Office of Defense Nuclear Nonproliferation Research and Development

University and Industry Technical Interchange (UITI2013) Review Meeting

The Noble Element Simulation Technique

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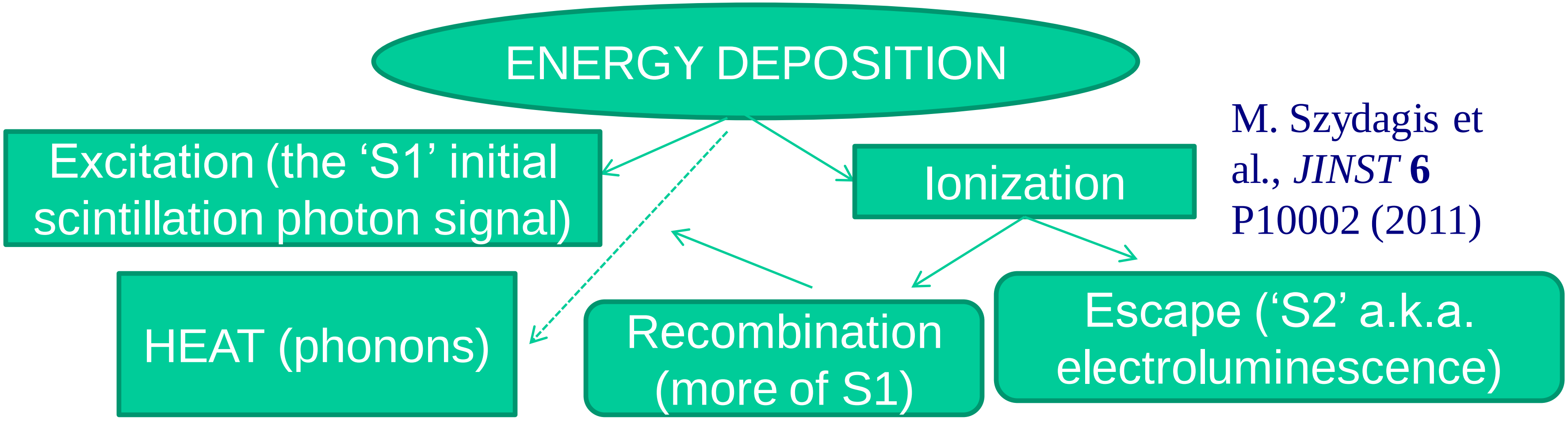
Introduction

- Project title: **NEST, The Noble Element Simulation Technique**
- Lead organization: **University of California Davis**. Participating organizations, including associated national laboratories: **Lawrence Livermore National Laboratory (LLNL)**. Principal Investigators: **Matthew Szydagis, Mani Tripathi**
- The NEST model is pertinent to the mission of nonproliferation because noble element detectors are applicable to reactor monitoring.
- The primary objective of the NEST model/code is providing high-quality, high-fidelity computer simulation of the microphysics of the excitation, ionization, and recombination processes arising as a result of energy depositions caused by gamma rays, neutrons, or neutrinos, in noble gasses and liquids.
- NEST can help eliminate the use of poor approximations of the real physics occurring used in the past and predict the non-linear response as a function of energy, dE/dx, electric field magnitude, and particle type.

Technical Challenges and Progress

- We can already reproduce the vast majority of nuclear and electron recoil data on scintillation light and ionization yields in liquid xenon (LXe).
- Gaseous xenon, gaseous argon, and liquid argon (LAr) are also viable target media for noble element based detectors, so their scintillation microphysics needs to be modeled as well.
- One technical challenge for both xenon and argon is getting accurate data on ultra-low-energy nuclear recoils, which would be induced by coherent scattering of nuclear reactor anti-neutrinos. These are needed for accurate computer modeling.
- The overarching long-term goal of NEST is applicability to all noble elements in all phases, with a demonstration of postdictive power for older data, and predictive power for new data.

Basic Physics Principles



M. Szydagis et al., *JINST* **6** P10002 (2011)

- Excitation and ionization are **anti-correlated**, and the ratio of exciton to ion production is O(0.1 - 1), depending on element, energy, recoil type
- Due to the **Lindhard effect**, nuclear recoils are more efficient at producing more nuclear recoils than producing electron recoils, and as a result they produce a reduced amount of light and charge
- Lower ionization density or higher drift field leads to less **recombination**

Foundational Equations

- Cornerstone: There is but ONE work function for production of a scintillation photon OR ionization electron. Others derive from it.
- W_{LXe} = 13.7 +/- 0.2 eV (E. Dahl, 2009) $N_q = (N_{e-} + N_\gamma) = E_{dep} / W$
- Photons $N_\gamma = N_{ex} + r\, N_i$ and electrons $N_{e-} = (1 - r)\, N_i$
- Two models of the recombination probability as a function of *E* or *dE/dx*, and field, chosen based upon the interaction's track length
  - Thomas-Imel Box (< O(10) keV electron recoils, and all nuclear ones)
  - Birks' Law of scintillators, with its parameters functions of field

$$r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v} \qquad \textbf{OR} \qquad r = \frac{A\frac{dE}{dx}}{1 + B\frac{dE}{dx}} + C, \quad B = A/(1-C)$$

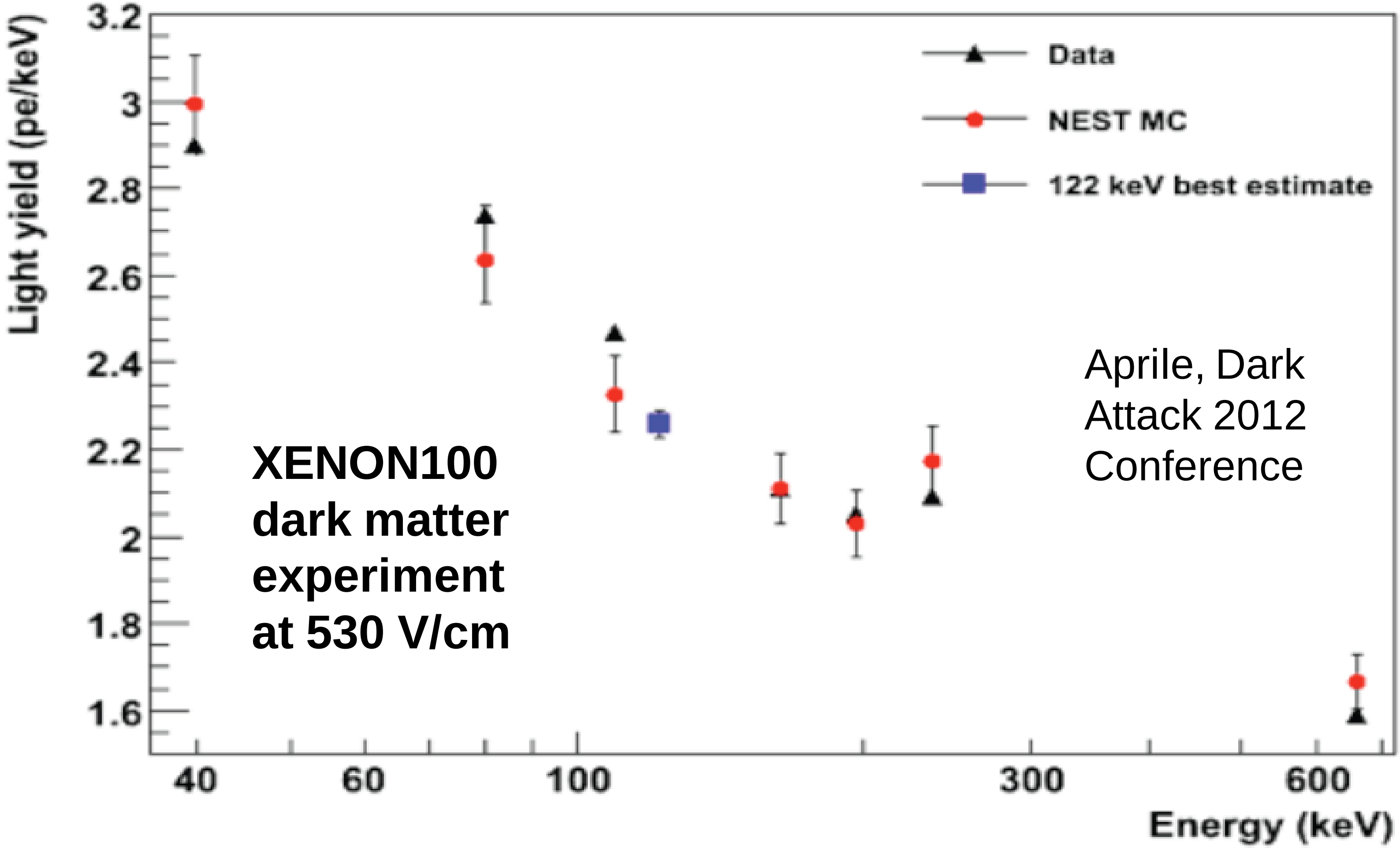
- Recombination causes noble light and charge yields per unit energy to be non-linear versus energy: twice the energy does not necessarily imply twice the signal, in either channel

Comparison to Data

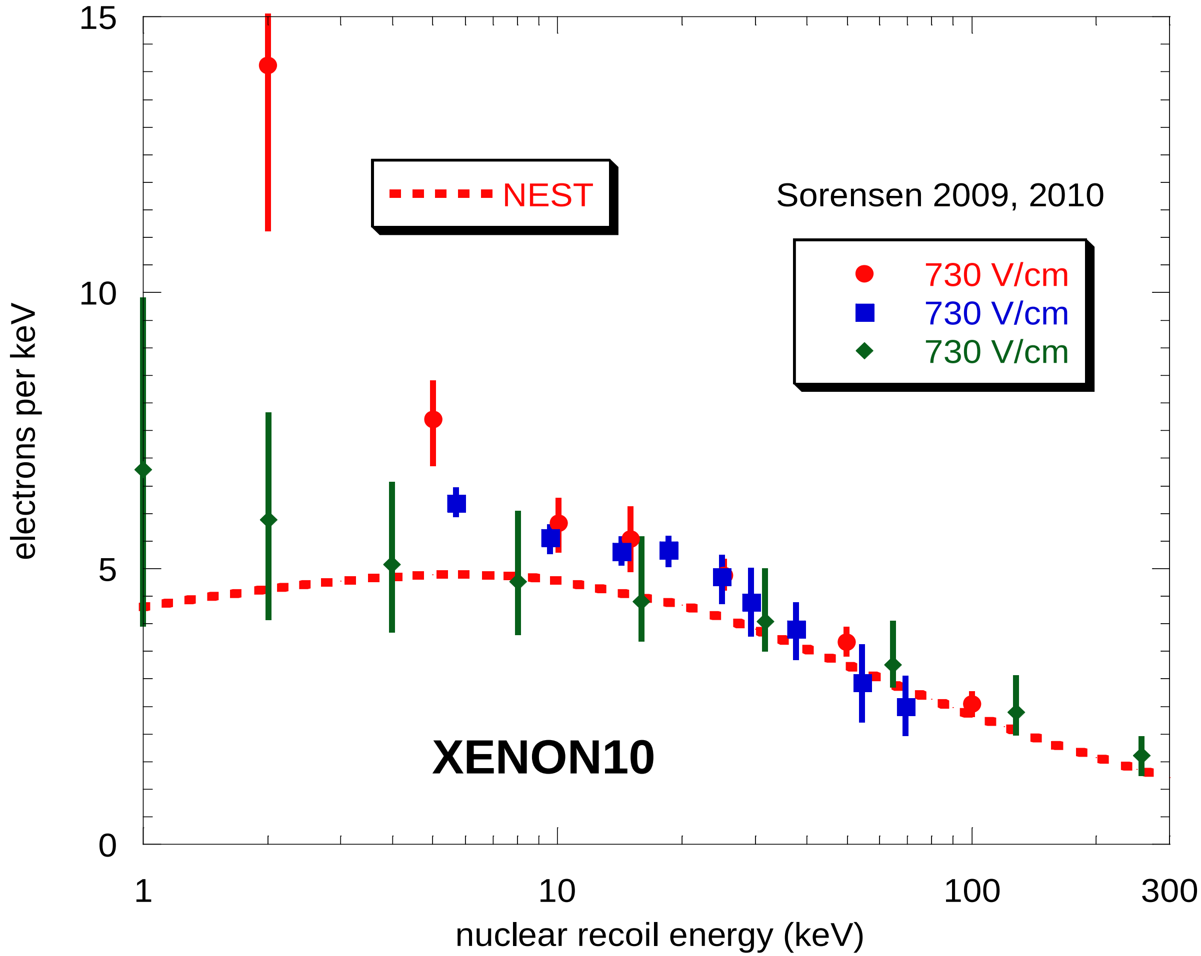
- Reviewing only NEST's "greatest hits" here, demonstrating not only its post-dictions but also its predictive power for new data, but only scratching the surface in 15 minutes.
- At non-zero field, NEST is based primarily on the Ph.D. thesis of Eric Dahl (Princeton University, 2009). Why?
  - His data is extensive in field (.06 to 4 kV/cm) and energy (> ~2 keV)
  - Dahl attempted to reconstruct the original, absolute number of quanta and estimate the *intrinsic* energy resolution
  - He used the "combined" energy, possibly the best energy estimator
- After models were built from old data sets, everything else is a prediction of new data, and NOT a fit or spline of the data points
- NEST paper (JINST) contains over 70 references (some rare)
- Going against long-standing assumptions from years back: for instance, yield is NOT constant vs. energy, at least for LXe.

LXe Electron Recoil Light Yield

- As the energy increases, dE/dx decreases, thus recombination decreases (less light ultimately, at the expense of more charge)



LXe Nuclear Recoil Charge Yield



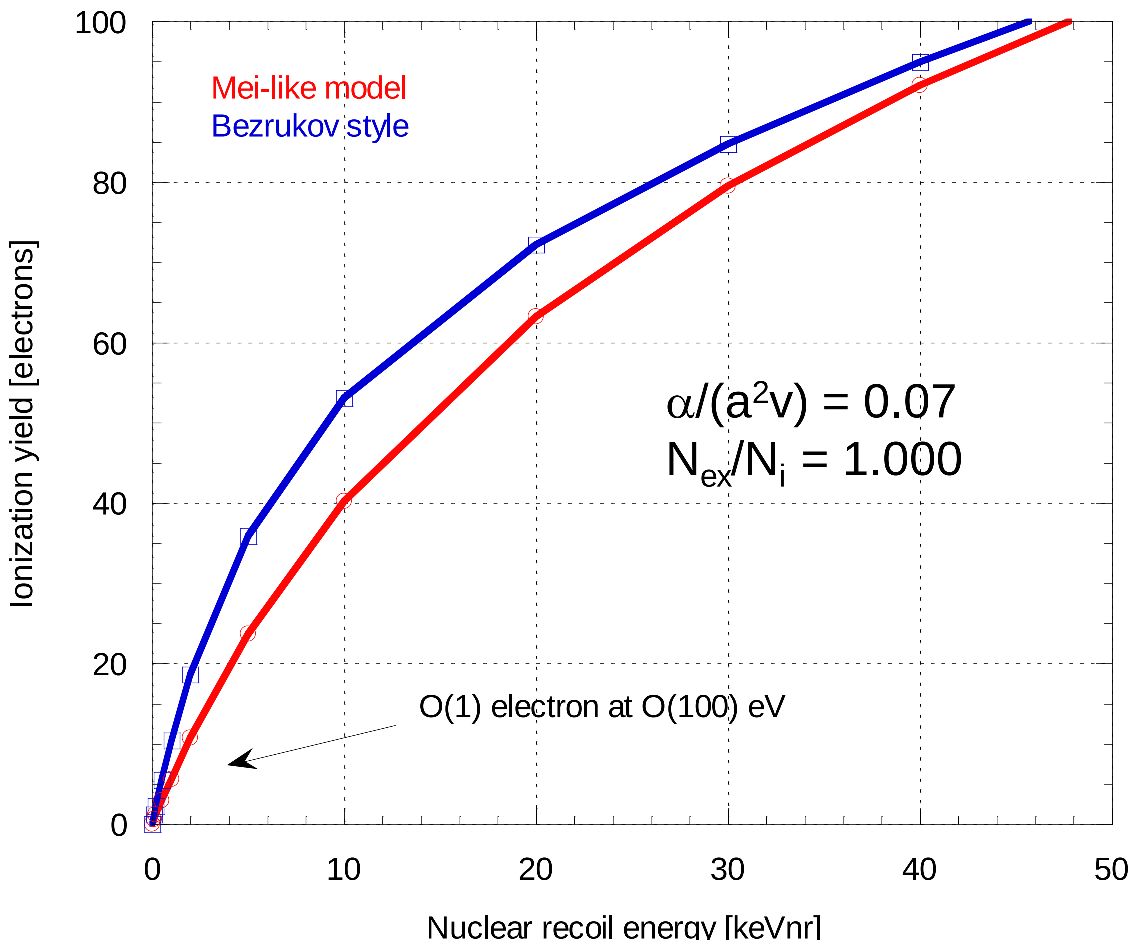
P. Sorensen et al., Lowering the low-energy threshold of xenon detectors, PoS (IDM 2010) 017

- Low-energy xenon recoil most critical for detection of nuclear recoil from neutrinos, for the purposes of reactor monitoring
- Data all over, but the NEST curve is largely conservative
- Nuclear recoil events will produce an increasing amount of charge per unit energy as the amount of light decreases as E->0 and is undetectable

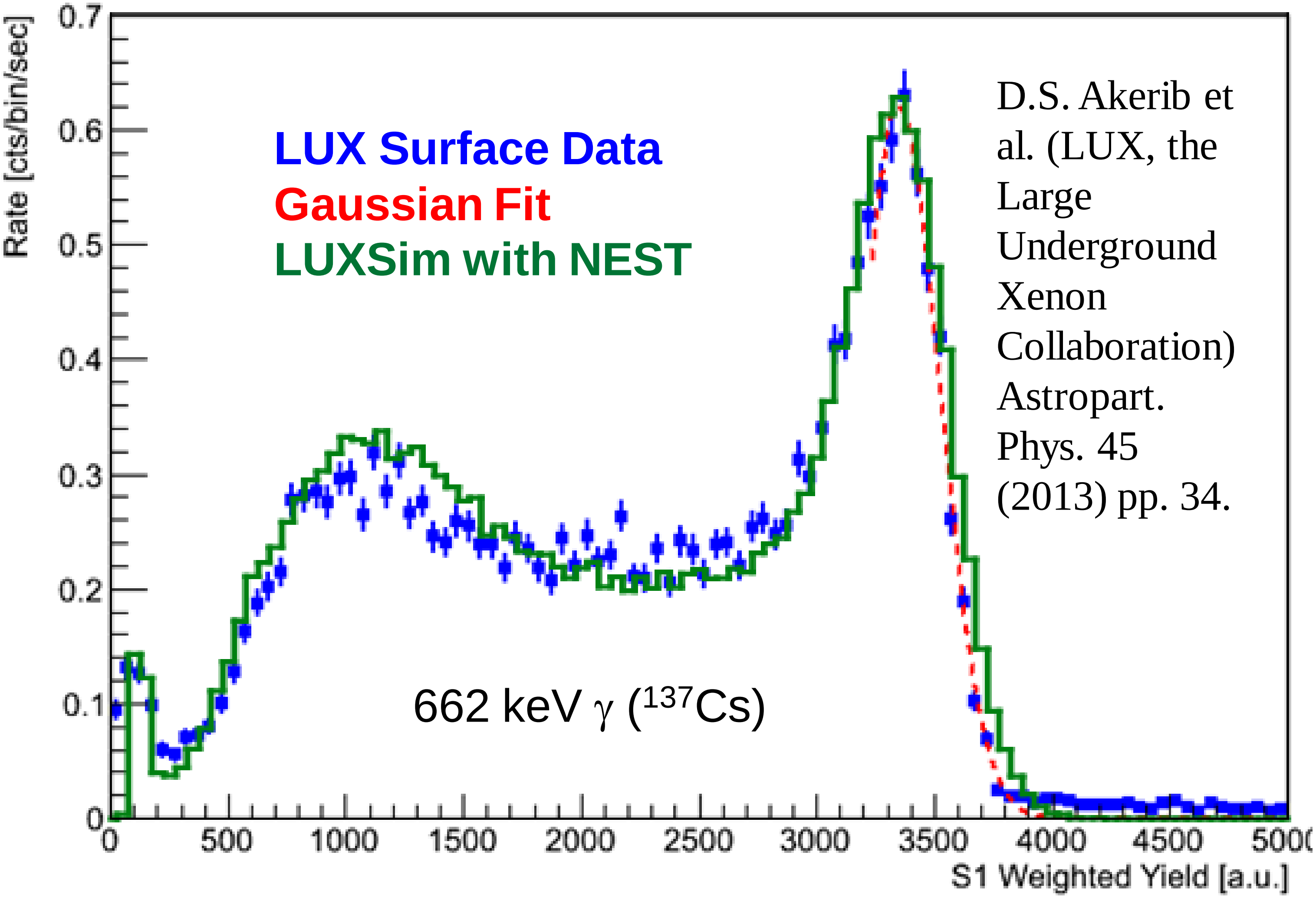
LAr Nuclear Recoil Charge Yield

- Real data will be able to disambiguate these different models
- The “Mei-like model” assumes that the sum of the light and charge yields continues to decrease smoothly as energy goes to zero
- The “Bezrukov style” model assumes that there is a slight increase instead at low energy (idea supported by some data)

Prediction performed here done to support the work reported on in **Sangiorgio et al., arXiv:1301.4290**



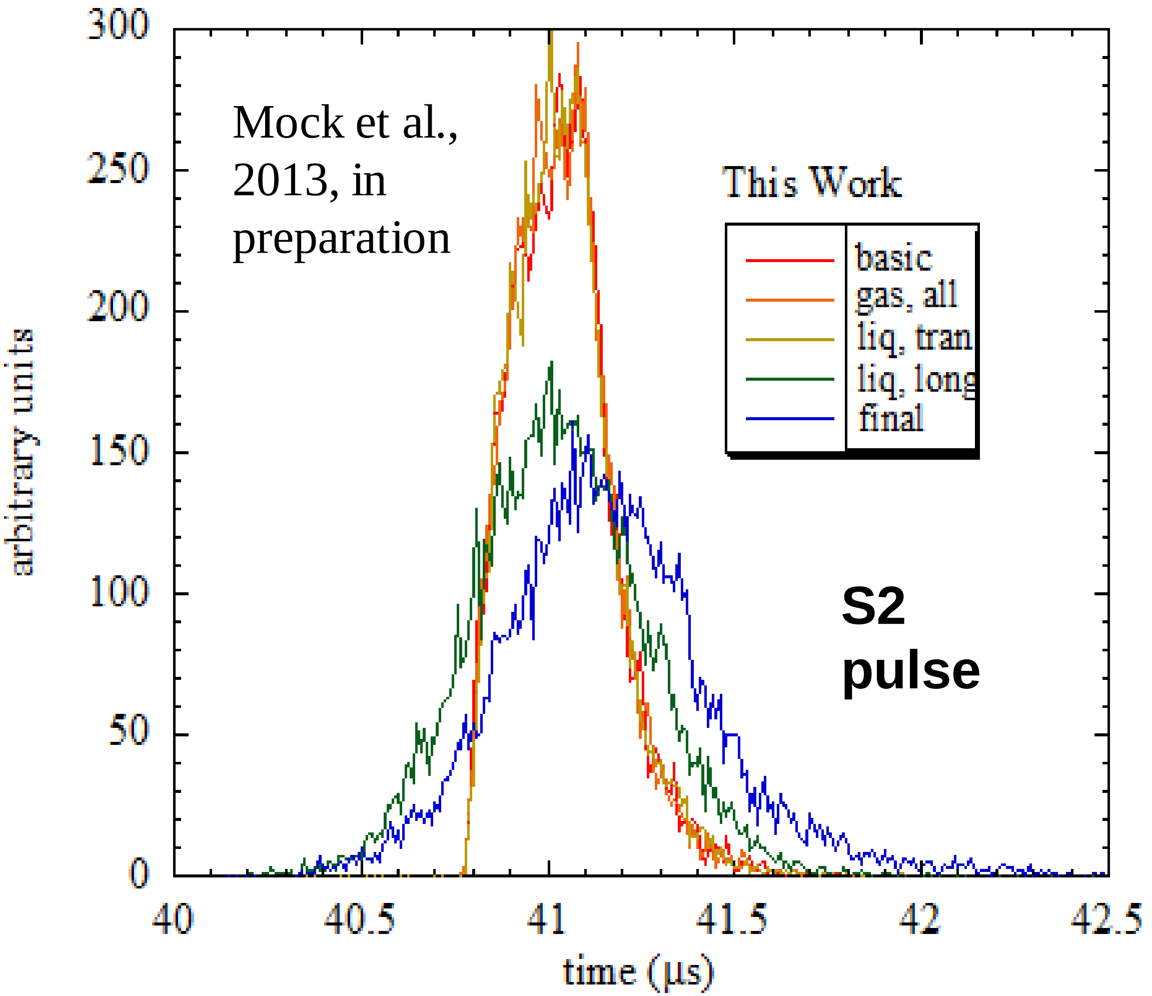
Energy Resolution



- To the best of my knowledge, this is the first time that a Monte Carlo peak width is not circularly informed by the data!
- Recombi-nation fluctuations modeled

Pulse Shape

- Both the S1 and S2 pulse shapes have been modeled in NEST
- Long list of effects
  - Single time
  - Triplet time
  - Singlet/triplet ratio
  - Recombination time
  - e^- drift speed
  - Diffusion
  - e^- trapping time
- Important for simulating a detector fully and realistically: making sim look like actual data



Conclusions and Future Work

- NEST can predict the response of a generic noble liquid (or noble gas) detector to either ionizing or non-ionizing radiation.
- Public code available for download to the entire physics community
- Liquid xenon is essentially finished, but there is still work being done for liquid argon, although it is progressing rapidly to the same level
- NEST applies to many fields of physics research, including dark matter, neutrinos, high-energy physics, and medical physics, so that working on it can provide good cross-disciplinary training for new students, toward a career in any one of a number of different fields