Simulation of Noble Liquid Detectors Using **NEST**

What's New?

http://nest.physics.ucdavis.edu/site/

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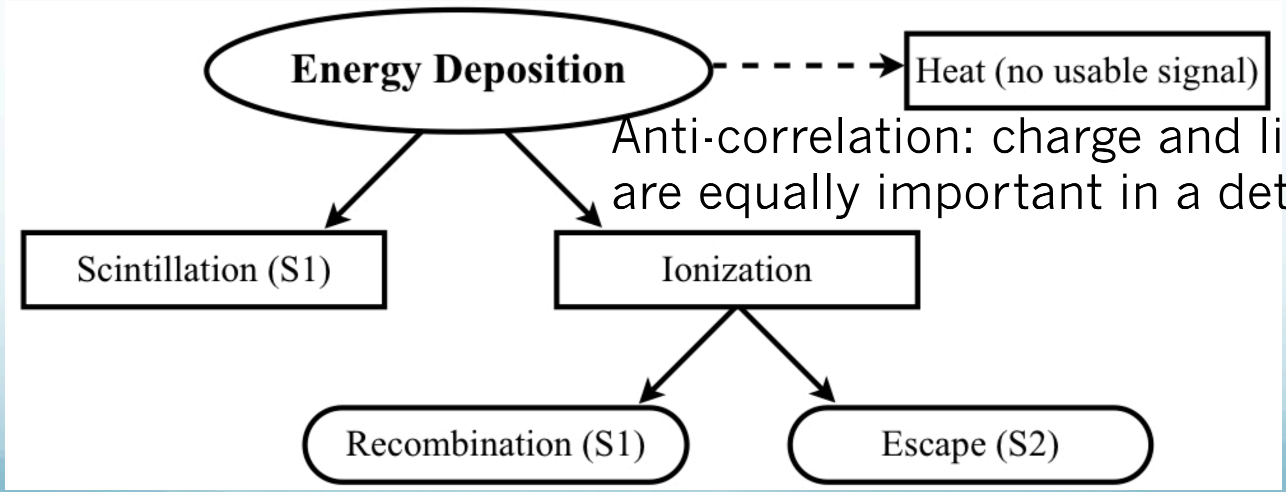
Why These Elements?

- Well suited to the **direct detection of dark matter**
  - Xenon and argon both used, in both large dark matter experiments and small-scale calibration efforts
  - 1- and 2-phase, and zero and non-zero field (TPCs)
- Broad, compelling ν physics programs, like LBNE
  - Neutrinoless double-beta decay (^{136}Xe): EXO, NEXT
  - Coherent ν-scattering, and reactor monitoring: RED
- PET scans for medical applications (511 keV γ's)
- $\mu^- \Rightarrow e^- + \gamma$ (evidence of new physics): MEG
- Sensitive to nuclear recoil (NR) and electron recoils (ER) detecting photoelectrons (phe) in PMTs

Noble Element Physics

- Energy ≠ S1: energy deposited into 3 channels ("heat" prominent for NR, reducing their S1 & S2)
- Excitation and recombination lead to the S1, while escaping ionization electrons lead to the S2
- Divisions at each stage are functions of particle type, electric field, and *dE/dx* or energy



Anti-correlation: charge and light are equally important in a detector

Handled by NEST

- **N**oble **E**lement **S**imulation **T**echnique is a data-driven model explaining both the scintillation and ionization yields vs. those (splines avoided)
- Provides a full-fledged Monte Carlo (in Geant4) with
  - Mean yields: light AND charge, and photons/electron
  - Energy resolution: key in discriminating background
  - Pulse shapes: S1 AND S2, including single electrons
- The canon of existing experimental data was combed and all of the physics learned combined

M. Szydagis et al., JINST 8 (2013) C10003. arXiv:1307.6601
M. Szydagis et al., JINST 6 (2011) P10002. arXiv:1106.1613
J. Mock et al., JINST in press (2014). arXiv:1310.1117

The Basic Principles

- The work function for creating an S1 photon or S2 electron does not depend on the interacting particle or its energy, but differences in yields are caused by the field, energy, and particle-dependent recombination probability of ionization electrons

- Recombination model is different for "short" tracks (< O(10) keV) and "long" tracks: using Thomas-Imel box (TIB) and Doke-Birks approaches, respectively

$$r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$

TIB model uses only total energy deposited, via number of ions

$$r = \frac{A\frac{dE}{dx}}{1+B\frac{dE}{dx}} + C$$

By contrast, Doke-Birks relies on the energy loss

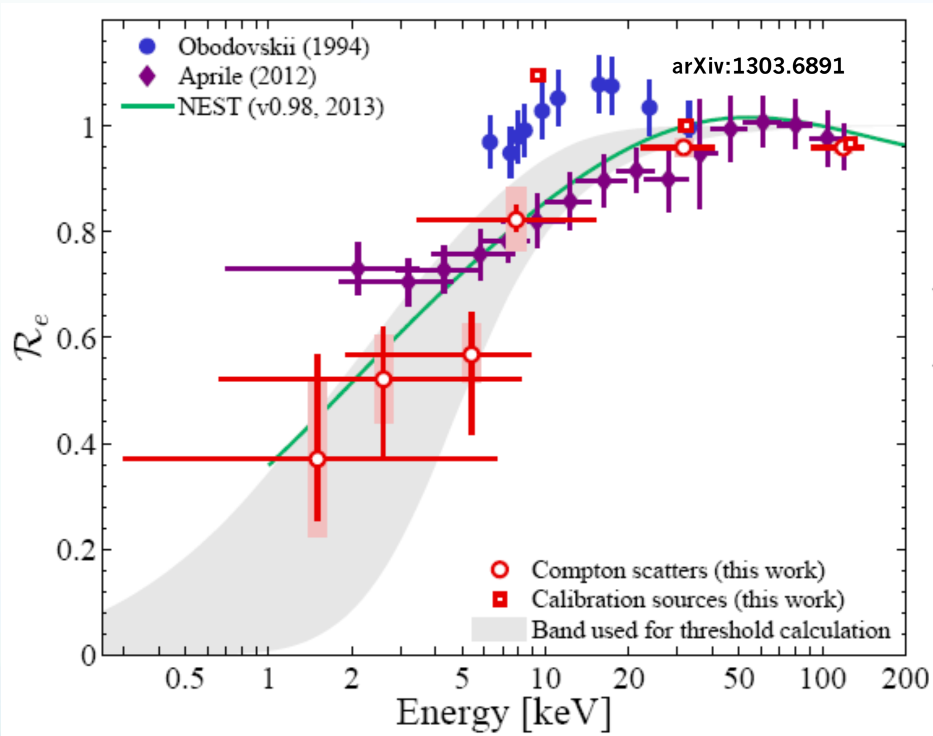
- This probability is what causes non-linear yields per unit of energy. "Constants" vary with field, with Doke and TIB opposite in trend vs. total energy

Life is Complicated

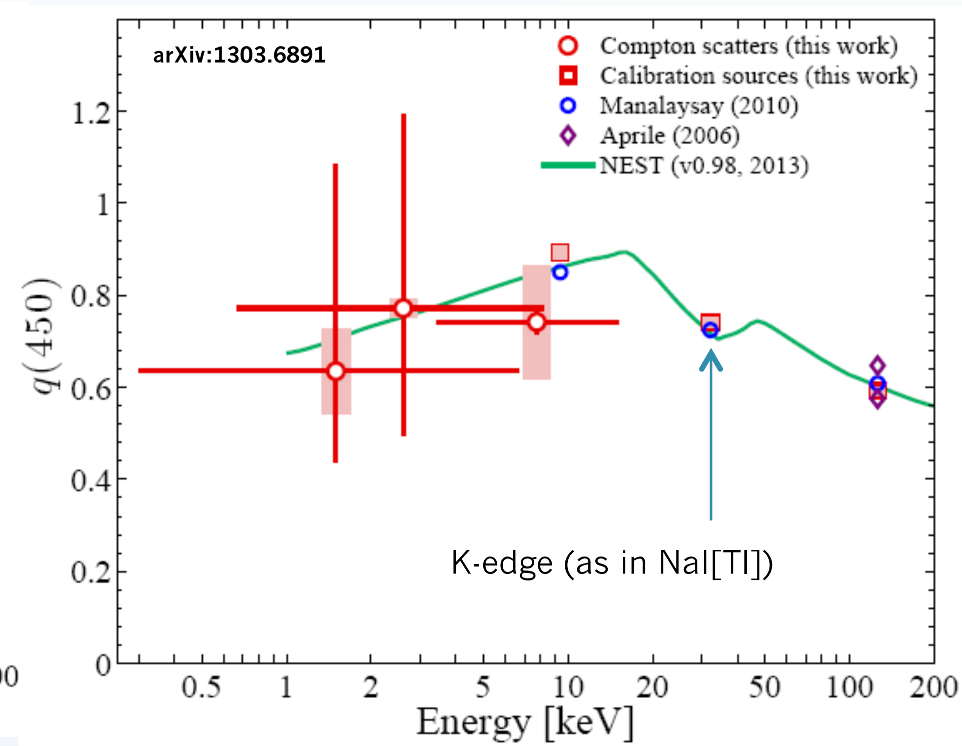
- Twice the energy does not necessarily translate to twice the signal, in either channel
- Long-standings ways of thinking about signals from noble-element-based detectors shattered
  - In liquid Xe gamma-ray yields not flat in energy
  - Field dependence of yields also energy-dependent
- The NEST team dug up old, rare works, forgotten....

ER Scintillation Yield

Zero field

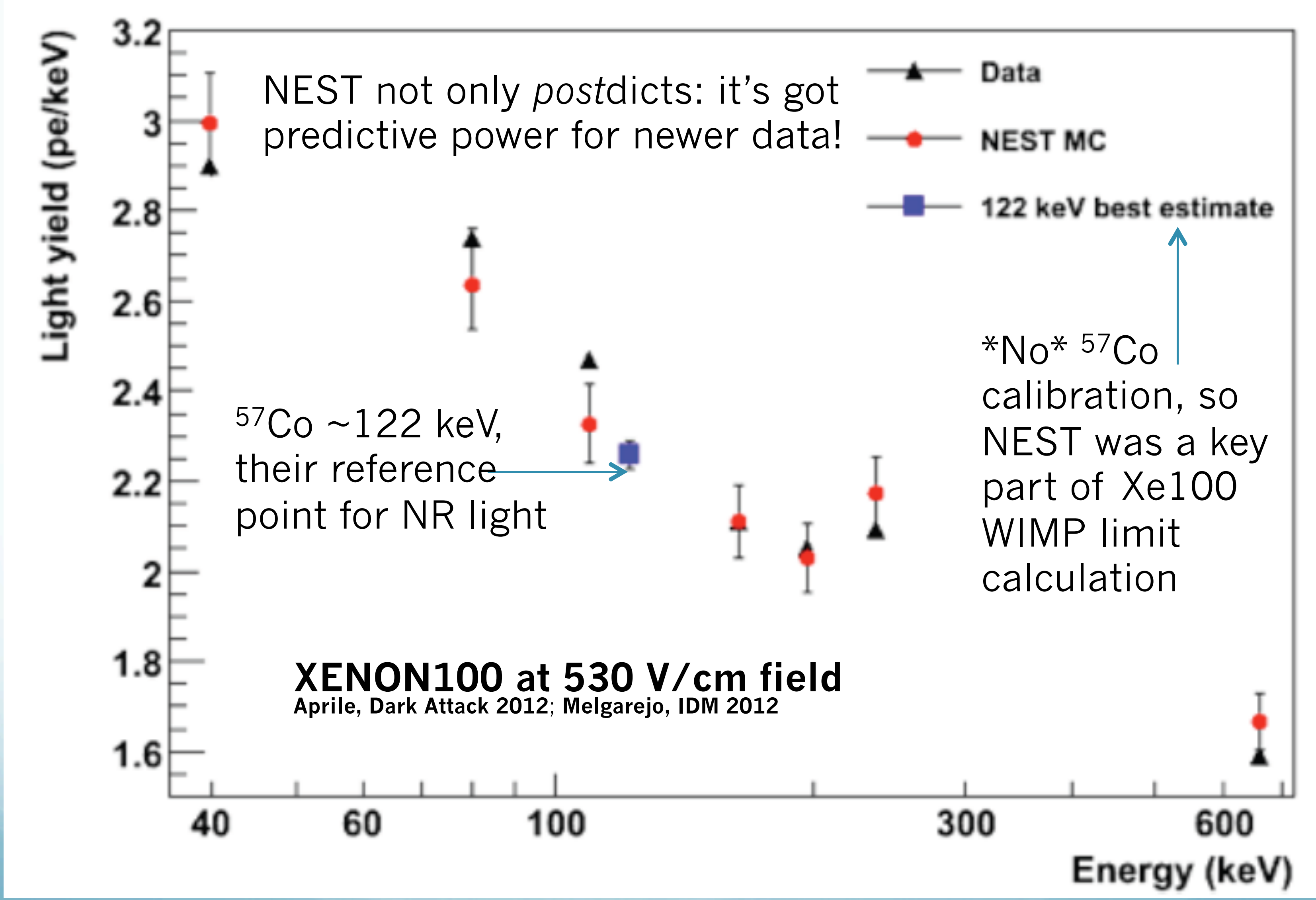


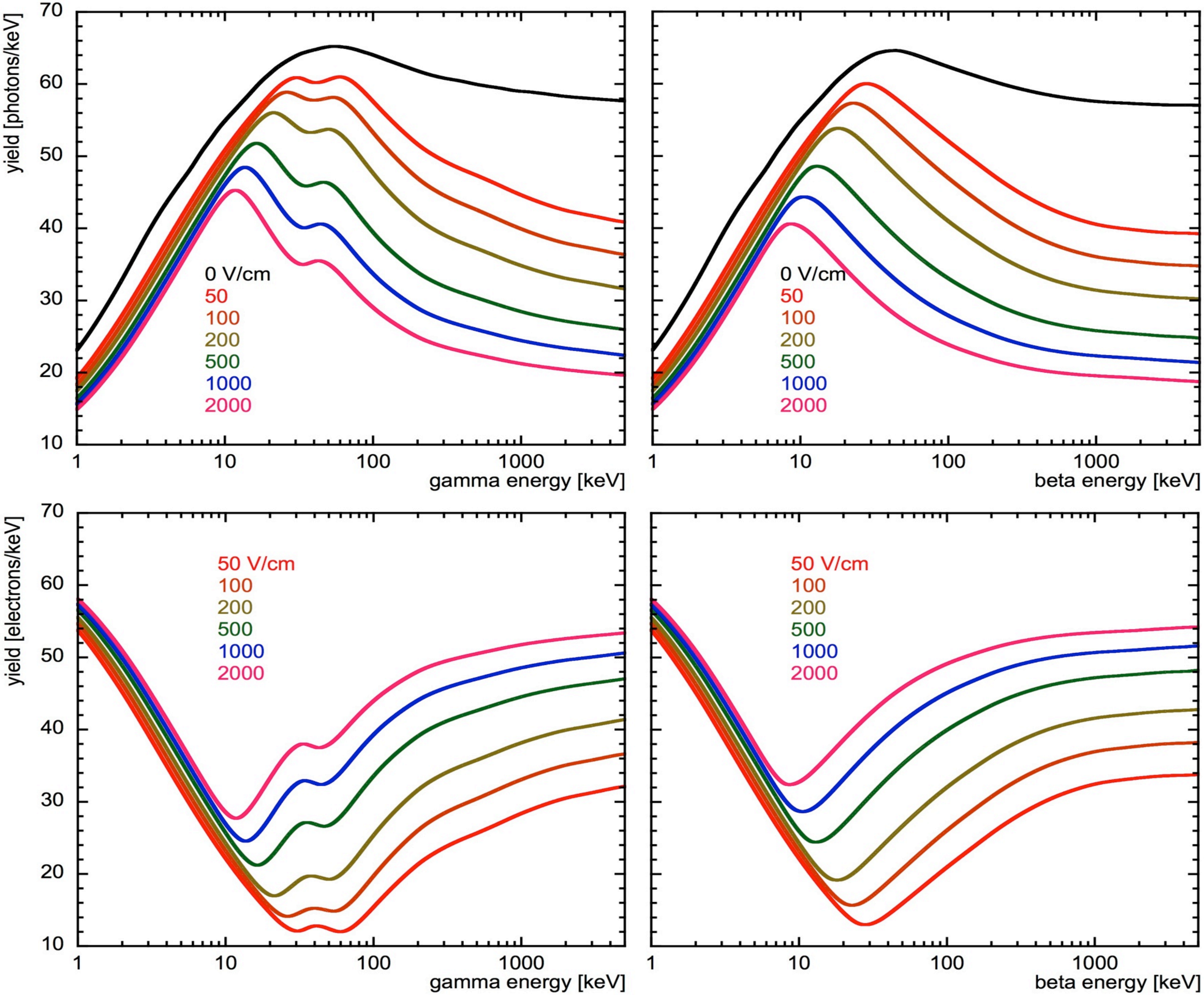
Non-zero field



- As the energy increases *dE/dx* decreases, thus recombination decreases: less light, at expense of more charge (Doke-Birks)
- At low energy recombination increases with increasing energy, leading to more scintillation light per unit of energy (TIB)

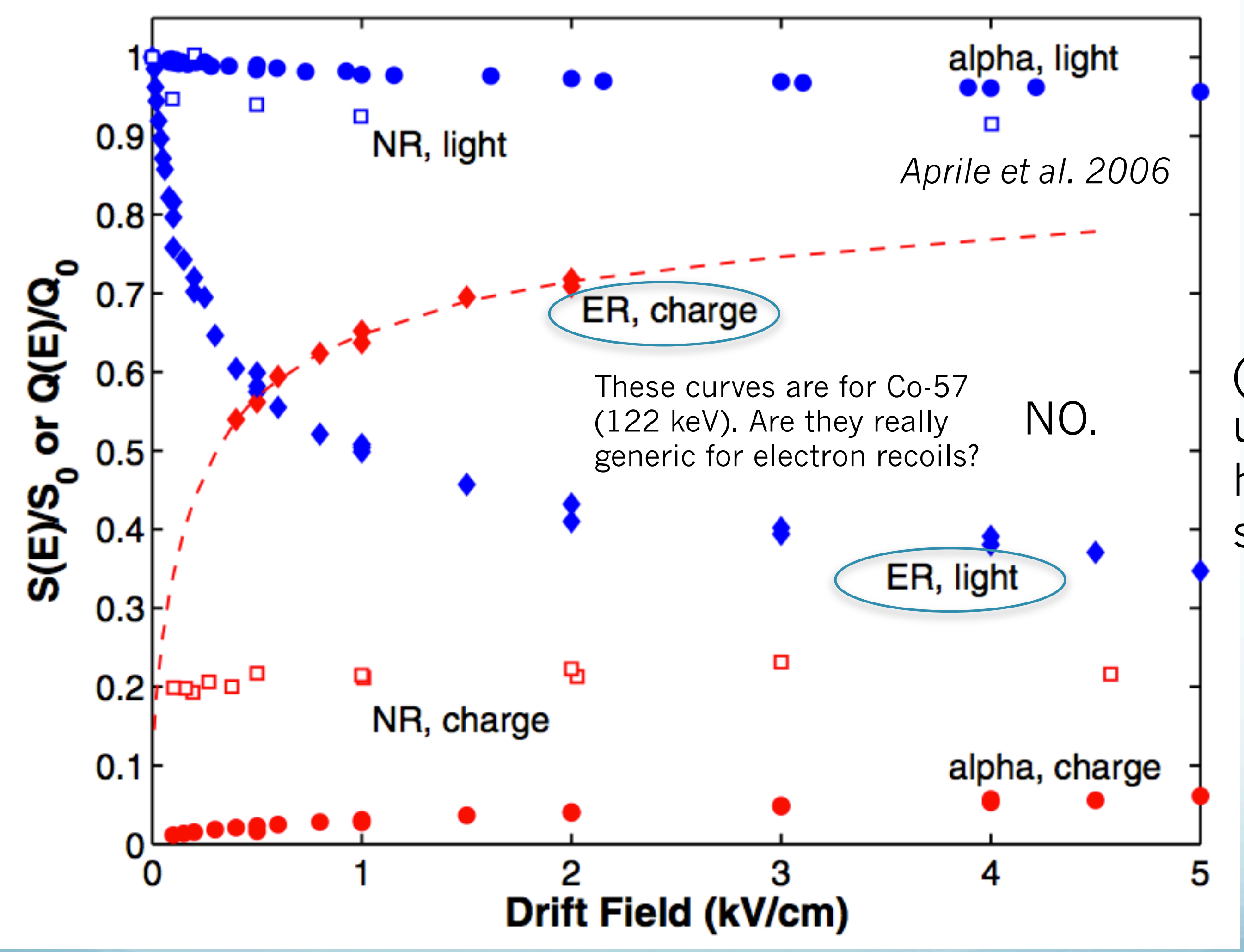
More Successful **Pre**dictions





yield [photons/keV]
0 V/cm
50
100
200
500
1000
2000
gamma energy [keV]
beta energy [keV]
yield [electrons/keV]
50 V/cm
100
200
500
1000
2000
gamma energy [keV]
beta energy [keV]

Oversimplification



(but to be fair, understanding has evolved since 2006)

NEST-Based Energy Scale

~~$E_{\mathrm{nr}} = (S1/L_y)(1/\mathcal{L}_{\mathrm{eff}})(S_{\mathrm{ee}}/S_{\mathrm{nr}})$~~

$\mathcal{L}$ and $\mathcal{L}_{eff}$ are NOT the same

$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$

W_{LXe} = 13.7 +/- 0.2 eV

- Energy a linear combination of the number of primary photons n_γ and electrons n_e generated
- Photon count equal to S1 phe (XYZ-corrected with calibration events) divided by detection efficiency (light collection x PMT QE), and electron count is S2 phe (XYZ-corrected) divided by the product of extraction efficiency and the number of phe per e^-
- Scale calibrated using ER ($\mathcal{L}$=1). Hitachi-corrected* Lindhard factor assumed for NR (k=0.11 not 0.166)
- Matches LUX data, and others' measurements

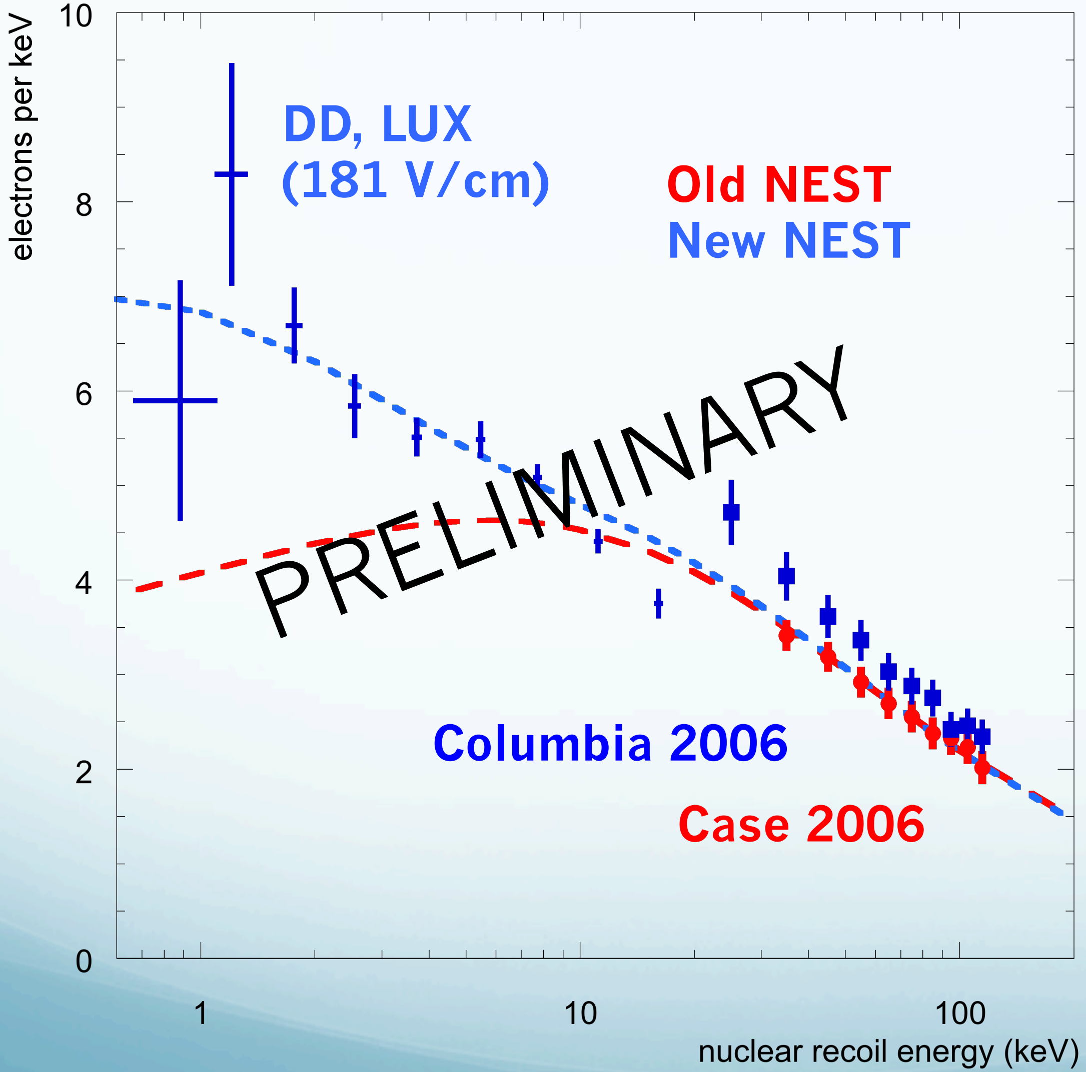
$$\mathcal{L} = \frac{kg(\epsilon)}{1 + kg(\epsilon)},$$

$$\epsilon = 11.5\,(E_{nr}/keV)\,Z^{(-7/3)},$$
$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon,$$

* P. Sorensen and C.E. Dahl, Phys. Rev D 83 (2011) 063501, [arXiv:1101.6080]

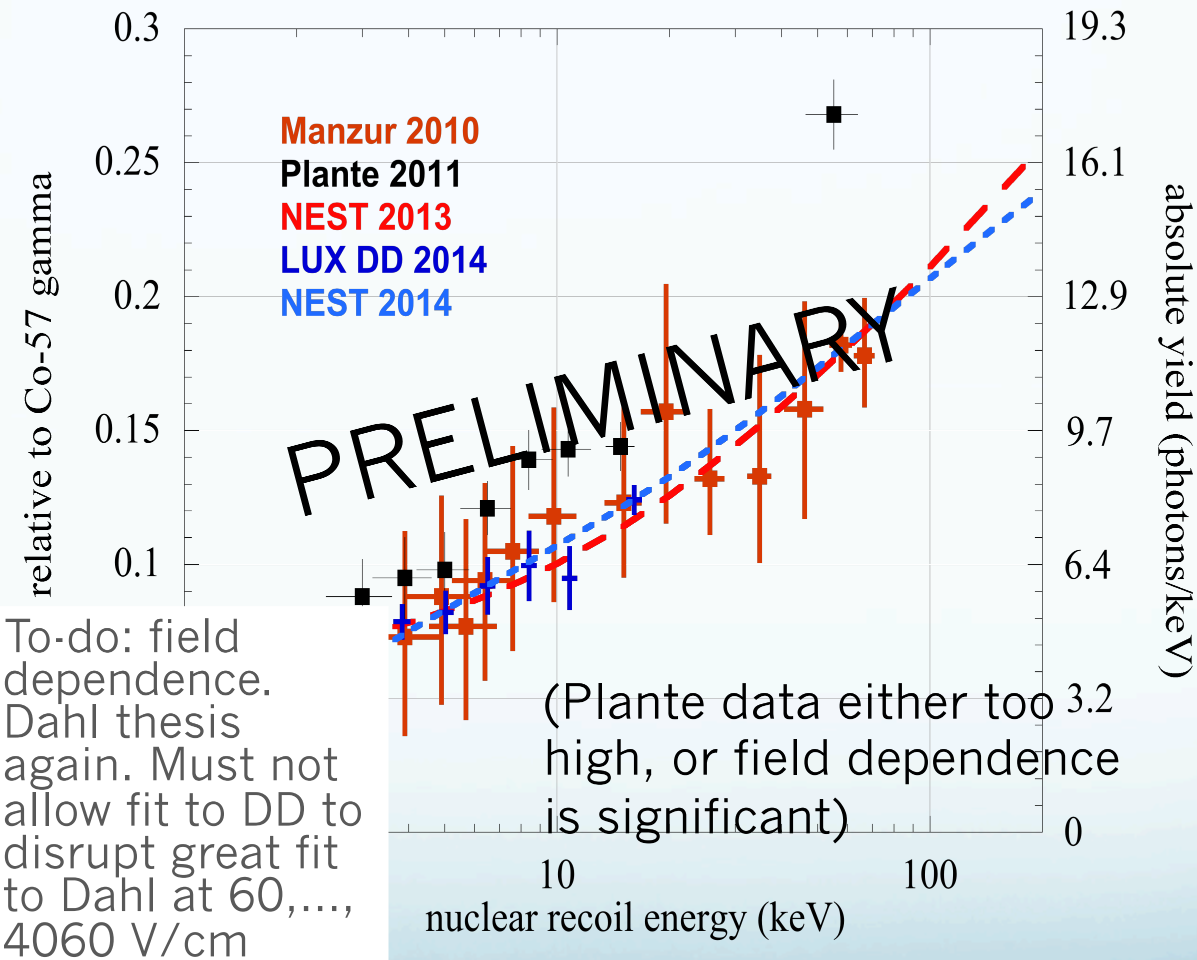
Q_y Almost Nailed

Is it perfect? No, but something decent that allows re-doing existing limits



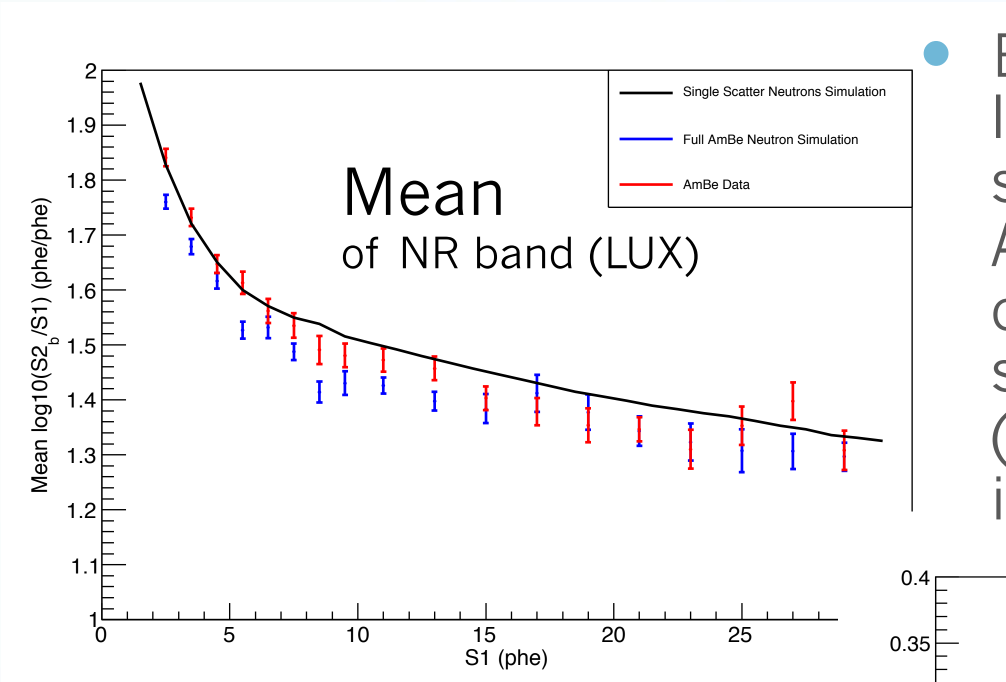
- DD is just latest piece of evidence that Q_y higher than in NEST (was intentionally conservative and dealing with too much freedom in fitting)
- Caution: with too many free parameters can fit an elephant
- Pro: matches trend in LUX tritium data and as energy goes to infinity, same N_{ex}/N_i and TIB recovered as old NEST. Will re-do low-E ER too

L_eff Even Better Now



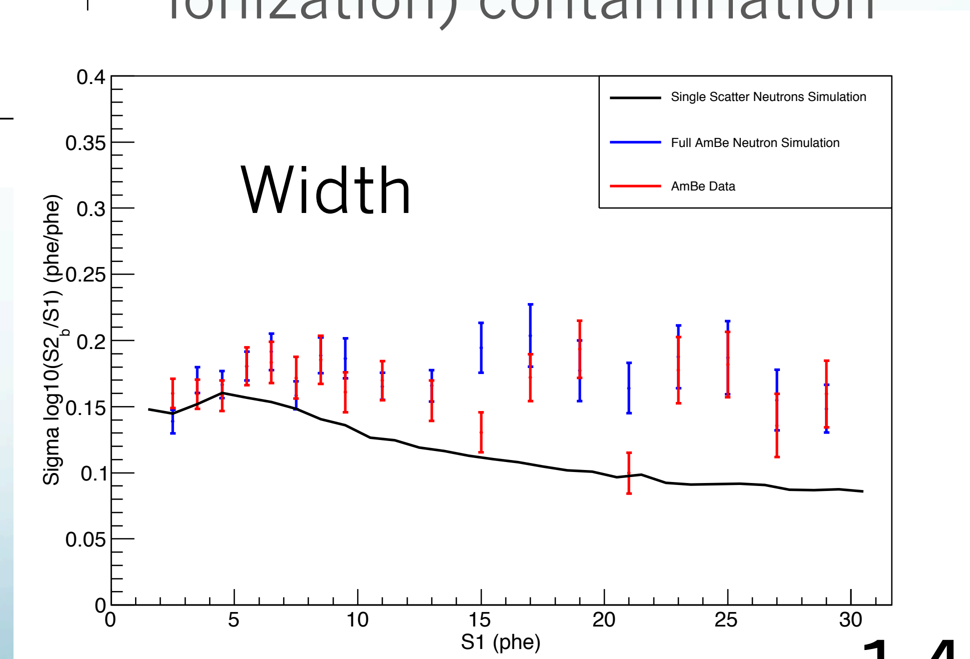
- To-do: field dependence. Dahl thesis again. Must not allow fit to DD to disrupt great fit to Dahl at 60,…, 4060 V/cm

NR Calibrations MC Vetting



- Both single-scatter (WIMP-like) and full AmBe simulations use NEST, but AmBe sim includes ER component (Compton scatters) + neutron-X event (multiple-scatter, single-ionization) contamination

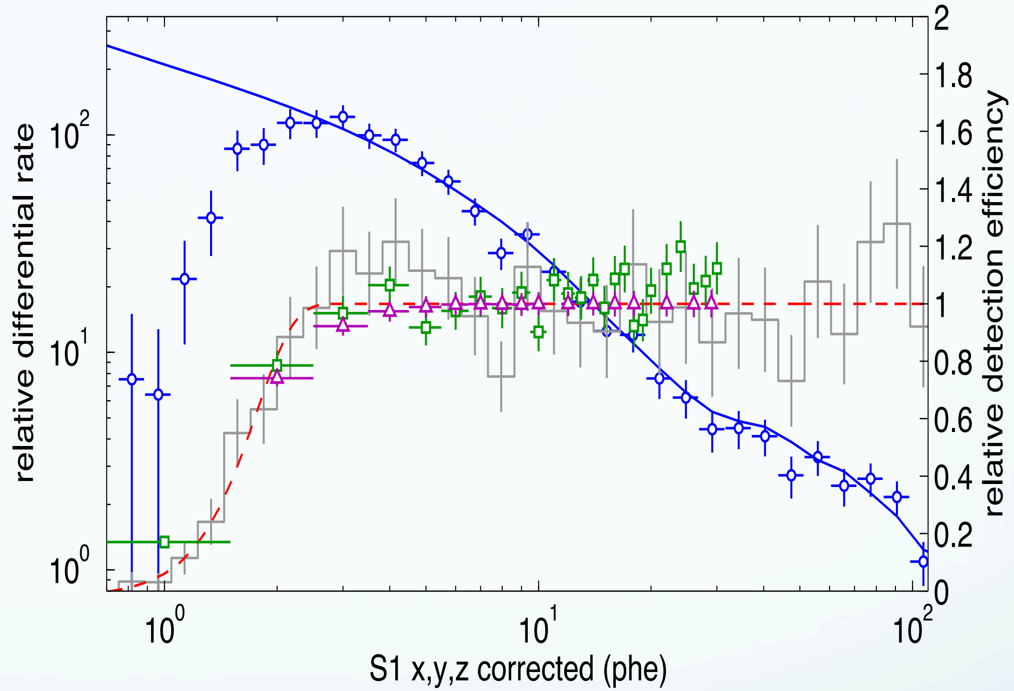
- Neutron-only effects shifting band mean and width in well-understood fashion, inapplicable to WIMP scattering. When they're included, there's agreement with data



Pulse Classification Efficiency

Example from the LUX direct dark matter detection experiment (see LUX PRL!)

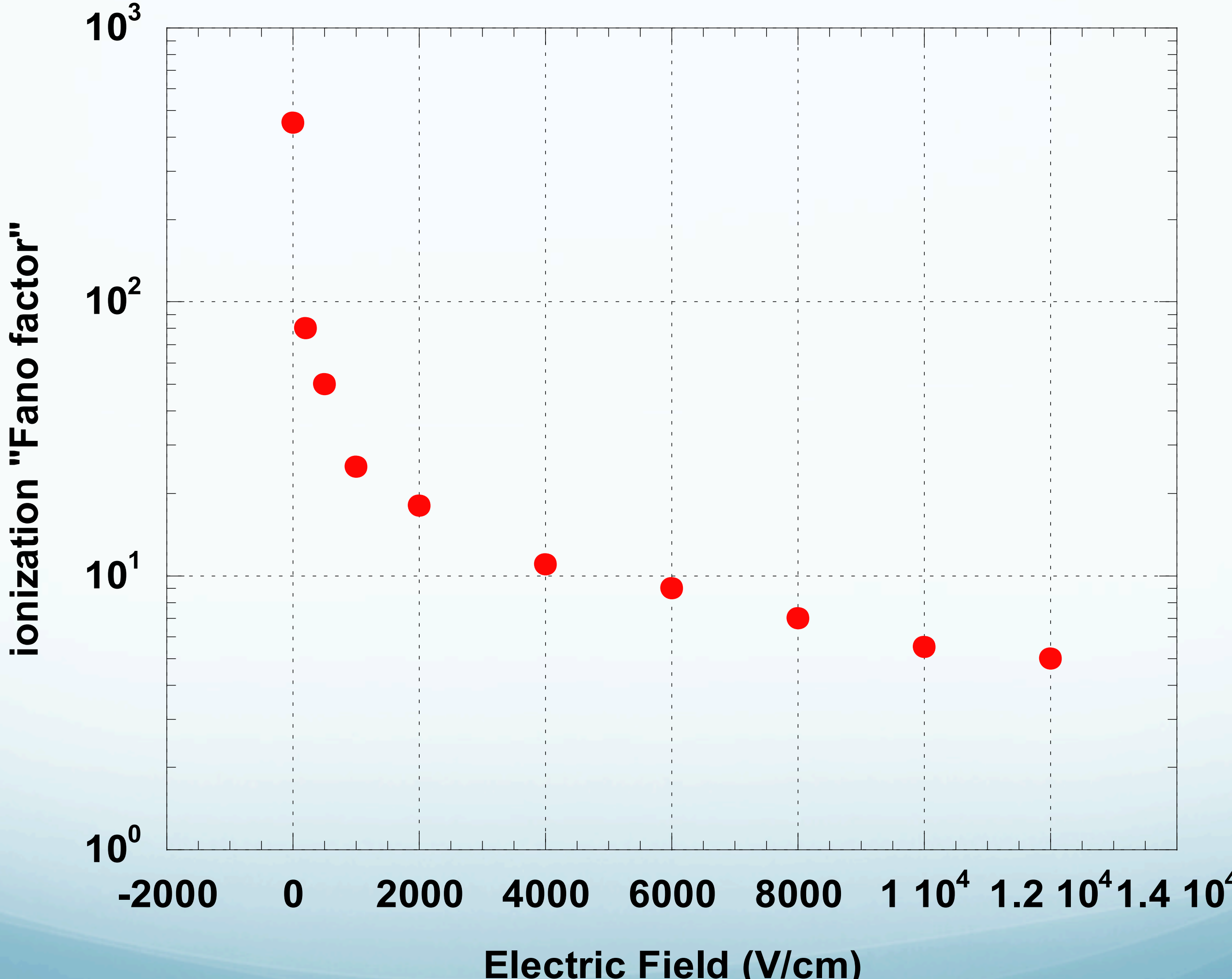
- Excellent agreement was observed when assuming NEST light yield and deriving NR efficiency, compared with ER (tritium)
- Efficiency for finding single-scatter events (1 S1 and 1 S2) as a function of S1 size, the driver of efficiency



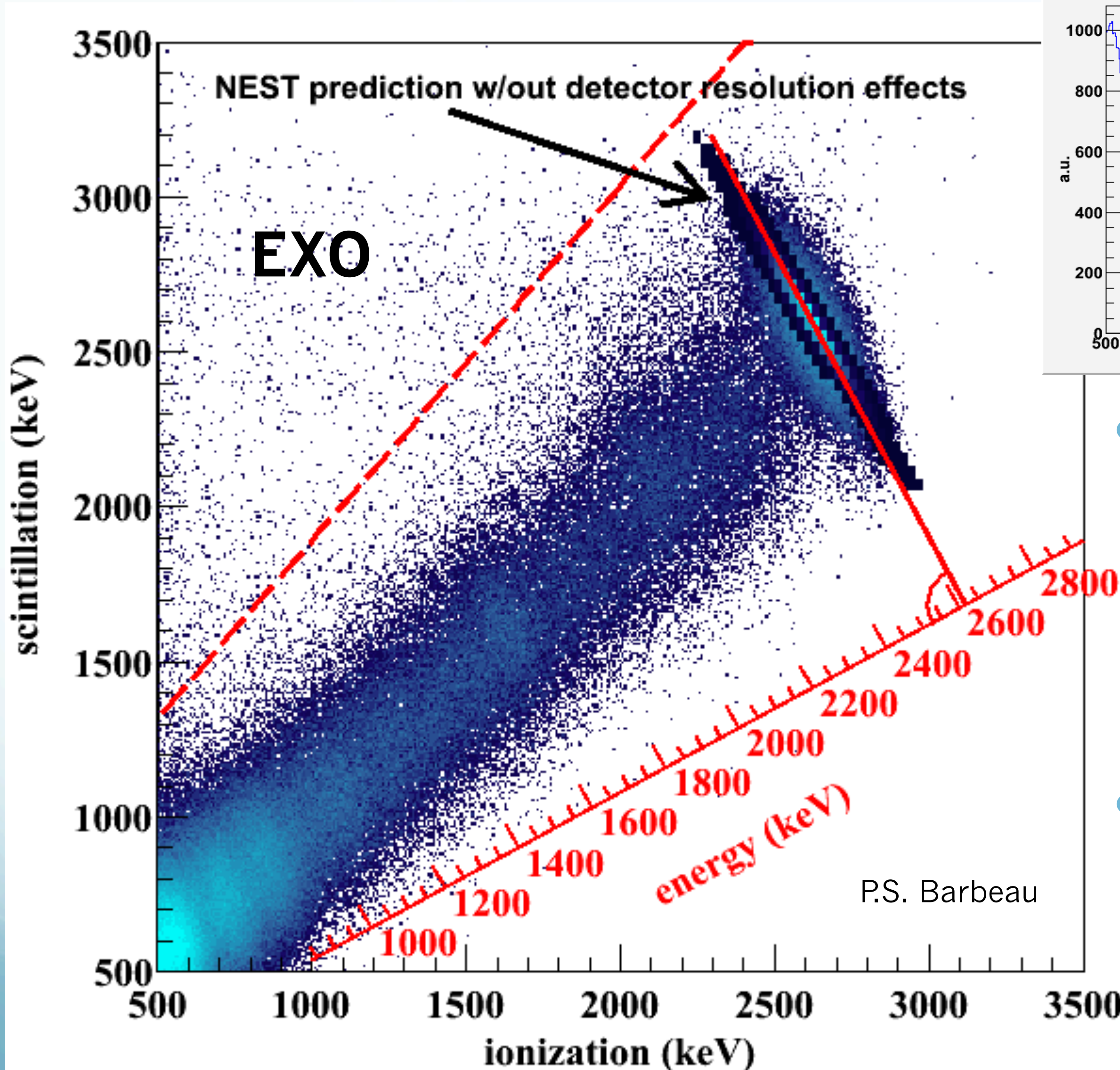
o AmBe neutron calibration data (left)
– Parameterized NEST-only simulation without event classification efficiency applied, in order to derive it

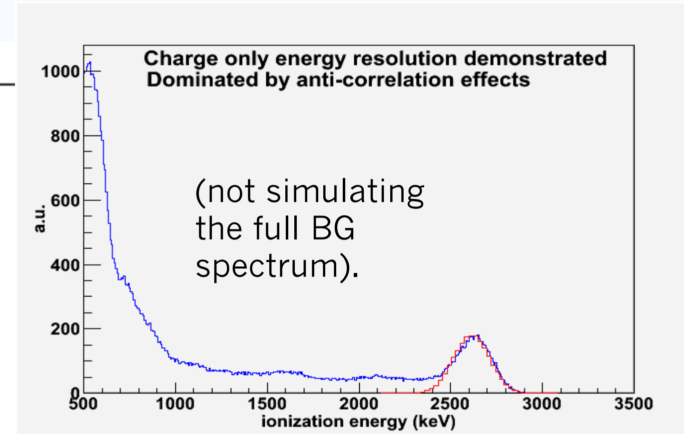
gray histogram & red (fit) efficiency from AmBe (right)
LUXSim full NR simulation processed like real data, flat in energy, with the efficiency organically included
Tritium-based efficiency

The Recombination Fluctuations



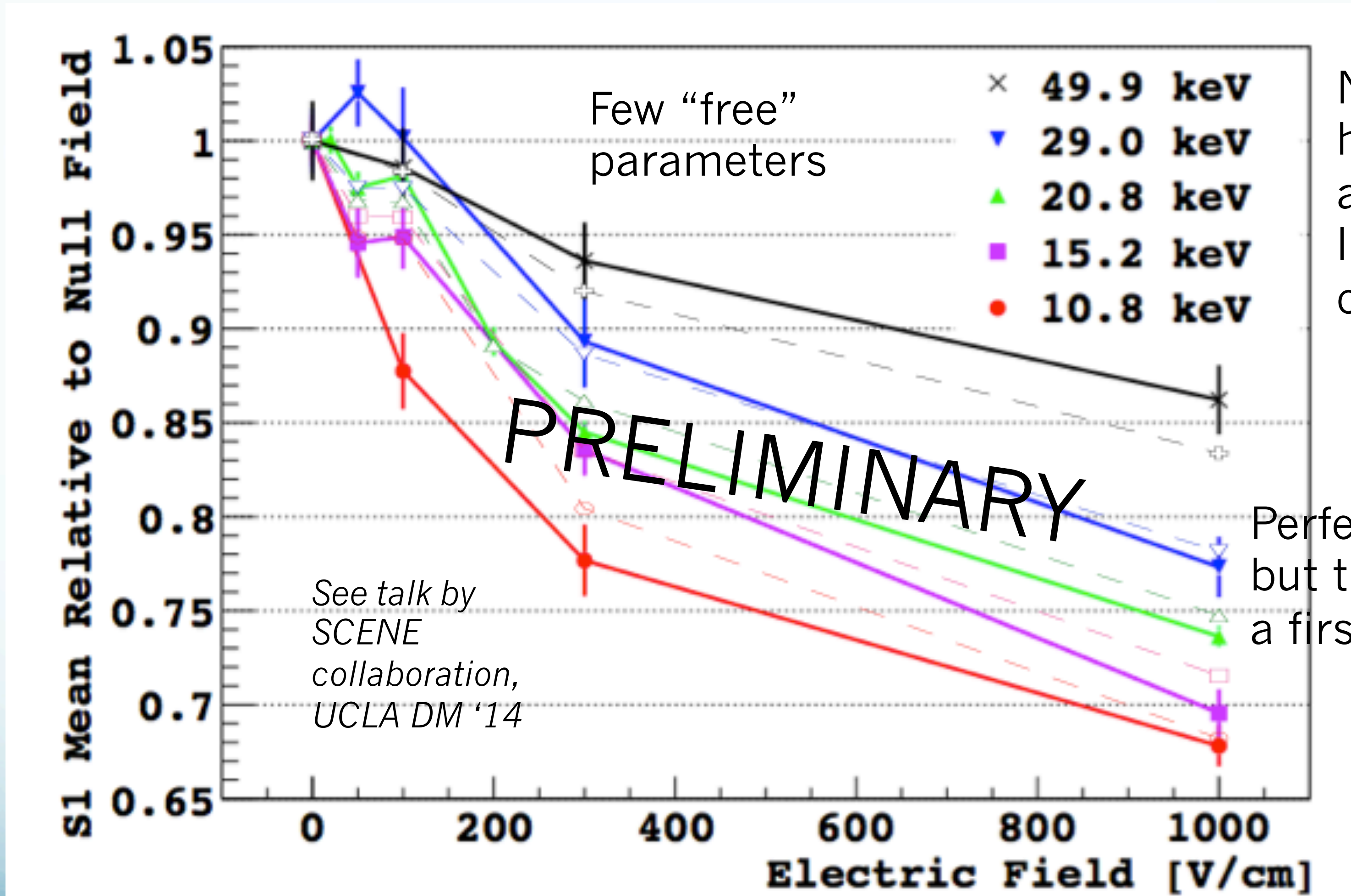
Energy Resolution: EXO





- Prediction for a field never studied before (376 V/cm) and a new energy (2.6 MeV gammas, whereas NEST vetted at 0.57)
- The recombination fluctuations modeled as worse than binomial with a field-dependent Fano-like factor (big)

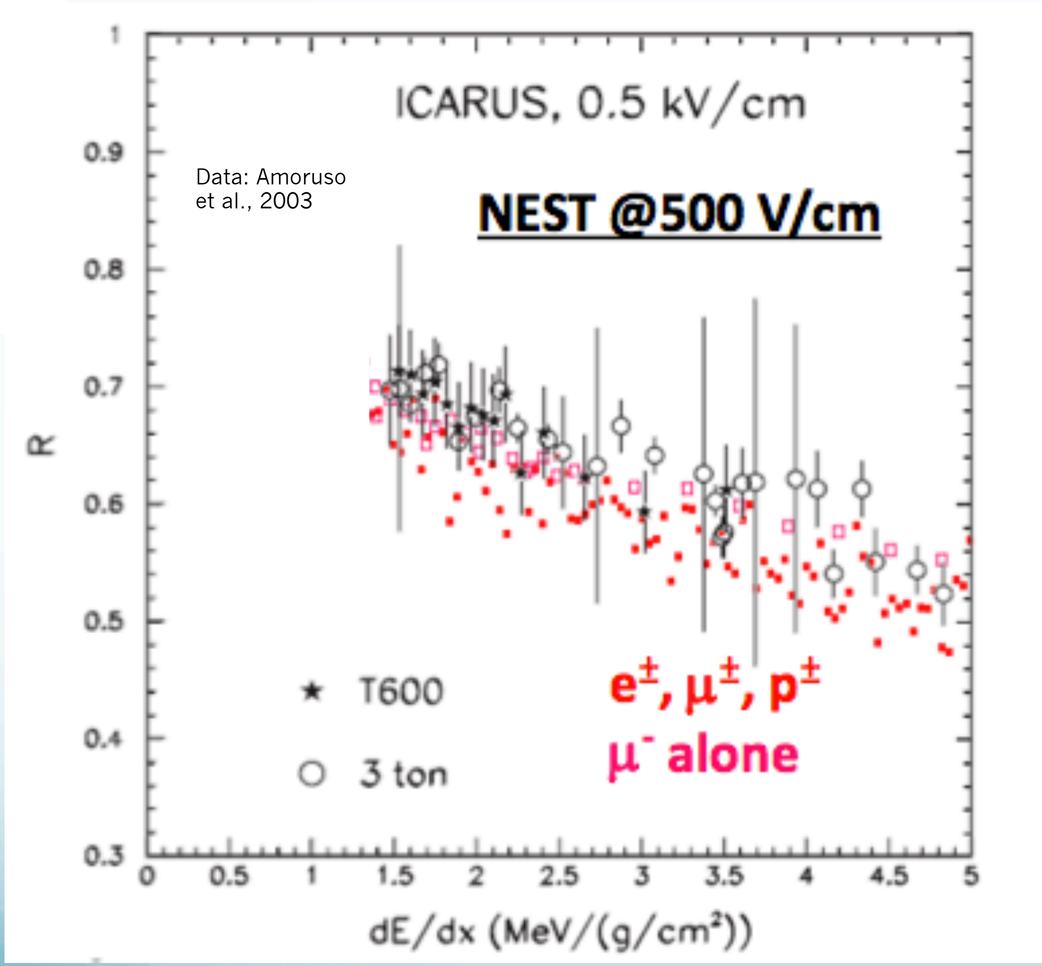
Can NEST do Argon?



NEST as hollow points and dashed lines (same colors)

Perfect? No, but this was a first stab..

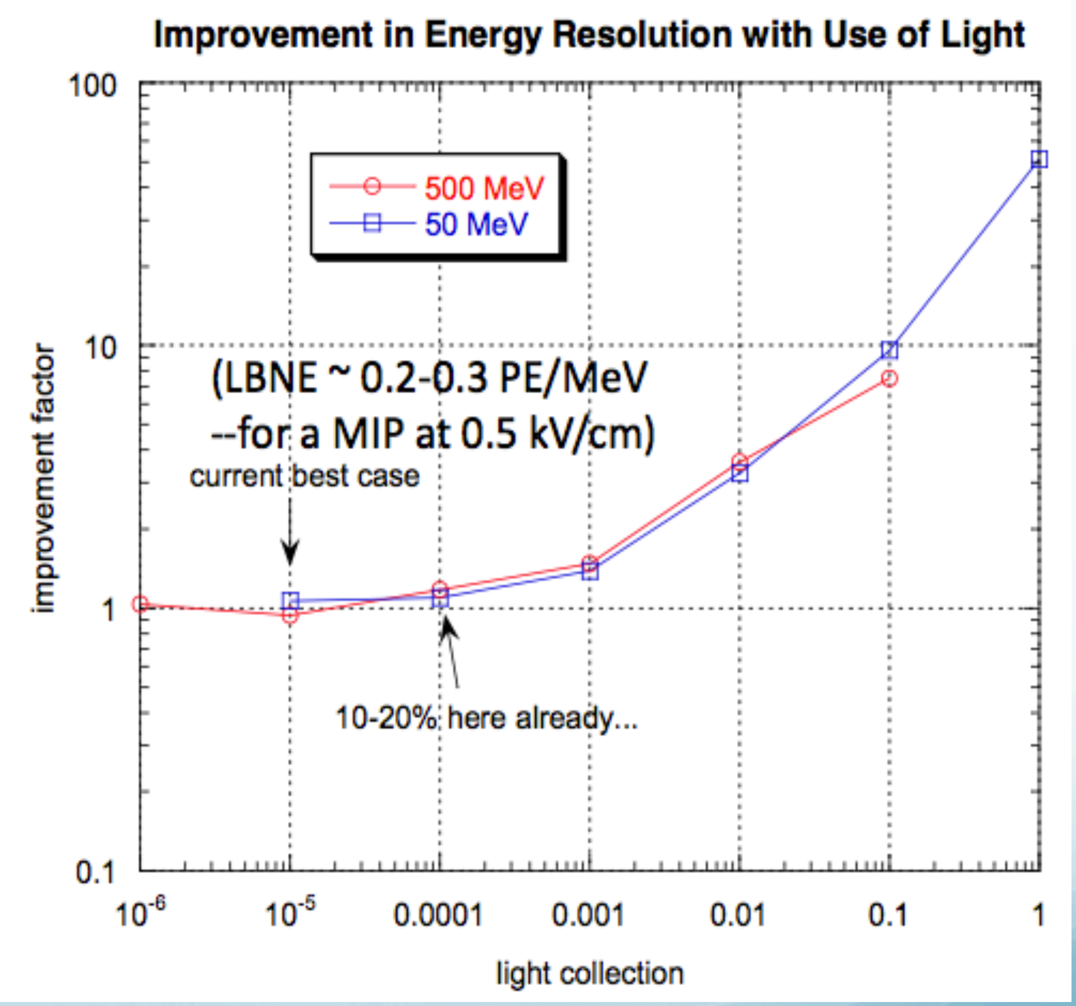
Model Building with Data



- R is the electron escape probability, so it is a useful simultaneous measure of both the charge and light yields
- NEST does argon, and does high energies too: *dE/dx* is the key
- But, the particle type matters, not just *dE/dx*, because of stochastic variation in the secondary track history, in steps

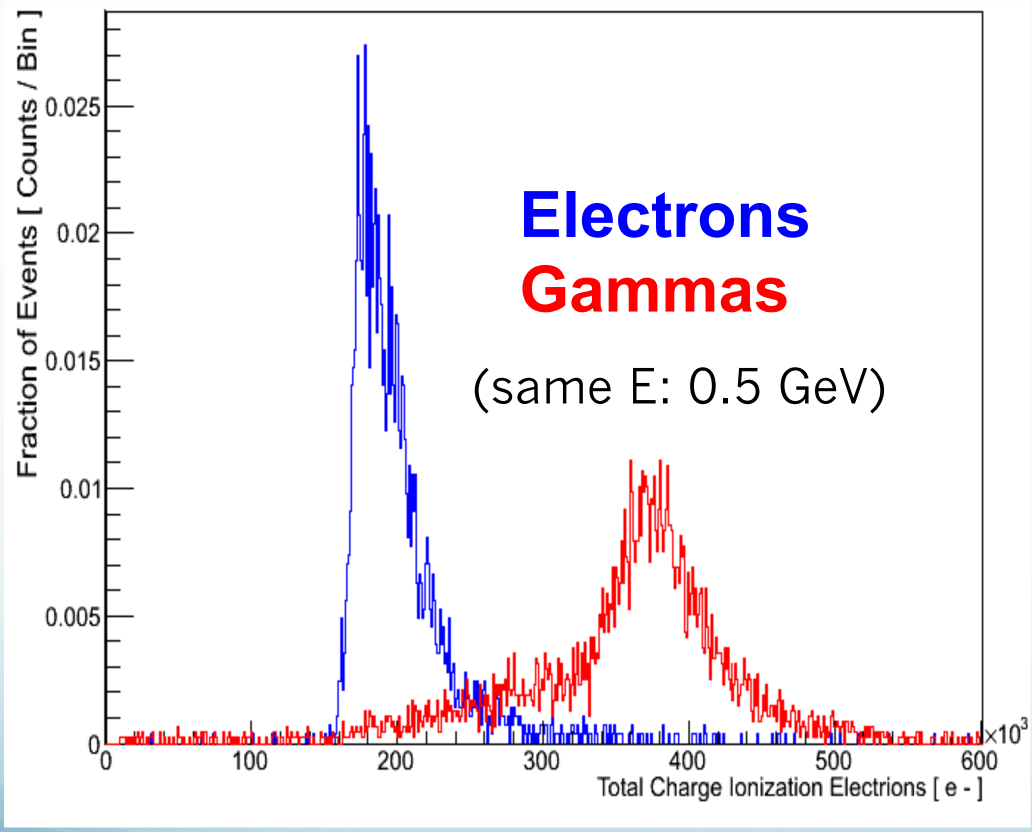
Energy Reconstruction

- Combining light with charge lets you empirically reduce the effects of the recombination fluctuations and the energy loss to scintillation, where ~half the energy goes
- Anti-correlation proven in both argon and xenon, but need great light collection to capitalize on it.



e^-/γ Separation

My interest was to adapt NEST for argon to address this critical issue



- Must detect electrons from a neutrino interaction (such as $\nu_e + n \rightarrow p^+ + e^-$) but discriminate against gamma BGs in LBNE
- Issue similar to ER/NR discrimination in xenon
- Electrons and gammas have different charge yields, and we can simulate that: gammas will pair produce and the resulting lower-energy e^-, e^+ have a bit different *dE/dx*