A Review of NEST Models

and Their Application to Particle Identification

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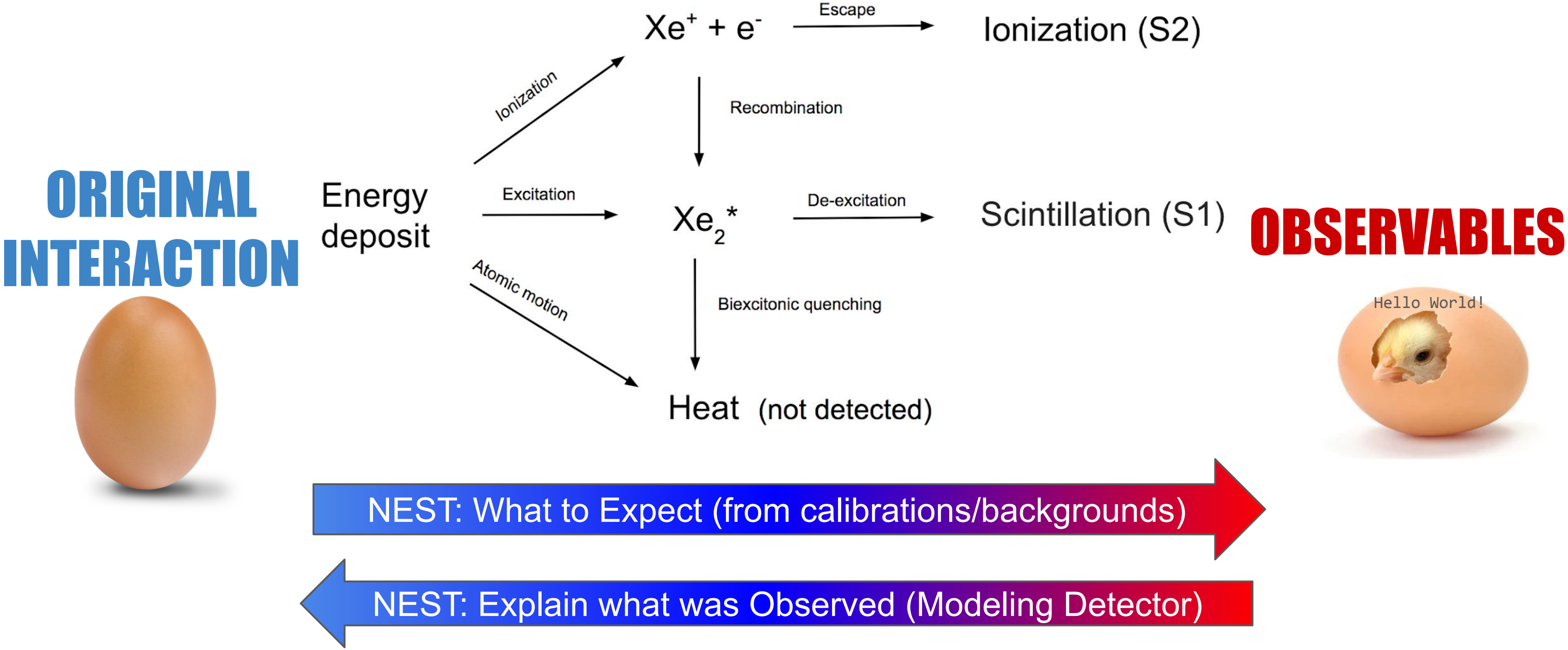
TeVPA 2024: Chicago, United States

About NEST: The **N**oble **E**lement **S**imulation **T**echnique

- nest.physics.ucdavis.edu & github.com/NESTCollaboration
- "Inter-collaboration" Collaboration
  - Members from LUX/LZ, XENON, DUNE, nEXO, and more
- Fast, stand-alone C++ code with robust example executable, execNEST
  - Python bindings available too!
  - Reproduces Xe & Ar scintillation and ionization response from most imaginable interaction types
  - Yields as a function of particle type, energy, field, density and target phase
- GEANT4 Integration
  - Takes energy depositions and returns light and charge yields
- Constantly evolving and updating with new & improved features
- Most plots from arxiv.org:2102.10209
  - Submitted for publication in *Frontiers in Detector Science and Technology*

The Whole Point:

Providing a Reliable Data-Driven Mapping from Observables to Fundamentals

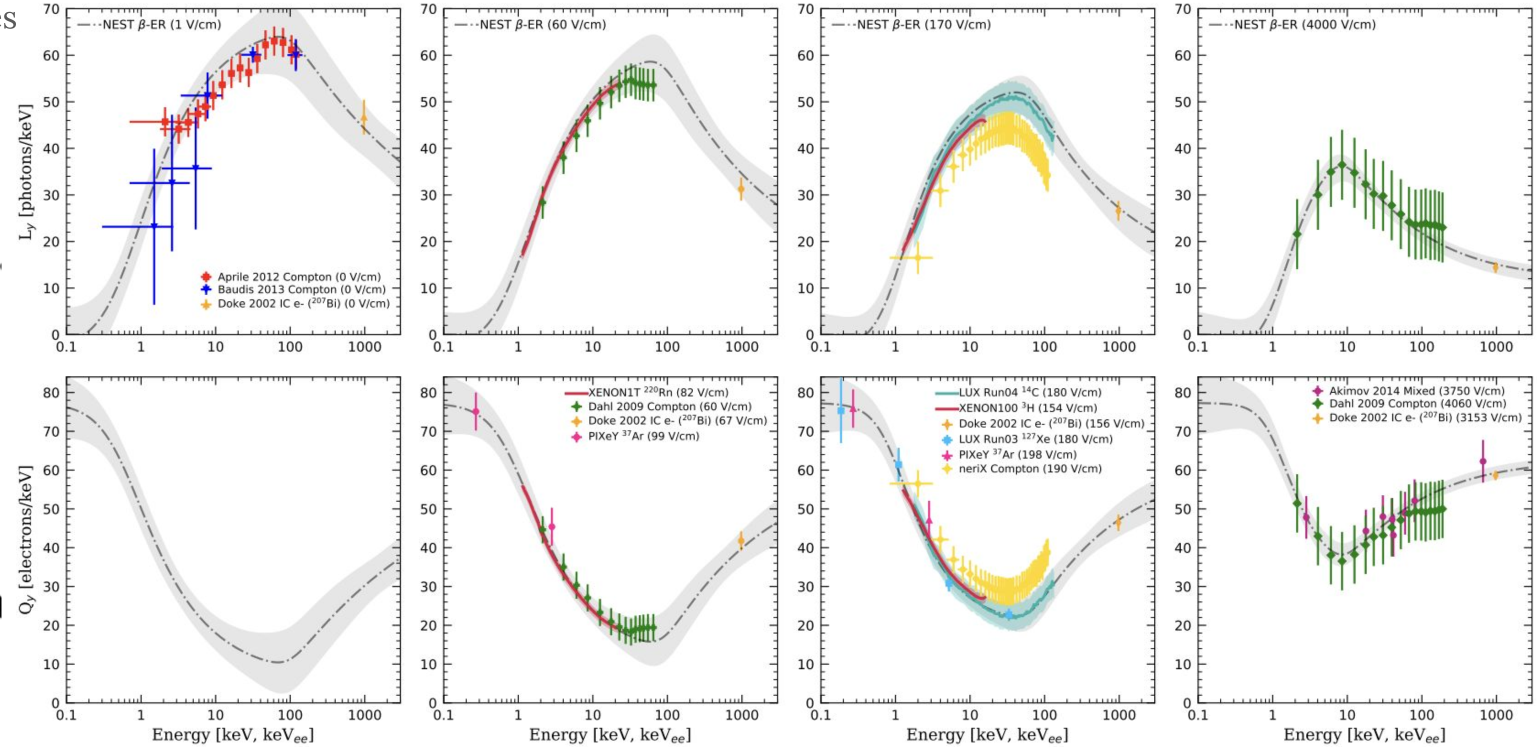


NEST's Xe Modeling in a Nutshell

- Empirical formulae reproduce data and build upon existing models
- Average energy per produced quanta: the Work Function, W
  - Density-dependent linear fit to GXe, LXe, and SXe data: W [eV] = 21.9 - 2.9ϱ
- Total quanta produced: $N_q = E/(W/L)$
  - L is the "Lindhard" quenching → 1 for electronic recoils, <1 for nuclear recoils
- Unique Charge Yield ($Qy = N_e/E$) Model
  - Empirical, calculated separately from N_q
- Light Yields ($Ly = N_{ph}/E$) calculated by the difference between total quanta and the charge yield
- Fluctuations About the Means!
  - Correlated (Fano-like) and anti-correlated (recombination) fluctuations
  - Uncorrelated (noise) fluctuations applied to individual signal channels based on detector design/performance

ER Yields: WIMP Backgrounds, ER Calibrations

- The ER Models are a sum of two sigmoids – allowing for smooth transition in yields between low and high energies, with well-behaved asymptotes
- Naked betas are crucial to model precisely; works well for Compton scatters too
- Shape chosen to transition between Thomas-Imel point-like scatters at low energies, and Doke-Birks track-like scatters at higher energies

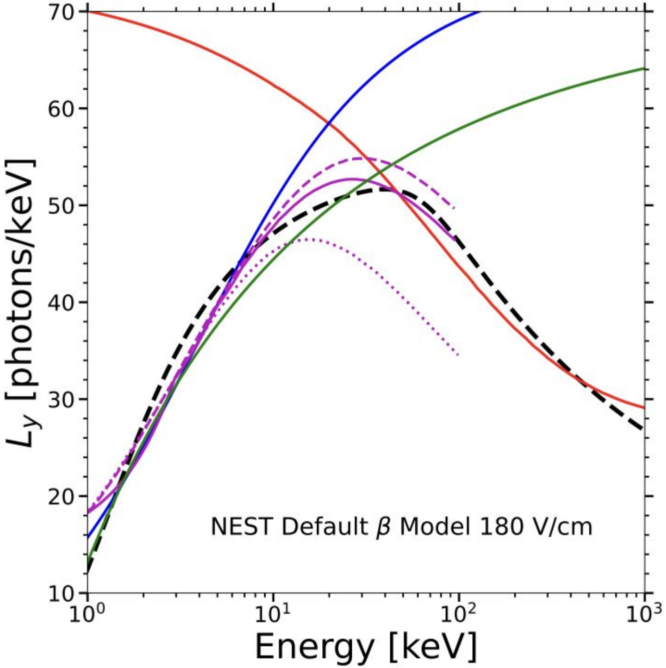


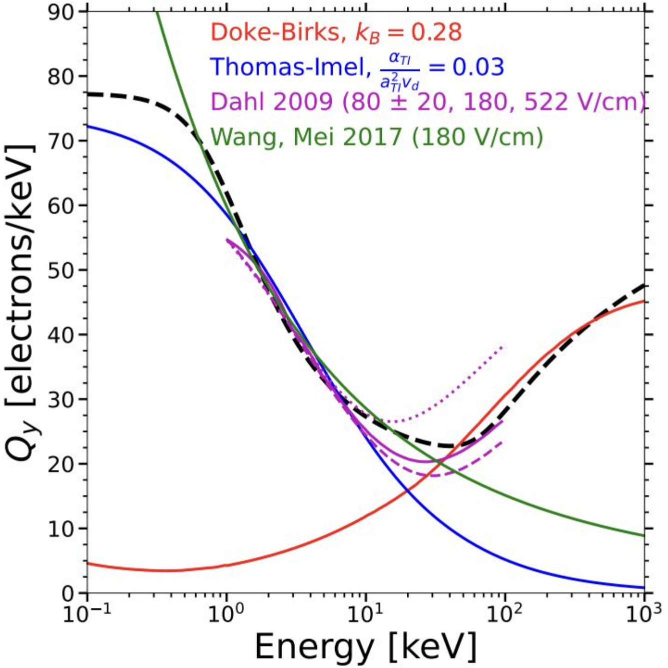
Low and High Energy Models are United!

Low-energy portion reduces to Thomas-Imel
High-energy portion reduces to Doke-Birks

Smooth stitching region at intermediate energies

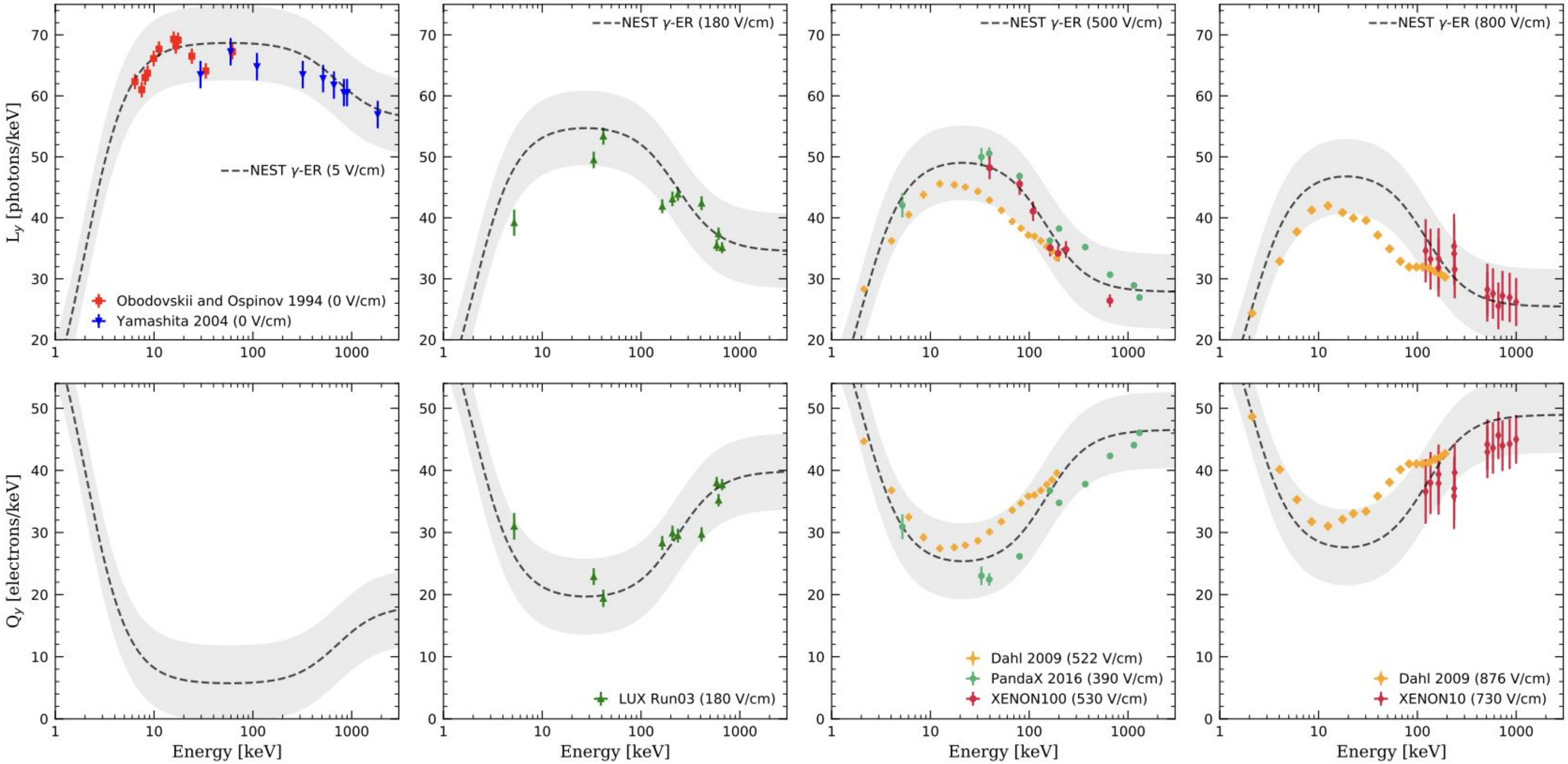
Well-behaved asymptotes to extrapolate to higher energies and below thresholds



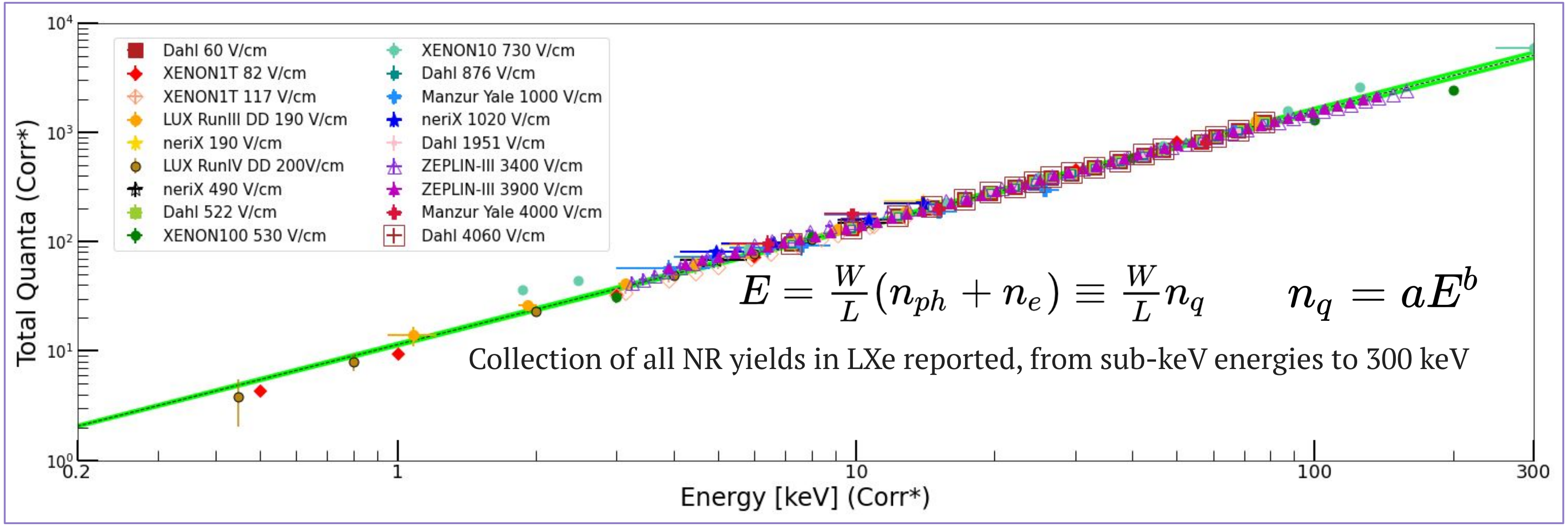


Photoabsorption Events: γ and xray recoils

Same form as β ER, different model parameters (differing recombination profile)



Nuclear Recoils: Total Quanta



- Unlike ERs, total quanta isn't linear as a function of energy → Quenching factor, *L*, to account for heat-loss
- Best-fit with a power law, with a = $11^{+2.0}_{-0.5}$ and b = 1.1 ± 0.05
- No observed field dependence, just like ERs
- Current work underway to improve the fit as E → 0 keV

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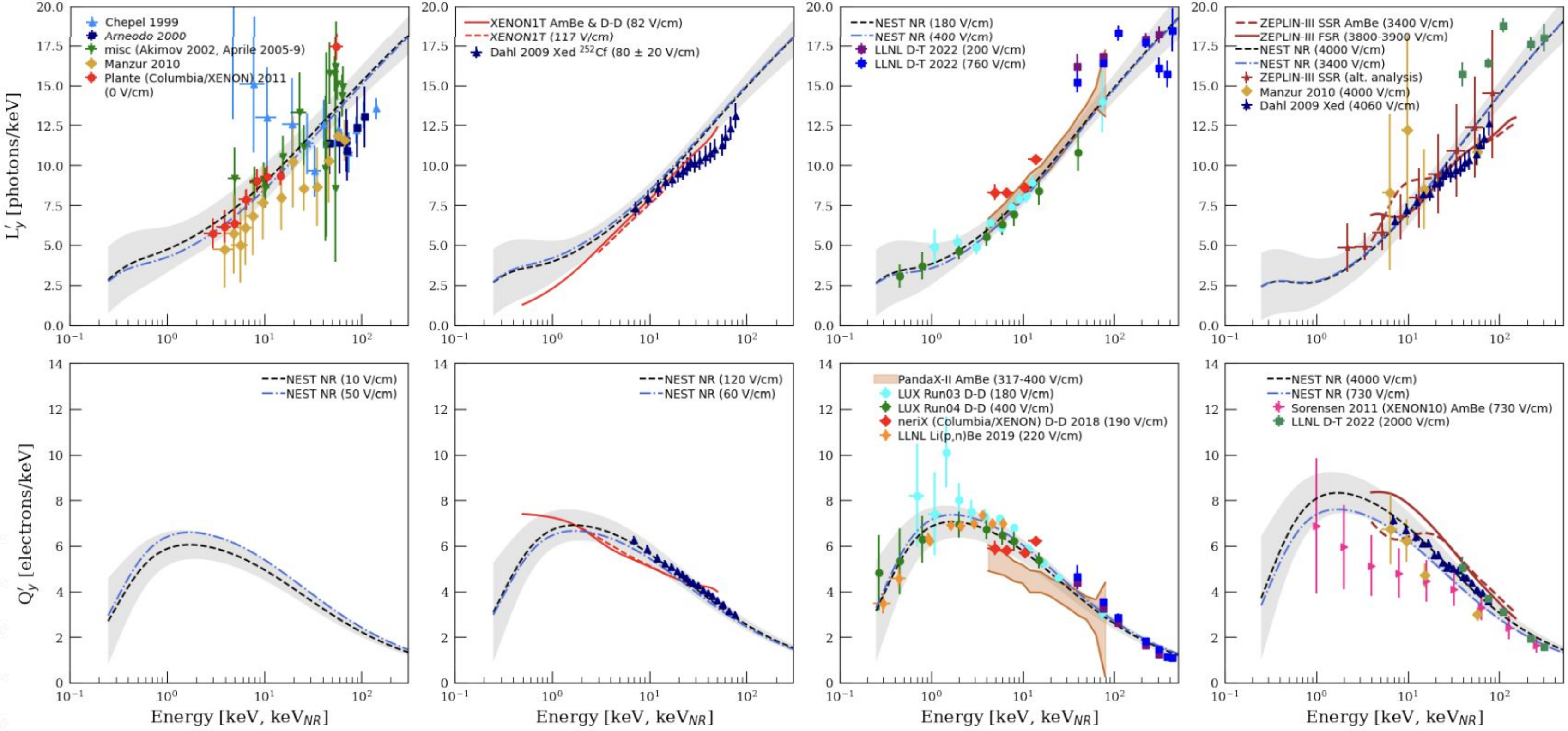
M. Szydagis, G.R.C. Rischbieter, et al. (Feb 19, 2021) Published in:*Instruments* 5 (2021) 1, 13 e-Print: 2102.10209 [hep-ex]

NR Yields: WIMP Interactions, CEνNS, Neutron Cals.

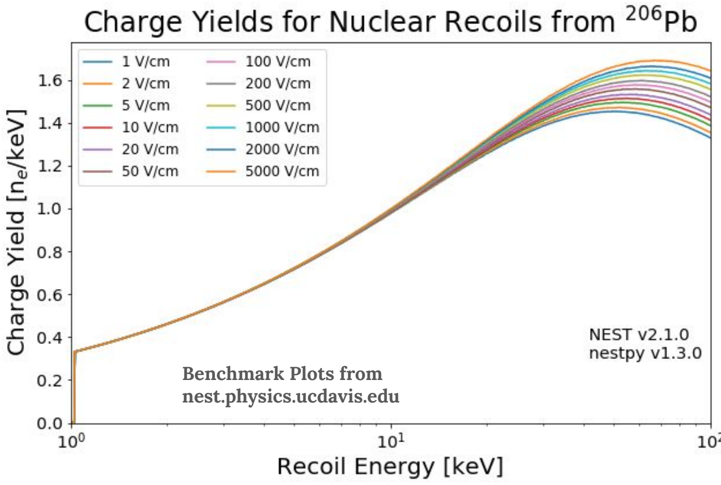
Flexibility in near-threshold modeling; separate roll-offs between light and charge

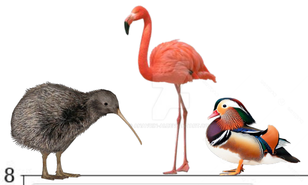


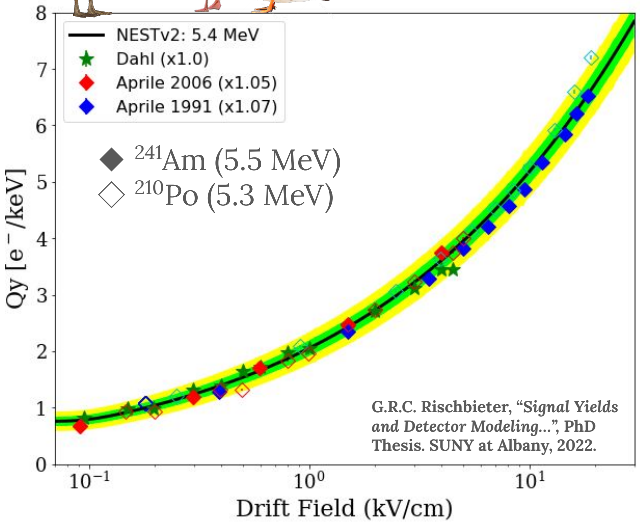
More Particles, More Models

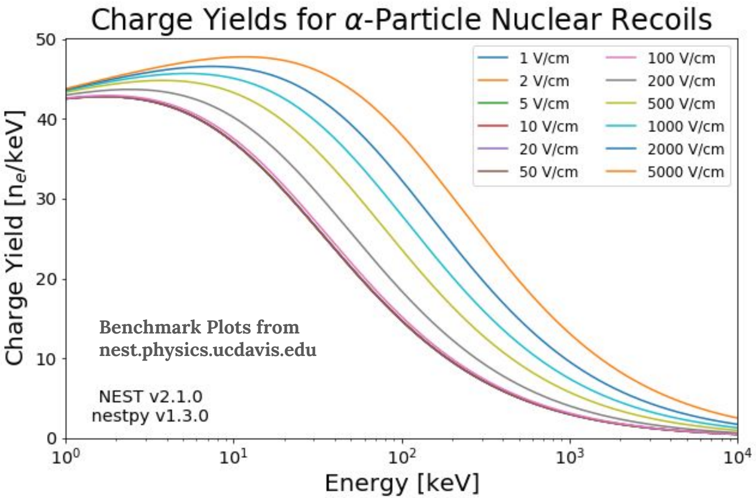
"Exotic" NR models included: alphas, heavy ions

Recoil Spectra Generators allow for easy simulation of SI WIMPs, ^{8}B neutrinos, and common calibration sources





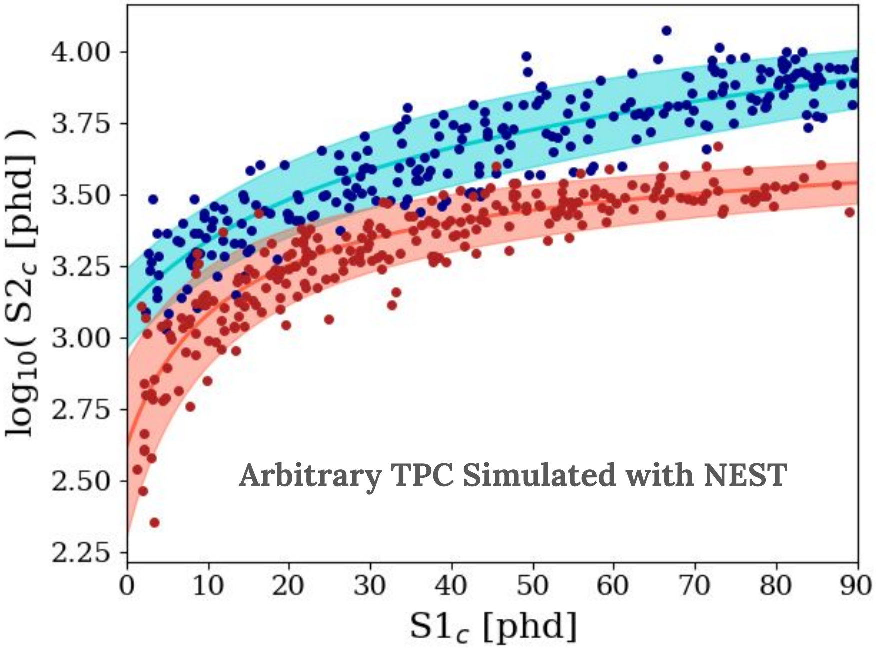




*Alpha yield plots outdated below 100 V/cm! Recently updated to match new data and new alpha models will be tagged in an upcoming release!

Beyond Mean Yields:

Fluctuations Models Create a Powerful MC Framework

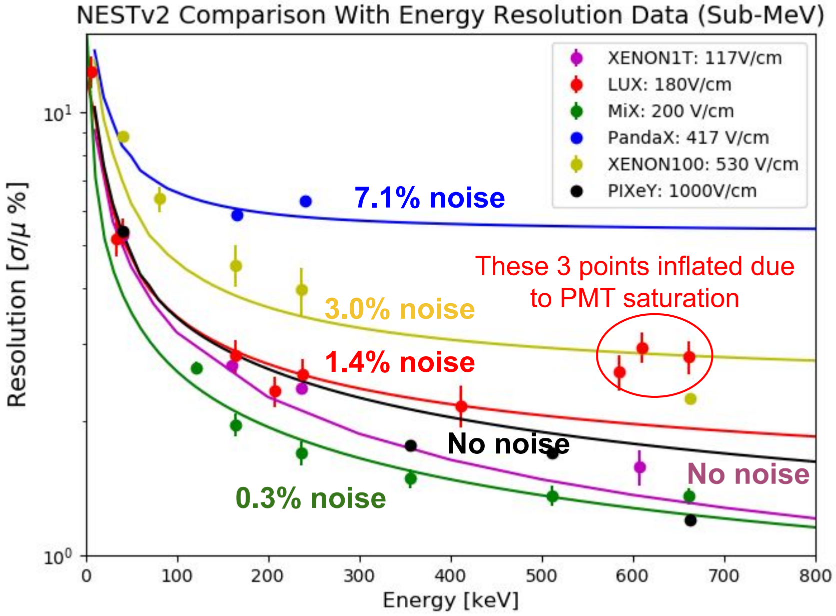


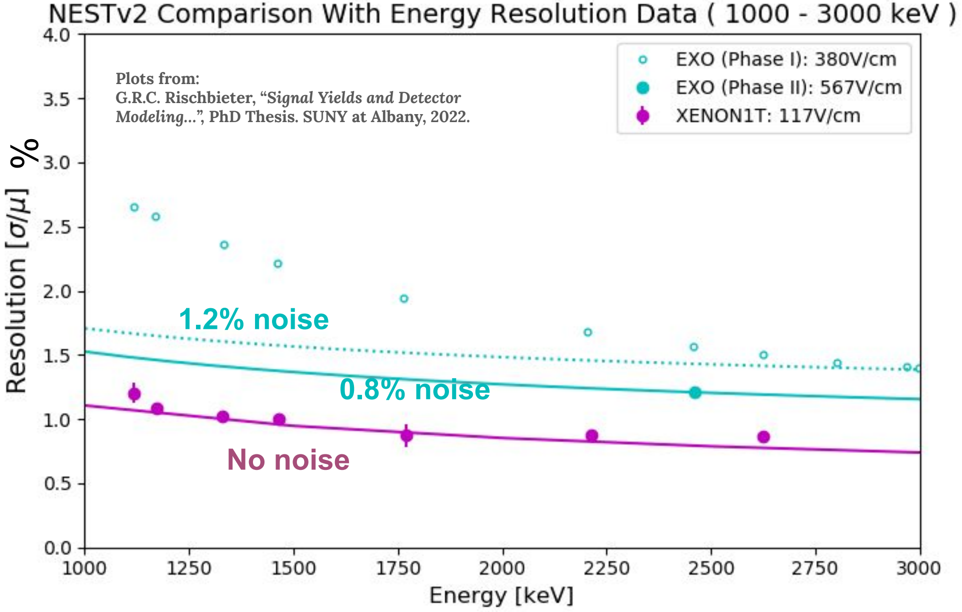
Plot from:
G.R.C. Rischbieter, "*Signal Yields and Detector Modeling...*", PhD Thesis. SUNY at Albany, 2022.

Statistical Fluctuations and Energy Resolutions

"Fano-like" fluctuations on total quanta → modeling the fundamental energy resolution vs energy and field

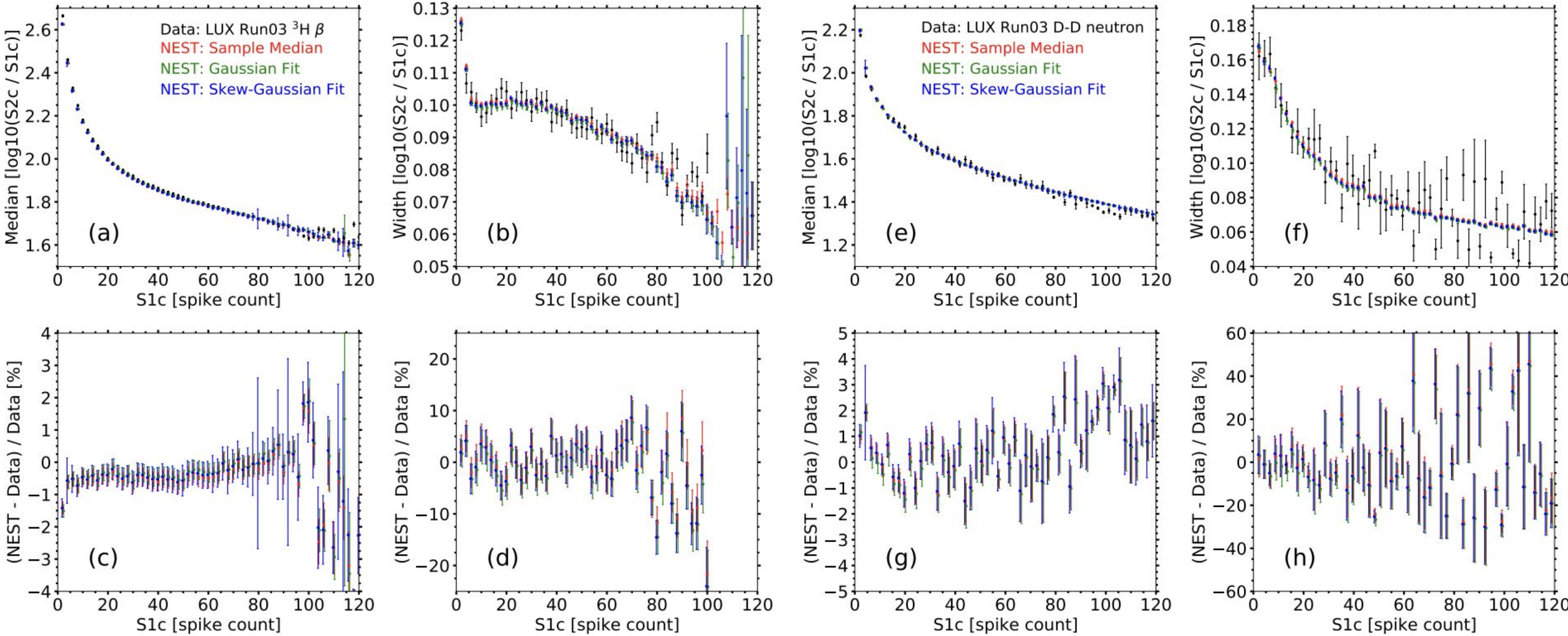
$\sigma_q^2 = F_q N_q$ where F_q is a field-, energy- ,and density-dependent fit





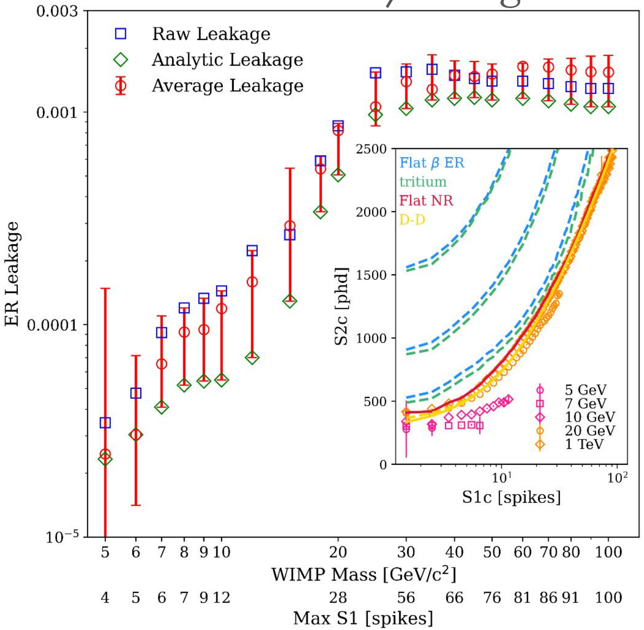
Adding in Recombination Fluctuations!

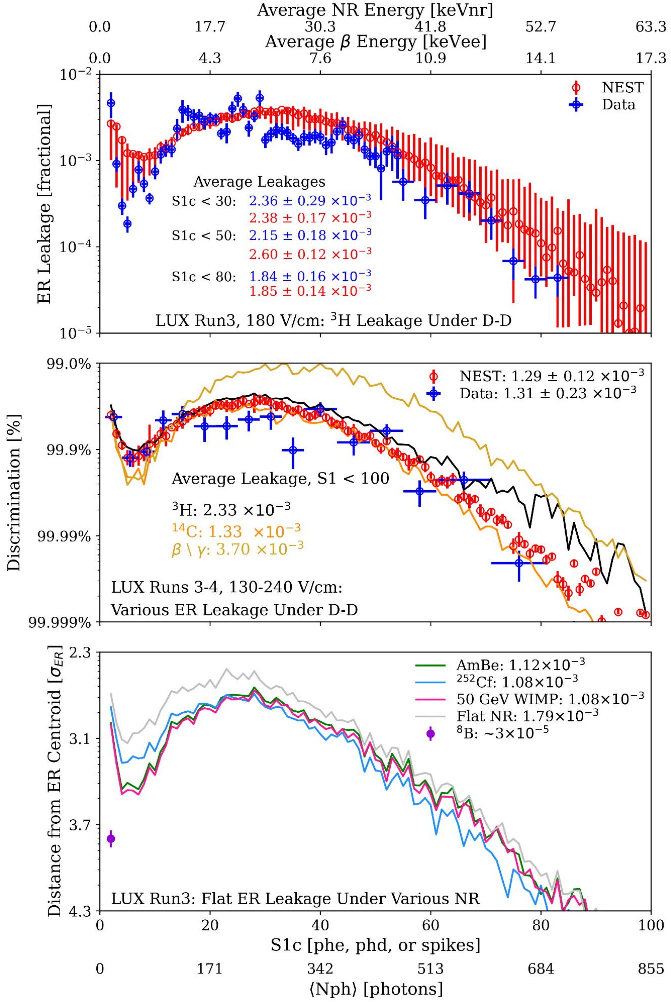
Reproducing Calibration Spectra: LUX Example
Matching Band Widths Requires An Accurate Recombination Model
Detector Geometries Used to Convert Quanta in Observables



ER,NR Discrimination

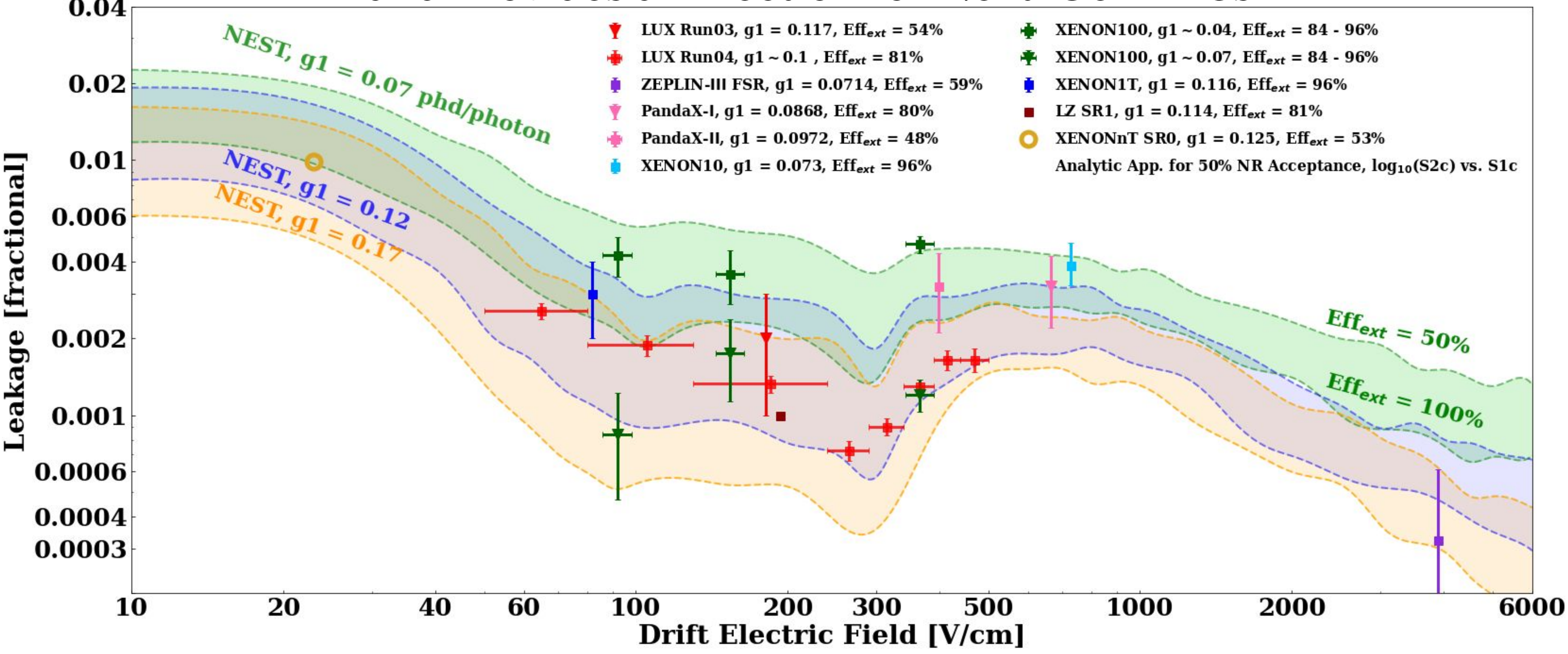
- Modeling and comparing discrimination power between WIMPs and ER backgrounds is crucial for understanding detector performance
- Able to accurately predict discrimination power for new detectors/backgrounds with NEST





The NEST Tapestry of Leakage:

Reproduces Older Data, Predicts Newer Data, and Provides a Direction for Next-Gen TPCs



Summary

- NEST is a powerful simulation framework, accurately describing the xenon signal yields
  - Computationally cheap! Millions of scatters in seconds!
- NEST's predictive power provides a key tool for preparing for the next generation of dark matter detectors
  - Not just WIMPs! "Exotic" DM models and neutrino elastic nuclear scattering can be modeled with NEST
- C++ and Python versions, in addition to Geant4 and MagBoltz interfacing
- Free to use, open source, and continuously improving
  - Feel free to reach out for help & getting started
- Argon too! Only discussed xenon today, but LAr models are available and ever-improving

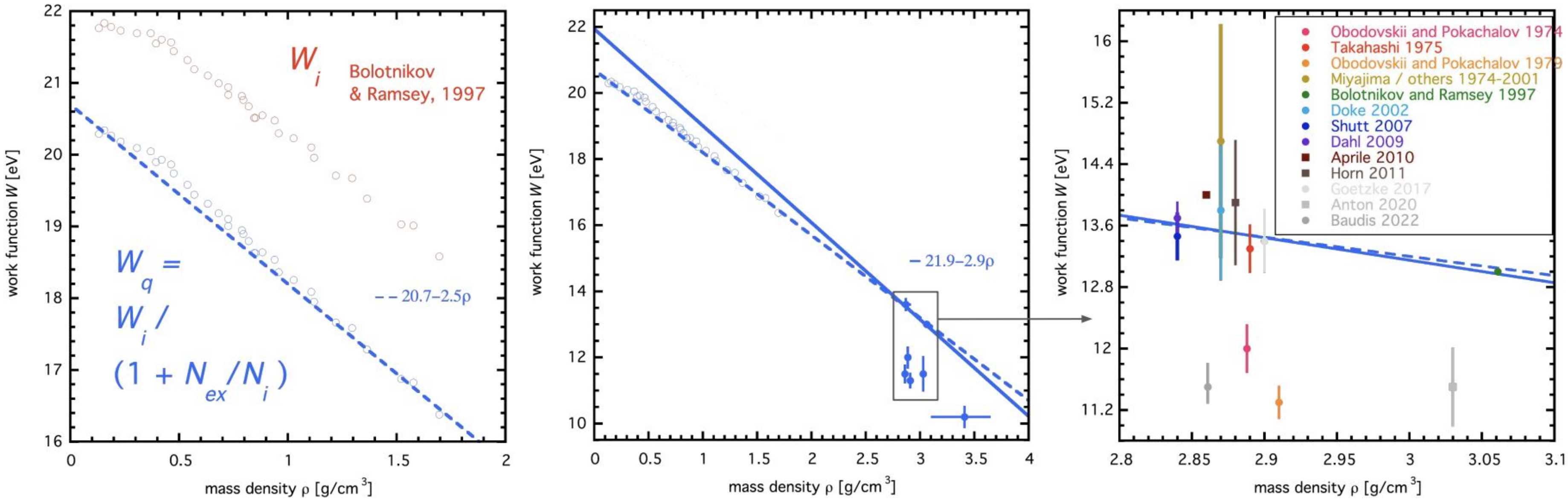
Thank you for your time!

Additional Plots and Resources

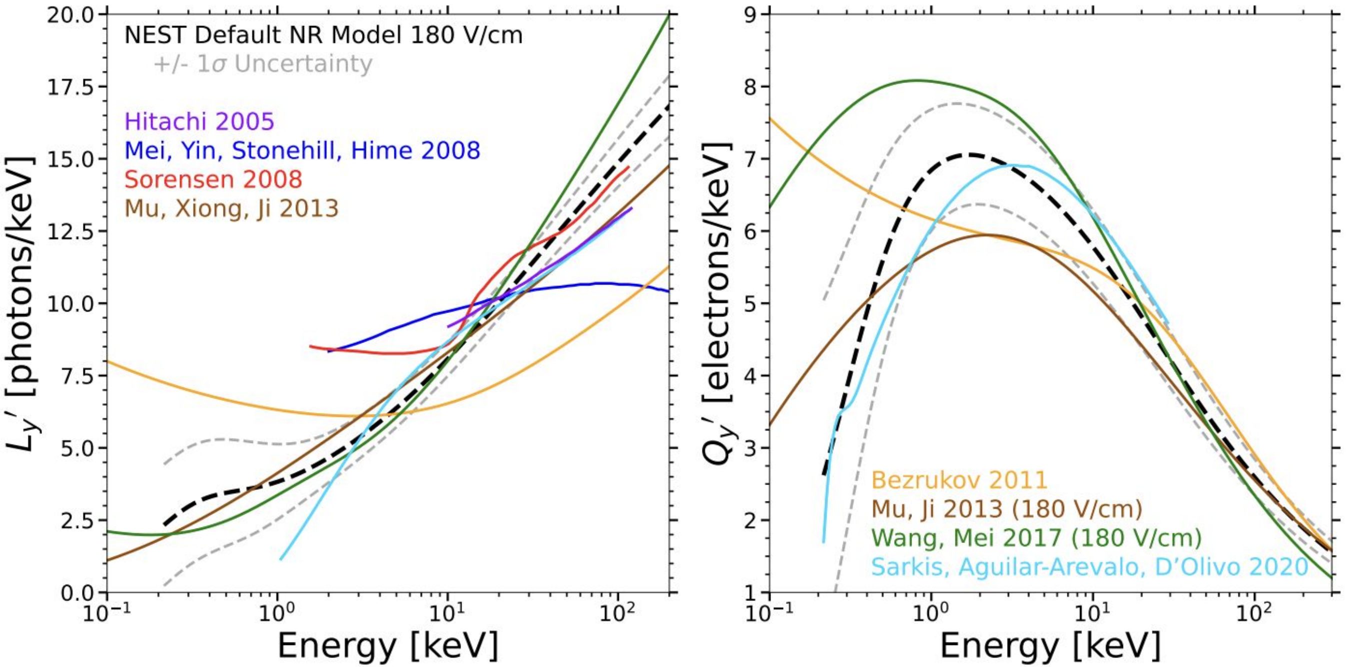
Density Dependence of the Xe Work Function

Tension exists between LXe measurements

NEST allows for corrections on yields when modeling with W ~ 11.5 eV for LXe



NR Model Comparisons:
NEST nestles in between the previous disagreements



Recombination Fluctuations:

To recombine or not to recombine, that's not the whole question!

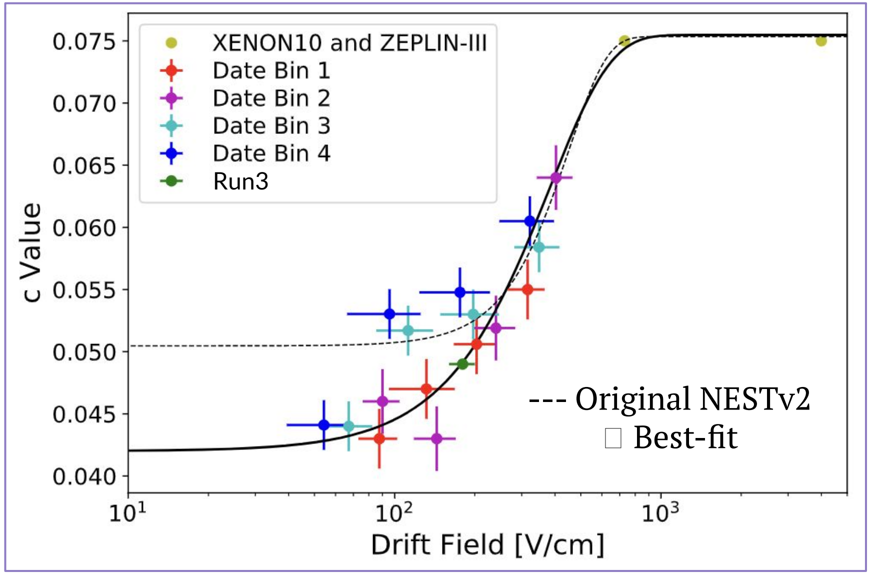
- Binomial models have never matched observations (see arXiv:1610.02076)
  - $\sigma_r^2 = r(1-r)N_i + (\sigma_p N_i)^2$
- Non-binomial component, scales with the number of pre-recombination ions
- Modeled as a skewed-Gaussian distribution, based on the electron fraction, y (related to the mean recombination probability) $y \equiv N_e/N_q$
  - Skewness required to match the attenuated fluctuations when recombination probability is low (C.E. Dahl, 2009)

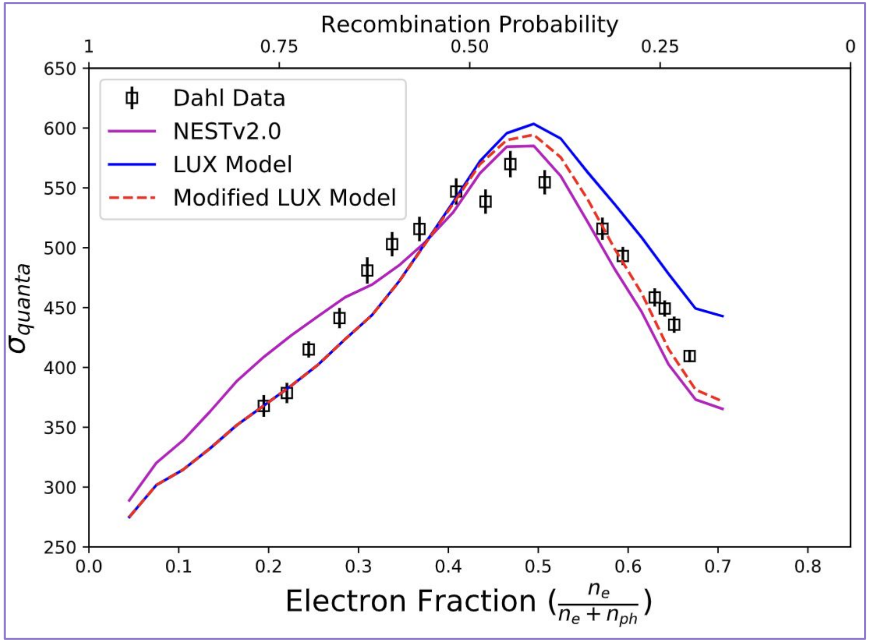
$$\sigma_p = A(\mathcal{E}) e^{\frac{-(\langle y \rangle - \xi)^2}{2\omega^2}} [1 + \mathrm{erf}(\alpha_p \frac{\langle y \rangle - \xi}{\omega\sqrt{2}})]$$

Field-dependent amplitude allows for accurate modeling of ER band widths

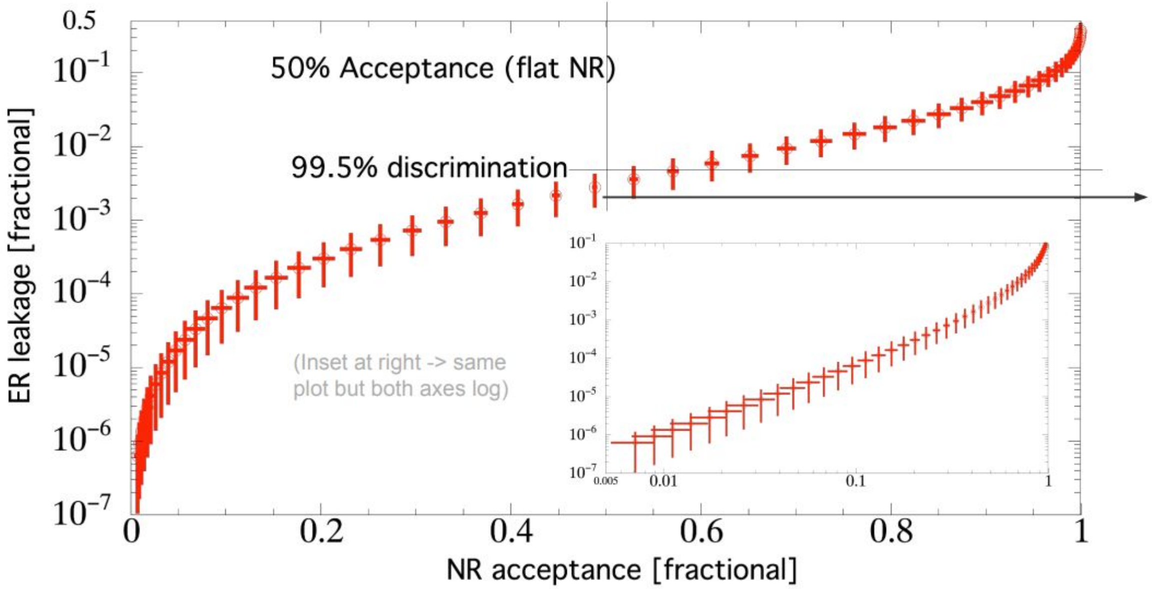
Recombination Modeling – Improving upon NEST with LUX and Dahl Data

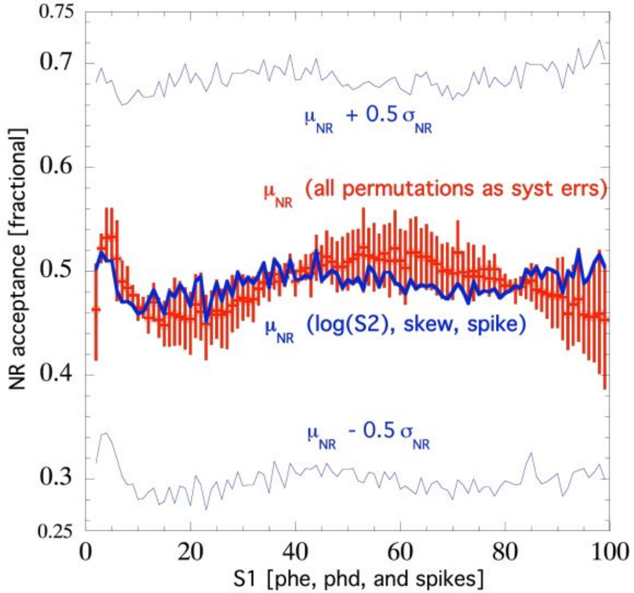
Improved modeling of β electronic recoils in liquid xenon using LUX calibration data
(LUX Collaboration) D.S. Akerib *et al.* Oct 9, 2019. 17 pages Published in: *JINST* 15 (2020) 02, T02007 Feb 28, 2020. e-Print: 1910.04211 [physics.ins-det]





NR Acceptance vs. ER Leakage Fraction





LAr Yields and Resolutions

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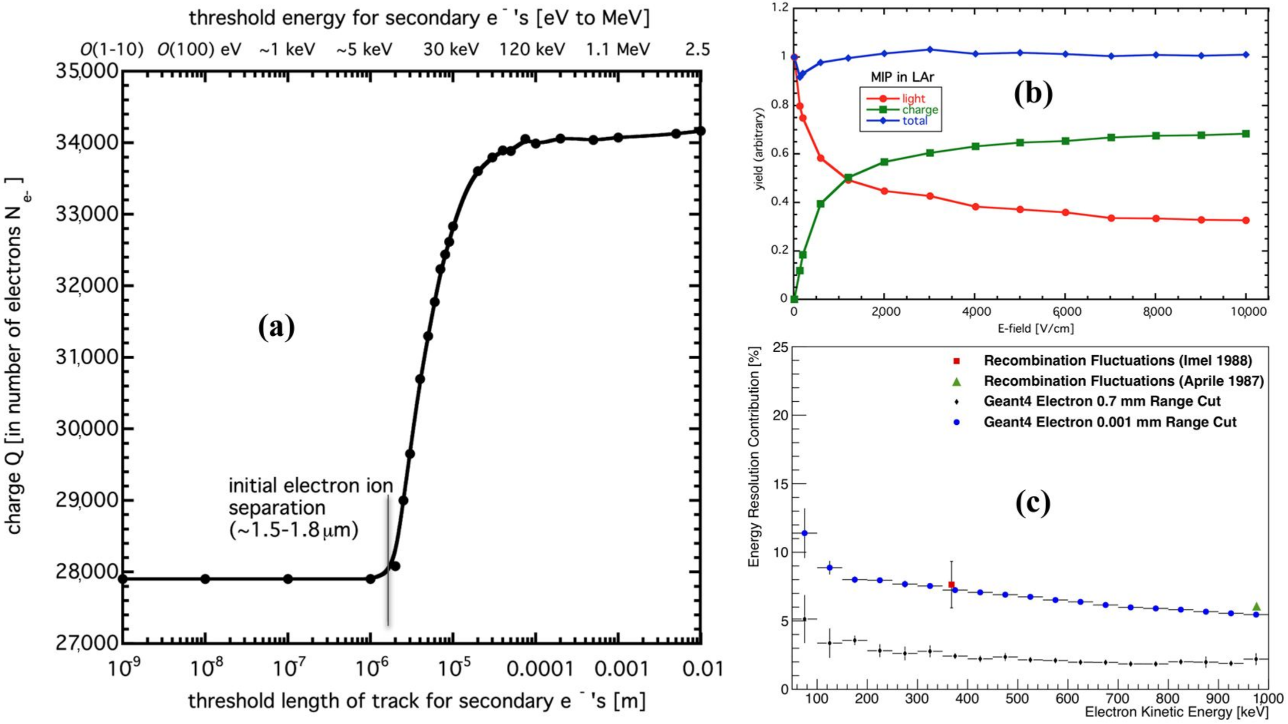

LAr Recombination fraction vs. dE/dx

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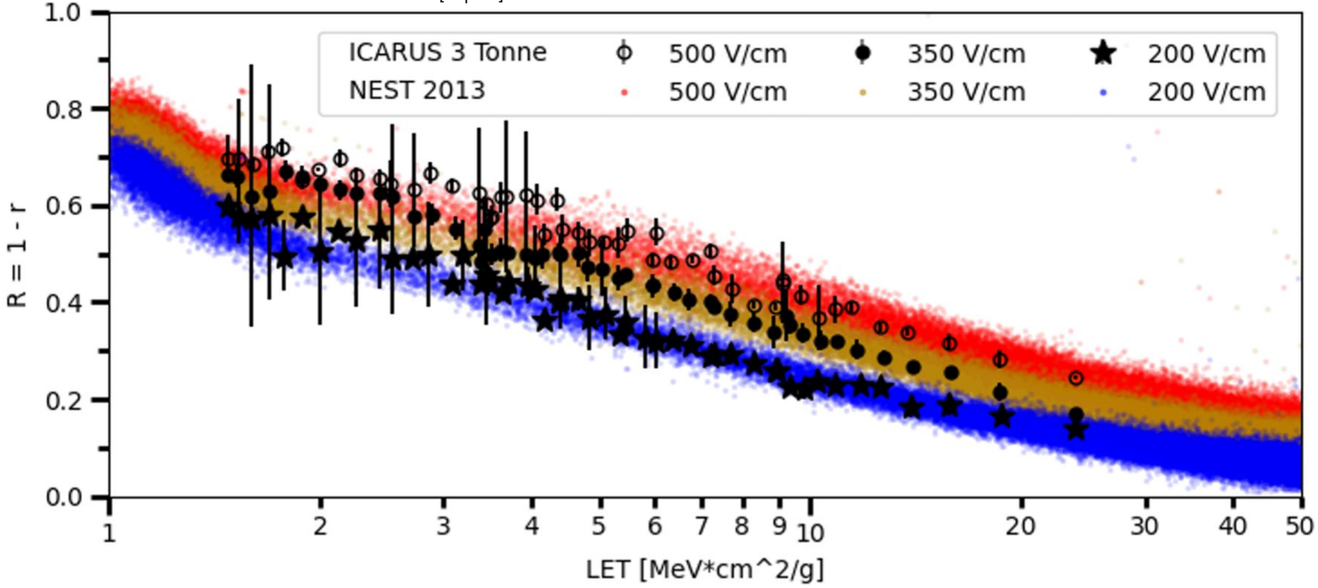
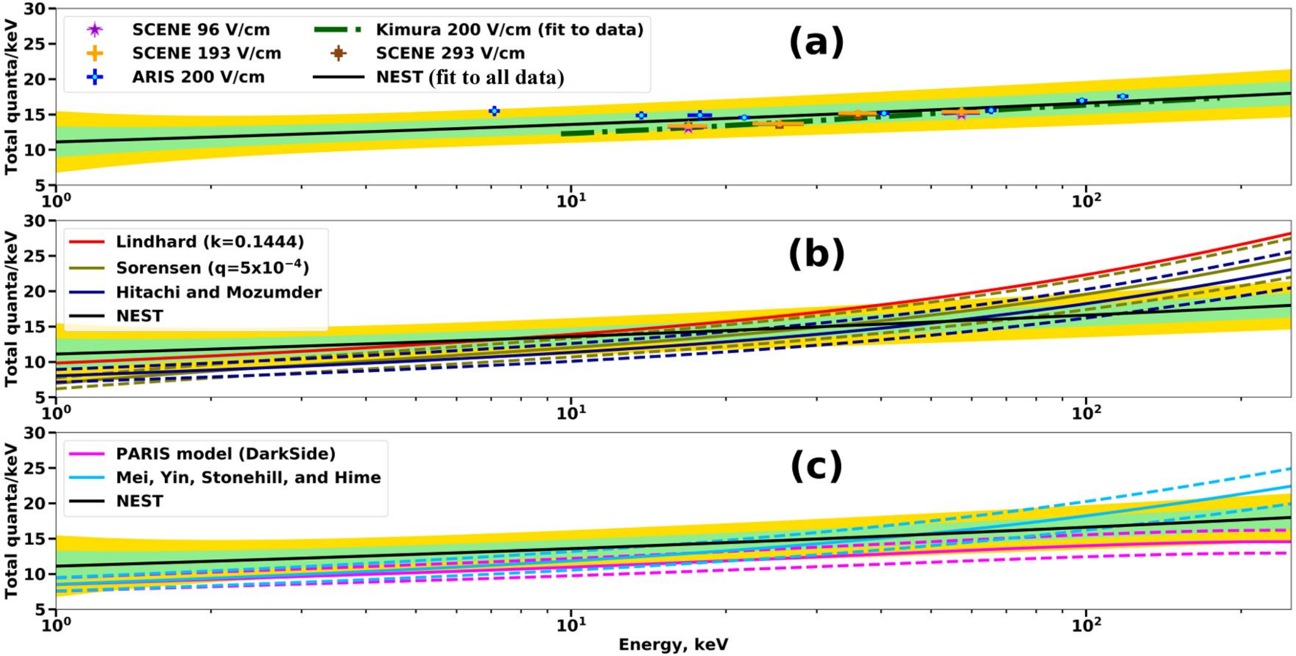


LAr Total Quanta Models compared to data and previous models



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