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# Beyond WIMPs in Direct Dark Matter searches (xenon realm)

*Sergey Burdin / University of Liverpool*

*23/3/2026*

*Beyond WIMPs*



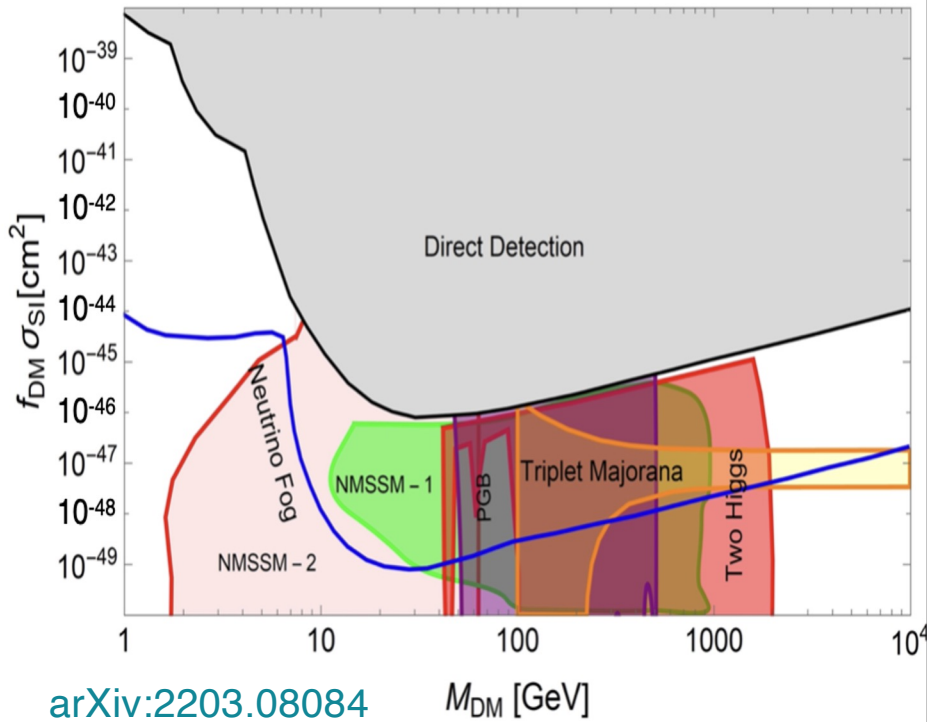
▲ LZ (7 t)

▲ XENONnT (6 t)

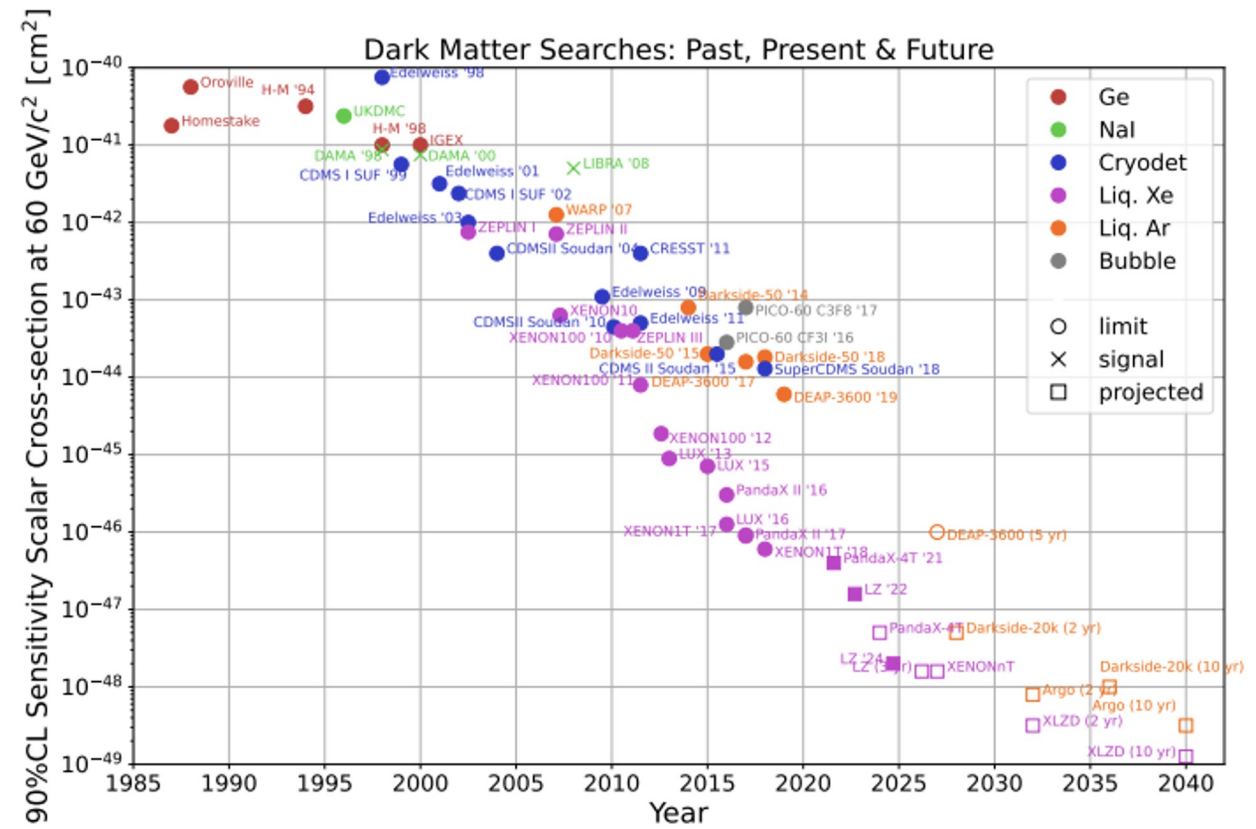
▲ PandaX-4T

Current Xenon-based Dark Matter search experiments

# Progress in Direct Dark Matter searches

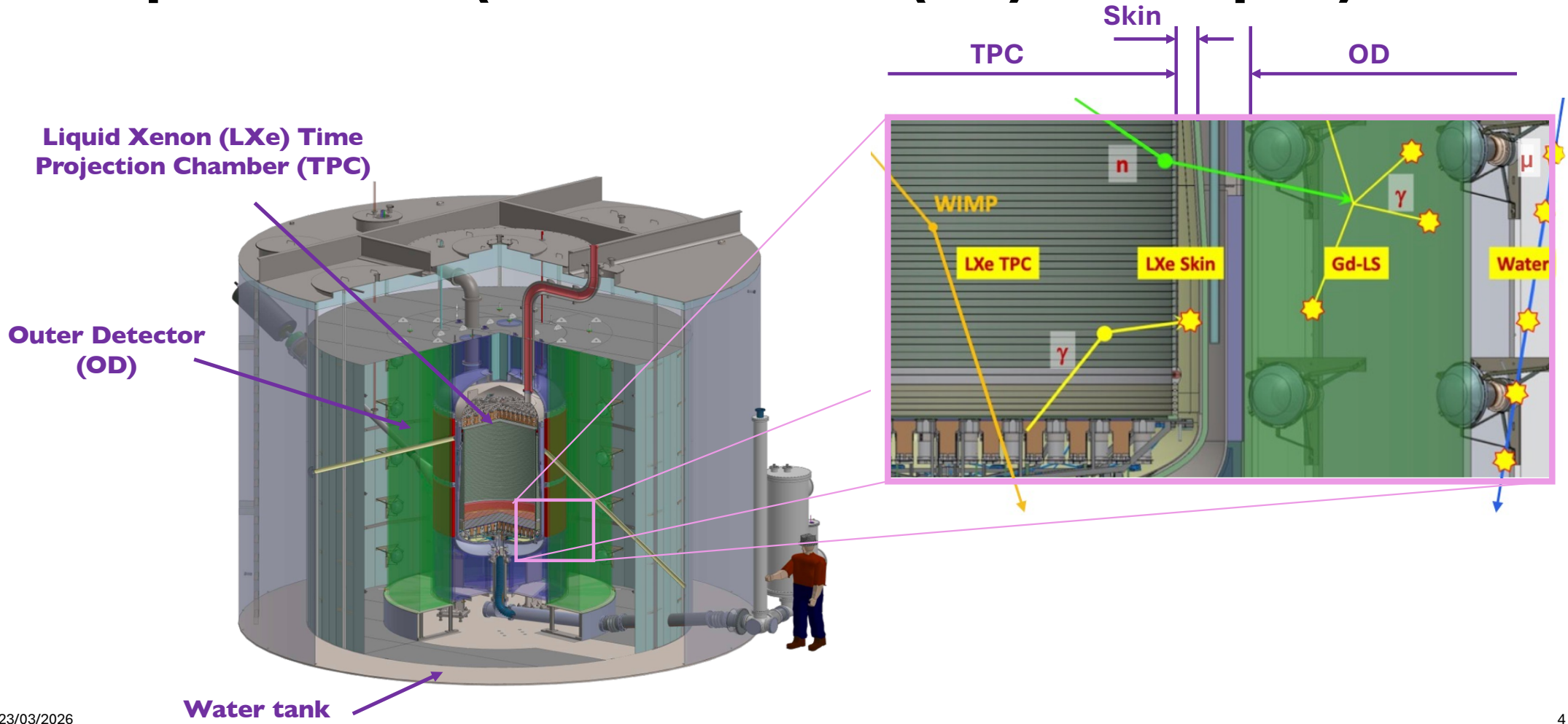


Quite a few models are being tested with the Direct Dark Matter searches

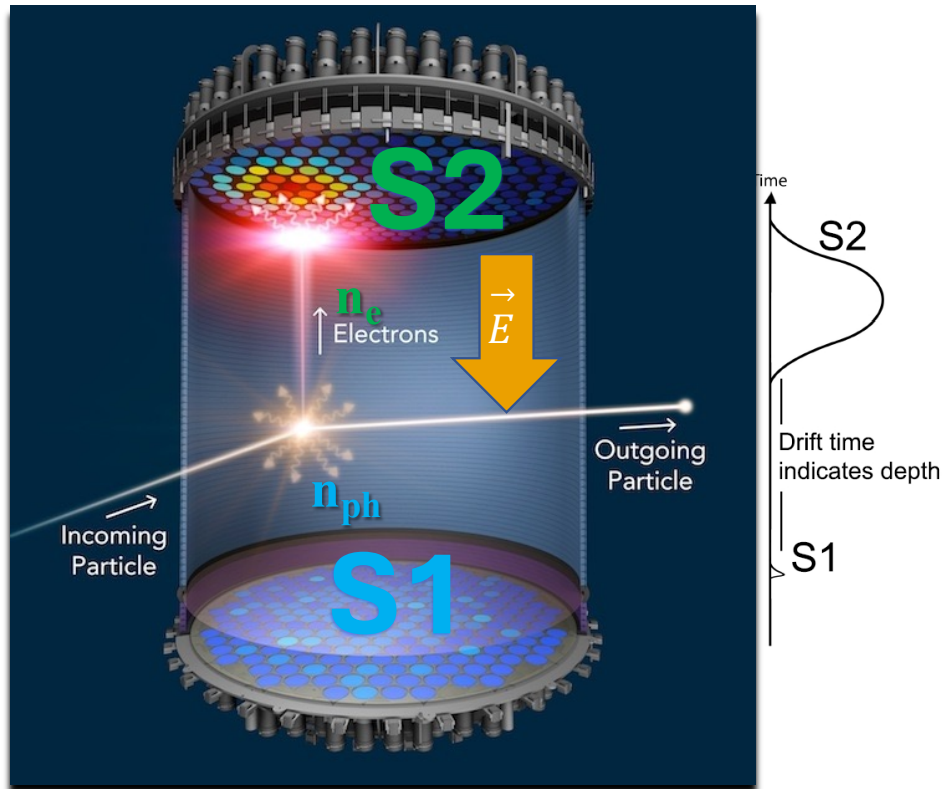


LZ Low-Mass Dark Matter and <sup>8</sup>B Solar Neutrino Results (webinar)

# Experiment (LUX-ZEPLIN (LZ) example)

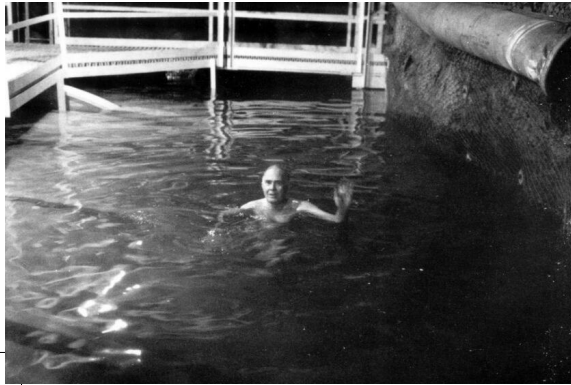
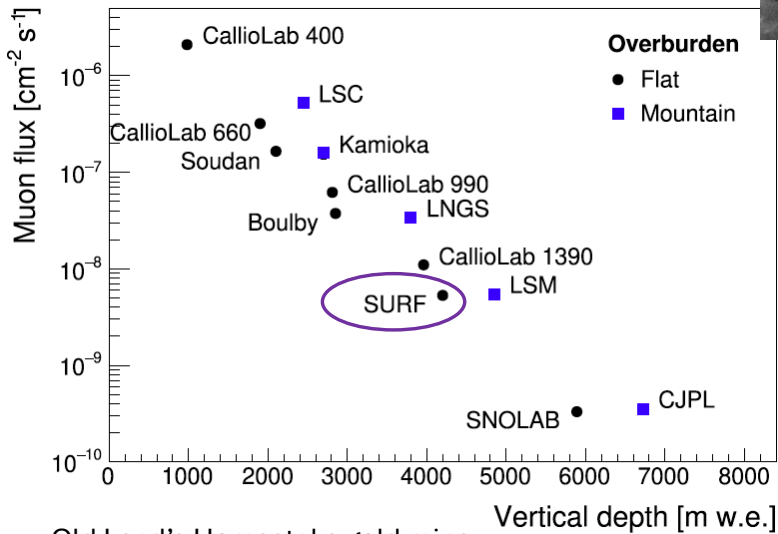


# Principles of Operation



- Scintillation photons  $n_{ph}$  are detected immediately after interaction by top and bottom PMT arrays  
 $\rightarrow S1 \sim n_{ph}$
- Ionisation electrons  $n_e$  drift up and produce scintillation light after extraction from liquid xenon and acceleration/amplification in the gaseous region  
 $\rightarrow S2 \sim n_e$ 
  - Pattern in the top PMT array  $\rightarrow$  x, y coordinates
  - Drift time  $\rightarrow$  z coordinate
- S2/S1 combination allows determination of recoil type:
  - $e^-, \gamma, \nu \rightarrow$  electron recoils (higher S2)
  - WIMP, n,  $\nu$  (CvNS)  $\rightarrow$  nuclear recoils (lower S2)
- DM would interact in the detector at most once  $\rightarrow$  NR Single Scatter signature
  - The sensitivity  $\sim O(1-10)$  DM events in  $\sim 1000$  live days  $\rightarrow$  strong background suppression is required

# Background Suppression: Location



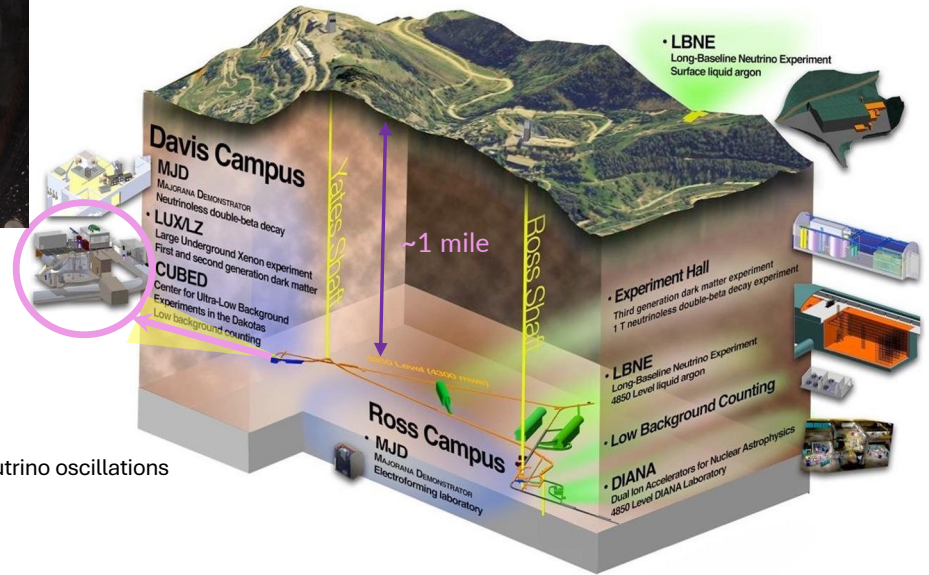
Ray Davis, photo courtesy of BNL



Gold from the mine



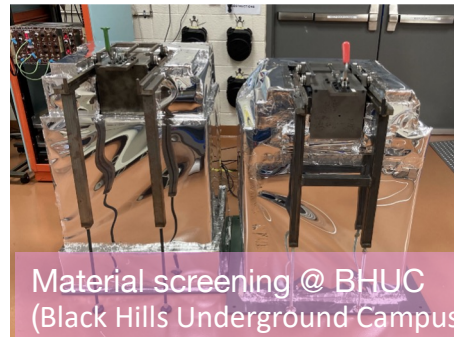
- Old Lead's Homestake gold mine
  - Home of the Davis' Homestake Experiment (1970-1994) detecting solar neutrinos which led to discovery of neutrino oscillations
- 4850 ft. (4300 m w.e.) underground at SURF in Lead (SD, USA)
- Muon flux  $6 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$



From S.Burdin's presentation @ Kashiwa DM 2023

# Background Suppression: Clean Materials

- Extensive campaign on selection of appropriate material for cryostat
- All materials radioassayed
  - High-purity germanium screening
  - Inductively-coupled plasma mass spectrometry
  - Neutron activation analysis
- Contamination control and cleaning
- Kr removal off-site
  - <300 ppq
- Rn removal with charcoal chromatography in-line



The LUX-ZEPLIN (LZ) radioactivity and cleanliness control programs

*Eur. Phys. J. C (2021) 80:1044*

Identification of Radiopure Titanium for the LZ Dark Matter Experiment and Future Rare Event Searches

*Astroparticle Physics 96 (2017) 1–10*

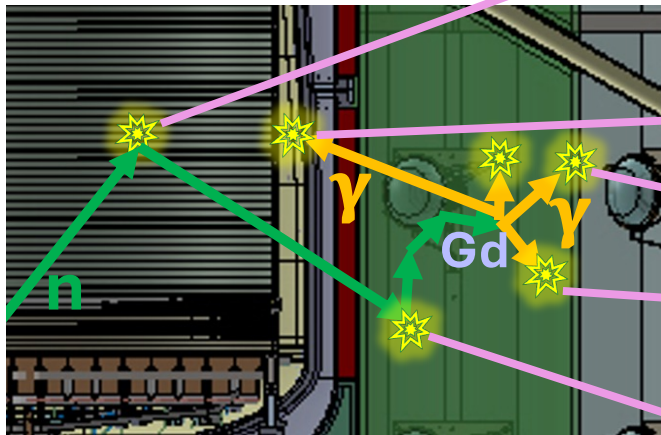
*LZ example*

# Fiducialization and Double-layer Veto System

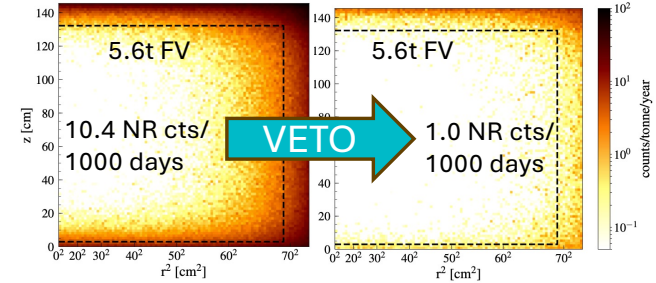
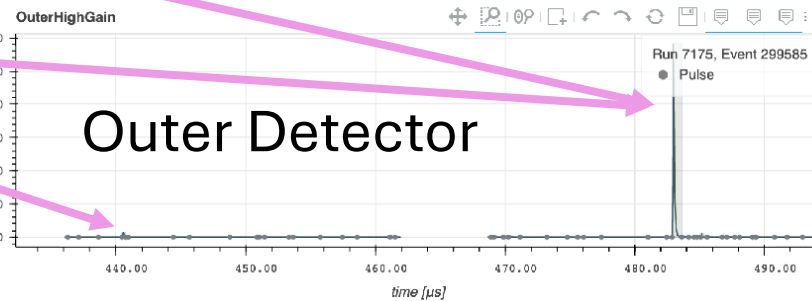
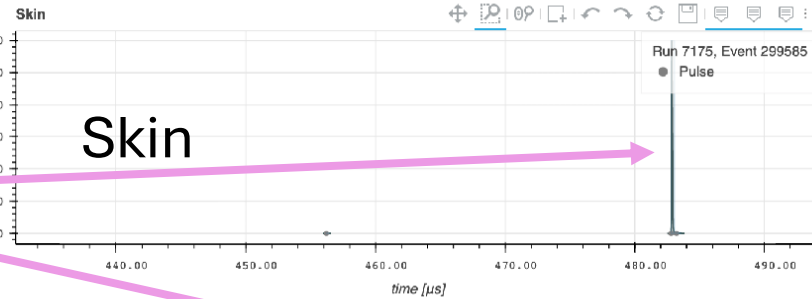
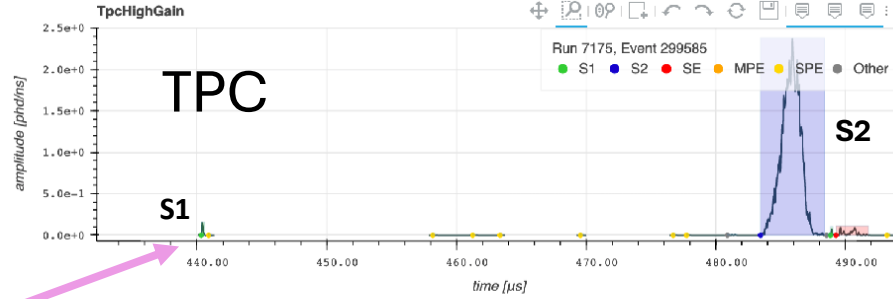
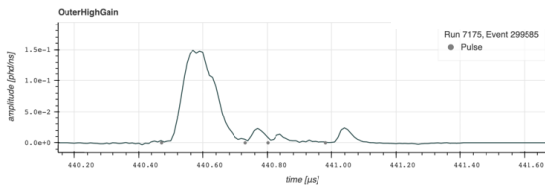
~30 keV<sub>nr</sub> nuclear recoil Single scatter in TPC Tagged by the OD

From DD calibration data

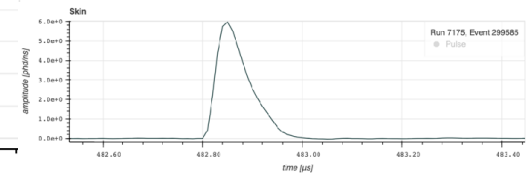
TPC Skin OD



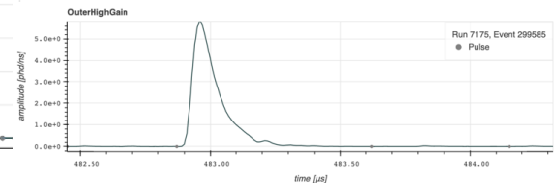
Prompt proton recoil ~17 phe



Skin catches one of the Gd post-capture  $\gamma$ -rays



Gd capture: ~680 phe

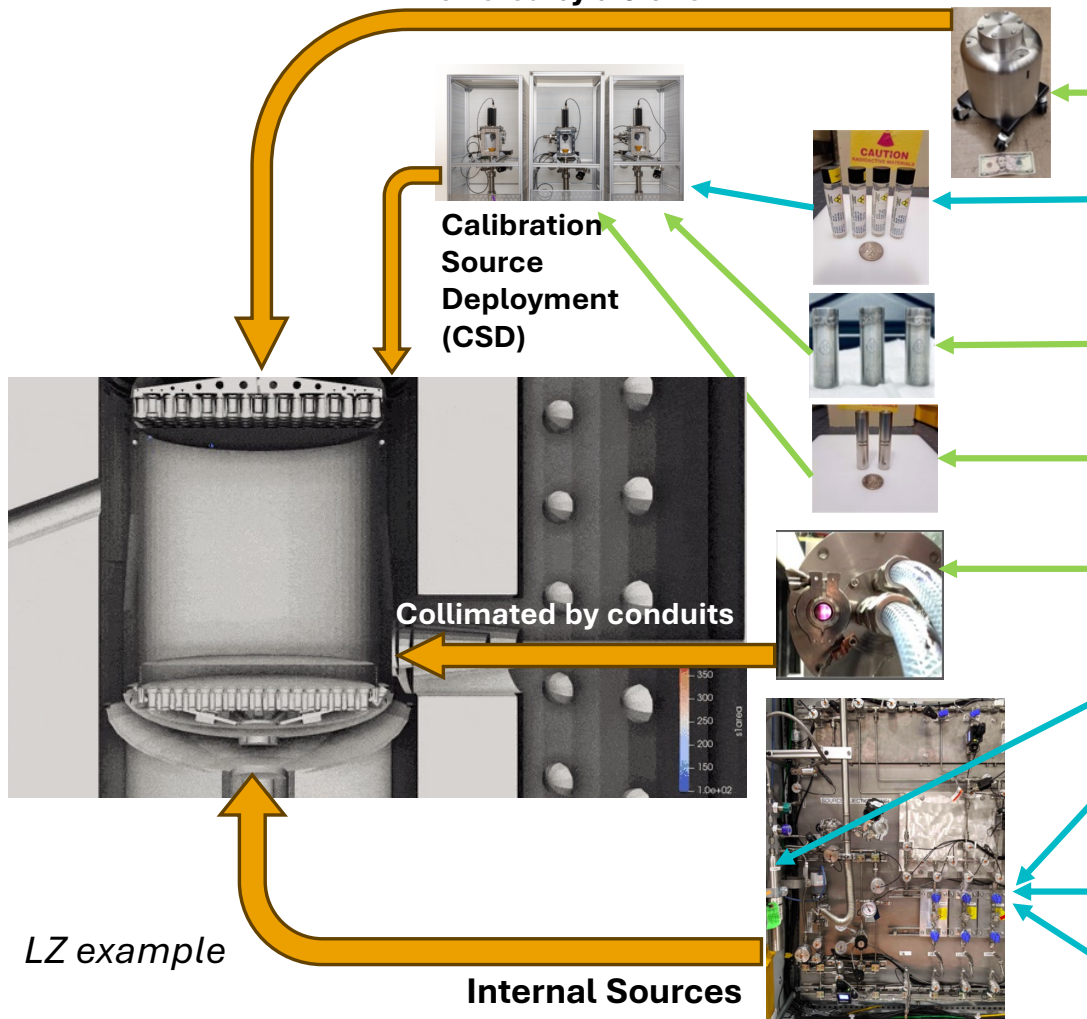


95% veto efficiency expected 89±1% measured

LZ example From S.Burdin's presentation @ Kashiwa DM 2023

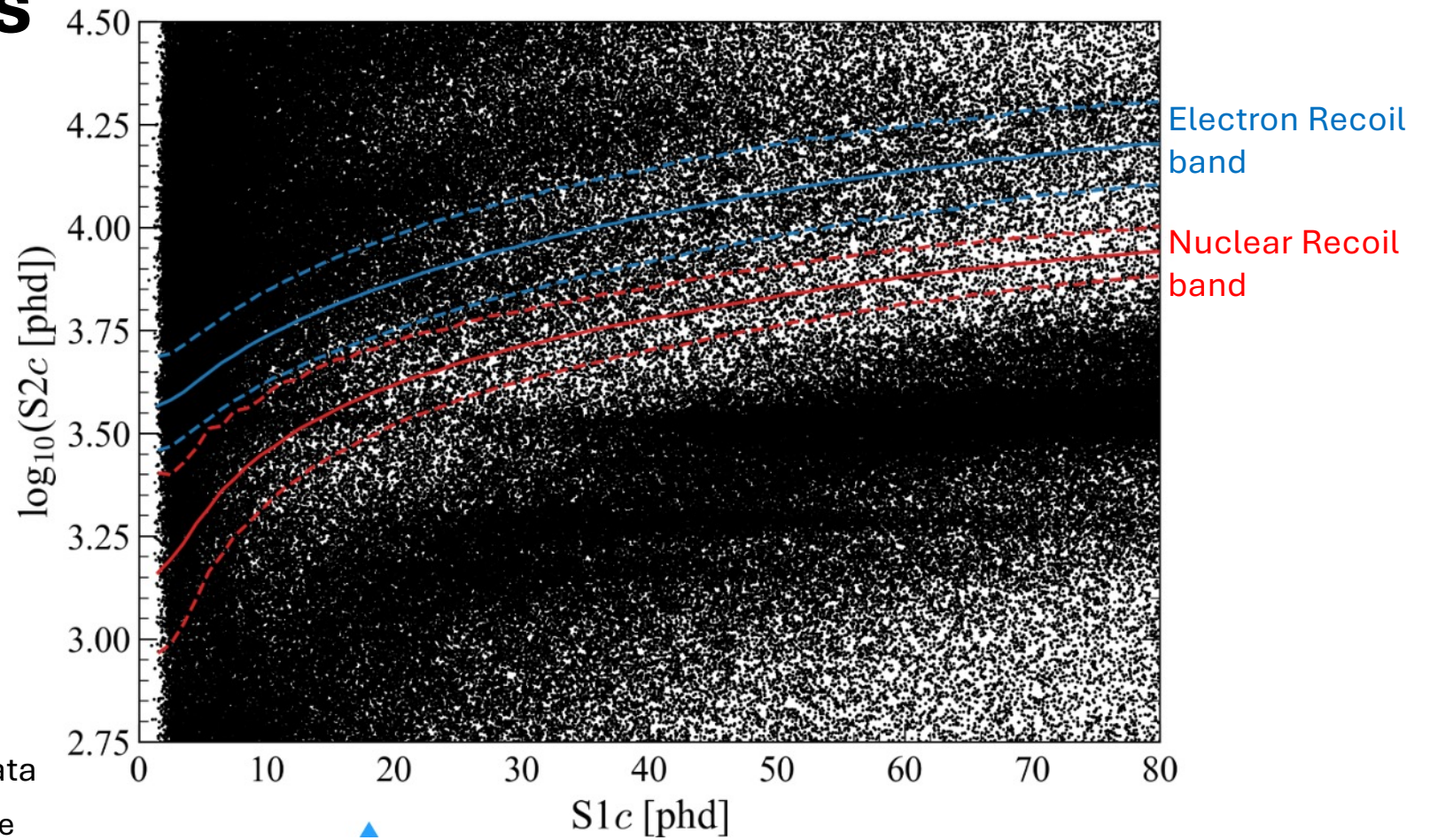
# Source Calibration

Lowered by a crane



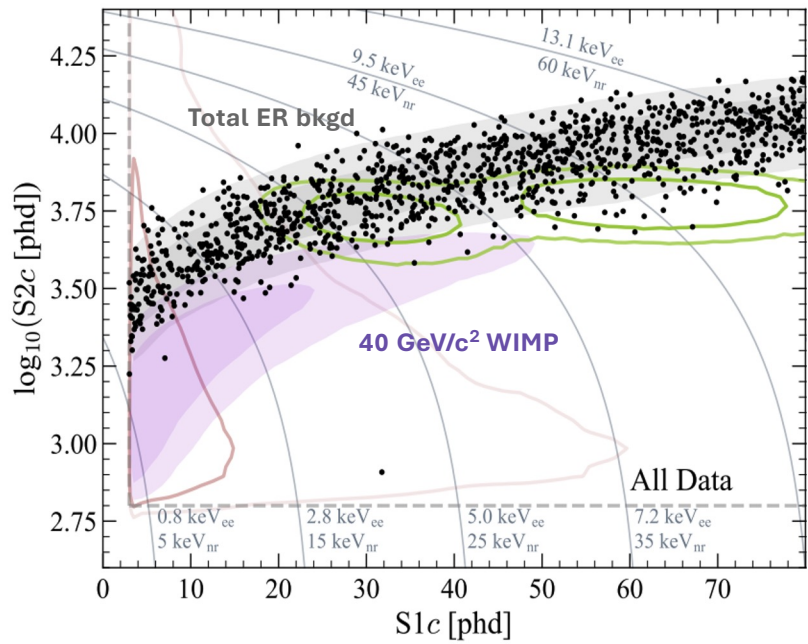
Source	Calibration
$^{88}\text{YBe}$ (152 keV neutron)	Low energy NR/ $^8\text{B}$ solar neutrino studies
Various gamma sources: $^{228}\text{Th}$ (2615 keV), $^{22}\text{Na}$ (1275 keV), $^{54}\text{Mn}$ (835 keV), $^{57}\text{Co}$ (122 keV)	Energy scale and resolution; Inter-detector timing
$^{241}\text{AmLi}$ (neutrons up to $\sim 1.5$ MeV)	OD calibration, neutron-tagging efficiency, S2 signal efficiency validation
$^{241}\text{AmBe}$ (neutrons up to $\sim 11$ MeV)	High Energy NR, OD calibration, neutron-tagging efficiency
Deuterium-Deuterium (DD) neutrons (Direct mode: 2.45 MeV, D-reflector: 270-420 keV, H-reflector: 10-200 keV )	TPC Nuclear Recoil (NR) band calibration, trigger efficiency, S1 cut acceptance
$\text{CH}_3\text{T}$ (continuum betas up to 18.6 keV)	Electron Recoil (ER) band calibration, S1 signal efficiency validation
$^{220}\text{Rn}$ (betas from $\text{Pb}212$ up to 102 keV)	High energy ER calibration for EFT studies
$^{83\text{m}}\text{Kr}$ (32.1 and 9.4 keV ER)	Energy scale and x-y spatial correction maps
$^{131\text{m}}\text{Xe}$ (164 keV ER)	Energy scale and electron lifetime monitoring

# Datasets

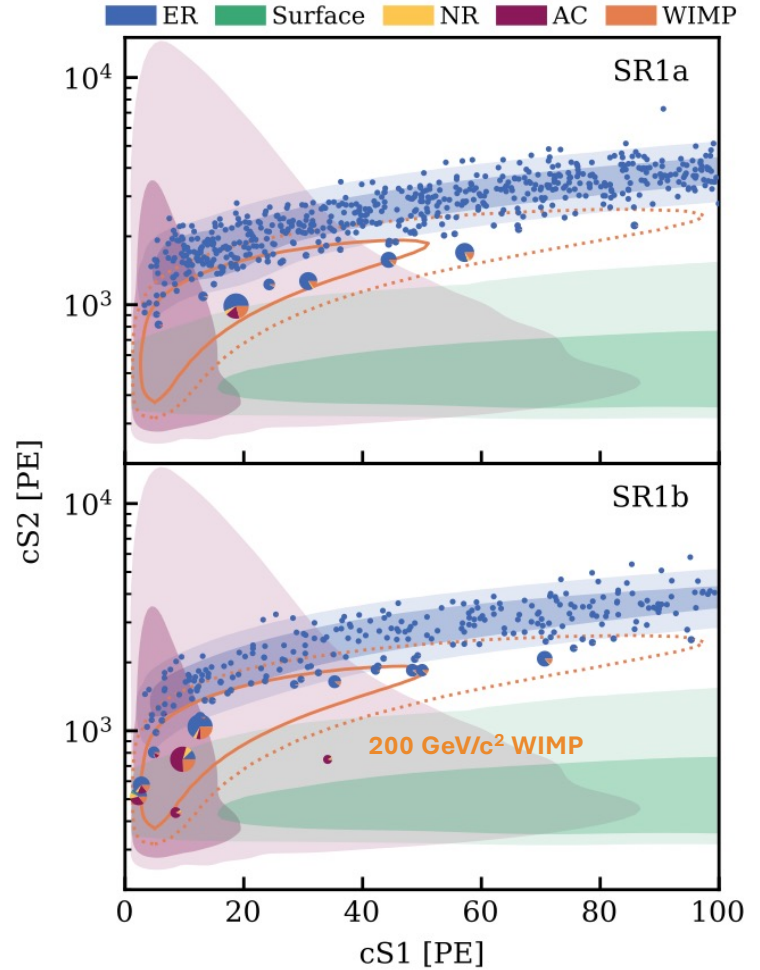
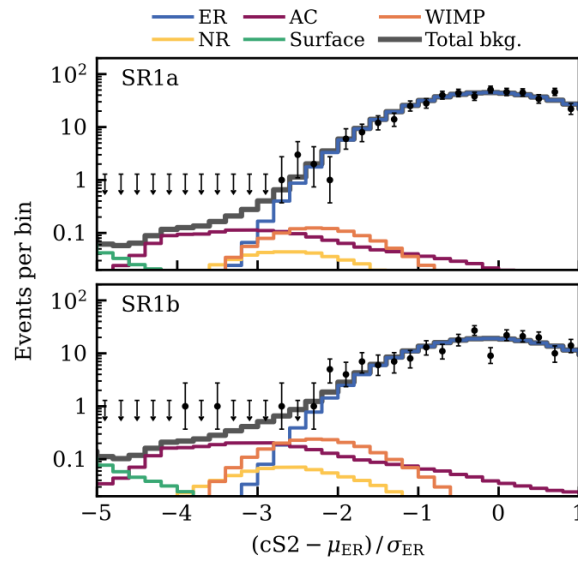


- All single-scatter data
  - LZ Run 1 example

# Cleaned Datasets



LZ WS2024 results: [PRL 135, 011802 \(2025\)](#)



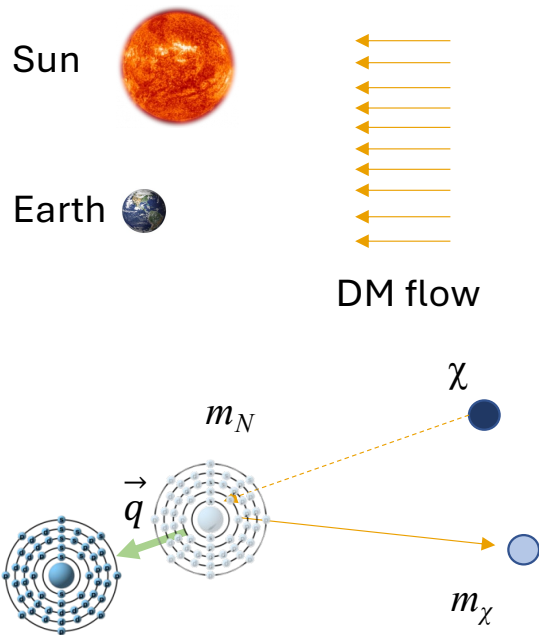
XENONnT Collaboration: Phys. Rev. Lett. 135, 221003 (2025)

# Spin Independent WIMP interaction

The simplest approximation is an elastic scattering on a nucleus

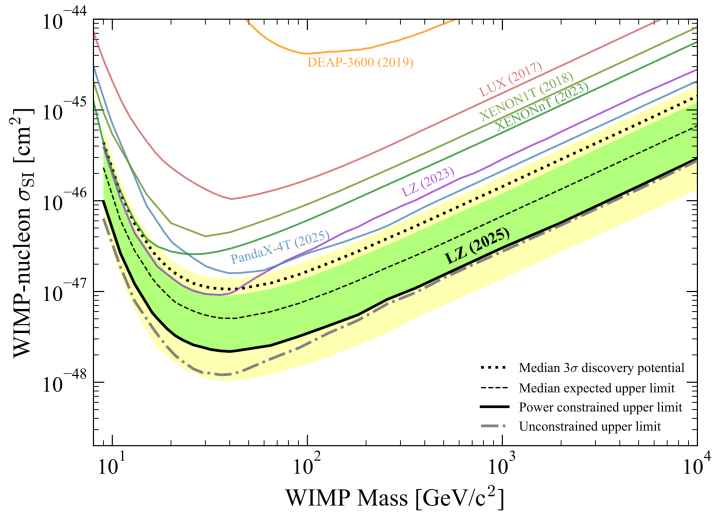
Momentum transfer

$|\vec{q}|^2 = 2\mu^2 v^2 (1 - \cos \theta)$ , where  $v$  is the DM particle velocity,  $\theta$  is the scattering angle and  $\mu = \frac{m_\chi m_N}{m_\chi + m_N}$  is reduced mass, where  $m_\chi$  and  $m_N$  are dark matter and target nucleus masses.

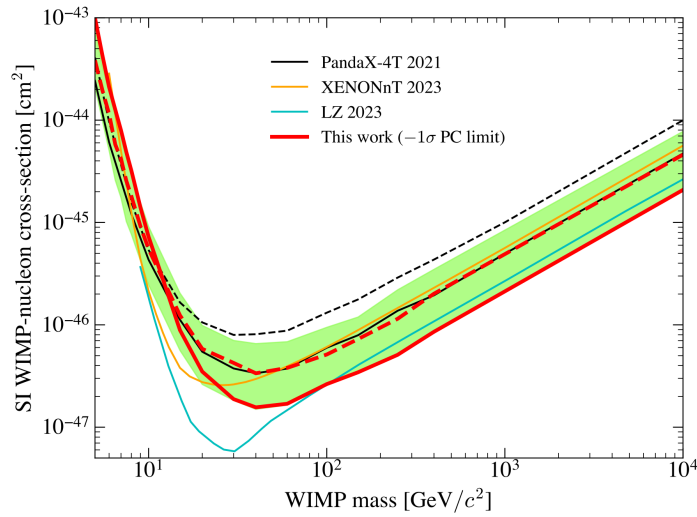


<https://snookerfreaks.com/>

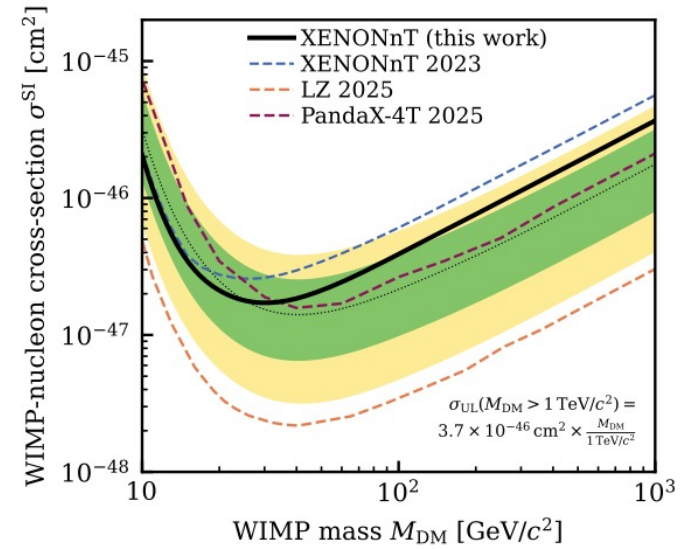
# WIMP SI results



LZ: PRL 135, 011802 (2025)



PandaX-4T: PRL 134, 011805 (2025)



XENONnT: PRL 135, 221003 (2025)

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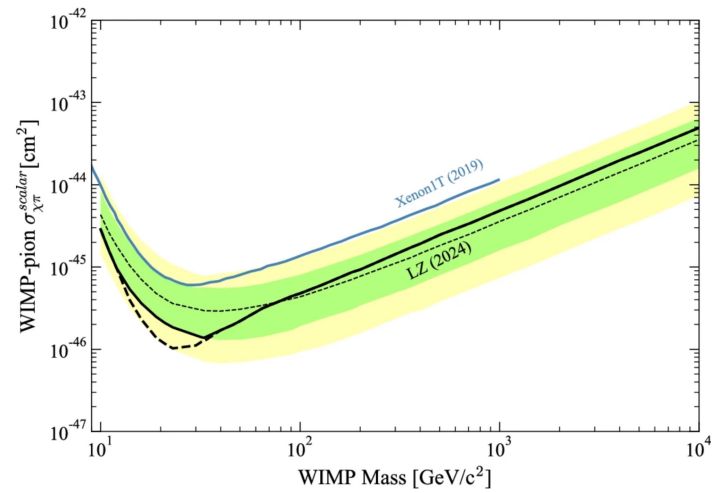
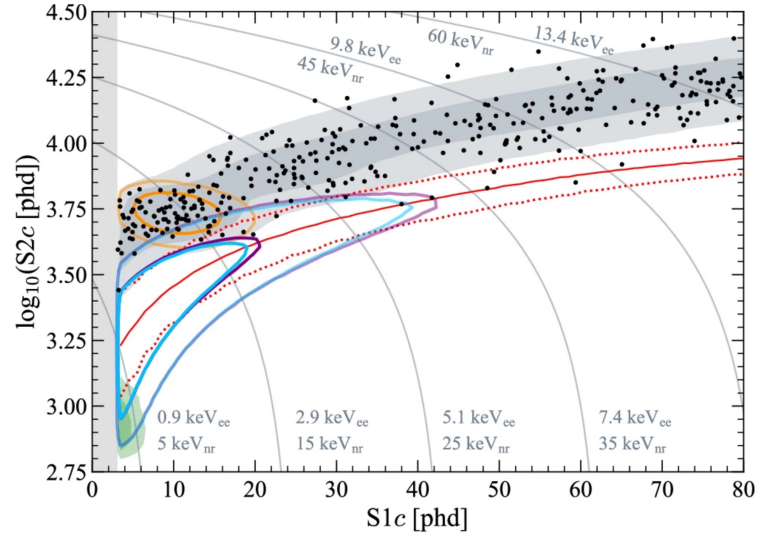
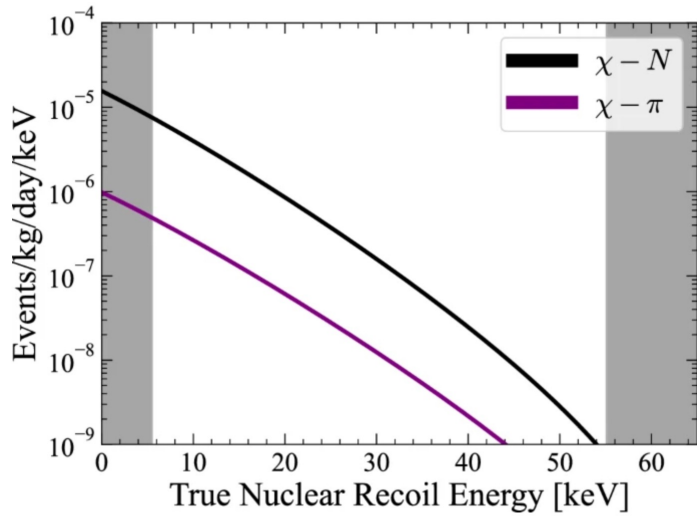
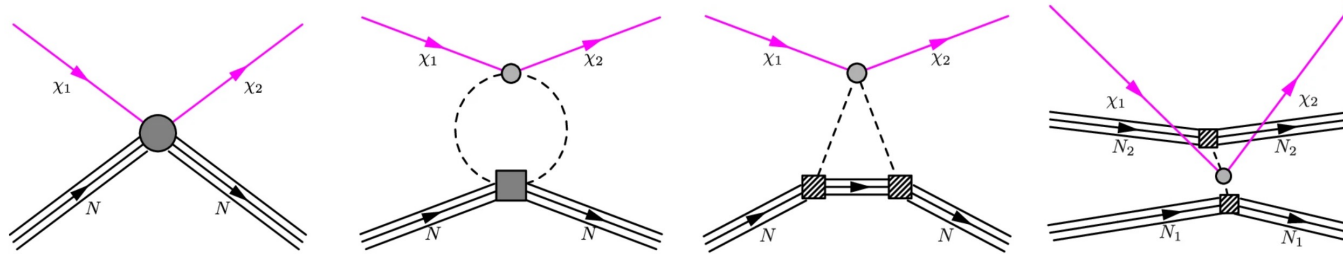
# Beyond Vanilla WIMPs in Direct DM searches

Two ways to go beyond vanilla WIMP analysis

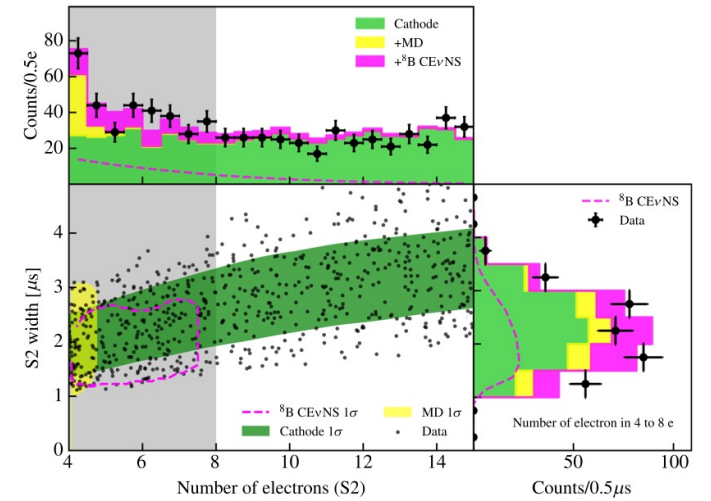
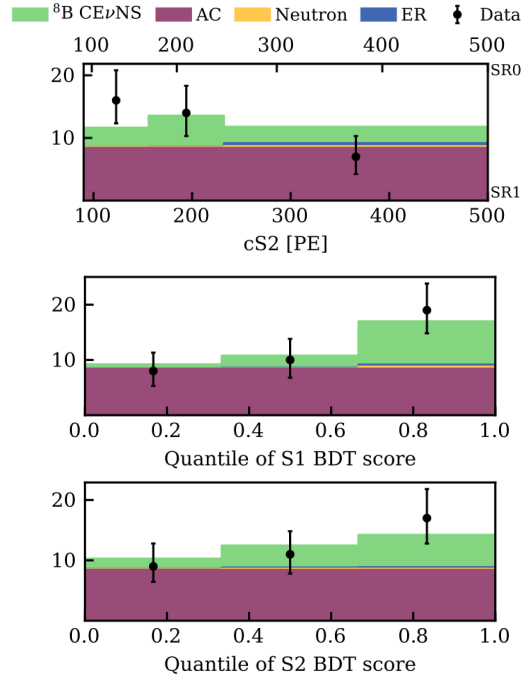
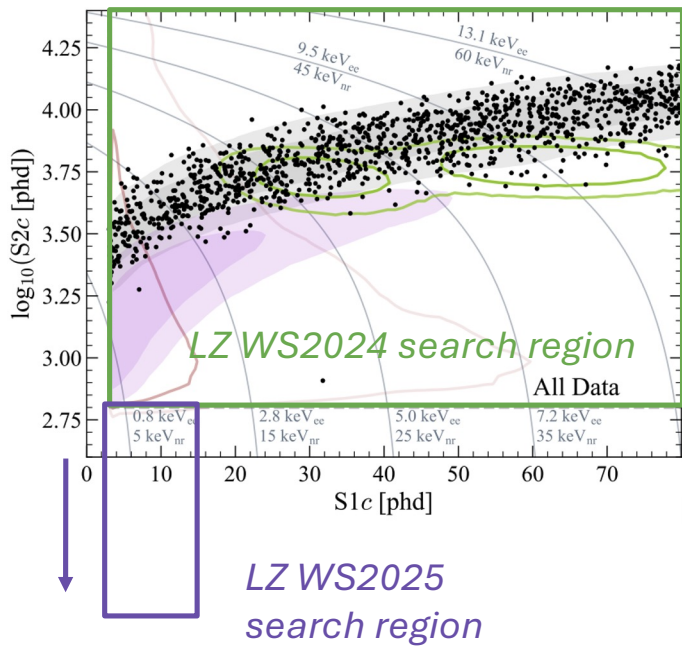
- Re-interpretation of the WIMP dataset
  - Pros
    - The sample is polished: calibrated, reconstructed, Data Quality validated
    - **The background is fully understood**
    - The main challenge is to create the new signal model for the theory to be tested
  - Cons
    - Unlikely to find anything new
- Extension of the WIMP dataset
  - Cons
    - A lot of effort is needed for calibration, reconstruction and validation of the extended dataset
    - A lot of effort is needed to characterise the background
    - Still need to create the new signal model
  - Pros
    - Can find something new!
- NB! Of course, the real analyses are mixtures of the above

# WIMP-pion coupling

LZ Collaboration. Probing the scalar WIMP-pion coupling with the first LUX-ZEPLIN data. *Commun Phys* 7, 292 (2024). <https://doi.org/10.1038/s42005-024-01774-8>



# Extension to lower NR

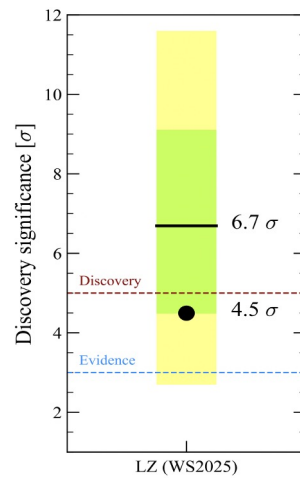
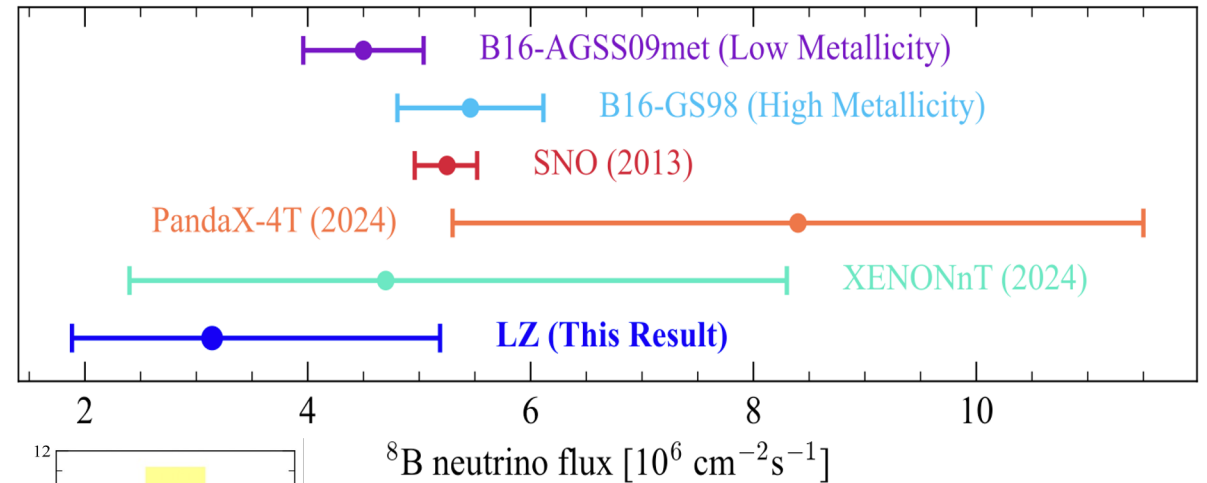
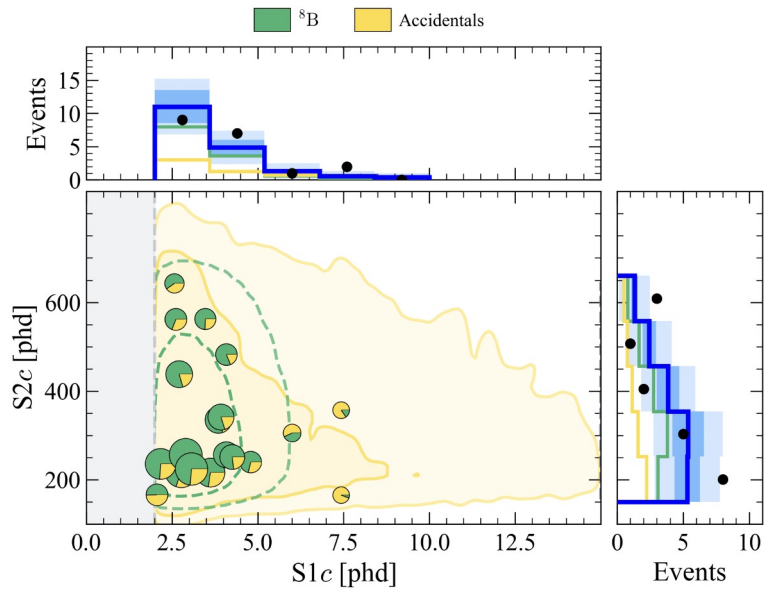


PandaX-4T: PRL 133, 191001 (2024)

- $\geq 3$ -fold S1 (signals in  $\geq 3$  PMTs)
- $S1c \in [2, 15]$  photons detected (phd)
- $S2 \in [3.5, 14.5] e^-$  (44.5 phd/e-)

XENONnT: PRL 133, 191002 (2024)

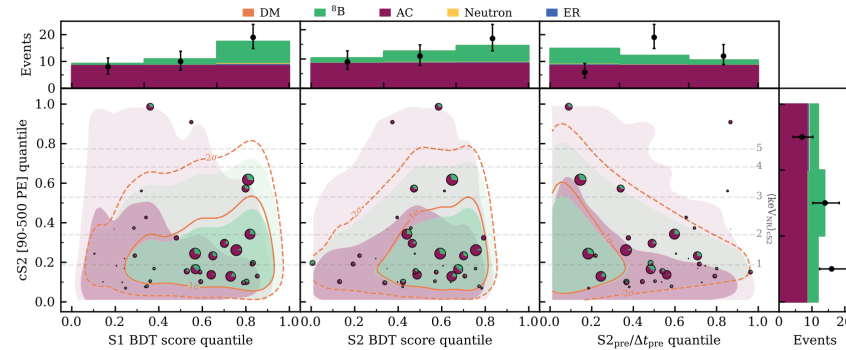
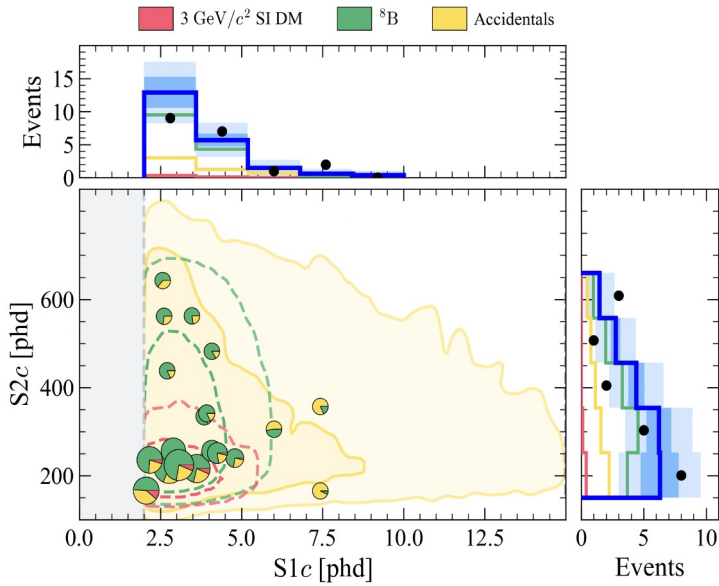
# Evidence for $^8\text{B}$ (CE $\nu$ NS)



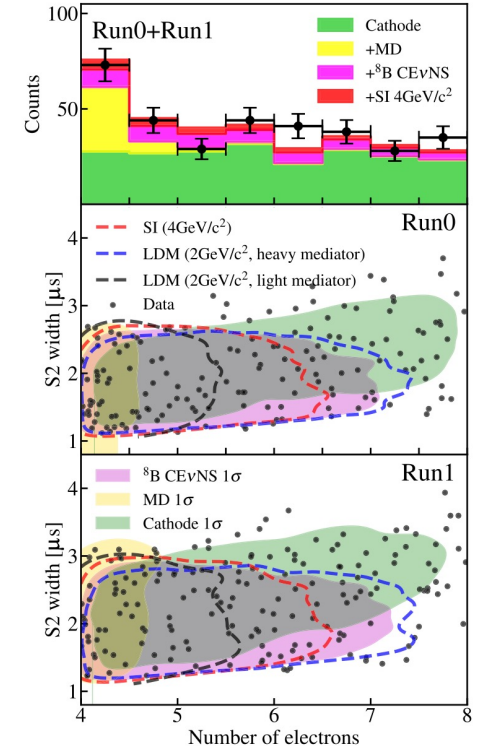
**LZ Low-Mass Dark Matter and  $^8\text{B}$  Solar Neutrino Results (webinar)**

Components	Expectation	Fit Results
$^8\text{B}$ CE $\nu$ NS	-	$12.3^{+7.0}_{-5.4}$
Accidental coincidences	$6.6 \pm 0.3$	$6.6 \pm 0.3$
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	$6.6 \pm 0.3$	$18.9^{+7.0}_{-5.5}$

# Search for light DM



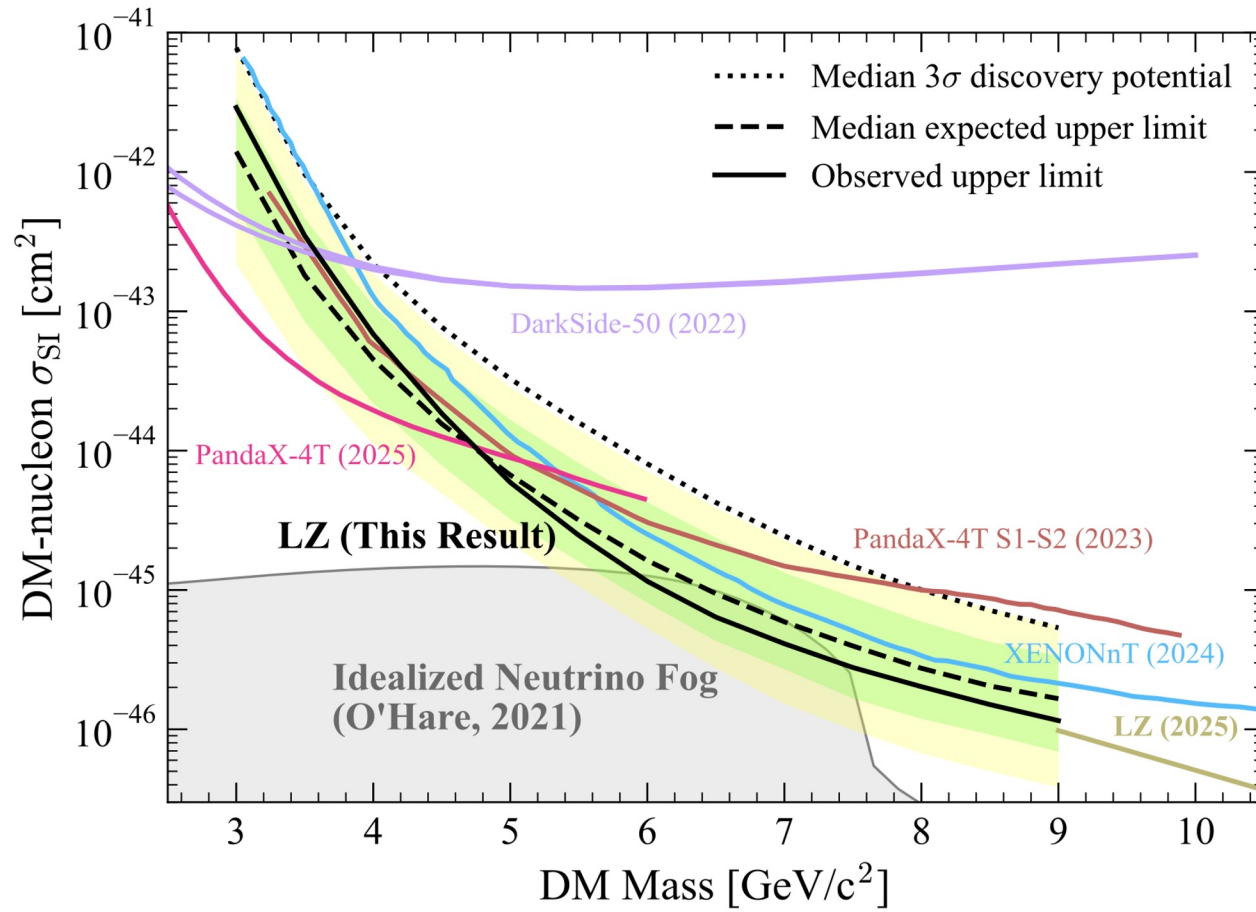
XENONnT: PRL 134, 111802 (2025)



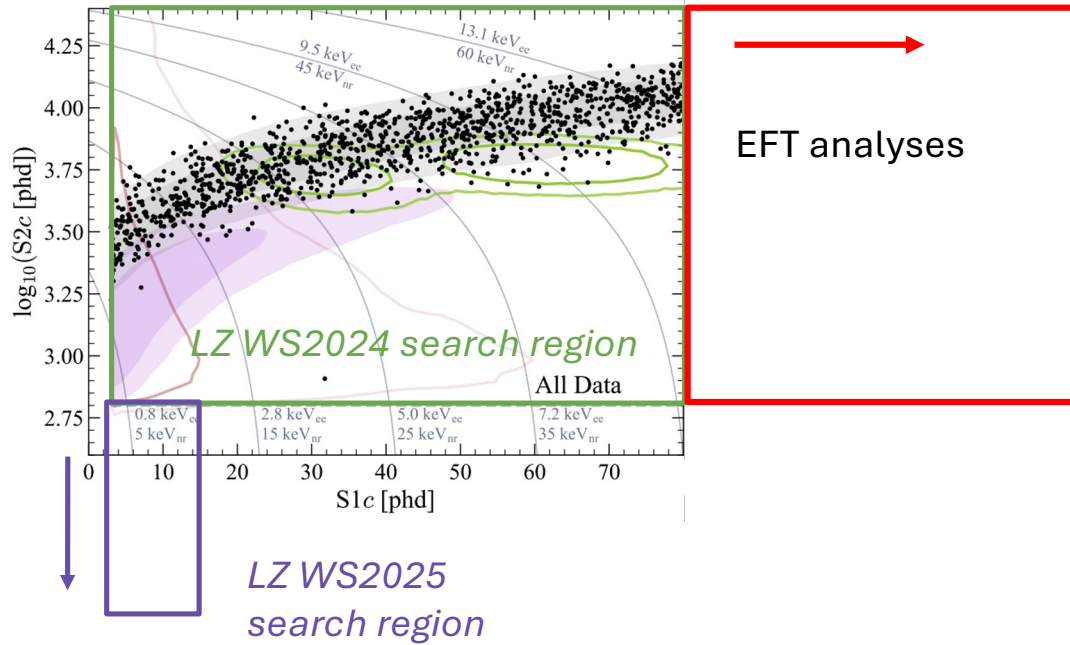
Components	Expectation	3 GeV/c <sup>2</sup> Fit
Spin-Independent DM	-	0.5 <sup>+5.1</sup> <sub>-0.5</sub>
<sup>8</sup> B CEνNS	20.6 <sup>+8.9</sup> <sub>-6.8</sub>	14.7 <sup>+3.1</sup> <sub>-2.7</sub>
Accidental coincidences	6.6 ± 0.3	6.5 ± 0.3
Detector neutrons	0.04 <sup>+0.25</sup> <sub>-0.04</sub>	0.1 <sup>+0.2</sup> <sub>-0.1</sub>
Total	27.2 <sup>+9.2</sup> <sub>-6.7</sub>	21.7 <sup>+7.1</sup> <sub>-4.2</sub>

Component	Expectation	Background-only	SI	LDM-e (heavy mediator)	LDM-e (light mediator)
			4 GeV/c <sup>2</sup>	2 GeV/c <sup>2</sup>	2 GeV/c <sup>2</sup>
DM (paired)	...	...	0.4 ± 0.4	...	...
<sup>8</sup> B CEνNS (paired)	3.4 ± 0.6	2.6 ± 0.6	2.5 ± 0.6	...	...
AC (paired)	2.5 ± 0.5	2.5 ± 0.4	2.5 ± 0.4	...	...
DM (US2)	...	...	18 ± 20	58 ± 34	8 ± 19
<sup>8</sup> B CEνNS (US2)	43 ± 7	50 ± 6	49 ± 6	42 ± 6	47 ± 6
Cathode (US2)	204 ± 32	227 ± 15	212 ± 19	191 ± 22	225 ± 17
MD (US2)	45 ± 5	45 ± 4	45 ± 4	45 ± 4	45 ± 4
NR charge yield deviation	...	0.8 ± 0.9σ	0.8 ± 0.8σ	...	...
ER charge yield deviation	...	0.0 ± 1.0σ	...	0.2 ± 1.0σ	0.0 ± 1.0σ

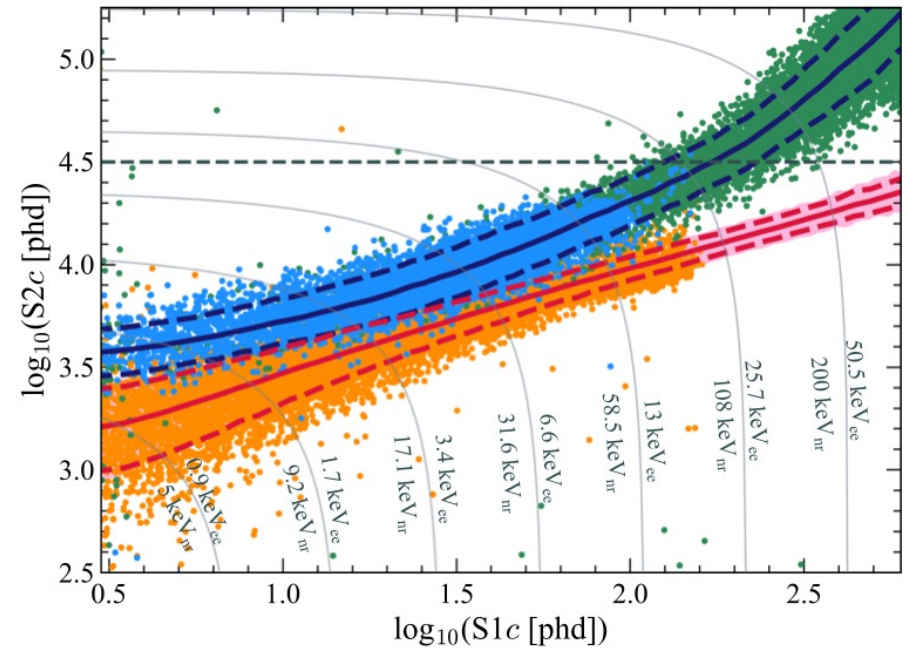
# Limits on light DM



# Extension to higher NR



tritium (light blue), D-D neutrons (orange), and <sup>212</sup>Pb (green)



LZ: PHYS. REV. D 109, 092003 (2024)

# Effective Field Theory analyses

$$\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = (v^\perp)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right),$$

$$\mathcal{O}_6 = \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right), \quad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right),$$

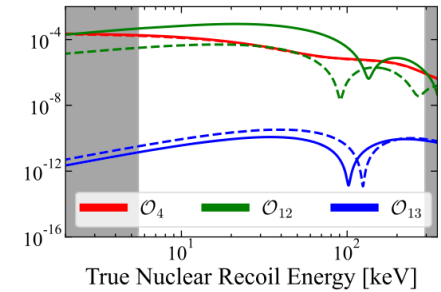
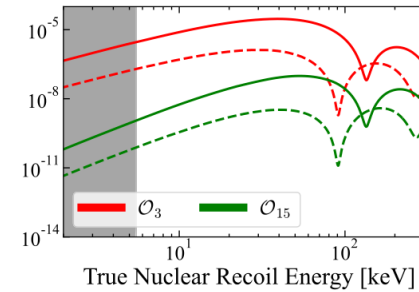
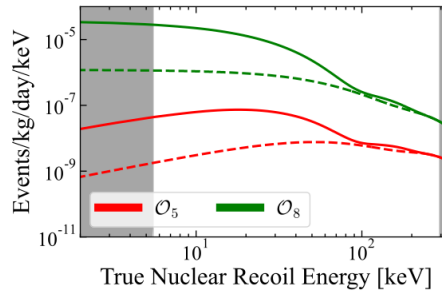
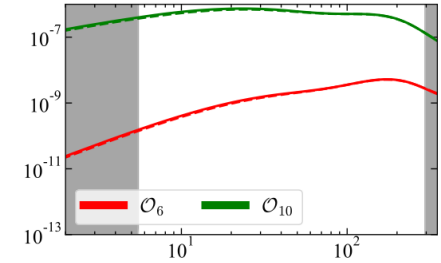
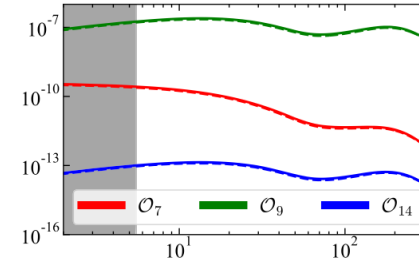
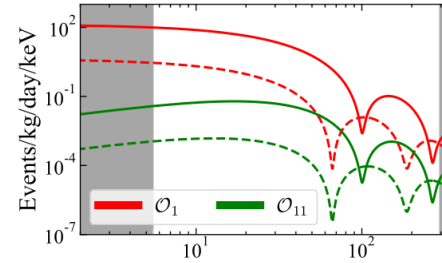
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}, \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N},$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp), \quad \mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right),$$

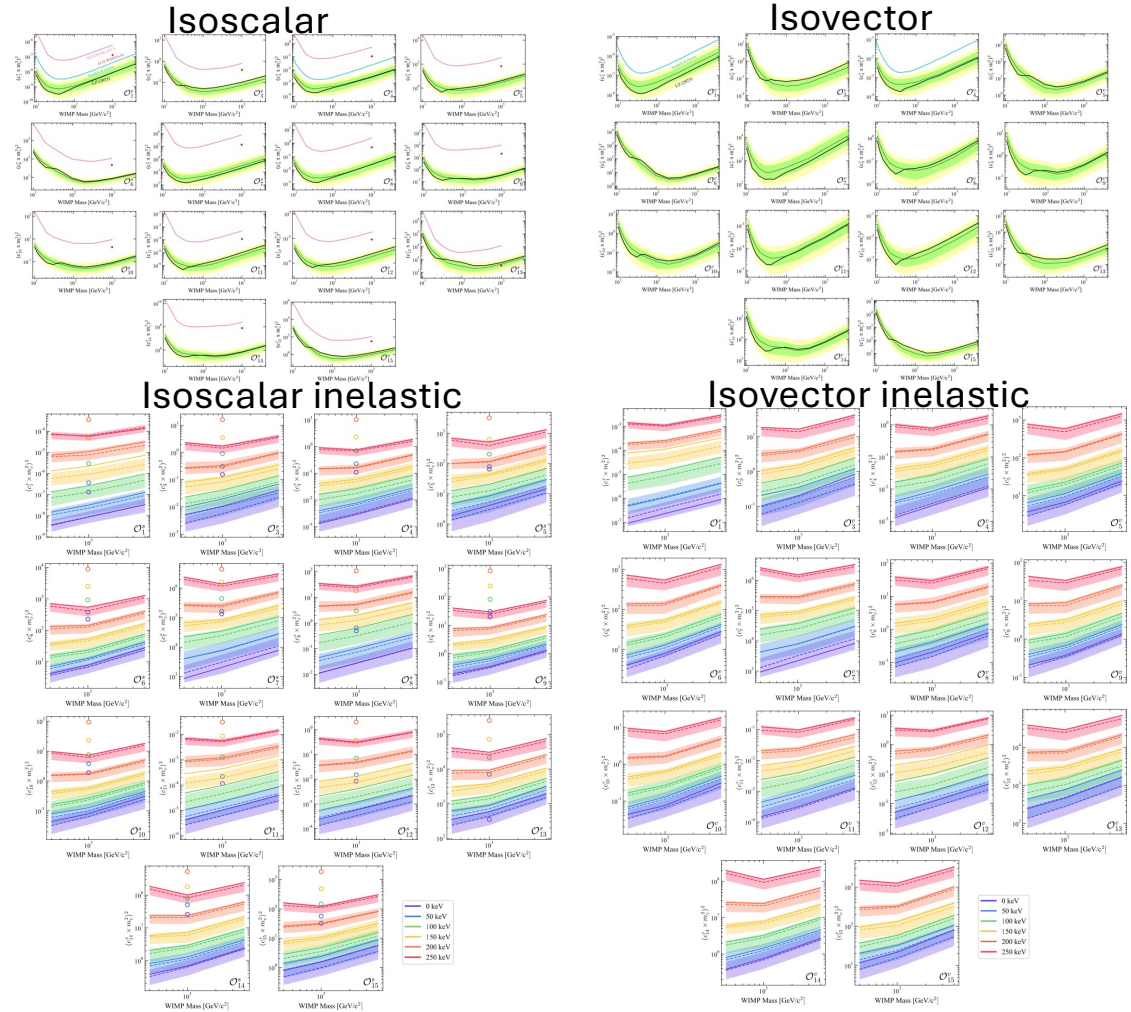
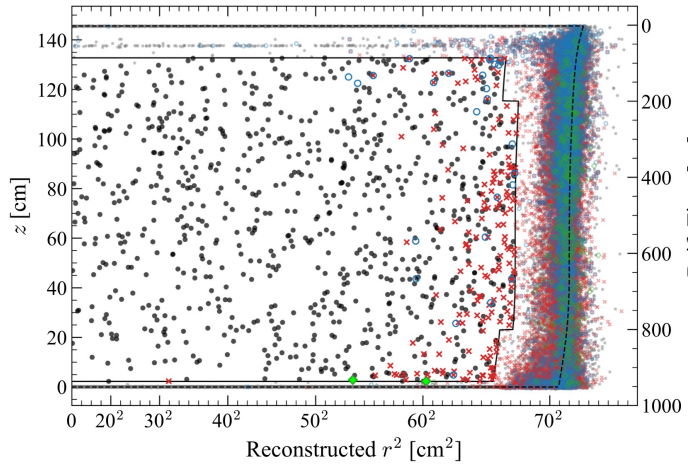
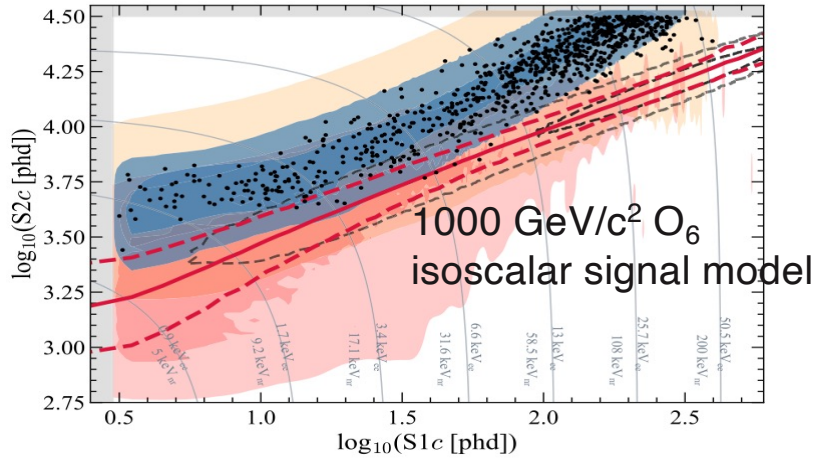
$$\mathcal{O}_{14} = i \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) (\vec{S}_N \cdot \vec{v}^\perp),$$

$$\mathcal{O}_{15} = - \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( (\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N} \right).$$

Some operators are increasing with the recoil energy  $\rightarrow$  extending the range to higher NR is beneficial

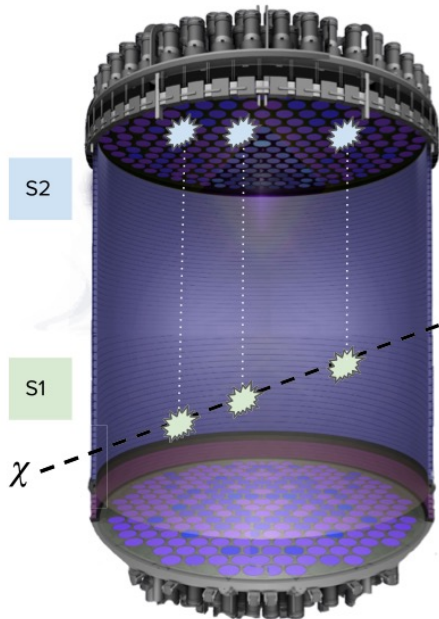


# EFT results



# Search for MIMPs

LZ: PHYS. REV. D 109, 112010 (2024)

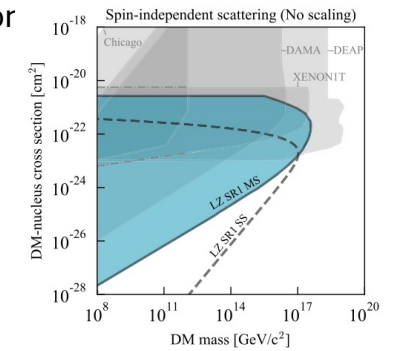
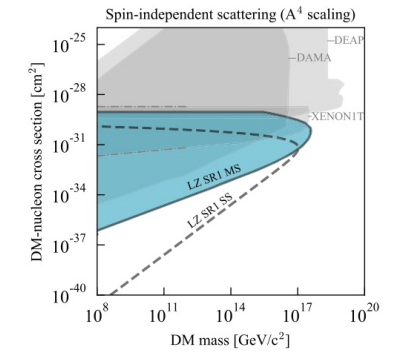
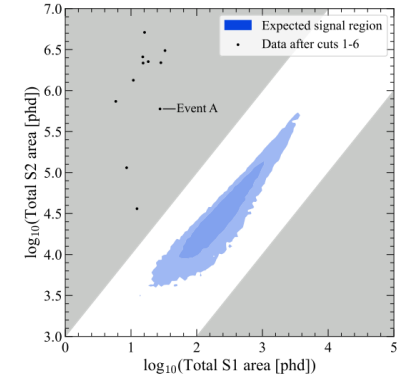
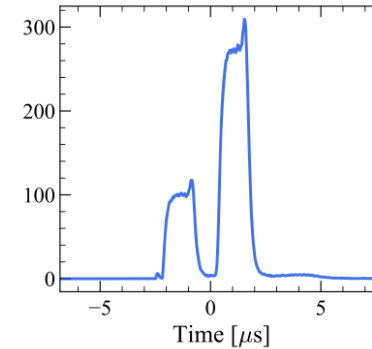
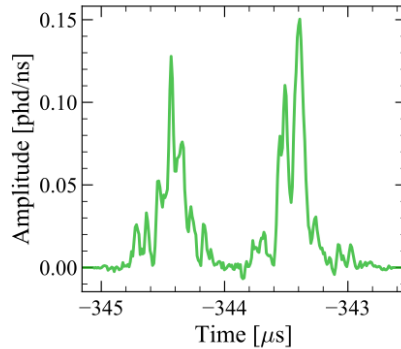


## Multiply Interacting Massive Particles (MIMPs)

- J. Bramante et al., Phys. Rev. D **98**, 083516 (2018)
- Multiple scatters are excluded from WIMP searches

• The signal cross-section 
$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{d\sigma_{\chi n}}{dE_R} A^4 |F_N(q)|^2$$

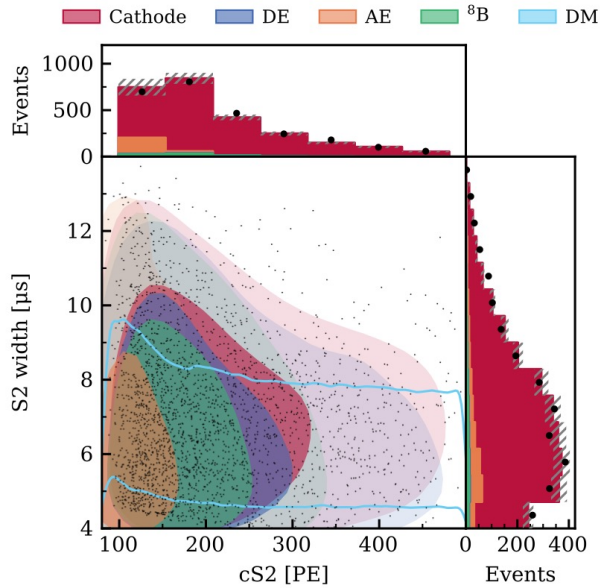
- Factor A4 could be not applicable for high DM-nucleon cross-section



Name	Description	Events
Initial selection	See Sec. III	10137
Multiplicity	> 1 S1s; > 1 S2s	1538
Good S1	No S1s are overly concentrated in one PMT or have a coincident signal in the OD	1400
Fiducial	≥ 2 S2s with $z \in (2, 135)$ cm and $r < 70$ cm	269
Collinearity	Reduced $\chi^2 < 2$ ; scatters are causally ordered along the track	237
Uniformity	Scatters are distributed along the track uniformly	67
Velocity	Reconstructed $v \in (50, 1200)$ km/s	11
ROI	Total S1 and total S2 area is within signal region	0

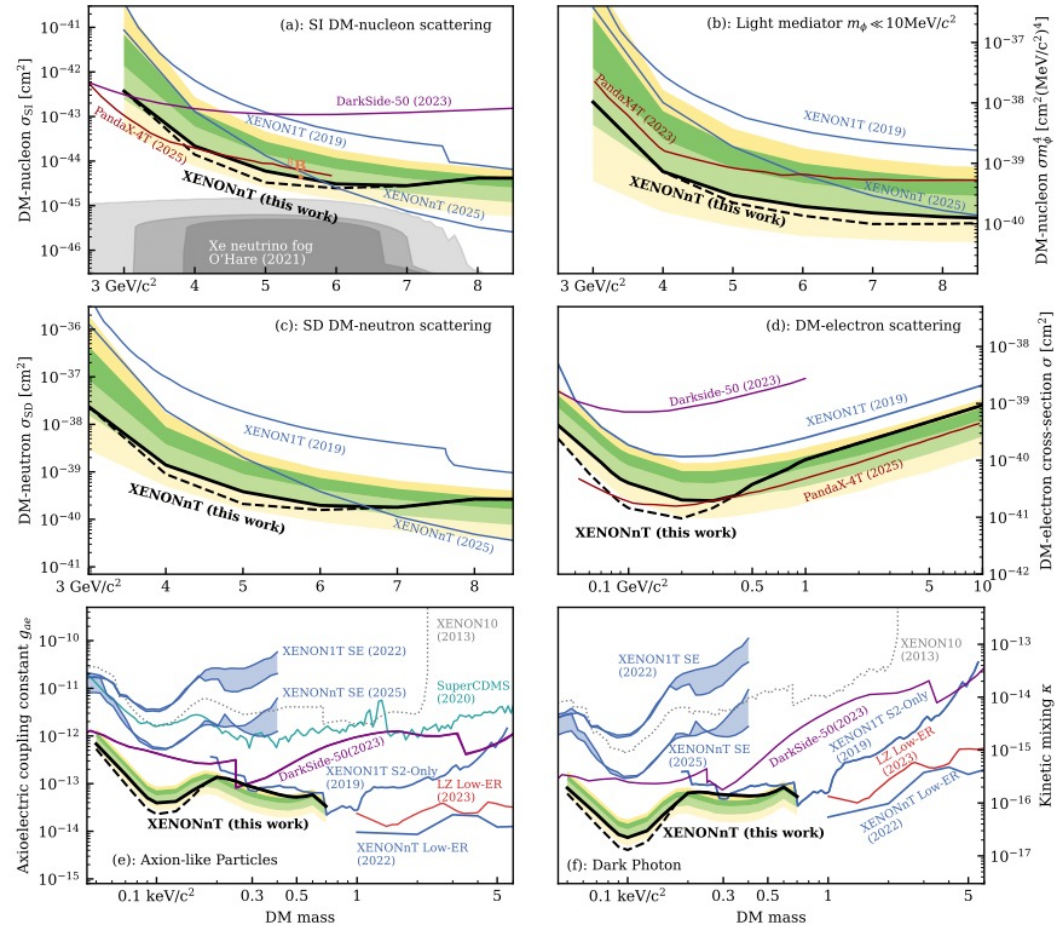
# S2-only searches: Light DM and ER

- Given S1 signal is much weaker, the S2-only sample could be more sensitive to light DM
  - No discrimination from the electron recoil background
  - No fiducialisation in depth which is determined from the time difference between S1 and S2
  - Still low S2 range is relatively clean allowing good sensitivity to low recoil signals
- The same sample can also be used for electron recoil processes



Science run (exposure)	SR0 (1.50t · y)	
Component	Expectation	Best fit
Cathode	480 ± 70	477 <sup>+25</sup> <sub>-24</sub>
Delayed electron	1.3 ± 0.5	1.3 ± 0.5
Accidental electron	97 ± 17	89 ± 13
<sup>8</sup> B CEνNS	21 ± 5	18 <sup>+5</sup> <sub>-4</sub>
Total background	600 ± 80	586 ± 28
Observed		583

XENONnT: arXiv:2601.11296



# Towards XLZD

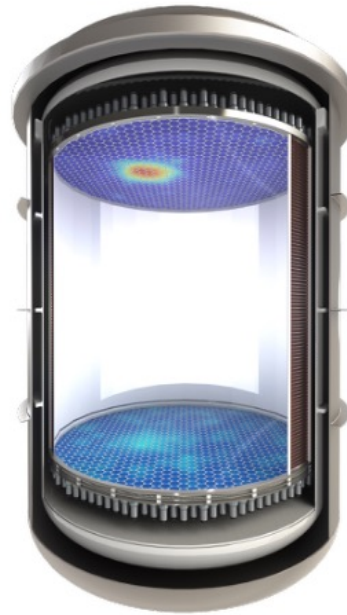
## Dark Matter

WIMPs  
Sub-GeV  
Inelastic  
Axion-like particles  
Planck mass  
Dark photons



## Neutrino nature

Neutrinoless double  
beta decay  
Neutrino magnetic  
moment  
Double electron  
capture



## Supernovae

Early alert  
Supernova neutrinos  
Multi-messenger  
astrophysics

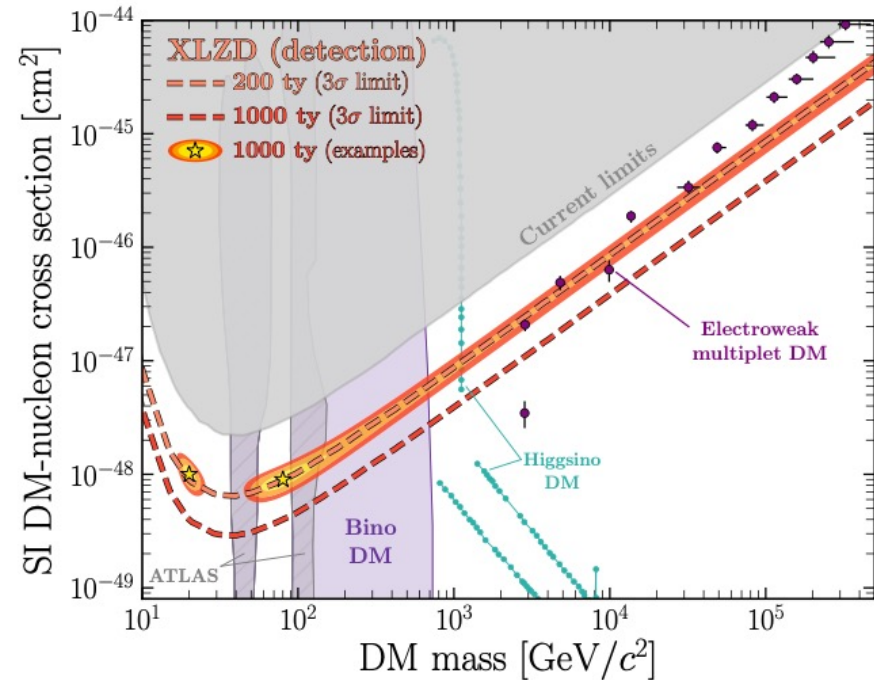
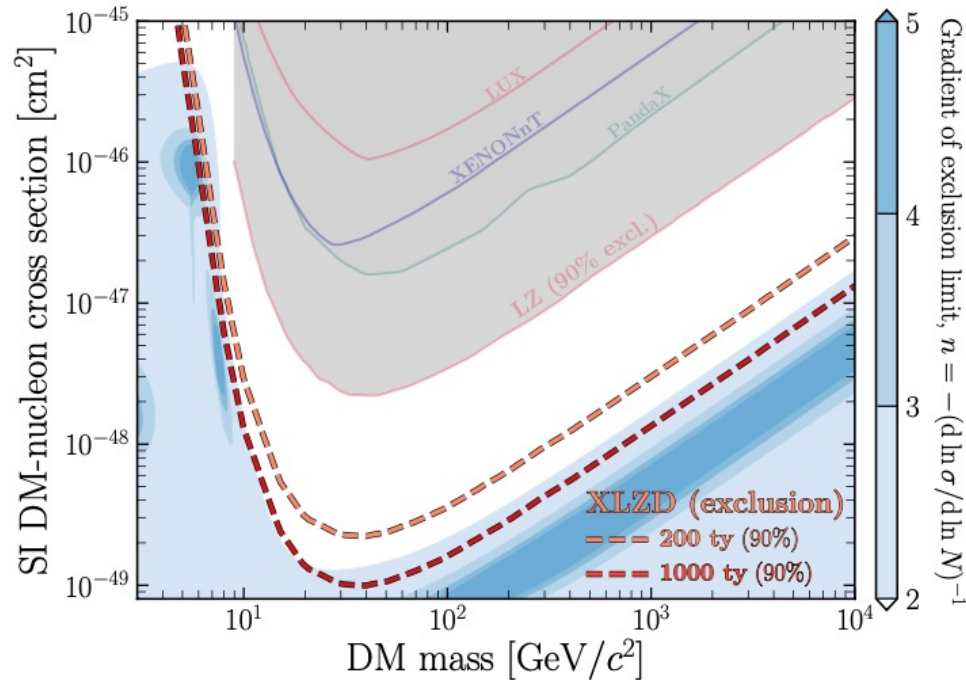


## Sun

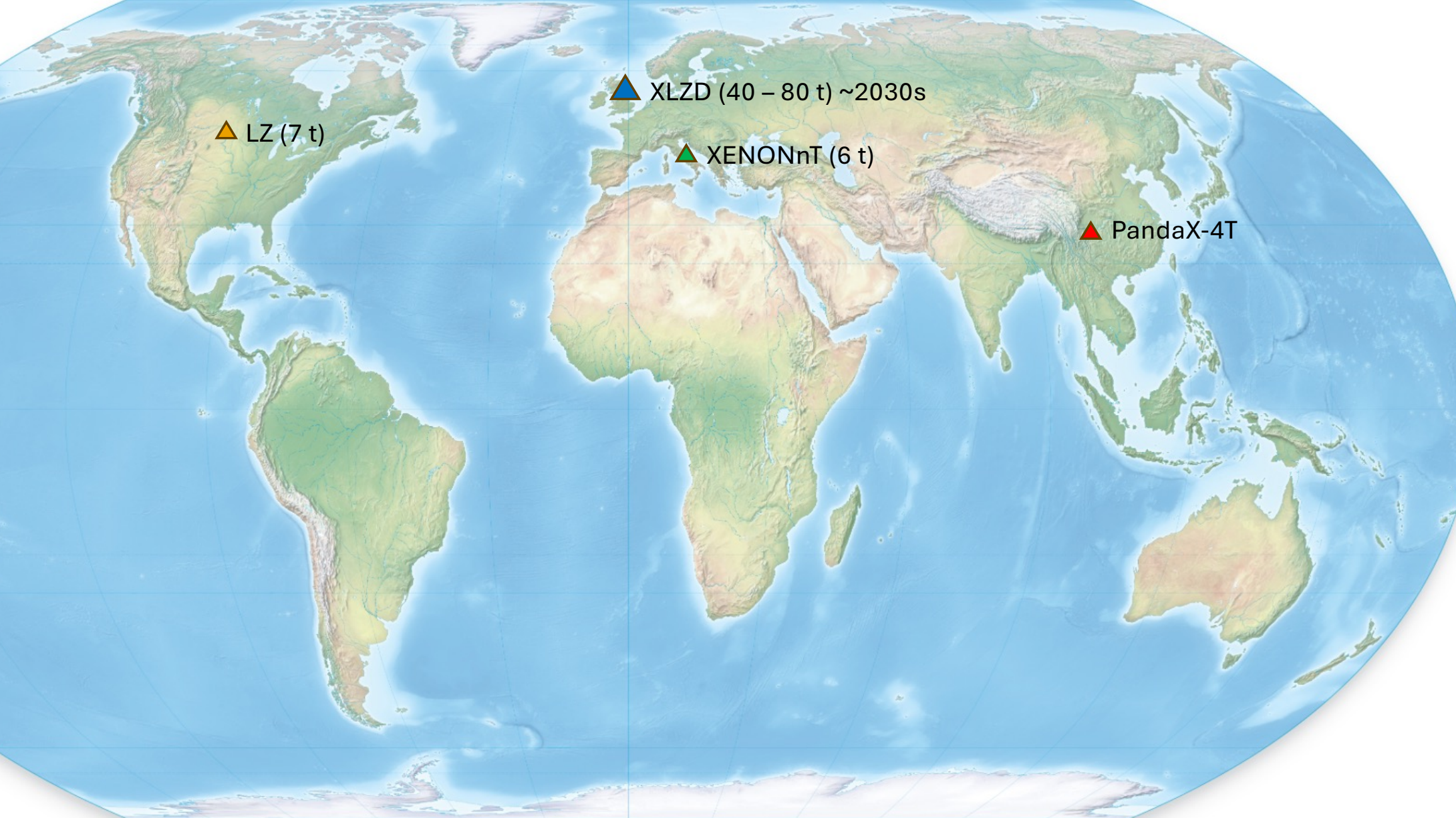
pp neutrinos  
Solar metallicity  
 ${}^7\text{Be}$ ,  ${}^8\text{B}$ , hep



# Last Generation Liquid Xenon Detector?



- Current technologies most probably will be unsuitable after reaching the “neutrino fog”
  - Light DM searches demonstrate reasonable sensitivity, but the model dependence will be challenging
- Strong driving force to achieve the maximum possible sensitivity with this detector



▲ LZ (7 t)

▲ XLZD (40 - 80 t) ~2030s

▲ XENONnT (6 t)

▲ PandaX-4T