DarkSide-20k and the Liquid Argon Dark Matter Program

Rafał Wojaczyński on behalf of
The DarkSide Collaboration

AstroCeNT CAMK, Warsaw

Cosmology in Miramare 2023, 28 August – 2 September 2023

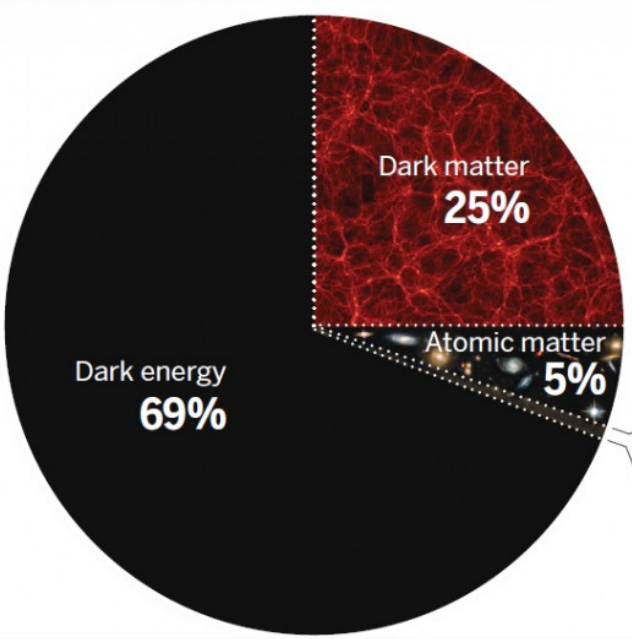
AstroCeNT
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

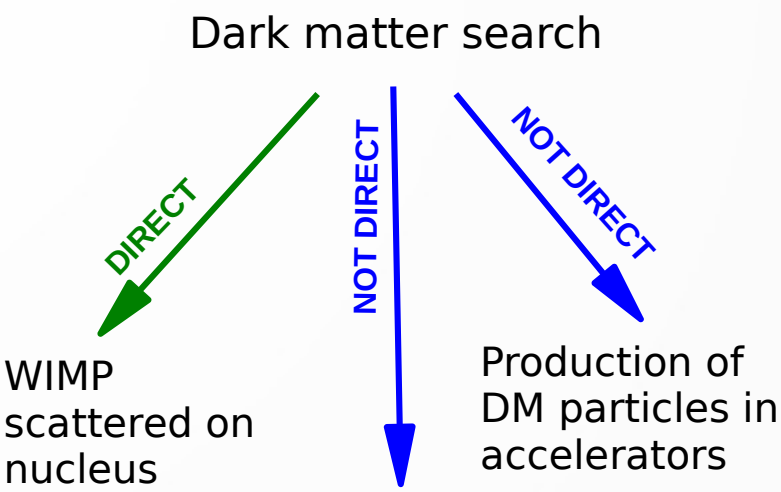
European Funds
Republic of Poland
FNP Foundation for Polish Science
European Union

Dark matter searches



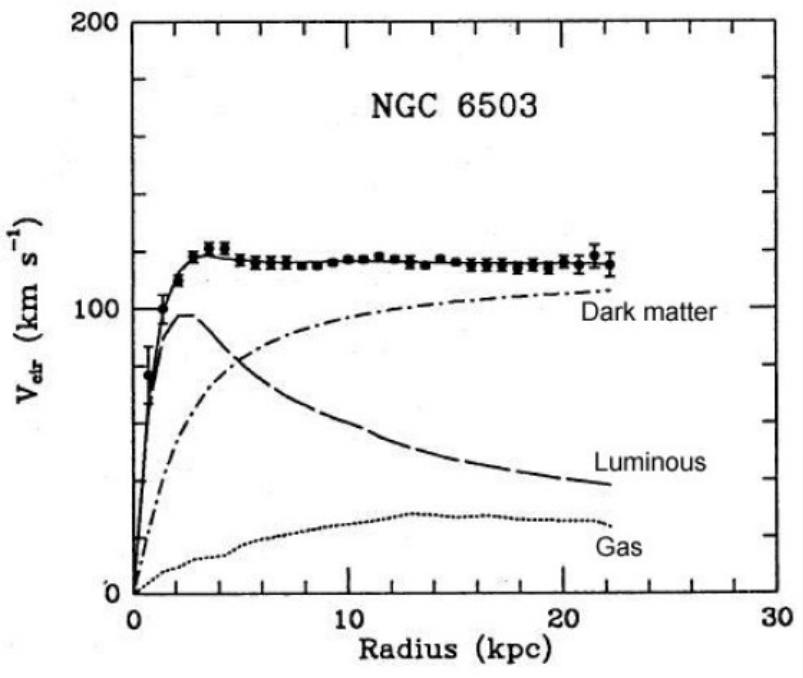
Dark matter :
1) baryonic e.g. MACHO: BH, neutron stars, brown dwars

2) non-baryonic
- hot: relativistic neutrinos
- cold: lower speed, **WIMP** 10 GeV- ~ TeV



Observation of DM annihilation / decay products:
- antimatter
- gamma photons
- neutrinos

1. The rotation curve of galaxies and the movement of galaxies in clusters
2. Gravitational lensing
3. Formation of large-scale structures
4. Heterogeneities in the microwave background radiation



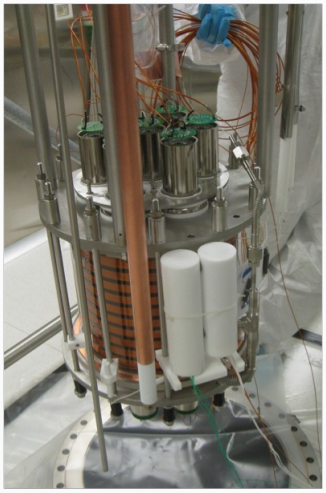
Begeman, Broeils, and Sanders, 1991

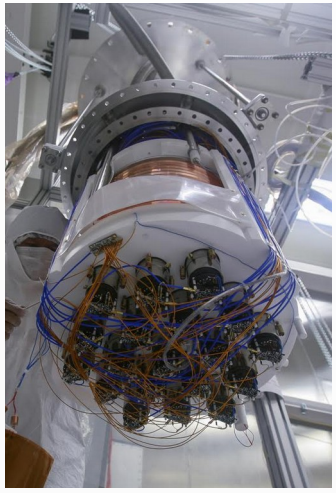
DarkSide program

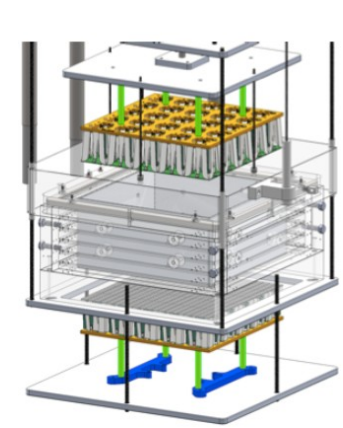
Direct detection search for **WIMP** dark matter

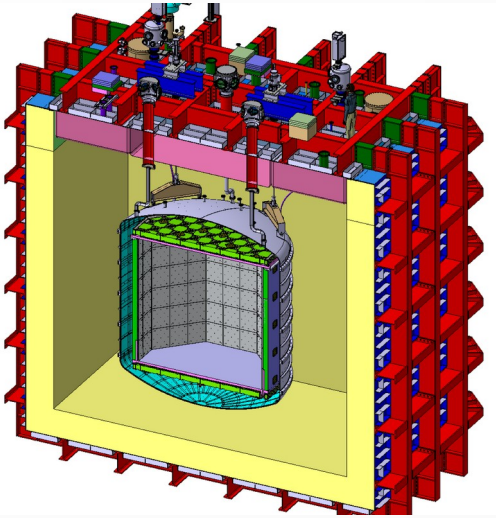
Based on a **two-phase argon** time projection chamber (**TPC**)

Design philosophy based on having very low background levels that can be further reduced through **active suppression**, for near **background-free** operation from both neutrons and β/γ's









2011-2013

DarkSide-10

10 kg
Gran Sasso, IT
First prototype

2013-2020

DarkSide-50

46 kg
Gran Sasso, IT
$3.78 \cdot 10^{-44}$ cm^2
@ 1 TeV (1.4 yr exposure)

2019-2022

Proto0

10 kg
CERN, CH
test of new DS-20k technologies

2026-

DarkSide-20k

51 t
Gran Sasso, IT
$6.3 \cdot 10^{-48}$ cm^2
@ 1 TeV (10 yr exposure)

Features of noble liquid detectors

- **Dense** and **easy to purify** (good scalability, advantage over gaseous and solid target)
- High **scintillation** & **ionization** (low energy threshold, not low enough to search < 1 GeV/c^2 DM)
- **Transparent** to own scintillation

For TPC:

- Amplification (electroluminescence gain) for ionization signal
- **Discrimination** electron/nuclear recoils **(ER/NR)** via **Pulse shape discrimination**

Liquid **Xenon**

- Denser & Radio pure
- Lower energy threshold

Liquid **Argon**

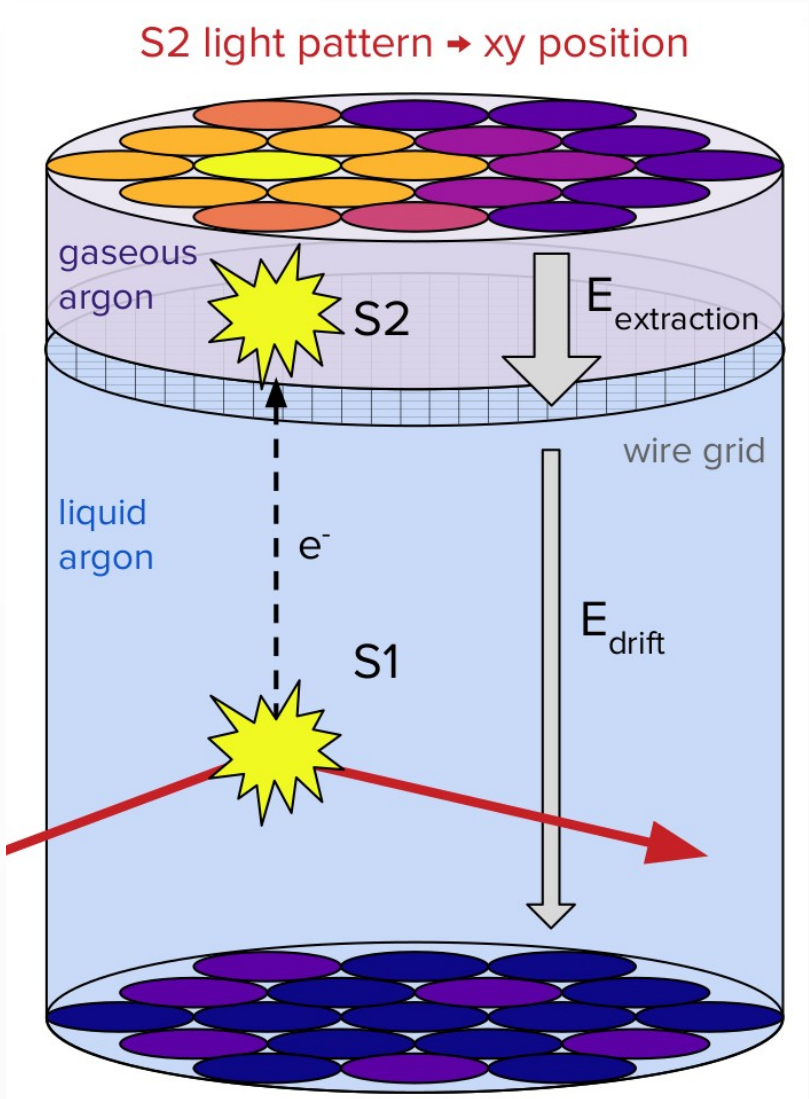
- lower temperature
- **Stronger ER discrimination** via pulse shape
- Intrinsic ER BG from ^{39}Ar
- Need wavelength shifter

The Time-Projection Chamber (TPC)

Based on DarkSide-50 TPC

S1: light produced in the liquid argon due to excitation and ionisation

S2: light produced in the gas argon pocket due to ionisation electrons drifted by an E field.

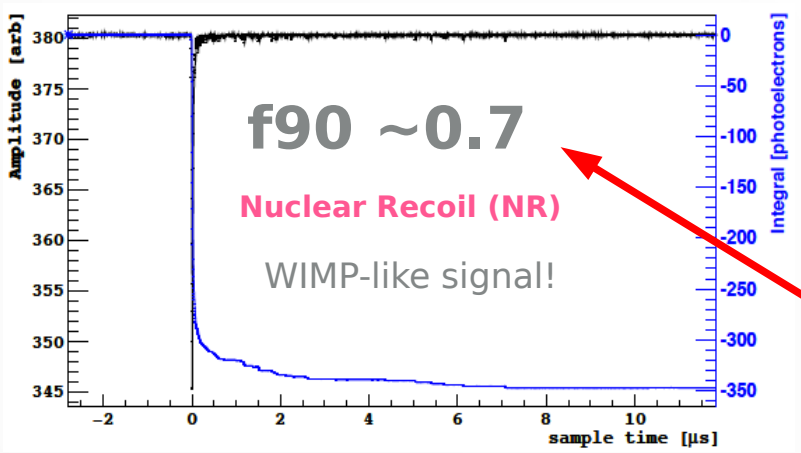


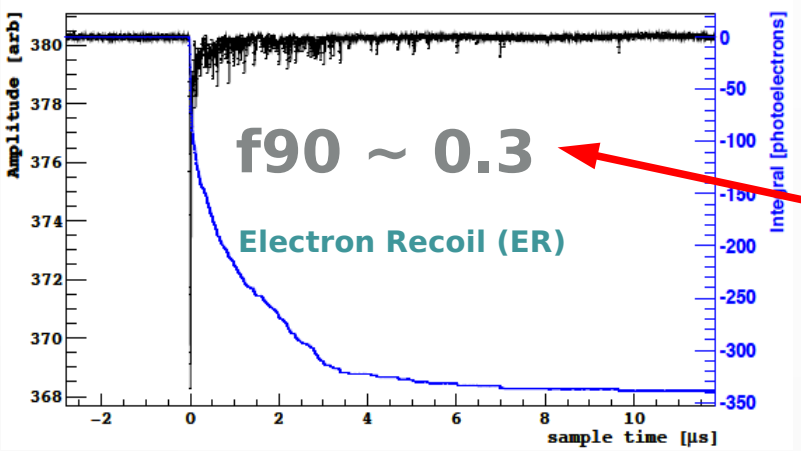
S2/S1 ratio and **Pulse Shape Discrimination (PSD)**

WIMPs will generate nuclear recoils (NRs)

Pulse shape discrimination (PSD)

Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states**

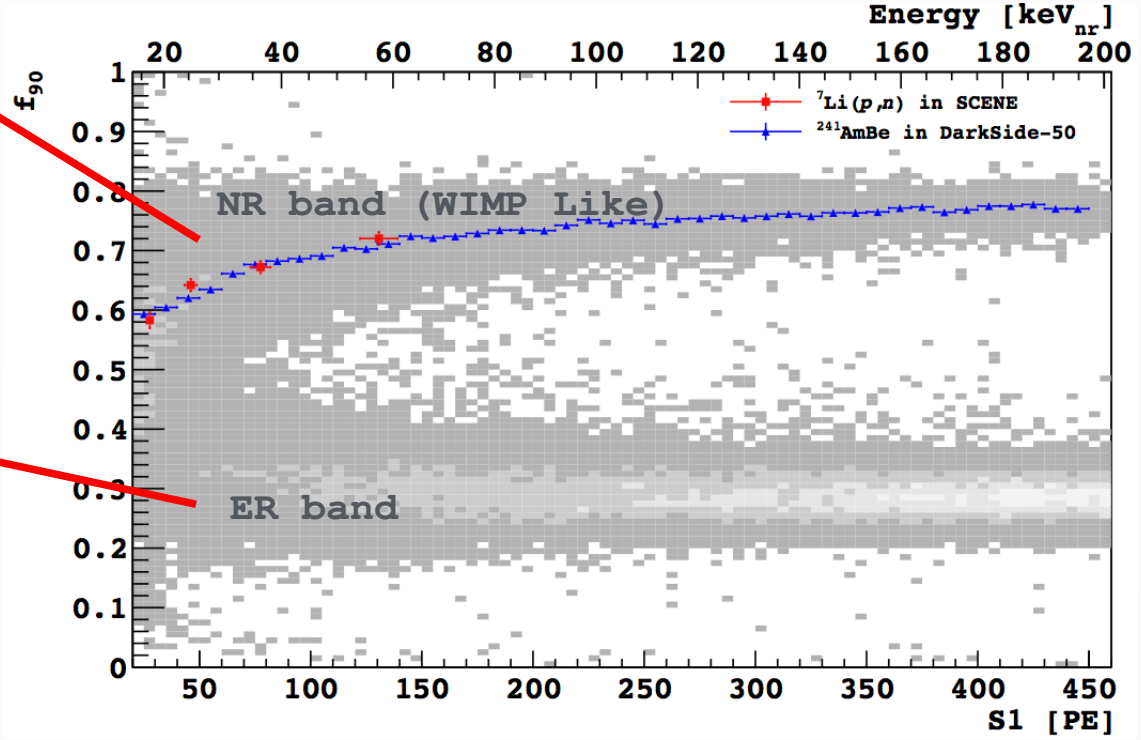




PSD parameter

F90: Ratio of detected light in the first 90 ns*, compared to the total signal

$$f90 = \frac{N_{prompt}}{N_{prompt} + N_{late}}$$

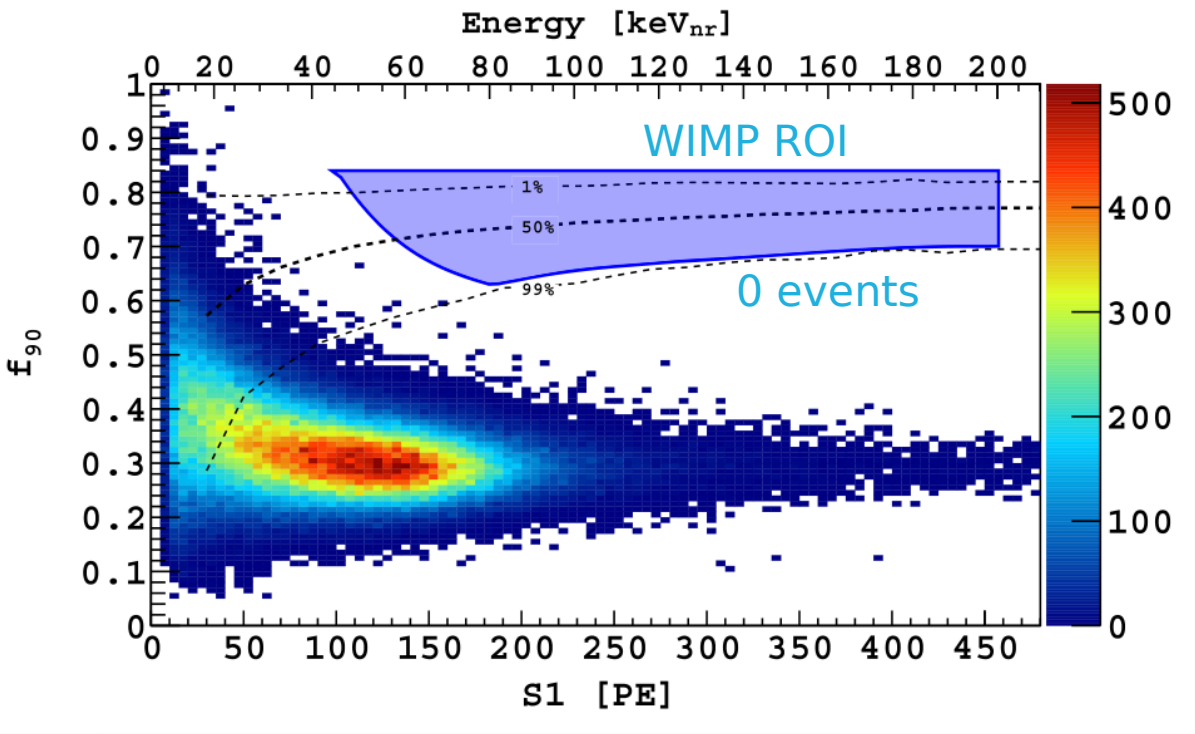


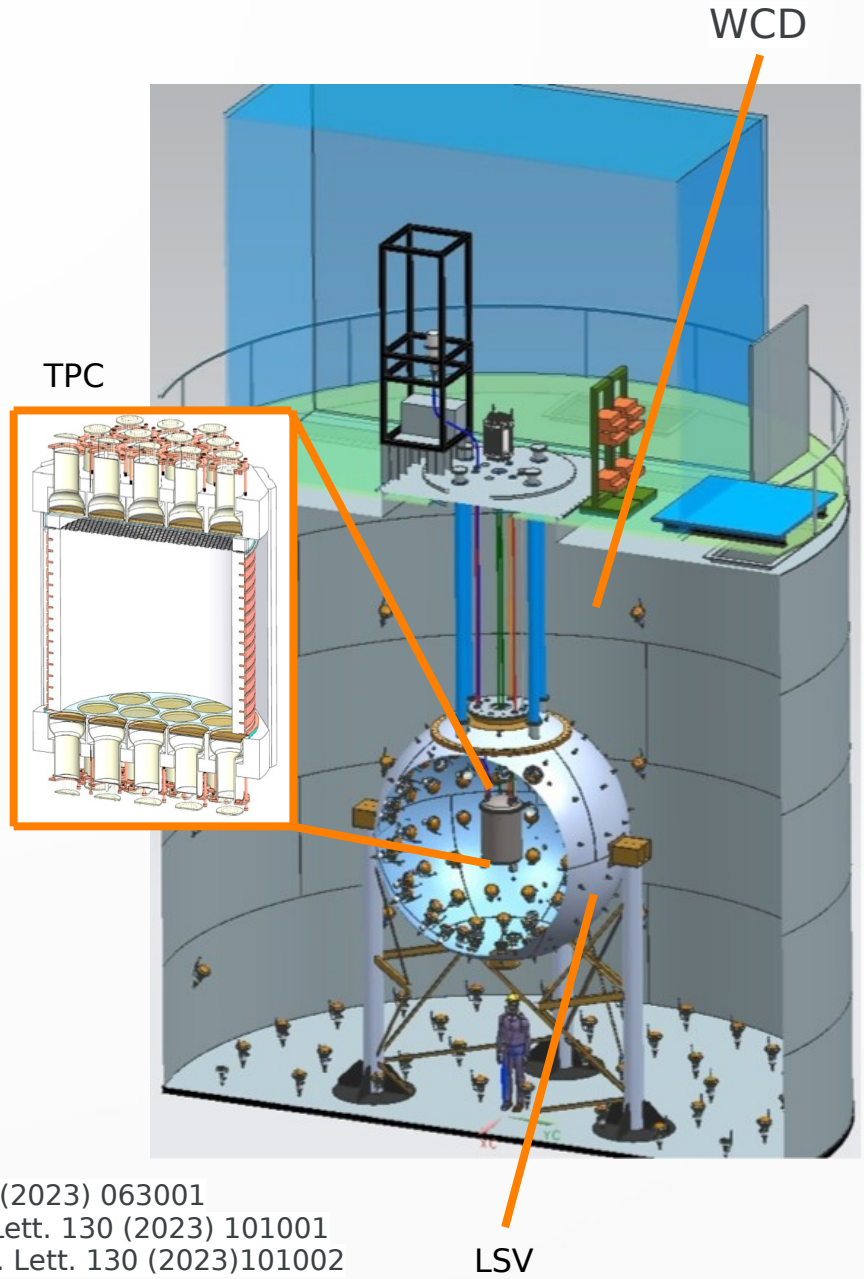
More for PSD: DEAP-3600, Eur. Phys. J. C 81, 823 (2021)

* the 90 ns is optimized value for DS50 and detector dependent parameter.

DarkSide-50: Detector overview

- Underground experiment at LNGS (3800 m w.e.)
- 50 kg LAr
- Two veto detectors:
    - Liquid Scintillator Veto (LSV)
    - Water Cherenkov Detector (WCD)
- 532.4 live days of UAr blinded data
- background < 0.1 for the full exposure
- 19 top and 19 bottom 3” PMT’s



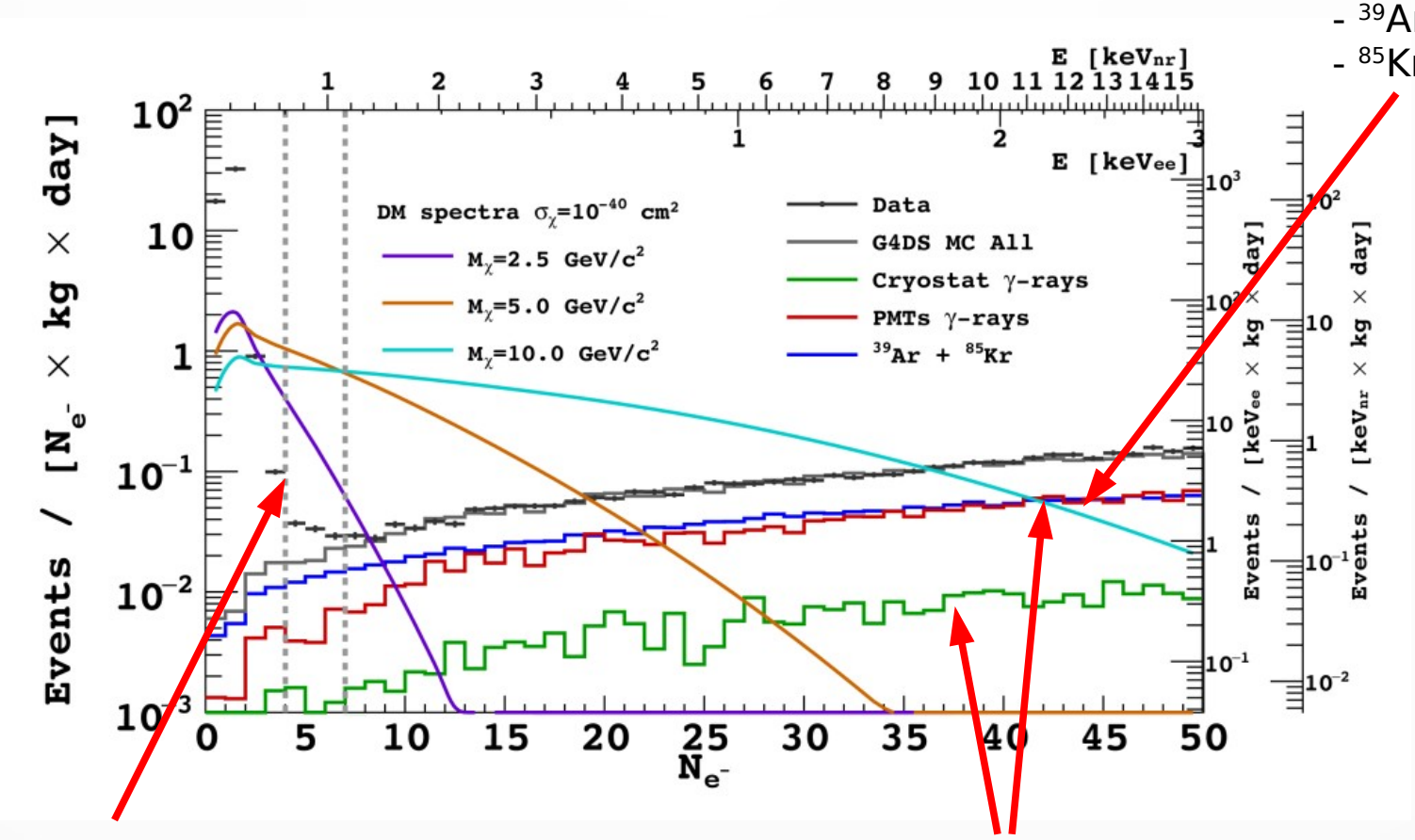


DS-50 sensitivity papers:
- **AAr 53.8 days:** PLB 743, 456–466 (2015)
- **UAr, 70.9 days:** PRD 93, 081101(R) (2016)
- **UAr, 532 days:** PRD 98, 102006 (2018)

Light-DM update:
- **WIMP-N:** Phys. Rev. D 107 (2023) 063001
- **Migdal effect:** Phys. Rev. Lett. 130 (2023) 101001
- **WIMP-electron:** Phys. Rev. Lett. 130 (2023)101002

DarkSide-50: backgrounds

Beta-decay:
- ^{39}Ar
- ^{85}Kr in LAr



Spurious electron events (1-4 Ne),
Impurities in argon interacting with drifting electrons from ionization (under investigation)

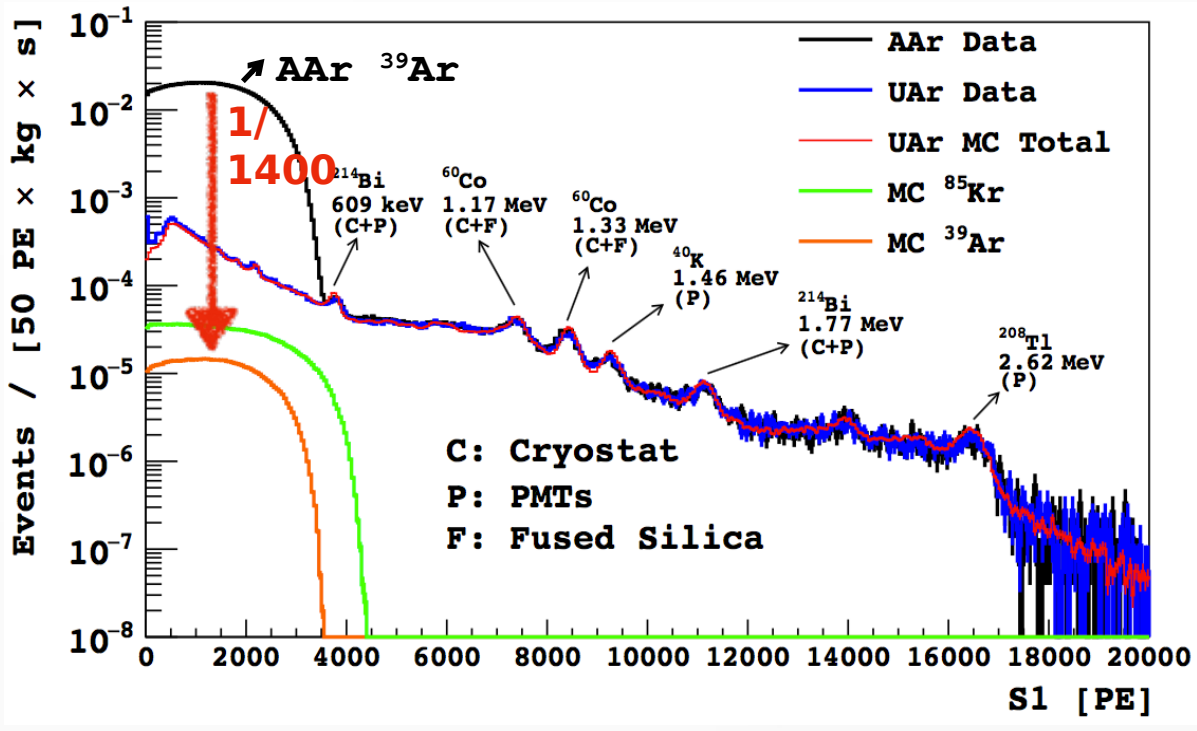
Main dominant backgrounds from PMT/Cryostat gamma-rays

DS-50 data: P. Agnes et al., Phys. Rev. Lett. 121, 081307 (2018)

Underground Argon

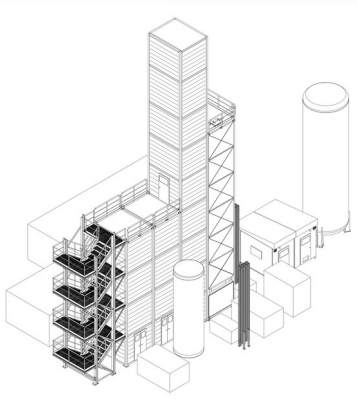
- Intrinsic ^{39}Ar radioactivity in **atmospheric argon** is the primary background for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective)
- ^{39}Ar is a **cosmogenic isotope**, and the activity in argon from **underground sources** can be significantly lower compared to **atmospheric argon**

^{39}Ar reduction factor of ~1400!



Extraction & isotope separation

- **Urania** (Extraction):
  - Takes place at argon extraction plant in Cortez, CO, to reach capacity of **330 kg/day** of Underground Argon

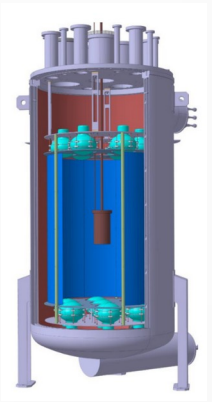


- **Aria** (Isotope separation):
  - 350 m tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon. **A factor 10 reduction of ^{39}Ar** per pass is expected.

Eur. Phys. J. C 81, 359 (2021)

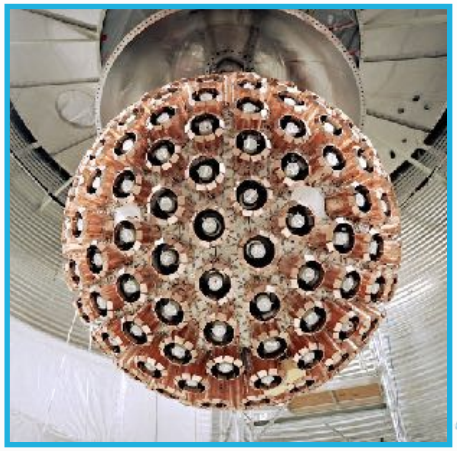
DArT:

- measurement of radiopurity of UAr in terms of Ar39 (batches from Urania and Aria)



2020 JINST 15 P02024

Global Argon Dark Matter Collaboration (GADM)

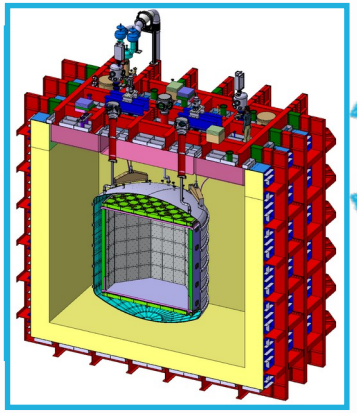


DEAP-3600
(SNOLAB, LAr: 3.3t)

More than 500 scientists from past and present argon-based experiments in a single international argon collaboration: **GADMC**

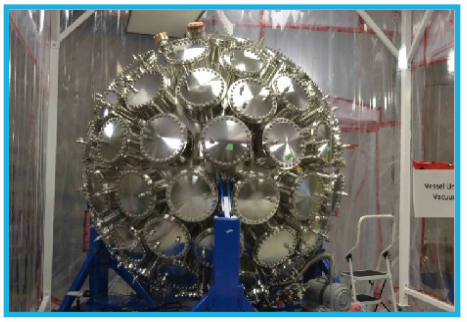
A sequential, two-steps program:

- DarkSide-20k (200 tonne yr fiducial), LNGS

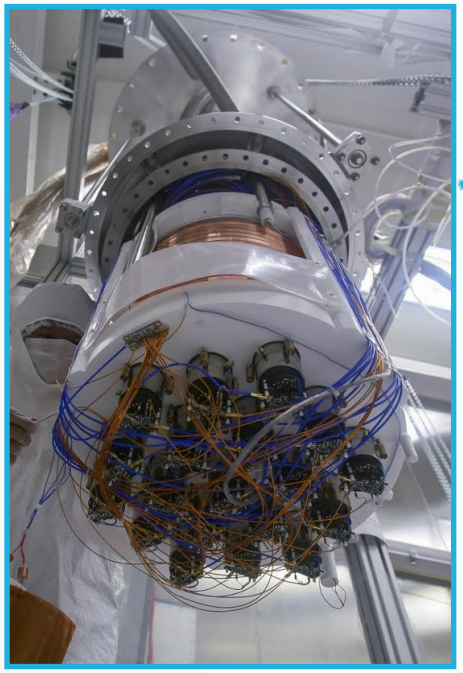


- Argo (3000 tonne yr fiducial)

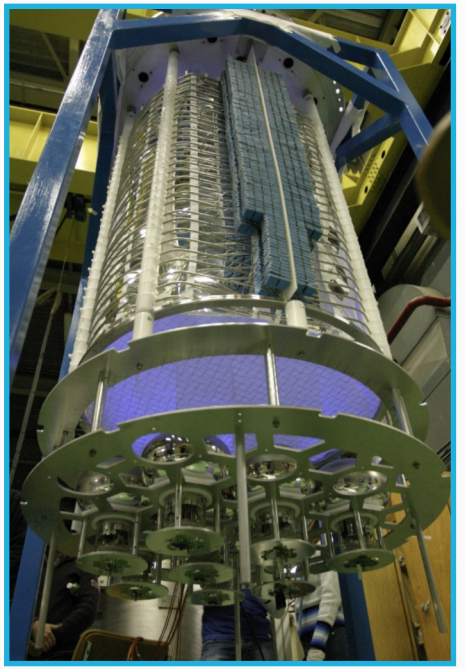
At SNOLAB



MiniCLEAN
(SNOLAB, LAr mass: 500 kg)



DarkSide-50
(LNGS, LAr: 46 kg)

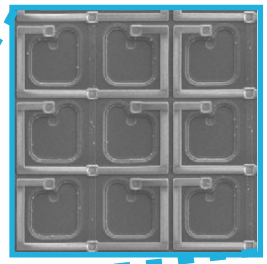


ArDM
(Spain, LAr: 850 kg)

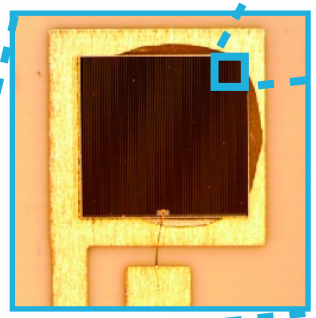
The goal: explore heavy dark matter to the neutrino floor and beyond with extremely low instrumental background

DS-20k: Photo sensors

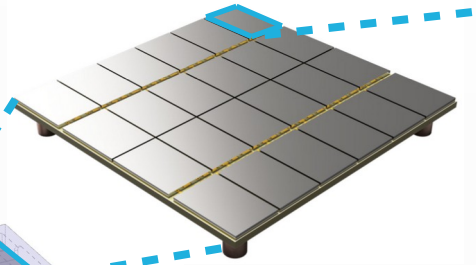
- Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.
- Key features:
  - Photon detection efficiency (PDE) ~45%
  - Low dark-count rate < 20 cps
  - Timing resolution ~ 10 ns



SPAD: Single photon avalanche diode
~25-30 μm²

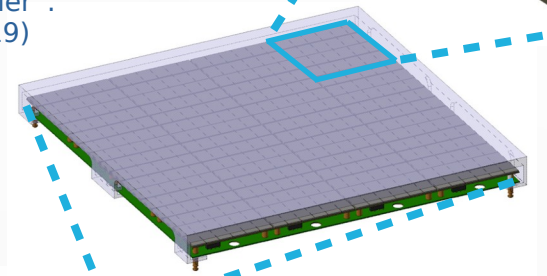


SiPM (~ 1 cm²): 94 900 SPADs

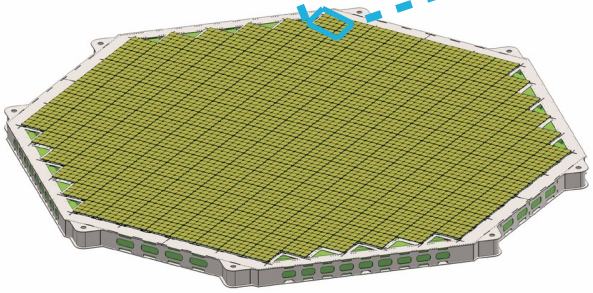


PDM (5 x 5 cm²) : Photo-detection module
- consist of 24 SiPMs
(largest single SiPM unit ever!)

A. Gola et al.
"NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler".
Sensors19(2), 308 (2019)

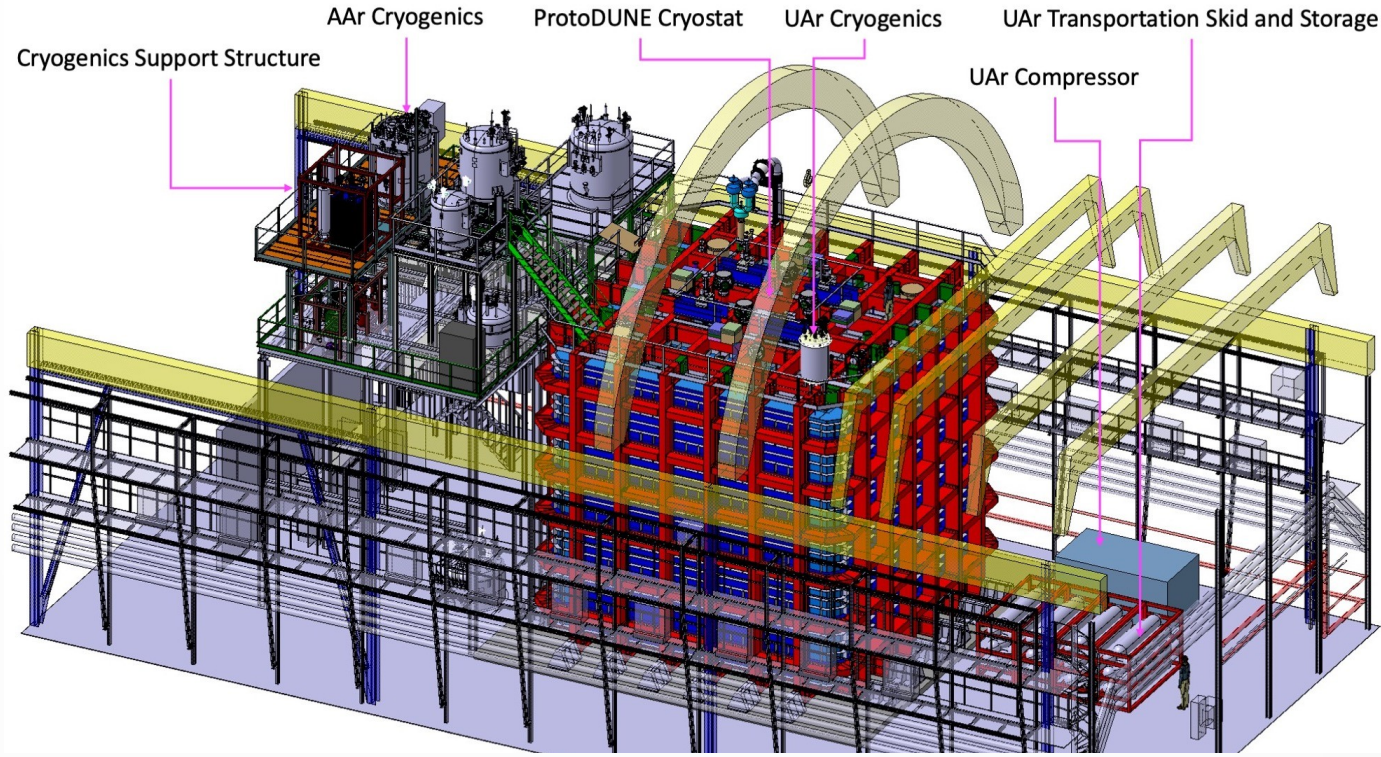


PDU (20 x 20 cm²): Photo-detection unit
- consist of 16 PDMs



TPC optical plane:
264 + 264 = 528 total PDUs ~ 21m²

DarkSide-20k Detector

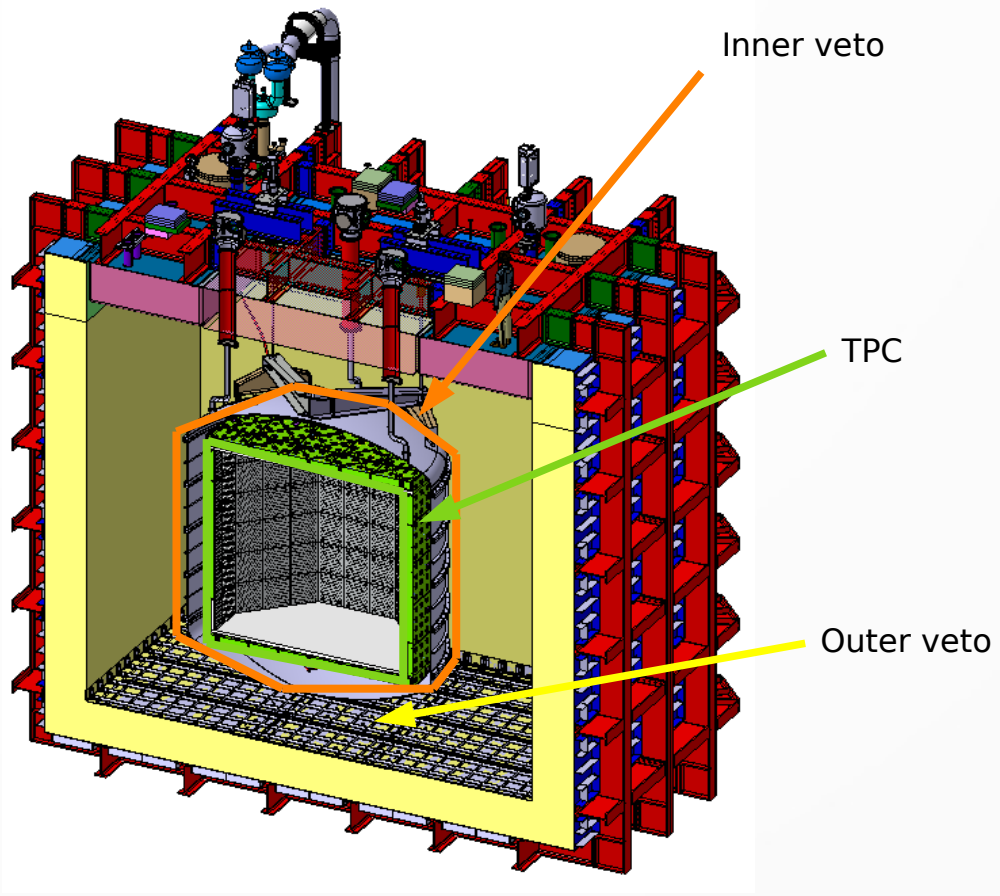


- Installed underground at the Gran Sasso National laboratories, in Italy (Hall-C)
- Covered with 1400m of rock (under the Gran Sasso mountain)
- 10 years of expected activity
- 21 m^2 instrumented with custom designed SiPM-based light detectors
- TPC filled with 50 t of UAr (20t fiducial)
- Target at 0.1 background event in 200 t yr exposure → world leading sensitivity
- Muon flux reduction factor ~10^6

DarkSide-20k: Overview of design

3 nested detectors:

- **Dual-phase LAr TPC**
  - filled with 50 t of UAr
  - viewed by PDUs (top and bottom)
  - goal to detect dark matter!
  - 0.1 background events (in 200 t year)
- **Inner Veto**
  - veto for neutrons and gammas
  - filled with 32 t of UAr
  - neutron capture with Gd-infused walls of TPC
- **Outer veto**
  - veto neutrons from cosmogenic muon showers
  - filled with 650 t of AAr
  - membrane cryostat 8x8x8 m^3

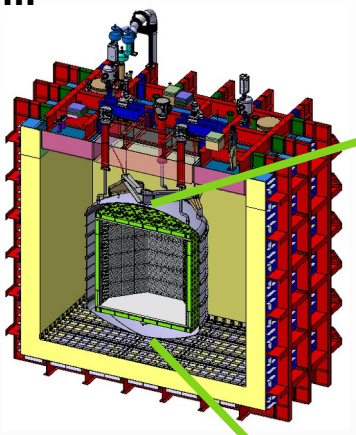


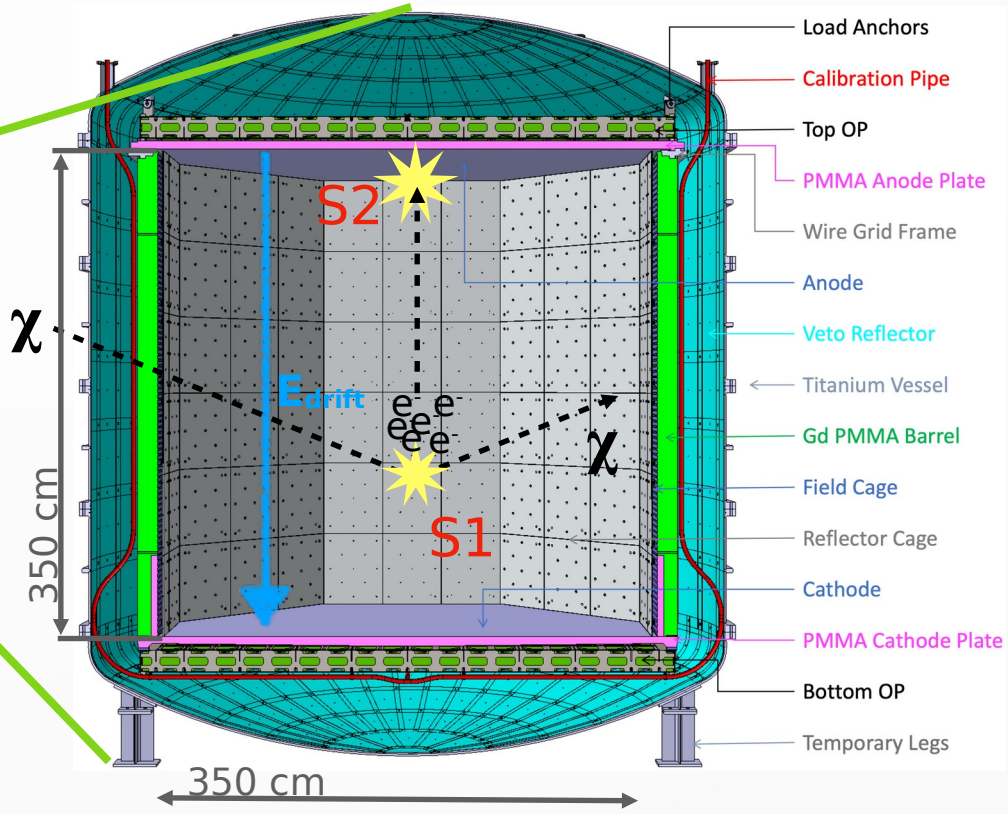
DarkSide-20k: TPC

TPC:

- Active mass: 49.7 t UAr
- Fiducial mass: 20 t UAr
- Gd-doped acrylic, PMMA (polymethylmethacrylate), vessel to capture neutrons
- Octagonal shape
- Cathode and anode coated with new transparent conductor (Clevios) and wavelength shifter
- Sides covered with multilayer polymeric reflector evaporated with wavelength shifter (TPB)
- Viewed by SiPM based photo detection units (PDUs) from top and bottom

UV 128 nm to visible range 420 nm





Other properties:

- Drift field (nominal) = 200 V/cm
- Extraction field (nominal) = 2.8 kv/cm
- Drift length = 348 cm

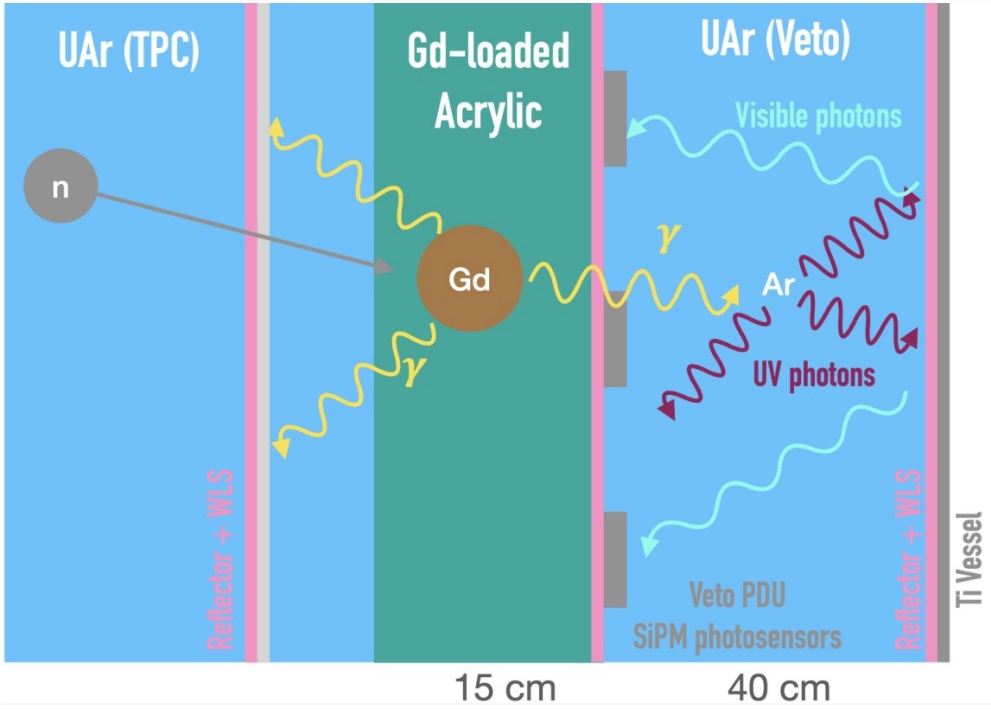
- Gas pocket thickness = (7.0 ± 0.5) mm
- Spatial resolution: xy < 5 cm, z ~ 1 mm

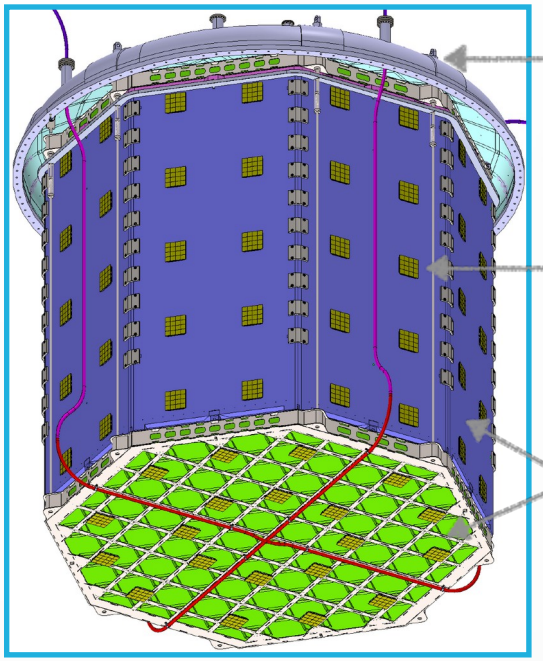
Inner veto detector

Neutrons elastically scattering from argon nuclei are indistinguishable from WIMPs signals. PSD is useless against neutron events.

Veto Structure

- 8 vertical panels of acrylic loaded with gadolinium (Gd-PMMA), form lateral walls of the TPC. Acrylic thickness: 15 cm.
- The UAr volume between the Ti vessel and Gd-PMMA serves as a veto volume with ~40 cm thickness.
- Reflector with WLS on all the surfaces





Veto Working Principle

1. Neutrons are moderated in the acrylic shell and then captured by gadolinium.
2. Gd emits multiple γ-rays with energy up to 8 MeV.
3. γ-rays interact in the liquid argon buffers.
4. LAr scintillation light is shifted and detected by ~3000 SiPM-based photosensors.

Current status of DS-20k

Infrastructure:

- Steel support for the cryostat built at Hall C in LNGS
- Procurement for cryogenics and cryostat cold structure in progress → installation in 2024H1
- TPC assembly procedure under discussion

Photo-electronics:

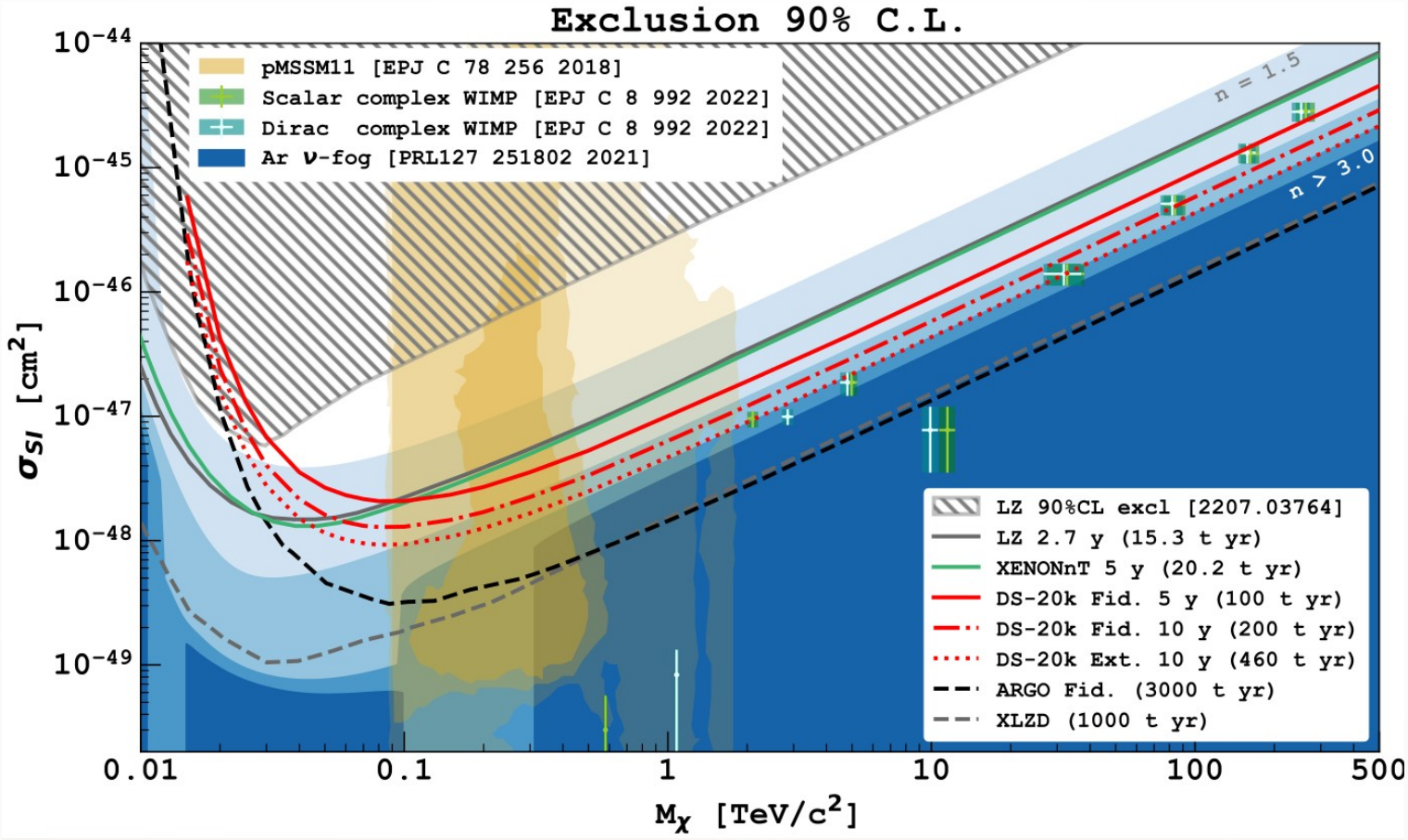
- SiPMs production at LFoundry, Italy. Delivery started in 2022.
- Nuova Officina Assergi (NOA) operational and testing SiPMs
- PDU Pre-Production in 2023Q3
- Naples PDU Test Facility ready for mass testing in 2023Q3
- vPDU production in UK starting in 2023Q3
- vPDU test facilities in commissioning (Naples, Liverpool, Edinburgh, AstroCeNT)

Nuova Officina Assergi (NOA)

LFoundry, Italy

DS-20k: Expected sensitivity

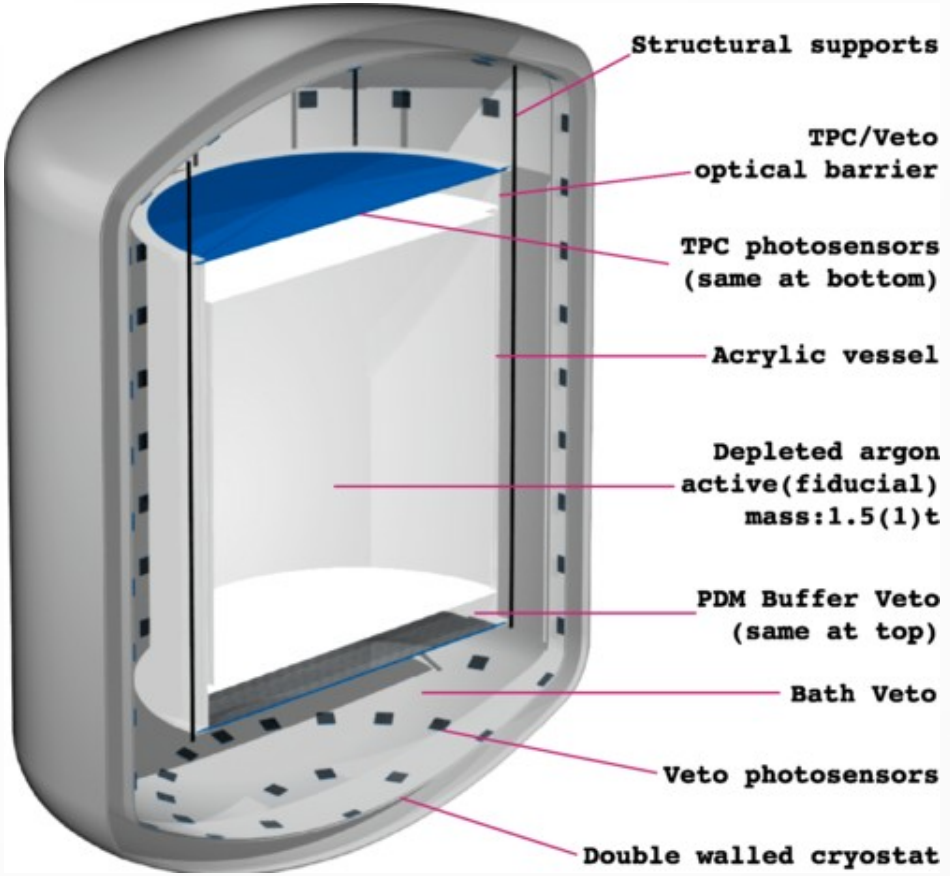
The sensitivity of DS-20k to spin independent WIMPs for different lengths of runs, with the full exposure and with the fiducial cuts applied, compared to LZ and XENONnT.



The present projection - based on a 10 yr run, giving a fiducial volume exposure of 200 t yr - is 6.3 x 10^{-48} cm^2 for 1 TeV/c^2 WIMP for the 90% C.L. exclusion.

DarkSide-Low Mass

- Active (fiducial) mass: 1.5 (1) tonnes underground argon
- **TPC height/diameter: 111 cm**
- Amplified in the gas region
- Low-radioactivity SiPMs and stainless steel from DS-20k, ultrapure acrylic from DEAP
- Sensitive to a single extracted electron



Sensitive to low mass WIMPs!!

Scintillation signal (S1):
threshold at ~2 keV_{ee} / 6 keV_{nr} - weak sensitivity to low mass WIMPs.

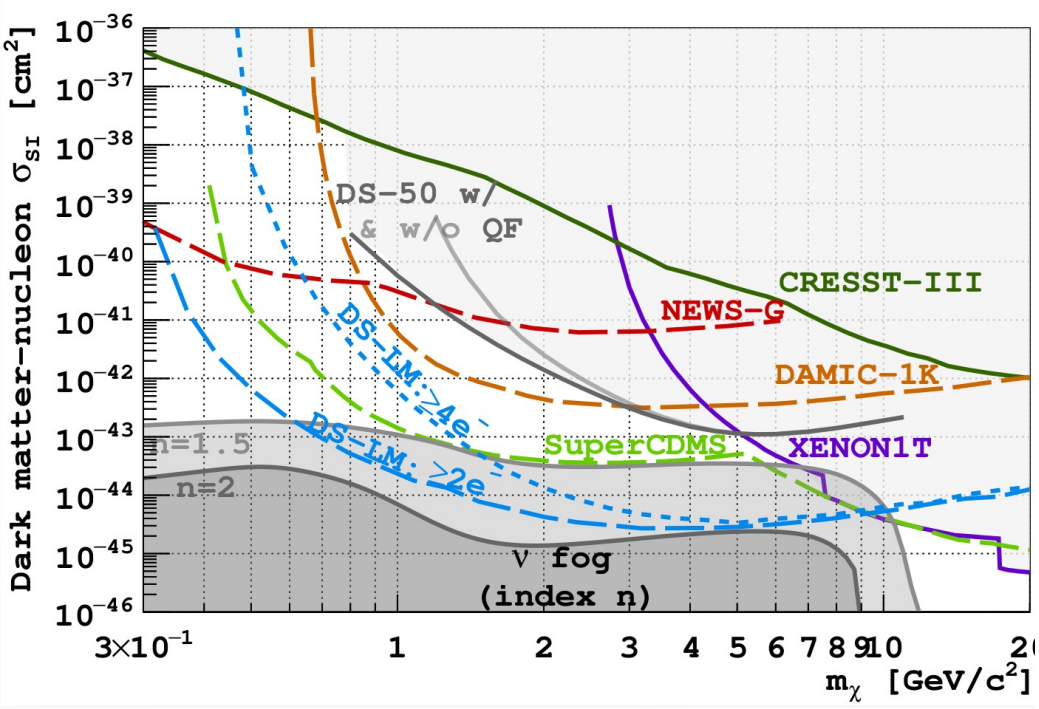
Ionization signal (S2):
threshold < 0.1 keV_{ee} / 0.4 keV_{nr}

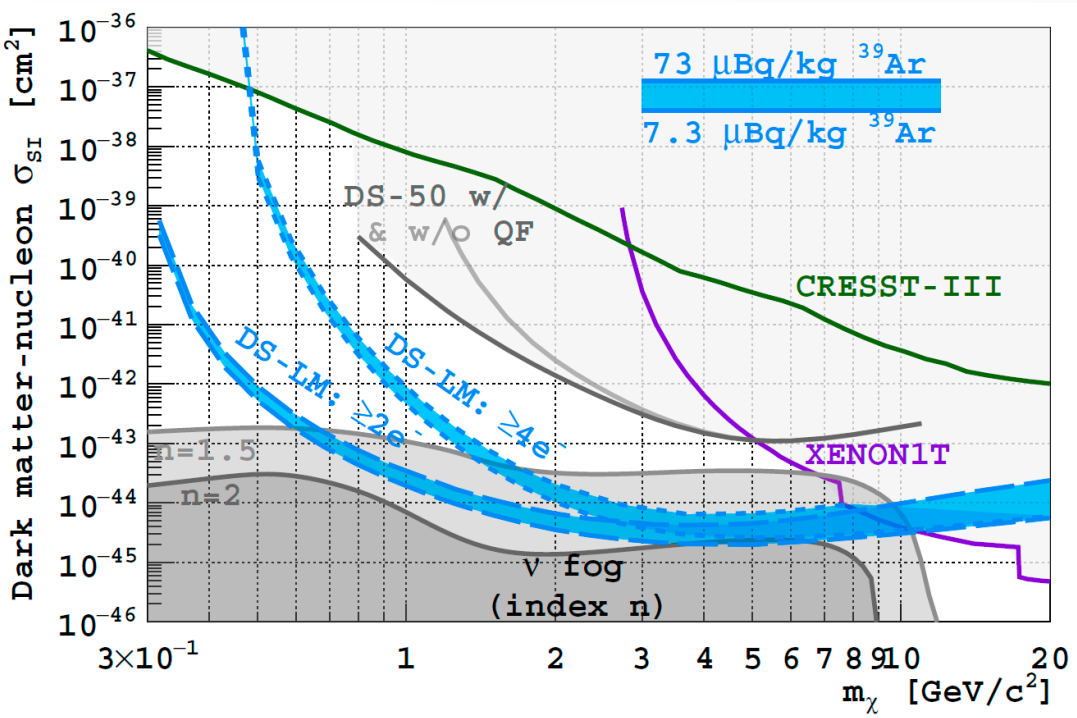
DarkSide-Low mass will use ionization (S2) only

P. Agnes et al., Phys. Rev. D 107, 112006, 2023

Ar has lighter mass than Xe. So, more efficient momentum transfer from low mass DM.

DarkSide-Low Mass: Sensitivity





Projected and current 90% C.L. upper limits on spin-independent DM-nucleon scattering

3σ evidence contours varying threshold and ^{39}Ar activity

P. Agnes et al., Phys. Rev. D 107, 112006, 2023

Summary

- TPC with underground Ar has excellent properties suited to high and low mass WIMP searches.
- Projects for scaling up of UAr extraction (URANIA) and purification (ARIA) are well developed.
- SiPM production started, Naples Test Facility ready for PDU mass testing.
- Construction of DS-20k cryostat started, to be operational in 2026.
- Aim at the better sensitivity than the current generation of WIMP search experiments.
- DarkSide-LowMass dedicated for lower WIMP masses, complementary to other detectors constructing or operating by DarkSide Collaboration.

Thank you!


ASTROCENT
Budker Institute of Nuclear Physics
BROOKHAVEN NATIONAL LABORATORY
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CPPM
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
FONDAZIONE BRUNO KESSLER
Fermilab
GSSI
Instituto de Física
INFN
IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY
NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"
LPNHE
PARIS
Politechnika Łódzka
POLITECNICO MILANO 1863
Novosibirsk State University
THE REAL SCIENCE
Pacific Northwest NATIONAL LABORATORY
SAPIENZA
UNIVERSITÀ DI ROMA
ROMA TRE
UNIVERSITÀ DEGLI STUDI
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE
UNIVERSITY OF SUSSEX
TIFPA
Trento Institute for Fundamental Physics and Applications
TRIUMF
THE UNIVERSITY OF CHICAGO
UMASS
UNIVERSITÉ DE SHERBROOKE
WARWICK
THE UNIVERSITY OF WARWICK
araid