Noble Element Simulation Technique Version 2.0

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on behalf of the NEST collaboration

NEST collaboration

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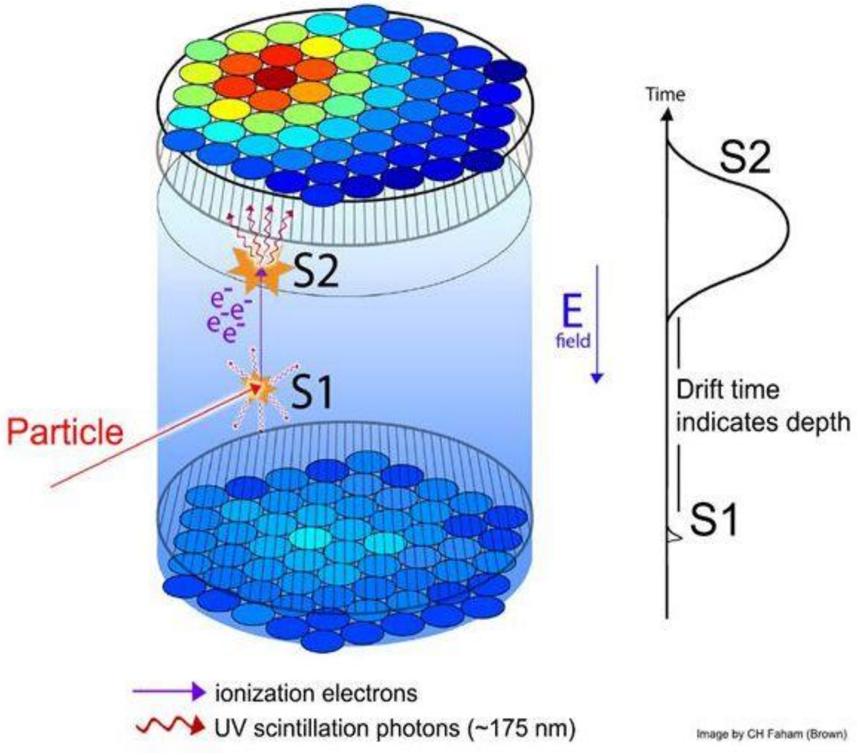
About NEST

- NEST (**Noble Element Simulation Technique**) is an unprecedentedly accurate and comprehensive simulation of the scintillation, ionization, and electroluminescence processes in noble elements.
- Appliciations:
  - Direct dark matter searches (LUX, LZ, XENON10, PandaX…)
  - Double beta decay searches (ever in a low energy ranges (nEXO, etc.)
  -Much more!



What's New?

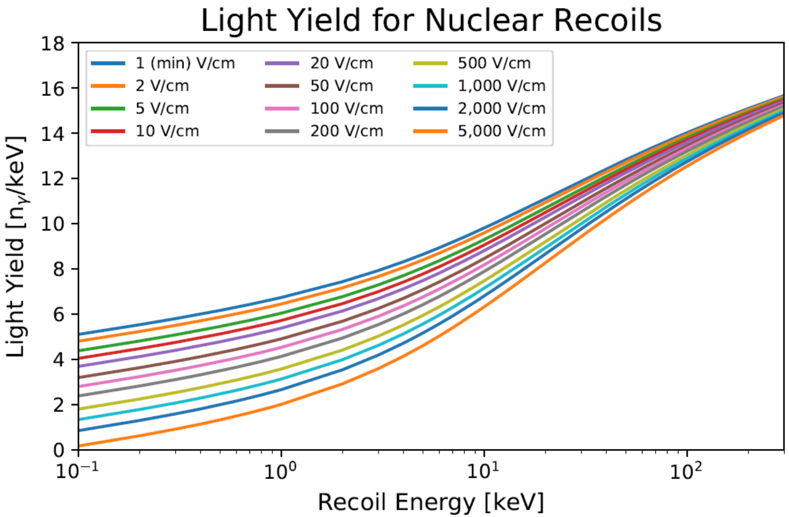
NESTv1.0	NESTv2.0
Only GEANT version	Standalone & GEANT versions
No alphas and heavy ions	Alphas and heavy ions simulations included
All equations based on theoretical models (Thomas-Imel box, Doke-Briks, etc.)	Using sigmoids (family of S-shape functions), which still closely resemble those models.

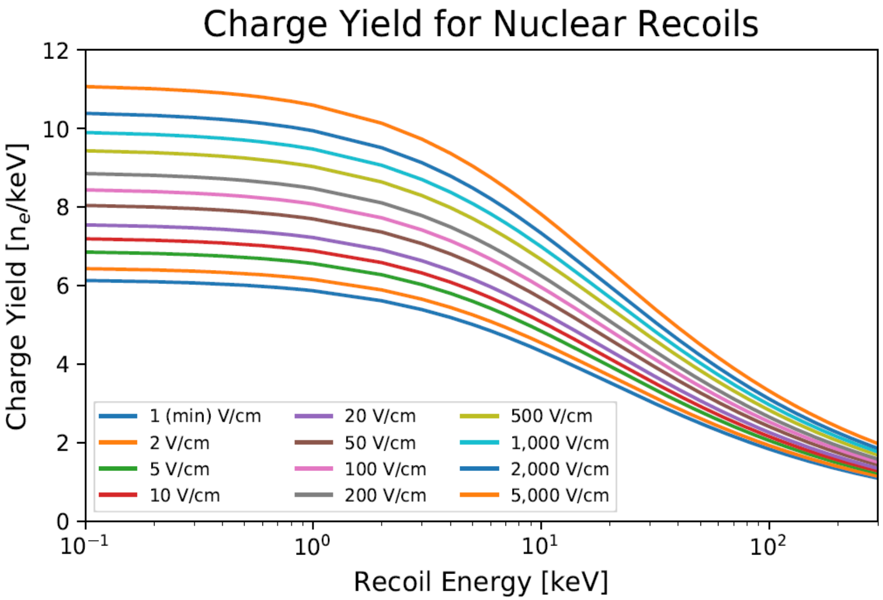
What’s New?

- Revisited old data, corrected for newer phenomena
    - Includes 2PE effect for VUV photons in PMTs
    - Allowed ‘zero-field’ to vary (i.e. took into account possible errors in detectors’ electronics)
    - Allowed extraction efficiency to vary
    - ER: β-model vs. γ-model
- Exciton-Ion ratio is energy-dependent
- Accurately models detector effects for S1-S2 bands (means, widths, leakages)

Nuclear Recoils

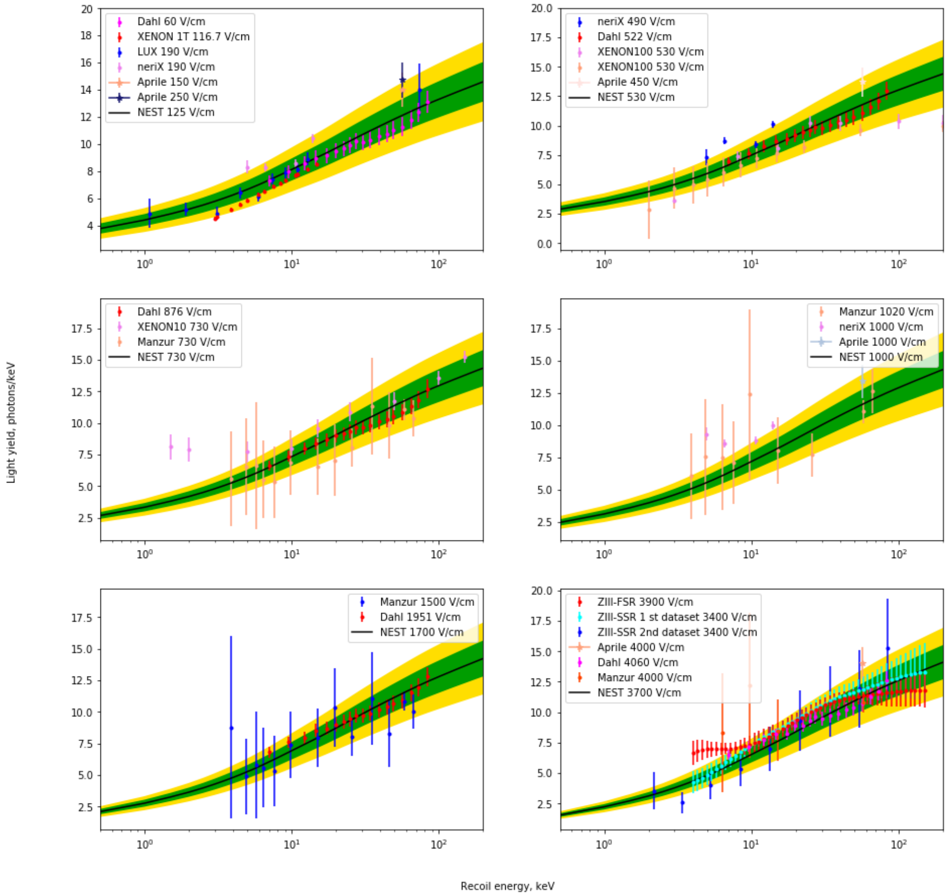
- Total quanta (light+charge) is now a power law
  - 12.6 * (Energy)^1.05
    - Elegant → almost linear
  - 12.6 ± 0.9 & 1.05 ± 0.05
- Mean-yields equations replaced with simple functions





$$Qy = \frac{1}{A * (energy + B) ^ {0.5}}$$

Nuclear Recoils

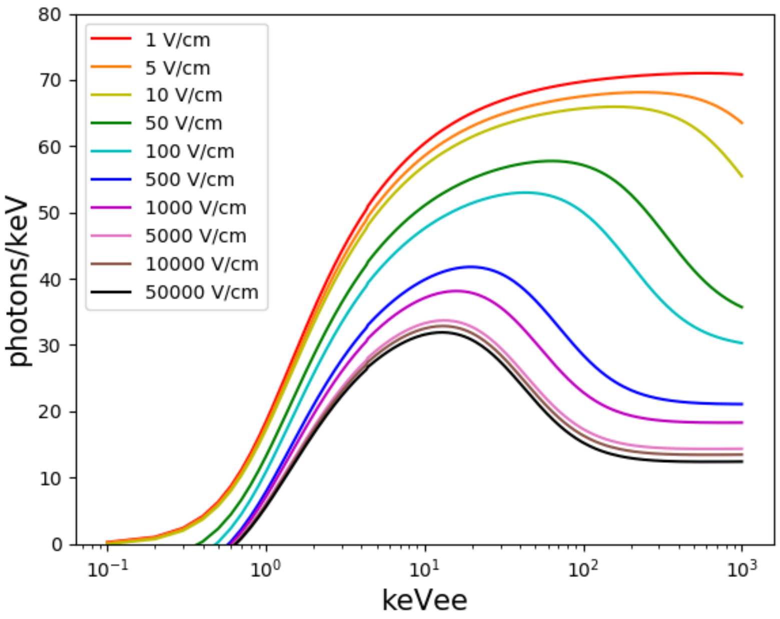


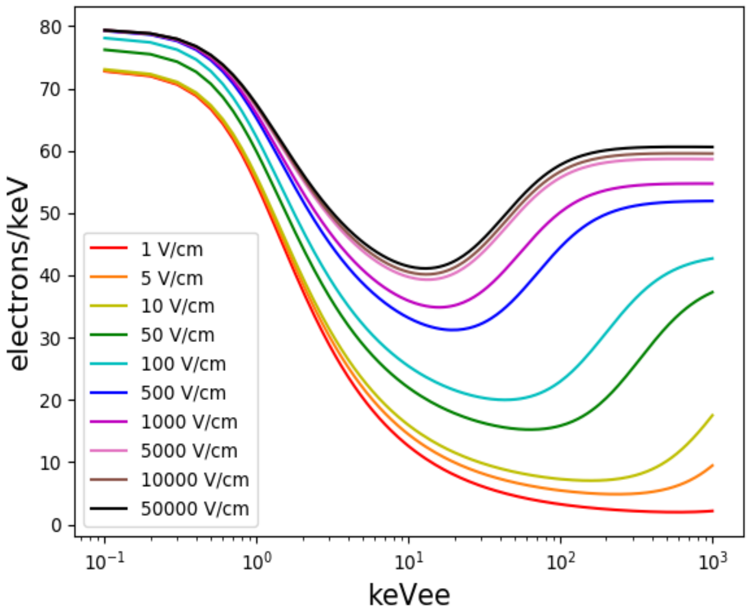
Agrees with known data in 1-sigma margin of error, including high fields experiments

Electronic Recoils -- Sum of Two Sigmoids

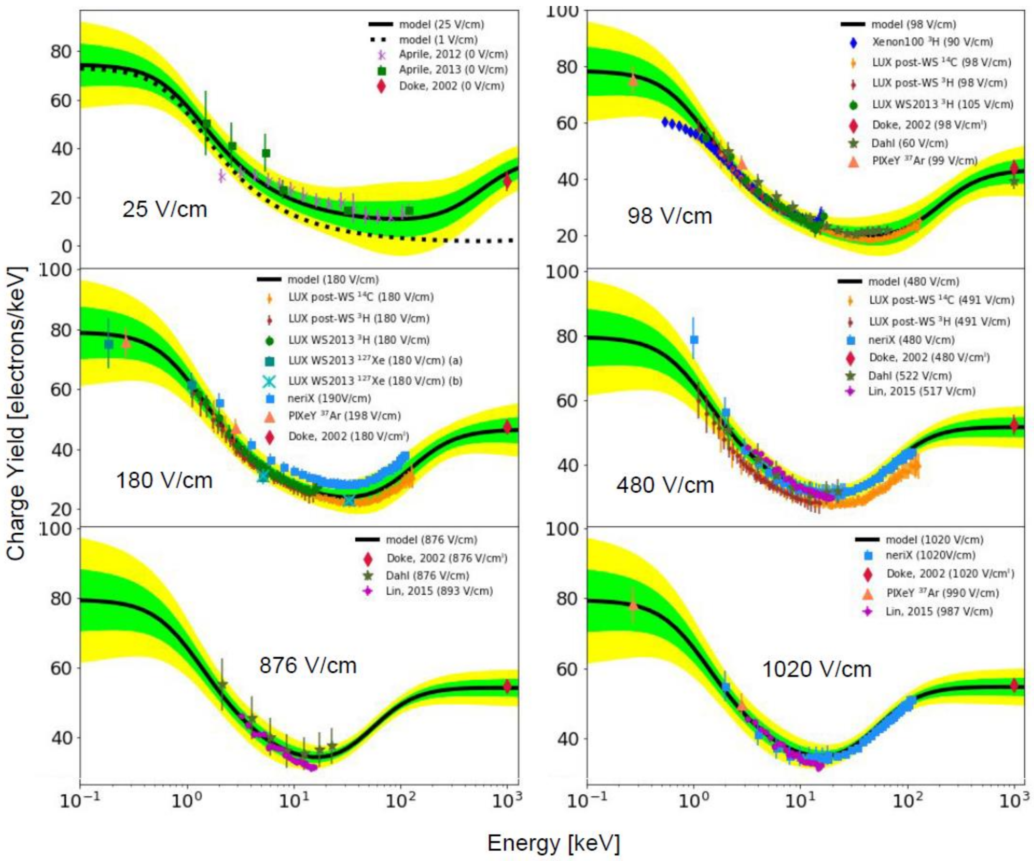
- Smooth transition between low and high energies
- Ly+Qy = const

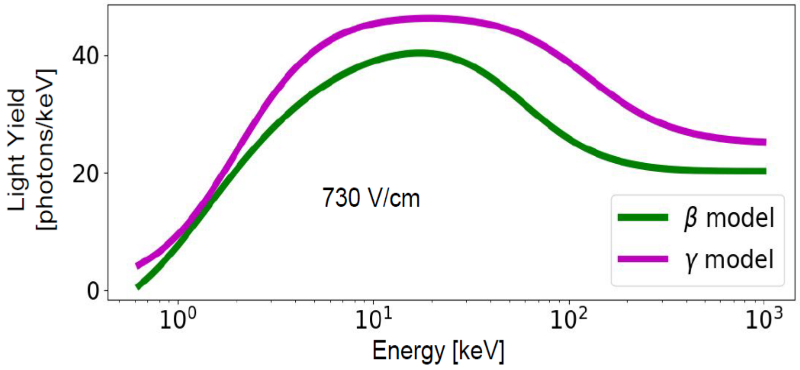
Beta electron recoils: Ly and Qy





Electronic Recoils



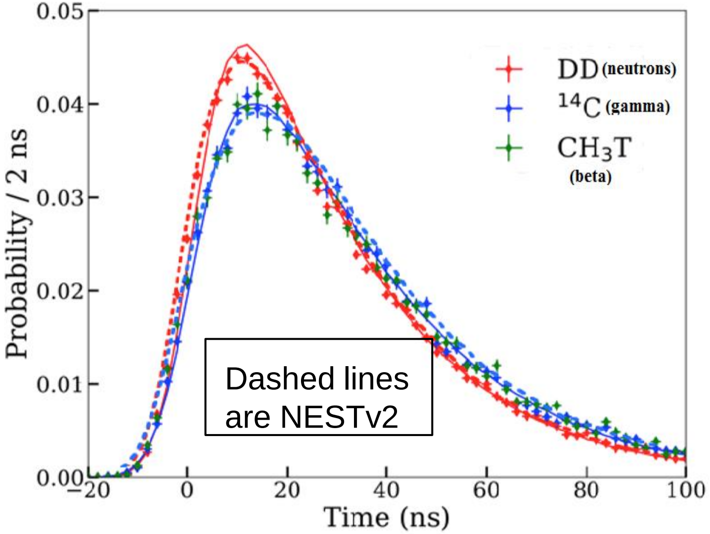


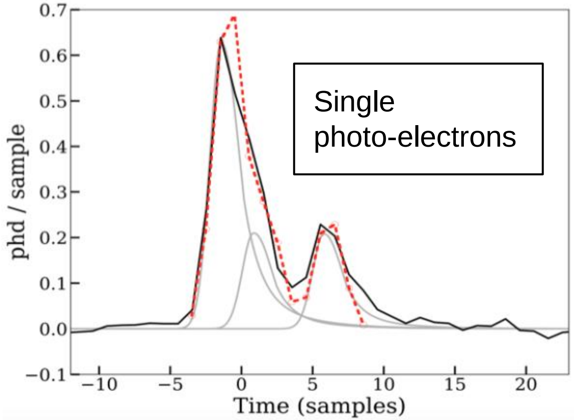
Two separate models for ER: beta and gamma

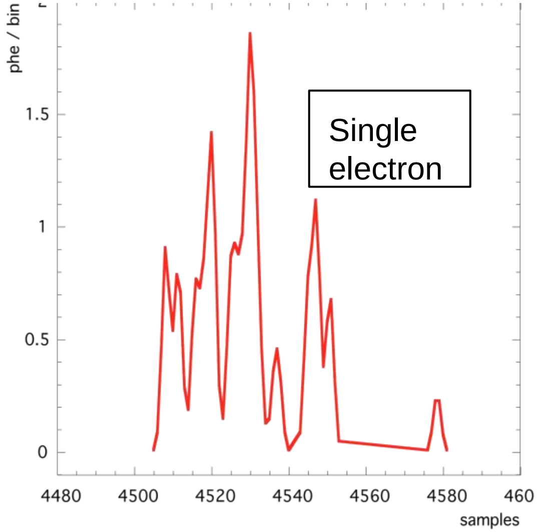
Pulse shapes and single electrons

- Matches LUX pulse shape discrimination
- Can also simulate single electrons!
- Simulates SE noise in LXe

Histograms of scintillation photons arrival times

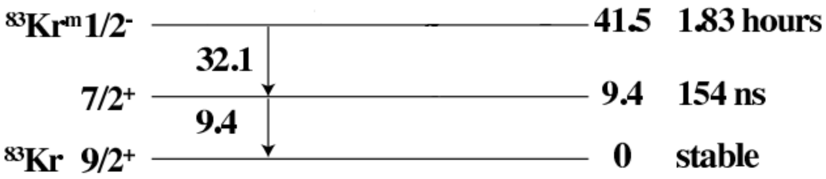


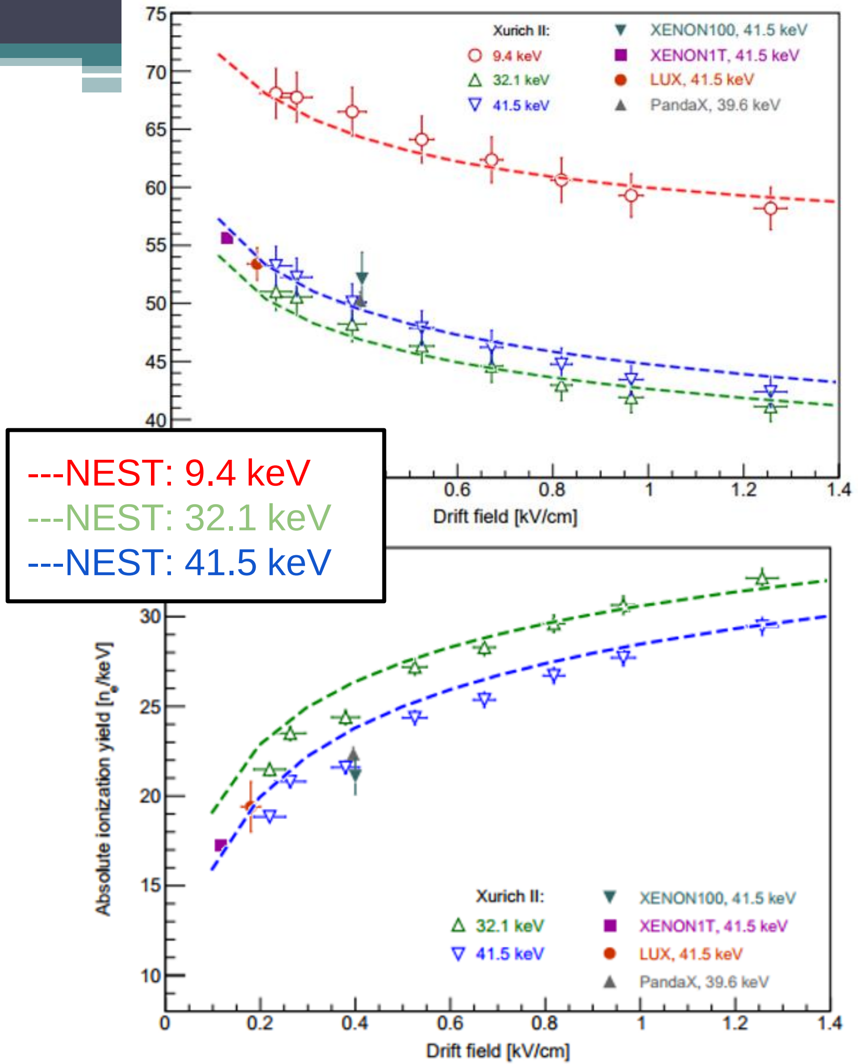




83mKr

- Robust time-dependent model
- Matches individual decays as well as ‘merged’ decay





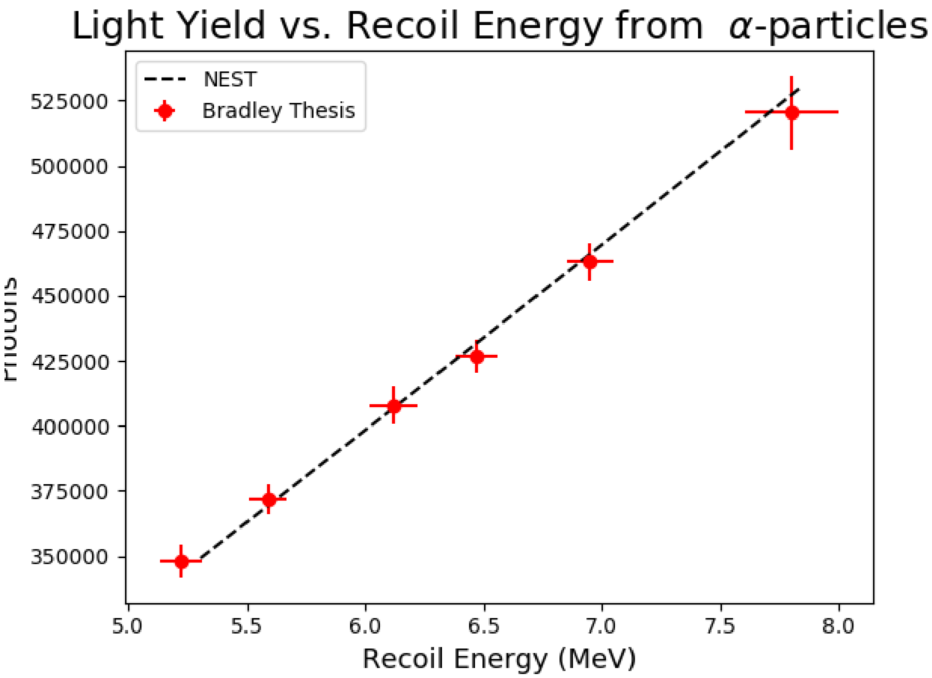
^{83m}Kr

- 1 σ agreement with LUX and XENON100

	Drift Field (V/cm)	Photons/keV, Electrons/keV	NEST Result
LUX Ly	180	53.4 ± 1.4	53.0
LUX Qy	180	19.4 ± 1.4	20.0
XENON100 Ly	366	52.5 ± 1.8	50.6

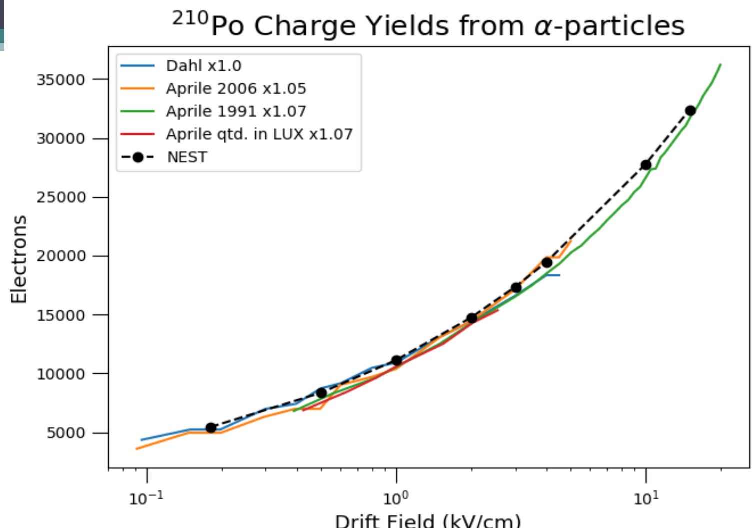
α-Model

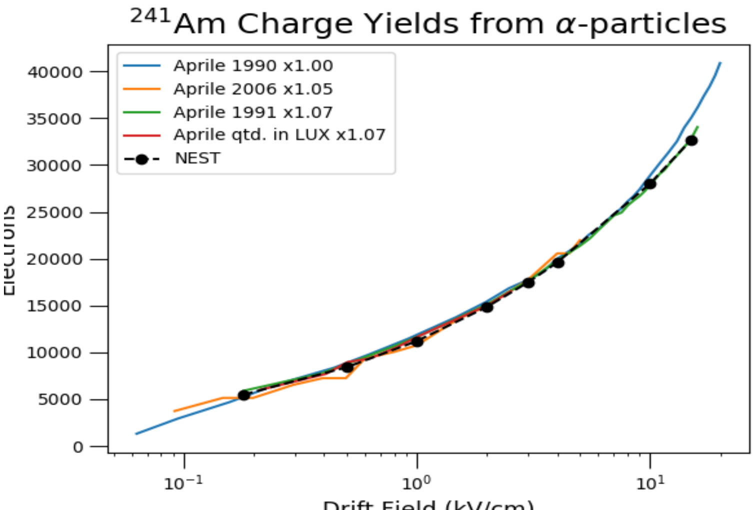
- L-factor fixed by fitting to Adam Bradley's thesis data
  - (LUX: 180V/cm)
- Still uses Thomas-Imel box model here
  - Energy-independent for simplicity



α-Model

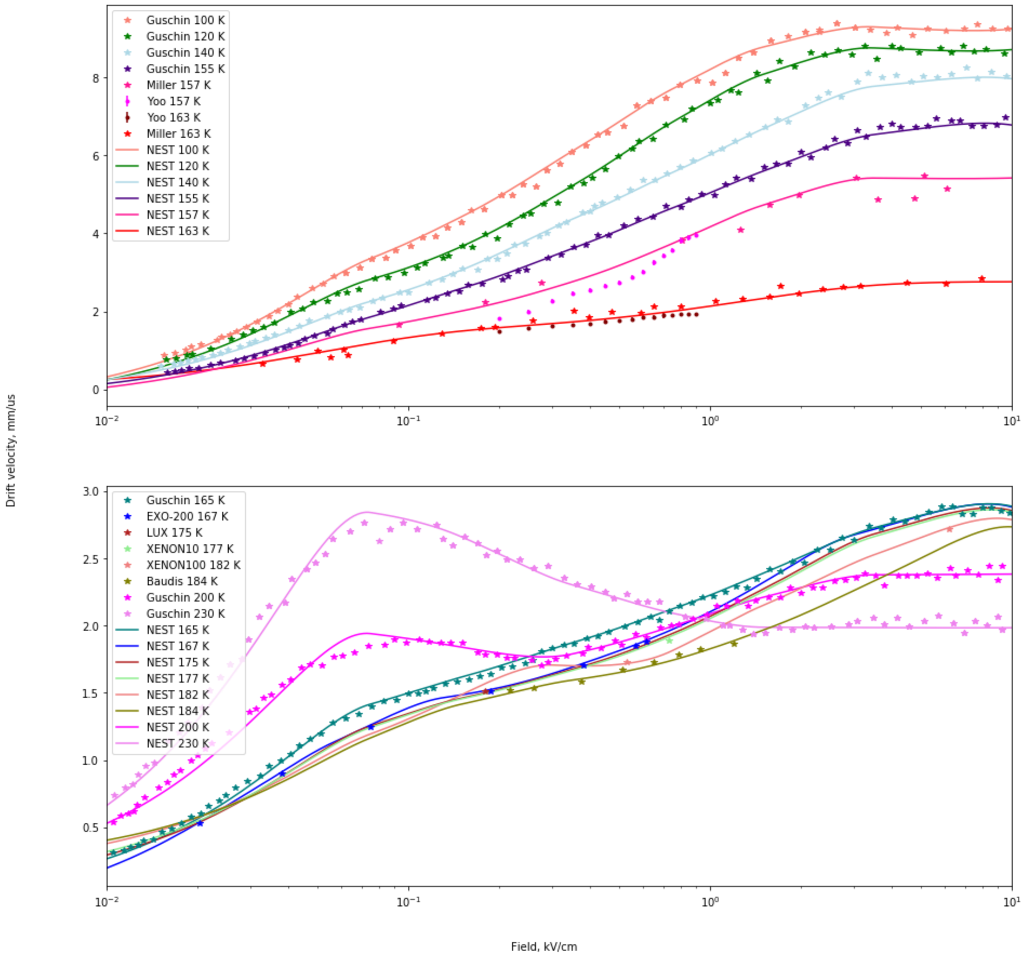
- Worked by slighly correcting data for extraction efficiency
- Good agreement for strong fields





Drift velocity

- NEST also simulates drift velocity for various xenon temperatures and states
- Has good agreement with old and new data



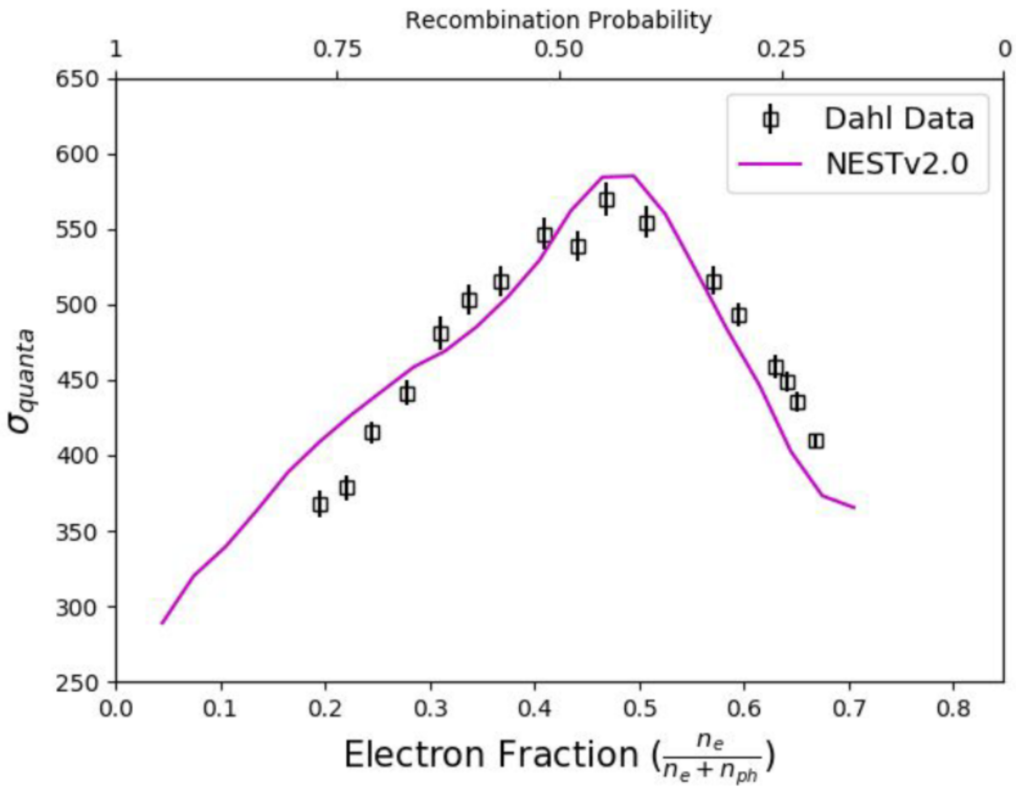
Energy Resolution

- Quantum Fluctuations
  - First estimates of fluctuations in energy resolution and fluctuations in quanta produced were by Ugo Fano in the 1940's.
  - There is energy "lost" when photons are produced in LXe from electron recoils!
  - $E = W^*(n_\gamma + n_e) \rightarrow$ Work Function: $W = 13.7$ eV
  - Fluctuations modeled using an empirical "Fano-like" factor proportional to sqrt(energy)*sqrt(field)
- Recombination Fluctuations
  - Binomial recombination has never matched data well.
  - Same equation as cited in LUX Signal Yields Publication: $\sigma_T^2=(1-p)^*n_i^*p + (\sigma_p n_i)^2$
    - σ_p in NEST is both field-dependent and energy-dependent

Recombination Fluctuations

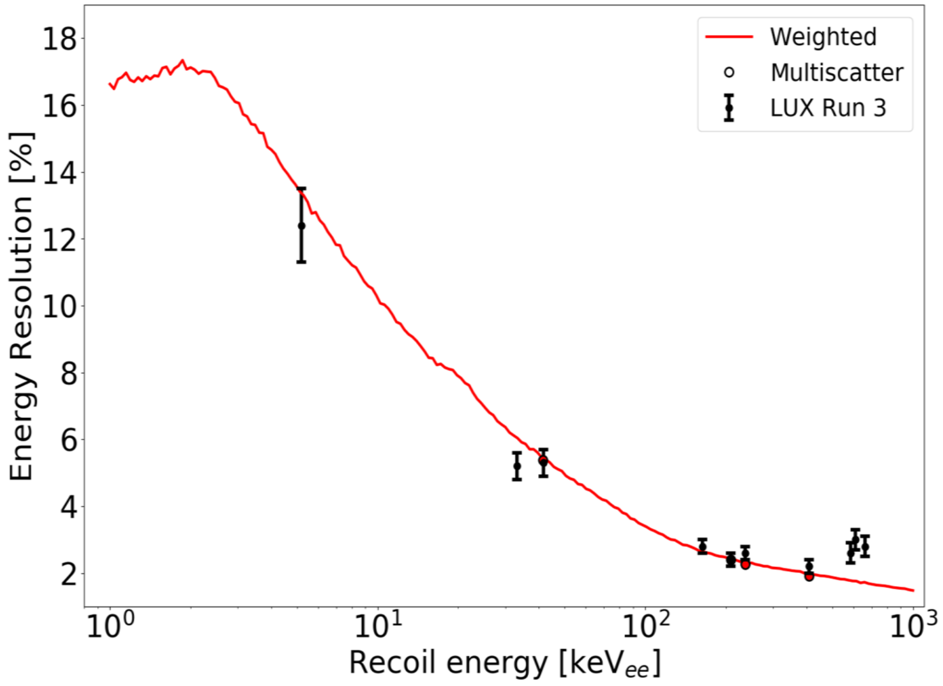
- Comparing to Eric Dahl's PhD thesis data.
- Corrected Dahl data for overestimation: corrected 15% downward for 2PE effect and extraction eff.

$\sigma_T^2 = (1-p) * n_i * p + (\sigma_p n_i)^2$

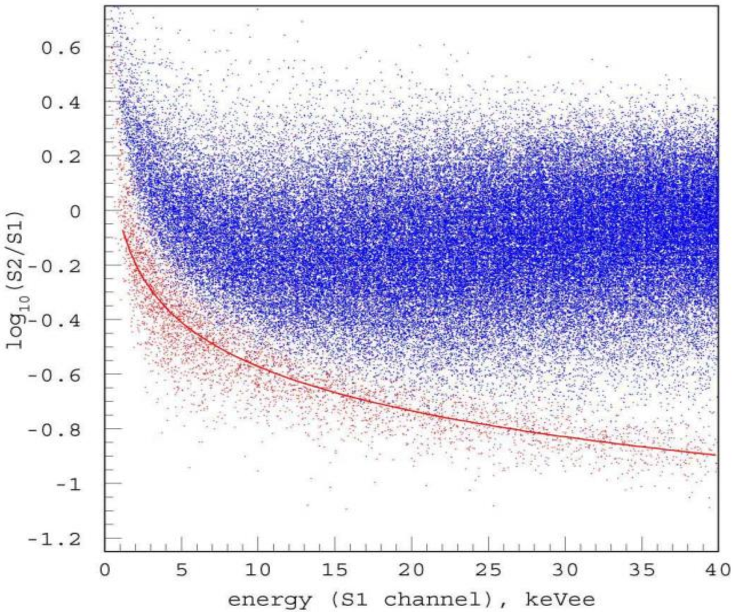


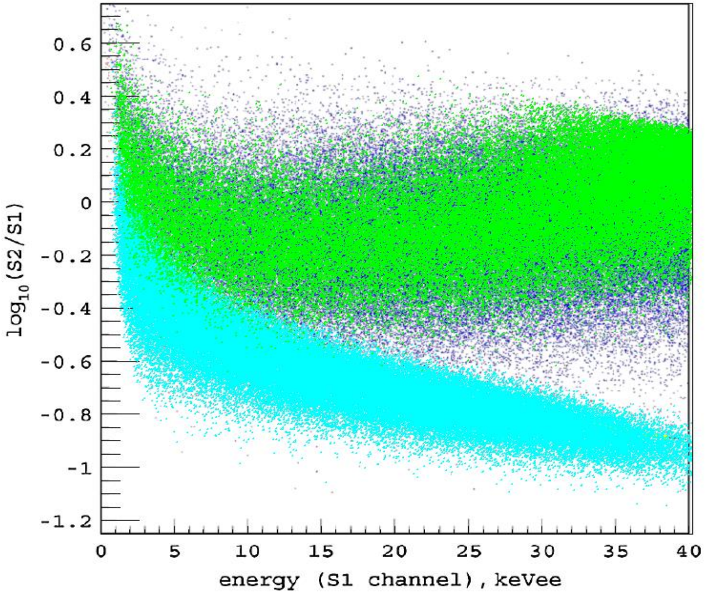
Energy Resolution: LUX

- Good fit to LUX Run 3
- β-model better at lower energies. Fit here uses a weighted combination of NEST's β and γ models



Energy Resolution: ZEPLIN-III



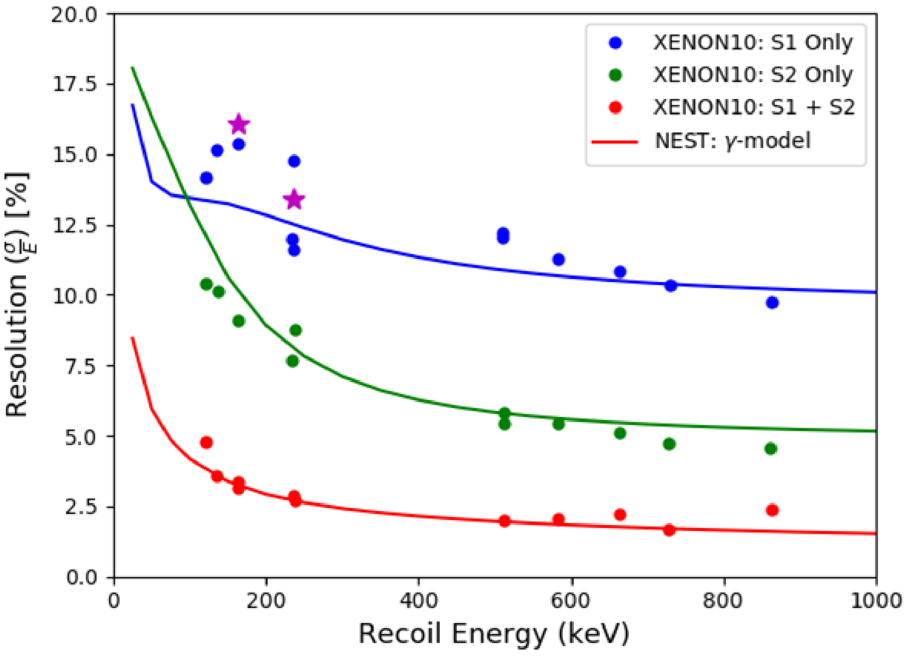


NEST matched original Z-III resolution (99.999% on AmBe and beta data) and AmBe and beta distributions (ever means)

Light blue → NESTAmBe data
Green → NEST β data

Energy Resolution: XENON10

- Good agreement with XENON10 energy resolution
  - Optimized a Fano-like factor for best agreement → Data suggested field & energy dependence
  - Data suggests that the Fano factor is both energy-dependent and field-dependent
- Magenta stars are ^{129m}Xe & ^{131m}Xe
  - Decay in many steps, used NEST to combine the yields from each decay and added them together
  - ^{83m}Kr model suggests that multi-step decays have subtle time-dependence

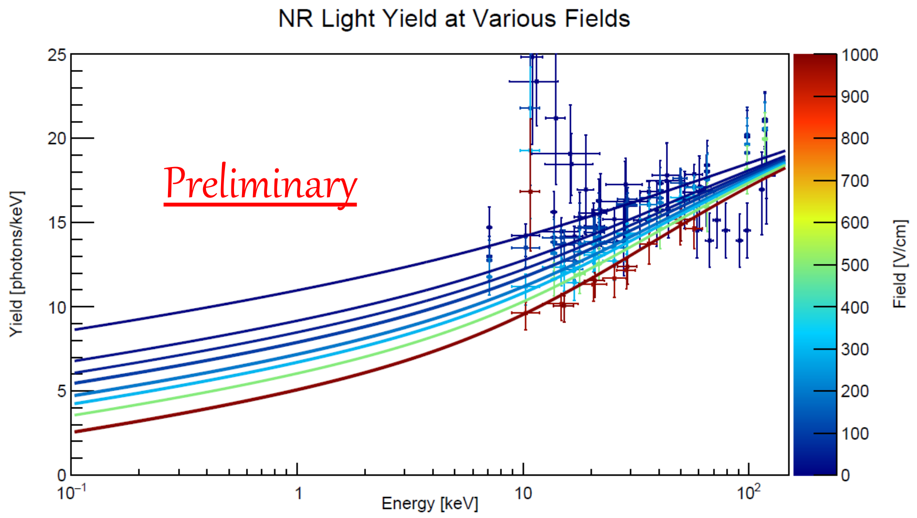


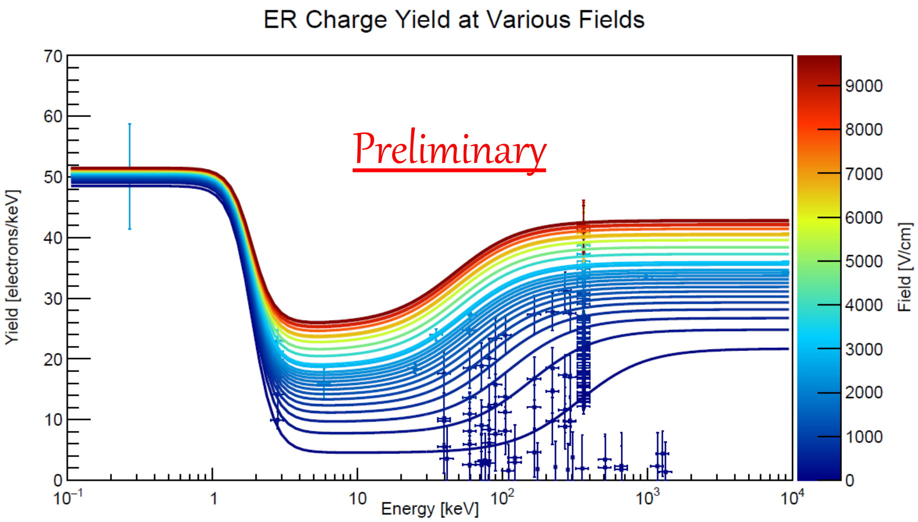
arxiv.org/pdf/1001.2834.pdf

Argon NEST

- Argon NEST is under-development version of NEST for argon
- Assumption: both Xe and Ar are noble elements – and formulae would be similar sigmoids for Ar too
- Empirical models for argon are very important – because theoretical models sometimes are contradictory to each other

Argon NEST





- Preliminary models for NR and ER are ready
- Kr and heavy ions models are under development

Conclusion

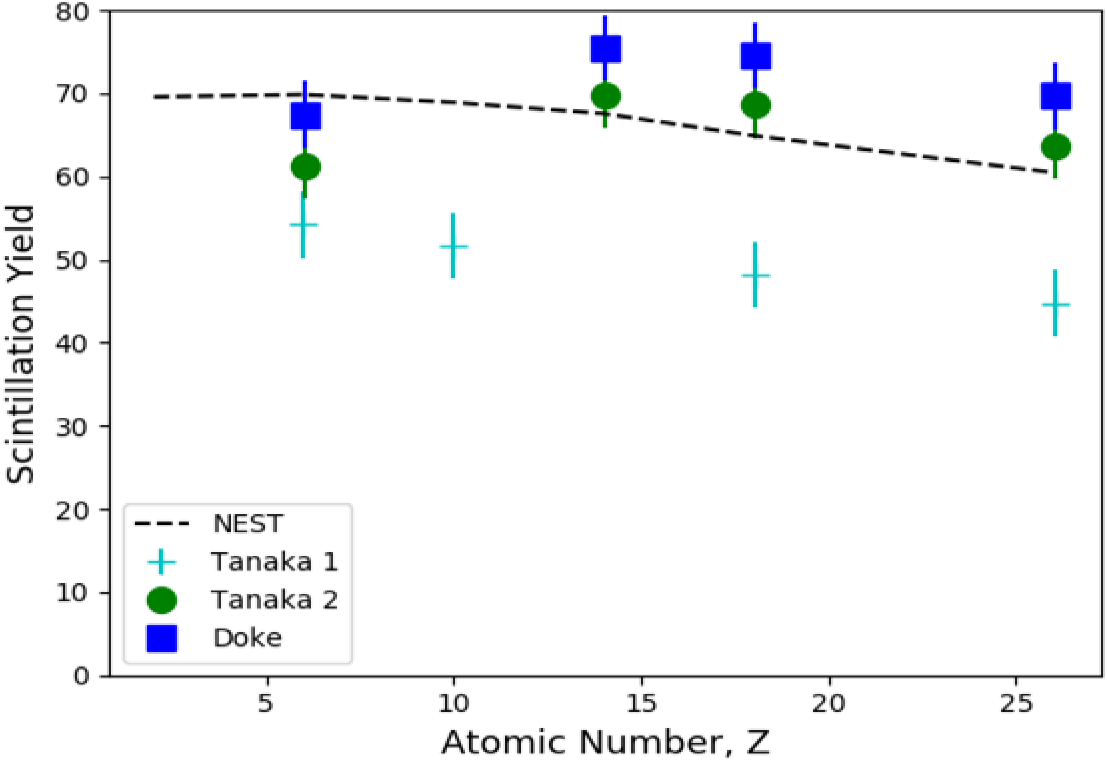
- NESTv2 is a powerful simulation tool, which now has two versions: standalone tool and GEANT4 library.
- Accurately simulates many different interactions in LXe and GXe (argon models currently in process)
- User-friendly code so you can add any other interactions that you might find useful.
- Get yourself a copy!
  - **https://github.com/NESTCollaboration/nest**
  - **nest.physics.ucdavis.edu**

Thank you for your attention!

Backup Slides

Heavy Nuclei

- Expanded the α-model to include scattering events with heavy ions
- Again, contradictory data sets, splits the difference

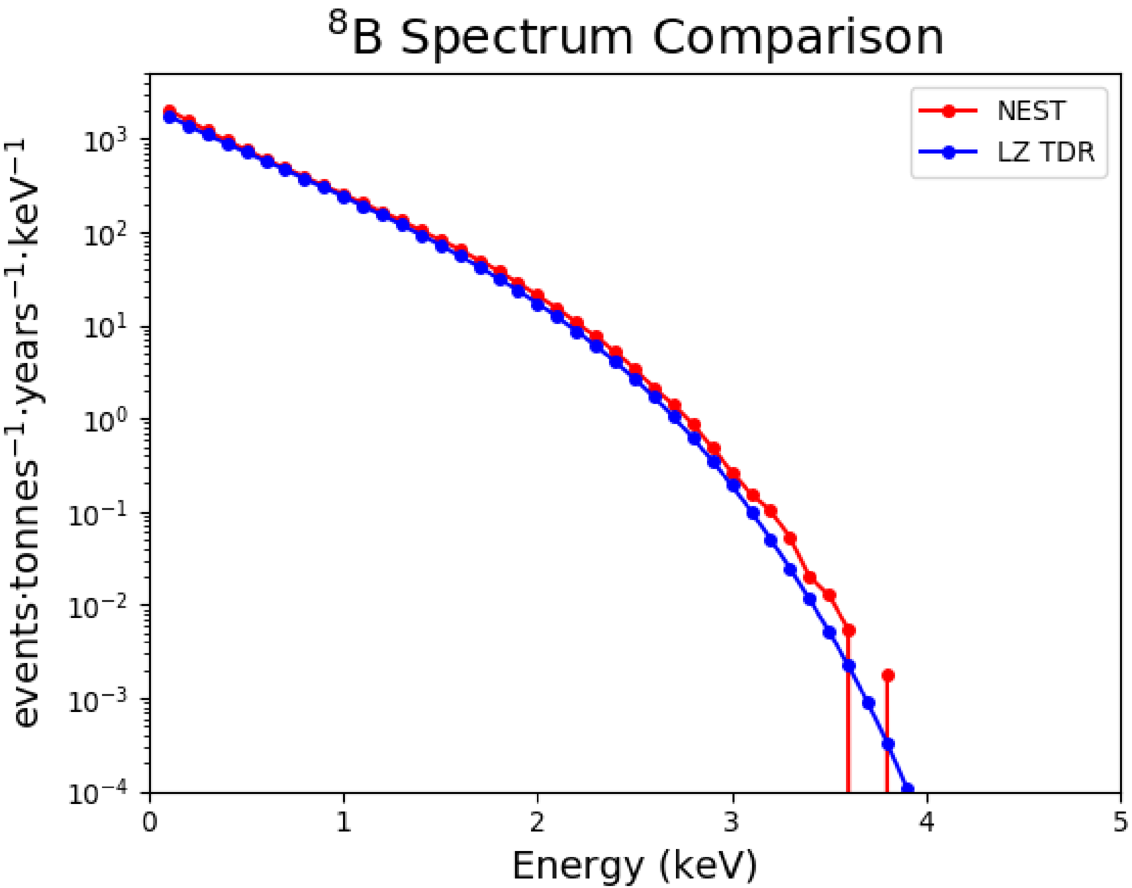


Absolute Scintillation Yields in Liquid Argon and Xenon for Various Particles
T. Doke, et. al. 2002.
[Japanese Journal of Applied Physics](), [Volume 41](),
[Part 1, Number 3A]()

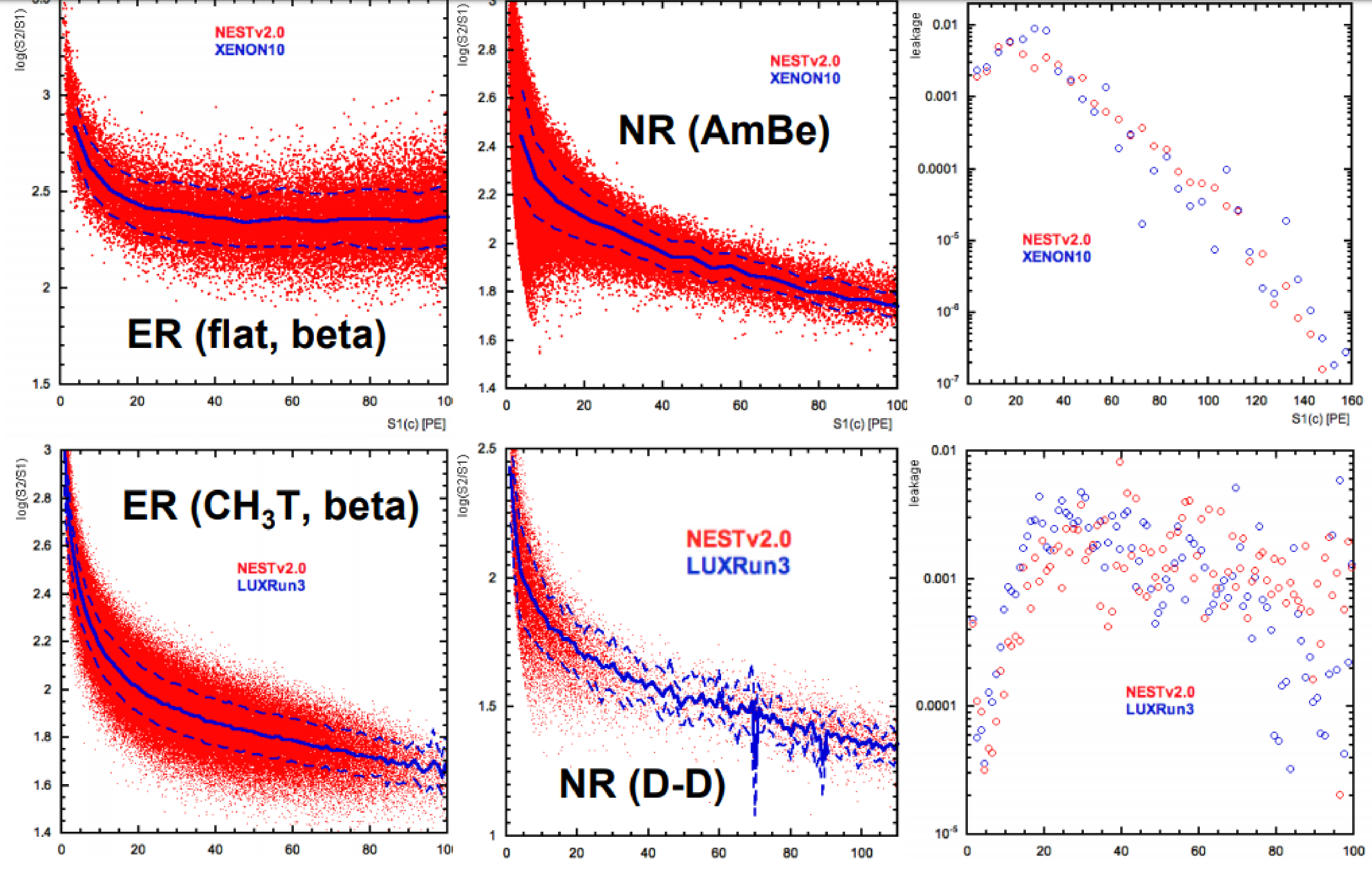
LET dependence of scintillation yields in liquid xenon
M. Tanaka, et. al. 2001

Boron-8

- Great agreement with LZ TDR ^{8}B spectrum.
- Not a look-up table!



LUX-ZEPLIN (LZ) Technical Design Report
B.J. Mount (Black Hills State U.) *et al.*. Mar 27, 2017. 392 pp.
LBNL-1007256, FERMILAB-TM-2653-AE-E-PPD
e-Print: **arXiv:1703.09144 [physics.ins-det]**



Going Full-Scale with Detector Effects

NESTv2 accurately reproduces NR and ER bands.

X10 detector file example provided with NESTv2. Easy to change and add your own detector!