Searching for WIMPs and other new physics with LZ

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On behalf of the LZ collaboration

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
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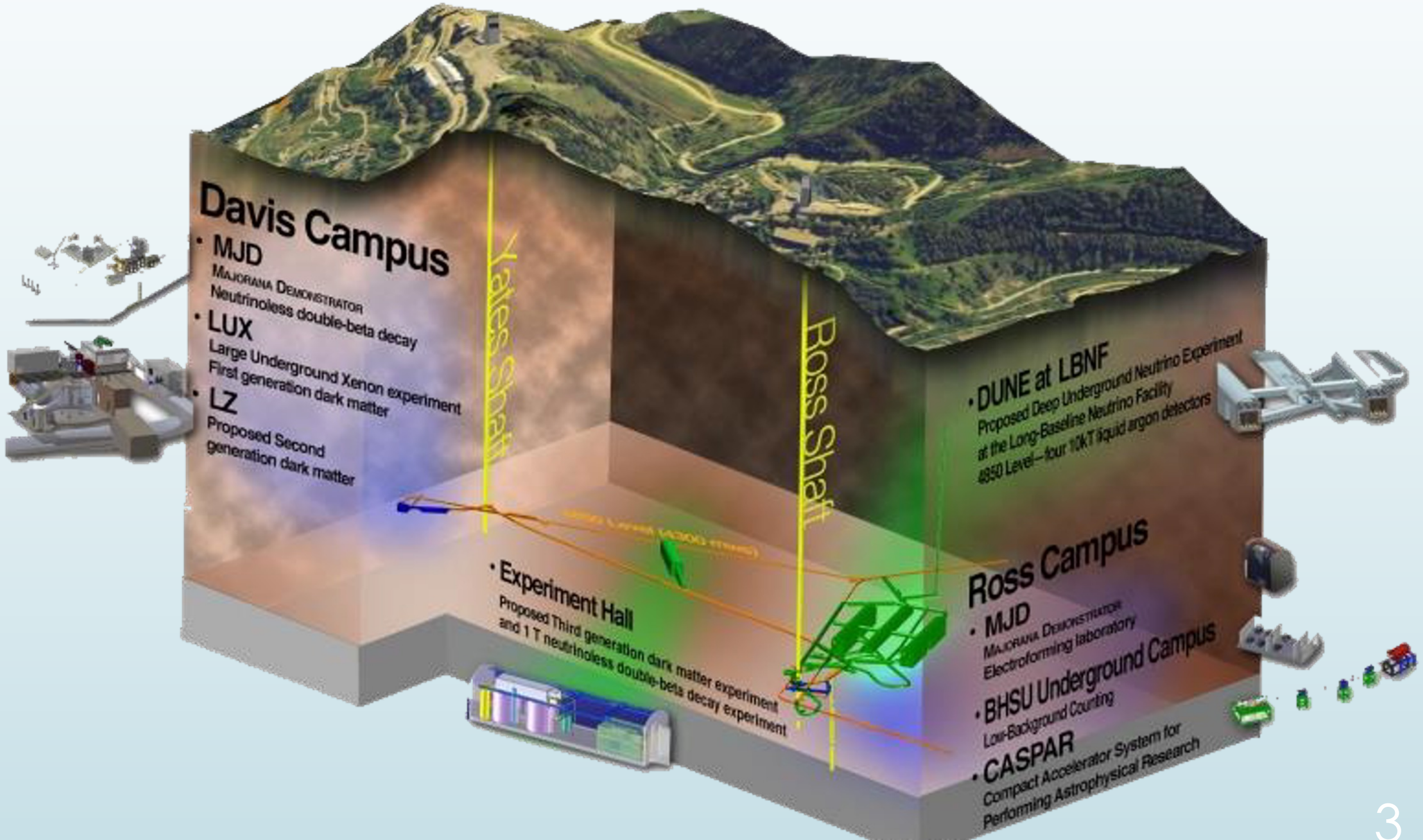
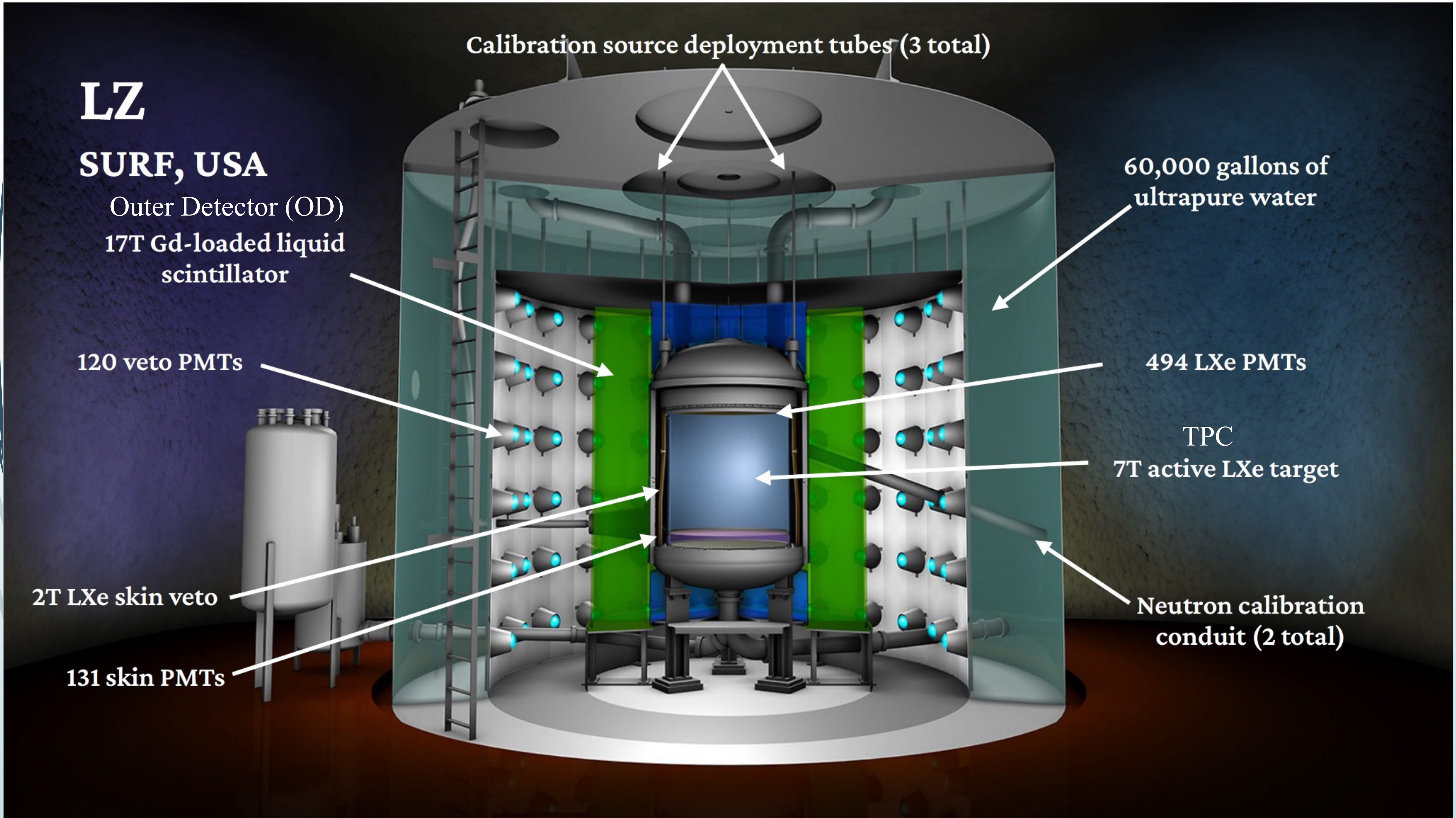
LZ @ Sanford Underground Research Facility (SURF)

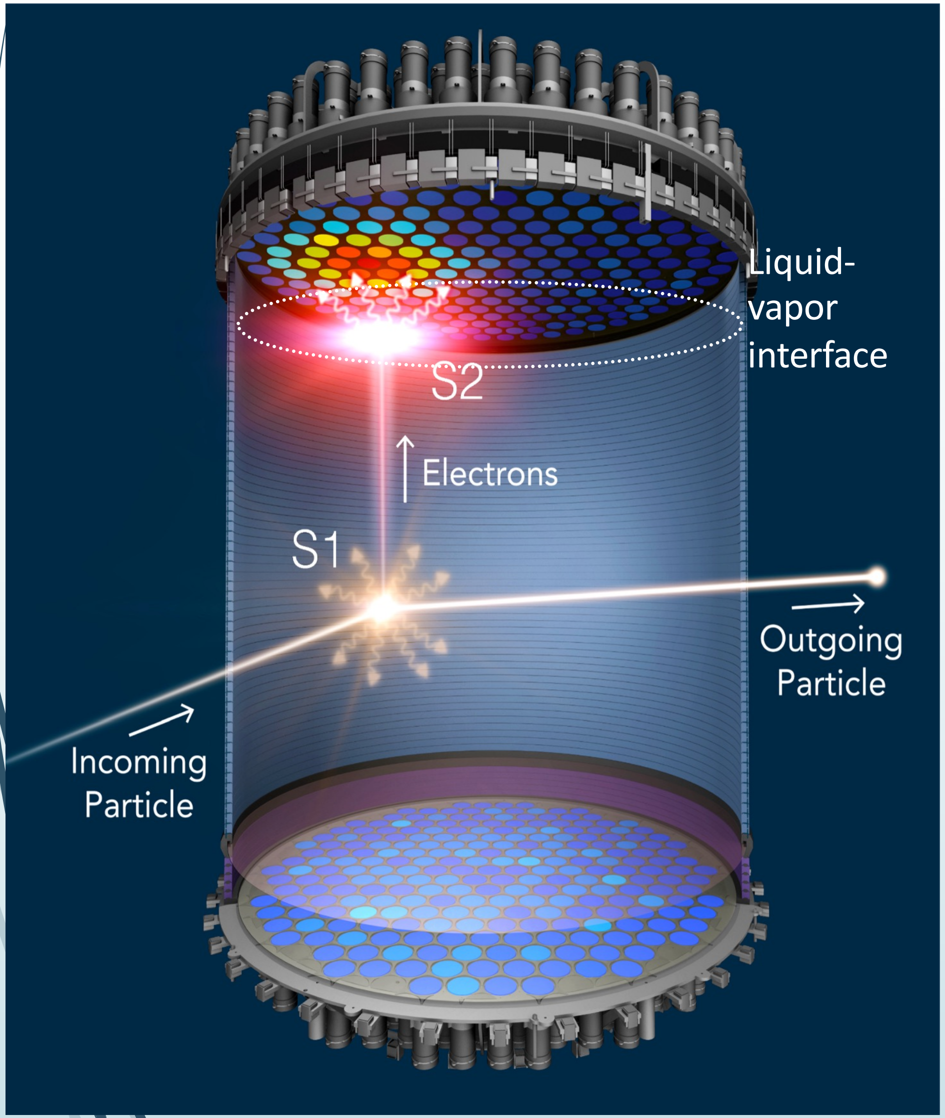
- LZ uses 10t of xenon to search for WIMP dark matter
- The detector is on the 4850 level (~1.5 km underground) → ~10^6 reduction in cosmic muon flux

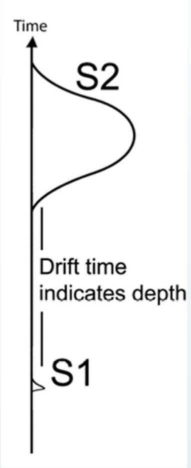


The LZ Detector

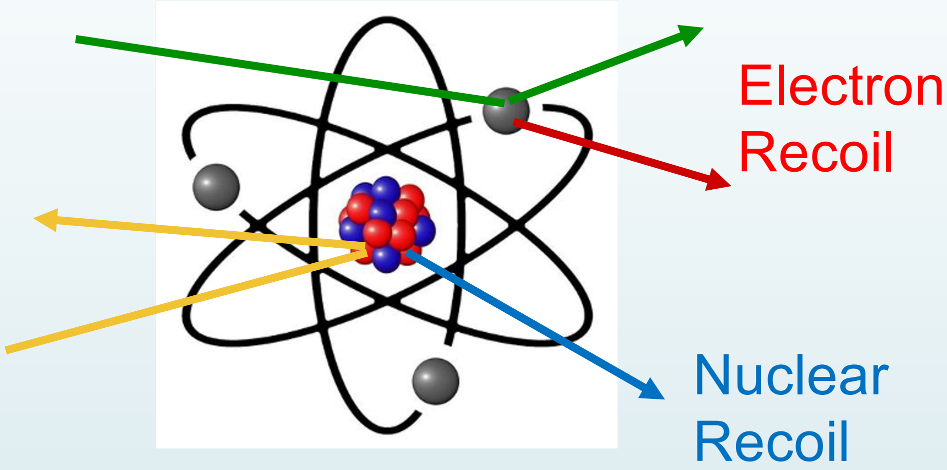


Dual Phase Xenon Time Projection Chamber (TPC)



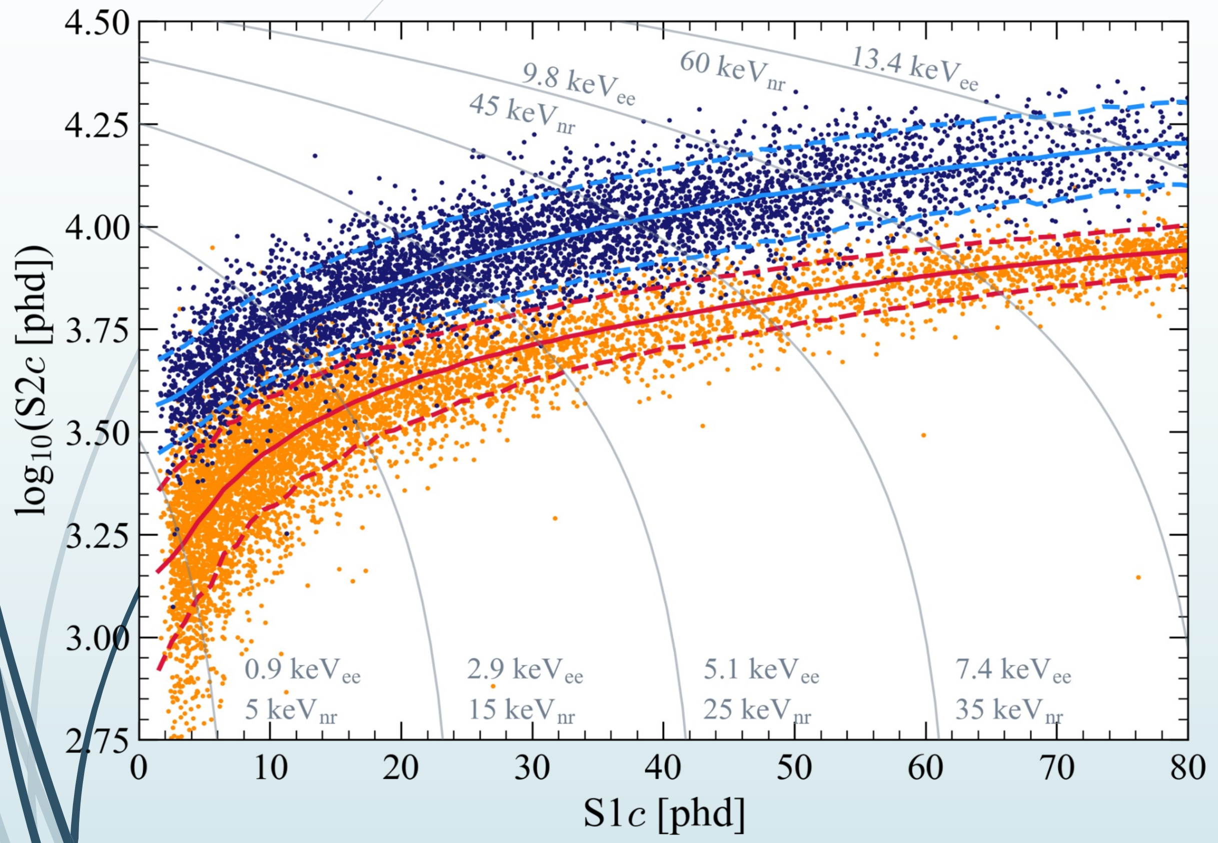


- Signal vs. background discrimination
  - Charge (S2)/ light (S1) ratio is different between electron recoils (ER) and nuclear recoils (NR)



- Electrons and gammas interact with atomic electrons, produce ER
- WIMPs (and neutrons) interact with Xe nuclei, produce NR

Calibration Data

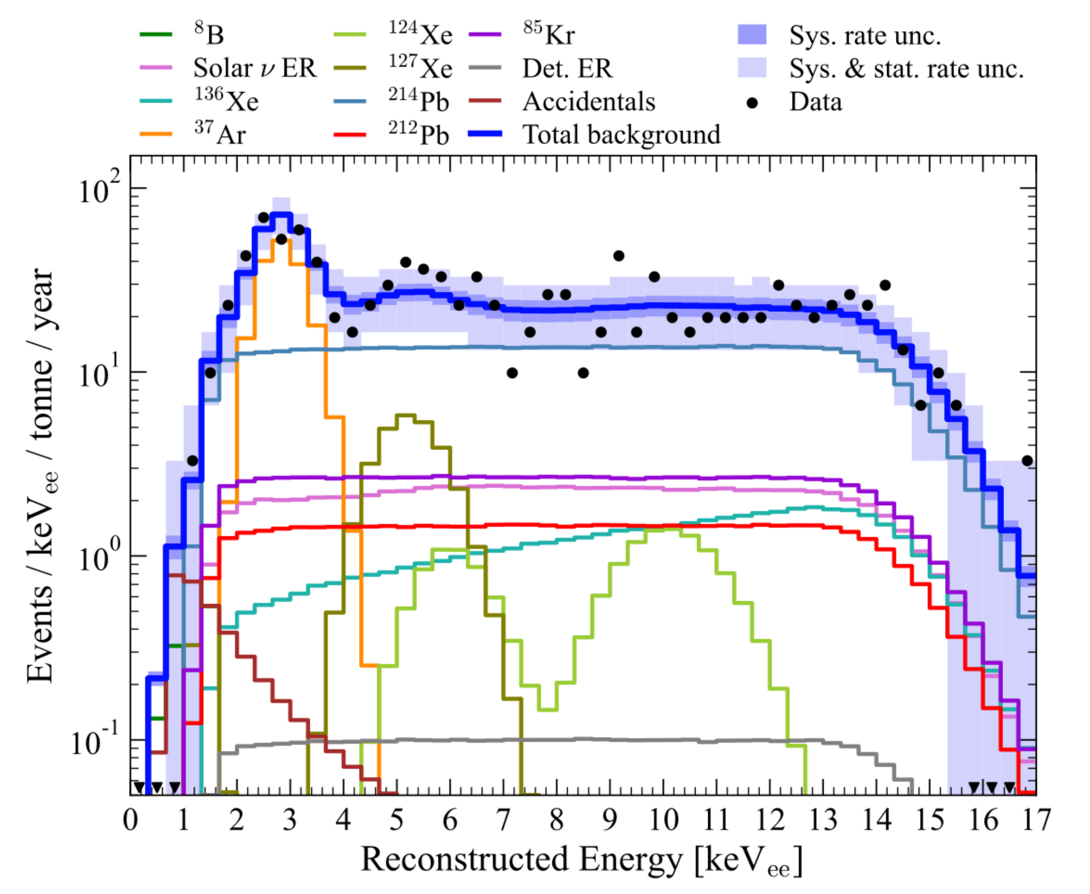


- Dark blue points: Tritium beta data (ER) (continuum betas up to 18.6 keV)
- Orange points: DD neutron data (NR) (2.45 MeV neutrons produced through Deuterium-Deuterium fusion)
- ER/NR discrimination: <0.5% ER leakage past the median of the NR population

*LZ Collaboration, [Phys. Rev. Lett. **131**, 041002 (2023)]*

Main backgrounds in Science Run 1

Reconstructed data energy spectrum vs. background model:



Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

*LZ Collaboration, [Phys. Rev. D **108**, 012010 (2023)]*

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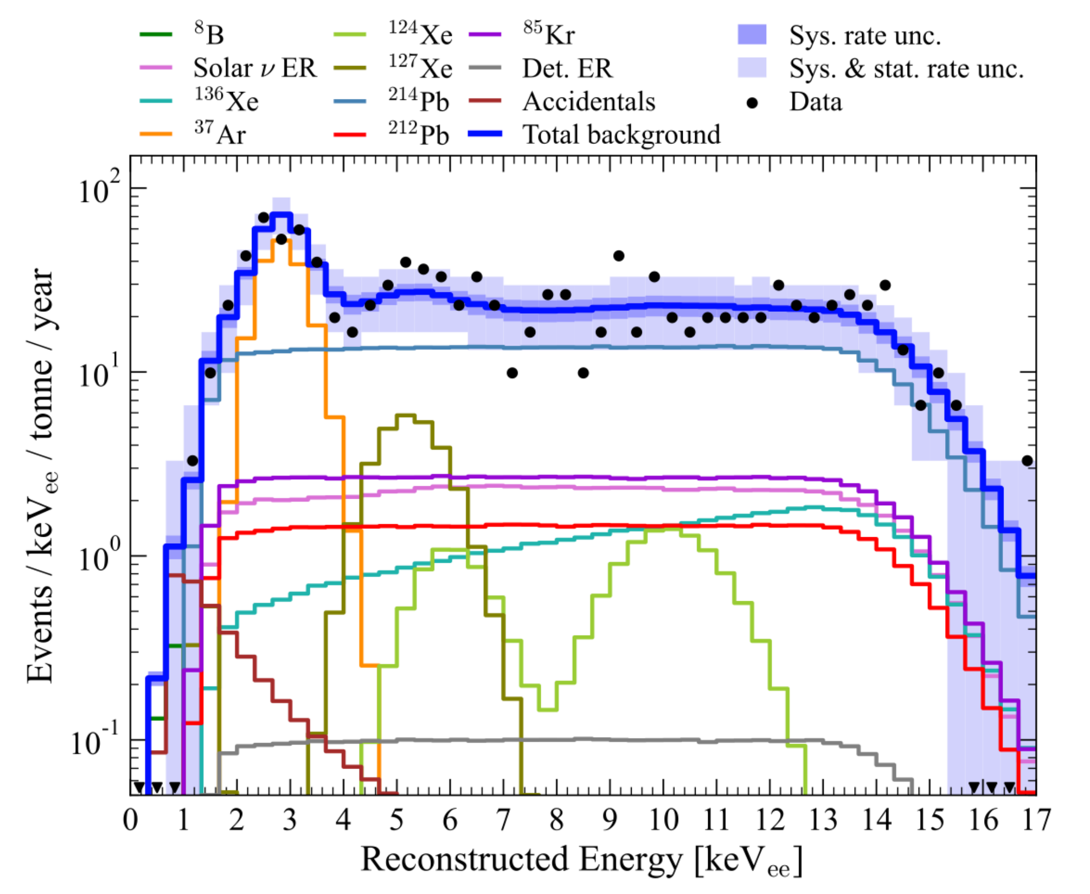

dominant background

Beta emitters: ^{214}Pb, ^{212}Pb, ^{85}Kr

Electron-captures: ^{127}Xe, ^{124}Xe

Neutrinos: ν ER, ^{8}B CEνNS

Detector Materials: ^{37}Ar, Detector neutrons

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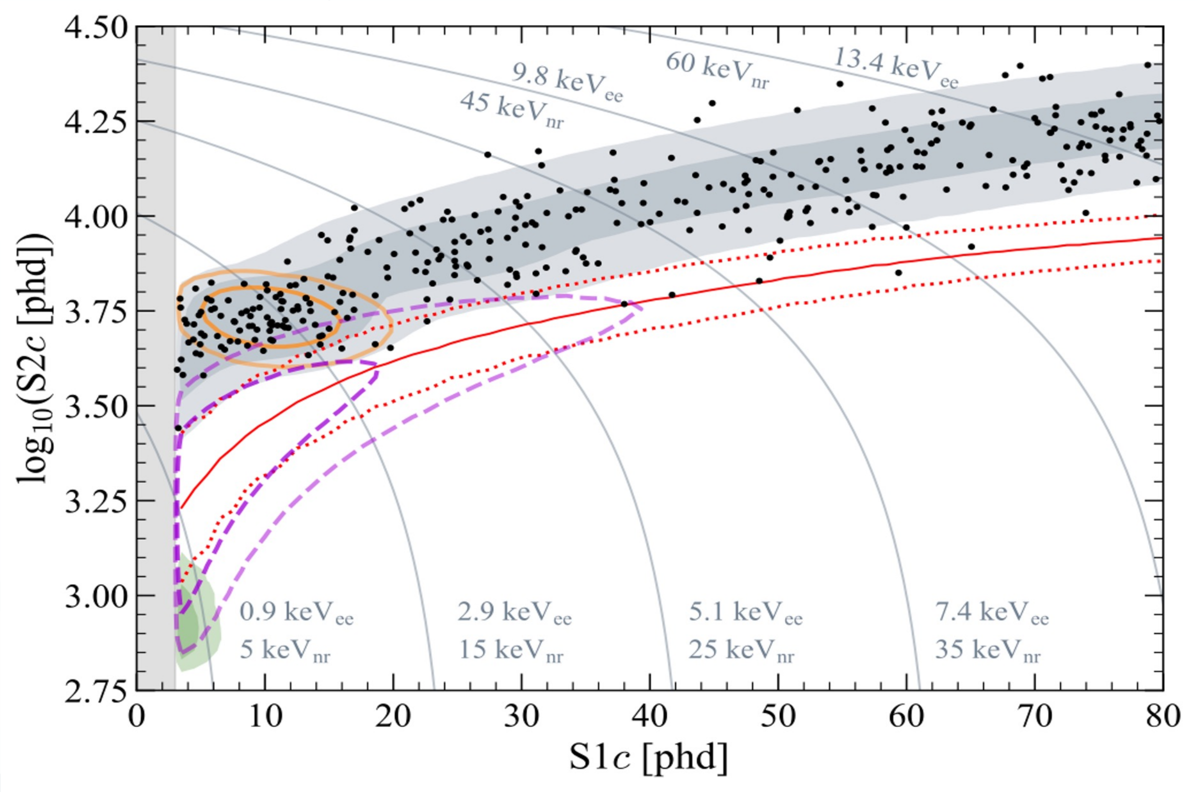
*LZ Collaboration, Phys. Rev. D **108**, 012010 (2023)*

Science Run 1 WIMP Search Data

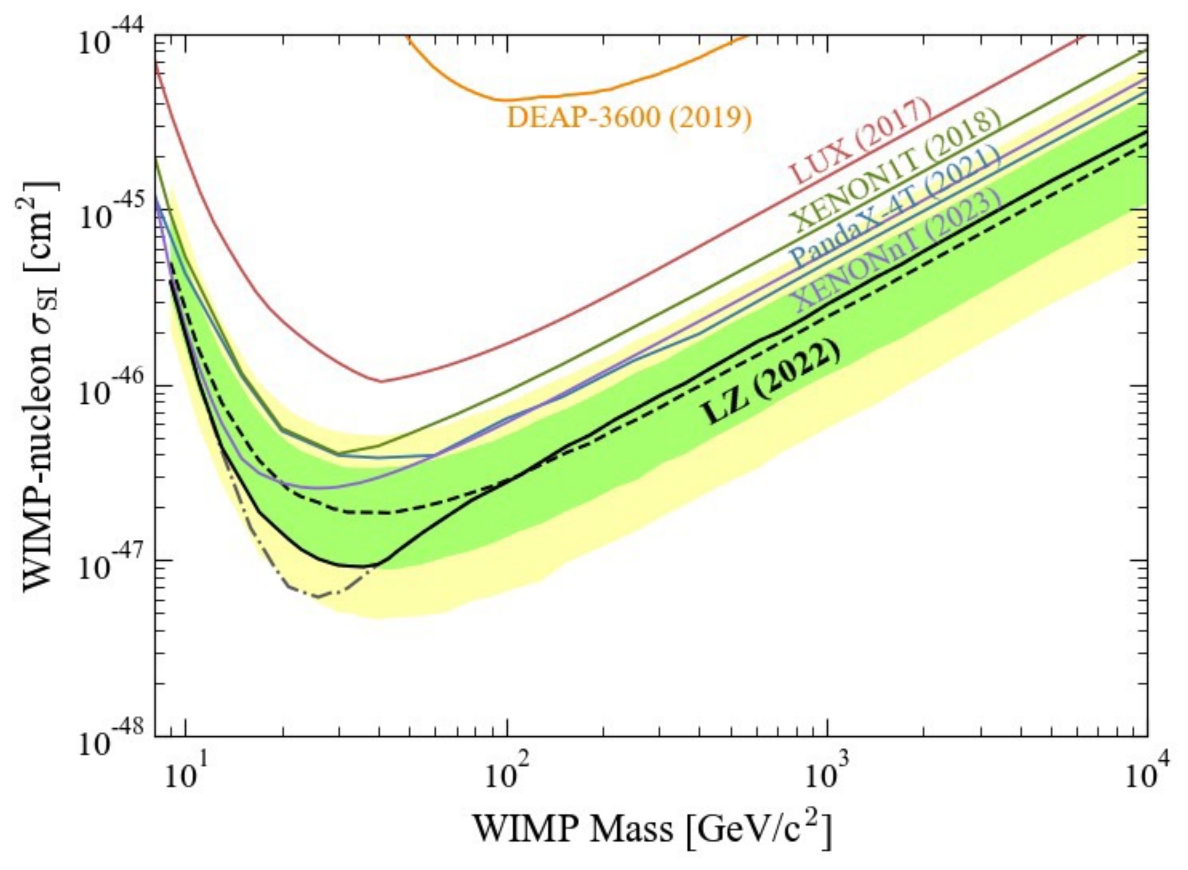


LZ Collaboration *Phys. Rev. Lett.* ***131****, 041002 (2023)*

- Shaded gray region: best fit ER background model
- Purple curves: 1σ and 2σ contours of a 30 GeV/c^2 WIMP
- Red curves - NR band
- Shaded green region: ^{8}B neutrino
- Orange ellipses: contours of ^{37}Ar
- 335 events observed within 60 ± 1 live days, FV=5.5 ± 0.2 t

LZ's First WIMP Search Result

- No evidence of WIMPs at any mass from Science Run 1 (60 live days of data)
- **Most stringent upper limit on WIMP-nucleon cross section (spin-independent) for WIMPs above 9 GeV/c^2**



- Green and yellow bands: 1σ and 2σ sensitivity bands
- Solid black line: exclusion limit
- Gray dot-dash line: exclusion limit before applying the power constraint
- Dashed-black line: median expected sensitivity

LZ Collaboration, Phys. Rev. Lett. ***131****, 041002 (2023)*

WIMP-Nucleon Effective Field Theory (EFT)

- Why EFT?
  - All possible mechanisms for the WIMP-nucleon interaction are considered
  - Allows comparison of experiments using different target nuclei
- Non-relativistic dark matter EFT : $\mathcal{L}_{int} = \sum_i c_i \mathcal{O}_i$
  - 15 Galilean-invariant operators up to quadratic order in $\frac{\vec{q}}{m_N}$, built with four Hermitian quantities

$\vec{S}_\chi$	:	WIMP spin	$\vec{q}$	:	momentum transfer
$\vec{S}_N$	:	nucleon spin	$\vec{v}^\perp$	:	WIMP-nucleon relative velocity component perpendicular to $\vec{q}$

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Spin-independent

Angular momentum dependent

Tensor spin orbit

Spin-dependent

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

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

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

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

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

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

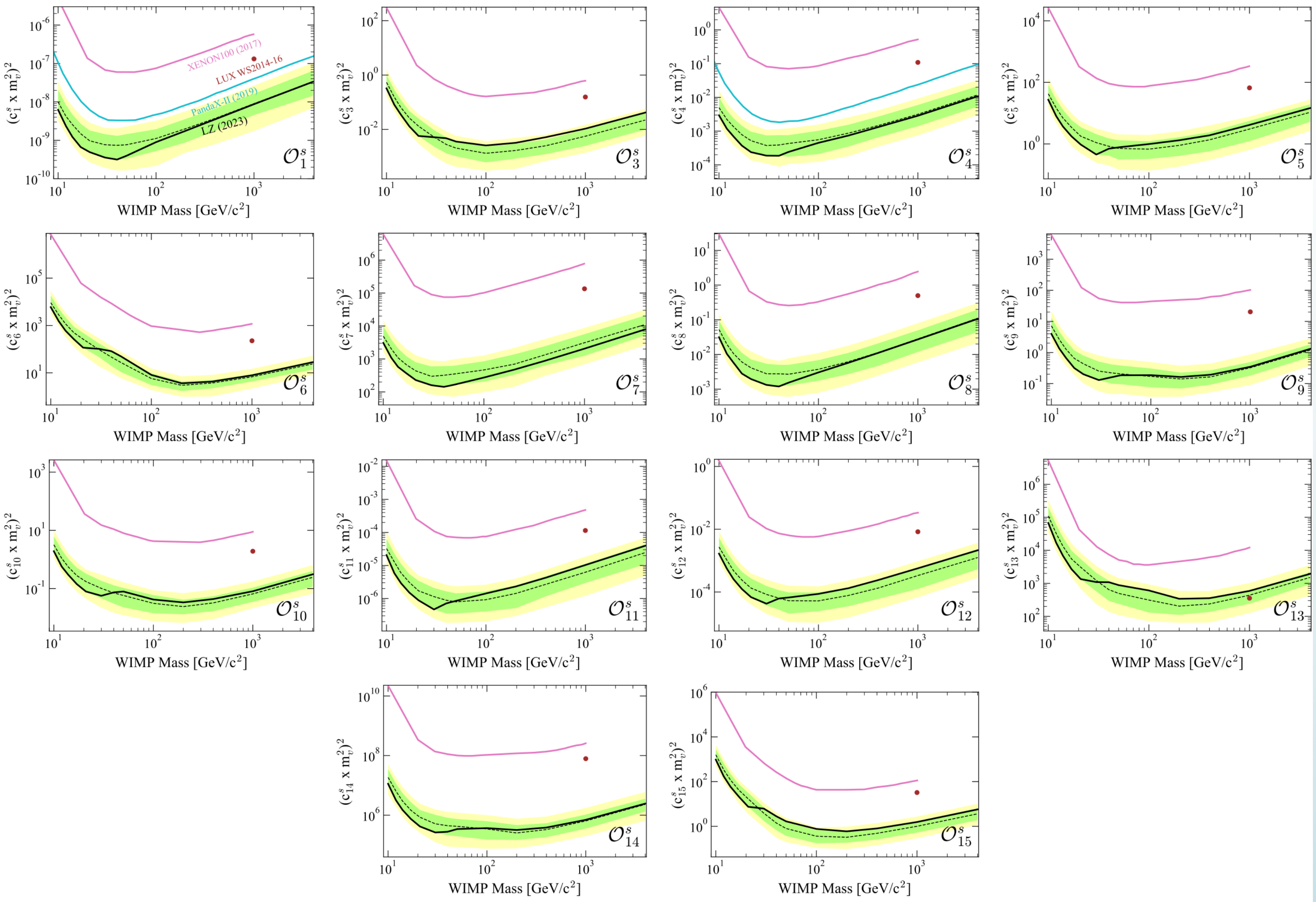
$$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^\perp\right),$$

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

*Nikhil Anand et.al Phys. Rev. C **89**, 065501*

Constraints on WIMP-Nucleon Effective Field Theory Couplings

- **LZ has the strongest upper limits on coefficients for nearly all EFT operators**



Black – 90% C.L. limit on WIMP-nucleon couplings for operators in the isoscalar bases (2023)

Cyan – PandaX-II (2019)

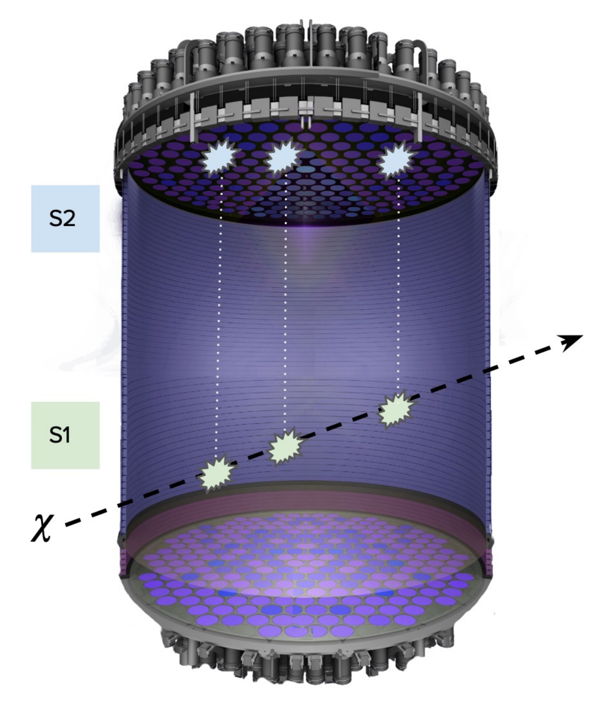
Magenta – XENON100 (2017)

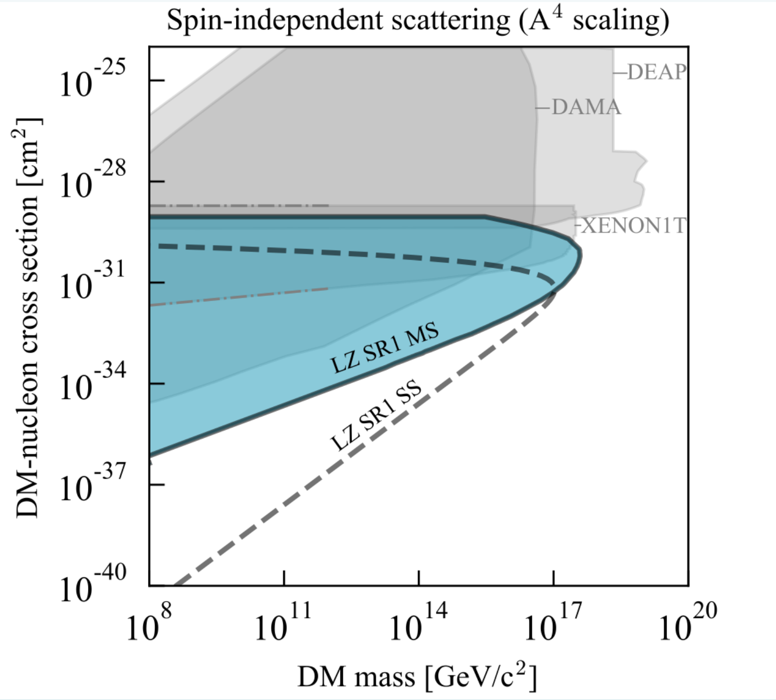
Brown dot – LUX (2014)

LZ Collaboration arXiv:2312.02030

Ultraheavy Dark Matter

- Dark matter models with masses >10 TeV/c^2 are weakly constrained
- LZ searches for ultraheavy dark matter particles through looking for multiple scatters forming a straight line, complementing the search in the single scatter channel
- **World leading limit on spin-independent per-nucleon interactions at high DM mass (up to $\gtrsim 10^{17}$ GeV/c^2)**

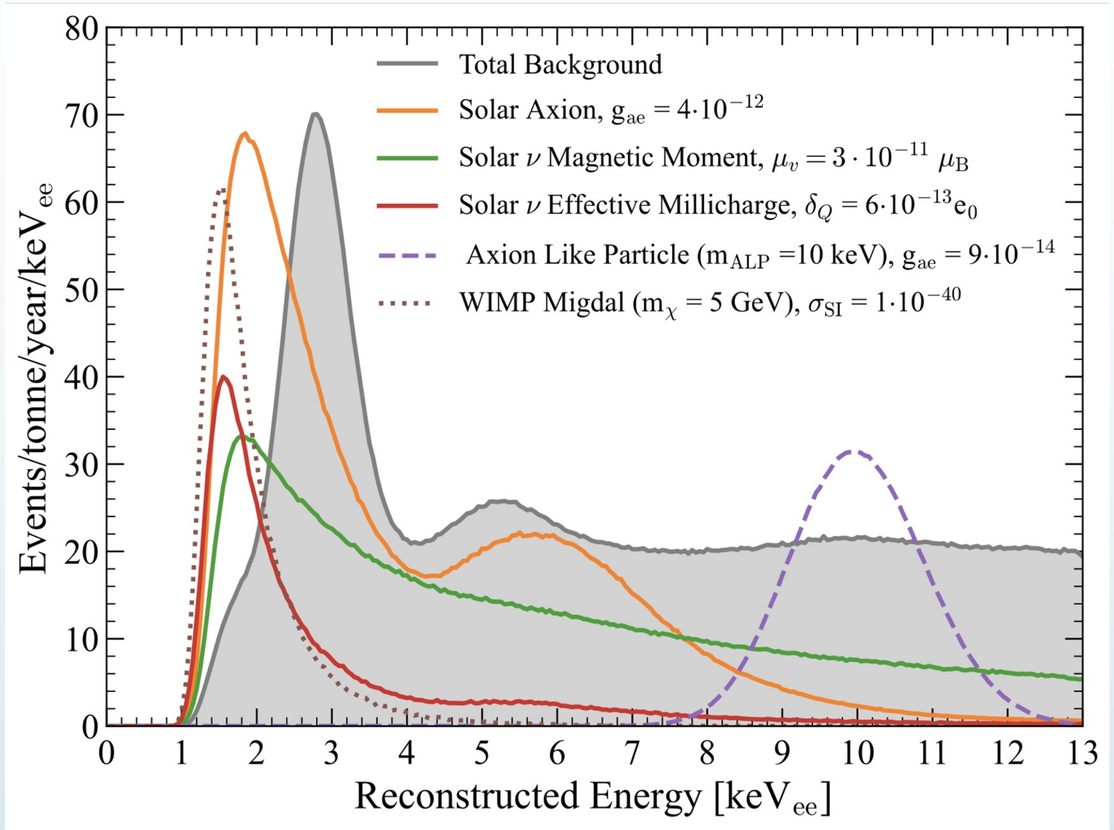




LZ Collaboration [*arXiv:2402.08865*]

Low Energy ER New Physcis Search in LZ

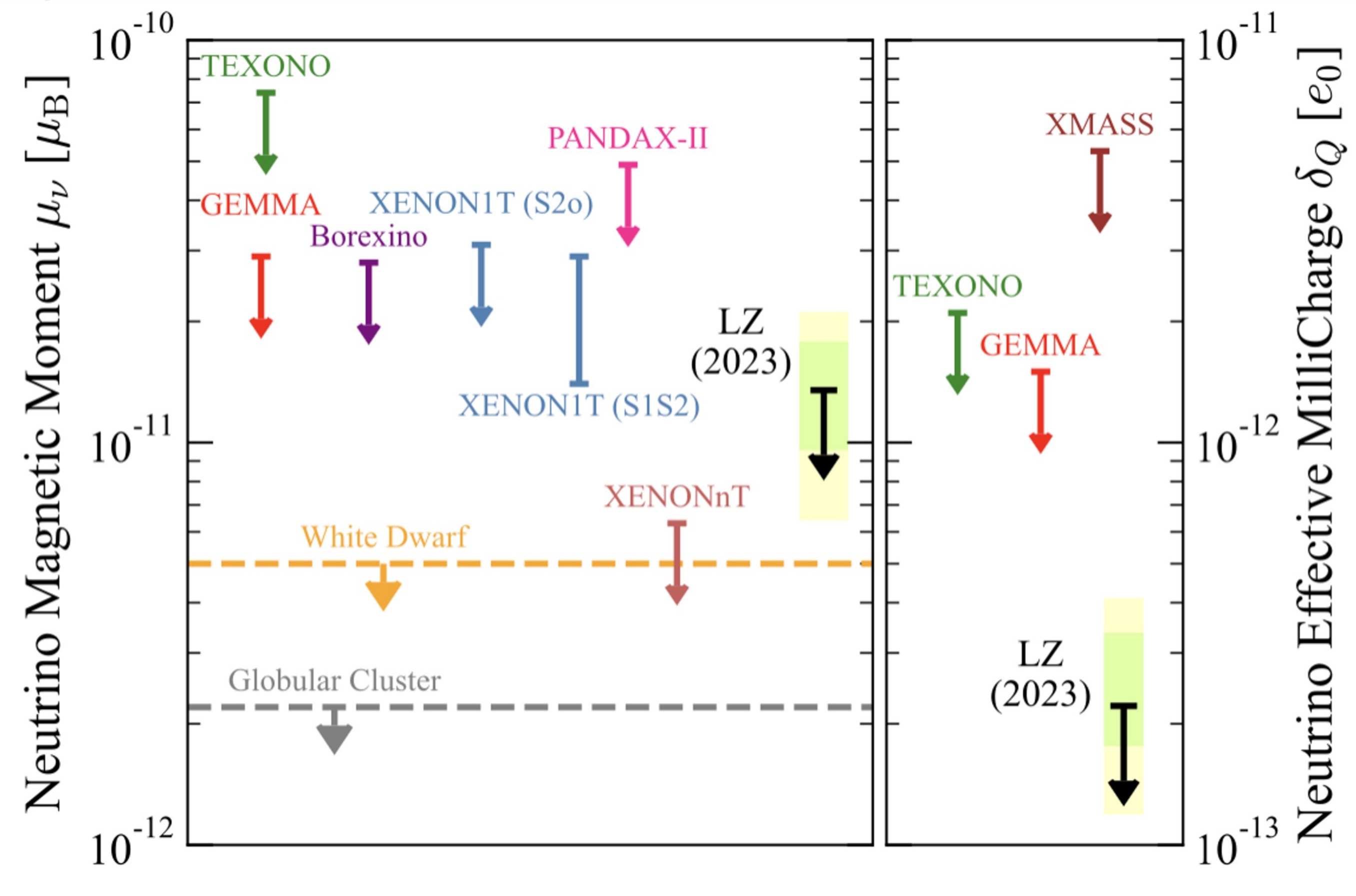
- New physics through ER interactions:
  - Solar axions
  - Neutrino magnetic moment & millicharge
  - ALPs and Hidden photons
  - WIMPs through Migdal Effect



*LZ collaboration, Phys. Rev. D **108**, 072006*

Neutrino electromagnetic properties

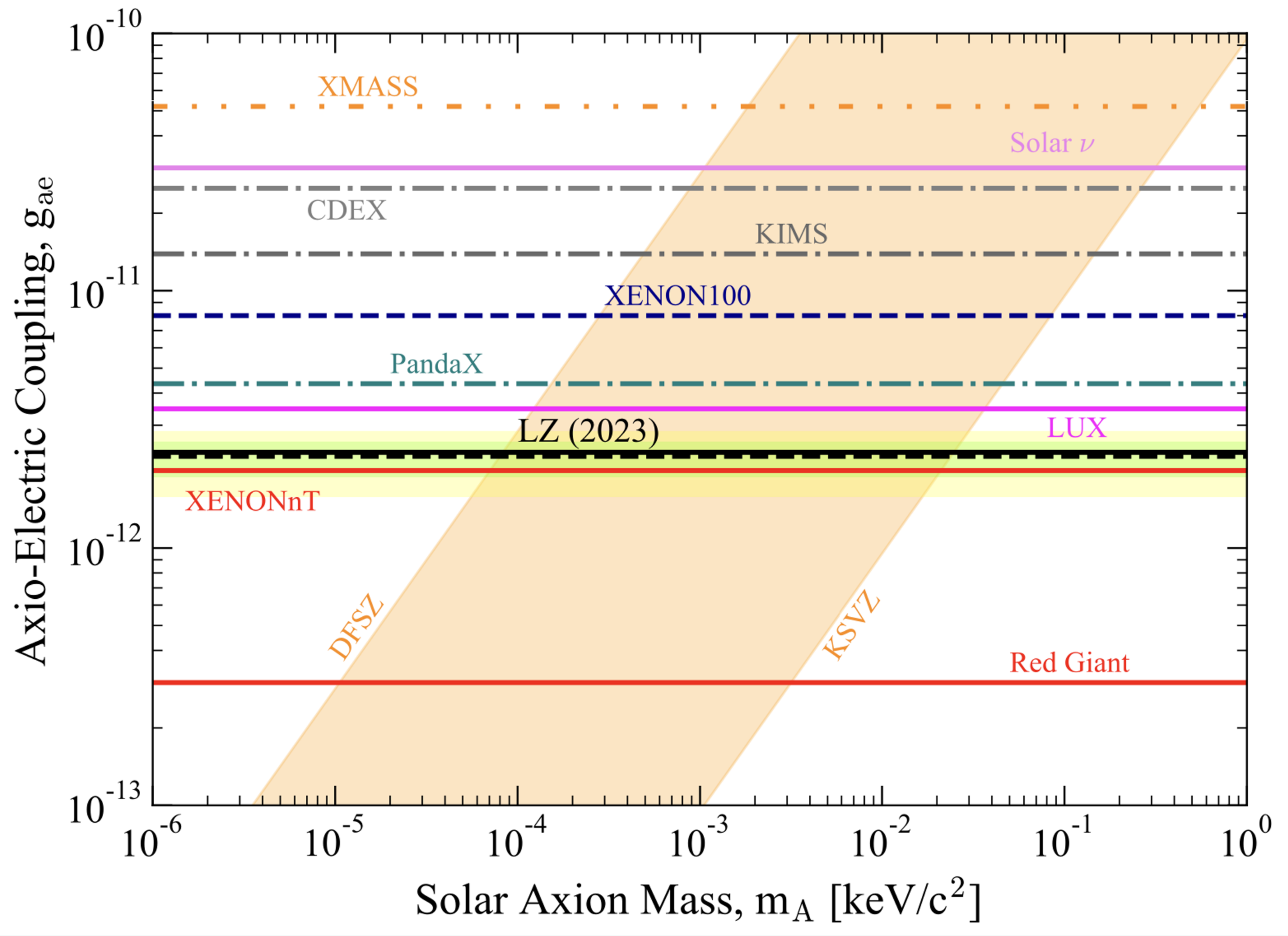
- Any observation of neutrino electromagnetic properties is a strong indicator of the neutrino being a Majorana particle
- **World leading limit on neutrino millicharge $\delta_Q = 2.24 \times 10^{-13}\ e_0$**
- LZ's 90% C.L. on neutrino magnetic moment $\mu_\nu = 1.36 \times 10^{-11}\ \mu_B$



LZ collaboration,
*Phys. Rev. D **108**, 072006*

Solar axions

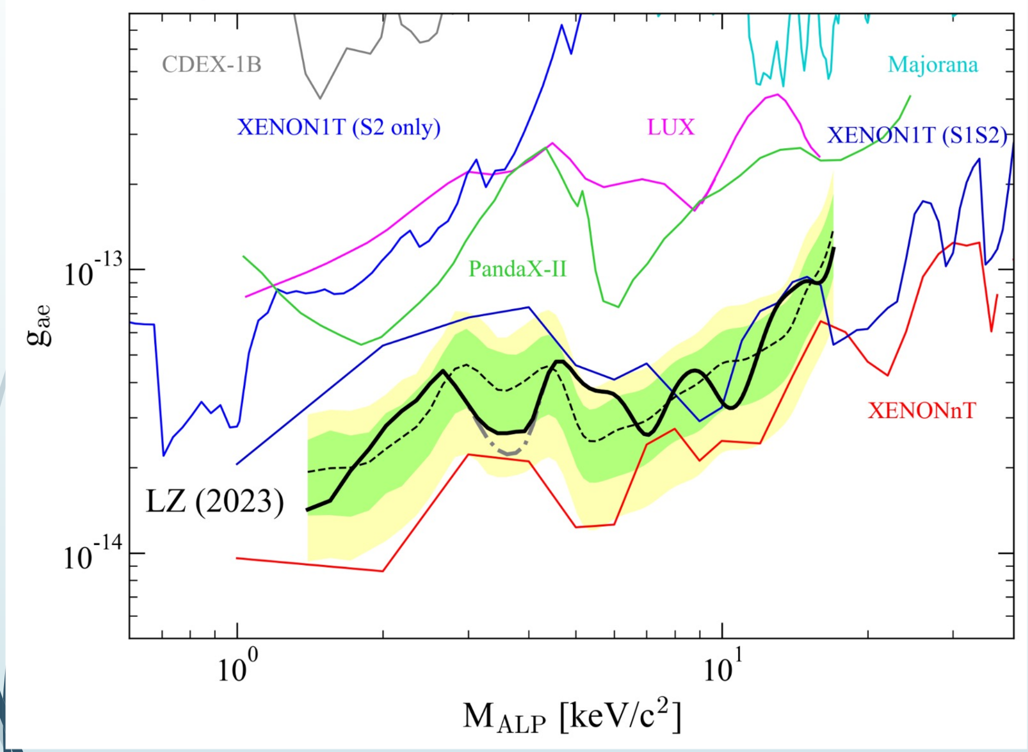
- Solar axions interaction with xenon via axio-electric effect
- LZ's 90% C.L. limit on $g_{ae} = 2.35 \times 10^{-12}$



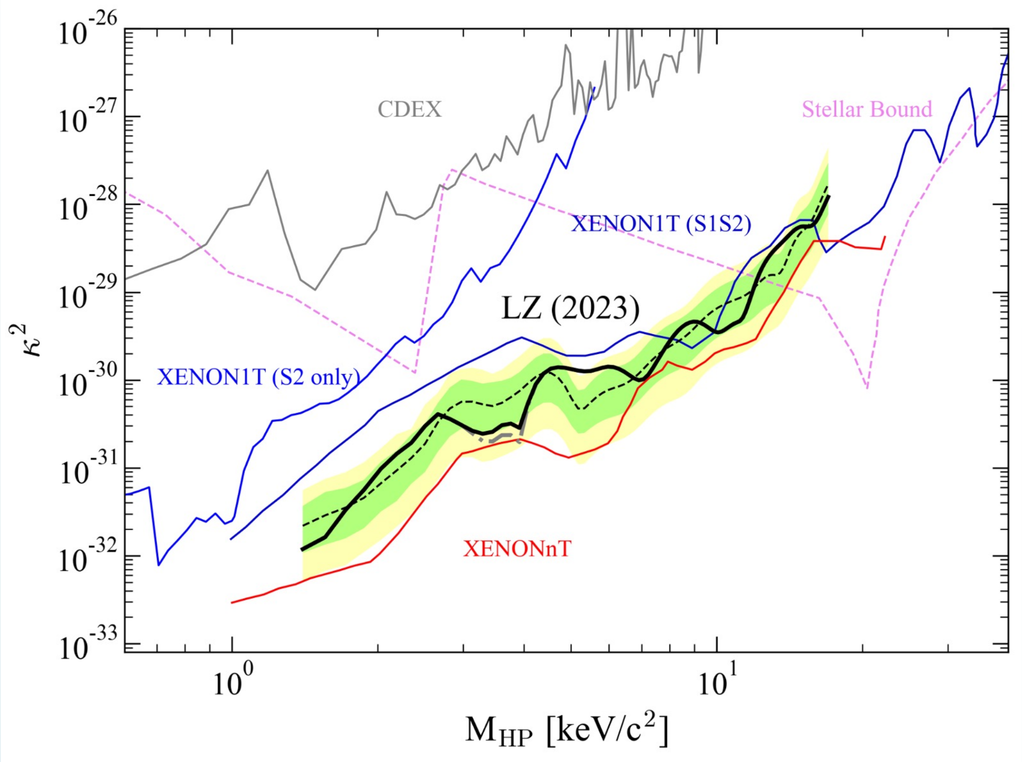
*LZ collaboration, [Phys. Rev. D **108**, 072006](#)*

ALPs + Hidden Photons

- Axion-Like Particles (ALPs):
  - Gauge pseudo-scalar boson from BSM global symmetry breaking



- Hidden (dark) Photons (HPs):
  - Gauge boson of new ‘dark’ U(1) symmetry

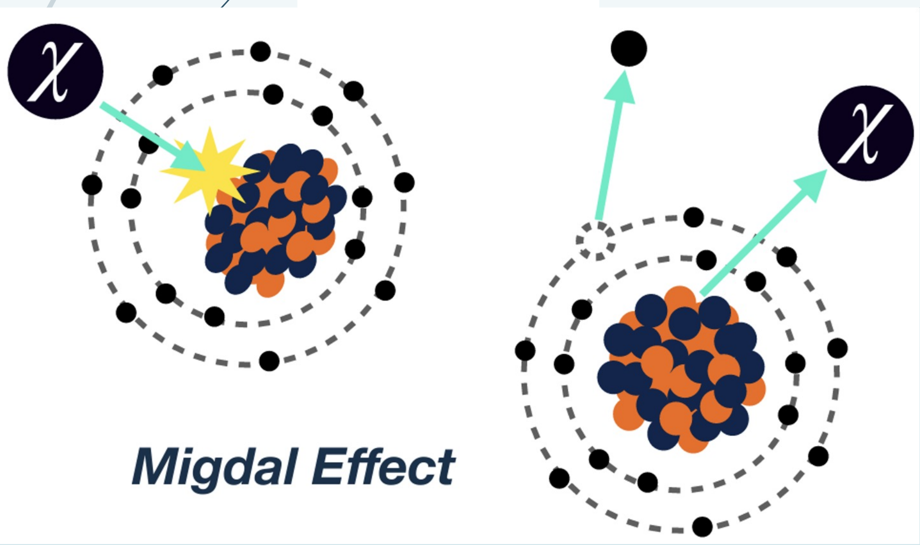


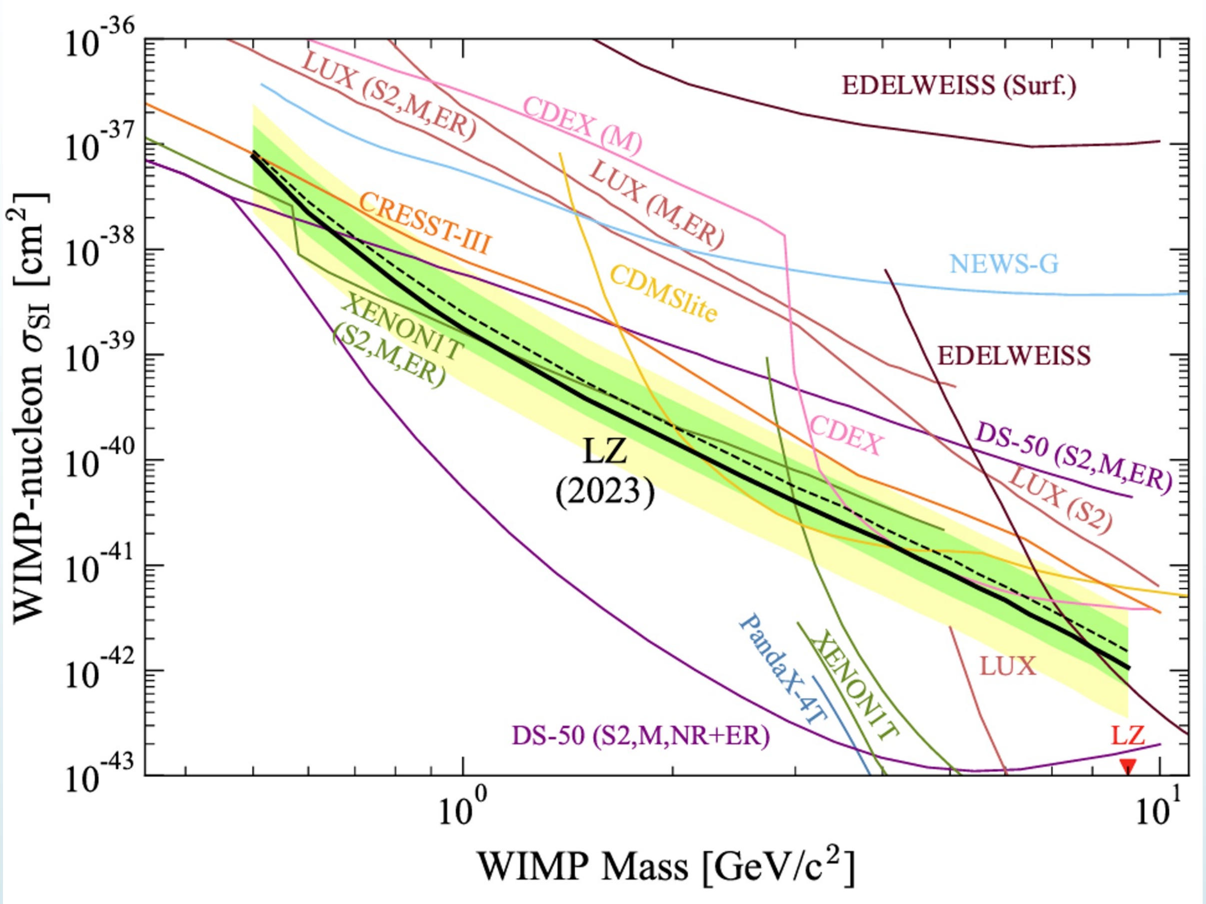
*LZ collaboration, Phys. Rev. D **108**, 072006*

Migdal effect: spin-independent WIMPs

- Can also search for WIMPs in ER channel:
  - Migdal effect: a nuclear recoil interaction accompanied by atomic excitation/ionization.

    Ref: *M. Ibe et al.*, *JHEP03,194 (2018)*

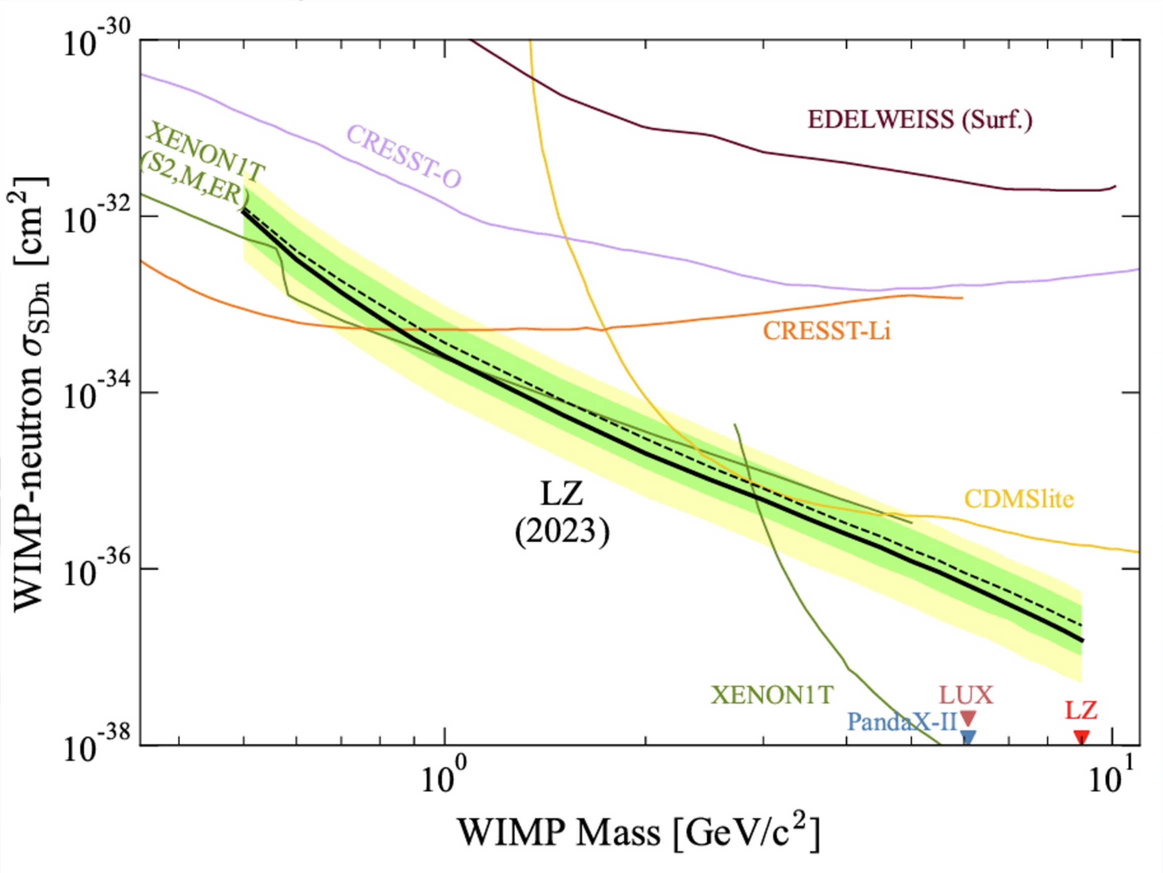


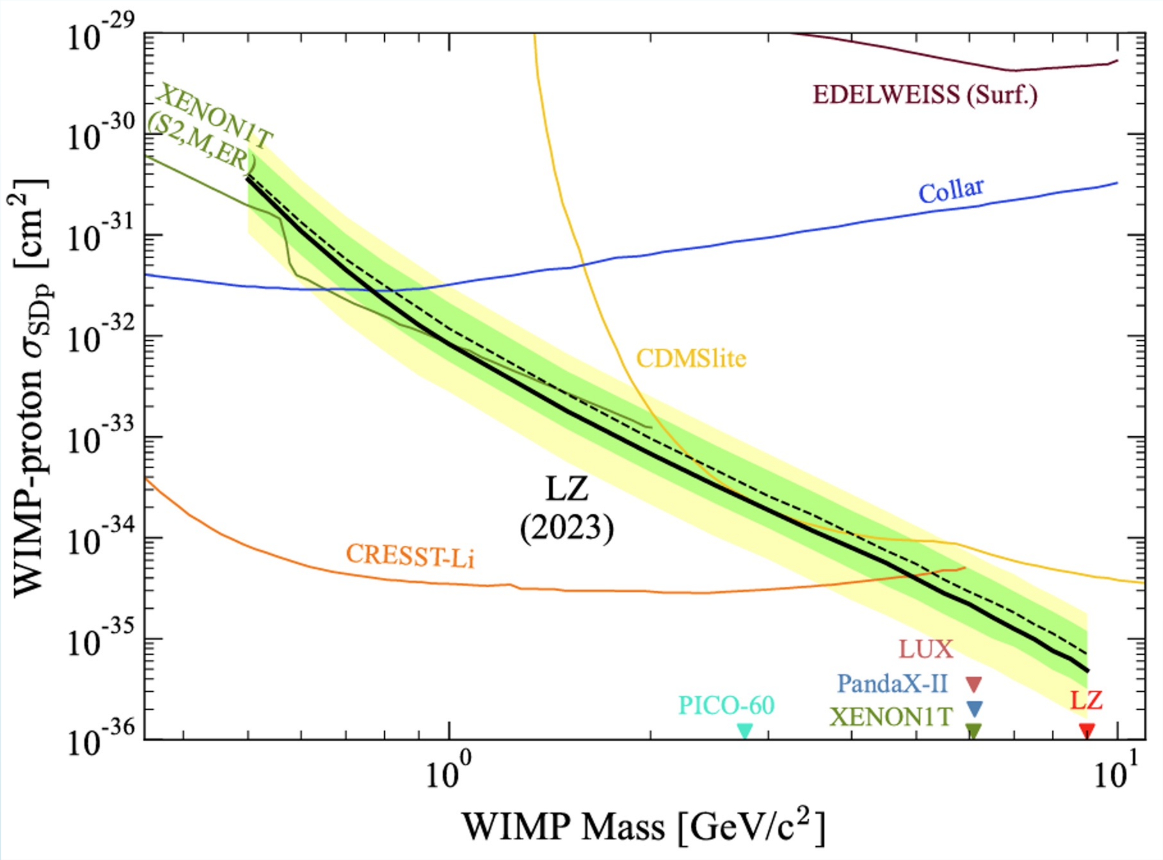


LZ Collaboration, *Phys. Rev. D **108**, 072006*

Migdal effect: spin-dependent WIMPs

- **LZ has world-leading SDn limit for WIMPs from 1.1 to 3 GeV**

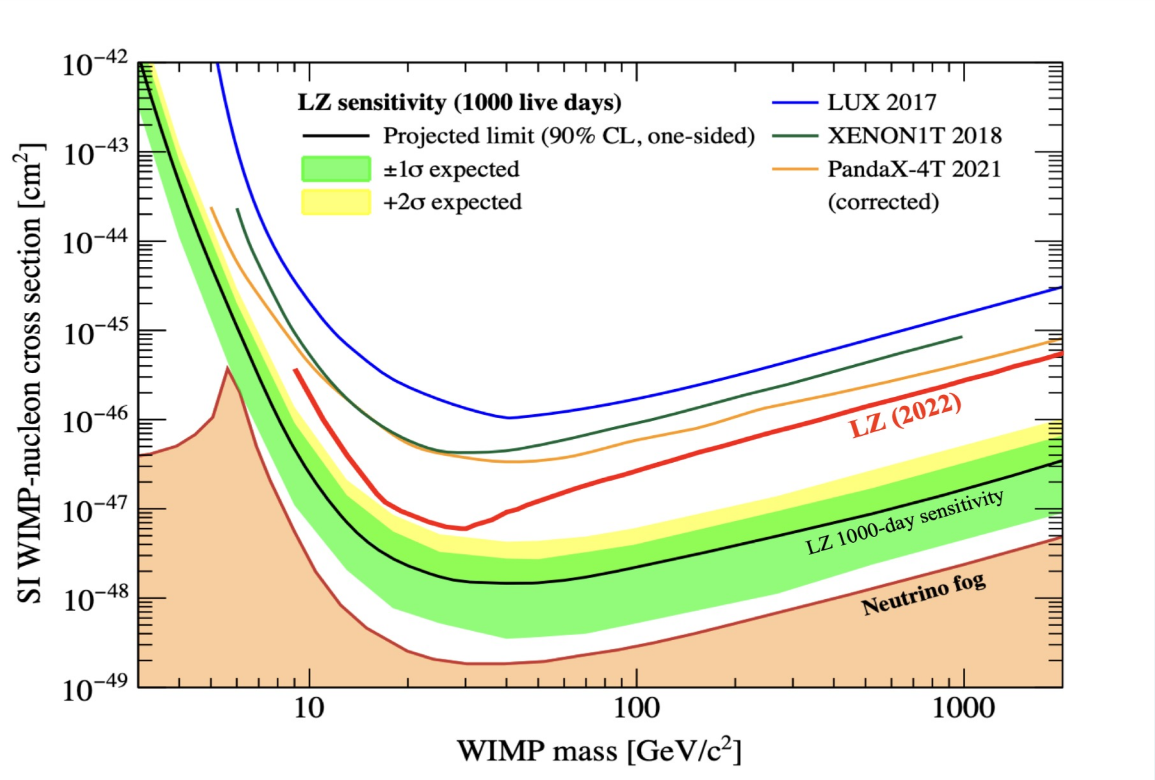




*LZ collaboration, Phys. Rev. D **108**, 072006*

LZ's Future Science Program

- Significant improvement on sensitivity to WIMP-nucleon couplings
- Neutrino studies: ^{8}B CEvNS, supernova neutrinos
- Neutrinoless double beta decay/electron capture
- …



LZ Collaboration, *Phys. Rev. D 101, 052002 (2020)*

Potential LZ Upgrades

- **HydroX:** H-doping of LZ for low-mass and spin-dependent WIMP search enhancement

- **CrystaLiZe:** Radon background reduction through freezing xenon (×500 exclusion against radon ingress)

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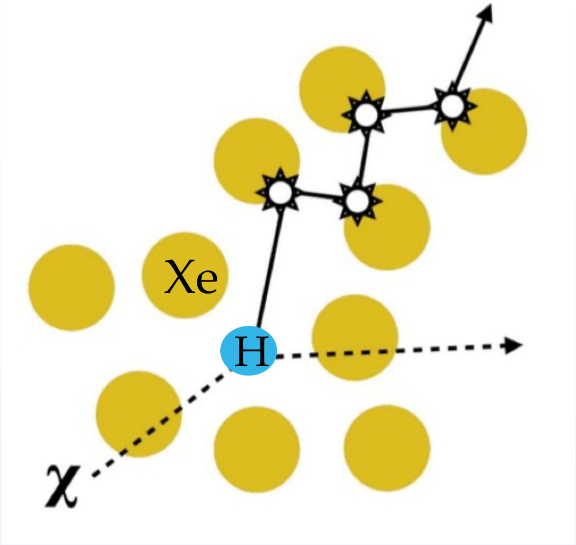

[Phys. Rev. Lett 132, 111801 (2024)]

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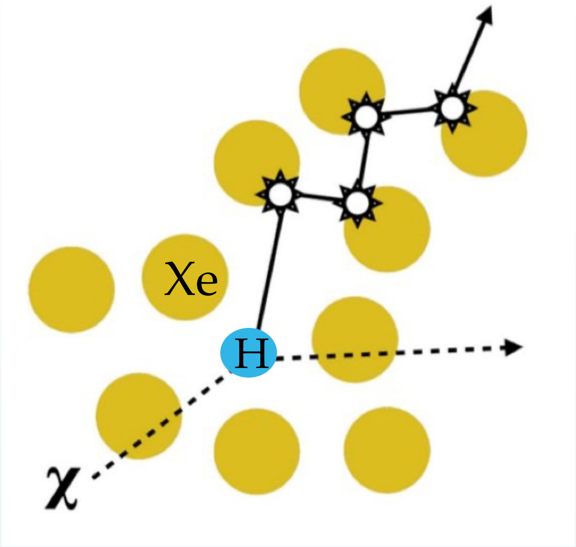
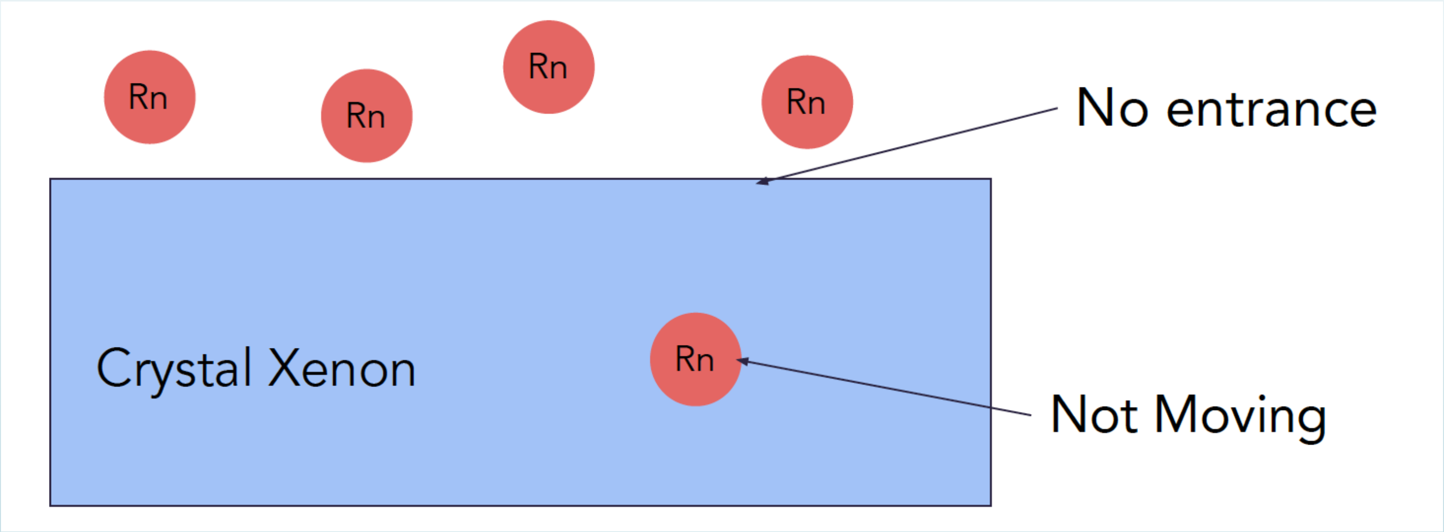


Phys. Rev. Lett 132, 111801 (2024)



Phys. Rev. D 109, L071102(2024)

Future Detectors

- Ultimate Goal: Detect Dark Matter or Reach Neutrino Floor/Fog
- XLZD consortium: joint effort from XENON, LZ, and Darwin experiments https://xlzd.org/
- Plan for a ~40-80 tonne xenon experiment
- **P5 recommended SURF expansion for a G3 experiment**
- See more details on the website and in the whitepaper: *J. Phys. G50, 013001 (2023)*