Impact of microphysics and simulations

Eric Dahl
Northwestern University / Fermilab

Next-gen 0nbb in Xe Workshop
Nov 13, 2025, Montreal

detector physics
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Outline / Questions for Discussion

- **Question:**
  What aspects of Detector Physics could/should we understand/simulate better than we do now?
  - Is there a model? Do we think we understand the underlying physics?
  - Is there sufficient data to constrain the model?
  - Is there a payoff? Is there value added over existing data-driven approaches?

- **Three case studies:**
  - Signal production (*i.e.* recombination)
  - Fluid dynamics (to mix or not to mix)
  - Light/charge emission from grids (confronting accidentals)

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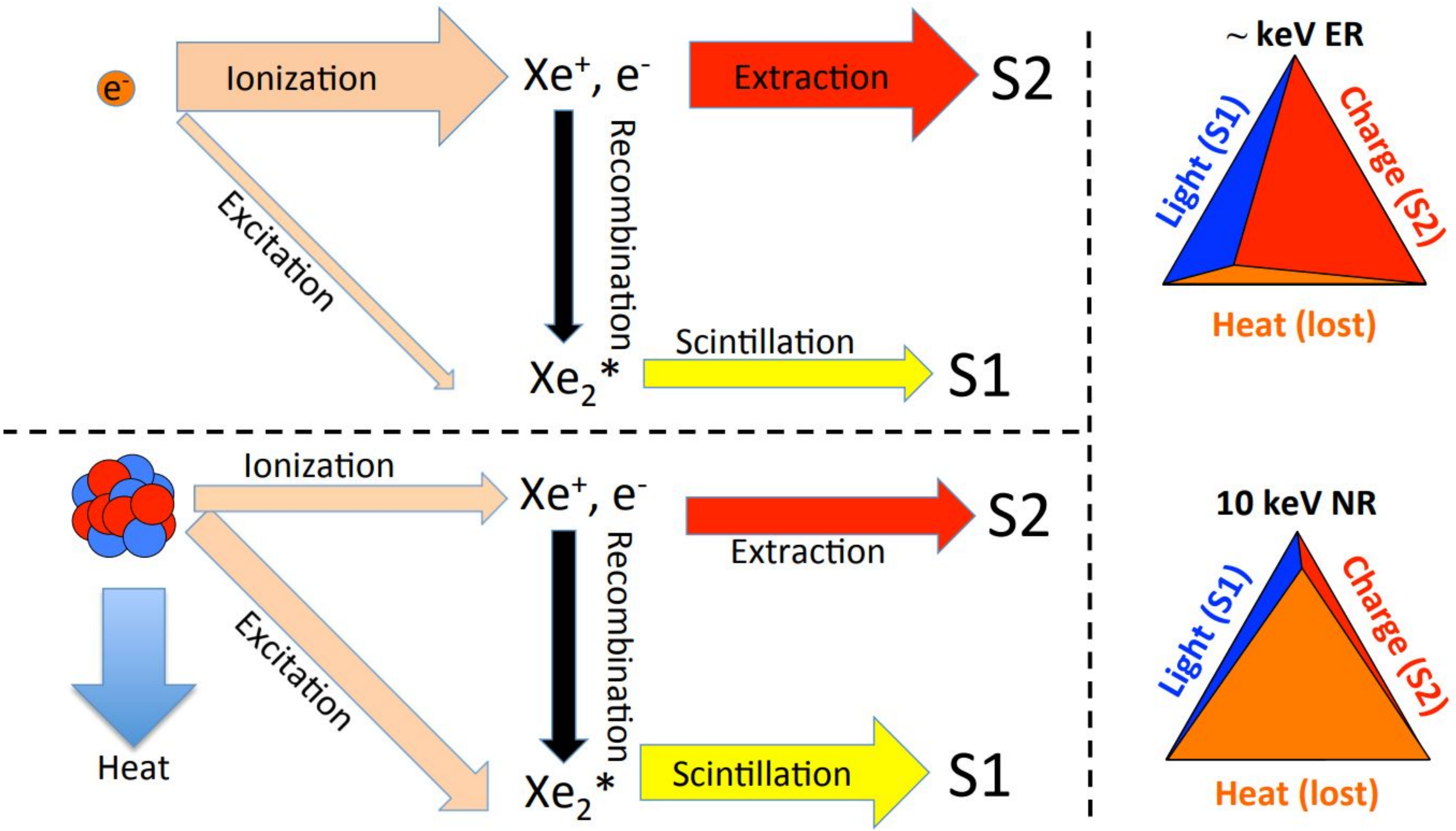
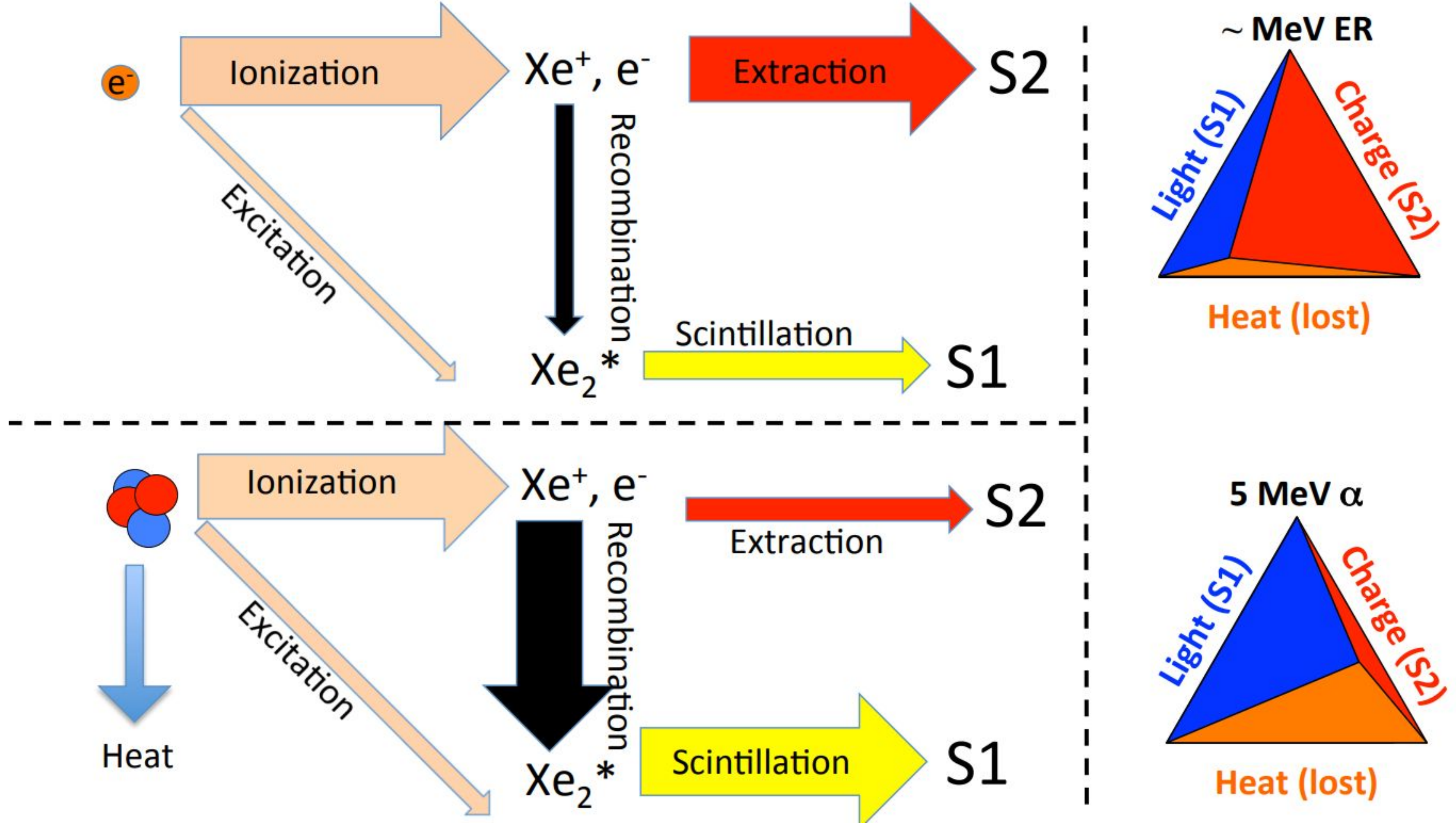
See also (from last night's blue-sky session):
- MS-reconstruction in dual-phase
- Topo-discrimination in gas-phase

Case Study 1: Recombination

Signal Production in LXe



Signal Production in LXe



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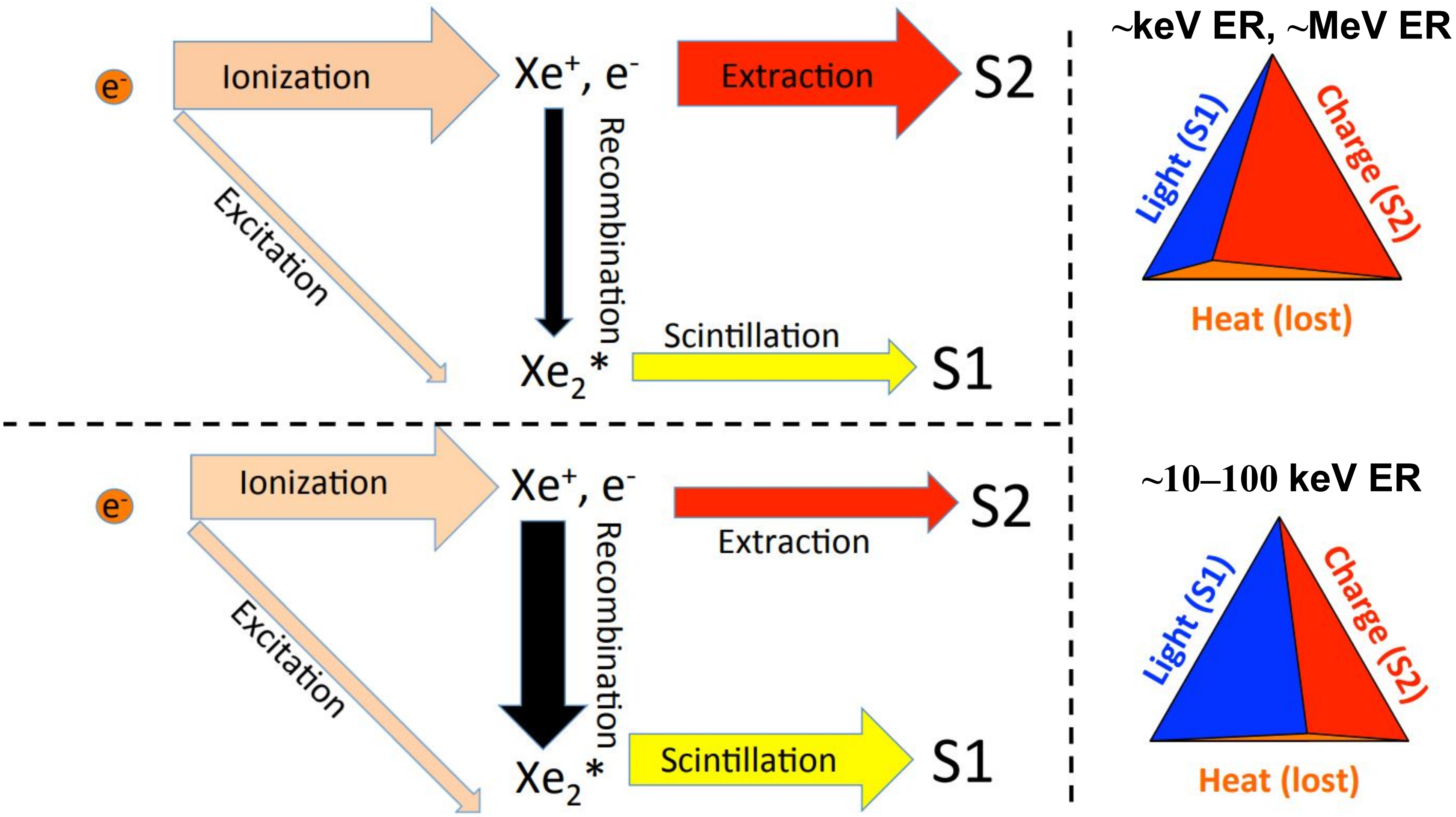
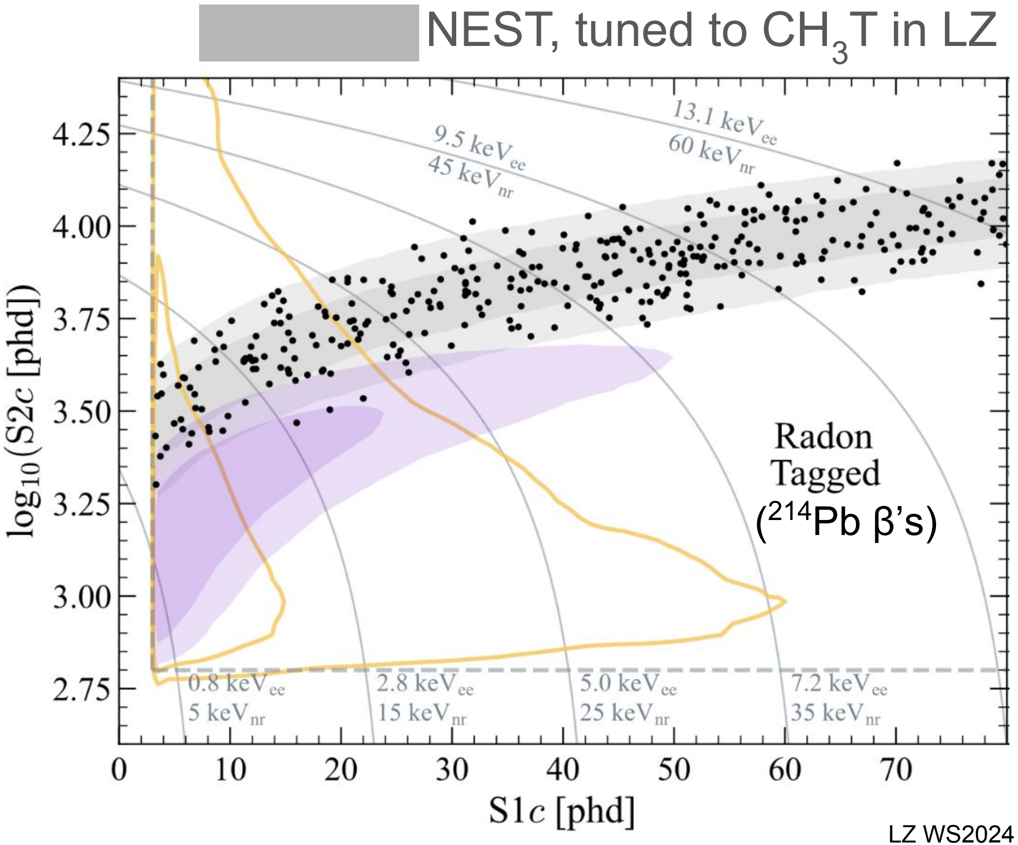


“Typical” approach to signal production simulations

- Tune NEST* to match in-situ calibration data

*Noble Element Simulation Technique [arXiv: 2211.10726]

An empirical simulation tool with many physics-inspired knobs.



LZ WS2024
Phys. Rev. Lett. 135, 011802 (2025)

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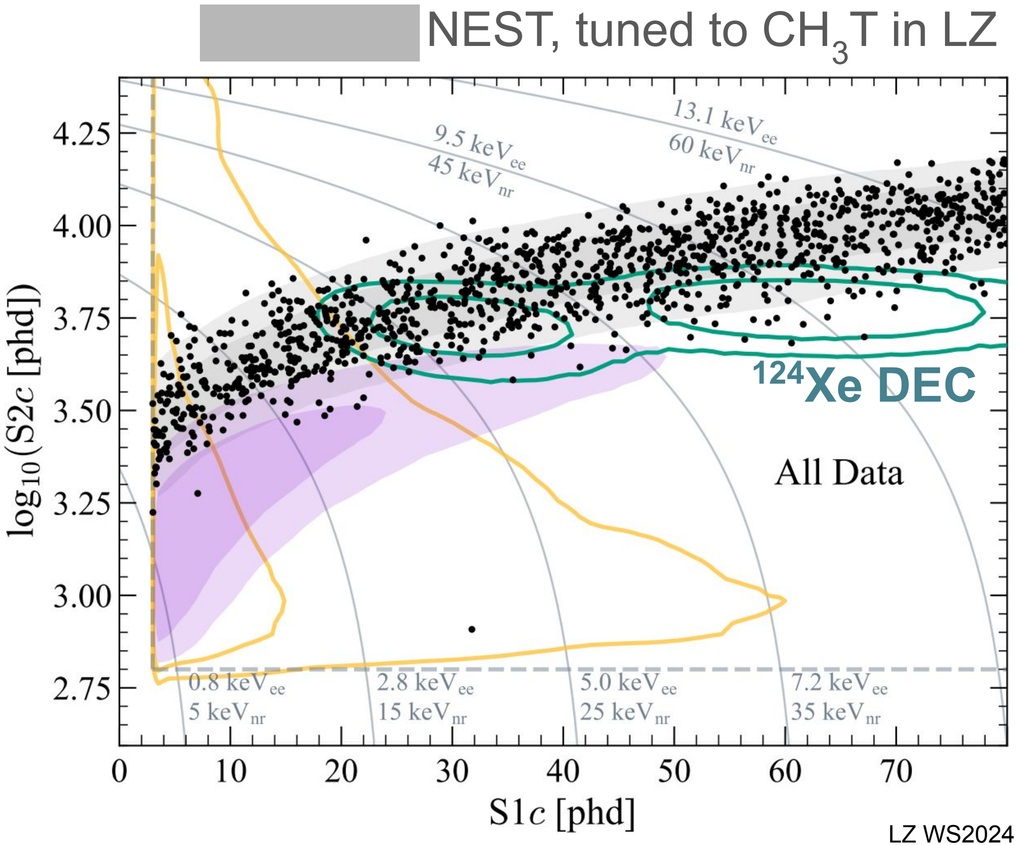

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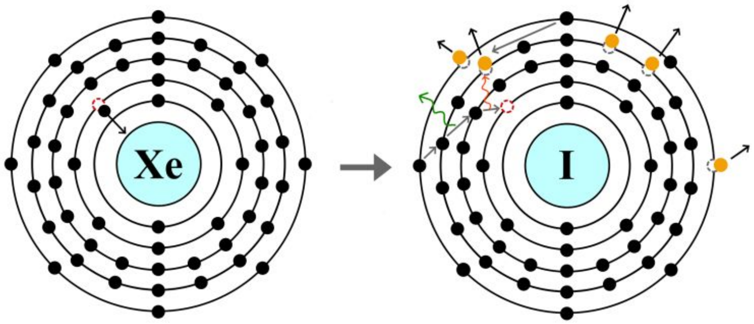
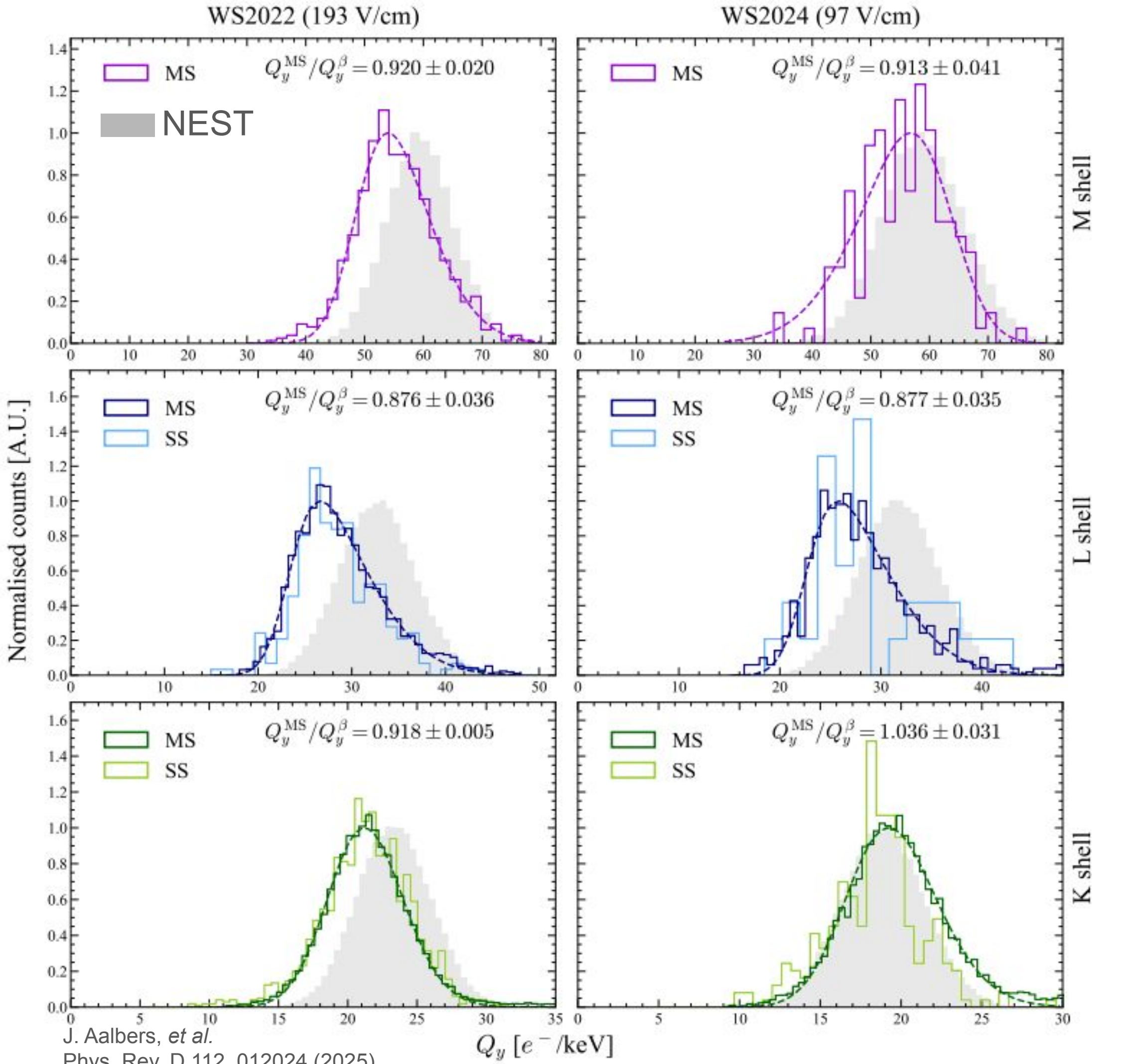
Single-EC events in LZ



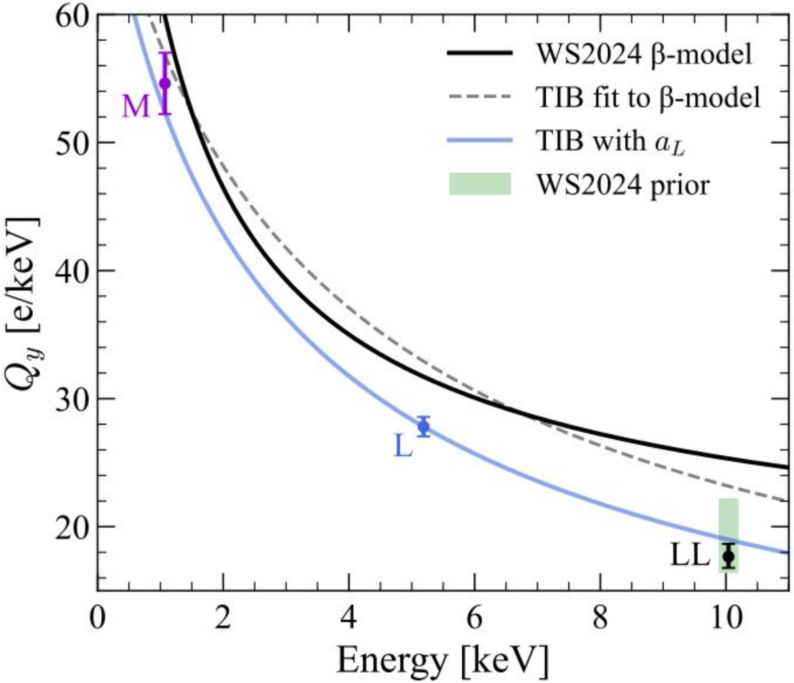
- ^{127}Xe and ^{125}Xe decays
  - Tagged by associated gammas
  - Energy deposition at decay site from atomic relaxation only



J. Aalbers, *et al.*
Phys. Rev. D 112, 012024 (2025)

The seed of a new recombination model?

Creative application of Thomas-Imel Box model



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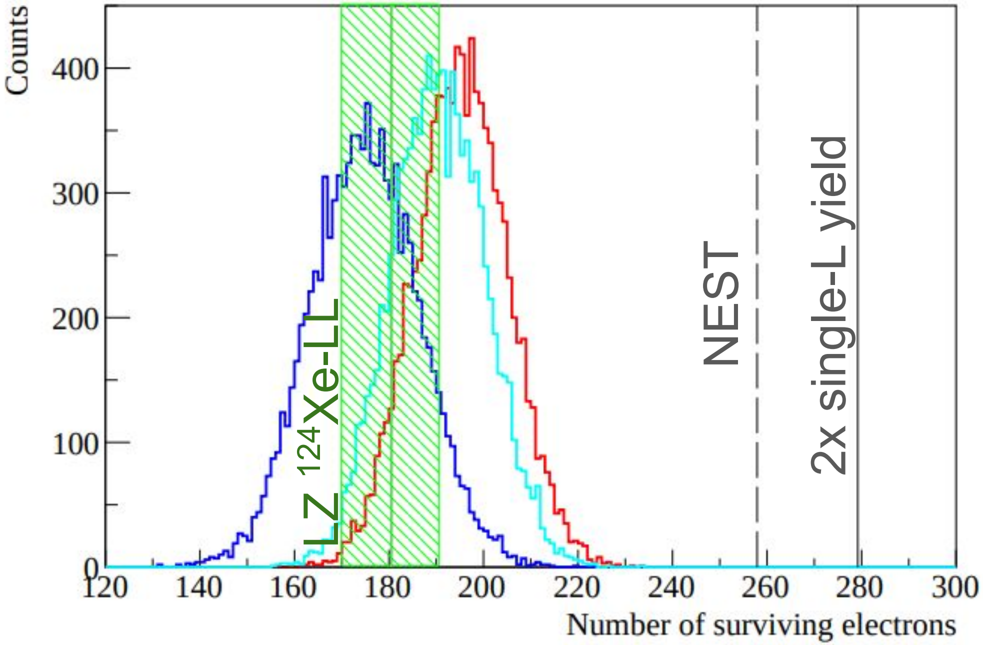
Composite track model, overlaying 2x L-shell captures



J. Xu, *et al.*
Phys. Rev. D 112, 012014 (2025)

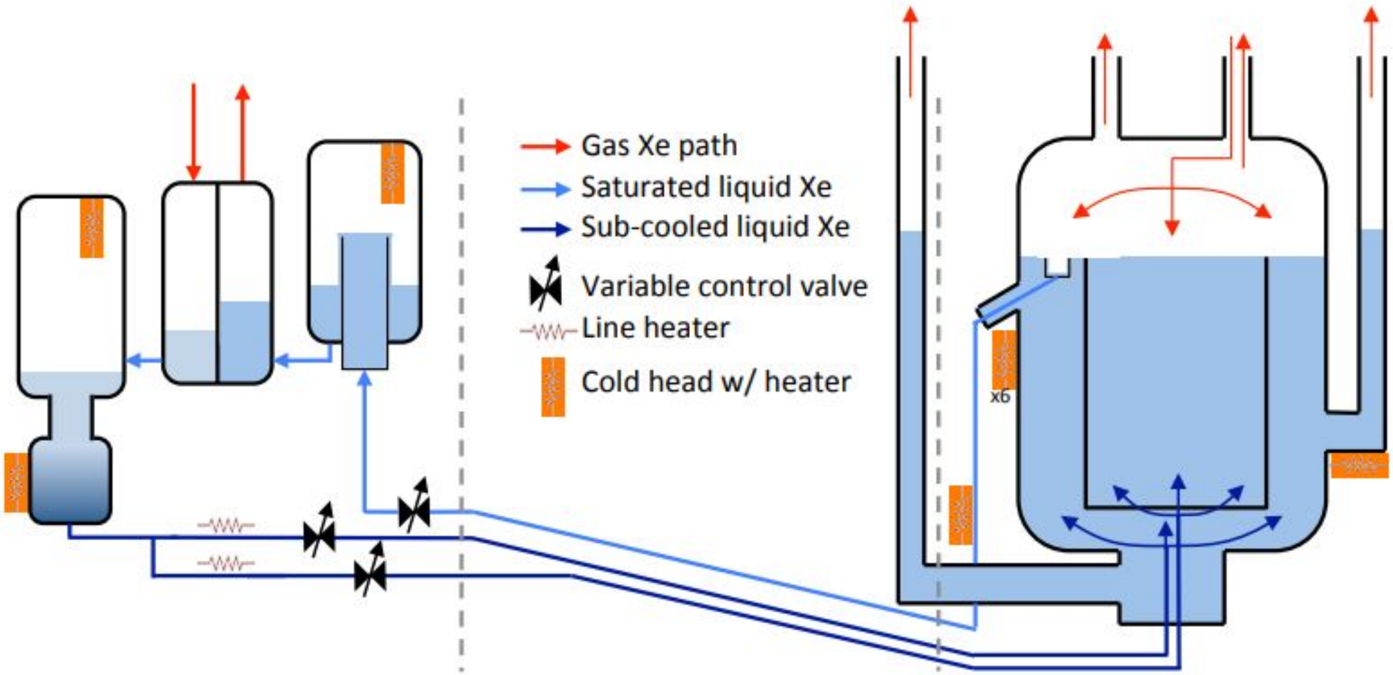
Recombination modeling – outlook

- Low-energy ER data may now be rich enough to constrain bottom-up recombination model
- Dream: combine with detailed ER-track sims to predict effects we cannot yet calibrate
  - Tails of recombination distributions
  - Recombination in rare events

- Impact (my opinion)
  - Internal view: not game changing
    - Always hard to trust models beyond reach of calibration data…
  - External view: builds confidence that we understand our detectors
    - Important if/when we report a discovery

Case Study 2: Mixing

Fluid flow in the TPC: Does it mix?

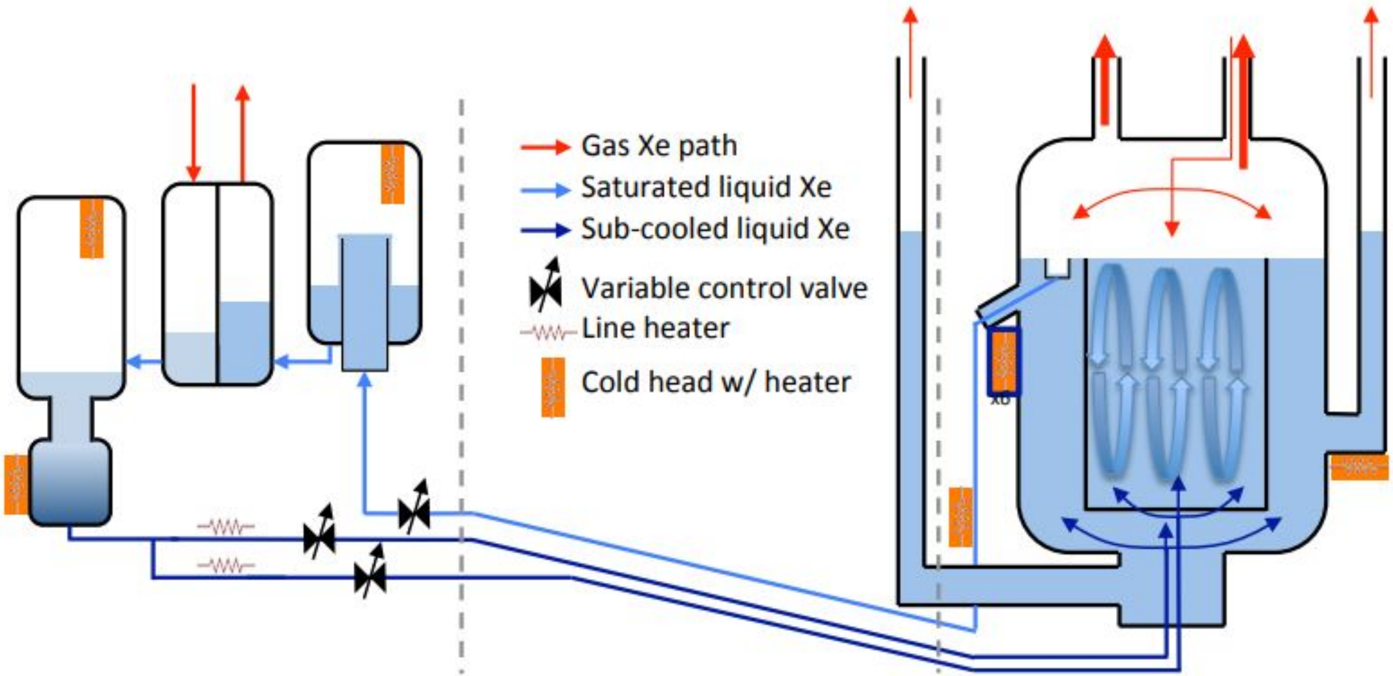


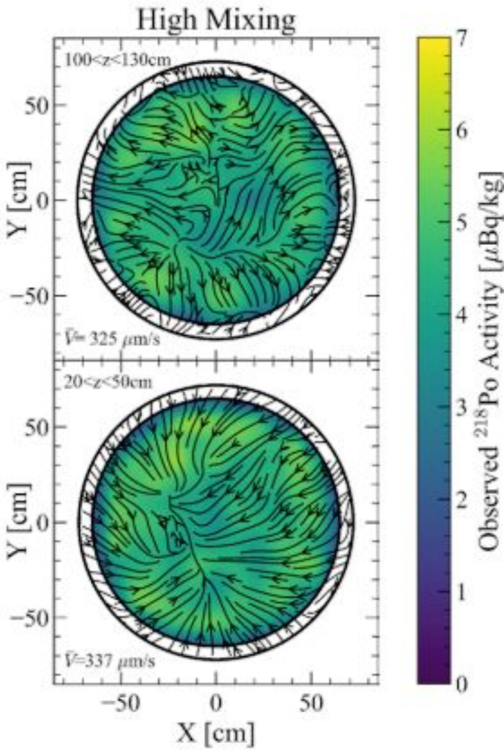
Predictions during LZ construction (a dramatic selection, colored by memory):

- Engineers:
  "It will never mix."
- Physicists:
  "It will definitely mix."
- Project Office:
  "Doesn't matter, just build it."

Fluid flow in the TPC: Does it mix?

J. Aalbers, et al
[arXiv:2508.19117]





Cool at sides and top to drive convection – essential for distributing internal sources

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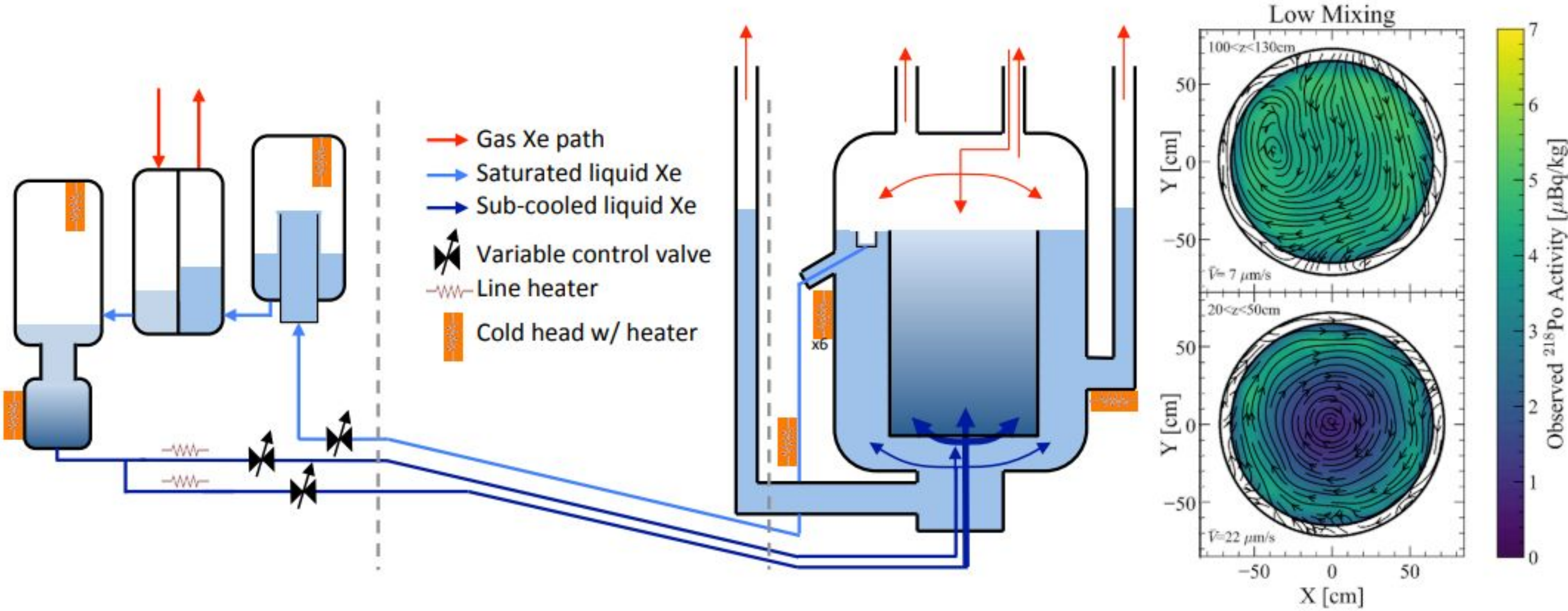
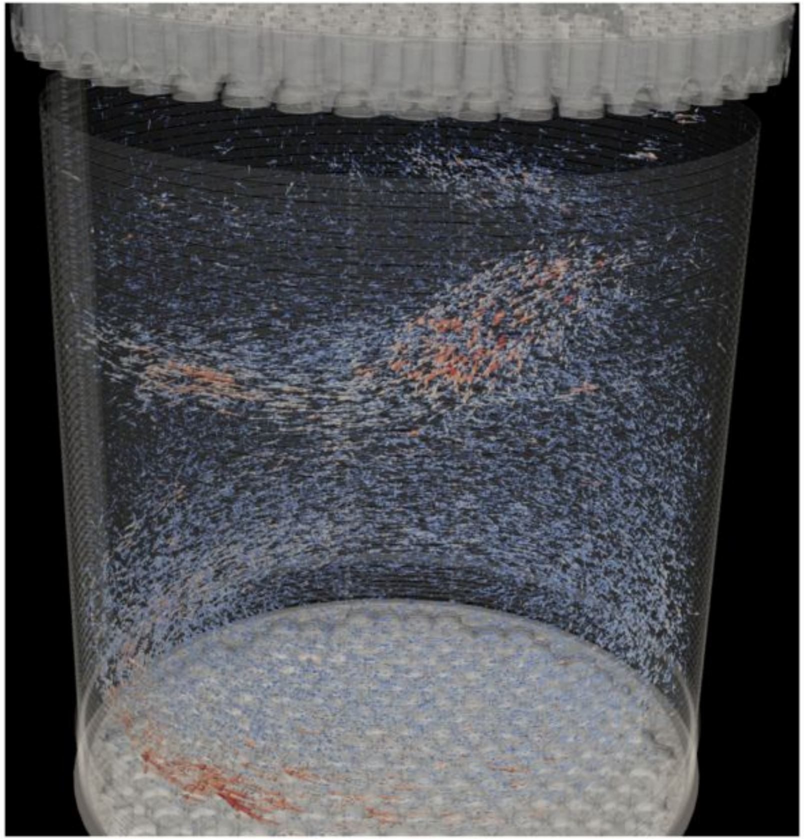


Inject sub-cooled xenon at bottom for slow, stratified xenon – allows tracking of individual atoms over hours

Fluid flow – outlook

- We have detailed measurements of mixed and unmixed flow
  - Assertion: Enough to constrain a robust computational fluid dynamics model
- We have found both states (and the ability to switch between them) to be exceedingly useful
- This capability should be explicitly designed into future detectors



Each arrow = one neutral ^{222}Rn – ^{218}Po pair

Case Study 3: Grid Emission

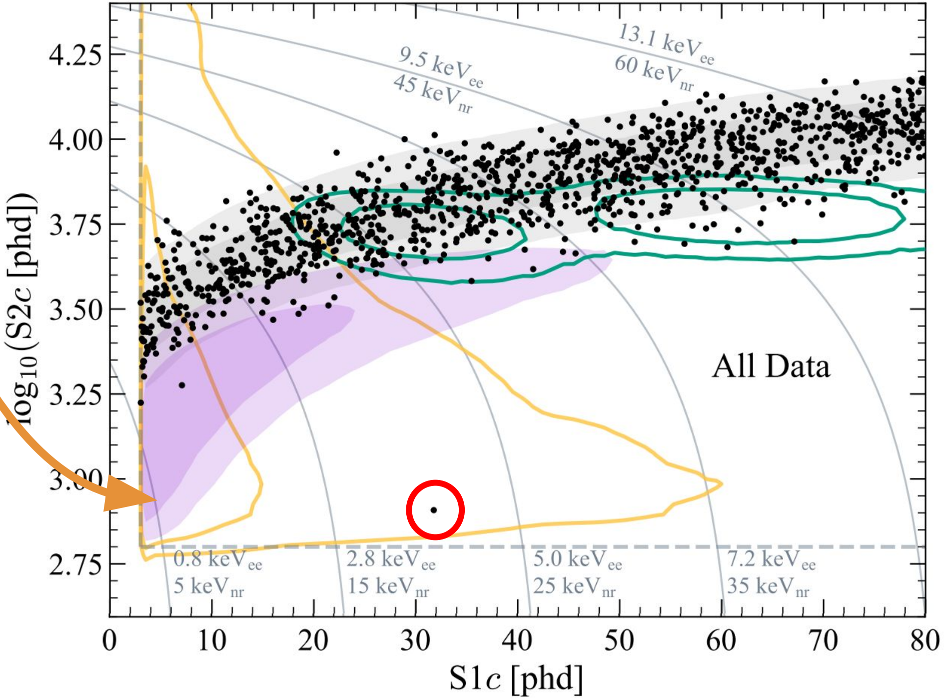
Light and Charge emission from grids

LZ WS2024
Phys. Rev. Lett. 135, 011802 (2025)

- Lone S1s and S2s combine to fake low-energy single-scatter events

- A non-issue at 0nbb energies…

- …but a major background for dark matter



Current (data-driven) approach: Constrain bkg rate using events with unphysical drift times (drift distance > TPC height)

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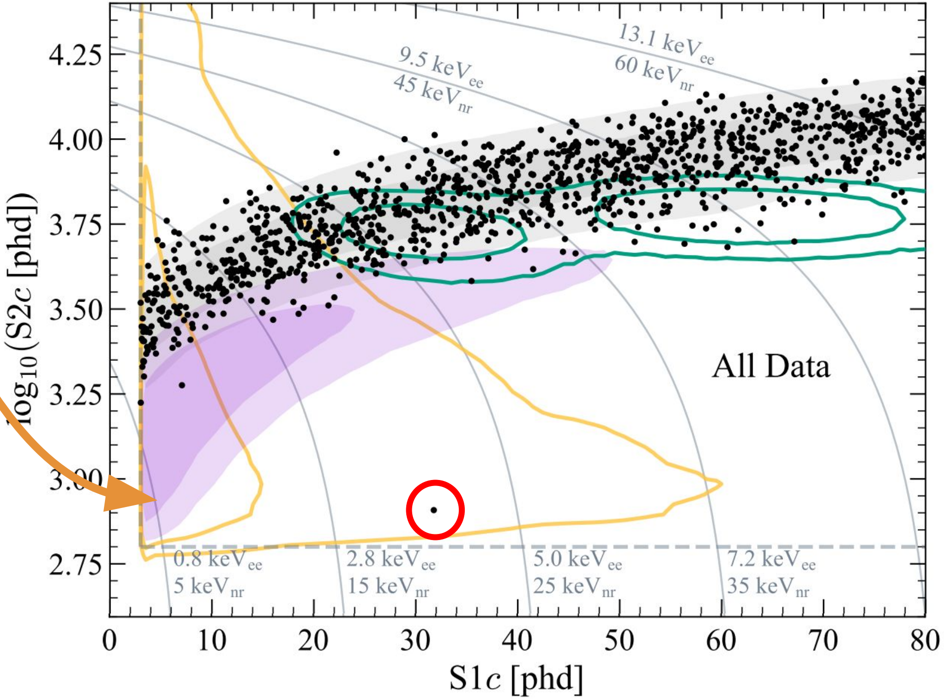
- …but **the** major background for next-gen dark matter



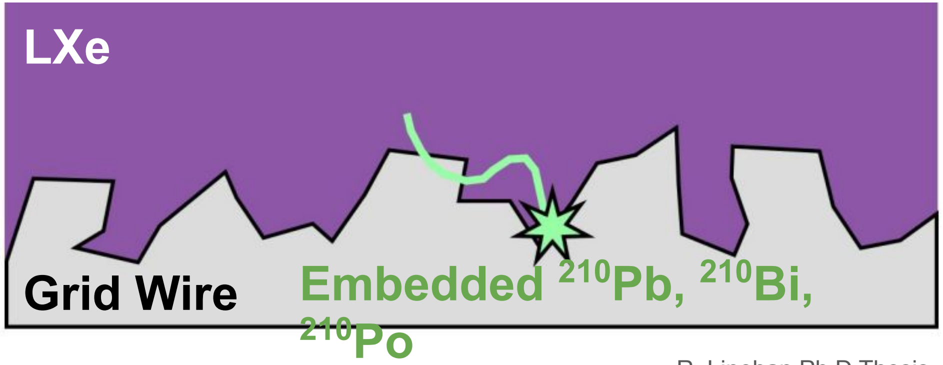
Current (data-driven) approach: Constrain bkg rate using events with unphysical drift times (drift distance > TPC height)

One known source of grid emission: ^{210}Pb-chain decays

- ^{222}Rn daughter plateout over wire lifetime -> embedded ^{210}Pb ($t_{1/2}$ = 22.2 years)

- Strong field, S1 shadowing both boost S2/S1 —
  Source of lone S2 pulses!

- Model needs to consider
  - Embedding depth
  - Surface roughness
  - Signal production at high field
  - Electron drift near wire
  - Complicated light collection



R. Linehan Ph.D Thesis
Stanford, 2022

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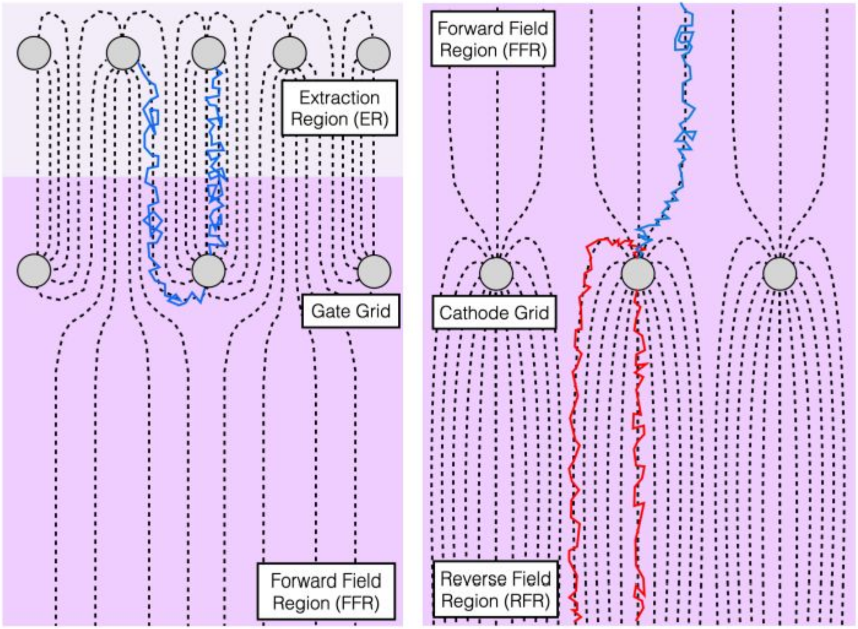

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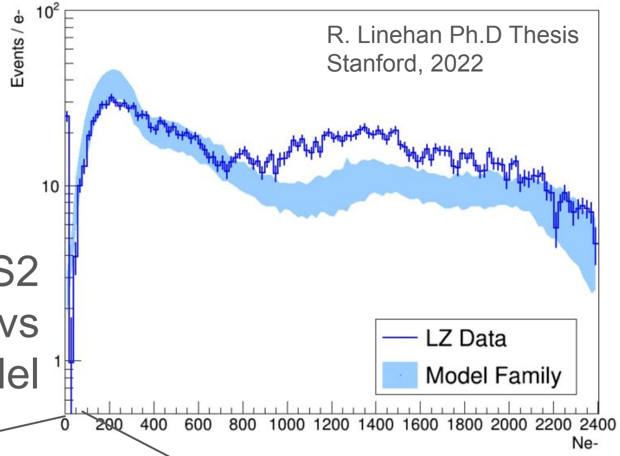
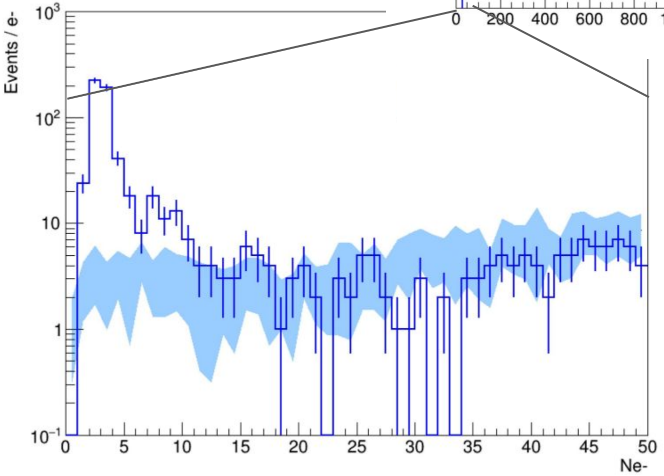
Gate-grid S1+S2 event spectrum vs model





(Model normalization anchored by ^{210}Po alpha rate)

Grid emission – outlook

- Far from having the full story here
  - Modeling lone-S2s > ~10 e^- looks promising
  - S1s and few-electron S2s need their own model…
- This model already has implications for grid production in XLZD
- Grids were critical path for LZ, and will likely be most challenging element of XLZD

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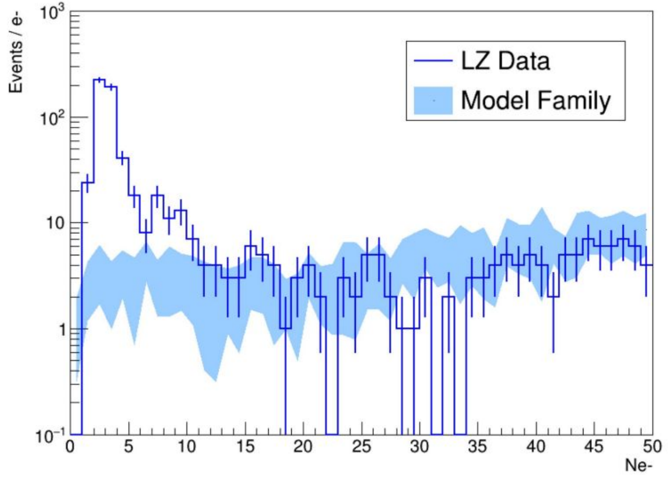

Discussion:

What aspects of Detector Physics could/should we understand / simulate better than we do now?

	Do we have a model?	Is there data to constrain model?	How useful would the model be?
ER track recombination	✅	✅	?
LXe TPC flow	✅	✅	✅
Lone S1s, S2s	✘, ?	✅	✅
…	…	…	…

Opinions may (should) vary…