# Modeling Xenon Detectors Better with NEST

Sophia Andaloro | Rice University
On behalf of the NEST Collaboration

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# What today's talk is about

- What can NEST do?
- What principles does NEST use to simulate various interactions?
- How can I use NEST most easily?
- NEST Present & Future Improvements
- Where do I go for more information?

# Who and What is NEST?

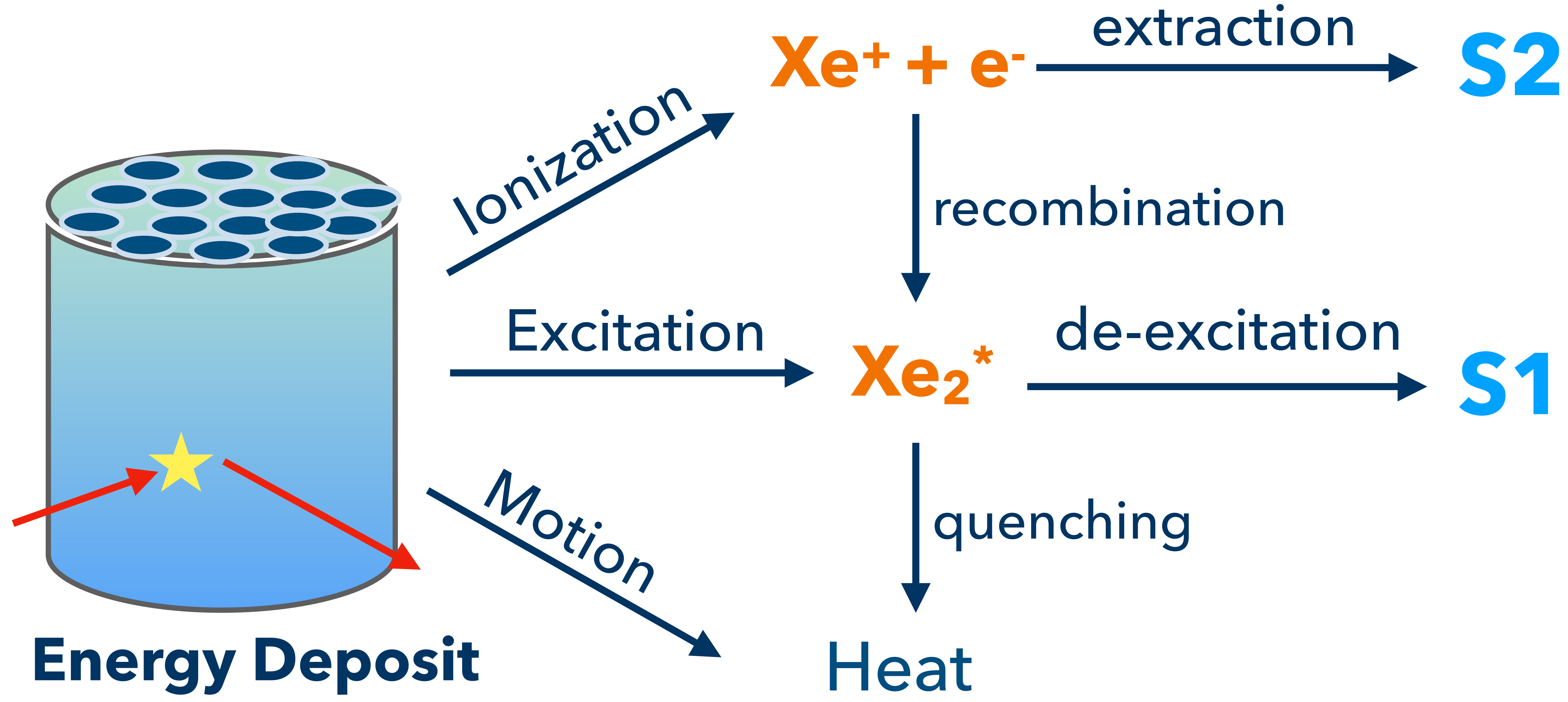
## Noble Element Simulation Technique

Ar

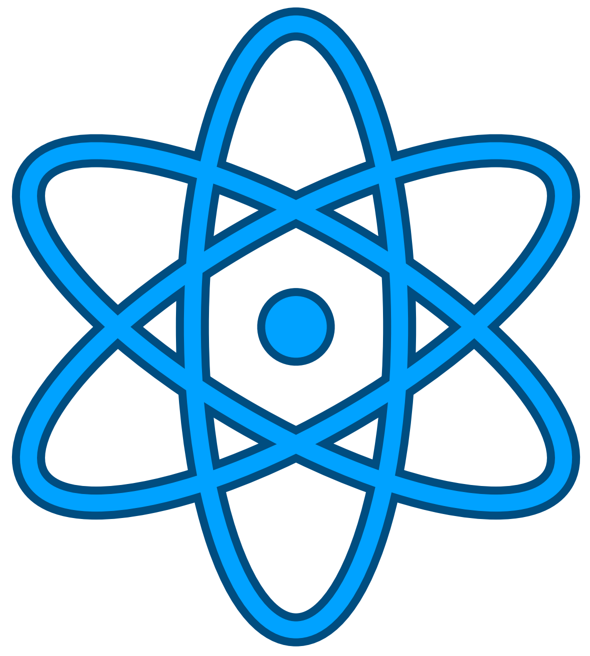
*Xe*

# The NEST Liquid Xenon (LXe) Model

**NEST: Model Detector**




**NEST: Simulate Signals**



## Macroscopic

- ❖ Fields (drift, gap)
- ❖ Density, Temp, Phase
- ❖ Geometry, PMTs…

## Microscopic

- ❖ Particle types
- ❖ Recombination, dE/dx
- ❖ Nex/Ni

| *ER* | *NR* | *Other* |
|---|---|---|
| Photons (γ) | Neutrons | α (alphas) |
| $\beta^{-}$, $\mu^{-}$ (leptons) | Heavy Nuclei | $^{83m}$Kr |
| expanding… | WIMPs | Protons |

# Nuclear Recoils in Liquid Xenon

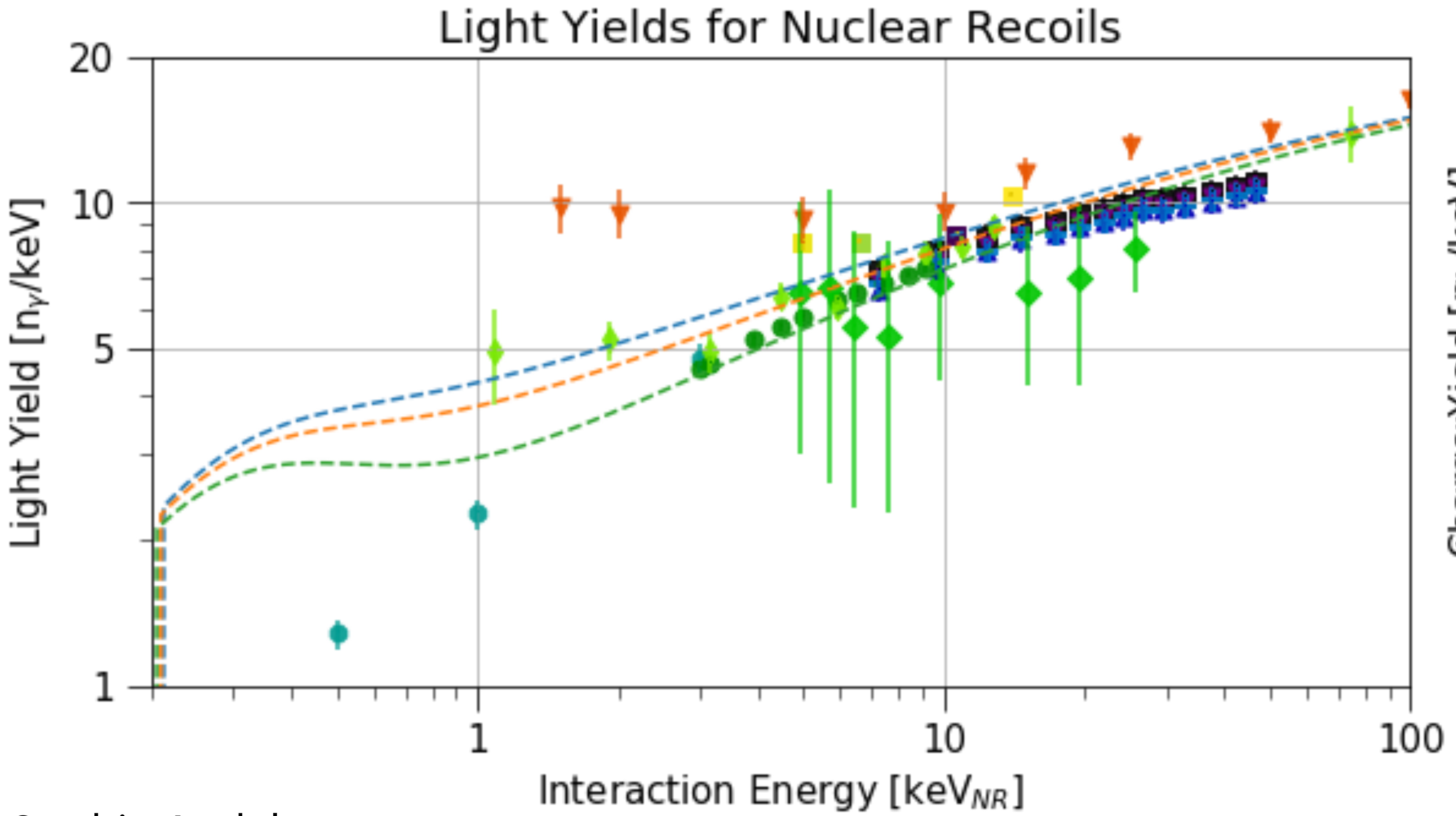
- Important for WIMPs, NR backgrounds
- NEST v2: More data —> more accurate, empirical
- Lindhard (loss to heat), recombination effects

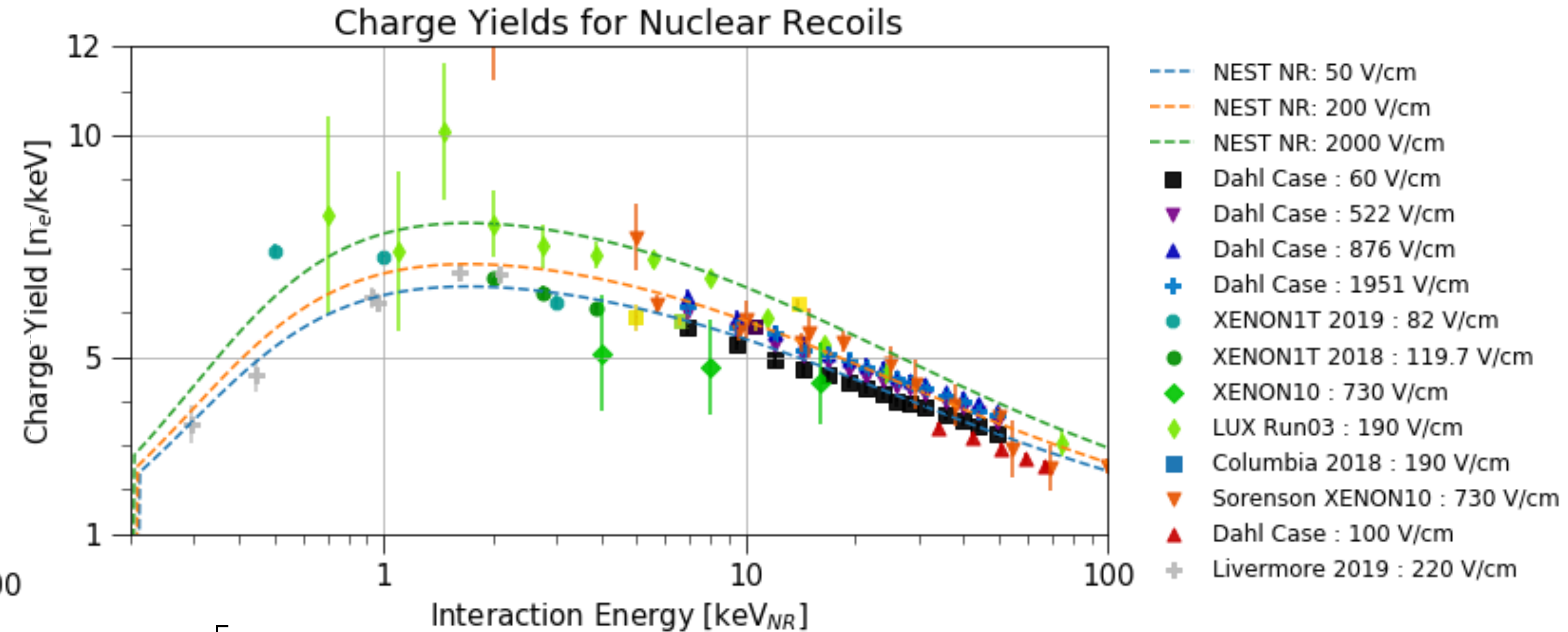
$$N_q = \frac{\mathscr{L} \cdot E}{W} = \alpha E^{\beta}$$

$$N_{e^-} = \frac{E}{TIB(\rho, F) \cdot \sqrt{E + \epsilon}} \cdot \left(1 - \frac{1}{1 + (\frac{E}{\zeta})^{\eta}}\right)$$

$$N_{\gamma} = (N_q - N_{e^-}) \cdot \left(1 - \frac{1}{1 + (\frac{E}{\theta})^{\iota}}\right)$$

*Blue: free parameters*
*Orange: Known input data*
*Green: Objective data to fit*



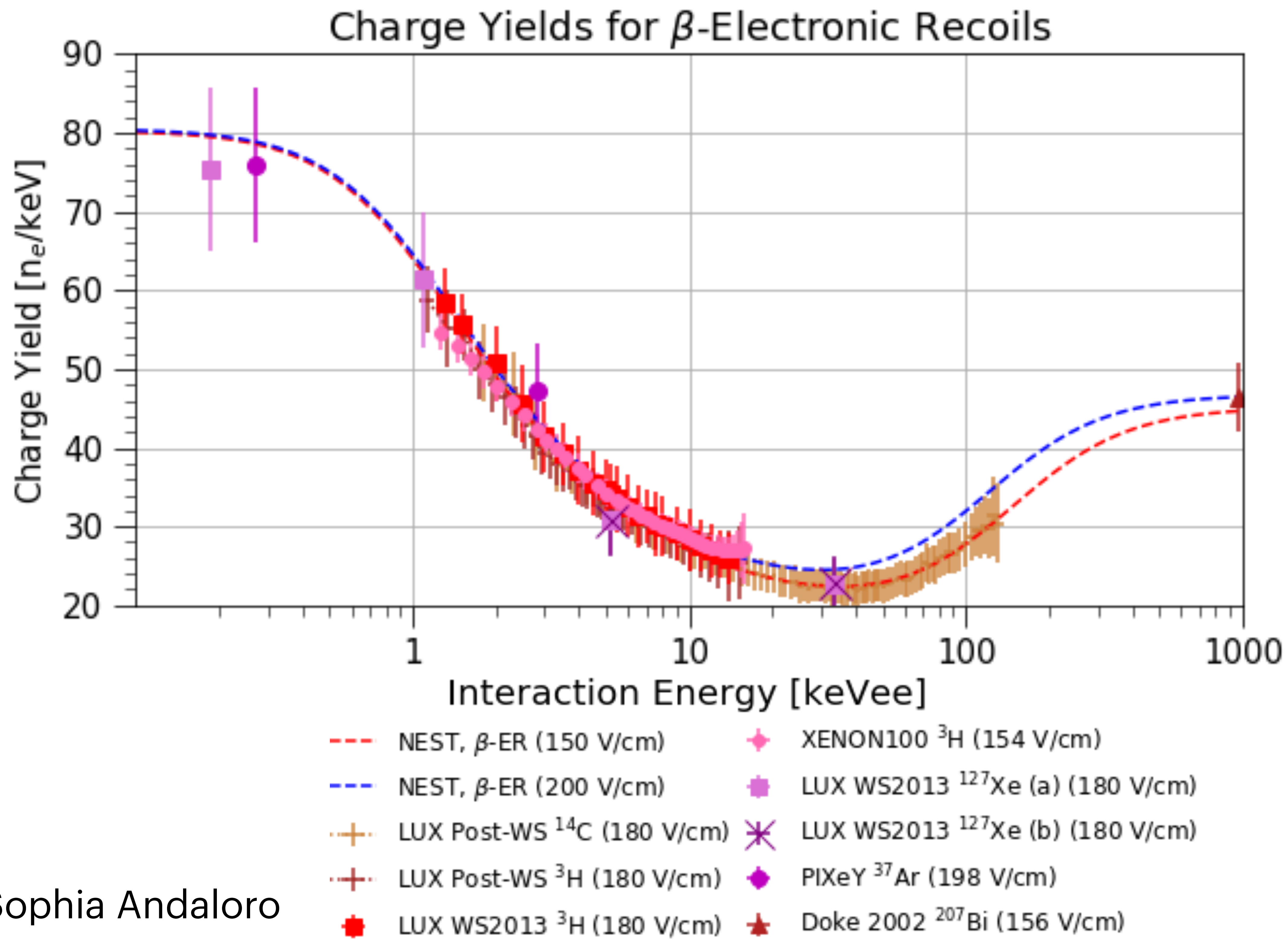
# Electronic Recoils in LXe: NEST v2

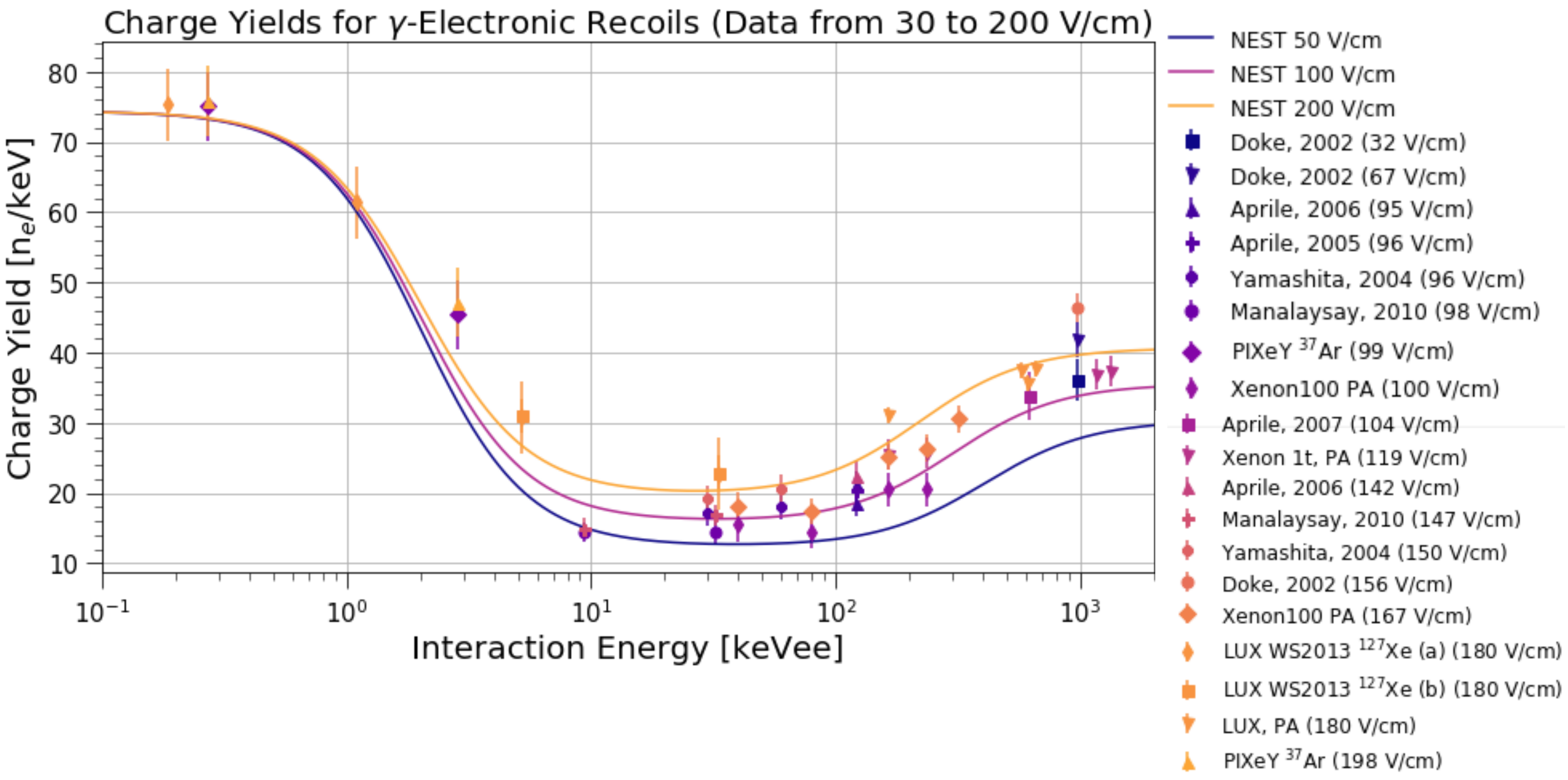
- ERs for background, low-energy, high-energy searches
- We split the ER model into 2! (β, γ)
- β, γ ionize Xenon differently
- Improved fits to data from sub-keV to MeV energies

$$N_q = \frac{E}{W} = N_{e^-} + N_\gamma$$

*Blue: free param (or func.)*
*Orange: Known input data*
*Green: Objective data to fit*

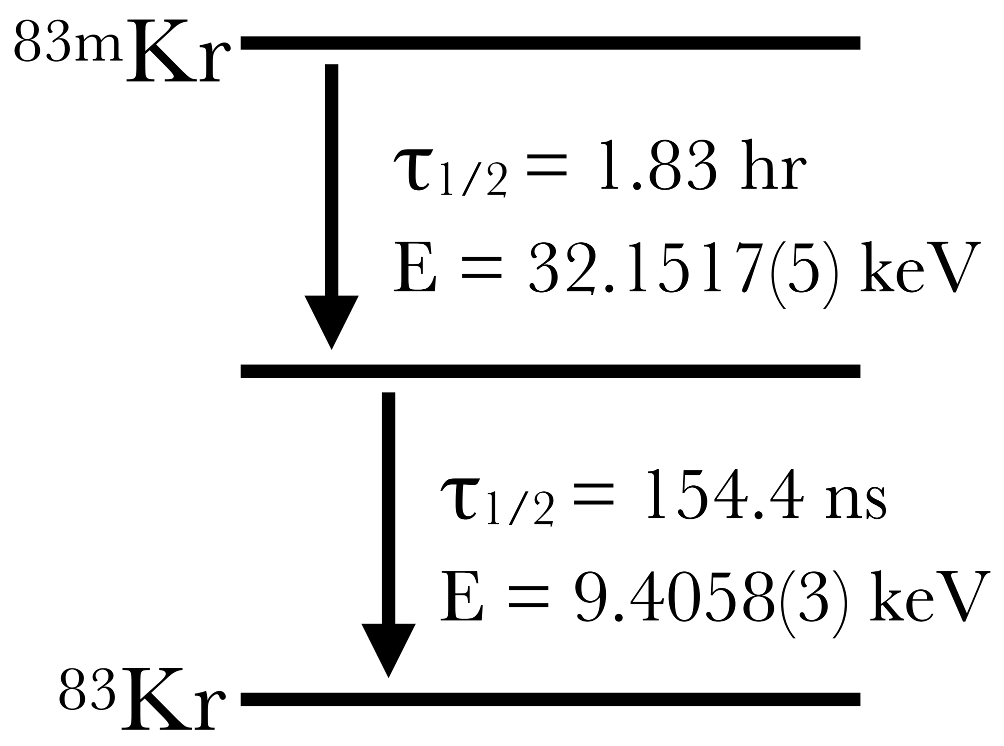
$$\frac{N_{e^-}}{E} = m_1 + \frac{m_2 - m_1}{(1+m_3 E^{m_4})^{m_5}} + \frac{m_6}{(1+m_7 E^{m_8})}$$

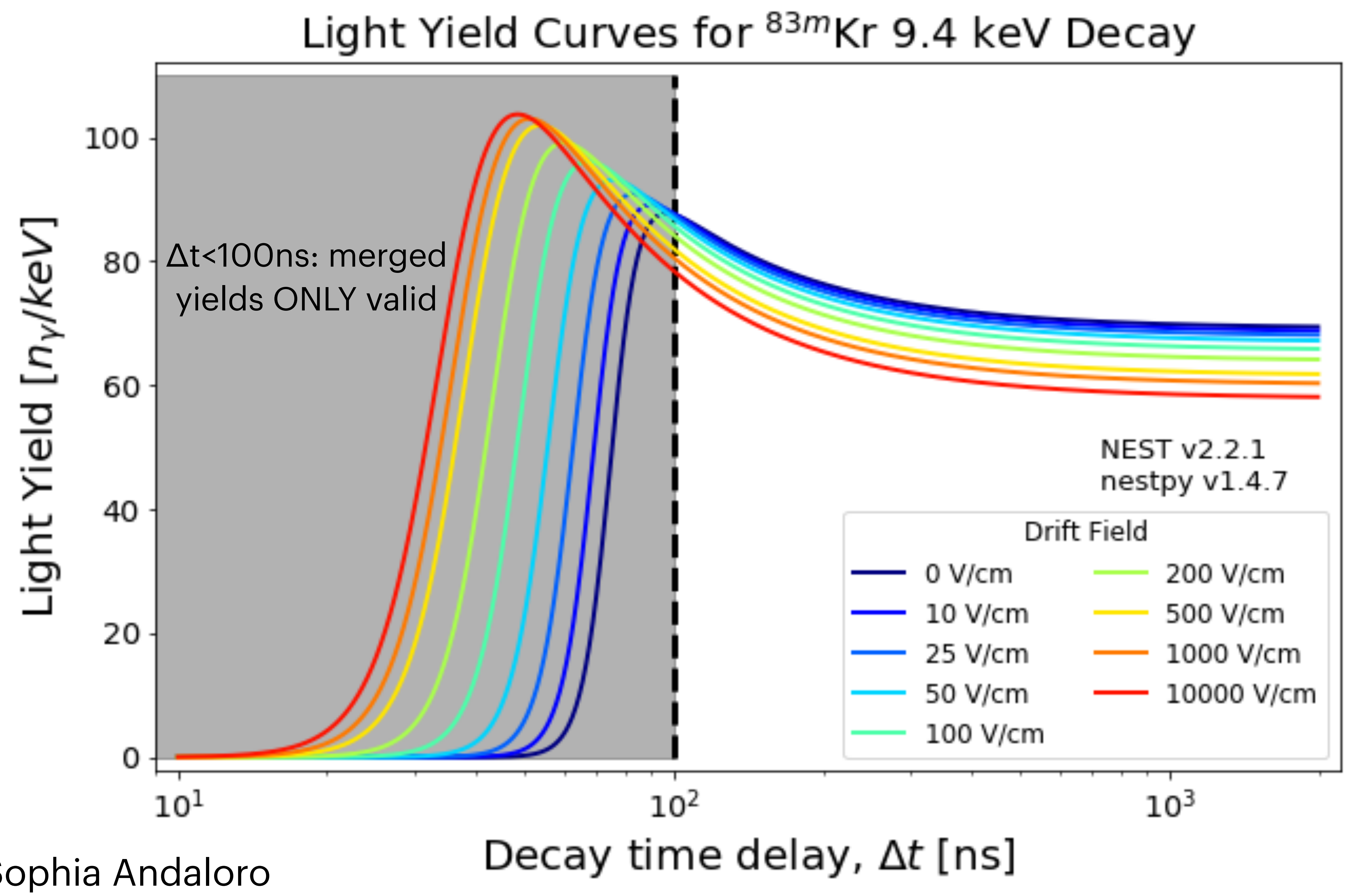


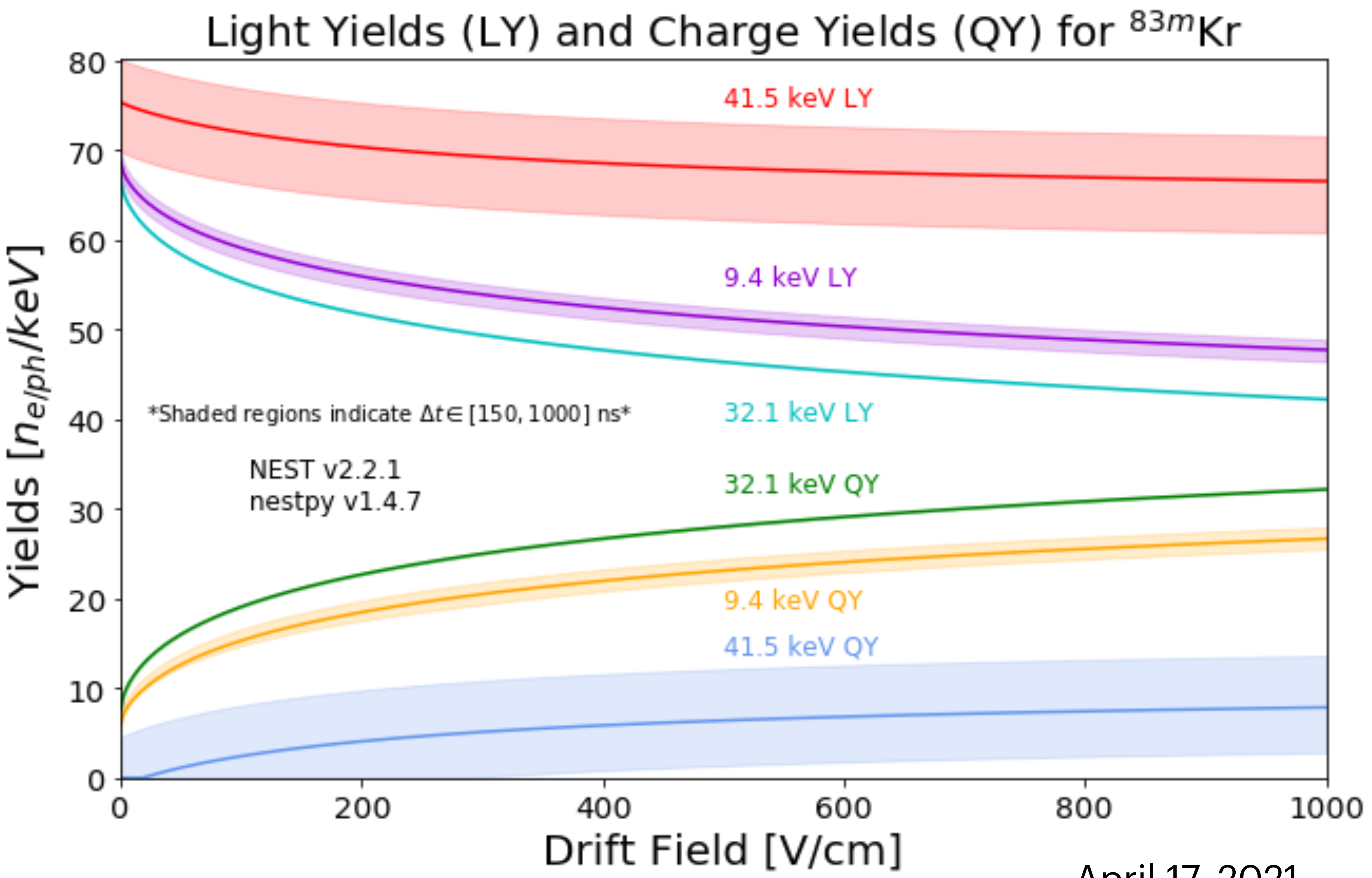



# Upgraded Yields for $^{83m}$Kr in LXe

- $^{83m}$Kr's 2 decays are mutually related by the decay time between them, $\Delta t$.
- NEST reproduces the time-dependent recombination effects from data.
- We lose separation power below 100 ns (merged S1s) - XENONnT/LZ may offer more data here.



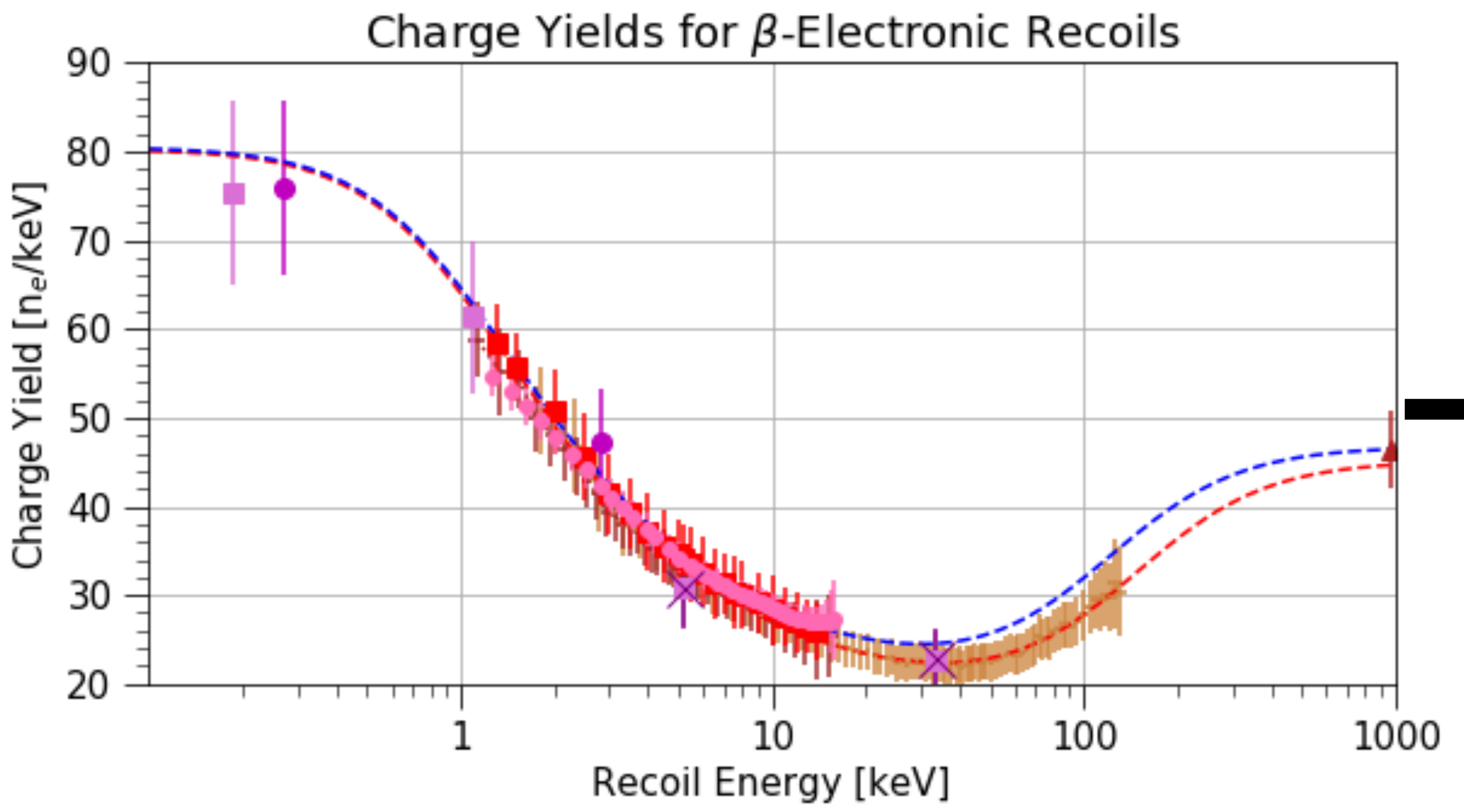



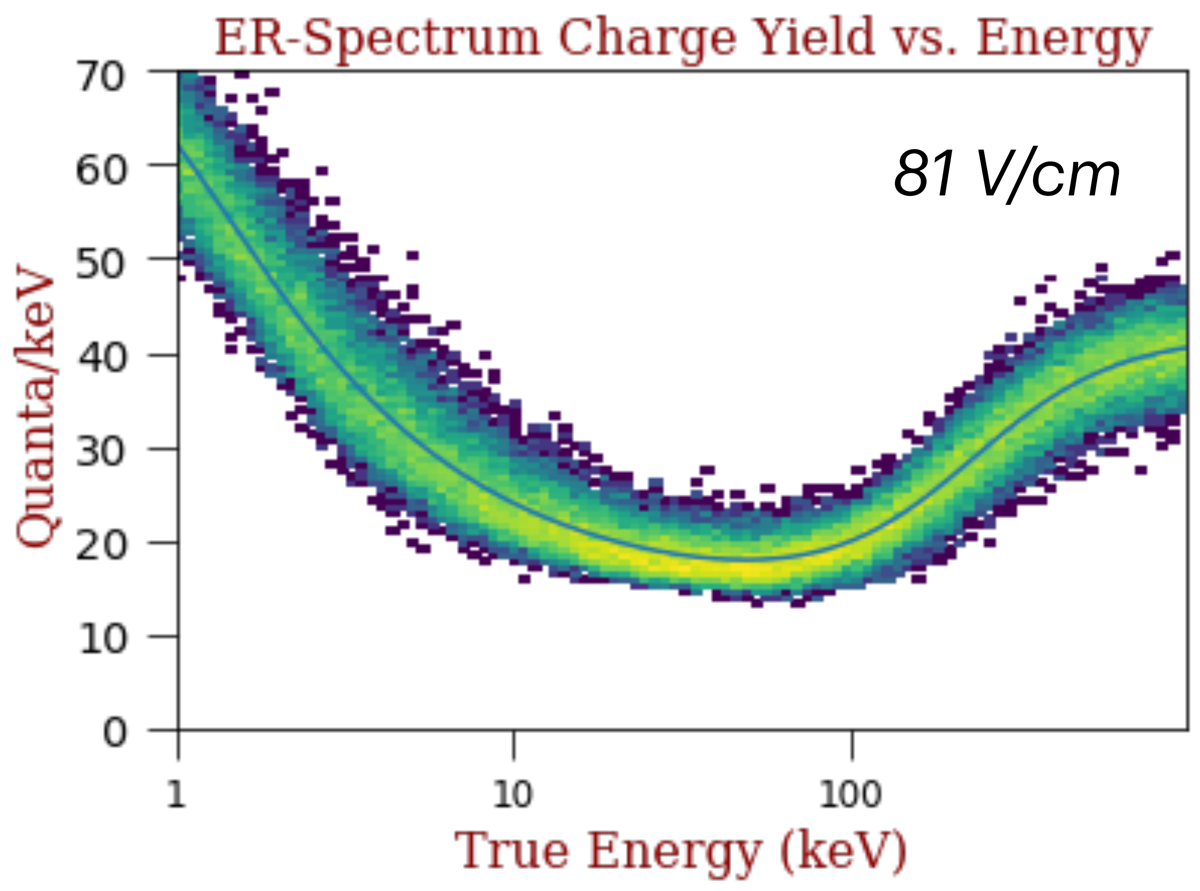
# Beyond Yields: Simulate TPC Signals with NEST

- We can do much more than just yields simulating
- Simulate quanta, S1 & S2, even can include photon arrival times.

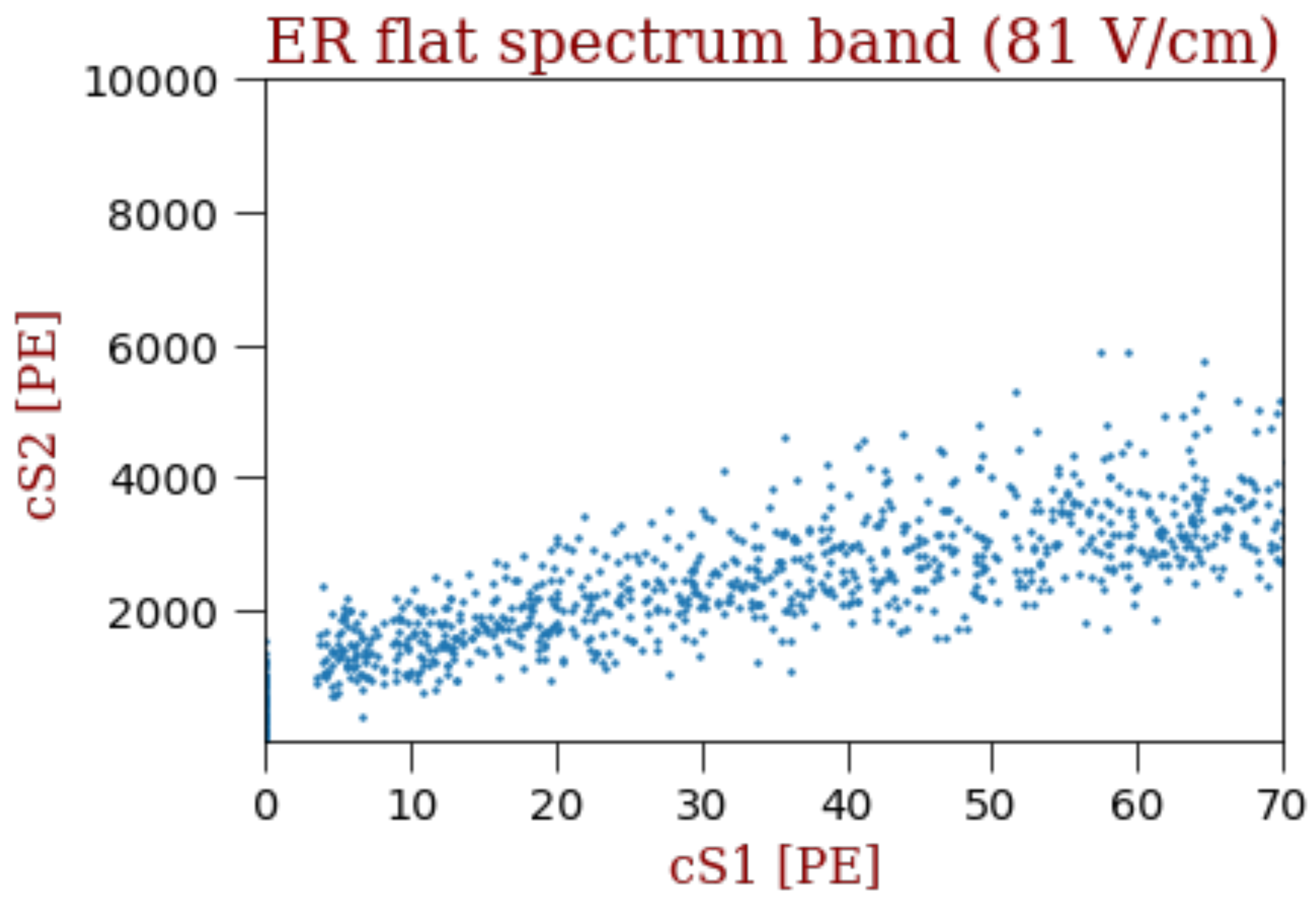
*From Yields*




*To Quanta*



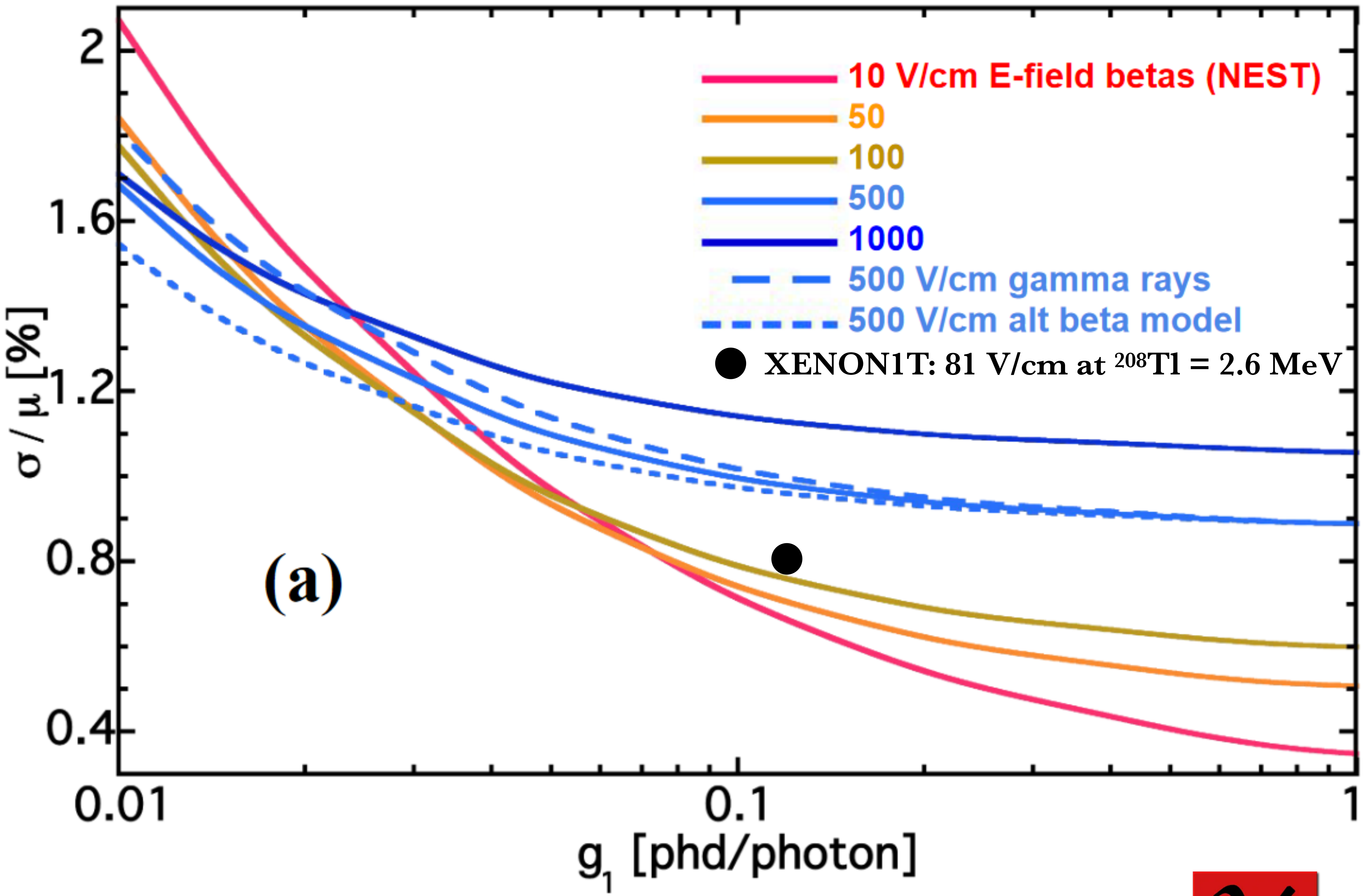

*To S1/S2 Signals*



# Beyond Yields: Detector Response

## Energy & Signal Reconstruction Accuracy: A case study

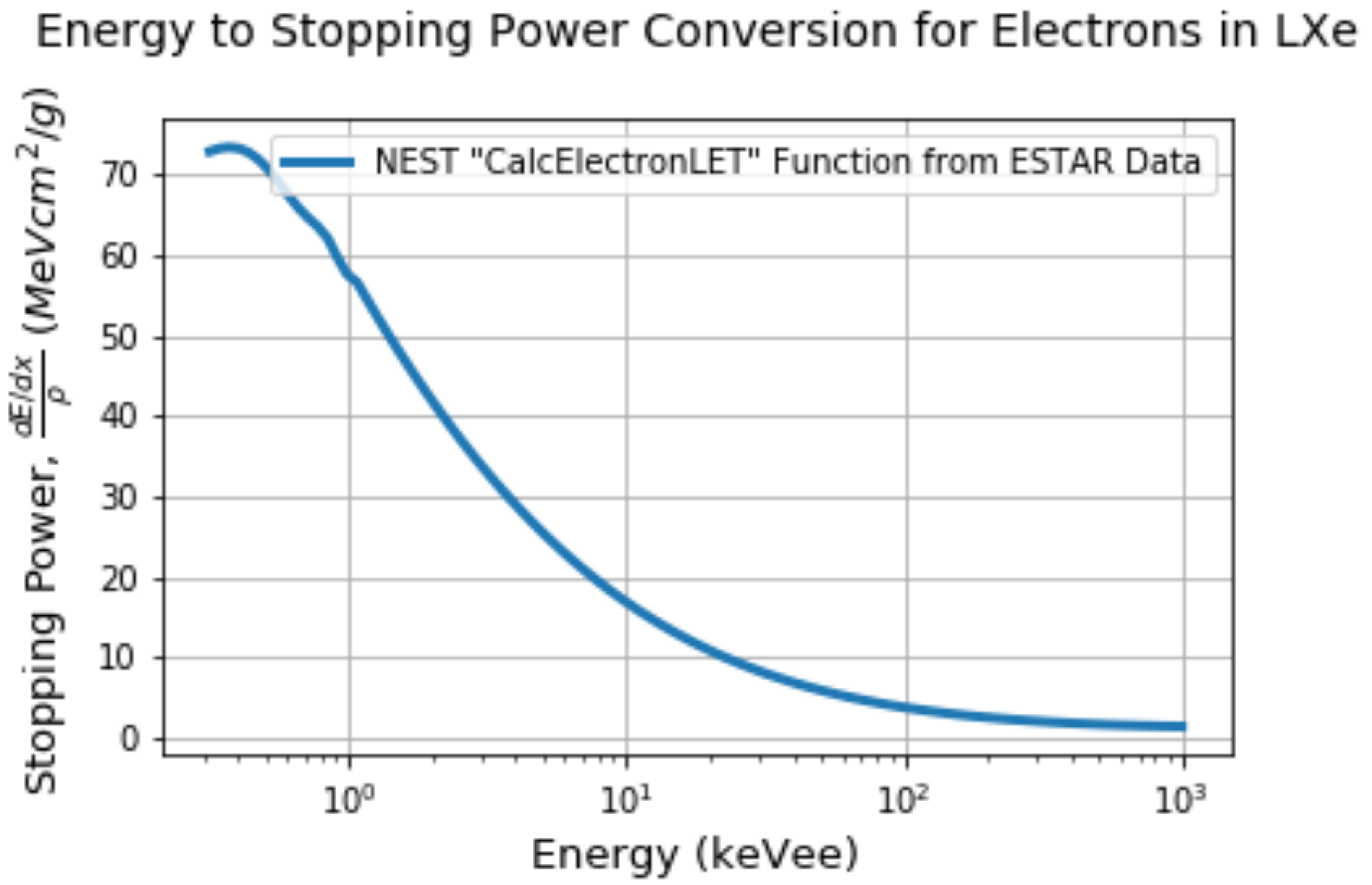
High-Energy CES Resolution ($Q_{\beta\beta}$ = 2.5 MeV)

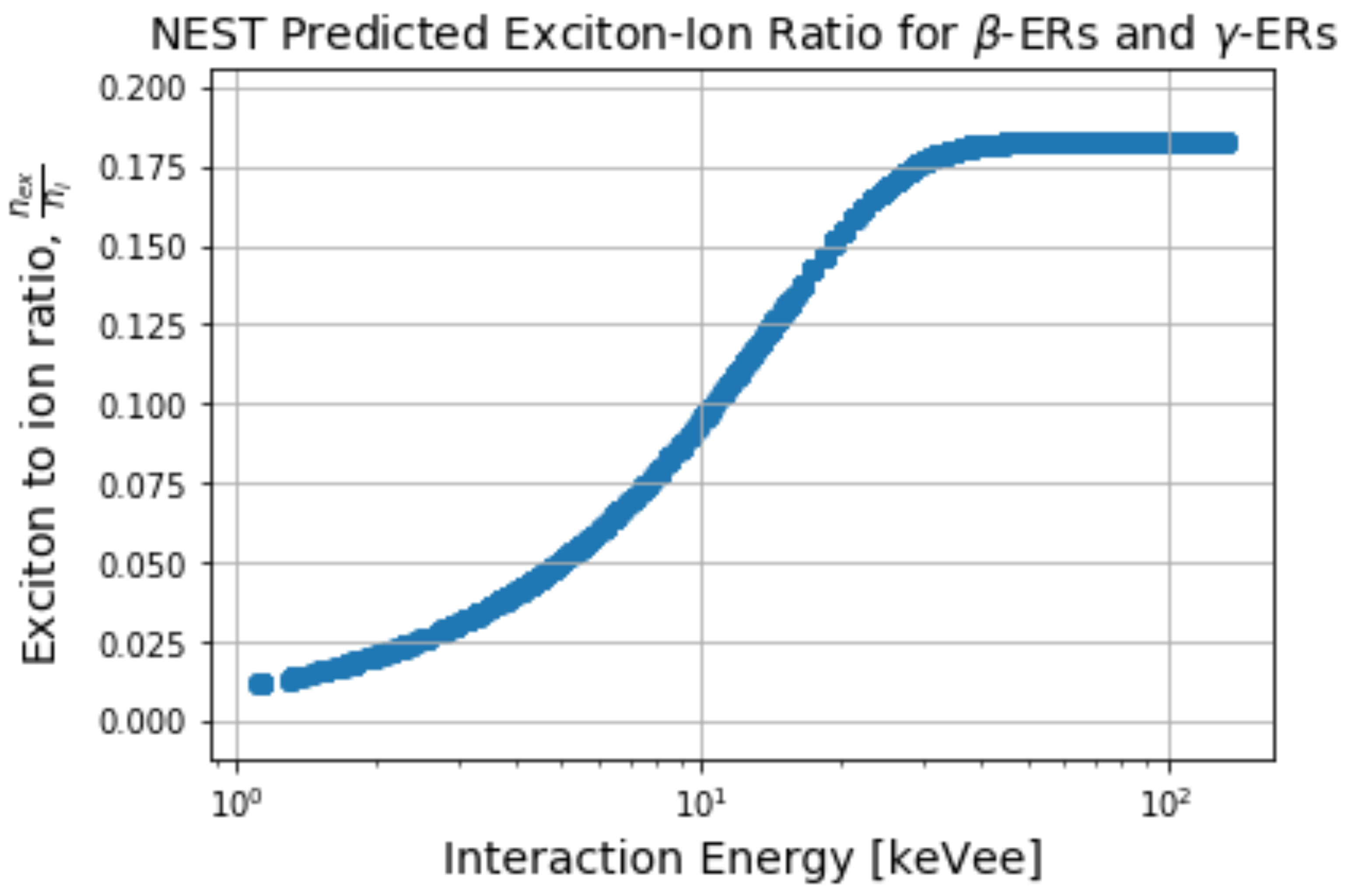


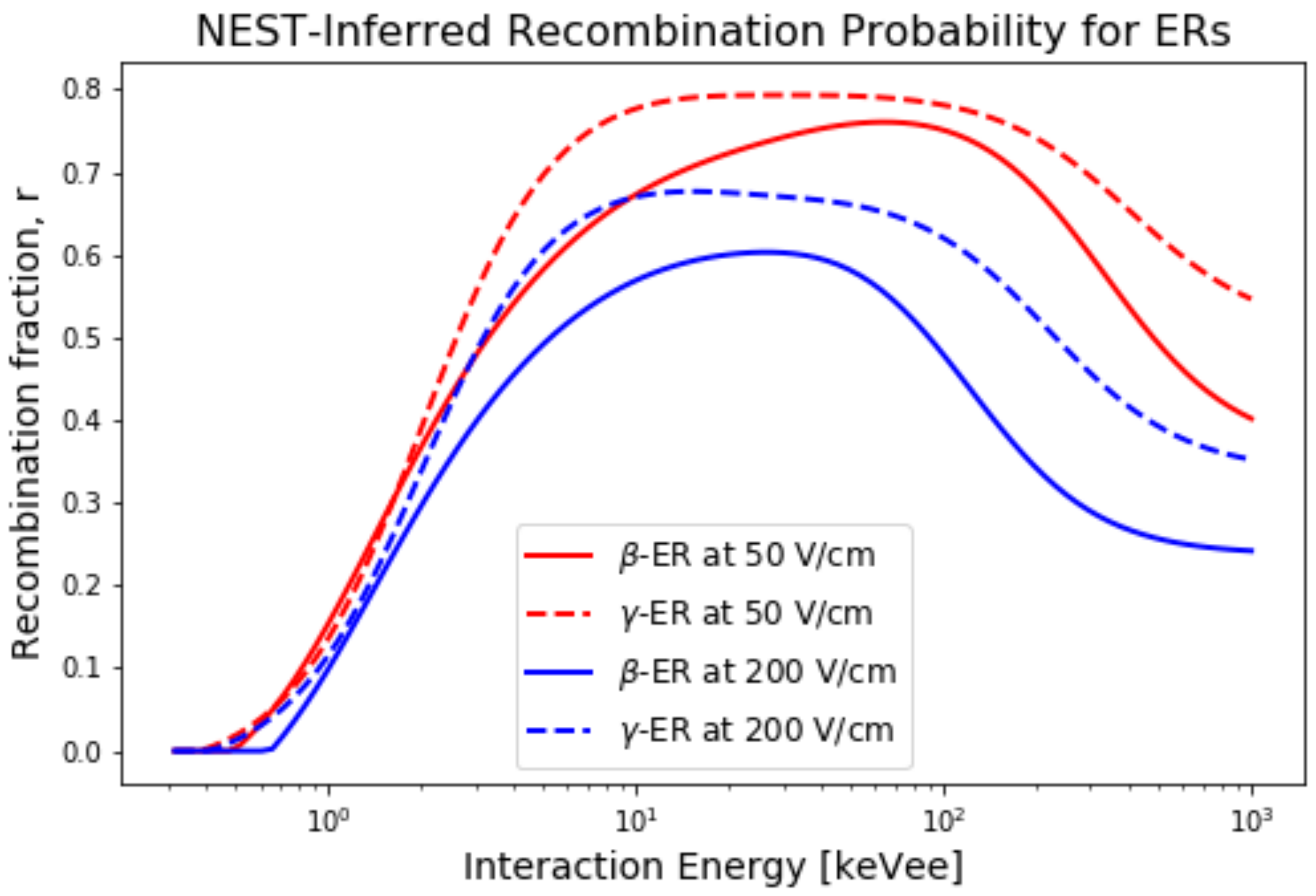

*arXiv:2102.10209 (Review of energy reconstruction)*

# NEST Updates

- Software-wise: faster, more reliable. Upgraded modern default detector underway
- Physics-wise: more data = more accurate, better models to match data & respect atomic physics.
- Liquid Argon model implemented already
- **ER Model**: splitting up into interaction types, coding ionizing differences using meaningful parameters (recombination, exciton-ion ratio) with R(E, F, θ) and nex_ni(E, F, θ)



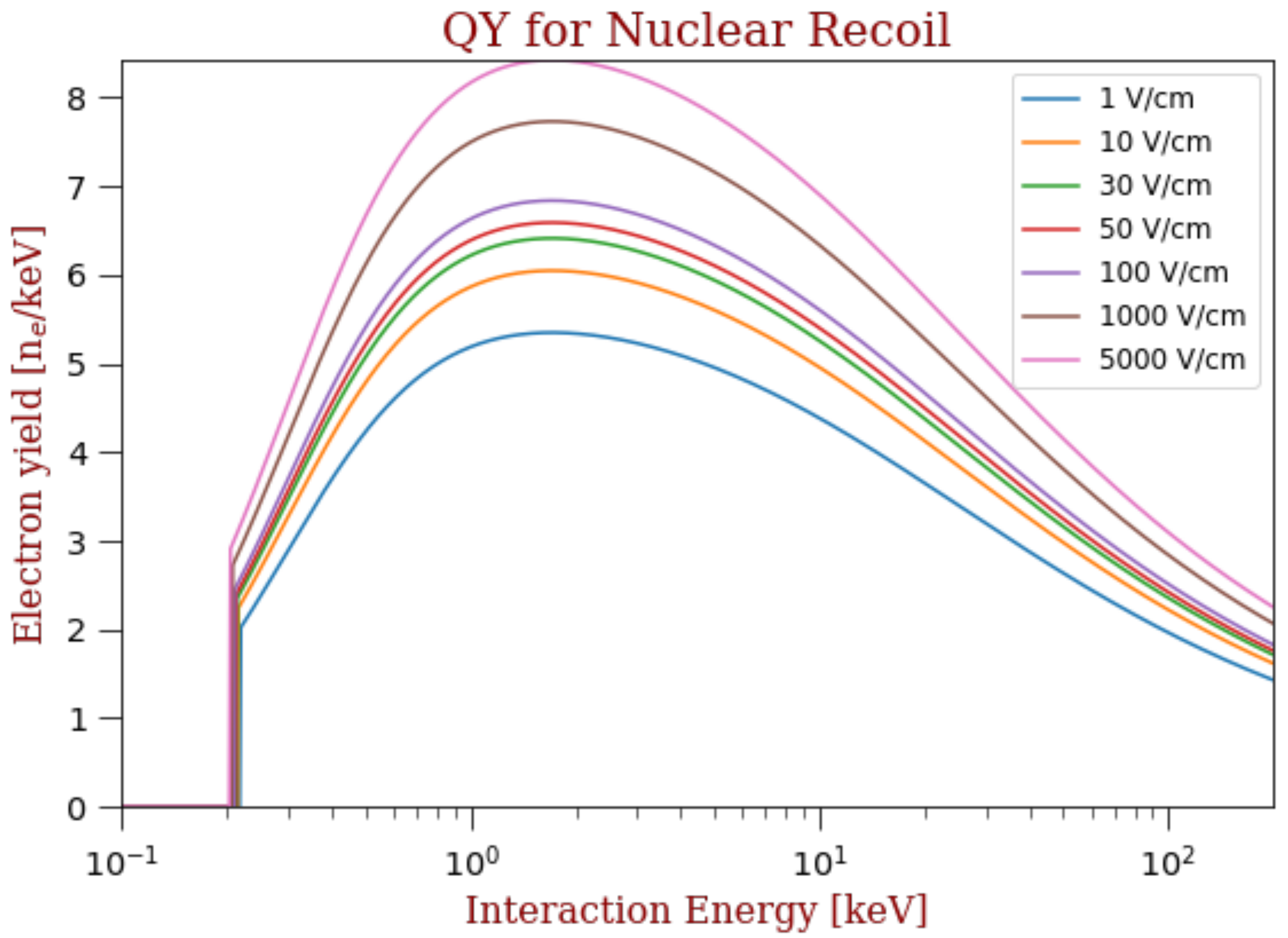



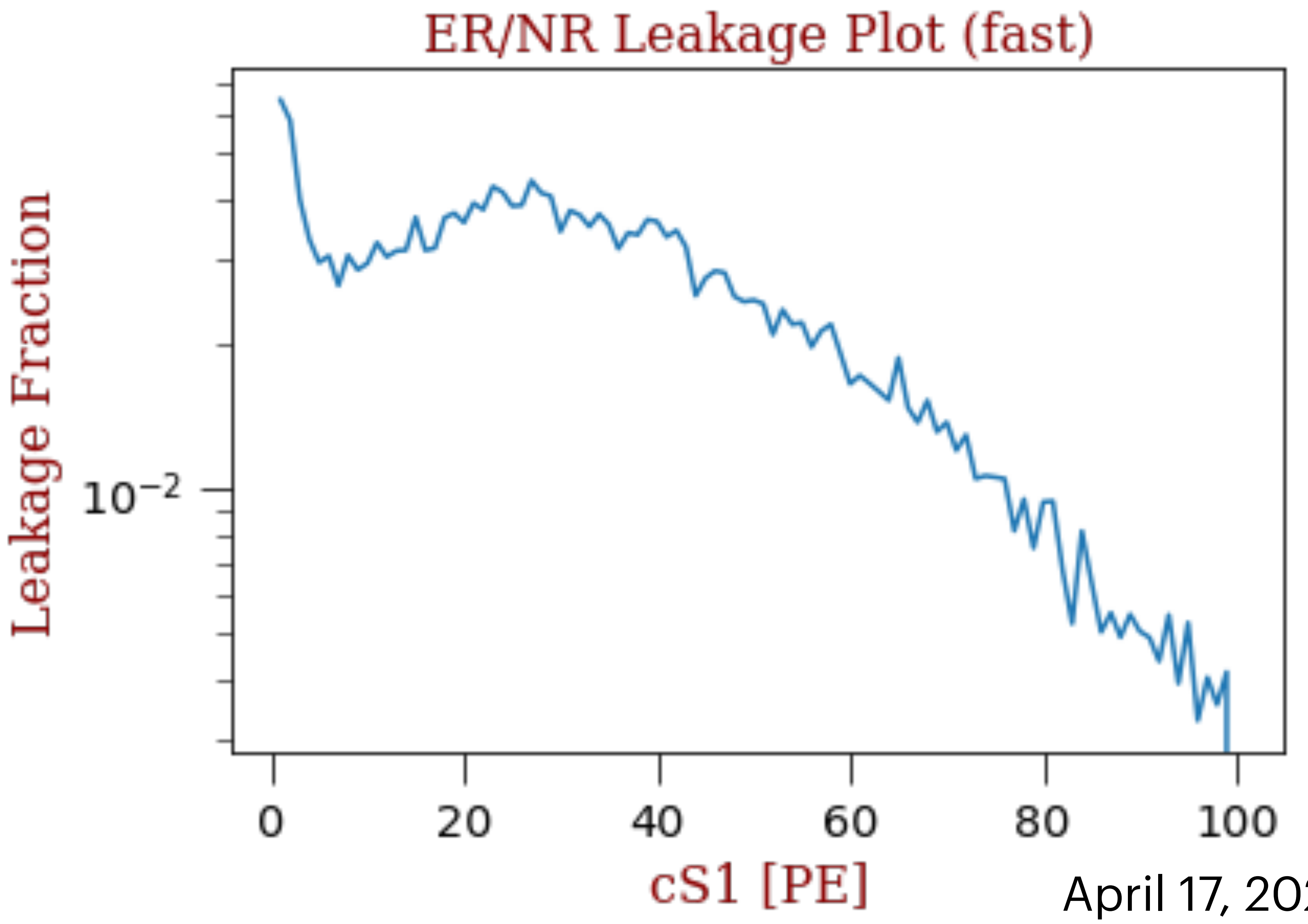
# Get Started with NEST in minutes!

- nestpy Tutorial: From quanta to leakage
- NEST C++ Tutorial
- Github: NEST and nestpy (ask questions via issue tracker)
- Website: for talks, papers and plots

*Go from yields…*




*To modeling and limit-setting!*





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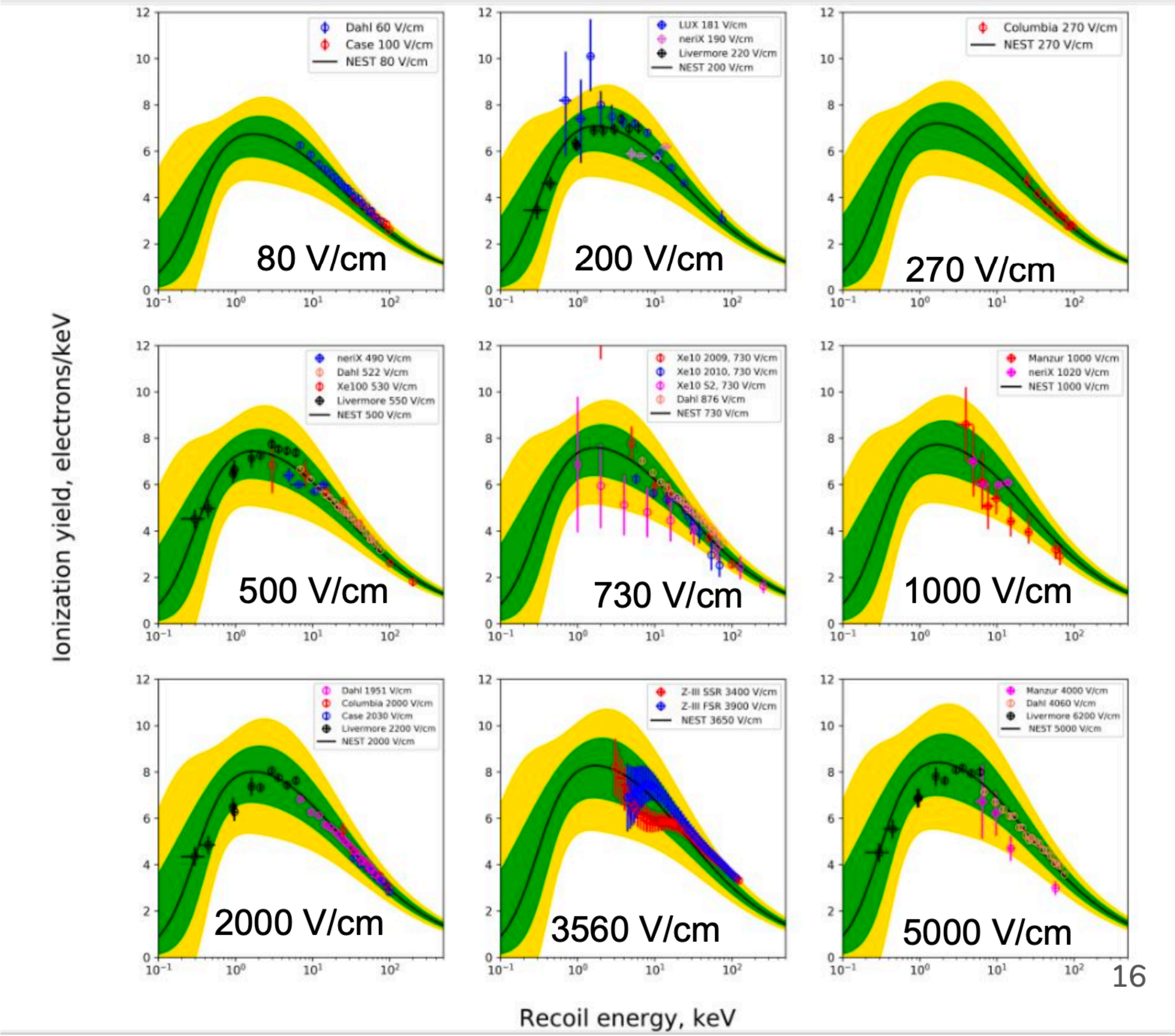
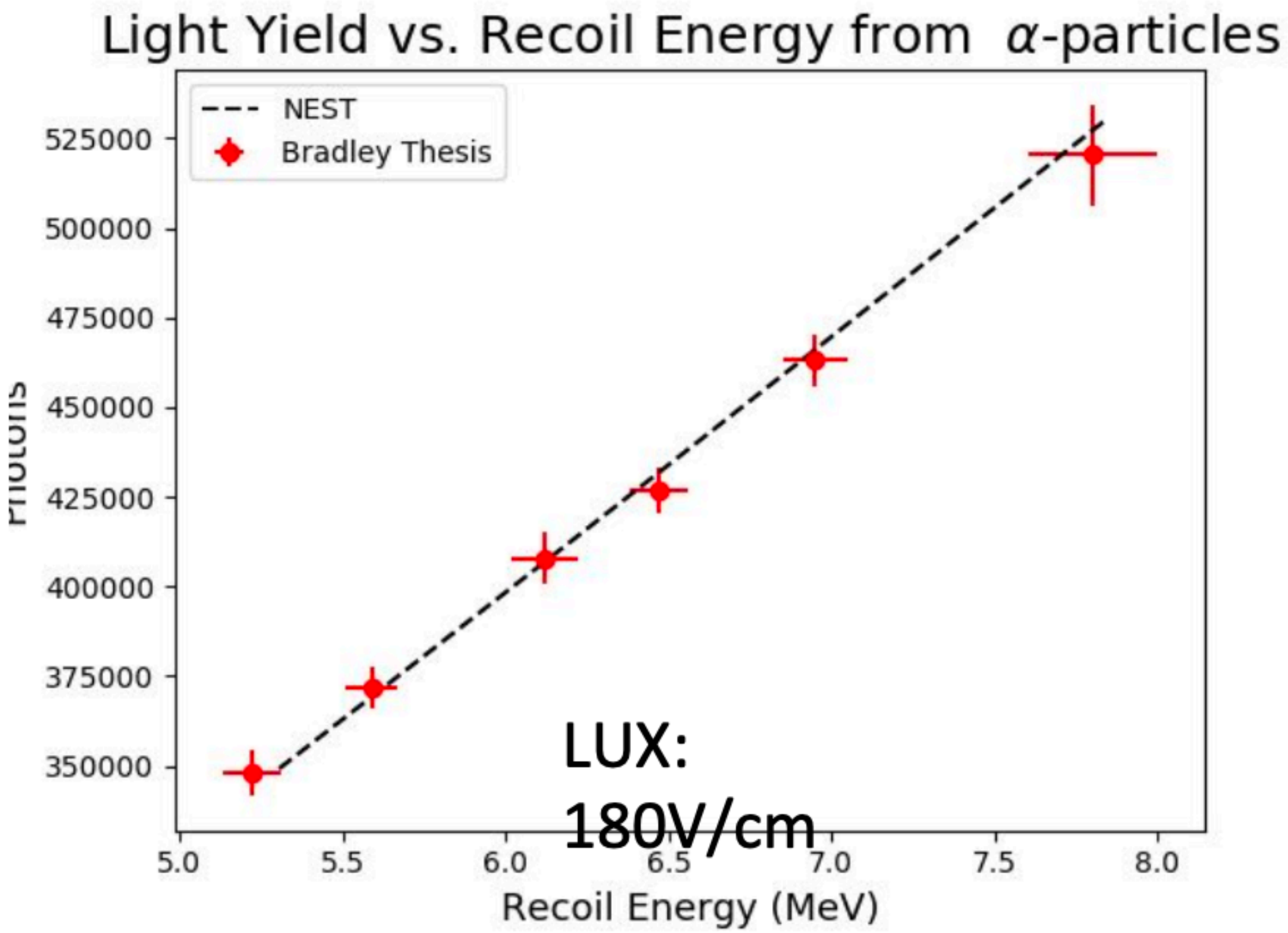
*S. Andaloro: DOE NNSA SSGF Funding: #NE-NA0003960. M. Szydagis: DOE #DE-SC0015535*

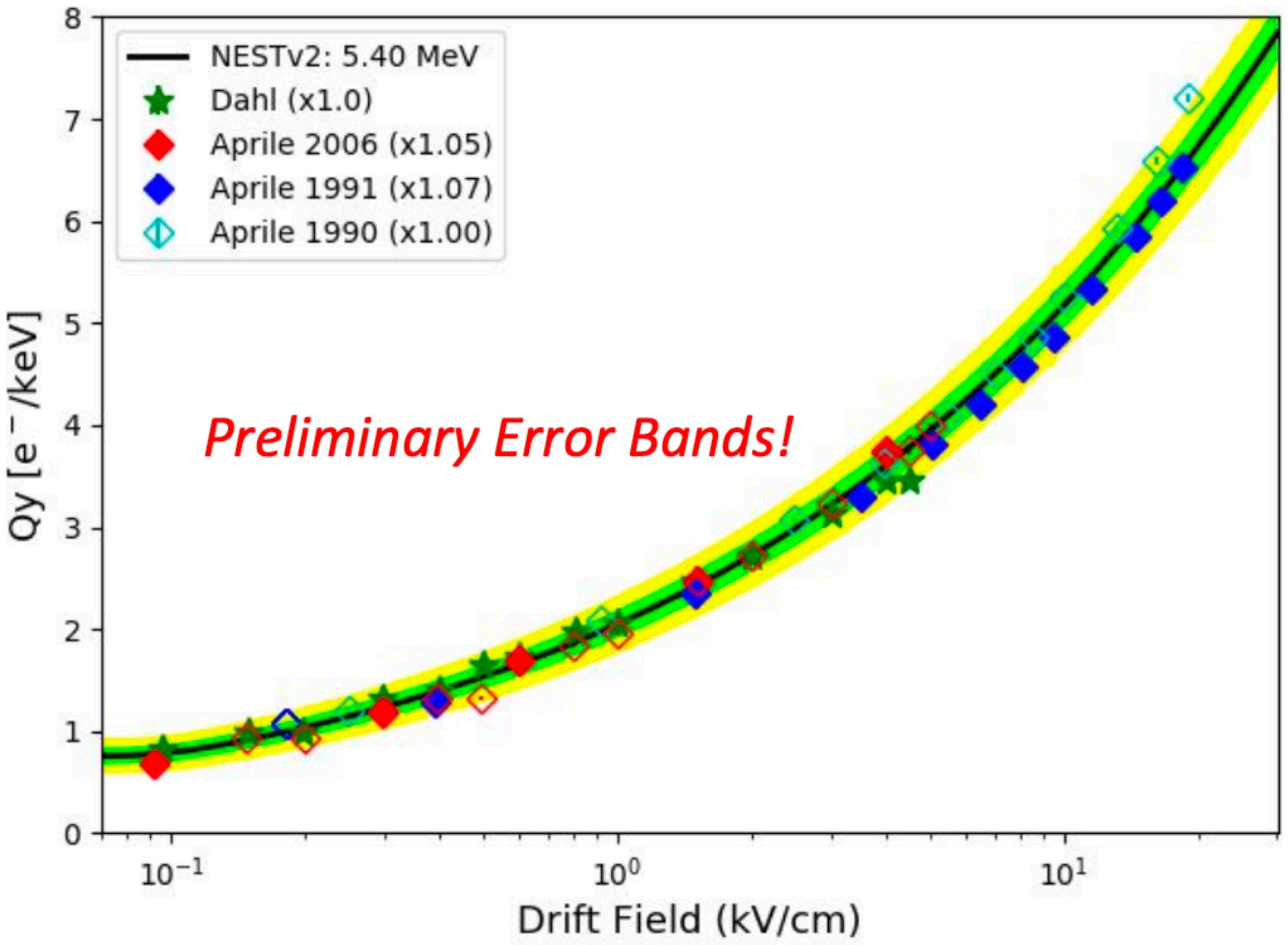
# BACKUP

# NR Model Statistics (Uncertainties)



# Alpha model in LXe





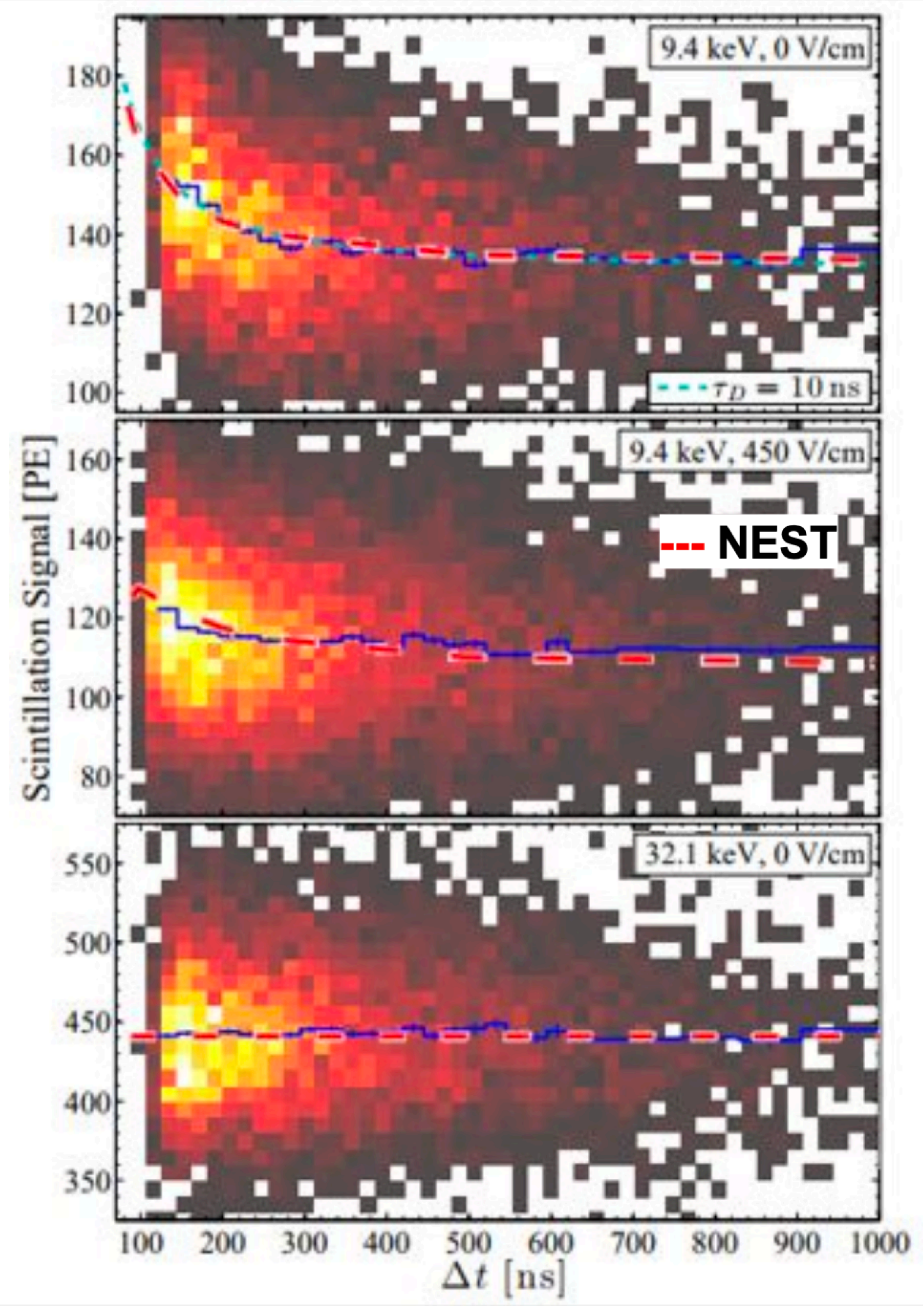
A.W. Bradley. LUX THERMOSYPHON CRYOGENICS AND RADON-RELATED BACKGROUNDS FOR THE FIRST WIMP RESULT. Doctoral Dissertation. Case Western Reserve University. May 2014.

E. Aprile et. al "A study of the scintillation light induced in liquid xenon by electrons and alpha particles," in *IEEE Transactions on Nuclear Science*, vol. 37, no. 2, pp. 9 553-558, Apr 1990.

Simultaneous measurement of ionization and scintillation from nuclear recoils in liquid xenon as target for a dark matter experiment. E. Aprile, C.E. Dahl, L. DeViveiros, R. Gaitskell, K.L. Giboni, J. Kwong, P. Majewski, Kaixuan Ni, T. Shutt, M. Yamashita. Jan 2006. Published in Phys.Rev.Lett. 97 (2006) 081302

# Kr83m time-dependent LY

- For 9.4 keV decay, the closer to the previous decay = the higher chance for recombination (more holes for electrons to find before drifting).
- Below 100 ns: data not available, yet, to model (LY are merged into 41.5 keV total energy below this)




**Response of liquid xenon to Compton electrons down to 1.5 keV**

Laura Baudis, Hrvoje Dujmovic (Zurich U.), Christopher Geis (Zurich U. & Unlisted, DE), Andreas James, Alexander Kish, Aaron Manalaysay, Teresa Marrodan Undagoitia, Marc Schumann (Zurich U.). Mar 27, 2013. 14 pp.

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