中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Exploring Low-Mass Dark Matter with the DarkSide Detectors

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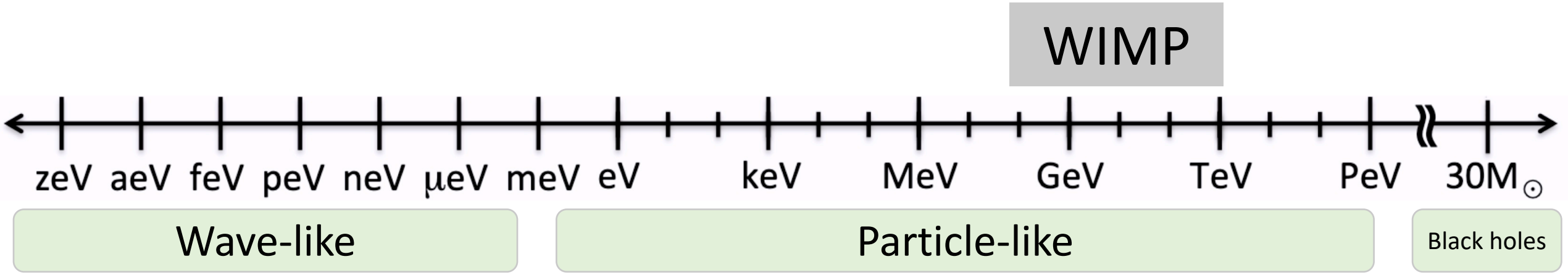
for the Global Argon Dark Matter Collaboration

ICHEP 2024

Prague, Czech Republic 07/18/2024

Direct Search for Dark Matter



- Weakly Interacting Massive Particles (WIMPs)

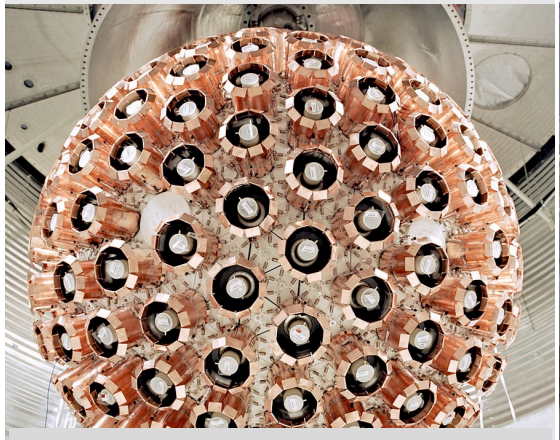
  > 10 GeV/c^2 high-mass;

  subGeV ~ 10 GeV/c^2 low-mass.
- Light dark matter.
- Dark matter searches with liquid argon -> The Global Argon Dark Matter Collaboration.

The GADMC

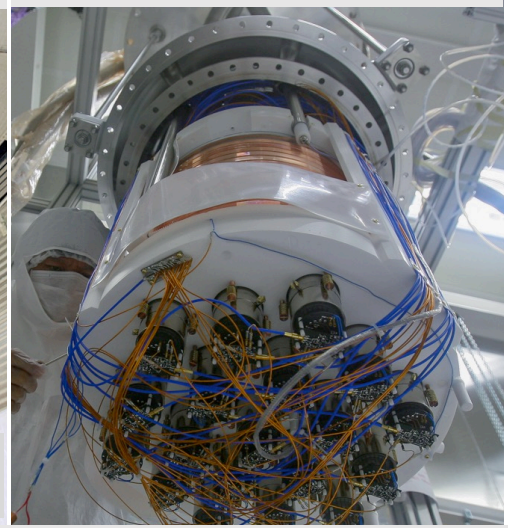
- Global Argon Dark Matter Collaboration;
- Established in 2017;
- >500 collaborators, >100 institutes, 14 countries.

DEAP-3600 @SNOLAB



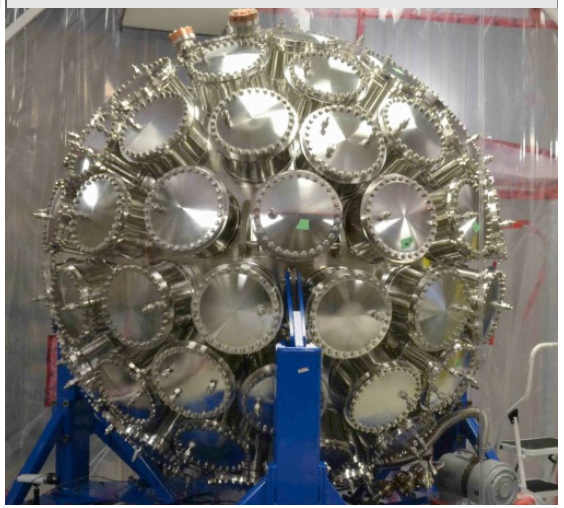
See Michela Lai's talk !

DarkSide-50 @LNGS



ArDM @LSC

miniCLEAN @SNOLAB



DarkSide-20k (high-mass 200 ty)

DarkSide-LowMass (low-mass 1 ty)

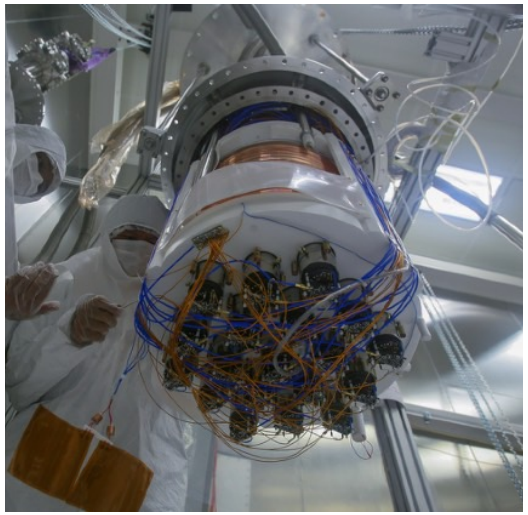
ARGO (high-mass 3000 ty)

The Roadmap of DarkSide

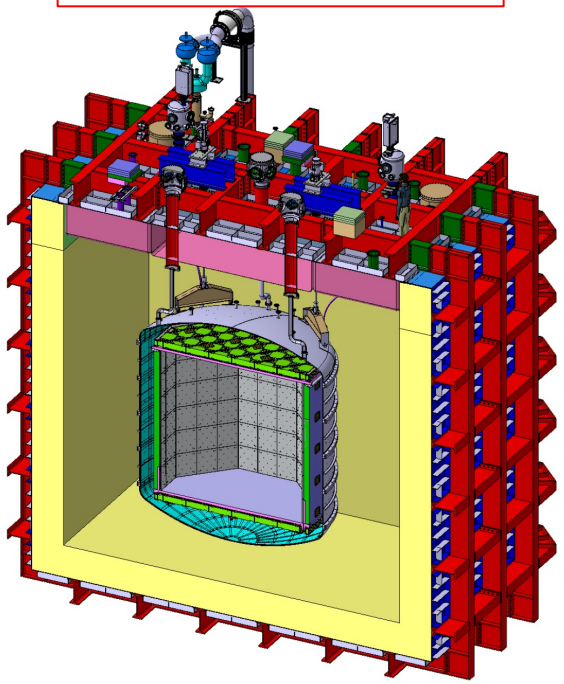
- ✓Dual-phase argon time projection chamber (DAr-TPC);
- ✓Argon from underground source.

Direct Dark Matter Search in the DarkSide-20k Experiment
By Daria Santone
Dark Matter session, July 18th, 09:55

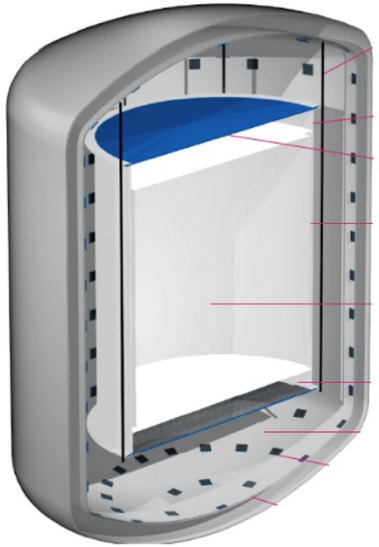
DarkSide-50
46.4 kg active



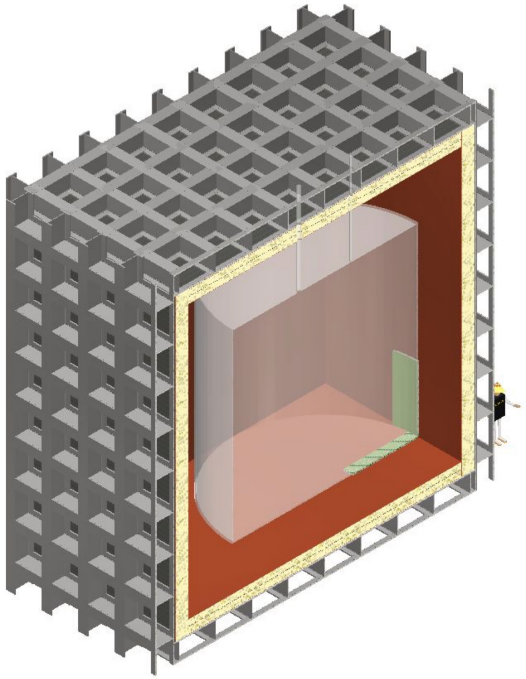
DarkSide-20k
49.7 tonnes active



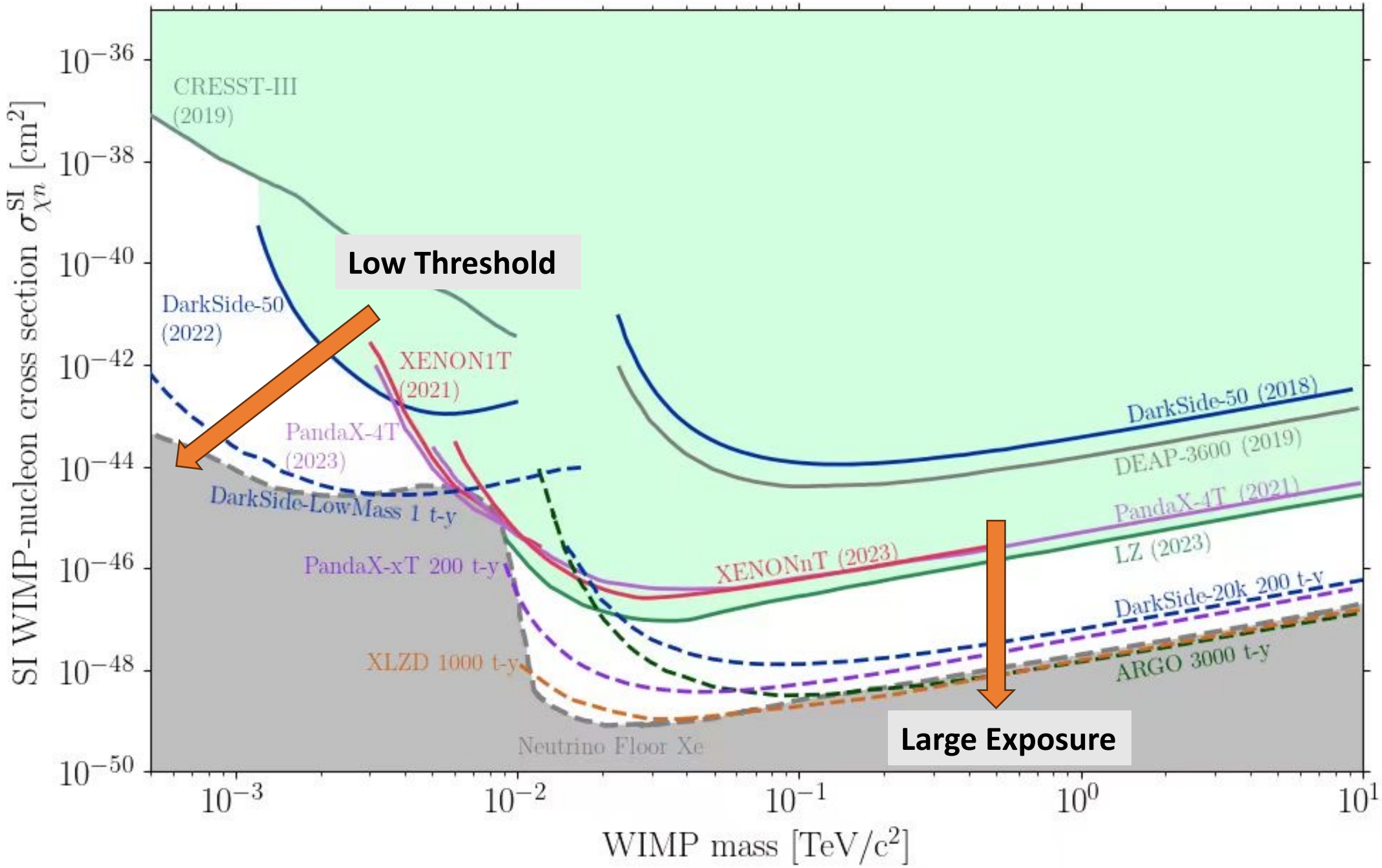
DarkSide-LowMass
1 tonne-year exposure



ARGO
3000 tonne-year exposure

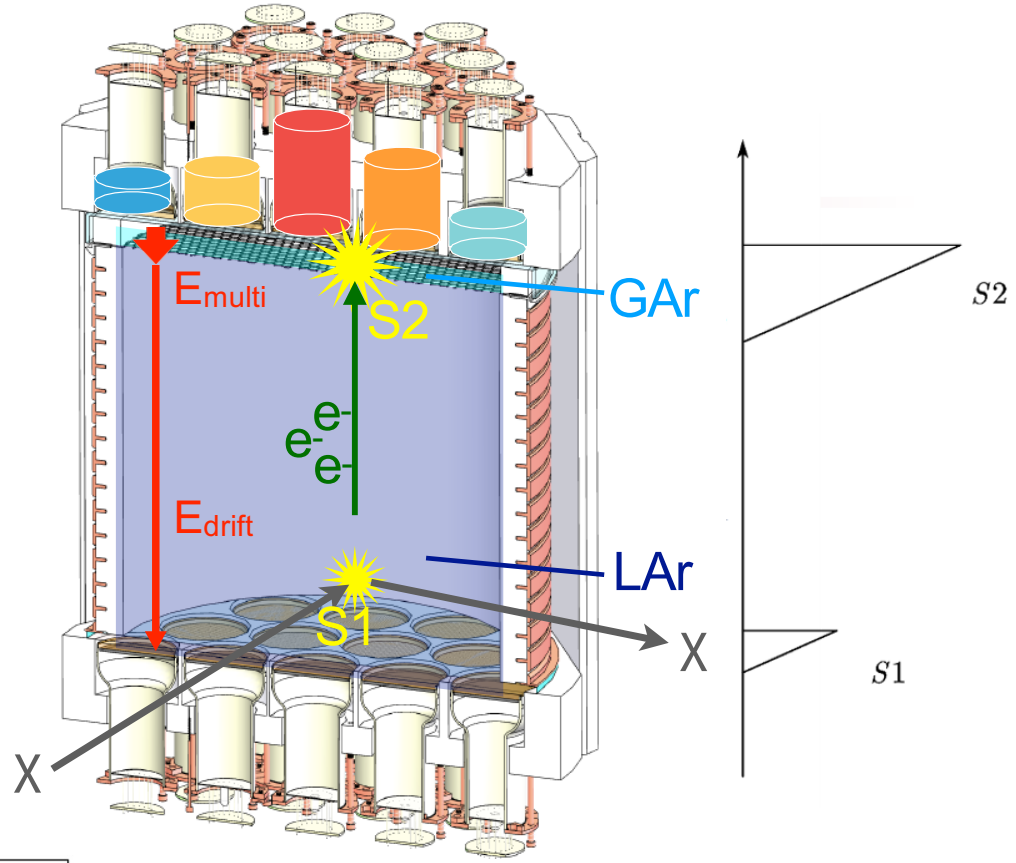


2013~2021 → **2026~** → **2029~** → **2030s**

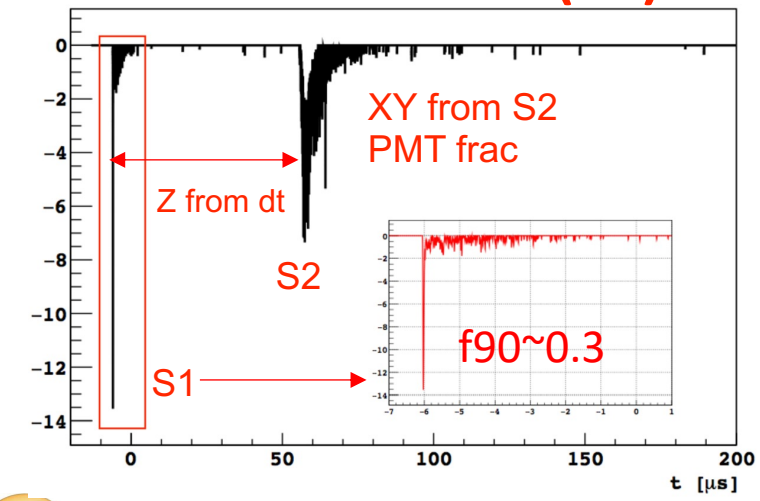

CRESST-III (2019)
Low Threshold
DarkSide-50 (2022)
XENON1T (2021)
PandaX-4T (2023)
DarkSide-LowMass 1 t-y
PandaX-xT 200 t-y
XLZD 1000 t-y
Neutrino Floor Xe
XENONnT (2023)
DarkSide-50 (2018)
DEAP-3600 (2019)
PandaX-4T (2021)
LZ (2023)
DarkSide-20k 200 t-y
ARGO 3000 t-y
Large Exposure
SI WIMP-nucleon cross section $\sigma^{SI}_{\chi n}$ [cm^2]
WIMP mass [TeV/c^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

DAr-TPC for High Mass

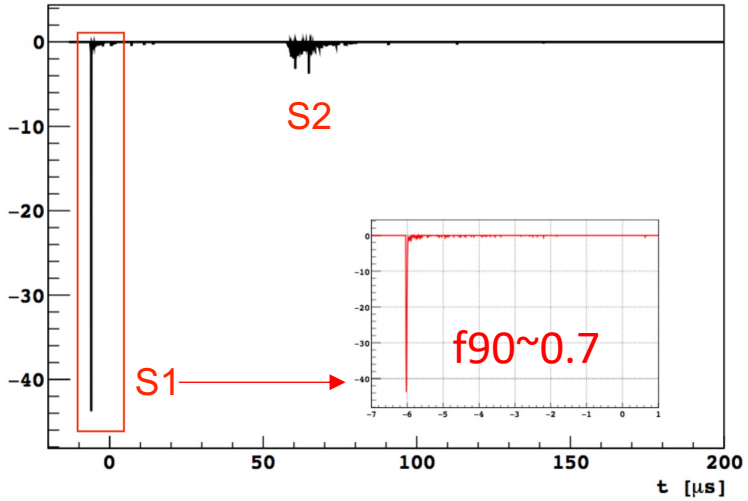
- Scintillation (S1) + Ionization (S2);
- 3D positioning using T_{drift} and S2 distributions;
- 128 nm -> wavelength shifter -> 420 nm;
- Pulse shape discrimination (PSD):
  - De-excitation time: singlet 6 ns, triplet 1.5 us;
  - Electron recoil background rejection > $1x10^8$;
  - f90: ratio of light in the first 90 ns (S1).

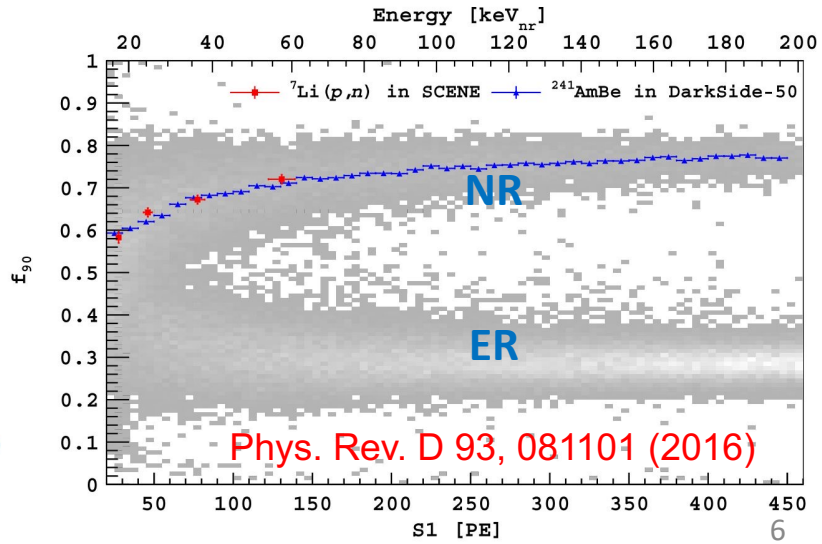


Electron Recoil (ER)



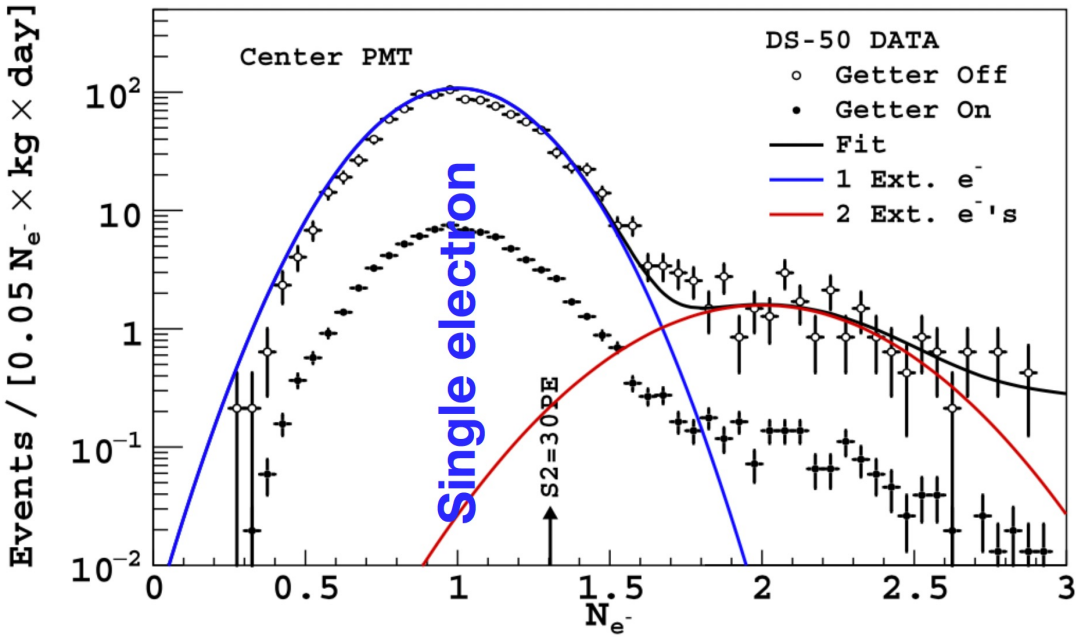
Nuclear Recoil (NR)



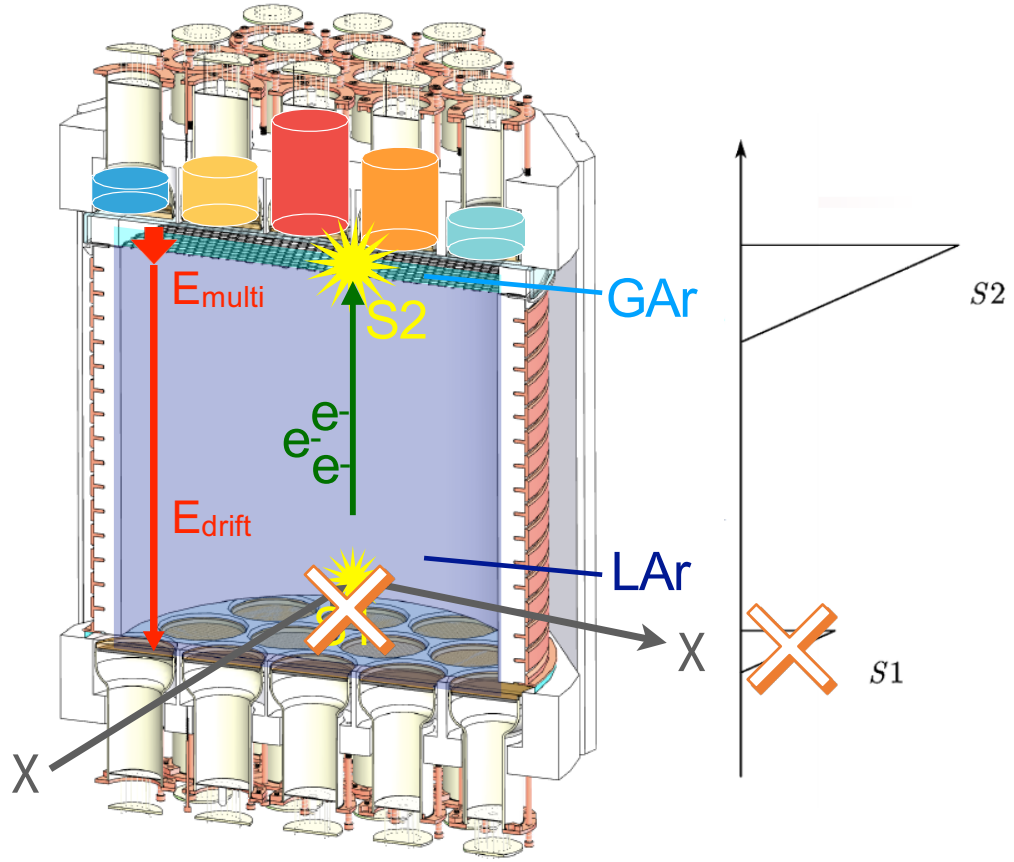


DAr-TPC for Low Mass

- Ionization (S2) signal only
  - ☹ NO PSD;
  - ☹ NO drift time for Z position.
  - ☺ Sensitive to single electron, g2 > 23 p.e./e^-;
  - ☺ Low threshold.



Phys. Rev. Lett. 121, 081307 (2018)



Scintillation signal (S1):

threshold at ~2 keVee / 6 keVnr;

Ionization signal (S2):

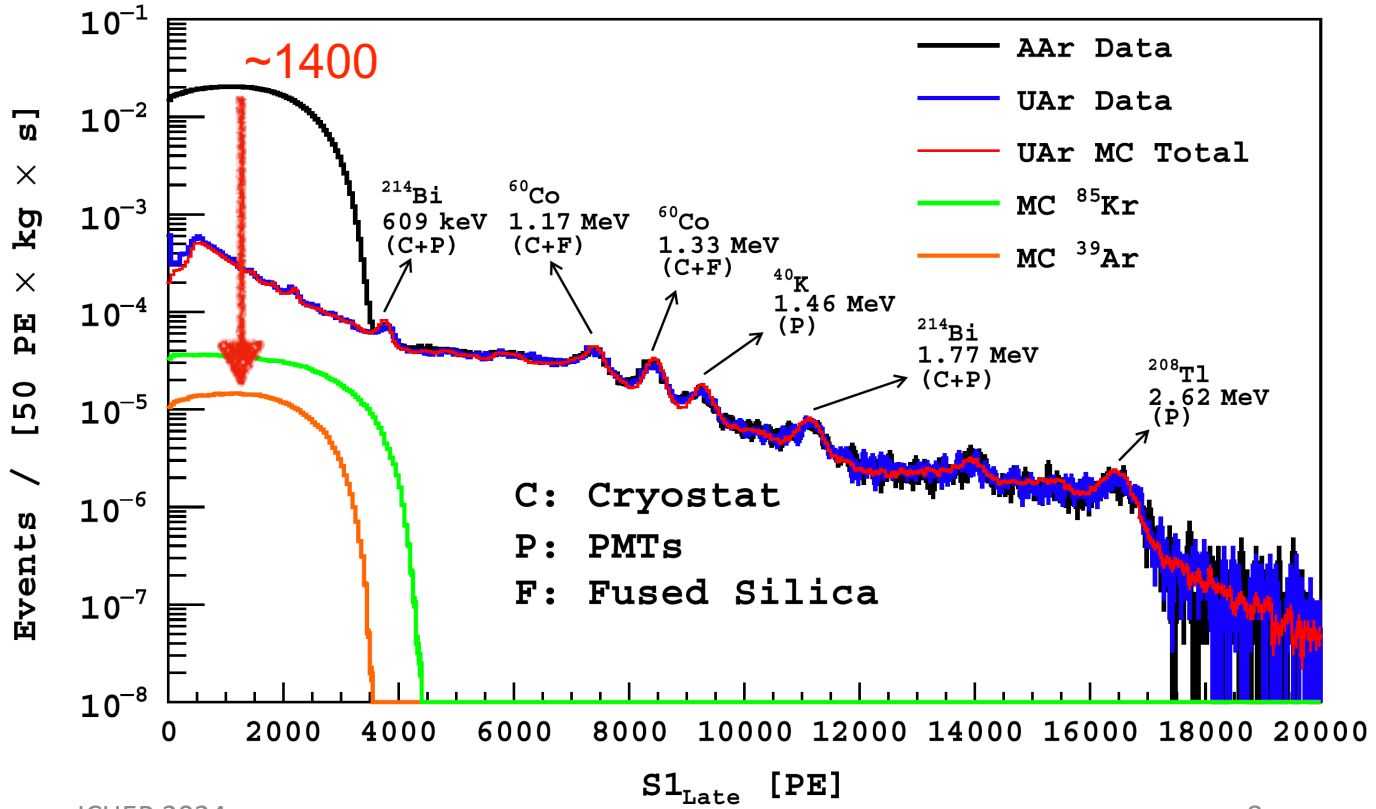
threshold < 0.1 keVee / 0.4 keVnr.

Underground Argon (UAr)

- Atmospheric argon (AAr) has intrinsic ^{39}Ar radioactivity ~1 Bq/kg;
- β decay with 565 keV endpoint, 269 years half-life;
- ^{39}Ar activities set the threshold at low energies.

- ^{39}Ar is a cosmogenic isotope;
- Argon from underground sources has significantly lower ^{39}Ar concentration than AAr;
- CO_2 well in Colorado, USA;
- 160 kg UAr extracted for DarkSide-50:
  - ➢ ^{39}Ar reduction factor ~1400.

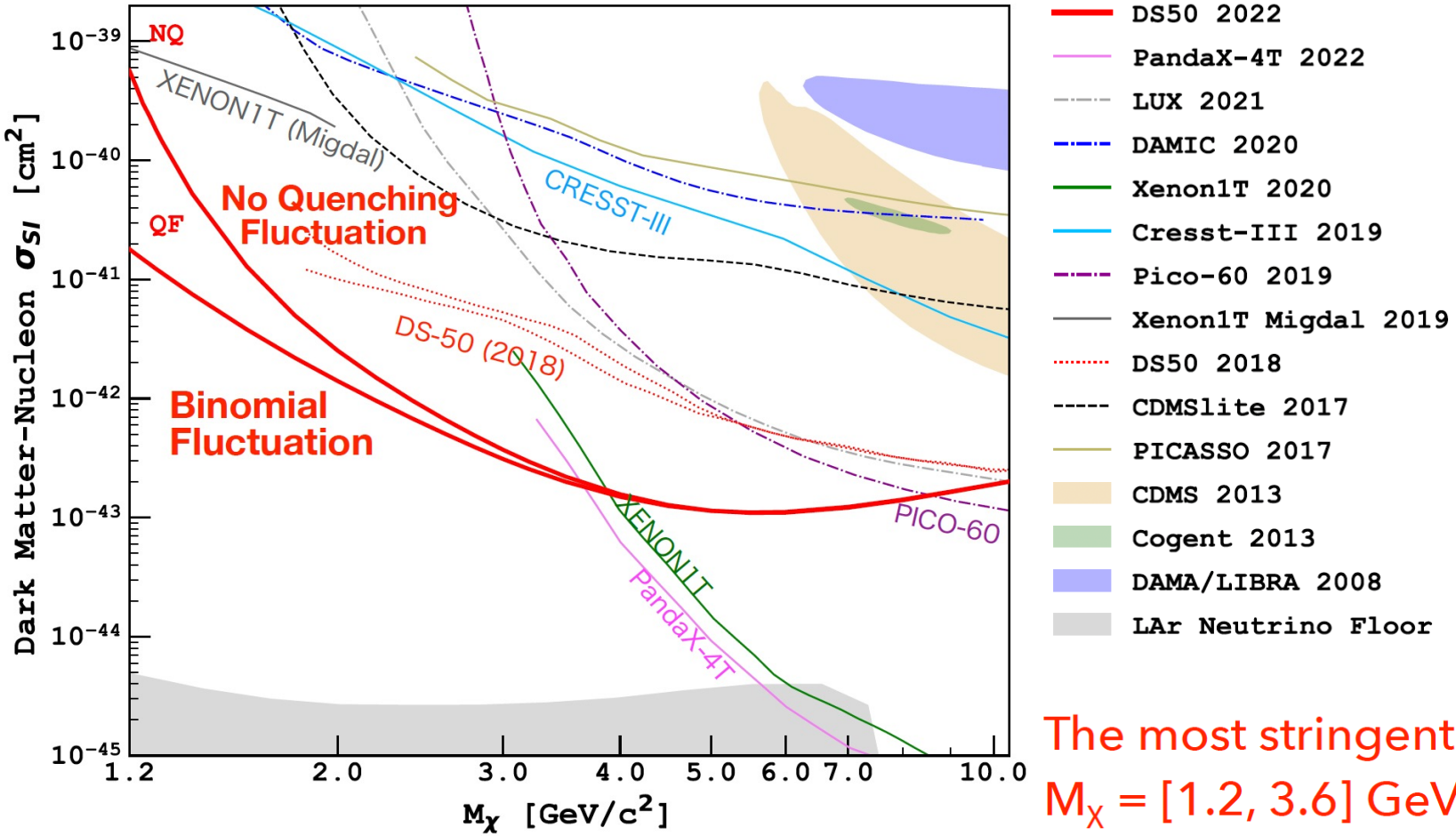
Phys. Rev. D 93, 081101 (2016)



DarkSide-50 Low-mass Results

Phys. Rev. Lett. 121, 081307 (2018)
Phys. Rev. D 107, 063001 (2023)

- Ionization only analysis (S2 only); N_{e^-}=4.
- 6.78 t-days results in 2018, 12 t-days results in 2023.

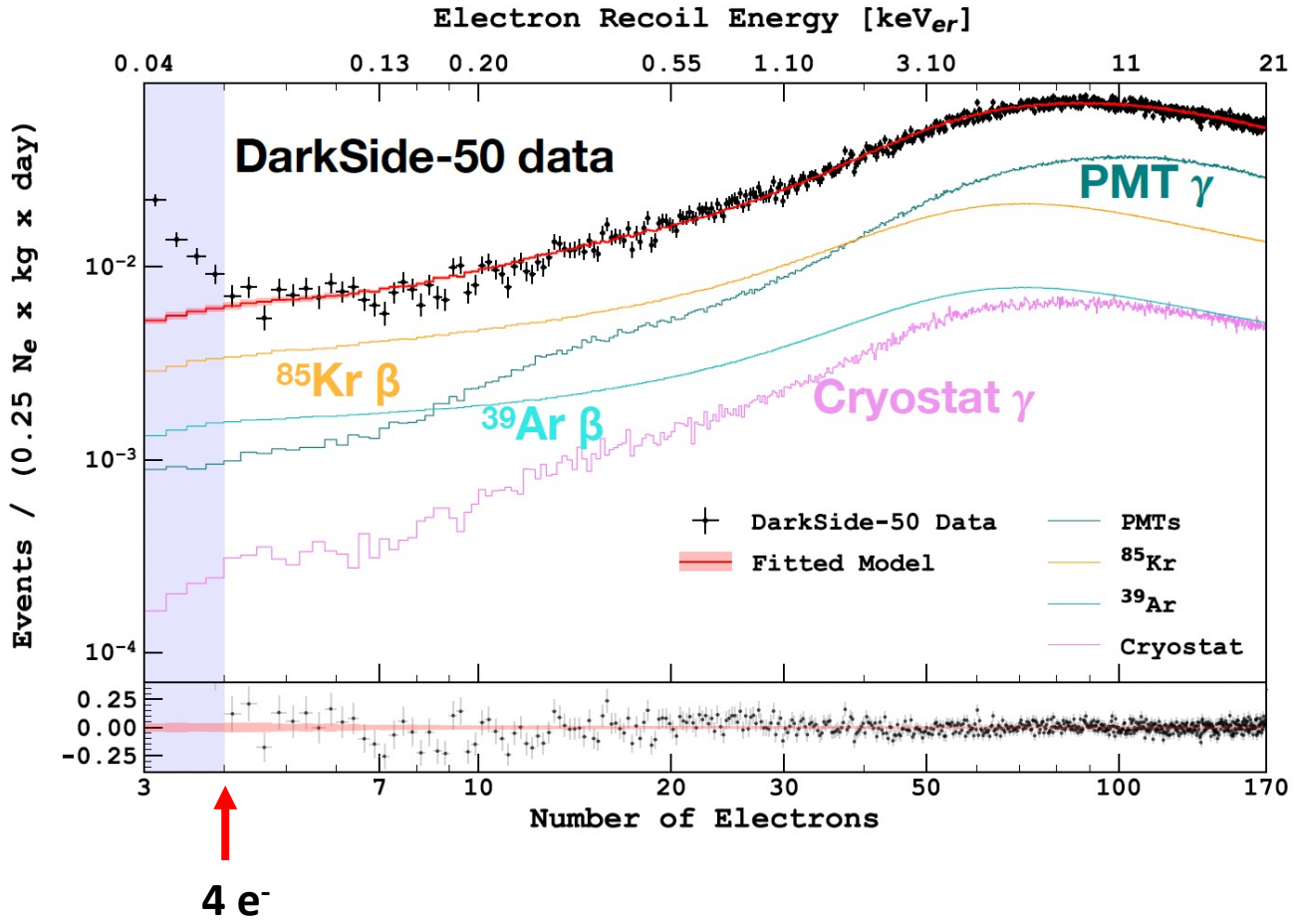


The most stringent limit at
M_χ = [1.2, 3.6] GeV/c^2

Lessons Learned from DarkSide-50

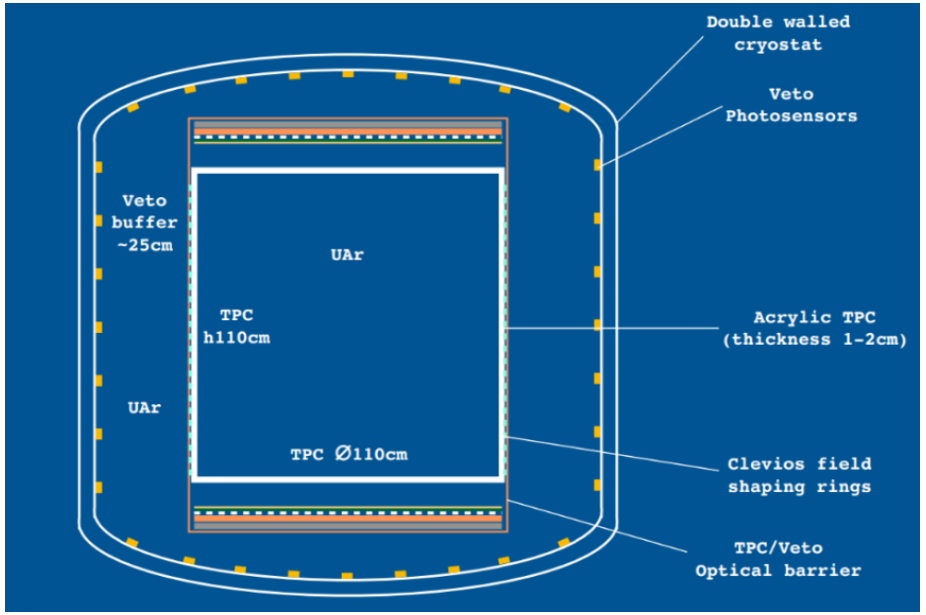
- Intrinsic β from ^{85}Kr and ^{39}Ar;
- γ from detector materials;
- Spurious electrons that set the threshold limit;
- LAr response in the low energy region.

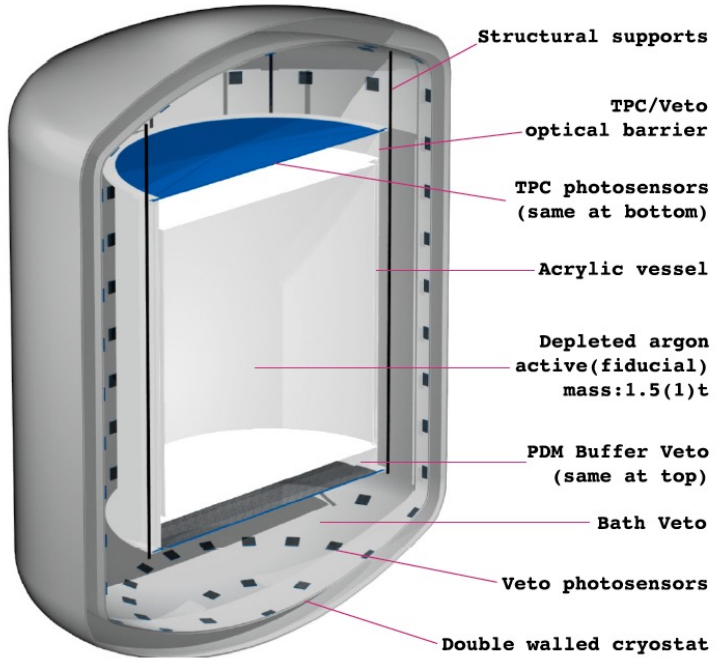
- Of course, the exposure is limited due to the size of the detector ~ 46 kg fiducial.



DarkSide-LowMass

- Dedicate to WIMP mass < 10 GeV/c^2.
- A tonne-scale dual-phase Ar TPC,
  - ~1 tonne active mass.
- Background mitigation:
  - Lower ^{39}Ar;
  - Ultra-pure photosensor;
  - Radiopure cryostat;
  - Radio-pure TPC material, e.g. acrylic from JUNO;
  - Buffer volume to suppress γ backgrounds;
  - Suppression of the spurious electrons.
- Additional strategy to lower the threshold:
  - High electric field to increase g2;
  - Xe doping.



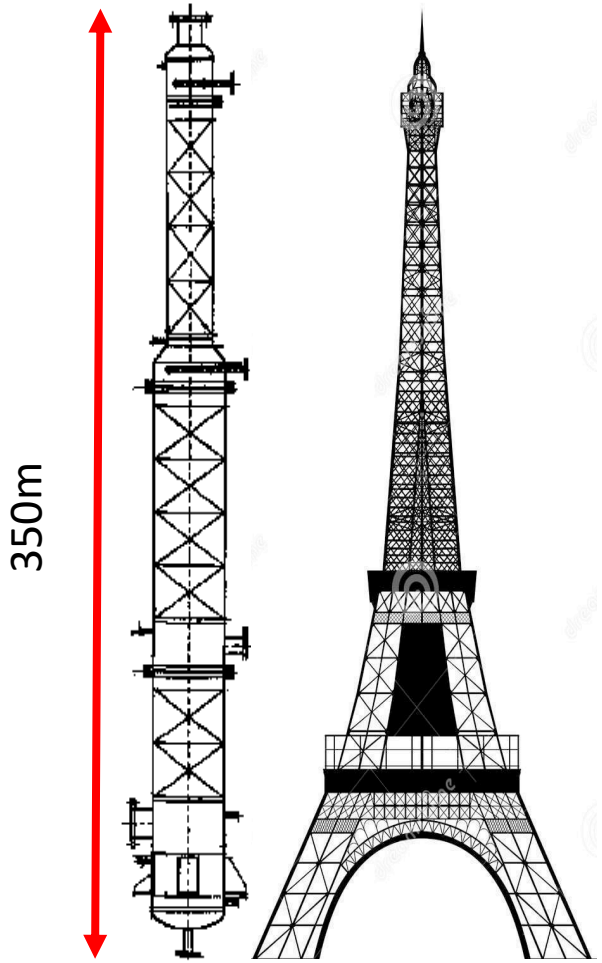


Phys. Rev. D 107, 112006 (2023)

Depleted Argon

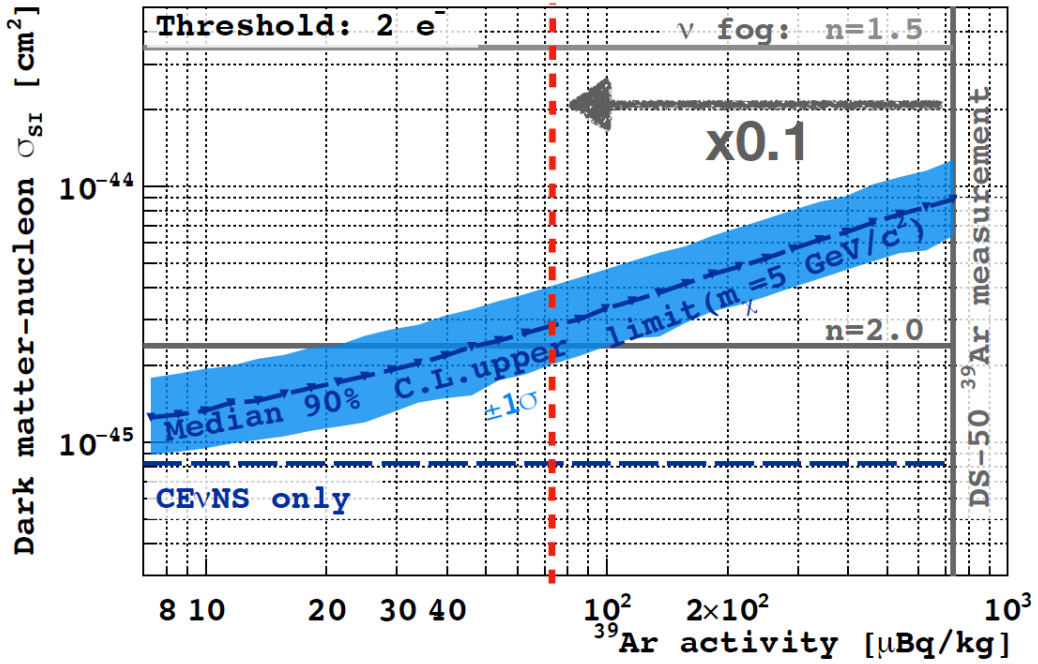
Production, Purification and Assay of Underground Argon for DarkSide-20k
By Devidutta Gahan
Dark Matter session, July 19th, 11:57

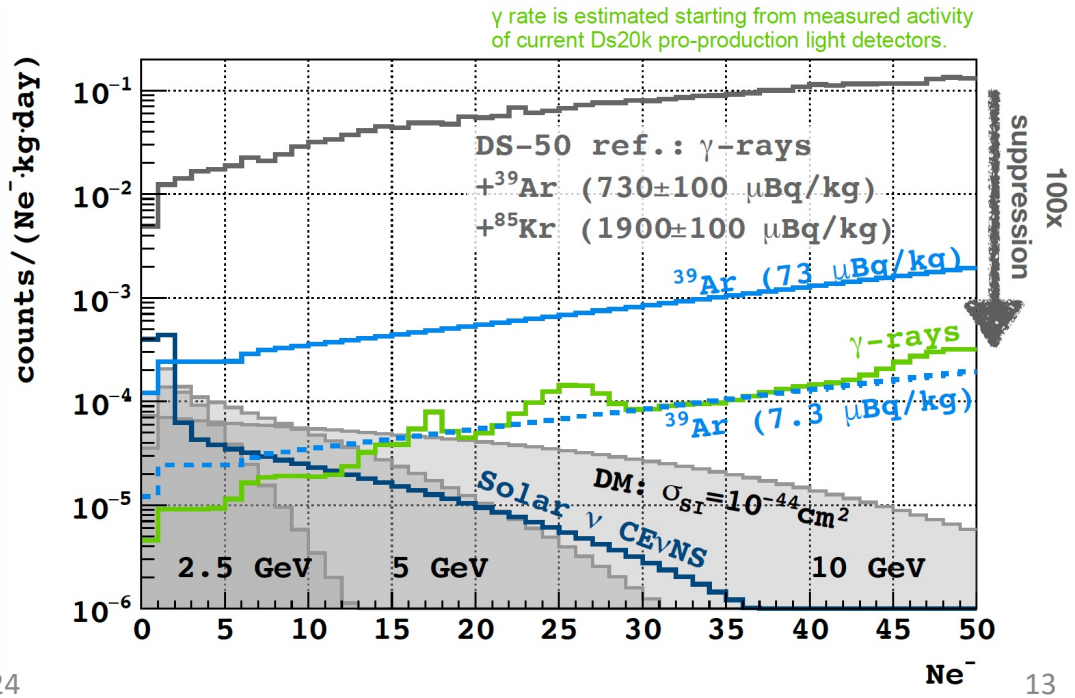
- Further reduce the residual ^{39}Ar from underground argon using the ARIA facility.
- The ARIA facility:
  - 350 m tall cryogenic distillation column in Sardinia, Italy;
  - Chemical purification rate O (1 tonne/day), e.g. for Kr removal;
  - UAr purity after ARIA: 99.999%;
  - Additional purification to separate ^{39}Ar from ^{40}Ar.
  - Seruci-0 tested, Seruci-1 under construction.
- Details about the cosmogenic activation: Astropart. Phys. 152 (2023) 102878



Depleted Argon

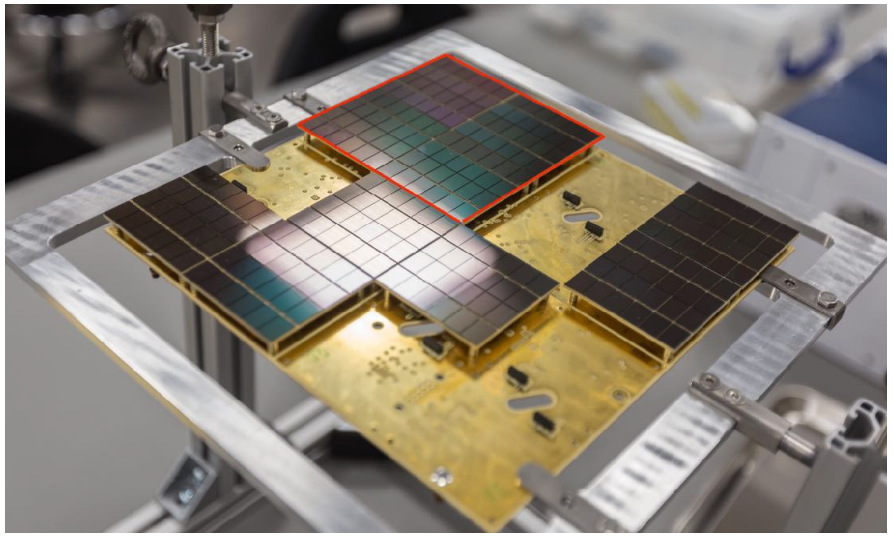
- In DarkSide-50:
  - ^{39}Ar ~0.73 mBq/kg;
  - ^{85}Kr ~1.9 mBq/kg.
- At least a factor of 10 reduction of ^{39}Ar per pass is expected with ~10 kg/day.
- After ARIA:
  - ^{39}Ar 7.3~73 µBq/kg;
  - ^{85}Kr negligible.



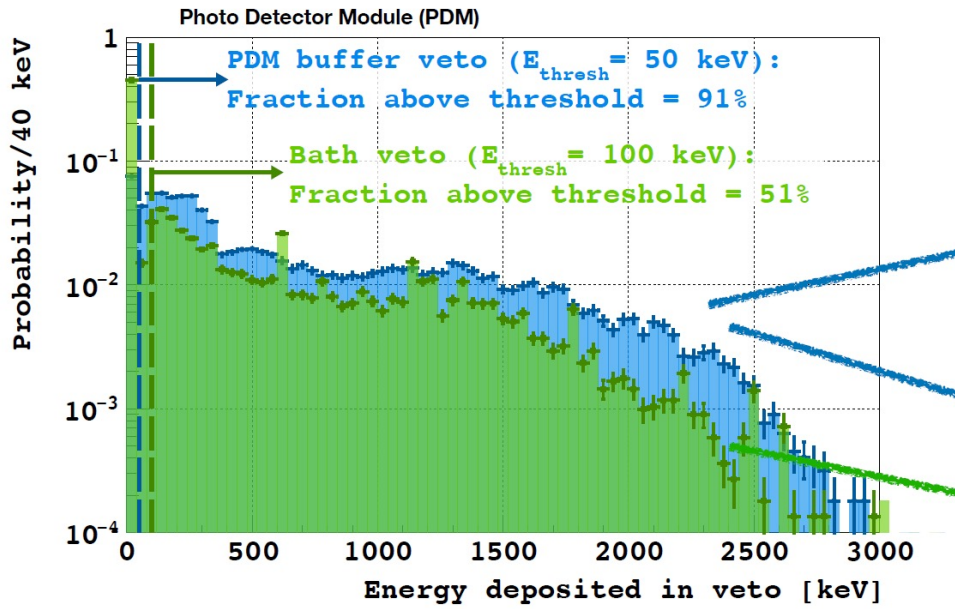


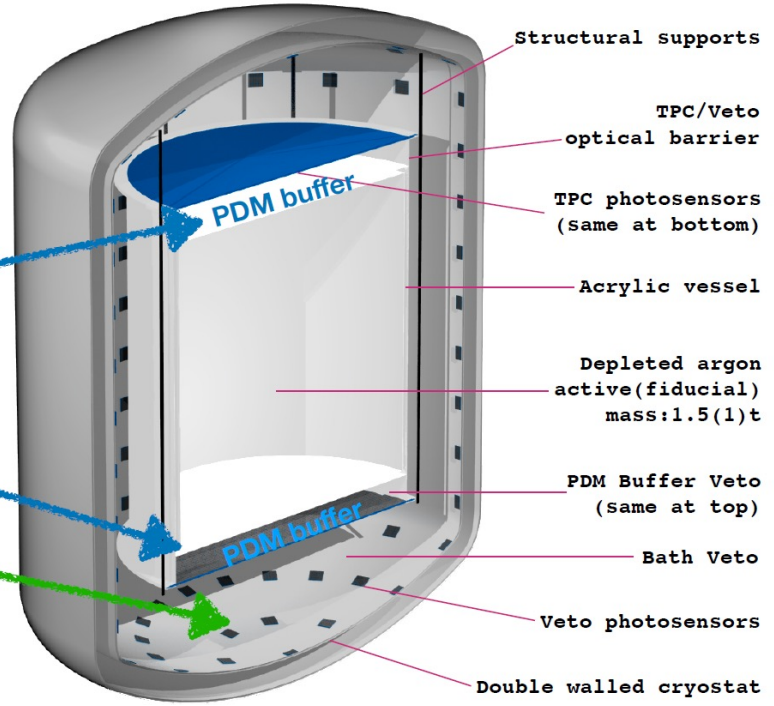
Gamma Backgrounds

- SiPM developed for DarkSide-20k:
  - Radiopure;
  - Compact packaging;
- Cryostat: ultra-pure SS or Ti.
- Designed buffer volumes.



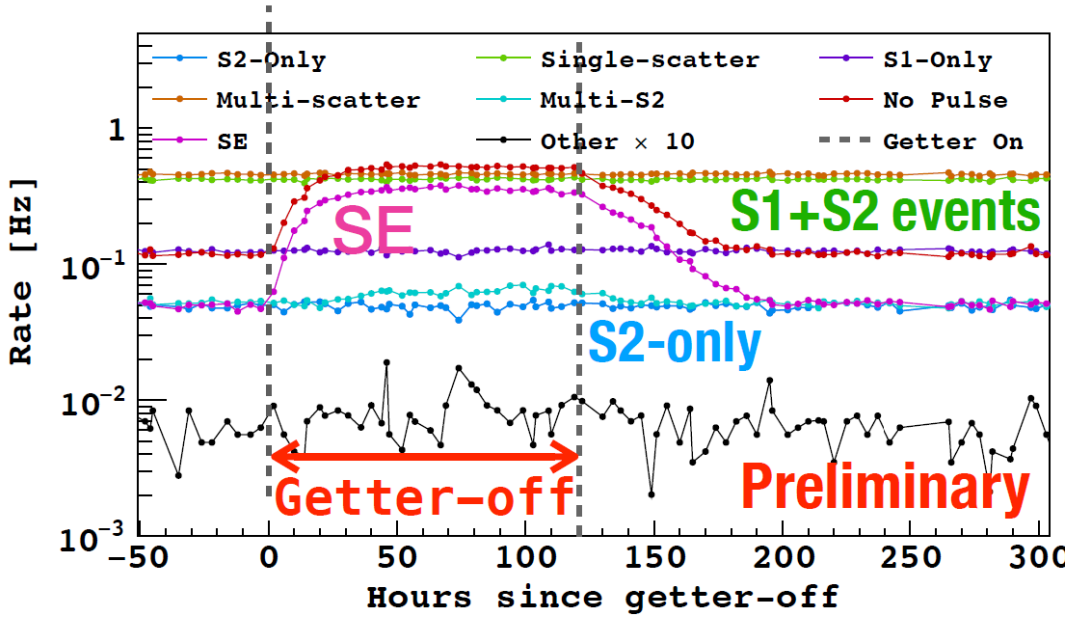
DarkSide-20k Veto PhotoDetector Units: construction and characterization
By Paolo Franchini
Poster session

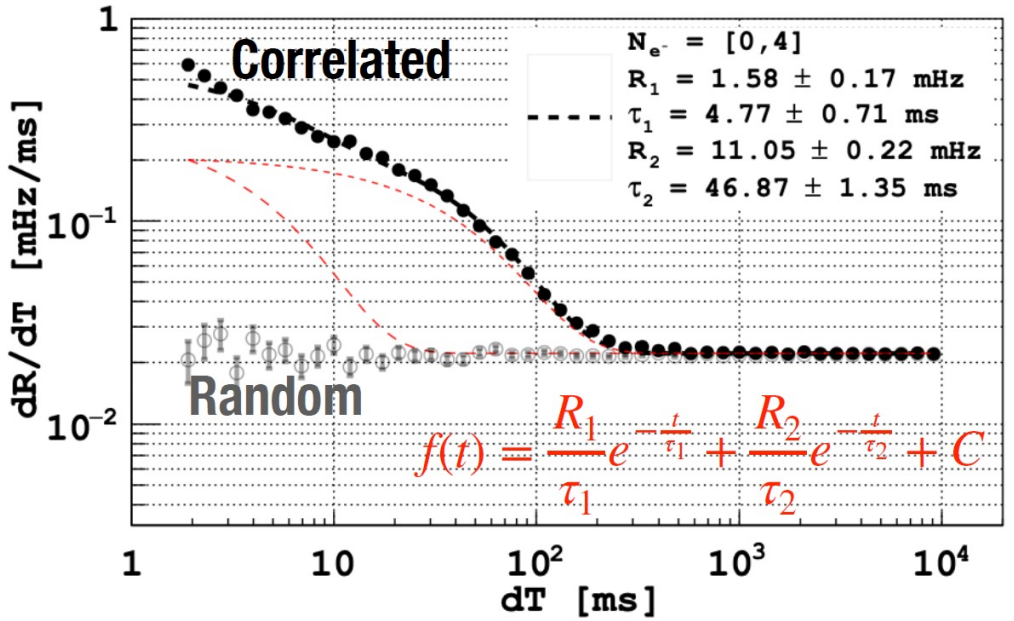




Spurious Electron (SE)

- Events < 4 e^- behave differently from the other S2-only events;
- Determines the threshold, can we reach 2 e^- ?
- SE study with DarkSide-50 data is ongoing.
- Possible sources: impurities, delayed electrons… R&D is ongoing.





A dedicated paper regarding the DarkSide-50 SE analysis will be posted on arXiv soon!

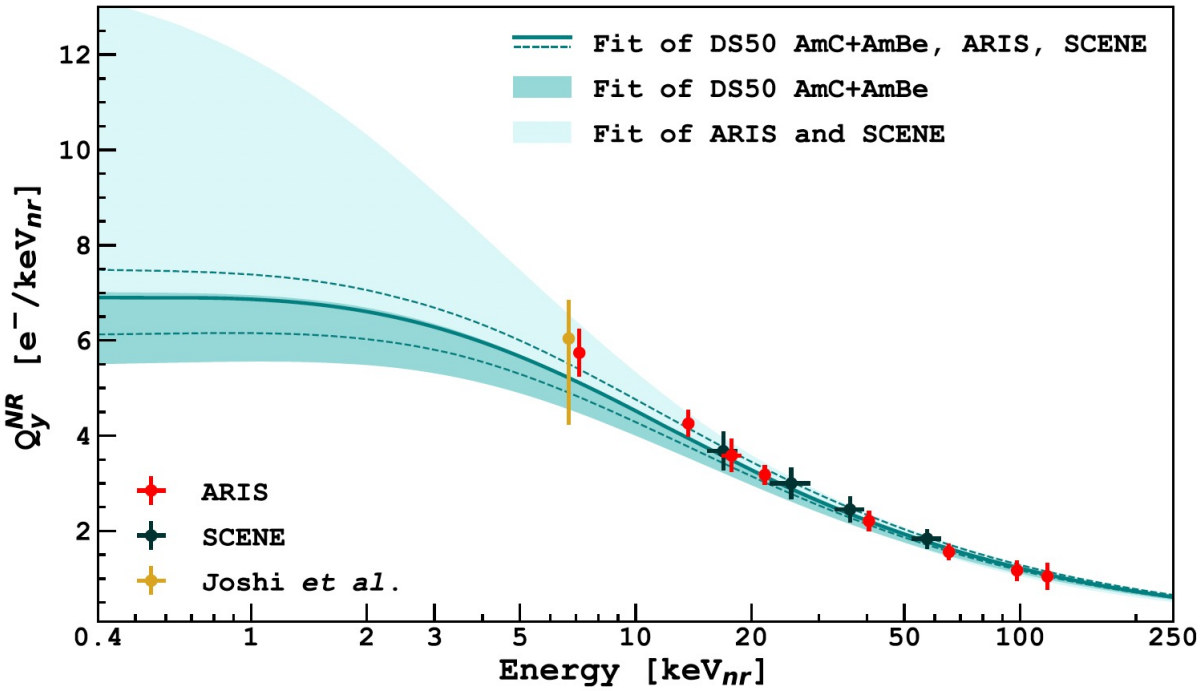
Calibration of Low-Energy Nuclear Recoil

- Calibration of the low-energy (< ~7 keVnr) nuclear recoil response in liquid argon is still missing;
- Crucial for the low-mass dark matter search analysis;
- Several stand-alone calibration experiments are ongoing for this purpose:
  - ReD and ReD+ in Italy, with ^{252}Cf and D-D gun, in operation:

    Eur. Phys. J. C (2021) 81:1014
    Eur. Phys. J. C (2024) 84:24

  - A dual-phase argon TPC test with a neutron beam is scheduled to operate in early 2025 at IHEP in China.

Phys. Rev. D 104, 082005 (2021)

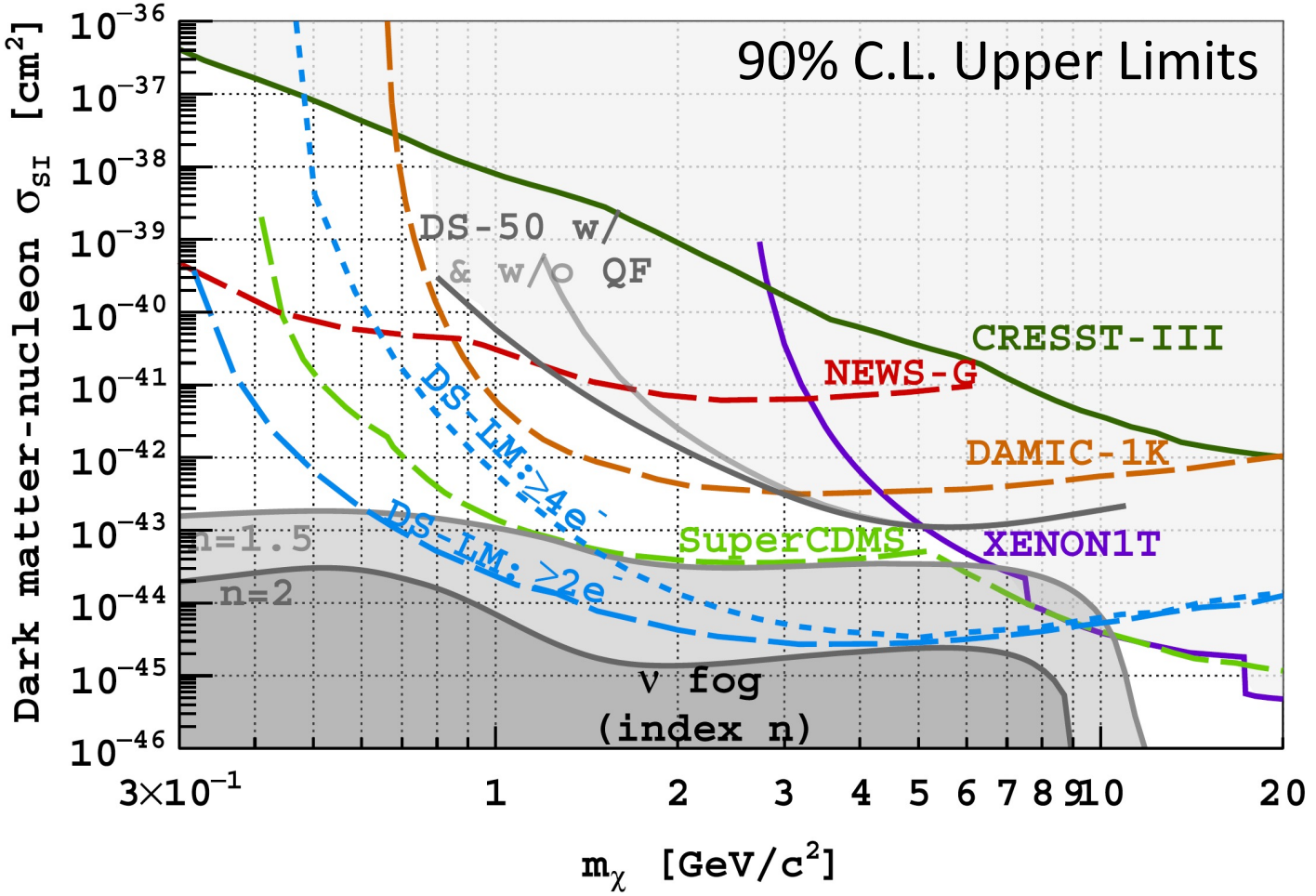


Sensitivity Prediction

- Assumptions:
  - ^{85}Kr expect to fully remove;
  - ^{39}Ar ~73 μBq/kg;
  - γ rate based on the assay of DarkSide-20k materials;
  - 1 tonne-year exposure.
- Neutrino fog is reachable!

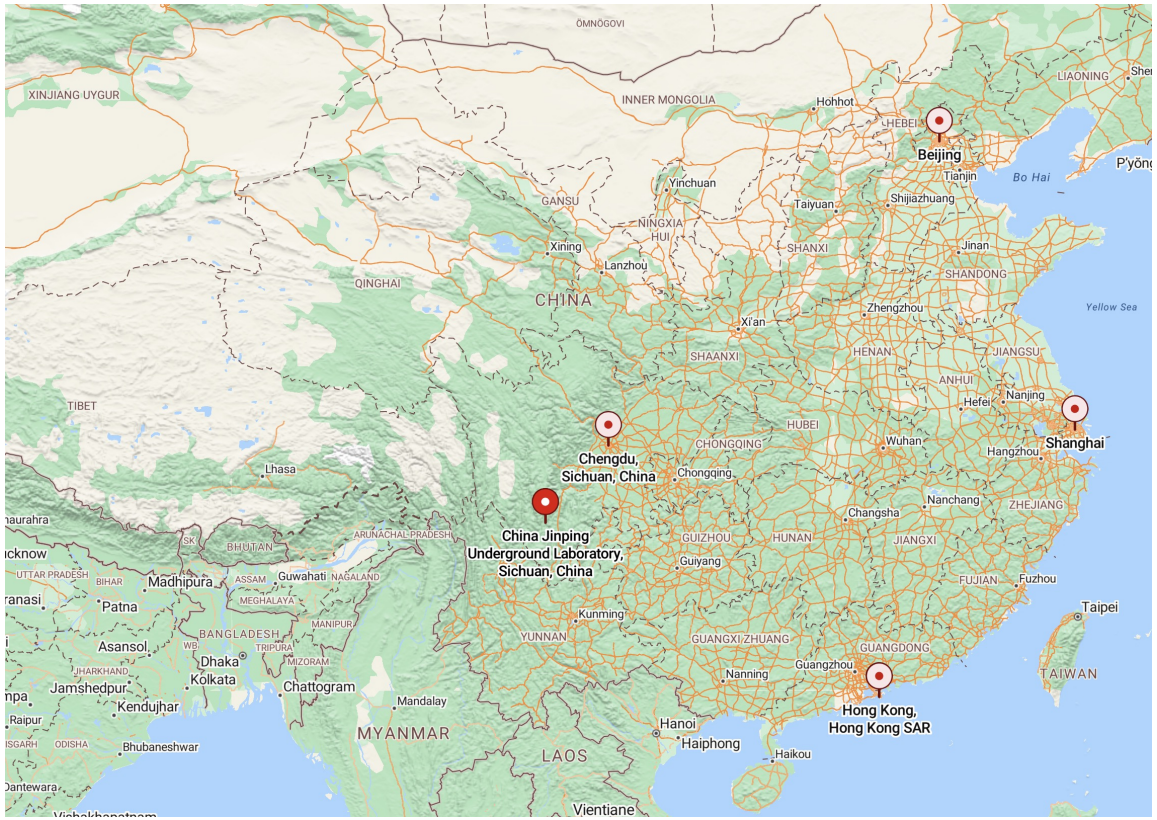
- Candidate lab: CJPL.
- R&D in progress;
- Construction is expected to start in 2027.

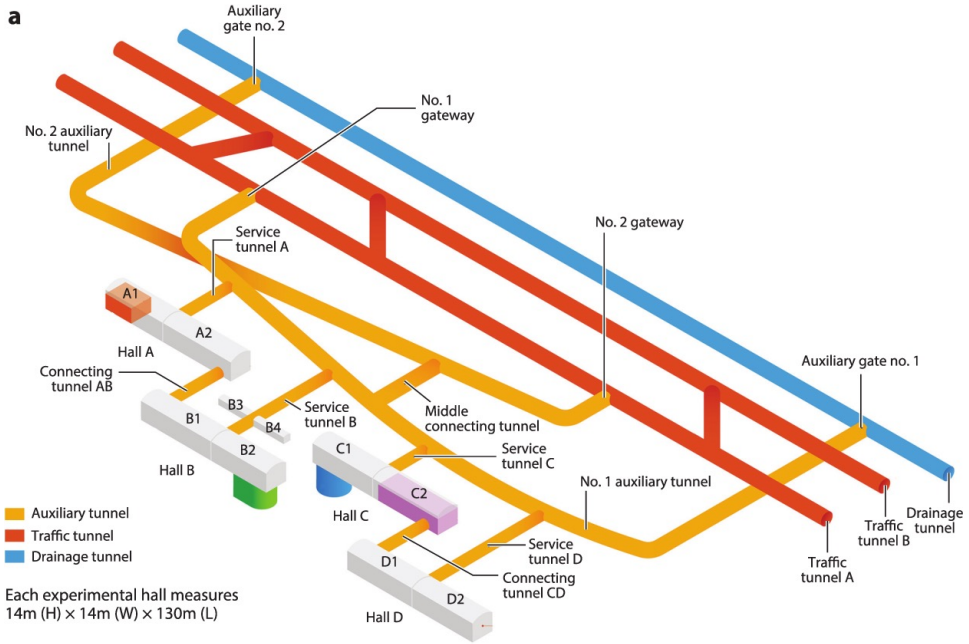
Phys. Rev. D 107, 112006 (2023)



China JinPing Underground Lab (CJPL)

- In Sichuan Province of China, close to Chengdu;
- Overburden ~2400 m rock;
- Lab construction is almost complete, ready for use by the end of 2024.





DarkSide-20k, Low-Mass Sensitivity

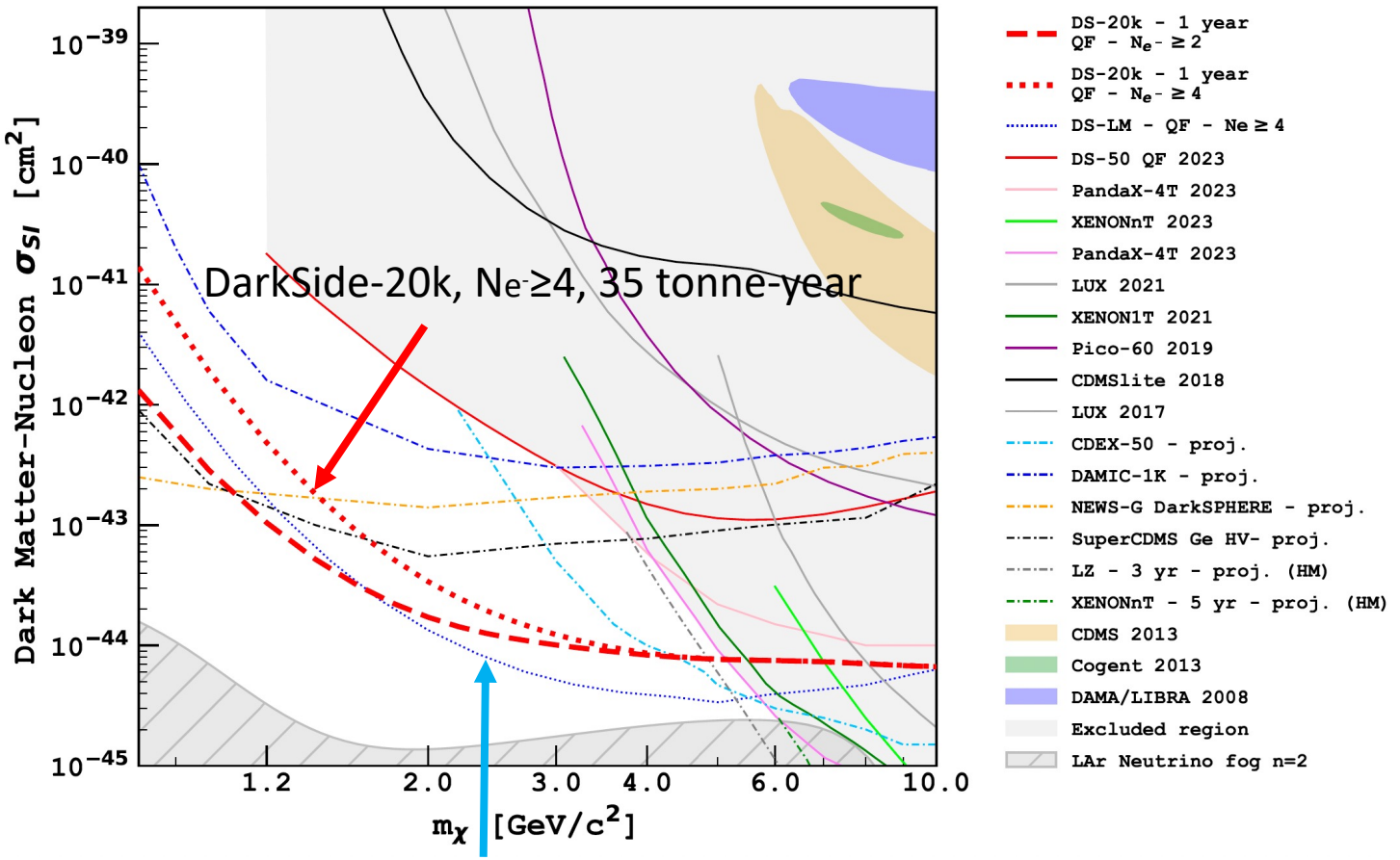
- With DarkSide-20k detector, a study on low-mass sensitivity has recently been conducted.

  arXiv:2407.05813

- 50 tonnes active mass;
- UAr with no further purification.

See Daria Santone's upcoming talk for more details on the DarkSide-20k detector.

arXiv:2407.05813



DarkSide-LowMass, Ne-≥4, 1 tonne-year

Summary

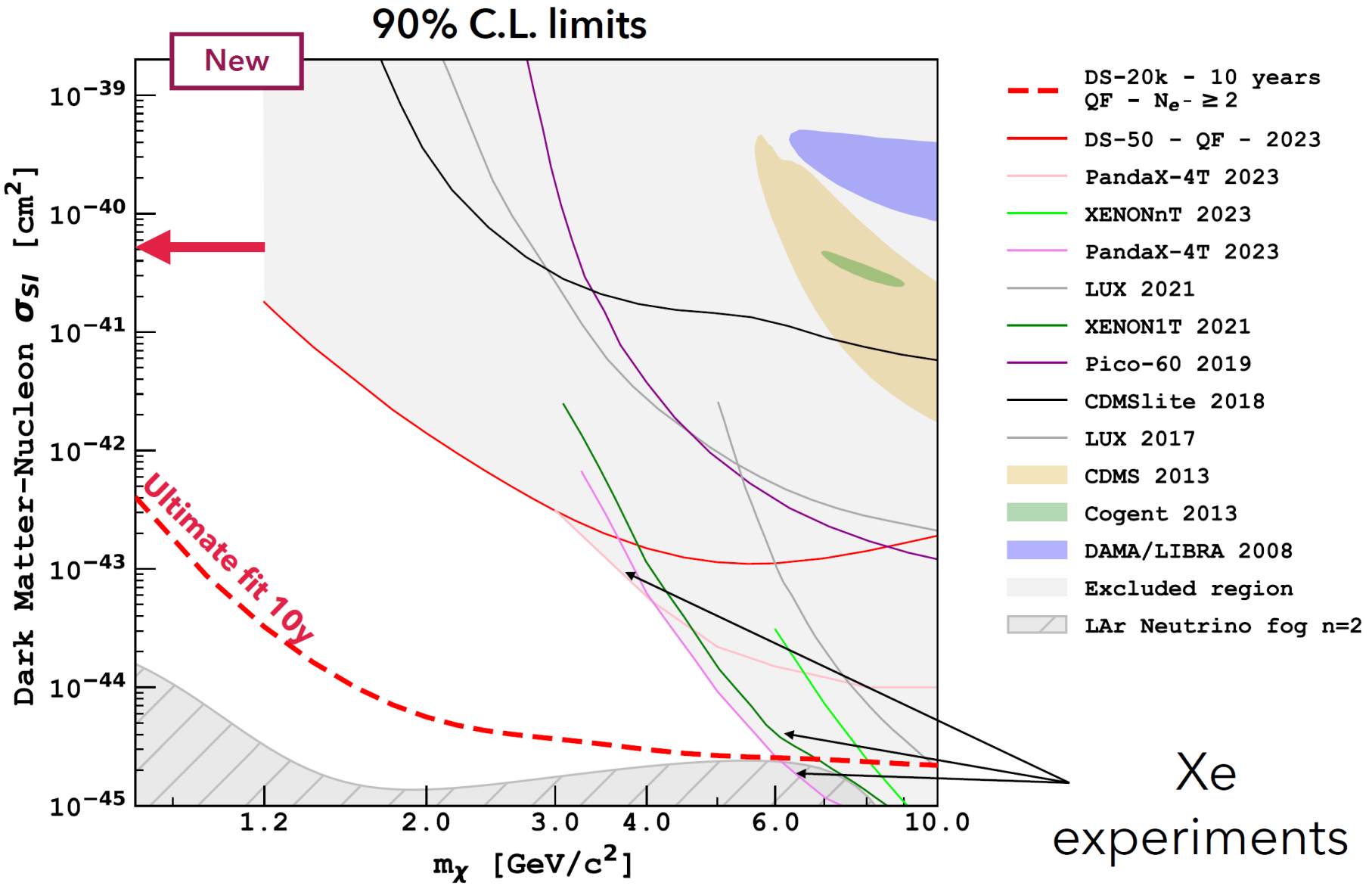
- DarkSide-50 demonstrates the capability of searching low-mass WIMPs with a dual-phase TPC;
- DarkSide-LowMass is proposed to have a clear path to the **ν**-fog in low-mass regions;
  - Depleted argon with further reduced ^{39}Ar concentration;
  - Significant γ background reduction due to radiopure materials and the veto system;
  - Other effort to reach lower threshold.
- Many R&Ds regarding DarkSide-LowMass are underway.
- Construction of the DarkSide-LowMass detector is expected to start in 2027.

Backups

DarkSide-20k sensitivity to low mass WIMPs

Assuming 10 years of data taking

➡ **Scales with $\sqrt{\text{exposure}}$**



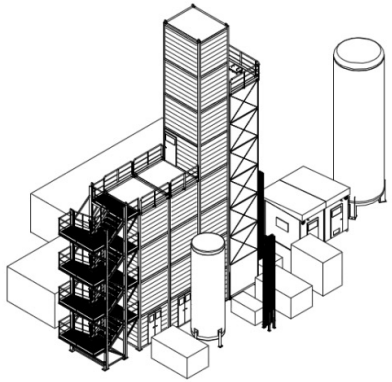
Xe experiments

DarkSide-20k will reach the neutrino fog around $m_\chi \approx 5$ GeV/c^2 after 10 years of data collection

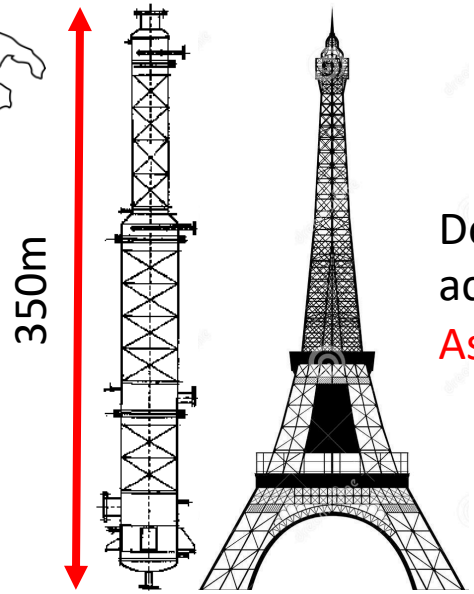
UAr Production Chain

URANIA (Extraction)

An industrial scale extraction plant in Cortez, CO, USA;
Extraction rate: 250~330 kg/day; UAr purity: 99.99%;
Plant assembly in progress.



LNGS



ARIA (Purification)

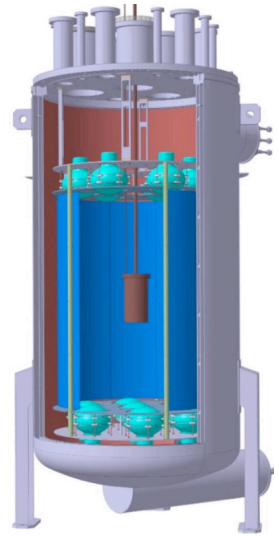
350 m tall cryogenic distillation column in Sardinia, Italy;
Chemical purification rate O (1 tonne/day);
UAr purity after ARIA: 99.999%;
Capable to separate ^{39}Ar from ^{40}Ar at O (10 kg/day).
Seruci-0 tested, Seruci-1 under construction.

Eur. Phys. J. C (2021) 81:359, Eur. Phys. J. C (2023) 83:453

DArT in ArDM (Radiopurity assay)

At Canfranc Lab, Spain (LCS);
A single-phase detector to measure the ^{39}Ar depletion factor;
Sensitive to measure UAr depletion factors in excess of 1000;
DArT will soon be installed inside ArDM.

First result in
2020 JINST 15 P02024

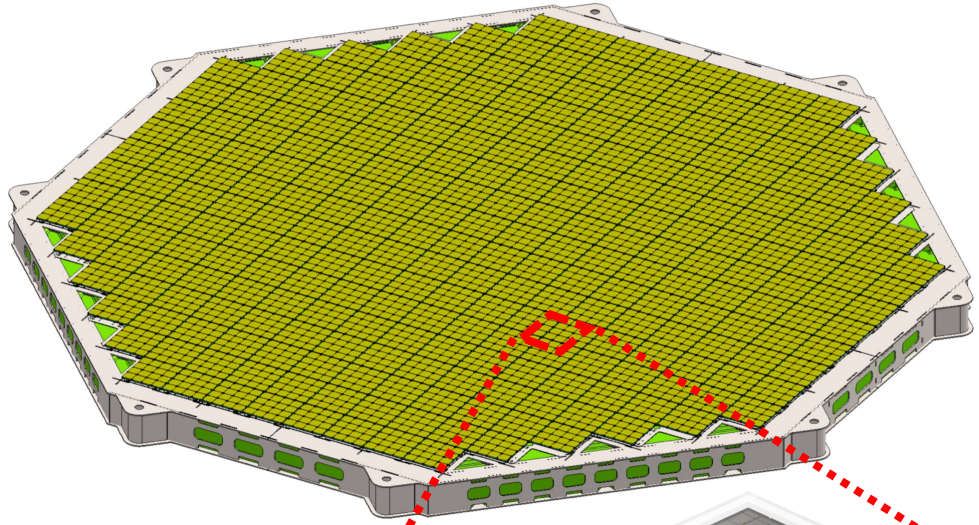


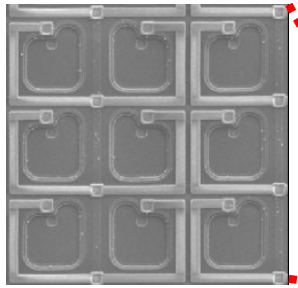
Details about the cosmogenic activation:
Astropart. Phys. 152 (2023) 102878

Photodetectors

- Cryogenic SiPMs developed with Fondazione Bruno Kessler (FBK):
  - PDE > 40% @ 420 nm;
  - DCR < 0.01 Hz/mm^2 @ 77K (7 VoV);
  - SNR > 8 (TPC);
- Need 27 m^2 for both TPC and veto.

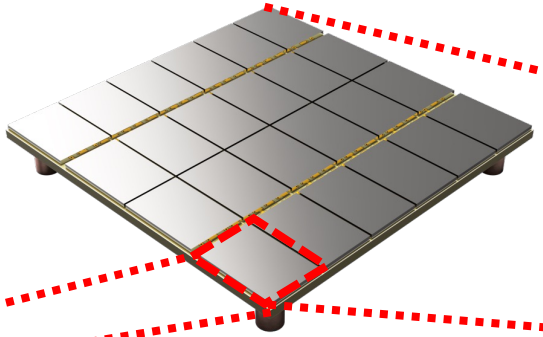
Optical Plane with 1056 channels





Pixels

SiPMs
Each chip: 8 x 12 mm^2



Tile (24 SiPMs)
5 x 5 cm^2

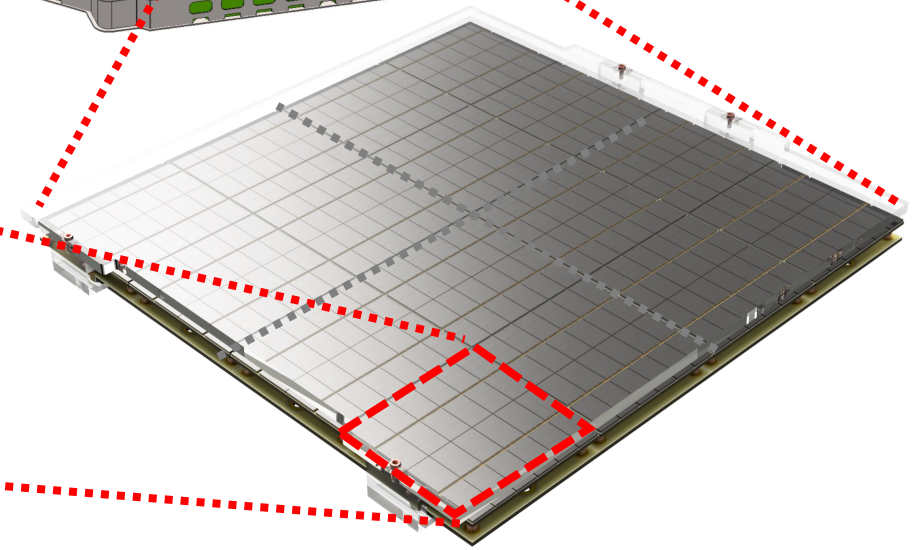


Photo Detection Unit (PDU)
(16 tiles) 20 x 20 cm^2
with 4 readout channels