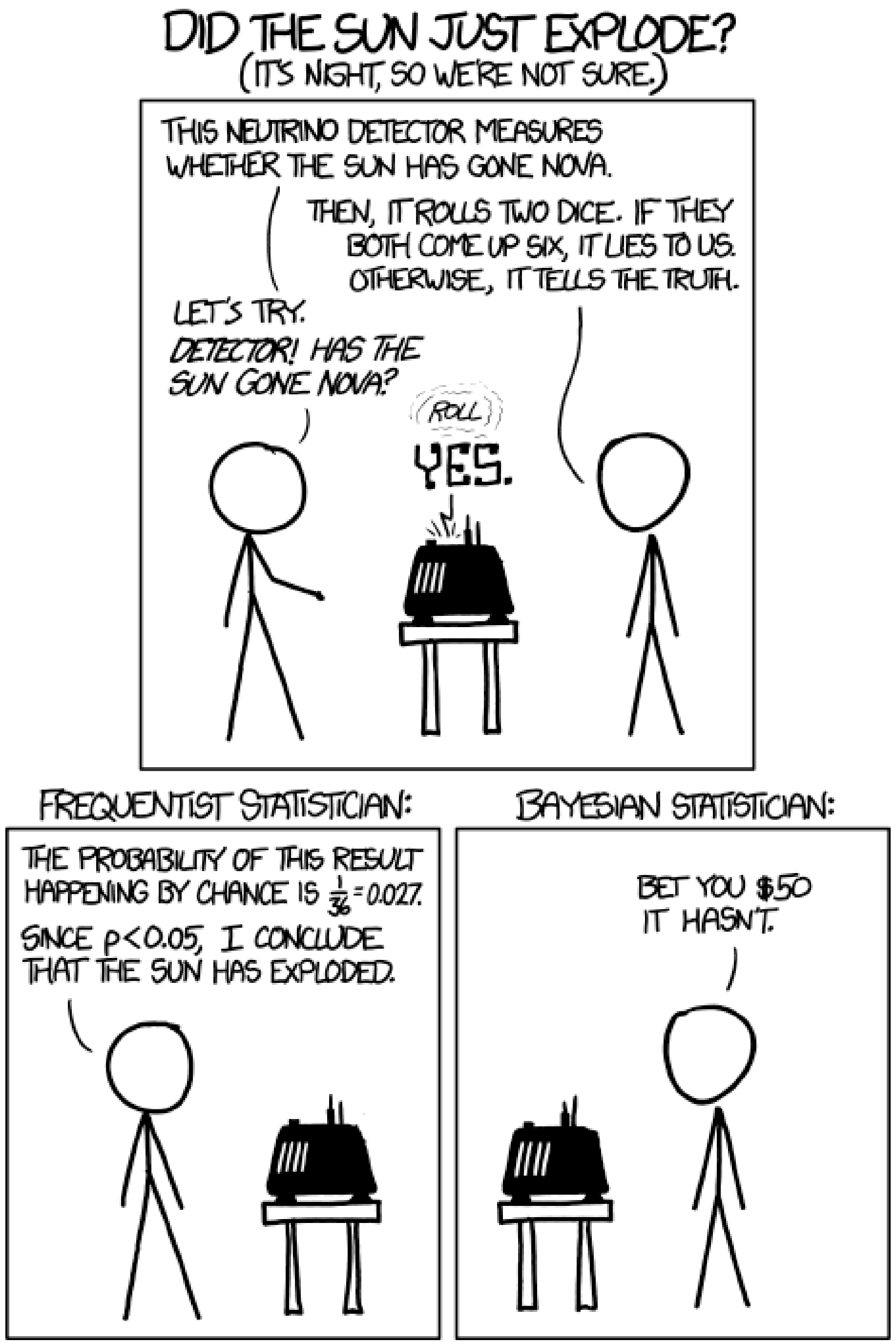
From dark matter to coherent ν-nucleus scattering in liquid noble gas detectors



xkcd.com/1132

Peter Sorensen
Advanced Detectors Group

(no need to read the comic, just admire the awesome, table-top neutrino detector with ~mm scale shielding)

This work (LLNL-PRES-607022) was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE- AC52-07NA27344.

Similarities in detection of dark matter vs coherent ν-nucleus scattering

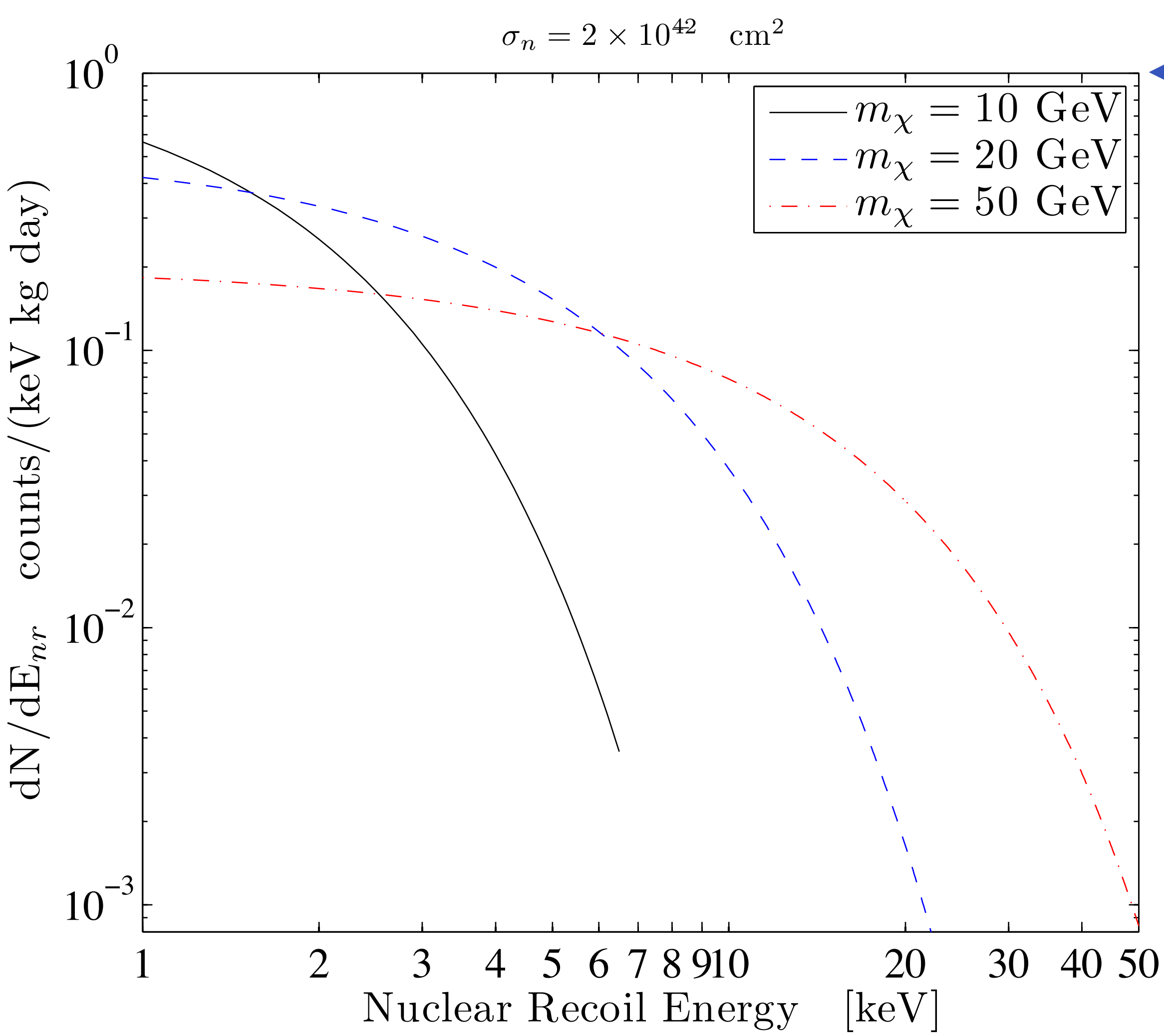
question	dark matter particle	coherent neutrino
mediated by Weak Force?	yes	yes
elastic nuclear scattering?	yes	yes
coherence?	$[(f_p Z + f_n(A-Z)]^2$	$[Z(4\sin^2\theta_W-1) + (A-Z)^2]$
rare event? (concern for bkg)	evidently!	basically (see next slide)
O(1) keV nuclear recoils?	most models, depends on m	yes, depends on E_ν
O(10) keV nuclear recoils?	most models, depends on m	sadly no, for reactor ν
standard model process?	no	yes

conclusion *(of which many in this room are aware)* is that
detecting dark matter appears to be difficult, but
detecting coherent ν scattering is DEFINITELY difficult

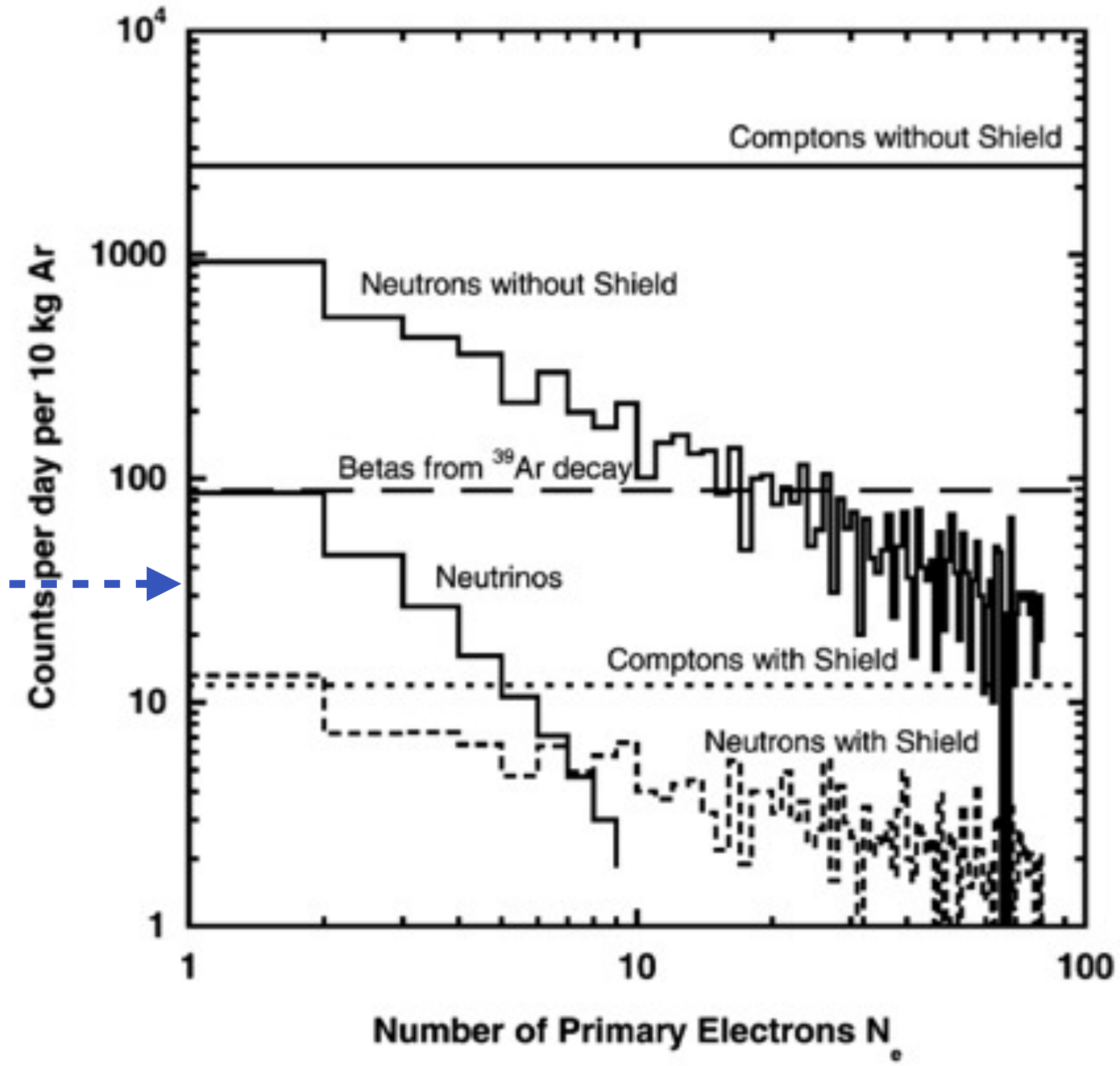
Another similarity: rates and spectra are theoretical

XENON10 bkg ~1 dru
LUX expected bkg ~7e-4 dru

dark matter elastic scatter on xenon

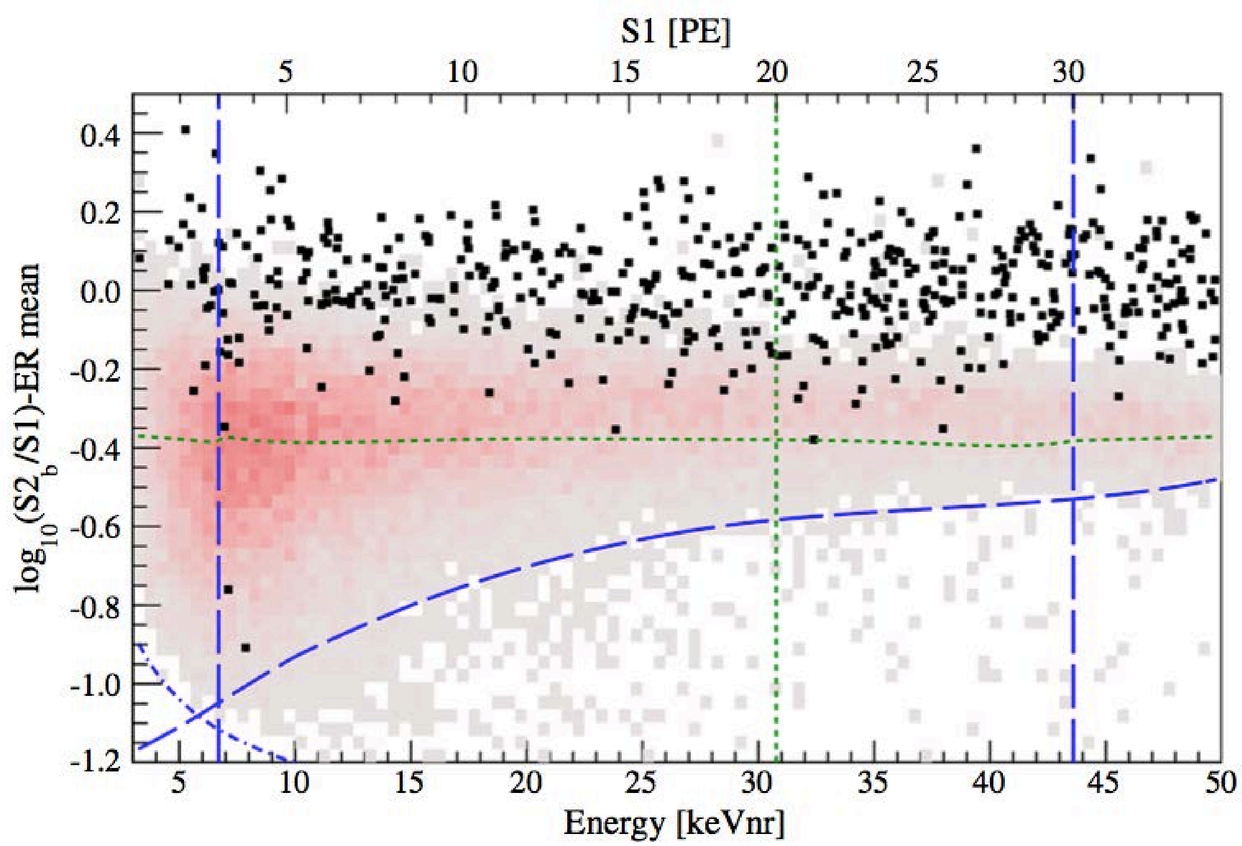


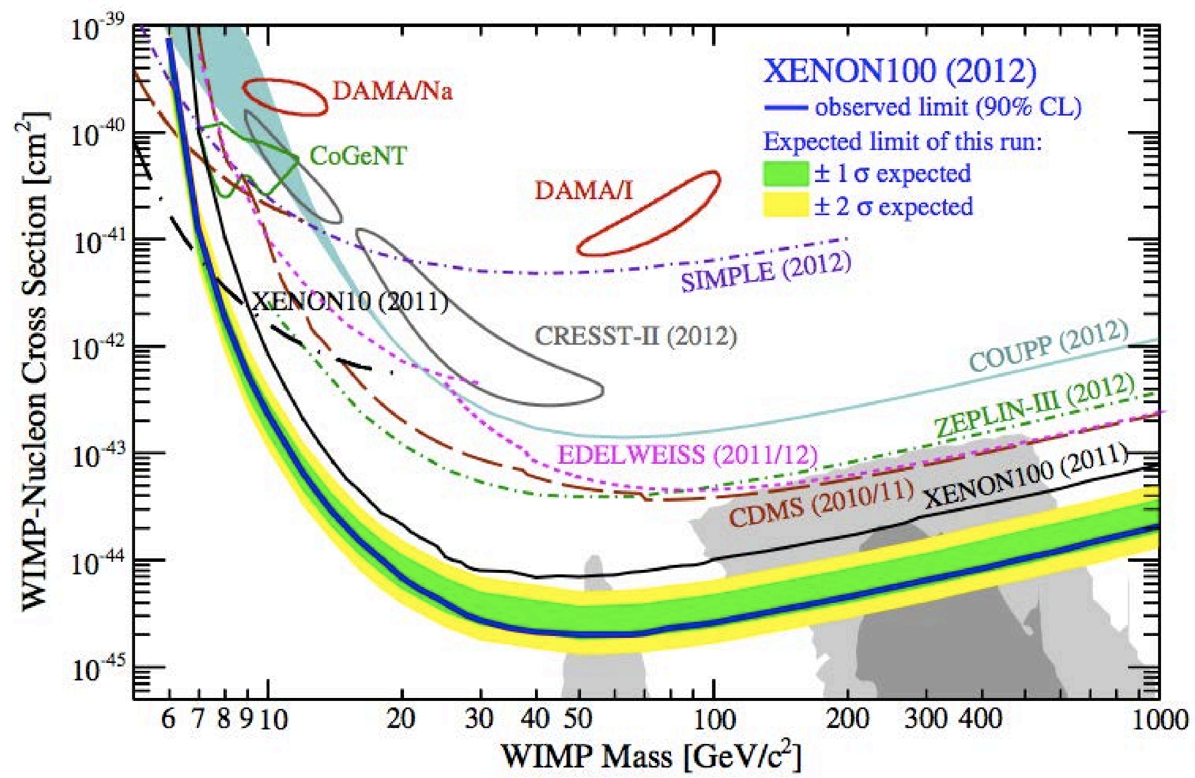
coherent ν on argon



Hagmann and Bernstein, IEEE Trans.Nucl. Sci. **51** 2154 (2004)

State of the art dark matter search with liquid xenon TPC

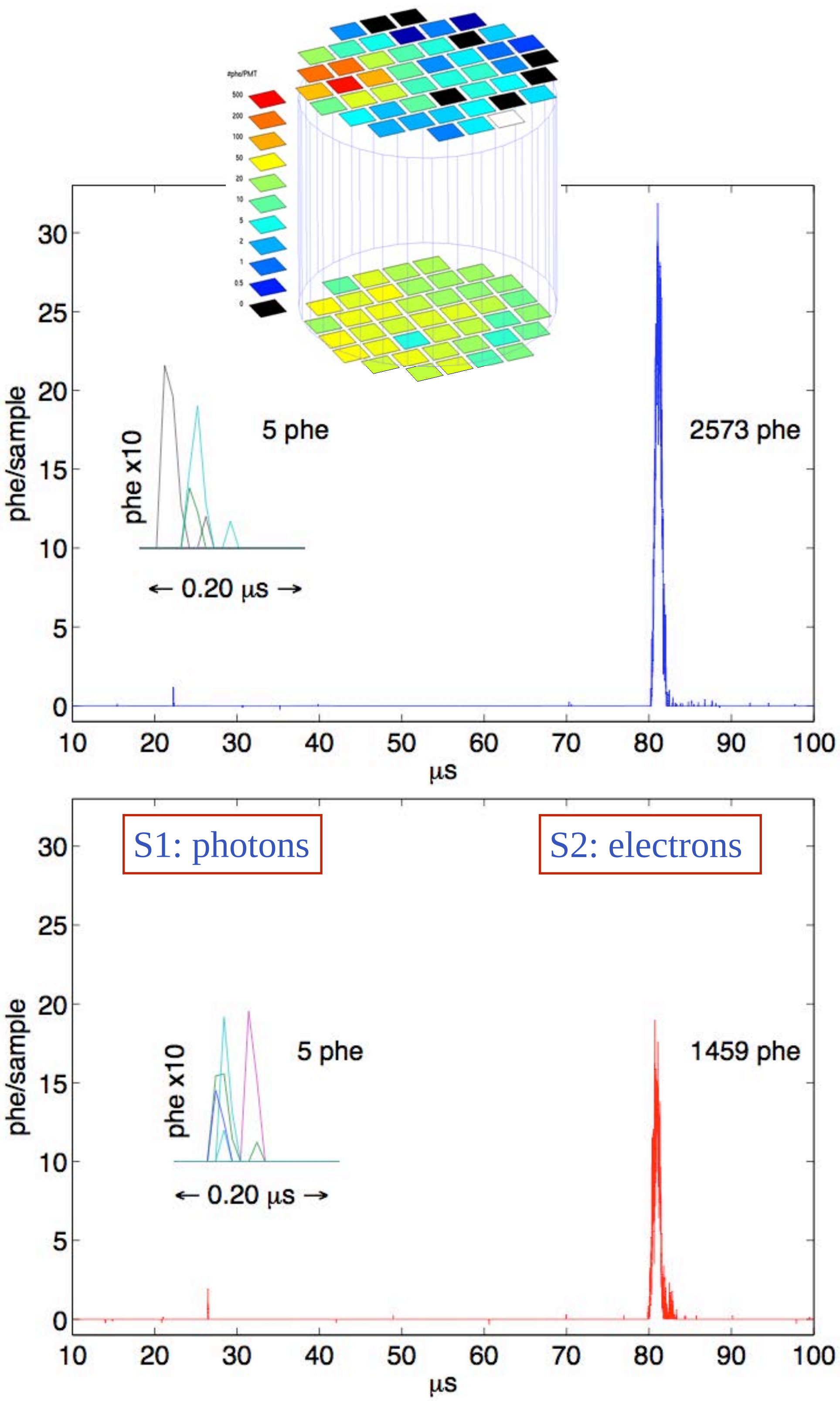




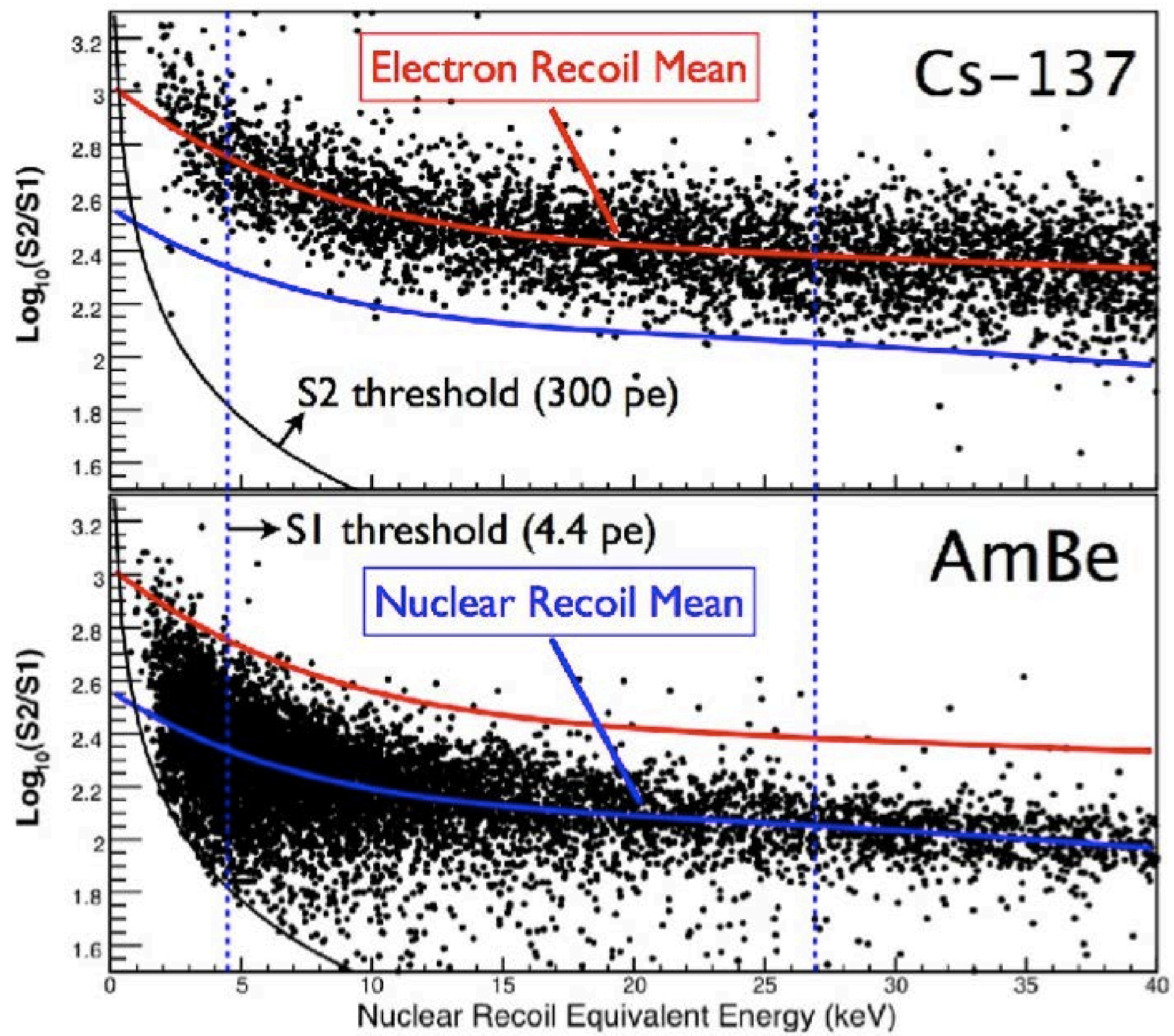
XENON100, Phys. Rev. Lett. 109 181301 (2012)

For me, the state of the art leaves many questions unanswered...
and is generally questionable in its treatment of
1. energy scale
2. sub-threshold S1 fluctuations

Back to 2008



XENON10, Phys. Rev. Lett. 100 021303 (2008)

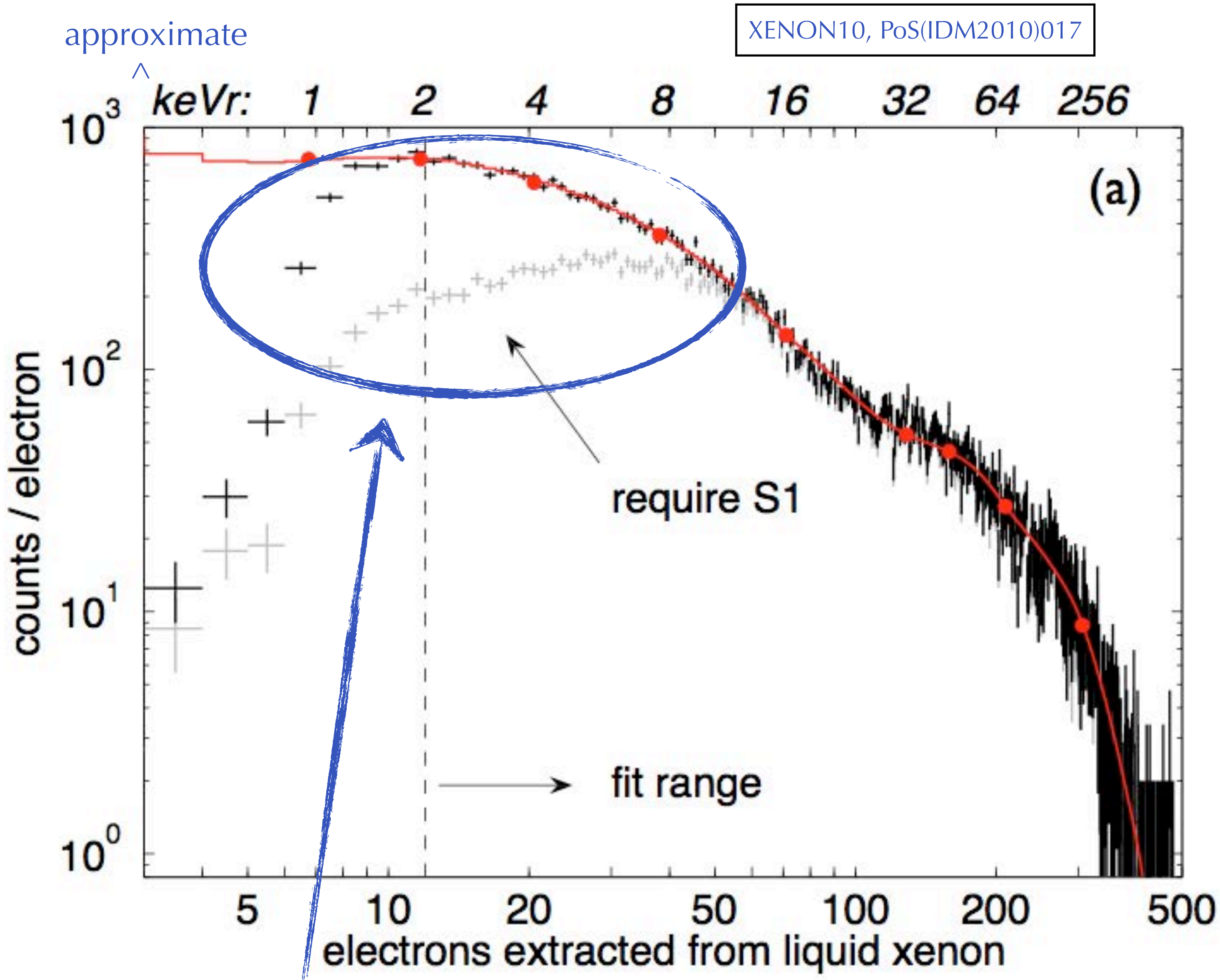


- why does ER band rise at low energy?
- why does NR band flare at low energy?
- Nuclear Recoil Equivalent Energy == S1?
- what is NOT conveyed by this plot?

(last question is easiest so lets start with that...)

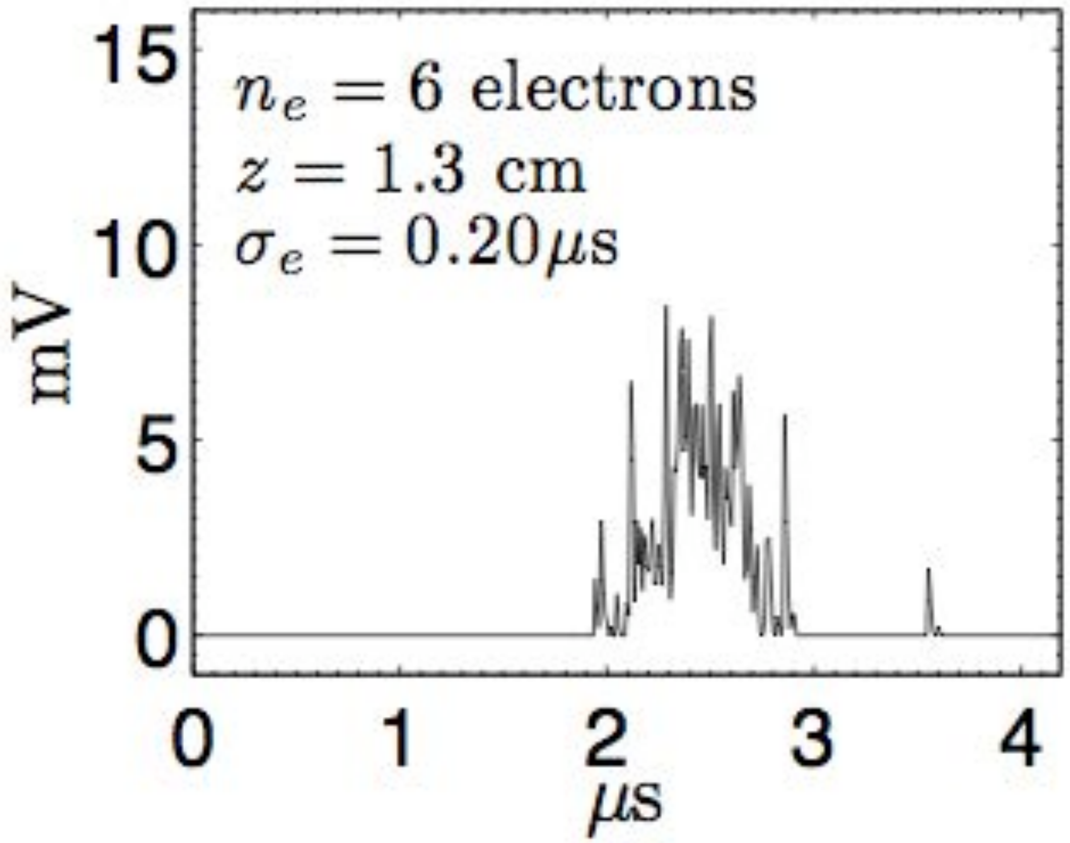
Dark matter search motivation for “S2-only” analysis

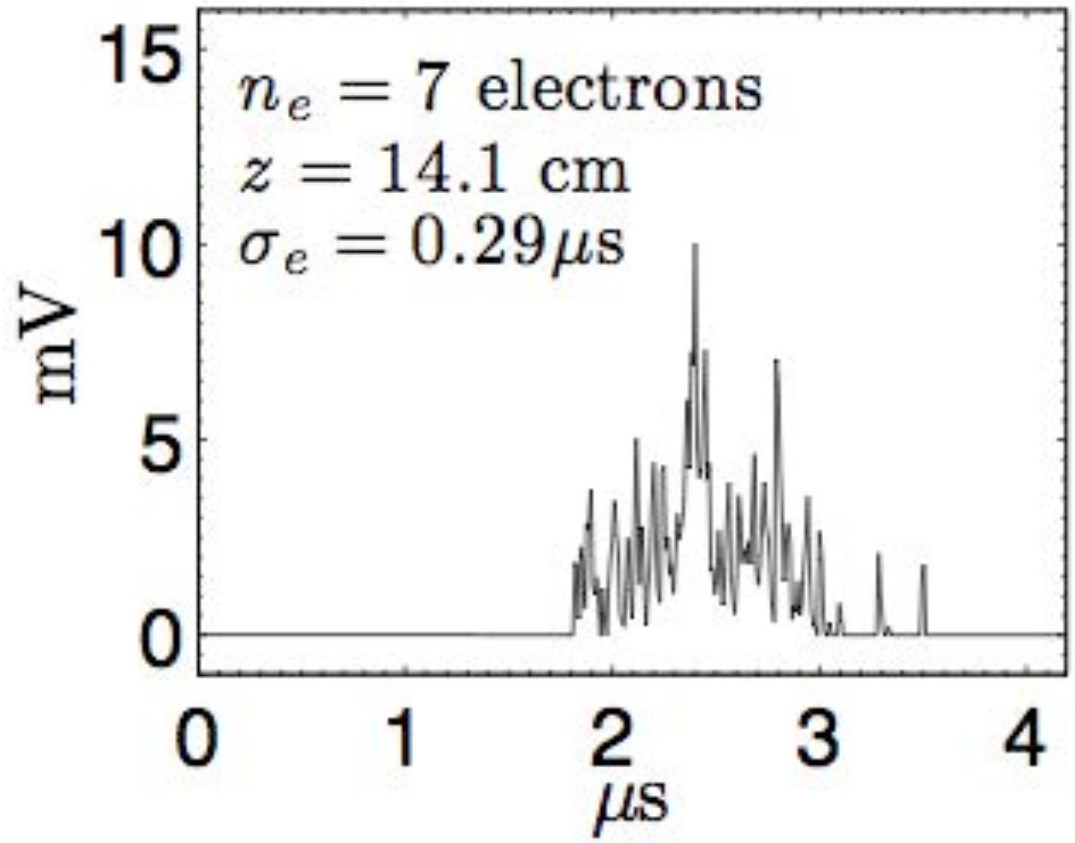
XENON10, PoS(IDM2010)017



- unexploited nuclear recoil response (XENON10 AmBe calibration data)
- this deficit is NOT visible on the usual discrimination plots
- not a priori useful, because without S1 we lose > x200 in background discrimination (as it turns out, it is useful)

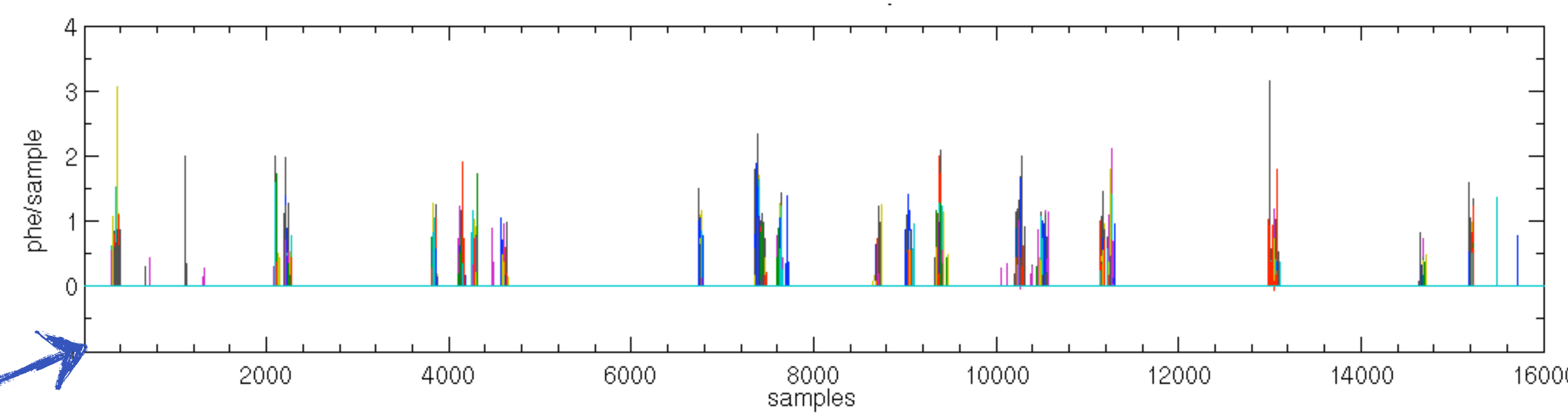
Typical low-energy single-scatter nuclear recoil signals in XENON10





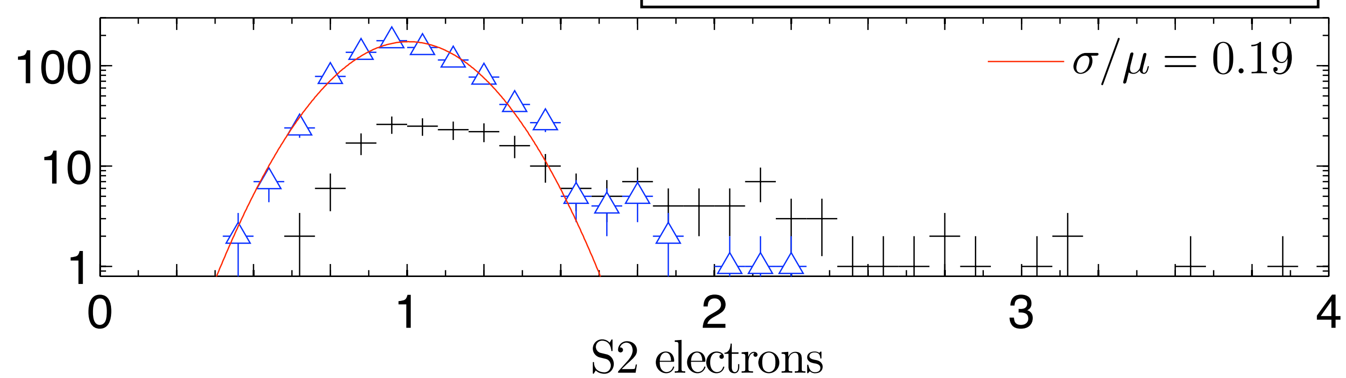
nuclear recoil energy E_{nr}	quanta created in xenon (photon or electron)	quanta in photomultipliers
1.4 keV (S1) 1.4 keV (S2)	5 photons 5 electrons	0 photoelectrons 125 photoelectrons
8 keV (S1) 8 keV (S2)	48 photons 34 electrons	4 photoelectrons 850 photoelectrons

Search for light dark matter in XENON10

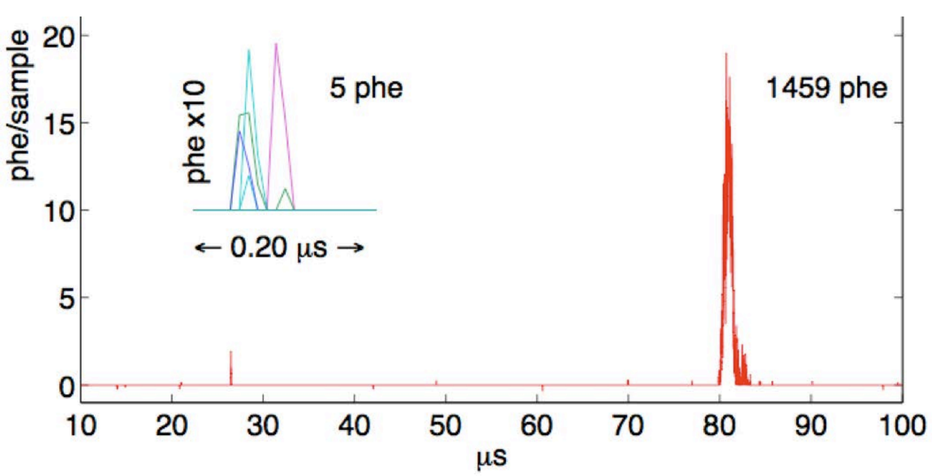


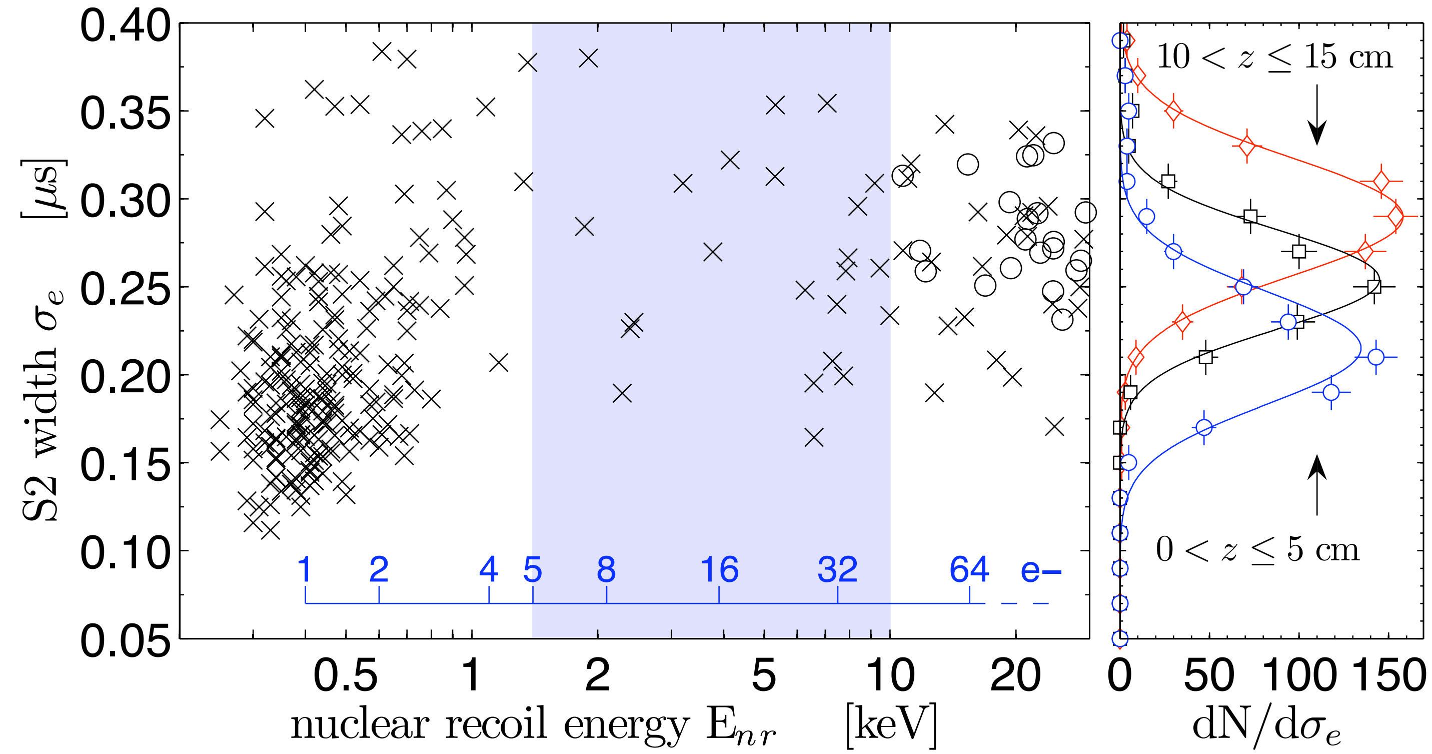
- electron (S2) signal only
- robust single e- signal (noise)
- "electron train" events (!?)
- No S2/S1 discrimination
- (x,y) vertex reconstruction
- minimal software selection
- (in principle) z coordinate from S2 width

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



reminder: this is how we usually get z:





z coordinate from electron diffusion

Sorensen, Nucl. Instr. Meth. A 635 41 (2011)

may be wishful thinking

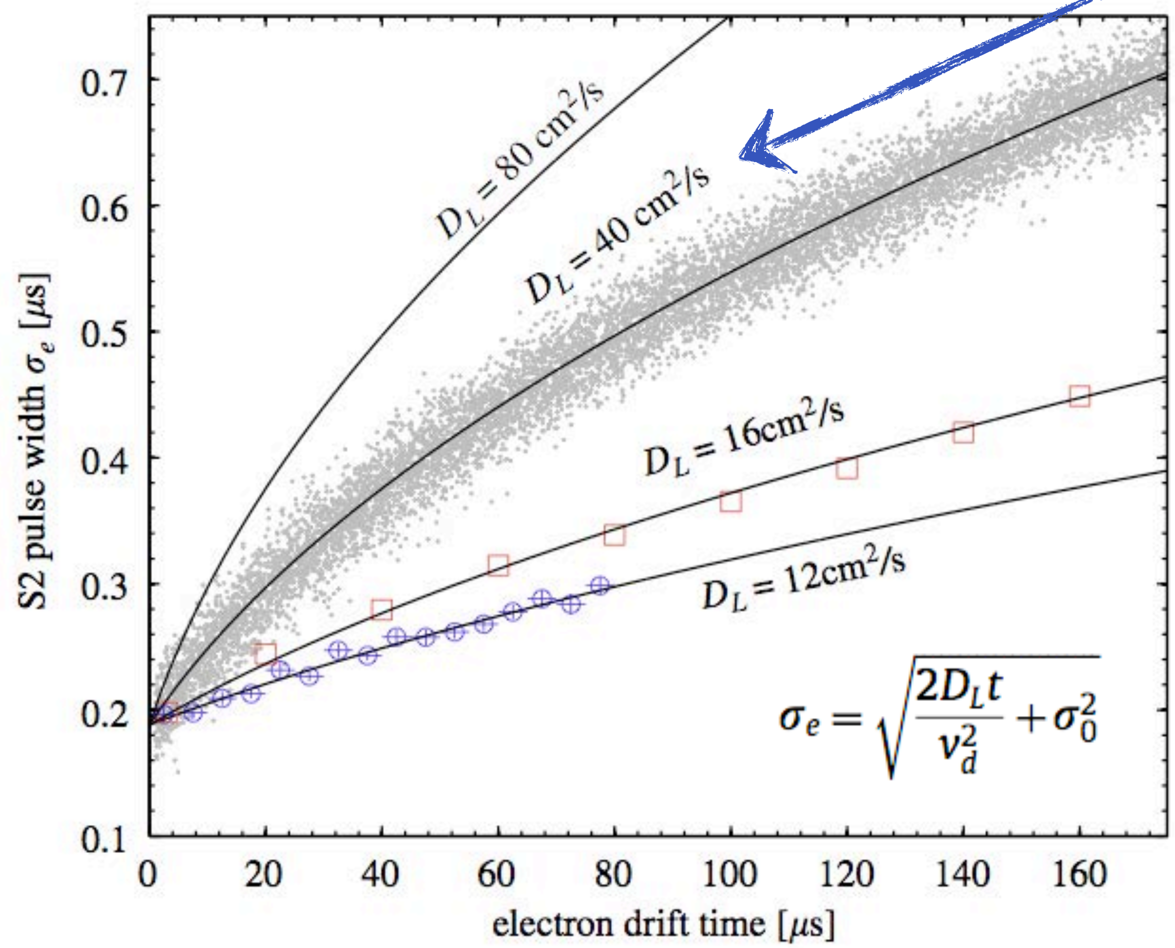


Fig. 2. Width of S2 pulses as a function of drift time through liquid xenon. Measurements from XENON10 [9] at E_d=730 V/cm and v_d=0.188 cm/μs (circles, 1σ error smaller than data points) and XENON100 [20] at E_d=530 V/cm and v_d=0.174 cm/μs (squares). The total drift distance was 15 and 30.6 cm, respectively. D_L was obtained from a fit of Eq. (5) in each case. The predicted width vs. drift time for two larger values of D_L are shown, assuming $\sigma_0 = 0.19$ μs and $v_d = 0.174$ cm/μs. A simulated distribution of events with Gaussian width $\sigma = 0.02$ μs is shown for D_L=40 cm^2/s.

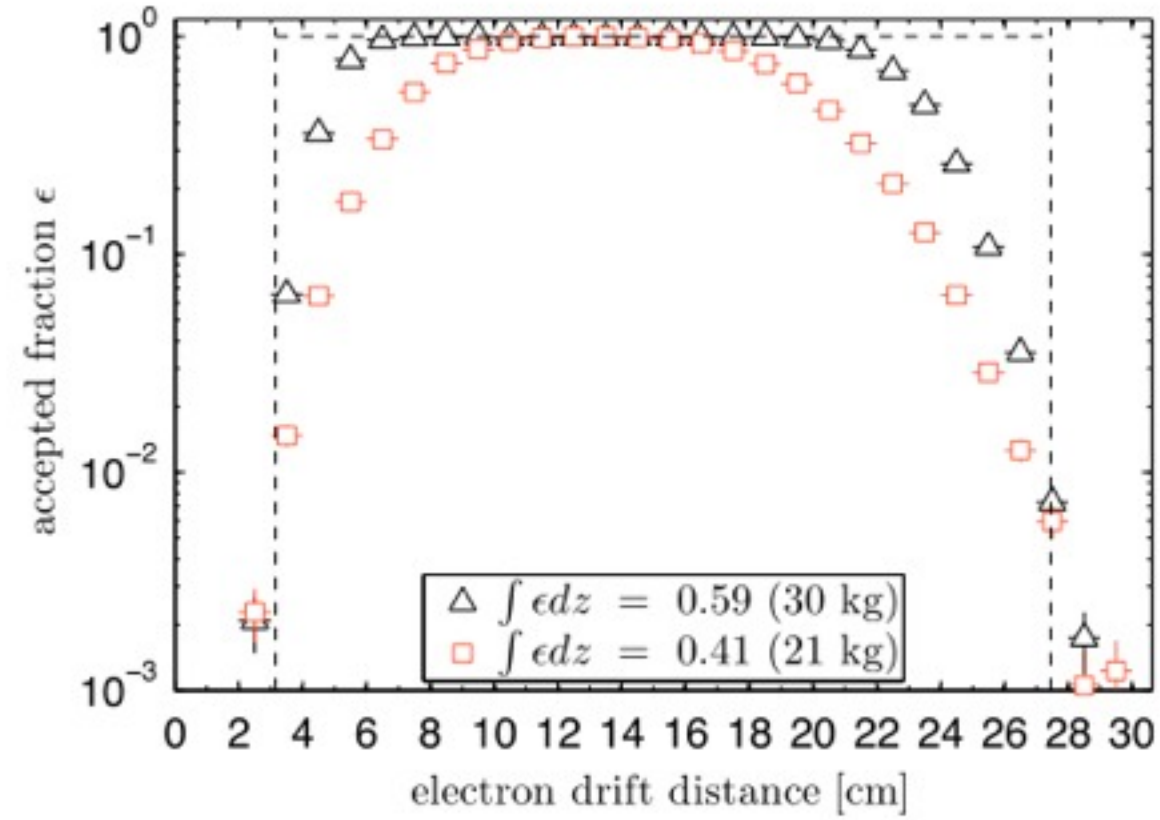
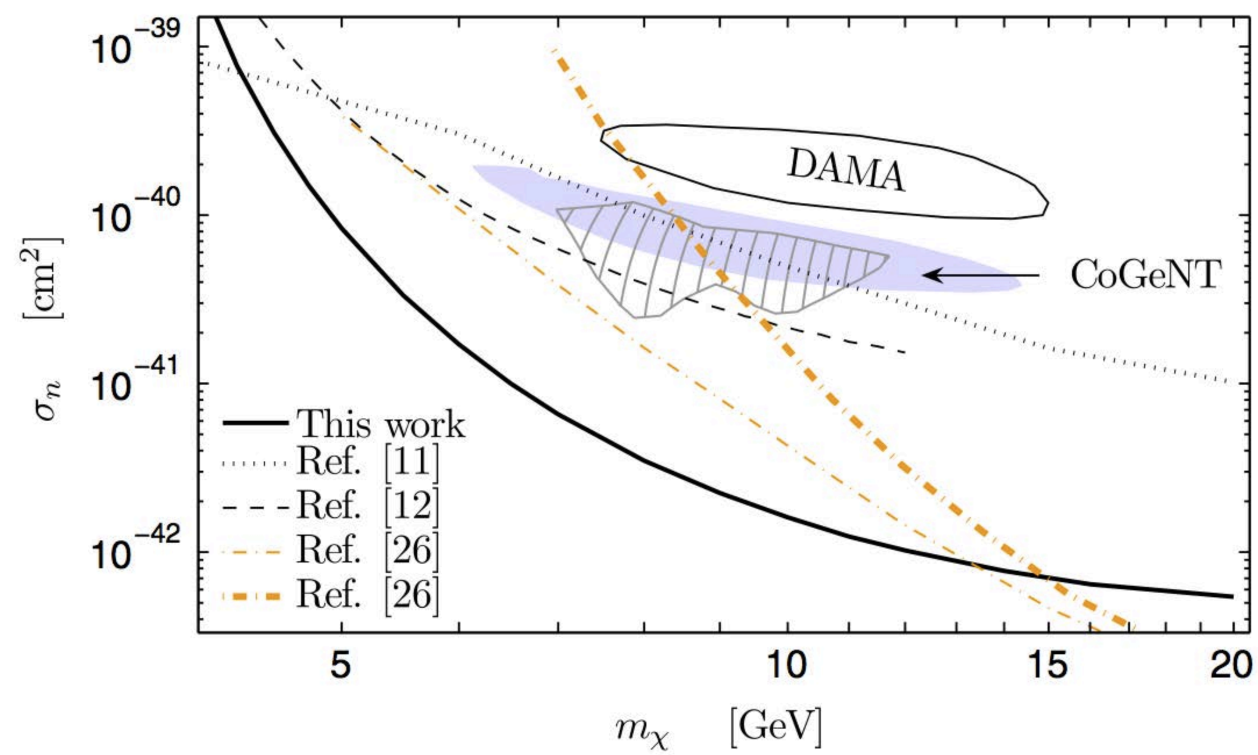


Fig. 4. Predicted fraction of accepted events in XENON100, with z coordinate reconstructed from S2 pulse width, for D_L=16 cm^2/s (□) and D_L=40 cm^2/s (△). σ_e cut bounds for each case are given in the text. Dashed lines indicate the accepted range of z coordinate in Ref. [2], using standard z reconstruction.

- still some ability to reject top/bottom edge events
- as you can guess, breaks down as n_e => 0

XENON10 elastic spin-independent dark matter sensitivity

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

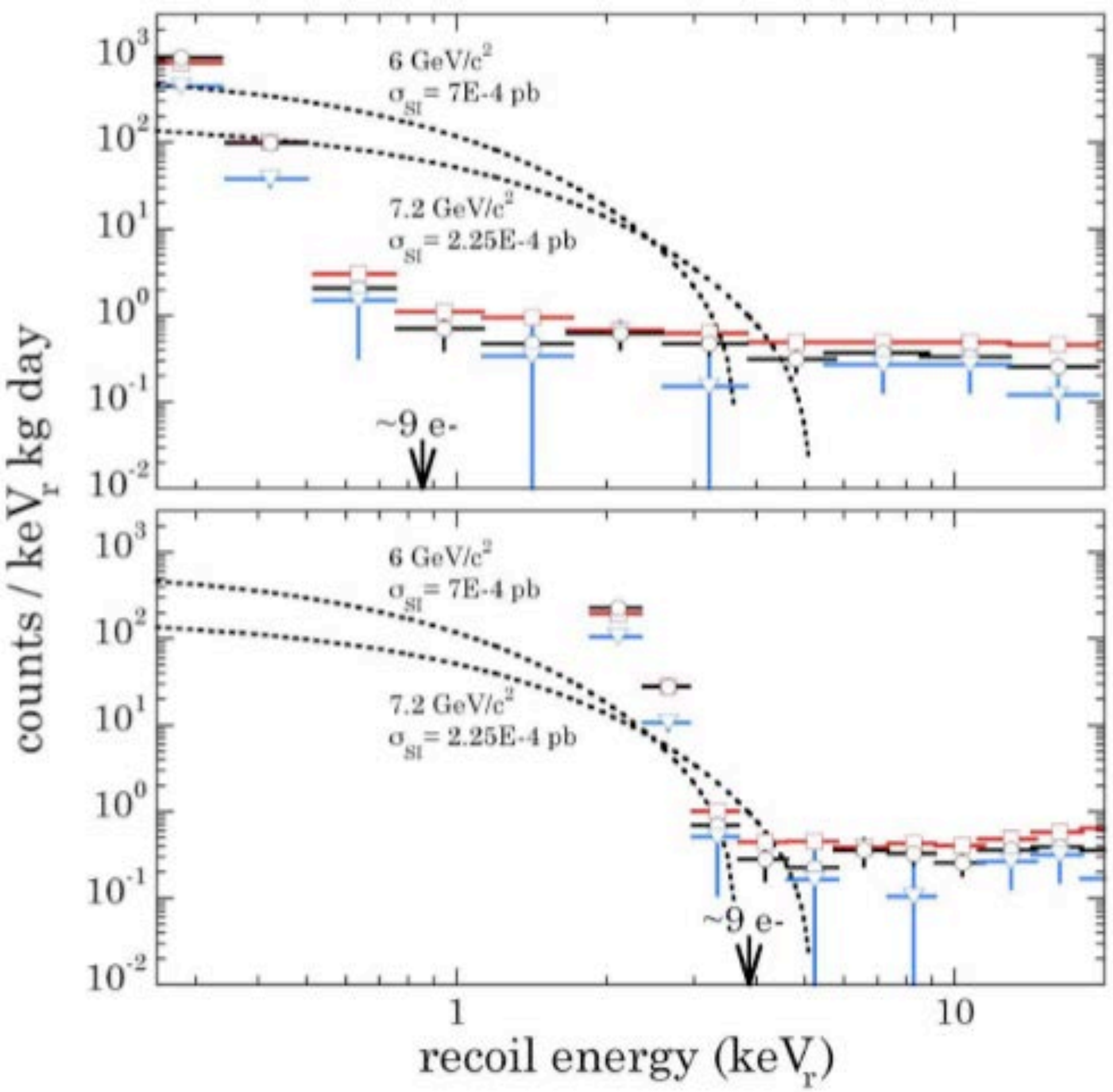


Achilles' Heel: nuclear recoil energy scale

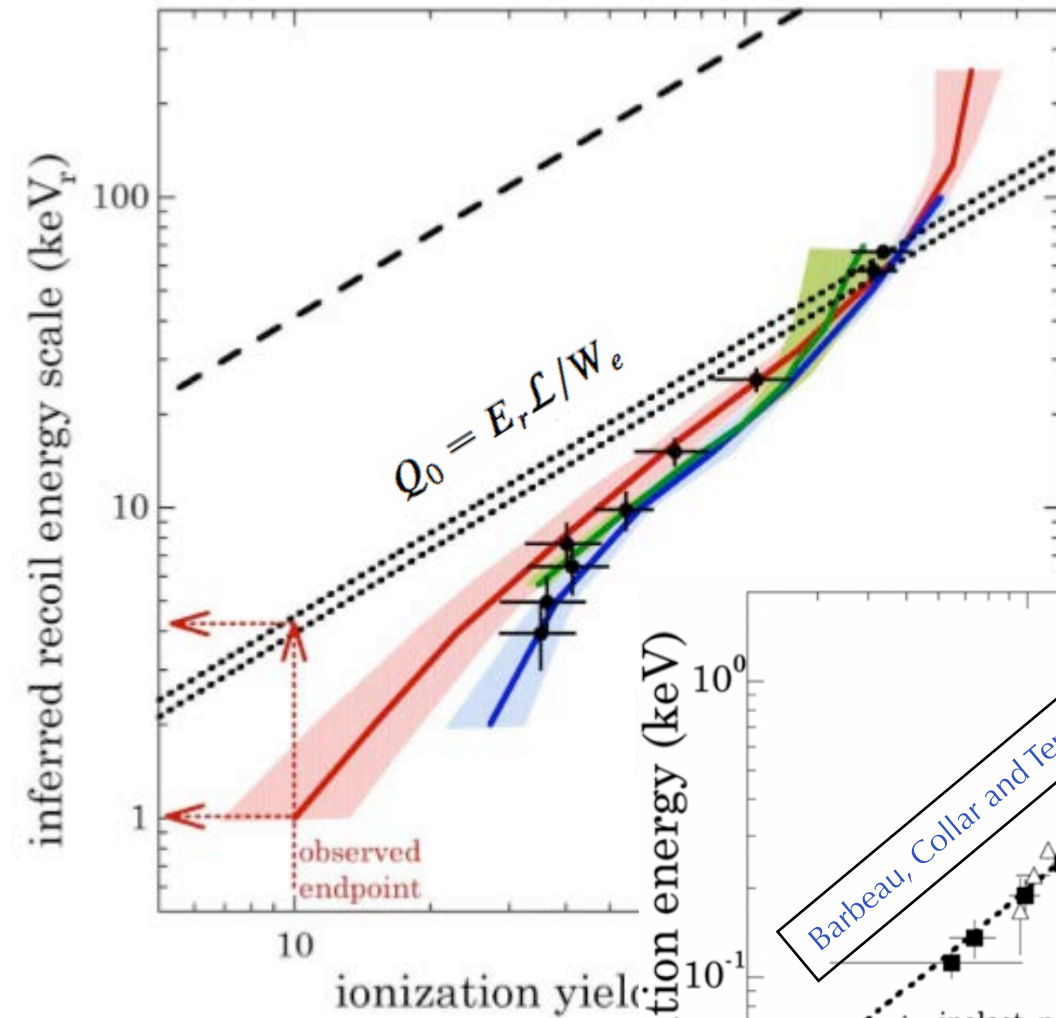
Criticism of nuclear recoil energy scale in liquid xenon

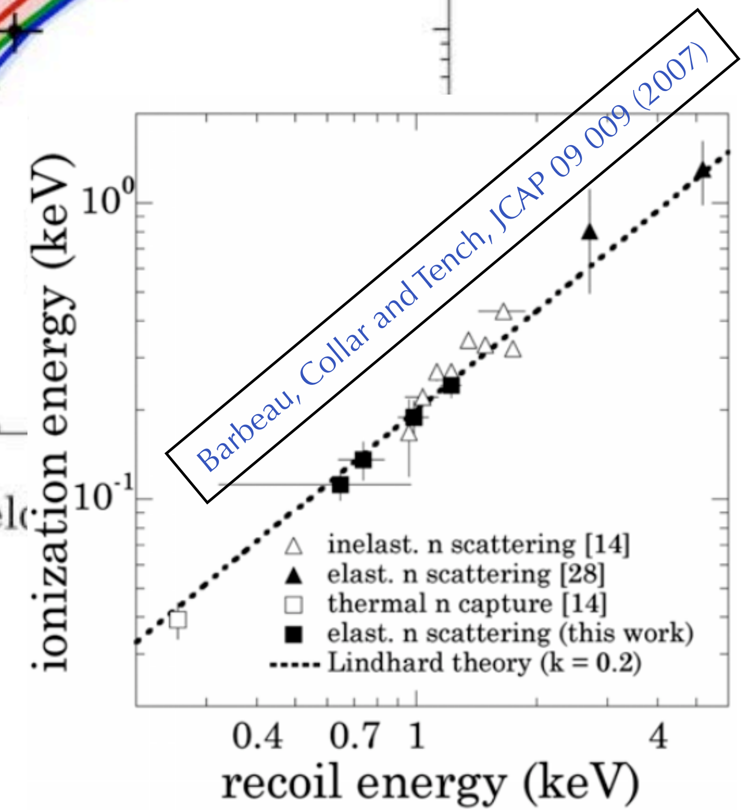
(need to understand this... it bears on future sensitivities to both dark matter and coherent ν)

Collar, arxiv:1010.5187 with data from XENON10, arxiv:1011.6439



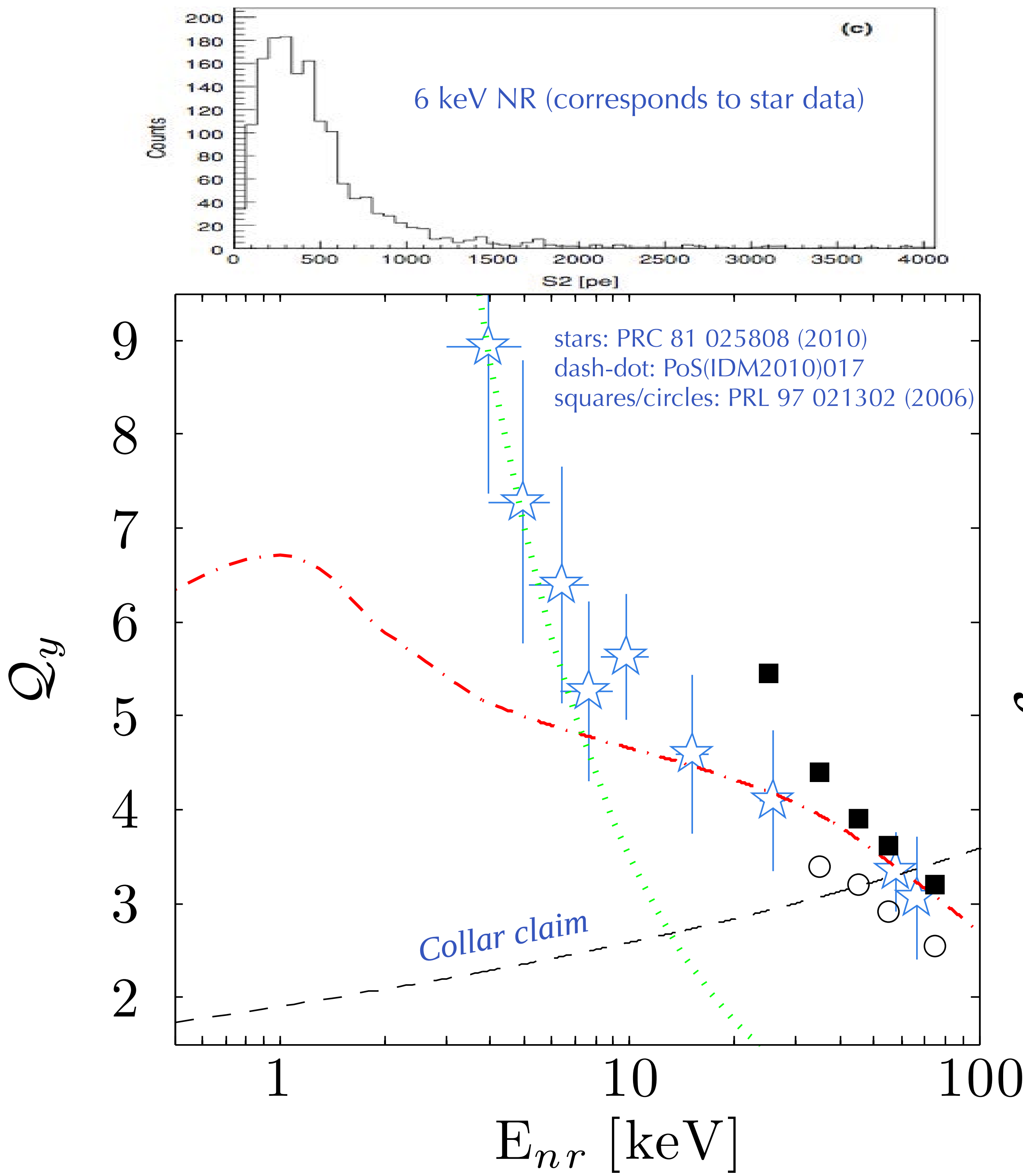
incorrect dotted lines based on incorrect speculation by Aprile et al. Phys Rev. Lett 97 021302 (2006)

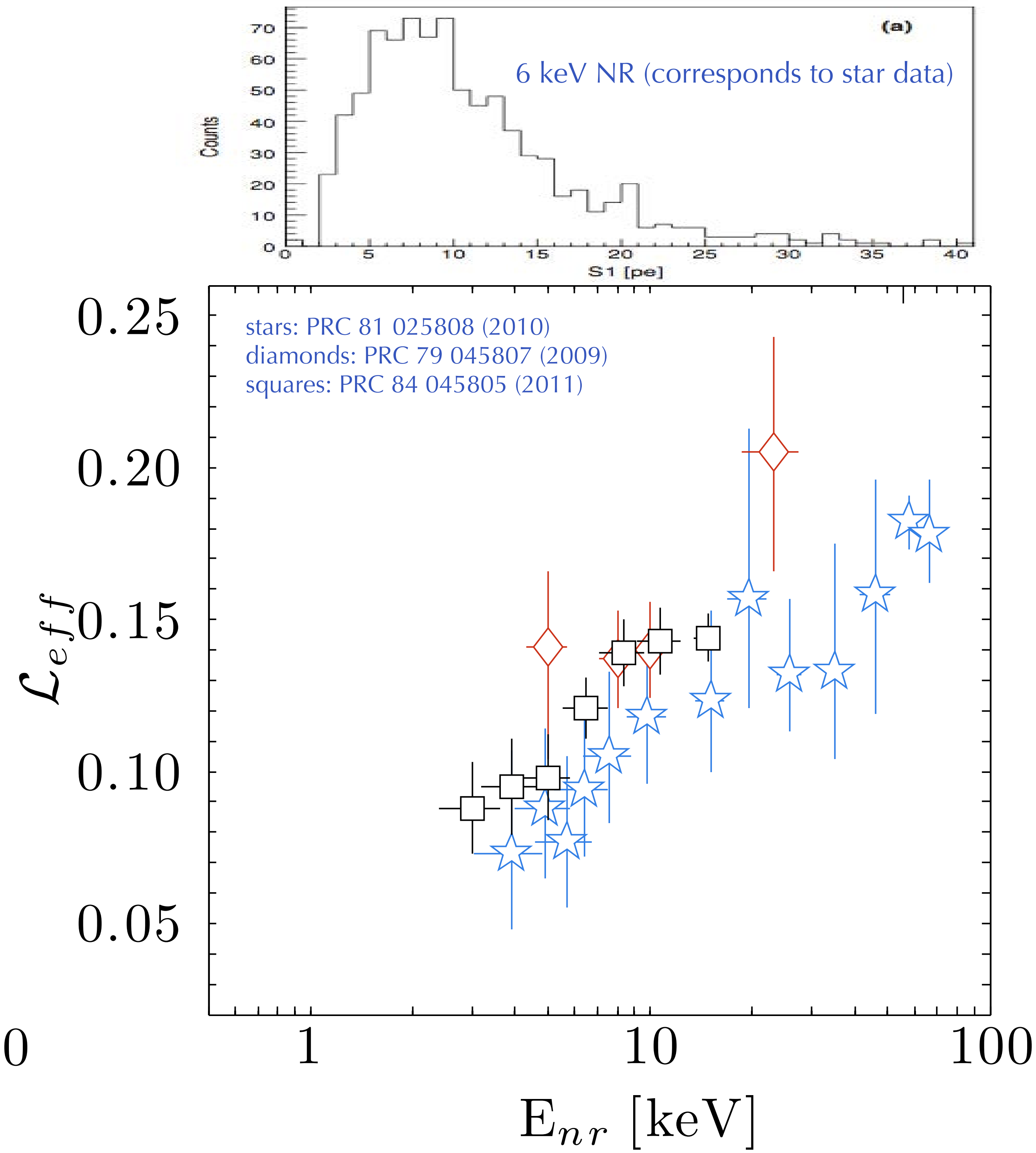




- history of confusion with liquid xenon energy scale
    - why doesn't scintillation response agree with Lindhard?
    - why doesn't ionization response agree with Lindhard?
- (top right) J.Collar appears to have assumed Lindhard is correct, with w ~ 80 eV (!!)
- the first half of the above sentence makes lots of sense, especially considering ionization data in germanium

Ionization and scintillation yield of liquid xenon for nuclear recoils

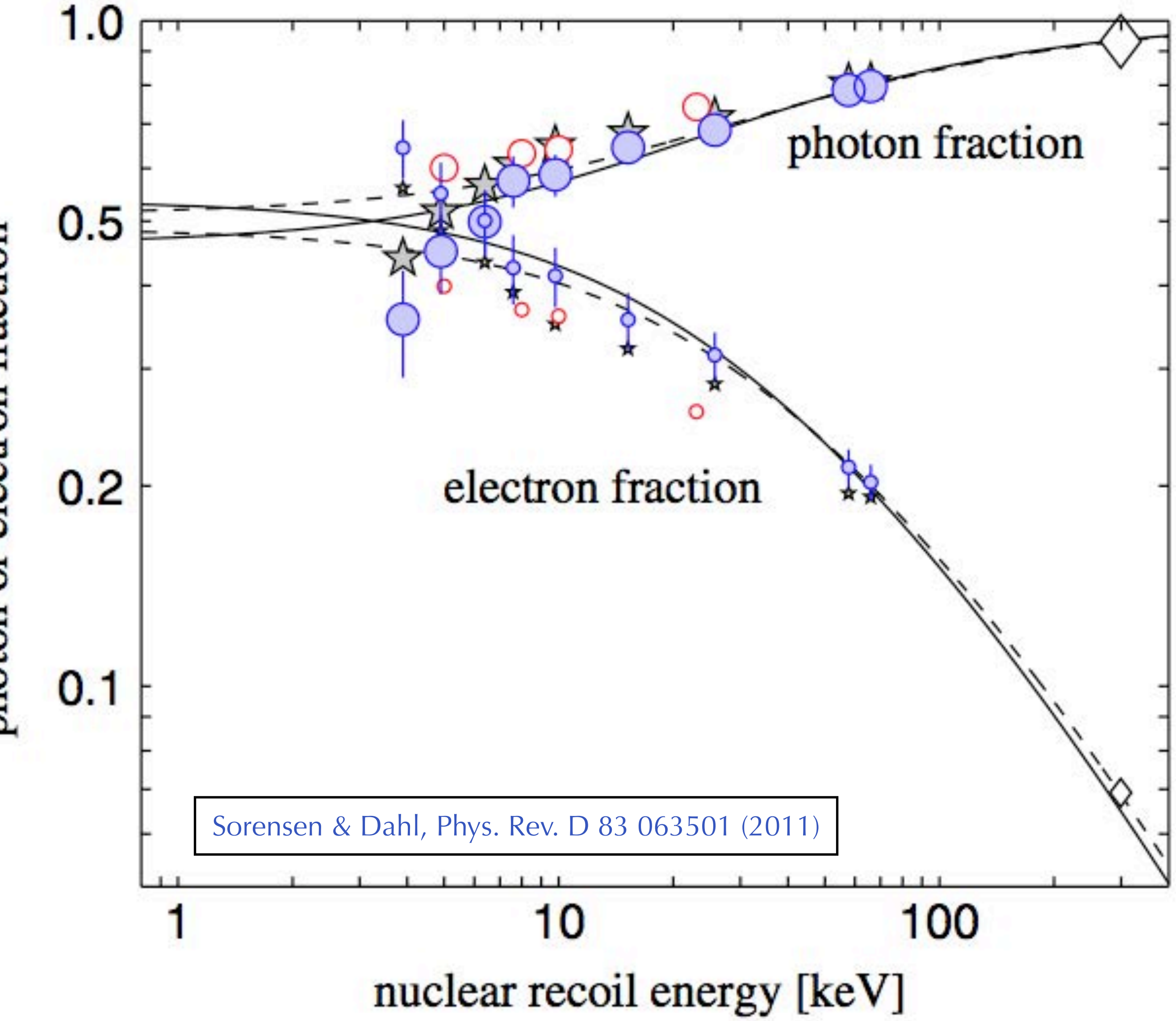




- I tend not to see the ~3 lowest energy Q_y data points (threshold bias!)
- large discrepancy between data and Collar/Aprile prediction.
- suggests we are (were!) missing something...

E_{nr} partitions into scintillation photons and electrons

Two-step solution: (1) Thomas-Imel recombination, and (2) Lindhard quenching



origin of scintillation: Xe* and Xe+
origin of ionization: Xe+

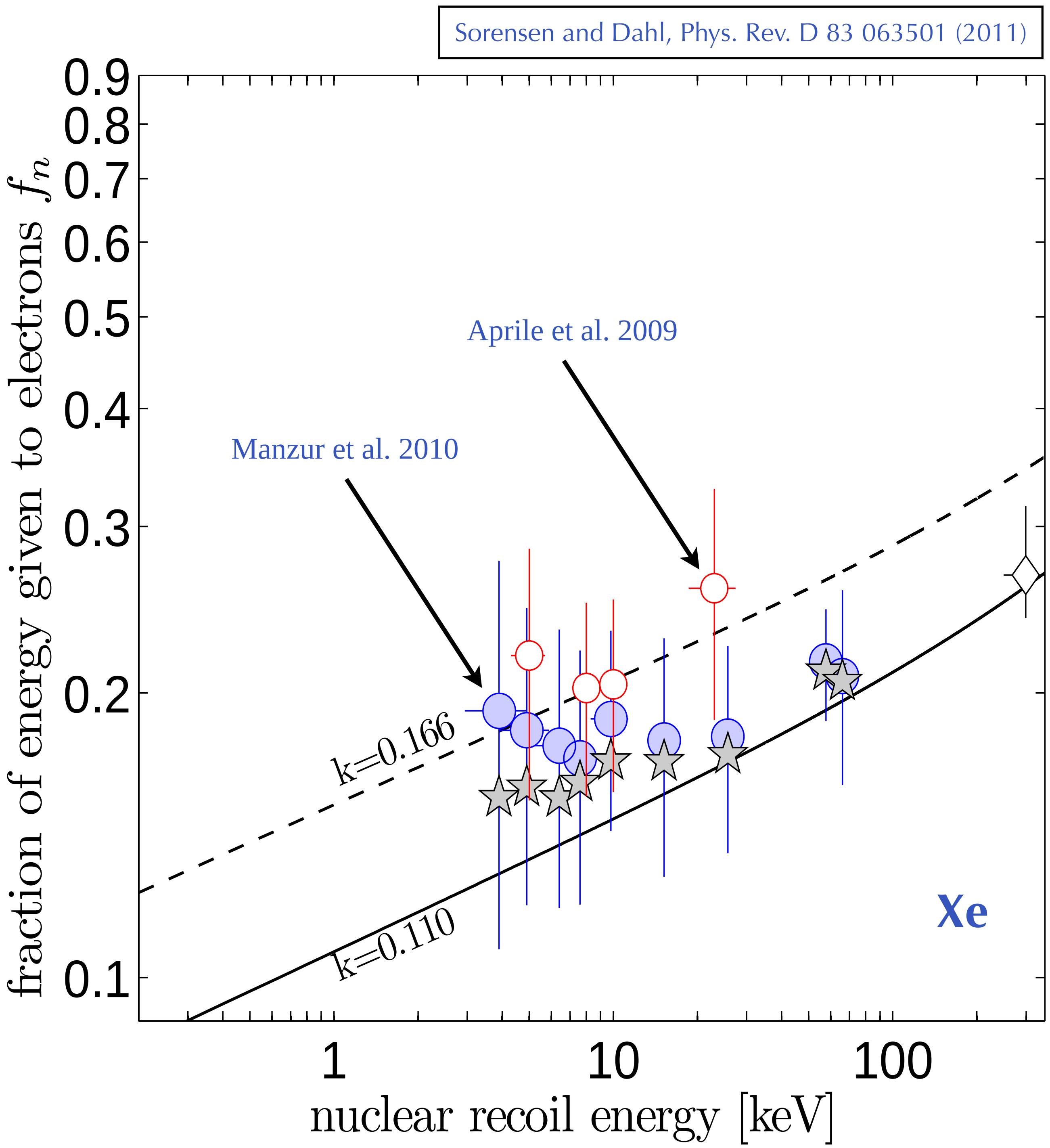
can write the electron fraction of the signal as
$F_e = \ln(1+\xi)/\xi \; [1/(1+N_{ex}/N_i)]$
with ξ and N_{ex}/N_i as free parameters.
$N_{ex}/N_i \sim 1$ for nuclear recoils in liquid xenon

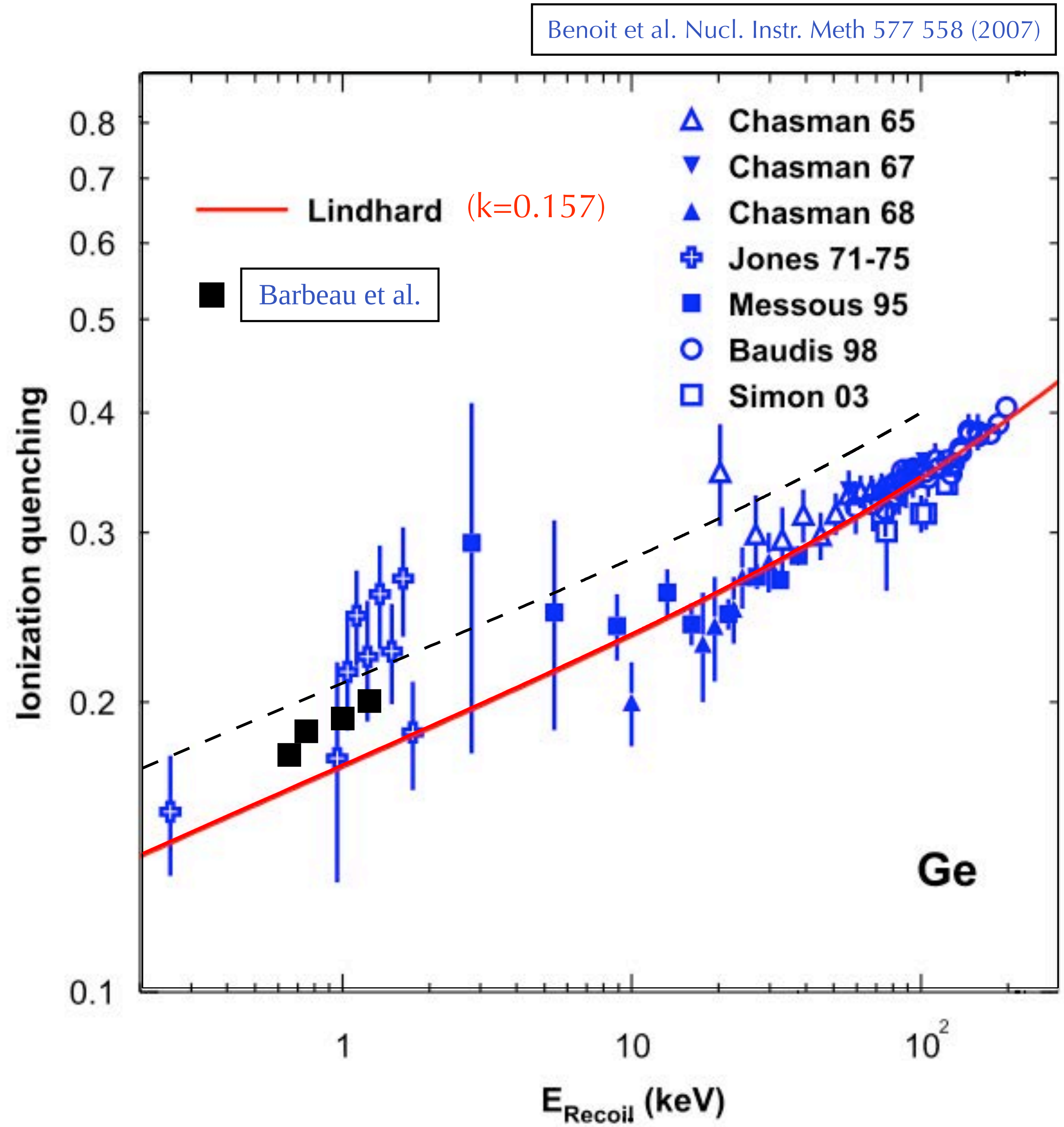
$$\left(\frac{d\varepsilon}{d\varrho}\right)_e \cdot \overline{\nu}'(\varepsilon) = \int_0^{\varepsilon^2} \frac{dt}{2\,t^{3/2}} \cdot f(t^{1/2}) \left\{ \overline{\nu}\left(\varepsilon - \frac{t}{\varepsilon}\right) - \overline{\nu}(\varepsilon) + \overline{\nu}\left(\frac{t}{\varepsilon}\right) \right\}$$

Mat. Fys. Medd. Dan. Vid. Selsk. **33,** no. 10 (1963)

More precisely, for an incoming particle of energy E we ask for that part η of the total energy loss, E, which is ultimately given to electrons, and that part ν, which is ultimately left in atomic motion. Since this division is a useful

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

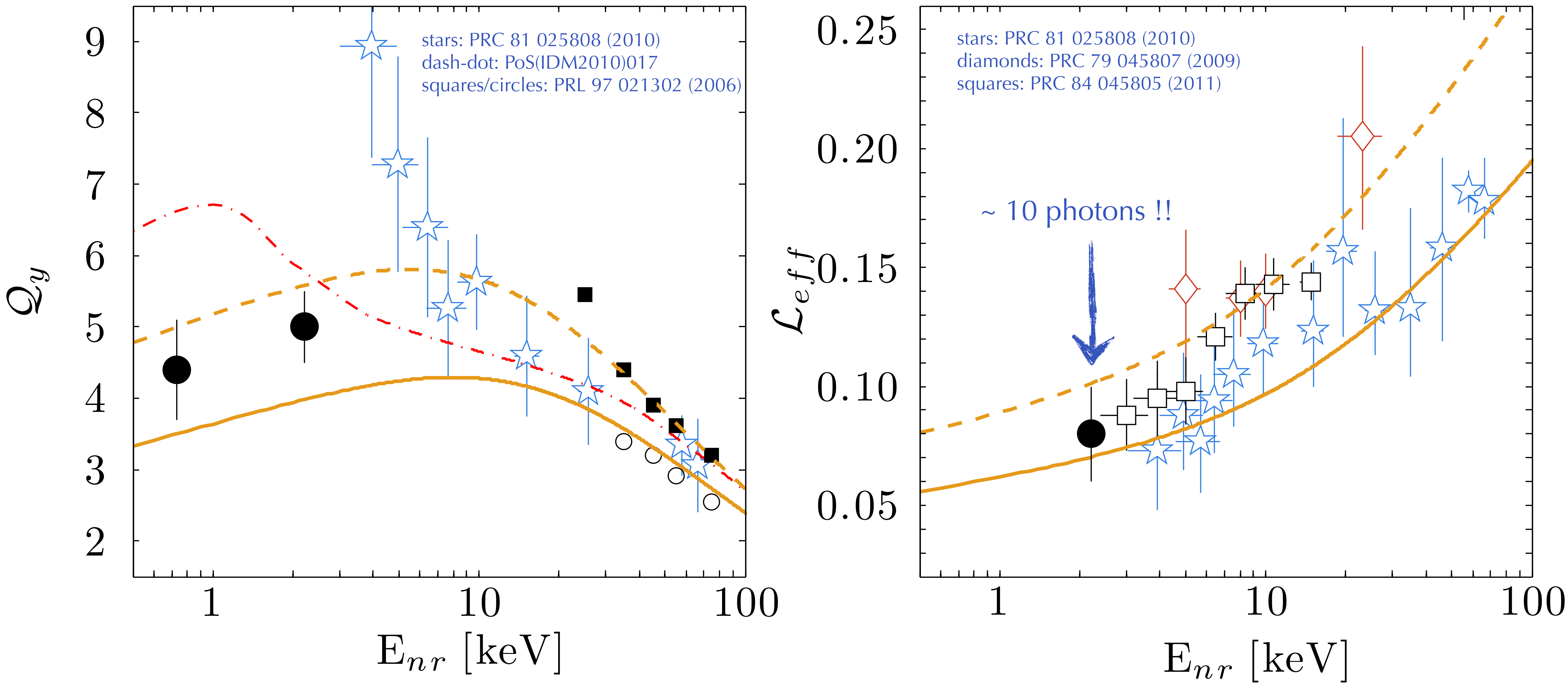




- paucity of data in xenon. germanium folks have a 50 year head start..
- clearly, we have some work to do to map out the quenching in xenon (and argon!)

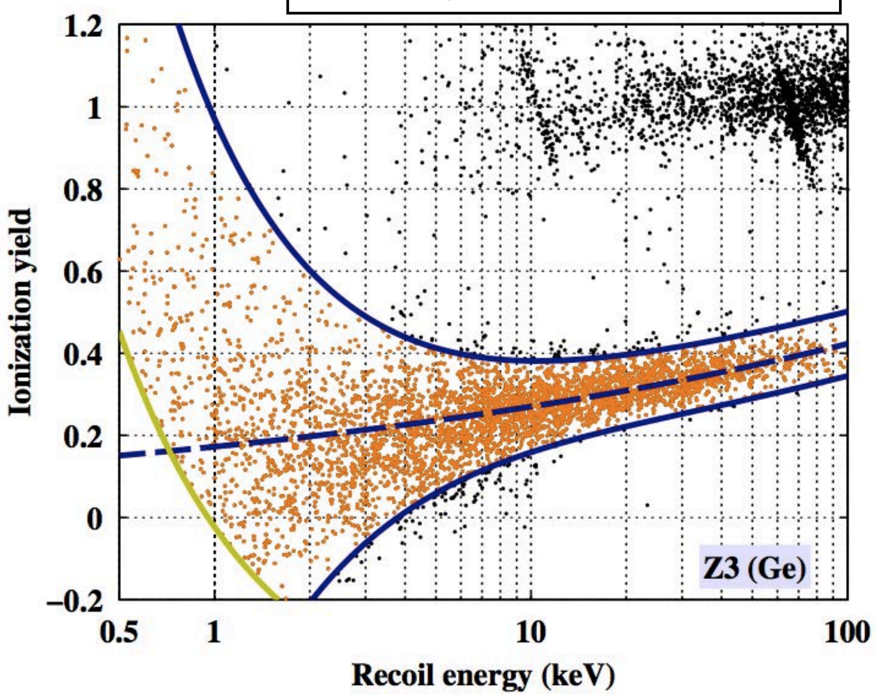
Ionization and scintillation yield of liquid xenon for nuclear recoils

(plus model)



- orange curves (solid and dashed) are model predictions from Phys. Rev. D 83 063501 (2011)
- (aside) large filled circles are hypothetical data that could be obtained from 24 keV and 73 keV endpoint
  - learned yesterday that RED may beat me to this (a welcome challenge/contribution)

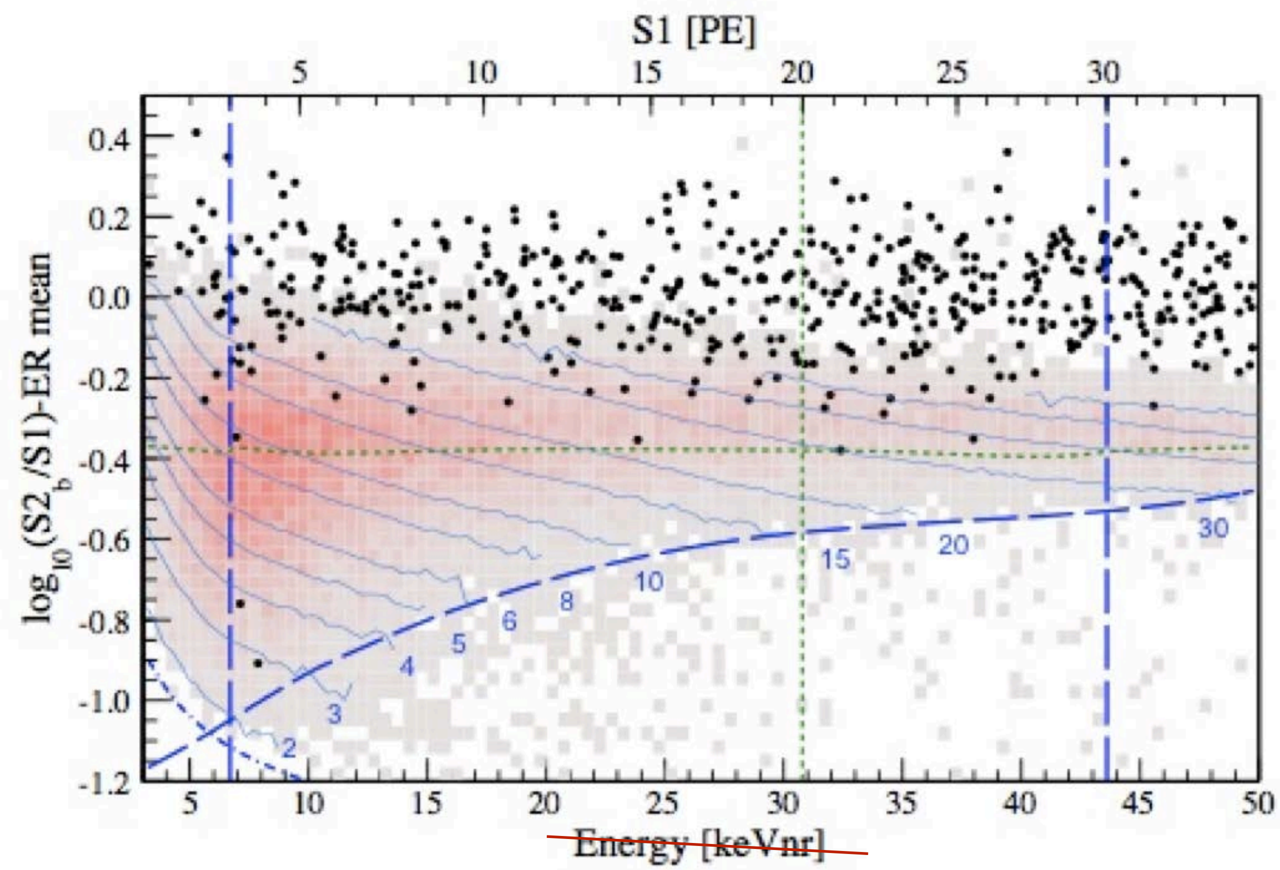
CDMS, Phys Rev D **82** 122004 (2010)



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

with contours overlaid as in

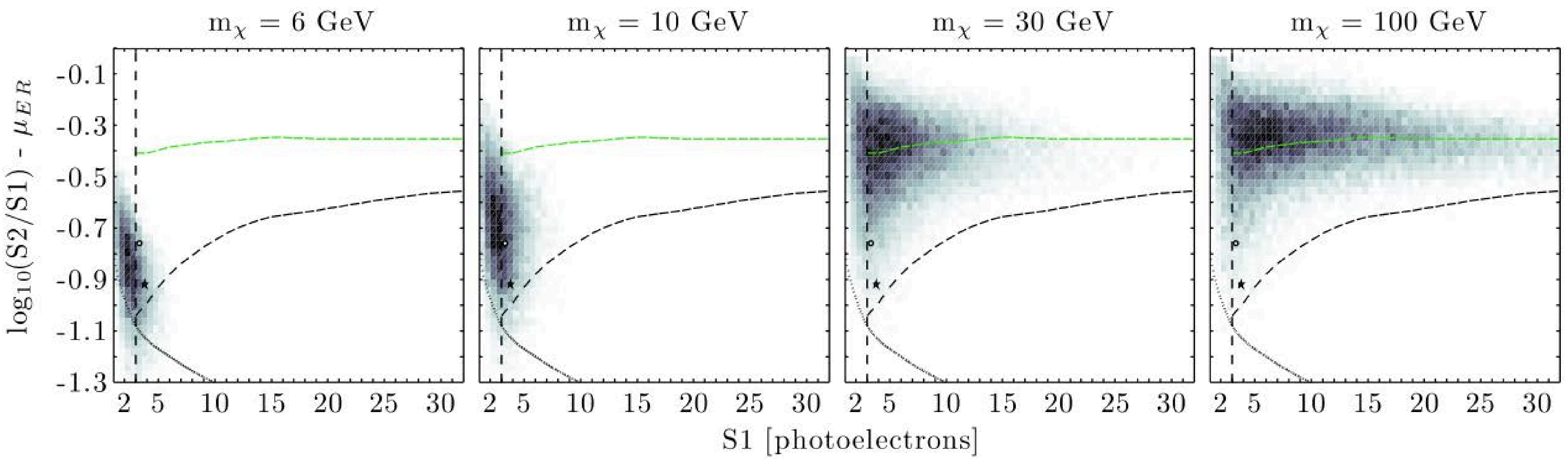
Sorensen, Phys. Rev. D **86** 101301(R) (2012)



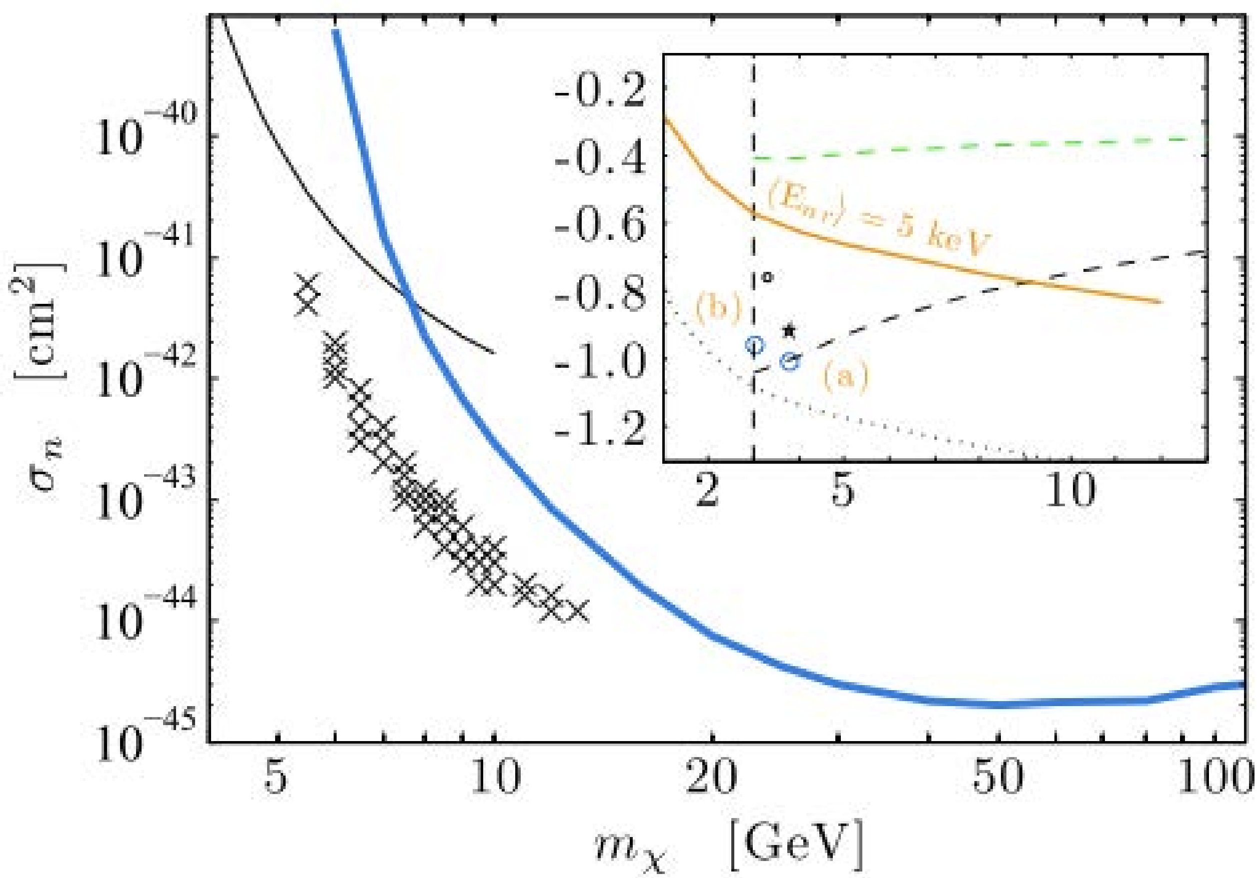
- x-axis: "Recoil Energy keV"
- (not that anyone asked... but) I buy it
- note some anticorrelation in phonon and ionization

- x-axis should read: "S1 photoelectrons"
- S1-only (L_{eff}) energy scale is correct at centroid only
- full simulation gives E_{nr} contours
  - agrees with model
  - fluctuations dominated by: Poisson S1, Poisson n_e, binomial PMT
  - explains observed NR band width!
  - NO evidence for recombination fluctuations for nuclear recoils!
  - self consistent but not absolutely correct (L_{eff} taken as a prior)

What will dark matter spectra look like in liquid xenon?

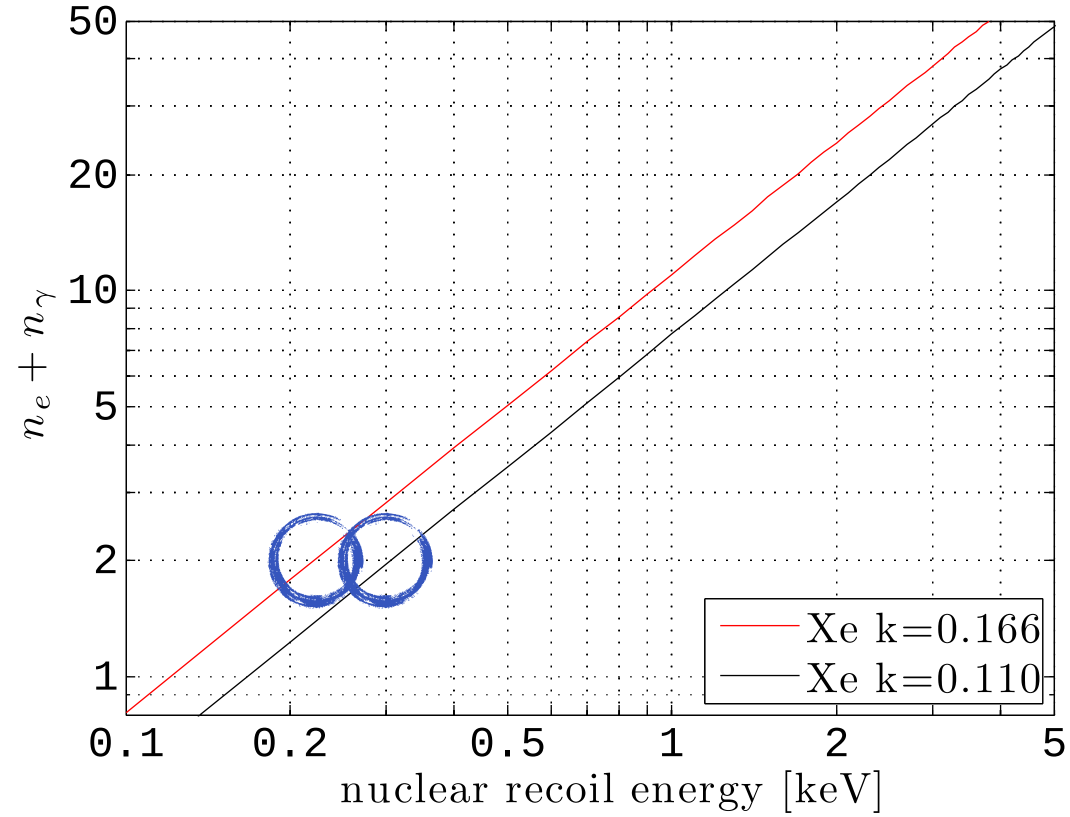


Sorensen, Phys. Rev. D **86** 101301(R) (2012)

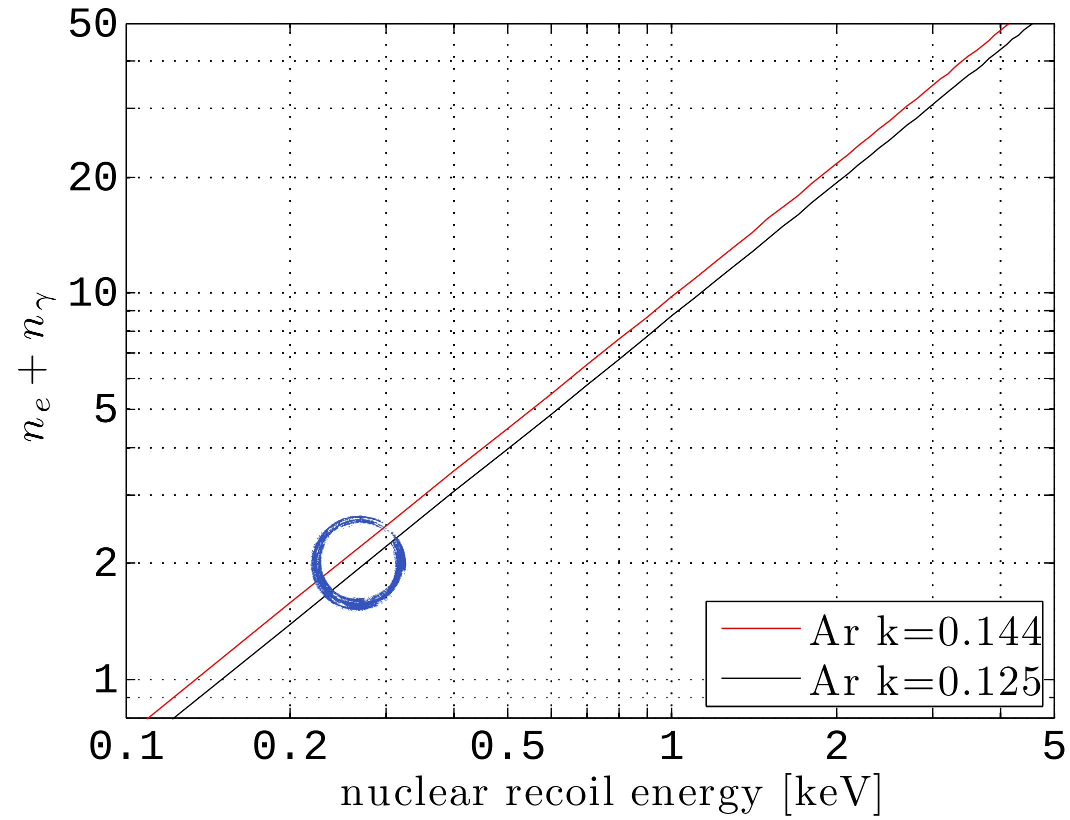


- Super! Another light dark matter anomaly...
- based on a consistent treatment of low-energy (not necessarily sub-threshold) fluctuations
- I do suggest this method
- I do not suggest using the XENON100 assumptions for Leff (as in this work)

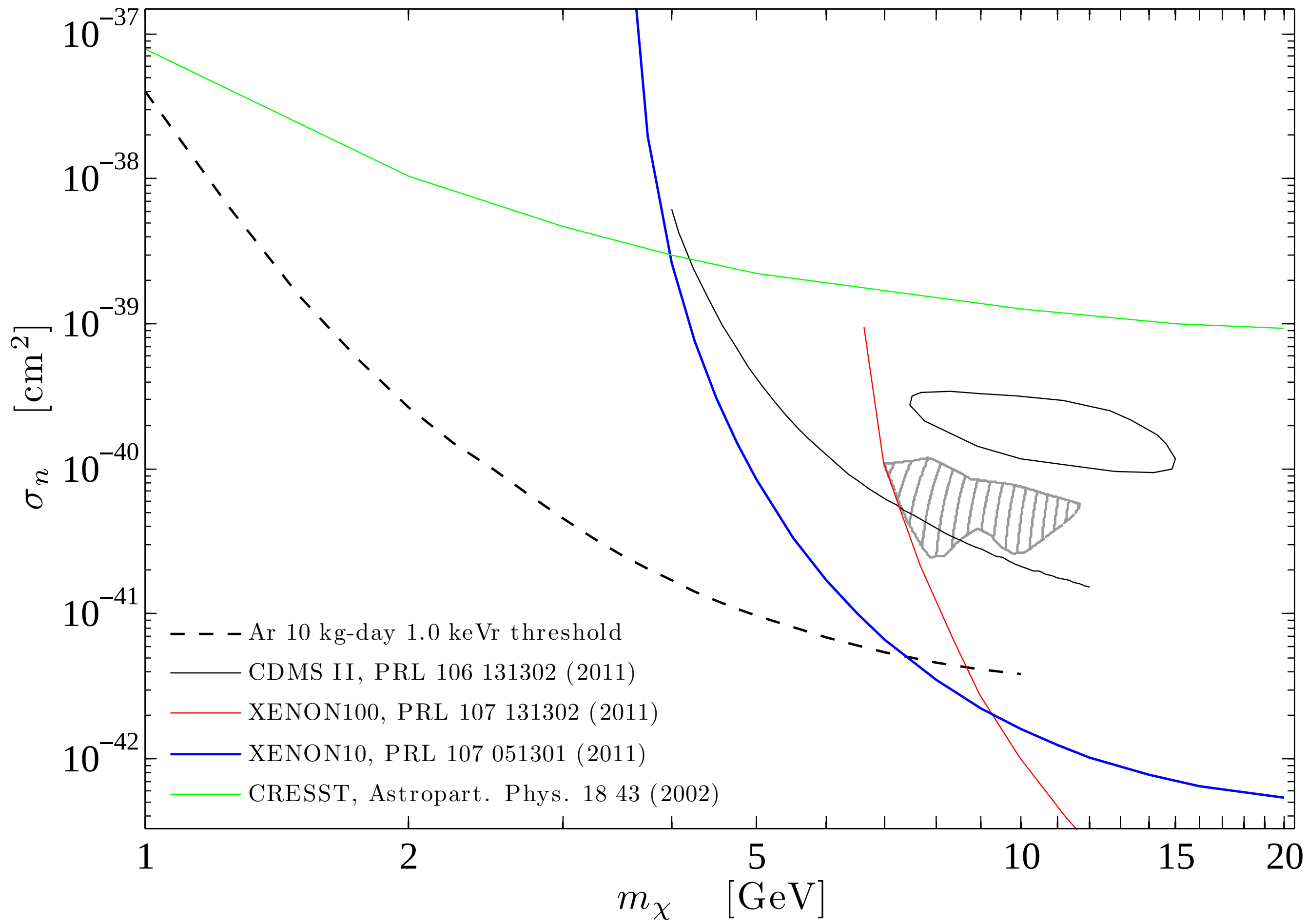
- for nuclear recoils, my $ is on Lindhard
  - don't know N_{ex}/N_i in argon, hence don't know e/γ fractions -- coin toss is a good guess
  - expect ultimate sensitivity of liquid noble gas TPC to reach about 300 eV (150 eV floor)
  - unless $N_{ex}/N_i << 1$ for nuclear recoils in argon (unlikely)
- probably good enough for catching some coherent reactor ν
- pretty clearly not the way to study beyond SM physics



- coda. for electron recoils, see data from Sangiorgio's talk.
  - same model applies **at low energy**, just remove Lindhard quenching
  - fit only ξ, assuming $N_{ex}/N_i = 0.2$ (from Doke et al 2002)
  - note that N_{ex}/N_i sets the scale of the electron fraction F_e , which is different for ER and NR (this has been a source of much confusion)

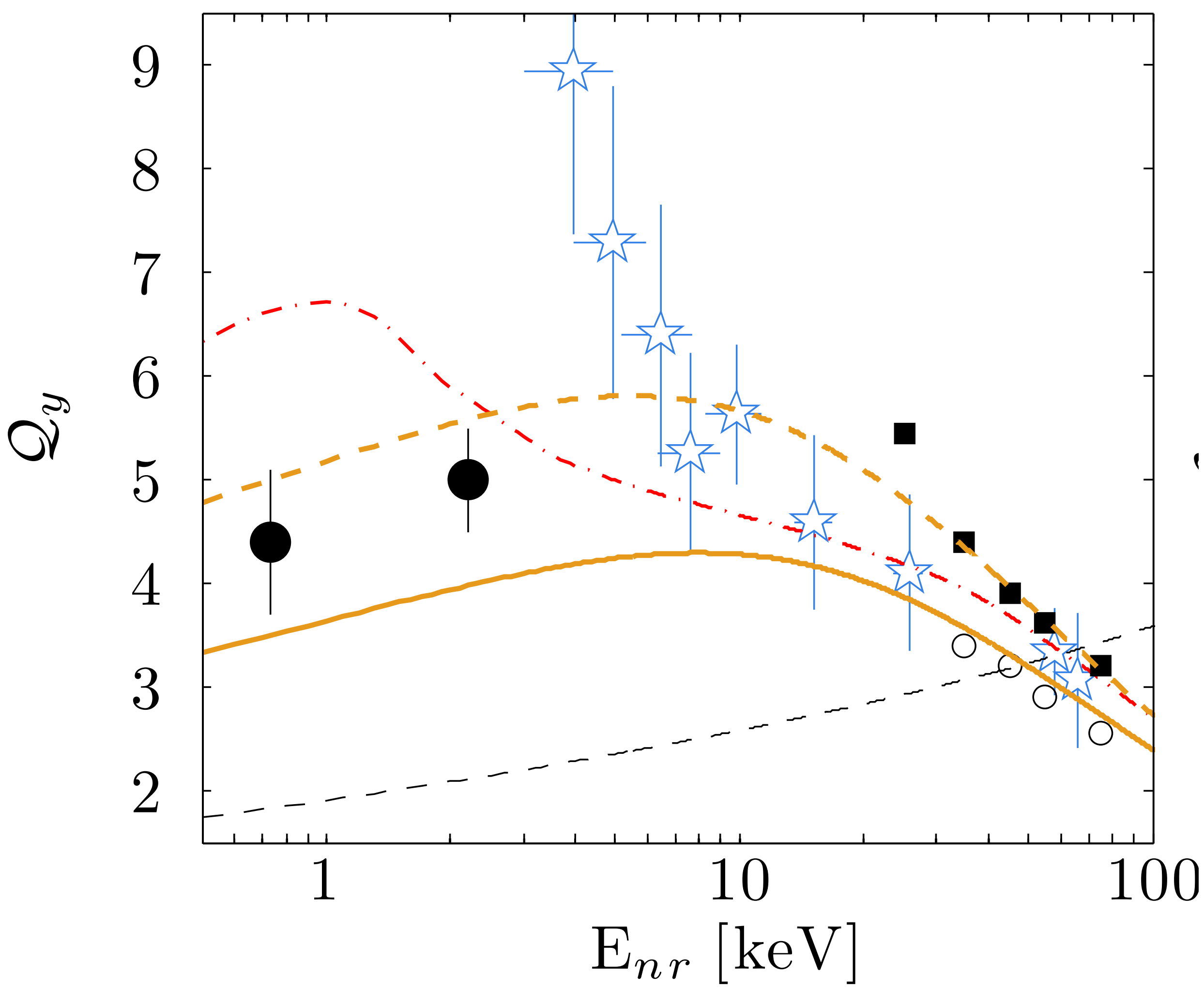


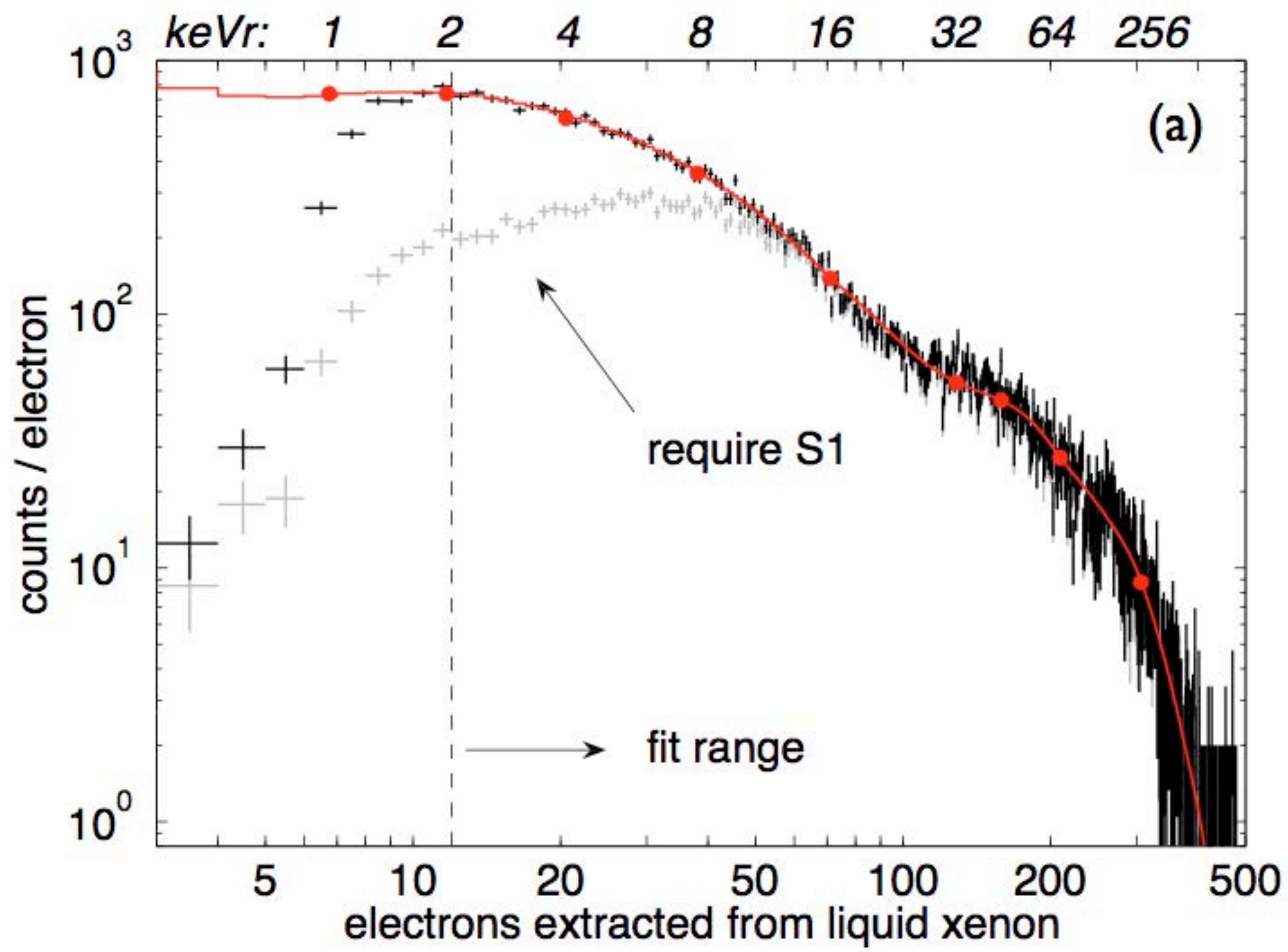
Prediction: look for a Darkside S2-only analysis



... and if they can do that, we should be able to catch some coherent ν !

Thanks!
(END)


$\mathcal{Q}_y$
9
8
7
6
5
4
3
2
1
10
100
E_{nr} [keV]


keVr: 1 2 4 8 16 32 64 256
10^3
10^2
10^1
10^0
counts / electron
(a)
require S1
fit range
5 10 20 50 100 200 500
electrons extracted from liquid xenon

Origin of scintillation and ionization in liquid noble gases

(i) R^*:

$$R^* + R \rightarrow R_2^*,$$

$$R_2^* \rightarrow 2R + h\nu,$$

(ii) R^+:

$$R^+ + R \rightarrow R_2^+,$$

$$R_2^+ + e \rightarrow R^{**} + R,$$

$$R^{**} \rightarrow R^* + \text{heat},$$

$$R^* + R \rightarrow R_2^*,$$

$$R_2^* \rightarrow 2R + h\nu.$$

Doke et al., Nucl. Instr. Meth. A 291 617 (1990)