Search for dark matter with the DarkSide-20k detector

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(for the DarkSide-20k collaboration)

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ASTROCENT
NICOLAUS COPERNICUS ASTRONOMICAL CENTER
OF THE POLISH ACADEMY OF SCIENCES

NATIONAL SCIENCE CENTRE
POLAND

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Republic of Poland

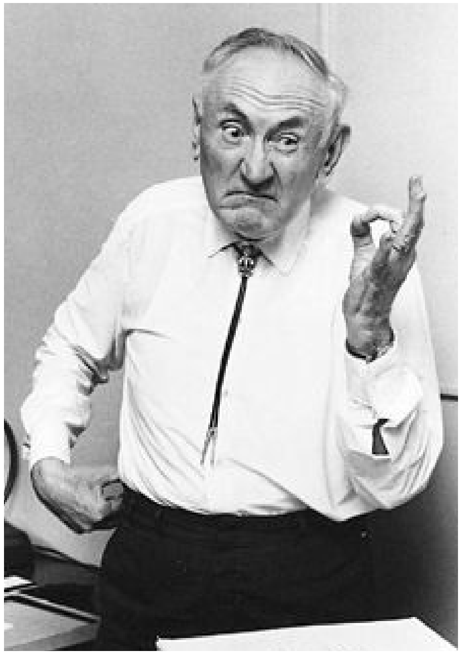
FNP Foundation for Polish Science

European Union European Regional Development Fund

Outline

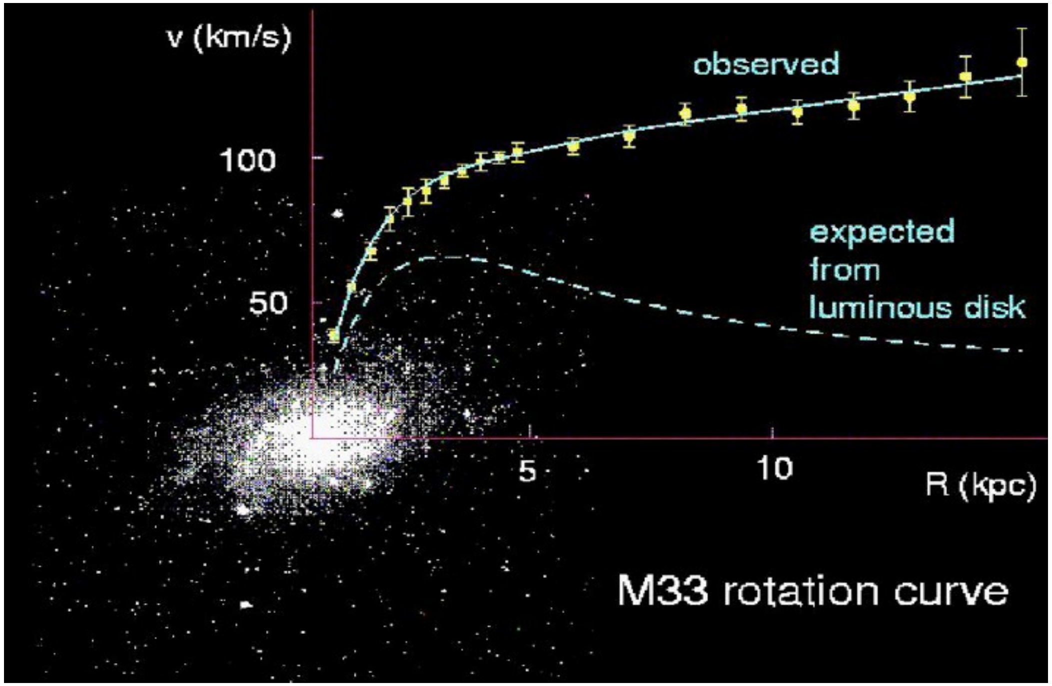
- Motivation
- Status and prospects of the WIMP search
- Global Argon Dark Matter Collaboration program
- DarkSide-20k:
  - Time projection chamber
  - Underground argon
  - Neutron veto
  - Wavelength shifters
  - Photodetector production and testing
- Low-mass sensitivity
- Argo
- Summary

Dark Matter: the missing mass

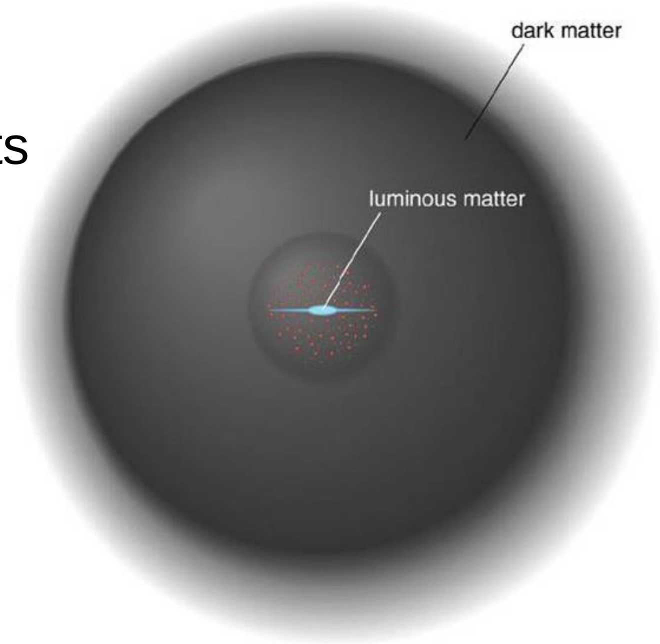


1933, Fritz Zwicky

1970, Vera Rubin

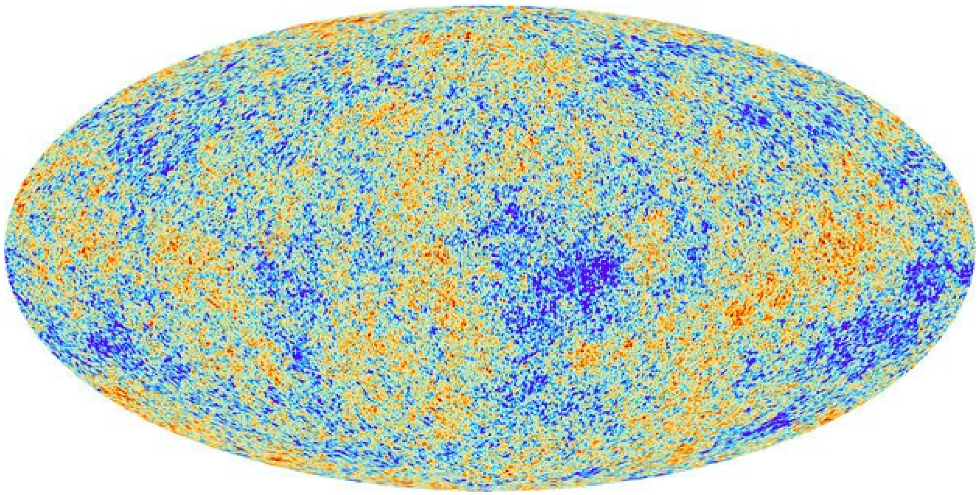


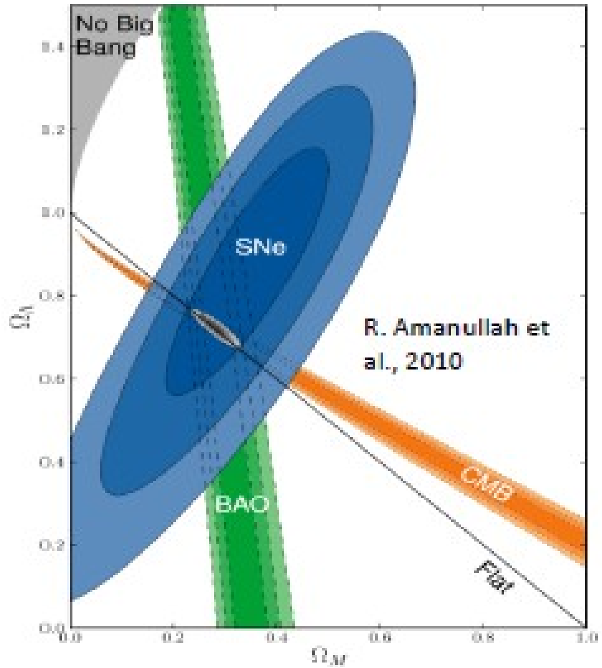
- Rotation curves measure the mass distribution
- Mass density distributed more broadly than visible objects
- Non-luminous halo required to describe rotation curves
- Found in 1933 by Zwicky from Coma Galaxy Cluster analysis
- Confirmed in 1970 by Vera Rubin for Andromeda
- Most of the matter is invisible (neither emits nor absorbs light)

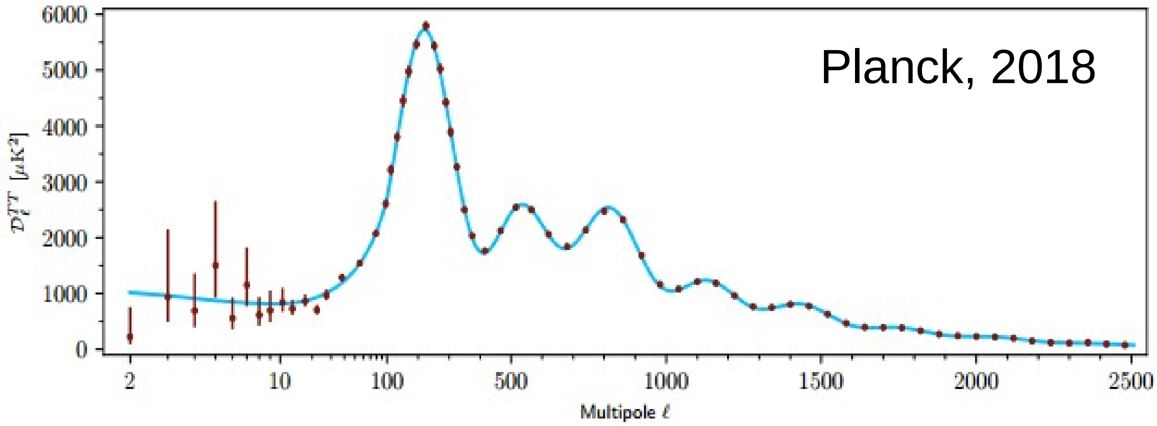


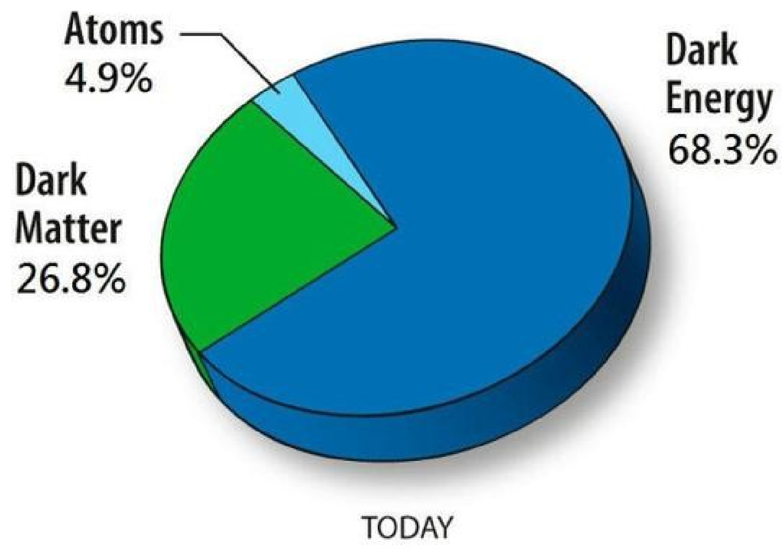
Evidence for Dark Matter

- Cosmic microwave background (CMB) observations, resulting in precise estimates (WMAP, Planck) supporting ΛCDM model



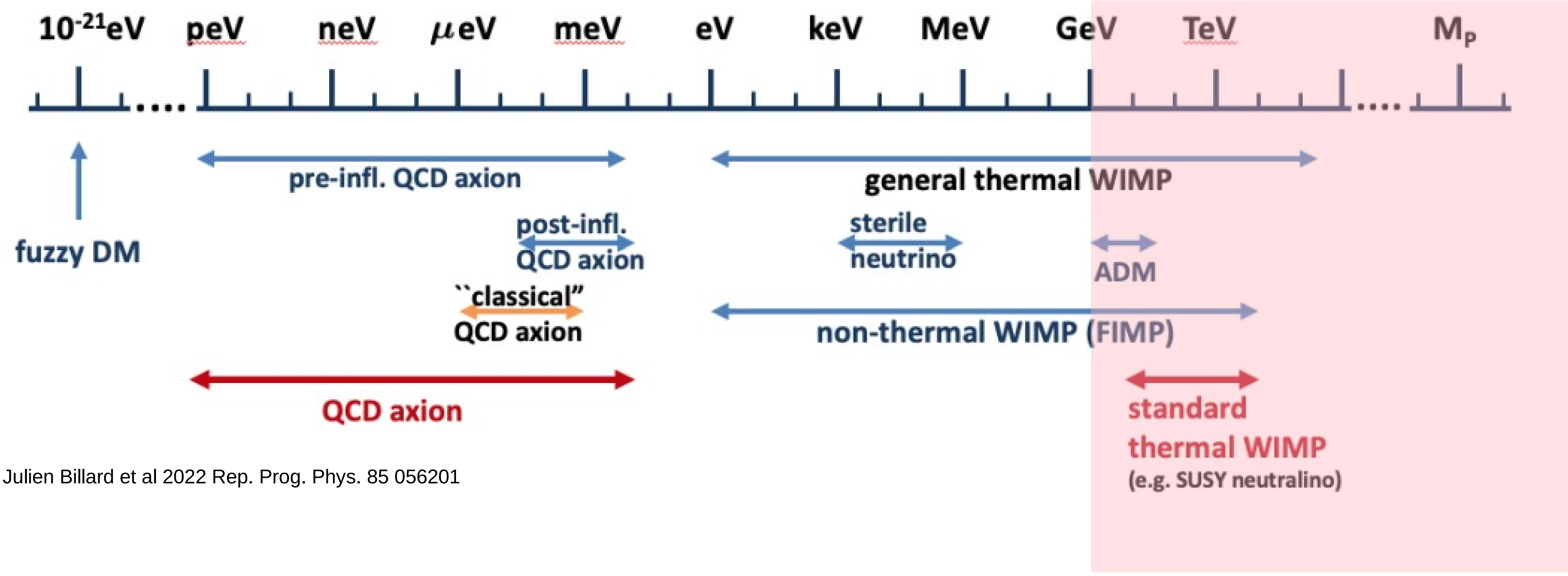






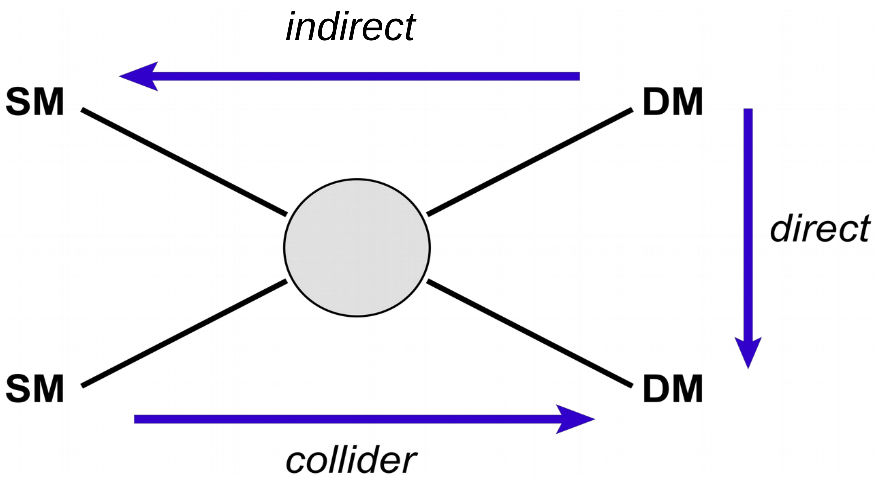
What is Dark Matter?

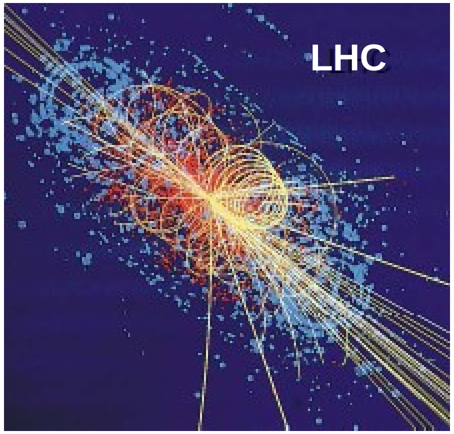
- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- <u>New Particles</u>
  - Weakly Interactive Massive Particles (WIMP), Asymmetric DM, Feebly Interacting Massive Particles (FIMP)



Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

Ways to look for Dark Matter particles





- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares/KM3NeT)
  - Positrons, antiprotons (AMS)
  - γ-rays (Fermi-LAT, CTA)
- **Direct detection**
- By producing them at accelerators (LHC, beam dump experiments)

Historical perspective

Direct dark matter detection started nearly 40 years ago from these 2 papers:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

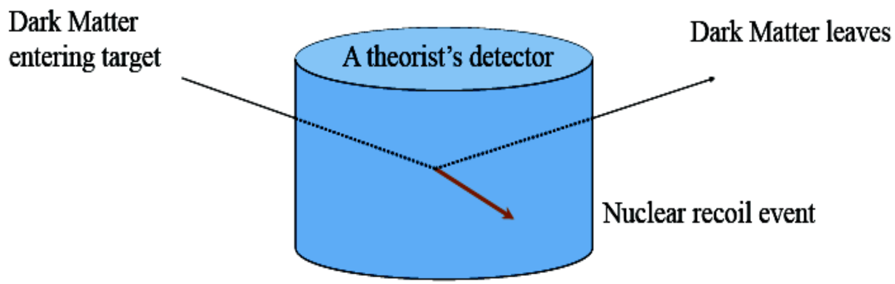
Detectability of certain dark-matter candidates

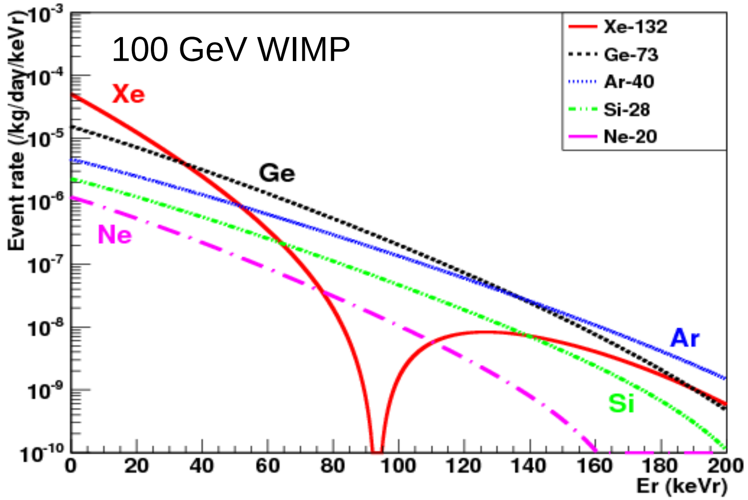
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

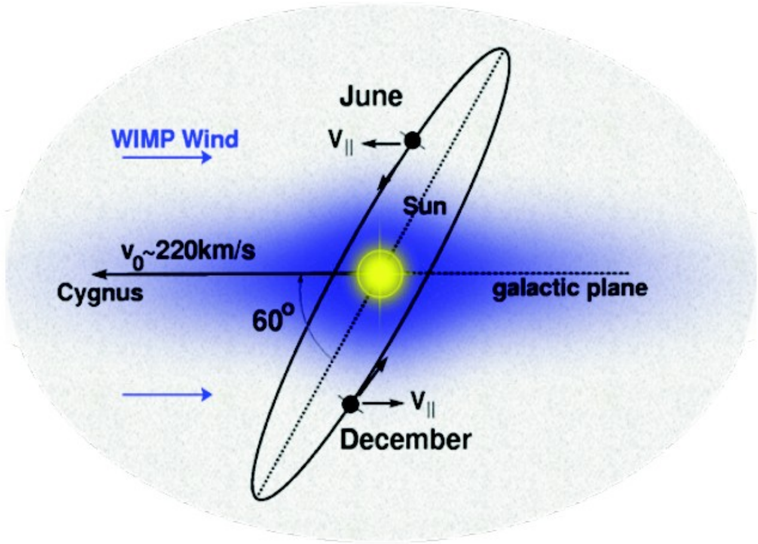
DM direct detection signature

- Only through rare interactions with ordinary matter
- After the interaction, recoiling nucleus deposits energy in the detector, which is detectable (**heat, light, electric charge, ...**)





Nuclear recoil spectrum
- featureless, ~exponential
- lower threshold → more sensitivity
- natural radioactivity is a background



Annual modulations in the event rate should be present!

Directionality
→ annual modulation of the signal

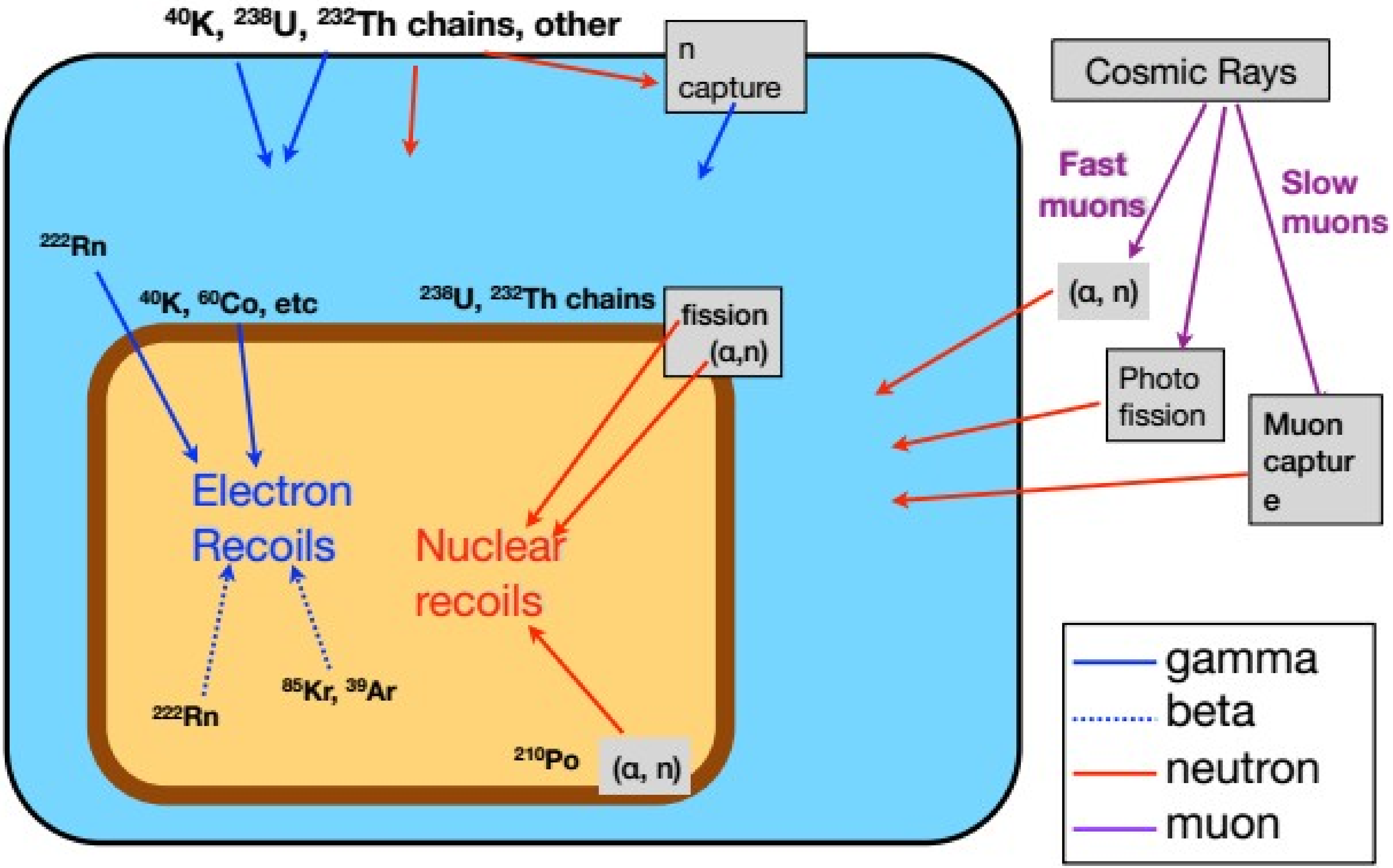
astrophysics

$$\frac{dR}{dE_R} = N_T \int_{v_{min}}^{\infty} dv\, v\, \Phi(v, v_E) \frac{d\sigma}{dE_R} \varepsilon(E_R)$$

detector response

particle/nuclear physics

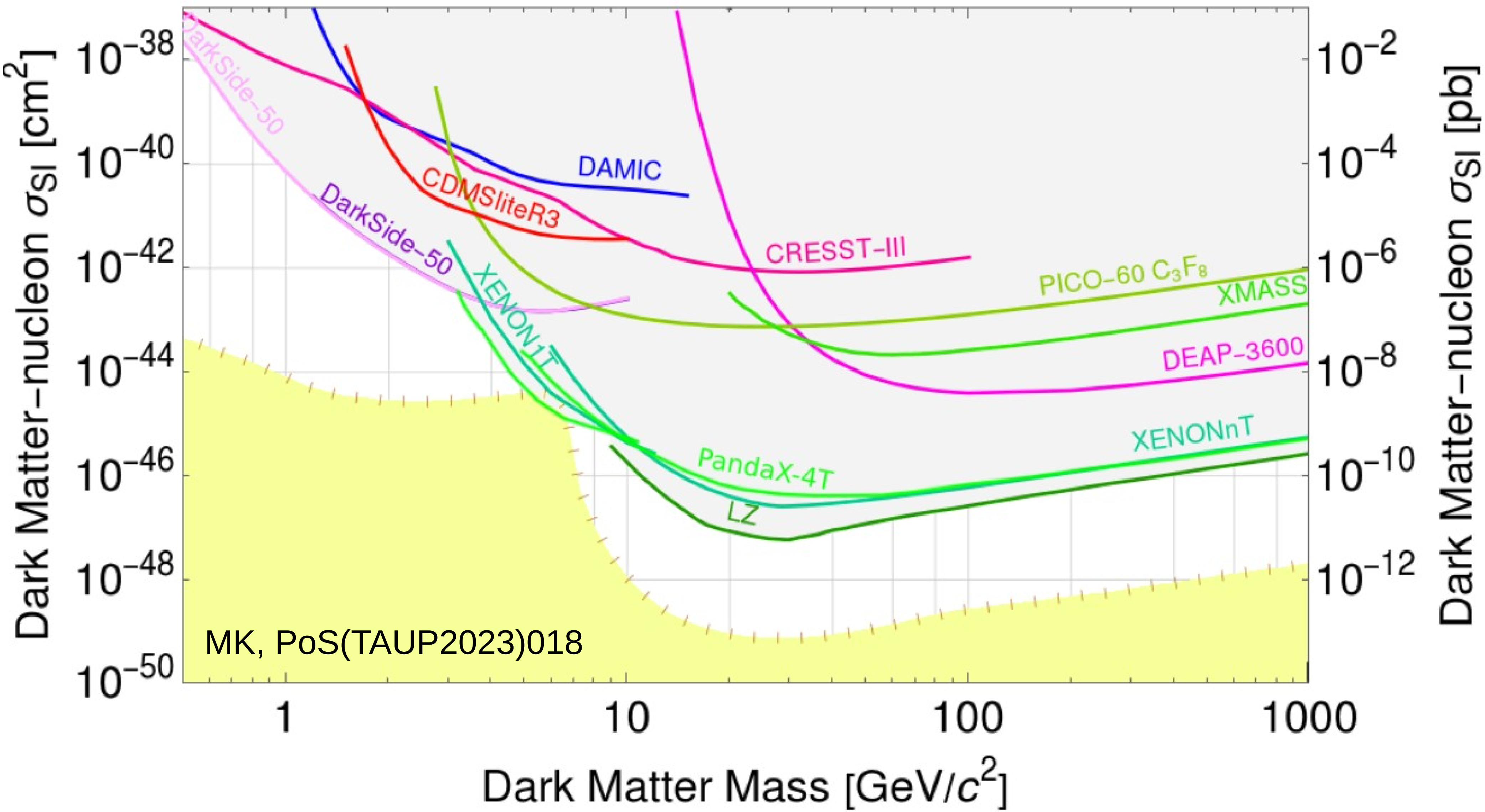
Backgrounds



Ambient backgrounds: 10^{11} time DM rate

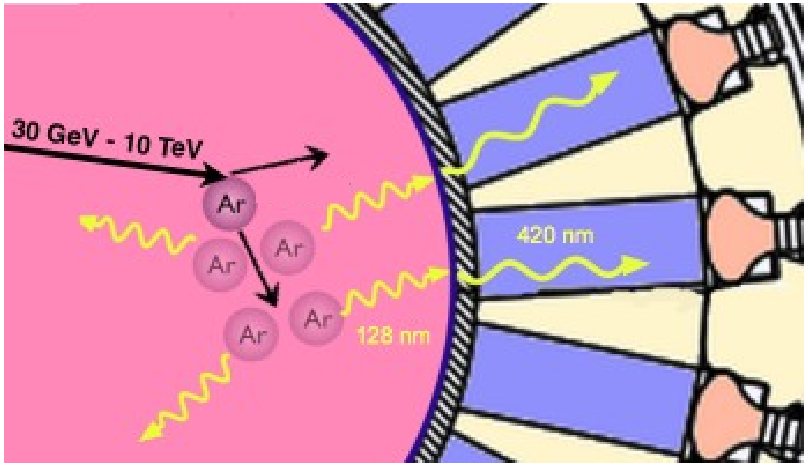
T. Shutt -LIDINE, Sept 22, 2017

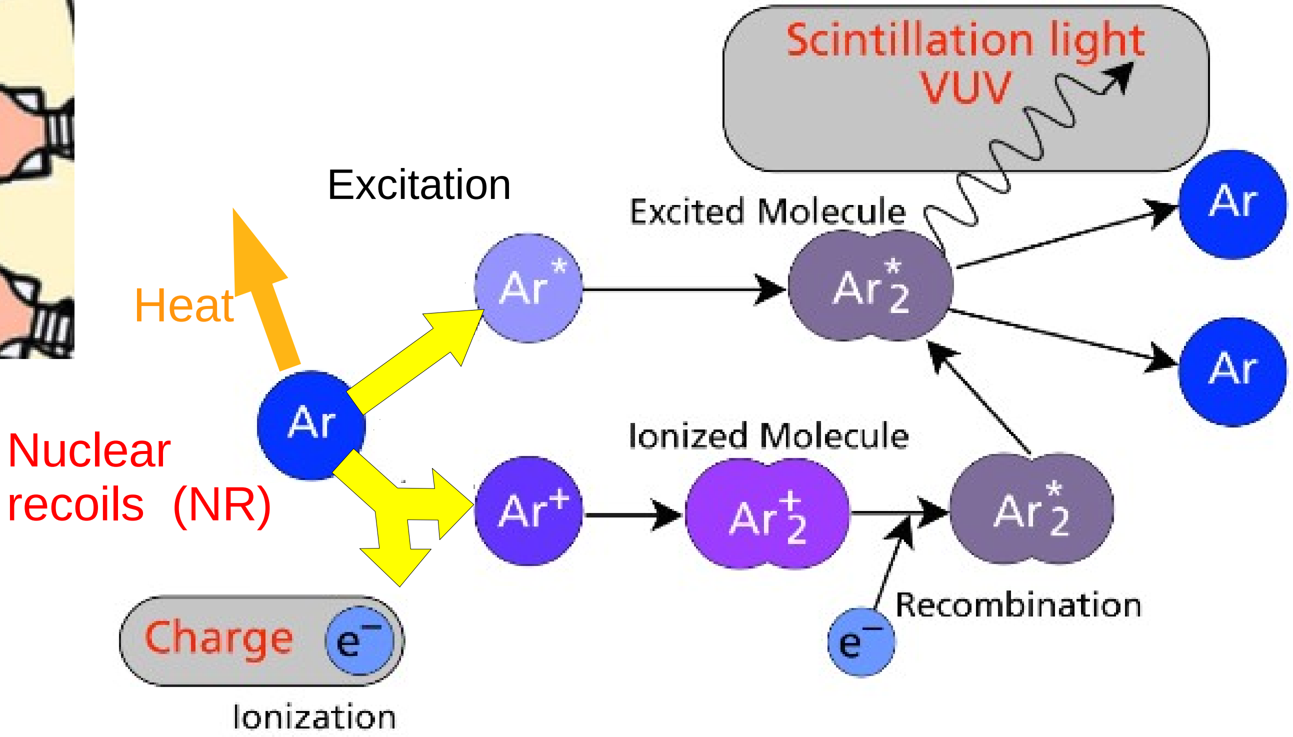
Direct detection landscape



- Spin-independent, with the usual assumptions: Standard Halo Model, isospin parity
- **LAr and LXe dominate searches in the spin-independent sector >~2 GeV/c2**
- Continued search towards the neutrino floor still very well motivated

Liquid noble detectors





Ar and Xe are used for WIMP detection.
- Ar inexpensive and advantageous for purification and background rejection

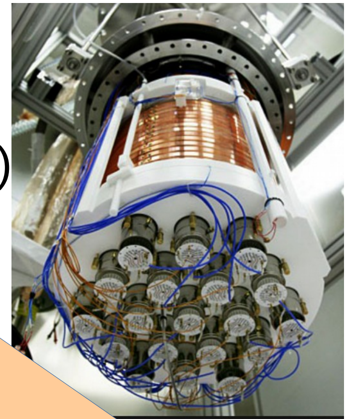
Why noble elements?
- High light yield, transparent to their own scintillation
- Easy to purify and scalable to very high masses
- (At least) two available detection channels: scintillation and ionization

Liquid argon (LAr) detectors

2010

10 kg

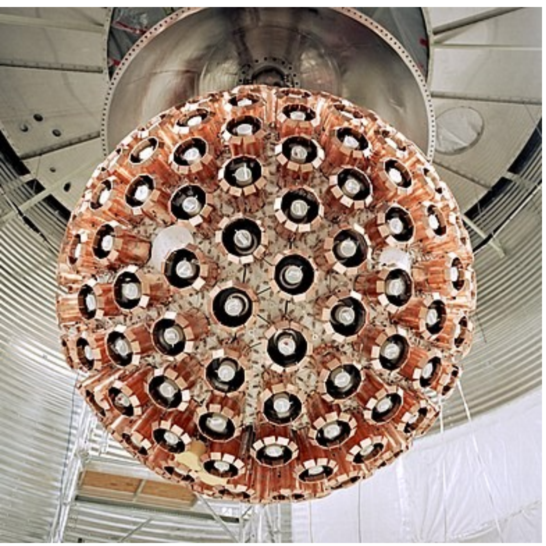
DarkSide-50
(50 kg, LNGS)



- More than 300 scientists from 15 countries and 60 institutions
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

100 kg

ArDM (1t, LSC)

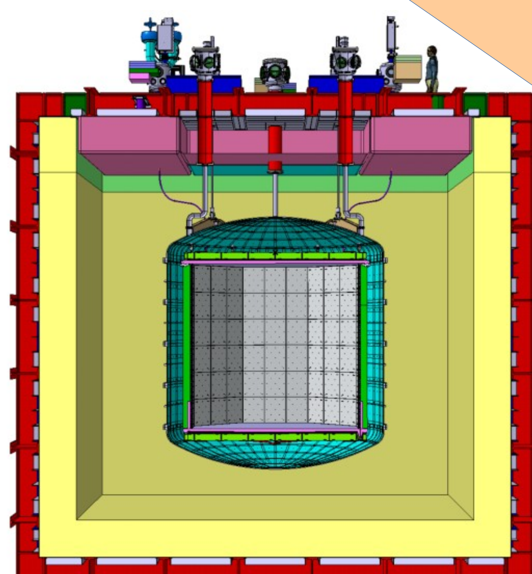


1000 kg

2015

DEAP-3600 (3.3t, SNOLAB)

Global Argon Dark Matter Collaboration formed



2020

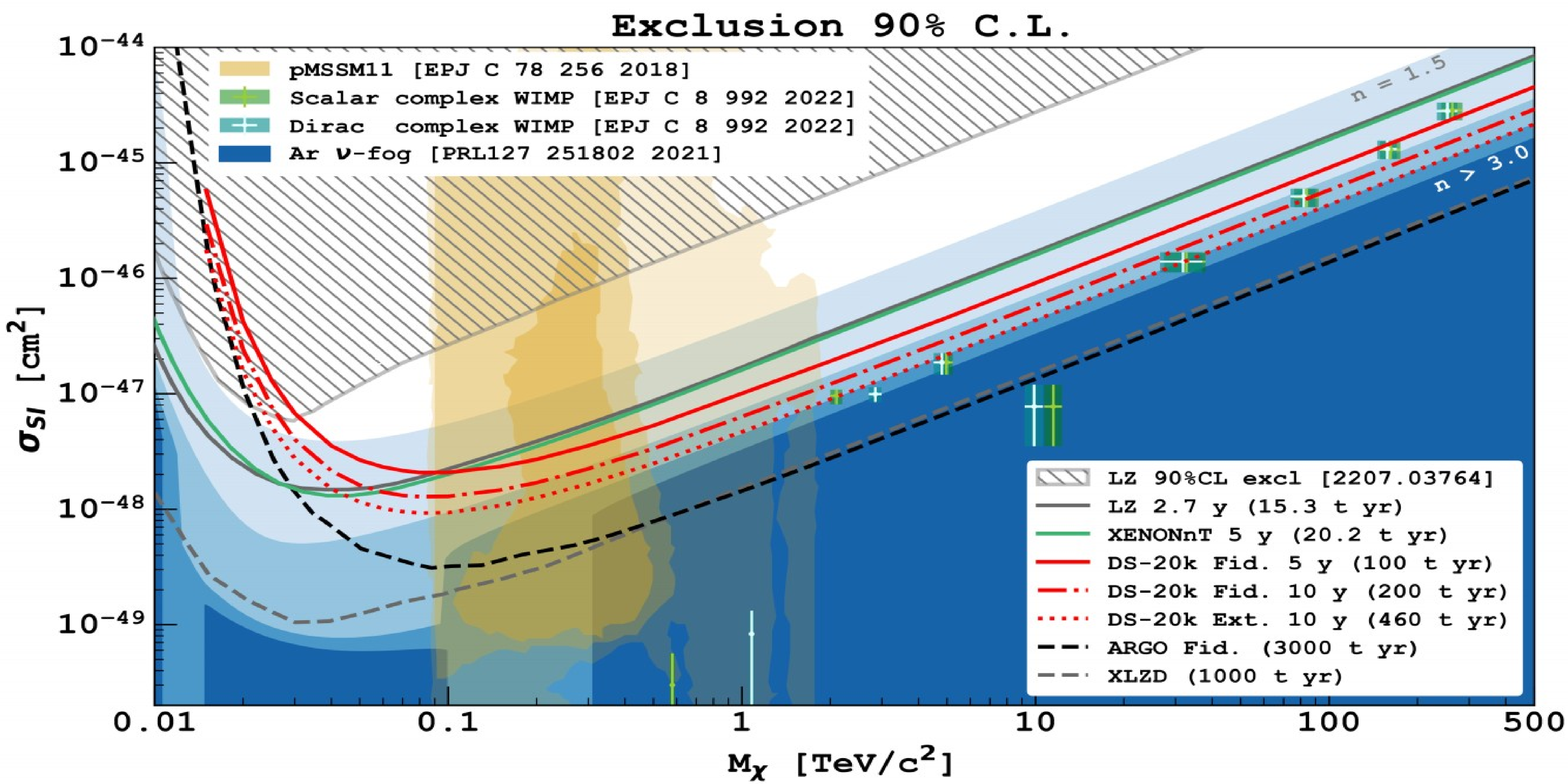
DarkSide-20k
(50t, LNGS)

100000 kg

ARGO: 400 t

Slide courtesy J. Monroe

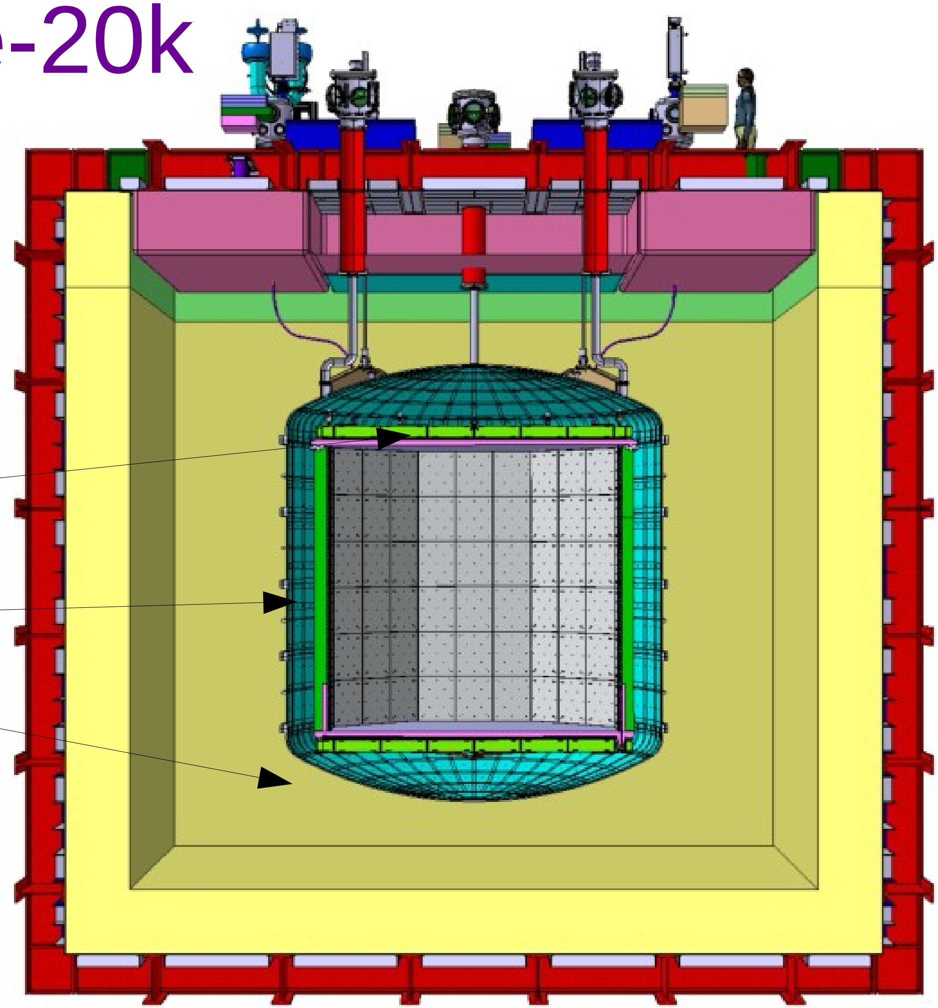
Status and prospects: high mass

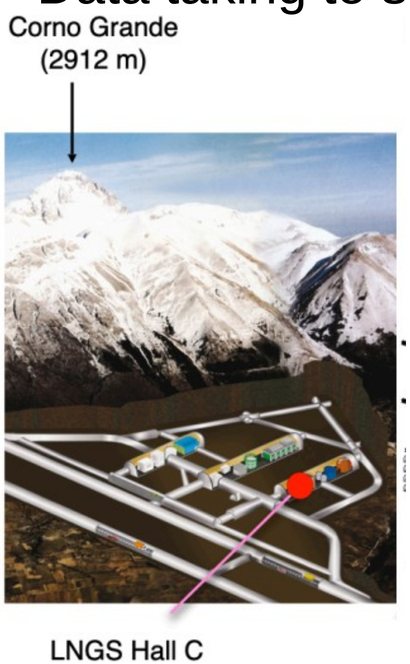


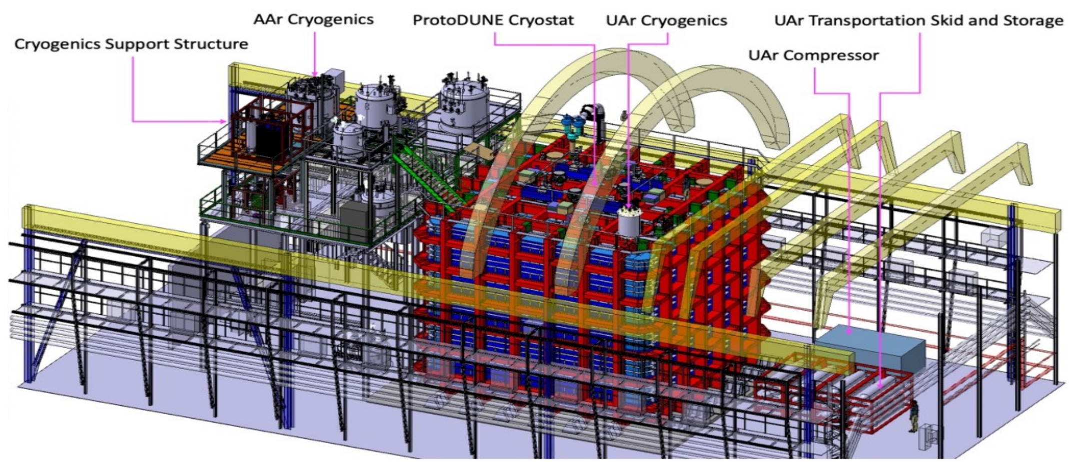
- Results from LZ, XENONnT and PandaX
- Multiple new results from LAr detectors, reducing the sensitivity gap
- Roadmap in place for reaching the neutrino floor
- **Scale-up requires global consolidation of efforts and R&D**

DarkSide-20k

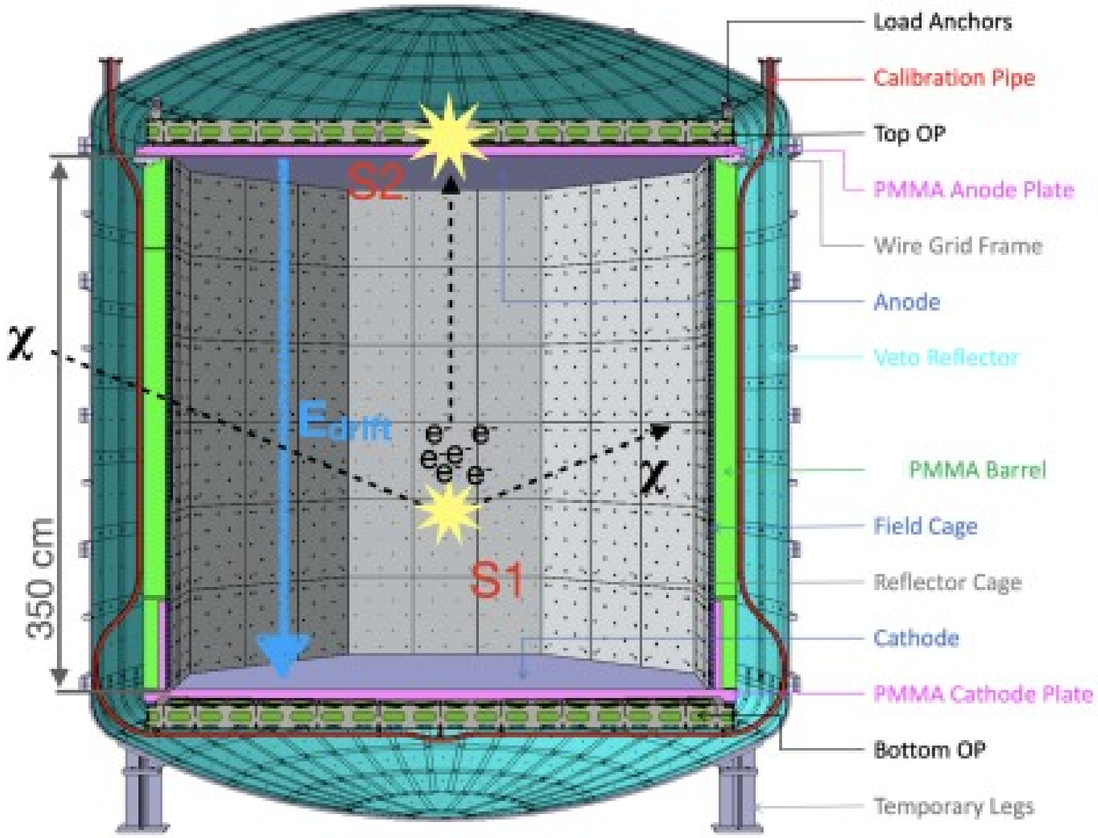
- ~300 physicists, 60 institutions, 11 countries
- Under construction at Gran Sasso (Italy)
- Concept:
  - Inner LAr time projection chamber (~50 tons) instrumented with **SiPMs**
  - Enclosed in an active LAr veto
  - Enclosed in a passive LAr shield tank
- Data taking to start in 2028



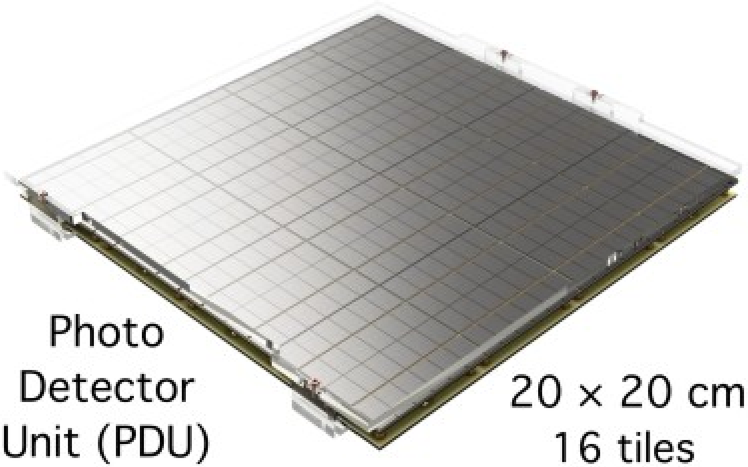


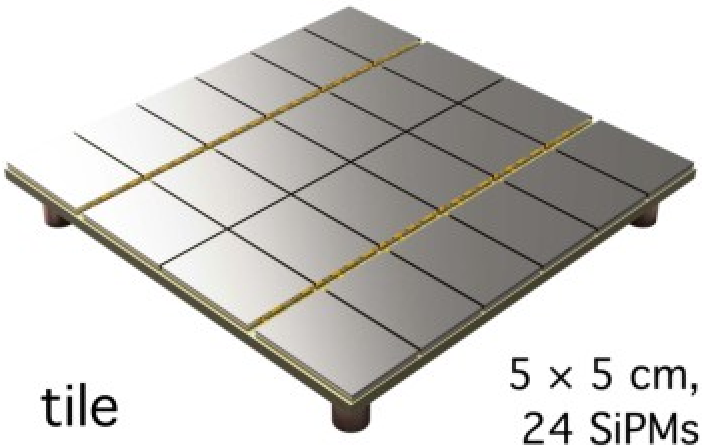


DarkSide-20k Time Projection Chamber (TPC)



- S1: energy and pulse shape discrimination (PSD)
- S2: energy information and the 3D position measurement of the event
- Resolution: 10 mm horizontal,1 mm vertical



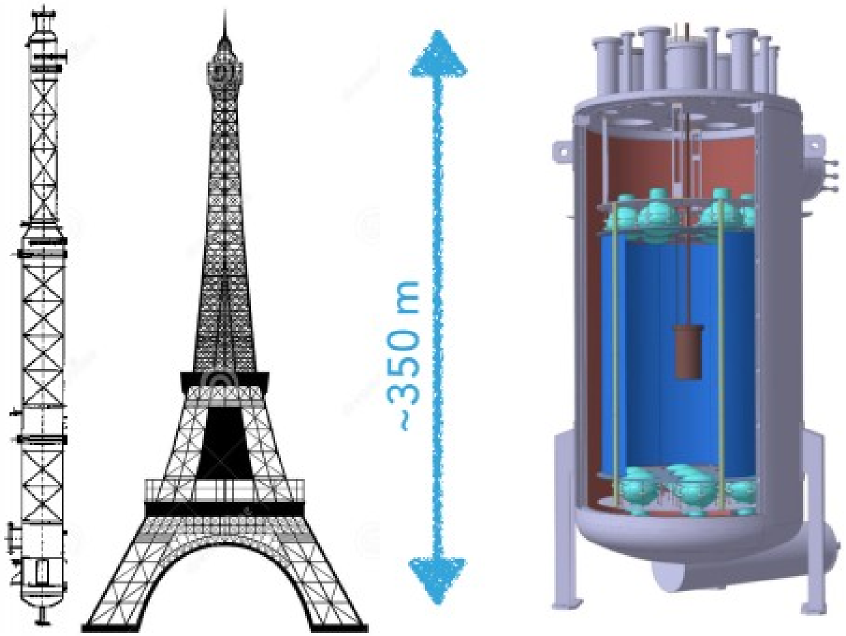


- Custom silicon photomultipliers (SiPM)
- Photon detection efficiency: 45%
- Timing resolution: 10 ns
- Dark-count rate < 20 cps
- 26 m^2 for the TPC and veto

Underground Argon (UAr)

- Trace amounts of cosmogenically produced ^{39}Ar (β emitter, 1 Bq/kg) are a background
- The collaboration exploits the source of underground Ar, >1400 times lower in ^{39}Ar

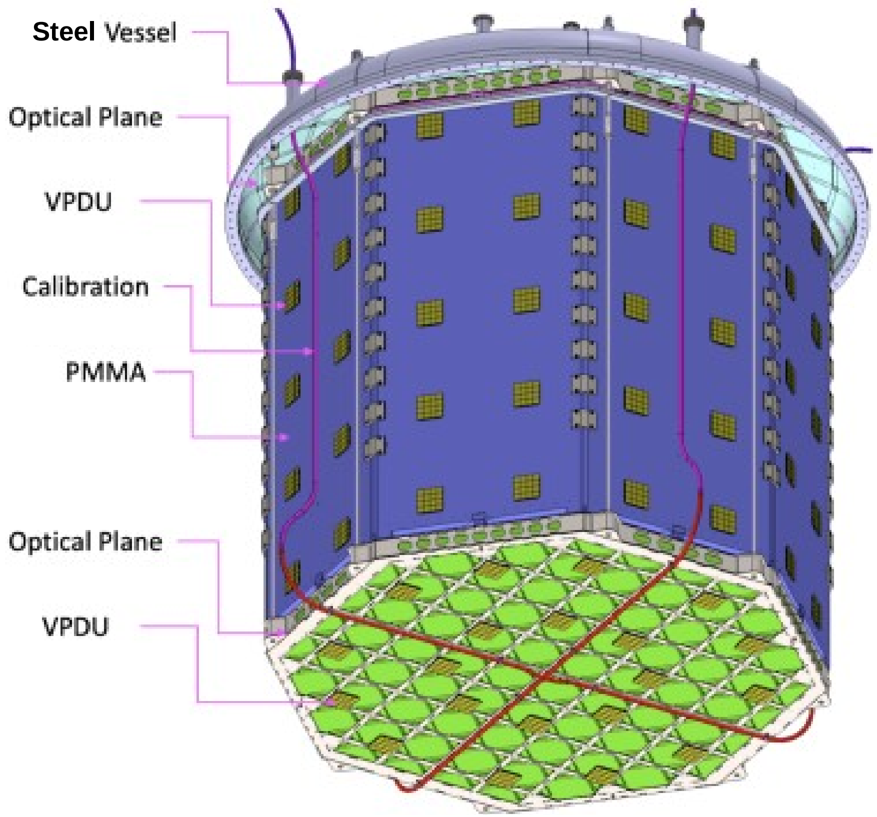
- **Urania** (Extraction):
  - Expansion of the argon extraction plant in Cortez, CO, to reach capacity of **330 kg/day** of Underground Argon
- **Aria** (Isotope separation):
  - Very tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon. **A factor 10 reduction of ^{39}Ar** per pass is expected with ~10 kg/day.
  - For DS-20k used only for chemical purification, with a much higher throughput
- **DArT** (assay):
  - A single phase low-background detector to measure the ^{39}Ar depletion factor of different underground argon batches at Canfranc Laboratory, Spain.



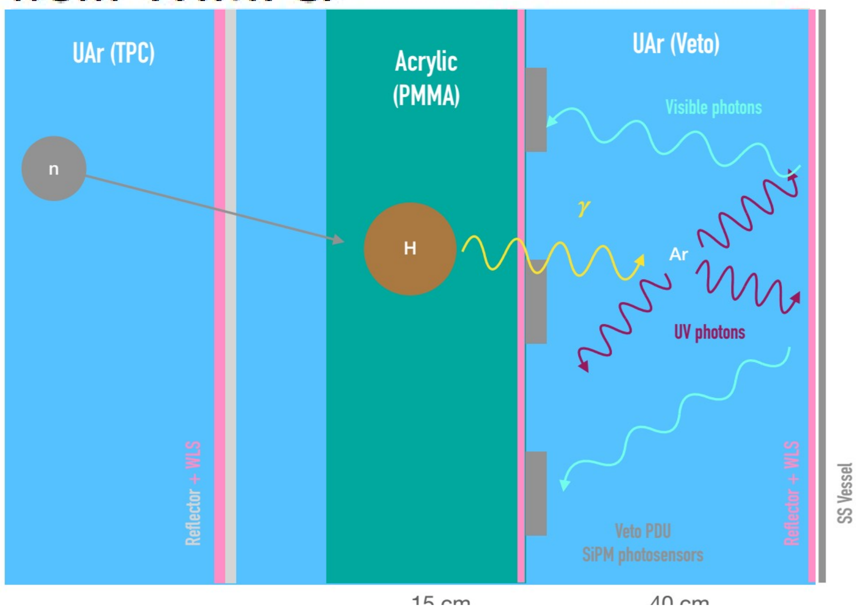
ARIA column

DArT in ArDM

DarkSide-20k: neutron veto



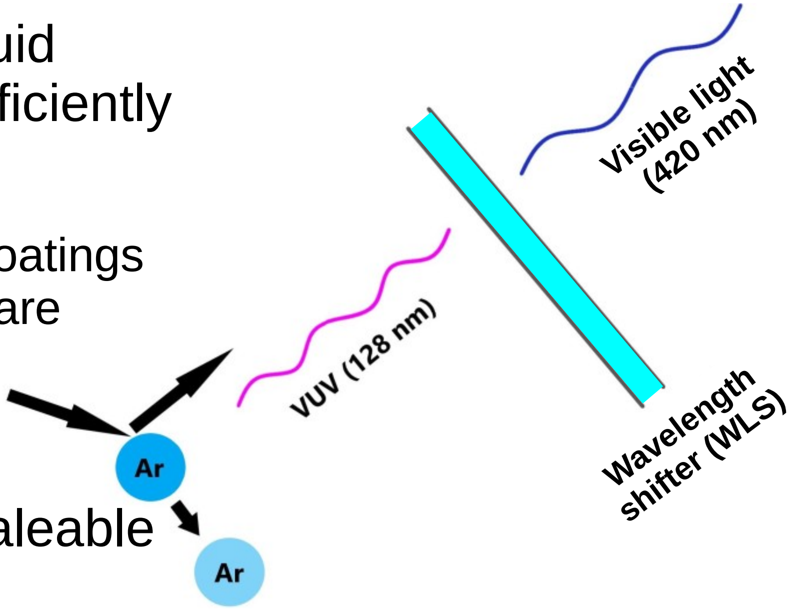
Neutrons elastically scattering from argon nuclei are indistinguishable from WIMPs.



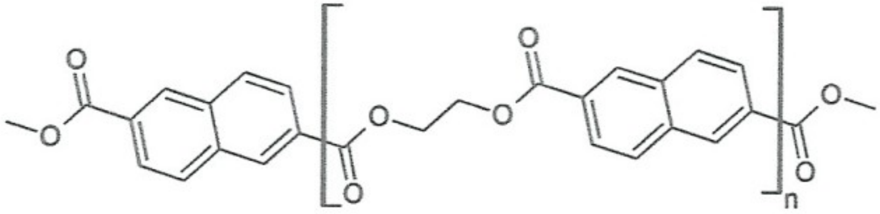
- 40 cm thick space between the steel vessel and PMMA
- 8 walls made of 15 cm thick PMMA
- Enhanced Specular Reflector (ESR) with polyethylene naphthalate (PEN) wavelength shifter foils: ~200 m^2
- Neutrons are moderated in PMMA and captured on hydrogen
- High energy de-excitation gamma is emitted
- Argon scintillation light is wavelength-shifted and detected by vPDUs

Polymeric wavelength shifters for LAr

- Necessary to convert ultraviolet scintillation of liquid argon (at 128 nm) to visible light, which can be efficiently detected
  - Production of standard vacuum evaporated WLS coatings difficult to scale up to large areas (hundreds of square meters and more)



- At **Astrocent** we proposed and demonstrated scaleable large format polymeric reflector and WLS for the DarkSide-20k
  - Polyethylene naphthapate (PEN) foil



  - The material is already procured

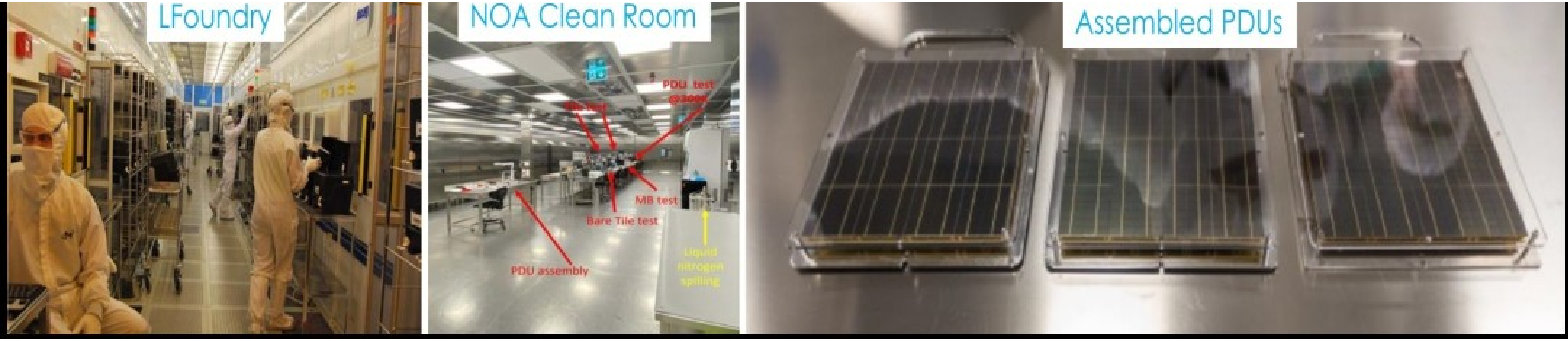
- We are responsible for the design, quality control and installation of the reflectors and WLS for the veto

Our publications:
JINST 20, C06042 (2025)
JINST 20, C05006 (2025)
JINST 20, C05033 (2025)
JINST 19, C05017 (2024)
JINST 19, C05019 (2024)
Nucl. Instrum. Methods Phys. Res. A 1034, 166683 (2022)
JINST 16, P12029 (2021)
Eur. Phys. J. C 81, 1099 (2021)
Instruments 5, 4 (2021)
Nucl. Instrum. Methods Phys. Res. A 968, 163631 (2020)
Eur. Phys. J. C 79, 291 (2019)

DarkSide-20k photodetectors

PDU Production: PDU: NOA@LNGS (ISO-6 clean room) Eur. Phys. J. C 85 (2025) 5

vPDU: Birmingham, STFC interconnect, Manchester, Liverpool



Assembled PDUs tested in a cryogenic test facility in Naples

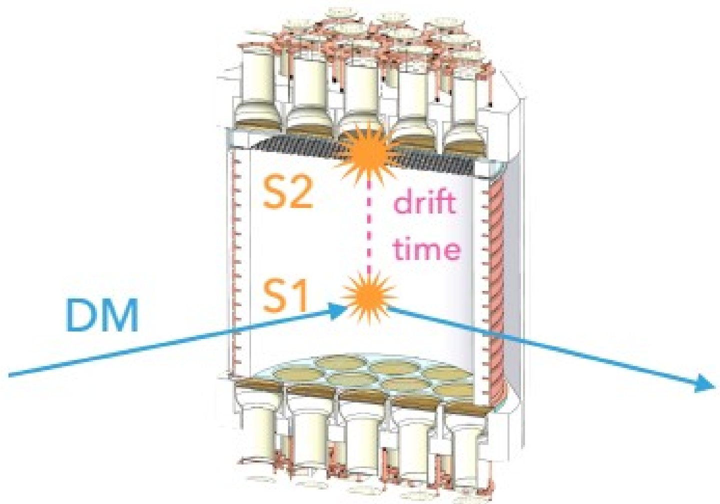
vPDUs cryogenically tested in facilities at **Astrocent**, Edinburgh and Liverpool

Majority of 120 vPDUs to be tested at **Astrocent** in Warsaw.

Testing campaign is currently in progress.

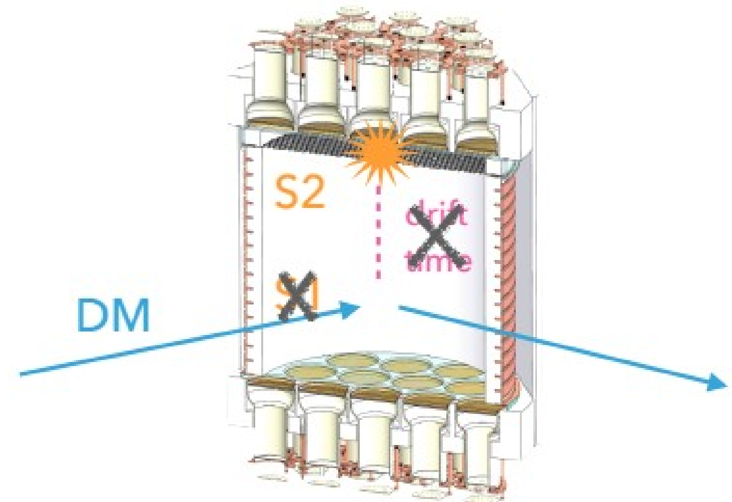
Low-mass WIMP search

High Mass Search
High Energy Events



- Scintillation (S1) & Ionization (S2)
- Pulse Shape Discrimination (PSD)
- Drift time provides vertical event position

Low Mass Search
Low Energy Events

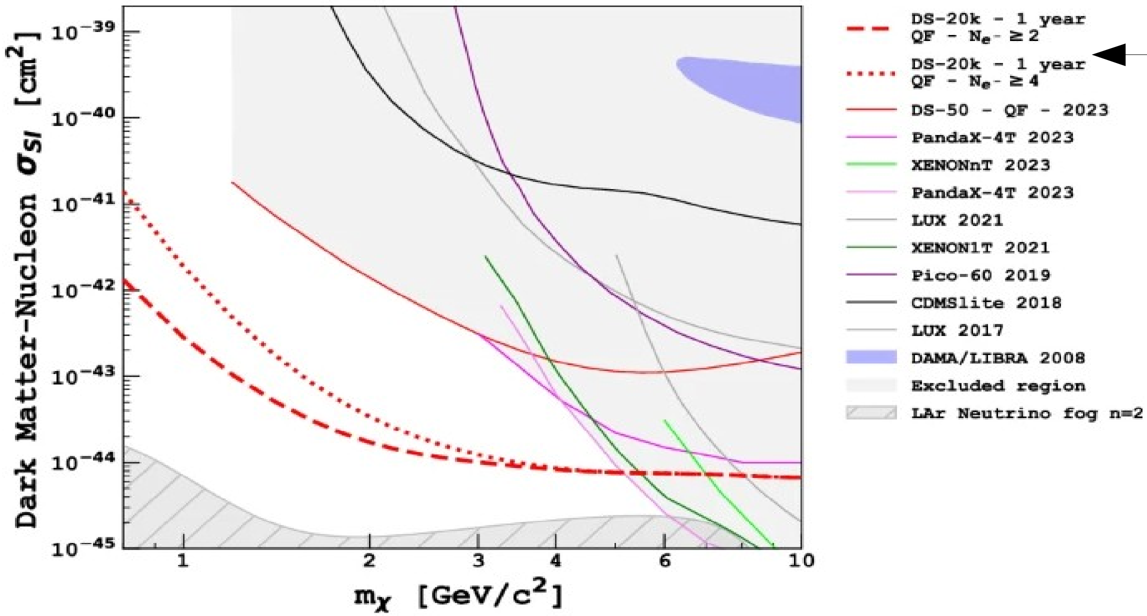


- Electrofluorescence in gas gap lets us detect single e- with high efficiency.
  →**Lower energy threshold**
- **No** PSD
- **No** vertical position

DarkSide-50 achieved leading sensitivity for low-mass WIMPs with S2-only analysis.

Low-mass WIMP sensitivity with LAr

Fig. 3: Expected DS-20k 90% C.L. exclusion limits for spin-independent WIMP–nucleon cross-section (σ_{SI}).

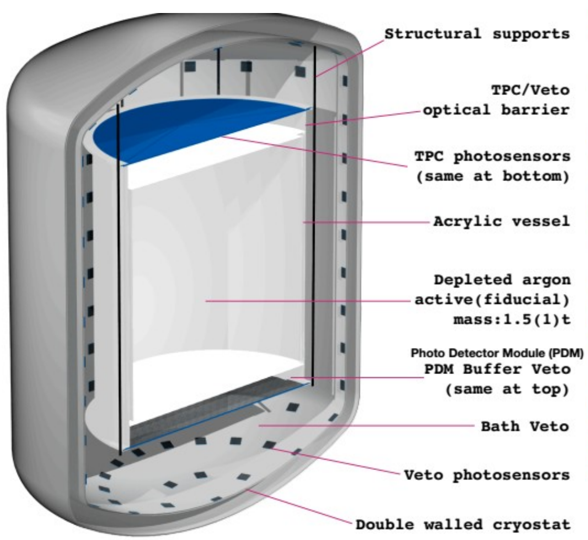


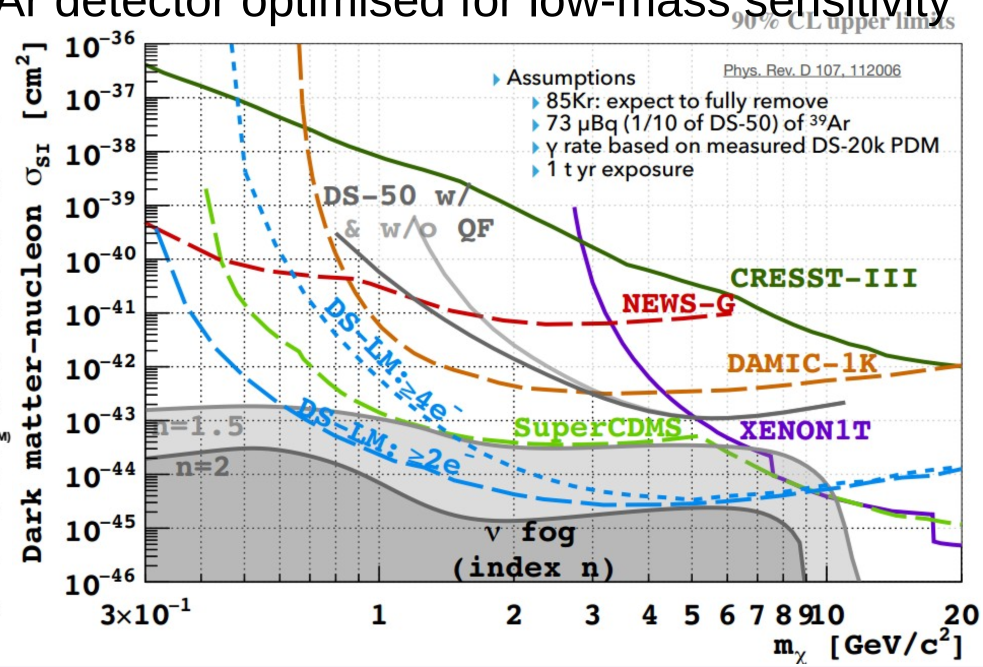
Nominal sensitivity projection for DarkSide-20k for the S2-only analysis.

Commun Phys 7, 422 (2024)

Neutrino fog reachable with a dedicated 1-tonne LAr detector optimised for low-mass sensitivity (currently at conceptual phase).

Phys. Rev. D 107, 112006





Argo: the ultimate detector

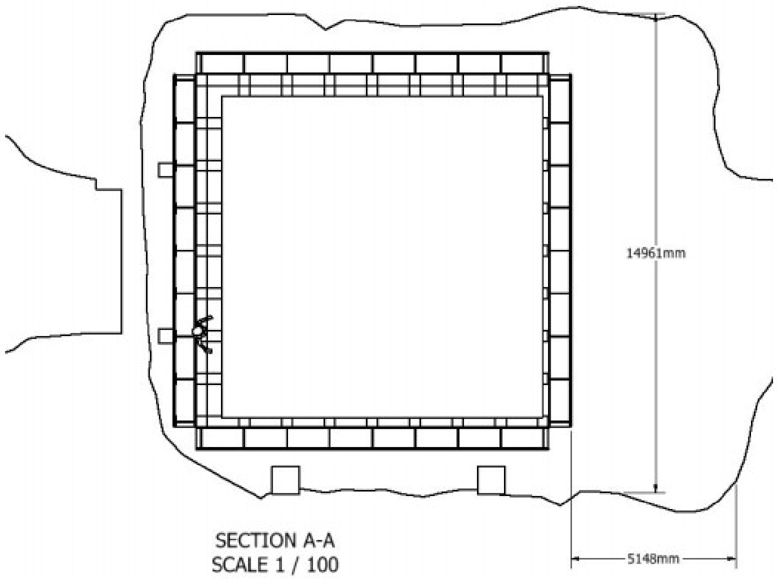
ARGO: Conceptual design

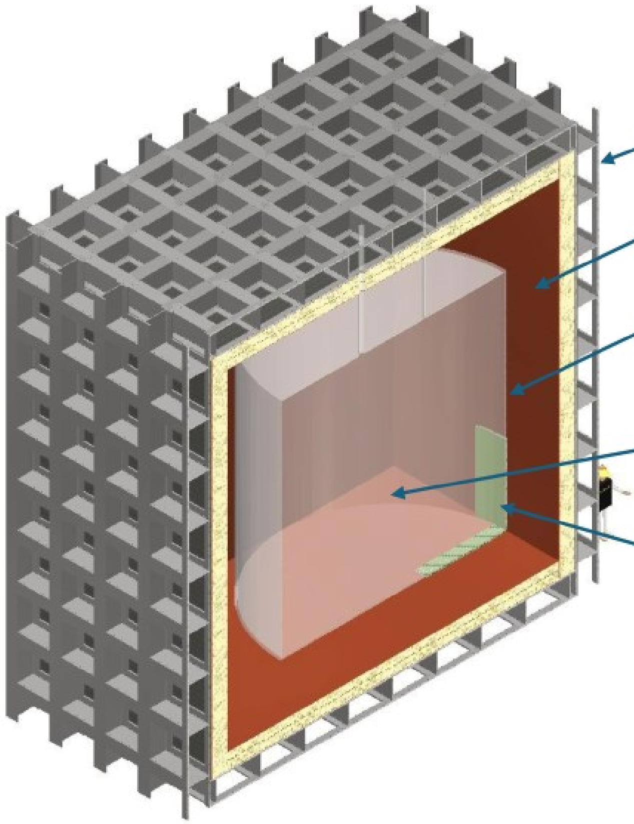
Low-radioactivity argon:
- total 400 tonnes, fiducial 300 tonnes

Pixelated digital photodetector readout

Preferred site: SNOLAB Cube Hall

Current focus in Canada is scintillation-only design, but configuration allows either this or TPC version.





Slide courtesy: Mark Boulay, SNOLAB Future Projects Workshop 2025

Polish contributions

- Jagiellonian University, Kraków
  - M. Czubak, M. Haranczyk, T. Pelczar, T. Mróz, M. Wójcik, **G. Zuzel**
  - Radiopurity assays, selection of materials, Rn monitoring

    -> See poster “Pb-210 and Po-210 as a background source in the DarkSide Experiment” by Milena Czubak
- Astrocent, CAMK PAN, Warszawa
  - I. Ahmad, S. Belayneh, S. Choudhary, A. Cortez, **M. Kuźniak**, M. Kuźwa, G. Nieradka, M. Olszewski, C. Sunny, **M. Wada**, A. Zabihi, P. Zakhary
  - DS-20k veto reflectors and WLS. vPDU cryo testing.
  - ReD and Aria operations and analysis
  - DS-50 analysis. DS-LM and Argo concepts and R&D.
- Warsaw University of Technology
  - A. Buchowicz, G. Galiński, **G. Pastuszak**
  - DAQ, online analysis/data compression

Summary

- Nature of dark matter is one of the most exciting mysteries in physics, with a real potential for groundbreaking discovery
- Liquid Argon based detectors well positioned in the global race for such discovery, with the ultimate sensitivity within reach in the next decades
- Exciting new and well motivated physics within reach of DarkSide-20k
- Construction in progress, installation on site at LNGS upcoming
- High impact contributions of the Polish groups to the Global Argon Dark Matter Collaboration program
- Contact me if interested in projects/openings for students or postdosc

Backup

Group profile

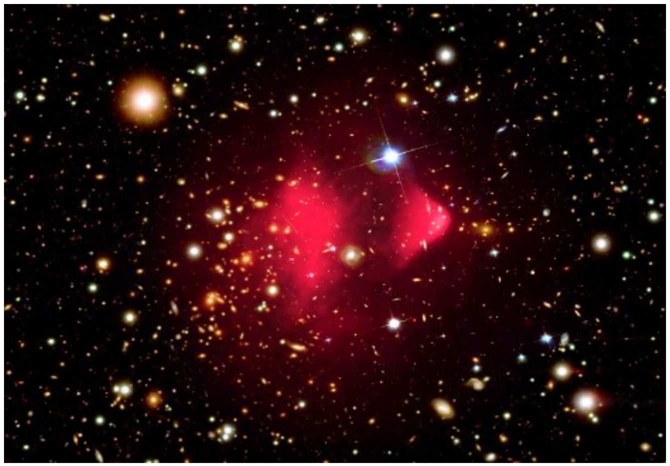
- Group members:
  - **Leader** Marcin Kuźniak
  - **PhD students:**
    - Sarthak Choudhary (graduated in June)
      - Pulse shape discrimination analysis + light collection optimization
    - Iftikhar Ahmad (graduated in February)
      - SiPM testing for DarkSide-20k
    - Samuel Belayneh
      - Reflectors and WLS for DarkSide-20k

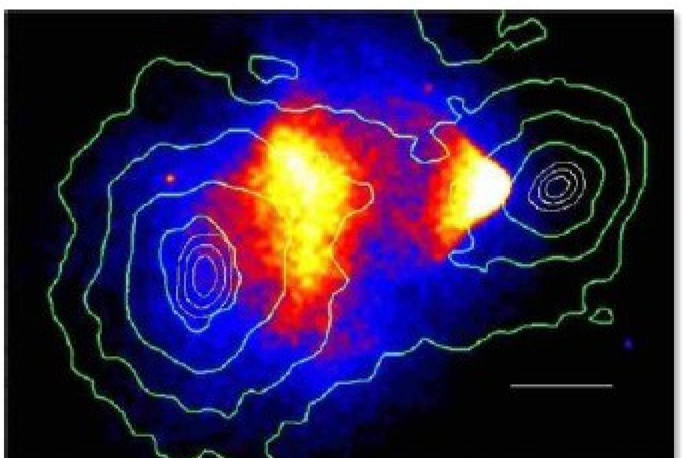
  - **Postdocs:**
    - Michał Olszewski
      - Monte Carlo simulations
      - DEAP-3600 WIMP data analysis
  - **MSCA Fellow:** Andre Cortez
  - **Support from technicians and an engineer**

- Past members: Theo Hugues, Cenk Turkoglu, Marek Walczak
- Access to electronics, chemistry and cryogenic (cleanroom) lab at CEZAMAT
- Cooperation agreement with the University of Warsaw, Chemistry Department

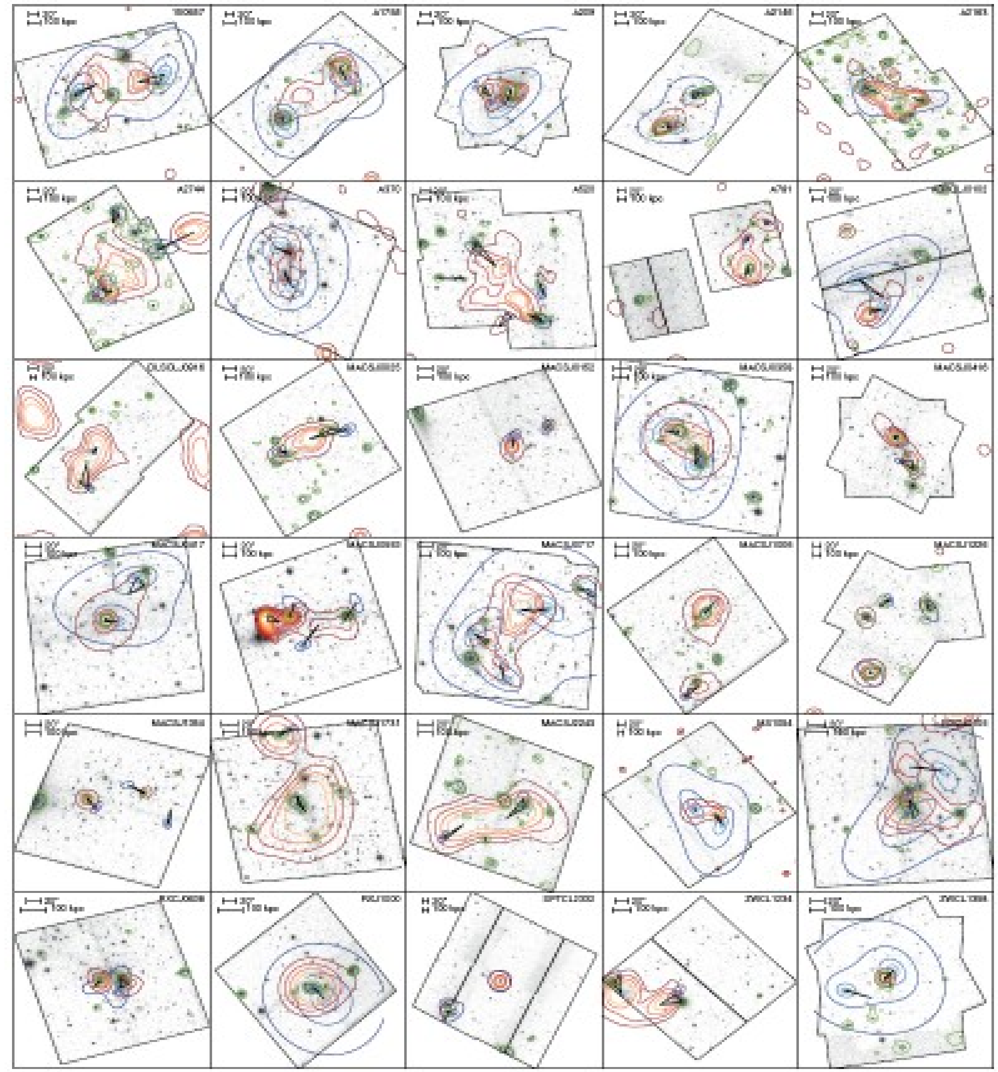
More evidence for Dark Matter

- Gravitational lensing observations (Bullet Cluster, ...)





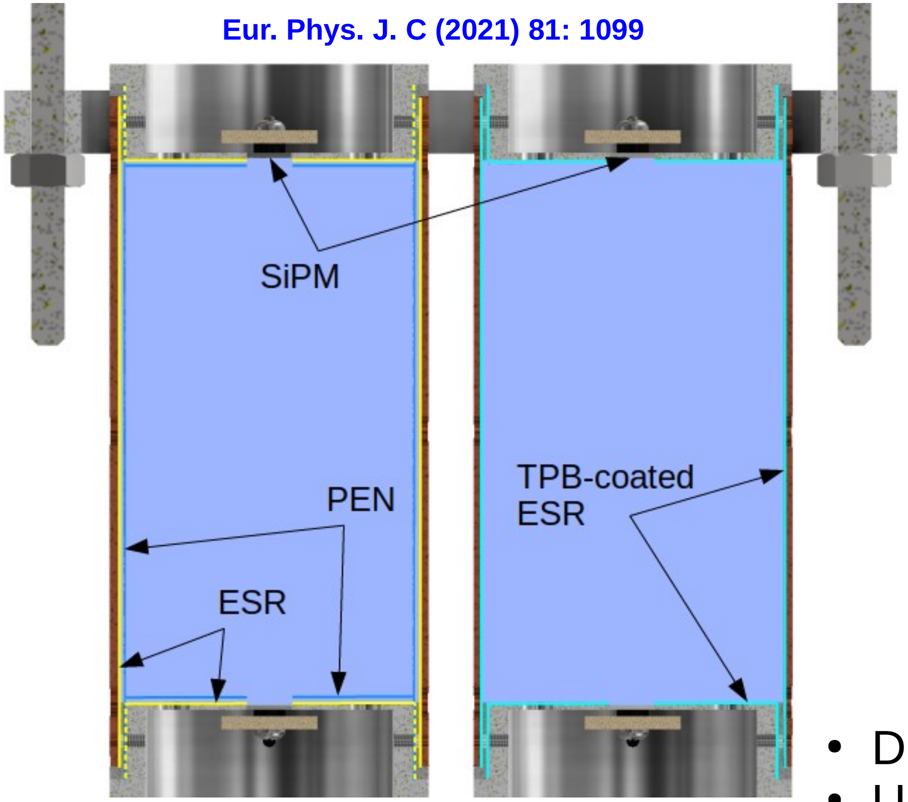
The bullet cluster, D. Clowe et al., 2006



D. Harvey & al., Science, March 27, 2015.
72 new colliding systems! (Also gives bounds on self-interacting DM.)

WLS test setup 2PAC designed/built @Astrocent

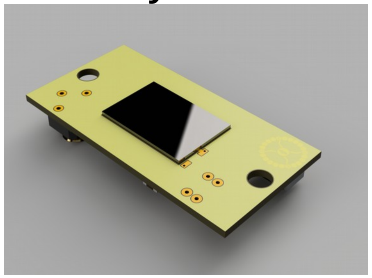
Eur. Phys. J. C (2021) 81: 1099

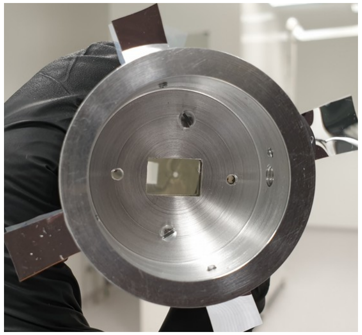


Approx. 5 cm diameter each

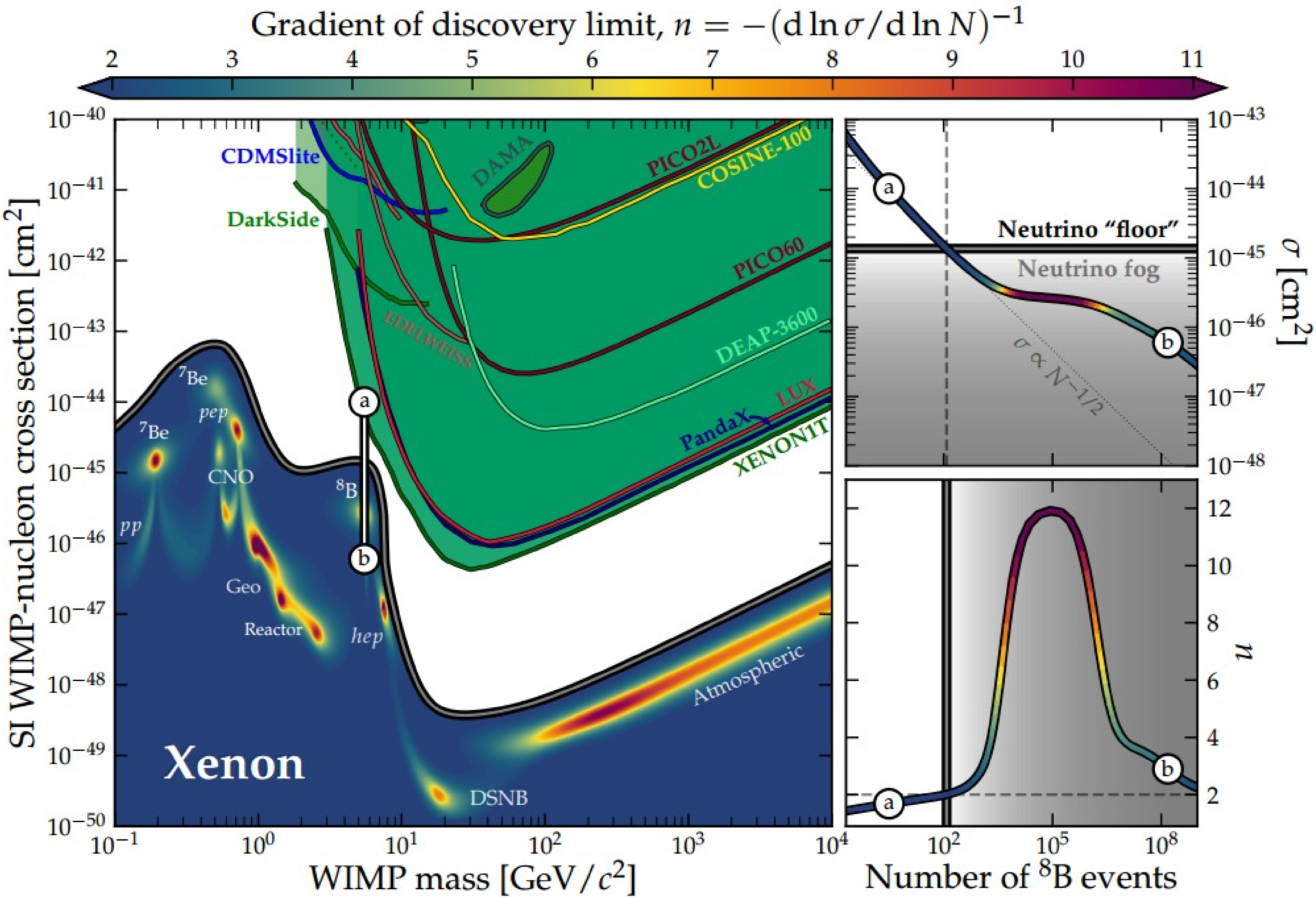
- Dual-chamber system immersed in a LAr bath at LNGS
- Using Teonex Q51, 25 micron thick (identified as the most promising in ex-situ measurements).

“DArT-eye” SiPMs





Designed, fabricated, optically characterized and simulated at AstroCeNT.



Phys. Rev. Lett. 127, 251802 (2021)

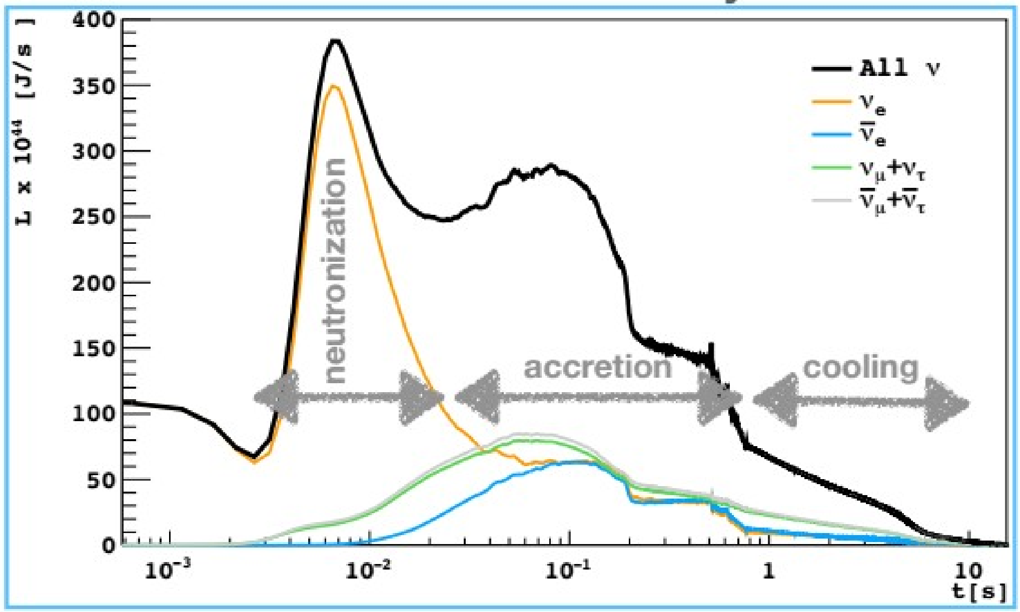
SENSITIVITY TO SUPERNOVA NEUTRINOS

- **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 ($\nu_e +^{40}$ Ar $\rightarrow^{40}$ K* $+ e^-$).

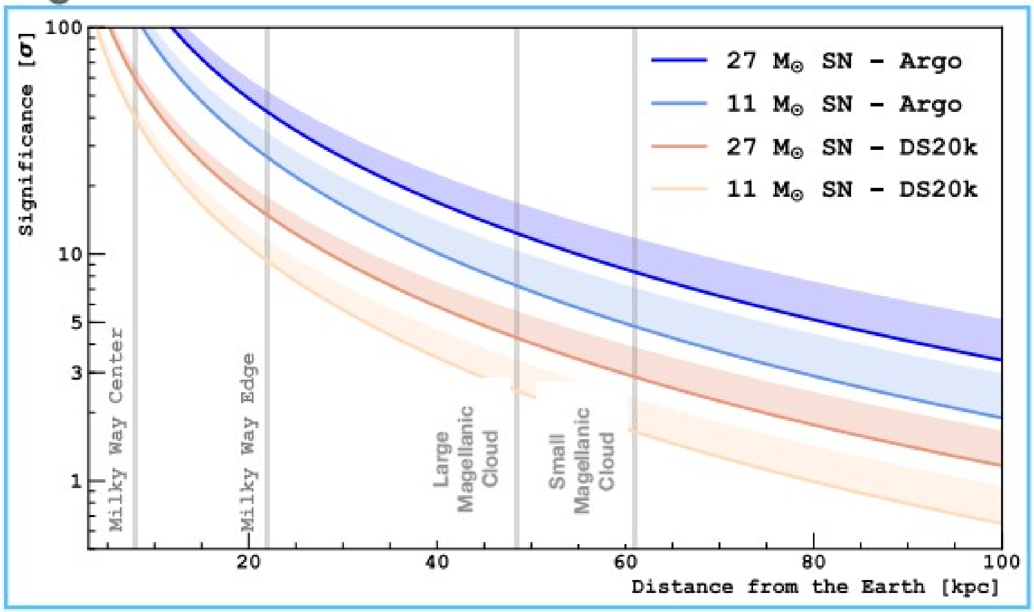
$\langle E_\nu \rangle$~10 MeV

- DS-20k (Argo, future detector) can detect **all flavor (anti)neutrinos** via coherent elastic neutrino-nucleus scattering (CEvNS).

Time evolution of neutrino luminosity from SN



Significance to $11M_\odot$ and $27M_\odot$



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.**

M. Wada, TAUP2025

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