Xenon detectors for light dark matter searches

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The main LXe collaborations & my involvement

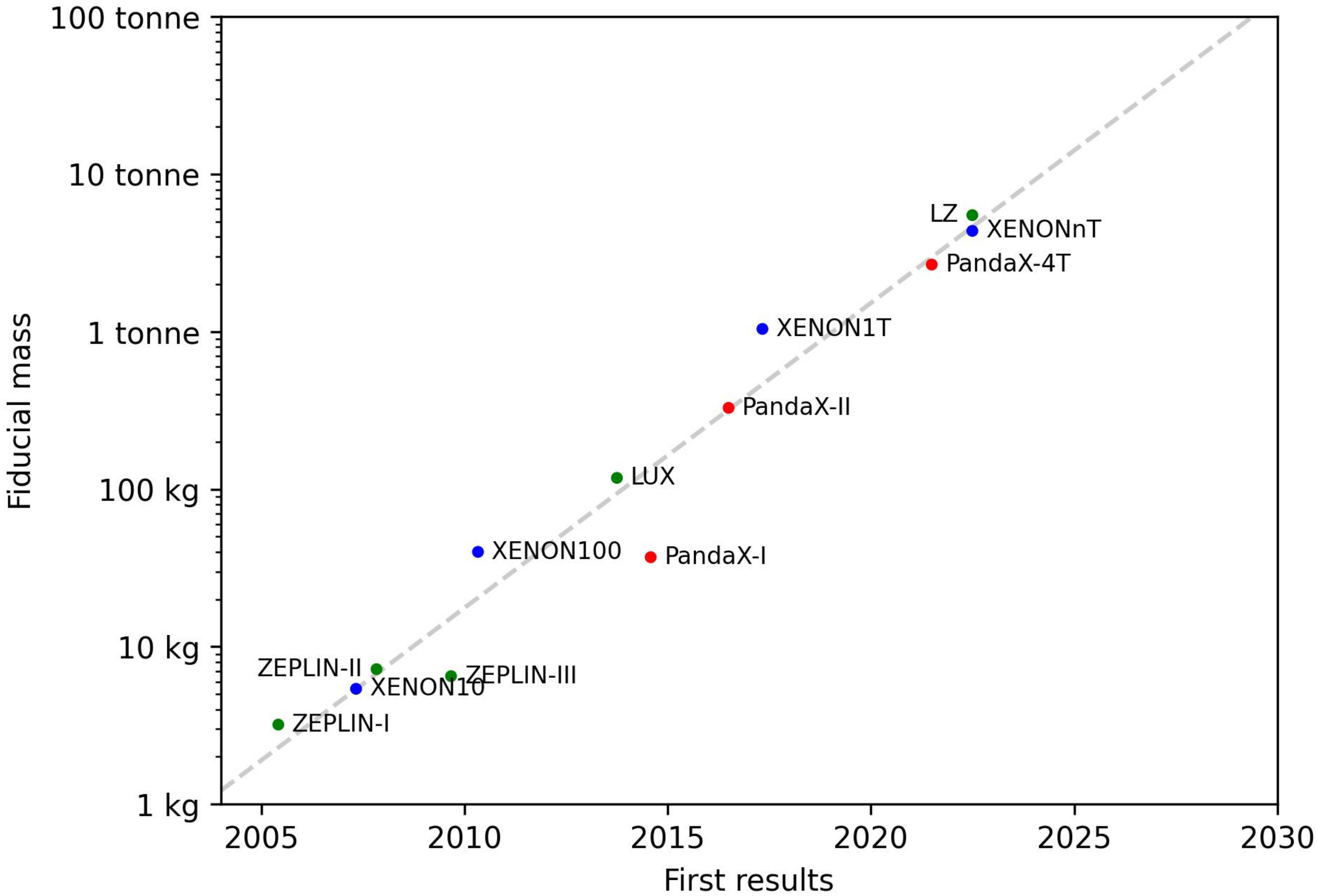
XENON
2014-2020 & 2023-present

LZ
2021-2023

PandaX
None – see talk by Shaobo Wang today!

XLZD
founding-present

Opinions expressed here are my own, not necessarily those of any collaboration!

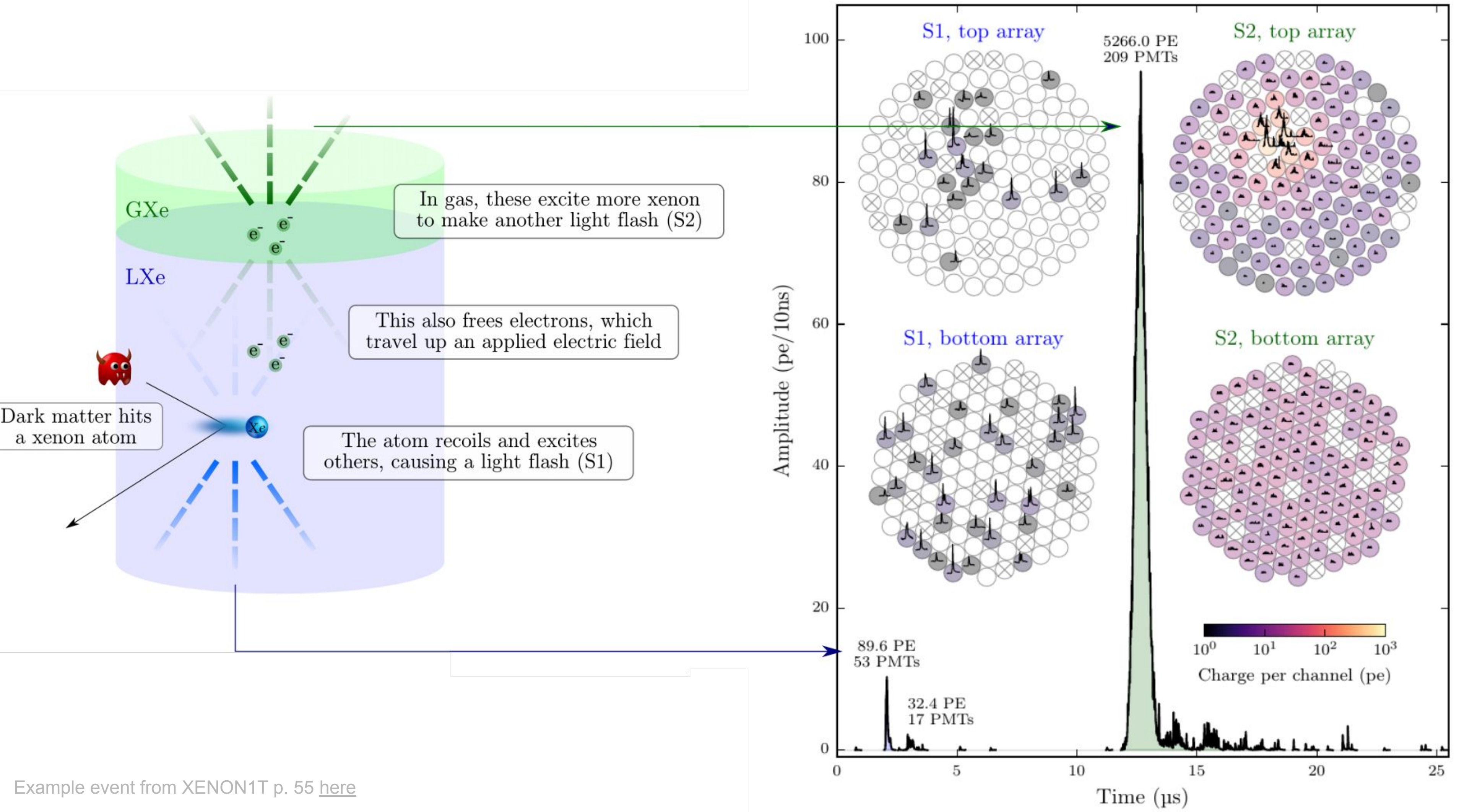


100 tonne
10 tonne
1 tonne
100 kg
10 kg
1 kg
Fiducial mass
2005
2010
2015
2020
2025
2030
First results
LZ
XENONnT
PandaX-4T
XENON1T
PandaX-II
LUX
XENON100
PandaX-I
ZEPLIN-II
ZEPLIN-III
XENON10
ZEPLIN-I

Xenon is *awesome*:

- Easy charge and light detection
  W≈13.7 eV, noble gas, 175nm scintillation light with ~30cm mean free path [ref]
- Excellent self-shielding
  Z =54, photoelectric attenuation length $1/Z^{4 \text{ to } 5}$
- Need far less xenon than lighter elements for same spin-independent rates
  A ≈ 131, but $\sigma \sim A^2$ at low q^2
- Still have spin-dependent sensitivity
  ~50% has nonzero nuclear spin & odd neutron number (^{129}Xe and ^{131}Xe)
- Only double-weak intrinsic radioactivity (^{136}Xe and ^{124}Xe)
  rates below solar neutrinos near the dark matter region of interest [XnT]
- Even with natural ~9% ^{136}Xe, competitive sensitivity to 0νββ! [XLZD]

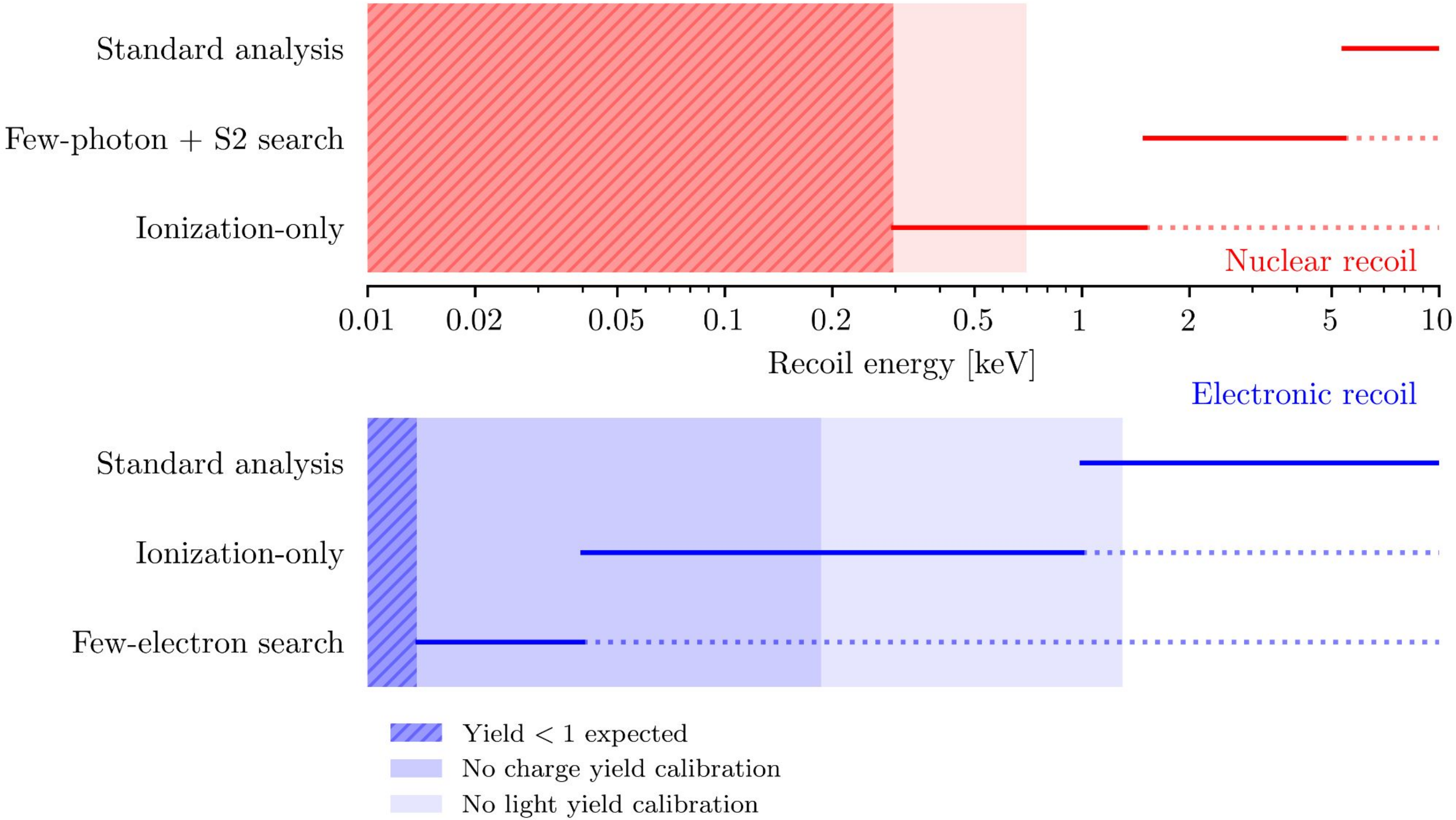
... it's also expensive, and its mass suppresses recoils of light dark matter



Example event from XENON1T p. 55 here

How can LXe detectors get strong light dark matter results?

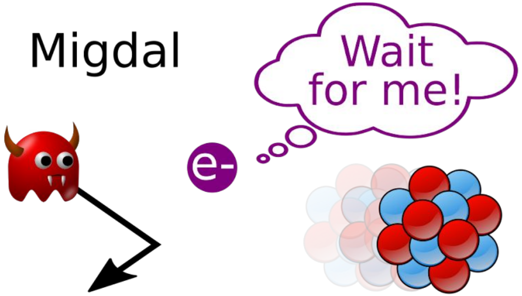
1) Lower the analysis threshold



How can LXe detectors get strong light dark matter results?

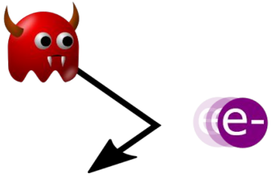
2) Look beyond simple nuclear recoil (as model-independent as we can…)

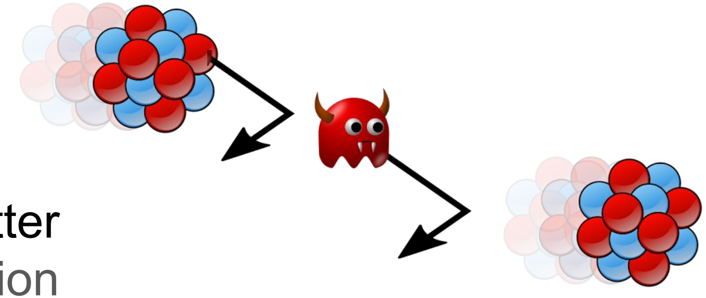
Migdal



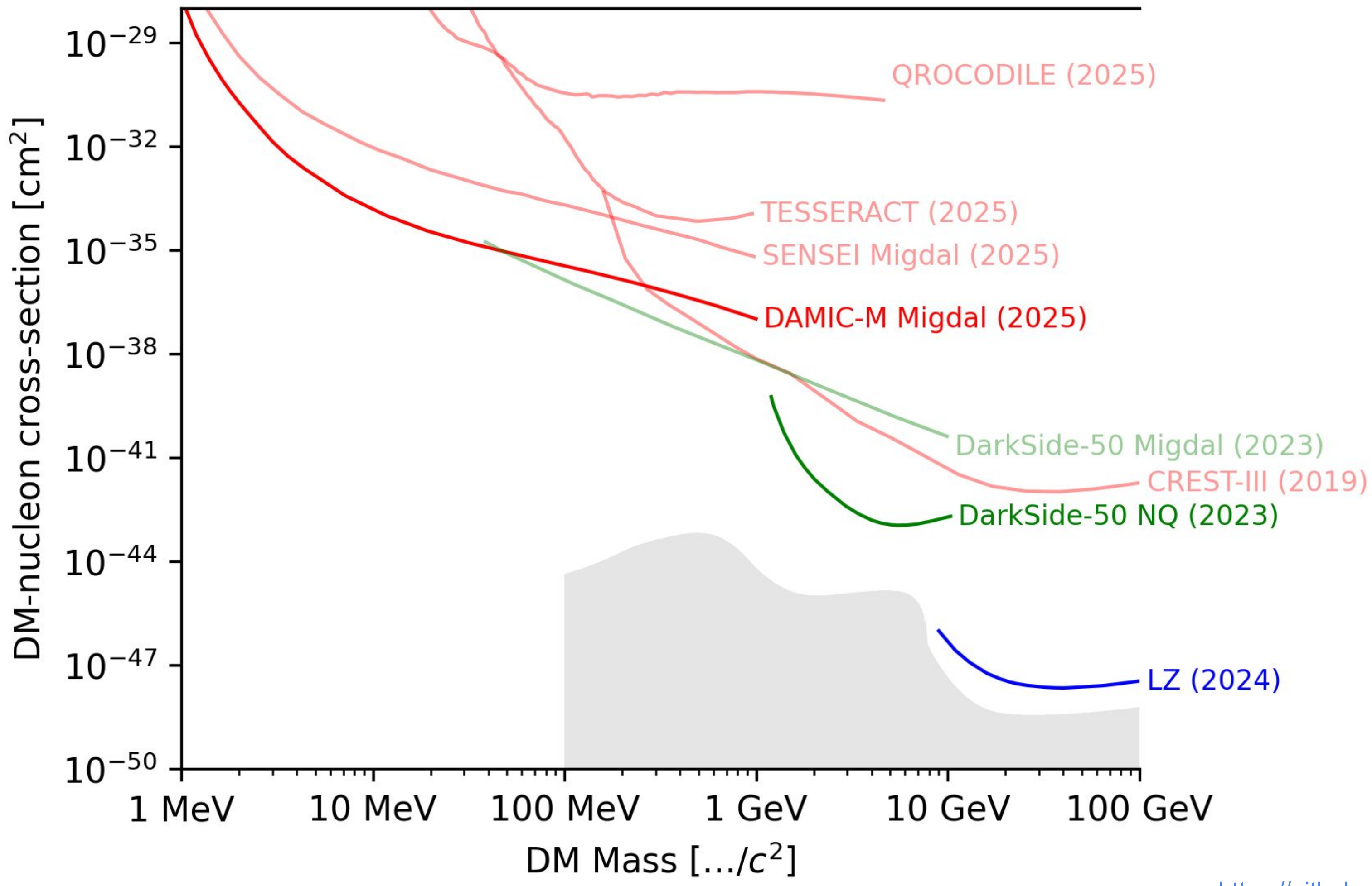
[Xu search 2307.12952]
[LZ/Bang UCLA DM 2023]
[Xu yields 2503.07562]
[LZ yields 2503.05679]

Electron scattering





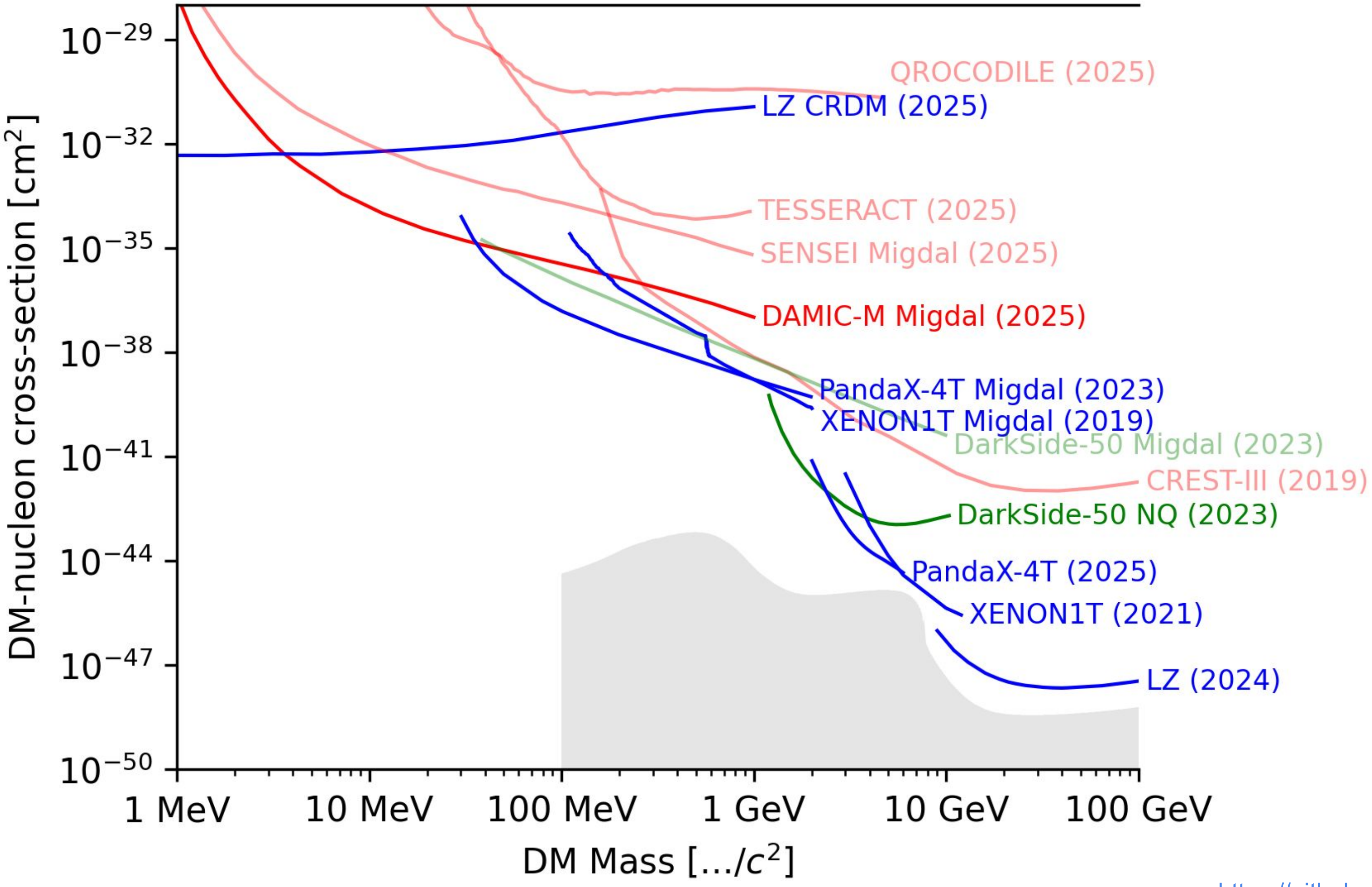
High-velocity dark matter
solar / cosmic ray reflection



$F_{DM}=1$

xenon
argon
solid

https://github.com/kdund/dd_limit_plot



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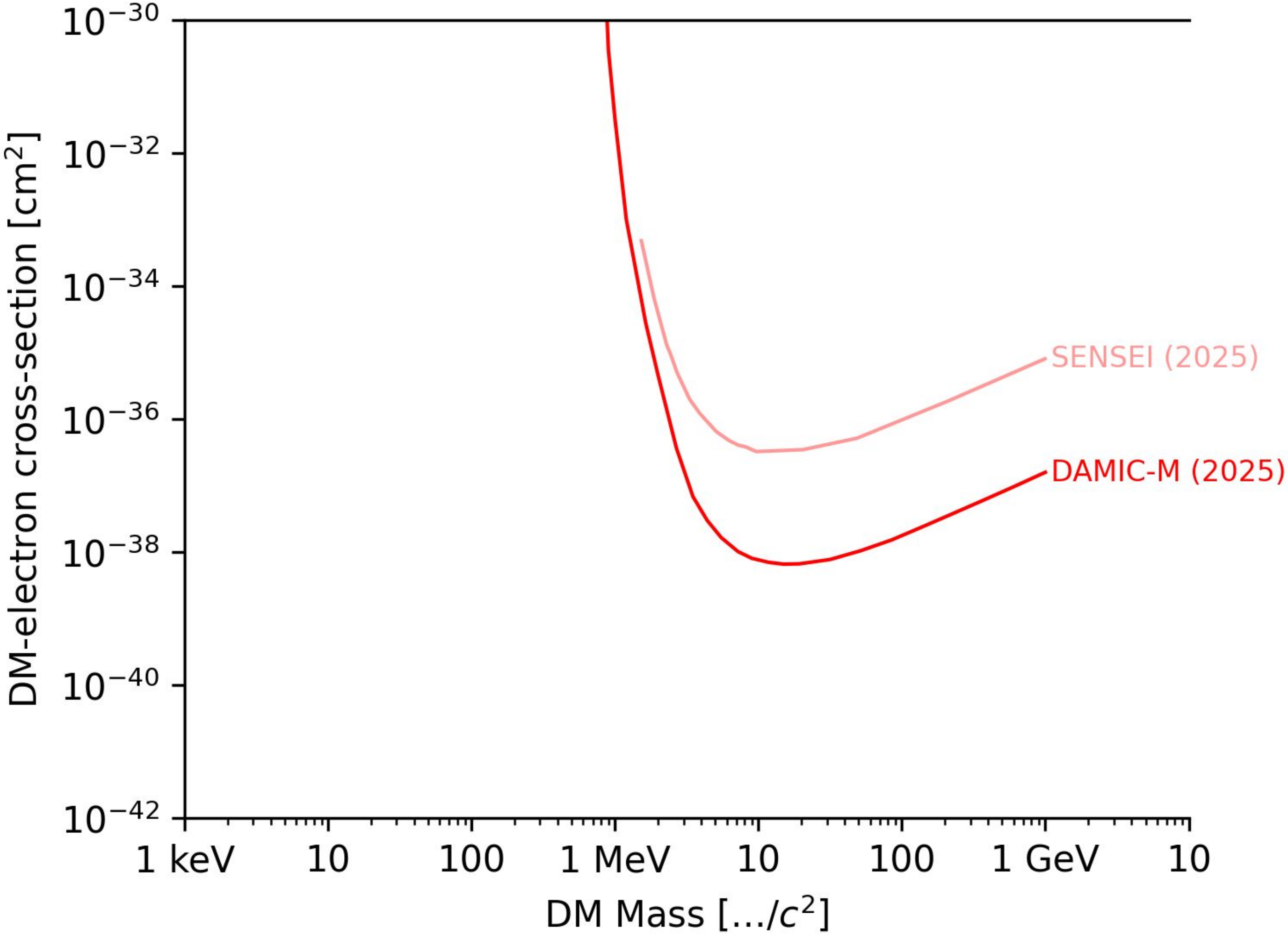

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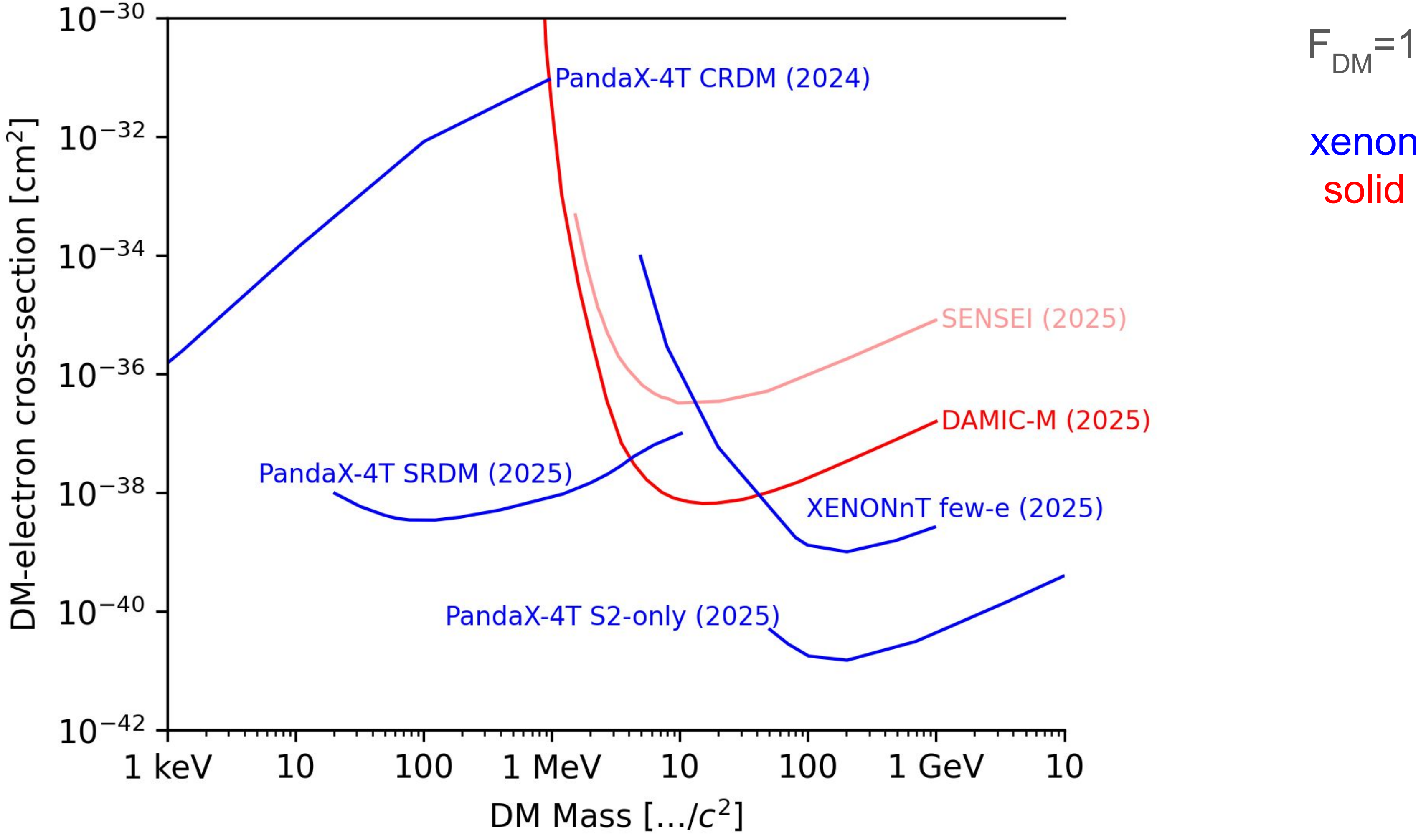
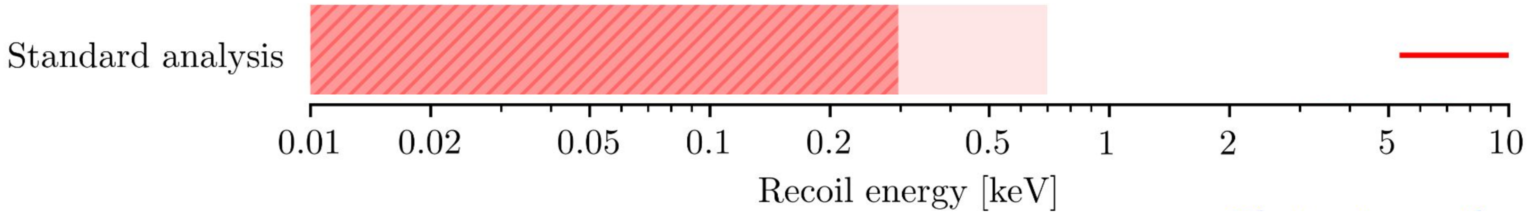
xenon

solid

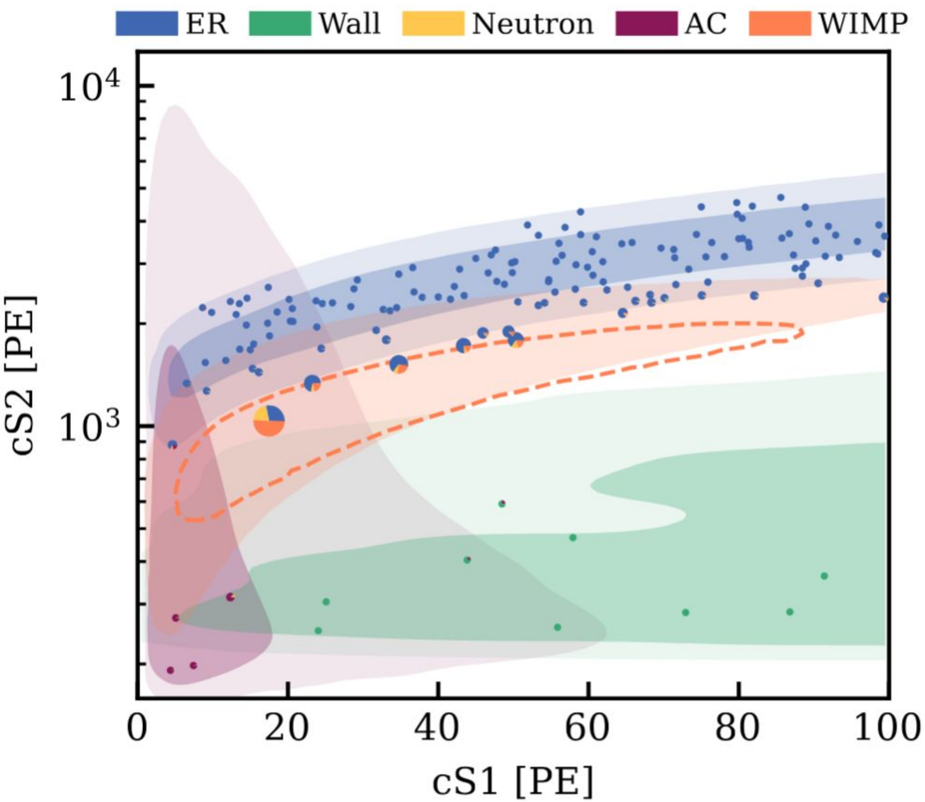


F_DM=1
xenon
solid
PandaX-4T CRDM (2024)
SENSEI (2025)
DAMIC-M (2025)
PandaX-4T SRDM (2025)
XENONnT few-e (2025)
PandaX-4T S2-only (2025)
DM-electron cross-section [cm²]
10⁻³⁰
10⁻³²
10⁻³⁴
10⁻³⁶
10⁻³⁸
10⁻⁴⁰
10⁻⁴²
1 keV
10
100
1 MeV
10
100
1 GeV
10
DM Mass [.../c²]

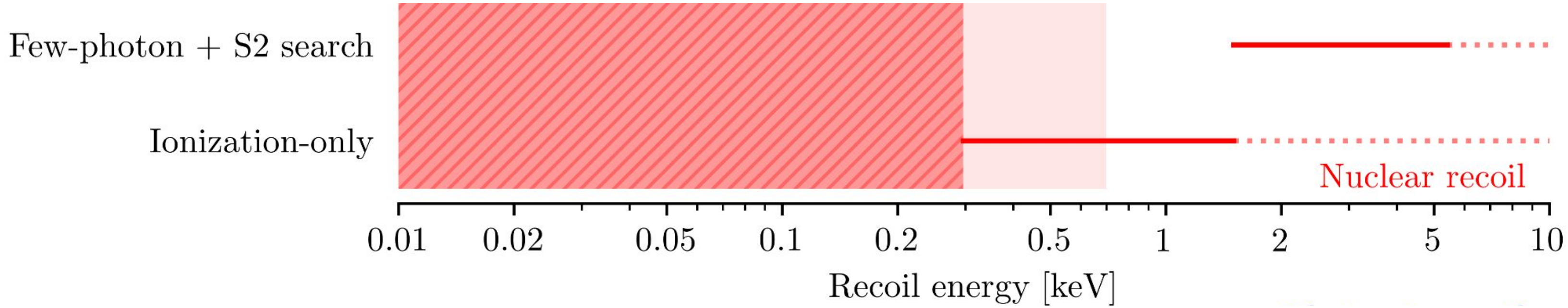


Main WIMP search analysis
LZ [2410.17036]
XENONnT [2303.14729]
PandaX-4T [2408.00664]

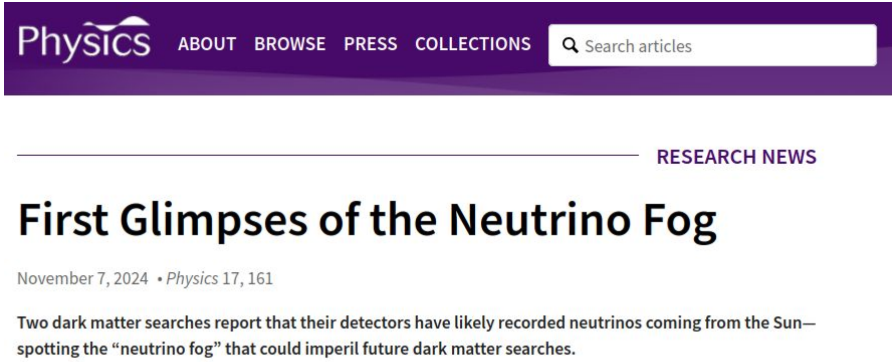
Threshold: 3 PMTs see S1



LZ CRDM [LZ 2503.18158]



Solar ^{8}B > 3σ: PandaX-4T [2407.10892] and XENONnT [2408.02877]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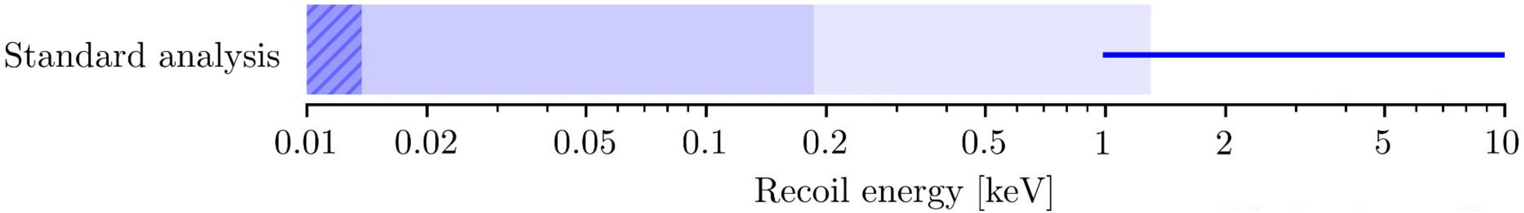
RESEARCH NEWS

First Glimpses of the Neutrino Fog

November 7, 2024 • *Physics* 17, 161

Two dark matter searches report that their detectors have likely recorded neutrinos coming from the Sun—spotting the "neutrino fog" that could imperil future dark matter searches.

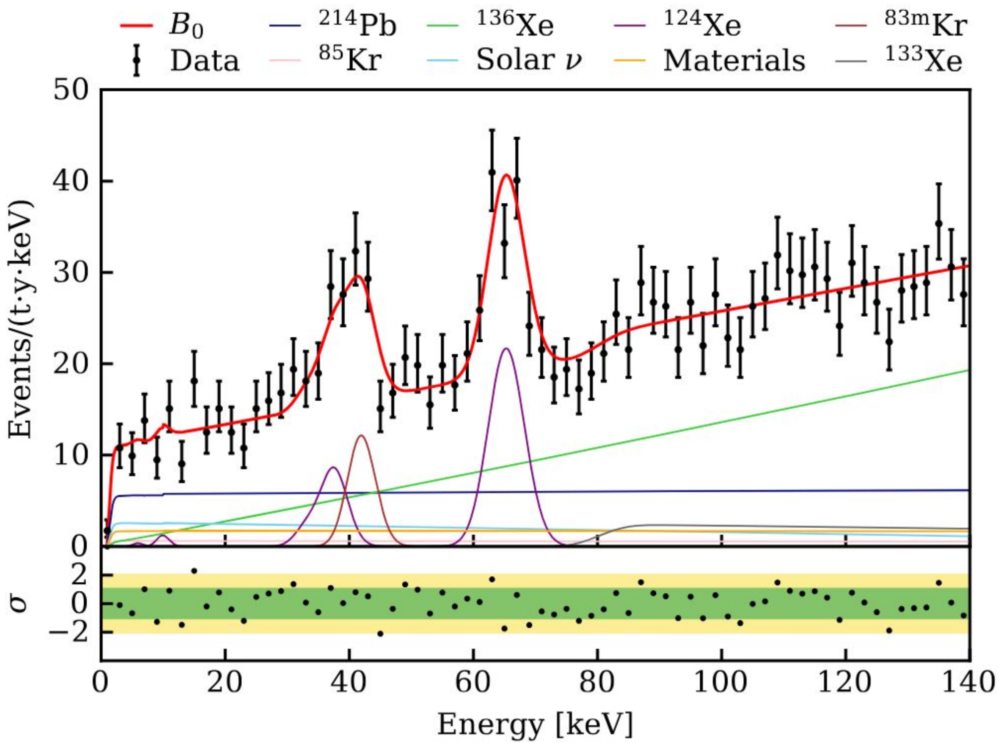
For S1 + S2, challenge is **accidental coincidences** (unrelated S1 + S2 pairs)
Especially understanding the lone few-photon background is hard



Standard ER analysis

for e.g. solar axions, bosonic DM abs.

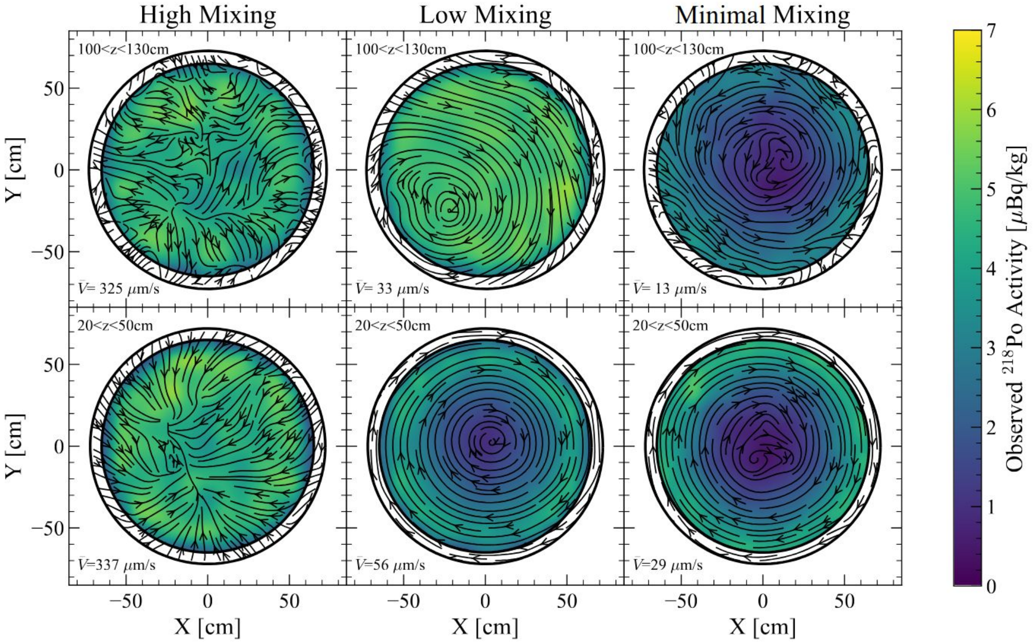
"XENON1T excess", ruled out
by XENONnT & others [XnT 2207.11330]



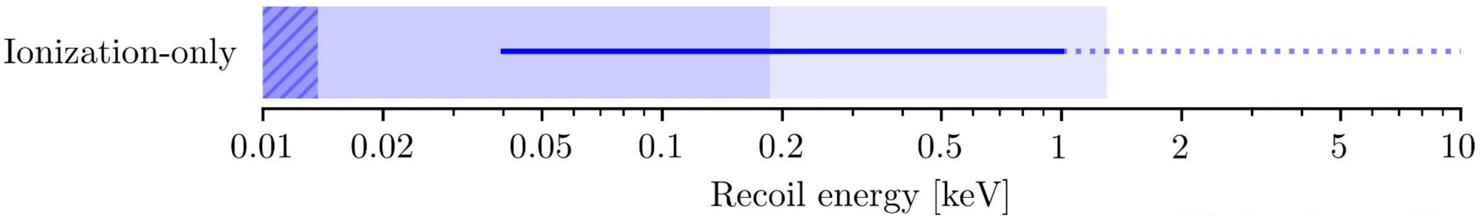
Main background is ^{214}Pb, a daughter of ^{222}Rn that infiltrates the xenon

- **XnT: online distillation** down to solar-ν level! [XnT 2502.04209]
- **Tagging** based on preceding α, τ=3.1 min & knowledge of liquid flow

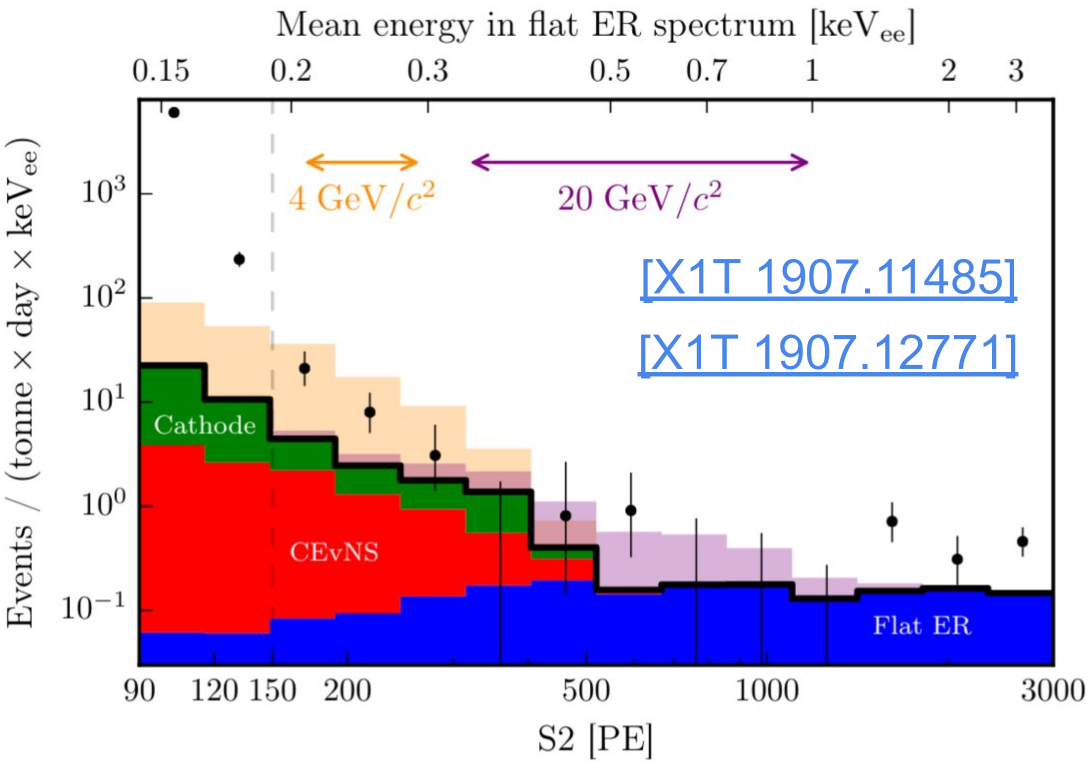
  [X1T 2403.14878], [LZ 2508.19117]



- LZ: Chromatography + not disturbing central region



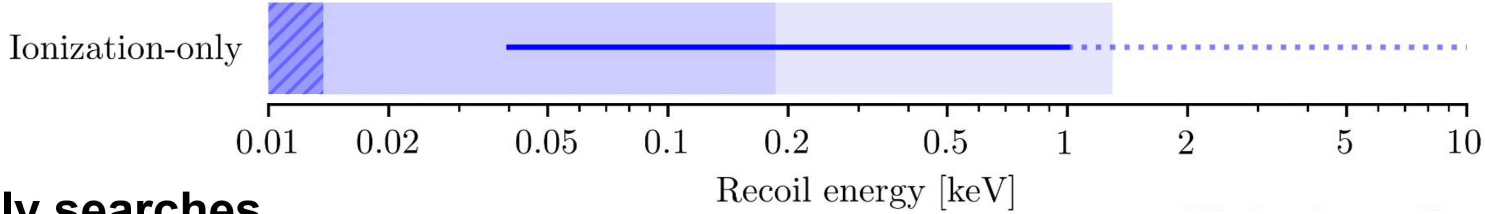
S2-only searches are great for ER: Migdal, DM-electron



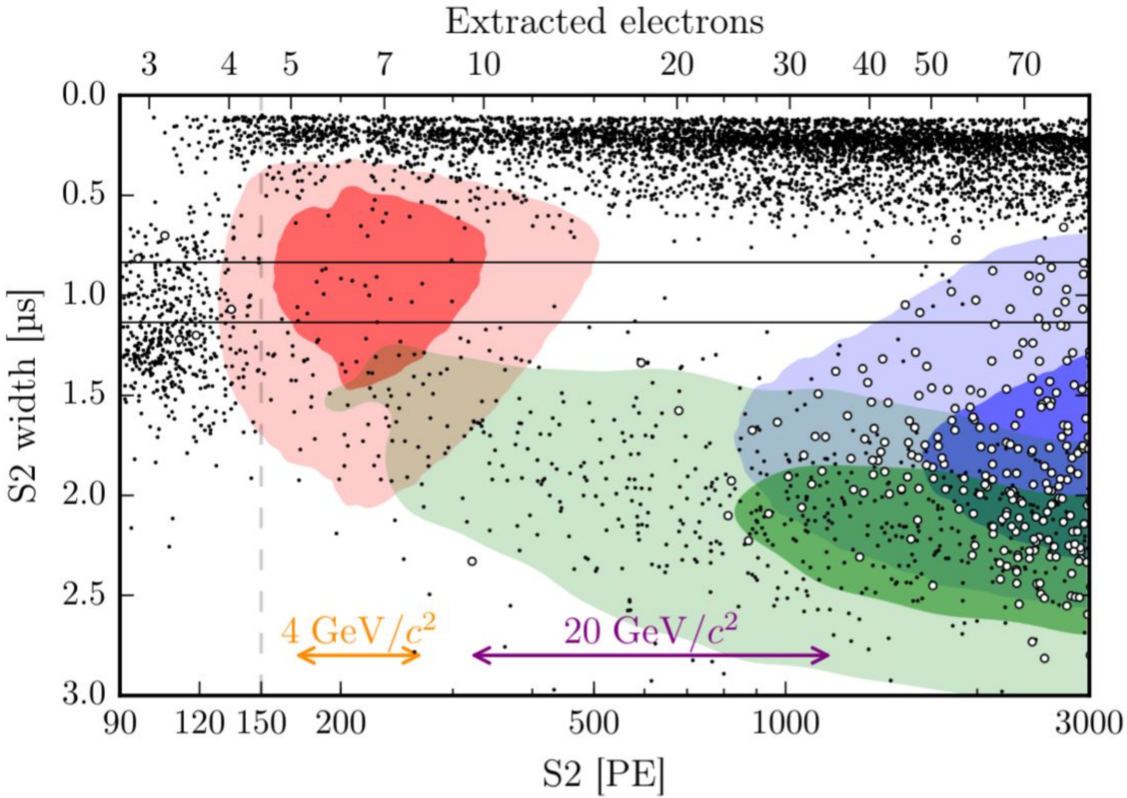
2019: incomplete / conservative background model.

ROI choice on separate data (NR ROIs shown here).

Newer and stronger results from PandaX-4T, with full background model:
[PandaX 2212.10067]
[PandaX 2308.01540]
[PandaX 2507.11930]



S2-only searches

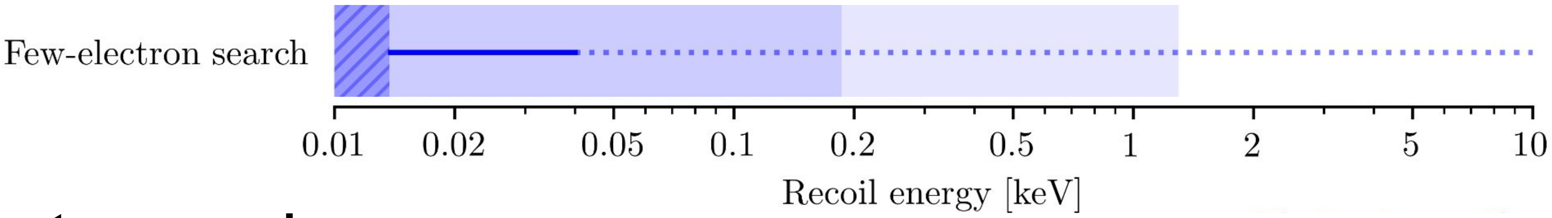


Solid dots: S2 events
Open dots: S1 + S2 events

Red: CEvNS
Green: cathode background
Blue: Flat ER background

Since XENON1T, LXe TPCs are large enough to z-fiducialize with S2-width alone 5-10 e^-

Cathode background estimated from data (many S1-tagged events)



Few-electron searches

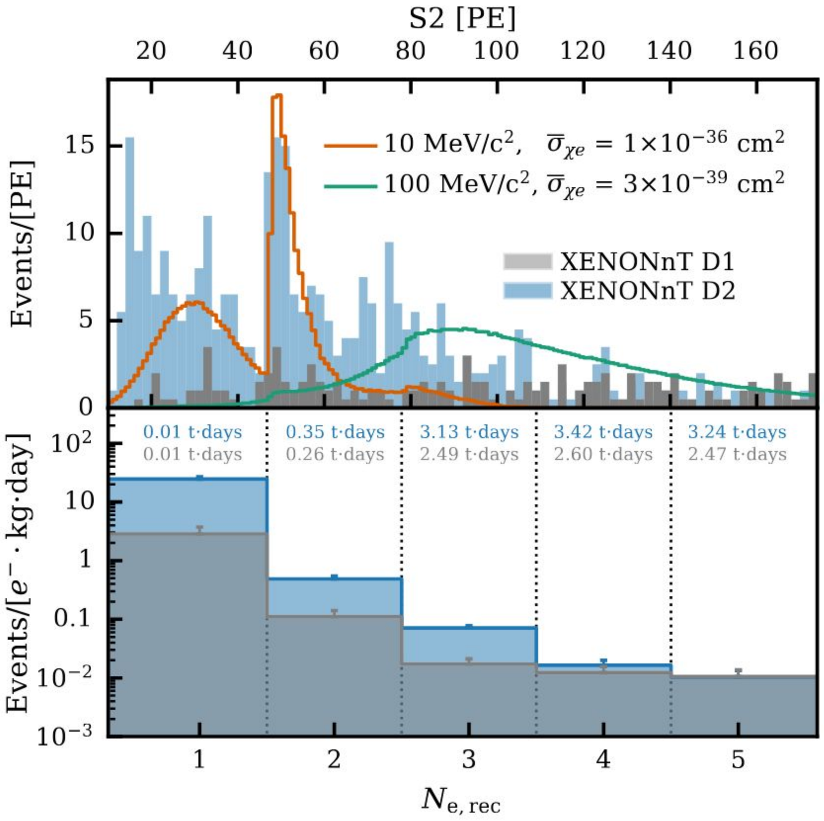
[X1T 2112.12116], [XnT 2411.15289]

Need *even stronger* selections

No complete background model yet,
strong hardware & analysis efforts ongoing!

Recent phenomenology studies:

[LZ 2510.06500], [DarkSide-50 2507.23003]



Few-electron backgrounds

Source	Observe / expect	Mitigate
Impurity capture + release [LZ, X*T, Ds50]	1 e^- (LZ, DarkSide) Follows large S2s, $1/t^{1+\text{ a bit}}$ Position correlation *Some* purity dependence	“Swiss cheese” vetos Purification?
Grid emission [LZ] PandaX micro-discharges?	Multi-electron Flaring hotspots Coincident photon emission	Photon tagging [LZ] Grid treatments?
Delayed photon emission + photoionization	1 e^- Power law following light	Find fluorescing / phosphorescing material?
Delayed extraction?	Inverse relation with purity: not seen in modern TPCs	Higher extraction field?
Radioactivity on/near grids	multi-e^-	Data-driven characterization Screening

The future is XLZD!

- Chase heavy WIMPs into the neutrino fog
- See $0\nu\beta\beta$ or exclude inverted ordering
- Observe many flavors and types of neutrinos
- … and many more unique physics opportunities

See our design book [XLZD 2410.17137] & Next-gen whitepaper [2203.02309]
& Knut's talk at TAUP 2025