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Dark Wave
National Science Centre Poland

SEARCHES for LIGHT DARK MATTER with DarkSide-20k and DarkSide-LowMass

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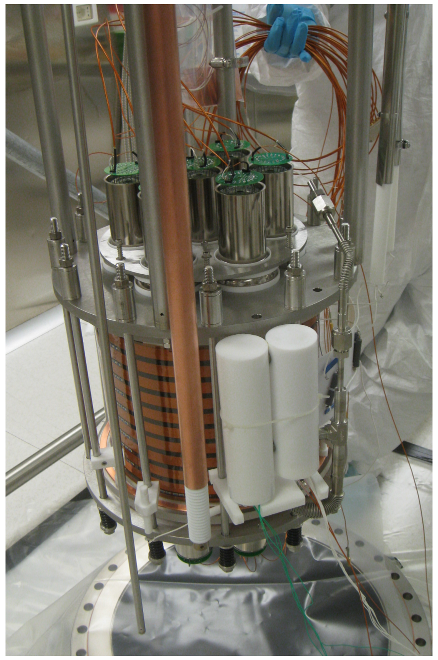
August 27 2025
TAUP 2025

AstroCeNT
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

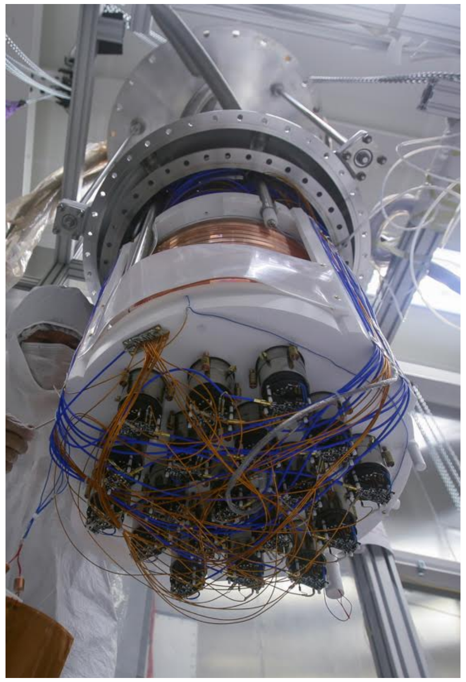
DARKSIDE PROGRAM

- **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

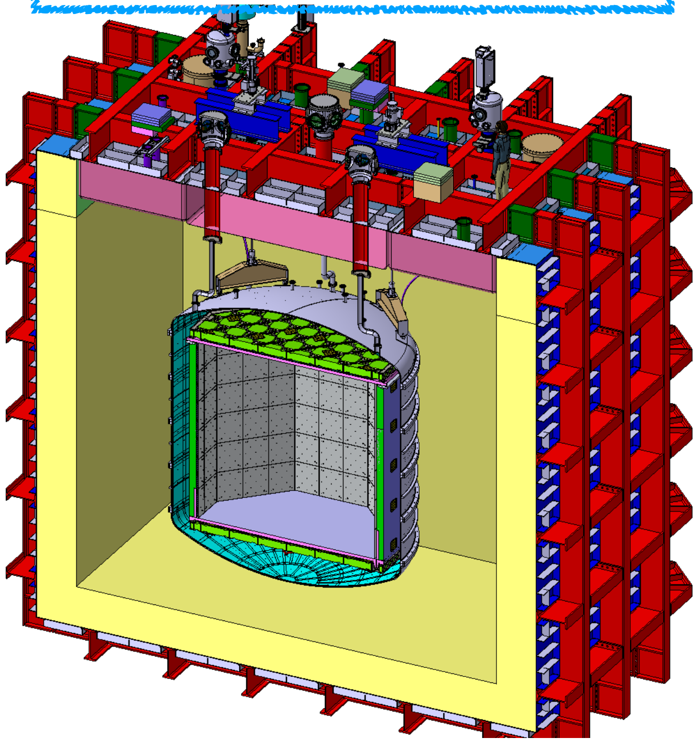
See more details in Walter Bonivento's talk!!



DarkSide-10



DarkSide-50



DarkSide-20k

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

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

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 **Xenon**

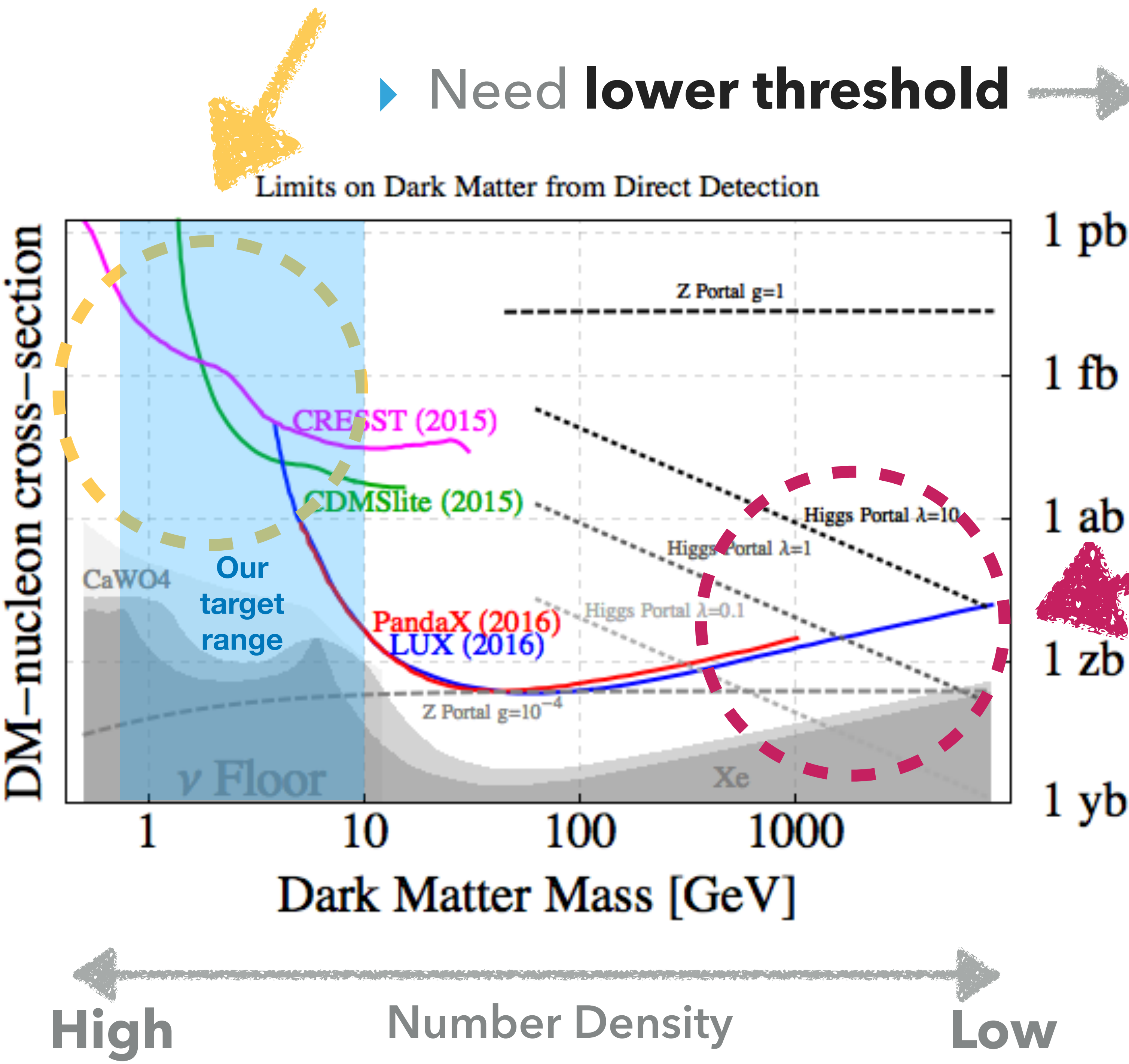
- Denser & Radio pure
- Lower energy threshold
- ~~Higher sensitivity at low mass WIMP~~

Liquid **Argon**

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

SENSITIVITY TO HIGH AND LOW MASS WIMPS

- Sharp rise at low mass is due to **detection threshold.**
- Need **lower threshold** → **Ionization signal (S2)**

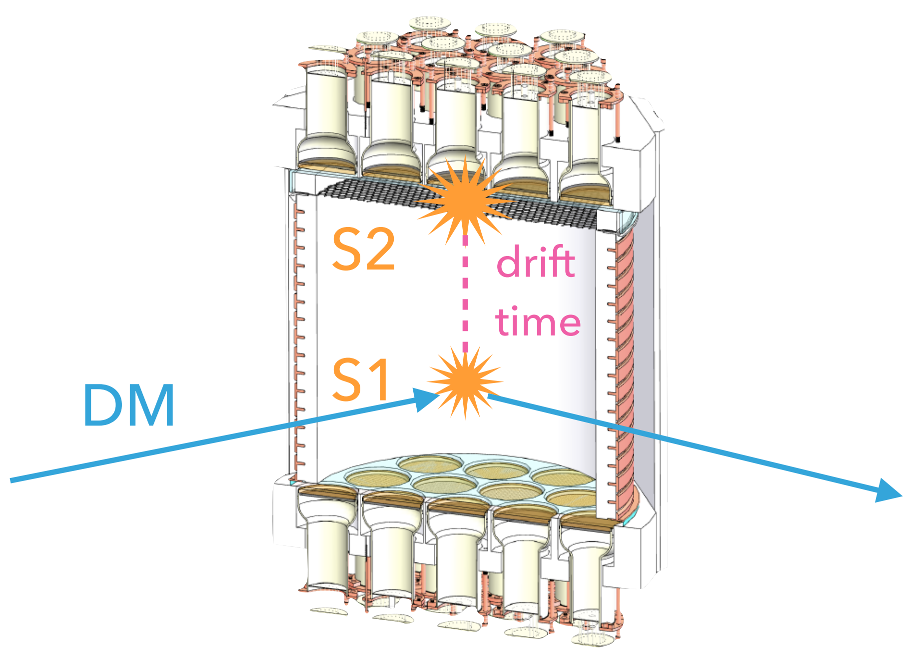


- Rise at high mass is due to **fixed energy density of WIMPs**.
- Need **large target mass.**
- Scalability is important!

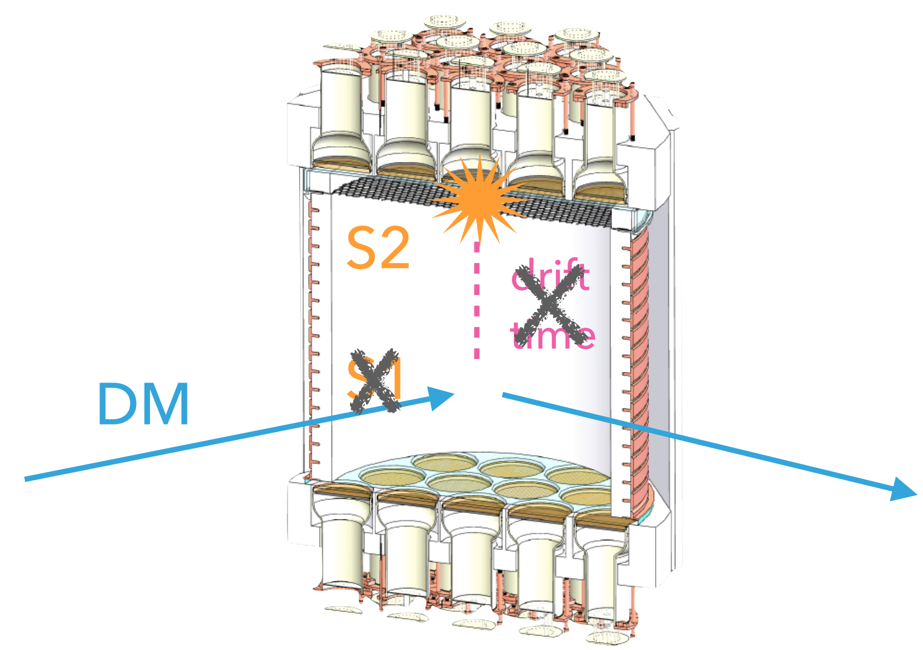
plot credit: http://resonaances.blogspot.ca

LIQUID Ar TPC FOR DARK MATTER SEARCHES

High Mass Search
High Energy Events



Low Mass Search
Low Energy Events

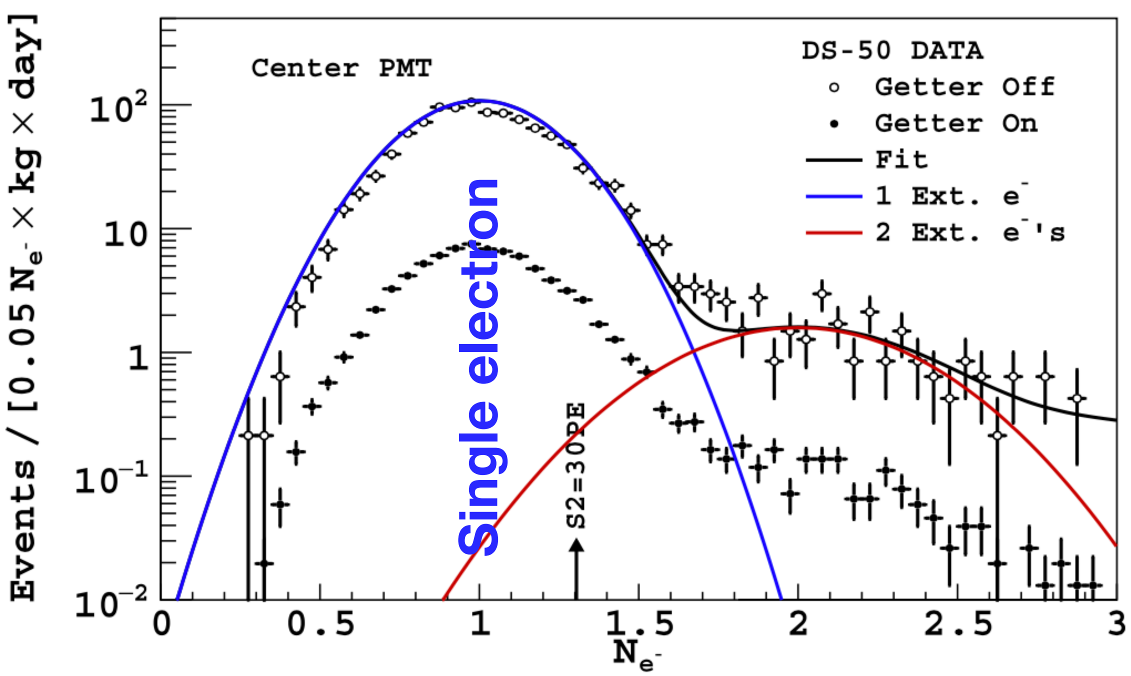


- Scintillation (S1) & Ionization (S2)
- Pulse Shape Discrimination (PSD)
- Drift time provides vertical event position

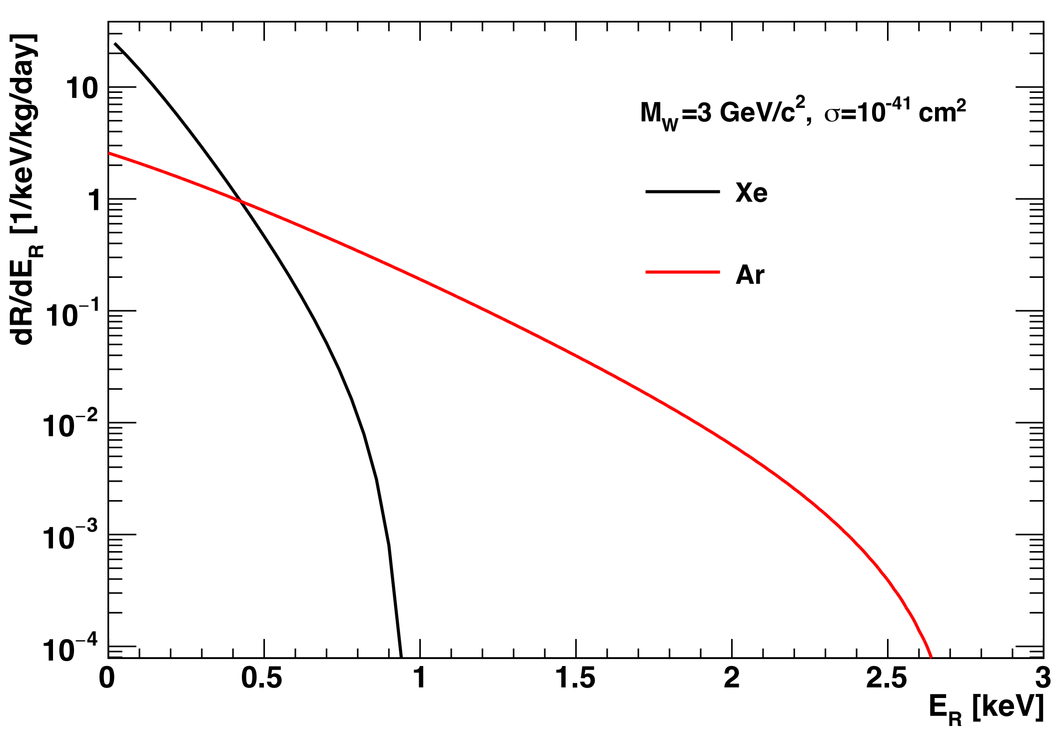
- Electrofluorescence in gas gap lets us detect single e- with high efficiency.
  →**Lower energy threshold**
- **No** PSD
- **No** vertical position

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



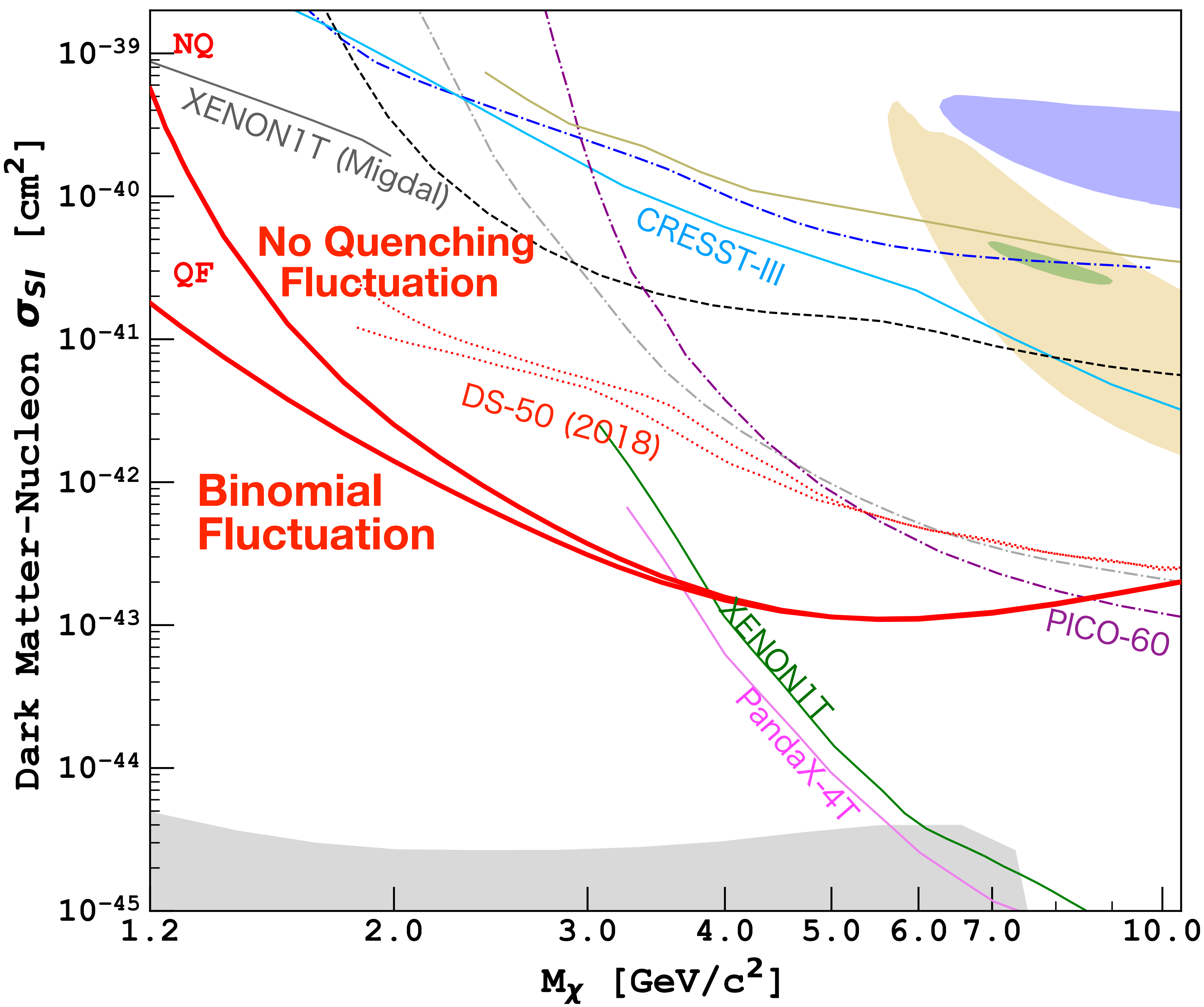
WIMP spectra in Xe and Ar



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

WHAT WE ACHIEVED IN DS-50

Phys. Rev. D 107, 063001

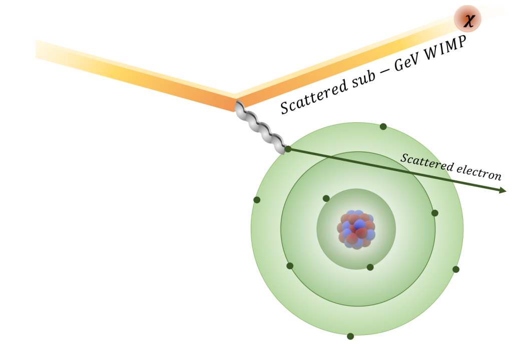


The most stringent limit at M_χ = [1.2, 3.6] GeV/c^2

Annual modulation analysis are also published!

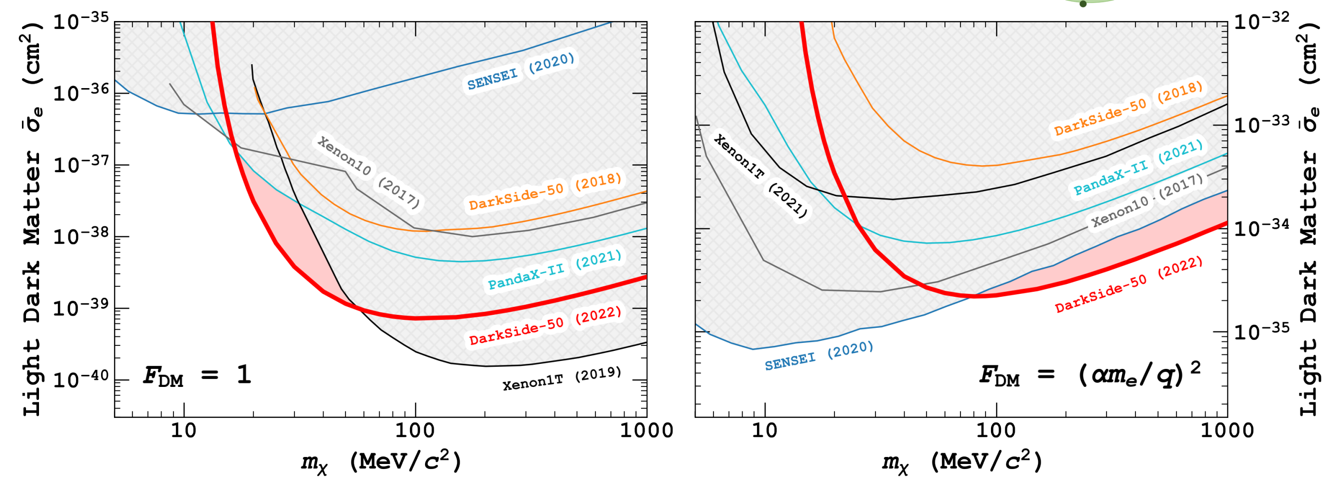
Phys. Rev. D 110, 102006 (2024)

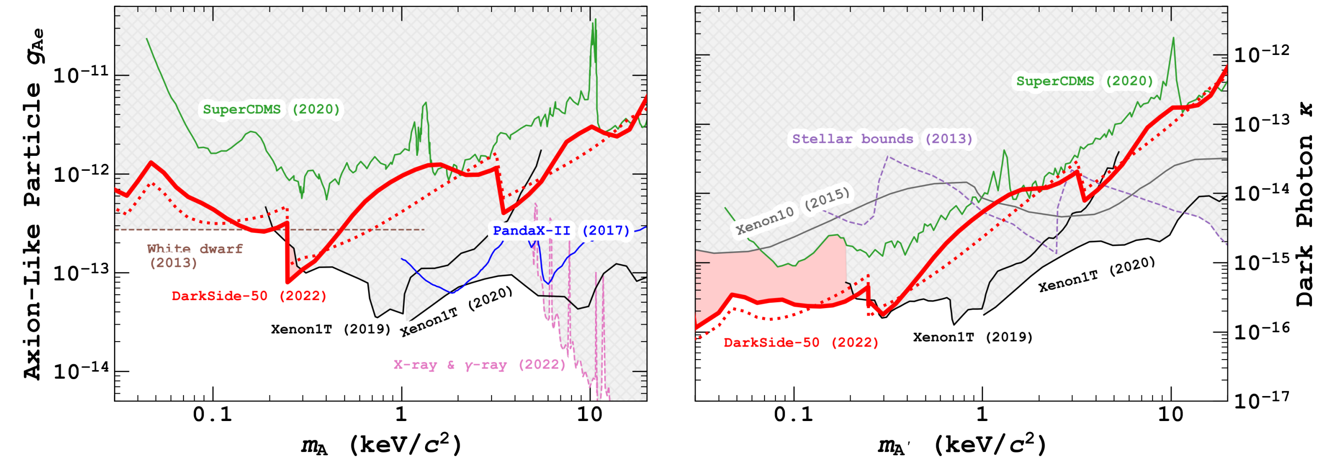
SUB-GEV DARK MATTER AND OTHER DARK MATTER MODELS

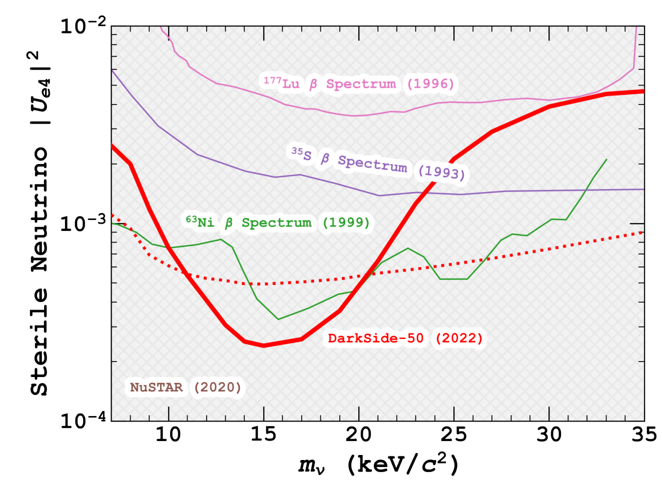


Phys. Rev. Lett. 130, 101002

- With the same dataset, we search for other dark matter models.
- In those candidates, DM signals are also ER.
- Ultra-light DM ($m_\chi \ll 1$ GeV) scatter off electrons.
- Two extreme cases of Dark Matter form-factor are considered
  - $F_{DM}=1$ heavy mediator
  - $F_{DM} \propto 1/q^2$ light mediator
- More for Axion-like particles, Dark photons, and Sterile neutrinos.

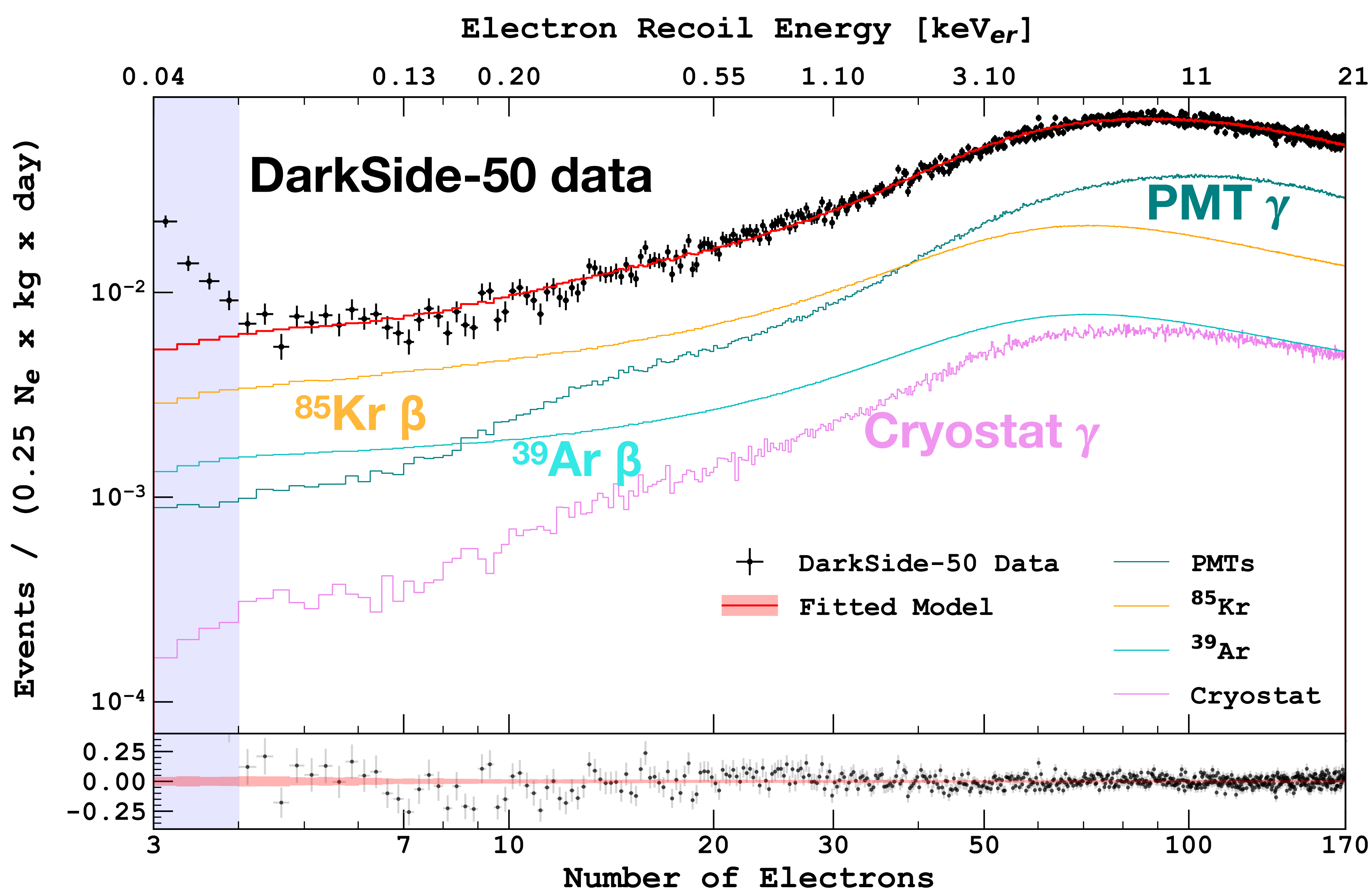






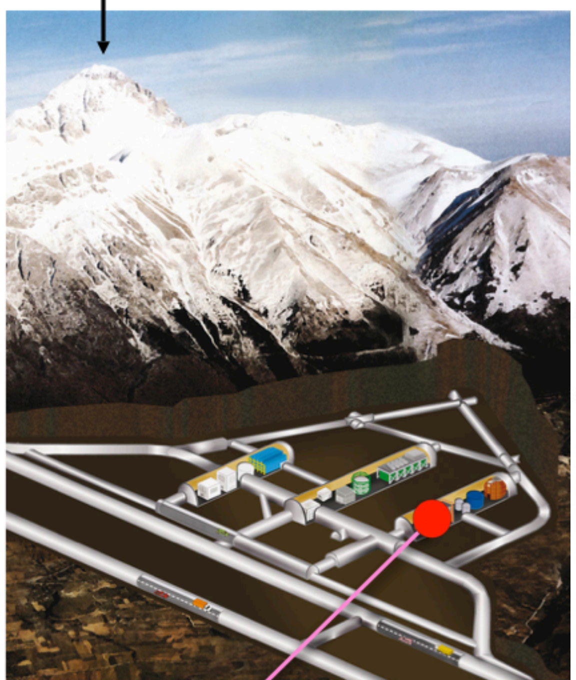
Also, results with Migdal effect Phys. Rev. Lett. 130, 101001

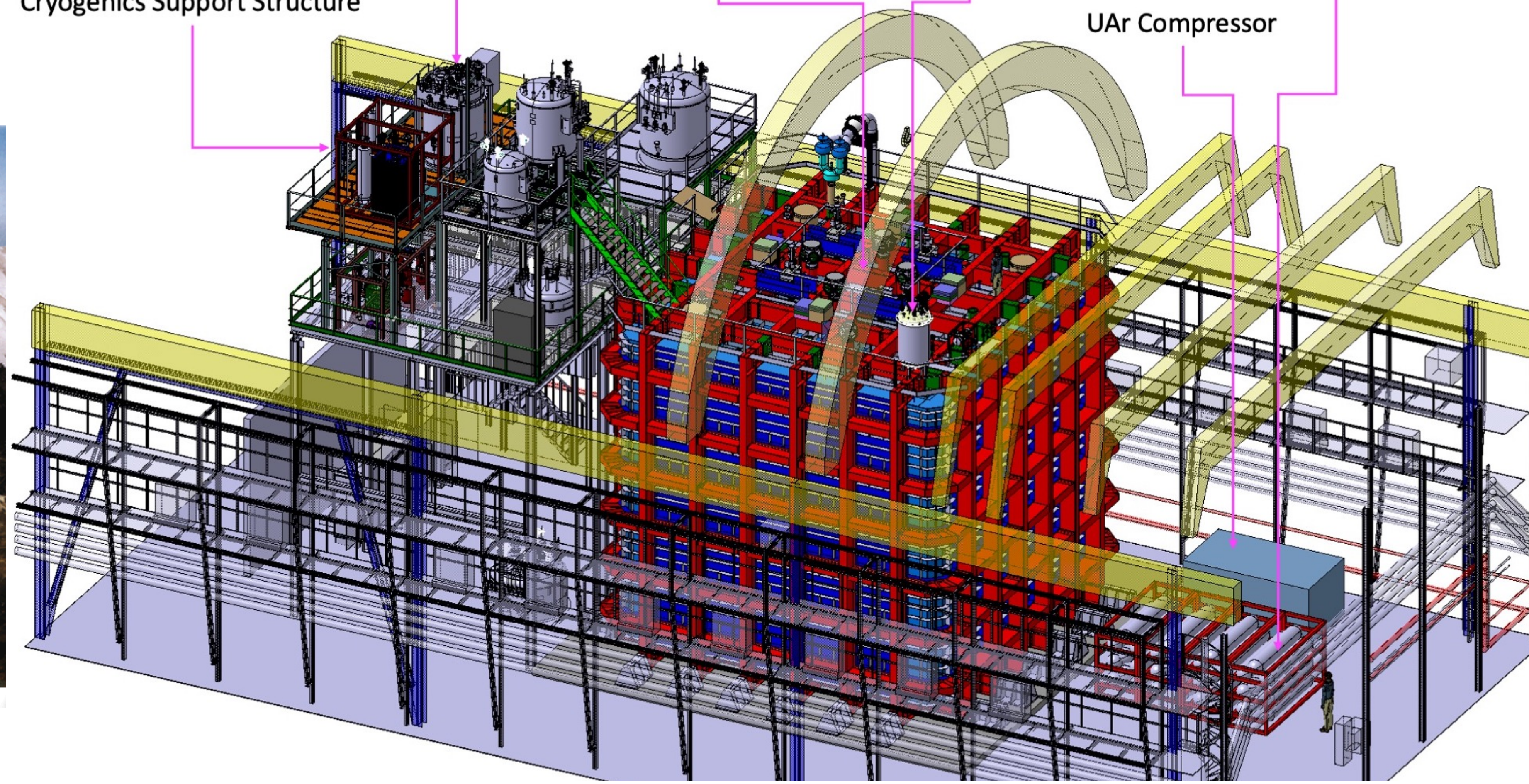
WHAT LIMITS SENSITIVITY?



- Internal βs from ^{85}Kr and ^{39}Ar
- γs from photosensors and cryostat
- Spurious electrons (setting the energy threshold)
  More details see arXiv:2507.23003
- Limited understanding of LAr responses

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

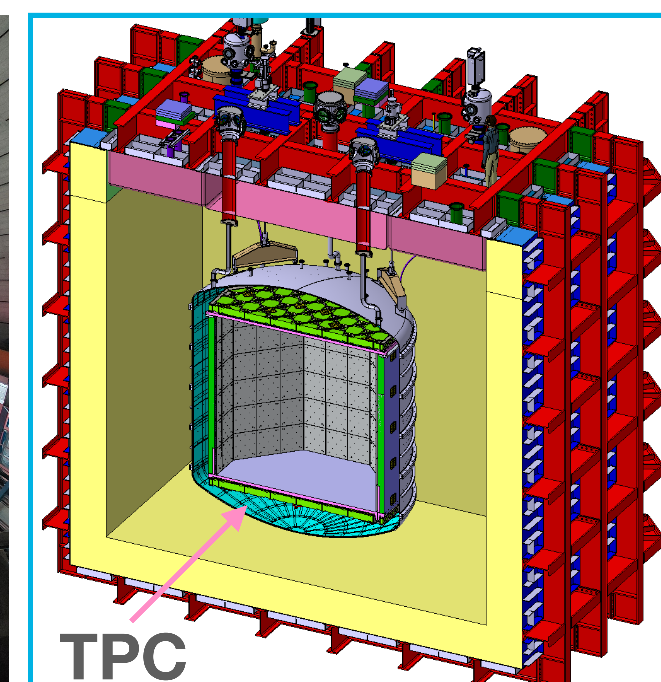


PHOTO SENSOR

- 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
- Mass production of the raw wafer in LFoundry company and assembly in a dedicated facility at LNGS (NOA).
- **SiPM with integrated electronics (ASIC) will reduce radioactive components.**

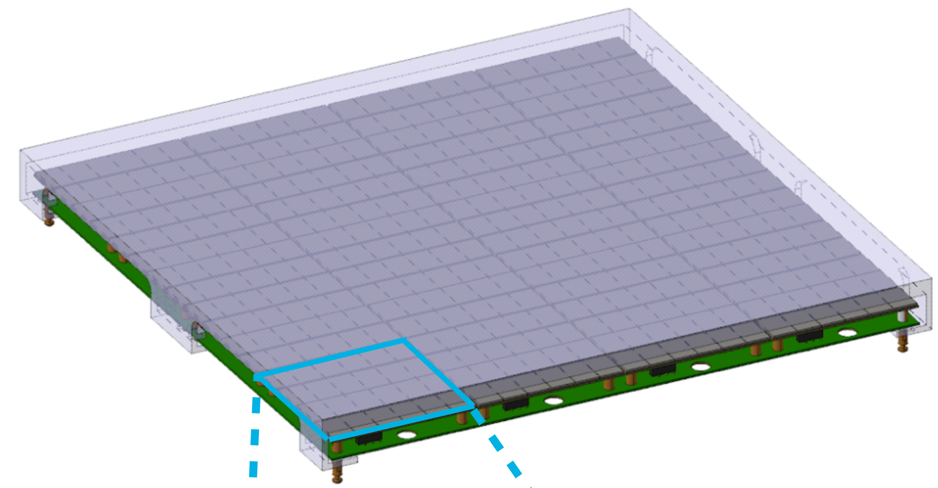
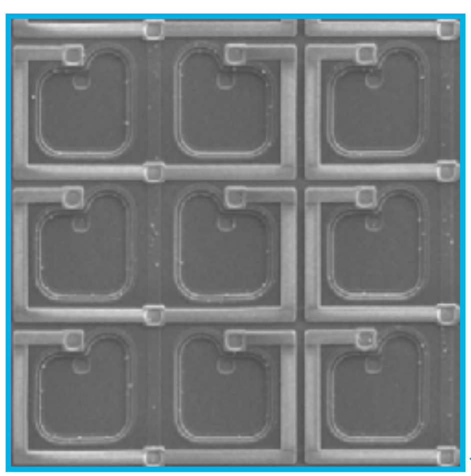
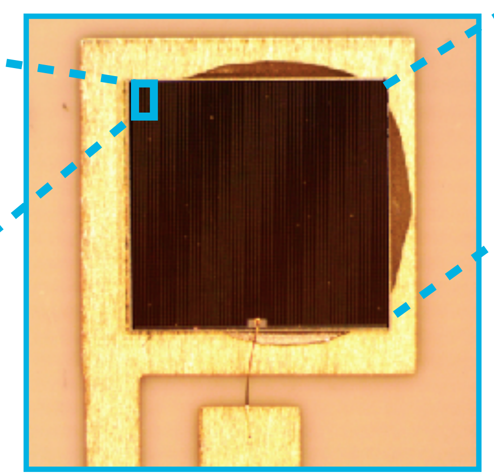


Photo Detector Unit (PDU) = matrix of 16 PDMs
20 x 20 cm^2



Single SPADs

~25-30 μm^2



Single SiPM

~1 cm^2

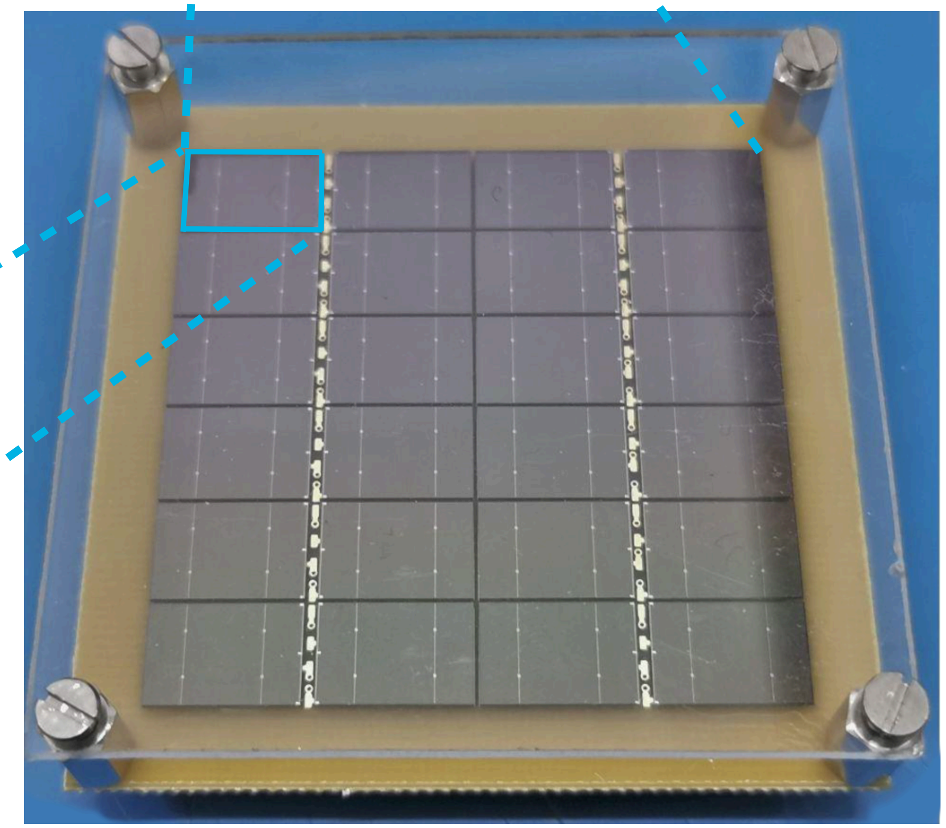
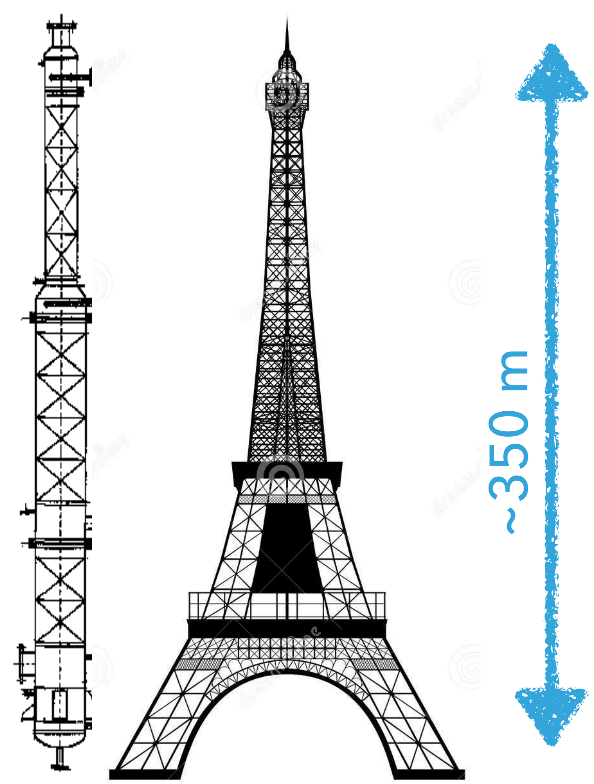


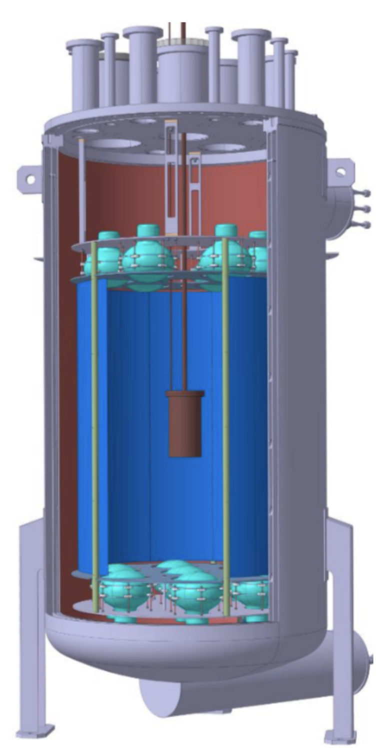
Photo Detector Module (PDM)
= matrix of 24 SiPMs, 5 x 5 cm^2
4 PDUs are summed and read as a single channel
(largest single SiPM unit ever!)

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 at Canfranc Laboratory, Spain.



ARIA column

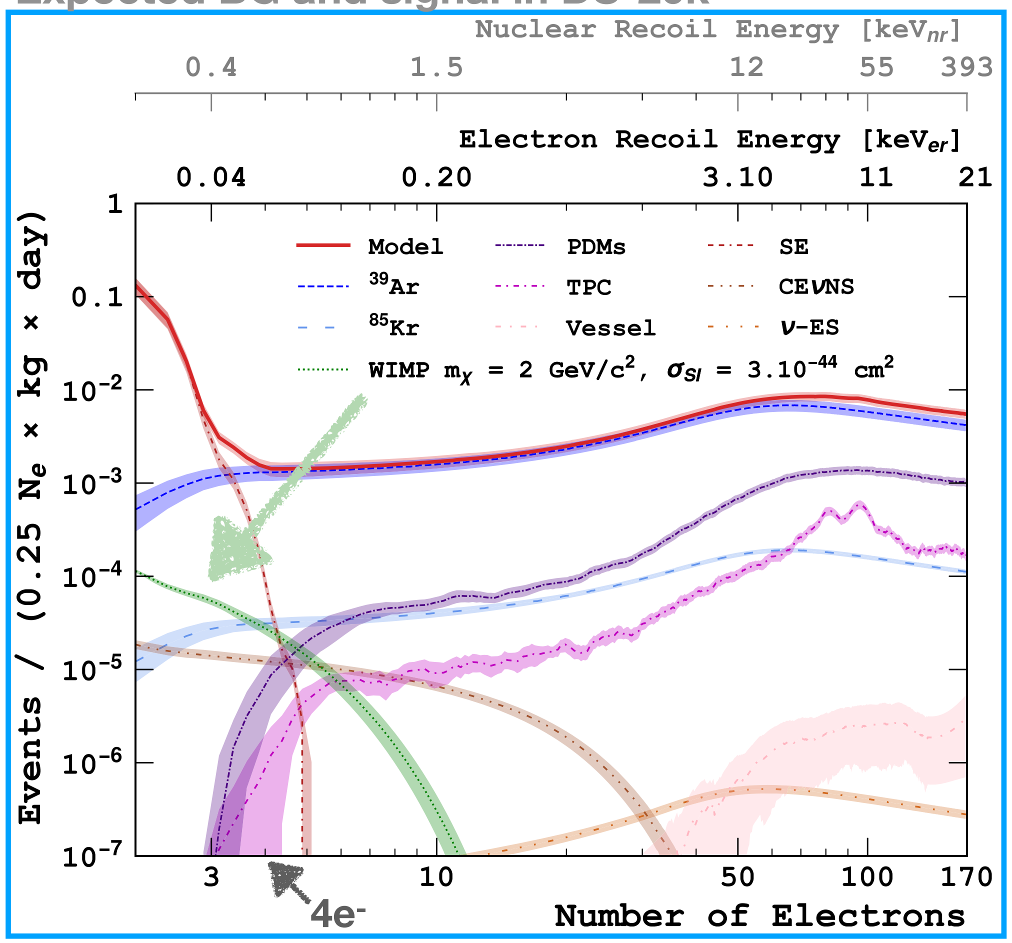


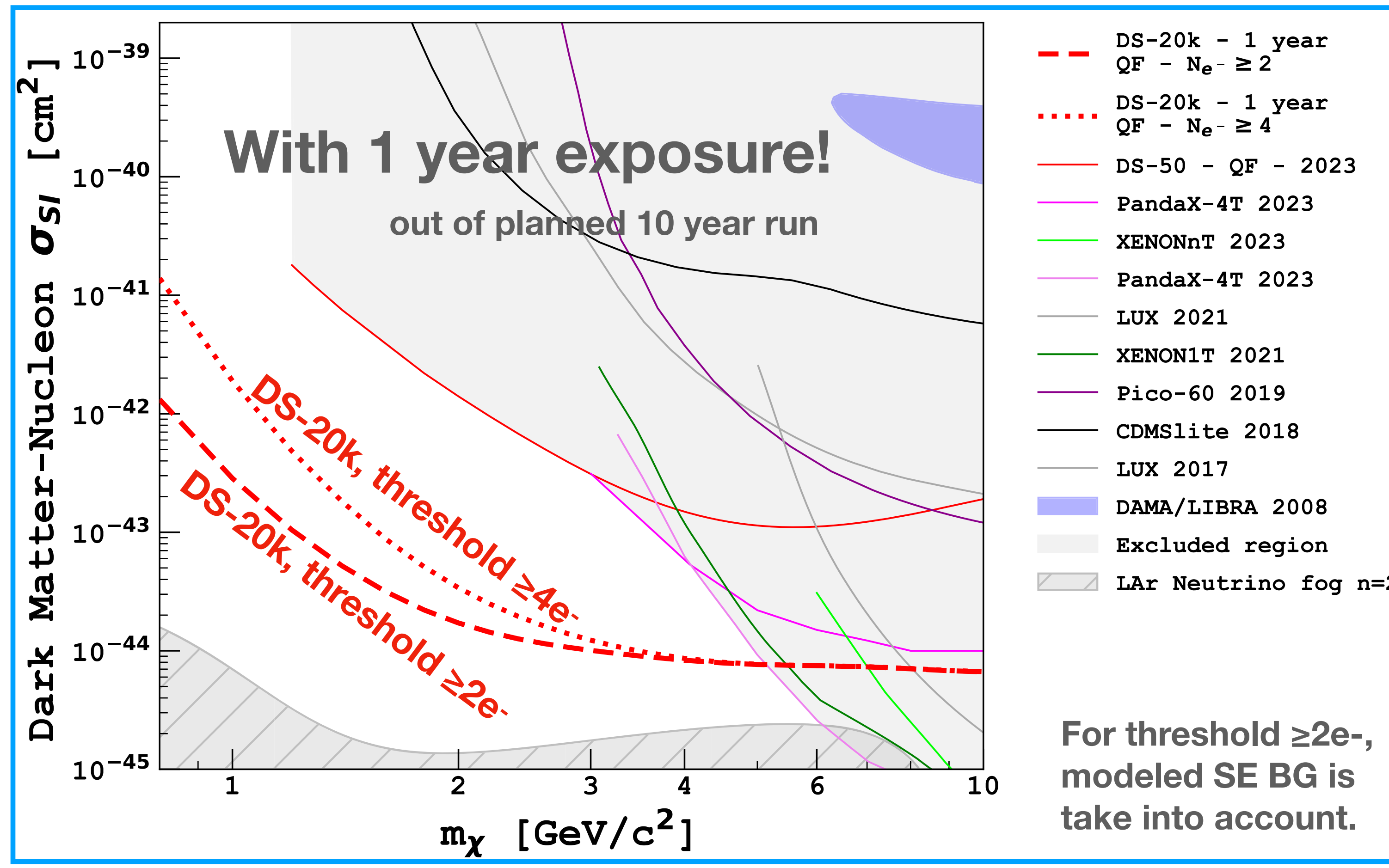
DArT in ArDM

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).

CRITERIA FOR FUTURE LAr TPC

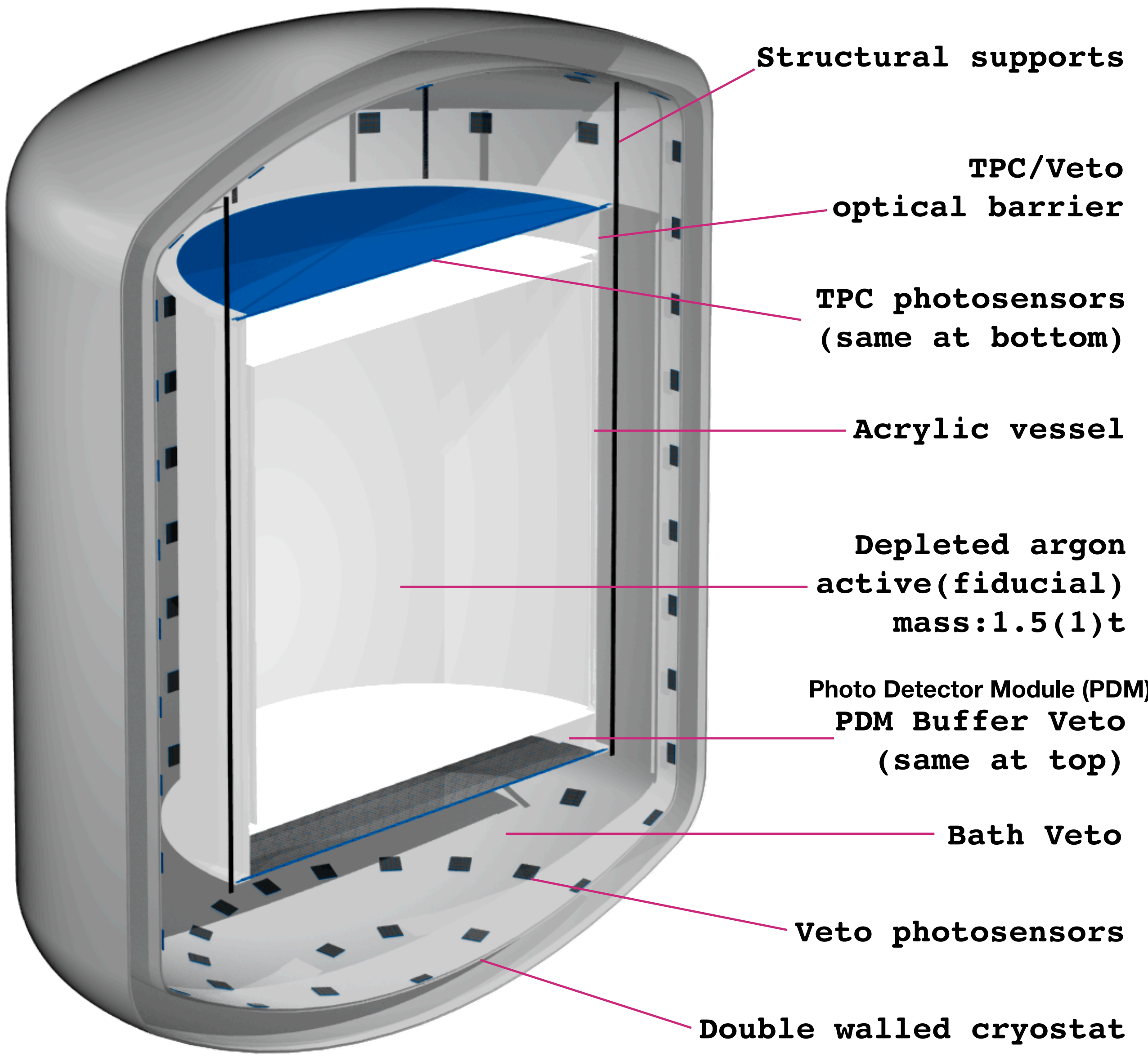
- Low activity of ^{39}Ar
- Low impurity
  - good electron lifetime
  - low rate of the single electron events
- Ultra-pure photo-sensor
- Pure cryostat (or cryostat further away)

Advantages

- Possibility to dope with Xe and/or other isotopes to lower detection threshold.
- Capability to clean LAr quickly after commissioning to reduce the SE background once primary source of impurities identified.

Phys. Rev. D 107, 112006

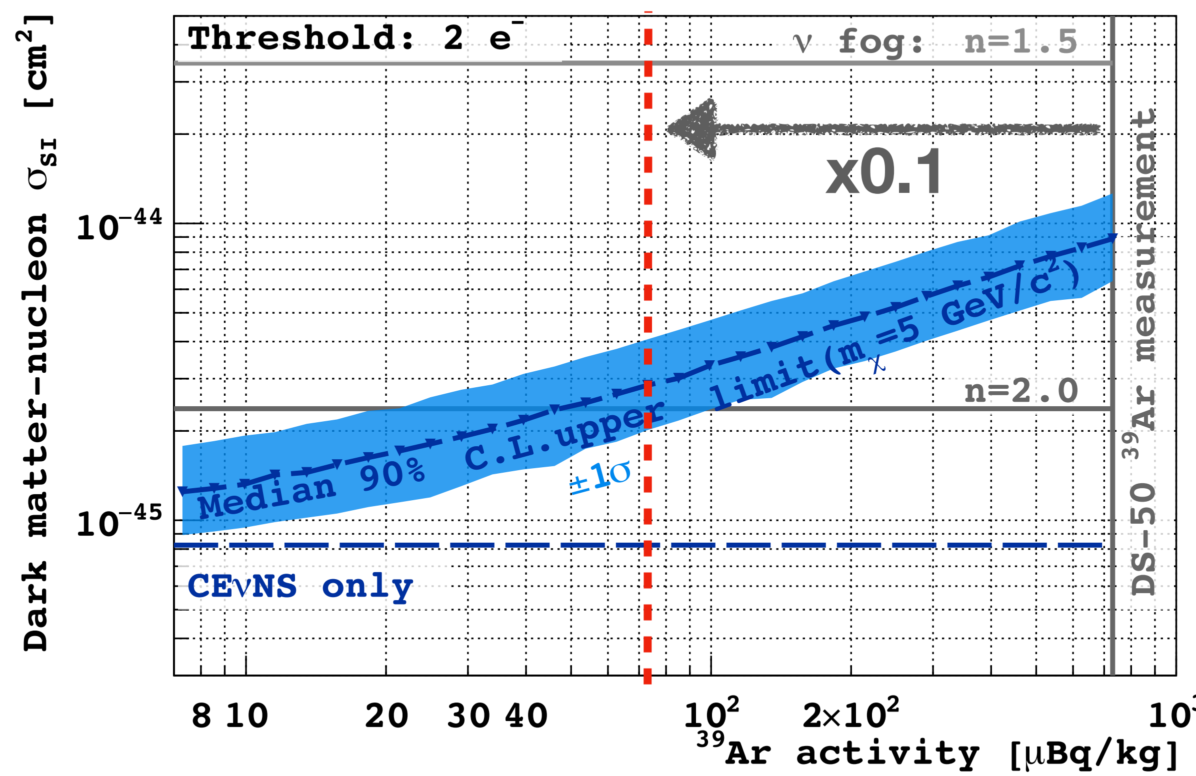
DarkSide-LowMass conceptual design

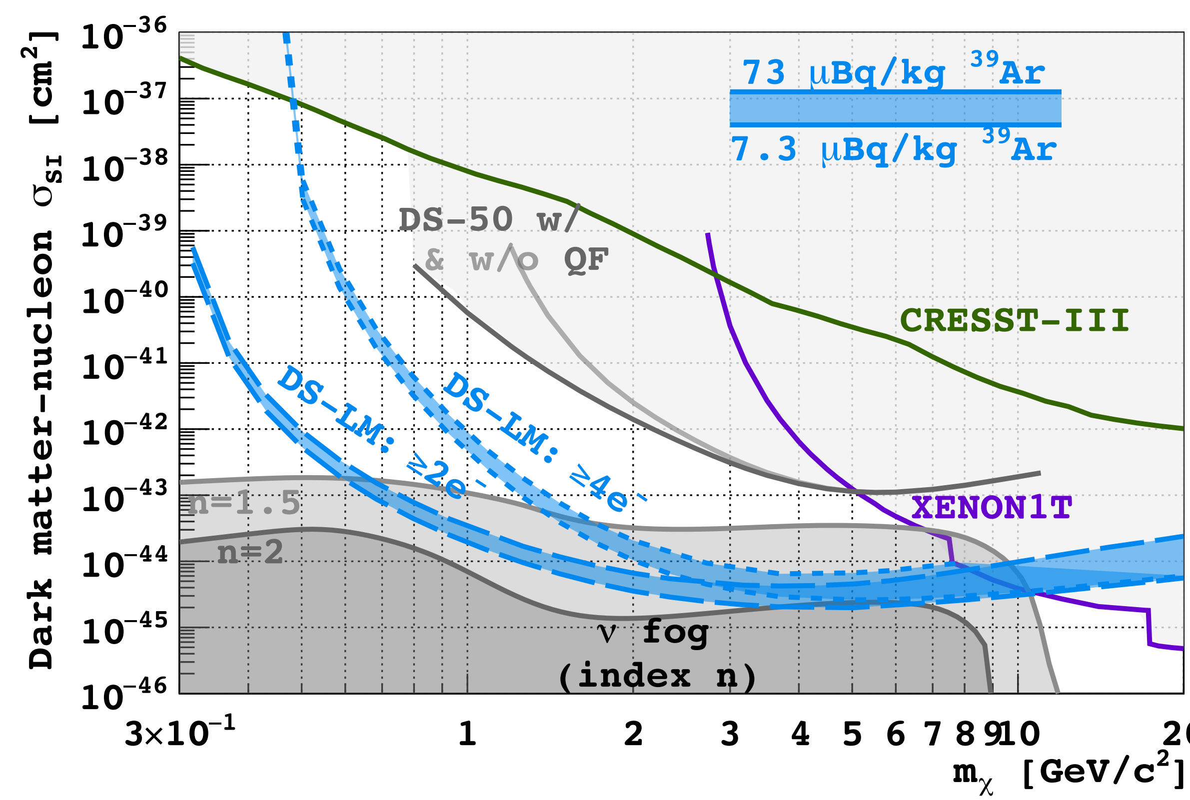


~6 t of LAr

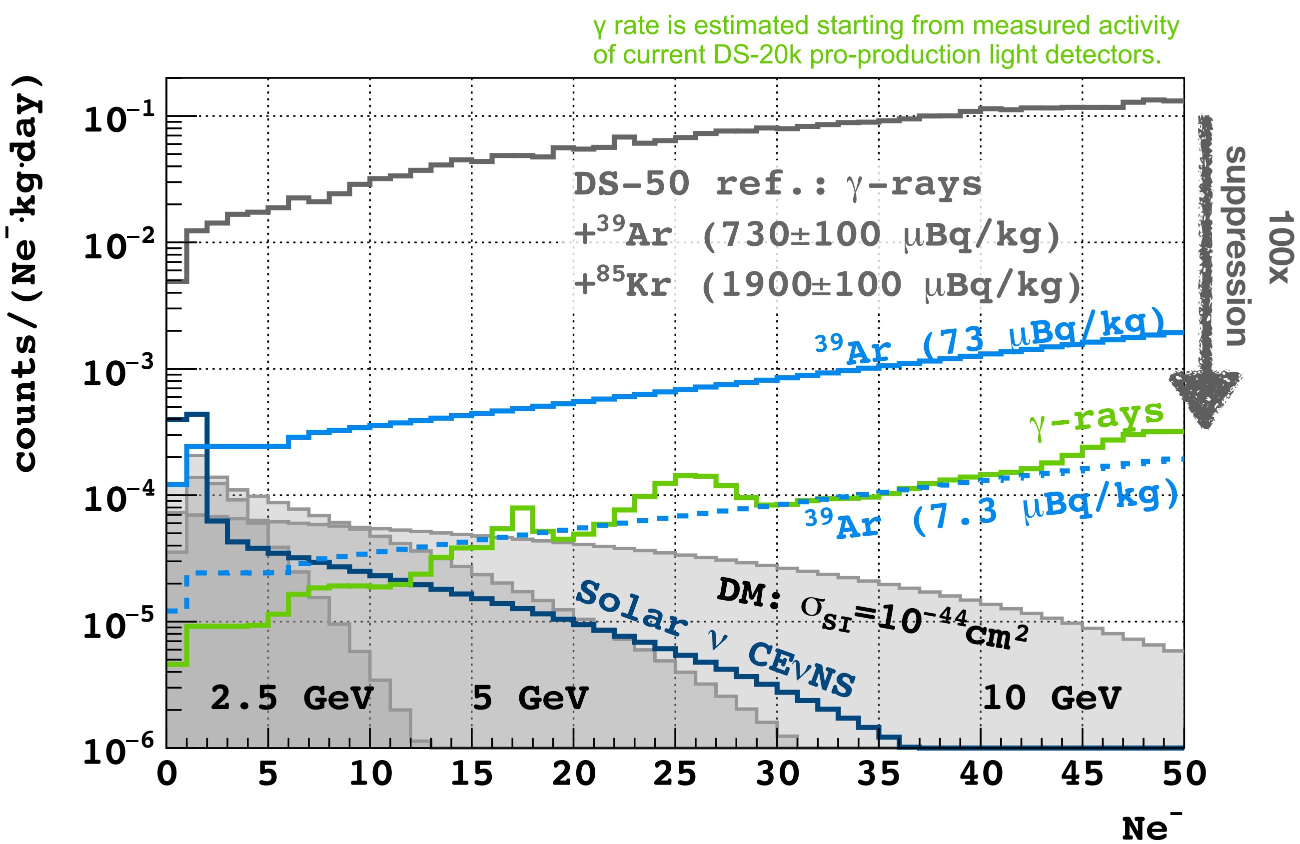
WHAT IF WITH HIGHER ^{39}Ar CONCENTRATION?

- DarkSide-50 established we can achieve at least 750 µBq.
- With one pass of ARIA (~75 µBq), DarkSide-LowMass can search down to neutrino fog at 5 GeV/c² DM mass.
- **Lowering the threshold** is more **important** to be sensitive to lower DM mass.

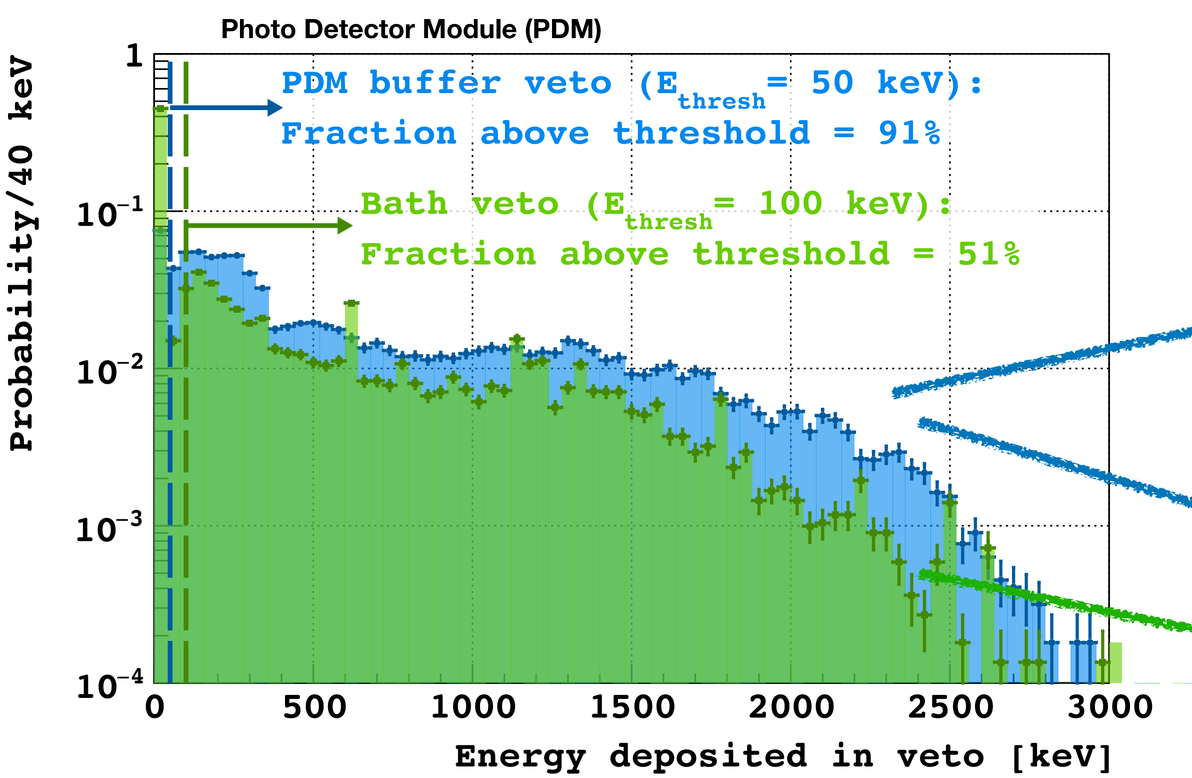


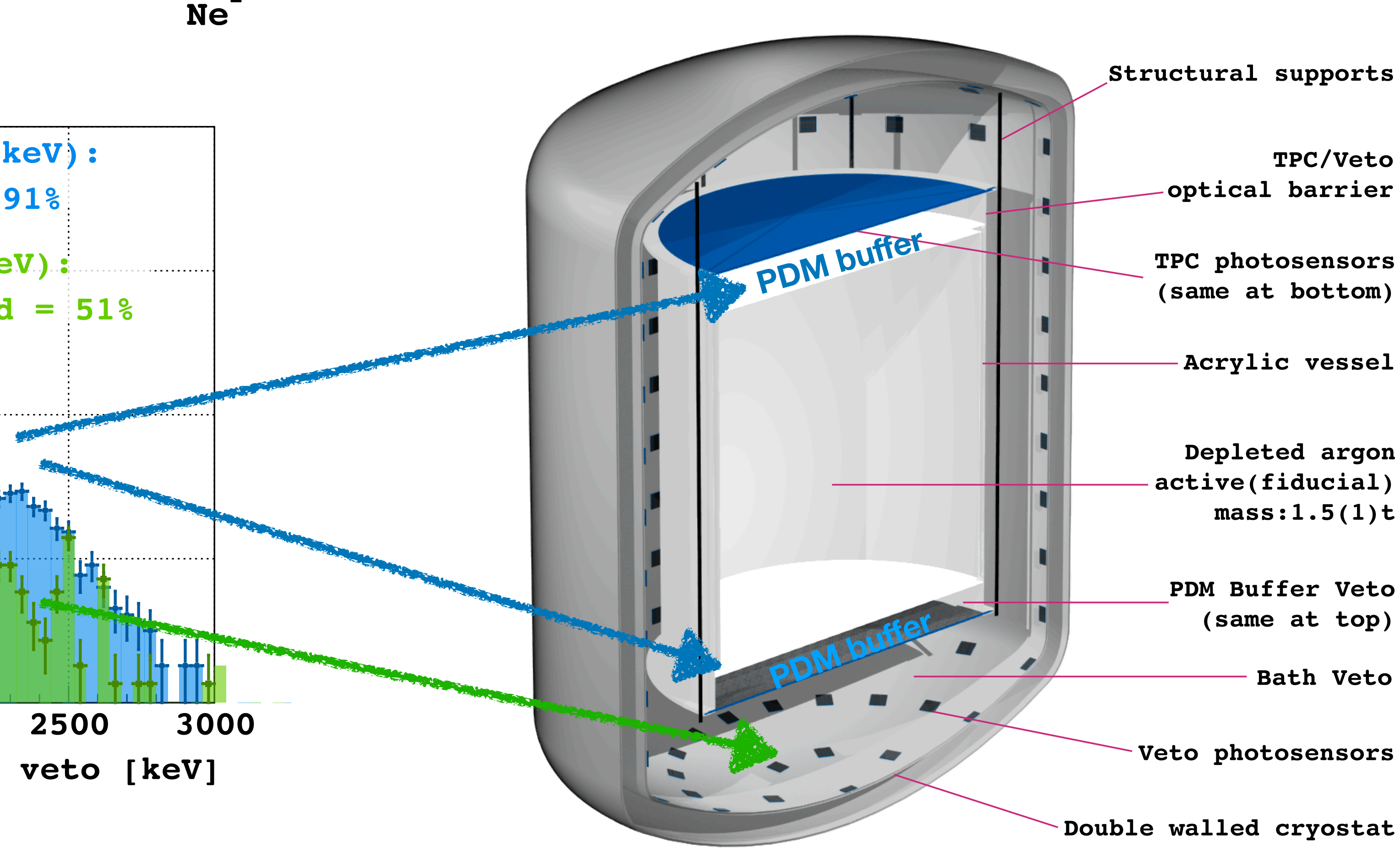


RADIOPURE DETECTOR



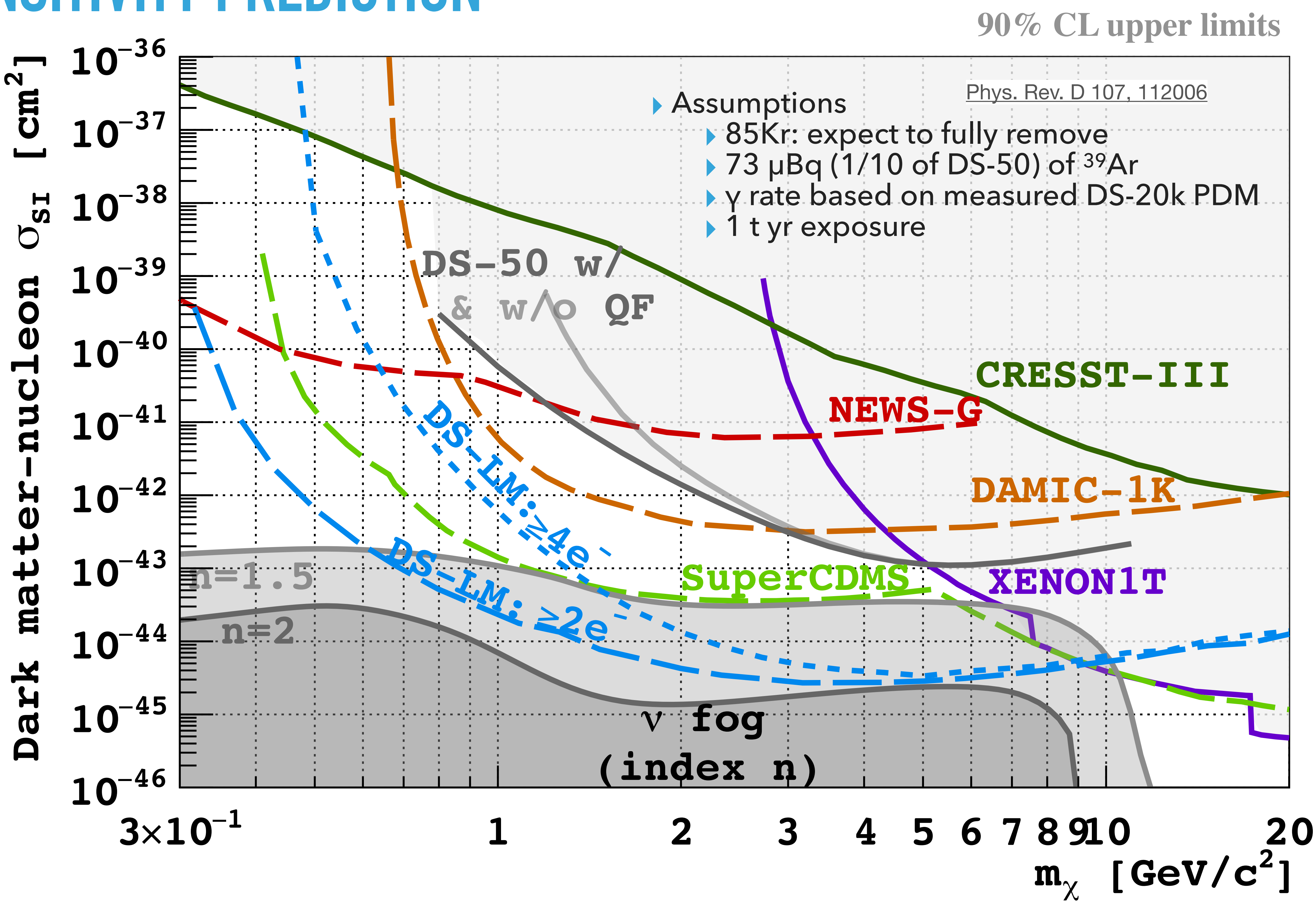
- Estimated γ-ray backgrounds using currently available technology
  - SiPMs from DS-20k
  - Acrylic from DEAP/DS-20k
  - Radiopure cryostat away from TPC
- Additional suppression with γ-ray veto system.





Phys. Rev. D 107, 112006

SENSITIVITY PREDICTION



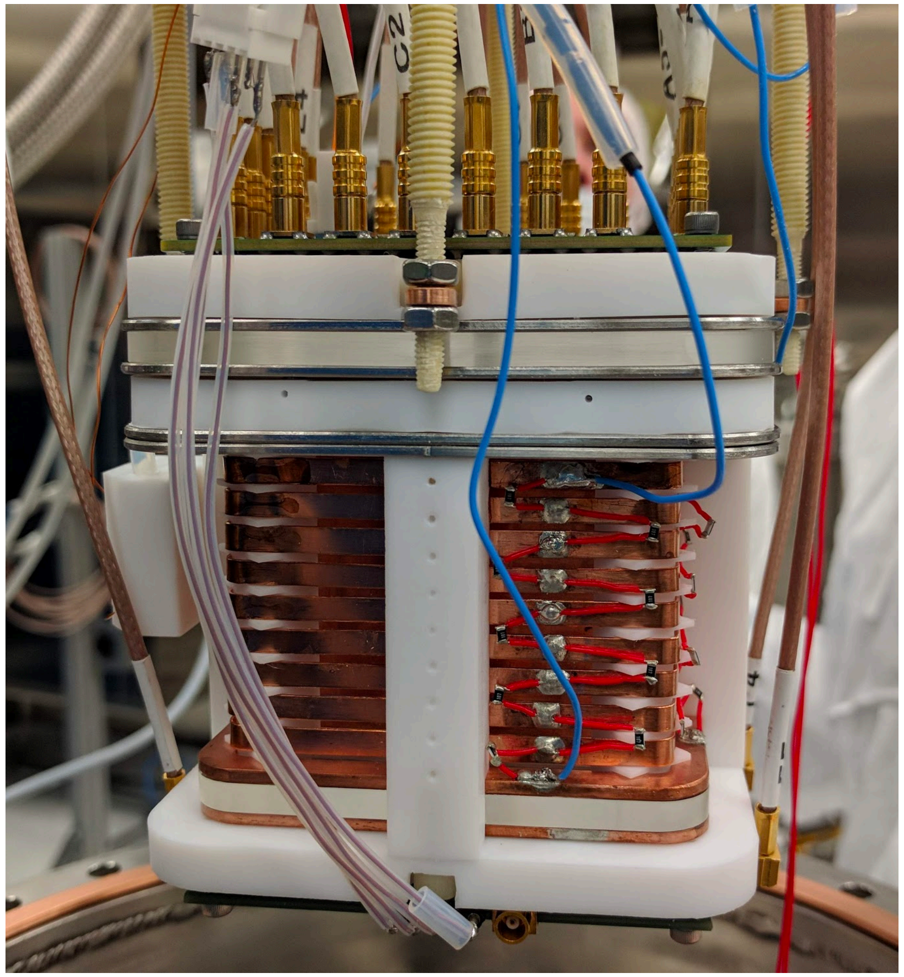
- With 1 t yr exposure, ν-fog is reachable!

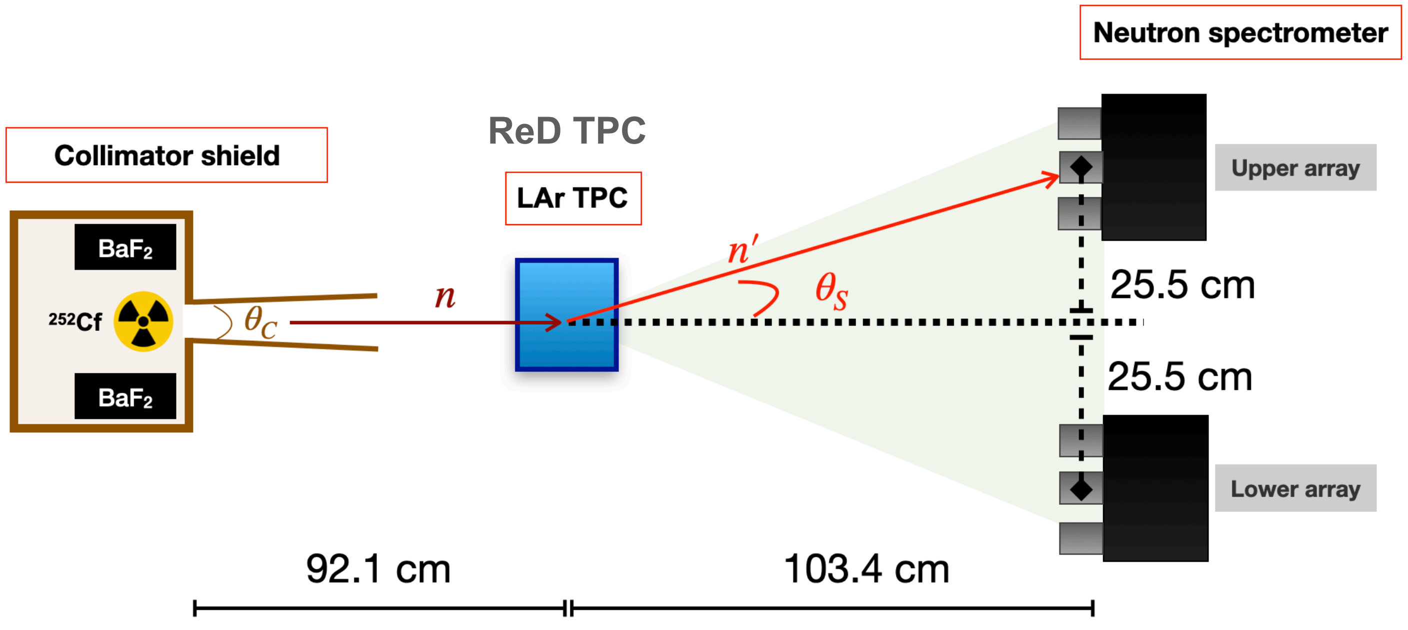
ReD EXPERIMENT

- Low energy nuclear recoil calibration is necessary to model DM signals.
- A small TPC with SiPM readout
- Directionality study completed
  - P. Agnes et al, Eur. Phys. J. C **84**, 24 (2024)
- Dedicated run with ^{252}Cf neutron source to measure the ionization yield in Ar for nuclear recoils down to 2 keV
- Analysis completed and final results to be presented at this conference

See more details in Luciano Pandola's talk!!

ReD TPC P. Agnes et al., Eur. Phys. J. C **81**, 1024 (2021)





Low energy Nuclear recoil calibration setup

SUMMARY

- DarkSide-50 has established the sensitivity of LAr for low mass dark matter.
- **DarkSide-20k** has potential to lead the searches **below 5 GeV/c².** See more details in Commun Phys 7, 422 (2024).
- **DarkSide-LowMass has a clear path to the ν-fog** with the technologies developed for DarkSide-20k.
- Significant γ-ray background reduction due to radio pure materials and the veto system.
- Room for additional sensitivity gains from:
  - **^{39}Ar reduction**: Improvements in UAr extraction with the Urania plant and isotopic purification with the Aria cryogenic distillation column,
  - **Lower energy threshold**: Lower SE backgrounds, better UAr purity, and optimized field design.
- Ongoing R&D for spurious electron suppression, low-energy recoil calibration measurements, and further energy threshold reduction.

Please check Phys. Rev. D 107, 112006 for more details!

Backup

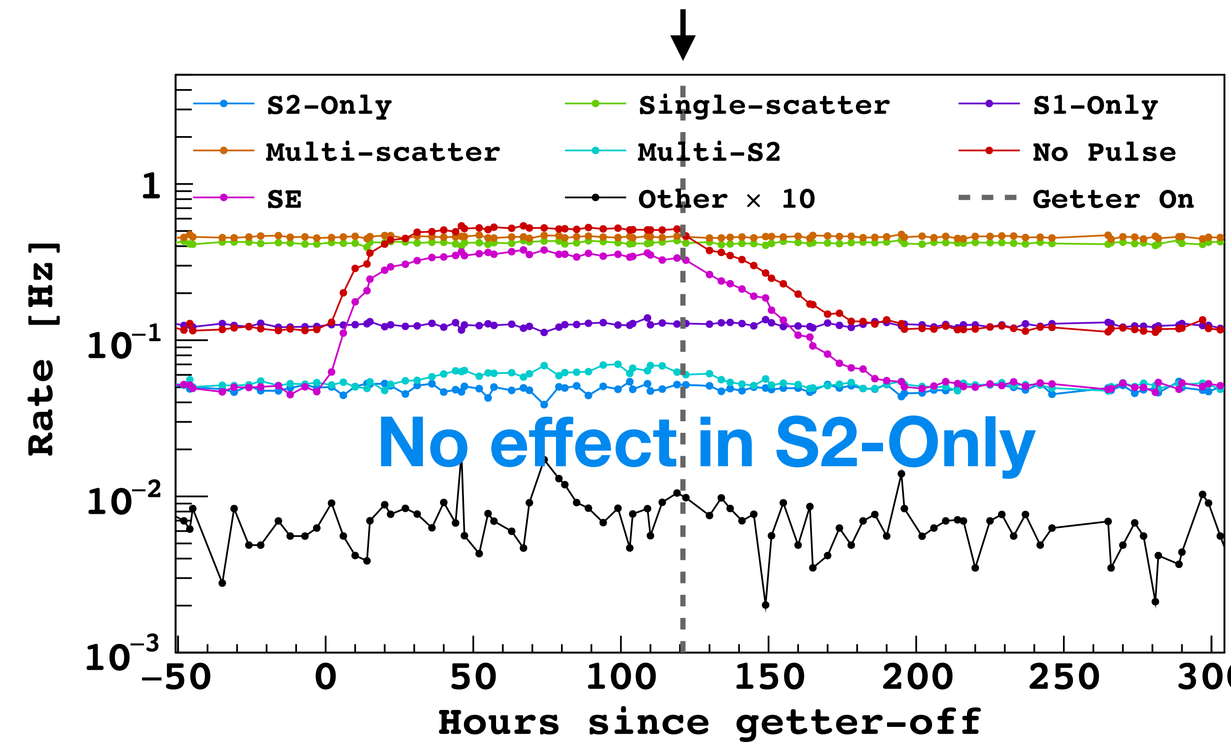
WHAT CAUSE SPURIOUS ELECTRONS?

- From correlation with absence of a purification system etc., up to ~50% of SE can be **impurity origin**.

  More details see arXiv:2507.23003

- **No** identified SE events related to **grid emission** (seen in xenon-based detector). Wire vs plane (ITO) on the cathode and anode make difference?

- Electron extraction efficiency is higher in Ar than Xe.



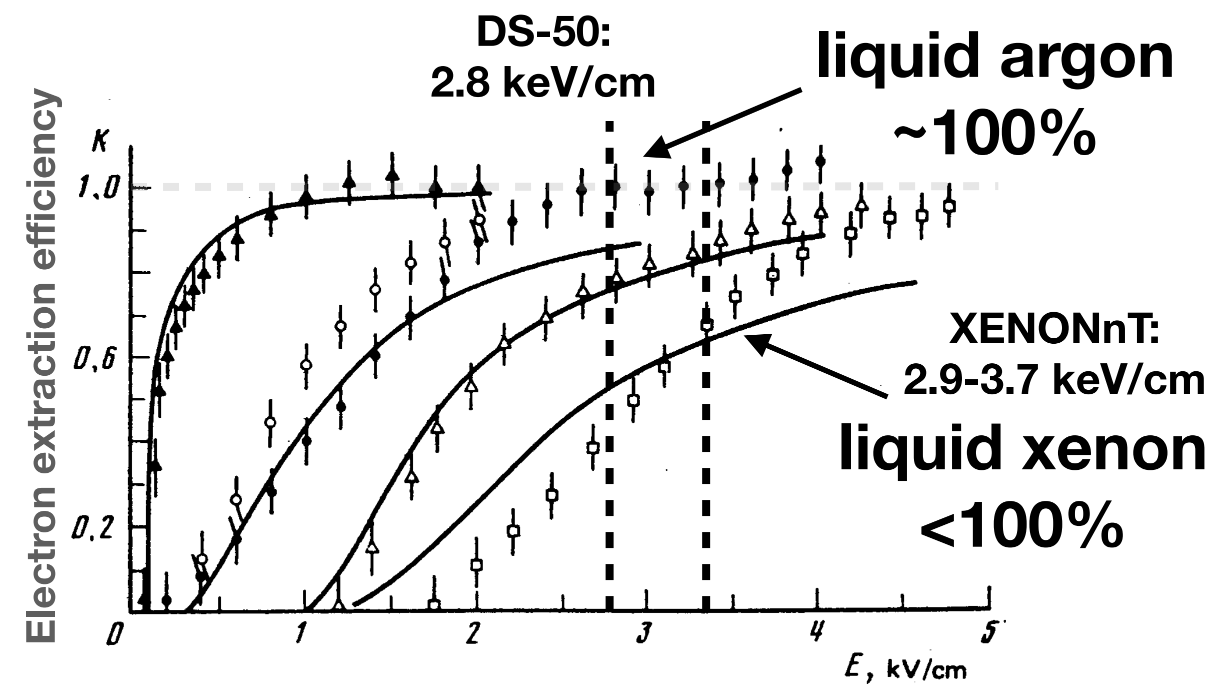


FIG. 1. Dependence of the coefficient of electron emission from solid (▲, 80 K) and liquid (●—fast component, ○—fast plus slow components, 90 K) argon, and solid (△, 160 K) and liquid (□, 165 K) xenon on the electric field intensity. Solid lines—calculations.

E. M. Gushchin et al., Sov. Phys. JETP 55(5), May 1982

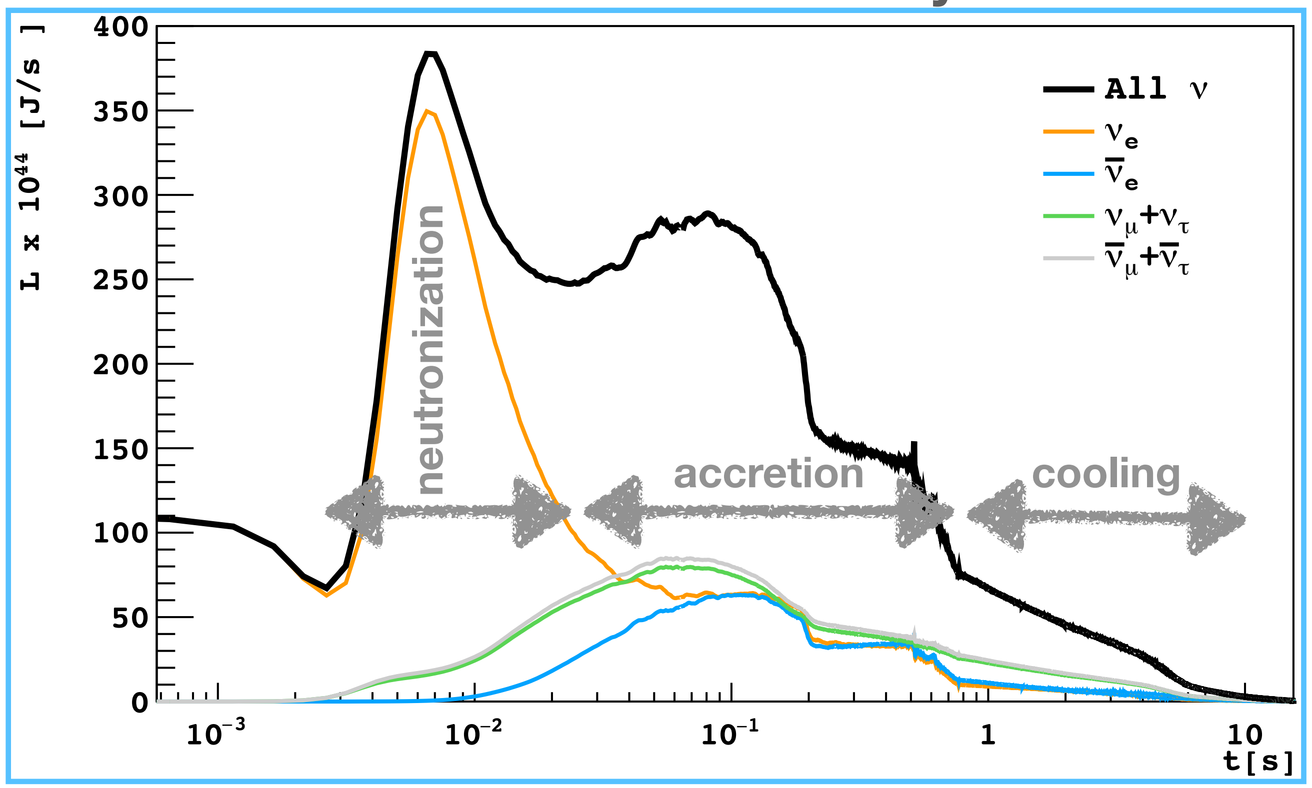
SENSITIVITY TO SUPERNOVA NEUTRINOS

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

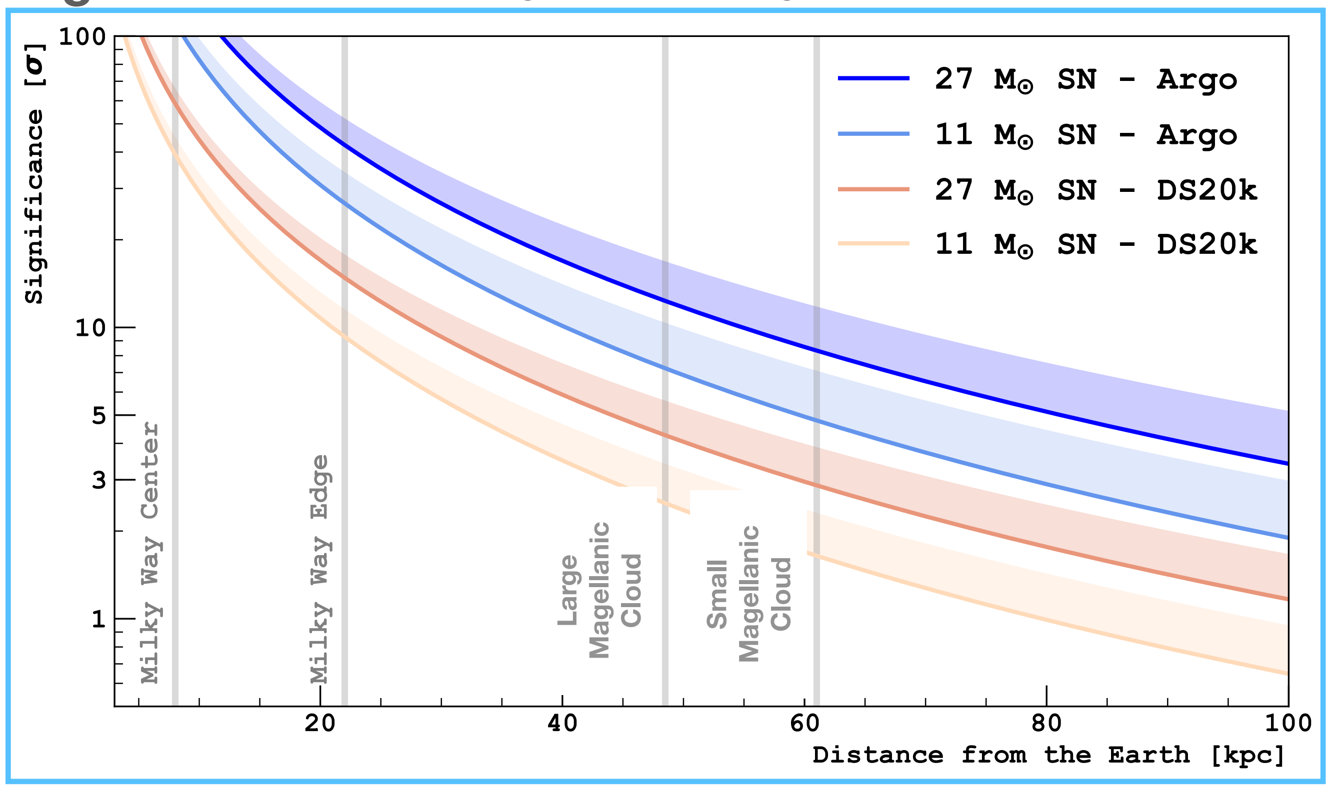
$\langle E_\nu \rangle$~10 MeV

- 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⊙ 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).

COSMOGENIC ACTIVATION IN TRANSIT

- Cosmogenic activation in transportation is inevitable.
- Detail activation calculations for plausible transportation paths, UAr purification at Aria.

	^{39}Ar	^{37}Ar [μBq/kg]	^{3}H
Urania→Aria	14.7 ± 1.3	806 ± 73	58 ± 12
Aria (1 mo., surface)	2.57 ± 0.33	294 ± 39	9.0 ± 2.8
Aria→LNGS	0.86 ± 0.11	118 ± 15	3.00 ± 0.95
Aria→N. America	5.73 ± 0.73	483 ± 64	20.0 ± 6.3

- ^{37}Ar: (EC, x-rays+e- ~ 277 or 2829 eV) $t_{1/2}$ = 35 days → Good calibration, removes itself
- ^{3}H: (β-, Qβ = 18.6 keV) $t_{1/2}$ = 12.3 years → Remove w/ chem. purification (ex situ: Aria, in situ: Getter)
- ^{39}Ar: (β-, Qβ = 565 keV) $t_{1/2}$ = 269 years → Sets floor: **Hard to go below ~1 μBq/kg.** For reference, 100× reduction relative to DS-50 gives 7.3 μBq/kg

LOCATIONS

Candidate locations:

- The China Jinping Underground Laboratory (CJPL), China
- SNOLAB, Sudbury, Ontario, Canada
- Boulby Underground Laboratory, UK
- The Gran Sasso National Laboratory (LNGS), Italy
- Any other place? Kamioka?

arXiv:2007.15925