Low Mass Dark matter searches with liquid Argon

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AstroCeNT

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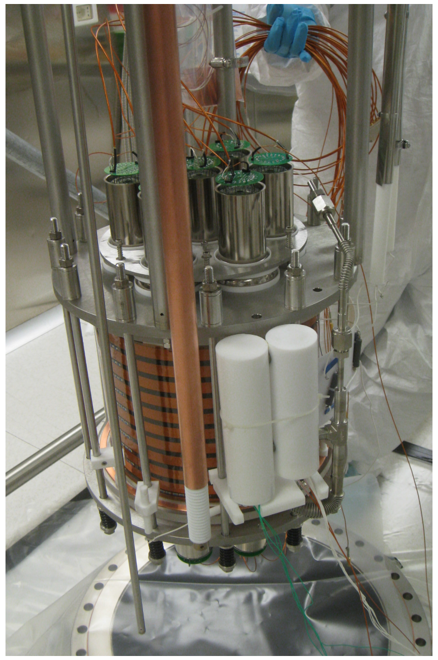
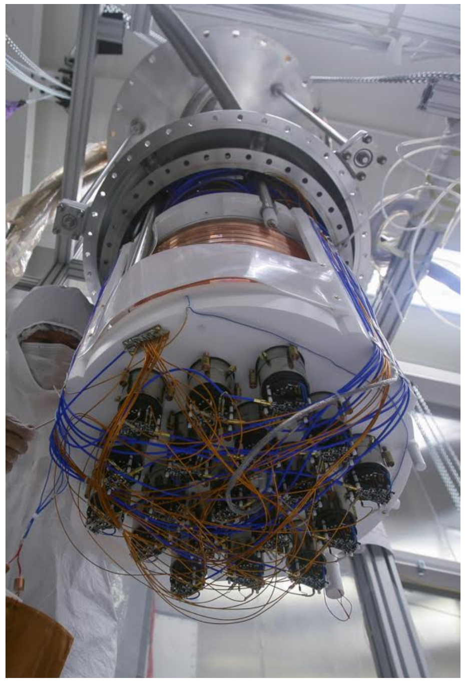
DARKSIDE PROGRAM

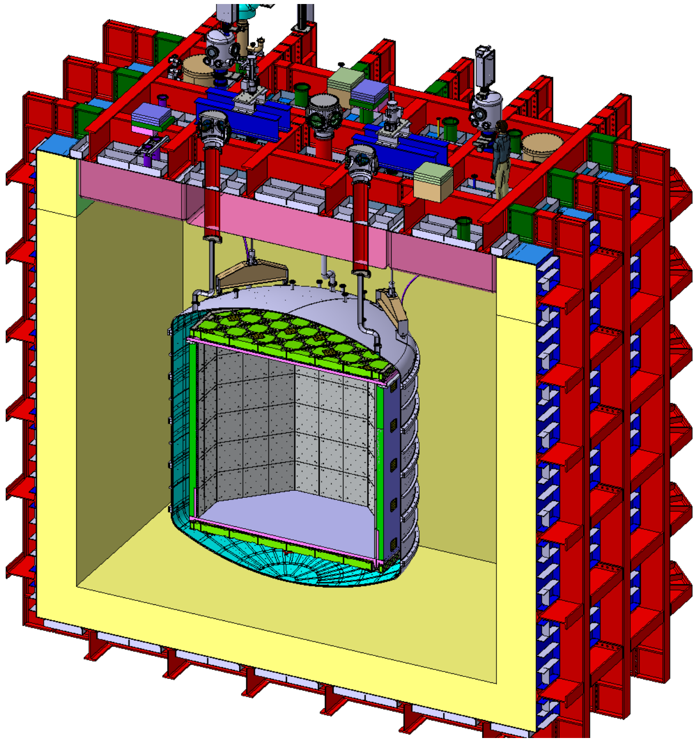
- **Direct detection** search for **WIMP** dark matter
- Based on a **two-phase argon** time projection chamber (**TPC**)
- Design philosophy based on having very low background levels that can be further reduced through **active suppression**, for **background-free** operation from both neutrons and β/γ's



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
- **No mechanical stress** on target materials (one origin of low-energy backgrounds)
- **Purification in situ** after commissioning

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**

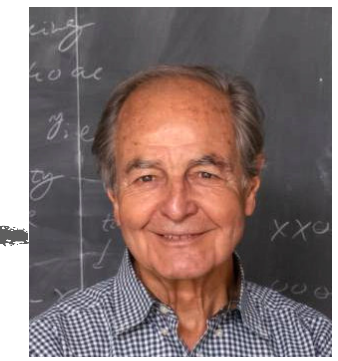
- Denser & Radio pure
- Lower energy threshold
- Sensitive to low mass WIMP

Liquid **Argon**

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

UNDERGROUND Ar

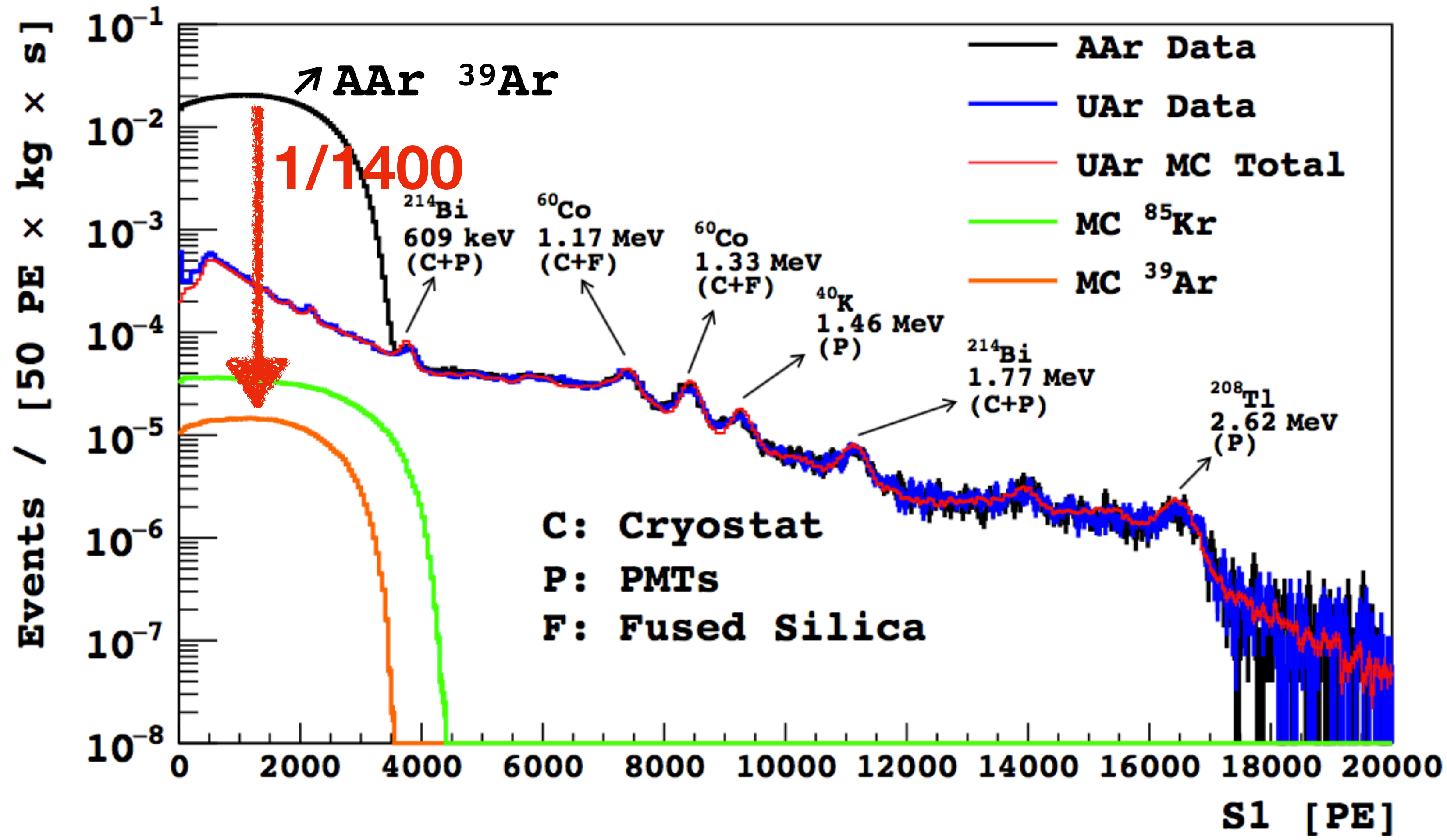
- Intrinsic ^{39}Ar radioactivity in **atmospheric argon** is the primary background for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective)
- ^{39}Ar is a **cosmogenic isotope**, and the activity in argon from **underground sources** can be significantly lower compared to **atmospheric argon**



Frank Calaprice

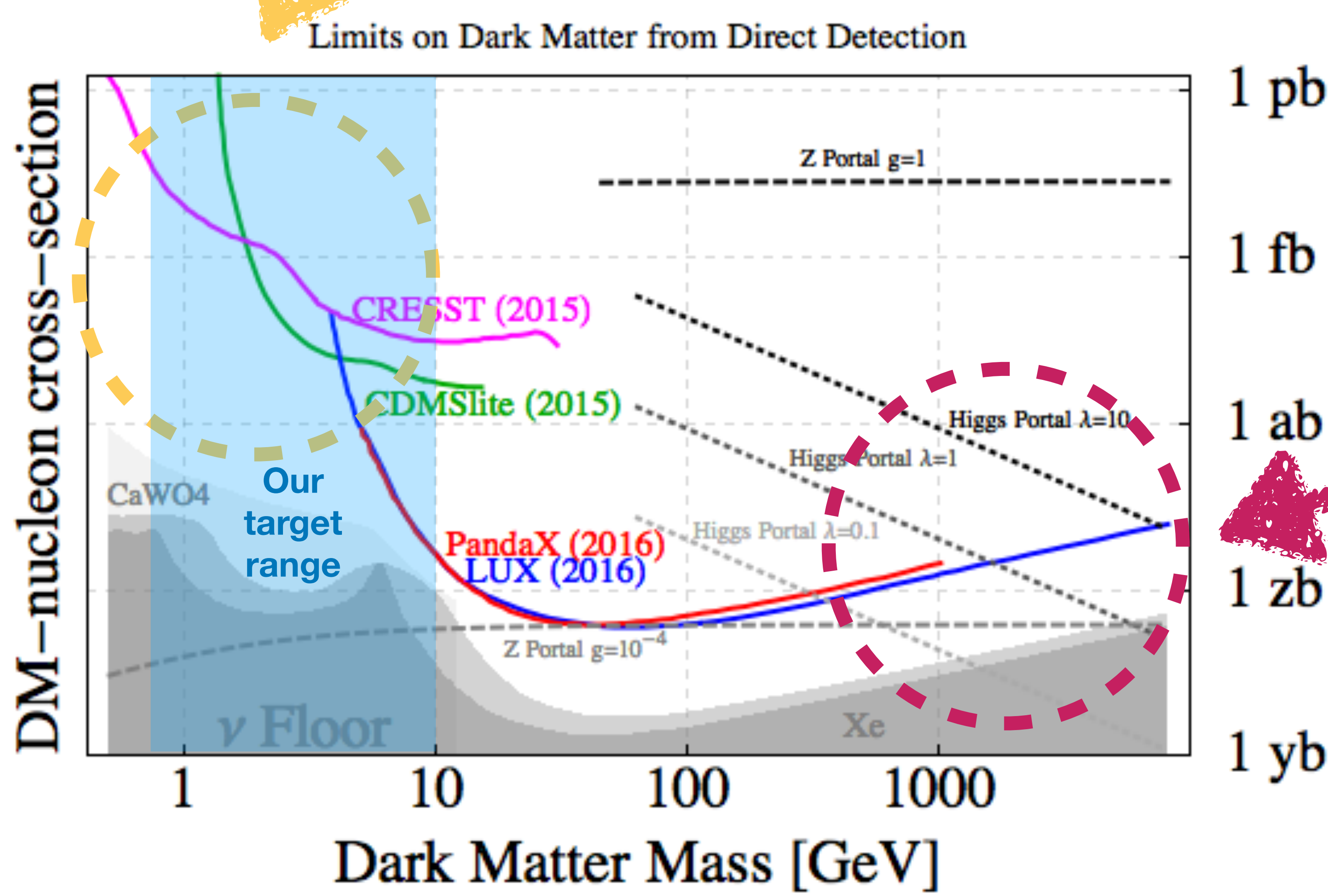
- We deployed 157kg of underground argon in 2015.

^{39}Ar reduction factor of ~1400!



SENSITIVITY TO HIGH AND LOW MASS WIMPS

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



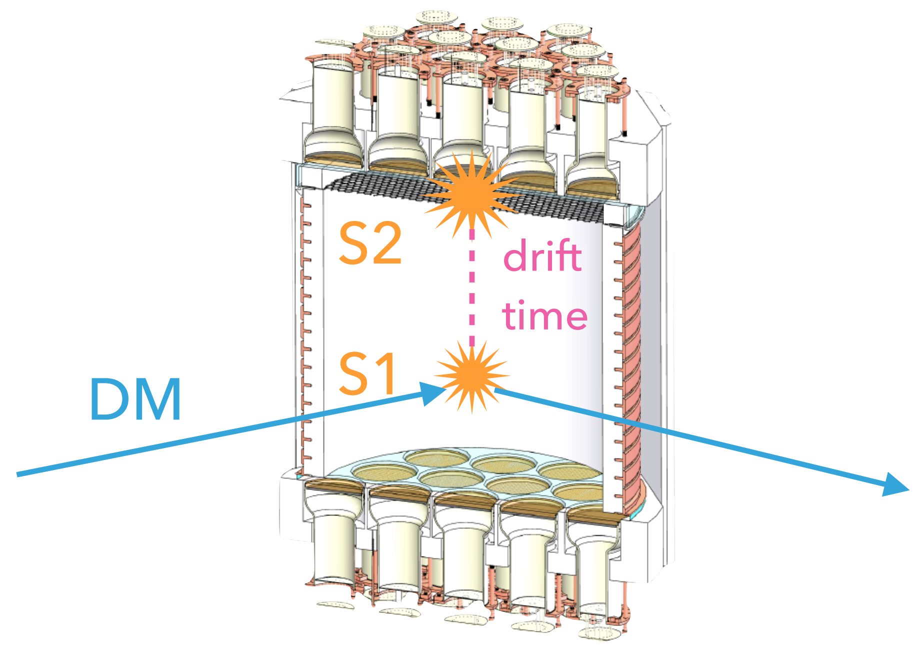
High — Number Density — Low

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

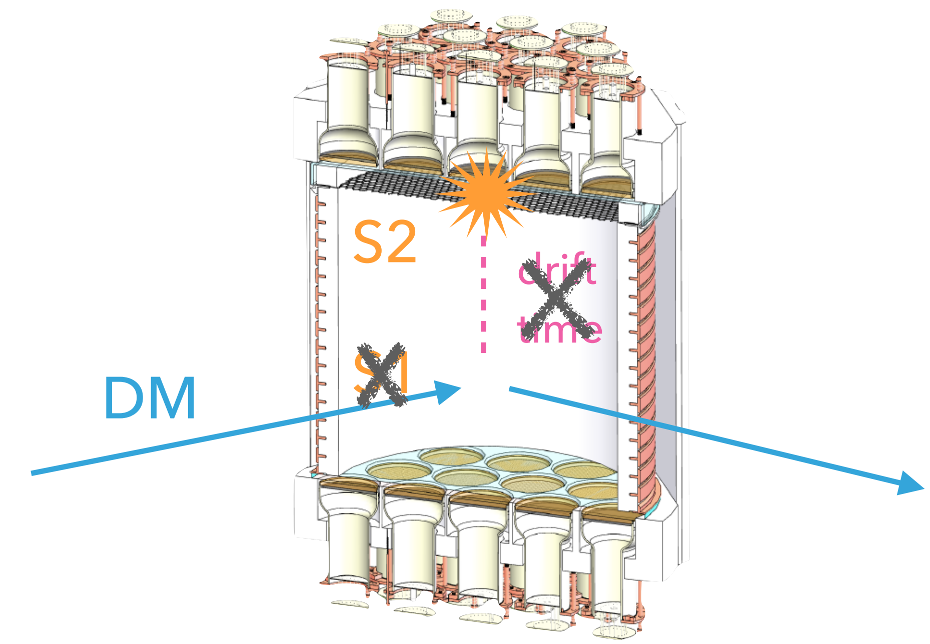
plot credit: http://resonaances.blogspot.ca

LIQUID Ar TPC FOR DARK MATTER SEARCHES

High Mass Search
High Energy Events



Low Mass Search
Low Energy Events



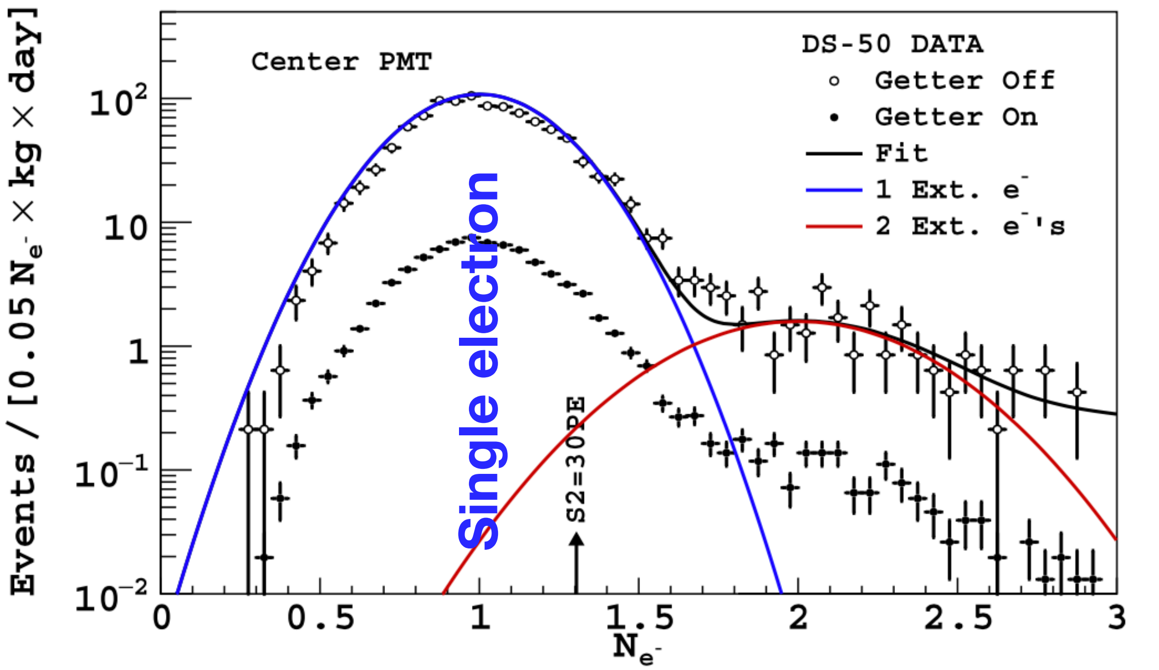
- Scintillation (S1) & Ionization (S2)
- Pulse Shape Discrimination (PSD)
- Drift time provides vertical event position

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

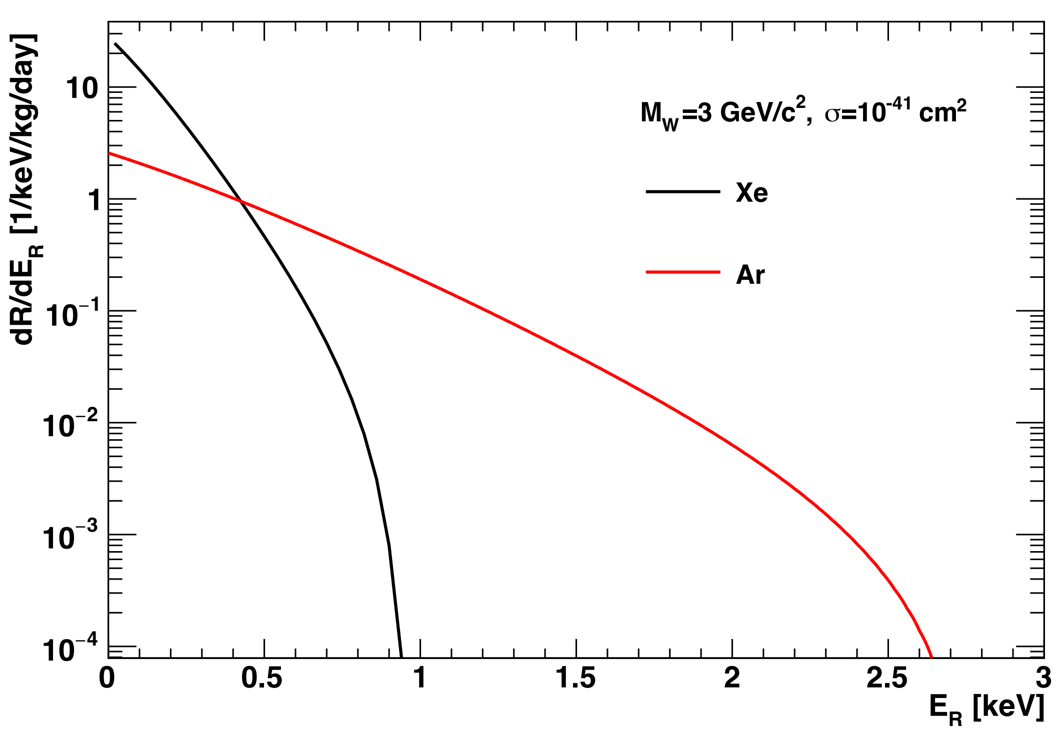
WHAT WE ACHIEVED IN DS-50

- **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



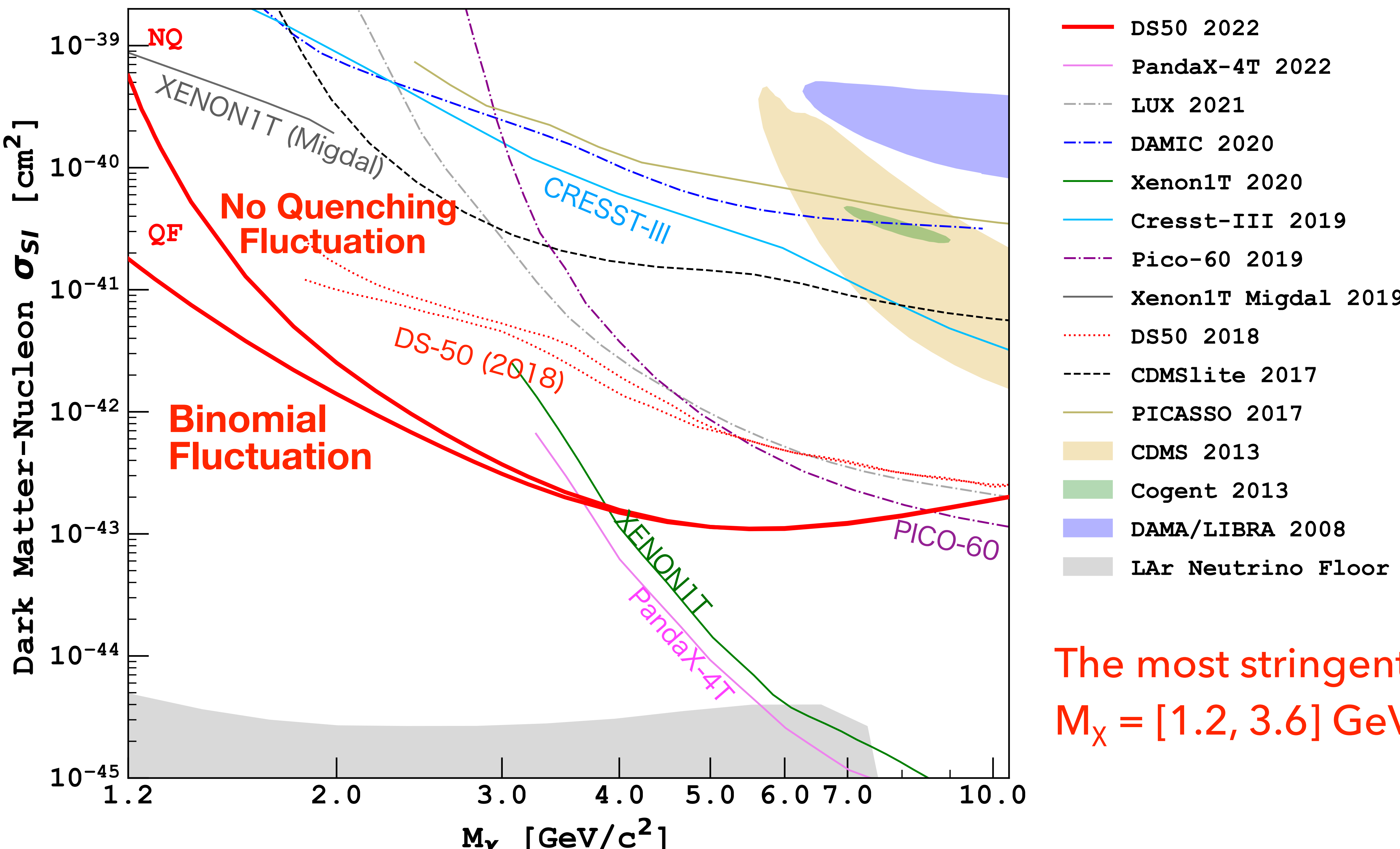
WIMP spectra in Xe and Ar



- 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

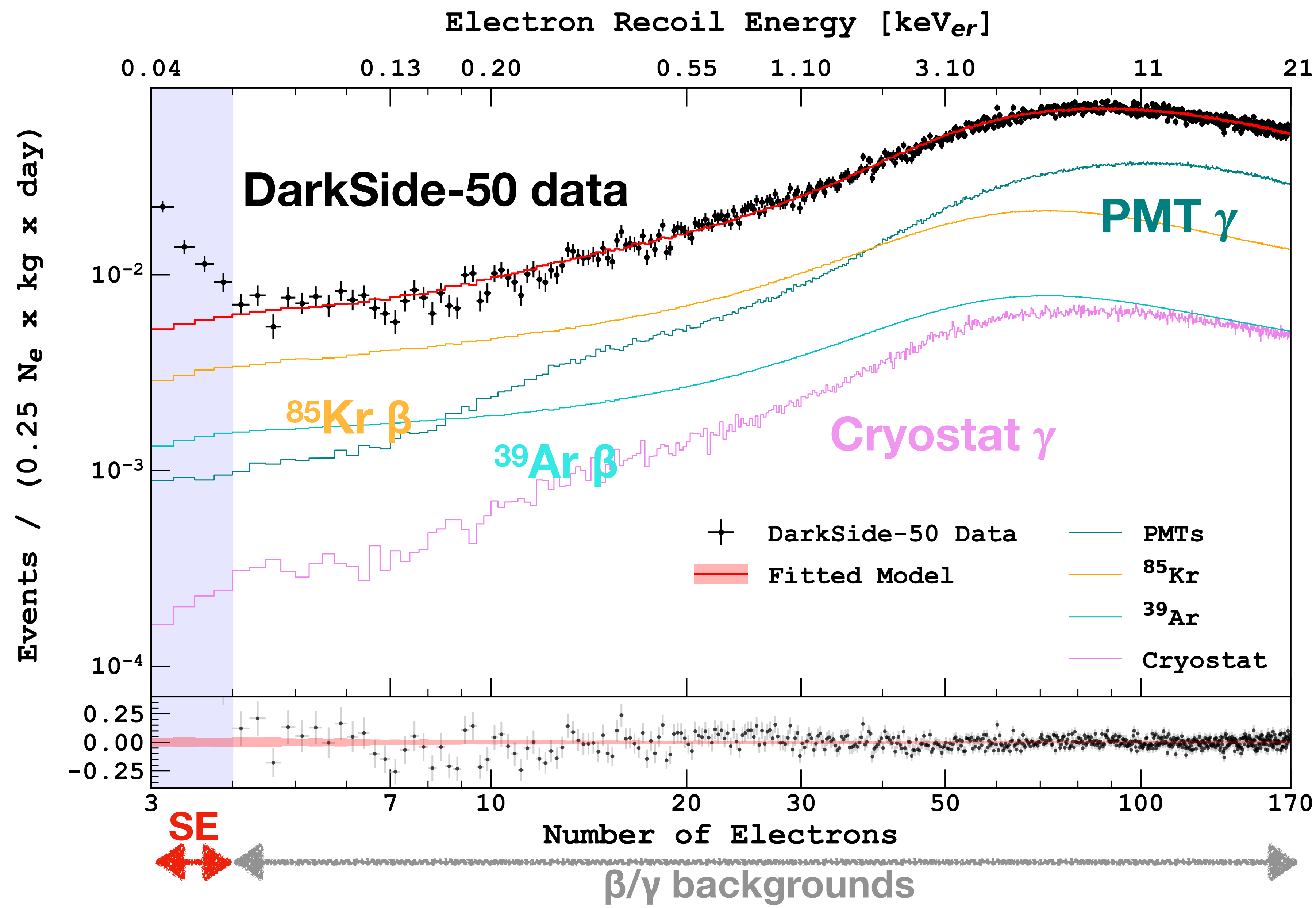


The most stringent limit at M_χ = [1.2, 3.6] GeV/c^2

Annual modulation analysis on arXiv!

arXiv:2307.07249

WHAT LIMITS SENSITIVITY?



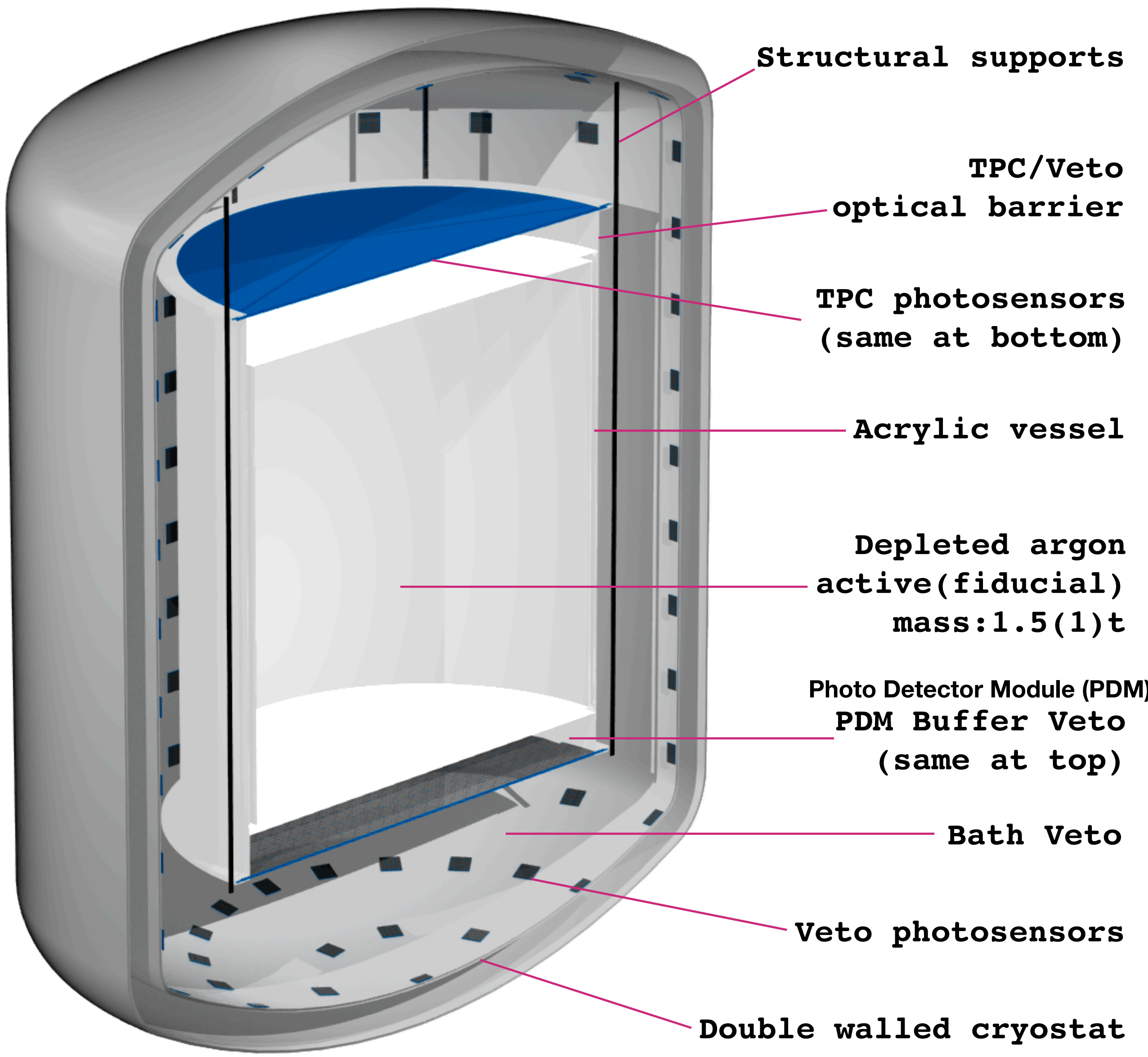
- Internal βs from ^{85}Kr and ^{39}Ar
- γs from photosensors and cryostat
- Spurious electrons (setting the energy threshold)
- Limited understanding of LAr responses

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 (or no) cryostat

Phys. Rev. D 107, 112006

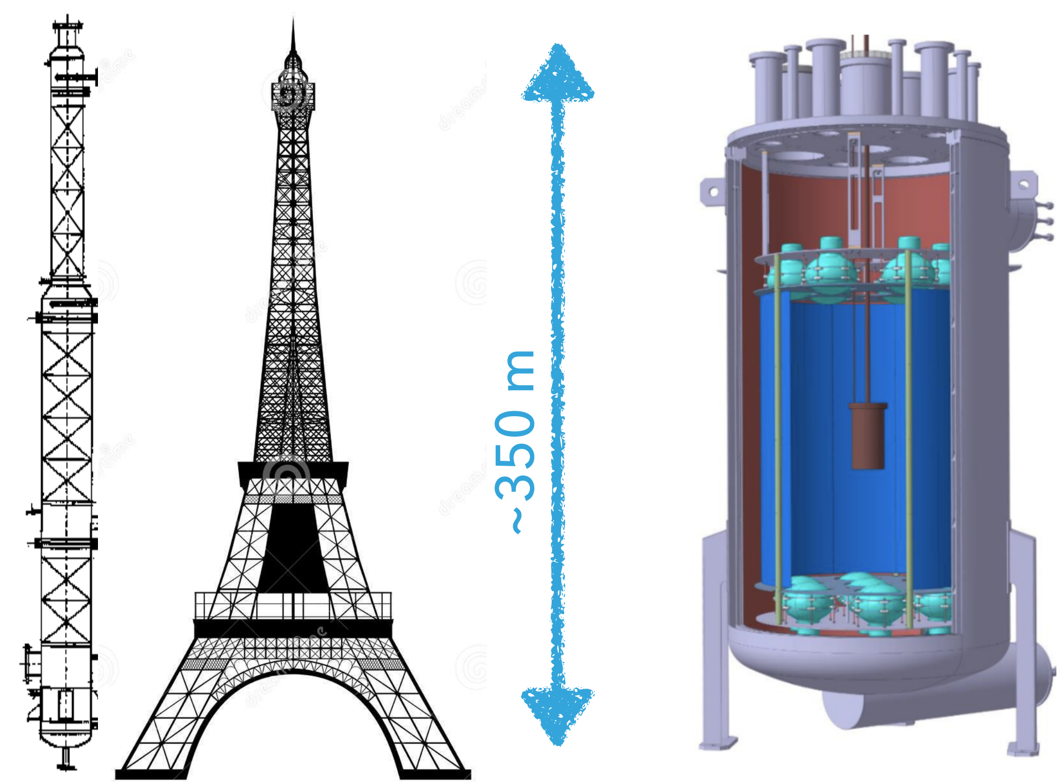
DarkSide-LowMass conceptual design



~6 t of LAr

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.

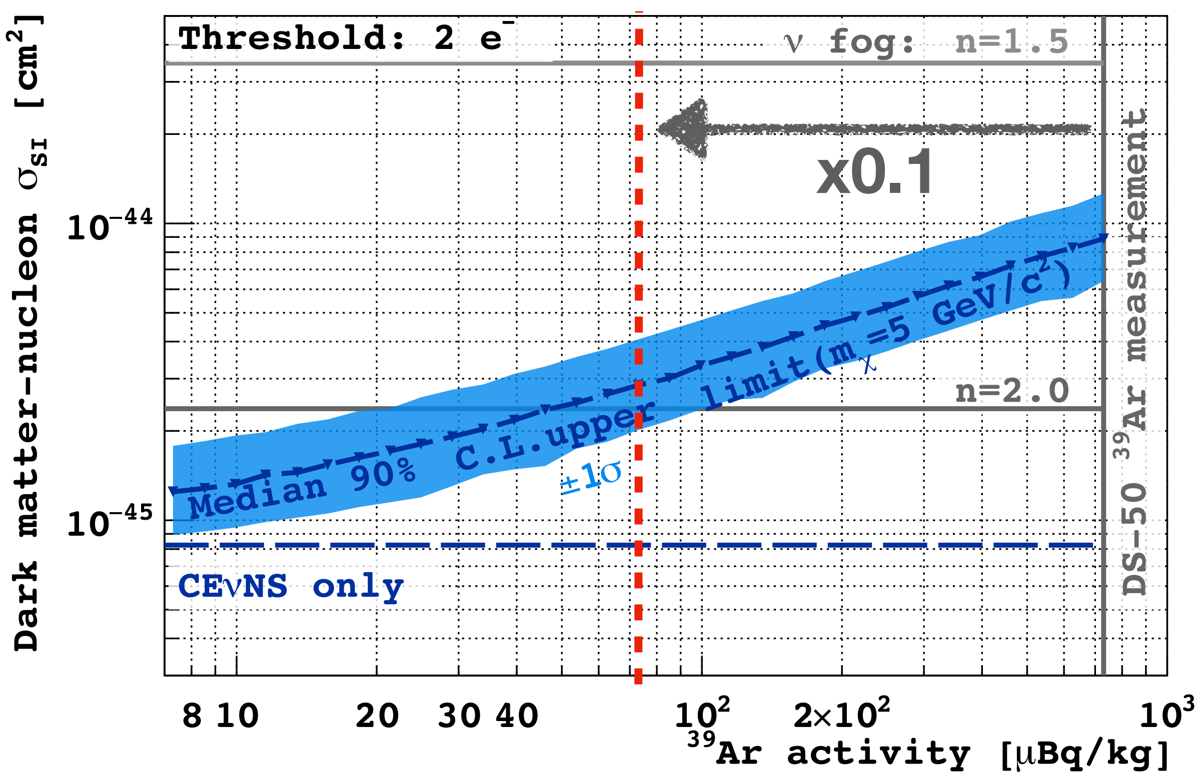


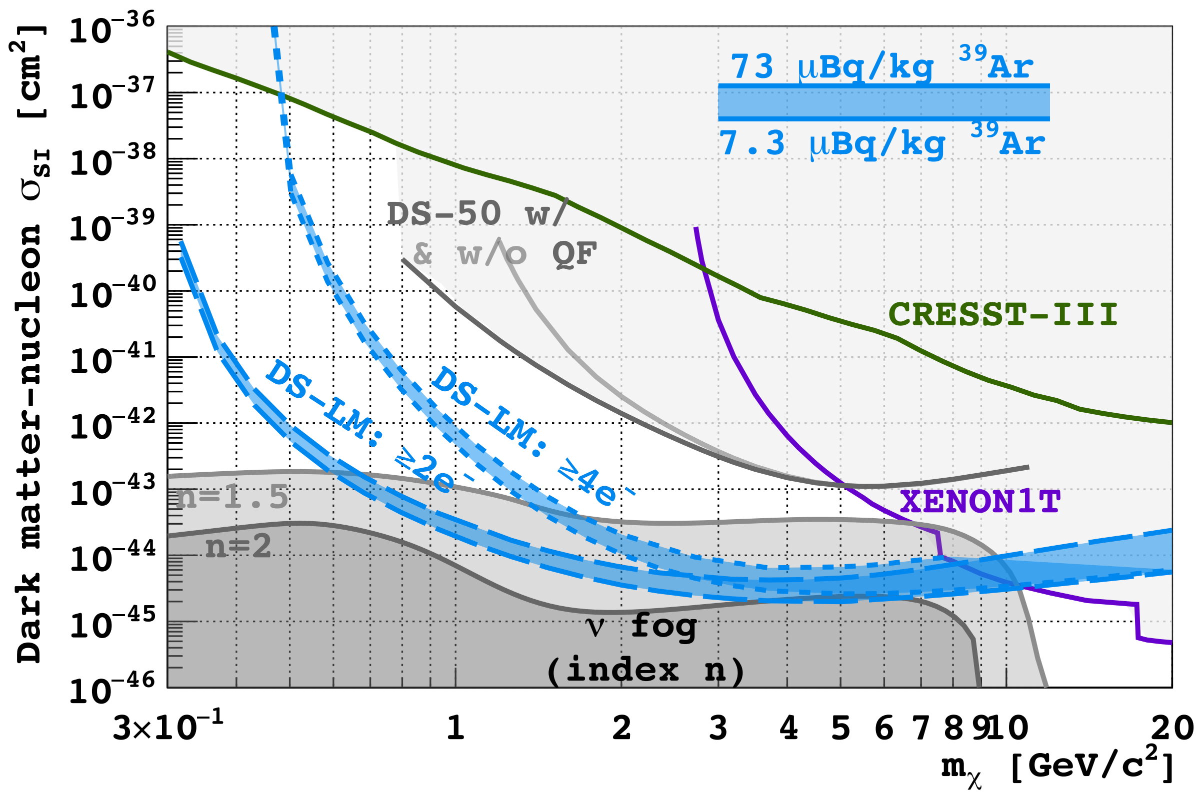
ARIA column

DArT in ArDM

WHAT IF WITH HIGHER ^{39}Ar CONCENTRATION?

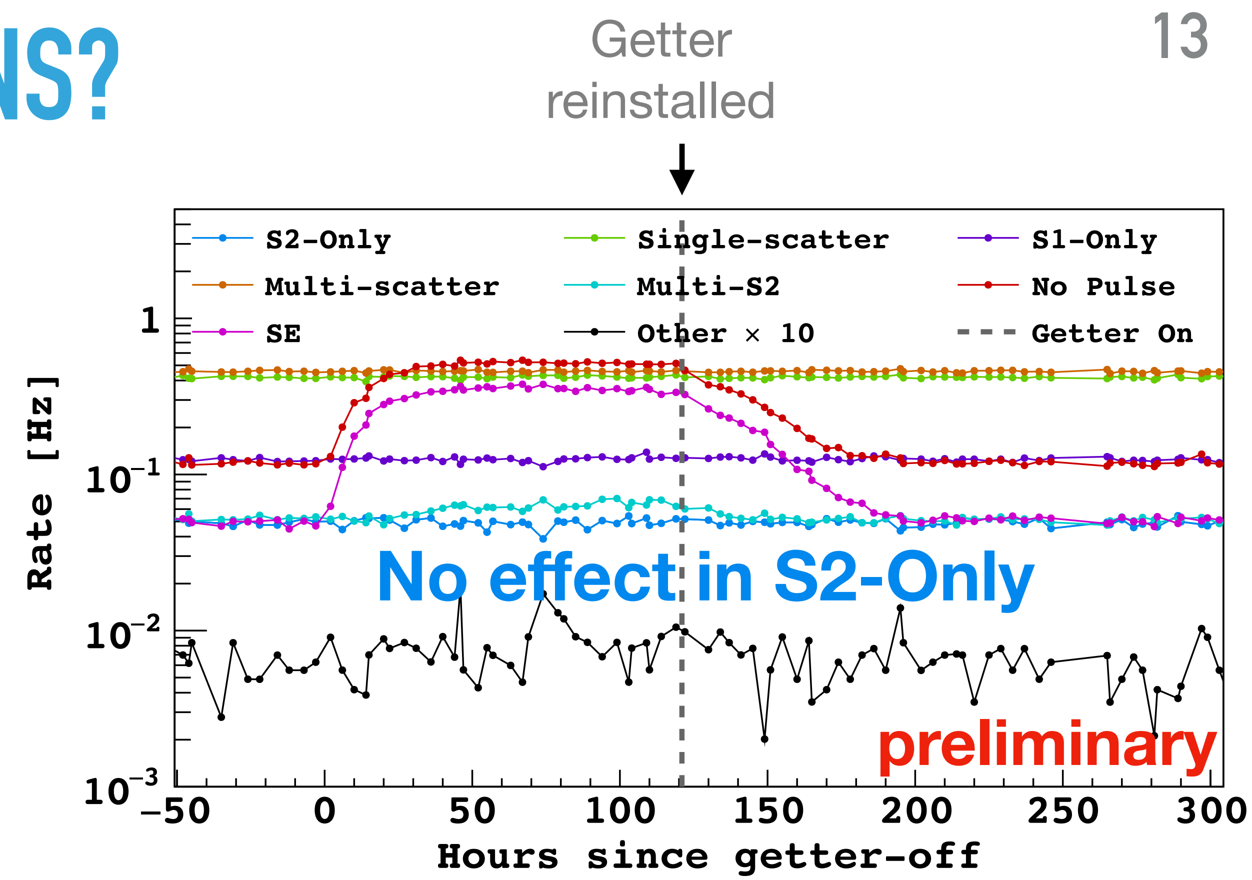
- DarkSide-50 established we can achieve at least 750 μBq.
- With one path of ARIA (~75 μBq), DarkSide-LowMass can search down to neutrino fog at 5 GeV/c² DM mass.
- **Lowering the threshold** is more **important** to be sensitive to lower DM mass.





WHAT CAUSE SPURIOUS ELECTRONS?

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



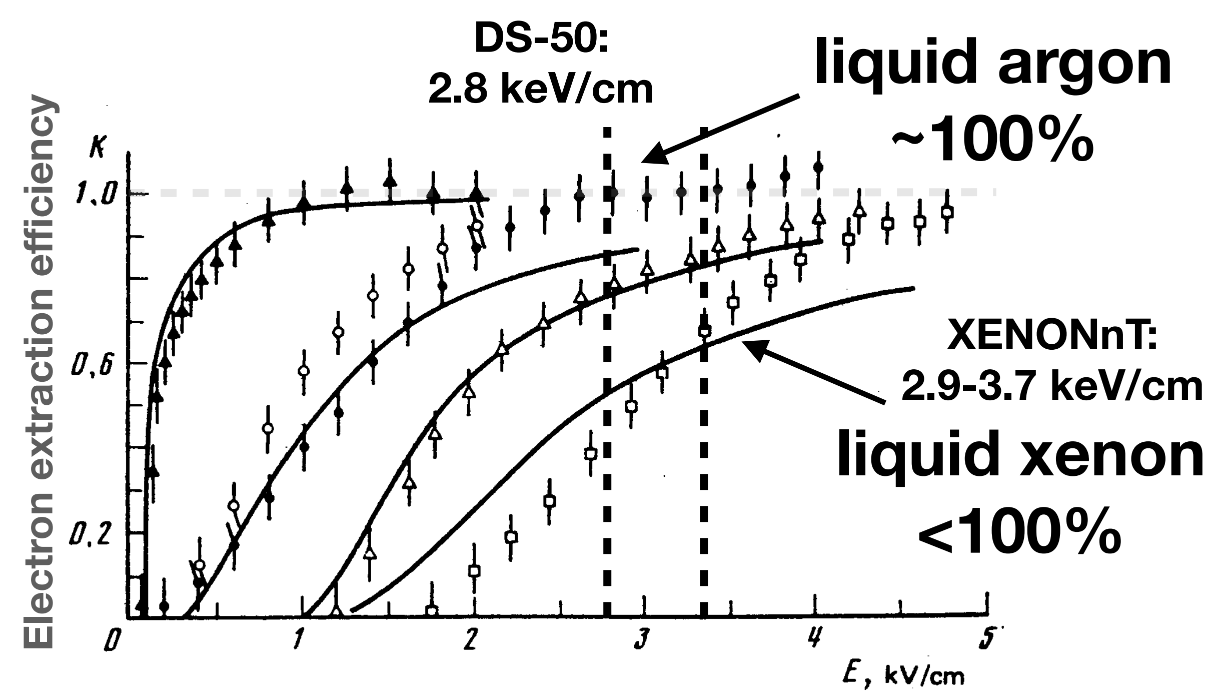
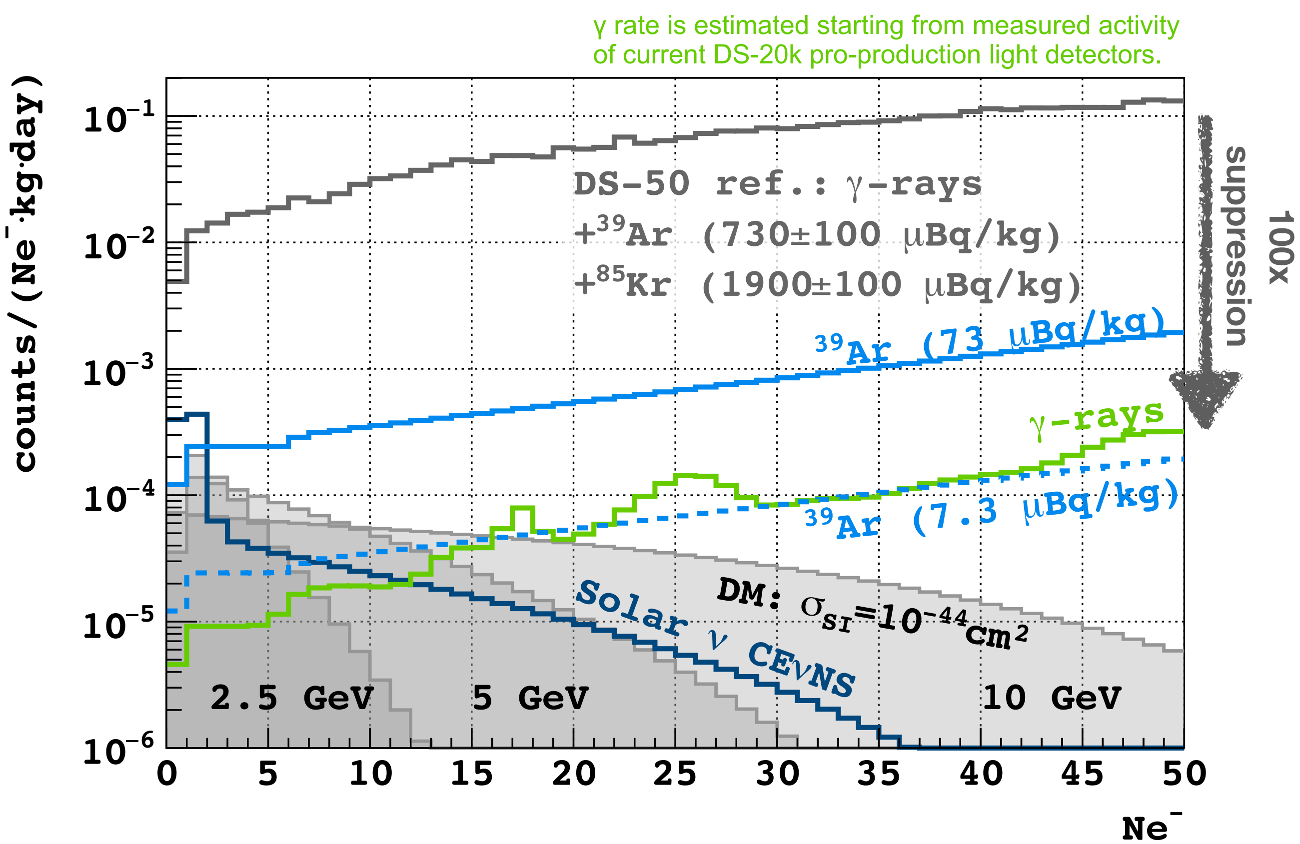


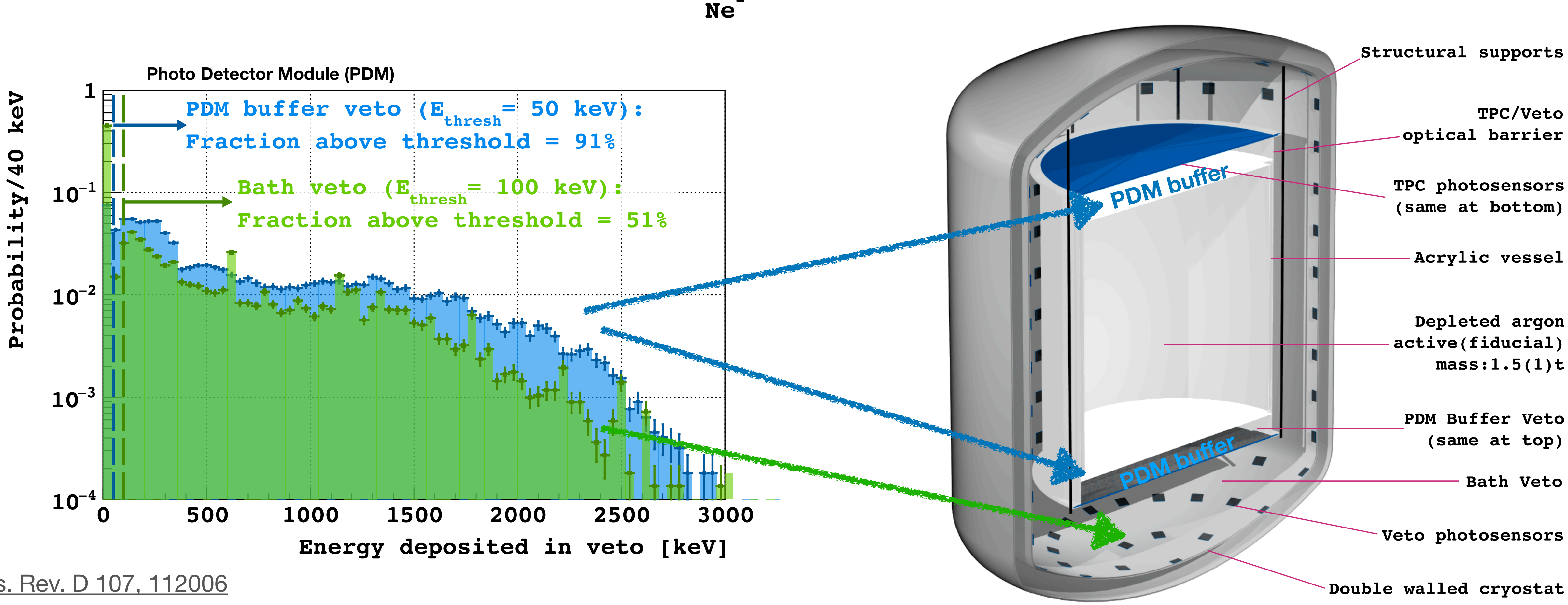
FIG. 1. Dependence of the coefficient of electron emission from solid (▲, 80 K) and liquid (●—fast component, ○—fast plus slow components, 90 K) argon, and solid (△, 160 K) and liquid (□, 165 K) xenon on the electric field intensity. Solid lines—calculations.

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

RADIOPURE DETECTOR



- Reduction of γ-ray backgrounds with improved radiopurity
  - SiPMs from DS-20k
  - Acrylic from DEAP
  - Radiopure cryostat away from TPC
- Additional suppression with γ-ray veto system.



Phys. Rev. D 107, 112006

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.**

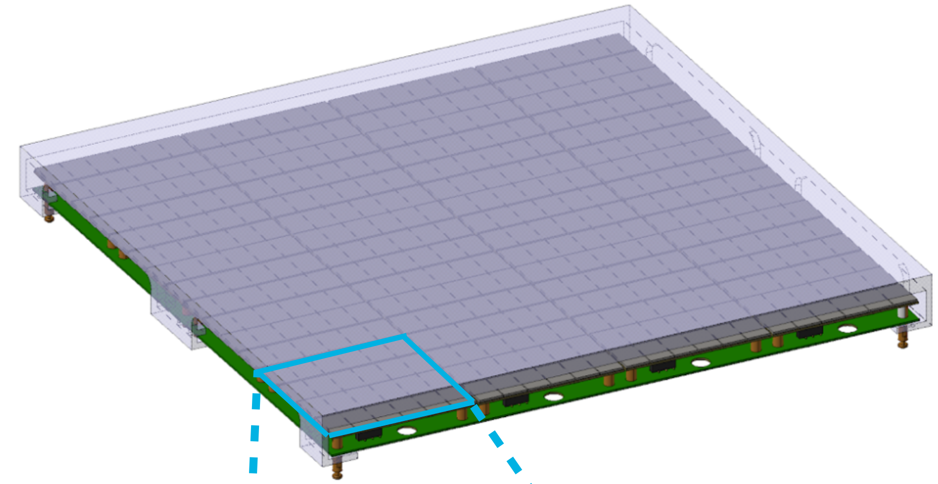


Photo Detector Unit (PDU) = matrix of 16 PDMs
20 x 20 cm^2

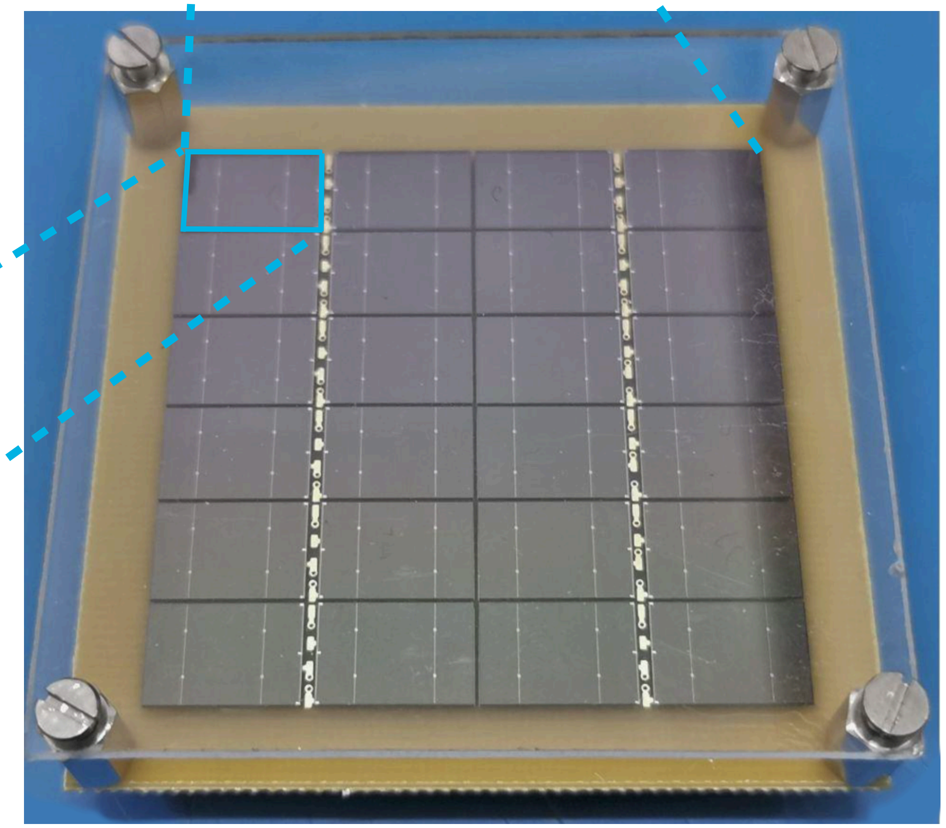
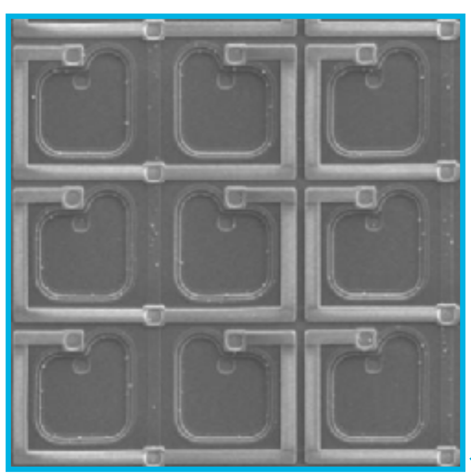
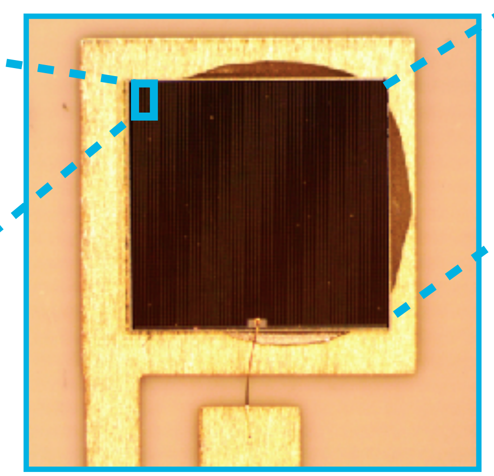


Photo Detector Module (PDM)
= matrix of 24 SiPMs, 5 x 5 cm^2
4 PDUs are summed and read as a single channel
(largest single SiPM unit ever!)



Single SPADs

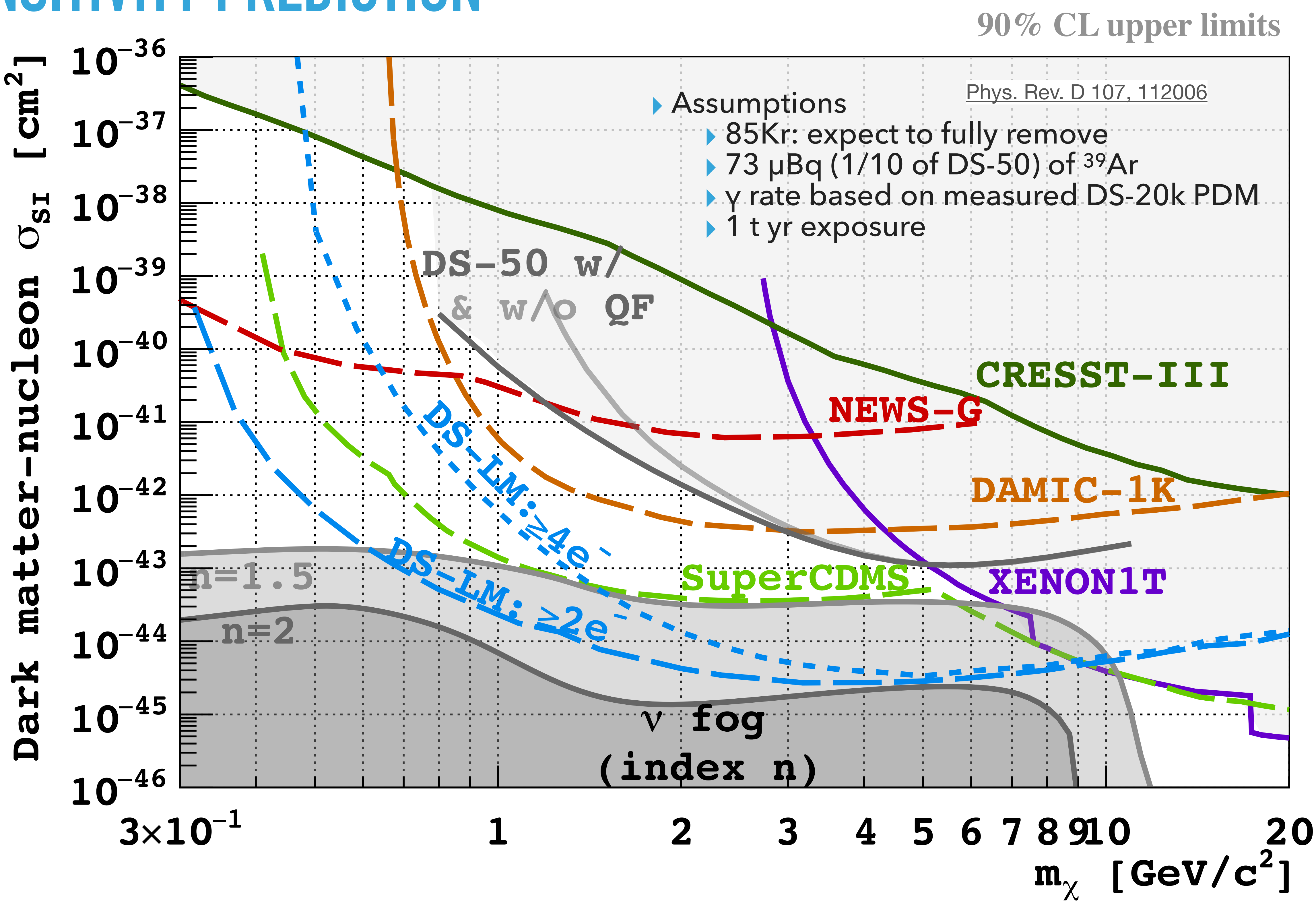
~25-30 μm^2



Single SiPM

~1 cm^2

SENSITIVITY PREDICTION



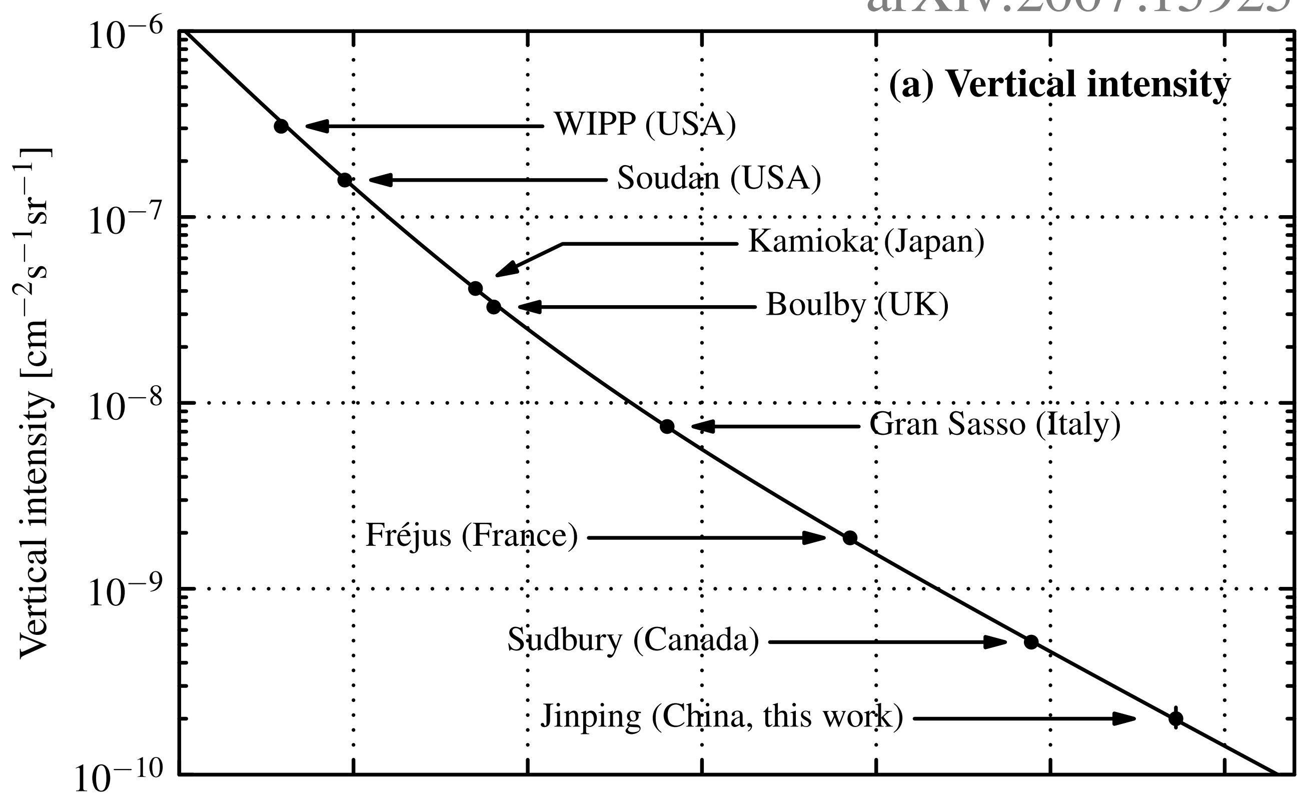
- With 1 t yr exposure, ν-fog is reachable!

LOCATIONS

Candidate locations:

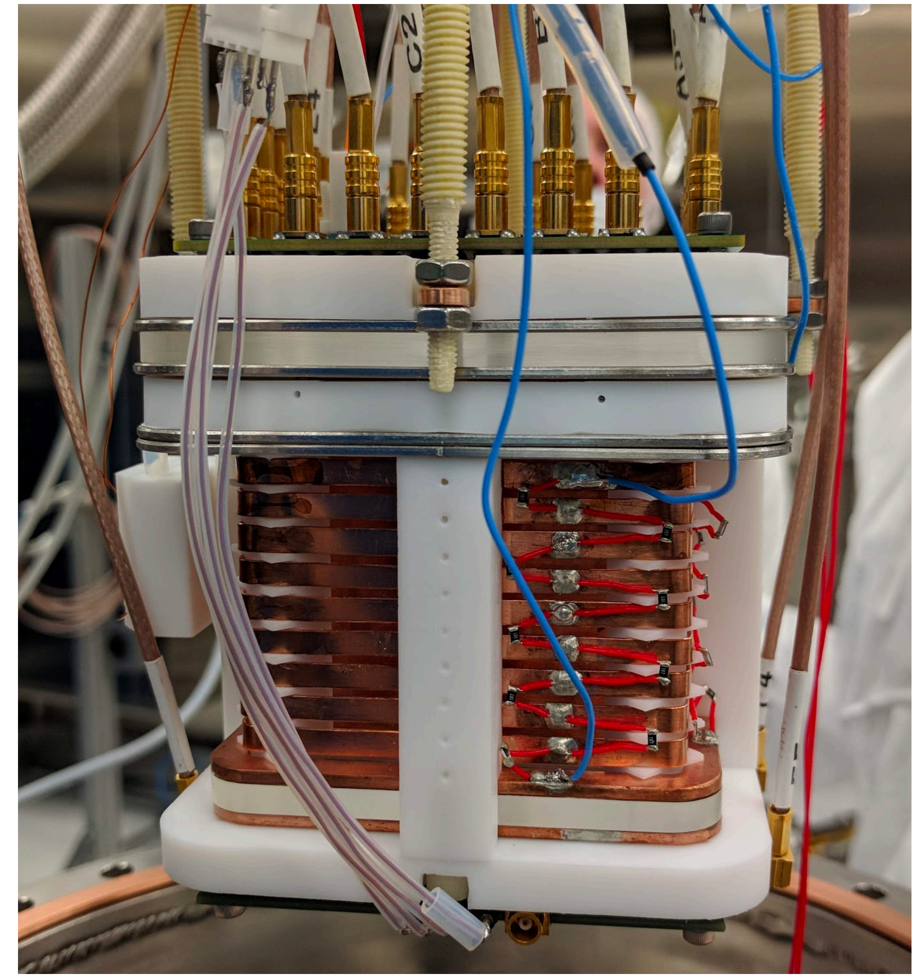
- The Gran Sasso National Laboratory (LNGS), Italy
- The China Jinping Underground Laboratory (CJPL), China
- Boulby Underground Laboratory, UK (SOLAIRE, DRD2 proposal)
- Any other place?

arXiv:2007.15925

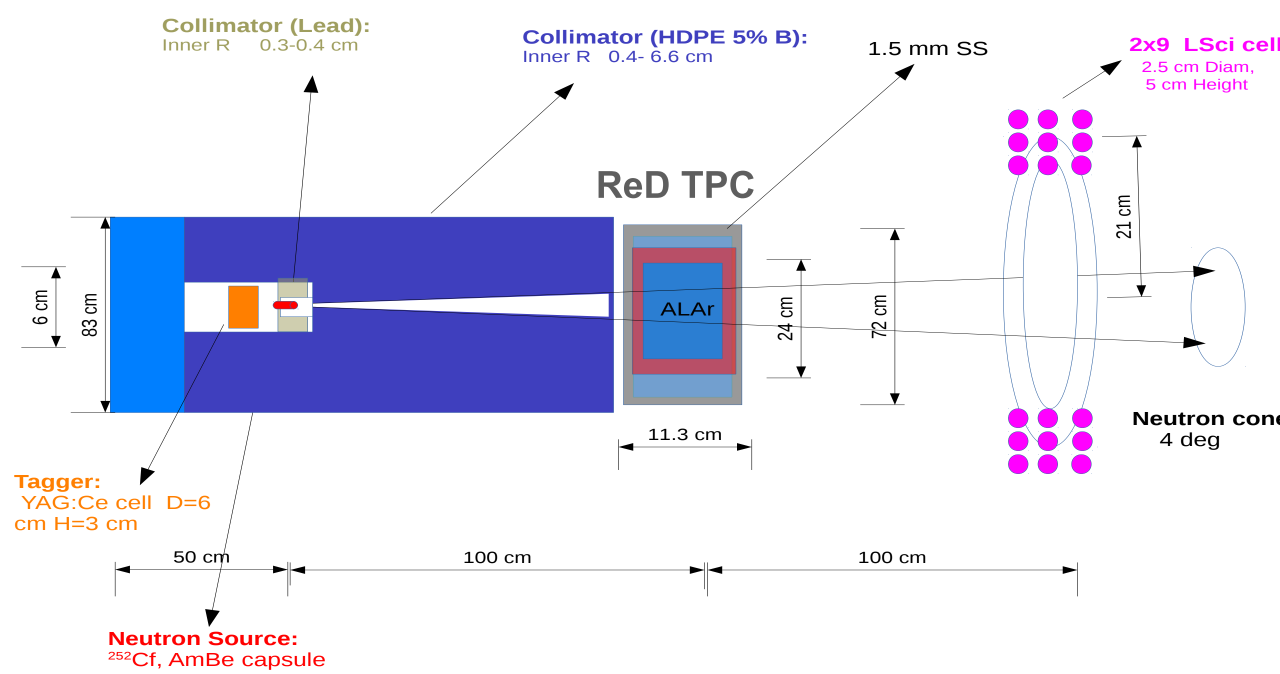


ReD EXPERIMENT

- Low energy Nuclear Recoil calibration is necessary to model DM signals.
- A small TPC with SiPM readout
- Finished the directionality study and prepare for low energy NR calibration
- New results with a Cf neutron source is underway.
- Calibration point down to 1-2 keV.



ReD TPC

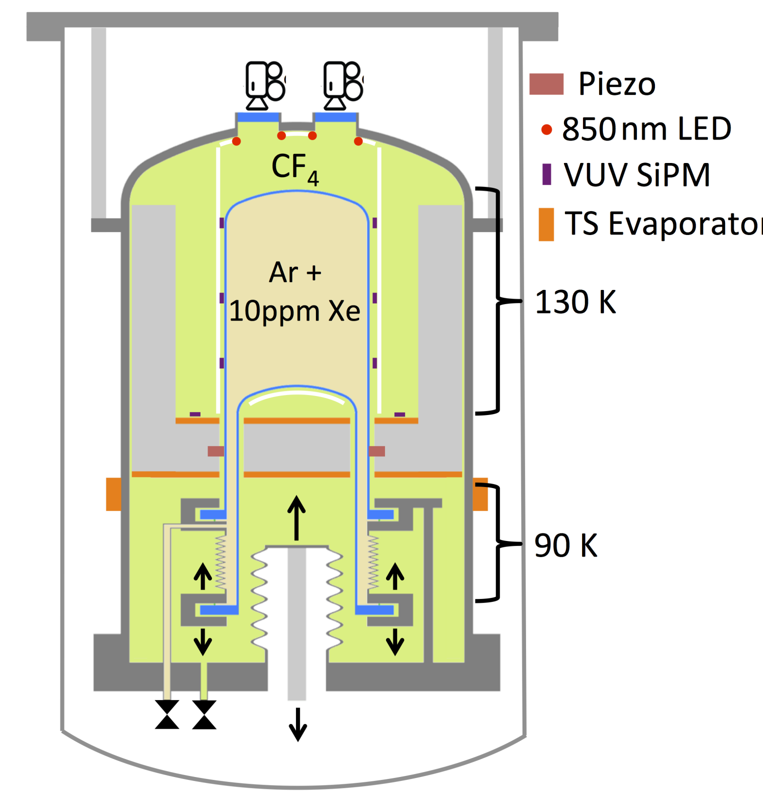


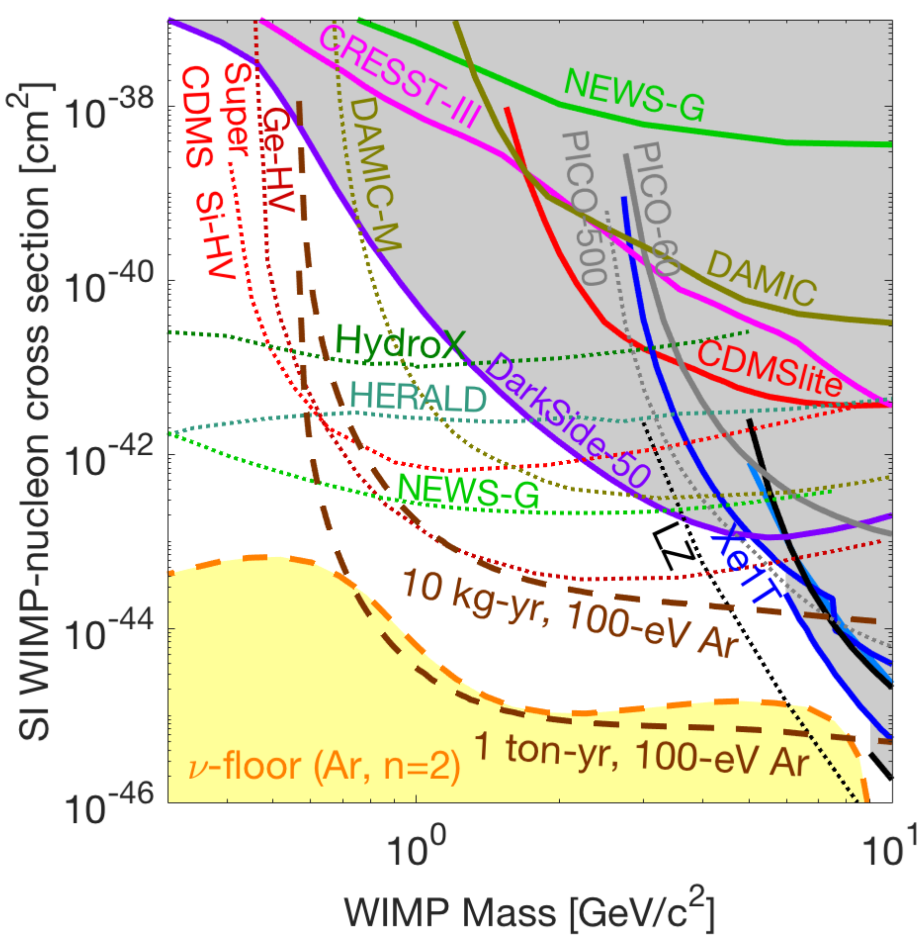
Low energy Nuclear recoil calibration setup

SCINTILLATING BUBBLE CHAMBER

- ER free bubble chamber + good energy resolution of liquid scintillator.
- No bubble formation from ERs via this heat channel.
- BG free even at low energy NRs (<1 keV).
- 1 ton-yr exposure with BG free could be achievable with extrapolation of the current technology.

SBC-LAr10 detector





SUMMARY

- LAr-based detectors have **several advantages for low mass DM searches.**
- DarkSide-50 has established the sensitivity of LAr for low mass dark matter.
- **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

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