CHARACTERIZATION OF ^{39}Ar ACTIVITY FOR DARKSIDE-20k WITH DArTinArDM

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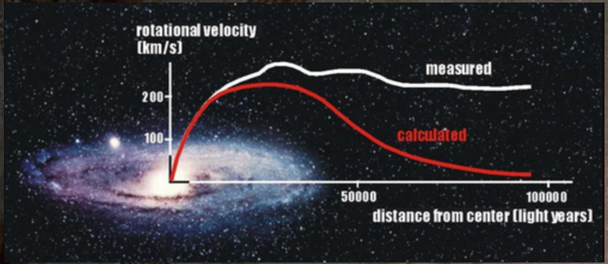
Evidences of Dark Matter

Rotational Velocity curves of spiral galaxies

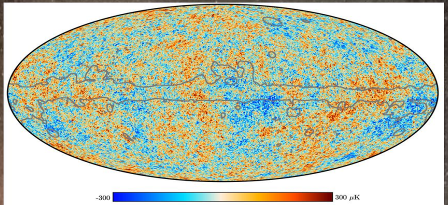


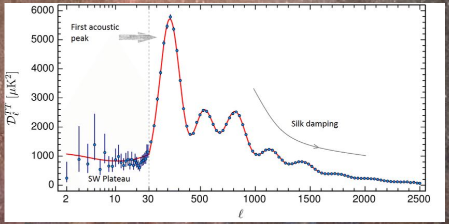
- While studying red-shifts in galaxy clusters in 1930s, F. Zwicky observed a very high mass-luminosity ratio.

⇒ more mass than visible

- Later in 1970s, multiple observations of flat galaxy rotation curves were done.

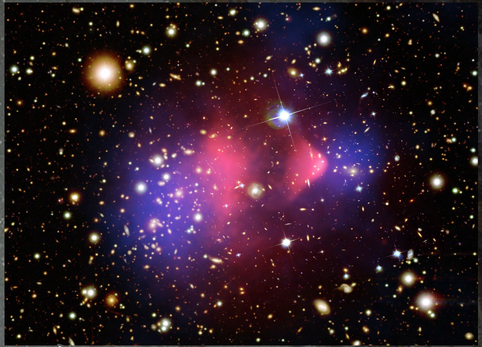
Anisotropies in cosmic microwave background (CMB) map





- CMB is an isotropic radiation produced 3.8×10^5 years after the big bang.
- It is along with it's acoustic peak spectrum together show that early gravitational potentials too strong to be produced by baryons alone.
- Indicates presence of cold dark matter.

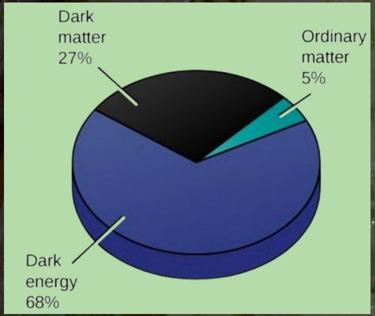
Gravitational lensing : Bullet Cluster



- Gravitational lensing was a prediction of general relativity, Implies the angle of deflection of light depends on the mass of object between the source and observer.
- The measured mass for large gravitational lenses is systematically ~5 times larger than the light-emission-inferred mass.
- This indicates some matter which is darker and less interacting

Candidate of Particle Dark Matter : WIMPs

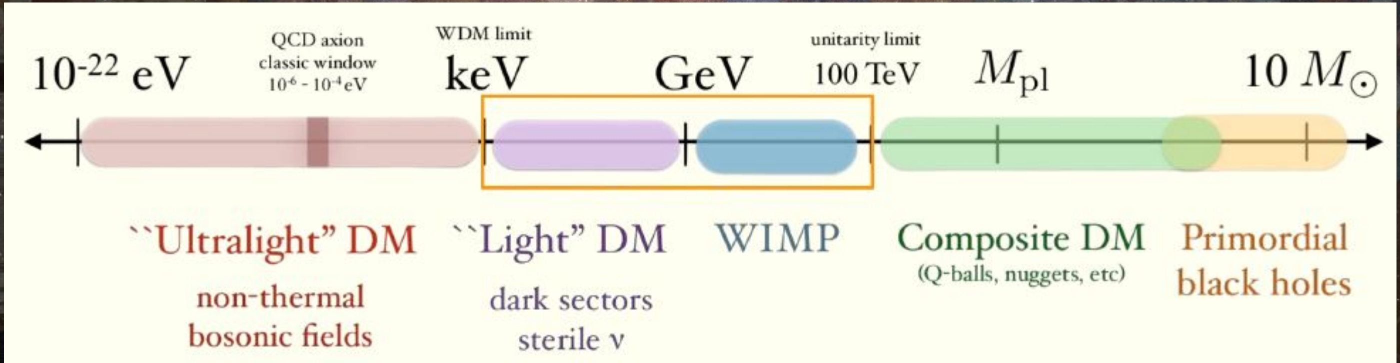
WIMPs : Weakly Interacting Massive Particles



With Occupying 27% of the total content of the universe, Dark Matter account for ~84% of matter content of the universe.

Dark Matter Properties

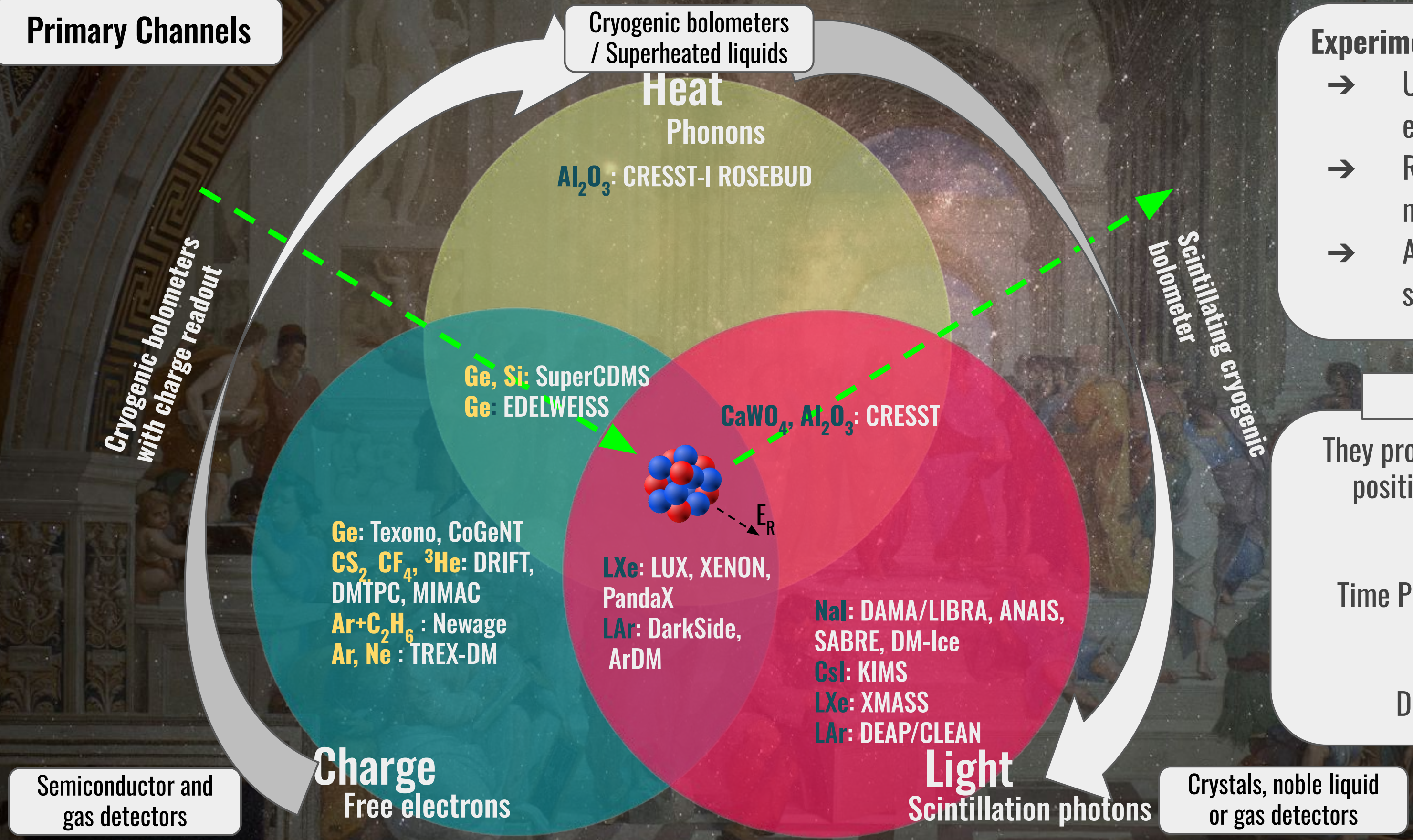
- Electrically neutral
- Non-baryonic/non-standard
- Massive
- Gravitational interaction
  But, no strong interaction
- Very stable/long-lived
- Cold



Direct detection of WIMPs

GOAL: To detect elastic scattering of WIMPs particles off atomic nuclei, producing very low nuclear energy recoils (~1–100 keV).

Primary Channels



Experimental Requirements

- ➔ Ultra-low background environment
- ➔ Radiopure detector materials
- ➔ Active and passive shielding

Charge + Light

They provide the advantage of event position reconstruction (in 3D)

↓

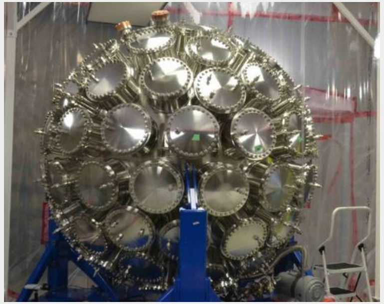
Time Projection Chambers (TPCs)

↓ Gas pocket on top of liquid volume (charge amplification)

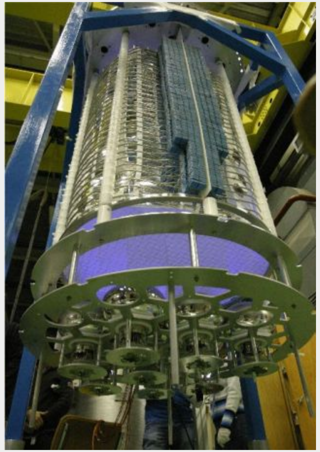
Dual - phase TPCs

Global Argon Dark Matter Collaboration (GADMC)

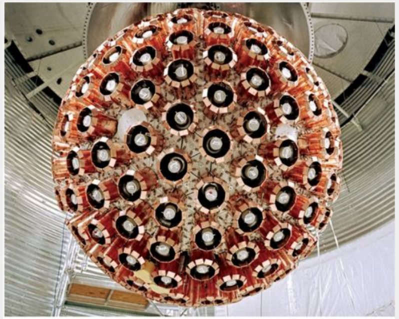
~ 100 institutions and more than 400 scientists from all the below shown experiments are contributing for the next generation direct dark matter search with Liquid Argon.



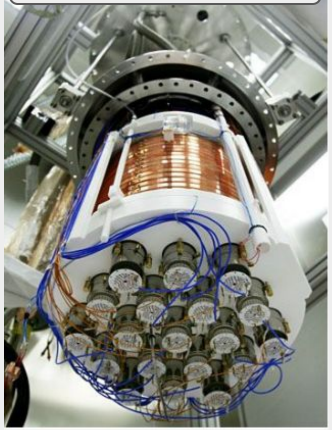
MiniCLEAN @SNOLAB



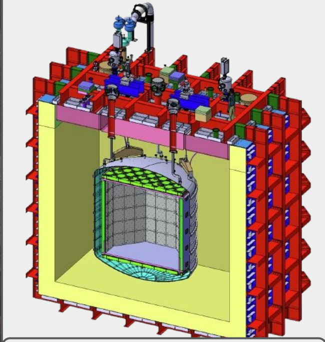
ArDM @LSC



DEAP 3600 @SNOLAB



DarkSide-50 @LNGS

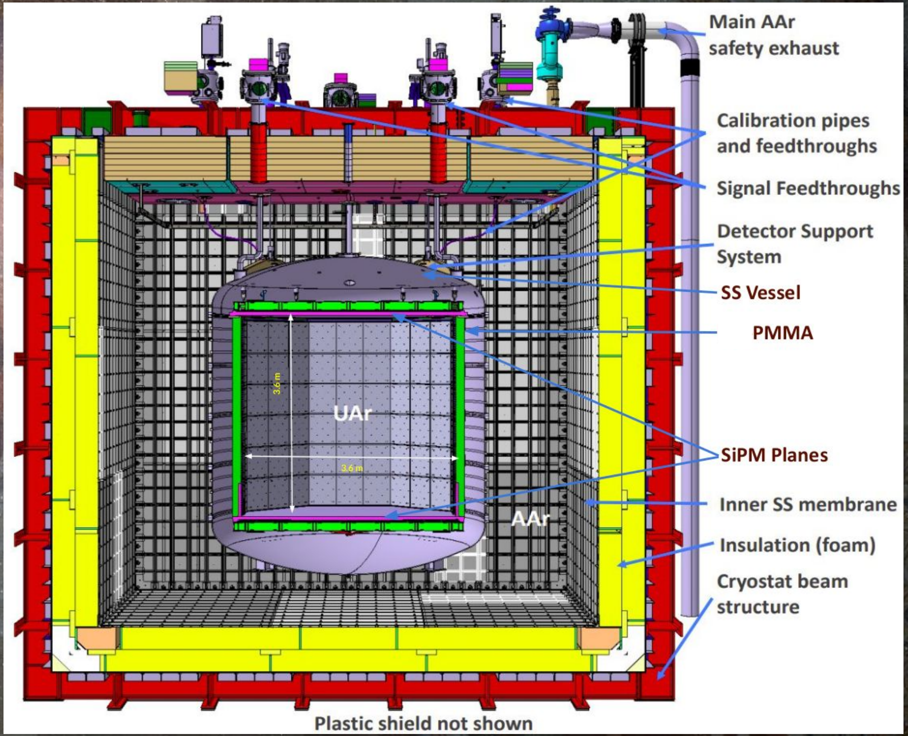


DarkSide-20k @LNGS

DarkSide-20k

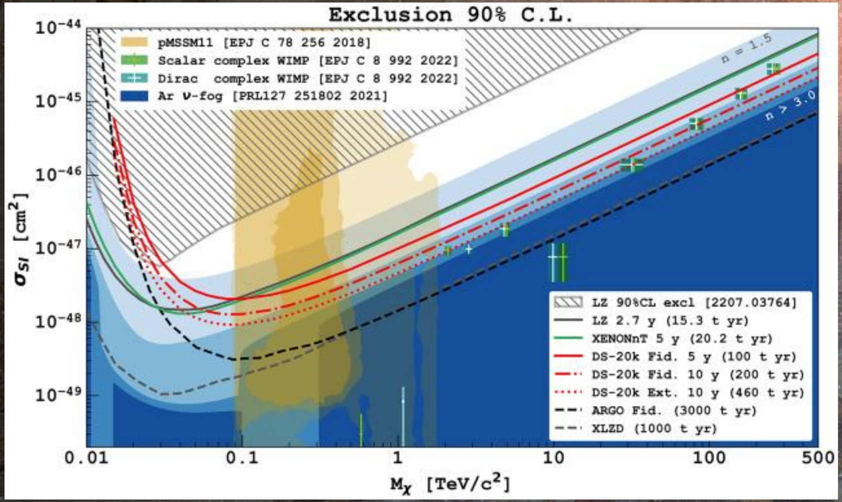
3800 m.w.e

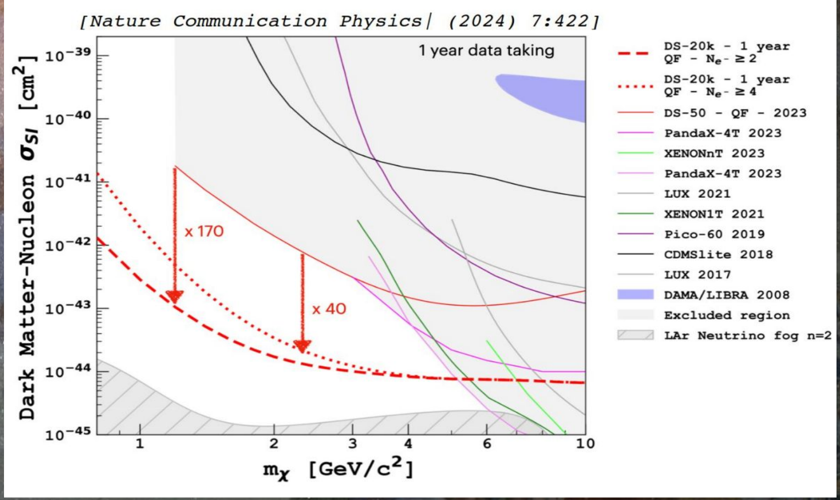
- DarkSide-20k is the next project of the GADMC after DarkSide-50.
- Under construction at Hall C of LNGS, Italy
- A 20-tonne fiducial dual phase TPC filled with UAr (50 tonnes total mass)
- TPC acrylic vessel surrounded by UAr + acrylic as a neutron veto.
- 21 m^2 of Cryogenic radiopure SiPMs
- The inner detector is immersed in the AAr bath (~700 tonnes)



DarkSide-20k

- ➔ Projected to lead the search for WIMPs over most of the canonical mass parameter space
- ➔ Exceptional sensitivity to light WIMPs in the ~1–10 GeV mass range
- ➔ Approaches the neutrino fog in liquid argon
- ➔ Best sensitivity to neutrinoless double electron capture in ^{36}Ar Sensitivity to SN and ^{8}B solar neutrinos





Argon in Dark Matter Detection

Why Argon?

- ❑ Negligible self absorption of photon → Efficient collection of scintillation light
- ❑ Lower atomic number → Improving sensitivity to low-energy nuclear recoils
- ❑ Excellent pulse shape discrimination (PSD) → Excellent background rejection
- ❑ High industrial availability and cheaper cost → Large multi ton detector are affordable

Many benefits yet ONE MAJOR PROBLEM : ^{39}Ar

Atmospheric Argon has

β^- decay with Q_β = 565 ± 5 keV (IAEA NDS)

Pure β emitter

$t_{1/2}$ = 269 y

Activity = 0.964± 0.001 Bq/kg (DEAP Eur. Phys. J. C 83, 642 (2023))

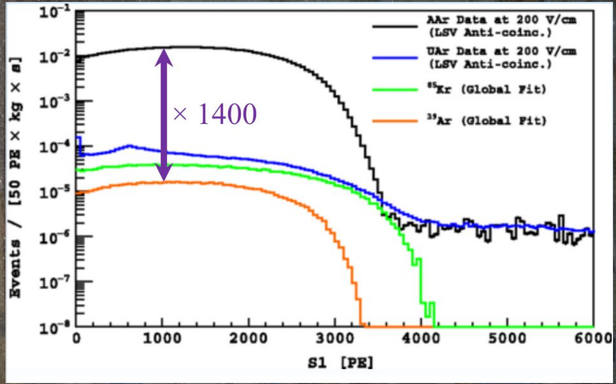
⬇

Will affect sensitivity of the detector

⬇

Solution

Use Underground Argon (UAr)

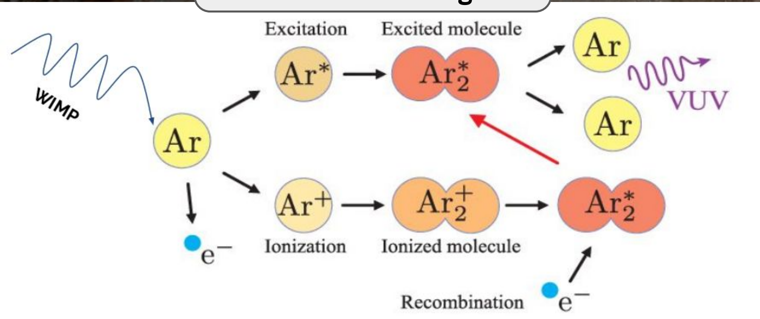


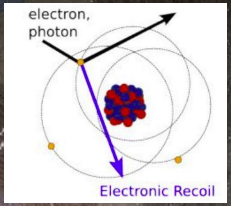
Significant reduction of ^{39}Ar

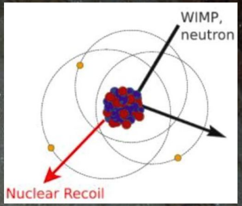
UAr has factor ≥1400 reduction in specific activity compared to AAr (DS-50)

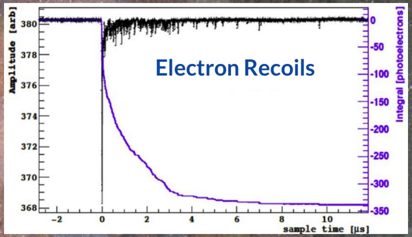
Particle Detection in Liquid Argon

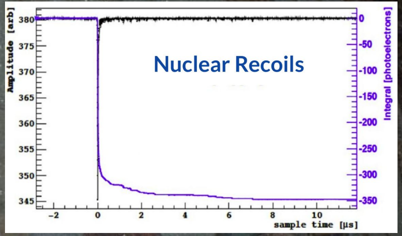
Mechanism of Primary scintillation in Argon









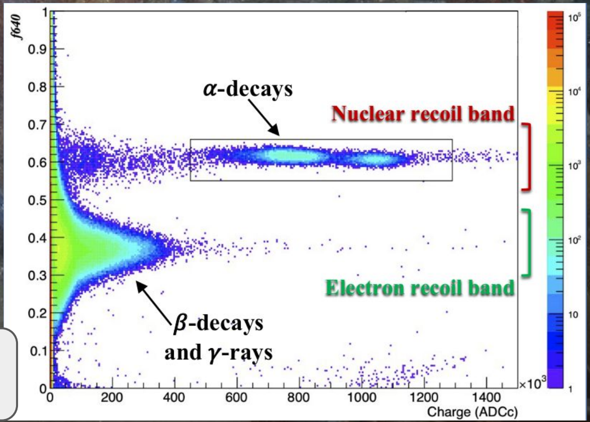


The characteristic emission of 128 nm photon is contributed by two exponential de-excitations:

Fast component: transition of singlet state ⇨ ground state (~ 7 ns)

Slow component: transition of triplet state ⇨ ground state (~ 1.6 μs)

PSD in Liquid Argon (LAr)



Underground Argon Program

A dedicated system for extraction, purification, characterization of underground argon (UAr) has been specially established for experiments under GADMC.

Extraction: Urania (Colorado, USA)
Procurement of 120 tonnes of UAr from CO_2 well.
Extraction of 250-330 kg/day, with 99.9% purity.

Characterisation: DArTinArDM (LSC, Spain)
Measurement of the ^{39}Ar depletion factor in UAr

Final Implementation: DarkSide-20k (LNGS, Italy)

Purification: Aria (Sardinia, Italy)
350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements.
Can process 1 tonne/day with 10^3 reduction of all chemical impurities.

DArTinArDM

@LSC, Spain

2400 m.w.e

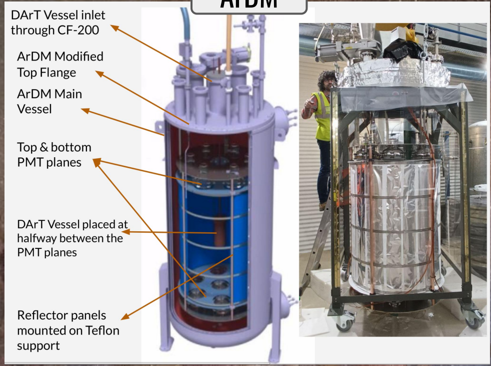
Why: Expected ^{39}Ar concentration ~ 10^{-19} g/g: beyond reach of ICP-MS
Goal: To measure the concentration of ^{39}Ar in underground argon samples (UAr) for DarkSide-20k in a dedicated experiment.
Setup: Depleted Argon Target volume inside Argon Dark Matter Tank.

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

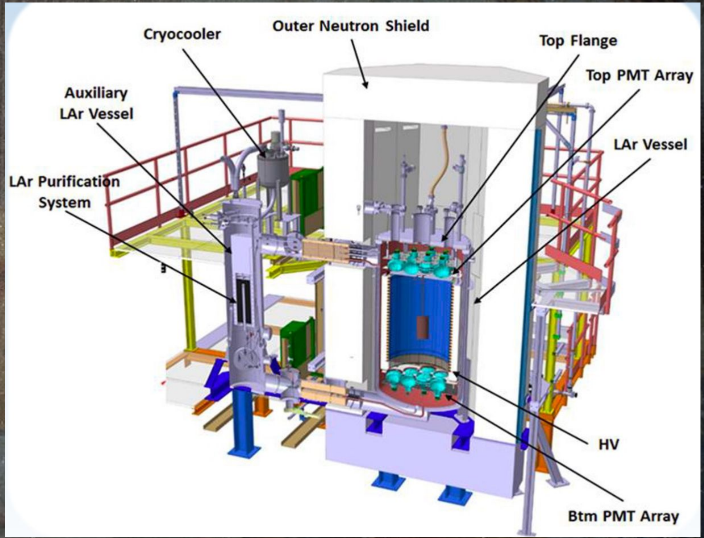
DArT

- OFHC copper
- ~1 litre (1.4 kg)
- Single phase
- 8 SiPM [4(T), 4(B)]
- ESR reflectors
- TPB-coated acrylic

ArDM



- Single-Phase LAr detector
- As an active veto
- 13 PMTs [6(T), 7(B)]



Projected Sensitivity: < 0.1 mBq/kg (DS-50 reported 0.73 mBq/kg), less than 40% statistical error in 1-week livetime. JINST 15 (2020) 02, P02024

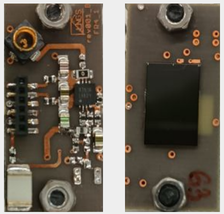
DArTinTestCryostat

Goal

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

Setup

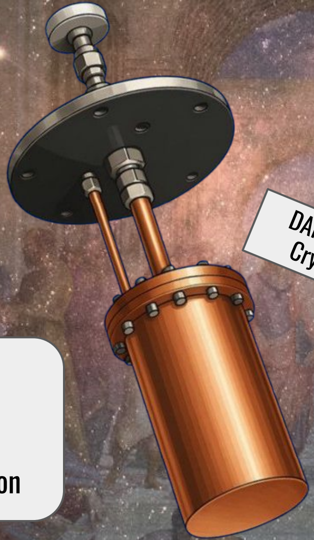
DArT SiPMs



- → Inner acrylic structure coated with TPB
- → Mylar reflector to enhance Light collection

Light readout by 2 1cm^2 SiPMs (DArTEye) from DS-20k

Acrylic inside copper

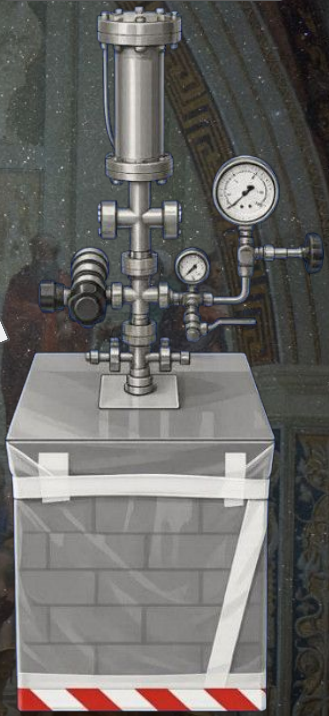


DArT inside Cryostat

Cryostat with pressurized LN_2 at 85 K

Cryostat in Lead shield

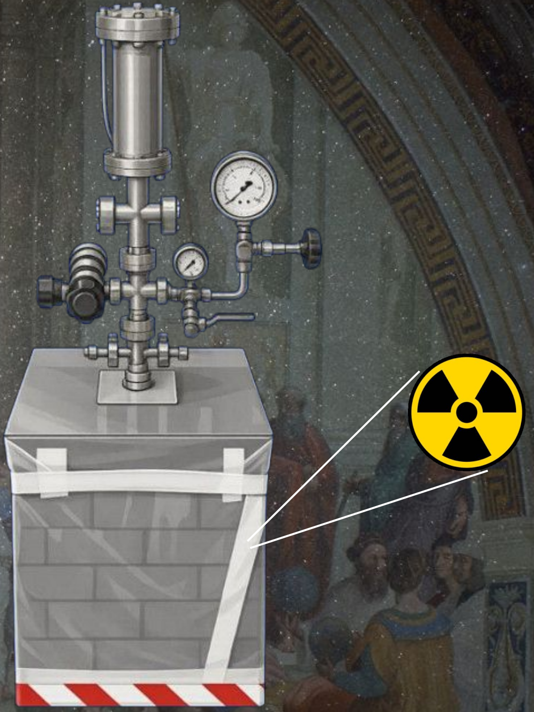
Lead shield flushed with Rn-free air



Run Overview

Data taking

Atmospheric Argon runs: With Argon 6.0, 1 ppm impurity level
Underground Argon runs: With UAr from DarkSide-50
ICP-MS analysis, wrt AAr Argon 5.0/6.0 (10/1ppm impurity level)
^{137}Cs runs: Adding a ^{137}Cs source (27 kBq) outside the cryostat inside the lead shield



Current Goal

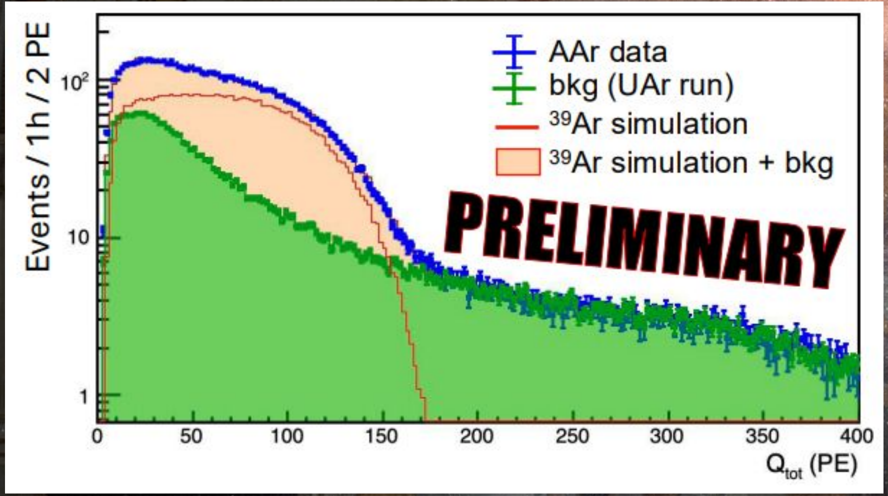
- ➔ A dedicated test setup to operate in parallel to the main detector DArTinArDM.
- ➔ Enabling first UAr order 0 quality check before the filling of main detector.

^{39}Ar activity in Atmospheric argon with DArTinTestCryostat

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

$$\mathbf{a}_{AAr} = \mathbf{A}_{AAr} / \mathbf{M}_{LAr}$$

- **$N(AAr_{run})$:** 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



Systematic Uncertainties

Type	Variation	Uncertainty on a_{AAr} (%)
Asymmetry factor for f_B	± 0.05	0.04
Threshold cut in mV	± 3 mV	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

Other 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)*

Refurbishment of ArDM

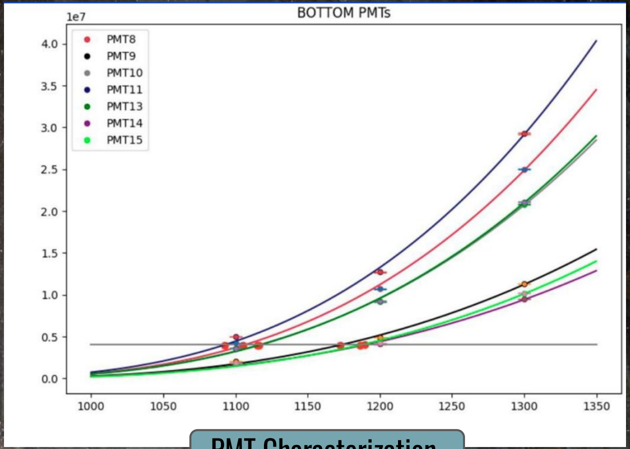
The refurbishment of ArDM was a must need step to use ArDM as an active veto for DArT

- ➔ 6 tonnes of Lead belt attached to the polyethylene shield
- ➔ New PMT planes mounted
- ➔ ESR reflector panels installed inside
- ➔ PMT planes have reflector coated with TPB

New PMT planes

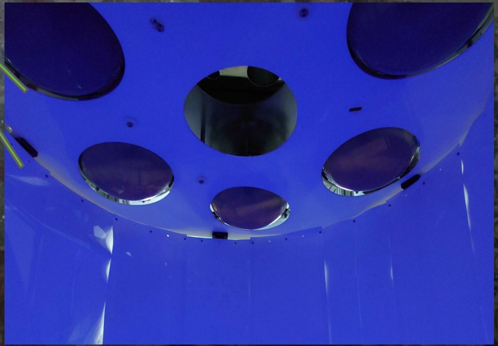
PE shield

Lead belt



PMT Characterization

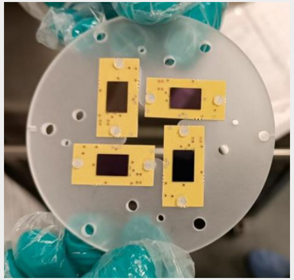
PMT planes & Reflectors coated with TPB

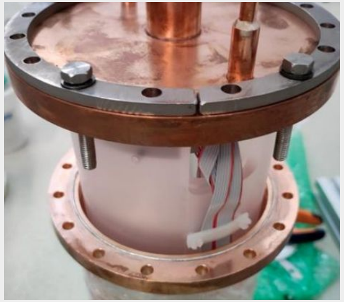


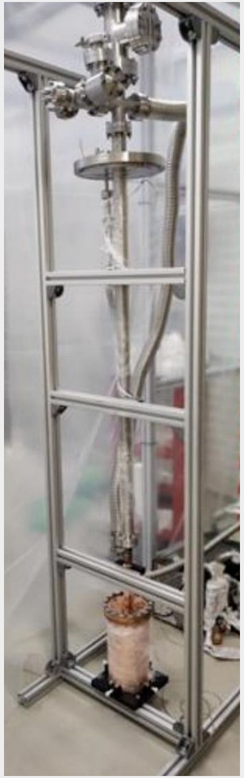
DArT 2.0: Construction

Cleaning

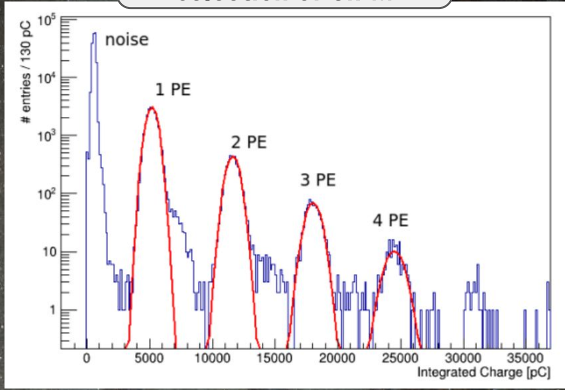
Assembly

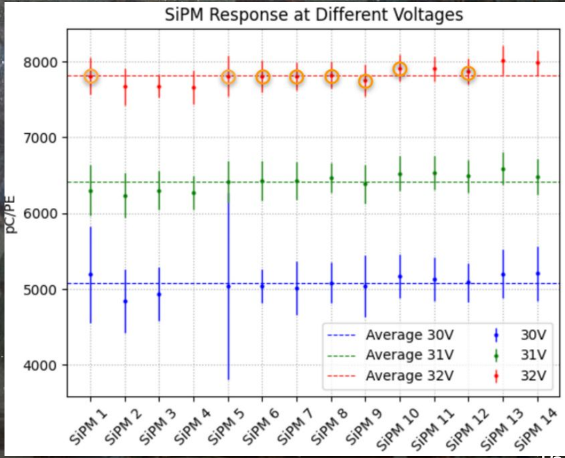




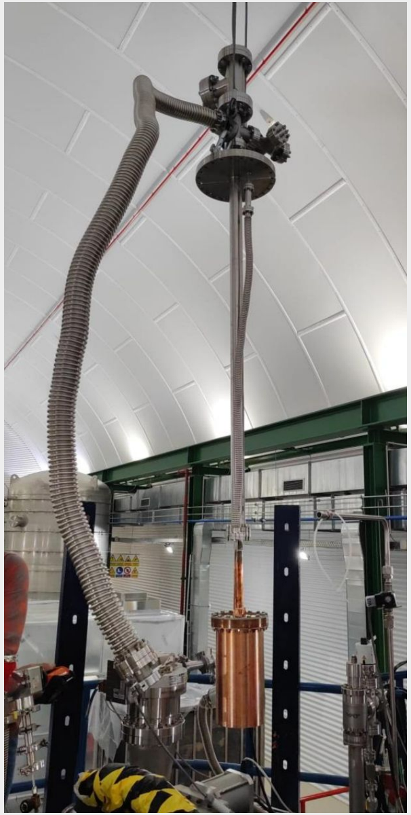


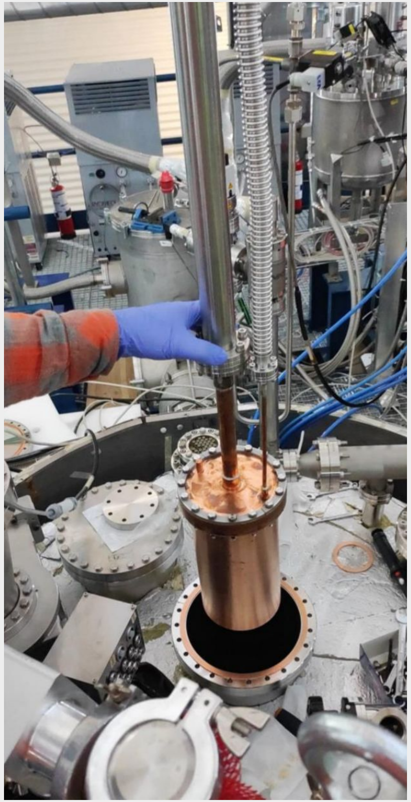
Characterization and selection of SiPM





DArT 2.0: Integration inside ArDM





Current Status

DArT has been installed inside ArDM
Filling of ArDM with AAr has been 80% complete
DArT has also been filled with AAr.
First Analysis of DArTinArDM is underway.

Next Steps

DArT1 – Test Setup
Finalizing the background simulation
Finalizing the publication on DArT1 in test setup
Ready to operate in parallel to DArTinArDM

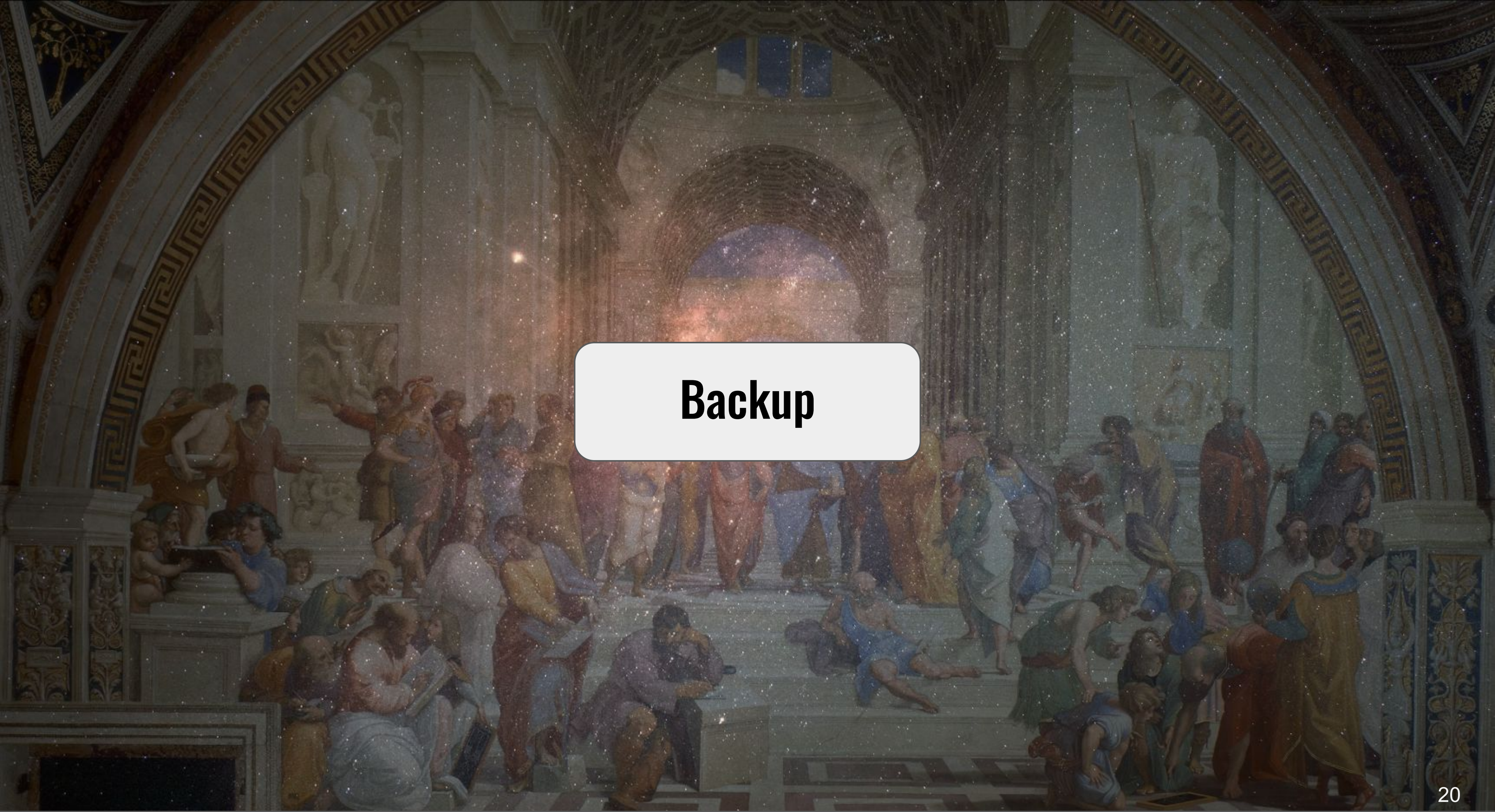
DArT2 – Cold Test
Define detector optical plane geometry and cold test setup in Geant4
Develop calibration simulation (evaluate possible sources)
Electronics simulation for 7 channels

DArTinArDM
Complete remaining 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

Summary

- Atmospheric argon is unsuitable for the next generation of rare events searches due to its intrinsic ^{39}Ar activity.
- Underground argon will be key to physics programs for future underground detectors such as DarkSide-20k, ARGO, Legend and DUNE.
- DArTinArDM will play an important role for every argon based rare event search experiment with precise measurement of ^{39}Ar activity.

Thank You



Backup

DarkSide-20k & GADMC

400 scientists

14 countries

Mostly INFN & NSF funded

Spanish contributions account for 2% of the ~100 M€ budget so far