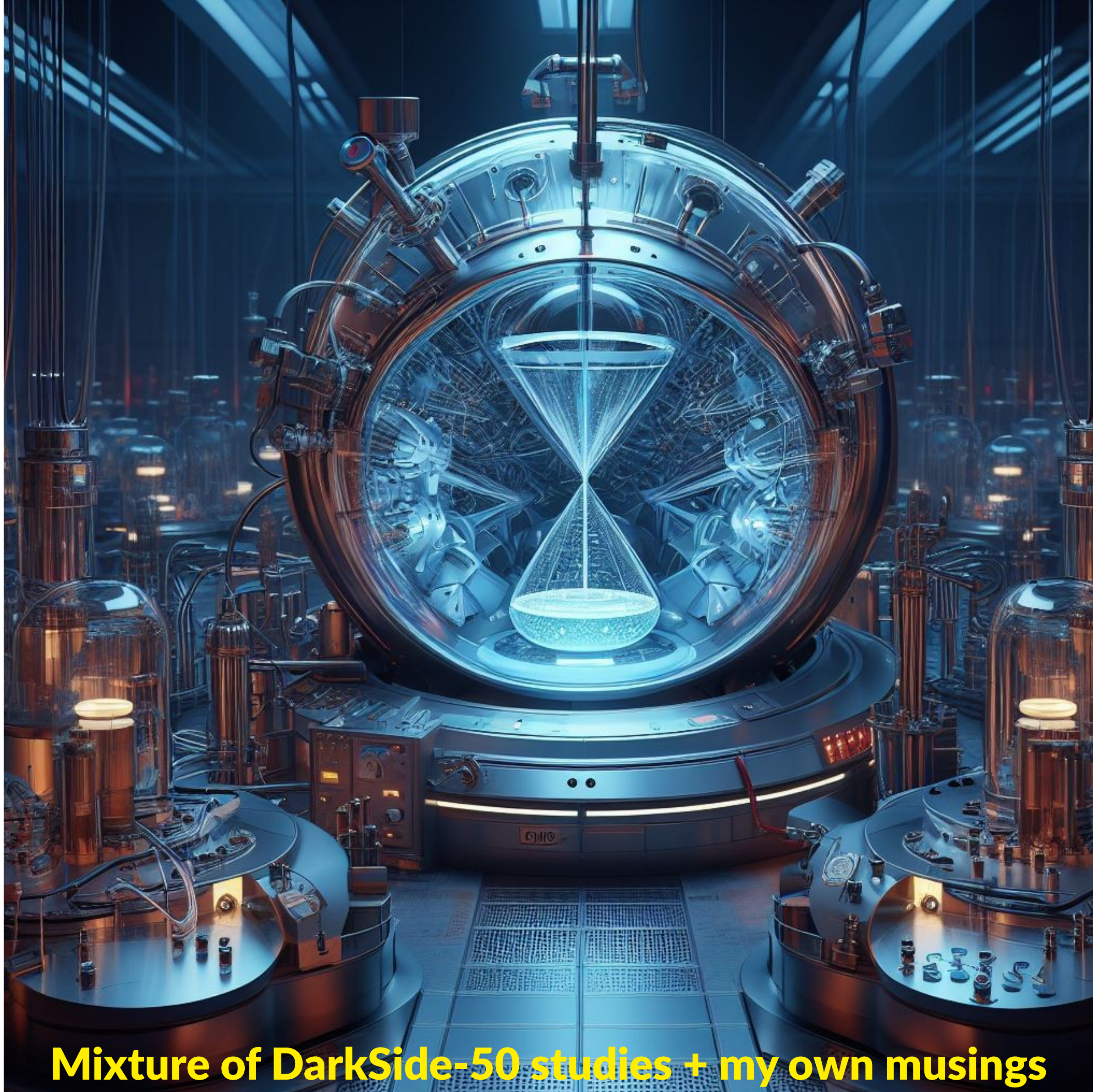
Lowering the threshold of dual-phase LArTPCs

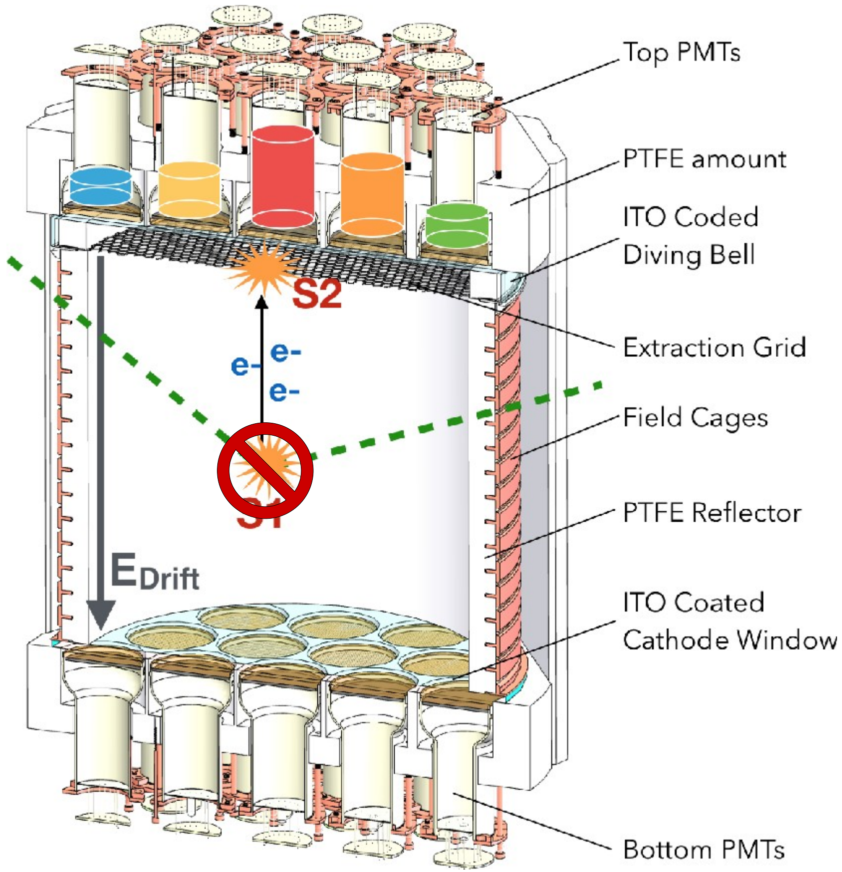
Shawn Westerdale
[w/ the Global Argon Dark Matter Collaboration]
CPAD : RDC 1
8 November, 2023

UCR PHYSICS & ASTRONOMY

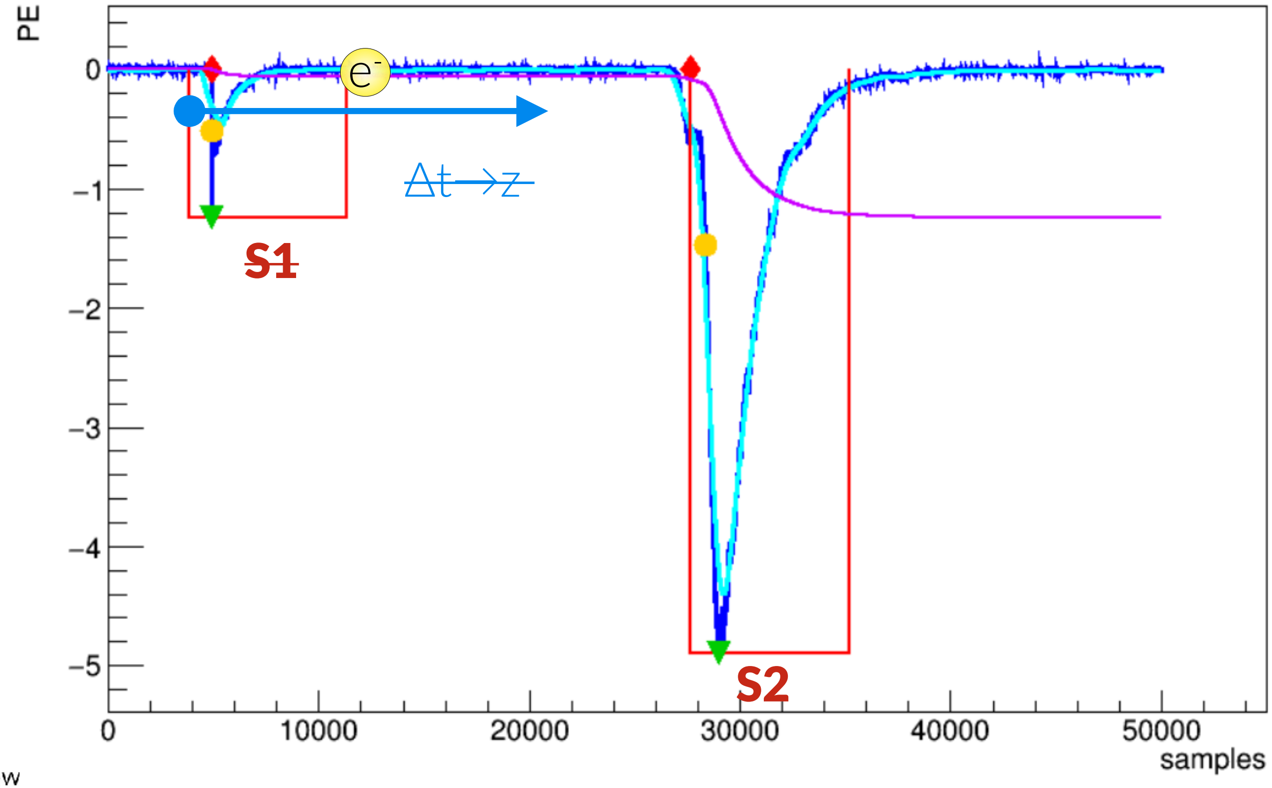
Bing AI, draw a low-threshold time projection chamber



Mixture of DarkSide-50 studies + my own musings



Drawing of DarkSide-50

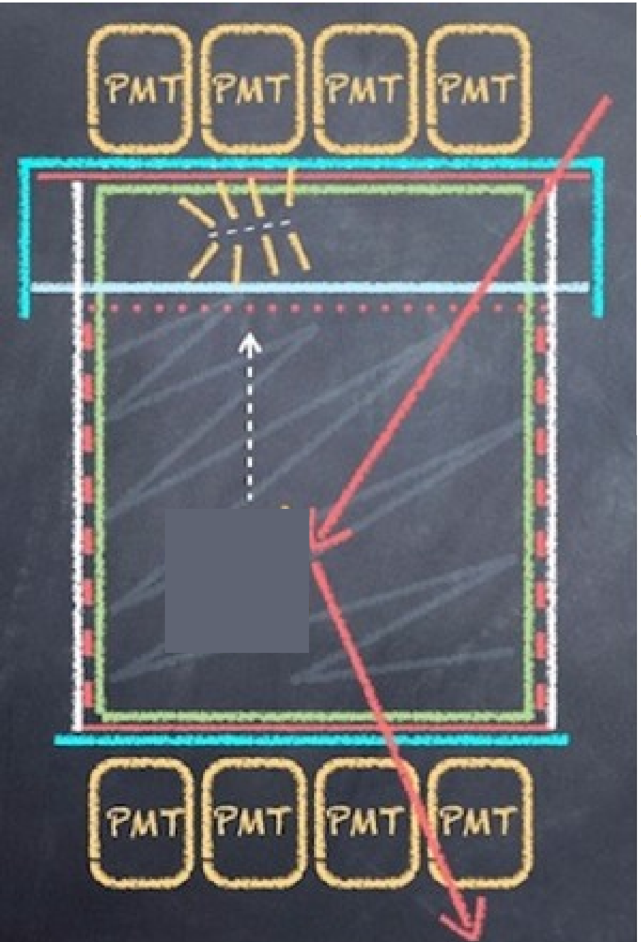


As a consequence, S2 can access lower energies than S1 → Low-threshold LArTPC via S2-only channel

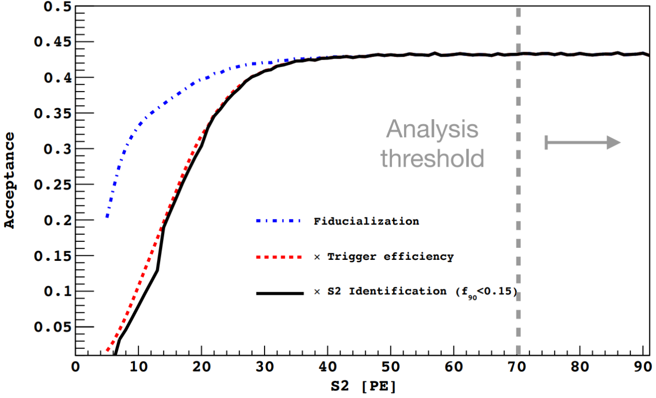
Challenges:

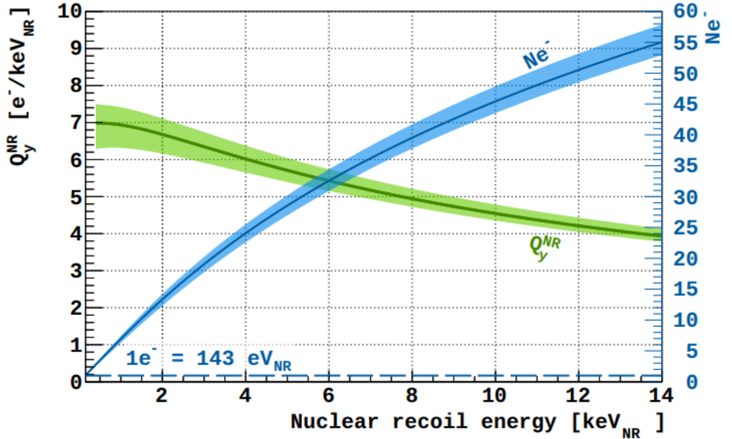
Cannot measure Δt → Can't fiducialize in z
Timing resolution limited by max e^- drift time
No PSD → No ER discrimination
Spurious electron backgrounds

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

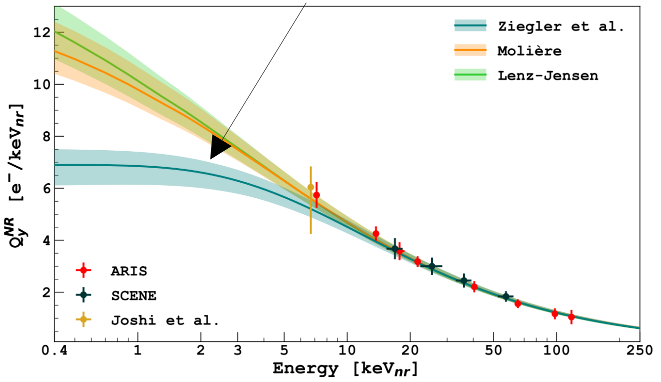


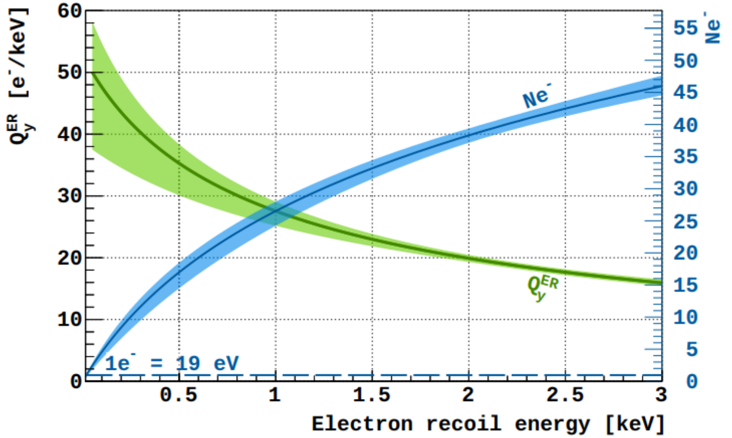
$N_e = S2/\eta$ where $\eta = (23 \pm 1)$PE/e





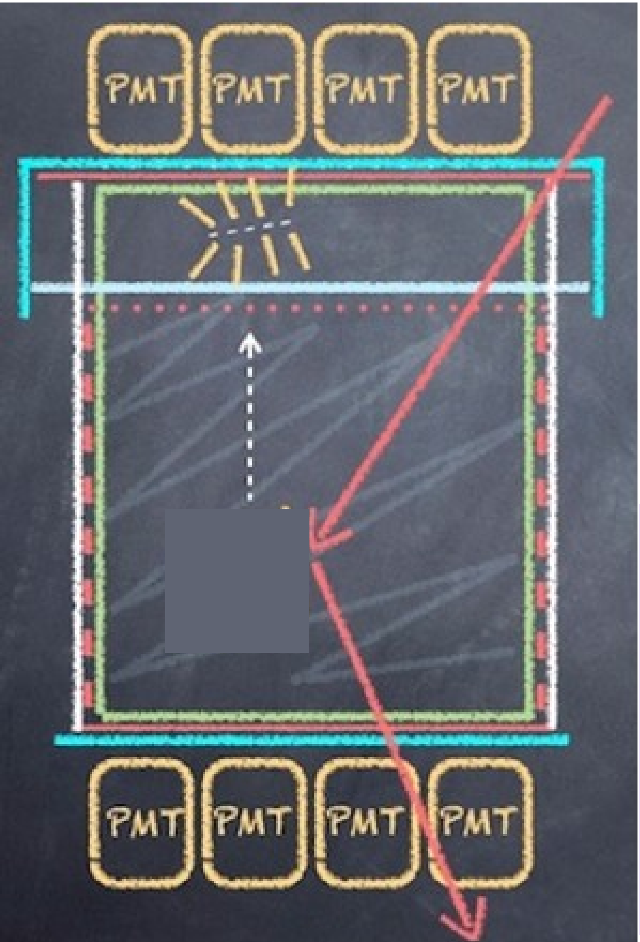
Need ex situ calibration to measure Qy at low energies

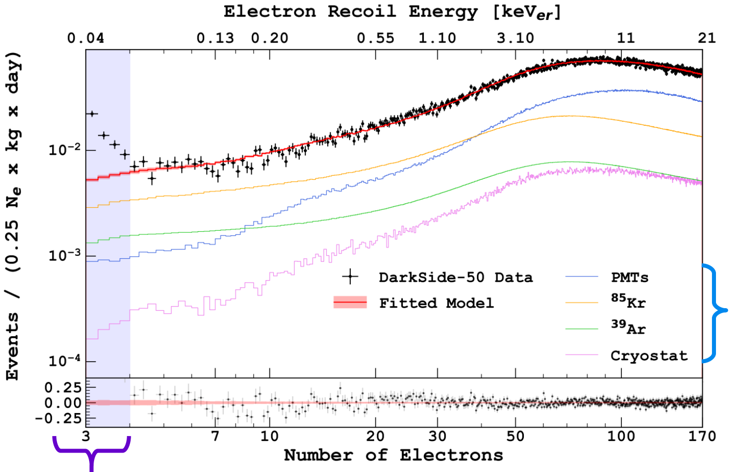


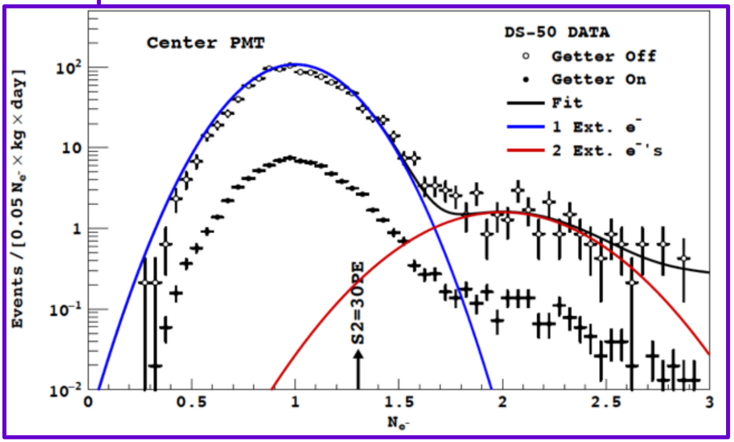


DarkSide Collab. Phys. Rev. D 104, 082005 (2021)

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

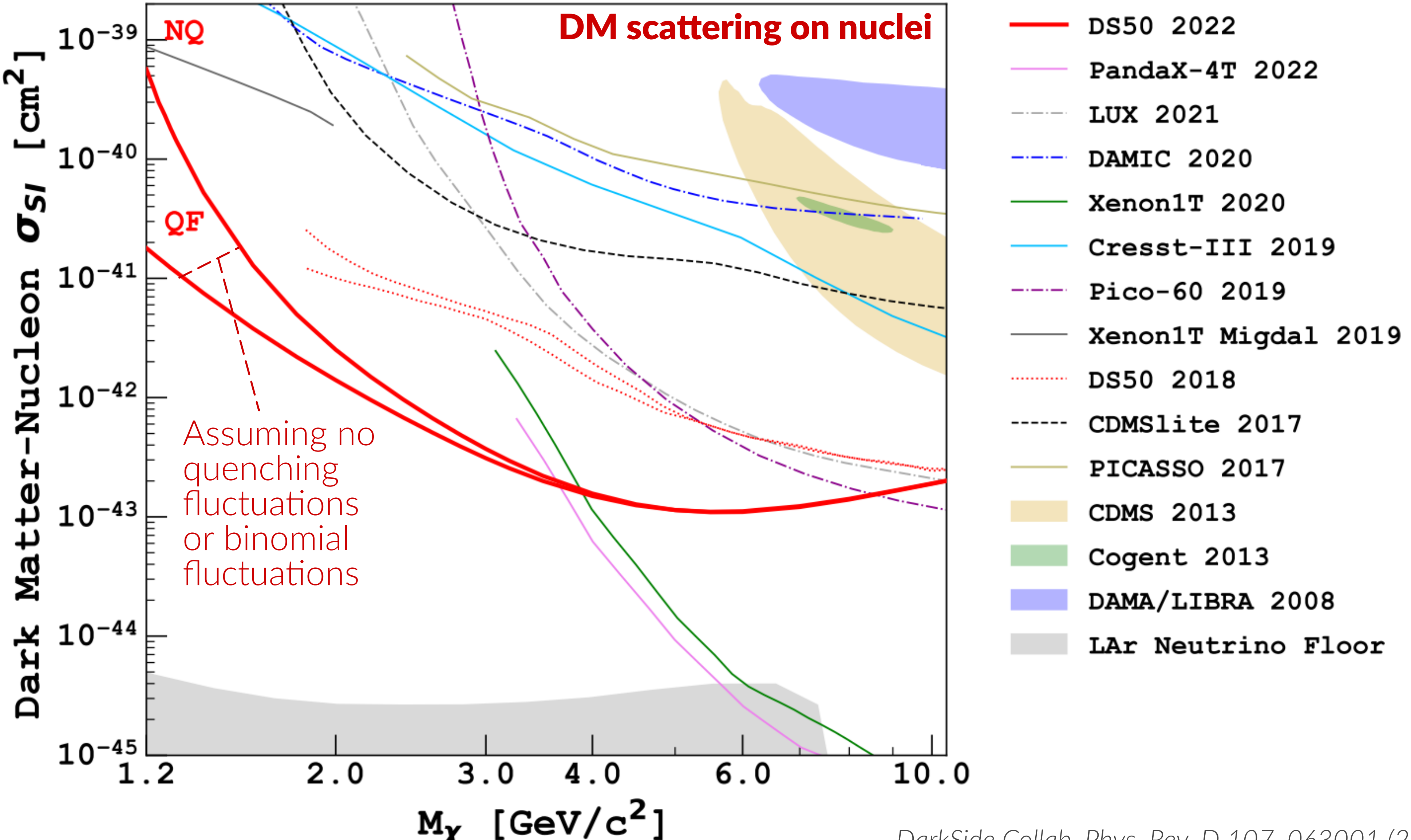
Correlations between SE and preceding S2 (time, xy position, S2 charge and t_{drift} vs. P_{SE})

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)

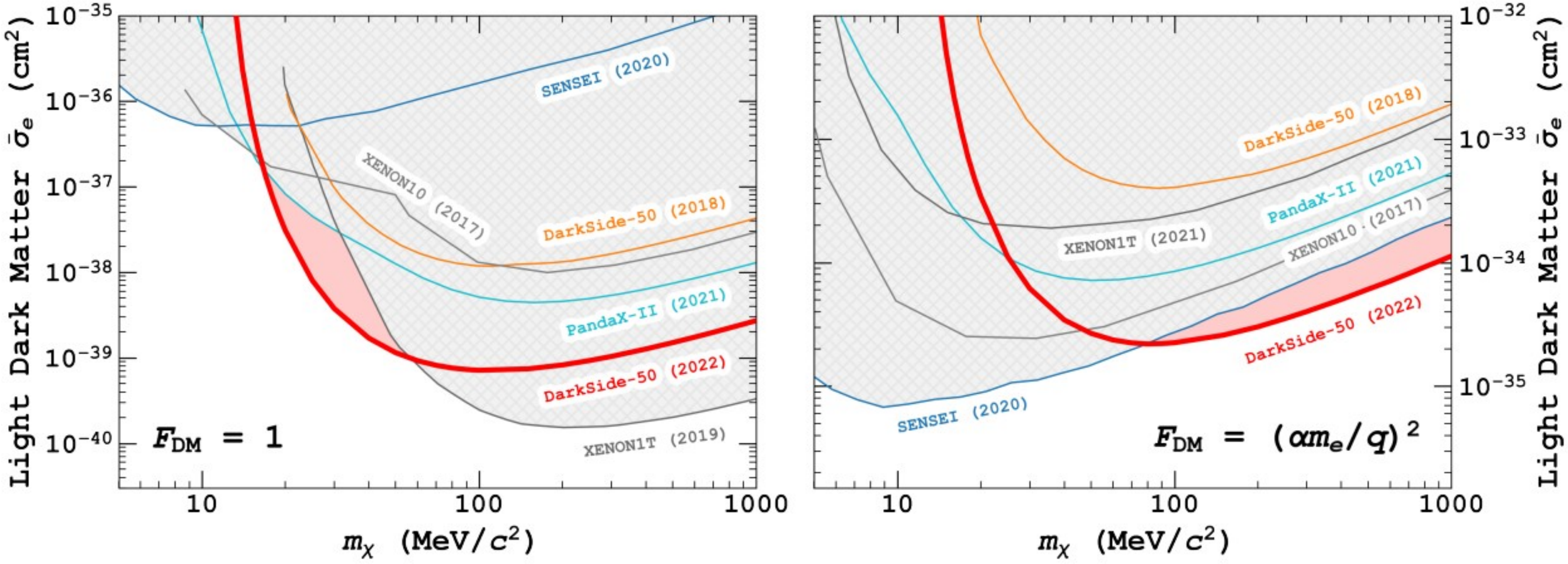
DM scattering on nuclei



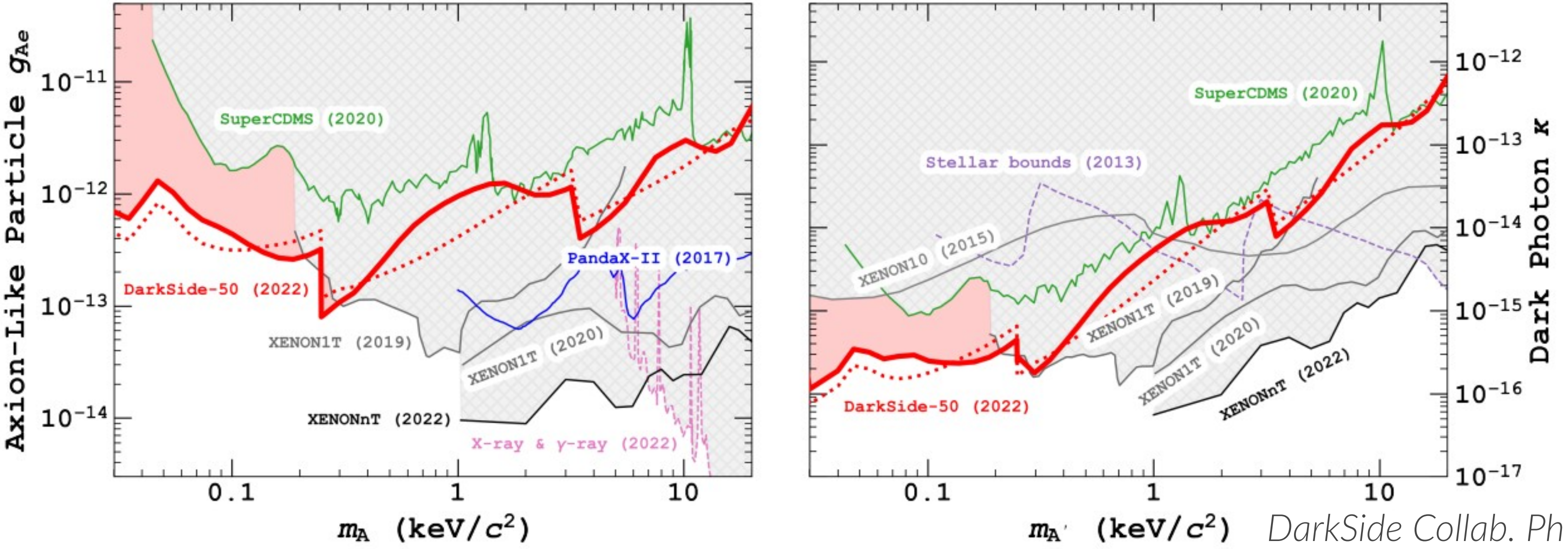
Assuming no quenching fluctuations or binomial fluctuations

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

DM w/ e^-'s in final state



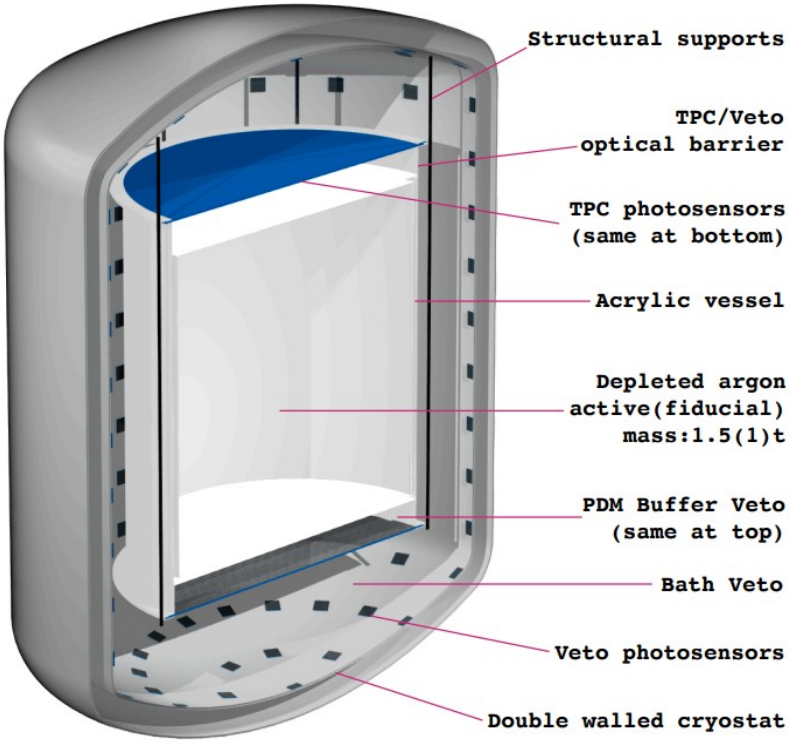
Scattering



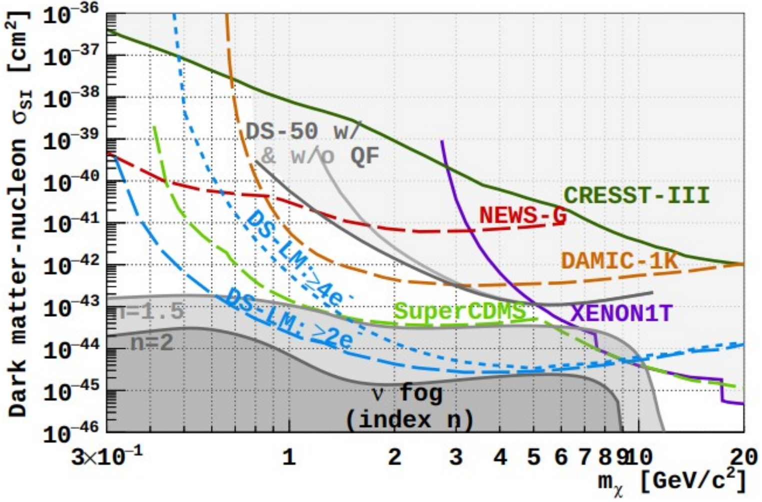
Absorption

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

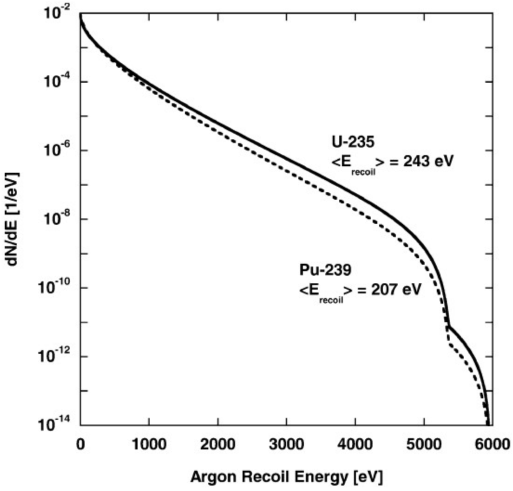
LArTPC in S2-only analyses: Powerful tool for low-threshold measurements



Light dark matter search



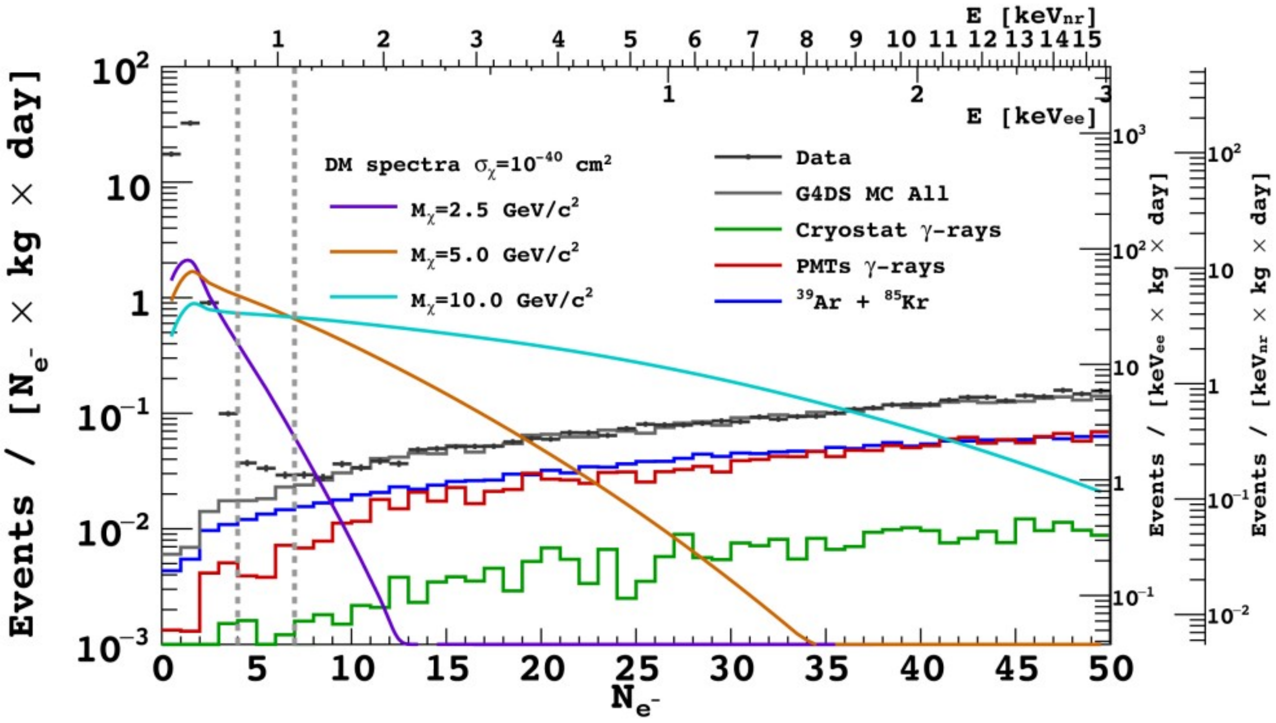
Reactor CEvNS



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?



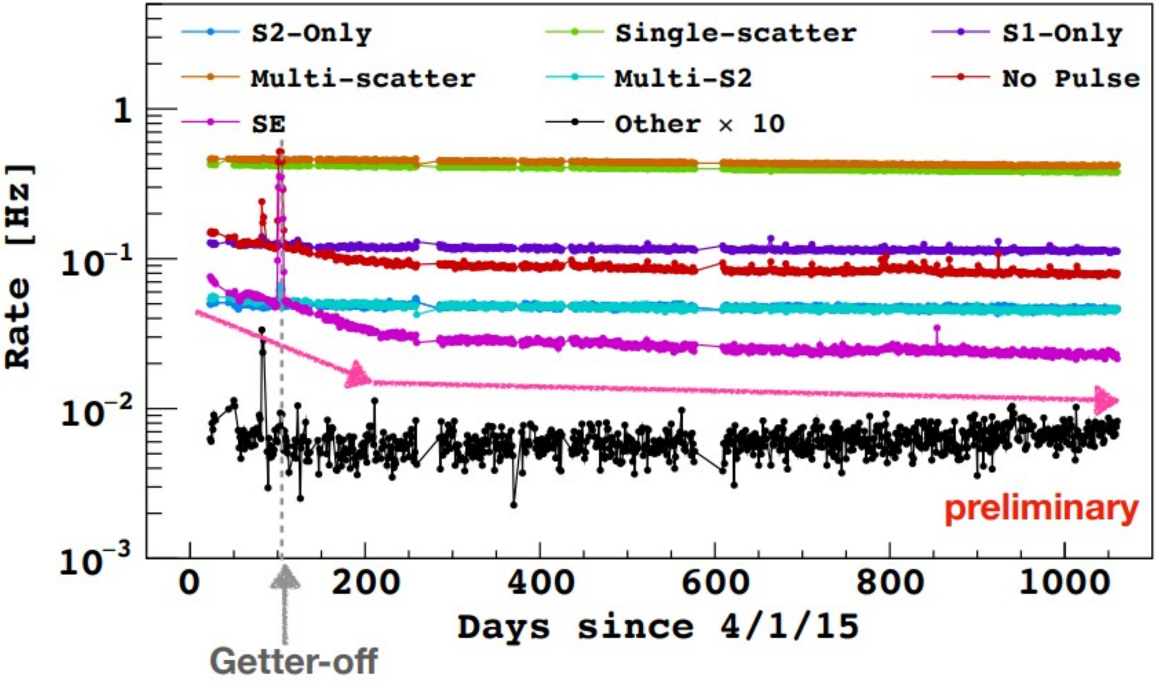
DarkSide Collab. Phys. Rev. Lett. 121, 081307 (2018)

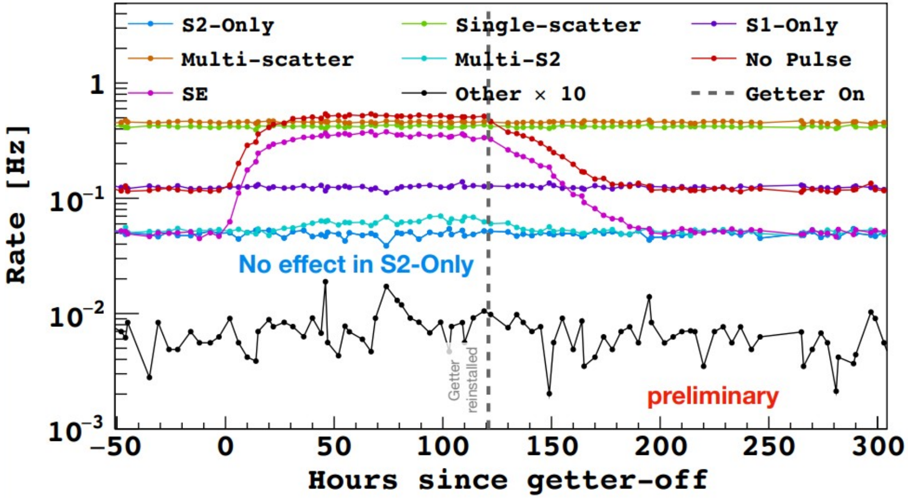
Threshold is set by

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

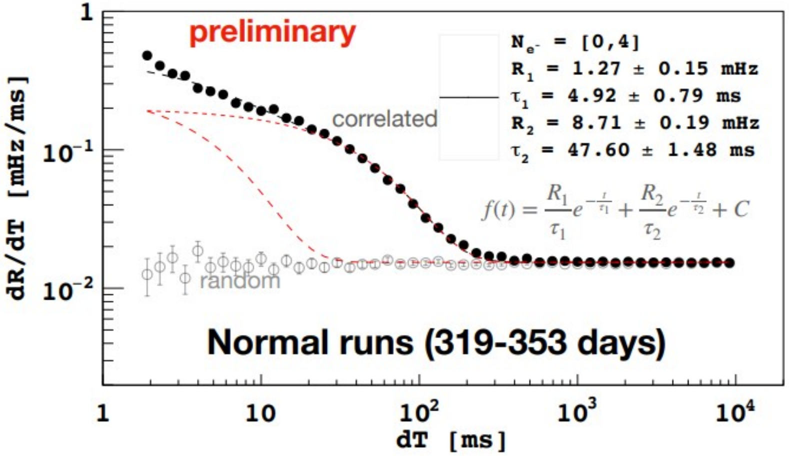
All of these are pathways for lowering the energy threshold

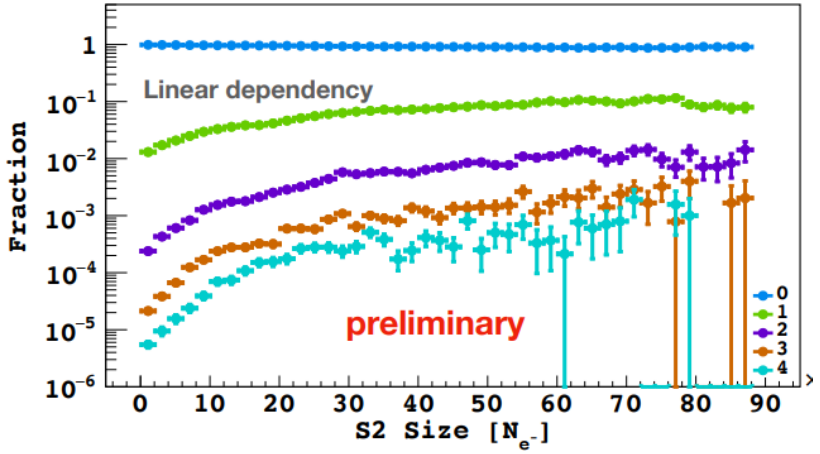
SE rate changes over time and appears to be related to impurities

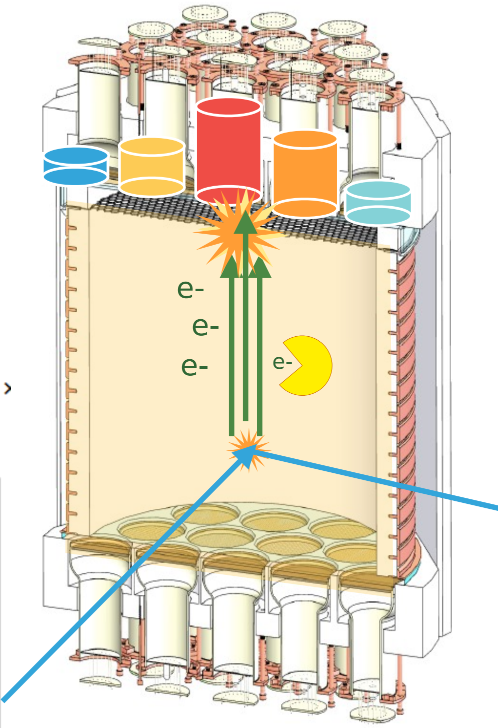


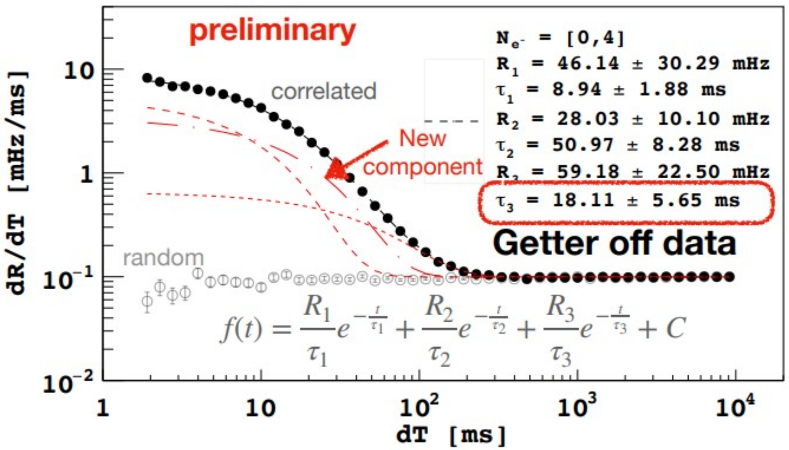


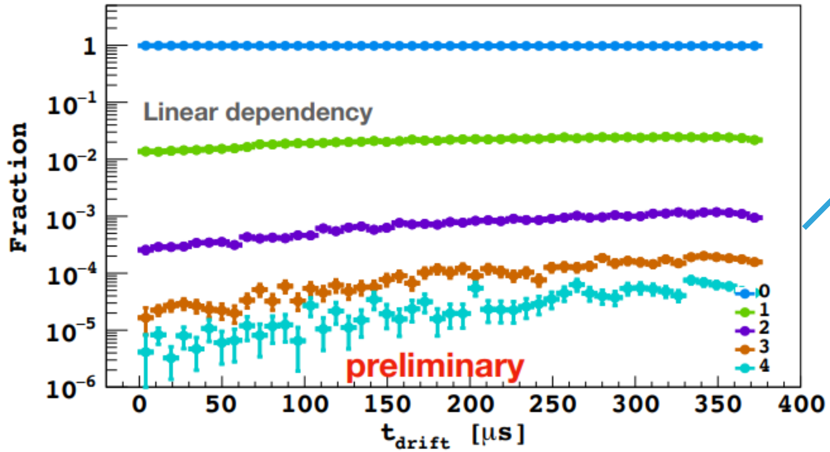
SEs appear to be correlated in time, space, and charge with ordinary events



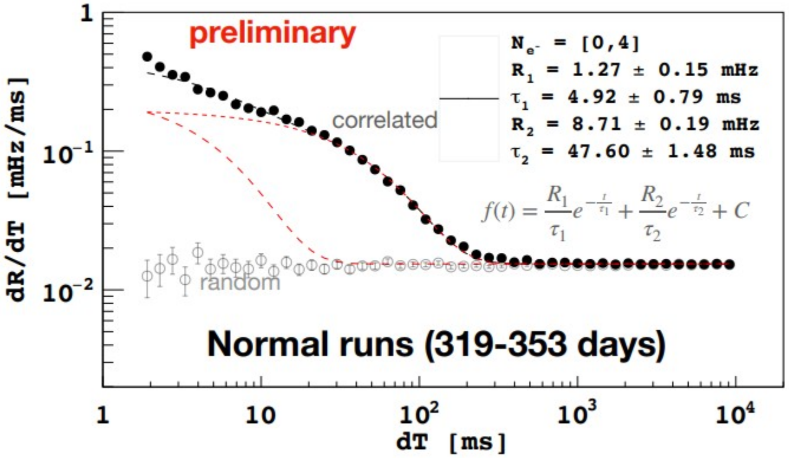


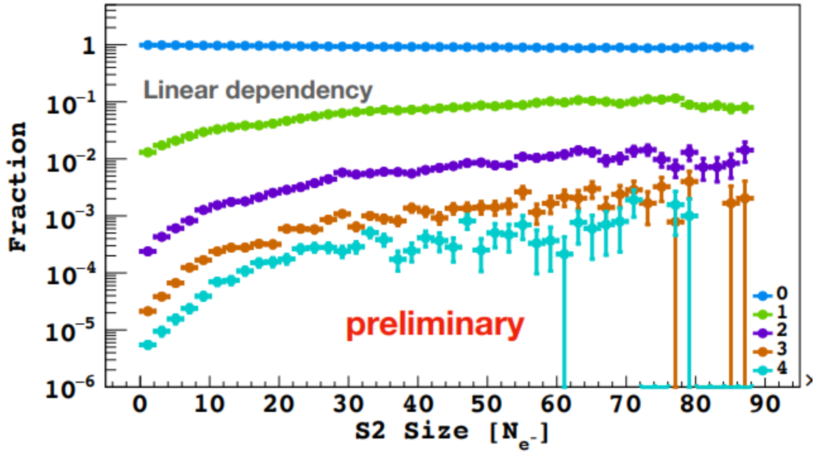


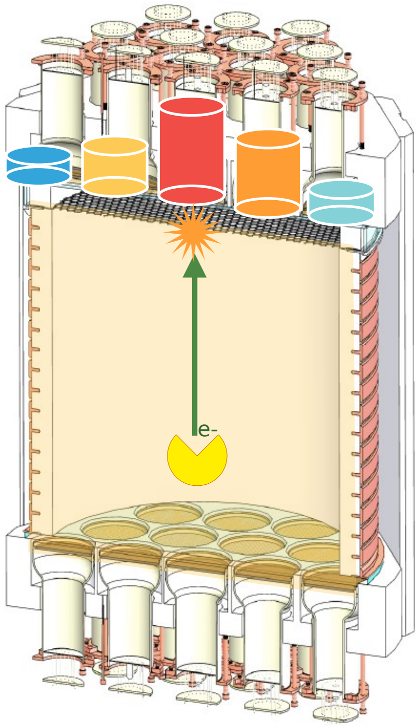


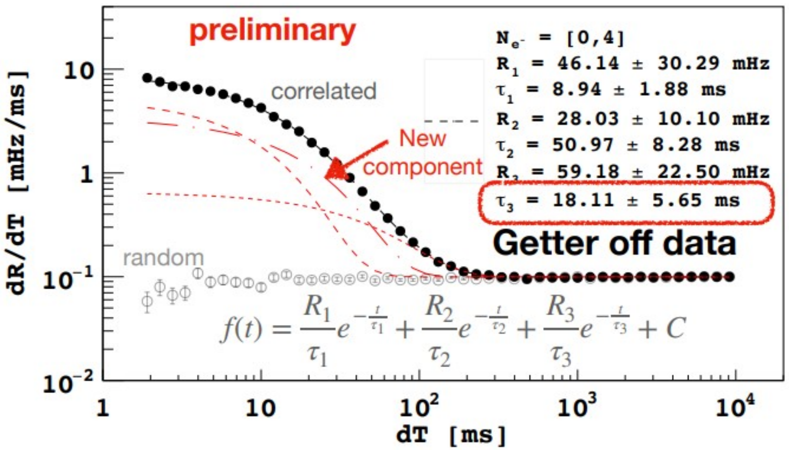


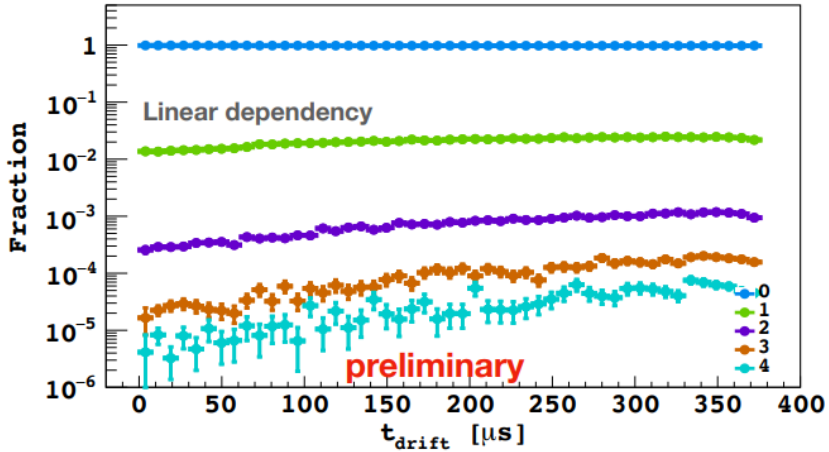
Hypothesis: Dominant SE production mechanism from impurities trapping e⁻



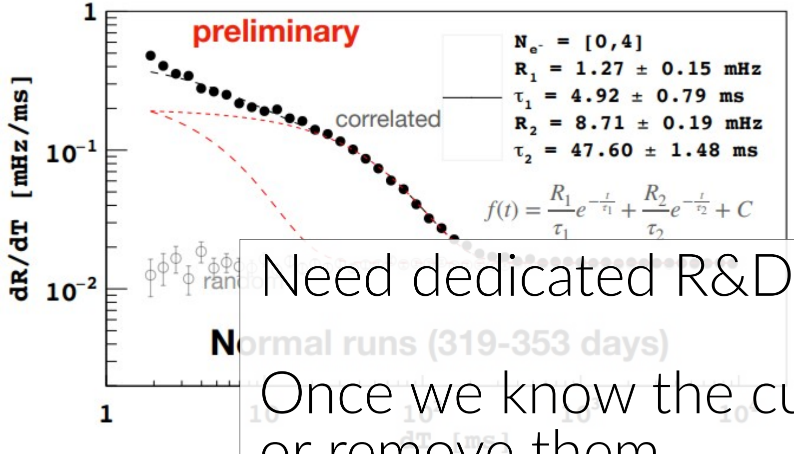


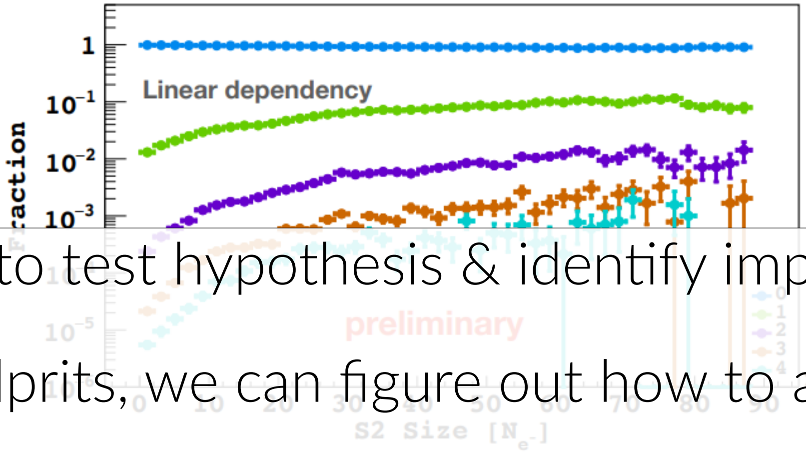






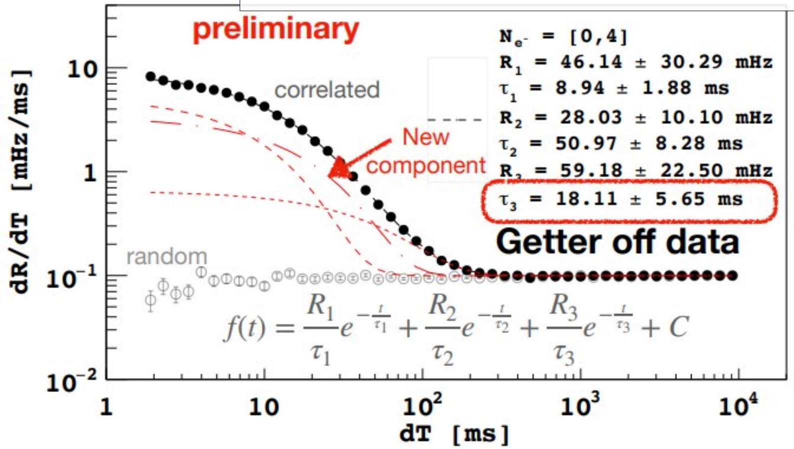
Hypothesis: Dominant SE production mechanism from impurities trapping e^-

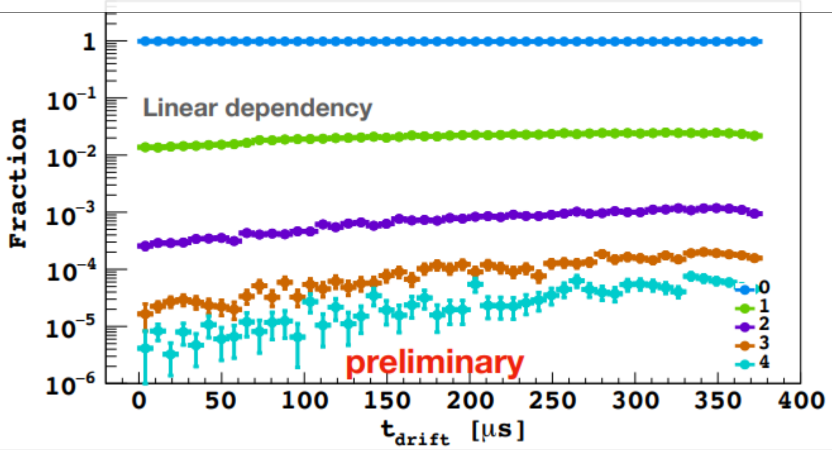


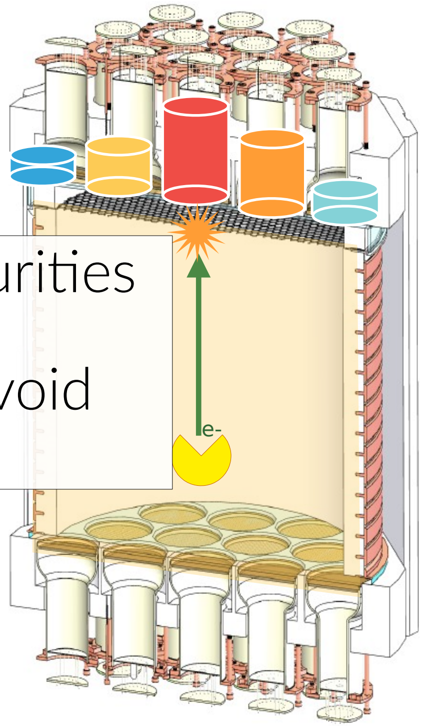


Need dedicated R&D to test hypothesis & identify impurities

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

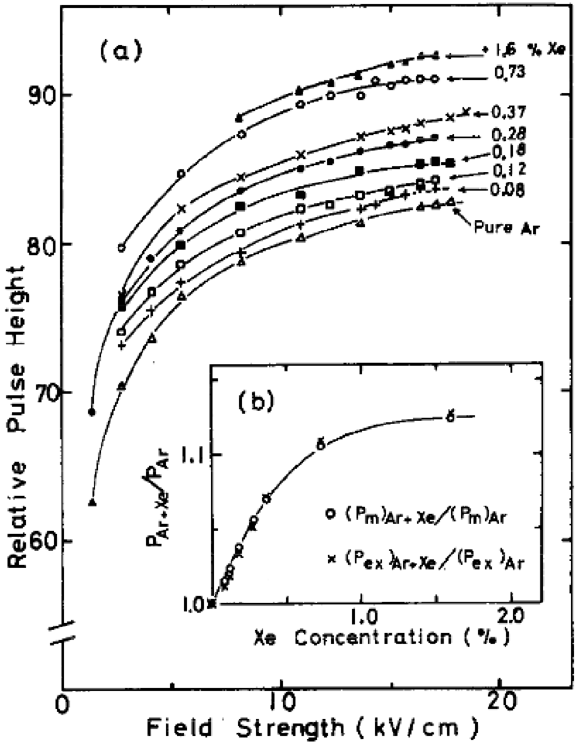


Fig. 1. a) Saturation curves of the pulse height produced by ^{207}Bi conversion electron for the different concentration of Xe. b) Relative ionization yields as a function of doped-Xe concentration.

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

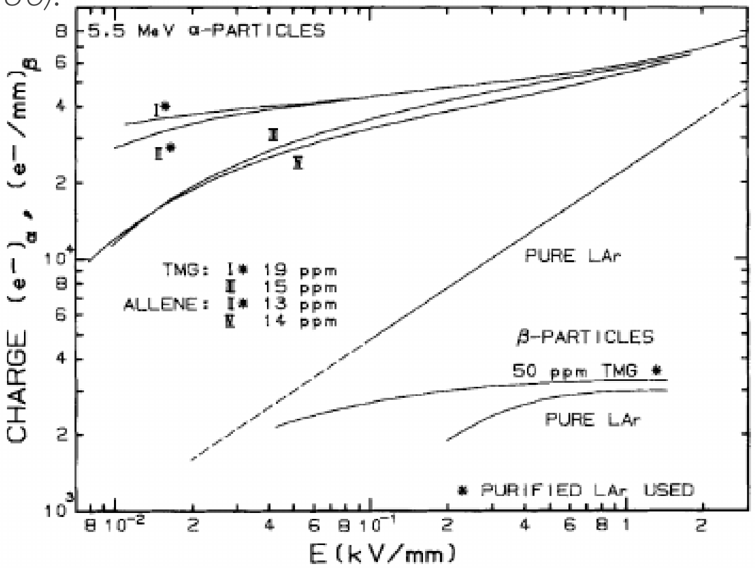
Nuclear recoils produce ionization through a cascade (one nucleus colliding with others, and so on) → effects may be non-linear

R&D needs:

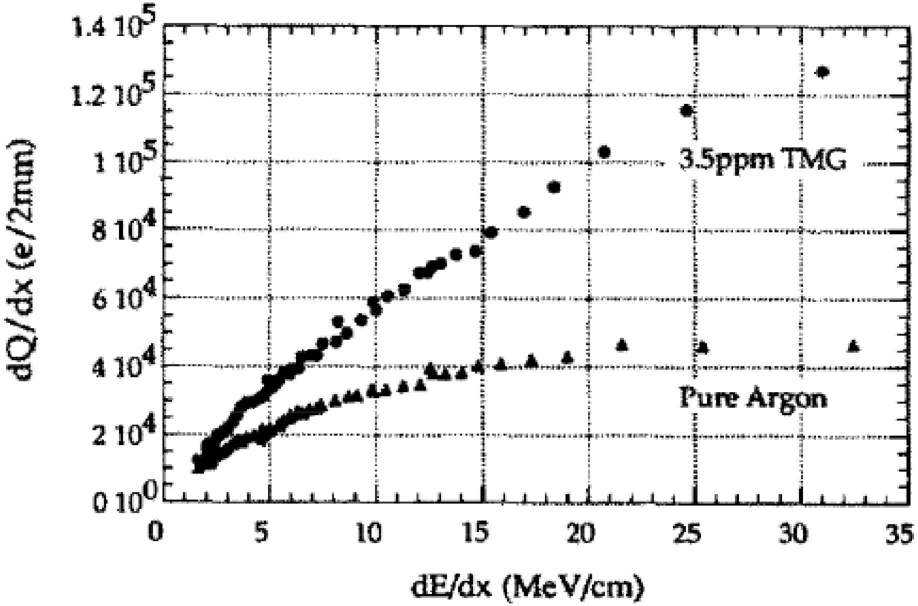
Need to measure Qy of low-energy NRs as a function of Xe concentration to see the effect side

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).

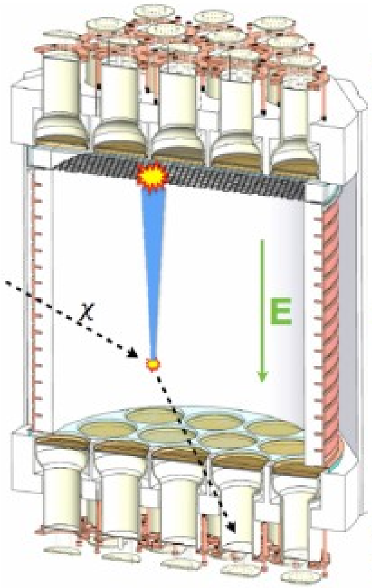


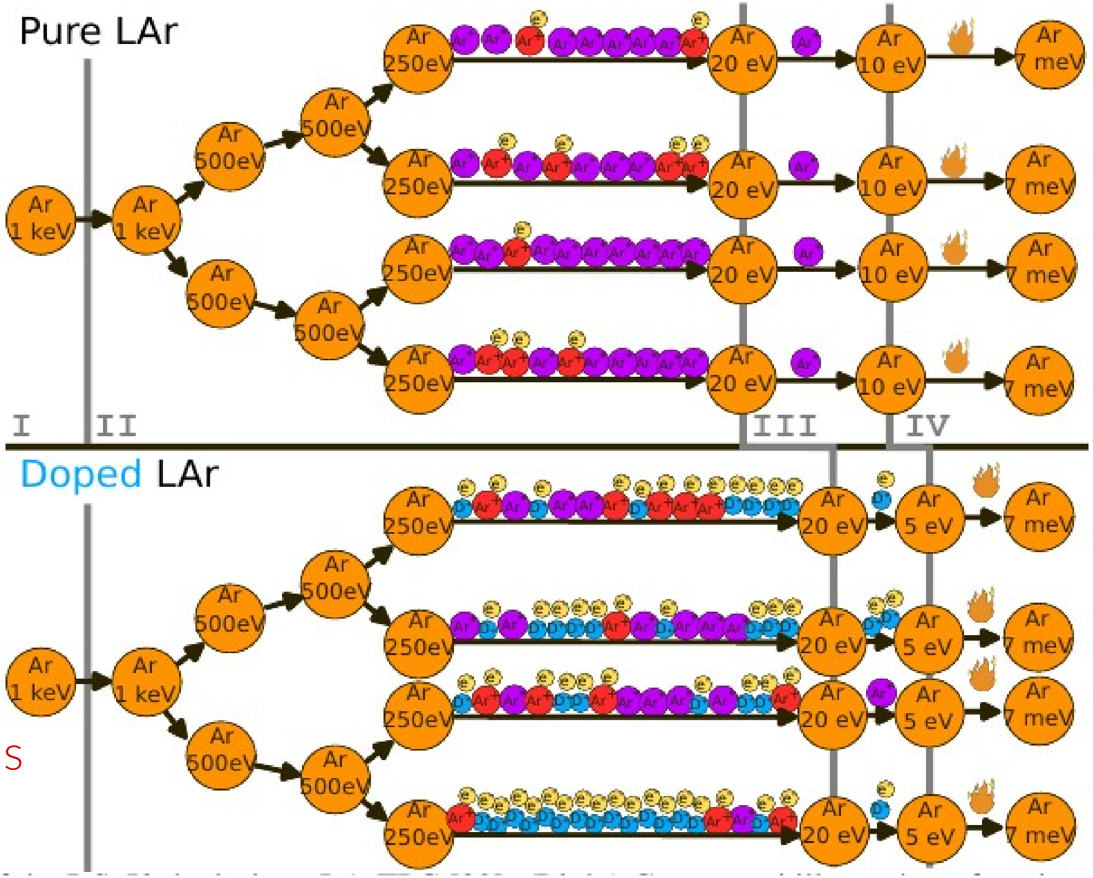
Dopants with 7.5–9.5 eV ionization energies have previously been studied in LAr, in the context of improving the resolution of high-energy ionization chambers

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

Turns inefficiently detected S1 into efficiently detected S2!

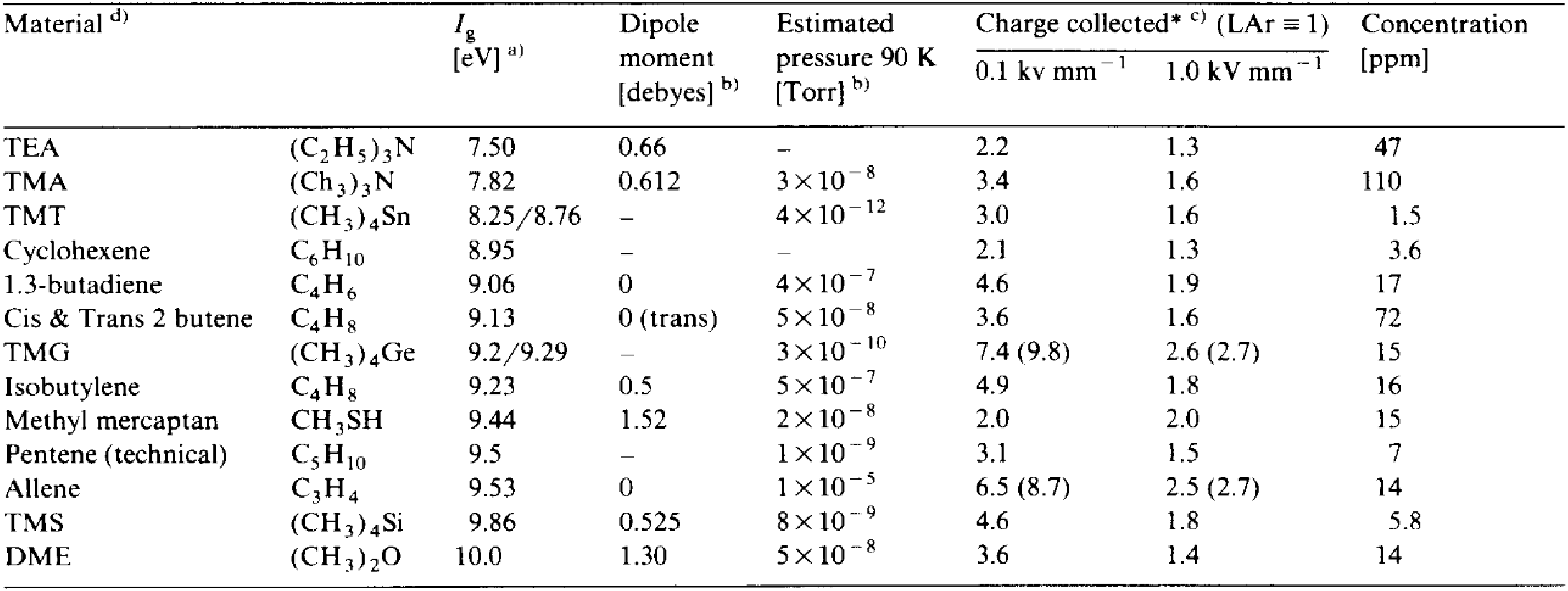
Potential benefits from doping





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

Some potential dopants

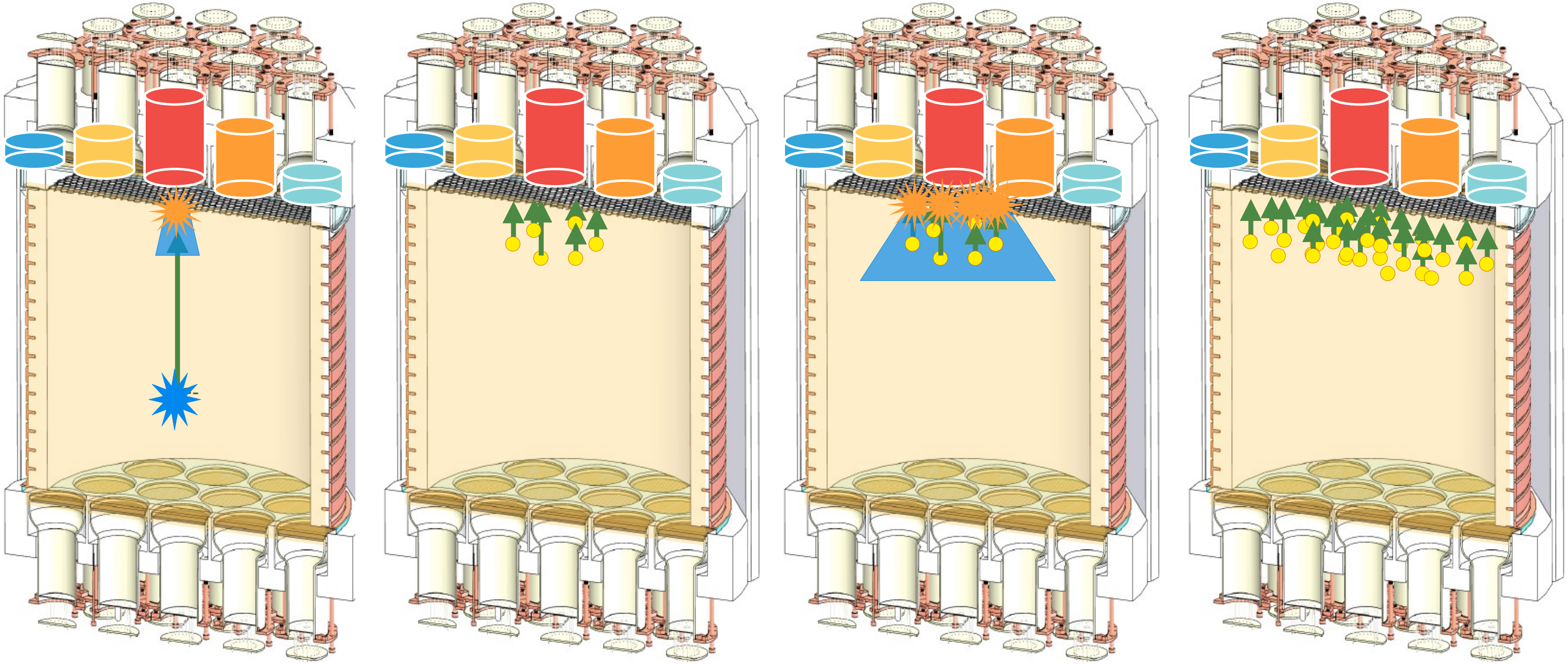


Material [d]		I_g [eV] [a]	Dipole moment [debyes] [b]	Estimated pressure 90 K [Torr] [b]	Charge collected* [c] (LAr ≡ 1)		Concentration [ppm]
					$0.1\ \mathrm{kv\ mm^{-1}}$	$1.0\ \mathrm{kV\ mm^{-1}}$	
TEA	$(C_2H_5)_3N$	7.50	0.66	–	2.2	1.3	47
TMA	$(Ch_3)_3N$	7.82	0.612	3×10^{-8}	3.4	1.6	110
TMT	$(CH_3)_4Sn$	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

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

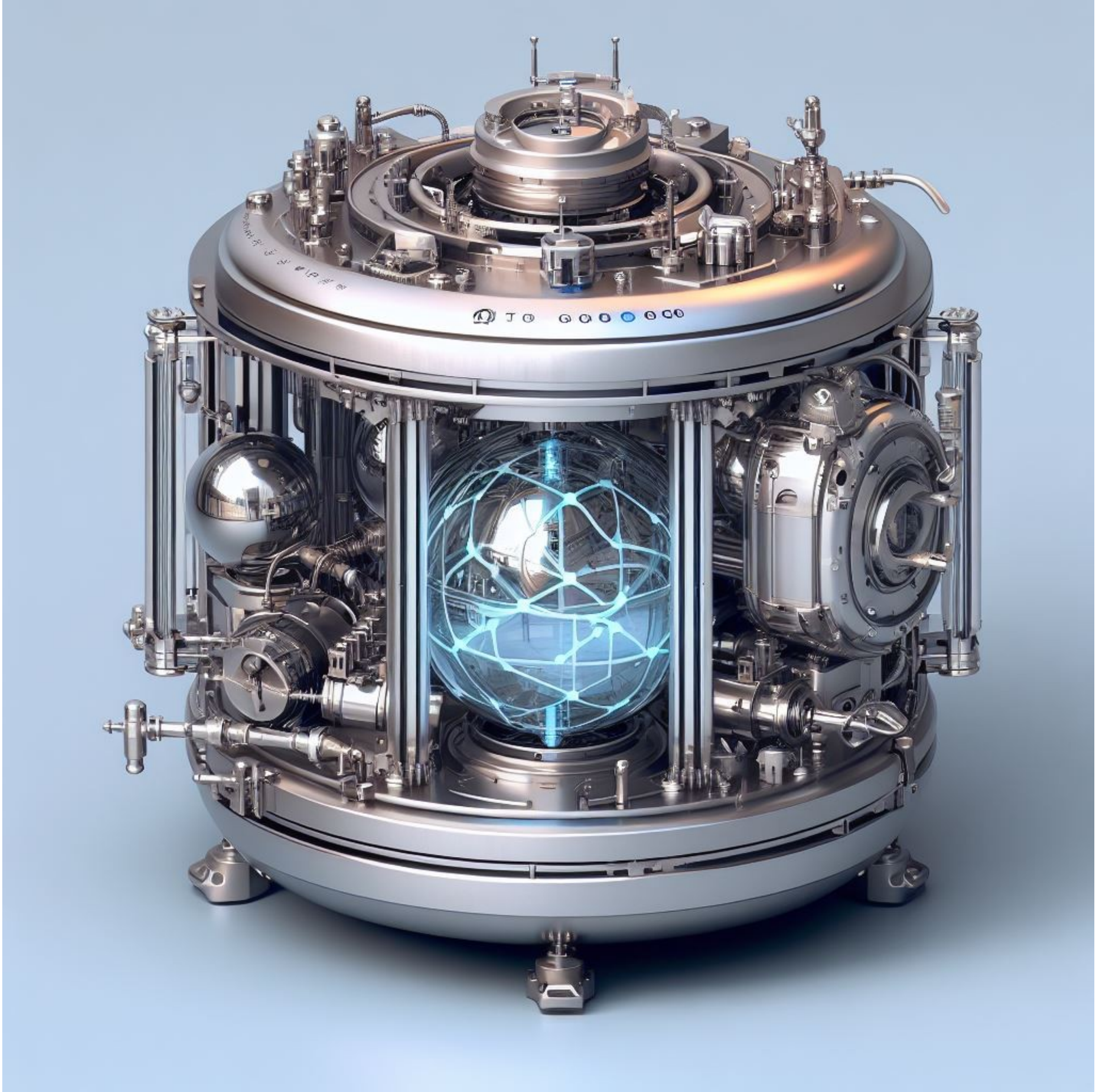
Doping LAr

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



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