Modeling Scintillation and Ionization Mechanisms in NEST for low energy recoils in Xenon

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Thanks to the fast-growing field of dark matter searches with liquid xenon, data for low energy are growing.

Xenon	Light	Charge
Nuclear Recoils	Chepel (1999) Arneodo (2000) Akimov (2002) Aprile (2005) Aprile (2009) Manzur (2010) Plante (2011) Lin (2015) LUX DD (2015) PIXey (2015)	Columbia (2006) Case (2006) Sorensen (2009) 730 V/cm XENON10 (2010) 730 V/cm Manzur (2010) XENON100 (2013) 530 V/cm ZEPLIN-III Lin (2015) LUX DD (2015) PIXey (2015)
Electronic Recoils	Obodovskii (1994) Dahl (2009) Manalaysay (2010) Aprile (2012) Baudis (2013) Lin (2015) PIXey (2015) NeriX (2015)	Dahl (2009) Akimov (2014) Lin (2015) LUX Xe127 (2015) PIXey (2015) NeriX (2015)

Published and **new** measurements for low energy recoils (<10 keV)

About low energy calibrations

Do we need a model?

Yes!

Do we need measurements to fit the model?

Definitely!

Do we need to calculate from microphysics to get the parameters?

It will be interesting to do that.

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

NEST is a(n):

- **Detector-independent, data-driven** simulation framework
- **Comprehensive physical model** of low energy interactions in liquid xenon
- External package compatible with **Geant4**, for easy integration into simulations
- **Stand-alone code** for fast calculations of yields in simplified situations (Excel sheet available so far)

NEST is free and publicly available:

http://www.albany.edu/physics/NEST.shtml

http://nest.physics.ucdavis.edu

This talk covers:

1. Low energy nuclear recoils

2. Low energy electron recoils

3. Recombination fluctuation and discrimination

Signal production in liquid xenon

$$N_q = E_{dep}/W_q$$

$$N_q = N_{ex} + N_i$$

$Xe^+ + e^-$ —Escape→ Charge → **S2**

$$n_e = (1-r)N_i$$

Ionization

Recombination

$$N_{ex}/N_i \sim 0.1$$

$$n_\gamma = (\frac{N_{ex}}{N_i} + r)N_i$$

Electron Recoil

Nuclear Recoil

Excitation

Xe_2^* —De-excitation→ Light → **S1**

Atomic motion

Penning quenching
(biexcitonic quenching)

$$n'_\gamma = n_\gamma \times f_l$$

$f_l \sim 1$ below 10 keV

$$N_q = E_{dep} \cdot L/W_q$$

Heat

L: Lindhard quenching for NR
Works well for total quanta,
should not be confused with L_{eff} which is only the light

NEST models this process start-to-finish for both ER and NR

NEST provides absolute number of electrons AND number of photons for a given energy, field and type.

$$n_e = L \times \frac{E_0}{W}\left(\frac{1}{1+N_{ex}/N_i}\right)(1-r)$$

$$n_\gamma = L \times f_l \times \frac{E_0}{W}\left[1-\left(\frac{1}{1+N_{ex}/N_i}\right)(1-r)\right]$$

arXiv:1412.4417

$$L = \frac{k\,g(\epsilon)}{1+k\,g(\epsilon)}$$

energy

$$f_l = \frac{1}{1+\eta\epsilon^\lambda}$$

energy

W = 13.7 eV

field energy

$$N_{ex}/N_i = \alpha\,F^{-\zeta}\,(1-e^{-\beta\epsilon})$$

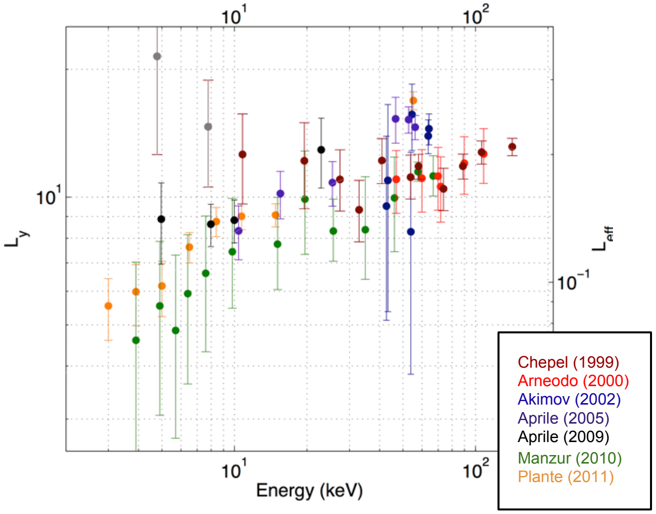
$$r = 1 - \frac{\ln(1+N_i\,\varsigma)}{N_i\,\varsigma}$$

$$\varsigma = \gamma F^{-\delta}$$

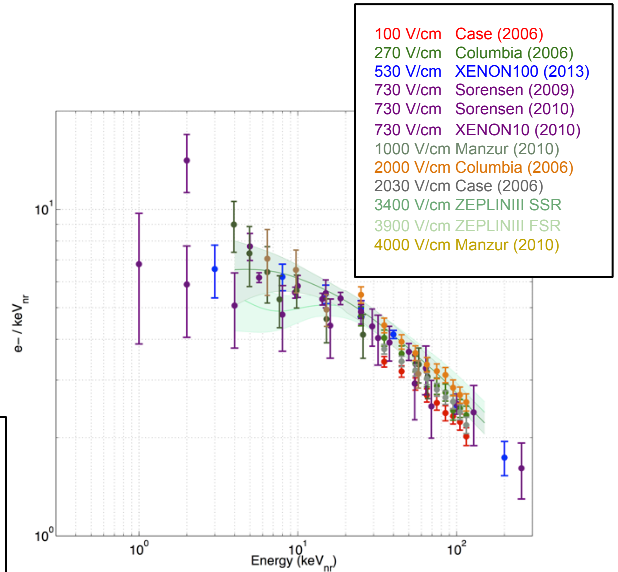
field

Thomas-Imel recombination model

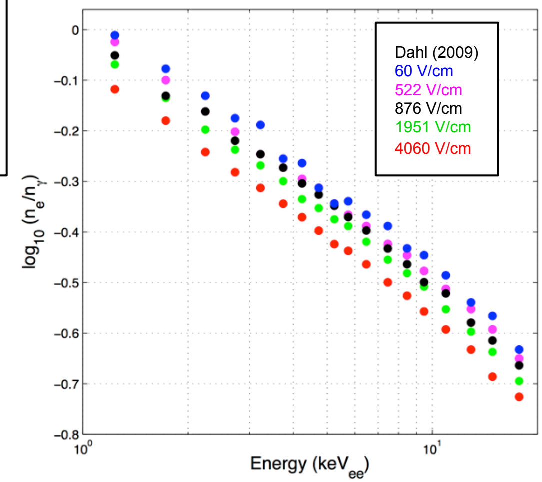
Global fit to the world's data (NR)



L_{eff} - scintillation yield



Q_y - ionization yield



Electron / photon ratio

To fit to all of these data, we construct a global likelihood function and optimize.

$$\mathcal{L} = \prod \frac{1}{\sqrt{2\pi}\,\sigma_{exp}} \exp\left(\frac{-(x_{exp}-\mu)^2}{2\,\sigma_{exp}^2}\right) \qquad \mu \in \left\{ \mathcal{L}_{eff},\ \mathcal{Q}_y,\ \frac{N_e}{N_{ph}} \right\}$$

arXiv:1412.4417: 2015 data not yet included, but pretty close to the predictions

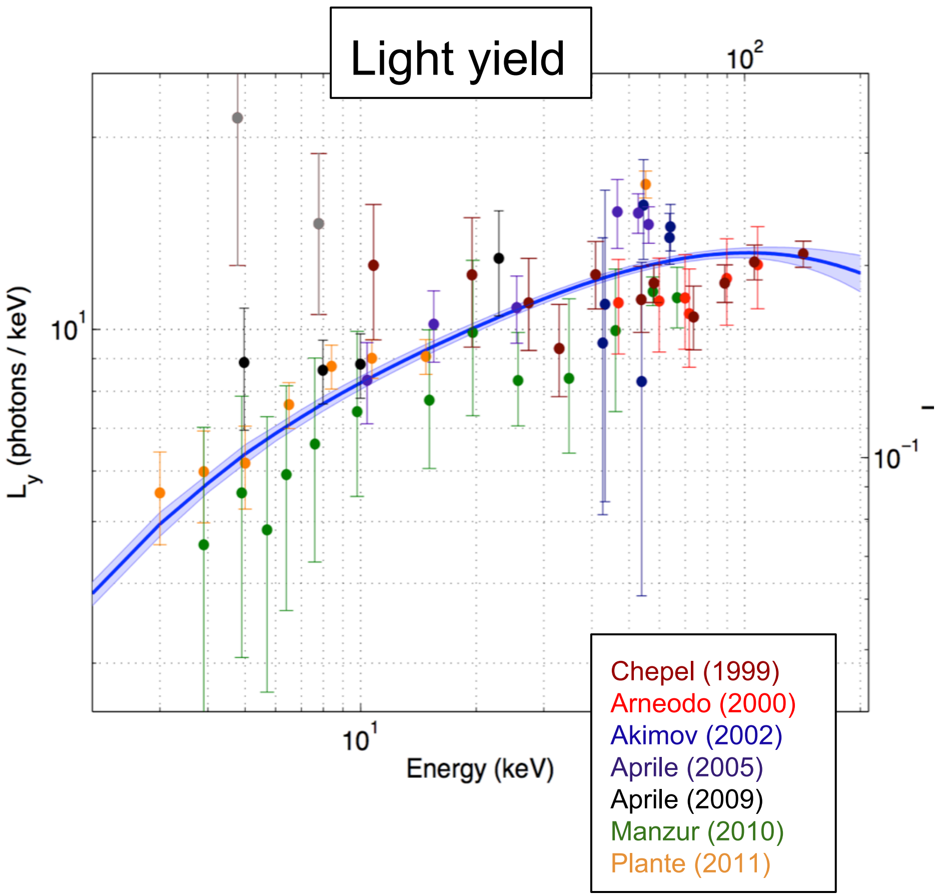
Advantages of the global analysis

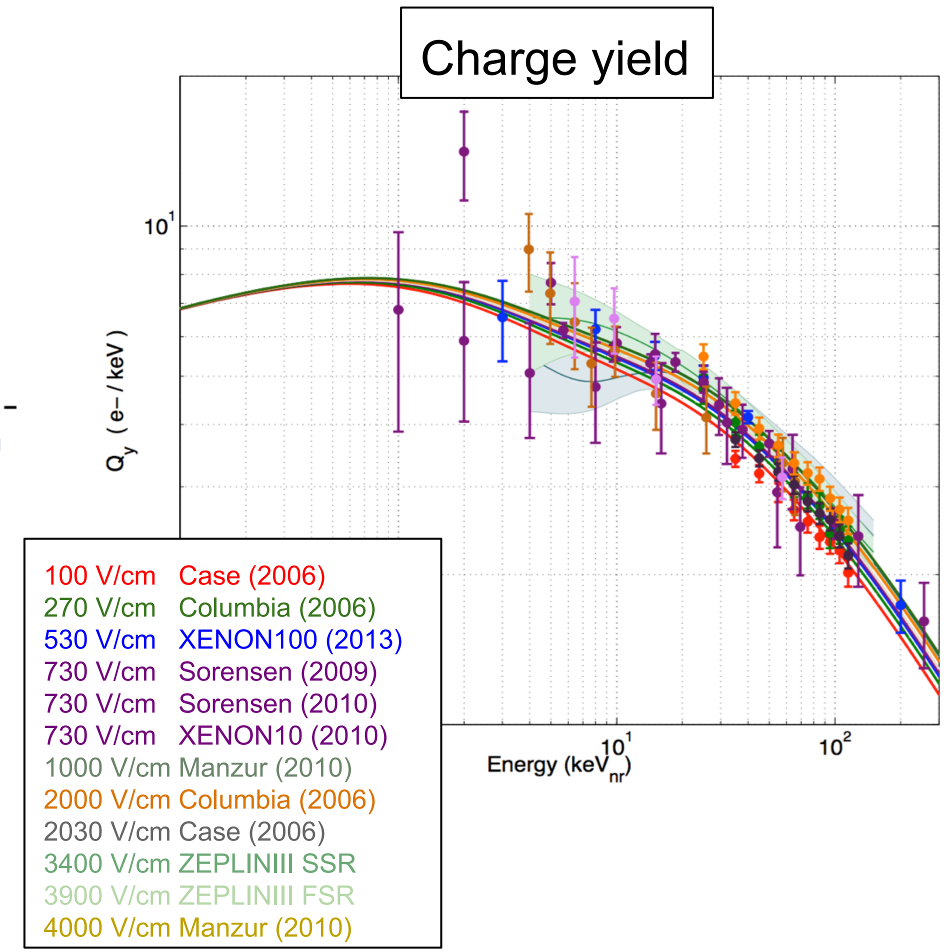
- Constrains light and charge simultaneously; one affects the other
    - Stronger constraints than looking at either individually
- Includes all measurements in the literature in an unbiased way
- Can easily incorporate new data as it becomes available

The resulting model allows us to interpret and simulate experimental data in a way that **reflects the cumulative body of research** on liquid xenon response.

Global fit to the world's data (NR)

Nuclear recoil model constrained with a global analysis of available data, see arXiv:1412.4417





NEST best fit for nuclear recoils

$$n_e = L \times \frac{E_0}{W} \left(\frac{1}{1 + N_{ex}/N_i} \right) (1 - r)$$

$$n_\gamma = L \times f_l \times \frac{E_0}{W} \left[1 - \left(\frac{1}{1 + N_{ex}/N_i} \right) (1 - r) \right]$$

$$L = \frac{k\, g(\epsilon)}{1 + k\, g(\epsilon)} \qquad f_l = \frac{1}{1 + \eta \epsilon^{\lambda}}$$

$$r = 1 - \frac{\ln(1 + N_i\, \varsigma)}{N_i\, \varsigma}$$

$$N_{ex}/N_i = \alpha\, F^{-\zeta} (1 - e^{-\beta \epsilon})$$

$$\varsigma = \gamma F^{-\delta}$$

$$\sigma_R^2 = n_e \times \mathcal{F} = (1 - r)\, N_i \times \mathcal{F} = (1 - r)\, \mathcal{C}\, N_i^2$$

TABLE I. Best fits and 68% confidence intervals of free parameters.

Parameter	Best Fit	68% conf.
α	1.240	+0.079 -0.073
ζ	0.0472	+0.0088 -0.0073
β	239	+28 -8.8
γ	0.01385	+0.00058 -0.00073
δ	0.0620	+0.0056 -0.0064
k	0.1394	+0.0032 -0.0026
η	3.3	+5.3 -0.06
λ	1.14	+0.45 -0.09
$\mathcal{C}$	0.00555	+0.00025 -0.00025

arXiv:1412.4417

Systematics in the literature

Energy scale / uncertainties

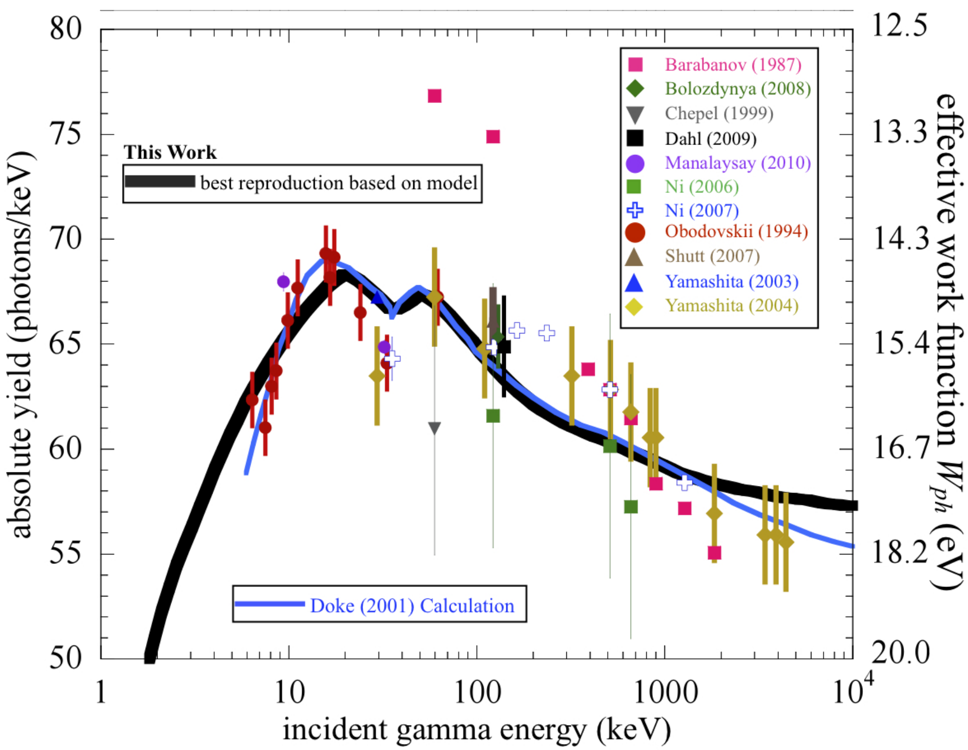
- Energy scales are determined differently in different papers
- Uncertainties in energy are inconsistently reported

Electron extraction efficiency from liquid

- Results in systematic up/down shift in measured charge yield

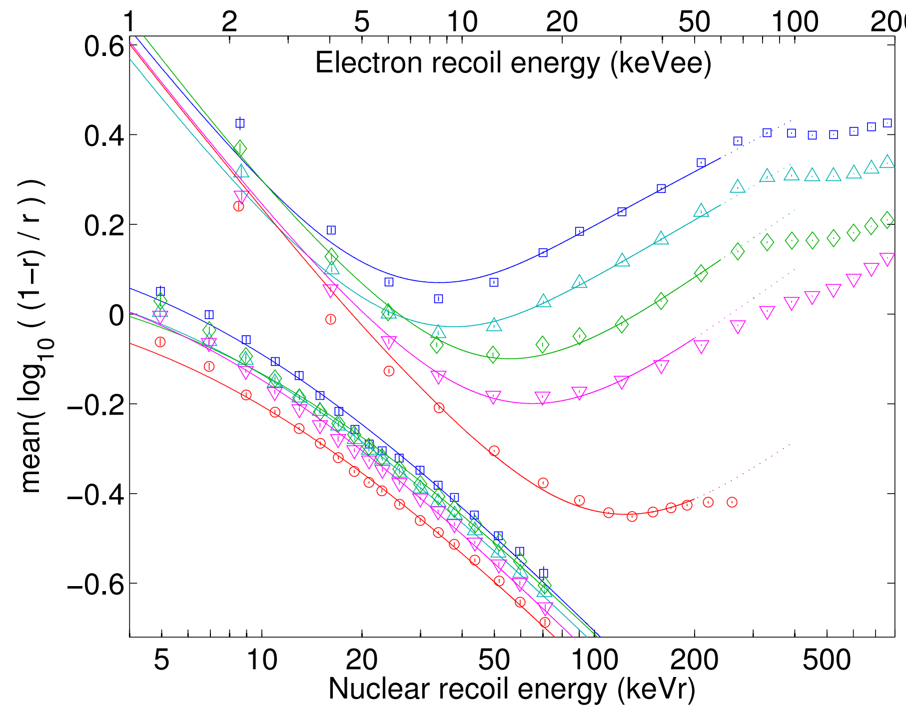
Scintillation and Ionization for Electron Recoils (early work)

Zero field scintillation (high energy)



Szydagis et al., JINST (2011), arXiv:1106.1613

Ionization/Scintillation at different fields (low energy)

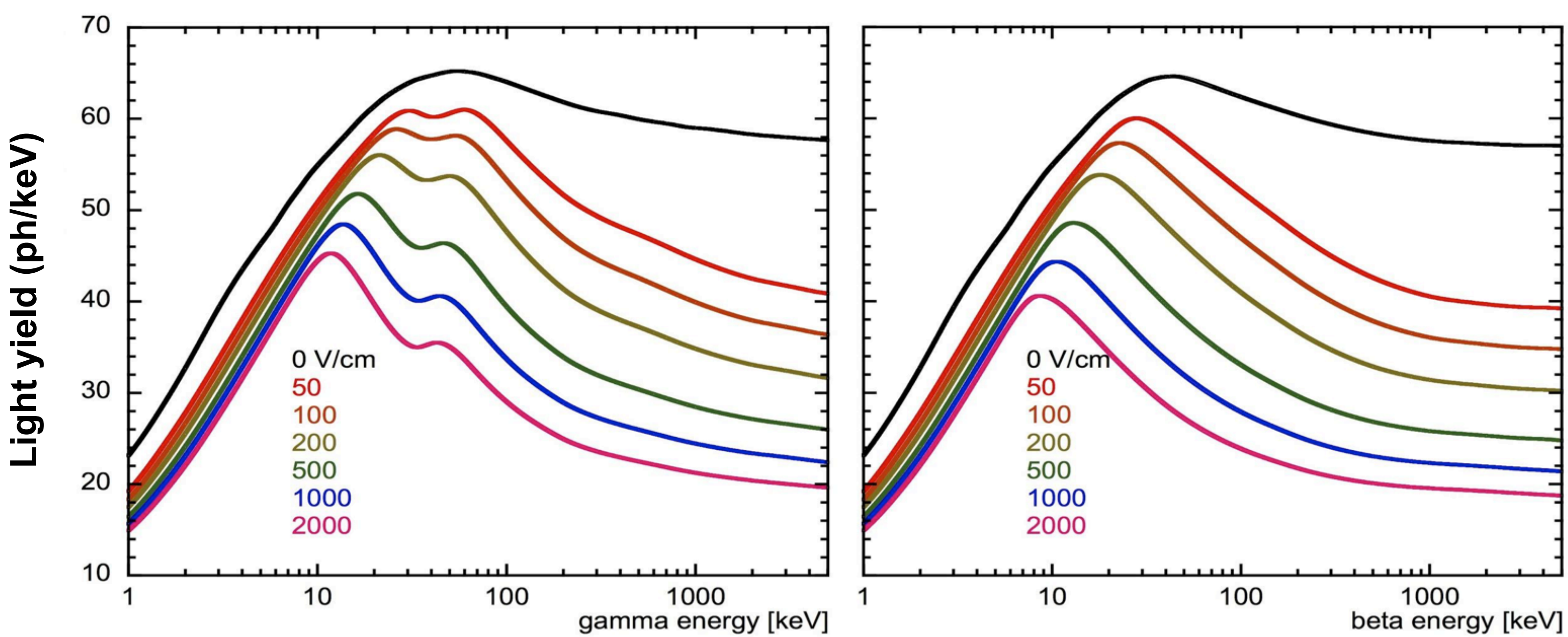


Dahl's PhD thesis (2009)

The current NEST ER model (v0.98) based on data from early work

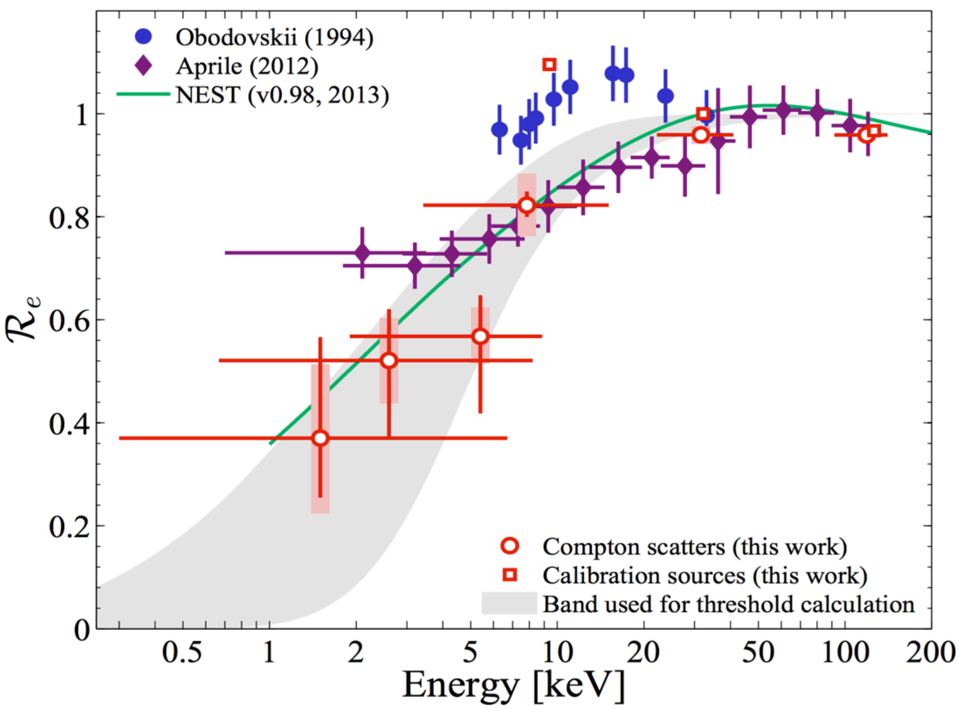
For long tracks (high energy), Birks-Doke law: $r = \frac{A\frac{dE}{dx}}{1+B\frac{dE}{dx}} + C, \quad C = 1 - A/B$

For short tracks (low energy), Thomas-Imel Box model: $r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$

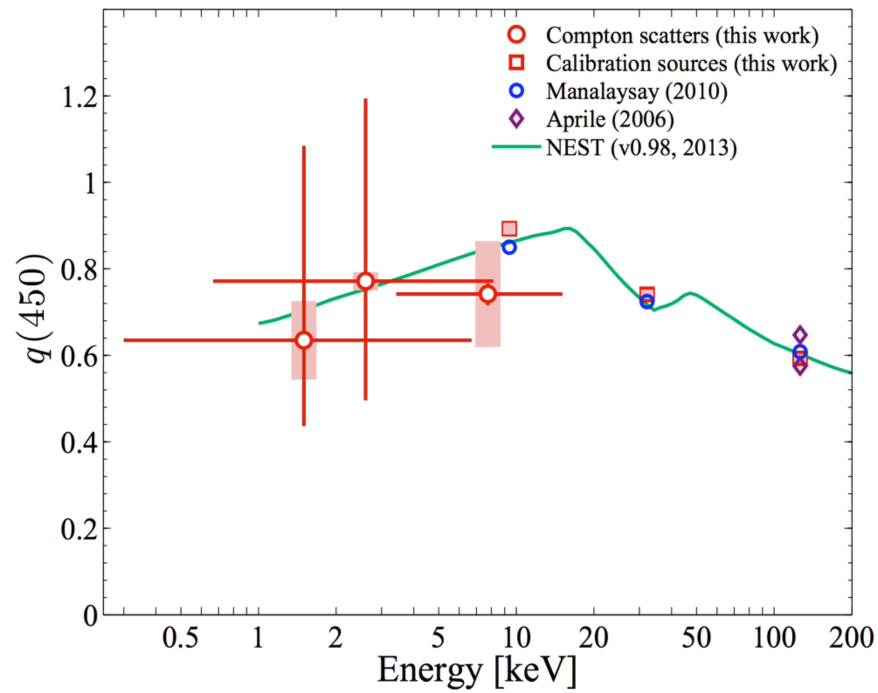


ER scintillation from direct measurements (Compton scattering, or mono-energetic lines)

Zero Field Scintillation

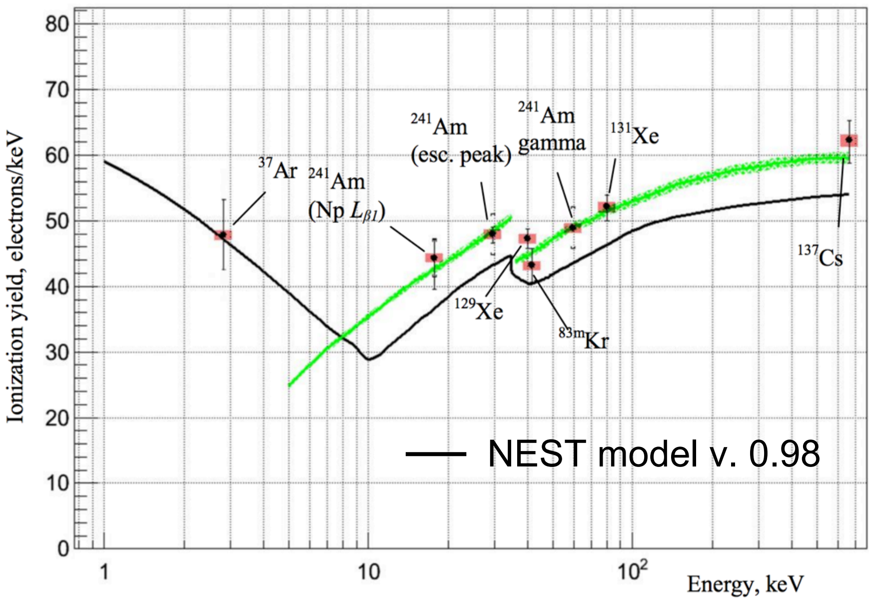


Scintillation Quenching at 450 V/cm

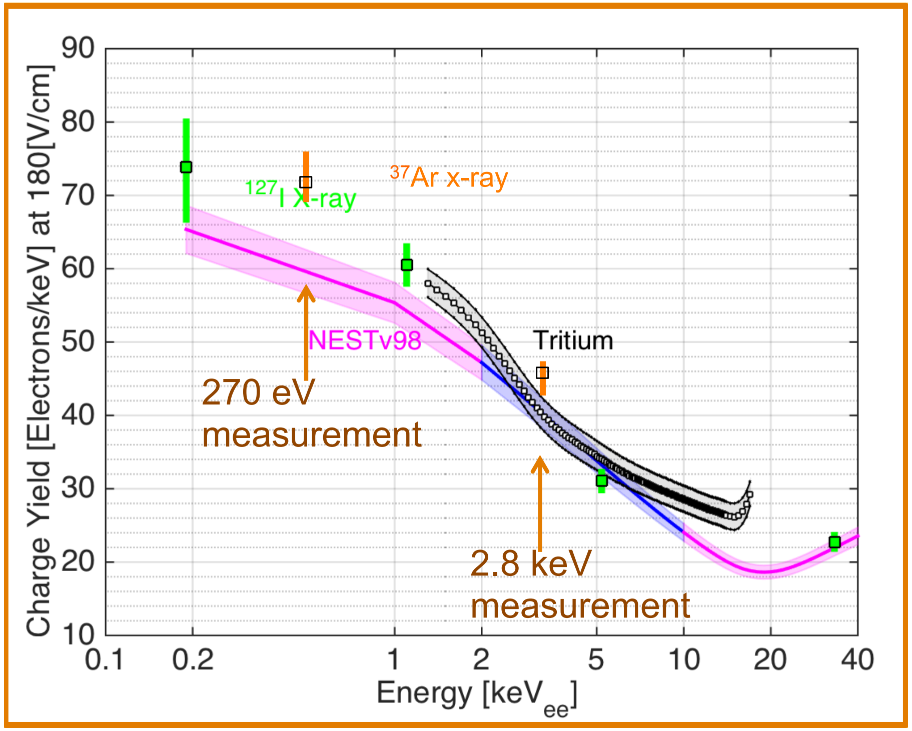


Aprile et al., Phys. Rev. D 86, 112004 (2012)
Baudis et al., Phys. Rev. D 87, 115015 (2013)

ER ionization from direct measurement – very few data



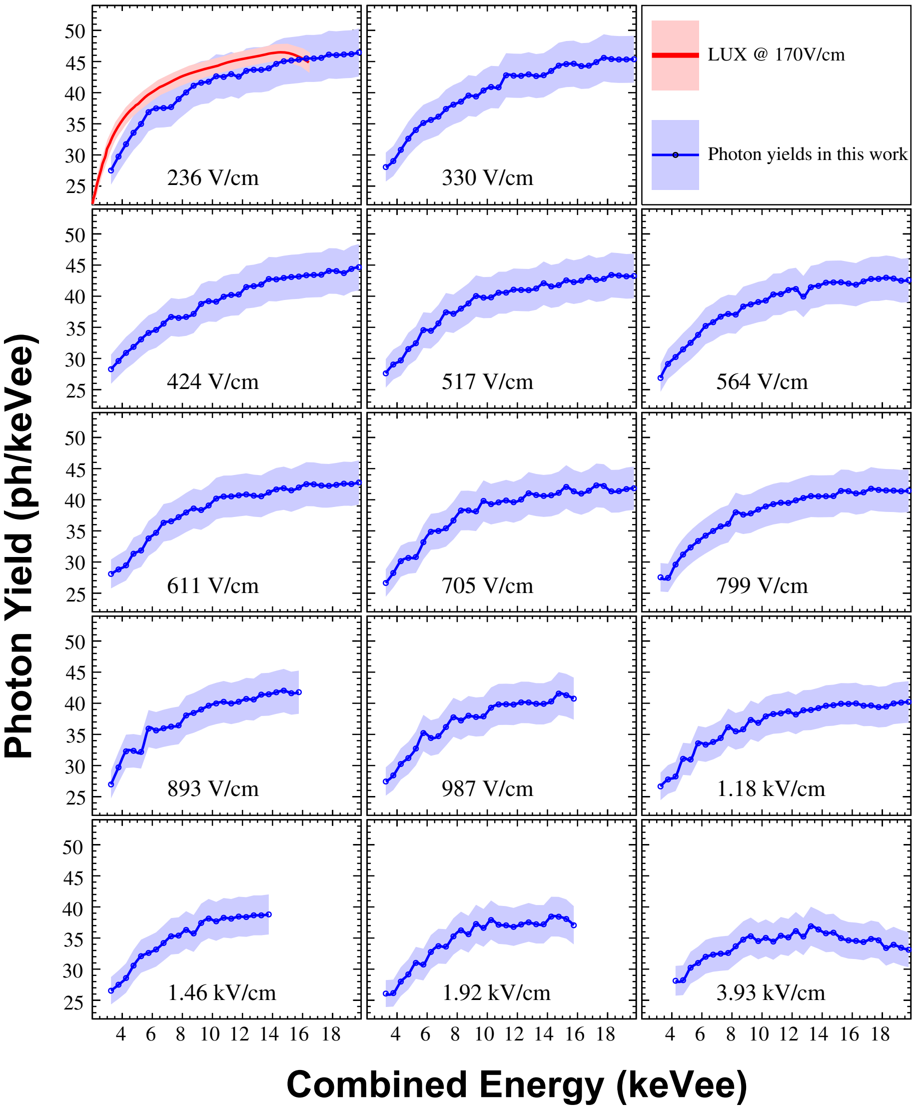
Akimov et al., JINST 9 (2014) P11014



D. Huang, LIDINE2015 (Xe127/LUX)
E. Boulton, LIDINE2015 (Ar37/PIXeY)

New results from L. Goetzke (this workshop)!

More recent indirect measurement results



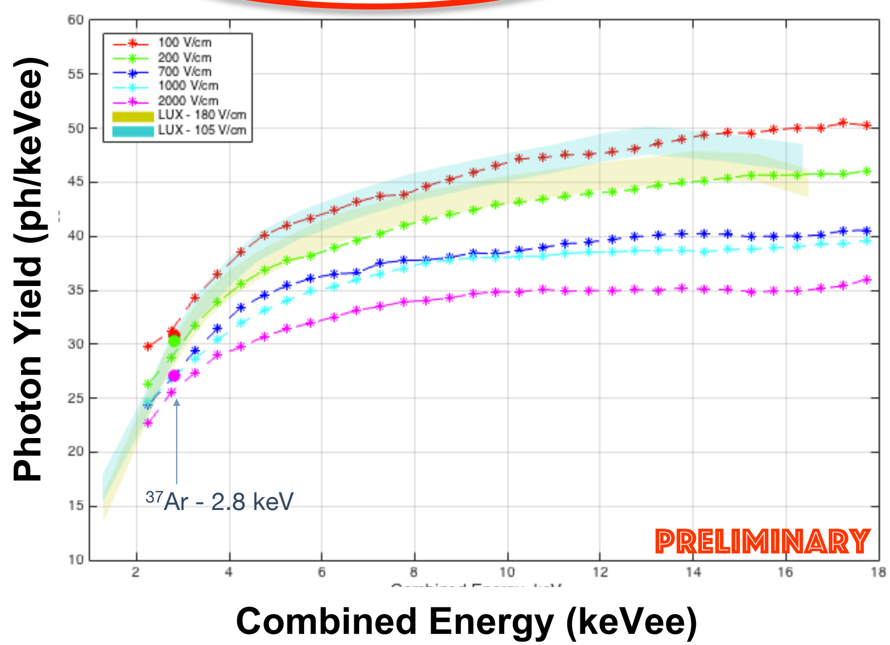
Lin et al., Phys. Rev. D 92, 032005 (2015)

Assumptions:

$$E = (n_\gamma + n_e)W_q$$

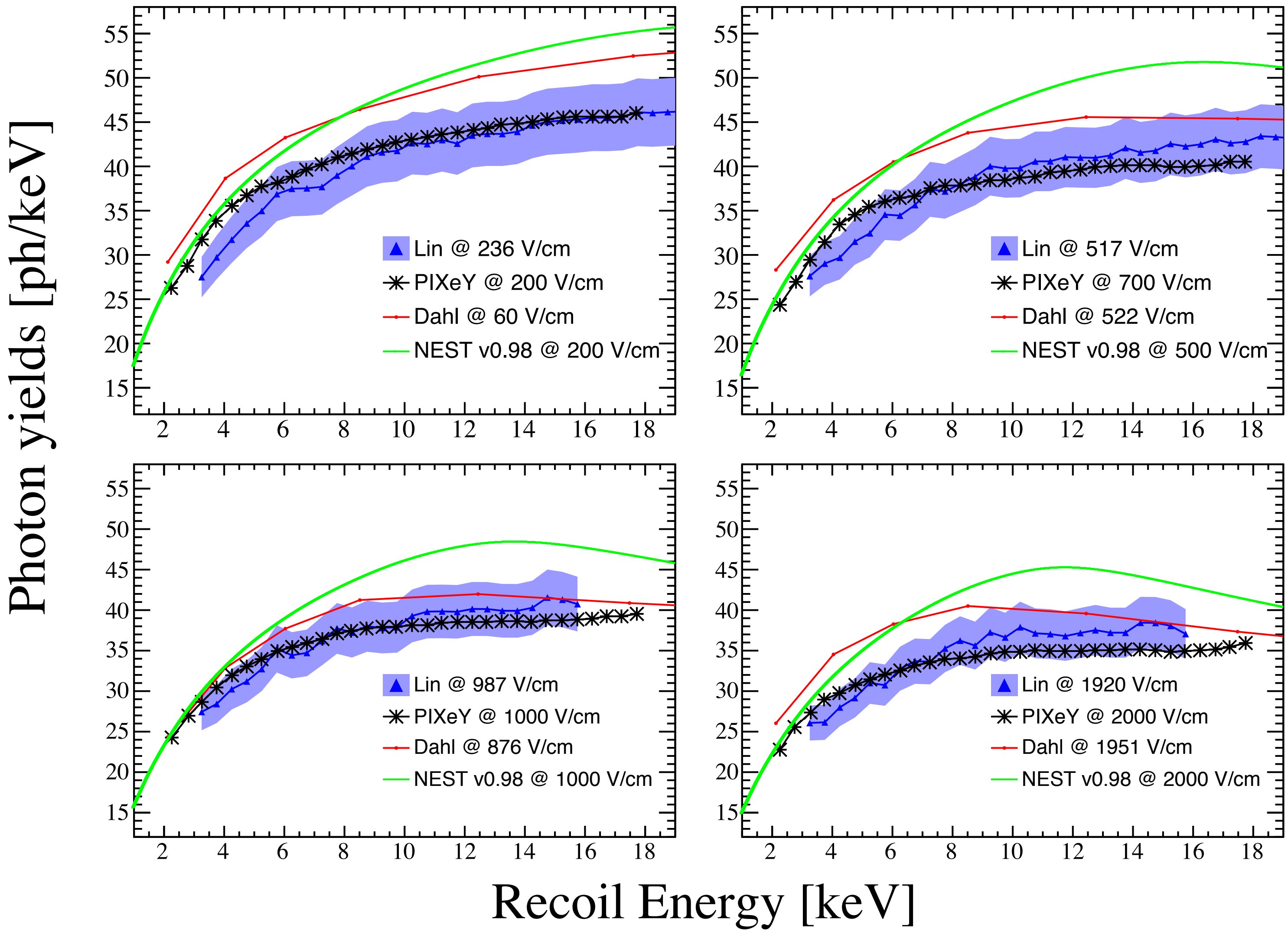
$$= (\frac{S1}{g_1} + \frac{S2}{g_2})W_q$$

$$W_q = 13.7\ \text{eV}$$

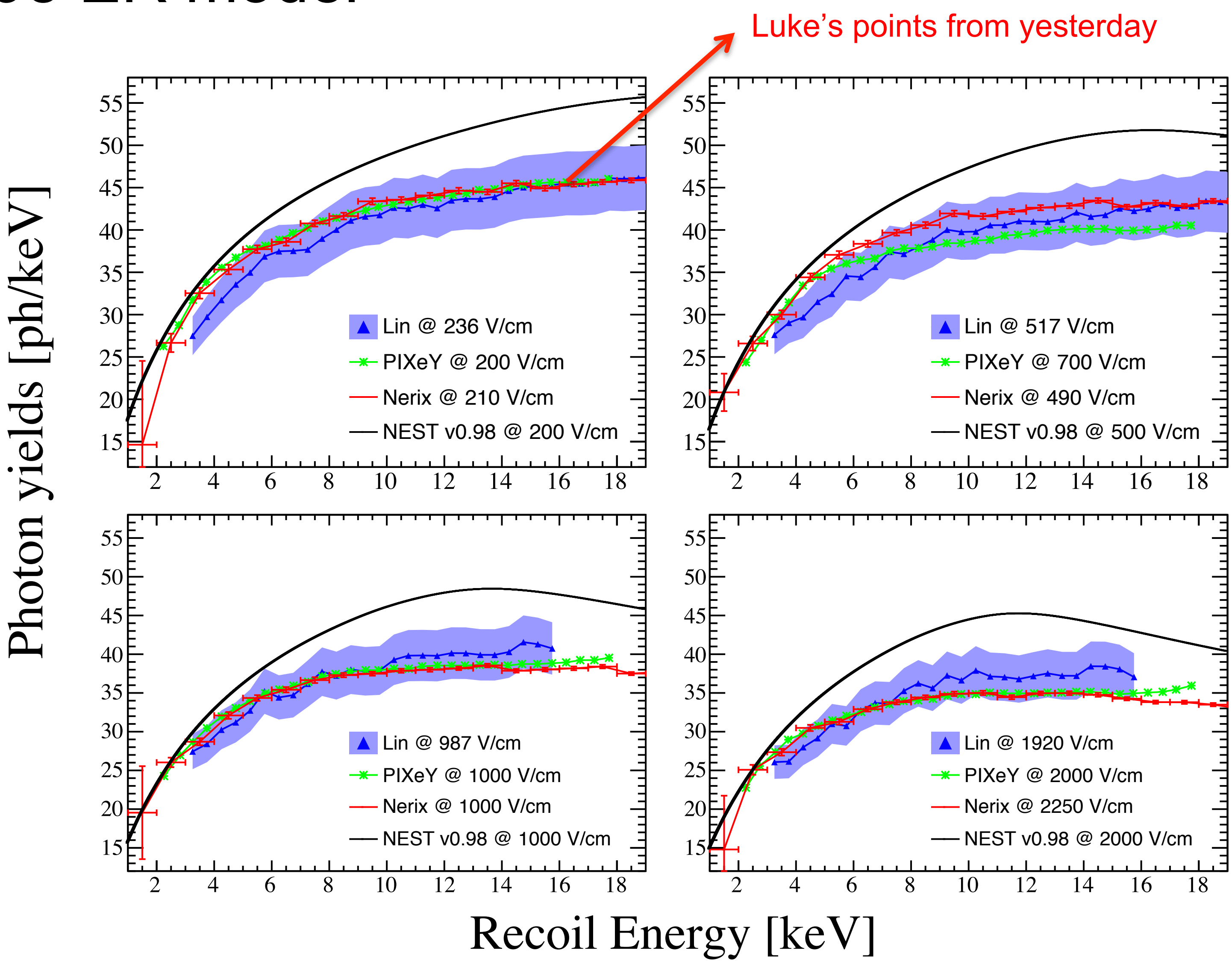


D. McKinsey & B. Edwards, LIDINE 2015

Comparing the indirect measurements with NEST v0.98 ER model



Comparing the recent measurements with NEST v0.98 ER model



Assumptions of W = 13.7 eV at low energy

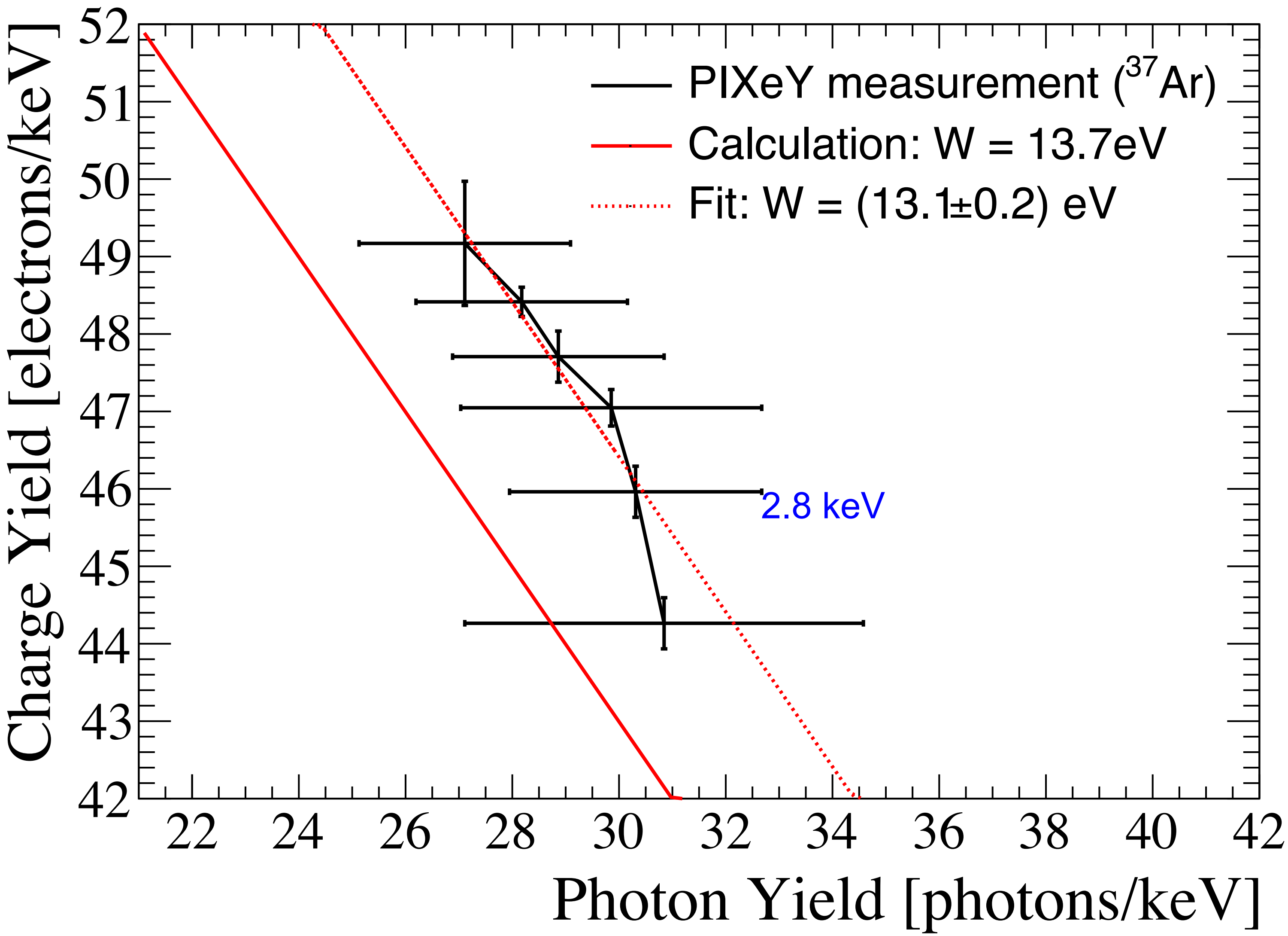


Figure made by Fei Gao from data points from [E. Boulton, LIDINE2015]

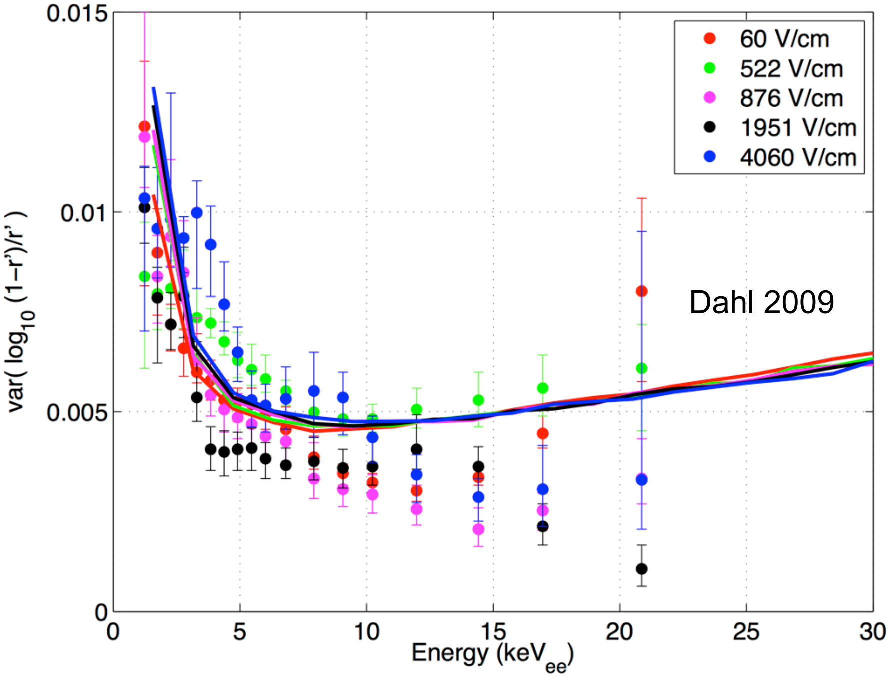
Need a new model for Electron Recoils

- Current NEST ER model (v0.98) describes new data within 10%, but needs to be improved
- Current NEST ER model (v0.98) is not analytical, require "full" Geant4 simulation of energy deposition
  - with small-scale energy-loss steps recorded
  - with tiny track length cut-off (threshold)
- It needs to merge Thomas-Imel & Doke-Birk laws at medium energy (starting at 5~10 keV and field dependent)
  - require knowledge of dE/dx and exact track structure
- E. Dahl has a modified Thomas-Imel model but require track structure simulation with PENELOPE

Modeling recombination fluctuations

In LXe, recombination fluctuations are very different than the expected due to a binomial process (Dobi 2014):

$$\sigma_{bin}^2 = r\,(1-r)\,N_i \qquad \sigma_{obs}^2 = \frac{1}{185} \times N_i^2$$



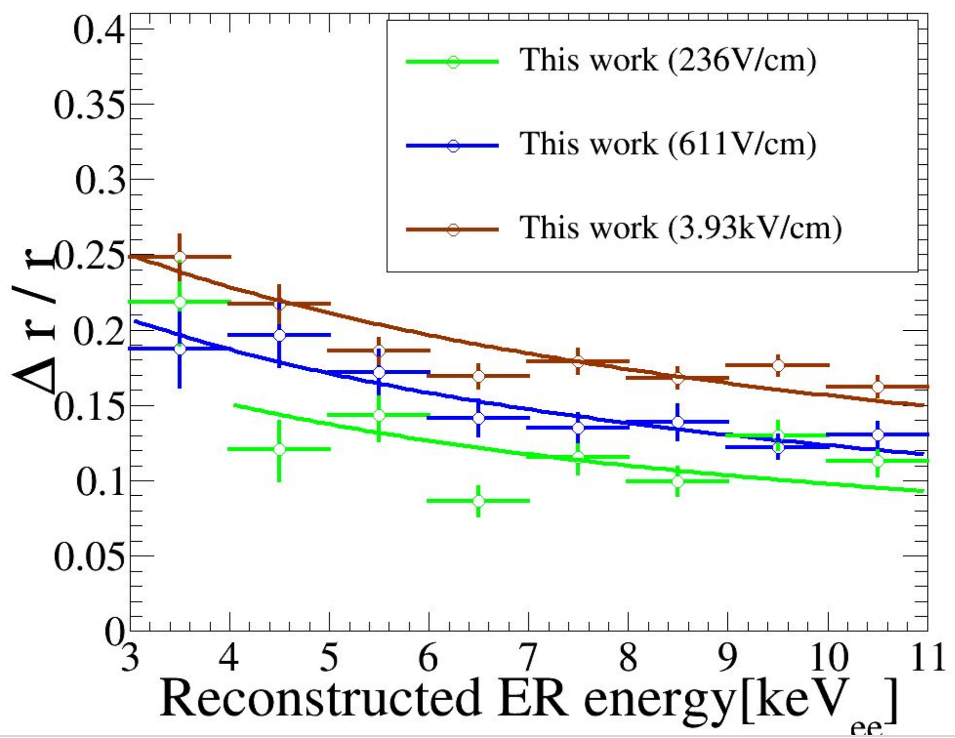
In NEST v1.0 NR model, a Fano-like factor proportional to N_i to fit to Dahl's data

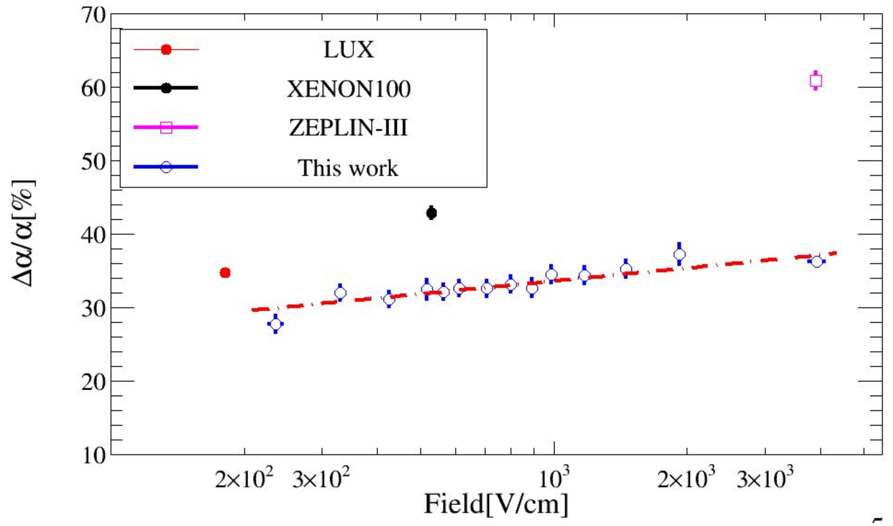
$$\sigma_R^2 = n_e \times \mathcal{F} = (1-r)\,N_i \times \mathcal{F} = (1-r)\,\mathcal{C}\,N_i^2$$

Probing the intrinsic recombination fluctuations (for Electron Recoils, Lin's talk yesterday)

$$r(\xi) = 1 - \frac{1}{\xi} ln(1+\xi), \xi = \frac{N_i \alpha}{4a^2 \mu F}$$

$$\Delta r = \left[\frac{1}{\xi} ln(1+\xi) - \frac{1}{1+\xi}\right] \frac{\Delta \alpha}{\alpha}$$





The NEST collaboration

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Prof. Tom Shutt

Prof. Dan Akerib

Conclusions

- NEST is a tool **by and for the liquid xenon** community for modeling detector response
- Global analysis allows the inclusion of all available data in an unbiased way
  - For low energy NR data, v1.0 is now public (arXiv: 1412.4417)
  - For low energy ER data, the current model (v0.98) is outdated. A modified TIB model is being developed (v1.0) incorporating all recent data
- Approaches to understand the intrinsic recombination fluctuations in order to predict ER/NR discrimination are underway