MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

TECHNISCHE UNIVERSITÄT WIEN

The experimental essentials of the LZ paper

arXiv:2609.02823

MBI Journal club

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Oct 15, 2026

Outline

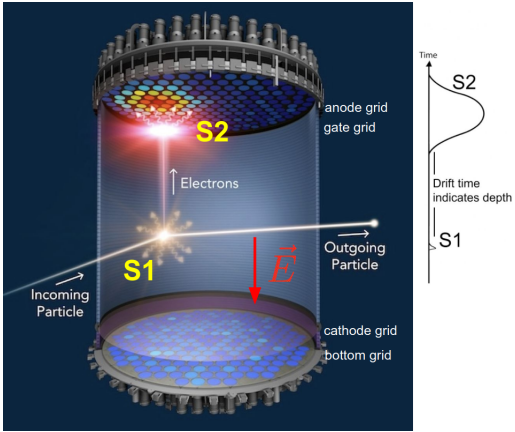
1 LZ Experiment

2 Science data

3 Statistical treatment and results

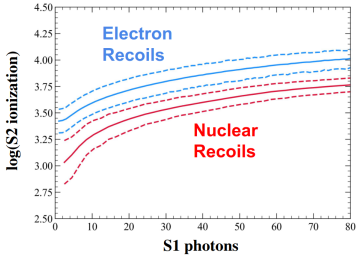
4 Summary

Experimental setup



TeVPA 2024

- Scintillation (S1), Ionization (S2)
  $\Rightarrow$ Particle discrimination via ionization yield
- 3D reconstruction of interaction within the TPC



Event reconstruction

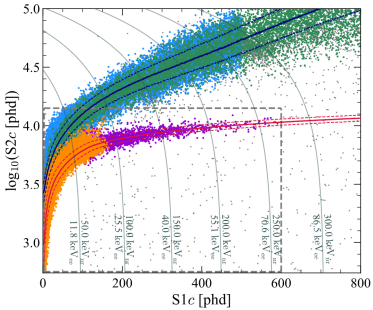
simplified

- Reconstruction and cleaning of raw data (PMT output)
- Event building (coincidence S1, S2)
- Correction for position dependent detector response effects:
  - Variations in light and charge collection
  - Electron losses during drift
  - Inhomogenities of electric fields
  - ...

S1, S2 $\rightarrow$ cS1, cS2:

Calibration and characterization of detector response

- Different calibration sources to populate both bands:
  - **ER**: ^{14}C & ^{212}Pb
  - **NR**: D-D & AmBe
- Larger fiducial volume to increase statistics
- Bands given by calibrated **NEST** model



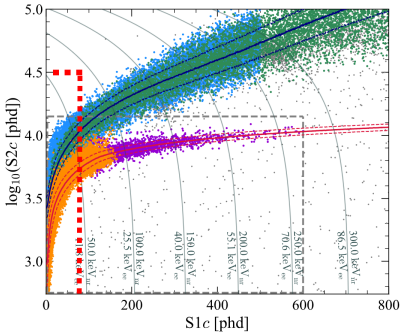
NEST (Noble Element Simulation Technique):

- Data-constrained phenomenological model of relevant microphysics
- Parametrization of production of scintillation photons and ionization electrons as function of E_R, recoil type and E-field

ROI and FV

Region Of Interest:

- Extended upper limit of cS1 from 80 to 600 phd
- Upper limit of $\log_{10}$(cS2) 4.15
- Usual model of SI elastic scattering has very low signal expectation at higher energies
- Other backgrounds become relevant at higher energies



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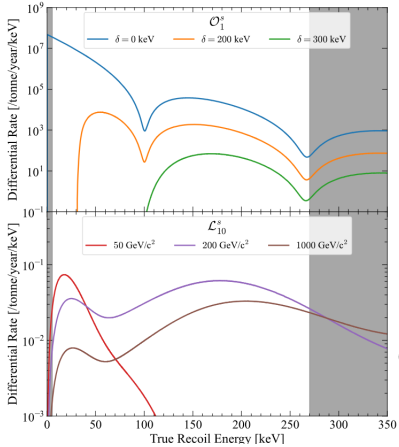
Why the increase?

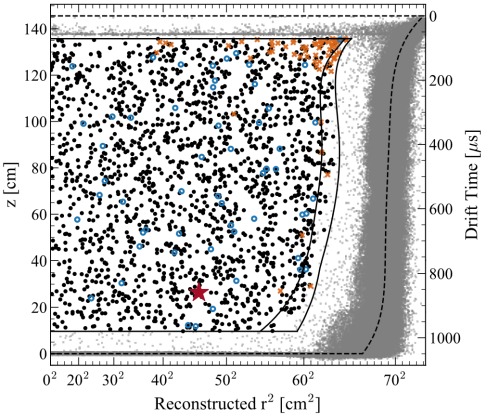
Operators derived from non-relativistic effective field theory (NREFT) or inelastic scatterings can provide signal spectra with relatively high prominence at higher energies



ROI and FV

Fiducial Volume:

- 4.71 $\pm$ 0.08 tonnes
- 14.5 % smaller compared to "standard" case
- Mainly due to wall related backgrounds:
  - Detector radioactivity
  - Plate-out of radon daughters
  - Multiple-scintillation single-ionization (MSSI) events



Veto detectors

- Xenon skin outside TPC active volume
- Gadolinium-loaded liquid scintillator surrounding the cryostat
- Prompt veto: Simultaneous events $\mathcal{O}(0.1\ \mu\text{s})$
  - Mostly γ-rays
- Delayed veto: Sufficiently large signals $\mathcal{O}(100\ \text{keV})$ shortly after TPC events (600 μs)
  - Neutrons being captured in the Gd-loaded scintillator
- Fit all data simultaneously to constrain background in science data

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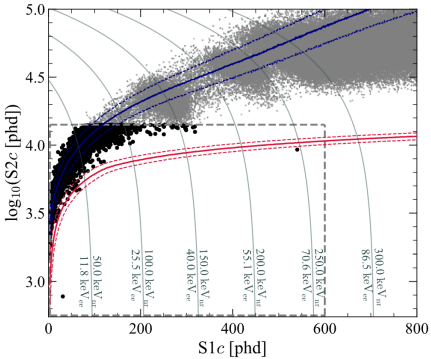
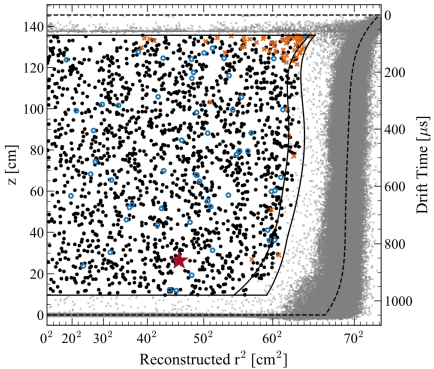
The one event to excite them all

220 d x 4.71 t = 2.84 tonne-years exposure





Event reconstructed at 248 ± 23 (stat) ± 23 (sys) keV

Investigation of possible origins (1/3)

- **Electron recoils**: 6.7 σ below median of modeled ER band
  $\rightarrow$ Highly unlikely

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- **Accidental Coincidences** (Accidental pairing of unrelated S1, S2 signals): Model is well tested, ACs predominantly appear at lower energies
  $\rightarrow$ Very unlikely
- **Calibration Contamination**: ^{57}Co source removed 25 min before event, but on other side of TPC, free mean path only 4 mm, no anomalous events during calibration period
  $\rightarrow$ Highly unlikely

Investigation of possible origins (2/3)

- **Muon-induced backgrounds**: Closest preceeding event 41 min before
  → Unrelated

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- **Muon-induced backgrounds**: Closest preceeding event 41 min before
  → Unrelated
- **Neutrons** (radioactive (α, n) reactions, spontaneous fission, cosmic ray muons):
  - Neutron needs at least 8 MeV
  - At those energies cross-section is highly forward peaked
  - Expect multiple scatters at lower energies
  - No signal in veto detectors

  → Single scatter at 250 keV highly unlikely

Investigation of possible origins (3/3)

- **Pulse shapes**:
  - S2 waveform consistent with single-site interaction
  - S1 pulse shape not conclusively distinguishes NR from ER

$\rightarrow$ NR interpretation not definitive

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- **Multiple-scintillation, single-ionization (MSSI)**: Multiple scatterings where some occur in a charge dead area, distorting the S1 to S2 ratio
  - Model validated against independent control samples
  - Pulse shapes inconsistent with important MSSI topology near cathode
  - Wall-related MSSI harder, but requires unusal energy deposition pattern

  → Unlikely, but wall-related MSSI cannot be completely ruled out

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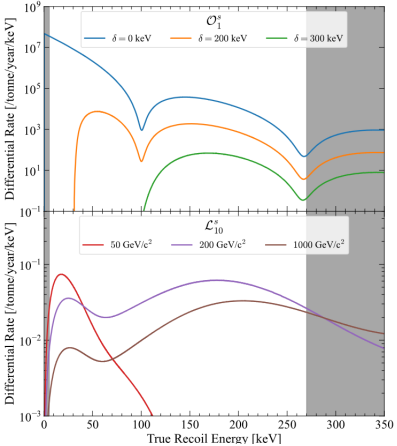
Statistical treatment

Likelihood:

$$\mathcal{L}(\theta) = \prod_{i=0}^{2} \left[\mathrm{Pois}(N_i|\mu_{\mathrm{tot},i}) \times \prod_{e=1}^{N_i} \frac{1}{\mu_{\mathrm{tot},i}} \left(\mu_{\mathrm{sig},i}(\vec{\lambda}) f_{\mathrm{sig},i}(\vec{x}_e) + \sum_{b=1}^{N_b} \mu_{b,i}(\vec{\lambda}) f_{b,i}(\vec{x}_e) \right) \right] \times \prod_{k=0}^{N_b+N_\lambda} g_k(\phi_k|\vec{\nu}_{\phi_k}),$$

- Unbinned extendend likelihood
- Sum over science data + prompt veto data + delayed veto data
- Constraint terms

Signal-strength fit



- Fix signal shape
  (typically given by DM mass)
- In case of inelastic scattering:
  Mass splitting at fixed DM mass
- Fit only normalization
  (cross-section, coupling constants, etc.)
- Scan through mass range

Test statistic

Defined via Profile Likelihood Ratio,
following recommendations in Eur. Phys. J. C 81, 907 (2021):

$$\lambda(\boldsymbol{\mu}) \equiv \frac{\mathcal{L}(\boldsymbol{\mu}, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\theta}})}$$

Consider two different statistics:

Limit setting:

$$\tilde{t}_\mu = \begin{cases} -2\log \frac{\mathcal{L}(\mu, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})} & \hat{\mu} \geq 0, \\ -2\log \frac{\mathcal{L}(\mu, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(0, \hat{\boldsymbol{\theta}}(0))} & \hat{\mu} < 0, \end{cases}$$

Discovery:

$$q_0 = \tilde{t}_0 = \begin{cases} -2\log \lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

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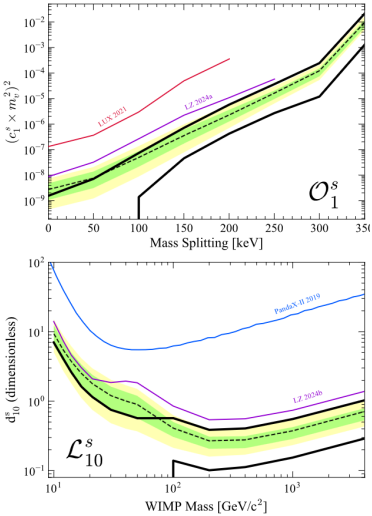
Conventions:

As a function of the shape parameter (mass):

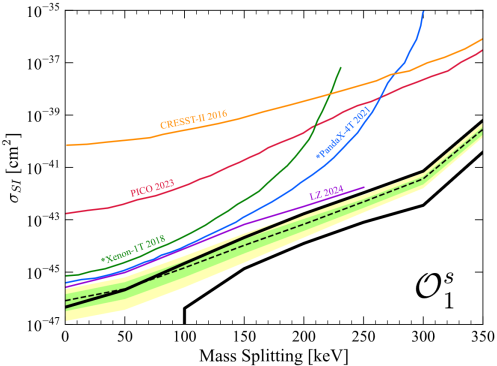
- Discovery significance: Local p-value (discovery statistic)
- Construct two-sided confidence intervals at 90 % CL
- Show lower limit of CI only if local p-value exceeds predefined threshold (usually 3 σ)

Results



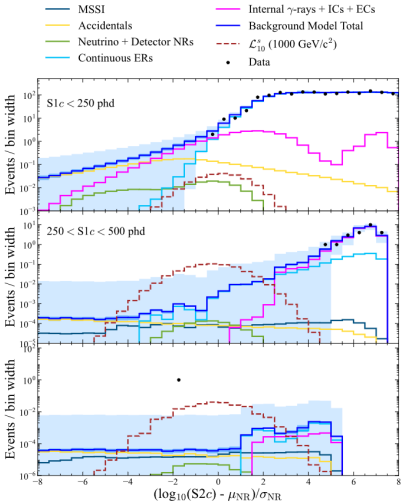
Interpretation as a cross-section:

$$(c_1^s \times m_\nu^2)^2 = \sigma_{SI}^N \frac{\pi \cdot m_\nu^4}{\mu^2}$$



Results

Source	Expected Events	Fit Result
Internal β decays	1341 ± 160	1340 ± 43
ν ER	140.6 ± 8.4	140.3 ± 8.4
^{136}Xe	110.0 ± 16.5	114.2 ± 16.1
CH_3T & ^{14}C	55.3 ± 3.1	55.2 ± 3.1
^{124}Xe	21.0 ± 6.3	22.6 ± 5.0
^{83m}Kr	17.1 ± 5.1	$17.0^{+3.5}_{-3.3}$
^{125}I	8.9 ± 2.7	9.8 ± 2.3
Detector ERs	8.5 ± 3.4	$9.4^{+1.7}_{-1.6}$
Accidental coincs.	2.7 ± 0.6	2.6 ± 0.6
^{127}Xe + ^{125}Xe	1.5 ± 0.3	1.2 ± 0.3
Atmospheric ν	$(1.1 \pm 0.2) \times 10^{-1}$	$(1.1 \pm 0.2) \times 10^{-1}$
^{8}B+hep ν	$(5.7 \pm 0.6) \times 10^{-2}$	$(5.7 \pm 0.6) \times 10^{-2}$
MSSI	$(4.9 \pm 4.9) \times 10^{-3}$	$(4.6^{+4.8}_{-4.6}) \times 10^{-3}$
Detector NRs	–	$[0, 0.118]$
$\mathcal{L}^*_{10}$ (1000 GeV/c^2)	–	$1.0^{+1.4}_{-0.7}$
Total counts	–	1713 ± 39
Observed counts	–	1710

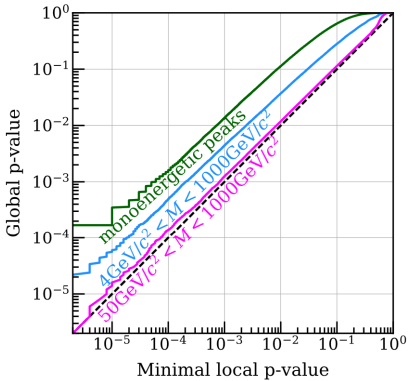


Look Elsewhere Effect

"The local p-value needs to be corrected to account for the fact that a statistical fluctuation might be observed for any of the possible signal hypotheses"
Eur. Phys. J. C 81, 907 (2021)

- Generate MC datasets under the background only hypothesis
- Calculate local discovery significance for every model (and mass, etc.) per dataset
- Take the minimum of all local p-values per dataset $\rightarrow f(p)$
- Calculate the global p-value:

$$p_{\text{data}}^{\text{global}} = \int_0^{p_{\text{data}}} f(p)dp$$



Significance of the LZ event

- **Maximum local significance** (across all models tested): **3.4** σ
- **Global significance** (after LEE correction): **2.6** σ

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