Latest Development of the Noble Element Simulation Technique (NEST)

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On behalf of the NEST Collaboration
https://nest.physics.ucdavis.edu

Sep. 23, 2022, LIDINE 2022

What is NEST?

- Noble Element Simulation Technique: an open source software to simulate noble element detectors, which does LXe, GXe, SXe; LAr (preliminary testing)
- Primary parameters: particle or interaction type, E-fields, density or phase, and energy or dE/dx (latter more crucial for Ar, MeV-GeV scale energies: ER)
- Using it means reducing your systematics by relying not only on your own calibration data, but upon **all of those who came before you**.
- Integrated into Geant4 and Garfield++. Other languages: ROOT, Python
- Get the full code here, from GitHub:
  - https://github.com/NESTCollaboration/nest
  - https://github.com/NESTCollaboration/nestpy
- Cite us using Zenodo: https://zenodo.org/record/7061832
- Release tags: https://github.com/NESTCollaboration/nest/tags
  - Most recent version: 2.3.11 has just been tagged (Sep.8, 2022)
    - LZ (SR1) and XENONnT (SR0) detector files included.

Developers from:

Unfunded, but still
REAL collaboration!

NEST

nest.physics.ucdavis.edu

UNIVERSITY AT ALBANY
State University of New York

Rensselaer

Colorado State University

RICE

ITEP

UC DAVIS

Berkeley
UNIVERSITY OF CALIFORNIA

UC San Diego

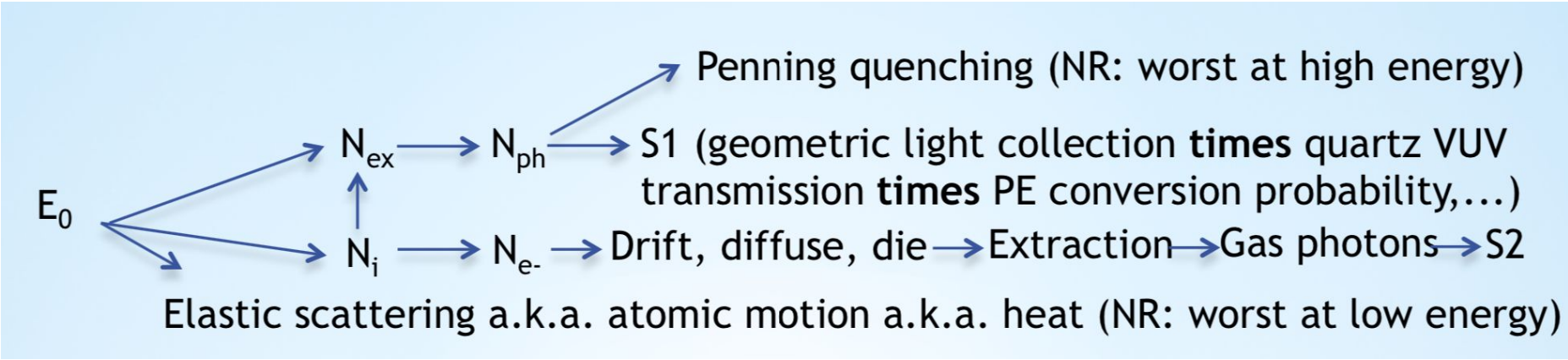
Lawrence Livermore
National Laboratory

- Has reps from XENON1T/nT/LUX/LZ/DARWIN, (n)EXO, RED, DUNE, SBN, MicroBooNE, COHERENT, and CENNS!
- Users from PandaX and DEAP as well to a degree
- Hoping to develop to be useful for NEXT for GXe, DarkSide for LAr

And, What Can It Simulate? Outputs

- **MC capabilities**: growing all the time, with multiple options like G4 (processes)
- **Mean scintillation light and ionization (charge) yields** vs. parameters earlier
- **Energy resolution**: the width in those yields, and their skewness
- **ER/NR discrimination**: leakage of events into signal region, *e.g.* in a WIMP search
- **Pulse timing profiles**, including widths and general shapes: both primary and secondary scintillation. Based on G4Scintillation class, except does ionization
- Built-in calculation of the **efficiency** or **threshold**, and the log10(S2) or S2/S1 band **means** & **widths**
- Basic spin-independent and spin-dependent **WIMP limit calculator** (Feldman-Cousins)
- **Detector effects** like photon detection < 100%, on top of detector-independent aspects such as (ABSOLUTE, not relative) yields
- **Noise**: correlated, anti-correlated, and uncorrelated sources all simulated now

The Microphysics of Energy Partitioning: It is Not Trivial!



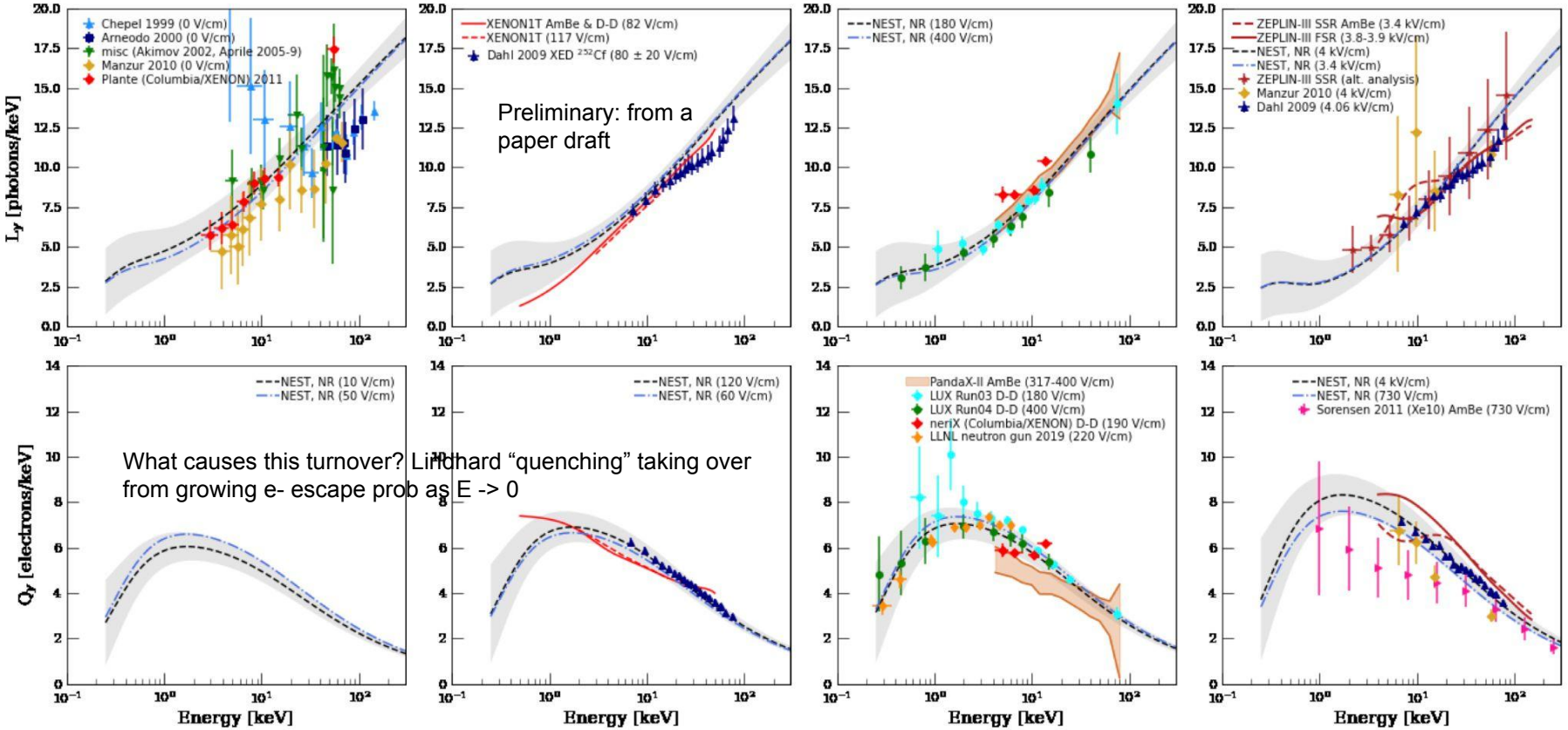
NEST started as a tool to provide a framework (usually referred as **NEST model**) to describe the process, then with global fitting of **all existing calibration data** to obtain parameters, to allow **accurate simulation** for current/future detectors.

- B. Lenardo et al., A Global Analysis of Light and Charge Yields in Liquid Xenon, IEEE Transactions on Nuclear Science (Volume: 62, Issue: 6, Dec. 2015); e-Print: arXiv:1412.4417 [astro-ph.IM and physics.ins-det]
- A paper with updated NEST Model is coming soon!

NR L_y and Q_y

light yields and charge yields

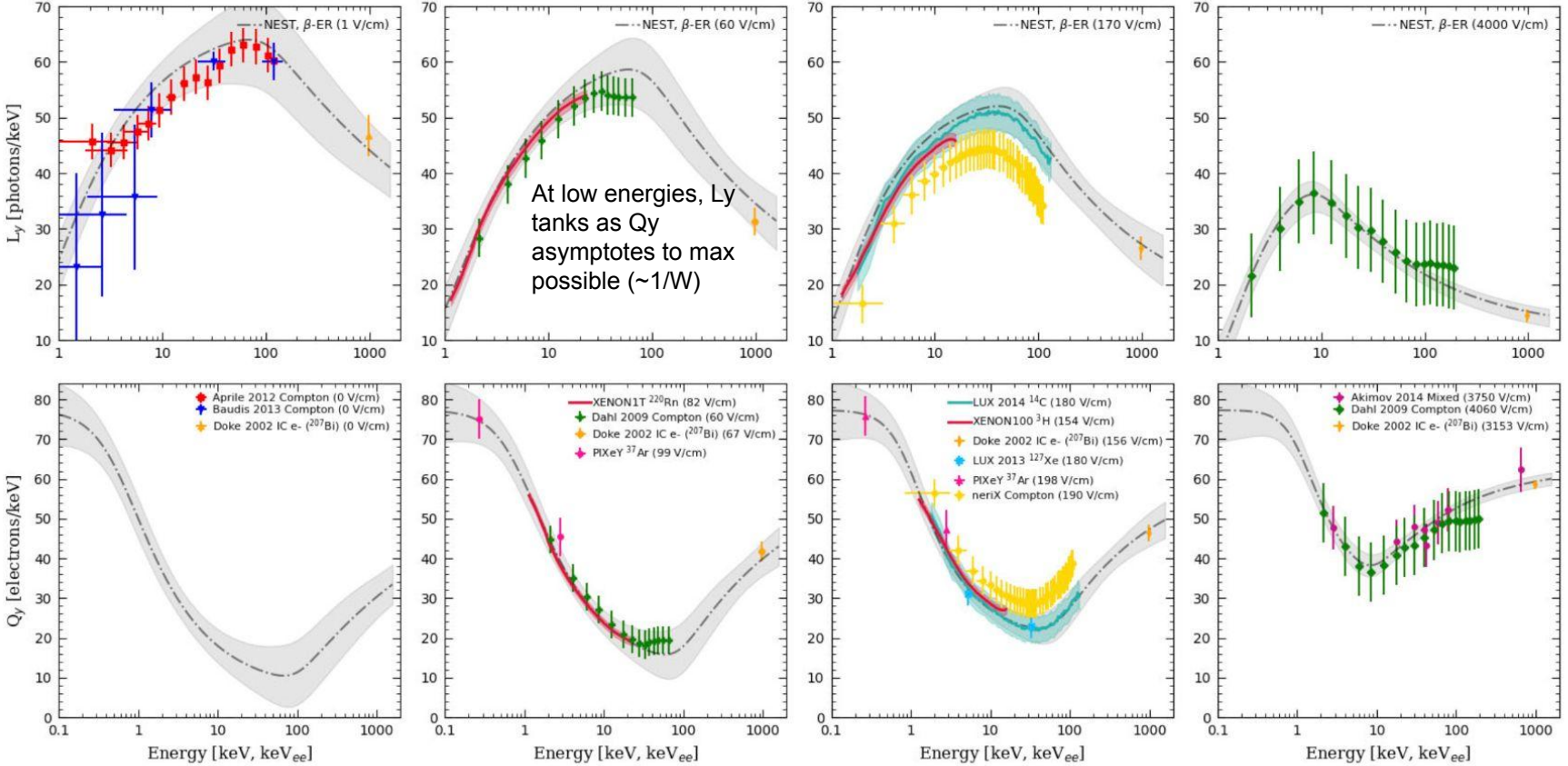
- Threading the needle -- between fully theoretical and fully empirical
- Provide users good defaults, but also great flexibility (customizable)



ER L_y and Q_y

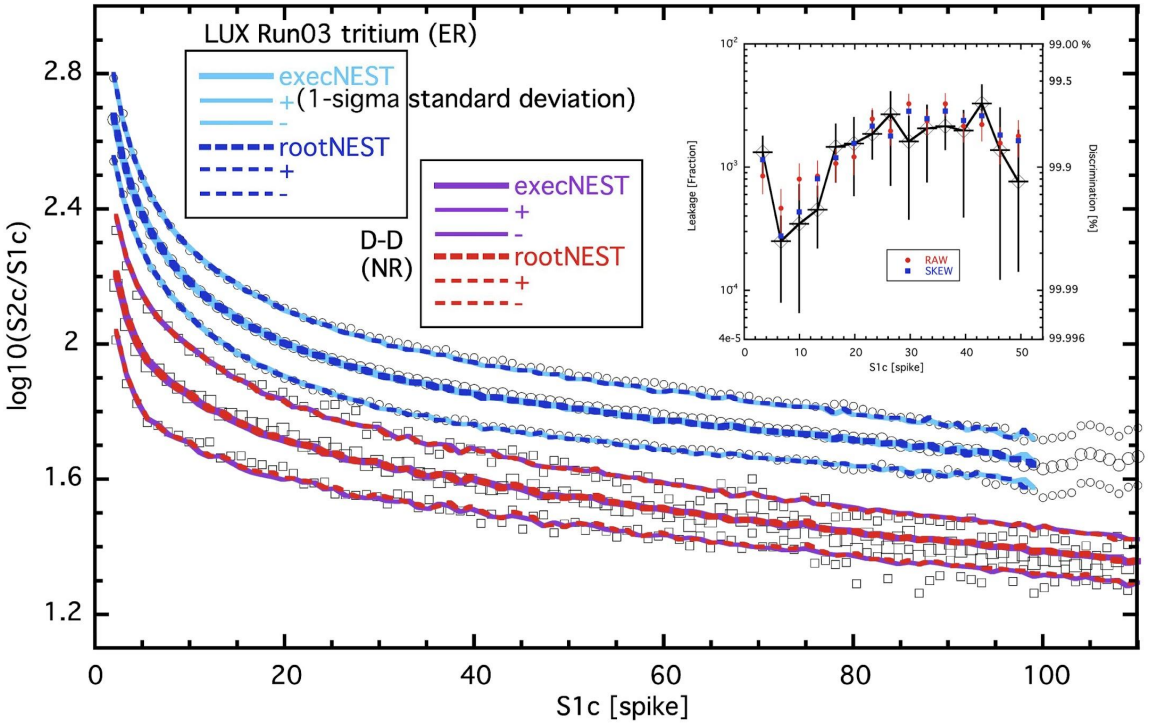
Higher field -> More Q, less L

- We split differences, but intelligently, or go conservative (e.g. less L_y)
- Future ER work will cleave Compton v. beta (gamma already distinct)
- Special model for XELDA yields already exists (Jacob McLaughlin, Dylan Temples, Greg Rischbieter)

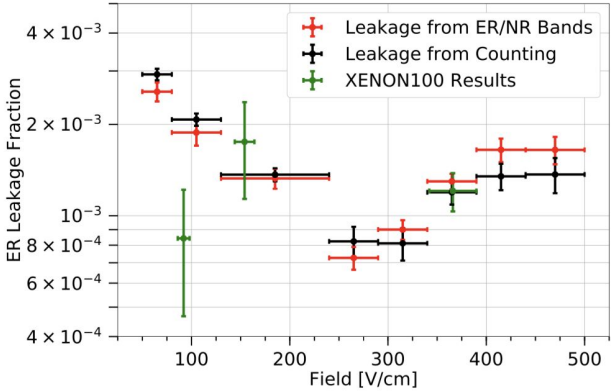


ER/NR Discrimination: S2/S1 in LXe

Number of predicted leakage events depends on drift field, light yield (g1), extraction efficiency.

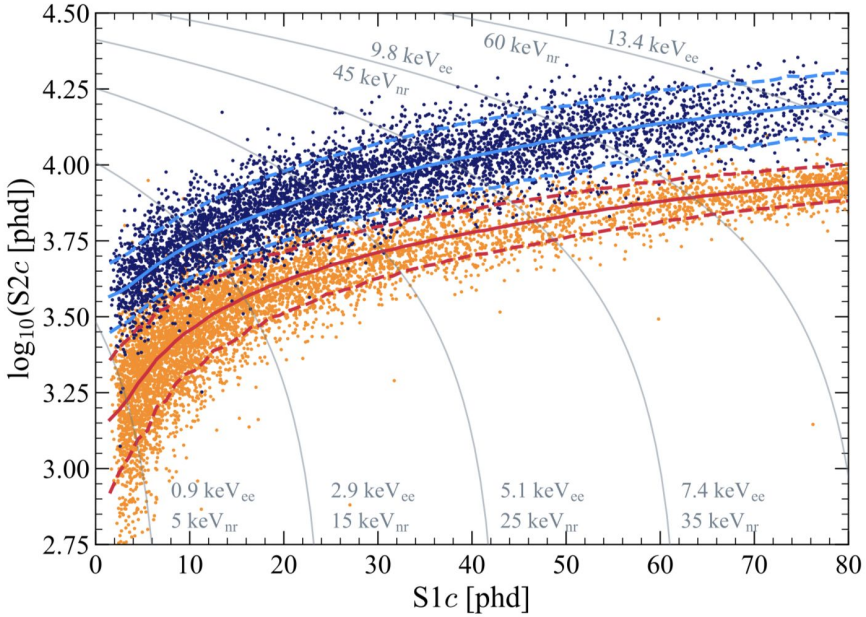


ER/NR disc. in LUX (2004.06304)



- ER/NR discrimination has been extensively studied using data from LUX, XENON100
- NEST simulated discrimination matches well with the LUX data

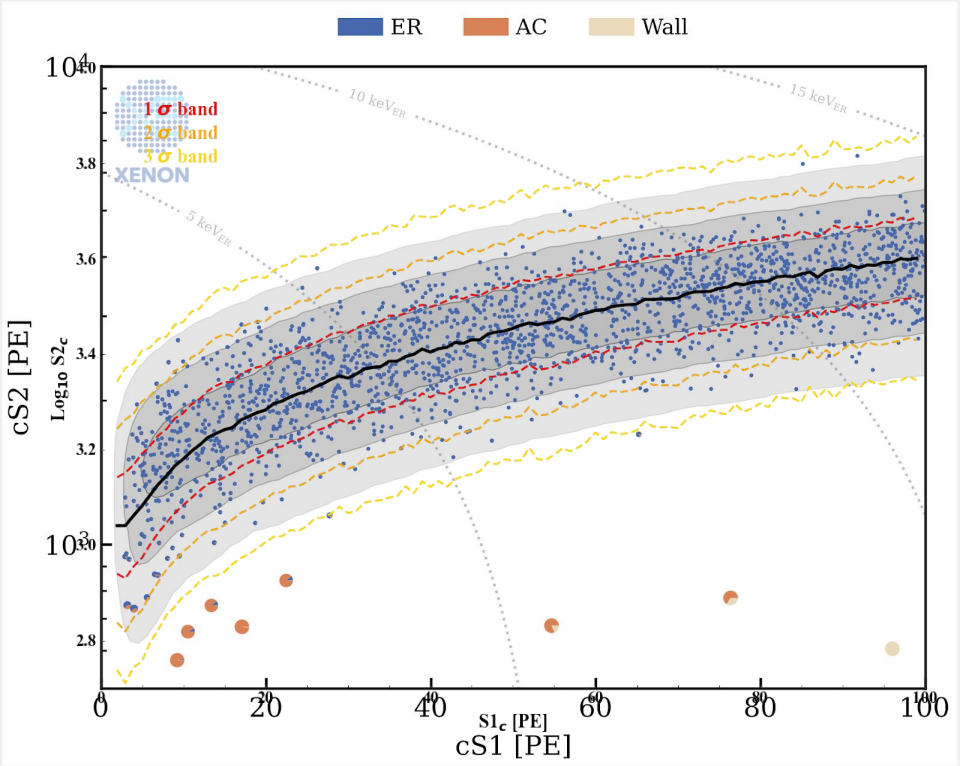
ER/NR bands and discrimination with LZ



- Blue/orange dots are data from ER (tritium) and NR (DD neutron)
- Solid blue (red) lines are the median of ER (NR) **simulated** from NEST v2.3.7
- Dashed lines are 10%/90% quantiles from NEST sim.
- LZ detector file included in [the latest NEST release v2.3.11]

LZ first science result: arXiv:2207.03764

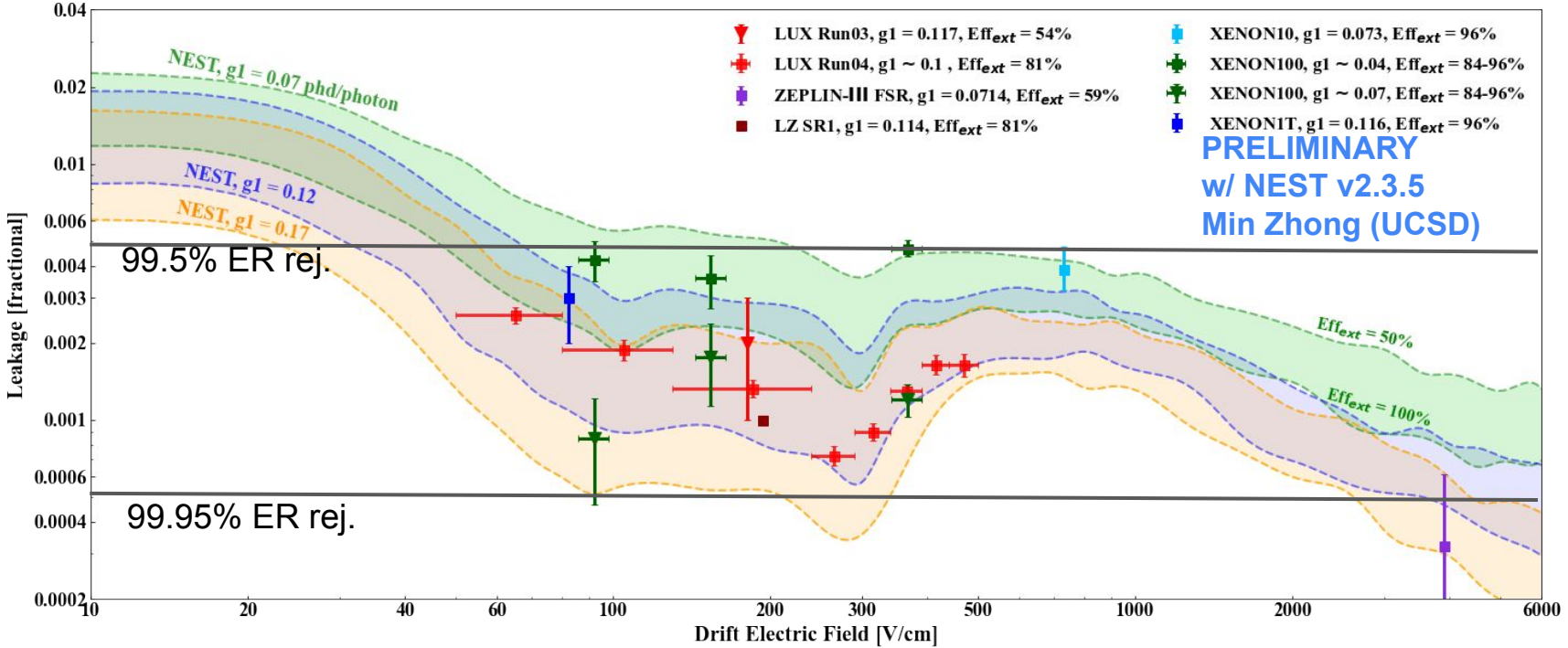
Comparing with XENONnT SR0 and NEST v2.3.11



- Blue dots from XENONnT ER calibration (Rn220) with 1-2-3 sigma shown in gray bands
- NEST v2.3.11 simulated ER overlaid: median: black lines, 1-2-3 sigma: dashed color lines
- XENONnT SR0 detector file included in the latest NEST release v2.3.11

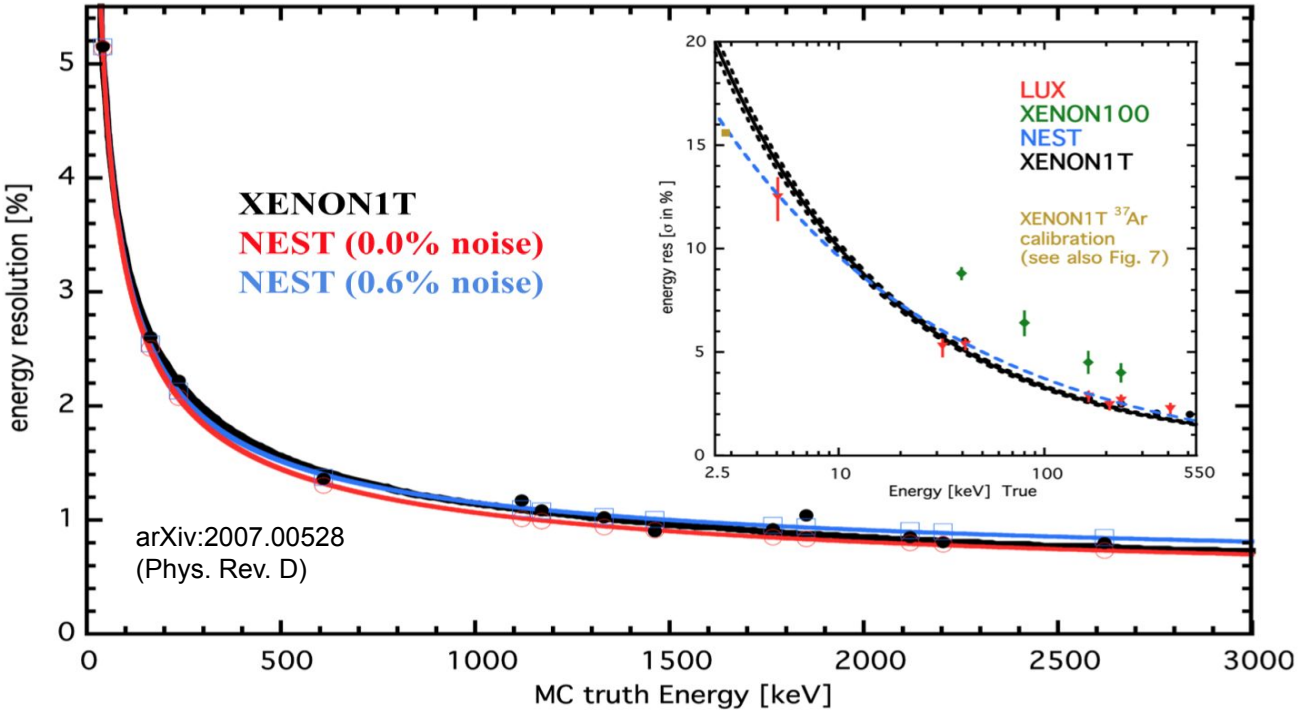
XENONnT first science result: arXiv:2207.11330
plot from Knut Moraa IDM 2022 talk

ER/NR discrimination: a NEST simulation for the future



- Higher g1 & extraction efficiency lead to smaller ER leakage
- Optimal drift field for future detector: 100~300 V/cm

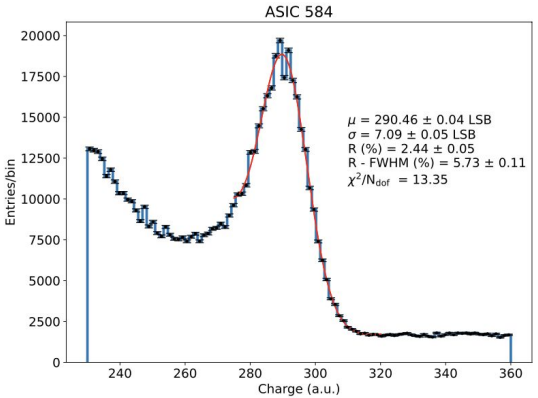
Examples of NEST Output for Energy Resolution

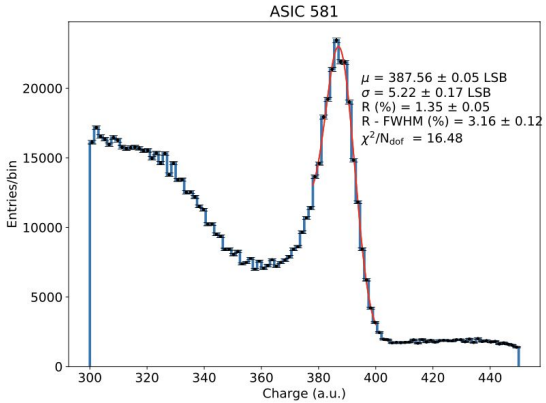


Next talk:
Energy resolution in LZ.

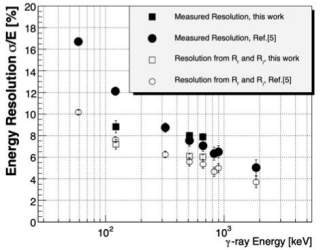
NEST predicted energy resolution matched well with data from XENON1T!

Energy resolution discrepancy (heard from yesterday)





- Intrinsic resolution in LXe @511keV should be 14% FWHM (but much larger volume).
- Can teflon affect recombination?
- Difference between planes (SiPM degradation?).



[K.Ni, et al, JINST, vol. 1, p. P09004, 2006]

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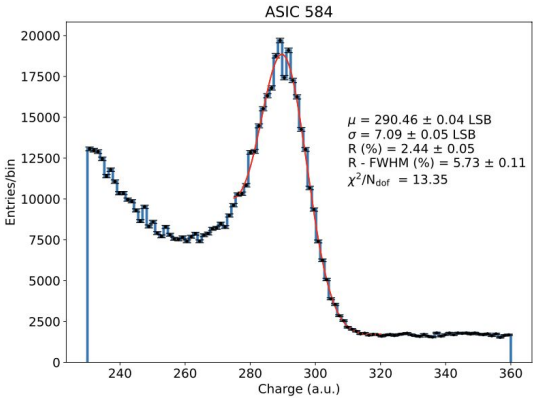

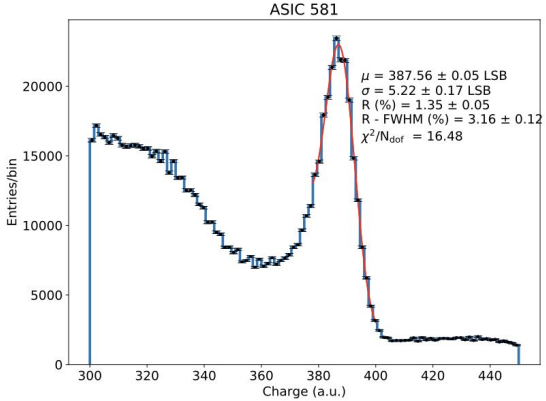

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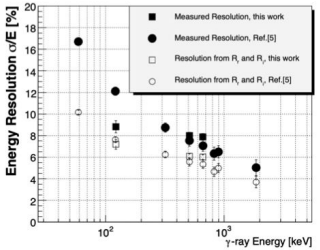

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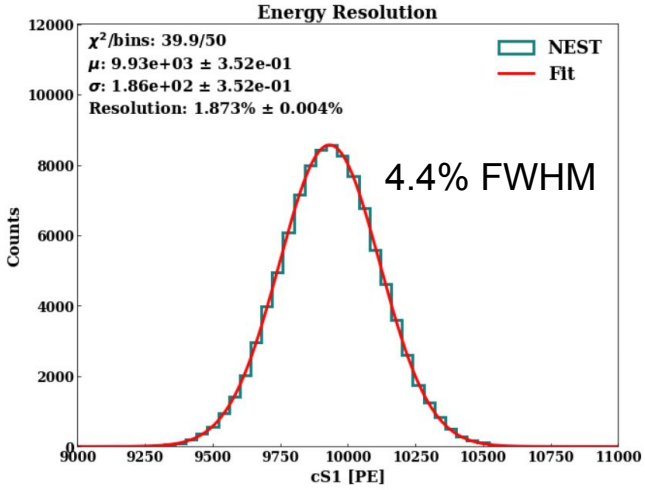
A quick simulation with NEST by Min

(assume g1 = 0.25, use 1 V/cm)



Summary and Outlook

- NEST is quite robust, balancing not just theory and experiment, but also speed (at MeV scale can still simulate millions of event/minute) and precision
- Constantly being updated, but also being careful to avoid ambulance chasing
  - Minor releases ~monthly, major ones ~bi-annual.
- NEST works for both Xenon (liquid & gas) and Argon, using similar often identical equations/formulae/functions
  - Excellent matches with data on yields, ER/NR, resolution for liquid xenon
  - Improved liquid argon fitting whenever data is available
- Future development: **Xe-doped liquid argon** would be valuable for many new applications