Quenching Factors and Calibration

Dan McKinsey
LUX Co-Spokesperson
Yale University Department of Physics

Dark Matter Silver Jubilee
Pacific Northwest National Laboratory

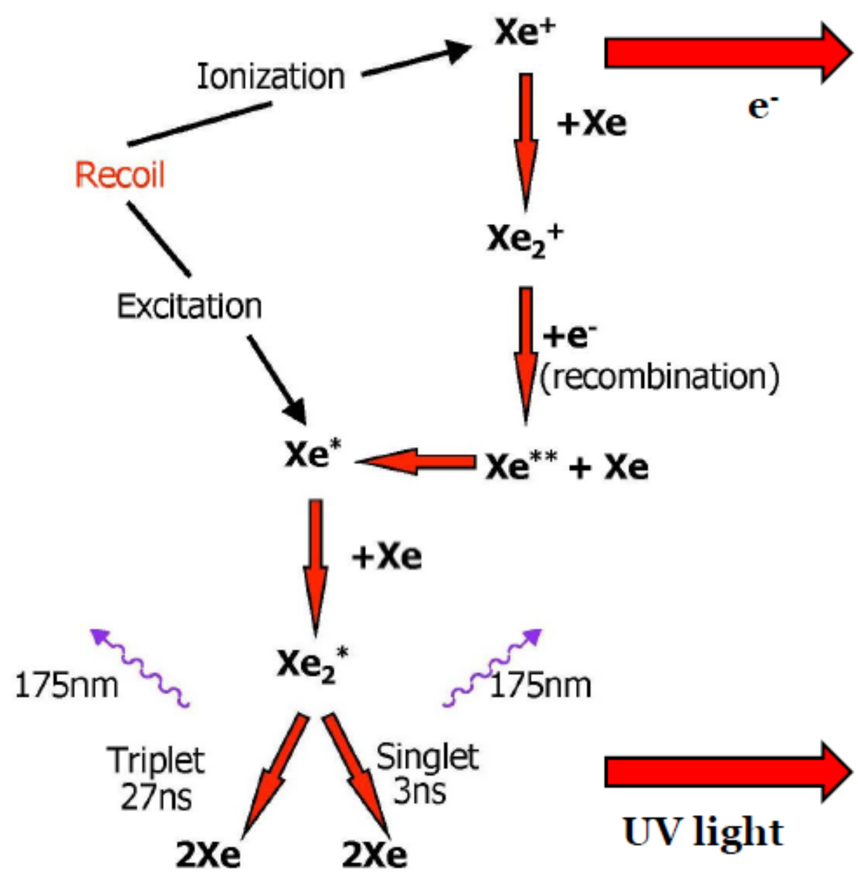
Direct WIMP Detection with Liquid Xenon

- Goal: observe recoils between a WIMP and a target nucleus
- Equation for WIMP interaction cross section

$$\frac{dN}{dE_R} \propto \left(\frac{e^{-E_R/(E_0 r)}}{E_0 r} \right) \cdot \left(F^2(E_R) \cdot I \right)$$

$$I \propto A^2 \quad \text{(for S.I. interactions)}$$

- Recoil energy deposited in three channels:
  - Scintillation (photons)
  - Ionization (charge)
  - Heat (phonons)



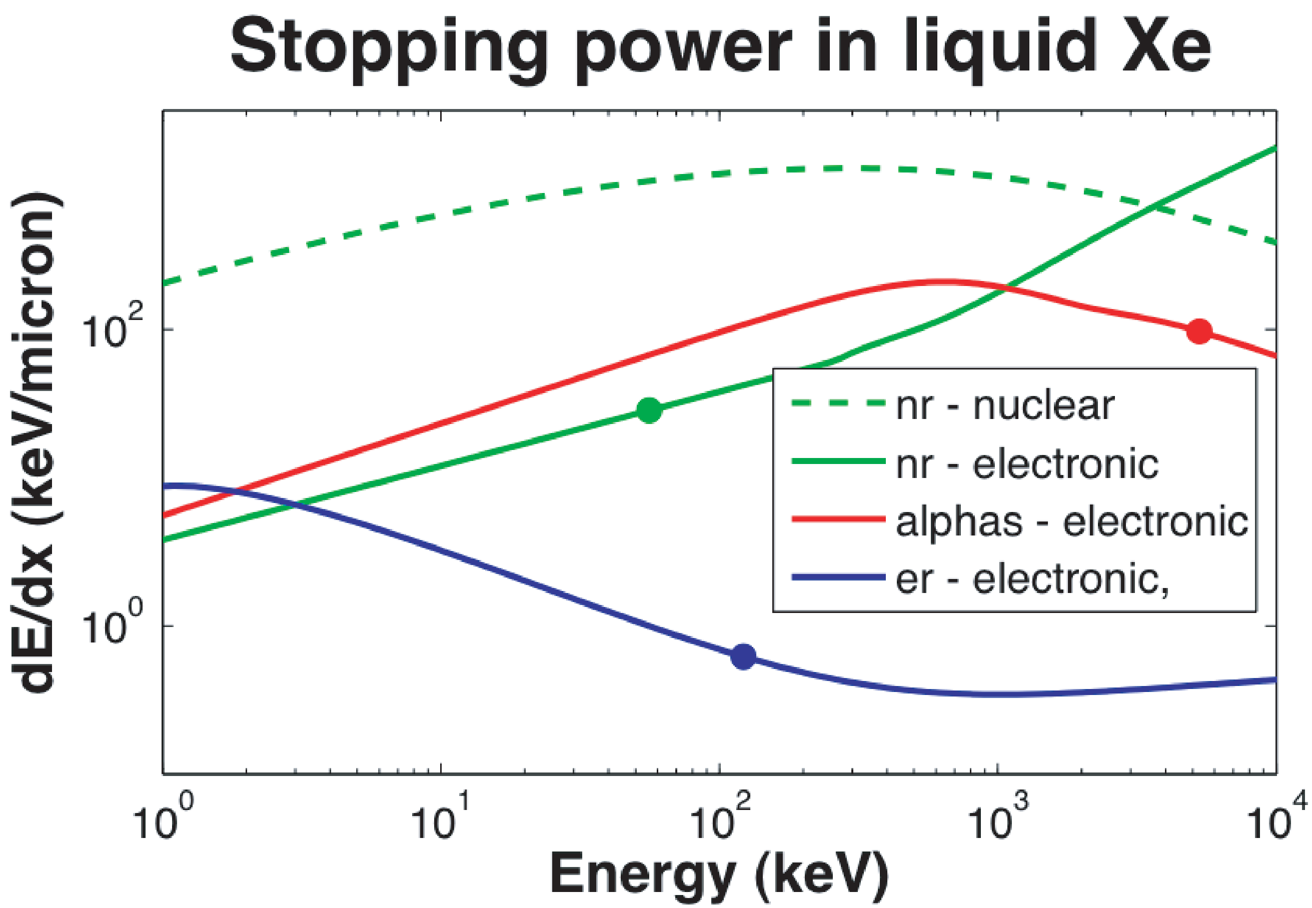
$$L_{eff} = \frac{\text{scintillation per unit energy for nuclear recoils}}{\text{scintillation per unit energy for electron recoils}}$$

In practice, we define the denominator based on
122 keV photoabsorption events from Co-57

In the XENON10 analysis, we assumed an energy-independent Leff of 0.19 for the WIMP search analysis, and for determining our cross-section limits.

Uncertainty in Leff was the main source of systematic uncertainty in determining the cross-section limits.

New measurement of Leff: A. Manzur et al., Phys. Rev. C 81, 025808 (2010).
(Also measured Sn at several drift fields)



Decreasing nuclear recoil stopping power at low energies

-> *a priori* expect a more electron-like signal at low energies

- $S_n < 1$?
- Recombination fluctuations?

$$E_{\rm nr} = \frac{S1}{L_{\rm y} \cdot \mathcal{L}_{\rm eff}} \cdot \frac{S_{\rm e}}{S_{\rm n}}$$

Factors affecting Leff (all of which are likely energy-dependent!)

- Lindhard effect (kinematically suppressed nuclear recoil – electron excitations at low energy). Difficult to calculate at low energies.
- Ion-electron recombination efficiency. Becomes more electron-like at low energies?
- Atomic excitation, both singlet and triplet. Atomic excitation more significant at low energies?
- Bi-excitonic quenching a la Birk's law. Should be less significant at low energies.

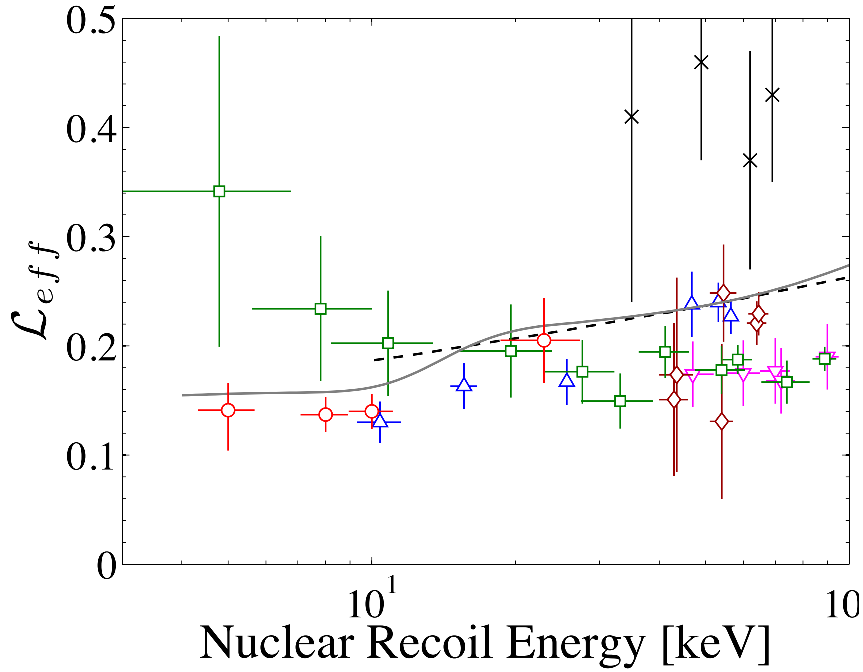
For discussion of models of these effects, see:

Sorensen, arXiv:1007.3549, Dahl and Sorensen arXiv:1101.6080,

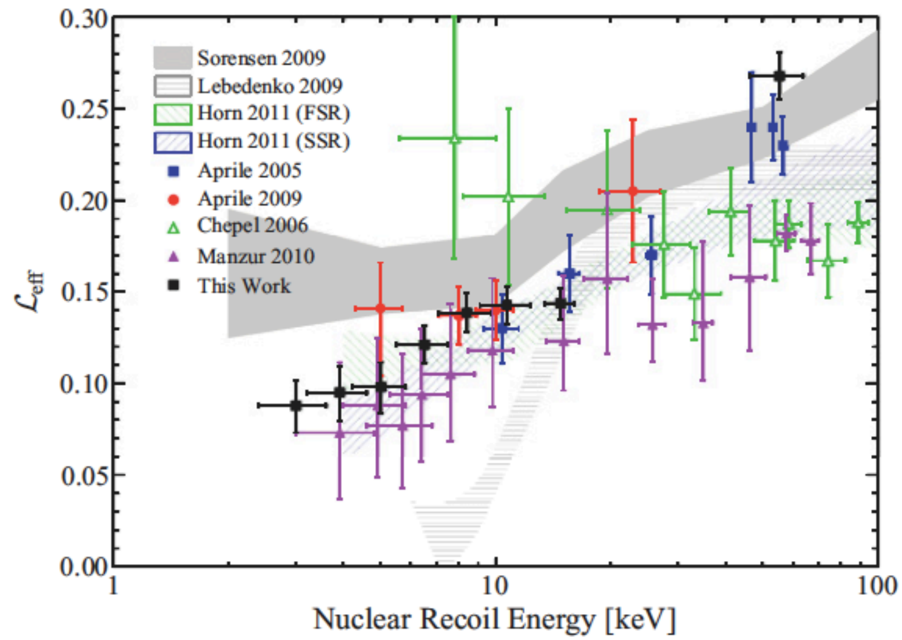
Bezrukov, Kahlhoefer, and Lindner, arXiv: 1011.3990

After some controversy, Leff is now believed to decrease at low energy

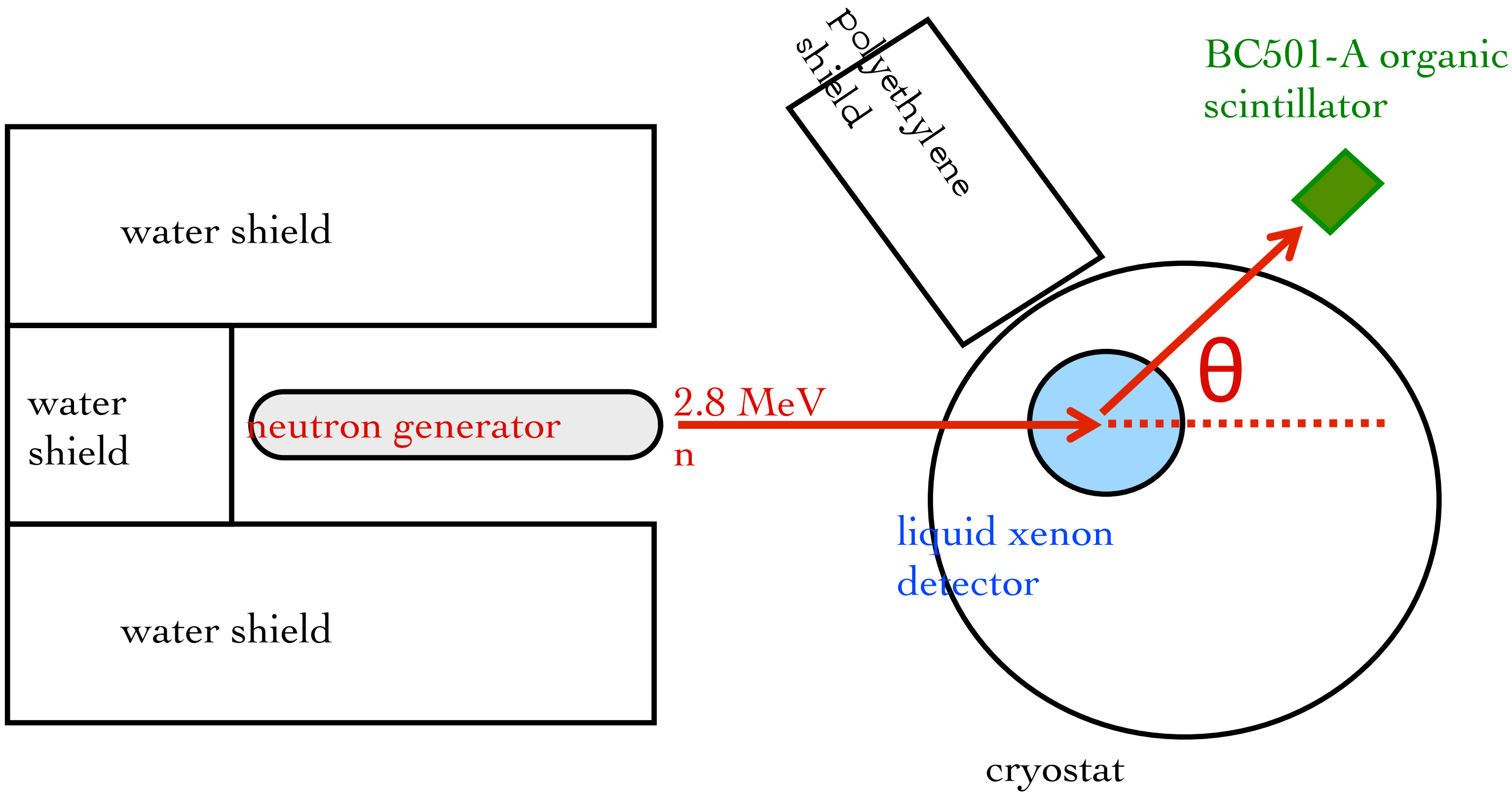
Aprile et al, 2009



Plante et al, 2011



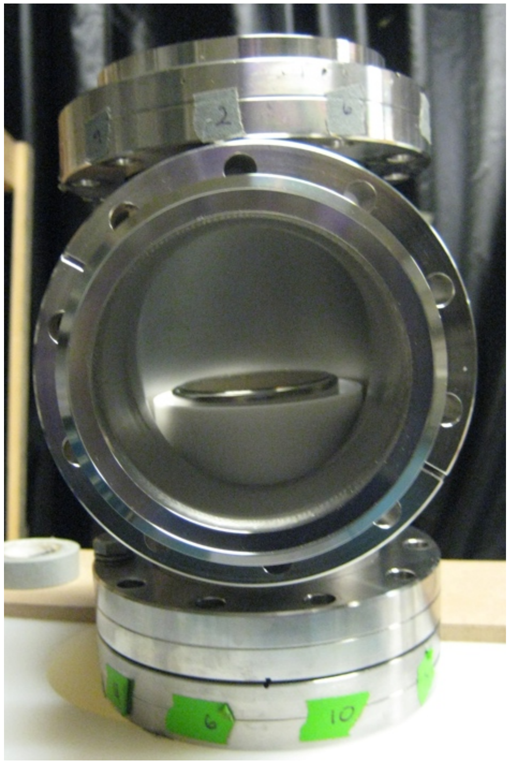
Experimental setup

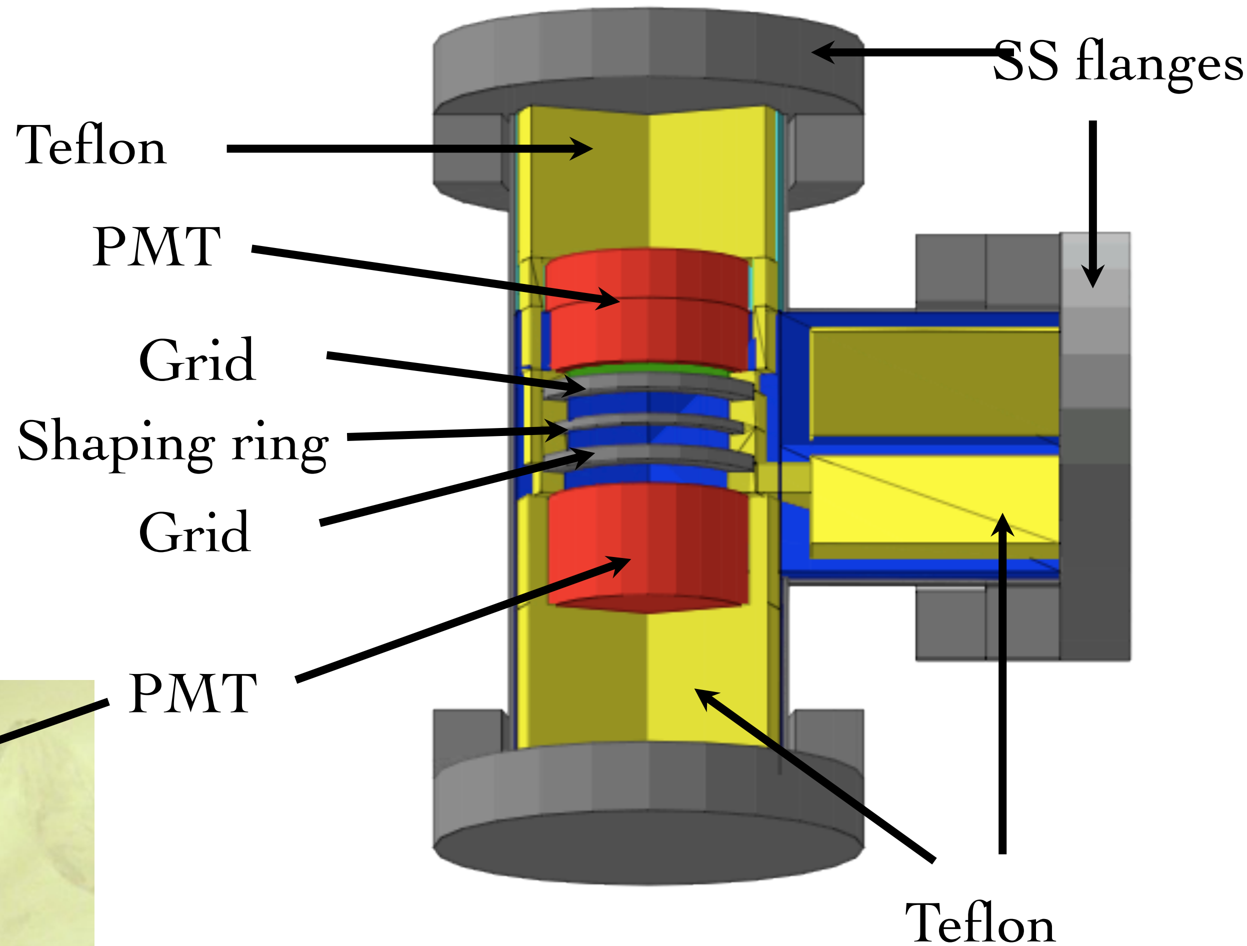


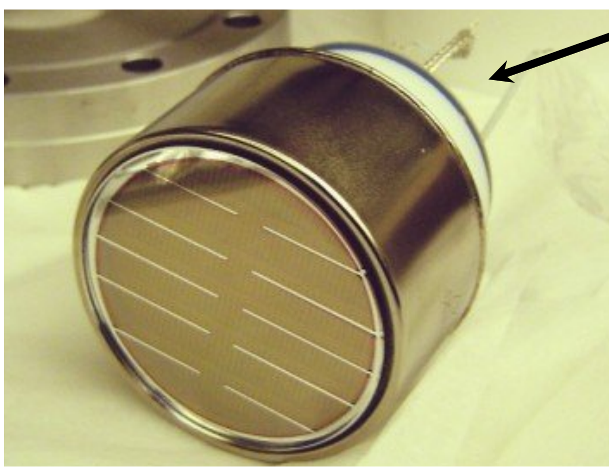
$$E_R = E_n \frac{2m_n M_{Xe}}{(m_n + M_{Xe})^2}(1 - \cos\theta)$$

Energies: 4 - 66 keVr

Liquid xenon cell

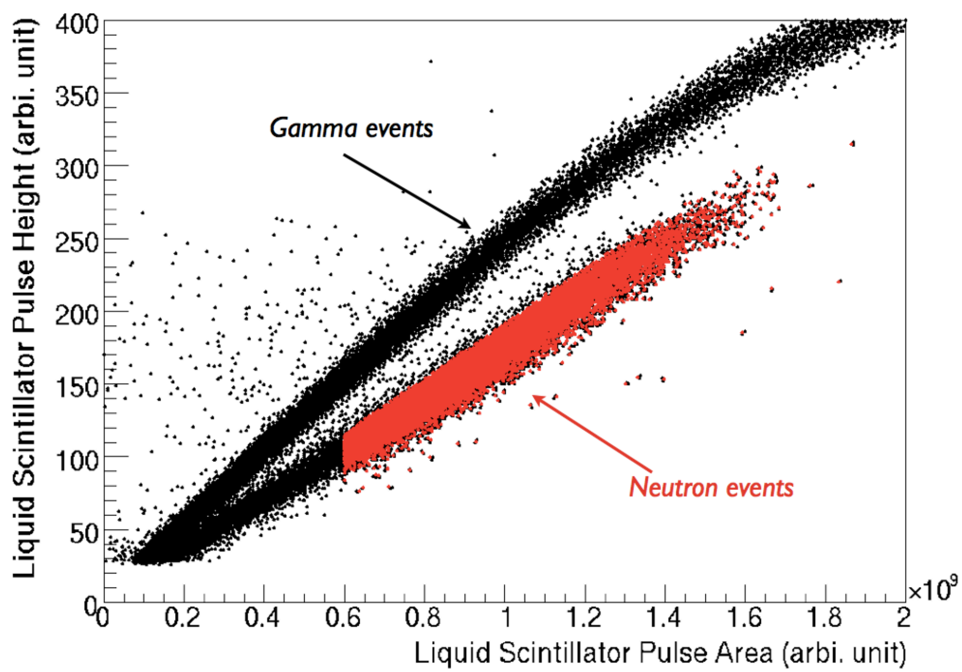


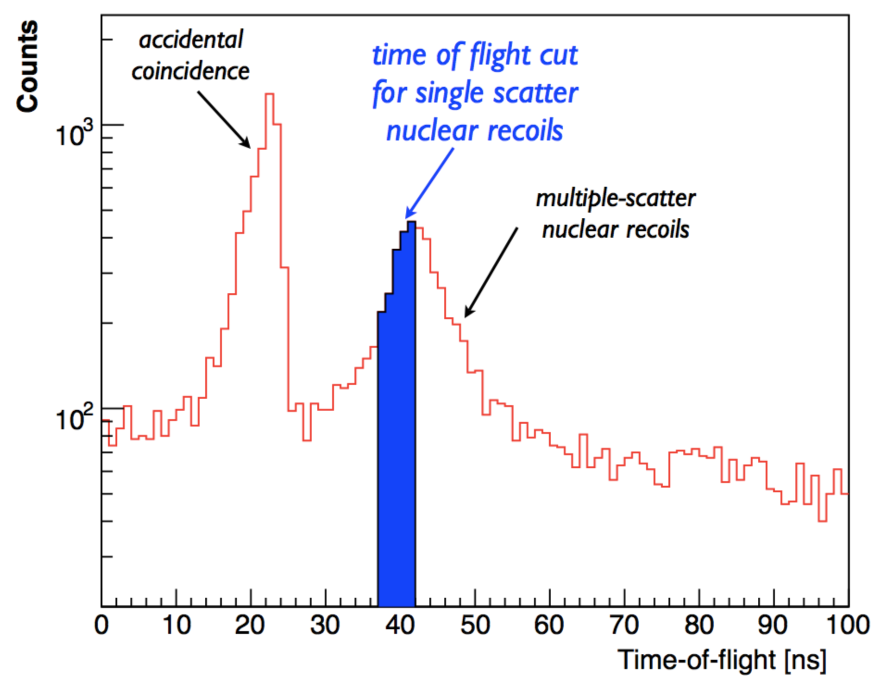




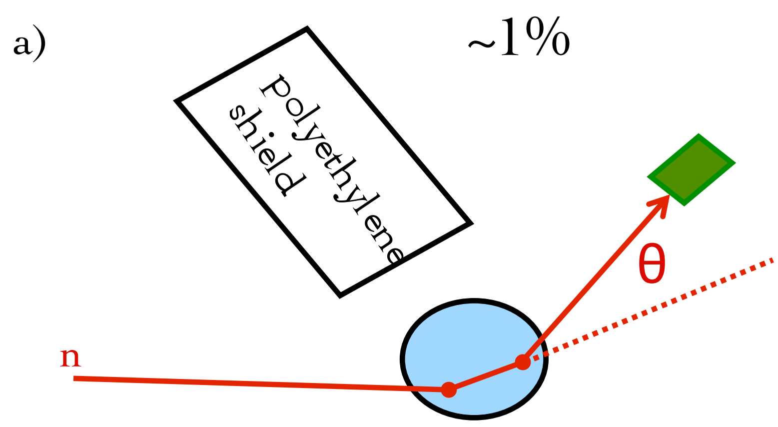
Selecting single nuclear recoils

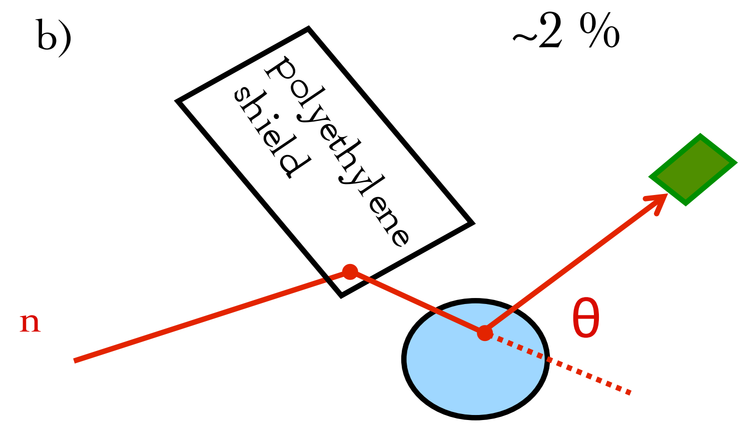
- Quality cuts Q0: remove noise event, high energy events, S1 asymmetry
- Select neutrons using PSD and time of flight (TOF)

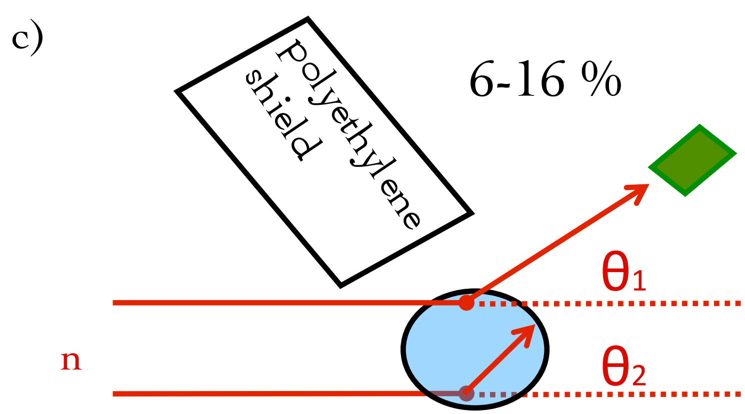




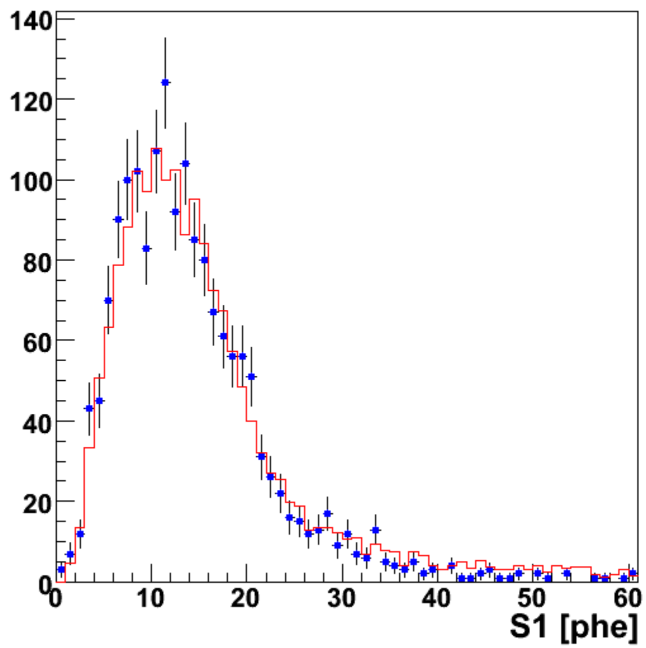
Systematic error

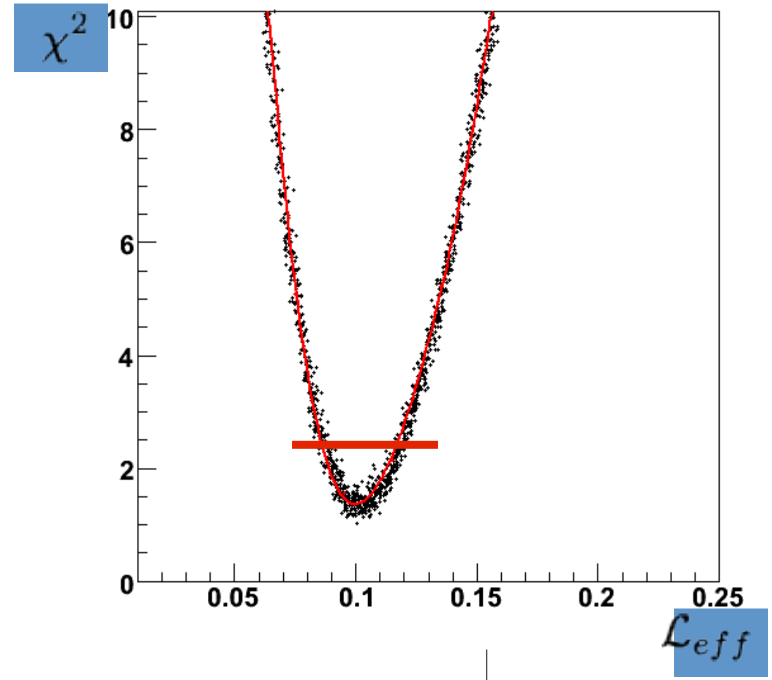






- a) Multiple elastic scatters
- b) Outside scatters
- c) Size and position
- d) Cross-section database ~2 - 4%



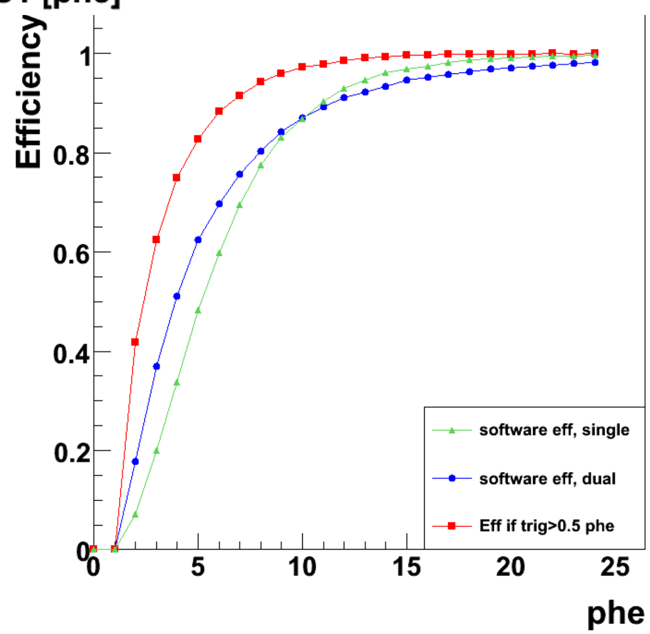


To compare MC & data:

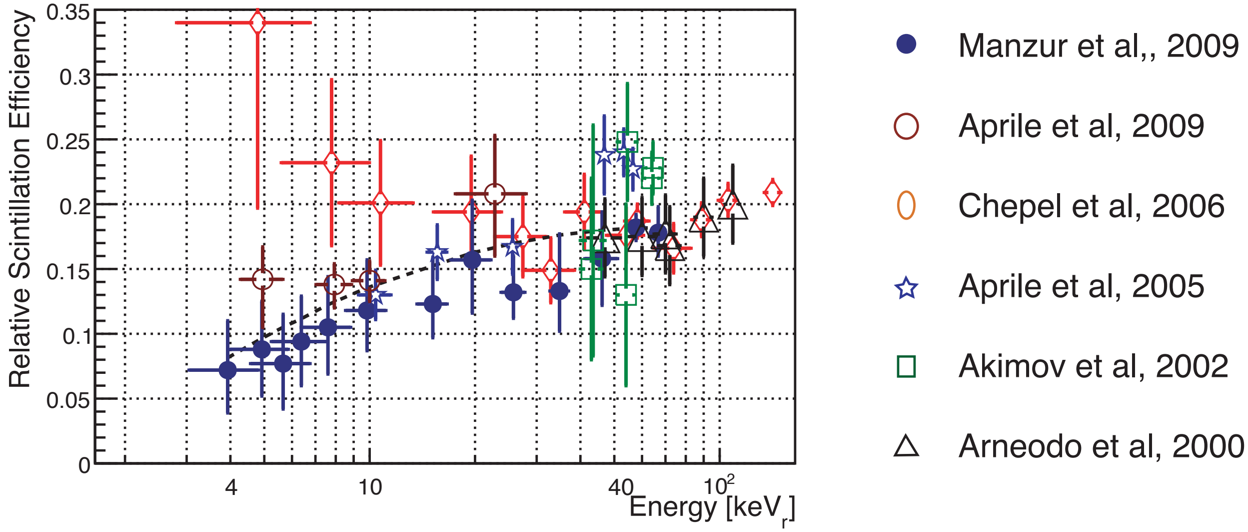
1 $E_R \rightarrow E_e$

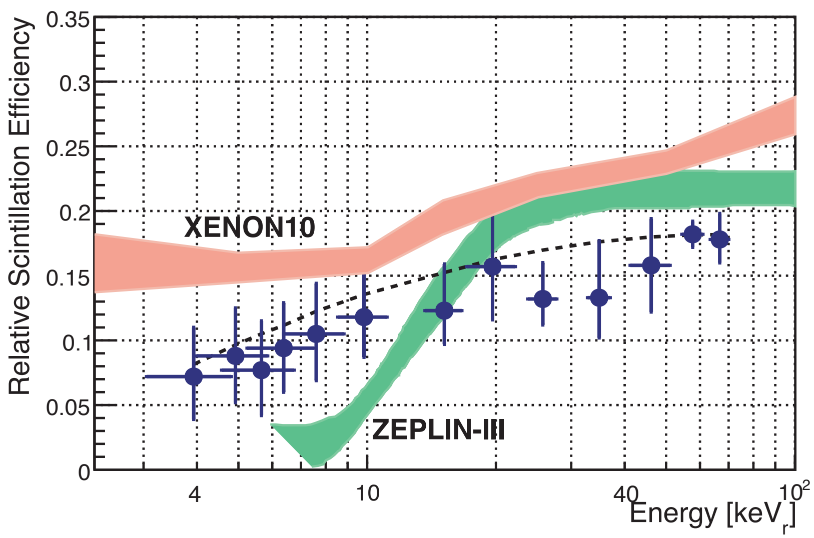
2 $\sigma = 3.2\sqrt{N_{phe}}$

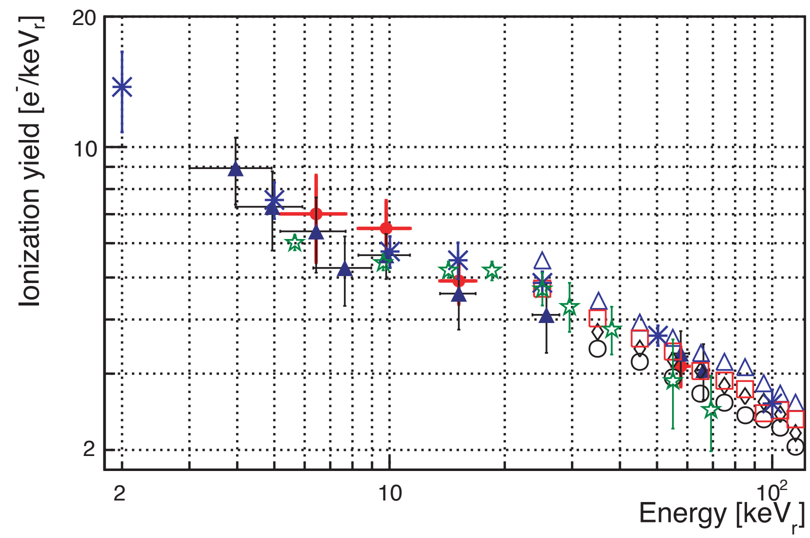
3 software + trigger efficiency



Leff results







$\mathcal{L}_{eff}$ **model**

$$\mathcal{L}_{eff} = q_{ncl} \times q_{el} \times q_{esc}$$

- q_{ncl} nuclear quenching (Lindhard factor), energy goes into heat.
- q_{el} electronic quenching. Bi-excitonic collisions

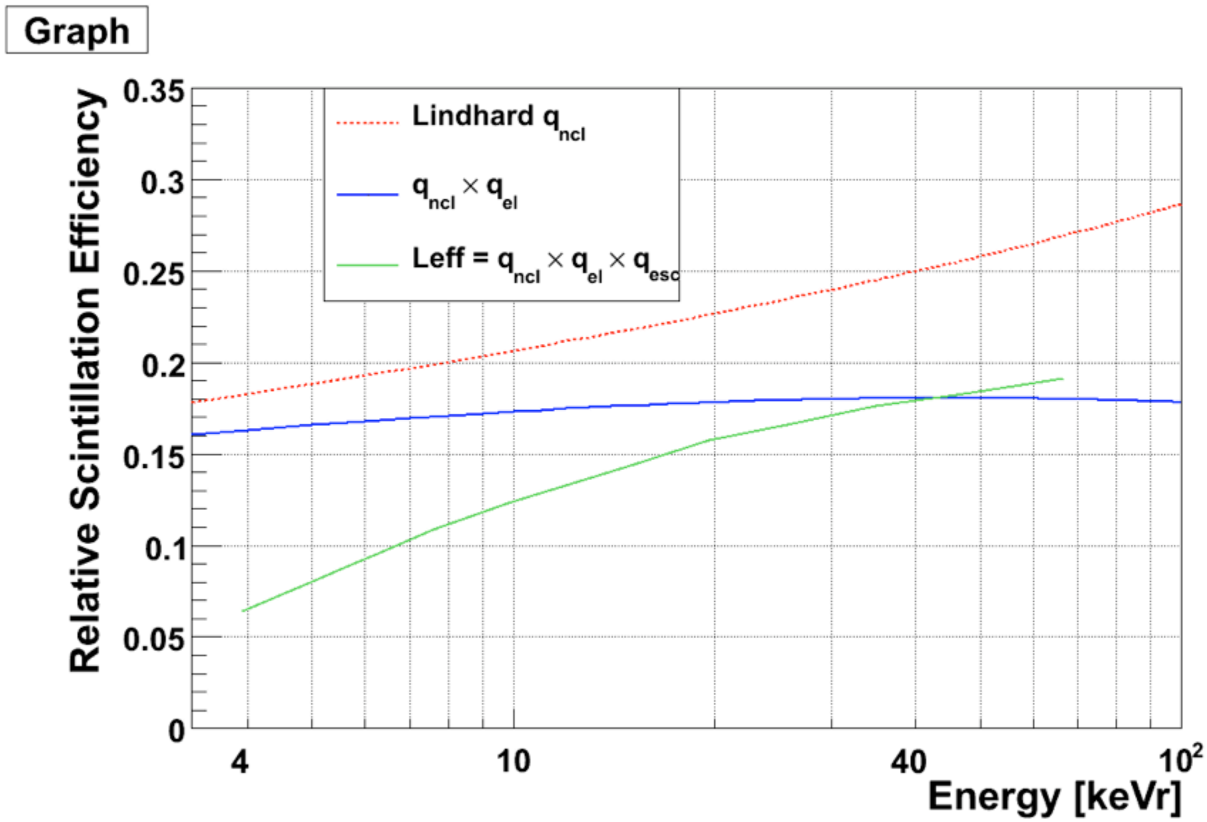
$$\mathrm{Xe}^* + \mathrm{Xe}^* \rightarrow \mathrm{Xe} + \mathrm{Xe}^+ + e^-$$

$$q_{el} = \frac{1}{1 + k\frac{dE}{dx}}$$

- Escape electrons

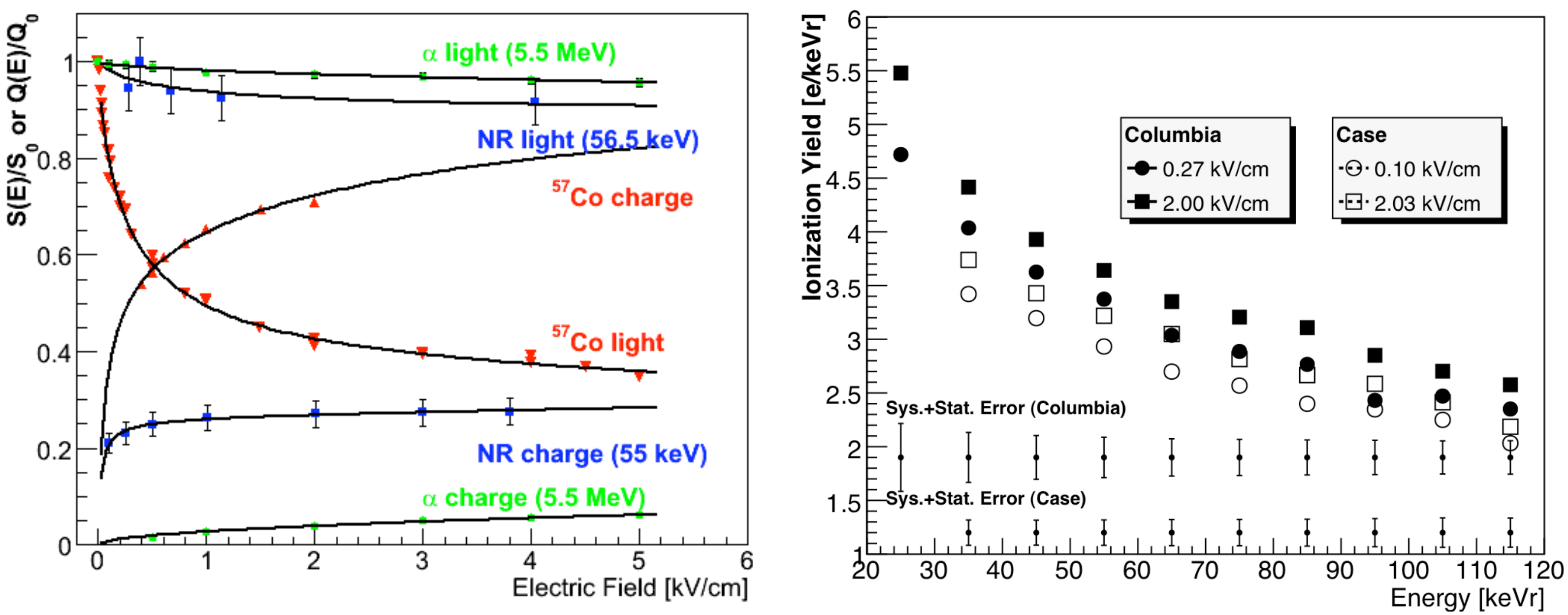
$$q_{esc} = \frac{N_{ex} + N_i - N_{esc}}{N_{ex}^{122} + N_i^{122} - N_{esc}^{122}} = \frac{\alpha + 1 - \beta}{\alpha + 1 - \beta^{122}}$$

$\mathcal{L}_{eff}$ model



Nuclear Recoil Ionization Yield and Field Dependence

Aprile et al., astro-ph/0601552, Phys. Rev. Lett 97, 081302 (2006).



Note modest (but not negligible) increase in nuclear recoil ionization yield at higher fields.

Results from Manzur et al

TABLE I. $\mathcal{L}_{\rm eff}$ and S_n values for the different nuclear recoil energies studied. The third column gives the $\mathcal{L}_{\rm eff}$ values relative to 122-keV γ rays. The first error is the statistical uncertainty, and the second error is the systematic uncertainty.

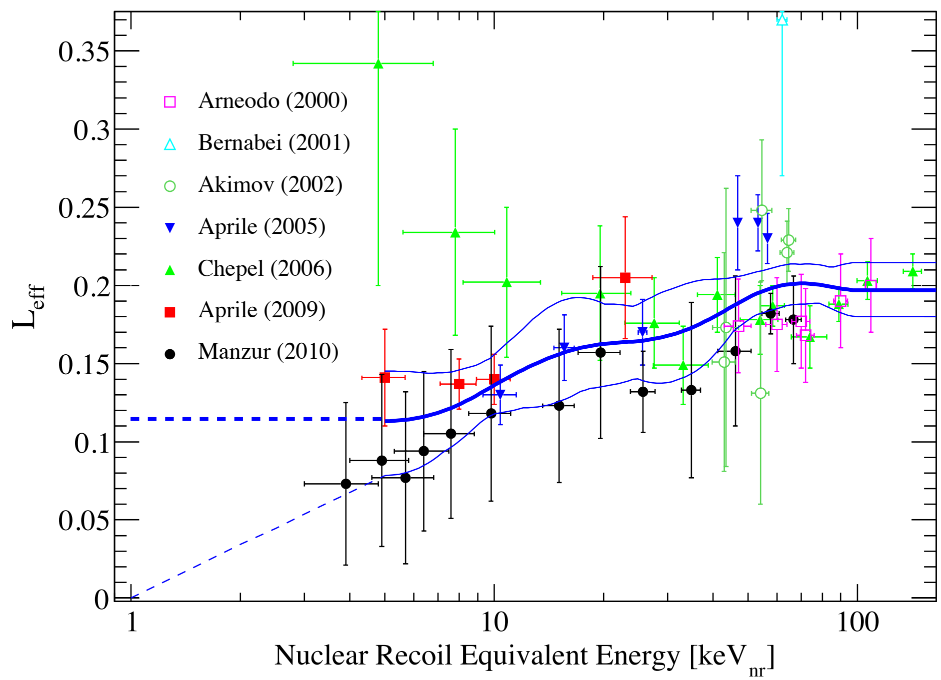
θ	E_r [keV$_r$]	$\mathcal{L}_{\rm eff}$ at 0.0 kV/cm	S_n 0.73 kV/cm	S_n 1.0 kV/cm	S_n 1.5 kV/cm	S_n 4.0 kV/cm
125	66.7 ± 3.3	$0.178^{+0.018+0.010}_{-0.016-0.009}$	0.91 ± 0.07	1.11 ± 0.09	0.88 ± 0.06	–
110	57.7 ± 3.2	$0.182^{+0.009+0.004}_{-0.009-0.002}$	0.95 ± 0.05	0.95 ± 0.06	0.93 ± 0.04	0.93 ± 0.06
95	46.1 ± 4.9	$0.158^{+0.038+0.010}_{-0.039-0.009}$	0.97 ± 0.08	–	0.82 ± 0.08	–
80	34.9 ± 2.1	$0.133^{+0.042+0.014}_{-0.029-0.012}$	1.33 ± 0.26	–	1.30 ± 0.25	–
67	25.7 ± 2.0	$0.132^{+0.025+0.001}_{-0.019-0.006}$	0.95 ± 0.06	0.91 ± 0.12	0.95 ± 0.07	–
58	19.6 ± 2.6	$0.157^{+0.046+0.008}_{-0.036-0.019}$	0.70 ± 0.06	–	1.03 ± 0.13	–
50	15.1 ± 1.5	$0.123^{+0.030+0.019}_{-0.023-0.014}$	0.83 ± 0.16	1.02 ± 0.20	1.01 ± 0.15	1.08 ± 0.18
40	9.8 ± 1.3	$0.118^{+0.027+0.029}_{-0.022-0.022}$	0.91 ± 0.17	1.64 ± 0.50	0.98 ± 0.18	1.62 ± 0.45
35	7.6 ± 1.2	$0.105^{+0.028+0.026}_{-0.022-0.029}$	0.79 ± 0.28	1.06 ± 0.30	0.79 ± 0.28	–
32	6.4 ± 1.1	$0.094^{+0.027+0.023}_{-0.022-0.029}$	0.92 ± 0.37	1.25 ± 0.45	0.93 ± 0.38	1.38 ± 0.52
30	5.7 ± 1.1	$0.077^{+0.028+0.027}_{-0.022-0.026}$	1.35 ± 0.67	–	1.18 ± 0.61	–
28	4.9 ± 0.9	$0.088^{+0.026+0.026}_{-0.023-0.032}$	1.16 ± 0.45	1.34 ± 0.50	0.87 ± 0.35	–
25	3.9 ± 0.9	$0.073^{+0.034+0.018}_{-0.025-0.026}$	1.19 ± 0.52	1.30 ± 0.38	1.88 ± 0.78	–

S_n still uncertain at low energies

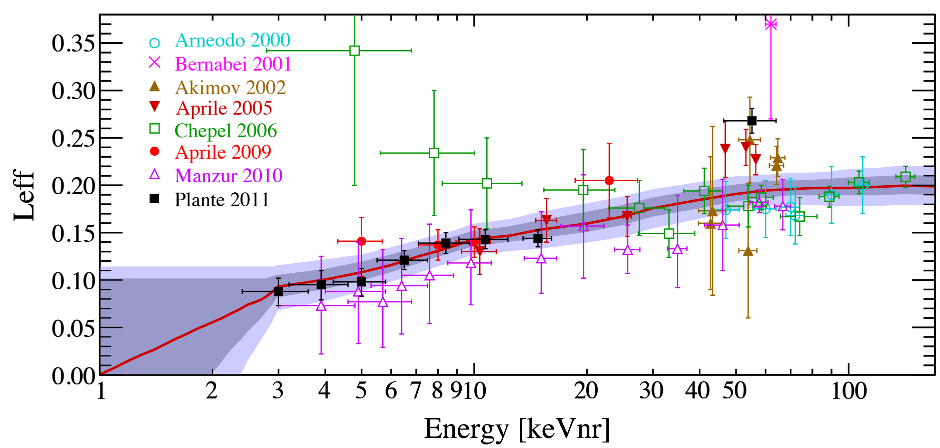
Extrapolating Leff

These Leff extrapolations (and upward Poisson fluctuations in light signal) are key for claimed low-mass WIMP sensitivity in XENON100.

XENON100, 2010
Constant Leff extrapolation used

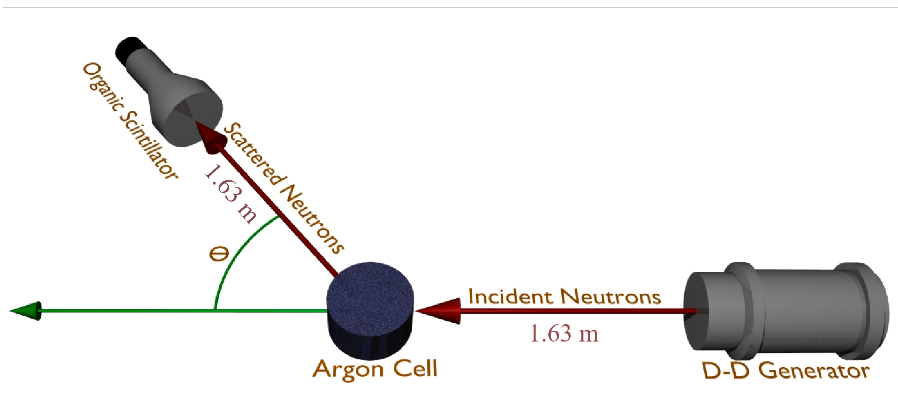


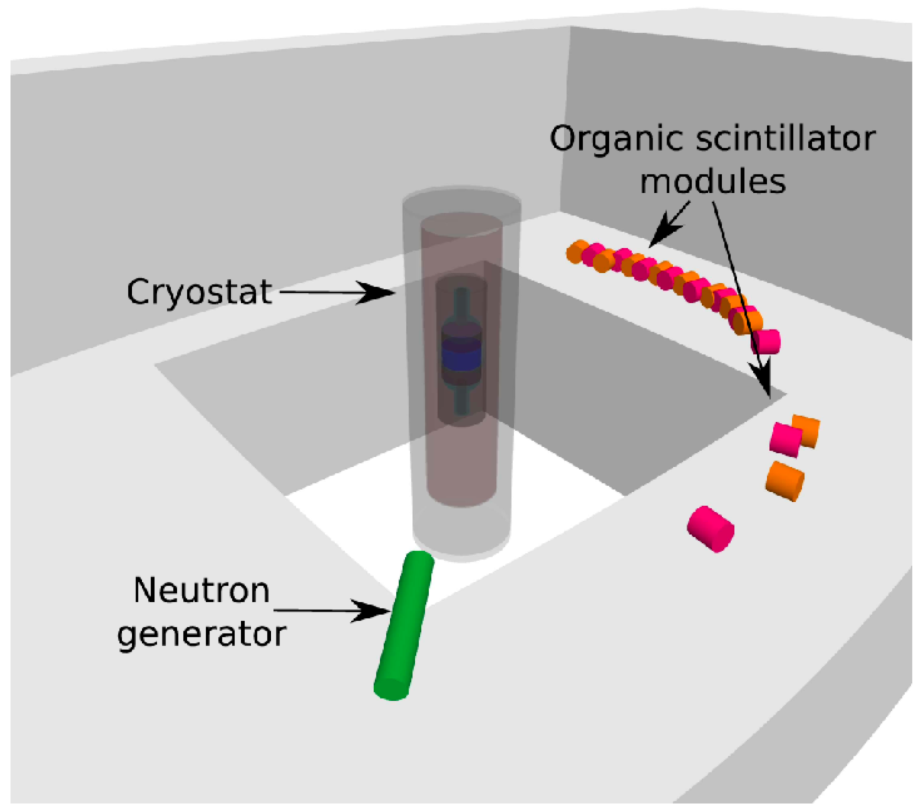
XENON100, 2011
Range of Leff extrapolations used



LAr and LNe Nuclear Recoil Scintillation Yields

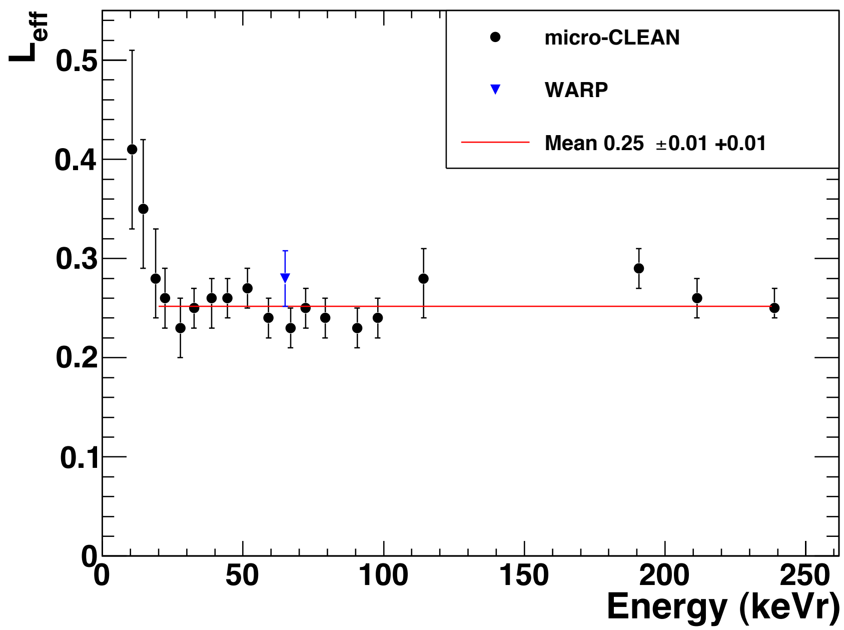
Measured using a d-d generator, MicroCLEAN, and an organic scintillator module



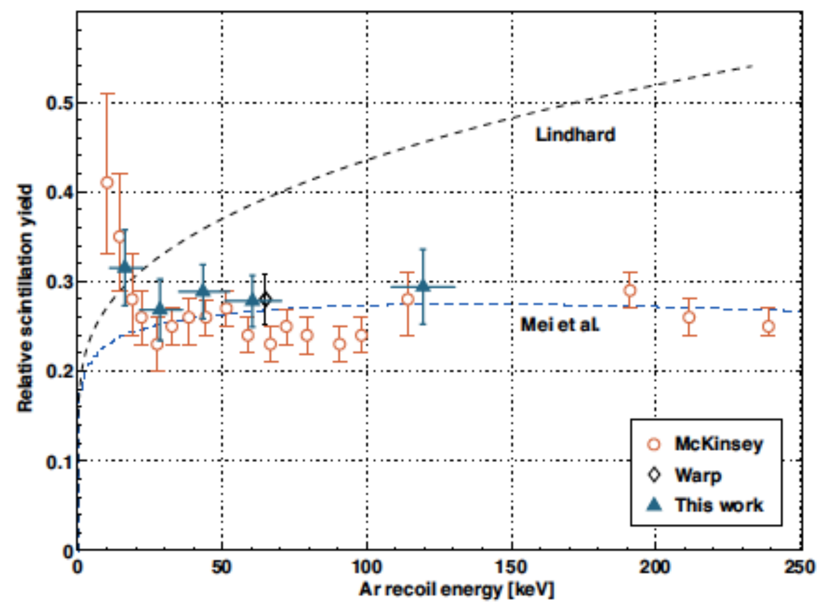


Liquid Argon Scintillation Efficiency

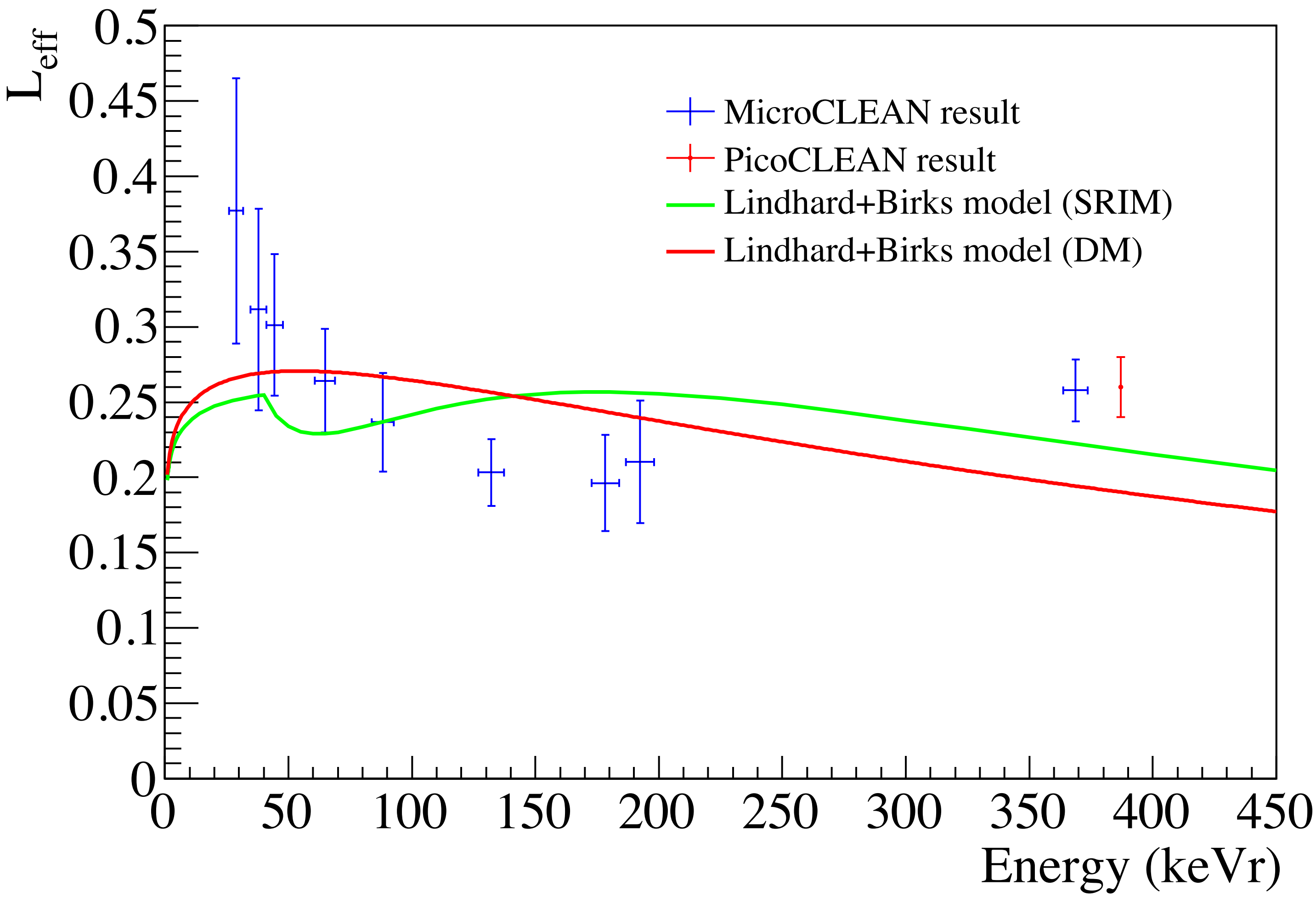
Gastler et al, arXiv:1004.0373

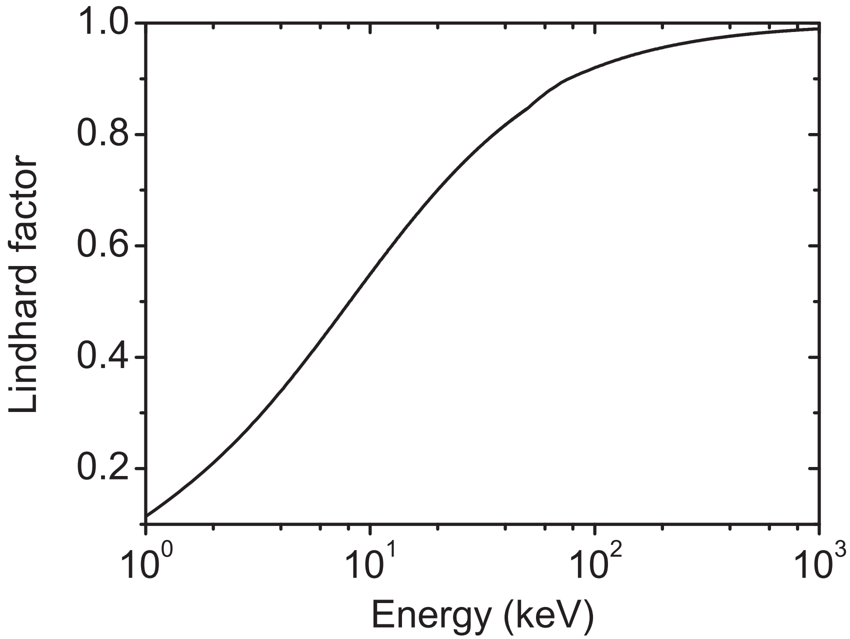


C. Regenfus et al, arXiv:1203.0849



LNe Leff (Lippincott et al, arXiv:1111.3260)

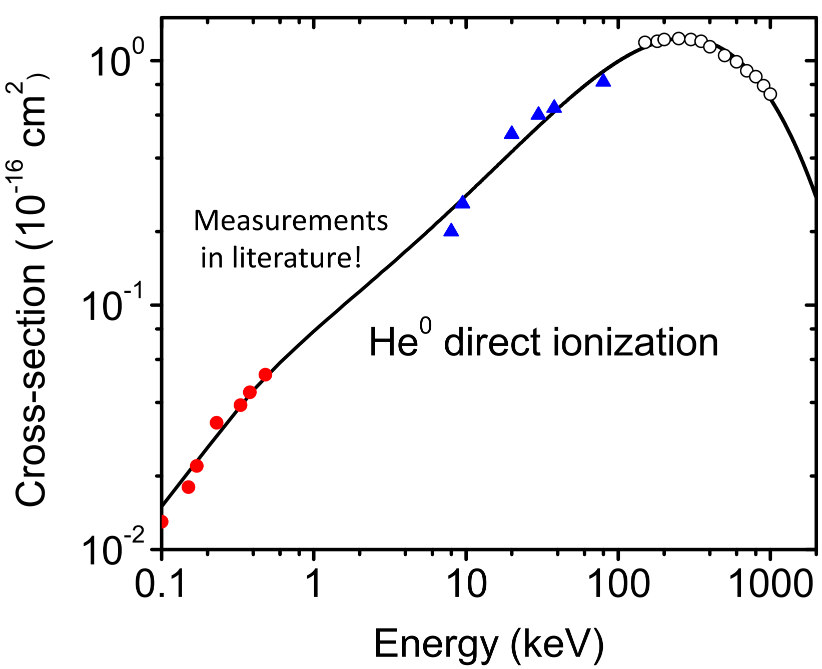


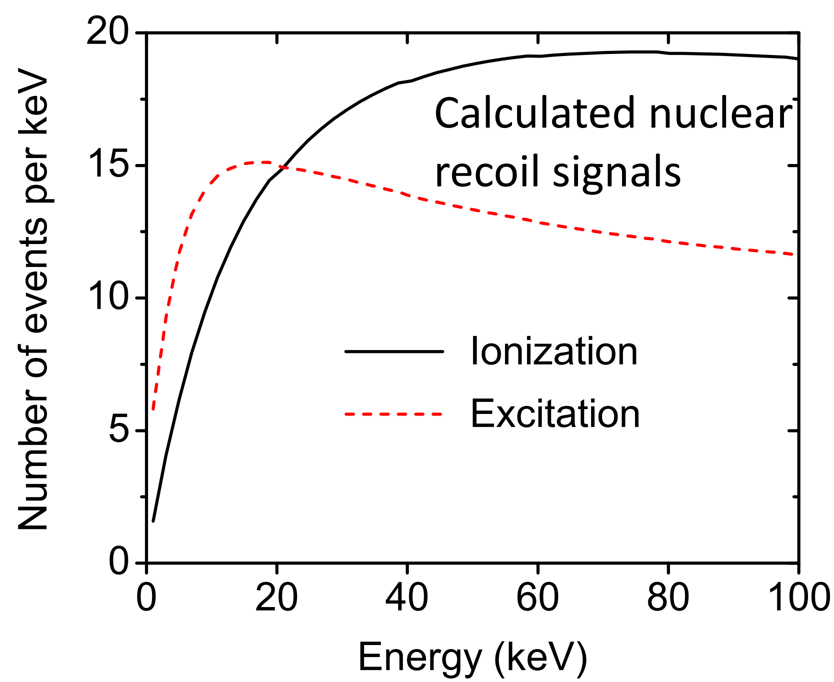


Liquid helium-4 predicted response (Guo and McKinsey, in preparation)

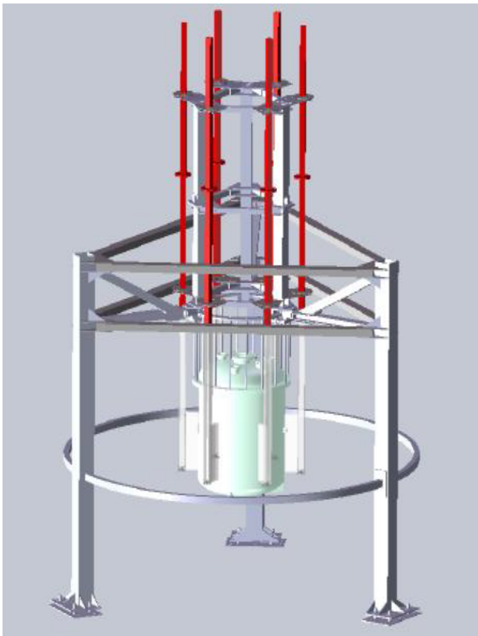
Lower electron scintillation yield (19 photons/keVee)

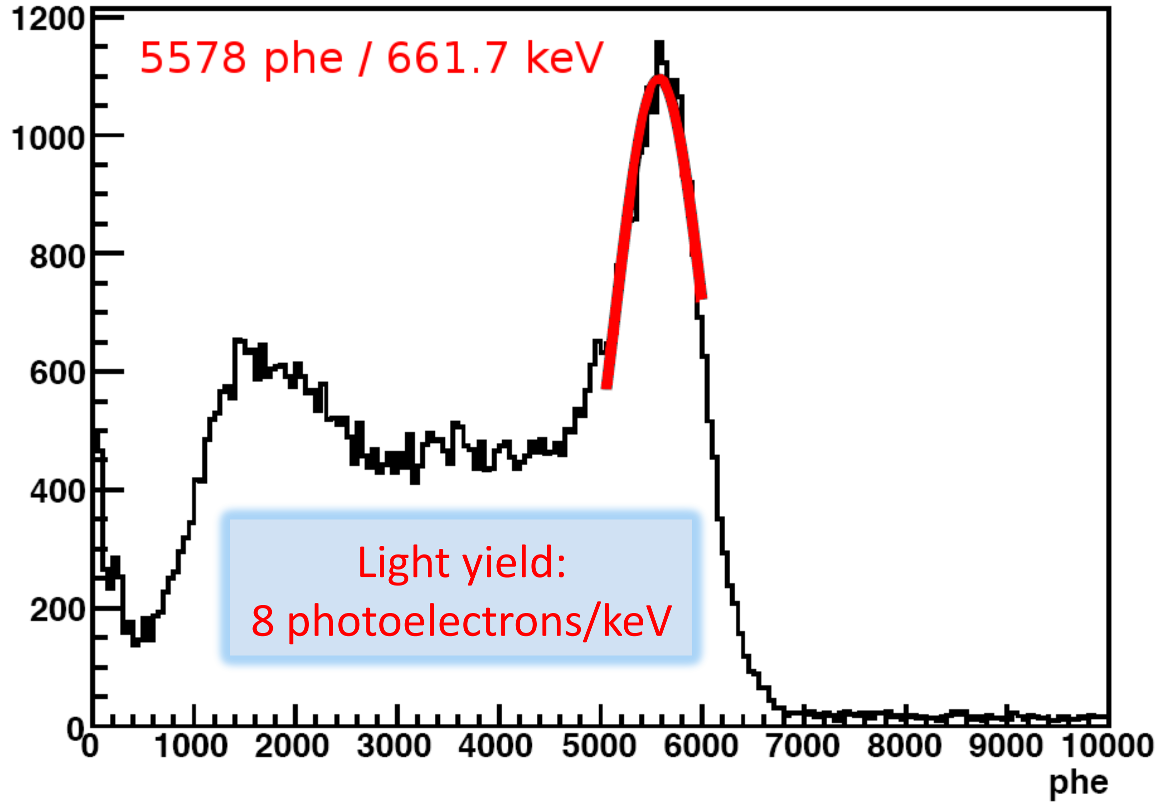
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity





LUX Calibrations



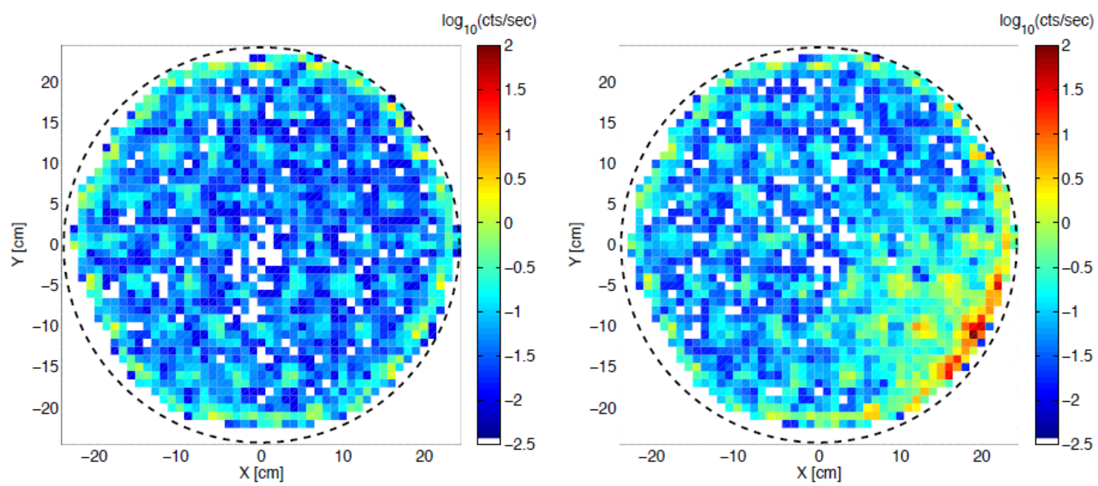


External calibrations:

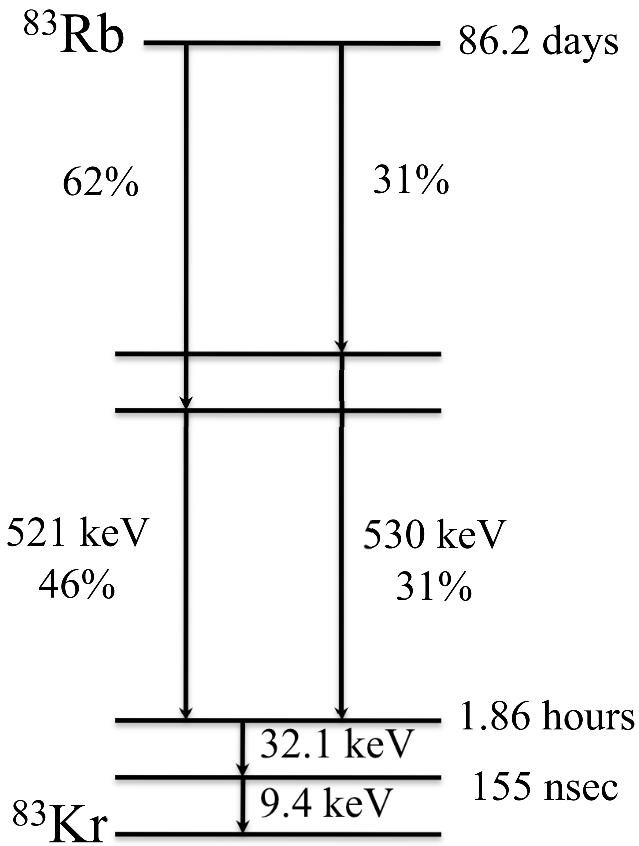
- ^{137}Cs , ^{133}Ba, ^{57}Co, ^{22}Na, ^{228}Th (γs)
- AmBe, ^{252}Cf (neutrons)

Internal calibrations:

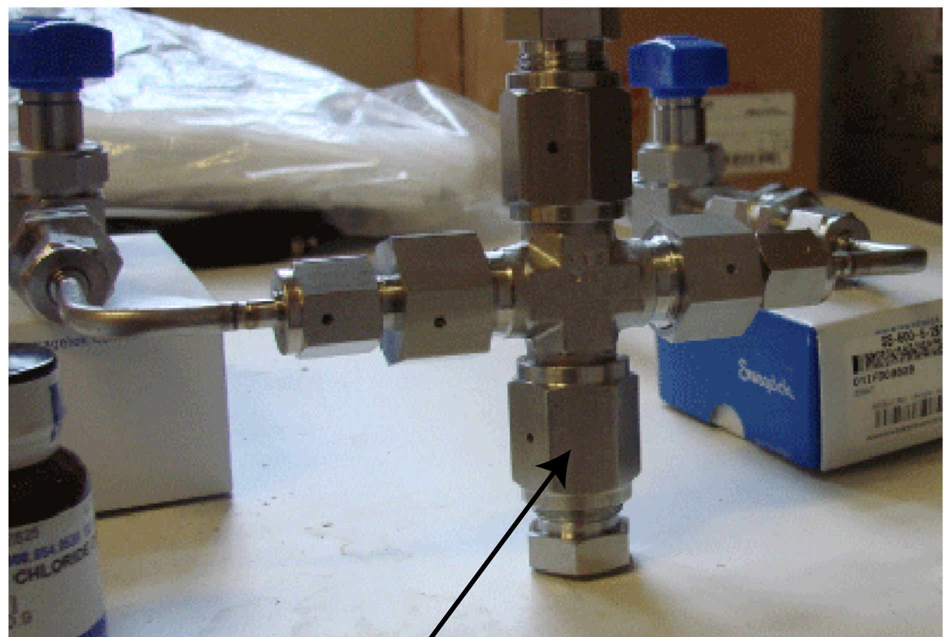
- ^{83m}Kr (conversion e^-)
- Tritium (βs)



Kr-83m calibration source development at Yale

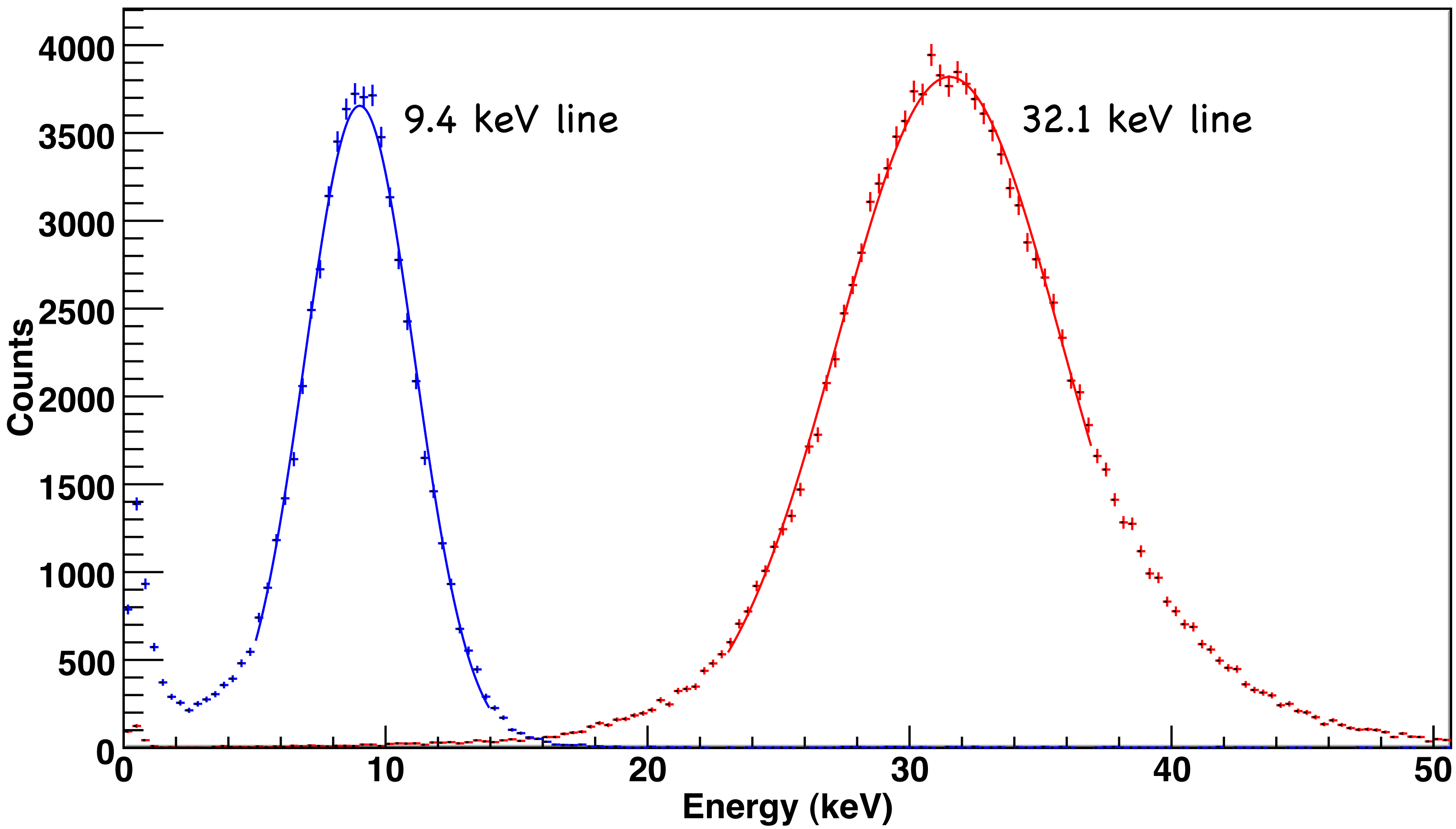


Rb-83 purchased in aqueous solution, then coated on zeolite. Continually emits Kr-83m, which can then be used to calibrate the liquid xenon detector response.



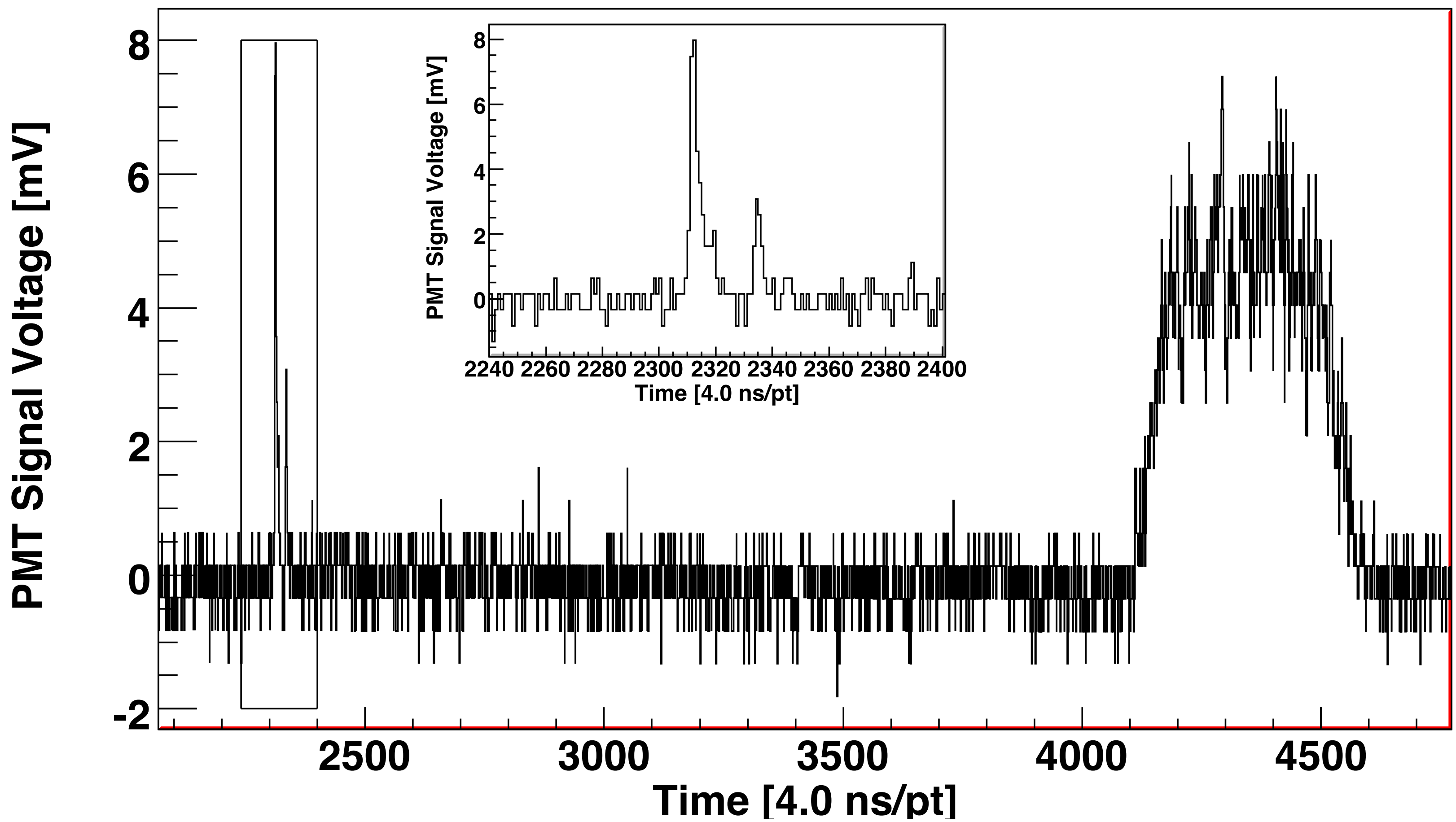
Rb-83 adsorbed on zeolite beads, in vacuum plumbing

LXe scintillation data from Kr-83m dissolved into LXe



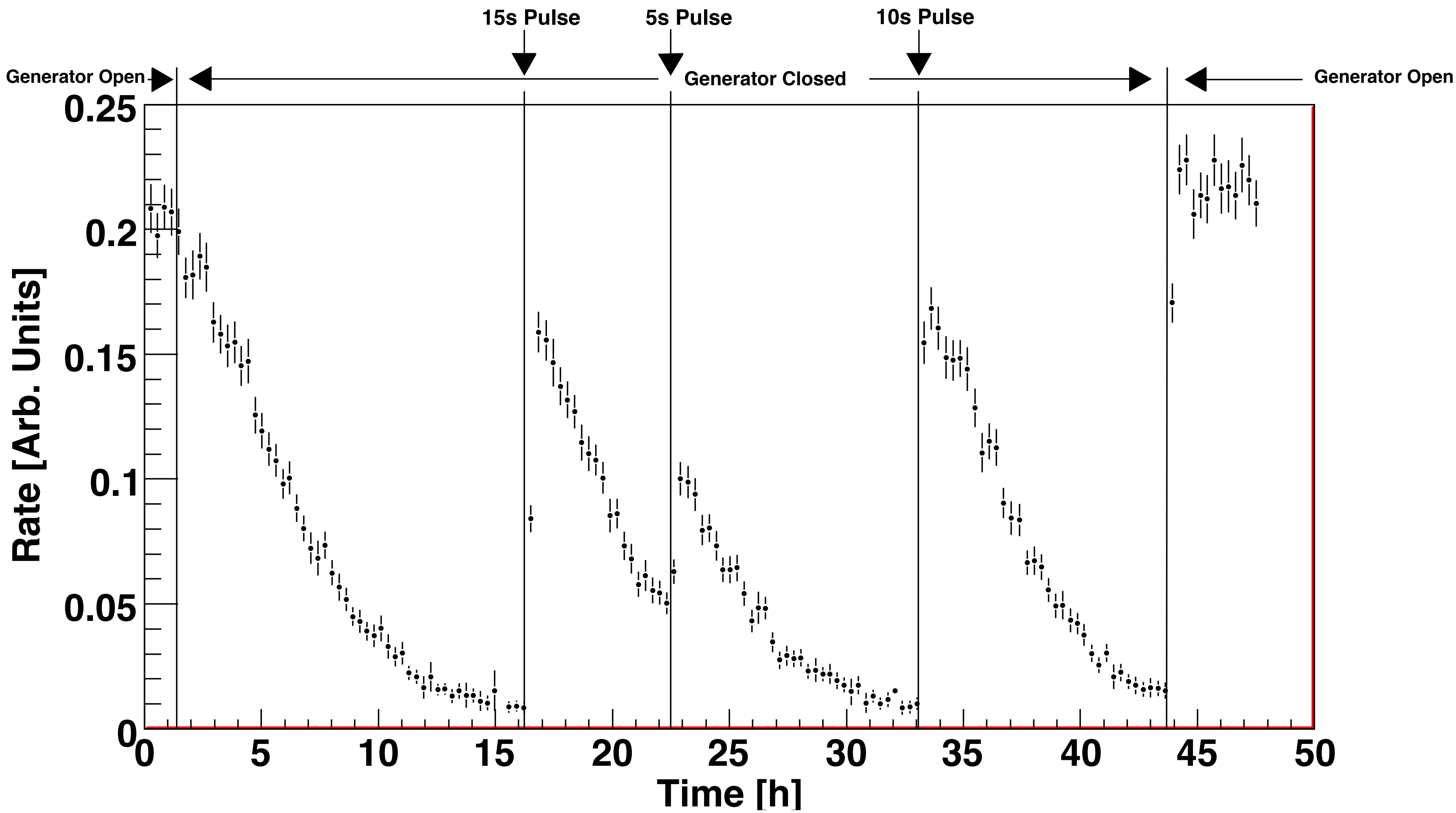
L. Kastens *et al*, Physical Review C **80**, 045809 (2009).

Typical Kr-83m event in 2-phase Xe



Also see Manalaysay et al, arXiv:0908.0616

Repeated Kr-83m introduction into 2-phase Xe detector



Conclusions and opinions

- Low-mass searches are a bit of a mess because of backgrounds, but also because of calibration issues. Need to be conservative in sensitivity claims!
- One should always distrust data in the lowest energy bin. One should be doubly distrustful of data **below** your lowest energy bin. Relying on upward Poisson fluctuations of your signal to get sensitivity at low WIMP masses is shaky business, especially at energies where there are no signal yield measurements. Not recommended.
- Some predicted upcoming themes in nuclear recoil calibration:
  - Internal calibration sources; leveraging Kr-83m data to get nuclear recoil scale.
  - New measurements of nuclear recoil charge yields.
  - Electric field dependence of nuclear recoil signal yields; $S_n(E)$