ER-NR Discrimination with S1 Pulse Shape

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What is XENONnT?

Dark Matter Direct Detection experiment located underground at the INFN Gran Sasso National Laboratory in Italy.
Primarily designed to search for Weakly Interacting Massive Particles (WIMPs), a leading dark matter candidate. Also looks for solar neutrinos and axions.

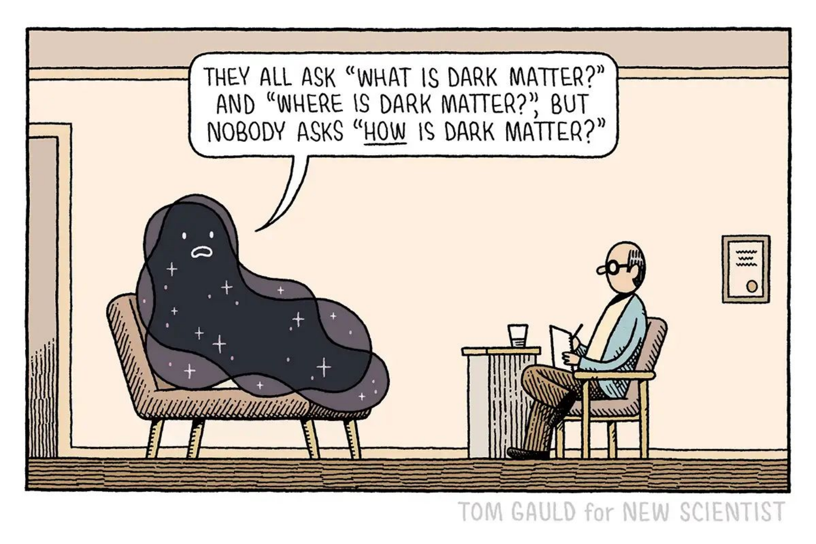
https://xenonexperiment.org/photos/

Dark Matter?

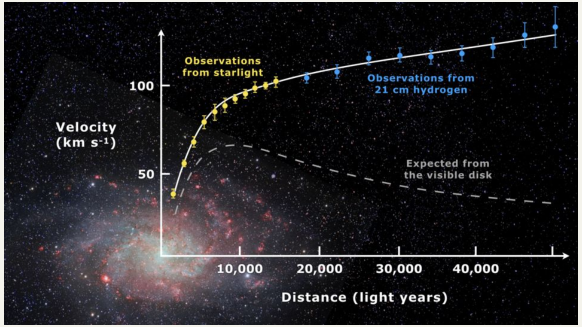
Type of non-baryonic matter we believe exists, due to gravitational interactions.

Makes up about 27% of the universe!

Does not interact with the electromagnetic force, making it very difficult to find.

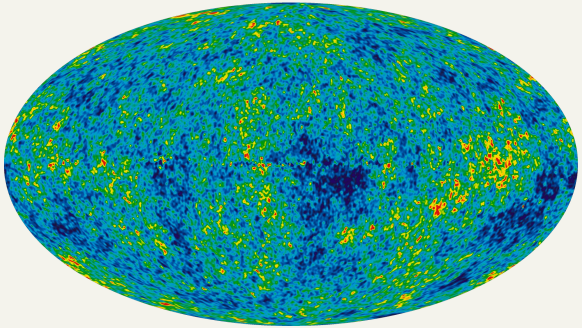


Dark Matter?



Galaxy Rotation Curves

Observations show that stars at the outskirts of galaxies orbit significantly faster than expected based on visible matter alone. This implies the presence of additional, unseen mass providing the necessary gravitational pull.



Cosmic Microwave Background

Precise measurements of the CMB indicate that a substantial amount of cold, non-baryonic matter is required to explain the observed structure and evolution of the universe.

Challenges to modified gravity theories

Alternatives that modify gravity instead of introducing dark matter often fail to account for the full range of observations, particularly in light of recent gravitational wave detections that align with predictions from dark matter-inclusive models.

How XENONnT Works

It uses a dual-phase time projection chamber (TPC) to measure both scintillation and ionization signals from particle interactions.

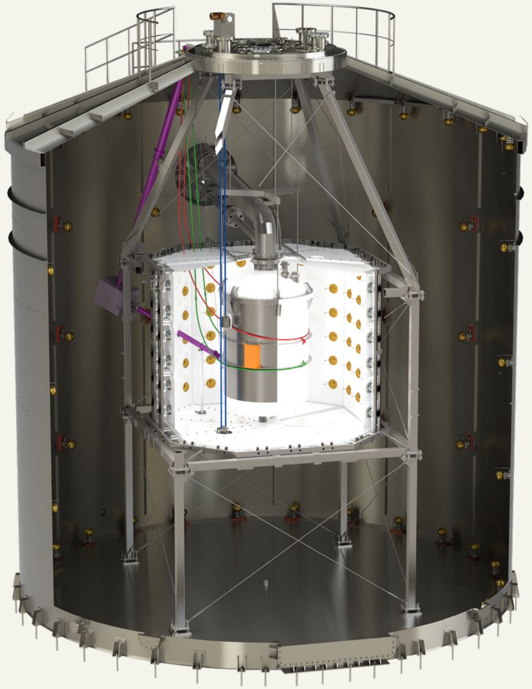
Located deep underground at LNGS in Italy to reduce cosmic ray backgrounds.

Water Cherenkov Muon Veto

- Large water tank surrounding the detector detects cosmic muons via Cherenkov radiation. Tags and rejects any event coincident with a muon signal.

Neutron Veto

- Instrumented volume around the TPC filled with gadolinium-loaded water to detect neutrons via capture gamma rays. Helps reject radiogenic and cosmogenic neutrons, which can mimic WIMP signals.



https://xenonexperiment.org/

What is S1 and S2?

https://hdl.handle.net/11245.1/7dbf4ab7-b10a-46f2-a39a-c9daba6d07ad

S1: Prompt scintillation light (VUV photons)

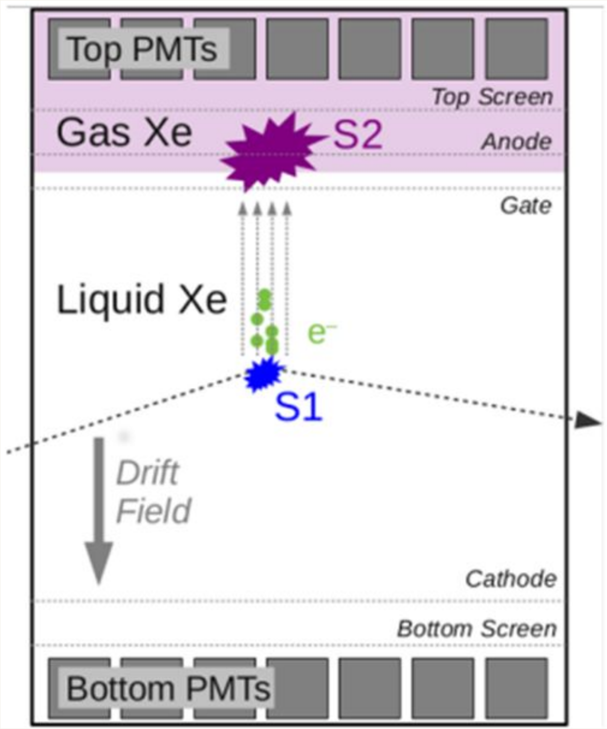
- Produced within nanoseconds at interaction site
- Collected by PMTs immediately

S2: Secondary electroluminescence

- Ionization electrons drift upward to gas phase
- Electrons extracted and accelerated, generating proportional light
- S2 is delayed (milliseconds) and broader

Time difference = depth (Z position)

S1/S2 ratio used to classify events

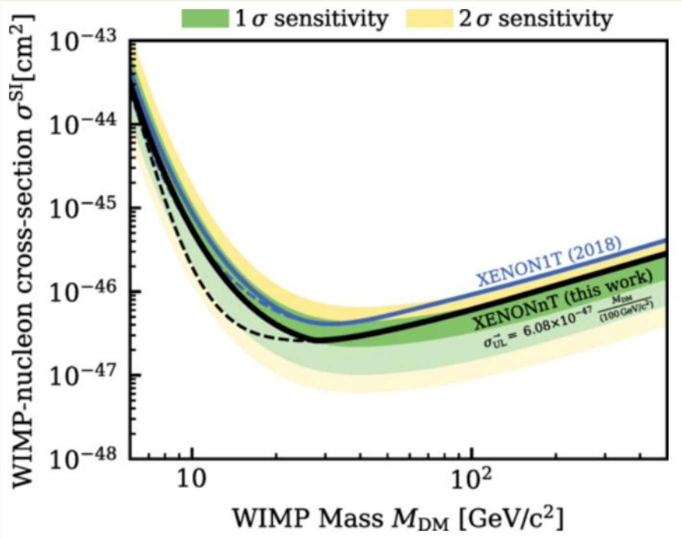


Recent WIMP Limit

Full Black Line: 90% confidence level upper limit. It tells you that any WIMP with a mass and cross section above that line is excluded by the data.

To push the exclusion limit lower (to test for weaker WIMP-nucleon interactions), you need a more sensitive detector.

https://doi.org/10.1103/PhysRevLett.131.041003



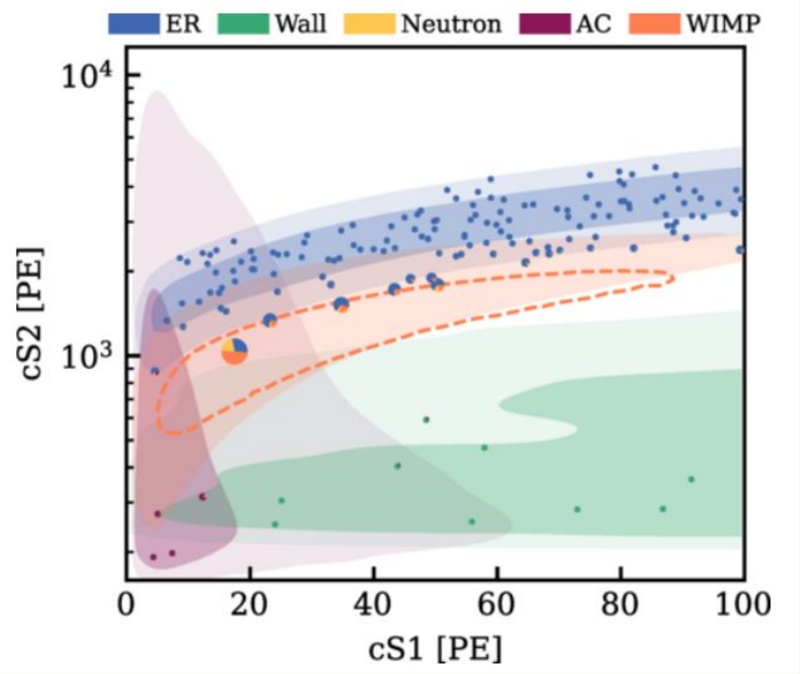
cS1-cS2 space

The amount of detected S1 light depends on the event's depth in the detector. Deeper events tend to produce larger observed S1.

To remove this position dependence, we use cS1, a position-corrected version of S1 that represents the light yield as if the event happened at a reference location (usually the center).

cS1 enables consistent event comparison, improves energy reconstruction, and is essential for analysis.

https://doi.org/10.1103/PhysRevLett.131.041003



Electronic Recoil vs. Nuclear Recoil

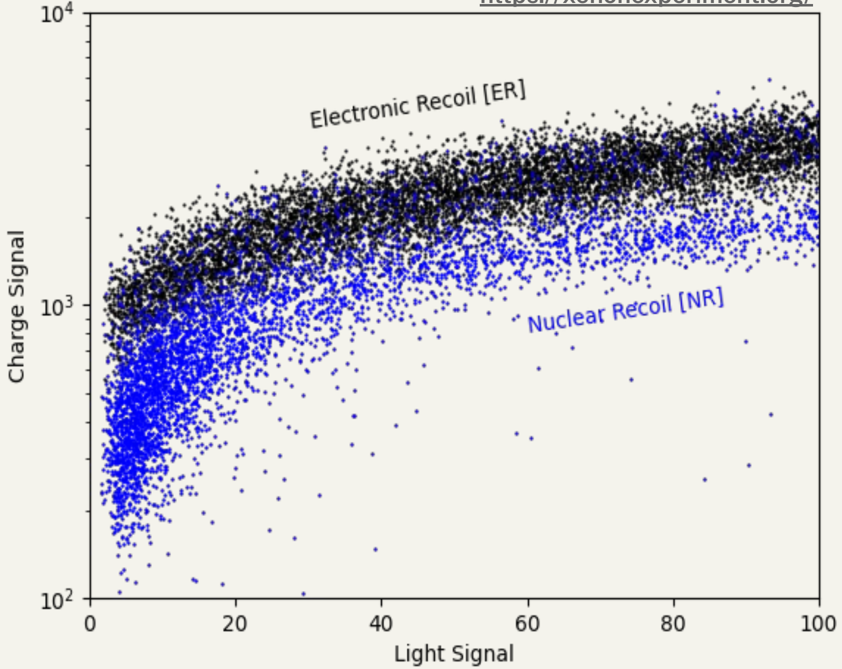
Electronic recoil (ER)

- Caused by β, γ, or neutrino–electron scattering
- Electrons recoiling off atoms
- Produces more ionization; larger S2/S1 ratio

Nuclear recoil (NR)

- Expected from WIMPs or neutrons
- Nucleus recoils output more energy to heat/scintillation; Smaller S2/S1 ratio

https://xenonexperiment.org/



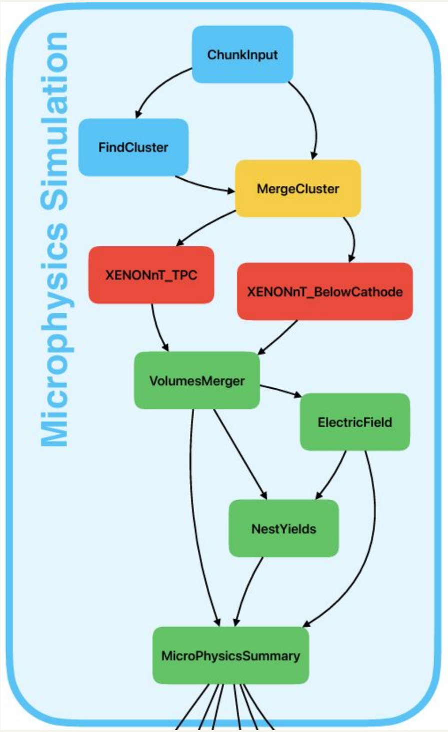
Why do we want to use the S1 pulse shape?

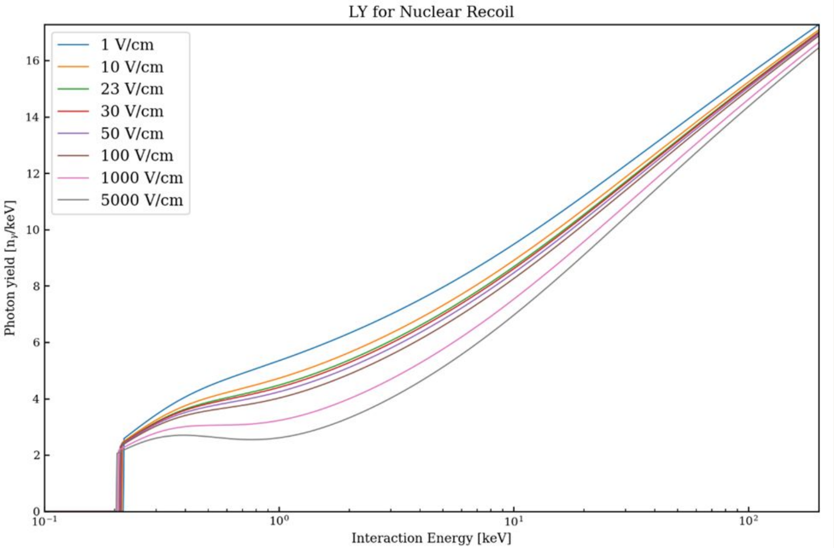
- Traditional analyses rely on cS1 vs. cS2 to infer event type and energy.
- To improve sensitivity to WIMPs, we can incorporate S1 pulse shape information.
- Electronic recoil vs. nuclear recoil separation is critical for background rejection.
- If ER and NR events produce distinct S1 shapes, we can use this to further suppress ER backgrounds and enhance signal discrimination.

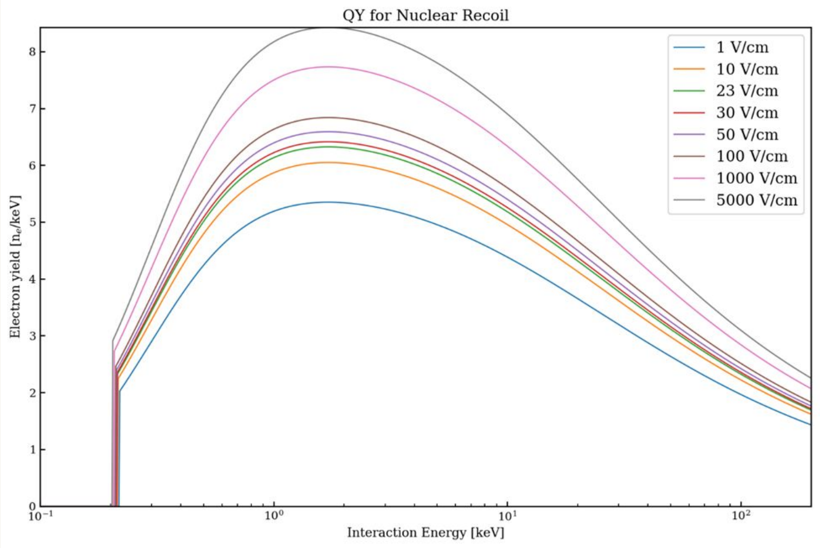
Simulation Data

Noble Element Simulation Technique (NEST) - simulation of the excitation, ionization, and corresponding scintillation and electroluminescence processes in
liquid noble elements. Makes the "input" for the simulation.

Framework for Unified Simulated Events (FUSE) - Uses NEST output to create events.





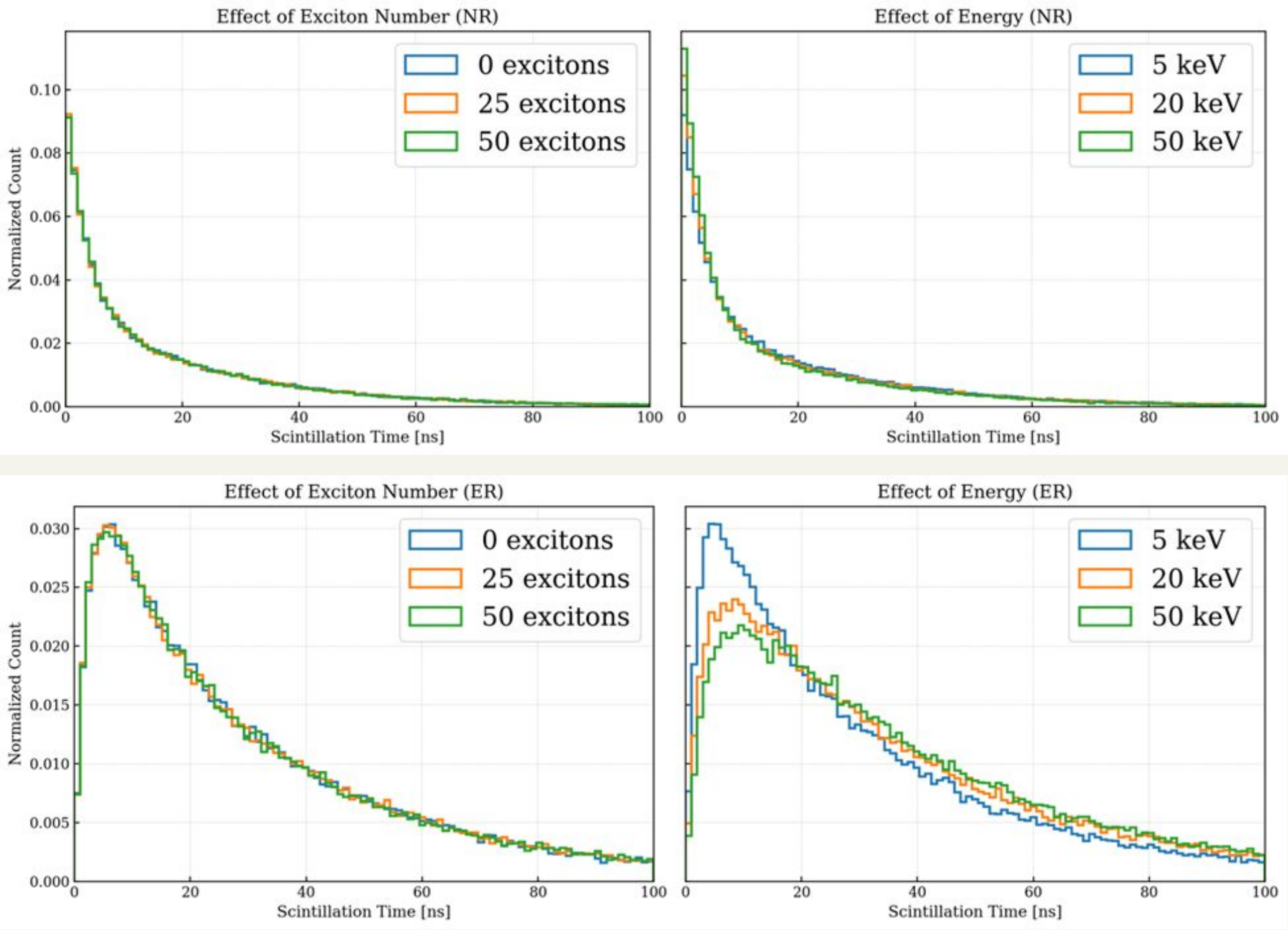


NEST gives you light yield and charge yield.

Light Yield and Charge Yield for NR vary at different drift field strengths.

NEST

Many factors can potentially influence the S1 pulse shape in NR and ER such as exciton fraction and recoil energy.
So, we are motivated to look for this difference in simulated and calibration data.

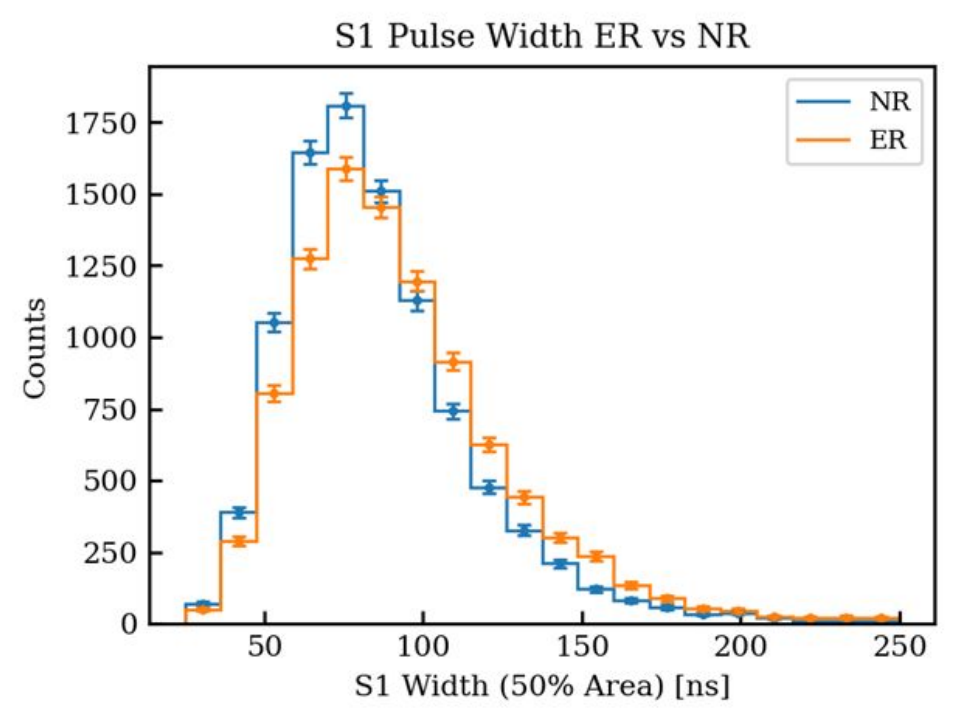


FUSE

ER - Interaction Type 8 (Beta)
NR - Interaction Type 0

ER Wider than NR, showing discrimination.

S1 Width is the time interval to cover 50% of the S1 Area. This is one of the features used to describe the S1 pulse shape.

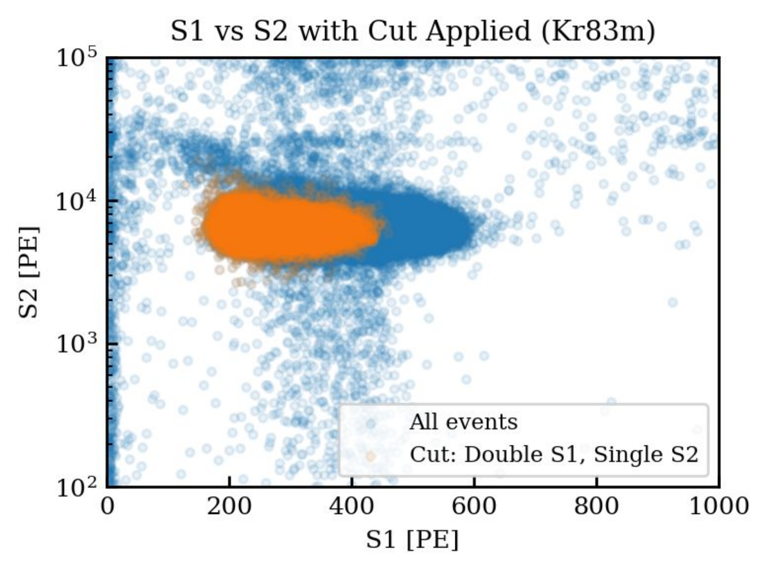


Calibration Data

Calibration data refers to the data collected during controlled exposures of the detector to known sources of particles or energy. These data are crucial for understanding and modeling the detector's response to different types of interactions and energy deposits.

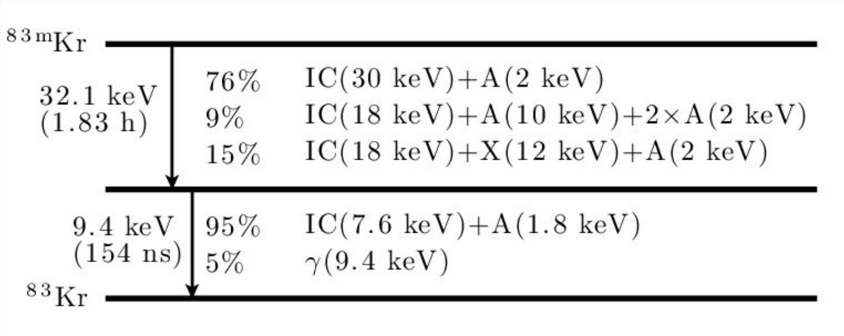
ER Calibration commonly uses ^{220}Rn or ^{83m}Kr

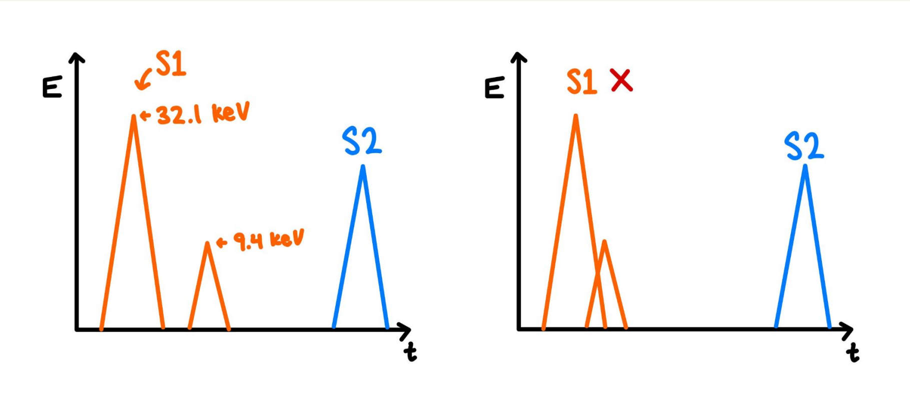
NR Calibration used Deuterium-Deuterium neutron generator: $^{2}H + ^{2}H \rightarrow ^{3}He + n + 3.27$ MeV



Calibration Data “Cuts”

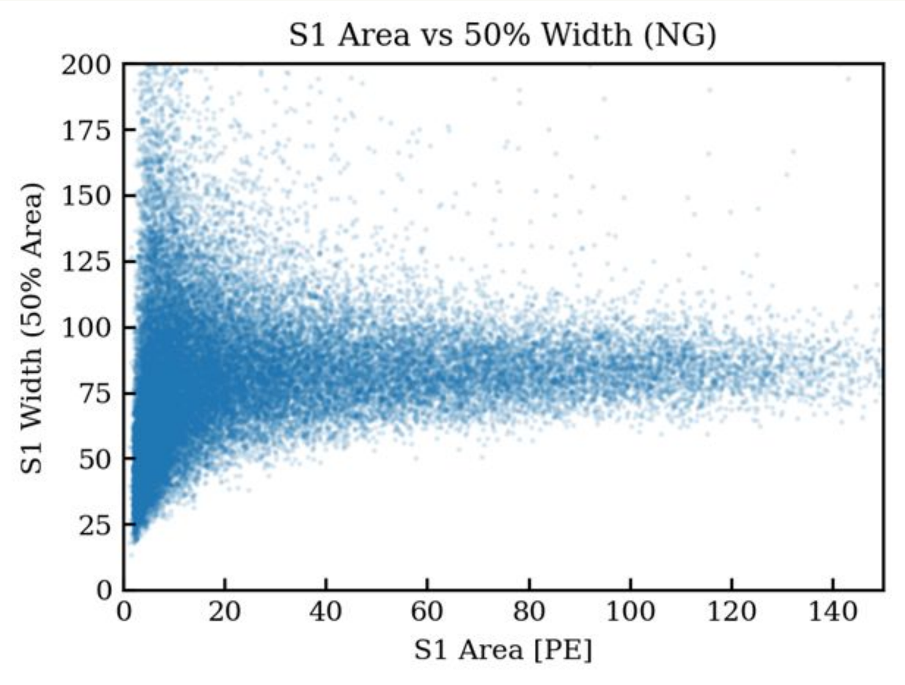
Double S1 Selection of 83mKr





Multiple Scatter - particle interacted more than once in LXe. WIMP Signals are single scatter, so multiple scatter events are background. Multiple scatters also distort the true light and charge yields.

S1 Area vs. Width



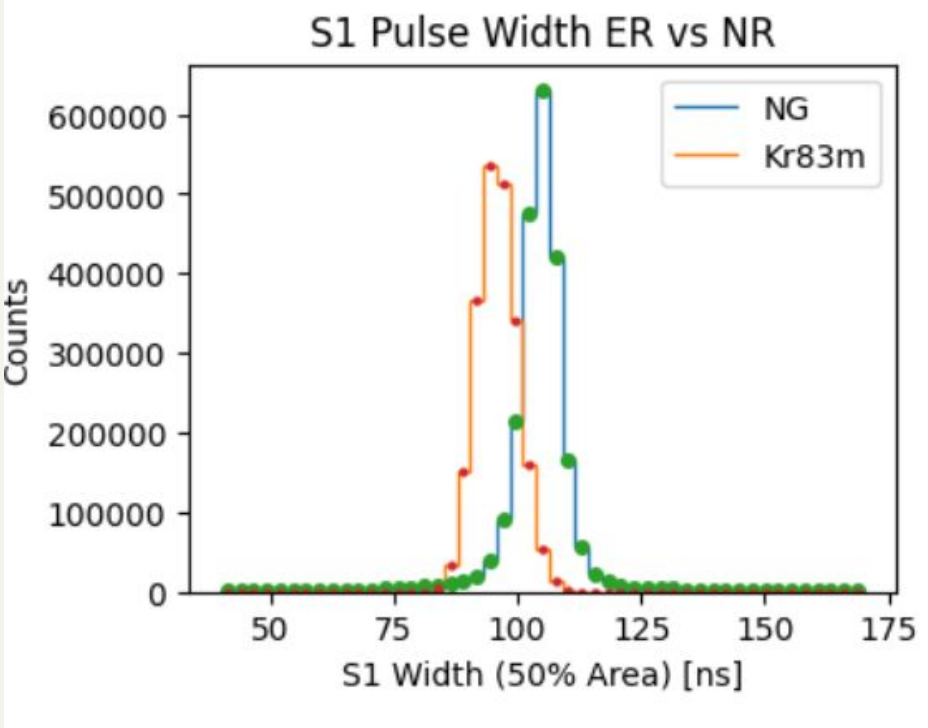
In neutron generator data, ER and NR events show differences in S1 size, which are visible in cS1–cS2 space

Here, S1 area and width are correlated, which makes it hard to isolate true pulse shape differences

To study ER vs NR differences from pulse shape alone, we must:

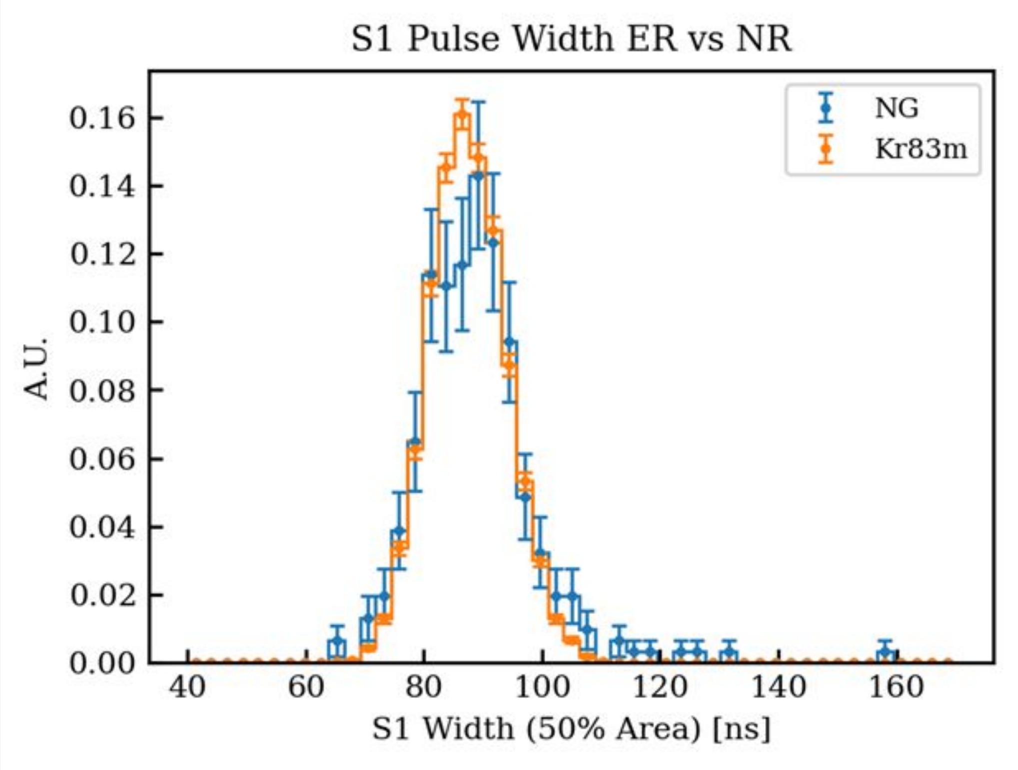
- Control for or remove effects of S1 size, position, energy
- Focus on normalized pulse shapes, not just total light

A moment of science...

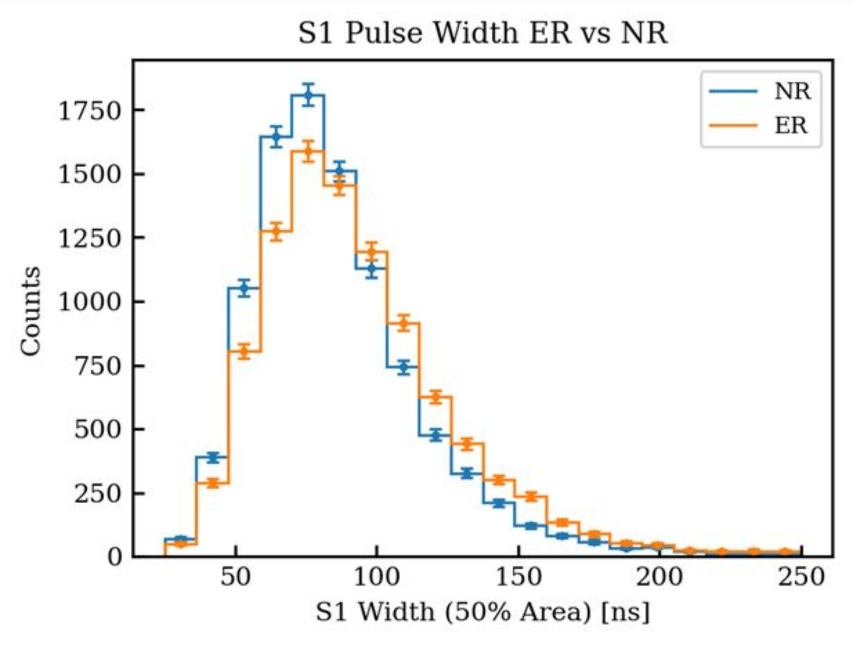


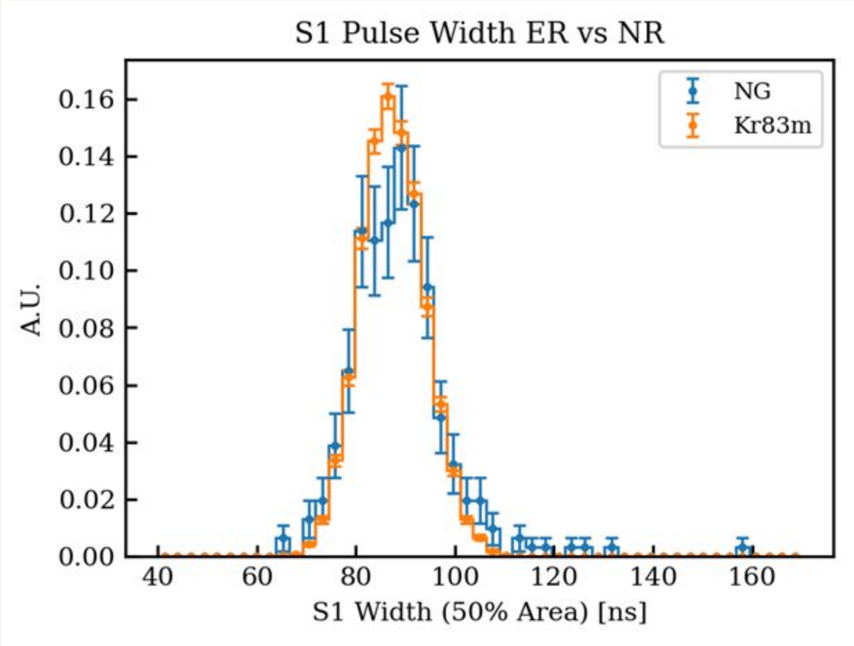
**This plot is NOT CORRECT

A moment of science…



Conclusions

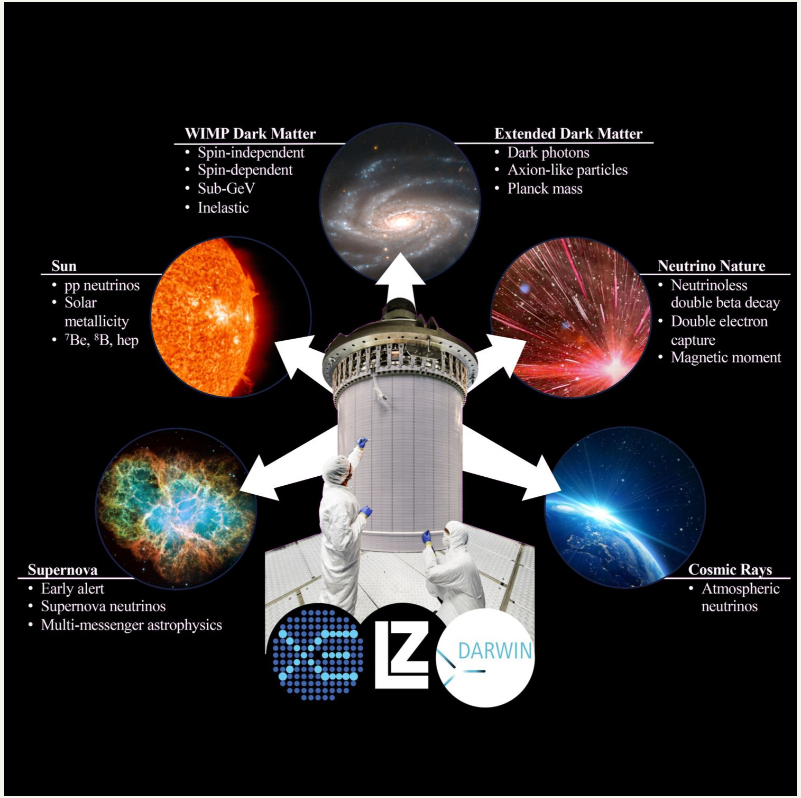




Prospective

In the XENONnT drift field we do not see clear evidence that the S1 timing is not different for ER and NR. This encourages us to look at different drift fields which may prove more useful.

XLZD drift field is much larger so we may look into this comparison with this new data. And hopefully have new methods to discriminate ER and NR and improve WIMP sensitivity.



Thank You!

To…

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- The other REU students that made this summer so great!
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Pulse Timing Selection

The neutron generator produces neutrons in pulses.

- The exact time of these generator pulses is recorded and synchronized with the main data acquisition system
- Currently, a selection is made based on the time difference between consecutive S1 main signals.
- Results in distinct peaks at multiples of 4.4 milliseconds, which corresponds to the known pulse period set for the neutron generator calibration tests. In contrast, background data shows a flat distribution without such peaks