The DarkSide experimental program: dark-matter detection with liquid argon targets

20th Rencontres du Vietnam

July 7–13

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Sezione di Cagliari

Thursday July 11th 2024

ICISE

PASCOS 2024

Overview

1. The physics case
2. Principles of direct dark matter detection
3. DarkSide status and perspectives

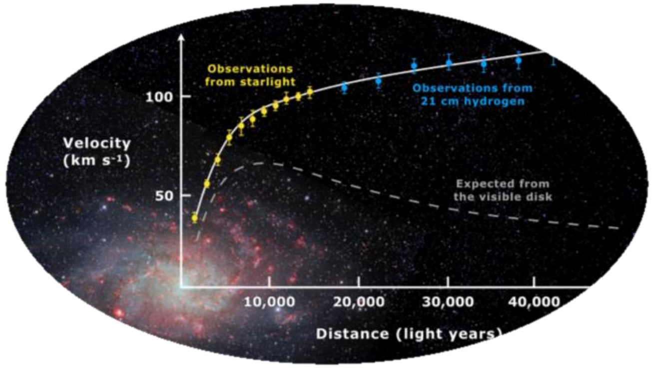
   - The experimental program of DarkSide-50
   - DarkSide-20k overview
   - Detector design and argon procurement
   - Sensitivity

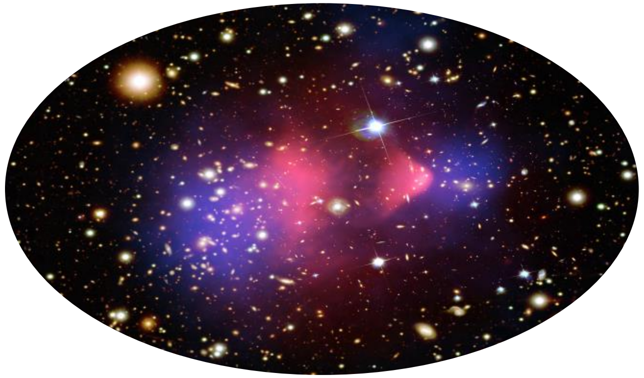
3. Conclusions

THE PHYSICS CASE

The evidence for the existence of Dark Matter (DM) is overwhelming, and it comes from a wide variety of astrophysical measurements, e.g.

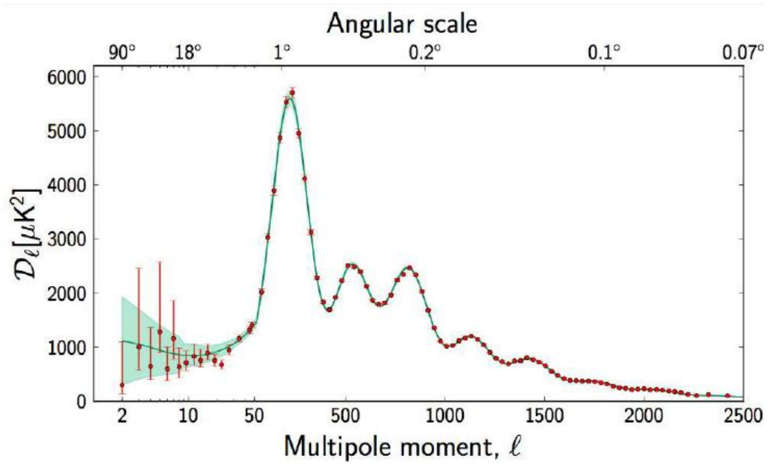
Velocity dispersion of spiral galaxies
1970s: Ford and Rubin discovered that galaxies rotation are flat. The simplest explanation is that **galaxies contain far more mass** than can be explained by the bright stellar objects in the galactic disks.





Bullet cluster and gravitational lensing
Lensing and optical observation of two galaxy clusters collision. The DM particles (blue) interacting only weakly could pass through each other more easily than the baryonic matter (pink).

Cosmic Microwave Background
CMB temperature anisotropy angular power spectrum seen by Planck, with the predictions for the best fit of the standard cosmological model parameters.



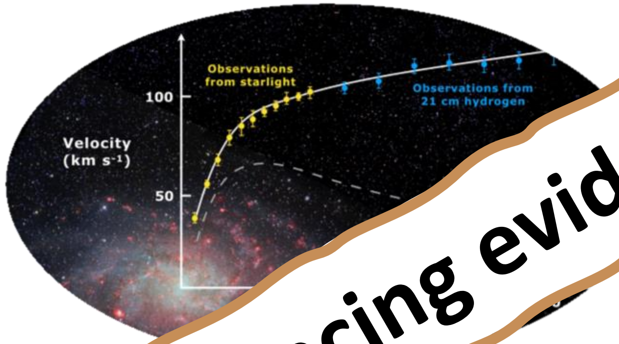
THE PHYSICS CASE

The evidence for the existence of Dark Matter (DM) is overwhelming, and it comes from a wide variety of astrophysical measurements, e.g.

Convincing evidences at different scales!

Velocity dispersion of spiral galaxies

1970s: Ford and Rubin discovered that galaxies rotation are flat. The simplest explanation is that **galaxies contain far more mass** than can be explained by the bright stellar objects in the galactic disks.



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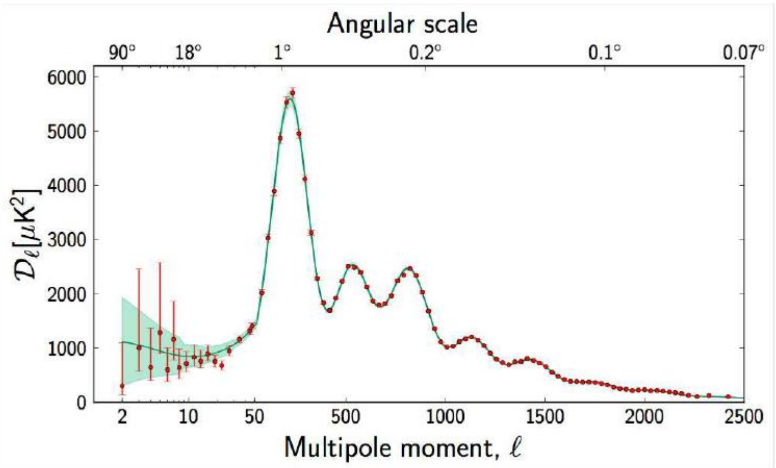
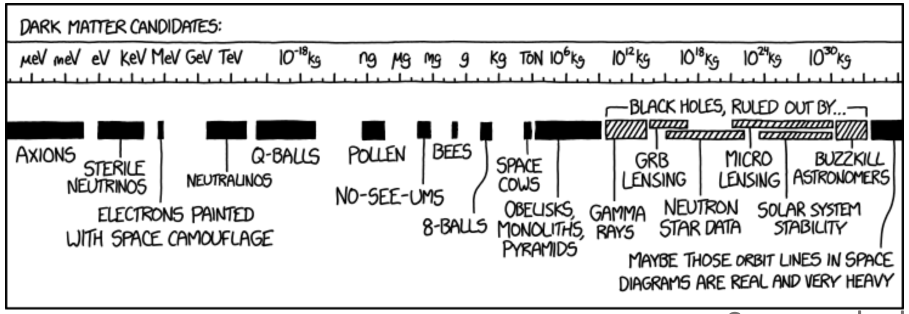
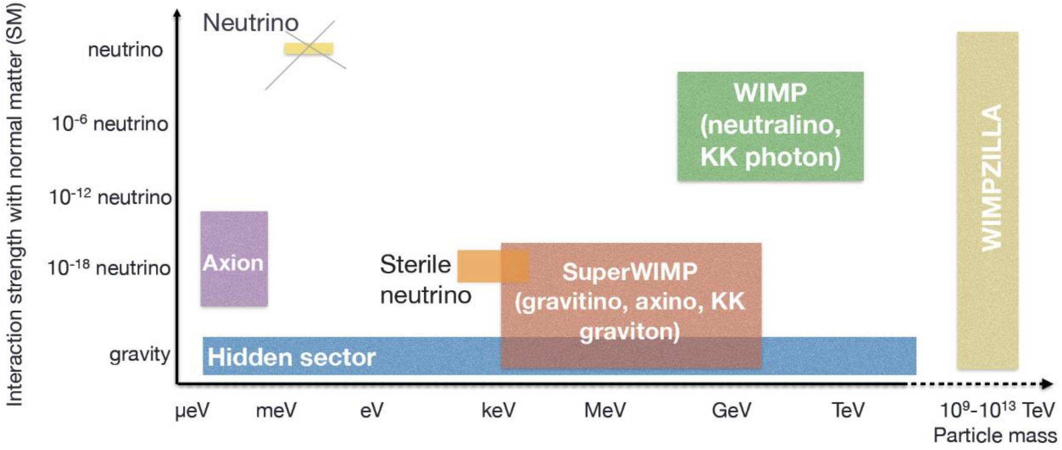


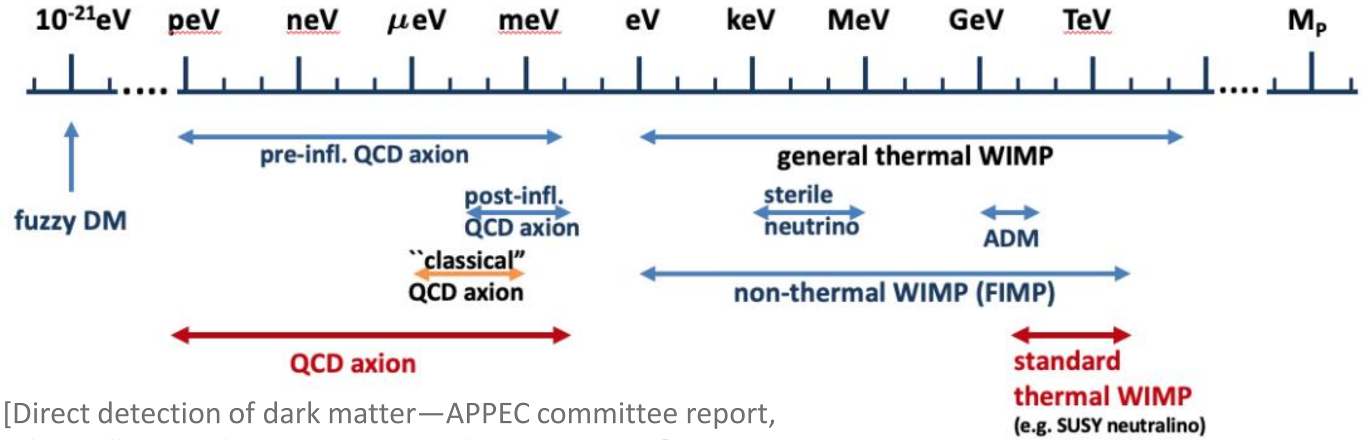
DM candidates



Source:xkcd



The most searched candidates are so-called Weakly Interacting Massive Particles (WIMP) that decoupled when non relativistic and are provided by many theories beyond the SM like SUSY

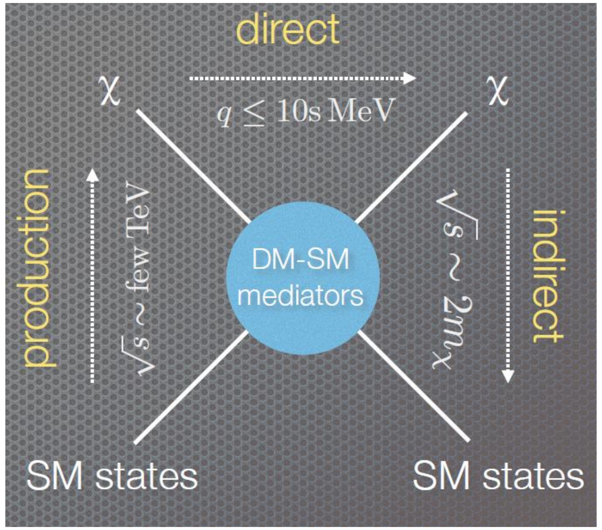


[Direct detection of dark matter—APPEC committee report, Julien Billard et al **2022** Rep. Prog. Phys. 85 056201]

Detection of Dark Matter

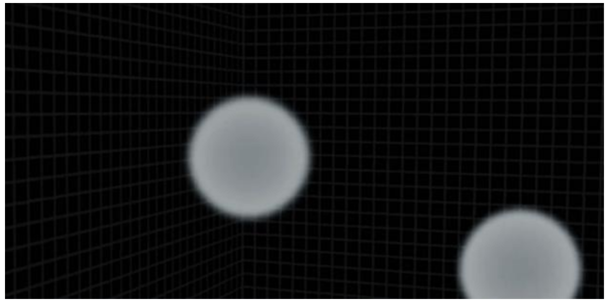
Accelerator searches

Missing ET, mono-'objects', etc…
Can it establish that the new particle is the DM?

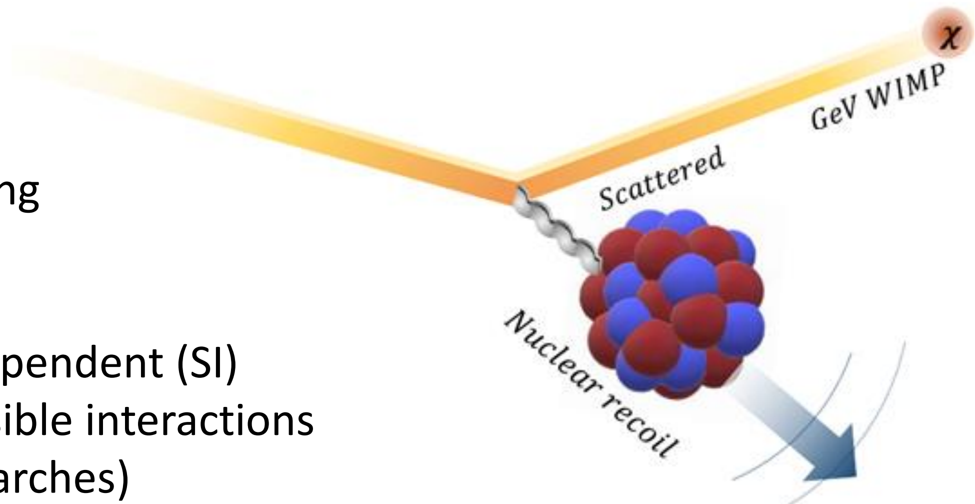


Indirect detection

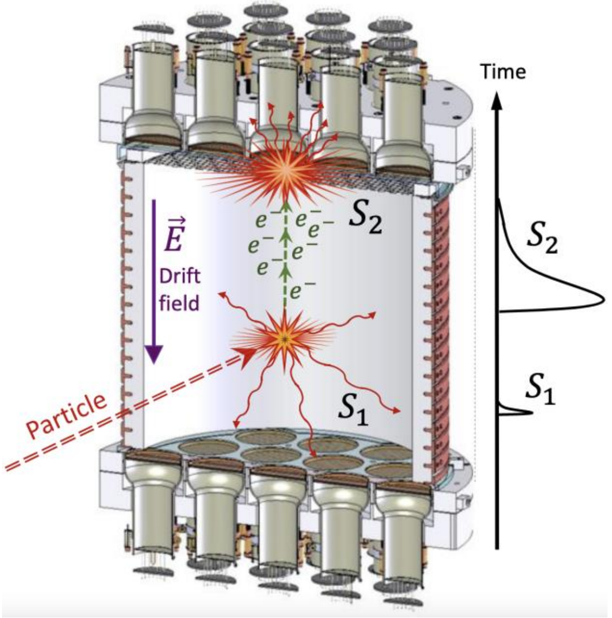
High-energy neutrinos, gammas
look at over-dense regions in the sky.
Astrophysics backgrounds difficult



Direct detection



- Nuclear recoils from elastic scattering
- Non relativistic
- Coherency: dependence on A.
- Spin-Dependent (SD) and Spin-Independent (SI)
- Mainly nuclear recoils but also possible interactions with electrons (Low mass WIMP searches)

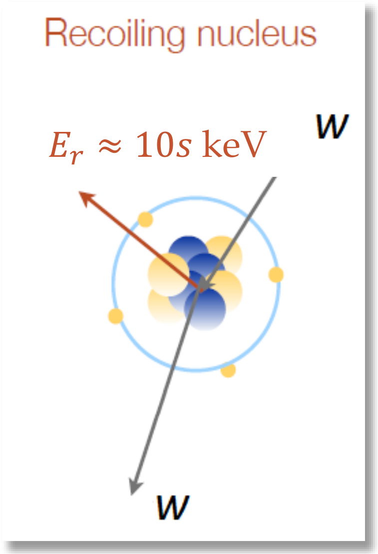


M. Cadeddu, The DarkSide experimental program, PASCOS 2024

The WIMP spectrum

$v_{min} = \sqrt{m_N E_R / (2\mu_{\chi N}^2)}$

Standard **recoil spectrum**, i.e. differential event rate **per unit detector** mass:



$$\frac{dR}{dE_R} \propto \frac{\sigma_{SI}^p}{2\,\mu_{\chi p}^2 M_\chi} A^2 |F(E_R)|^2 \rho_0 \int_{v_{min}}^{\infty} \frac{f_1(v)}{v} dv$$

Physics

σ_{SI}^p → WIMP-nucleon cross section

M_χ → WIMP mass

Target material

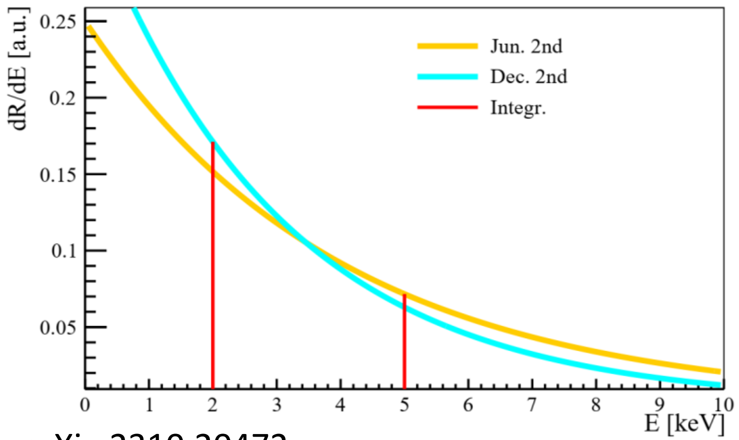
A → atomic mass of target
E_{th} → Energy threshold
$F(E_R)$ → The finite size of the nucleus is implemented with a nuclear **form Factor**

Astrophysics (DM halo)

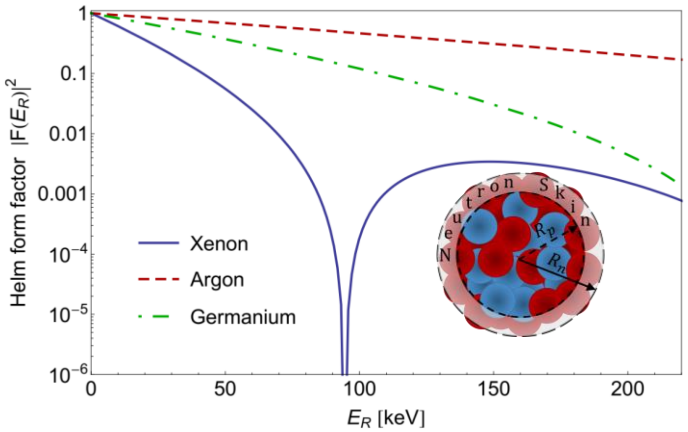
ρ_0 → local WIMP mass density

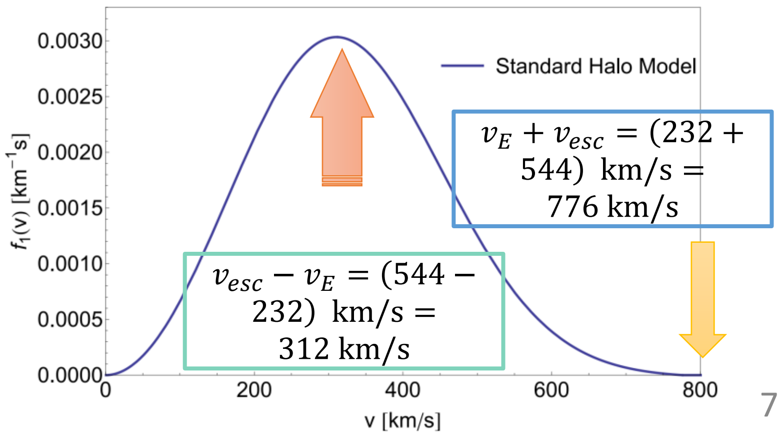
$f(v)$ → WIMP velocity distribution

v_{min} → minimum WIMP speed required to transfer an energy E_r

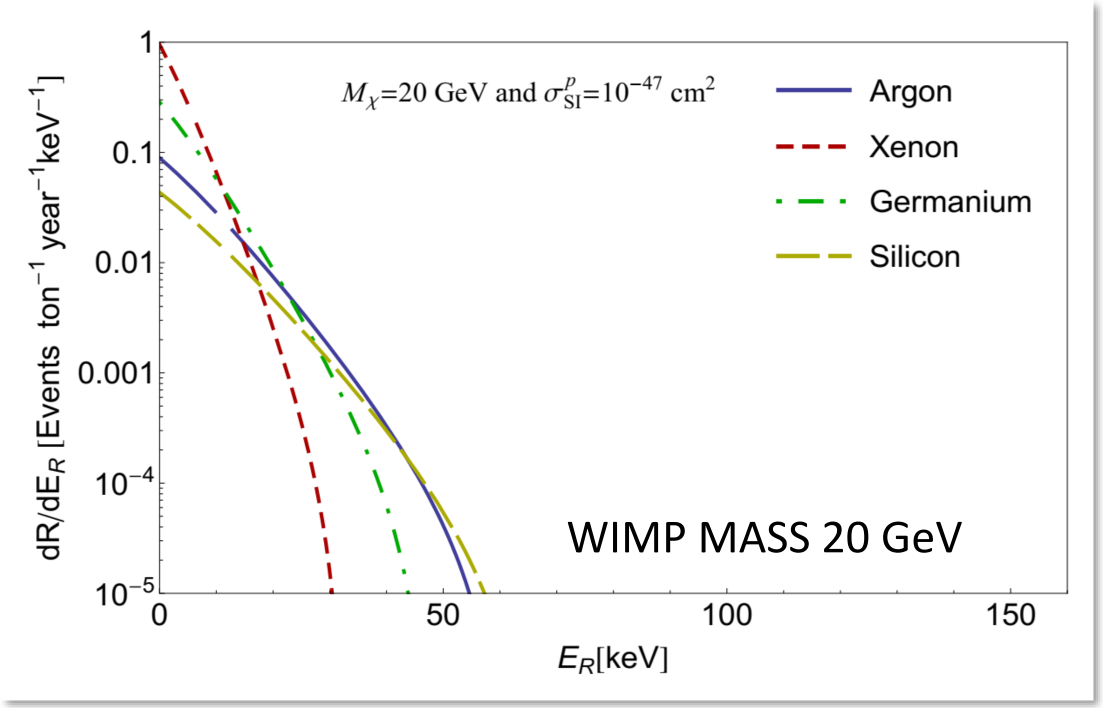


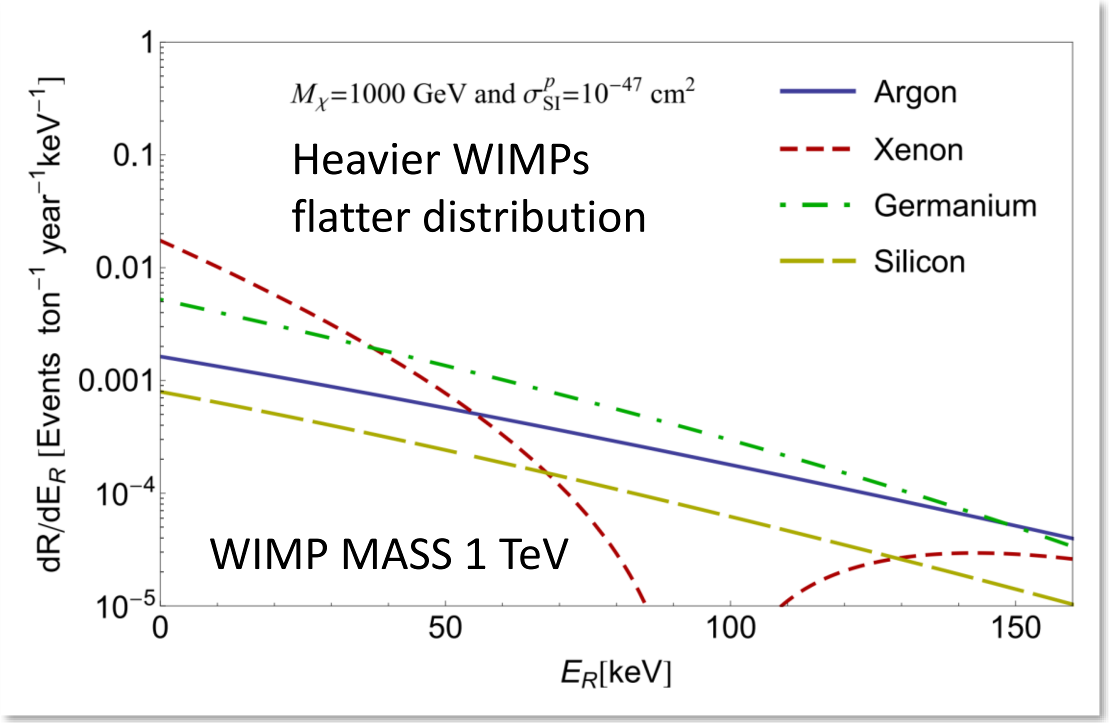
arXiv:2310.20472





Final WIMP spectra





In a real experiment there will be also a **nuclear recoil acceptance function**, $A(E_R)$, which takes into account all the backgrounds cuts, the WIMP signal selection efficiency and the experimental resolution.

The total number of WIMP events is then given by

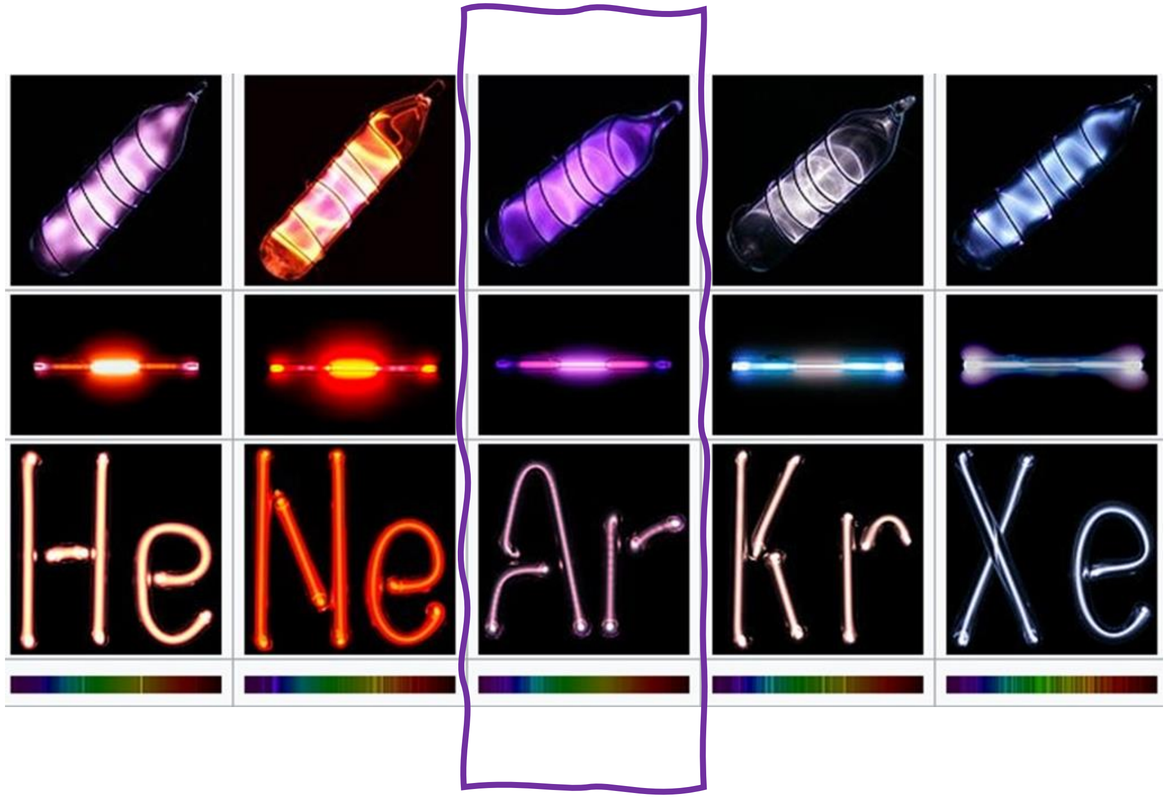
$$N_\chi = M\,T \int_{E_{th}}^{E_{up}} A(E_R) \frac{dR}{dE_R}\, dE_R$$

Experimental exposure [tonne x year]

Direct searches with liquid noble elements

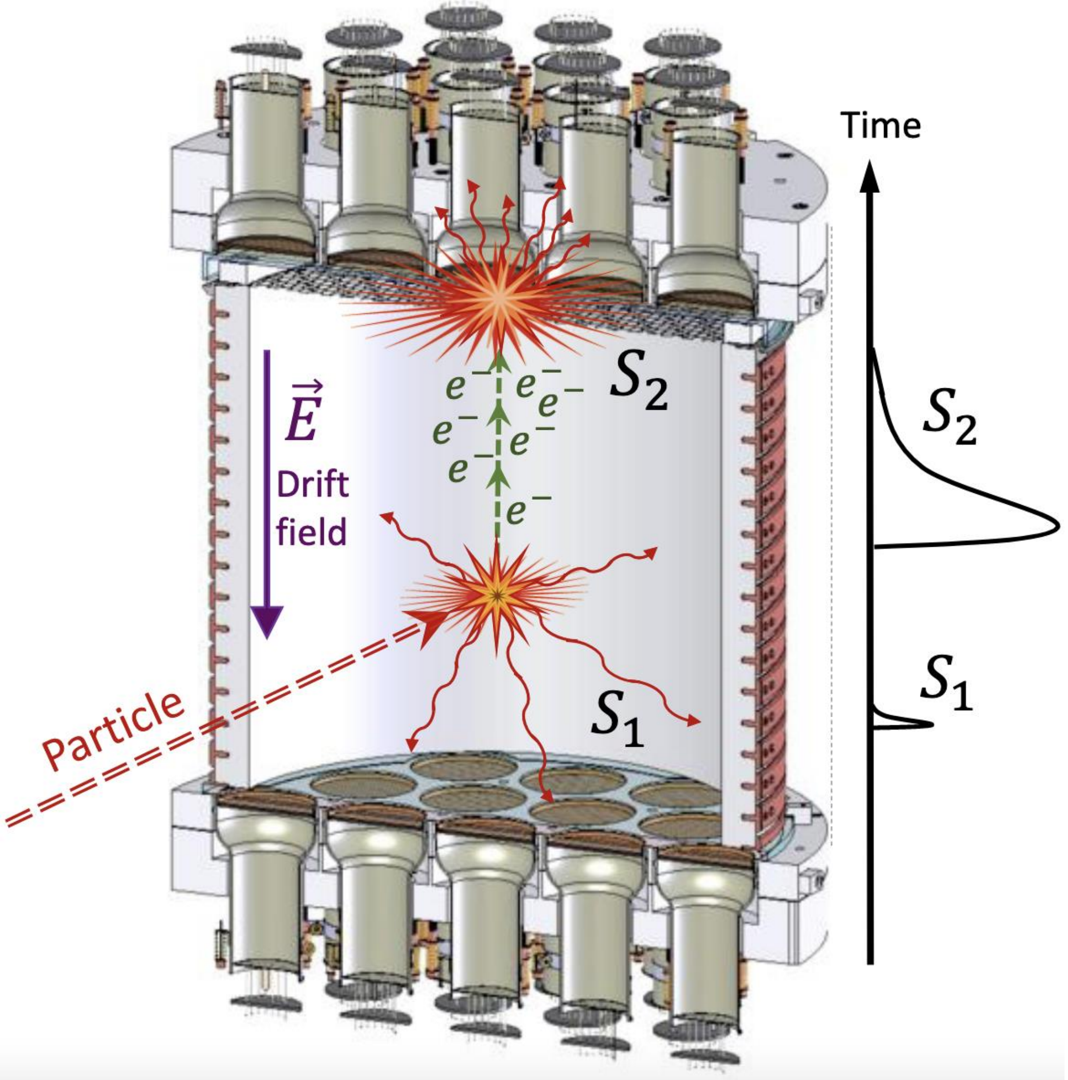
In this sector, liquid noble elements are commonly used:

- High density, inexpensive
  - Good scalability to large masses
- Easy to purify
- Large ionization/scintillation yields
- Low energy threshold (O(10 keV))
- Background suppression
  - Passive/active shielding
  - Low intrinsic radioactivity
  - ER background discrimination with Pulse Shape Discrimination (PSD) expecially in argon



Complementarity of different elements: great value in case of an excess

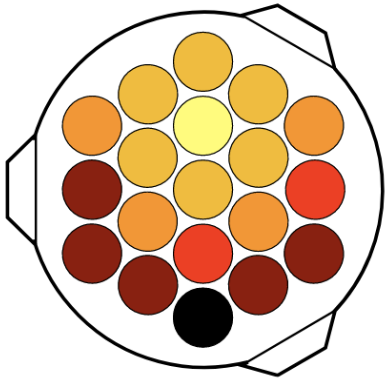
Dual-phase argon TPC: working principle



- Light collected by top and bottom photosensors

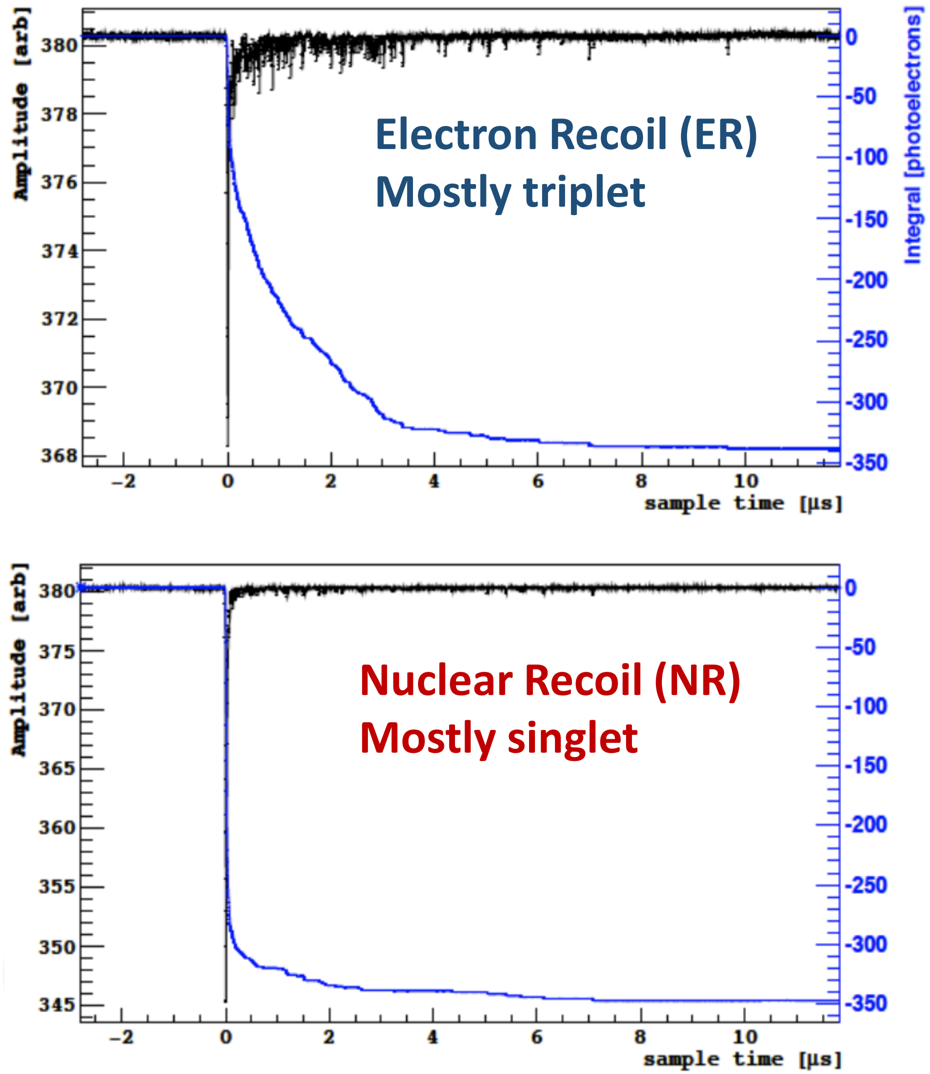
- **S1** = Primary scintillation in liquid Ar
- **S2** = Secondary electroluminescence in Ar gas pocket

- Event 3D reconstruction:
  - S1 & S2 → full energy deposition
  - Drift time ($t_{S_2} - t_{S_1}$) → vertical (z) position
  - S2 Channel top light pattern → xy position

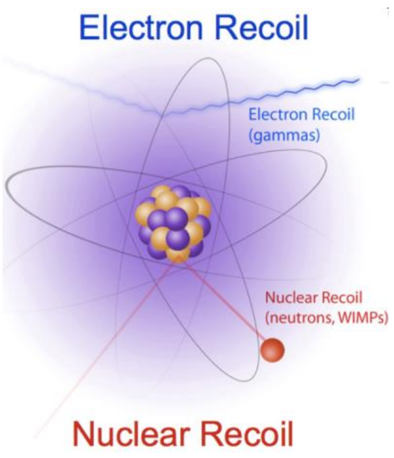


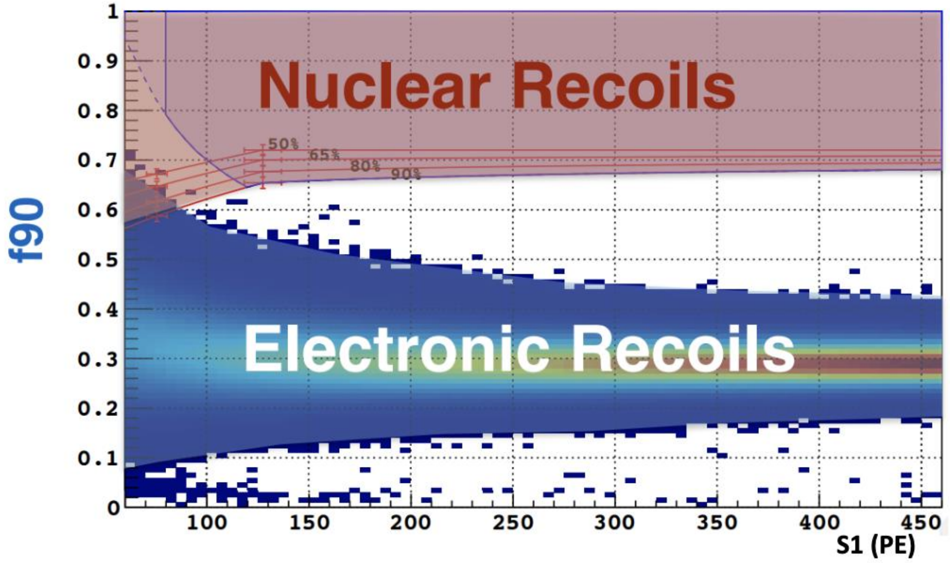
S2 light fraction

Pulse shape discrimination (PSD) in argon



- Argon scintillation has a fast component with a **7 ns decay time (singlet)**, or a slower component with **1.6 μs (triplet) decay time** depending on the nature of incident particle.
- NR produces more $\tau_{singlet}$ and less $\tau_{triplet}$ states than ER.
- ✓ f_{90} = the fraction of S1 light collected in the first 90 ns.
- ✓ f_{90} rejection better than $\sim 1.5 \times 10^7$ [10.1016/j.physletb.2015.03.012]





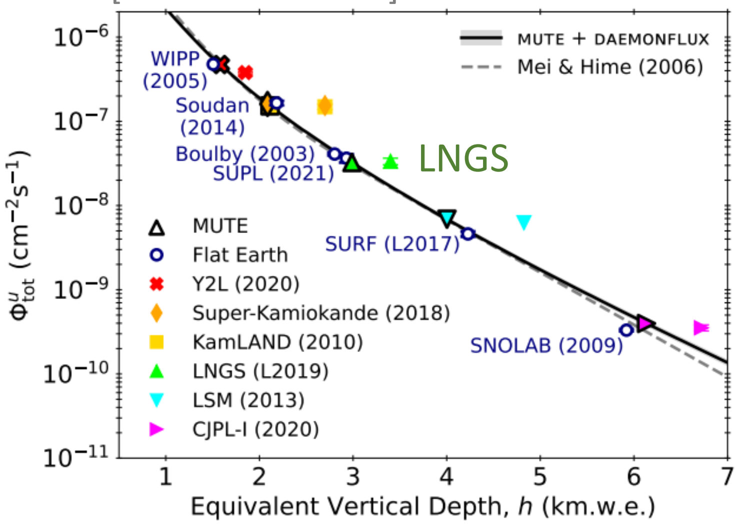
Thanks to PSD, electron recoil backgrounds can be identified and removed in WIMP searches!

Backgrounds

External:

- **muons** (cosmic)
  - underground lab
- **gamma** (natural radioactivity)
  - *passive shielding*
  - material selection
  - PSD discrimination

[Arxiv:2406.10339]

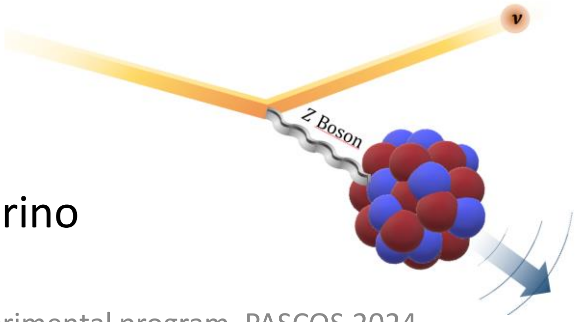


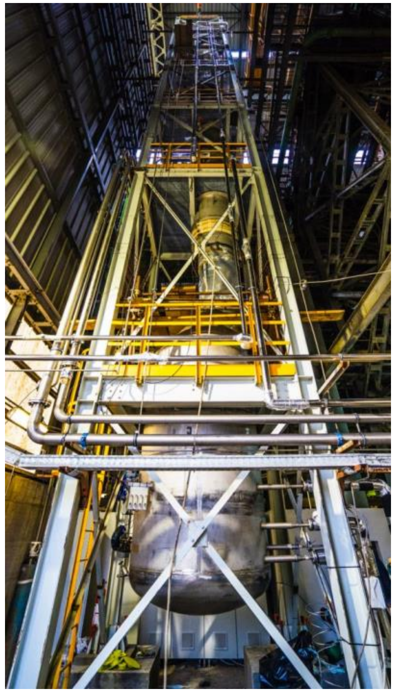
- **neutrons** (natural radioactivity and cosmogenic induced)
  (Can mimic the WIMP signal)
- underground lab
- *passive and active shielding*
- material selection low U, Th contamination

- **Neutrinos (mostly solar and atmospheric)**
  (can mimic the WIMP signal)
- coherent elastic neutrino nucleus scattering (**CEνNS**) and neutrino elastic electron scattering [arxiv:2307.08842]

Internal:

- ^{85}Kr and Radon, removed by **filtering**
- Argon: ^{39}Ar ->Reduced using underground Ar
- readout (PMTs, SIPM, ecc)
- residual surface α or β-decay, removed by **fiducialization**



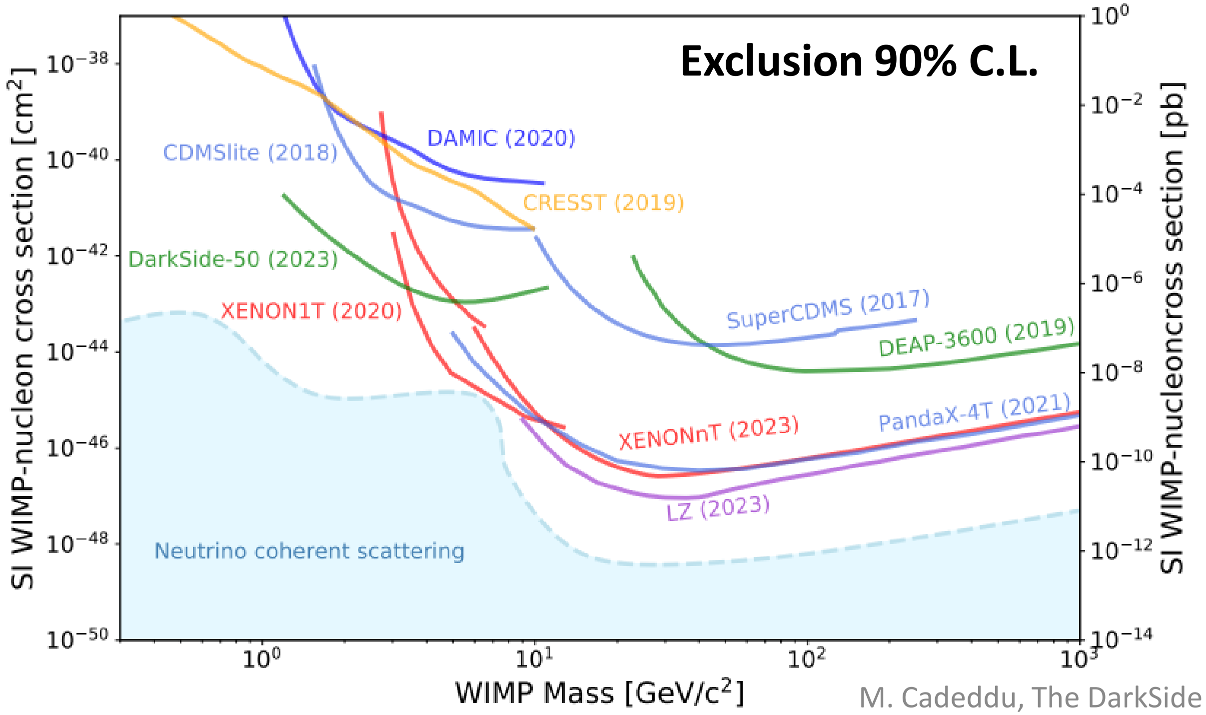


Neutrinos

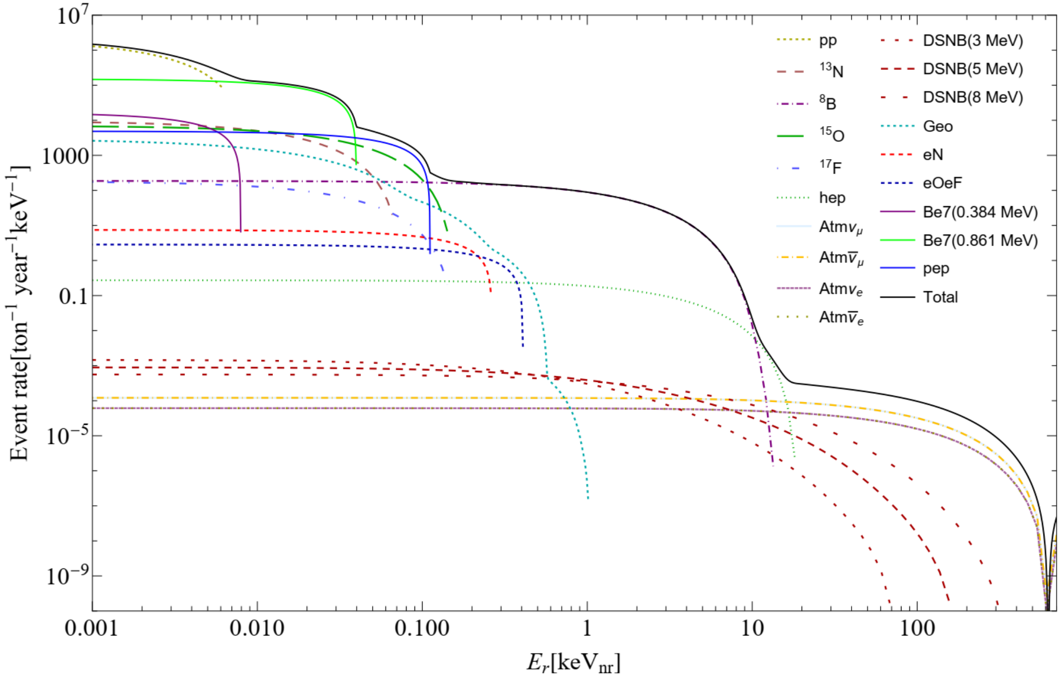
➢ Coherent elastic neutrino-nucleus scattering (CEνNS) can produce nuclear recoils that mimic WIMPs

Neutrino floor/fog

Limit on experimental sensitivity for any detector!
[arxiv:2109.03116]



➢ Solar ^{8}B at low energies
➢ Atmospheric ν at high energies



How to go beyond?

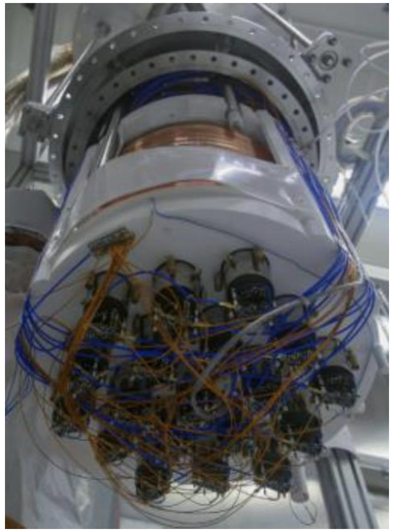
- ➢ Directionality (see the RED experiment [arxiv:2307.15454])
- ➢ Spectral information
  - ➢Effective background subtraction requires decreasing systematics
  - ➢Precise measurements and description of CEνNS cross section [arxiv:2402.16709] & improved sub-GeV atmospheric ν models

The DarkSide program

2012 | 2013-2021 | 2027-2037 | Far future...

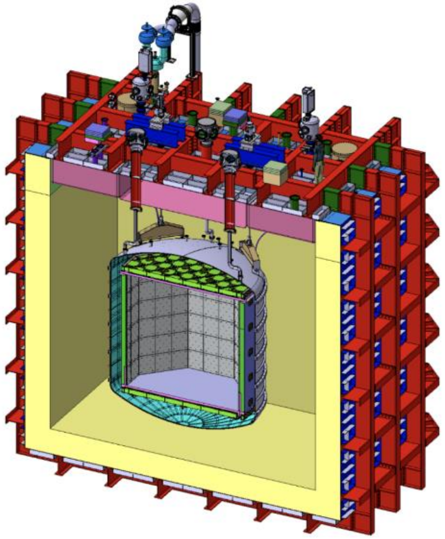
DarkSide-10

Technical prototype No dark matter goal



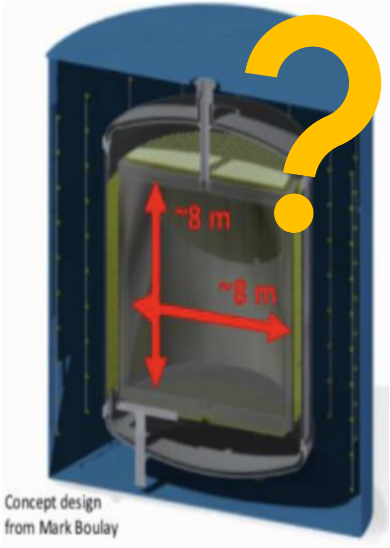
DarkSide-50

Science detector. First bkg-free results with UAr. Best limits for low mass WIMP search.



DarkSide-20k @LNGS

Novel photosensor technology. First peek into the neutrino fog. Nominal exposure: 200 t y



Argo @SNOLAB

Ultimate LAr DM detector. Push well into the neutrino fog. Nominal exposure: 3000 t y

The past: success of DarkSide-50

- 50 kg dual-phase argon TPC operated at Laboratori Nazionali del Gran Sasso (LNGS) [arxiv:1410.0653]

  - Challenge: intrinsic $^{39}\mathrm{Ar}$ -β decay

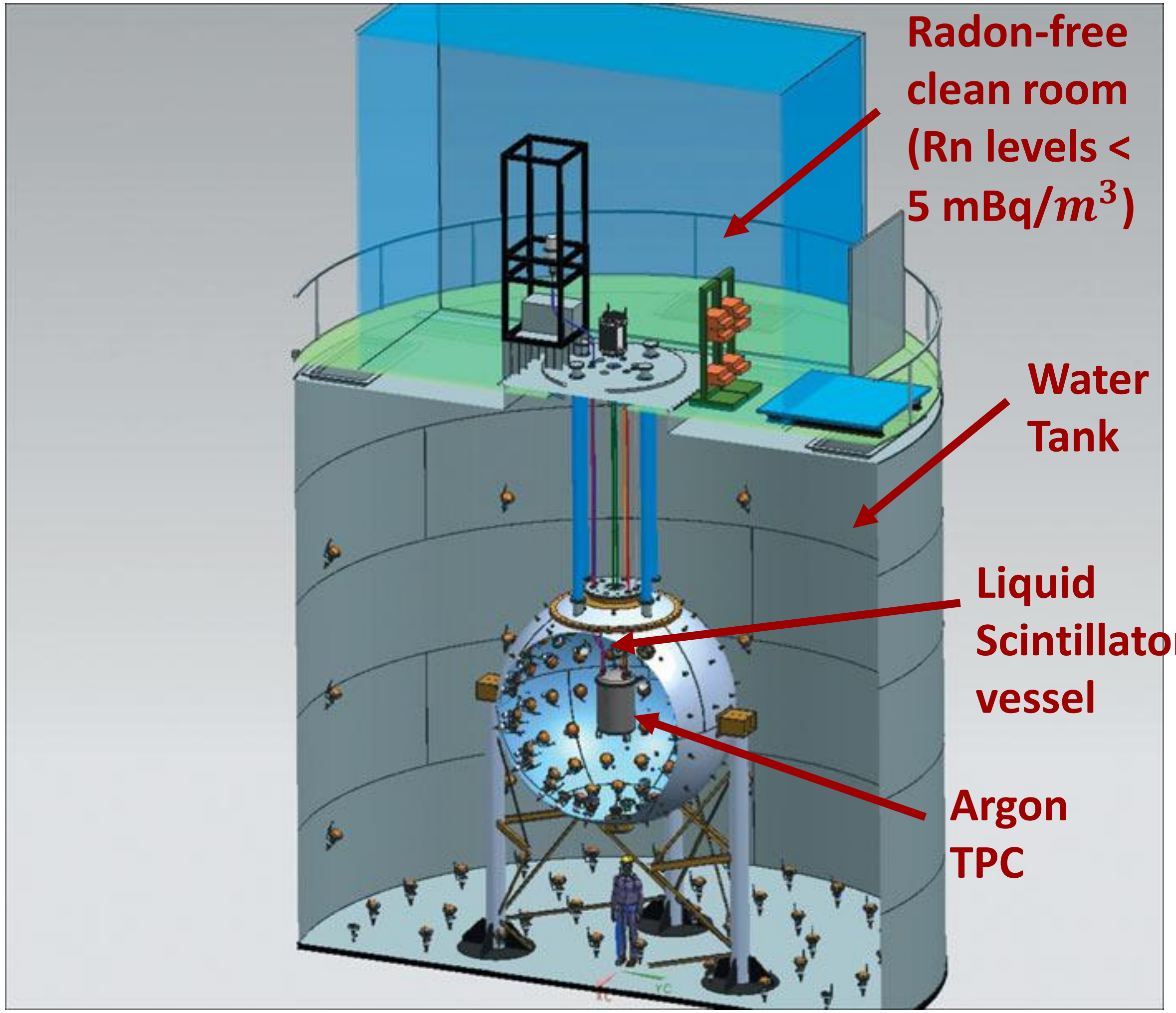
Solution: extract low radioactivity argon from underground (UAr) source ($^{39}\mathrm{Ar}$ depletion factor >1400)

Active shielding:

- Neutron and $\gamma's$ Veto: 4 m diameter filled with 30-tonne boron-loaded liquid scintillator with veto efficiency above 99.8 %

- Muon Veto (Water Cherenkov Detector 1000-tonne Cosmic Ray Veto) with veto efficiency above 99.5%

- Designed to be background-free (<0.1 background events in the nominal exposure) in the S1+S2 analysis (high mass WIMP region)



Low WIMP mass searches in DarkSide-50

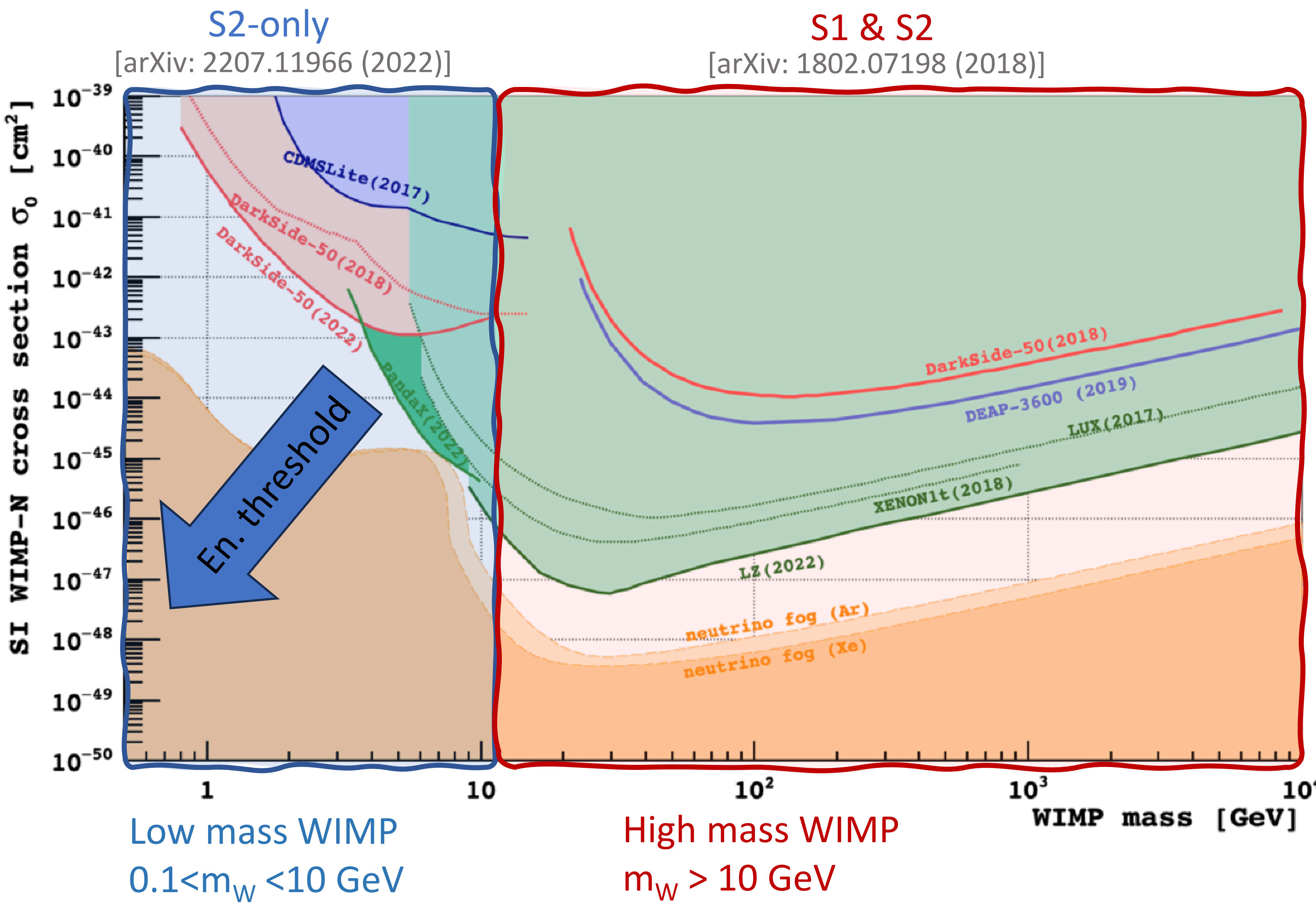
DarkSide-50 low mass: ionization (S2-only) analysis

PROS:

- S2 signals are amplified in GAr: **possible to identify single ionization electron**
- Energy threshold for nuclear recoils down to 0.6 keV_{nr} (corresponding to 4 electrons)
- **Unique sensitivity to few GeVs DM**

CONS:

- PSD and Z-coordinate reconstruction are unavailable
- Minimal fiducialization (only radial)
- No more bkg-free → **Background model needed**



Recent DS-50 results

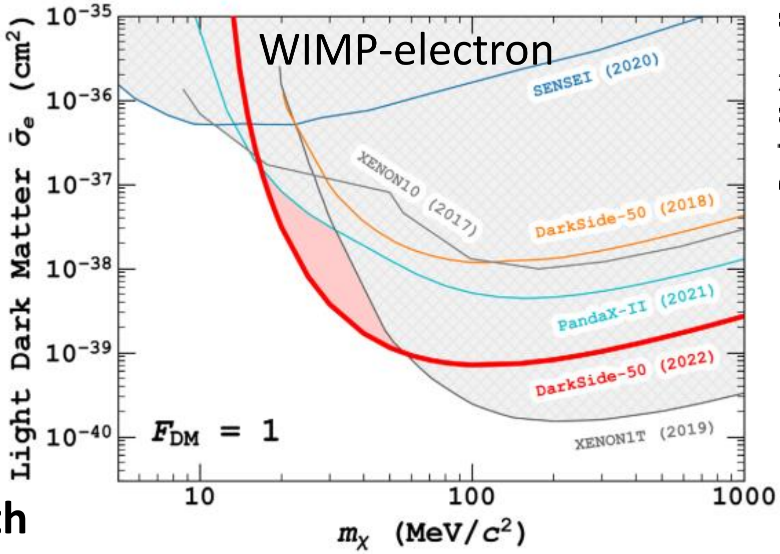
- **DarkSide-50 most recent analyses:**

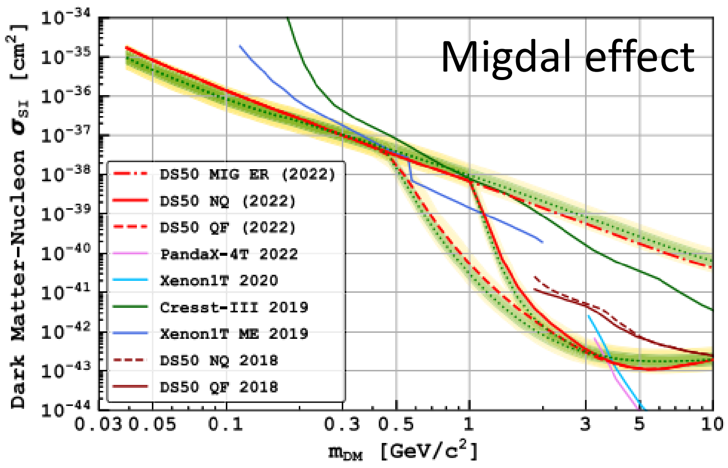
- **WIMP-Nucleus** arXiv: 2207.11966 (2022)
- **Migdal effect** arXiv: 2207.11967 (2022)
- **WIMP-electron** arXiv: 2207.11968 (2022)

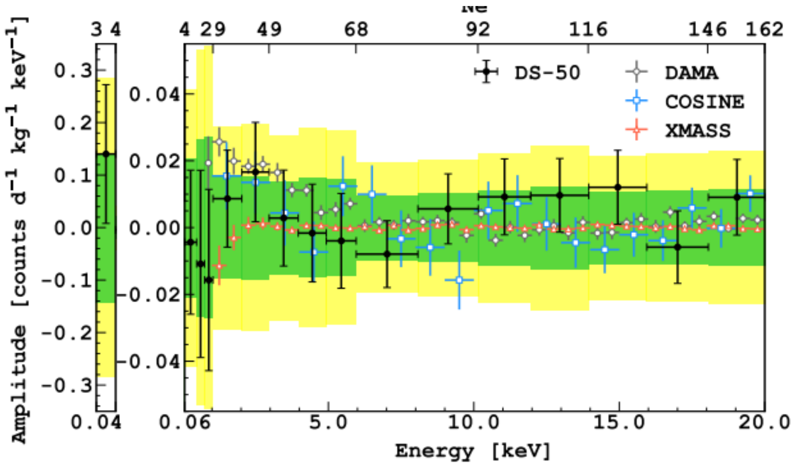
- **Search for dark matter annual modulation with DarkSide-50** arXiv:2307.07249 (2023)

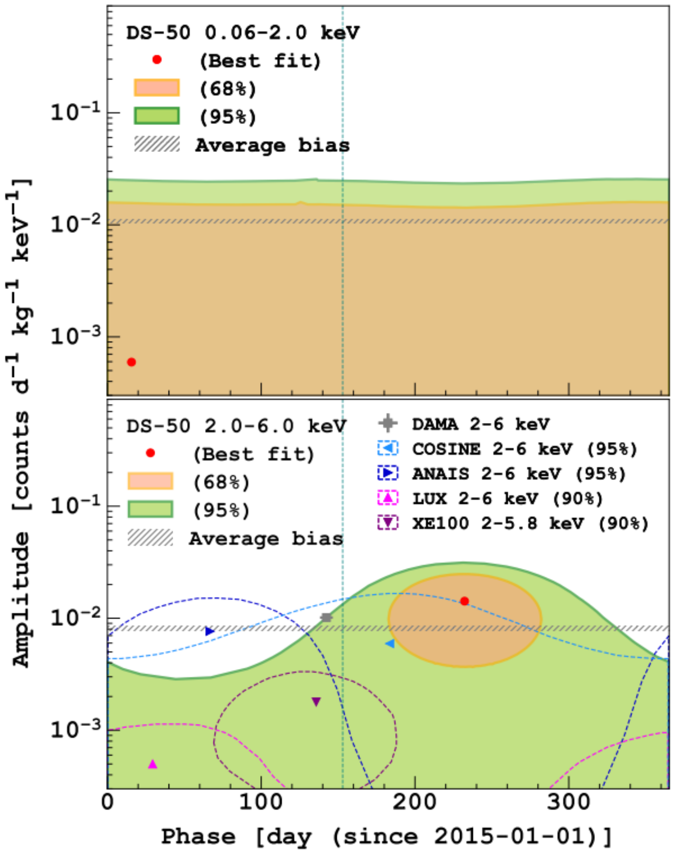
“ [...] We searched for annual modulation signature using the ionization signal of the DarkSide-50 liquid argon TPC. ***No significant signature compatible with dark matter is observed in the electron recoil equivalent energy range above 40 eVee****, the lowest threshold ever achieved in such a search.”*

Relies on «Long term DS-50 temporal stability» [arXiv: 2311.18647 (2023)]



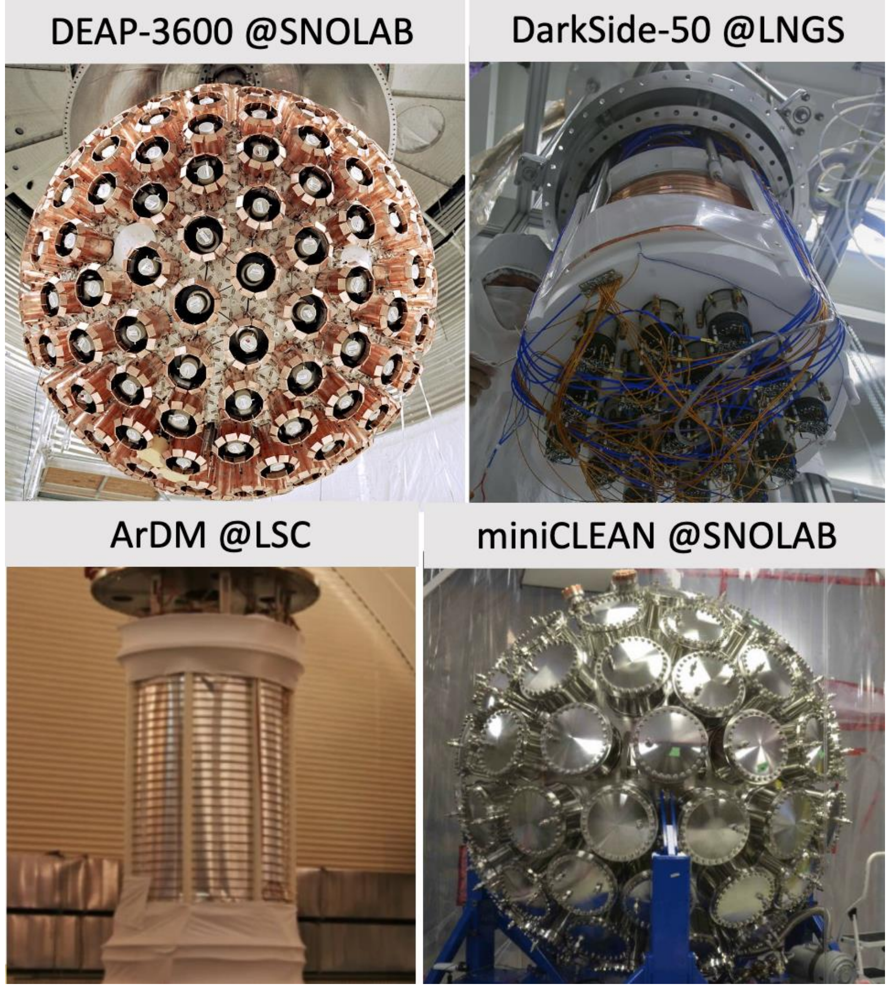






Global Argon DM Collaboration

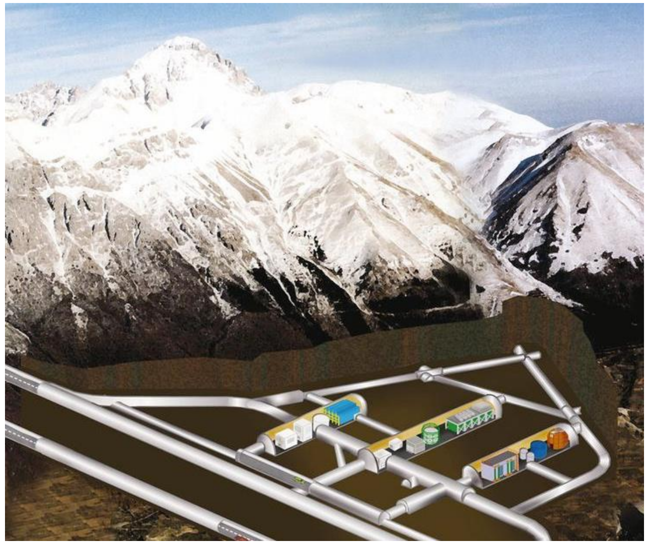
All joined together in 2017 to build future LAr-based dark matter detectors



> 500 Collaborators, > 100 institutes distributed across 14 countries

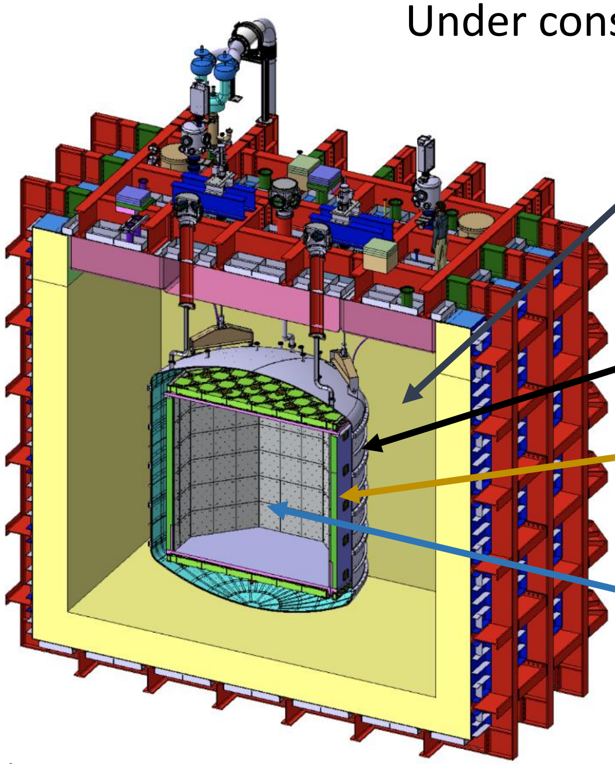
DarkSide-20k

- DarkSide-20k in Hall C @Laboratori Nazionali del Gran Sasso LNGS (Italy)
- Below ~1400 m of rock (3400 m.w.e)
- Muon flux reduction factor ~10^6



Under construction at LNGS

- ~50 (20) tonnes active (fiducial) UAr in a dual phase TPC
- 32 tonnes of UAr acting as neutron veto
- 650 tonnes of Atmospheric Ar (AAr) acting as muon veto
- Light Readout: large array of custom cryogenic low-noise SiPMs (TPC readout: ~ 21 m^2 cryogenic SiPMs)



Position reconstruction resolution:

- ~1 cm in XY
- ~1 mm in Z

Underground argon and purification

Extraction

^{39}Ar radioactivity in AAr:
- β emitter ($T_{1/2}$: 269 yr, Q: 565 keV). $\sim$1 Bq/kg in AAr.

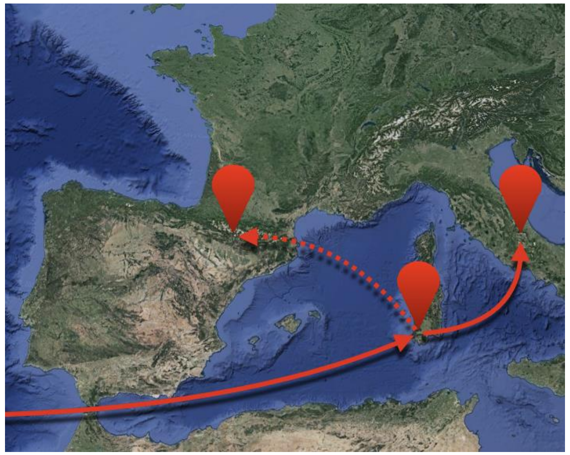
URANIA, Colorado (US)
- Industrial scale extraction plant;
- Expected argon purity at outlet: 99.99%;
- UAr extraction rate: 250-330 kg/day and 120 t over two years

Purification

ARIA: UAr distillation plant
- Cryogenic distillation column in Sardinia (IT)
- Three sections: bottom reboiler, 28 central modules (12 m each), top condenser, $\sim$350 m
- Chemical purification rate: 1 t/day

- First module operated according to specs with nitrogen in 2019 [Eur. Phys. J. C (2021) 81:359]
- Ar run completed at the end of 2020 [Eur. Phys. J. C 83, 453 (2023)]
- Now working on the full assembly

Assaying and delivery



DArT : Measurement of the activity of the ^{39}Ar @LSC, Canfranc, Spain
- Single-phase inner detector for 1.42 kg of liquid UAr
- Will be installed inside ArDM detector, acting as an active veto.
- ^{39}Ar depletion factor sensitivity: U.L. 90% CL. 6×10^4 [2020 JINST 15 P02024]

DarkSide-20k physics reach: high mass

WIMP

- **Nominal exposure**:

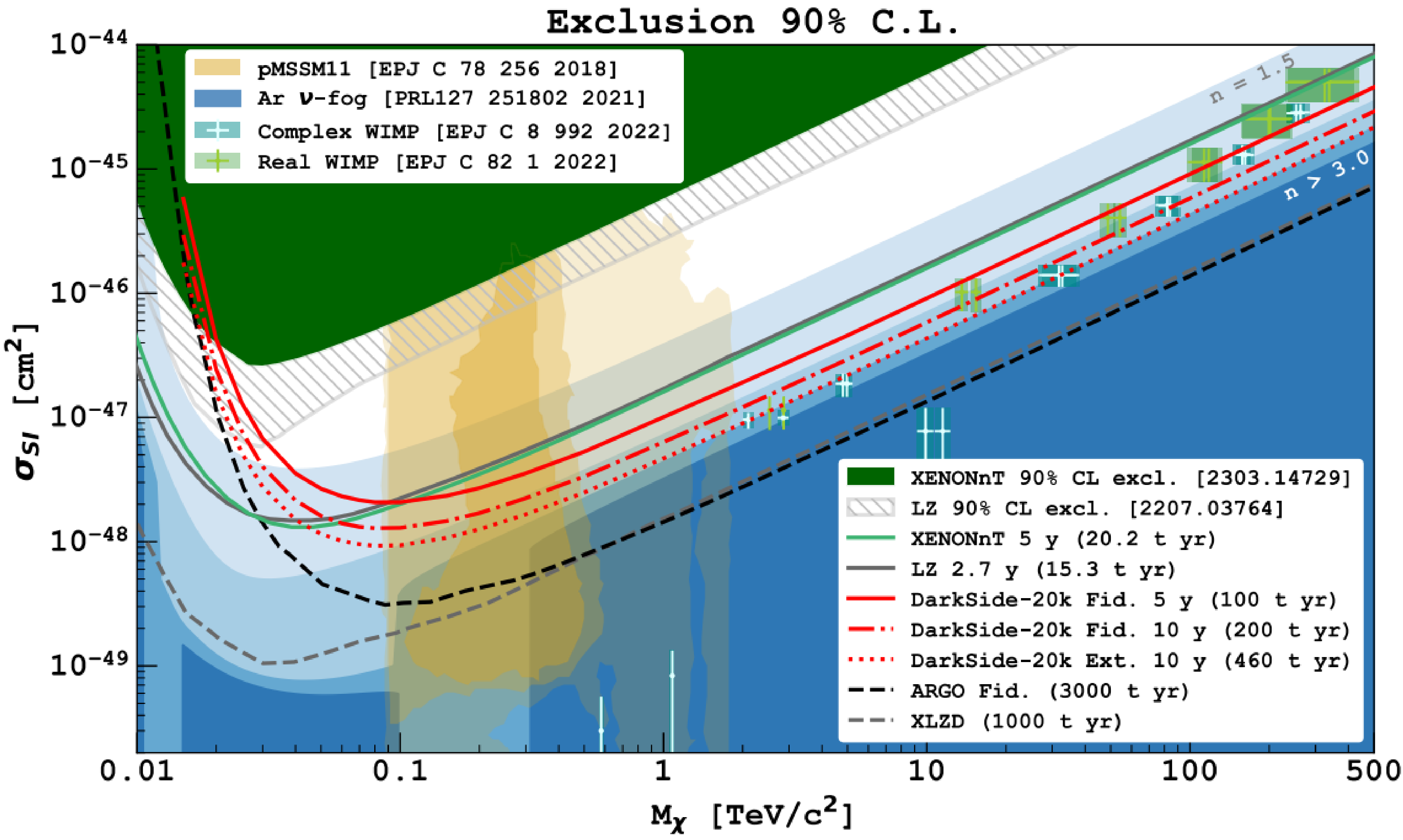
  Fid. 10 y → (20×10) t yr

- **Instrumental background**:

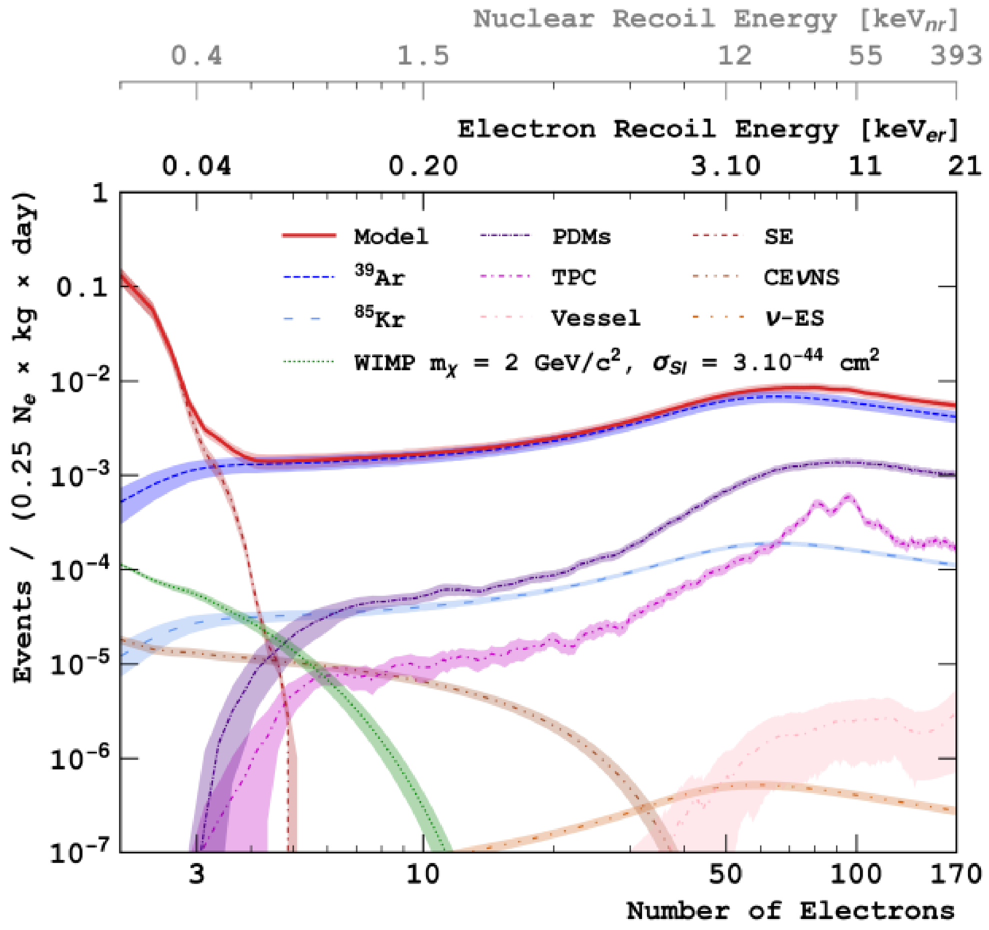
  DS-20k aims to have <0.1 bkg events in 200 t yr

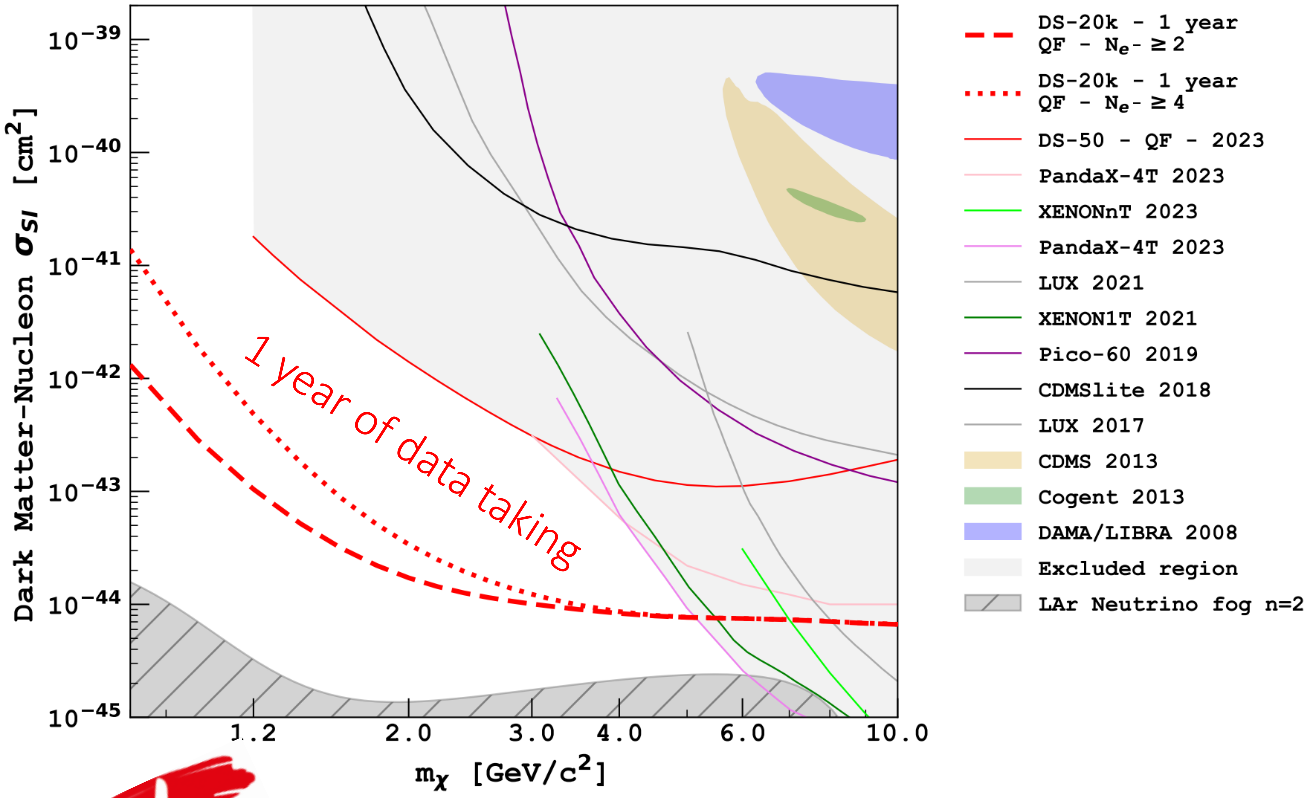
- **Expected neutrinos**:

  ~ 3.3 events in 200 t yr



DarkSide-20k sensitivity to light dark matter particles





Check the presentation today @IDM 2024 (L'Aquila) by Marie van Uffelen and arXiv:2407.05813!

Conclusions

- Dark matter is still one of the biggest enigmas of our century.
- Liquid argon TPC technology has proven to be a very powerful tool for discovering WIMPs, thanks to the success of DarkSide-50!
- The R&D phase for the DS-20k detector is complete, and construction has started in Hall C of LNGS.
- The underground argon procurement and characterization projects are ongoing (URANIA, ARIA, and DArT-ArDM).
- Data taking is expected in 2027.