Searching for Dark Matter and Astrophysical Signals at the LUX-ZEPLIN Experiment

Trinity R. Stenhouse | trinity.stenhouse.24@ucl.ac.uk

Supervisor: Dr Amy Cottle

UCL

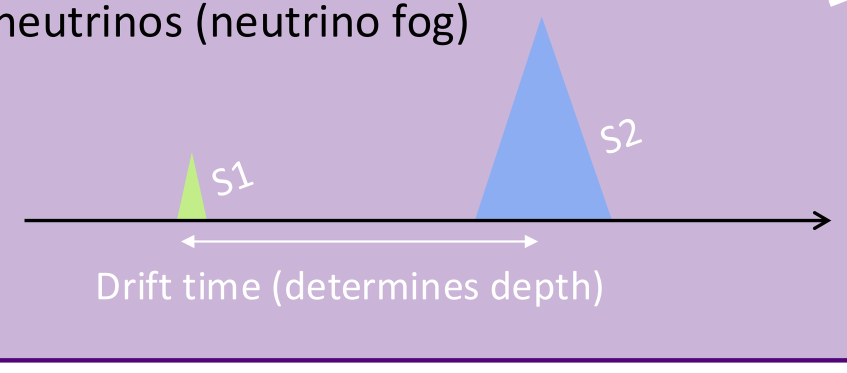
1. The LUX-ZEPLIN Detector

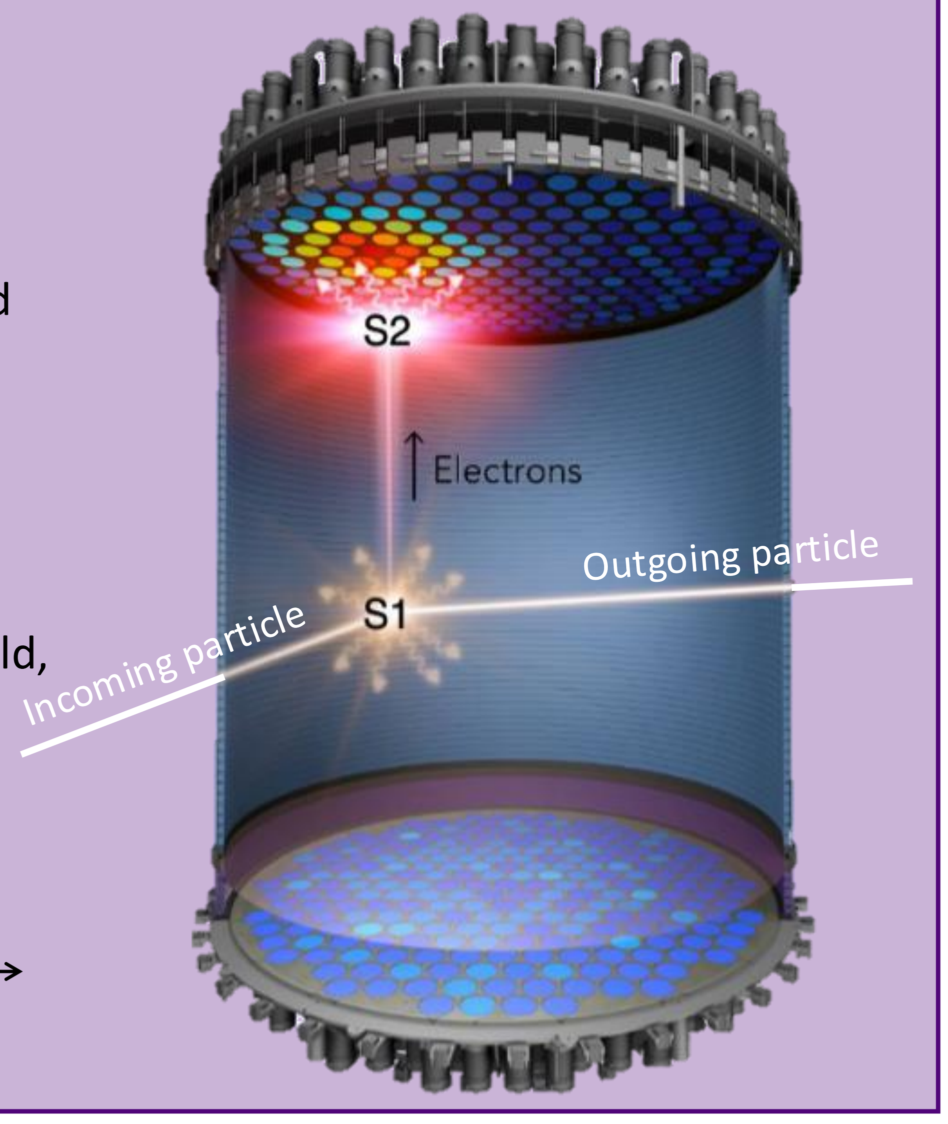
- 10 tonne (7 active) liquid Xenon time projection chamber (TPC) [1]
- S1: prompt scintillation
- S2: secondary scintillation from ionised electrons

$$\left(\frac{S2}{S1}\right)_{ER} > \left(\frac{S2}{S1}\right)_{NR}$$

allows background discrimination

- Complex backgrounds from electric field, radioactive decays and soon, solar neutrinos (neutrino fog)



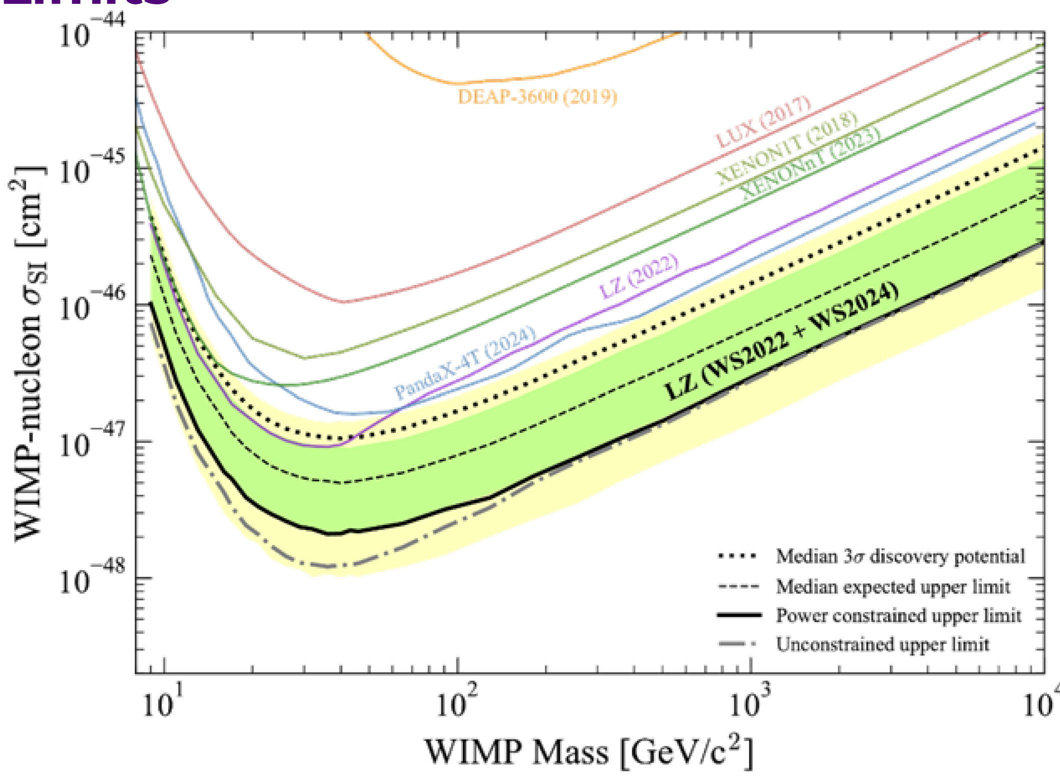


2. Weakly Interacting Massive Particles

- For correct abundance of dark matter from thermal production, expect self-annihilation cross-section of $\langle \sigma v \rangle = 3 \times 10^{-26}$ → **cold dark matter**
- LZ is optimised to detect **WIMPs**, the leading candidate for cold dark matter
- LZ uses **Xenon** as we expect maximal momentum transfer from WIMPs to Xenon

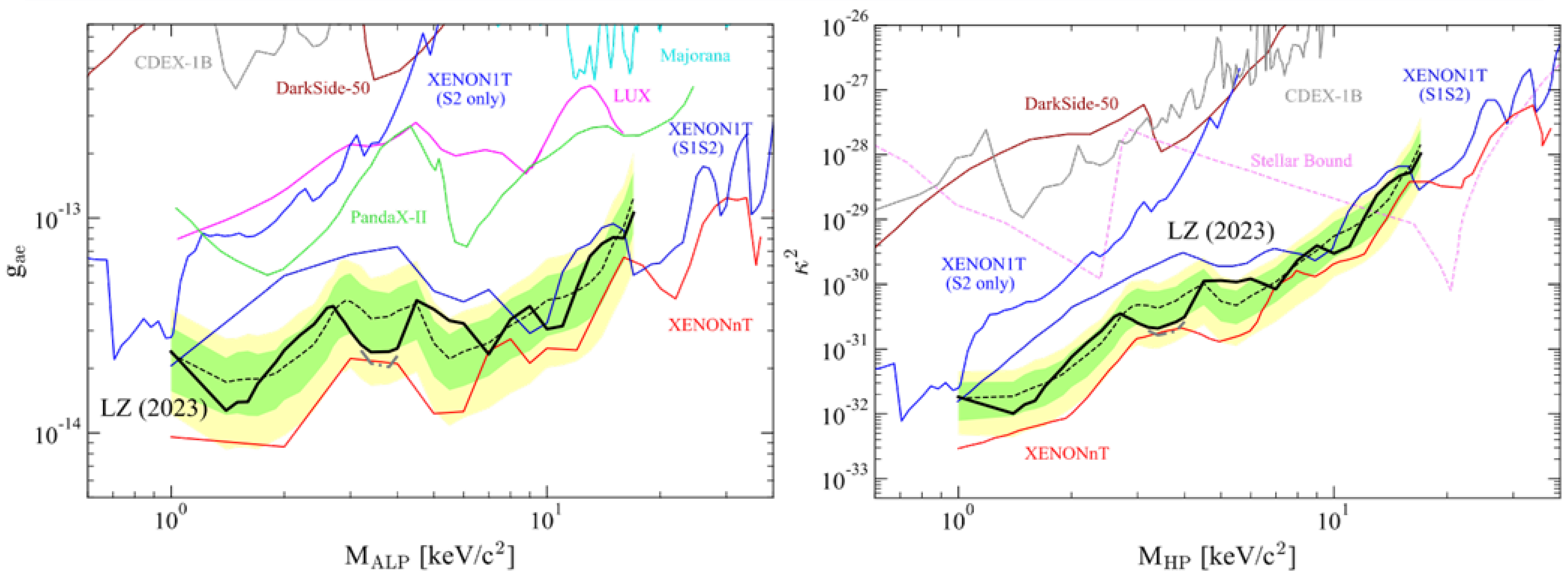
Current World-Leading Limits

- Combine WS2022 and WS2024 for total exposure of **4.2 tonne-years** [2]
- Fits performed using **frequentist profile likelihood ratio** in (S1c, $\log_{10}$S2c)*
- Good agreement with **background only** hypothesis: zero WIMPs between 9 GeV/c^2 and 100 TeV/c^2



*c=corrected – correction factor for S1 and S2 areas depending on where the signal originates in the TPC

3. Axion-Like Particles and Hidden Photons



- **Axions**: pseudo-scalar Nambu-Goldstone boson from **new U(1)** global chiral symmetry included in QCD Lagrangian, look for axion-electron coupling; this occurs via the **axio-electric effect**, analogous to the photoelectric effect
- Axion-like particles (**ALPs**): **similar pseudo-scalars** predicted to result from higher dimensional gauge fields. Generally less constrained than QCD axions – wider parameter space
- Hidden photons (**HPs**): hypothetical **new U(1)' vector gauge boson**. Their absorption by a bound electron is analogous to photoelectric effect, with photon energy replaced by hidden photon rest mass

[3]

7. What's next for LZ?

- Continuing the WIMP search (only 280 of projected 1000 live days analysed)
- Build on hints of signal from XenonNT and PandaX, our competitor experiments
- Using our data to constrain BSM physics and other dark matter candidates
- Planning for the next generation dark matter experiment – XLZD!

Acknowledgements

Many thanks to the UCL dark matter group for all their help and support, and of course my supervisor Dr Amy Cottle.

4. Magnificent CEvNS

- Coherent elastic neutrino nucleus scattering (CEvNS). Low energy neutrinos (E_ν < 100MeV) coherently scatter off the Xenon nucleus rather than individual nucleons
- We first expect to encounter ^{8}B solar neutrinos. Cross-section predicted by SM, deviation from a $\propto N^2$ prediction can be a signature of BSM physics

E_ν: neutrino energy
T: NR energy
M: Nuclear mass
$Q = \sqrt{2MT}$: Momentum transfer

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

Fermi Constant

Form factor: F=1 → full coherence

Mixing angle $\theta_W \sim 0.23$

Kinematics: ping-pong ball hits bowling ball

Weak nuclear charge $Q_W = N - (1 - 4\sin^2\theta_W)Z$

$\sin\theta$ = 0.231, so protons unimportant → $\frac{d\sigma}{dT} \propto N^2$

- Xenon is neutron rich, M=129-132 for >72% of isotopes

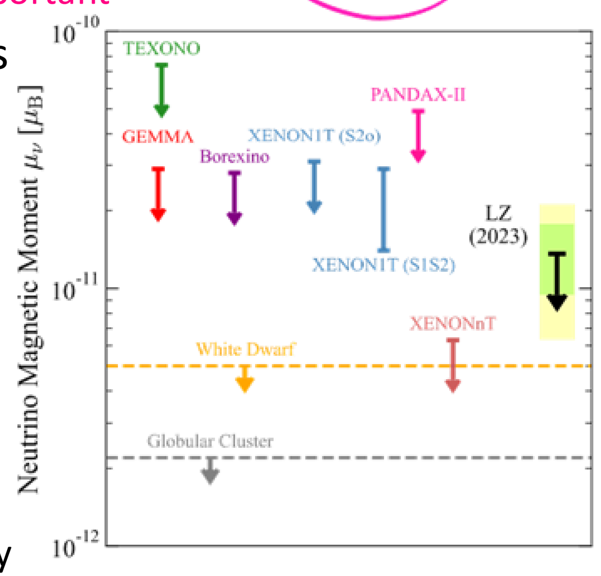
Physics reach of CEvNS

Sterile neutrinos?

Majorana neutrinos?

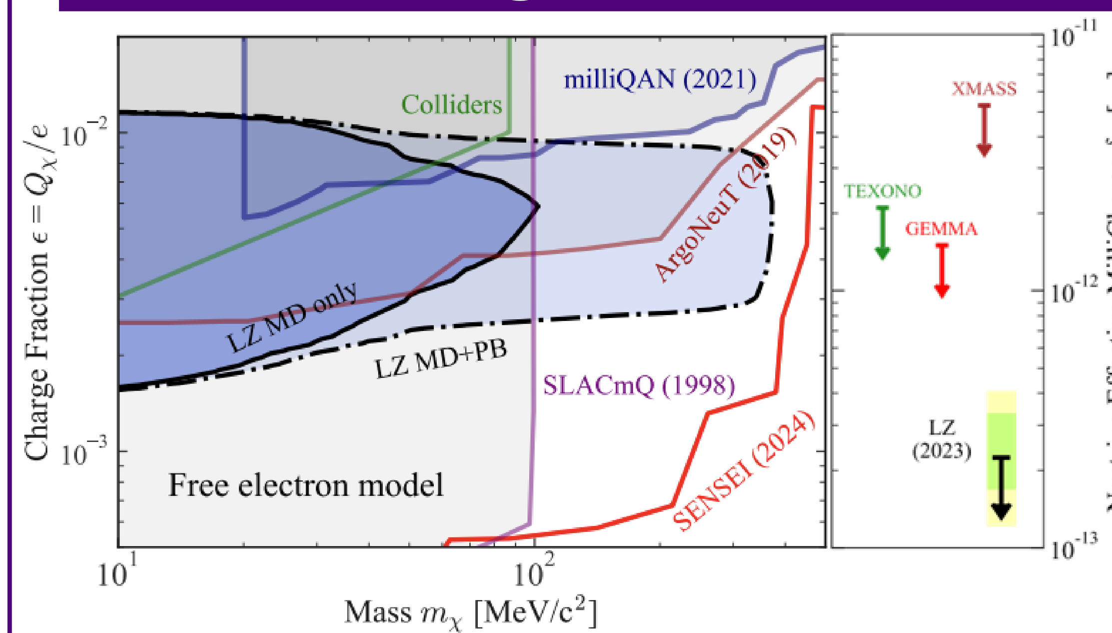
Majorana masses would enhance NMM up to potentially LZ energies. We would measure lower CEvNS σ_{Weak} (NR) especially at low recoil energies, as EM interactions would dominate $\sigma_{NMM} \propto \left(\frac{\mu_\nu^2}{T}\right)$, low energy ER measurements published

Non-Standard Interaction (NSI) Measurements



90% C.L. upper limit on effective neutrino magnetic moment (NMM)

5. Millicharged Particle Searches



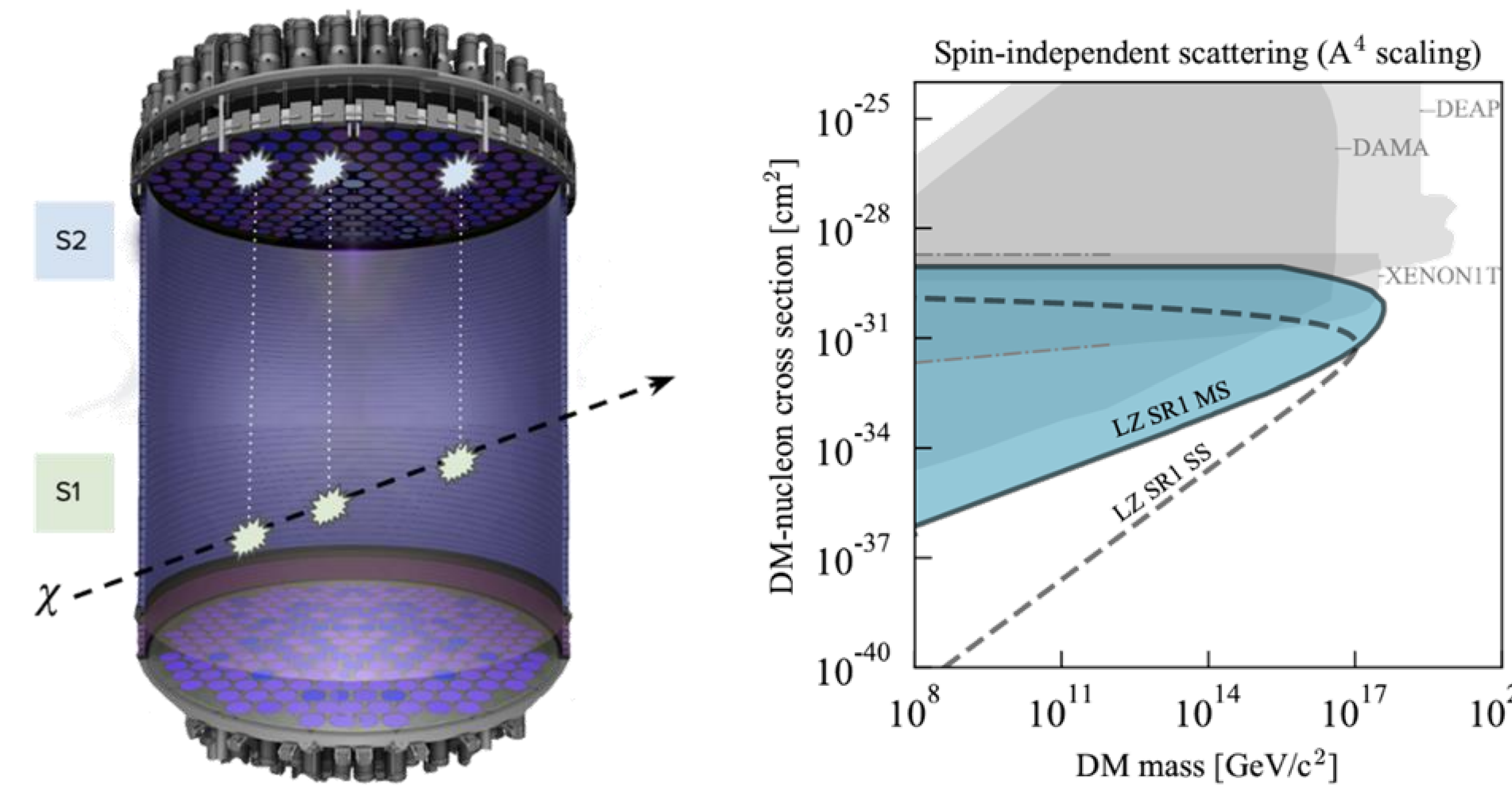
90% C.L. limit on fractional charge ϵ = Q_χ/e derived from atmospheric production channels as a function of mass m_χ, using free electron model for interaction of mCP and electrons (left), 90% C.L. upper limit on neutrino effective millicharge (right)

- mCPs: particles with a fraction of electron's charge $Q_\chi = e\epsilon$
- Important for string theory, GUTs and dark sector studies
- We consider cosmic ray proton atmospheric interactions and mCPs produced by meson decay and proton bremsstrahlung

[3,4]

6. Heavy Dark Matter Searches

- **Planck-scale dark matter** candidates with larger scattering cross-sections—Multiply Interacting Massive Particles (**MIMPs**)
- Signal topology: characteristic track of events; no such events found in 2022 dataset after data selection cuts applied – 2024 in progress
- Demonstrated competitive sensitivity in search for Planck-scale dark matter



[5]

8. Summary

- LZ has set the world leading limit on WIMP cross section, σ_{SI} = 2.2 × 10^{-48}cm^2 at 43GeV/c^2 in the WS2024 analysis
- Using the detector's exceptional sensitivity, it is possible to explore other rare physics phenomena, many of which have been overviewed here
- We are currently analysing the WS2024 dataset attempting to find low mass WIMPs and build on hints of signal from XenonNT and PandaX

References

[1] LZ Collaboration, "LUX-ZEPLIN (LZ) Technical Design Report." arXiv, 2017. https://doi.org/10.48550/arXiv.1703.09144.
[2] LZ Collaboration, "Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment." arXiv, October 17, 2024. https://doi.org/10.48550/arXiv.2410.17036.
[3] LZ Collaboration, Aalbers, J., et al. "A Search for New Physics in Low-Energy Electron Recoils from the First LZ Exposure." arXiv, 2024. 10.1103/PhysRevLett.133.221801.
[4] LZ Collaboration, "First Search for Atmospheric Millicharged Particles with the LUX-ZEPLIN Experiment." arXiv, December 6, 2024. https://doi.org/10.48550/arXiv.2412.04854.
[5] LZ Collaboration, "New Constraints on Ultraheavy Dark Matter from the LZ Experiment." Physical Review D 109, no. 11 (2024): 112010. Published February 13, 2024. https://doi.org/10.48550/arXiv.2402.08865.