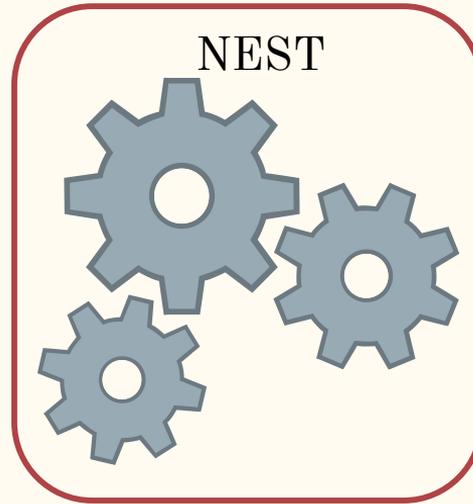# Simulation of Noble Element Detectors with NEST

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Kian Trengove on behalf of the NEST collaboration

What is NEST

NEST is an open-source software toolkit for simulating the microphysics of Xenon and Argon for noble element detectors.

- **Particle Type**
- **Energy**
- **Electric Field**
- *Detector parameters*

NEST

- **Light and charge production**
- *Pulse areas/shapes*
- *Reconstruct energy and positions*
- *Background discrimination*

Electronic Recoils (ER) - beta

We start with the work function (W_q) and the charge yield (Q_y).

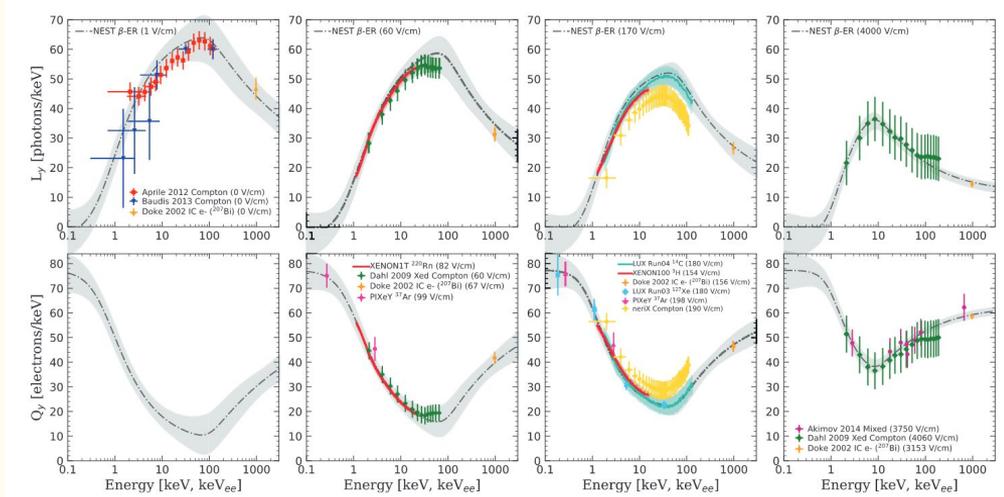Q_y is the sum of two sigmoids, with constants depending on the drift field and density.

The light yield (L_y) then follows from complete anti-correlation with Q_y.

Specific numbers shown are for Xenon:

$W_q = 21.94 - 2.93\rho$ - units are eV and g/cm^3

Bold parameters depend additionally on the electric field:

$$Q_y(E) = \mathbf{m_1} + \frac{m_2 - \mathbf{m_1}}{1 + \left(\frac{E}{\mathbf{m_3}}\right)^{\mathbf{m_4}}} + \mathbf{m_5} - \frac{\mathbf{m_5}}{\left[1 + \left(\frac{E}{\mathbf{m_7}}\right)^{m_8}\right]^{\mathbf{m_{10}}}}$$

ER beta model

Electronic Recoils (ER) - gamma

The γ ER model is treated separately from the main β ER model.

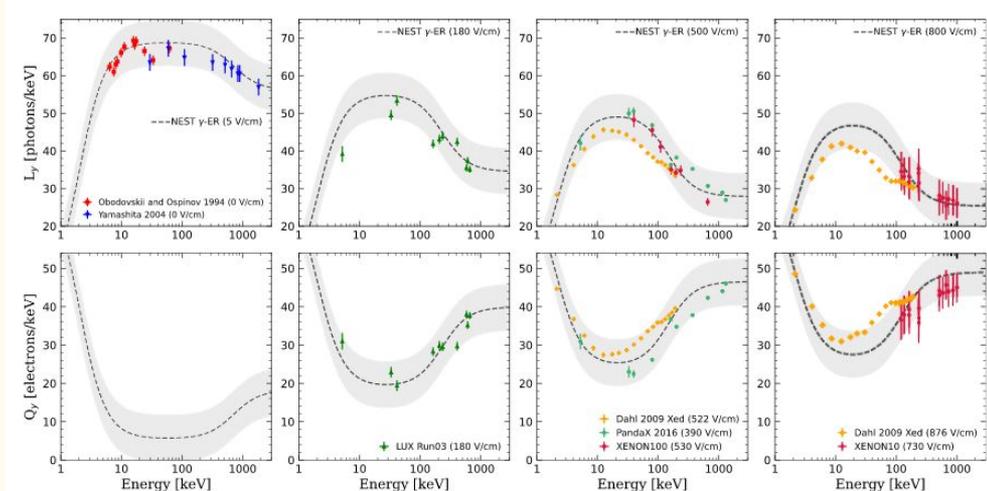The main difference is that the Q_y parameters are different to capture the different behavior.

Otherwise, the logic is the same.

Specific numbers shown are for Xenon:

$W_q = 21.94 - 2.93\rho$ - units are eV and g/cm³

Bold parameters depend additionally on the electric field:

$$Q_y(E) = \mathbf{m_1} + \frac{m_2 - \mathbf{m_1}}{1 + \left(\frac{E}{\mathbf{m_3}}\right)^{\mathbf{m_4}}} + \mathbf{m_5} - \frac{\mathbf{m_5}}{\left[1 + \left(\frac{E}{\mathbf{m_7}}\right)^{m_8}\right]^{\mathbf{m_{10}}}}$$

ER gamma model

4

Nuclear Recoils (NR)

$$N_q = aE^b$$

For NR, we start with the total quanta (N_q) and the charge yield (Q_y).

And the charge yield:

$$Q_y(E) = \frac{1}{\varsigma(\mathcal{E}, \rho)(E + \epsilon)^p} \left(1 - \frac{1}{1 + \left(\frac{E}{\zeta}\right)^\eta}\right)$$
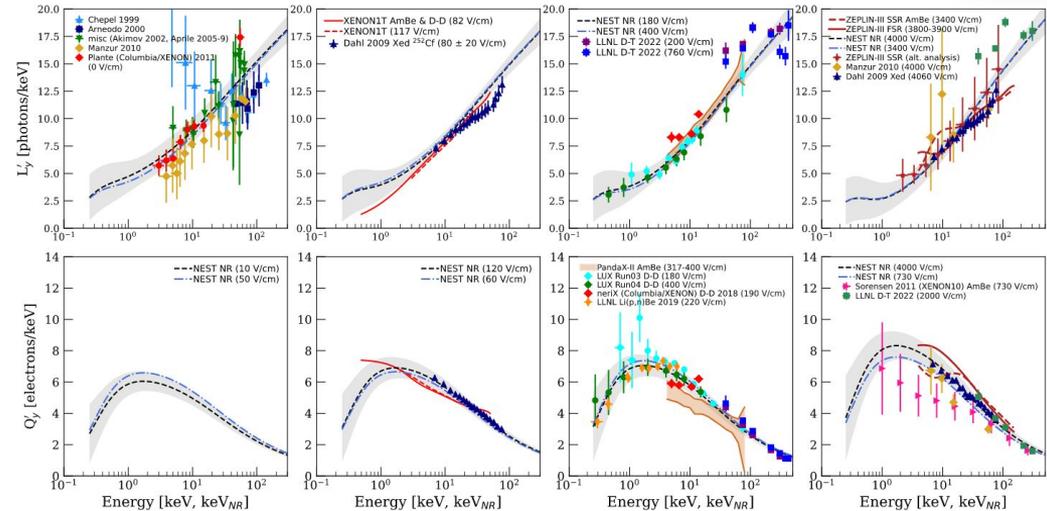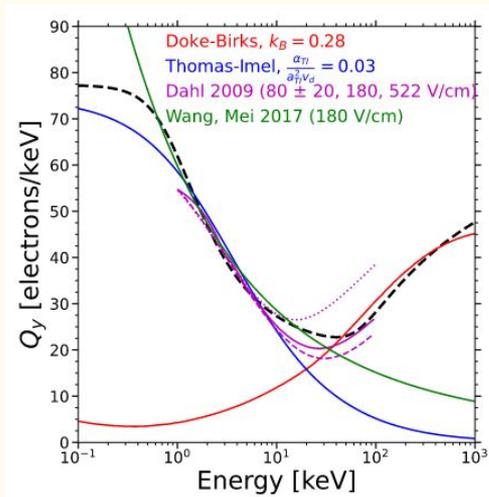
The light yield (L_y) is not completely anticorrelated unlike in ER.

$$L_y(E) = \left(\frac{N_q}{E} - Q_y\right) \left(1 - \frac{1}{1 + \left(\frac{E}{\theta}\right)^\iota}\right)$$

Empirical vs First Principles

ER:

The form chosen for the Q_y mimics two models in different energy regimes:
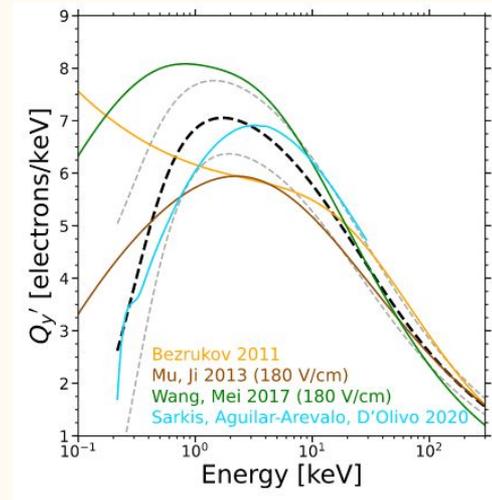
- Low Energy: Thomas-Imel Box
- High Energy: Doke-Birks

The different energy regimes (changes at ~15 keV) have qualitatively different behaviors depending on whether well-defined tracks are formed.

NR:

The NR model matches the Lindhard model at low energies, but departs at high energies.

Importantly, the NEST NR model is much simpler, taking the form of a simple power law for N_q as opposed to nested power laws inside a rational function.
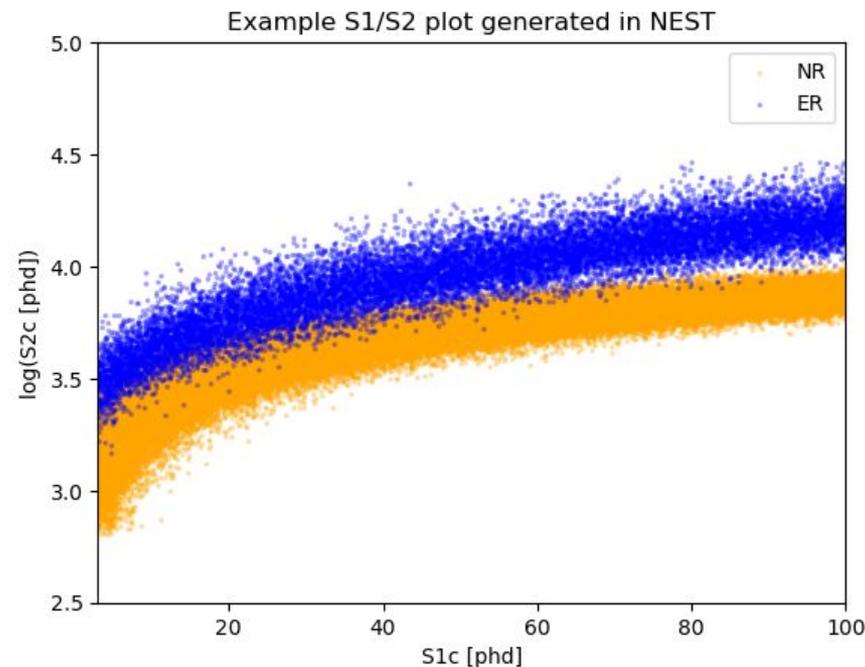
Modelling Pipeline

We begin with modeling the total quanta (either directly for NR or through W_q for ER) and Q_y and L_y.

From Q_y and L_y we can determine the Exciton/Ion ratio. We then perform fluctuations using a Fano-like factor and model recombination as a skew-gaussian pdf.
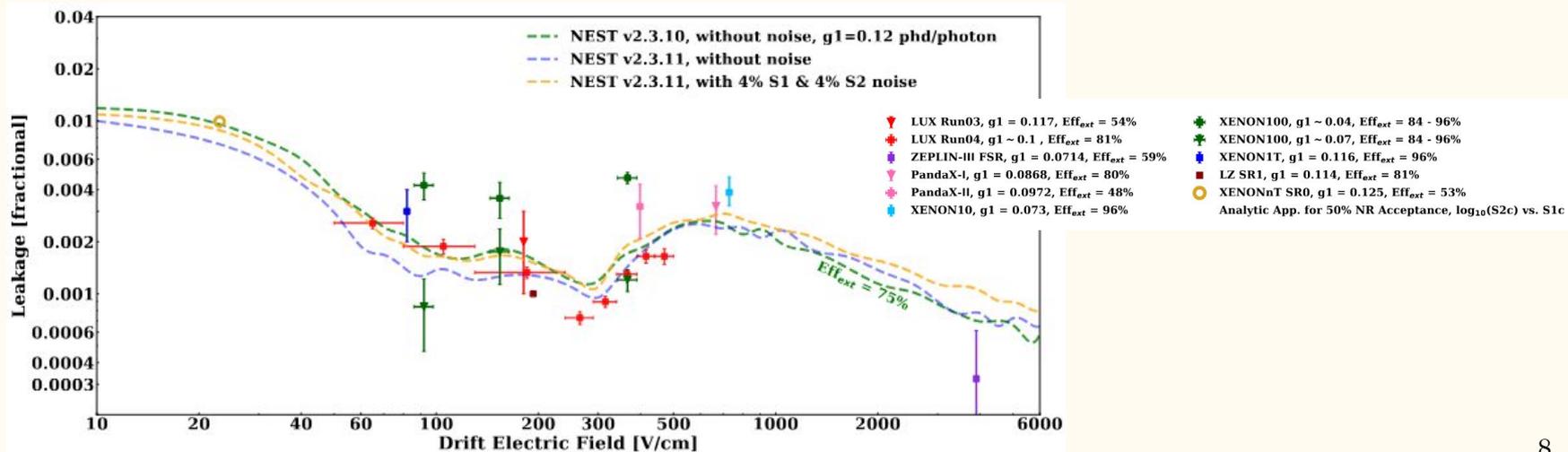
After fluctuations and recombination excitons/ions becomes photons/electrons and we directly model S1 (prompt scintillation) and S2 (secondary scintillation) with $S1 = N_{ph} \, g_1$ and $S2 = N_{e-} \, g_2$

Example S1/S2 plot generated in NEST

Background discrimination / leakage

One of the main reasons for using Noble Element detectors, particularly liquid time projection chambers (TPCs) is their ability to distinguish between ER and NR events.
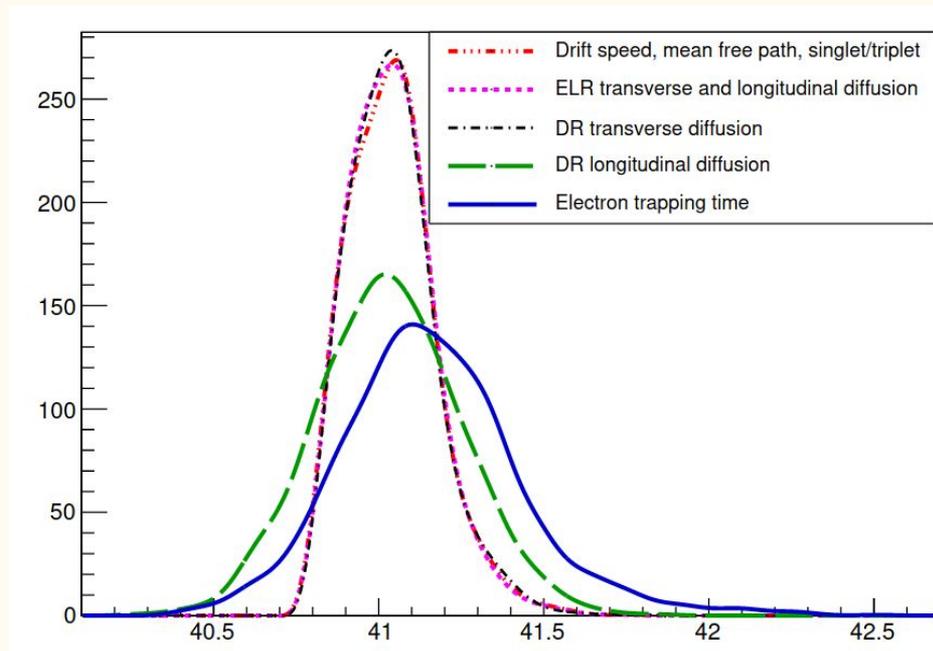
We can model this leakage/discrimination using NEST.

Pulse Area and Shape

NEST has four different options for calculating pulse areas:

- Counting PMT hits
- Modeling the pulse area as a parametric equation
- A hybrid between counting PMT hits and parametric mode
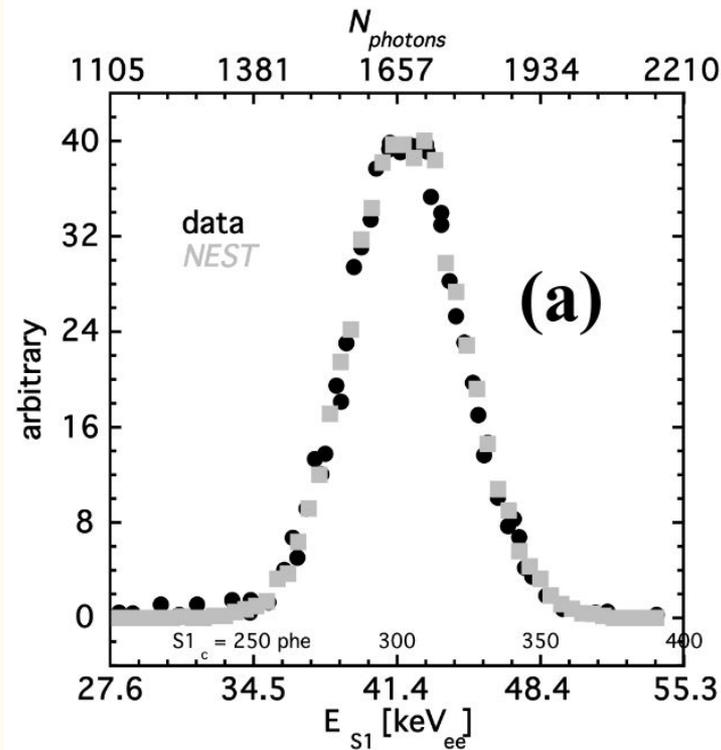- Simulating the full waveform and integrating for the area

Above: An example of an S2 pulse modeled in NEST, broken down as we include more parts of the model.

Argon

Modelling Argon detectors in NEST is in active development and a lot of work has already been done and is publicly available on the NEST github.

In many cases LAr NEST only requires fitting existing NEST parameters to argon calibrations.

One of the main places where we are focusing our efforts is in modelling the pulse shapes in argon, which does significantly deviate from xenon.

A comparison between NEST simulations and DarkSide Kr^{83m} calibrations.

Questions and Comments?