The LZ high energy recoil event and possible dark matter explanations

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Helsinki, October 2026

Contents

The LZ event

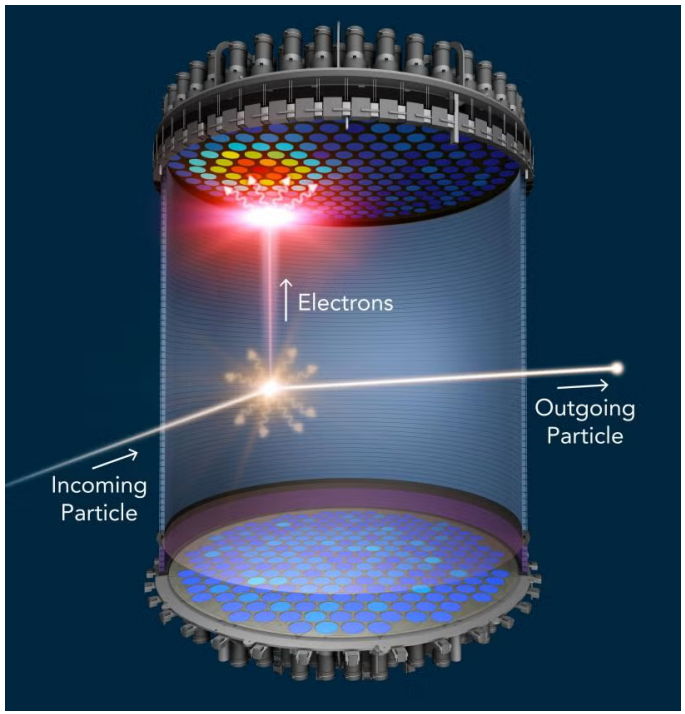
Inelastic DM

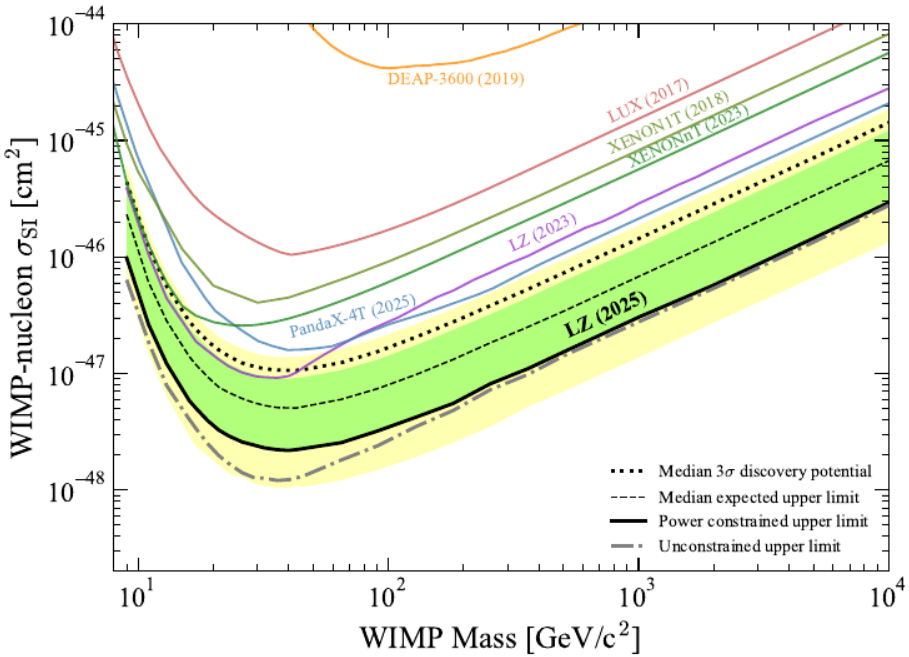
Boosted DM

Conclusions

The LZ experiment

- The Lux-Zeplin experiment is a multi-ton liquid Xenon time projection chamber, located in the Sanford underground research facility in South Dakota.
- First science run in 2021. World-leading bounds on WIMP dark matter published[1] in 2025, based on 4.2 ton years exposure (280 days).

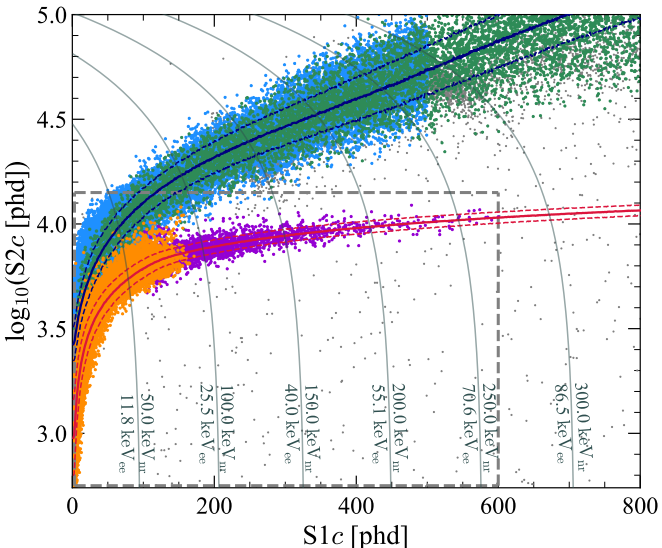


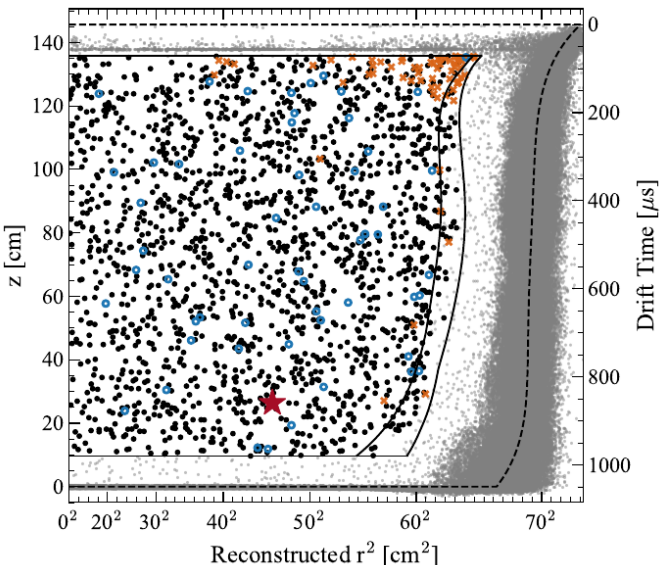


[1] LZ collaboration: ArXiv:2410.17036

The LZ experiment

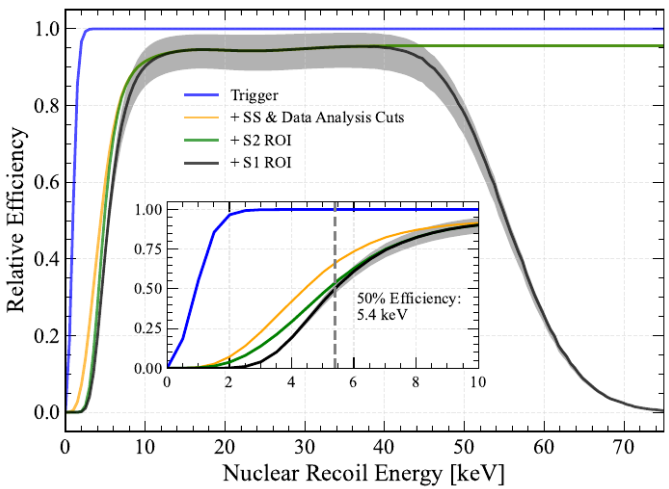
- The experiment measures two signals: prompt scintillation (S1) and delayed electroluminescence (S2).
- S1 is generated by the initial scattering and measures the energy deposited in the event.
- S2 is generated by electrons drifted to the gaseous phase on the top of the tank, and measures the ionization efficiency of the event.
- The drift time between S1 and S2 allows to determine the z-coordinate of the event, while the PMT hit patterns allows to reconstruct the (x, y)-position.
- Nuclear and electron recoils can be identified based on the S2/S1-ratio.

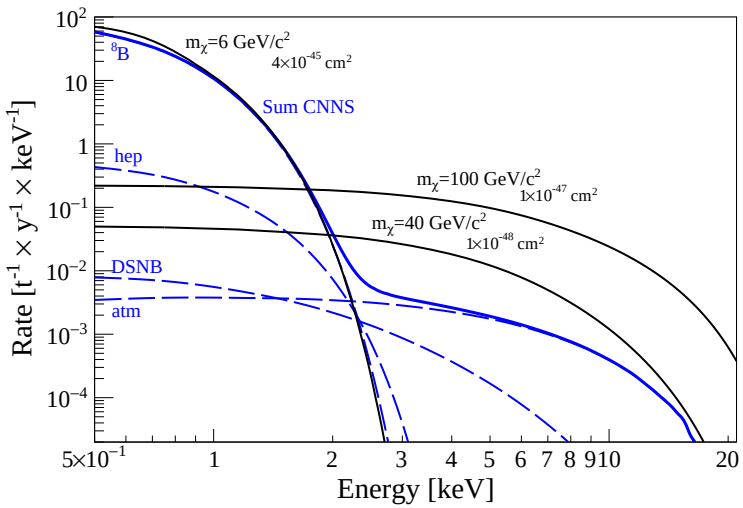




The LZ experiment

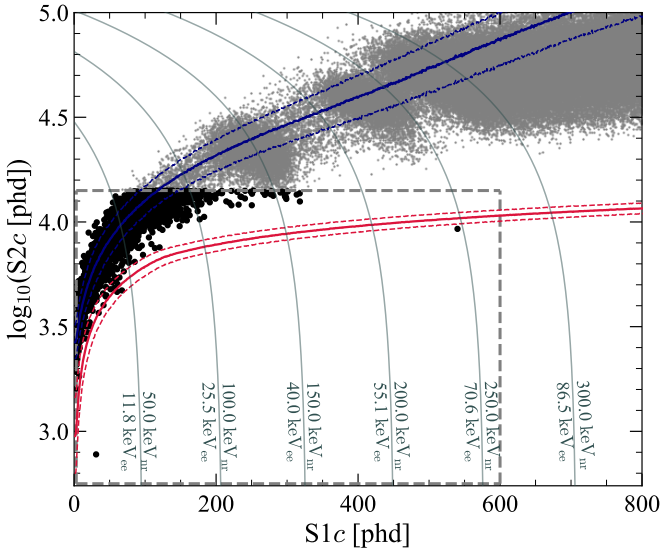
- The standard WIMP search looks for events in the nuclear recoil region, below S1 < 80 phd.
- This search has $> 50\%$ efficiency for nuclear recoils between 5.4 keV and 55 keV, with $\sim 95\%$ efficiency in most of that range.
- In this low-energy window no excess is observed, resulting in world-leading constraints for spin-independent (SI) DM.
- The focus on the low recoil energy region is justified due to the expected DM spectrum for SI scattering.

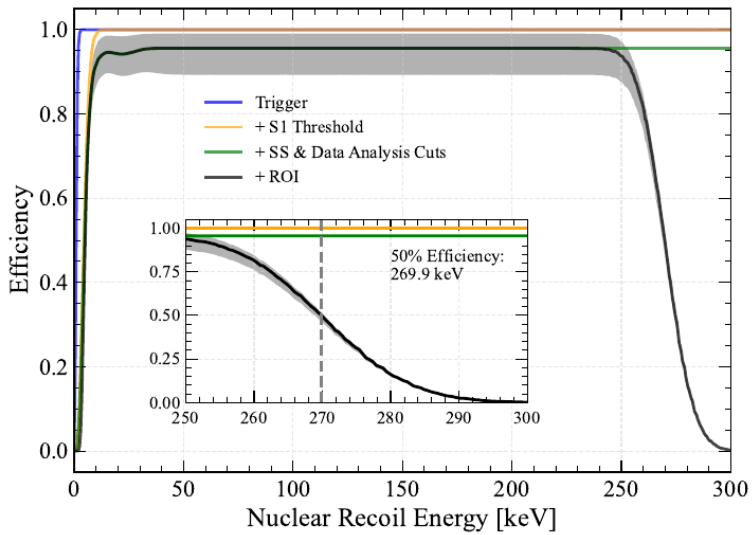




High recoil energy search

- To target models beyond the SI scenario, LZ performed an analysis[2] with extended nuclear recoil energy window, using 2.84 ton years exposure (220 days).
- The search extends the S1-window to 600 phd, with $> 50\%$ efficiency below 270 keV nuclear recoil energy.
- One event is observed at 248 keV nuclear recoil energy, 1.5σ below the median of the NR-band in the (S1,S2)-plane.
- The PMT pulse shape is consistent with a nuclear recoil event.

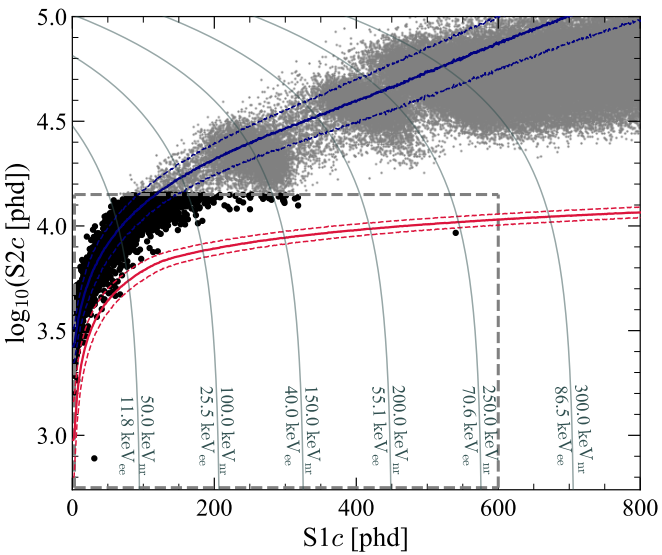


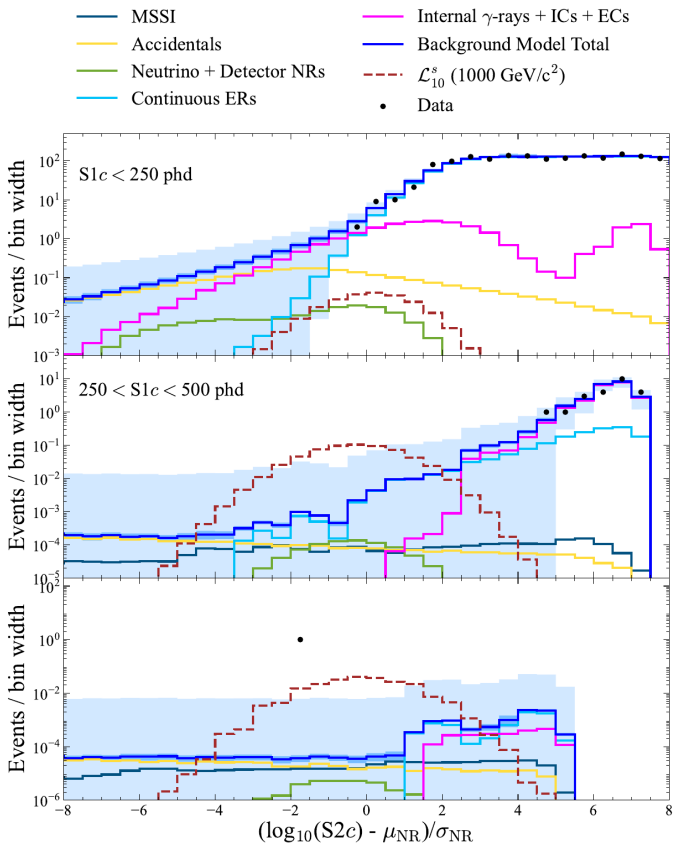


[2]LZ collaboration: ArXiv:2609.02823

High recoil energy search

- At high energy, the separation between NR and ER bands is large, and there is almost no expected background.
- Based on likelihood ratio test, LZ reports 3.4σ local significance in favor of various DM models vs background only, with 2.6σ global significance after look elsewhere effect.





Contents

The LZ event

Inelastic DM

Boosted DM

Conclusions

Inelastic DM

- The main challenge in explaining the LZ event with dark matter is to avoid recoil events at lower energy, where LZ sees no excess.
- Inelastic DM was among the first proposed solutions[3].
- The nuclear recoil event rate is given by

$$\frac{dR}{dE_{\rm nr}d\Omega} = \frac{1}{64\pi^2}\frac{\rho_\chi}{m_\chi^3 m_T^2}\int \langle|\mathcal{M}|^2\rangle \delta(\vec{v}\cdot\hat{q} - v_{\rm min}) f(\vec{v}) d^3v,$$

  which for velocity-independent $\mathcal{M}$ yields an integral of $f(v)/v$ from $v > v_{\rm min}$.

- $v_{\rm min}$ is the minimum DM velocity reguired to give nuclear recoil energy $E_{\rm nr}$, given by

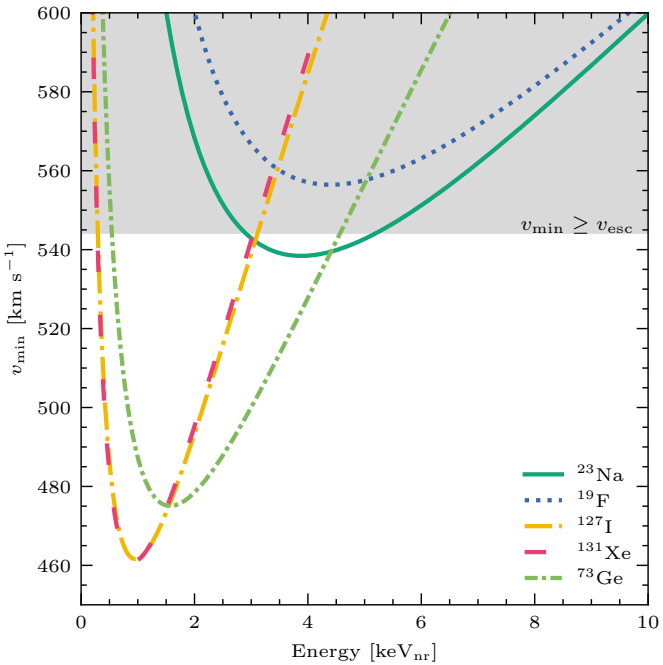
$$v_{\rm min} = \frac{1}{\sqrt{2m_T E_{\rm nr}}}\left(\frac{m_T E_{\rm nr}}{\mu} + \delta\right),$$

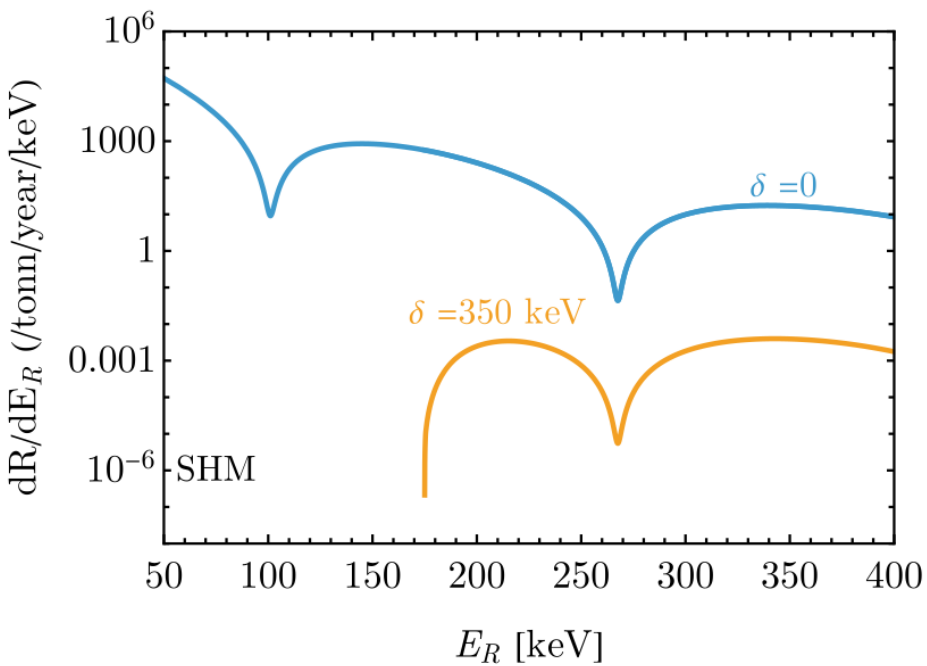
  where δ is a mass splitting between initial and final state DM particles. For elastic scattering $\delta = 0$.

[3] See e.g. Fan and Reece: ArXiv:2609.01504

Inelastic DM

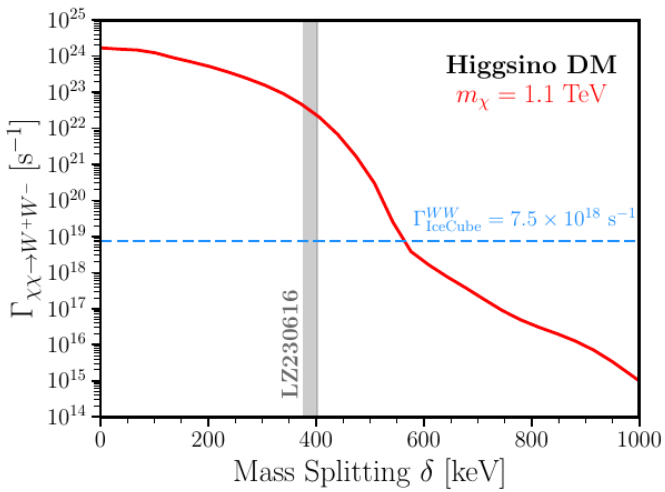
- For $\delta > 0$, nuclear recoils can be kinematically allowed only within a recoil energy window.
- In MSSM, Higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$ naturally have a small mass splitting and couple off-diagonally to the Z-boson, therefore disallowing elastic scattering and giving rise to inelastic DM.
- It was quickly noticed that MSSM Higgsino with $m_{\rm DM} = 1.1$ TeV, $\delta = 350$ keV reproduces the correct relic abundance and a nuclear recoil spectrum in Xenon that can fit the LZ event.





Solar neutrino constraints

- The Higgsino model is constrained due to IceCube observations of the solar neutrino flux.
- The gravitational pull of the sun accelerates DM particles to higher velocities, allowing more efficient inelastic scattering in the sun.
- The scattered DM particles lose energy and become captured by the sun. Eventually their number density inside the sun grows and they begin to annihilate, resulting in observable neutrino flux.
- Non-observation of such flux by IceCube rules out the basic scenario[4]. However, some non-thermal models might still be viable, depending on the DM velocity distribution. Also inelastic DM models not based on MSSM could remain viable.



[4] See e.g. Nguyen, Linden, Hooper: ArXiv:2609.11833

Contents

The LZ event

Inelastic DM

Boosted DM

Conclusions

Boosted DM

- Boosted DM refers to scenarios, where a small fraction of DM is excited to high velocities, well above the galactic escape velocity[5].
- The typical boost mechanisms are
  - Decaying DM, where the daughter particle obtains a large kinetic energy.
  - DM scattered by energetic astroparticles, such as cosmic rays, supernova neutrinos etc.
- Boosted DM can increase the available recoil energy. However, for SI scattering, the majority of events are still expected at low recoil energy.
- Boosted DM with momentum dependent interactions can lead to a spectrum that peaks at high recoil energy[6].

[5] Bringmann and Pospelov: ArXiv:1810.10543

[6] See e.g. Kannike, Raidal and Strumia: ArXiv:2609.07742, Heikinheimo and Zimmermann: ArXiv:2609.11600

Boosted DM flux

- For cosmic-ray boosted DM, the boosted flux is given by

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi}{m_\chi}\int_{T_i^{\rm min}}^{\infty}\frac{d\Phi_{\rm LIS}}{dT_i}\frac{d\sigma_{\chi i}}{dT_\chi}dT_i,$$

$$T_i^{\rm min} = \left(\frac{T_\chi}{2} - m_i\right)\left[1 \pm \sqrt{1 + \frac{2T_\chi(m_i+m_\chi)^2}{m_\chi(2m_i - T_\chi)^2}}\right],$$

  where T_χ (T_i) is the kinetic energy of the DM (CR) particle. $\Phi_{\rm LIS}$ is the CR flux, obtained from AMS measurements.

- The DM-nucleus differential cross section is

$$\frac{d\sigma_{\chi i}}{dT_\chi} = \frac{m_\chi m_i}{4\pi T_i}\left[\frac{1}{2j_i+1}\frac{1}{2j_\chi+1}\sum_{\rm spin}|\mathcal{M}^{\rm Nuc}|^2\right].$$

- $\mathcal{M}^{\rm Nuc}$ is the DM-nucleus scattering amplitude, which can be expressed in terms of nuclear response functions in non-relativistic effective theory[7].

[7] Anand, Fitzpatrick and Haxton: ArXiv:1308.6288

Boosted DM recoil rate

- The nuclear recoil rate due to boosted DM is

$$\frac{dR}{dE_{\rm R}} = \sum_t \epsilon N_t \int_{T_\chi^{\rm min}}^{\infty} \frac{d\Phi_\chi}{dT_\chi} \frac{d\sigma_{\chi t}}{dE_{\rm R}} dT_\chi,$$

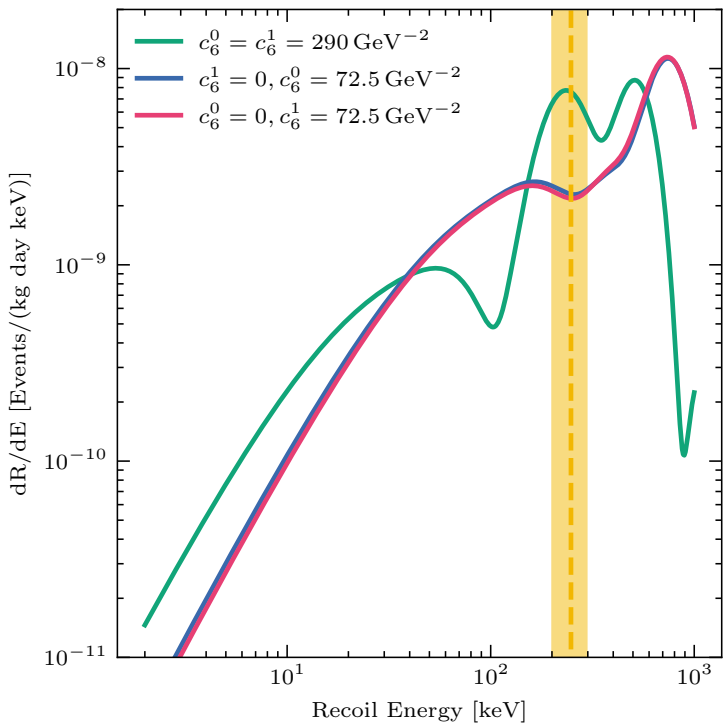
  where the differential cross section is as above.

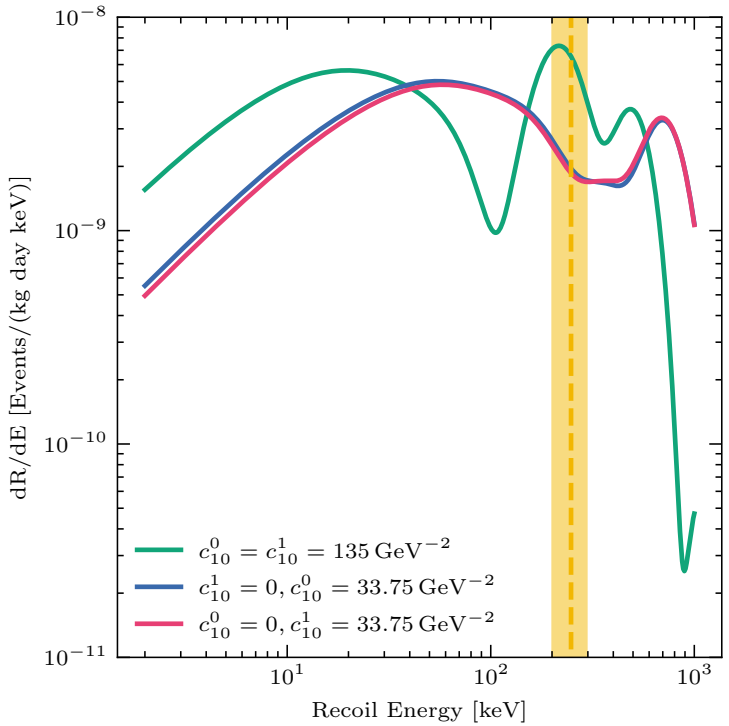
- The non-relativistic effective theory operators for DM-nucleus interactions are

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$
$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$
$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$
$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$
$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

Boosted DM recoil rate

- For example, the operators $\mathcal{O}_6$ and $\mathcal{O}_{10}$ yield differential cross sections that scale as q^4 and q^2, respectively.
- This dependence enters twice, in the DM-CR scattering and in the DM-Xe scattering in LZ. The resulting spectrum has a maximum close to the observed event.



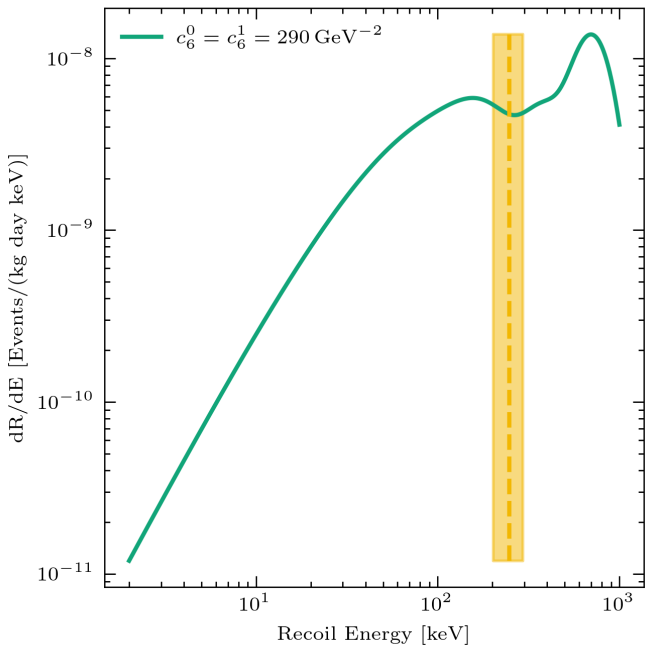


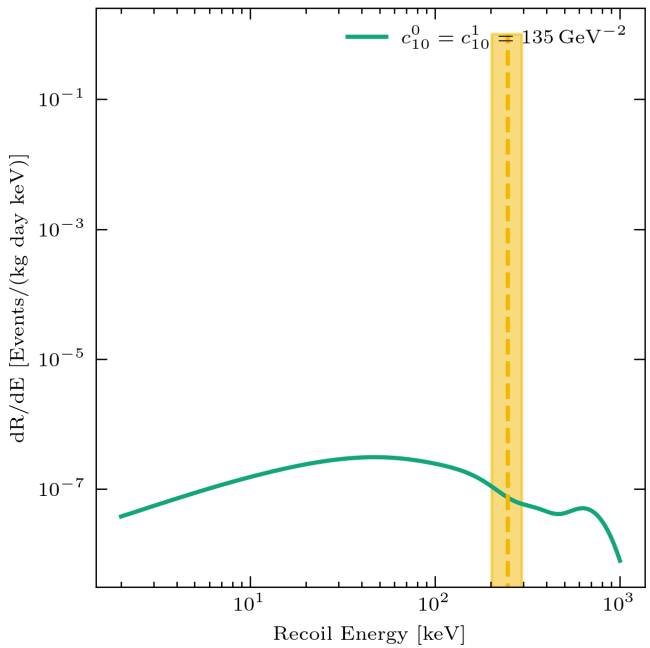
Constraints from neutrino experiments

- Neutrino experiments (e.g. KamLAND, JUNO) that utilize liquid scintillators as target materials often have kilotonne-scale target mass, but are typically not sensitive to DM as the energy threshold in these experiments is $\mathcal{O}(\text{MeV})$.
- The above scenario of boosted DM with momentum dependent interactions can however produce a recoil spectrum in Hydrogen target that reaches several MeV.
- For Hydrogen nucleus (i.e. free proton), there is no exponential suppression at high momentum transfer due to the form factor.
- The organic liquid scintillators are hydrocarbons. The recoil rate in Hydrogen nuclei rules out the above model.

Constraints from neutrino experiments

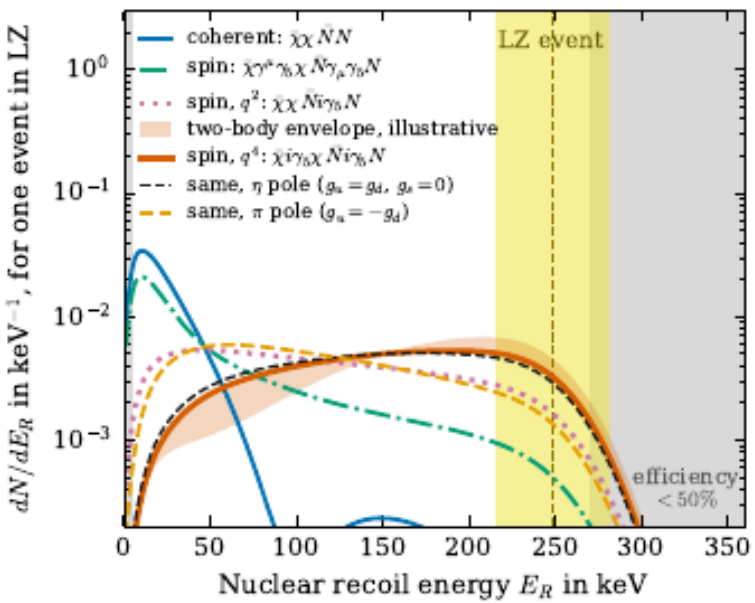
- The scattering in Hydrogen can be avoided by tuning the DM-Nucleon couplings so that DM only couples to the neutron. Then the CR boosting mechanism must be via light nuclei with odd neutrons, such as Be9.
- The resulting spectrum for $\mathcal{O}_6$ and $\mathcal{O}_{10}$ is a worse fit compared to proton-only coupling.
- Furthermore, even this scenario is likely ruled out via the deuteron (heavy water) target in SNO.





Constraints from neutrino experiments

- The constraints from neutrino experiments can be avoided if the DM is heavier. However, then the non-boosted halo component becomes visible in LZ and other experiments.
- Boosted DM from decaying parent particle[8] can avoid the constraints, as then the spectrum is (nearly) monoenergetic.
- For example, a 10 GeV DM particle χ_1 with a mass splitting of ~ 130 MeV that decays into $\chi_2 + S$ with lifetime $\sim 10^5$ times age of the universe, where S is a light dark sector particle, produces an acceptable spectrum.



[8] See e.g. Kannike, Raidal and Strumia: ArXiv:2609.07742

Contents

The LZ event

Inelastic DM

Boosted DM

Conclusions

Conclusions

- The LZ experiment has observed a single event that looks like a nuclear recoil at 248 keV.
- It is difficult to explain the event with known backgrounds.
- The LZ already has more than twice as much unanalyzed data than what was used for this analysis. Also XenonNT should be sensitive to the same signal.
- Main DM candidate models are inelastic DM or boosted DM. Both face constraints due to various neutrino experiments, but there are ways to avoid them.
- If more events would be found in future analyses, this would allow to identify the models that can better reproduce the spectrum.