Noble Element Simulation Technique Version 2.0

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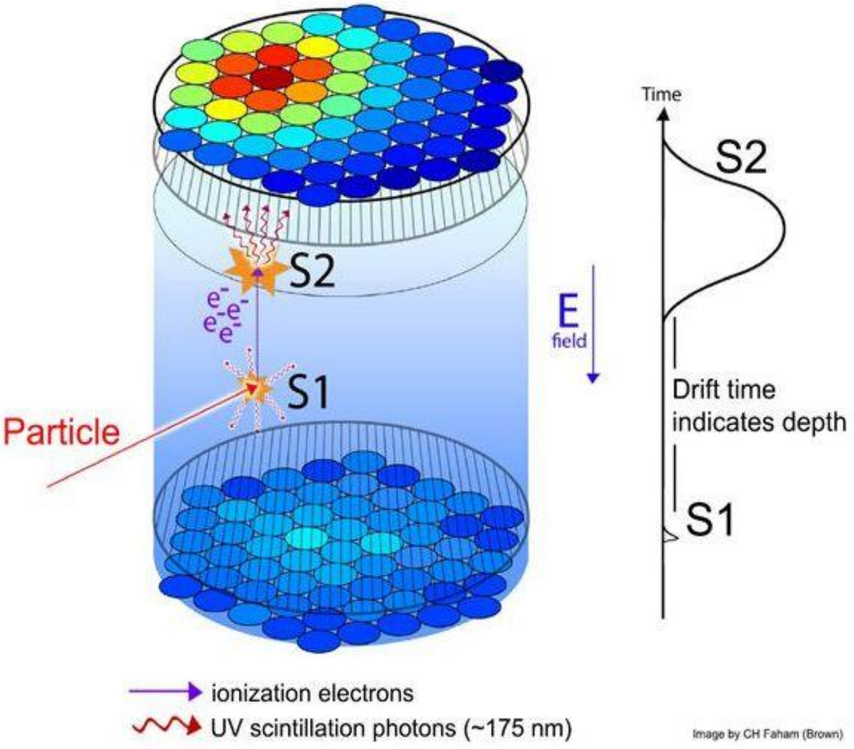
ICPPA-2018, Moscow, Russia

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 (RED, nEXO, etc.)
  -PET scans
  -Much more!



What's New?

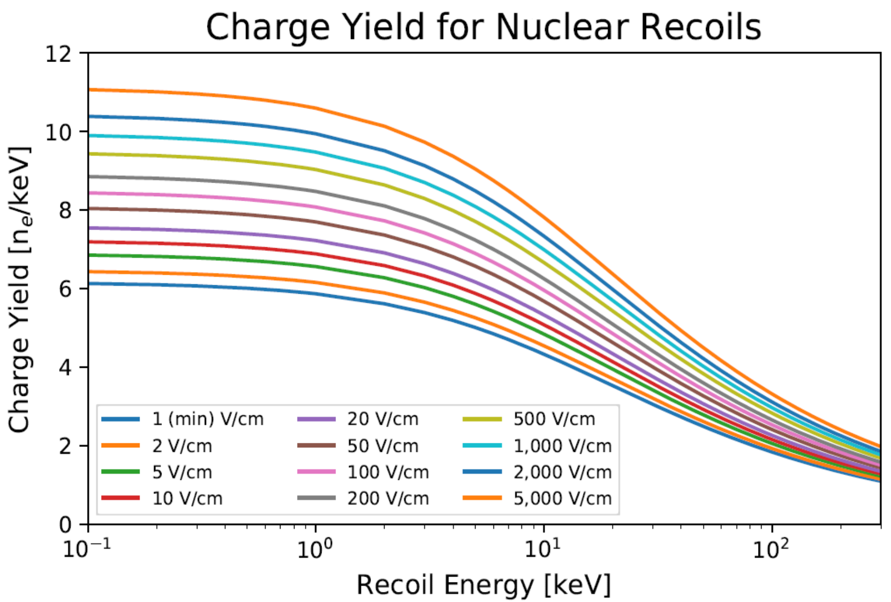
NESTv1.0	NESTv2.0
Only GEANT version	Standalone & GEANT versions
No alphas and heavy ions	Alphas and heavy ions simulations included
All equations based on theoretical models (Thomas-Imel box, Doke-Briks, etc.)	<u>Using sigmoids (family of S-shape functions)</u>, which still closely resemble those models.

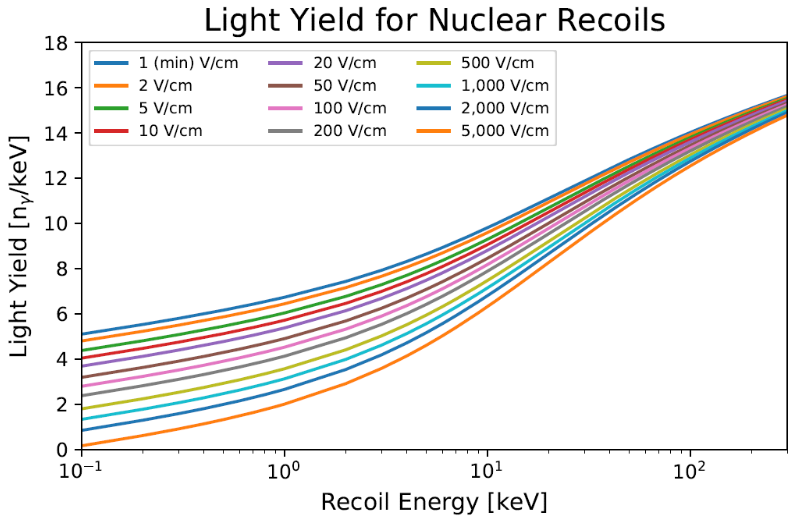
What's New?

- 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

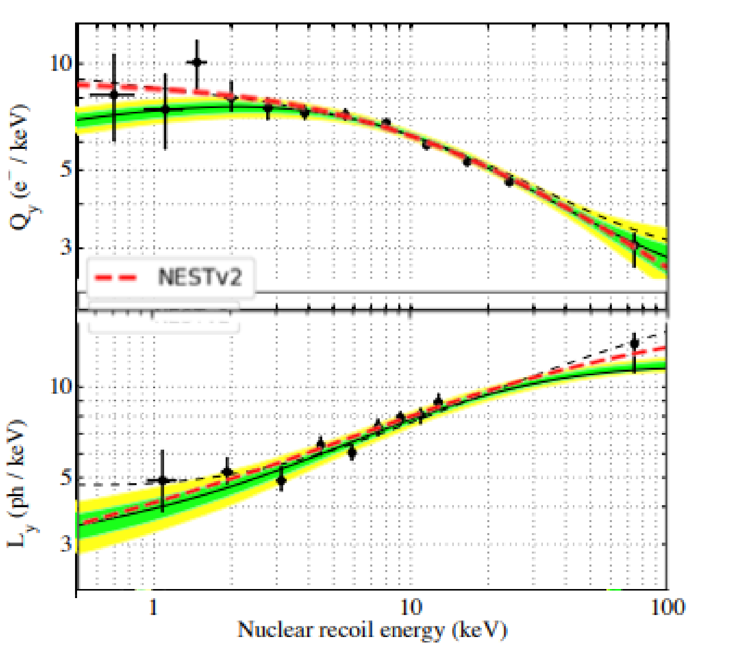




$$Qy = \frac{1}{A * (energy + B) ^ 0.5}$$

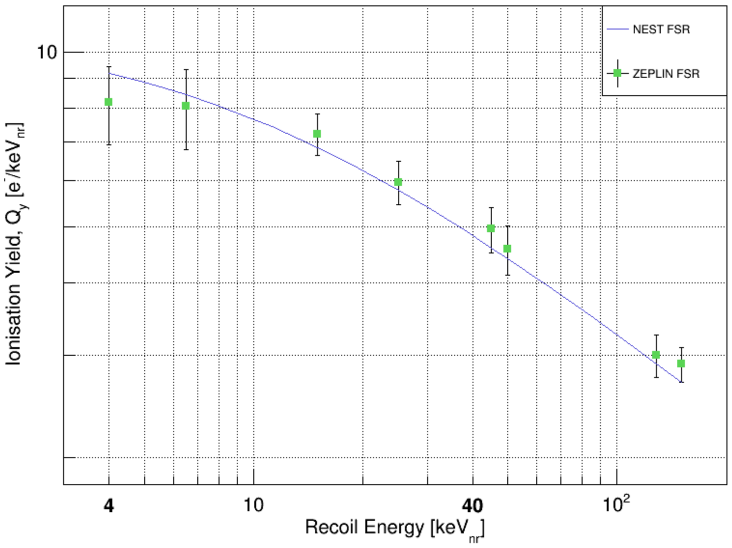
LUX D-D (neutron) comparisons (180 V/cm)

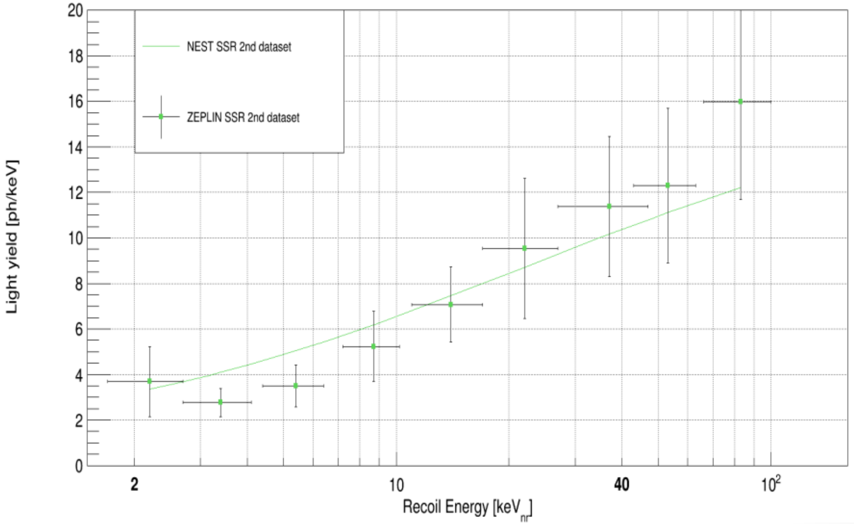
- Better match to light and charge yields than before!
- Solid and dashed black lines are the Lindhard and Bezrukov parameterizations, respectively.



Improved Limits on Scattering of Weakly Interacting Massive Particles from Reanalysis of 2013 LUX Data
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Dec 10, 2015. 7 pp.
Published in **Phys.Rev.Lett. 116 (2016) no.16, 161301**

ZEPLIN-III comparisons (3.4 and 3.9 kV/cm)





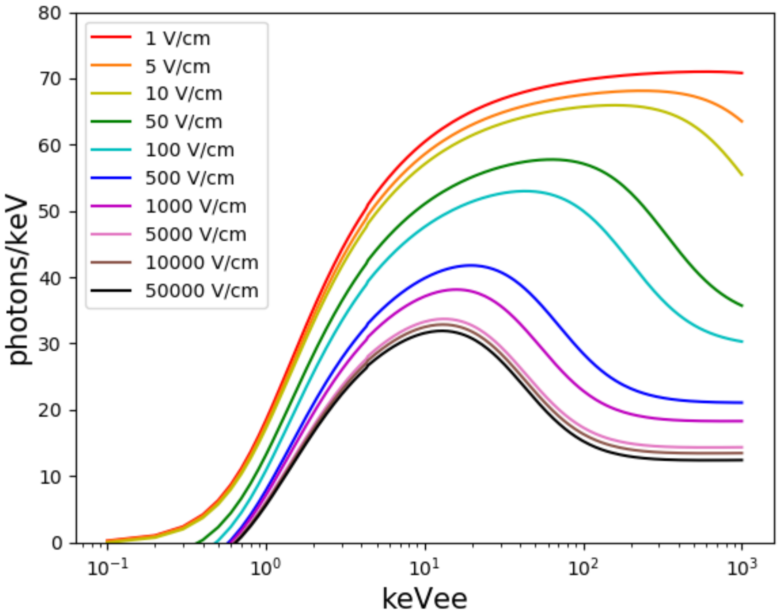
- Good match to data from FSR&SSR runs!

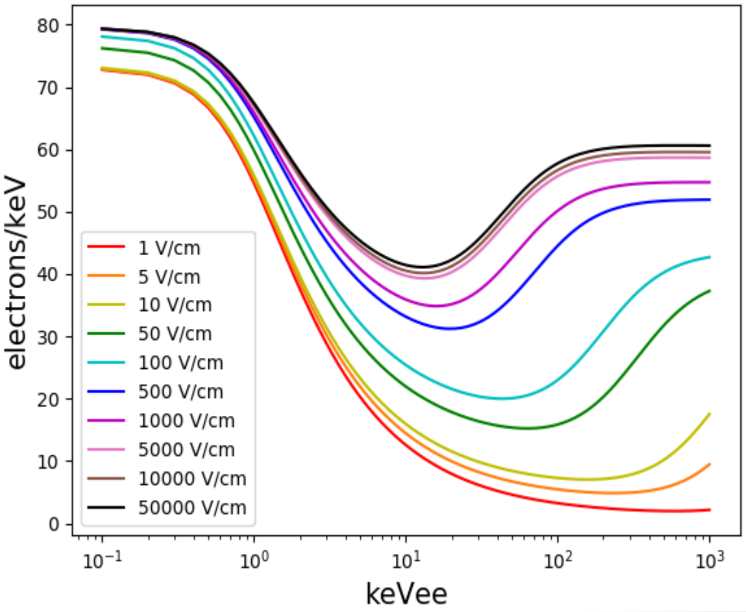
Nuclear recoil scintillation and ionization yields in liquid xenon from ZEPLIN–III data
ZEPLIN-III Collaboration (*M.Horn et al.*). June 3, 2011. 7 pp.
Published in **Phys.Lett. B705 (2011) 471-476**

Electronic Recoils

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

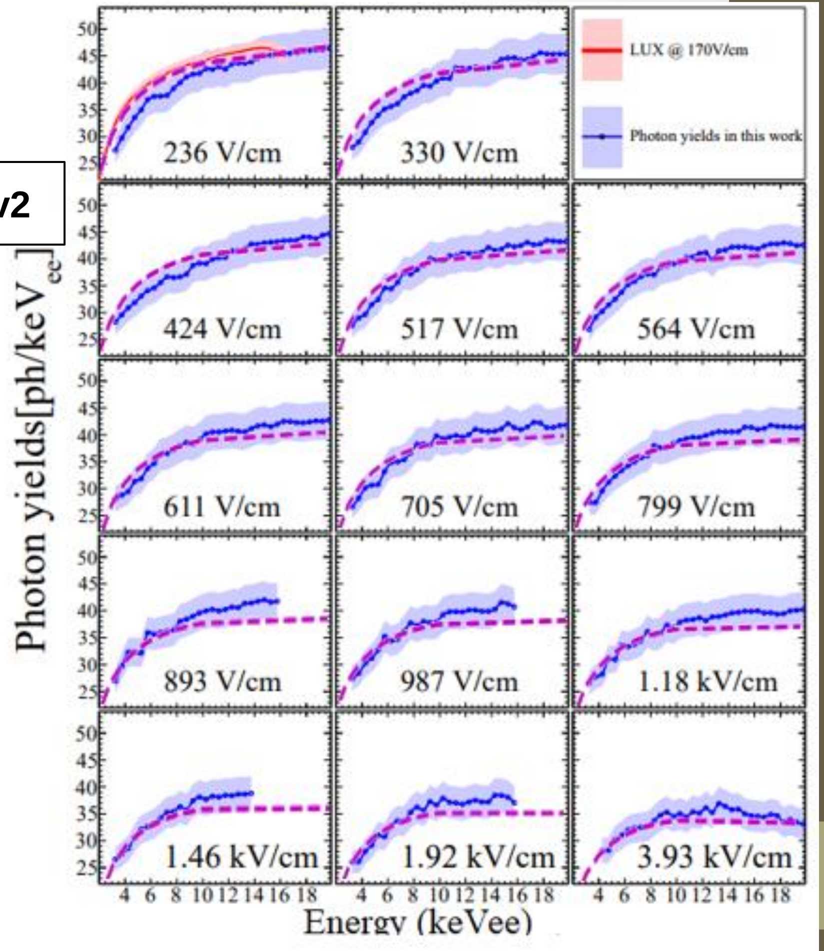
Beta electron recoils: Ly and Qy





LY data comparison for different fields

- LY from ^{137}Cs →Compton Scatters
    - NEST is the purple dashed lines (Original Plot cited below)
- Always matches within 1 σ

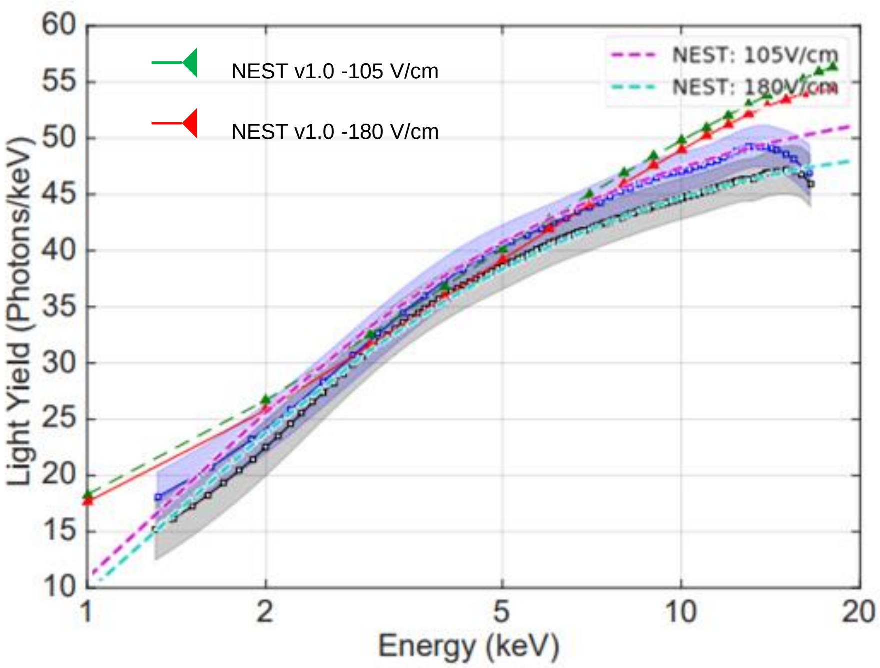


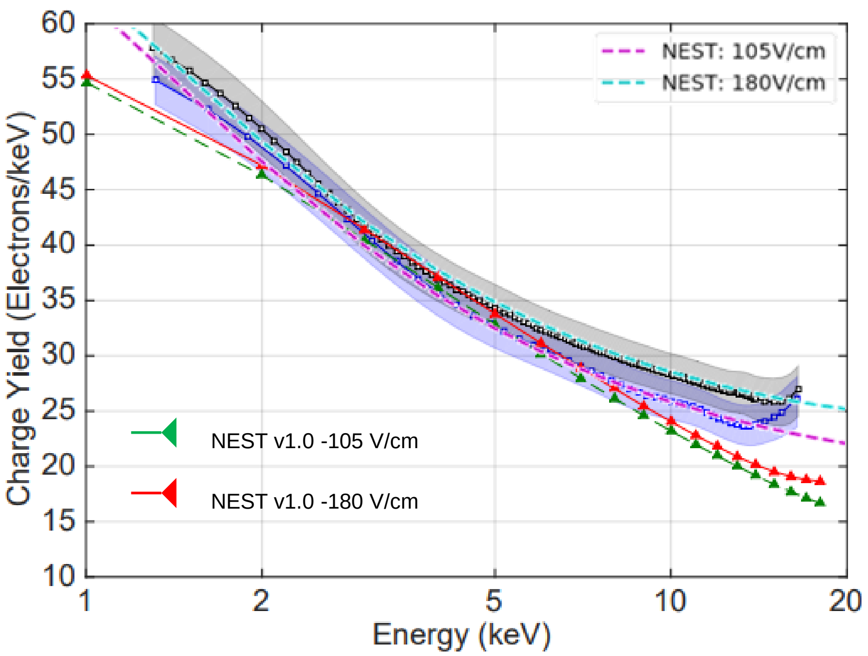
[Scintillation and ionization responses of liquid xenon to low energy electronic and nuclear recoils at drift fields from 236 V/cm to 3.93 kV/cm](#)
Qing Lin, Jialing Fei, Fei Gao, Jie Hu, Yuehuan Wei, Xiang Xiao (Shanghai, Jiao Tong U.), Hongwei Wang (SINAP, Shanghai), Kaixuan Ni (Shanghai, Jiao Tong U.). May 3, 2015. 9 pp.
Published in **Phys.Rev. D92 (2015) no.3, 032005**

LUX Tritium

Tritium calibration of the LUX dark matter experiment
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Dec 9, 2015. 12 pp.
Published in **Phys.Rev. D93 (2016) no.7, 072009**

- Great agreement with both light and charge yields
- Note: Blue bands are LUX data

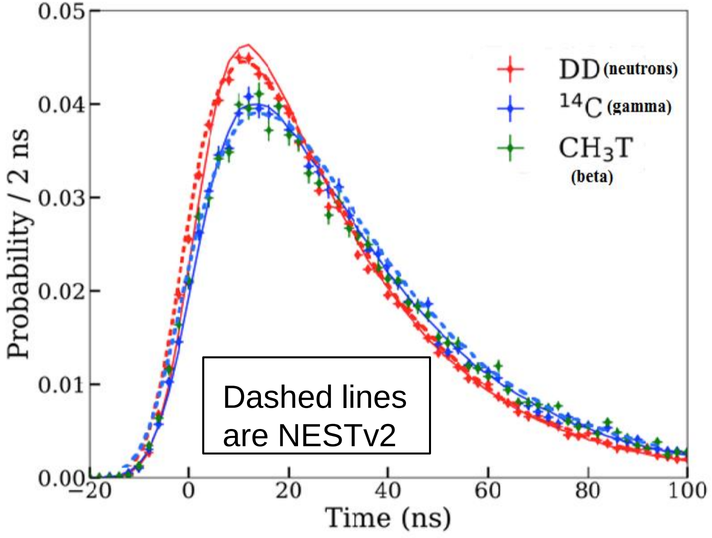


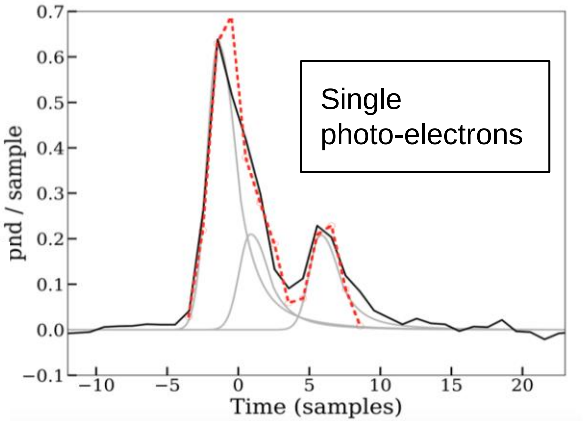


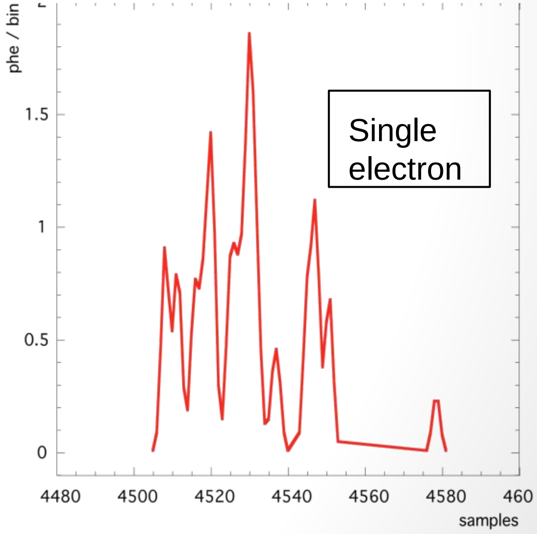
Pulse shapes and single electrons

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

Histograms of scintillation photons arrival times



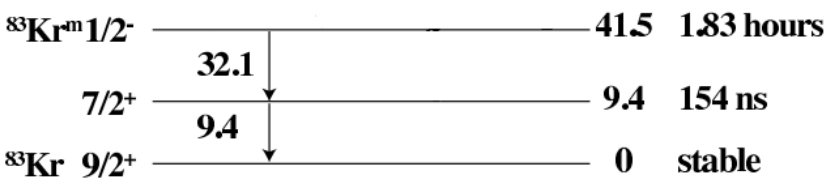


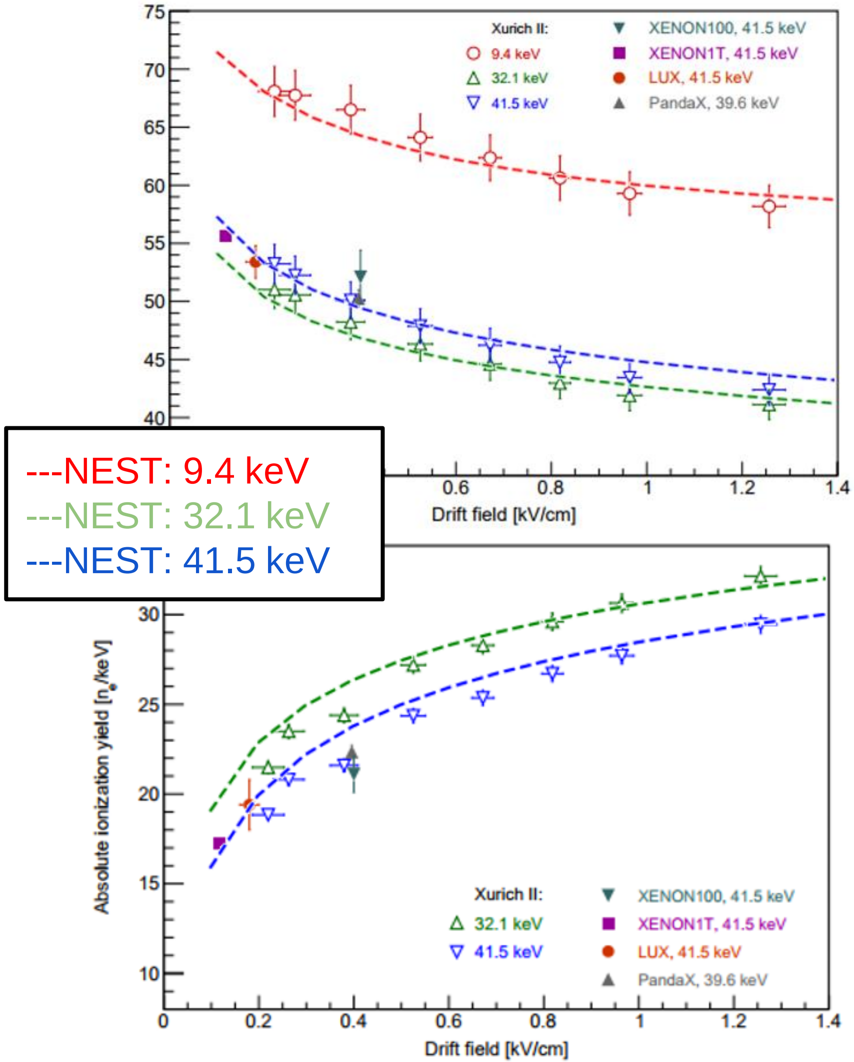


[Liquid xenon scintillation measurements and pulse shape discrimination in the LUX dark matter detector]
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Feb 16, 2018. 16 pp.
Published in **Phys.Rev. D97 (2018) no.11, 112002**

^{83m}Kr

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





A Dual-phase Xenon TPC for Scintillation and Ionisation Yield Measurements in Liquid Xenon
Laura Baudis, Yanina Biondi, Chiara Capelli, Michelle Galloway, Shingo Kazama, Alexander Kish, Payam Pakarha, Francesco Piastra, Julien Wulf.
Dec 22, 2017. 11 pp

^{83m}Kr

- 1 σ agreement with LUX and XENON100

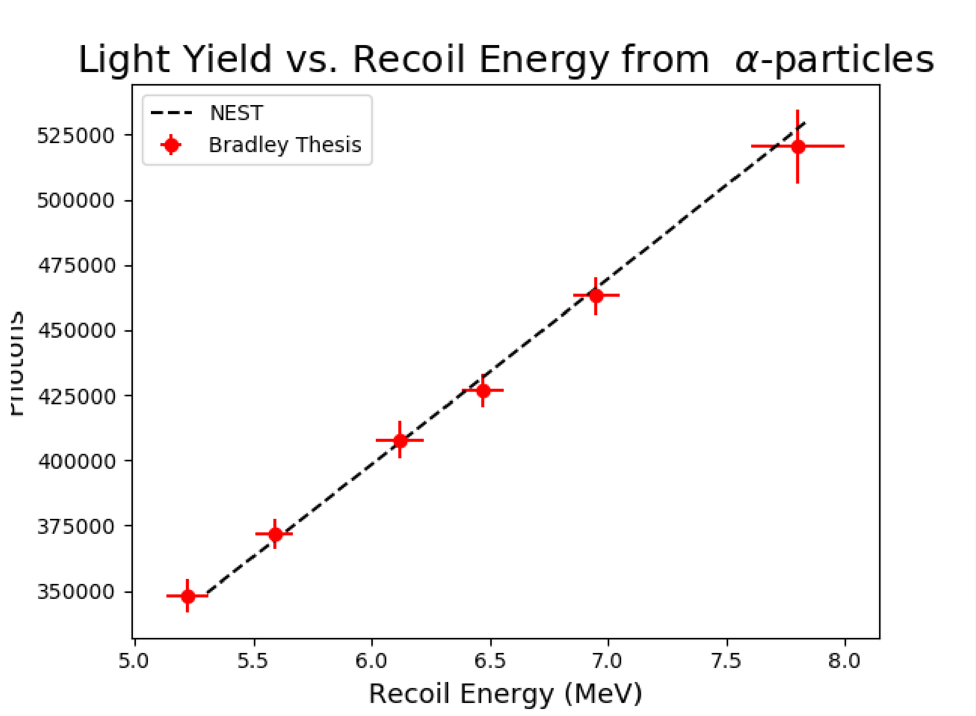
	Drift Field (V/cm)	Photons/keV, Electrons/keV	NEST Result
LUX Ly	180	53.4 ± 1.4	53.0
LUX Qy	180	19.4 ± 1.4	20.0
XENON100 Ly	366	52.5 ± 1.8	50.6

Signal yields, energy resolution, and recombination fluctuations in liquid xenon
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Oct 6, 2016. 12 pp.
Published in **Phys.Rev. D95 (2017) no.1, 012008**

Signal Yields of keV Electronic Recoils and Their Discrimination from Nuclear Recoils in Liquid Xenon
XENON Collaboration (E. Aprile (Columbia U.) *et al.*). Sep 28, 2017. 11 pp.
Published in **Phys.Rev. D97 (2018) no.9, 092007**
DOI: 10.1103/PhysRevD.97.092007

α-Model

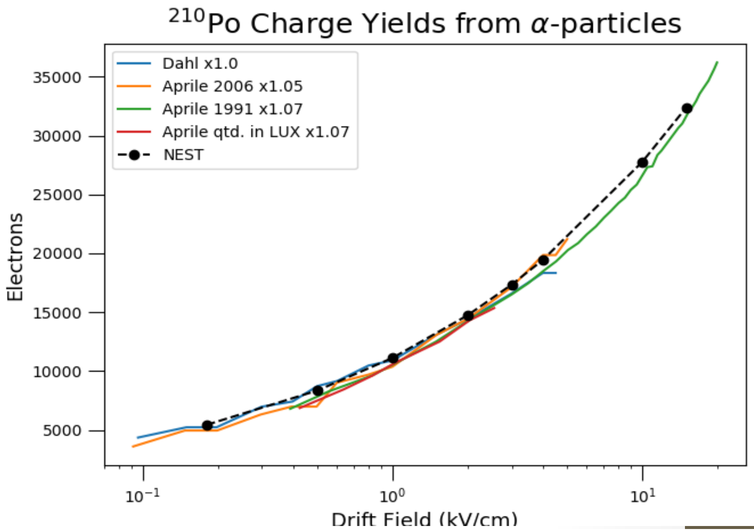
- L-factor fixed by fitting to Adam Bradley's thesis data
    - (LUX: 180V/cm)
- Still uses Thomas-Imel box model here
    - Energy-independent for simplicity

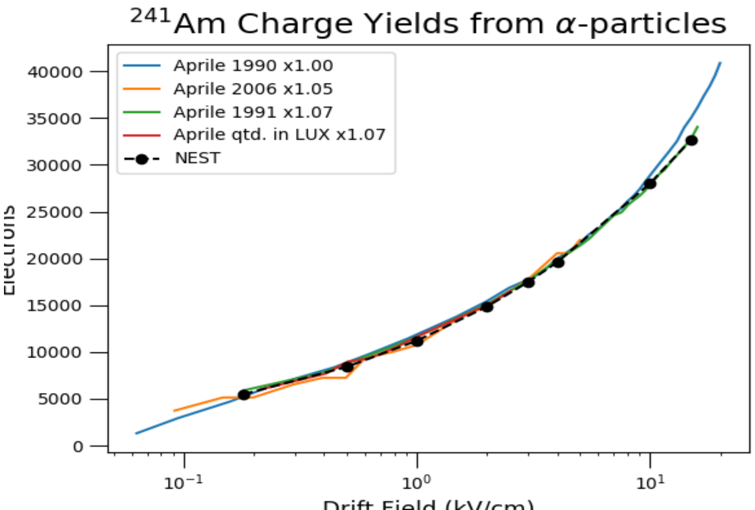


A.W. Bradley. **LUX THERMOSYPHON CRYOGENICS AND RADON-RELATED BACKGROUNDS FOR THE FIRST WIMP RESULT.** Doctoral Dissertation. Case Western Reserve Univeristy. May 2014.

α-Model

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





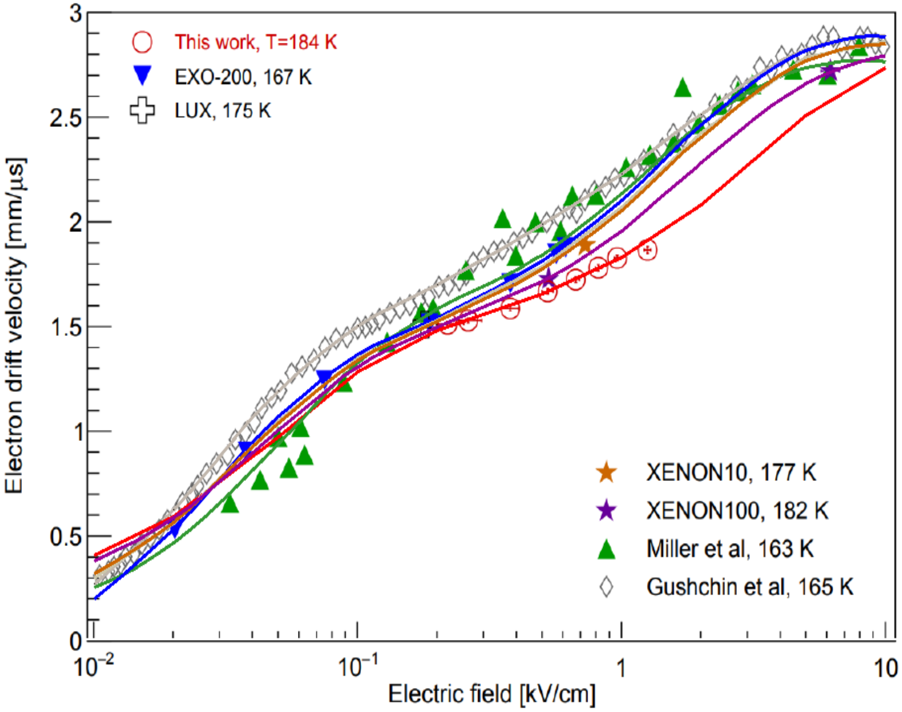
Simultaneous measurement of ionization and scintillation from nuclear recoils in liquid xenon as target for a dark matter experiment
E. Aprile, C.E. Dahl, L. DeViveiros, R. Gaitskell, K.L. Giboni, J. Kwong, P. Majewski, Kaixuan Ni, T. Shutt, M. Yamashita. Jan 2006.
Published in **Phys.Rev.Lett. 97 (2006) 081302**

E. Aprile, et.al. **Ionization of liquid xenon by 241Am and 210Po alpha particles.** Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 307, Issue 1,1991.

E. Aprile et. al "A study of the scintillation light induced in liquid xenon by electrons and alpha particles," in *IEEE Transactions on Nuclear Science*, vol. 37, no. 2, pp. 553-558, Apr 1990.

Drift velocity

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



A Dual-phase Xenon TPC for Scintillation and Ionisation Yield Measurements in Liquid Xenon
L.Baudis et al.. April 30, 2018. 11 pp.
Published in **Eur. Phys. J. C (2018) 78: 351.**
DOI: https://doi.org/10.1140/epjc/s10052-018-5801-5

Energy Resolution

- Quantum Fluctuations
  - First estimates of fluctuations in energy resolution and fluctuations in quanta produced were by Ugo Fano in the 1940's. **On the Theory of Ionization Yield of Radiations in Different Substances.** U.Fano. Phys. Rev. **70**, 44 – Published 1 July 1946
  - There is energy "lost" when photons are produced in LXe from electron recoils!
  - $E = W*(n_\gamma + n_e)$ → 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

Signal yields, energy resolution, and recombination fluctuations in liquid xenon
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Oct 6, 2016. 12 pp.
Published in **Phys.Rev. D95 (2017) no.1, 012008**
DOI: 10.1103/PhysRevD.95.012008

Recombination Fluctuations

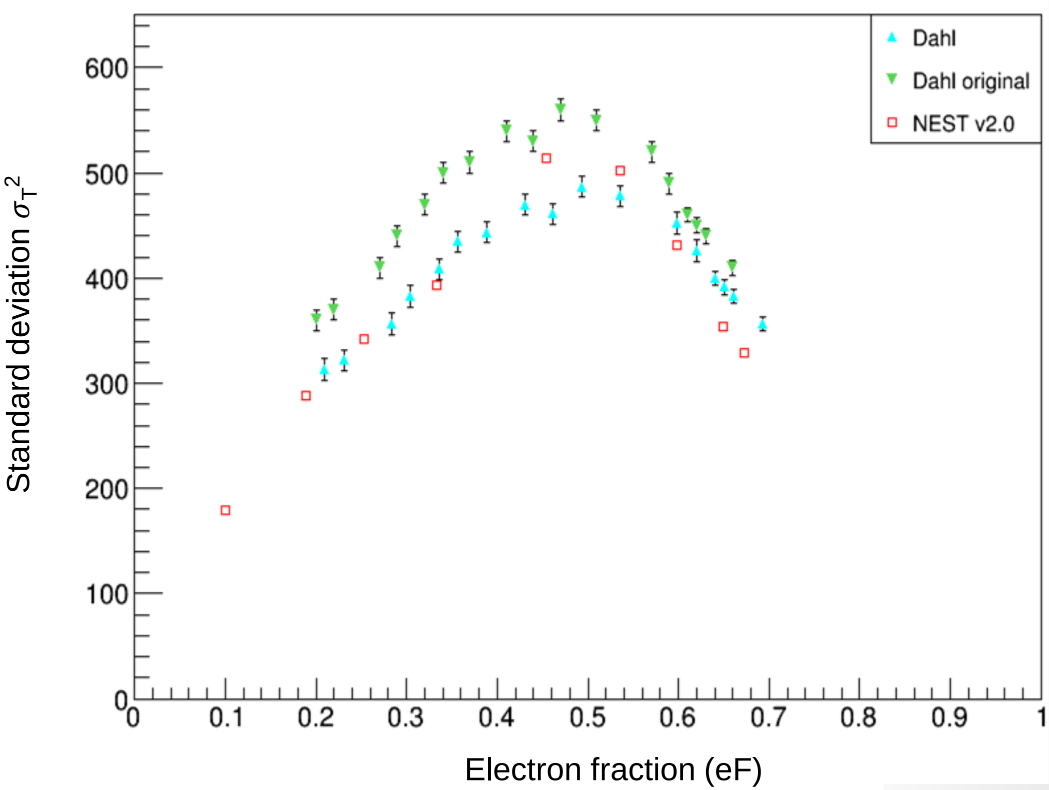
- Comparing to Eric Dahl's PhD thesis data.
- Corrected Dahl data for overestimation: corrected 15% downward for 2PE effect and extraction eff.

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

$$\sigma_p = -a*(p-0.54)^2 +c$$

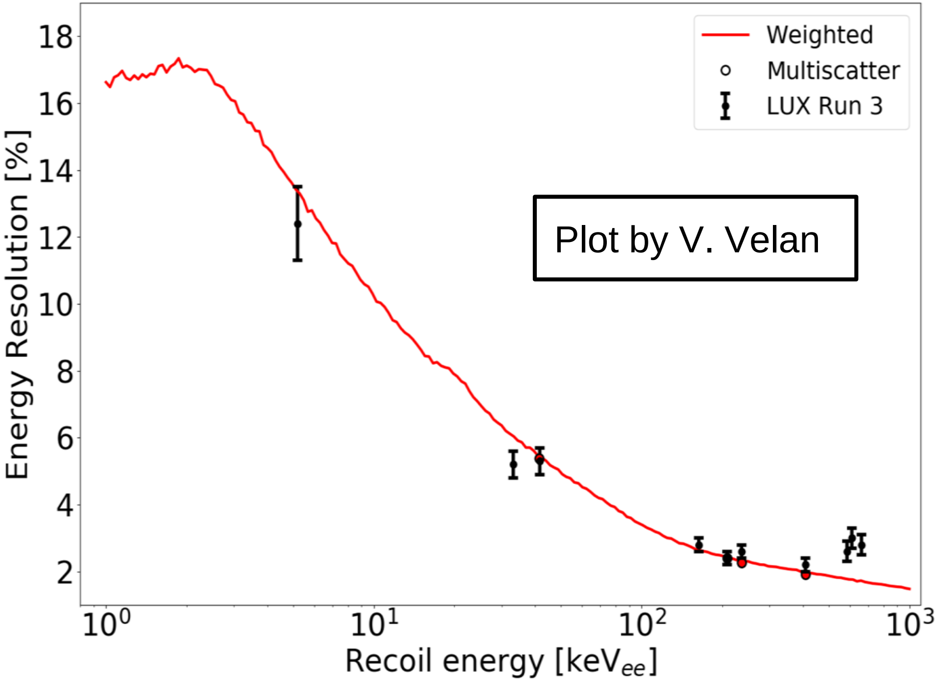
$$\sigma_p = e^{-\frac{(eF-0.5)^2}{0.17}}$$

The Physics of Background Discrimination in Liquid Xenon, and the First Results from XENON10 in the Hunt for WIMP Dark Matter. C.E. Dahl. Doctoral Dissertation. Princeton University. September 2009



Energy Resolution: LUX

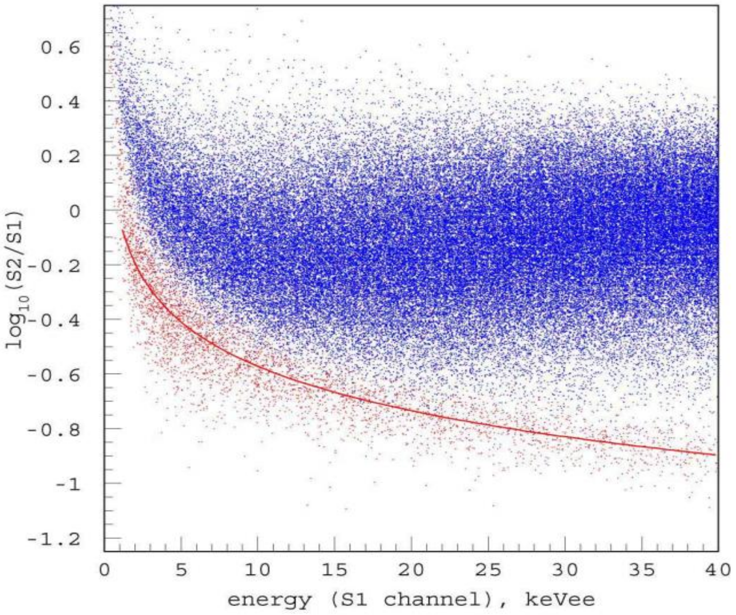
- Good Fit to LUX Run 3.
- β-model better at lower energies. Fit here uses a weighted combination of NEST's β and γ models.

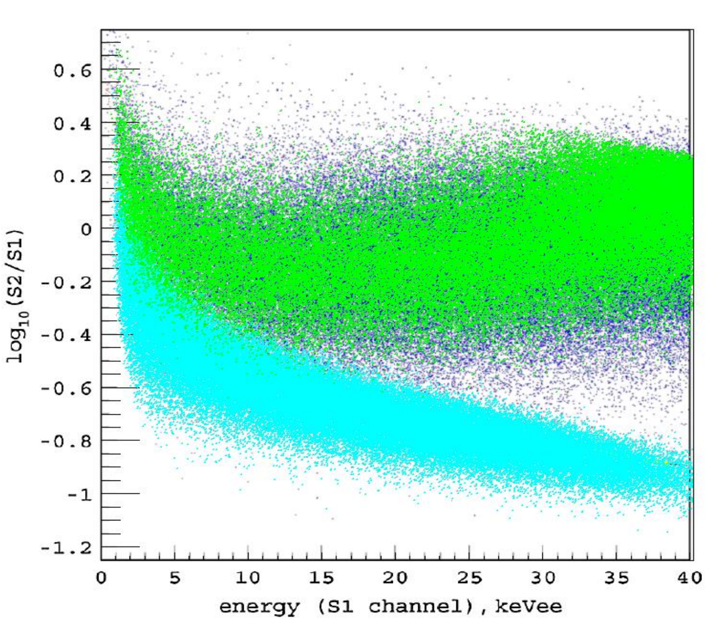


Signal yields, energy resolution, and recombination fluctuations in liquid xenon
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Oct 6, 2016. 12 pp.
Published in **Phys.Rev. D95 (2017) no.1, 012008**
DOI: 10.1103/PhysRevD.95.012008

Energy Resolution: ZEPLIN-III

Light blue → NESTAmBe data
Green → NEST β data



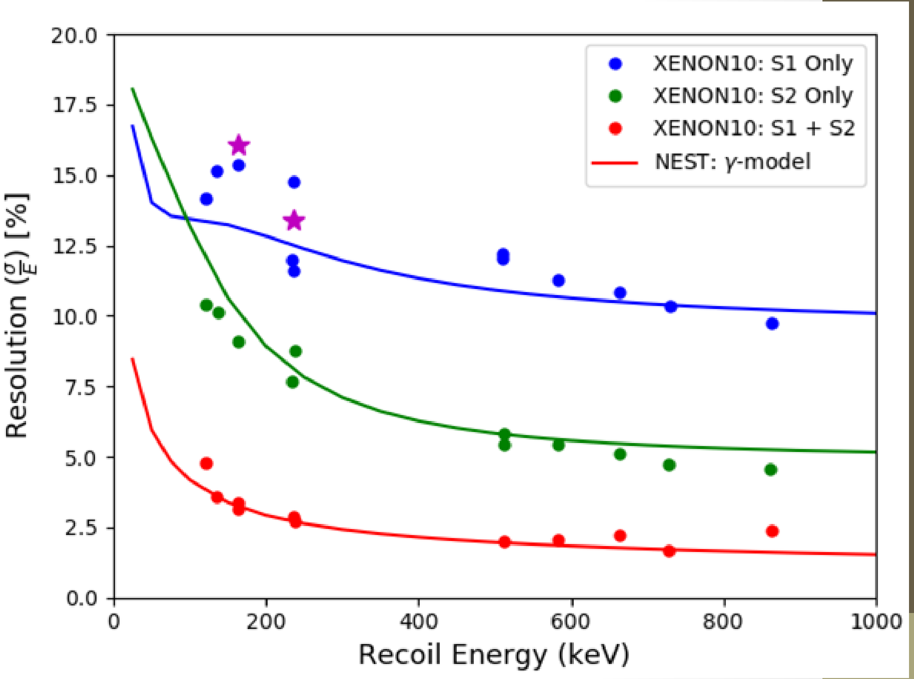


- NEST matched original Z-III resolution (99.999% on AmBe and beta data) and AmBe and beta distributions (ever means)

Limits on the spin-dependent WIMP-nucleon cross-sections from the first science run of the ZEPLIN-III experiment
ZEPLIN-III Collaboration (V.N. Lebedenko (Imperial Coll., London) *et al.*). Jan 2009. 4 pp.
Published in **Phys.Rev.Lett. 103 (2009) 151302**

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

Conclusion

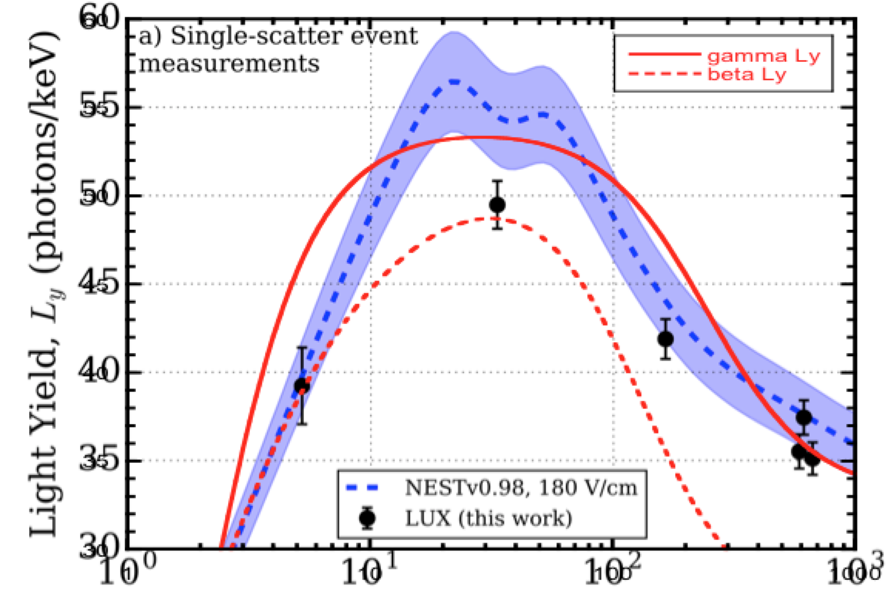
- NESTv2 is a powerful simulation tool, which now has two versions: standalone tool and GEANT4 library.
- Accurately simulates many different interactions in LXe and GXe (argon models currently in process)
- User-friendly code so you can add any other interactions that you might find useful.
- Get yourself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

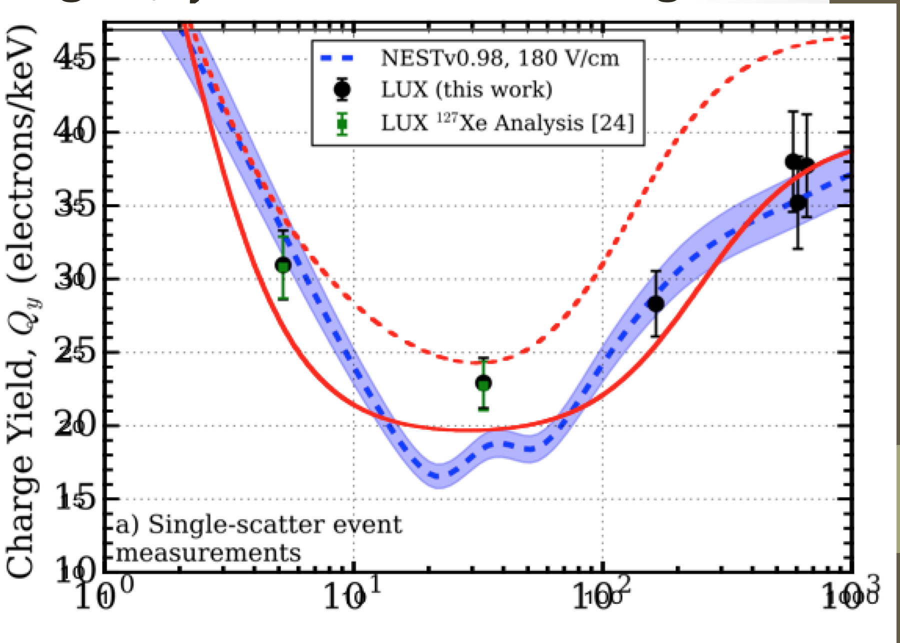
Thank you for your attention!

Backup Slides

ER from γ-rays

- LUXRun3 (180V/cm)
- **β**-model does better at lower energies, **γ**-model matches high





ER in GXe

density (g/cc)	keVee	W_sc (eV)	NEST W_sc (eV)
0.08	622	61 +/- 18 [1]	66 **
0.0057	5.9	111 +/- 16 [2]	97.8
0.0899	60	75 +/- 11 [3]	69.4

[1] **Ionization and scintillation of nuclear recoils in gaseous xenon**
NEXT Collaboration (J. Renner (LBL, Berkeley & UC, Berkeley) et al.). Sep 9, 2014. 13 pp.
Published in **Nucl.Instrum.Meth. A793 (2015) 62-74**

** Gamma Model found 83.8 eV for 662 keVee

[2] **Absolute primary scintillation yield of gaseous xenon under low drift electric fields for 5.9 keV X-rays**

Carmo, S.J.C. et. al. 2008.

Published in **Journal of Instrumentation**, **Volume 3**.July 16, 2008

[3] A. Parsons *et al.*, "High pressure gas scintillation drift chambers with wave-shifter fiber readout," in *IEEE Transactions on Nuclear Science*, vol. 37, no. 2, pp. 541-546, Apr 1990.
doi: 10.1109/23.106674

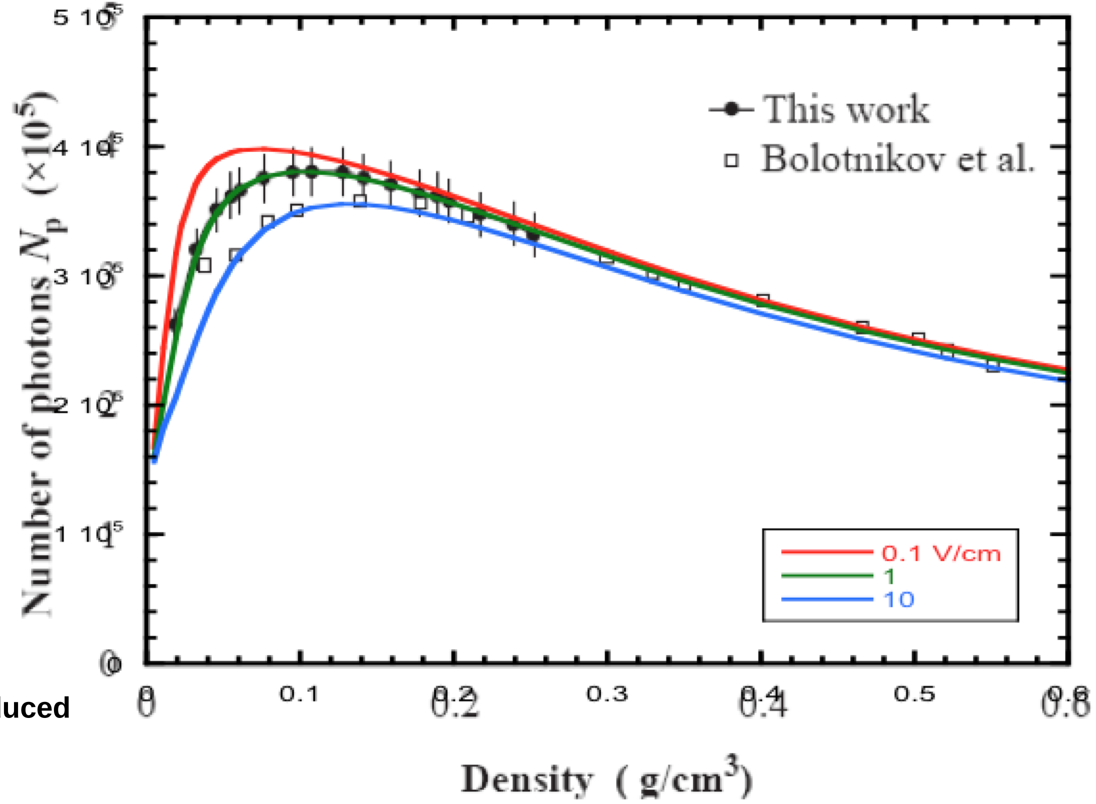
*Light yields (1000 / W) were nearly constant for field ranges ~200-25000 V/cm

[1] states W_i = 24.7 eV -- NEST result is 30.2 eV

Gamma Model: 27.5 eV

α-Model for GXe

- Most GXe α data is contradictory (data shown is 0 V/cm).
- NESTv2 splits many of the differences between contradictions.
    - Floating “zero-field” was critical here!

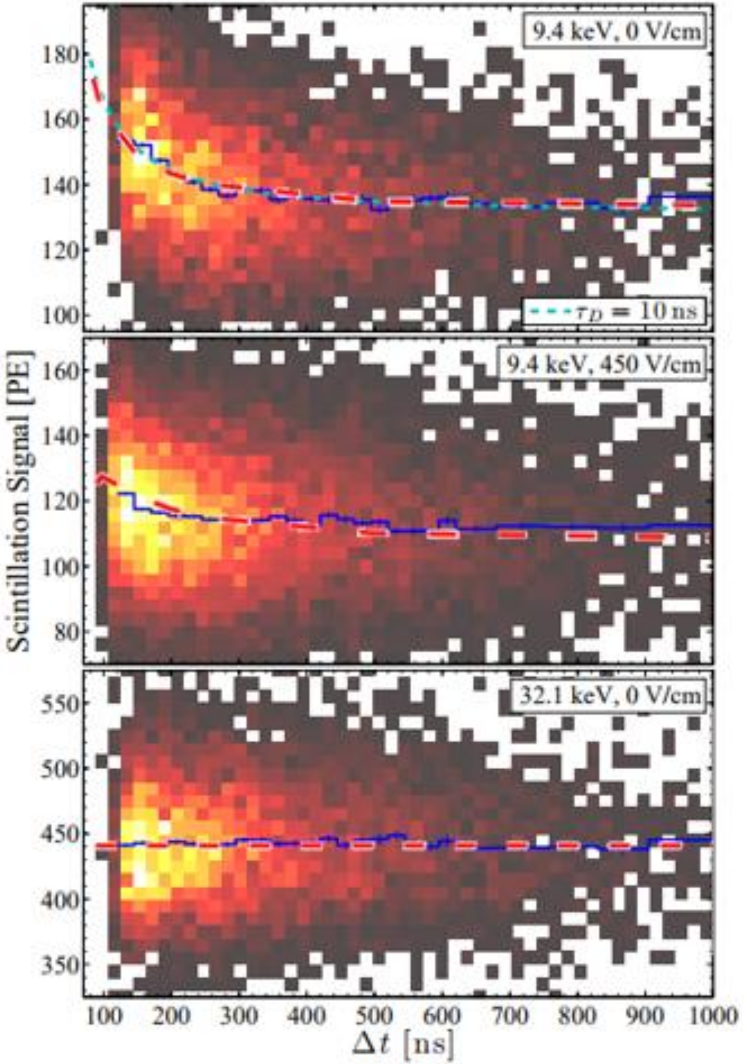


M. Miyajima et. al. **Absolute number of photons produced by alpha-particles in liquid and gaseous xenon**. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 63, Issue 3, 1992, Pages 297-308,ISSN 0168-583X

Scintillation Signal v. Time

Based on ^{57}Co yield of $0.97*Ly_{32.1}$, needed zero-field of 10V/cm.

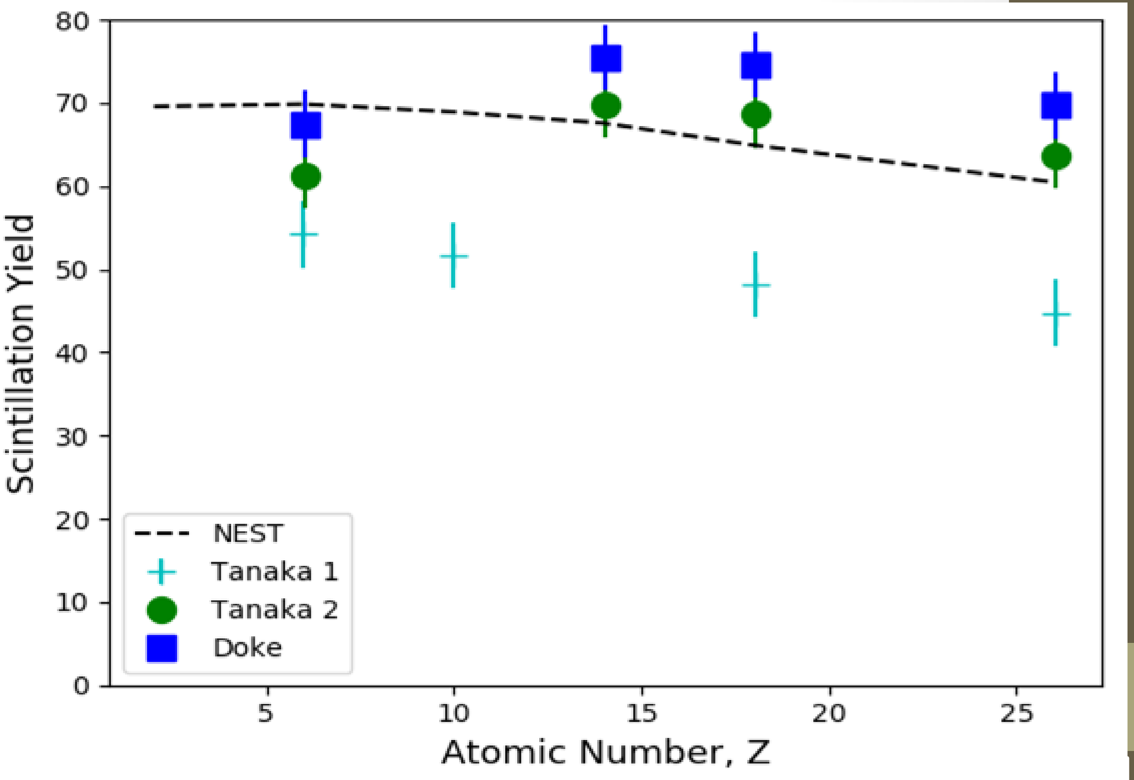
Fixed g1 to be 0.206



Response of liquid xenon to Compton electrons down to 1.5 keV
Laura Baudis, Hrvoje Dujmovic (Zurich U.), Christopher Geis (Zurich U. & Unlisted, DE), Andreas James, Alexander Kish, Aaron Manalaysay, Teresa Marrodan Undagoitia, Marc Schumann (Zurich U.). Mar 27, 2013. 14 pp.
Published in **Phys.Rev. D87 (2013) no.11, 115015**

Heavy Nuclei

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

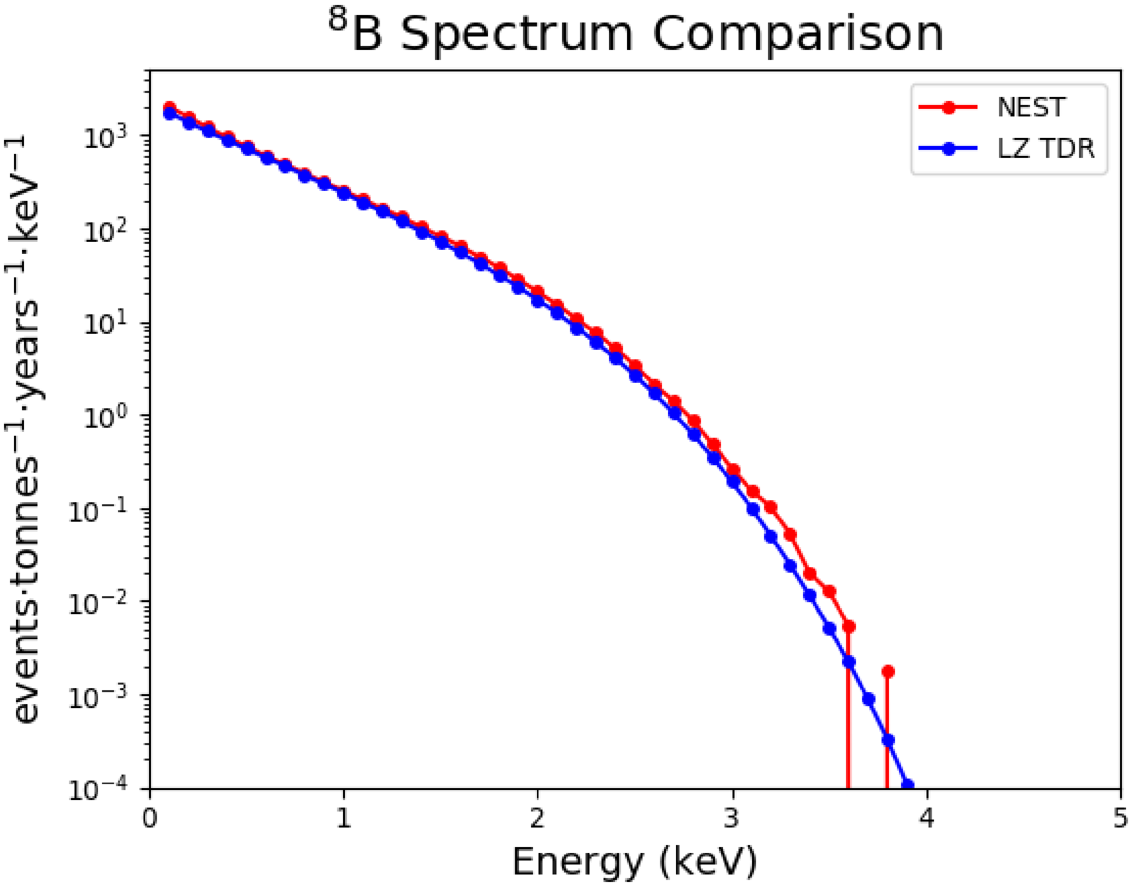


Absolute Scintillation Yields in Liquid Argon and Xenon for Various Particles
T. Doke, et. al. 2002.
Japanese Journal of Applied Physics, Volume 41, Part 1, Number 3A

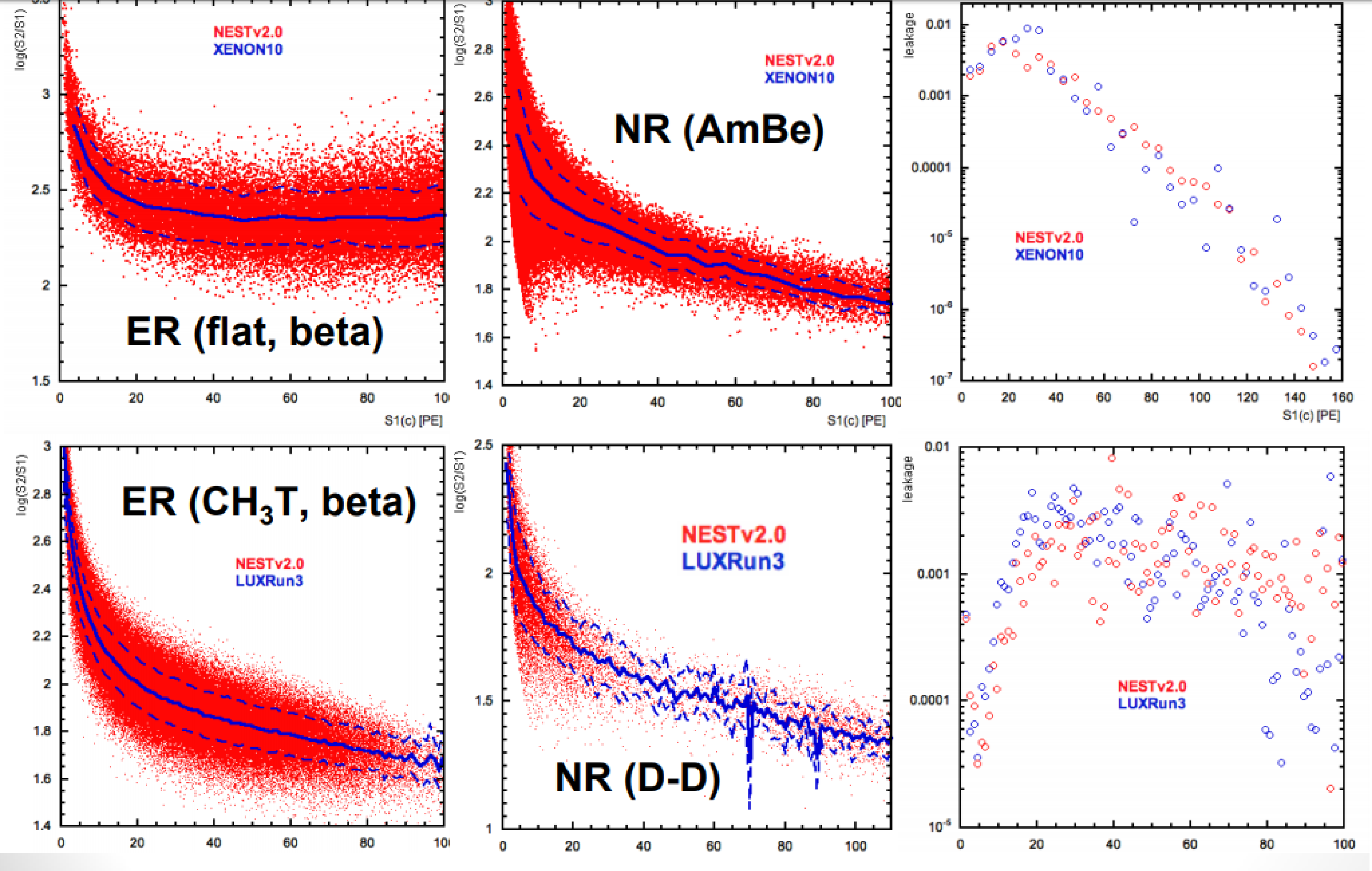
LET dependence of scintillation yields in liquid xenon
M. Tanaka, et. al. 2001

Boron-8

- Great agreement with LZ TDR ^8B 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!