DD Reflector Neutrons as a Probe of Low Energy Xenon Microphysics

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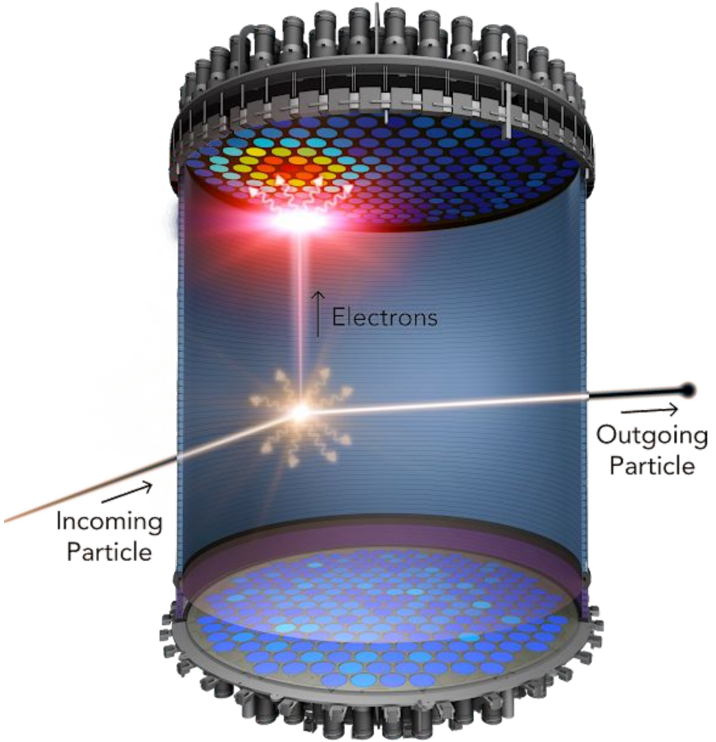
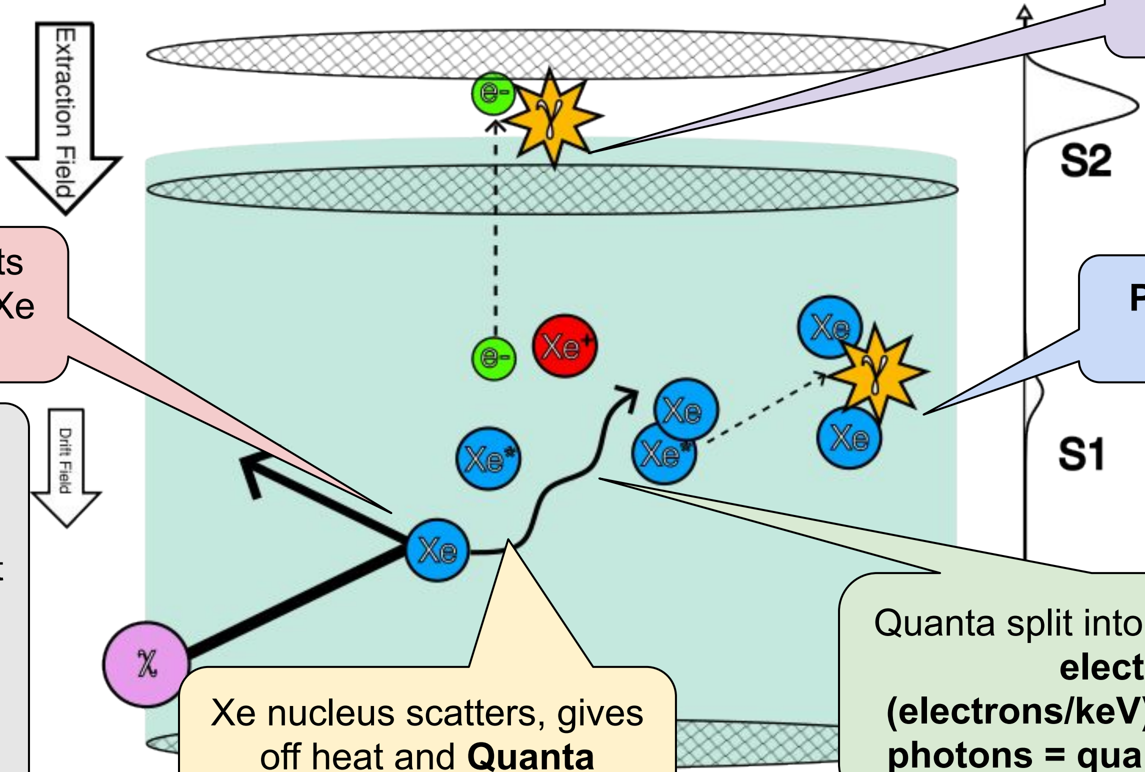
on behalf of the LZ collaboration
WiN - 2025

LUX-ZEPLIN in 30 Seconds

- Direct dark-matter detection experiment
- Located underground at SURF, South Dakota
  - Recently released the best limits on SI cross-section for 9 GeV - 10 TeV WIMPs
- Two-phase Xe TPC design - mature and well understood tech
  - Observe scintillation directly with PMTs - S1
  - Drift ionization with electric field, observe electroluminescence - S2



From Recoils to Signals



Electrons detected as the S2 pulse

Photons detected as the S1 pulse

Recoil deposits energy **E** into Xe nucleus

α, β : How many quanta?

γ : How many split into photons?

ϵ : How does the splitting change with energy?

Xe nucleus scatters, gives off heat and **Quanta**

$\mathbf{N_Q = \alpha E^{\beta}}$

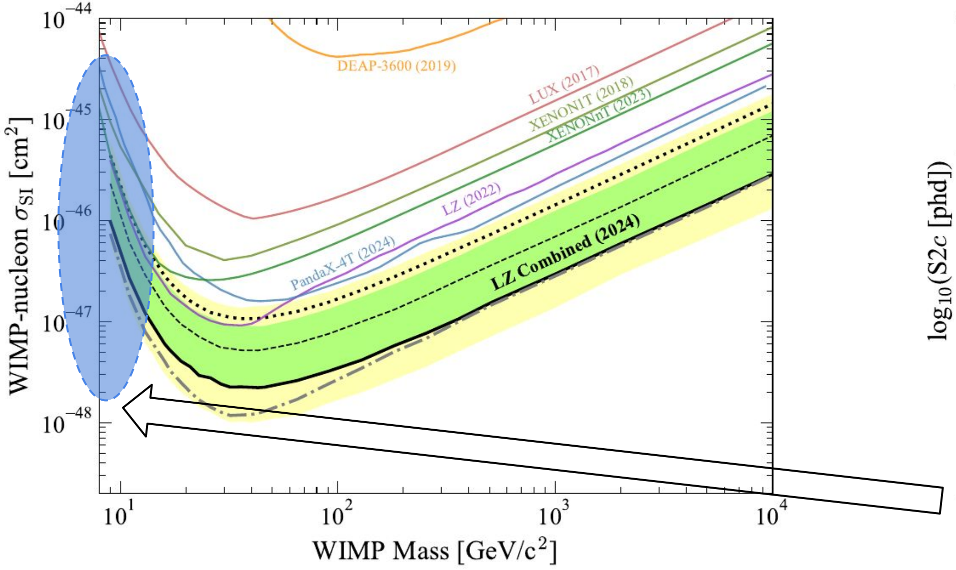
Quanta split into free **photons** & **electrons**

(electrons/keV) ∝ $[\gamma\ (E + \epsilon)]^{-1}$

photons = quanta - electrons

Calibrations up to Now

- Standard WIMP masses required higher energy calibrations (above few keV)
- But if we want to push to lower masses, need to understand low energy region



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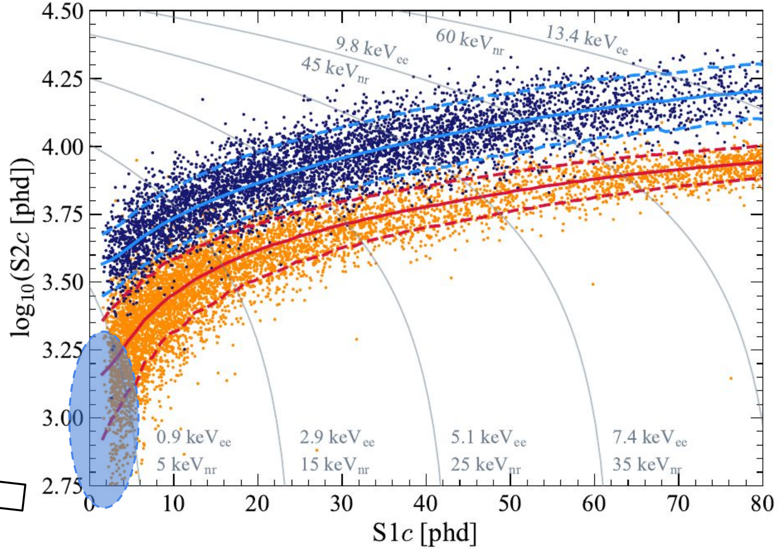

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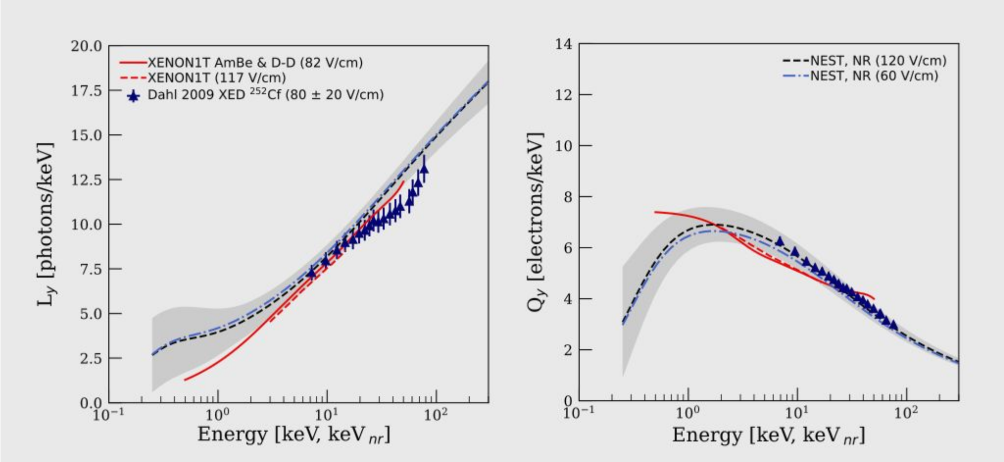
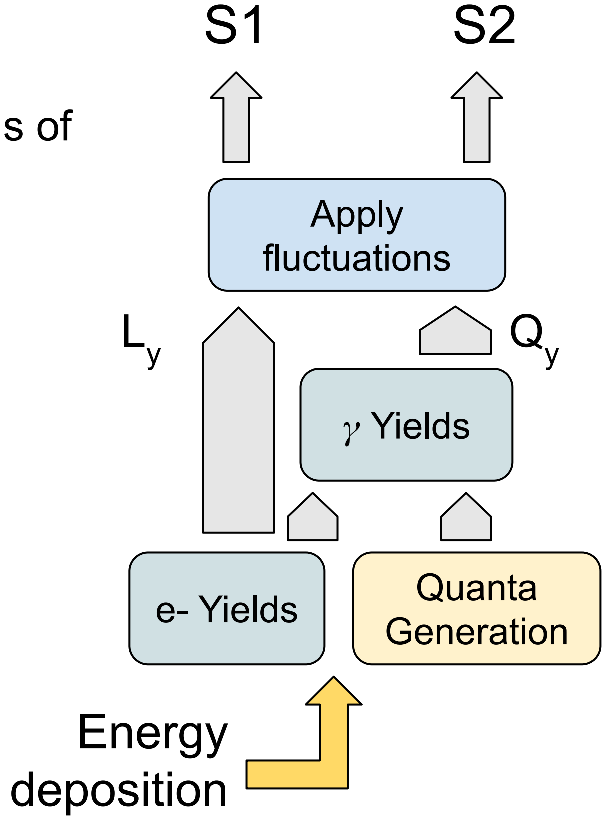
Microphysics & NEST

- Noble Element Simulation Technique (NEST) is a semi-empirical model able to give quantitative predictions of the response to recoils
- Historically good data at higher energies, but not well constrained at < 1keV
- Need in-situ calibration in this regime

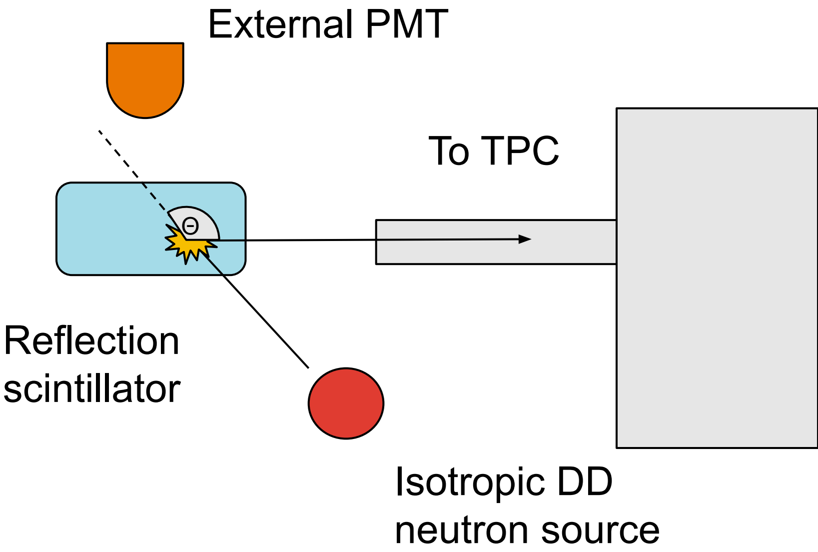




M. Szydagis et. al. *A review of NEST models for liquid xenon and an exhaustive comparison with other approaches.* Frontiers in Detector Science and Technology 2813-8031 10.3389/fdest.2024.1480975

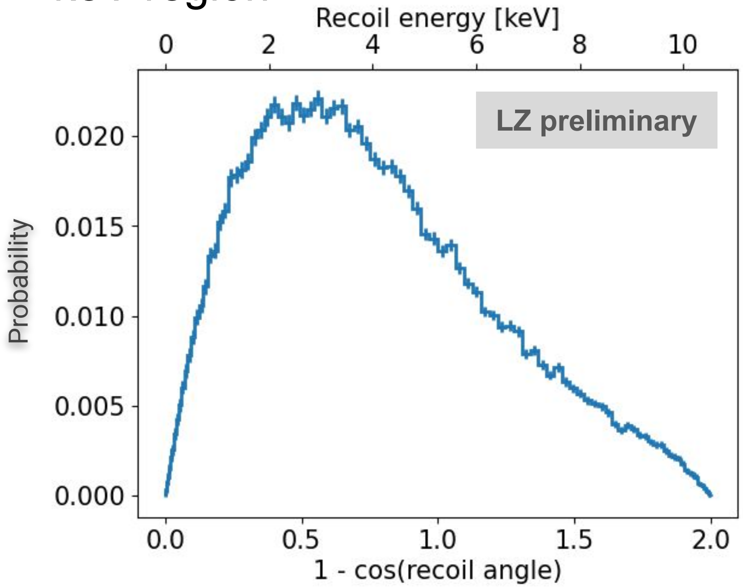
Calibrating with D-Reflector

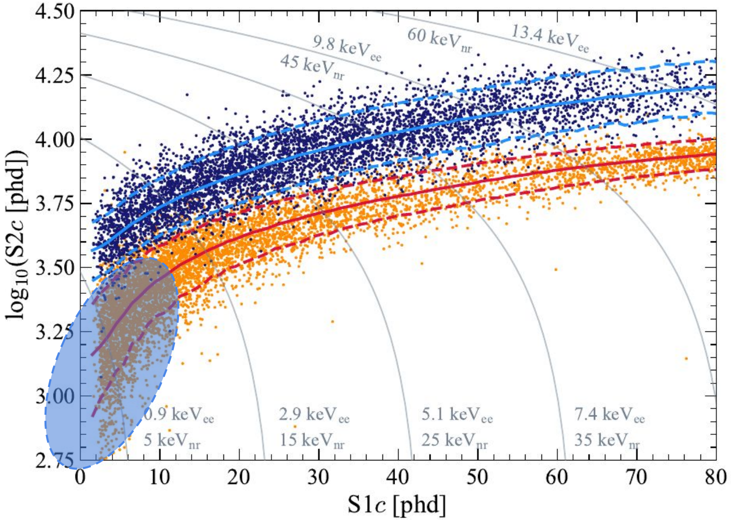
- Traditionally would shoot 2.45 MeV neutrons directly into TPC - however, able to operate in “D-Reflector” mode:
  - Place a deuterium-loaded target near the neutron source
  - By tuning the angle between the source and TPC, can select quasi-monoenergetic low-energy neutrons
  - A PMT instruments the target, to allow for timing selection of good events
- Selecting sharp backscatters results in ~350 keV neutrons entering TPC



Recoil Spectrum for D-Reflector Neutrons

- Energy that can be deposited in a single recoil is constrained by kinematics
- Monoenergetic neutrons ≠ monoenergetic recoils
- Simulate recoil energy spectrum for 350 keV neutrons - good coverage of < 2 keV region





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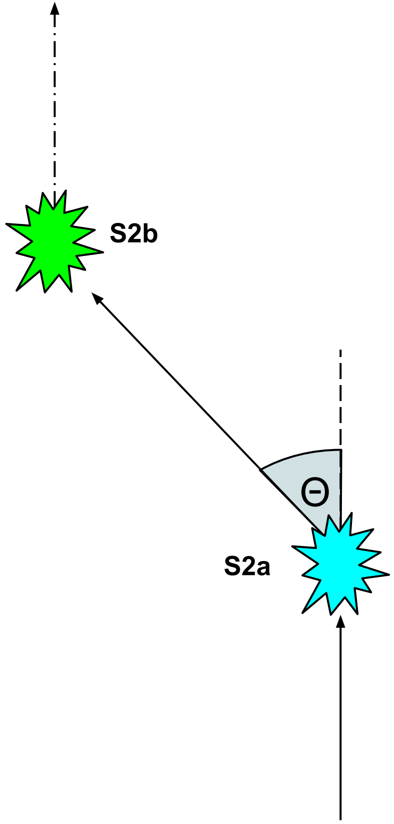
Multiple Scatters

- The 350 keV neutrons generated have a mean free path O(10 cm) in Xe - many events will be Multiple Scatters (MS)

- Can use position of two vertices to reconstruct scattering angle of first recoil:

$$E_{recoil} \propto [1 - \text{Cos}(\theta_{recoil})]\, E_{neutron}$$

Able to reconstruct recoil energy per event - exactly the input to our models!

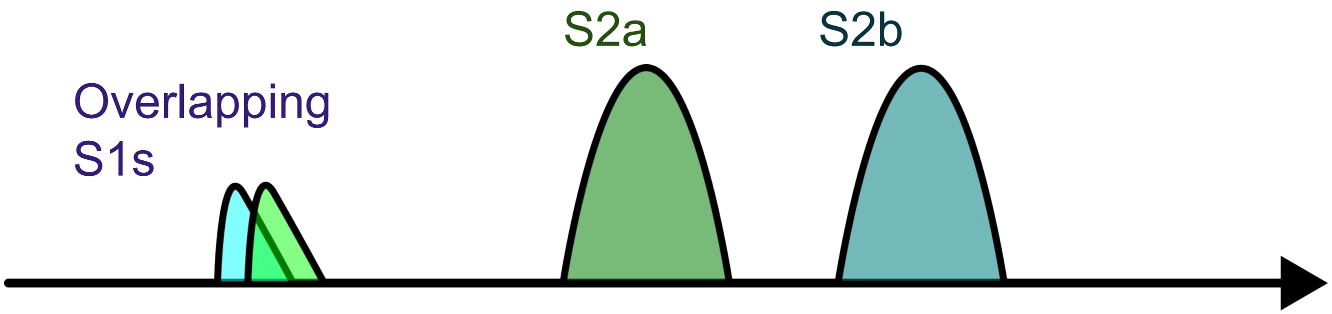


But There's a Tradeoff

- Recoils separated by < 50 ns - S1s overlap!
- Any measurements related to the light yield are very hard to do: Observables are

$$E_a\,,\, S2_a\,,\, S2_b\,,\, (S1_a + S1_b)$$

- Historically, this resulted in MS data being used only for measuring charge yield, with other analyses falling back to single scatters - *Losing lots of good data!*



Is There Something We Can Do?

- Could try building a likelihood containing the observables we see:

$$\mathscr{L}(S1_{a+b}, S2_a, S2_b \mid \text{NEST parameters})$$

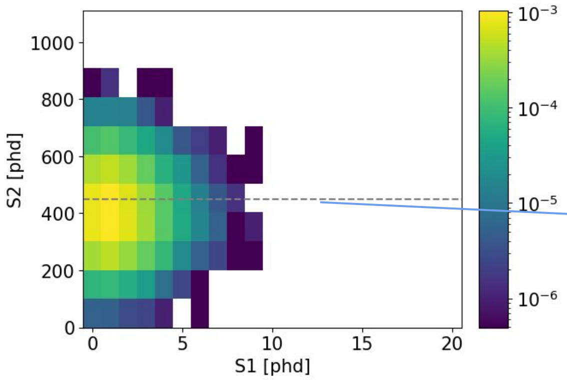
- NEST is very good at generating Monte Carlo-based likelihoods for SS - but naively filling up a 3D histogram for MS would be expensive
- Can instead try computing MS likelihood using two SS templates:

$$\mathscr{L}(S1_{a+b} \mid S2_a, S2_b) = \int \mathscr{L}(S1_a \mid S2_a) \times \mathscr{L}(S1_{a+b} - S1_a \mid S2_b)$$

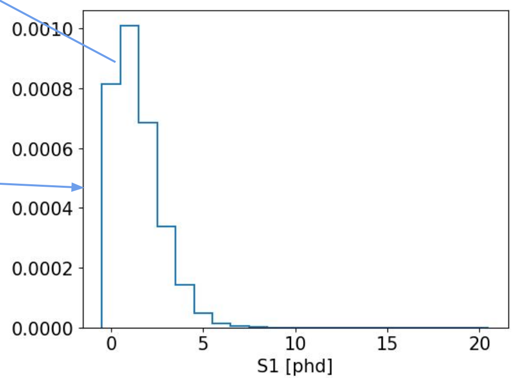
Constructing the MS Likelihood

- To start off, generate MC templates for ($S1_a$, $S2_a$) and ($S1_b$, $S2_b$)
- From these templates, able to retrieve $\mathscr{L}(S1 \mid S2)$ for all S2 bins

$$\mathscr{L}(S1_{a+b} \mid S2_a, S2_b) = \int \mathscr{L}(S1_a \mid S2_a) \times \mathscr{L}(S1_{a+b} - S1_a \mid S2_b)$$



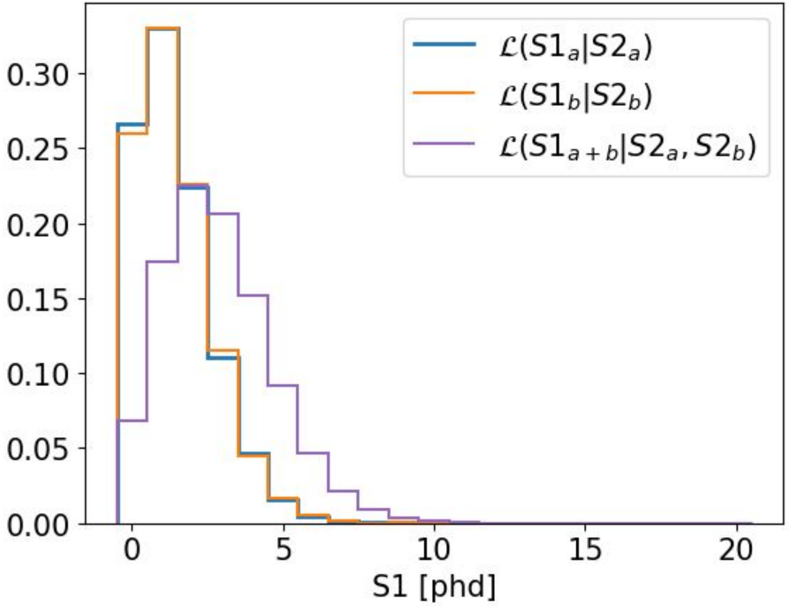
For a given $S2_a$



Constructing the MS Likelihood

$$\mathcal{L}(S1_{a+b} | S2_a, S2_b) = \int \mathcal{L}(S1_a | S2_a) \times \mathcal{L}(S1_{a+b} - S1_a | S2_b)$$

- Given an $S2_a$ & $S2_b$, perform the above sum over possible S1 values to obtain $\mathcal{L}(S1_{a+b} | S2_a, S2_b)$
- Repeat over all possible $S2_{a,b}$ to get the full $\mathcal{L}(S1_{a+b}, S2_a, S2_b)$

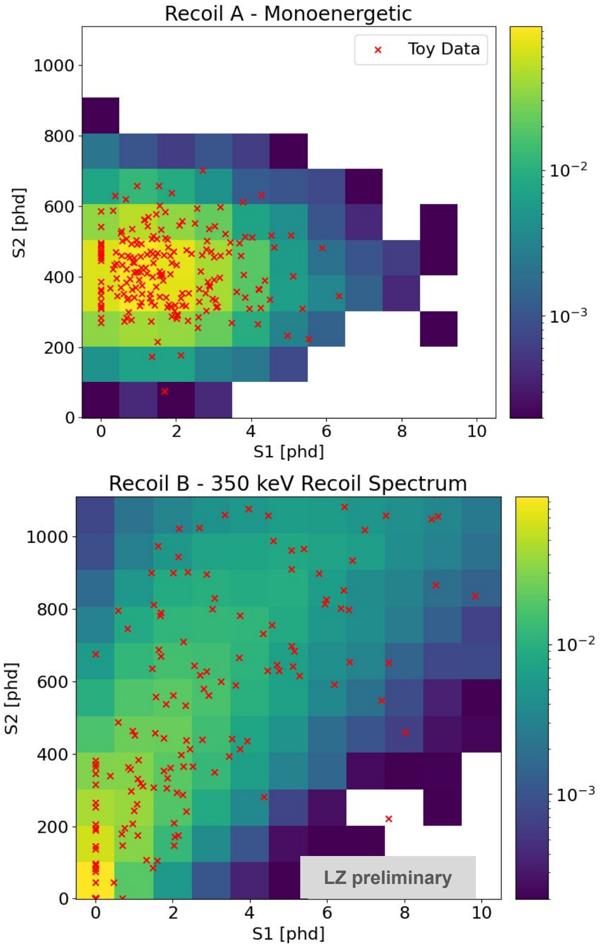


Fitting a Toy Example

End goal is to be able to fit MS D-Reflector neutrons. Data is still being collected & understood, so for now test machinery on toy example:

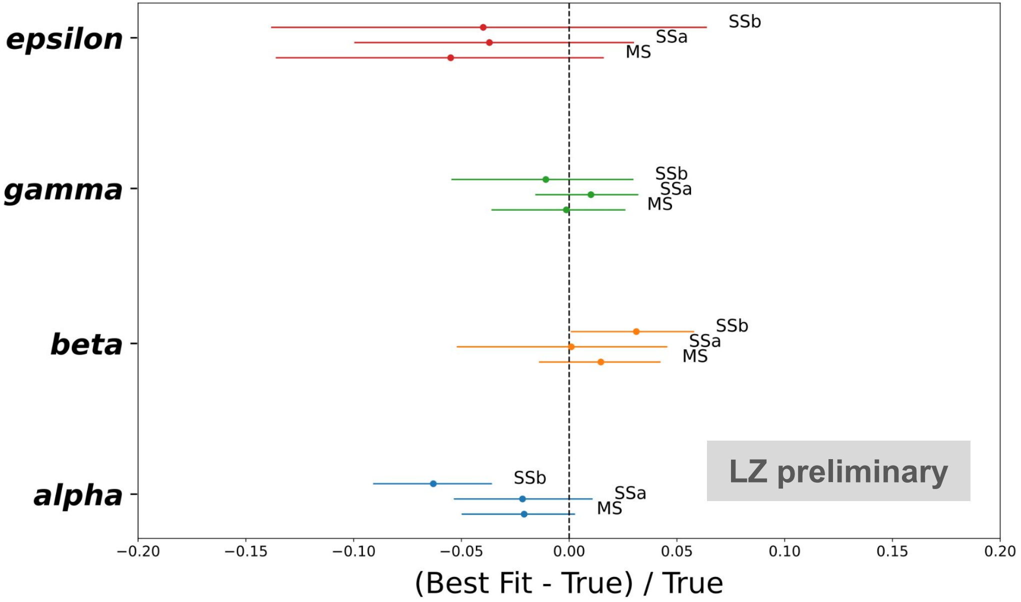
- Generate a 2 keV recoil SS dataset A - first recoil, known energy
- Generate a D-Reflector neutron-like recoil SS dataset B - second recoil, unknown energy
- Build an ($S1_a+S1_b$, $S2_a$, $S2_b$) MS dataset

- Can the MS dataset be fit with the MS likelihood?
- Are constraints on parameters better with an MS dataset?



Fitting the Model

- Use MCMC to estimate posterior distributions (median & 1-sigma percentiles shown) of 4 main parameters in the NEST NR model
- MS fit runs ~1M steps x 200 walkers in 2 hours on an AMD EPYC 7763 - computationally feasible
- Compare each of the SS datasets with the MS
- While still proof-of-concept, MS dataset able to constrain data better than SS from the whole D-Reflector spectrum



Conclusion

- Low energy frontier in Xe TPCs requires some novel approaches to calibrations analyses
- MS datasets can be very useful - ability to reconstruct energy of one of the scatters can help to constrain parameters
- Toy model shows it’s possible to overcome some of the limitations of a traditional MS analysis by explicitly computing a likelihood for the $S1_a$+$S1_b$ term
- Application of this technique to new D-Reflector neutron data is on the horizon, with hopefully good results on our understanding of Xe microphysics at lower energies

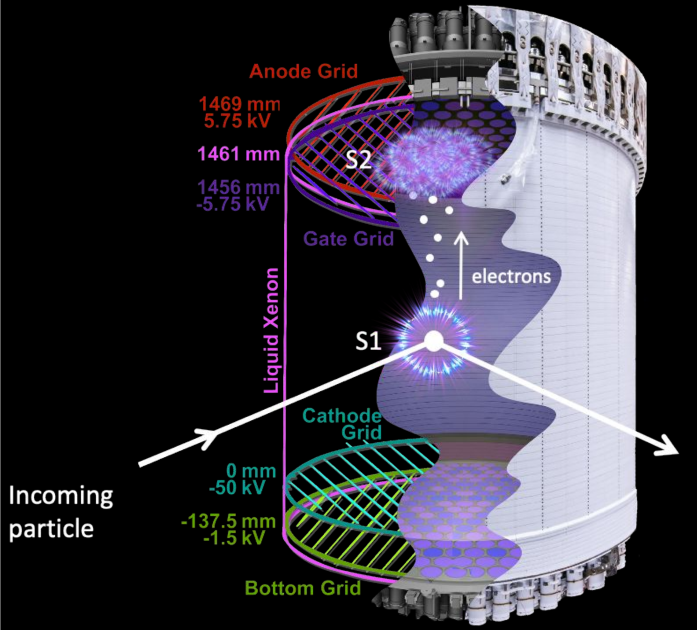


Image by Nicolas A. (Imperial College London)

Thank you!

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References

[1] J. Aalbers et. al. *Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment.* arXiv 2410.17036

[2] J. Aalbers et. al. *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment.* Phys. Rev. Lett. 131, 041002. 10.1103/physrevlett.131.041002

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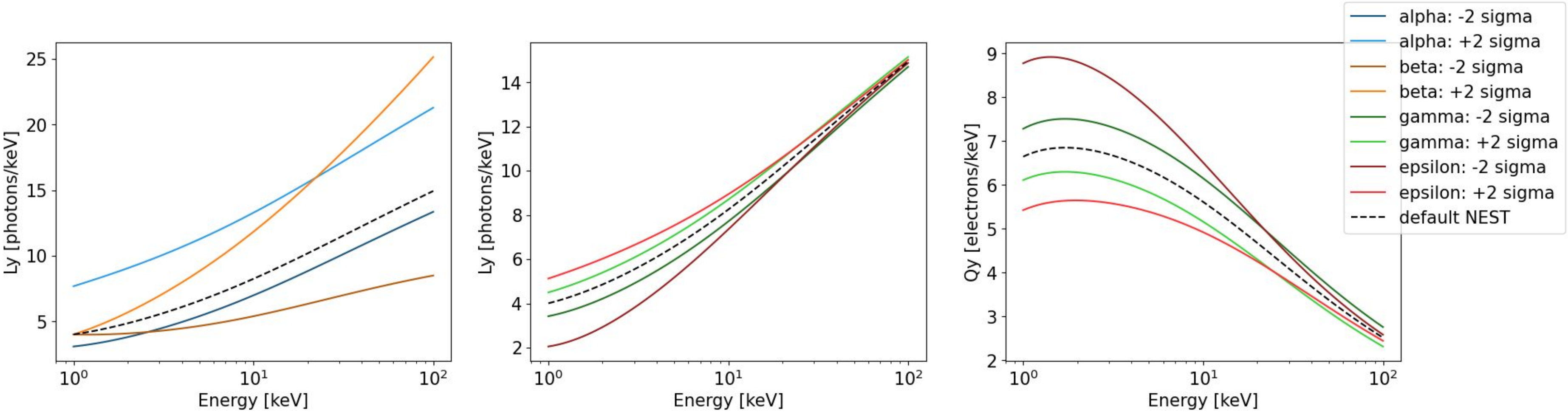
NEST Parameter Variation & Yields



alpha	$11^{+2.0}_{-0.5}$
beta	$1.1^{+0.5}_{-0.5}$
gamma	$0.0480^{+0.0021}_{-0.0021}$
epsilon	$12.6^{+3.4}_{-2.9}$ keV