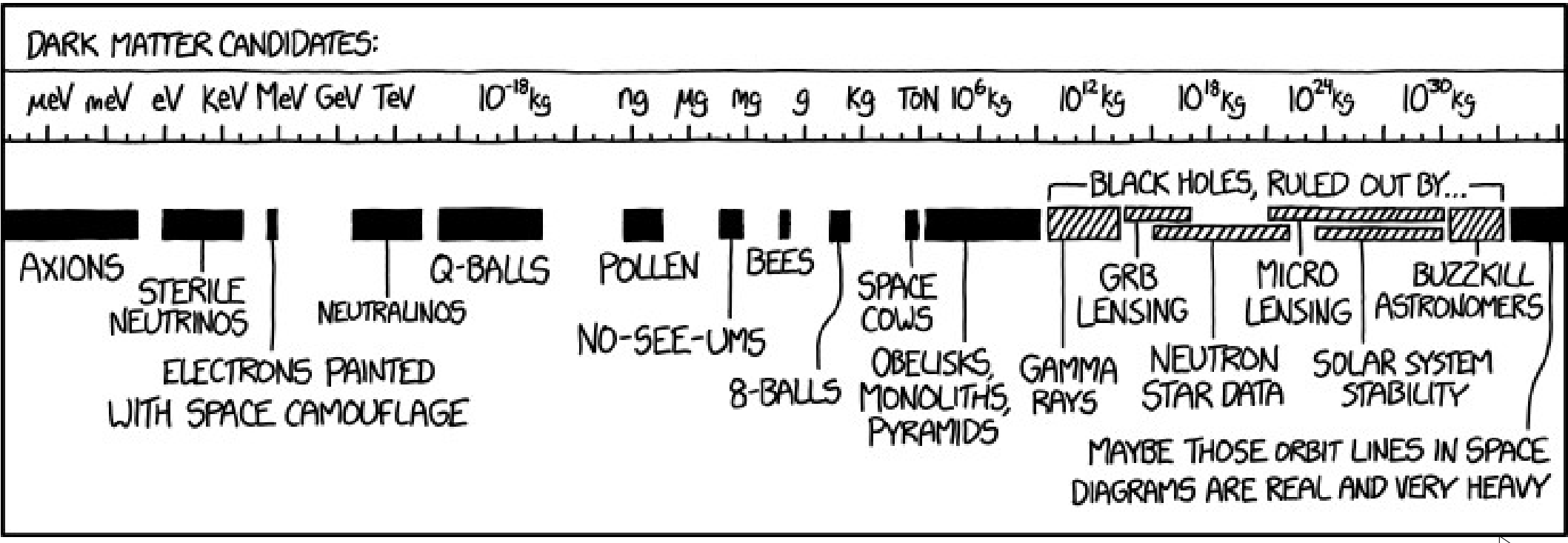
Detecting low-mass dark matter with liquid argon

Shawn Westerdale
with the GADMC
GUINEAPIG Workshop
20 August, 2024

UCR PHYSICS & ASTRONOMY

Bing AI, draw guineapigs making a LArTPC

Mixture of DarkSide studies and my own musings



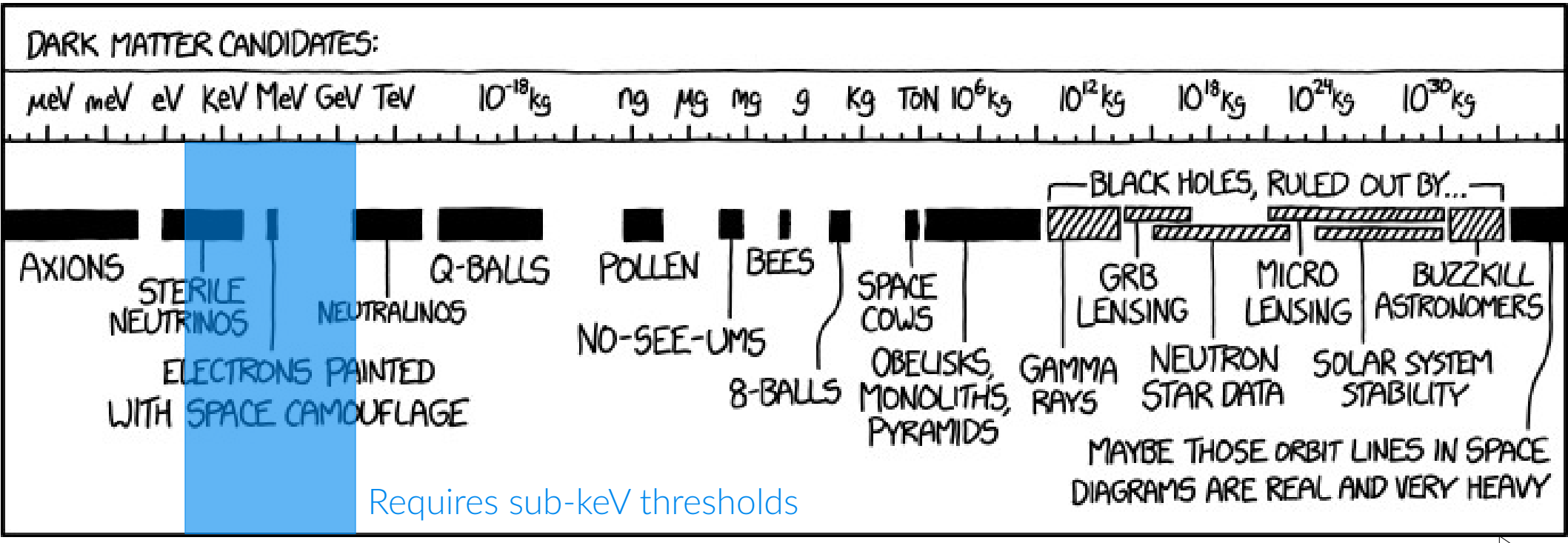
Wave DM
Absorption
EM resonance

Light DM
Single scatter
ER/NR
Absorption

WIMP
Single scatter
NR

Ultra-heavy DM
MIMPs
Multi-scatter/tracks

Macroscopic DM
Cosmic probes



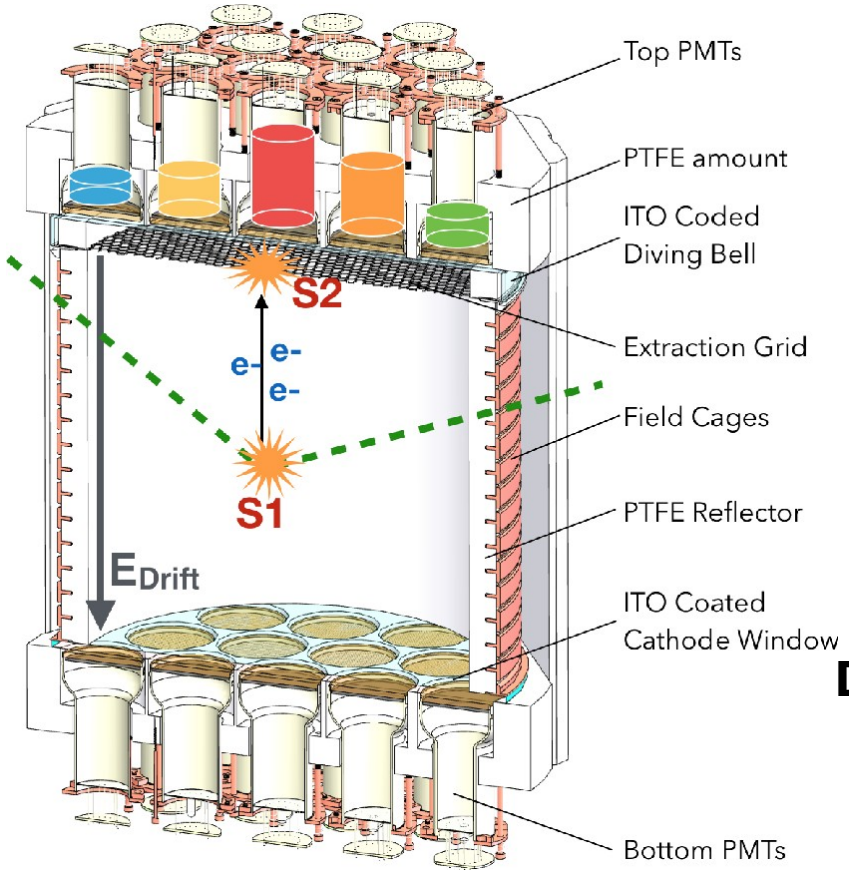
Wave DM
Absorption
EM resonance

Light DM
Single scatter
ER/NR
Absorption

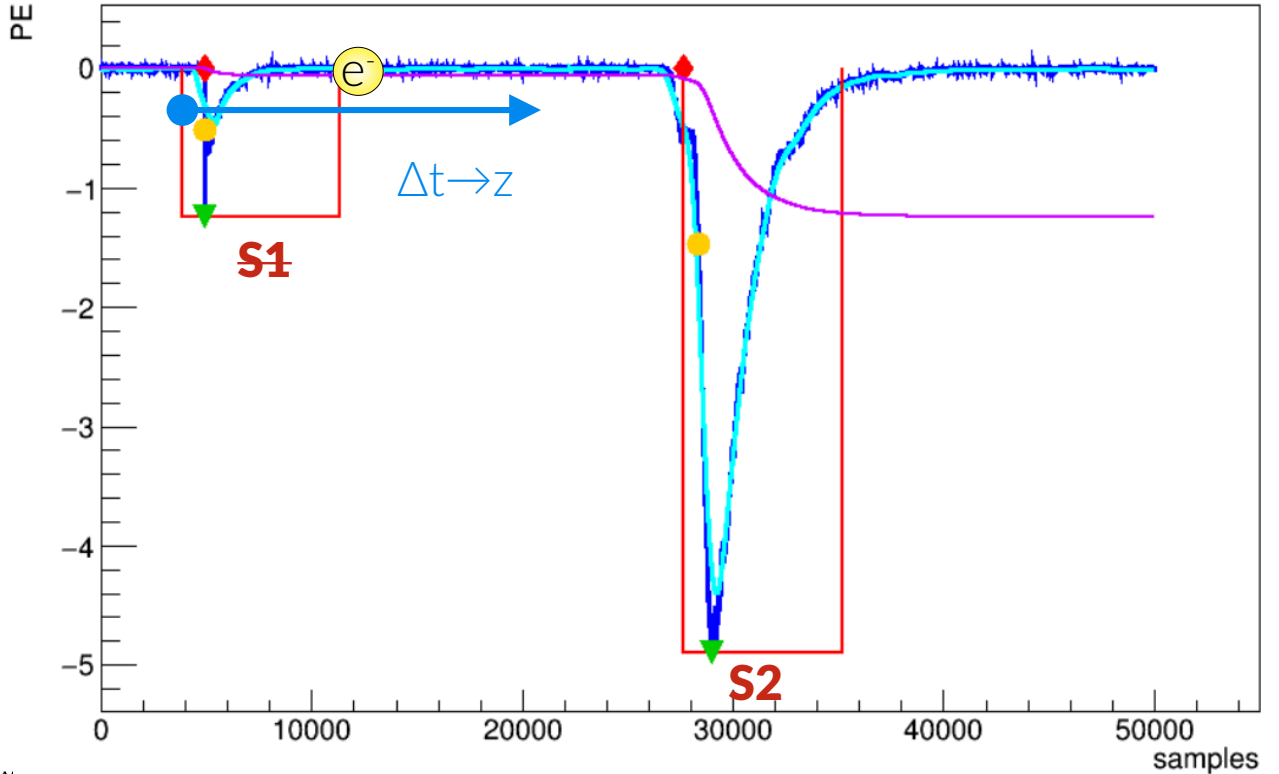
WIMP
Single scatter
NR

Ultra-heavy DM
MIMPs
Multi-scatter/tracks

Macroscopic DM
Cosmic probes



Drawing of DarkSide-50

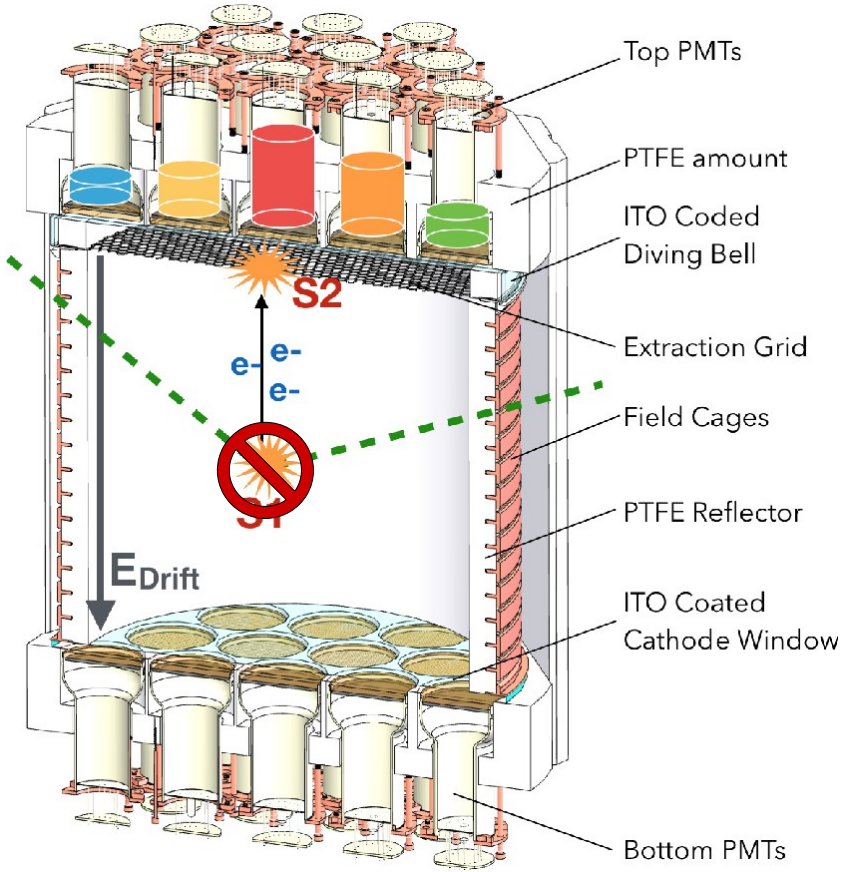


Dual-phase LArTPCs

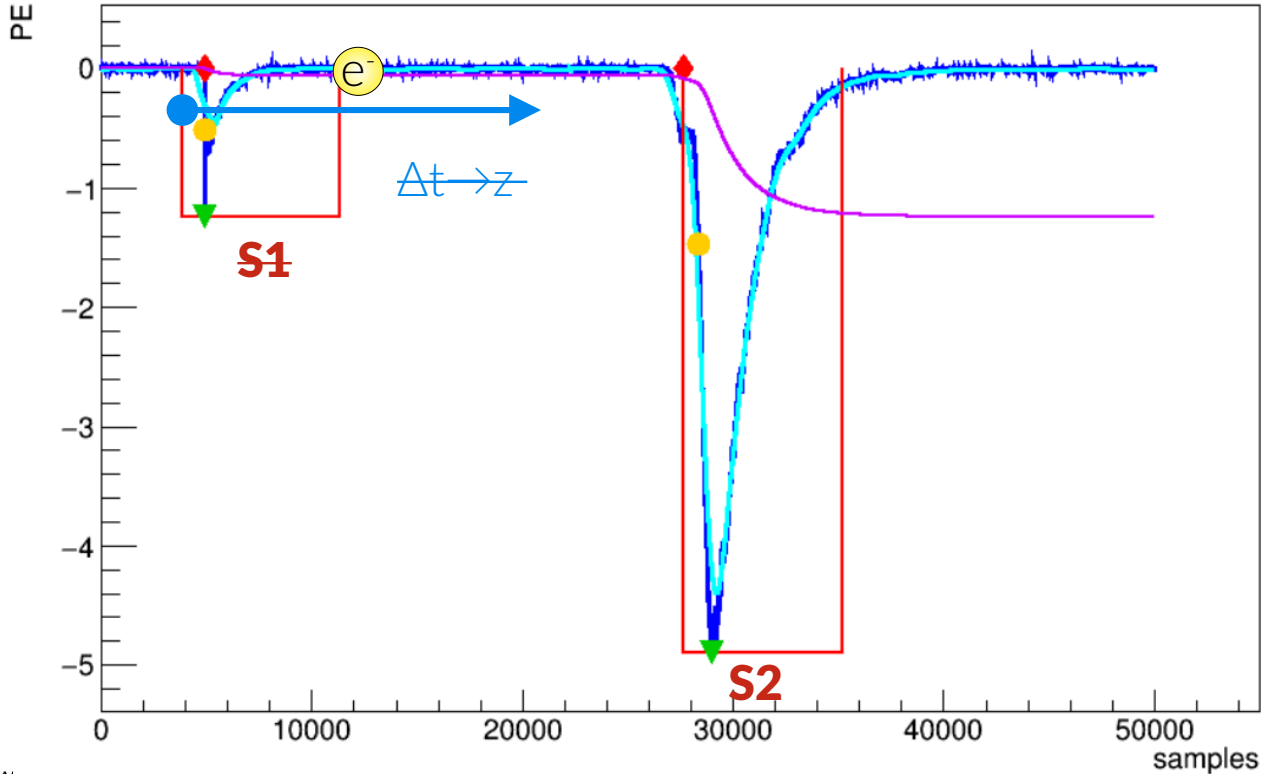
S1: Prompt scintillation, energy, PSD
Detect ~20% of photons

S2: Ionization electrons, position, n scatters
Detect nearly all electrons

Strong probe of ~100 GeV WIMPs, great bkgd discrimination



Drawing of DarkSide-50

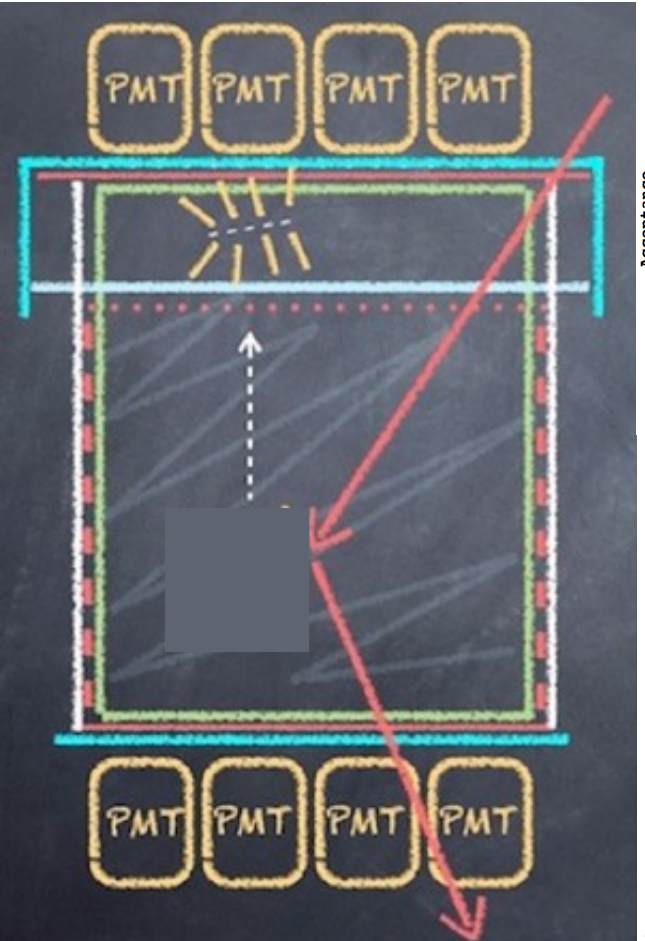


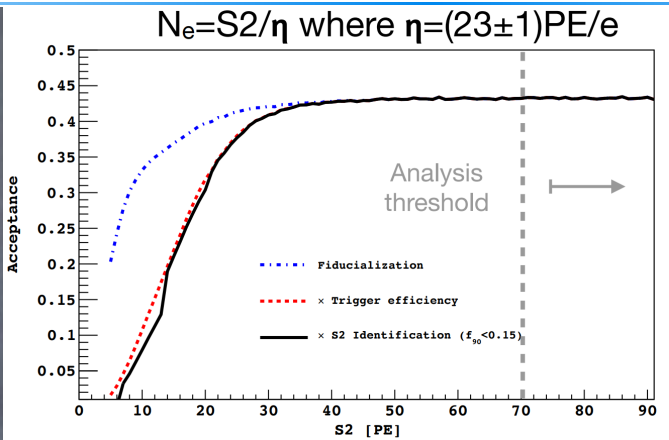
As a consequence, S2 can access lower energies than S1 → Low-threshold LArTPC via S2-only channel

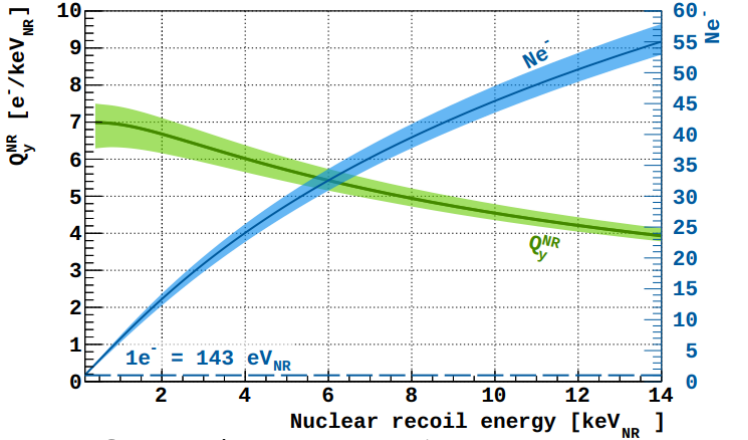
Challenges:

- Cannot measure Δt → Can't fiducialize in z
- Timing resolution limited by max e^- drift time
- No PSD → No ER discrimination
- Spurious electron backgrounds

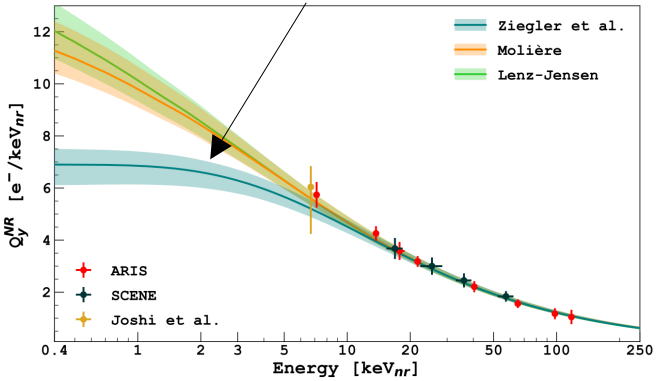
Low-threshold S2-only analyses, but lose PSD and z position reconstruction

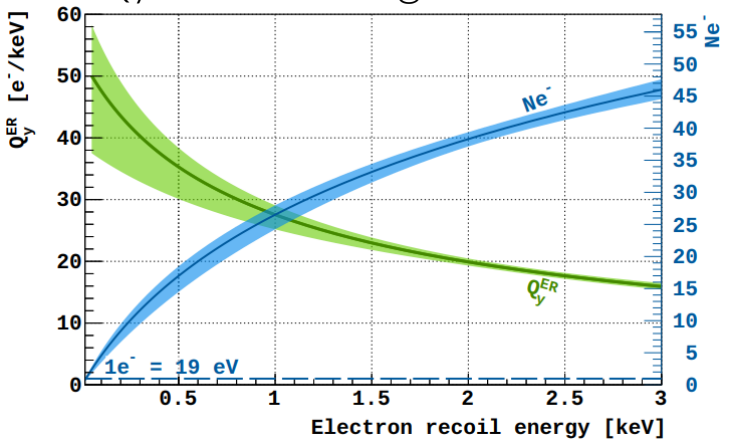






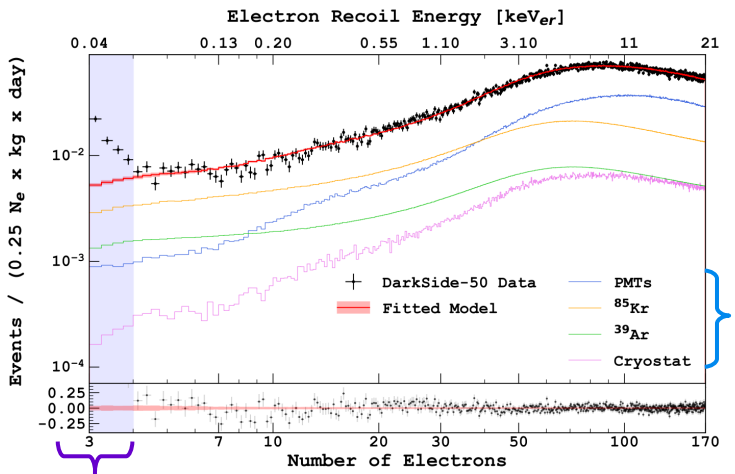
Need ex situ calibration to measure Qy at low energies

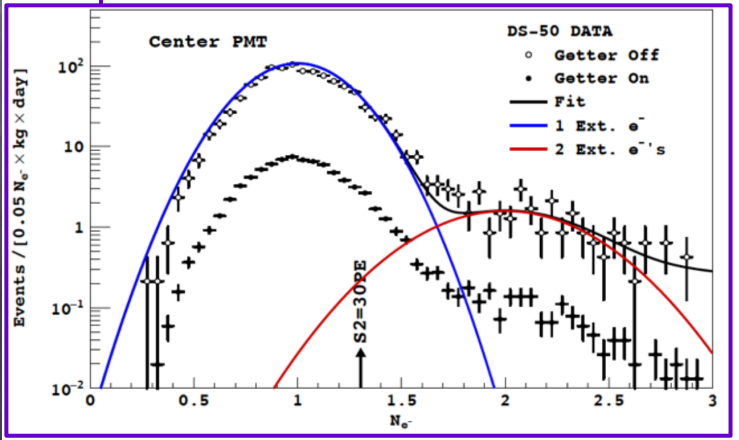




DarkSide Collab. Phys. Rev. D 104, 082005 (2021)

Low-threshold S2-only analyses





Loss of pulse shape discrimination (PSD)

Electromagnetic backgrounds from dominate
- γ-rays from internal radioactivity
- β-decays from ^{39}Ar and ^{85}Kr
  - ^Use underground/depleted Ar

Spurious e$^-$'s dominate lowest energy bins

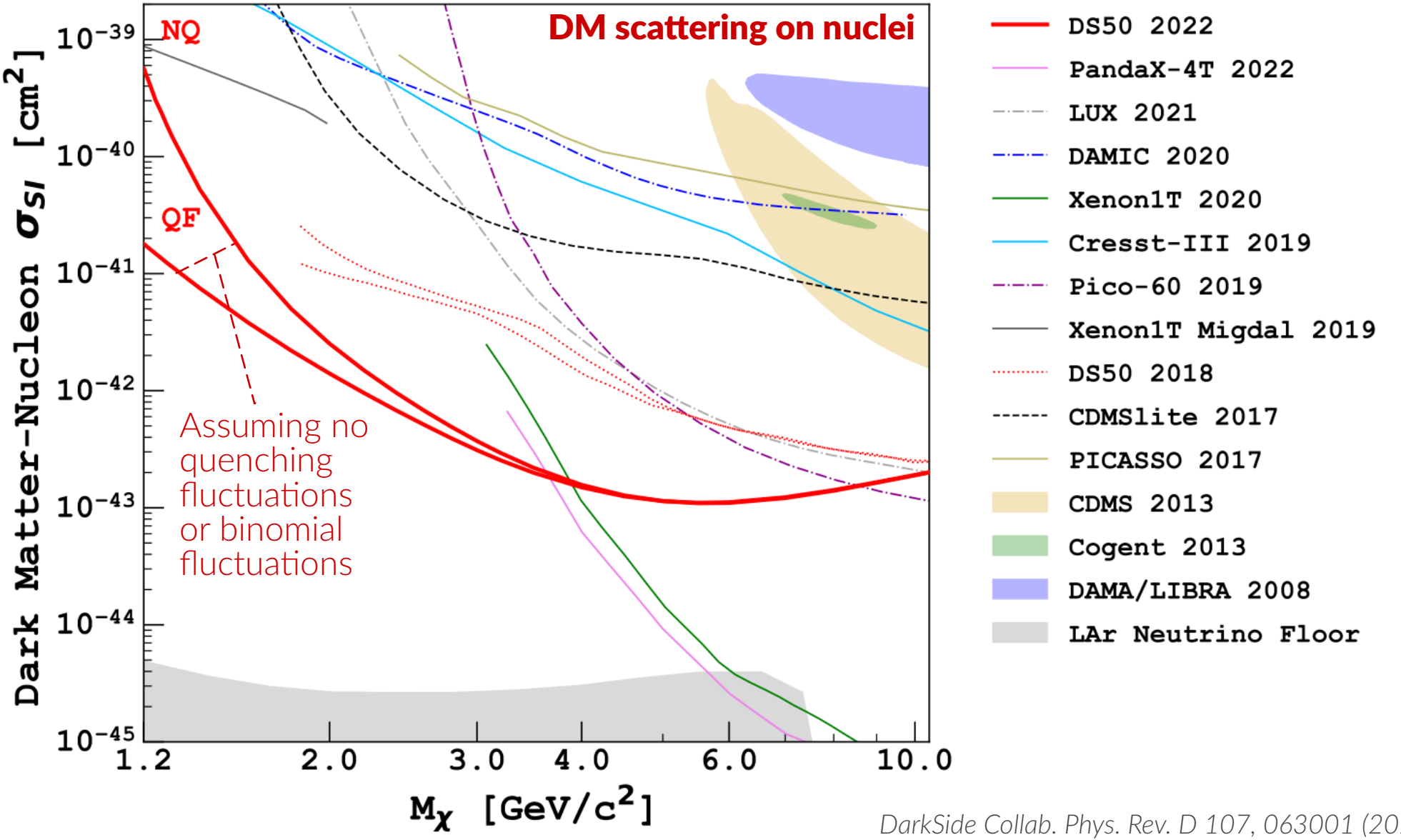
Full origin being investigated

Correlations between SE and preceding S2 (time, xy position, S2 charge and t_{drift} vs. P_{SE})

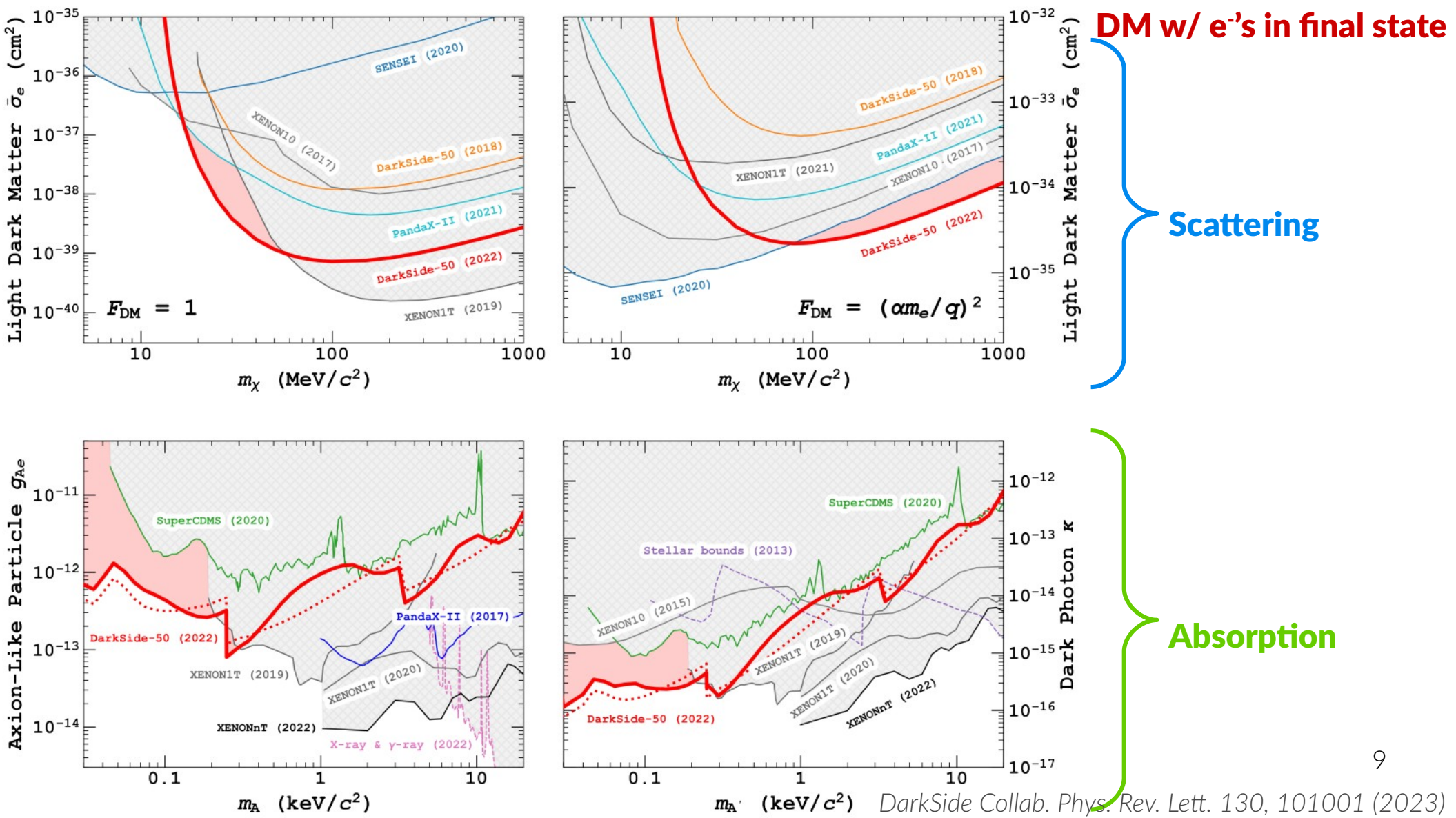
Possibly due to drifting electrons capturing on impurities and forming metastable states

Follow preceding S2 by O(5-50 ms)

DarkSide Collab. Phys. Rev. D 107, 063001 (2023)

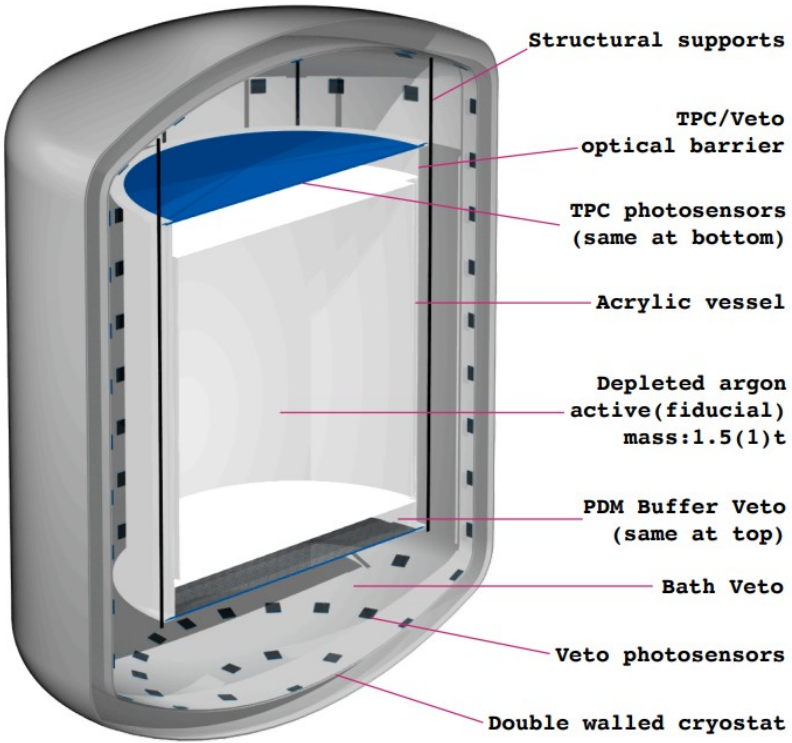


DarkSide Collab. Phys. Rev. D 107, 063001 (2023)

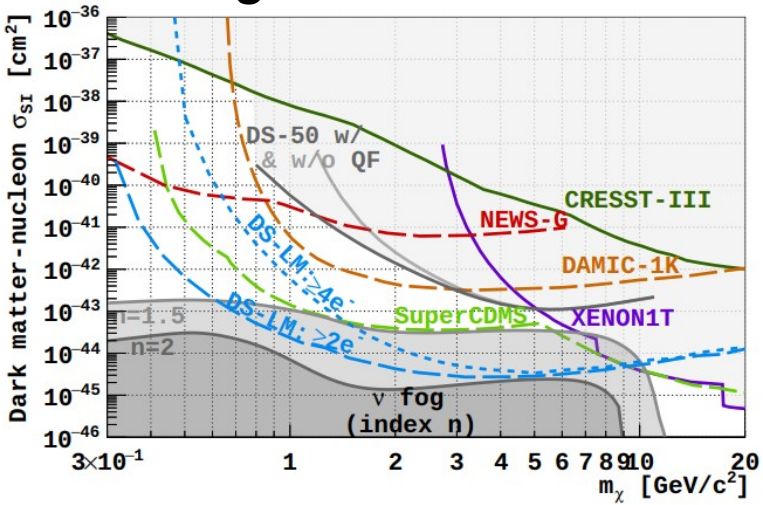


DarkSide Collab. Phys. Rev. Lett. 130, 101001 (2023)

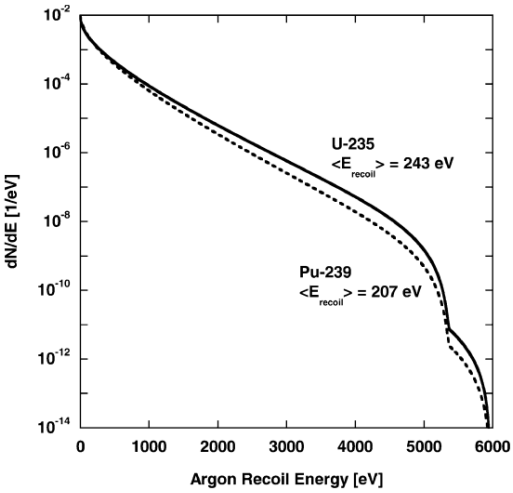
LArTPC in S2-only analyses: Powerful tool for low-threshold measurements



Light dark matter search



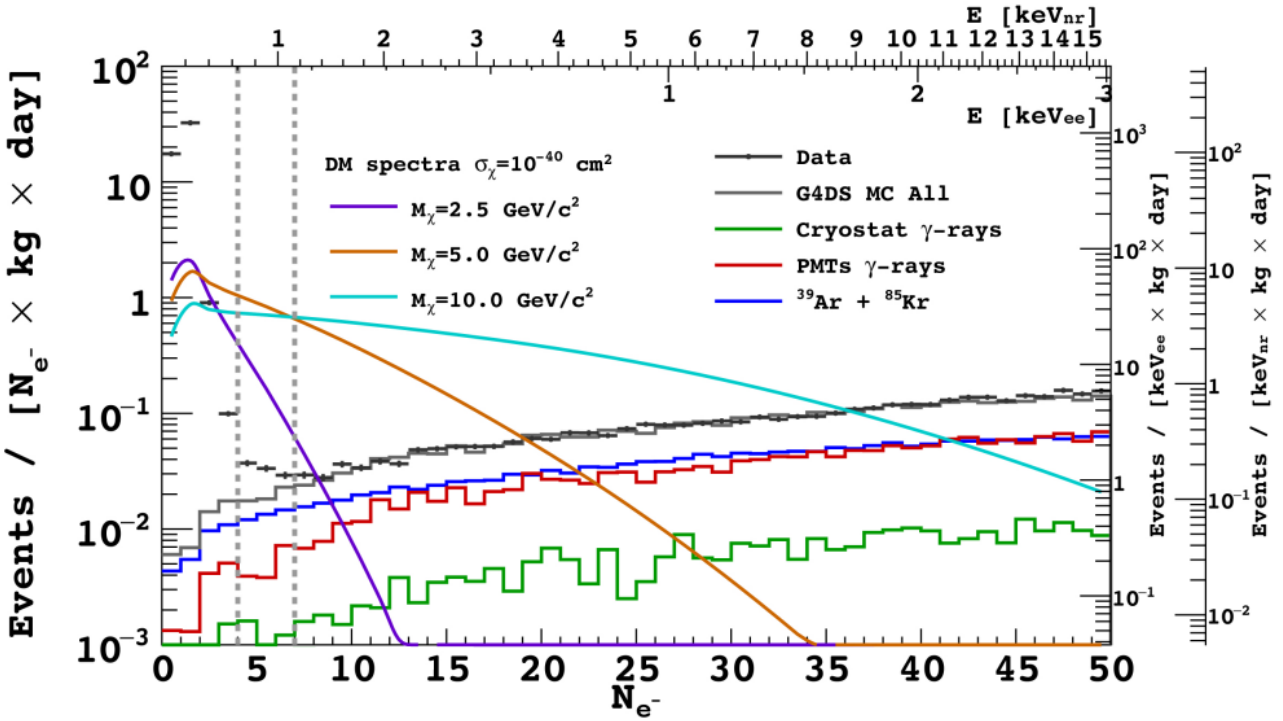
Reactor CEvNS



Hagmann & Bernstein, IEEE Trans.Nucl.Sci. 51 (2004) 2151

DarkSide-LowMass conceptual design + sensitivity projections [GADMC Phys. Rev. D 107, 112006]

How do we lower the threshold?



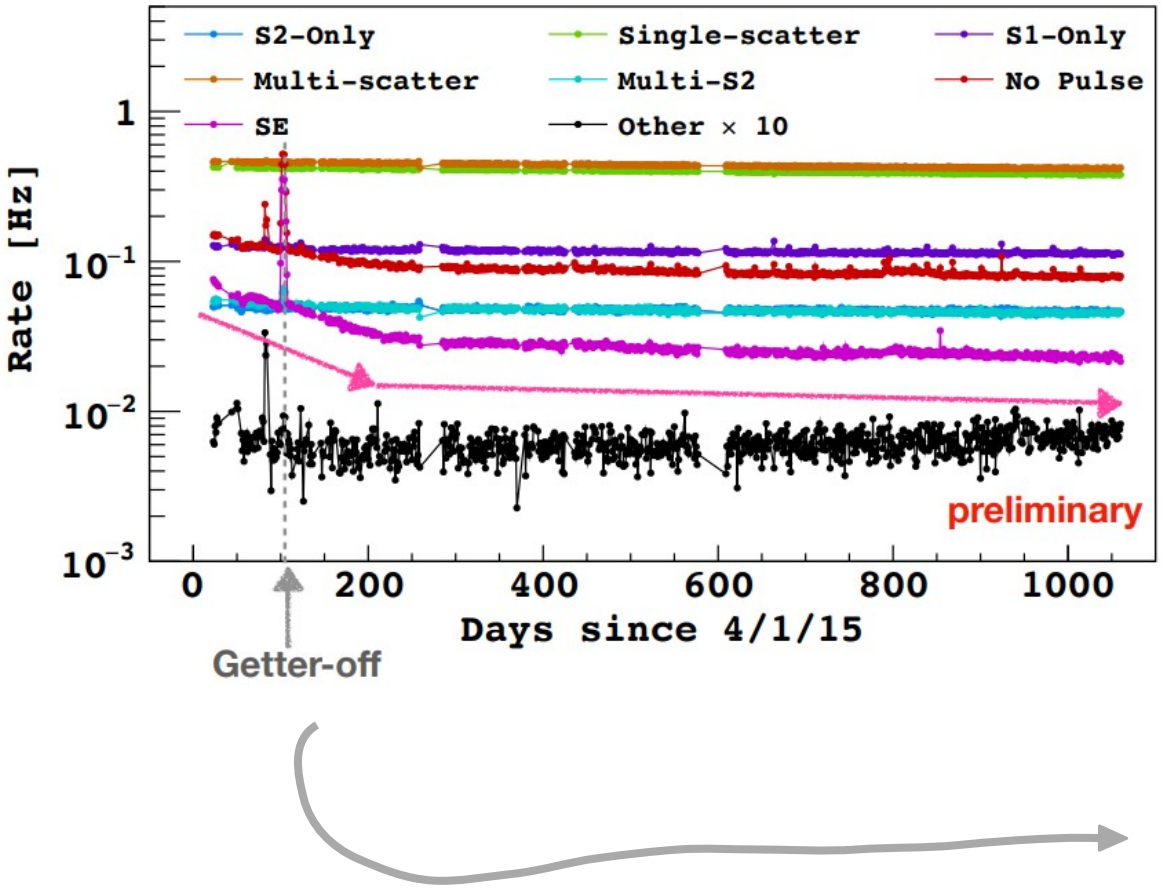
DarkSide Collab. Phys. Rev. Lett. 121, 081307 (2018)

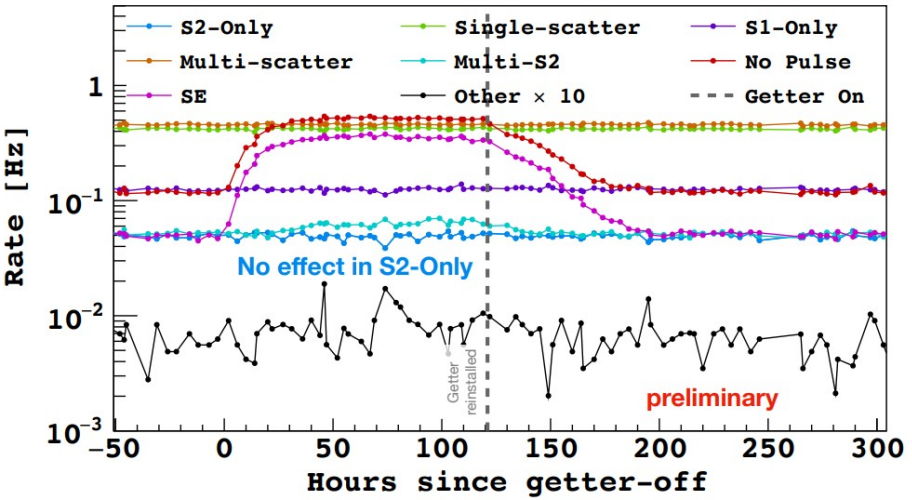
Threshold is set by

Spurious electrons
Medium's ionization energy
Partitioning between ionization & scintillation photons
heat

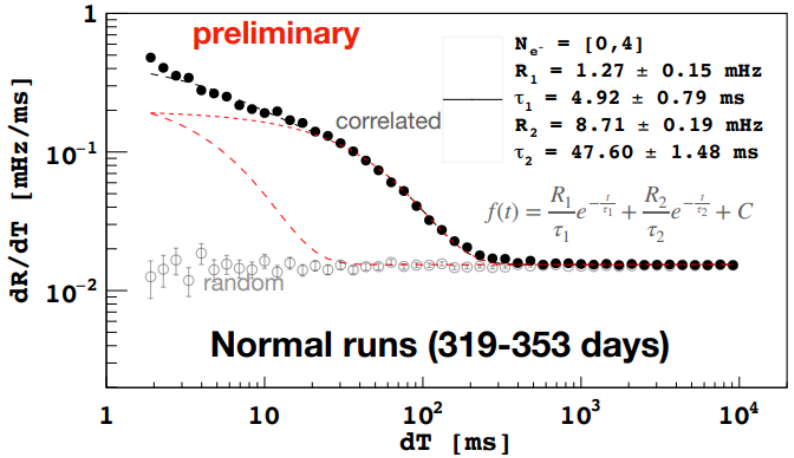
All of these are pathways for lowering the energy threshold

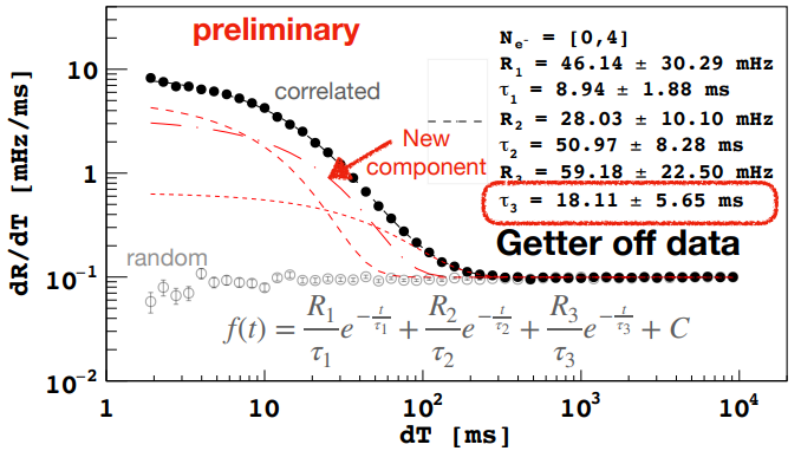
SE rate changes over time and appears to be related to impurities

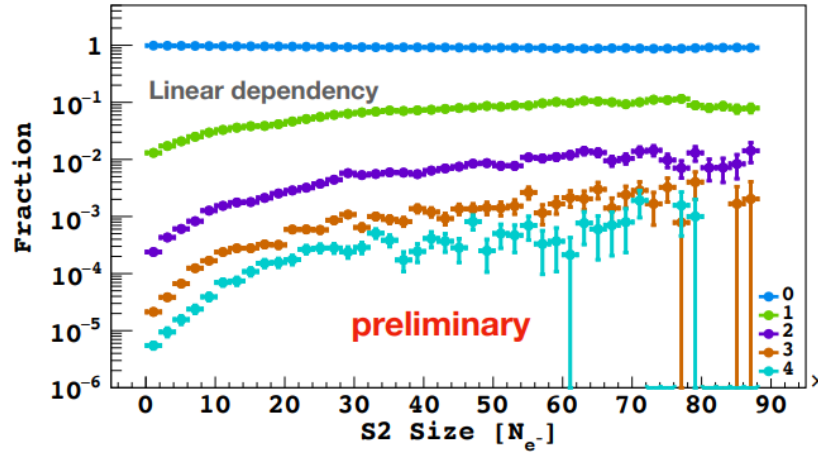


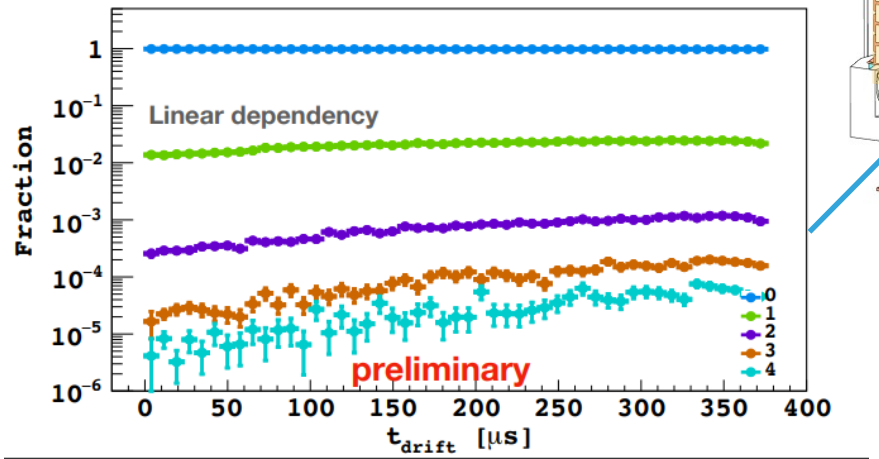


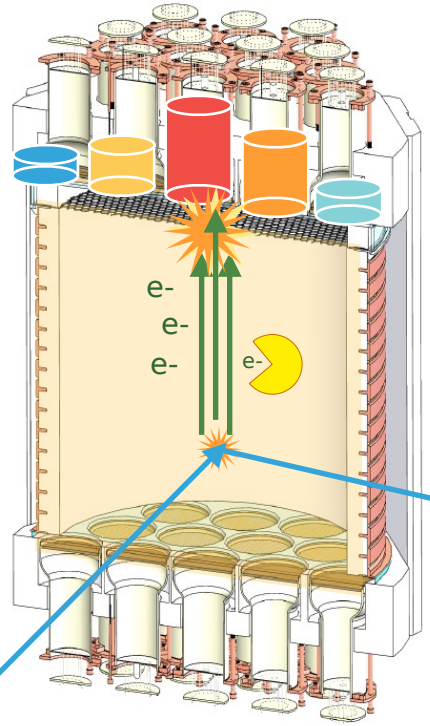
SEs appear to be correlated in time, space, and charge with ordinary events



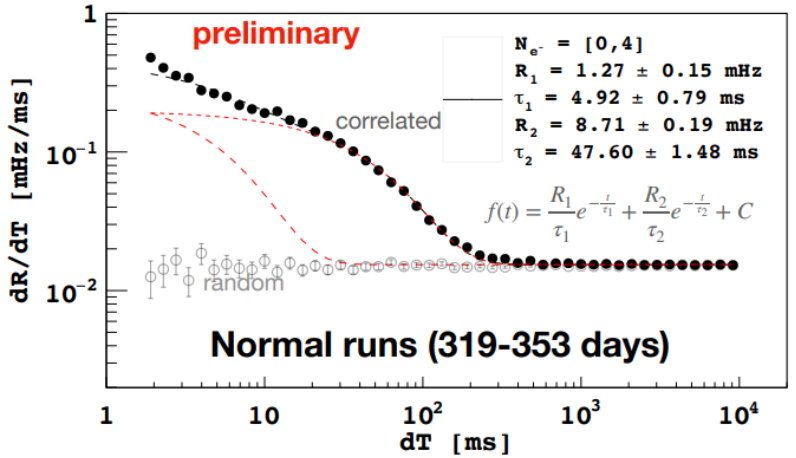


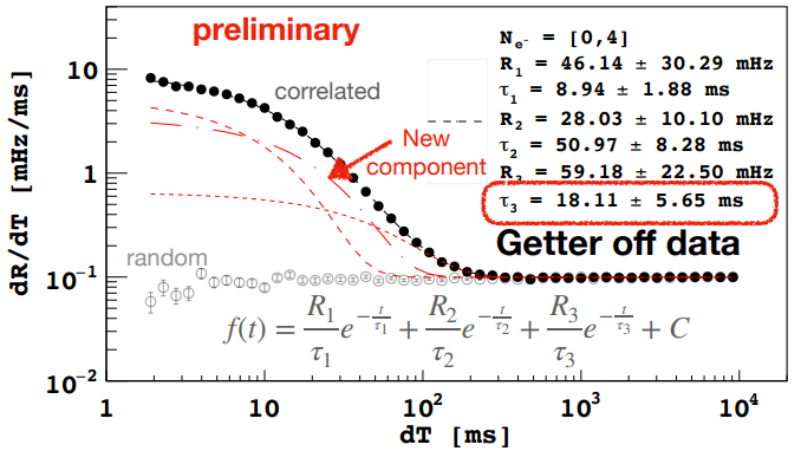


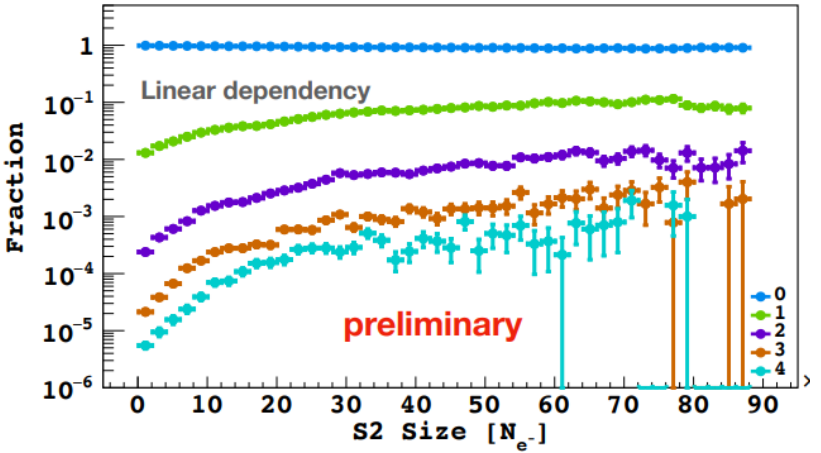


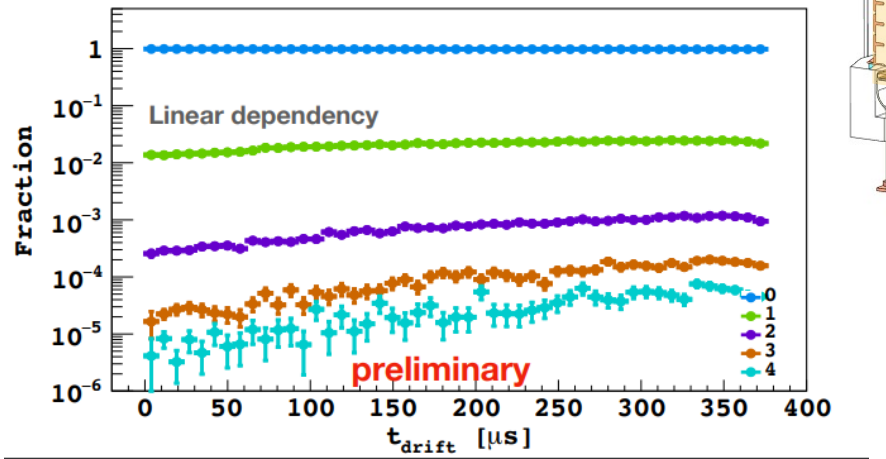


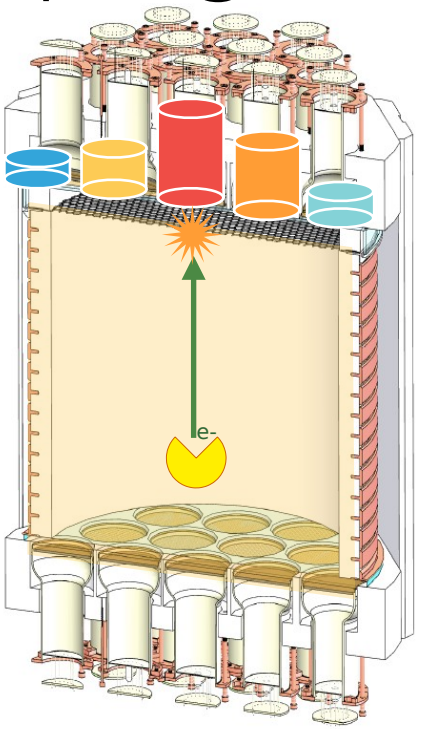
Hypothesis: Dominant SE production mechanism from impurities trapping e^-



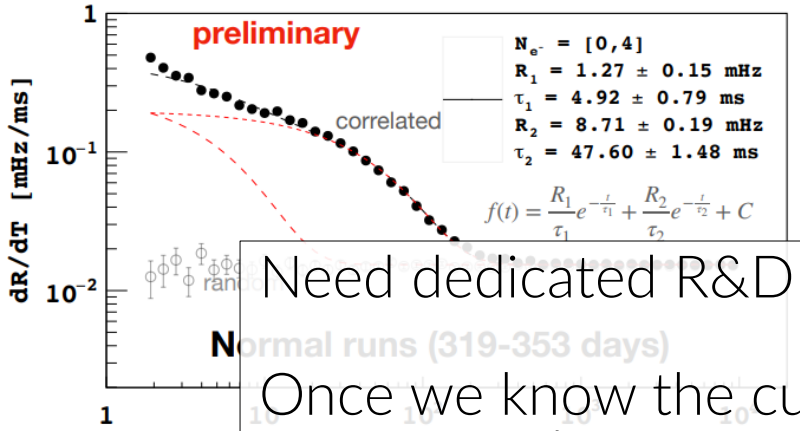


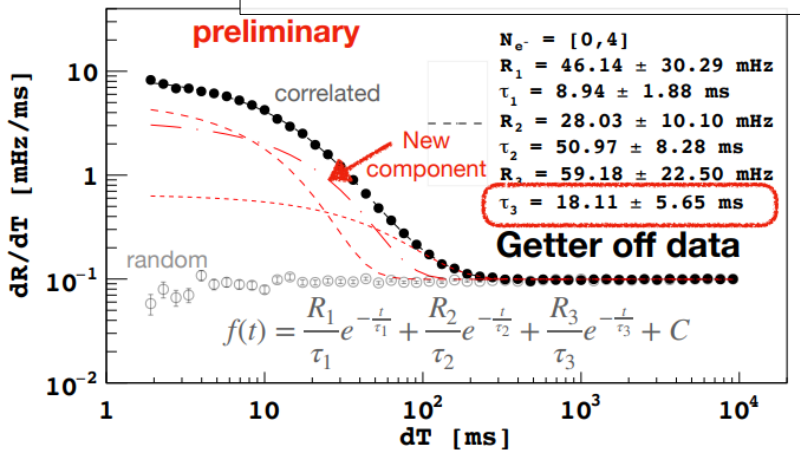


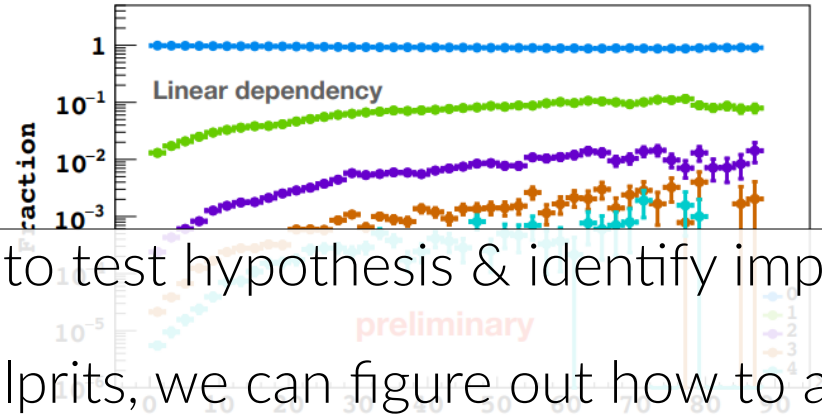


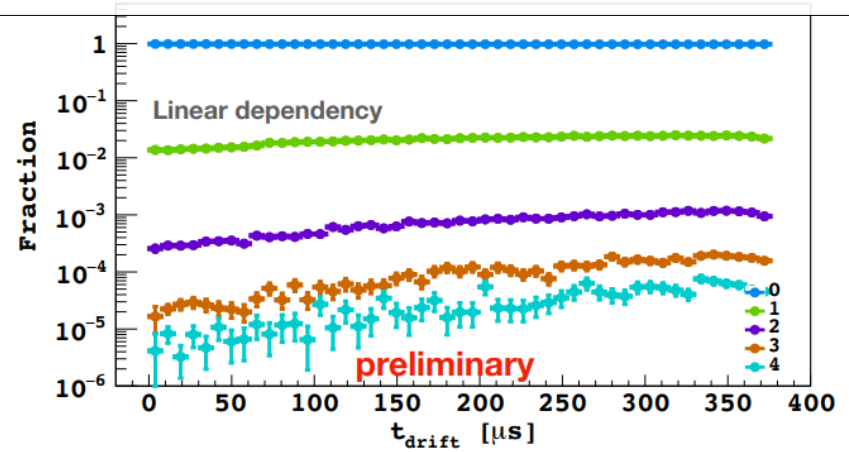


Hypothesis: Dominant SE production mechanism from impurities trapping e⁻



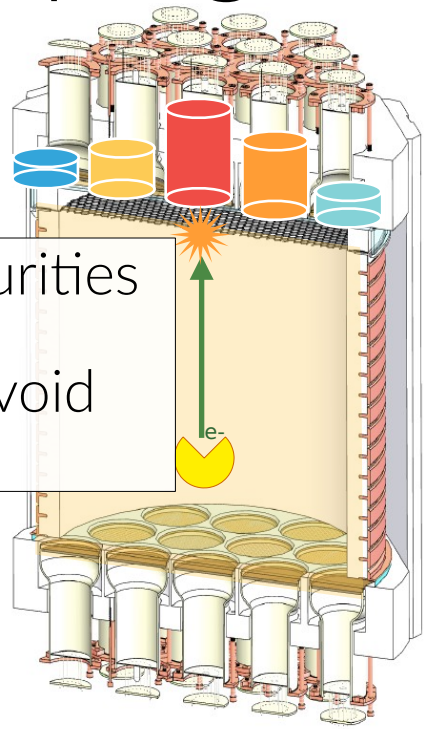






Need dedicated R&D to test hypothesis & identify impurities

Once we know the culprits, we can figure out how to avoid or remove them



Other ideas: enhance detector response by doping LAr

Kubota et al. Phys. Lett. 49A, 5 (1974): 933

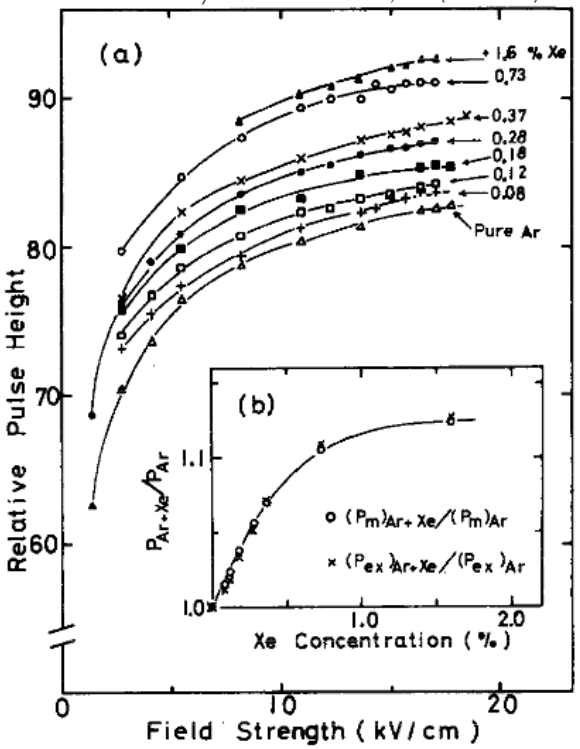


Fig. 1. a) Saturation curves of the pulse height produced by ^{207}Bi conversion electron for the different concentration of Xe. b) Relative ionization yields as a function of doped-Xe concentration.

Idea:

Xe ionization energy is 12.1 eV
Ar ionization energy is 15.8 eV, W-value ~ 24 eV
Xe-doped LAr effective ionization potential ~ 10.7 eV
[B. Raz and J. Jortner, Proc. Roy. Sot. London A 317 (1970) 113.]

Even at low Xe concentration, each ionization takes less energy from the nucleus, and nuclei can continue to produce ions even down to lower energies

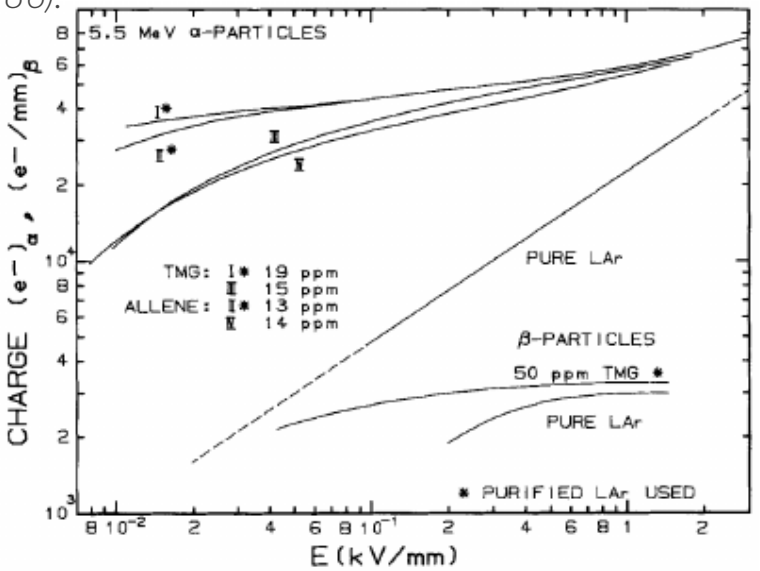
Nuclear recoils produce ionization through a cascade (one nucleus colliding with others, and so on) → effects may be non-linear

R&D needs:

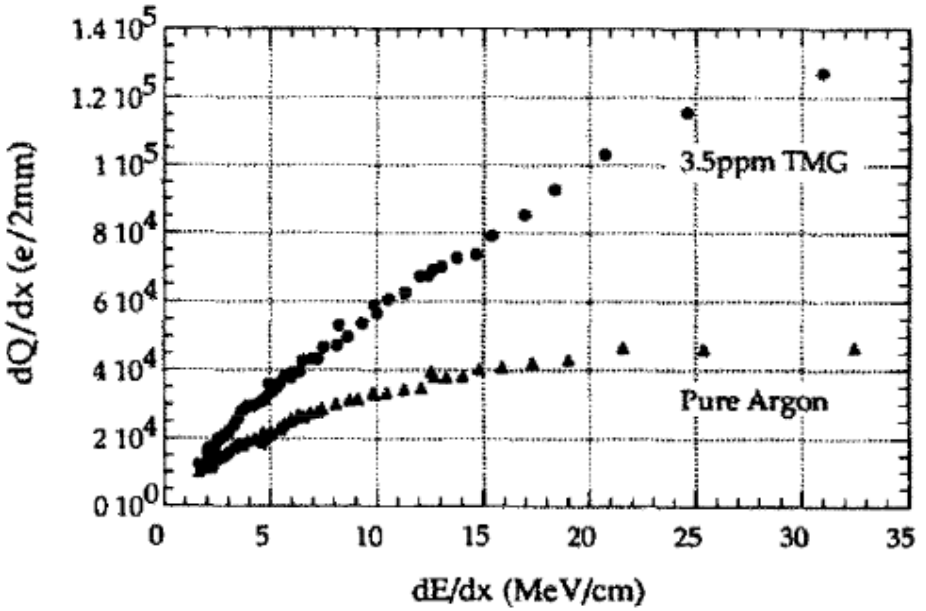
Need to measure Qy of low-energy NRs as a function of Xe concentration to see the effect side

Other ideas: Photo-sensitive dopants—potentially great improvements, more R&D

D. F. Anderson, Nucl. Instrum. Methods Phys. Res. A 245, 361 (1986).



P. Cennini et al., Nucl. Instrum. Methods Phys. Res. A 355, 660 (1995).

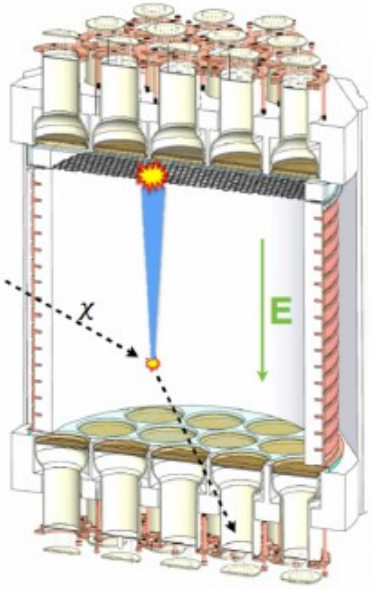


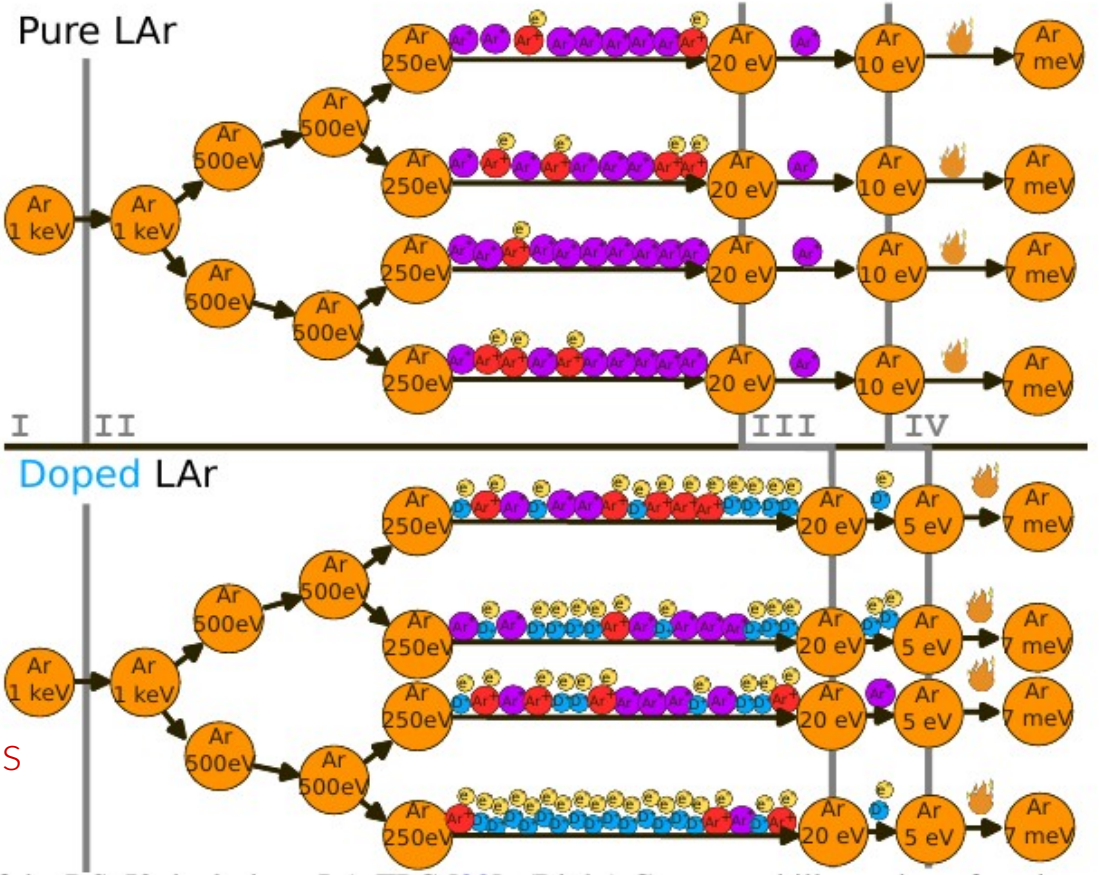
Dopants with 7.5–9.5 eV ionization energies have previously been studied in LAr, in the context of improving the resolution of high-energy ionization chambers

Larger effects at higher ionization energies → energy otherwise lost as heat goes into ionization

Turns inefficiently detected S1 into efficiently detected S2!

Potential benefits from doping





At sufficiently high concentrations H in dopants may act as a light DM target!

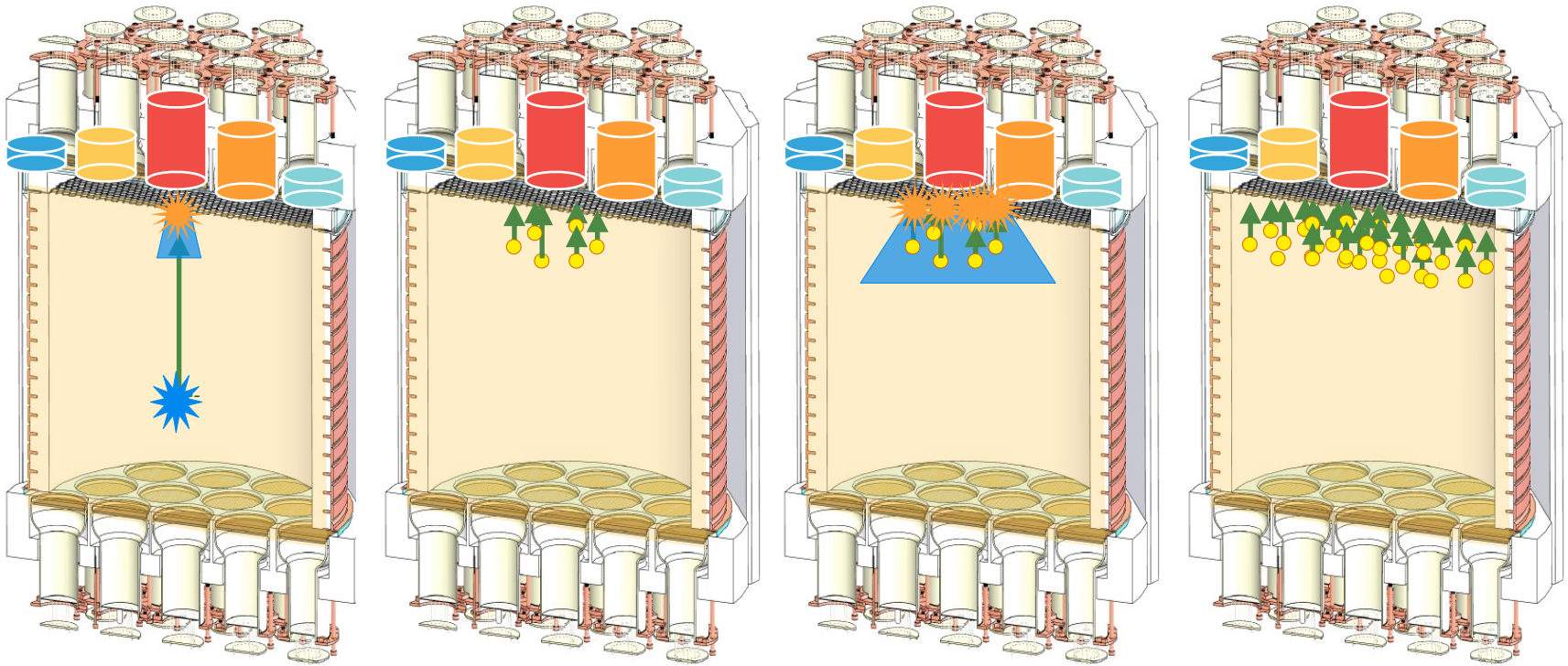
Some potential dopants

Material [d]		I_g [eV] [a]	Dipole moment [debyes] [b]	Estimated pressure 90 K [Torr] [b]	Charge collected* [c] (LAr ≡ 1)		Concentration [ppm]
					0.1 kv mm^{-1}	1.0 kV mm^{-1}	
TEA	$(C_2H_5)_3N$	7.50	0.66	–	2.2	1.3	47
TMA	$(Ch_3)_3N$	7.82	0.612	3×10^{-8}	3.4	1.6	110
TMT	$(CH_3)_4Sn$	8.25/8.76	–	4×10^{-12}	3.0	1.6	1.5
Cyclohexene	C_6H_{10}	8.95	–	–	2.1	1.3	3.6
1.3-butadiene	C_4H_6	9.06	0	4×10^{-7}	4.6	1.9	17
Cis & Trans 2 butene	C_4H_8	9.13	0 (trans)	5×10^{-8}	3.6	1.6	72
TMG	$(CH_3)_4Ge$	9.2/9.29	–	3×10^{-10}	7.4 (9.8)	2.6 (2.7)	15
Isobutylene	C_4H_8	9.23	0.5	5×10^{-7}	4.9	1.8	16
Methyl mercaptan	CH_3SH	9.44	1.52	2×10^{-8}	2.0	2.0	15
Pentene (technical)	C_5H_{10}	9.5	–	1×10^{-9}	3.1	1.5	7
Allene	C_3H_4	9.53	0	1×10^{-5}	6.5 (8.7)	2.5 (2.7)	14
TMS	$(CH_3)_4Si$	9.86	0.525	8×10^{-9}	4.6	1.8	5.8
DME	$(CH_3)_2O$	10.0	1.30	5×10^{-8}	3.6	1.4	14

D. F. Anderson, NIM. A 245, 361 (1986).

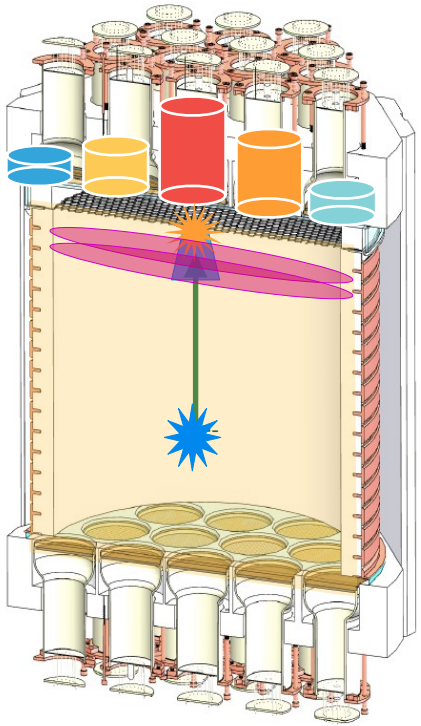
TMG studied by ICARUS, Allene studied by Doke, Hitachi, Masuda, Ichinose, LaVerne et al.

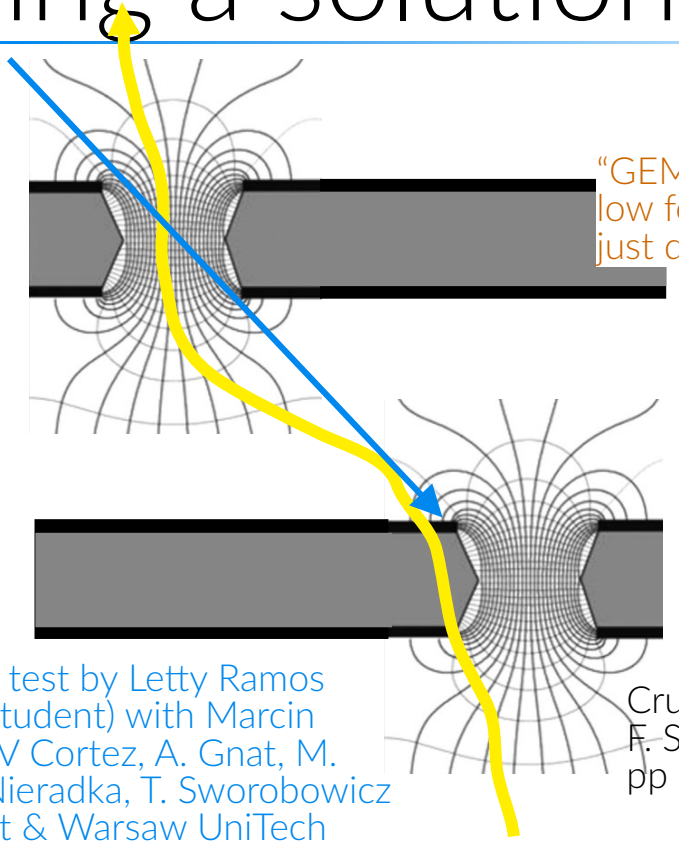
Challenge for photosensitive dopants: S2 feedback



Need to prevent S2 from re-entering liquid or shift S2 to below dopant's ionization energy

Challenge for photosensitive dopants: Testing a solution





"GEM" in LAr at voltage too low for electroluminescence just directs electron traffic

PEN "GEM" test by Letty Ramos (UCR PhD student) with Marcin Kuzniak, AFV Cortez, A. Gnat, M. Kuzwa, G. Nieradka, T. Sworobowicz at AstroCent & Warsaw UniTech

Crudely adapted from F. Sauli NIM A 805 (2016) pp 2–24

Two GEM-like structures (without the Gas and without the Electron Multiplication) to form a "grid" that is transparent to electrons but opaque to VUV photons

R&D needs

Modeling and reducing SEs

- Dedicated R&D to identify primary mechanisms
- Improved chemical purity, likely at the ppb level and better
- Investigate other subdominant SE production mechanisms

Calibration

- Calibrate charge and scintillation yield of low-energy ERs and NRs
- Need to understand the **fluctuations** about mean yields at low energy

Doping LAr

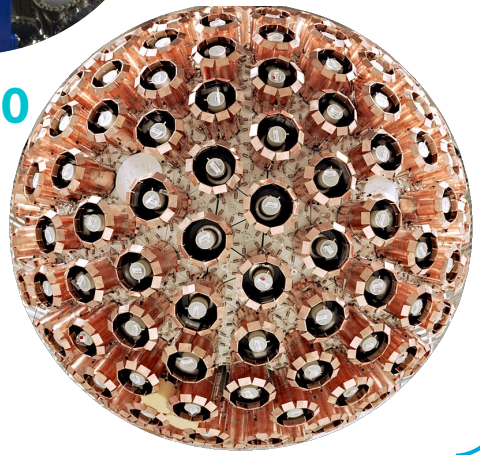
- Calibrate doped LArTPCs to low-energy ERs and NRs vs. dopant concentration
- Develop high-purity doping techniques—need to add dopant w/o adding impurities
- Assess and improve the stability of dopant in LAr
- For photo-sensitive dopants, need to prevent S2 feedback

A Saga Begins

ArDM
Canfranc

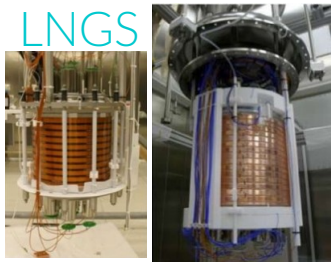
MiniCLEAN
SNOLAB

DEAP-3600
SNOLAB

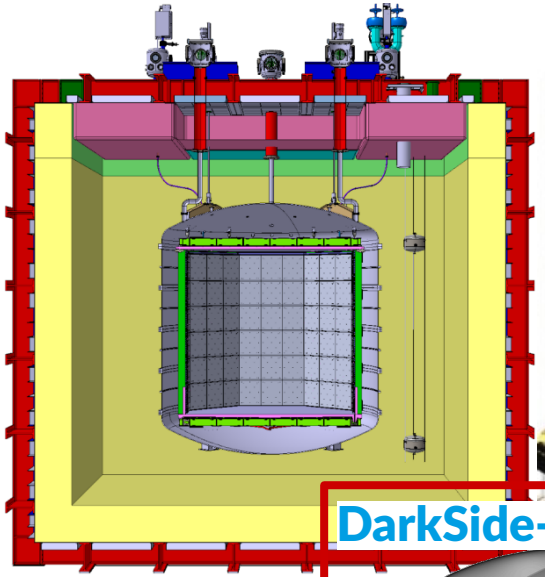


DarkSide-50
LNGS

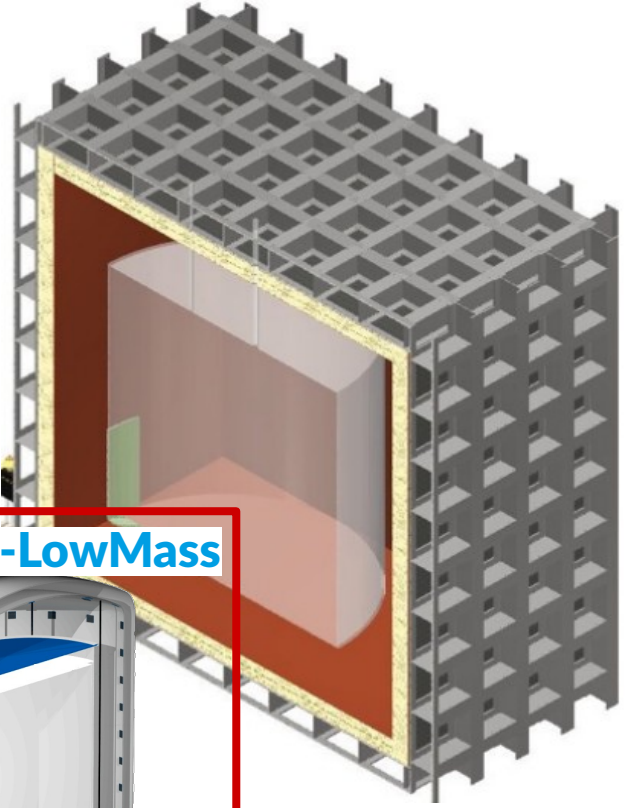
DS-10
LNGS



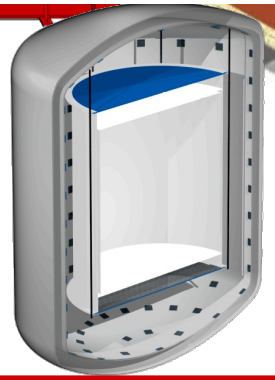
DarkSide-20k
LNGS



Argo
SNOLAB



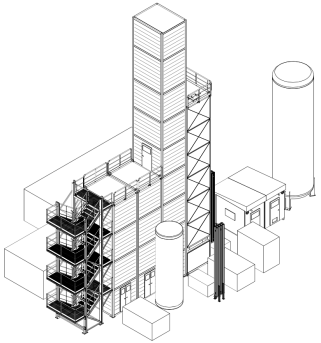
DarkSide-LowMass



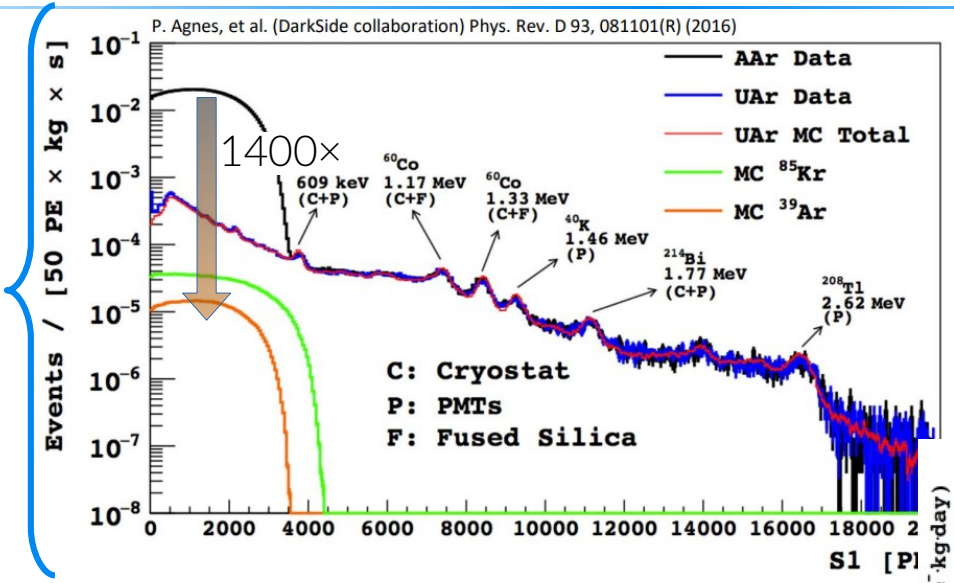
2011 2013 2016 2026 2030+

Radiopure underground argon

Urania

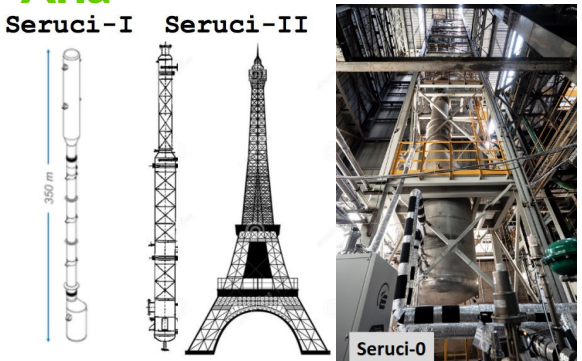


UAr extraction plant
250 kg/d
99.99% purity

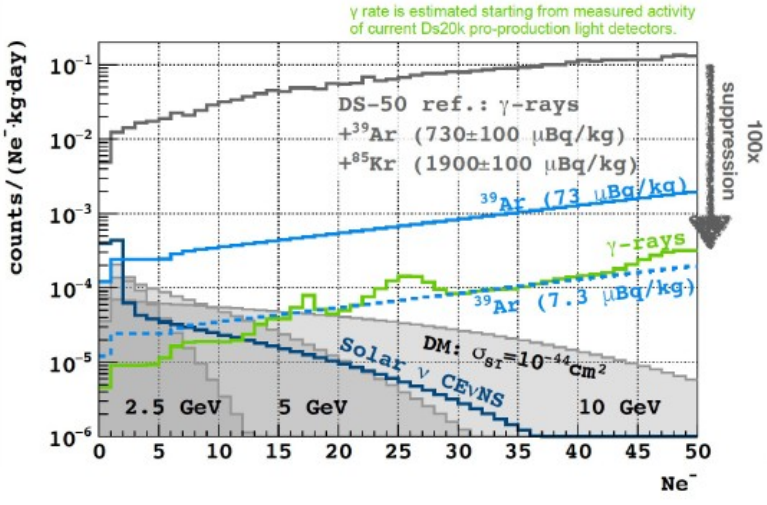


A hipster dark matter scientist who was into argon while it was still underground

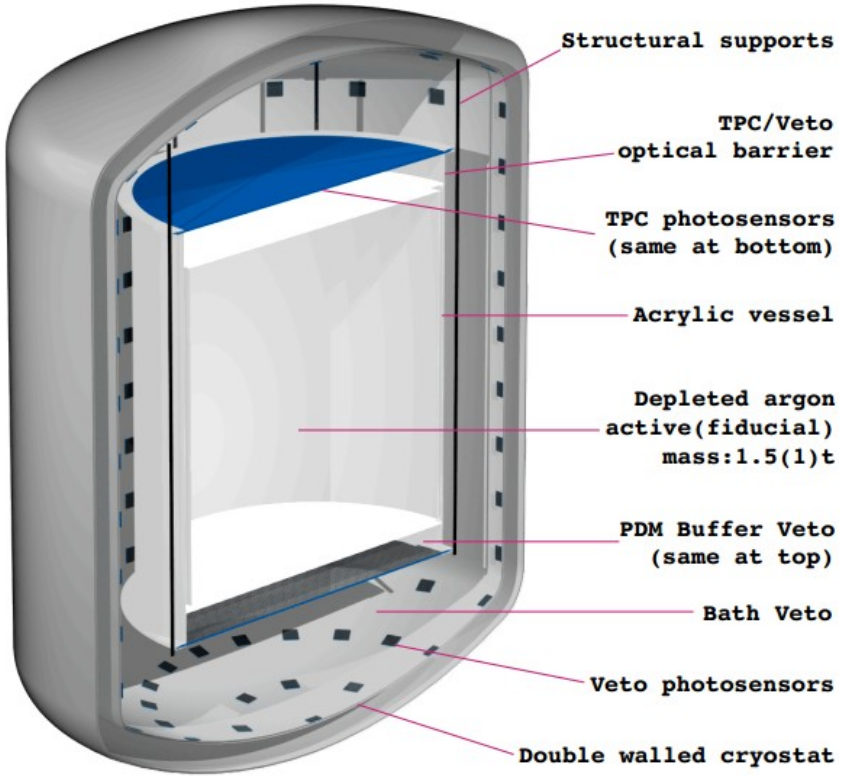
Aria

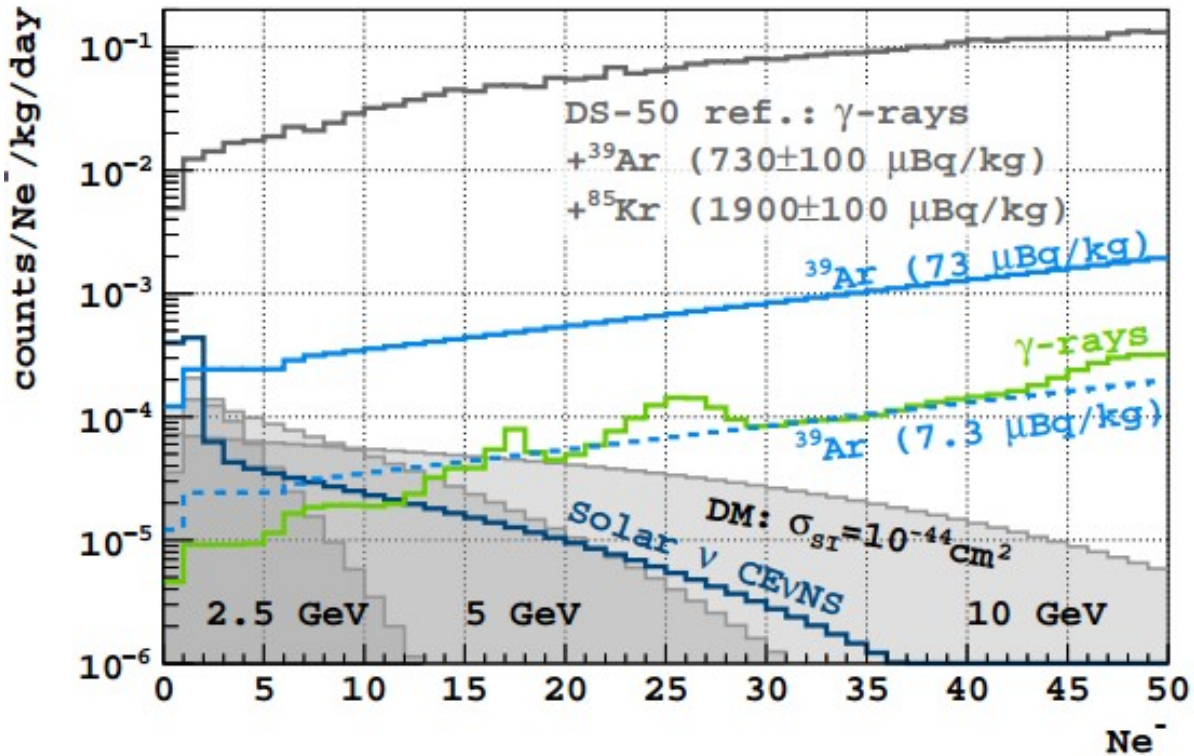


Chemical purification: 10^3× reduction at O(1 tonne/day)
^{39}Ar depletion: 10× at O(10 kg/day)



DarkSide-LowMass: Optimized for S2-only analyses





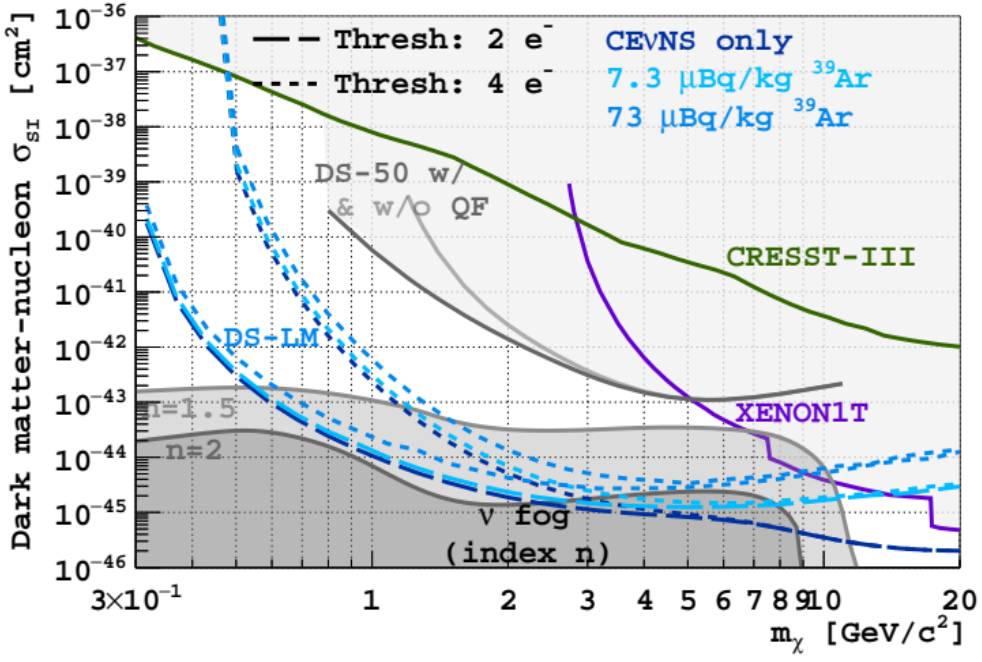
Cryostat immersed in water tank (not shown)

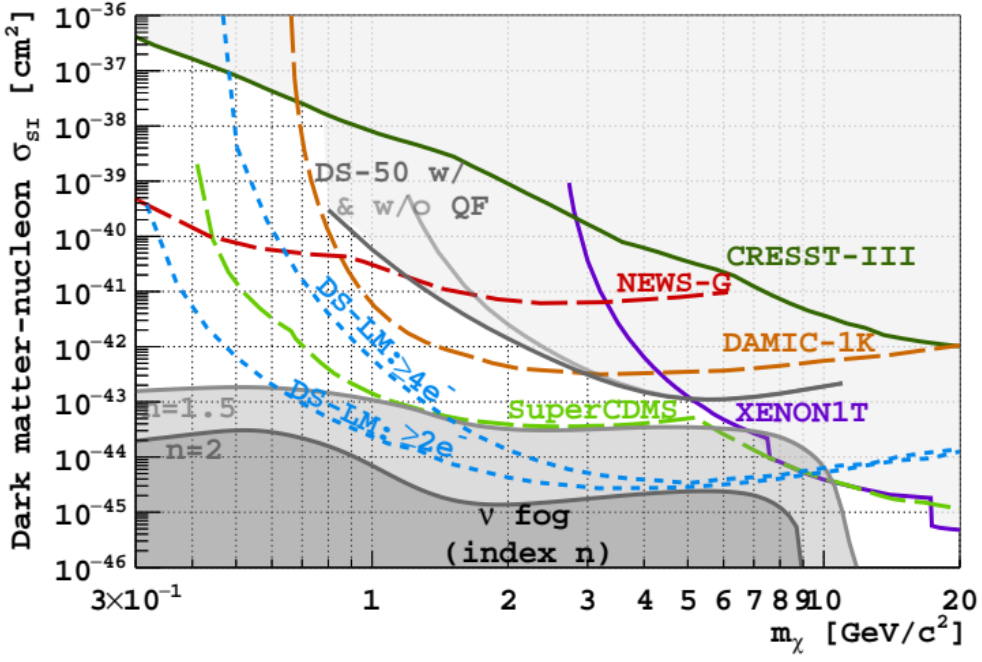
Not shown: spurious electron backgrounds

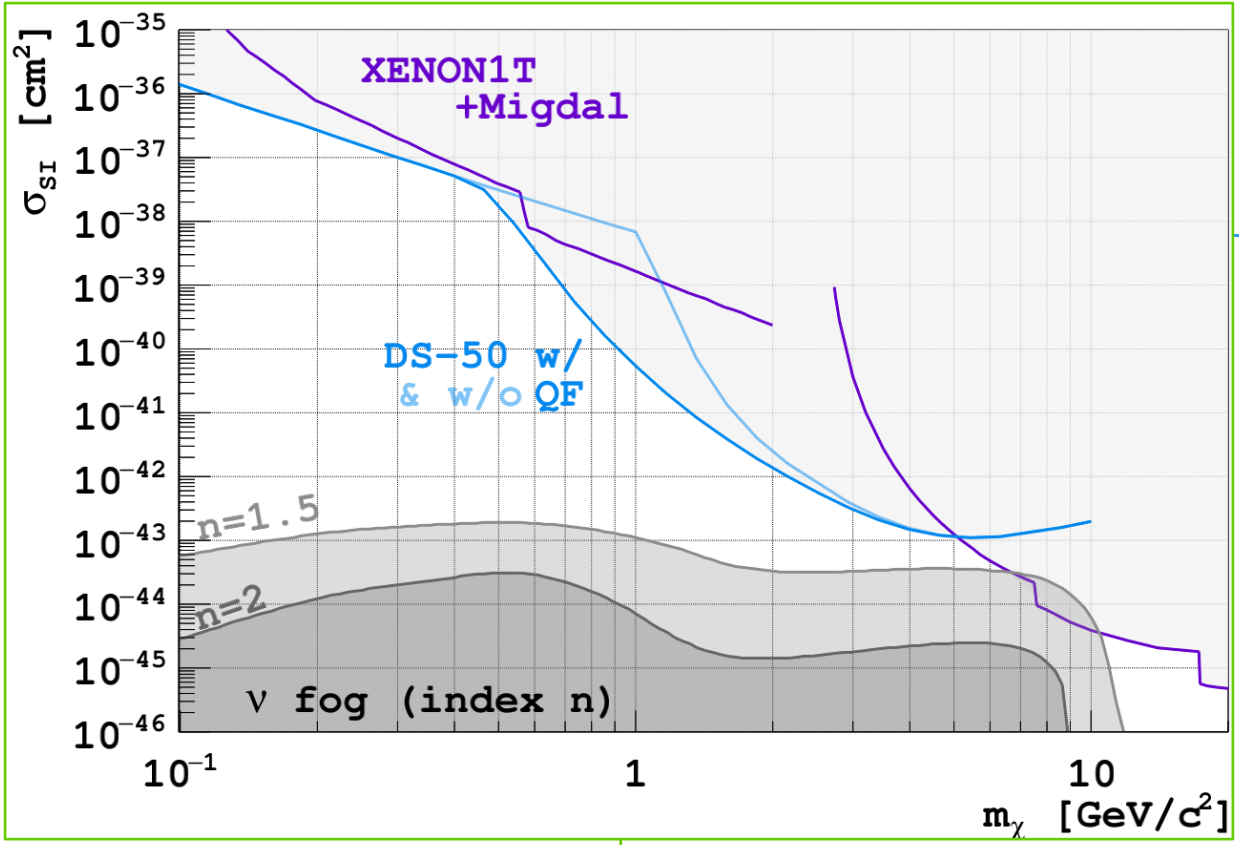
Global Argon Dark Matter Collaboration *Phys. Rev. D 107, 112006 (2023)*

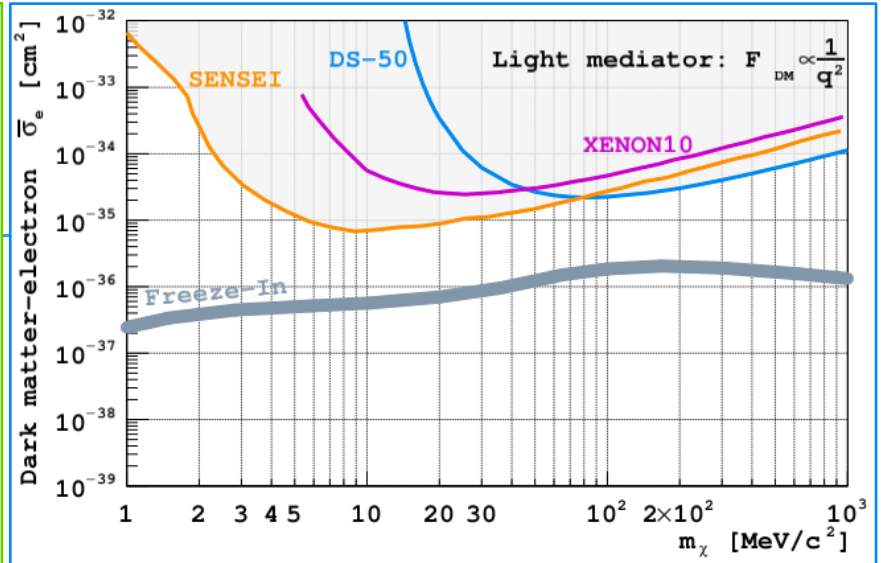
→ R&D to understand SEs in LAr→ Ar&D?

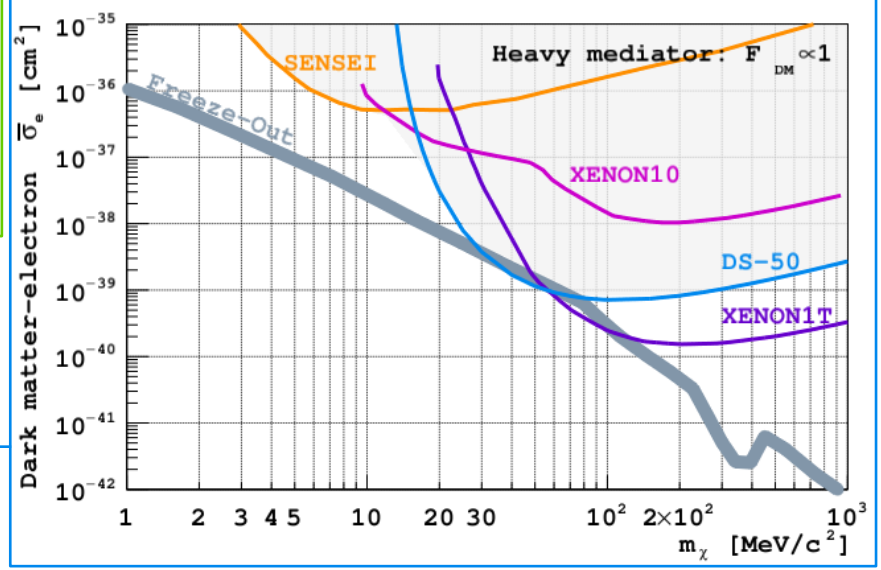
DarkSide-LowMass: Sensitivity to the ν fog in 1 tonne year exposure





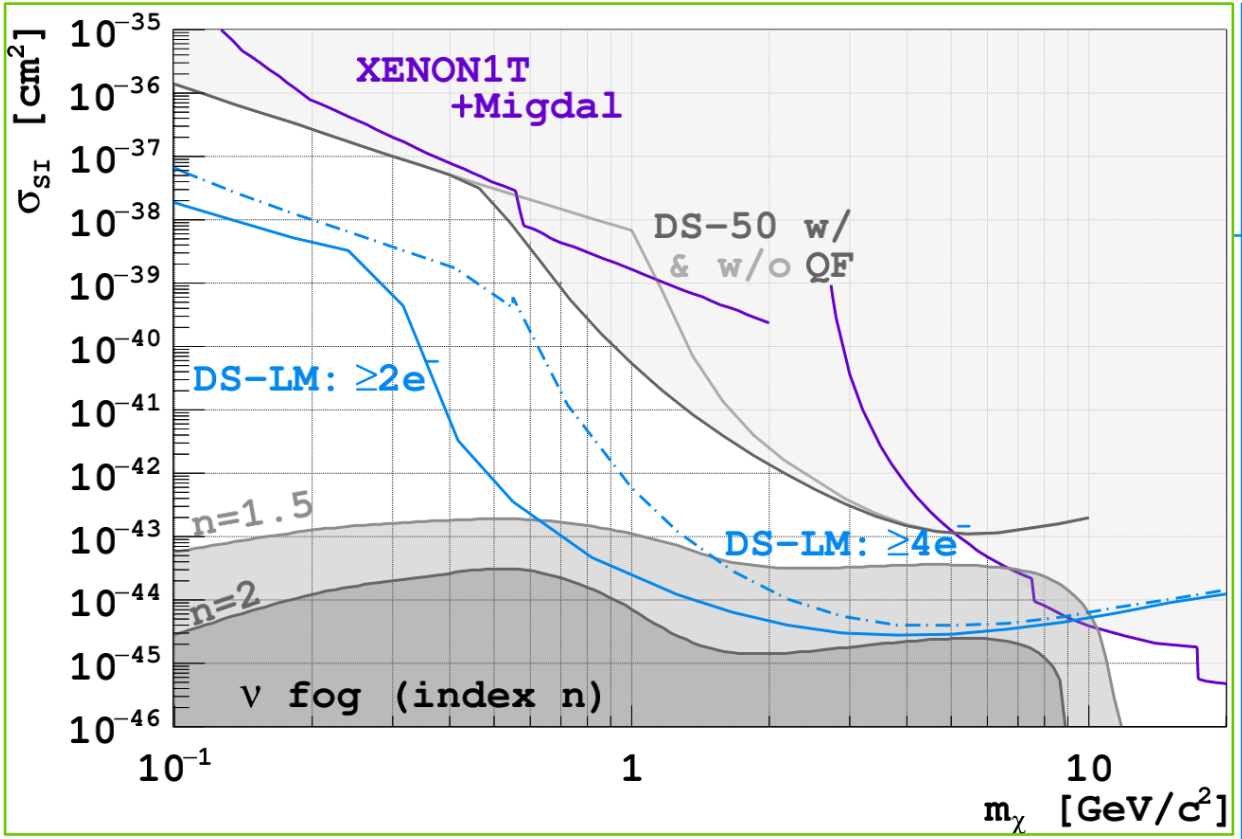


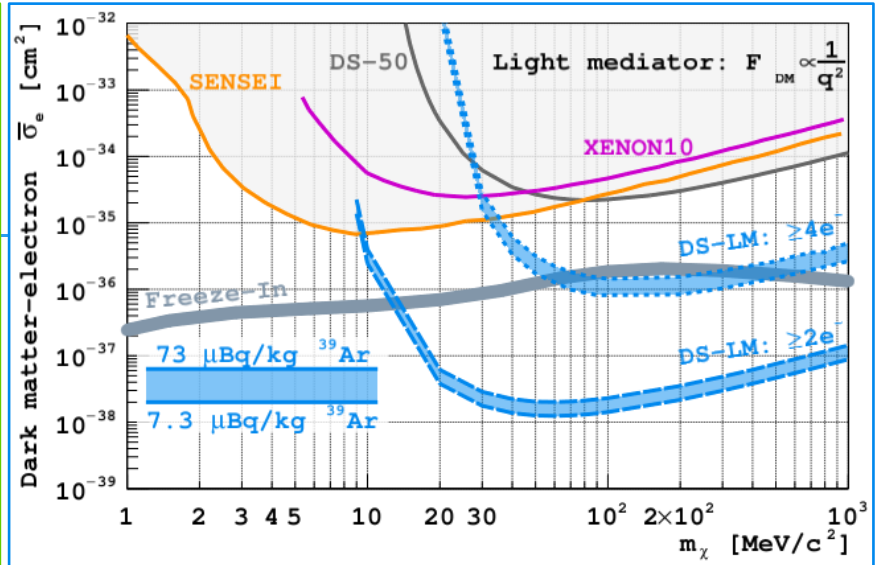


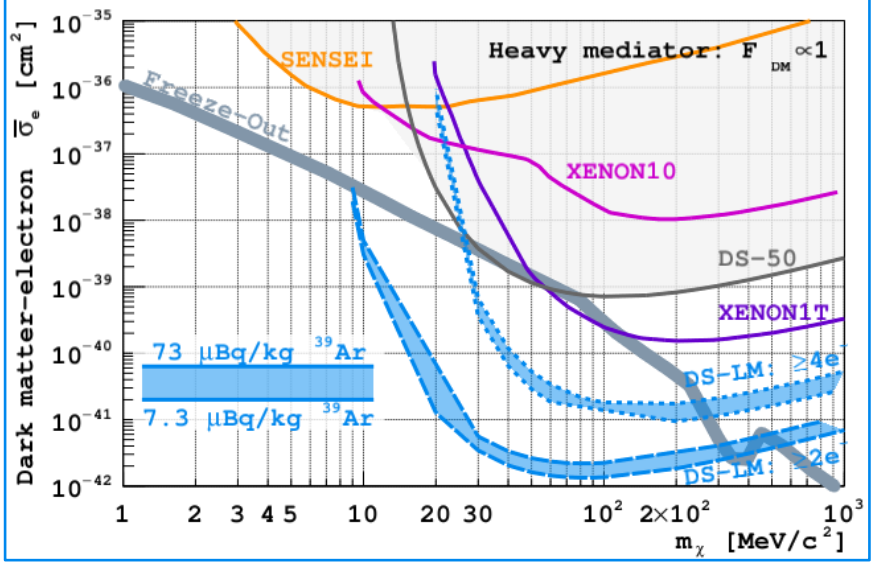


DarkSide Collaboration. "Search for dark matter-nucleon interactions via Migdal effect with DarkSide-50". arXiv:2207.11967 (2022)

DarkSide Collaboration. "Search for dark matter particle interactions with electron final states with DarkSide-50". arXiv:2207.11968 (2022)





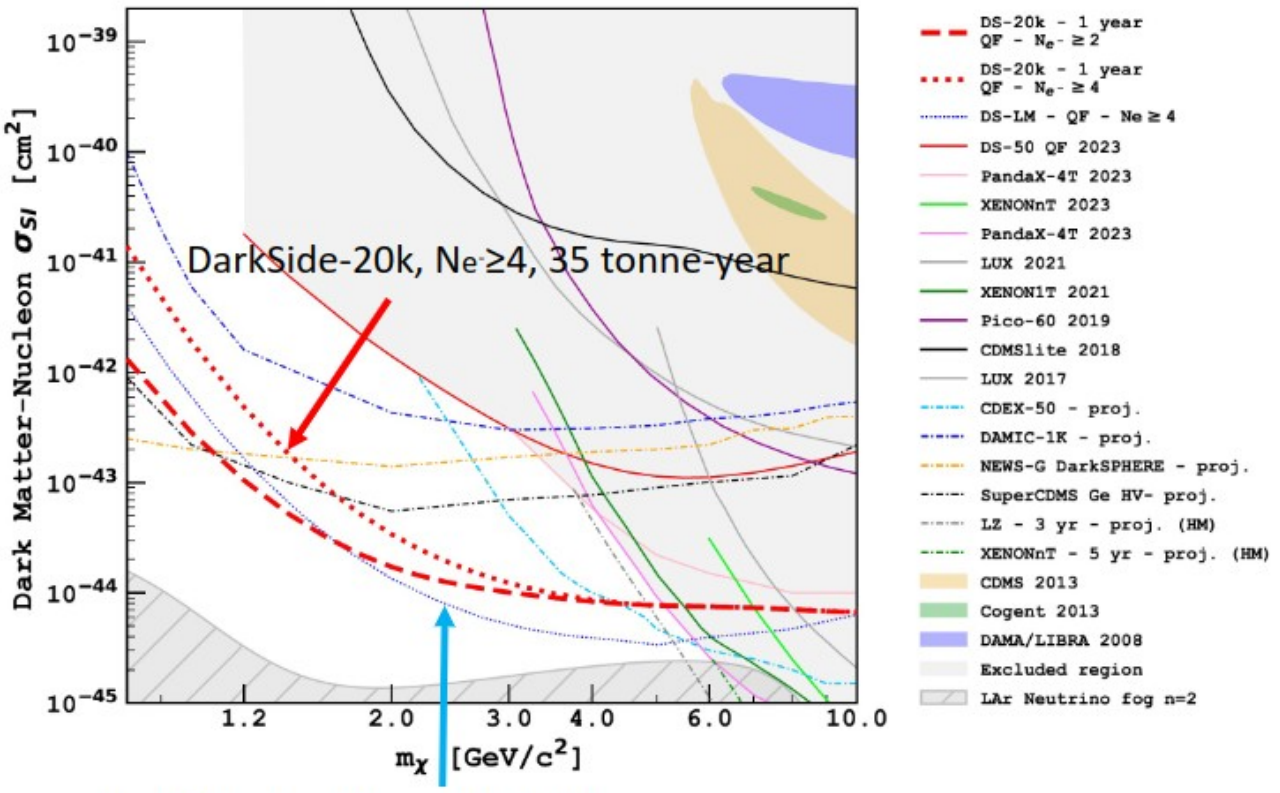


Nuclear couplings: Sensitivity to GeV-scale candidates down into the neutrino fog

Electronic couplings: Sensitivity to sub-GeV candidates covering cross sections that explain the relic abundance in freeze-in and freeze-out production mechanisms

DarkSide-20k

arXiv:2407.05813



DarkSide-LowMass, Ne⁻≥4, 1 tonne-year

END