



## An Introduction of

# The Noble Element Simulation Technique Version 2.0



Greg Rischbieter,

On Behalf of the NEST Collaboration  
IDM, Brown University, July 2018

<https://github.com/NESTCollaboration/nest>



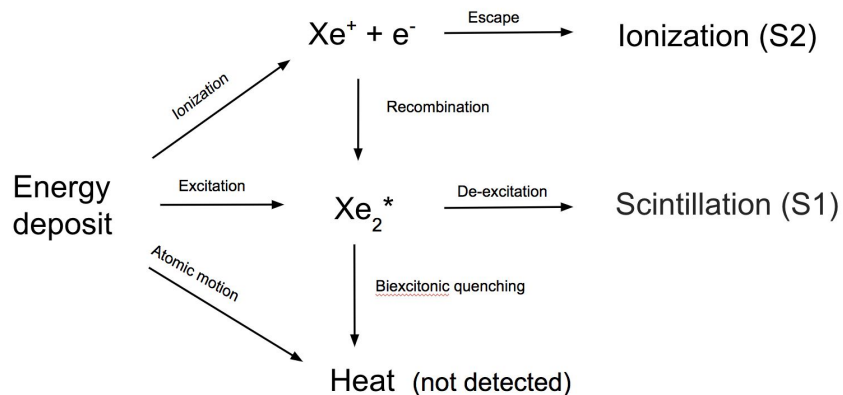
# About NEST

- “Inter-collaboration” Collaboration
  - Members from LUX, LZ, XENON, DUNE, and nEXO.
- Fast C++ simulation of more interactions in LXe and GXe than ever before!
  - Important to for identifying interactions from actual light and charge yields
  - LAr models being worked on for future release!
- [nest.physics.ucdavis.edu](http://nest.physics.ucdavis.edu)

Website includes link to GitHub download page for full code!  
Get it while supplies last!



## Signal production in xenon



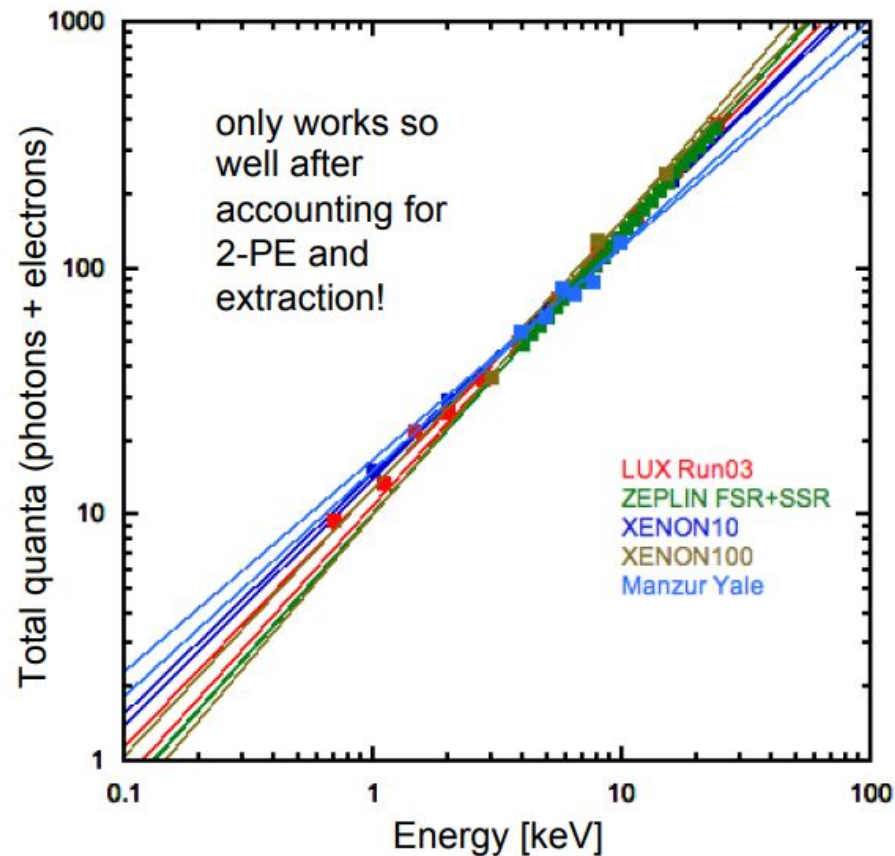
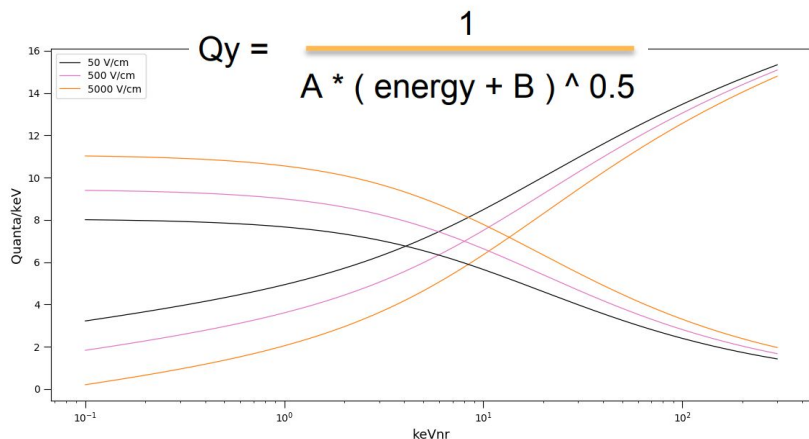
# What's New?

- Comprehensive models for all particle types
- Switched most of the equations to simpler functions
  - Older models (TIB and Doke-Birks) weren't fitting the data anymore.
  - e.g. sigmoids, which still closely resemble those older models.
- Revisited old data, corrected for newer phenomena
  - Includes 2PE effect for VUV photons in PMTs
  - Allowed 'zero-field' to vary
  - Corrected for less-than-perfect extraction efficiency
  - ER:  $\beta$ -model vs.  $\gamma$ -model
- Exciton-Ion ratio is energy-dependent
- For ER & NR, total quanta and charge yields are calculated first
  - Exciton-ion ratio and recombination probabilities are then reverse-engineered.
- Accurately models detector effects for S1-S2 bands (means, widths, leakages)
  - See plots in Vitaly Kudryavtsev's talk from Tuesday



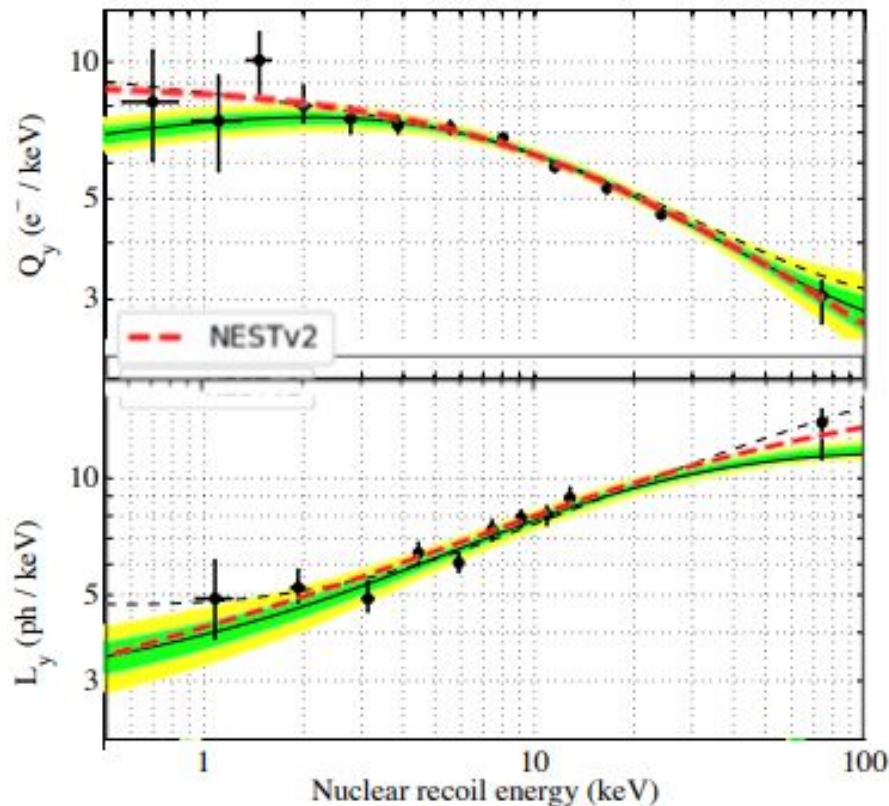
# Nuclear Recoils

- Total quanta is now a power law
  - $12.6 * (\text{Energy})^{1.05}$ 
    - Elegant → almost linear
  - $12.6 \pm 0.9$  &  $1.05 \pm 0.05$
  - Consistent with ~1 quanta at 100 eV
- No more Lindhard model
  - All\* mean-yields equations replaced with simple functions



# LUX D-D Comparisons

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



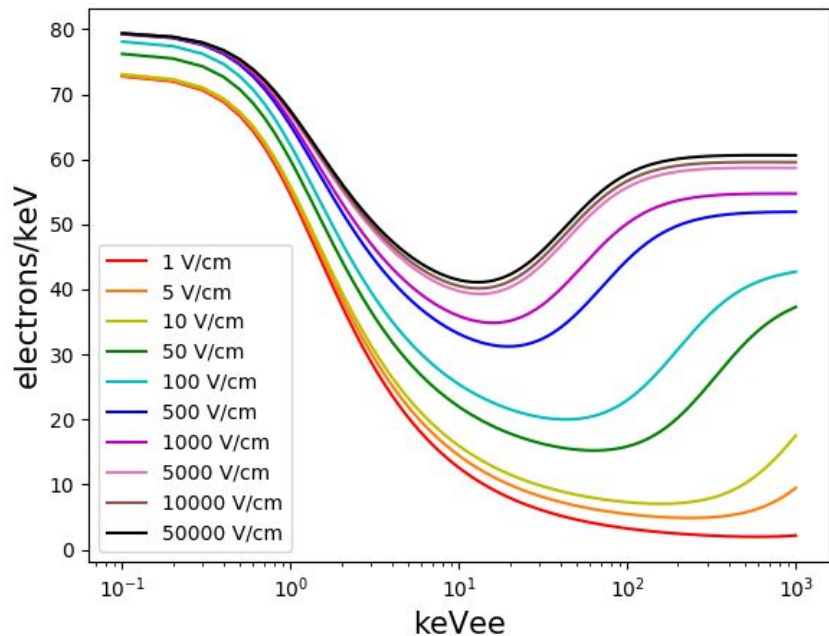
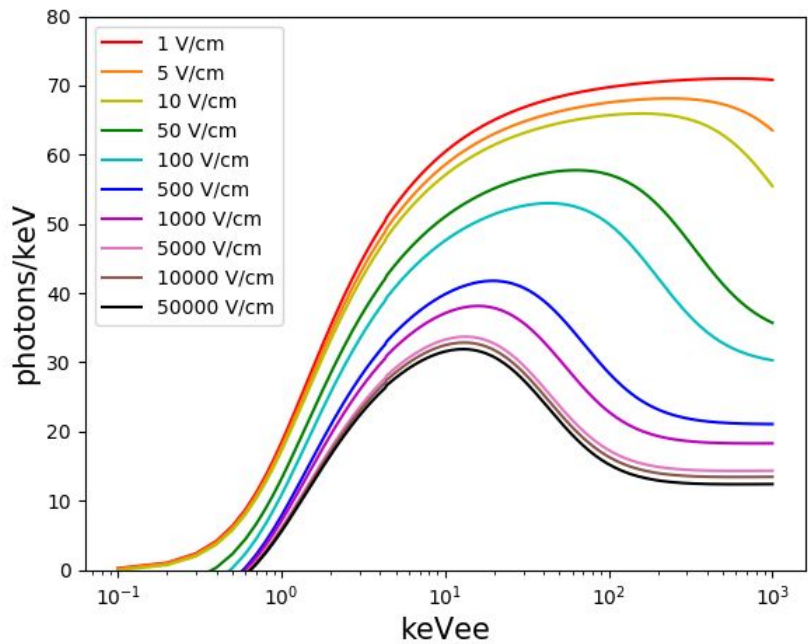
## Improved Limits on Scattering of Weakly Interacting Massive Particles from Reanalysis of 2013 LUX Data

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

# Electronic Recoils -- Sum of Two Sigmoids

- Smooth transition between low and high energies



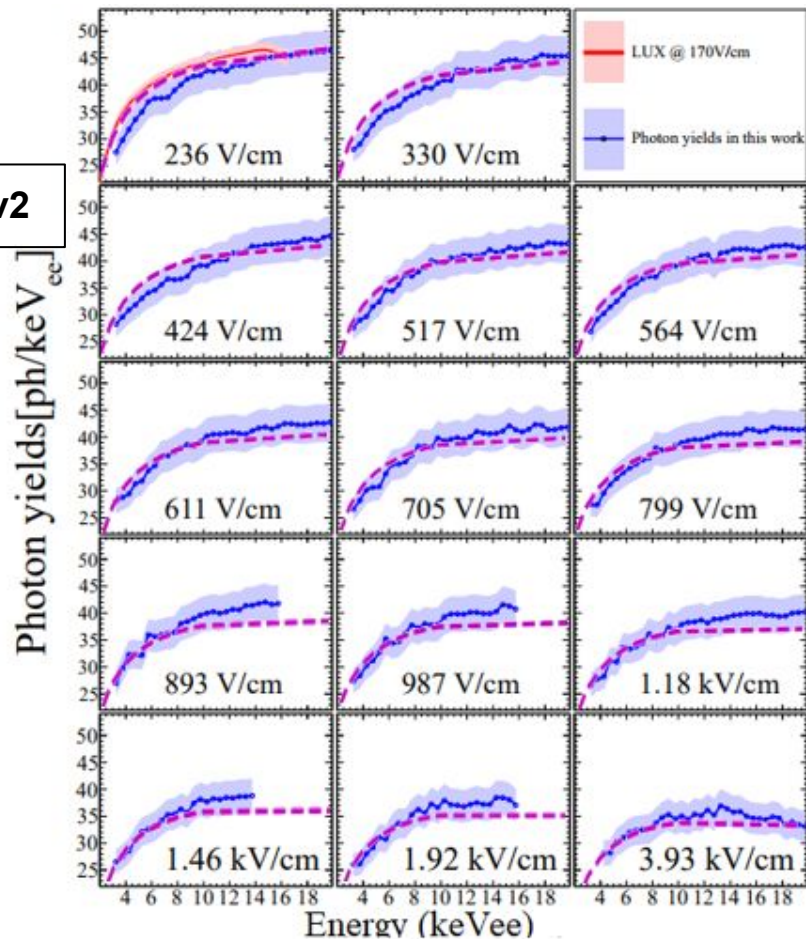
# Matches Data for a large range of fields

--- NESTv2

- LY from  $^{137}\text{Cs}$   $\rightarrow$  Compton Scatters
  - NEST is the purple dashed lines
  - (Original Plot cited below)
- Always matches within  $1\sigma$

**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**



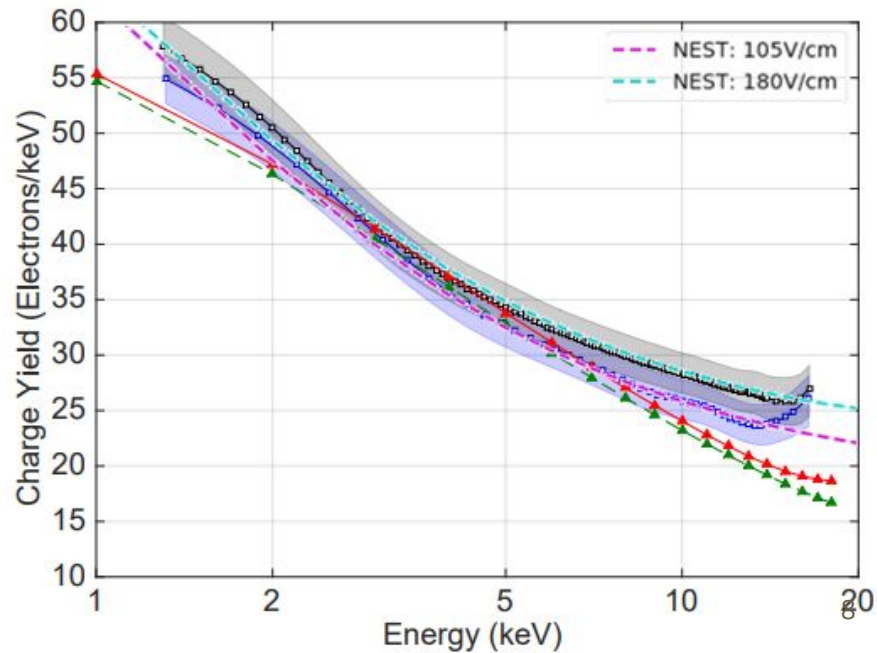
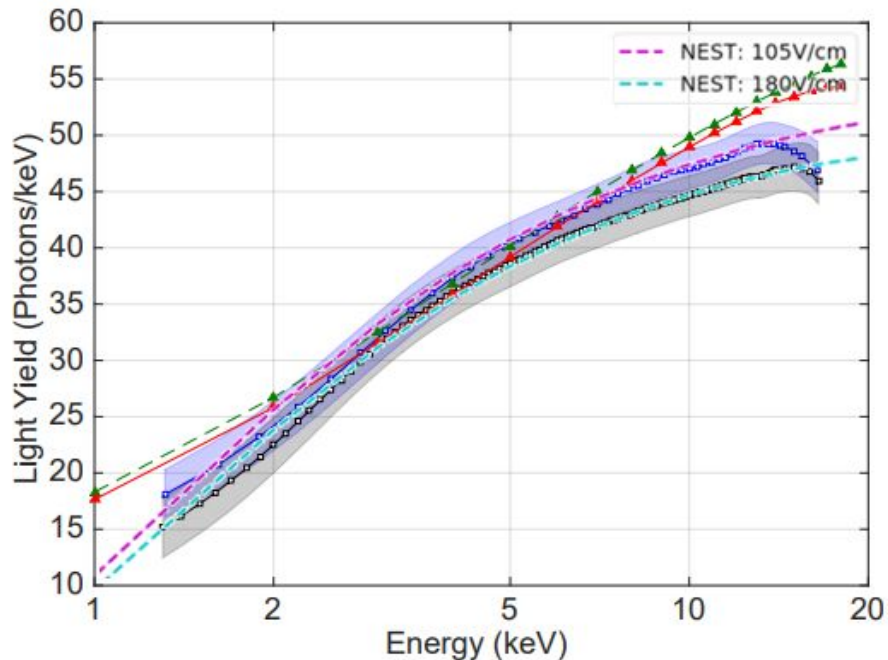
# LUX Tritium

## 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.

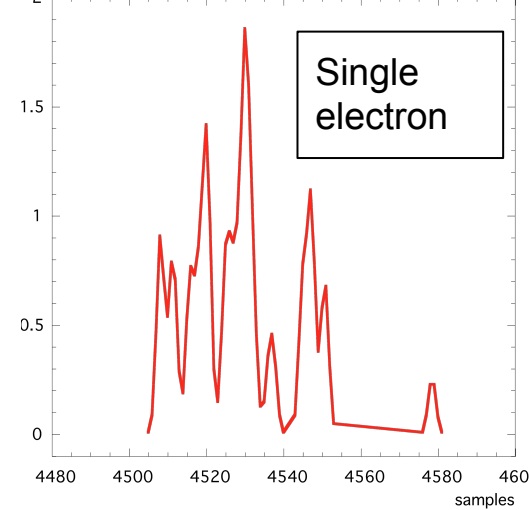
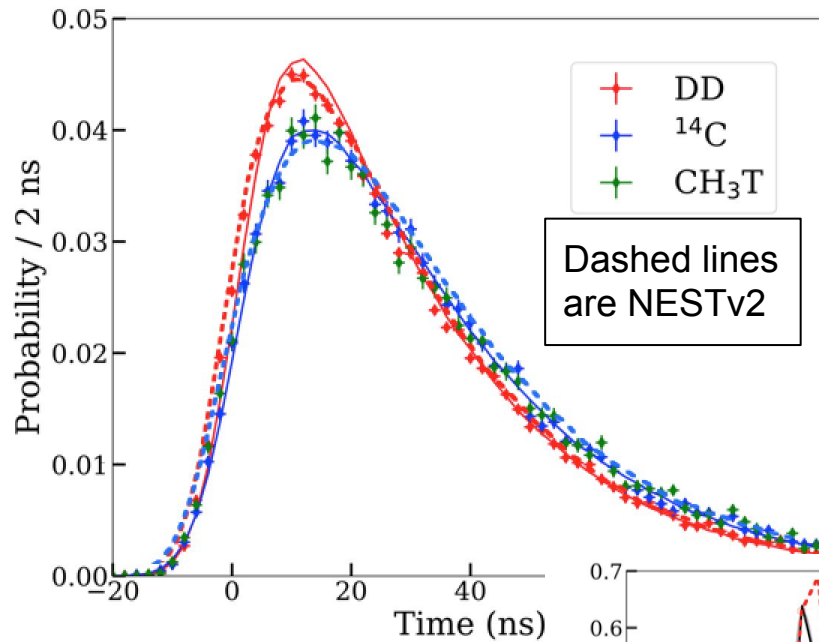
Published in **Phys.Rev. D93 (2016) no.7, 072009**

- Great agreement with both light and charge yields
- Note: legend refers to NESTv2; red and green lines are previous NEST

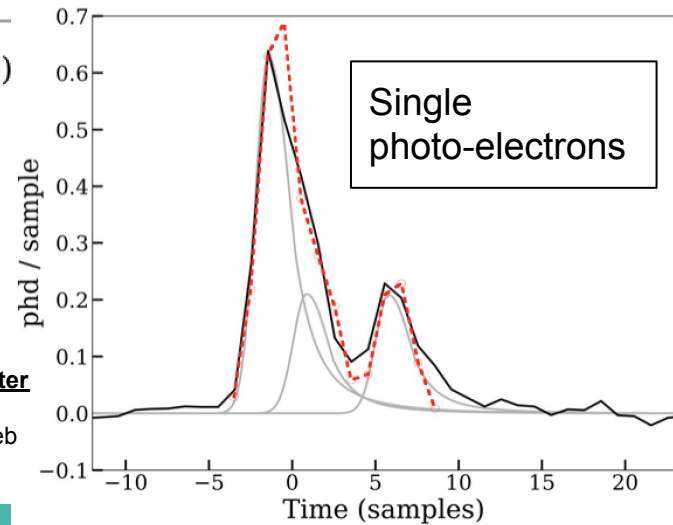


# Pulse Shapes

- Matches LUX pulse shape discrimination.
- Can also simulate single electrons!
- Simulates both components of SE noise in LXe (K. Kamdin's talk up next)



ABOVE:  
Histograms of S1  
photon 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.

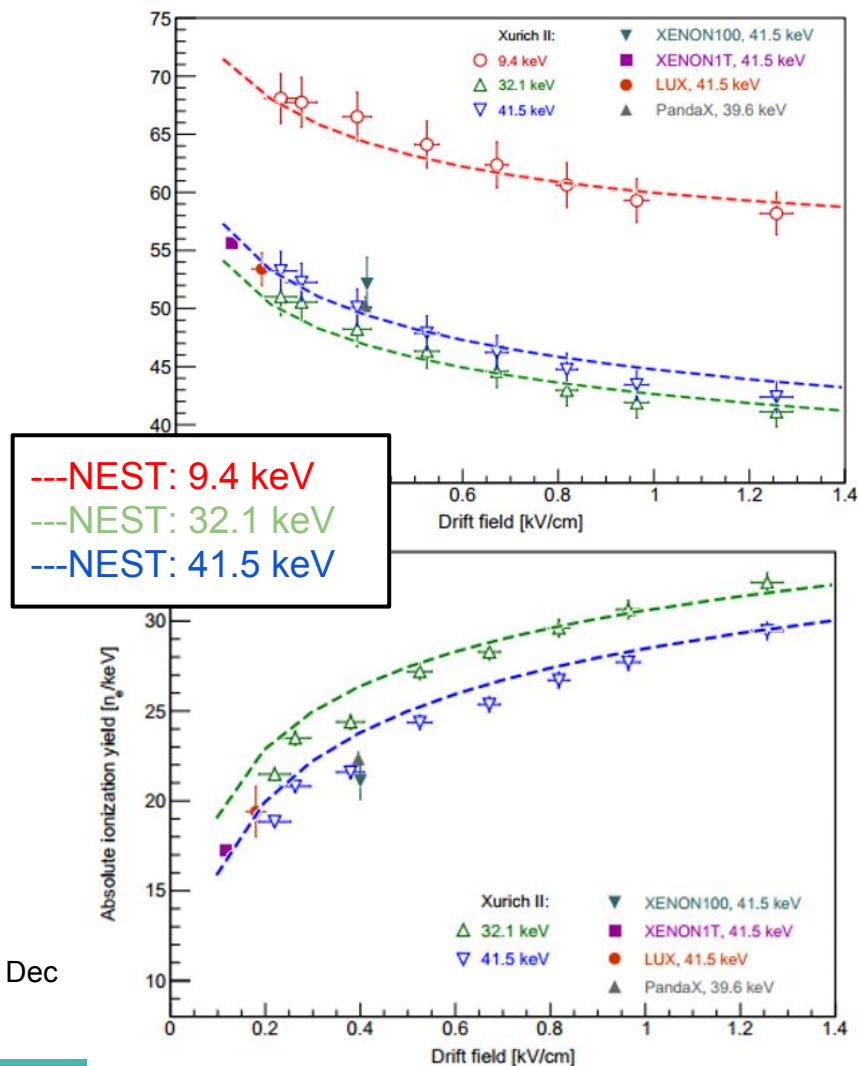
Published in **Phys.Rev. D97 (2018) no.11, 112002**

# 83mKr

- 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



# 83mKr

- 1  $\sigma$  agreement with LUX and XENON100

|             | Drift Field (V/cm) | Quanta/keV     | NEST Result |
|-------------|--------------------|----------------|-------------|
| LUX Ly      | 180                | $53.4 \pm 1.4$ | 53.0        |
| LUX Qy      | 180                | $19.4 \pm 1.4$ | 20.0        |
| XENON100 Ly | 366                | $52.5 \pm 1.8$ | 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.

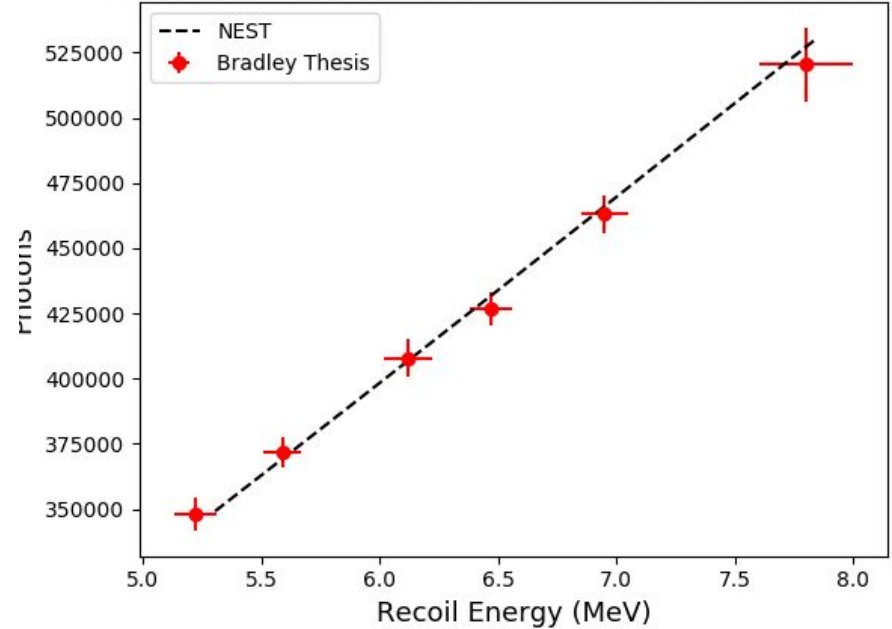
Published in **Phys.Rev. D97 (2018) no.9, 092007**

DOI: [10.1103/PhysRevD.97.092007](https://doi.org/10.1103/PhysRevD.97.092007)

# $\alpha$ -Model

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

Light Yield vs. Recoil Energy from  $\alpha$ -particles



# $\alpha$ -Model

- Again, only worked by correcting data for extraction efficiency, as on slide 5 (NR).
  - See Tuesday's talk by Ethan Bernard
- 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.

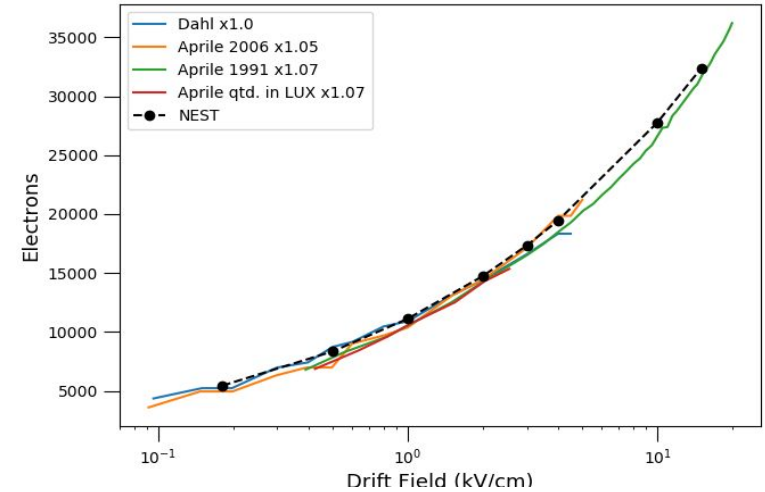
Published in **Phys.Rev.Lett.** **97 (2006) 081302**

E. Aprile, et.al. **Ionization of liquid xenon by  $^{241}\text{Am}$  and  $^{210}\text{Po}$  alpha particles.**

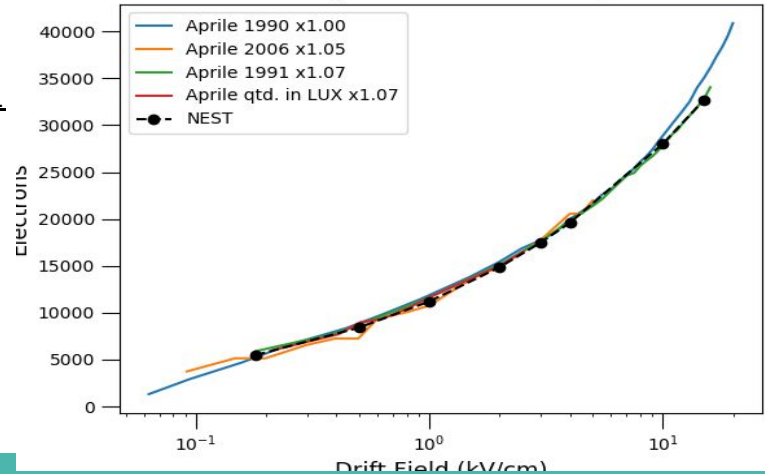
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 307, Issue 1, 1991.

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.

### $^{210}\text{Po}$ Charge Yields from $\alpha$ -particles



### $^{241}\text{Am}$ Charge Yields from $\alpha$ -particles



# 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!
- $E = W \cdot (n_\gamma + n_e) \rightarrow$  Work Function:  $W = 13.7$  eV
- Fluctuations modeled using an empirical “Fano-like” factor proportional to  $\sqrt{\text{energy}} \cdot \sqrt{\text{field}}$

- Recombination Fluctuations

- Binomial recombination has never matched data well.
- Same equation as cited in LUX Signal Yields Publication:  $\sigma_T^2 = (1-p) \cdot n_i \cdot p + (\sigma_p n_i)^2$ 
  - $\sigma_p$  in NEST is both field-dependent and energy-dependent

**Signal yields, energy resolution, and recombination fluctuations in liquid xenon**

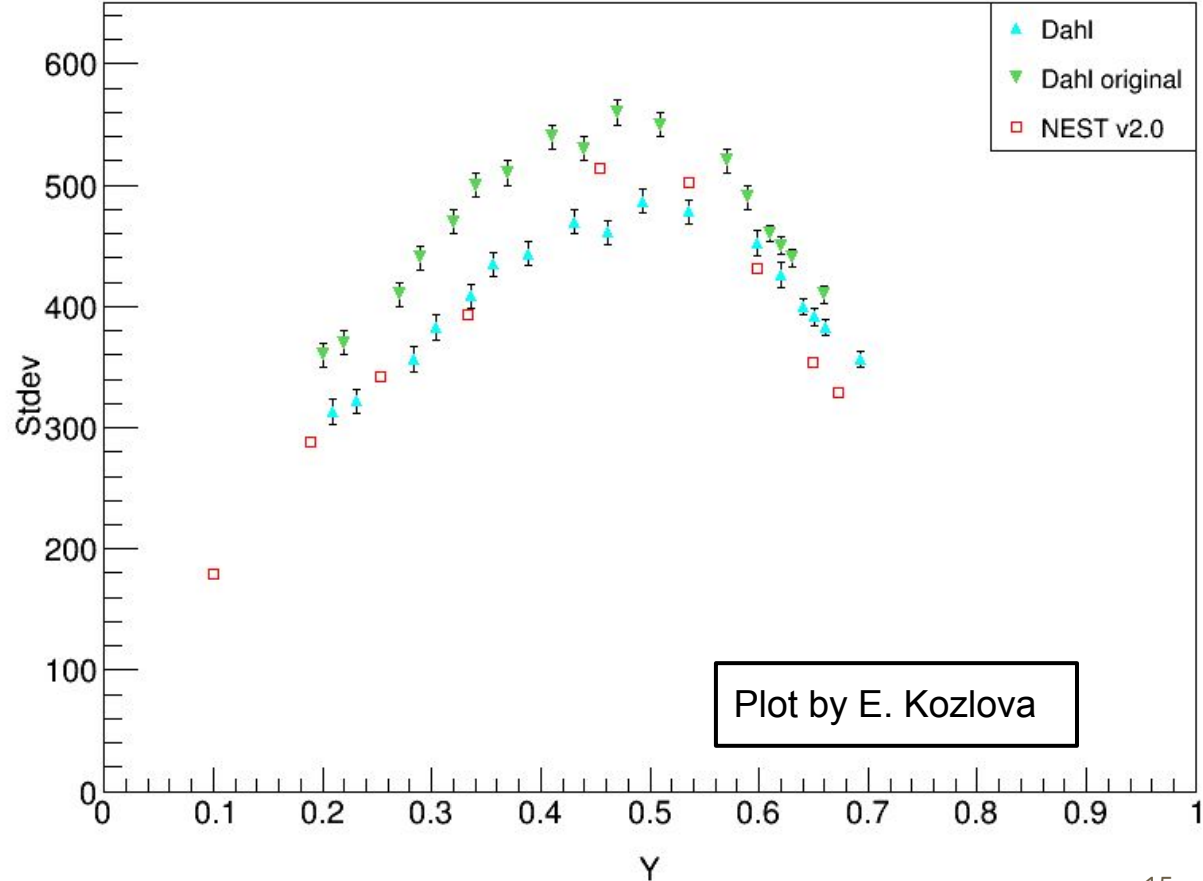
LUX Collaboration (D.S. Akerib (Case Western Reserve U. & SLAC & KIPAC, Menlo Park) *et al.*). Oct 6, 2016. 12 pp.

Published in **Phys.Rev. D95 (2017) no.1, 012008**

DOI: [10.1103/PhysRevD.95.012008](https://doi.org/10.1103/PhysRevD.95.012008)

# Recombination Fluctuations

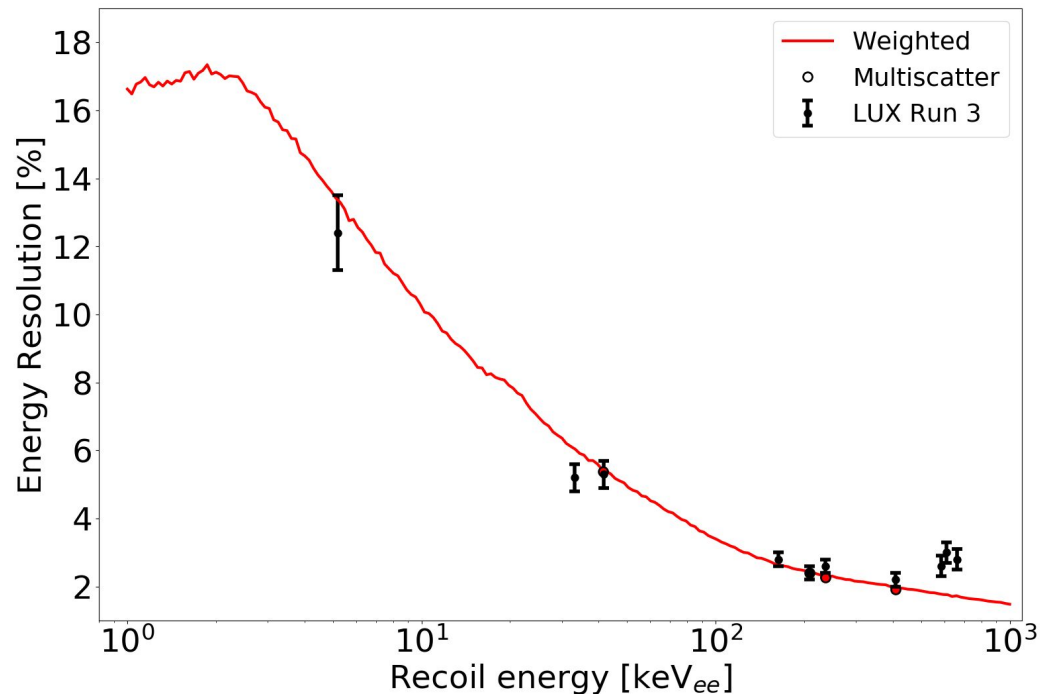
- Comparing to Eric Dahl's PhD thesis data.
- x-axis is the electron fraction.
- Corrected Dahl data for overestimation
  - Corrected 15% downward for 2PE effect and extraction eff.



# Energy Resolution: LUX

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

Plot by V. Velan



## 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.

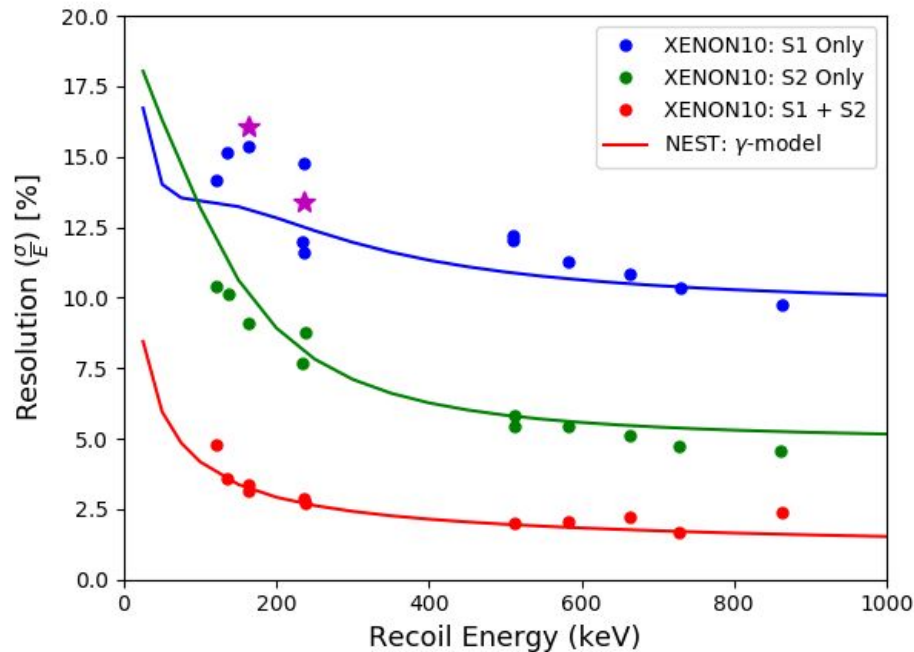
Published in *Phys.Rev.* **D95** (2017) no.1, 012008

DOI: [10.1103/PhysRevD.95.012008](https://doi.org/10.1103/PhysRevD.95.012008)

# Energy Resolution: XENON10

[arxiv.org/pdf/1001.2834.pdf](https://arxiv.org/pdf/1001.2834.pdf)

- 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  $^{129m}\text{Xe}$  &  $^{131m}\text{Xe}$ 
  - Decay in many steps, used NEST to combine the yields from each decay and added them together
  - $^{83m}\text{Kr}$  model suggests that multi-step decays have subtle time-dependence



# Dark Matter in NESTv2

- Uses WIMP spectrum equations following methods described in 2010 publication by McCabe. **Astrophysical uncertainties of dark matter direct detection experiments.** Christopher McCabe. Phys. Rev. D **82**, 023530 – Published 29 July 2010
- I have plans to incorporate Nuclear Dark Matter spectra using equations from a 2016 paper from the Royal Holloway University of London.

**Can Tonne-Scale Direct Detection Experiments Discover Nuclear Dark Matter?**

A. Butcher, R. Kirk, J. Monroe, S.M. West (Royal Holloway, U. of London). Oct 6, 2016. 23 pp.  
Published in **JCAP 1710 (2017) no.10, 035**

# LAr -- Fitting to NR Charge Yields

Plot by J. Mueller

- Coming Soon!

## Measurement of Scintillation and Ionization Yield and Scintillation Pulse Shape from Nuclear Recoils in Liquid Argon

SCENE Collaboration (H. Cao (Princeton U.) *et al.*). Jun 18, 2014. 29 pp.  
Published in **Phys.Rev. D91 (2015) 092007**

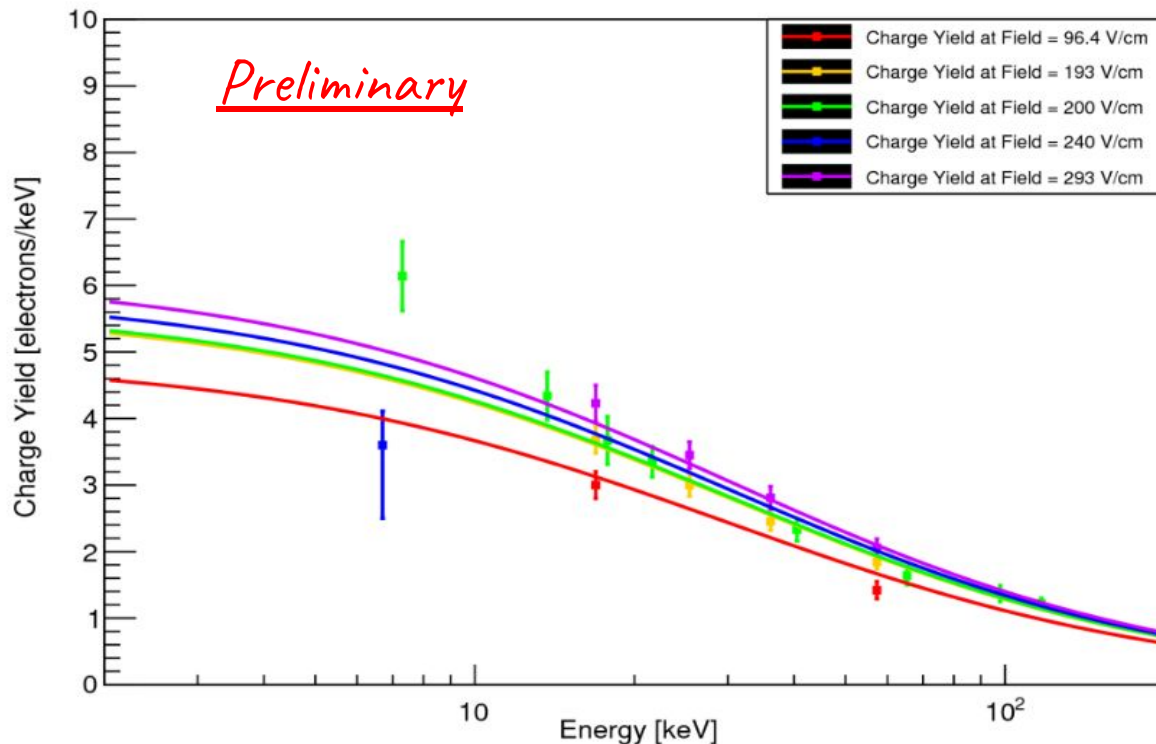
## First measurement of the ionization yield of nuclear recoils in liquid argon

T.H. Joshi *et al.*. Feb 10, 2014. 5 pp.  
Published in **Phys.Rev.Lett. 112 (2014) 171303**

## Measurement of the liquid argon energy response to nuclear and electronic recoils

P. Agnes (Houston U. & APC, Paris) *et al.*. Jan 20, 2018. 14 pp.  
Published in **Phys.Rev. D97 (2018) no.11, 112005**

Charge Yield (Various Fields)



# Conclusion

- NESTv2 is a powerful simulation tool that you can use, and it takes seconds to run!
- Accurately simulates many different interactions in LXe and GXe, while Argon models are being worked on as we speak.
  - User-friendly code so you can add any other interactions that you might find useful.
- You can build your own detector model and begin calculating light and charge yields!
- Get yourself a copy!
  - <https://github.com/NESTCollaboration/nest>
  - [nest.physics.ucdavis.edu](http://nest.physics.ucdavis.edu)

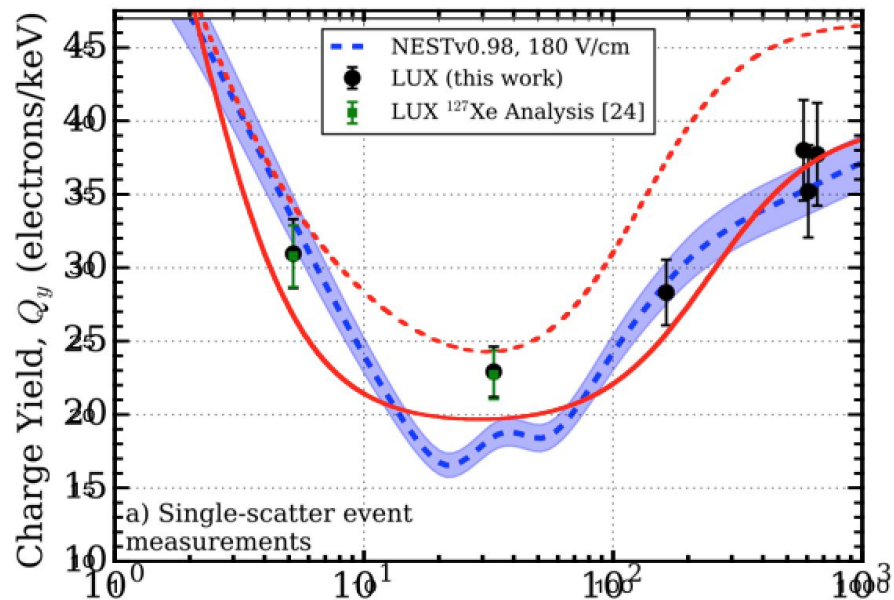
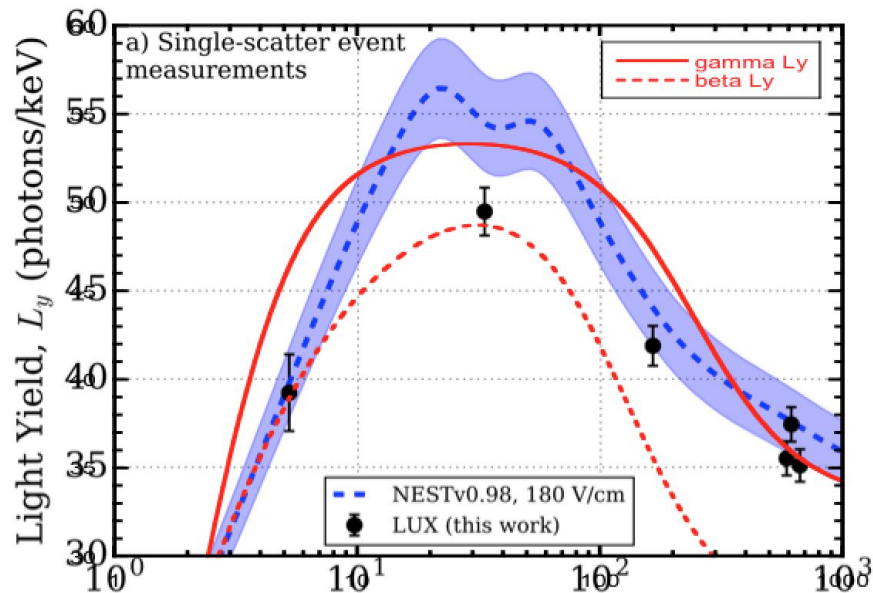
# Thank You!!

# Backup Slides

Besides the many many in the previous slide's attachment!

# ER from $\gamma$ -rays

- LUXRun3 (180V/cm)
- $\beta$ -model does better at lower energies,  $\gamma$ -model matches high energies



# 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

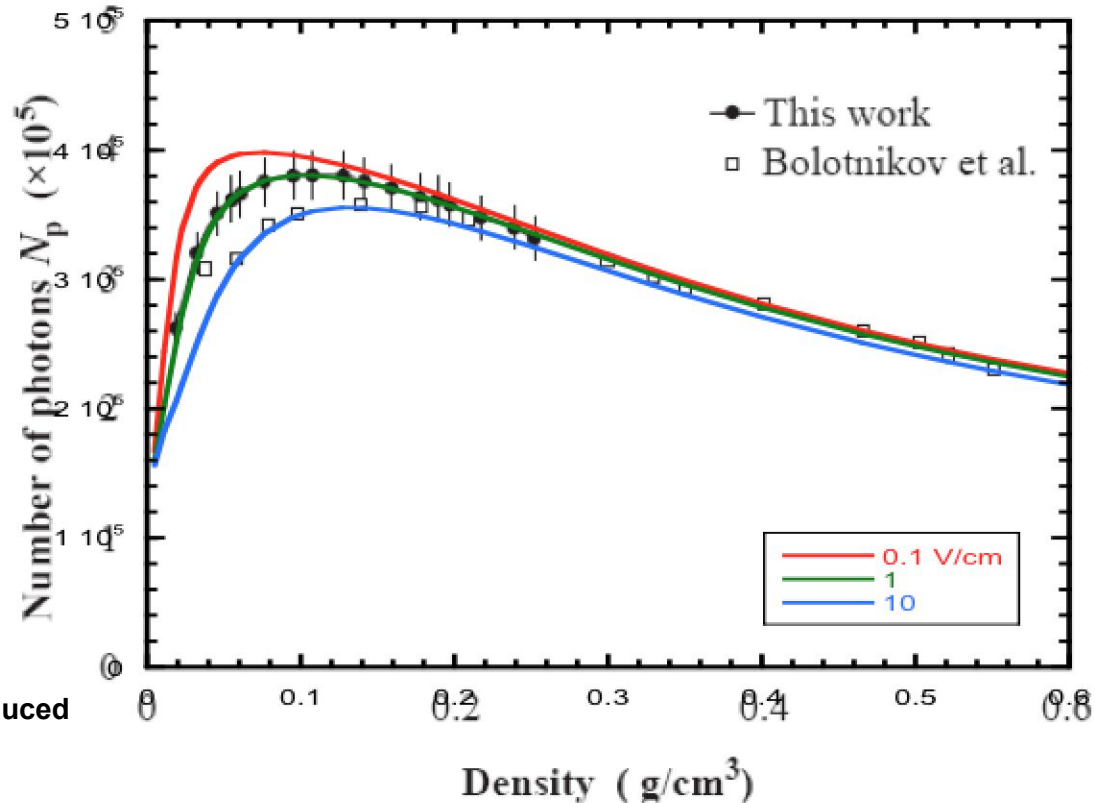
\*Light yields ( 1000 / W ) were nearly constant for field ranges ~200-25000 V/cm

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

Gamma Model: 27.5 eV

# $\alpha$ -Model for GXe

- Most GXe  $\alpha$  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

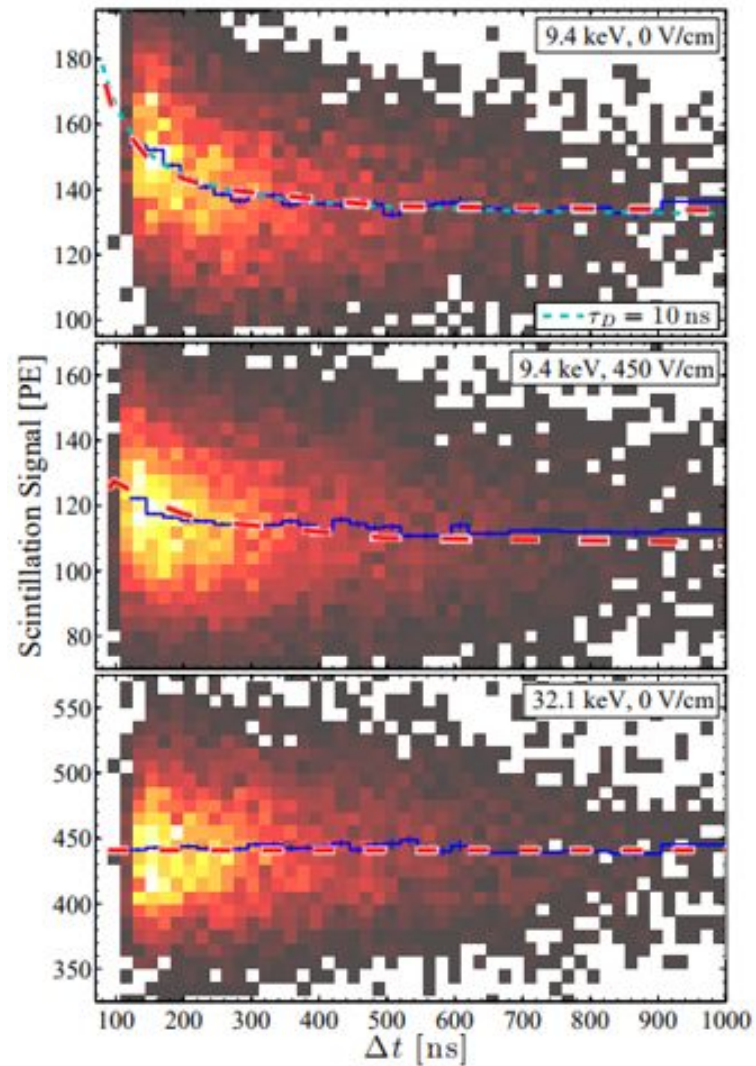
Based on  $^{57}\text{Co}$  yield of  $0.97 \cdot \text{Ly}_{32.1}$ , needed zero-field of 10V/cm.

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  $\alpha$ -model to include scattering events with heavy ions
- Again, contradictory data sets, splits the difference

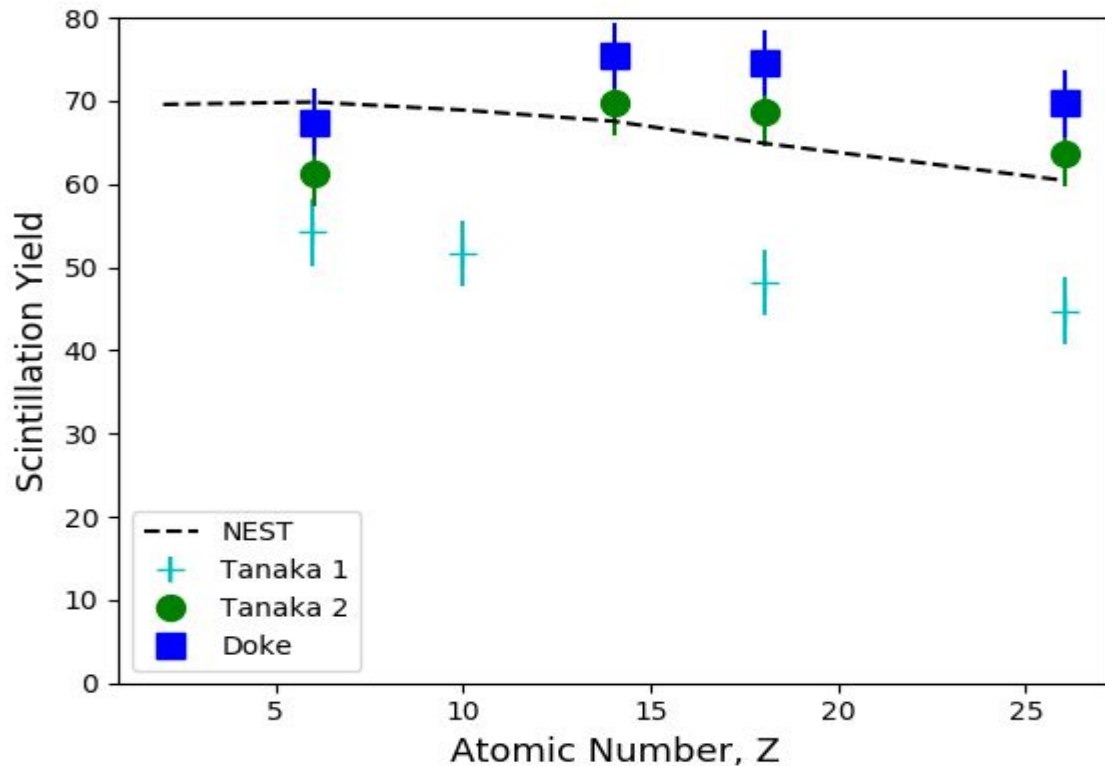
## Absolute Scintillation Yields in Liquid Argon and Xenon for Various Particles

T. Doke, et. al. 2002.

[Japanese Journal of Applied Physics, Volume 41, Part 1, Number 3A](#)

## LET dependence of scintillation yields in liquid xenon

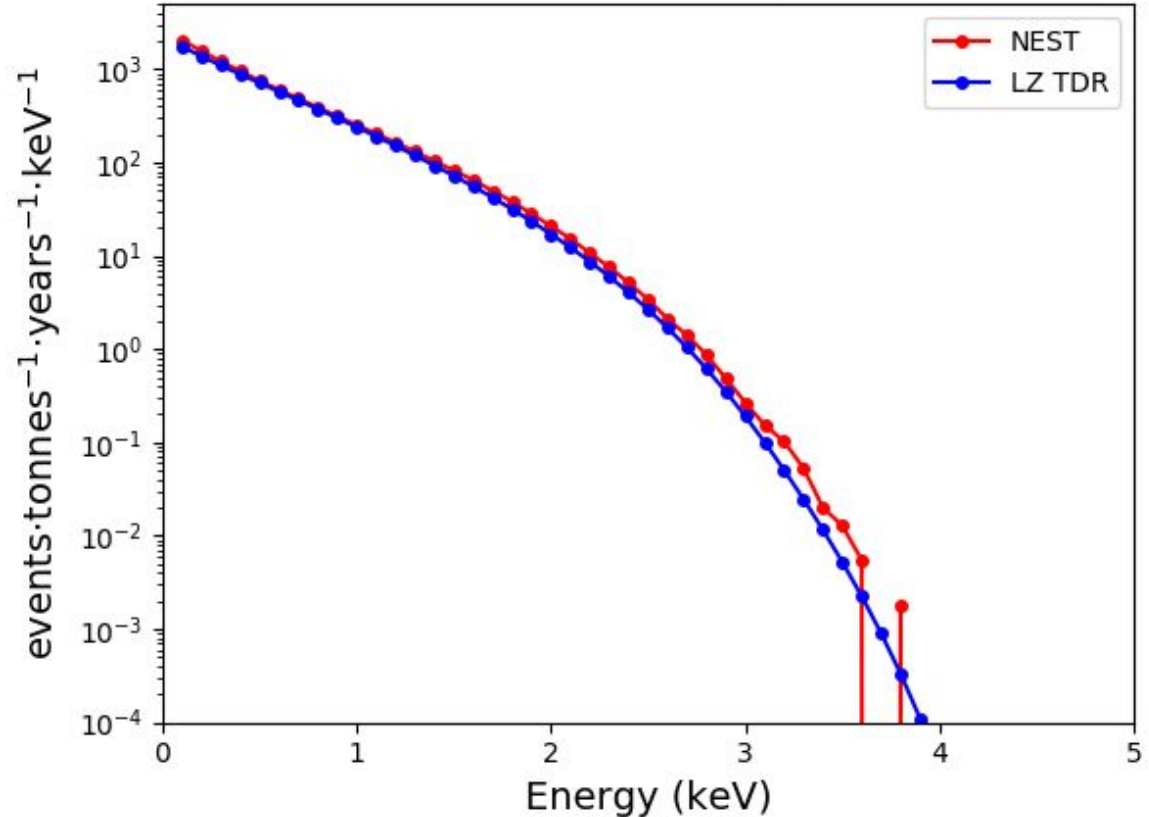
M. Tanaka, et. al. 2001



# Boron-8

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

## $^8\text{B}$ Spectrum Comparison



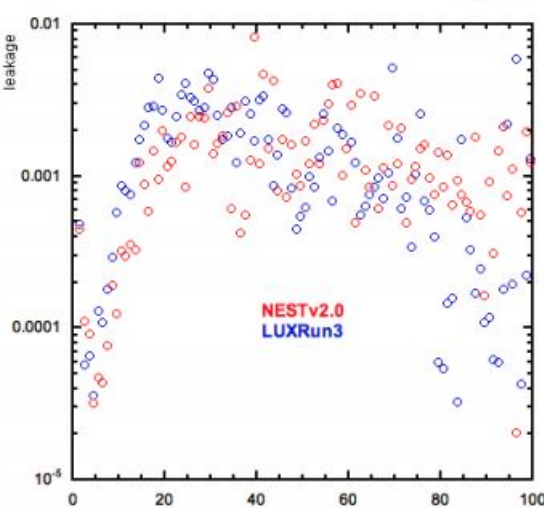
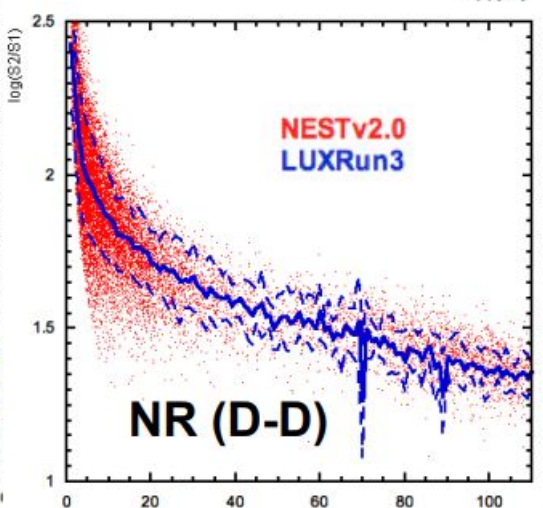
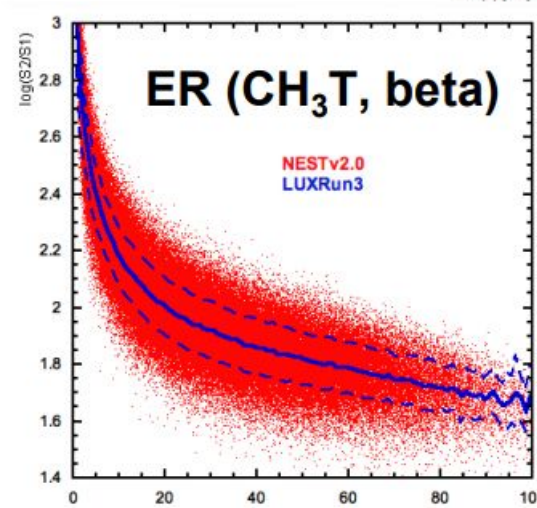
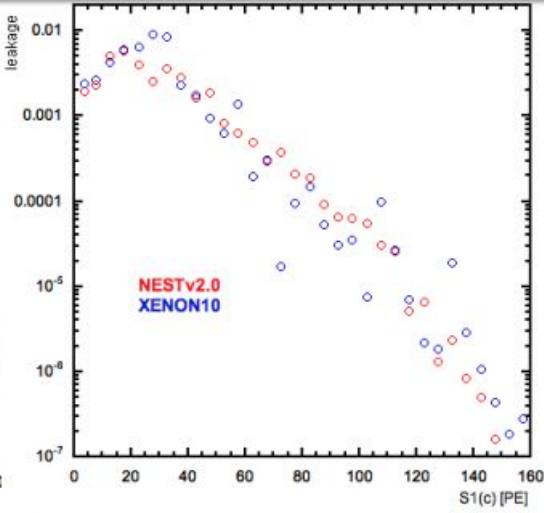
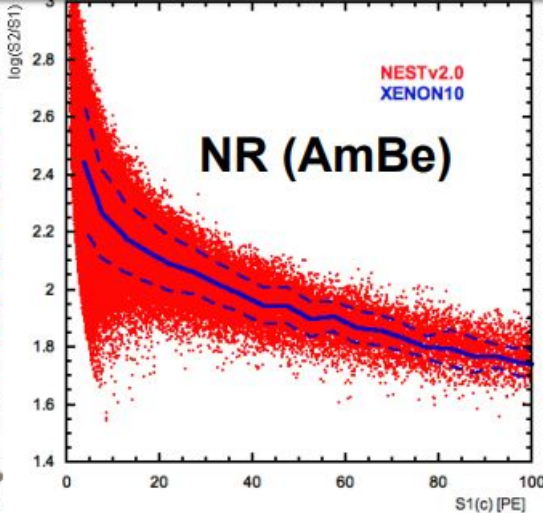
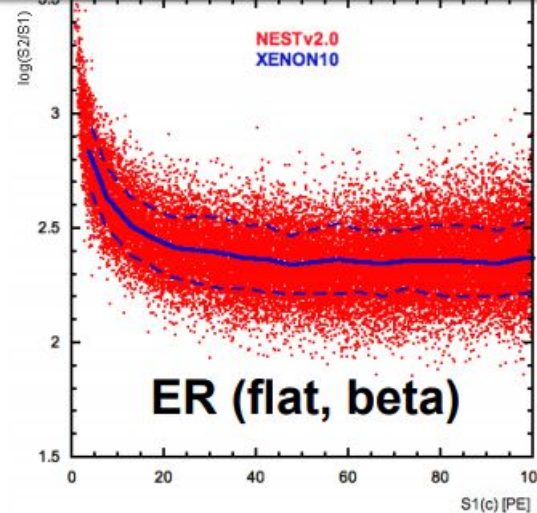
**LUX-ZEPLIN (LZ) Technical Design Report**

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](https://arxiv.org/abs/1703.09144) [physics.ins-det]

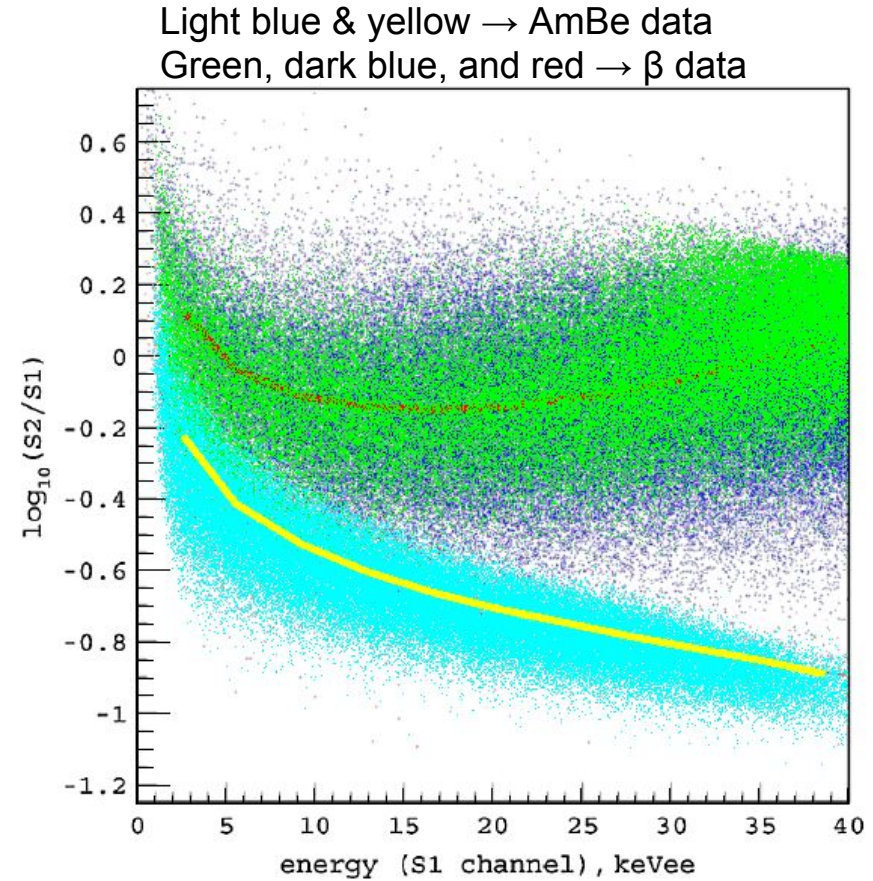
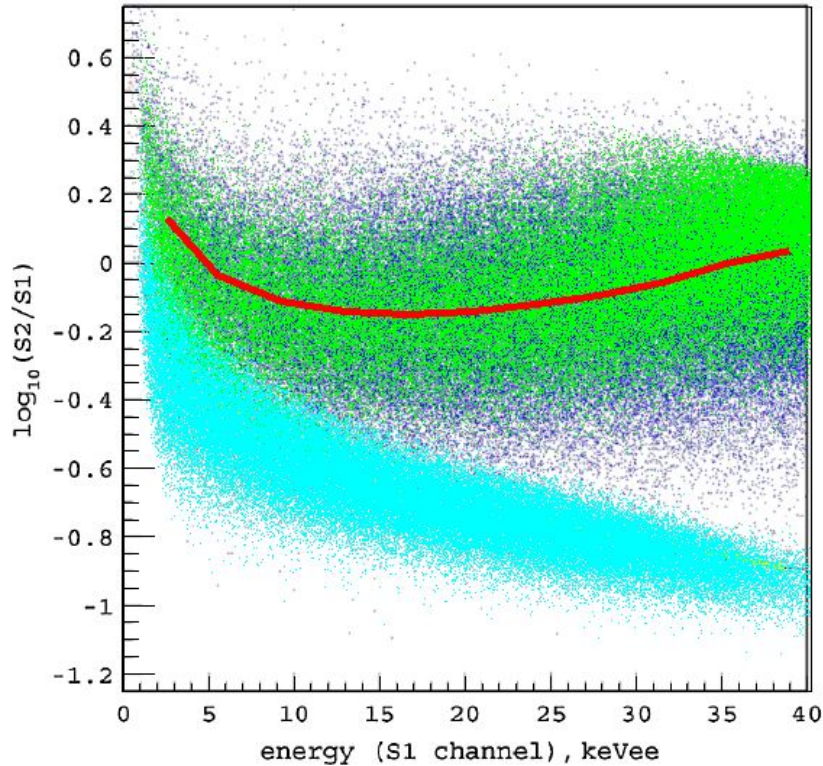


# Going Full-Scale with Detector Effects

NESTv2 accurately reproduces NR and ER bands.

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

# ZEPLIN-III Resolution comparison



**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