Optimising the LUX-ZEPLIN Neutron Veto with MOO

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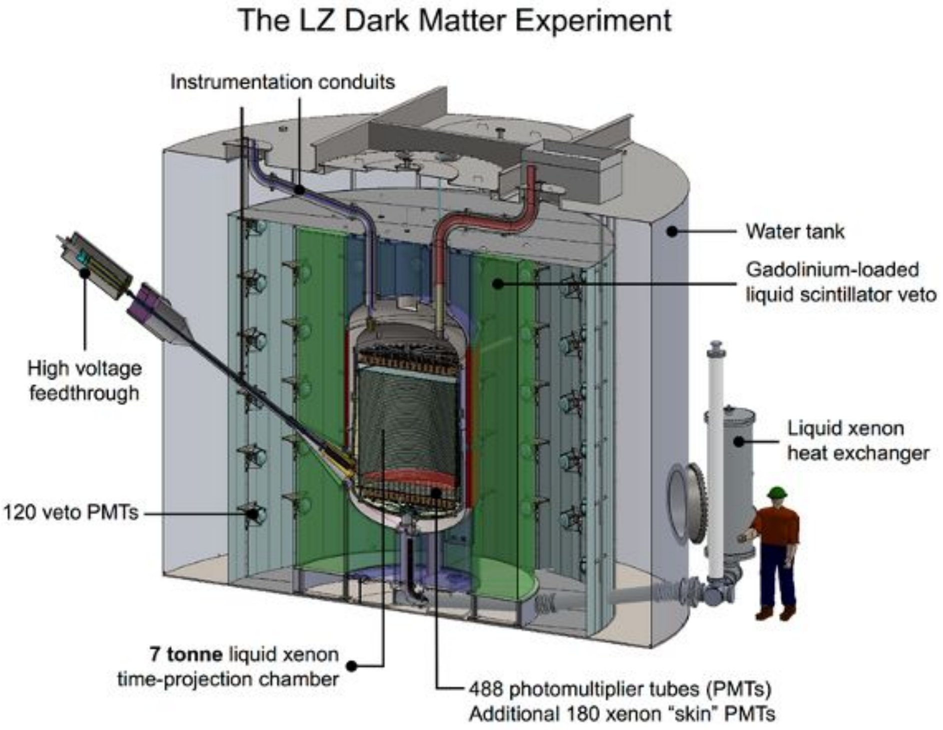
The LUX-ZEPLIN Dark Matter Experiment

LZ is a direct dark matter detection experiment, using 7T xenon time projection chamber to look for WIMP-xenon nuclear recoils, located ~1500m underground at SURF, South Dakota

Searching for signals from WIMP - xenon interactions. Neutrons interactions mimic those of WIMPs and are thus an important background.

Detected signal is pair of scintillation (S1) and ionisation (S2) pulses in top and bottom PMT arrays.

Latest result (WS2024[1]), set world leading limits on WIMP spin-(in)dependent cross-section for m_{DM} > 9 GeV.



1: https://arxiv.org/abs/2410.17036

Vetoing Neutrons with the Outer Detector (OD)

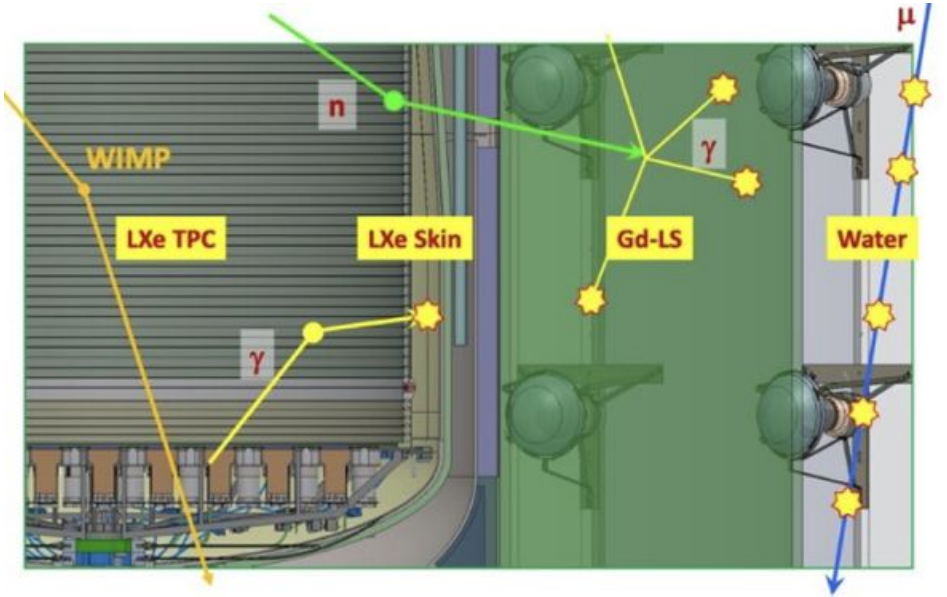
Background neutron produces an indistinguishable signal from WIMPs, so requires a dedicated external veto detector.

We use Gadolinium doped liquid scintillator (GdLS), to capture neutrons. Neutron captures produce gamma rays, which produce a scintillation signal that can be detected by OD PMT array.

multiple interactions = not WIMP

Neutrons can be Vetoed by looking for signals in the OD in coincidence with an event in the TPC.

We additionally have an instrumented skin sub-detector for gamma tagging.



Neutrons in LZ come from (alpha, n) reactions and spontaneous uranium fission. Radio-assays of all detector materials allow us to accurately constrain their rate. In the WS2024 dataset we expect **1±1 neutrons in 220 live-days** before vetoes.

How the Outer Detector Veto Works

After a single scatter pulse (S1) a time window is opened, if an event in the OD falls in this window and is above a set threshold in pulse area (summed over PMTs) the event is vetoed.

We have different veto for different events:

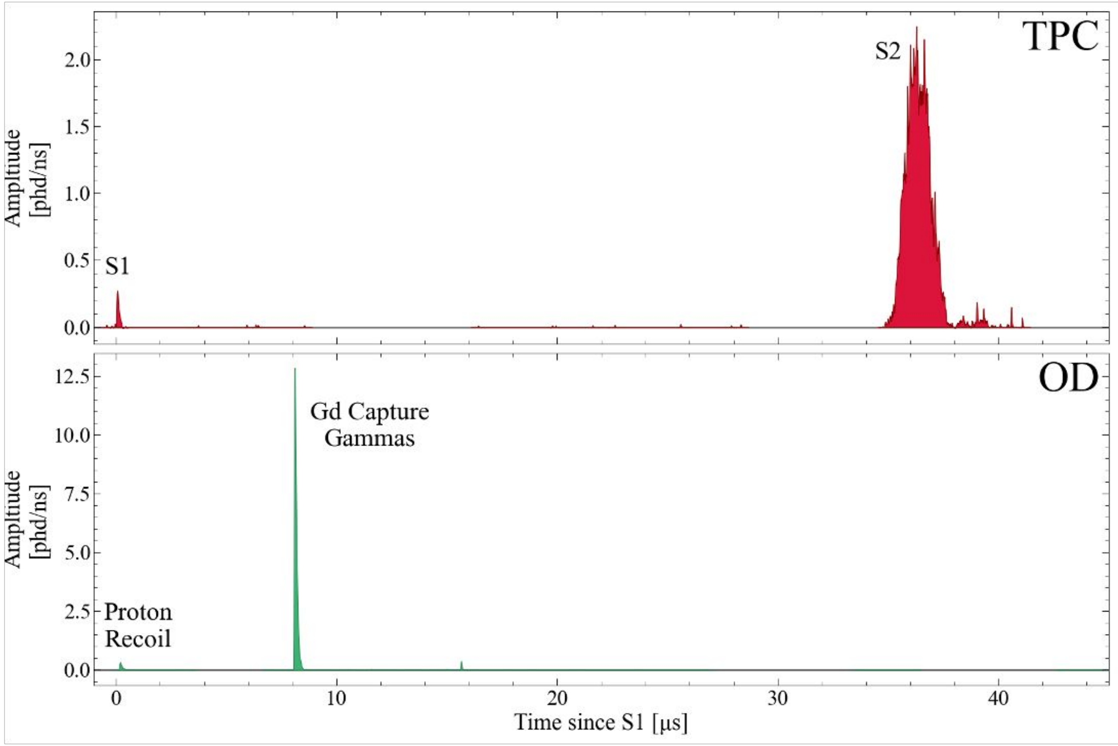
-proton recoils: short window, low threshold

(OD *prompt* veto)

-Gd capture: long window, high threshold

(OD *delayed* veto)

The delayed veto is the most important for neutrons. We want to optimized the Veto in terms of **Efficiency** and **Deadtime**



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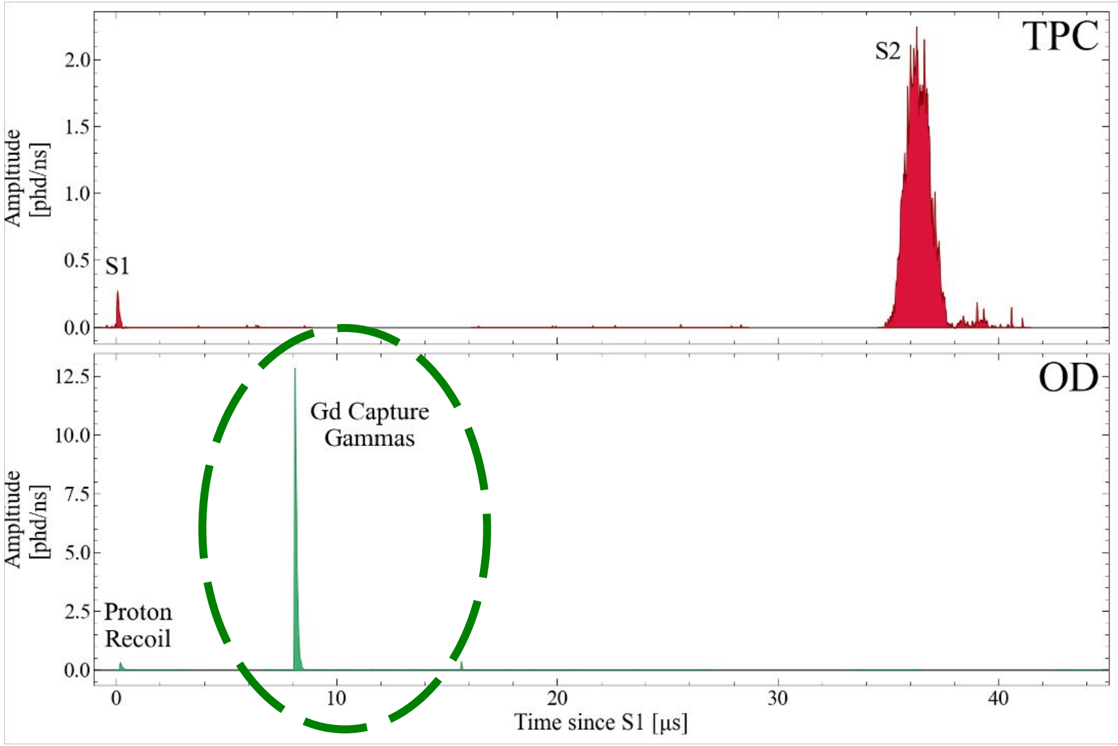


Neutron Veto Efficiency from AmLi Calibration Data

Efficiency: Probably that a neutron will be correctly identified and Vetoed

This can be estimated using AmLi neutron calibrations. We look for neutron scatters in the TPC and determine the fraction that is correctly vetoed

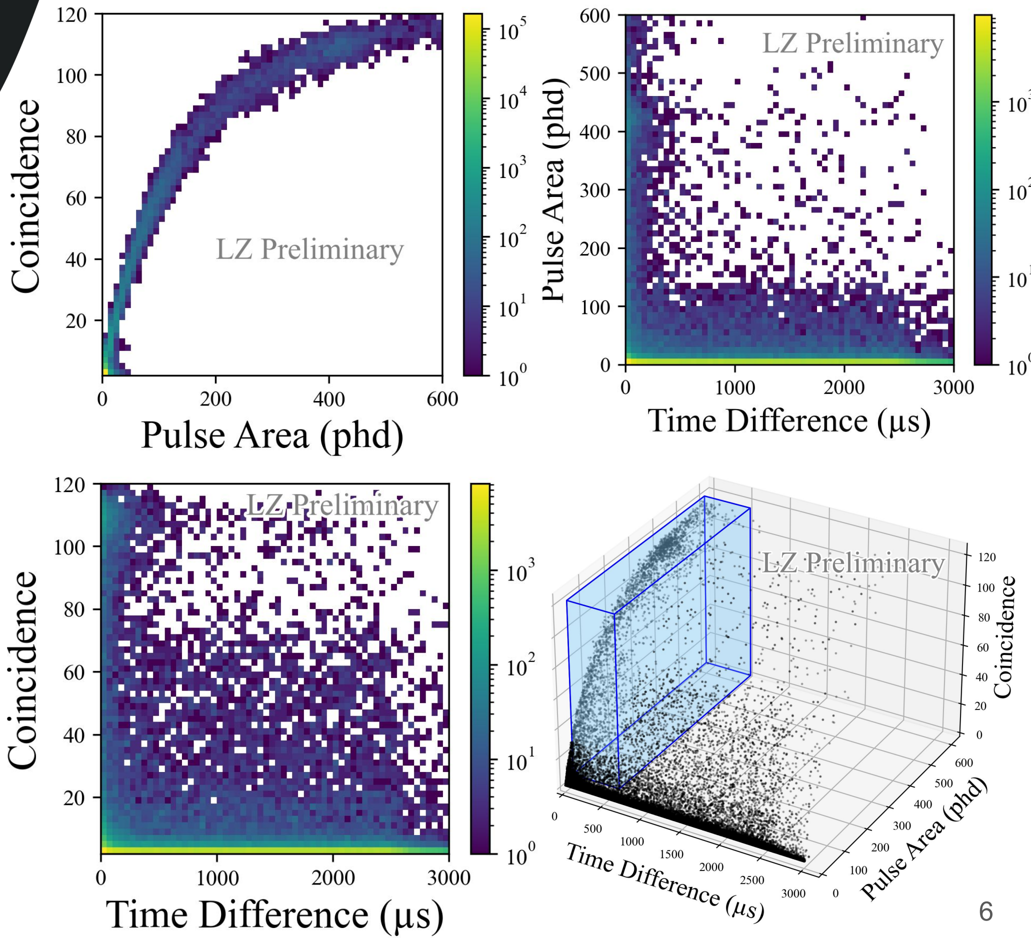
This depends on the veto parameters:

-Time window

-Pulse Area Threshold

-Coincidence Threshold (ignored as highly correlated with pulse area)

We would like to tune the parameters to maximise efficiency



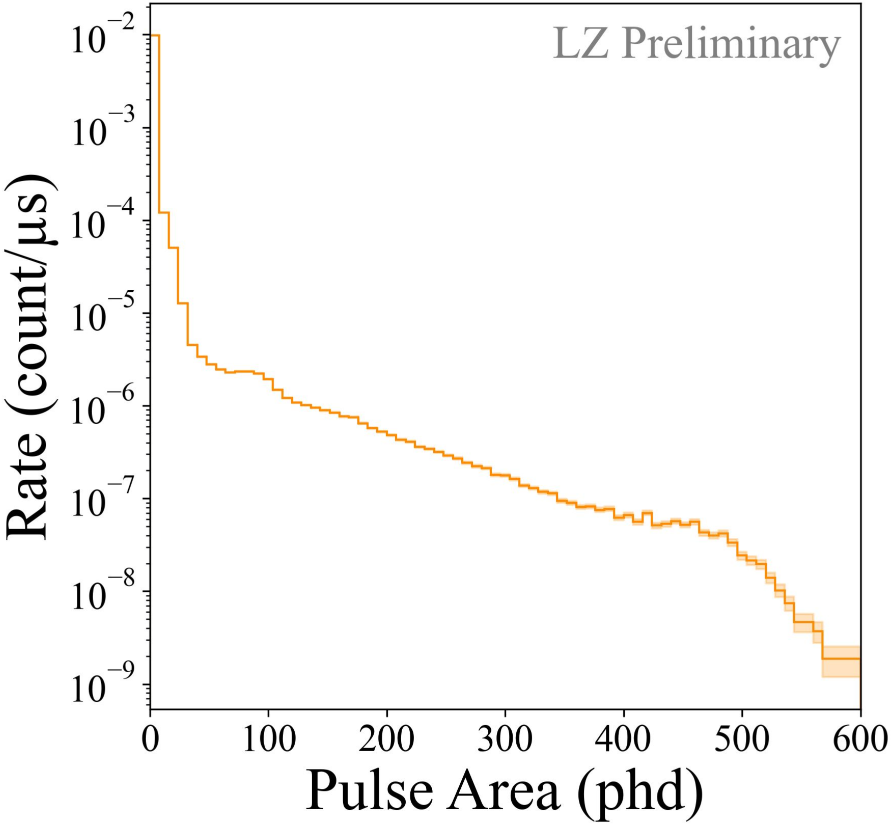
Veto Induced Deadtime

Deadtime: The probability that a non-neutron event will be incorrectly vetoed

The OD has a non-negligible background rate, there is a certain probability that an non-neutron event (WIMP/electron recoil etc…) will be vetoed incorrectly. This result in an effective decrease in live-time and exposure.

The deadtime fraction is estimated from background data; the probability of a false veto can be estimated from the rate above a given threshold multiplied by window length.

We would like to tune the veto parameters to minimize deadtime.



Approx. Energy Scale: ~200(phd/Mev)

Multi Objective Optimisation (MOO)

Maximizing/minimizing the efficiency/deadtime involves a compromise:

Increase efficiency → Increase time Window → Higher background rate → **More deadtime**

Decrease deadtime → Reduce time window → Fewer neutron capture pulses → **Worse efficiency**

This can natural be viewed through the lens of **multiobjective optimisation (MOO)**.

We look for the set of choices that gives us an optimal compromise.

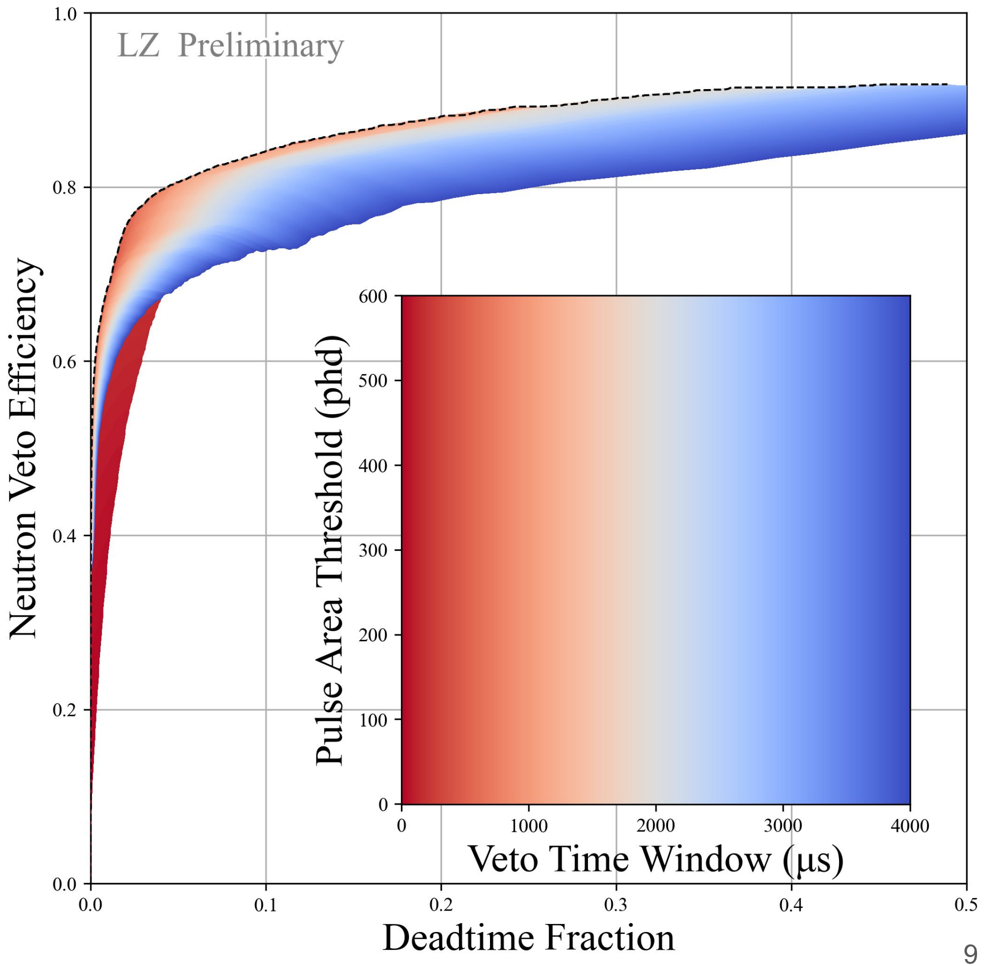
Mapping from Design Space to Objective Space

Approach taken in this work:

We look at the mapping from **design space** (window, threshold) to **objective space** (deadtime, efficiency).

Compute all pairs of points in design space (grid search) and find the boundary in objective space – this is the **Pareto Optimal Frontier.**

We evaluate physics impact by scanning along Pareto frontier, we want to find the point that maximises WIMP discovery potential.



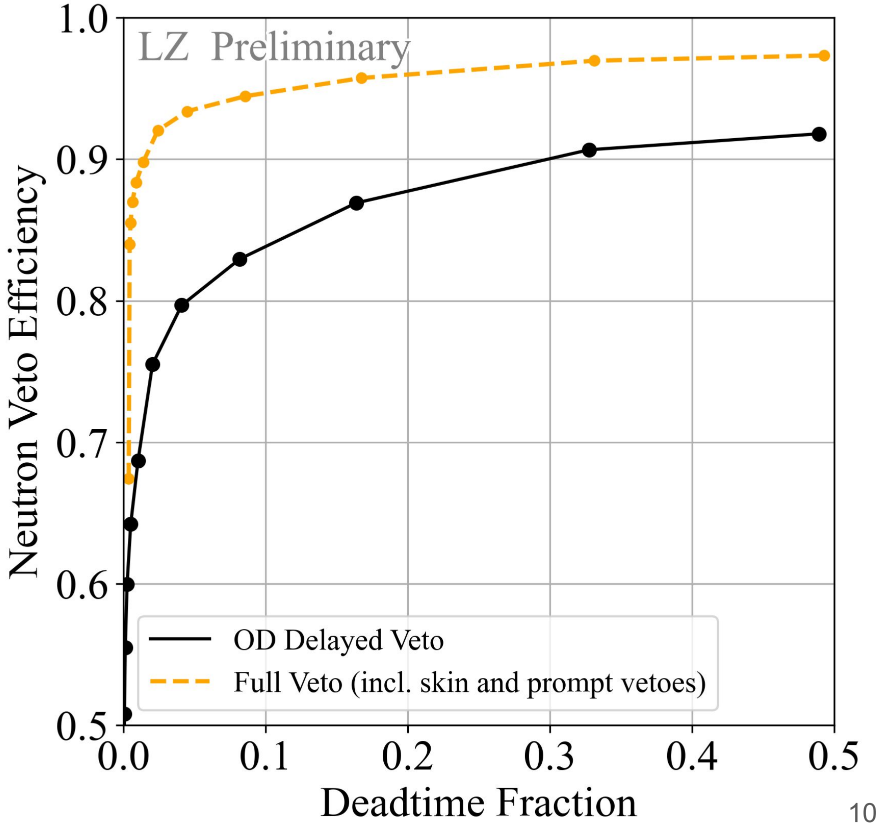
Test Points and Corrections

For simplicity and clarity we select test points along the Pareto frontier.

A correction is applied to the pure OD-delayed veto efficiency to account for additional efficiency gained from complementary vetoes:

- Xe Skin veto
- OD prompt veto

The xenon Skin's main purpose is identifying gammas but has secondary ability to detect neutron though xenon nuclear recoils and through neutron capture gamma.



Optimising with respect to Physics Impact

Carry out “cut & count” analysis with expected WIMP, neutron and accidental yields. Obtained from scaled WS2024 yields for neutrons and accidentals to 1000 live days.

Take signal region as the 2σ WIMP contour and scale the rate for overlap of probability density:

Neutrons: (Background targeted by veto)

3.2 neutrons in 1000 live days

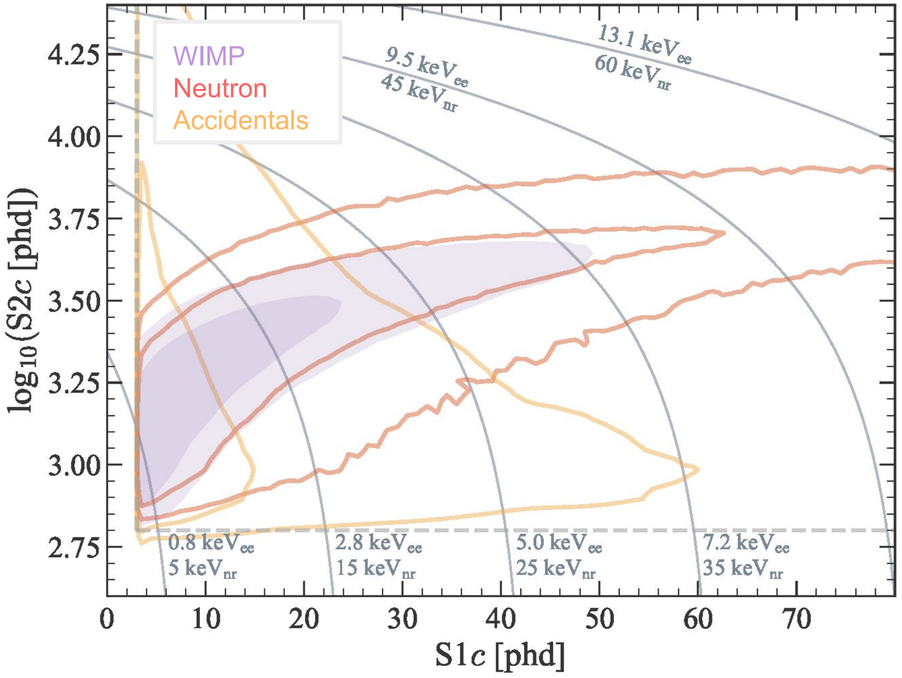
Accidentals: (Background not targeted by veto)

4 accidentals in 1000 live days

WIMPs: (Desired Signal)

6 WIMP scenario - optimistic

4 WIMP scenario - plausible given 2024 result



Expected Discovery Significance

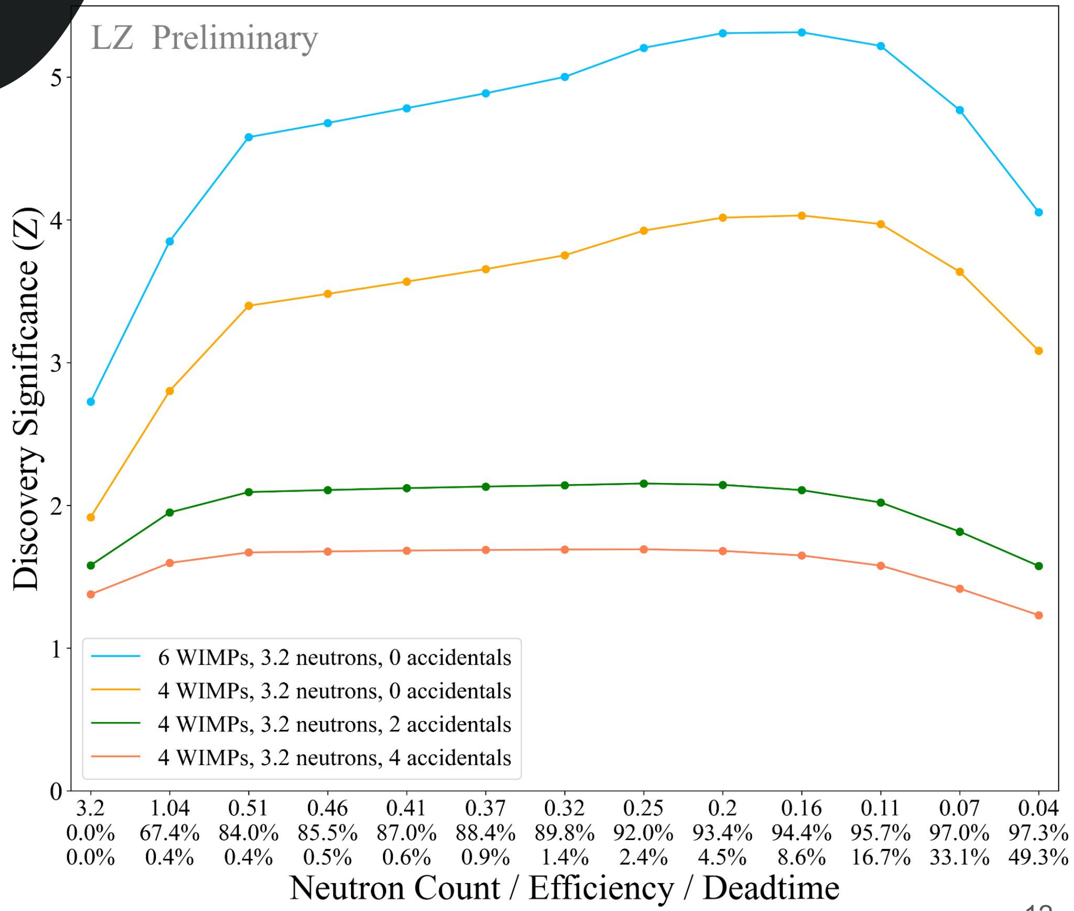
Choose 4 scenarios:

1. Optimistic (assumes 1.5 WIMPs in WS2024)
2. Plausible (just missed 1 WIMP in WS2024)
3. Low accidental rate
4. Increased accidental rate

Conclusion:

- Neutron veto boosts discovery sensitivity substantially in the absence of any other backgrounds
- In the presence of additional backgrounds discovery sensitivity drops quickly and shows weaker dependence on veto parameters
- (Not shown) Peak position stable against reasonable variations in neutron (x2) and accidental rates

- Without accidental background optimal choice is 94% eff. with 8.6% deadtime
- In the presence of backgrounds optimal choice is 92% eff. with 2.4% deadtime



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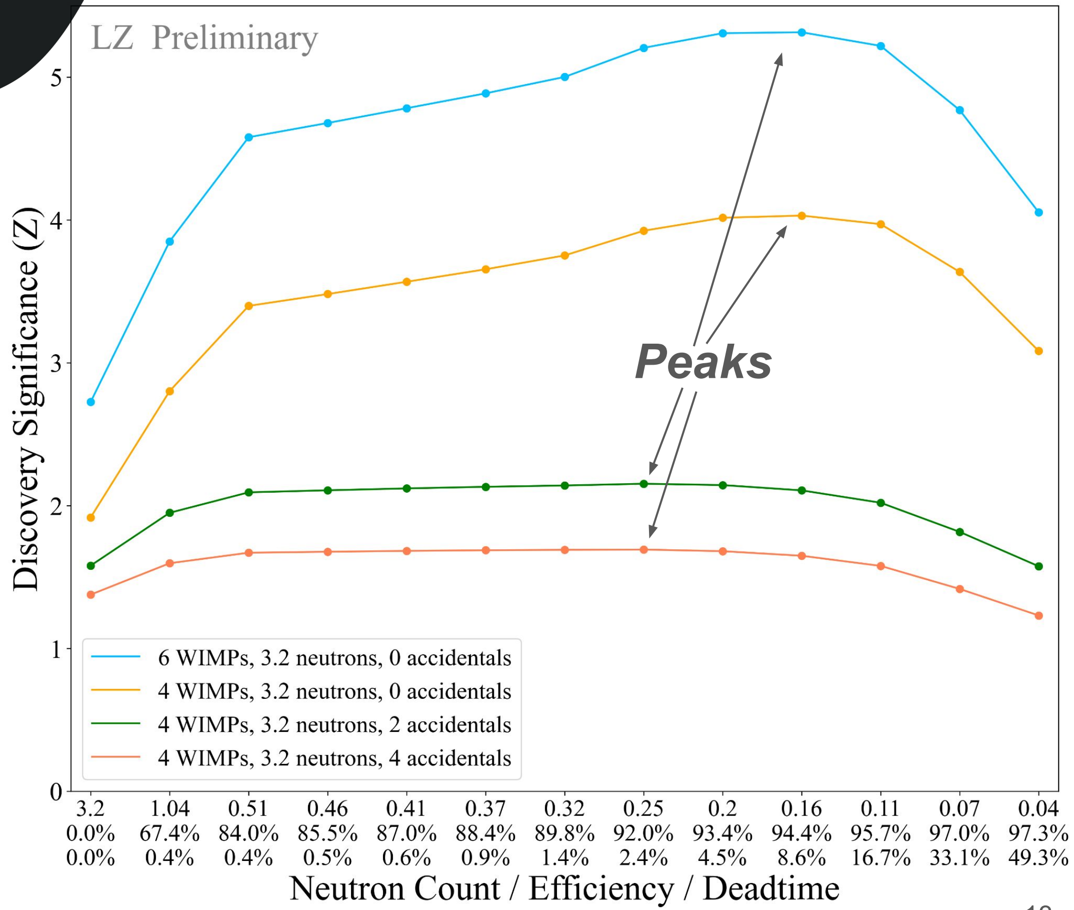
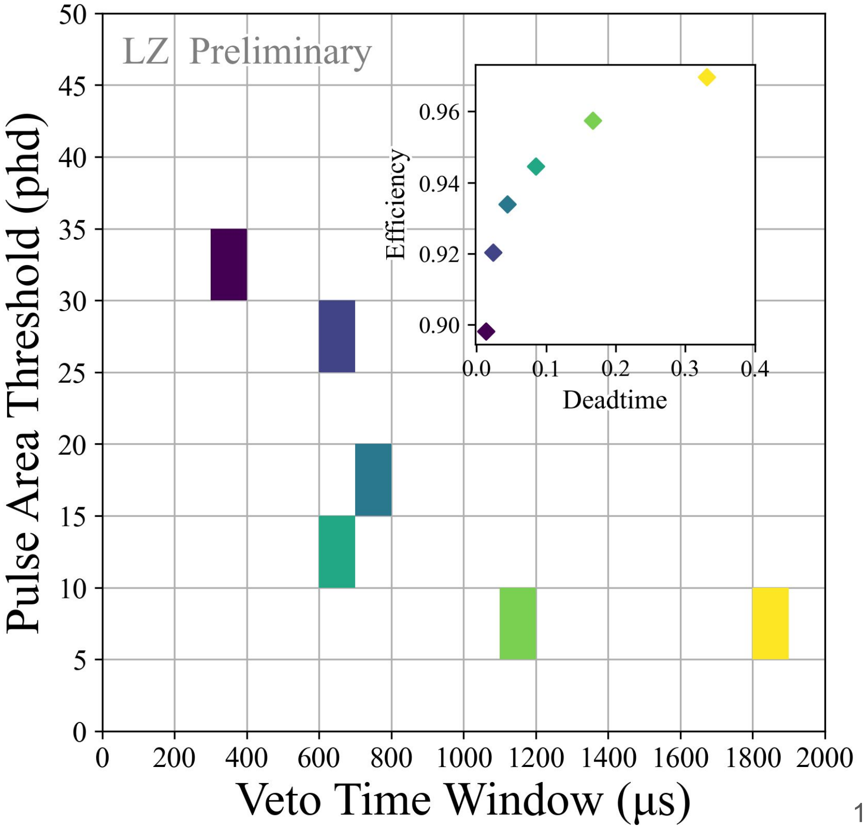


Mapping Back to Design Space

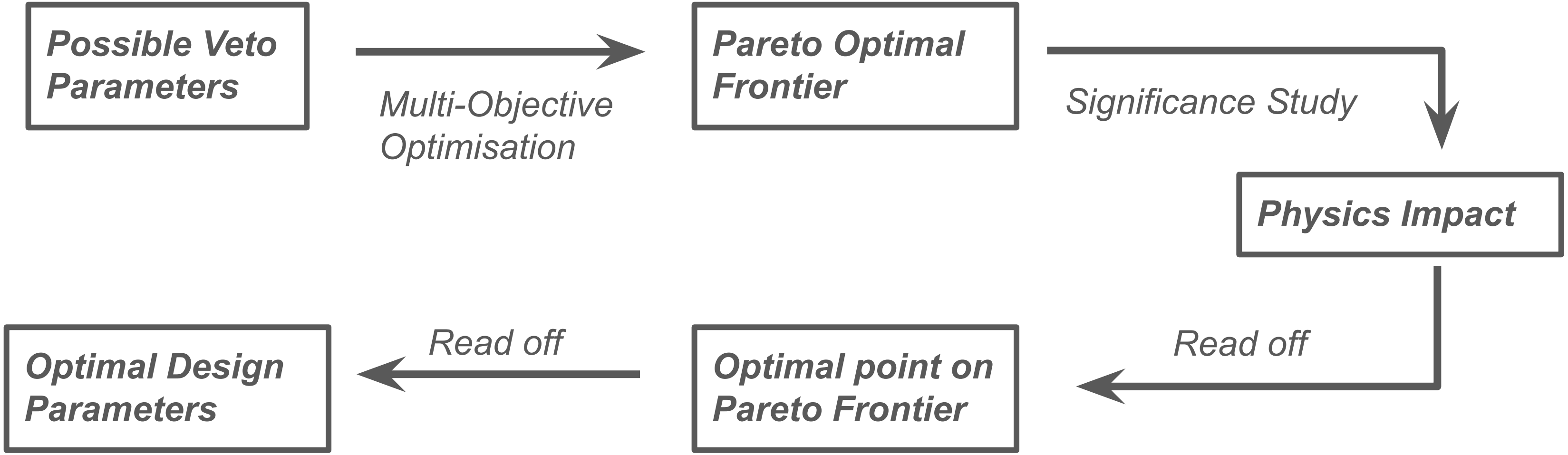
To get optimal veto parameter (window, threshold) we need to:

1. Find maximum significance test point for given scenario
2. Map this point back to design space

Bin widths have been chosen to reflect uncertainties in mapping back from objective space to design space.



Summary



Using the MOO approach allow us to tune and fully understand Efficiency Deadtime trade off in terms of physics impact.

Optimal choices from this study:

neutron backgrounds only: ***94% efficiency, 9% deadtime → 600 (μs) window, 15 (phd) threshold***

additional accidental backgrounds: ***92% efficiency, 2% deadtime → 600 (μs) window, 30 (phd) threshold***

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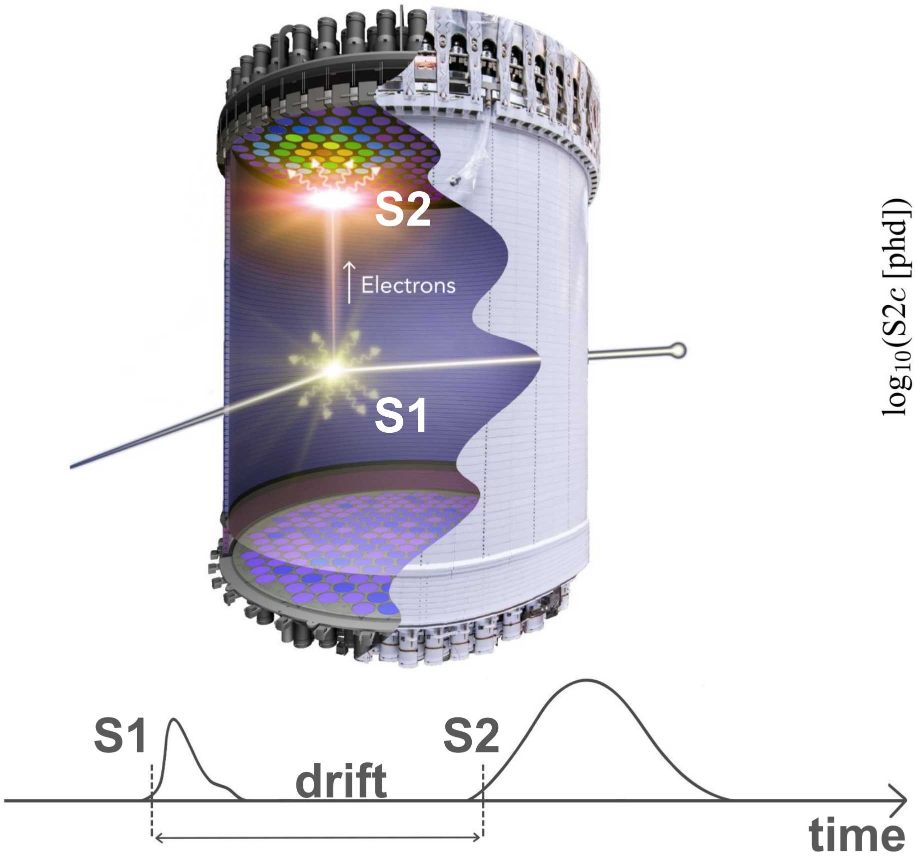
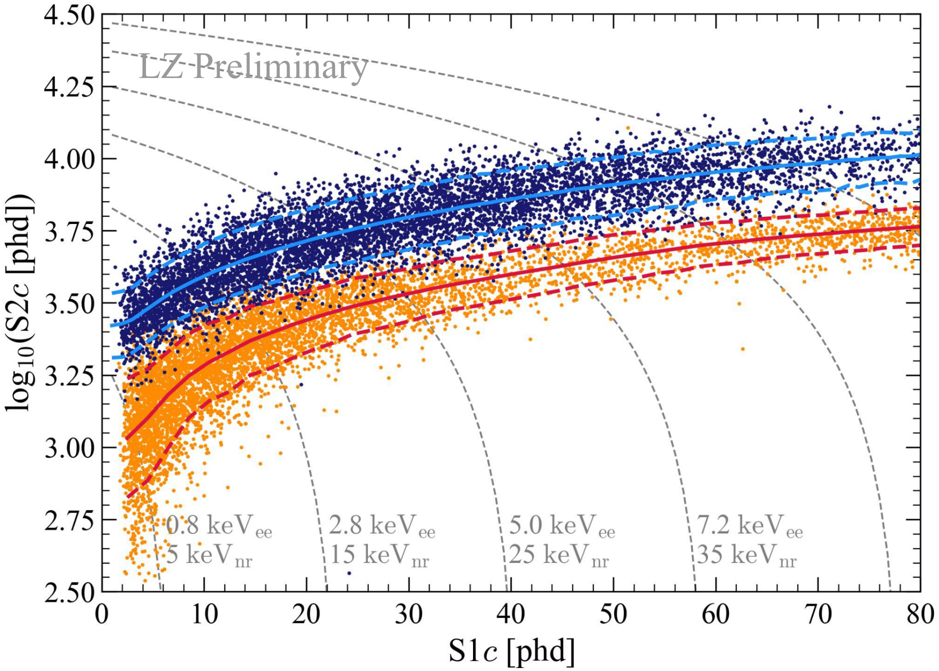
Backups

The Time Projection Chamber + ER/NR Bands

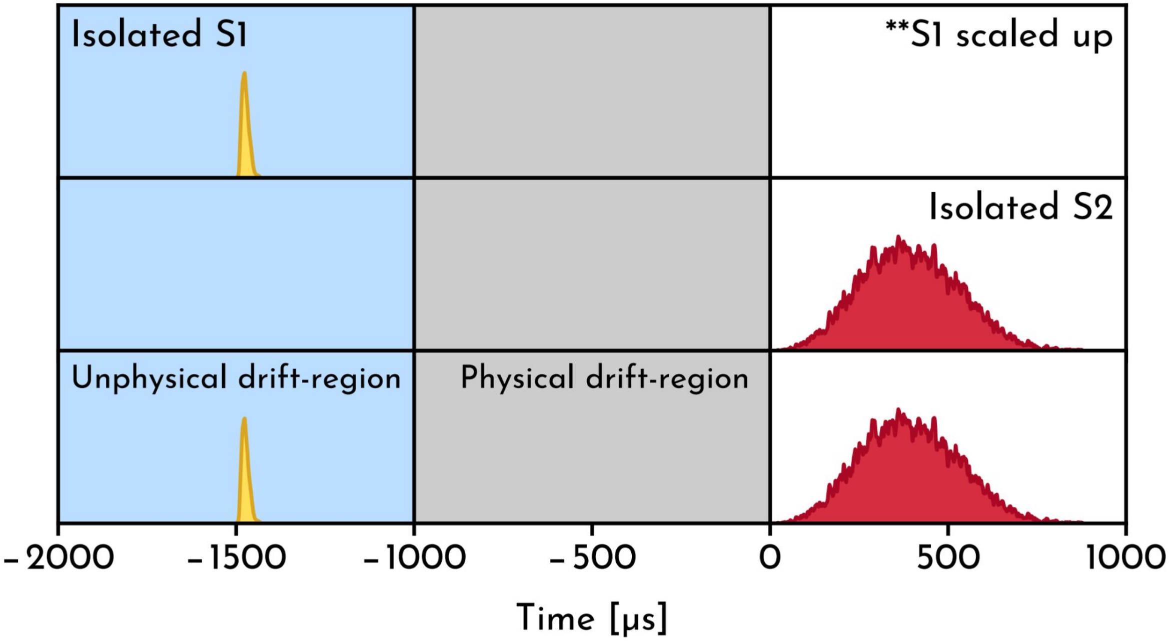




Tritium source - Electron Recoil band

DD Neutron Generator - Nuclear Recoil band

Accidentals



Pile-up of unrelated S1-like and S2-like pulses
Looks like a single scatter and can mimic a WIMP

Detailed Statement on Neutron Background

Neutrons in LZ come from (alpha, n) reactions in the detector material, and spontaneous uranium fission.

The extensive radioassay of all materials prior to detector construction allow us to accurately constrain their rate.

In the WS2024 dataset, after all event selection requirements but before the neutron vetoes, we expect **1±1 neutrons in the 220 livedays**. The uncertainty is driven by uncertainties in the neutron spectra and the absolute rate of alpha decays in the detector material.

This value is in agreement with the rate measured in a sideband of the WS2024 data.

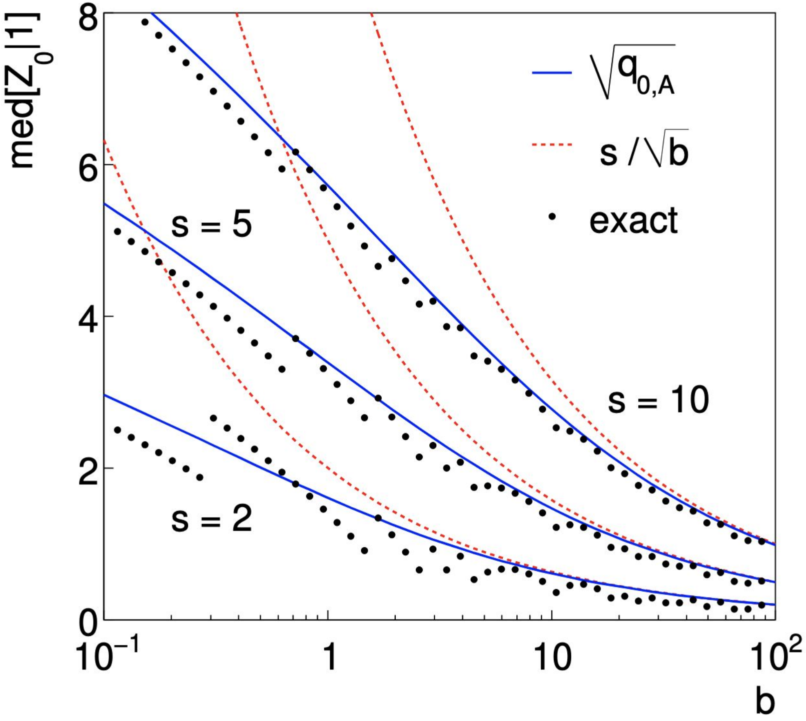
Azimov Approximation

Estimate significance in cut and count:

Use the ‘Azimov’ formula from Cowan et. al. [2]

$$\mathrm{med}[Z_0|1] = \sqrt{q_{0,\mathrm{A}}} = \sqrt{2\left((s+b)\ln(1+s/b) - s\right)}$$

Good approximation for a broad range of s and b



2: https://doi.org/10.48550/arXiv.1007.1727