Noble Element Simulation Technique Version 2.0

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on behalf of NEST collaboration

NEST collaboration

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Colorado State University

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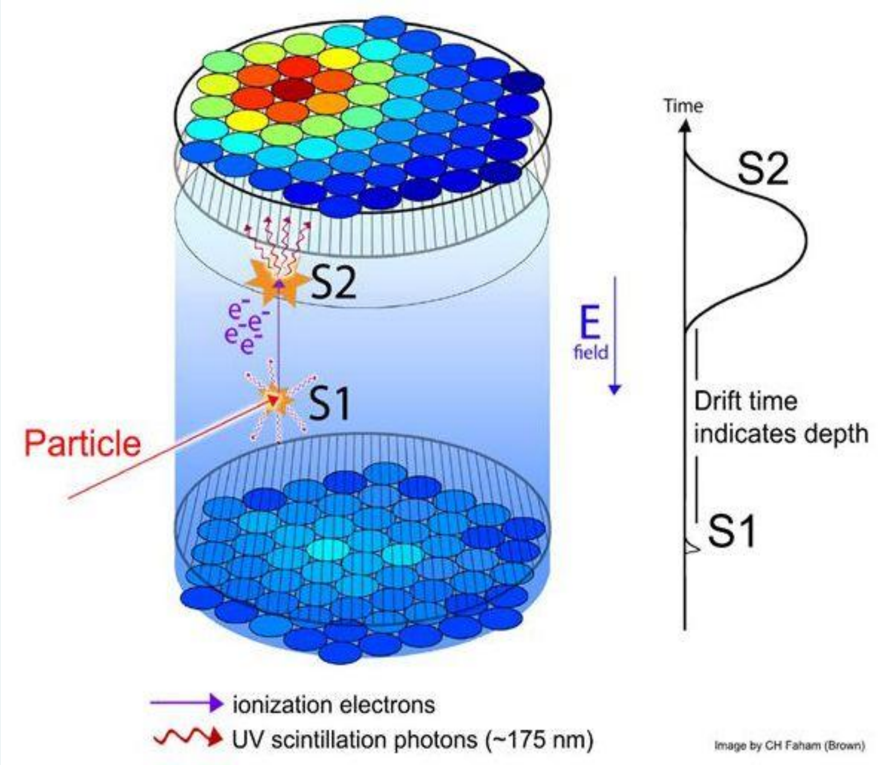
About NEST

- NEST (**Noble Element Simulation Technique**) is an unprecedentedly accurate and comprehensive simulation of the scintillation, ionization, and electroluminescence processes in noble elements.
- Appliciations:
  - Direct dark matter searches (LUX, LZ, XENON10, PandaX…)
  - Double beta decay searches
  - CEvNS
  - Much more!



About NEST

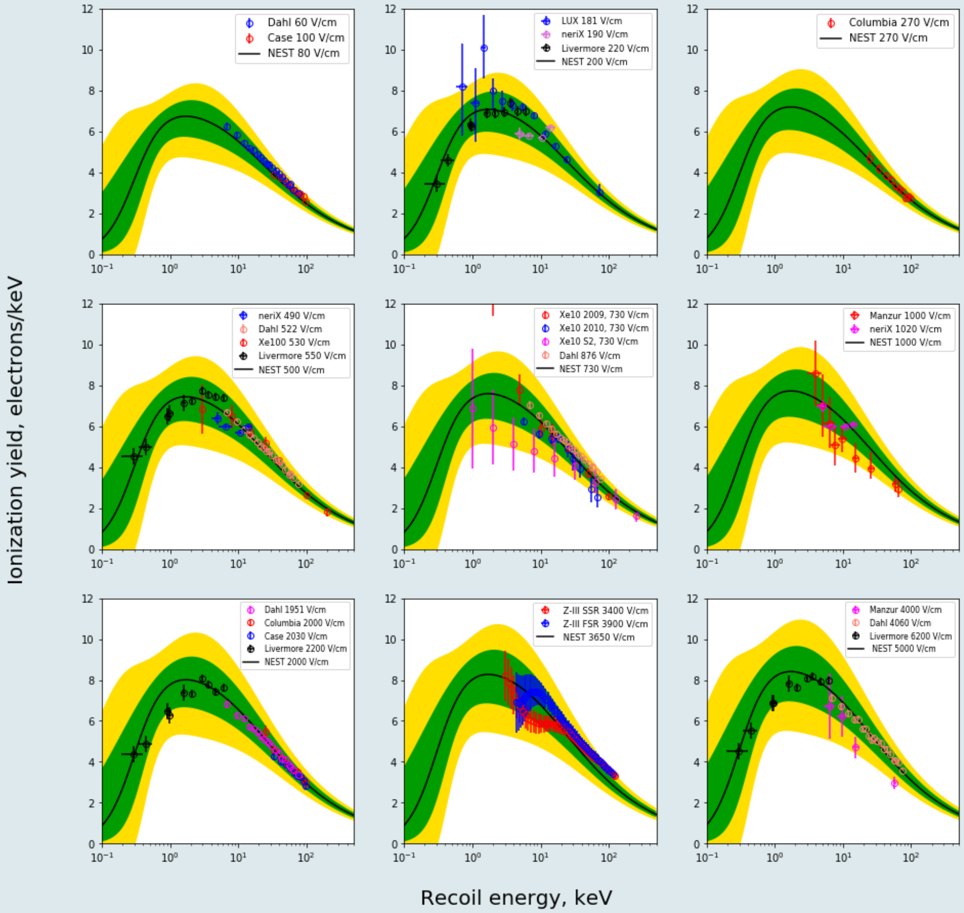
```
[aspelene@aspelene nest130119]$ ./testNEST 10 gamma 511 511 218 -1
*** Detector definition message ***
You are currently using the default XENON10 (changed version) template detector.


g1 = 0.076 phd per photon       g2 = 18.1131 phd per electron (e-EE = 99.0178%, SE_mean,width = 18.2928,5.55044)        Density = 2.8611 g/mL    central vDrift = 1.53908 mm/us
                                                                W = 13.6908 eV  Negative numbers are flagging things below threshold!   phe=(1+P_dphe)*phd & phd=phe/(1+P_dphe)
E [keV]         field [V/cm]    tDrift [us]     X,Y,Z [mm]      Nph     Ne-     S1 [PE or phe]  S1_3Dcor [phd]  spikeC(NON-INT) Ne-Extr S2_rawArea [PE] S2_3Dcorr [phd]
511.000000      218.000000      27.518703       33, -14, 108    19997   17375   1875.634141     1563.028451     1563.028451     16981   372089.241519   313977.292530
511.000000      218.000000      46.101887       29, 14, 79      19555   17347   1785.404024     1487.836687     1487.836687     16813   368593.989719   313666.269861
511.000000      218.000000      44.632275       -7, 30, 81      16078   20758   1380.211882     1150.176569     1150.176569     20134   442183.010849   376037.806971
511.000000      218.000000      53.845306       15, -25, 67     17517   20168   1626.602925     1355.502437     1355.502437     19475   427190.635730   364812.655710
511.000000      218.000000      52.957826       4, -18, 68      15527   21838   1552.693377     1293.911147     1293.911147     21126   463315.275529   395502.830997
511.000000      218.000000      37.530780       12, 15, 92      21401   15303   1973.891763     1644.909803     1644.909803     14866   325764.336070   276141.140341
511.000000      218.000000      37.235463       14, -32, 93     19275   18512   1774.008333     1478.340278     1478.340278     18015   395850.801737   335506.399504
511.000000      218.000000      26.105013       -23, 27, 110    19915   16427   1792.109753     1493.424794     1493.424794     16099   352829.894006   297534.567776
511.000000      218.000000      38.934541       39, -30, 90     16937   20066   1493.121908     1244.268256     1244.268256     19513   429356.446017   364185.521522
511.000000      218.000000      37.110086       26, 41, 93      19347   18056   1755.892244     1463.243537     1463.243537     17570   386174.287539   327286.342777
S1 Mean         S1 Res [%]      S2 Mean         S2 Res [%]      Ec Mean         Ec Res[%]       Eff[%>thr]
1700.957035     10.776170       403758.099359   11.247163       511.000000      0.000000        100.000000
If your energy resolution is 0% then you probably still have MC truth energy on.
```

- NEST takes particle type (NR, ER, etc.), initial energy(energies), drift field and direction (-1 for random generation in detector volume) and predicts all parameters of the signal (S1, S2, etc.)
- NEST is capable of energy reconstruction simulation (picture on slide shows different mode – pure MC energy).

NEST v1.0 vs NEST v2.0

NESTv1.0	**NESTv2.0**
Only GEANT version	Standalone (C++ and Python) & GEANT versions
No alphas and heavy ions	Alphas and heavy ions simulations included
All equations based on theoretical models (Thomas-Imel box, Doke-Birks, etc.)	Using sigmoids (family of S-shape functions), which still closely resemble those models.

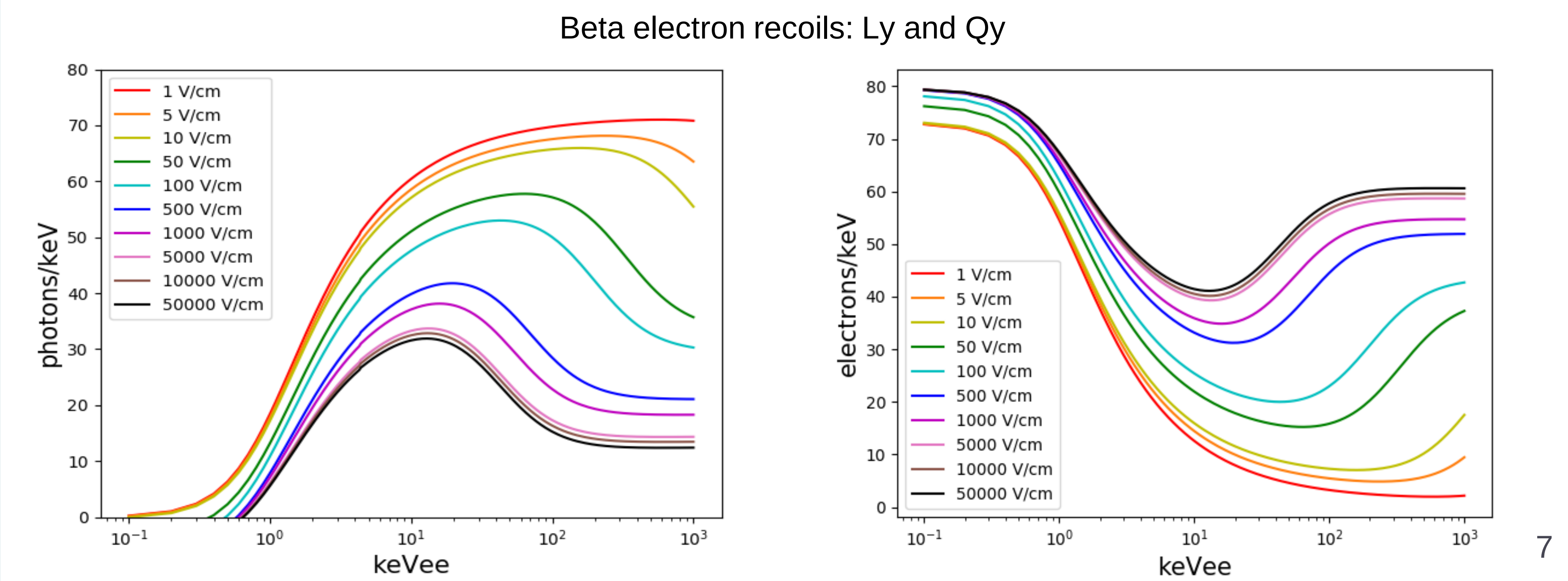
Nuclear recoils



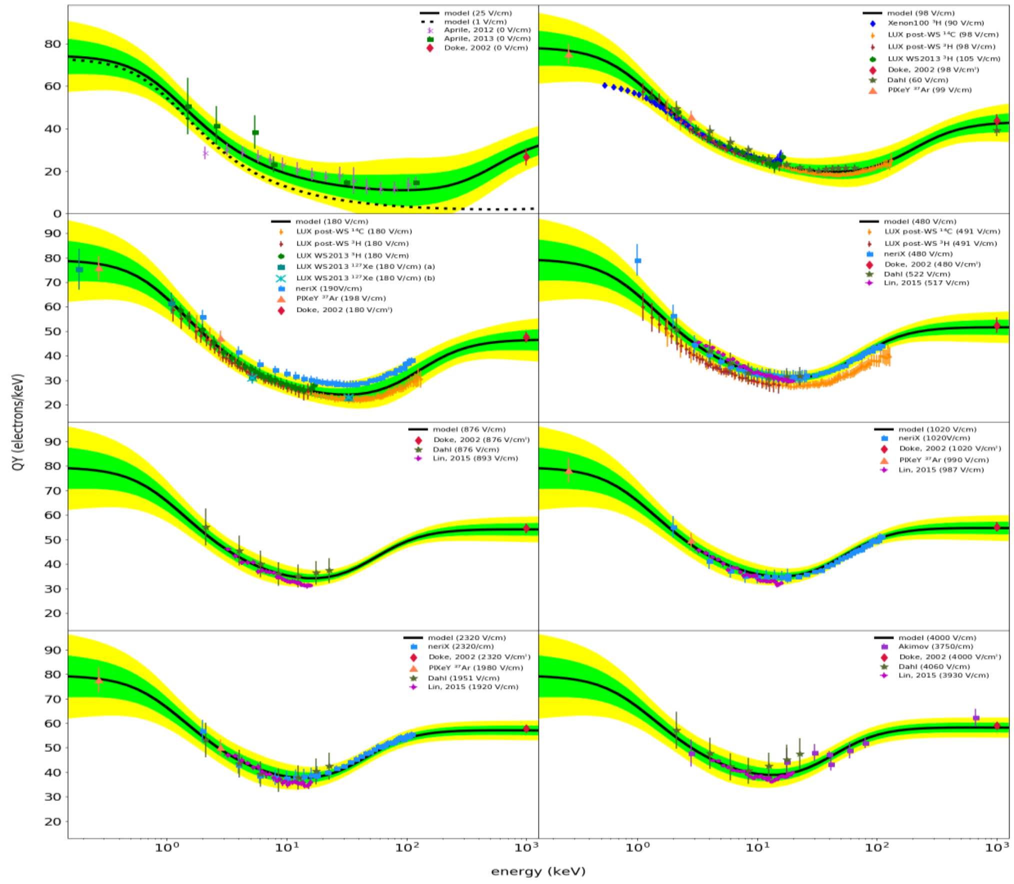
- Total quanta (light+charge) is a power law
  - $N_q = \alpha E^{\beta}$
  - Charge and light are not anticorrelated at low energies
  - $N_e = \frac{E}{TIB*\sqrt{E+\varepsilon}} * \left(1 - \frac{1}{1+(\frac{E}{\zeta})^{\eta}}\right)$
  - $N_{ph} = \left(N_q - N_e\right) * \left(1 - \frac{1}{1+(\frac{E}{\theta})^{\iota}}\right)$
  - Agreed with all data (including Livermore) in 1-sigma

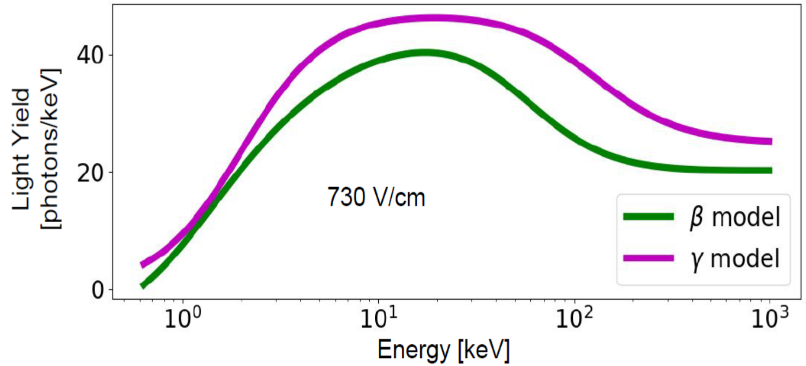
Electronic Recoils

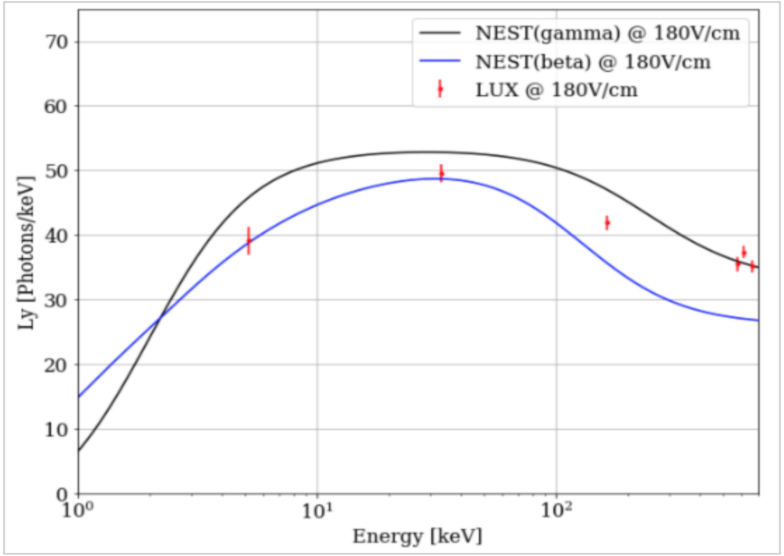
- Smooth transition between low and high energies
- Ly+Qy = const
- Different models for beta and gamma



Electronic Recoils



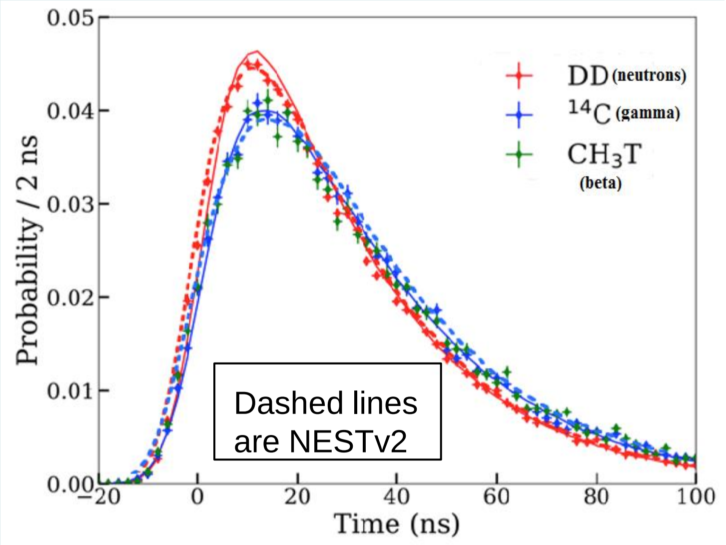


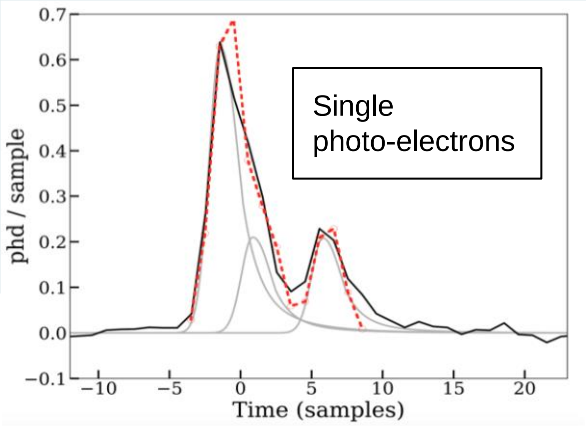


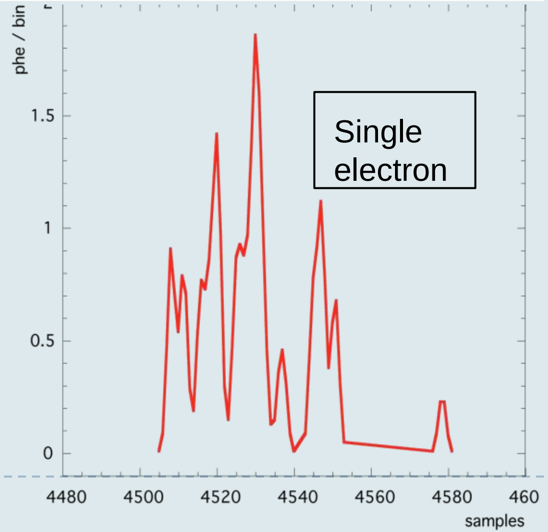
Pulse shapes and single electrons

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

Histograms of scintillation photons arrival times

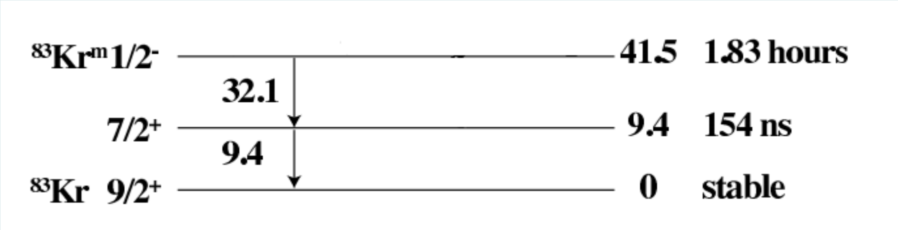


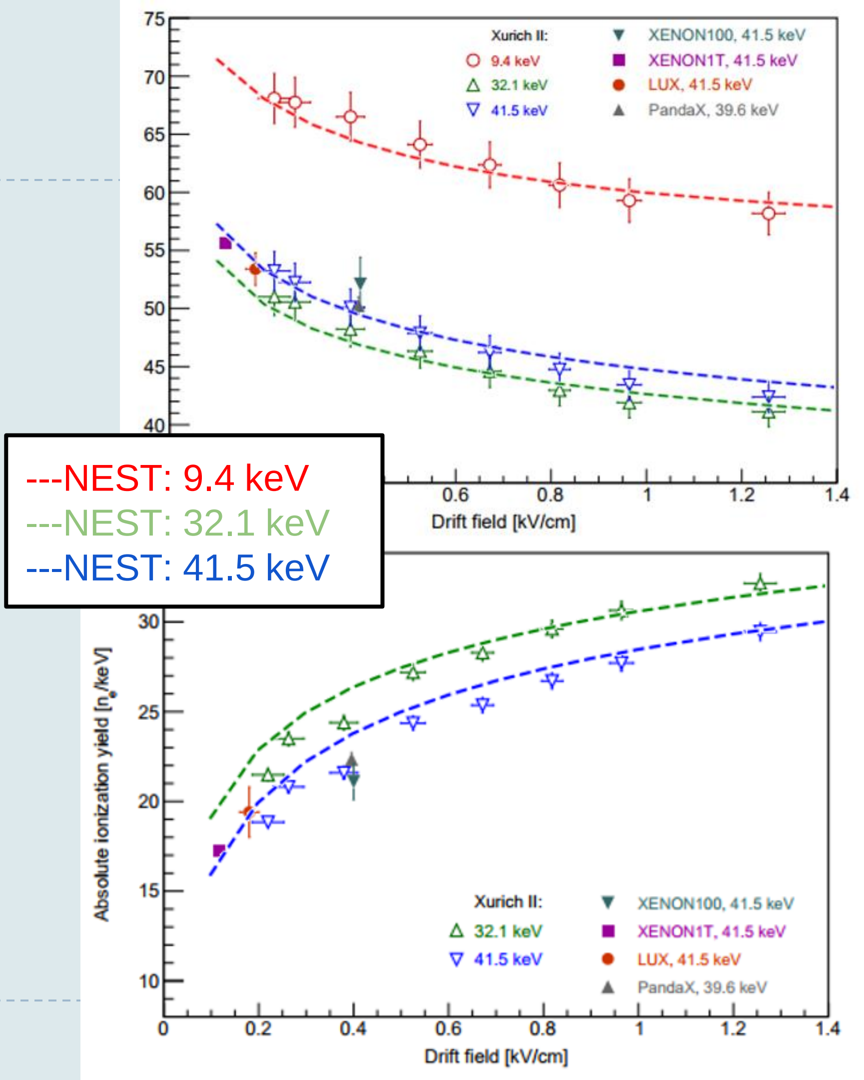




^{83m}Kr

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





^{83m}Kr

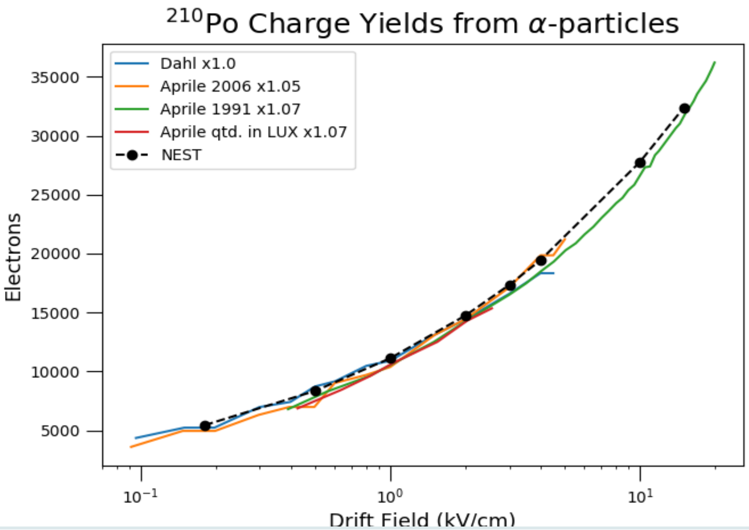
- 1 σ agreement with LUX and XENON100

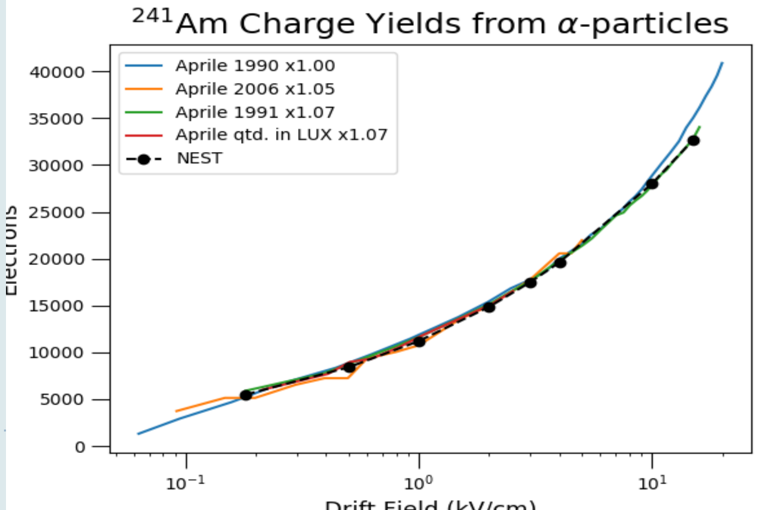
	Drift Field (V/cm)	Photons/keV, Electrons/keV	NEST Result
LUX Ly	180	53.4 ± 1.4	53.0
LUX Qy	180	19.4 ± 1.4	20.0
XENON100 Ly	366	52.5 ± 1.8	50.6

α-Model

- $N_q = \frac{L*E}{W}$
- $L = \alpha E^{\beta}$
- $N_{ph} = \frac{N_q * \frac{N_{ex}}{N_i}}{1 + \frac{N_{ex}}{N_i}} + R * N_i$
- R is TIB parameter
- $\frac{N_{ex}}{N_i}$ and L-factor are based on data
- $N_e = (N_q - N_{ph})$

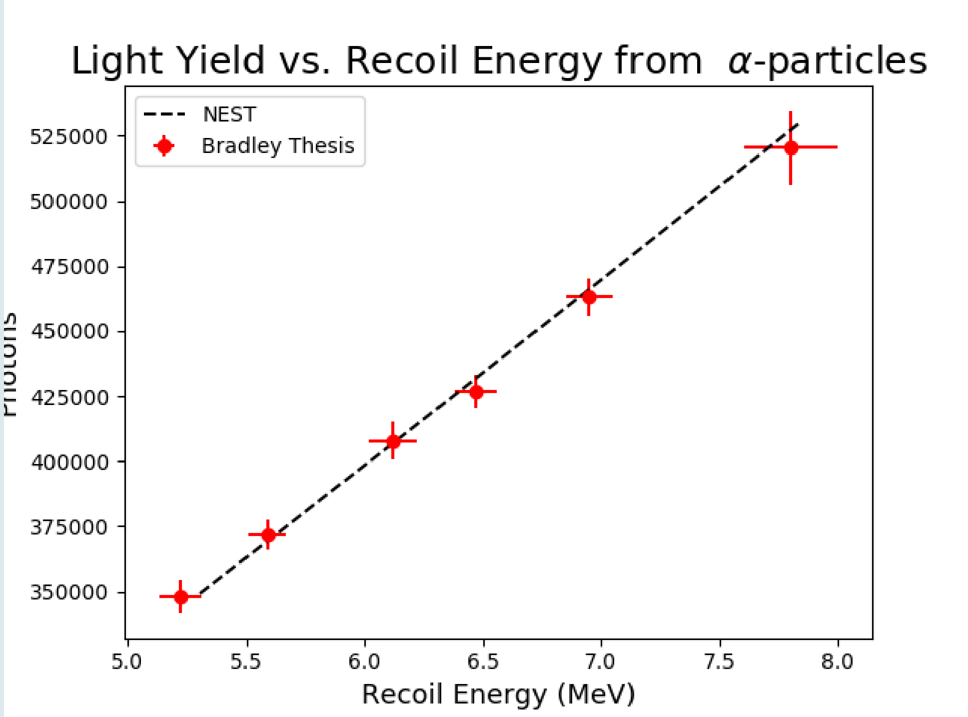
- Worked by slighly correcting data for extraction efficiency
- Good agreement for strong fields



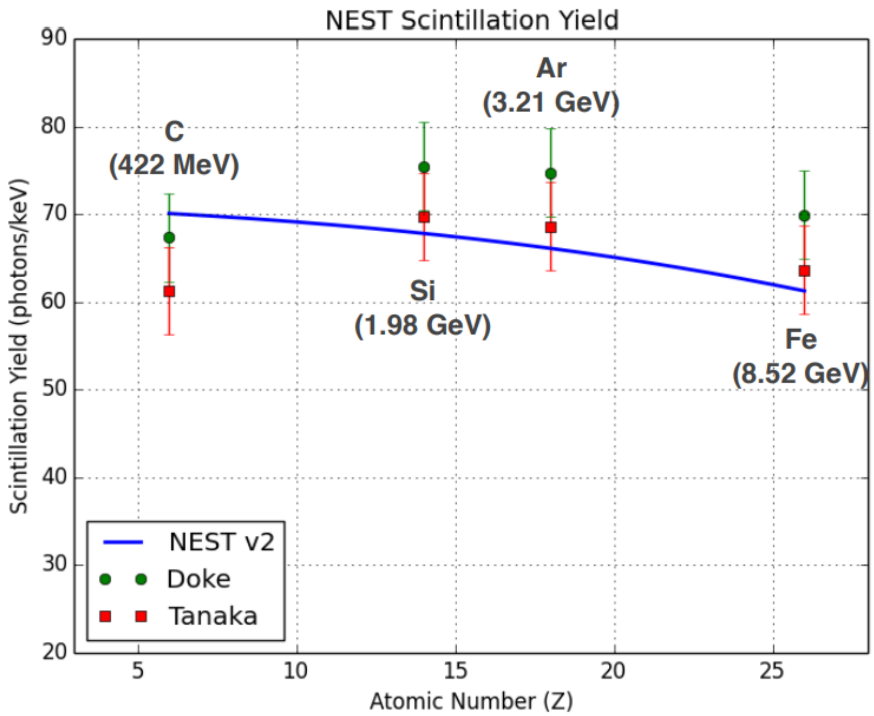


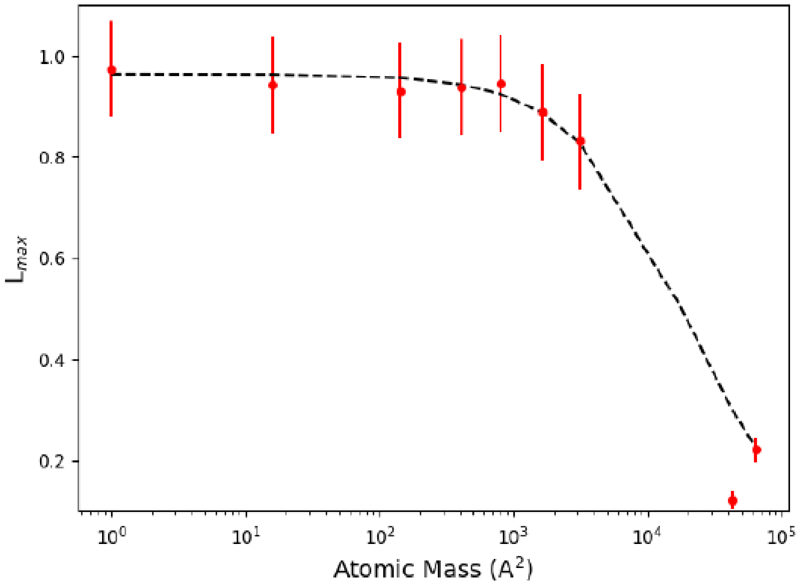
α-Model

- L-factor fixed by fitting to Adam Bradley's thesis data
  - (LUX: 180V/cm)
- Still uses Thomas-Imel box model here
  - Energy-independent for simplicity



Heavy ions model

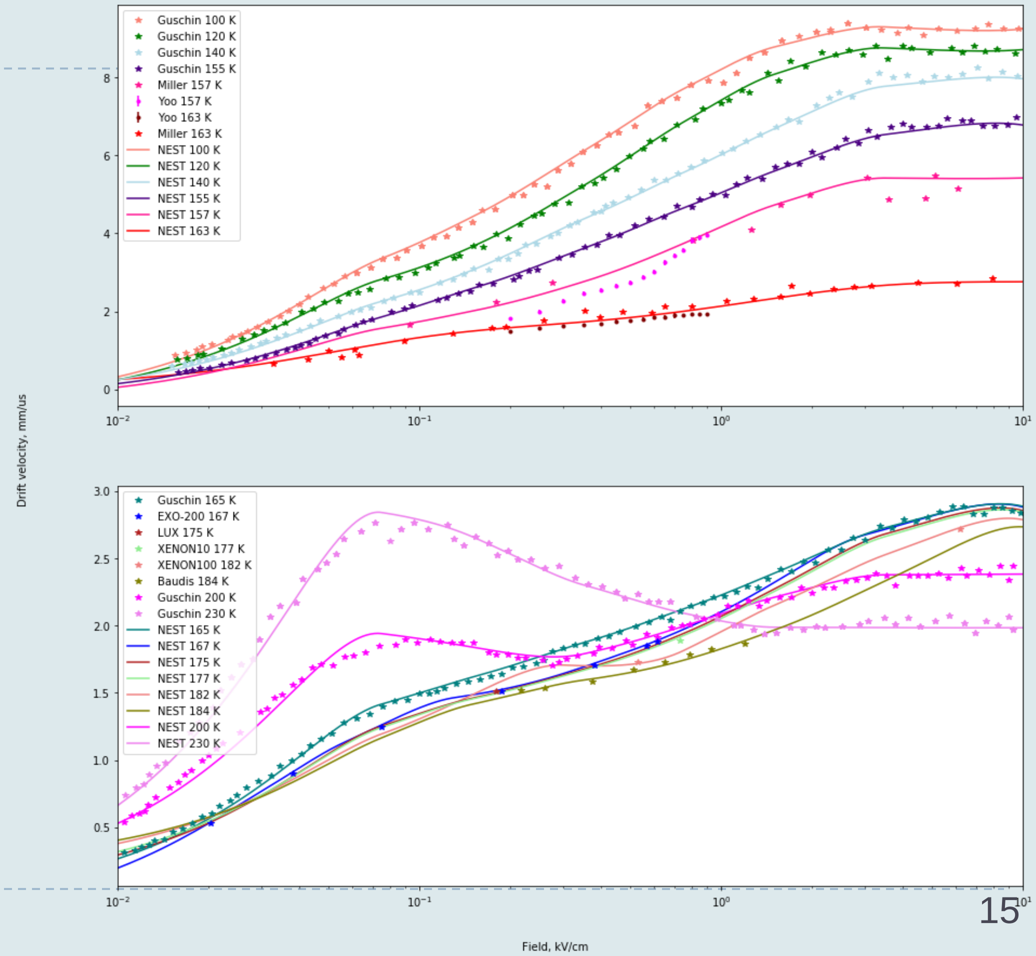




$$L = \frac{a}{1 + (\frac{A^2}{b})^c}$$

Drift velocity

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



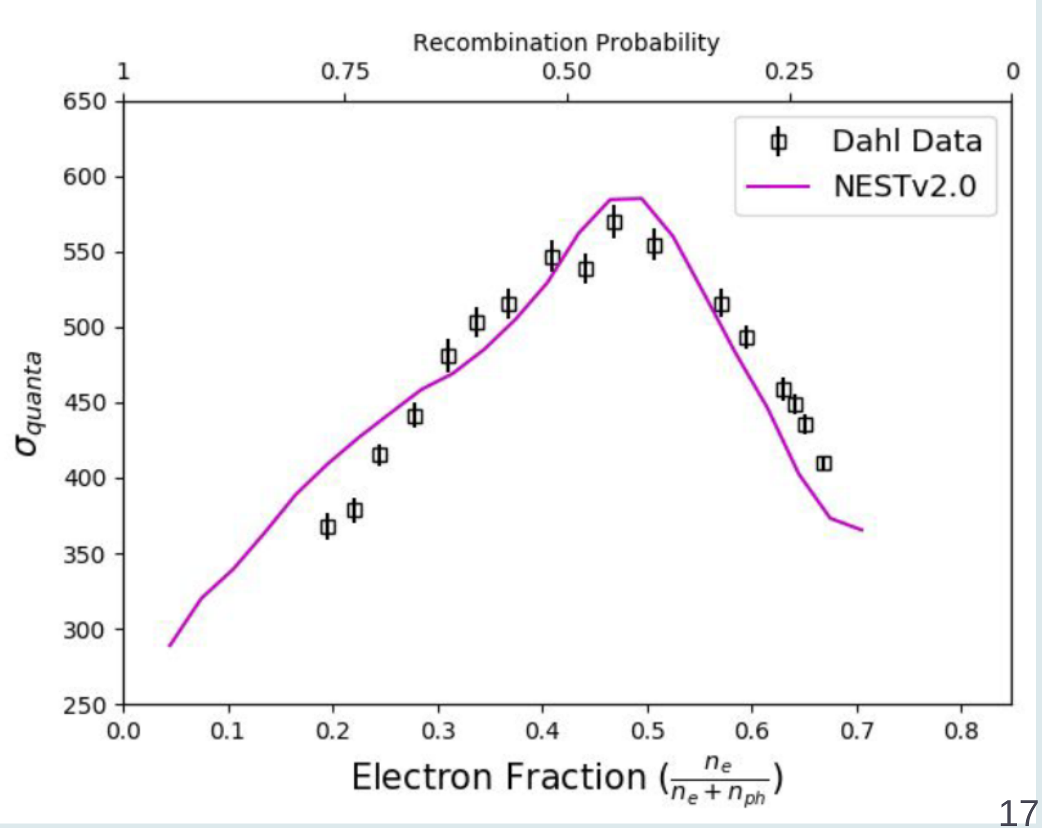
Energy Resolution

- 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

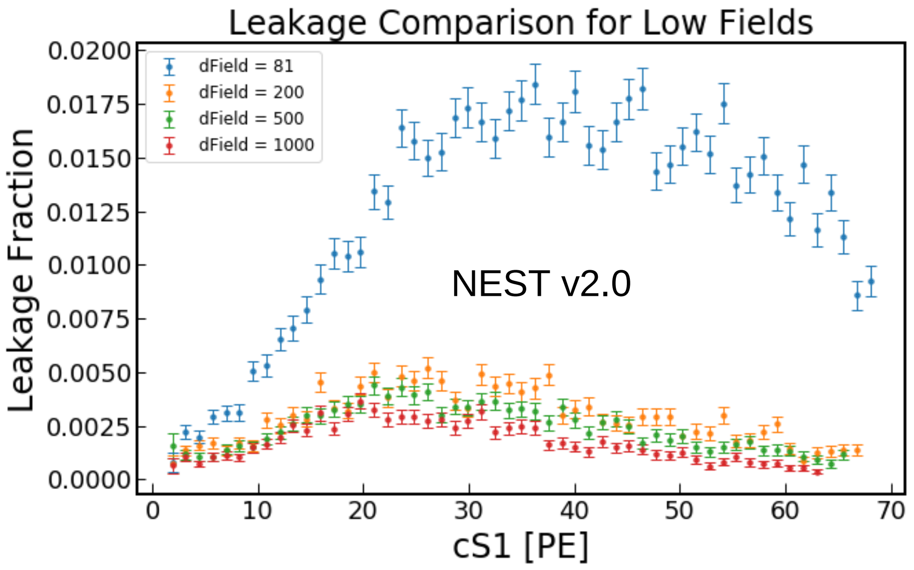
Recombination fluctuations

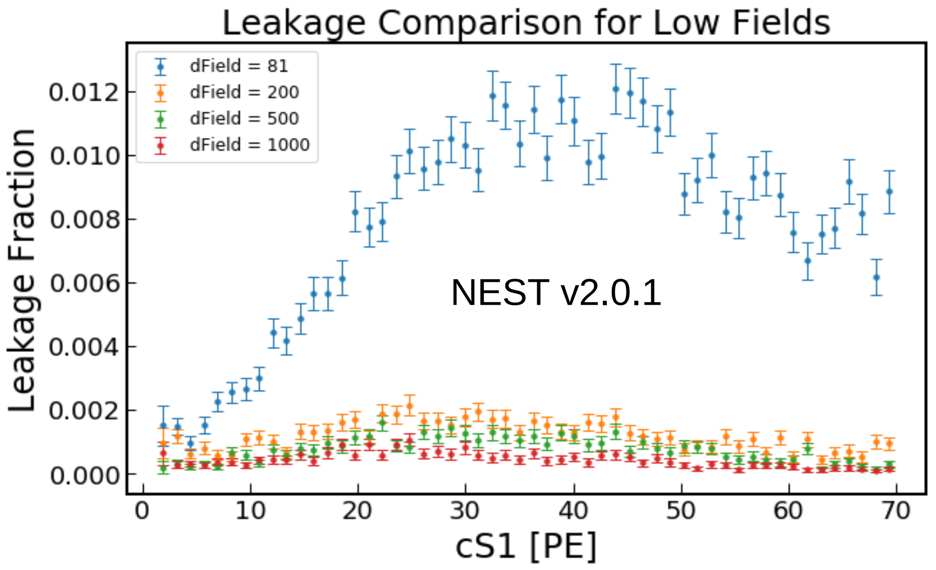
- Comparing to Eric Dahl's PhD thesis data.
- Corrected Dahl data for overestimation: corrected 15% downward for 2PE effect and extraction eff.

σ_T^2=(1-p)*n_i*p + $(\sigma_p n_i)^2$



Discrimination: v.2.0 vs v2.0.1





Mass	1.3 t	1.3 t
($cS1$, $cS2_b$)	Full	Reference
ER	627±18	1.62±0.30

g1 and g2 parameters were taken for XE1T-like detector

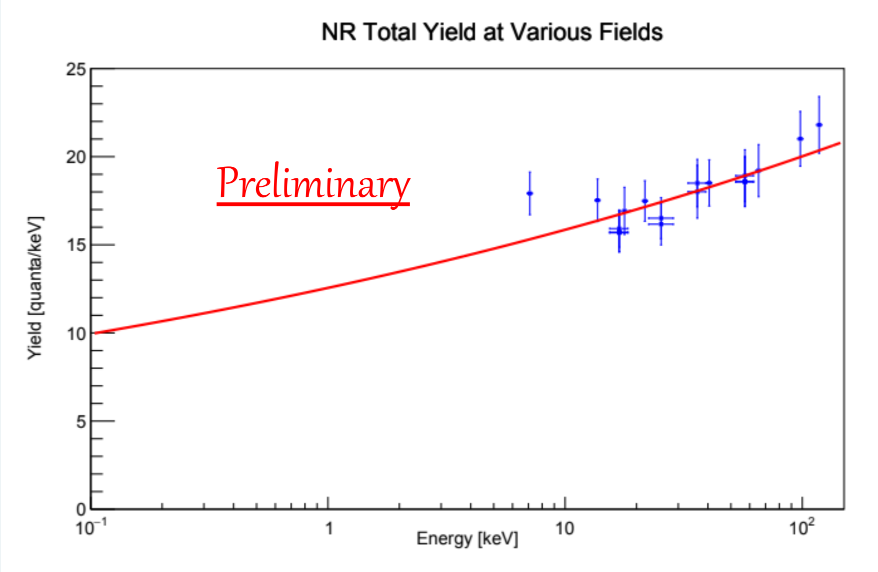
Leakage:1.62/627 = 0.0026

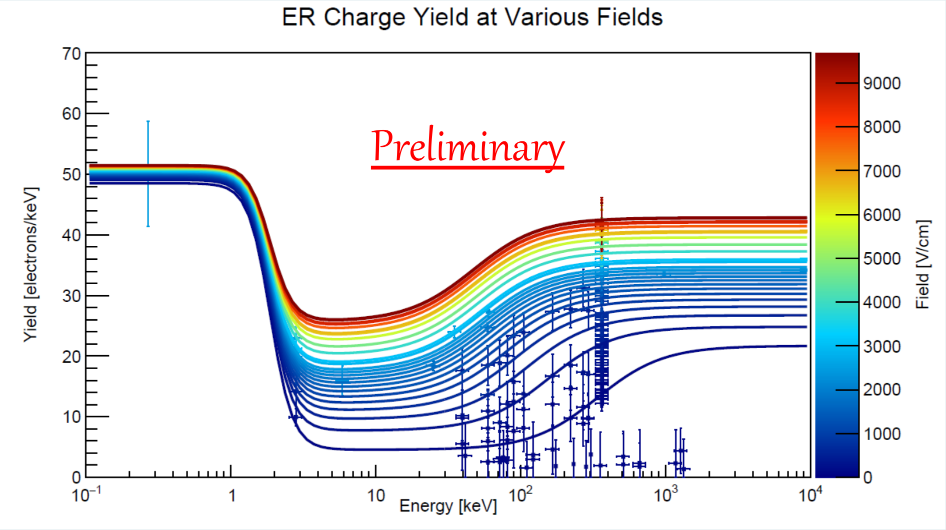
arXiv:1805.12562

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

Argon NEST





- Preliminary models for NR and ER are ready
- Heavy ion and fluctuations model are under development

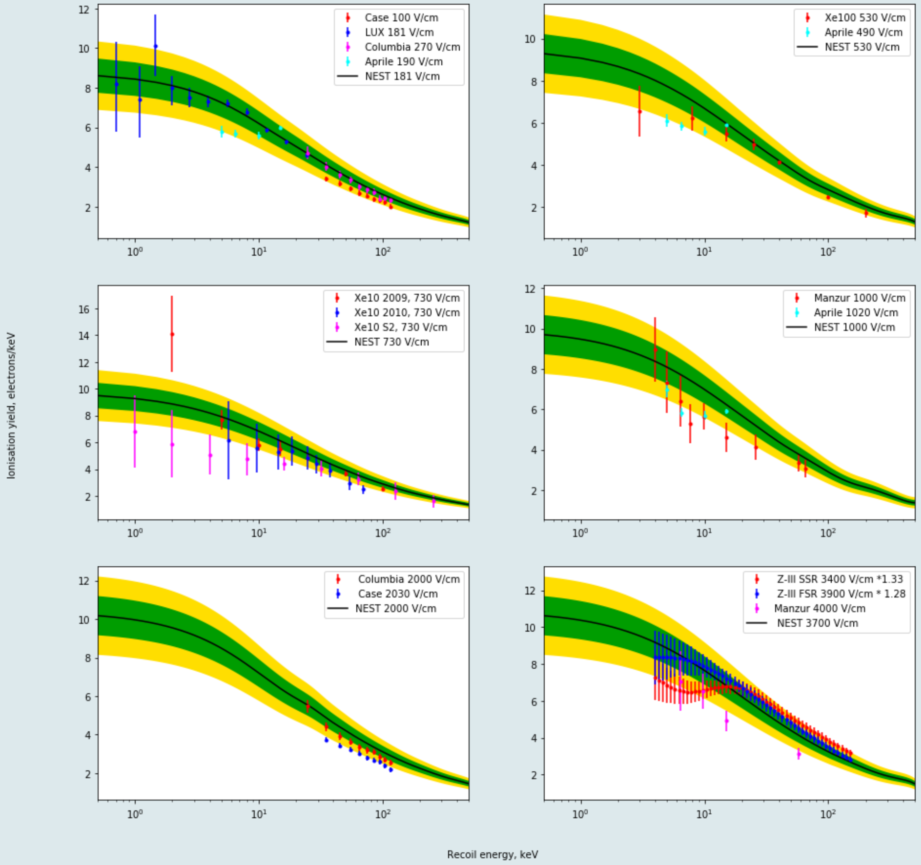
Conclusion

- NESTv2 is a powerful simulation tool, which now has two versions: standalone tool and GEANT4 library.
- Accurately simulates many different interactions in LXe and GXe (argon models currently in process)
- Now has an update for the newest data
- User-friendly code so you can add any other interactions that you might find useful
- Get yourself a copy!
  - **https://github.com/NESTCollaboration/nest**
  - **nest.physics.ucdavis.edu**
  - https://github.com/NESTCollaboration/nestpy (python version)

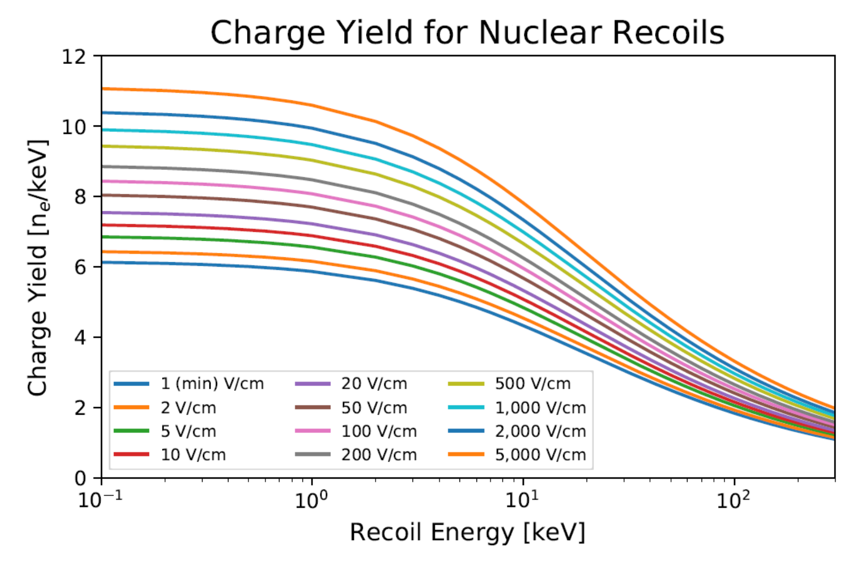
Thank you for your attention!

Backup slides

Nuclear Recoils: v2.0



- Total quanta (light+charge) is a power law
  - 12.6 * (Energy)^1.05
  - Charge and light are anticorrelated



Agreed with all data in 1-sigma before Livermore results…