A GLOBAL ANALYSIS OF LIGHT AND CHARGE YIELDS IN LIQUID XENON

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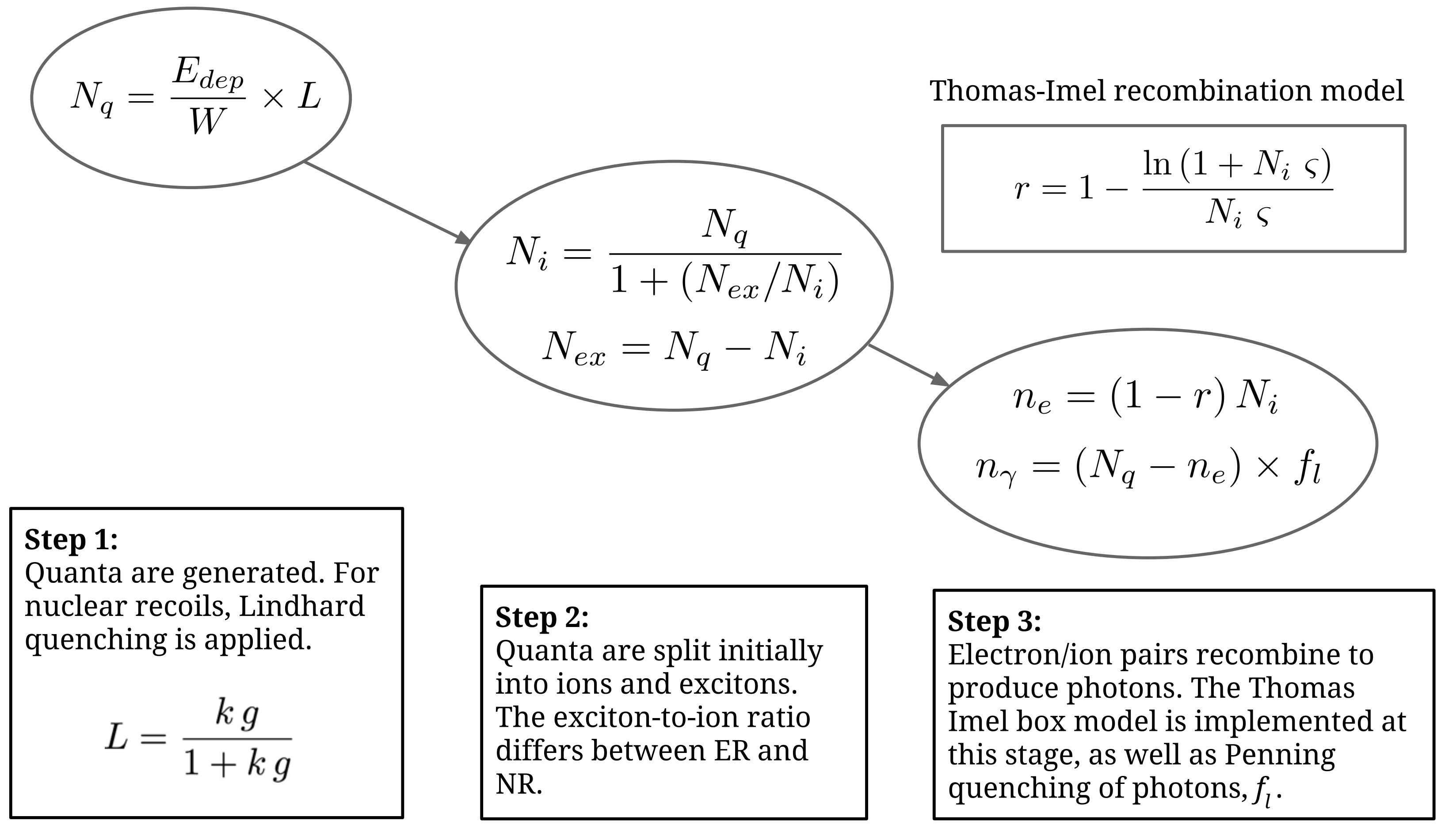
MOTIVATION

Liquid xenon is currently of great interest as an active medium in the detection and measurement of ionizing radiation. Applications under study include research in direct dark matter detection, neutrino physics, nuclear non-proliferation, and medical imaging. Due to the wide application of the technique, it is important to develop a detector-independent understanding of how xenon responds to incident radiation.

Here we construct a very general model of nuclear recoil interactions that predicts both light and charge yields. We constrain it using a comprehensive survey of measurements of both quantities and the ratio between the two. The fit treats all data equally in an attempt to create an unbiased picture of yields in the medium.

THE MODEL FOR NUCLEAR RECOILS



$$N_q = \frac{E_{dep}}{W} \times L$$

$$N_i = \frac{N_q}{1 + (N_{ex}/N_i)}$$

$$N_{ex} = N_q - N_i$$

Thomas-Imel recombination model

$$r = 1 - \frac{\ln(1 + N_i\,\varsigma)}{N_i\,\varsigma}$$

$$n_e = (1 - r)\,N_i$$

$$n_\gamma = (N_q - n_e) \times f_l$$

Step 1:
Quanta are generated. For nuclear recoils, Lindhard quenching is applied.

$$L = \frac{k\,g}{1 + k\,g}$$

Step 2:
Quanta are split initially into ions and excitons. The exciton-to-ion ratio differs between ER and NR.

Step 3:
Electron/ion pairs recombine to produce photons. The Thomas Imel box model is implemented at this stage, as well as Penning quenching of photons, f_l.

PARAMETERIZATION OF THE MODEL

We make the variables N_{ex}/N_i and ς explicit functions of field and energy. In addition, we allow the k factor in Lindhard's theory and α and β from the Penning quenching formula to float freely in the fit. In order to allow continuous calculation of yields down to zero field, we introduce a nuisance parameter F_0, which we interpret as the effective field with no external drift field applied.

The precise functional forms displaying the dependence on each of the free parameters is shown below:

$$N_{ex}/N_i = \alpha\,F^{\,\zeta}\,(1 - e^{-\beta\epsilon})$$

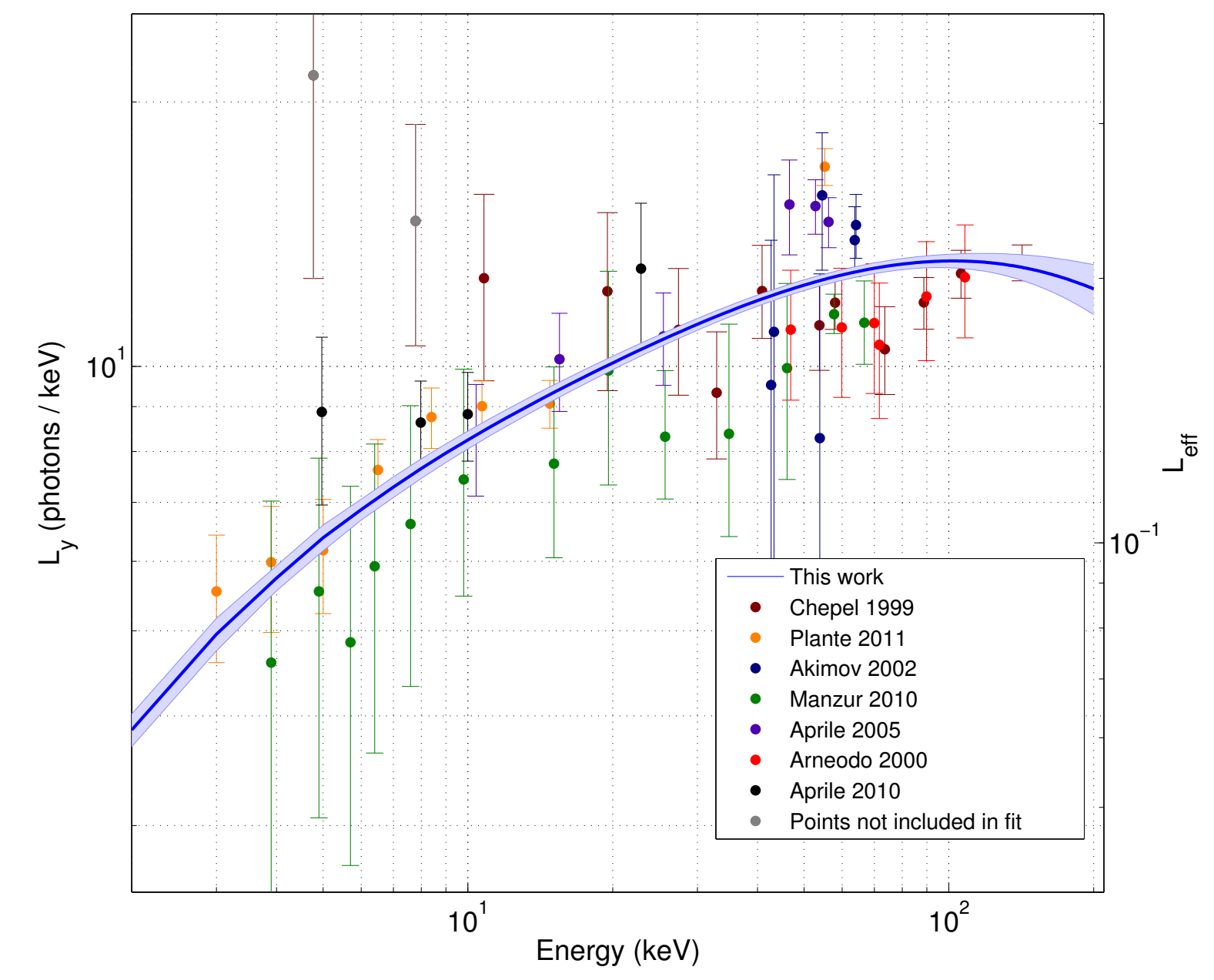
$$\varsigma = \gamma\,F^{\,\delta}$$

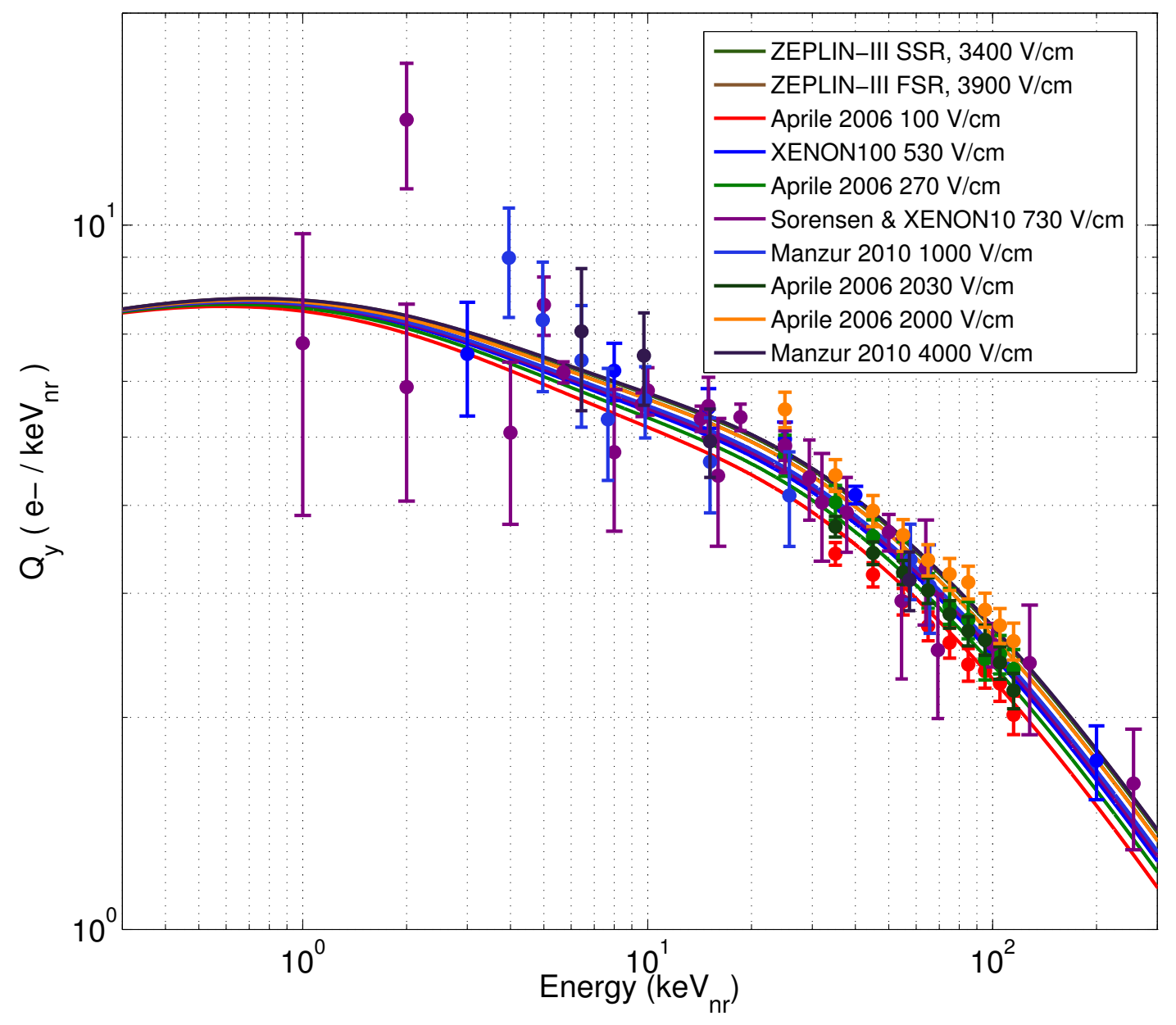
$$f_l = \frac{1}{1 + \alpha\,\epsilon^{\beta}}$$

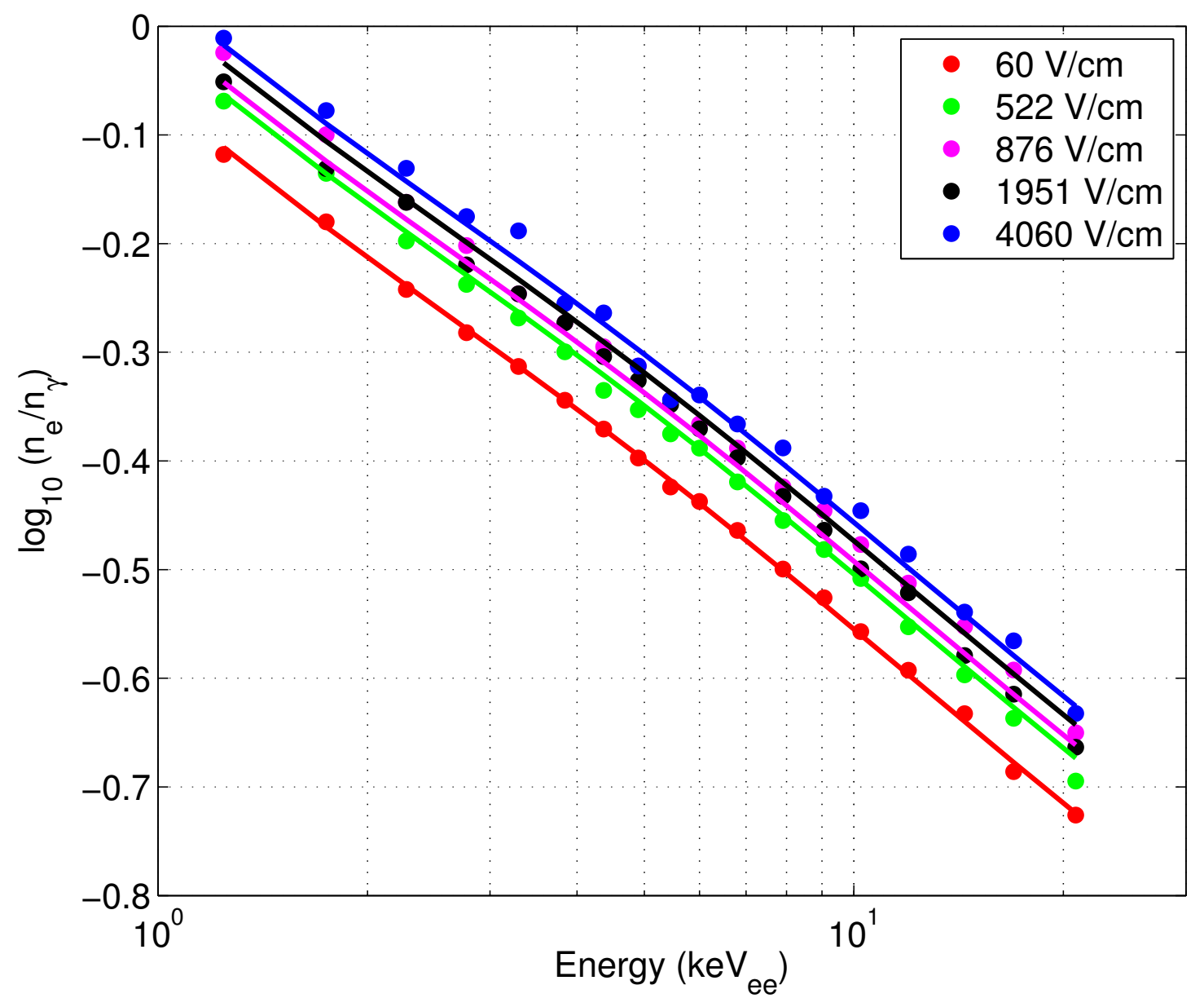
In the above, F is the applied drift field and ϵ is a dimensionless number proportional to the energy deposited. The functional form of $g(\epsilon)$ is given by Lindhard's theory of quenching due to energy loss to thermal motion. A table of all the free parameters in the model is shown to the right.

Free parameters
α
ζ
β
γ
δ
k
η
λ
F_0

GLOBAL FITS TO THE WORLD'S DATA







Parameter	Best Fit	68% conf.
α	1.240	+0.079 -0.073
ζ	0.0472	+0.0088 -0.0073
β	239	+28 -8.8
γ	0.01385	+0.00058 -0.00073
δ	0.0620	+0.0056 -0.0064
k	0.1394	+0.0032 -0.0026
η	3.3	+5.3 -0.06
λ	1.14	+0.45 -0.09
F_0	1.0	+14.5 -1.0

The model is constrained using three categories of data sets that each consist of multiple measurements of yields in liquid xenon:

1. The absolute NR charge yield, $\mathcal{Q}_y$, is constrained using twelve measurements across different energies at a range of electric fields
2. Absolute light yield L_y is constrained with an additional seven measurements of the parameter $\mathcal{L}_{eff}$, the zero-field scintillation yield relative to that of the 122 keV γ-ray from ^{57}Co.
3. Overall constraints on both are using measurements of the ratio of charge to light n_e/n_γ using measurements at several fields.

In total, there are 327 data points included in the fit, and the fit yields $\chi^2_{red} = 1.33$.

Fitting is accomplished using global cost functions of the form:

$$\mathcal{L}(\vec{\theta}|x) = \prod_i \frac{\sqrt{2}}{\sqrt{\pi}(\sigma_+ + \sigma_-)} \exp\left(\frac{-(x_i - x_{model})^2}{2\sigma^2_{+/-}}\right)$$

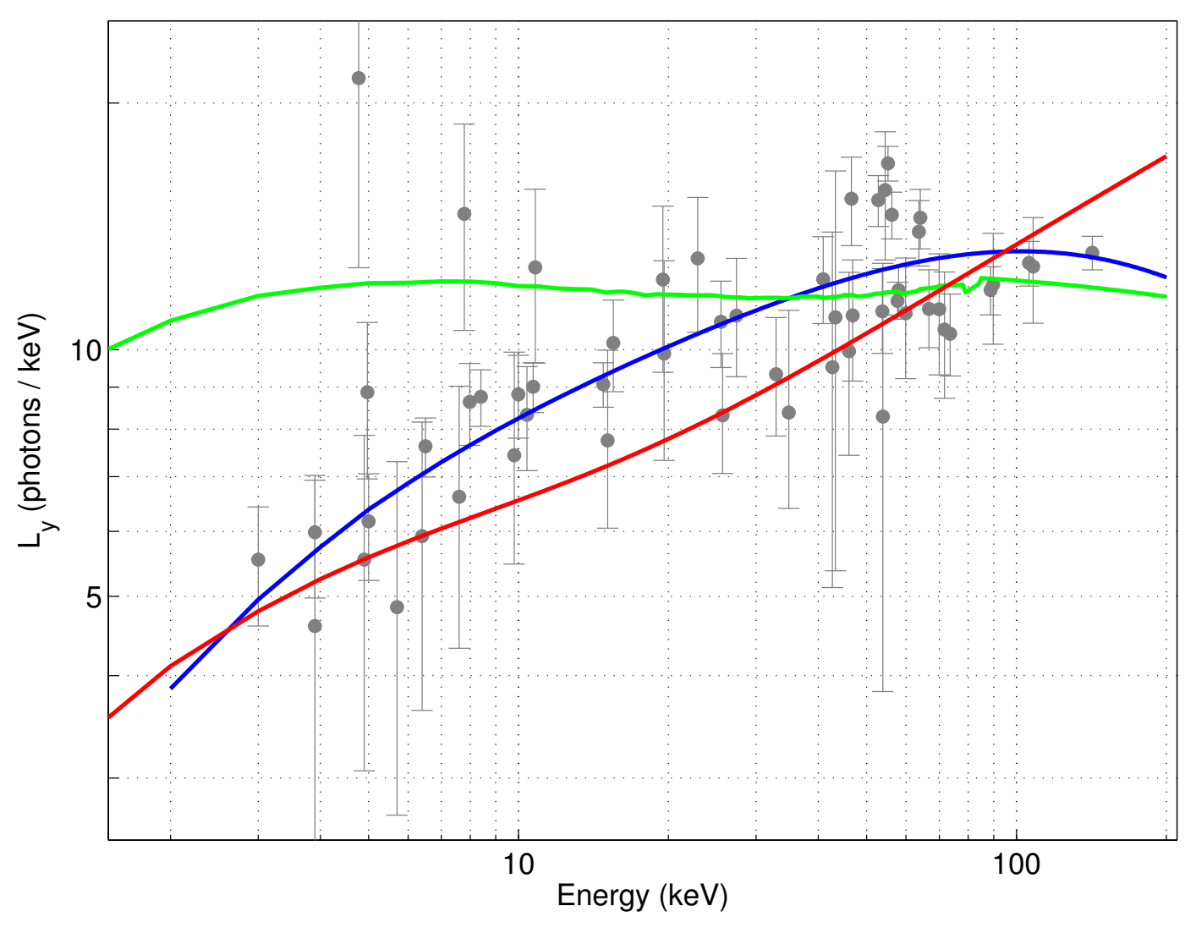
$$\chi^2 = \sum_i \frac{(x_i - x_{model})^2}{\sigma_i^2}$$

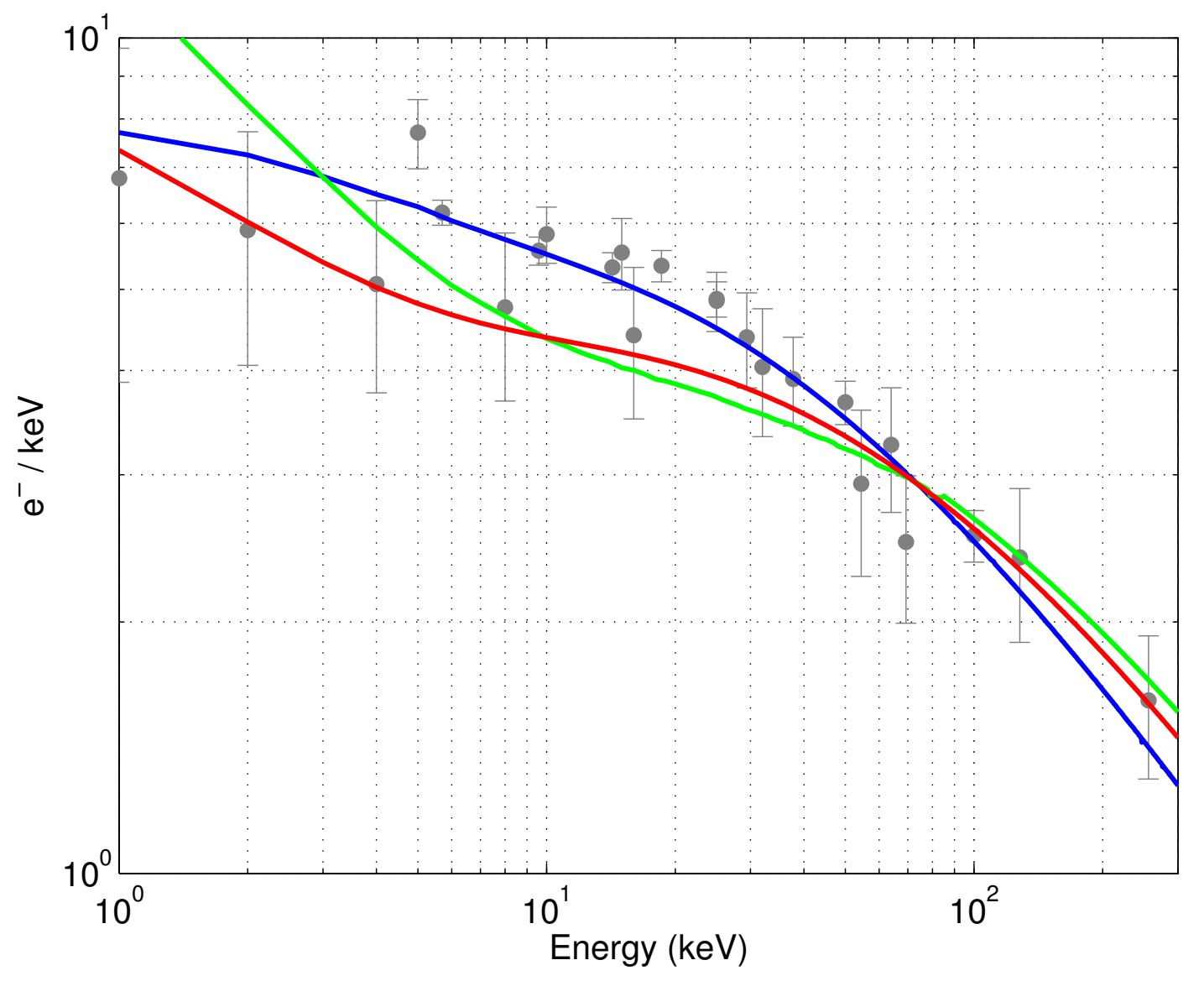
$$x_{model} \in \left\{\mathcal{Q}_y, \mathcal{L}_{eff}, \frac{n_e}{n_\gamma}\right\}$$

These are then optimized using multiple fitting algorithms in order to ensure that we find the global best fit to the data. A global scan across the parameter space is compared to the output of both a simulated annealing fitter and a Metropolis-Hastings Markov Chain Monte Carlo (MCMC) sampling algorithm and found to agree. The output of the MCMC is used to calculate statistical errors on the model, shown on the L_y curve above. The statistical uncertainties on $\mathcal{Q}_y$ are similar.

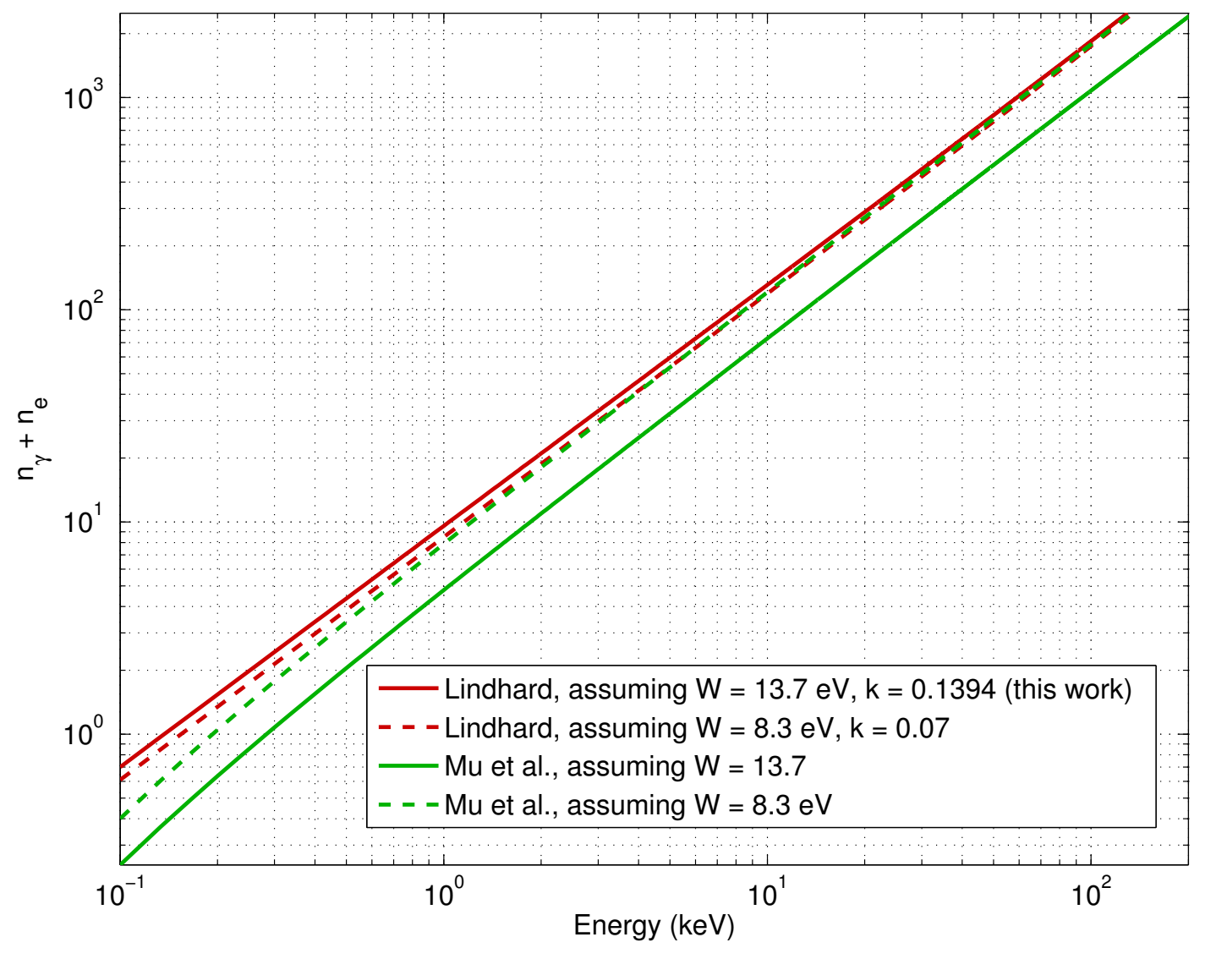
TESTING ALTERNATIVE MODELS

Alternative models of nuclear recoil quenching are also incorporated into the global fit framework for comparison. In the literature, the quenching factor L has been investigated from several theoretical perspectives, and alternatives to Lindhard's theory have been proposed for liquid xenon at low energies.





In these two figures, we study the effect of two alternatives described in Bezrukov et al. (2011). These models, due to Ziegler et al. (red) Lenz and Jensen (green), differ from Lindhard (blue) in that they use different theoretical expressions for the nuclear stopping power. They are modified such that an overall constant factor is allowed to float to fit them to the global dataset. We find that these alternatives fit the data with a χ^2/d.o.f. $= 2.88$ and χ^2/d.o.f. $= 4.32$ respectively, compared to χ^2/d.o.f. $= 1.33$ of the Lindhard model.



Recent work by Mu et al. (preprint, 2014) suggests a new model of the electronic stopping power, and predicts a quenching factor L significantly lower than that of Lindhard. Within the global framework, this predicts too few quanta (N_q too small). However, it can be brought into agreement by additionally assuming a lower value for W. Our model assumes $W = 13.7\,$eV, a value motivated by previous work. Here we show that the predicted number of quanta can be brought into agreement by assuming $W = 8.3\,$eV, which is within twice the experimental uncertainty on the measurement cited by Mu et al.

SUMMARY

This work provides a model of light and charge yields from nuclear recoils in liquid xenon, constrained simultaneously using measurements of both quantities. The approach incorporates an anti-correlation between the two and helps break degeneracies between quantities that can independently affect one or the other. We are able to obtain a tightly constrained mean for the semi-empirical NEST model, and find that it provides a better fit than many alternatives suggested in the literature. These results could be used to predict yields and extrapolate to low energies, allowing lowered thresholds in analyses of data from liquid xenon experiments.

ACKNOWLEDGEMENTS

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