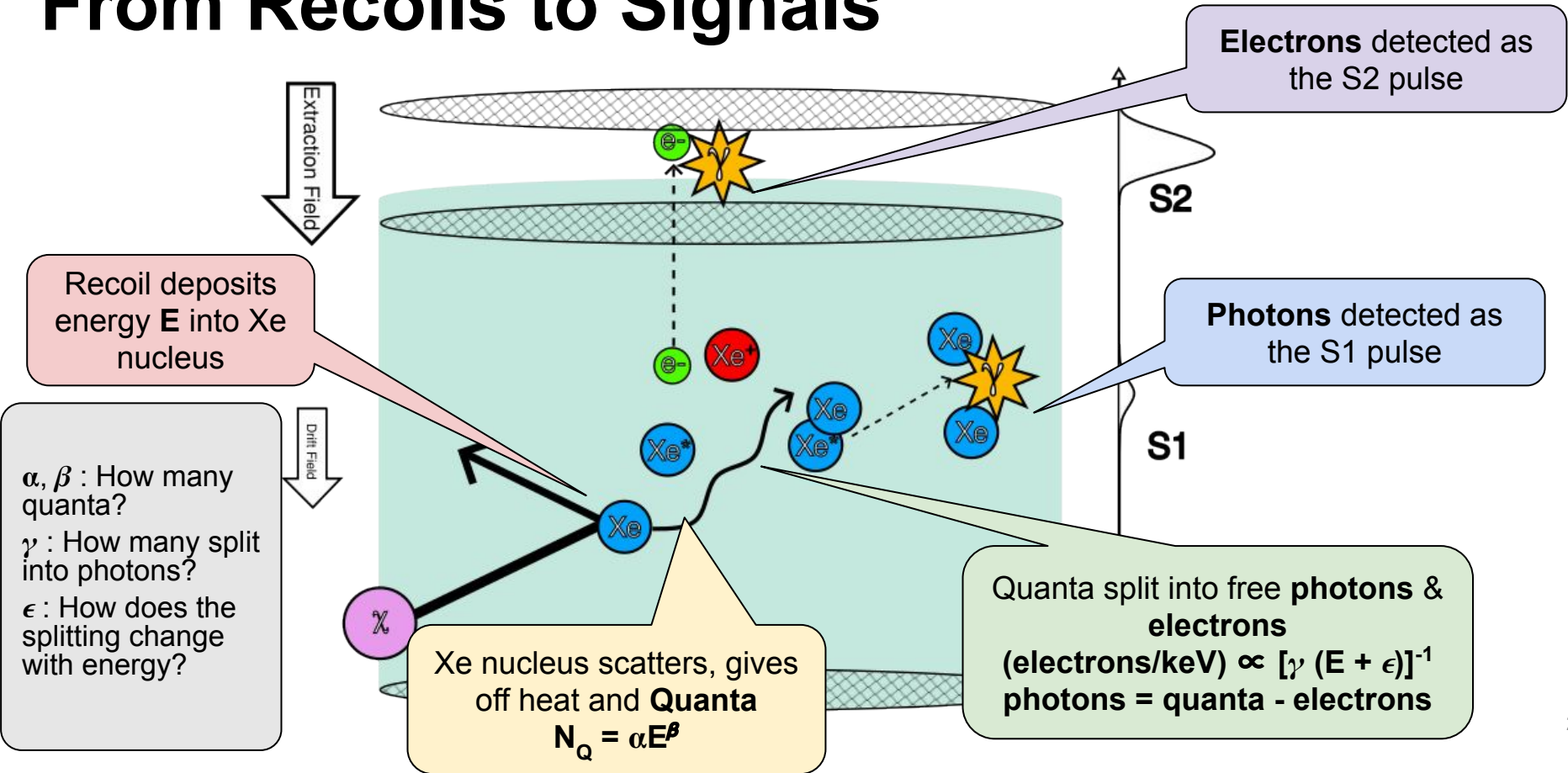


DD Reflector Neutrons as a Probe of Low Energy Xenon Microphysics

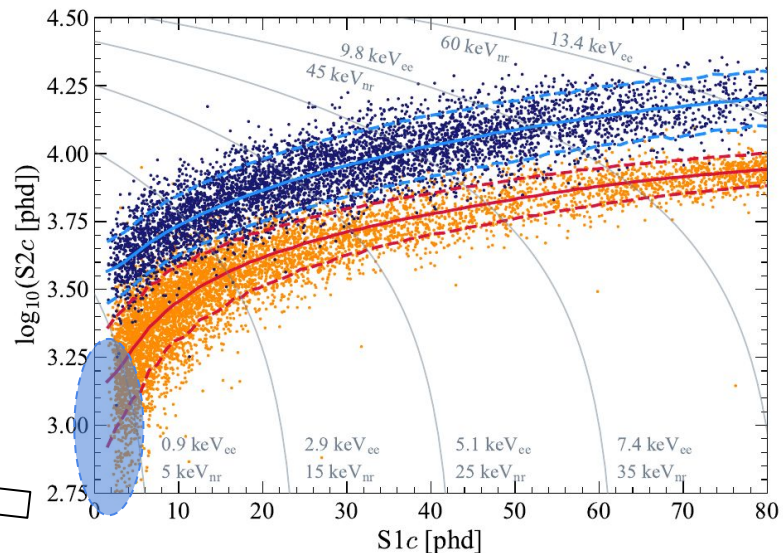
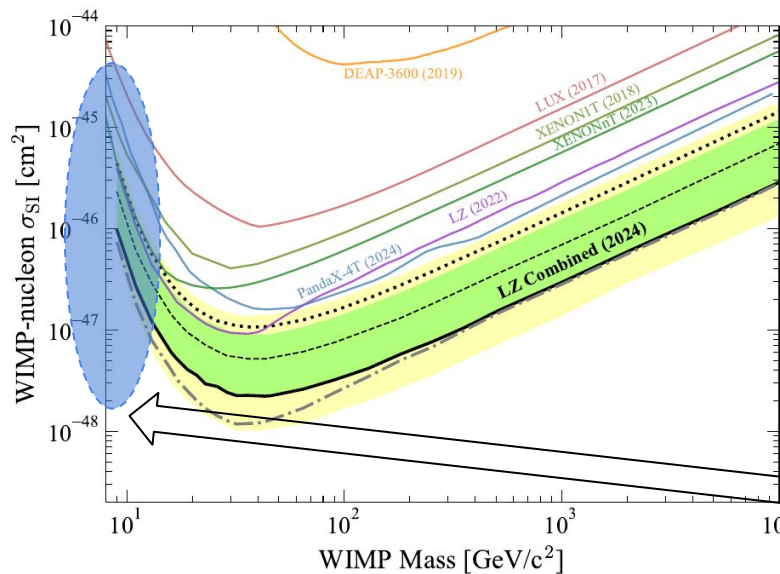
Jacopo Siniscalco
on behalf of the LZ collaboration
IoP HEPP Annual Conference 08/04/25

From Recoils to Signals



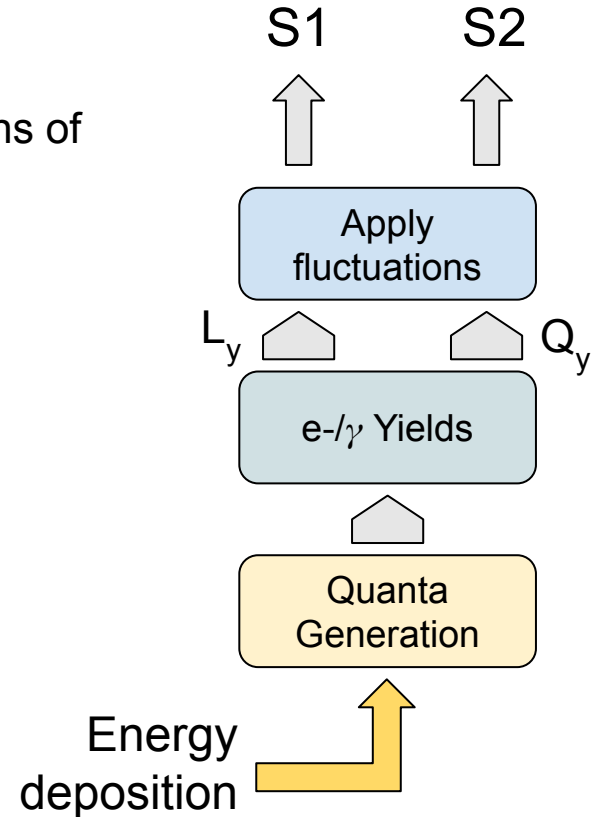
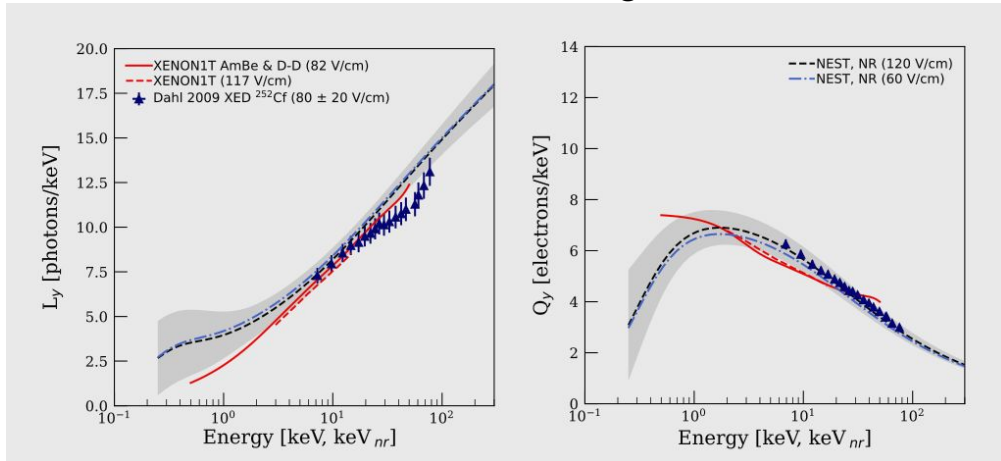
Calibrations up to now

- Standard WIMP masses required high energy calibrations
- But if we want to push to lower masses, need to understand low energy region



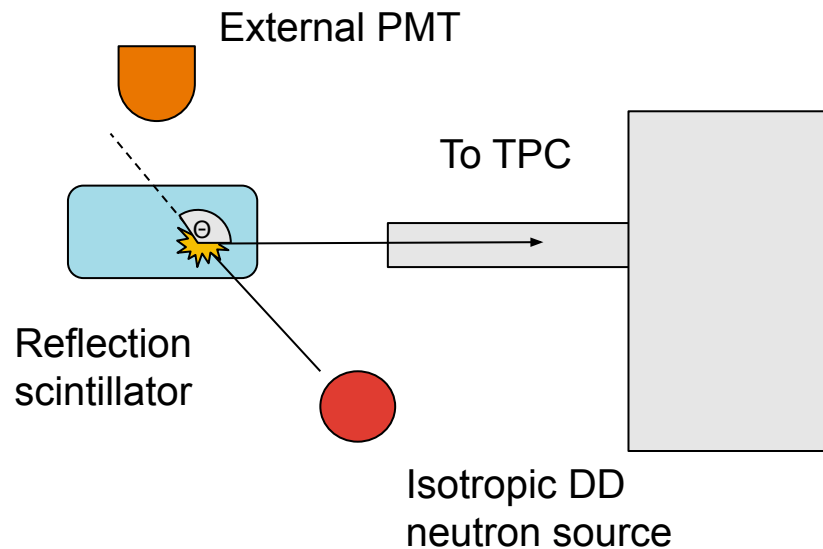
Microphysics & NEST

- 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 $< 1\text{keV}$
- Need in-situ calibration in this regime



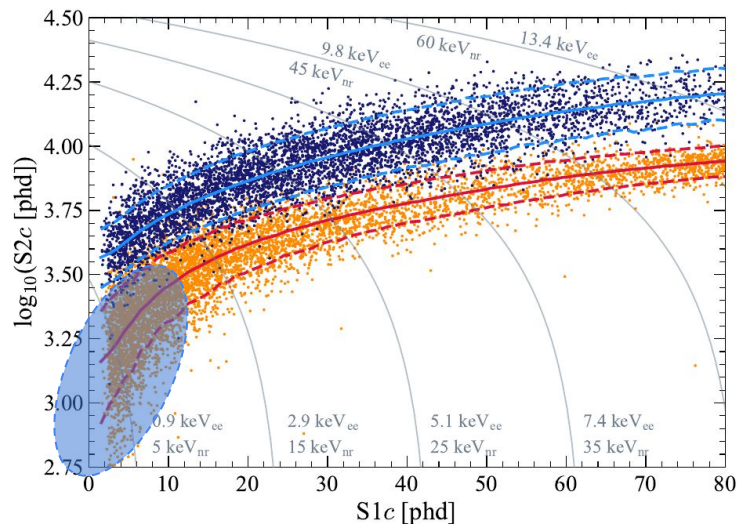
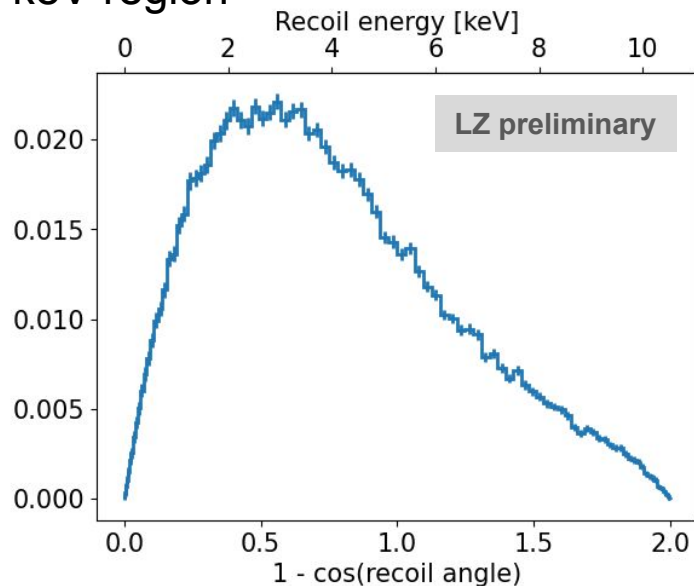
Calibrating with D-Reflector

- 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 \neq monoenergetic recoils
- Simulate recoil energy spectrum for 350 keV neutrons - good coverage of < 2 keV region

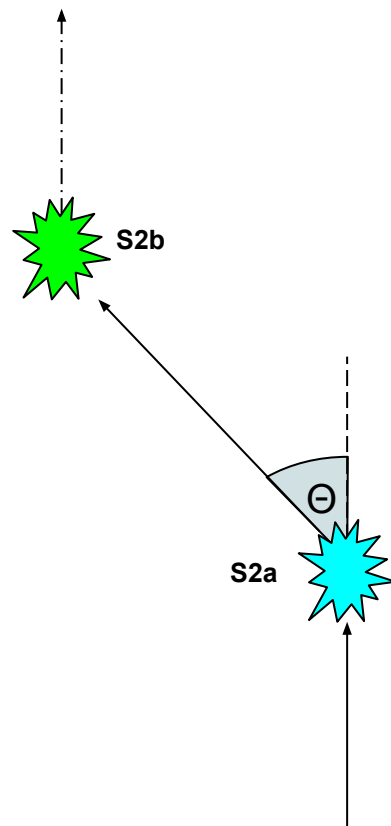


Multiple Scatters

- The 350 keV neutrons generated have a Mean Free Path $O(10 \text{ cm})$ in Xe - many events will be Multiple Scatters (MS)
- Can use position of two vertices to reconstruct scattering angle of first recoil:

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

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

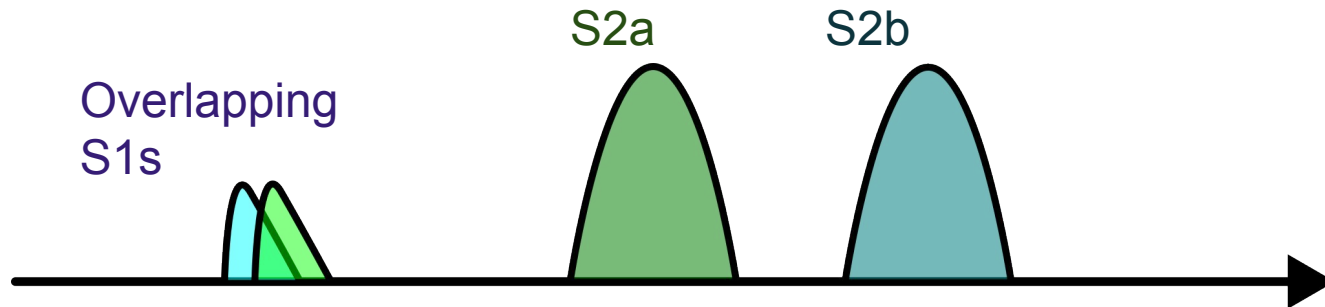


But There's a Tradeoff

- 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:

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

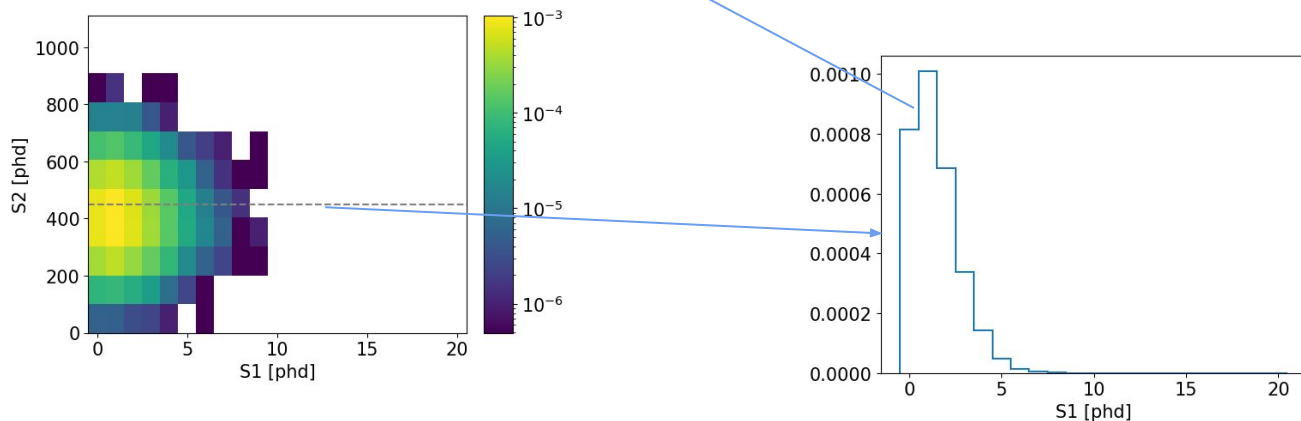
- NEST is very good at generating Monte Carlo-based likelihoods for SS - but naively filling up a 3D histogram for MS would be expensive
- Can instead try computing MS likelihood using two SS templates:

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

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 $\mathcal{L}(S1 | S2)$ for all $S2$ bins

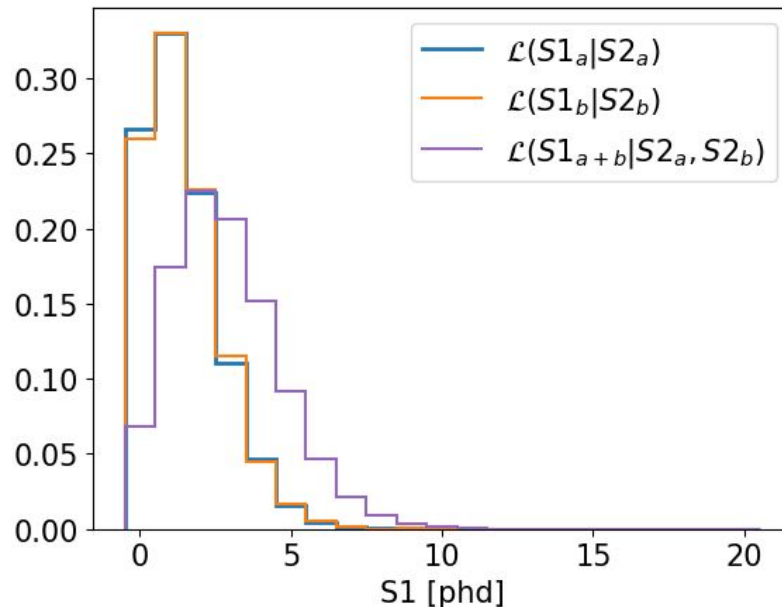
$$\mathcal{L}(S1_{a+b} | S2_a, S2_b) = \int \mathcal{L}(S1_a | S2_a) \times \mathcal{L}(S1_{a+b} - S1_a | S2_b)$$



Constructing the MS Likelihood

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

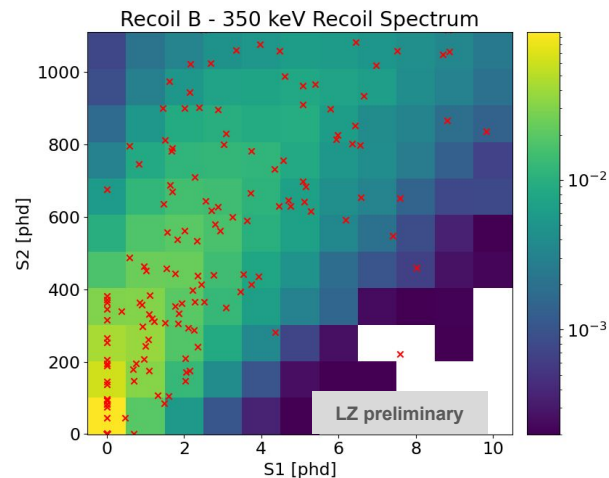
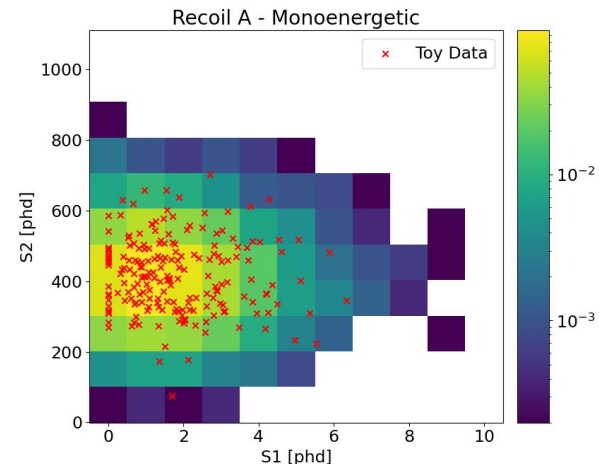
- Given an $S2_a$ & $S2_b$, perform the above sum over possible $S1$ values to obtain $\mathcal{L}(S1_{a+b} | S2_a, S2_b)$
- Repeat over all possible $S2_{a,b}$ to get the full $\mathcal{L}(S1_{a+b}, S2_a, S2_b)$
- To make this performant, JIT-compile & vectorize with numba



Fitting a Toy Example

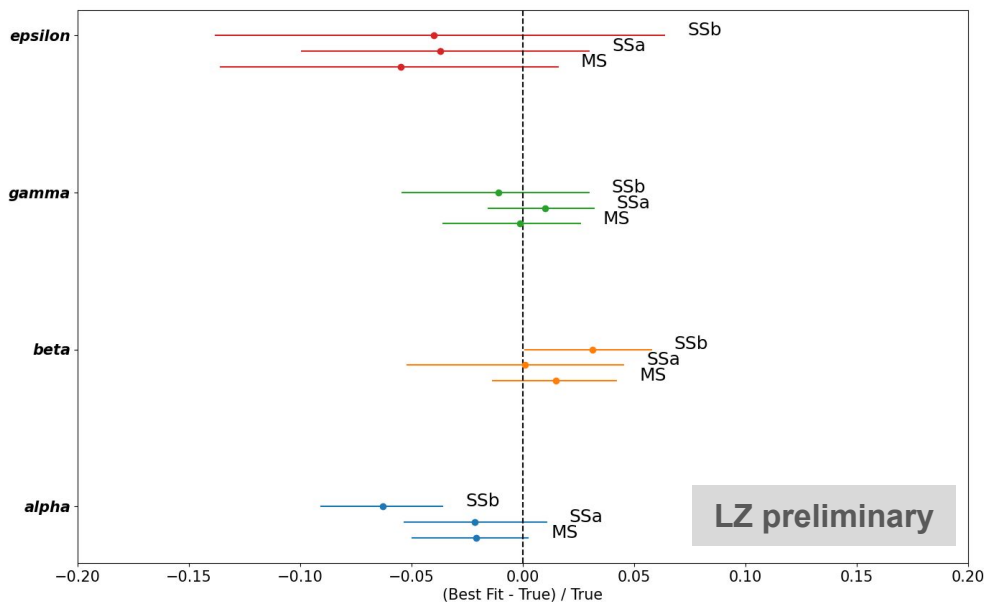
End goal is to be able to fit MS D-Reflector neutrons. Data is still being collected & understood, so for now test machinery on toy example:

- 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 hrs 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

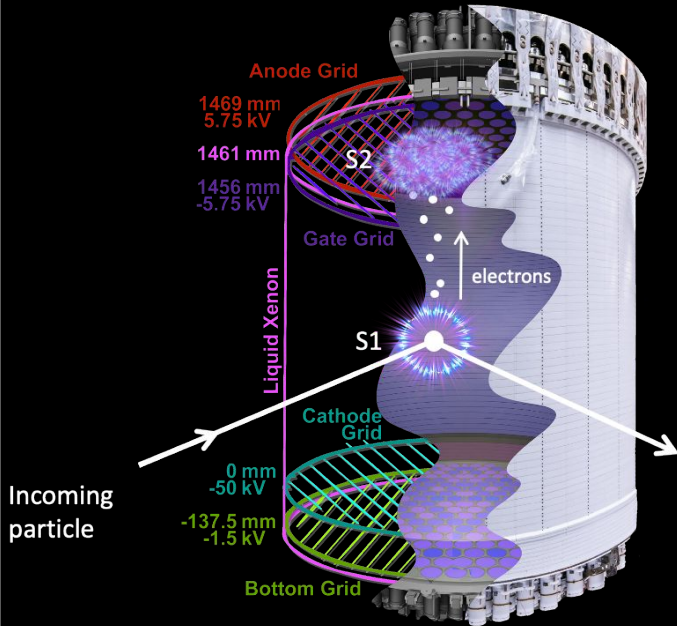


Conclusion

- 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

Thank you!

Thanks to our sponsors and 38 participating institutions!



Incoming particle



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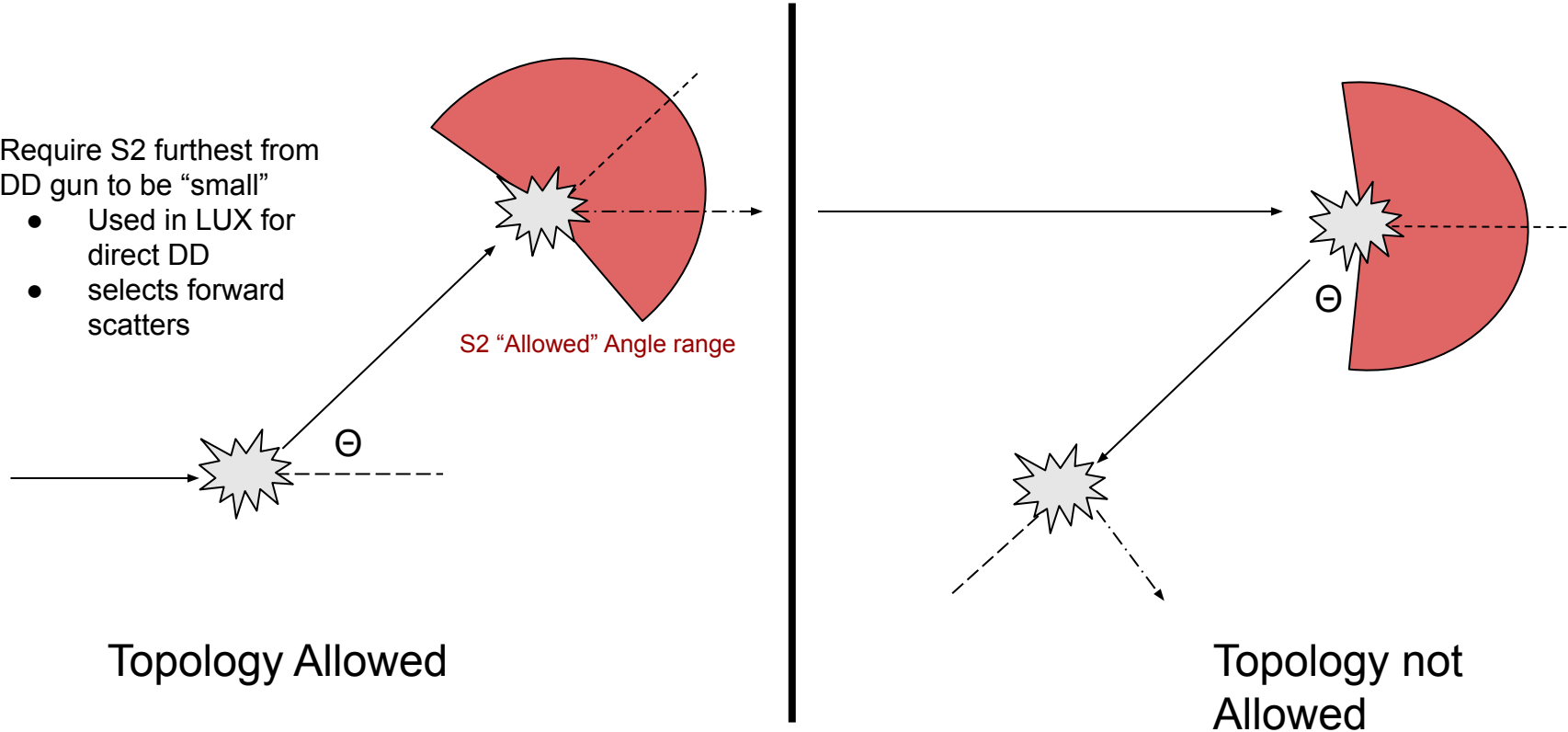
References

- [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](https://arxiv.org/abs/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](https://doi.org/10.1103/physrevlett.131.041002)
- [3] 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](https://doi.org/10.3389/fdest.2024.1480975)

Double Forward Scatter

Require S2 furthest from DD gun to be "small"

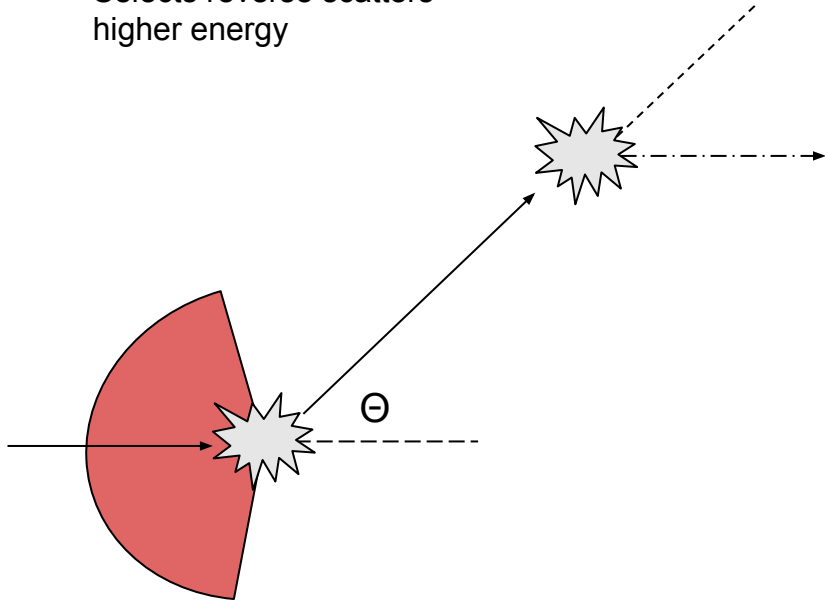
- Used in LUX for direct DD
- selects forward scatters



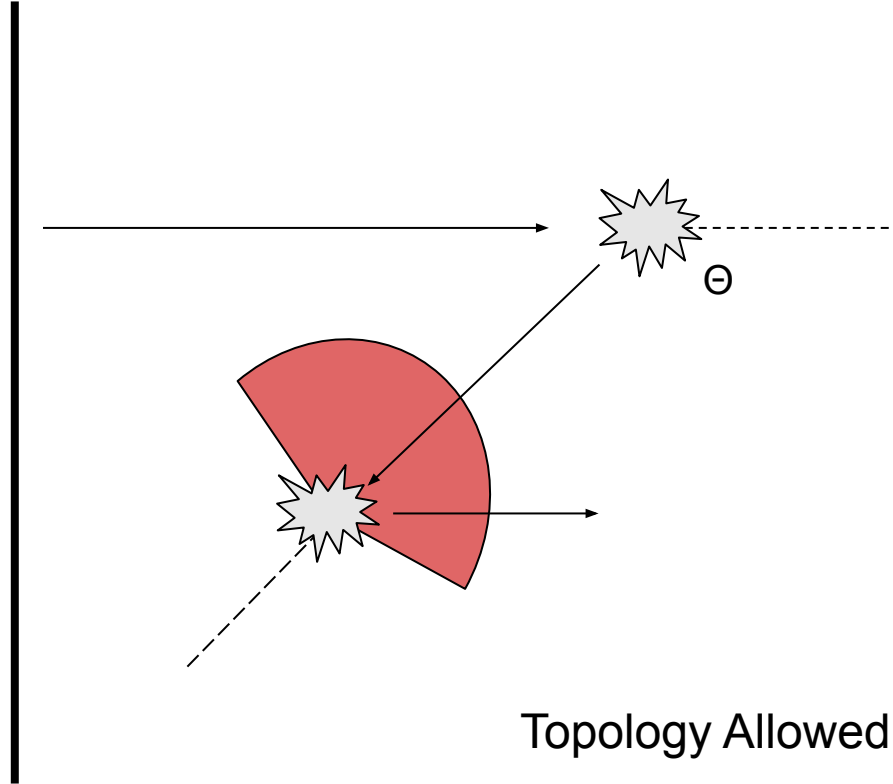
Double Back Scatter

Require closest S2 to be big

- Selects reverse scatters - higher energy



Topology not Allowed



Topology Allowed