DarkSide-20k

Liquid Ar-Based Dark Matter Search Experiment

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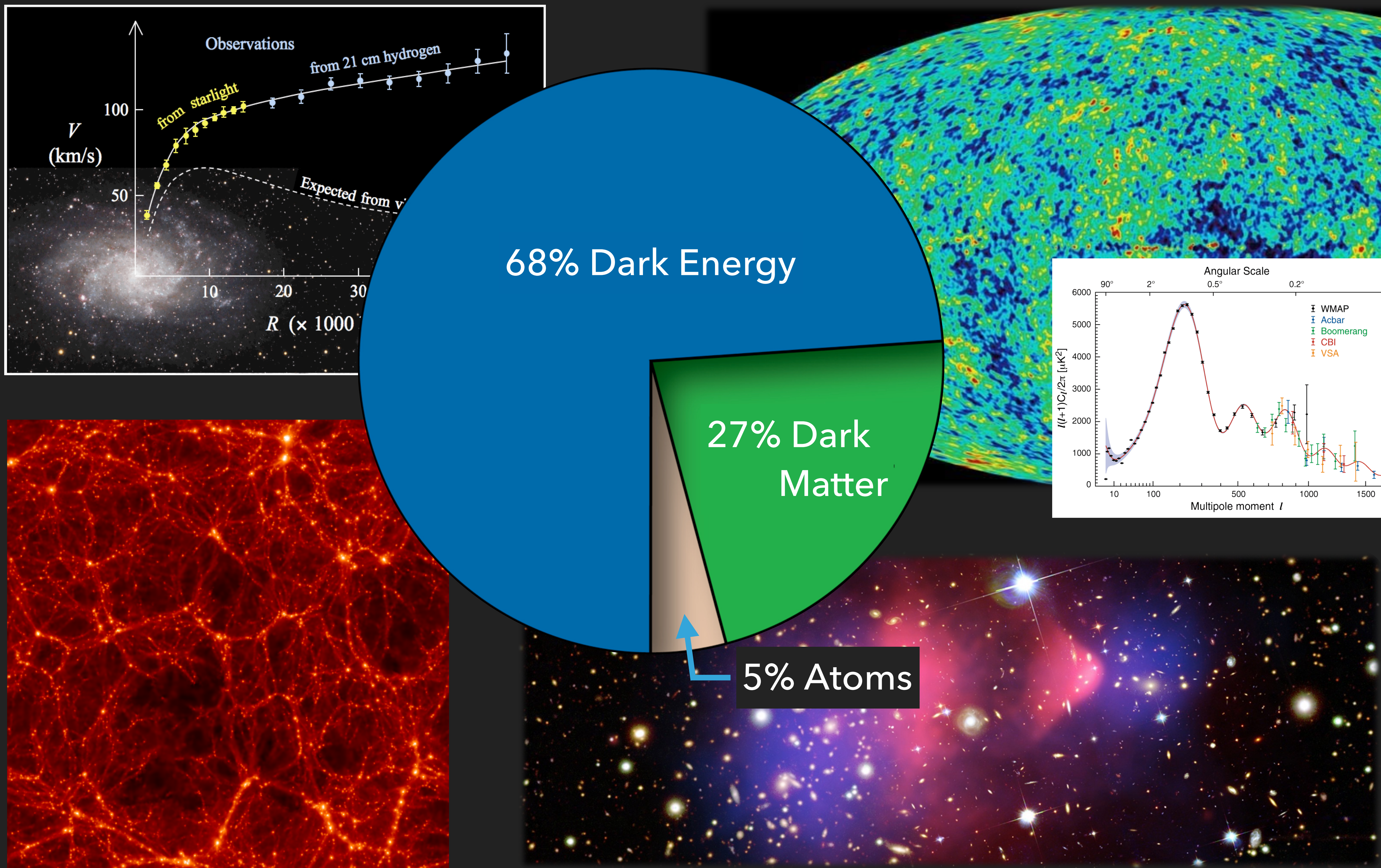
AstroCeNT, Warsaw

for the DarkSide-20k Collaboration

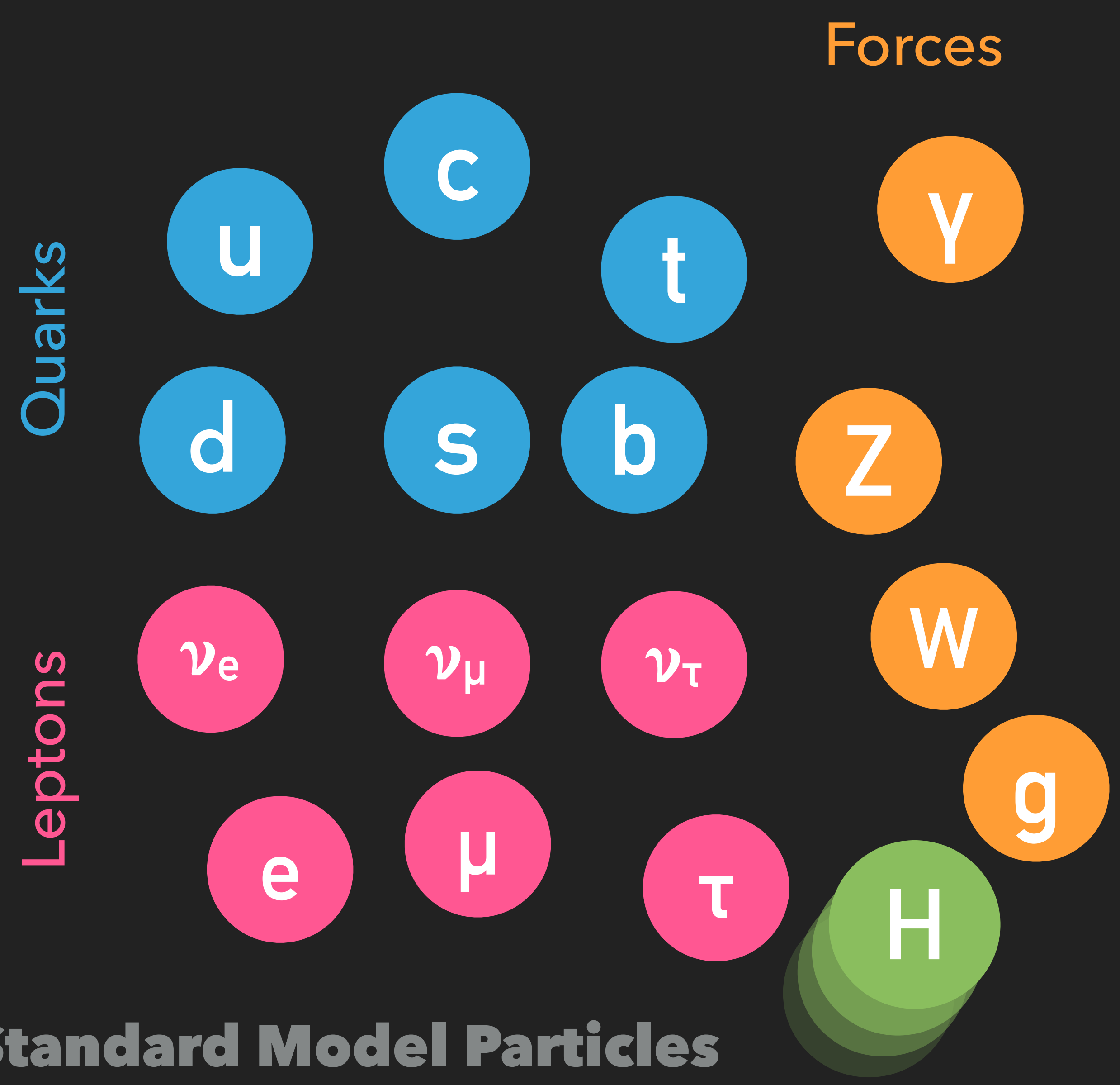
January 9 2025

TMEX2025

EVIDENCE FOR DARK MATTER



DARK MATTER PROPERTIES



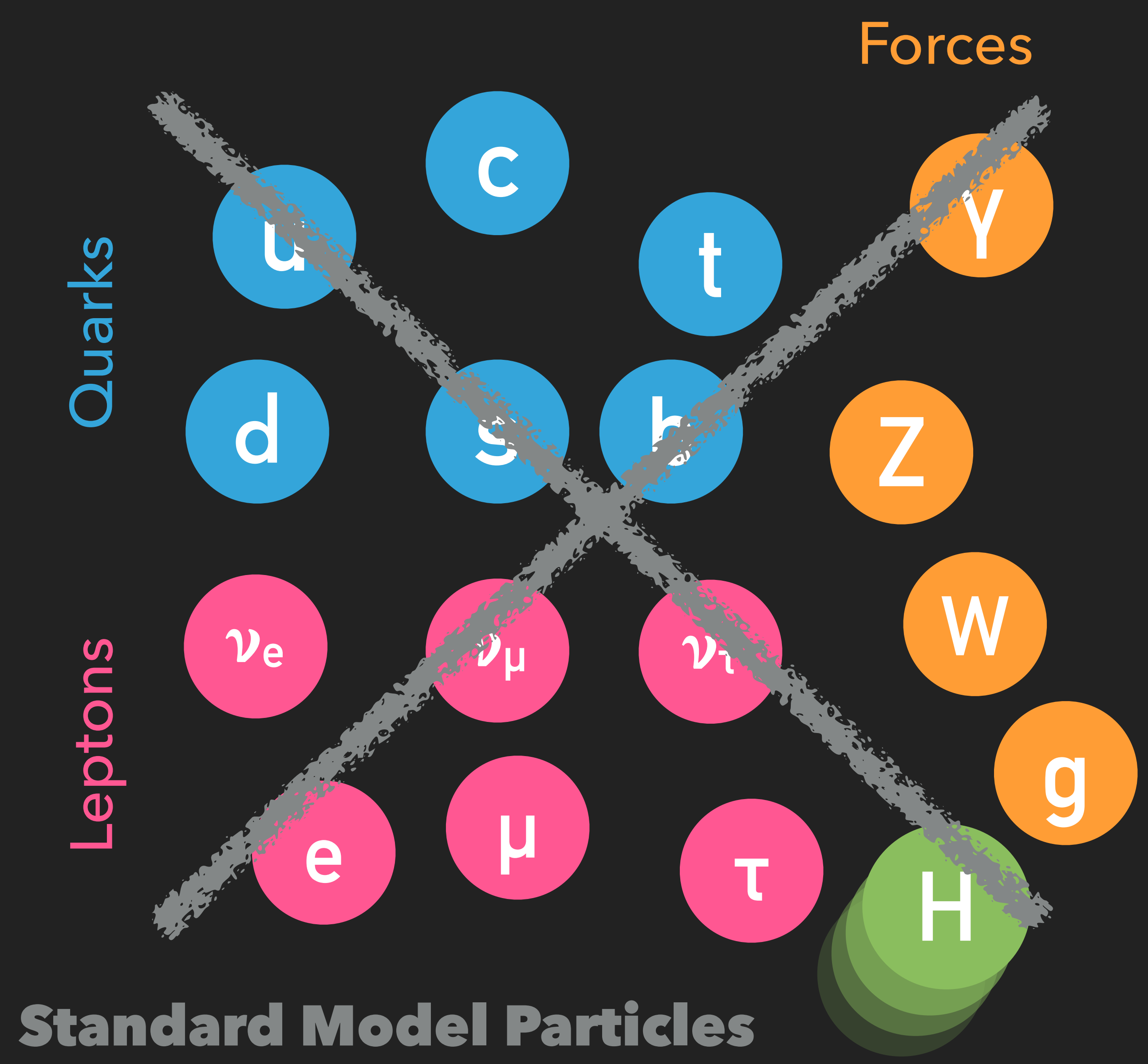
Standard Model Particles

- Gravitationally interacting
- Stable particle
- Not Hot (Heavy)
- Not Baryon (Big Bang nucleosynthesis)

New Physics Beyond Standard Model!!

One of the candidates is WIMPs.

DARK MATTER PROPERTIES



- Gravitationally interacting
- Stable particle
- Not Hot (Heavy)
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New Physics Beyond Standard Model!!

One of the candidates is WIMPs.

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
- **No mechanical stress** on target materials (one origin of low-energy backgrounds)
- **Purification in situ** after commissioning

For TPC

- High electron **mobility** and **low diffusion**
- Amplification (electroluminescence gain) for **ionization signal**
- **Discrimination** electron/nuclear recoils **(ER/NR)** via **ionization/scintillation ratio**

Liquid **Helium**

- Form superfluid
- Quite low energy threshold via roton excitations
- Sensitive to low mass DM

Liquid **Xenon**

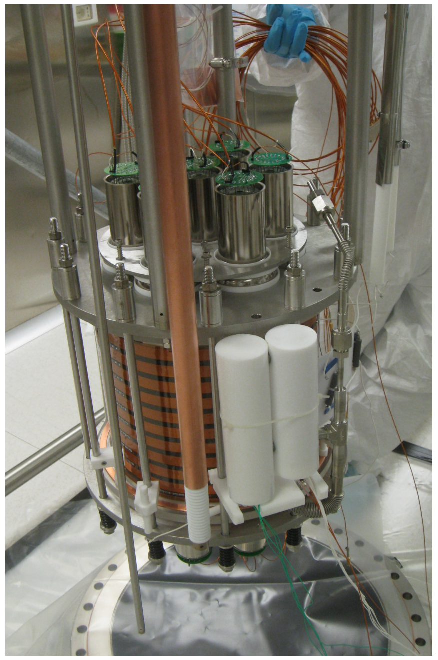
- Denser & Radio pure
- Lower energy threshold
- Sensitive to low mass WIMP

Liquid **Argon**

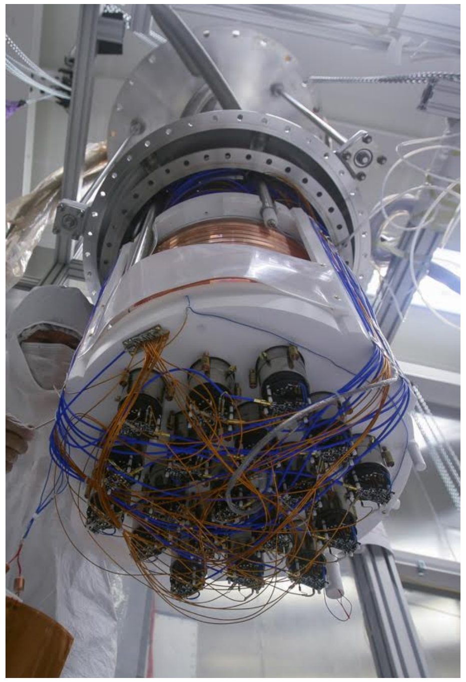
- lower temperature (Rn removal is easier)
- **Stronger ER discrimination** via pulse shape
- Intrinsic ER BG from ^{39}Ar
- Need wavelength shifter
- Higher sensitivity at low mass WIMP

DARKSIDE PROGRAM

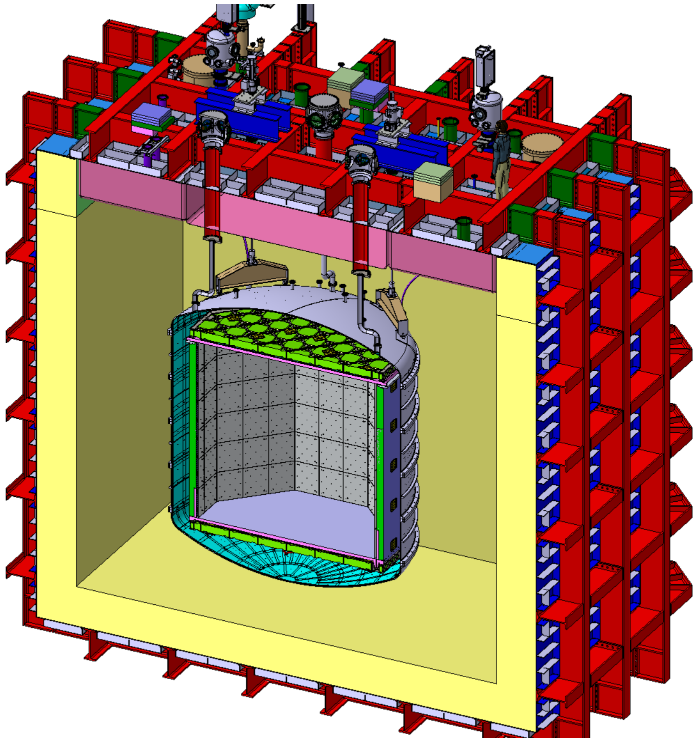
- **Direct detection** search for **WIMP** dark matter
- Based on a **two-phase argon** time projection chamber (**TPC**)
- Design philosophy based on having very low background levels that can be further reduced through **active suppression**, for **background-free** operation from both neutrons and β/γ's



DarkSide-10



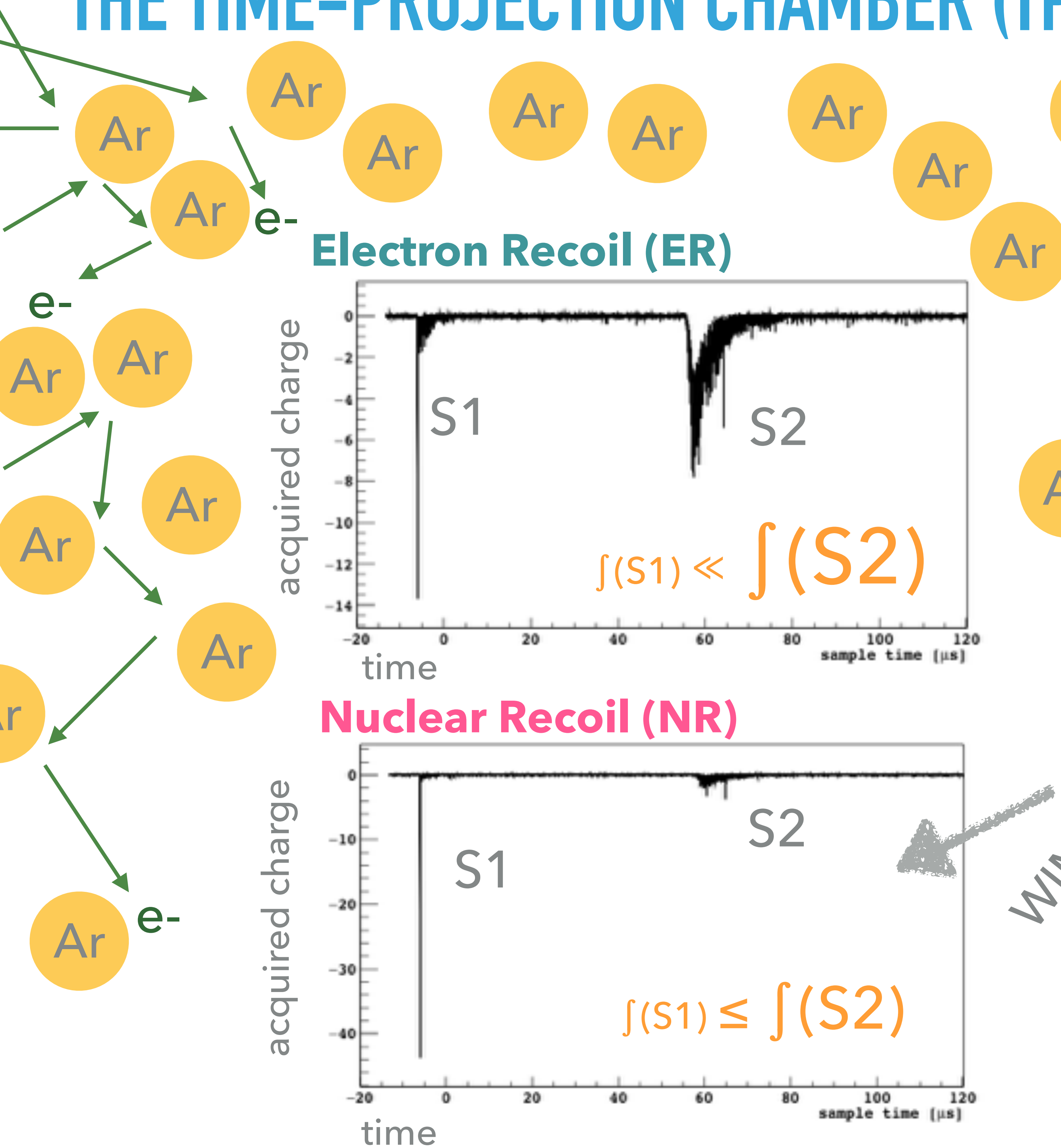
DarkSide-50

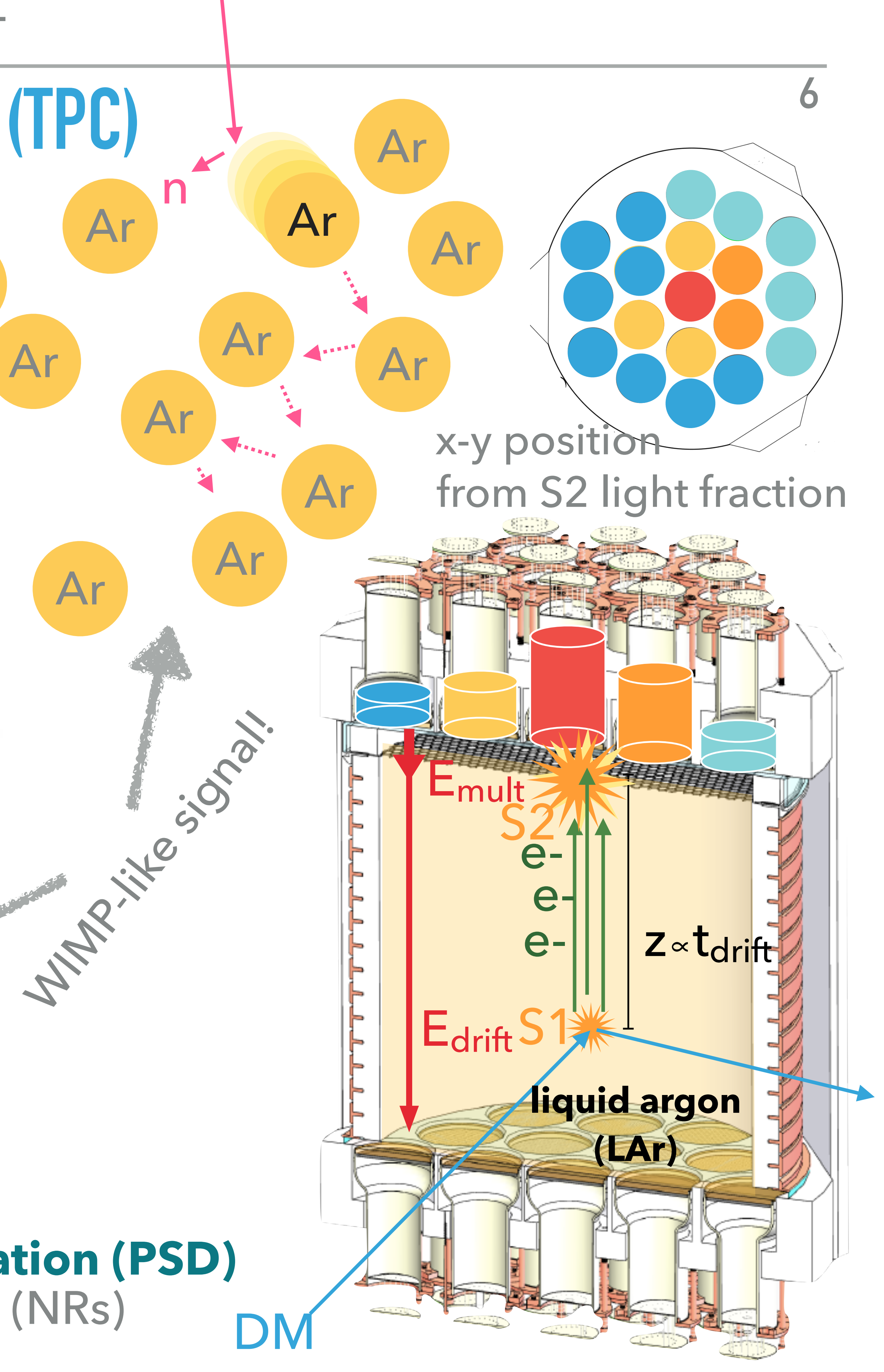


DarkSide-20k

and **DarkSide-LowMass**
for low-mass dark matter searches

THE TIME-PROJECTION CHAMBER (TPC)





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

WIMPs will generate nuclear recoils (NRs)

PULSE SHAPE DISCRIMINATION

β & γ Rejection

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

A. Hitachi et al. Phys. Rev. B 27 (1983) 5279

M. G. Boulay and A. Hime, Astropart. Phys. 25 (2006) 179

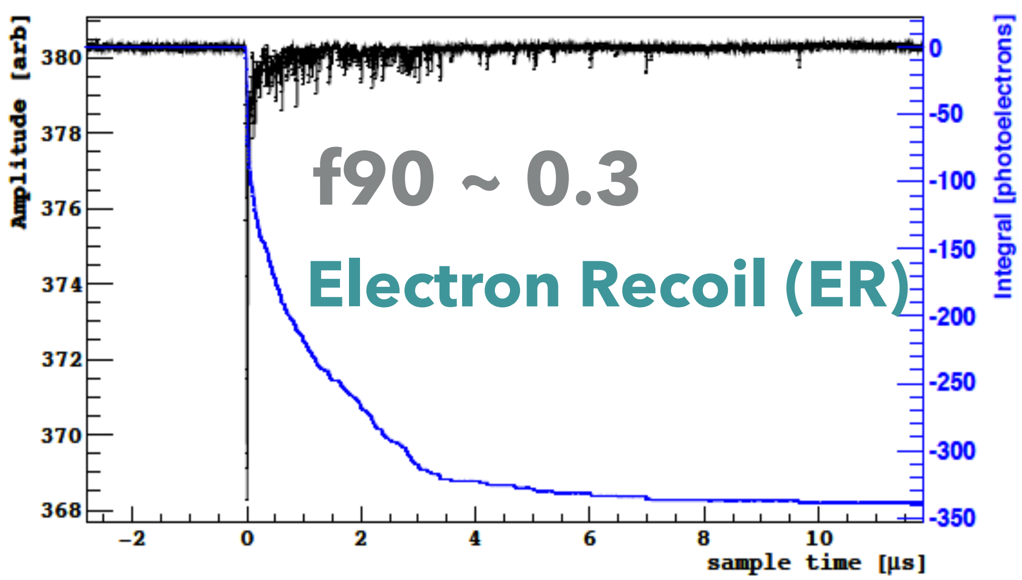
τ singlet ~ 7 ns

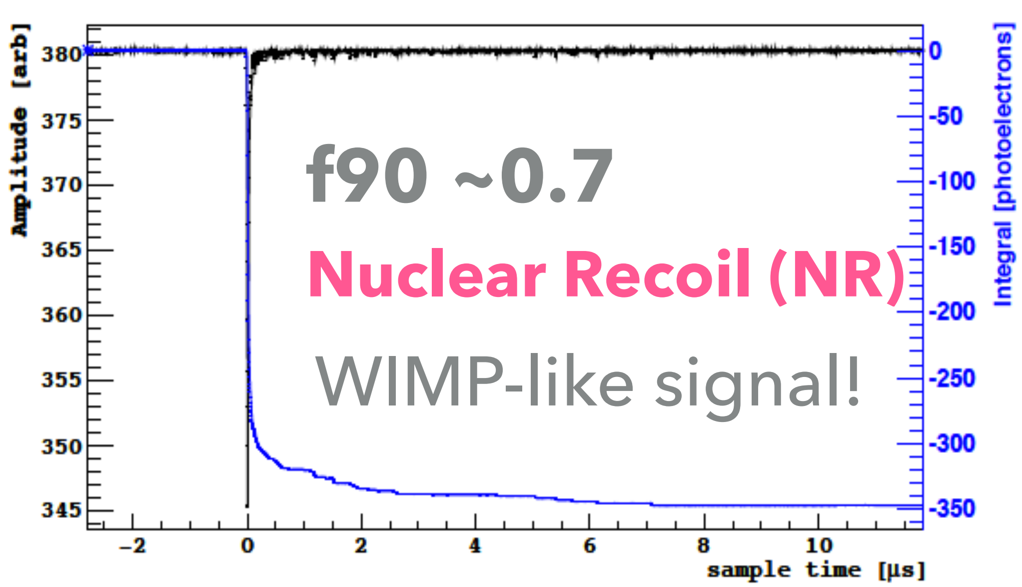
τ triplet ~ 1500 ns

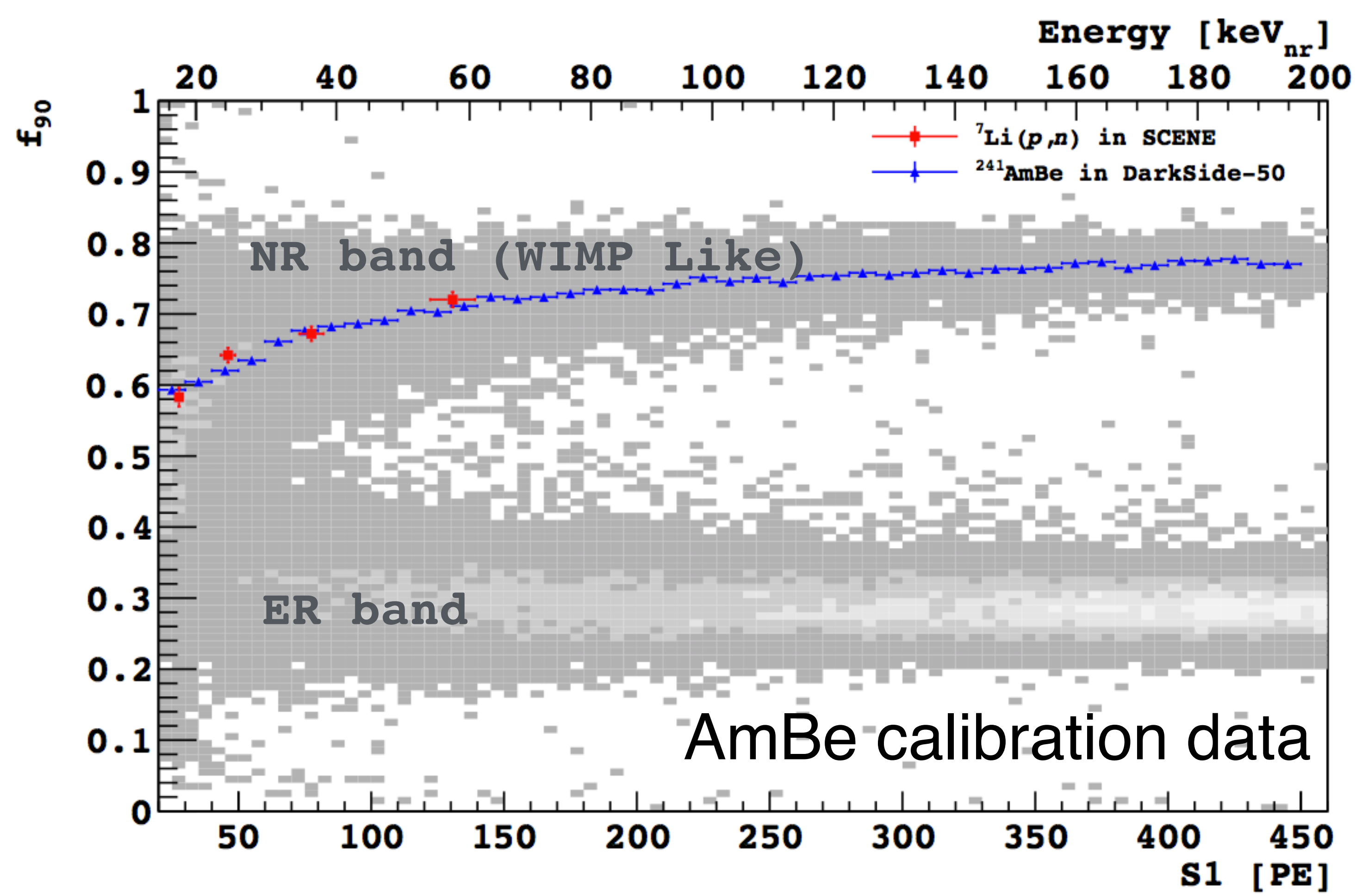
PSD parameter

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

~ Fraction of singlet states







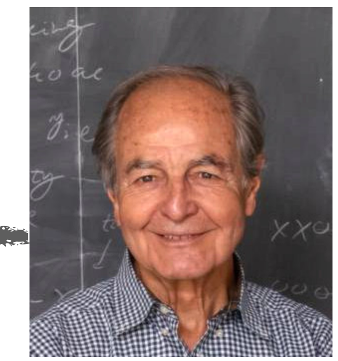
More for PSD: DEAP-3600, Eur. Phys. J. C 81, 823 (2021)

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

UNDERGROUND Ar

β & γ Rejection

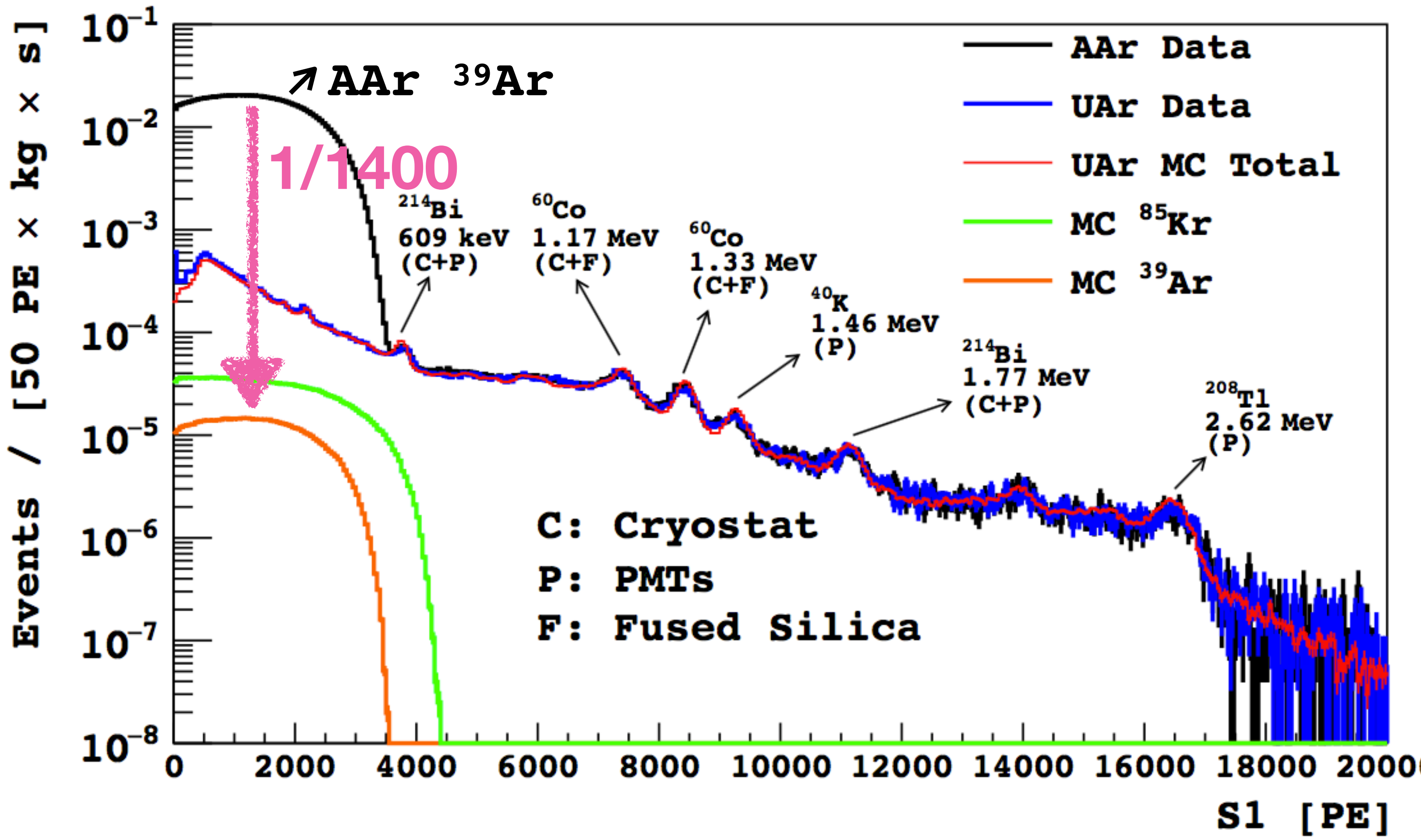
- Intrinsic ^{39}Ar radioactivity in **atmospheric argon** is the primary background for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective)
- ^{39}Ar is a **cosmogenic isotope**, and the activity in argon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



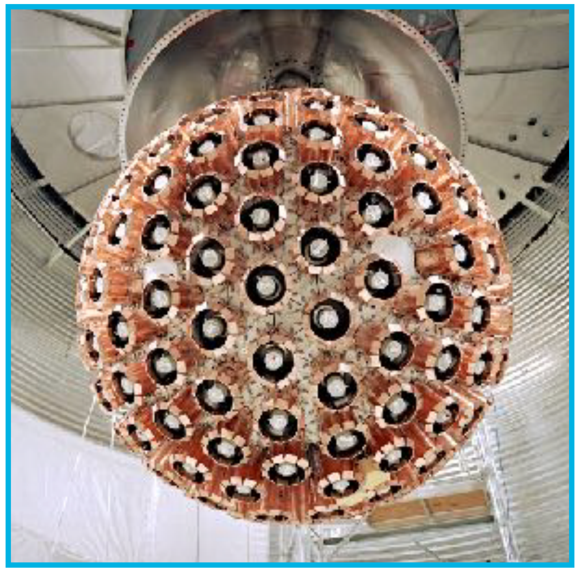
Frank Calaprice

- We deployed 157kg of underground argon in 2015.

^{39}Ar reduction factor of ~1400!

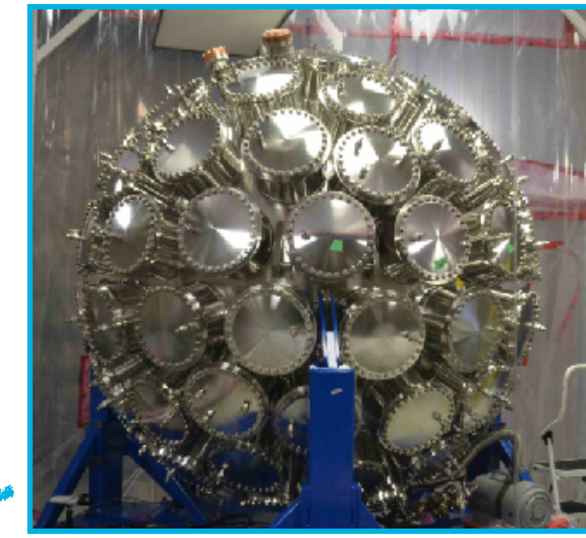


GLOBAL ARGON DARK MATTER COLLABORATION



DEAP-3600

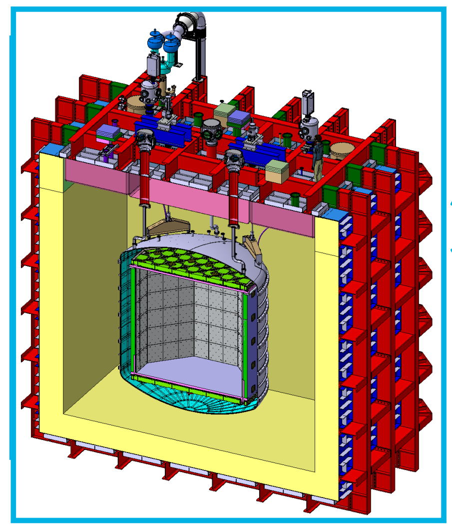
More than 400 scientists from past and present argon-based experiments in a single international argon collaboration: **GADMC**



MiniCLEAN

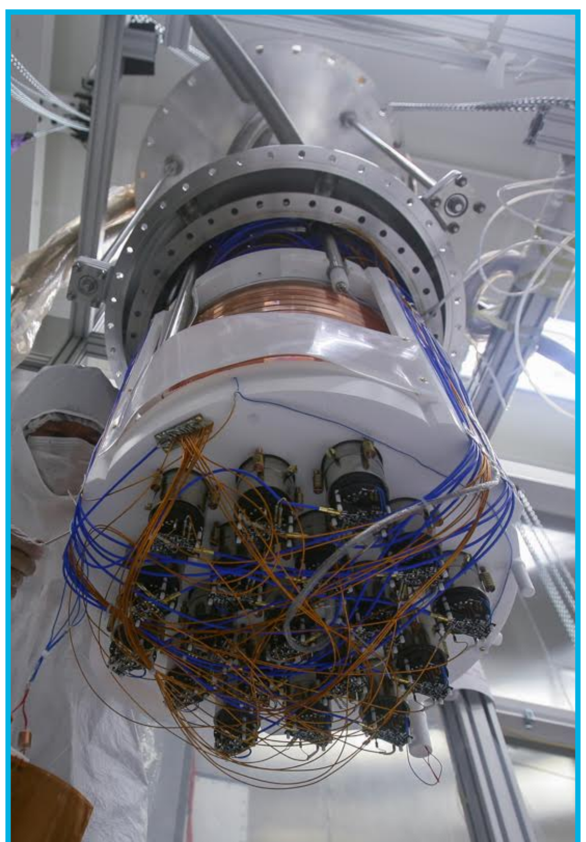
A sequential, two-steps program:

- DarkSide-20k (200 tonne yr fiducial)

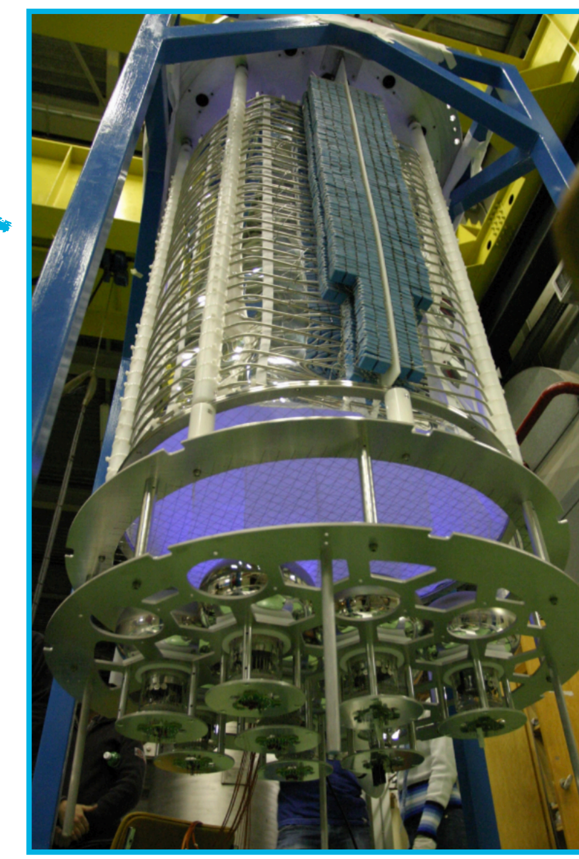


- Argo (3,000 tonne yr fiducial)

At SNOLAB
~203X



DarkSide-50

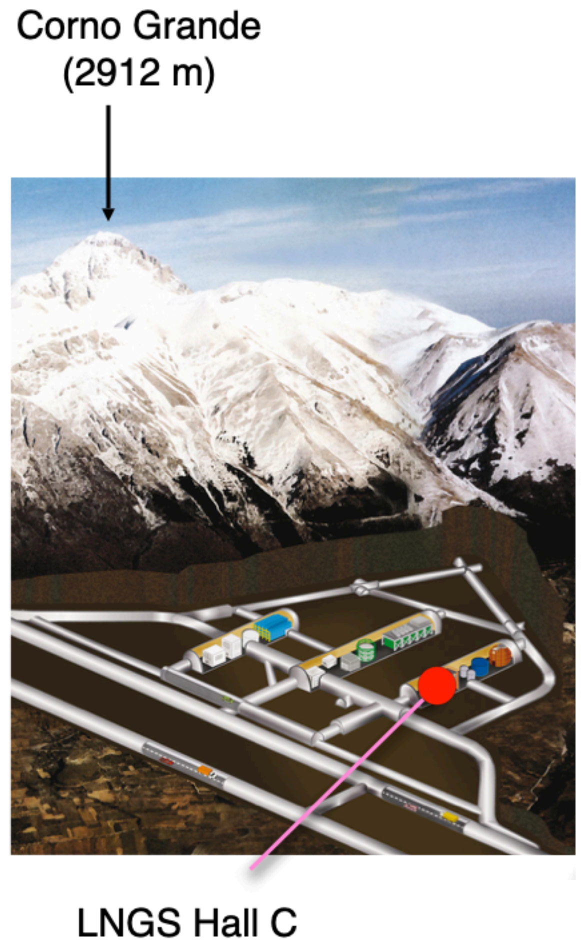


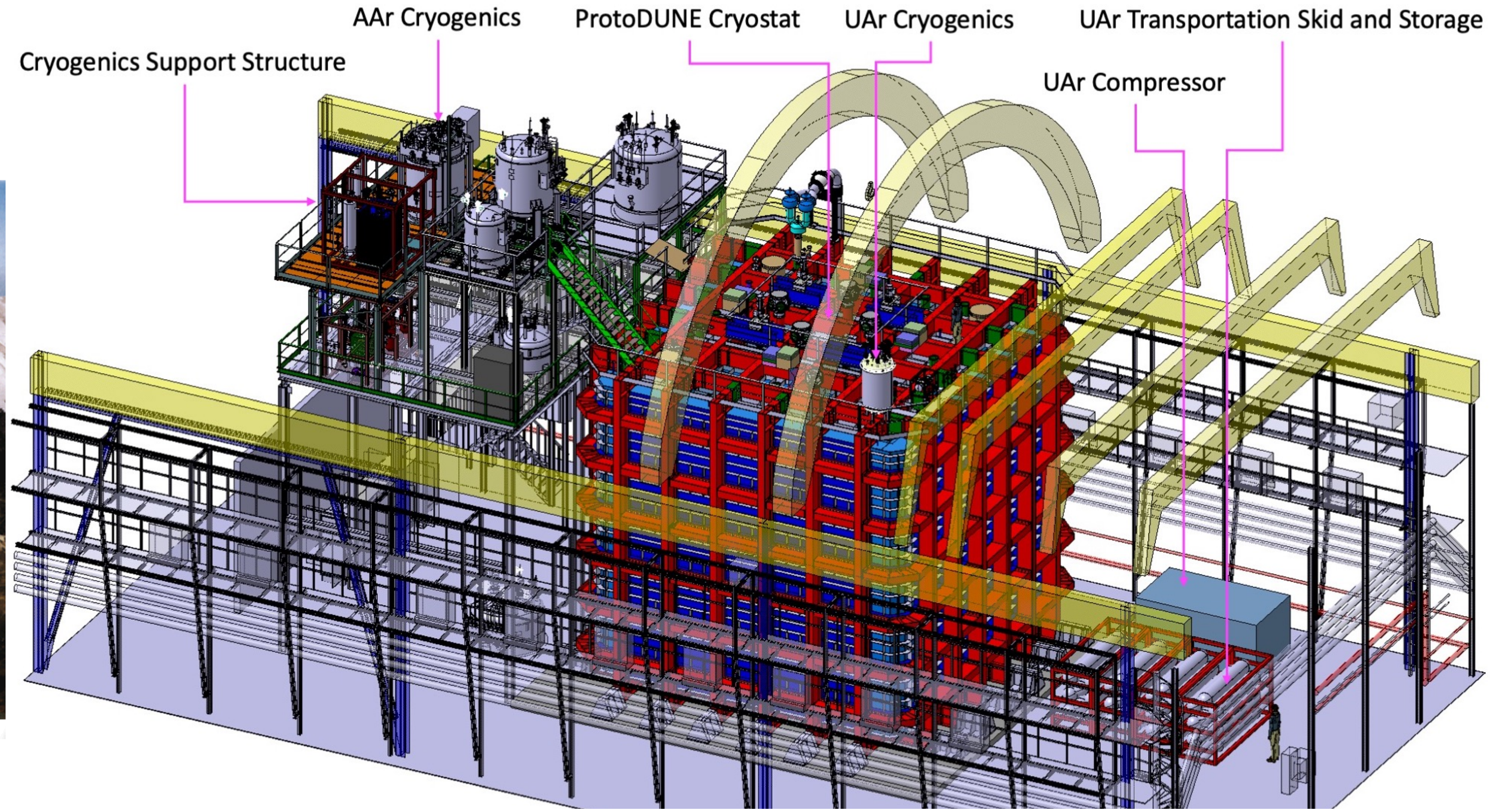
ArDM

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

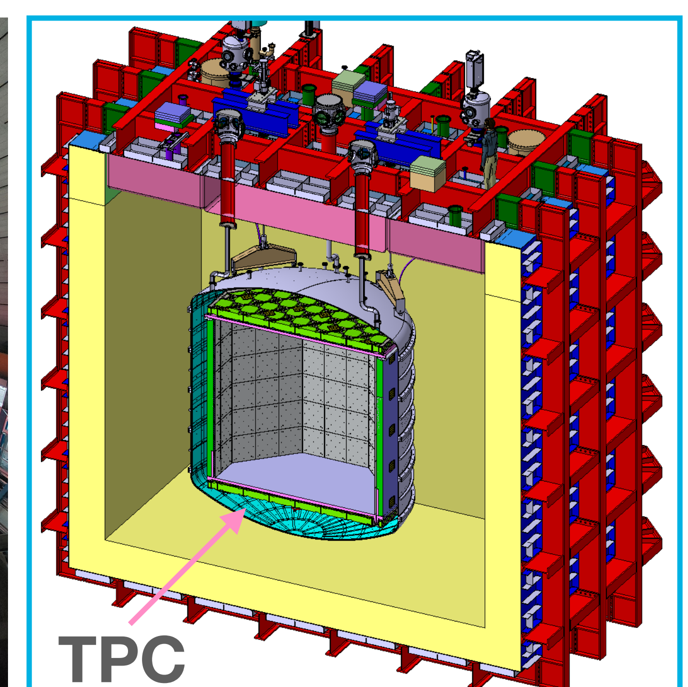

Gran Sasso
3800 m w. e.
Deep underground location at LNGS, Italy.
Slovenia
Zagreb
Como
Milan
Verona
Venice
Trieste
Padua
Turin
Croatia
Bosnia and Herzegovina
Genoa
Bologna
Zadar
Sarajevo
Pisa
San Marino
Monaco
Cannes
Florence
Split
Italy
Adriatic Sea
National Institute for Nuclear Physics...
Corse
Rome
Podgorica
Bari
Naples
Pompeii
Matera
Taranto
Lecce
Sardegna
Tyrrhenian Sea
Cagliari
Reggio

DARKSIDE-20K DETECTOR

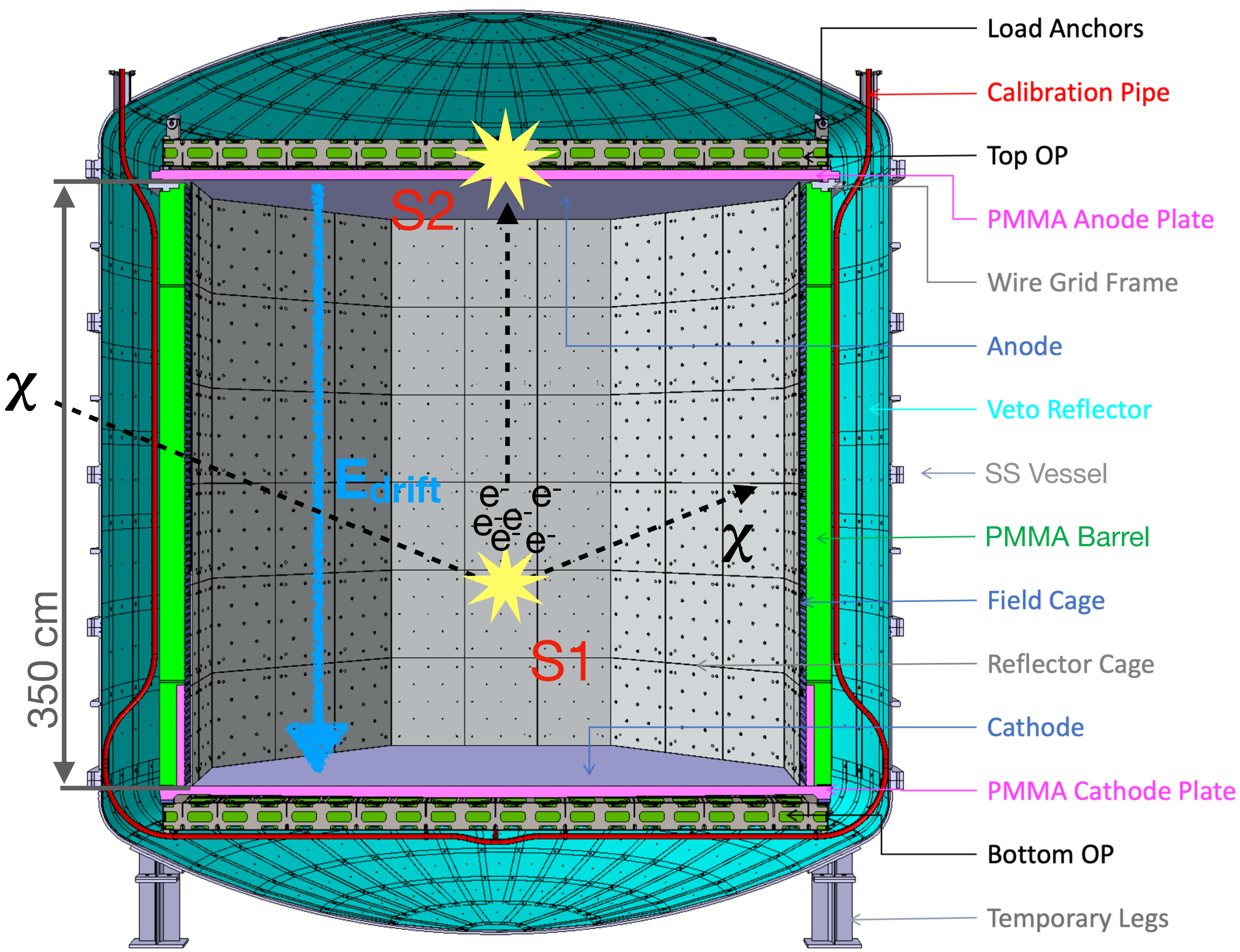


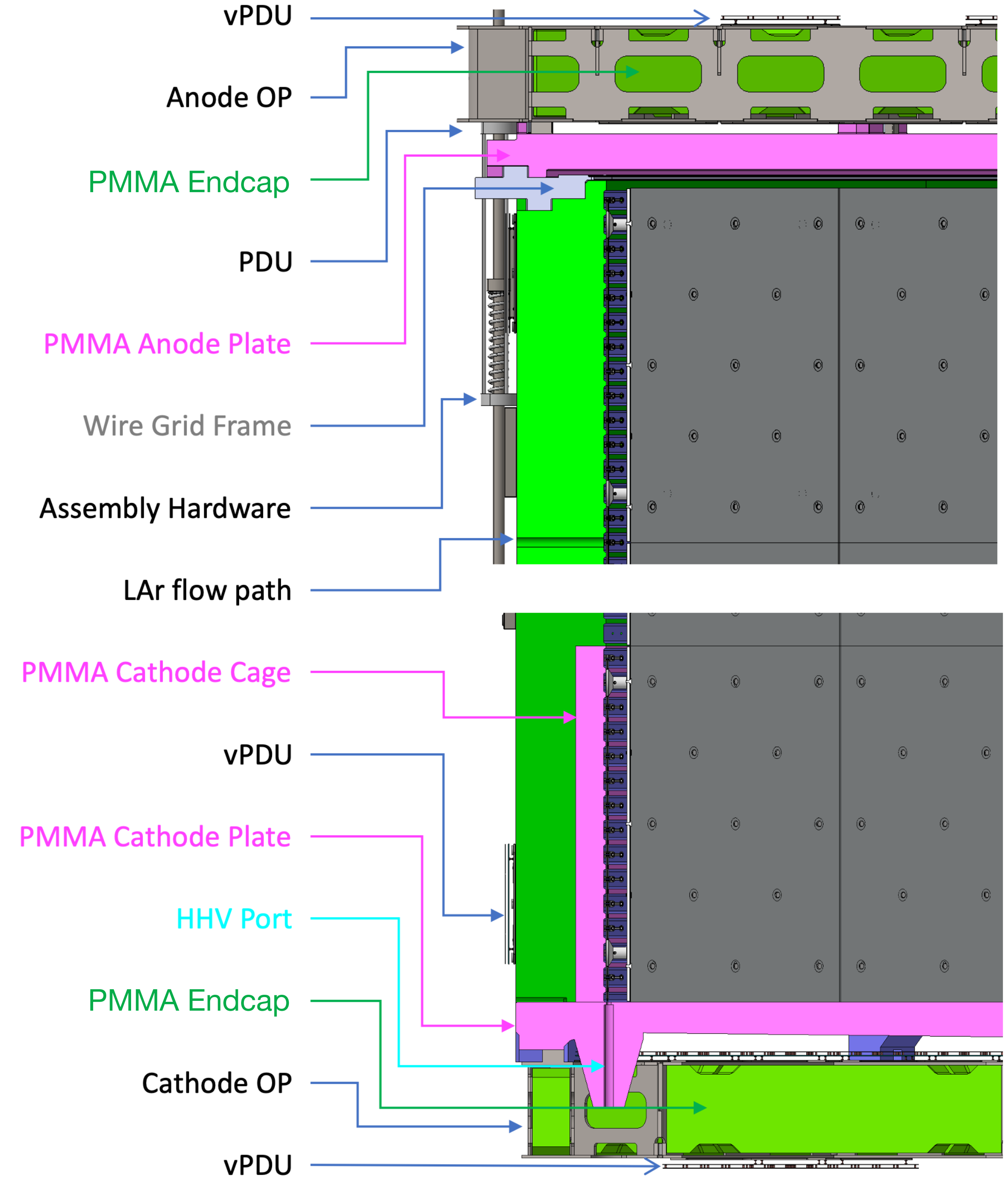


- DarkSide-20k will be installed underground at the Gran Sasso National laboratories, in Italy.
- The detector has a nested structure:
  - Stainless Steal Vessel contain liquid underground argon (100 t)
    - Acrylic (PMMA) TPC filled with 50 t of UAr
    - Neutron veto buffer between TPC and SS vessel
  - Membrane cryostat like the ProtoDune one



TIME PROJECTION CHAMBER





- Acrylic, PMMA (polymethylmethacrylate), vessel to capture neutrons
- Octagonal shape
- Cathode and anode coated with new transparent conductor (Clevios) and wavelength shifter
- Grooves with Clevios for field cage (No copper rings)
- Wire grid for extraction and electroluminescence fields
- Sides covered with multilayer polymeric reflector evaporated with wavelength shifter (TPB)
- SiPMs planes external to anode and cathode

UNDERGROUND ARGON

- **Urania** (Extraction):

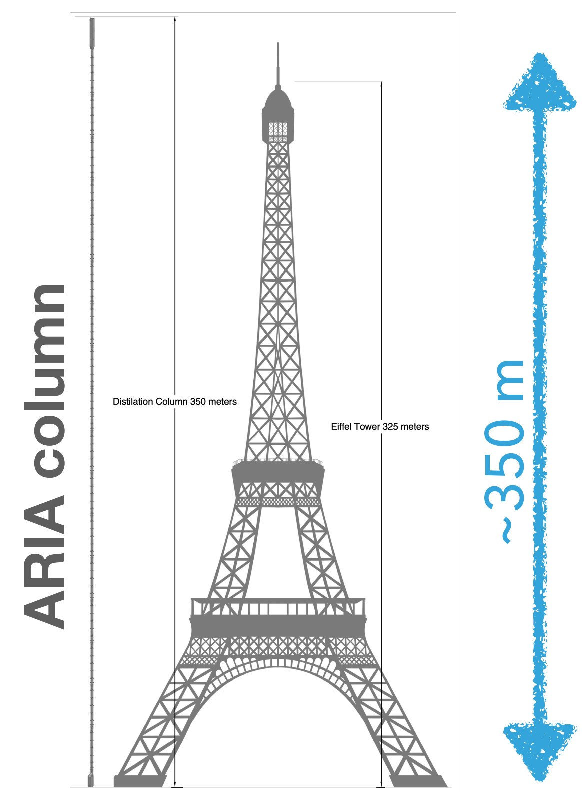
  - Expansion of the argon extraction plant in Cortez, CO, to reach capacity of **330 kg/day** of Underground Argon

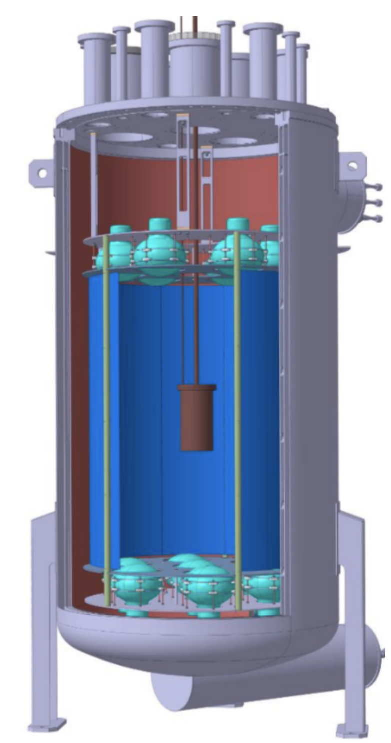
- **Aria** (Isotope separation):

  - Very 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 with ~10 kg/day.

- **DArT** (assay):

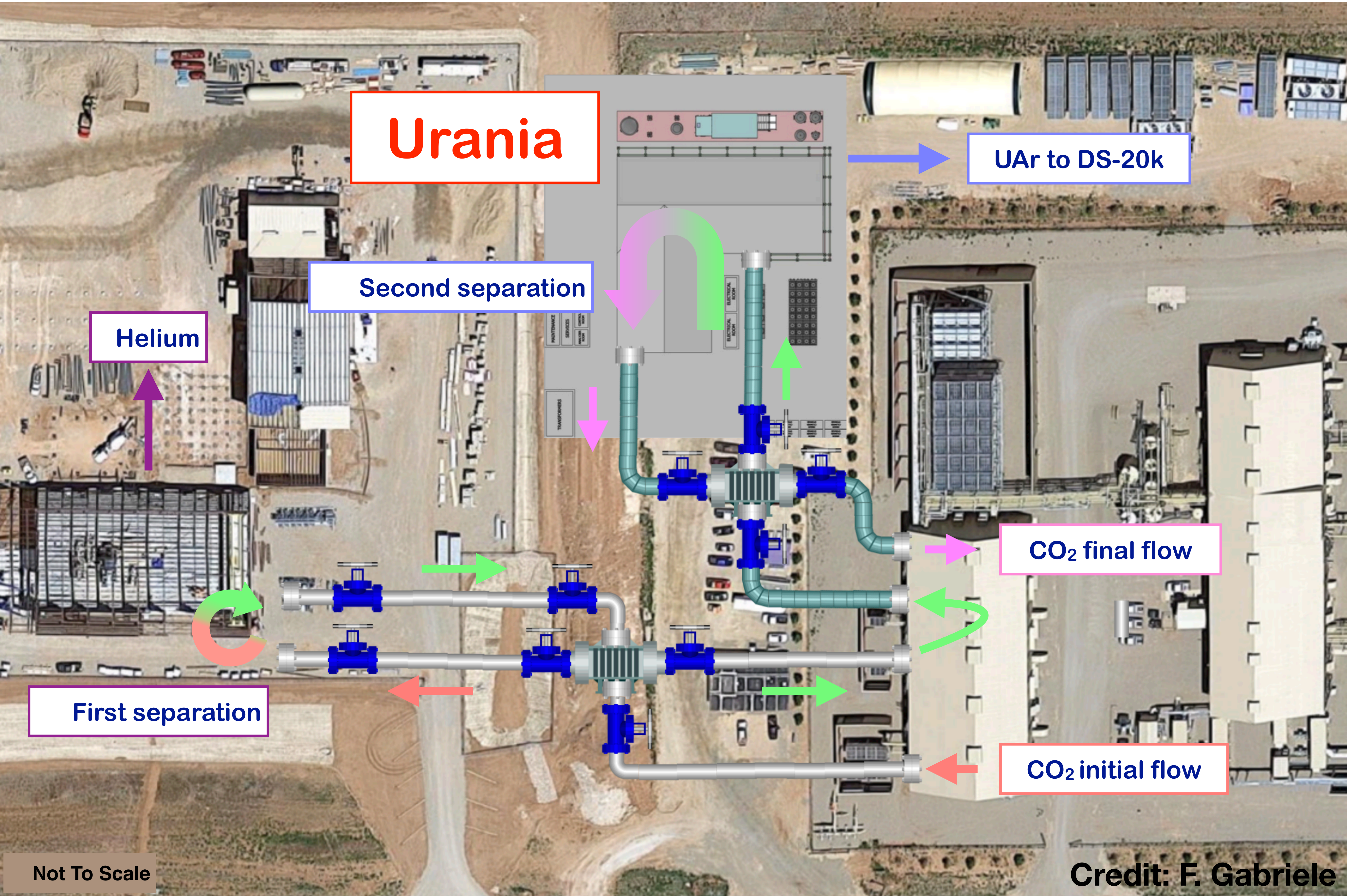
  - A single phase low-background detector to measure the ^{39}Ar depletion factor of different underground argon batches.



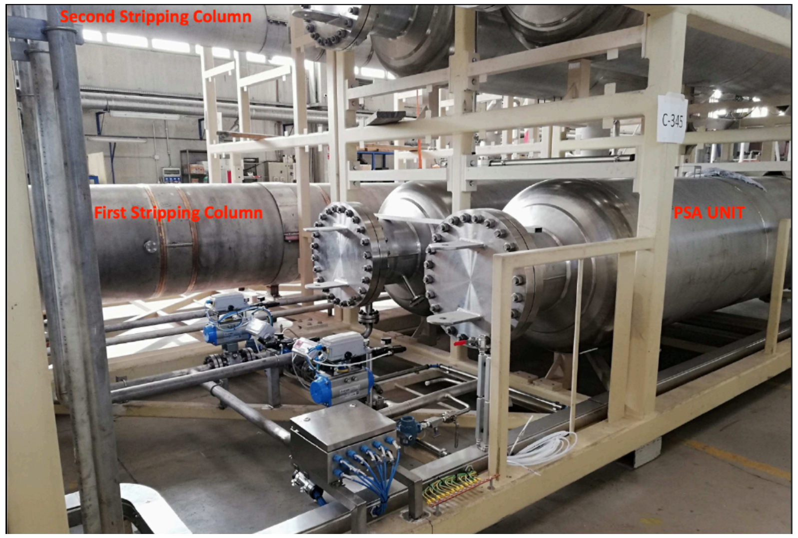


DArT in ArDM

EXTRACTION


Urania
UAr to DS-20k
Second separation
Helium
CO2 final flow
First separation
CO2 initial flow
Not To Scale
Credit: F. Gabriele

URANIA UPDATE



Production of components

Leak test

Shipping & Storage

Urania Site Construction

ARIA UPDATE

- The demonstrator column (26 m) that consists of three modules was **successfully tested** in 2019 with LN_2 and with argon in 2021.

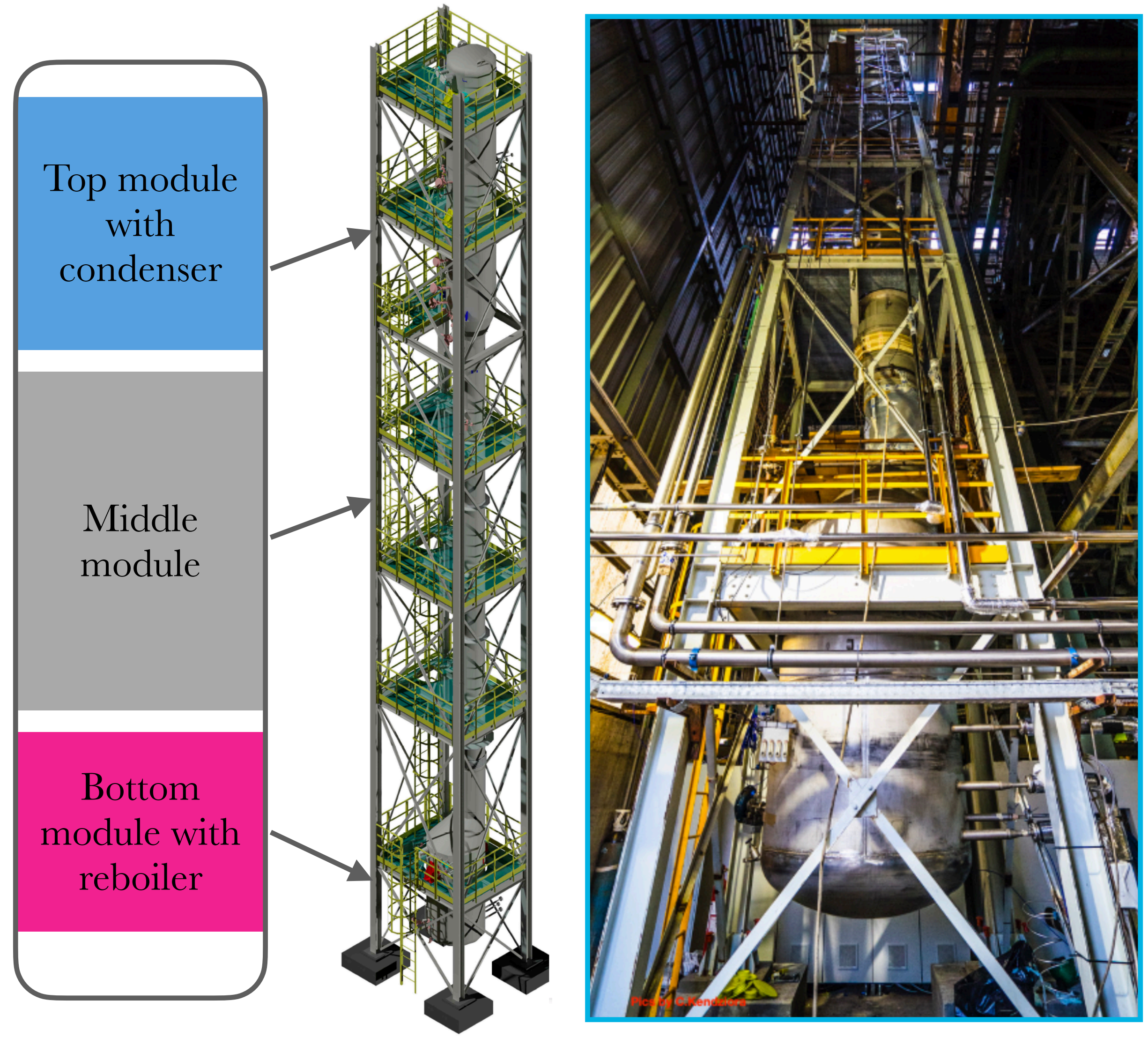
  Eur. Phys. J. C 81, 359 (2021)

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

- **The results are in agreement with the expectations** and validate the concept and design of the plant.

- Successful **test installation** of the first module (of 28 central ones) in the shaft at Seruci mine.

- Refurbishing of shaft and support structure is on going.

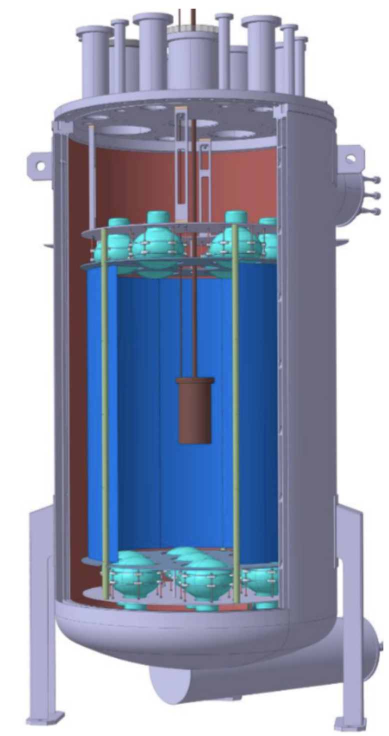


Prototype ARIA column ~26 m

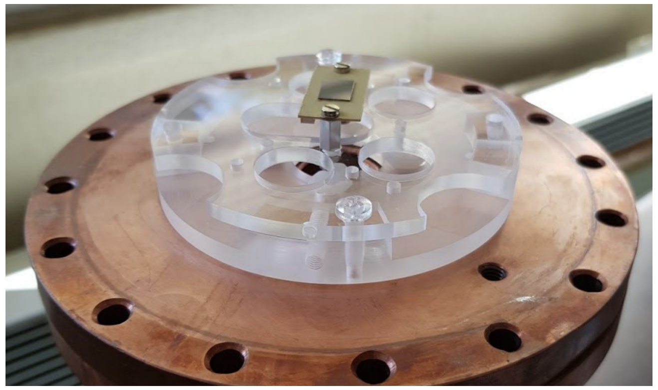
Test installation of the module

ARGON RADIO-PURITY MEASUREMENT

- **DArT:** a single phase low-background detector to measure the ^{39}Ar depletion factor of different underground argon batches (URANIA+ARIA).
- Cylinder made of 99.99% OFHC Cu, 1.42 kg of LUAr. PMMA support structure with TPB coating. Two 1 cm^2 SiPMs.
- To be installed inside the ArDM apparatus (Canfranc Laboratory, Spain) filled with LAr (850 kg AAr) used as active veto.
- Sensitivity to the depletion factor of 1000 with 10% precision in one week run.



DArT in ArDM



DArT SiPM

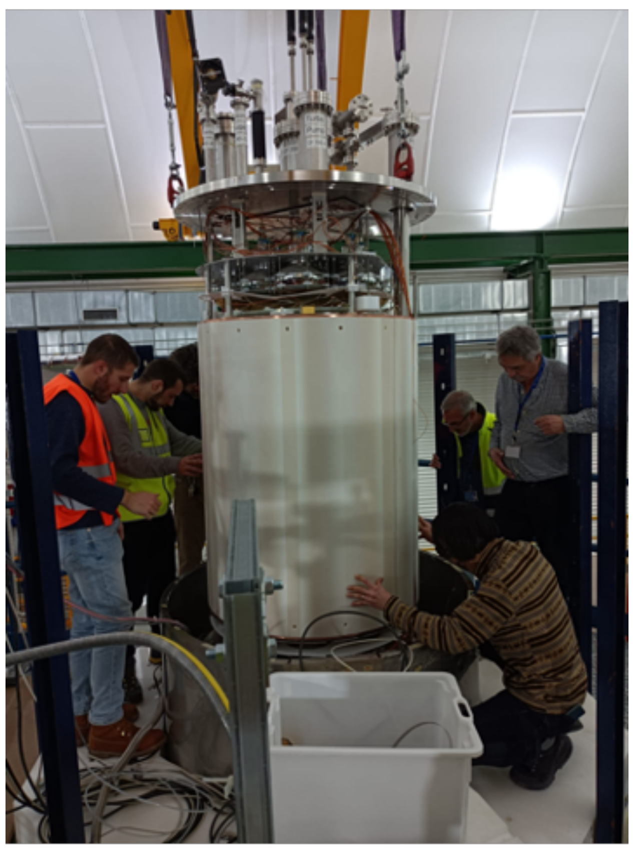
DArT was installed at LSC in April 2021 and the following installation in ArDM was in 2023.

More details of DArT: JINST 15 P02024 (2020)

DArT UPDATE

Infrastructures for cleaning and assembly procedures

Old ArDM extracted….



Insertion
in final configuration.

Credits: L. Luzzi

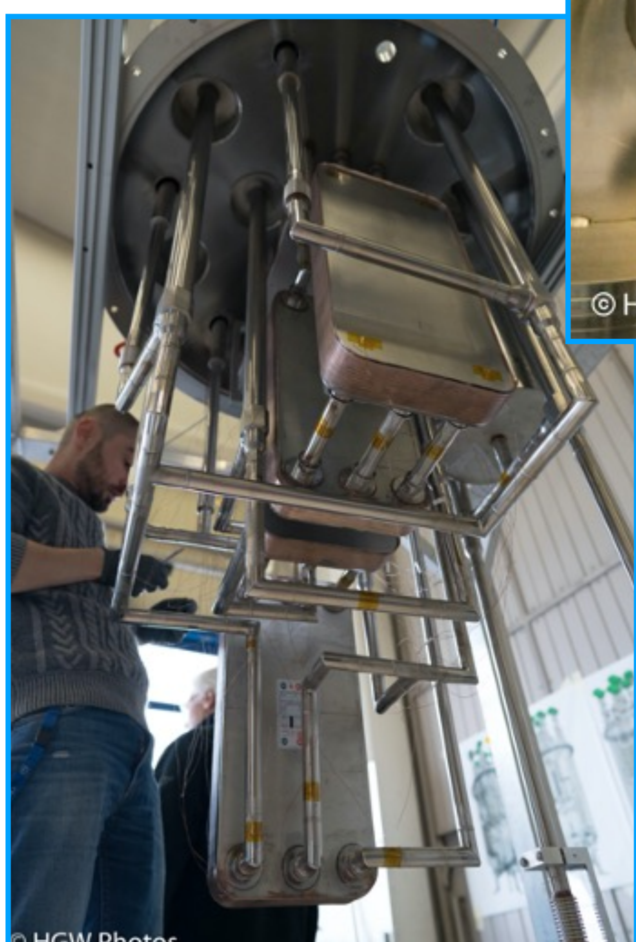
Measurement of UAr from DarkSide-50 is up coming…

CRYOGENIC SYSTEM FOR TPC

- Integrated test of the UAr cryogenics is ongoing at CERN.
- Up to 10 kW (latent heat + heat exchanging) adjustable condenser box.
- 1000 SLM circulation speed with two homemade pumps in parallel.
- The first test was taken in July 2021.
- More tests are planned later this year.

DarkSide unique condenser design

Fully instrumented condenser system



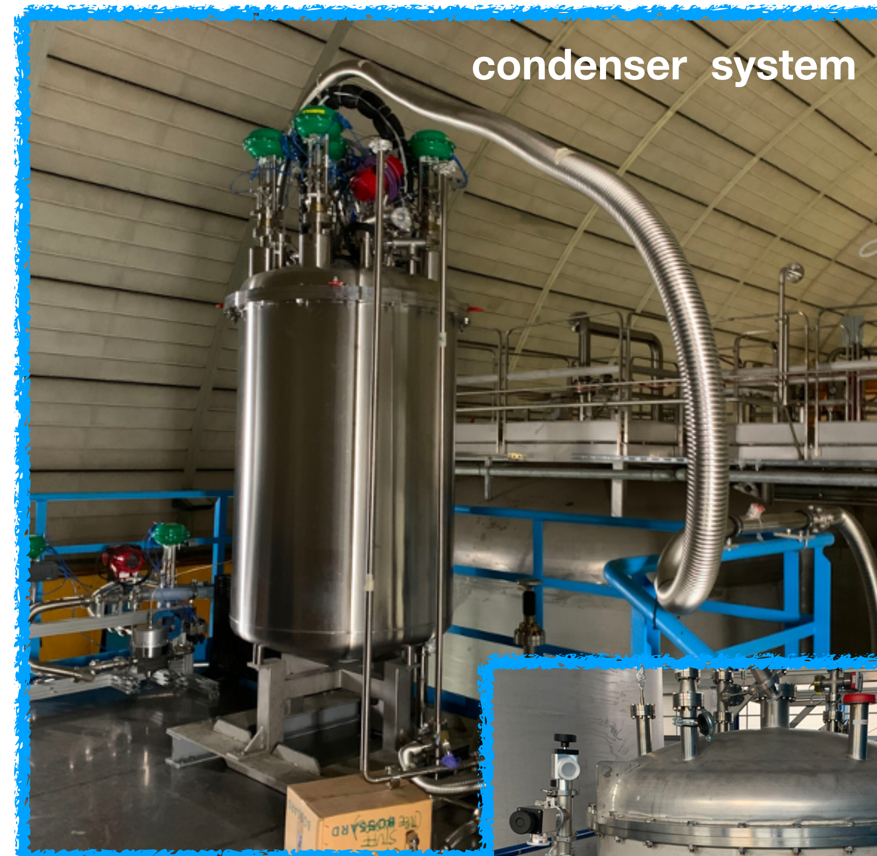
In-house fabrication of the gas handling system

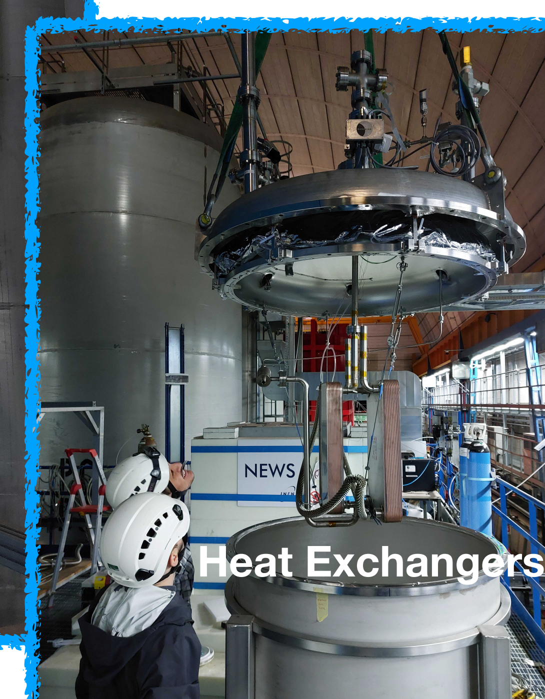
TPC Cryogenic system (test installation) at CERN

MOCKUP @LNGS

- Mockup to check TPC mechanical assembly and characterization of the cryogenic system.
- Currently, cryogenic system characterization, such as maximum flow rate, stability, and emergency behavior, is on going.
- Mockup TPC will be installed in the beginning of 2025!

The performance paper is on arXiv:2408.14071



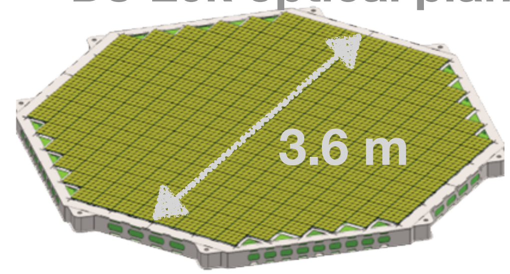


Credit: P. Salomone

PHOTO SENSOR

- Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.
- Key features
  - Photon detection efficiency (PDE) ~45%
  - Low dark-count rate < 0.01 Hz/mm^2 at 77K (7 Volts overVoltage)
  - Timing resolution ~ 10 ns
- The 21m^2 for the TPC (2112 channels) + 512 channel for Veto detector. Mass production of the raw wafer in LFoundry company and assembly in a dedicated facility at LNGS (NOA).

Ds-20k optical plane



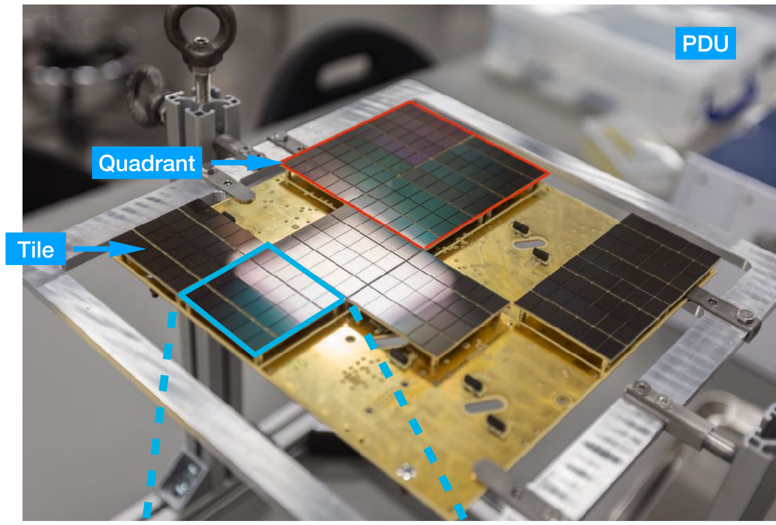


Photo Detector Unit (PDU) = matrix of 16 PDMs
20 x 20 cm^2

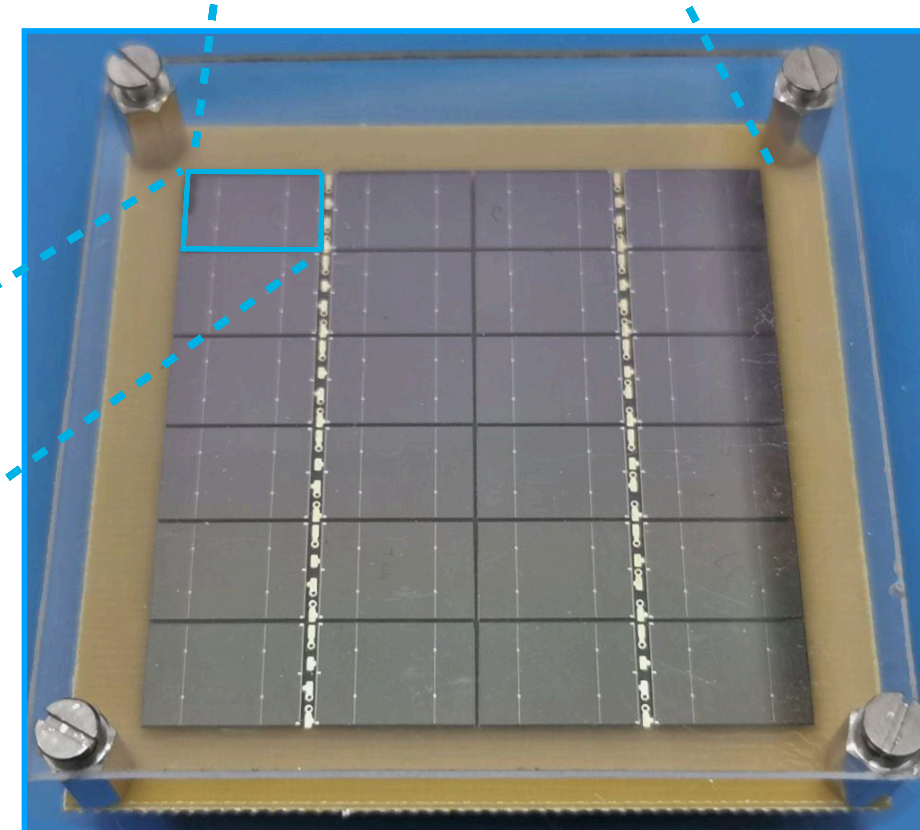
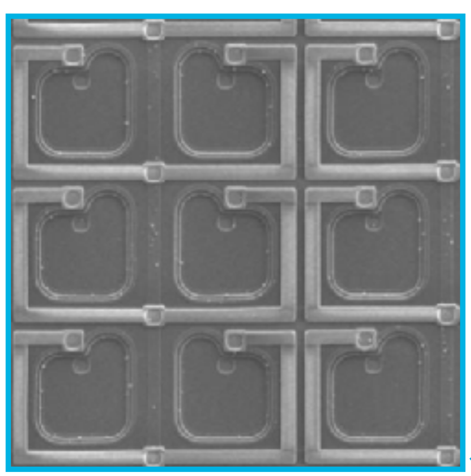
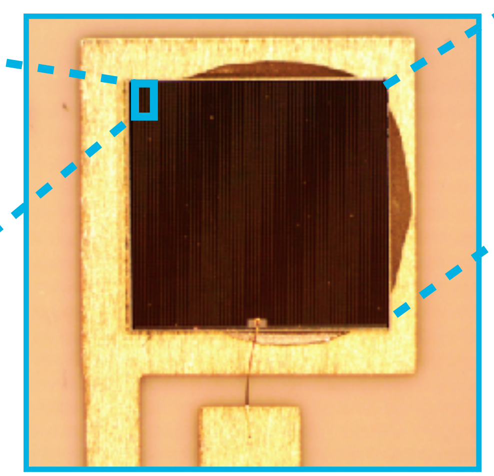


Photo Detector Module (PDM)
= matrix of 24 SiPMs, 5 x 5 cm^2
4 PDUs are summed and read as a single channel
(largest single SiPM unit ever!)



Single SPADs

~25-30 μm^2



Single SiPM

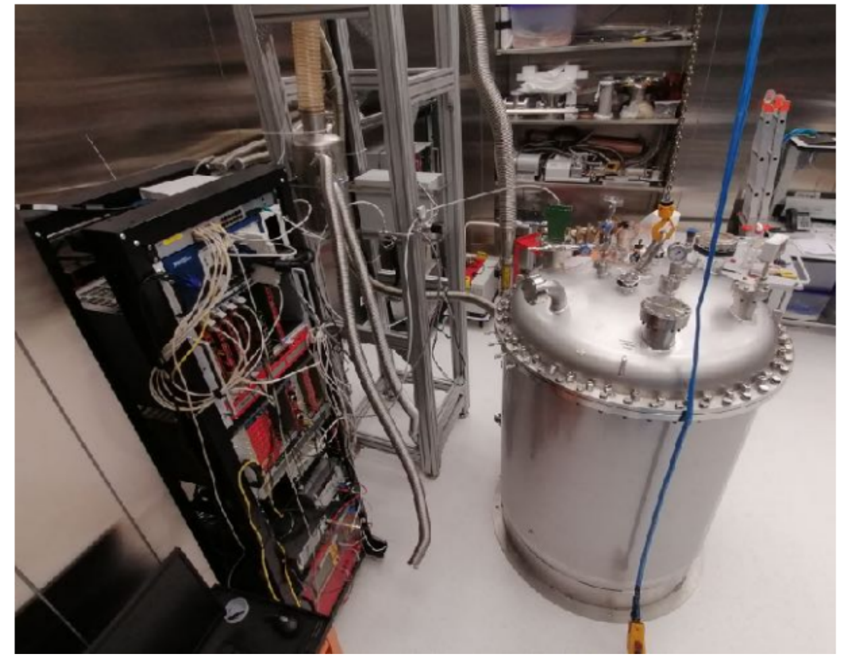
~1 cm^2

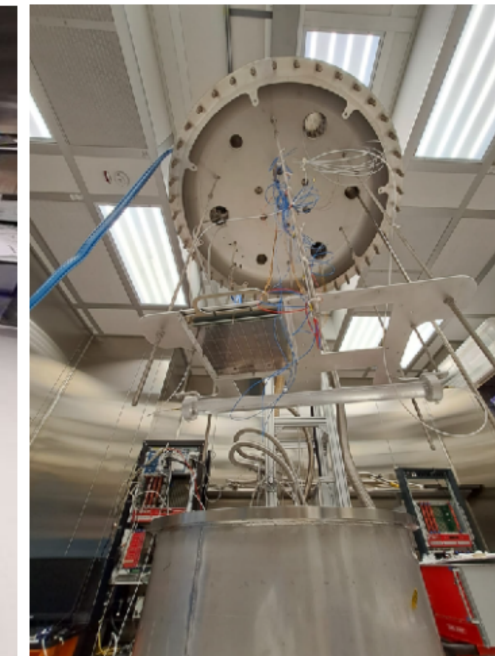
NUOVA OFFICINA ASSERGI (NOA)

- INFN Facility managed by LNGS – clean room class ISO 6
- Two main rooms:
  - CR3: 3.0 m x 350 m^2 -> photodetector production area, equipped with highly sophisticated packaging machines for the assembly of photosensors in a dust-controlled environment
  - CR2: 5.8 m x 68 m^2 -> large volume detector assembly
- To be equipped with dedicated Rn-abatement system (currently, Rn level in CR3: 6-10 Bq/m^3)
- Operative since Nov. 2022, completed in 2023
- Currently populated with machines needed by DarkSide for SiPM packaging, test and integration
- 2023, start-up of activities, characterization of silicon wafers procured for the in-house production of the PhotoDetector Units (PDU).
- 2024, production and quality assurance of DS-20k SiPM (described in arXiv:2412.18867).

PDU TEST FACILITY IN NAPOLI

- ~800 L double wall **cryostat** with domed flange
- ~100 ps pulsed **laser for calibration**
- > 300 readout channels with 5 CAEN VX2740 ADC Boards
- Custom support structure with room for 16 PDUs inside the cryostat
- Custom illumination system with PMMA rods as diffusers
- High end local servers for DAQ and Acquisition with O(1 PB) storage
- Fully automated cold box, remotely controllable with fast FILL and DRAIN
- Two external 3000L each reservoirs
- Ready to test PDUs!



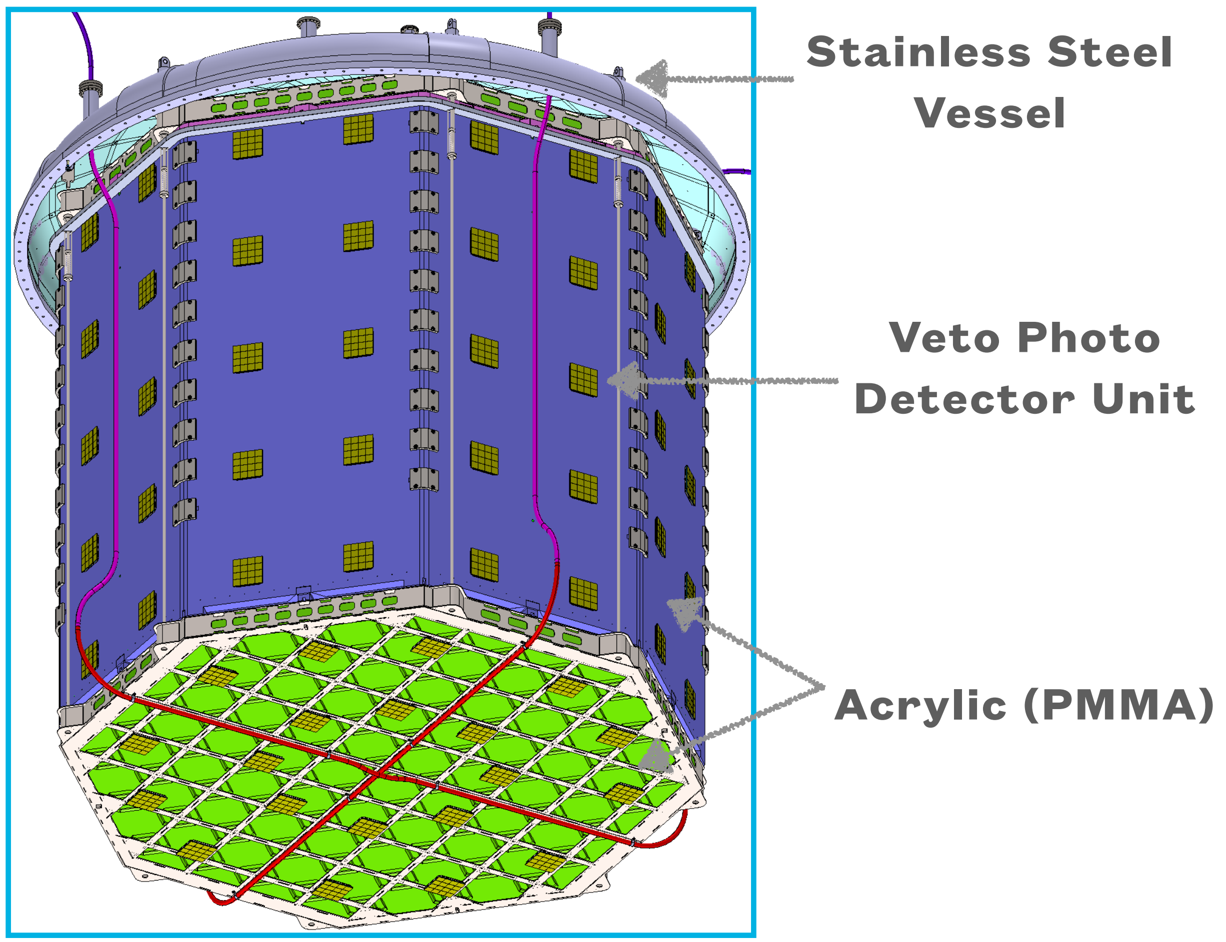


VETO DETECTOR

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

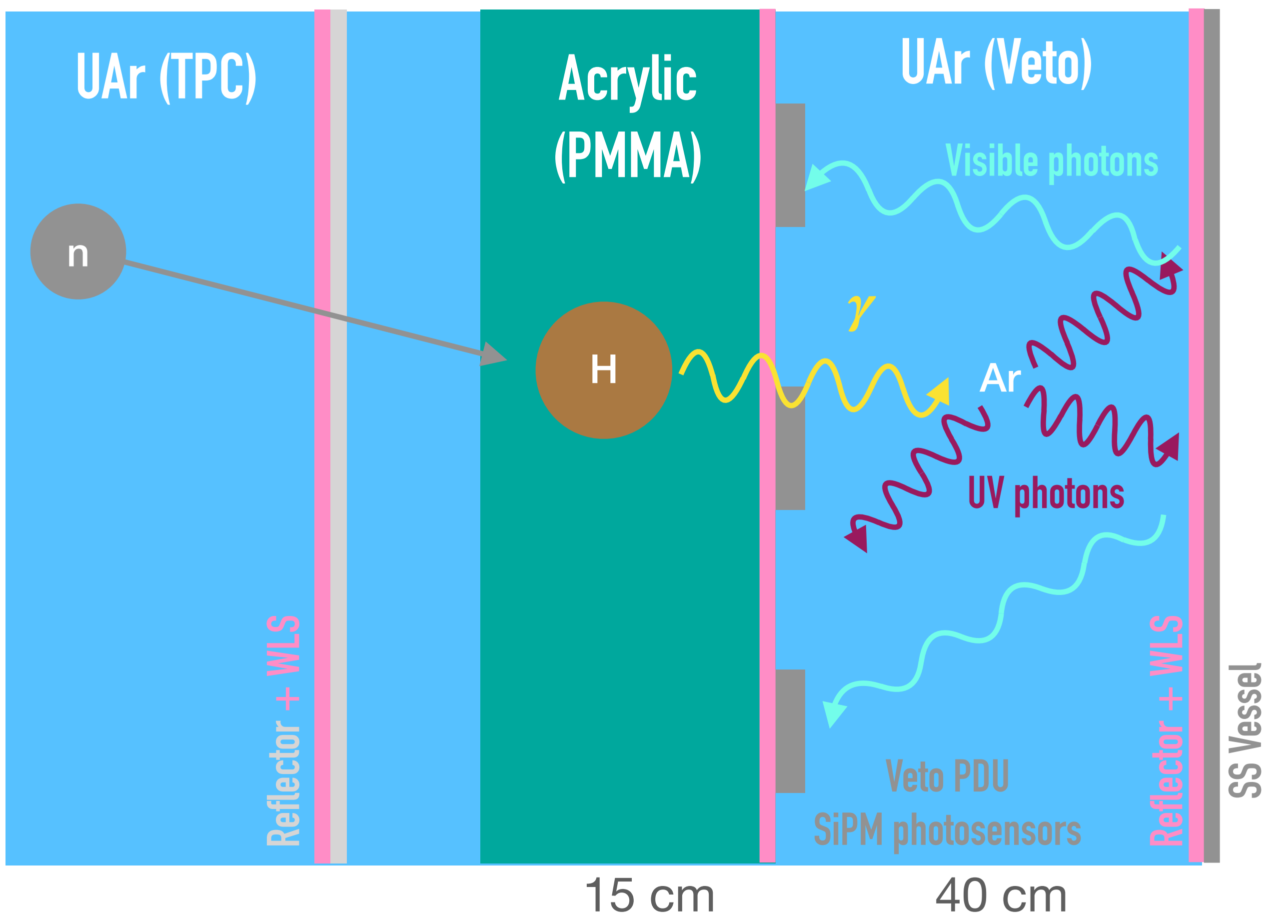
Veto Structure

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



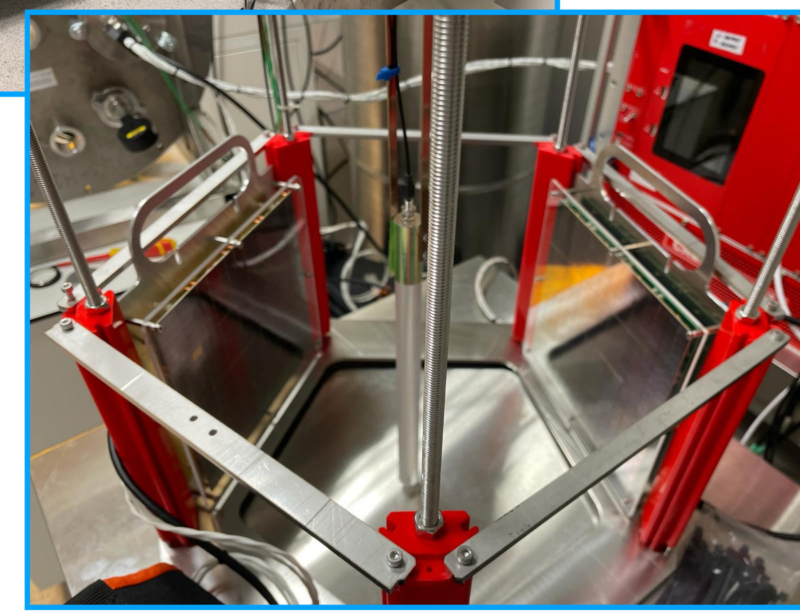
Veto Working Principle

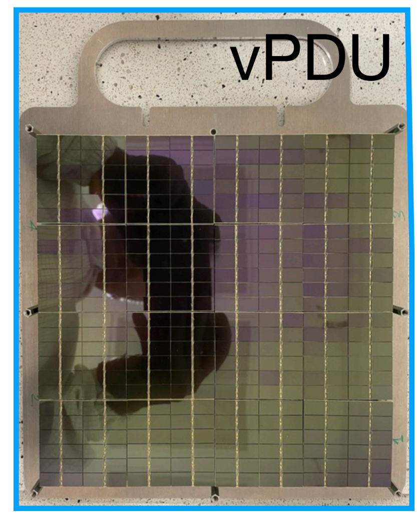
1. Neutrons are moderated in the acrylic shell and then captured by hydrogen.
2. H emits a γ-ray with energy of 2.22 MeV.
3. γ-rays interact in the liquid argon buffers.
4. LAr scintillation light is shifted and detected by ~1920 SiPM-based photosensors.



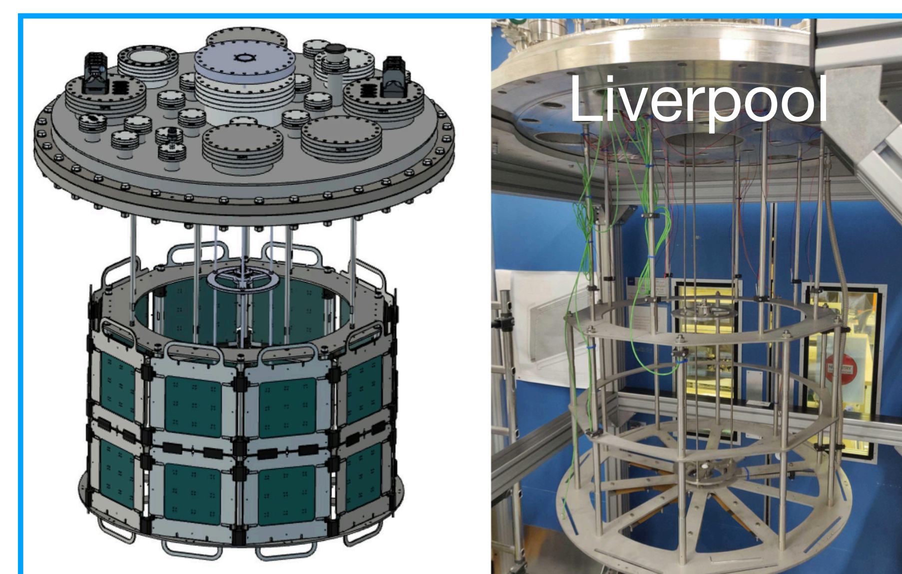
VETO PDU TESTING

- ASIC amplifier designed by INFN Torino.
- Production of vPDU is in Birmingham, STFC interconnect, Manchester, and Liverpool
- Three testing facilities: AstroCeNT, Edinburgh, and Liverpool.



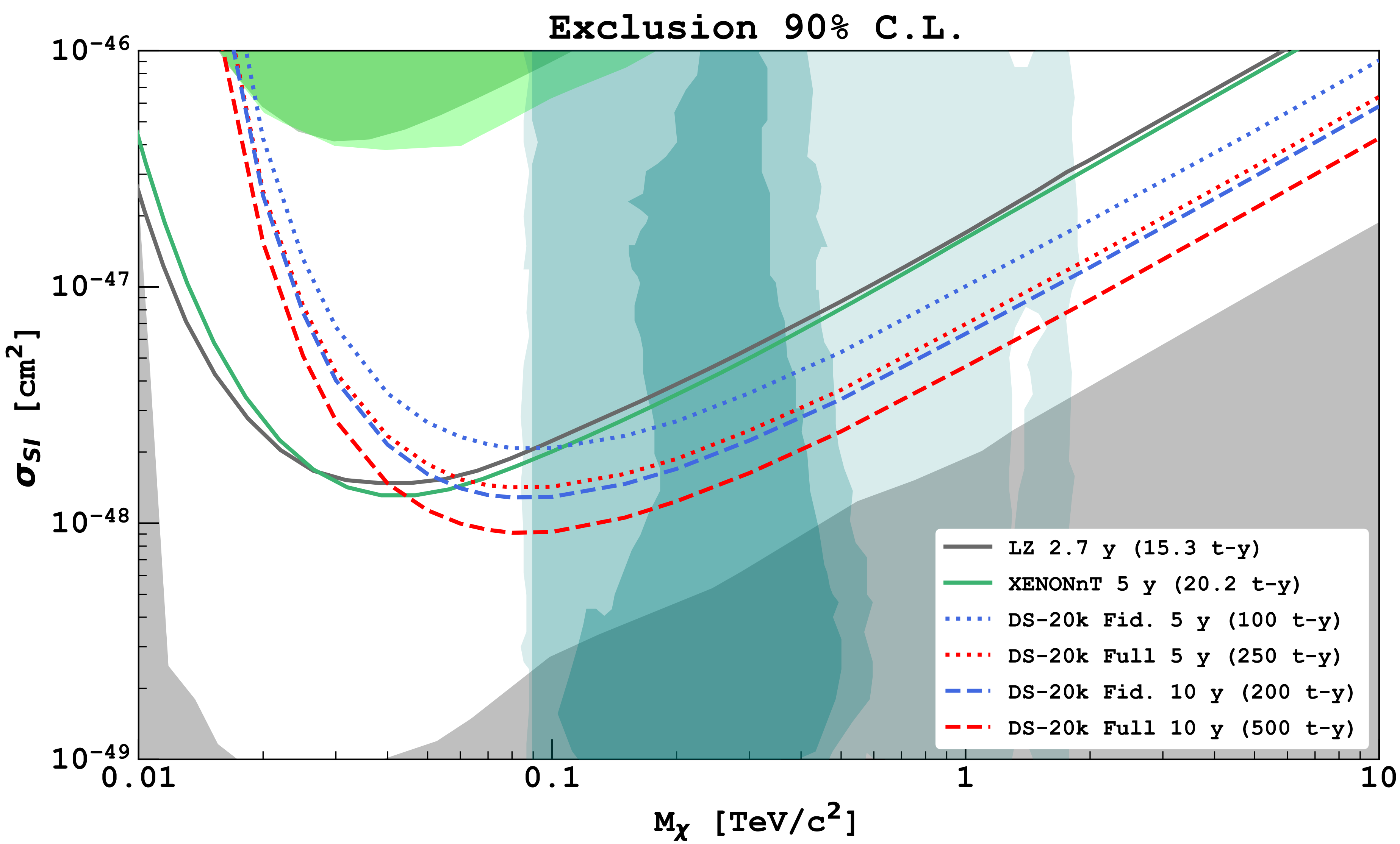


- All facilities are ready for production and testing.



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.



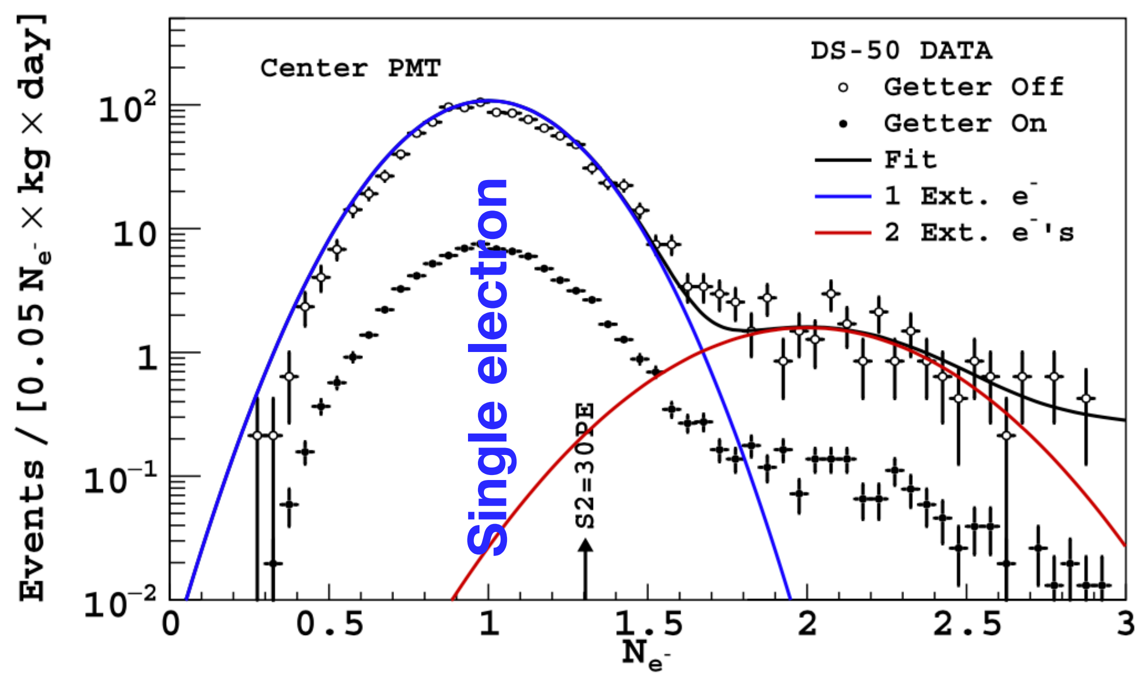
- The present projection - based on a 10 yr run, giving a fiducial volume exposure of 200 t yr - is 6.3×10^{-48} cm^2 for 1 TeV/c^2 WIMP for the 90% C.L. exclusion.

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

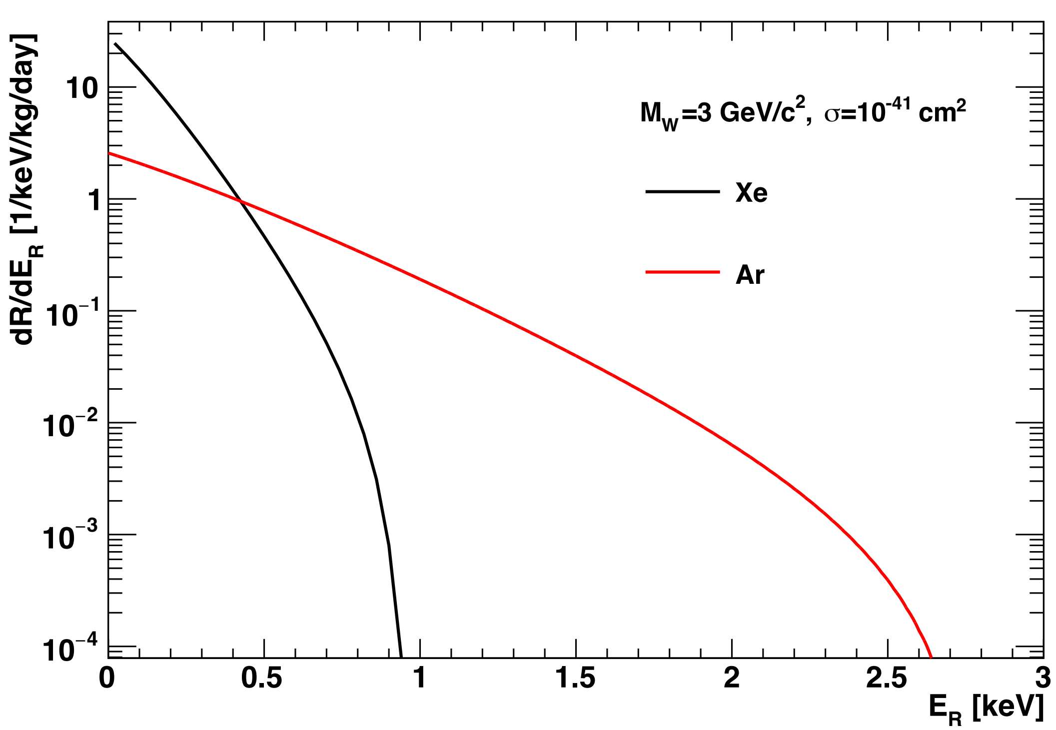
WHAT WE ACHIEVED IN DS-50

- **Scintillation signal** (S1): threshold at ~2 keV_{ee} / 6 keV_{nr}
- **Ionization signal** (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr} **Can go lower threshold!**

- Use Ionization (S2) Only.
    - Amplified in the gas region (~23 PE/e^- or more)
    - **Sensitive to a single extracted electron!**
    - The electron yield for nuclear recoils increases at low energy



WIMP spectra in Xe and Ar

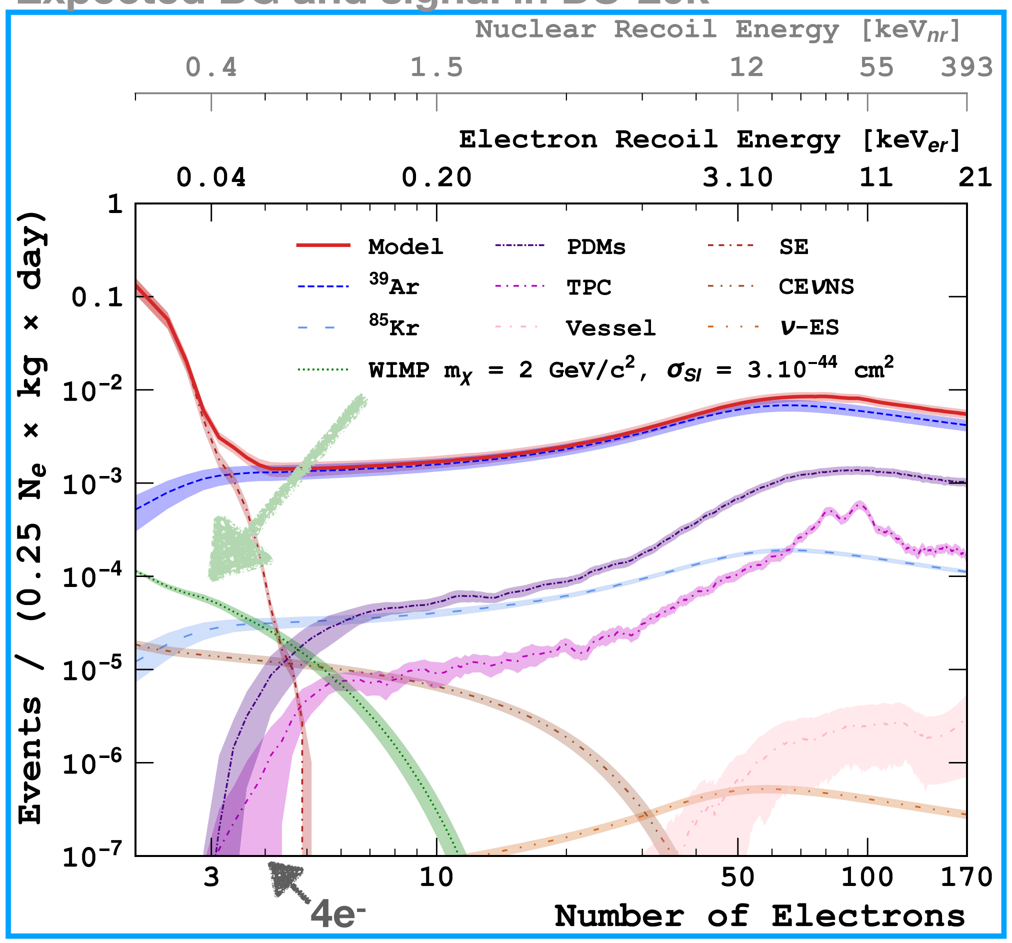


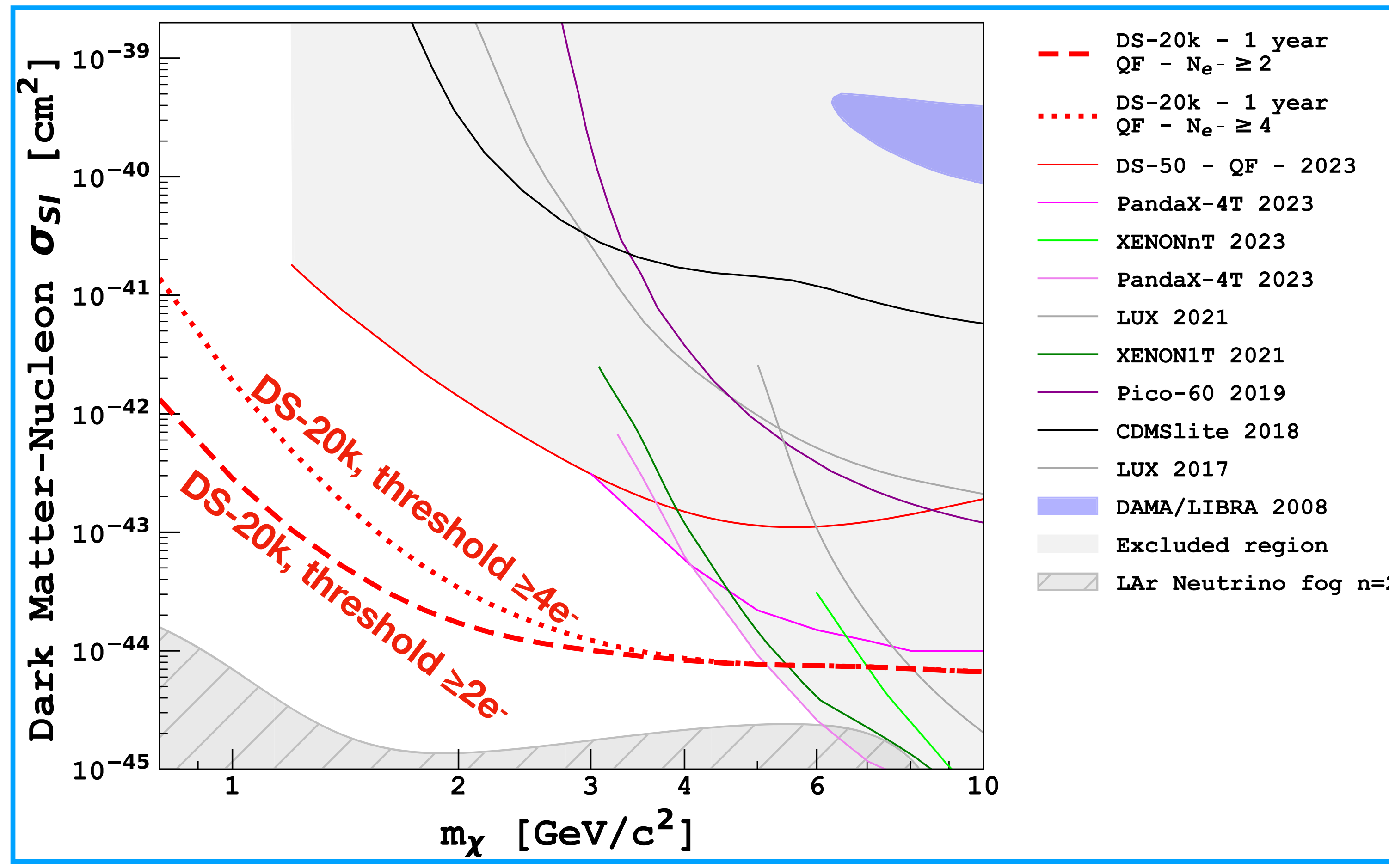
- Ar has lighter mass than Xe. So, more efficient momentum transfer from low mass DM.

EXPECTED LOW MASS DM SENSITIVITY

- Using **S2** (ionization signal) **only**.
- **Detailed background study**, information from DarkSide-50 data.
- Expected BG reduction in ^{85}Kr and photosensors gives DarkSide-20k with **a leading role below 5 GeV/c²**.

Expected BG and signal in DS-20k





- Also, prediction for other light DM candidates (Axion like particles, dark photons, sterile neutrino, and light dark matters via electron scattering) are studied.

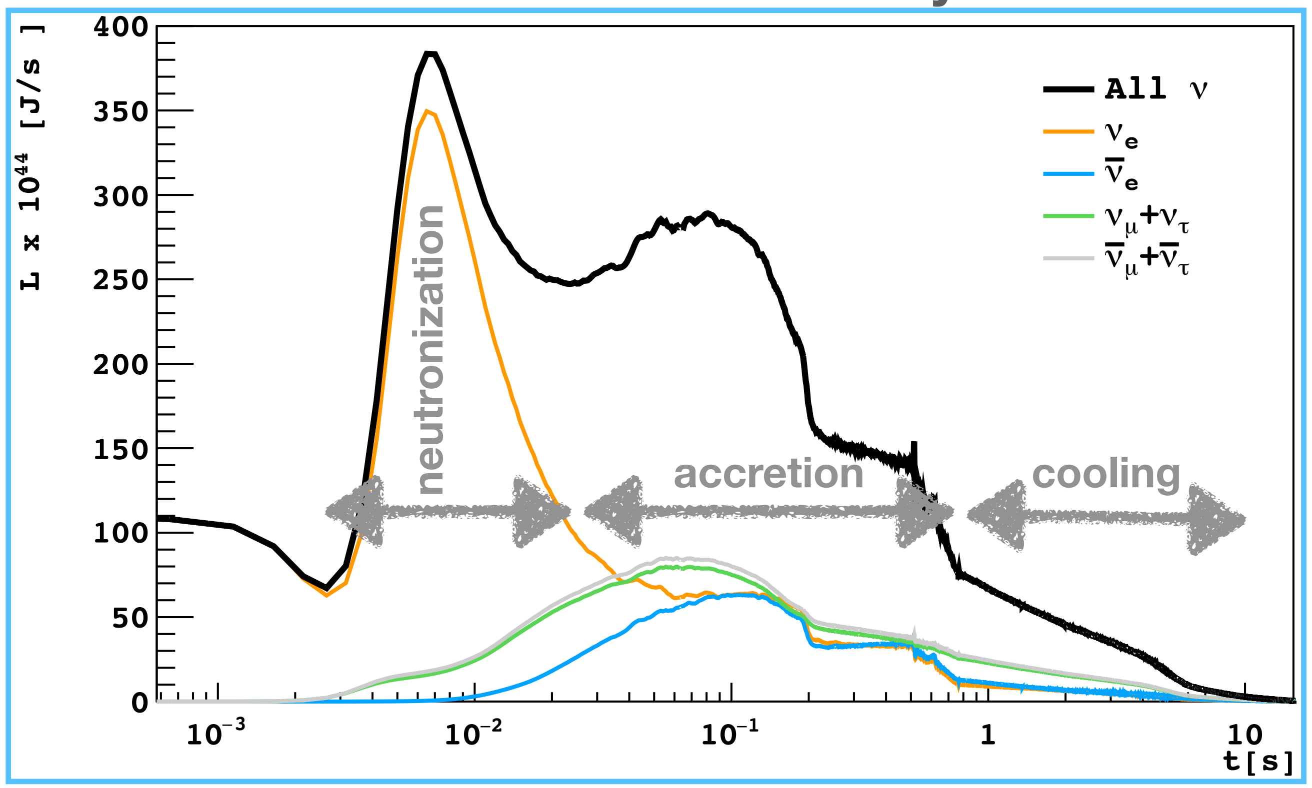
See more details in Commun Phys 7, 422 (2024).

SENSITIVITY TO SUPERNOVA NEUTRINOS

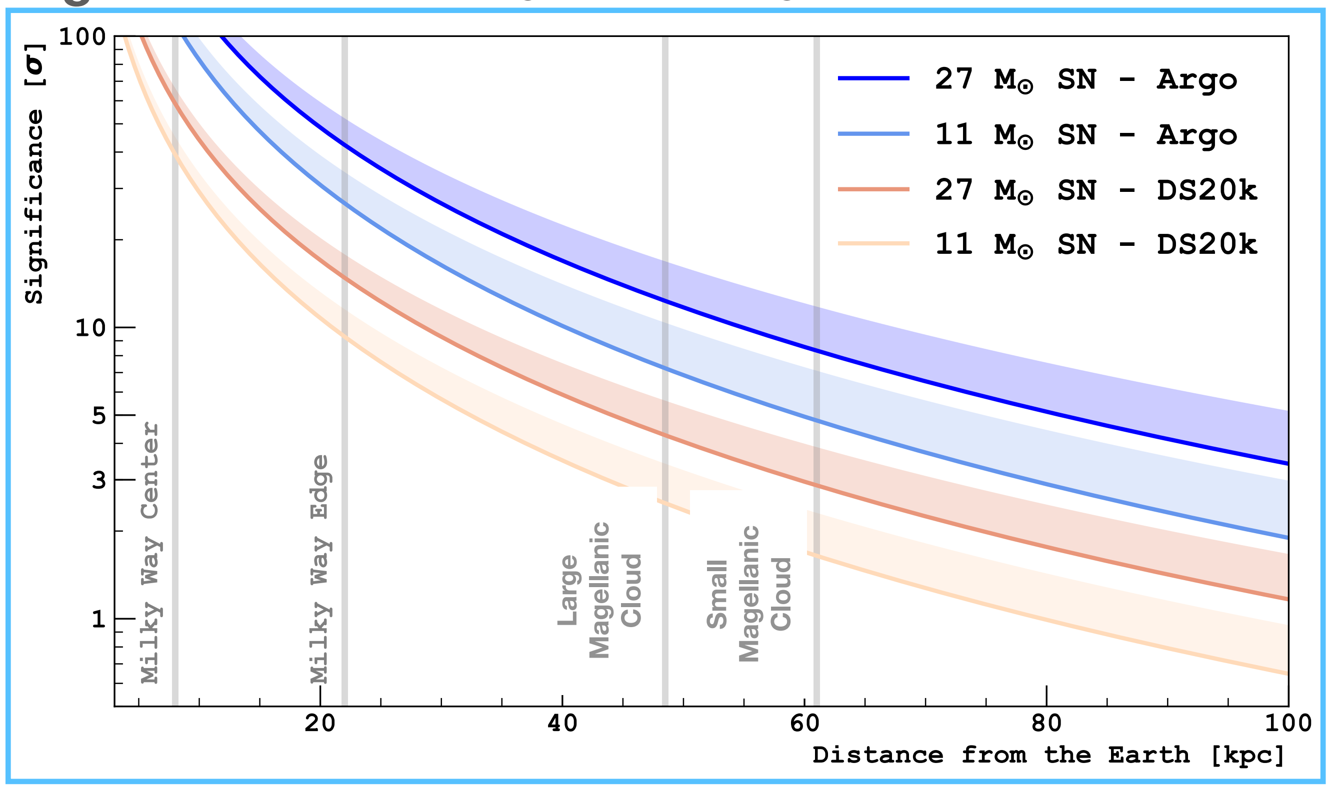
- **Supernovae** can provide constraints to the **neutrino absolute mass** and **mass ordering**. (One SN every 50 years <30 kpc.)
- Water Cherenkov and scintillator detectors (SK, HK, IceCube, KM3NeT, and JUNO) mostly **sensitive** $\bar{\nu}_e$ via inverse beta decay (IBD) and ν_e via elastic scattering ($\nu_e + e^- \rightarrow \nu_e + e^-$).
- DUNE is mostly **sensitive** ν_e via charge current interaction ($\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$).
- DS-20k (Argo, future detector) can detect **all flavor (anti)neutrinos** via coherent elastic neutrino-nucleus scattering (CEvNS).

$\langle E_\nu \rangle$~10 MeV

Time evolution of neutrino luminosity from SN



Significance to 11M⊙ and 27M⊙



Bands represent lower ^{39}Ar up to a factor 10.

- Using **S2** (ionization signal) **only**.
- **Detailed background study**, information from DarkSide-50 data.
- Ds-20k has potential to **discover supernova bursts throughout our galaxy.**

See more details in JCAP 03, 043 (2021).

SUMMARY

- TPC with underground Ar has excellent properties suited to high and low mass WIMP searches.
- Large effort for DarkSide-20k is ongoing in all parts and the construction started in LNGS.
- DarkSide-20k will start data taking in the beginning of 2027 for 10 years.
- DarkSide-20k has the best sensitivity to low mass dark matters.

  Commun Phys 7, 422 (2024)
- DarkSide-20k serve as a neutrino observatory with sensitivity to supernova neutrinos.

  JCAP 03, 043 (2021)