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

**Olivia Valentino on behalf of the LZ Collaboration**

**20th Patras Workshop on Axions, WIMPs and WISPs - Tenerife**

**September 2025**

IMPERIAL

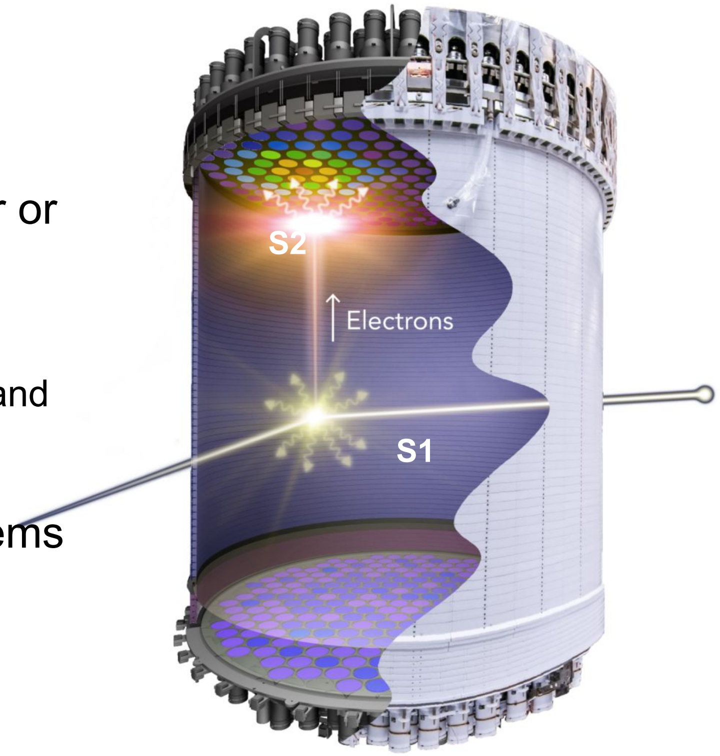
# The LUX-ZEPLIN (LZ) experiment

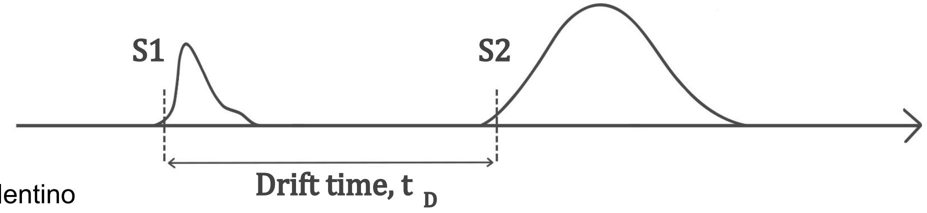
LZ features a 7-tonne dual-phase Xe time projection chamber (TPC) read out by two arrays of VUV PMTs

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

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

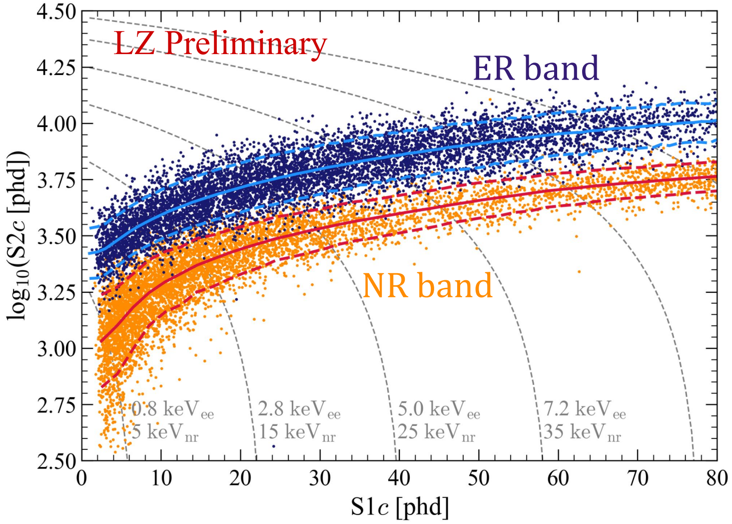
LXe Skin and Outer Detector (OD) serve as veto systems



# 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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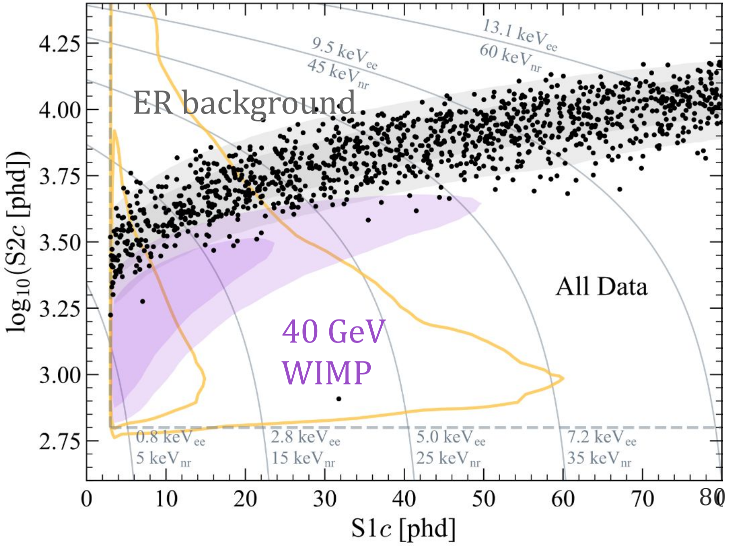
The WIMP search 2024 (WS2024) dataset showed evidence of abnormal leakage from the ER band into the NR band




J Aalbers, et al., Phys. Rev. Lett. **135** (2025), 011802

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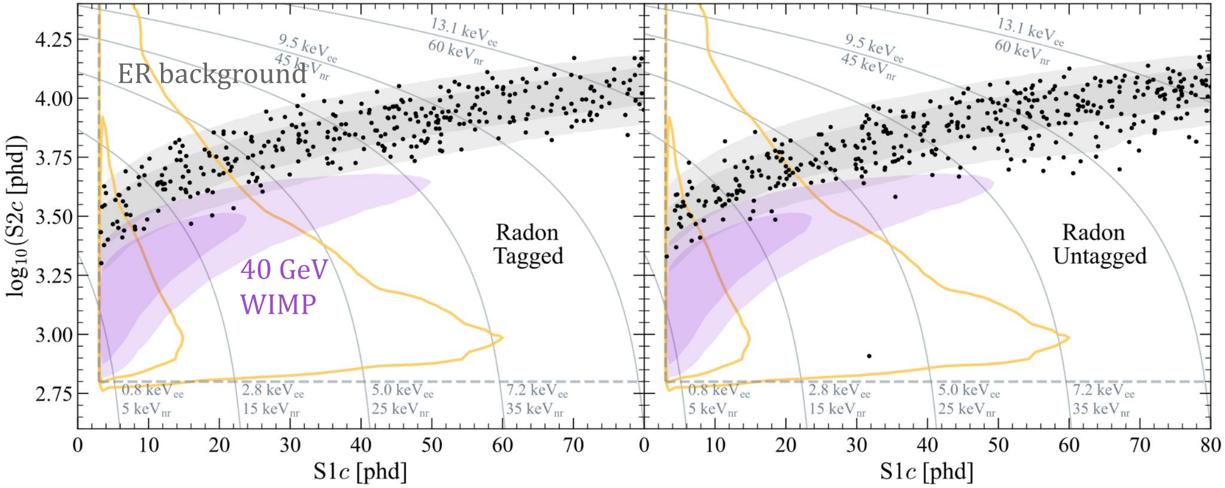
*1st hypothesis:* Leakage from standard ER events in long acquisitions

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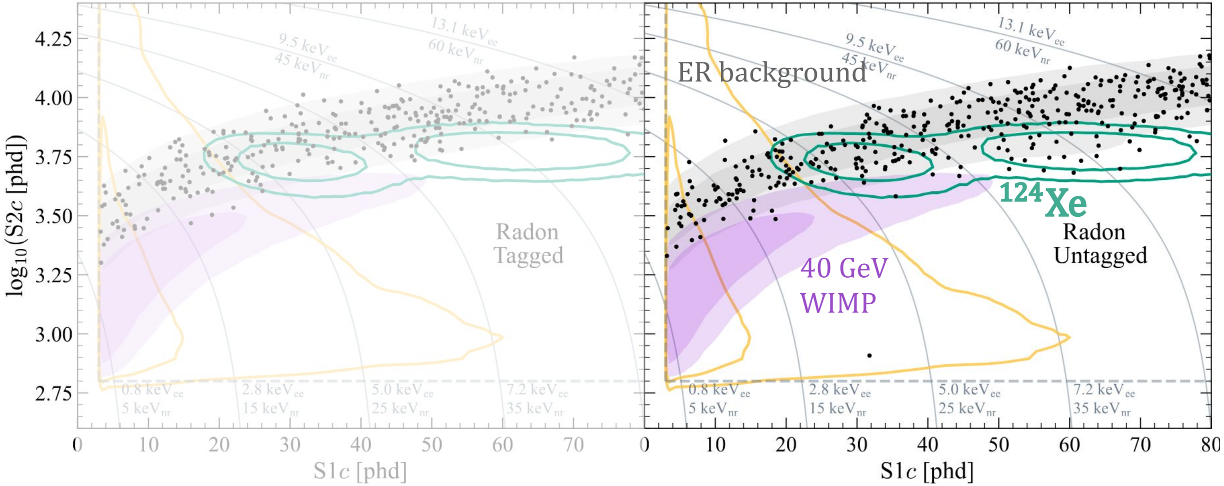
*1st hypothesis:* Leakage from standard ER events in long acquisitions, e.g. radon progeny

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






J Aalbers, et al., Phys. Rev. Lett. **135** (2025), 011802

# Double electron captures in LXe-based in DM searches

The XELDA experiment has shown that electron capture (EC) decays of $^{127}Xe$ appear more **"NR-like"**, due to enhanced recombination at the decay site

DECs should exhibit at least the same enhancement as single ECs

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

- $T_{1/2}$ = **(1.09 ± 0.14$_{stat}$ ± 0.05$_{sys}$ ) × 10$^{22}$ yr**
- 0.095% natural abundance

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

- Exposures are becoming very large
- 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 |

D. J. Temples et al., *Physical Review D* 104.11 (2021): 112001.
Xenon collaboration, *Nature*, 2019, 568.7753: 532-535.
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 into the NR band, which can affect our sensitivity to dark matter if not properly modeled

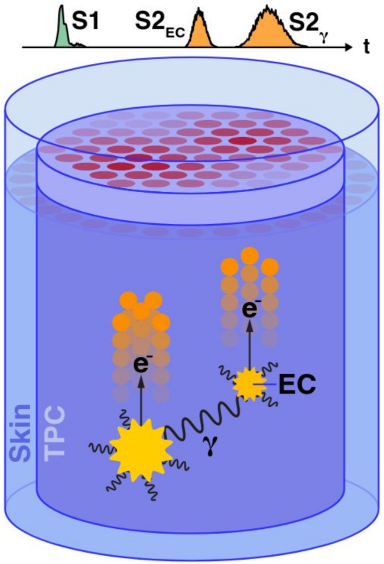
***Understanding of this effect is crucial!***

***Aim:***

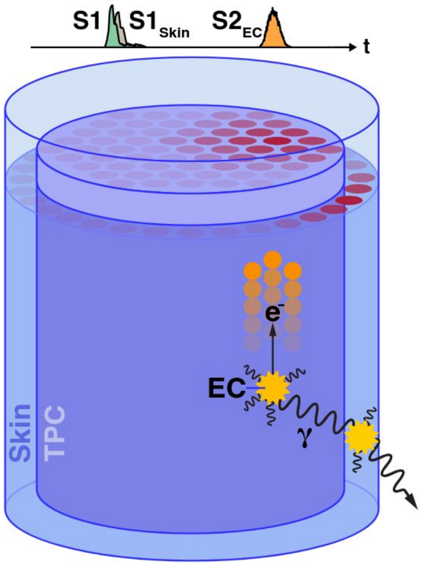
Use **single EC** in LZ to evaluate the enhancement in recombination and inform that of $^{124}$Xe DEC decays

# Single EC selection strategy

Select low energy $^{125}$Xe and $^{127}$Xe atomic cascades via high energy tag of **nuclear de-excitation gamma-ray**




Multiple scatter (MS)




Single scatter (SS)

# Results: charge suppression

Charge yields are obtained via:

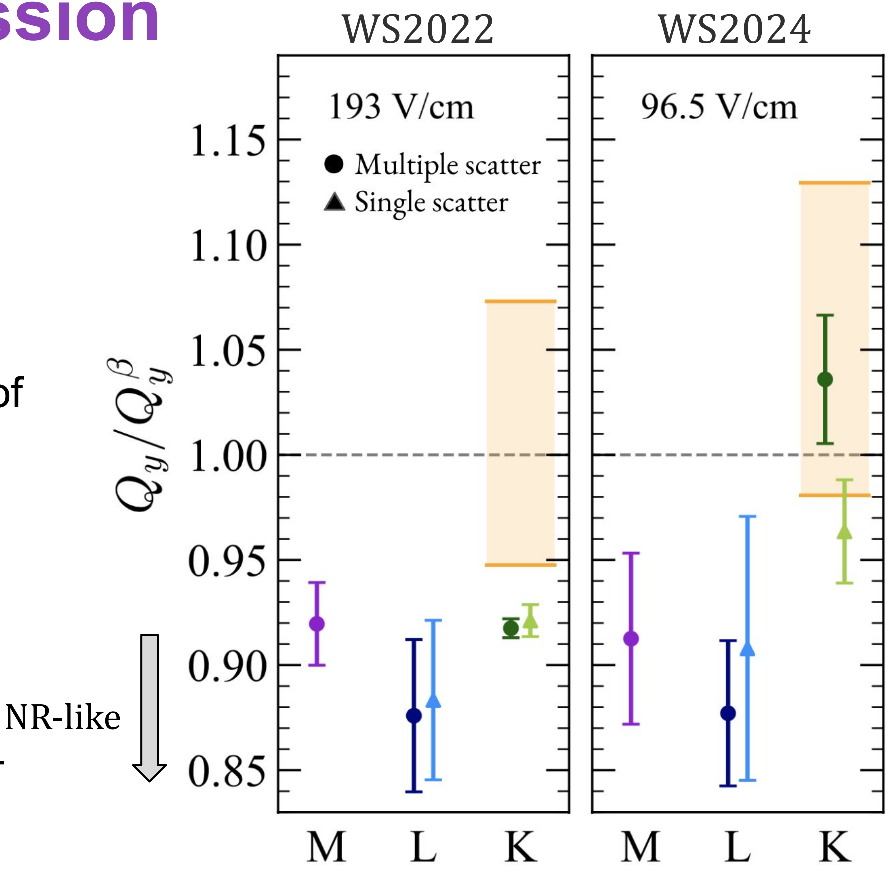
$$Q_y = \frac{S2c}{g_2 E}$$

→ True energy of vacancy shell (K, L, M, …)

Results are then compared to charge yield of a $\beta$ of equivalent energy taken from NEST:

$$Q_y^{\mathrm{EC}} / Q_y^{\beta}$$

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




J Aalbers, et al., Phys. Rev. D **112** (2025), 012024

# $^{124}$Xe DEC modeling in WS2024

**LM component:** 7.1 ± 1.4 counts expected

Enhancement was fixed at result for single L shell EC

**LL component:** 12.3 ± 2.5 counts expected

Recombination enhancement was allowed to float in the background model

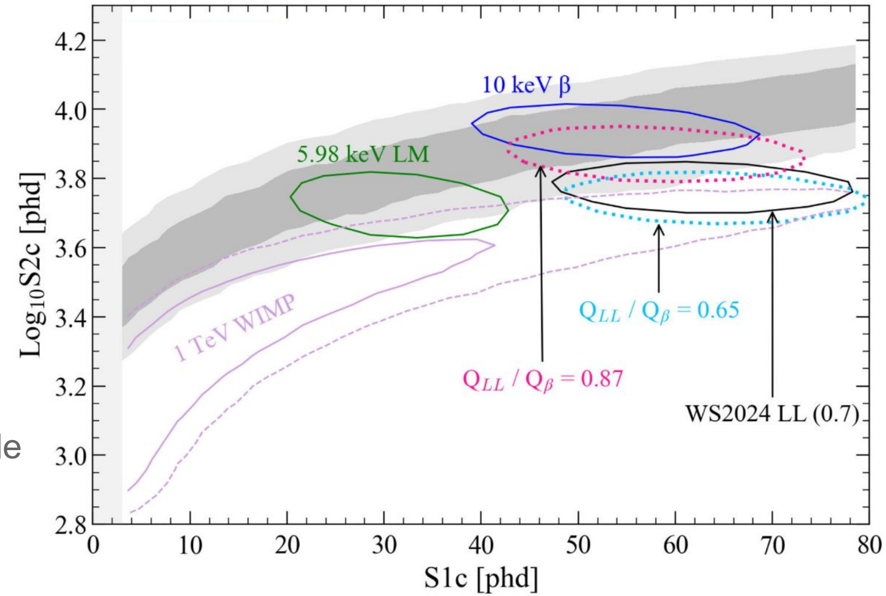
**0.65 < $Q^{LL}/Q^{\beta}$ < 0.87**

Thomas-Imel Box model with x2 ionisation density

Result for single L shell EC

Best fit parameter:

**0.70 ± 0.04**




J. Thomas and D. A. Imel, Phys. Rev. A 36, 614 (1987)

# Conclusions

*Take away messages:*

- Observed leakage of events from ER band into the NR band inconsistent with beta decays
- Explained by DEC decays of $^{124}Xe$ with enhanced recombination
- Modeled it exploiting *in situ* measurements of single ECs

It is remarkable that we see potential backgrounds in xenon-based dark matter searches from the **rarest decays ever measured!**

Published paper on this topic: J Aalbers, et al., Phys. Rev. D **112** (2025), 012024

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

# LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
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Thanks to our sponsors and participating institutions!

# Thank you

## Poster session on Thursday for more discussion!

# Backup

# Electron capture decays in xenon isotopes

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

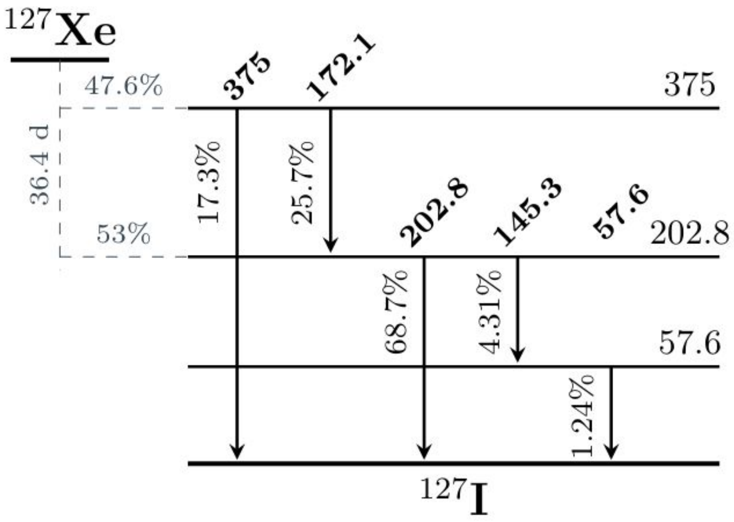
They undergo EC to excited state of iodine with:

- $t_{1/2}$= 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) |

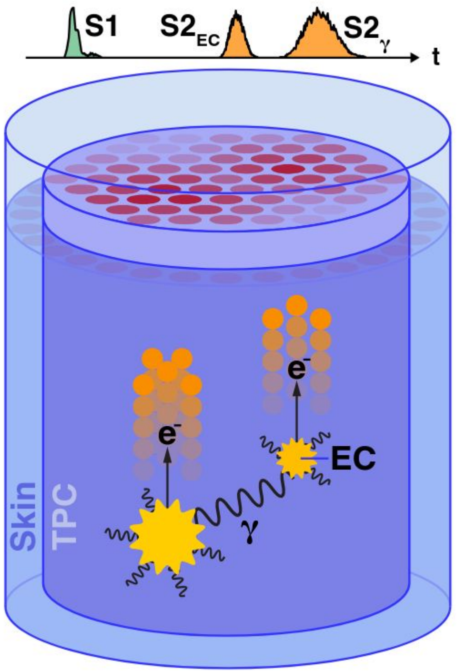


# Isolating EC events in LZ

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

1. **Multiple scatter selection (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

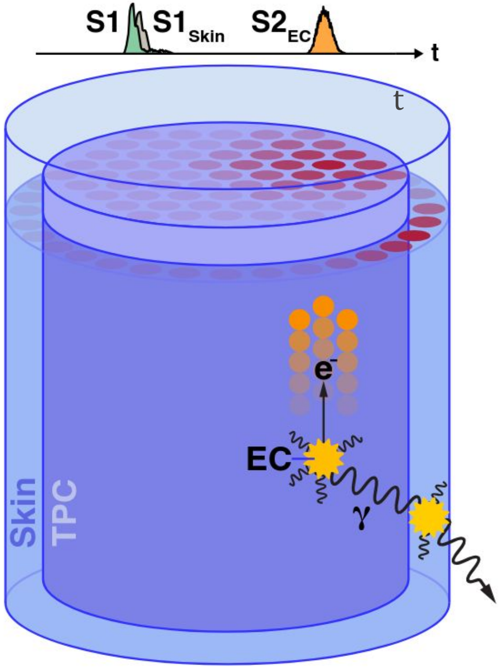


# Isolating EC events in LZ

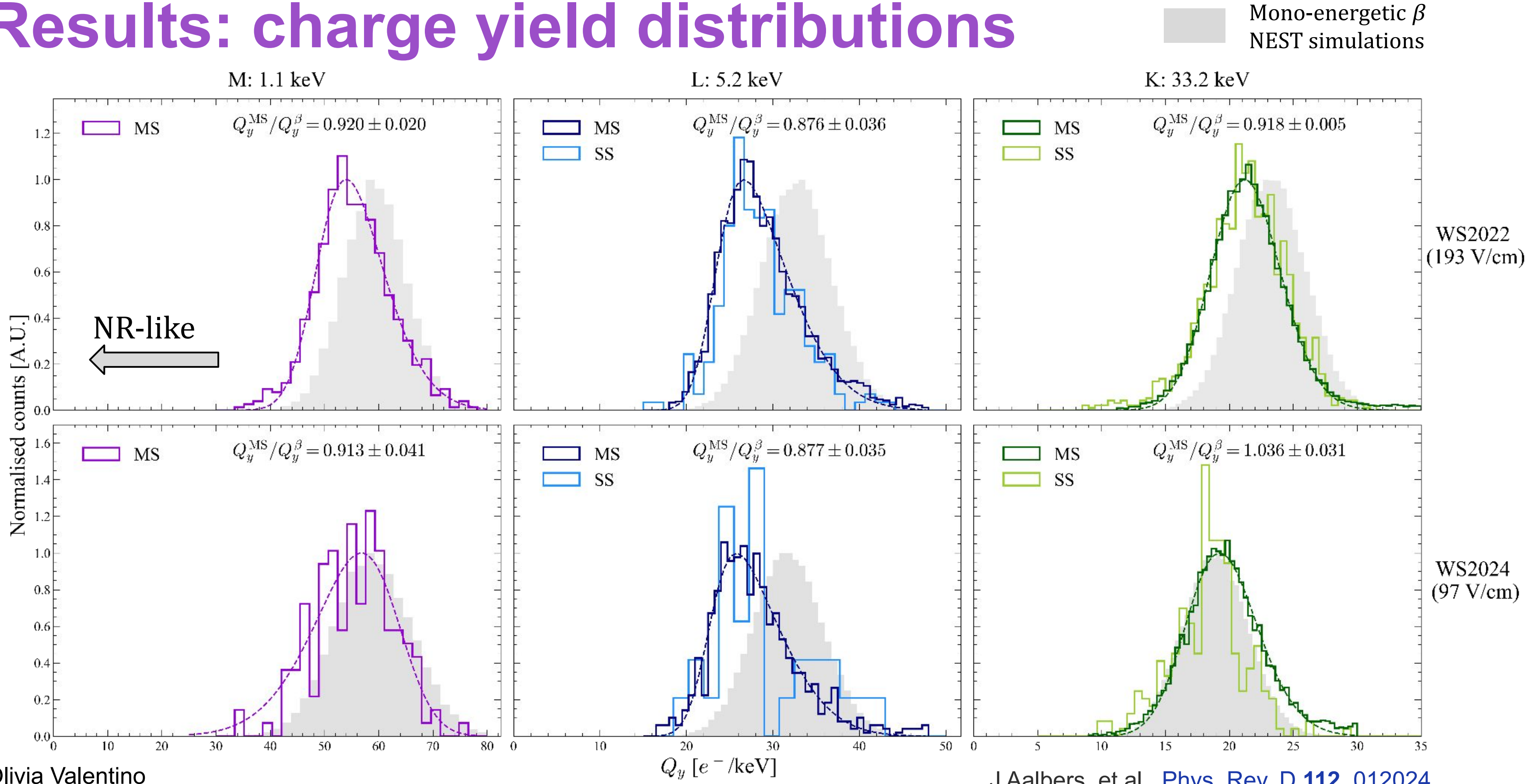
To isolate the atomic cascade in single EC we have two selection strategies:

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



# Results: charge yield distributions

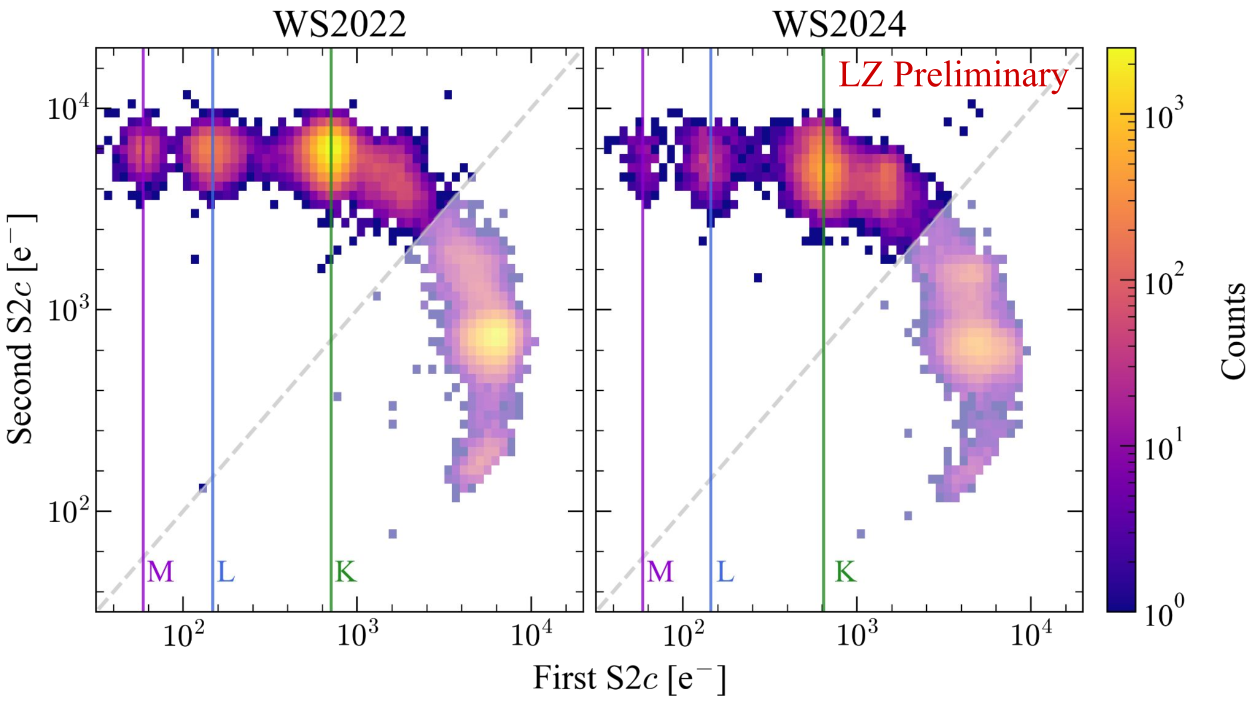





J Aalbers, et al., Phys. Rev. D **112**, 012024

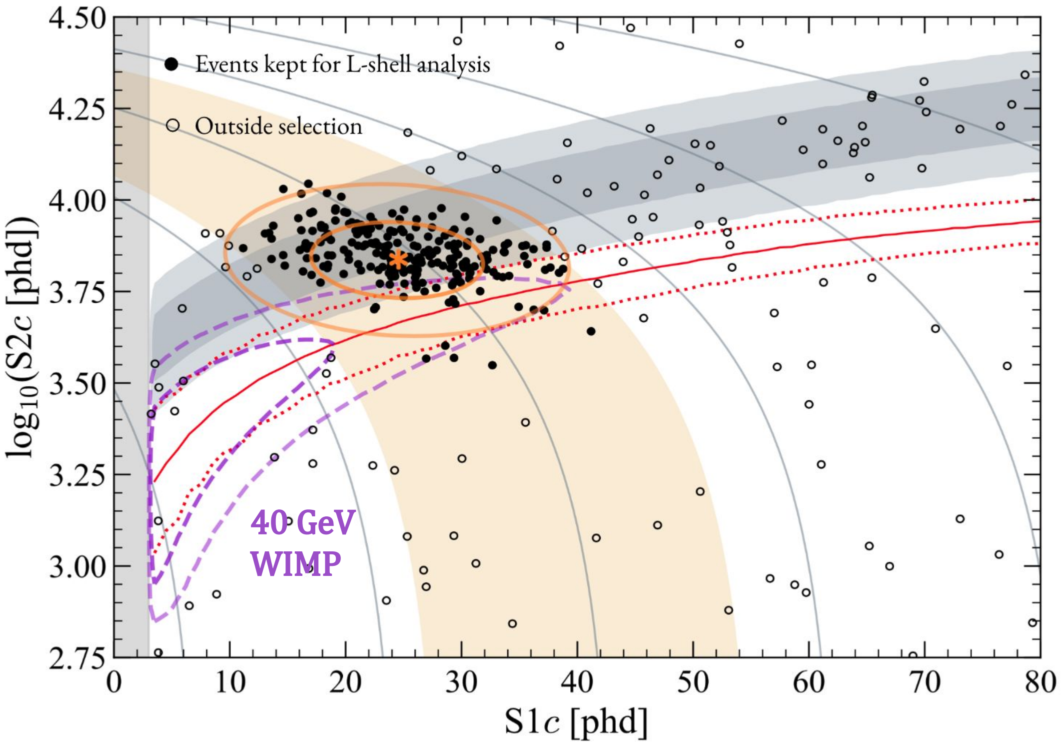
# Isolating EC events in LZ: MS selection

- 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)



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# Summary table

| Run | Source | $Q_y^{\mathrm{EC}}$ [$e^-$/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) | $33.63 \pm 0.03_{\mathrm{stat}} \pm 0.33_{\mathrm{sys}}$ | $0.917 \pm 0.001_{\mathrm{stat}} \pm 0.009_{\mathrm{sys}}$ |



J Aalbers, et al., Phys. Rev. D **112**, 012024

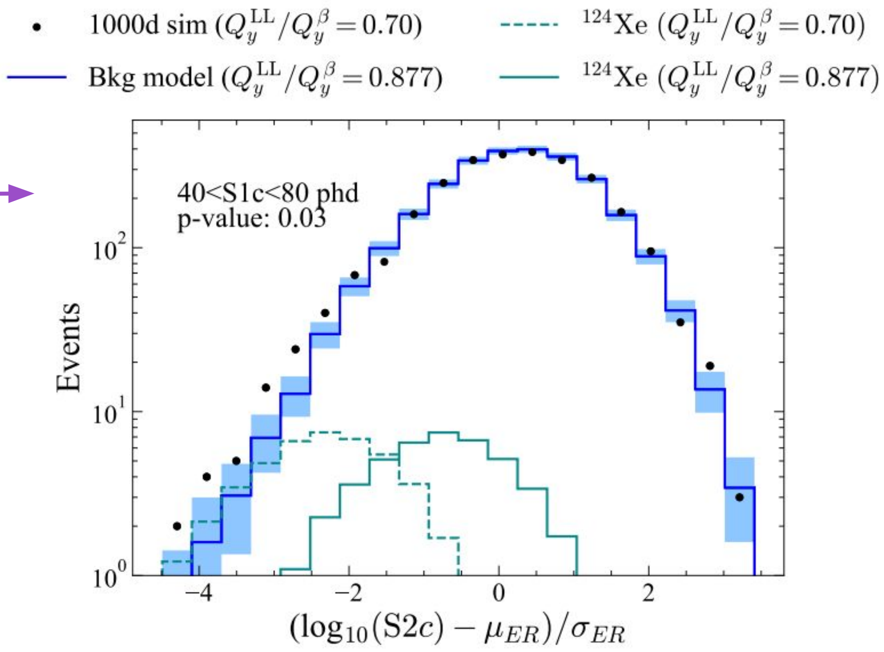
# Impact on WIMP searches

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



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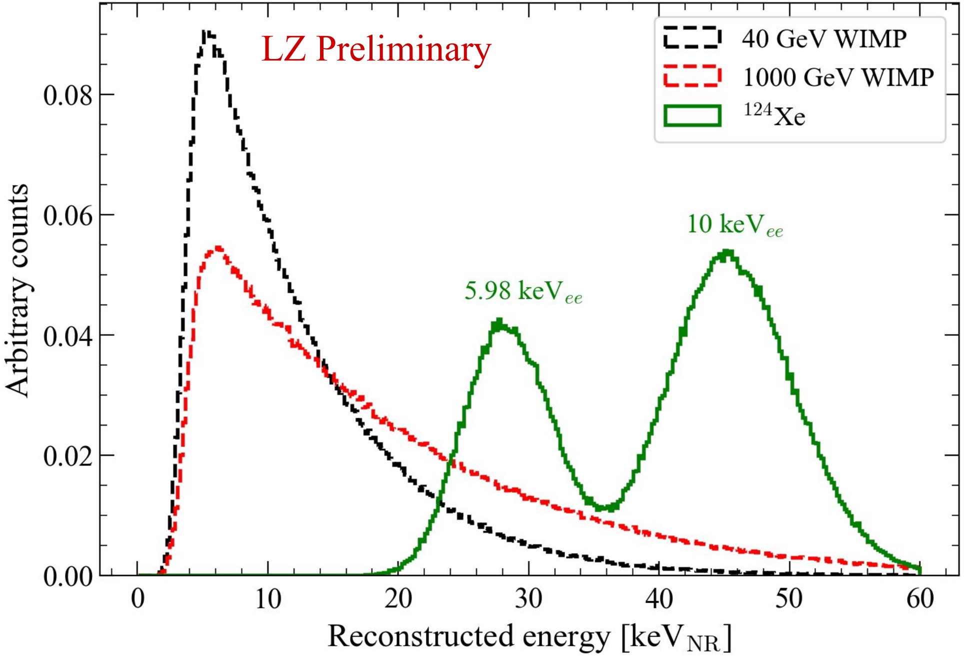
# Simulated energy spectrum of $^{124}$Xe

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 $\xi$ parameter via:

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

$\xi$ is related to the ionisation density

We assume that ECs and $\beta$ interactions produce the same $N_i$, within different boxes of sizes $a_L$ $a_M$ and $a_\beta$

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

J. Thomas and D. A. Imel, Phys. Rev. A 36, 614 (1987)