GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

The **DarkSide-20k** Experiment

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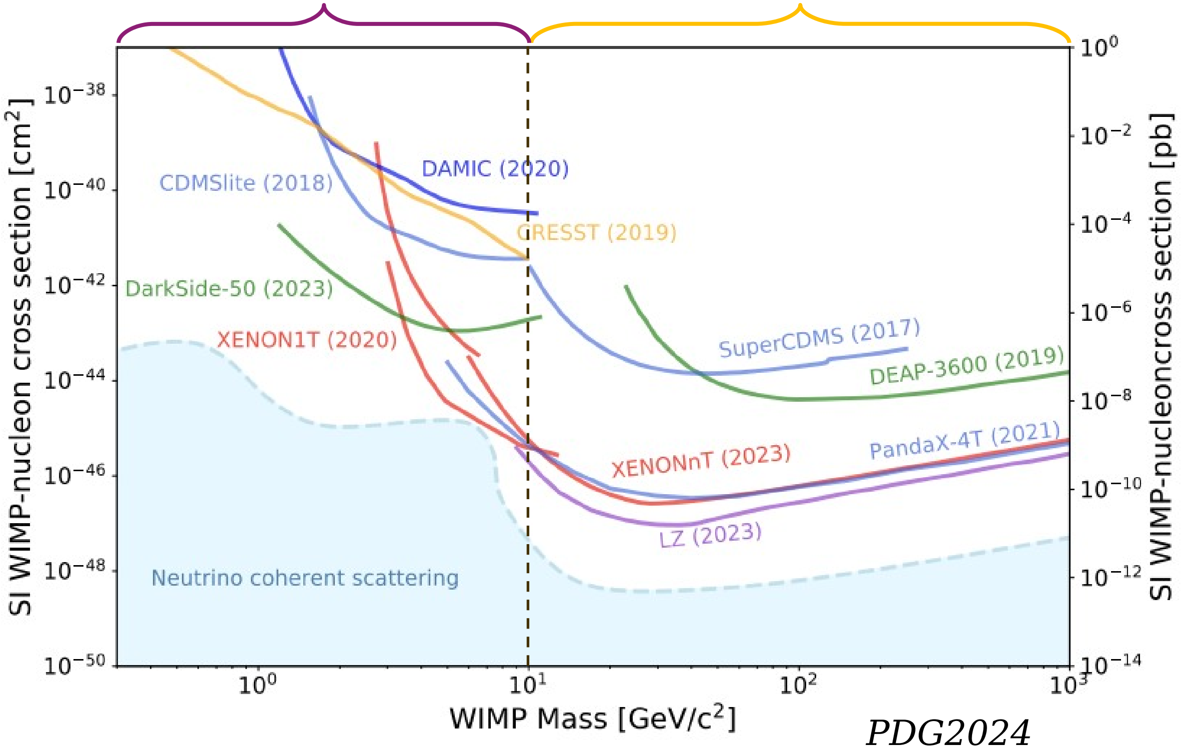
On behalf of the DarkSide Collaboration

DARKSIDE

WIMPs as candidates for dark matter

- Weakly Interacting Massive Particles (**WIMPs**) play a **prominent role** as DM candidate
- **Weak scale** interaction lead to correct density in the universe
- Masses: standard WIMP **few GeV to ~100 TeV**. Can be relaxed down to **few MeV** assuming different coupling to SM
- Motivated by several theories

Low mass WIMP **High mass WIMP**



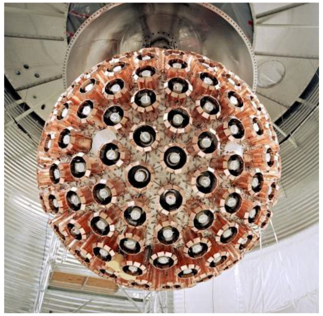
PDG2024

Direct search for WIMP in liquid Argon

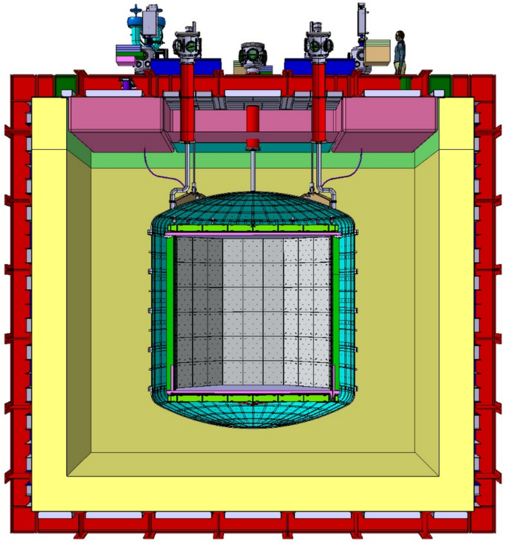
Global Argon Dark Matter Collaboration - **GADMC**

Combined expertise from 4 LAr experiments
Over 400 collaborators from 100 different institutes

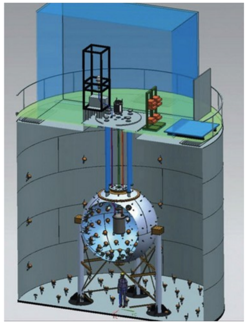
MiniCLEAN
@ SNOLAB



DEAP
@ SNOLAB



DarkSide-20k (DS-20k)
@ LNGS



DarkSide-50 (DS-50)
@ LNGS

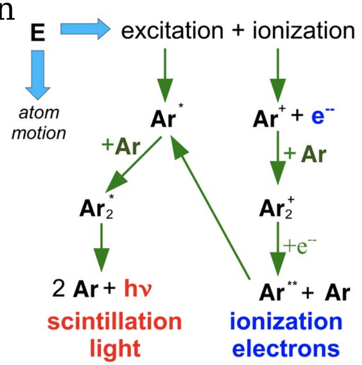
ArDM
@ CanFranc

GOAL: To explore dark matter to the **neutrino floor** and beyond with extremely **low instrumental background**

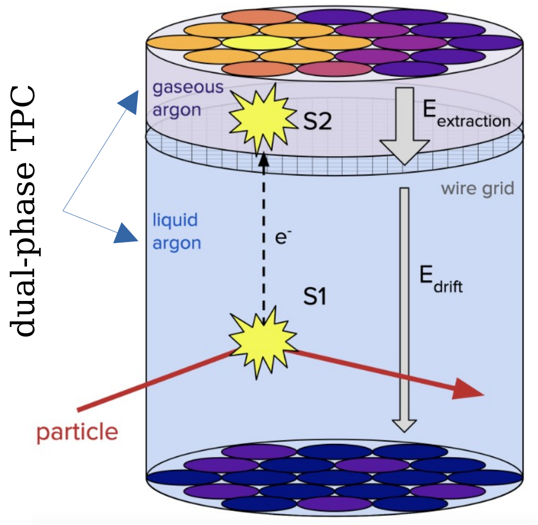
Argon and Time Projection Chamber (TPC)

Why Argon?

- Effective chemical and cryogenic purification
- Good scintillator, high ionization
- Powerful discrimination against background via pulse shape



Two de-excitation times:
Singlet **~7** *ns* ; Triplet **~1.5 μs**



Nuclear recoil (NR): Large probability to populate singlet state

Electron recoil (ER): Mostly populate the triplet state

Neutrons generate NRs while **β and γ** generate ERs

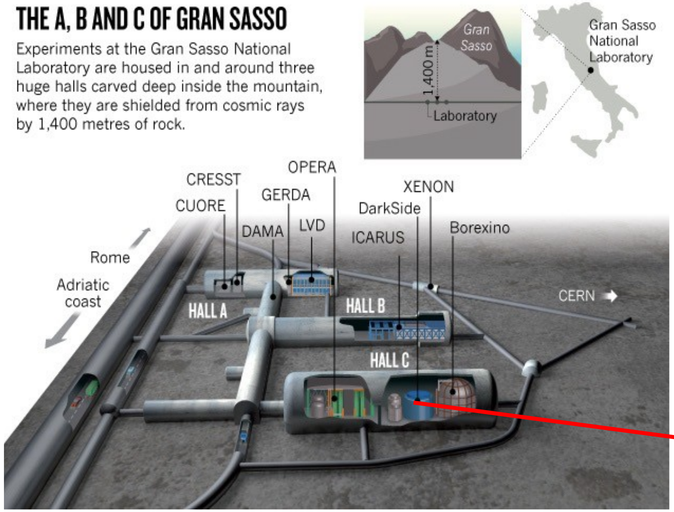
WIMPs generate NRs

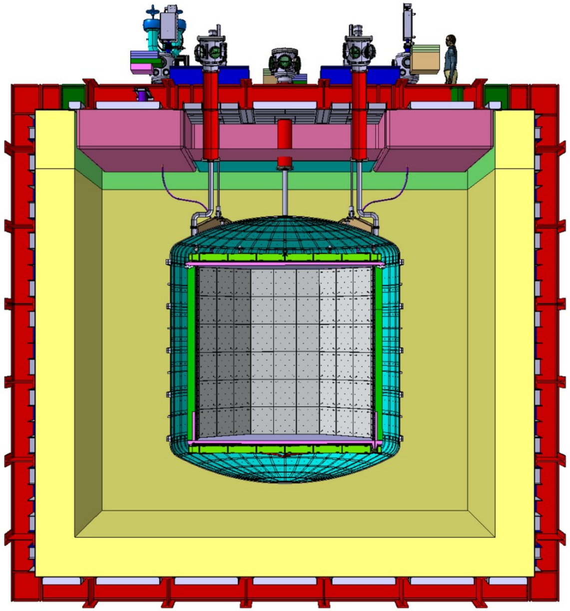
S1: primary scintillation in LAr (energy information and pulse shape discrimination)

S2: secondary scintillation from electroluminescence of electrons in gaseous Ar (energy information and position reconstruction)

DarkSide-20k

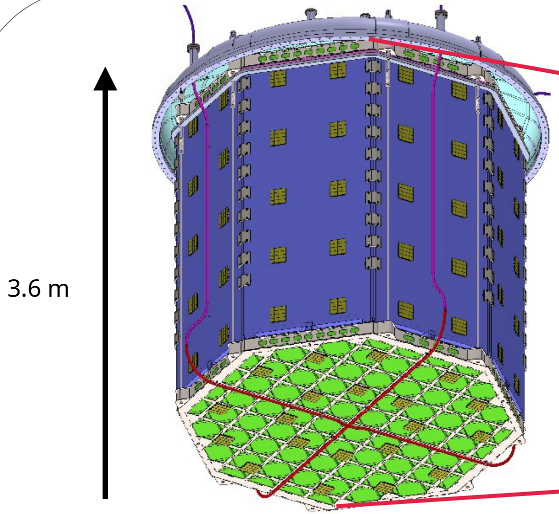
- **LAr dual-phase TPC** experiment designed to detect WIMP scattering interactions from the dark matter halo.
- TPC surrounded by **acrylic panels** (PMMA).
- Utilizes **Underground Argon** (UAr).
- Light Readout: large array of **cryogenic low-noise SiPMs**.

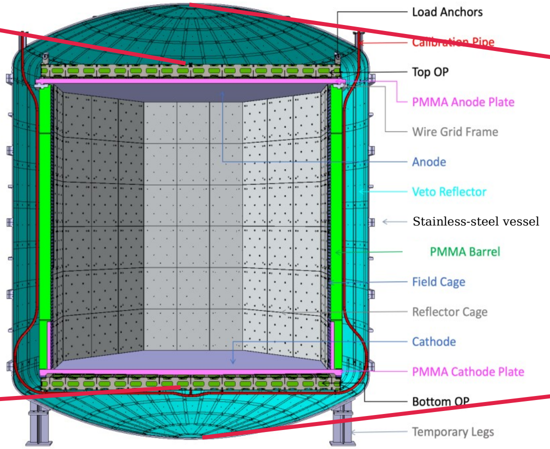


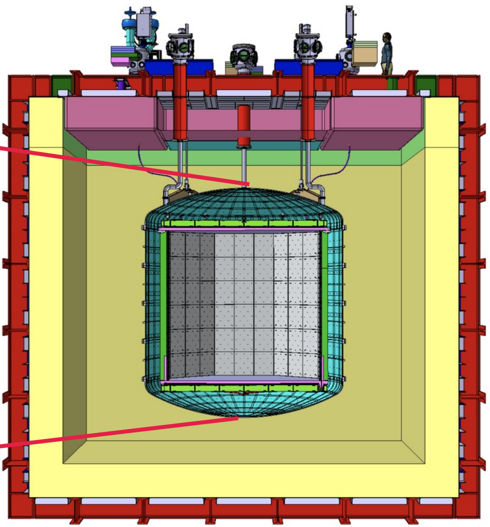


- DarkSide-20k installation has started. Data taking planned to start in 2027
- Located in HALL C at LNGS, Italy at a depth of 3400 m of water equivalent

DarkSide-20k Design







Dual-phase TPC

- 50 t of UAr (20 t fiducial)
- Two optical planes covering **21 m²** with cryogenic SiPMs
- Reflectors in the inner and outer walls
- Anode and cathode transparent **pure acrylic** covered with **Clevios** (conduction) and **TPB** (wavelength shifter)

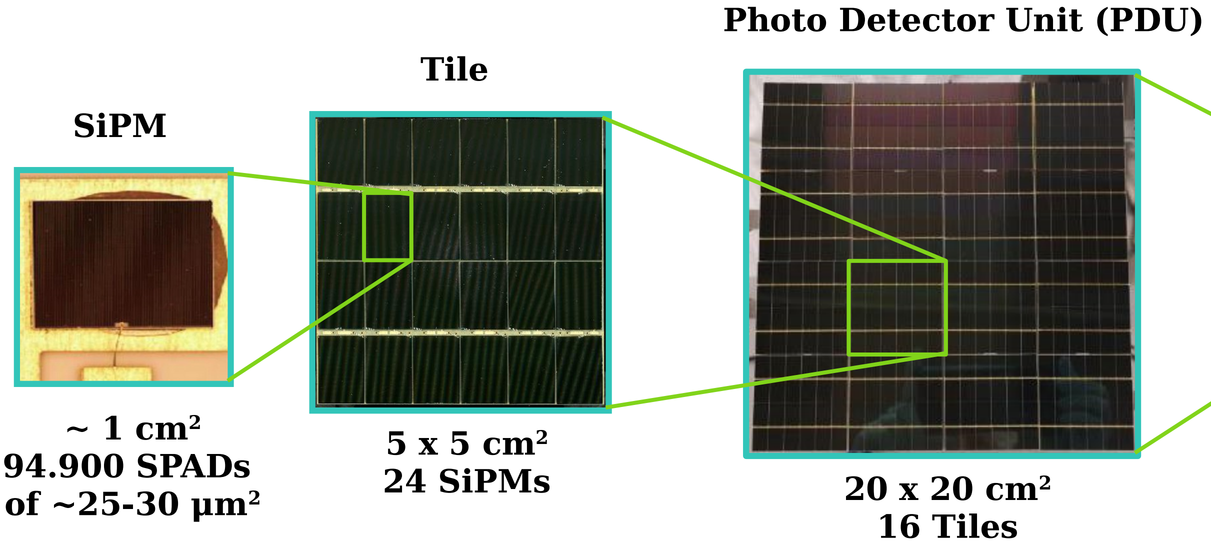
Neutron Veto:

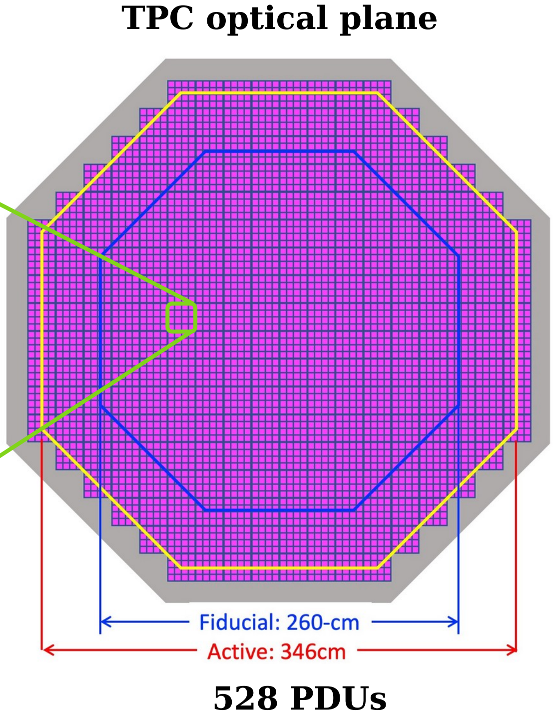
- 32 t of UAr
- Equipped with SiPMs covering **5m²**
- **40 cm** space between the stainless-steel vessel and PMMA.

Outer Cosmic Veto:

- 650 t of **Atmospheric Argon** (AAr)
- Membrane "ProtoDUNE-like" cryostat 8x8x8 m³
- SiPM arrays near cryostat walls

Light readout: Large SiPM array





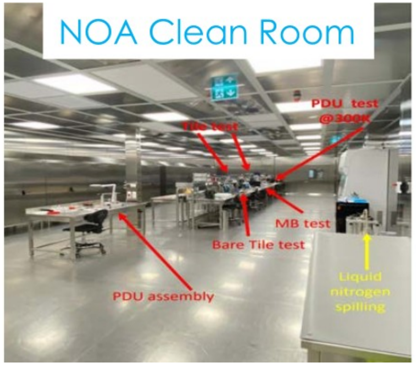
Custom **cryogenic SiPMs** developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.

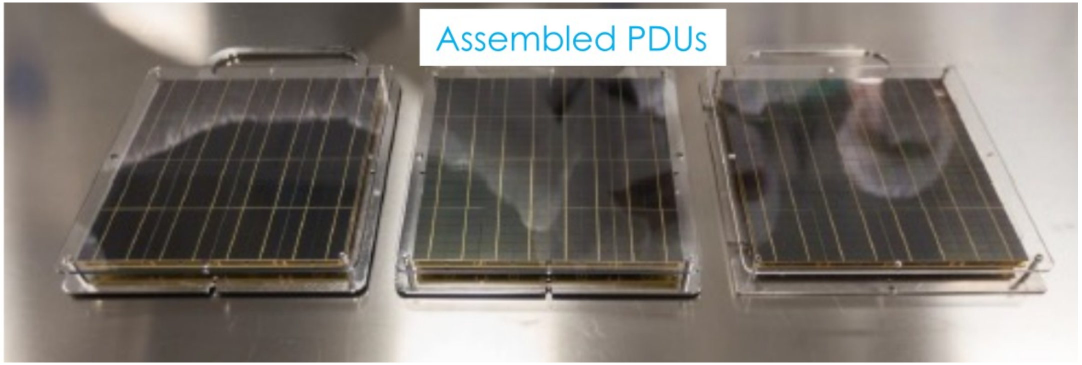
- Photon detection efficiency (PDE) **~45%**
- Low dark-count rate **< 0.01 Hz/mm²** at 77K (7 VoV)
- Timing resolution ~ 10 ns
- SNR > 8 for 10 x 10 cm²

- **SiPM** testing and characterization and **Tile/PDU** assembly and testing at **NOA** (Nuova officina Assergi), LNGS, Italy
- 4 Tiles are summed up together in a single DAQ channel
- 120 PDUs in the neutron veto
- 30 PDUs in the outer veto

DS-20k PDU production and test

PDU Production: TPC PDUs at NOA – vPDUs at Birmingham, STFC interconnect, Manchester and Liverpool

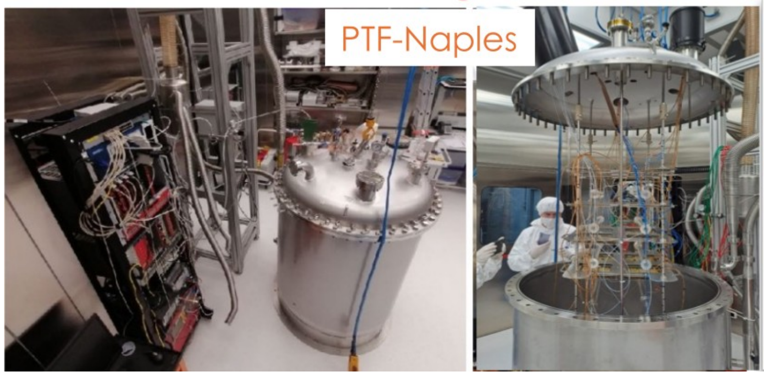


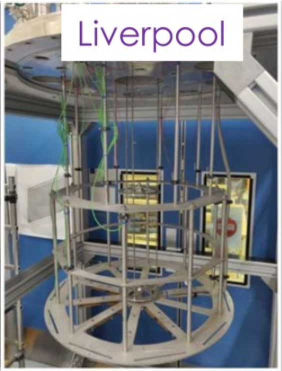


SiPM production at **LFoundry**, Italy

PDU packaging and assembly in **NOA**, an ISO-6 clean room at **LNGS**

PDU and vPDU Testing

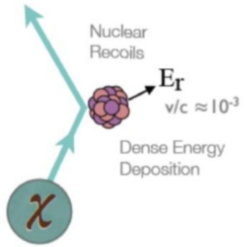




Assembled PDUs will be tested in a cryogenic test facility in **Naples** – vPDUs will be tested in facilities at **AstroCeNT**, **Edinburgh** and **Liverpool**

WIMP signal and backgrounds

WIMP signal

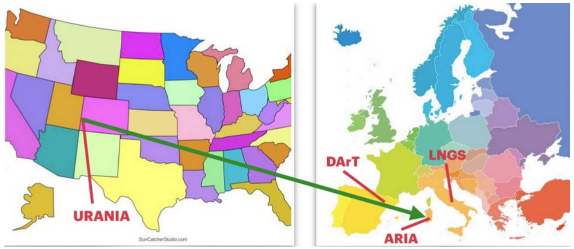


- Nuclear recoil
- Single scattering
- Recoil energy up to 200 keV_{nr}

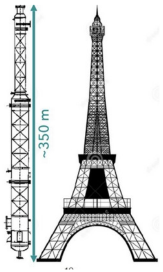
Background source	Mitigation strategy
^{39}Ar β decay	Use underground Ar + Pulse shape discrimination (PSD)
γ from rock and γ,e from materials	PSD Selection of materials & procedures
Radiogenic neutron (α,n) reaction in detector materials	Material screening & selection, MC study Definition of Fiducial volume in the TPC Veto to reject neutron signals
Surface contamination due to Rn progeny	Surface cleaning Reduce the number of surfaces Installation of Rn abated system
Muon induced background	Cosmogenic veto
Neutrino coherent scattering	Irreducible

Underground Argon

- Intrinsic ^{39}**Ar radioactivity** in atmospheric argon induces high rate of events preventing the scale up of dual-phase detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where PSD is less effective).
- ^{39}Ar activity in **AAr:1 Bq/kg** while for **UAr: 0.73 mBq/kg**. Reduction factor of **~1400** (DarkSide-50 in 2015)

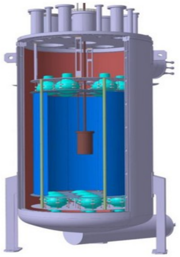


Urania (Extraction):
UAr extraction plant in Colorado, USA. Expansion of the argon extraction plant, to reach capacity of **330 kg/day** of UAr.



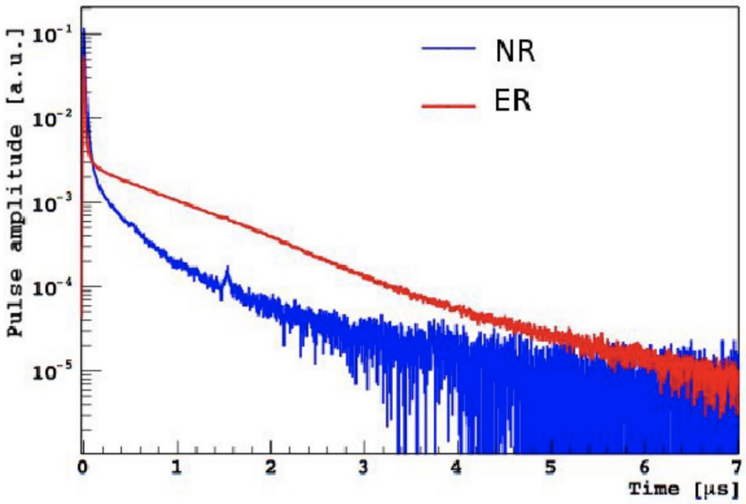
Aria (Isotope separation):
A **~350m** tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical (for DS-20k) and isotopic purification of UAr (not used for DS-20k).
A factor 10 reduction of ^{39}Ar per pass is expected with **~10 kg/day**.

DArT (assay):
A single phase low-background detector to measure the ^{39}Ar depletion factor of different UAr batches. Located in **ArDM** experiment at Canfranc lab, **~2500 m.w.e**.



Electron Recoils and PSD

- ERs in LAr give **slower** signals than NRs
- Distinct S1 pulse shape in LAr - fast (singlet) and slow (triplet) component

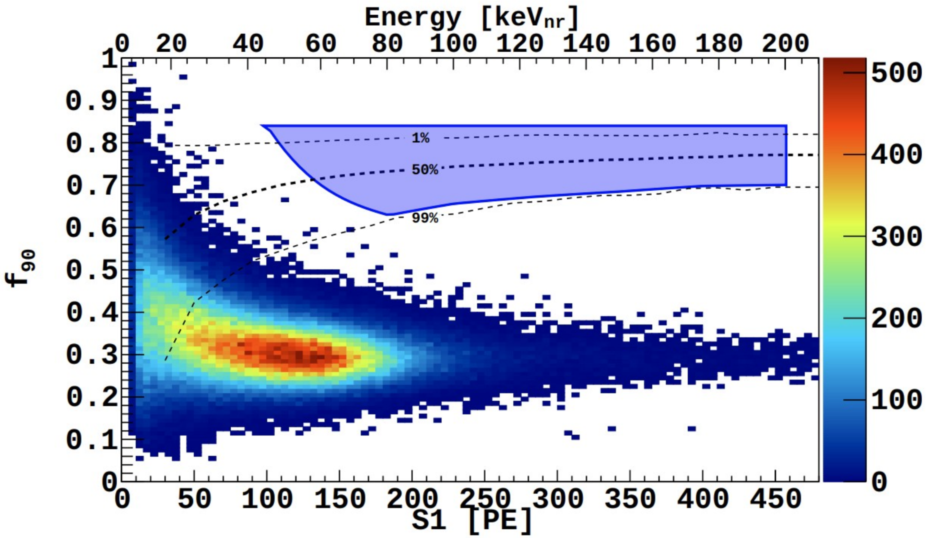


Expected:

- TPC= 50 t → 36 Hz of ^{39}Ar
- Veto = 35 t → 26 Hz of ^{39}Ar

Mitigated with pulse shape discrimination

The discrimination parameter is the **prompt fraction** defined as a ratio of detected light in an initial time interval (**90 ns** for DS-50), compared to the total signal



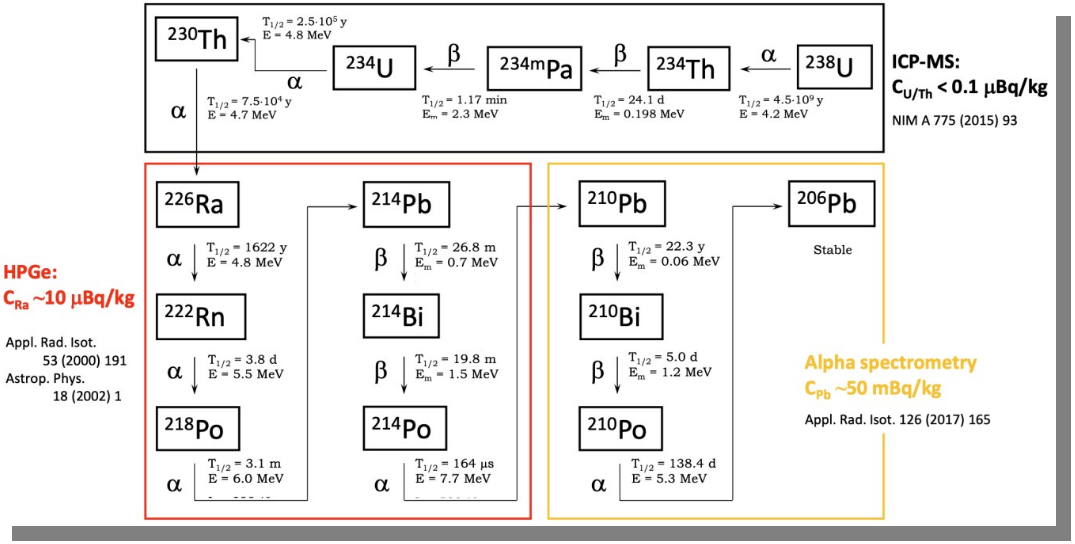
DS50 Collaboration., Phys.Rev.D 98 (2018) 102006

The **DEAP-3600** experiment has exploited the pulse shape discrimination to achieve ER background rejection of **2.4×10^8**

Neutron background

Neutron background is the most dangerous:
- NR undistinguishable from potential WIMP.
- PSD is useless against neutron events.

Main Neutron sources:
- ^{238}U and ^{232}Th contamination of the detector material - release neutrons via (α,n) reaction
- Cosmic ray induced neutron production



Complete control needed over every component that goes into the detector

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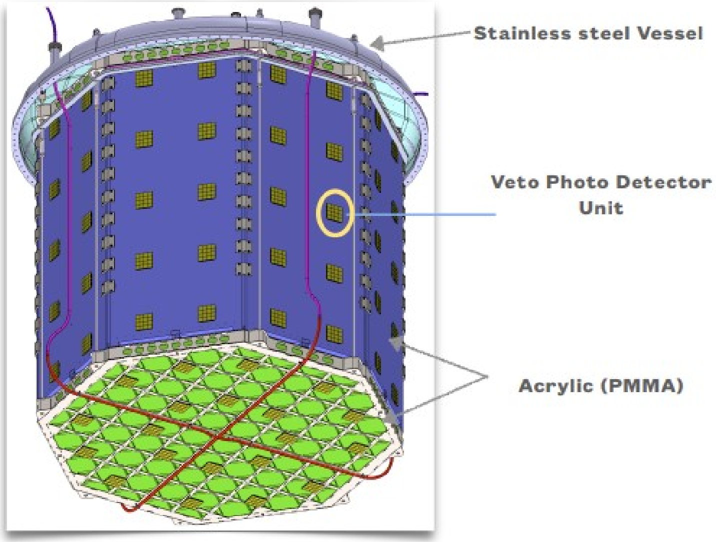
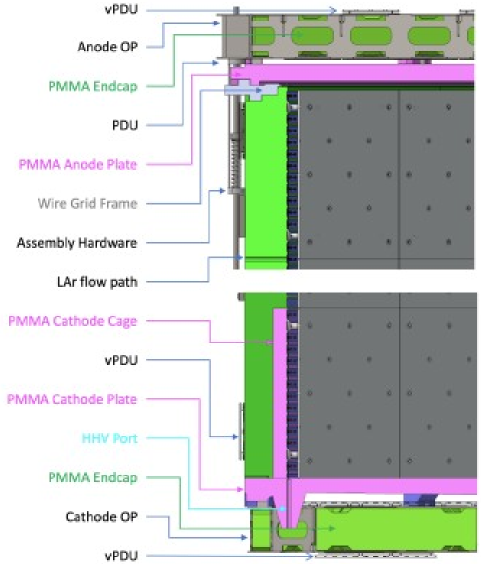
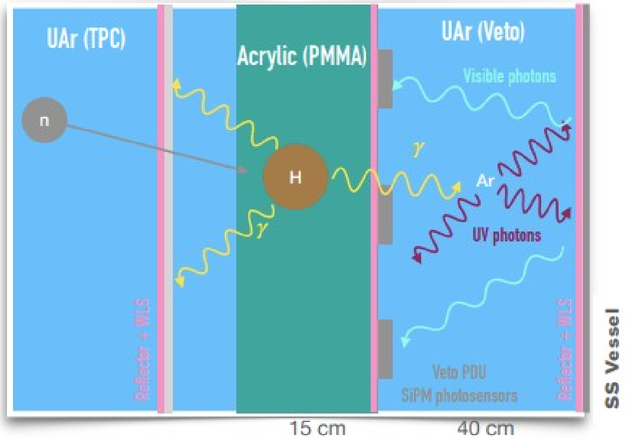
Material screening campaign
- Big effort engaging laboratories around the world:
  - CIEMAT
  - SNO
  - Jagiellonian University
  - Canfranc
  - Boulby
  - LNGS
- Hundreds of assays carried-out
- 3 different techniques: ICP-MS, HPGe, alpha spectrometry

Neutron Veto strategy







- Neutrons are moderated in the acrylic shell and then captured mainly by **Hydrogen** or **Argon**.
- The capture emits **γ-rays**
- γ-rays interact in **Argon** of either the **Neutron Veto** or **TPC**.
- LAr scintillation light is wavelength shifted and detected by **480 channels (120 PDUs)**

Neutron background – MC simulation

To ensure that DS-20k achieves its science goals: detailed study of the **NR backgrounds** in the detector and the γ rate is required.

- Geant4-based **SaG4n** code: Calculation of **(α,n) neutron yields**. Includes the chemical composition of the materials, uncertainties and different interaction models/tables (TALYS, JENDL/TENDL) (https://arxiv.org/pdf/2405.07952v2)
- Geant4-based DarkSide Monte Carlo simulation toolkit (**G4DS**): include a **full description** of all the detectors belonging to the DarkSide program. Extensively validated on DS-50 data (2017 JINST 12 P10015)

Neutrons generated (in G4DS) are **tracked** in their propagation through different materials of the detector.

All the **energy deposits** are collected (primary neutrons + secondary particles).

Three major sources of neutrons

Walls of LNGS experimental hall (Hall-C)

- Far from the active LAr volume, very high number of events needs to be simulated
- Subject to a biasing technique that reduces the computational resources needed to obtain a statistically significant sample

Cryostat

- Neutrons coming from insulating foam inside cryostat walls
- Polyurethane insulating foam is major contributor to neutrons
- Biasing technique also needed to increase sample size

Inner detector (stainless-steel vessel + TPC)

- Neutrons produced uniformly in the relevant detector volumes and with appropriate energy spectra

Neutron background – MC simulation

Extensive MC simulations allow evaluation of residual backgrounds and performance of neutron veto

Cuts applied to the simulated events:

- Single elastic NR
- Inside the fiducial volume (extended volume also under study)
- In the energy region of interest for WIMP search [30,200] keV_{nr}

WIMP-like events

Veto cuts:

- Energy deposits in either the Veto buffer or the TPC in time window 200 ns < Δt < 0.8 ms after the NR
  - E_{TPC} > 50 keV_{ee}
  - E_{veto} > 200 keV_{ee}

to easily identify detected signal and not introduce too high dead-time due to uncorrelated event pile-up

$$\text{Neutron background efficiency} = \frac{\text{Number of neutrons surviving cuts}}{\text{Total number of simulated neutrons}}$$

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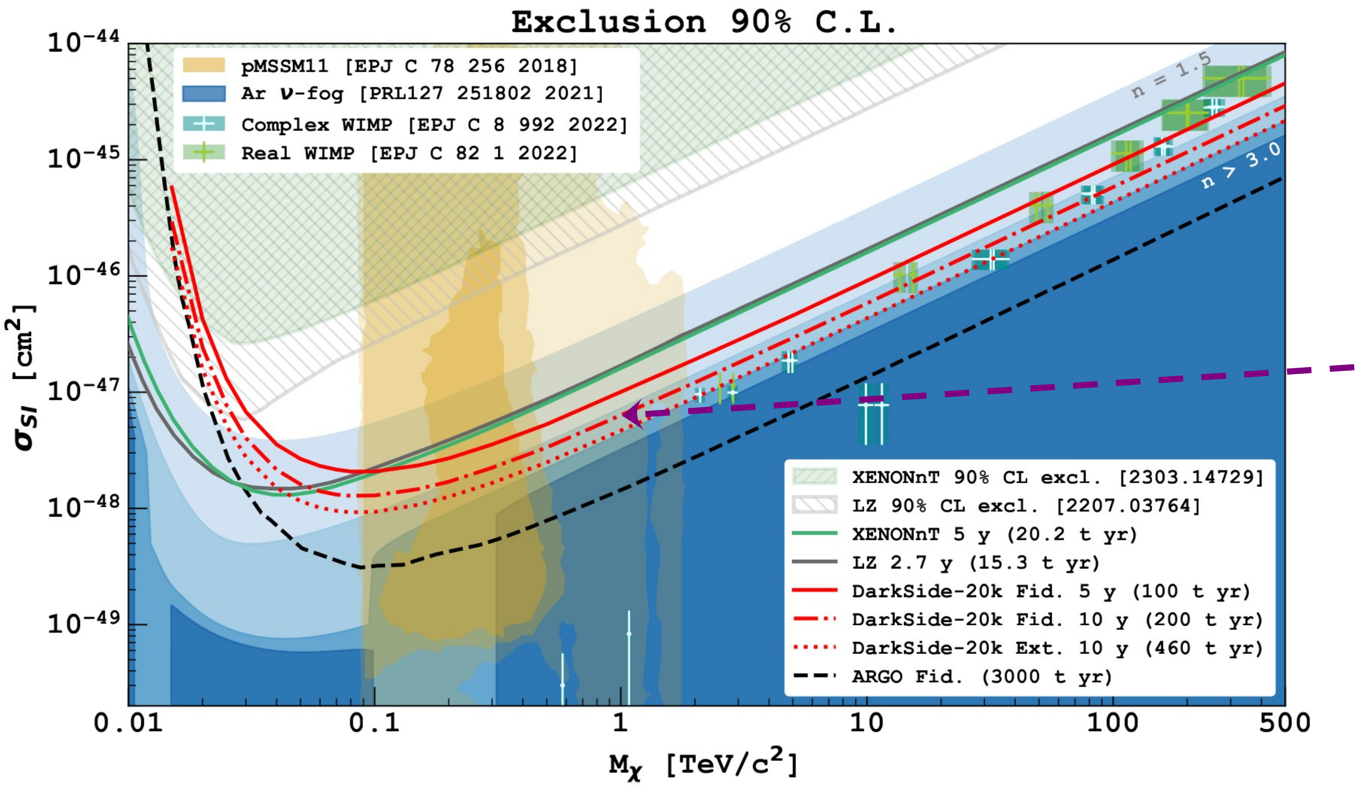
Residual neutron background = **Neutron background efficiency** x **Activity (from screening campaign)** x **Neutron yield (from SaG4n)** x **Mass (grouped per major detector components)** x **Live-time**

Expected high mass WIMP sensitivity DS-20k

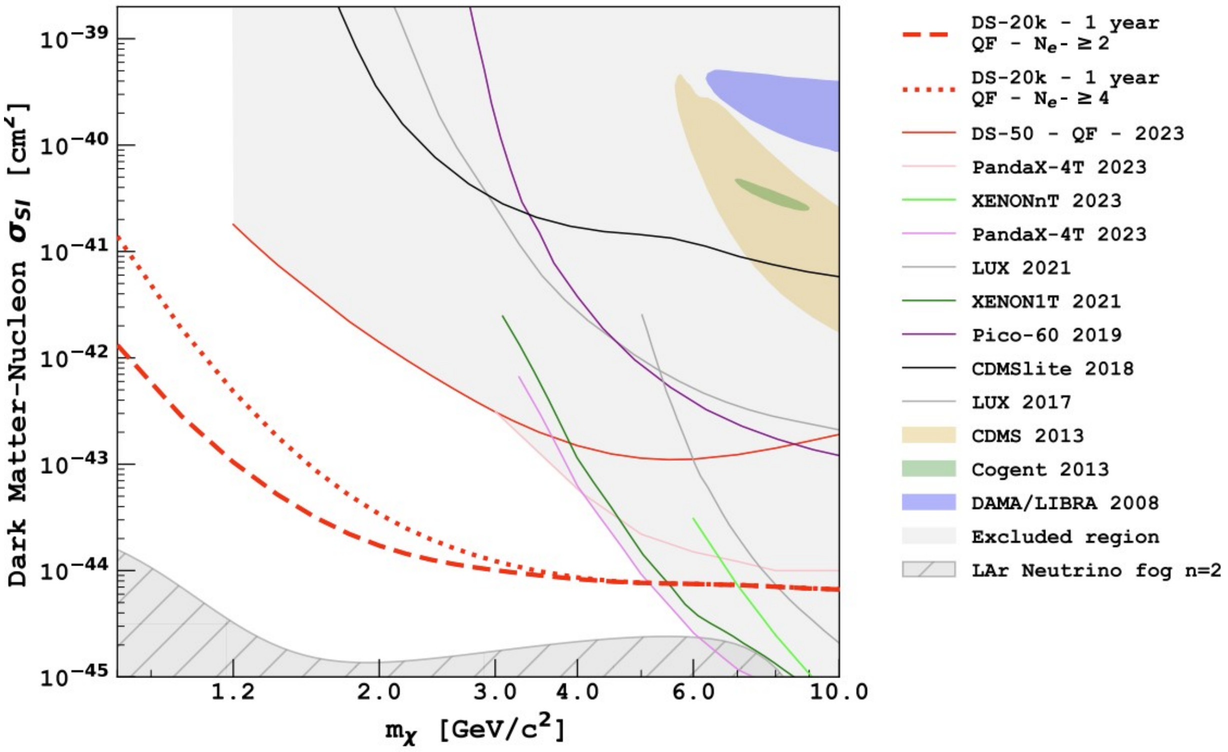


Sensitivity to high mass WIMP-nucleon scatter cross section of **6.3×10^{-48} cm^2** for a **1 TeV/c^2** WIMP for a total exposure of 200 tonnes x years.

Both signals (S1 scintillation and S2 ionization) used.

Publication in preparation

Expected low mass WIMP sensitivity DS-20k



arXiv:2407.05813 (2024)

- Using **S2** (ionization signal) only.
- **Detailed background** study, information from DarkSide-50 data.
- Prediction for many **light DM** candidates.
- First assessment of DarkSide-20k sensitivity to low mass dark matter particles
- Further strengthens the physics reach of DarkSide-20k with a leading role **below 5 GeV/c²**

SUMMARY

- DarkSide-20k is promoting **technological breakthroughs** in several directions: underground argon extraction & purification, SiPM technology, background assay campaign
- Joint global expertise in the Global Argon Dark Matter Collaboration
- Achieving **very low instrumental backgrounds** to the dark matter search is realistic and will allow to expand the reach beyond heavy WIMPs!
- The construction of DS-20k has started.
- Data taking will start in 2027!

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THANK YOU FOR YOUR ATTENTION!