NEST liquid argon mean yields note

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on behalf of the NEST collaboration

Abstract: This note summarizes the NEST mean yield models for Nuclear Recoils (NR), Electronic Recoils (ER), and alpha particles in LAr relation to existing data, and compares them to the original NEST Xe models. The fit procedure and general process used to constrain the model parameters is also described.

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Nuclear Recoil Model

Data: All points from the NR total yield dataset and NR light yield dataset are used in these fits. This includes the null field points in the NR light yield dataset which are well known to be contradictory towards the lower energies. Only the two points from the Bondar et al. 2017 paper are excluded from the NR charge yield dataset, though it is worth noting that these points are extreme outliers from the rest of the data.

Fit Procedure: The total yield and charge yield are chosen as independent models and light yield is modeled as the difference between the total yield model and the charge yield model. The models are a function of both the deposited energy and the drift field. The fits are done as a 2D χ^2 minimization over the entire dataset, which allows the model to be informed in regions of energy/field space that are not well represented by regions that are well represented. The total yield data set is formed from the intersection of the light and charge yield datasets; a total yield point is constructed from the sum of light yield and charge yield measurements at the same field and energy where available.
We first fit the total yield model and take it as fixed. The model is a simple power law in the deposited energy. There is no field dependence.

$$\text{TY(E [keV], F [V/cm]) [quanta]} = \alpha * E^{\beta}$$

Parameter	Xenon	Argon
α	$11^{+2.0}_{-0.5}$	11.10 ± 1.4
β	1.1 ± 0.05	1.087 ± 0.01

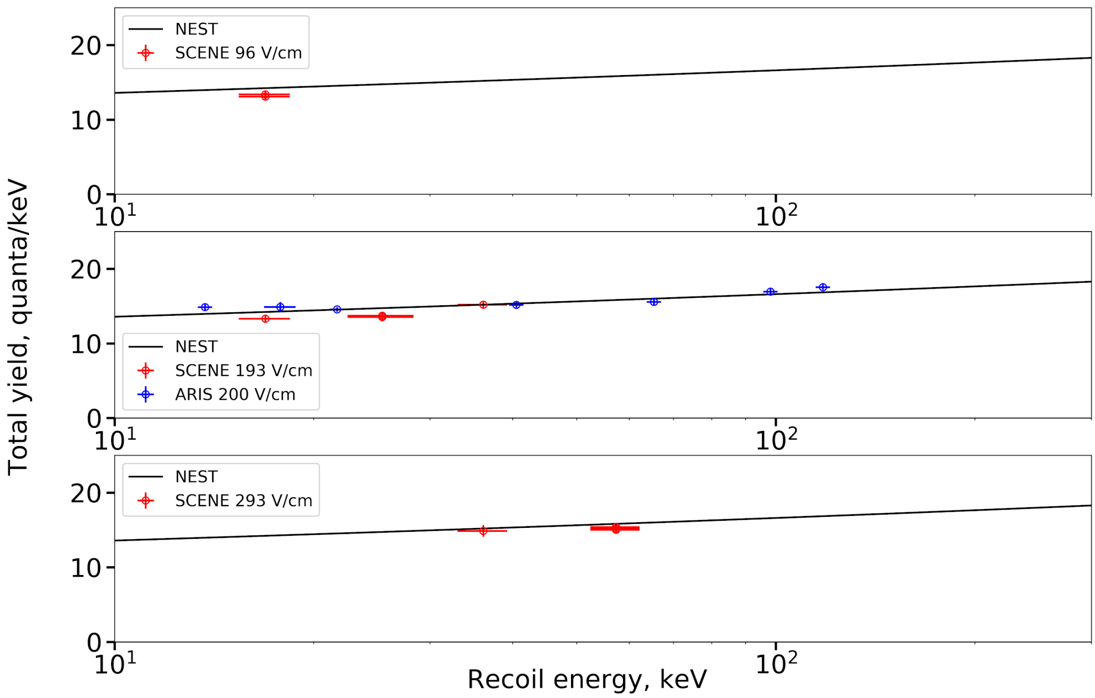

Figure 1: NR Total Yield compared with data for three separate field values.

With the total yield model pinned down, we can then proceed to fit the charge yield model. Because the light yield is modeled as the difference between the total yield and the charge yield, it is possible to constrain the charge yield model with both the charge yield dataset and the light yield dataset. This is done by creating a pseudo-charge yield dataset from the light yield dataset by using the previously fit total yield model. This does add additional uncertainty in the converted dataset, but this is propagated appropriately using the uncertainty in the total yield model. The resulting dataset formed by the union of the native charge yield dataset and the converted light yield dataset is then fit with the charge yield model. The model used is identical to the one currently implemented in NEST for xenon.

$$\mathrm{QY(E\ [keV],\ F\ [V/cm])\ [e/keV]} = \frac{1}{\gamma * F^{\delta}} * \frac{1}{\sqrt{E+\epsilon}} * \left(1 - \frac{1}{1+\left(\frac{E}{\zeta}\right)^{\eta}}\right)$$

Parameter	Xenon	Argon
γ	0.0480 ± 0.0021	0.1 ± 0.005
δ	-0.0533 ± 0.0068	-0.0932 ± 0.0095
ϵ	$12.6^{+3.4}_{-2.9}$	2.998 ± 1.026
ζ	0.3 ± 0.1	0.3 (Fixed)
η	2 ± 1	2.94 ± 0.12

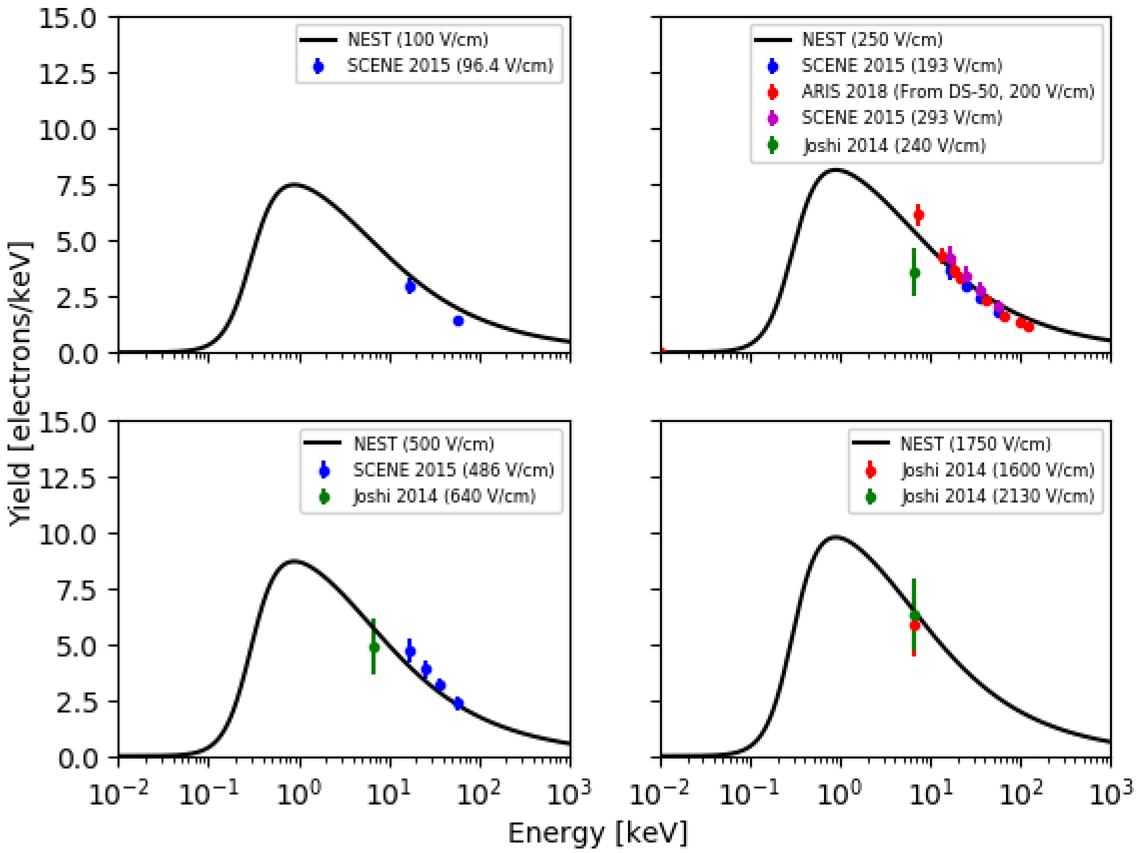

Figure 2: NR Charge Yield compared with data for four distinct field ranges.

There is one final thing to note with respect to the light yield models. Whereas in general the light yield is modeled as the difference between the total yield and the charge yield, there were some adjustments to the low energy behavior to better match the theoretical expectation that the yield drops to zero as it nears the work function. Specifically, the last piece of the charge yield model was removed so that only the part with the power law field dependence and the part with the inverse square root dependence on energy remain. This results in the following model for light yield:

$$\mathrm{LY}(\mathrm{E\ [keV]},\ \mathrm{F\ [V/cm]})\ [\gamma/\mathrm{keV}] = \alpha * E^{\beta-1} - \frac{1}{\gamma^* F^{\delta}} * \frac{1}{\sqrt{E+\epsilon}}$$

Although this breaks anticorrelation of the light and charge yields, this effect is only noticeable at the sub-keV level.

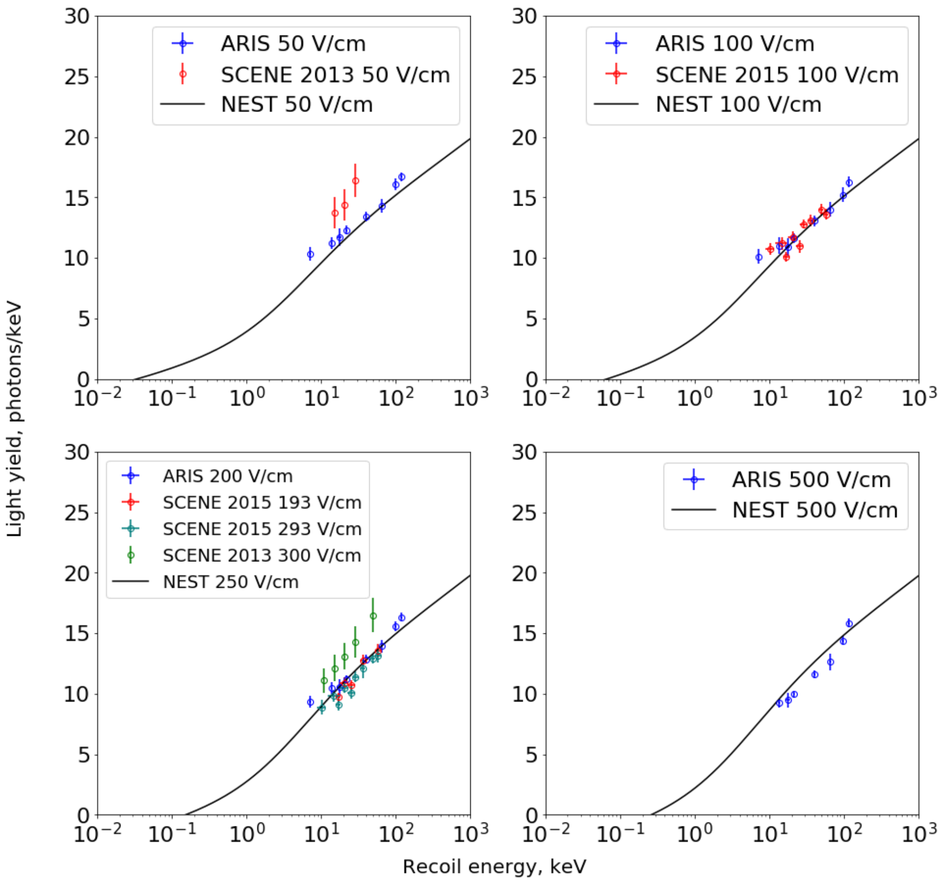

Figure 3: NR Light Yield compared with data for four distinct field ranges.

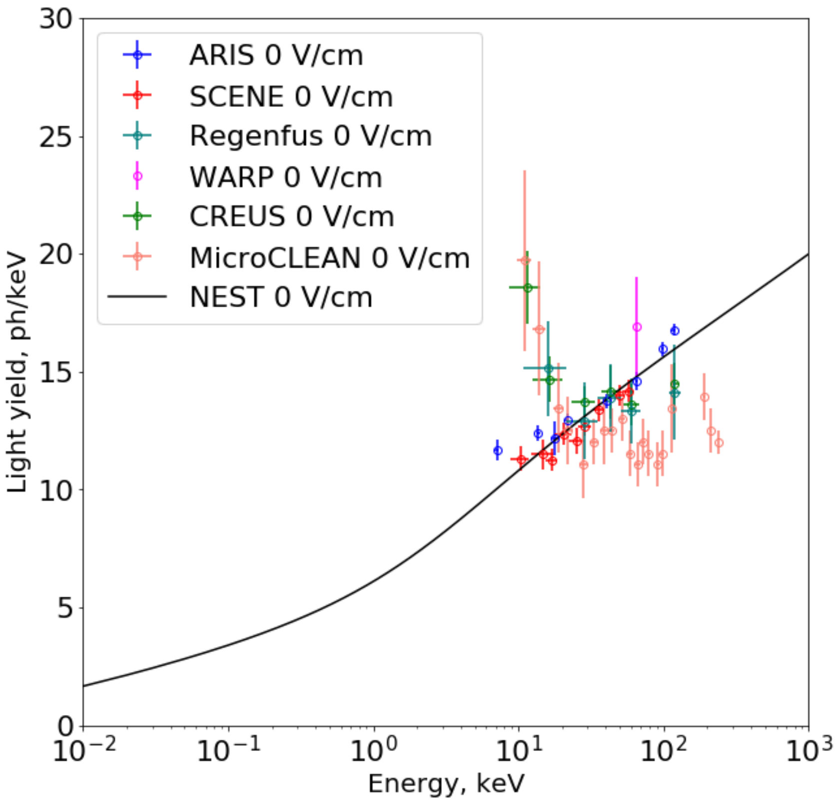

Figure 4: NR Light Yield compared with data at null field.

List of sources:

1. R. Brunetti, E. Calligarich, M. Cambiaghi et al, *WARP liquid argon detector for dark matter survey*, New Astronomy Reviews, 2005
2. D. Gastler, E. Kearns, A. Hime et al., *Measurement of scintillation efficiency for nuclear recoils in liquid argon*, Physical Review C, 2012
3. C. Regenfus, Y. Allkofer, C. Amsler et al., *Study of nuclear recoils in liquid argon with monoenergetic neutrons*, Journal of Physics: Conference Series, 2012
4. T. Alexander, H. Back, H. Cao et al.,*Observation of the dependence on drift field of scintillation from nuclear recoils in liquid argon*, Physical Review D - Particles, Fields, Gravitation and Cosmology, 2013
5. T. Joshi, S. Sangiorgio, A. Bernstein et al.,*First measurement of the ionization yield of nuclear recoils in liquid argon*, Physical Review Letters, 2014
6. H. Cao, T. Alexander, A. Aprahamian et al.,*Measurement of scintillation and ionization yield and scintillation pulse shape from nuclear recoils in liquid argon*, Physical Review D, 2015
7. W. Creus, Y. Allkofer, C. Amsler et al., *Scintillation efficiency of liquid argon in low energy neutron-argon scattering*, Journal of Instrumentation, 2015
8. The DarkSide Collaboration, P. Agnes, I. Albuquerque et al., *Low-mass Dark Matter Search with the DarkSide-50 Experiment*, arXiv:1802.06994, 2018

Electron Recoil Model

Data:

There are some datasets and points excluded from ER:

- Doke dataset which converted from charge. It is nearly the same as the first Doke set, but both of them do not agree well with other points (maybe due to density reasons - right now we're assuming that density is constant which is not absolutely correct). When both sets are used, fits become much worse, because these points are inconsistent with the behavior of these other points in this energy/field range.
- ARIS "negative" point and Sangiorgio 0.27 keV point (because of high errors which mess up fits on low energies, but that point agrees in the margin of error with final fit).
- Also two artificial points based on first principles were added for better convergence on low energies (aren't shown on plots). The reason for that is the small amount of data at this energy range.

All other sets were used including the set from the Kimura LIDINE talk.

Main model:

For ER, the original NEST beta model was chosen (despite that most of our ER argon points are gamma – Xe gamma model was worse for adaptation). The model has following form:

$$Q_y(E\ [keV],\ F\ [V/cm])[e/keV] \ = \ \alpha * \beta + \frac{\gamma - \alpha*\beta}{(p_1 + p_2 * Energy^{p_3})^{p_4}} + \frac{\delta}{(p_5 + DokeBirks * Energy^{LET})}$$

$$L_y(E\ [keV],\ F\ [V/cm])\ [\gamma/keV] \ = \ N_q \ - \ Q_y$$

Nq is taken as 51.9 quanta/keV (calculated result from Doke data is 51.3±2.63 quanta/keV)

Due to the length of models and large number of parameters, we'll present them by parts like in the original NEST code.

Notes: 1) Argon has one more additional parameter in *Energy*^*p*3 part – for argon it's (*Energy* + 0.5)^*p*3.

2) ArDensity is constant right now and ArDensity = 1.3954 g/cm^3.

3) Energy is taken in keV, field in V/cm.

Parameter	Xenon	Argon
α	$32.988 - \frac{32.988}{(1 + \frac{Field}{(0.026715 * exp(\frac{XeDensity}{0.33926}))})^{0.6705}}$	$32.988 - \frac{552.988}{(15.5578 + \frac{Field}{(-4.7 + 0.025115 * exp(\frac{ArDensity}{0.265360653}))})^{0.208889}}$
β	$1 + \frac{0.4607}{(1 + (\frac{Field}{621.74})^{-2.2717})^{53.502}}$	$2.01952 + \frac{20.9}{(1.105 + (\frac{Field}{0.4})^{4.55})^{7.502}}$

γ	$\frac{1000}{Wxenon} + 6.5 * (1 - \frac{1}{1+(\frac{Field}{47.40}$	$0.642039*(\frac{1000}{Wargon} + 6.5 * (5 - \frac{0.5}{(\frac{Field}{1047.408})^{0.01851}}))$
δ	28	10.3842
DokeBirks	$1652.264+\frac{1.415935e10 - 1652.264}{1+(\frac{Field}{0.02673144})^{1.564691}}$	$1052.264+\frac{1.415935e10 - 1652.264}{-5+(\frac{Field}{0.328038})^{1.74654}}$
p1	1	1
p2	1.304	10.304
p3	2.1393	24.3509
p4	0.35535	0.10535
p5	1	0.7
LET	-2	-2.11259

Model results:

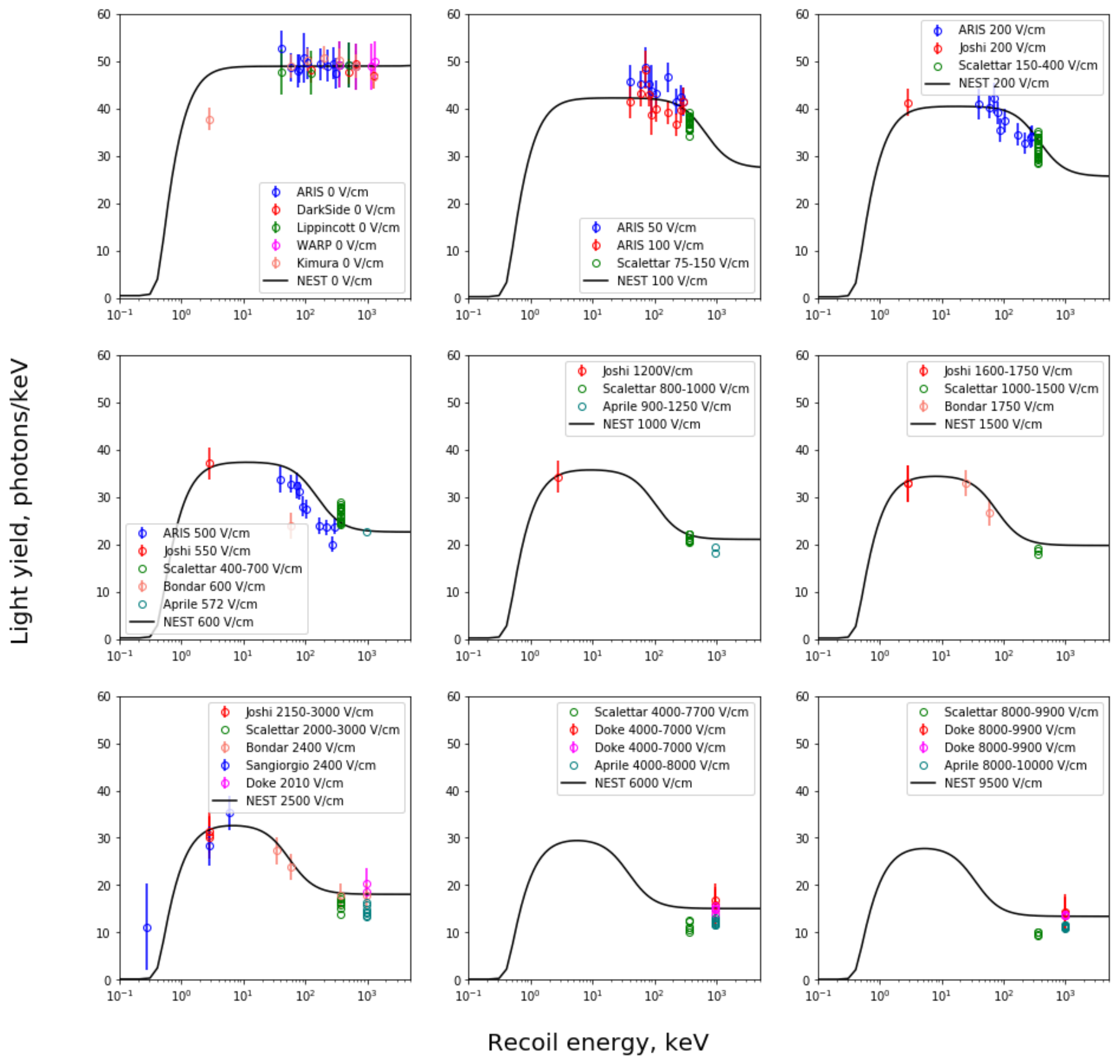

Figure 5: Light yield model comparison with data

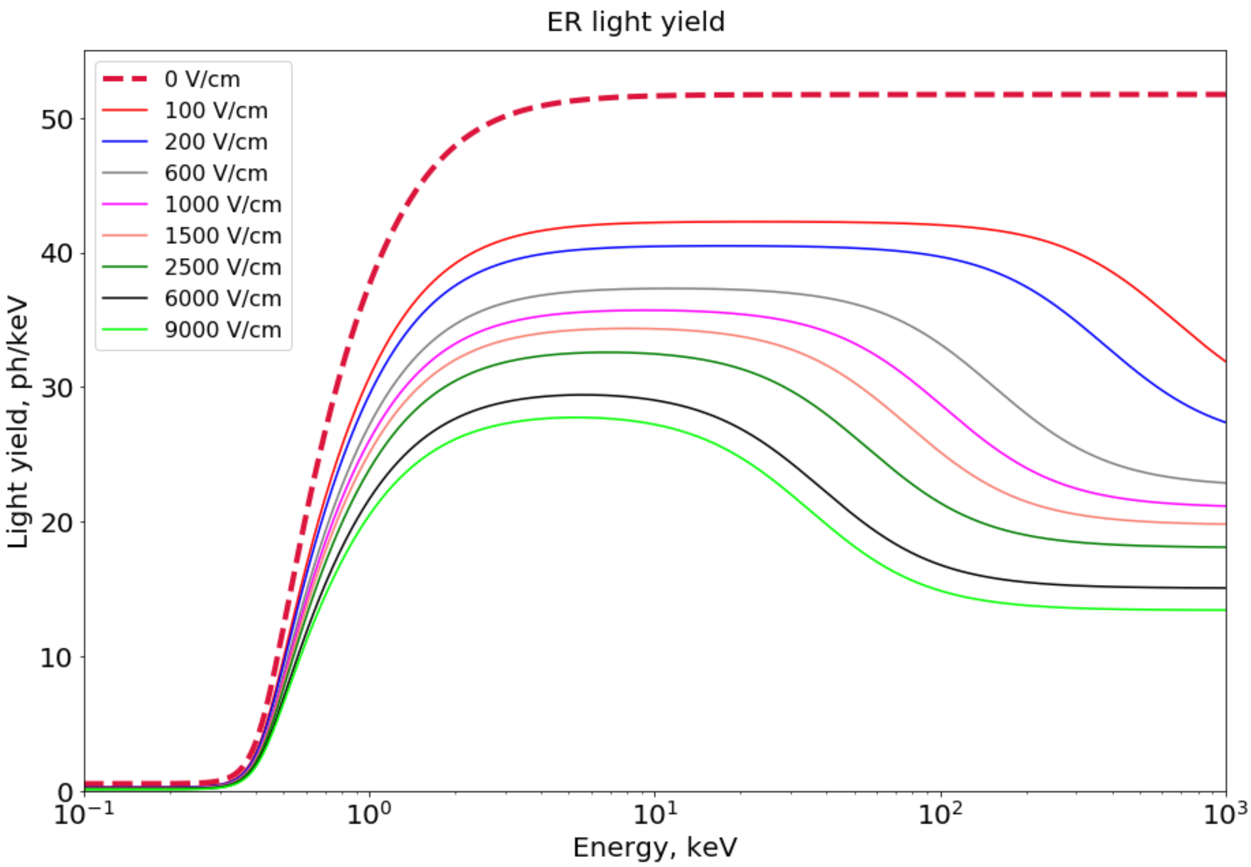

Figure 6: Light yield benchmark plot

Charge yield:

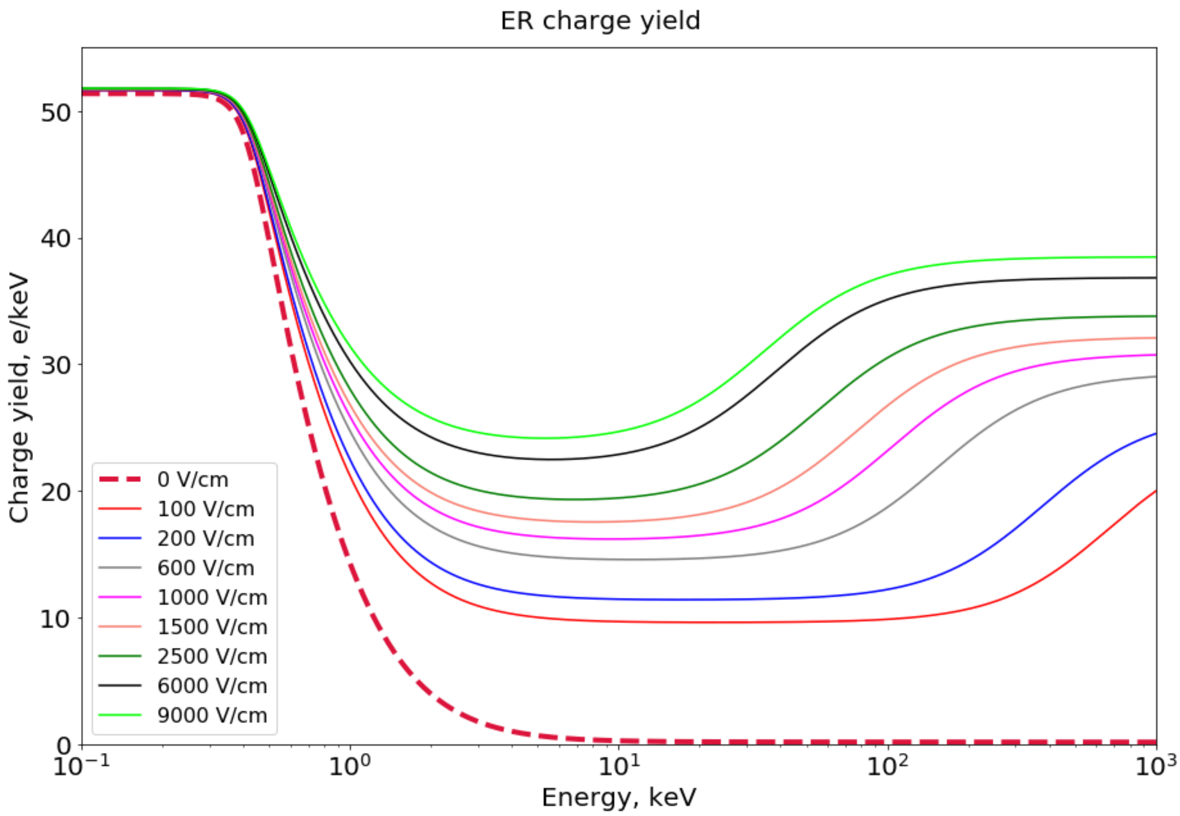

Figure 7: Charge yield benchmark plot

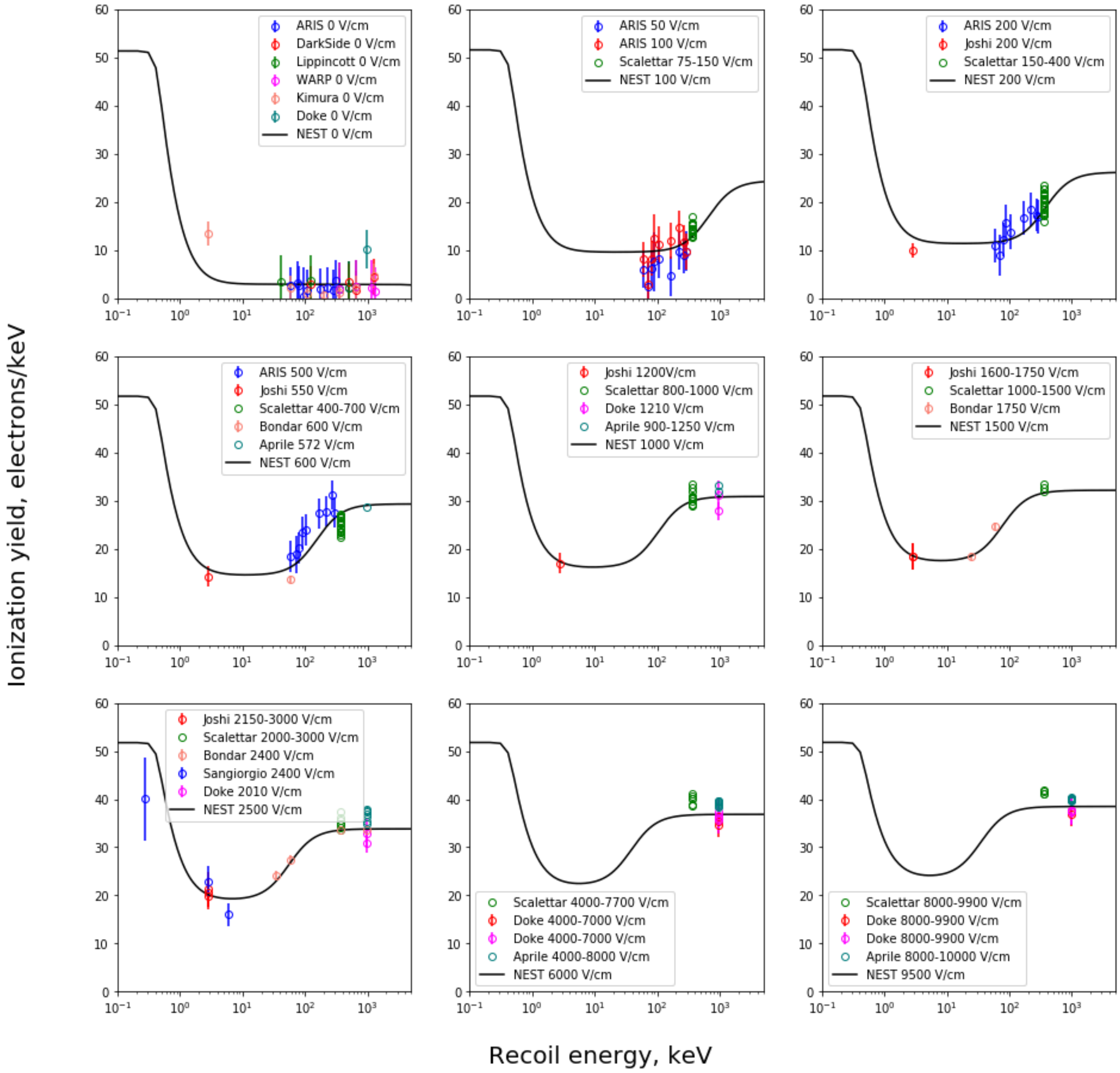

Figure 8: Charge yield model comparison with data

List of sources:

1. R. Scalettar, P. Doe, H. Mahler et al. *Critical test of geminate recombination in liquid argon*, Physical Review A, 1982
2. T. Doke, A. Hitachi, J. Kikuchi et al, *Absolute scintillation yields in liquid argon and xenon for various particles,* Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, 2002
3. S. Sangiorgio, T. Joshi, A. Bernstein et al.,*First demonstration of a sub-keV electron recoil energy threshold in a liquid argon ionization chamber*, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment, 2013
4. T. Joshi, S. Sangiorgio, A. Bernstein et al., *First measurement of the ionization yield of nuclear recoils in liquid argon*, Physical Review Letters, 2014
5. A. Bondar, A. Buzulutskov, A. Dolgov et al., *X-ray ionization yields and energy spectra in liquid argon*, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2016
6. P. Agnes, J. Dawson, S. De Cecco et al., *Measurement of the liquid argon energy response to nuclear and electronic recoils*, arXiv:1801.06653

7. W. Lippincott, S. Cahn, D. Gastler et al., *Calibration of liquid argon and neon detectors with Kr83m*, Physical Review C - Nuclear Physics, 2010
8. T. Alexander, D. Alton, K. Arisake et al., *Light yield in DarkSide-10: A prototype two-phase argon TPC for dark matter searches*, arXiv:1204.6218, 2013
9. M. Kimura, T. Washimi, M. Tanaka, K. Yorita, LIDINE 2019 talk
10. T. Washimi , M. Kimura, M. Tanaka, K. Yorita, *Scintillation and ionization ratio of liquid argon for electronic and nuclear recoils at drift-fields up to 3 kV/cm*, Nuclear Inst. and Methods in Physics Research, 2018

Alpha Model

Data:

Unfortunately there is a very small amount of data (we found only 3 sources) and most of the data are not in quanta/keV but in arbitrary units like S/S0 (light yield divided by light yield at zero field).

For transformation theoretical assumptions from original NEST v1 article were used:

- L-factors and total yields for all energies were calculated like in the above article
- After that S0 (light yield at zero field) for all energies were calculated (and used for the light yield data transformation)
- Qinf (charge yield at infinite field, basically Ni or number of ions) was calculated as S0/1.21 (that number is 1+Nex/Ni, where Nex/Ni ratio is taken from Hitachi article)
- Also all light yield data was multiplied by quenching factors.

Model:

Because of the small amount of data (only three energy points) both light and charge models are only field-dependent and independent from each other. Both have "Lindhard-like" form, but they are treated as purely empirical functions without real relation to Lindhard theory.

Charge model:

$$Q_y(E\ [keV],\ F\ [V/cm])[e/keV] = k * (A - (A * B + \frac{A}{1.21} * (1 - \frac{C*ln(1+\frac{A}{1.21}*\frac{D}{3})}{\frac{A}{1.21}*D}$$

))

Parameter	Value
k	1/6200
A	64478398.7663
B	0.173553719
C	0.02852
D	$\frac{0.01}{E}$
E	$(4.71598 + Field^{7.72848})^{0.109802}$

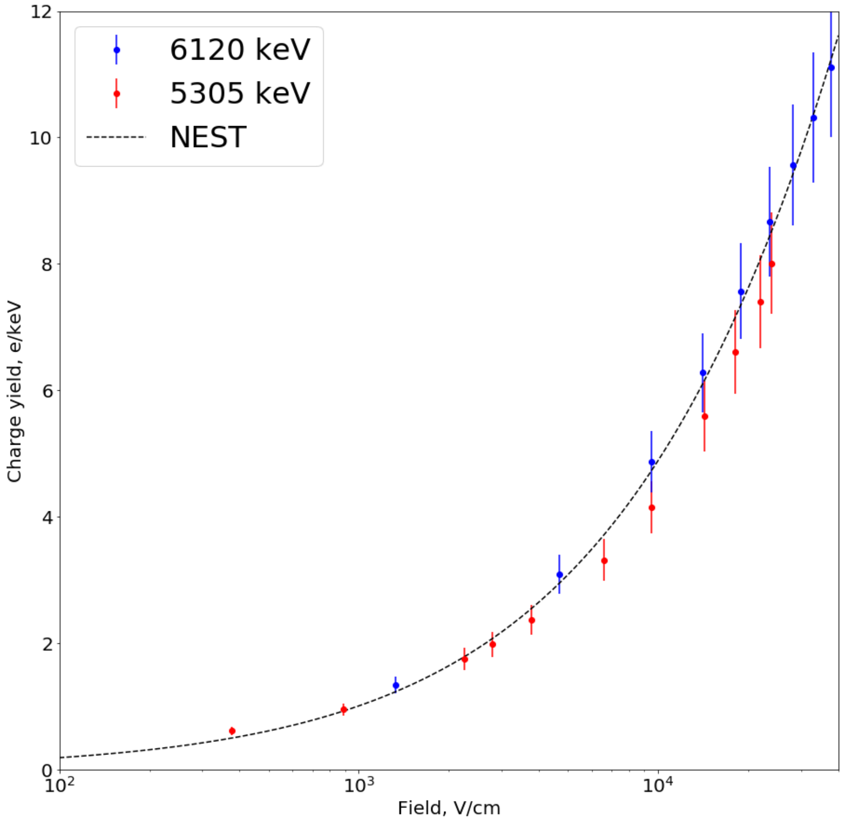

Figure 9: Charge yield model comparison with data from Po-210 and Cf-252

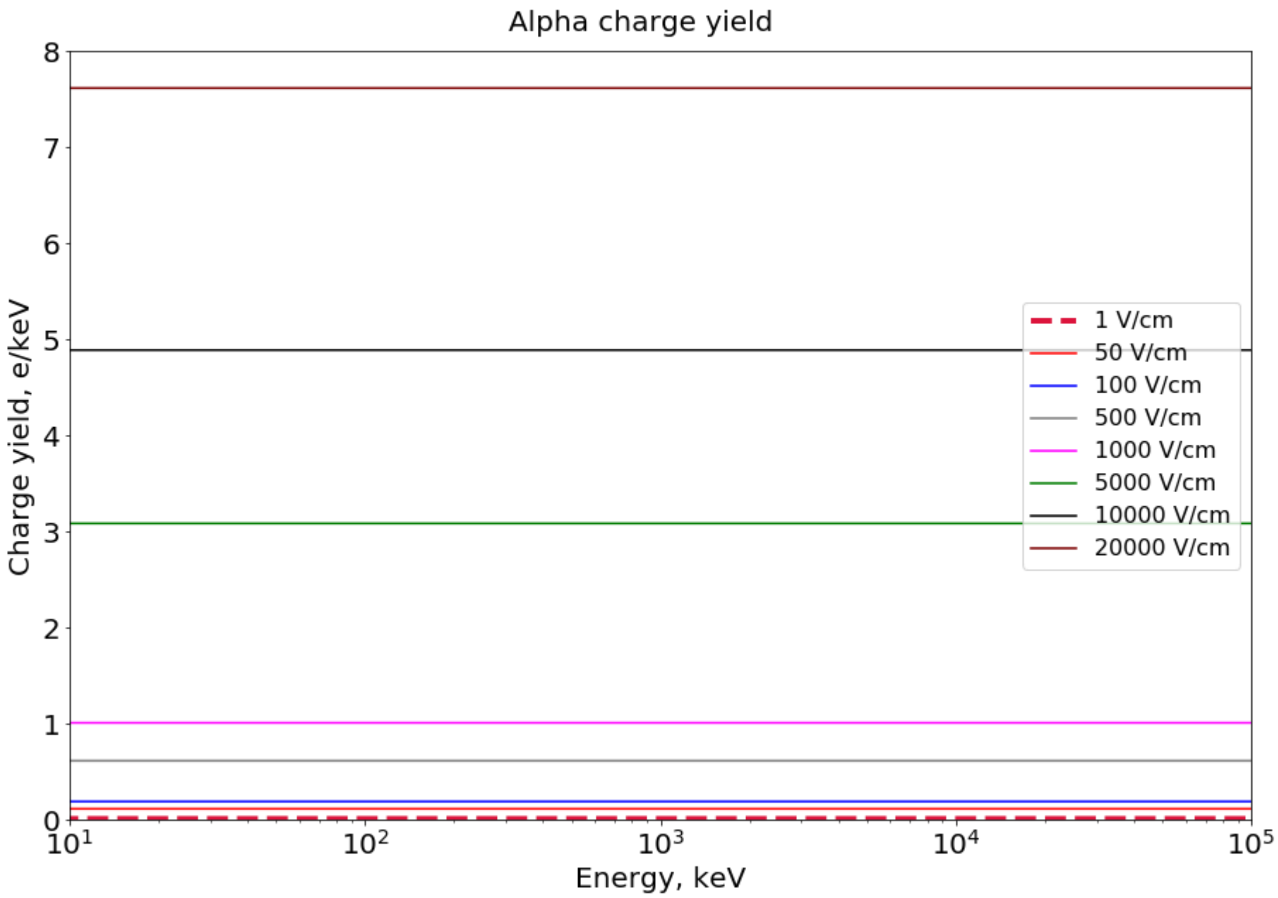

Figure 10: Charge yield benchmark plot

Light yield:

$$L_y(E\,[keV],\ F\,[V/cm])\,[\gamma/keV] = qu * k * \left(A * B + \frac{A}{1.21} * \left(1 - \frac{C * ln\left(1 + \frac{A}{1.21} * \frac{D}{3}\right)}{\frac{A}{1.21} * D}\right)\right)$$

Parameter	Value
k	1/6500
qu	$\frac{1}{1.5 * Field^{-0.012}}$
A	278037.250283
B	0.173553719
C	2
D	$\frac{0.653503}{E}$
E	$\left(4.98483 + \left(\frac{Field}{10.0822}\right)^{1.2076}\right)^{0.97977}$

Reason for additional qu(“pseudo-quenching”) parameter is a experimentally observed peak at medium fields from both Hitachi and Agnes papers (that phenomena isn’t observed in xenon):

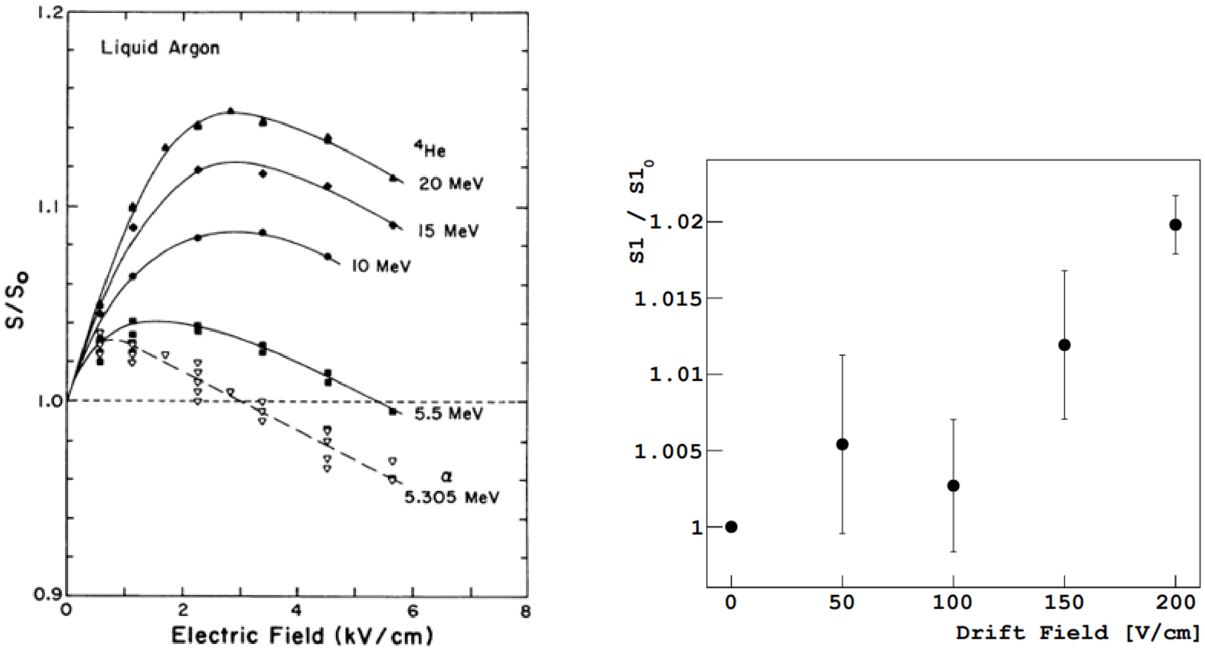

Figure 11: Left: peak on Po-210 data (Hitachi). Right: peak on Po-218 data (Agnes).

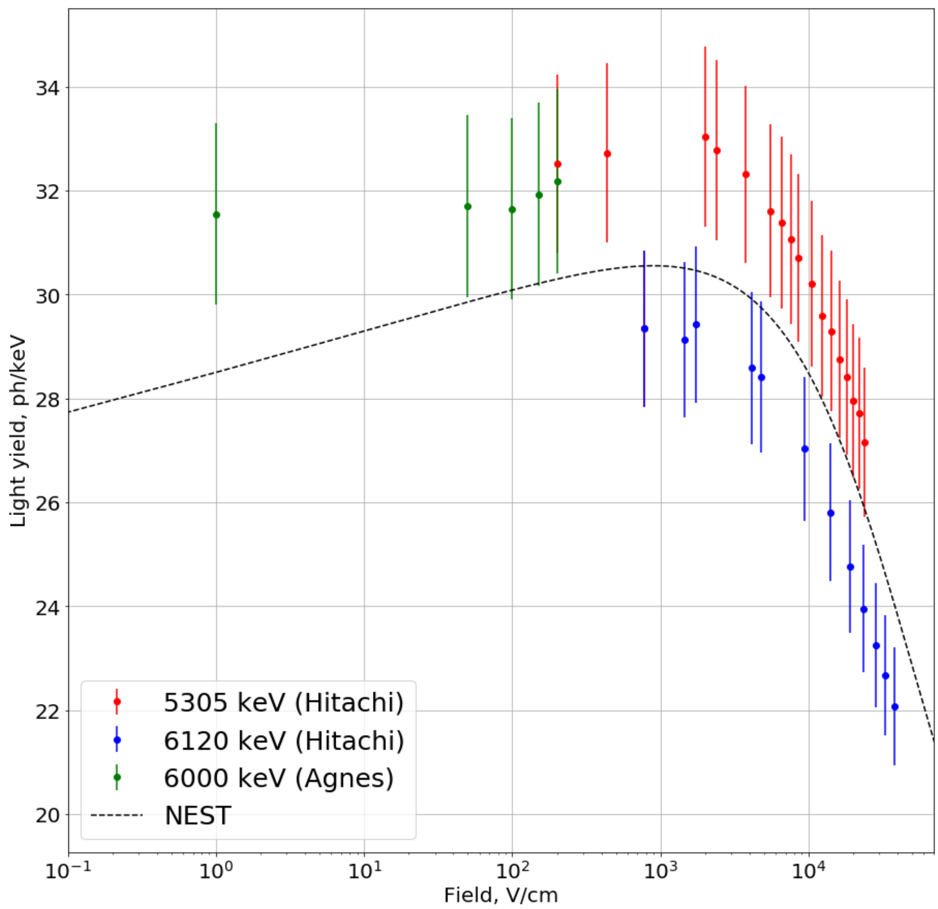

Figure 12: Light yield model comparison with data from Po-210, Po-218 and Cf-252

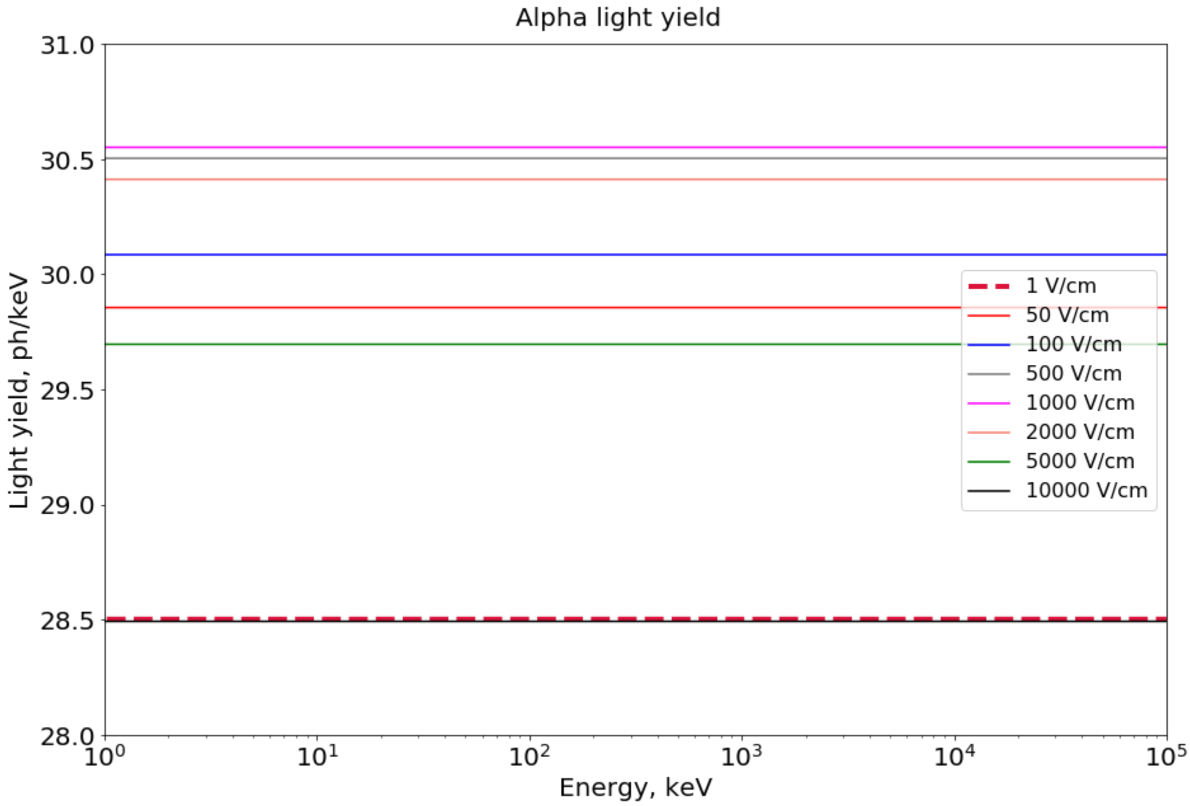

Figure 13: Light yield model benchmark plot

Errors for light yield is calculated as square root of sum of squares: $\Delta x = \sqrt{\sum (\Delta x_i)^2}$, where the main source of errors are errors from data (only Agnes data has them) and errors from quenching factor values. Charge yield data has no reported errors, so for now we assumed 10% errors.

List of sources:

1. A.Hitachi et al., *Scintillation and ionization yield for a particles and fission fragments in liquid argon*, Physical Review A, 1987
2. P. Agnes, et al., *Effect of Low Electric Fields on Alpha Scintillation Light Yield in Liquid Argon*, arXiv:1611.00241, 2016
3. A.Hitachi et al., *Effect of an electric field on luminescence quenching in liquid argon*, Physical Review B, 1992

Datasets:

You can see all sources for datasets here.