

The *Noble Element Simulation* Technique (**NEST**) at the University at Albany

SUNY Department of Physics

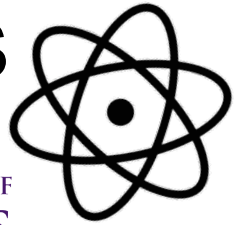


UALBANY

(NOT covering the snowball chamber –
it was co-invented w/ Prof. Cecilia Levy;
it's like the cloud & bubble chambers)



DEPARTMENT OF
PHYSICS
UNIVERSITY AT ALBANY
STATE UNIVERSITY OF NEW YORK



Matthew Szydagis

Oct. 23, 2026

CPAD in Seattle

Thank You!

(sorry I was not here all week! Travel for LZ...)

- I'm honored to receive this award. This recognition unexpected
 - I could not have done it without the work of a GREAT MANY individuals (listed at the end here)
 - My postdoc mentor Mani Tripathi of UCD (here this week) requires a specific shout-out
- I also thought I had too many gray hairs to be considered “early” career still
(warning: I am a very non-linear presenter, but I think unrelated to age!)
- As the founder/creator of the software, and leader/spokesperson, of a real, separate collaboration (from LZ, LUX, etc.) like the GEANT4 (software-only) collaboration, I acknowledge that nothing would have been possible without community support
 - Especially in the face of severely limited funding, even for sims (~cheap!)

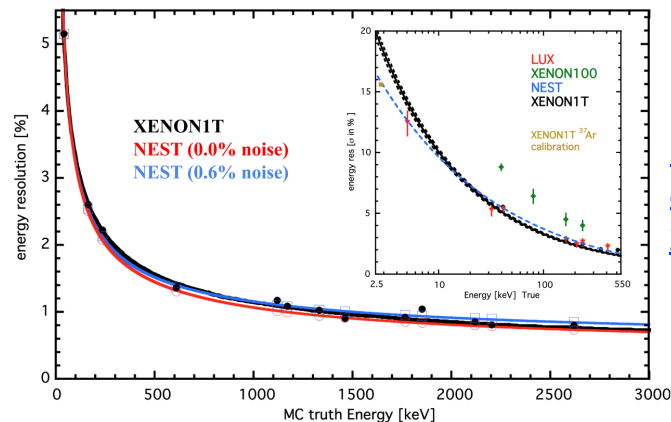
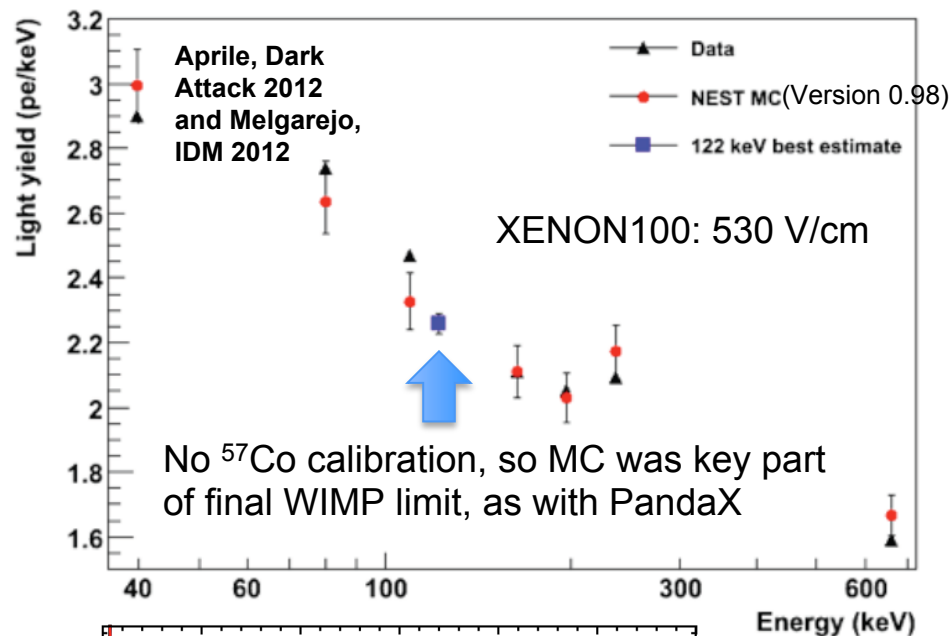
What is **NEST**? Motivated by Discovery Science in **HENP**

(I pushed for @Snowmass)

- Software: the Noble Element Simulation Technique, created at UC Davis
 - Available on GitHub: <https://github.com/NESTCollaboration/nest> Don't re-invent the wheel!
- Monte Carlo simulation package for dark matter (direct WIMP detection) as well as neutrino experiments (but not limited to them: PET too)
 - Xenon and Argon (some approximations for other elements in place too), liquid and gas (sometimes other phases too like solid and super-critical fluid!)
 - Single and dual-phase TPCs / non-TPC detectors: both non-zero and zero drift electric fields
- Particle types: not just ER (electron recoil) and NR (nuclear recoil)
 - ER is split into beta and gamma as well as EC and DEC and other types
 - Alpha and ion yields, some hypothetical but others experimentally verified
 - Custom energy spectra possible, like uniform, exponential, and Gaussian
- Light and charge yields as functions of field, energy, and interaction type
 - But also pulse shapes, for primary (S1) and secondary (S2) scintillation: time profiles

More Factoids

- Not entirely empirical: it has made successful predictions
 - Not just post-dictions or ad-hoc fits
 - Not perfect, but treat as your first pass
- NEST helped lead to a breakaway from relative yields for ER and NR and empirical-only calibrations
- Not tied to only LZ / its predecessors: used by all, informed by all
- It doesn't just do mean yields
 - It does energy resolution
 - Width models for both S1 and S2
- Mentioned in the PDG Review
 - For instance: in 2022-23
 - <https://pdg.lbl.gov/2023/reviews/rpp2022-rev-particle-detectors-non-accel.pdf>

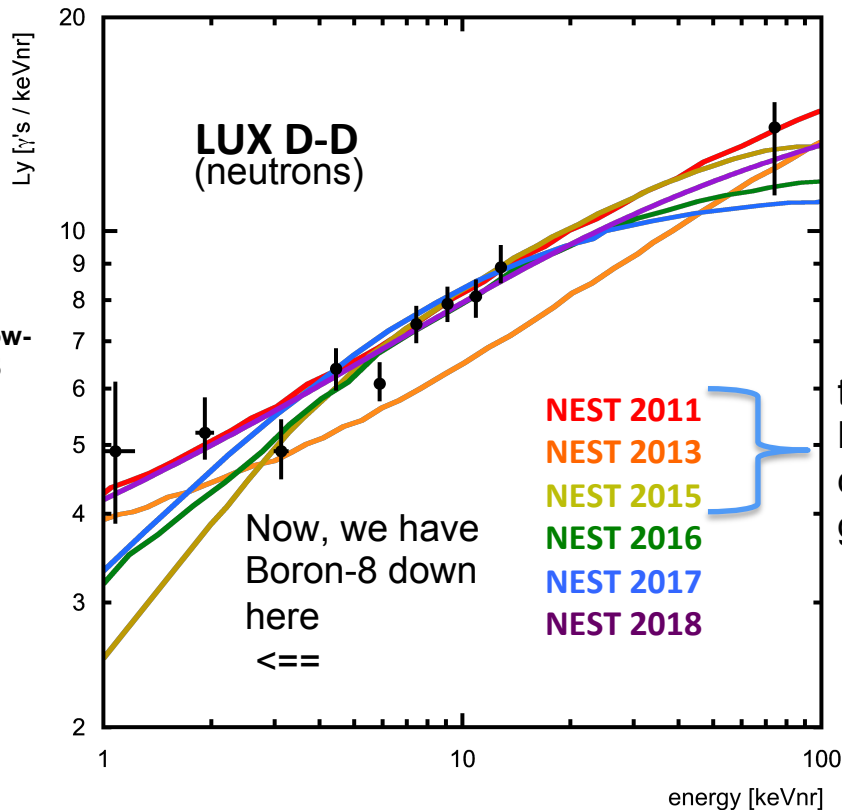


<https://arxiv.org/pdf/2007.00528>

Sample of Past History SEMI-empirical. Emphasis on the SEMI

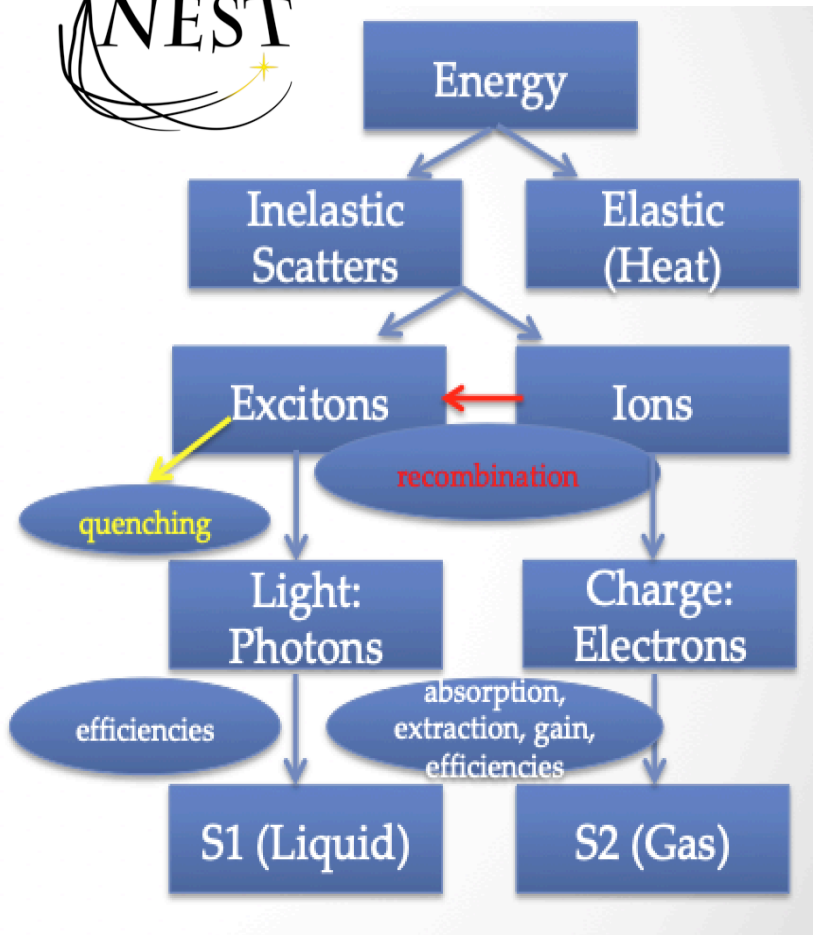
- Nuclear recoil light yield vs. energy at low E-fields
 - Systematics not included in plot
- NEST based on data, but does not entirely ambulance-chase
 - There was a little bit of that To be conservative on low-mass WIMPs: 2013, 2015
 - Major early NEST contribution was Co-57 absolute S1 light yield
- Should've stuck to guns (Lindhard-motivated) with Peter S. and Eric D.
 - Came full circle over 7 years, but always within a couple of sigma of the LUX D-D

Stability Over Time >> Ambulance Chasing



A traditional WIMP signal is exponential-like, so even for medium to high masses, the region below 10 keV is the MOST important to model for potential signal events

The charge yield is a similar great story except for the sub-keV regime: was pressured



NEST's Very Precise Modeling

<https://arxiv.org/pdf/2211.10726.pdf>

$$W_q [eV] = 21.94 - 2.93\rho = \frac{W_i}{1 + N_{ex}/N_i}$$

$$N_{ex}/N_i = (0.0674 + 0.0397\rho) \times \text{erf}(0.05E)$$

$$N_{ph} = [N_{ex} + r(E, \mathcal{E}, \rho)N_i] = S1 / g_1 \quad \text{and} \quad N_{e^-} = [1 - r(E, \mathcal{E}, \rho)]N_i = S2 / g_2$$

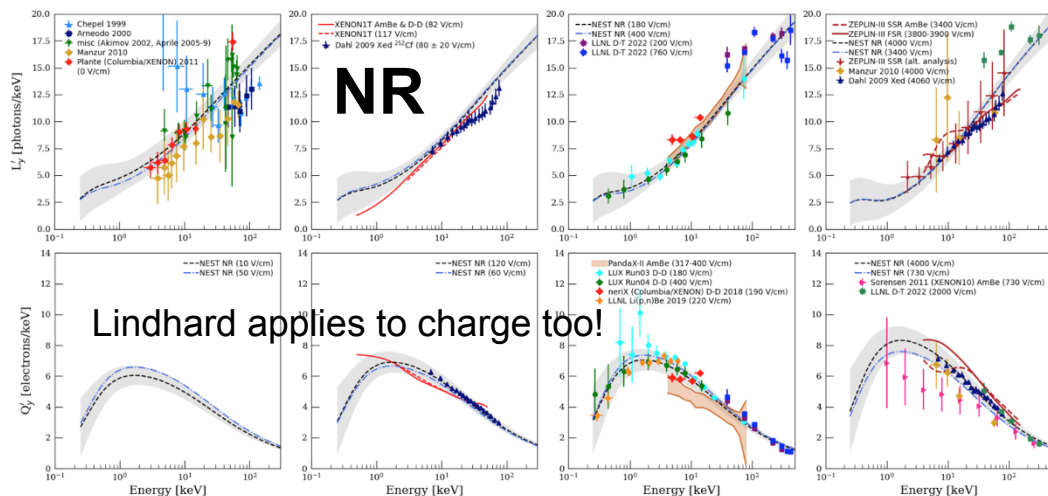
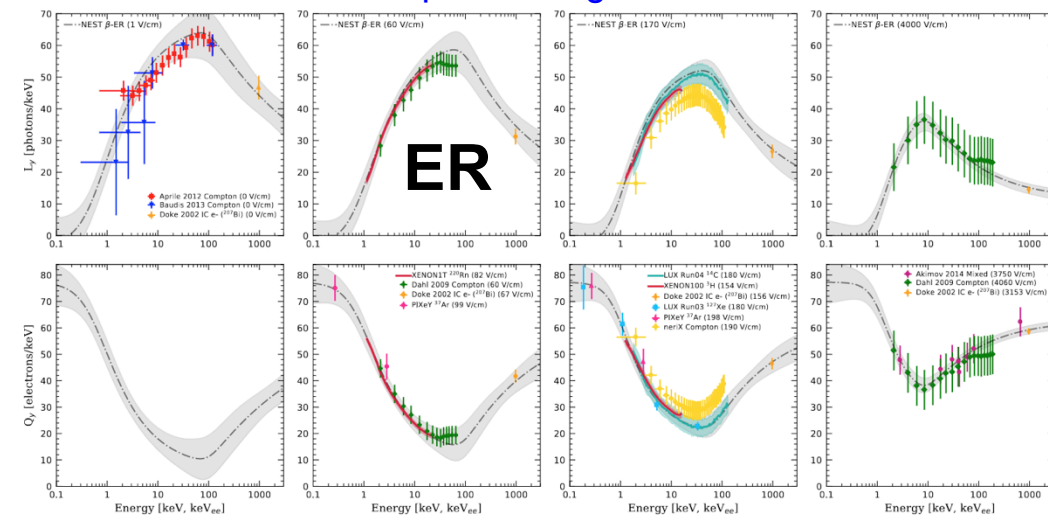
$$N_q \equiv N_{ex} + N_i = N_{ph} + N_{e^-} = E / W_q, \quad \text{where} \quad N_{e^-} = Q_y E, \quad \text{and} \quad N_{ph} = N_q - N_{e^-}$$

$$Q_y(E, \mathcal{E}) = m_1(\mathcal{E}) + \frac{m_2 - m_1(\mathcal{E})}{[1 + (\frac{E}{m_3(\mathcal{E})})^{m_4(\mathcal{E})}]^{m_9}} + m_5(\mathcal{E}) - \frac{m_5(\mathcal{E})}{[1 + (\frac{E}{m_7(\mathcal{E})})^{m_8}]^{m_{10}(\mathcal{E})}} \quad \text{(Electron Recoils, ER)}$$

$$N'_q = aE^b, \quad \text{where} \quad a = 11^{+2.0}_{-0.5} \quad \text{and} \quad b = 1.1 \pm 0.05$$

(Nuclear Recoils, NR: primed variables here)

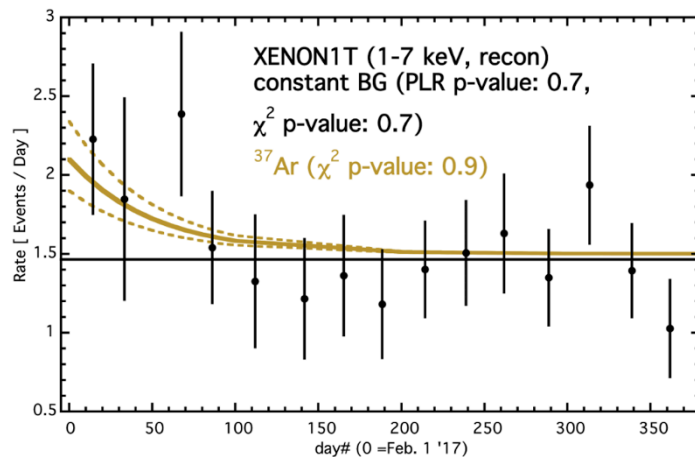
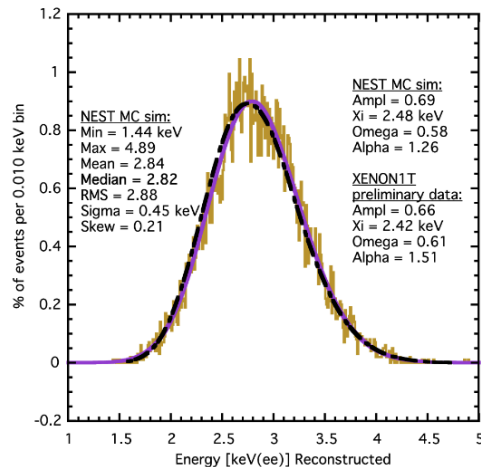
$$Q'_y(E, \mathcal{E}, \rho) = N_{e^-} \text{ per keV} = \frac{1}{\varsigma(\mathcal{E}, \rho)(E + \epsilon)^p} \left(1 - \frac{1}{1 + (\frac{E}{\varsigma})^\eta} \right)$$



Lindhard applies to charge too!

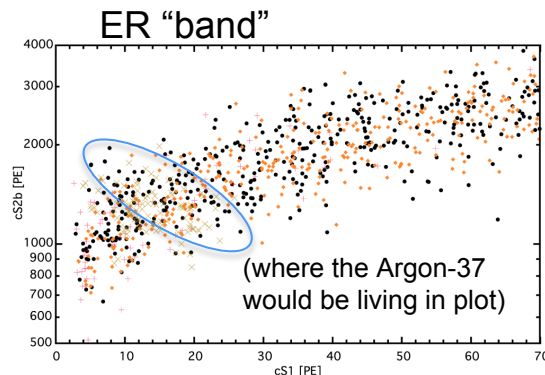
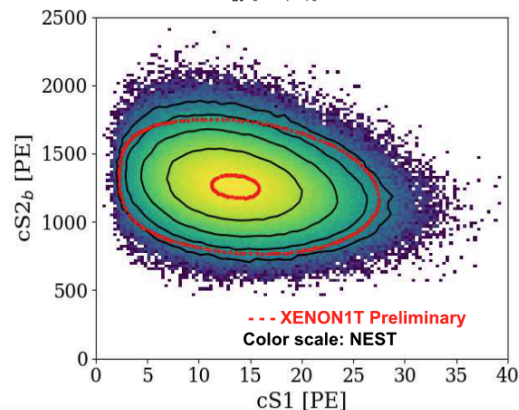
- Betas and Compton scatters shown as examples for ERs
 - *Yields for gamma or x ray photoabsorption a bit different*
- The two sigmoids model two distinct regimes in energy
 - The Thomas-Imel (low) and Doke/Birks (high- E) regions
- The field dependence is very obvious reading horizontally
 - Anti-correlation exists in energy as well, when reading vertically
- Light yield for NRs roughly monotonic with increasing E
- Charge yield has a maximum
 - Competition between quenching factor and recombination prob.

Mimicry of Real Data w/ NEST • It was useful for testing a potential signal!



- NEST matched 1T's data very well even *cf.* to XENON1T sims
- It models non-LZ work quickly, down to energy resolution

<https://arxiv.org/abs/2007.00528>
-> Phys. Rev. D



(XENON1T story) *The New York Times*

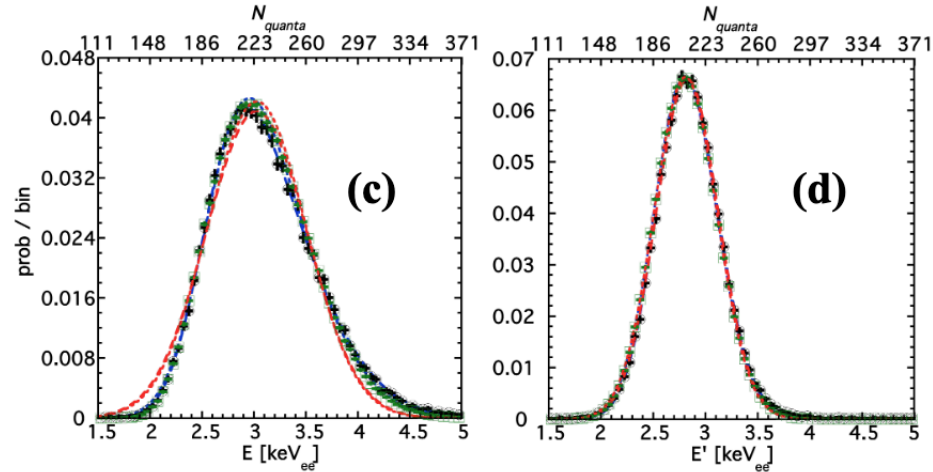
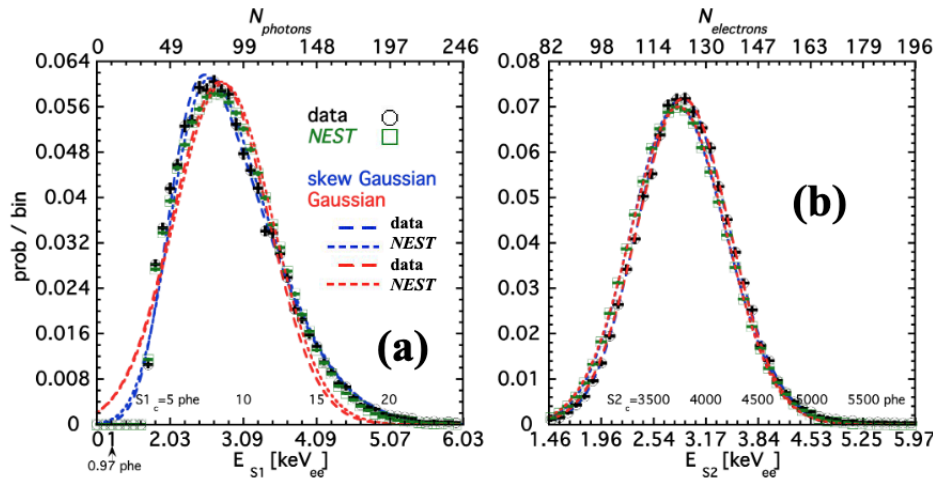
Important: XENON says this is impossible, they ruled out Ar-37

OUT THERE

Seeking Dark Matter, They Detected Another Mystery

Do signals from beneath an Italian mountain herald a revolution in physics?

They said all along it was tritium



<https://arxiv.org/pdf/2102.10209.pdf>

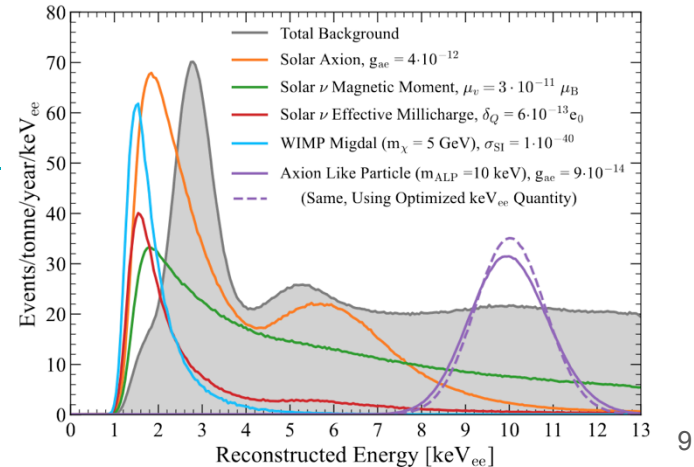
A Newer E Recon. Technique

(cite score 2.6)

- NEST Instruments paper (36 mos.)
 - #4 most cited (from 314 papers, all fields)
 - #5 most viewed (4,817 views).
 - #6 most downloaded (1,109 downloads, competing with DUNE's CDR!!!!!! 1,474)
- Part of special collection. NEST paper on E resolution and reconstruction, in LAr too (including in DUNE) + for $0\nu\beta\beta$ decay

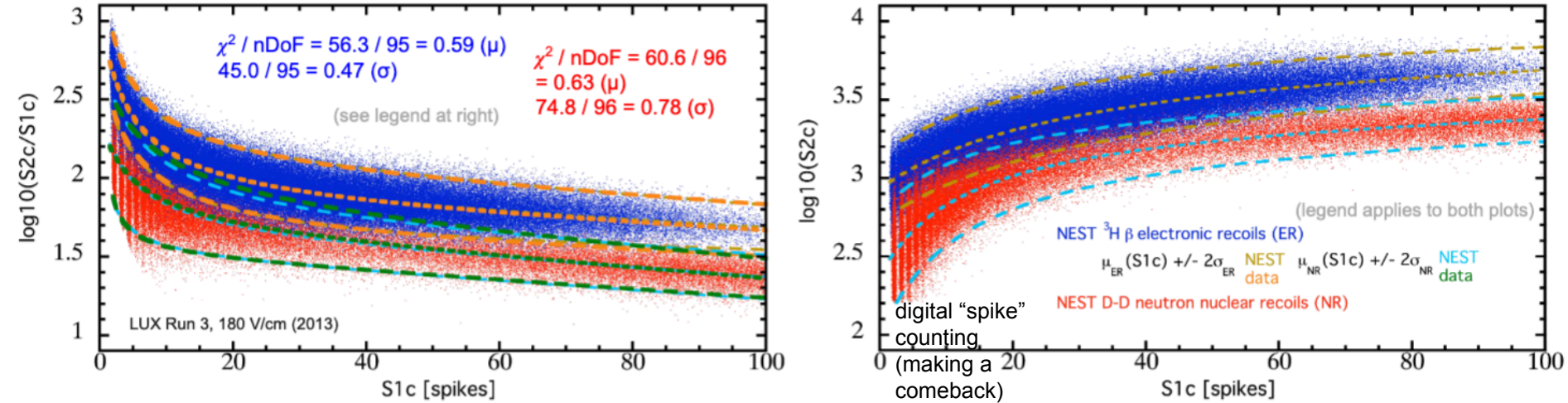
<https://arxiv.org/pdf/2307.15753.pdf>

First usage by a major experiment (LZ)



Continuous Data: Beta Spectrum and Neutron Recoil 'BANDS'

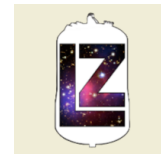
- * S1 pulses come from the L_y : namely, $S1 = g_1 * N_{ph}$, where $N_{ph} = L_y$ times energy, and g_1 is photon det. eff.
- * S2 pulses come from the Q_y : namely $S2 = g_2 * N_{e-}$, where $N_{e-} = Q_y$ times energy, and g_2 is a gain factor (>1)



NEST loads a fully customizable detector parameter file for your detector. A huge number of parameters, but most important are g_1 , g_2 , N -fold coincidence level (photo-sensors), and field

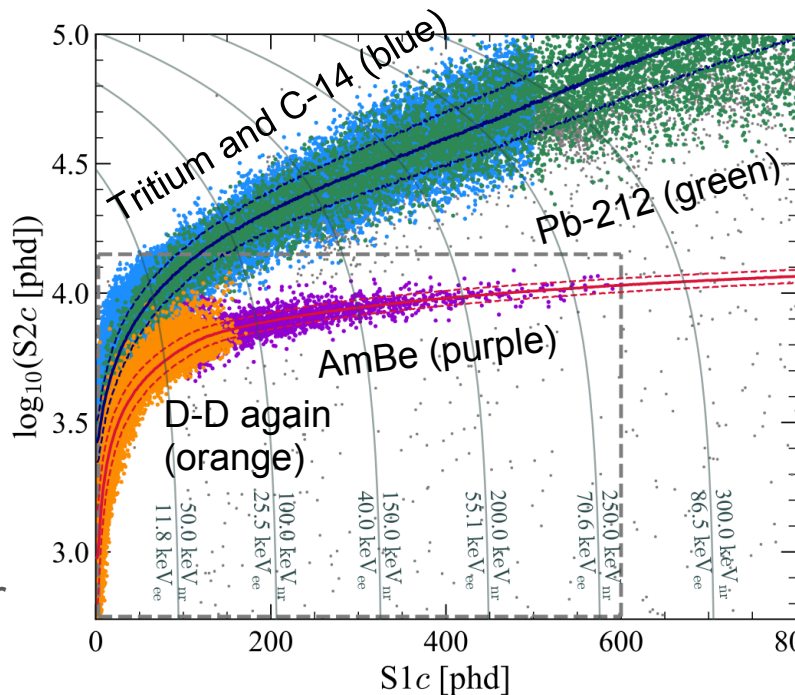
- g_2 must be broken down into its stages (<https://iopscience.iop.org/article/10.1088/1748-0221/15/02/T02007/pdf>)

Recent LZ Result: Big <https://arxiv.org/pdf/2609.02823>



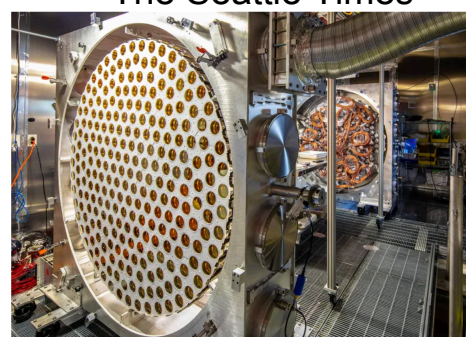
- NEST was critical in nailing the ER and NR band means and widths

- MC sims & calibration working together in a symbiotic relationship
- NEST did need tweaking for EC, DEC



Scientists hunting dark matter found something strange

Sept. 1, 2026 at 7:42 pm The Seattle Times

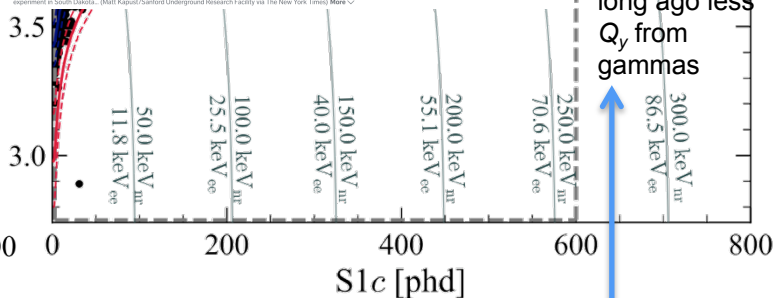


Photomultiplier tube arrays being prepared for the LZ Dark Matter Experiment at the Sanford Underground Research Facility in Lead, S.D. A lone signal from an experiment in South Dakota... (Matt Kaput/Sanford Underground Research Facility via The New York Times) More >

Also in the NYT!

What are these points below the beta band?

NEST predicted long ago less Q_β from gammas



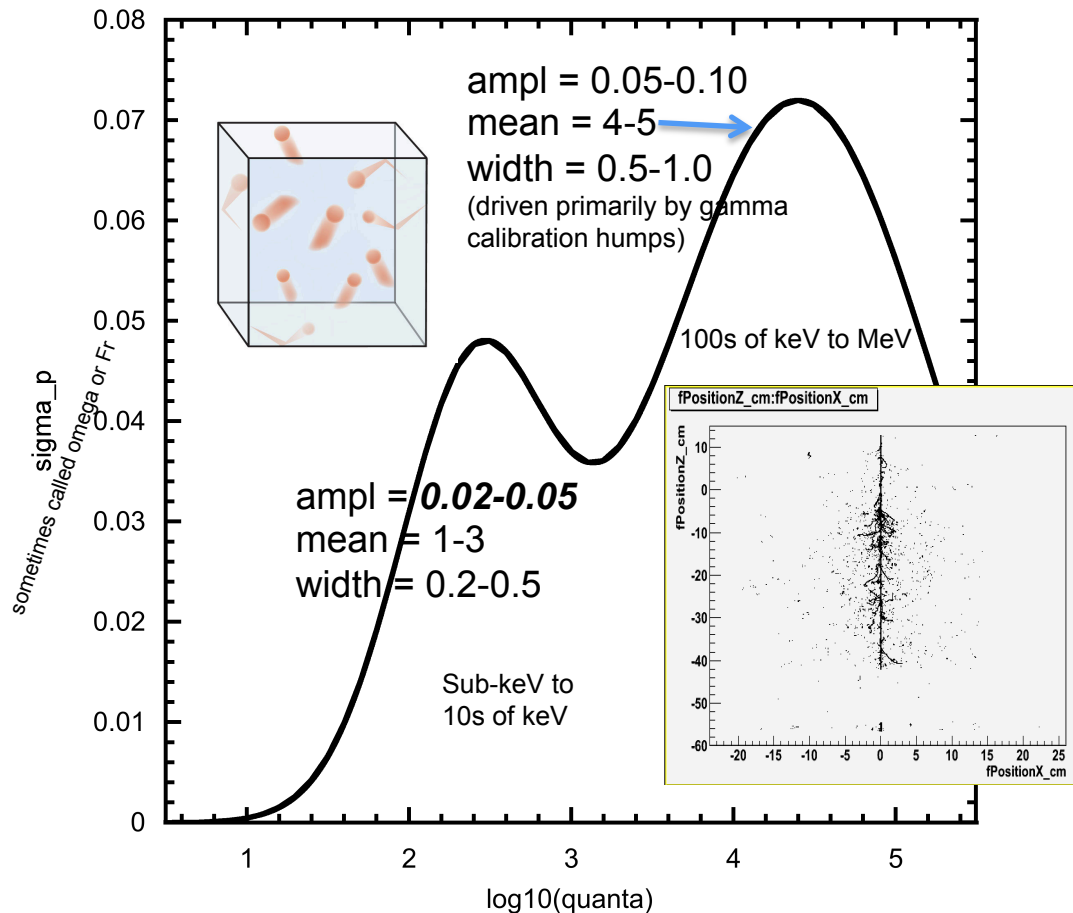
<https://link.aps.org/doi/10.1103/447w-94h3> (LZ PRD)

GdLS is CRITICAL to LZ!

Going back in time to

<https://arxiv.org/abs/1307.6601>

NEW Dual Skew Gaussian for Recombination Fluctuations

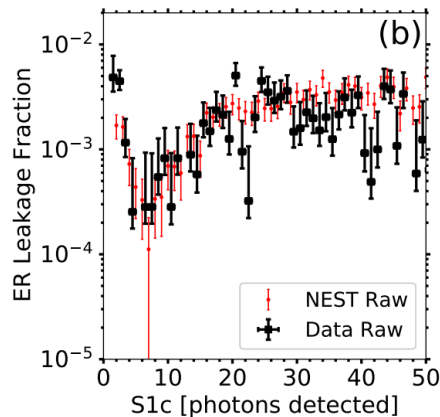
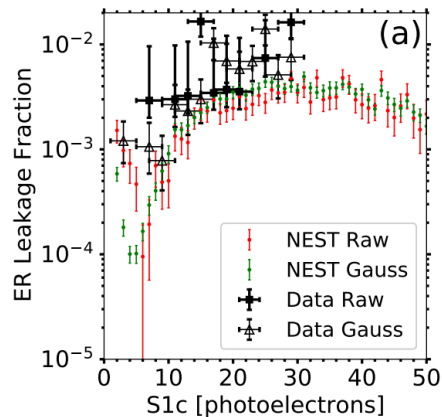


- The width of the ER band for a dark-matter search region driven primarily by that first peak
 - Famously non-binomial in LXe
- But.. we care about higher energies now! (EFT, HENR)
- NEST did ignore a known problem for years, on S1 and S2 resolutions
 - Because, for mono- E bumps, the combined- E scale hides problem
- Empirical-only patch for now but we'll circle back to first principles eventually
 - Likely explanation: boxy and cylindrical tracks (T-I and Doke)

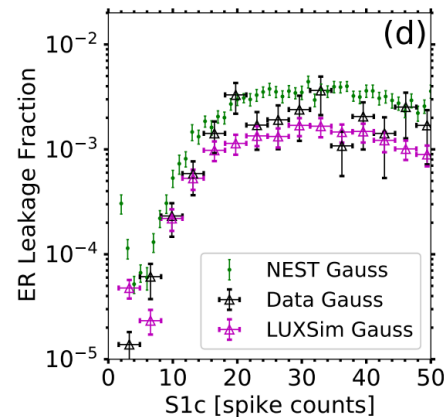
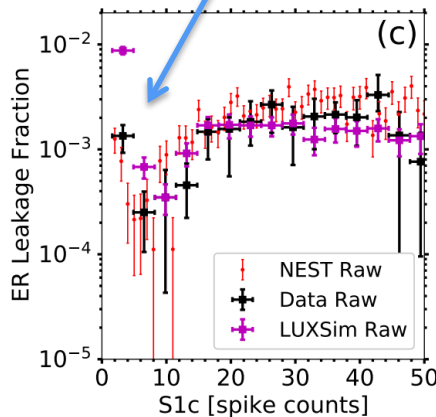
Leakage Dependence at Low-Energy Pulses

arXiv:2211.10726 (v3)

- Based only on last model's lower-energy peak. Signal (NR) vs. BG (ER)
- As a function of S1 or energy, the NR and ER bands start in a fuzzy overlap, then separate, then “kiss” at medium energies, and then separate hugely



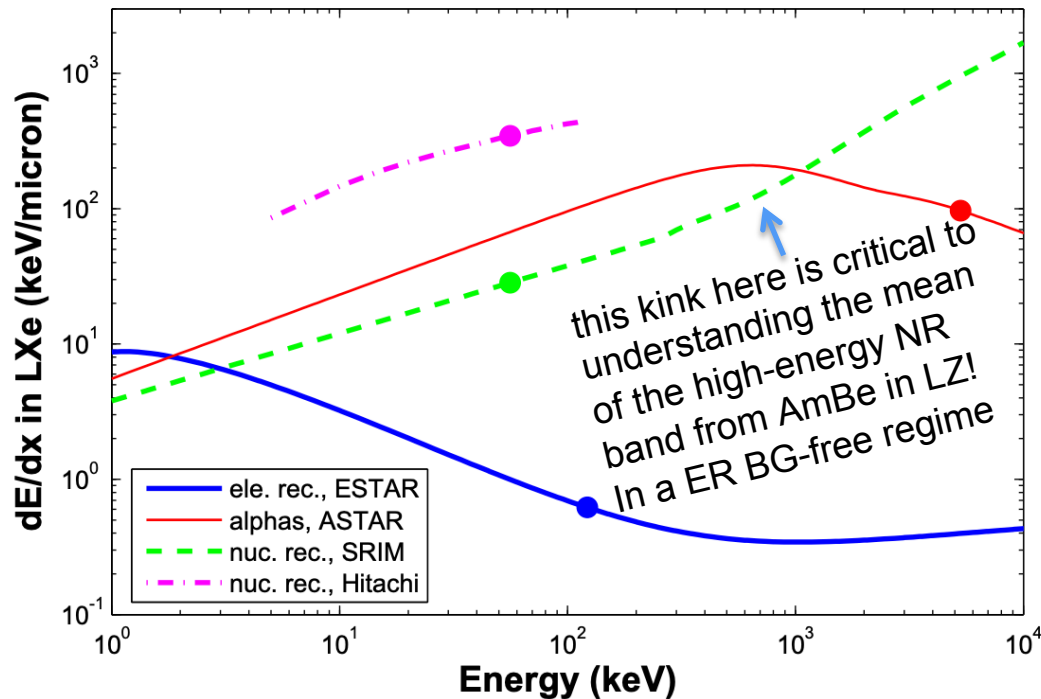
The checkmark shape was a prediction (pre-LUX)
Naïve extrapolation was wrong



Another Tweak: But an Old Paper NEST Based on Helped!

<https://inspirehep.net/literature/709143>

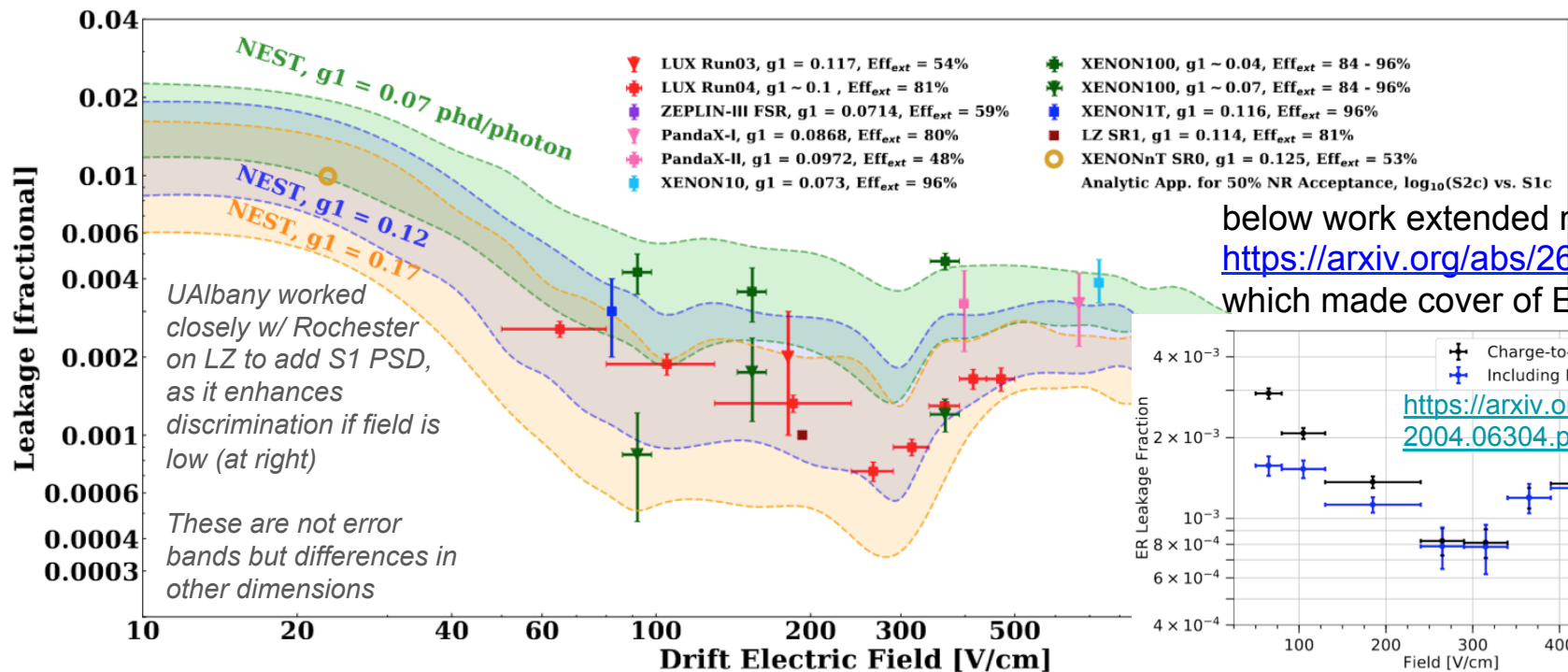
Aprile et al. landmark study in PRL proving NRs observable



- Forgotten plot at end of an important paper with much more significant plots, based on real data
- Until EFT operator-based searches, no one cared about $O(100 \text{ keV}_{\text{nr}})$ in Xe
 - So, this was a low priority for NEST as well
- But, no need to add fudge factors or kludges: existing NEST functions and parameters workable

The Future of LXe: Key Plot From the Latest NEST Paper

Each point in it is an average over an S1 range (see Slide 13)



below work extended now in <https://arxiv.org/abs/2603.26877>, which made cover of EJPC!

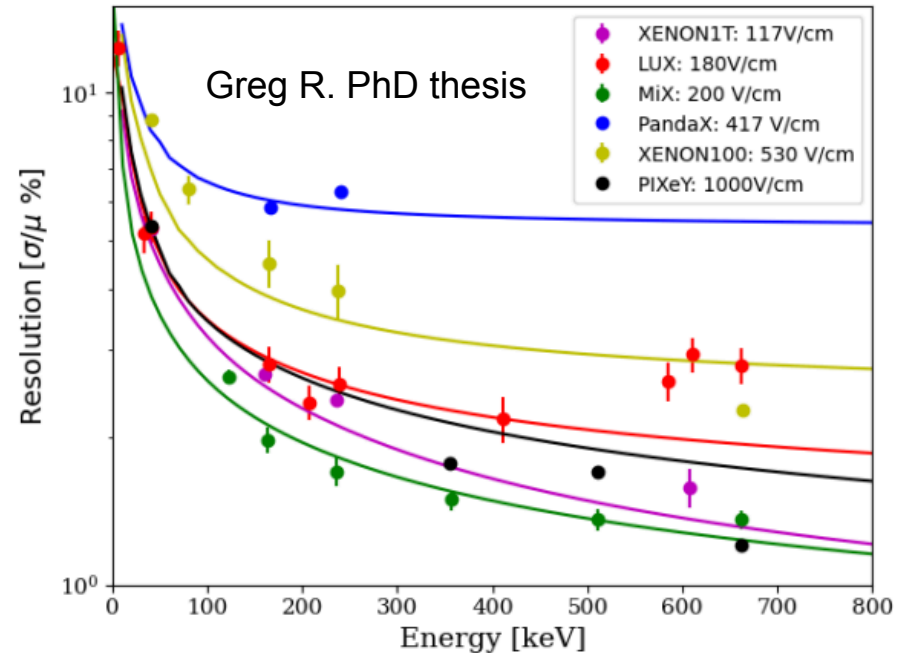
PSD = Pulse Shape Discrimination (S1)

Work carried forward from LUX -> LZ

- Band widths for continuous spectra, mono- E peak resolutions from γ photo-absorption contain the same contributions
 - from the LXe “microphysical” details
- Correlated “noise”
 - Energy and density-dependent Fano factor F_q applied to the total quanta
- Anti-correlated fluctuations
 - Excitations and recombination
- Uncorrelated noise
 - Known: g1 and the g2 “family”
 - Unknown: linear Gaussian terms
- Over-reliance on the unknown terms has been going down and down over the years to $\sim 0\%$
 - but E -dep. Fano still seems real and necessary to include

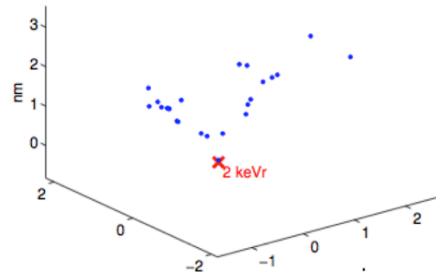
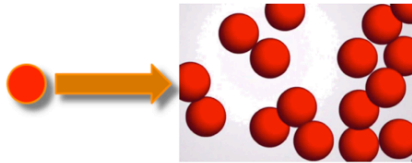
Back to Monoenergetic Peaks

<https://scholarsarchive.library.albany.edu/cgi/viewcontent.cgi?article=4005&context=legacy-etd>

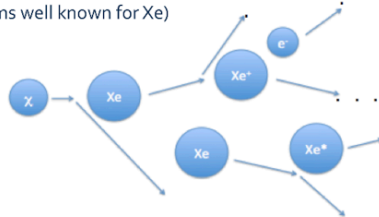


LZ seems to have hit the bottom: lowest energy res. at $Q_{\beta\beta}$ 16

The Future of the Noble Element Sim Technique NEST



(12-6 LJ van der Waals
terms well known for Xe)

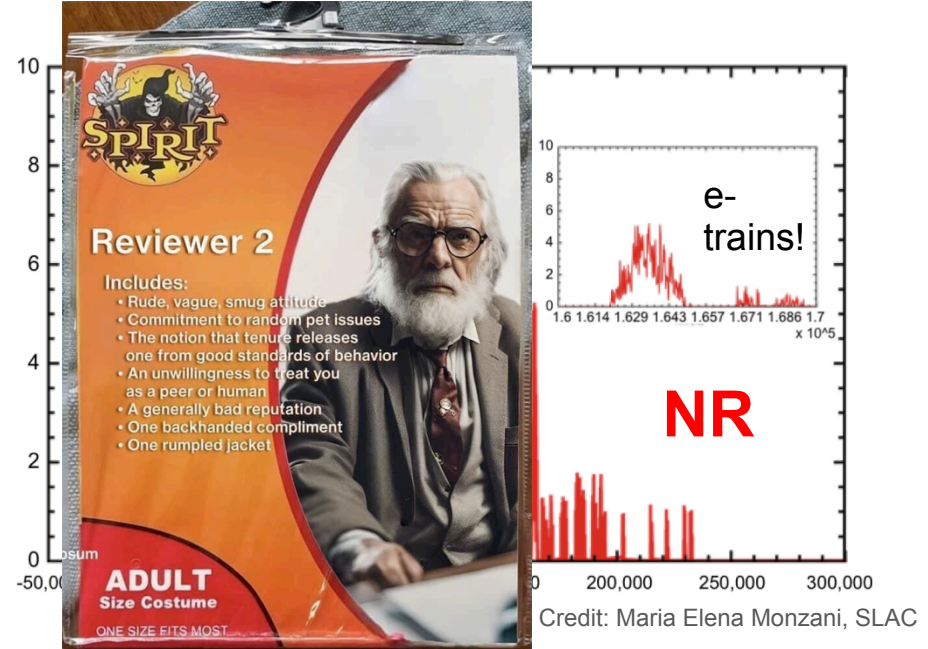
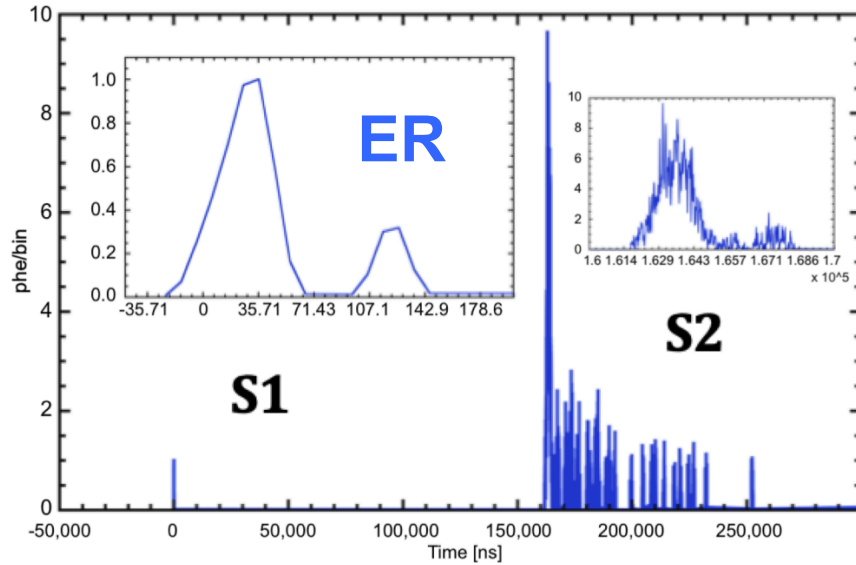


- + Currently based upon empirical models
 - + Doke/Birks' Law, Thomas-Imel box model of recombination, Lindhard, SRIM, Bezrukov, Mei & Hime, Sorensen & Dahl
- + Digging deeper into first principles
 - + Molecular dynamics (MD), DFT, Hartree-Fock, quantum chemistry calculations
- + Collaborate with condensed matter theorists and nuclear physics theorists
 - + Do real cross-section calculations for elastic and inelastic scatters (excitation, ionization), and electron recapture

I unfortunately never have time to get to this!

DFT =
Density
Functional
Theory

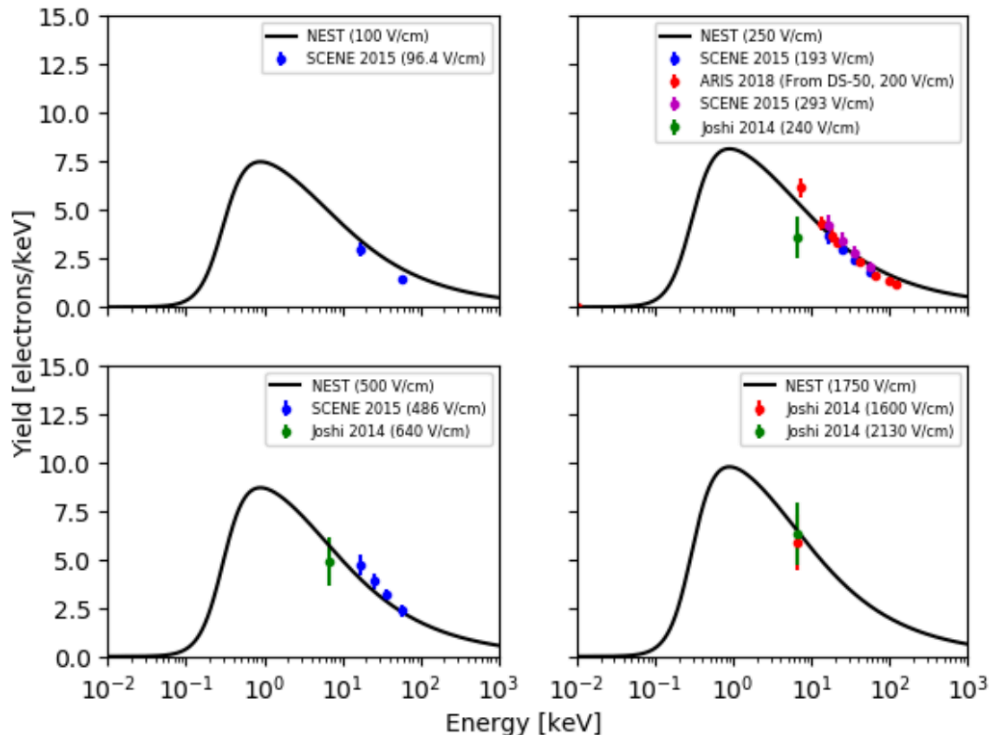
Pulse Shapes in the Here and Now: The Forgotten Feature



- This is built upon earlier work: <https://iopscience.iop.org/article/10.1088/1748-0221/9/04/T04002> (newer not published, like leakage plots. Why?)

I Never Have The Time to Cover Liquid Argon (+GXe, etc.)

On the total opposite end of energy from this: we absolutely do have models useful for DUNE. Data from ICARUS reproduced in Instruments paper



- Choosing only these plots to show: Qy at low energies
 - Relevant to S2-only searches for low-mass WIMPs
- Call to action: still waiting on DarkSide to try out NEST
- In addition to informal note on site (https://docs.google.com/document/d/1vLg8vvY5bcdl4Ah4fzyE182DGWt0Wr7_FJ12_B10ujU/edit?tab=t.0) we have paper

<https://doi.org/10.3390/instruments5010013>

Charge Yield Equations: Retroactively Justified / Validated

in NEST Frontiers paper

- Perfect example of cross-pollination: This came from grabbing ideas from LAr modeling for ER in DUNE, seriously! Being used for WIMP quest in LXe NRs!

(' is NR, not ER) modified Thomas-Imel box model of recombination from LArIAT

$$Q'_y = \frac{N_{e-}}{E} = (1-r) \frac{N_i}{E} = \frac{\ln(a' + \xi)}{\xi} \frac{N_i}{E} = \frac{\ln(a' + \xi)}{\xi} \frac{N_q/E}{1 + \alpha_x} = \frac{\ln(a' + \xi)}{\xi E} \frac{aE^b}{1 + \alpha_x}$$

$$dE/dx = \beta' \epsilon_Z^{0.5} = 120\sqrt{\epsilon_Z} = 120\sqrt{0.001E} = 120\sqrt{0.001}\sqrt{E} = 3.8\sqrt{E} \quad \text{see the 2005 dE/dx plot from earlier!}$$

$$Q'_y \approx 5 \frac{\ln(1 + \varsigma \frac{dE}{dx})}{\varsigma \frac{dE}{dx}} = 5 \frac{\ln(1 + 0.036 \cdot 3.4 \sqrt{E + 12.6})}{0.036 \cdot 3.4 \sqrt{E + 12.6}} = \frac{5}{3.4} \frac{0.677}{\varsigma \sqrt{E + \epsilon}} = \frac{1}{\varsigma \sqrt{E + \epsilon}}$$

At the end: this is where NEST empirical charge model for NR started

THIS SHOWS THAT EVEN EQUATIONS ORIGINALLY CONSIDERED 100% EMPIRICAL WERE PHYSICAL
This has happened many times (like power-law L -factor for total quanta in NR: consistent with a power of 1.0)

Past and/or Present Contributors to NEST

no particular order!

- Jon Balajthy
- Grant Block
- Jason Brodsky
- Ethan Brown
- Jacob Cutter
- Sophia Farrell
- Junying Huang
- Alvine Kamaha
- Yung Nok Lau
- Ekaterina Kozlova
- Chloe Liebenthal
- Daniel McKinsey
- Kirsten McMichael
- Ryan McMonigle
- Michael Mooney
- Justin Mueller
- Kaixuan Ni
- Greg Rischbieter
- Kian Trengove
- Mani Tripathi
- Chris Tunnell
- Vetri Velan
- Shawn Westerdale
- Madison Wyman
- Min Zhong
- Zehong Zhao
- Cecilia Levy
- Greg Blockinger
- Nishat Parveen
- Collin Farquhar
- Alex Flesher
- Emily Mangus
- Andrew Schwartz
- Brian Lenardo
- Kareem Kazkaz
- Aaron Manalaysay
- Jeremy Mock
- Nichole Barry
- Sergey Uvarov
- Michael Woods
- Nicholas Walsh
- Adalyn Fyhrie
- Daniel Thorngren
- Richard Ott
- James Morad
- Jamison Blanchard
- Augustine Zhao
- Robert Svoboda
- Melinda Sweany
- Evan Angelico
- Dustin Stolp
- Jacob Pasner

Past and/or Present Contributors to NEST (Many on LZ!)

- Attila Dobi
- Maria Elena Monzani
- Quentin Riffard
- Luke Kreczko
- Paola Ferrario
- Albert Baker
- Sky Shi
- Scott Kravitz
- Ryan Linehan
- Vladislav Soshnikov
- Robert James
- Yanina Biondi
- Lukas Gerritzen
- Noah Everett
- Dacheng Xu
- Lanqing Yuan
- Pierce Comerford
- Chami Amarasinghe
- Alberto Uson
- Olga Razuvaev
- Sam Eriksen
- Nicholas Carrara
- Michael Mulhearn
- Sebastian Vetter
- Joran Angevaare
- ...people I missed!

Publications

- <https://arxiv.org/abs/1106.1613>
 - <https://doi.org/10.1088/1748-0221/6/10/P10002> (peer-reviewed version of record: JINST)
- <https://arxiv.org/abs/1307.6601>
 - <https://doi.org/10.1088/1748-0221/8/10/C10003> (JINST conference proceedings)
- <https://arxiv.org/abs/1310.1117>
 - <https://doi.org/10.1088/1748-0221/9/04/T04002> (JINST “technical paper”)
- <https://arxiv.org/abs/1412.4417>
 - <https://doi.org/10.1109/TNS.2015.2481322> (Transactions in Nuclear Science)
- <https://arxiv.org/abs/2007.00528>
 - <https://doi.org/10.1103/PhysRevD.103.012002> (Physical Review D)
- <https://arxiv.org/abs/2102.10209>
 - <https://doi.org/10.3390/instruments5010013> (MDPI Instruments)
- <https://arxiv.org/abs/2211.10726>
 - <https://doi.org/10.3389/fdest.2024.1480975> (Frontiers in Detector Science)

Conclusion



“People who say it cannot be done, should not interrupt those who are doing it”

— **Bernard Shaw**

(this quote is a huge inspiration of mine)

(sadly, I don't have that car nor license plate any longer!!)