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Grasping the Fundamental Physics of Xenon

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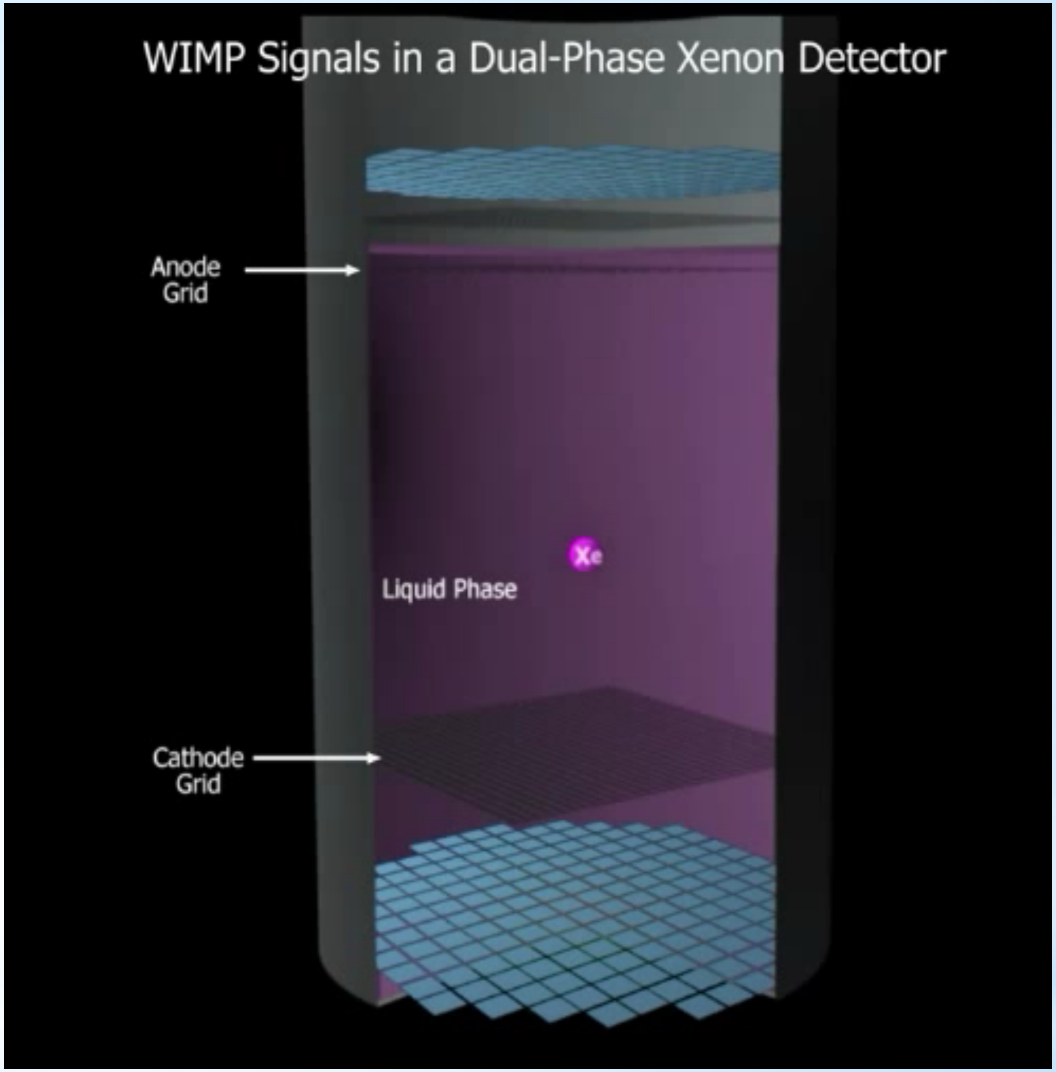
The Motivation

- The case for dark matter: wealth of indirect evidence but *conclusive* direct detection remains elusive
  - Galactic rotation curves, gravitational lensing, CMB, BAO, large-scale structure observations and simulations, Bullet Cluster multi-spectral overlay study, nucleosynthesis
- Direct searches for dark matter using noble liquids, in particular xenon in recent years, have obtained the best sensitivities in the field for moderate to high-mass dark-matter Weakly Interacting Massive Particles
  - XENON10, XENON100, ZEPLIN, LUX, PandaX, XENON1T, LZ
  - High Z and density (good self-shielding), scalable (liquid), two-channel energy reconstruction, many advantages
- Along with the development of this technology, there has been a continued effort to better understand the detailed scintillation and ionization responses

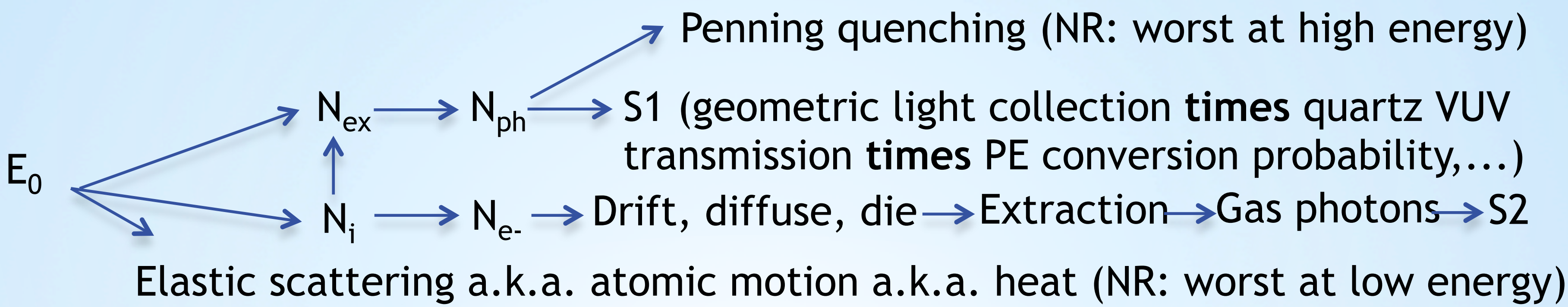
Image: NASA

* A Detector Example

* The dual-phase xenon detector, an example of a time-projection chamber (TPC), with many PMTs
* S1 (primary) and S2 (secondary) scintillation, the latter from charge
    * Their ratio discriminates between nuclear and electron recoil (NR & ER)
    * The sum gives you energy
* Fiducialization with multiple-scattering rejection powerful: WIMPs will exclusively lead to single-scatter recoils



Animation credit: The LUX collaboration, but created prior to commencement of detector operations, so the values of parameters are approximate and representative



- Chain reaction set off by just 1 NR or ER leads to many NRs and ERs, with 3 main processes occurring
  - Billiard-ball scattering, electron excitation, and ionization
- Working theory of the physics leading to scintillation (light collection) and escaping ionization electrons (charge collection)
- Focusing heavily upon liquid xenon for today's talk
  - But, gaseous xenon, argon, and other noble elements and phases work within same general framework

Energy Partition

* Concepts are incorporated into NEST (Noble Element Simulation Technique) which is a Monte Carlo tool
* Recent improvements in our understanding found in B. Lenardo et al., arXiv:1412:4417 and on the NEST web sites
  * http://www.albany.edu/physics/NEST.shtml
  * http://nest.physics.ucdavis.edu/site/
* The older NEST papers
  * J. Mock et al., JINST 9 (2014) T04002. arXiv:1310.1117
  * M. Szydagis et al., JINST 8 (2013) C10003. arXiv:1307.6601
  * M. Szydagis et al., JINST 6 (2011) P10002. arXiv:1106.1613
* Examples of both postdictive and predictive power of approach presented here today
* Free parameters used at every step have physical meaning

The Rundown

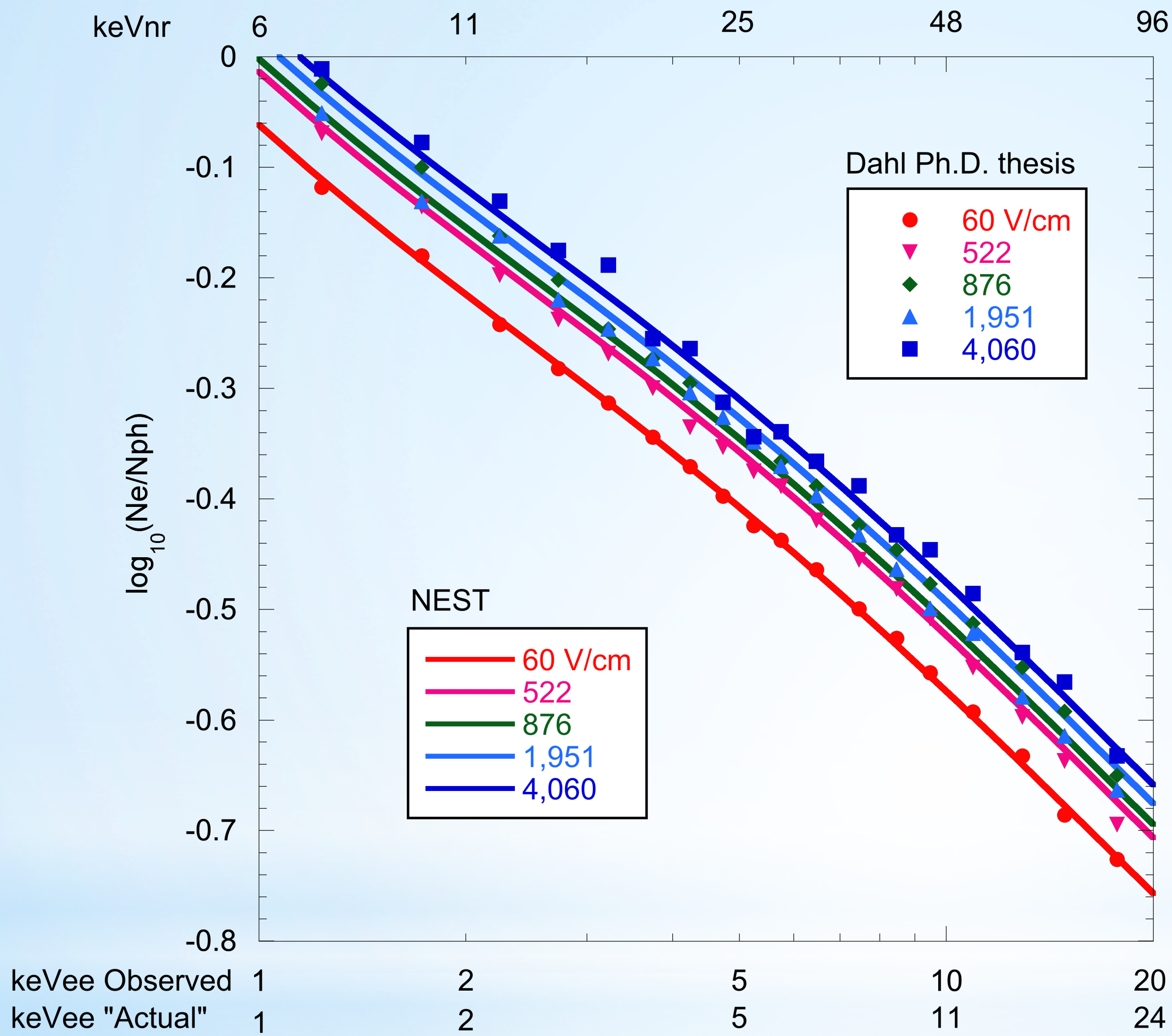
Image: Trade Winds Store

* W = 13.7 +/- 0.2 eV (higher than xenon excitation or ionization potentials because of cases where electrons fail to jump levels)
  * Determined empirically from energy scale of ERs, combining the reconstructed photon and electron counts, just like in Germanium
  * Sources: C.E. Dahl thesis, Princeton 2009, and many other works
* If N_{ex}/N_i = 0.15 for ER (best-fit NEW model, 0.06 outdated) then
* Observe the unification and simplification: Traditional $W_i = E_0/N_i = [(N_{ex} + N_i) * W]/N_i = (N_{ex}/N_i + 1) * W = 1.15 * 13.7 \text{ eV} \sim 15.8 \text{ eV}$
  * Compare to Takahashi 1975 result of 15.6 +/- 0.3 eV; others similar
  * This is <u>not</u> forced: pieces fit naturally with a new understanding
* S1 and S2, N_{ph} and N_{e-}, N_{ex} and N_i, these are all (see Conti 2003) **anti-correlated**. For ER this means ~fixed sum. NR is tricky (L)

E. Conti et al., Phys. Rev. B68 (2003) 054201
T. Takahashi et al., Phys. Rev. A12 (1975) 1771

Implementation

*NR Charge/Light Ratio



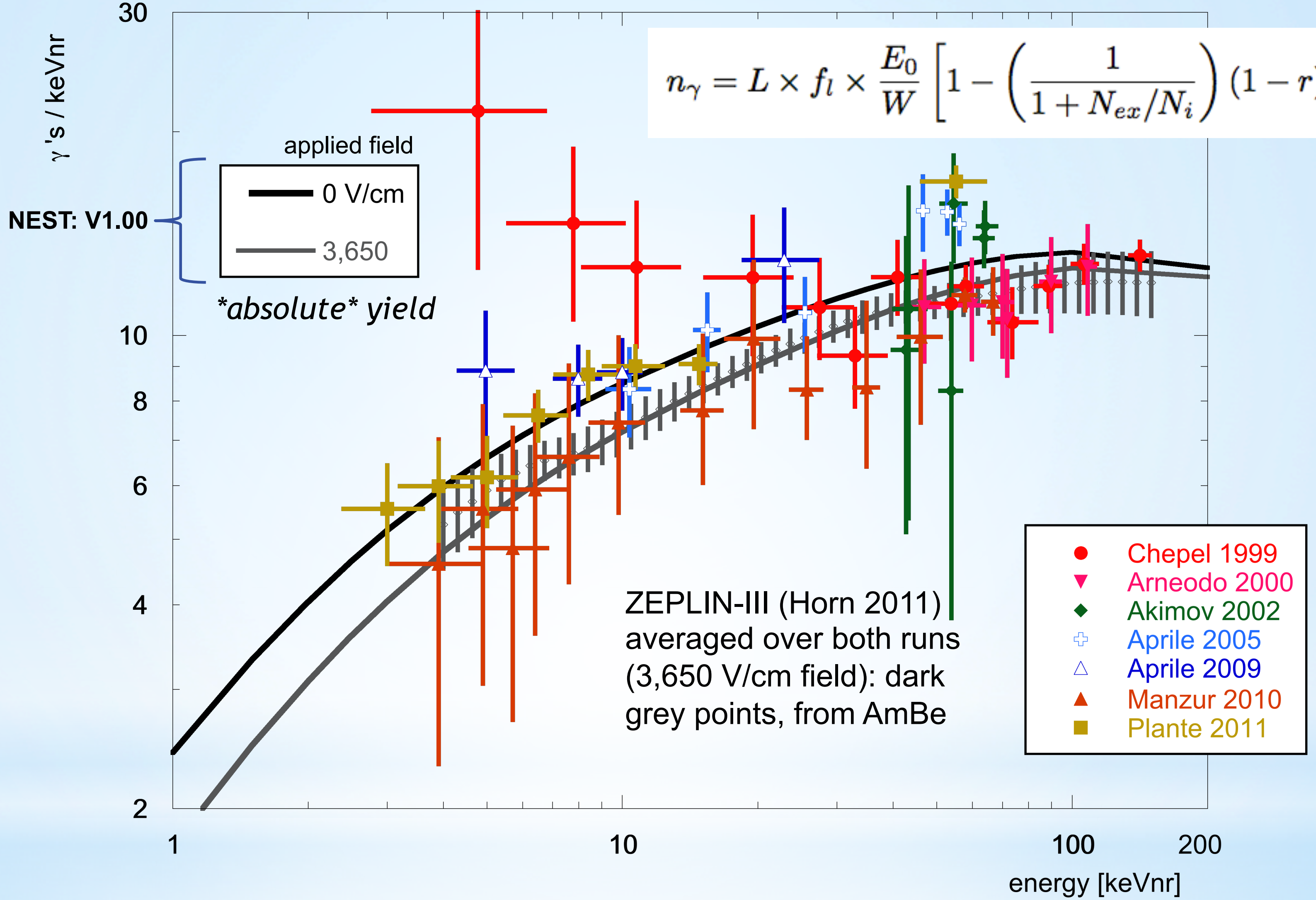
$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$

The keVnr (or keVr) energy scale is an estimate of the actual energy of the recoil for NR. keVee is same but without a L(indhard) factor

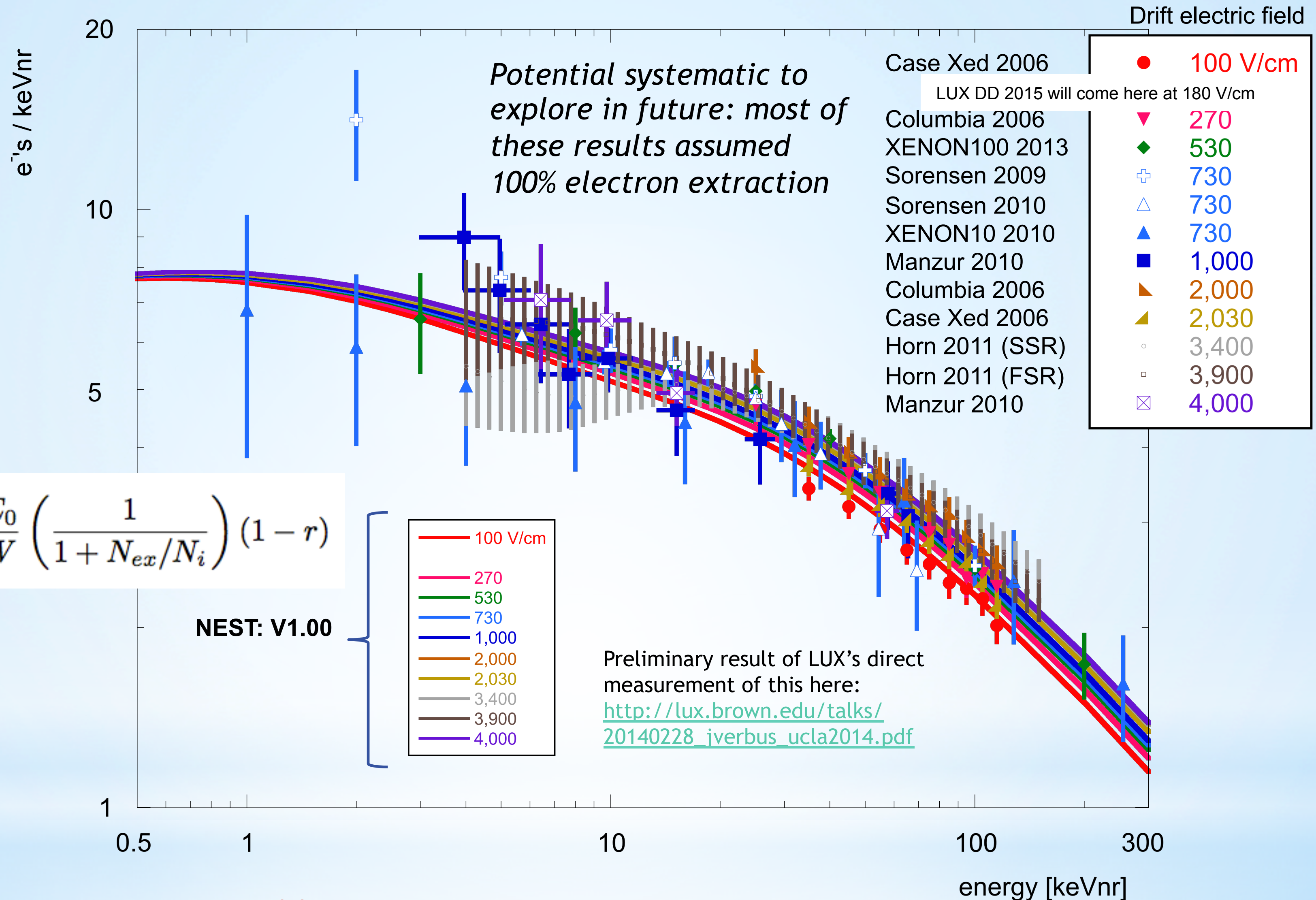
The keVee (or keVer) energy scale (or "electron equivalent") is an estimate of the actual energy of the recoil for ER. For NR, it is the ER for which the average total number of quanta is the same (traditionally used only the S1, but this created a field-dependent energy)

*NR Scintillation Yield

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



NR Ionization Yield



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

*By the Numbers

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

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

* Reduction in free parameters over older NEST
  - Less splining and more physical motivation

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

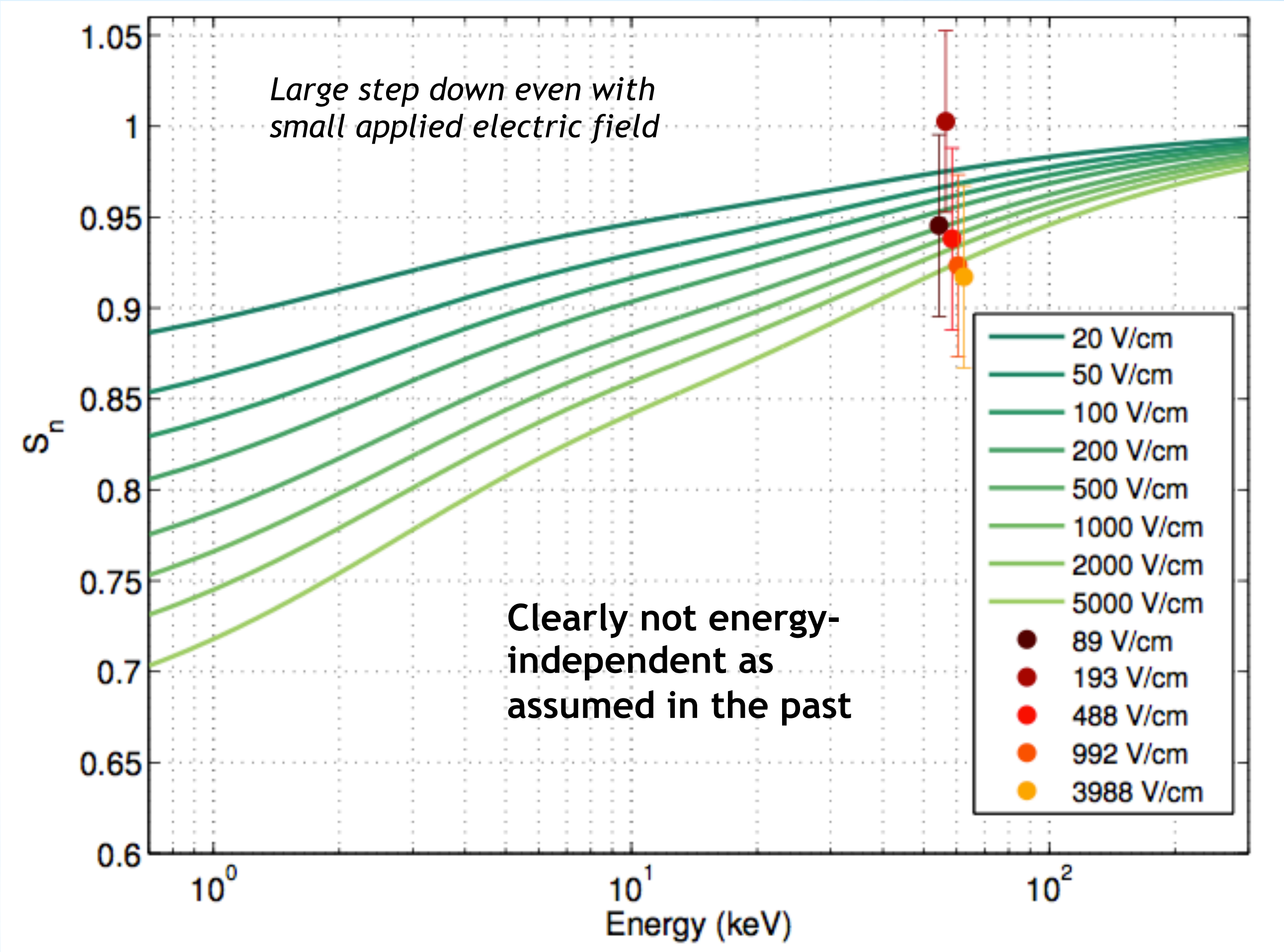
* Combined fit of light, charge simultaneously

* Global fit over as much data as possible
  - Moving far beyond Dahl data

quenching of photon yield (high dE/dx)

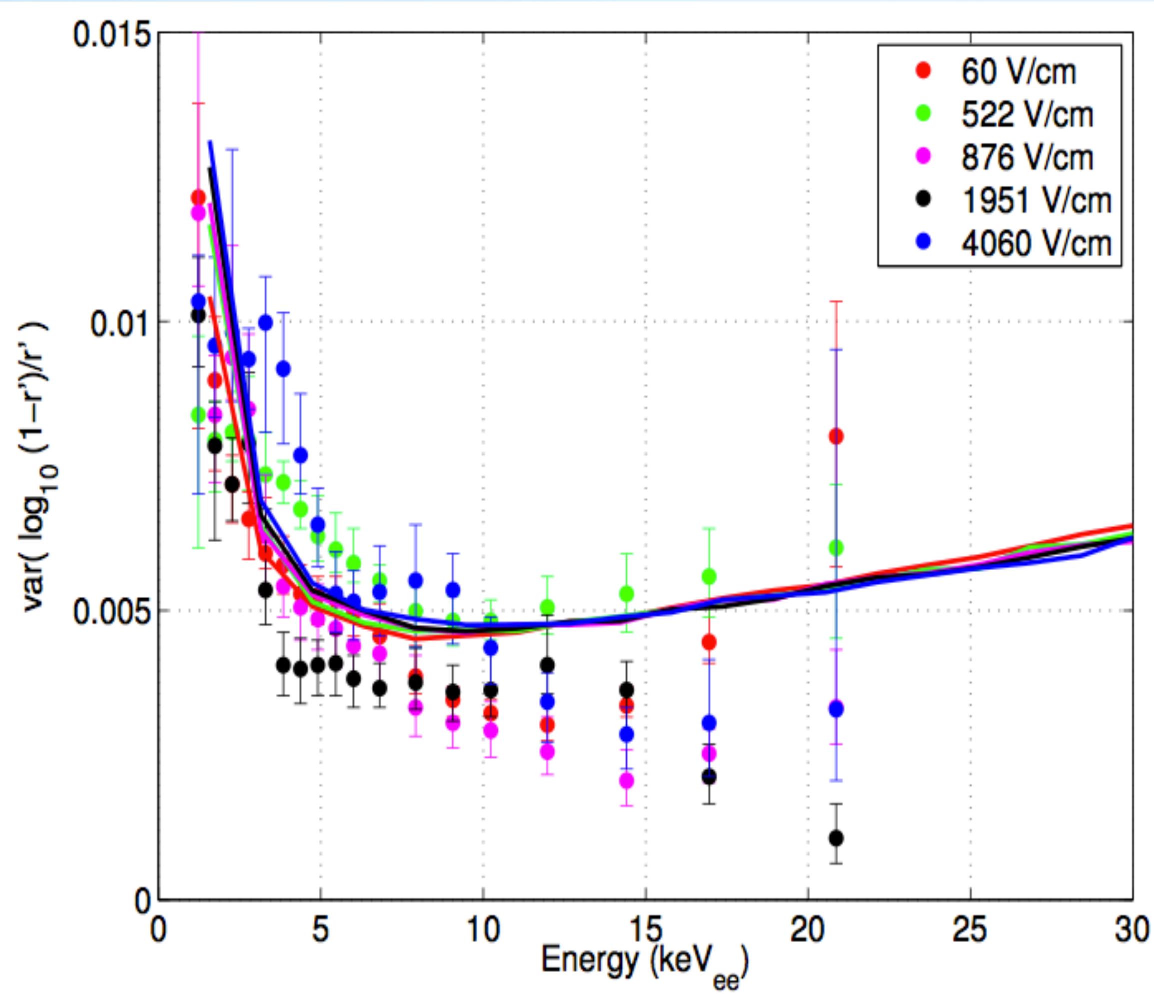
* Over-conservativeness (low yields) removed

* S_n is scintillation light yield relative to zero E-field
* Only useful direct data at 56.5 keVnr (Aprile 2005)
* Continuity of zero and non-zero field models achieved with effective minimum field
* Light yield goes down as charge up (more escape)



*Relative Yield v. Field

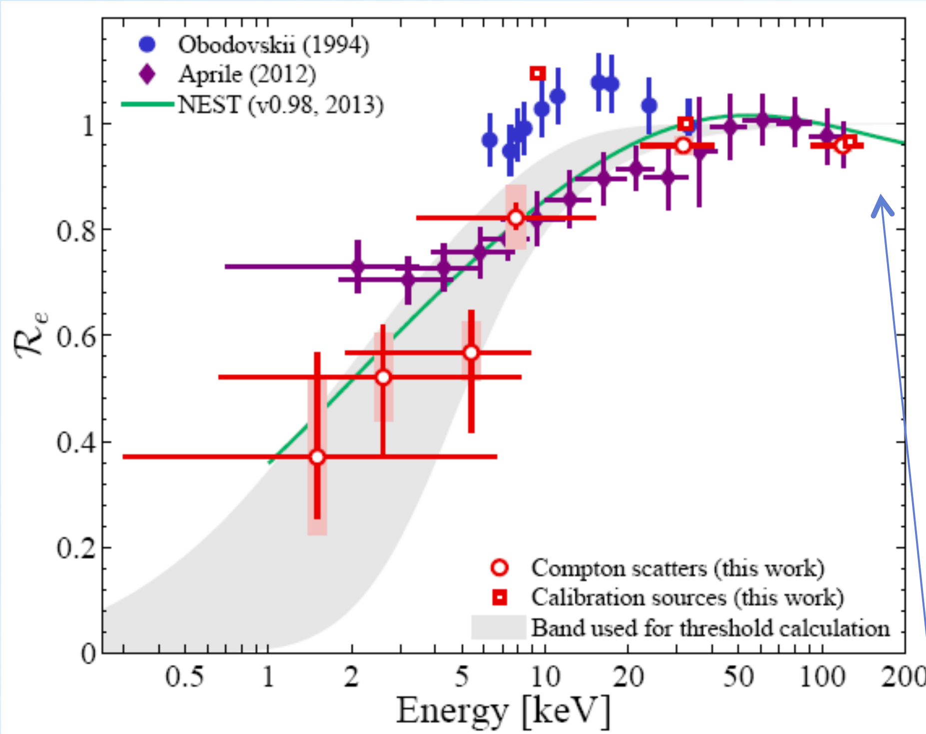
* NR Band Width



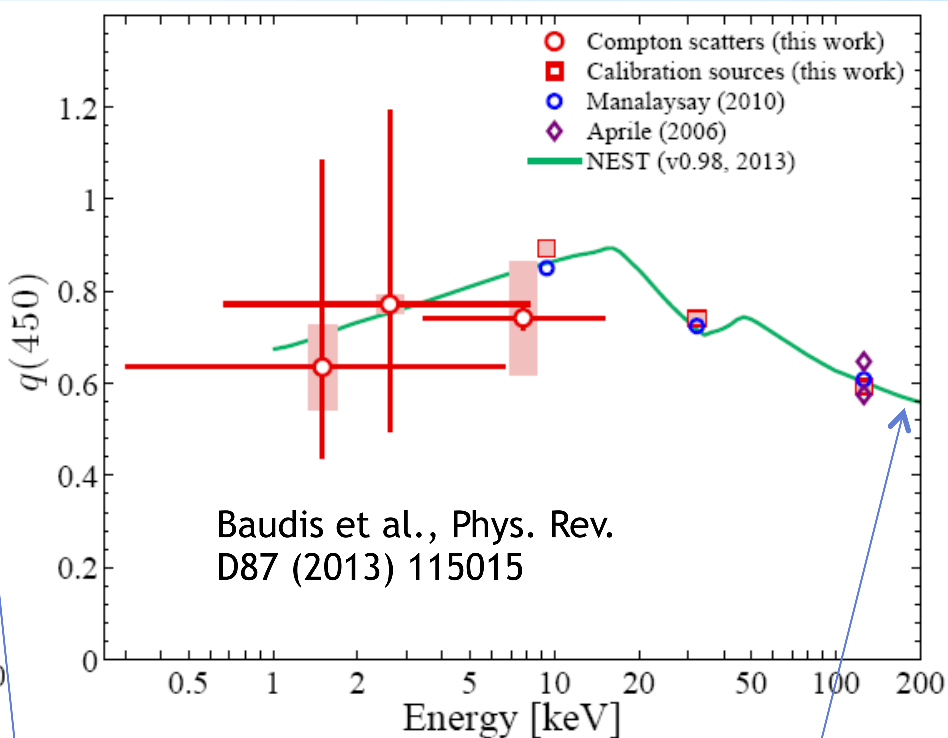
* Energy resolution in xenon long known not to be that expected from binomial recombination
* Solution is to utilize a a special variable-width Poisson function
  * Compromise between unphysical Gaussian and a slow binomial
* Recombination Fano-like factor proportional to N_i (A. Dobi thesis)

*ER Scintillation Yield

Zero applied electric field

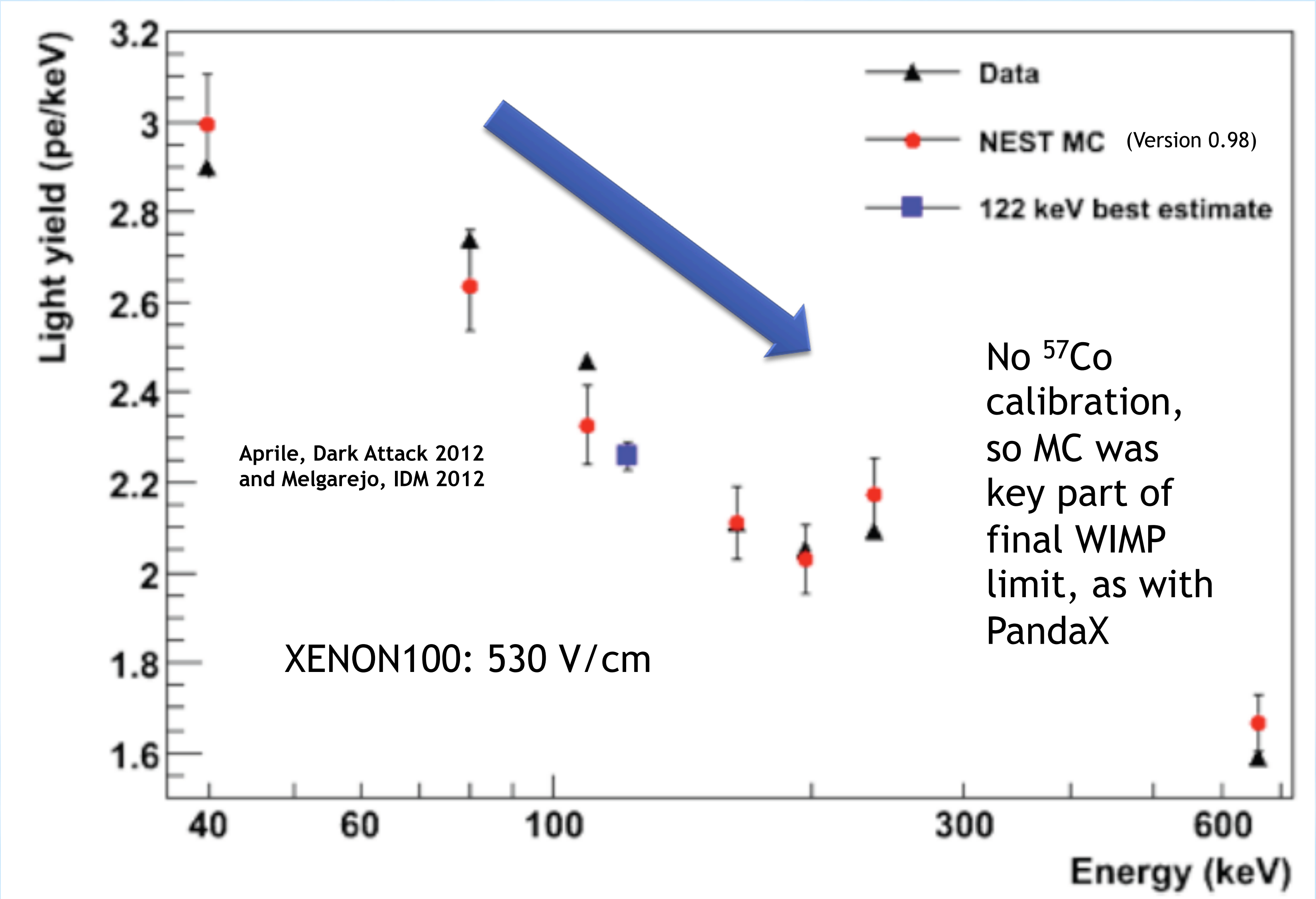


Non-zero field (450 V/cm)

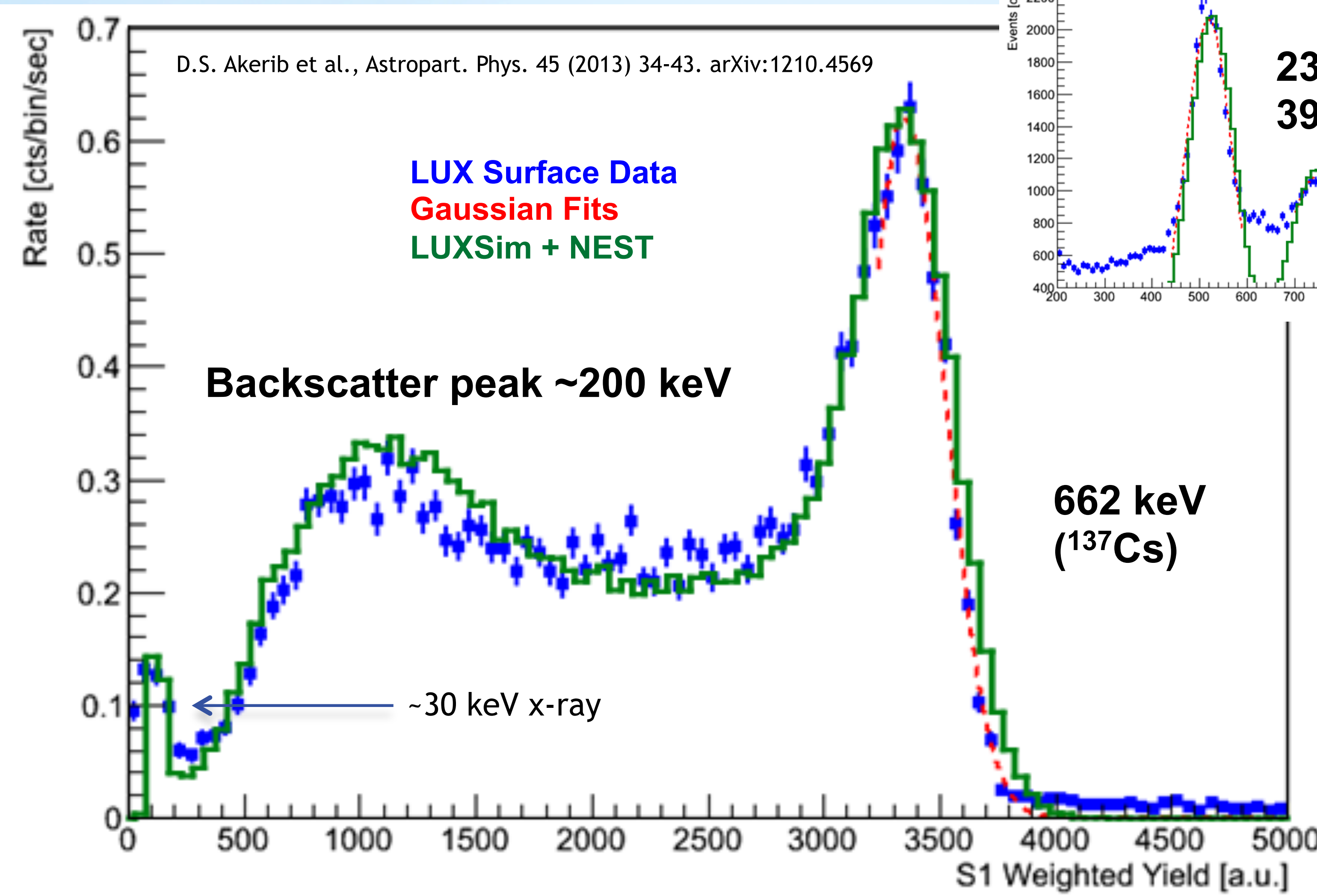


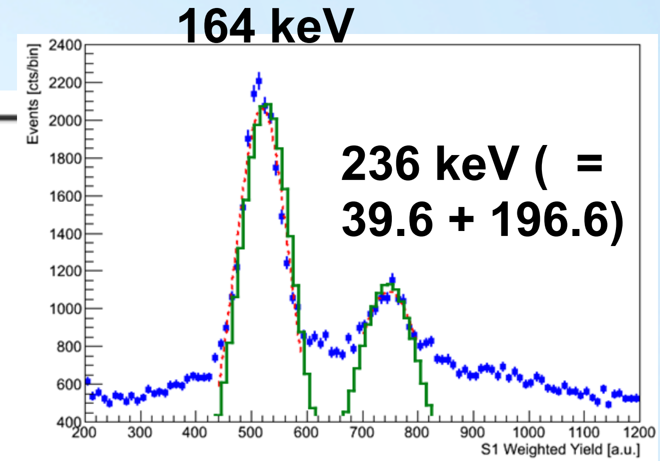
At high energies, recombination and thus yields behave differently

For ER, fit to electron data only and gammas/x-rays must follow: simpler approach



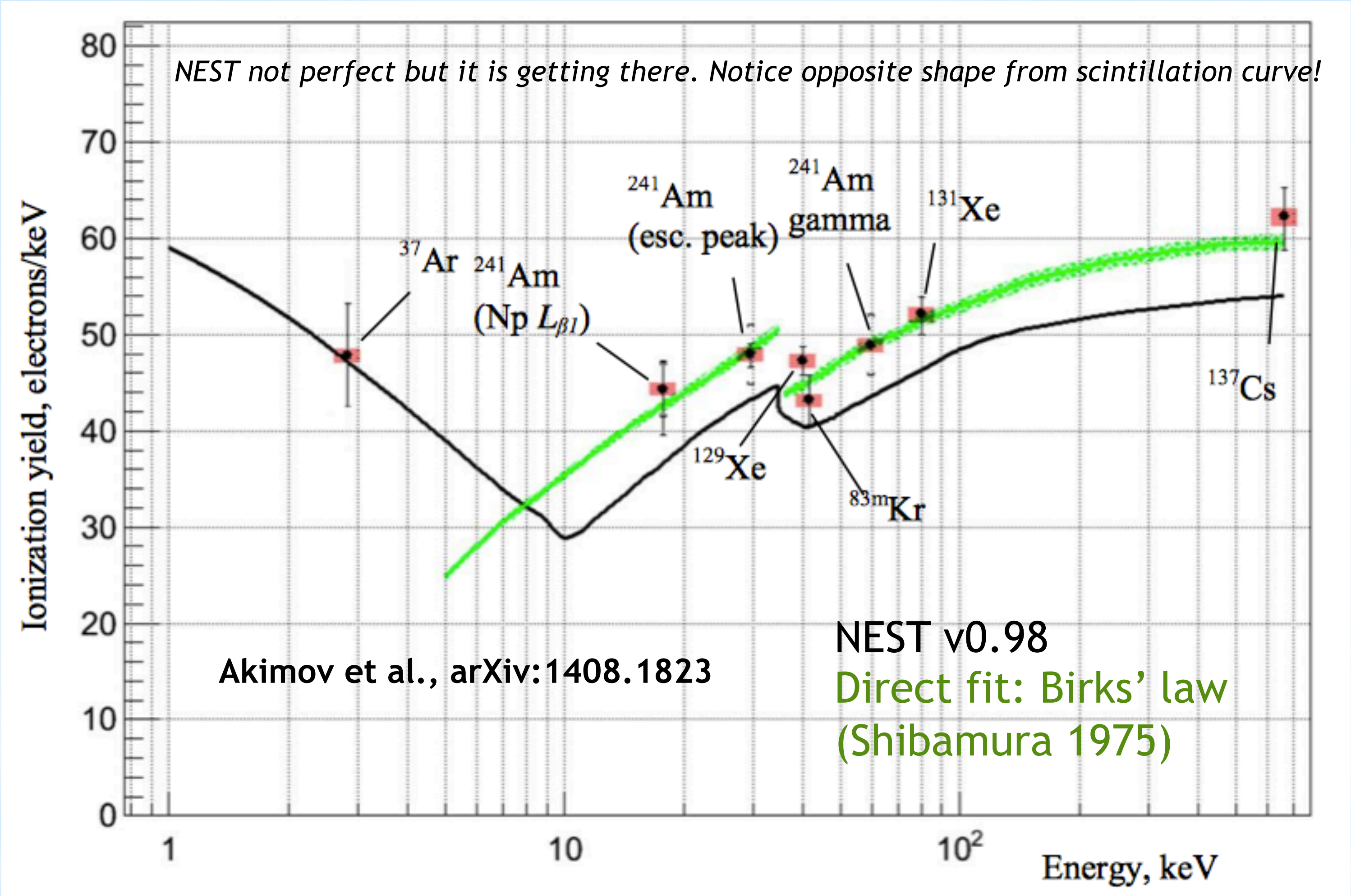
* A True Prediction for ER



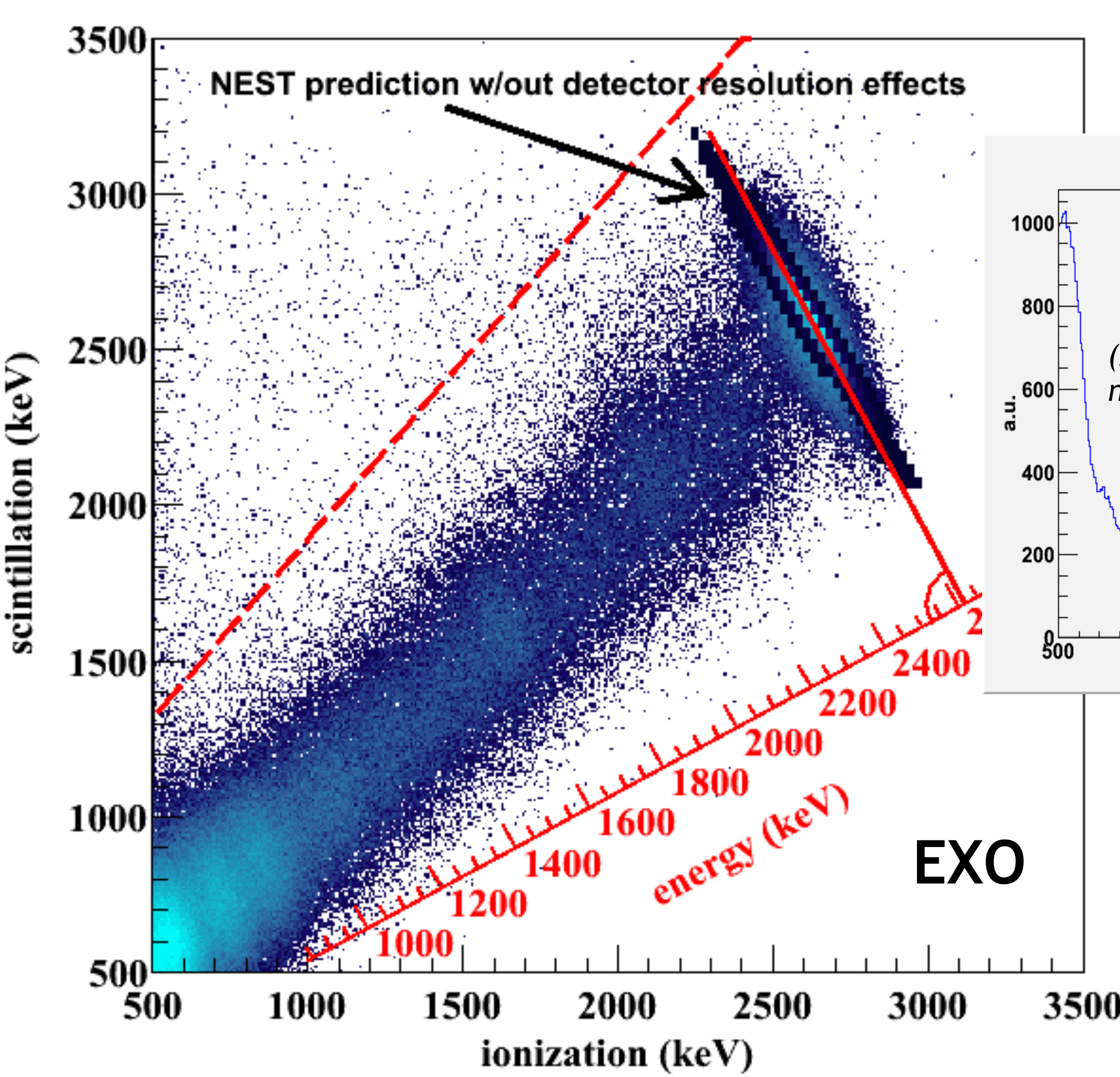


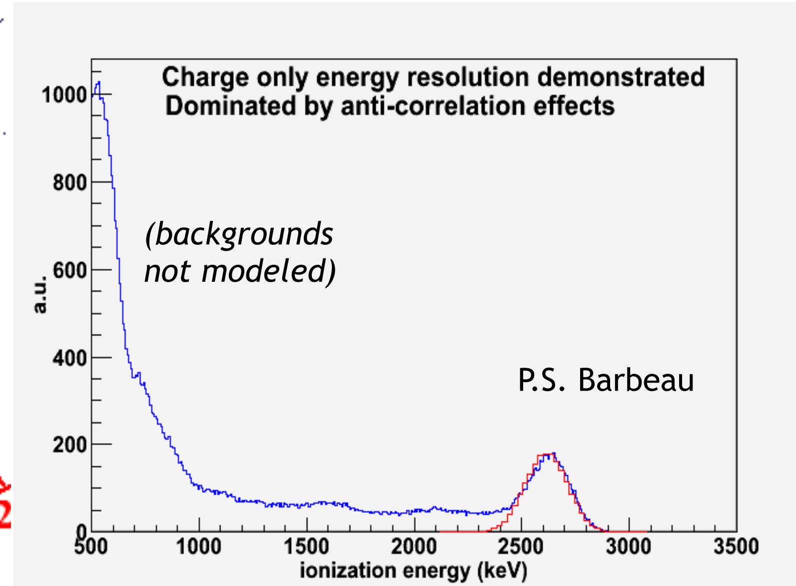
Activated xenon from being on surface (cosmic-ray neutrons)

* ER with Detector Effects



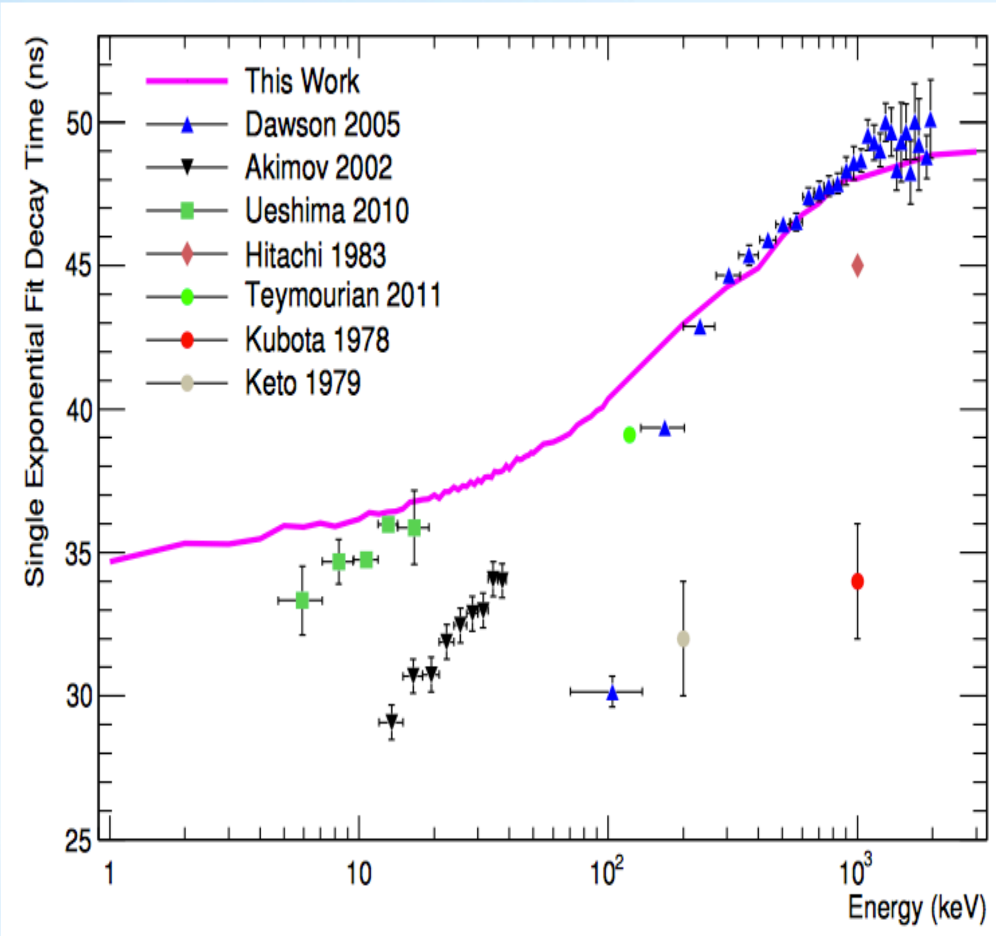
*ER Ionization Yield

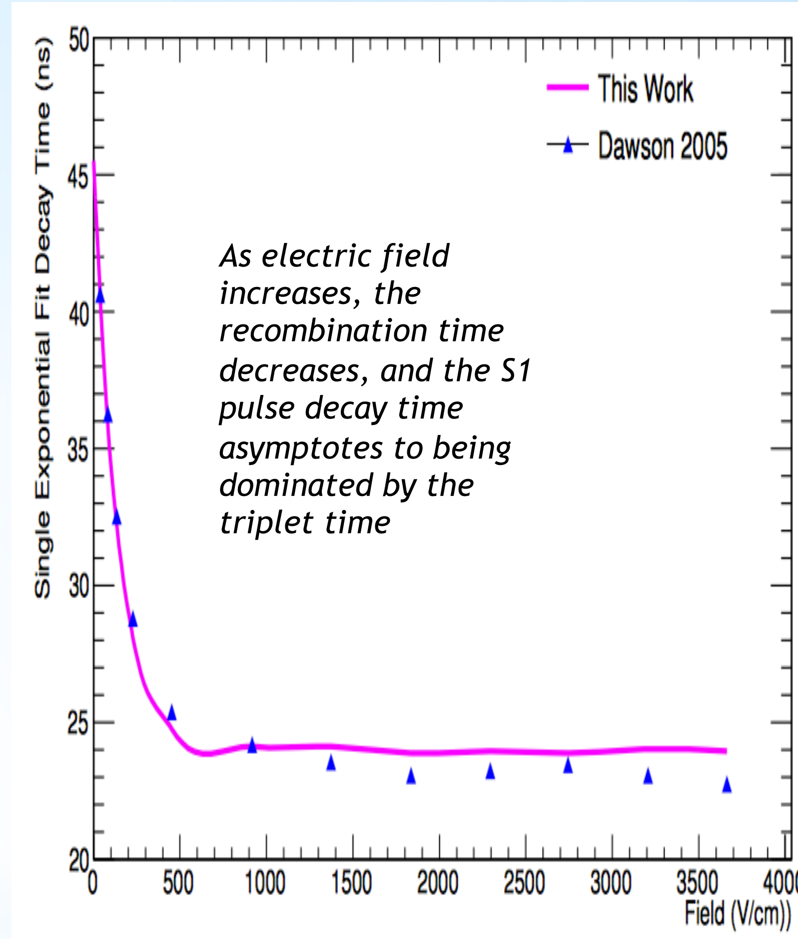




Broad applicability of xenon and NEST: dark matter, neutrinoless double-beta decay, also for coherent neutrino scattering at low energy

*ER Energy Resolution

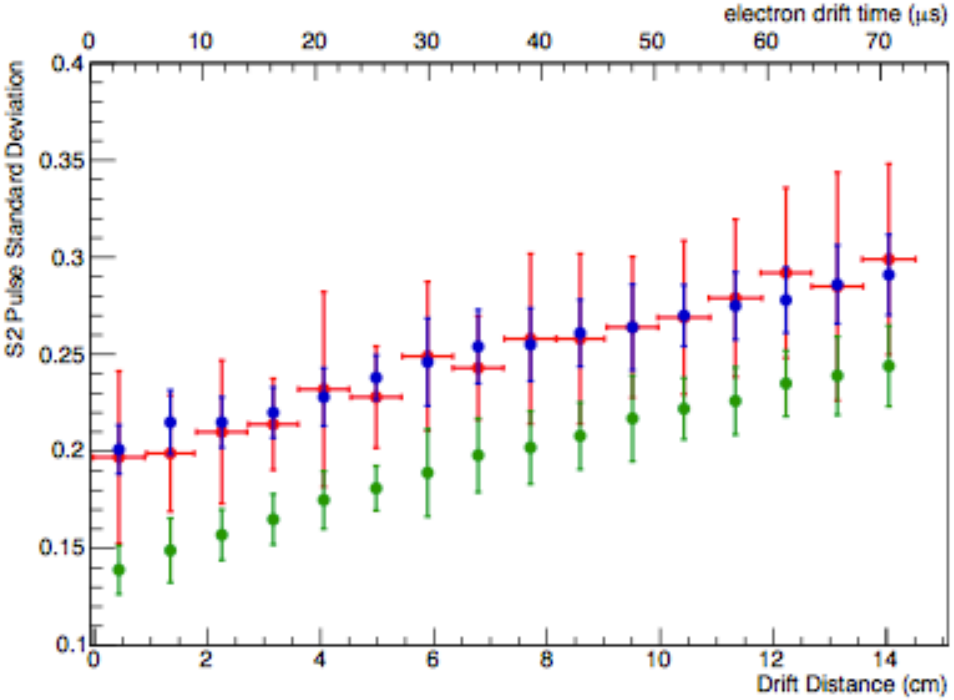


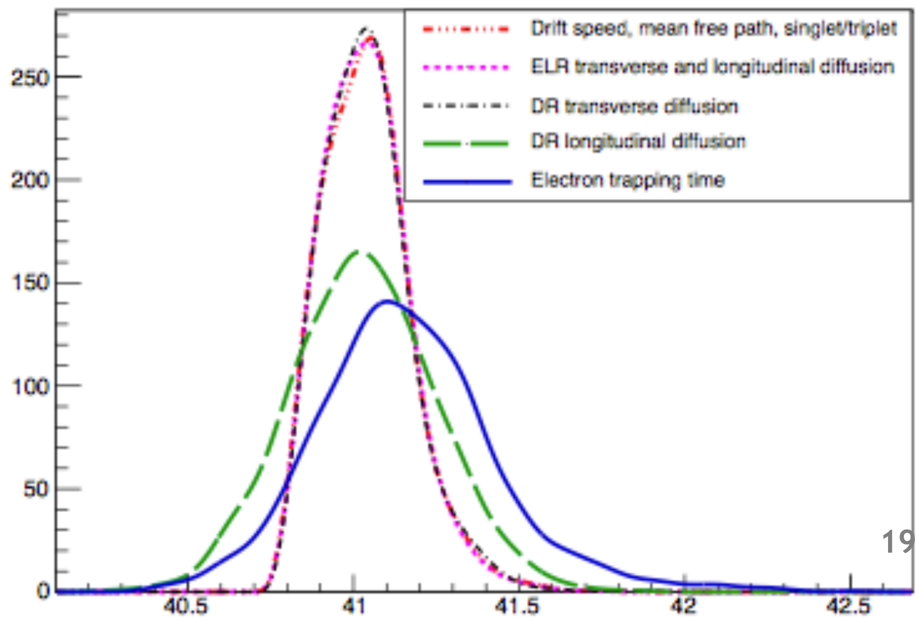


Singlet lifetime	3.1 ± 0.7 ns
Triplet lifetime	24 ± 1 ns
Singlet/Triplet - ER from direct excitation (γ induced)	0.17 ± 0.05
Singlet/Triplet - ER from recombination (γ induced)	0.8 ± 0.2
Singlet/Triplet - ER from both processes (α induced)	2.3 ± 0.51
Singlet/Triplet - NR (neutron induced)	7.8 ± 1.5

* S1 Pulse Shape

S2 Pulse Shape





XENON10 data (Sorensen 2008)

Model (0 or 1 free parameter):
Without e- extraction delay
With extraction delay at L/GXe

* Can input various electron effects into simulation to get increasingly accurate picture of S2 signal shape in time (NEST aims for full detector sim, for everyone)
* We can (crudely) model the absolute yield of UV photons produced in the gas gap of a XeTPC per successfully extracted electron vs. field

* Conclusions

* Dark matter is probably there, and there is a fairly agnostic way to directly look for one candidate, WIMPs, by waiting for nuclear recoils to produce a signal, while electron recoils are the main background
* Two-phase XeTPCs are a great way to look for WIMPs
* NEST is an ever-evolving codebase/software and corresponding collection of semi-empirical models that works really well not only for incorporating old data, but for predicting new results *a priori* and designing new experiments with careful simulation
* In near future, switching gears to quantum chemistry, atom by atom, closer to first-principles approach

NEST

*Questions?