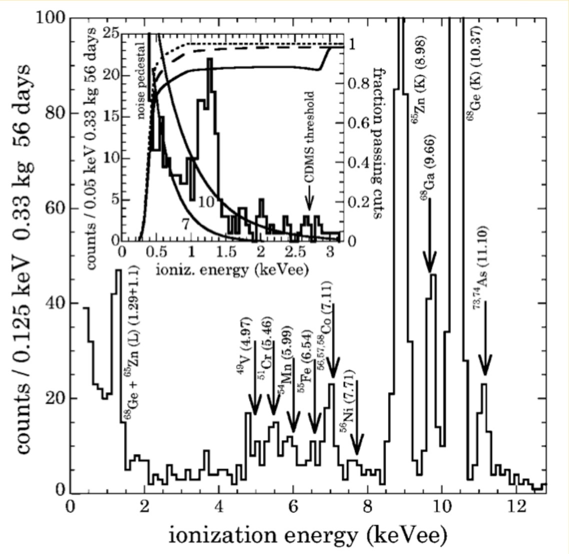
Preamble: two questions a DM direct detection experiment would like to answer:

(1) what type of particle just hit the detector?
(e.g. alpha, beta, ... neutron)

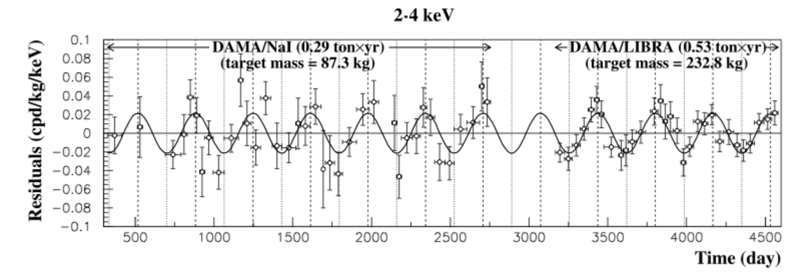
(2) what energy did it leave in the detector?

don’t know (1)

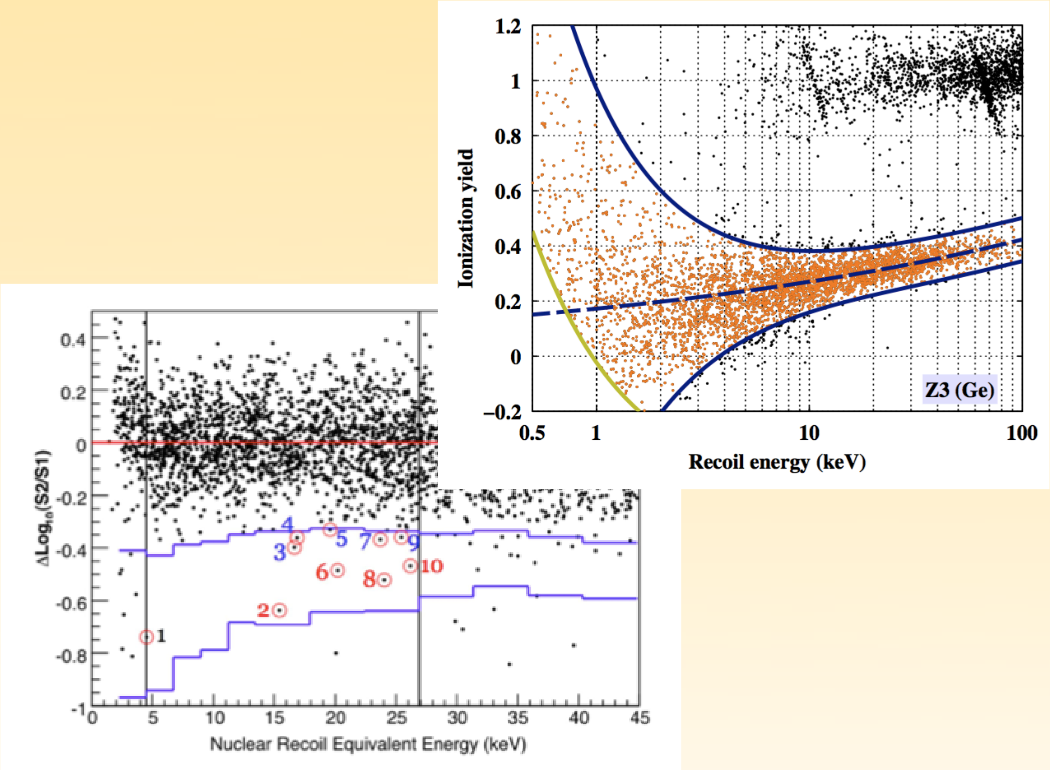
do know (1)



CoGeNT, Phys. Rev. Lett. 106 131301 (2011)



DAMA, Eur. Phys. J. C 56 333 (2008)

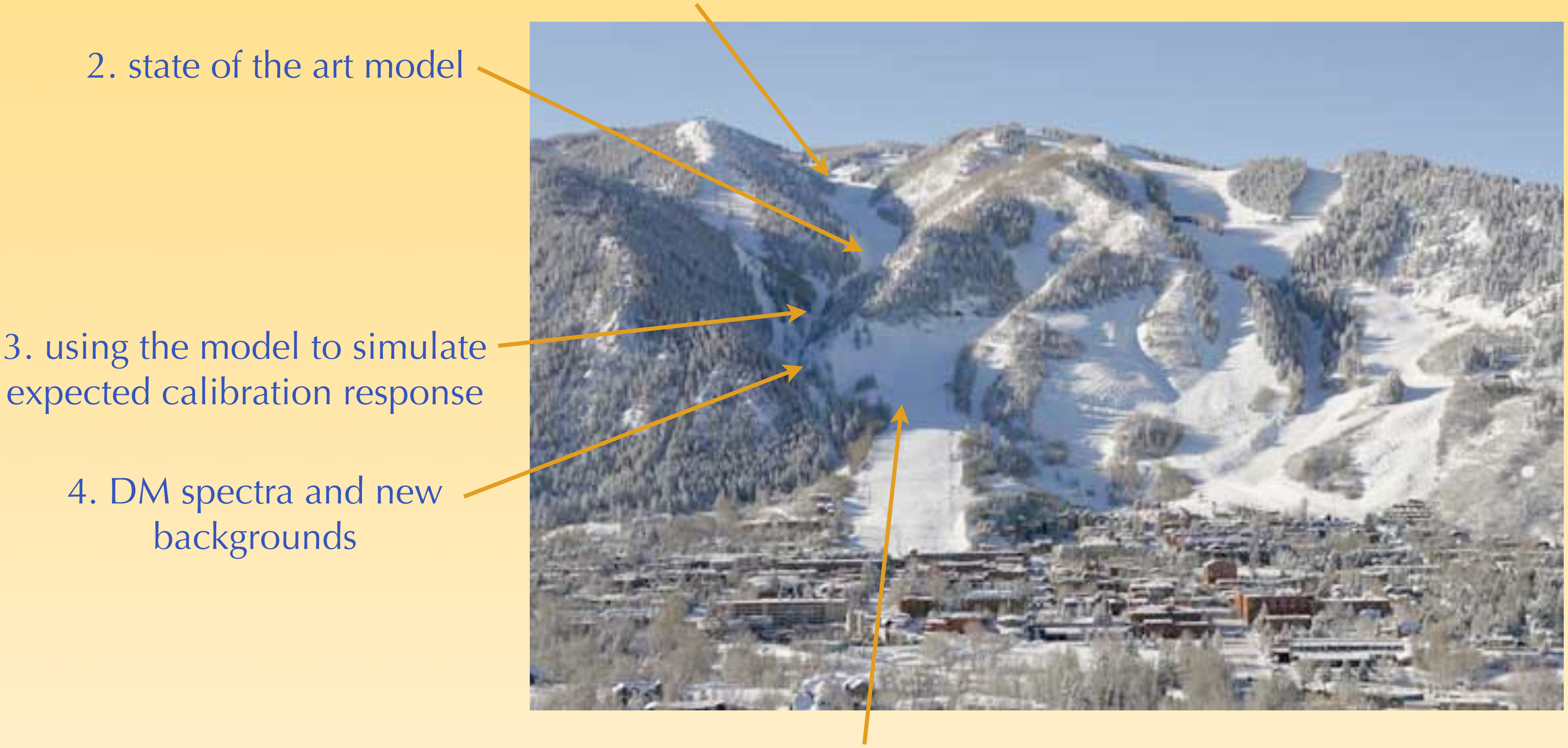


CDMS, Phys Rev D **82** 122004 (2010)

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

Focus of this talk

(2) what energy did it leave in the detector?



1. neutral particle energy reconstruction in liquid xenon

2. state of the art model

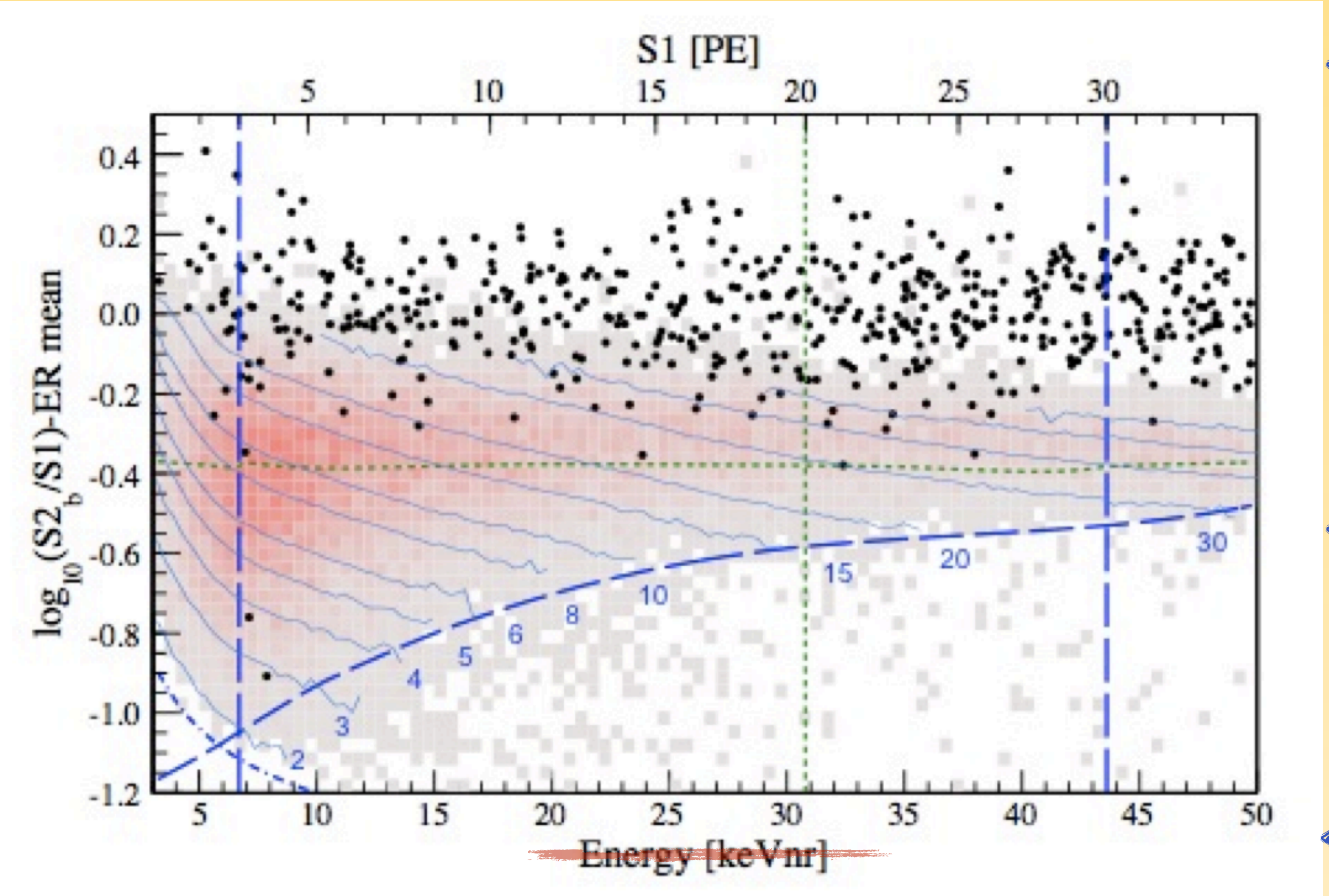
3. using the model to simulate expected calibration response

4. DM spectra and new backgrounds

5. learning from LUX

general motivation:
discrimination is not perfect, and backgrounds are not irreducible... so it is prudent to model what expected DM signal will actually look like in your detector (its NOT the same as the calibration data).

A closer look at liquid xenon nuclear recoil energy reconstruction



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

measured quantity

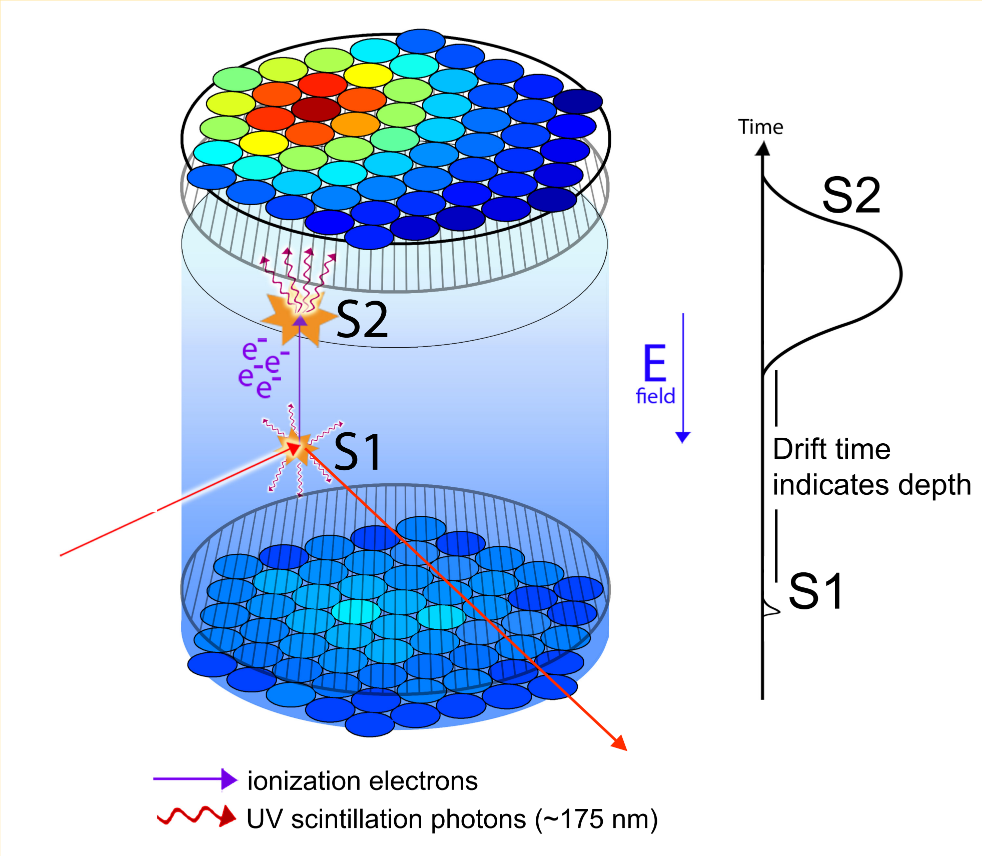
correctly derived quantity

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

both derived quantities assume the same Leff curve!

Back to basics: measured quantities in liquid xenon are photons and electrons

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



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

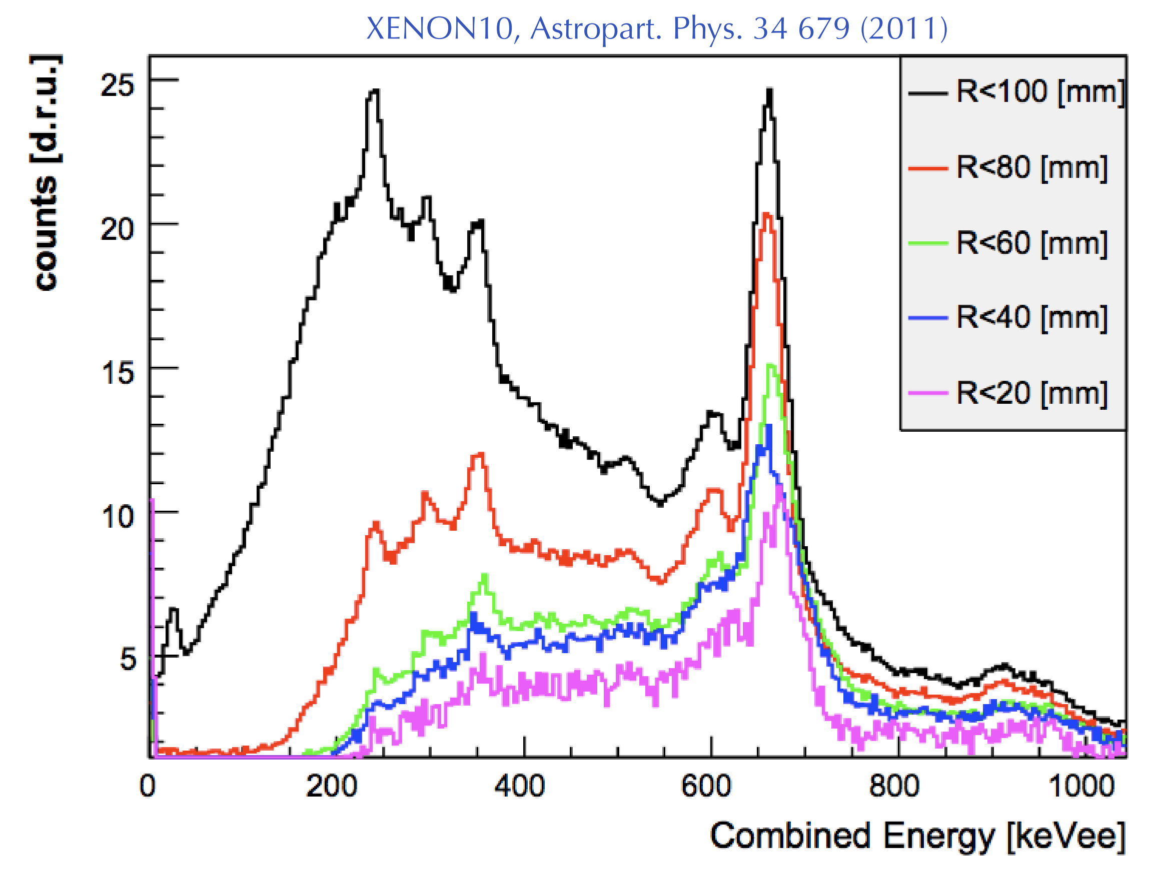
n_γ and n_e
are what you really want to know

Electronic signal from nuclear recoils is quenched: Lindhard theory

Electromagnetic interactions

$$E_{\mathrm{er}} = \epsilon(n_\gamma + n_e)$$

well-known that combined energy gives the best resolution



XENON10, Astropart. Phys. 34 679 (2011)

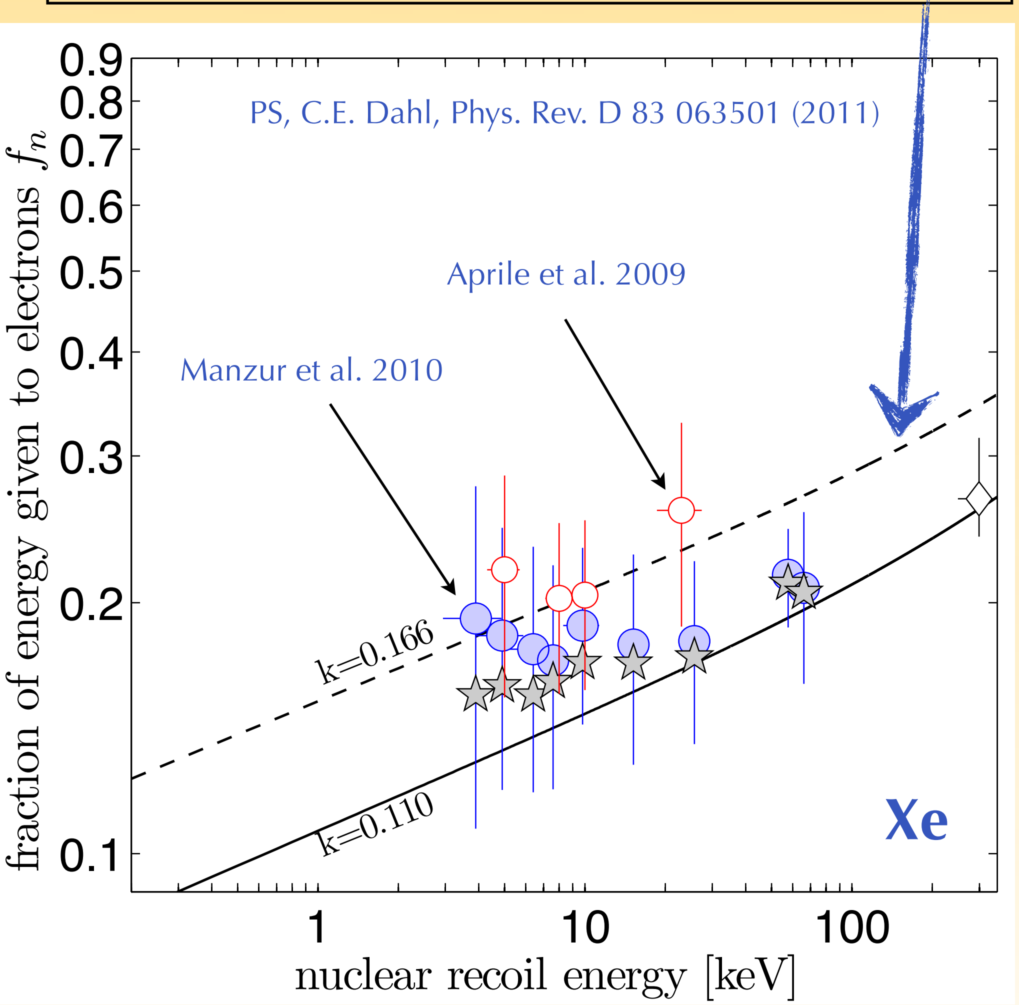
Neutral particle interactions

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

ϵ = 13.8 eV, the average energy to create a single quanta (e or γ)

f_n = energy dependent Lindhard prediction for signal quenching

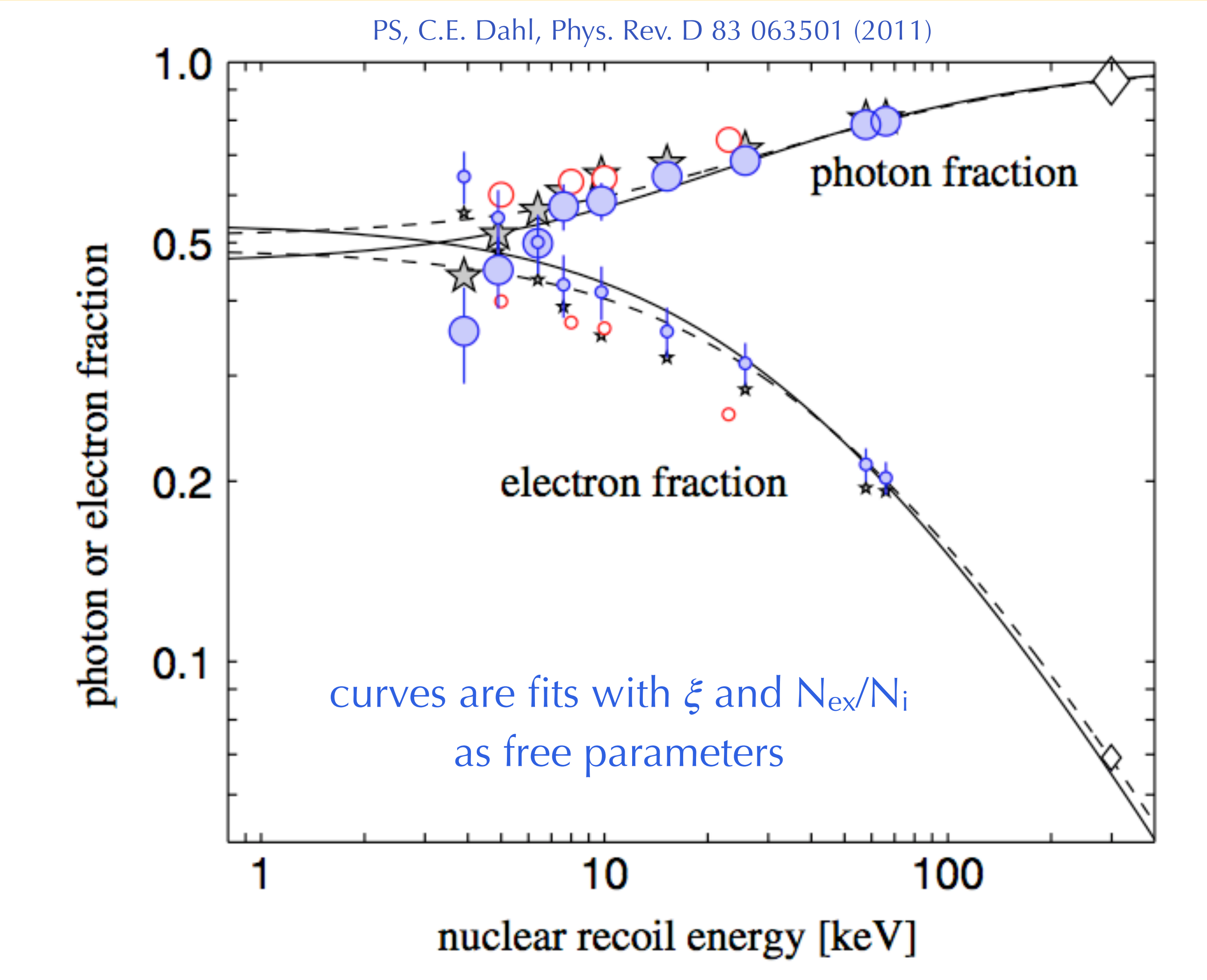
Lindhard prediction for ***f_n***
(parameterized by the electronic stopping power k)



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

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

this has caused a lot of confusion concerning measured versus expected liquid xenon scintillation response
(L_{eff}, the “effective” Lindhard factor)



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, f_n
(2) Thomas-Imel model gives partioning

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:

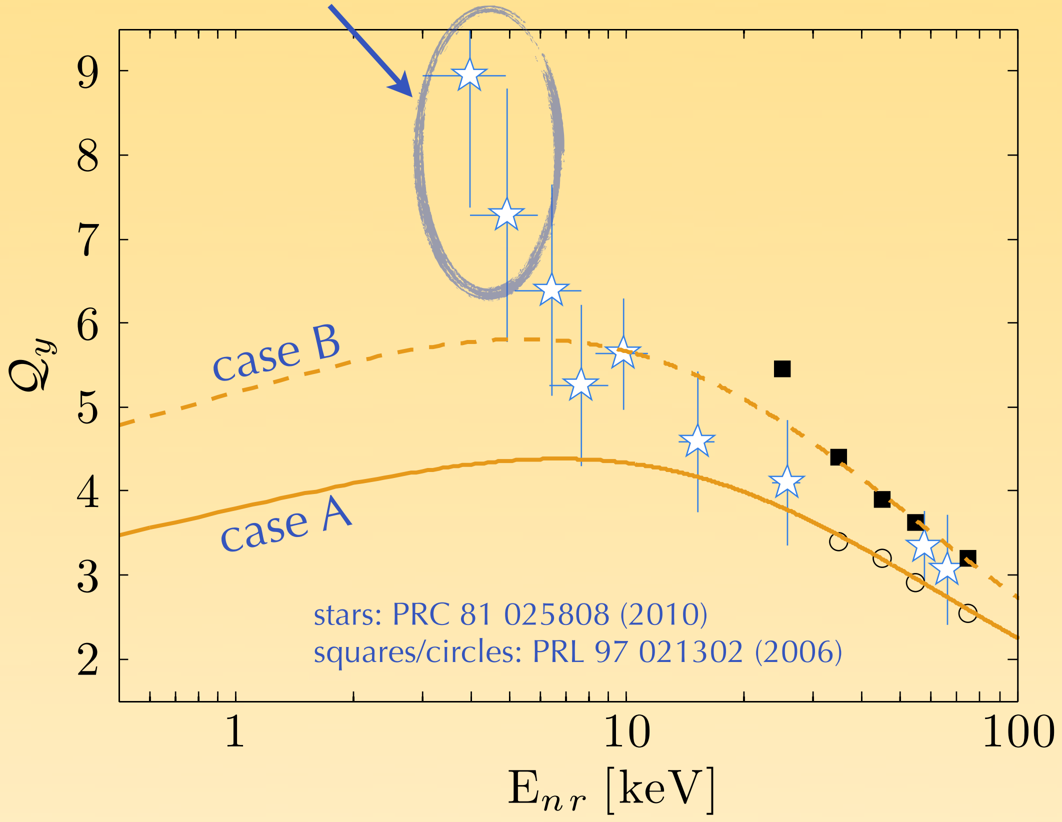
$$\mathcal{L}_{eff} = \frac{(1-\mathcal{F}_e)f_n}{\epsilon}\boxed{\frac{\alpha_1 S_e}{L_y S_n}}$$

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

reminder:
1. origin of ionization: Xe+
2. origin of scintillation: Xe* and Xe+

Model compared with neutron scattering data

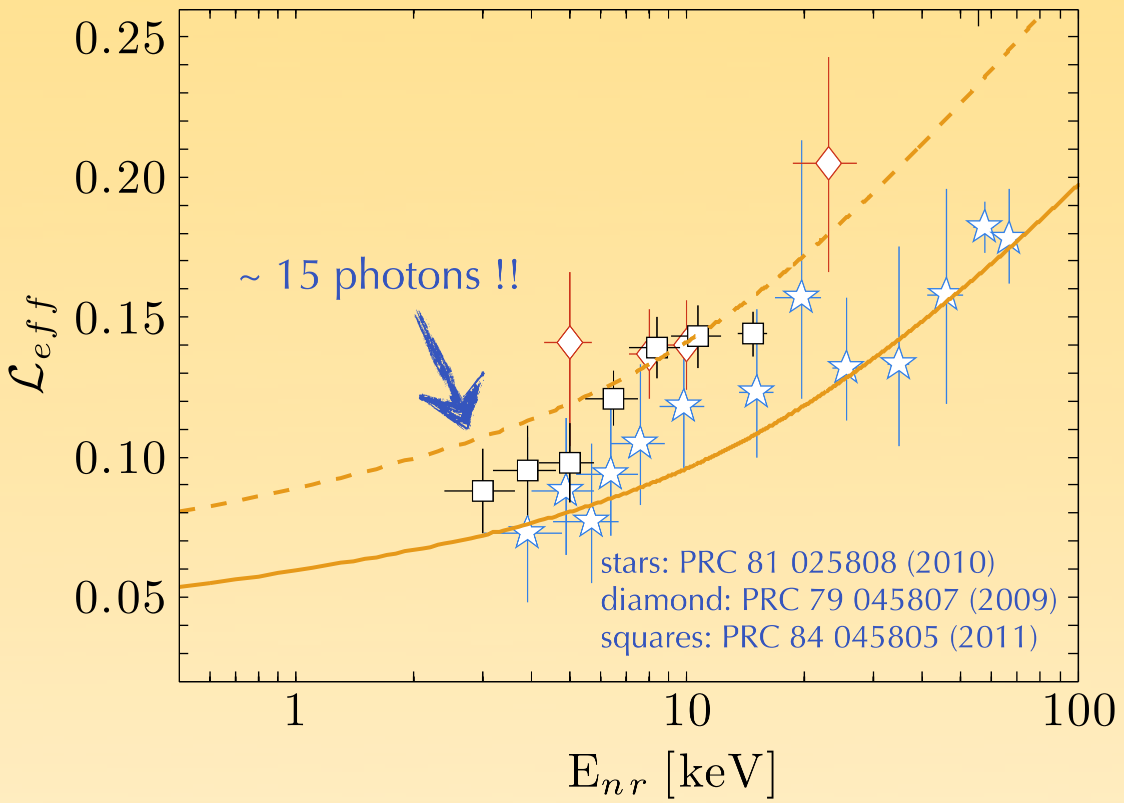
electrons / keV



suspect threshold bias
cf. JCAP 09 (2010) 033

stars: PRC 81 025808 (2010)
squares/circles: PRL 97 021302 (2006)

photons / keV * 0.015



~ 15 photons !!

stars: PRC 81 025808 (2010)
diamond: PRC 79 045807 (2009)
squares: PRC 84 045805 (2011)

curves: model prediction

case A:

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

case B:

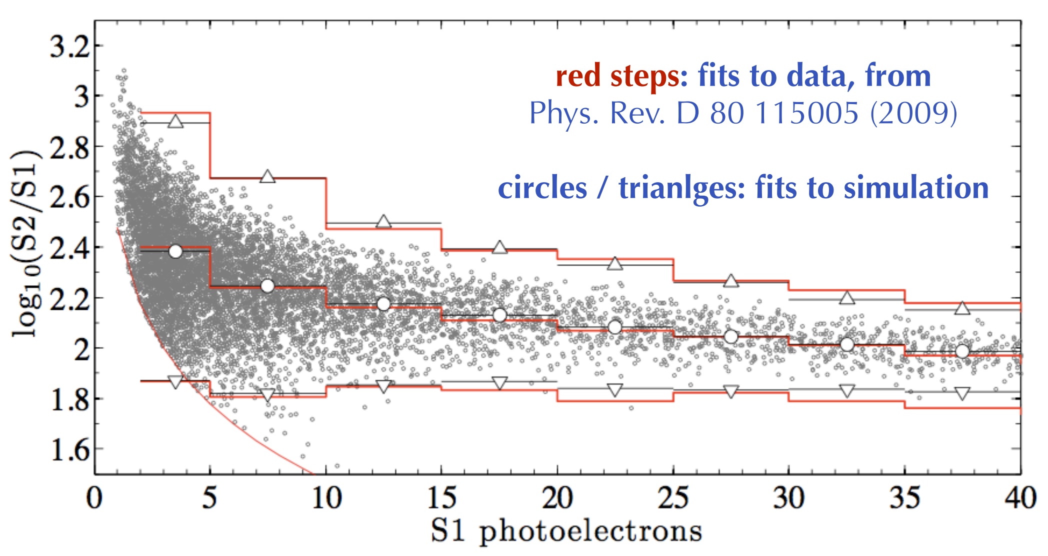
- k = 0.166
- $4\xi/N_i = 0.032$
- $N_{ex}/N_i = 1.09$

Model compared with broad spectrum neutron data

(showing XENON10, agreement is very similar for XENON100)

- Band simulation using model case A
- NR band width dominated by
    1. Poisson fluctuations in n_e and n_γ
    2. Photomultiplier resolution

simulation

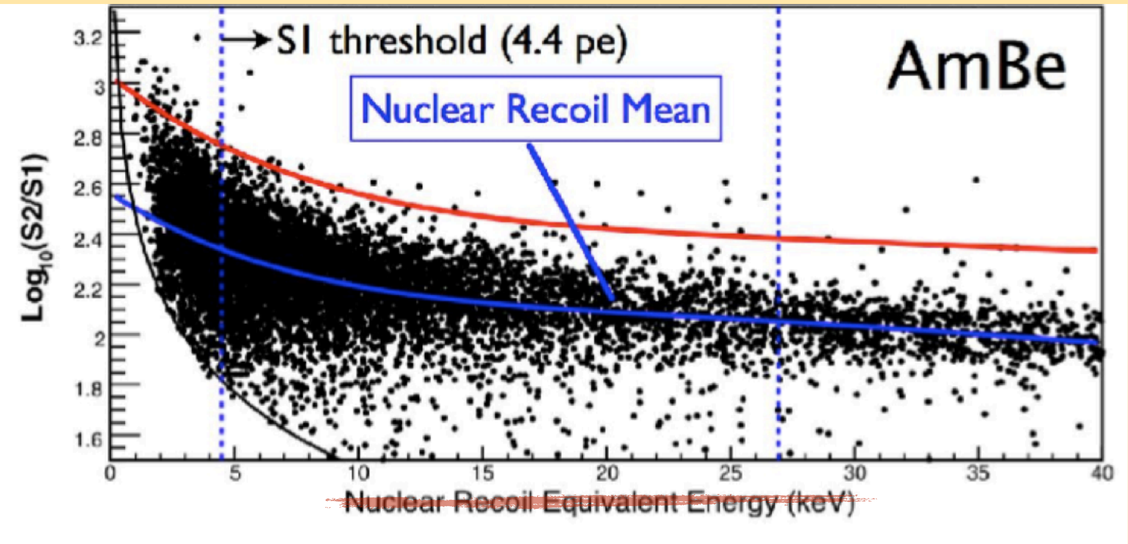


red steps: fits to data, from Phys. Rev. D 80 115005 (2009)

circles / trianlges: fits to simulation

data

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

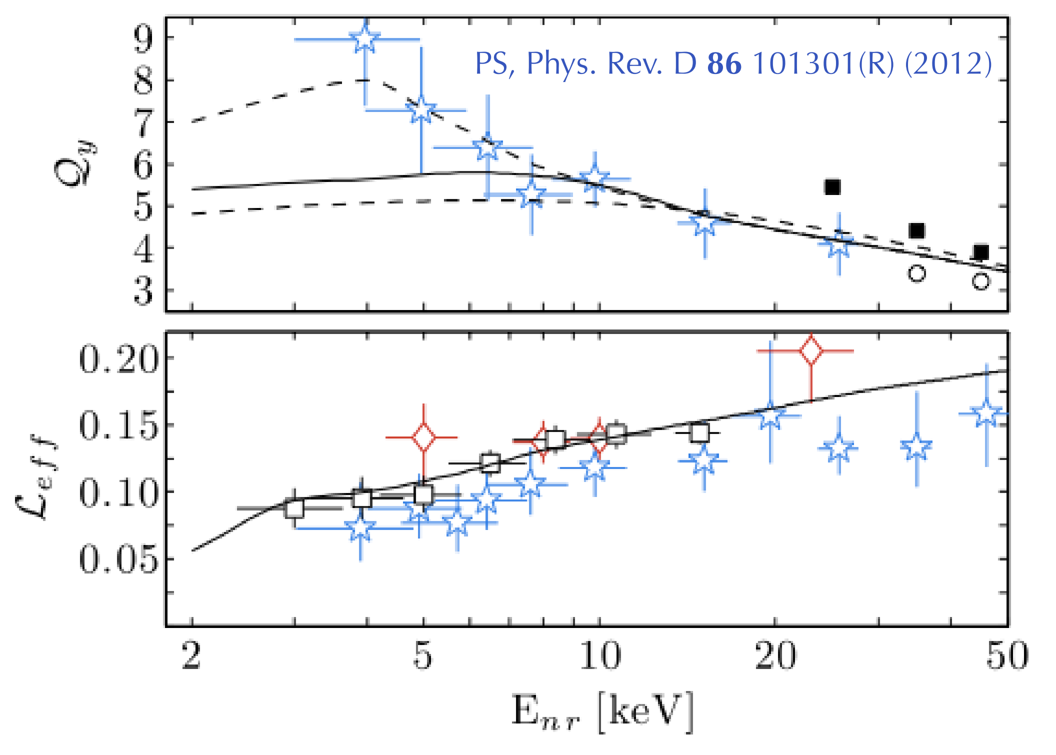


S1 photoelectrons

It is possible to derive similar curves even without this model

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

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

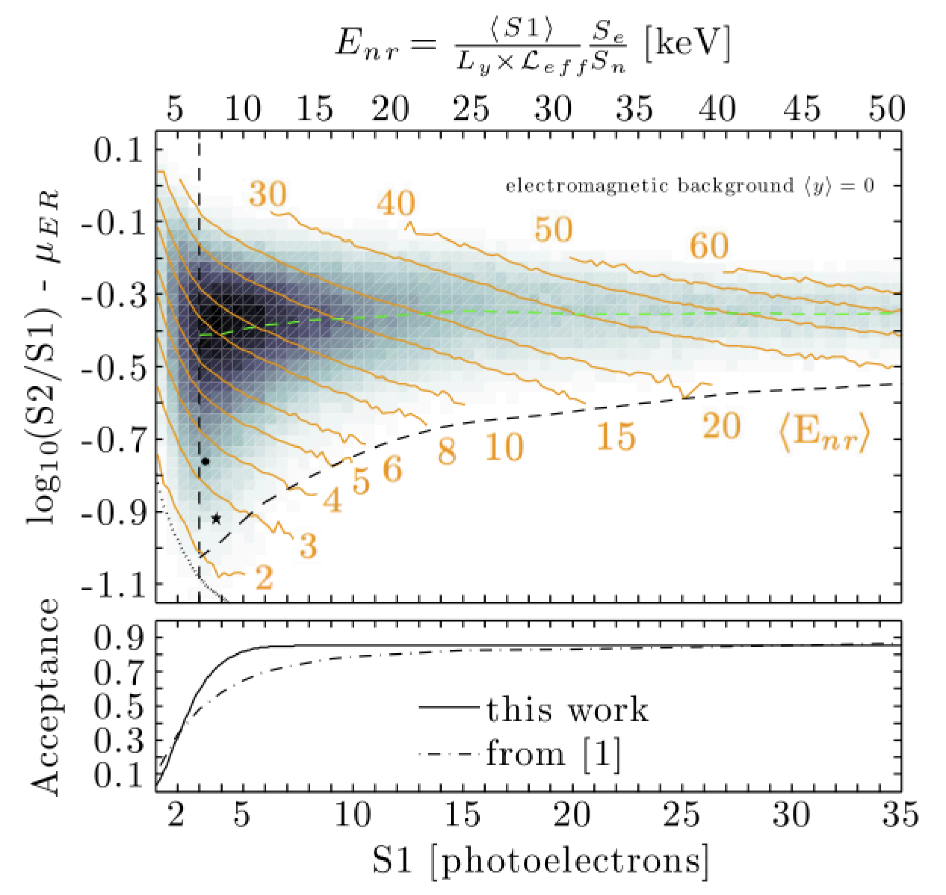


PS, Phys. Rev. D **86** 101301(R) (2012)

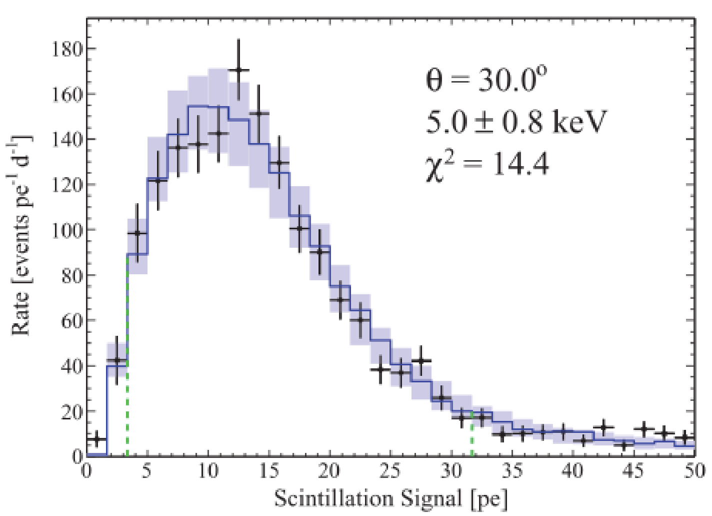
If one is given Leff and the distribution y = log10(S2/S1)...

since Leff ∝ S1 and Qy ∝ S2,
Qy is uniquely specified

Useful for simulating response of hypothetical detectors:

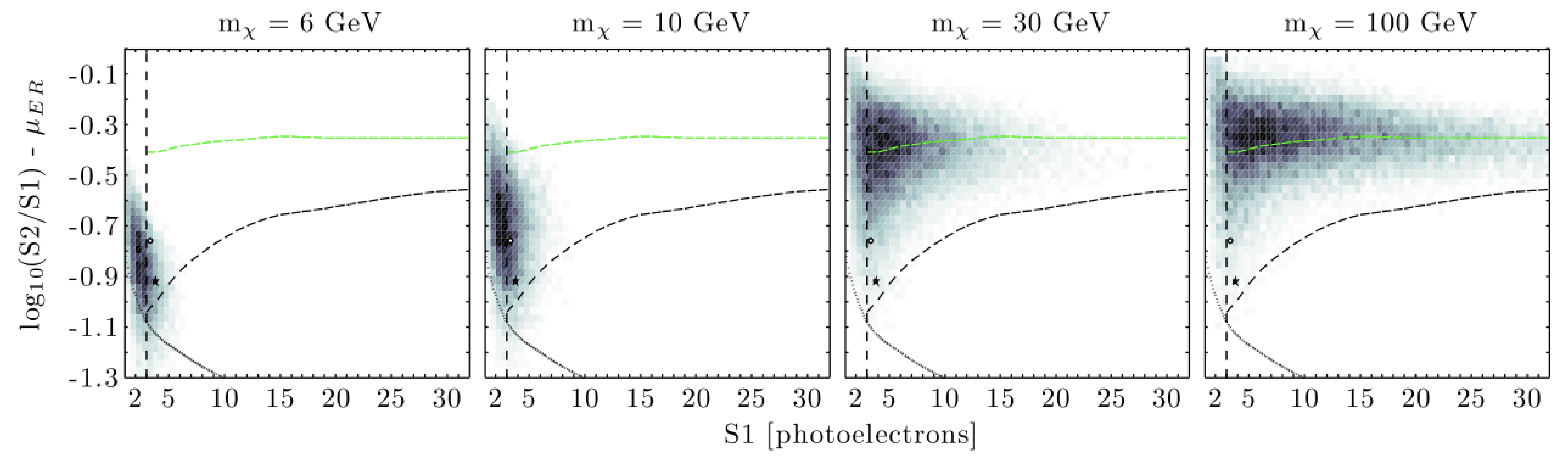


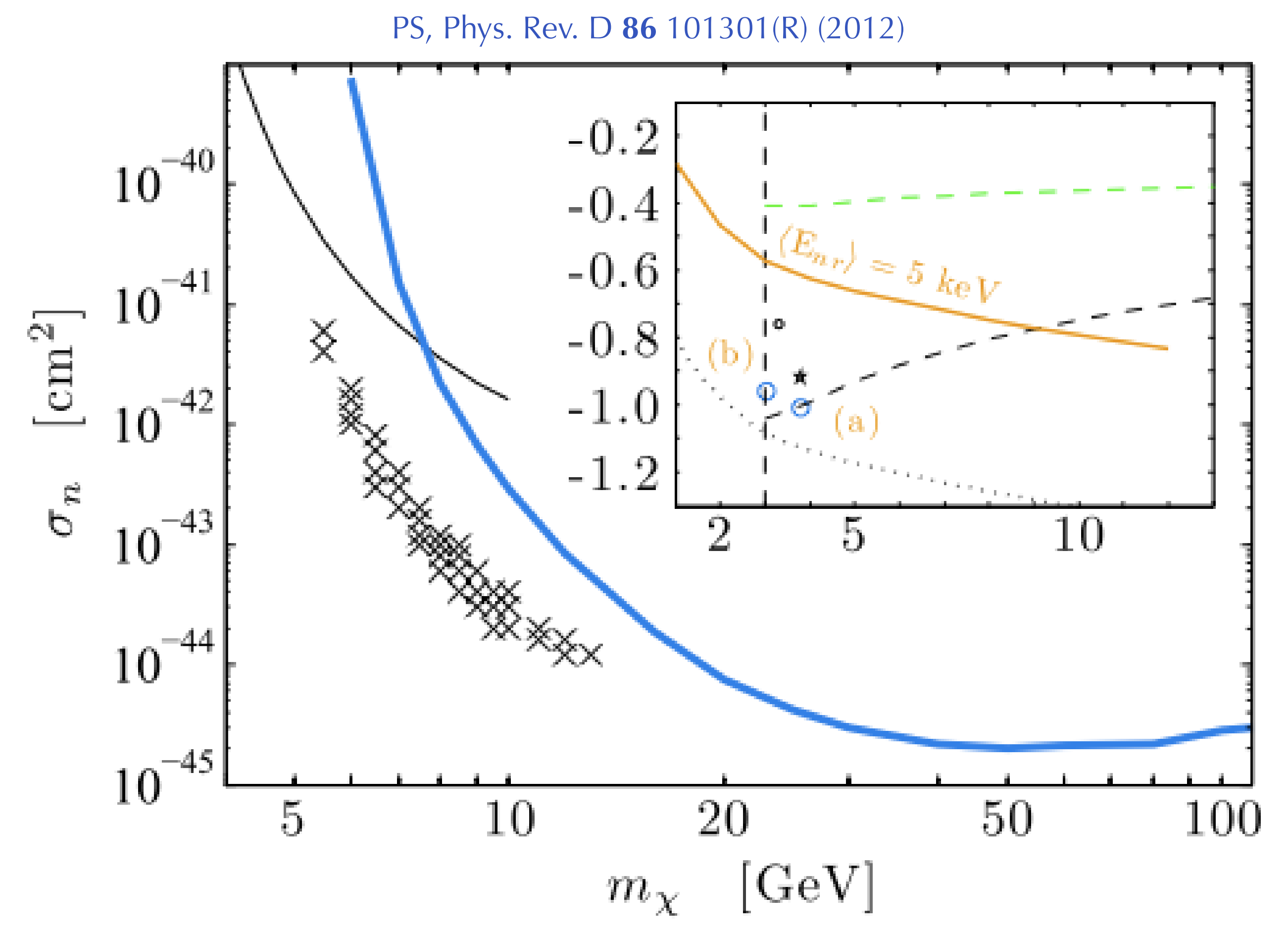
an even simpler way to
understand the <Enr> curves:



Plante et al., Phys. Rev. C 84 045805 (2011)

dark matter elastic scattering spectra in liquid xenon




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

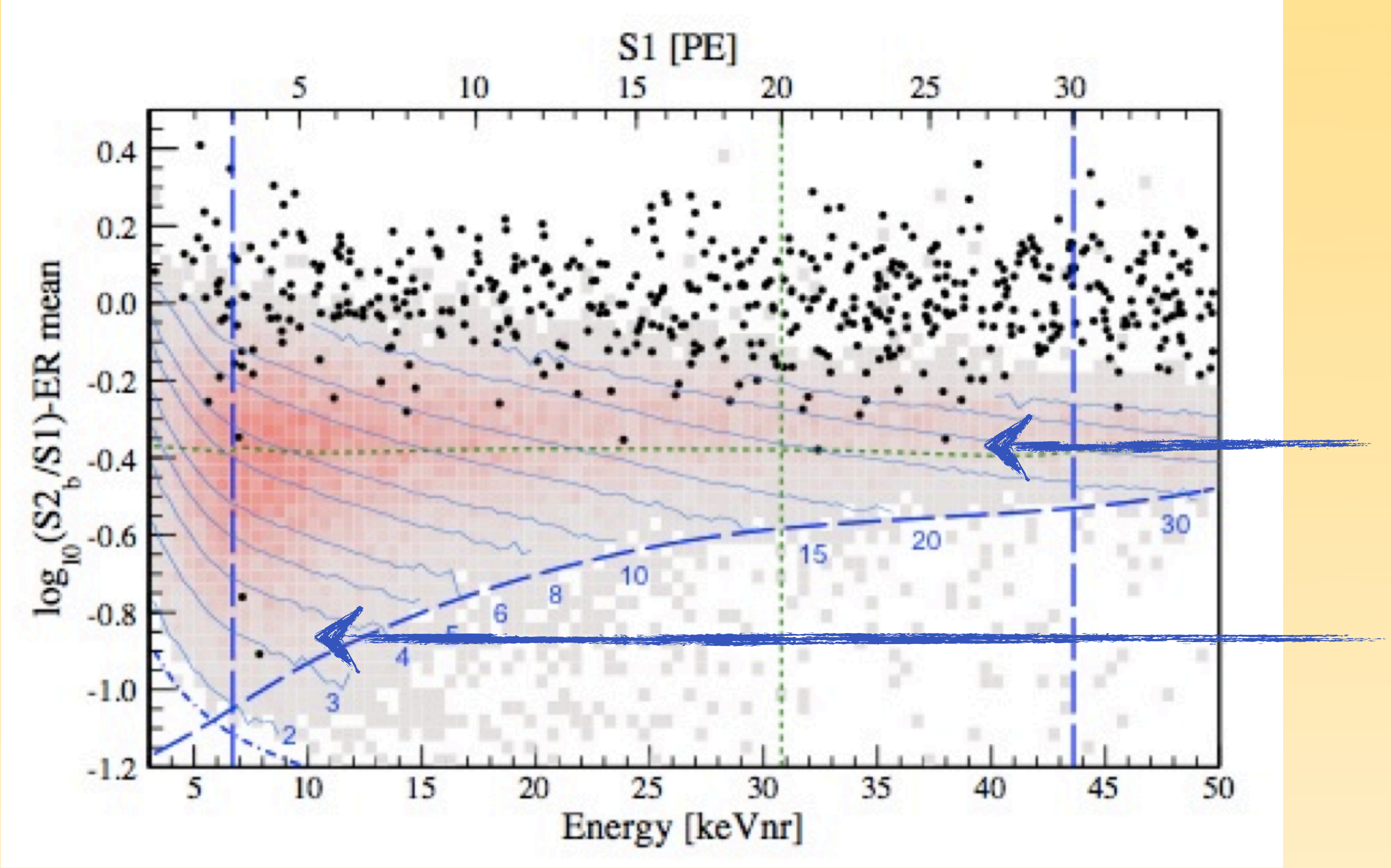
using model: case C

- Super! Another light dark matter anomaly...
- based on a consistent treatment of low-energy fluctuations
- light DM signal appears at -3σ from calibration centroid
- acceptance region is defined for calibration data; this is NOT the same as the acceptance for a given DM mass

- note CMB bounds imply m>7.6 GeV, Natarajan, Phys. Rev. D 85, 083517 (2012)

Different background concerns when searching for light dark matter!

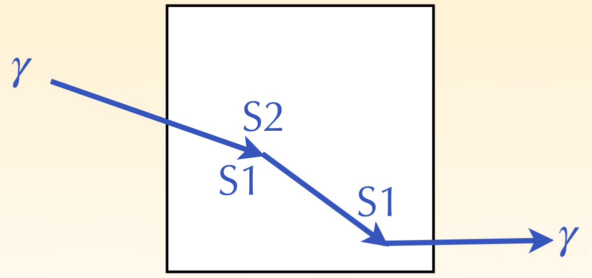
we just saw that the lowest energy events are **always** far from the ER band statistical leakage...
(lower left corner of acceptance box)
but it appears that other background mechanisms can populate this region.



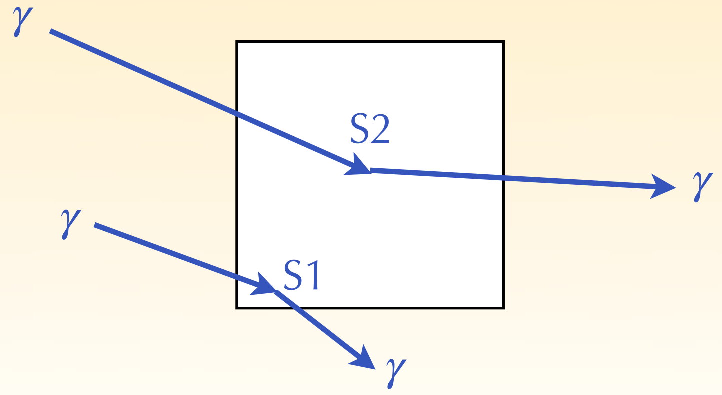
statistical leakage from ER band bkg;
solution is to lower NR acceptance

appears to be some bkg correlated with ER band bkg;
solution is to ____ ?

XENON100: its "gamma X"



Gaitskell: its random coincidence

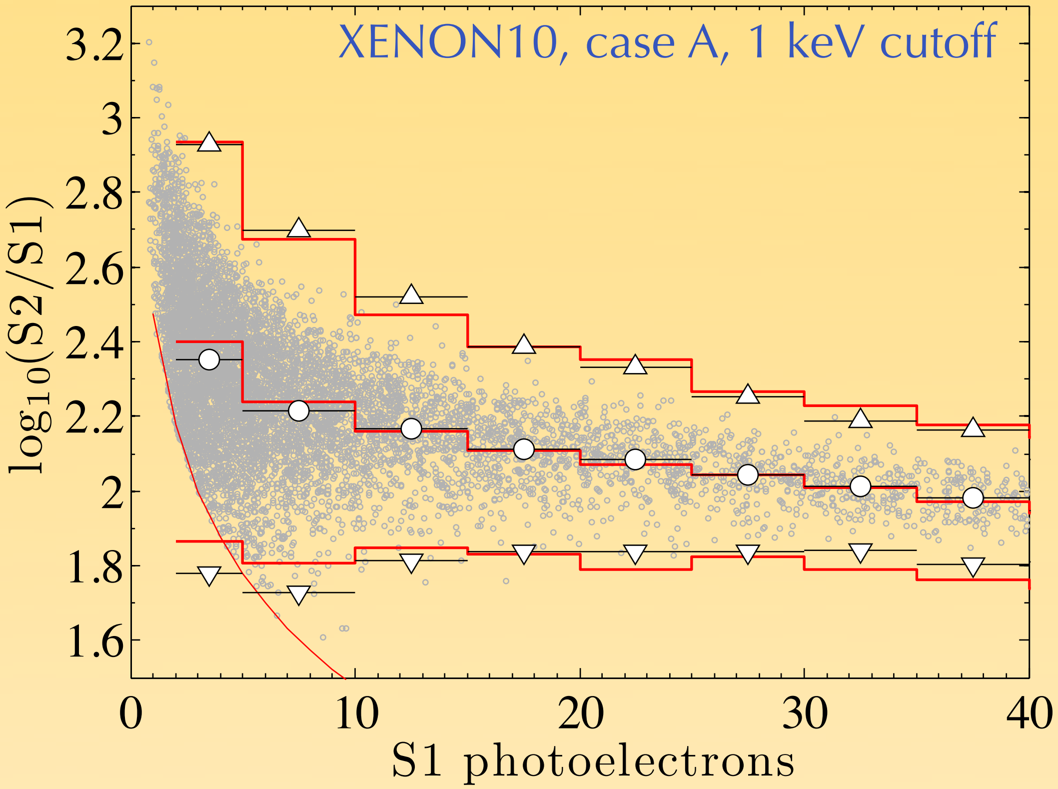


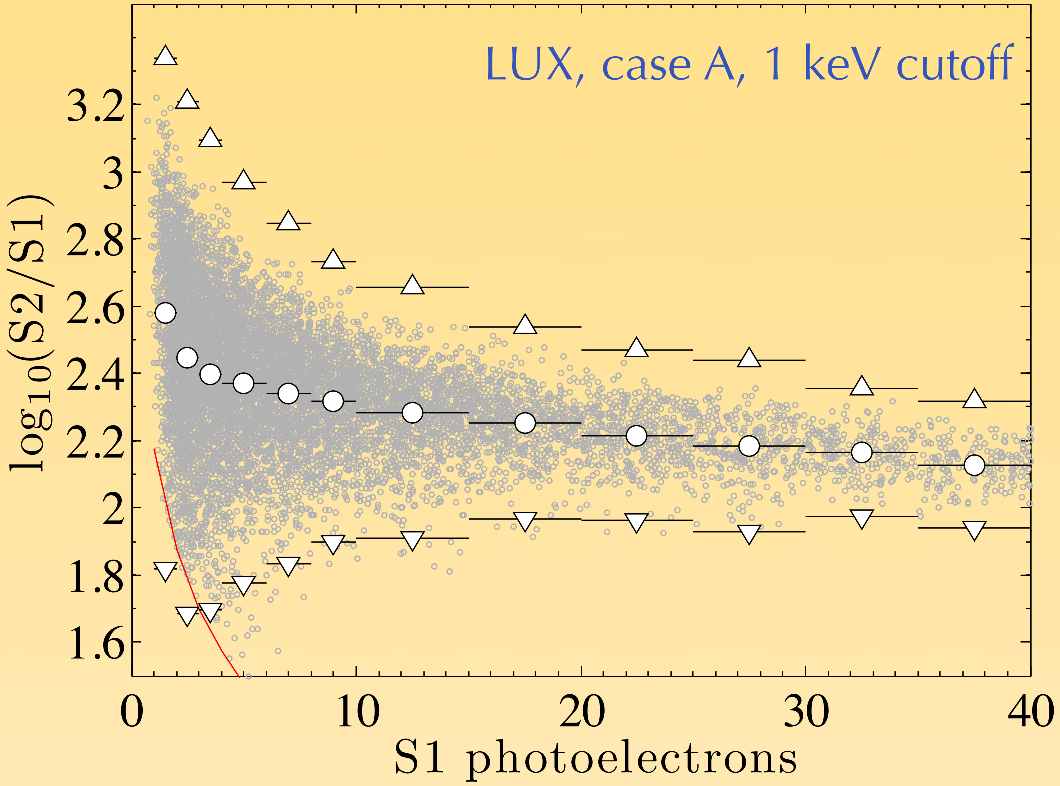
- gamma X should populate higher-energy region first, but that isn't what is observed

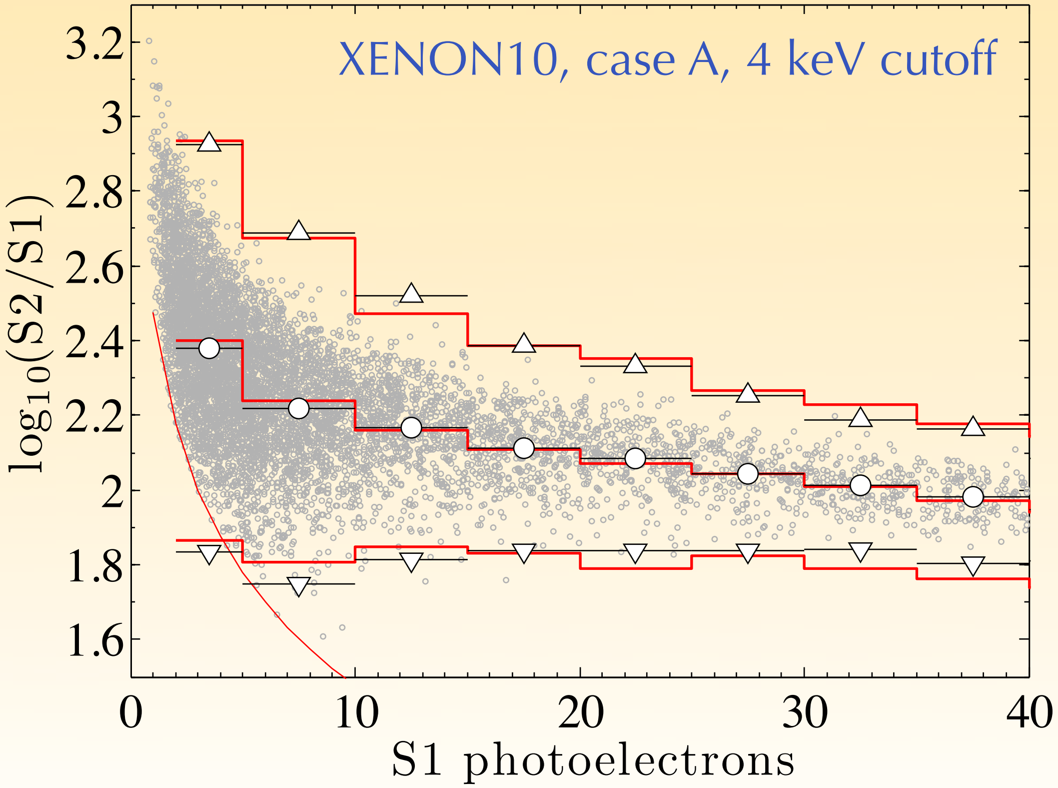
- in principle, random coincidence rate can be calculated, based on measured S1-only rate; minimizing that rate would mitigate the background for light dark matter search..

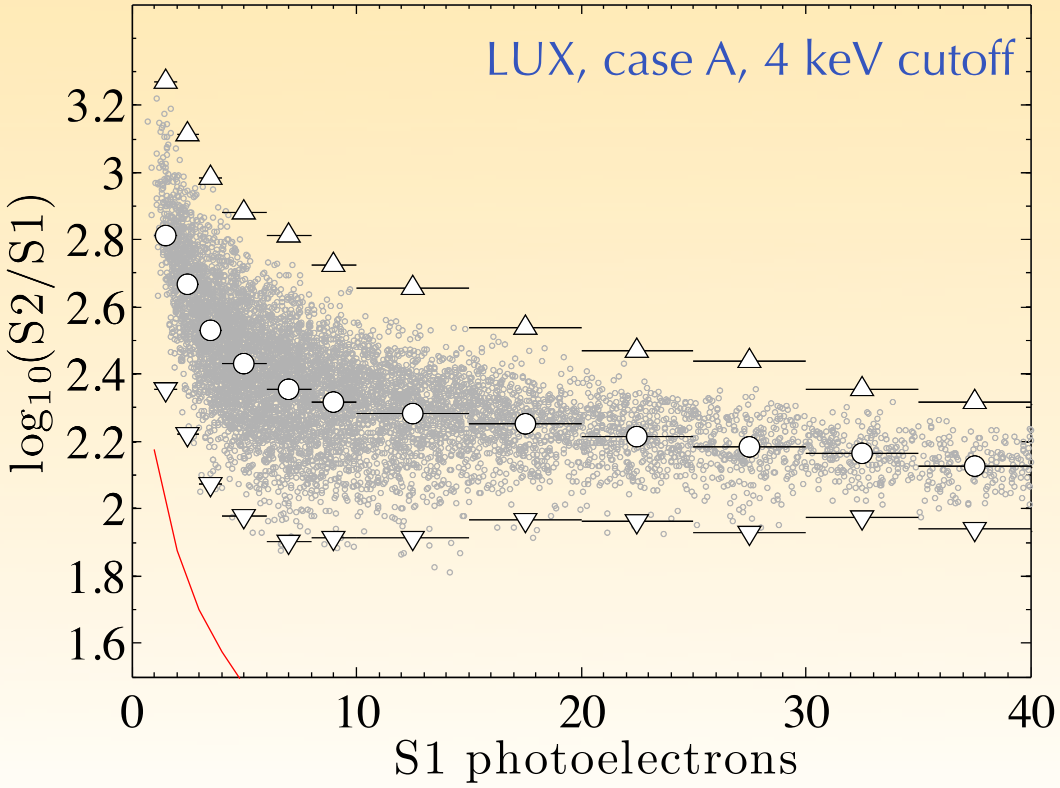
LUX will give us new information about <5 keV NR response of xenon

due to its unprecedented α_1 ~ 0.15





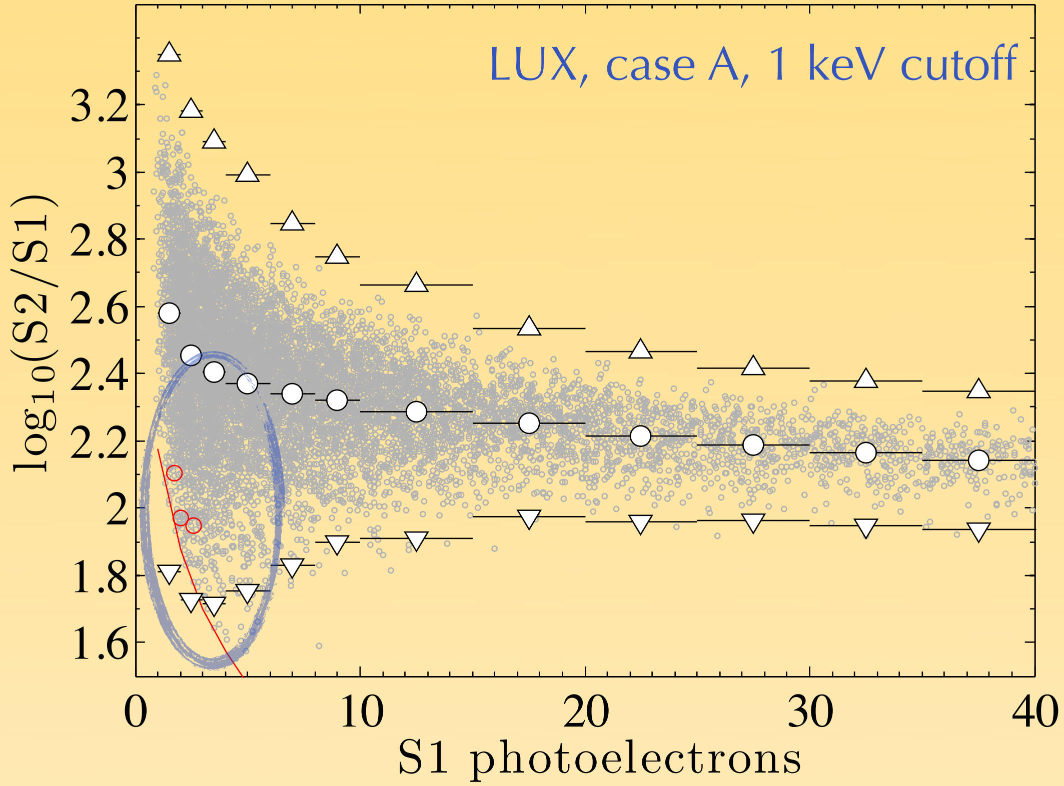


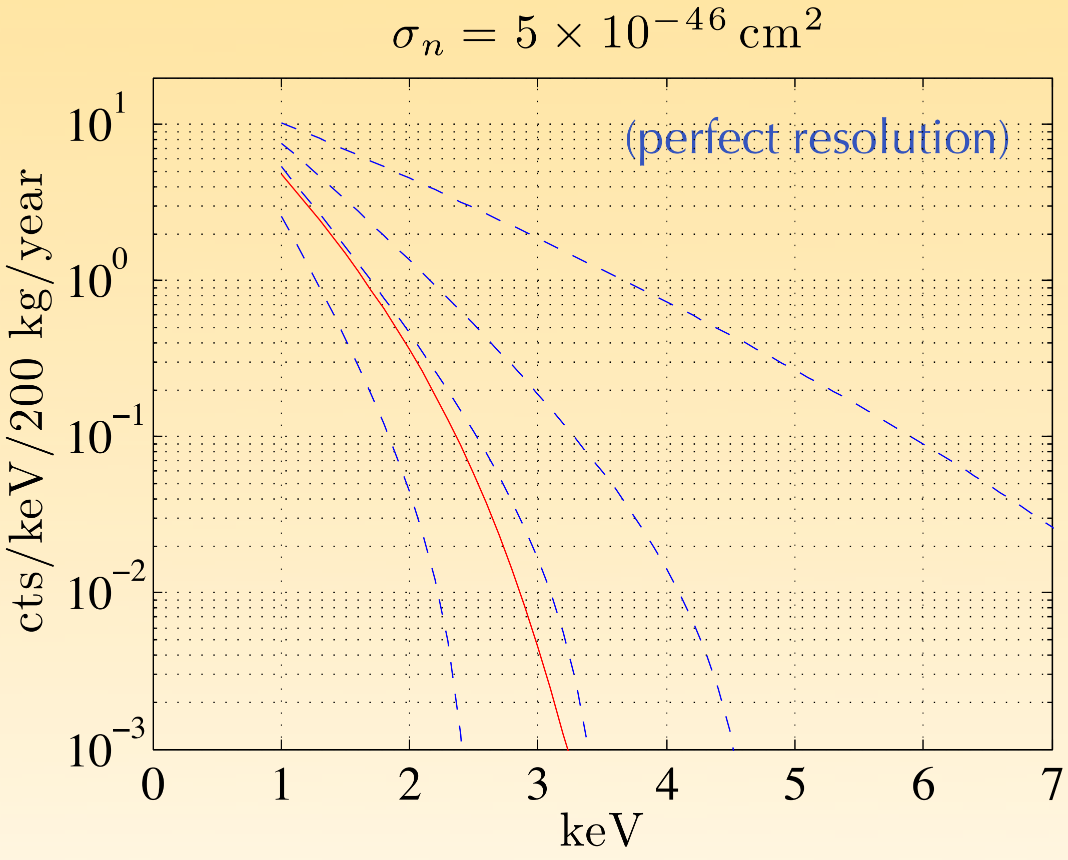


Light DM looks a lot like solar ^{8}B coherent neutrinos

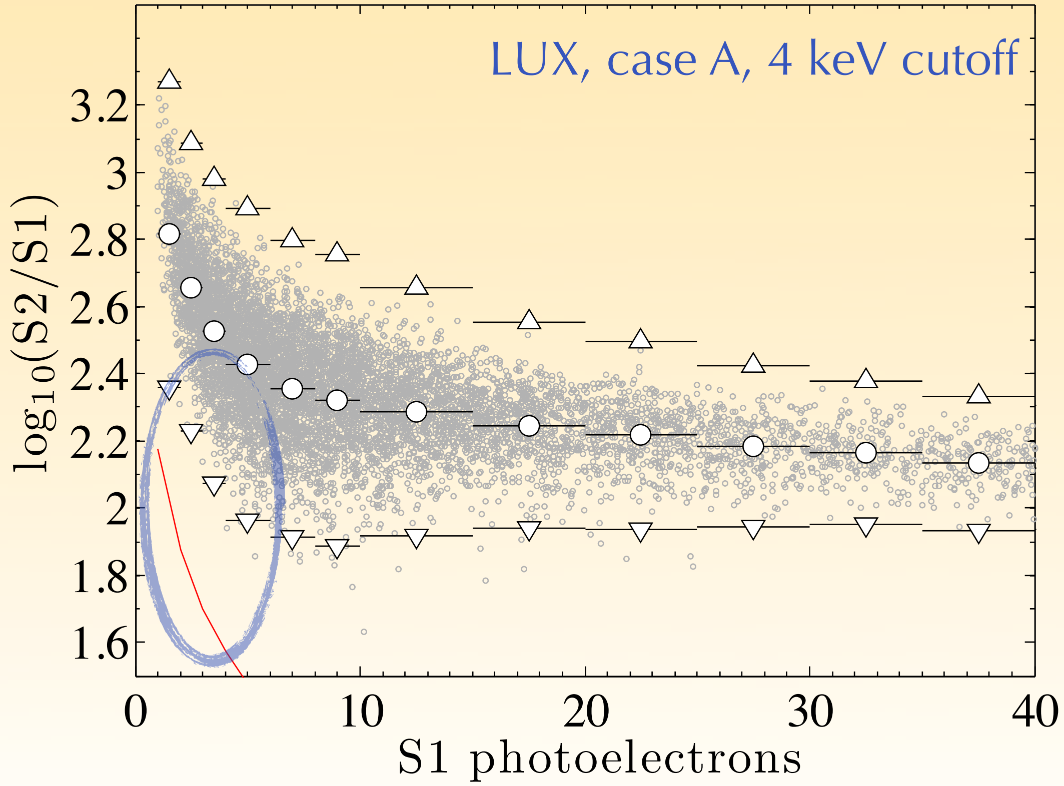
- prospect of observing ^{8}B coherent neutrinos in LUX may be quite high, due to the excellent α_1 ~ 0.15 in LUX
- compare: α_1 ~ 0.06 in XENON100
- depends on fundamental liquid xenon response (i.e. below what energy can NR no longer generate n_e and n_γ
- if there is a “kinematic cutoff” at e.g. 4 keV, we’ll know from the band shape (bottom right)
- wednesday, talk by Tali on neutrino backgrounds

(just a guess: LUX response using model case C)





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



Some summary points

- clear need for consensus on low-energy electron and photon yields from NR in liquid xenon (dedicated experiments)
- despite lingering systematic uncertainty, the expected DM signal morphology in liquid xenon detectors is well understood
- light DM signal appears far from the vanilla "expected" signal region.. looks more or less like the XENON100 events
- this region is far from statistical leakage of EM background, but must now contend with "new" (EM) background pathology
- if DM is O(10 GeV), hopefully it has $\sigma > 10^{-45}$ cm^2 (or else we may have a ^{8}B problem)