UNIVERSITY OF LIVERPOOL

Machine Learning and Crystal Xe R&D for Improving the Sensitivity of Existing Dark Matter Searches

Tea Hall
Supervised by Dr. Ewan Fraser & Prof. Sergey Burdin
with thanks to University of Texas at Austin's LZ/CrystaLiZe group

HEP Annual Meeting 2026

Dark matter direct detection experiment

- Aim: detect Weakly Interacting Massive Particles (WIMPs)

Dual-phase time projection chamber (TPC)

- 7t of active liquid Xe (LXe)

Two signals from interactions:

- Prompt scintillation (S1)
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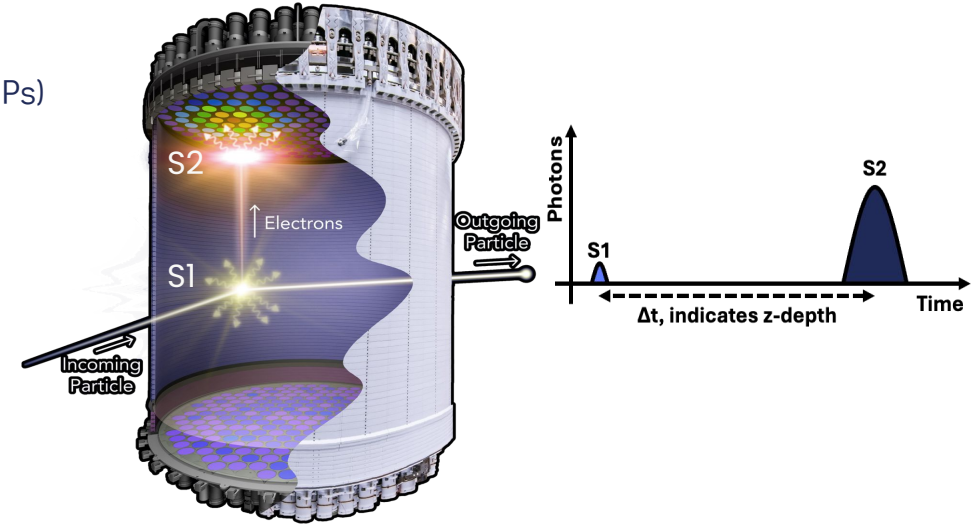

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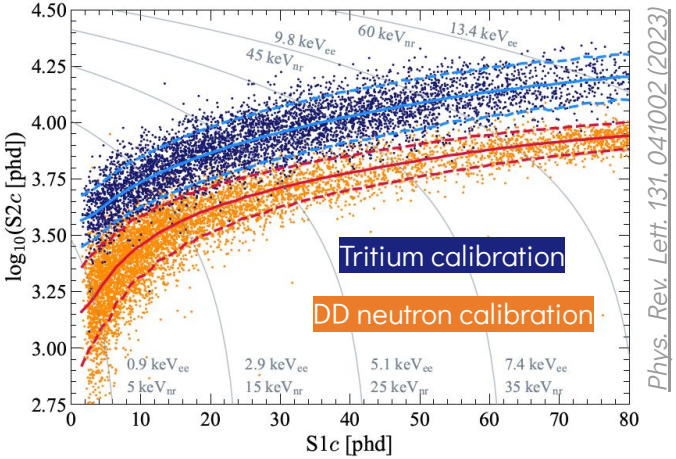

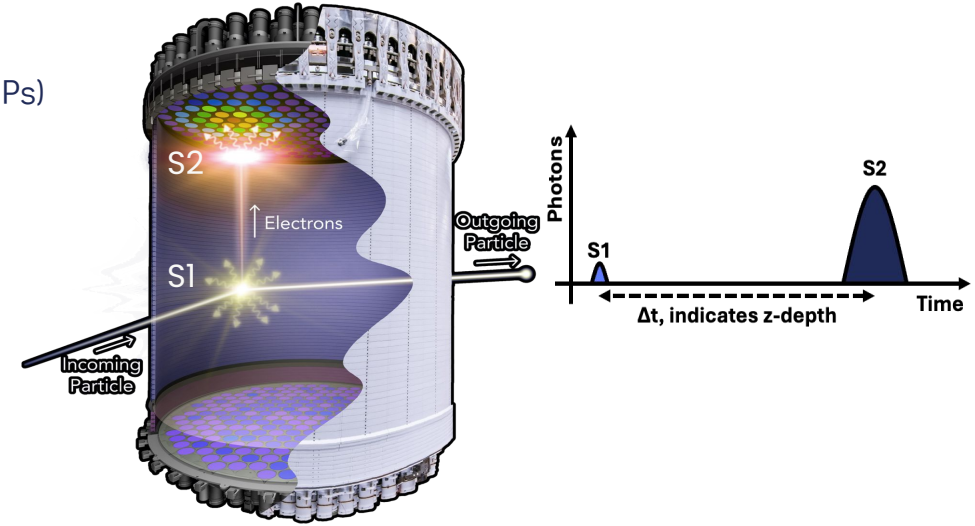

S2/S1 → interaction type:

- Nuclear recoil (NR) – small ratio, e.g. WIMPs, neutrons
- Electron recoil (ER) – large ratio, e.g. β's, γ's

3D reconstruction:

- (X, Y) - S2 light pattern
- Z - Δtime between S1 and S2

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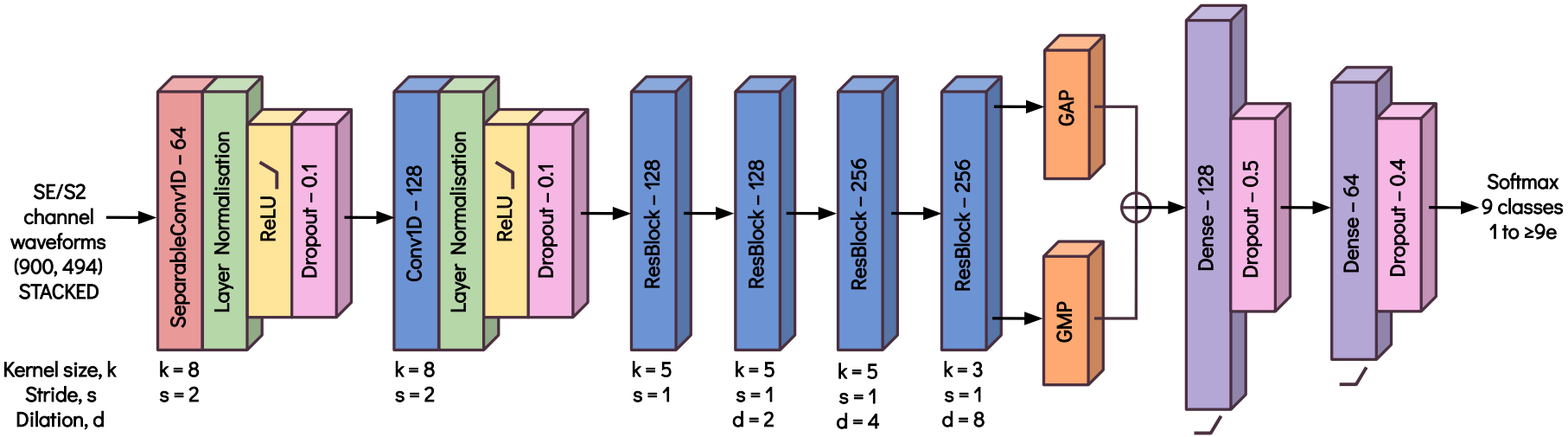

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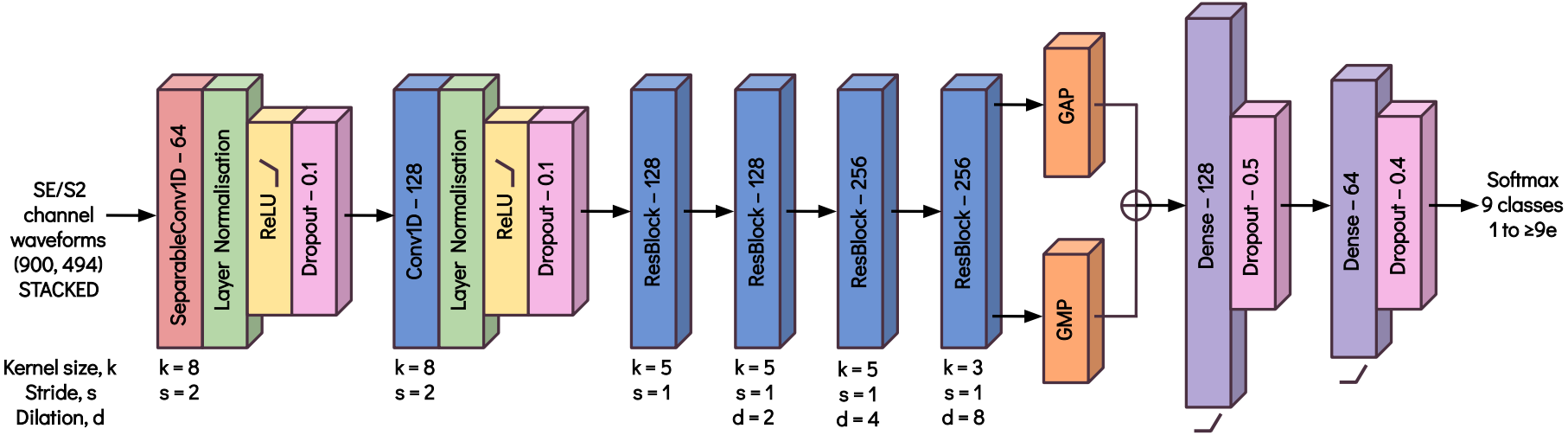

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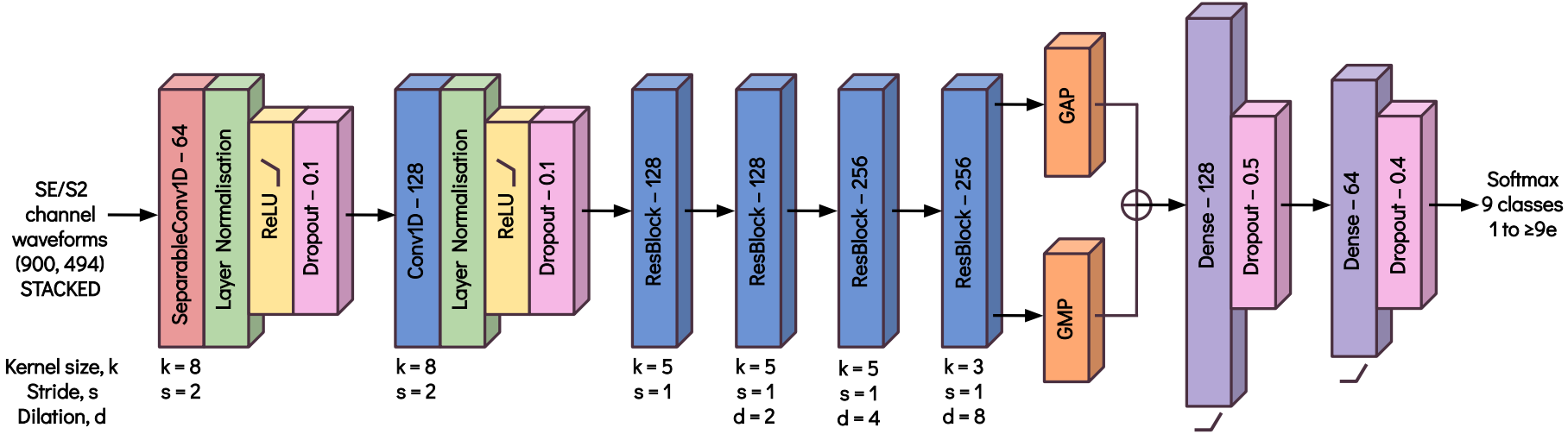

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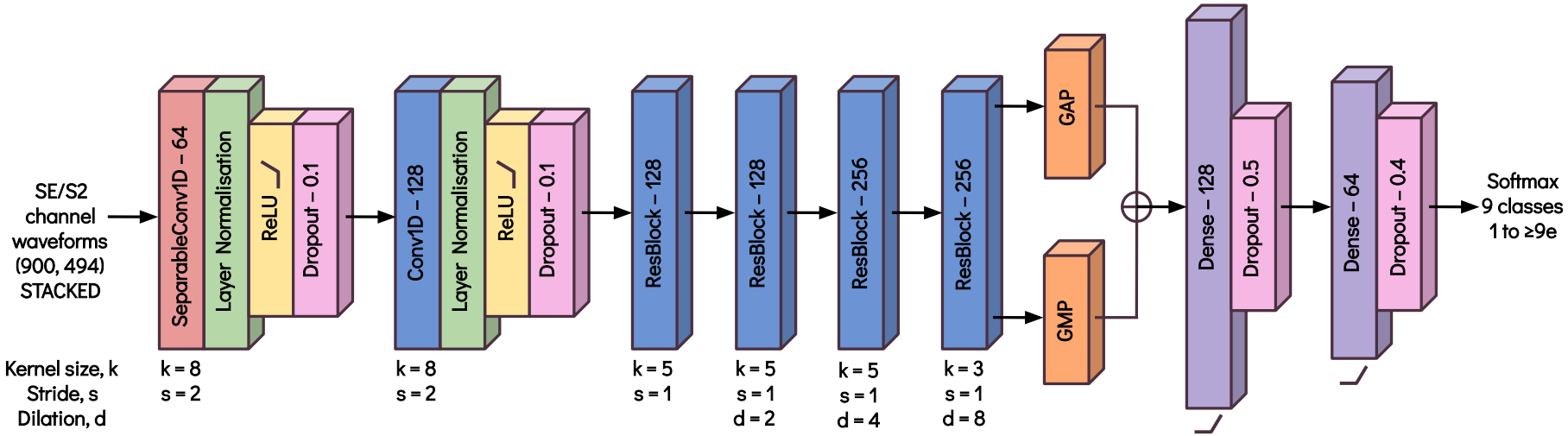

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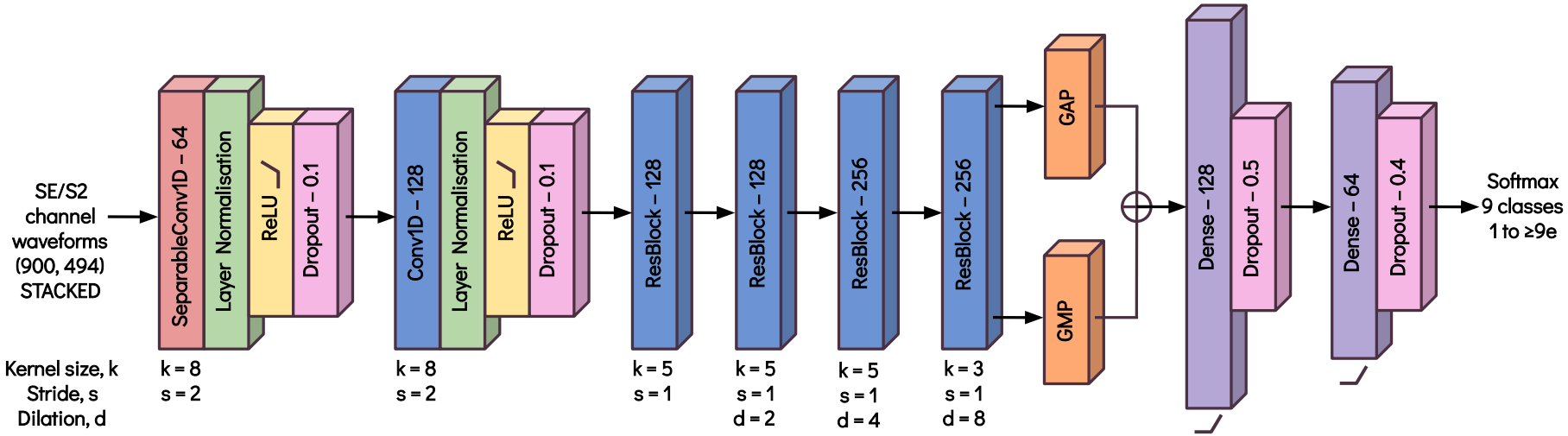
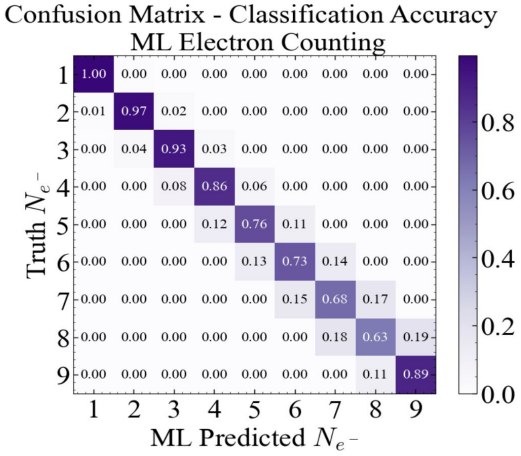


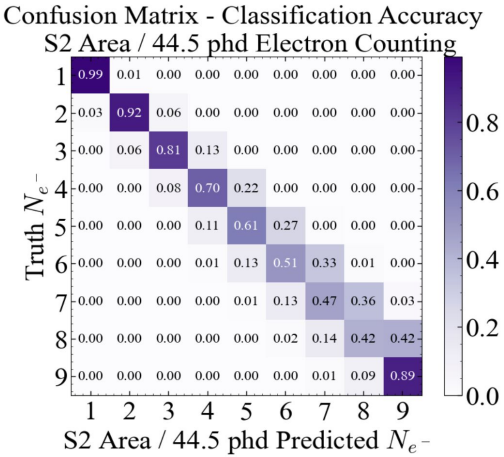
Model trained on 1-10e waveforms from electron bomb simulations.

- Channel waveforms from all TPC channels – 494 PMTs across two arrays
- $N_{e,\,true}$ labels from MCTruth simulation z-vertices
- Modified class-distance weighted cross-entropy loss [arXiv:2412.01246]
  - Reduced training time vs standard categorical cross-entropy loss

Model Performance

ML e^- counting > standard approach





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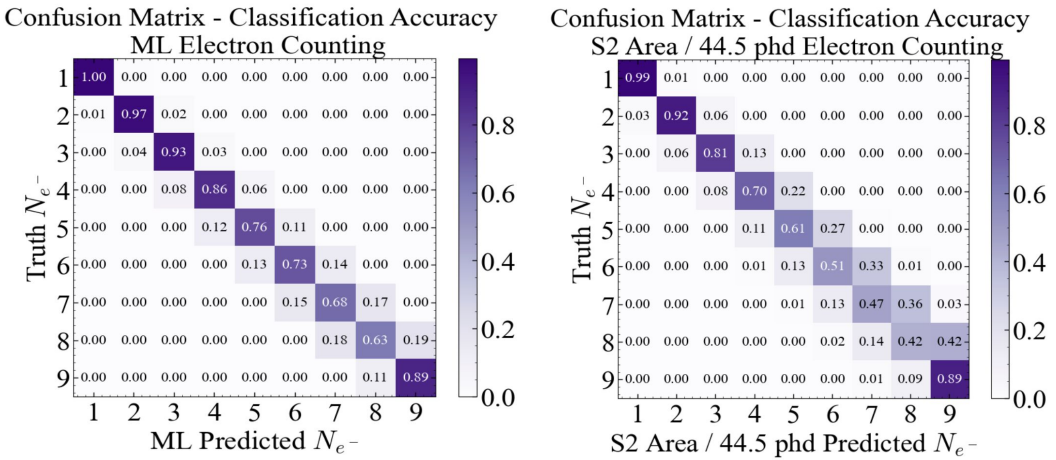

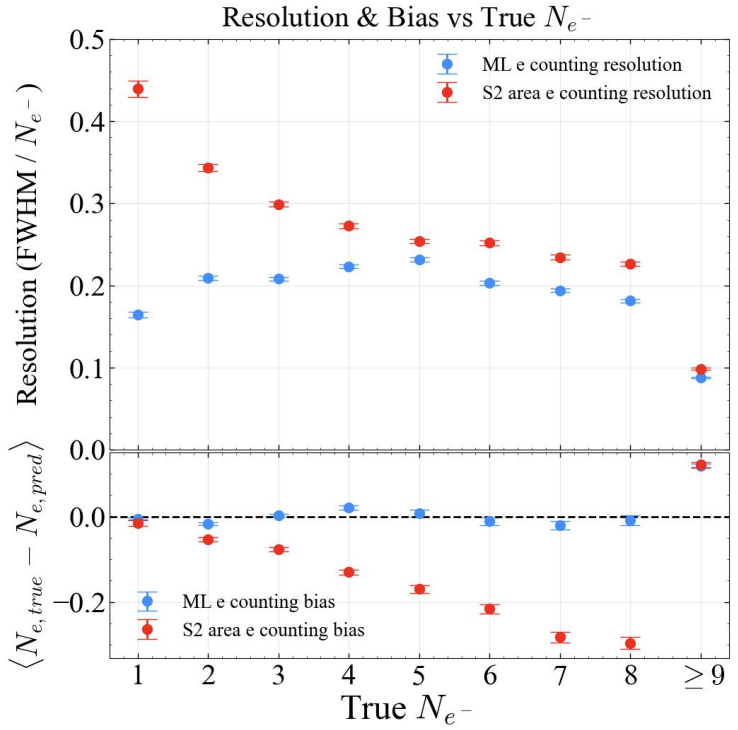

Full waveform vs integral only → better discriminating power

- Less misclassification & leakage → bias centred around zero
- More information → better resolution

S2 approach overpredicts, increasing bias with increasing S2 size

- Area-only susceptible to gain fluctuations, PMT afterpulsing, etc.

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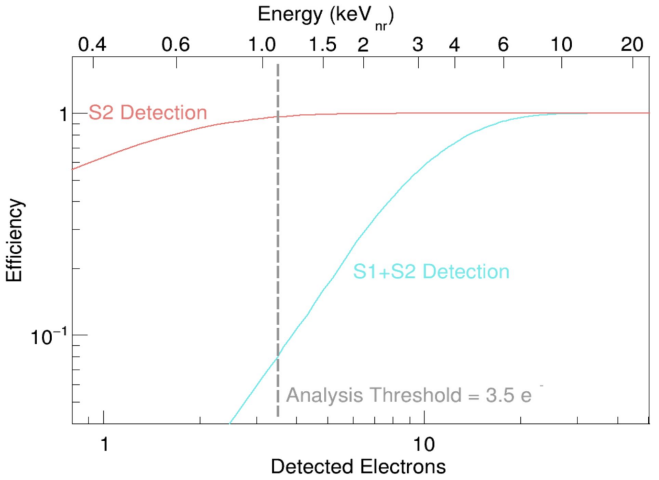

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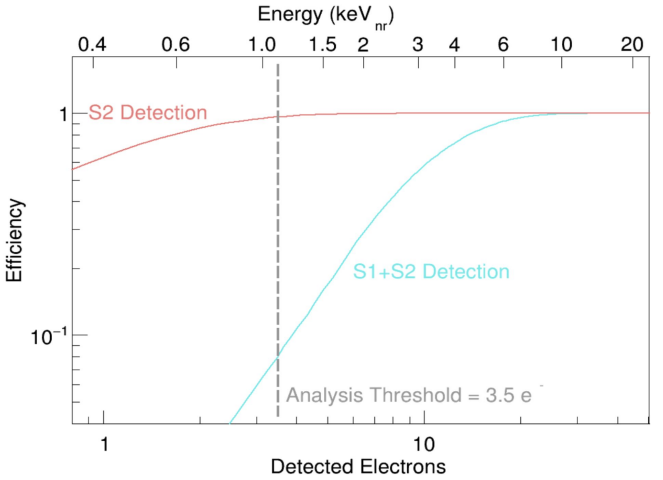
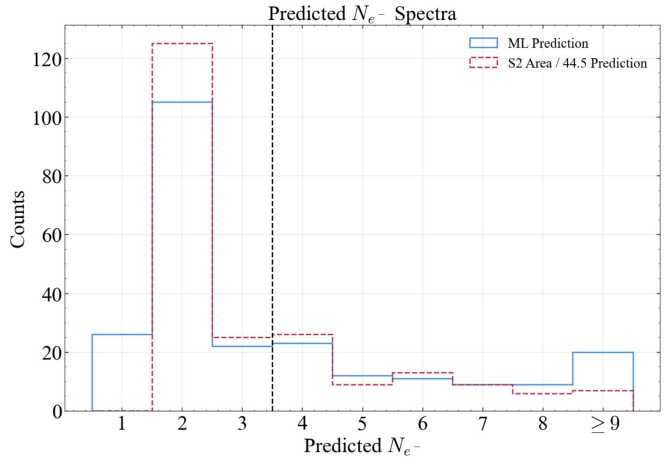
- New cut at $4e^-$ in discrete N_e space → 25% reduction of S2s at threshold





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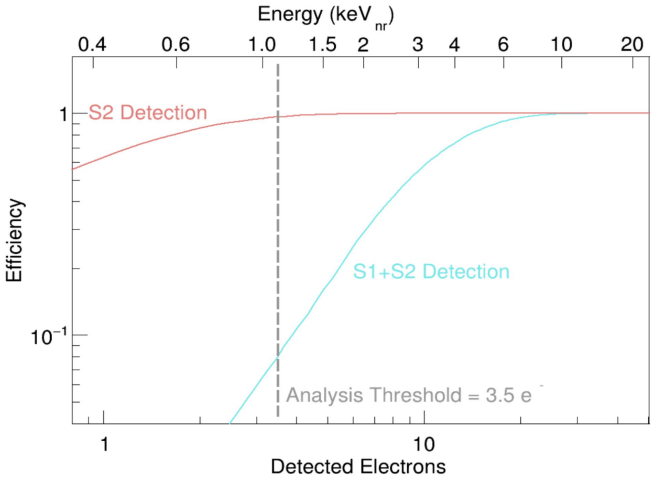

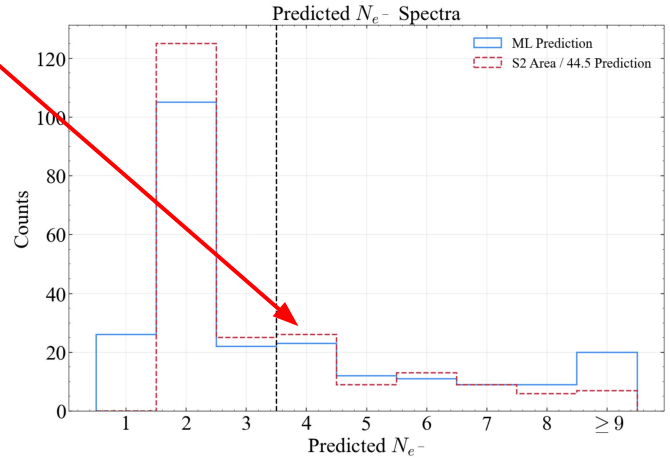

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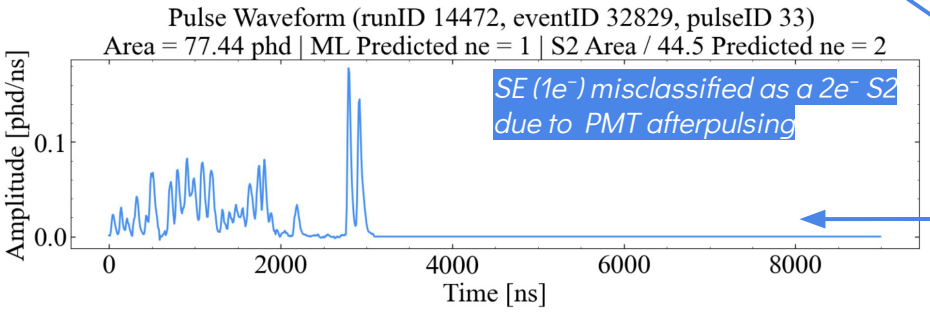
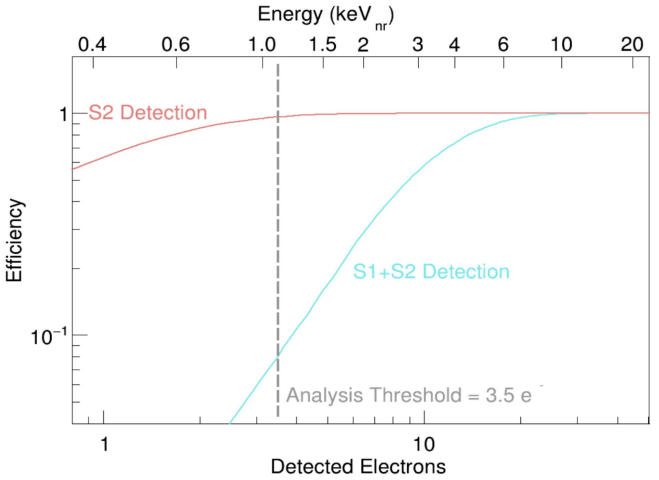
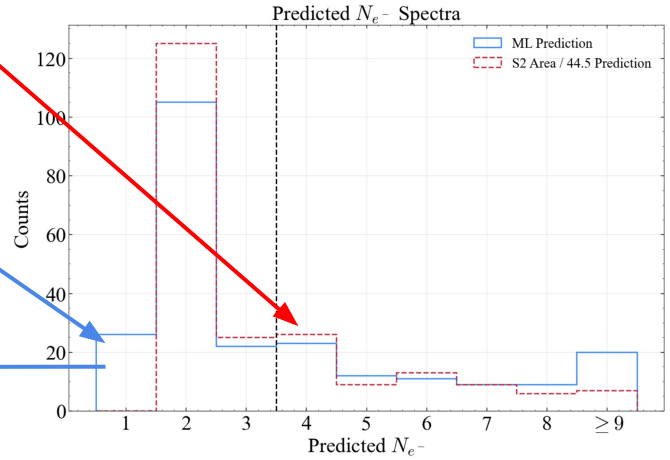
Identification of $1e^-$ events misclassified as S2s by pulse classifier







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Reduce S2-only analysis threshold & conduct search in 1–5e^- regime

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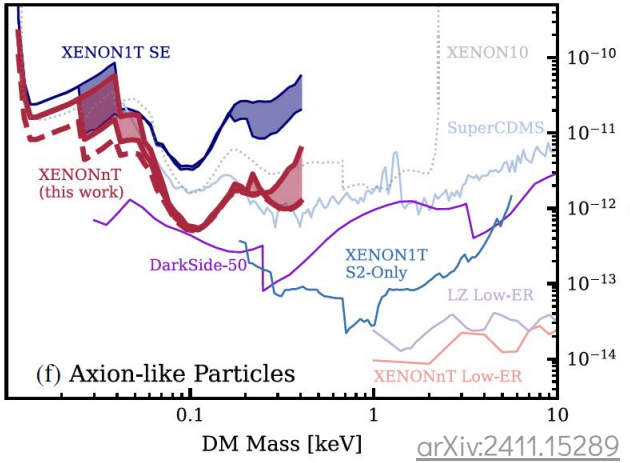
- World-leading limit in S2-only regime to ALPs
- Limited by spurious e^- emission from grids→ ~2.9x loss in fiducial mass



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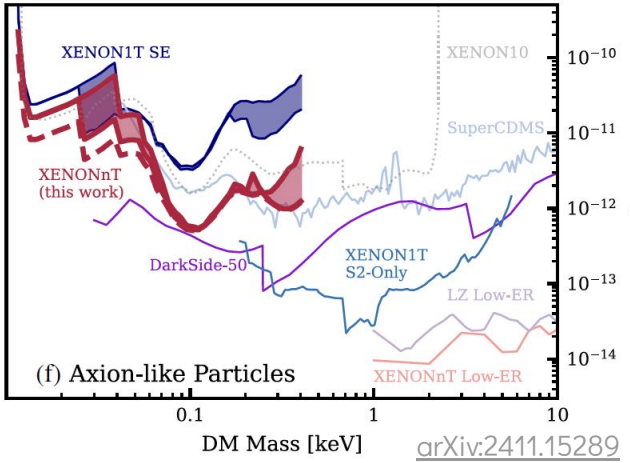
- Larger active volume → more fiducial mass
- Alternative electrode grid design



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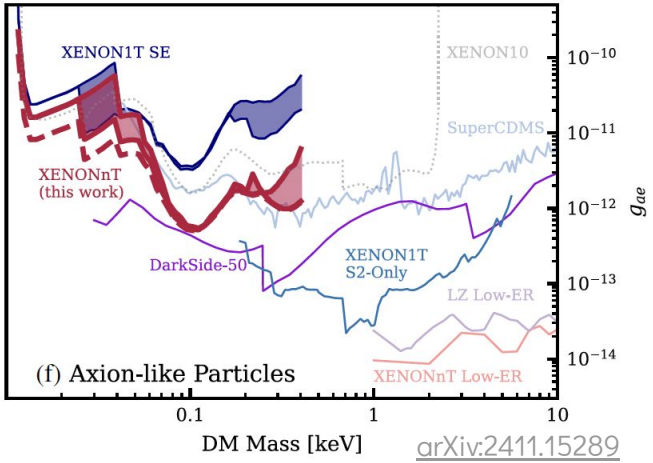
Analysis requirements for a light DM search with LZ

- Aggressive exclusion cuts e.g. hotspots
- Robust background modelling
- Fiducial volume tuned in (x,y,z)
  - Z-reconstruction from e^- arrival times → ML model in development

Discrete N_e counting can help LZ place competitive limits in these regime!



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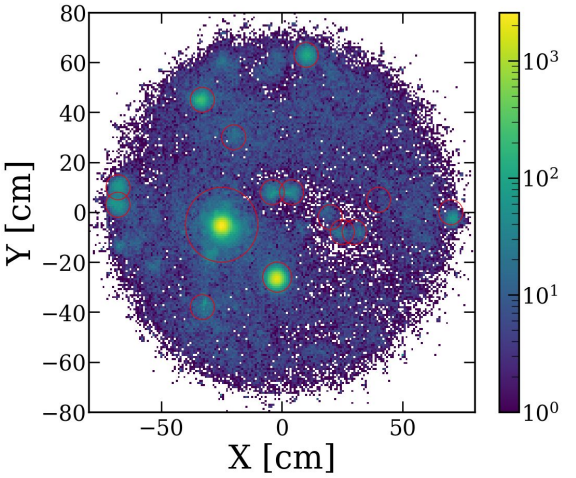
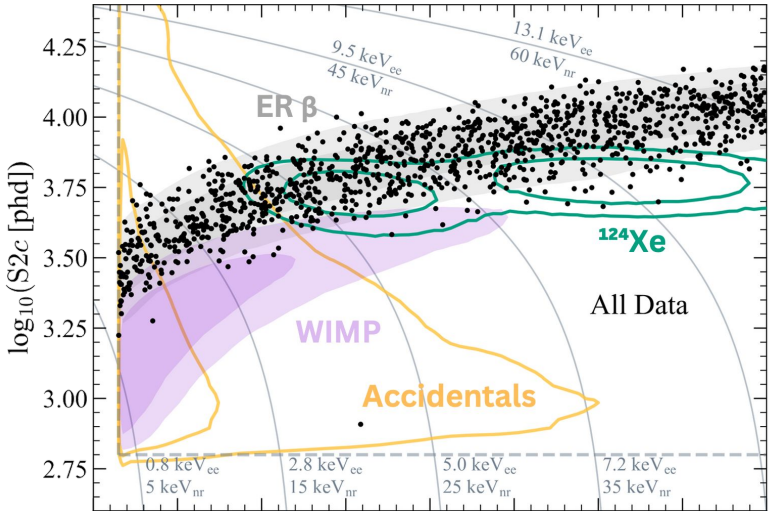


CrystaLiZe – A Neutrino Limited Dark Matter Search

Existing noble liquid dark matter searches are dominated by Radon

- Rn chain events make up ~67% of events in LZ's WS2024



Phys. Rev. Lett. **135**, 011802

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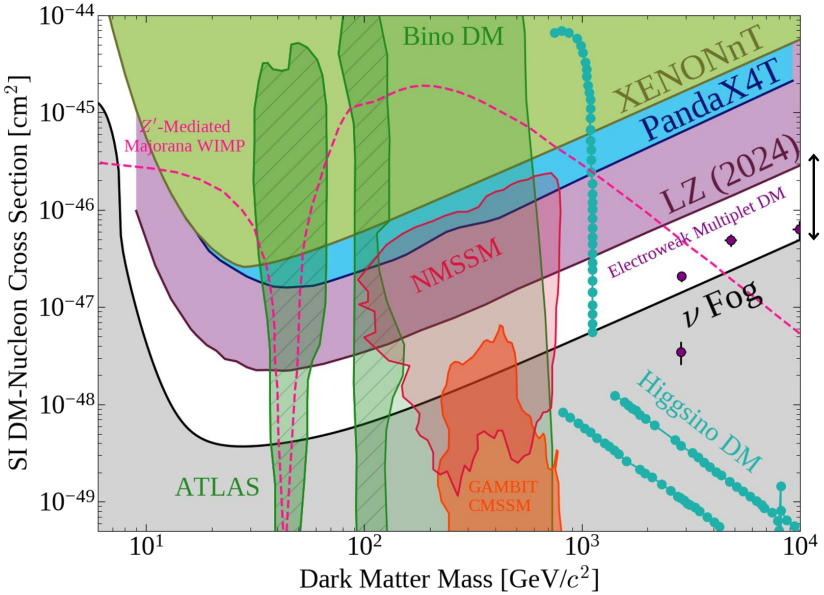
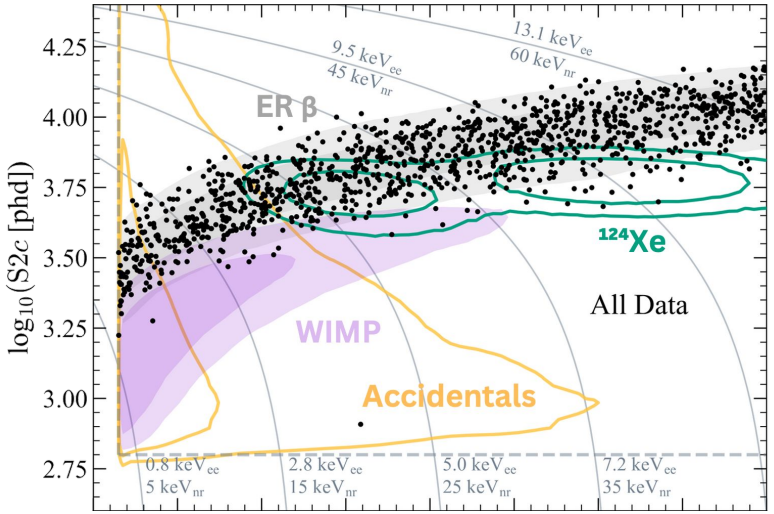


10x Sensitivity improvement requires **20x Rn Mitigation**



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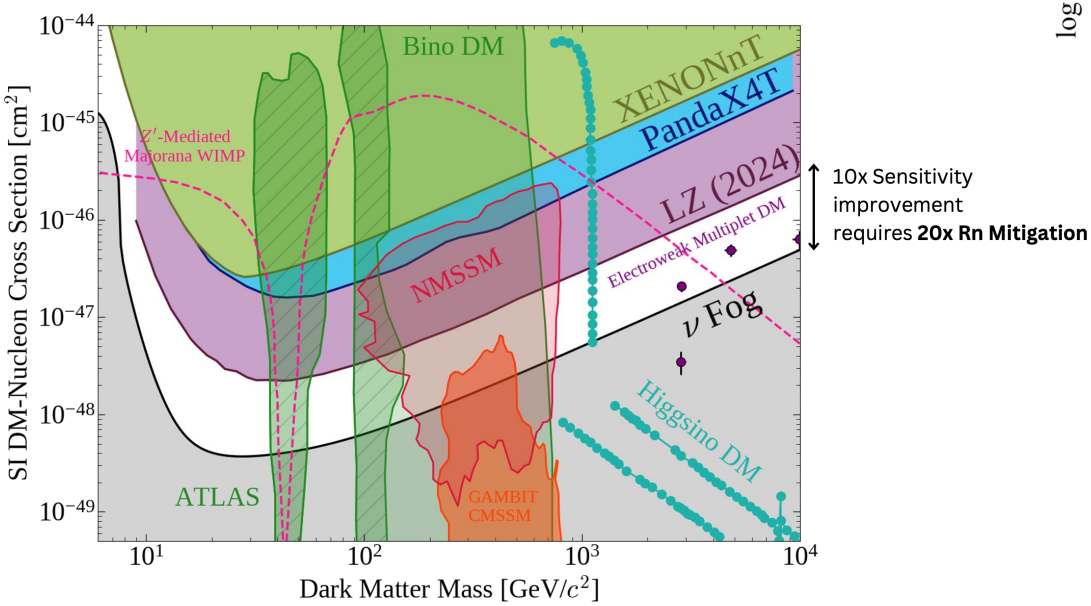

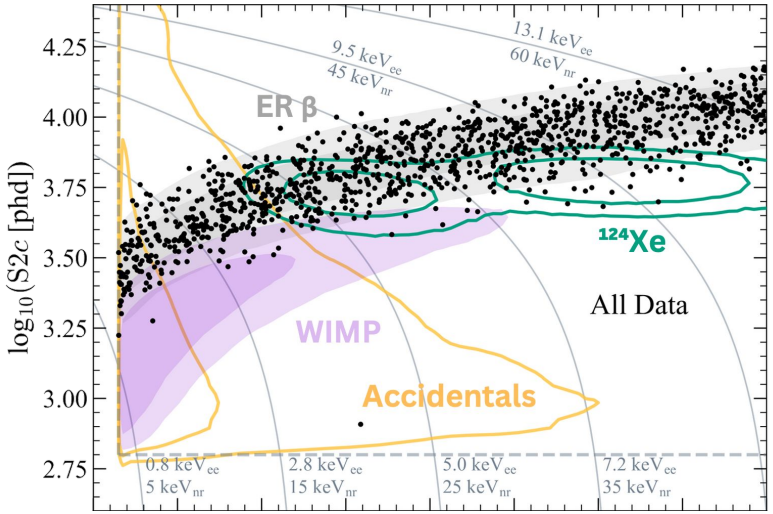

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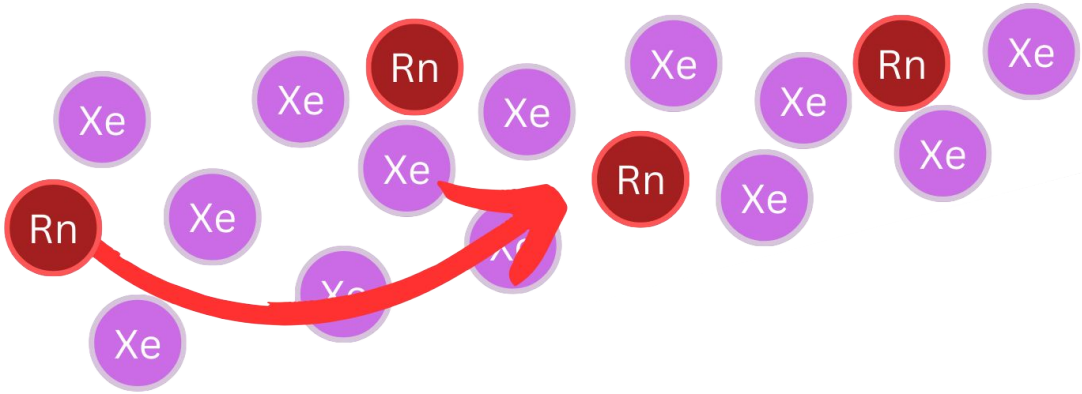
How can Rn be mitigated?

- Purify the Xe more effectively
- Tag Rn events during detector operation
- ★ **Stop Rn from entering**

A liquid noble detector allows Rn to be circulated during operation



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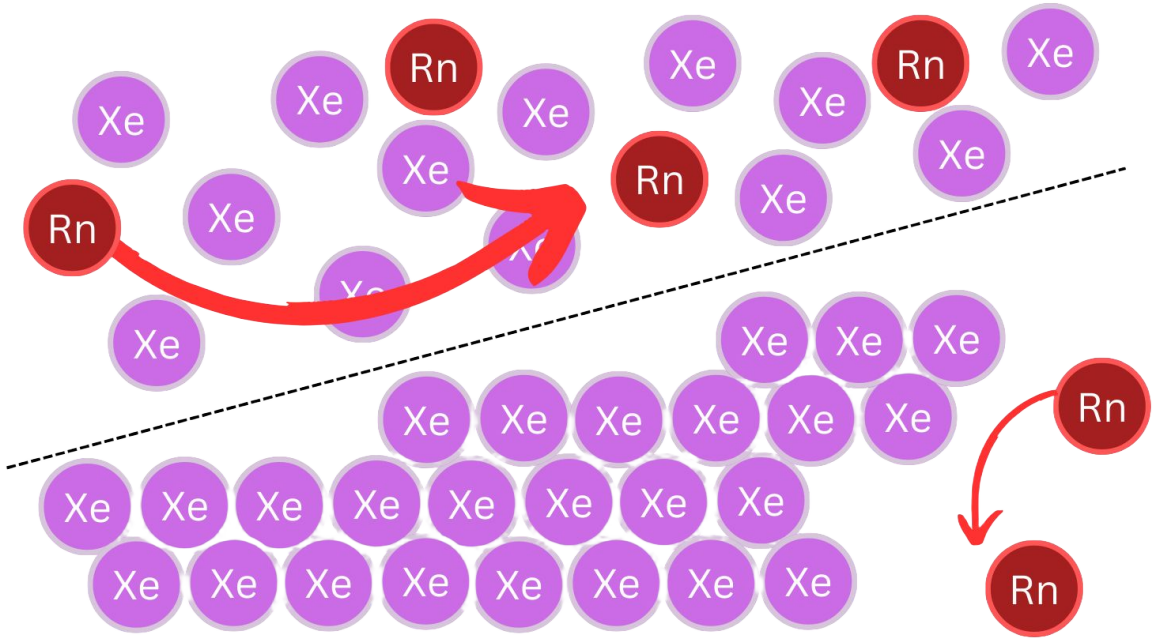

While a frozen noble detector allows Rn to be removed from the bulk of the detector

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- 4 SiPMs
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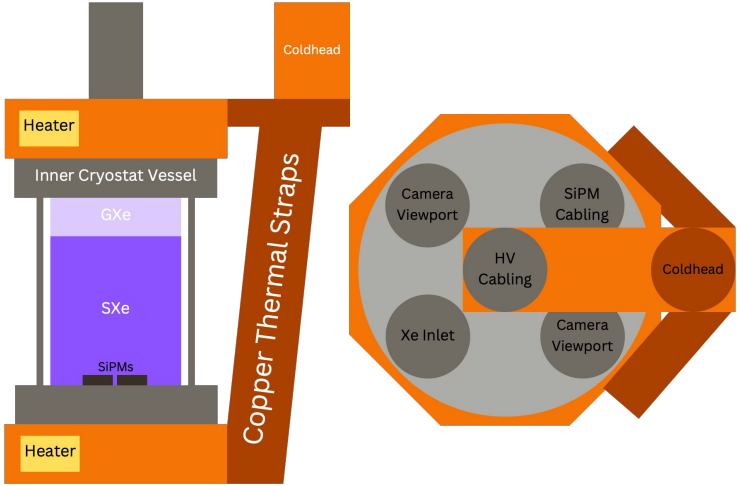

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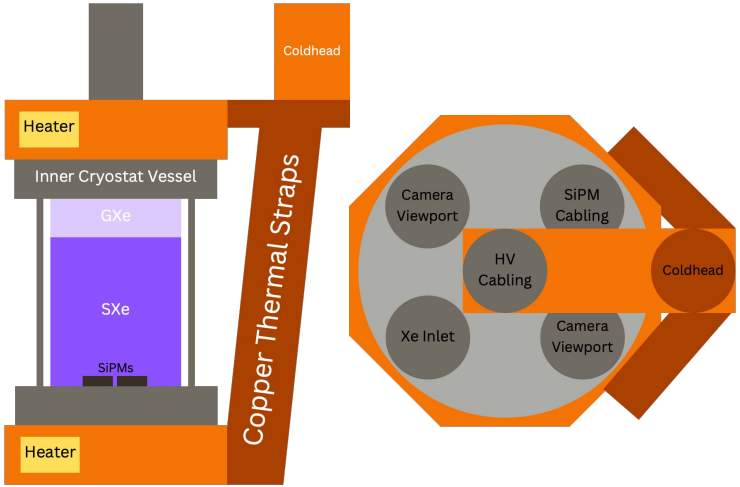
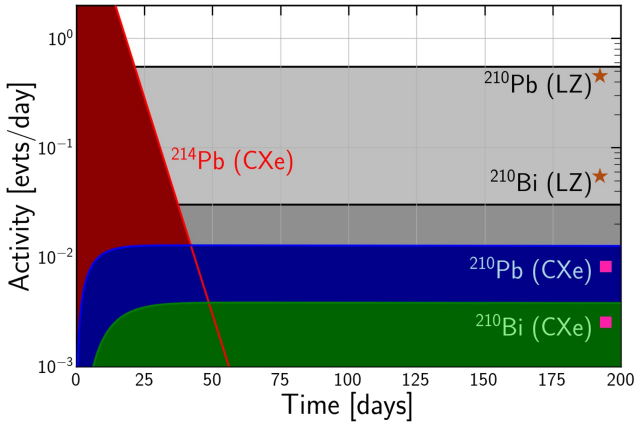
CXe has major benefits vs LXe

- Rn excluded by > 600x ⟶ increased fiducial volume
- Improved electron mobility
- 2x reduction in accidental coincidences

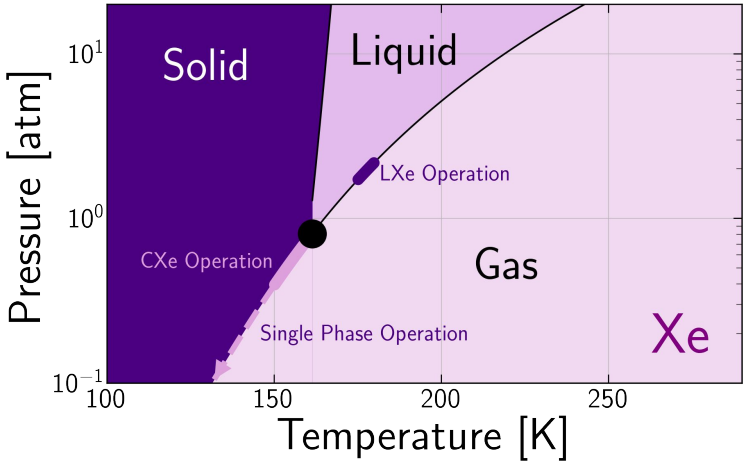




CrystaLiZe – Freezing Xe

Bridgeman method for CXe growth [arXiv:2312.15082]

- ~1.2 K/cm temperature gradient across system
- Slow descent along the phase boundary from triple point



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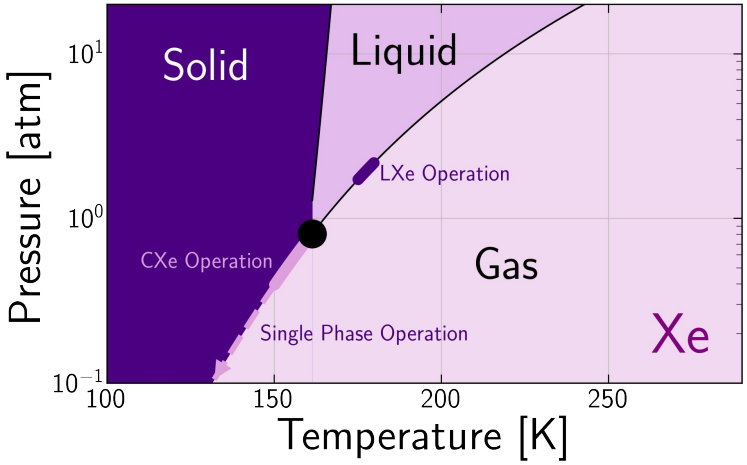
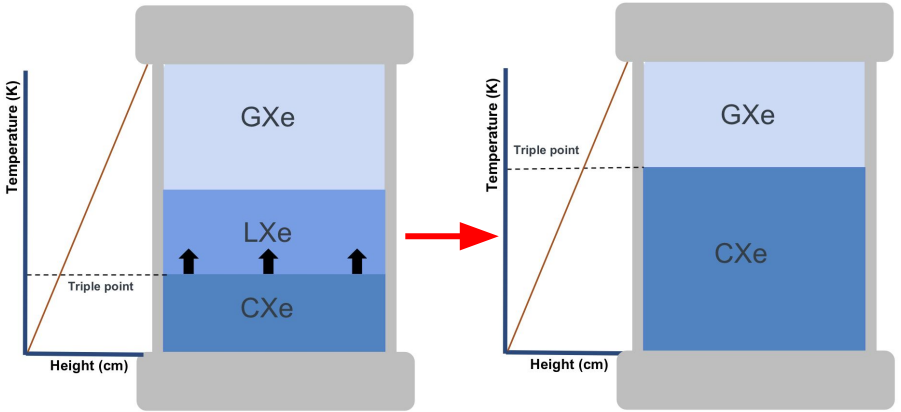
Aim: freeze quickly and maintain high VUV transparency

- Low gradient – promotes radial growth → bad crystal
- High gradient – uniform upward growth → good crystal





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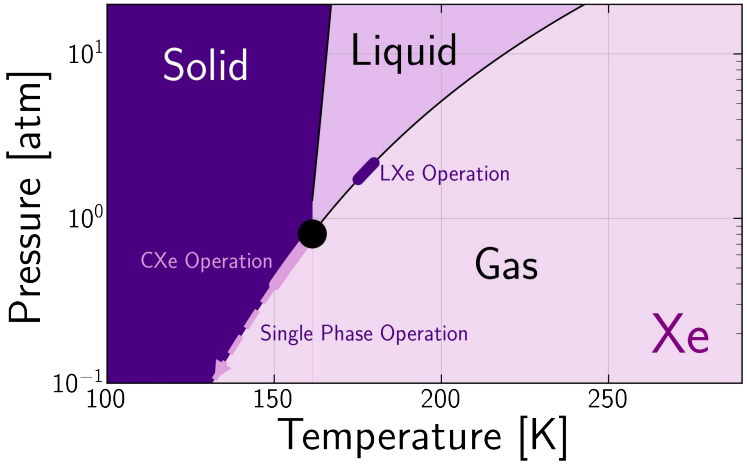
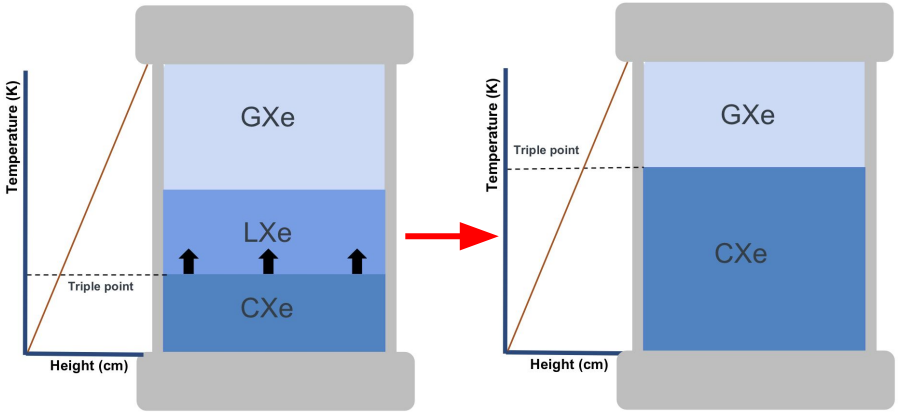
- Low gradient – promotes radial growth → bad crystal
- High gradient – uniform upward growth → good crystal

Two heaters to control the gradient with PID

- Large cooling rate at start → slow down at end to avoid freezing opaquely





CrystaLiZe – Freezing Xe

Bridgeman method for CXe growth [arXiv:2312.15082]

- ~1.2 K/cm temperature gradient across system
- Slow descent along the phase boundary from triple point

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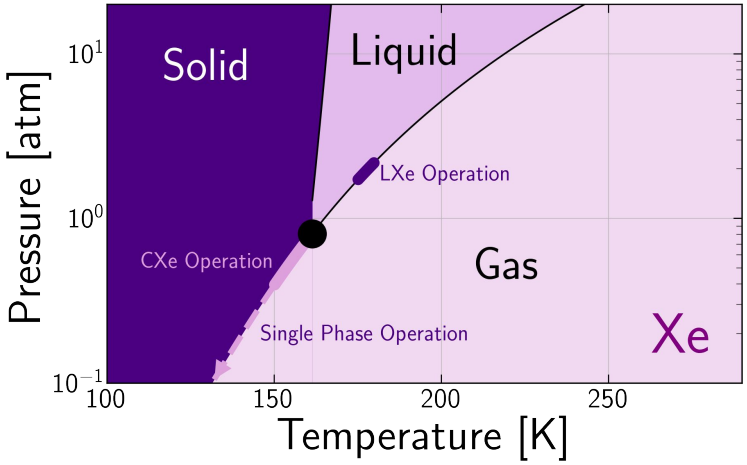
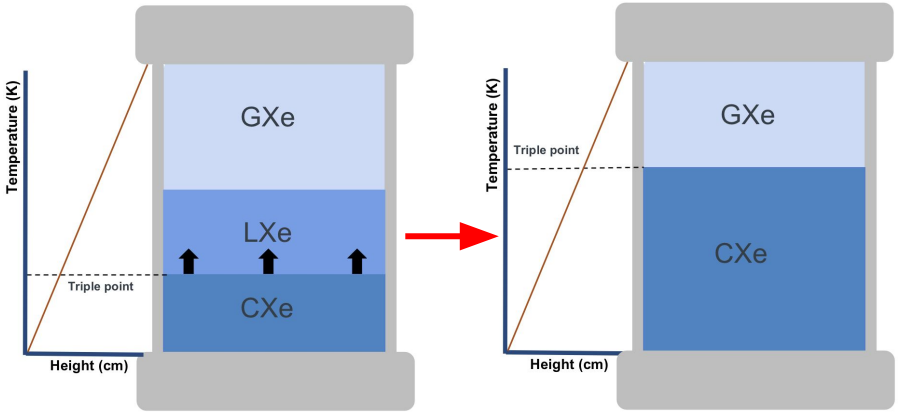
Time to freeze (TTF) reduced from > 1 week → 18 hours

- Ongoing investigations with various Xe masses on TTF
- Current projection to freeze LZ in O(month)

YouTube Watch Xe freeze in CrystaLiZe!





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Me & the smallest vessel :)

Summary

Electron counting

- 1D ResNet CNN successfully discretely counts e^-'s
  - Unbiased & improved resolution
- Cut in reconstructed N_e space reduces S2-only analysis threshold excess by 25%
- Enables a future LZ S2-only search for light DM
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CrystaLiZe

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  - 20x reduction required to hit neutrino fog
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Discrete electron counting and CXe R&D contribute to the improvement in direct dark matter experiments sensitivities, through extracting more information from the data we have, to developing new detector techniques for the future!

Post LTA

- Returning to Liverpool within the next month
- Finalise Outer Detector studies (spatial neutron veto → implementation to analysis framework)
- Lead the S2-only analysis in the 1 to $5e^-$ regime (< GeV/c^2) for dark photons, ALPs, solar reflected and halo DM

UNIVERSITY OF LIVERPOOL

THANK YOU