Lighting up dark matter in underground liquid argon with DarkSide

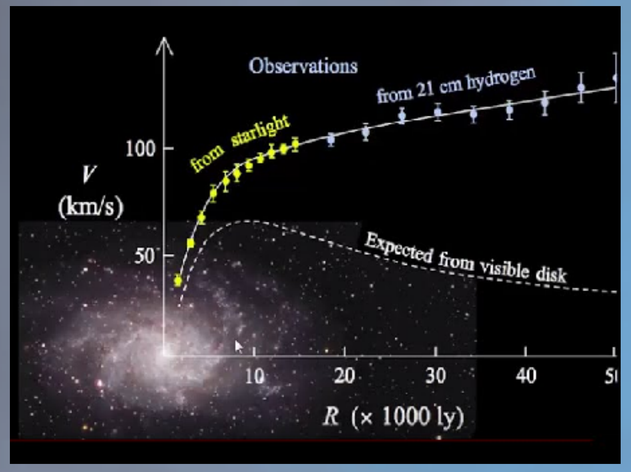
Davide Franco - APC

on behalf of the DarkSide-20k Collaboration

Exploring the Dark Side of the Universe - Tools 2024 - 5th World Summit

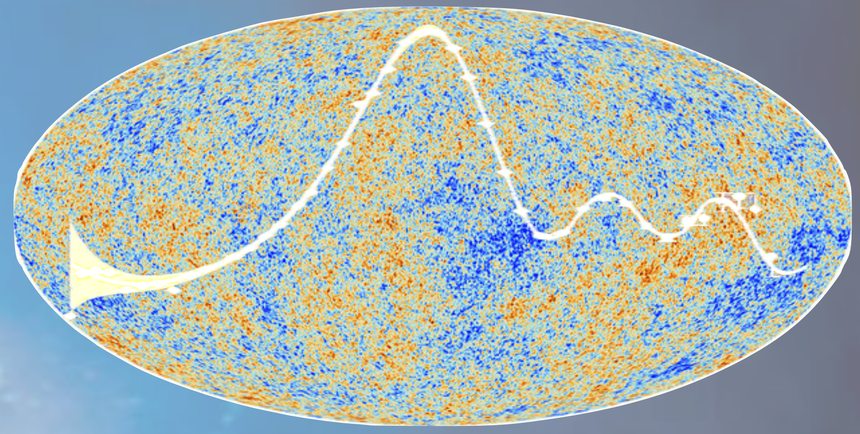
Jun 2 – 7, 2024 - Île de Noirmoutier, France

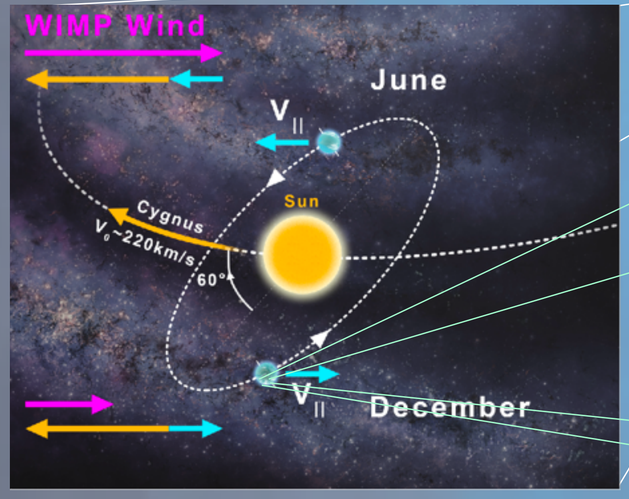
Looking for dark matter

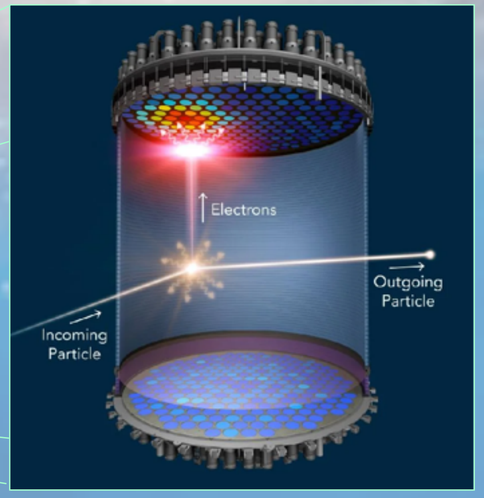


Dark Matter

Wide range of astronomical evidences of the existence of gravitational effects, not arising from ordinary matter





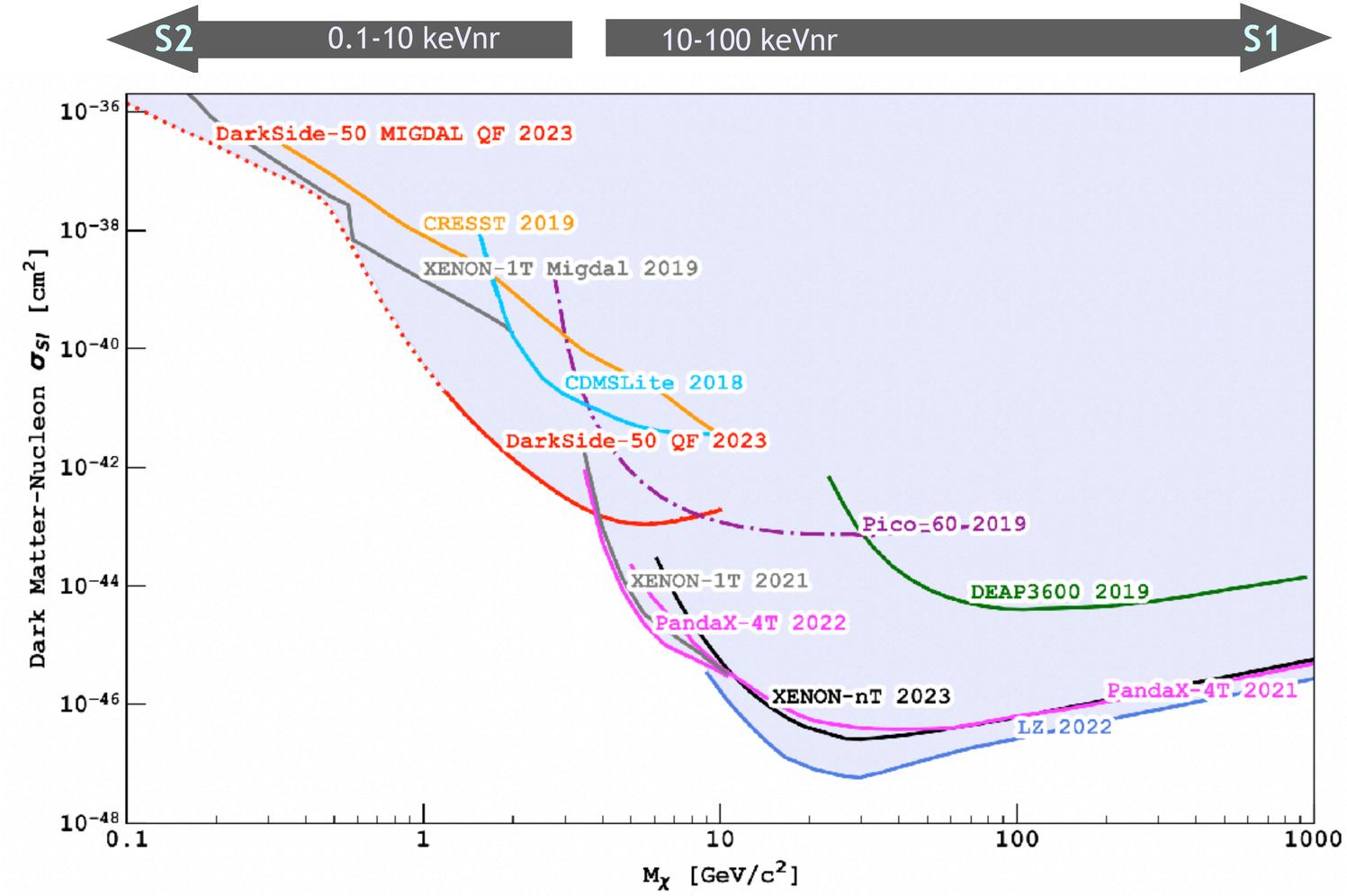


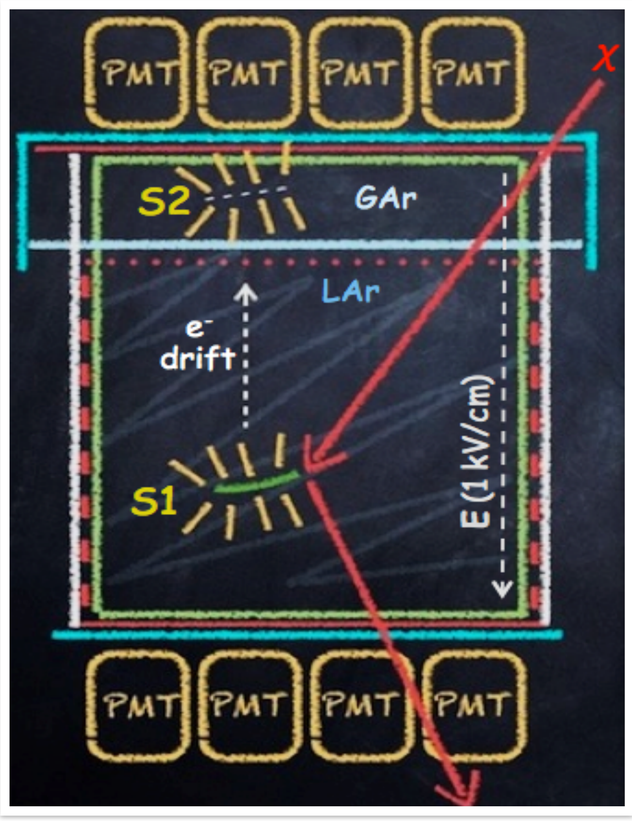
The Candidate

A massive, neutral, stable, cold, non-baryonic, weakly-interacting particle

WIMPS: Weakly Interacting Massive Particle?

Dual-Phase Noble Liquid TPCs for Dark Matter Search

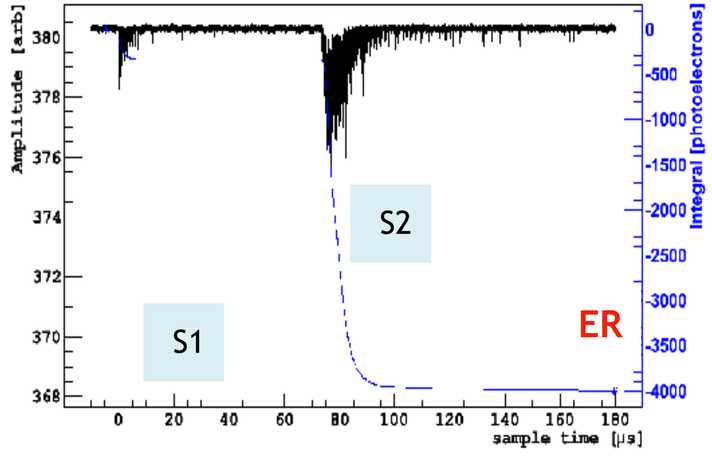


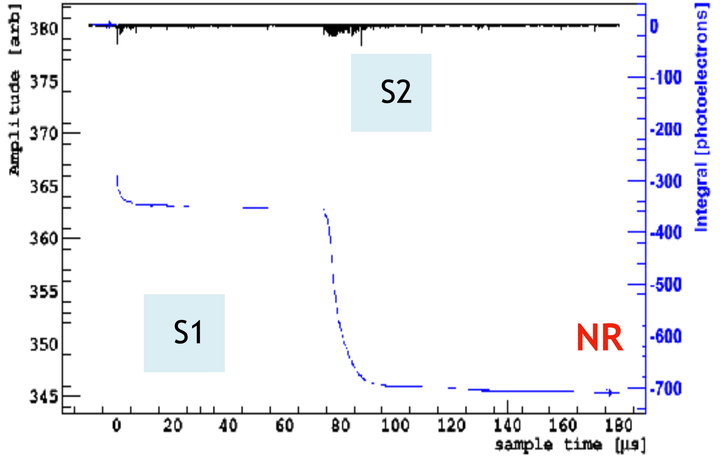


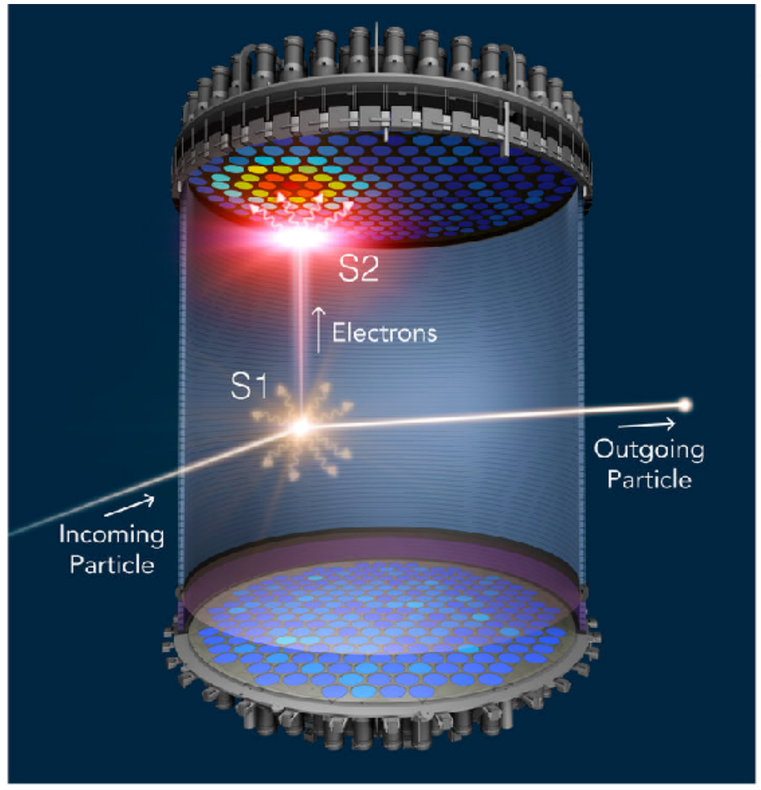
Dual-Phase Noble Liquid TPCs for Dark Matter Search

Dual-phase TPCs

- X and Y position resolution at O(1 cm) resolution
- Z position resolution at O(1 mm)
- Efficient fiducialization
- Multi-scatters interaction rejection
- “Fast” response (=> active vetoes)



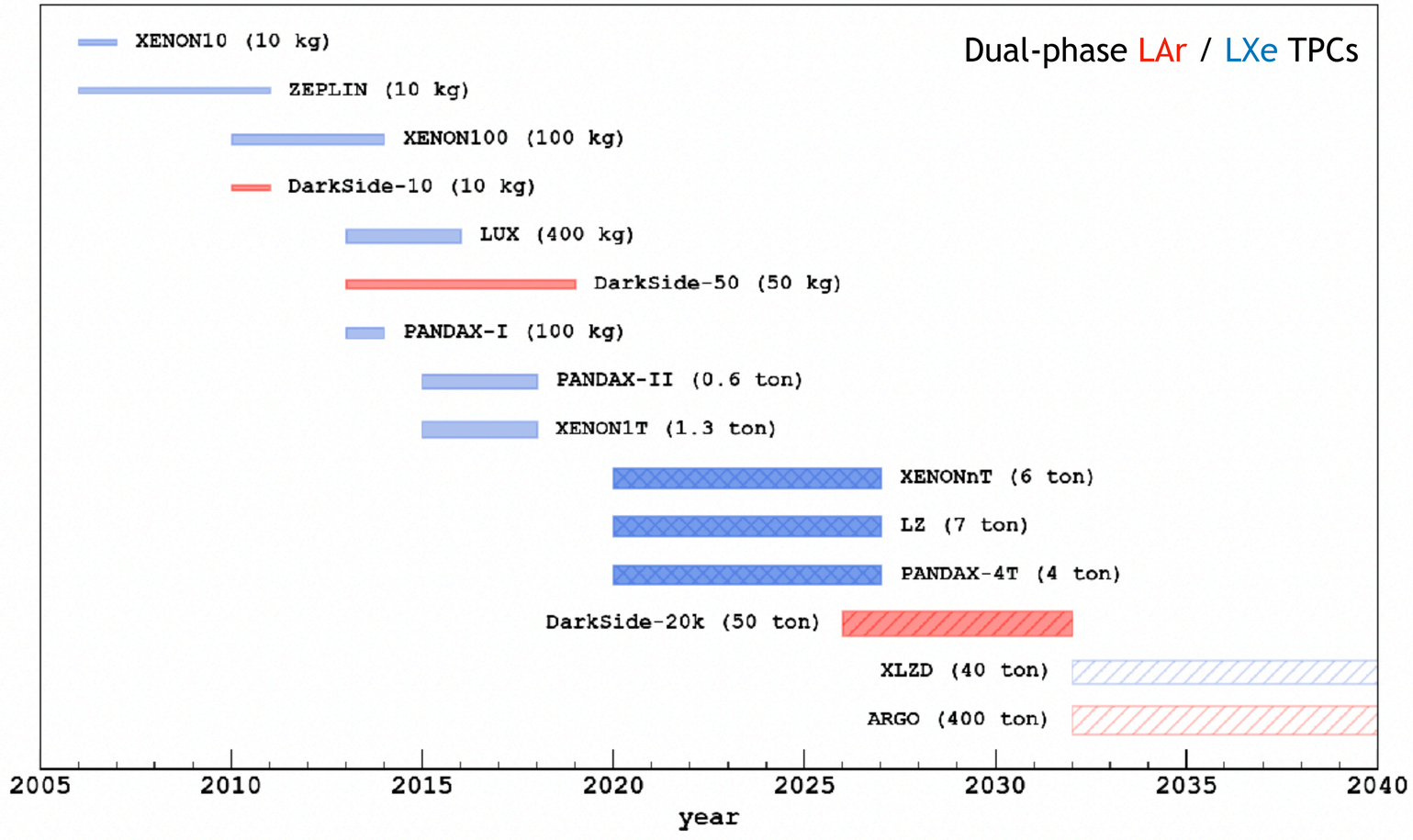




Dual-Phase Noble Liquid TPCs for Dark Matter Search

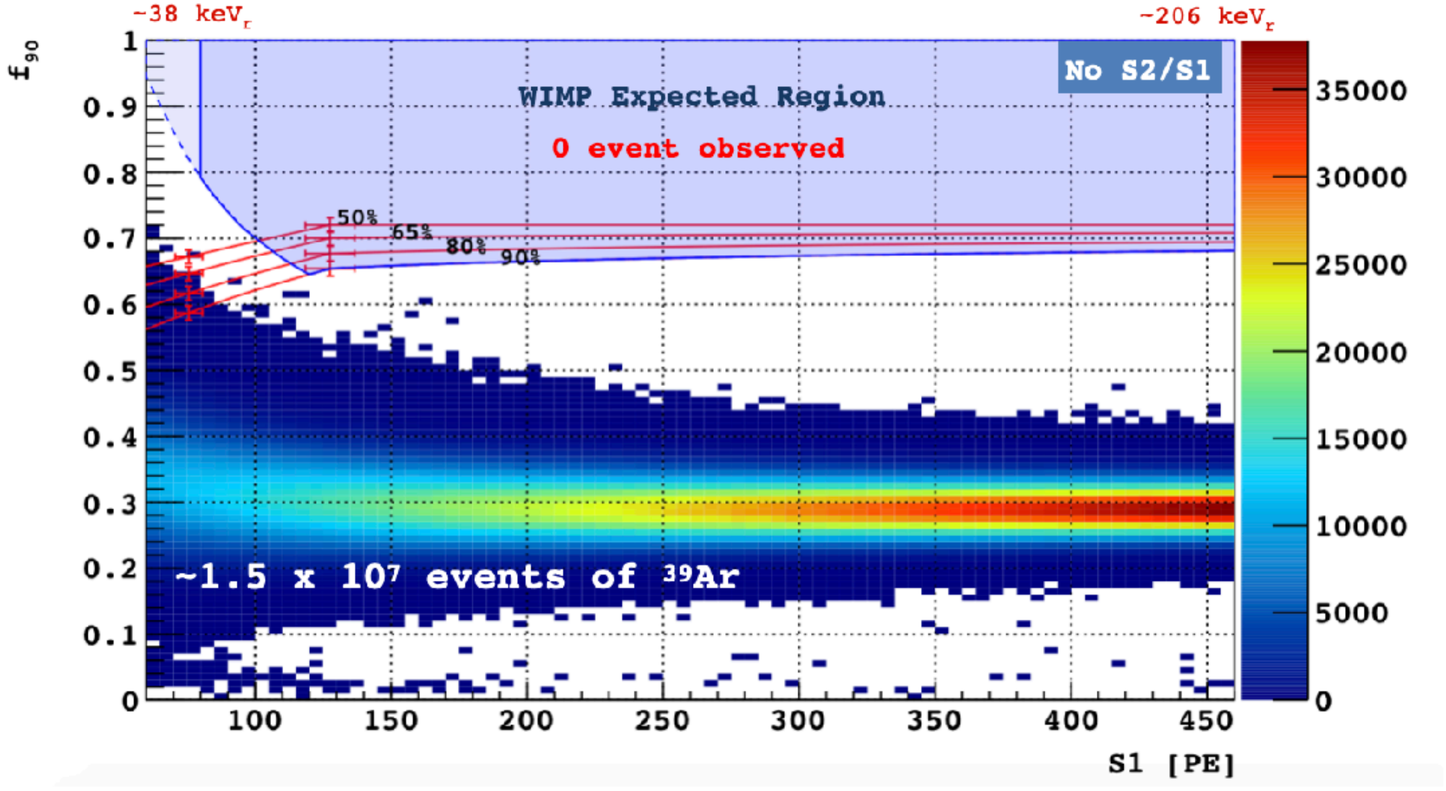
Noble Liquids

- **Noble**
  => no radiochemical impurities
- **Scalable**
  => O(10-100 ton)
- High **scintillation** yield (x 4 organic scintillator)
  => high resolution
- Excellent particle **identification**
  => background suppression
- High **ionization** yield
  => very low energy thresholds
- Low electron **diffusion** and mobility
  => accurate event topology in a TPC

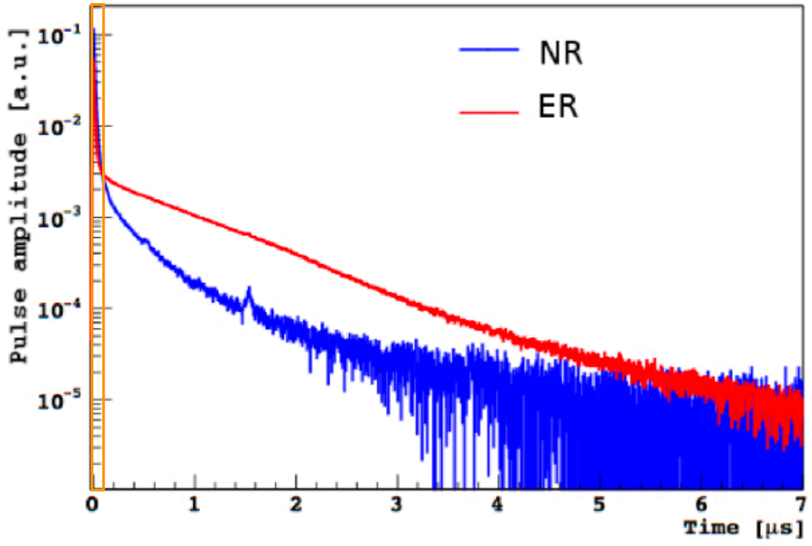


Why liquid argon?

The Scintillation Pulse Shape Discrimination



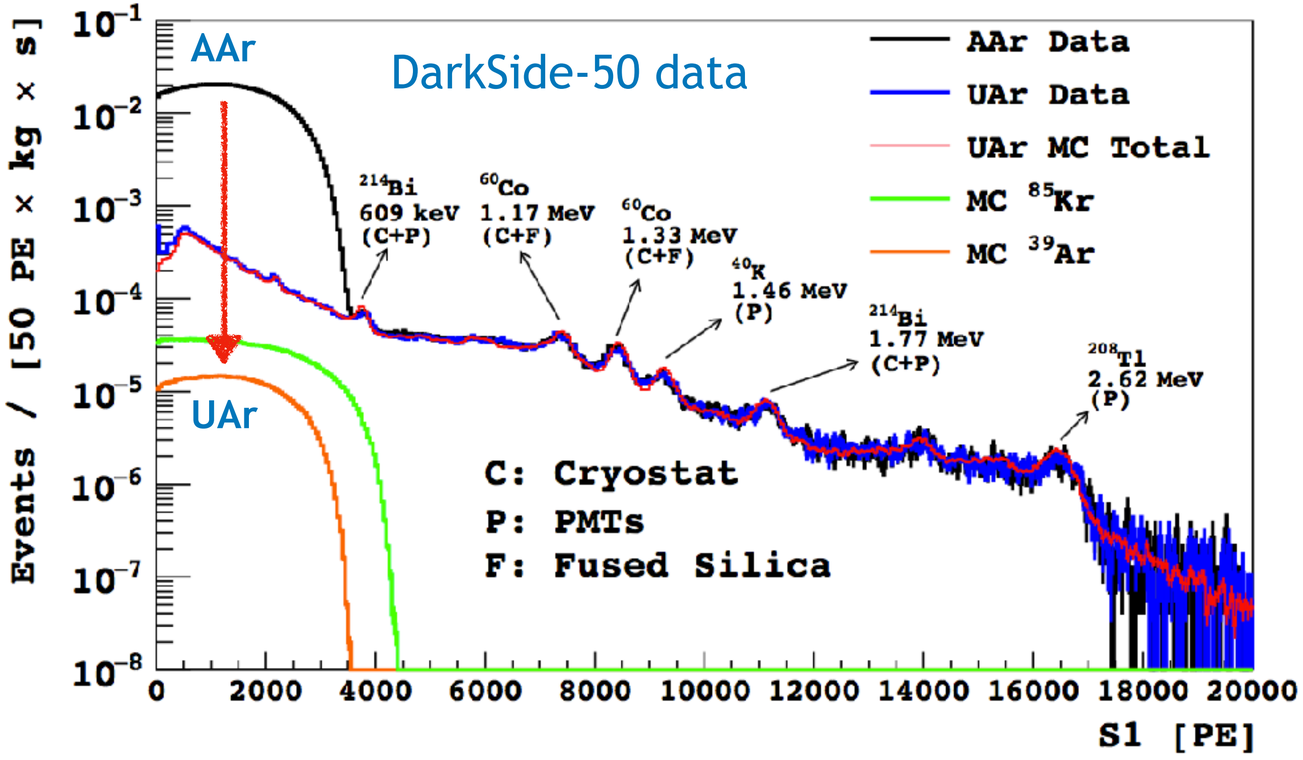
f90: fraction of detected light in the first 90 ns



Potential for a **background-free** multi-ton experiment

Why ~~not~~ liquid argon?

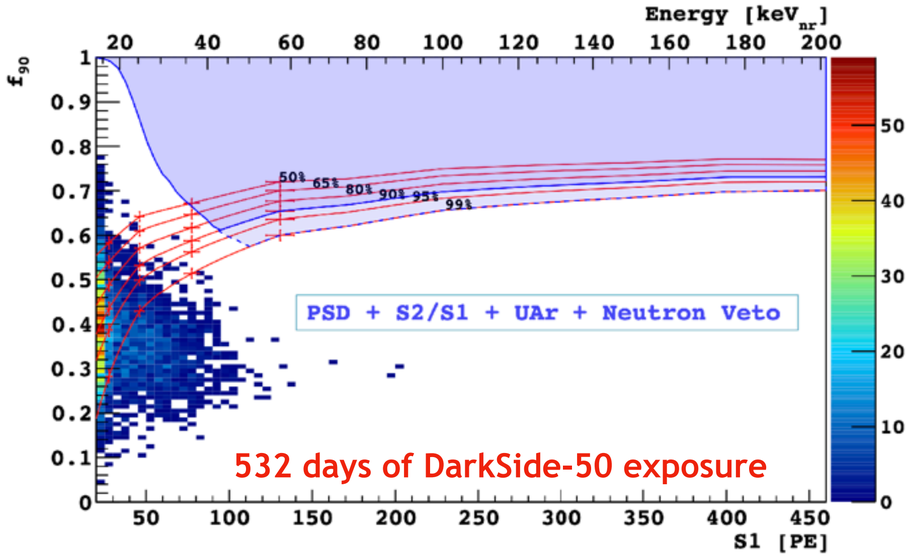
Underground Argon



^{39}Ar reduction factor in UAr: ~1400

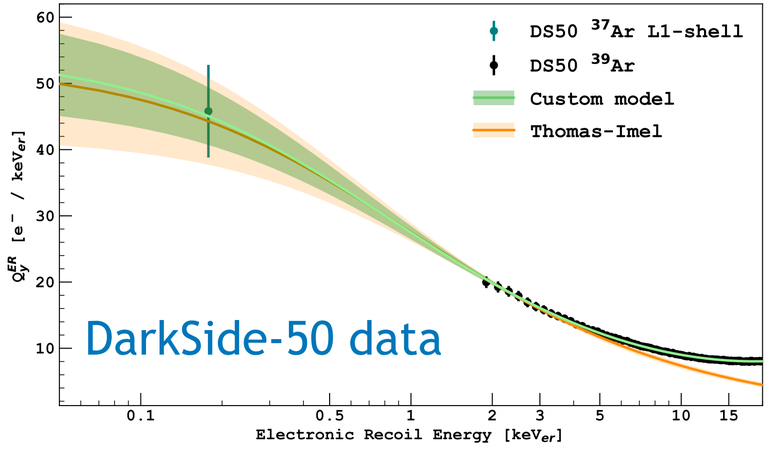
Cosmogenic ^{39}Ar in **atmospheric argon** is the primary background (~1 Bq / kg)

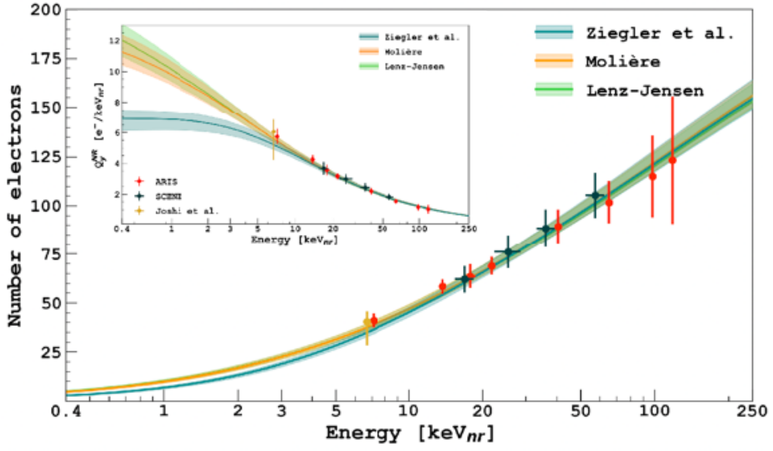
Argon extracted from deep underground is naturally shielded against cosmic rays



Lowering the energy threshold with DarkSide-50

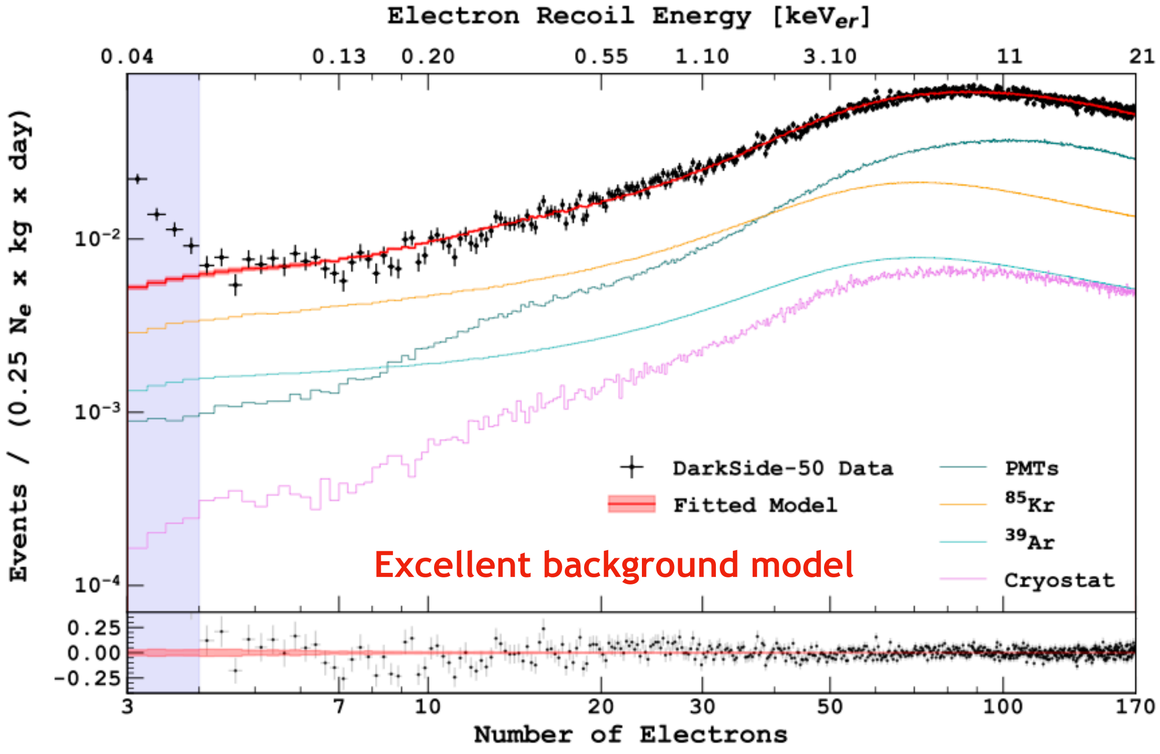
Low-energy calibration



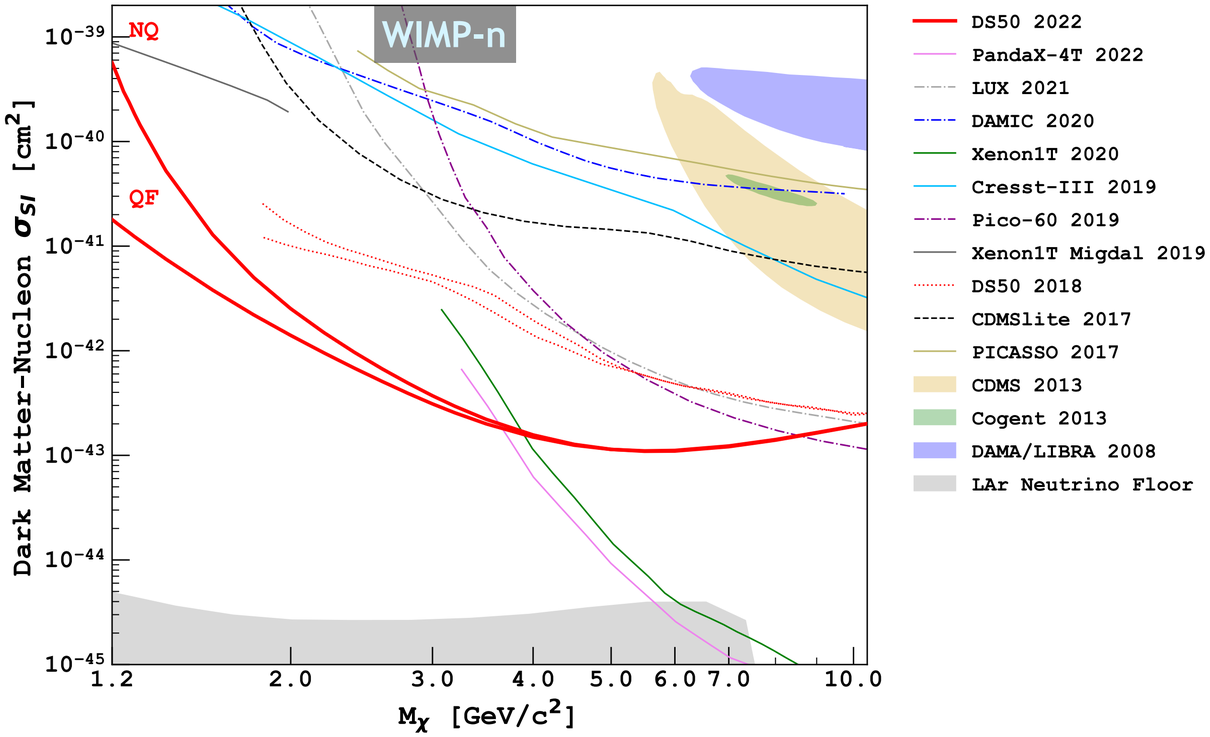


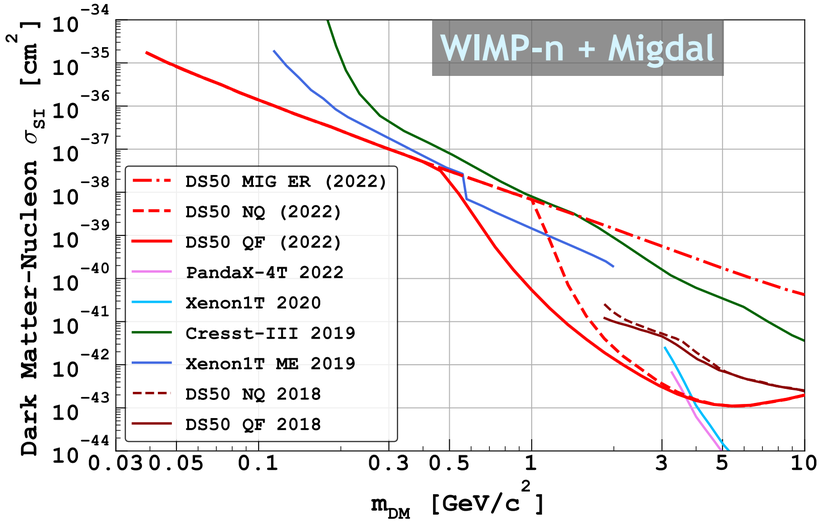
Phys.Rev.D 104 (2021) 8, 082005

- Scintillation (S1)
  - Detection efficiency (g1) ~ 16%
- Ionization (S2)
  - Efficiency to extract 1 e- in the gas pocket ~ 100%
  - Amplification factor (g2) = ~23 pe / e-



Sensitivity to light dark matter

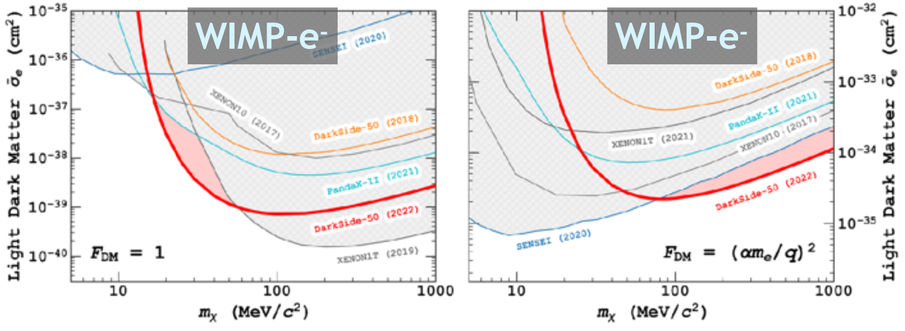


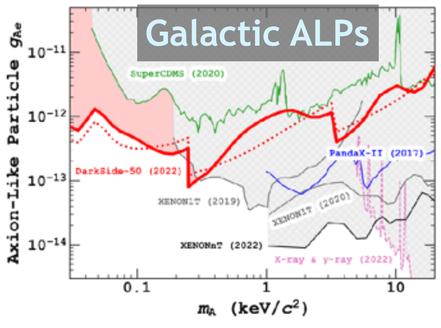


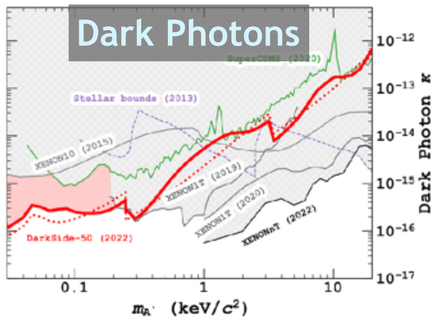
DarkSide-50, Phys. Rev. D 107 (2023) 063001

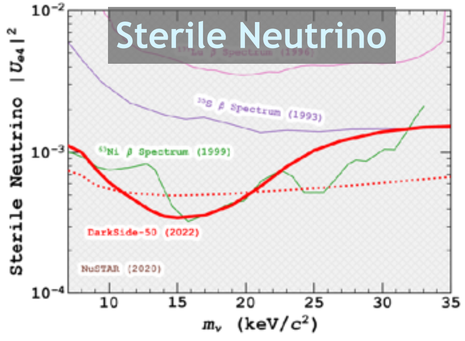
DarkSide-50, Phys. Rev. Lett. 130 (2023) 101002

DarkSide-50, Phys. Rev. Lett. 130 (2023) 101001



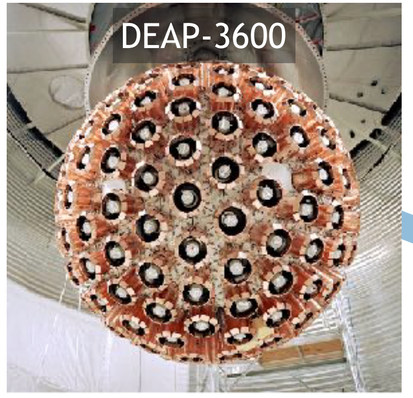


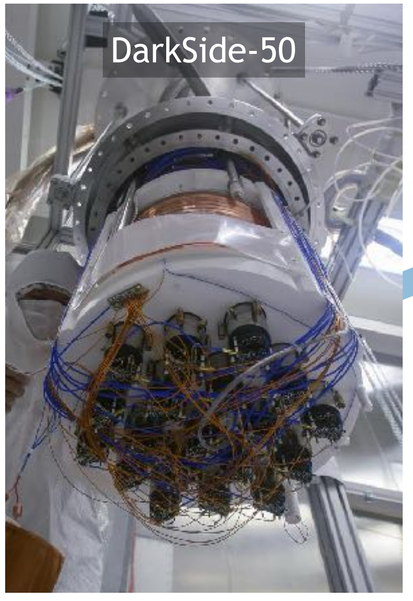




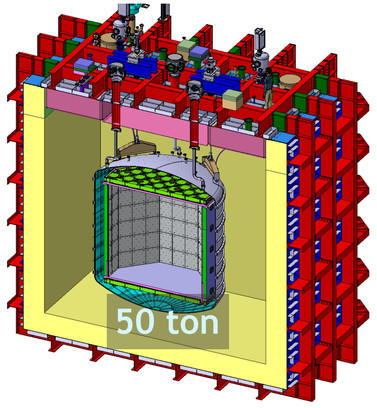
The Global Argon Dark Matter Collaboration

Combined expertise from four LAr experiments to explore dark matter to the neutrino floor and beyond

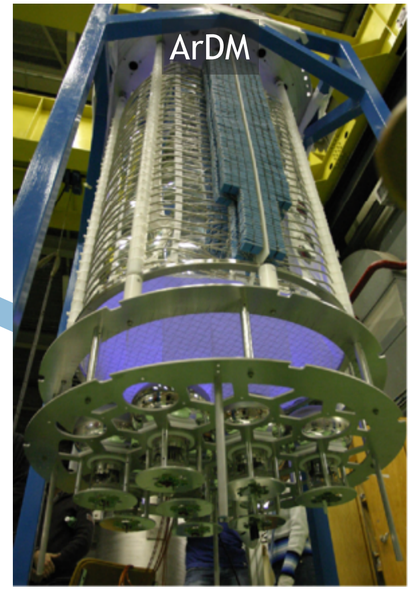




DarkSide-20k



ARGO

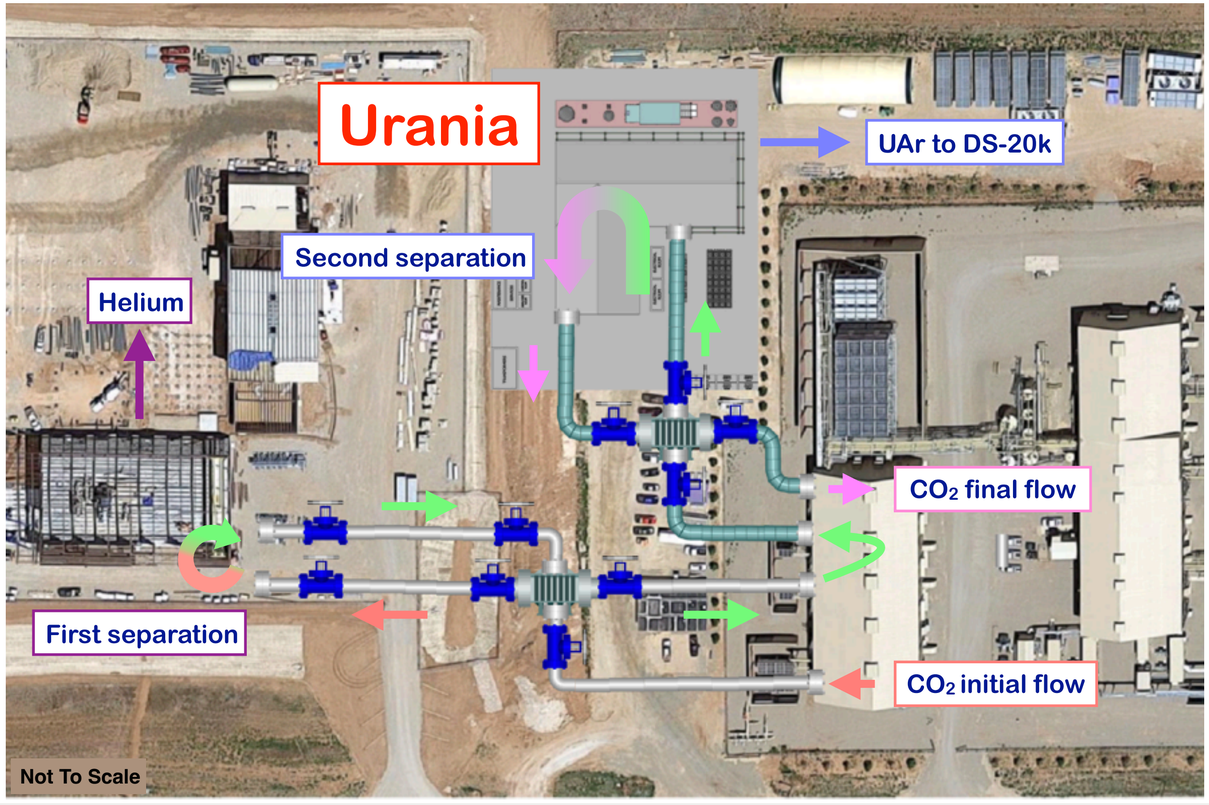


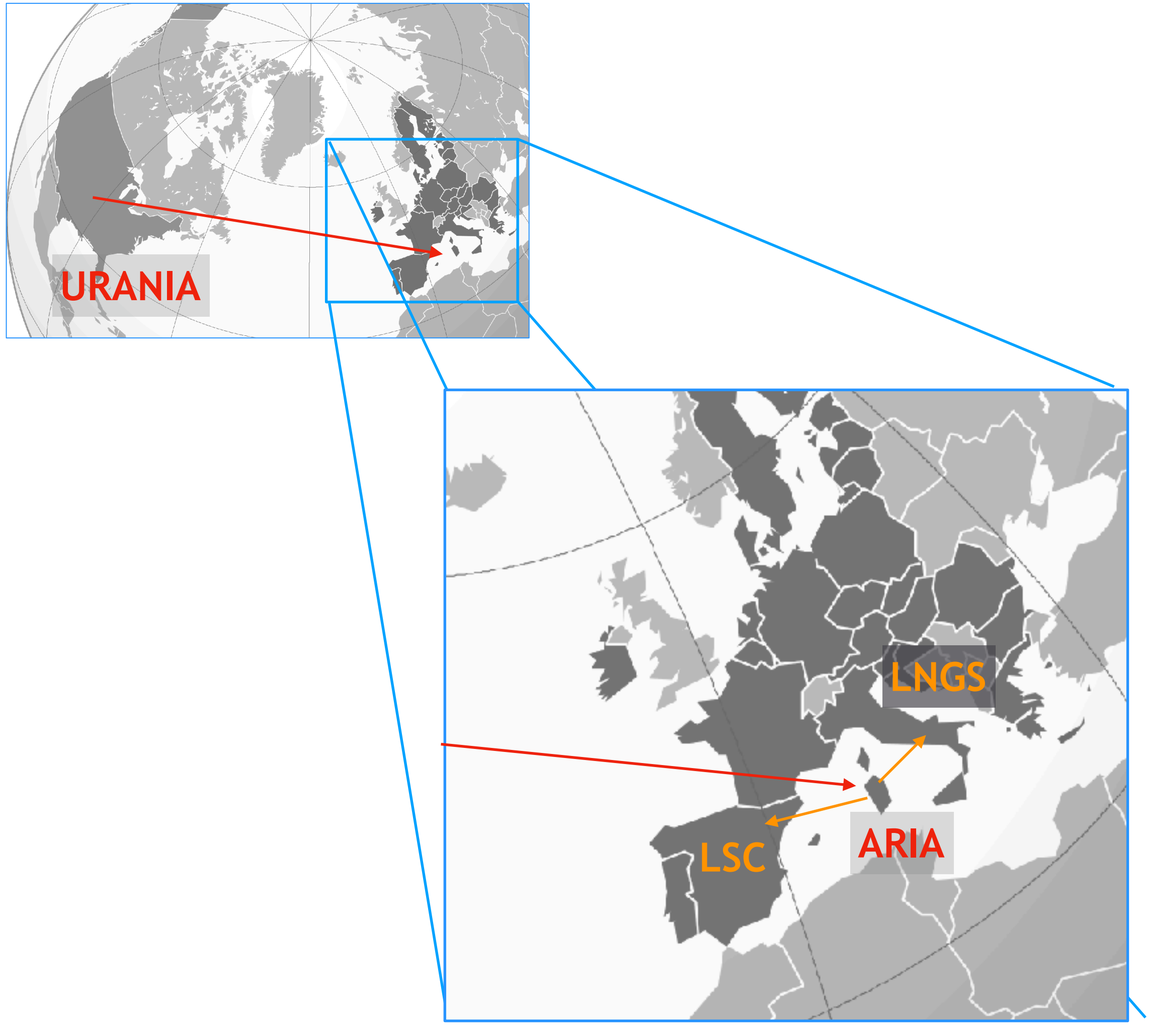
The Underground Argon

Extraction with Urania

Expansion of the industrial scale plant in Cortez, to reach capacity of **250 kg/day** of Underground Argon

Initial purity: 99.99%





The Underground Argon

Purification with ARIA

~350 m distillation column in Seruci mine (Sardinia)

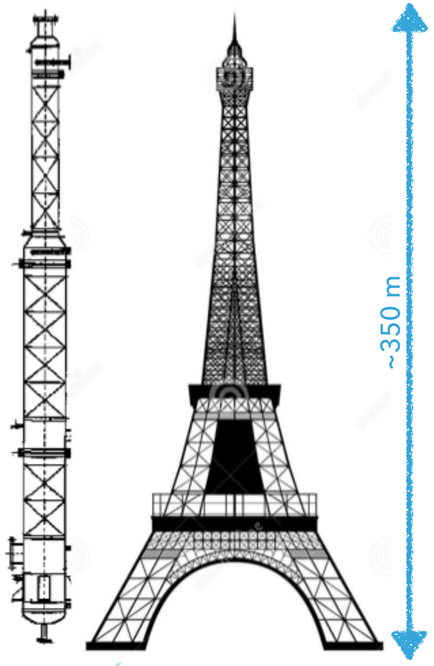
Process O (1 tonne / day) with 10^3 reduction of all chemical impurities

x10 $^{39}Ar/^{40}Ar$ reduction at the rate of 10 kg/day

The demonstrator column (26 m) successfully tested in 2019 with LN2 and in 2021 with argon

Isotopic separation of Ar-36, Ar-38, and Ar-40 has been demonstrated.

Successful test installation of the first module (of 28 central ones) in the mine shaft



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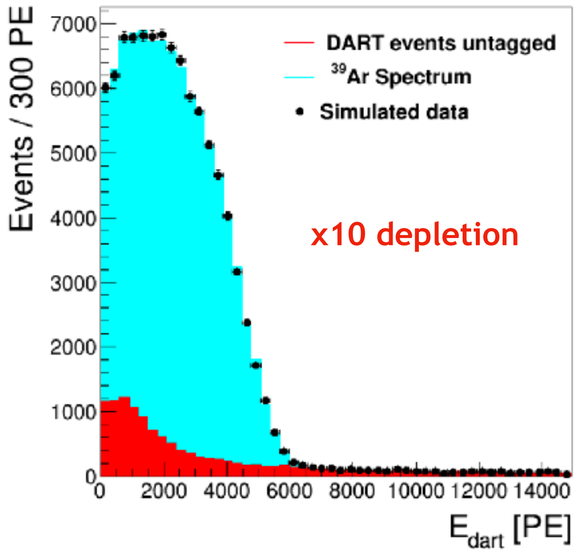
The Underground Argon

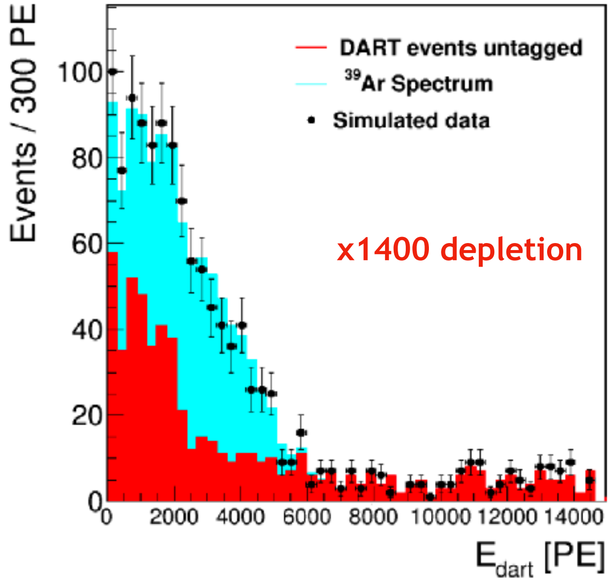
Assay with DArT

Single phase low-background detector to measure the 39Ar depletion factor of different underground argon batches.

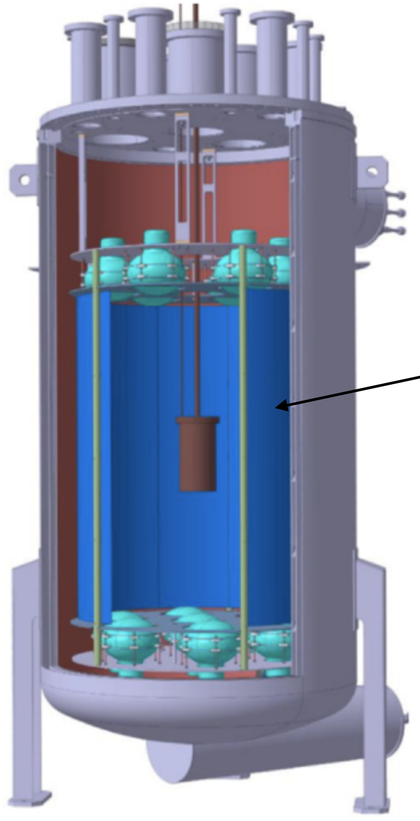
To be installed inside the ArDM apparatus (Canfranc Laboratory, Spain) filled with LAr (850 kg AAr) used as active veto.

Sensitivity to the depletion factor of 1,000 with 10% precision with 7 days exposure.



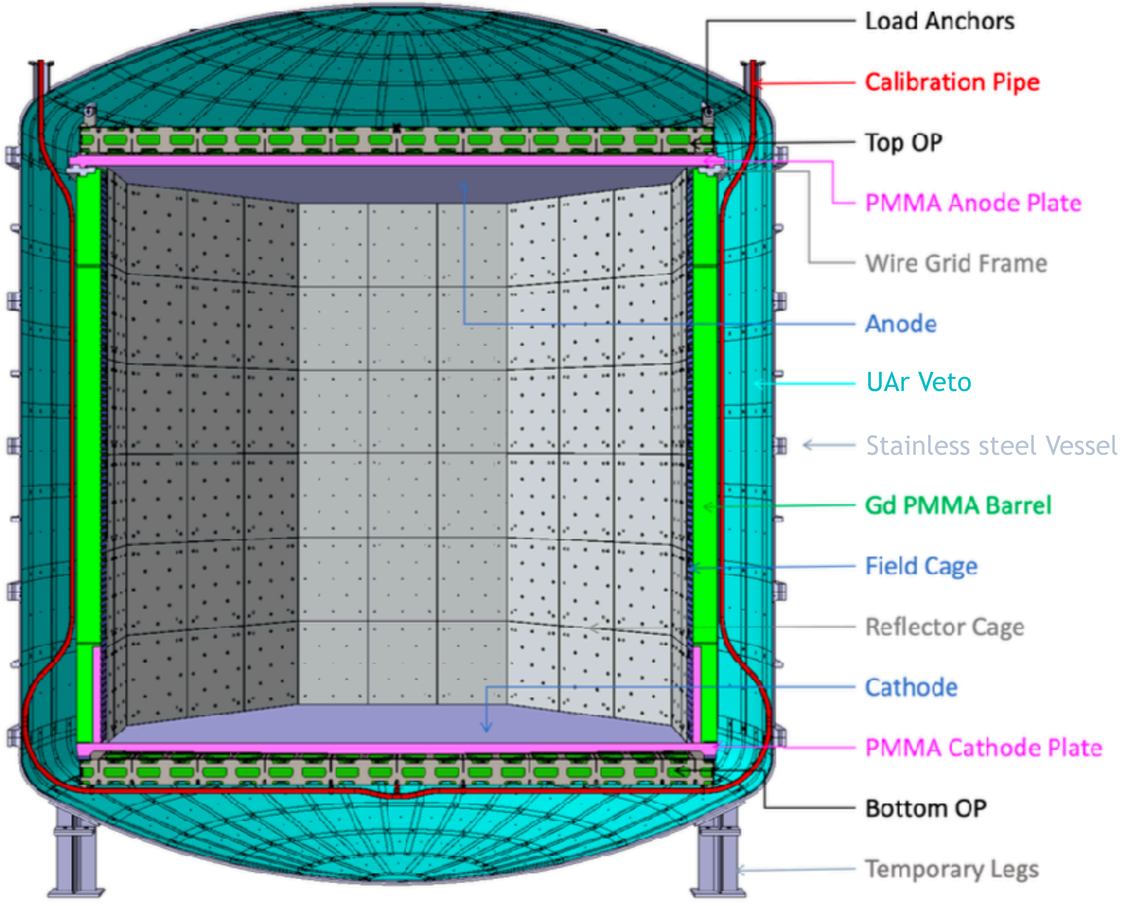


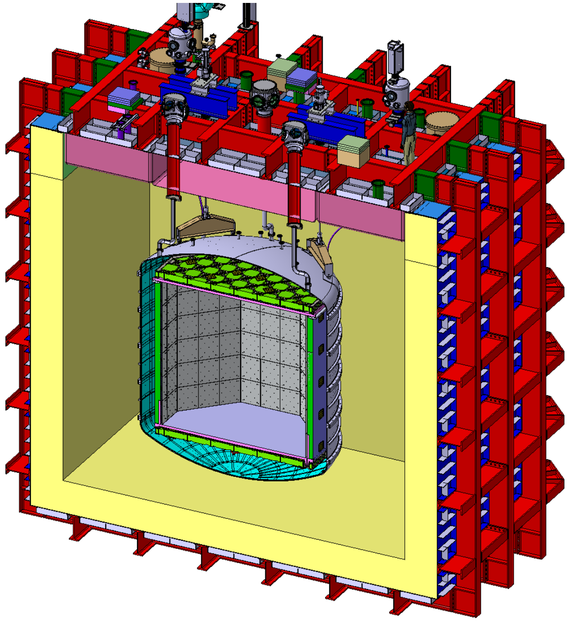
Simulation with 1 week exposure

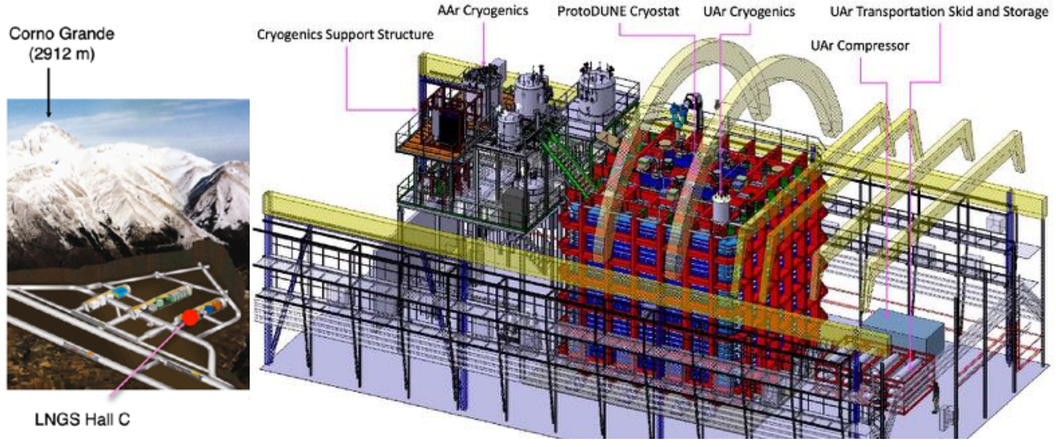


ArDM: anti-coincidence looking at Compton scatterings

The DarkSide-20k Detector

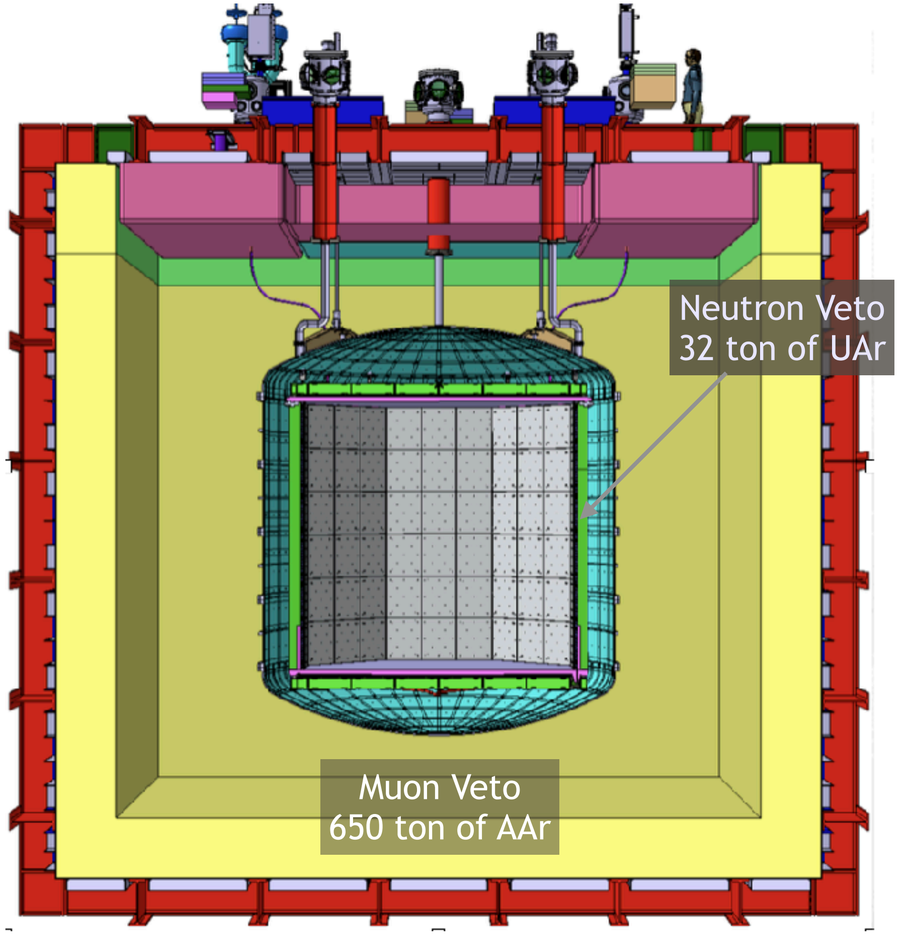




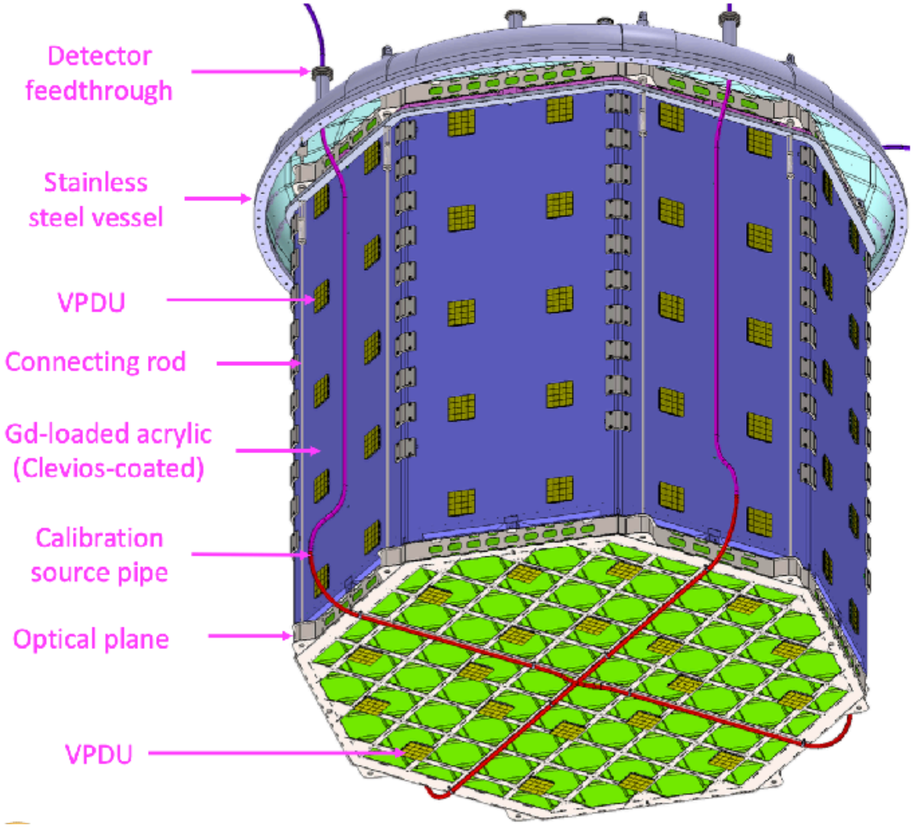


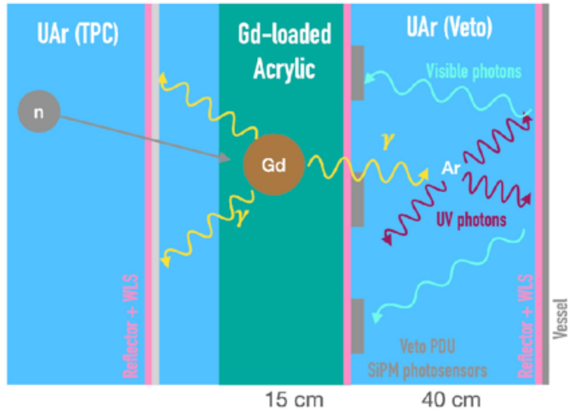
The Muon and Neutron Vetoes

Muon Veto



Neutron Veto





https://doi.org/10.48550/arXiv.2404.18492

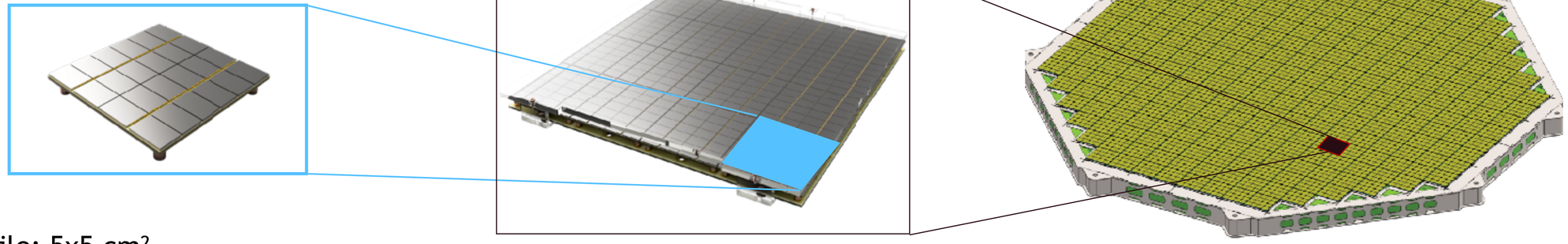
The PhotoDetection

TPC

- Two optical planes
- ~21 m^2 in total
- ~100% coverage of cryogenic SiPMs
- 2112 channels to achieve ~ 1 cm xy resolution
- Transparent anode and cathode
- ESR reflector on lateral walls
- Internal surfaces evaporated with TPB

Inner and outer veto

- Same SiPM technology
- 512 (5 m^2) +128 (1 m^2) channels respectively



- Tile: 5x5 cm^2
- 24 SiPMs directly mounted on a FEB
- NUV-HD-CRYO developed by FBK and produced by LFoundry

- PDU: 20x20 cm^2
- 16 Tiles Assembled on a Motherboard
- 4 readout Channel

- Optical planes: ~2x10 m^2
- Total PDUs used (TPC): 528
- Readout Channels: 2112

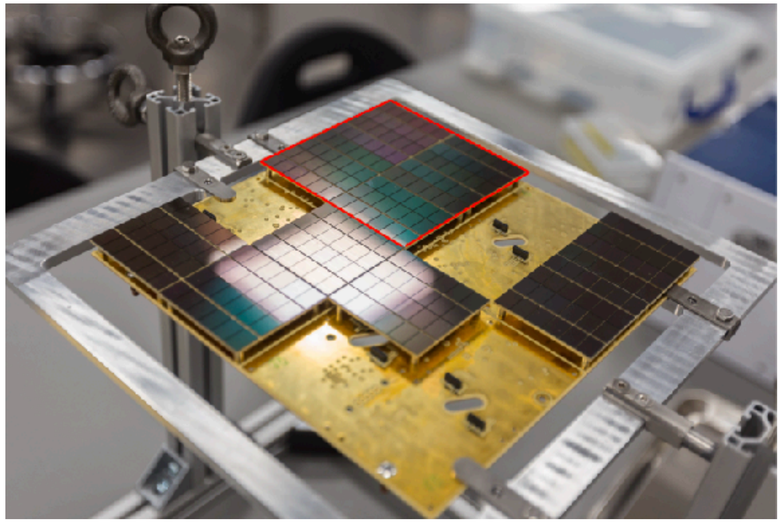
SiPM Packaging, Test, and Integration

NOA (Nuova Officina Assergi)

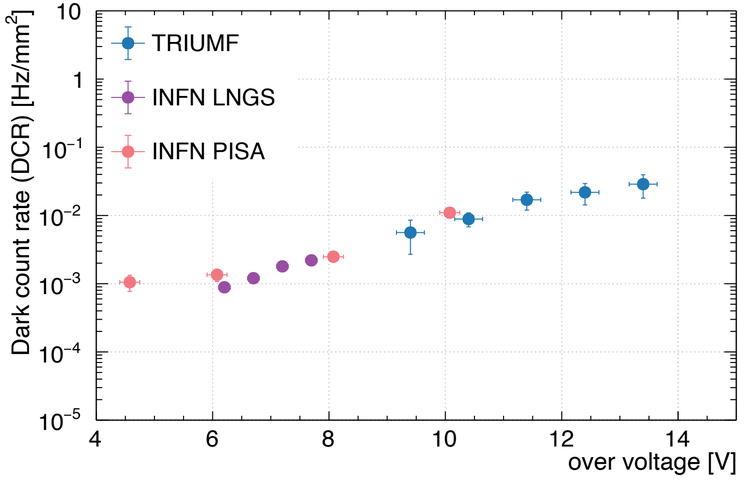
- INFN Facility managed by LNGS – clean room class ISO 6
- Two main rooms:
  - CR3: 3.0 m x 350 m^2 -> photodetector production area, equipped with highly sophisticated packaging machines for the assembly of photosensors in a dust-controlled environment
  - CR2: 5.8 m x 68 m^2 -> large volume detector assembly
- Equipped with dedicated Rn-abatement system (currently, Rn level in CR3: 6-10 Bq/m^3)
- Operative since Nov. 2022, completed in 2023
- 2023, so far: start-up of activities, characterization of silicon wafers procured for the in-house production of the PhotoDetector Units (PDU).

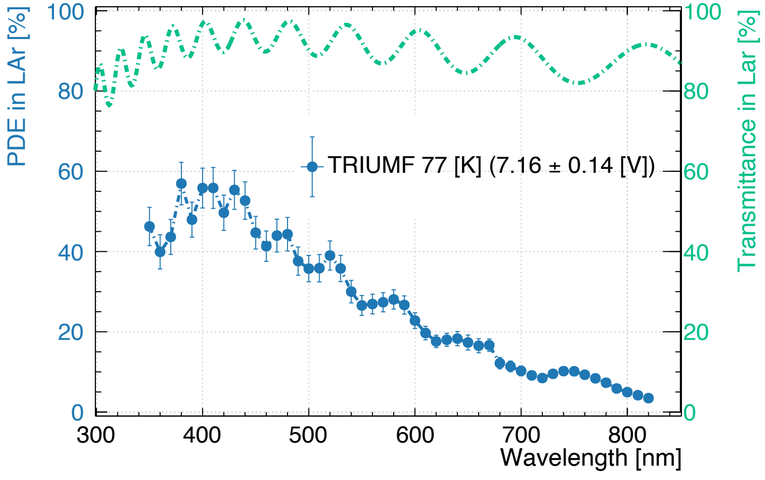
Plus several PDU test facilities in Naples, Lancaster, Birmingham, Liverpool, Warsaw

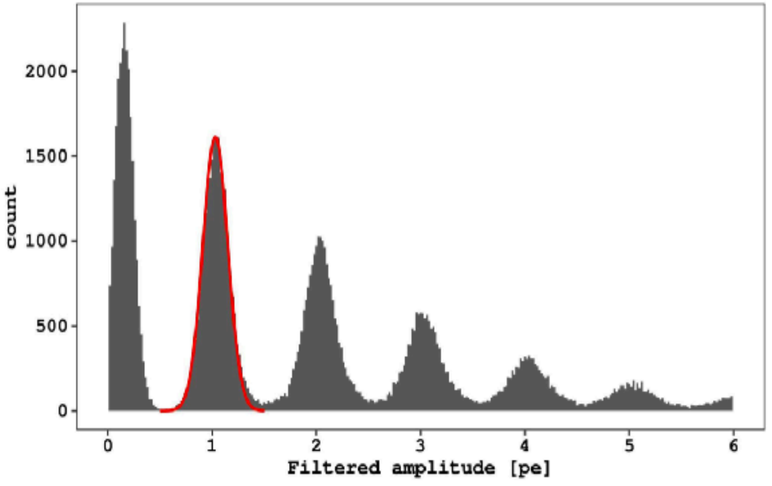
SiPM/PDU Performance



parameter	spec required	spec achieved
PDE @ 420 nm	> 40%	~50%
DCR (87 K)	250 Hz / tile	~20 Hz / tile
correlated noise probabilities (afterpulses, cross talk)	< 50% + 50%	<10% + 35%
SiPM gain	> 1E6	> 1E6
SNR after ARMA filter	> 8	> 8
time resolution	~ 10 ns	~15 ns







Trigger-less DAQ

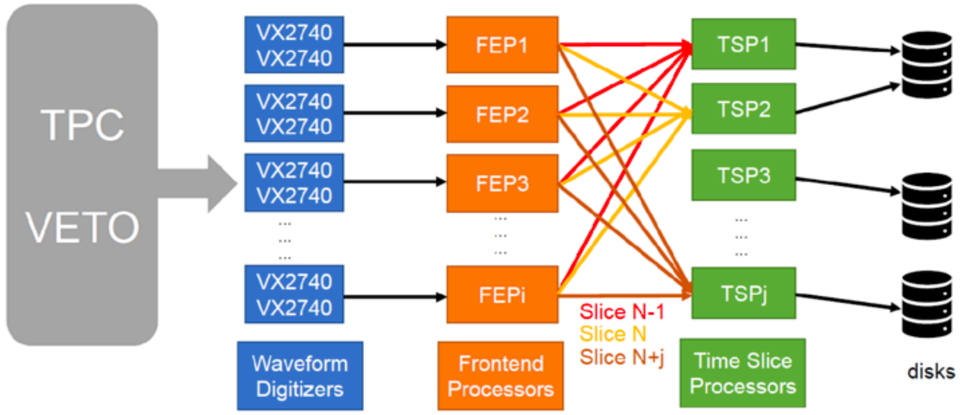
1) Identification of waveform (WF) segments containing a signal

2) WF segments from 64 digitizers are transferred to a Front-End Processor

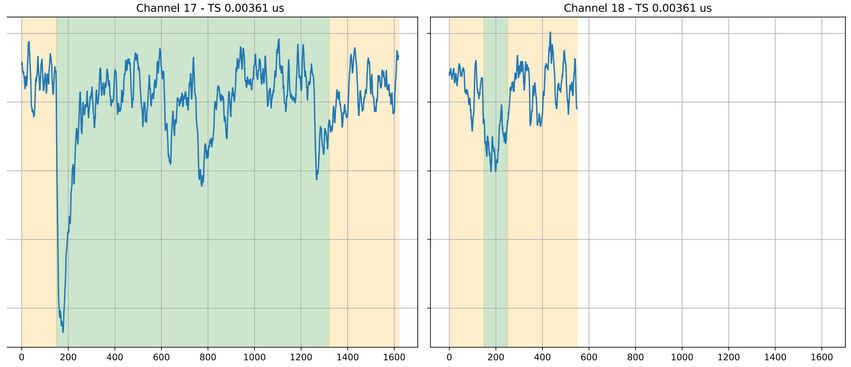
3) WF segments are filtered

4) Hit finder applied to each filtered WF segment

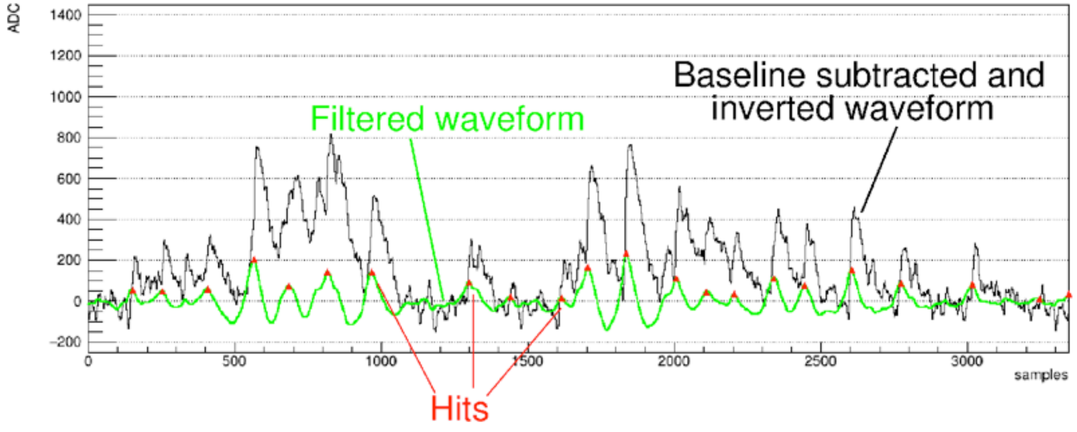
5) Hits are transferred to Time Slice Processors, processed to derive additional variables, and stored



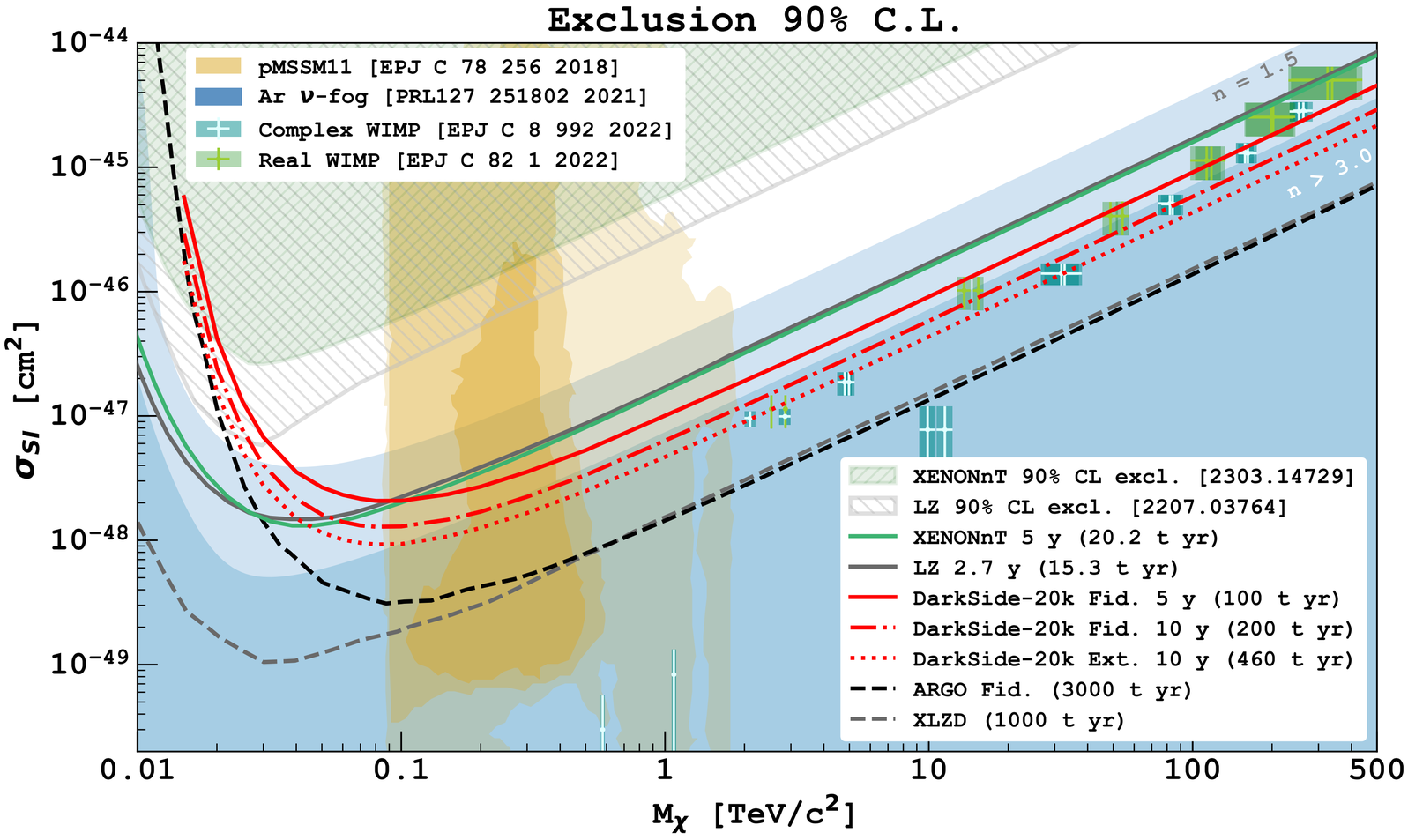
Identification of WF segments



Filtering at hit finder



Sensitivity to “high-mass” WIMPs

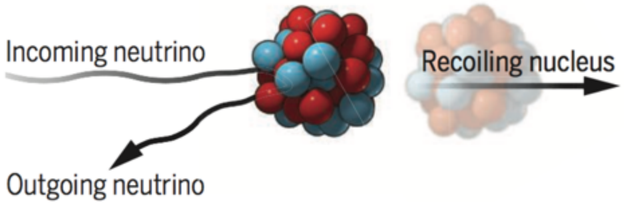


Sensitivity to light dark matter to be released soon!

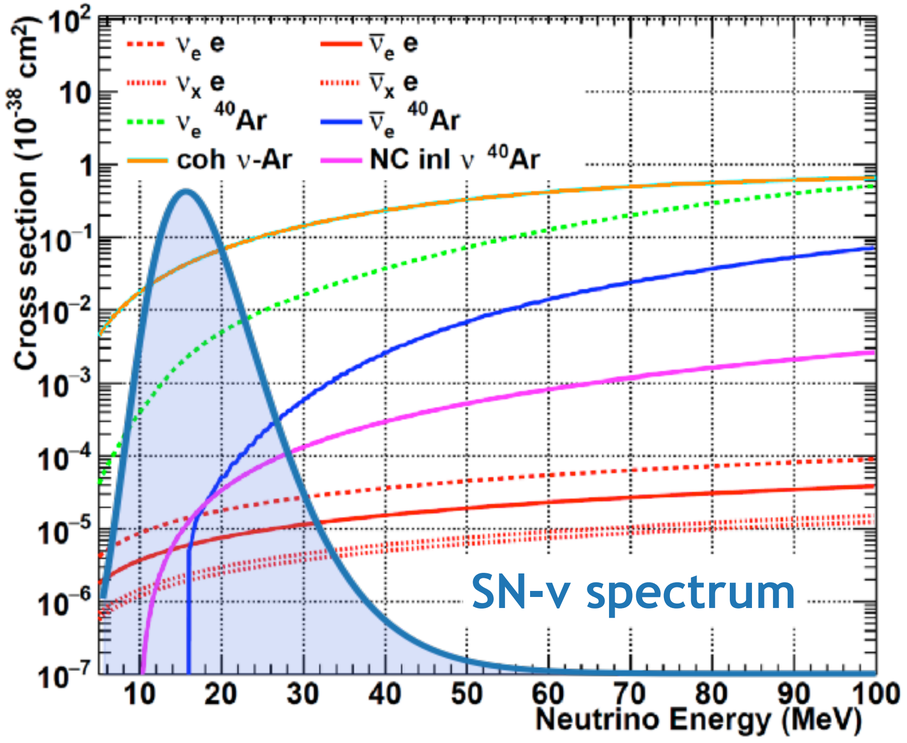
Supernova neutrinos via coherent scattering

CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

measured for the first time with the COHERENT CsI[Na] detector in 2017 (Science 357, 1123, 2017)



$$Q_W^2 = (N-(1-4\sin^2\theta_W)Z)^2 \approx N^2$$



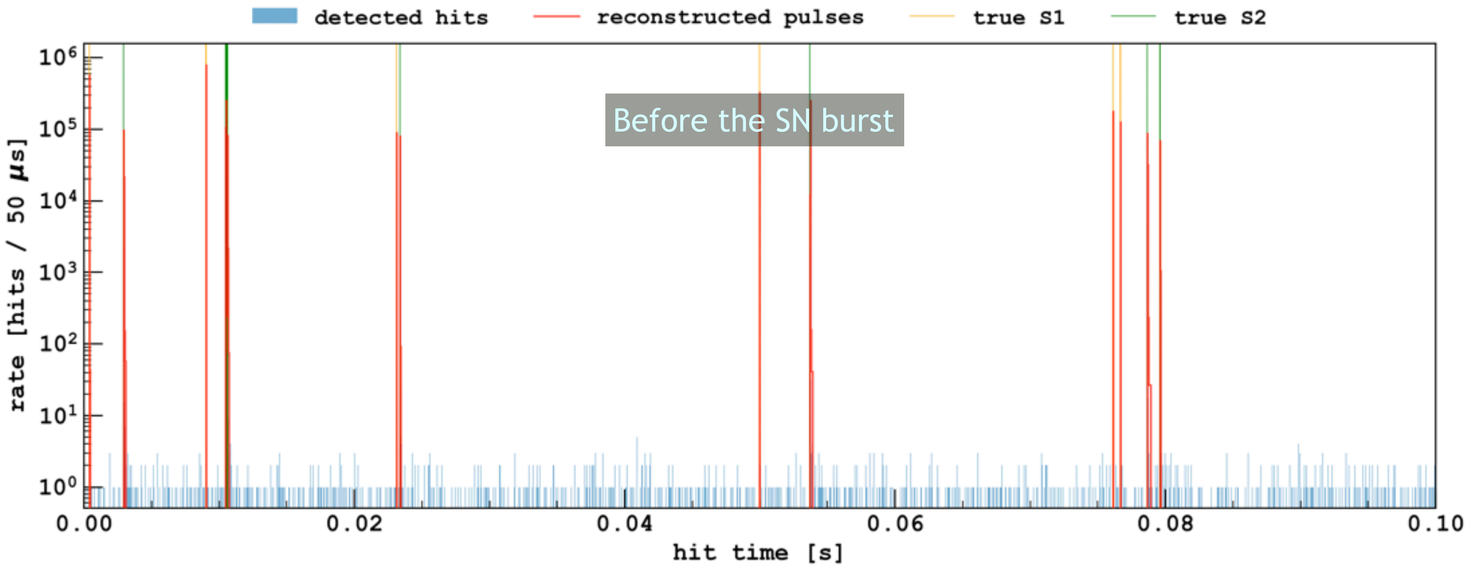
Advantages

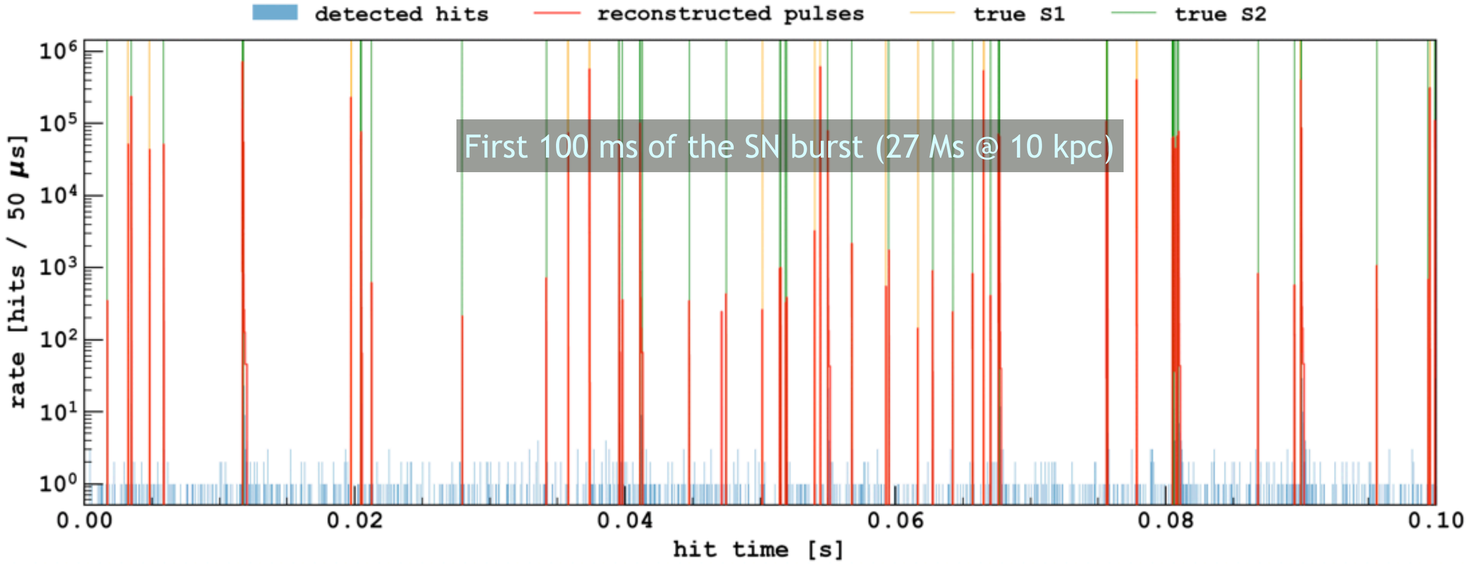
- highest **cross section** in the SN-ν energy range
  - "small" detectors become sensitive to SNs
- **Insensitive** to neutrino flavours
  - Measurement of the entire SN-ν flux
  - Sensitivity to the neutronization burst
  - Complementary to CC and ES from giant detectors

Disadvantages

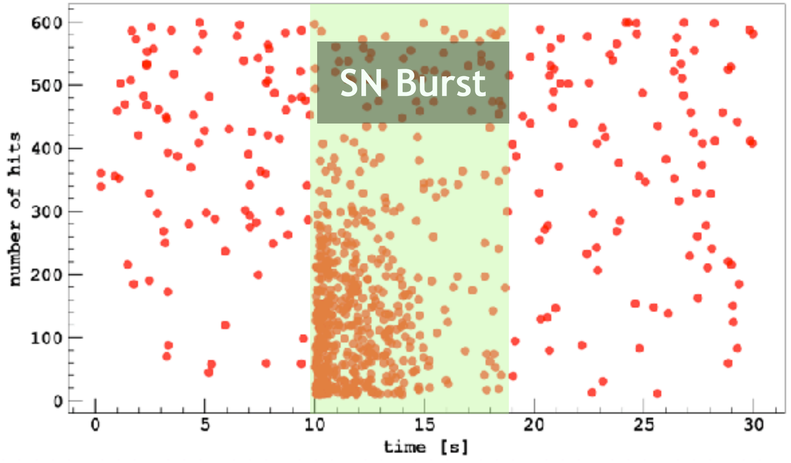
- **keV / sub-keV** recoils due to:
  - Kinematics
  - Nuclear recoil quenching
  - Electric-field induced quenching

SN burst in DarkSide-20k

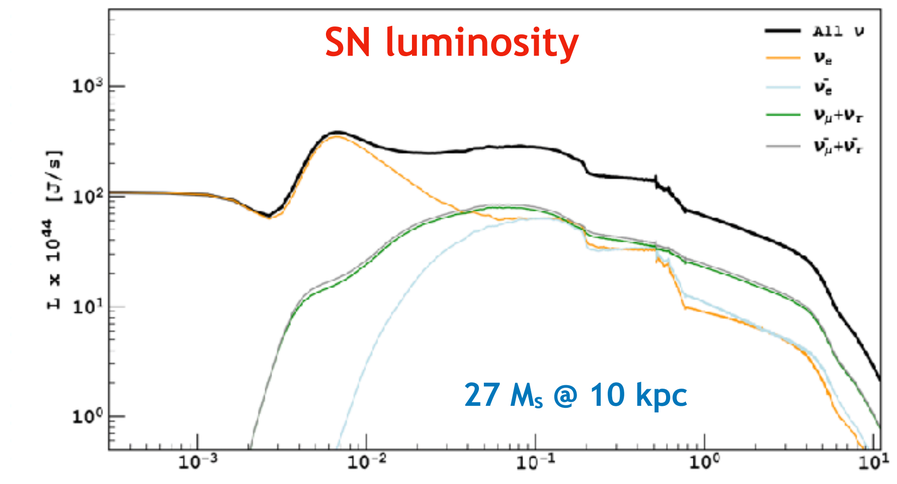


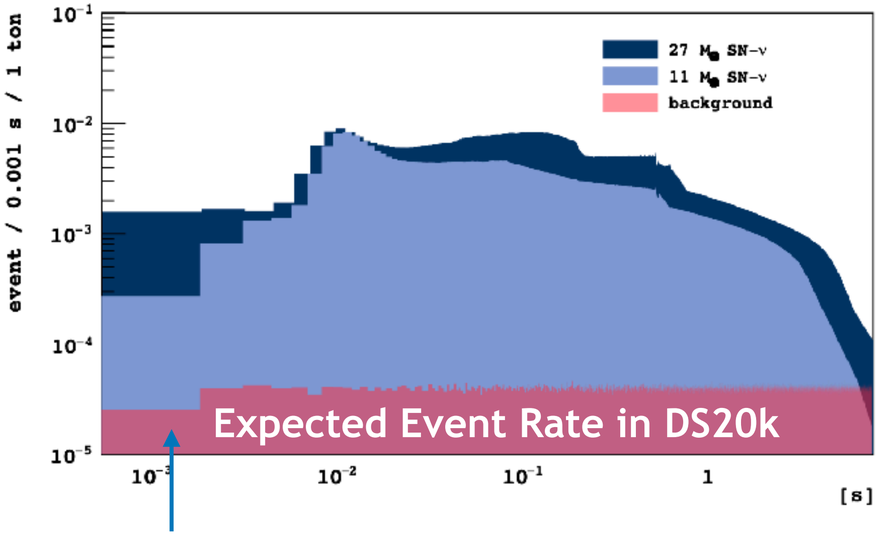


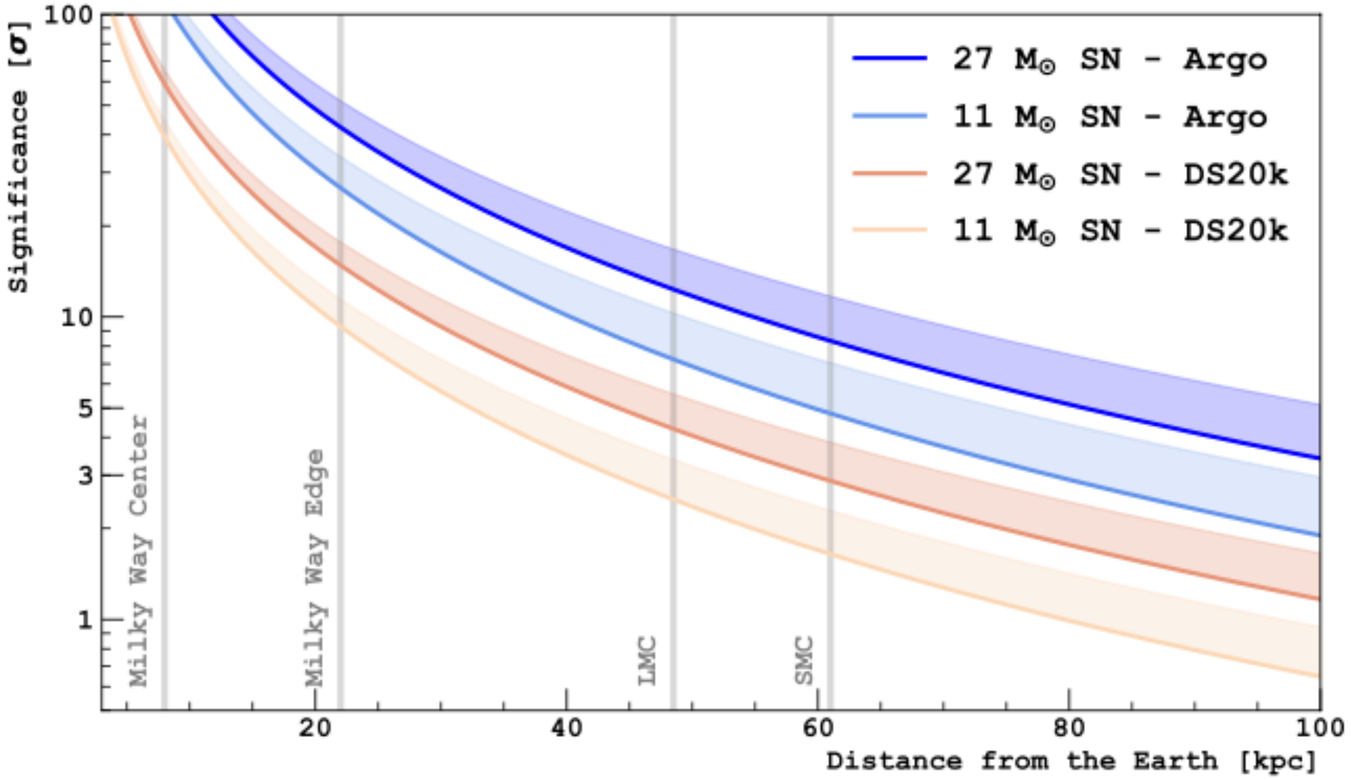
- Full radioactive background simulation from most recent screening material campaign
- Waveform simulation with realistic electronic noise
- Simulation of SiPM dark counts, after-pulses, and cross-talks
- Full DAQ emulation
- S1/S2 pulse finder / reconstruction (98% identification efficiency at 1 ionization electron)



Sensitivity to SN neutrinos







Event time resolution is dominated by the electron drift time

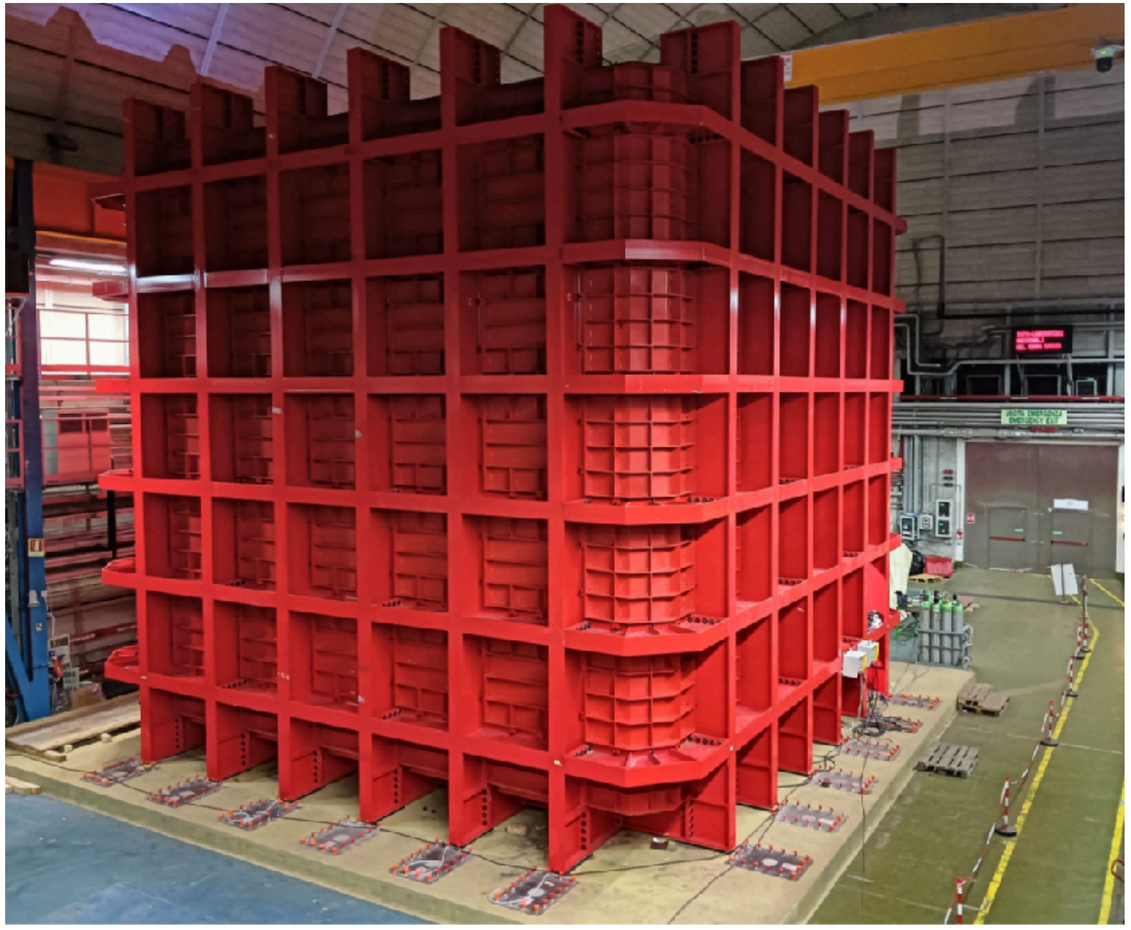
(maximum drift time ~ 3.5 ms)

Conclusions

- **Construction** of two-phase argon TPC with 50 t active mass (20 t fiducial mass) on going:
  - The **largest** dark matter detector ever built
  - Commissioning expected by end 2026

- High **sensitivity** to
  - high-mass WIMPs
  - light dark matter particles
  - core-collapse supernova neutrinos

- Custom **forefront technologies**, among which:
  - Very large array of cryogenic low-noise SiPMs
  - Underground-extracted argon
  - 350 m distillation column



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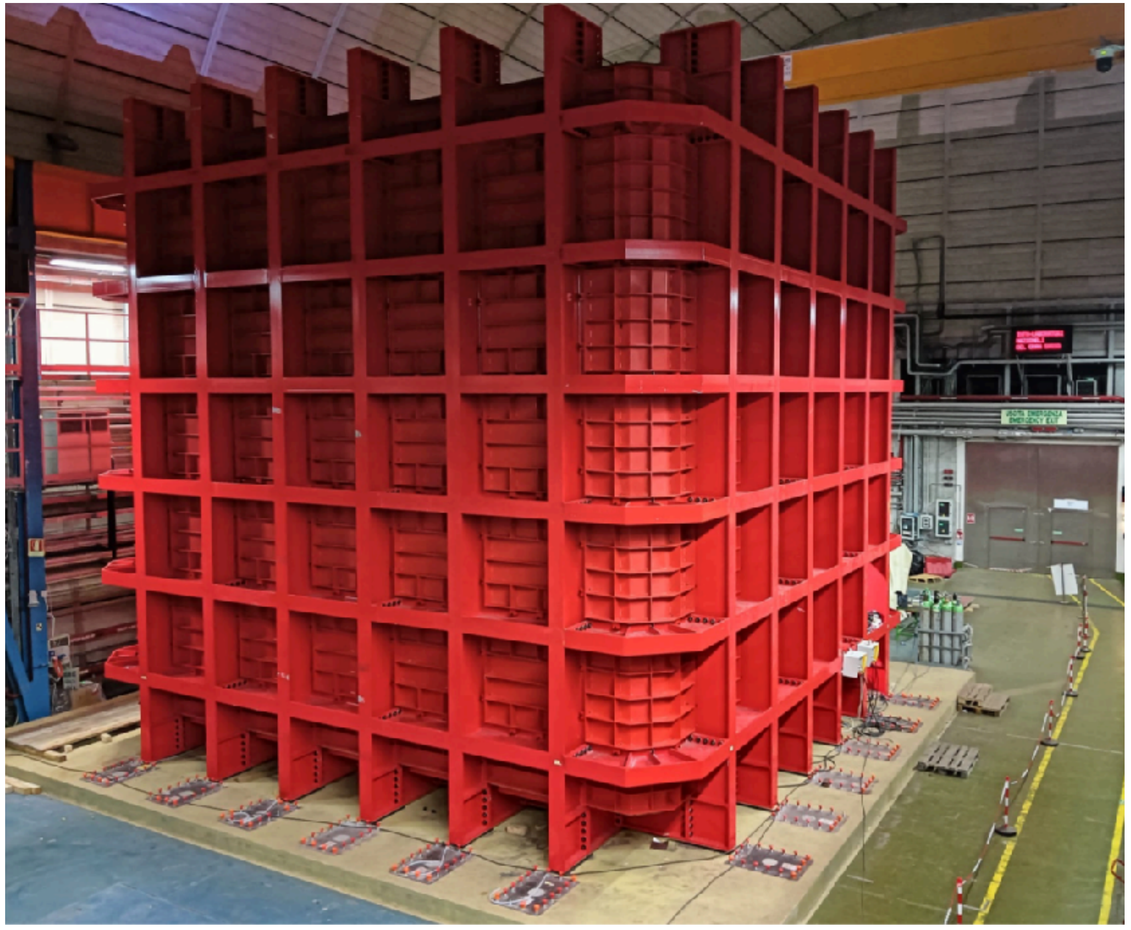

Thank You!