Using Computer Vision to Reject Instrumental Background in LUX-ZEPLIN and Multi-Vertex Inelastic Dark Matter Signal Searches

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on behalf of the LZ Collaboration

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

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- 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.
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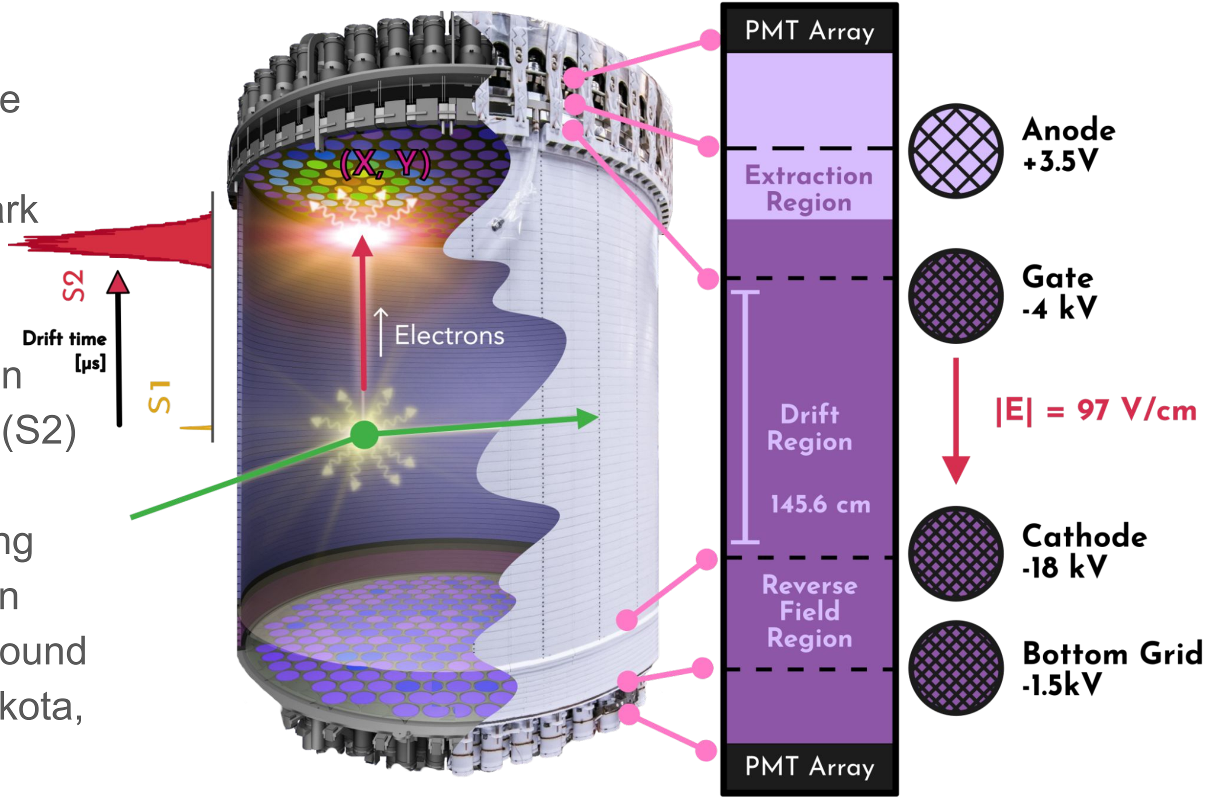
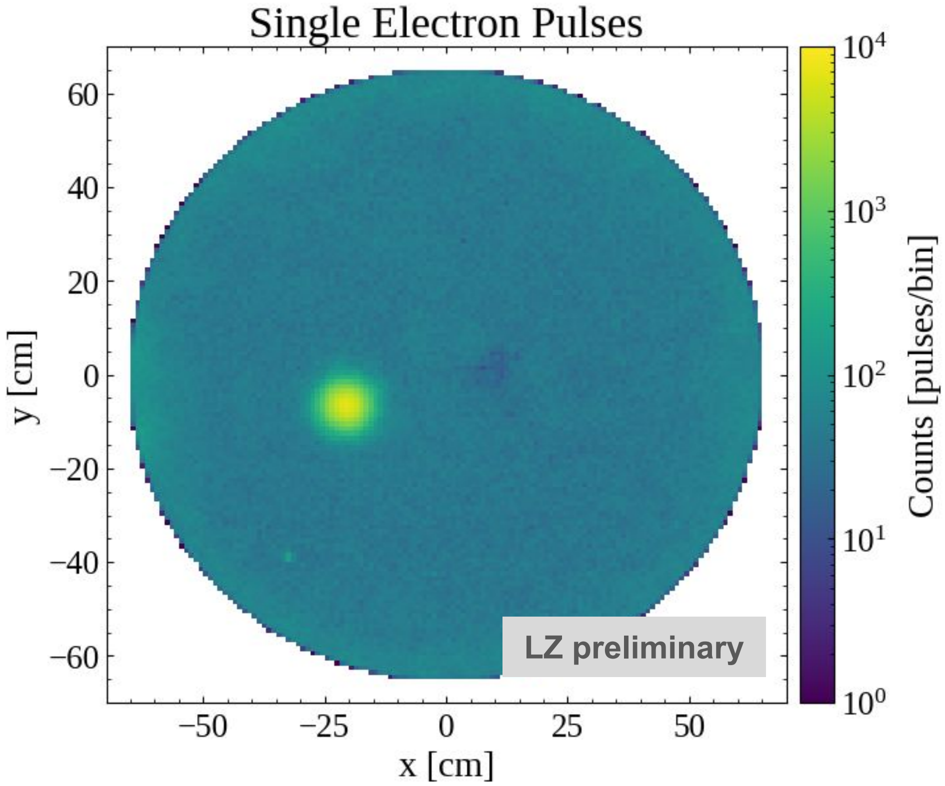
LUX-ZEPLIN

- ➢ Dual-phase liquid xenon time projection chamber (TPC)
- ➢ Searches for recoils from dark matter and rare event interactions
- ➢ Measures prompt scintillation (S1) and delayed ionisation (S2) signals
- ➢ 3D event reconstruction using drift time and PMT hit pattern
- ➢ Located at Sanford Underground Research Facility, South Dakota, USA



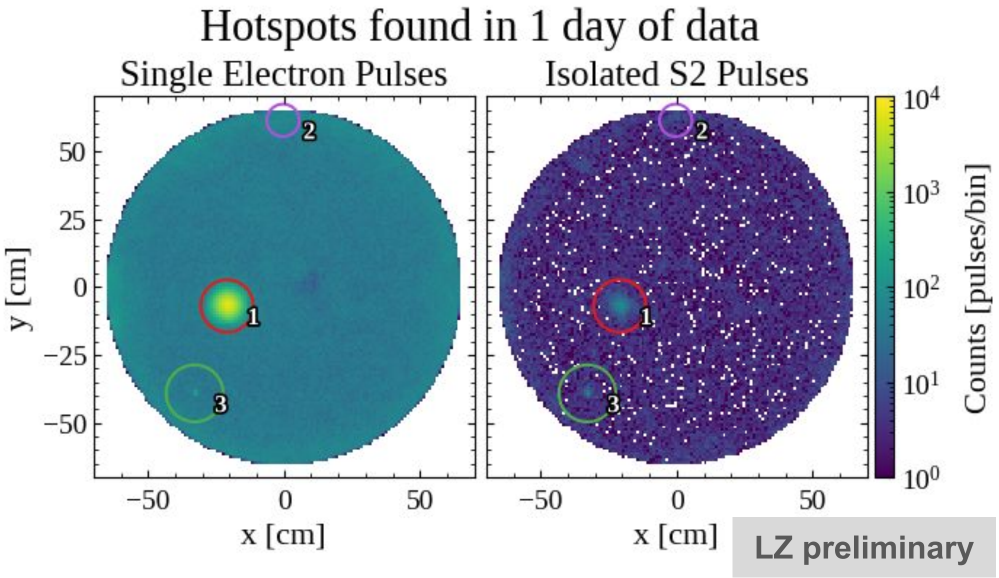
Hotspots in LZ

- ➢ Appear as localised excesses in the TPC XY coordinates
- ➢ Can be a result of charge build up on the grids
- ➢ Leads to an excess of ***Single Electrons (SEs)*** and ***Isolated S2 pulses (iS2s)***, in one area
- ➢ These contribute to our ***accidental background*** rate



Using computer vision (CV) to find features

- Traditional cut
  - Time-based SE/S2 rate cuts remove high-activity periods
  - Miss weaker hotspots
  - Discards full time windows
- CV/visual approach
  - Threshold image and apply OpenCV blob detection
    - Gaussian smoothing + multi-threshold blob detection to identify connected high-rate regions
  - Convert blobs → circular exclusion regions
  - Reject hotspots while preserving exposure



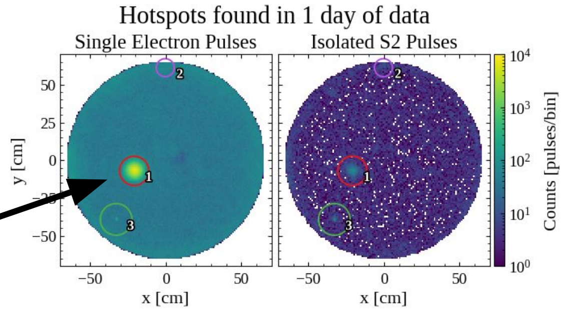
OpenCV blob detection [1] is the algorithm used to select features from histograms of pulses in the TPC XY space

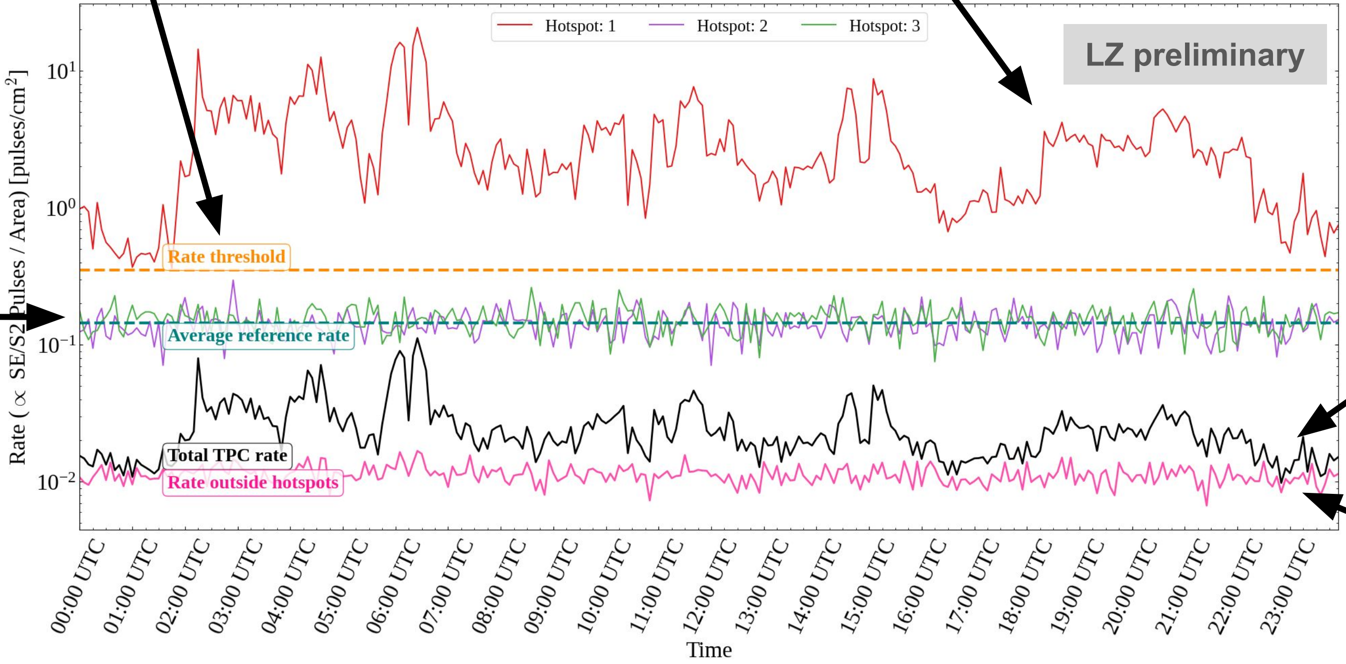
[1] OpenCV Documentation (v3.4), https://docs.opencv.org/3.4/

Generating exclusions

Rate threshold to differentiate hotspots from other features

Colours align from tagging image



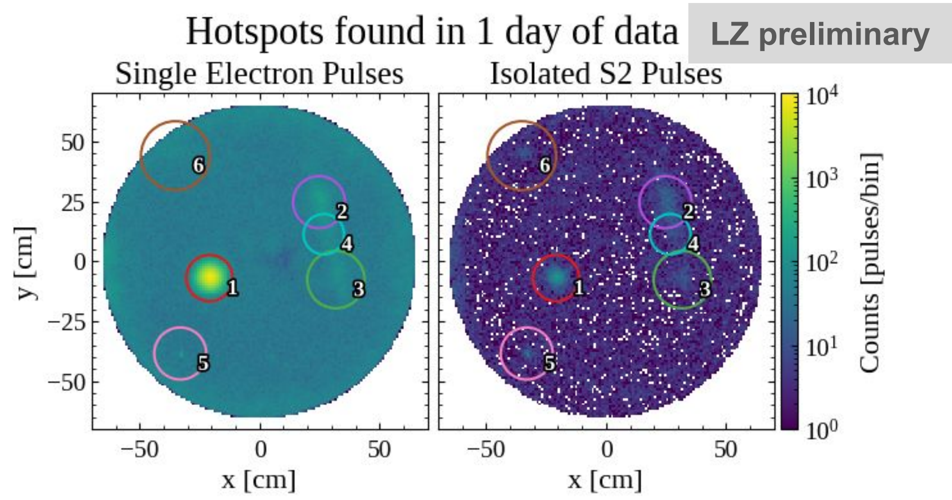


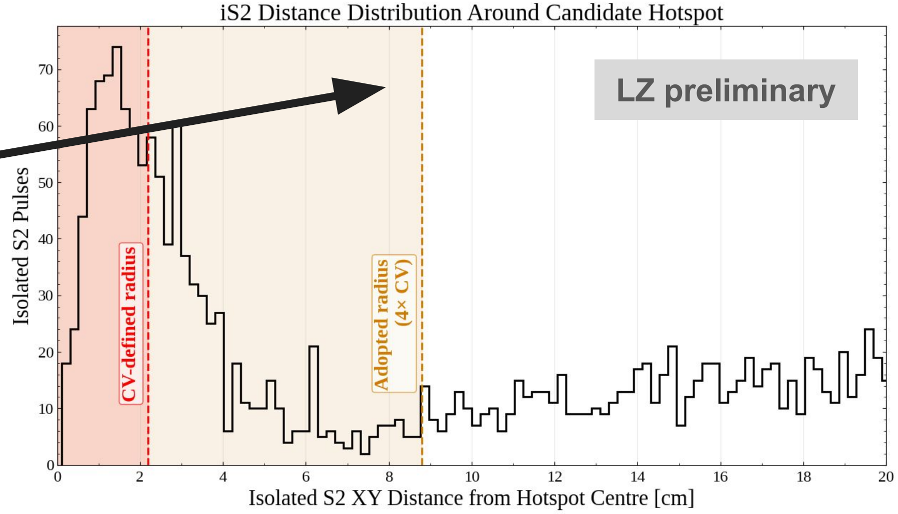
Reference spot taken outside the tagged areas

Removing the tagged hotspot areas brings the total TPC rate down to a more consistent baseline

Tuning process

- ➢ Two steps to tuning cut
  - ○ CV detector parameters (e.g. blob size limits, image params, hotspot radii scaling)
  - ○ Exclusion generation parameters
- ➢ CV detection tuned to highlight hotspot features, while reducing extraneous features/background variation
  - ○ Radius manually increased to balance hotspot exclusion against exposure loss
- ➢ Once the features have been tagged, the exclusions can be tuned based on the rate threshold and binning widths to differentiate hotspots from other articles



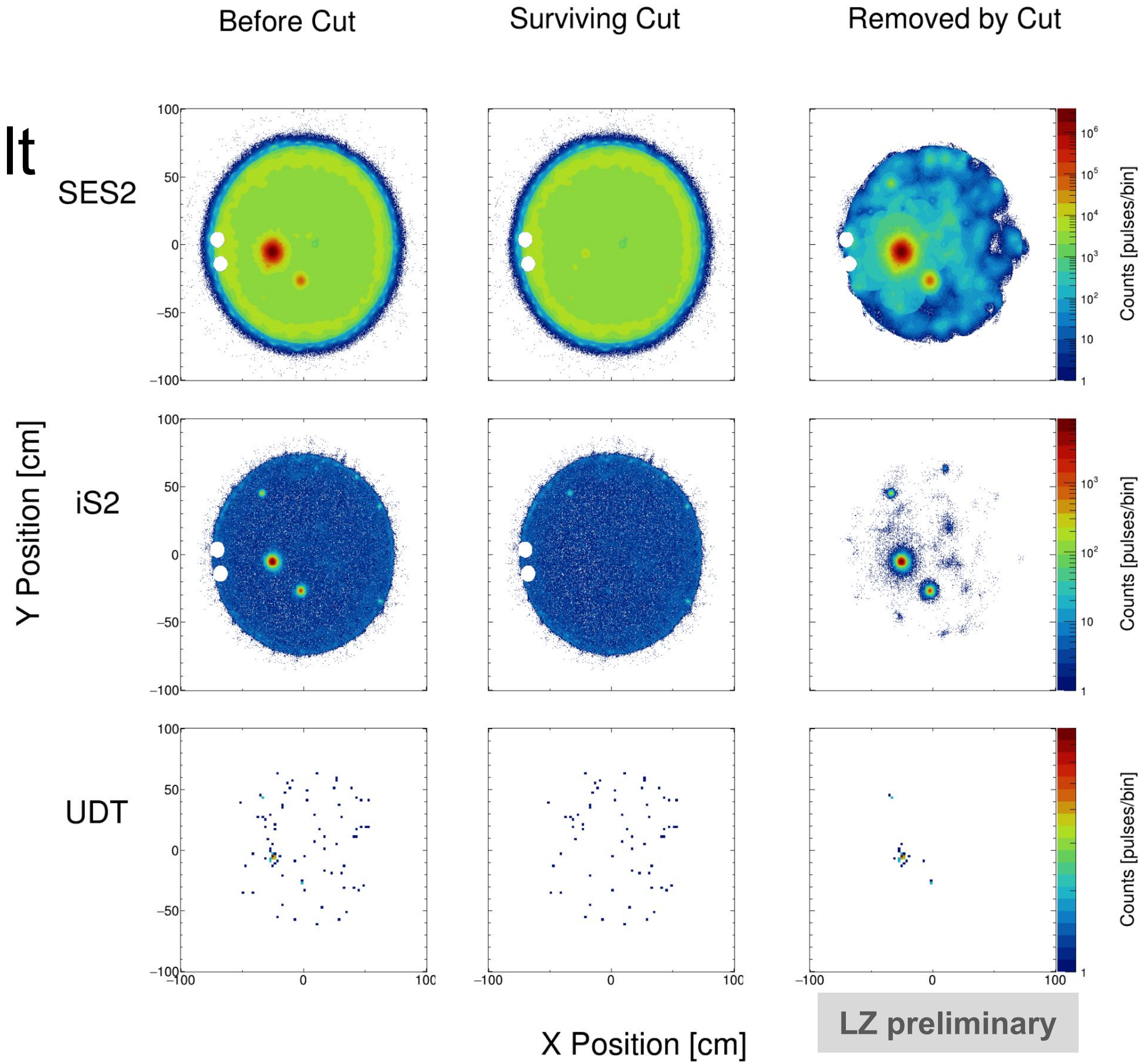


Cut application result

➢ Plots here show the result of applying the ***Spatial Hotspot*** cut

➢ It can be seen that the cut specifically targets localised excesses
  - Removes the tagged features only when rate exceeds the rate threshold set

➢ Reduces the average SE/S2 rate by 72.2%, while preserving 98.5% of exposure



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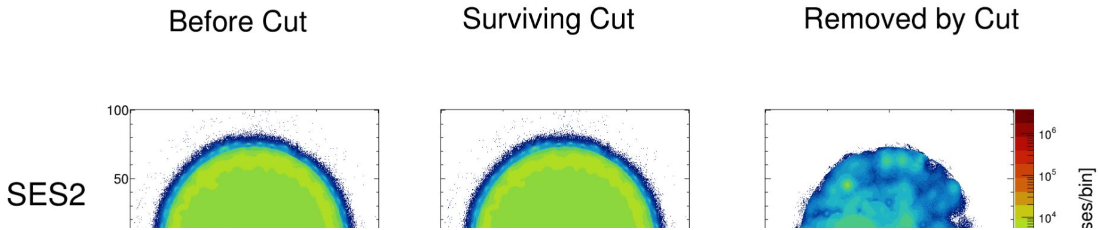

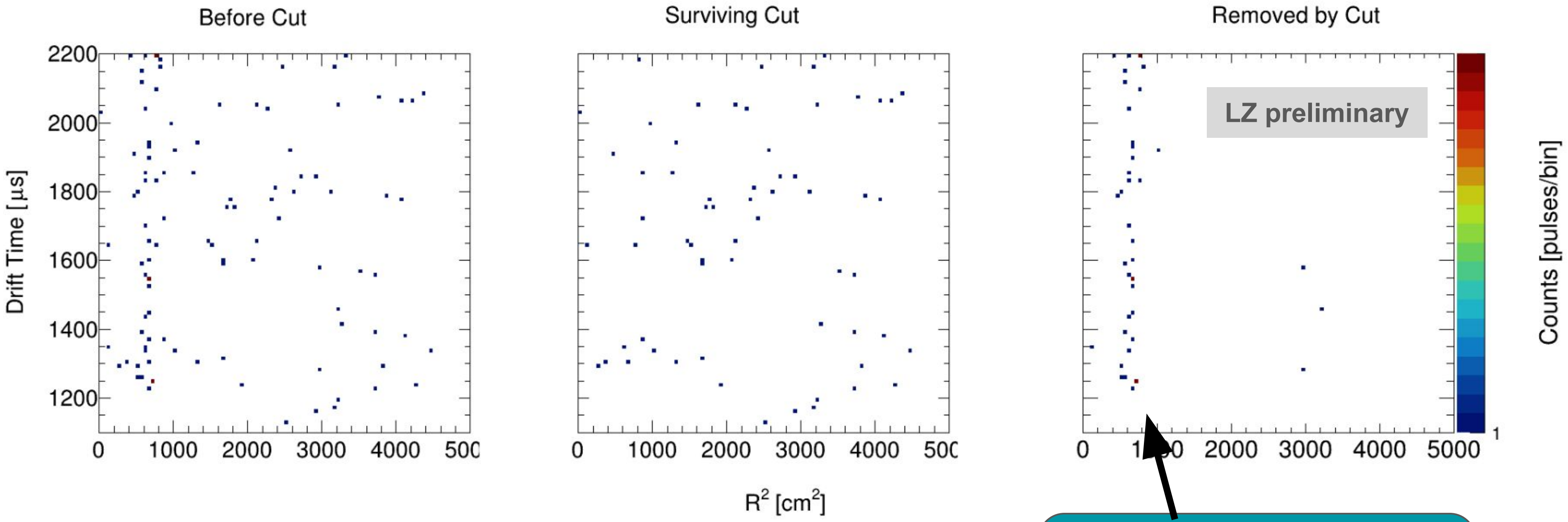

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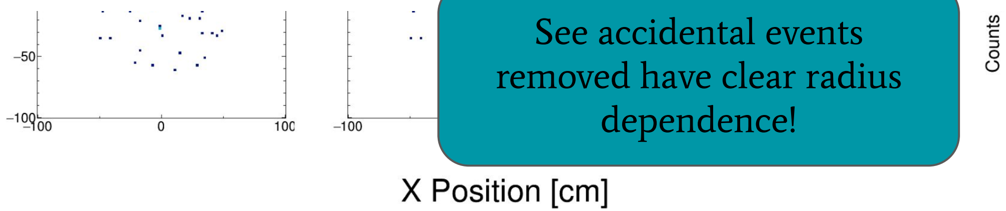
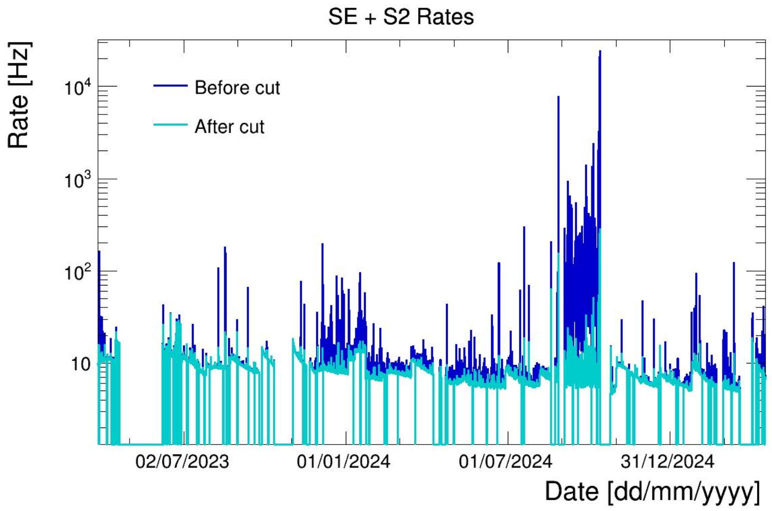
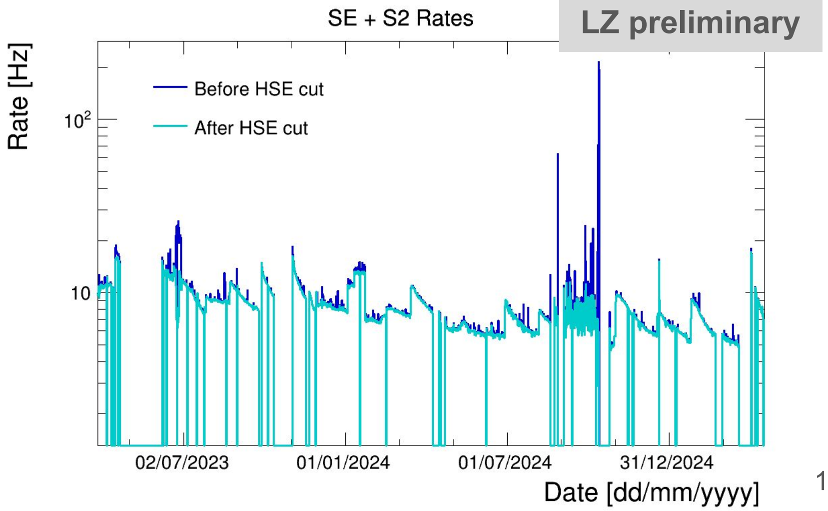


High Single Electron Rate Cut

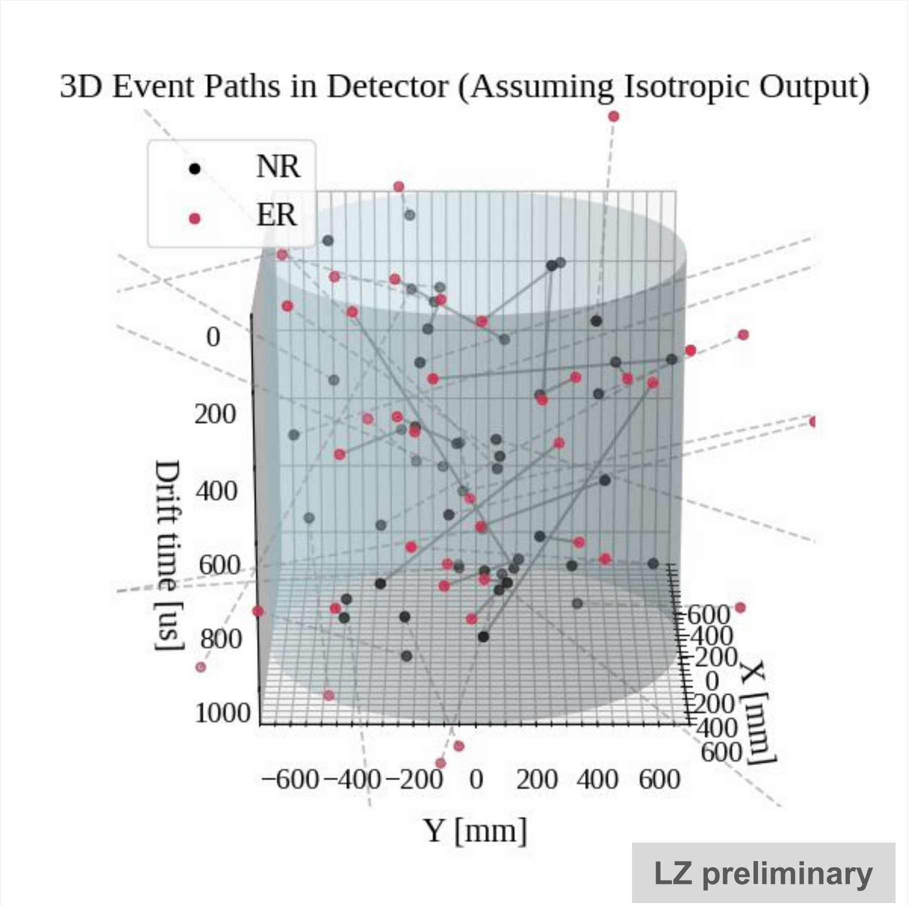
- Spatial cut is limited in that it only removes data within found circles
- A backup to this cut is to introduce a secondary ***High Single Electron (HSE)*** cut
- This follows on from application of the spatial cut, and removes all events (any XY) for the time bin in which the SE rate is still elevated
- This targets periods in which a hotspot was so intense, it raised the rate in the whole TPC





Multi-vertex Magnetic Inelastic Dark Matter Search

Not one, but two vertices!

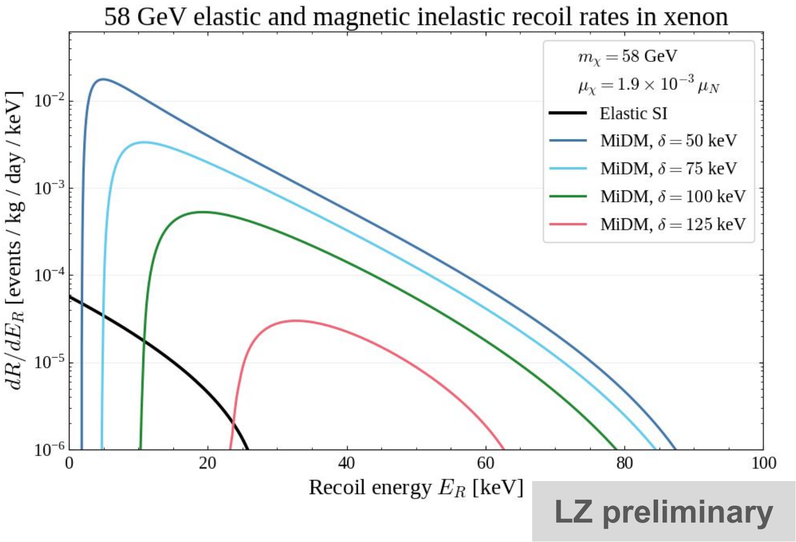


Physics of MiDM

- Assumption: WIMP has an excited state χ^* with a mass splitting δ (iDM) and magnetic dipole moment $\mu\chi$ (MiDM only)
- Inelastic scattering against nucleus allowed, and elastic scattering highly suppressed/forbidden
- Additional non-zero magnetic dipole moment $\mu\chi$ favours targets with large nuclear magnetic moments
- Higher minimum velocity requirement due to mass splitting:

$$v_{min} = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N E_R}{\bar{\mu}} + \delta\right)$$

- Larger mass splitting -> higher recoil energies

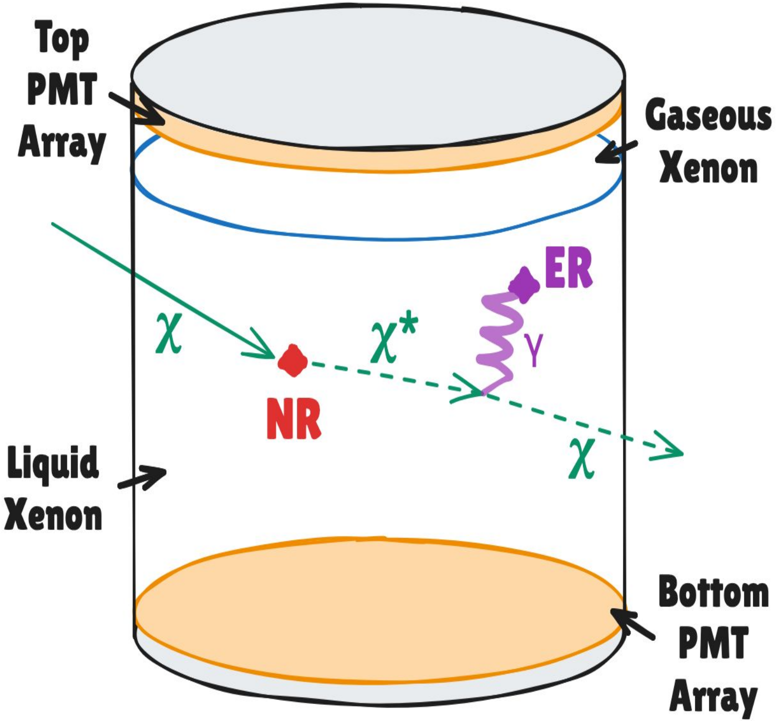


Event Topology

- Initial Nuclear Recoil (NR) with Xe
- Some time later, gamma ray emission (ER) from WIMP de-excitation
- For MiDM, expect lifetime ~μs scale

$$\tau = \frac{\pi}{(\delta^3 \mu_\chi^2)} \simeq \mu s$$

- 600 km/s over 1 μs = 0.6m displacement
- If decay time < event length and both scatters inside TPC:
  - NR S1 -> ER S1 -> NR S2 -> ER S2
  - NR S1 -> ER S1 -> ER S2 -> NR S2
  - NR S1 -> NR S2 -> ER S1 -> ER S2
- Low background due to distinct event topologies
  - Applying a minimum time separation between the S1s removes most MS neutrons and gammas



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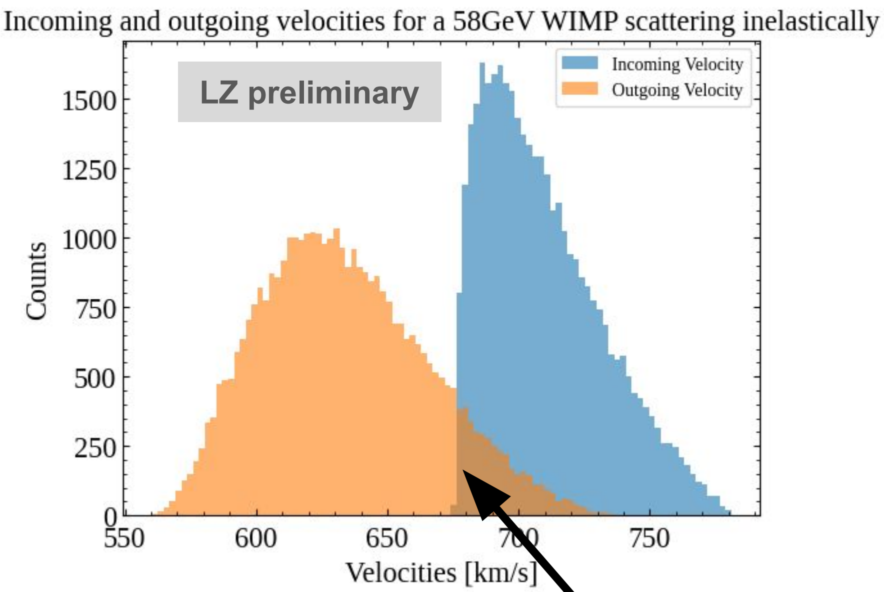


Minimum incoming velocity cut-off from mass splitting!

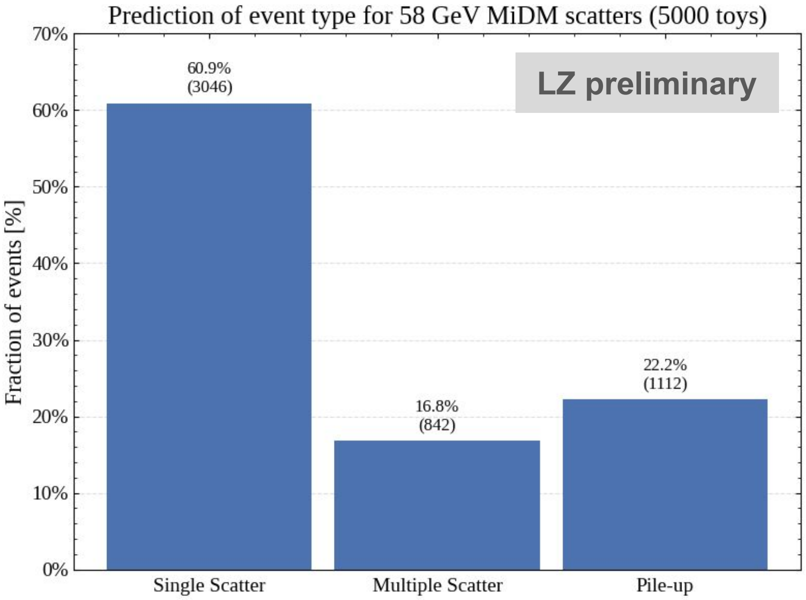
Opportunity in LZ

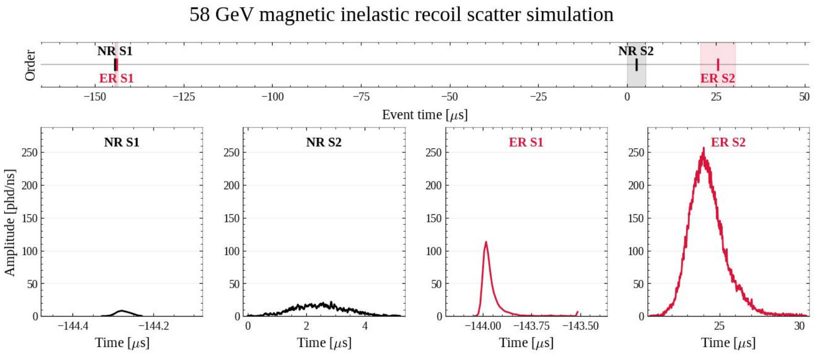
- ^{129}Xe (~27.4% abundance) + ^{131}Xe (~21%) have larger magnetic moments for preferential scattering
- Larger size TPC means more likely to record both NR and ER scatters from interaction and decay
  - (~5.5 tonnes vs 48kg FV for XENON100 [2])
- Current reconstruction allows us to analyse all three possible event topologies
- Exposure from ^{8}B analysis: 5.7 ± 0.2 tonne-years
  - ~193x higher exposure than XENON100
- For now considering specific MiDM case, but plan is to extend to a general iDM model

[2] Aprile, E., et al. "Search for magnetic inelastic dark matter with XENON100." Journal of Cosmology and Astroparticle Physics 2017.10 (2017): 039-039.

Preliminary Simulations

- ➢ Initial sims using *NESTpy* [3]
- ➢ Modelling an inelastic NR followed by gamma emission of mass splitting energy some lifetime later
- ➢ Allows us to see a rough split of the topologies we'd expect in LZ's volume
  - SS - only NR in detector
  - MS - Both in detector but S1s split by < resolution (~400ns)
  - PileUp - Both in detector and lifetime >= 400ns
- ➢ The pile-up categorised events, with two clear scatters in the detector, are where this analysis will be most powerful
  - Usually considered background events for normal WIMP searches, but our signal events are here!



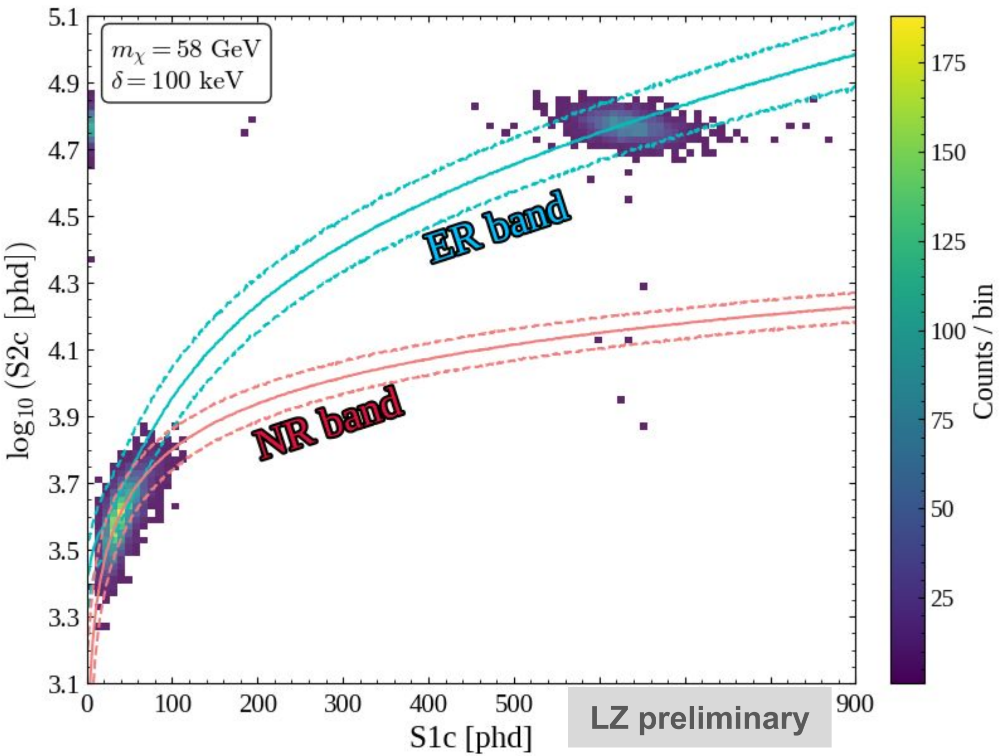


[3] NEST Collaboration, Noble Element Simulation Technique, https://nest.physics.ucdavis.edu/ (via NESTpy Python bindings)

ER line here from gamma emission

Preliminary Simulations

- ➢ These sims are also allowing us a preliminary consideration of cuts to include:
  - E.g. NR/ER energy bounds for scatters in event (clearly separated), pulse ordering, pulse time splittings
- ➢ Next steps will involve:
  - Complete simulations
  - Background analysis
  - Perform search on currently acquired data



NR band based on a model extrapolated from lower energies and based on DD and AmBe calibrations

Conclusion

- Hotspot mitigation
  - Developed a computer vision–based spatial hotspot cut for LZ
  - Identifies localised excesses using Gaussian-smoothed, blob-detected XY maps
  - Reduces SE/S2 background rates by ~72% while preserving ~98% exposure
  - Improves on traditional time-based cuts by retaining exposure while targeting a larger proportion of hotspot related events
- MiDM search
  - Multi-vertex MiDM signatures provide a low-background, distinctive topology
  - LZ’s large target mass and exposure offer strong discovery potential
  - Preliminary NESTpy simulations used to study signal topologies and selections
  - Ongoing work: full simulations, background modelling, and first data analyses

Thank you for listening!