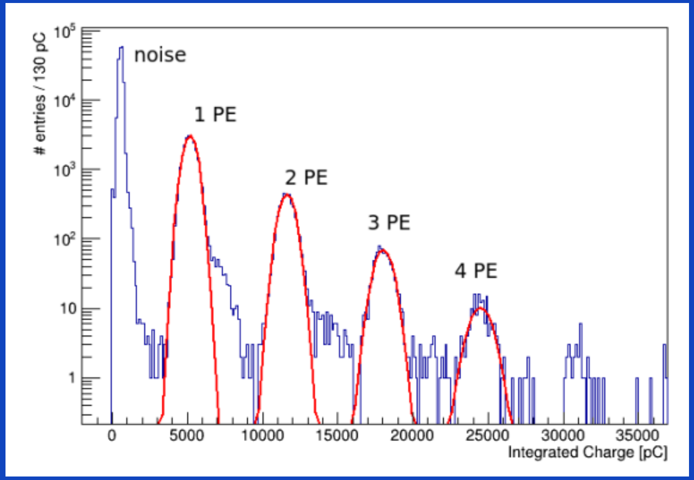
Reflector Coated with TPB

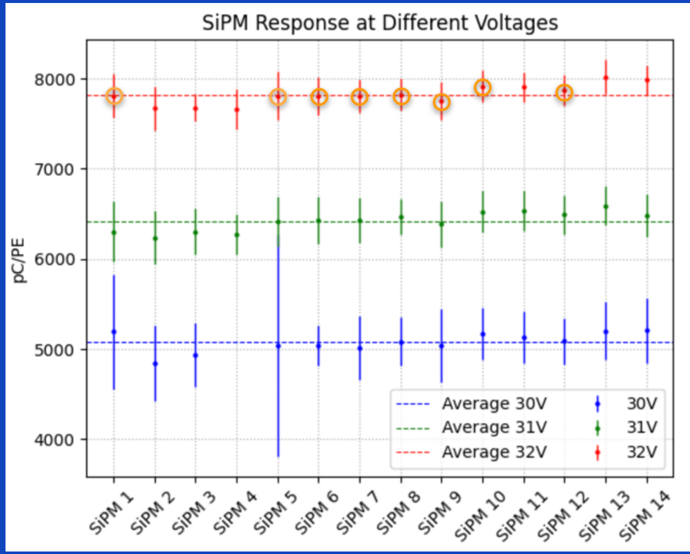
PE Shield

Pb Belt

DArT-2.0: Construction

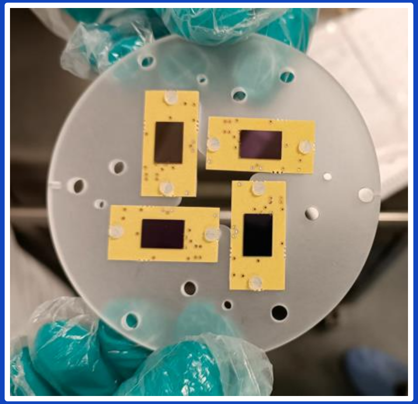
Characterization and selection of SiPMs

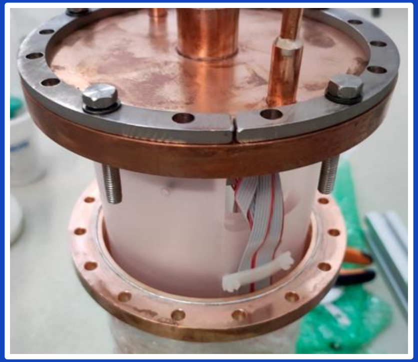




Cleaning

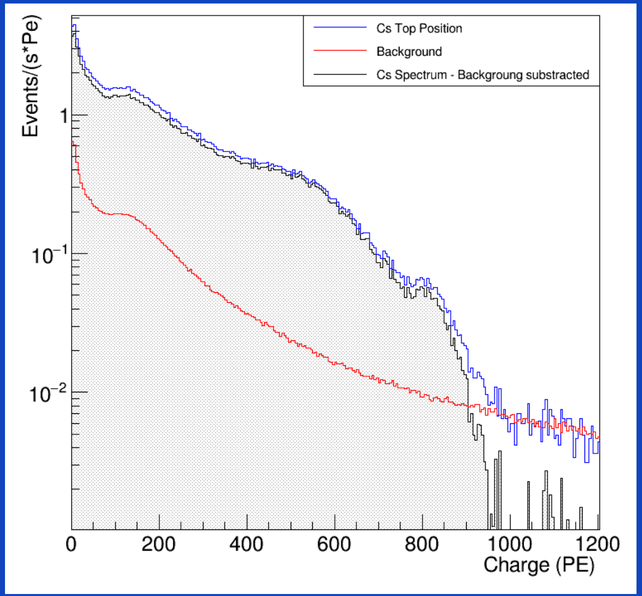
Assembly

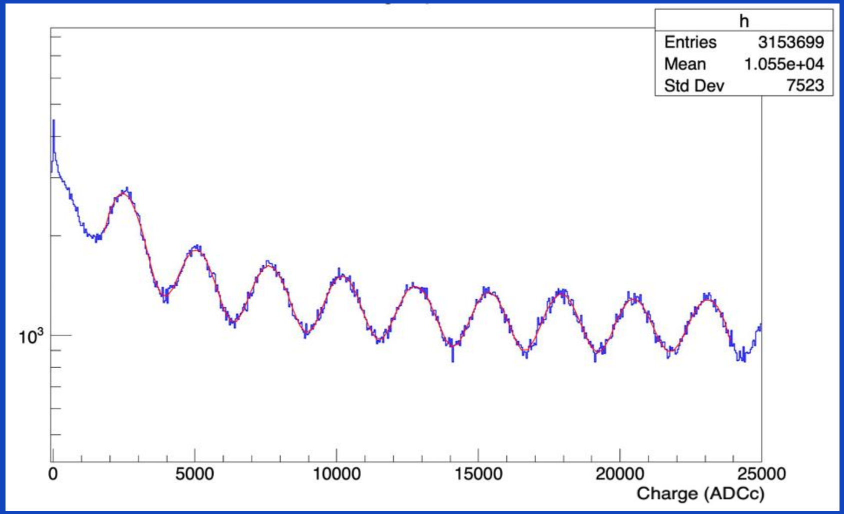


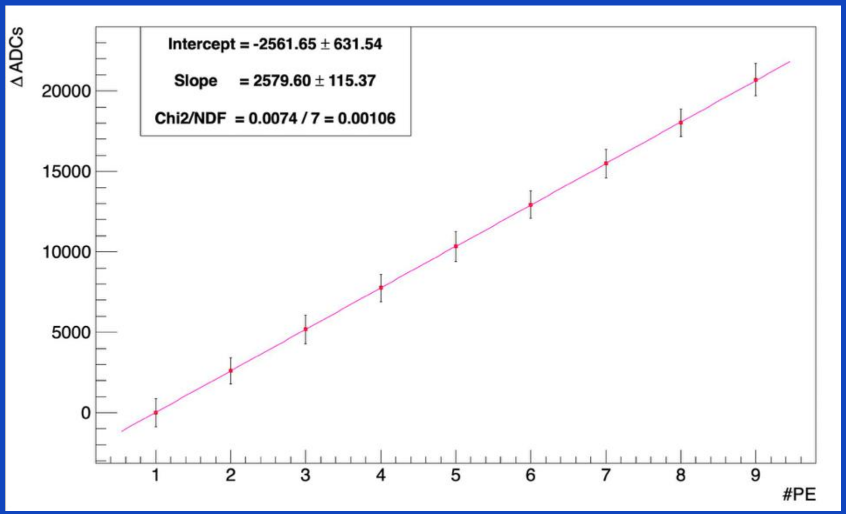


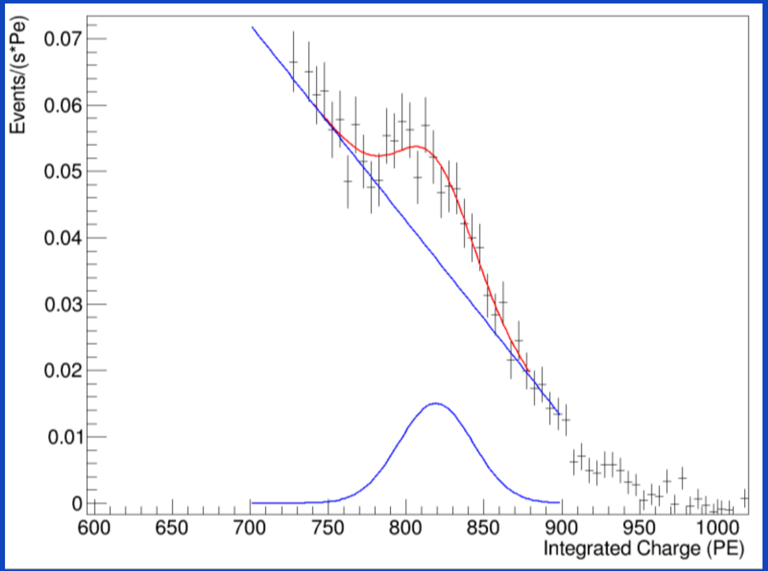
DArT-2.0: First measurement with Liquid AAr

- A test measurement outside ArDM was preformed to assess the entire system with DArT-2.
- From this data acquisition we obtained the following key results:
  - A new characterization of the SiPM, now installed in the detector.
  - Study of the noise spectrum.
  - Using data with a ^{137}Cs , we measured the improvement in light yield.







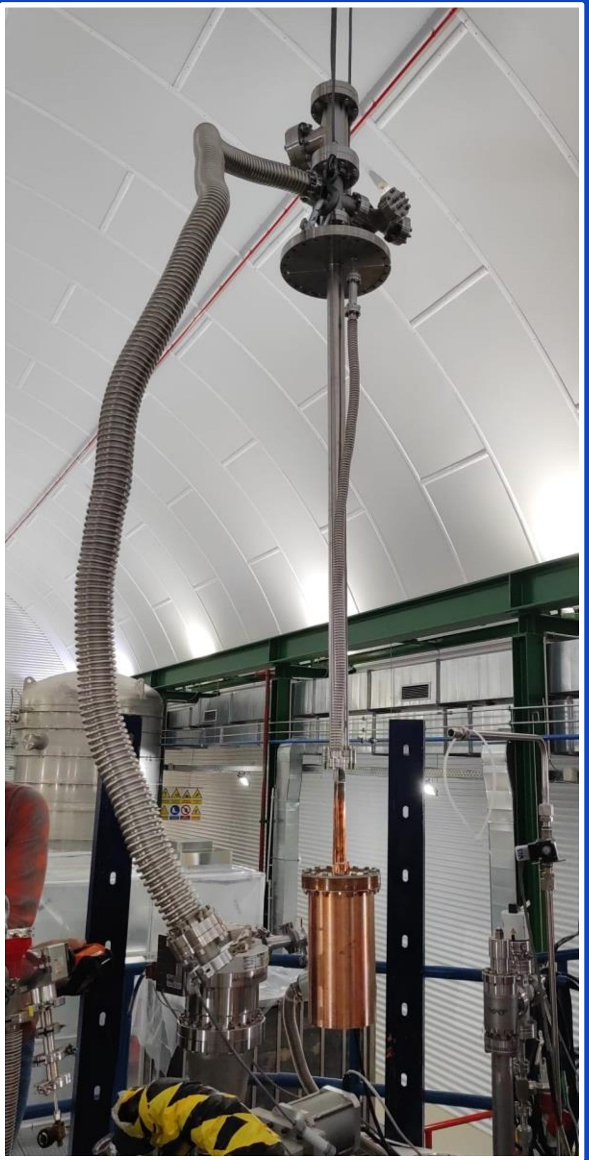


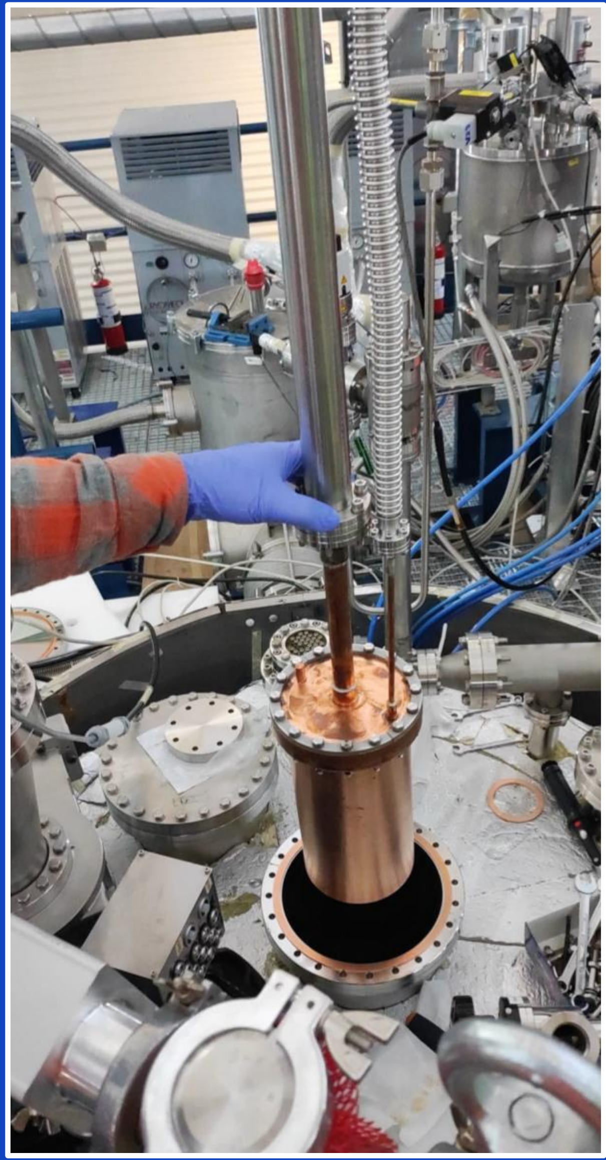
The difference in gain between all SiPM is less than 0.04%.

The values are compatibles with the previous characterization in cold outside DArT.

LY = 1.23 ± 0.01 PE/keV

DArT-in-ArDM: DArT-2.0 integration in ArDM

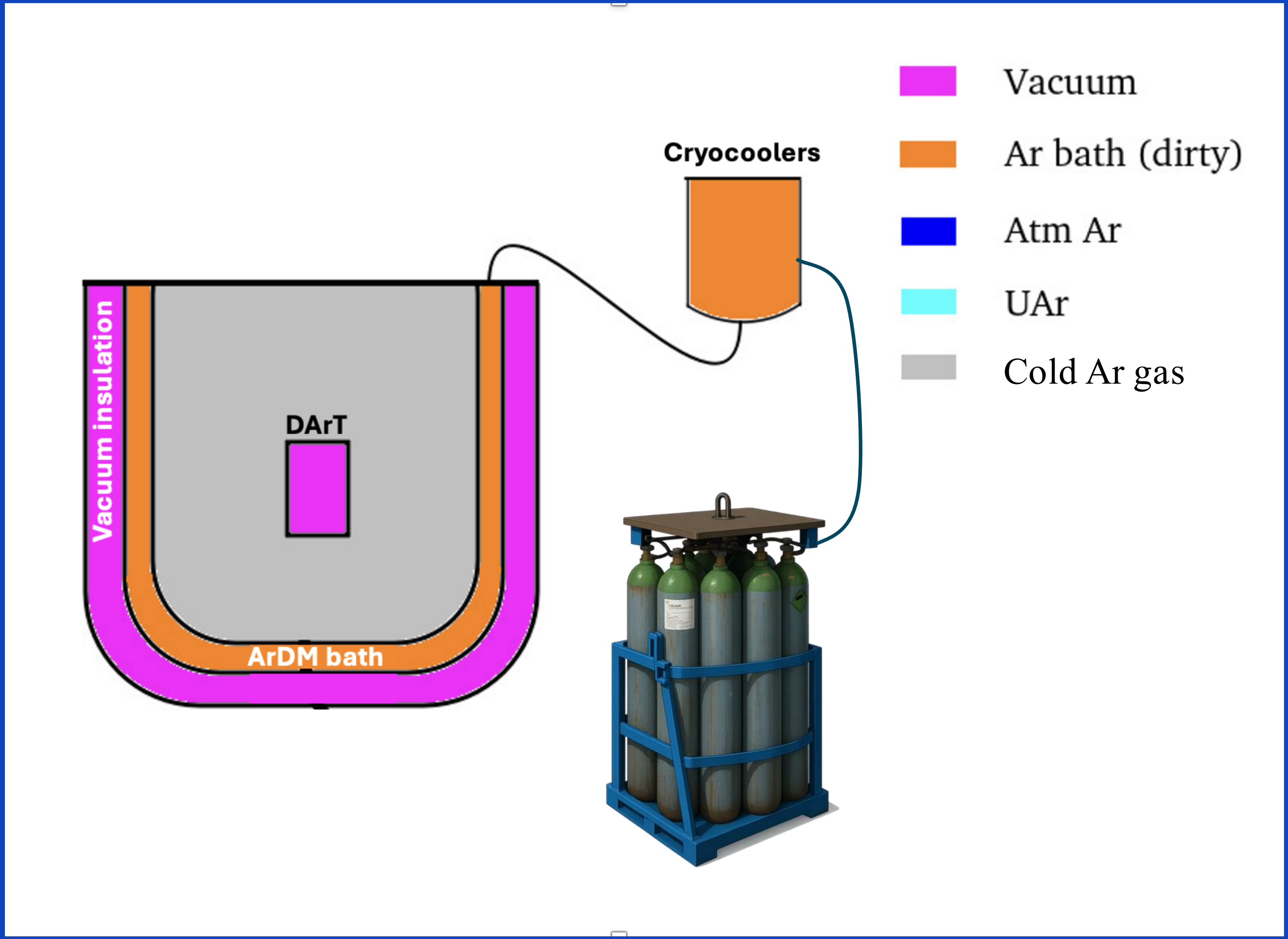




DArT-2.0 was integrated in ArDM.

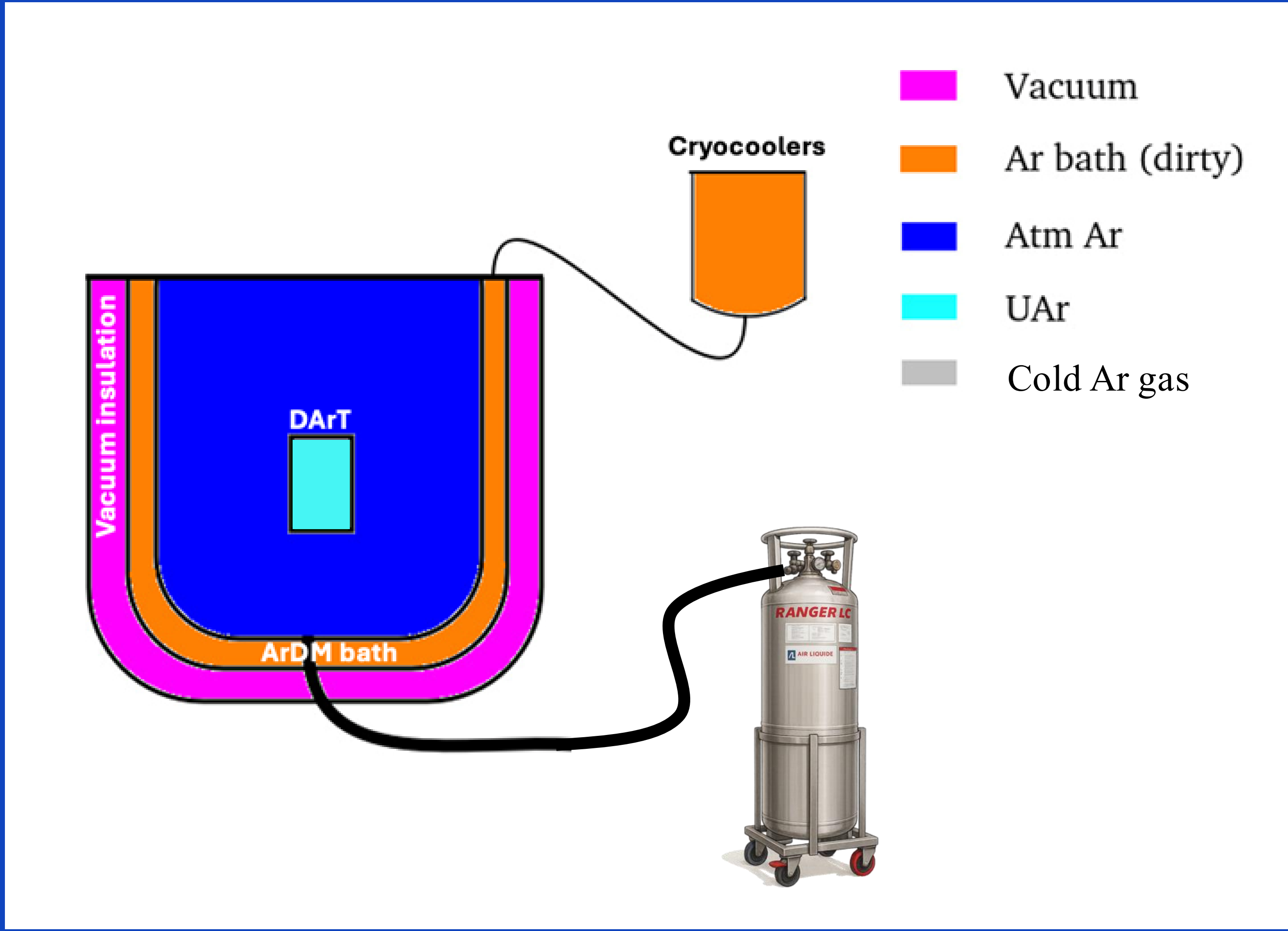
Now we are starting the filling of ArDM.

DArT-in-ArDM: Cooling down the detector



- Two cryocoolers operating; detector cooling toward LAr temperature.
- Pressure regulated by solenoid valves; inject Ar when **P < 920 mbar**.
- Bath filling completed this past weekend.

DArT-in-ArDM: Filling the main volume of ArDM



- **~1 tonne of AAr** to be transferred in the coming weeks.
- Once ArDM is full, we will start the first test measurements with **DArT-in-ArDM** using **AAr** and **UAr** (from DarkSide-50).
- We will be **ready well ahead** of the first incoming UAr batches from Urania.

Conclusions

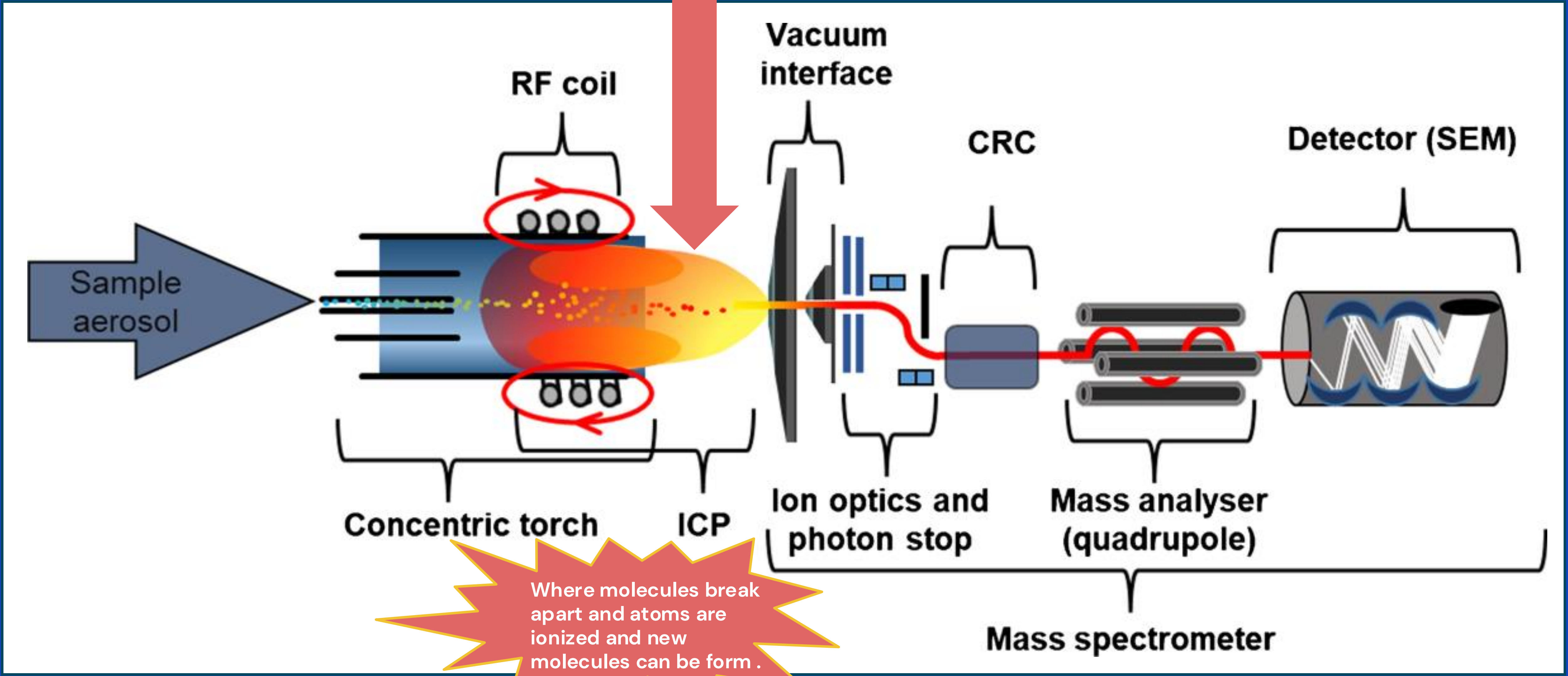
- The **pulse shape discrimination (PSD)** capabilities of Argon make it an ideal choice for the next generation of low-background experiments.
- **Atmospheric argon (AAr)** is unsuitable for the next generation of rare events searches due to its intrinsic **^{39}Ar** activity.
- **Underground Argon (UAr), depleted in ^{39}Ar,** solves the problem.
- There is an ambitious program to extract, purify and characterize **~120 tonnes of UAr**.
- **Early next year**, fresh UAr will be extracted using the **URANIA** plant.
- The **ARIA** facility will chemically purify UAr at a rate of **1 tonne/day**.
- **DArT-in-ArDM** is ready **to assay the intrinsic activity** of the entire UAr production for **DarkSide-20k**.
- This program will have a strong impact in **DM searches, 0νbb, CEνNS** and more. Stay tuned!

Backup

ICP-MS Analysis
With the UAr of Ds-50

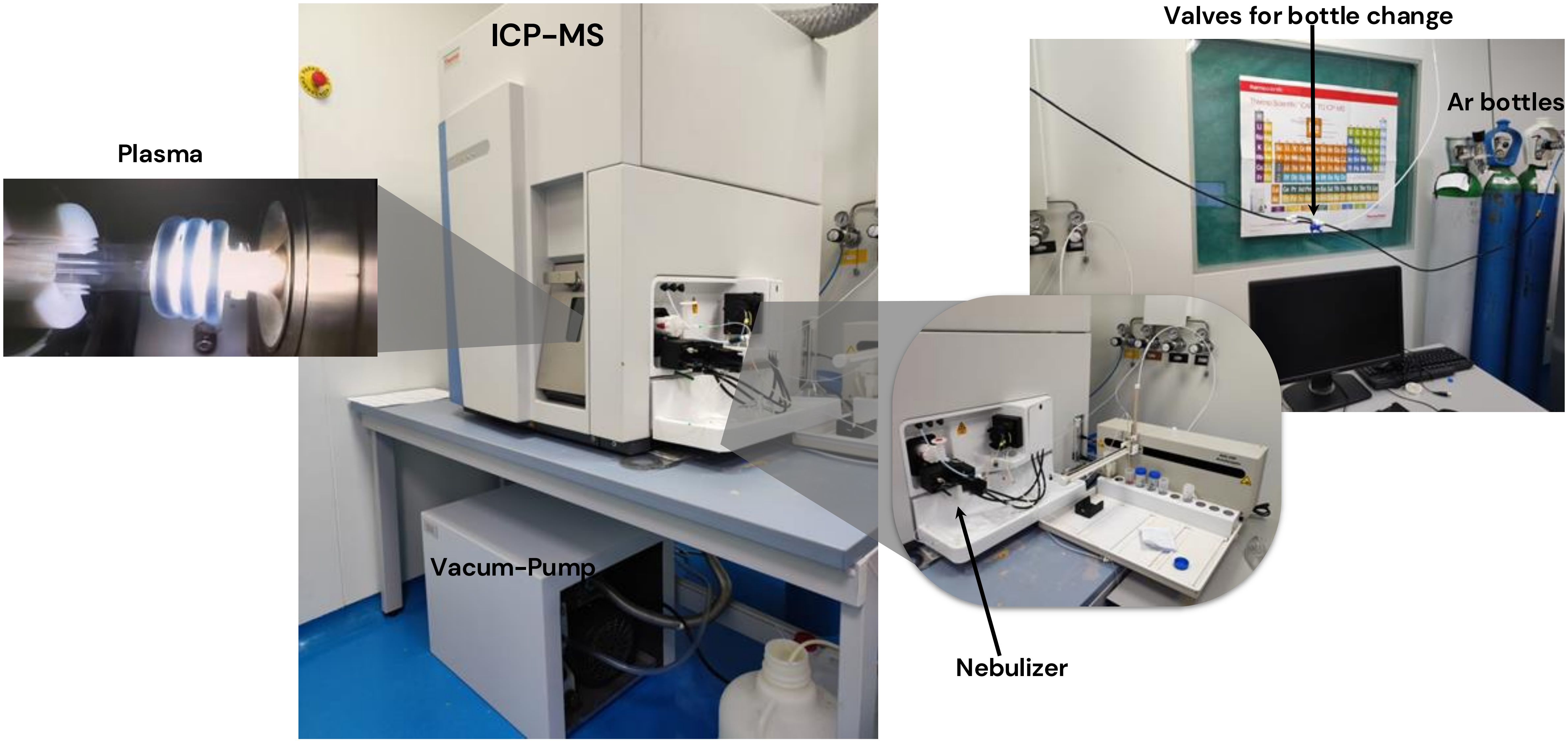
ICP–MS scheme

Plasma generated with gas Ar



Where molecules break apart and atoms are ionized and new molecules can be form .

Experimental Setup



Experimental Setup

There are some masses, corresponding to the most abundant elements in the gas and its interferences, that the ICP-MS doesn't measure → **Forbidden Masses**

The ICP-MS has two different working modes:

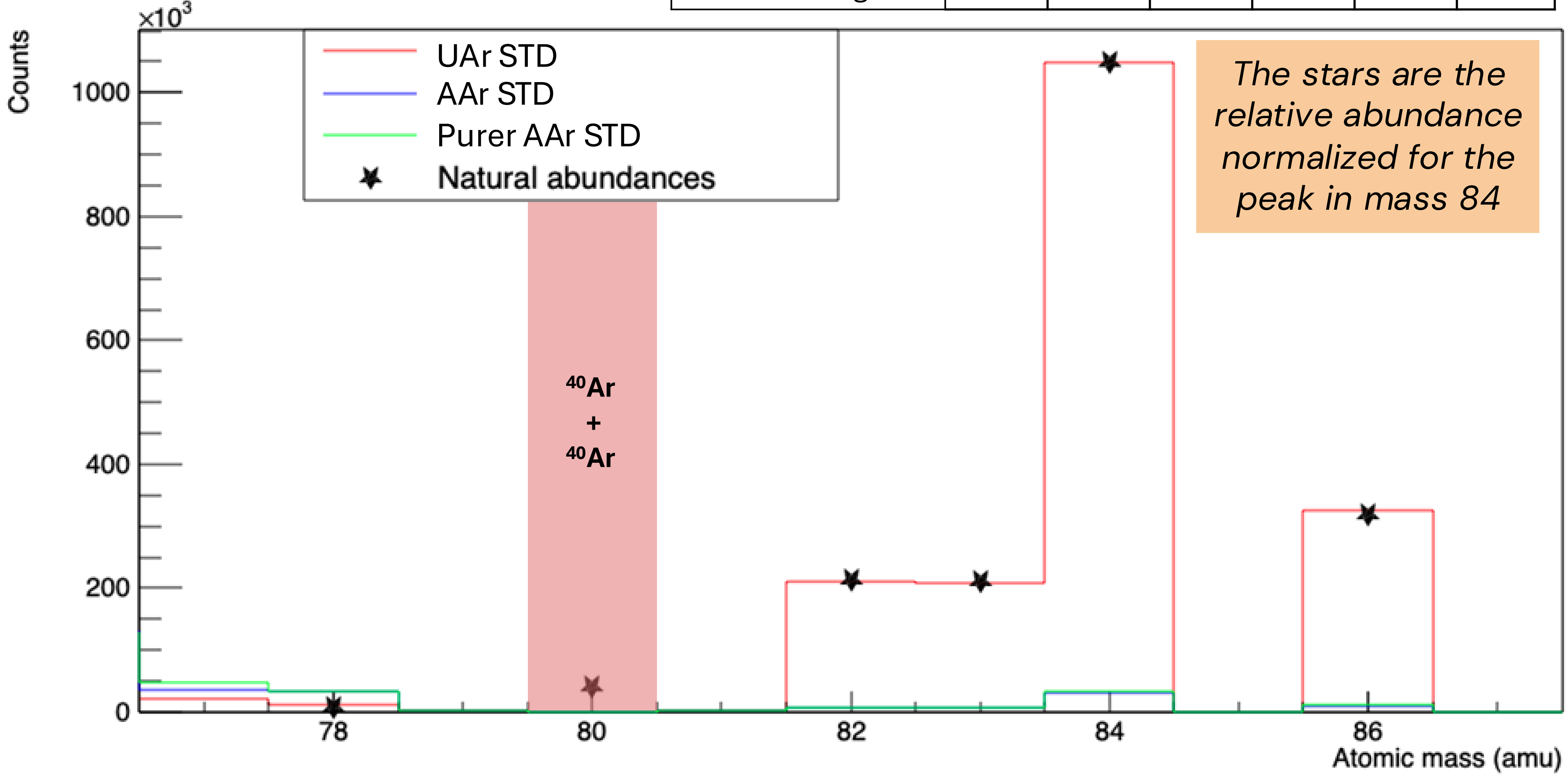
- **Standard mode** (STD).
- **With collision cell**: to reduce the spurious signal given by polyatomic ions: collision with a non-reactive gas (He). This process is called kinetic energy discrimination (KED).

In KED mode some masses forbidden in STD mode can be measured.

Measurement in STD (Zoomed in the Kr)

ICP-MS in Standard mode

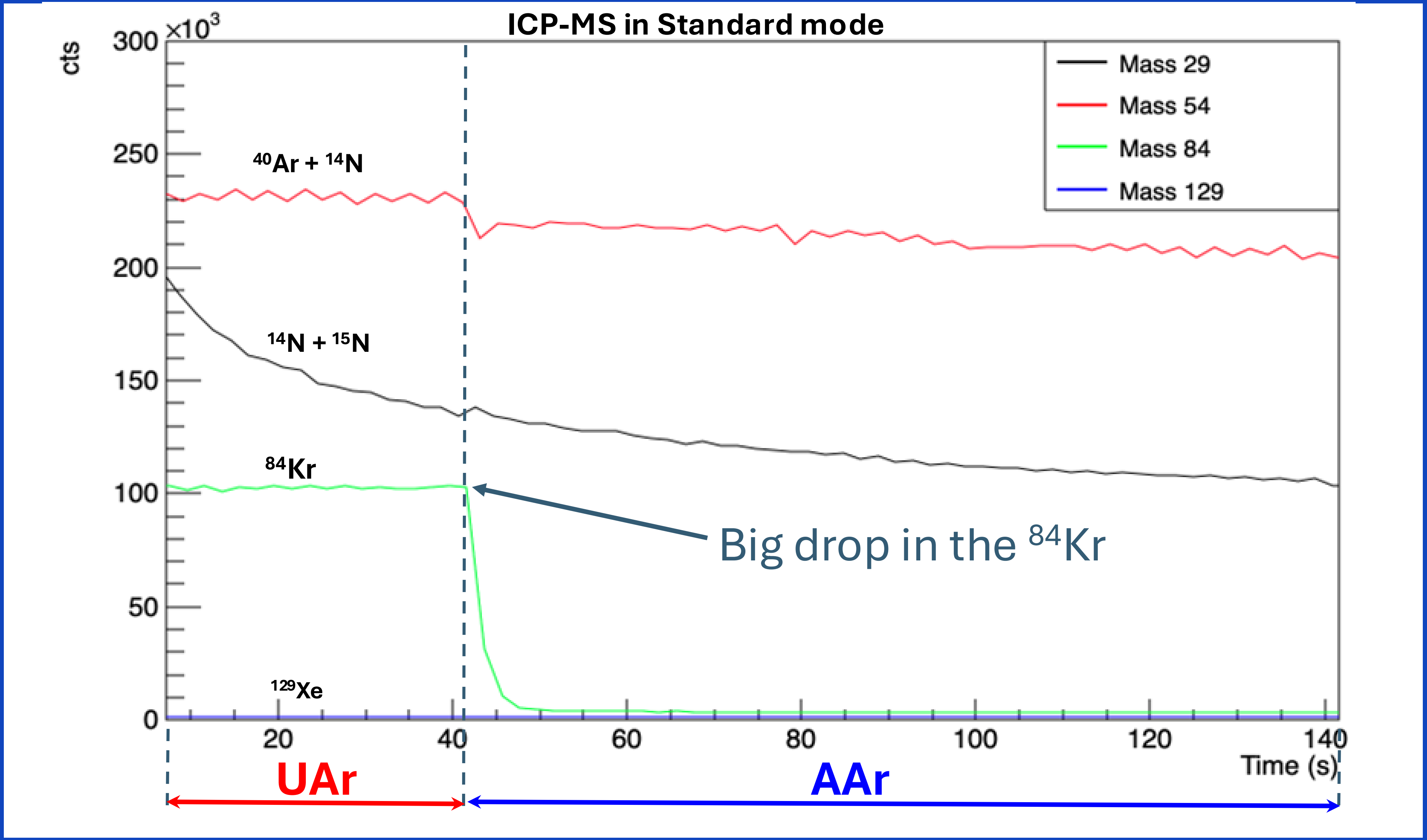
	Natural abundances					
Atomic mass	78	80	82	83	84	86
Percentage	0.35	2.25	11.6	11.5	57.0	17.3



The stars are the relative abundance normalized for the peak in mass 84

The presence of Kr in the UAr of DS-50 is confirmed.

Monitoring some masses with ICP-MS



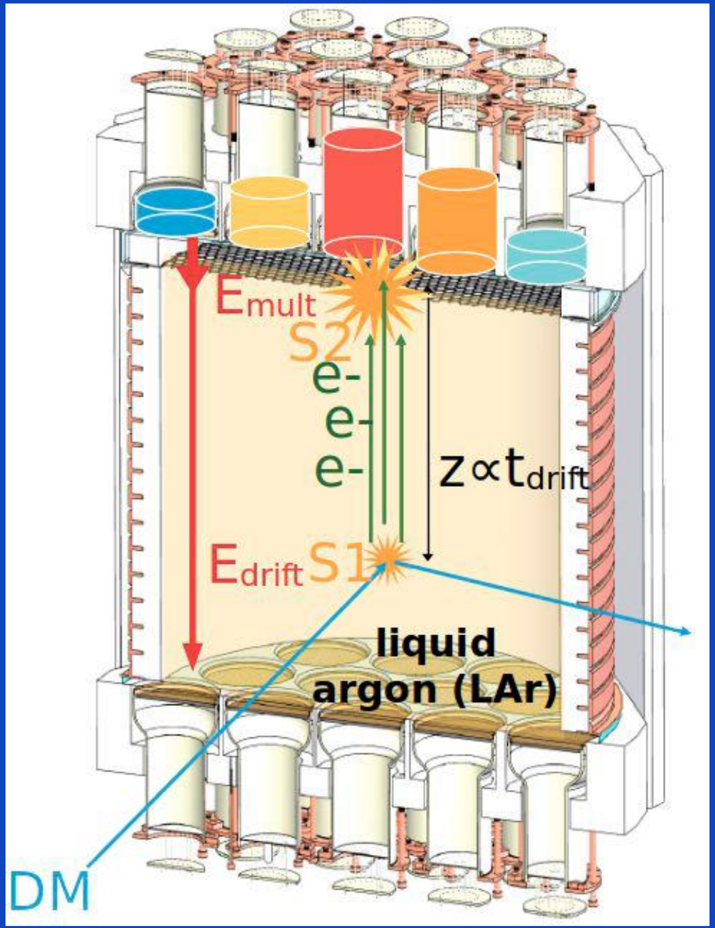
The change in the mass of the ^{84}Kr can be observed in just a few seconds.

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

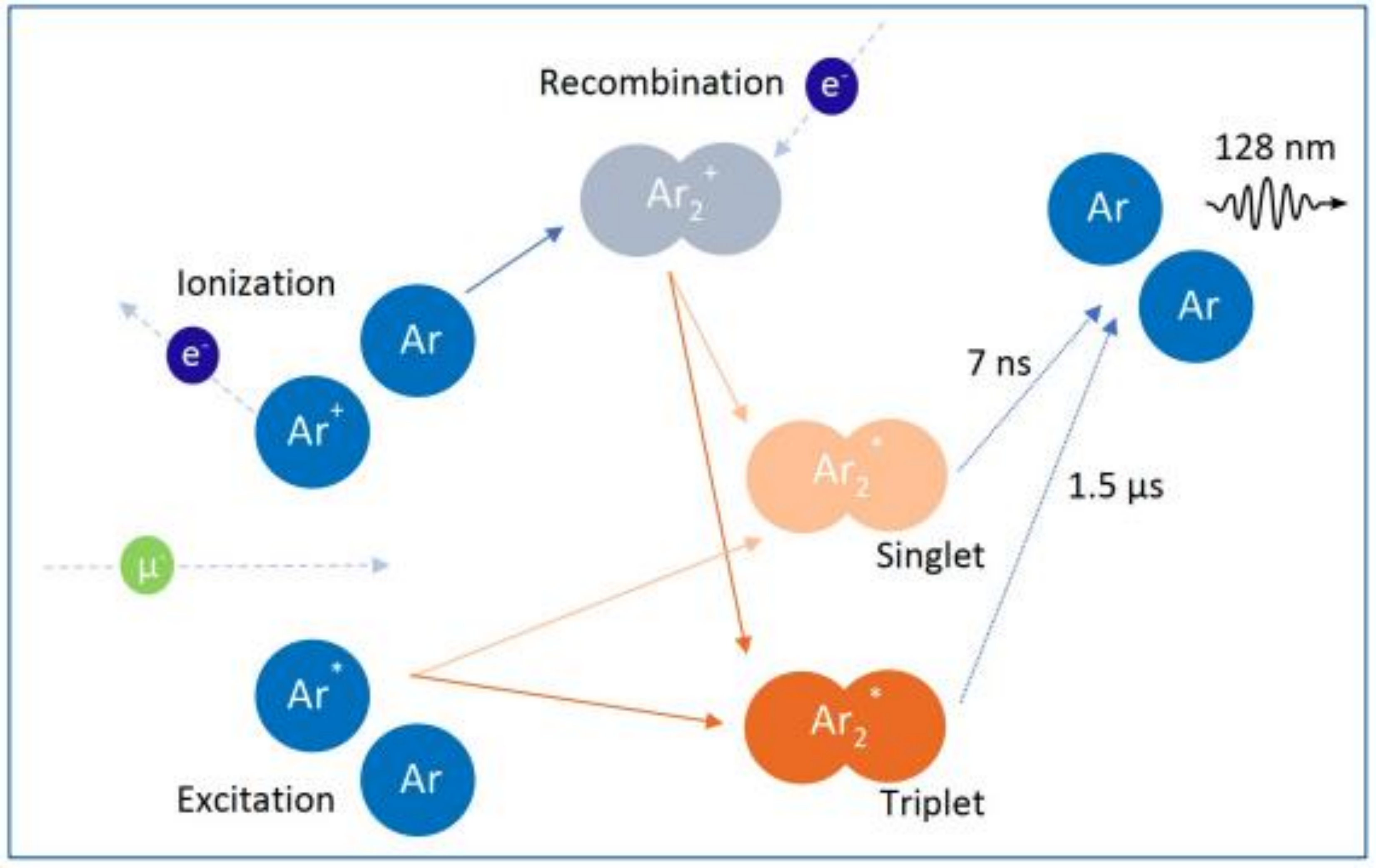
light pattern in detection plane provides XY information

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

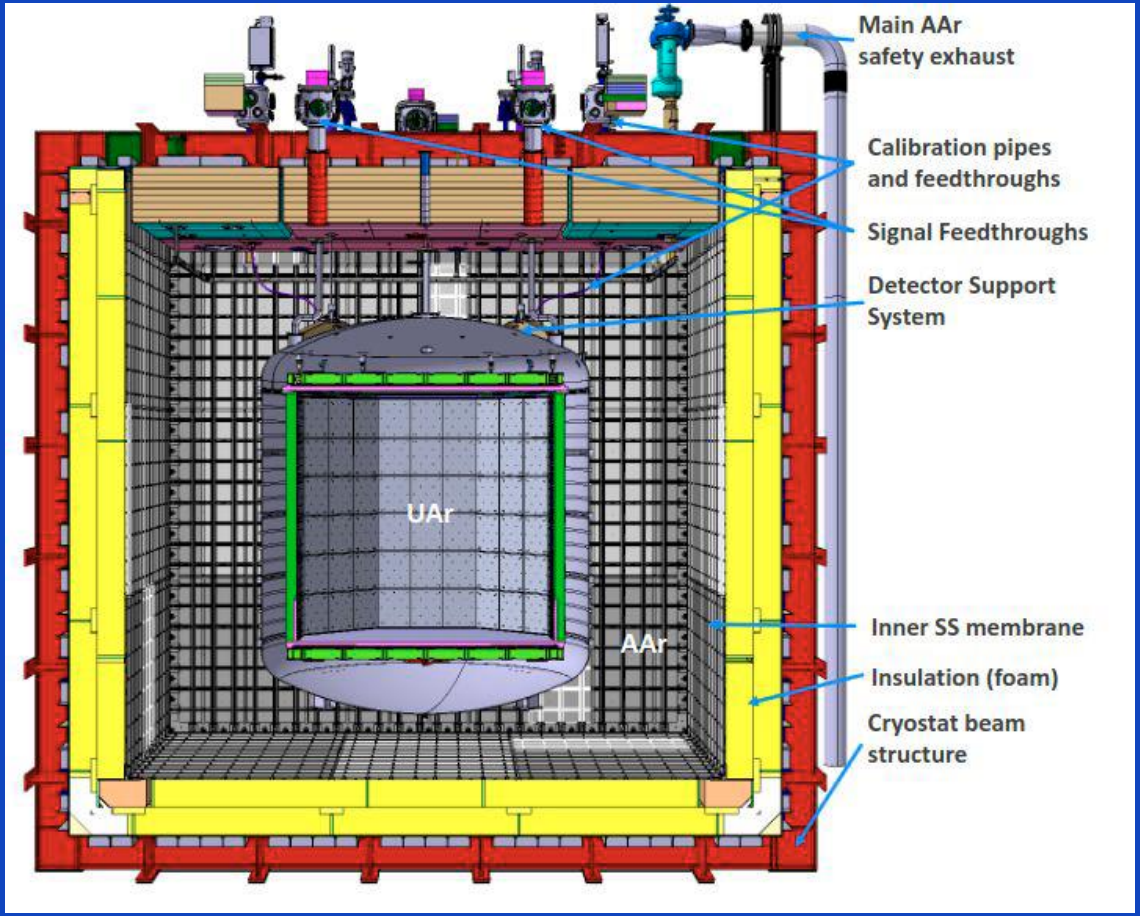
S2/S1 provides particle discrimination

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

Ar Excitation and ionization process



DarkSide-20k



90 tonnes of UAr

50 TPC (20 fiducial) + 40 Veto

650 tonnes of AAr as buffer and muon veto

ProtoDune-like cryostat

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

First detector of the Global Argon Dark Matter Collaboration

UAr in other experiments: Legend-1000

- **LEGEND-200**: Initial phase deploying ~200 kg of enriched germanium detectors (^{76}Ge) in liquid argon (LAr) at LNGS. Taking data with ~140 kg.
- **LEGEND-1000**: Planned to employ 1000 kg of ^{76}Ge in UAr.

^{42}Ar

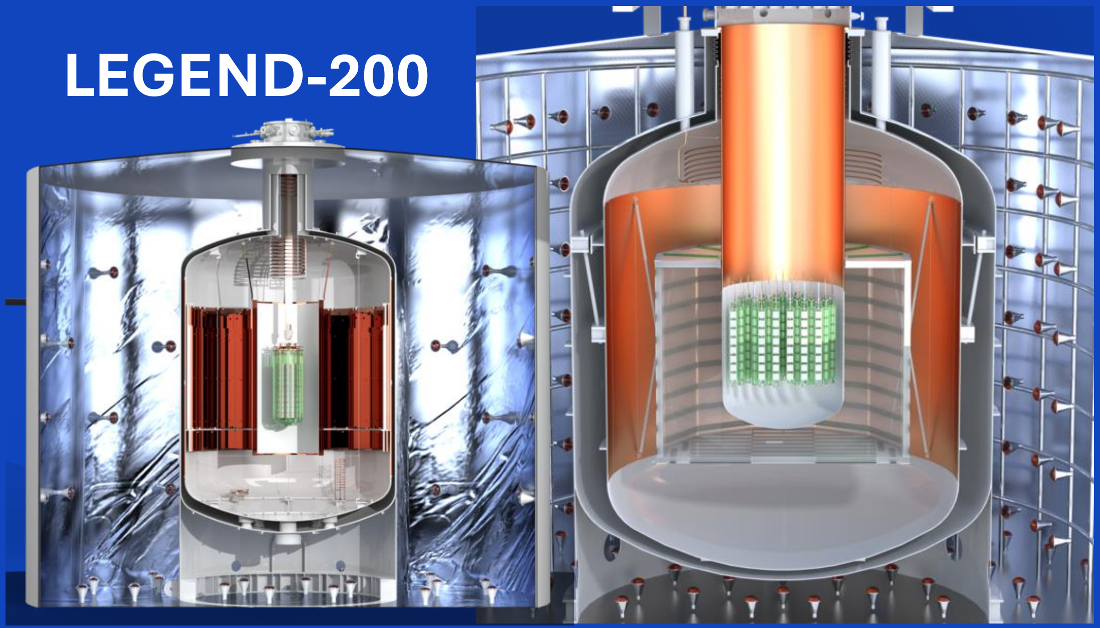
Intrinsic activity of ^{42}Ar in AAr

Cosmogenic: $^{40}Ar(\alpha, 2p)^{42}Ar$

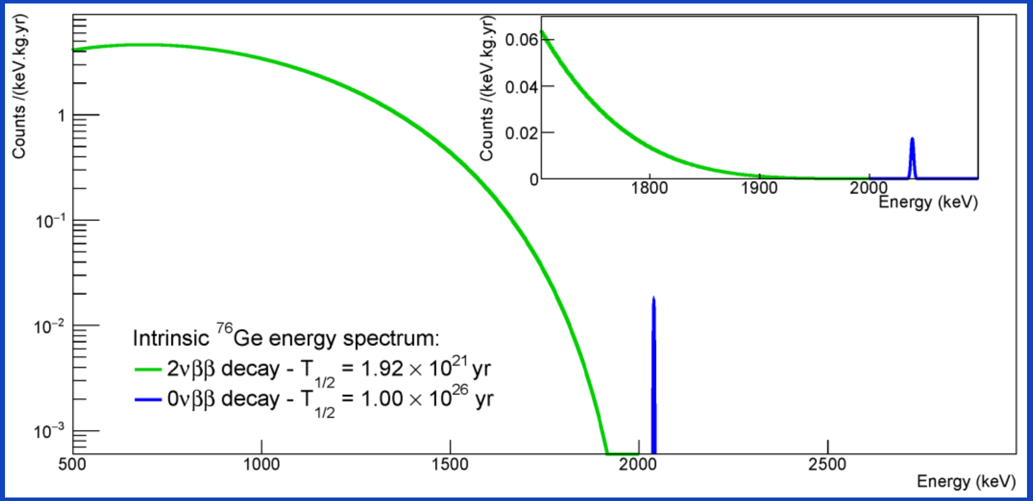
- β^- decay to ^{42}**K** with Q_β **= 599 keV**
- $t_{1/2}$ = 32.9 y
- 40.4 ± 5.9 μBq/kg
  - ^{42}**K** is a β^- with a $t_{1/2}$ = 12.4 h
  - β^- decay to ^{42}**Ca** with Q_β **= 3.5 MeV**

LEGEND-1000

LEGEND-200

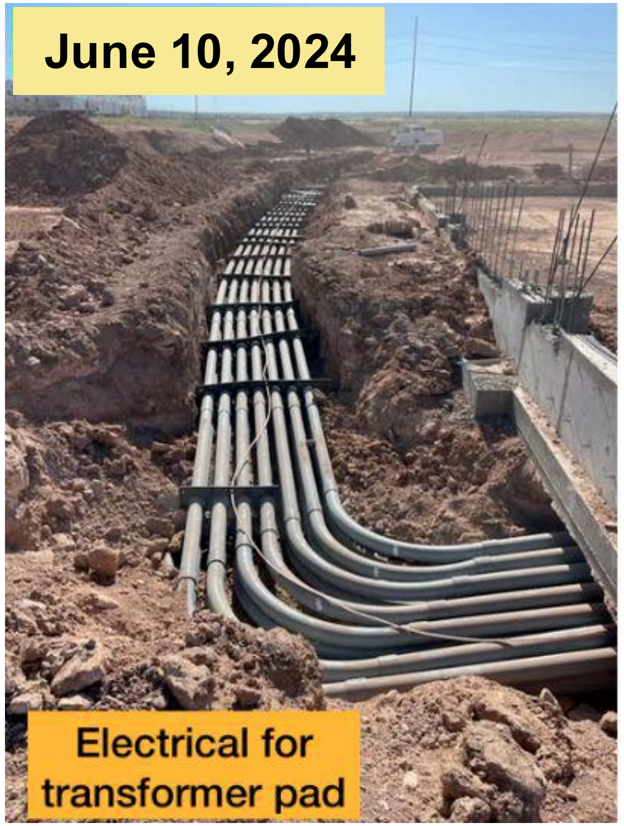


Same ROI of the $\beta\beta$ decay of ^{76}Ge: $Q_{\beta\beta}$ = 2.04 MeV



Urania ➡ Plant built and assembled at Polaris. Stored in Houston.

Urania ➡ Installation on site (Cortez, Colorado)



Commissioning run this year!

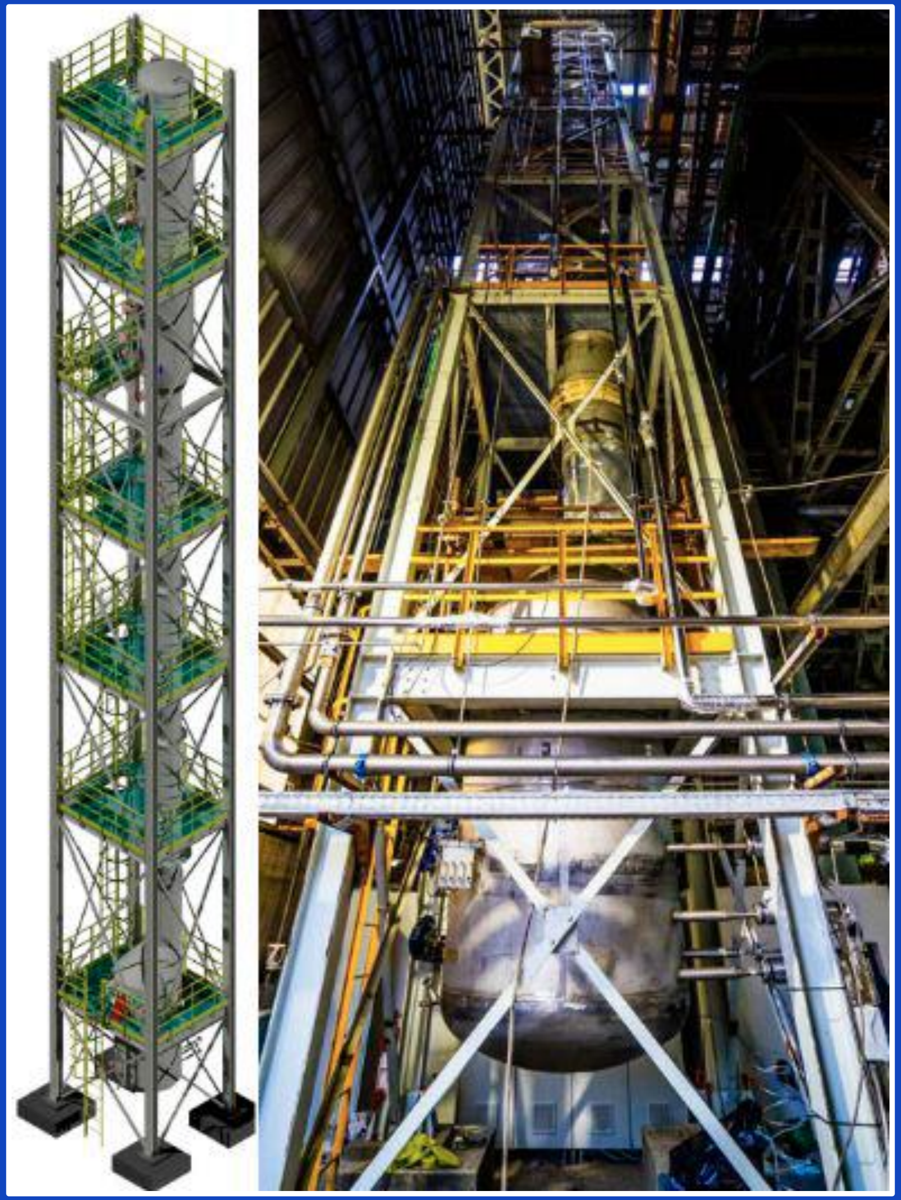
Aria ➡ Seruci-0

Reduced scale cryogenic distillation column (total ~26 m)

- 1 Central modules 12 m
- 1 Condenser top module: 7 m
- 1 Reboiler bottom module: 5 m

First operation with nitrogen in:
2019 Eur. Phys. J. C (2021) 81:359

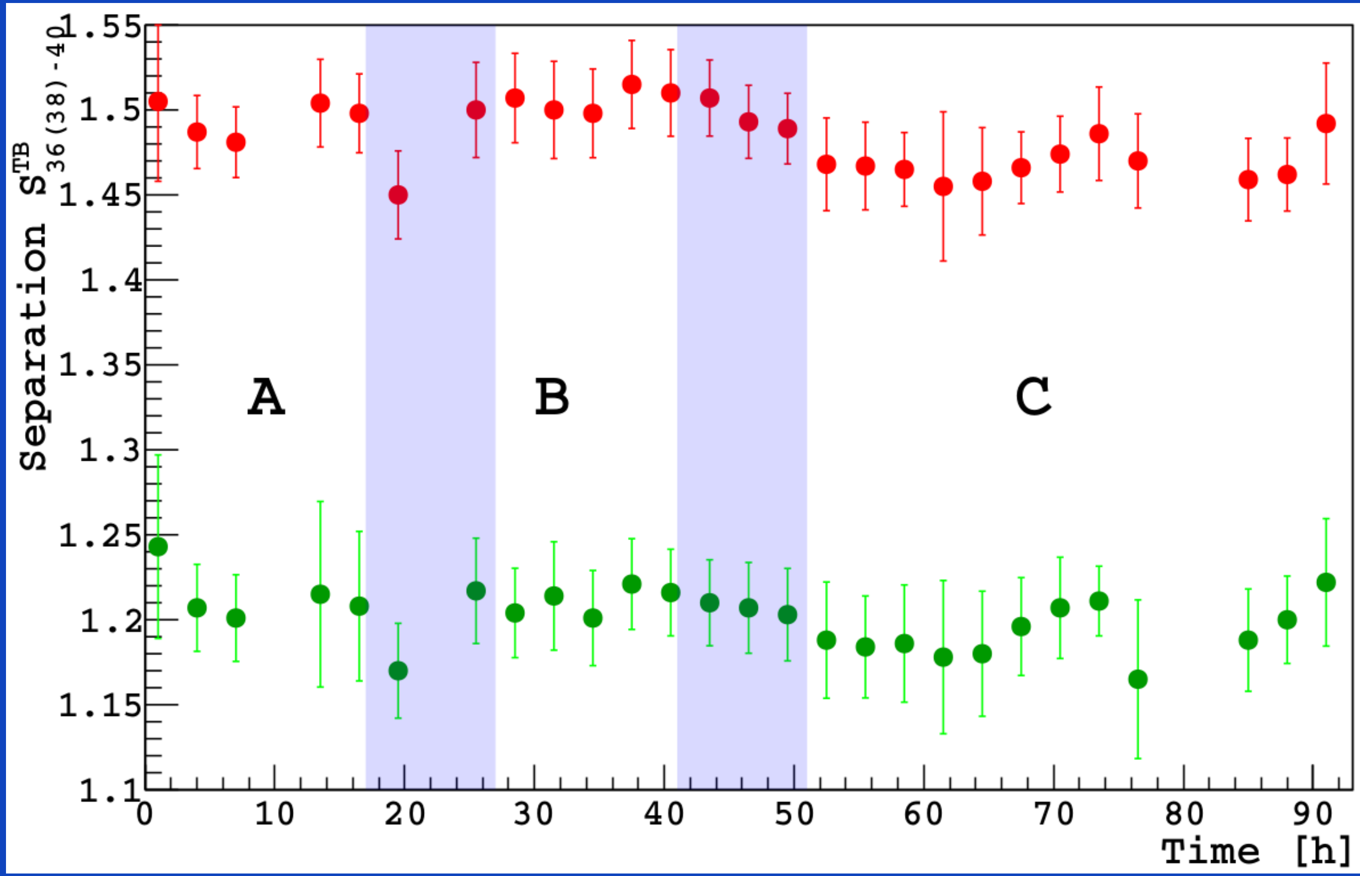
Second operation with argon in:
2021 Eur. Phys. J. C (2023) 83:453



Aria ➡ Seruci-0

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

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

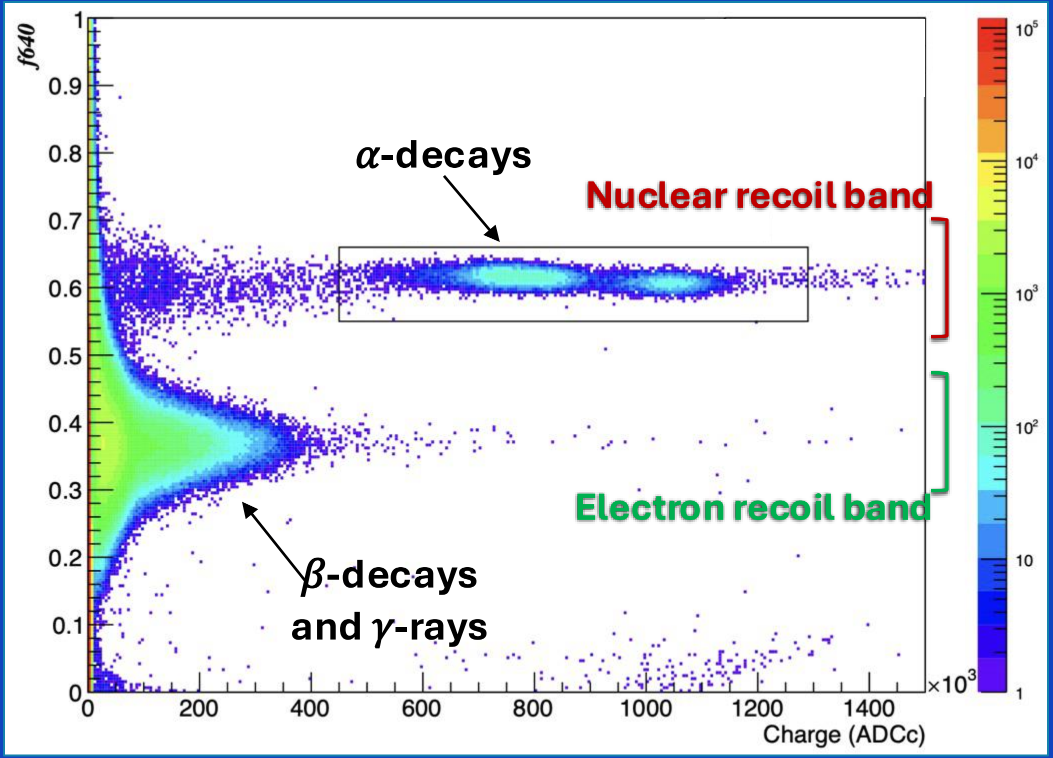


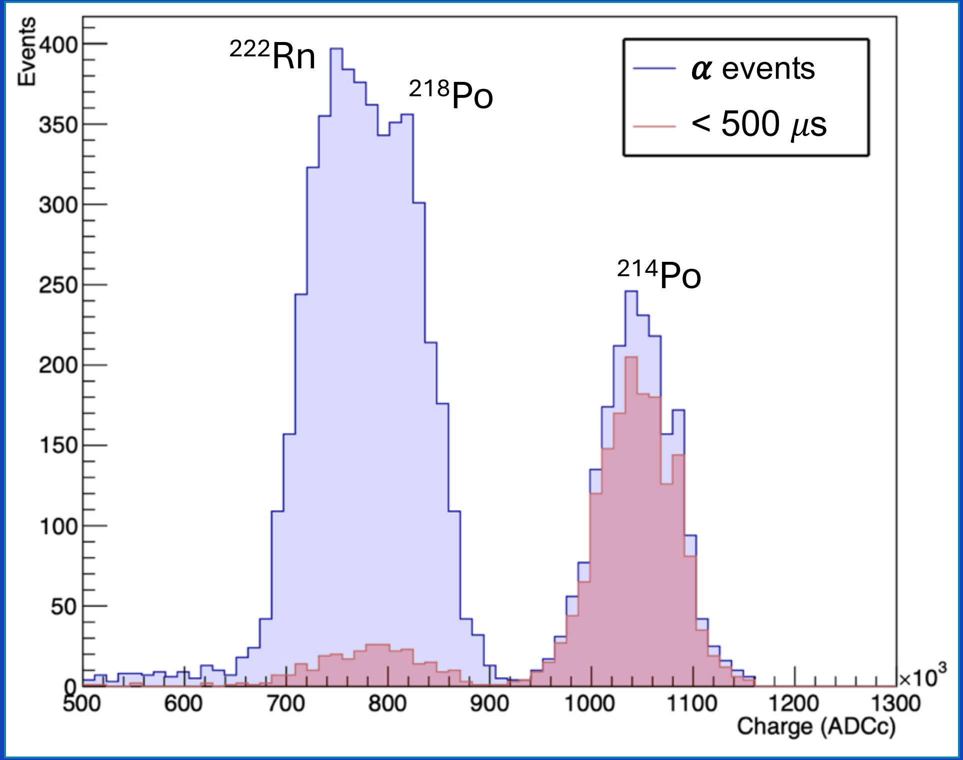
$$S_{36-40} = S_{T-B} = \frac{\left(\frac{x_{36}}{x_{40}}\right)_T}{\left(\frac{x_{36}}{x_{40}}\right)_B}$$

$$S_{38-40} = S_{T-B} = \frac{\left(\frac{x_{38}}{x_{40}}\right)_T}{\left(\frac{x_{38}}{x_{40}}\right)_B}$$

Characterization of events in LAr

Pulse shape discrimination (PSD)

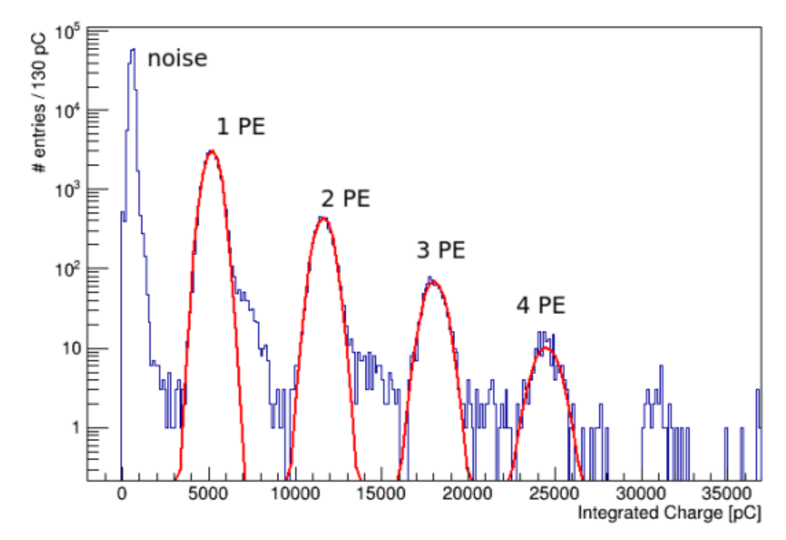




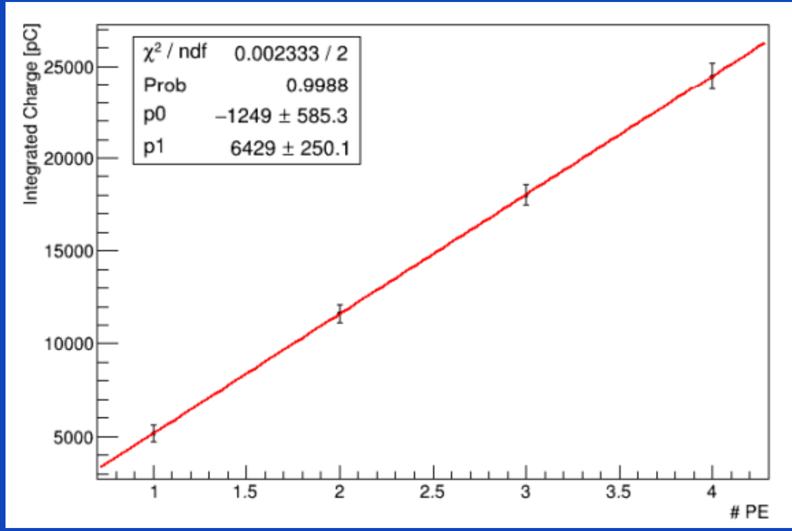
Measured $t_{1/2}(^{214}\text{Po}) = 166.6 \pm 2.6\ \mu s$

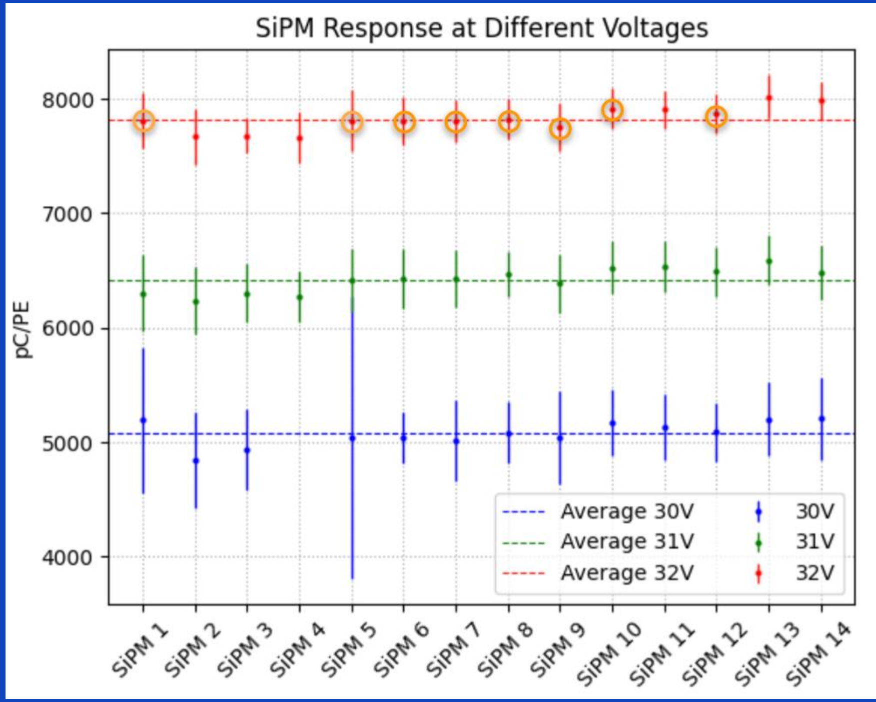
PSD + BiPo coincidence → Compatible with the value measured with more precise experiments: $t_{1/2}(^{214}\text{Po}) = 164.3\ \mu s$

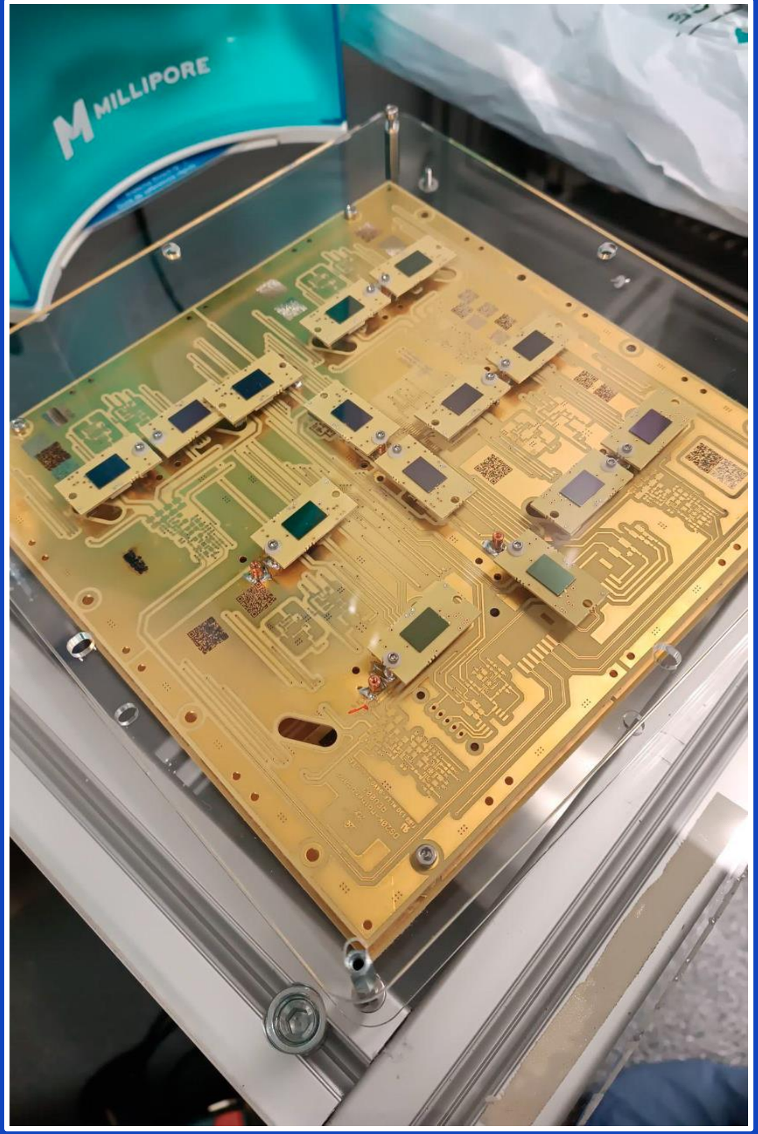
DArT-2.0: Characterization of the SiPM



SiPMs with similar response were selected based on their performance in cold.





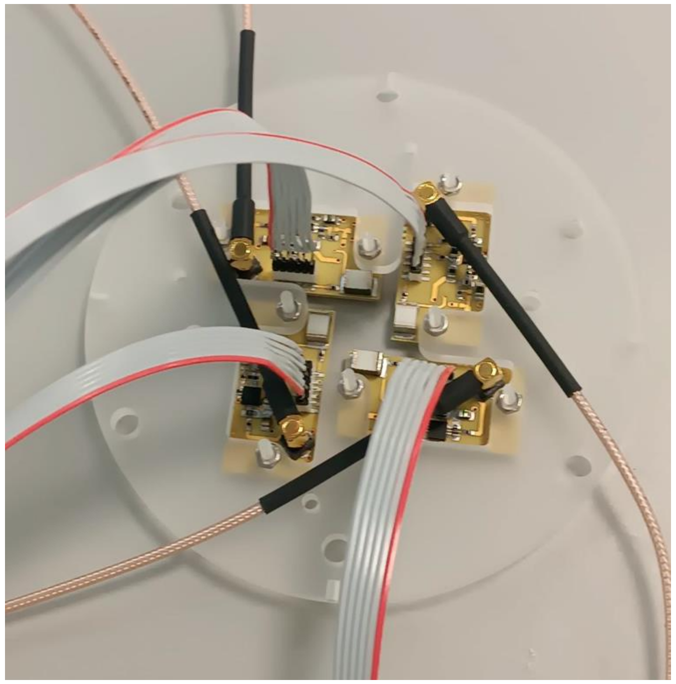


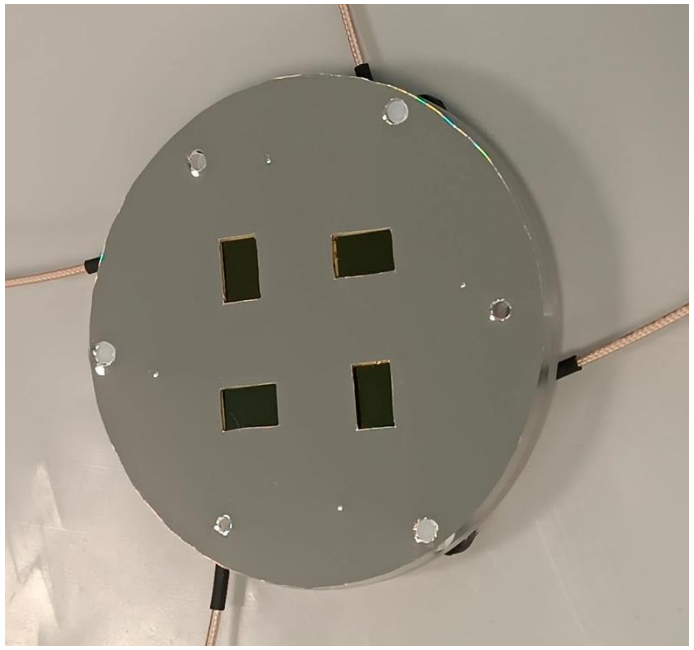
DArT-2.0: Cleaning and assembly

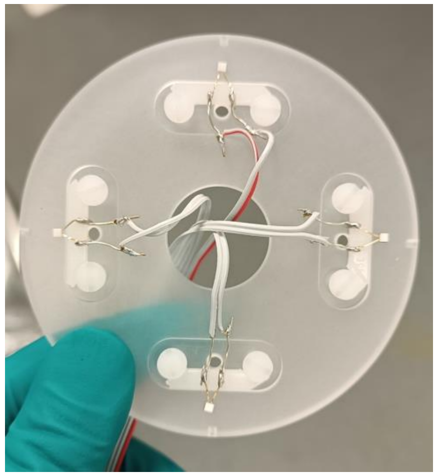
All the manipulations on DArT-2 performed in clean rooms/clean tents of LSC.

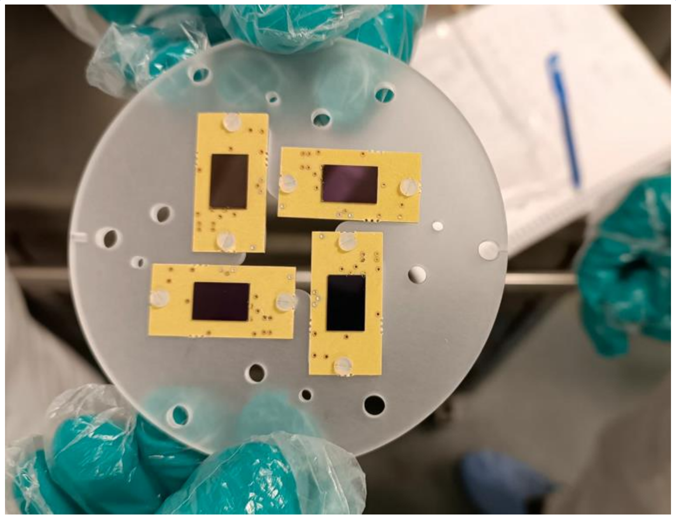
Exhaustive cleaning, specially of the metal parts: degreasing and rinsing in ultra sonic bath, etching and passivation.

DArT-2.0: Assembly SiPM planes and reflector





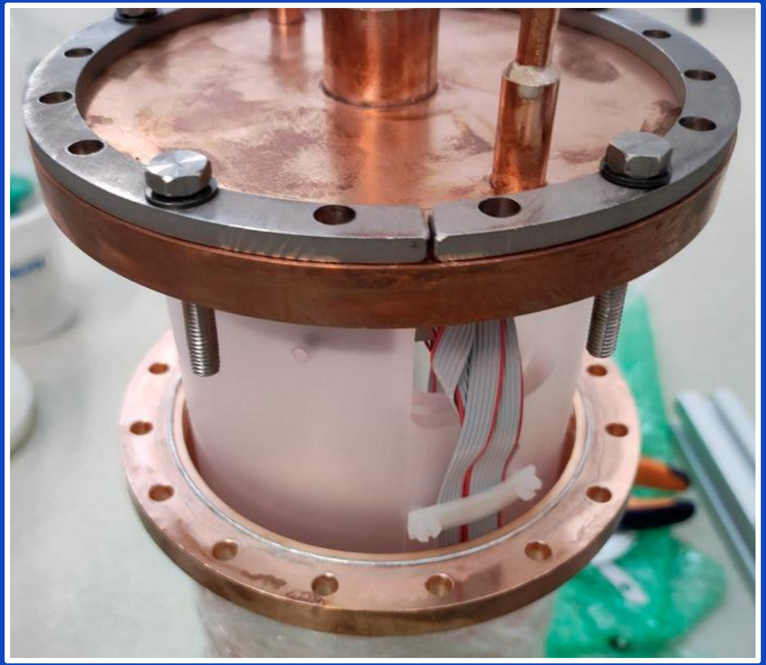


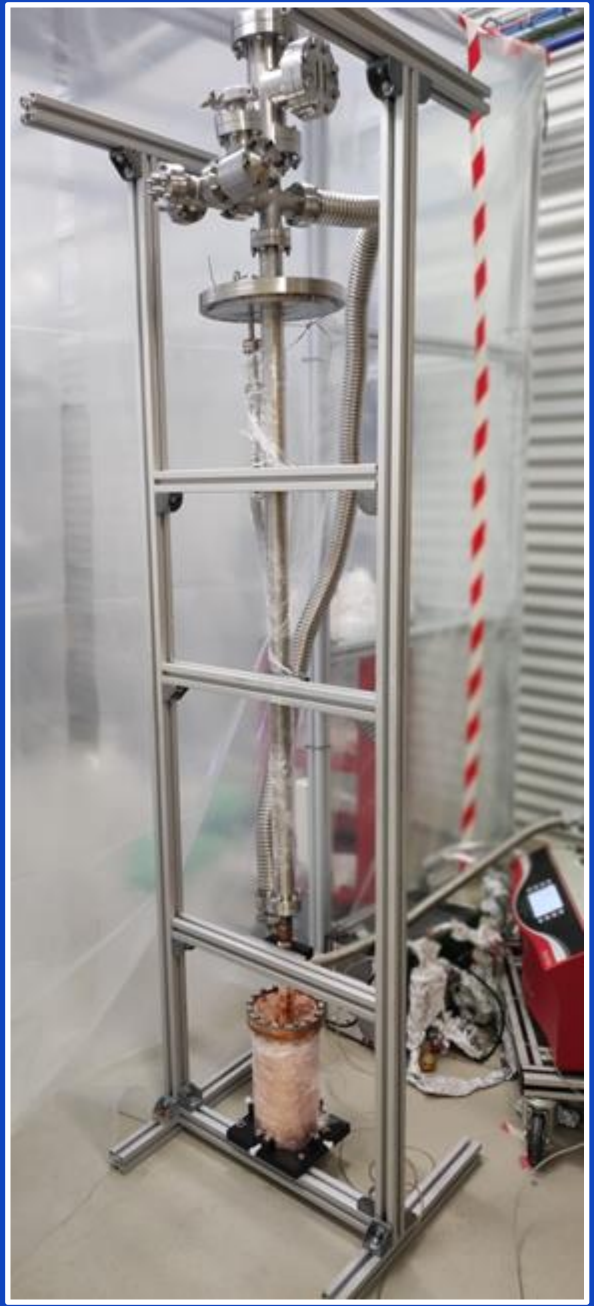


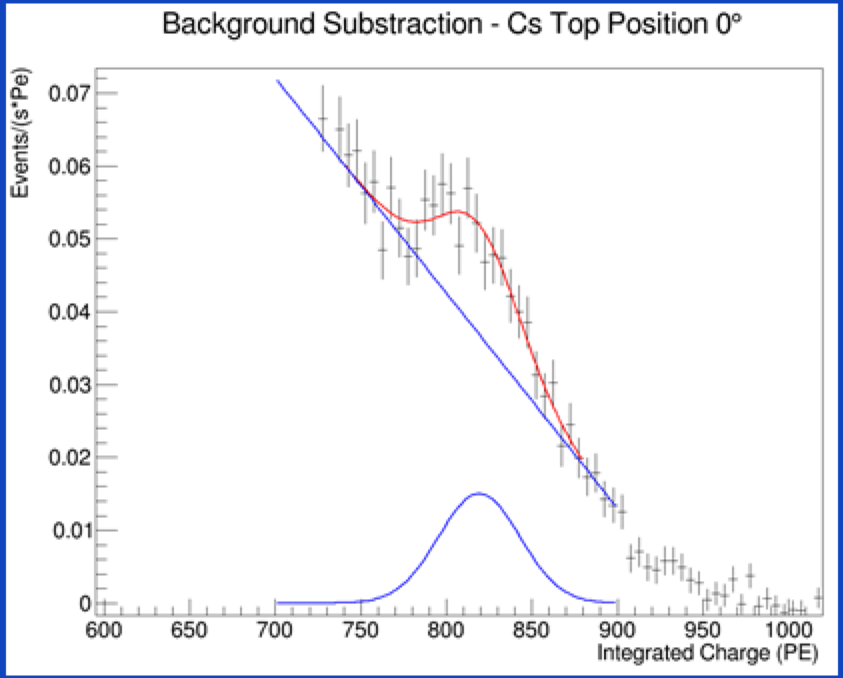
DArT-2.0: Closing the detector

Indium closure done:

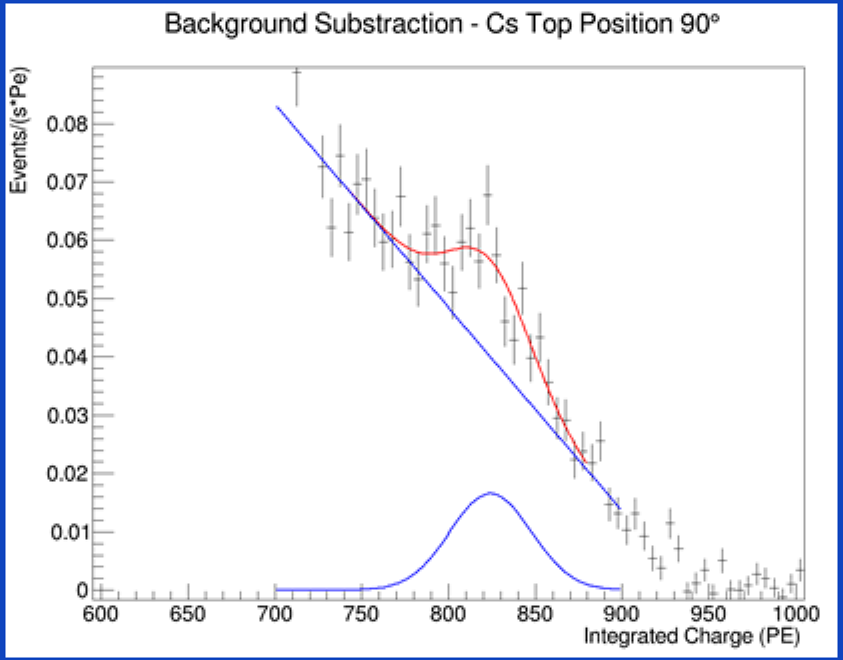
Tight at 10^{-9} mbar l / s



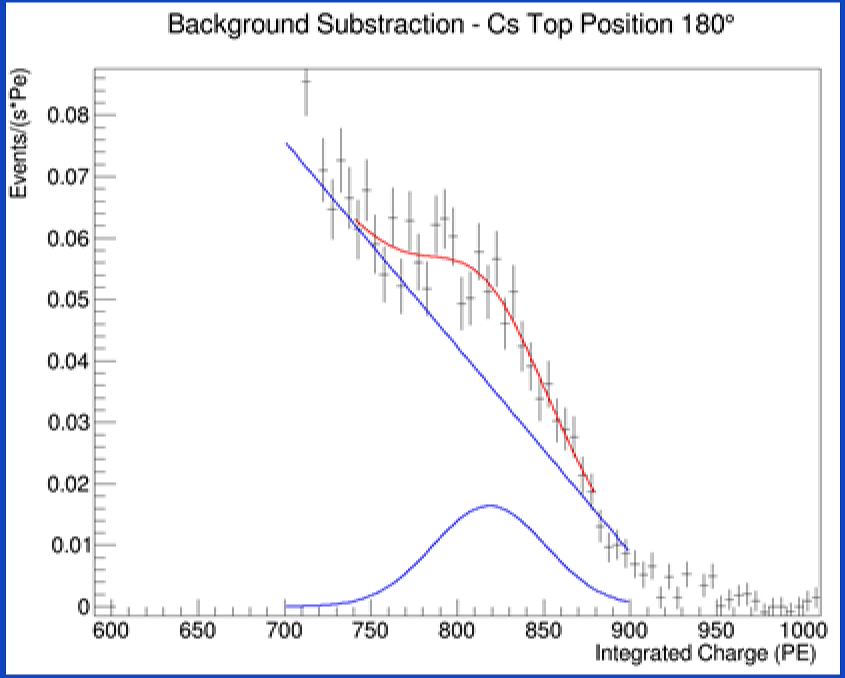




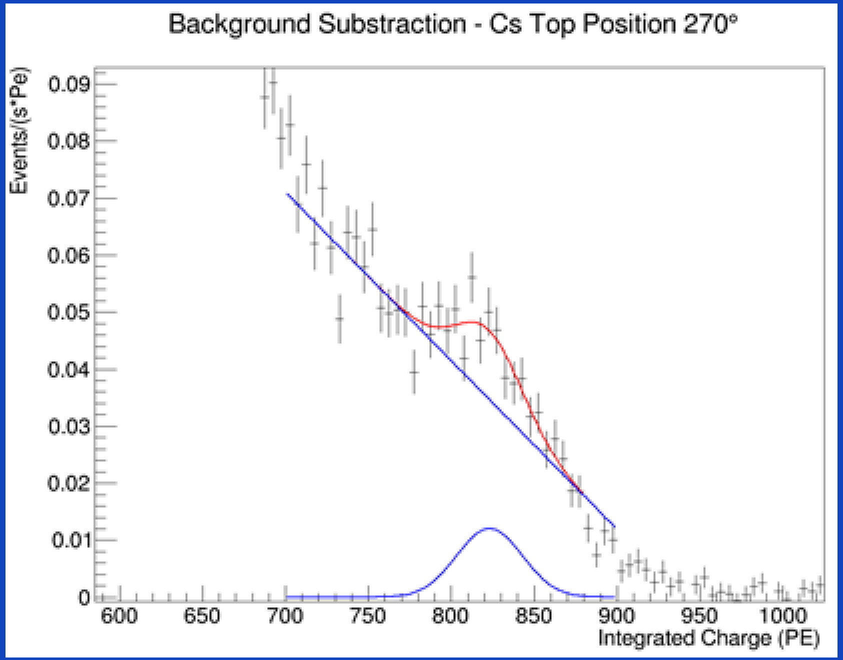
μ= 819 ± 4
σ= 24 ± 4
χ^2 = 16.0
NDf= 23



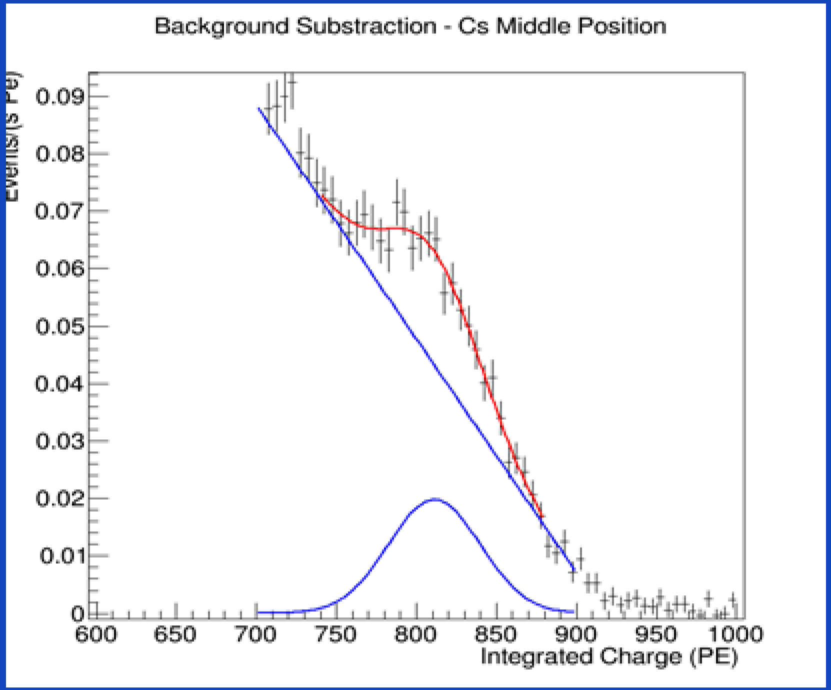
μ= 824 ± 4
σ= 23 ± 7
χ^2 = 26.5
NDf= 23



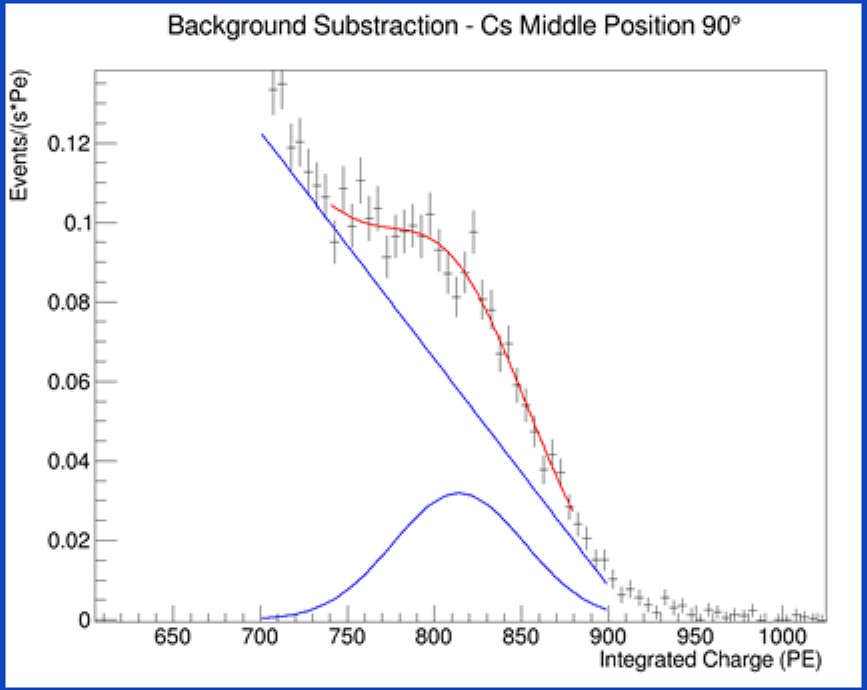
μ= 818 ± 7
σ= 32 ± 11
χ^2 = 22.3
NDf= 23



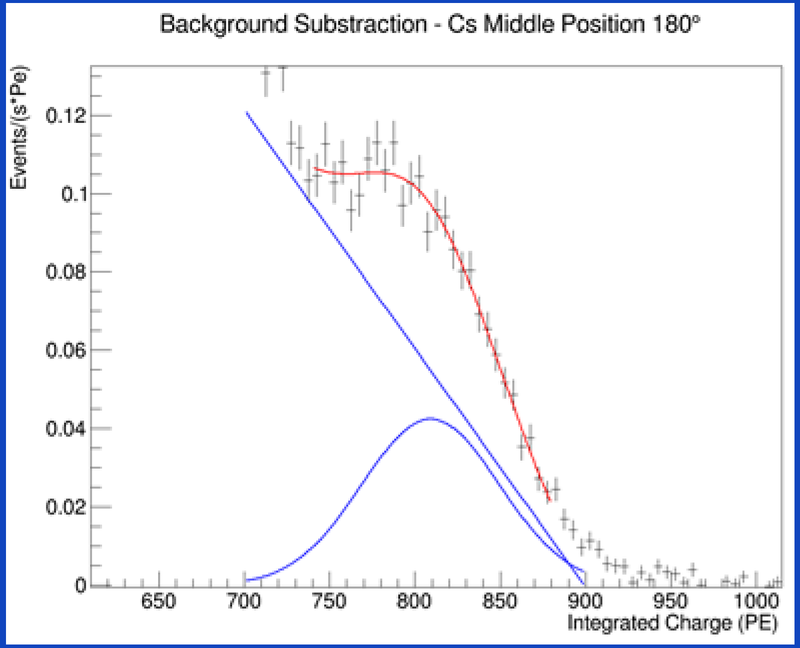
μ= 823 ± 4
σ= 20 ± 5
χ^2 = 25.0
NDf= 23



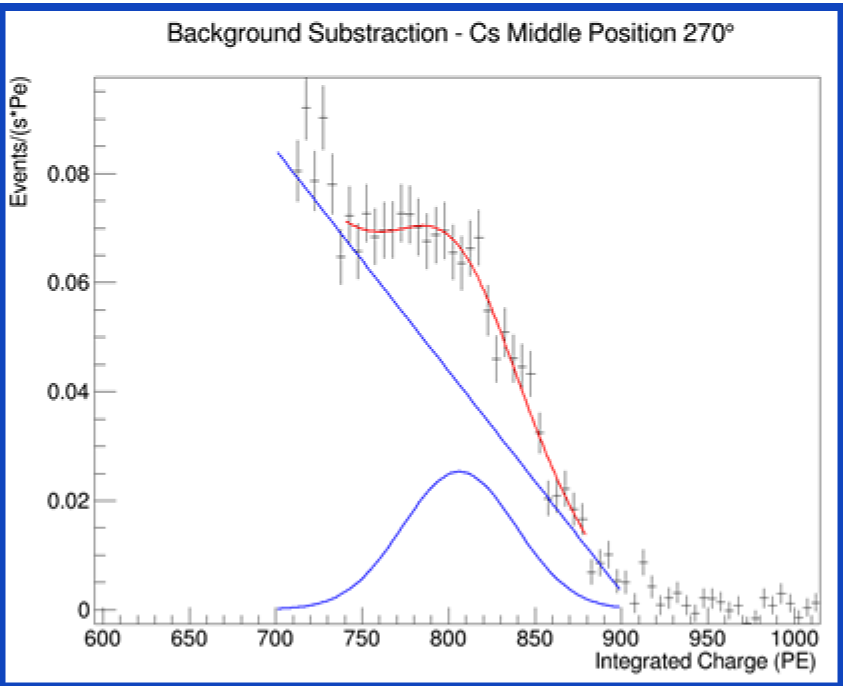
$\mu = 811 \pm 3$
$\sigma = 29 \pm 5$
$\chi^2 = 10.6$
NDf= 23



$\mu = 814 \pm 5$
$\sigma = 38 \pm 12$
$\chi^2 = 28.3$
NDf= 23



$\mu = 809 \pm 5$
$\sigma = 40 \pm 9$
$\chi^2 = 20.5$
NDf= 23



$\mu = 806 \pm 5$
$\sigma = 32 \pm 7$
$\chi^2 = 19.8$
NDf= 23

Calibration Measurements

Cs Position	Calibration (PE/keV)
Top Position 0º	1.24 ± 0.01
Top Position 90º	1.25 ± 0.01
Top Position 180º	1.24 ± 0.01
Top Position 270º	1.24 ± 0.01
Middle Position 0º	1.23 ± 0.01
Middle Position 90º	1.22 ± 0.01
Middle Position 180º	1.22 ± 0.01
Middle Position 270º	1.21 ± 0.01

- Coincidence in all runs
- Systematic errors

Mean calibration = 1.23 ± 0.01 PE/keV

UAR activation

Calculations done by Susana Cebrián (UNIZAR), to be compare with **0.7 mBq/kg**, the activity of the UAR.

					Flight 8 h		Flight 12 h		Sea level 15 d		Sea level 30 d		Sea level 45 d	
Isotope		R	err	f flight	A	err	A	err	A	err	A	err	A	err
		(kg-1 d-1)			(microBq/kg)		(microBq/kg)		(microBq/kg)		(microBq/kg)		(microBq/kg)	
39Ar	n	759	128	257.5	5.324	0.898	7.985	1.347	0.930	0.157	1.860	0.314	2.790	0.471
	mu	172	26	18.0	0.085	0.013	0.127	0.019	0.211	0.032	0.422	0.064	0.632	0.096
	p	3.6	2.2	956.4	0.094	0.057	0.141	0.086	0.004	0.003	0.009	0.005	0.013	0.008
	g	113	21	169.2	0.520	0.096	0.780	0.144	0.138	0.026	0.276	0.051	0.415	0.077
	total	1048	133		**6.02**	**0.90**	**9.03**	**1.36**	**1.28**	**0.16**	**2.57**	**0.32**	**3.85**	**0.49**
		(from R. Saldanha et al, PRC 100, 024608 (2019)												
3H	n	168	53	257.5	**25.7**	**8.1**	**38.6**	**12.2**	**4.5**	**1.4**	**9.0**	**2.8**	**13.4**	**4.2**
		(DS estimate)												

					Flight 8 h		Flight 12 h		Sea level 15 d		Sea level 30 d		Sea level 45 d	
Isotope		R	err	f flight	A	err	A	err	A	err	A	err	A	err
		(kg-1 d-1)			(mBq/kg)		(mBq/kg)		(mBq/kg)		(mBq/kg)		(mBq/kg)	
37Ar	n	51	7.4	257.5	1.000	1.000	1.497	0.217	0.152	0.022	0.264	0.038	0.348	0.051
	p	1.3	0.4	956.4	0.095	0.029	0.142	0.044	0.004	0.001	0.007	0.002	0.009	0.003
	g	3.5	0.7	169.2	0.045	0.009	0.067	0.013	0.010	0.002	0.018	0.004	0.024	0.005
	th n	0.9	0.3	257.5	0.018	0.006	0.026	0.009	0.003	0.001	0.005	0.002	0.006	0.002
	total	56.7	7.5		**1.16**	**1.00**	**1.73**	**0.22**	**0.17**	**0.02**	**0.29**	**0.04**	**0.39**	**0.05**
		(from R. Saldanha et al, PRC 100, 024608 (2019)												