



*A Symphony of
Scintillation*

Noble Element Simulation Technique, MC Code for Both Scintillation and Ionization in Noble Elements

<http://nest.physics.ucdavis.edu>

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**M. Szydagis, N. Barry, K. Kazkaz, J. Mock, D. Stolp, M. Sweany, M. Tripathi, S. Uvarov,
N. Walsh, and M. Woods, "NEST: A Comprehensive Model for Scintillation Yield in
Liquid Xenon," *JINST* 6 P10002 (2011)**

The People of the **NEST** Team

UC Davis and LLNL

A small but passionate group of individuals who love their work

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UCD undergraduates and
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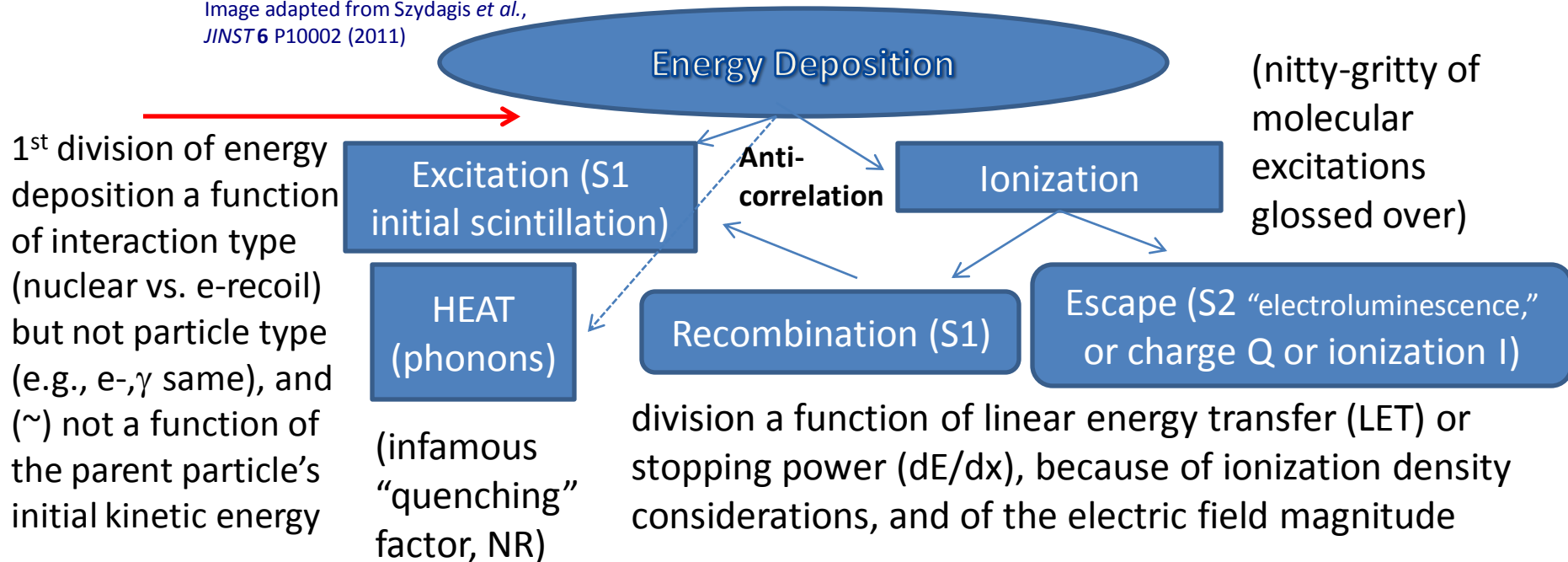


What is NEST?

- That name refers to both a model (or, more accurately, a collection of models) explaining the scintillation and ionization yields of noble elements as a function of particle type (ER, NR, alphas), electric field, and energy or dE/dx
- --As well as to the C++ code for GEANT4 that implements said model(s), overriding the default
- Goal is to provide a full-fledged MC sim with
 - Mean yields (light AND charge)
 - Energy resolution (and background discrimination)
 - Pulse shapes (S1 AND S2)
- Combed the wealth of data for liquid and gaseous noble elements and combined everything learned
- We cross boundaries: ν 's, DM, HEP, “enemies”

Basic Physics Principles

Image adapted from Szydakis et al.,
JINST 6 P10002 (2011)



- The ratio of exciton to ion production is $O(0.1)$
- S1 is NOT E, because energy depositions divide into 2 channels, S1 and S2, non-linearly: idea from Eric Dahl
- Nuclear recoils also have to deal with Lindhard

Basic Physics Principles

- Cornerstone: There is ONE work function for production of EITHER a scintillation photon or an ionization electron. All others derive from it.
- $W_{LXe} = 13.7 \pm 0.2 \text{ eV}$ $N_q = (N_{e^-} + N_\gamma) = E_{dep} / W$
C.E. Dahl, Ph.D. Thesis, Princeton University, 2009
- $N_\gamma = N_{ex} + r N_i$ and $N_{e^-} = (1 - r) N_i$ (N_{ex} / N_i fixed)
- Two recombination models, short and long tracks
 - Thomas-Imel "box" model (below $O(10)$ keV)
 - Doke's modified Birks' Law from 1988 Doke et al., NIM A 269 (1988) p. 291
- *Recombination probability* makes for non-linear yield: 2x energy does not mean 2x light or charge

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

Comparison With Data

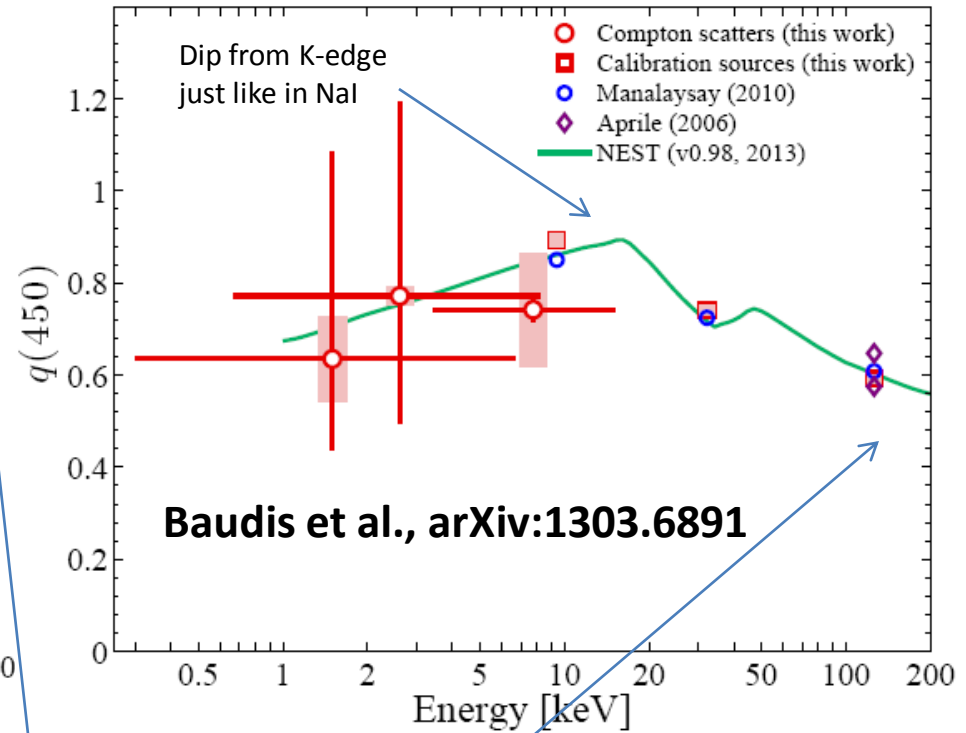
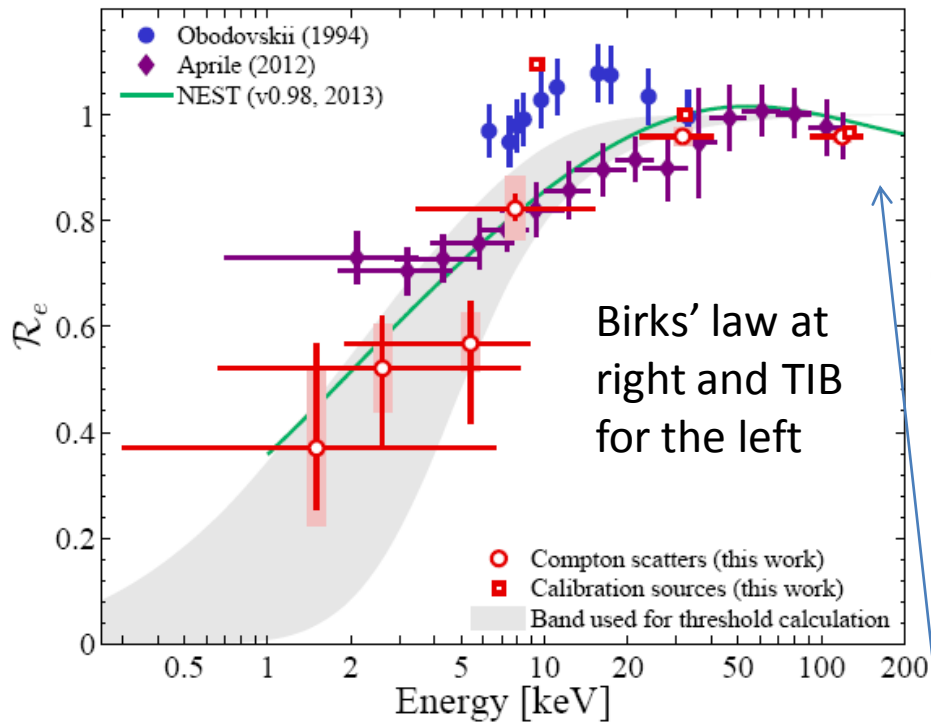
- Reviewing only NEST's "greatest hits" here, demonstrating not only its post-dictions but also its predictive power for new data, but only scratching the surface in 20 minutes
- At non-zero field, NEST based primarily on the Dahl thesis
 - His data is extensive in both field (60 to 4,060 V/cm) and energy
 - Dahl attempted to reconstruct the original, absolute number of quanta and estimate the *intrinsic* resolution you can't avoid
 - Used combined energy, possibly the best energy estimator
- After models built from old data sets, everything else is a prediction of new data, and NOT a fit / spline of data points
- NEST paper (JINST) contains over 70 references (some rare)
- Going against long-standing assumptions from years back: for example, yield NOT flat versus energy, at least for LXe. No such thing as a generic 'ER' curve. I dug up old papers long forgotten. The ancient results come back in cycles

ER Mean Light Yield in LXe

(See Aaron Manalaysay's talk)

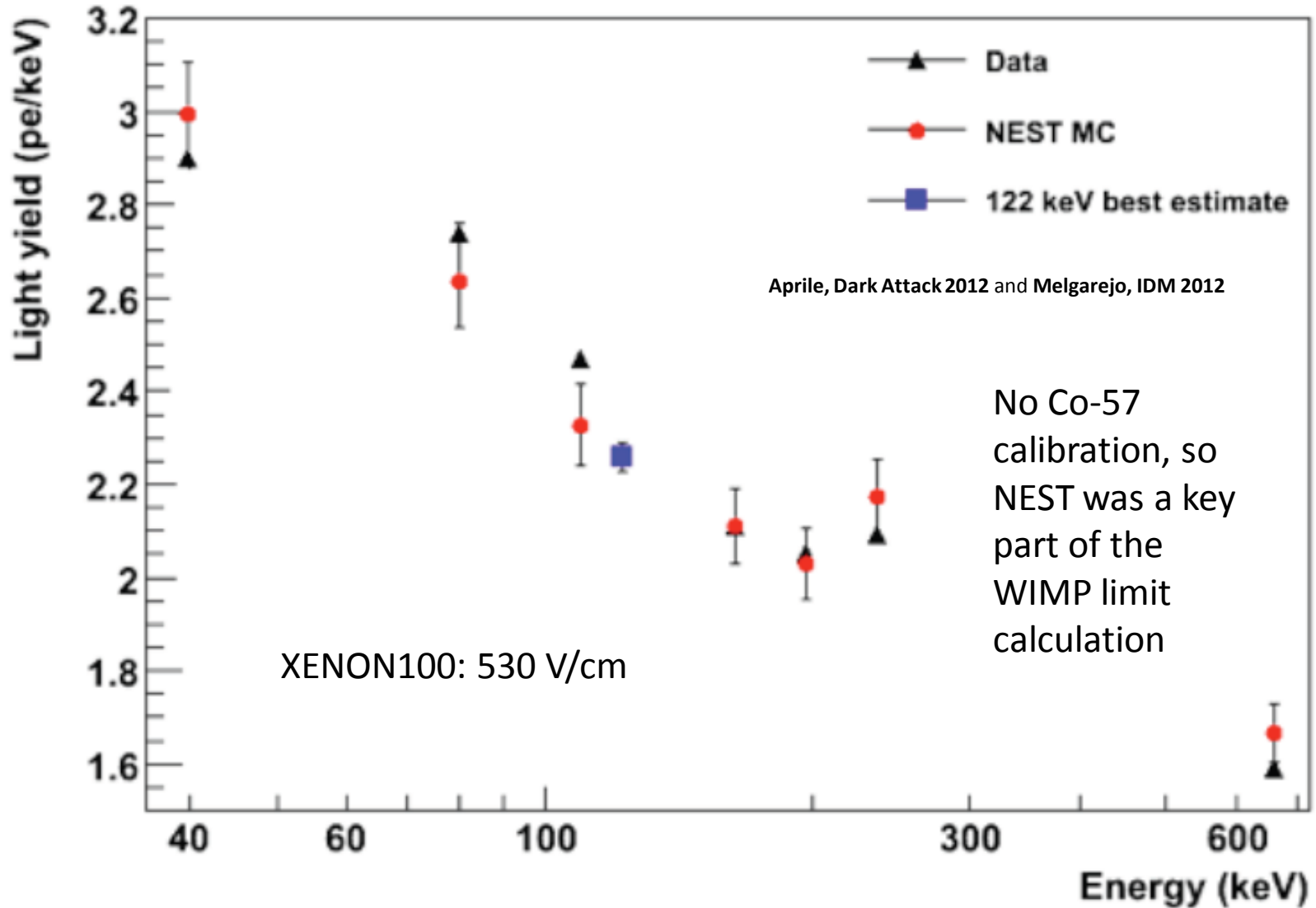
Zero Field

Non-zero Field (450 V/cm)

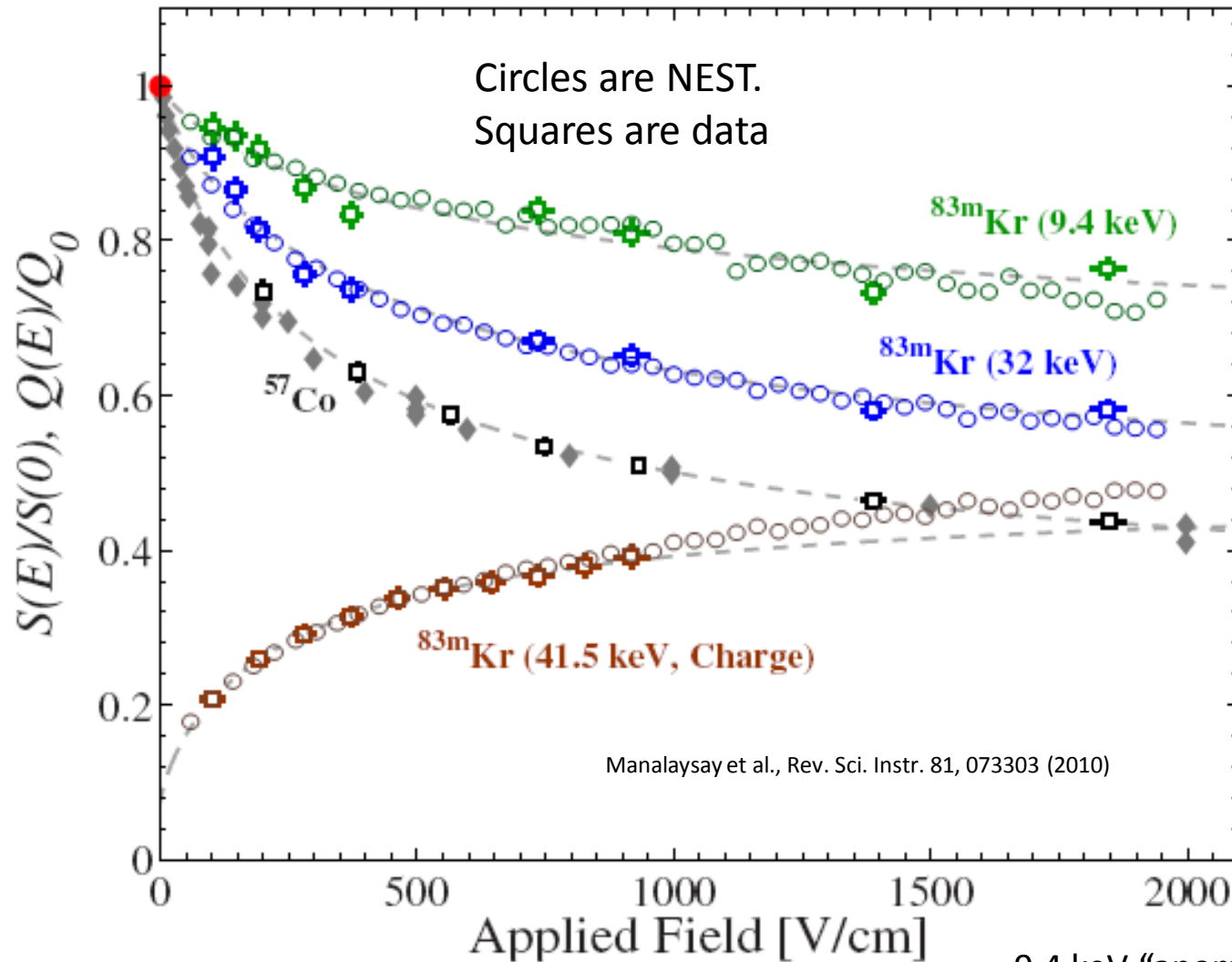


As we approach minimally-ionizing, the curve asymptotes

ER Mean Light Yield in LXe



ER Charge Yield, including Kr-83m

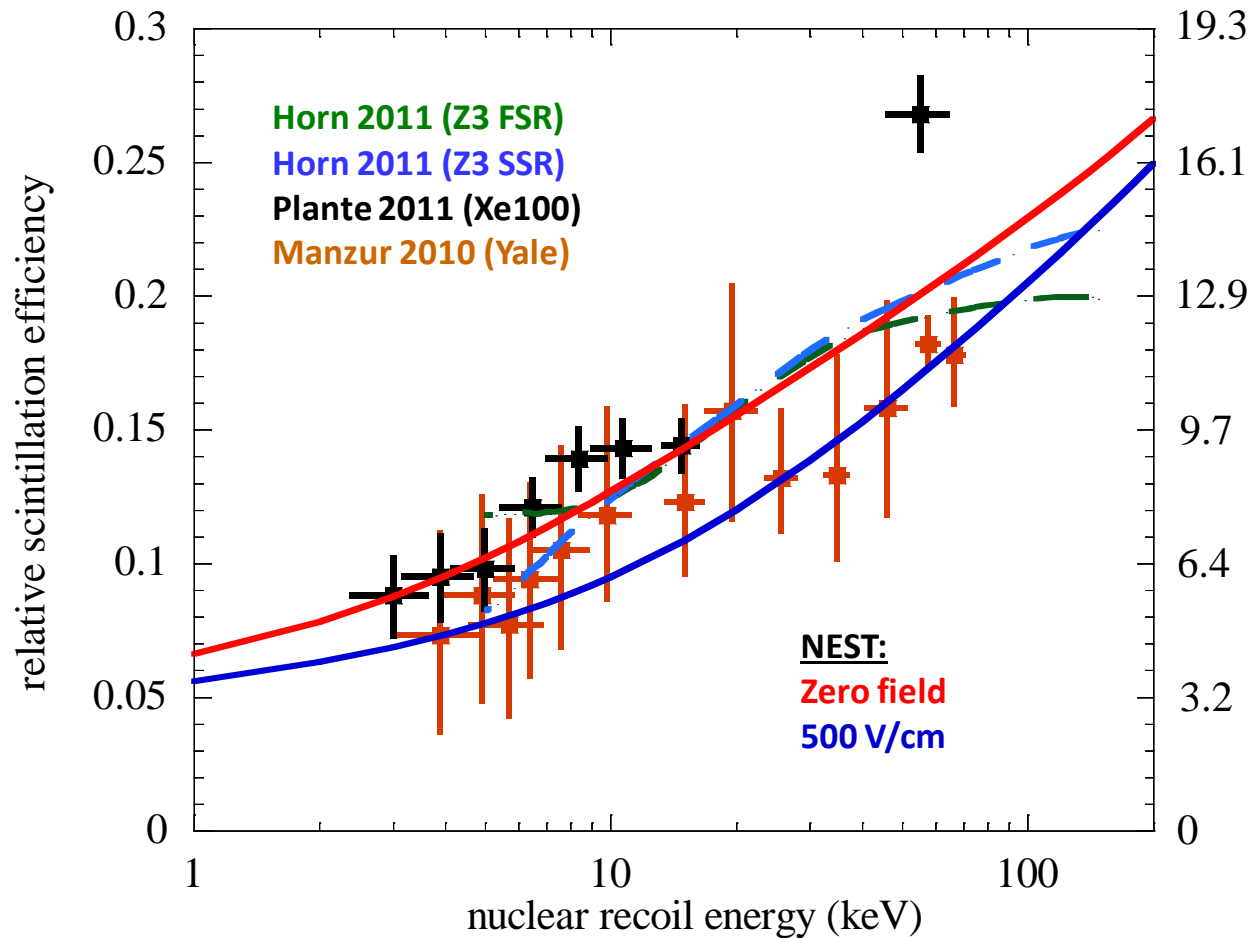


have benefited from technological advancements, leading to more accurate measurements. Recent 9.4 keV data is poorly predicted by the Thomas-Imel model. Curiously, agreements can be achieved by approximating the ^{83m}Kr de-excitation as only a gamma ray and applying the Doke/Birks model despite the low energy. Without such adjustments these data contradict Dahl [11] in this energy

9.4 keV “anomaly” was identified in the NEST JINST paper ~1 year before Columbia study

NR Light Yield in LXe

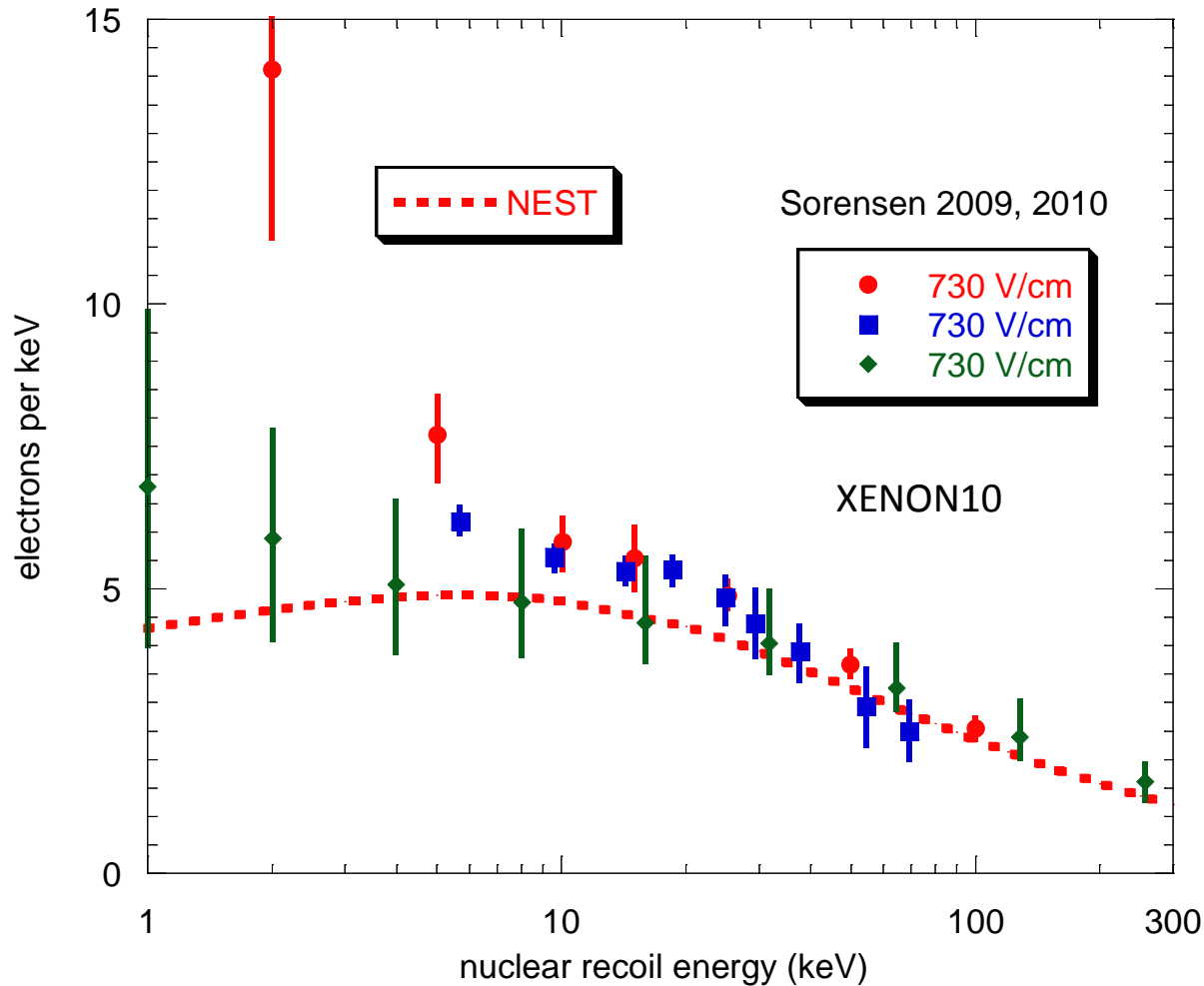
(Using very simple assumptions)



We don't need to reference the Co-57 line anymore. Model gives us absolute numbers.

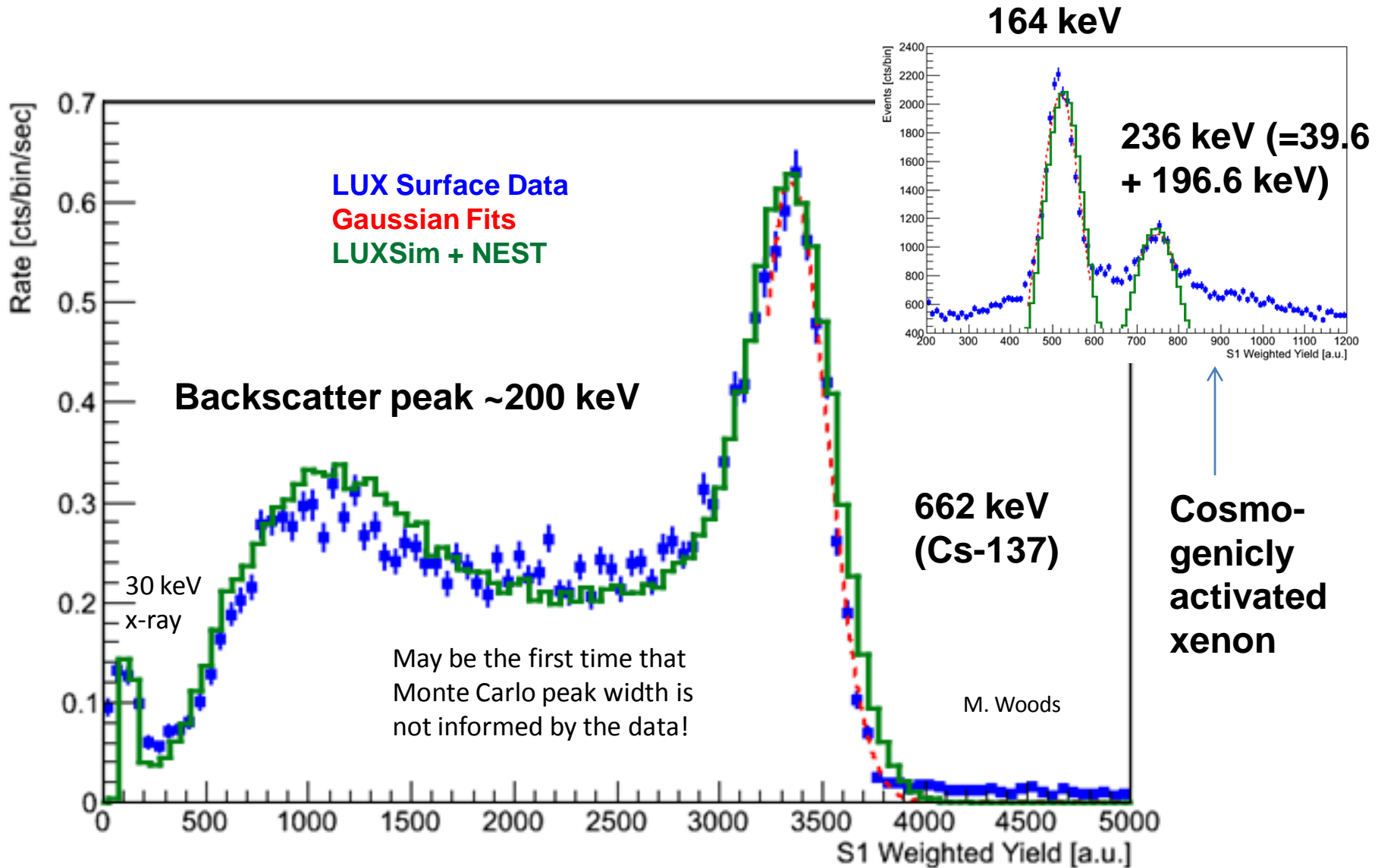
NR Charge Yield in LXe

Curve straight-jacketed: sum of quanta fixed by Lindhard theory, while Dahl gives us ratio

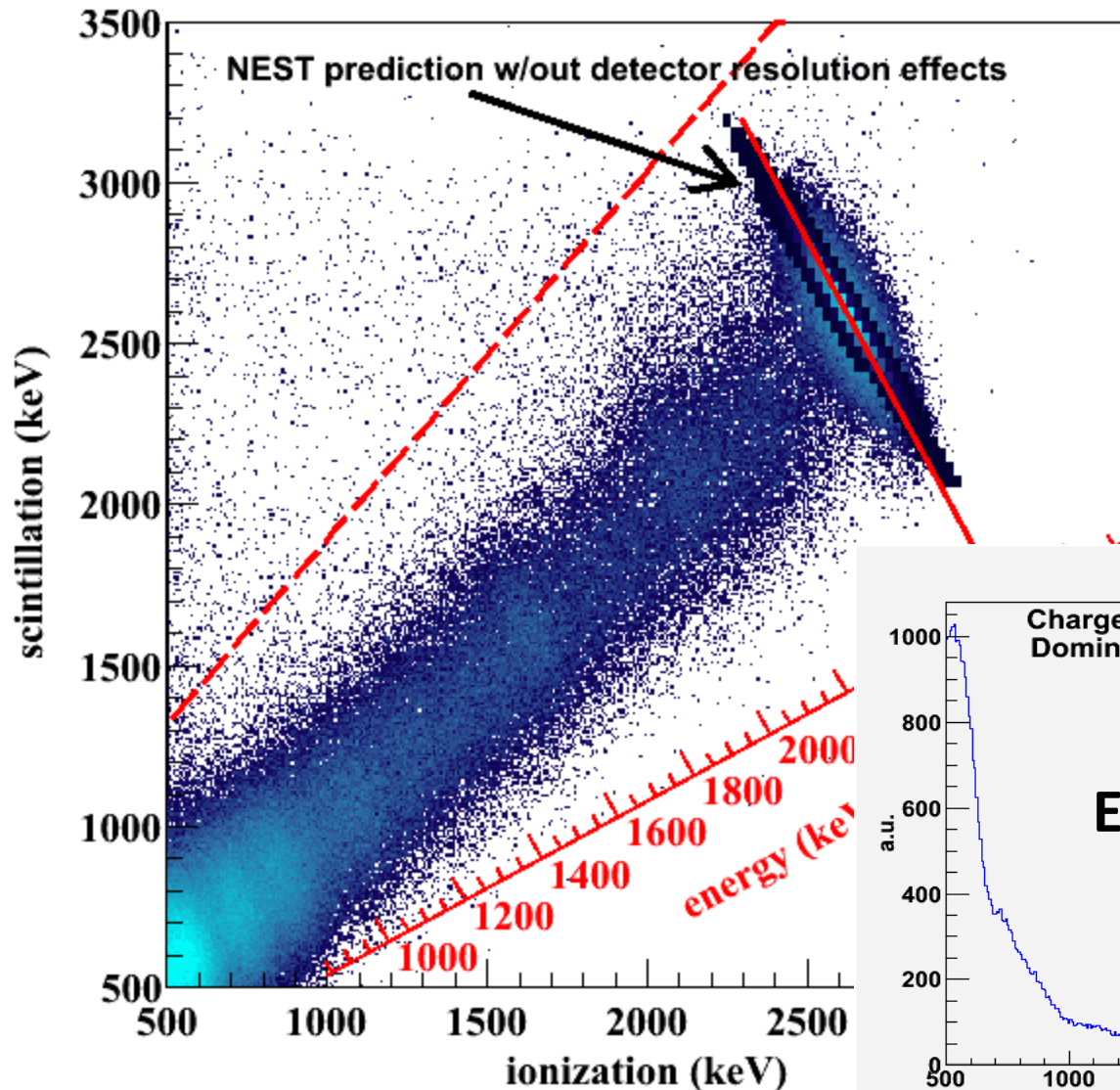


P. Sorensen et al., Lowering the low-energy threshold of xenon detectors, PoS (IDM 2010) 017 [[arXiv:1011.6439](https://arxiv.org/abs/1011.6439)].

ER Energy Resolution: Light

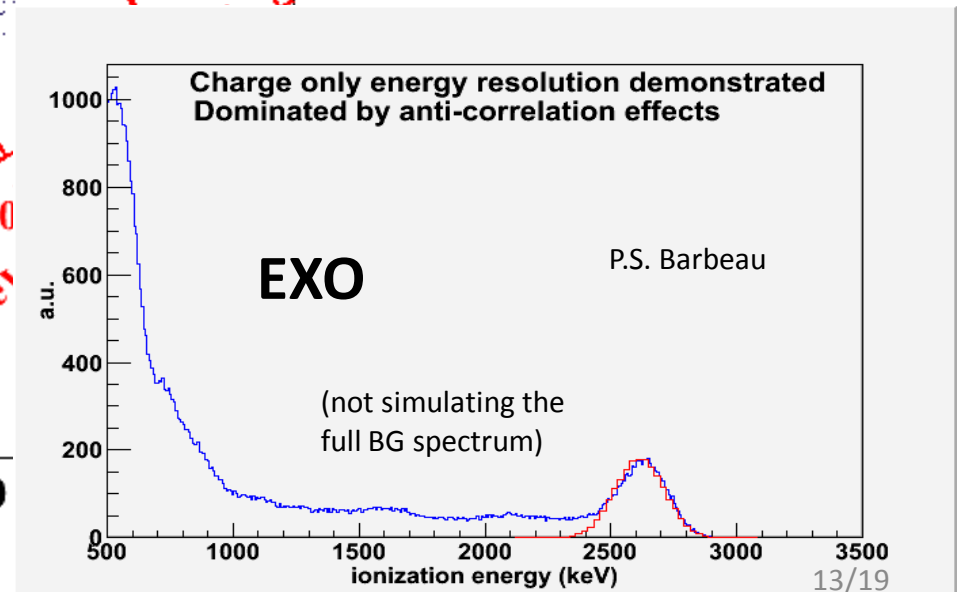


ER Energy Res: Charge + Light

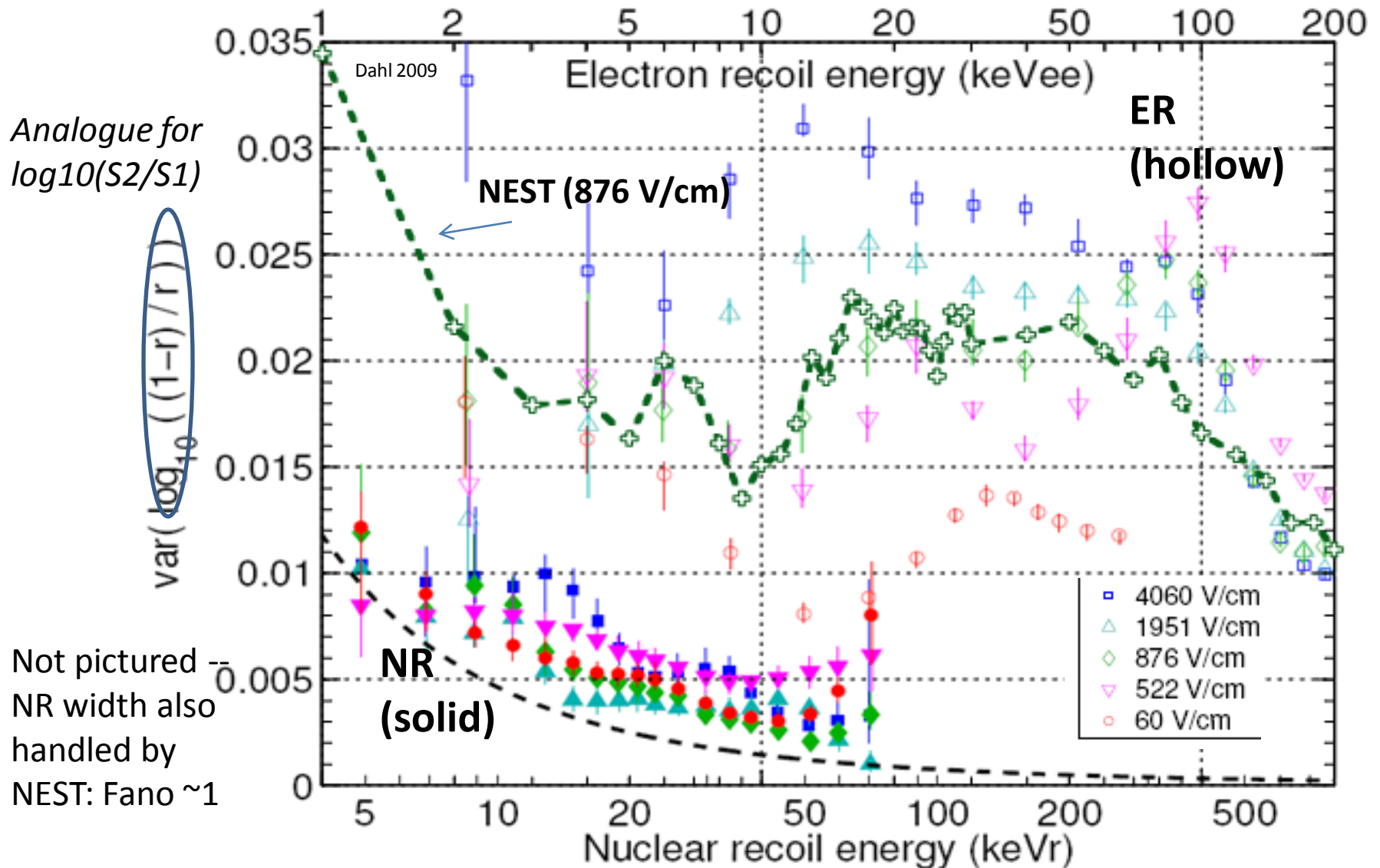


Recombination fluctuations have been modeled as worse than binomial, with a field-dependent Fano-like factor $O(10)$ - $O(100)$ which disappears at low energies. Based on

Conti et al., Phys. Rev. B 68, 054201 (2003)
Aprile et al., NIM A 302, p. 177 (1991)



ER Resolution: $\log(S2/S1)$ Band

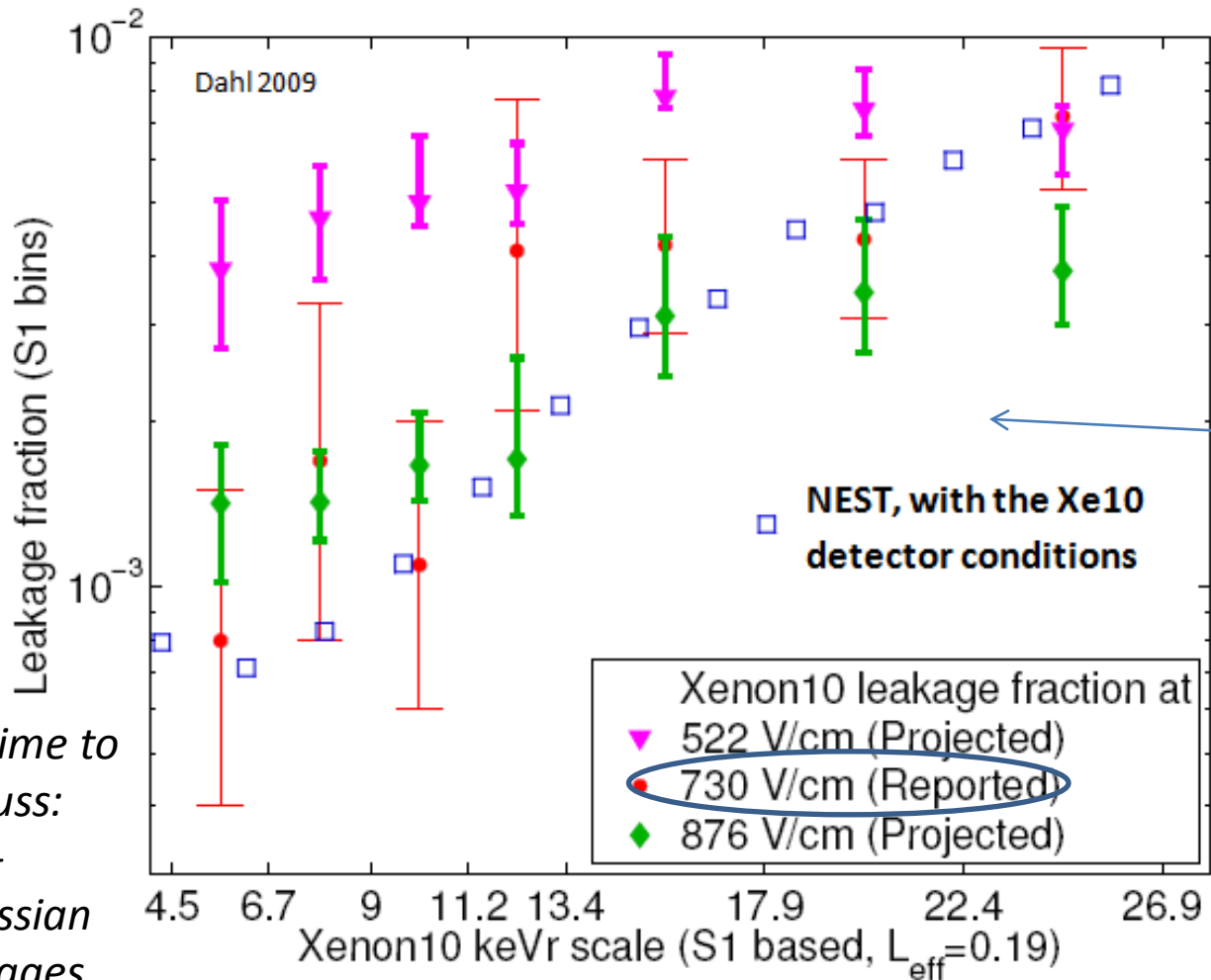


Analogue for $\log_{10}(S2/S1)$

$$\text{var}(\log_{10}((1-r)/r))$$

Not pictured --
NR width also
handled by
NEST: Fano ~ 1

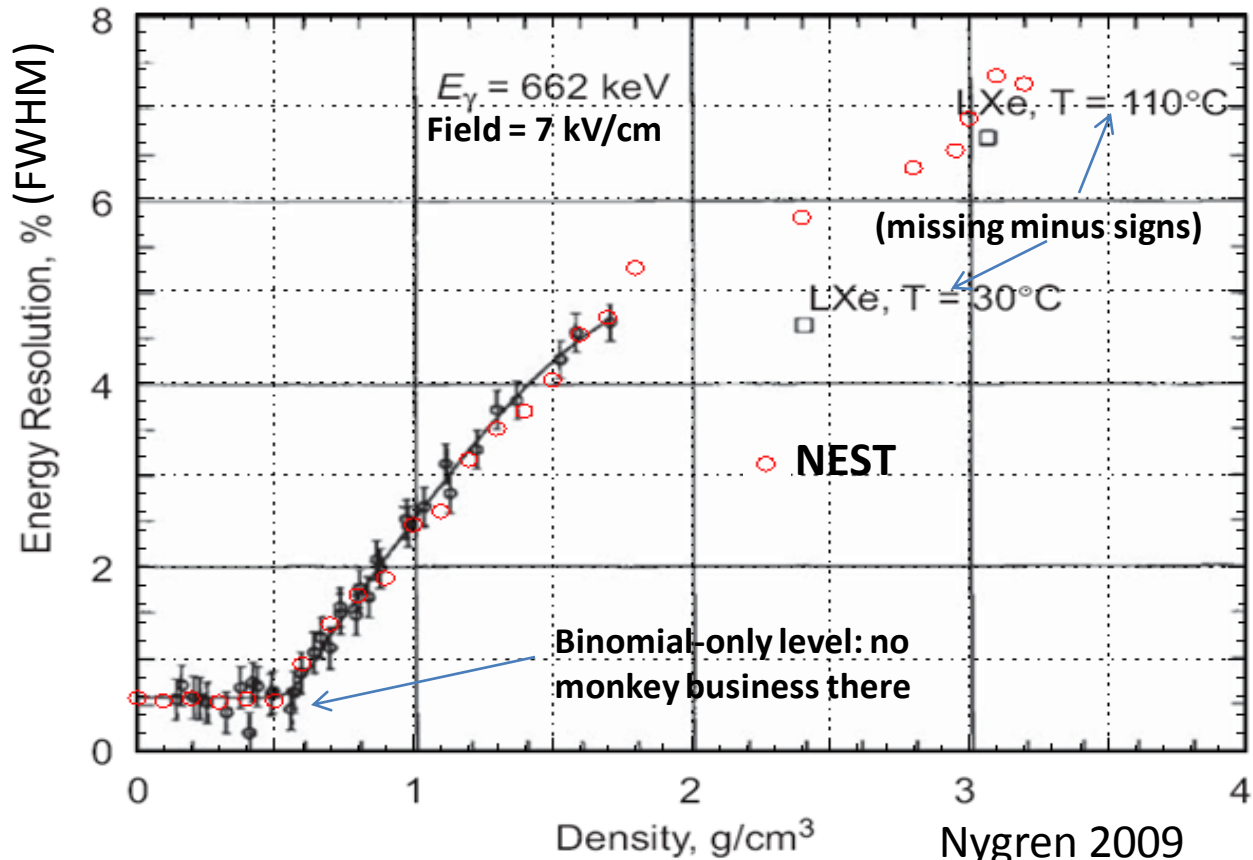
NR vs. ER Discrimination



No time to discuss: non-Gaussian leakages

Culmination plot. ER and NR band means and widths must all be right. Trend counter-intuitive: worse result *away* from threshold

Gaseous Xenon



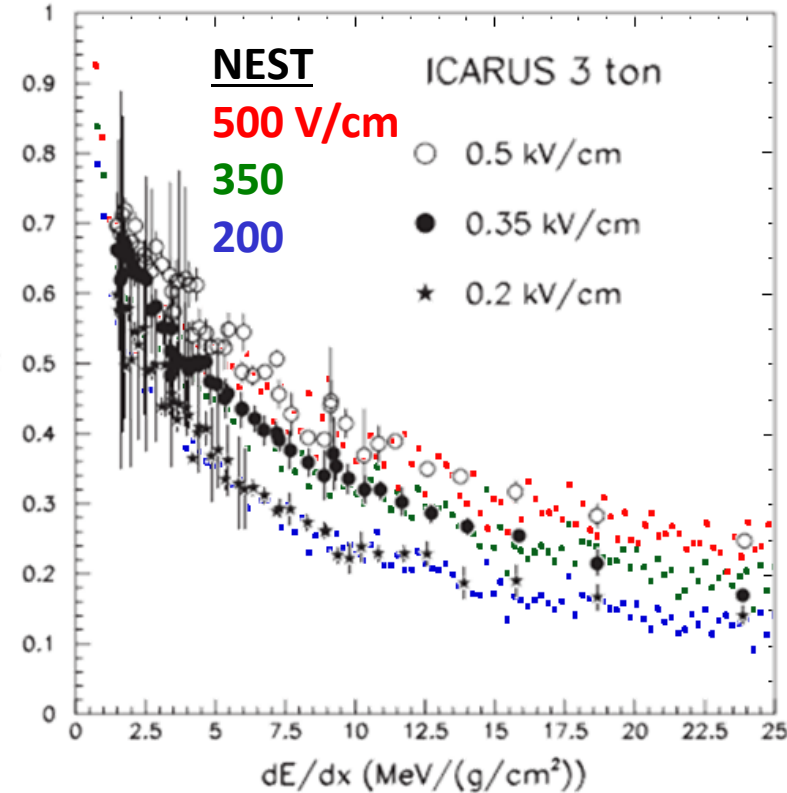
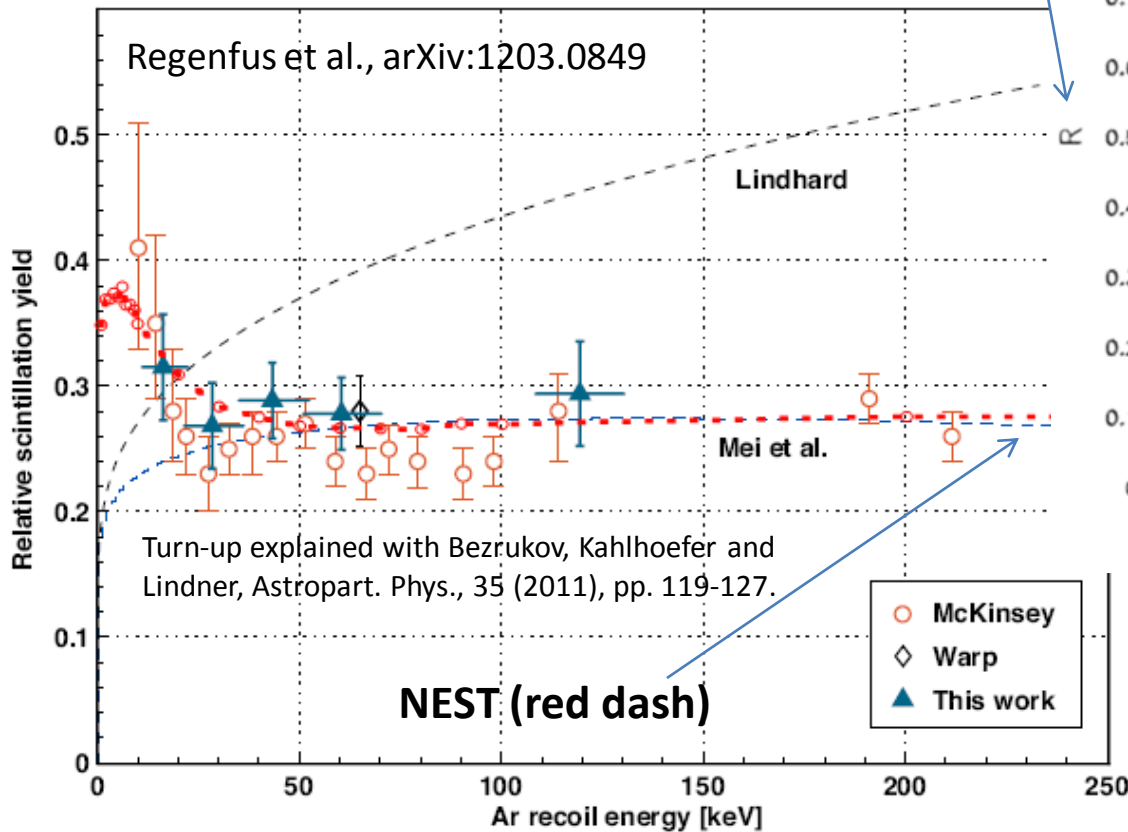
Nygren 2009

Bolotnikov et al. 1997

Liquid Argon NR and ER

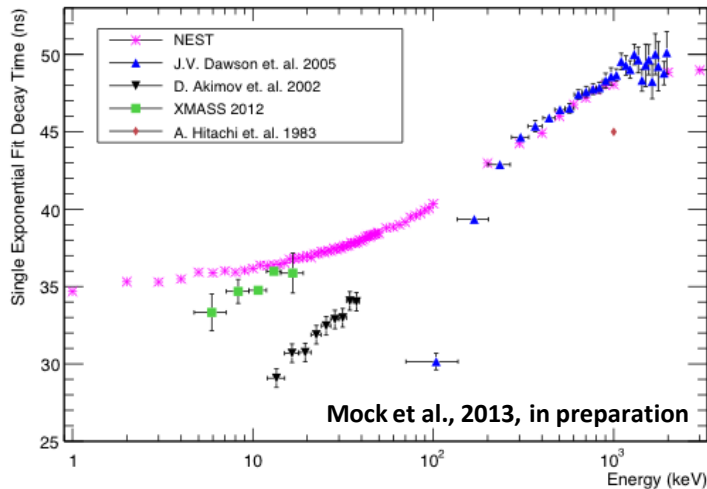
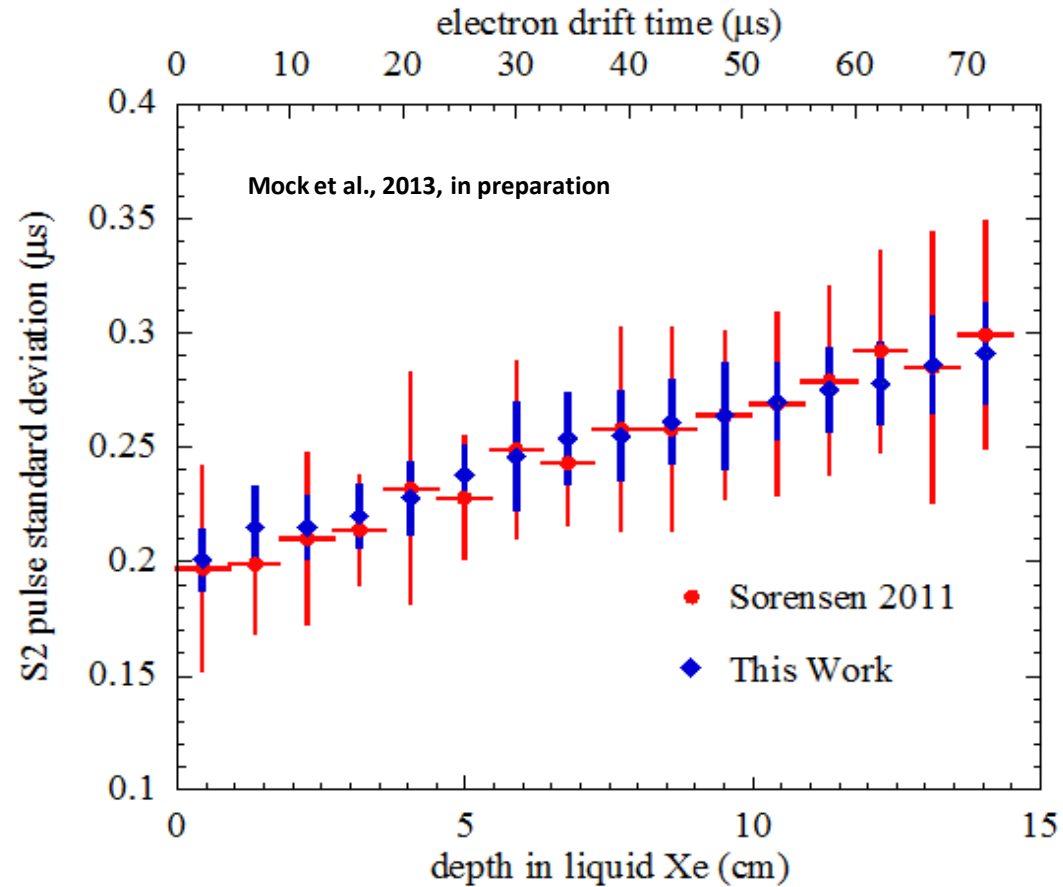
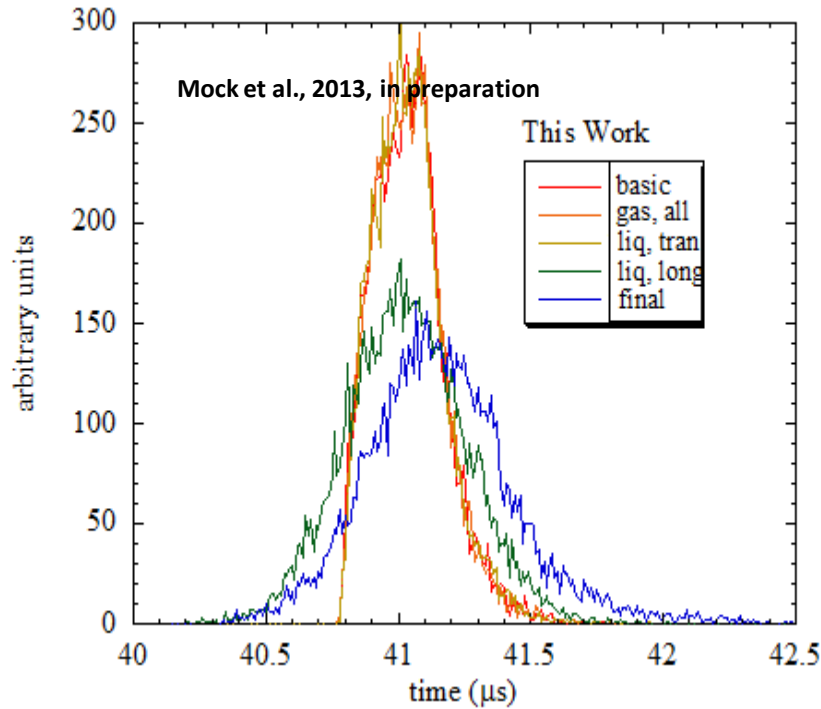
Note: RAT, codebase pre-dating NEST, already does zero-field LAr very well (cf. Mastbaum talk)

$R = 1 - r$ is a way of checking both light and charge yields, concurrently



Amoruso et al., NIM A 523 (2004) 275–286

Pulse shape: LXe examples



S1 effects included: singlet time, triplet time, ratio (function of particle type), recombination time (function of dE/dx and field)

S2 effects: drift speed, singlet, triplet, diffusion, electron trapping before extraction

Conclusions

- Simulation package NEST has a firm grasp of microphysics.
- **Though NEST does not track individual atoms or excimers, it is closer to first principles, considering the excitation, ionization, and recombination physics, resorting to empirical interpolations as indirect fits or not at all**
- Extensive empirical verification against past data undertaken using multiple papers instead of only one experiment
- Liquid xenon is essentially finished, but there is still work being done for liquid argon, although it is progressing rapidly
- User-editable code for the entire community
- **Our understanding of the microphysics is only as good as the best data. Models are beautiful but nature is ugly. NEST is constantly improving. Always on look-out for more physical motivations. Currently, all parameters justifiable except for the size of the recombination fluctuations (in liquid xenon).**