Multiple Scatter Neutron Background Measurements in LUX-ZEPLIN

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LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

- 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.
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LZ Collaboration Meeting at SURF, June 2023

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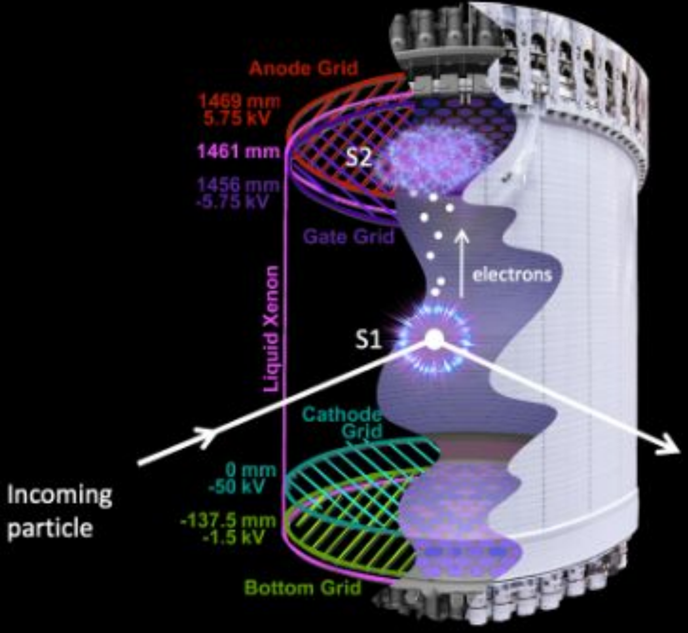

Image by Nicolas A. (Imperial College London)

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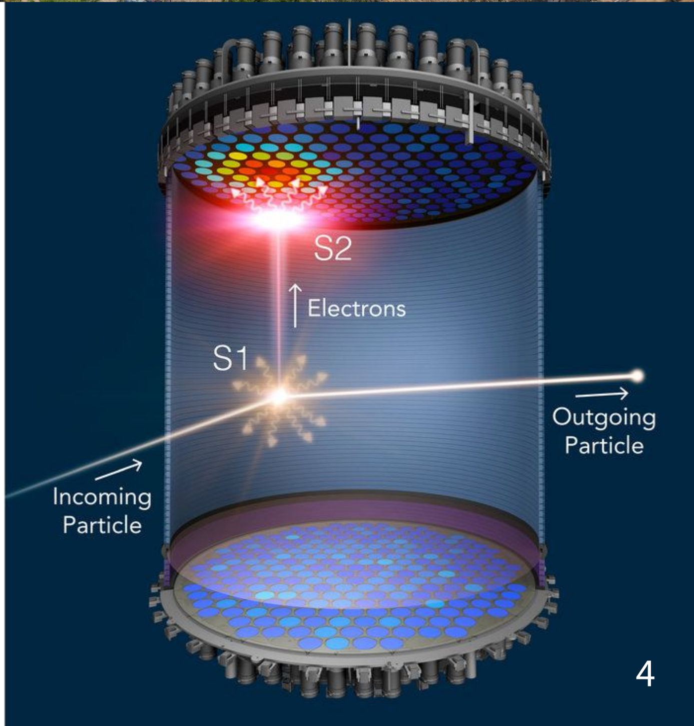
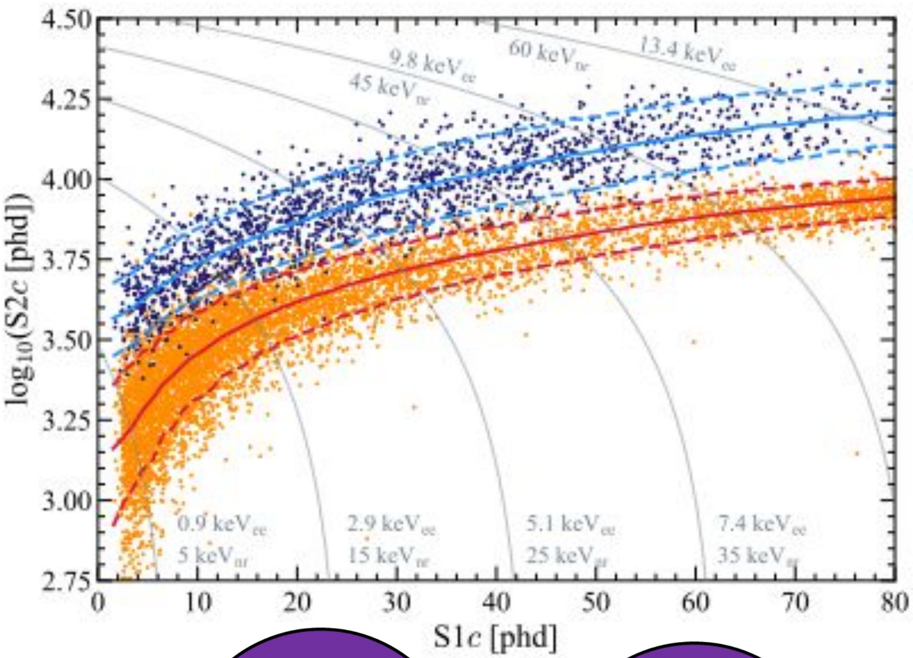
The LUX-ZEPLIN Experiment

- **LUX-ZEPLIN (LZ)** is a dual-phase time projection chamber (TPC) filled with liquid xenon, aiming to directly detect WIMP (weakly interacting massive particle) dark matter.
- The detector is located a mile underground at SURF, in South Dakota.
- An incoming particle will excite the xenon, and cause photons to be emitted (**S1 signal**).
- The xenon will also be ionised, and an electric field drifts the electrons to the gaseous region at the top of the detector, causing electroluminescence (**S2 signal**).



Identifying Particles



- The sizes of these S1 and S2 signals tell us about the type of interaction that occurred.
    - **Electron recoil (ER)** events will sit in the blue band.
      Gammas, beta particles, …
    - **Nuclear recoil (NR)** events will sit in the red band.
      WIMPs, neutrons, …

- How do you distinguish between WIMPs and neutrons? You have to understand your neutron background!

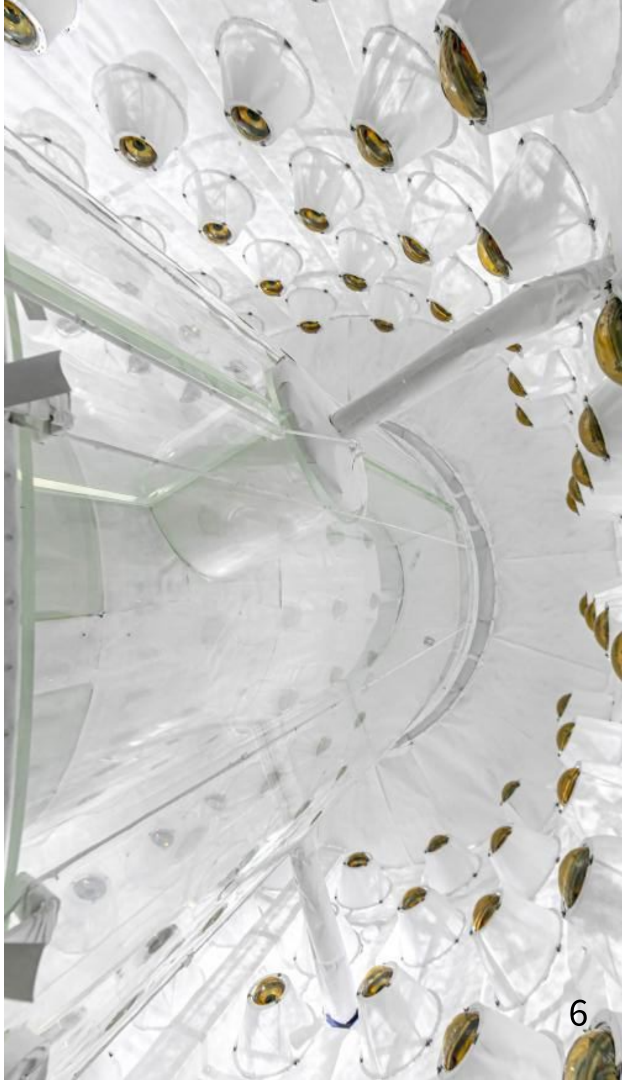
Understanding the Neutron Background

There are a couple of ways in which we can study the neutron background:

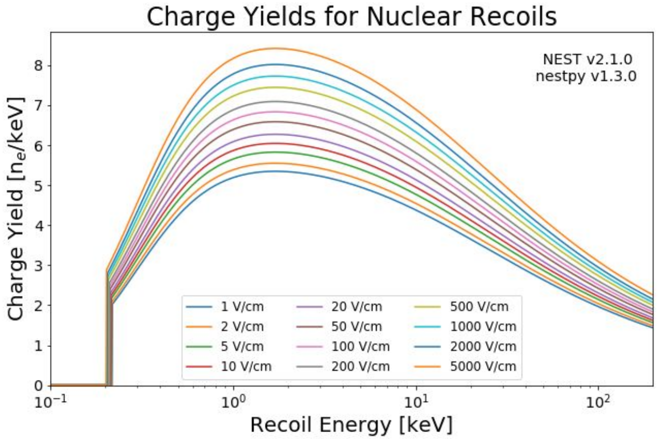
- Using the gadolinium-doped liquid scintillator outer detector (OD) to tag neutrons that interact in the TPC.
- Looking at the rate of multiple scatter (MS) neutron events in the TPC to infer the rate of single scatter (SS) neutron events.
  (WIMPs will only scatter once, at most!)

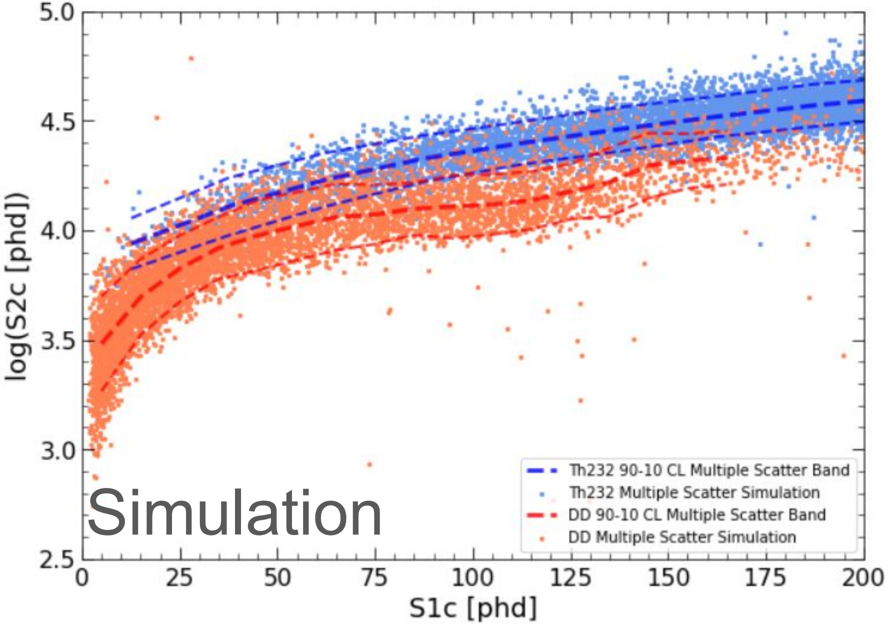
$$\boxed{N_{SS}^{data} = \frac{N_{SS}^{sim}}{N_{MS}^{sim}} N_{MS}^{data}}$$

So we need to be able to identify MS NR (neutron) events!



The Multiple Scatter Problem…

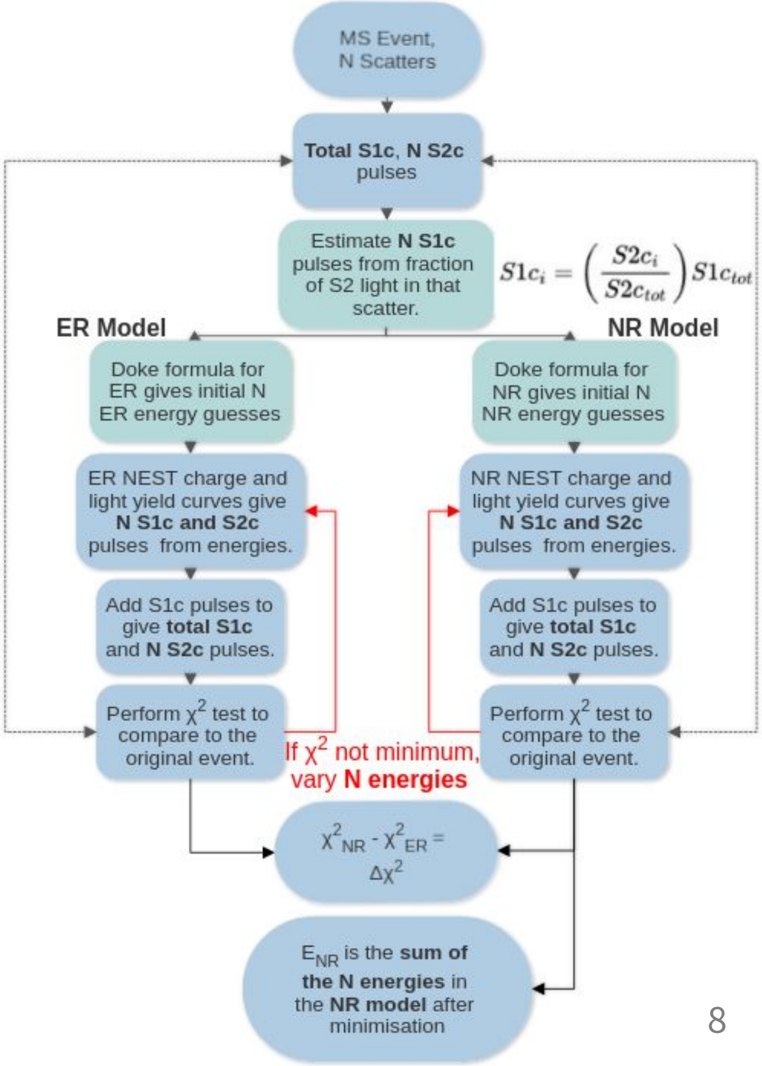




- For SS events the ER and NR populations are well defined.
- MS events have **1 S1** (photons from all scatters arrive an irresolvable time after each other), but **N S2s**.
  (For an event with N scatters)
- Simply summing these S2s causes the **NR events to rise** with each additional scatter, and the NR events collide with the ERs.
- This is because the charge and light yields of liquid xenon are non-linear as a function of recoil energy.

The $\Delta\chi^2$ Analysis Method

- The proposed solution to this is to look at MS events in a new parameter space.
- A new variable, **$\Delta\chi^2$**, essentially quantifies how ‘NR-like’ or ‘ER-like’ a given event is.
- Every event is modelled as both ER and NR, with a χ^2 value (with respect to the original data values) minimised by varying the individual scatter energies.
- The difference is then $\Delta\chi^2$. To give a 2D parameter space, $\Delta\chi^2$ is plotted against the sum of the fitted scatter energies in the NR model.



MS Event,
N Scatters

Total S1c, **N S2c** pulses

Estimate **N S1c** pulses from fraction of S2 light in that scatter.

$$S1c_i = \left(\frac{S2c_i}{S2c_{tot}}\right) S1c_{tot}$$

ER Model

Doke formula for ER gives initial N ER energy guesses

ER NEST charge and light yield curves give **N S1c and S2c** pulses from energies.

Add S1c pulses to give **total S1c** and **N S2c** pulses.

Perform χ^2 test to compare to the original event.

NR Model

Doke formula for NR gives initial N NR energy guesses

NR NEST charge and light yield curves give **N S1c and S2c** pulses from energies.

Add S1c pulses to give **total S1c** and **N S2c** pulses.

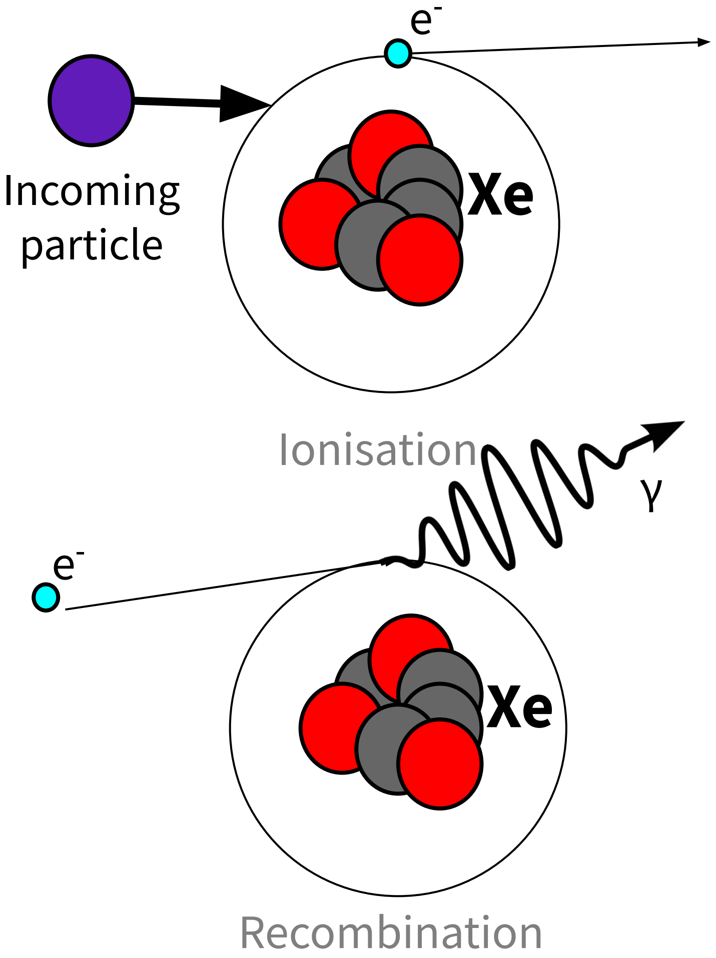
Perform χ^2 test to compare to the original event.

If χ^2 not minimum, vary **N energies**

$\chi^2_{NR} - \chi^2_{ER} = \Delta\chi^2$

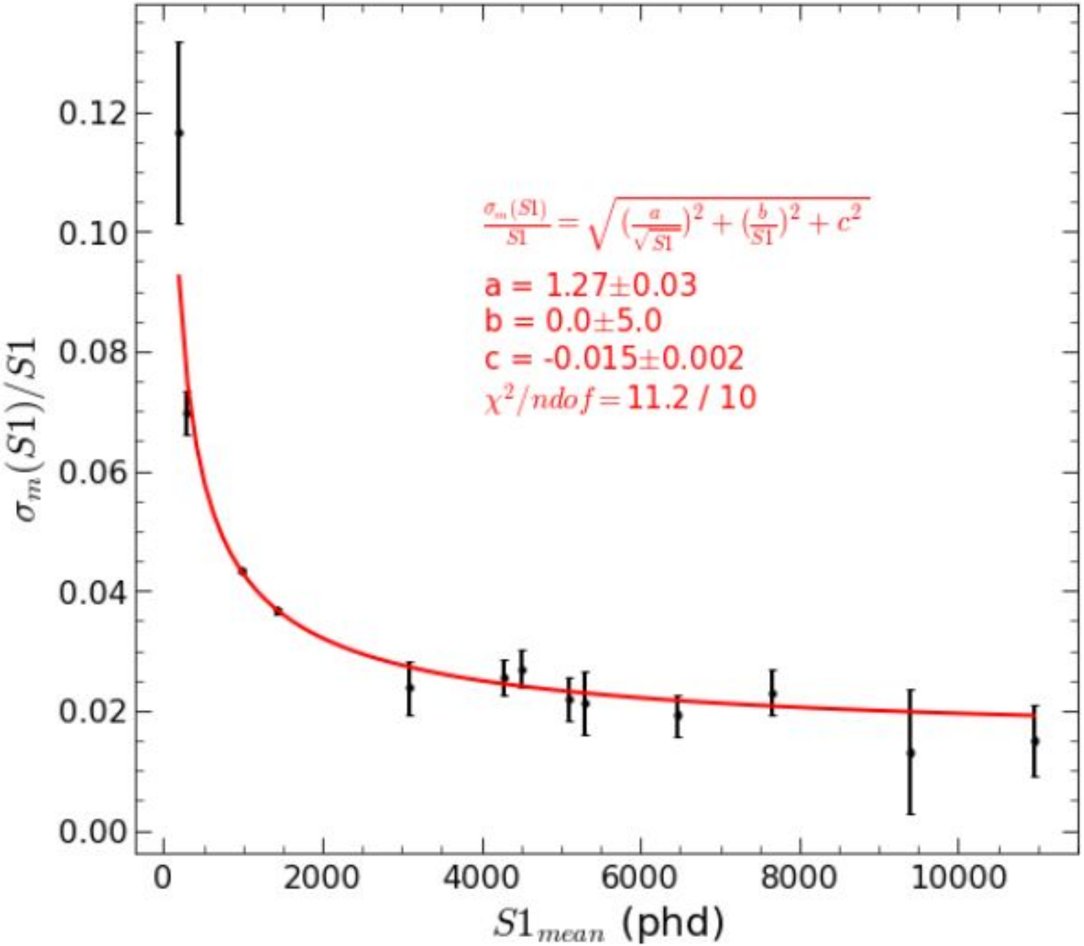
E_{NR} is the **sum of the N energies** in the **NR model** after minimisation

S1 S2 Correlations



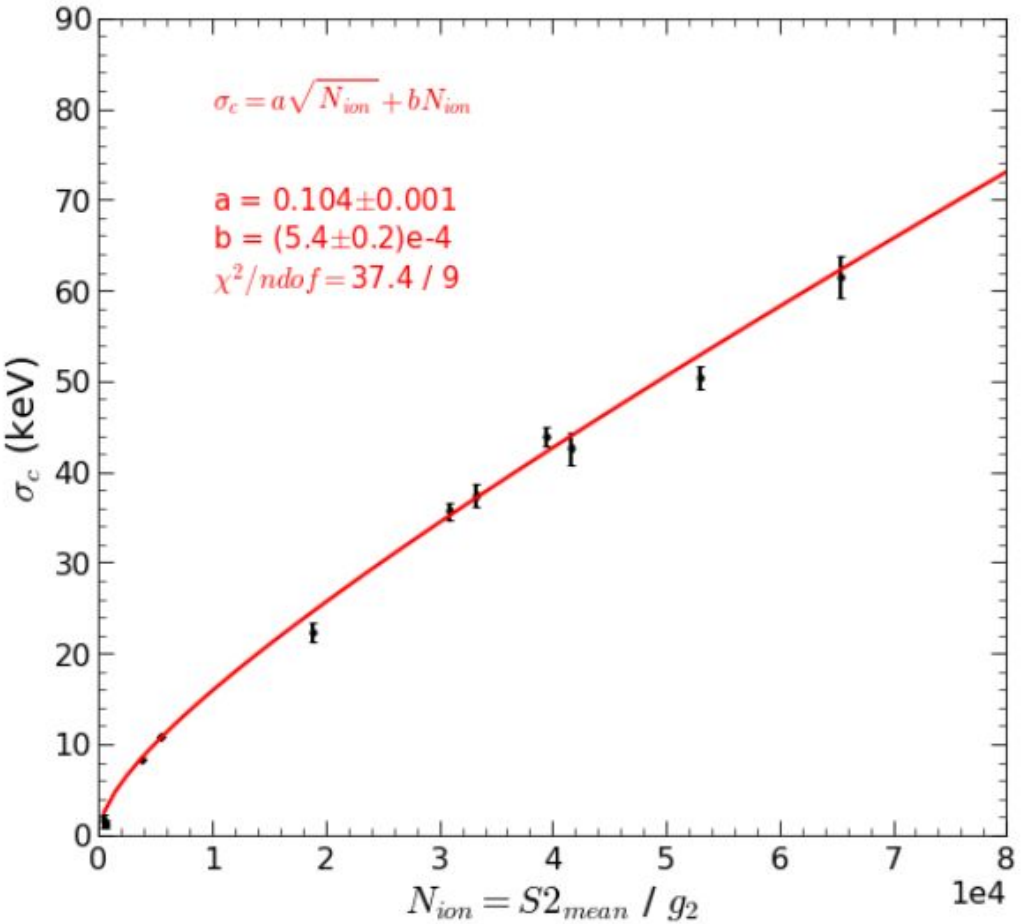
- In the χ^2 fits of both NR and ER models, an uncertainty on the S1 and S2 signals must be given.
- These uncertainties are due to **fluctuations in the measurement** of the respective quantities (detector dependent), and also due to **fluctuations in recombination** of electrons and ions (detector independent).
- The recombination fluctuations cause an inverse correlation between S1 and S2.
- In this work, the signal uncertainty components were separated out using measured S1, S2, and energy distribution widths for different sources.

Fluctuations in the Measurement of S1



- The fluctuations in the measurement of the S1 signal were fitted with the standard calorimeter resolution function.
- For the fluctuations in the measurement of the S2 signal, this was consistent with zero across all energies.

Recombination Fluctuations



- Similarly, the recombination fluctuations were characterised as a function of the number of ions.
- Due to the S2 measurement fluctuations being seen to be negligible, this will be the dominant component of S2 signal fluctuations.

Calculating χ²

$$\underline{x} = \begin{pmatrix} S1_{event} - S1_{model} \\ S2_{event}(1) - S2_{model}(1) \\ S2_{event}(2) - S2_{model}(2) \\ \dots \\ S2_{event}(N) - S2_{model}(N) \end{pmatrix}$$

- To incorporate the S1 S2 anti-correlations into the definition of χ^2 for both the NR and ER models, it must be defined using a covariance matrix.
- This means that the definition becomes a matrix equation rather than the more common form shown below.

here , $S1 = \Sigma_i S1(i)$

For an N scatter event

$$\chi^2 = \frac{(S1_{event} - S1_{model})^2}{\sigma^2_{S1}} + \sum_{i=1}^{N} \frac{(S2_{event}(i) - S2_{model}(i))^2}{\sigma^2_{S2(i)}} \rightarrow \boxed{\chi^2 = \underline{x}^T \underline{\underline{\Omega}}^{-1} \underline{x}}$$

The Covariance Matrix, Ω

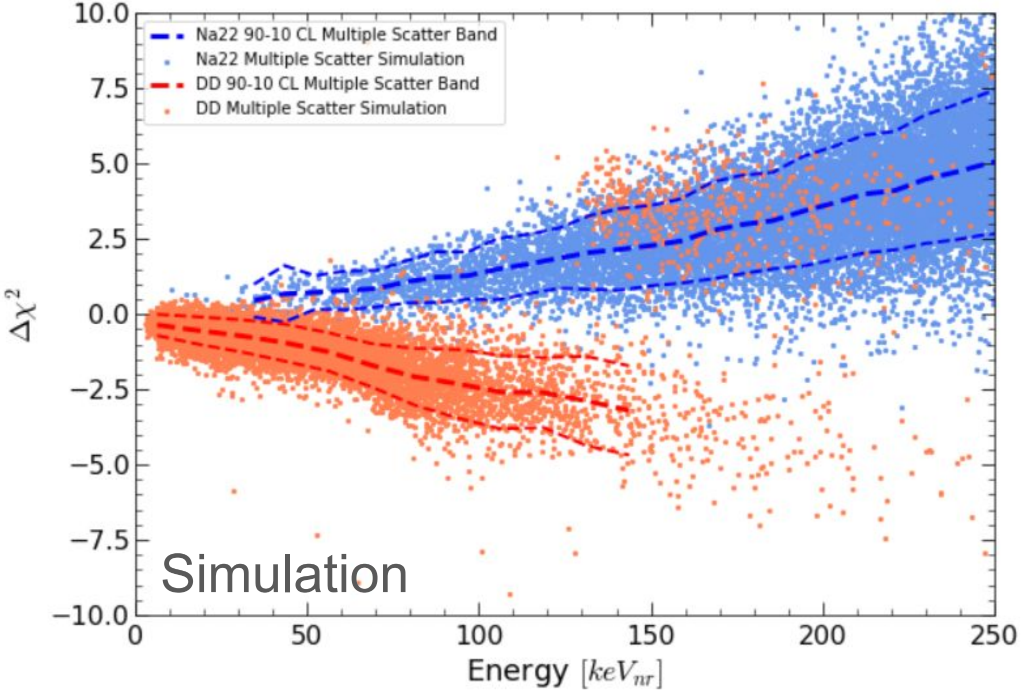
- The (0,0) term describes the total fluctuation in the total S1. This includes fluctuations in the S1 measurement, but also fluctuations in the correlation with all S2s, since S1 (total) is the combination of all S1s.
- The remaining diagonal terms describe the total fluctuation in each S2. Each of these comprises fluctuations in the S2 measurement, and a single term for the correlation fluctuations of *that S2*.
- The first row and first column terms describe the anti-correlation between each of the S2s and the total S1.

In the NR model, the correlation (green) terms are set to zero, as we assume a negligible correlation contribution.

$$\underline{\underline{\Omega}} = \begin{pmatrix} \sigma_m^2(S1) + \sum_{i=1}^{N} \sigma_c^2(S2(i)) & -\sigma_c^2(S2(1)) & -\sigma_c^2(S2(2)) & \ldots & -\sigma_c^2(S2(N)) \\ -\sigma_c^2(S2(1)) & \sigma_m^2(S2(1)) + \sigma_c^2(S2(1)) & 0 & \ldots & 0 \\ -\sigma_c^2(S2(2)) & 0 & \sigma_m^2(S2(2)) + \sigma_c^2(S2(2)) & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ -\sigma_c^2(S2(N)) & 0 & 0 & \ldots & \sigma_m^2(S2(N)) + \sigma_c^2(S2(N)) \end{pmatrix}$$

The Impact

- This method utilises all the information about individual S2 sizes that is lost when the S2s are just summed, and so is able to achieve better discrimination between MS ER and NR events.
  (Note that the DD simulation population in the ER band is the inelastic peak of Xe129)



Science Run 1 SS Neutron Background Estimate

- In the first science run of LZ (60 days live time), after the application of data quality cuts, there were **0 MS NR events identified**.
- For an SS event to be a WIMP candidate, it would have to have no veto signal from the OD. Therefore, this is the ideal cut to impose on MS as well (maximise MS and SS cut similarity).
- This causes low statistics as most neutrons (~80%) will have an OD signal. Therefore, we also look at MS events *with* an OD signal, or just remove the OD requirement all together.
- Systematic uncertainties associated with varying the cross-section library were studied and found to be negligible.

	No OD Signal	OD Signal	No OD Requirement
SR1 SS Neutron Estimate	$0^{+4.0}$	$0^{+0.05}$	$0^{+0.04}$

(Note that these results were obtained before S1 S2 correlations were factored in to the algorithm)

Summary

- Multiple scatter neutron events can be used to estimate the number of single scatter events, but discrimination between ER and NR events was difficult.
- A new method has been presented here that allows for better discrimination of MS ER and NR events by utilising information from all of the event scatters.
- This method was used in LZ Science Run 1 to provide a limit on the number of single scatter neutrons seen.
- There have since been improvements to the method to take into account anti-correlation between S1 and S2 signals due to recombination fluctuations.