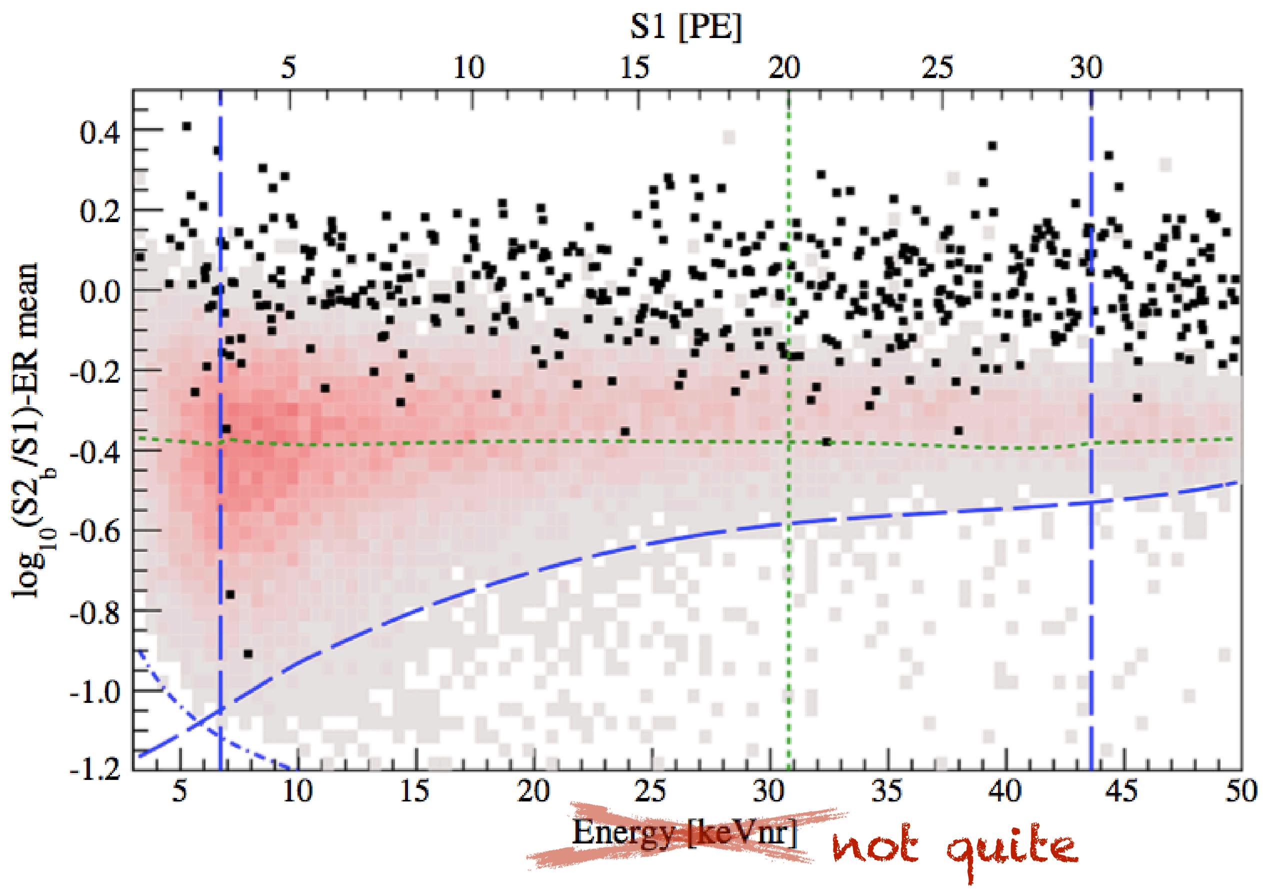
Getting through the awkward phase:
keV nuclear recoil energy reconstruction in liquid xenon particle detectors grows up*

* nine going on ____

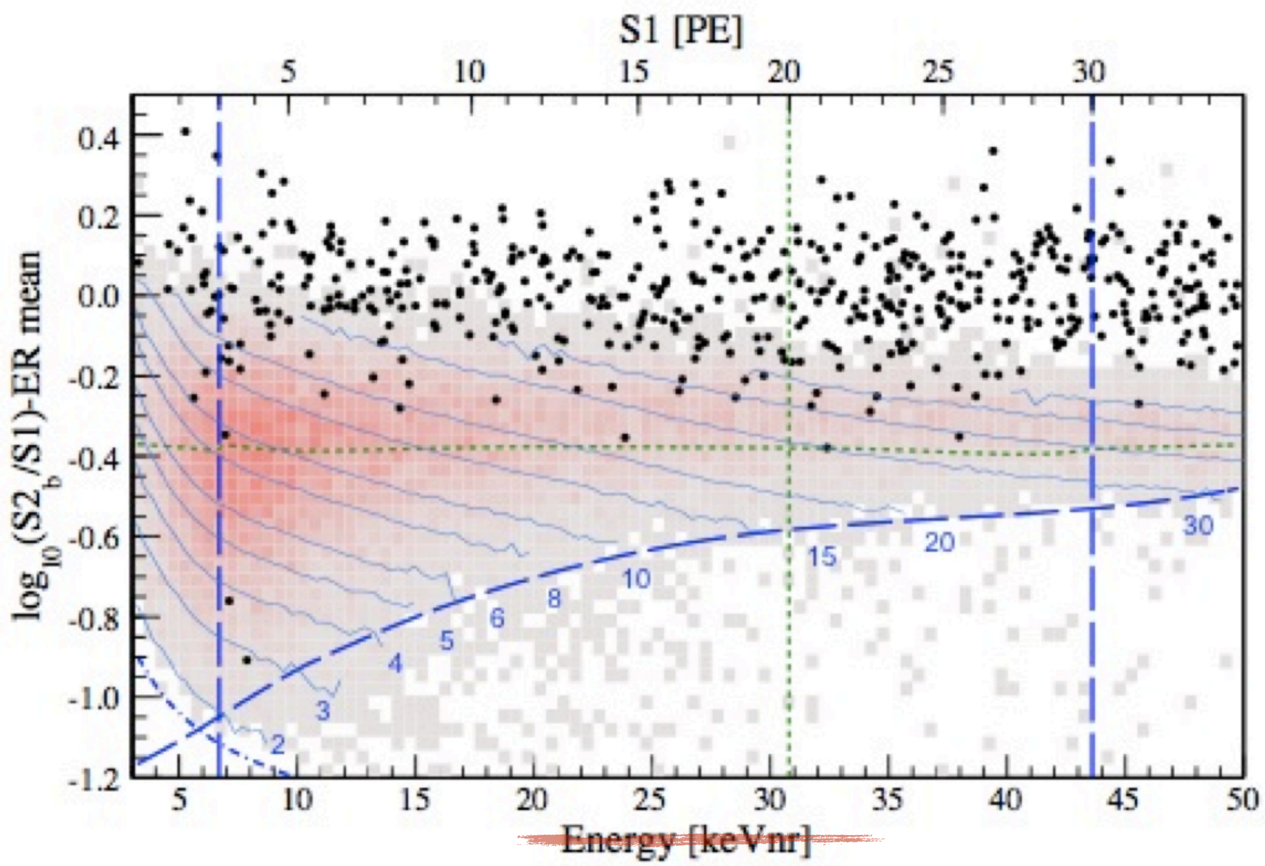
July 2012



XENON100, Phys. Rev. Lett. 109 181301 (2012)

measured quantity

incorrectly derived quantity, except close to the centroid of NR distribution



measured quantity

correctly derived quantity, overlaid *

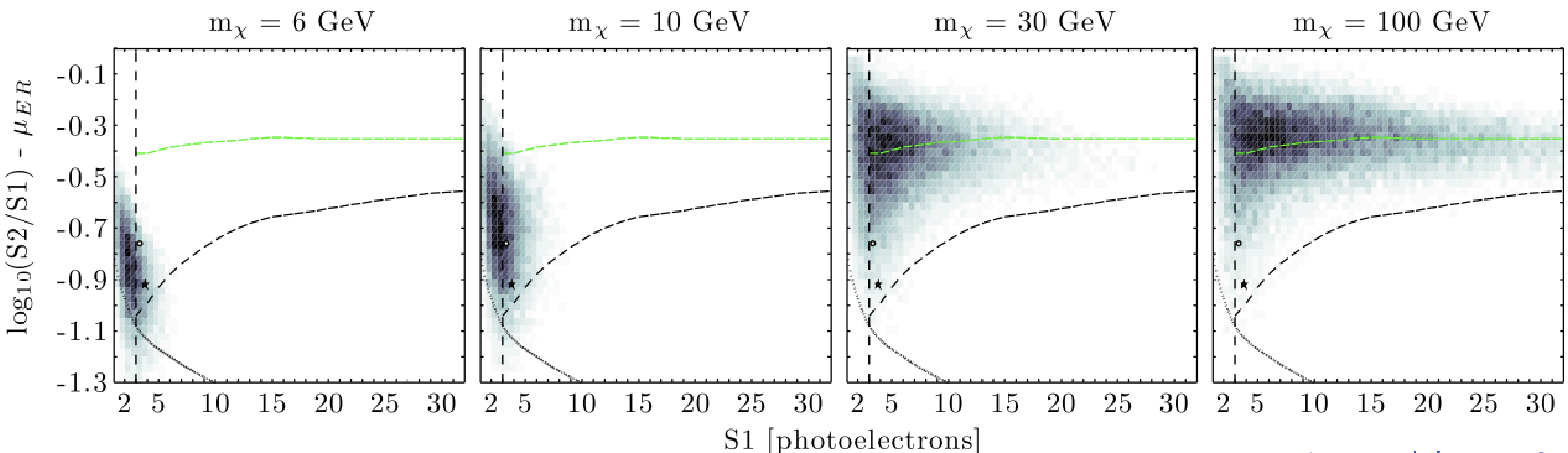
PS, Phys. Rev. D 86 101301 (2012)

incorrectly derived quantity, except close to the centroid of NR distribution

* both derived quantities assume the same Leff curve

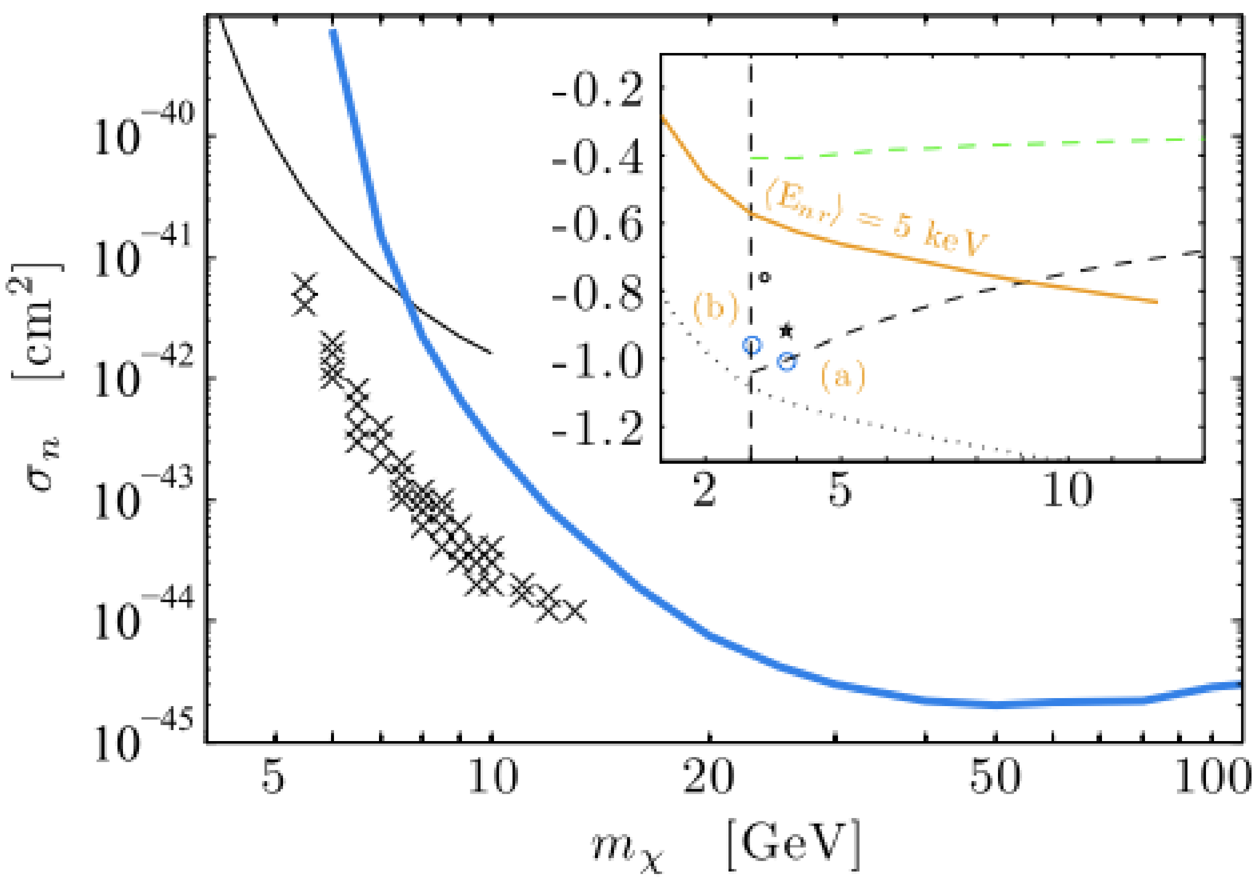
I guarantee the shape of the curves, not the energies

August 2012



using model: case C

PS, Phys. Rev. D **86** 101301(R) (2012)



based on a consistent treatment of low-energy fluctuations, as described in JCAP 09 (2010) 033

Comment on "On the subtleties of searching for dark matter with liquid xenon detectors"

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In a recent manuscript (arXiv:1208.5046) Peter Sorensen claims that XENON100's upper limits on spin-independent WIMP-nucleon cross sections for WIMP masses below 10 GeV "may be understated by one order of magnitude or more". Having performed a similar, though more detailed analysis prior to the submission of our new result (arXiv:1207.5988), we do not confirm these findings. We point out the rationale for not considering the described effect in our final analysis and list several potential problems with his study.

PACS numbers: 95.35.+d, 14.80.Ly, 29.40.-n,
Keywords: Dark Matter, WIMPs, Direct Detection, Xenon

In a recent manuscript [1], P. Sorensen examines our results from a 225 live-days dark matter run with XENON100 [2] and claims that the XENON100 upper limit on WIMP-nucleon cross sections at WIMP masses below 10 GeV might be significantly stronger than our published result. We are aware of the raised issues and take the opportunity to comment here. While we welcome the author's endorsement of our main conclusion, namely the lack of an observed dark matter signal in this run, we do not support his statement of one order of magnitude improvement in sensitivity for low-mass WIMPs after having performed a similar analysis prior to the submission of our manuscript to PRL.

We agree with the argument that in principle one might use the additional information carried by the proportional light signal, S2, in order to obtain a better measure of the energy of each scattering event in our detector. We would thus exploit not only S1, the prompt scintillation signal, but the fully available phase space. Indeed, as shown in [3] we have used the combined S1 and S2 information to significantly improve the energy resolution of our detector for interactions of gamma rays at various energies and to understand its main background sources [4]. On the other hand, as we discuss in more detail later, we are still unable to use the information in the S2-channel at the energies of interest to a dark matter search, for we lack measurements of the ionization yield, Q_y, of liquid xenon for nuclear recoils of a few keV. We also agree with the statement that low-mass WIMPs are expected to show a different S2/S1 versus S1 distribution than the one expected from calibration data with an ^{241}AmBe neutron source. In fact, we have studied these effects in detail, in a similar fashion as followed in the paper by P. Sorensen: we have inferred Q_y based on our ^{241}AmBe nuclear recoil calibration data and on the measured $\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}})$ and have used Monte Carlo simulations to

It isn't clear if XENON100 agree with me or not...

arXiv:1304.1427

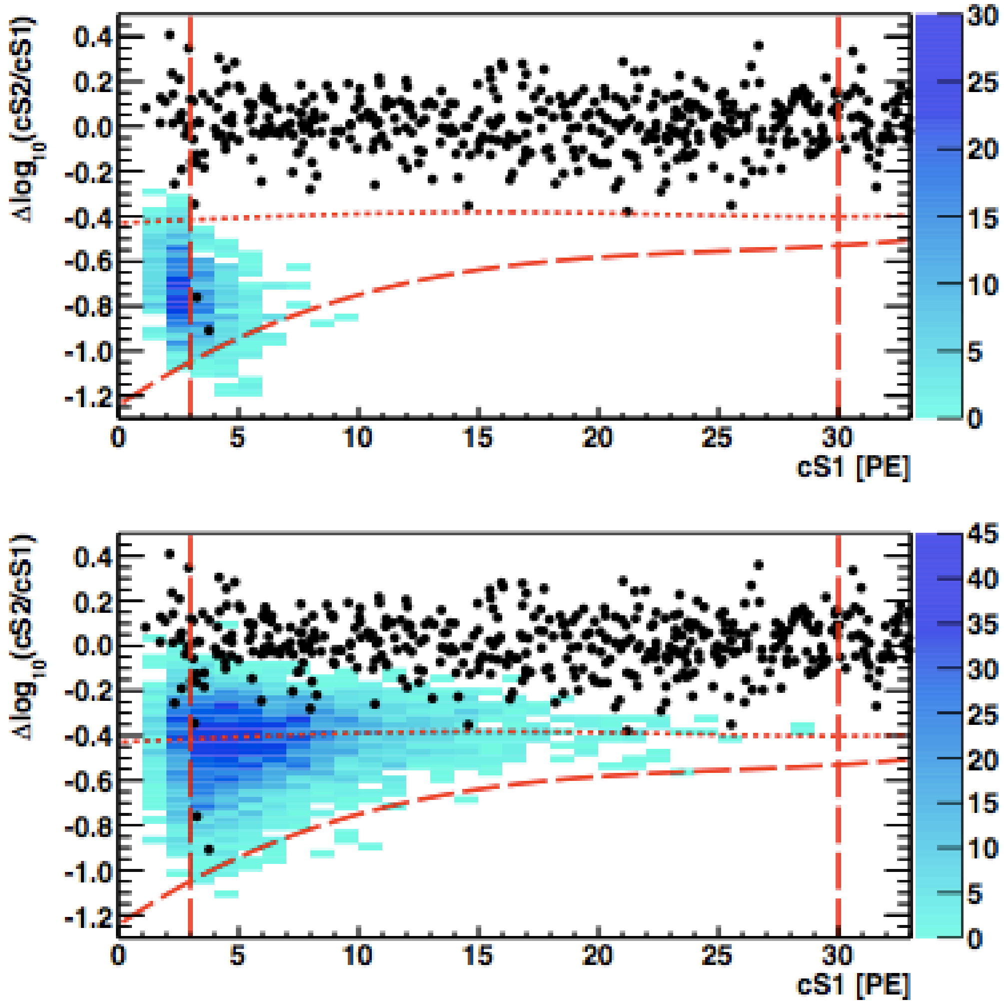
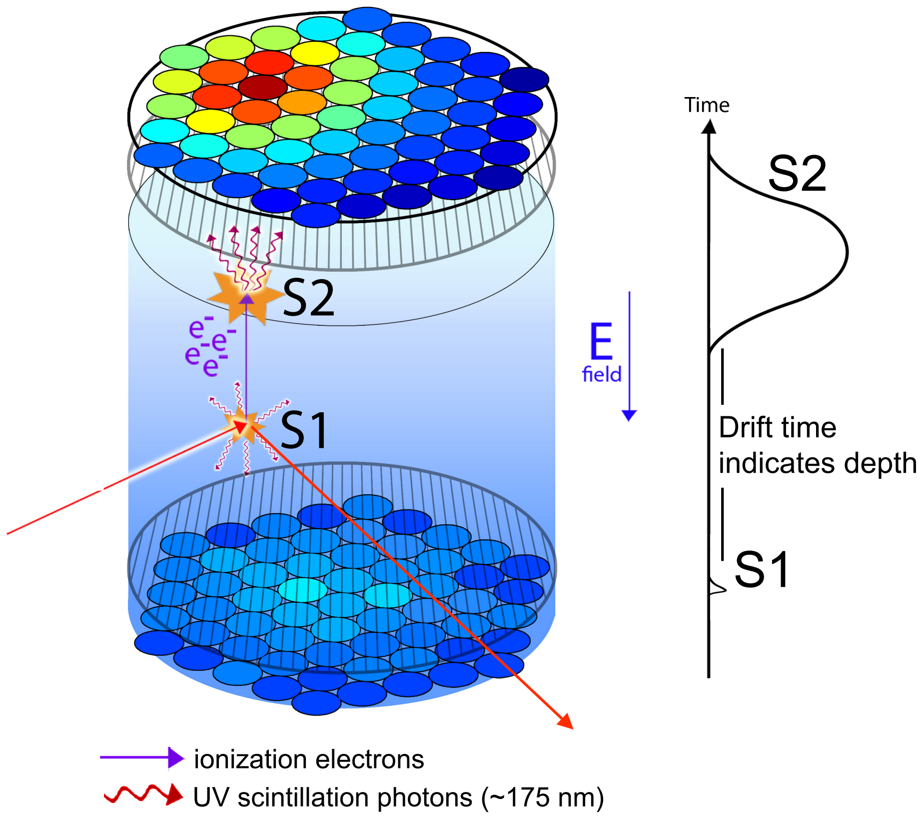


FIG. 10: Two–dimensional distributions of expected cS1 and cS2 signals for (top) an 8 GeV c^{-2} WIMP and for (bottom) a 25 GeV c^{-2} WIMP with spin-independent WIMP-nucleon cross-sections of 3×10^{-41} cm^2 and of 1.6×10^{-42} cm^2, respectively. In both cases, the same assumptions applied to create the recoil spectra in Fig. 9 are used. In both figures, the vertical red lines represent boundaries of 3-30 PE. The horizontal (long-dash) red curve represents the mean (μ) -3σ for the elastic nuclear recoil distribution and the horizontal (short-dash) red curve represents the 99.75% electron recoil rejection line as discussed in Ref. [2].

OK, it seems that they do.

n_γ and n_e

are what you really want to know



LUX, Nucl. Instr. Meth. A 668 1 (2012)

$S2 = \alpha_2 \, n_e$

$S1 = \alpha_1 \, n_\gamma$

$\alpha_1 \sim O(0.10)$ and $\alpha_2 \sim O(10)$

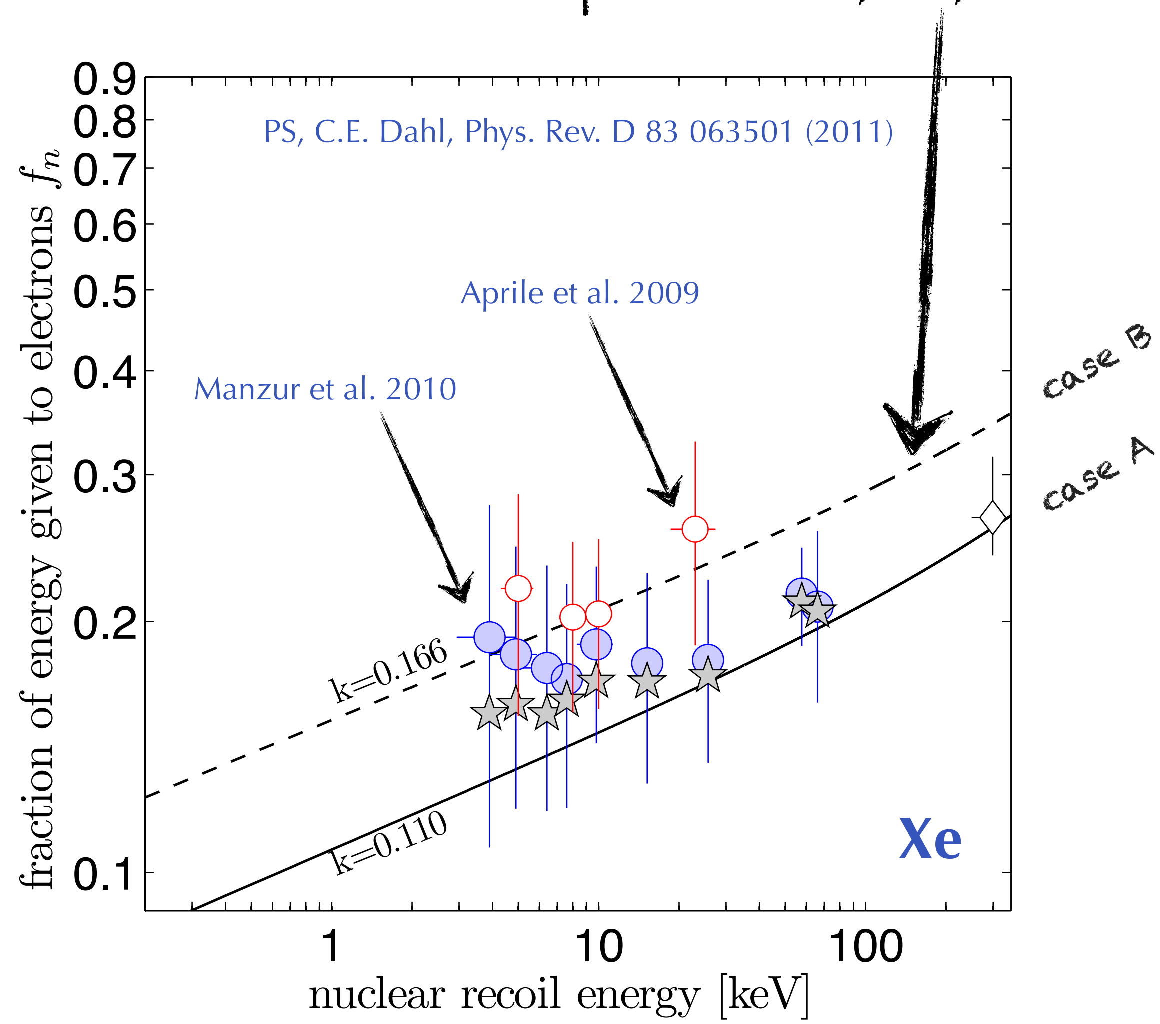
are the probability to detect each quanta

Electronic signal from neutral particles is quenched

$$E_{\rm nr} = \epsilon(n_\gamma + n_e)/f_n$$

quenching applies to the TOTAL electronic excitation

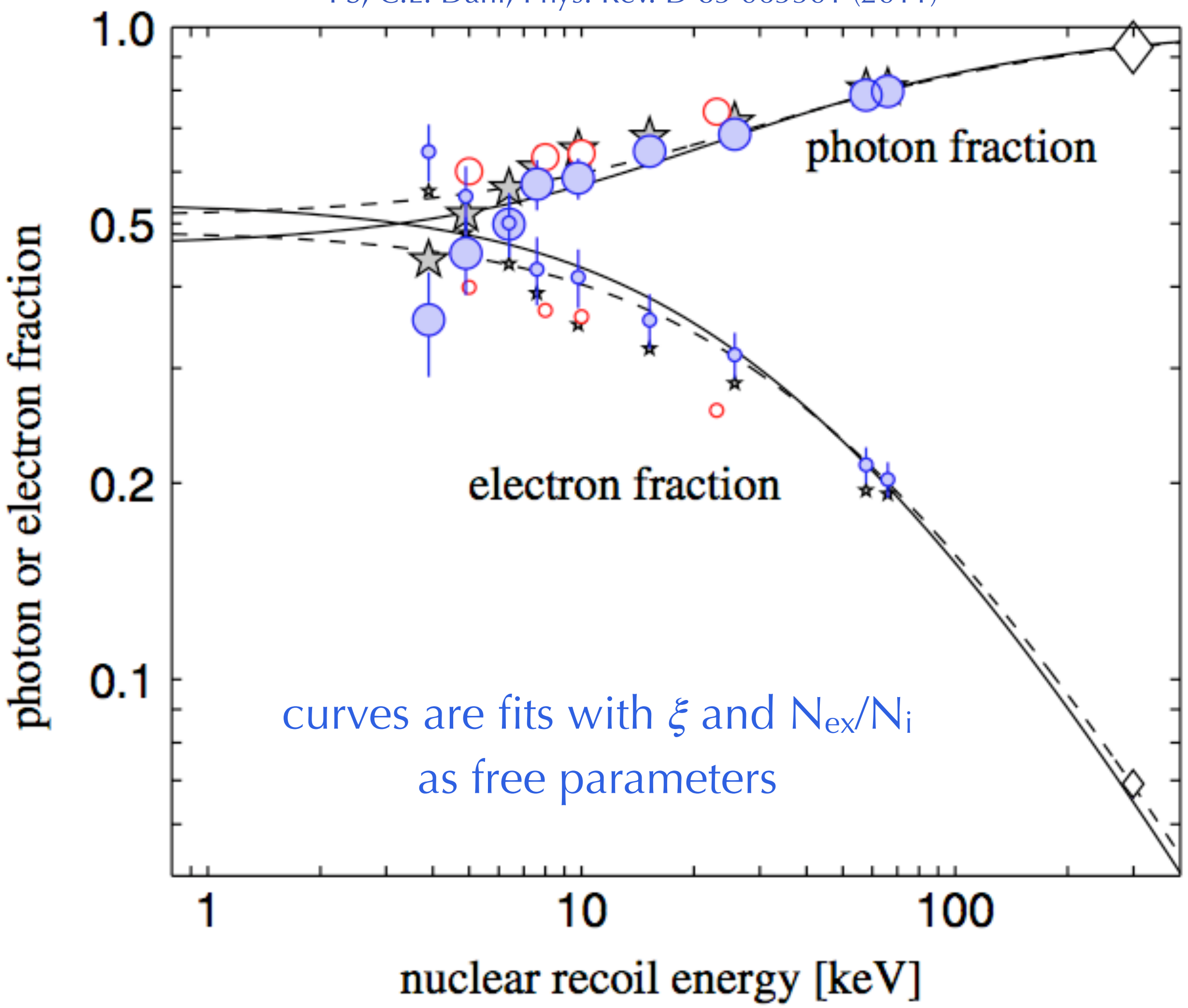
Lindhard prediction for f_n



ϵ = 13.8 eV, the average energy to create a single quanta (e or γ)
f_n = energy dependent Lindhard prediction for signal quenching

In liquid xenon, quenched E_{nr} partitions into scintillation photons and electrons

PS, C.E. Dahl, Phys. Rev. D 83 063501 (2011)



curves are fits with ξ and N_{ex}/N_i as free parameters

Two-step model:
(1) Lindhard model gives quenching, $\boldsymbol{f_n}$
(2) Thomas-Imel model gives partioning (first noted by Shutt, Dahl)

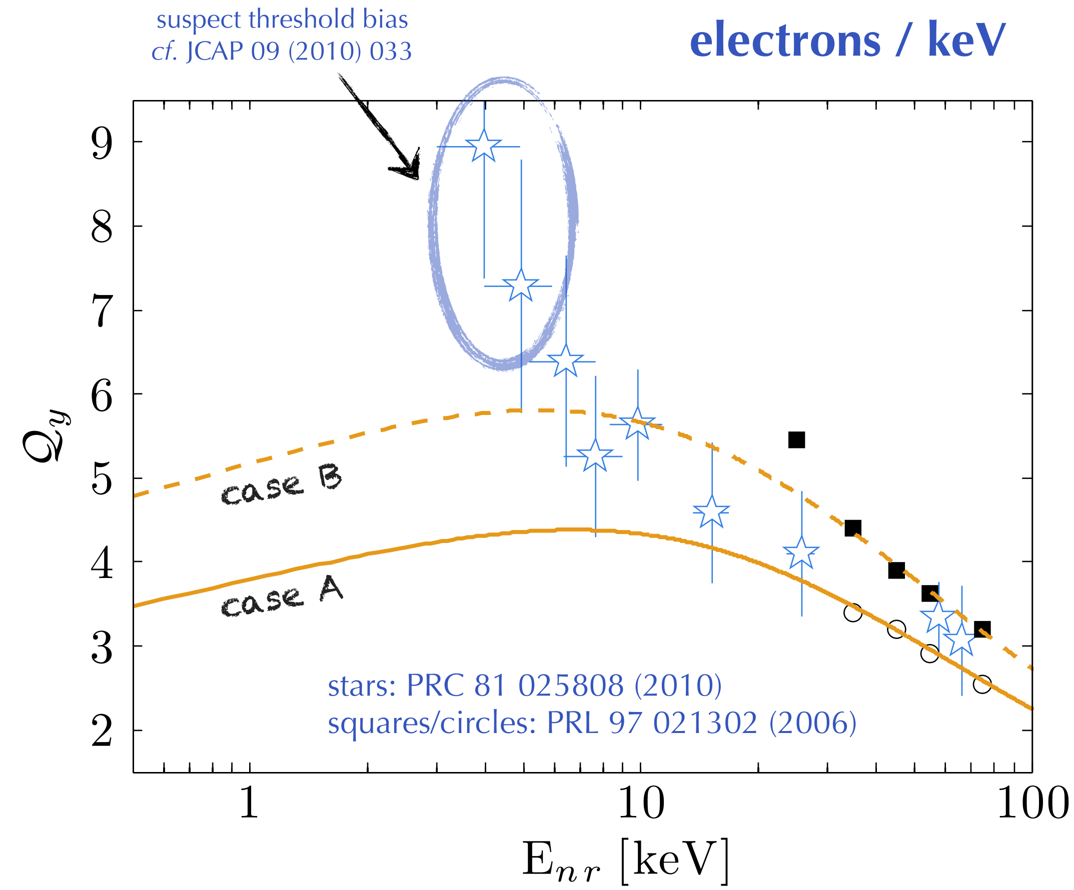
electron fraction: $$\mathcal{F}_e = \frac{\ln(1+\xi)}{\xi(1+N_{ex}/N_i)}$$

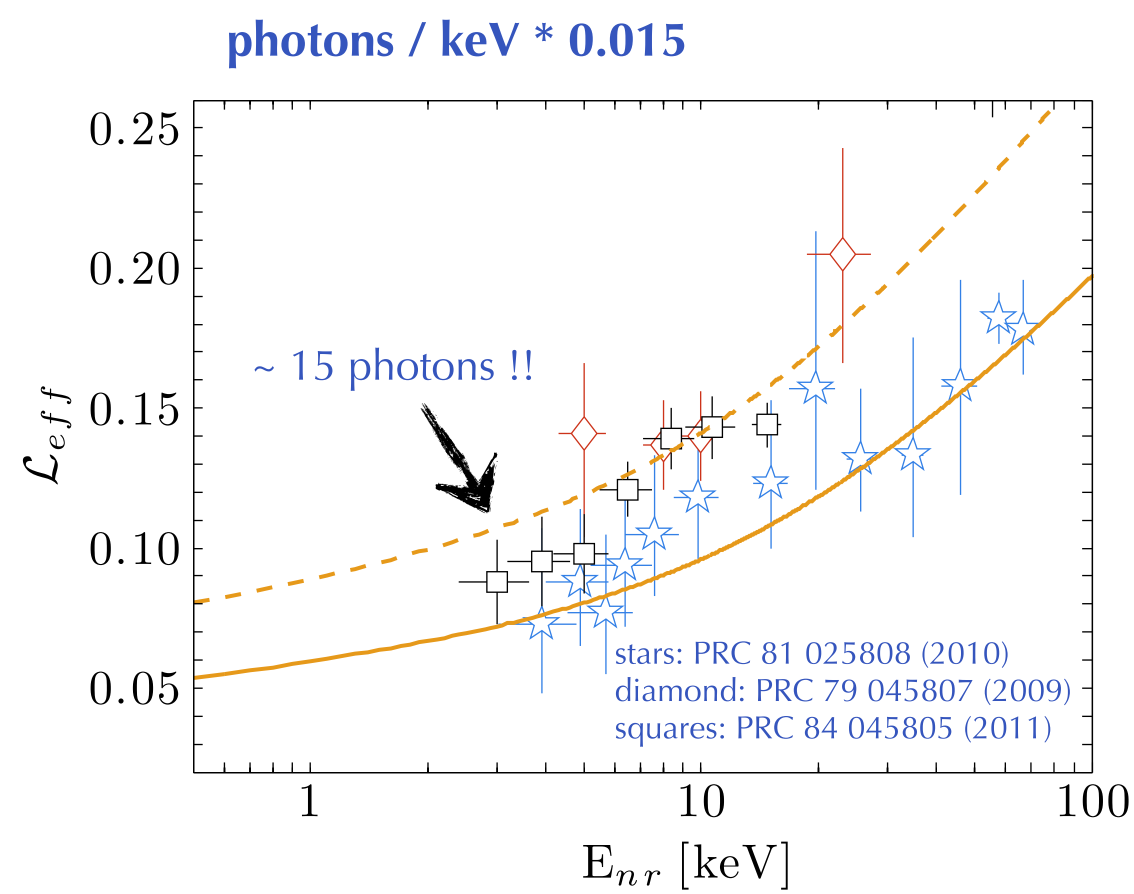
electron yield: $$\mathcal{Q}_y = \frac{\mathcal{F}_e f_n}{\epsilon}$$ $= S2/(\alpha_2\ E_{nr})$

"effective" photon yield: $$\mathcal{L}_{eff} = \frac{(1-\mathcal{F}_e) f_n}{\epsilon} \frac{\alpha_1 S_e}{L_y S_n}$$

this is the "effective" bit, an ad-hoc constant with a value of ~0.015

Model compared with neutron scattering data





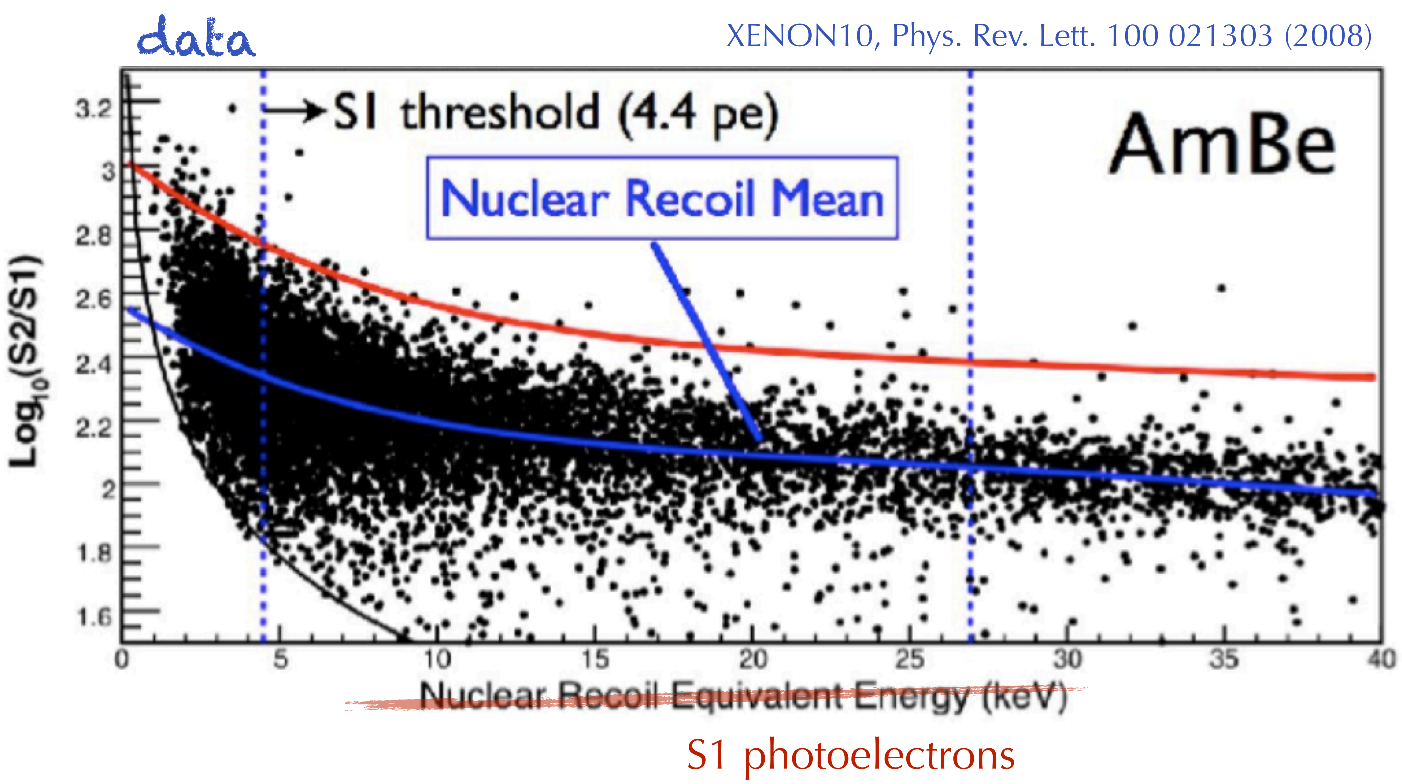
model prediction case A:

- k = 0.110
- $4\xi/N_i = 0.037$
- $N_{ex}/N_i = 1.00$

model prediction case B:

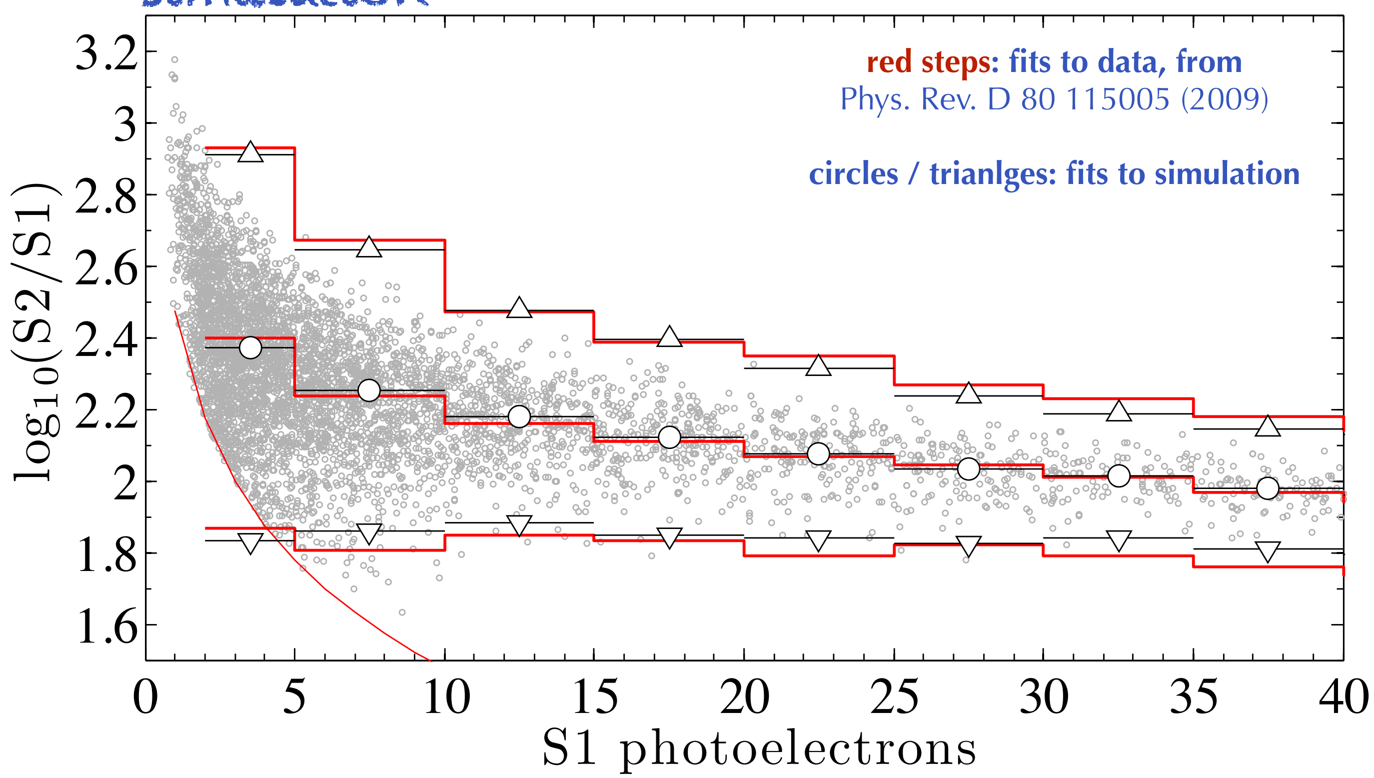
- k = 0.166
- $4\xi/N_i = 0.032$
- $N_{ex}/N_i = 1.09$

Does the model reproduce the data?



Yes

simulation

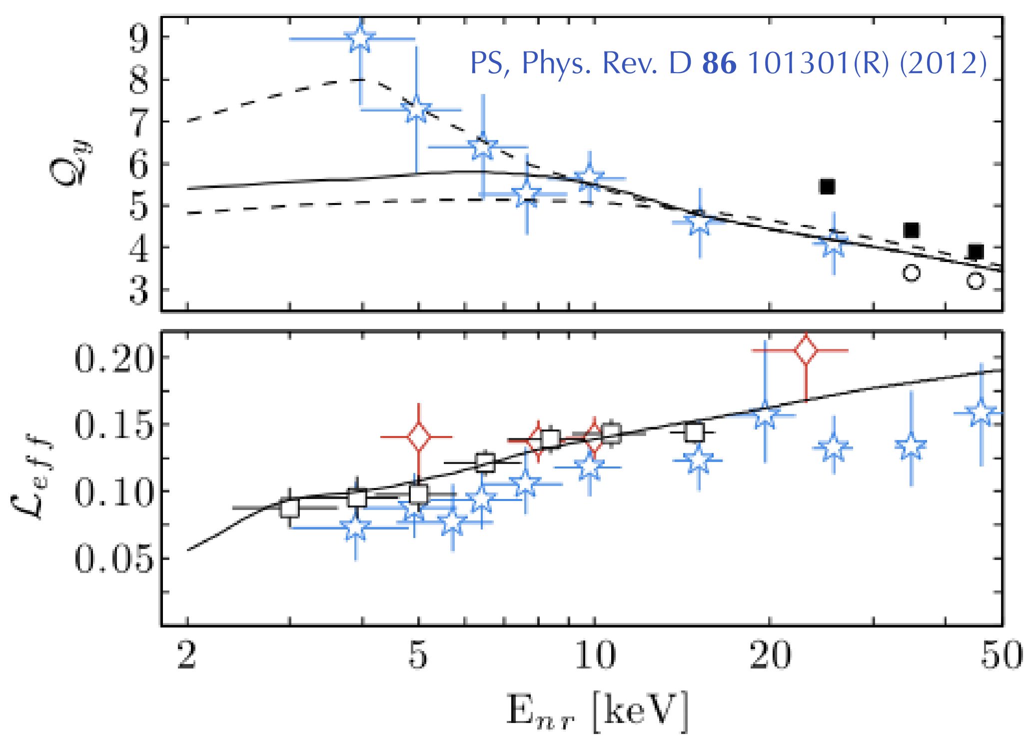


- Band simulation using model case A
- Method described in JCAP 09 (2010) 033
- (showing XENON10, agreement is very similar for XENON100)
- NR band width dominated by
    1. Poisson fluctuations in n_e and n_γ
    2. Photomultiplier resolution

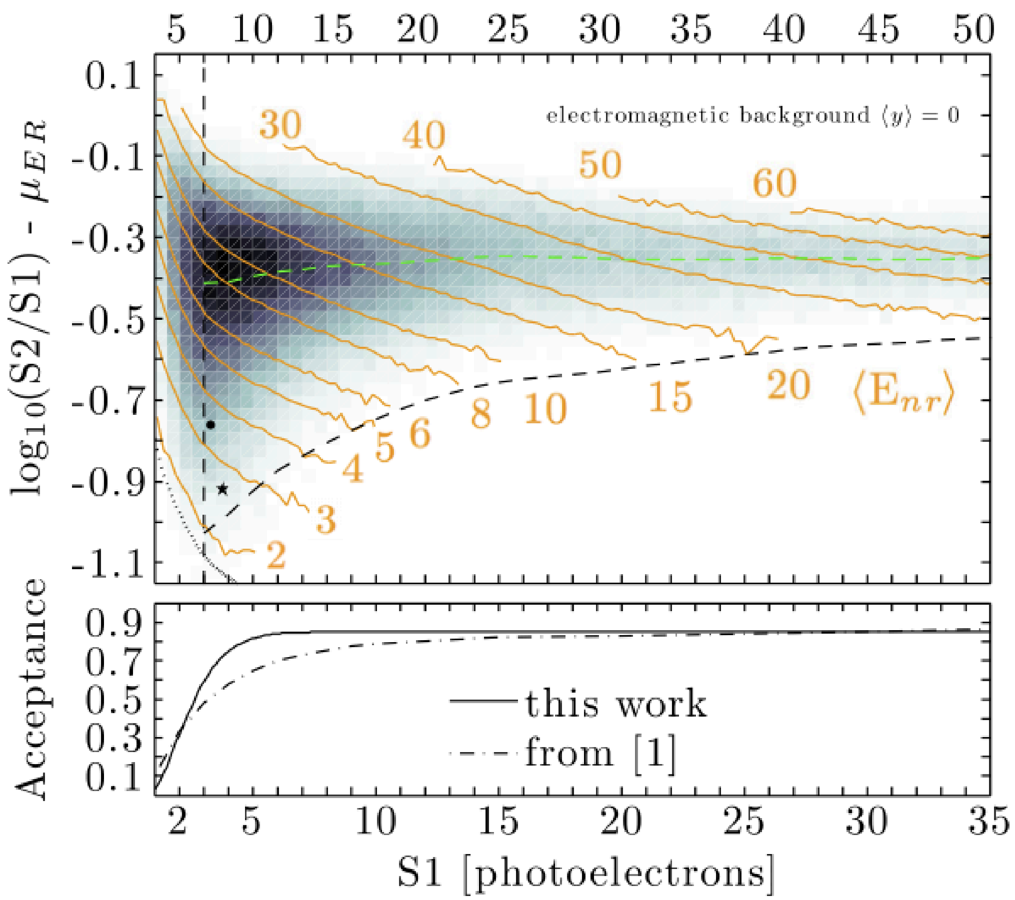
It is possible to derive self-consistent calibration curves without the model

y = log10(S2/S1) ∝ log10(Qy/Leff)

lets call this set of (solid) curves "case C"



$$E_{nr} = \frac{\langle S1 \rangle}{L_y \times \mathcal{L}_{eff}} \frac{S_e}{S_n} \text{ [keV]}$$

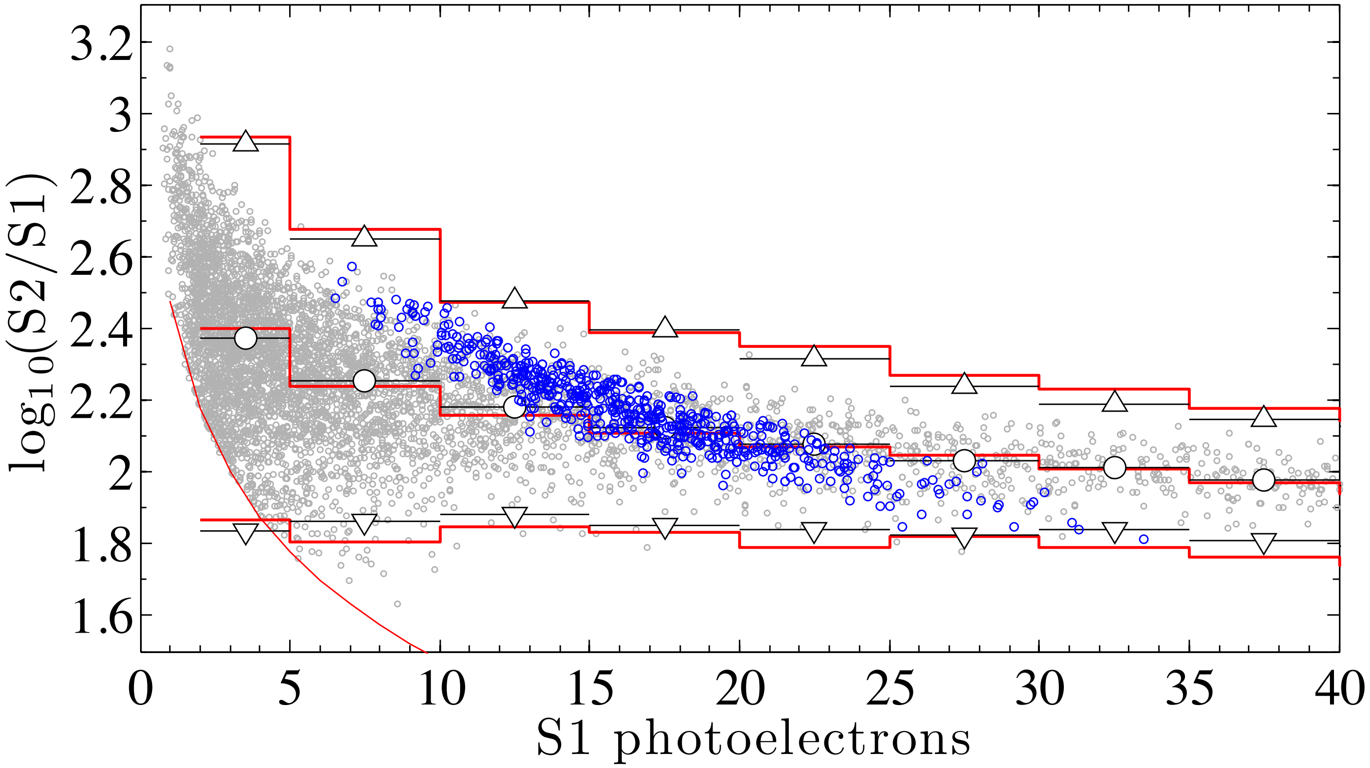


by using a fancy analysis technique known as... algebra!

Same as slide 12, but showing also 25 keV mono-energetic response

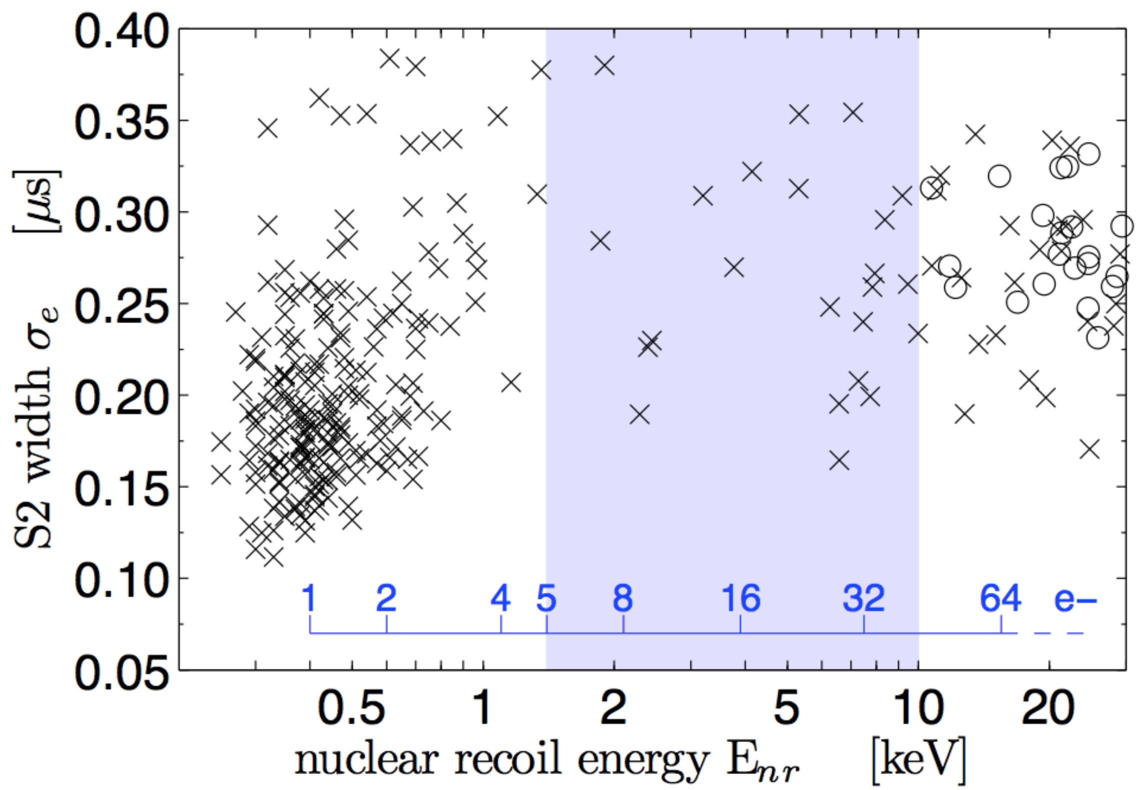
- 25 keV is far from threshold, measurements look robust
- Once Leff/Qy are known at e.g. 25 keV, values at other energies are constrained

simulation



All this bears on the XENON10 S2-only analysis

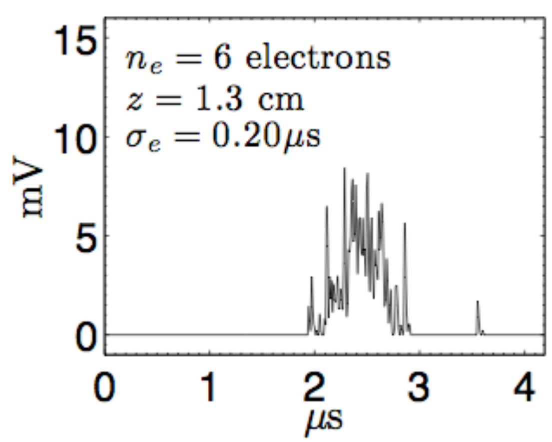
XENON10, Phys. Rev. Lett. 107 051301 (2011)

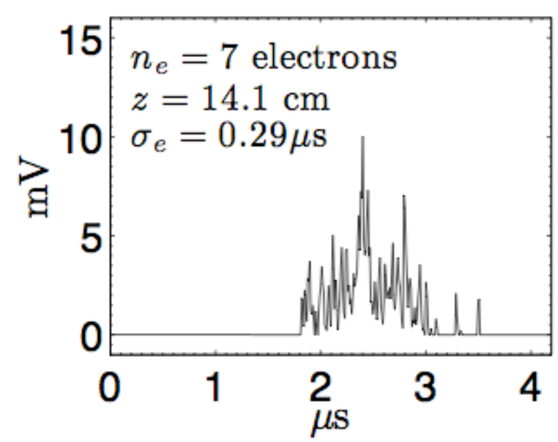


robust down to a single electron

extrapolation. quoting from the paper, p2:

> We emphasize that our energy calibration (Fig. 1, solid curve) relies on extrapolation of Lindhard's theory [28] below 4 keV.





the extrapolation we used is none other than model case A from these slides

Two questions

Should I believe the model?

Yes

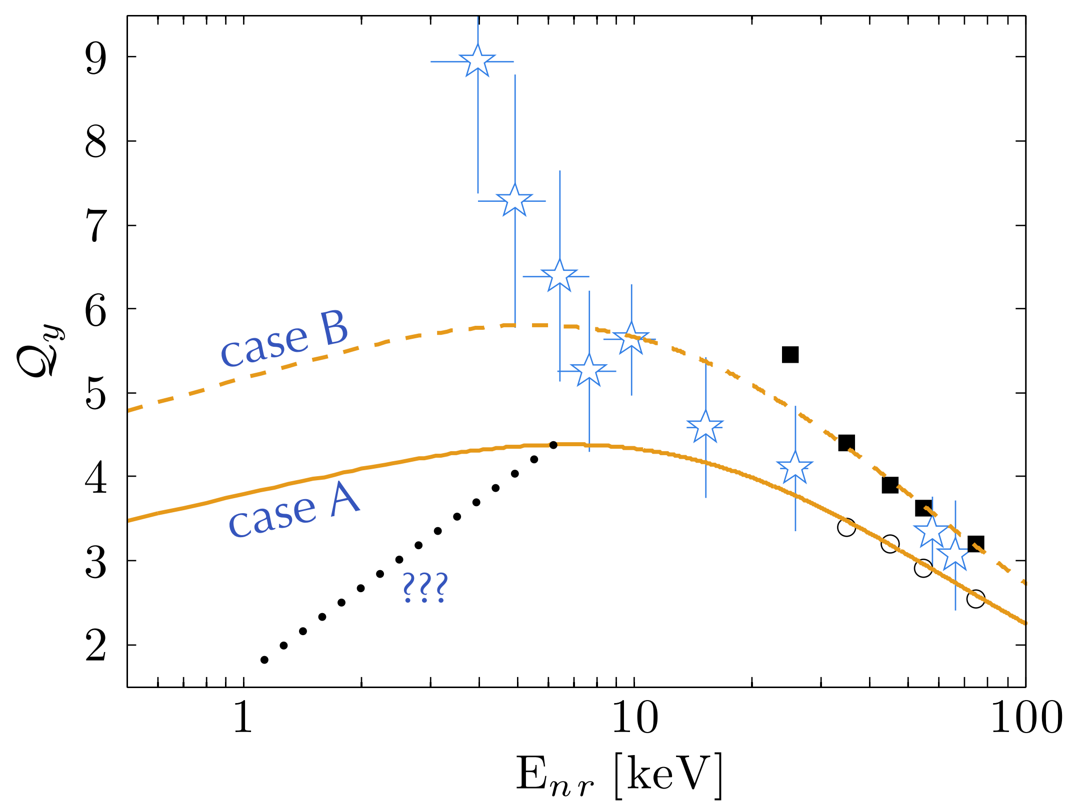
- Looks reasonable (good, even) for high energies (roughly E>6 keV)
  - Case A is conservative
  - Case B is not
  - Case C is not (its also not "the model")
- Lindhard theory works very well in Ge, down to <1 keV, and in principle is agnostic across elements

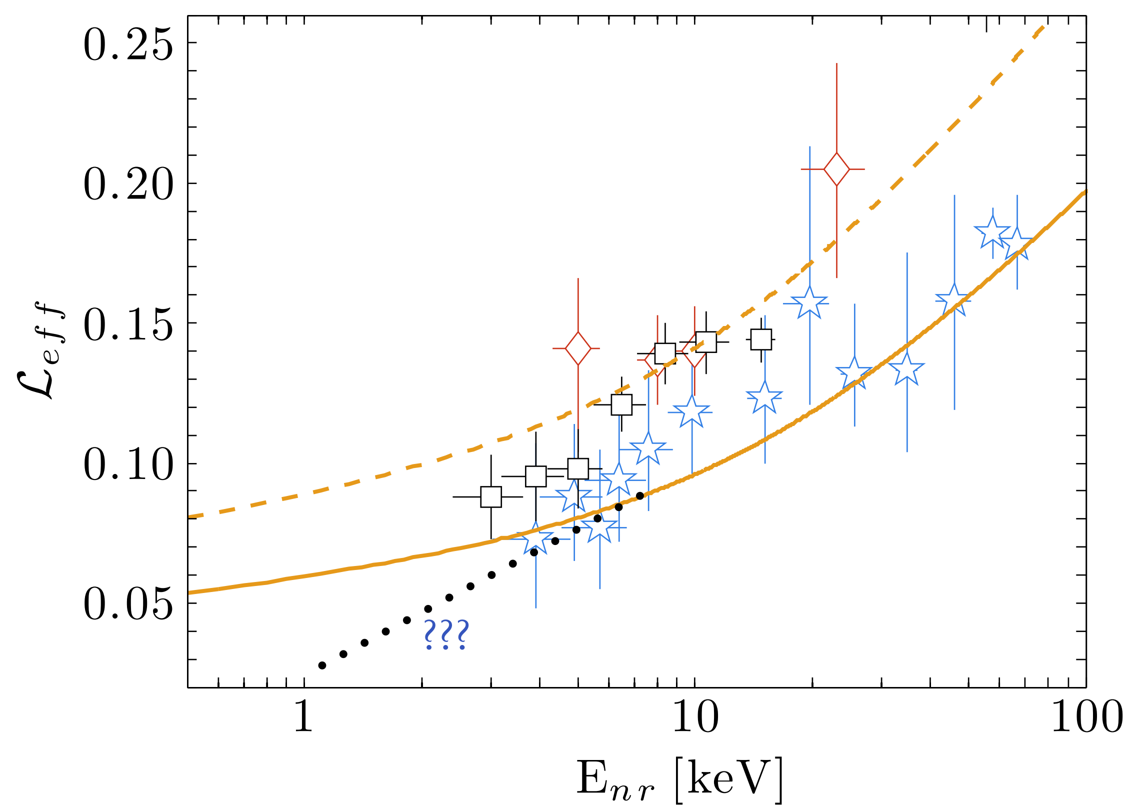
Should I believe the model extraplation?

Yes / No

- Xe may behave differently than Ge, vis-a-vis Lindhard theory
- Lindhard theory must break down at some E, maybe this is higher in Xe compared to Ge
- Xe S2 measurements are suspect for E<6 keV
- Xe S1 measurements are challenging for E<6 keV
- Everyone else is detecting DM, xenon (the element, not the collaboration) must be doing something wrong

How low can we reasonably push these curves?

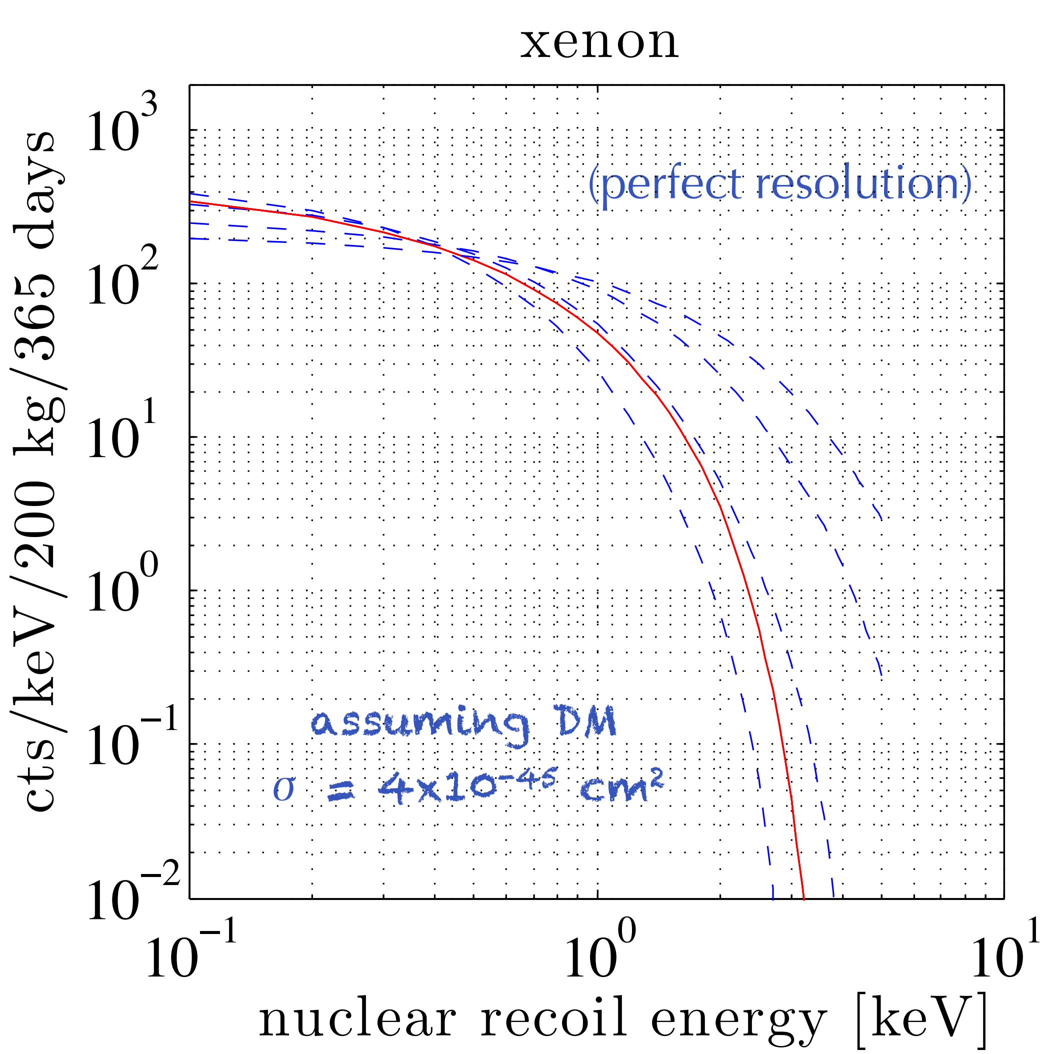




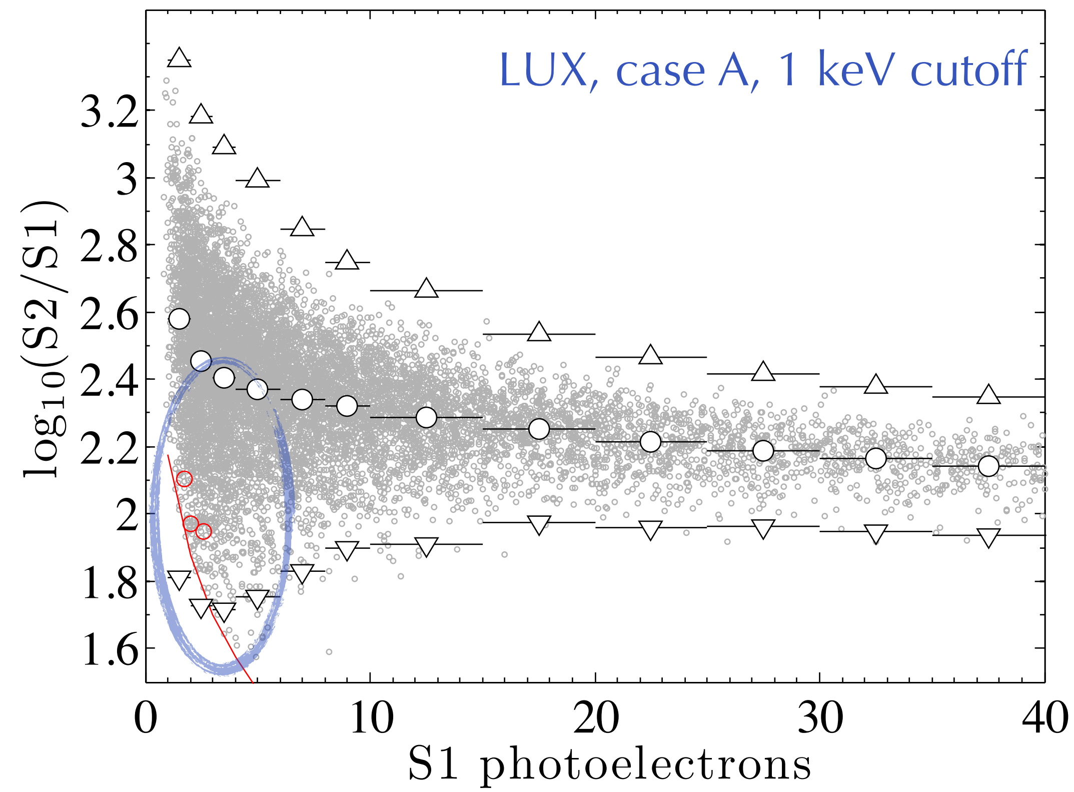
- I dont know (yet)
- ANY reasonable answer must also reproduce measured NR band (cf. slide 13)
- Xe experiments owe it to the community to answer this

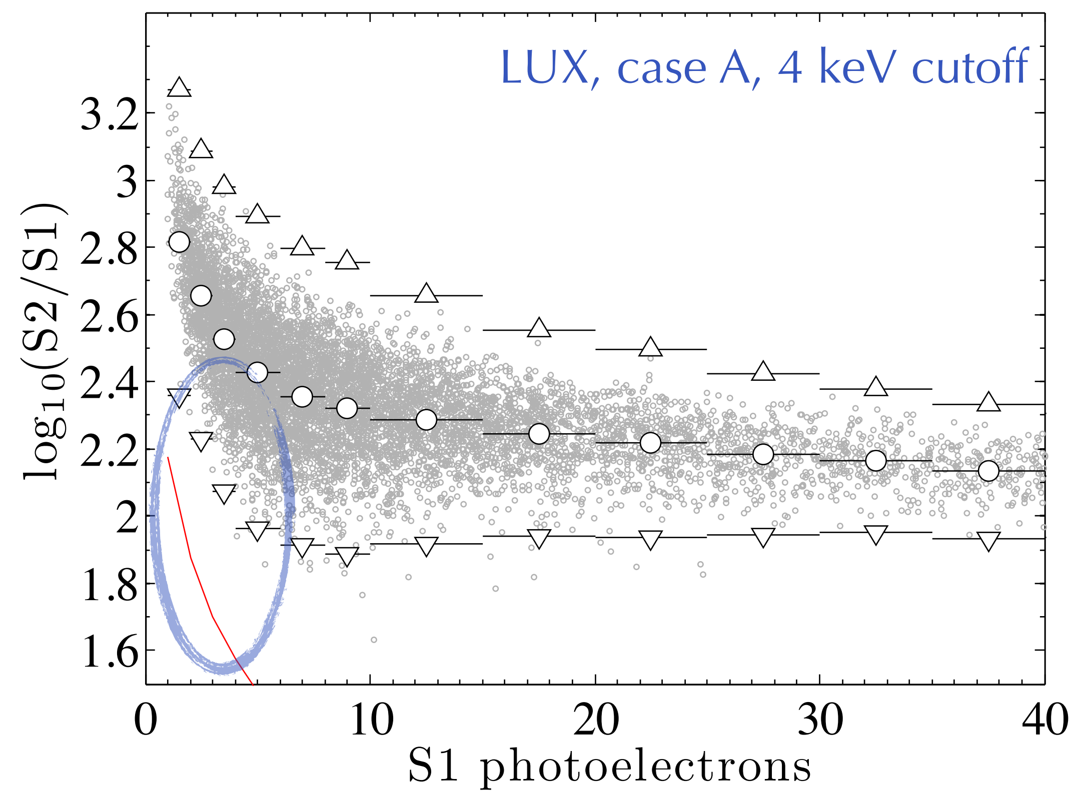
Light DM looks a lot like solar ^{8}B coherent neutrinos

- prospect of observing ^{8}B coherent neutrinos in LUX (α_1 ~ 0.15) compare: α_1 ~ 0.06 in XENON100
- depends on fundamental liquid xenon response ($n_e + n_\gamma$) to NR
- if there is a "kinematic cutoff" at e.g. 4 keV, we should know from the NR band shape



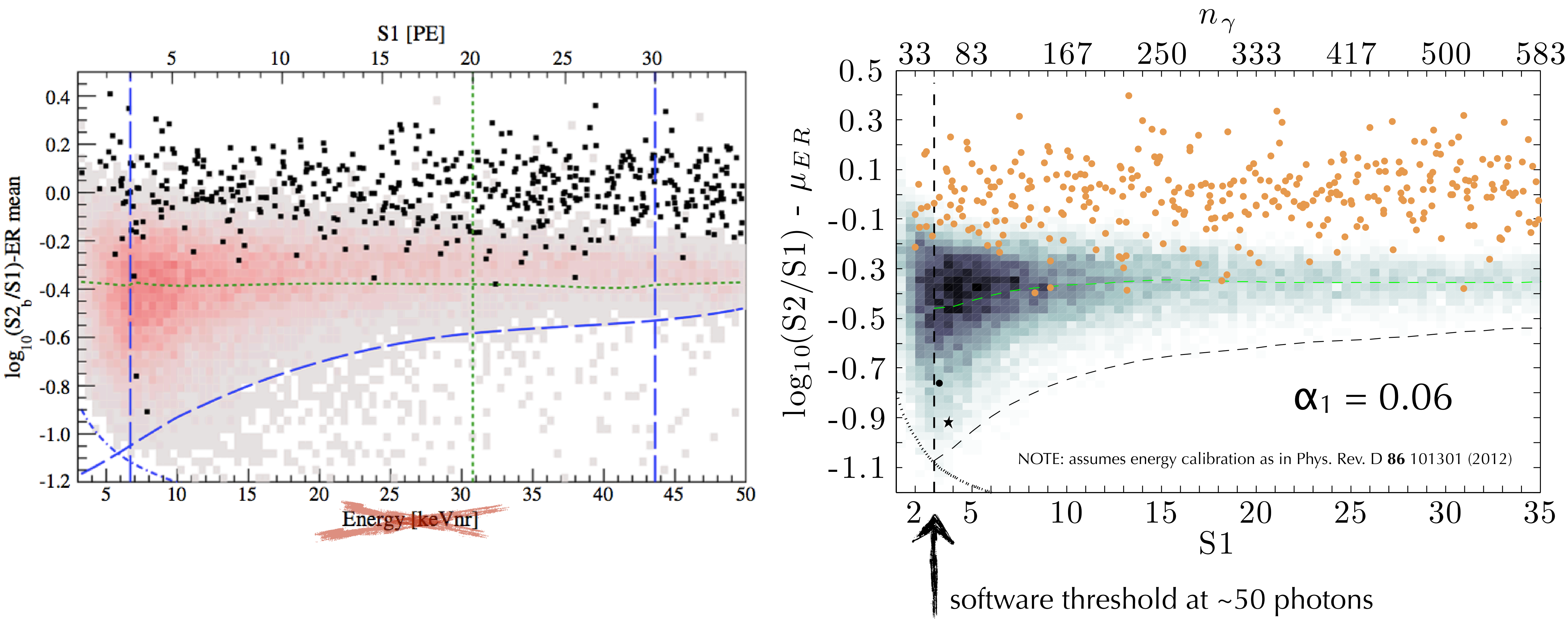
dashed: DM masses 5, 6, 7 and 10 GeV
solid: ^{8}B coherent neutrinos





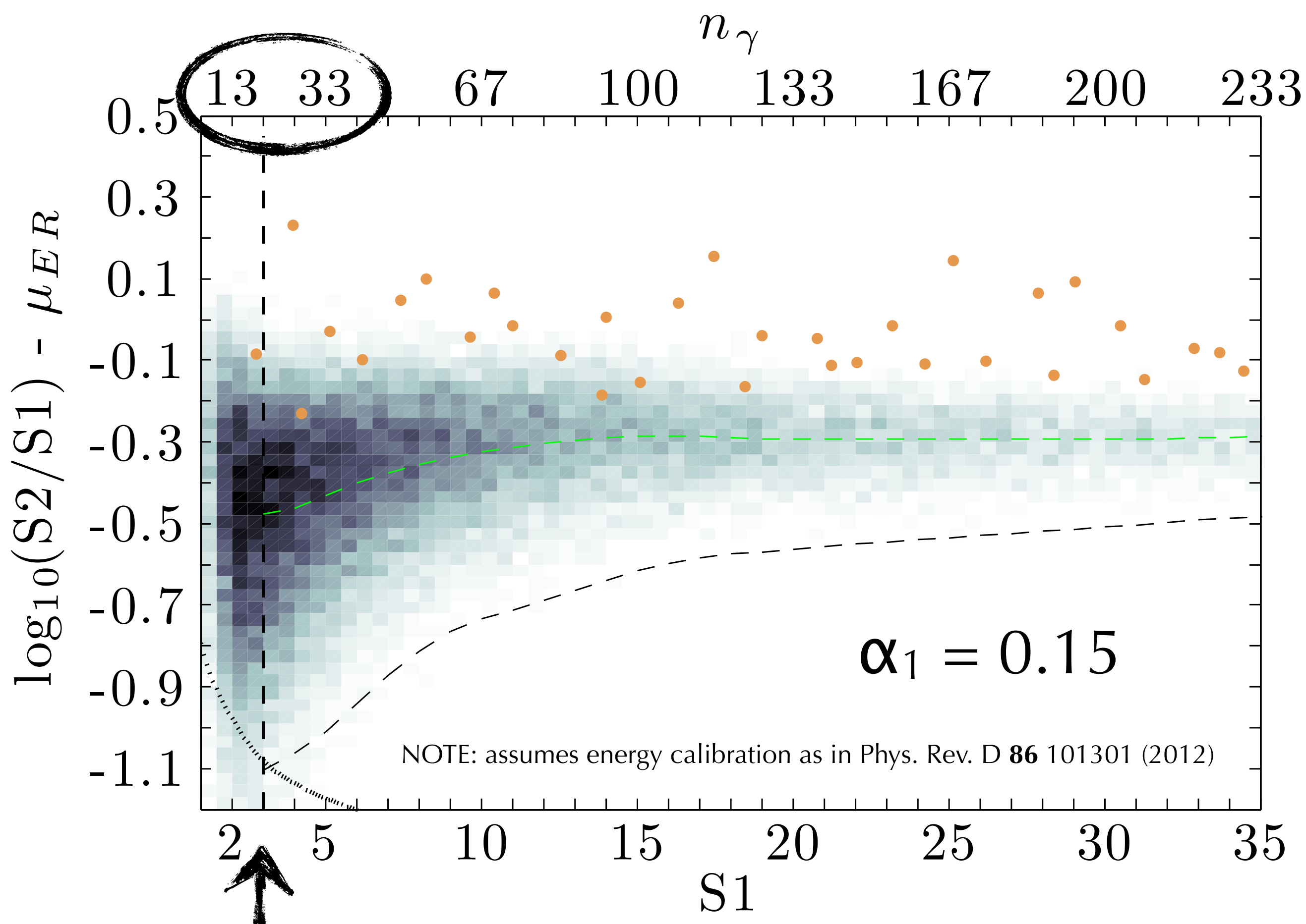
XENON100 results

simulation of a XENON100-like detector



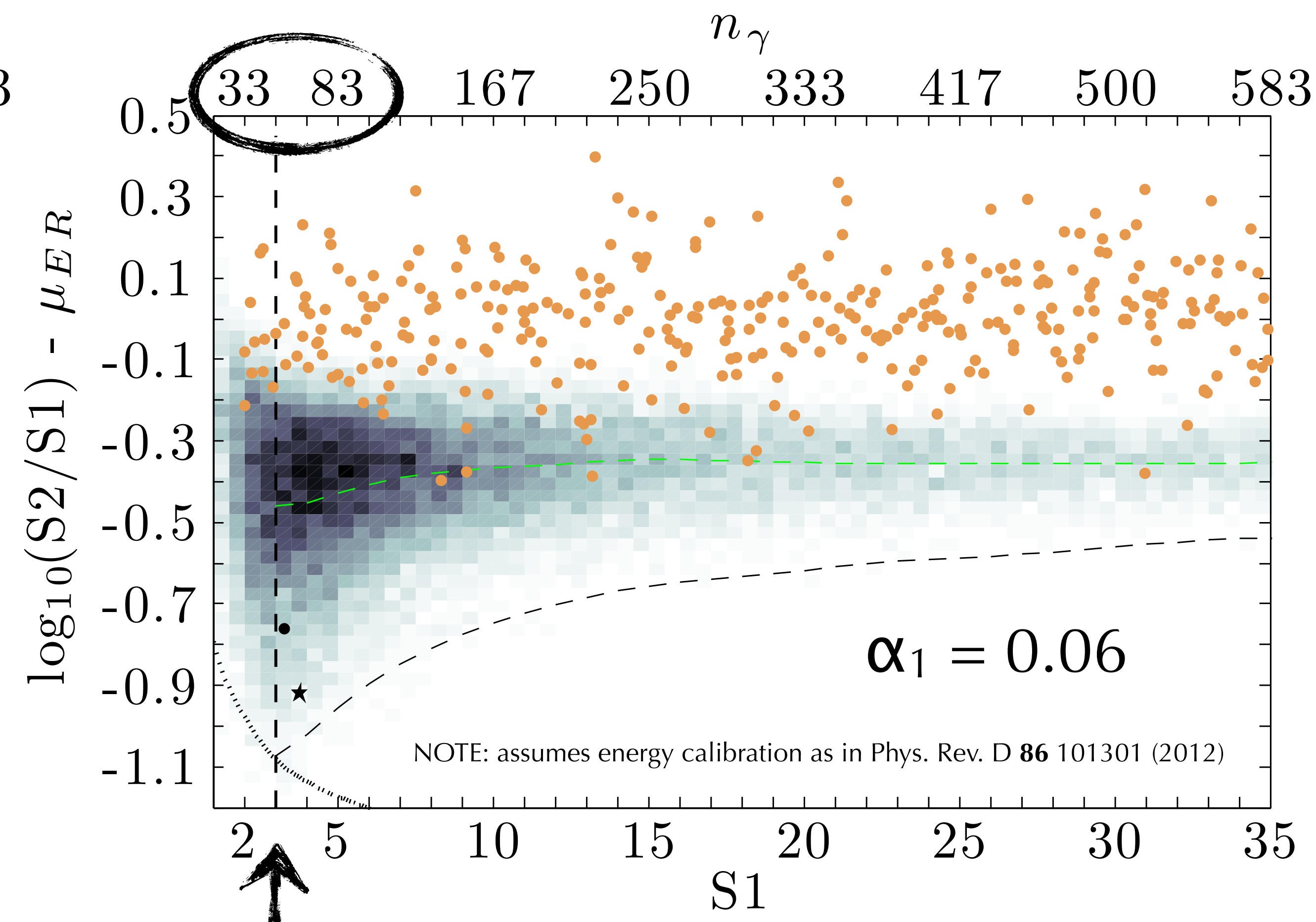
NB: apparent difference in band width is a binning artifact -- the lower dashed line is -3σ in both plots

simulation of LUX-like detector
100kg x 76d



software threshold at ~20 photons

same simulation of a XENON100-like detector
34kg x 225d



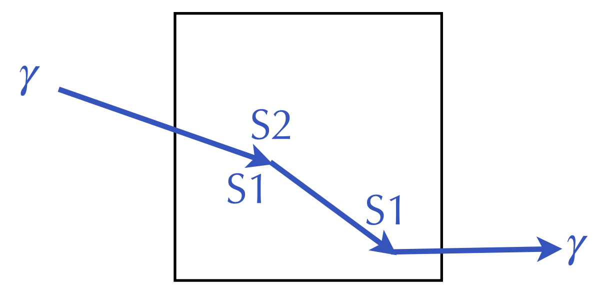
software threshold at ~50 photons

LUX will have a factor x2+ lower photon detection threshold, period.

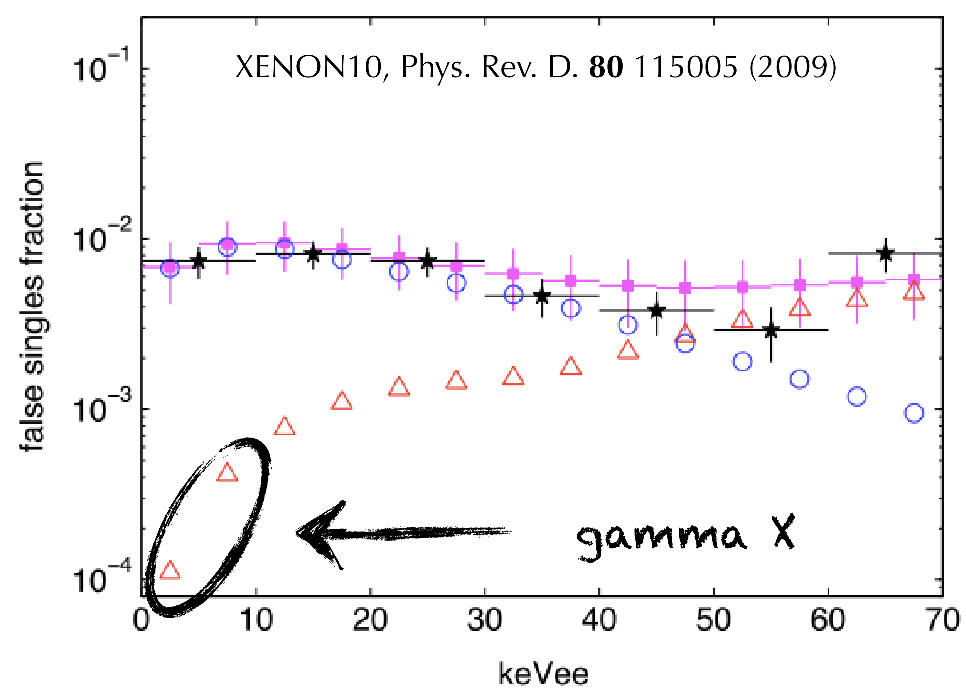
- n_γ does not depend on energy calibration (L_{eff}, Q_y)
- probably leads to a few keV in energy threshold, relative to XENON100
- lower background rate => increased discovery potential

Extra slides follow

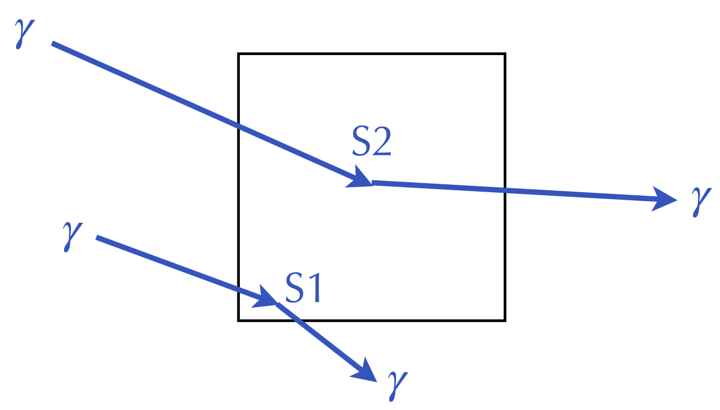
"gamma X"



XENON100 quotes this mechanism in the context of their 2 events.
I dont buy it.
why? gamma X fraction is increasing with energy.
So, where are all the higher energy gamma X events??



"random coincidence"



this is a more plausible mechanism.

This rate could be calculated, based on measured S1-only rate. Has not been done..