La Thuile 2022– Les Rencontres de Physique de la Vallée d'Aoste 6-12/March/2022

DarkSide-20k and the direct detection of Dark Matter with argon

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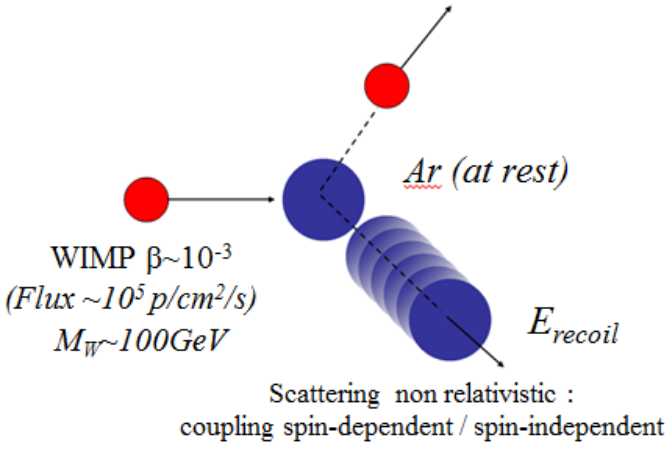
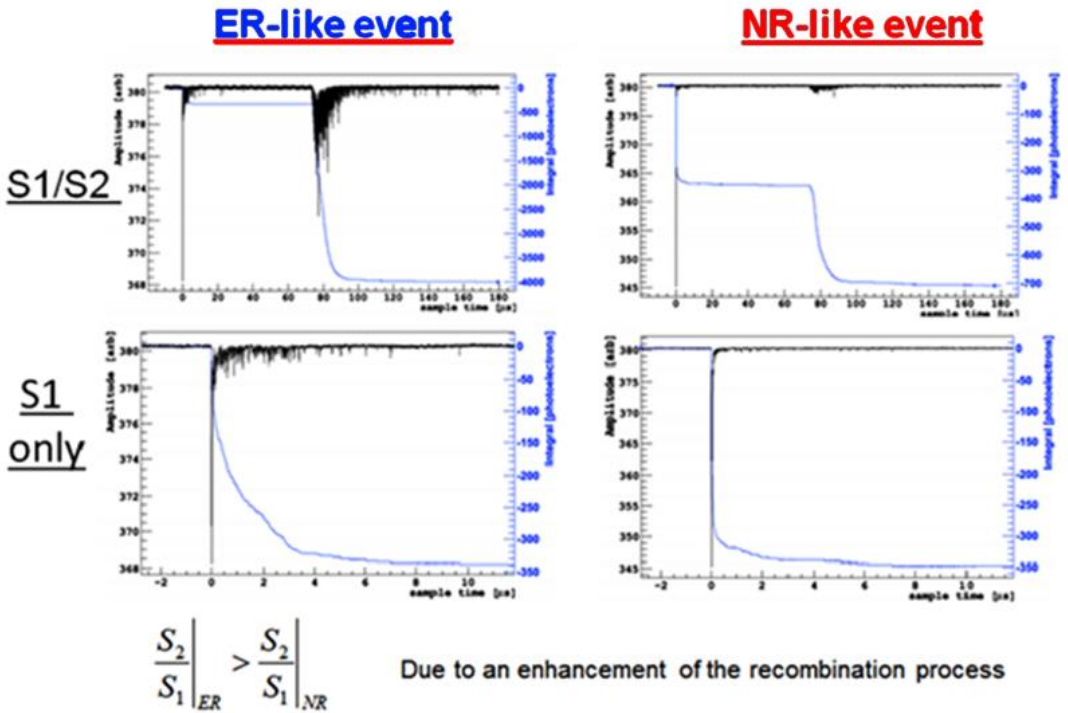
Outline

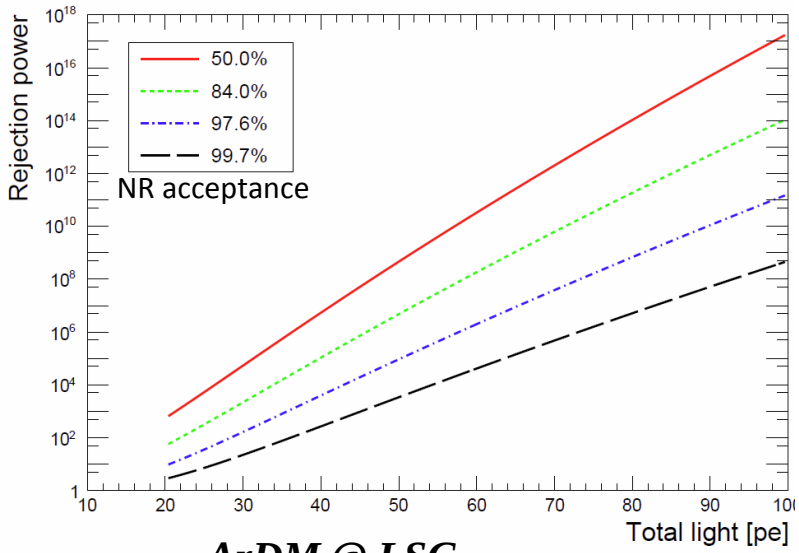
- The Global Argon Dark Matter Community
- The Darkside-20k experiment @ LNGS
- Design, physics goal
- SiPM and radiopurity
- Measurement of the Ar-39 in UAr
- Prospects and conclusions

Ar + TPC: A dream technology



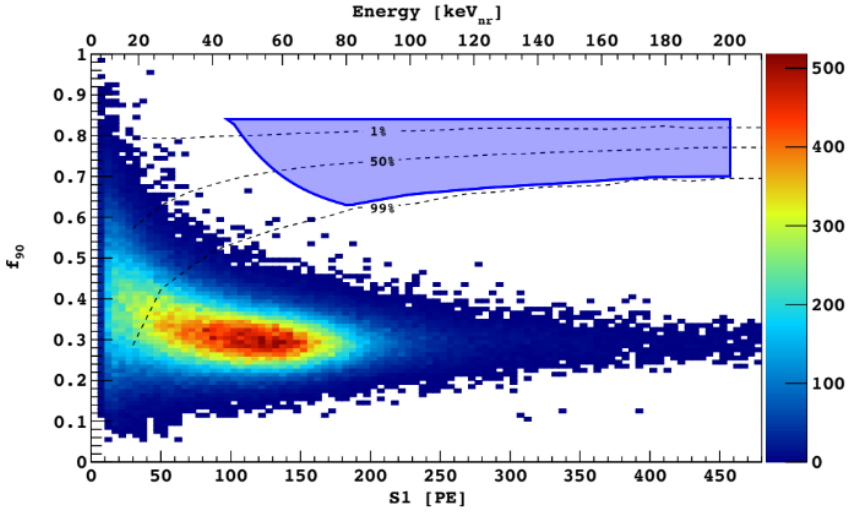
- Large Exposure (Mass × Time) : ~100s tonne×year
- Low Energy Threshold : <10 keV
- Event topology : $\gamma, e^-, n\ldots$
- Low Background Rate : <0.1 evt in 100s (t×yr)
- Discrimination between Signal and Bkg: > 10^8



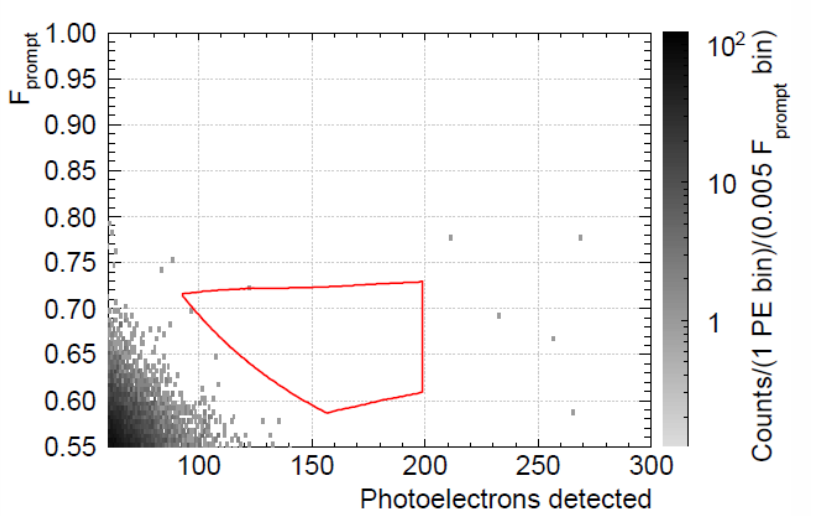


ArDM @ LSC
JCAP 12 (2018) 011

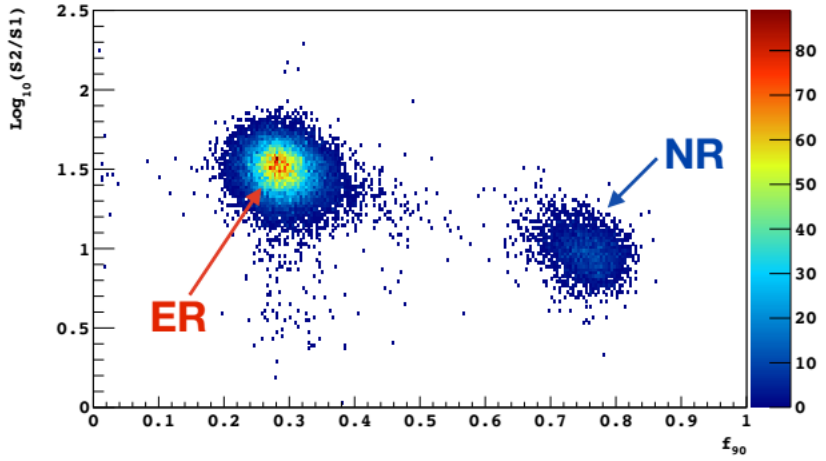
Background rejection with Ar



DarkSide-50@LNGS
Phys.Rev.D 98 (2018), 102006



DEAP3600@SNOLAB
Phys.Rev.D 100 (2019) 2, 022004



Scintillation Pulse shape + charge vs light

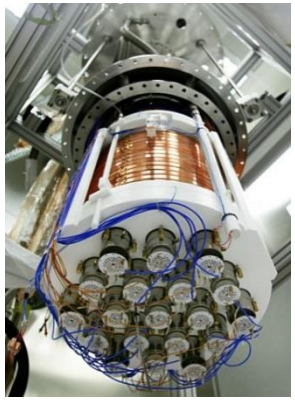
Frontiers

- large mass (tens to hundreds of tons) and long drift (some meters scale)
- Very low thresholds (~keV)
- New sensors
- Extreme radiopurity

GADMC: towards 200 t·yr

- There is a remarkable and unique opportunity of having large exposures (~200 t·yr) **in background free mode** with an argon TPC
- The dual-phase LAr-TPC is able to exceed the current experimental limits, reaching the neutrino floor
- ***GADMC***: Collaboration with groups from DS-50, ArDM, DEAP-3600 and MiniCLEAN (major expertise in Argon based detectors) ~500 people, about 100 Institutions

DarkSide-50@LNGS

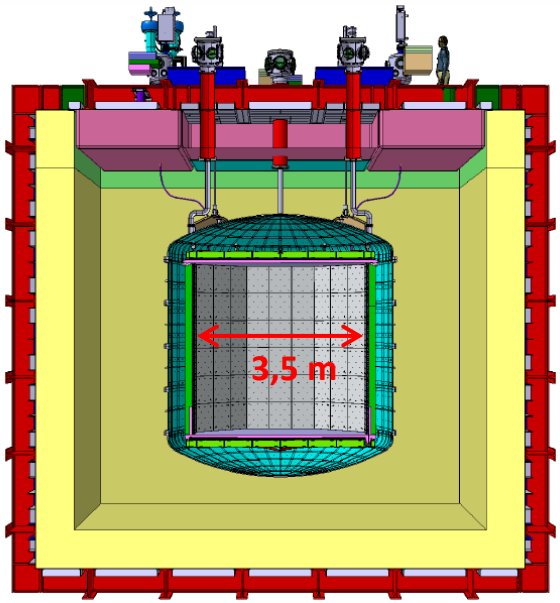


Mini Clean@SNOLAB

DEAP-3600@SNOLAB

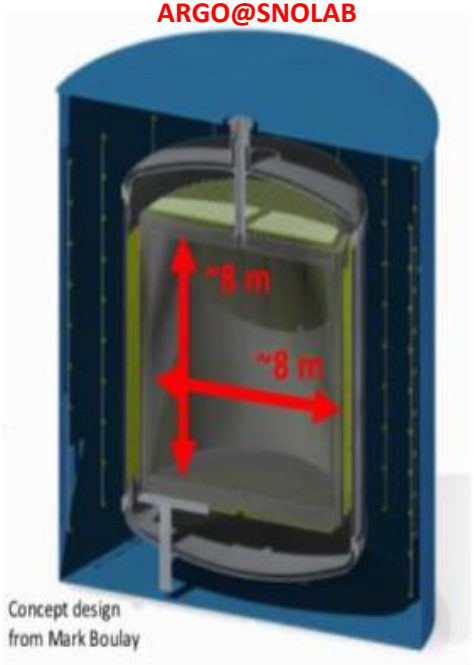
ArDM@LSC

DarkSide-20k@LNGS



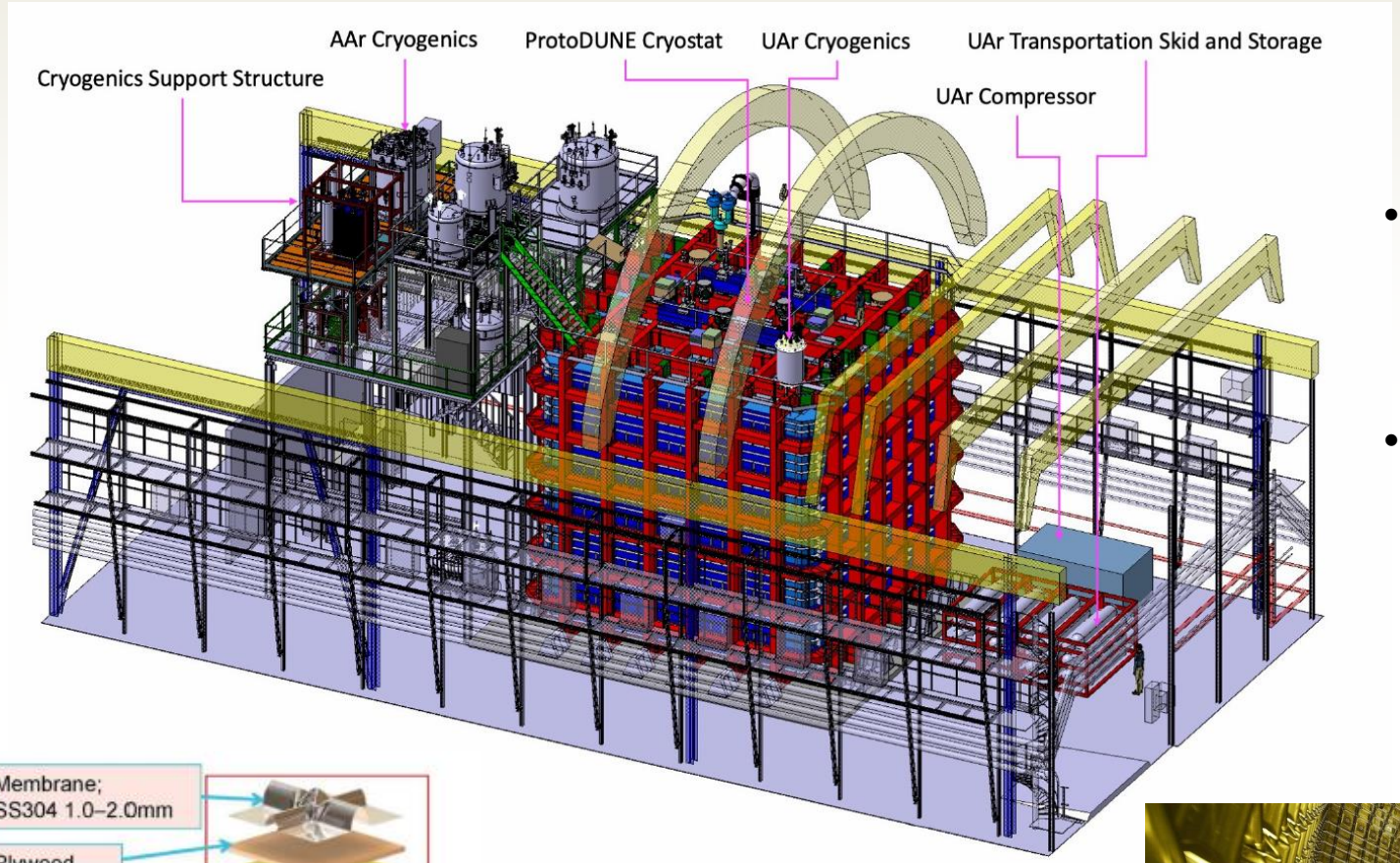
Construction in 2022
Data taking from 2025
51 t total mass
20 t × 10 yr

ARGO@SNOLAB

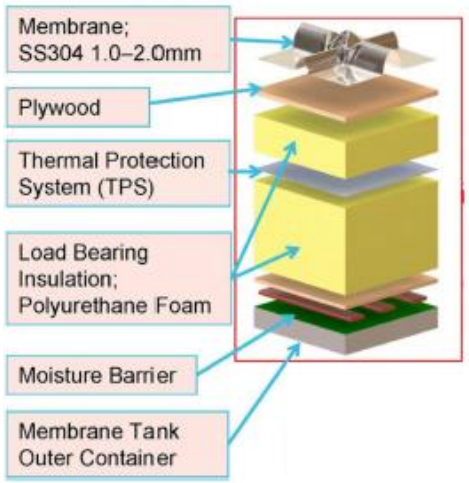


Conceptual studies in progress
3 kt x 10 yr

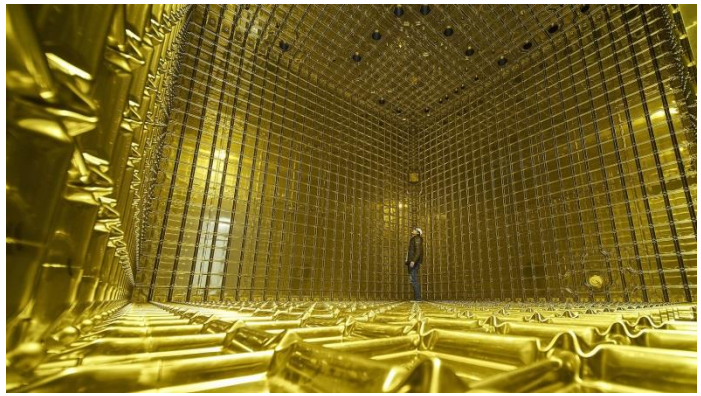
The Design of DarkSide-20k



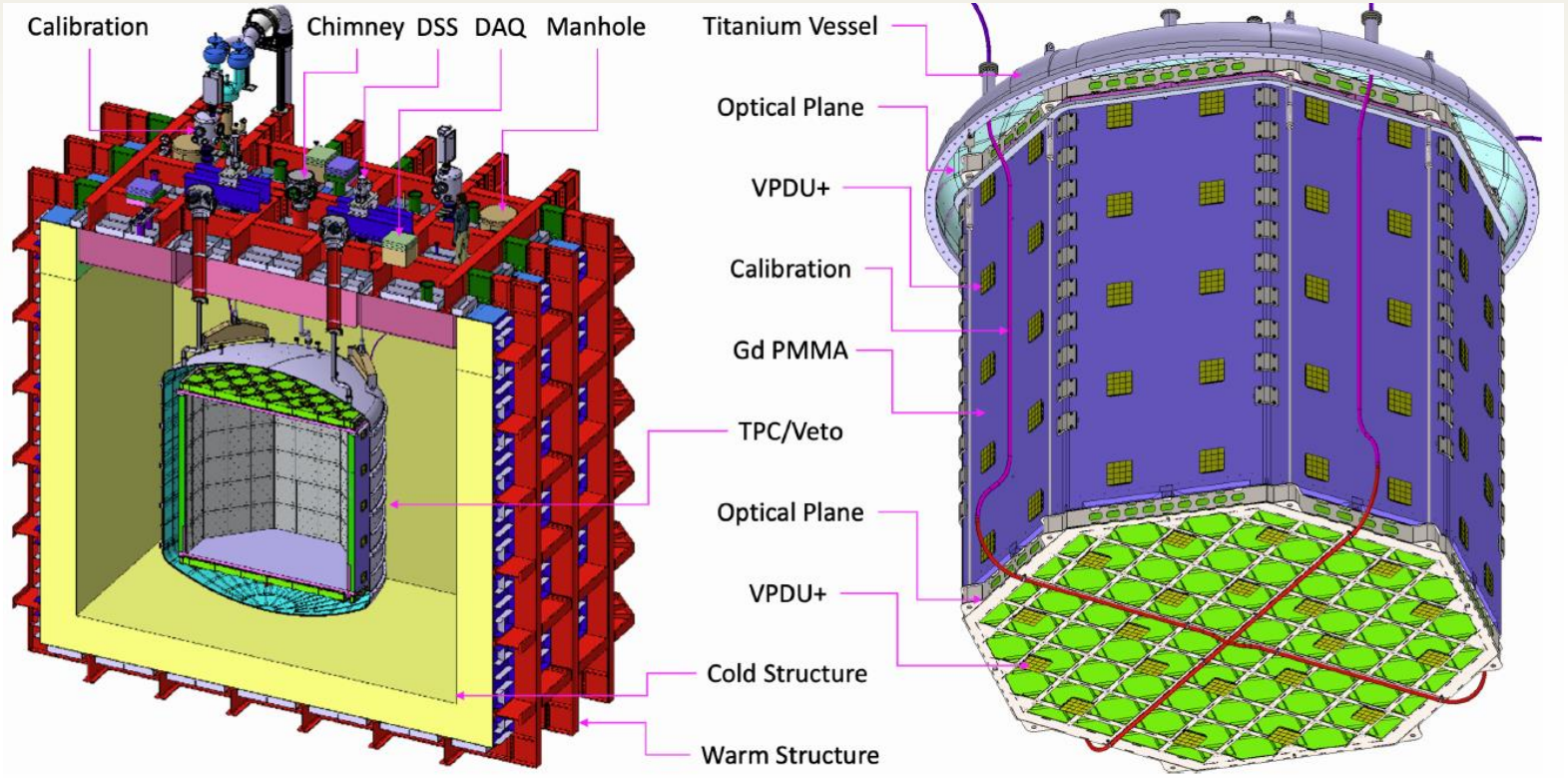
- ≈650 t AAr in a membrane cryostat, proto-DUNE like
- 2 independent cryogenics purification loops

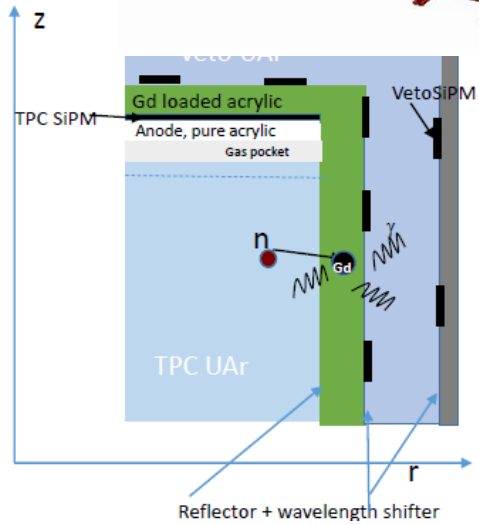


Construction of the cryostat will start in 2022



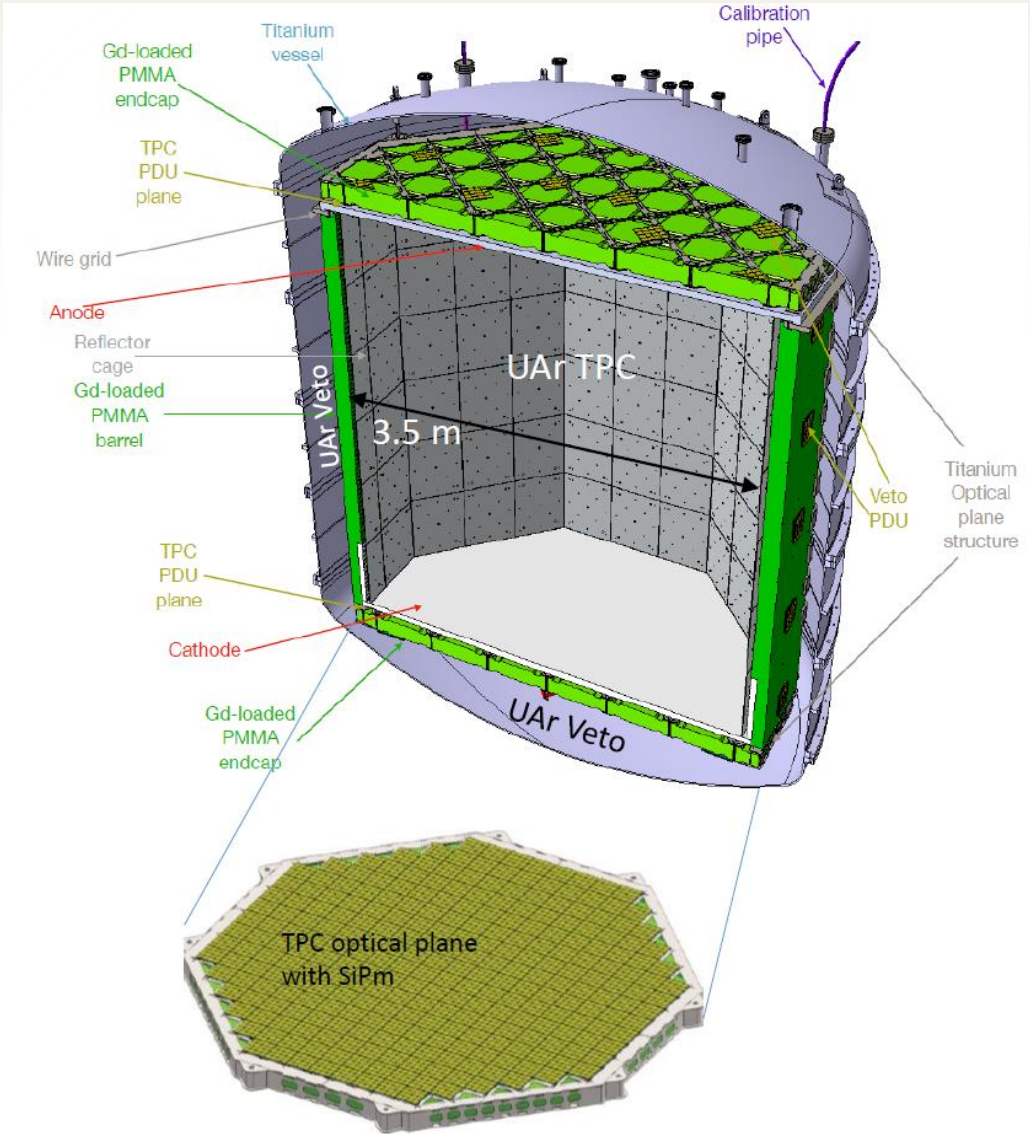
The Design of DarkSide-20k





- 50 t (20 t FV) low-radioactivity Ar (UAr)
- 21 m^2 cryogenic SiPMs
- 5 m^2 cryogenic SiPMs in the Veto
- 99 t UAr in total in a Ti vessel
- TPC lateral walls + additional top/bottom planes in Gd loaded (1%) acrylic (n- thermalization/capture)

The Design of DarkSide-20k

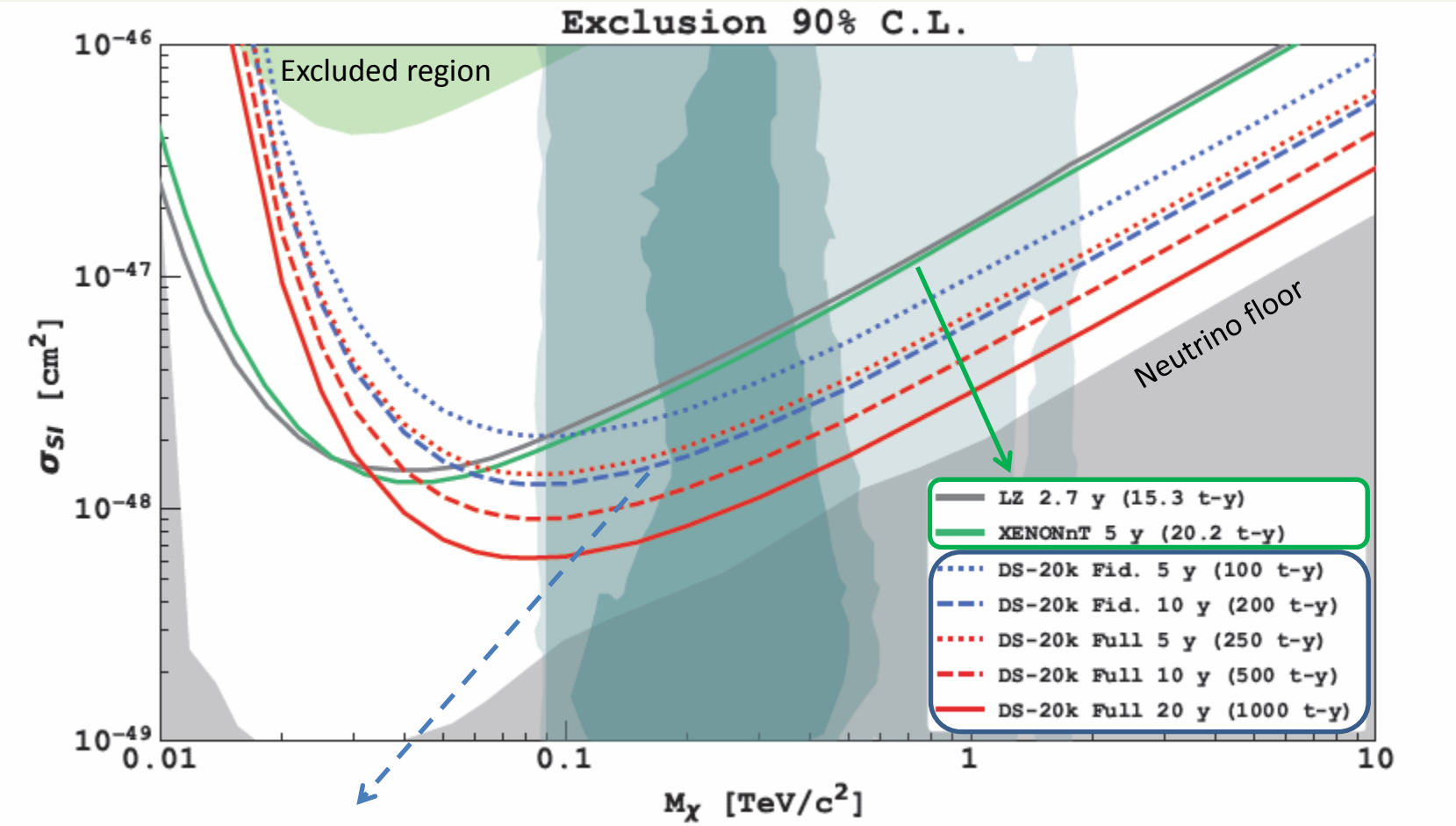


- Maximum **drift length** 348 cm
- Electron drift lifetime >5 ms
- Octagonal inscribed circle **Ø(87K) 350 cm**
- Gas pocket 7.0±0.5 mm
- Drift field **200 V/cm**
- Extraction field 2.8 kV/cm
- Luminescence field 4.2 kV/cm
- >**10 phe/keV** in the TPC (S1)
- >20 PE/e^- (S2)
- 2 phe/keV in the Veto
- ~cm (xy) and ~mm (z) position resolution

- TPC anode/cathode: transparent pure acrylic covered with Clevios (**conductor**) + TPB (**shifter**)

- TPC lateral walls: grooves with Clevios for shaping the field cage (no copper rings)

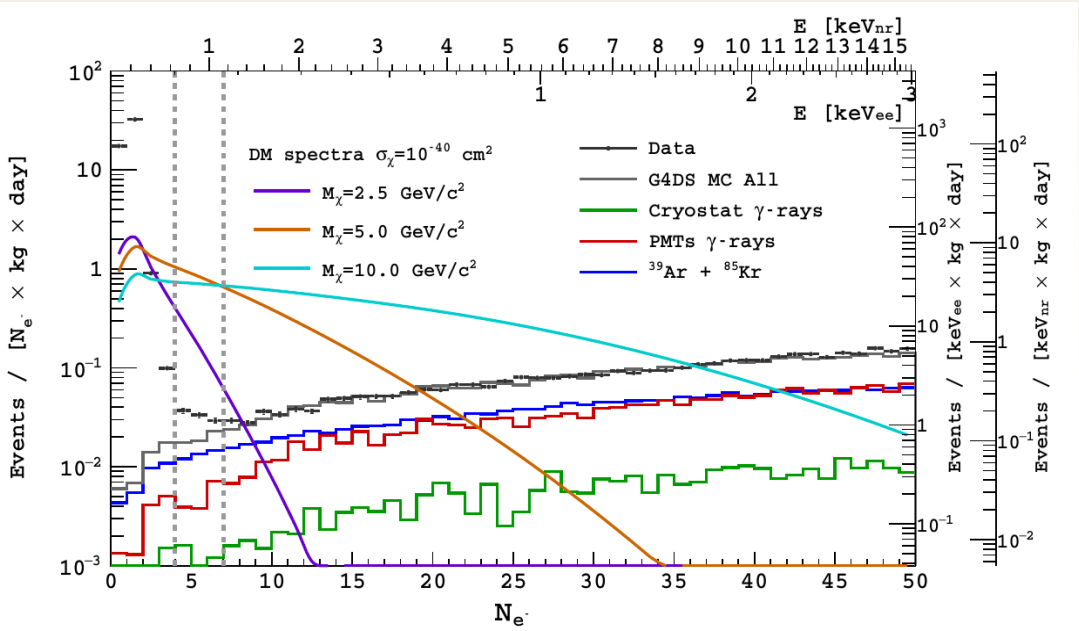
Expected sensitivity (SI)

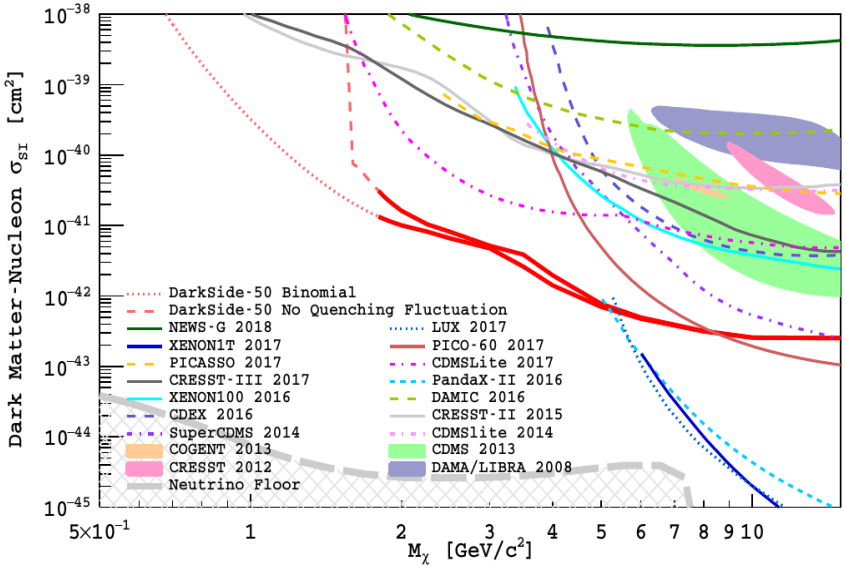


- **6.3 × 10^{-48} cm^2 for 1 TeV/c^2 WIMP (90% C.L.)**
- **2.1 × 10^{-47} cm^2 (5σ) discovery**
- **nominal exposure: (20×10) t·yr**
- **background: 0.1 events**

Turquoise filled contours are from pMSSM11 model, E. Bagnaschi et al., Eur. Phys. J. C 78, 87 (2018).

Low Mass



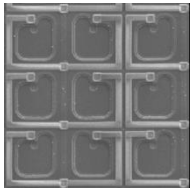


S2-only events
E_{th}<0.6 keV_{nr}

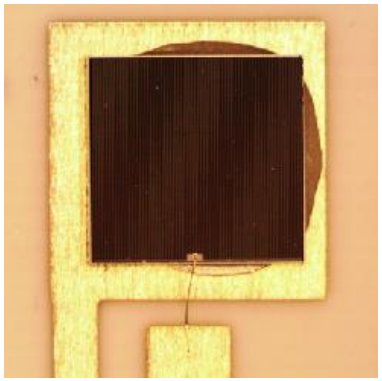
DarkSide-50@LNGS
Phys.Rev.Lett. 121 (2018)

- world-best limit below 3 GeV/c^2
- Soon new limits on WIMP-nucleon with/without Migdal, WIMP-electrons, solar and galactic axions, sterile neutrinos

Technology breakthrough 1: development of large area cryogenic radiopure SiPM



Single **SPAD**
~25-30 µm²



SiPM ~ 1 cm²

- Radiopure ~ 2 mBq/PDM dominated by the substrate(for SiPM and front-end)
- High PDE (~ 45%), >90% fill factor
- Gain > 10^6
- <5 cps/tile dark count rate (87 K)
- Time resolution ~ 10 ns (sigma)
- Power consumption <100 µW/mm²

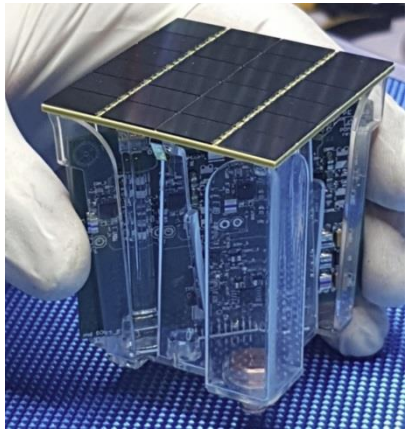
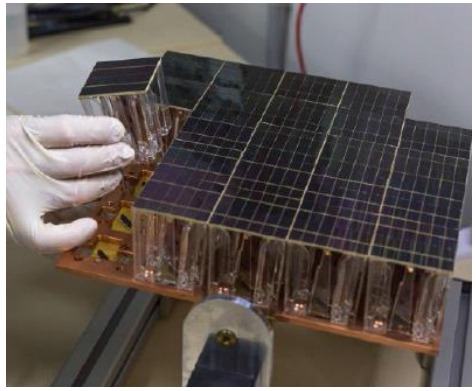


Photo Detector Module (**PDM**)
matrix of 24 SiPMs,
(5 x 5 cm²)

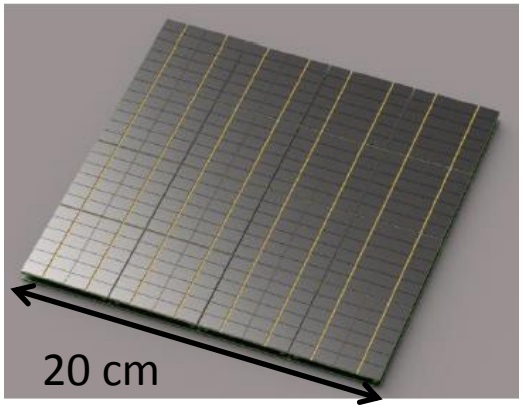
- 8280 PDMs (+2000 in the Veto)
- 21 m² (TPC) + 5 m² (VETO)
- Mass production of the raw wafer in LFoundry
- Packaging facility (NOA) at LNGS

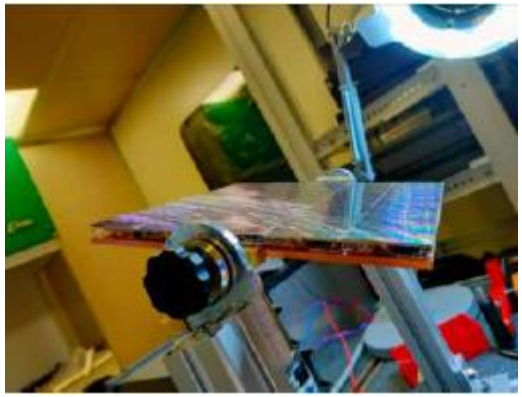
Prototype of the Photo Detector Unit (**PDU**)



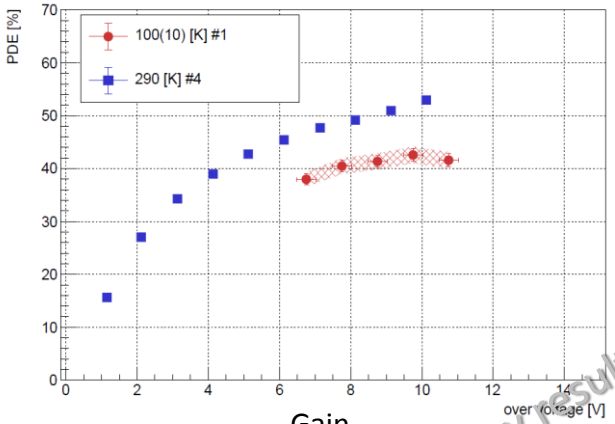
Baseline solution

- 16 tile assembled on the MB
- Single PCB for Tile and amplifier
- Sum of 4 tile signals (4 outputs)

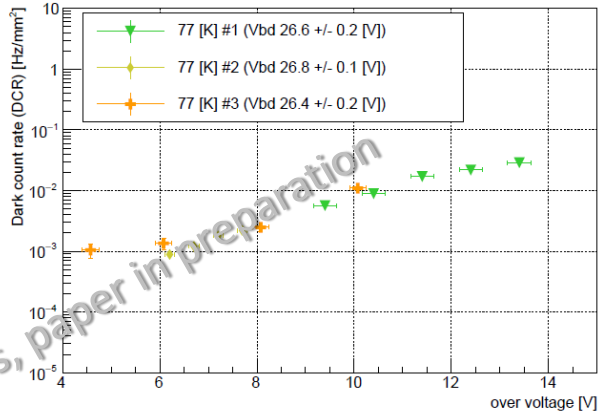


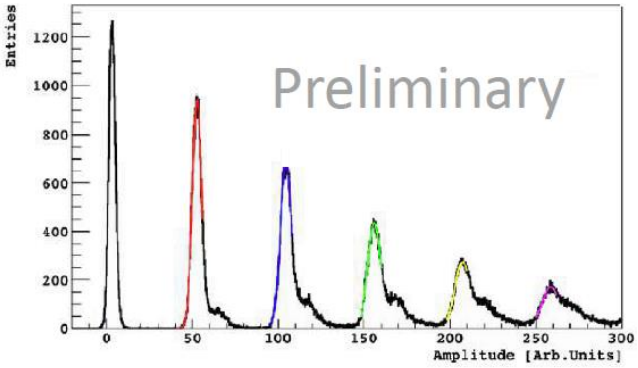


Photon Detection Efficiency

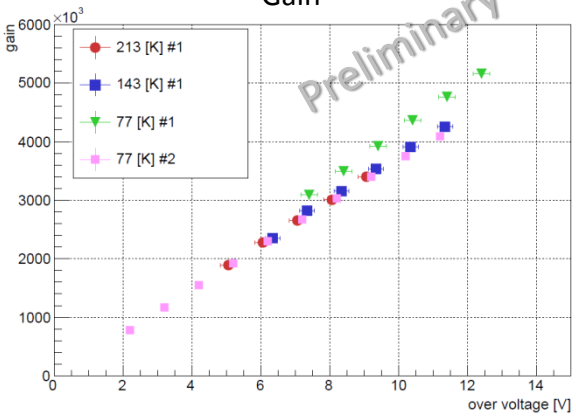


Dark Count rate

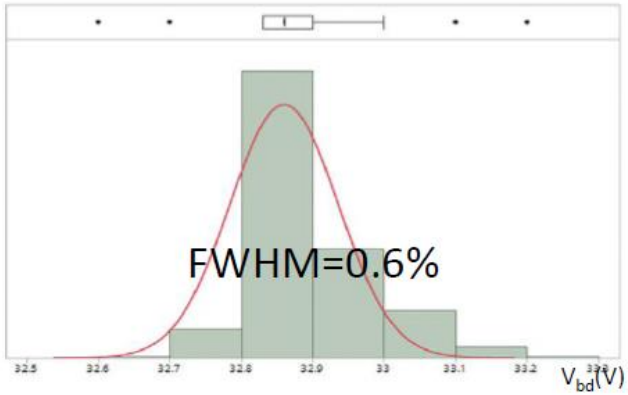




Gain



Preliminary results, paper in preparation



Breakdown voltage
(2e4 SiPm, Different wafers)

Technology breakthrough 2: Radiopurity

Very demanding background requirements (< 0.1 in 10 yr exposure):
PSD alone is not sufficient

Strategy:

➢ Assay all materials of the detector

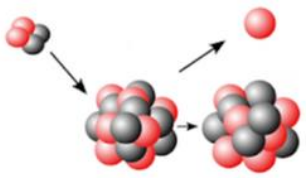
- Worldwide effort **Canada, Italy, France, Poland, Russia, Spain, UK, US**…
- Counting facilities in four Underground laboratories involved (Boulby, LNGS, LSC, SNOLAB)
- 3 different techniques employed: ICPMS, HPGe, Po extraction for Upper, Middle and Lower ^{238}U chain
- Hundreds of assays carried-out
- Platform to store and manage the results of the material assay campaign

➢ Full characterization and calculation of the materials background

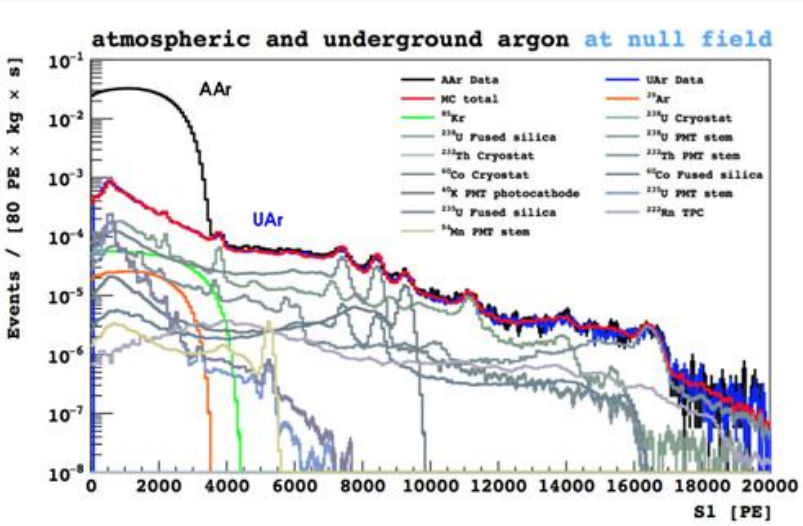
- Control of the cosmogenic activation of materials
- Control of the surface contamination
- Evaluation of the radioactive budget of the experiment including activation UG
- Evaluation of the systematic uncertainty from the material composition
- New MC tools for (α, n) calculations

DArkSide is the first experiment with the (a,n) neutron background fully calculated with Geant4

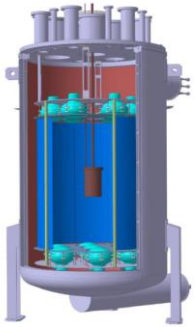
Simple and versatile tool provided to the community **SaG4n**
(http://win.ciemat.es/SaG4n/)
"Neutron production induced by α-decay with Geant4",
Nucl. Instrum. Methods A 960, 163659 (2020)



UAr: Extraction – Purification – Measurement

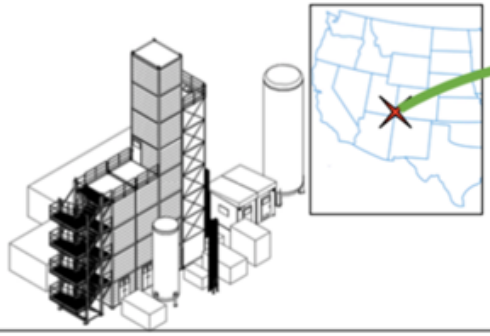


International effort underway to procure radiopure argon extracted from underground reservoirs



Characterisation: DArT

Measurement of the ^{39}Ar depletion factor



UAr transported via boat for final purification at Aria

Production: Urania

- Commercial-scale plant to extract UAr
- Located in Southwestern Colorado
- UAr extracted from CO_2 well gas at the tonne scale

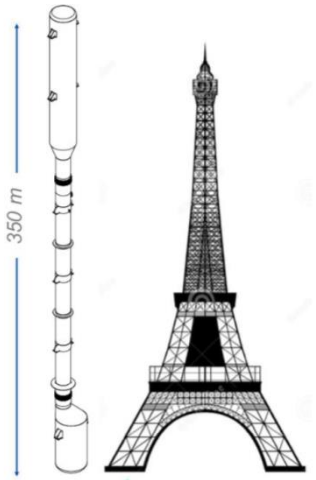
Purification: Aria

- 350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements
- Located in refurbished carbon mine shaft in Sardinia, Italy
- Will chemically purify the UAr for DS-20k to detector grade

Extraction and purification

- **URANIA** project: Procurement of UAr extracted from the CO_2 wells in Cortez mine, Colorado (~330 kg/d, 99.99% purity) → Plant in construction

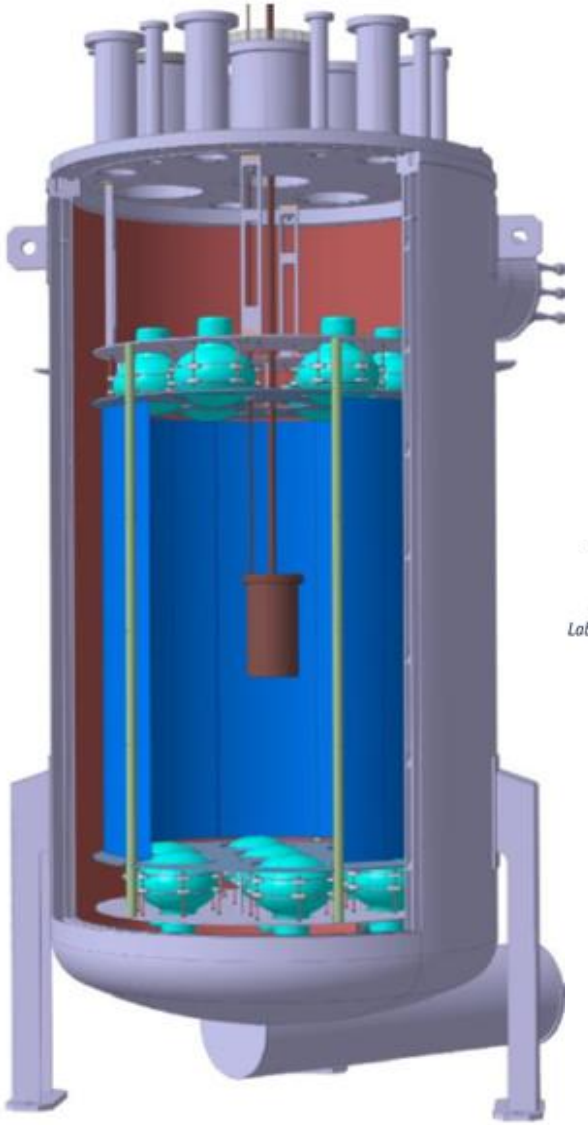
- **ARIA** project: Ar chemical purification and isotopic separation by cryogenic distillation (Sardinia, Italy)



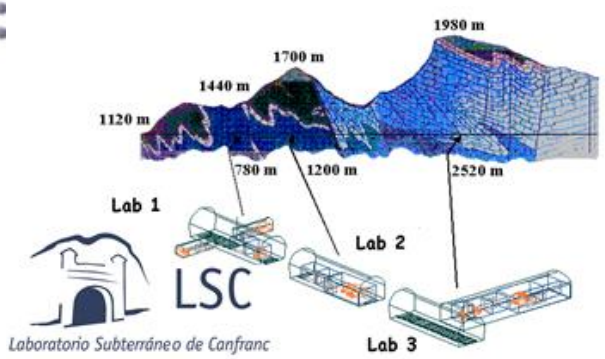
- 350 m height, 31.8 cm inner cryogenic distillation column
- 28 central modules (12 m each) + top condenser
- First module operation with Nitrogen in 2019 (*Eur.Phys.J.C* 81 (2021) 4, 359)
- Production rate with ARIA in chemical purification mode (DarkSide-20k): ~1ton/day
- Production rate with ARIA in isotopic separation mode(factor of 10 per pass): several kg d^{-1}
- Wider column foreseen for the ARGO detector

- Medical applications (isotope supply)

UAr radiopurity measurement: DArT in ArDM



LSC in Spain



Main Lab under mount Tobazo

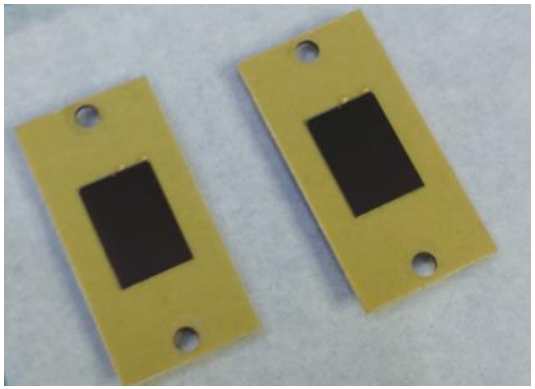
- ~850 m rock
- ~2500 mwe
- 1400 m^2

ArDM

- Double-phase EL-TPC
- 850 kg active volume (≈2 t total)
- Cryogenic low rad. PMT arrays (R5912 2×12)
- 50 cm passive neutron shield (Poly, 20 ton)
- Data taken 2014-2018

DArT design

- OFHC copper vessel with two top pipes. Total weight → 7 kg and volume → 3 L.
- Two 1 cm^2 SiPMs at top and bottom with the electronics integrated.
- External acrylic support structure. Cylinder + two SiPM supports.
- Internal acrylic cylinder and two disks covered with TPB (200 $\mu g/cm^2$).
- Reflector around SiPMs and between acrylic cylinders.
- **Active volume of 1.4 kg. 620 evt/week for UAr (0.73 mBq/kg).**



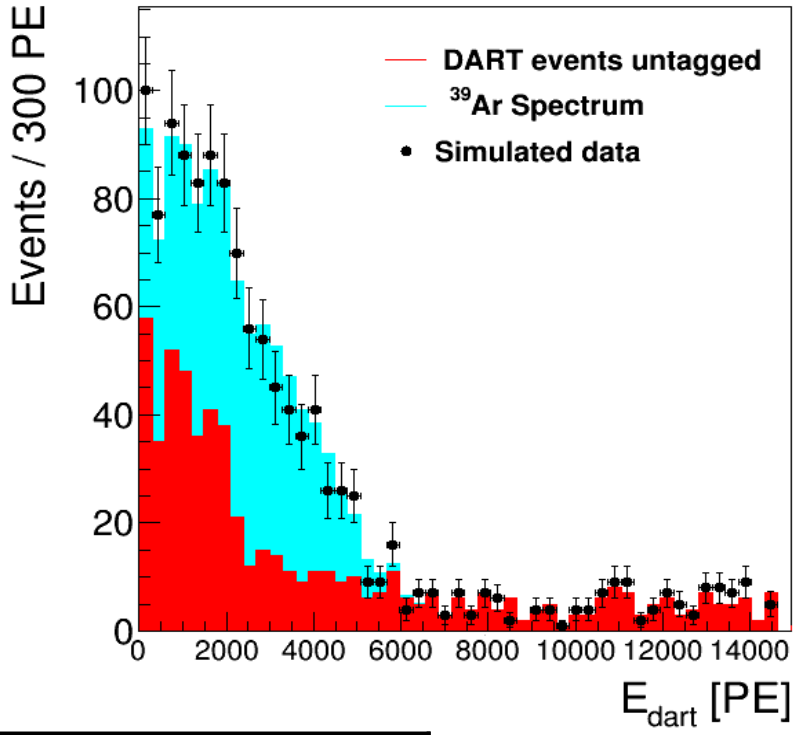
DArT Sensitivity

Sensitivity from a fit:

$$d = n_S S + n_B B$$

d = simulated data
S = signal
B = background

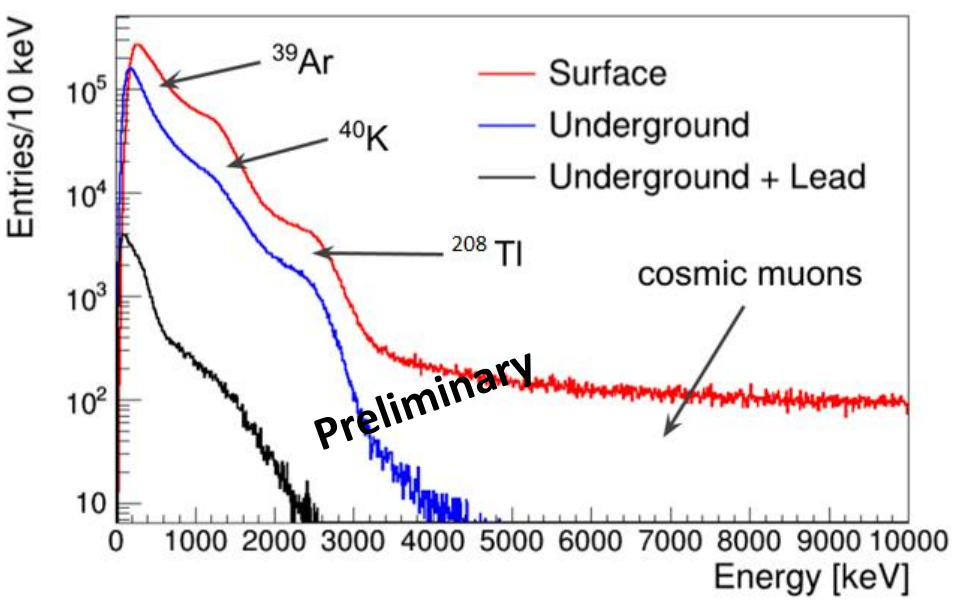
"Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon"
JINST 15 (2020) 02, P02024.

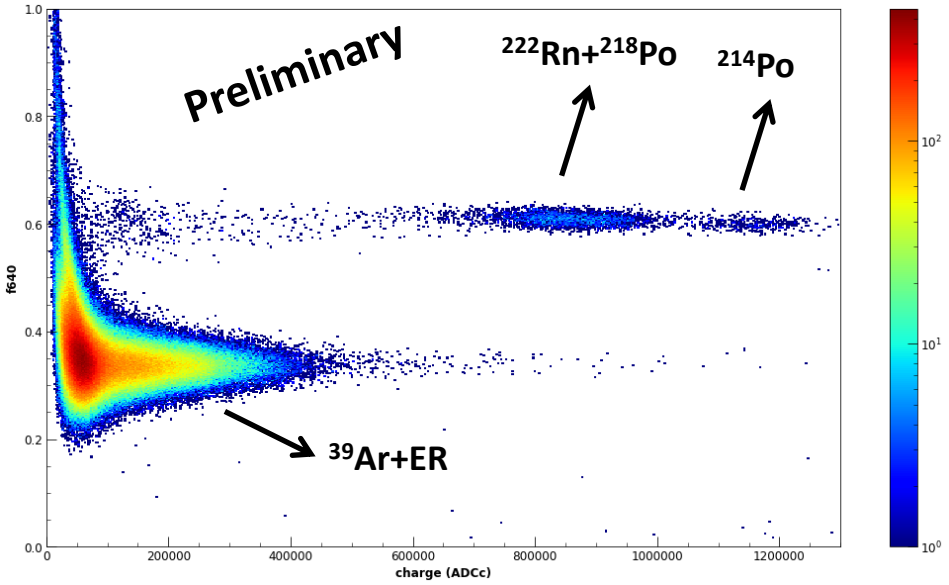


Depletion factor with respect to AAr	Statistical uncertainty [%]
10	0.4
100	1.3
1400	6.7
14000	41.1

DS-50

DArT underground @ LSC





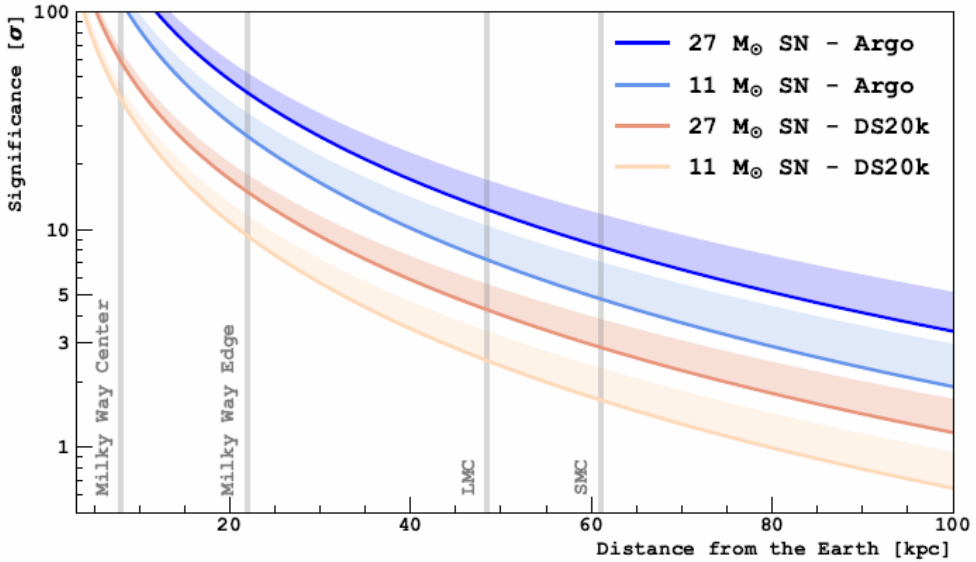
Installation in ArDM during 2022

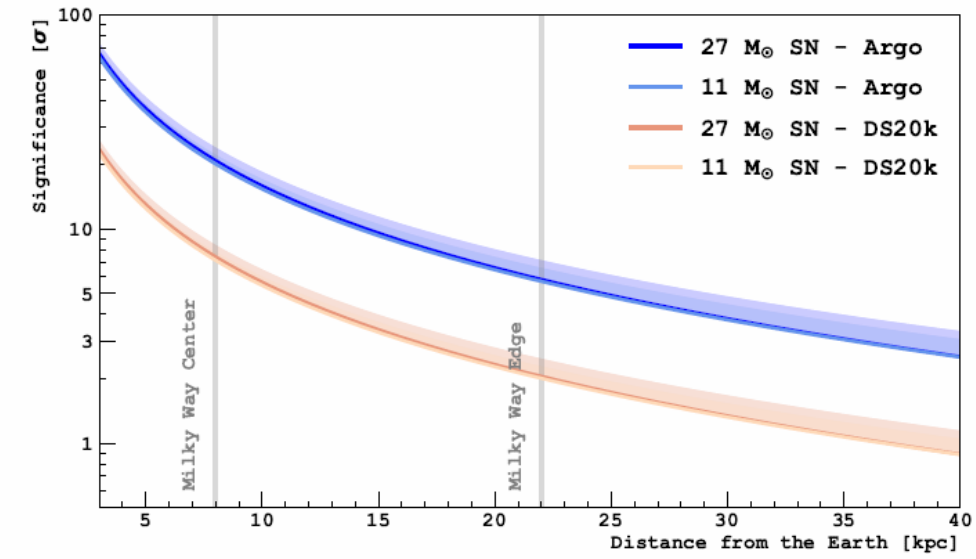
Conclusions

- Argon: outstanding ER background rejection in direct dark matter search experiments
- Joint global expertise in the Global Argon Dark Matter Collaboration (GADMC)
- R&D for DarkSide-20k completed
- Outstanding technology developments
- International effort underway to procure radiopure argon

Backup

Core collapse supernova via CENnS





DS-20k coll.
JCAP 03 (2021) 043

Entire SN flux

Neutronization burst- only

Noble liquids technology for particle physics

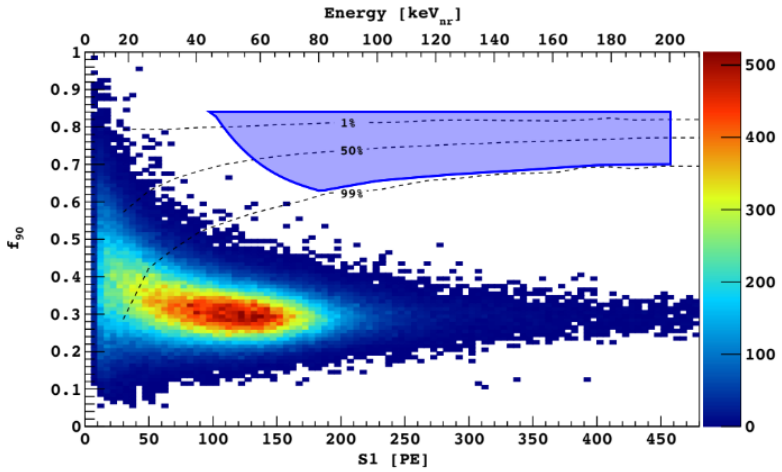
- ***low energy threshold***
  (high scintillation/ionization yield)
- ***large mass***
  (available in large quantity/affordable)
- ***ultra low background***
  (radiopure and clean)
- ***background rejection***
  (pid through pulse shape, light/charge, dE/dx)

Element	*Z(A)*	*Boiling point (Tb) @1bar [k]*	*Liquid density @Tb [g/cm³]*	*Energy loss dE/dx (MeV/cm)*	*Radiation length X_0(cm)*	*Collision length λ(cm)*	*Ionization [e^-/keV]*	*Scintillation [γ/keV]*	*Cost*
Ne	10(20)	27.1	1.21	1.4	24	80	46	7	
Ar	***18(40)***	***87.3***	***1.40***	***2.1***	***14***	***80***	***42***	***40***	
Kr	36(84)	119.8	2.41	3.0	4.9	29	49	25	
Xe	***54(131)***	***165.0***	***3.06***	***3.8***	***2.8***	***34***	***64***	***46***	

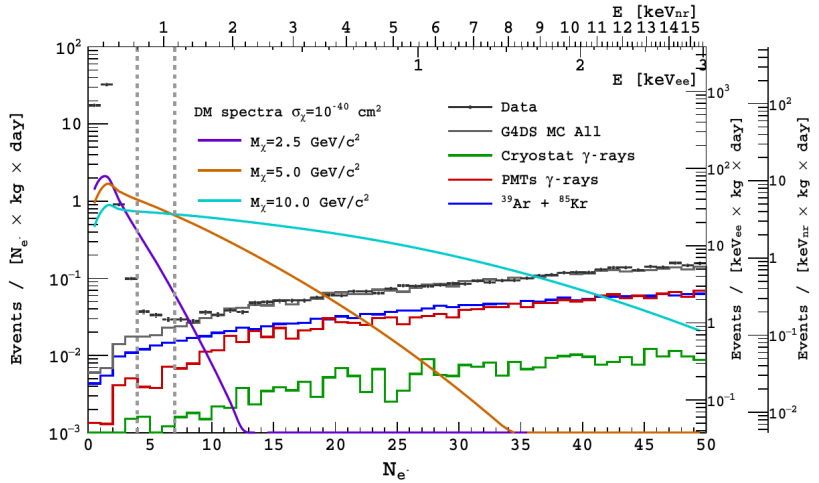
DS-50 @ LNGS and DEAP-3600 @ SNOLAB

- 46.4 kg of Active LAr
- 4 m(d) sphere veto: 30 tonne boron loaded LS
- 1 kt ultrapure water
- (16 660±270) kg d exposure: No WIMP-like event in the search box → 90% CL E.L.

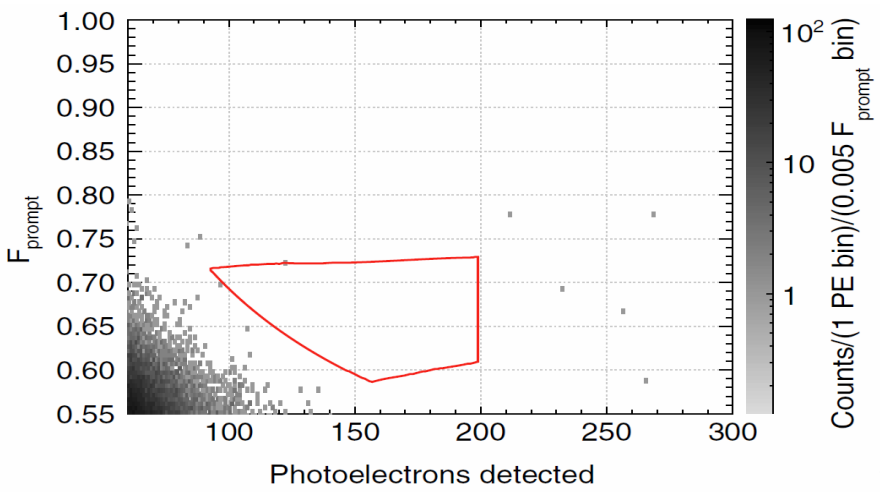
Phys. Rev. D 98, 102006



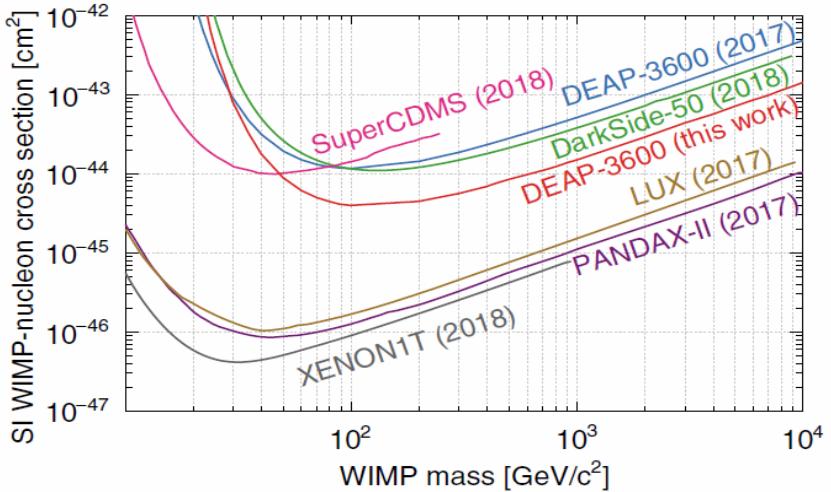
Phys.Rev.Lett. 121 (2018)



- 3279 kg of LAr in an acrylic sphere (85 cm radius)
- 45 cm long UVA acrylic light guides
- 7.8 m (h) × 7.8 m (d) water tank
- 758 tonne·day exposure (231 live-days)
- ER suppression 4×10^{-9} with 90 % NR-acceptance



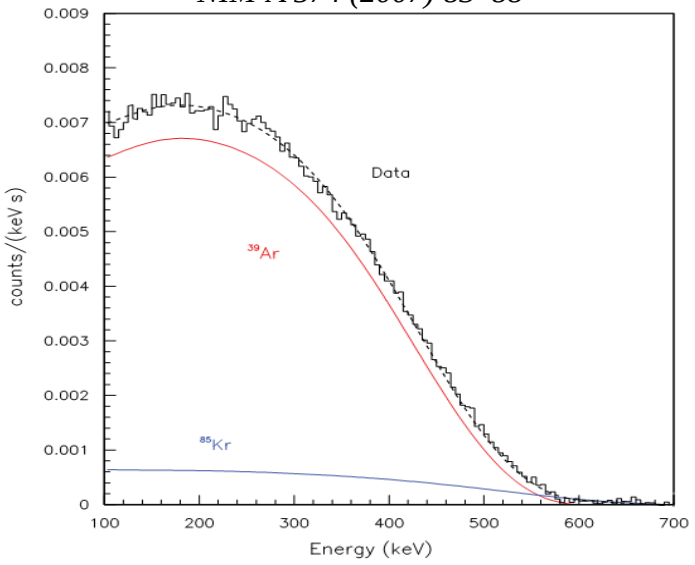
Phys. Rev. D100,022004 (2019)

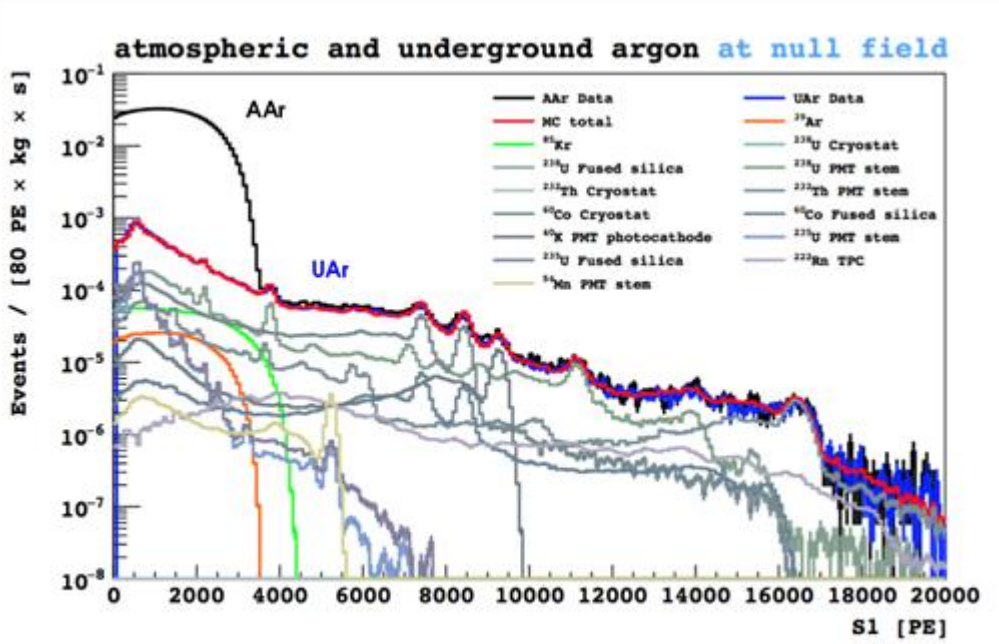


^{39}Ar in AAr

- β-emitter with 565 keV endpoint (cosmogenic, ~17 mBq/m^3 in atmosphere)
- $T_{1/2}$=269 y
- Pure beta emitter, no accompanying gamma radiation
- Present in relatively abundant quantities in AAr due to the production process

"Measurement of the specific activity of Ar-39 in natural Argon"
NIM-A 574 (2007) 83–88





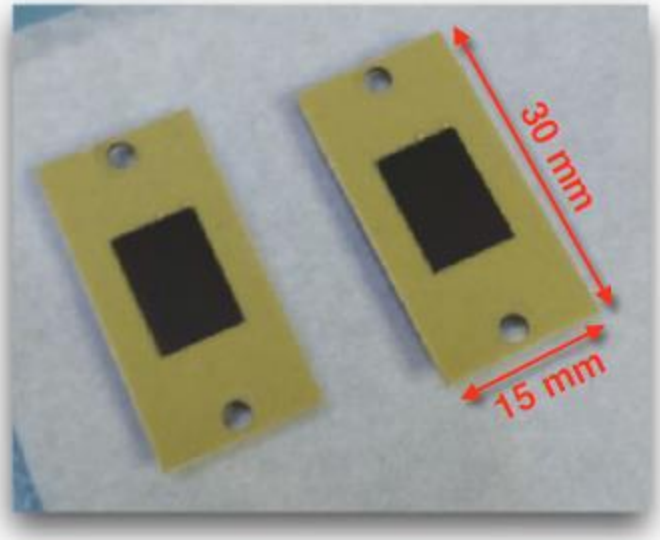
1.01 ± 0.02(stat) ± 0.08(syst) Bq/kg of ^{nat}Ar (isotopic abundance ~ 8×10^{-16} in mass)

Pileup problems in multi-ton TPCs!!!

1400 ± 200 ^{39}Ar depletion factor in UAr with respect to AAr

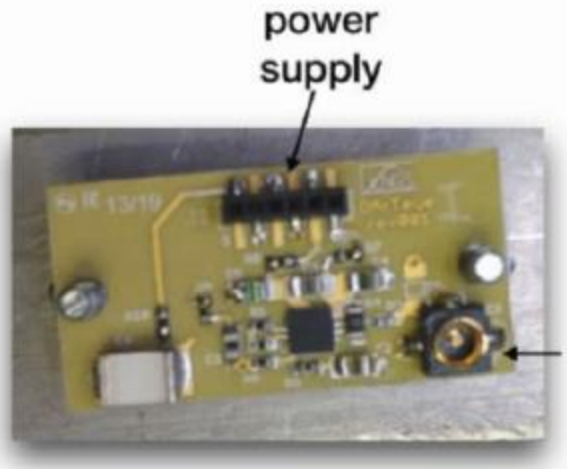
Phys. Rev. D ***93****, 081101 (2016)*

DArTeye: the DArT readout (LNGS)



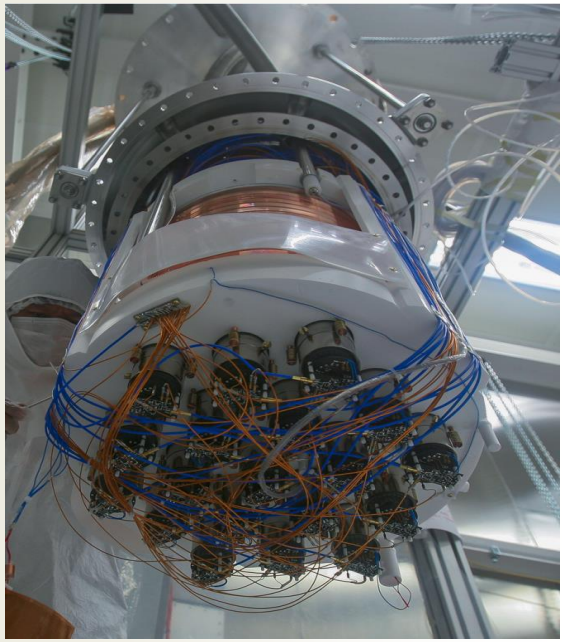
SiPM:
cell size 25 μm
R_q = 10 MΩ
doping x3

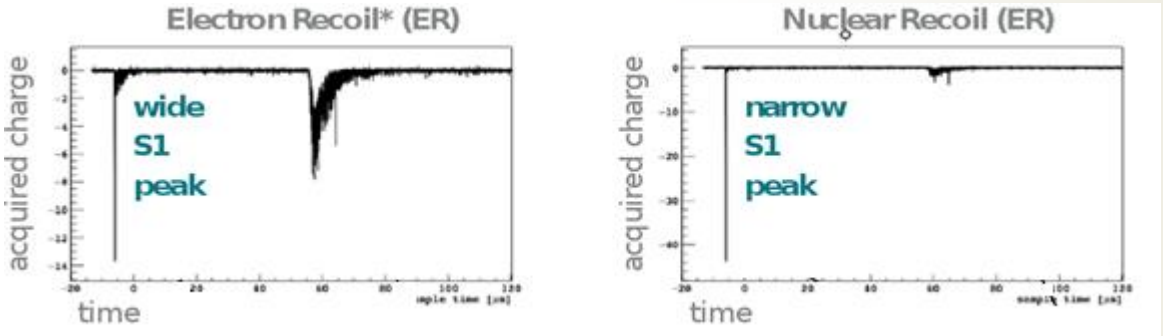
design: LNGS
components: Cagliari
assembly: LNGS
wire bonding: PU

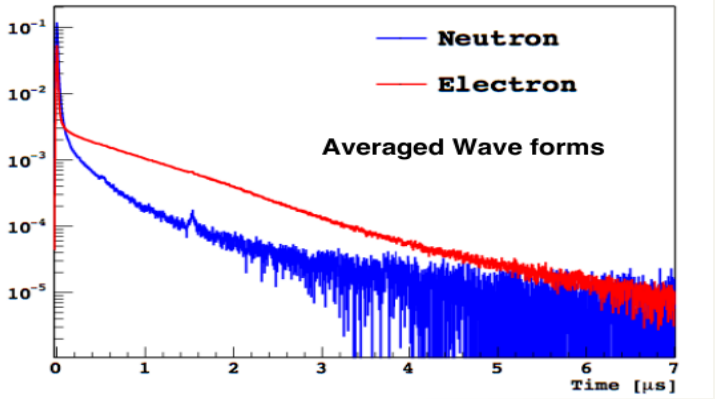


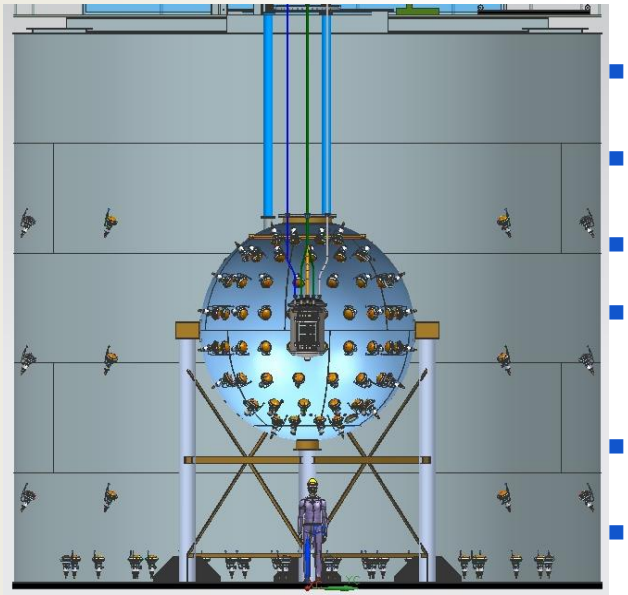
devices:
1. not radiopure
2. radiopure

DarkSide-50







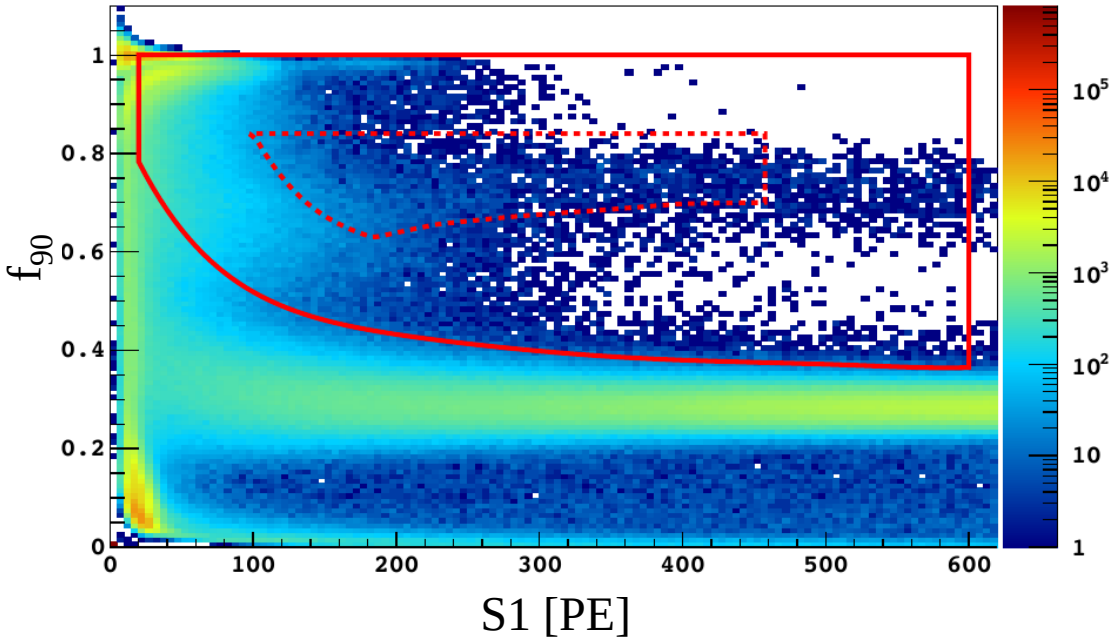


- Ø 36.5 cm x 36.5 cm TPC
- 46.4 kg of Active LAr (150 kg of UAr)
- 38 3” Hamamatsu R11065 PMTs
- 4 m(d) sphere veto: 30 tonne boron loaded liquid scintillator (120 PMTs, eff > 99.8 %)
- 1 kt ultrapure water - Cherenkov Veto (80 PMTs, eff > 99.8 %)
- Installed @ LNGS (3400 m.w.e)

High WIMP mass search

- Studying the backgrounds with
  - The first 71 days of data - PRD 93, 081101 (2016)
  - Monte Carlo Simulations with G4DS - JINST 12, P10015 (2017)
- identify and reduce background sources
- Goal: blinded-box with < 0.1 bg events in the exposure (dashed line)
- Unblinding

f_{90}: fraction of S1 light collected in the first 90 ns



Type of bkg	Estimated evts passing the cut
Surface α	0.001
Cosmogenic n	<0.0003
Radiogenic n	<0.005
ER	0.008
Total	**0.09±0.04**

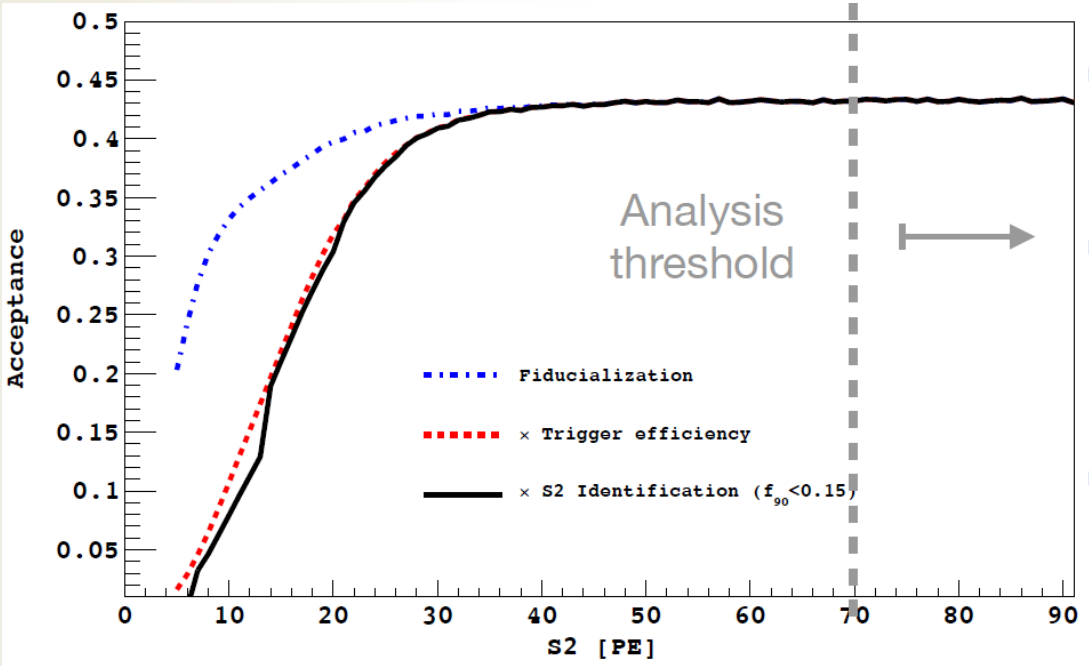
Low WIMP mass search (S2-only)

- Light WIMPs (~2 GeV) might produce low energy NR
- Other lighter DM candidates (~50 MeV) might induce low energy ER
- Low-energy interactions → S1 too small (E_{th} ~13keV$_{nr}$)
- S2 charge signal sensitive to a single e^-

  Hardware trigger efficiency 100% above 30 PE

  E_{th}<0.6 keV$_{nr}$ sensible to low mass WIMP

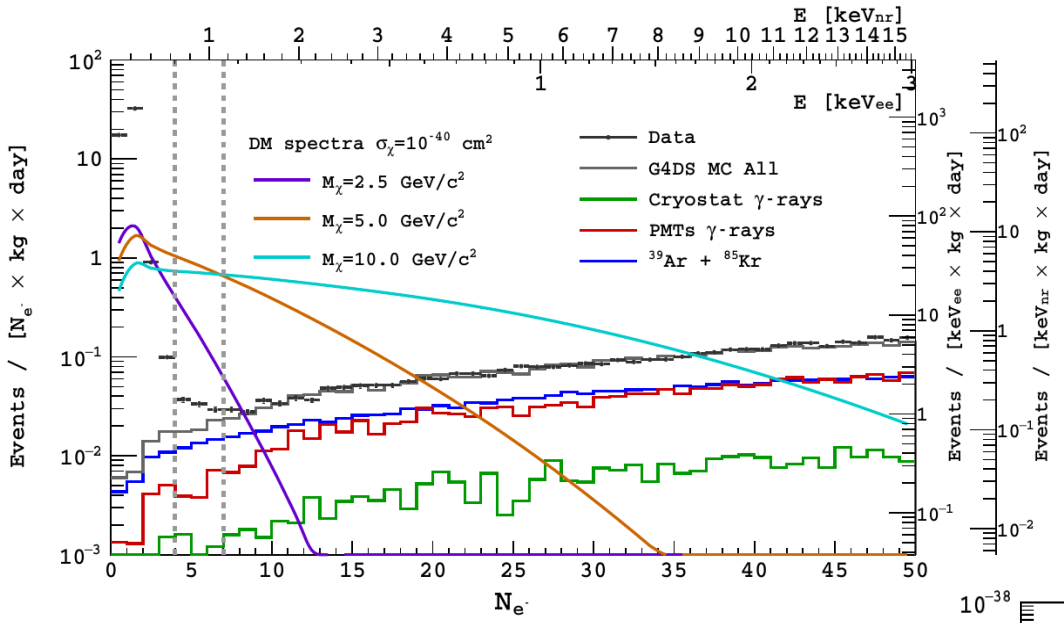
  S2 yield = 23 (1) PE/e^-,



Background:

- electrons captured 0.5 x 10^{-5} e^-/e^- ER
  Analysis threshold set to N_{e^-}= 3
- Low E phenomena from the TPC walls (Fiducialization: volume under inner 7 PMTs)
- Large S1 with S2 in the ROI

Low WIMP mass: above 1.8 GeV



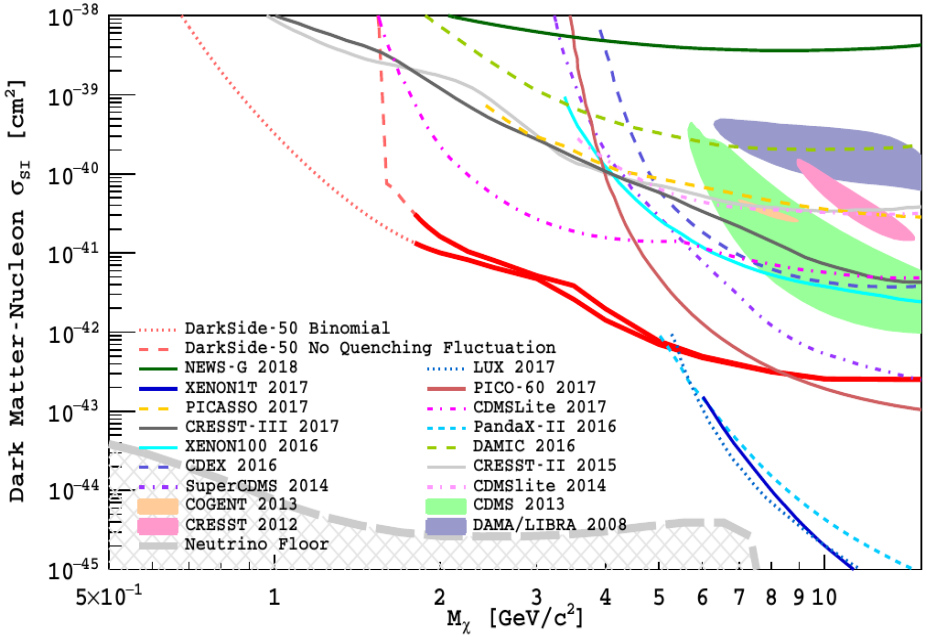
- ER energy scale: ^{37}Ar
- NR energy scale: AmBe and AmC

- At low energy excess of events (between $N_{e^-} = 4$ and $N_{e^-} = 7$)
- N_{e^-} spectra expected for recoils induced by dark matter particles with 2.5, 5 and 10 GeV/c^2 for 10^{-40}cm^2 xsec

Fits performed using two thresholds $N_{e^-} = 7$ (down to ~3 GeV) and $N_{e^-} = 4$

Two models with and w/o fluctuations in the energy quenching (E_{th}=0.6 keV$_{nr}$)

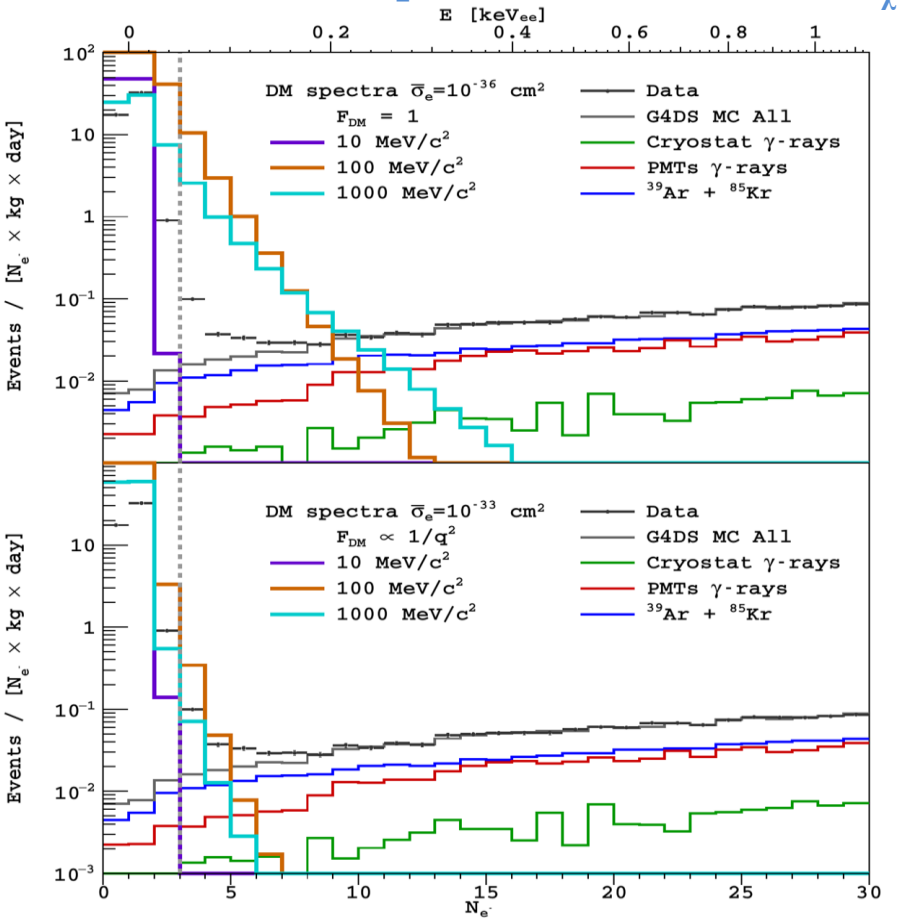
Competitive results at $M_\chi > 1.8$ GeV/c^2
Phys.Rev.Lett. 121 (2018)

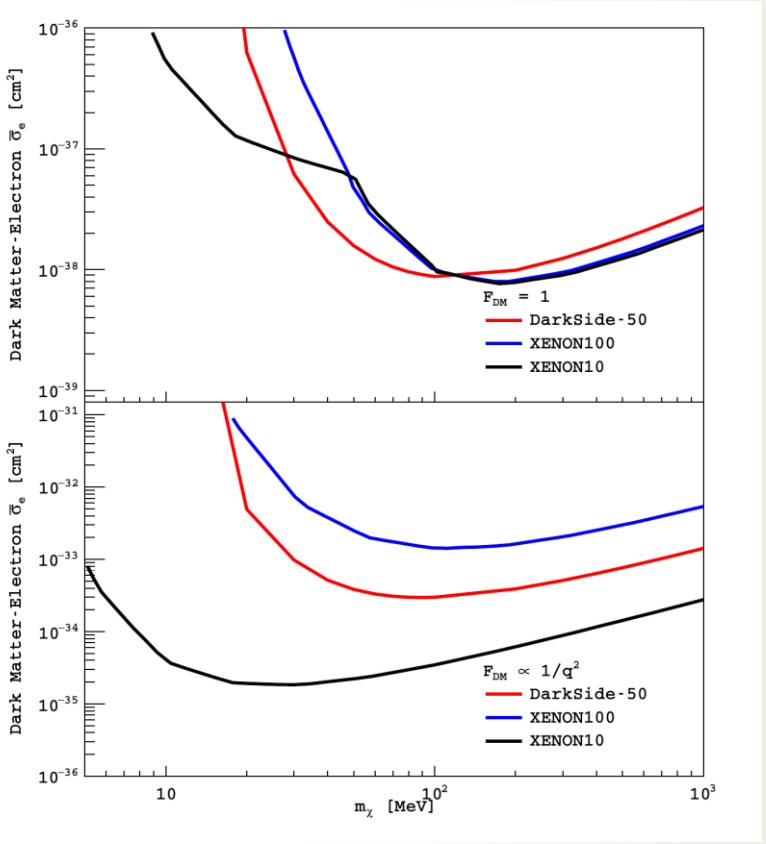


Low WIMP mass: sub-GeV

- ER analysis
- Binned profile likelihood method - threshold @ $N_{e^-} = 3$
- Two extreme cases considered, light mediator & heavy mediator

→ **Constraints improved for 30 MeV < M_χ < 100 MeV and heavy mediator ($F_{DM}(q) = 1$)**

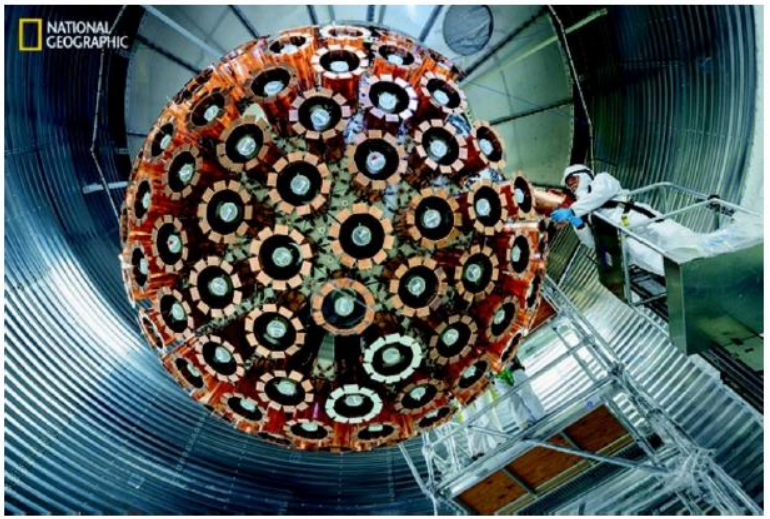




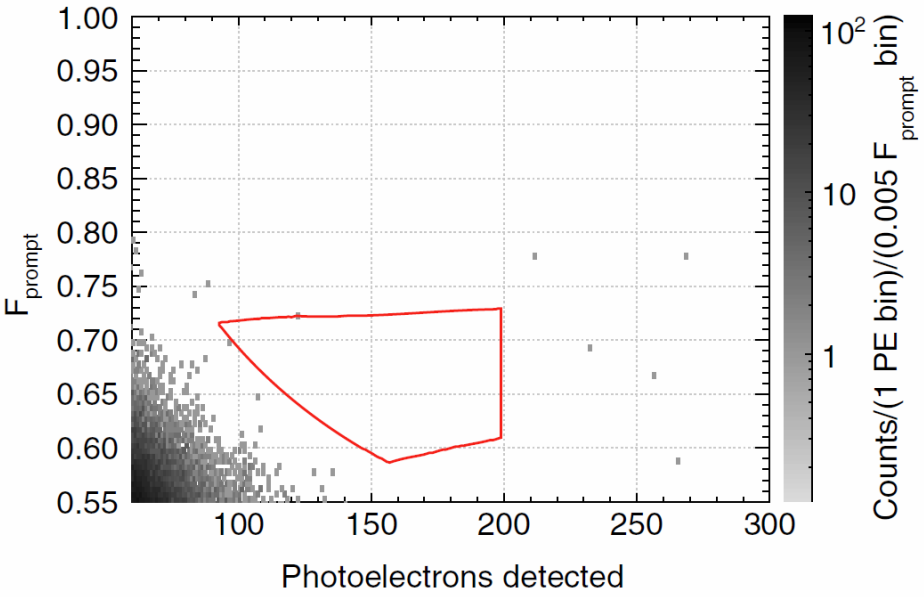
arXiv: 1802.06998

DEAP-3600 @ SNOLAB

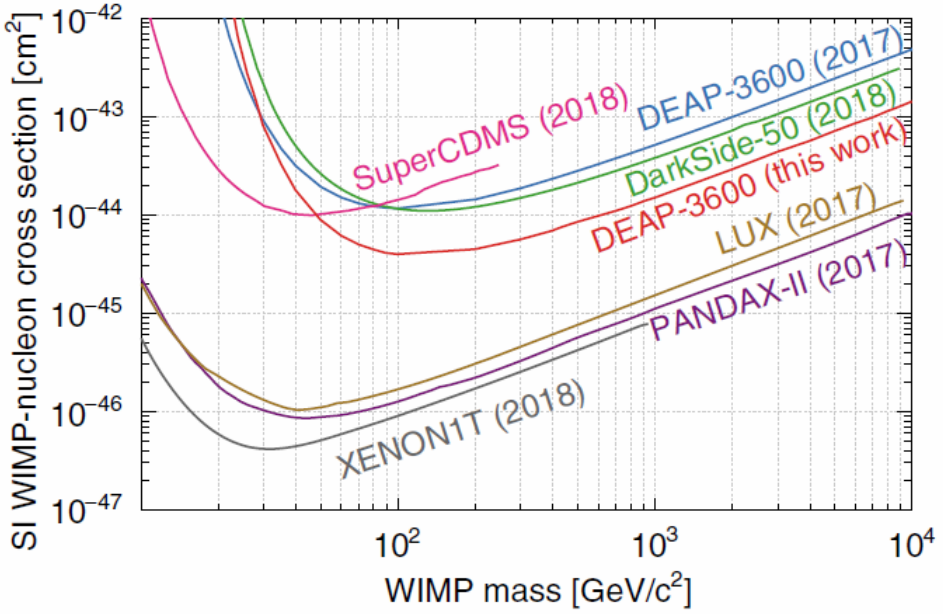
- 3279 kg of LAr in an acrylic sphere (85 cm radius)
- 45 cm long UVA acrylic light guides
- 7.8 m (h) × 7.8 m (d) water tank
- 758 tonne·day exposure (231 live-days)



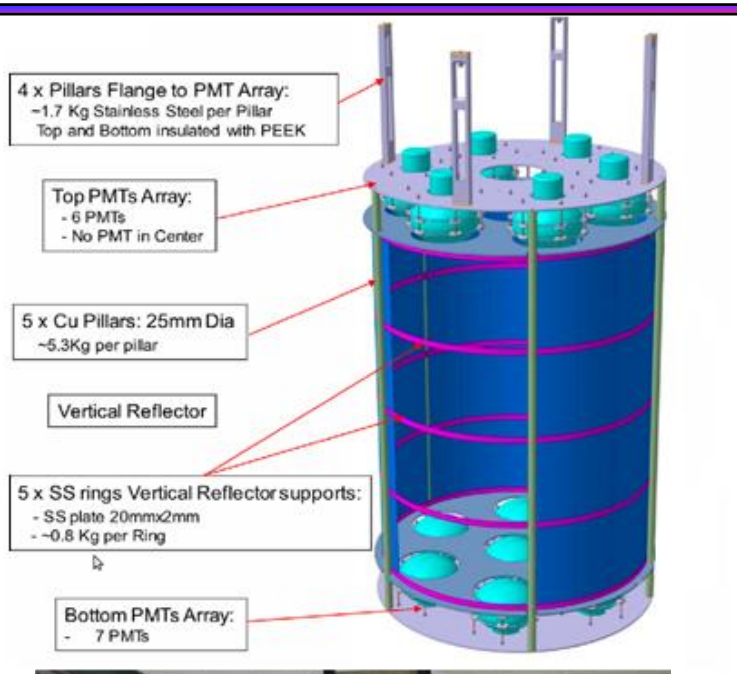
Pulse shape analysis:
ER suppression 4×10^{-9} with 90 % NR-acceptance
EPJC 80, 303 (2020)

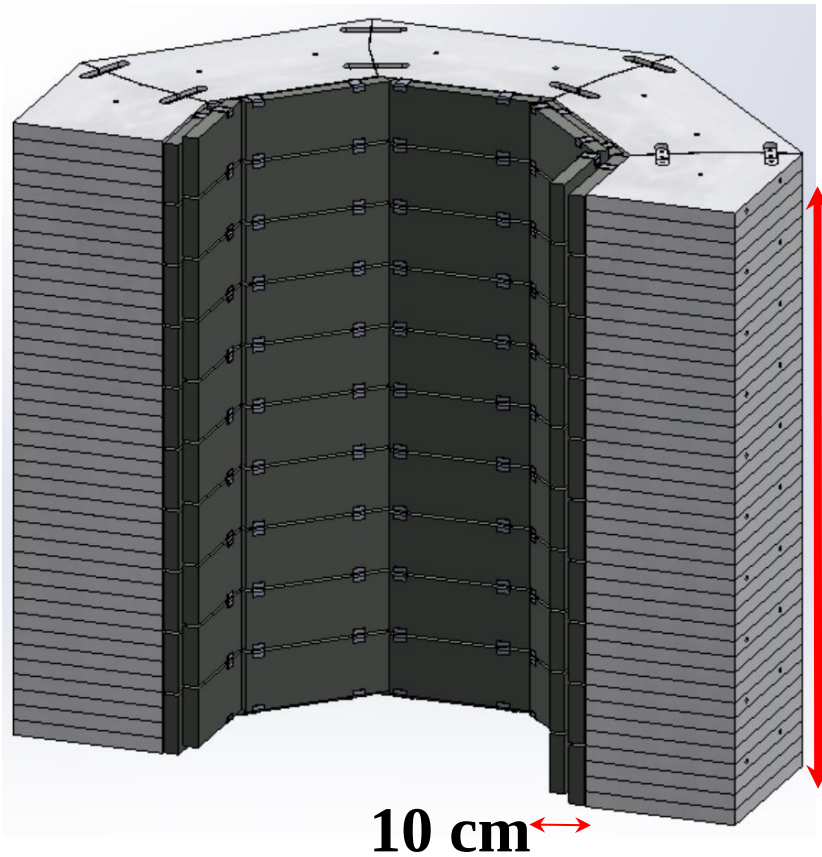


PHYS. REV. D100,022004 (2019)



Active veto and passive shield



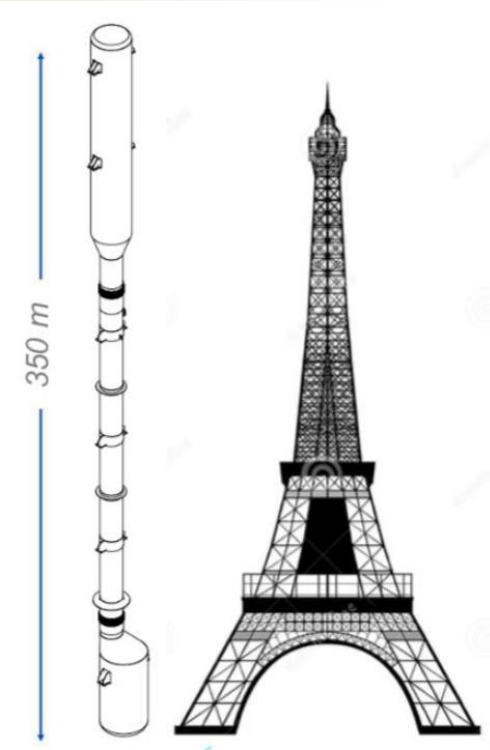


- External polyethylene shielding (20 t)
- Inner Pb shielding (6.5 t)

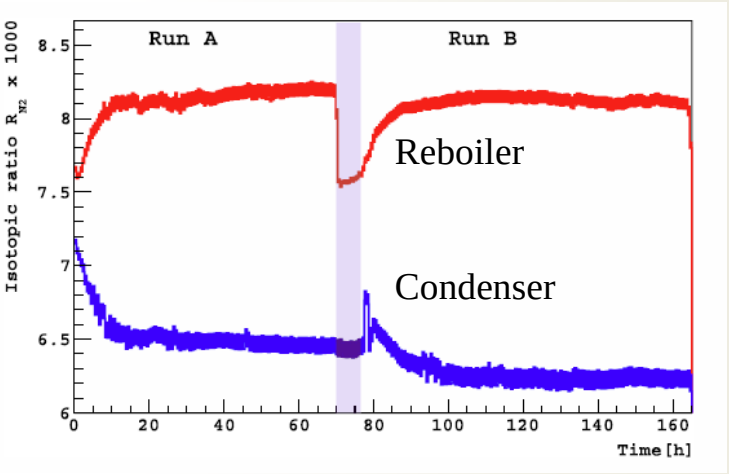
ARIA

- SERUCI-0: short version of the Aria column using only the reboiler, the condenser, and one central module
- SERUCI-1: 28 middle modules

- Top module (Condenser) - 7m
- Middle modules -12m
- Bottom module (boiler) - 5m



Successful nitrogen distillation run of the SERUCI-0 prototype installed outside the Carbosulcis coal mine



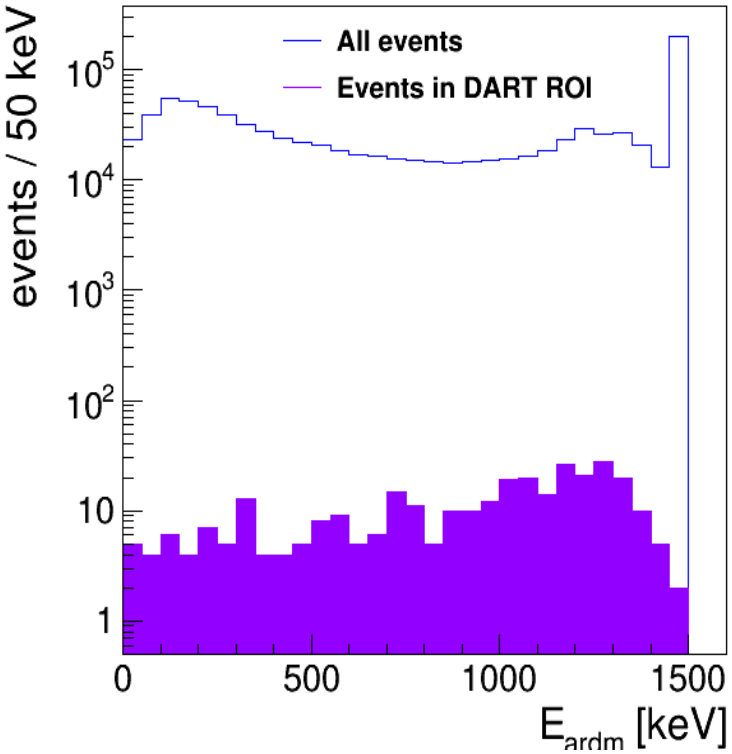
DArT underground @ LSC

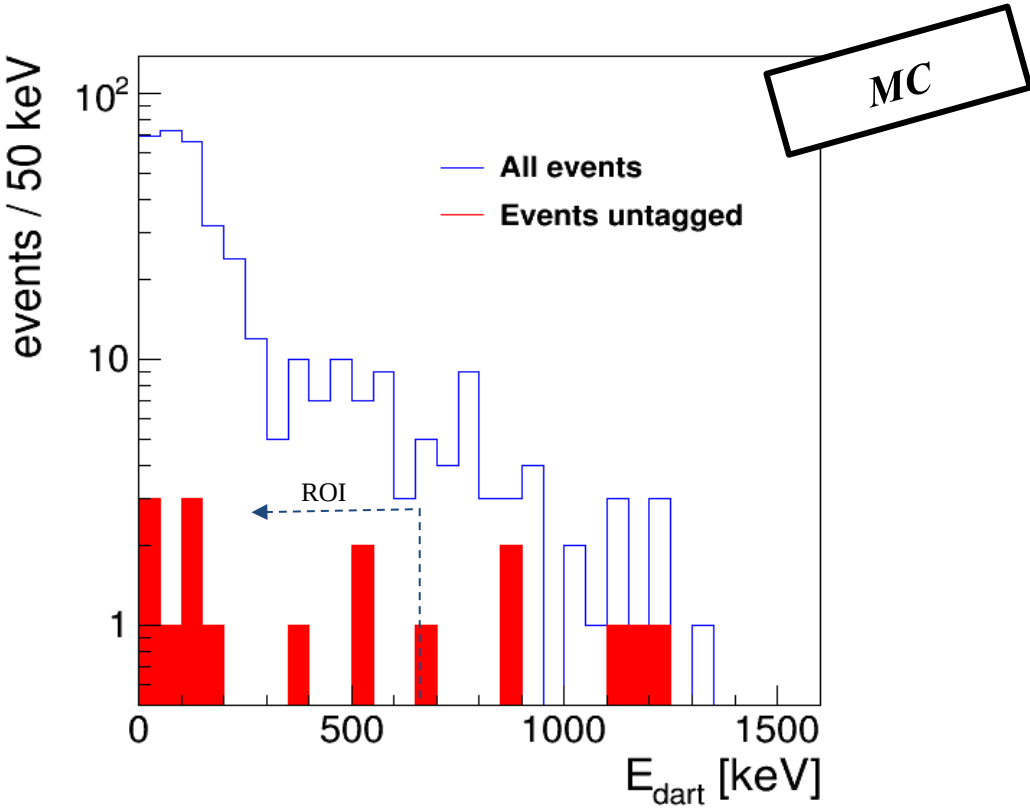
- DArT installed at LSC in April 2021. Data acquisition underground ongoing with AAr in the test cryostat
- Installation in ArDM foreseen in 2021

Signal and background in DArT

ROI: $1 < E_{dart} < 600$ keV **Untagged evts: $E_{ardm} < 10$ keV (veto)**

Cryostat ^{40}K: events in **ArDM 909200**, events in **DART ROI 324**, **Untagged 11**





- Expected number of ^{39}Ar events <u>in 1 week</u>:
  - ~4×10^8 in ArDM (610 Hz from AAr)
  - ~620 in DArT (1 ℓ) - UAr, 0.73 mBq/kg (from DS-50)
  - ~85 in DArT (1 ℓ) - UAr, 0.10 mBq/kg (depletion factor 10^4)