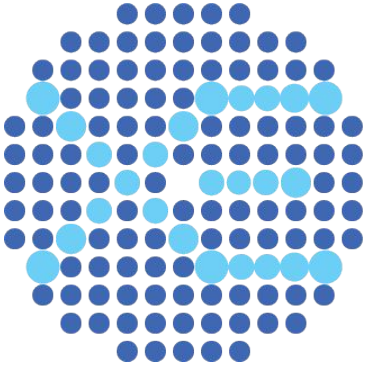
TESTING THE RESILIENCY OF XENONnT BACKGROUND REDUCTION TECHNIQUES

Taylor Brown | XENON Experiment

2024 NSF REU at Columbia University's Nevis Laboratories



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Acknowledgements

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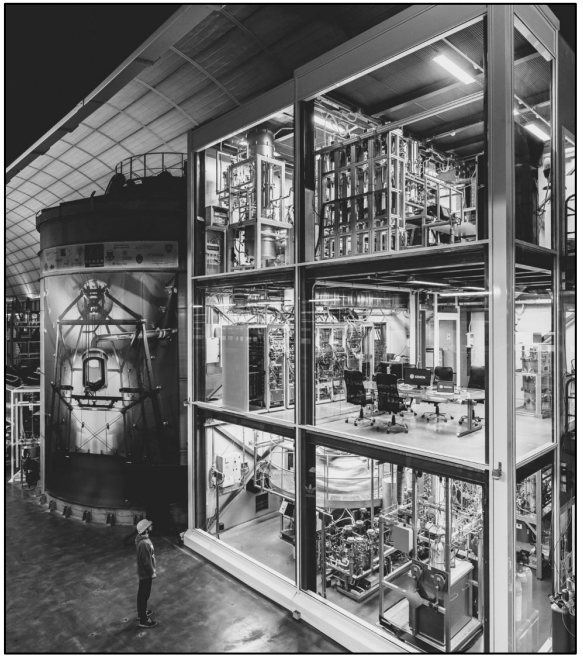
XENONnT: A Direct Search for Dark Matter

- Weakly Interacting Massive Particles (WIMPs)
- Dual-phase Time Projection Chamber (TPC) filled with liquid xenon
- Rare signal search for WIMP interactions



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(simplified) Overview of Data Analysis Process

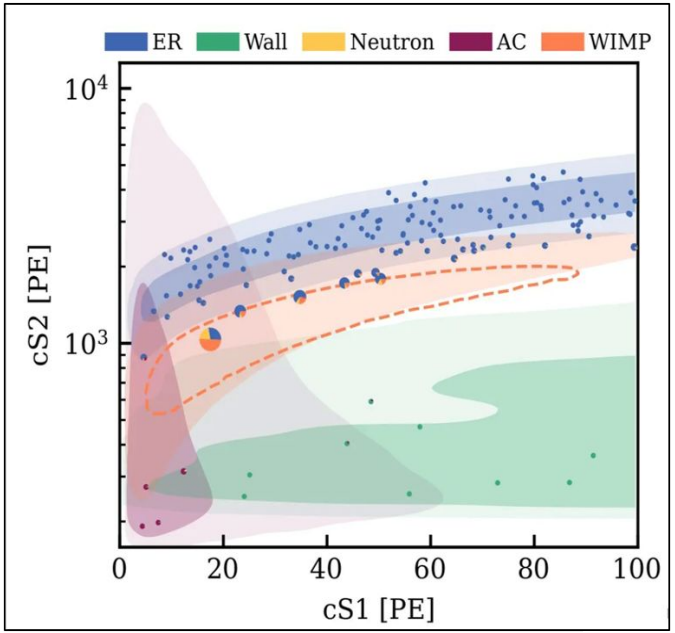
1. Emission and reconstruction models
2. Fit to calibration data to constrain parameters
3. Determine regions of interest (ROIs)
4. Science Run
5. Reconstruct and plot science data
6. Unblind ROIs

5σ deviation excess = Dark Matter discovery!!

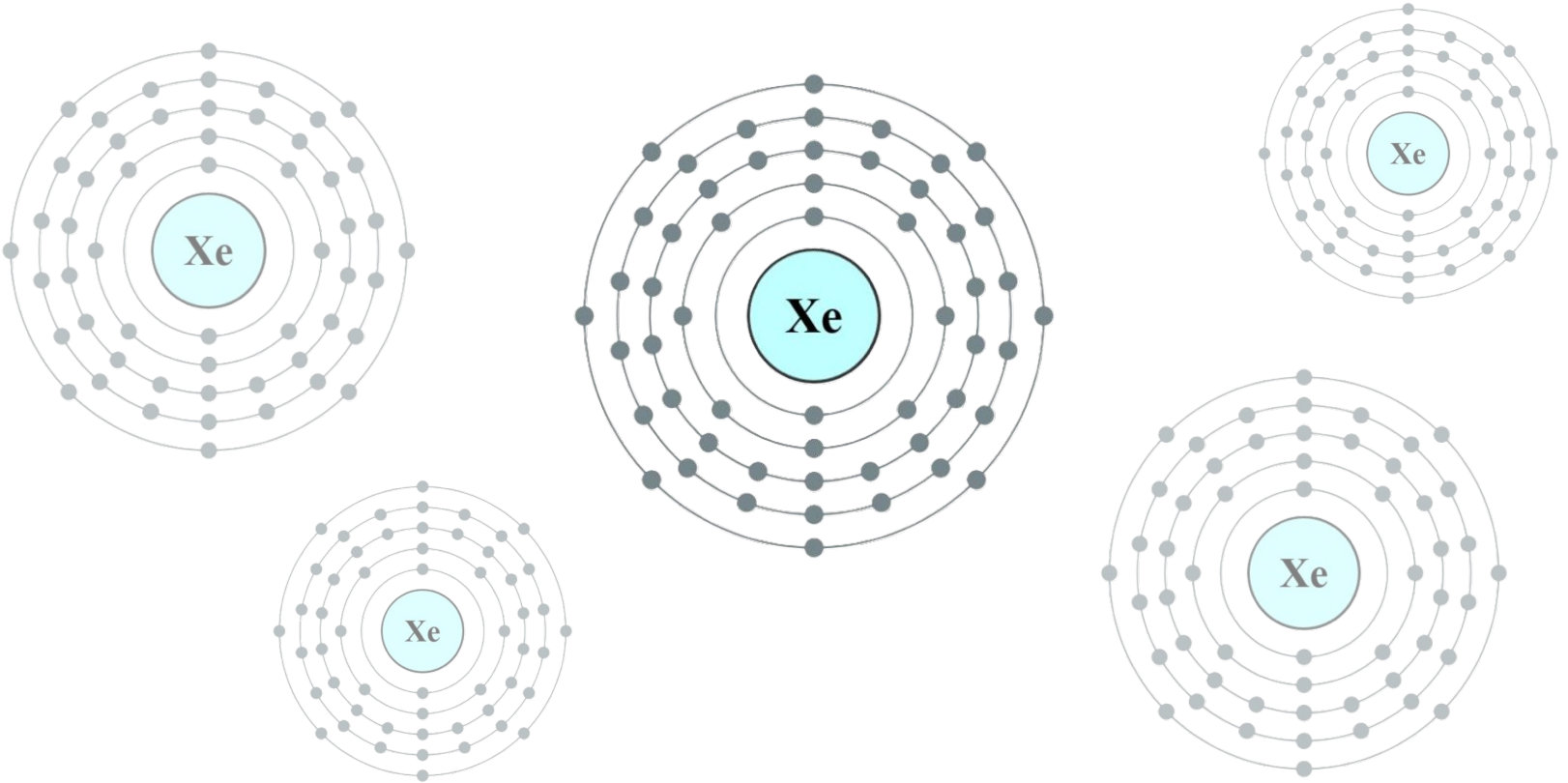
Event Signals

- Majority of XENONnT event signals fall into one of two categories:
  - Nuclear Recoils (NRs)
  - Electronic Recoils (ERs)
- ERs dominate background

Distinguishing between ER and NR signals and determining their regions in the parameter space is critical!!



A Glimpse into the TPC



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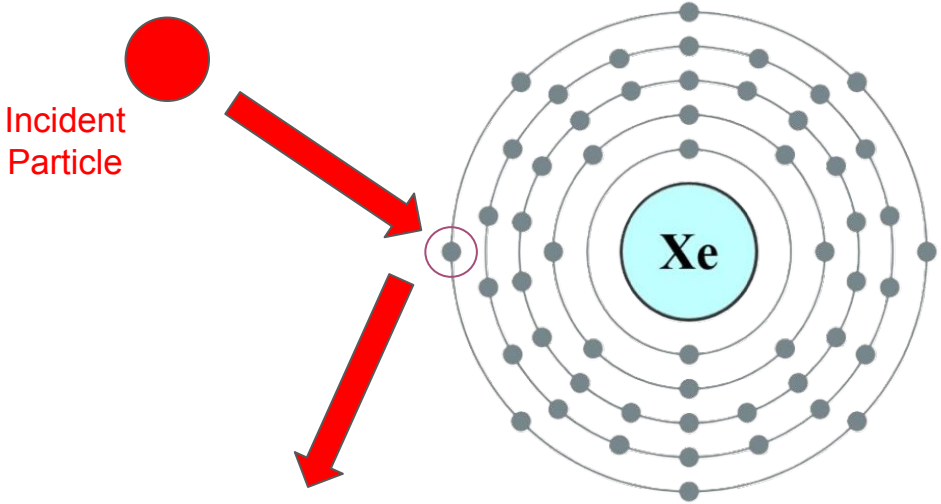

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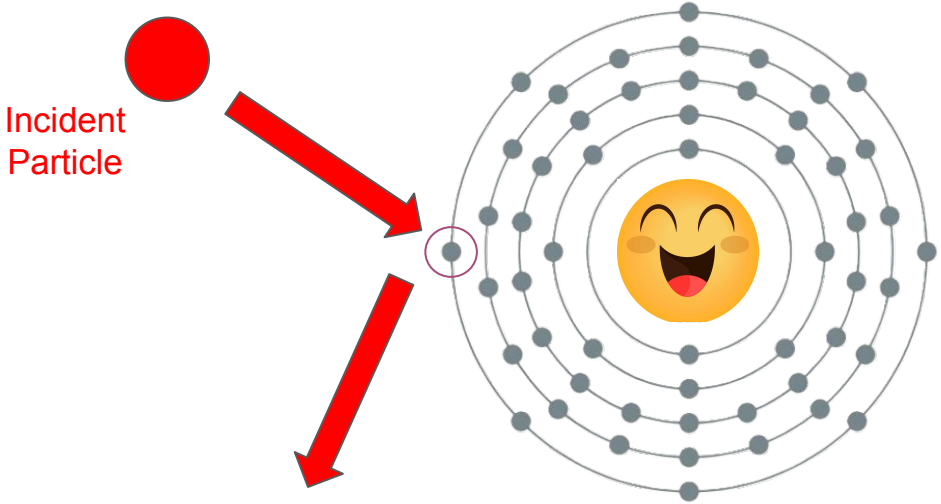

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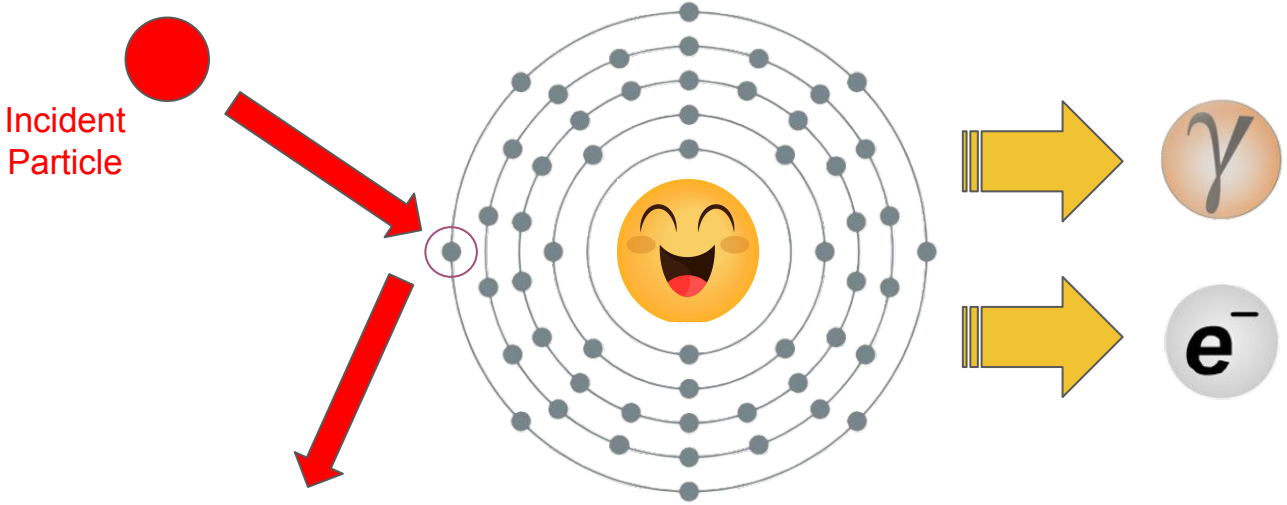

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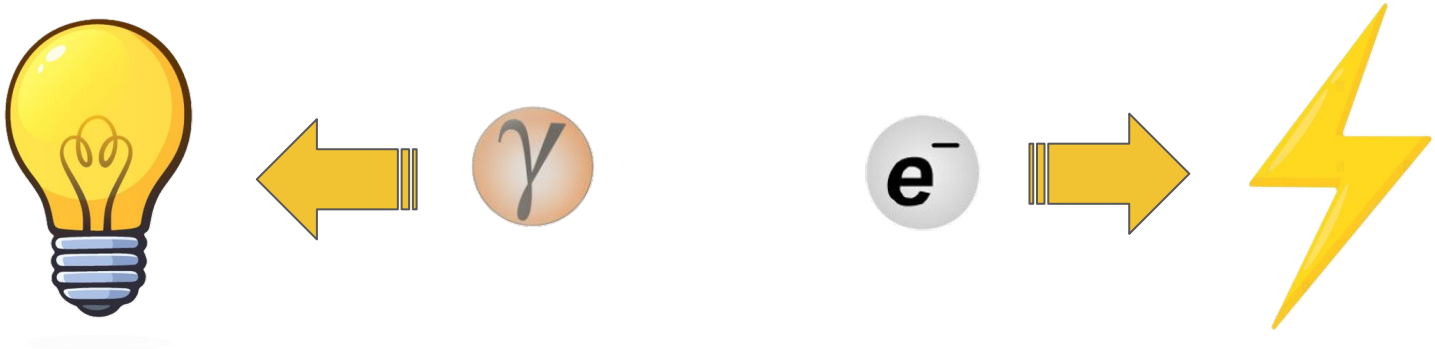
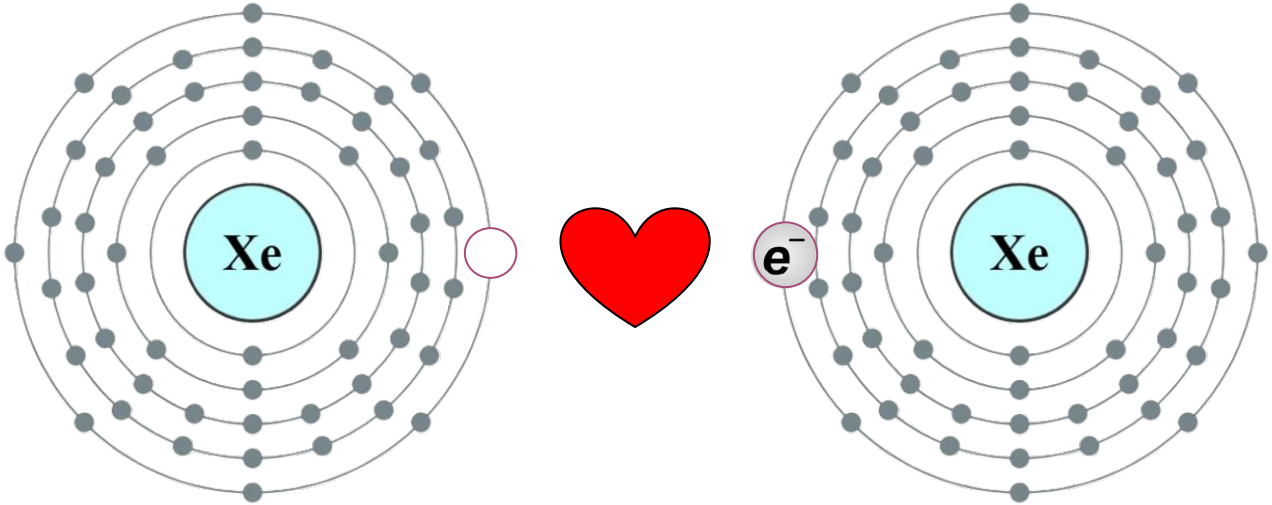


S1
(Scintillation
Signal)

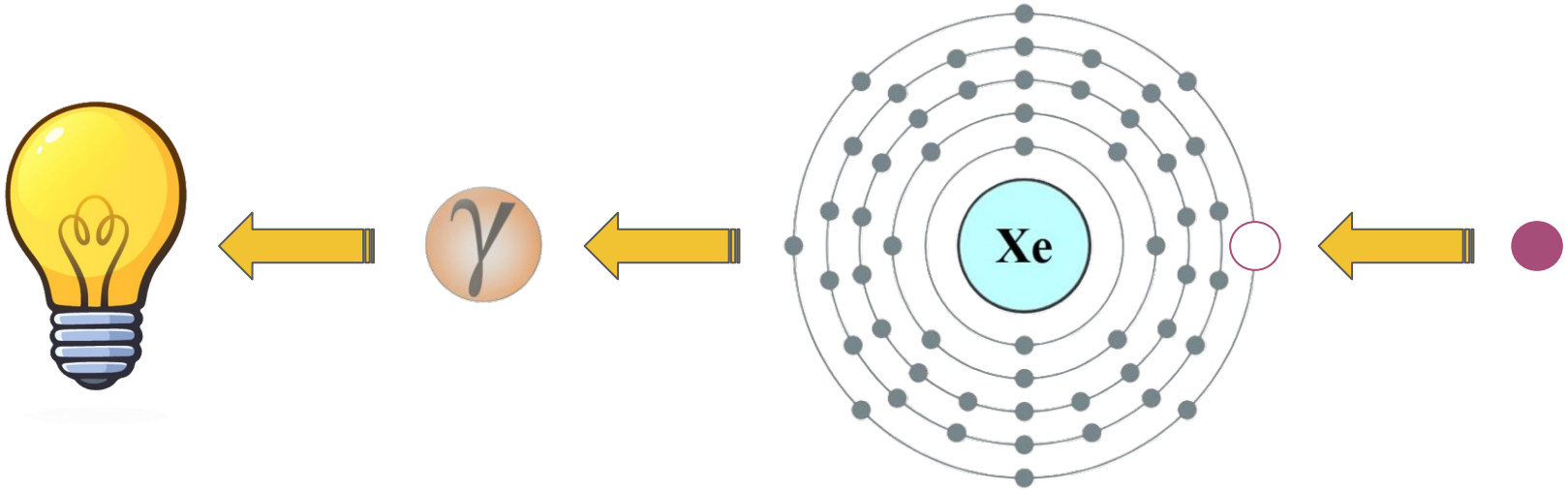
S2
(Ionization
Signal)

A Glimpse into the TPC



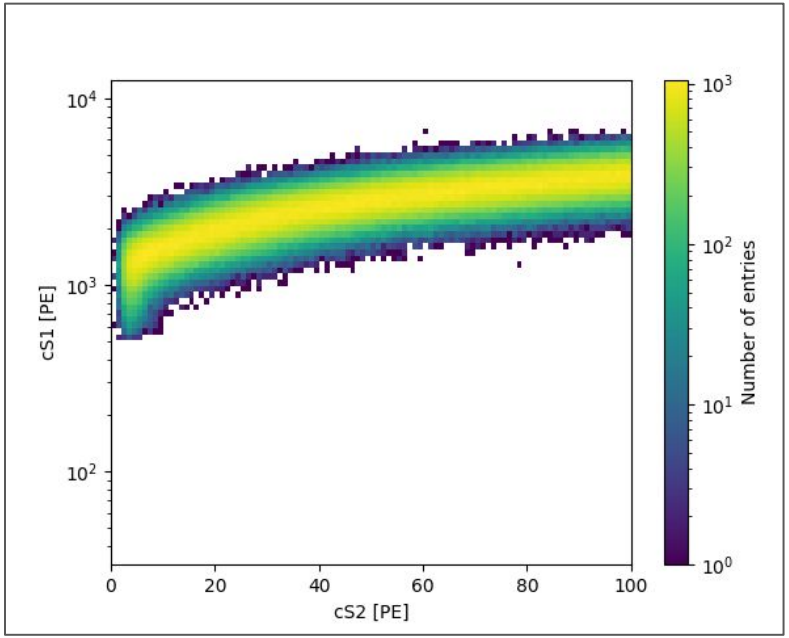
Excited Dimer
(Excimer)

A Glimpse into the TPC



Modeling ER Events in Liquid Xenon

- **Emission Model**
  - How do ER events occur within the TPC?
- **Reconstruction Model**
  - How are ER event signals reconstructed?
  - What biases/detector effects need to be accounted for?



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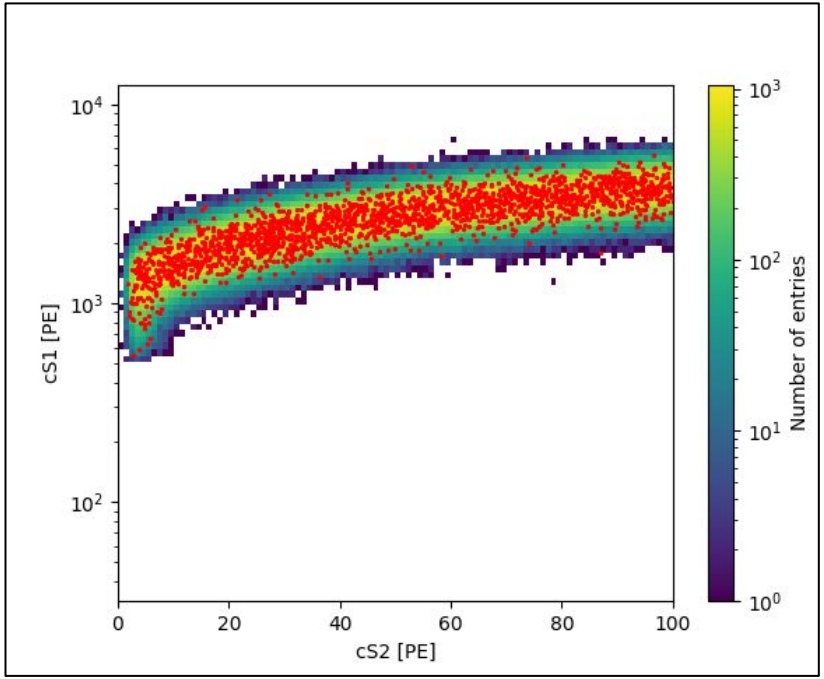
Visualizing ER Events in Liquid Xenon

- Models used to create ER simulation
- Sample ~ 2000 events from simulation to create toy data set
- **Fit to Calibration Data**
  - Constrain parameters by fitting to calibration data in the region of interest



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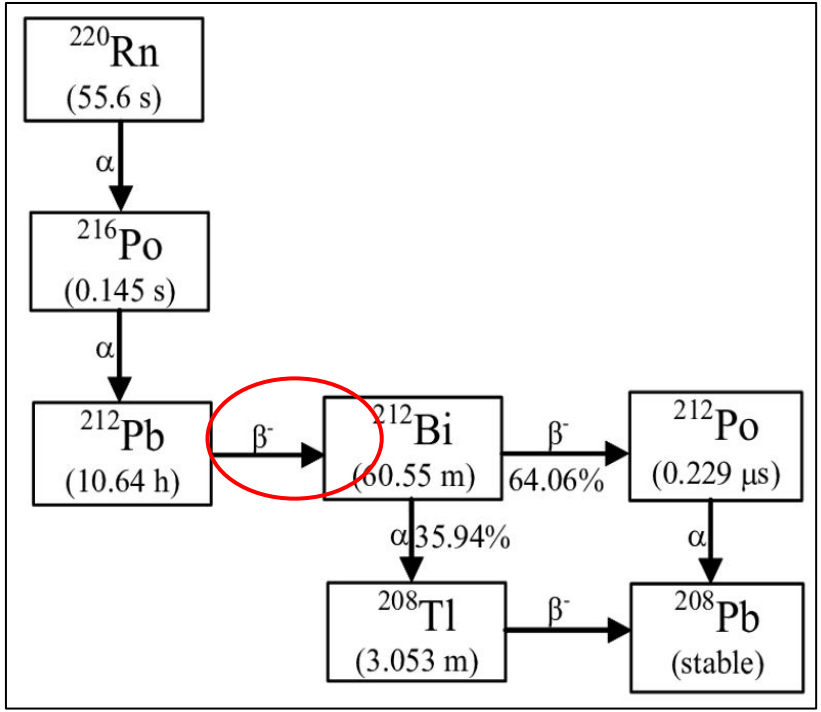
ER Calibration Data

- Rn220 dissolves into LXe
- Decays into Pb212
- Releases β-radiation
- β-radiation gives an ER energy spectrum in the WIMP region of interest
  - Below ~ 10 keV



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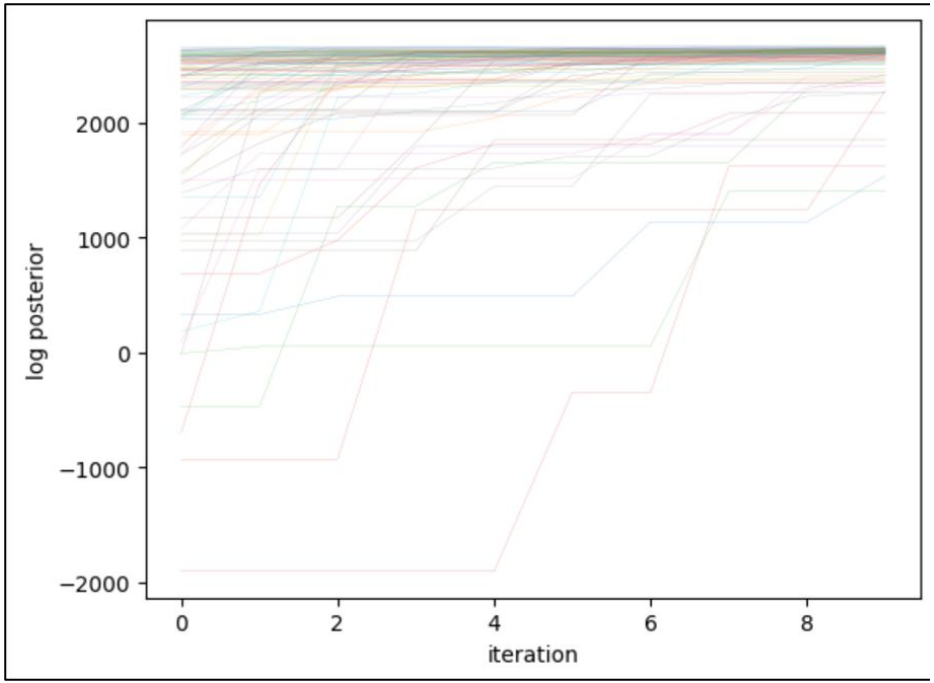
Fit to the Calibration Data

Fit to Calibration Data

- Constrain parameters by fitting to calibration data in the region of interest
- Markov Chain Monte Carlo (MCMC)
  - 100 walkers, 10 iterations
  - Attempting to match the posterior parameters
- GOF evaluation



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Goodness of Fit Evaluation

- Evaluating how well the ER model describes the calibration data
- Binned Poisson $\chi 2$ test
- P-value
  - Quantifies how well the model describes the calibration data
  - How sensitive is our measure of accuracy for our model to mis-modeling in the data?

How do the model and fit respond to imposter ER events in the calibration data?

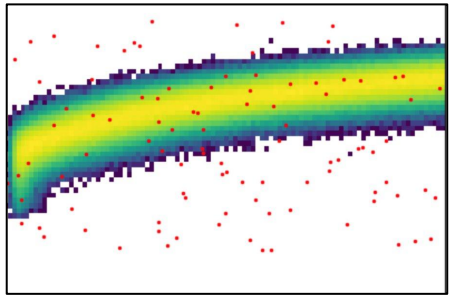
At what point can the ER model, MCMC, and Goodness of Fit (GOF) evaluations detect mis-modeling?

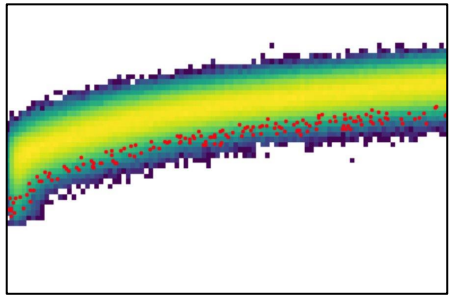
How does this change depending on the type and magnitude of the mis-modeling?

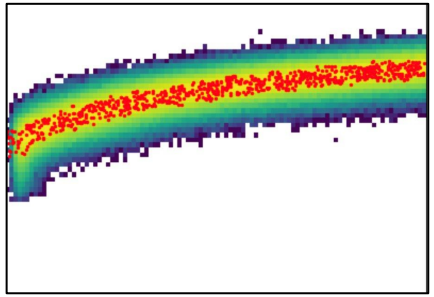
Potential Sources of Mis-modeling

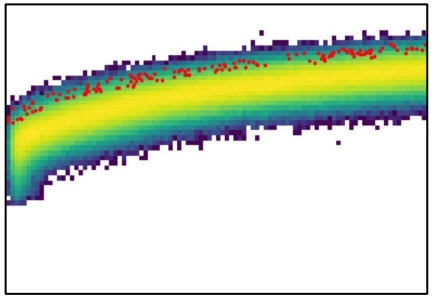
- Current rate, type, and magnitude of mis-modeling is unknown
- Potential sources may include:
  - Mistakenly paired S1 and S2 signals
  - Neutrons/muons that were not recognized by the veto tanks
  - Uncertainties in the reconstruction/emission models

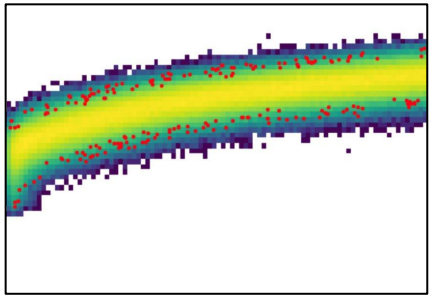
Types of Mis-modeling



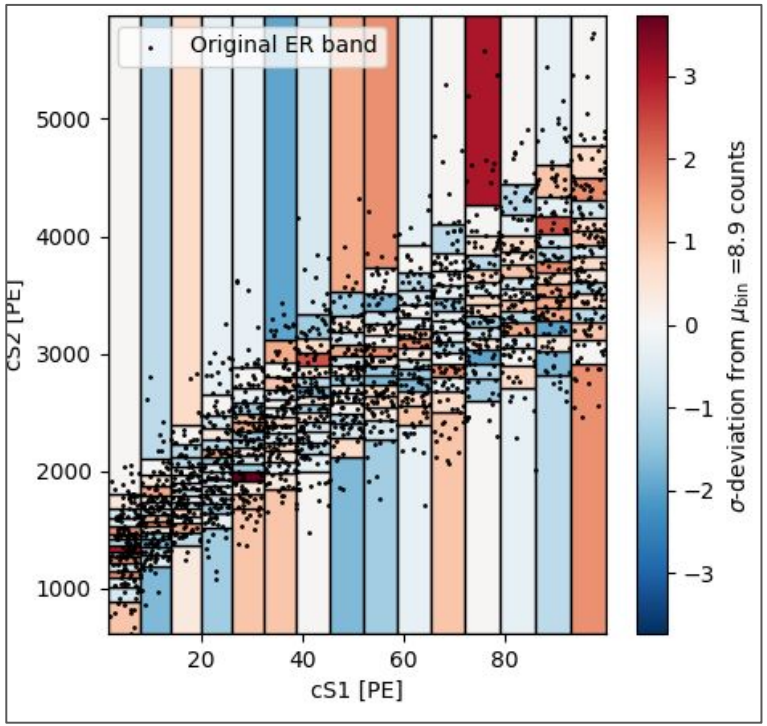




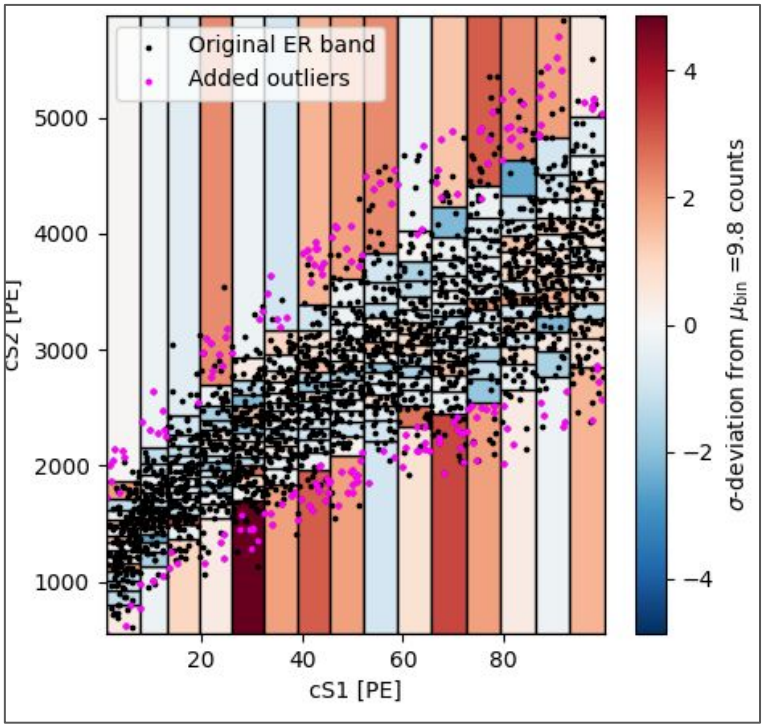




GOF Evaluation With Imposter Events



P-value = 0.597



P-value = 0

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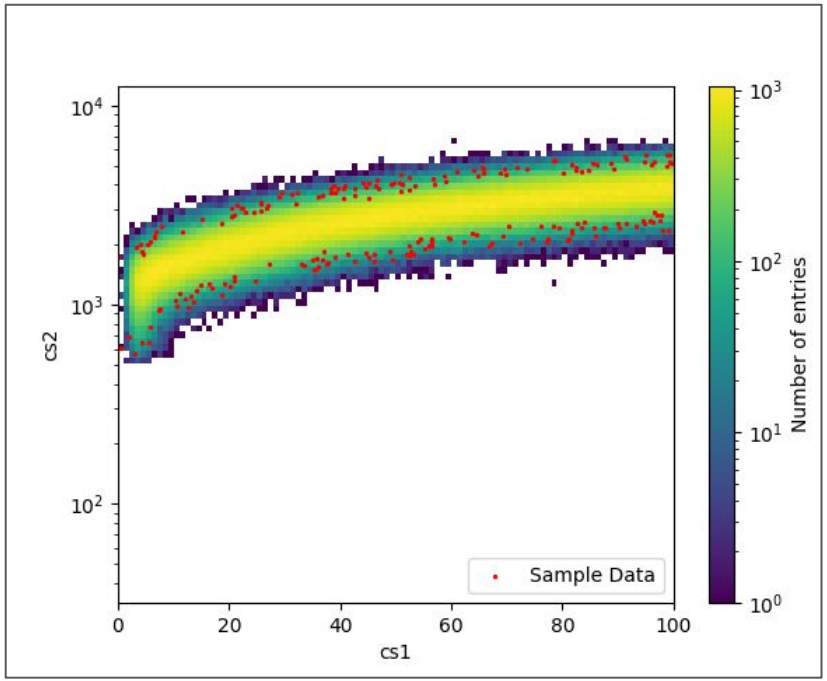
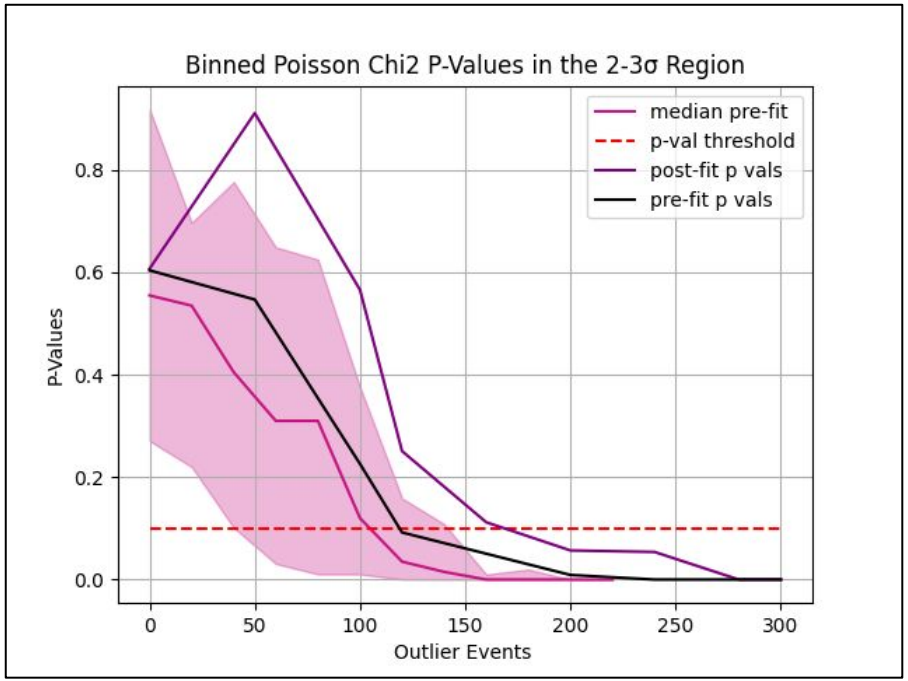
Mis-modeling in the Symmetric 2 to 3σ Region





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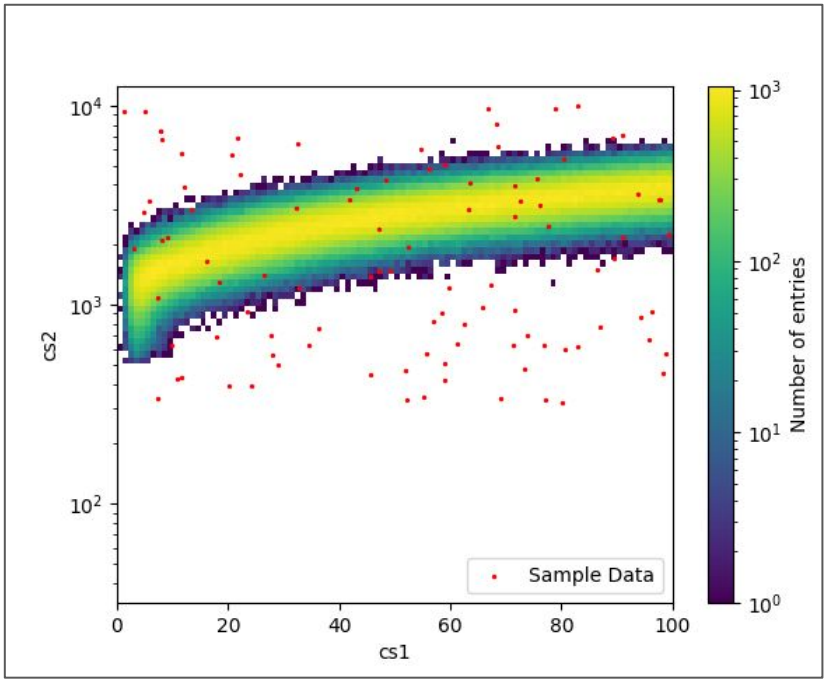
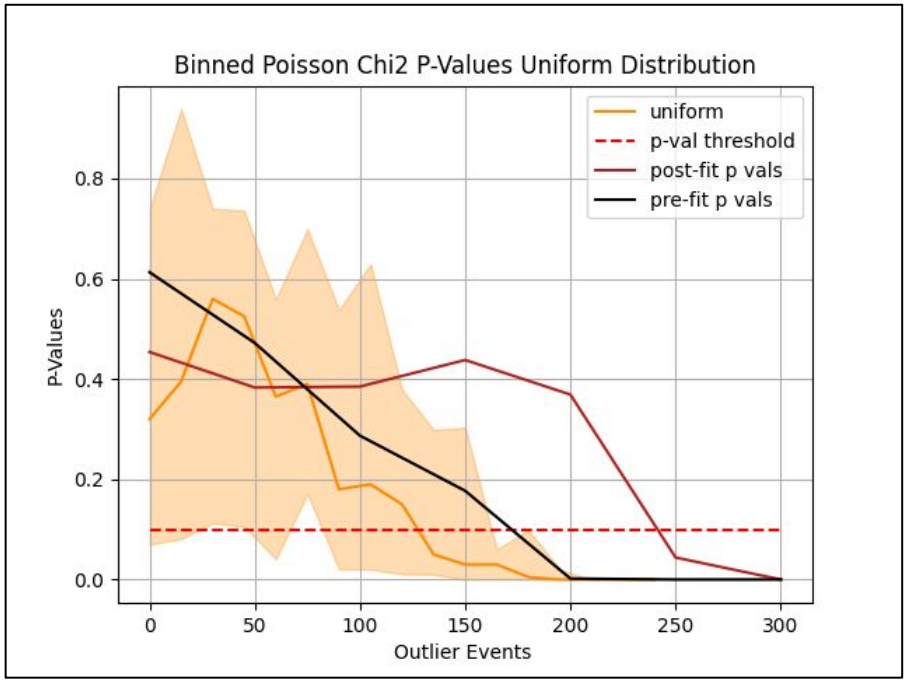
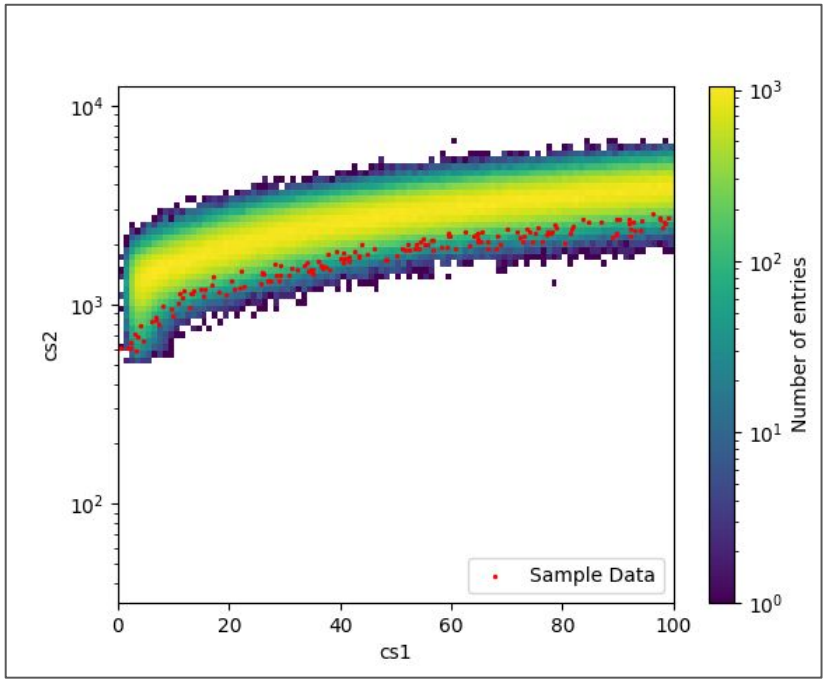
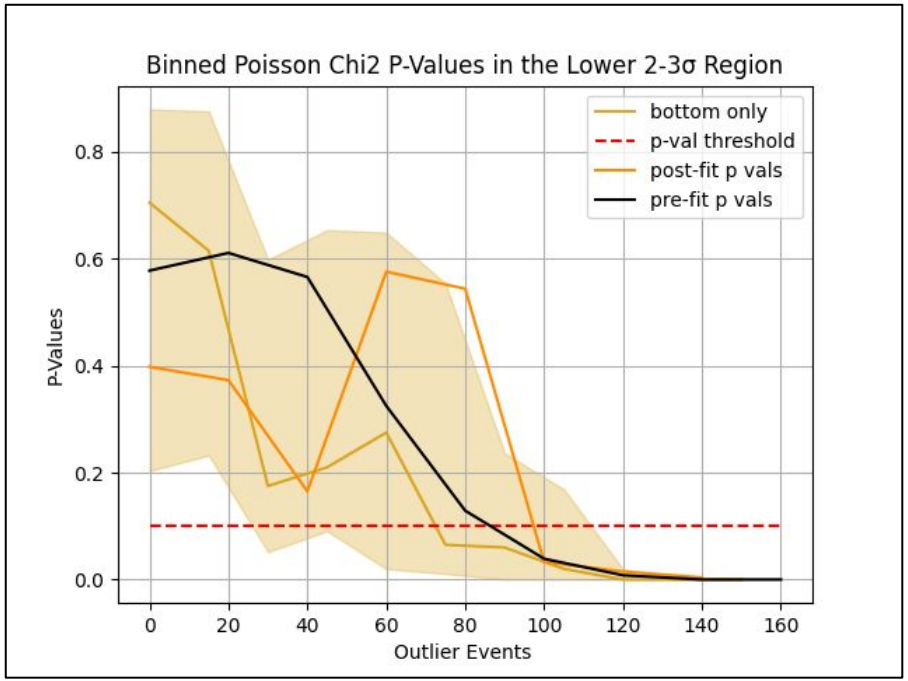
Uniformly Distributed Mis-modeling





Mis-modeling in the -2 to -3σ Region





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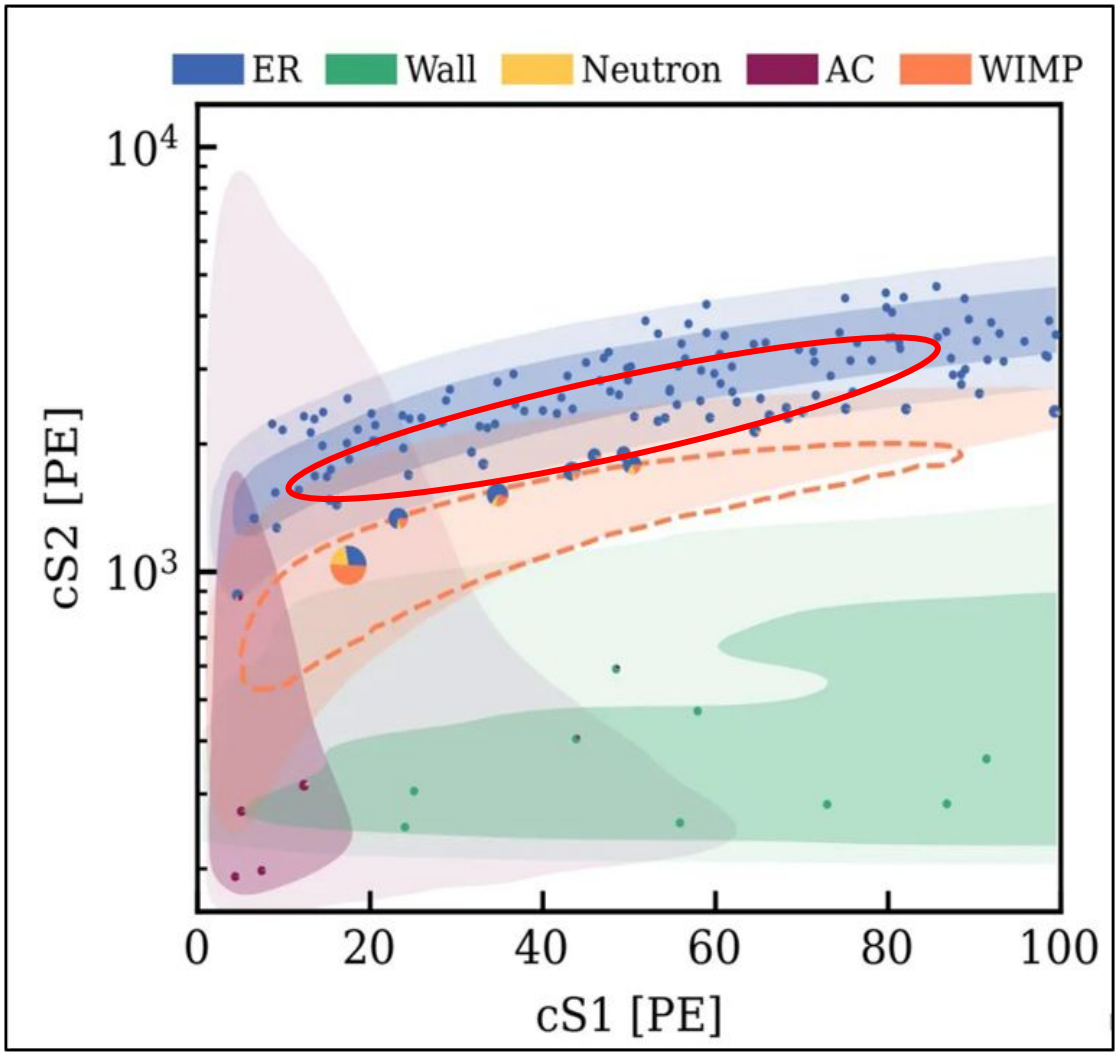

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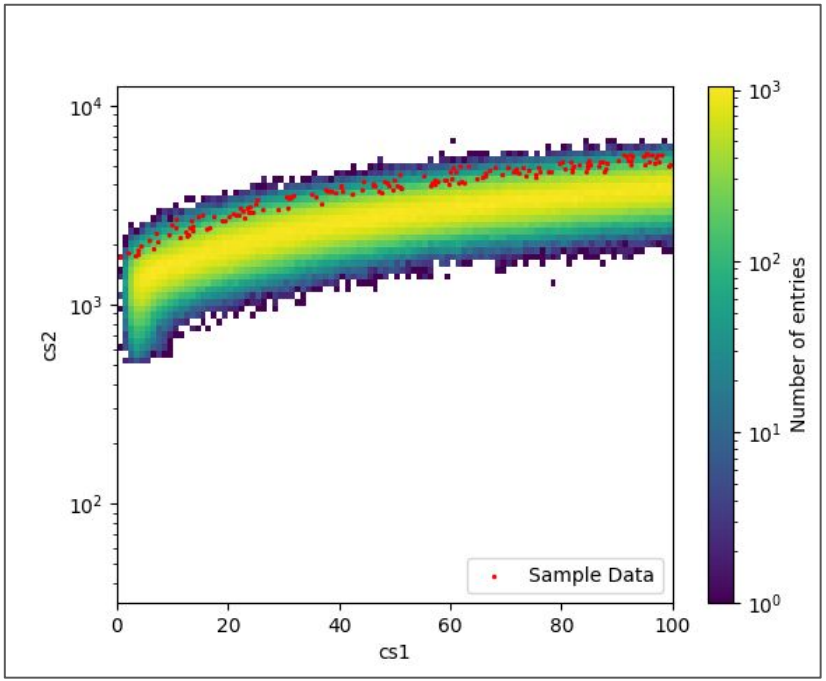
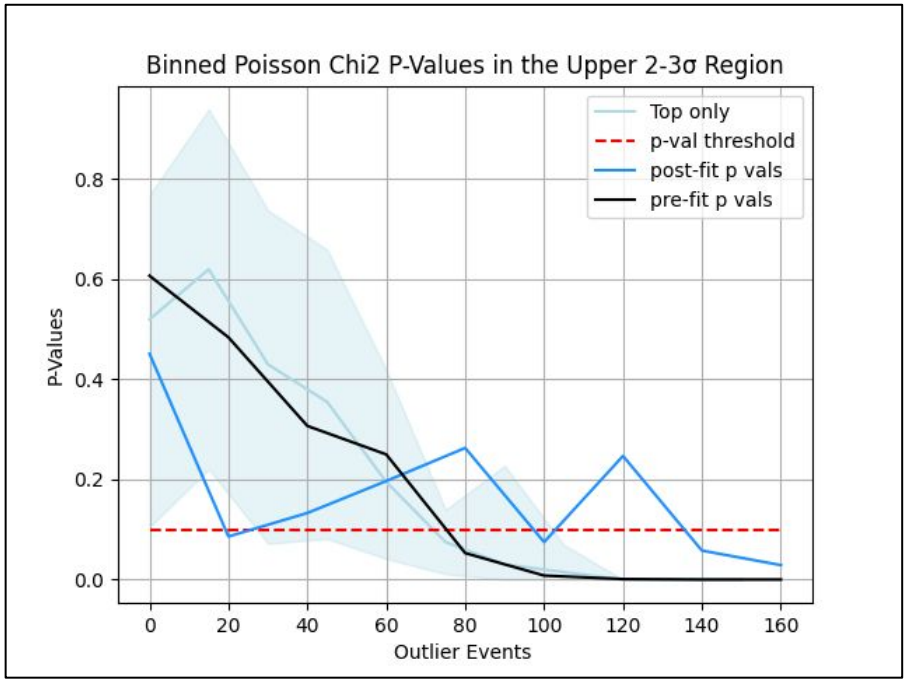
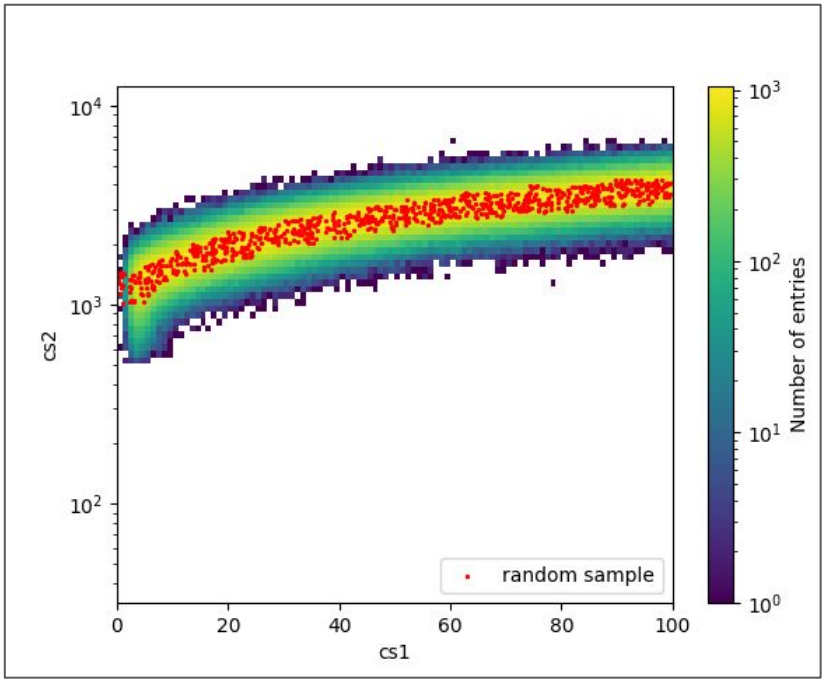
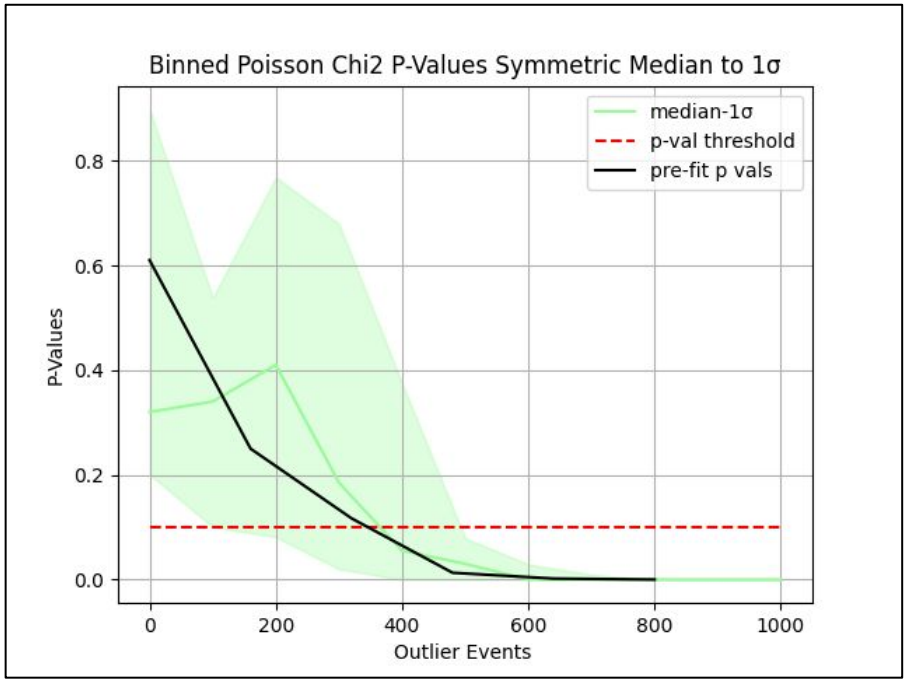
Mis-modeling in the +2 to +3σ Region





Mis-modeling in the Median + 1σ Region





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Thresholds For When Mis-modeling Becomes Detectable

Uniformly distributed:

Pre-fit: ~200 events (9%) Post-fit: ~300 events (13.6%)

-2 to -3σ deviations:

Pre and Post-fit: ~140 events (6.5%)

+2 to +3σ deviations:

Pre-fit: ~120 events (5.6%) Post-fit: ~160-180 events (7.4-8.3%)

2 to 3σ deviations:

Pre-fit: ~220 events (9.9%) Post-fit: ~280 events (12.3%)

Median + 1σ deviation:

Pre-fit: ~700 events (26%)

Next Steps

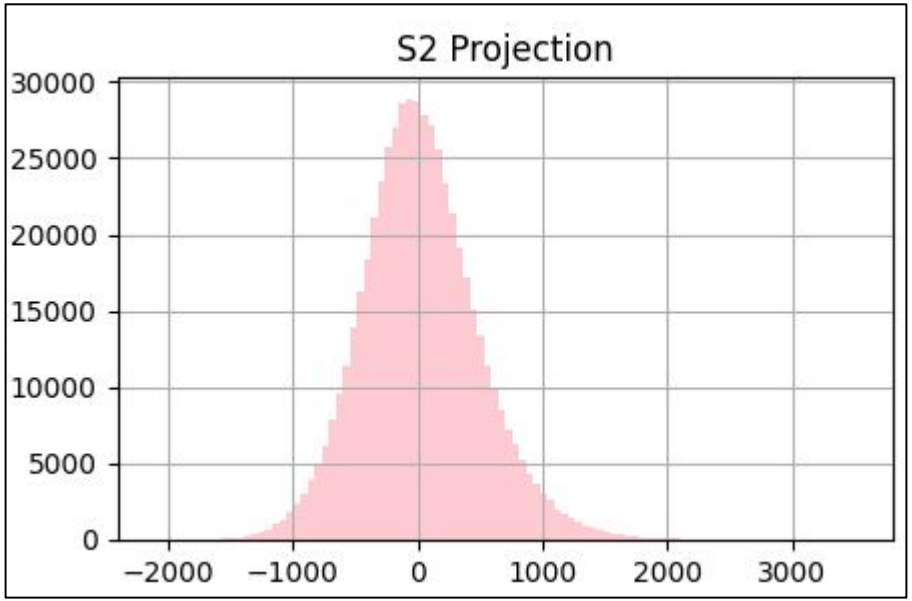
Are different GOF evaluations more sensitive to various types of mis-modeling?

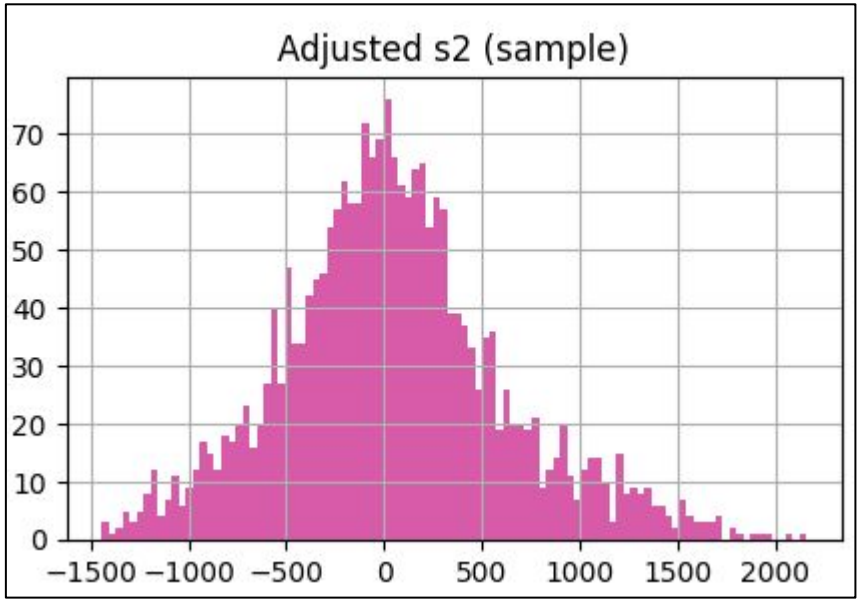
Using a targeted test to look at the data in regions where we can expect to more easily detect mis-modeling.

For instance, would a Komolgorov-Smirnov (KS) Test comparing the distributions of a data set prior to and after the MCMC be more effective at detecting uniformly distributed outliers than the Binned Poisson $\chi 2$?

S-2 Projection and Associated KS Tests

- Subtracting the S2 medians of a simulation and sampled data set to compare distributions in a 1D histogram





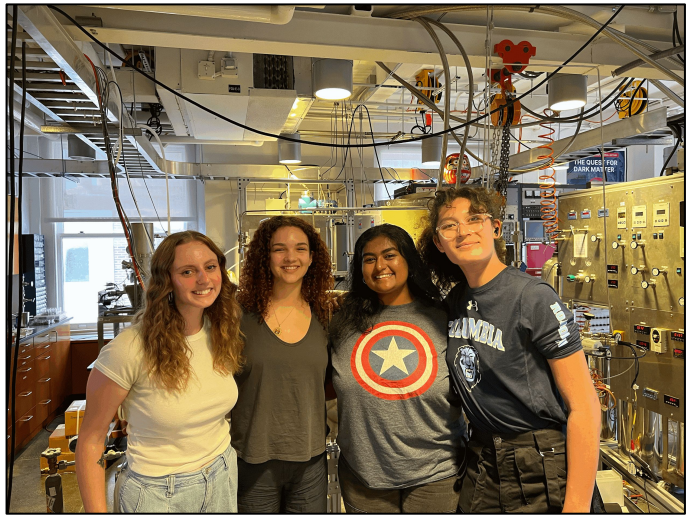
Summary and Conclusions

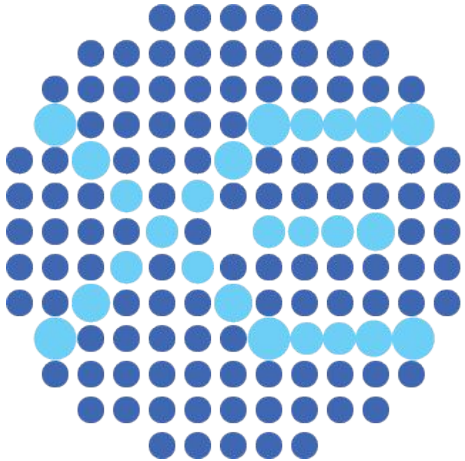
If you have imposter events in your data set, your ER model will not be describing ER events, and your ROI will be improperly constrained.

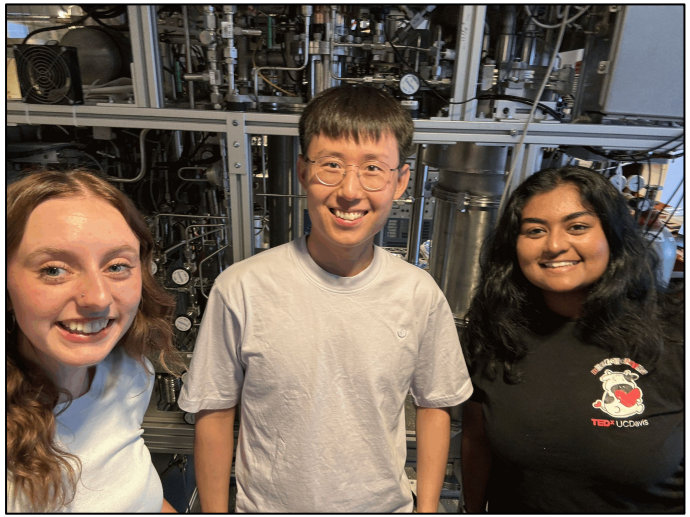
Appletree is capable of fitting large deviations in the calibration data.

Being aware of the sensitivities of our models and GOF evaluations allows for more critical analysis of the data, and ultimately more accurate results.

Thank you!
Questions?







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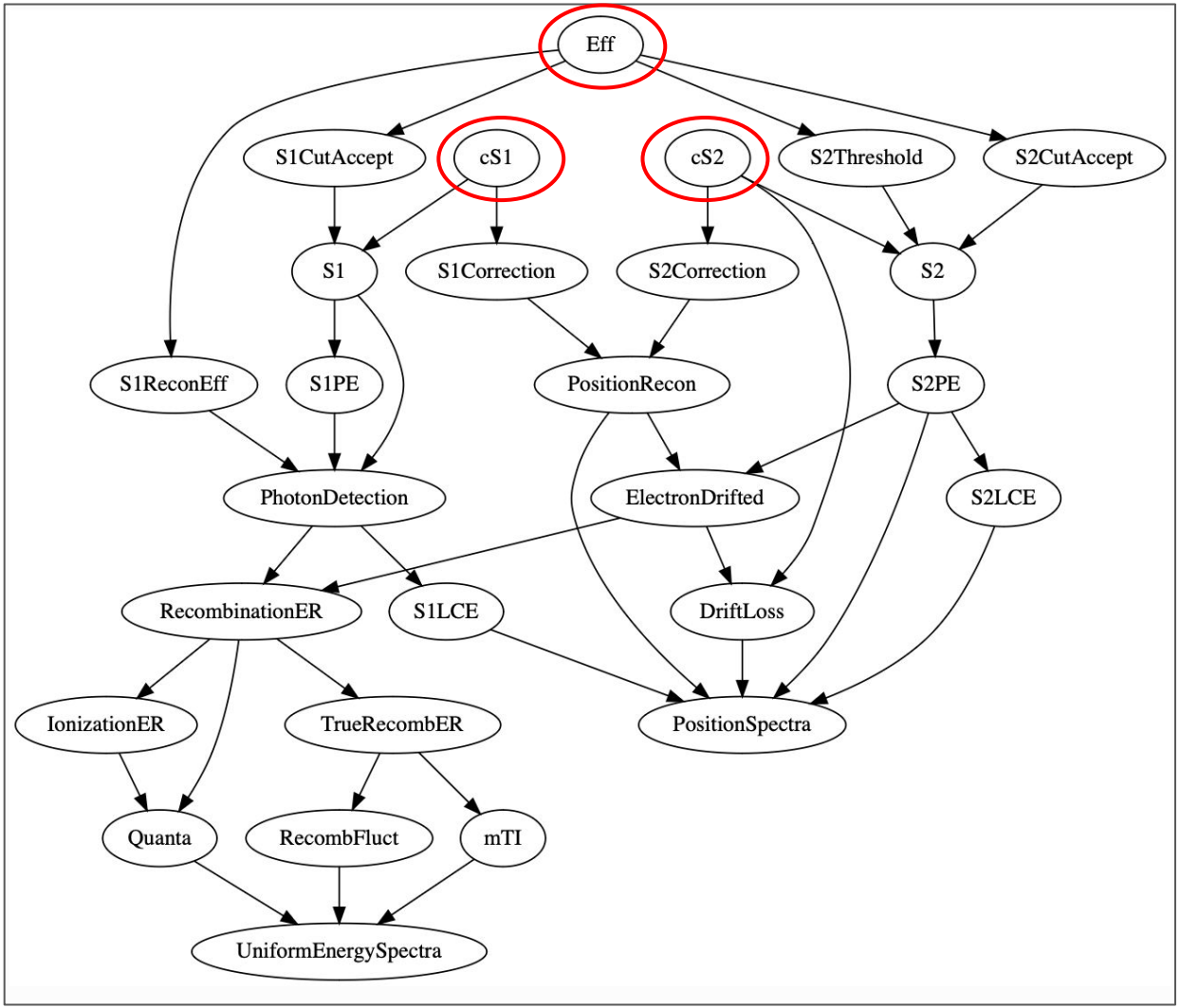
Appletree (like the deli)



Executing the Emission Model

$$N_q \sim Binom(\frac{\epsilon}{W}, L)$$

$$N_i \sim Binom(N_q, \frac{1}{1+ < N_{ex}/N_i >})$$

$$N_e \sim Binom(N_i, 1-r)$$

$$N_\gamma = N_i - N_e + N_{ex}$$

Parameters

Parameter	Prior	Marginal posterior	Unit
W	13.7 ± 0.2	$13.7^{+0.2}_{-0.2}$	eV
f	0.059	0.059	-
ER parameters			
$\langle N_{\mathrm{ex}}/N_{\mathrm{i}} \rangle$	0.06 - 0.20	$0.13^{+0.04}_{-0.04}$	-
γ	free	$0.13^{+0.03}_{-0.02}$	-
δ	free	$0.34^{+0.07}_{-0.07}$	-
ω	free	57^{+15}_{-12}	keV
q_0	free	$1.32^{+0.17}_{-0.20}$	keV
q_1	free	$0.47^{+0.07}_{-0.05}$	keV
q_2	free	$0.030^{+0.002}_{-0.002}$	-
q_3	free	$0.47^{+0.40}_{-0.31}$	keV