Electron capture decays in the LUX-ZEPLIN (LZ) experiment

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IMPERIAL

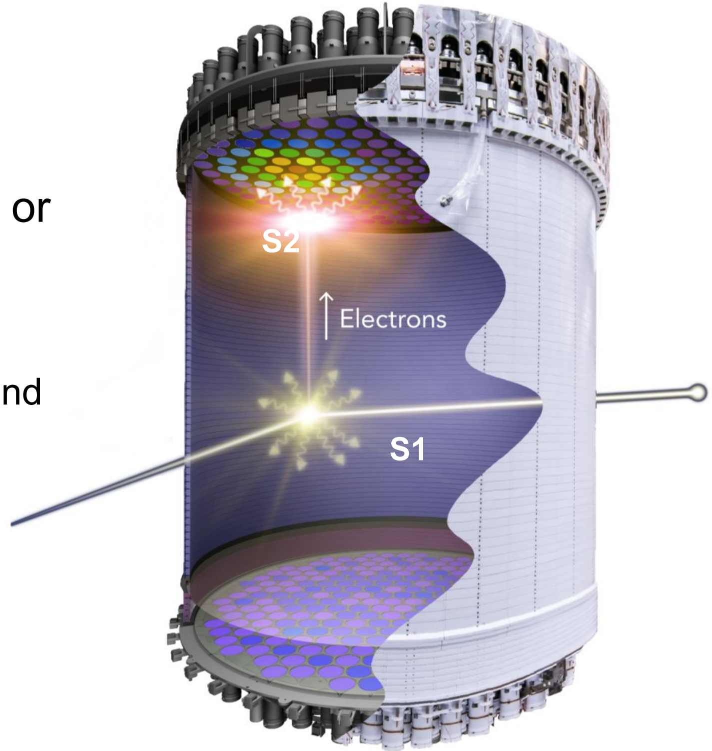
The LUX-ZEPLIN (LZ) experiment

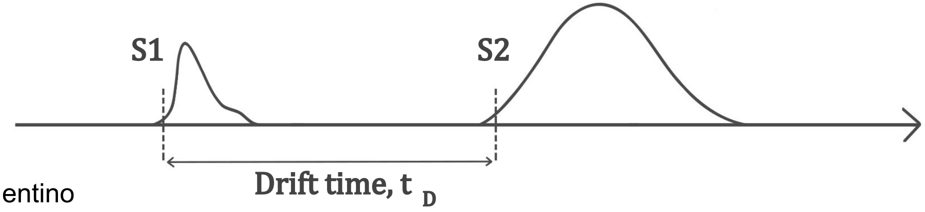
LZ features a 7-tonne dual-phase Xe time projection chamber (TPC) read out by two arrays of VUV PMTs

Particles scattering in the active volume cause nuclear or electron recoils and deposit energy via:

- **Excitation** → prompt scintillation (S1)
- **Ionisation** → electron clouds drift upwards to gas phase and produce electroluminescence (S2)

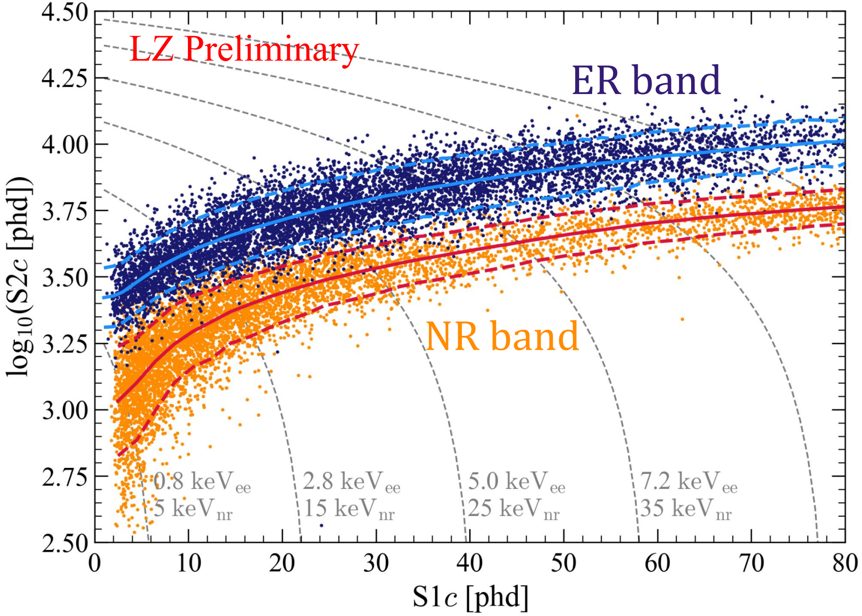
Skin and Outer Detector (OD) serve as veto systems





Investigating leakage into the NR band

LXe TPCs are able to discriminate background-like **electron recoils (ER)** from signal-like **nuclear recoils (NR)** via the charge-to-light signals ratio



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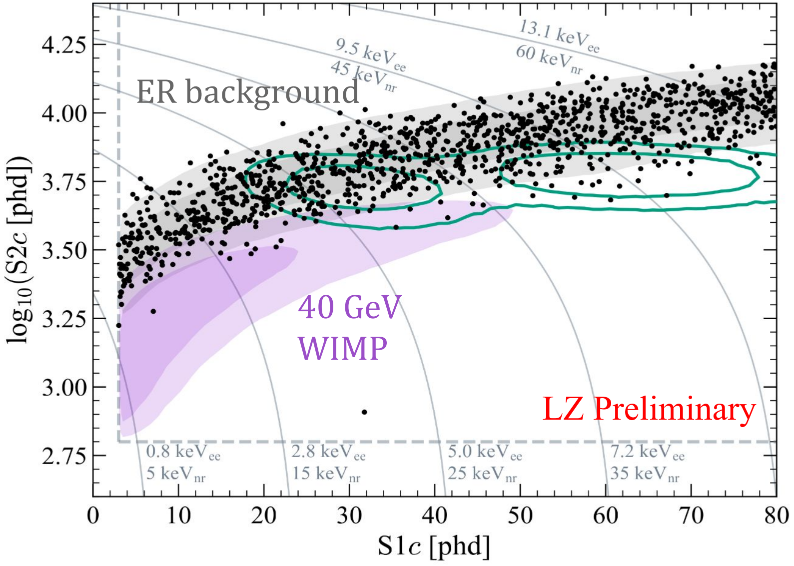

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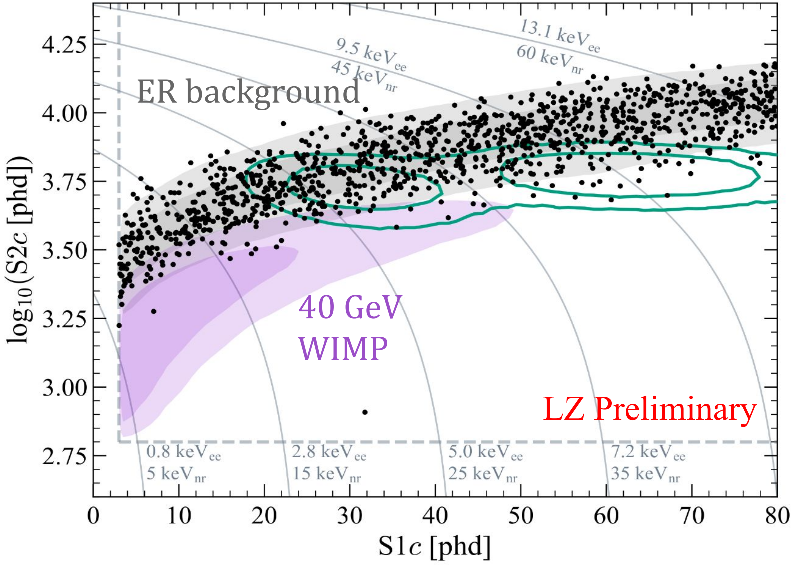
1st hypothesis: Leakage from standard ER events in long acquisitions, e.g. radon progeny*

*See Simran's talk



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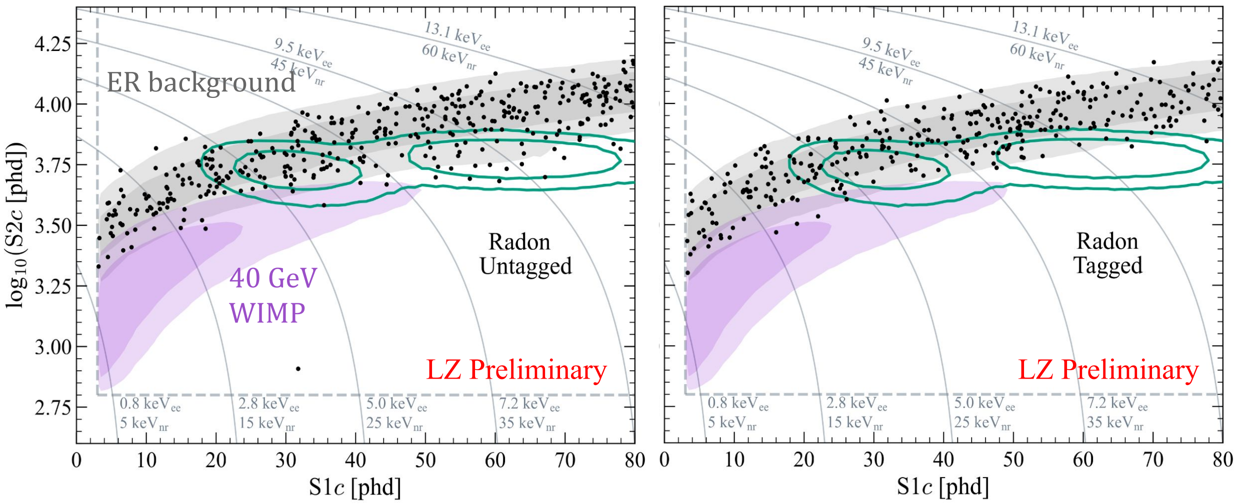

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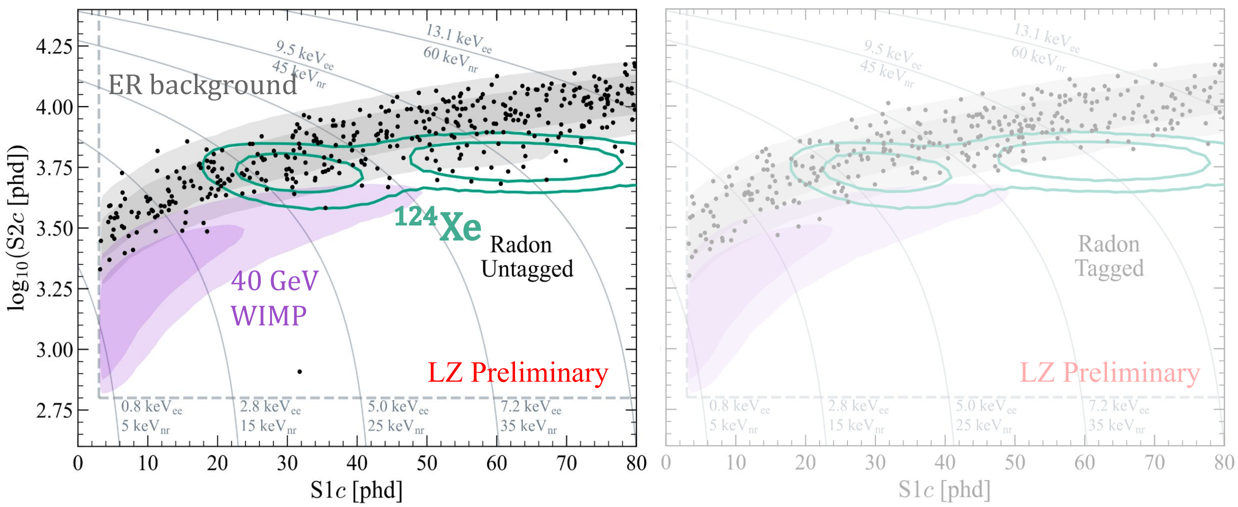
2nd hypothesis: Double electron captures (DEC) of ^{124}Xe with enhanced recombination



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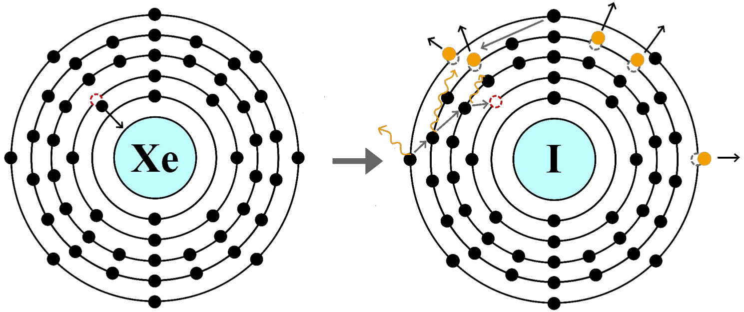
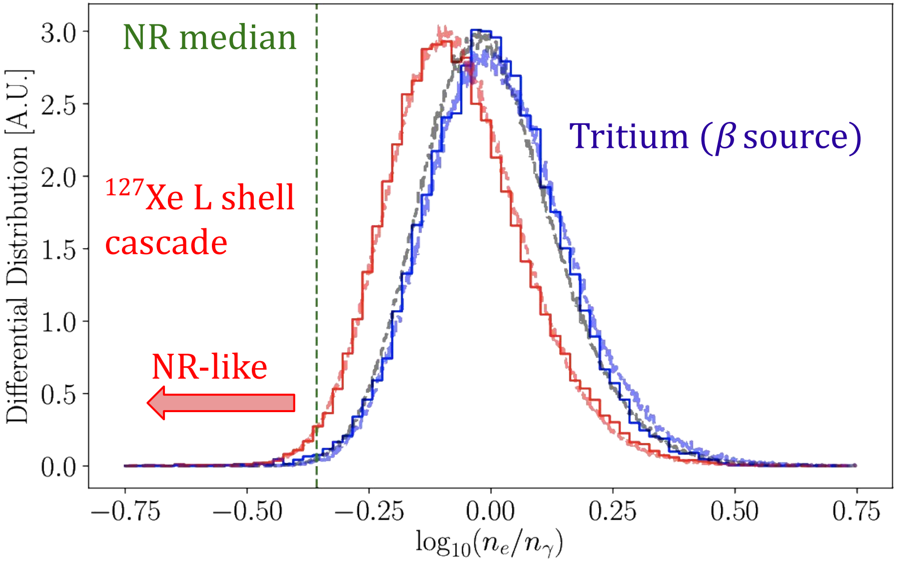
Electron capture decays in LXe-based DM searches

The XELDA[1] experiment has shown that electron capture (EC) decays of ^{127}Xe appear more **NR-like**

This is attributed to enhanced recombination at the decay site





[1] D. J. Temples et al., " *Physical Review D* 104.11 (2021): 112001.

Double electron captures in LXe-based in DM searches

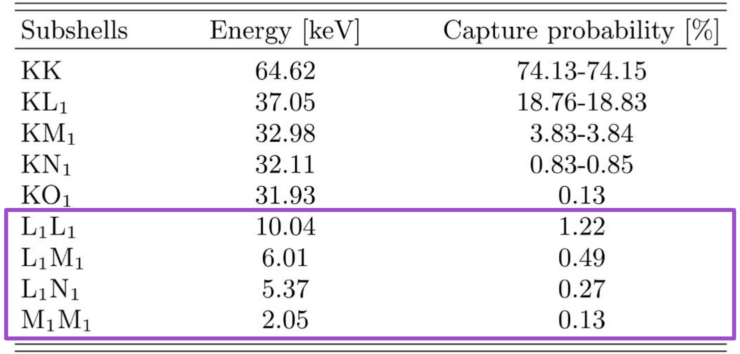
It is expected that DECs would exhibit at least the same enhancement in recombination as single ECs from very ionisation-dense sites

DEC of ^{124}Xe: the **rarest decays known!**

- $T_{1/2}$ = **$(1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr** [1, 2]
- 0.095% natural abundance

In current and future DM searches these decays become a non-negligible backgrounds:

- Exposures are getting longer
- Some decay modes fall into the WIMP region of interest (ROI)



Subshells	Energy [keV]	Capture probability [%]
KK	64.62	74.13-74.15
KL_1	37.05	18.76-18.83
KM_1	32.98	3.83-3.84
KN_1	32.11	0.83-0.85
KO_1	31.93	0.13
L_1L_1	10.04	1.22
L_1M_1	6.01	0.49
L_1N_1	5.37	0.27
M_1M_1	2.05	0.13

O. Nitescu, et al., *arXiv preprint arXiv:2402.13784 (2024).*

[1] Xenon collaboration, *Nature, 2019, 568.7753: 532-535.*

[2] J Aalbers, et al., *Journal of Physics G: Nuclear and Particle Physics 52.1 (2024): 015103.*

Double electron captures in LXe-based in DM searches

Challenge: The “NR-likeness” of these decays would appear as a leakage of ER events in the NR band, which can affect our sensitivity to dark matter if not properly modeled

Understanding of this effect is crucial!

Aim: exploit non-negligible rate of single EC in LZ to evaluate the enhanced recombination they exhibit and inform that of ^{124}Xe DEC decays

Electron capture decays in xenon isotopes

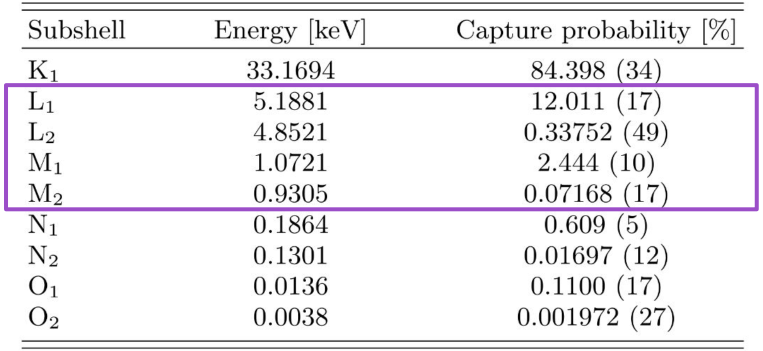
^{125}Xe and ^{127}Xe are produced via neutron capture

They undergo EC to excited state of iodine with:

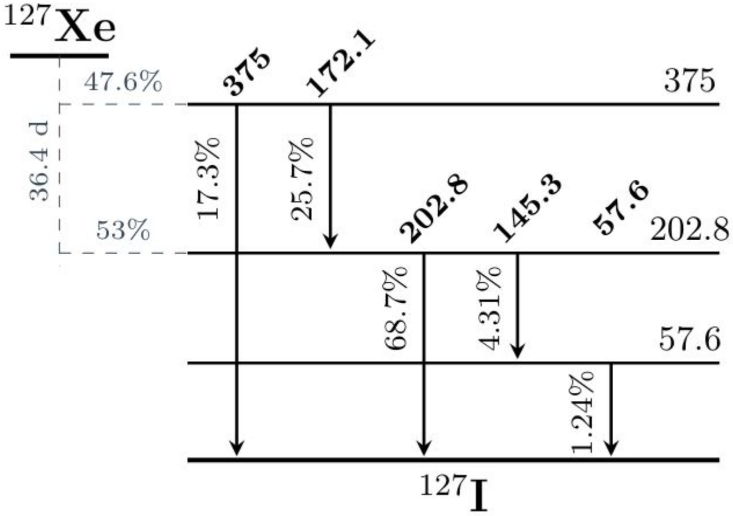
- $T_{1/2}$= 36.4 d for ^{127}Xe
- $T_{1/2}$= 16.9 h for ^{125}Xe

The signal is formed of:

- Nuclear de-excitation **gamma**(s)
- Atomic cascade



Subshell	Energy [keV]	Capture probability [%]
K_1	33.1694	84.398 (34)
L_1	5.1881	12.011 (17)
L_2	4.8521	0.33752 (49)
M_1	1.0721	2.444 (10)
M_2	0.9305	0.07168 (17)
N_1	0.1864	0.609 (5)
N_2	0.1301	0.01697 (12)
O_1	0.0136	0.1100 (17)
O_2	0.0038	0.001972 (27)



Isolating EC events in LZ

To isolate the atomic cascade in single EC we have two selection strategies:

1. Multiple scatter selection
2. Single scatter selection

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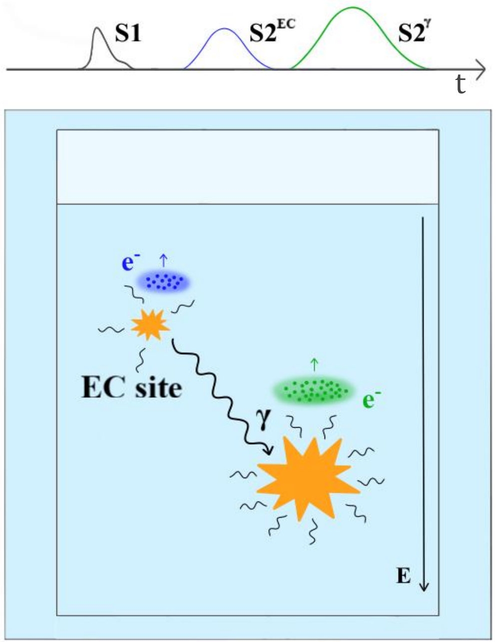
1. **Multiple scatter selection (MS)**
2. Single scatter selection

- If the gamma ray is high in energy it will travel enough in LXe to create a distinct photo-absorption site from the cascade
- We only select events where the gamma goes downwards, making the cascade the first of the S2s to reach the liquid surface



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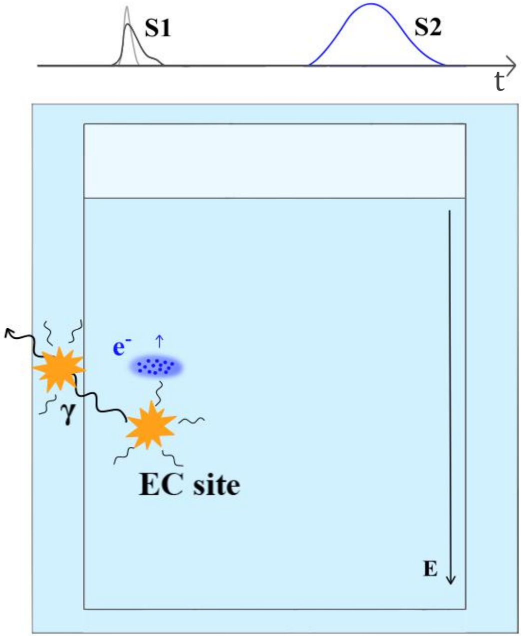
Isolating EC events in LZ

To isolate the atomic cascade in single EC we have two selection strategies:

1. Multiple scatter selection
2. **Single scatter selection (SS)**

- If the capture occurs at the edge of the TPC the gamma ray can escape and is absorbed in the skin, yielding a **skin tag**
- Resulting event in TPC is a **single scatter**
- Trade-off between wall backgrounds and statistics



Intermezzo: obtaining charge yields

Charge yields are obtained via: $Q_y = \frac{S2c}{g_2 E}$

Corrected S2 area: distribution of S2 size fitted with skewed Gaussians to obtain the mean.
Skewness attributed to Auger and fluorescence components in vacancy relaxation

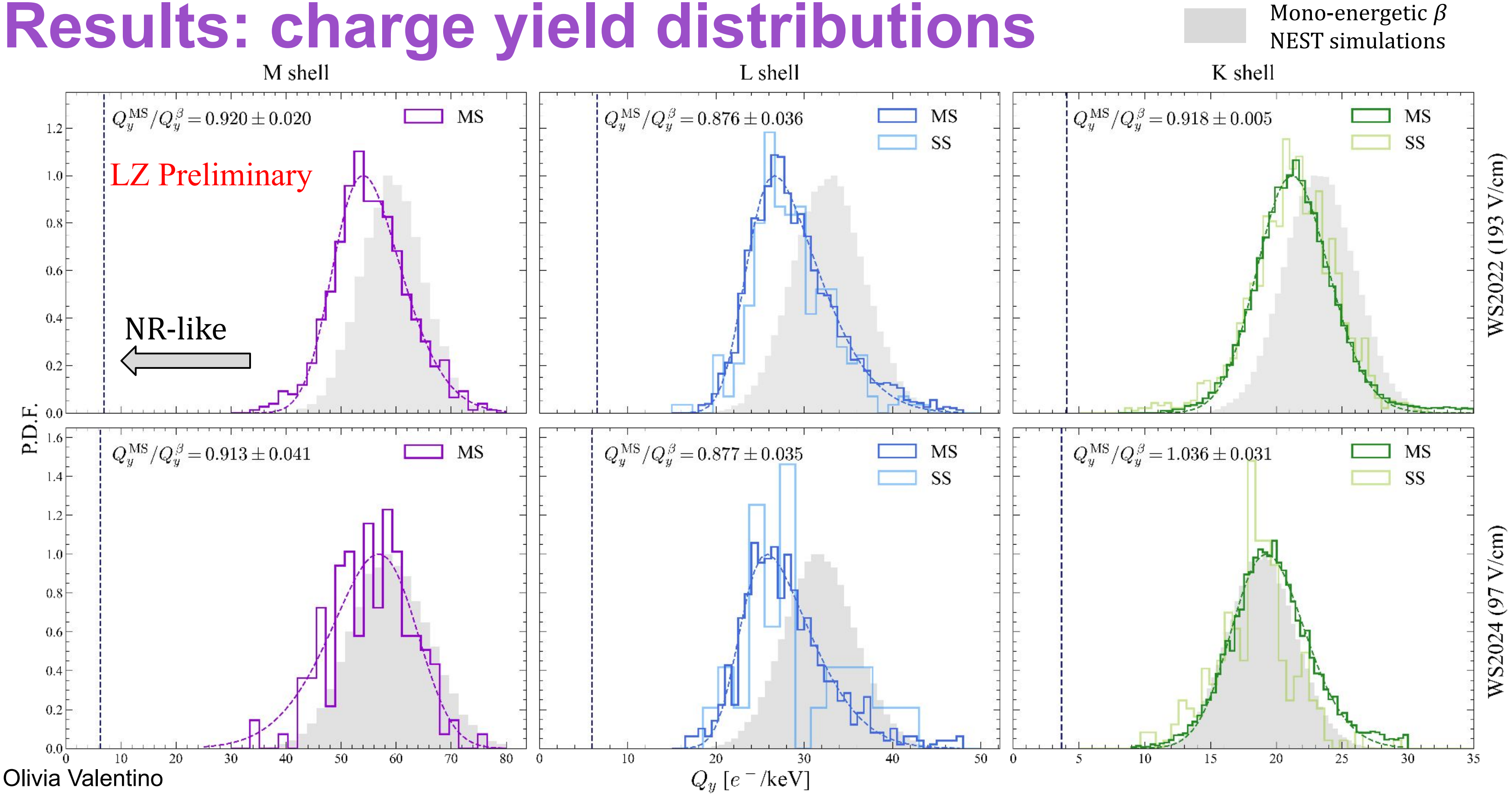
True energy of vacancy shell

Results are then compared to charge yield of a *β* of equivalent energy taken from NEST: $Q_y^{\mathrm{EC}}/Q_y^{\beta}$

Comparison to *β* for K-shells is more complex as they can be **multi-site**:

- ~28 keV X-ray + L shell vacancy

Results: charge yield distributions



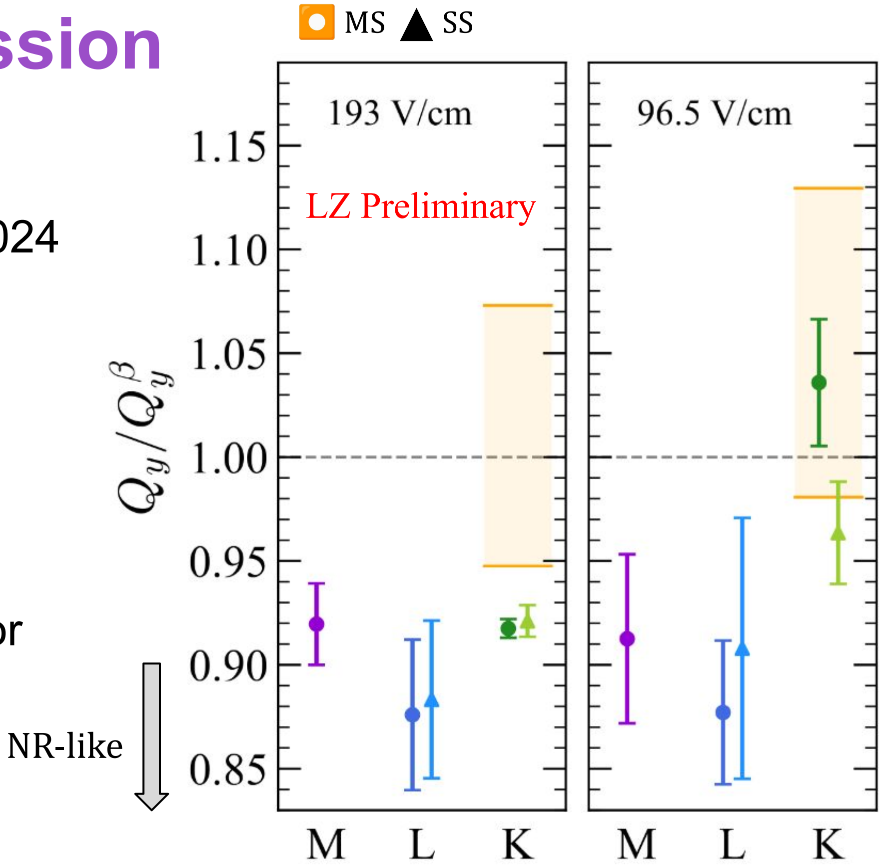
Results: charge suppression

Good agreement between SS and MS measurement, except for K shell in WS2024

Yellow bands: multisite expectation

- Upper limit: X-ray modeled as ***β***
- Lower limit: X-ray modeled as ***γ***
- In both: L vacancy modeled as *β*

No evident trend with field in this range for M and L shells



DEC modeling in WS2024

LL and **LM** ^{124}Xe DEC components were included in the WS2024 background model:

- We expect 7.1 (LM) + 12.3 (LL) = 19.4 counts + 20% uncertainty

For **LM** events $\mathbf{Q^{LM}/Q^{\beta} = Q^{L}/Q^{\beta} = 0.87}$

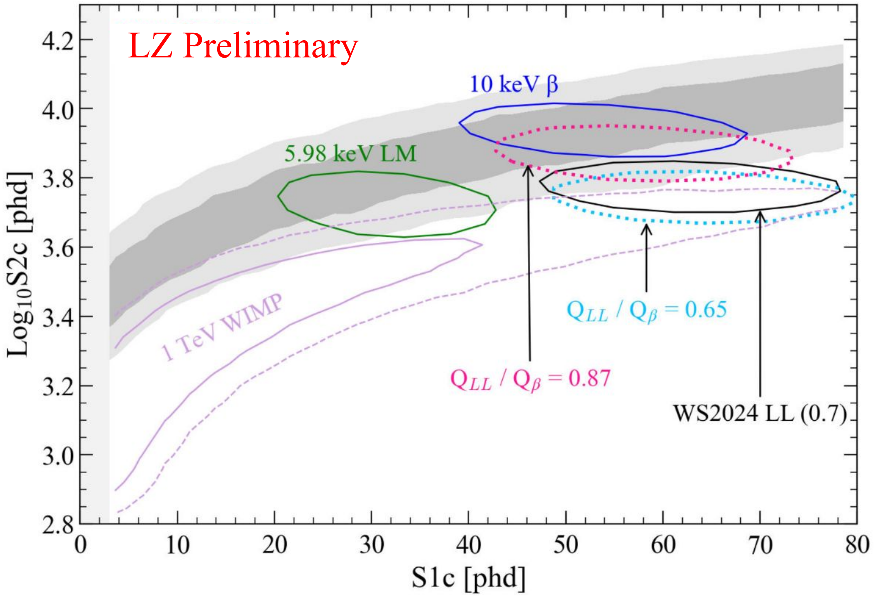
For **LL** events $\mathbf{Q^{LL}}$ was floated:

$$0.65 < Q^{LL}/Q^{\beta} < 0.87$$

x 2 ionisation density

Q^{L}/Q^{β}

Best fit parameter: $\mathbf{Q^{LL}/Q^{\beta} = 0.70 \pm 0.04}$



Conclusions

Take away messages:

- Observed an unexpected leakage of from ER band into the NR band
- Managed to explain this by DEC decays of ^{124}Xe with enhanced recombination
- Modelled it exploiting *in situ* measurements of single ECs

This study underlines the importance of DEC decays of ^{124}Xe as a background for xenon-based dark matter searches. This is remarkable!

Paper in preparation on this topic:

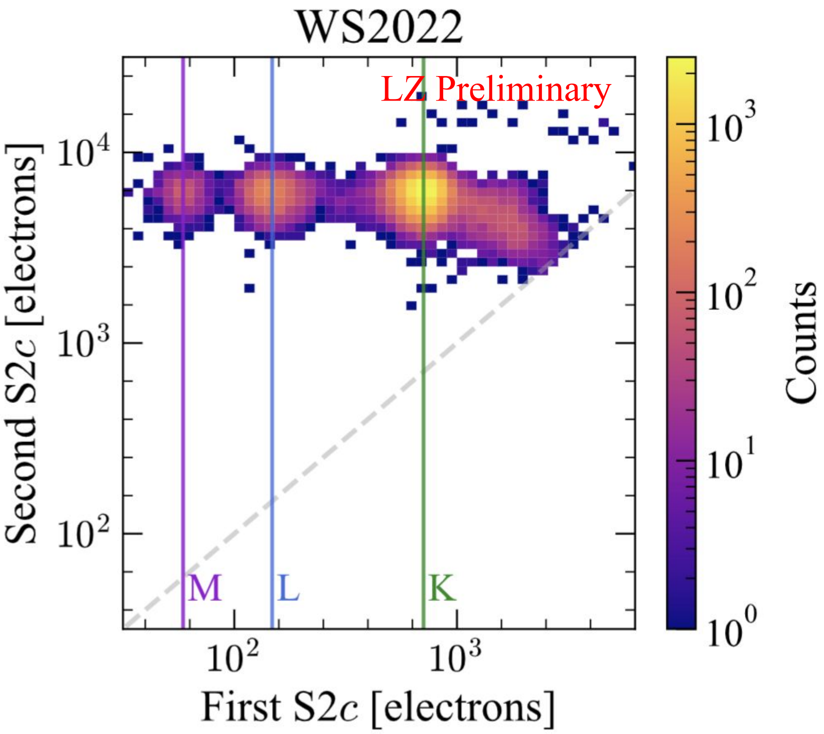
Measurements and models of enhanced recombination following inner-shell vacancies in liquid xenon

Thank you!

Backup

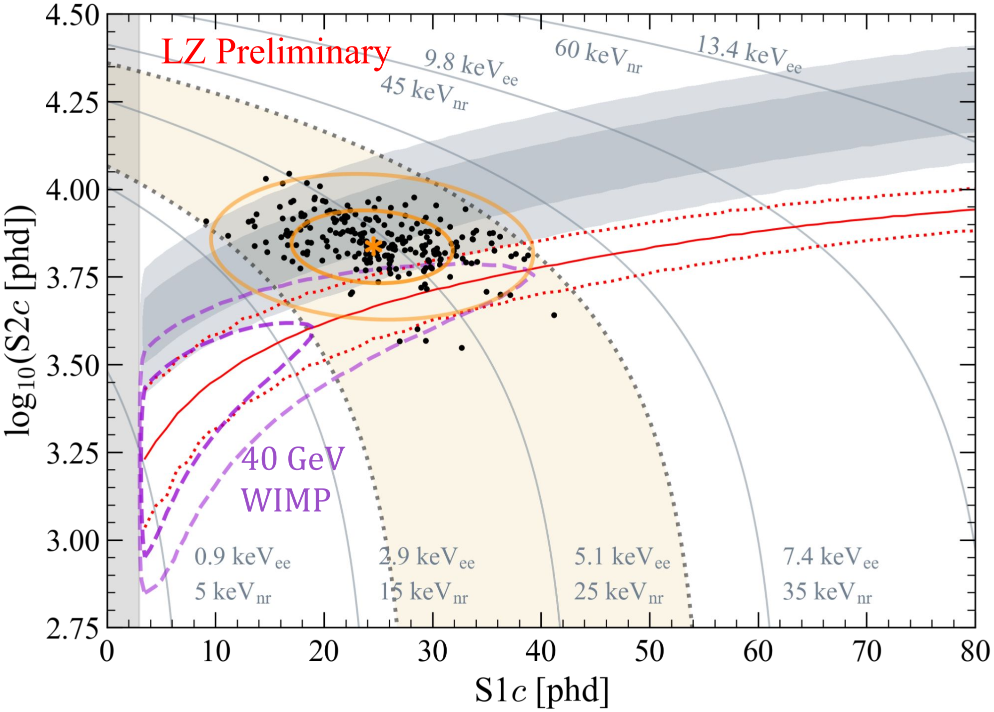
Isolating EC events in LZ: MS selection

- Similar selection strategy for WS2022 and WS2024 dataset
- K, L and M shell populations are isolated in both runs



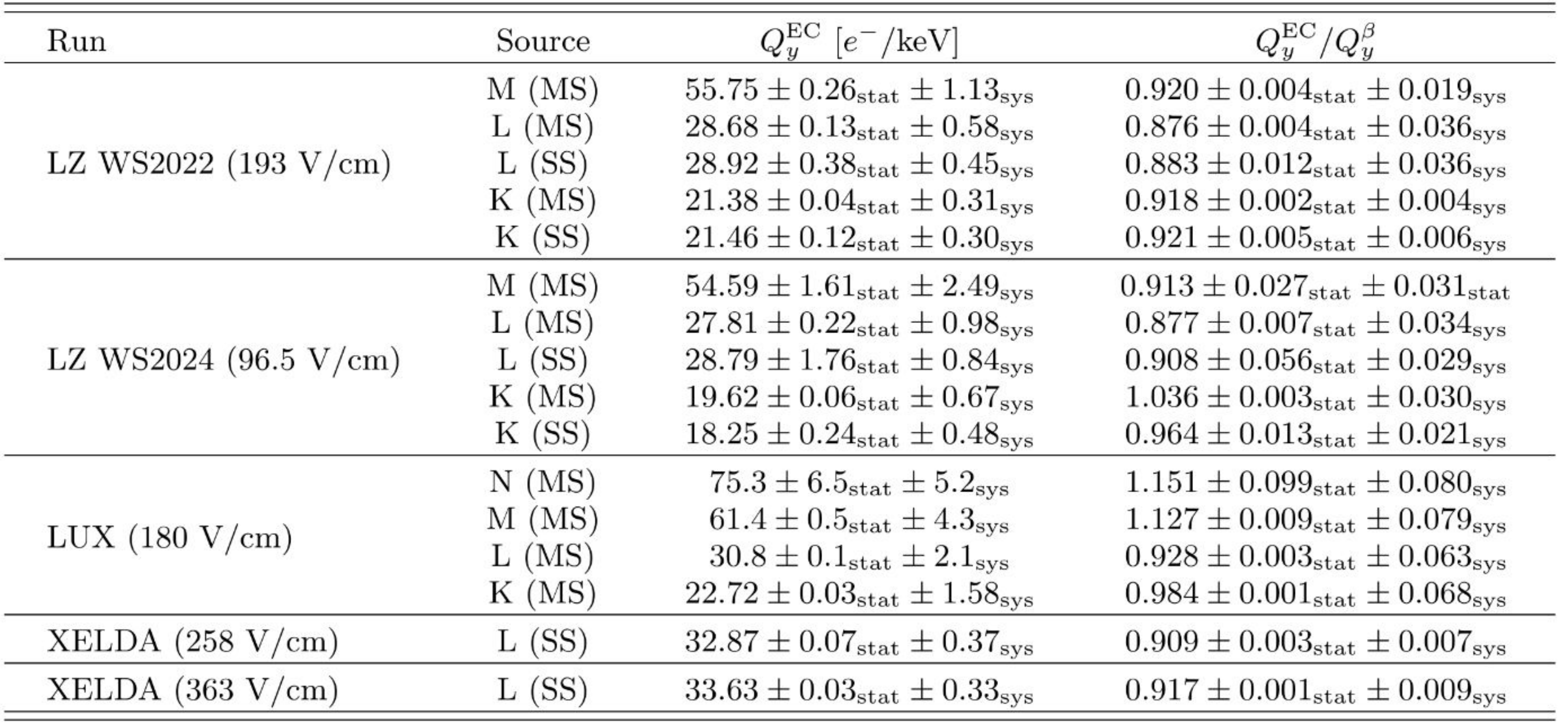
Isolating EC events in LZ: SS selection

- Black points are **L shell** captures of ^{125}Xe and ^{127}Xe within chosen energy range (tan)
- Distinct shift downwards can be observed in the population from the ER background (grey) into the NR band (red)



Summary table

LZ Preliminary



Run	Source	Q_y^{EC} $[e^-/\mathrm{keV}]$	$Q_y^{\mathrm{EC}}/Q_y^{\beta}$
LZ WS2022 (193 V/cm)	M (MS)	$55.75 \pm 0.26_{\mathrm{stat}} \pm 1.13_{\mathrm{sys}}$	$0.920 \pm 0.004_{\mathrm{stat}} \pm 0.019_{\mathrm{sys}}$
	L (MS)	$28.68 \pm 0.13_{\mathrm{stat}} \pm 0.58_{\mathrm{sys}}$	$0.876 \pm 0.004_{\mathrm{stat}} \pm 0.036_{\mathrm{sys}}$
	L (SS)	$28.92 \pm 0.38_{\mathrm{stat}} \pm 0.45_{\mathrm{sys}}$	$0.883 \pm 0.012_{\mathrm{stat}} \pm 0.036_{\mathrm{sys}}$
	K (MS)	$21.38 \pm 0.04_{\mathrm{stat}} \pm 0.31_{\mathrm{sys}}$	$0.918 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{sys}}$
	K (SS)	$21.46 \pm 0.12_{\mathrm{stat}} \pm 0.30_{\mathrm{sys}}$	$0.921 \pm 0.005_{\mathrm{stat}} \pm 0.006_{\mathrm{sys}}$
LZ WS2024 (96.5 V/cm)	M (MS)	$54.59 \pm 1.61_{\mathrm{stat}} \pm 2.49_{\mathrm{sys}}$	$0.913 \pm 0.027_{\mathrm{stat}} \pm 0.031_{\mathrm{stat}}$
	L (MS)	$27.81 \pm 0.22_{\mathrm{stat}} \pm 0.98_{\mathrm{sys}}$	$0.877 \pm 0.007_{\mathrm{stat}} \pm 0.034_{\mathrm{sys}}$
	L (SS)	$28.79 \pm 1.76_{\mathrm{stat}} \pm 0.84_{\mathrm{sys}}$	$0.908 \pm 0.056_{\mathrm{stat}} \pm 0.029_{\mathrm{sys}}$
	K (MS)	$19.62 \pm 0.06_{\mathrm{stat}} \pm 0.67_{\mathrm{sys}}$	$1.036 \pm 0.003_{\mathrm{stat}} \pm 0.030_{\mathrm{sys}}$
	K (SS)	$18.25 \pm 0.24_{\mathrm{stat}} \pm 0.48_{\mathrm{sys}}$	$0.964 \pm 0.013_{\mathrm{stat}} \pm 0.021_{\mathrm{sys}}$
LUX (180 V/cm)	N (MS)	$75.3 \pm 6.5_{\mathrm{stat}} \pm 5.2_{\mathrm{sys}}$	$1.151 \pm 0.099_{\mathrm{stat}} \pm 0.080_{\mathrm{sys}}$
	M (MS)	$61.4 \pm 0.5_{\mathrm{stat}} \pm 4.3_{\mathrm{sys}}$	$1.127 \pm 0.009_{\mathrm{stat}} \pm 0.079_{\mathrm{sys}}$
	L (MS)	$30.8 \pm 0.1_{\mathrm{stat}} \pm 2.1_{\mathrm{sys}}$	$0.928 \pm 0.003_{\mathrm{stat}} \pm 0.063_{\mathrm{sys}}$
	K (MS)	$22.72 \pm 0.03_{\mathrm{stat}} \pm 1.58_{\mathrm{sys}}$	$0.984 \pm 0.001_{\mathrm{stat}} \pm 0.068_{\mathrm{sys}}$
XELDA (258 V/cm)	L (SS)	$32.87 \pm 0.07_{\mathrm{stat}} \pm 0.37_{\mathrm{sys}}$	$0.909 \pm 0.003_{\mathrm{stat}} \pm 0.007_{\mathrm{sys}}$
XELDA (363 V/cm)	L (SS)	$33.63 \pm 0.03_{\mathrm{stat}} \pm 0.33_{\mathrm{sys}}$	$0.917 \pm 0.001_{\mathrm{stat}} \pm 0.009_{\mathrm{sys}}$

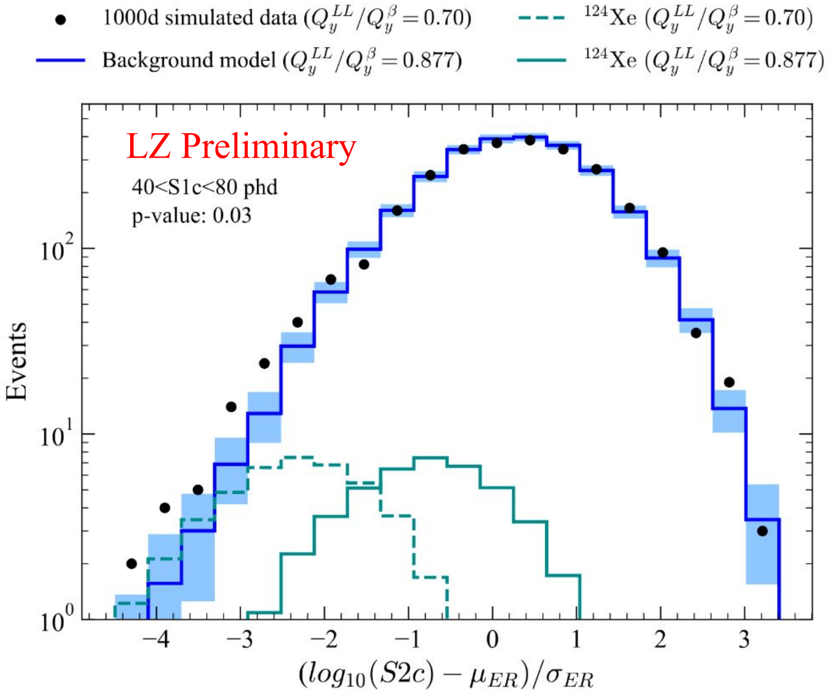
Impact on WIMP searches

Sensitivity study of **1,000 live day exposure** was performed

Two possibilities explored:

1. Modelling LL-capture like an L-capture
2. Modelling LL with best-fit, but:
   - Including MM as M
   - Including LM & LN as L
   - Varying branching ratios by ±40%

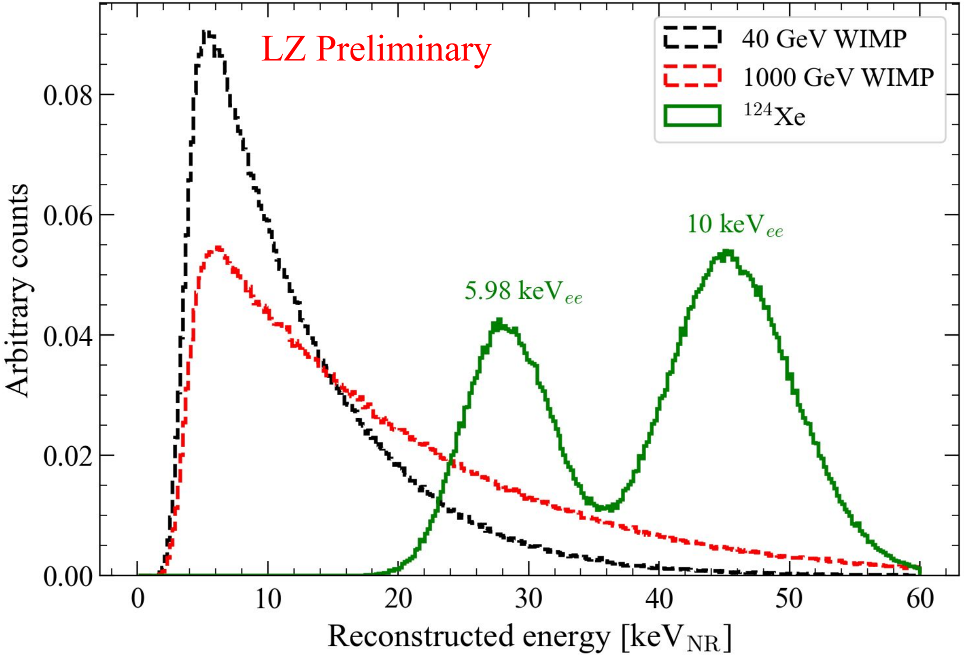
In each case, the worst impact is a **~10% reduction in sensitivity** for > 30 GeV/c^2 WIMP masses



Energy spectrum of ^{124}Xe

Energy spectrum of LL and LM components of ^{124}Xe compared to spectrum of 40 GeV and 1000 GeV WIMP

Counts are arbitrarily normalised independently



The Thomas-Imel box model

This model places the recombination inside **a box of size *2a*** in which all charges are **uniformly distributed**

Recombination is controlled by the ξ parameter via:

$$Q_y = \frac{\ln(1+\xi)}{W\xi\left(1+N_{\mathrm{ex}}/N_i\right)} \qquad \xi = \frac{N_i\alpha}{4a^2v_d}$$

ξ is related to the ionisation density

We assume that ECs and β interactions produce the same N_i, within different boxes of sizes a_L a_M and a_β

The difference in recombination is wholly attributed to differences in ionization density (and box size)