



THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

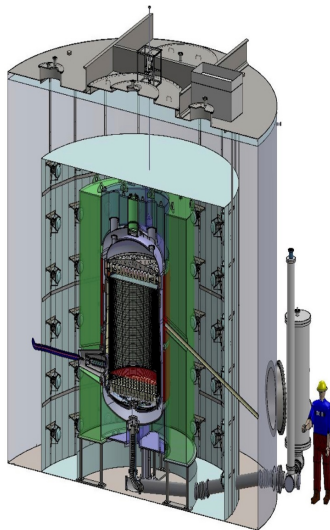
Discussion: Search for dark matter particle interactions in an extended nuclear recoil energy window with the LUX-ZEPLIN (LZ) experiment

Adrian Šaina

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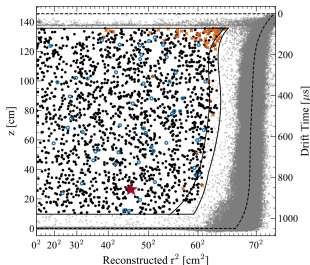
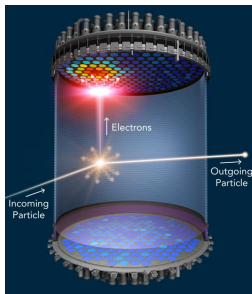
LUX Zeplin: the entire detector

- Dual-phase (**TPC**): 7 tonnes of liquid xenon target material surrounded by PMTs at top and bottom
- LXe outer **Skin** veto: scintillation readout to identify γ -rays entering or exiting the TPC
- TPC and Skin surrounded by **outer detector** veto: 229 tonnes of ultra-pure water + 17 tonnes of gadolinium-loaded liquid scintillator → shielding and detection of γ -rays, neutrons and muons



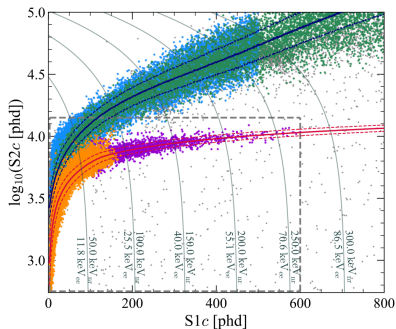
LUX Zeplin: the TPC

- Electric field from electrodes causes ionised electrons to drift towards liquid-gas interface
- PMTs detect prompt scintillation light (S1) and delayed electroluminescence light (S2)
- S2 hit pattern allows for positional reconstruction in (x, y) plane, time interval between S1 and S2 pulses provides z : FV definition



Signal discrimination in the TPC

- Determination of recoil types relies on the ratio of S1 and S2 signal strengths, measured in photons detected (phds)
- Electron recoils: γ -ray and β -decay interactions
- Nuclear recoils: WIMP-like dark matter, neutrons and coherent scatterings of neutrinos



Usual searches for WIMPs

- Usual direct detection analyses focus on spin-dependent and spin-independent parametrisations of the interaction
- In general, event rate of nuclear recoils is equal to:

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi} \int d^3v f(v) v \frac{d\sigma}{dE_R}$$

Spin-independent scattering:

- No coupling to WIMP and nucleon spins, independent of momentum transfer: $\mathcal{M} \propto A \rightarrow \sigma \propto A^2$
- $\frac{d\sigma}{dE_R} \propto A^2 F^2(q)$

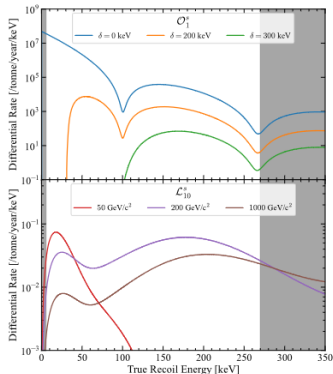
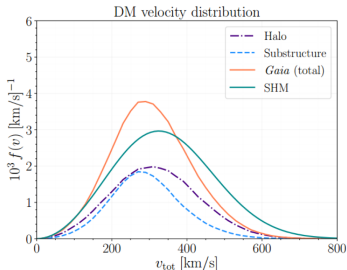
Spin-dependent scattering:

- Coupling to nucleon spin $\rightarrow \frac{d\sigma}{dE_R} \propto S_A(q)$

SI and SD scattering recoil spectra

Event rate suppressed at larger recoil energies due to two reasons:

1. halo kinematics: high recoil energy requires higher velocity
2. form factors/structure functions



This analysis: NREFT approach

- Treat WIMP-nucleon interaction as four-particle contact interaction:

$$\mathcal{L} = \chi \mathcal{O}_\chi \chi N \mathcal{O}_N N$$

- These operators can be reduced to a basis of four Hermitian quantities:

$$i \frac{\vec{q}}{m_N}, v^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu}, S_\chi, S_N$$

- $\mathcal{O}_1 = 1 \rightarrow$ SI model, $\mathcal{O}_4 = S_\chi \cdot S_N \rightarrow$ SD model
- These can be further modified to allow for inelastic scatters $\rightarrow$ mechanism that leads to suppression of low energy recoils
- this analysis tested elastic recoils arising from $\mathcal{L}_1 - \mathcal{L}_{20}$ and inelastic recoils from $\mathcal{O}_1^{s,v}$ and $\mathcal{O}_4^{s,v}$



The data sample

- 220 days of livetime between 27th March 2023 and 1st of April 2024
- WIMP ROI: S1c in the range 3 – 600 phd, S2c in the range 102.75 – 104.15 phd
- Fiducial volume of 4.71 ± 0.08 tonnes
- signal efficiency of nuclear recoils: 96%
- Application of vetoes to further reduce γ -ray and neutrino background:
 - prompt veto: events with a signal of size > 2.5 phd in the Skin within $\pm 0.25 \mu\text{s}$ of the TPC S1, or 4.5 phd in the OD within $\pm 0.3 \mu\text{s}$
 - delayed veto: events with Skin or OD signals above 300 or 200 keV, respectively, that are within $600 \mu\text{s}$ of the TPC S1

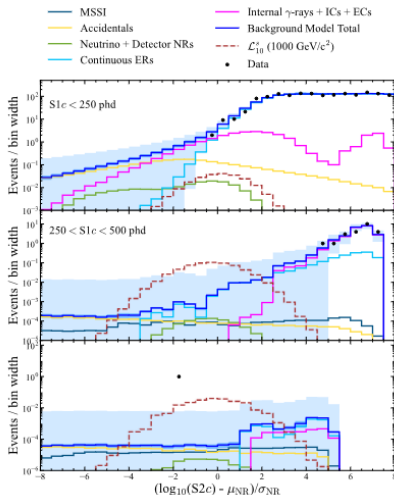


Calibration and background modelling

- ER detector response: measured using in-situ β -decays of tritium and ^{14}C
- NR detector response: measured with neutrons from Deuterium-Deuterium fusion and $\text{AmBe}(\alpha, n)$ reactions
- Detector response to background sources calibrated from this:
 - internal β -decays: ^{214}Pb , ^{212}Pb , ^{85}Kr
 - long lived isotopes: ^{136}Xe , ^{124}Xe
 - solar ν electron capture
 - γ -rays from detector materials
 - multiple-scintillation-single-ionization (MSSI) events
 - and more: untagged neutrons, accidental S1&S2 coincidences

Background modelling

- Background simulated using modified GEANT4, accidentals simulated by drawing random pairs from isolated S1 and S2 pulses
- Construct PDFs in $S1c, \log_{10}(S2c)$ space from simulations $\rightarrow$ expected events in ROI





Fitting

- Simultaneous fit of all three samples (science, prompt veto, delayed veto) using an extended unbinned likelihood, producing a TS value
- Profiled likelihood: Gaussian priors on background sources
- Example model with highest local significance, $\mathcal{L}_{10}$, fits $n_s = 1.0^{+1.4}_{-0.7}$
- Local significance evaluated using ≥ 30000 background-only pseudoexperiments per model
- Look-elsewhere effect also evaluated using background-only simulations, reducing significance to 2.6σ
- Goodness-of-fit tests performed on all three data samples: model describes the data well; no pull larger than 2σ

Confidence intervals, event containment regions

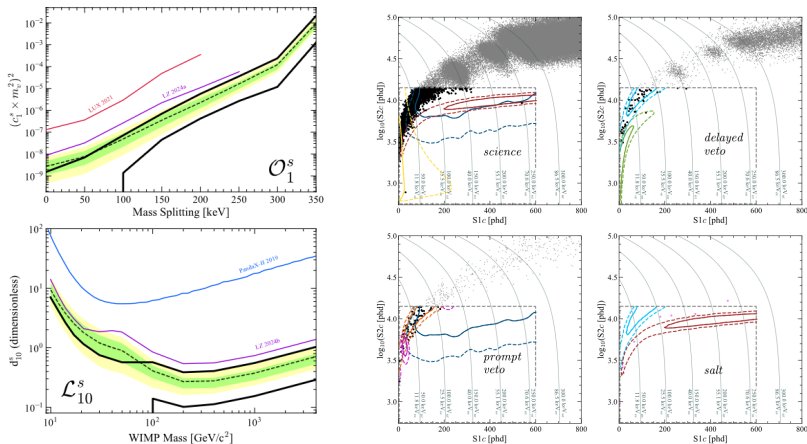


Figure: Left: inelastic SI top, $\mathcal{L}_{10}^s$ bottom; right: $\mathcal{L}_{10}^s$ (brown), MSSI (dark blue), accidentals (yellow), combined ER (light blue), detector NR (green)



Let's discuss!

- Final sanity checks:
 - no scintillation/ionisation abnormalities in the detector in spatial/temporal vicinity of event in question
 - accidental, atmospheric neutrinos, MSSl events possible sources of background in this parameter region: however this would be in the extreme tail of these distributions, so a lack of events in the main region where they are expected results in a small fitted normalisation for these events; similar argument for neutrons
- Timing of event is interesting: 16th of June 2023, close in time to annual modulation peak at June 2nd → especially relevant given the high recoil energy of event



Impact of paper

- **papers focusing on existing constraints:** solar capture neutrinos [1], [2], [3], LZ high energy sideband [4], [5], LHC constraints [6]
- **model building and connections to other signals:** Milky Way γ -ray excesses [7], [8], LZ, AMS02 and Fermi [9], early Universe production [10]
- **future discriminating tests:** argon detectors [11], future colliders [12]
- **alternative production mechanisms:** boosted dark matter [13], [14]