NOBLE ELEMENT SIMULATION TECHNIQUE: CURRENT STATUS AND FUTURE PLANS

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on behalf of NEST collaboration

NEST COLLABORATION

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UC San Diego

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RICE

MEPhI
National Research Nuclear University • Moscow Engineering Physics Institute • MEPhI

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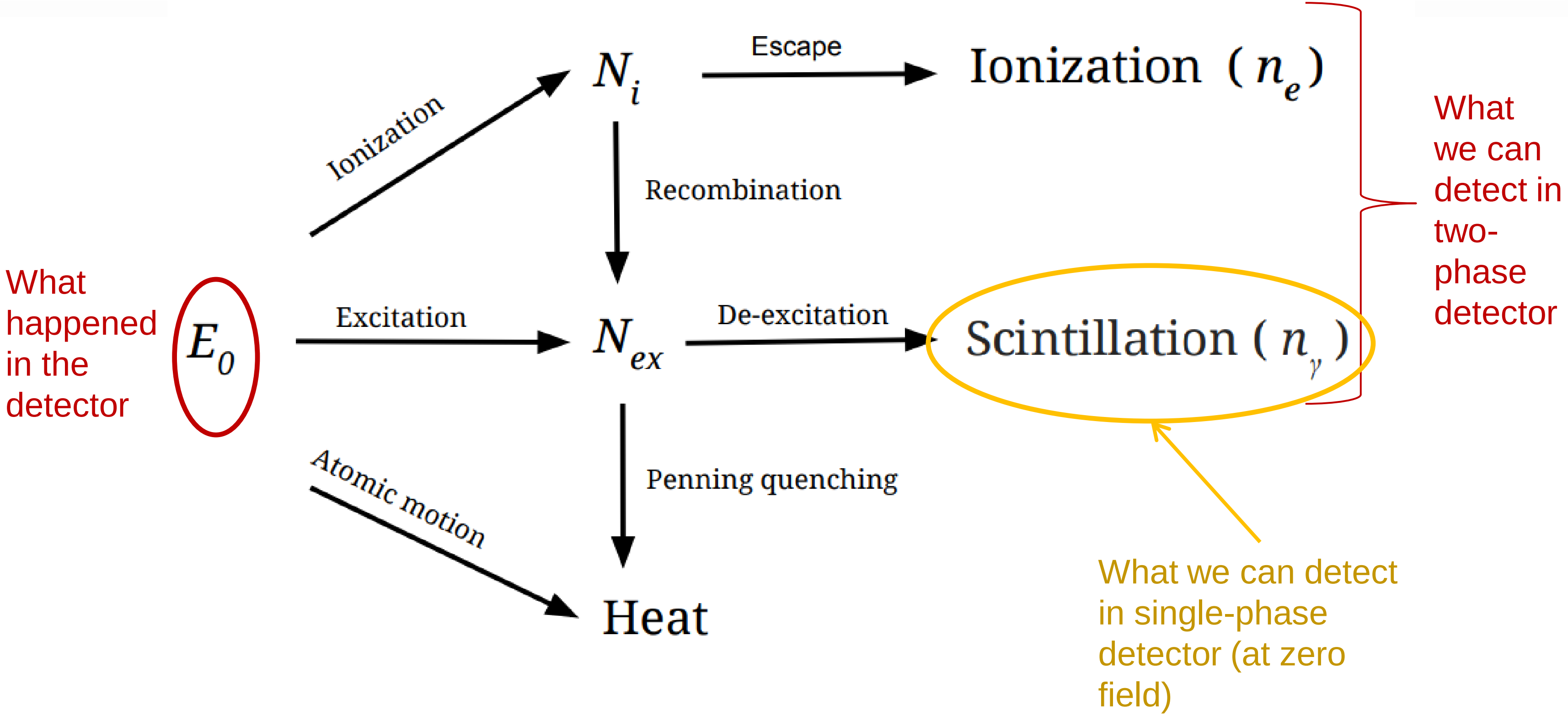
State University of New York

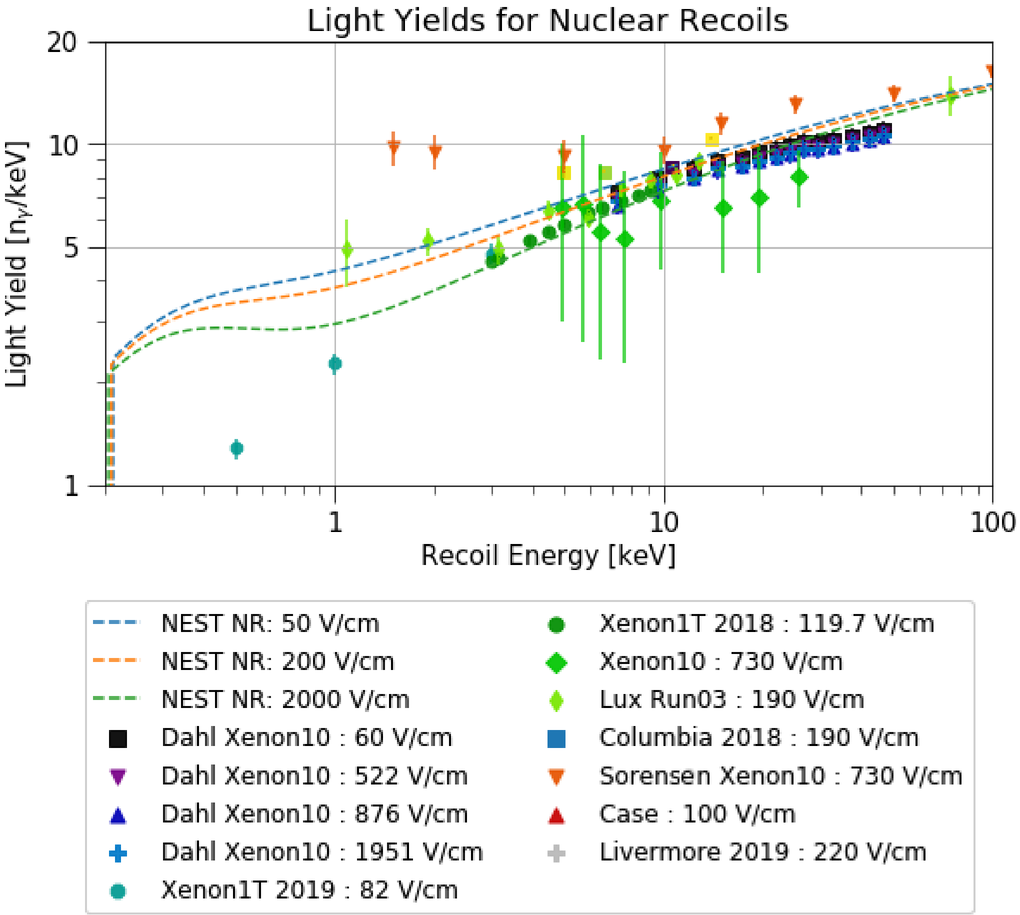
SIGNAL IN TWO-PHASE DETECTORS



ABOUT NEST

- "Inter-collaboration" collaboration
  - Members from LUX, LZ, XENON, nEXO, RED100, COHERENT, DUNE, ICARUS, MicroBooNE and SBN
- Exists in both C++ and Python
  - Now only for all xenon phases, but argon is very close to implementation in code too (models are already exist!)
- GEANT4 integration
  - Also has ROOT integration for leakage calculations
- Detector simulation
  - Takes into account detector geometry and design (number of PMT, temperature/pressure, etc.
- nest.physics.ucdavis.edu

NUCLEAR RECOILS

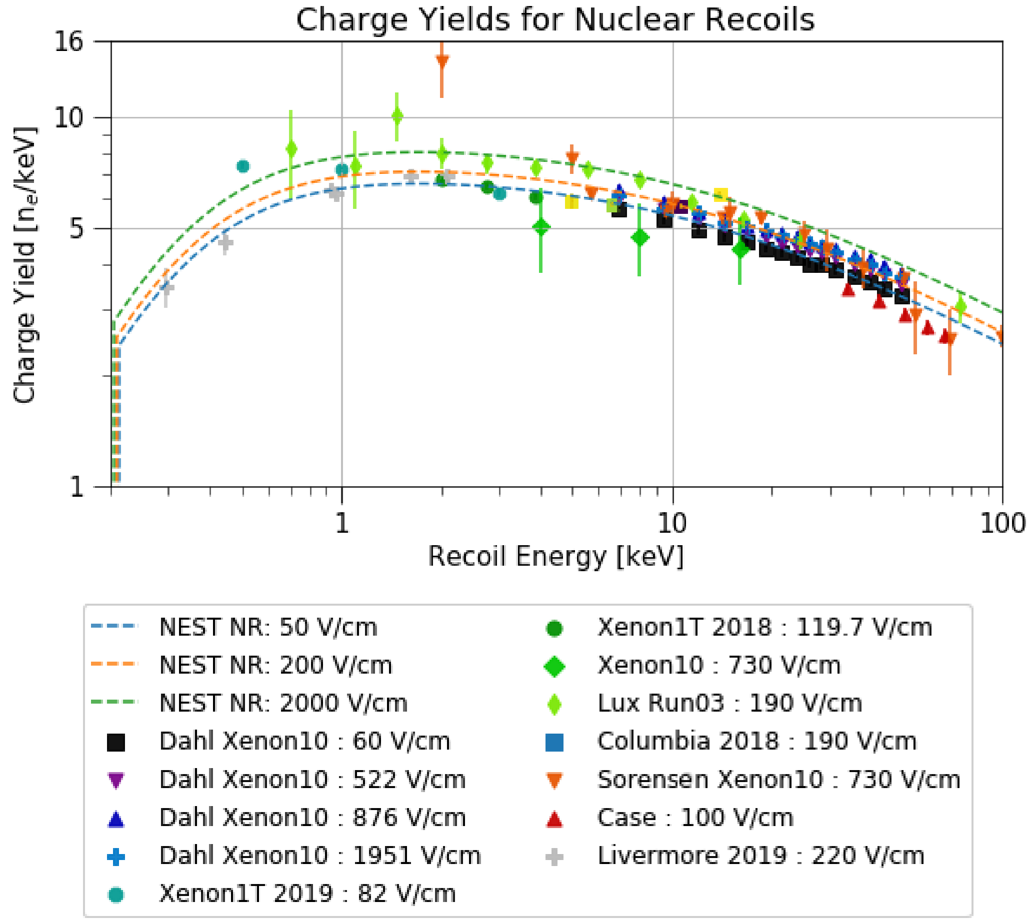


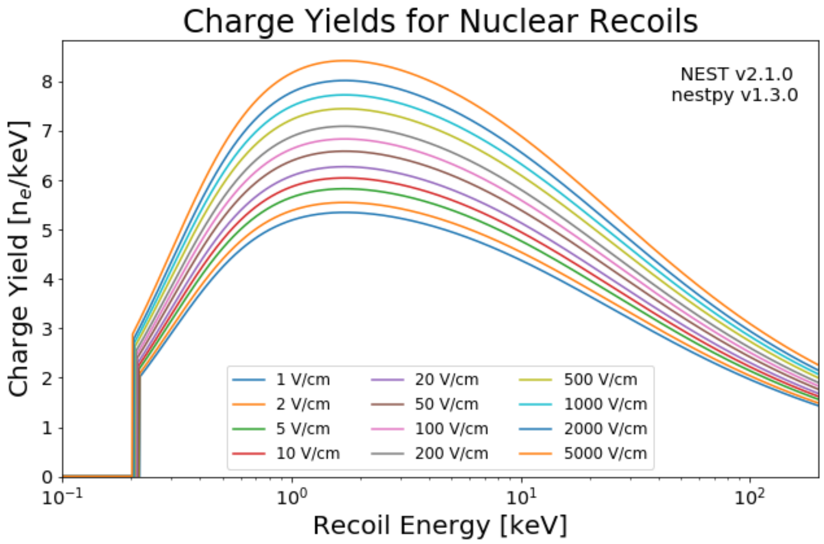
- Total quanta N_q (light+charge) is a power law
  - $N_q = \alpha E^\beta$
  - Charge and light are not anticorrelated at low energies
  - $N_e = \frac{E}{TIB*\sqrt{E+\varepsilon}} * (1 - \frac{1}{1+(\frac{E}{\zeta})^\eta})$
  - $N_{ph} = (N_q - N_e) * (1 - \frac{1}{1+(\frac{E}{\theta})^\iota})$
  - TIB $= \gamma * Field^\delta * (\frac{\rho}{\rho_0})^{0.3}$
  - $\alpha, \beta, \gamma, \delta, \varepsilon, \zeta, \eta, \theta, \iota$ are free parameters
  - ρ_0 is 2.9 g/cm^3 for xenon

Plots by V.Velan and S. Andaloro

NUCLEAR RECOILS

Plots by V.Velan and S. Andaloro



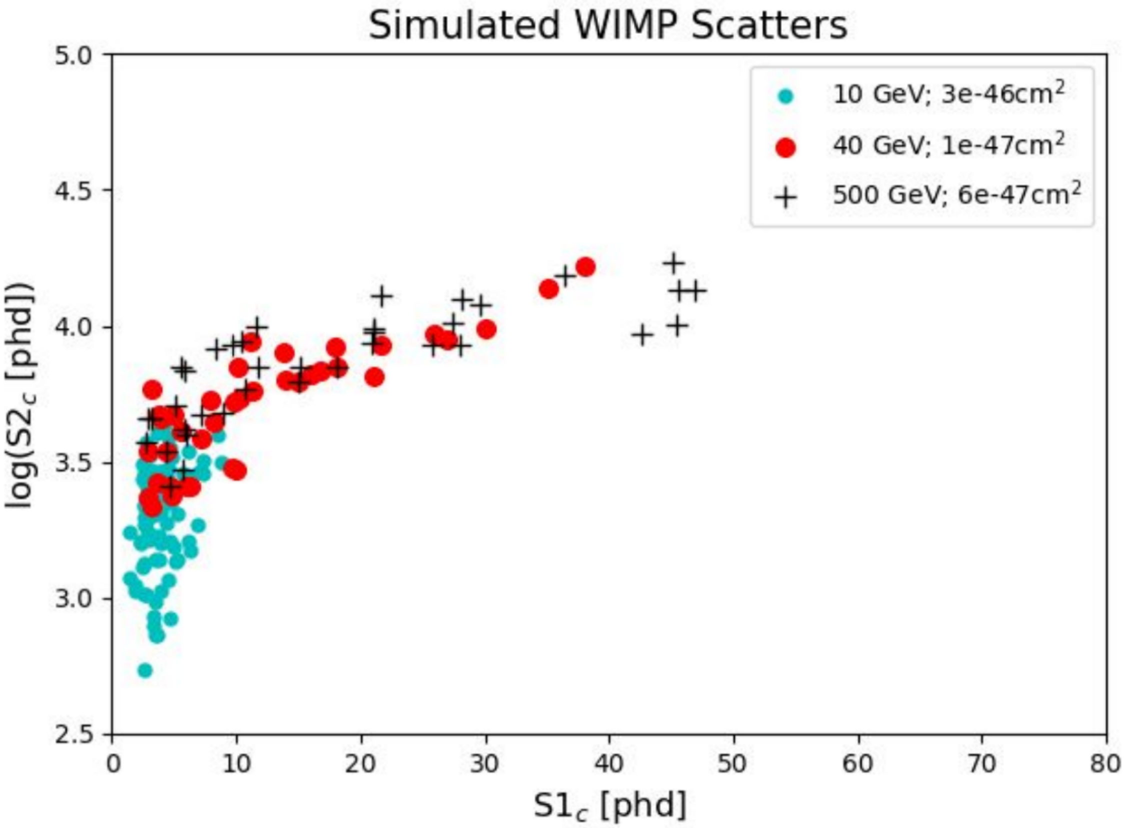


More information in our detailed note

All benchmark plots are by V.Velan and S. Andaloro

NUCLEAR RECOILS: WIMPS

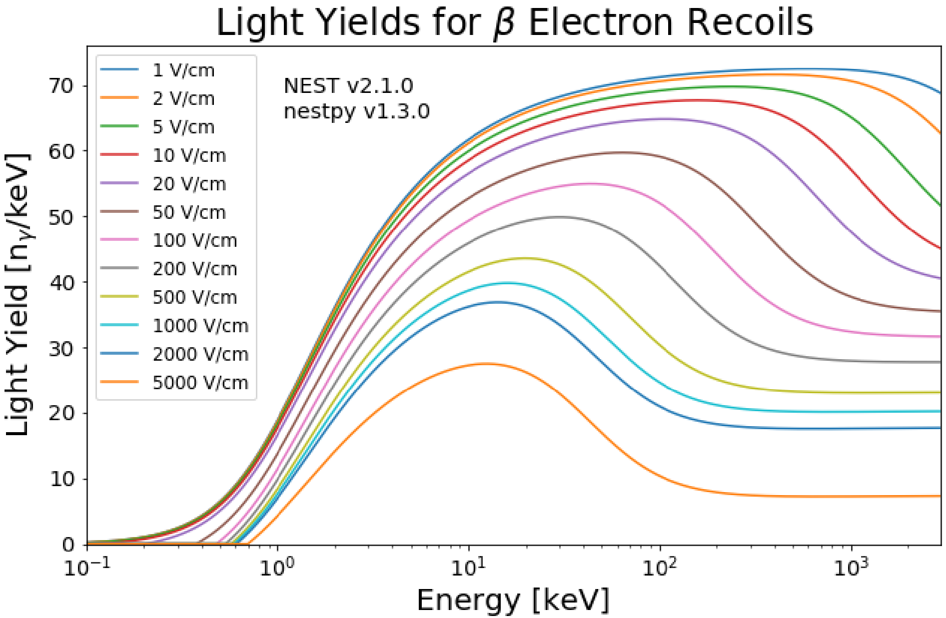
NEST NR model has separate option for WIMP simulation

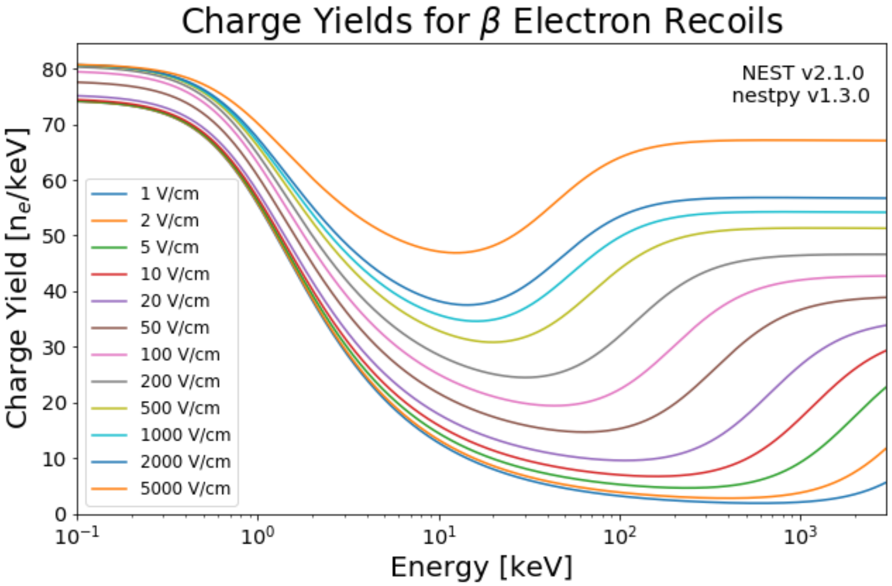


From:
Projected WIMP Sensitivity of the LUX-ZEPLIN (LZ) Dark Matter Experiment
LUX-ZEPLIN Collaboration (D.S. Akerib (SLAC & KIPAC, Menlo Park) *et al.*). Feb 16, 2018.
arXiv:1802.06039

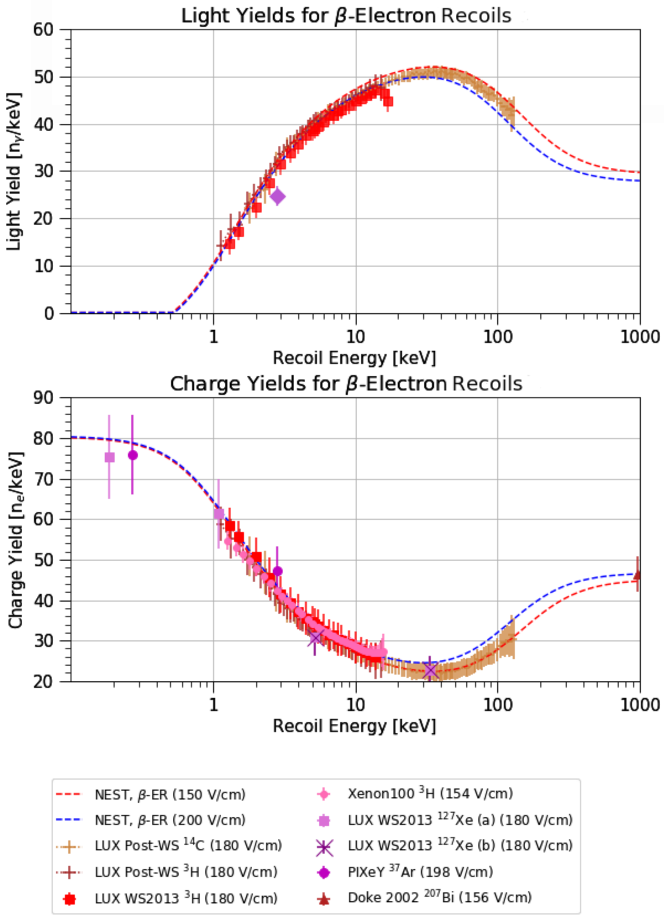
ELECTRON RECOILS

- Smooth transition between low and high energies
- Ly+Qy = const



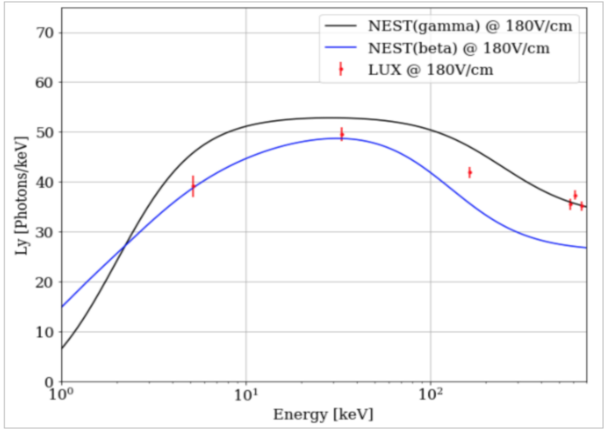


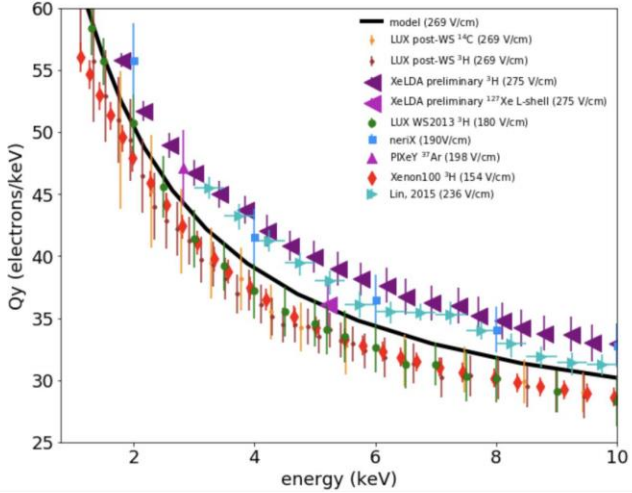
ELECTRON RECOILS



- Different models for beta (e.g electron emission) and gamma (e.g. photo-absorption) because of different physics of the interactions
- Separate inner-shell electron capture model is planned

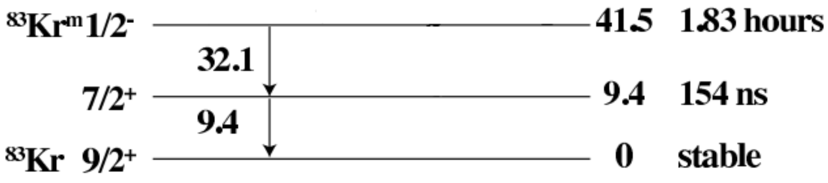
Plots by V.Velan, S. Andaloro, G. Rischbieter and J. Balathy

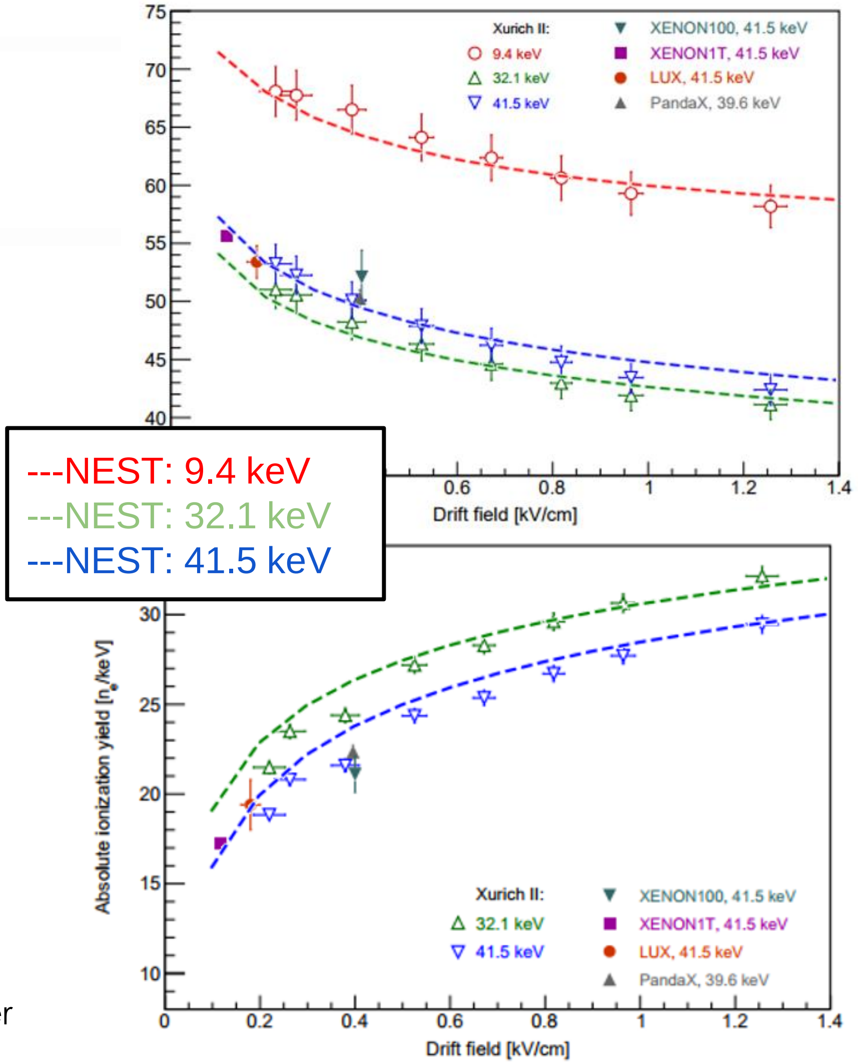




83mKr

- Robust time-dependent model
- Matches individual decays as well as 'merged' decay



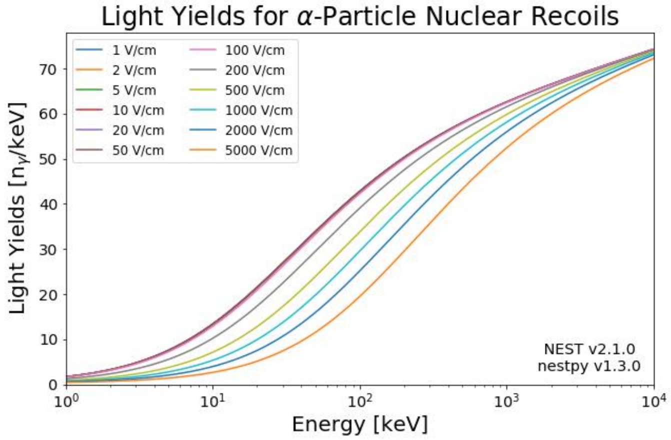


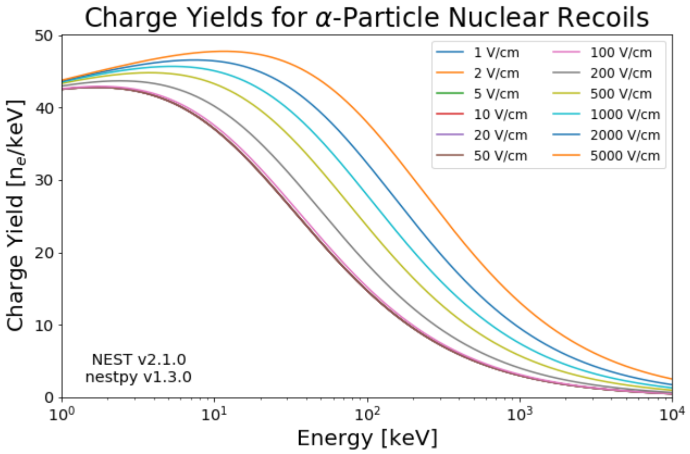
Plots by G. Rischbieter

α- PARTICLES

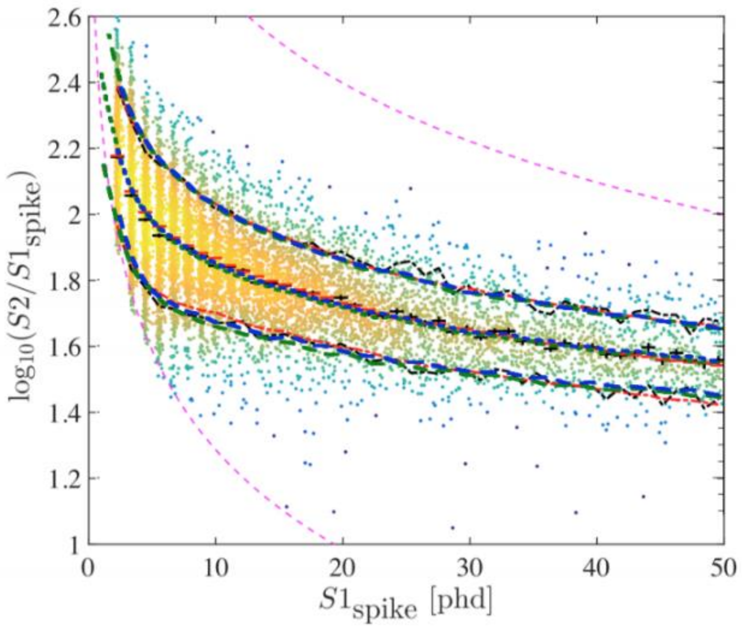
- $N_q = \frac{L*E}{W}$
- $L = \alpha E^{\beta}$
- $N_{ph} = \frac{N_q * \frac{N_{ex}}{N_i}}{1+\frac{N_{ex}}{N_i}} + R * N_i$
- R is Thomas-Imel Box parameter
- L is "Lindhard factor", α and β are free parameters
- $\frac{N_{ex}}{N_i}$ (exciton-ion ratio) and L-factor are based on data
- $N_e = (N_q - N_{ph})$

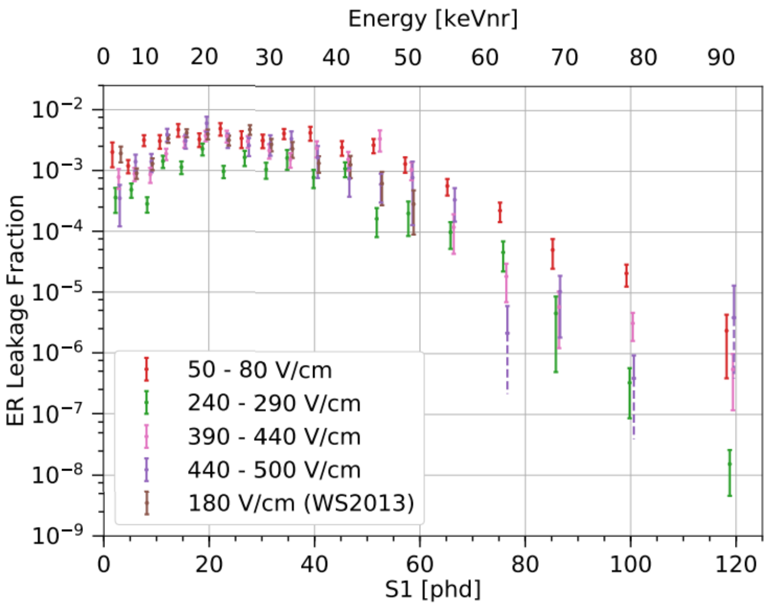
- Good agreement for strong fields





LEAKAGES AND FLUCTUATIONS

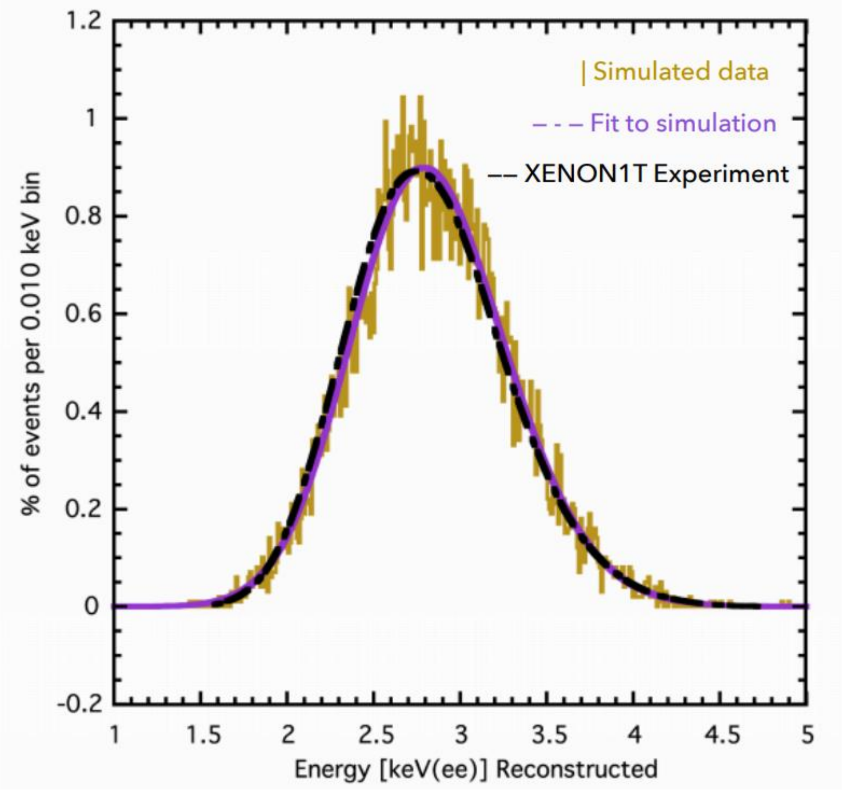




- NEST is also capable of simulating ER/NR bands leakage (in combination with ROOT)

Plots by G. Rischbieter

ENERGY RECONSTRUCTION



Ar-37 peak reconstructed by NEST

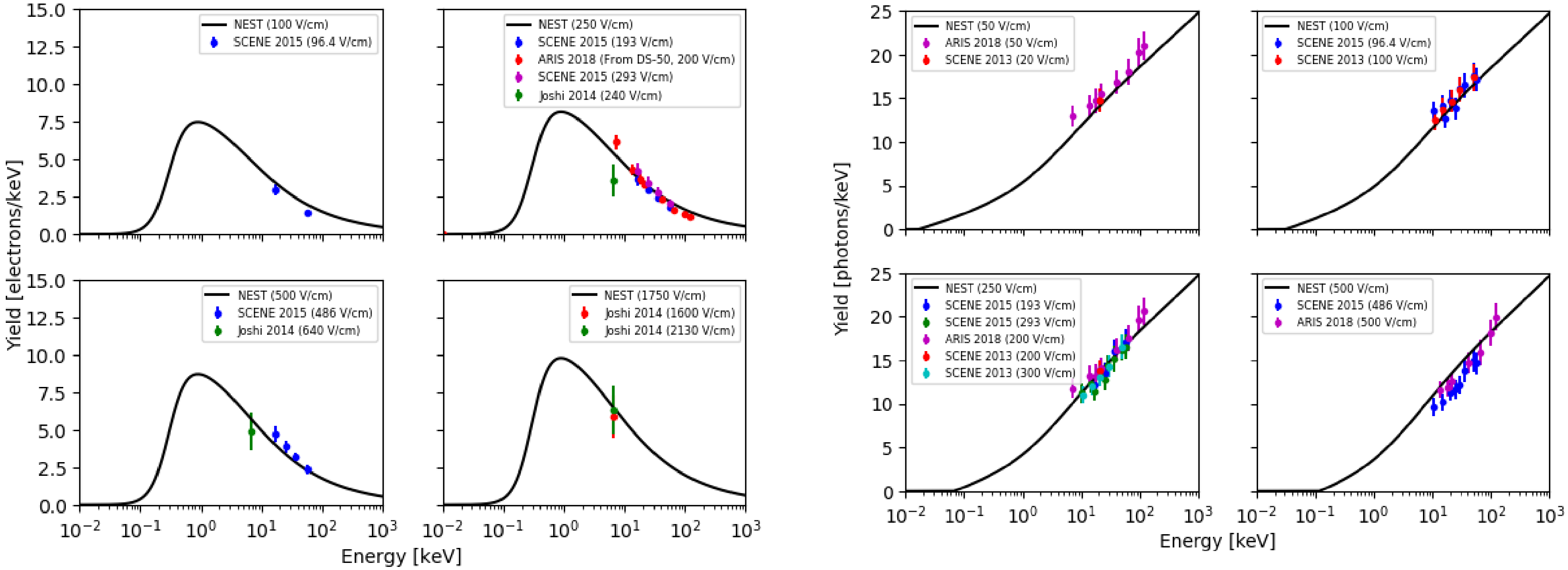
NEST has two options of work: “pure Monte-Carlo” and “reconstruction” which simulates reconstruction process of real data

Plot by S. Andaloro

ARGON NEST

- Argon NEST is under-development version of NEST for argon
- Assumption: both Xe and Ar are noble elements – and formulae would be similar sigmoids for Ar too
- Empirical models for argon are very important – because theoretical models sometimes are contradictory to each other
- Mean yield models for NR, ER, alpha and drift velocity model already exist!
- Recombination fluctuations model is under construction
- Argon models will be included in main NEST code soon

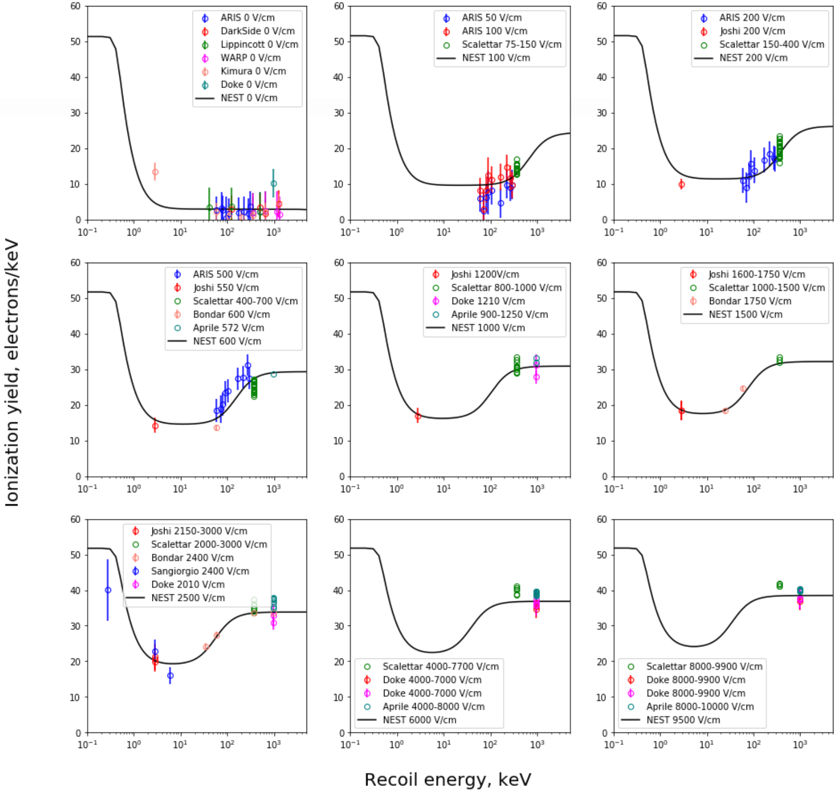
ARGON NEST: NUCLEAR RECOILS

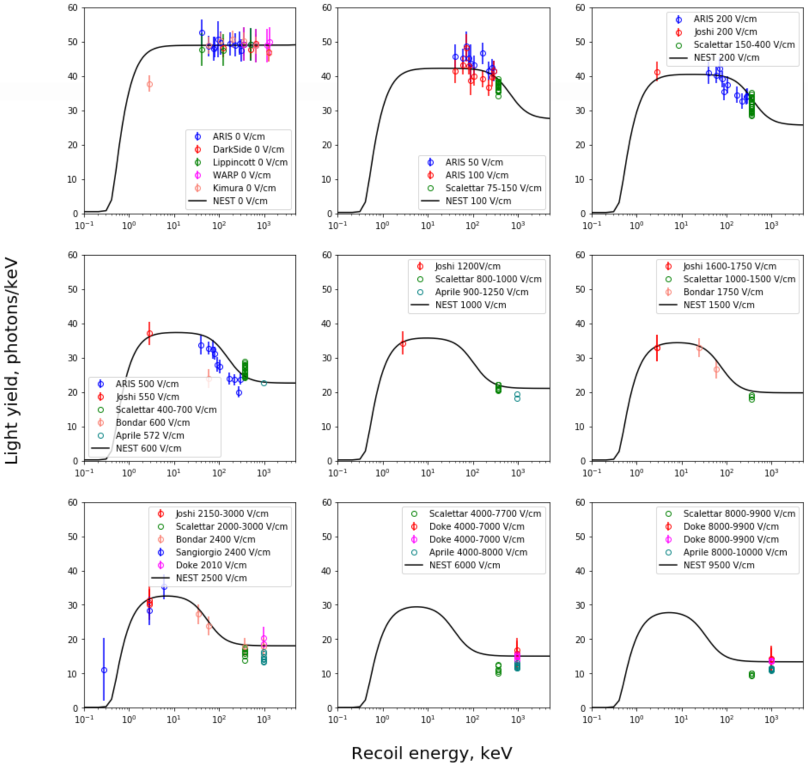


Models are based on xenon NR model

Plots by J. Mueller

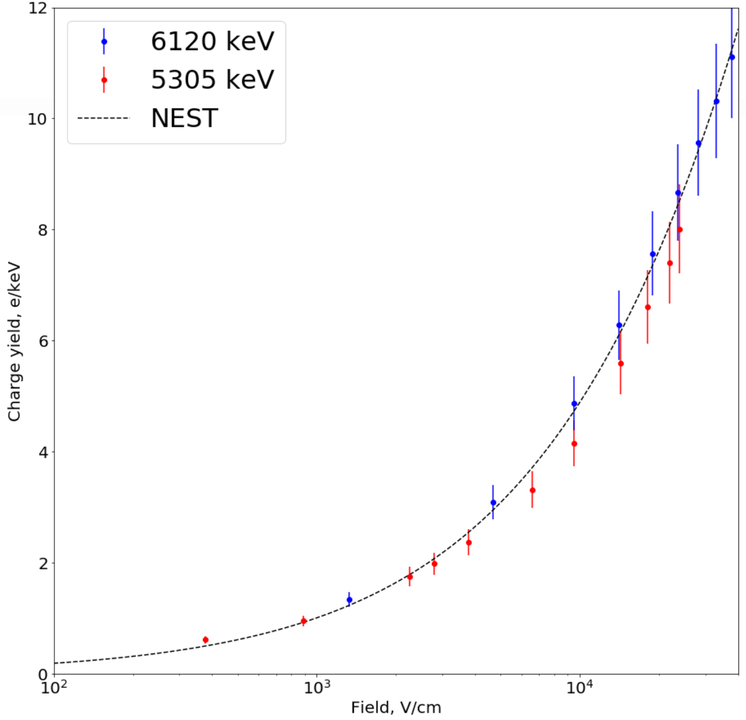
ARGON NEST: ELECTRON RECOILS

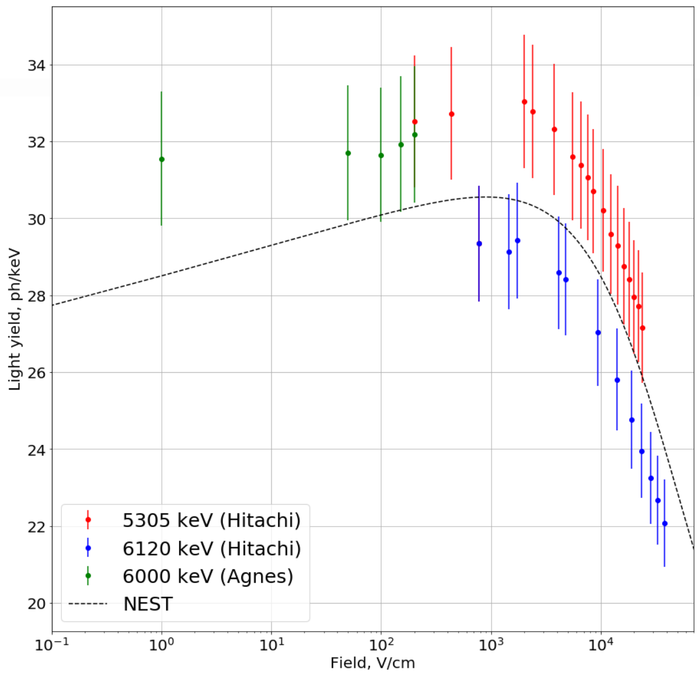




- Models are based on xenon ER beta model
- Unfortunately there aren't enough data for separate gamma model

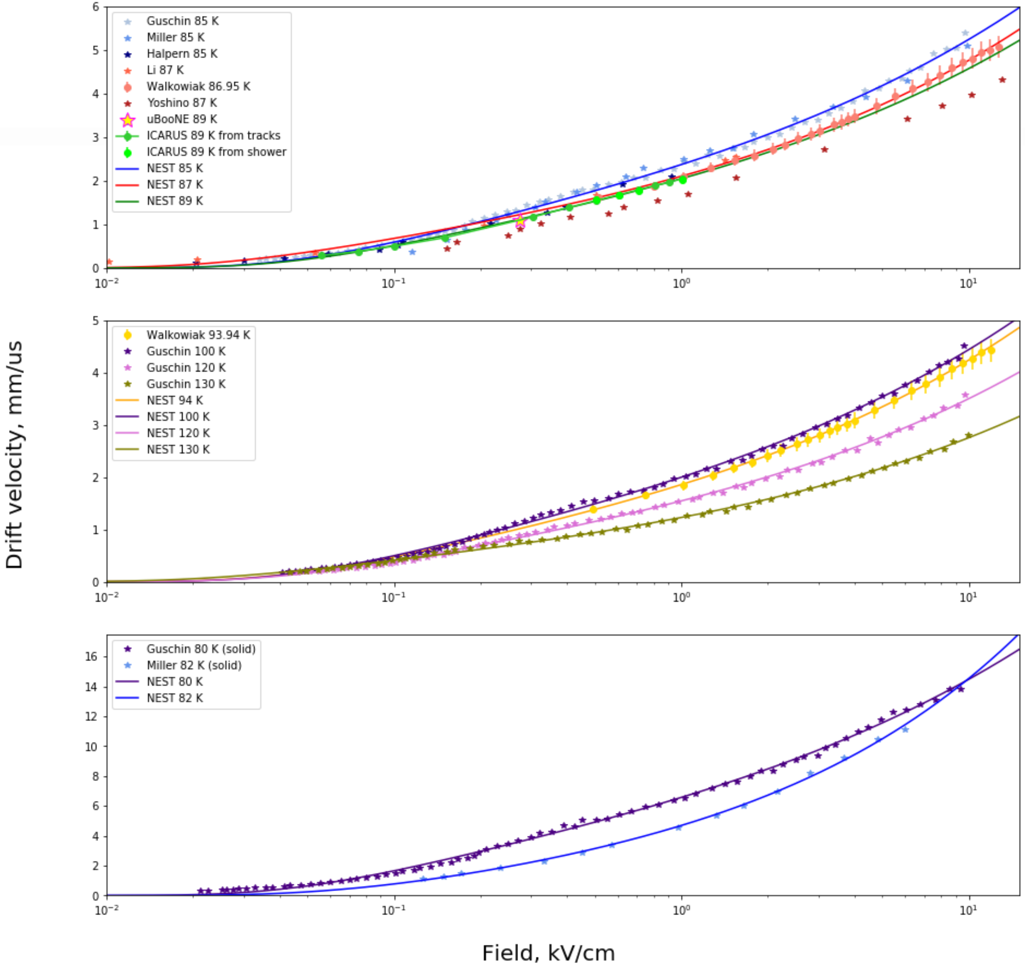
ARGON NEST: ALPHA MODEL





- Model takes into account light yield "peak" reported by Hitachi and Agnes
- Possible theoretical explanation: ionization track density, fields in Ar can extract additional quanta

ARGON NEST: DRIFT VELOCITY



- Now only for liquid and solid phases
- Also empirical as for xenon

CONCLUSION

- NEST is a powerful simulation tool, which now has two versions: standalone tool and GEANT4 library.
- Accurately simulates many different interactions in all xenon phases
- Argon mean yield models are ready
- If you want to read more about NEST:
  - NR analysis note
  - Heavy ion note
  - Argon mean yields note
  - All notes are available on NEST site
  - ~~We'll write a cool big paper someday, we promise~~
- Get yourself a copy!
  - https://github.com/NESTCollaboration/nest
  - nest.physics.ucdavis.edu
  - https://github.com/NESTCollaboration/nestpy (python version)

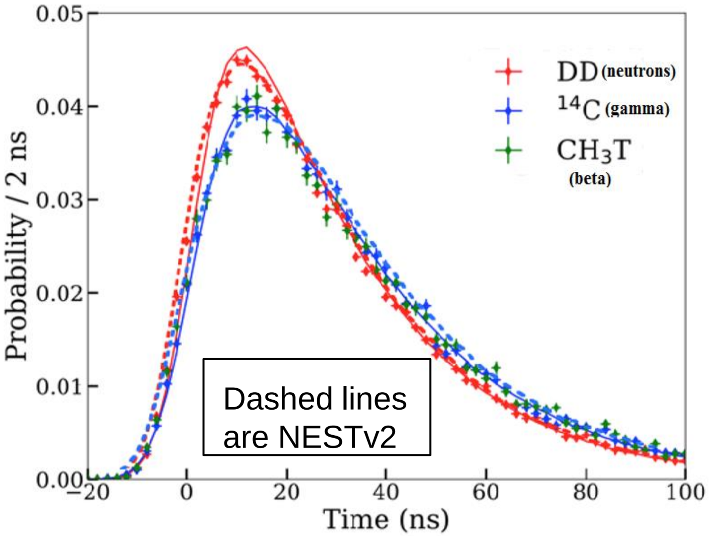
THANK YOU FOR YOUR ATTENTION!

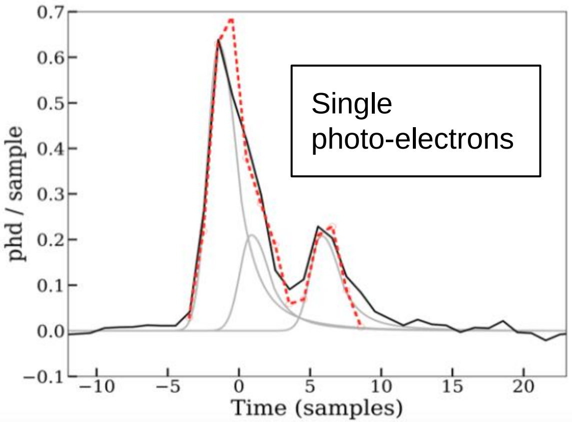
BACKUP SLIDES

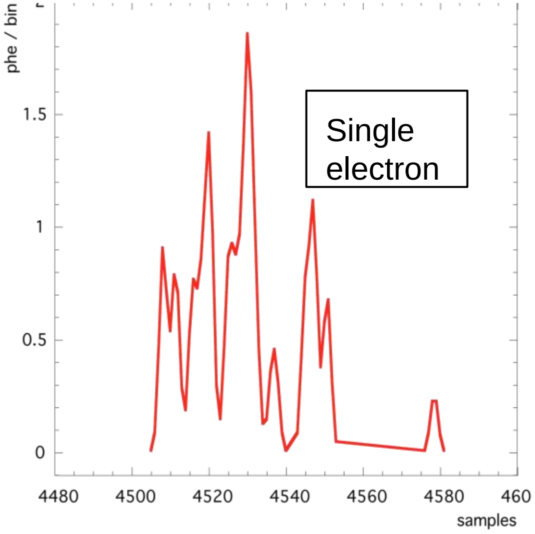
PULSE SHAPES AND SINGLE ELECTRONS

- Matches LUX pulse shape discrimination
- Can also simulate single electrons!
- Simulates SE noise in LXe

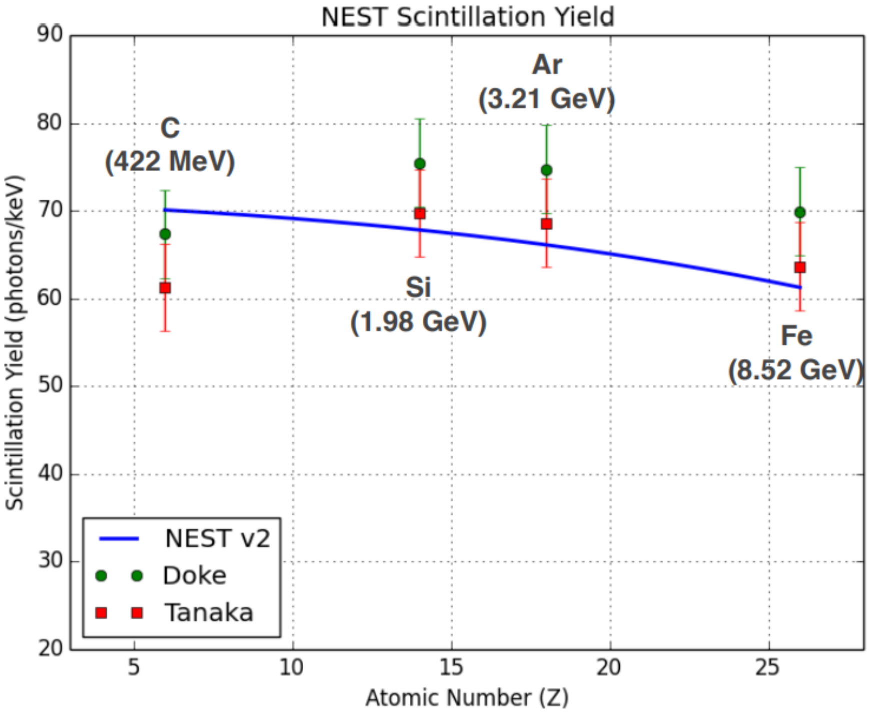
Histograms of scintillation photons arrival times

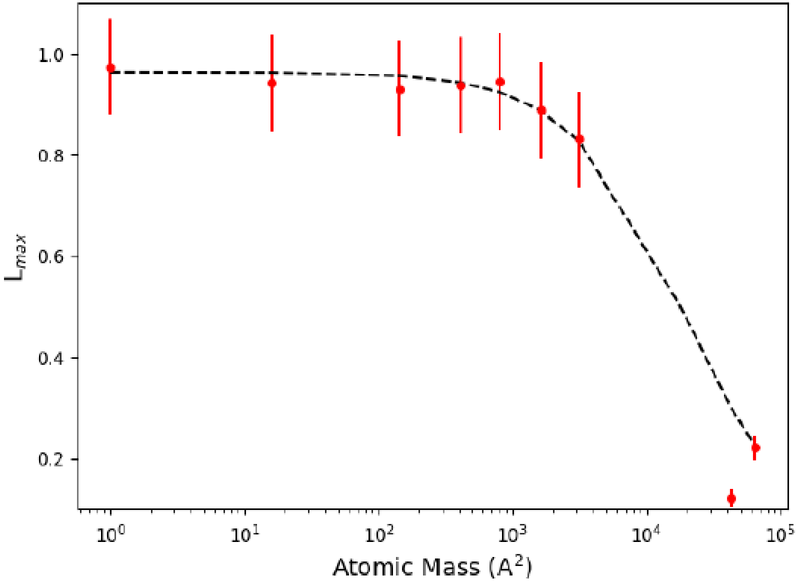






HEAVY IONS MODEL

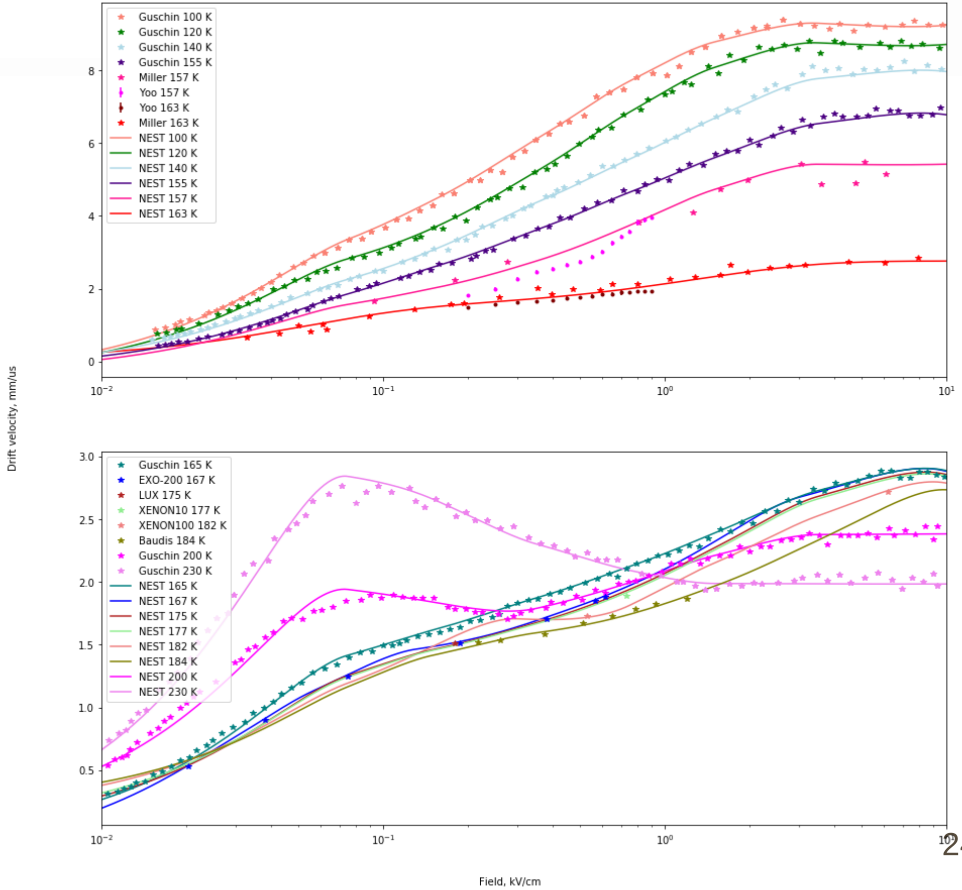




$$L = \frac{a}{1 + (\frac{A^2}{b})^c}$$

DRIFT VELOCITY

- NEST also simulates drift velocity for various xenon temperatures and states
- Has good agreement with old and new data



ENERGY RESOLUTION

- Quantum Fluctuations
  - First estimates of fluctuations in energy resolution and fluctuations in quanta produced were by Ugo Fano in the 1940's.
  - There is energy "lost" when photons are produced in LXe from electron recoils!
  - $E = W^*(n_\gamma + n_e)$ → Work Function: $W = 13.7$ eV
  - Fluctuations modeled using an empirical "Fano-like" factor proportional to sqrt(energy)*sqrt(field)
- Recombination Fluctuations
  - Binomial recombination has never matched data well.
  - Same equation as cited in LUX Signal Yields Publication: $\sigma_T^2=(1-p)^*n_i^*p + (\sigma_p n_i)^2$
    - σ_p in NEST is both field-dependent and energy-dependent

RECOMBINATION FLUCTUATIONS

- Comparing to Eric Dahl's PhD thesis data.
- Corrected Dahl data for overestimation: corrected 15% downward for 2PE effect and extraction eff.

$\sigma_T{}^2$=(1-p)*n_i*p + $(\sigma_p n_i)^2$