Direct detection of dark matter with liquid xenon TPC detectors

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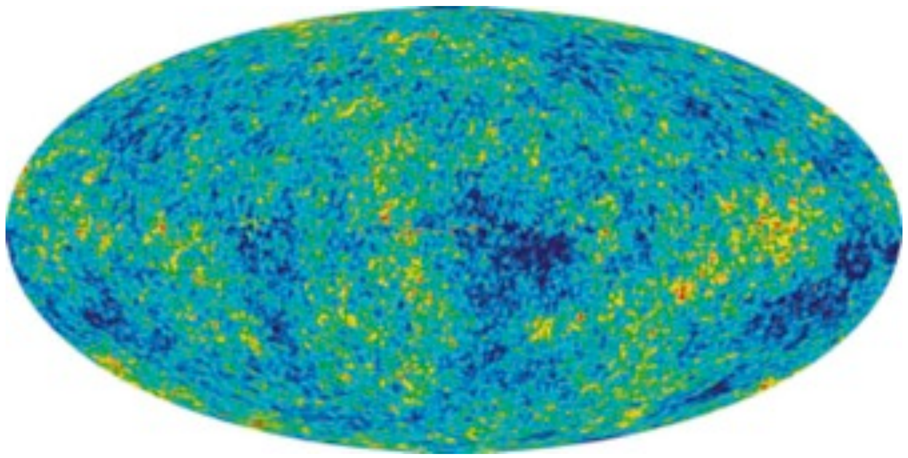
KITP Workshop:
Direct, Indirect and Collider Signals of Dark Matter
Santa Barbara, CA

~~0 preliminaries~~
I refresher on XENON10 response to charged/neutral particle interactions
II a second look at XENON10 data
III inelastic interactions / new exclusion limits / O(GeV) light DM
V expectations for LUX

Dark matters and Λ-CDM



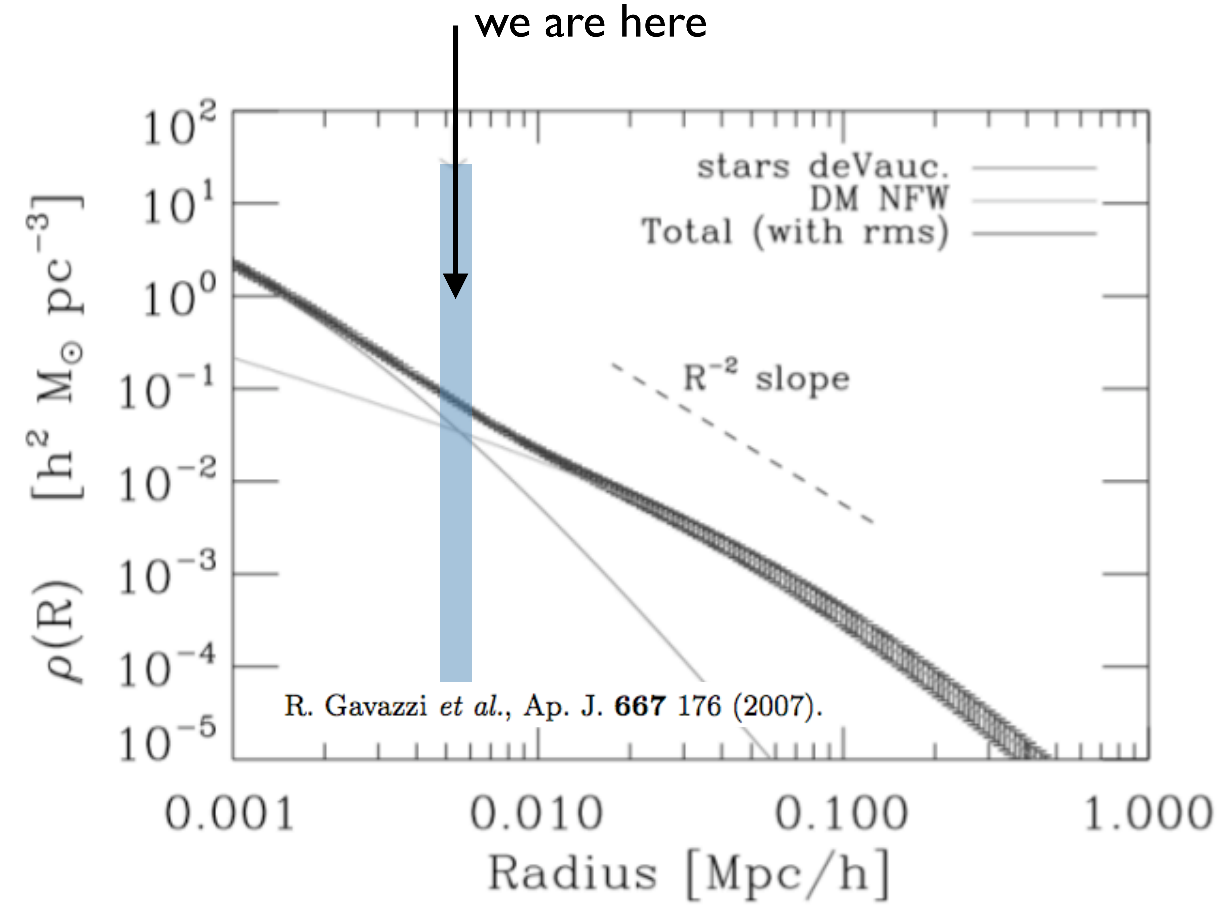
WMAP 5-year data (2008)
+
SDSS and SN

based on best fit to Λ-CDM cosmological model:

↓

- Ω_{total} = 1.02 ± 0.02
- Ω_c = 0.233 ± 0.013
- Ω_b = 0.0462 ± 0.0015
- Ω_Λ = 0.721 ± 0.015
- Ω_ν < 0.0076
- H_0 = 70.1 ± 1.3 km s^{-1} Mpc^{-1}

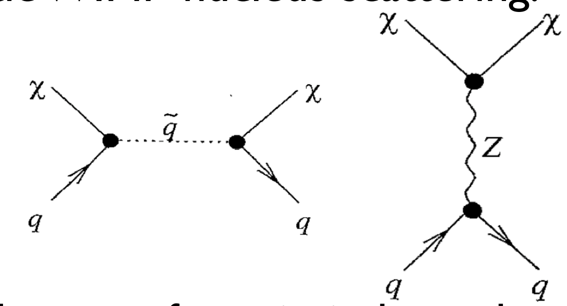
Dark matter particles by definition **do not interact electromagnetically**, and so should **scatter** preferentially from **nuclei**



> galactic mass density profile (22 galaxies)
> obtained from combined (weak + strong) lensing observations

Elastic event rates in earth-bound detectors

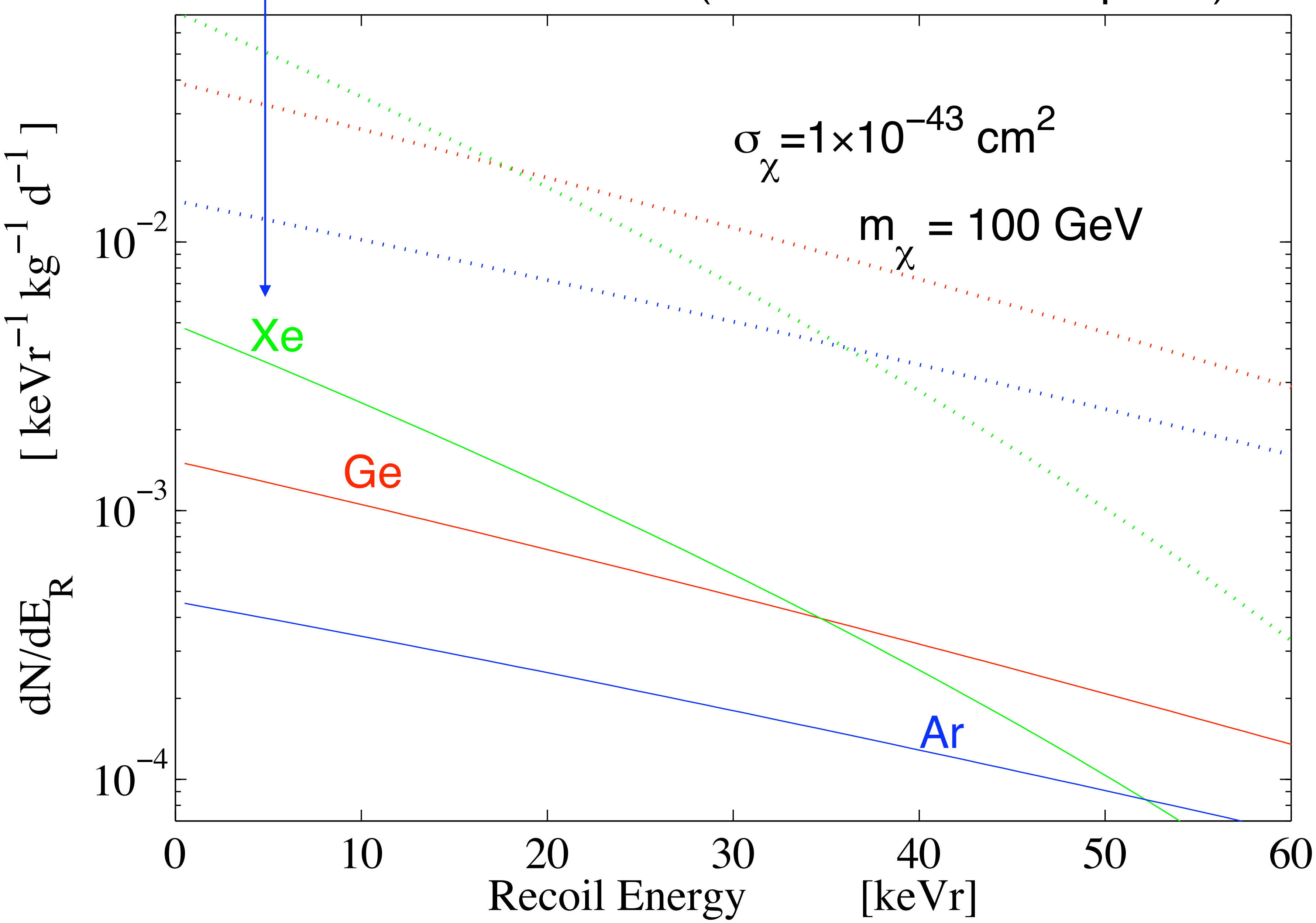
elastic WIMP-nucleus scattering:



A^2 coherence for spin-independent

for E_{thr} = 4 keVr and a 5 kg Xe target, expect ~ 15 events in 2 months

Predicted event rate (standard* halo assumptions)



$$\frac{dR(0, v_{esc})}{dE_R} = \frac{k_0}{k_1}\frac{R_0}{E_0 r}\left(e^{-E_R/E_0 r} - e^{-v_{esc}{}^2/v_0^2}\right)$$

Lewin and Smith, Asropart. Phys. **6** 87 (1996)

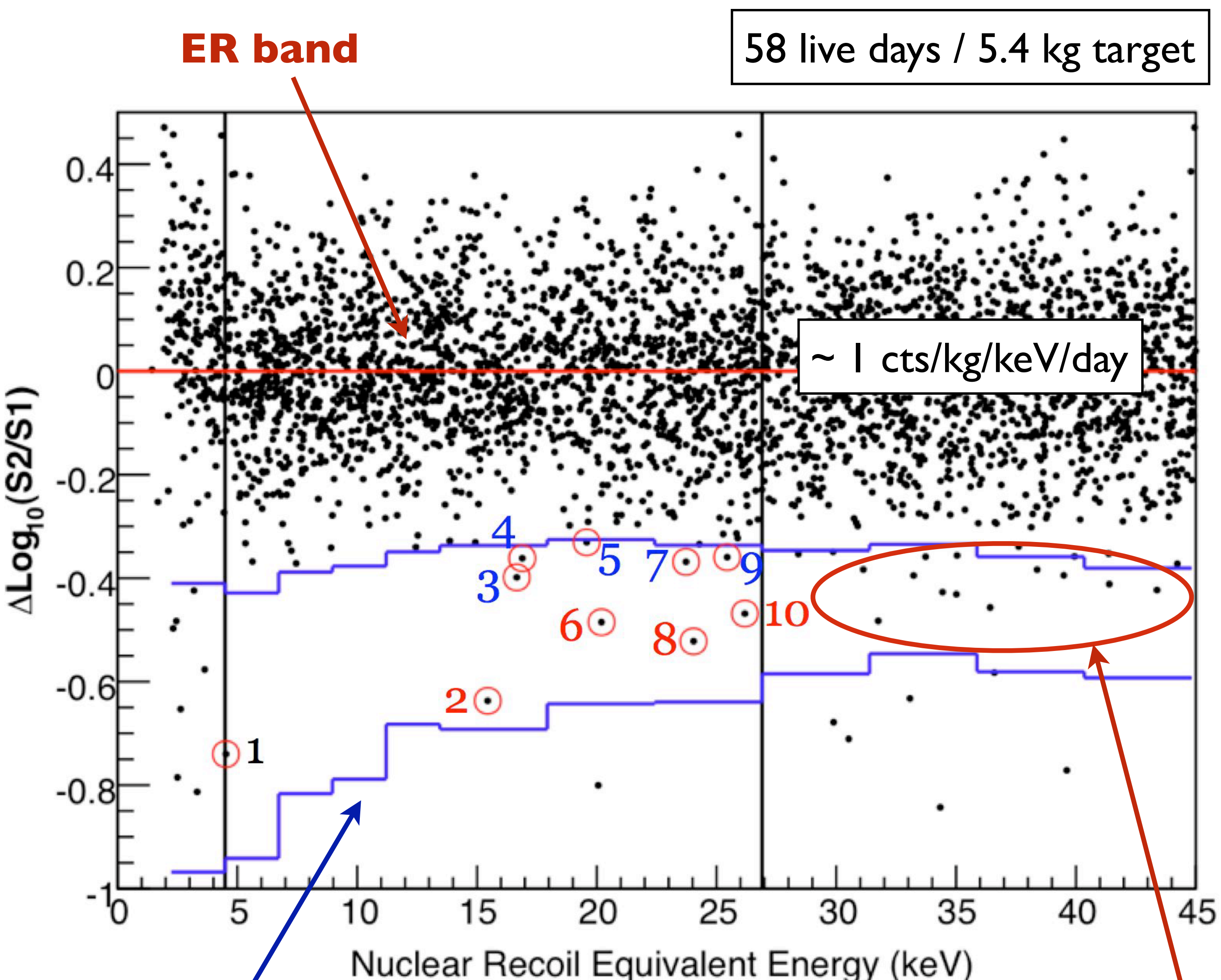
* ρ=0.3 GeV c^{-2} and v_0=220 km/s

(about 3 100 GeV DM particles / liter)

XENON10 results (2007)

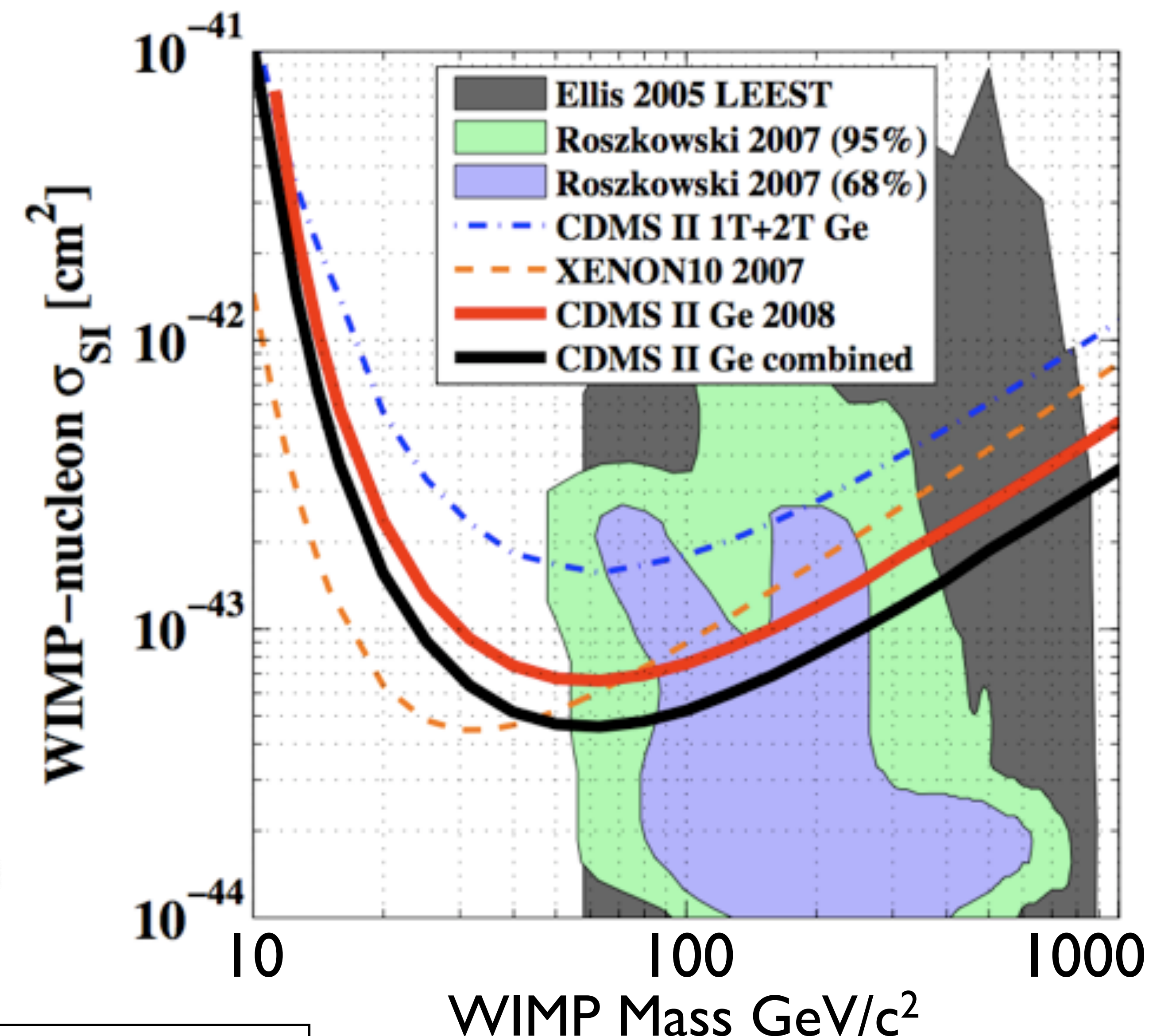
Phys. Rev. Lett. **100** 021303 (2008)

ER band



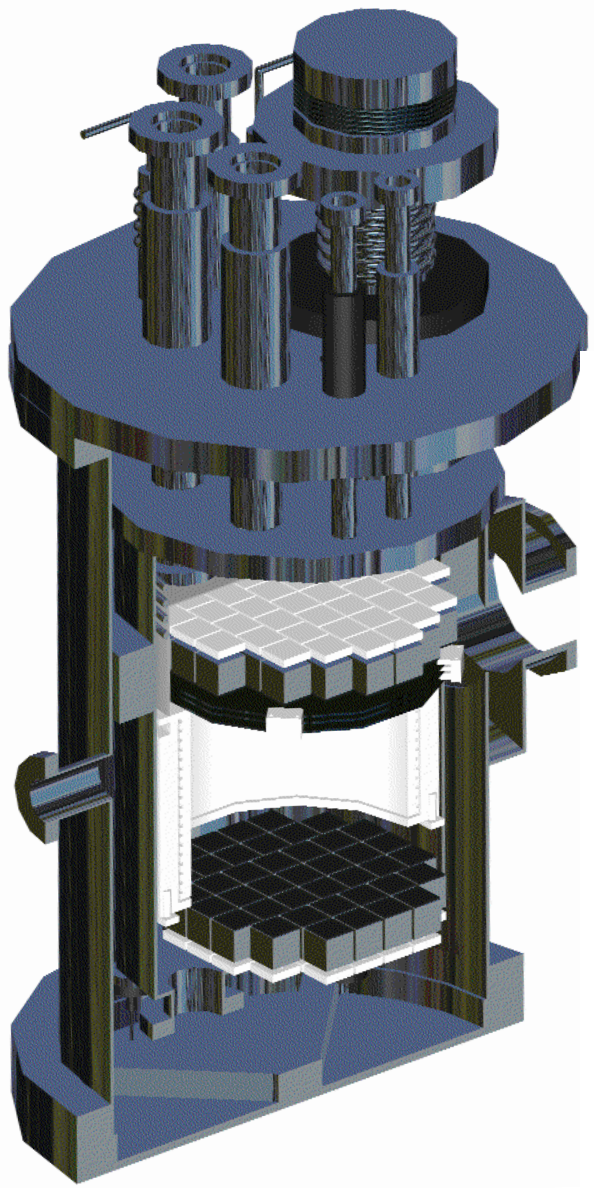
NR 50% acceptance box (from neutron cal.)

background events outside blind analysis window (cuts were not optimized above ~27 keVr)

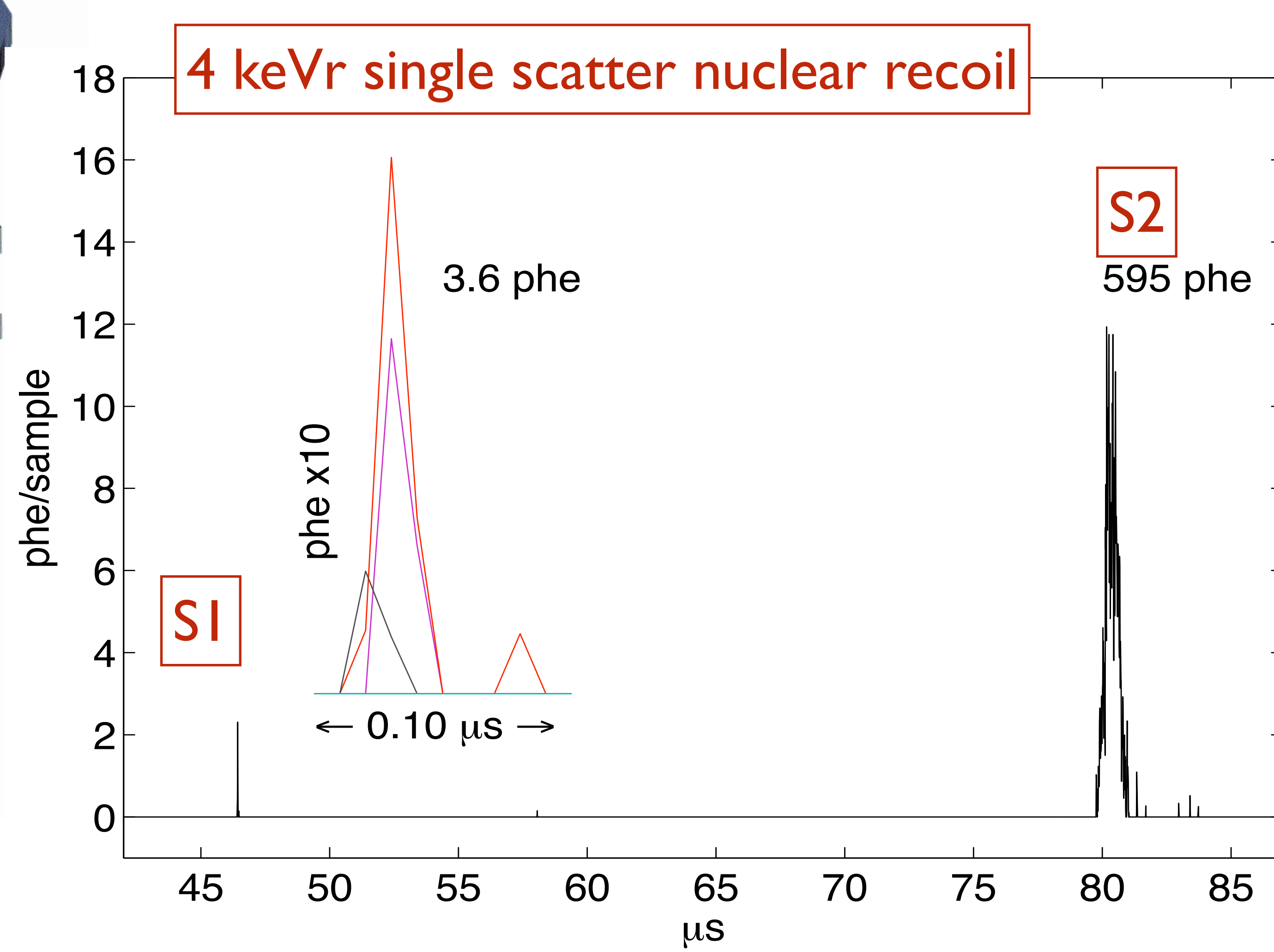


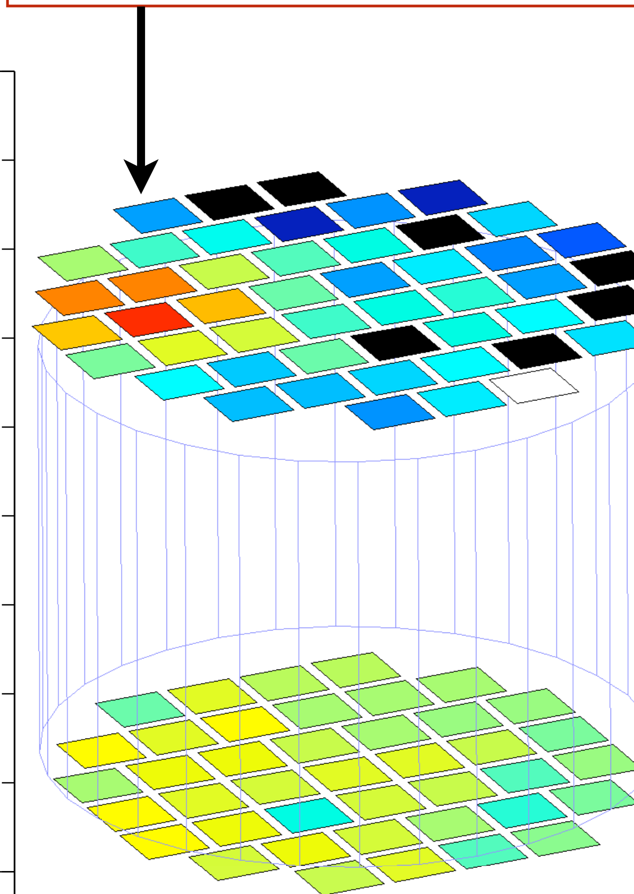
XENON10 detector

14 kg Xe (~5 kg target)

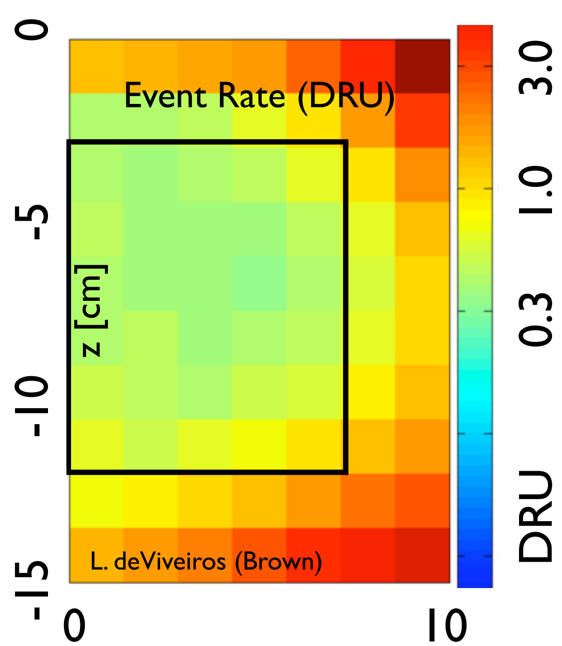


S2 hit pattern gives (x,y)



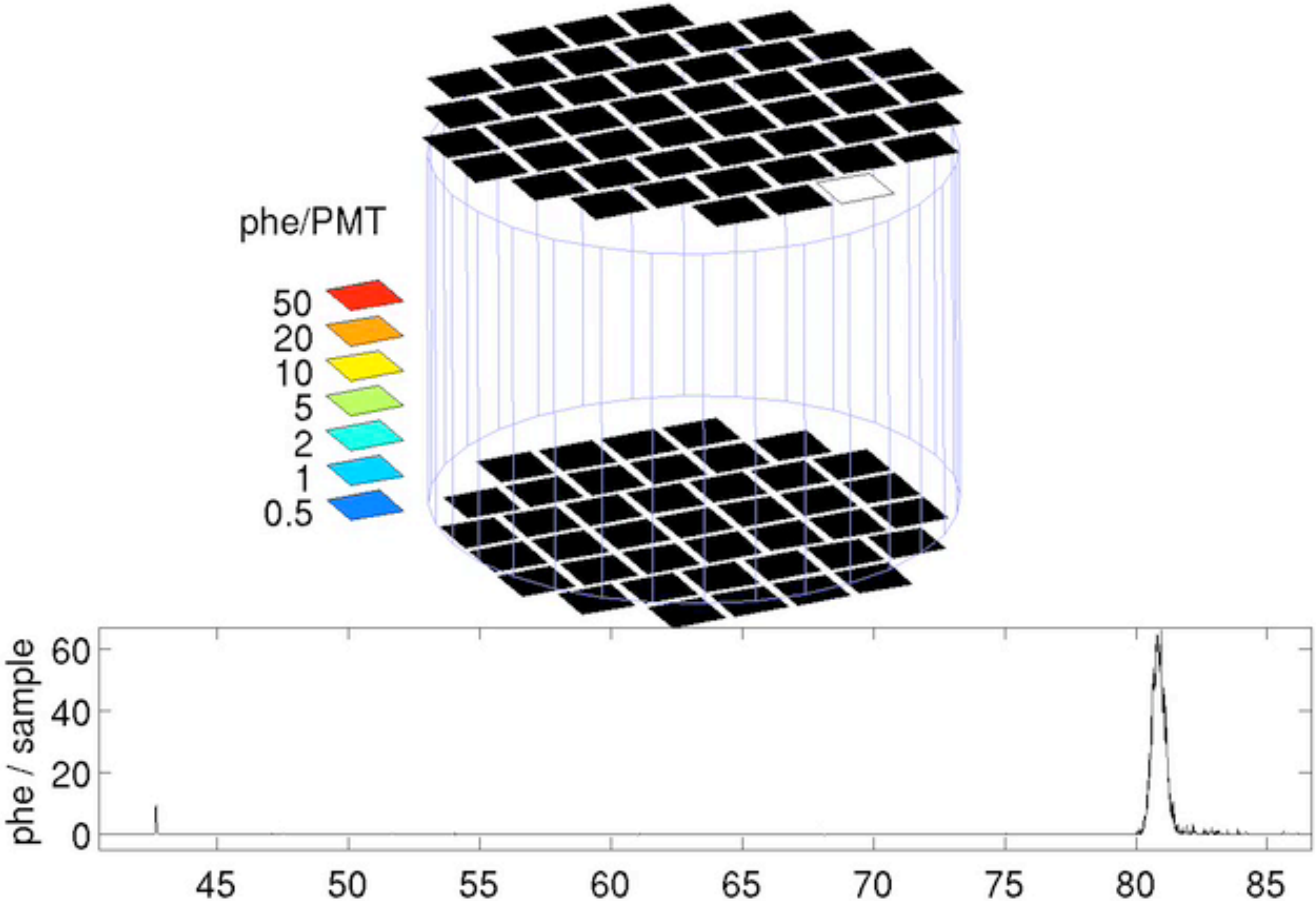


t_{S2} - t_{S1} gives z coordinate

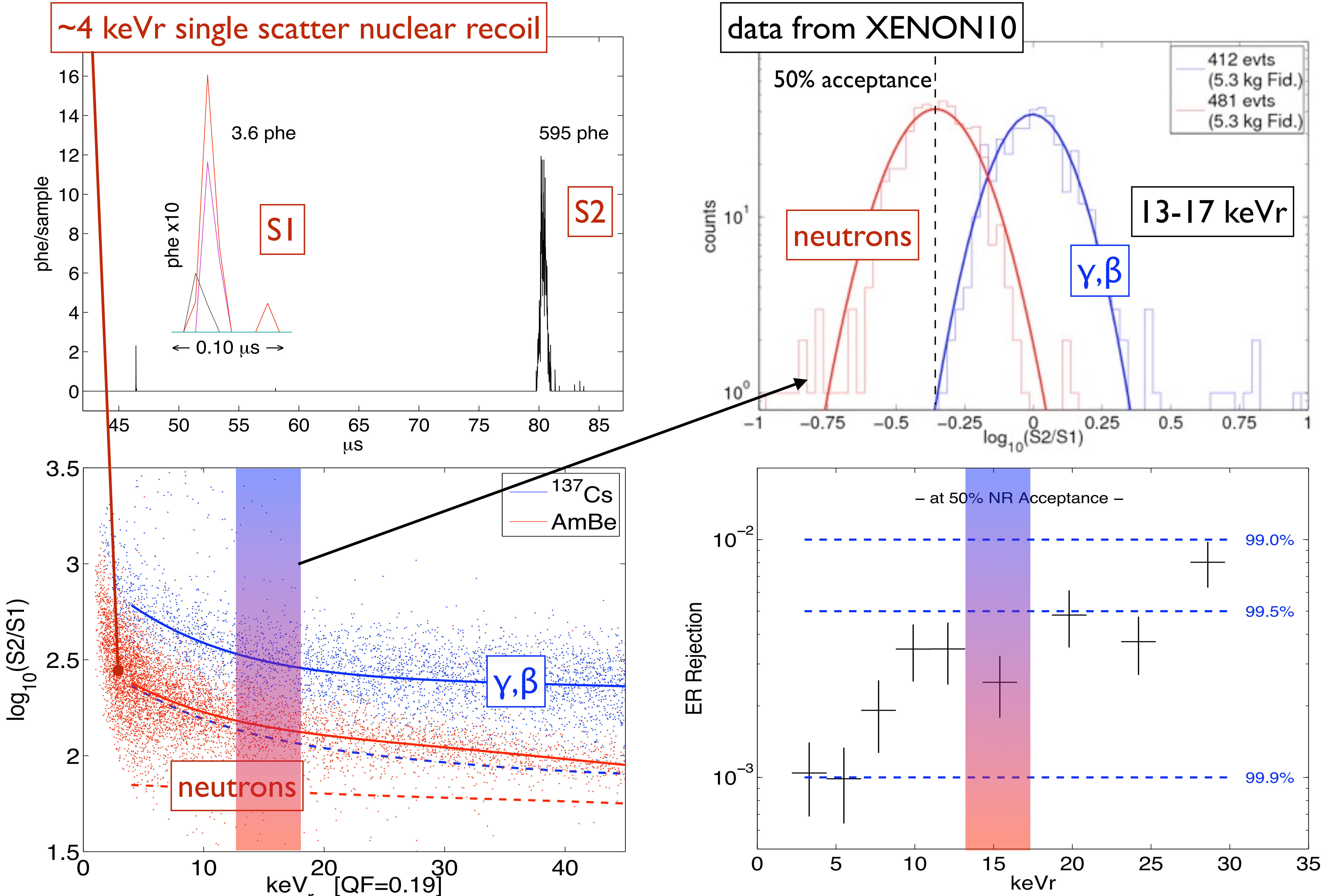


S1: primary scintillation
S2: secondary scintillation
(proportional to ionization)

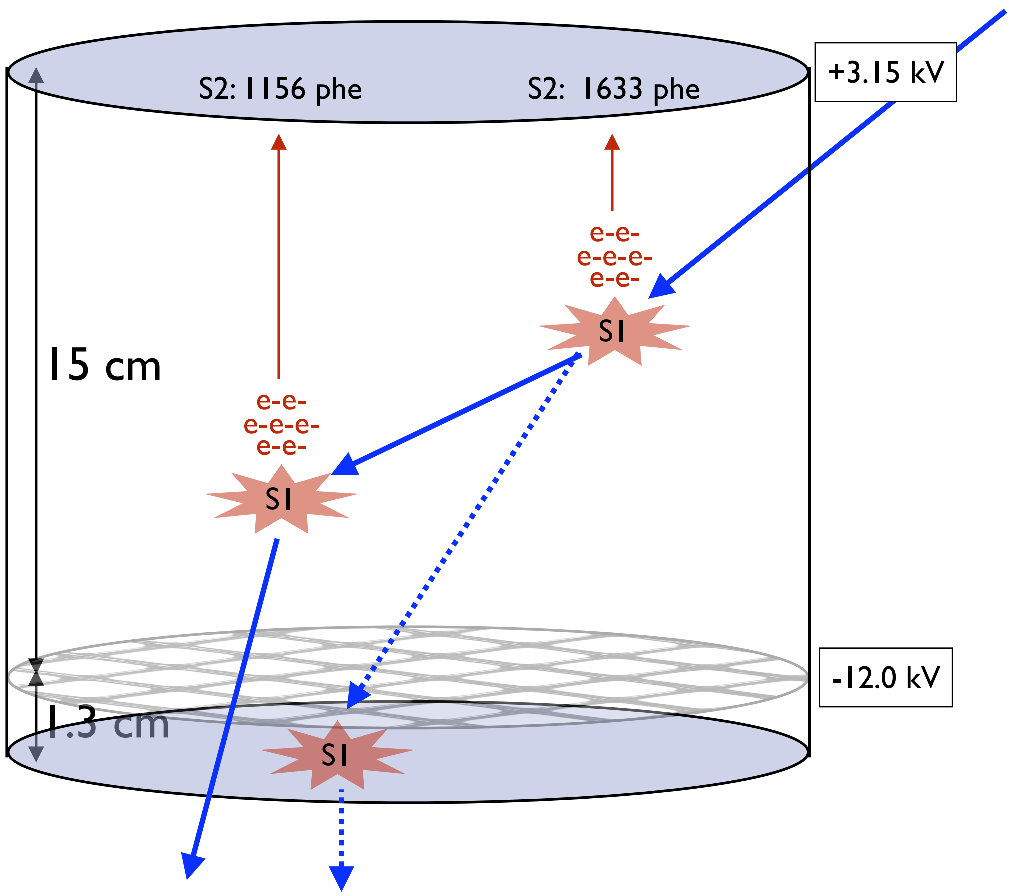
XENON10 event animation

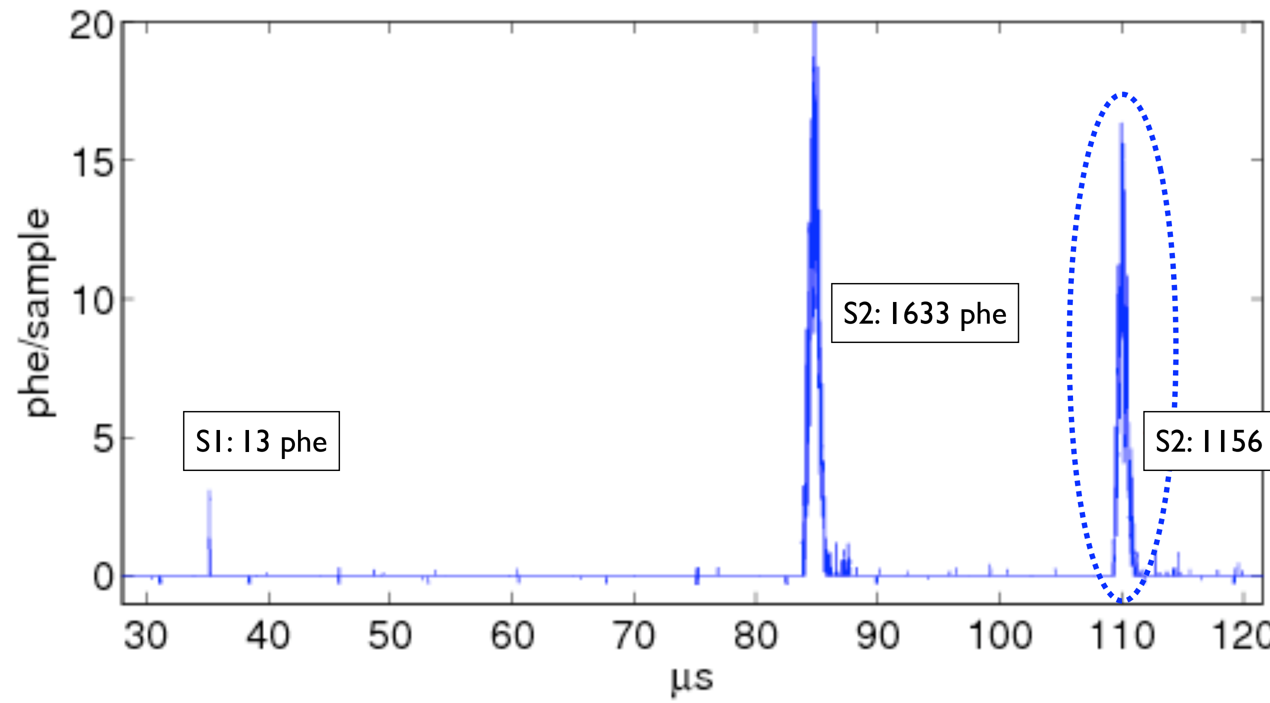


Discrimination in Xe: Electron Recoil vs Nuclear Recoil



Origin of the non-Gaussian tails in the background



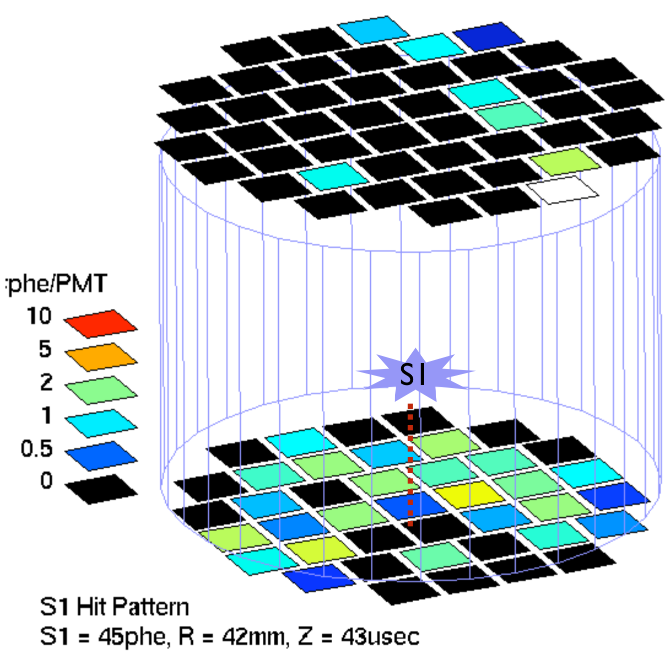


— normal multiple scatter

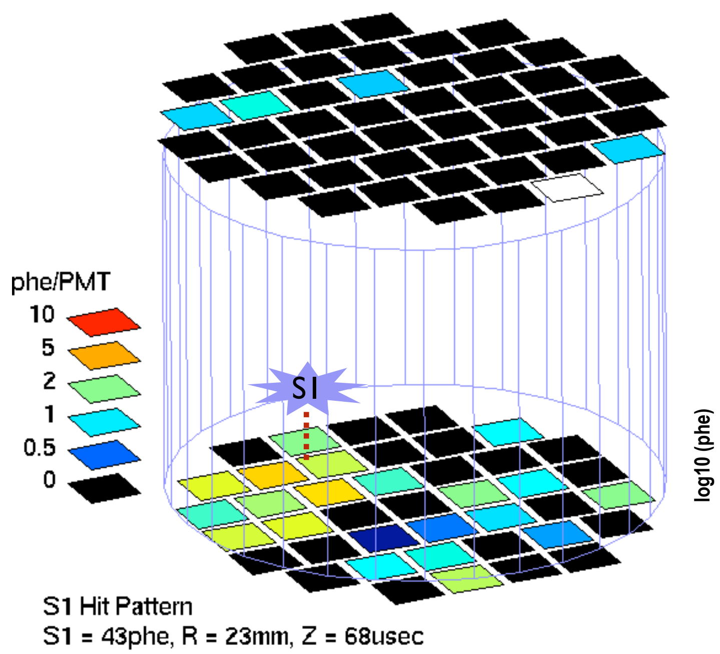
···· false single scatter (colloquially referred to as a “gamma X” event)

How to spot a Gamma X Event: S1 Hit-Pattern

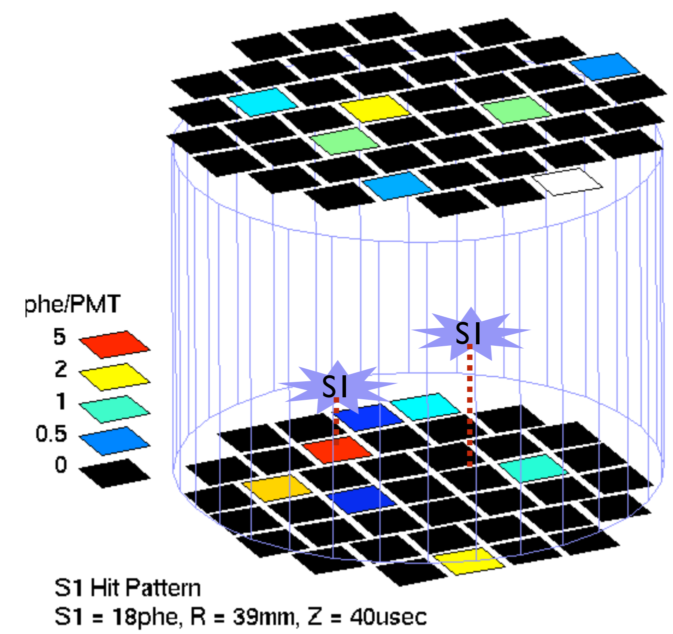
Scatter in center of FV



Scatter close to bottom of FV



Gamma X scatter

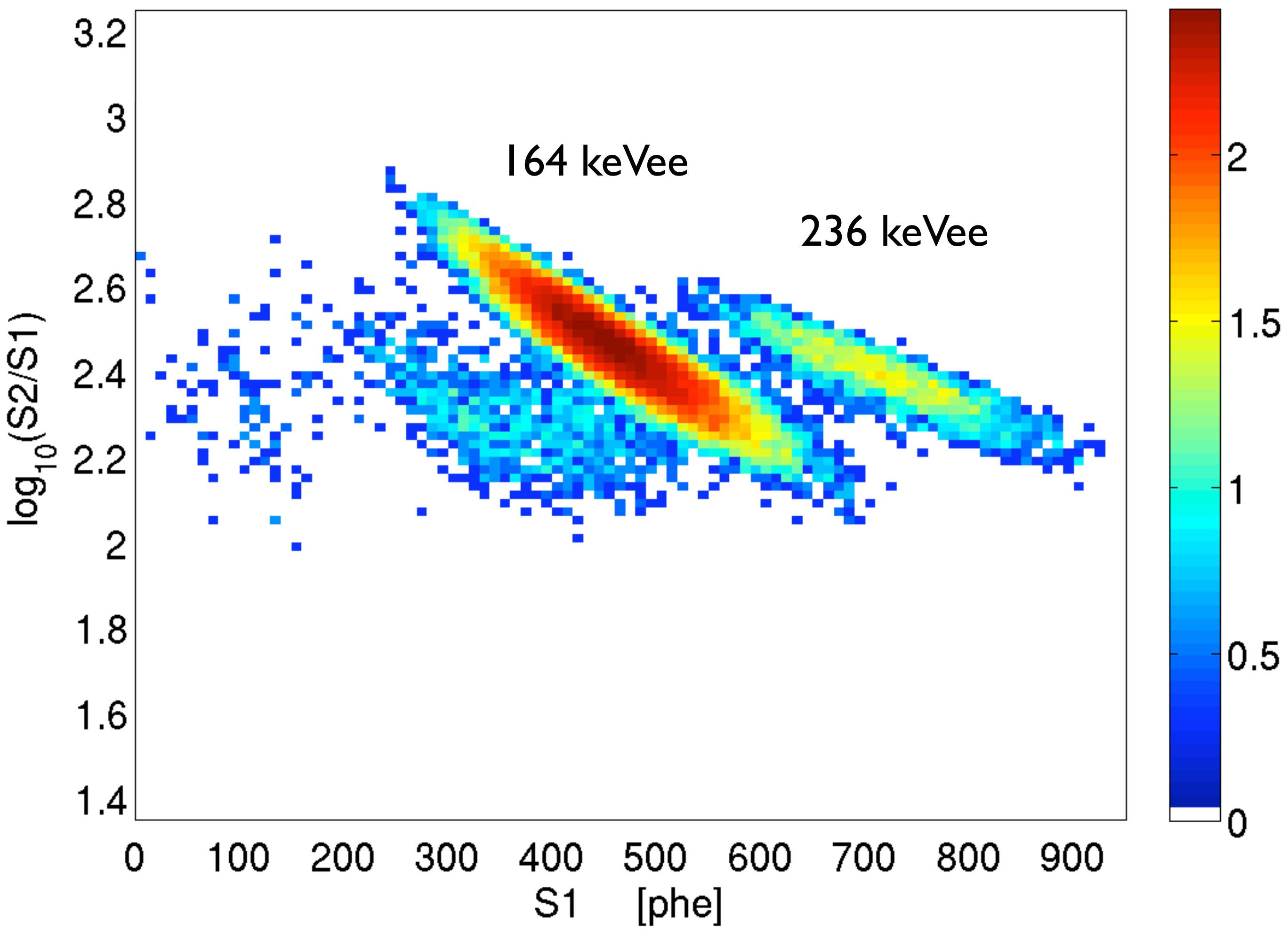


Events in Fiducial Volume => diffuse Hit Pattern	Events near bottom => more localized Hit Pattern	Events below cathode => highly localized Hit in ~ 1,2 PMTs

Phys. Rev. Lett. **100** 021303 (2008) ⟶

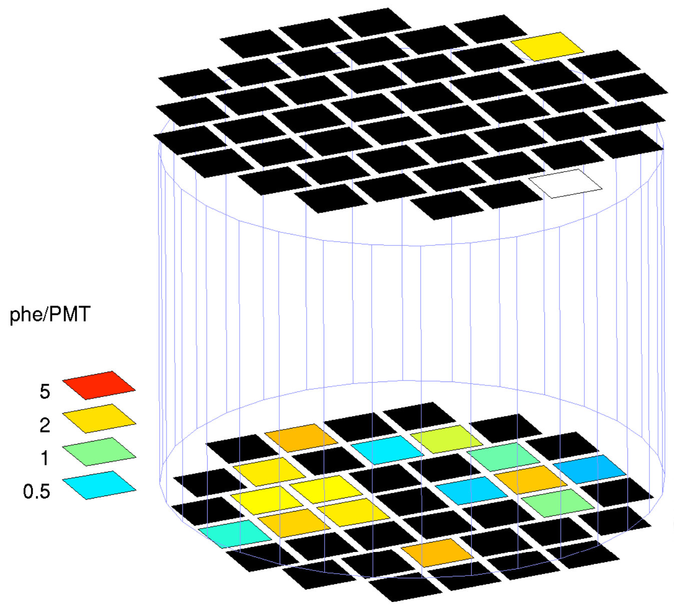
$$S1_{RMS} = \sqrt{\frac{1}{n}\sum(S1_i - \overline{S1})^2}$$

Improved algorithm to identify false single scatters

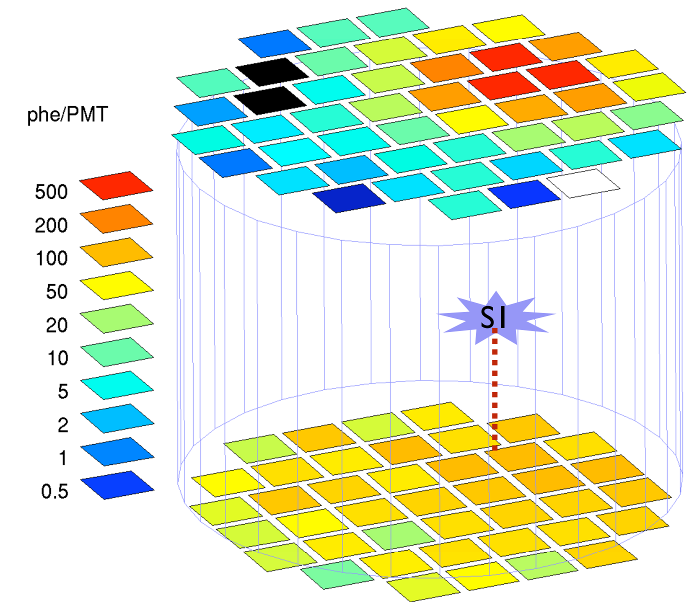


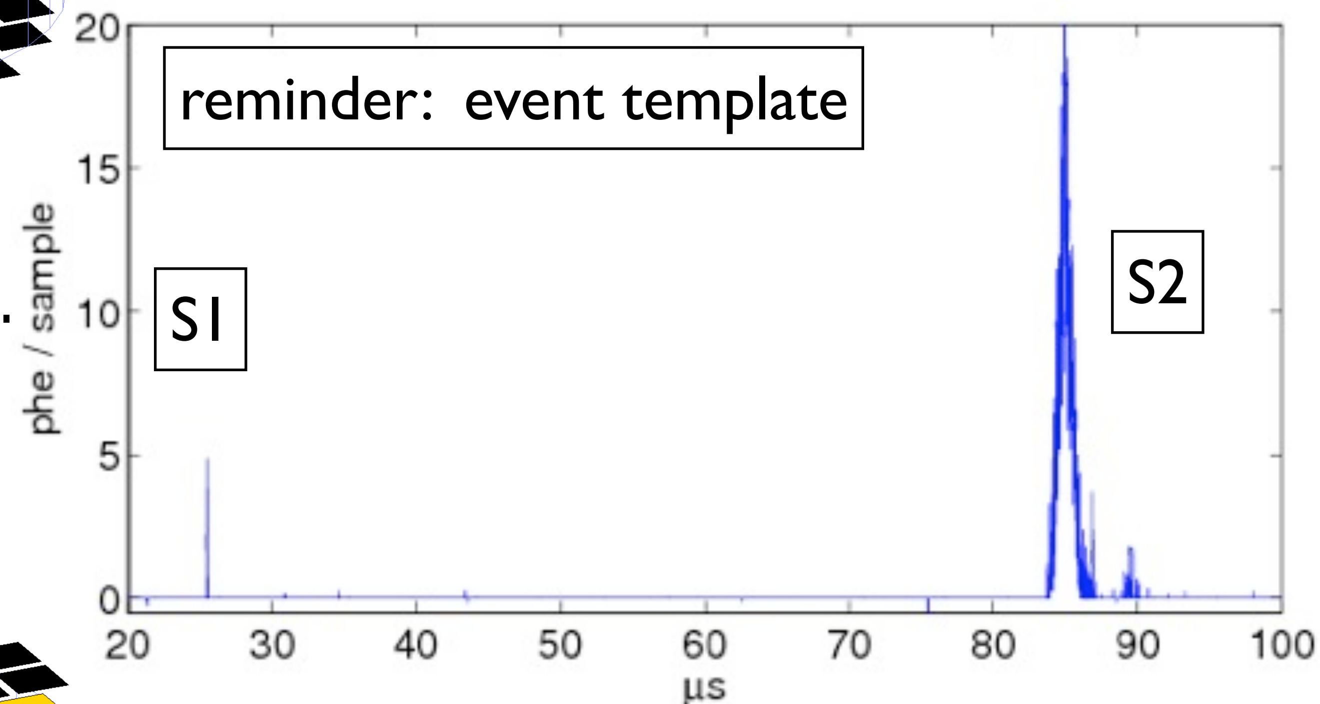
The distribution of α_i for each photo-multiplier tube was measured from calibration data, obtained after introducing neutron-activated xenon into the XENON10 detector. As described in [26], this produced an internal, homogeneous source of 164 keV gamma rays from the de-excitation of ^{131m}Xe. For each event, we then calculated the Poisson probability p_i of obtaining the observed hit-pattern, given the expectation α_i. Two cut parameters were defined as $\mathcal{P}_{b,t} = \log_{10}(\Sigma\ \alpha_i/p_i)$.

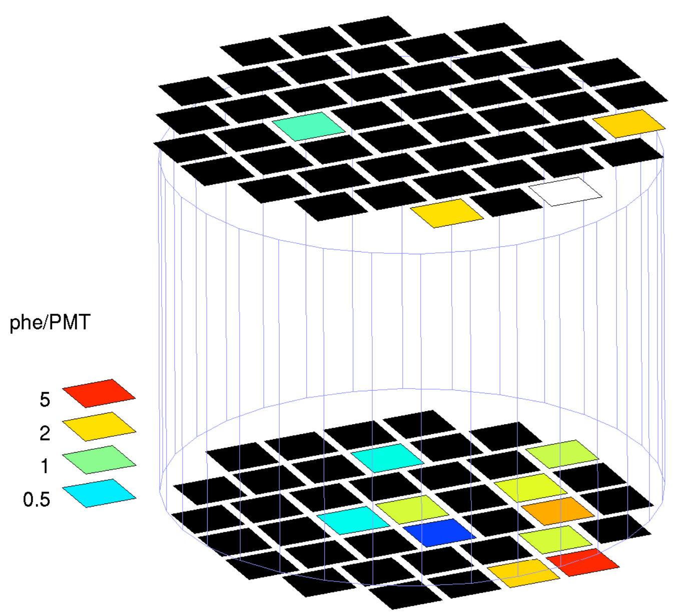
An example



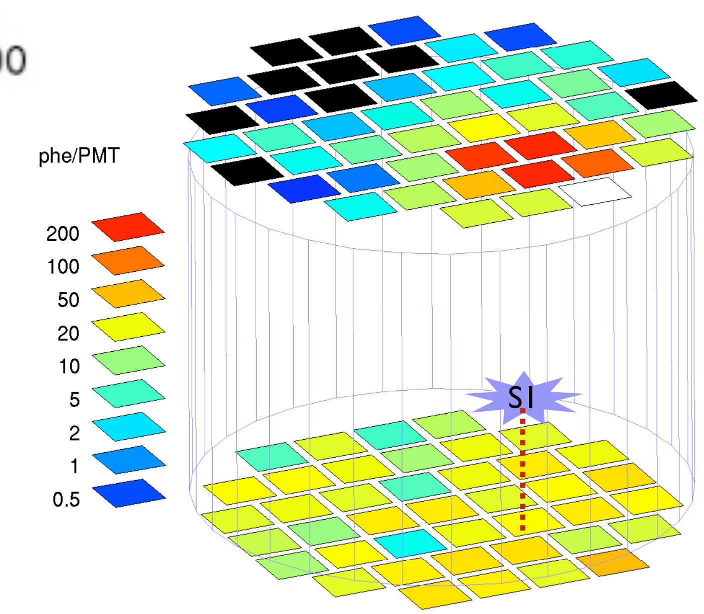
"normal" 24 keVr event (ER cal. data)





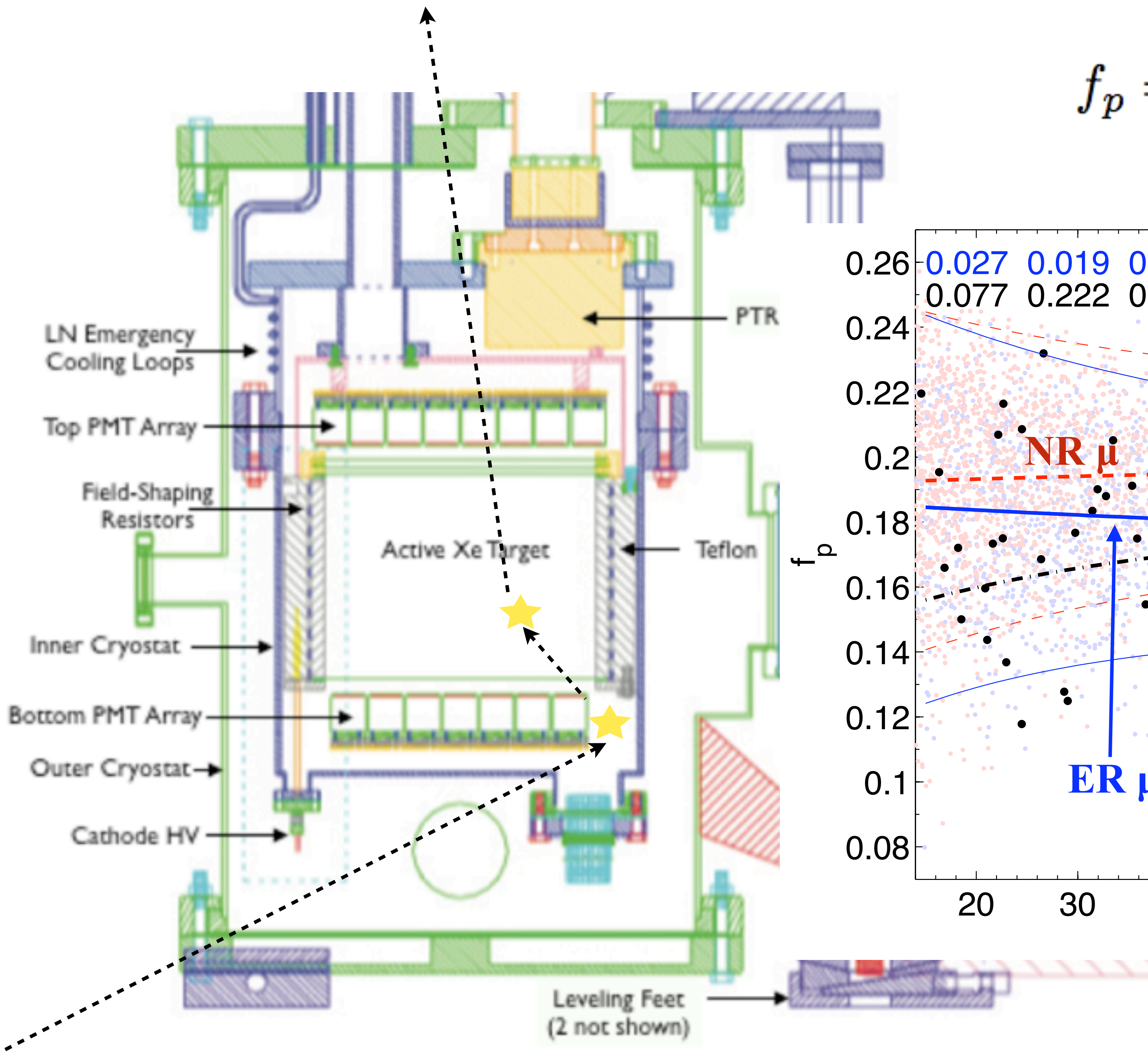


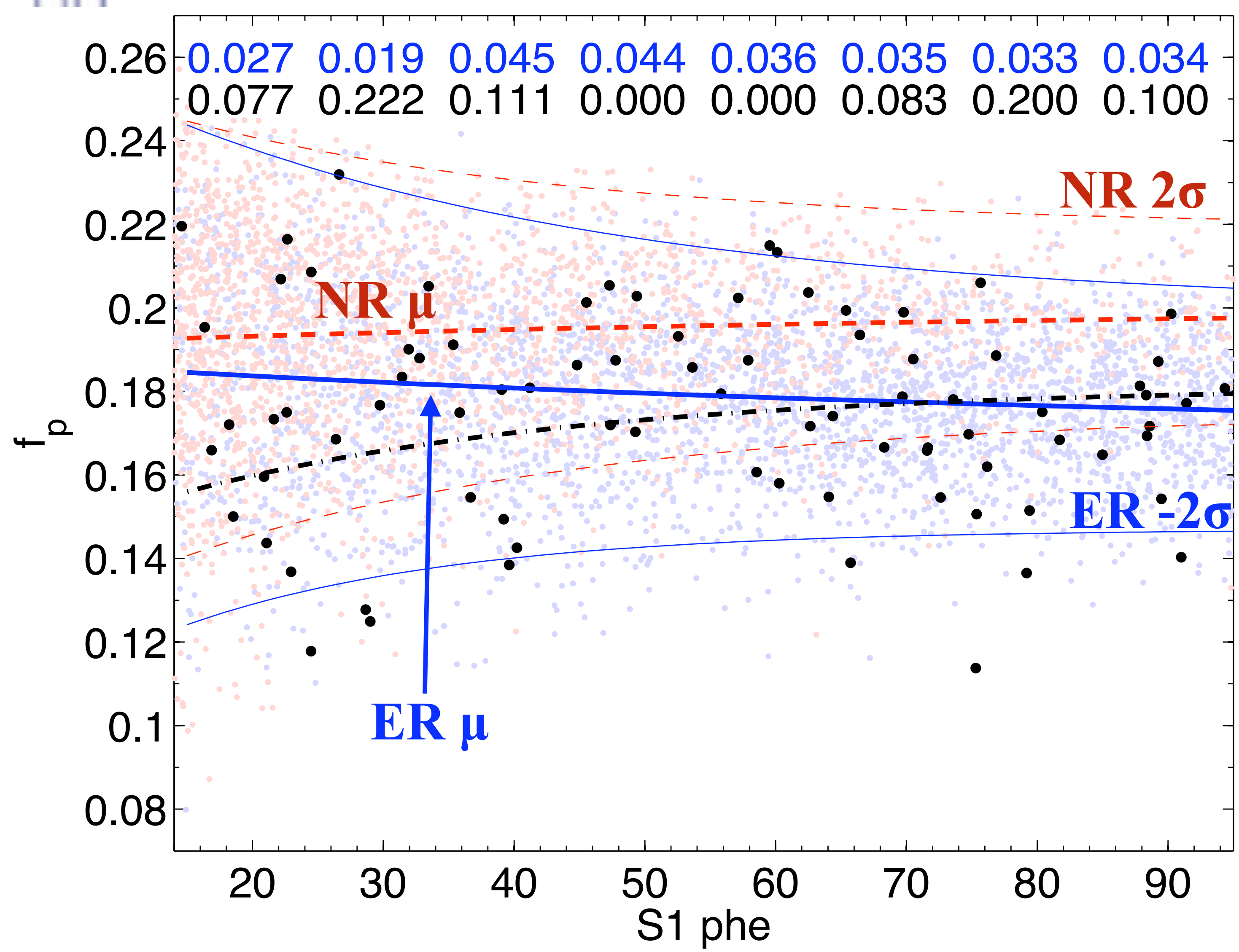
anomalous 24 keVr event (ER cal. data)



Pulse shape discrimination (resurrected!)

$$f_p = \frac{\int_{t_i}^{t_0+t_w} S1(t)dt}{\int_{t_i}^{t_f} S1(t)dt}$$

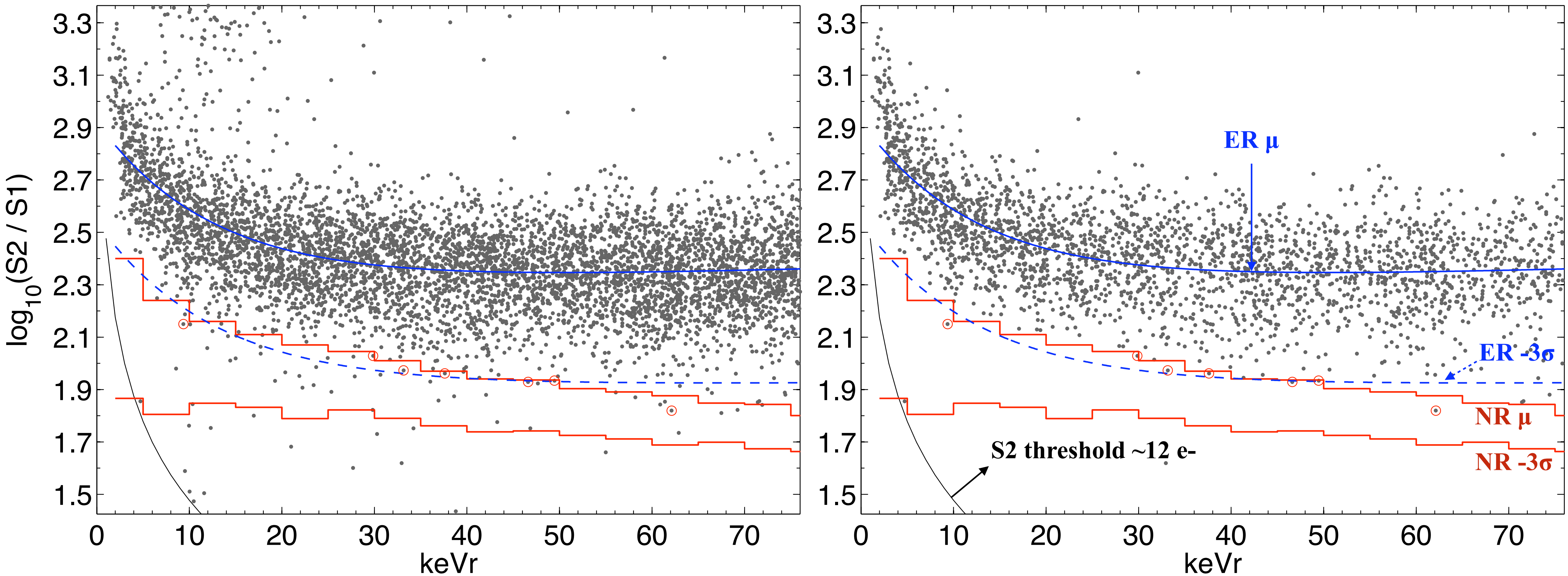




Assessing the cut performance on ER calibration data

all valid events in the 5.4 kg target

the same data after all cuts



electron recoils from 662 keV gammas

False single scatter fraction: data vs MC

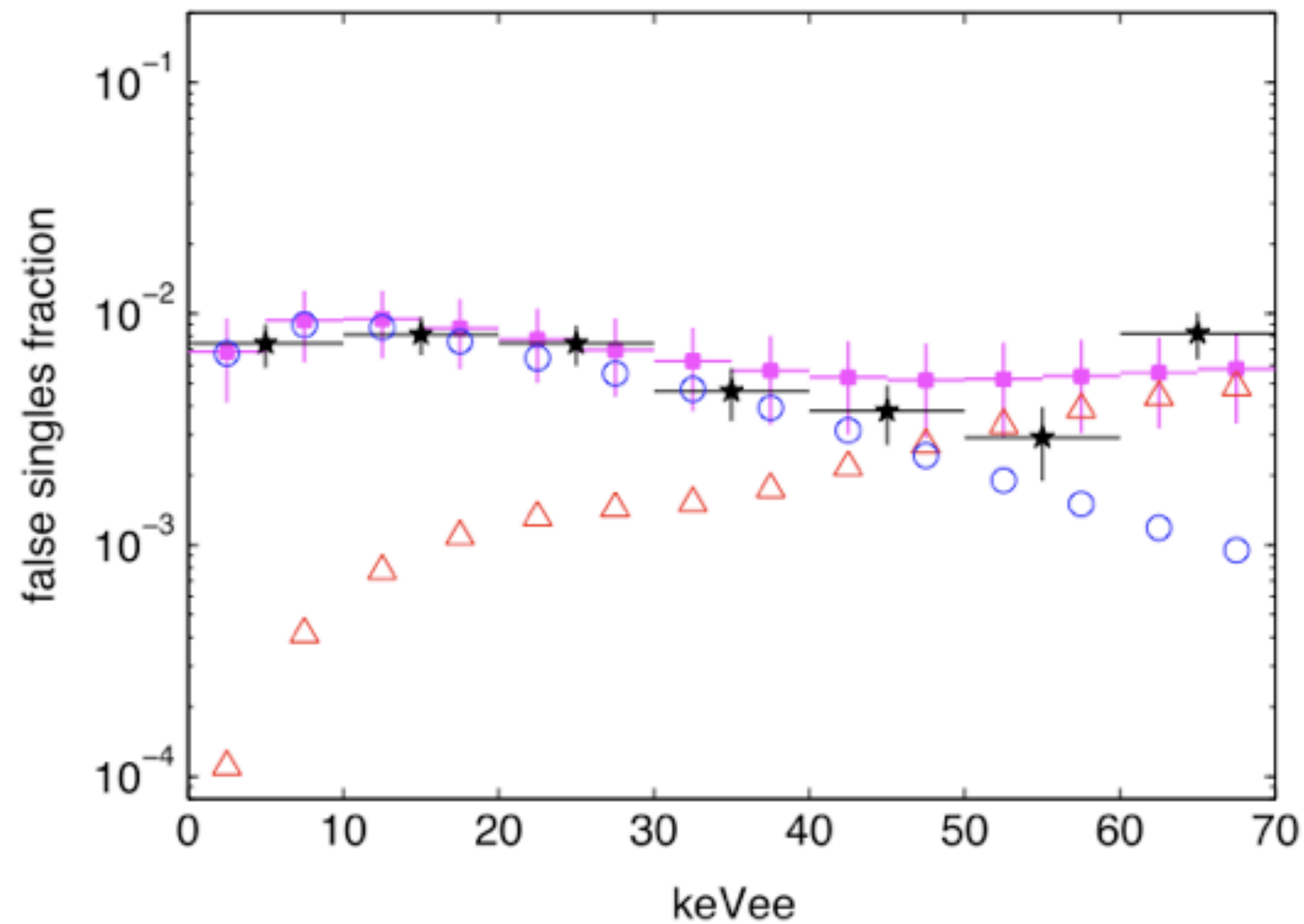
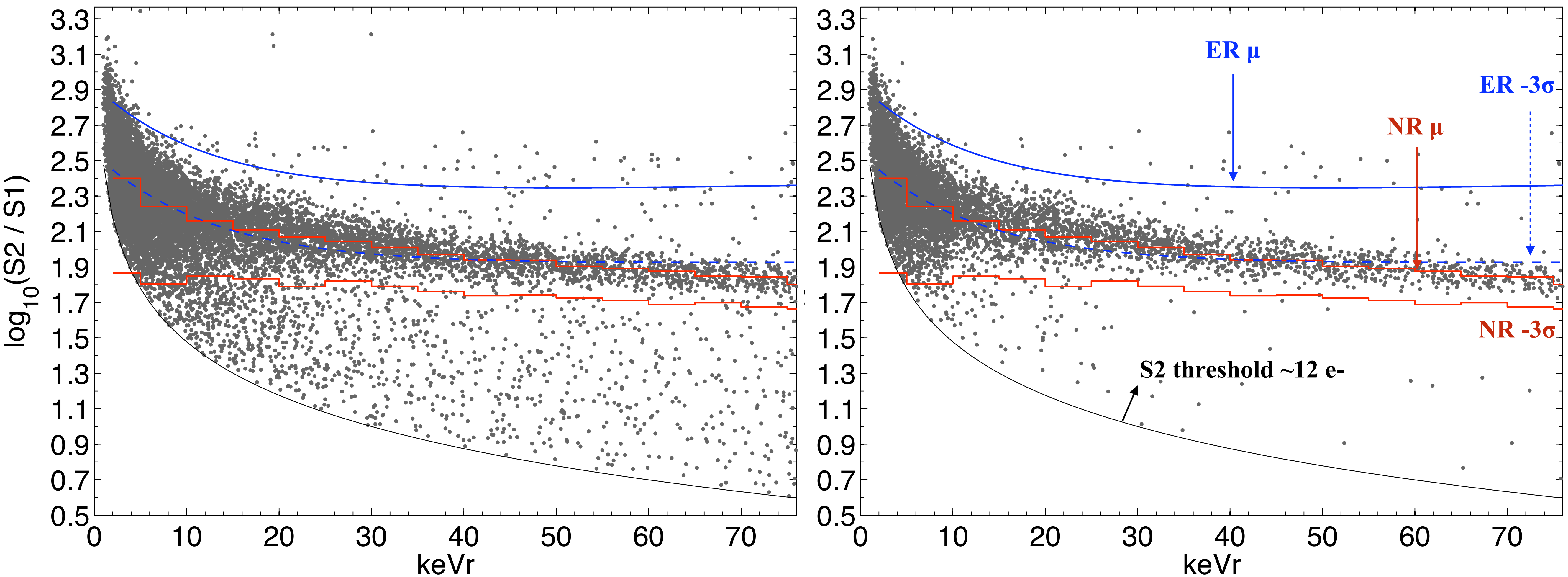


FIG. 3 (color online). The fraction of leakage events remaining among single gamma ray scatters in the electron recoil calibration data set (black stars). Also shown is the Monte Carlo prediction for false single scatters, with an additional scatter below the cathode grid (red triangles), or in the outer 8.7 kg of xenon (blue circles). The sum of the two Monte Carlo components is indicated by pink squares. Note that the *x* axis is electron (not nuclear) recoil equivalent energy; 20 keVee = 76 keVr.

Assessing the cut performance on NR calibration data

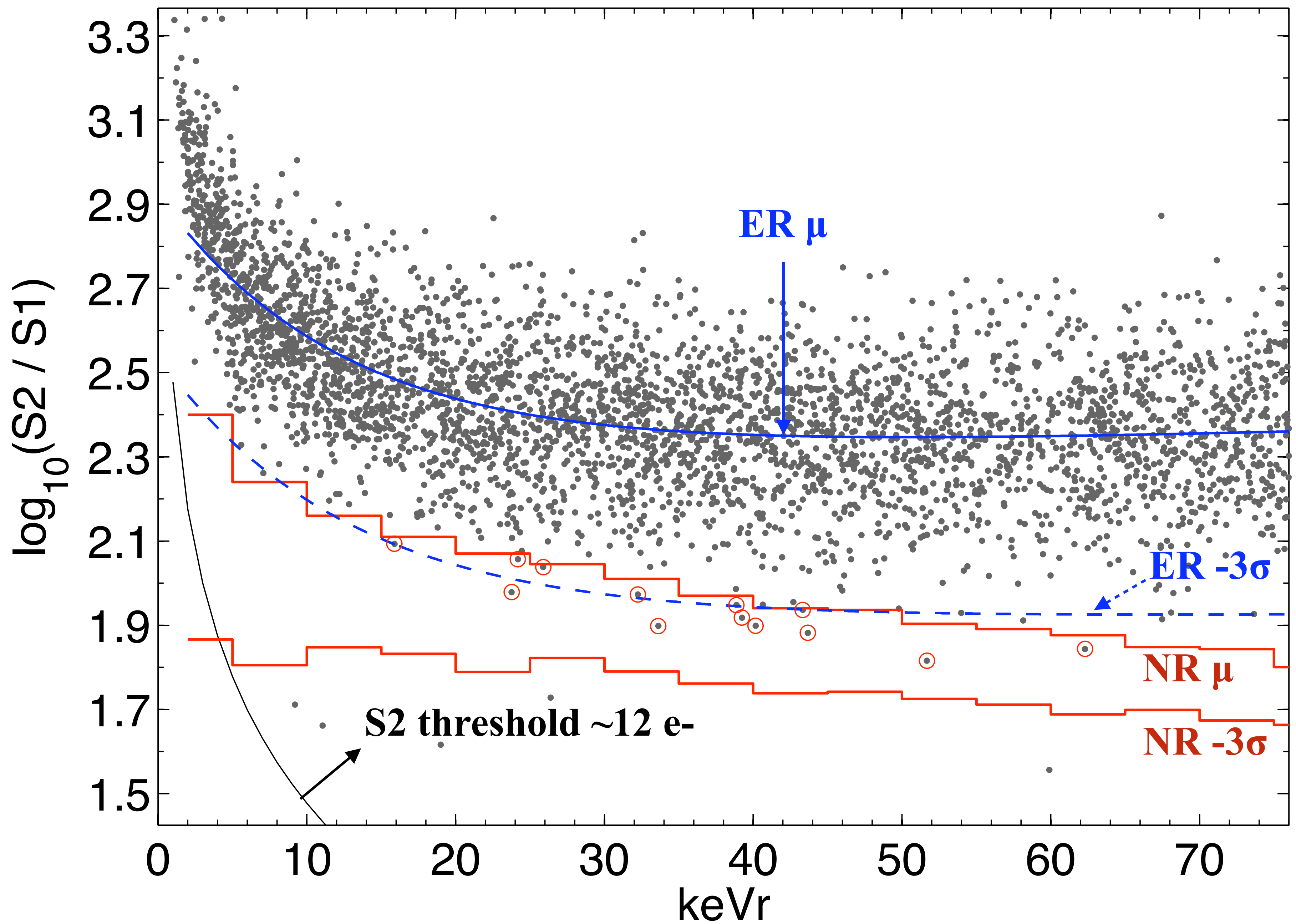
all valid events in the 5.4 kg target

the same data after all cuts



nuclear recoils from AmBe neutrons

XENON10 58. live days of dark matter search data



Slight dulling of Occam's Razor:

Inelastic Dark Matter

D Tucker-Smith and N Weiner, Phys Rev D **72** 063509 (2005)

in brief:

(i) A dark matter particle, χ_1, with zero or highly suppressed elastic scattering cross sections off of nuclei.
(ii) A second state, χ_2, heavier than χ_1 by an amount $\delta = m_2 - m_1$, which is of the order of a typical halo WIMP kinetic energy. Generally, we need $\delta \sim$ 100 keV for weak-scale values of the χ_1 and χ_2 masses.
(iii) An allowed scattering off of nuclei with an inelastic transition of the dark matter particle, i.e., $\chi_1 + n \longrightarrow \chi_2 + n$.

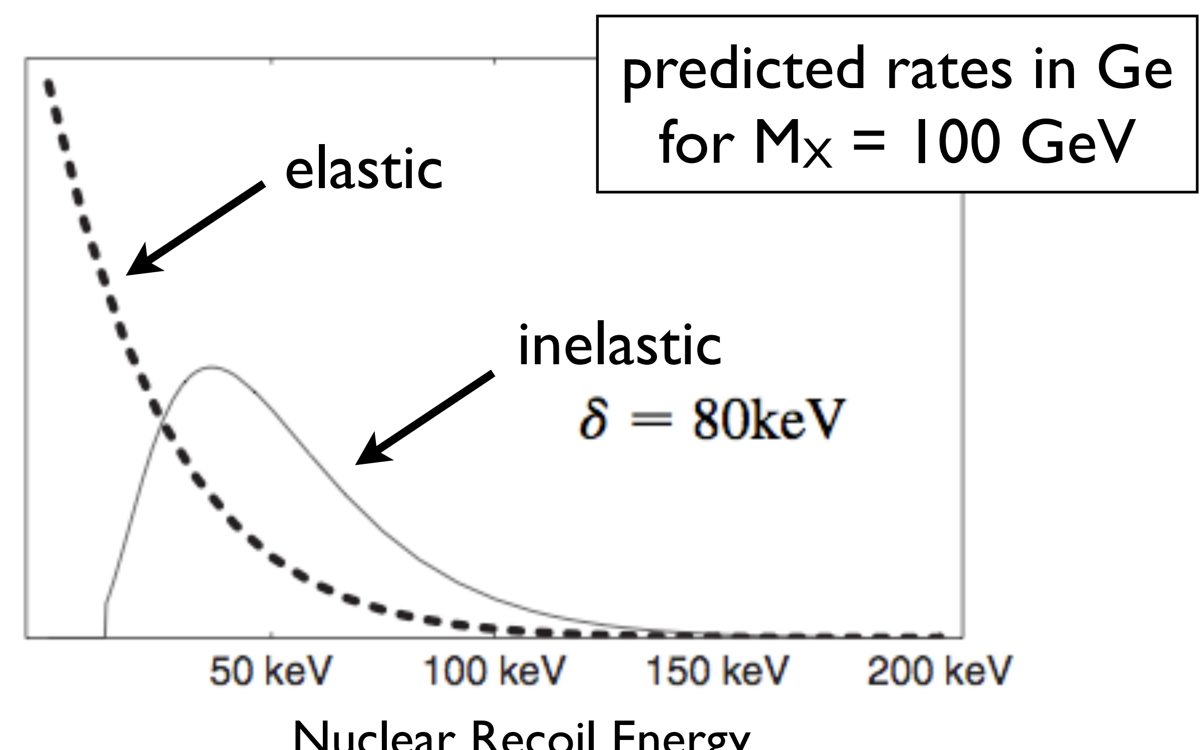
consequences:

Broadly speaking, the iDM scenario can have three effects on dark matter experiments:
(i) An overall suppression of signal, favoring heavier targets over lighter ones.
(ii) An energy-dependent suppression of signal, suppressing rates of low energy events more than those of high energy events.
(iii) An enhancement of the modulated signal relative to the unmodulated signal.

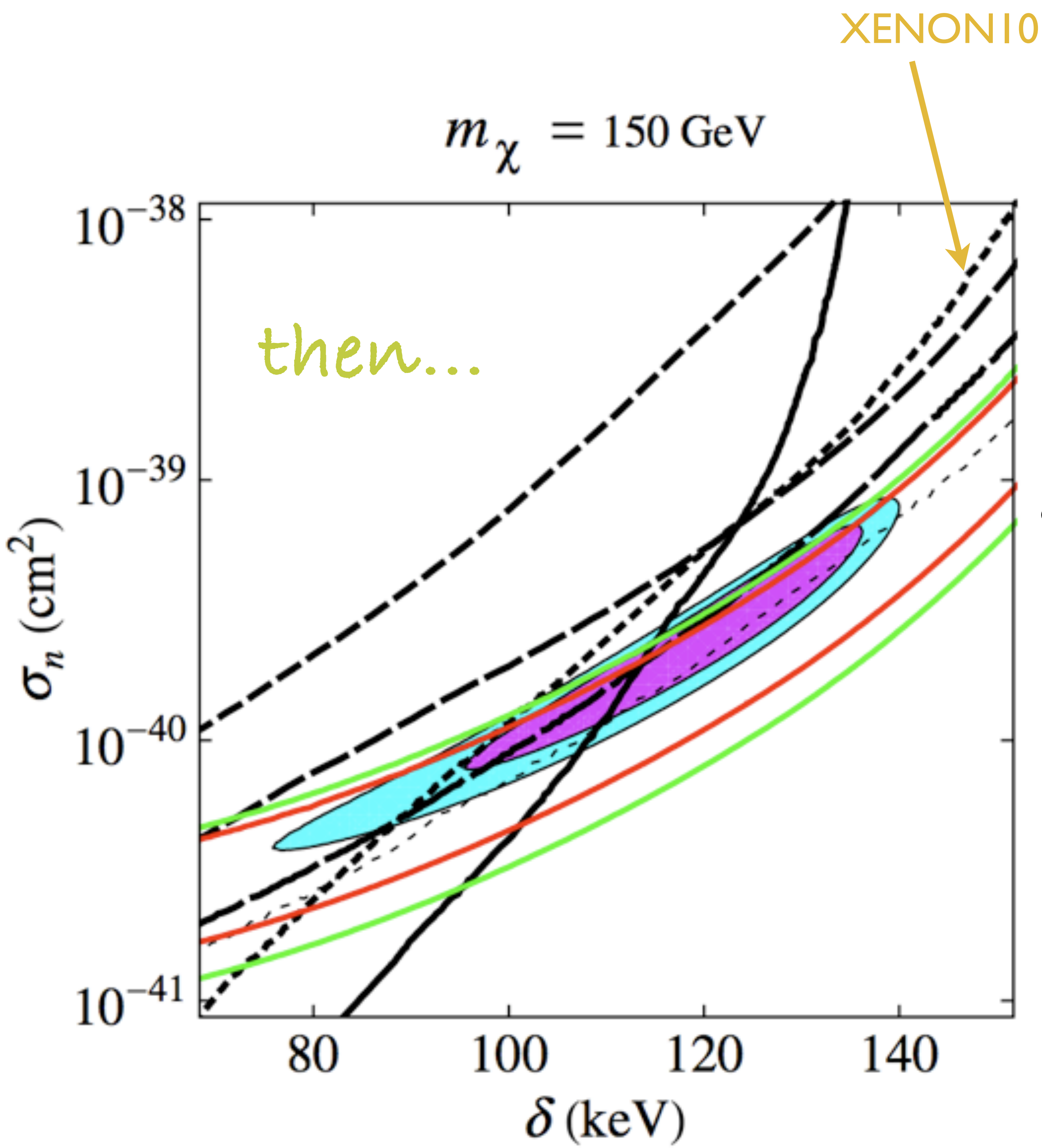
need at least

$$v_{\min} \simeq \sqrt{2\delta/\mu}$$

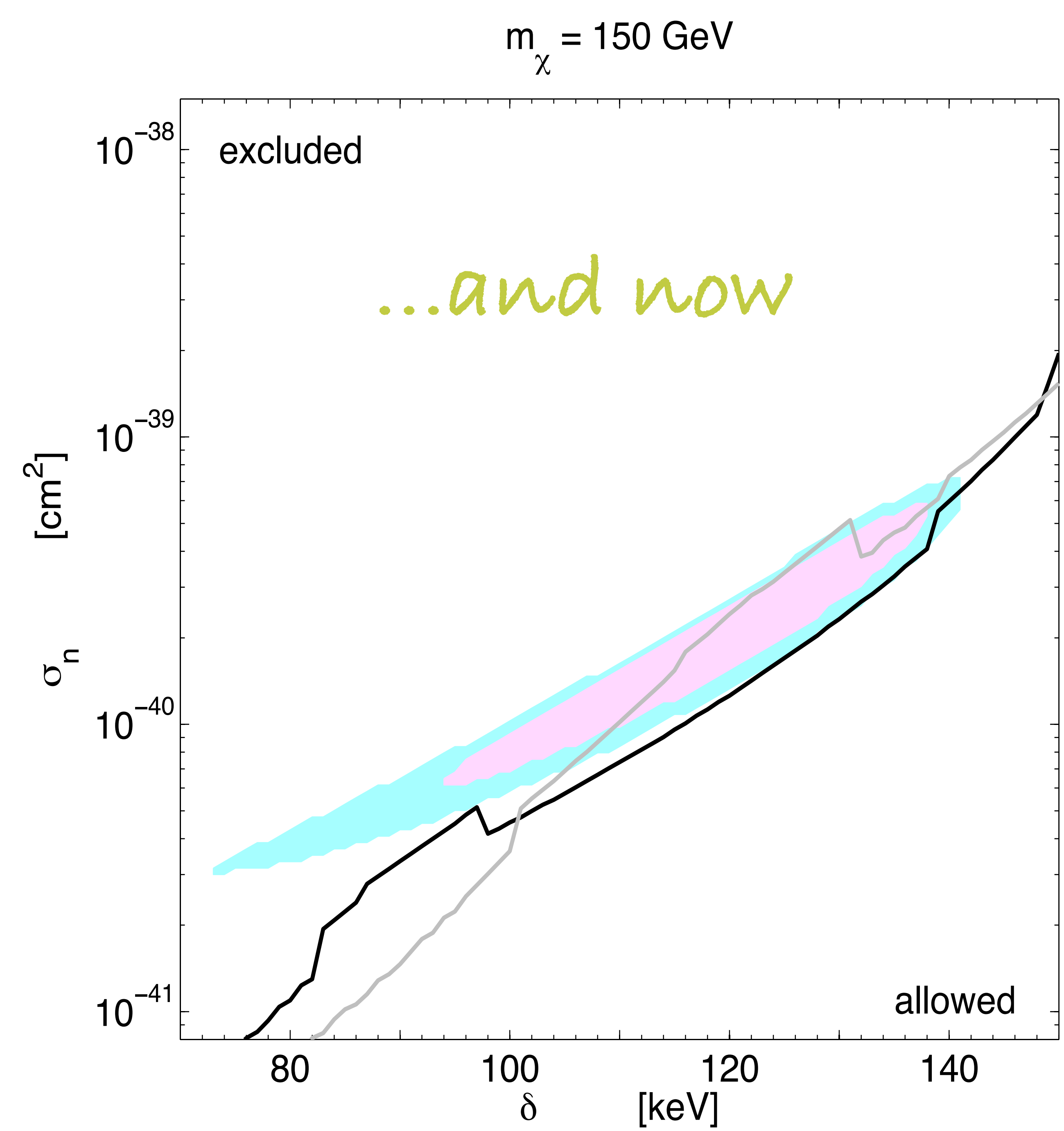
to scatter



iDM Allowed Parameter Space

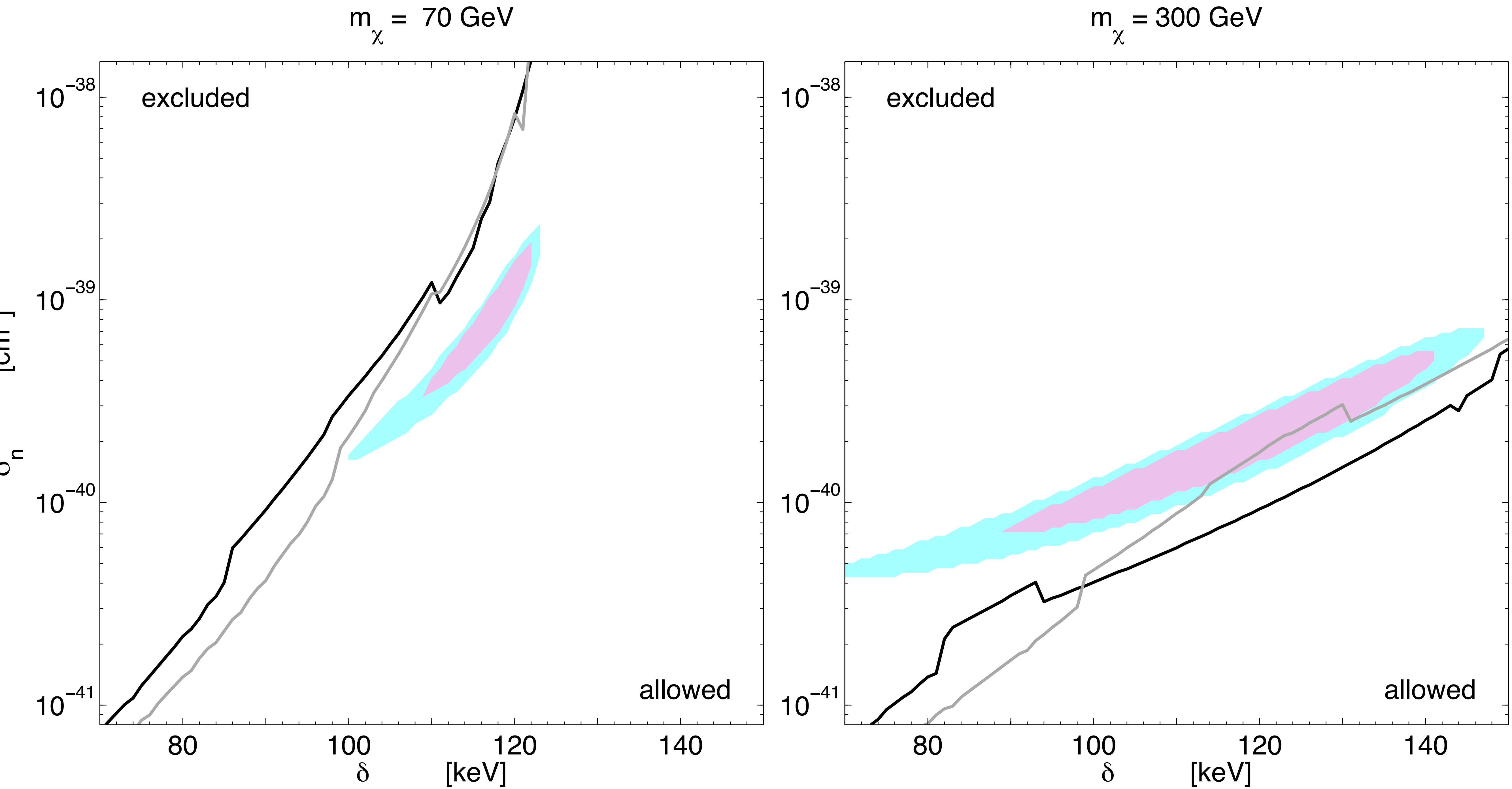


Phys Rev D **79** 043513 (2009)

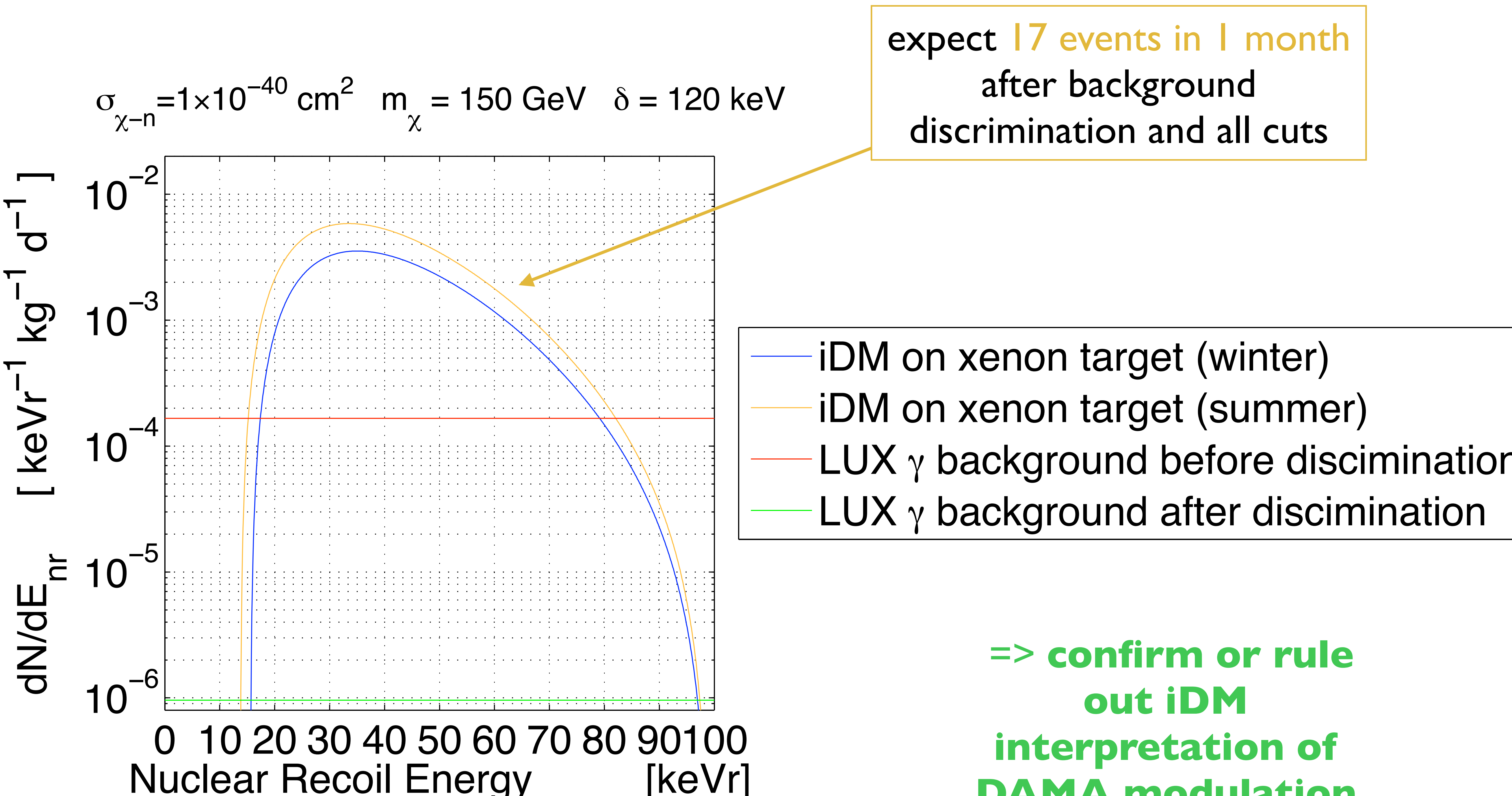


arxiv: 0910.3698

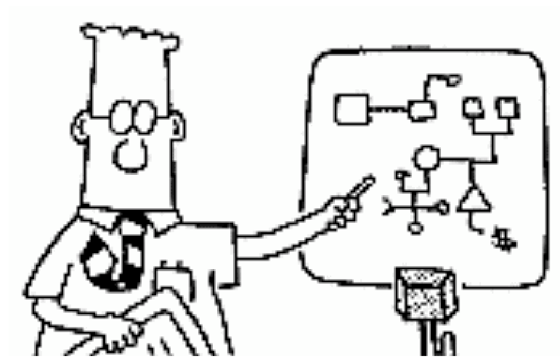
iDM exclusion limits



LUX iDM Sensitivity after 1 Month Live



=> confirm or rule out iDM interpretation of DAMA modulation summer 2010

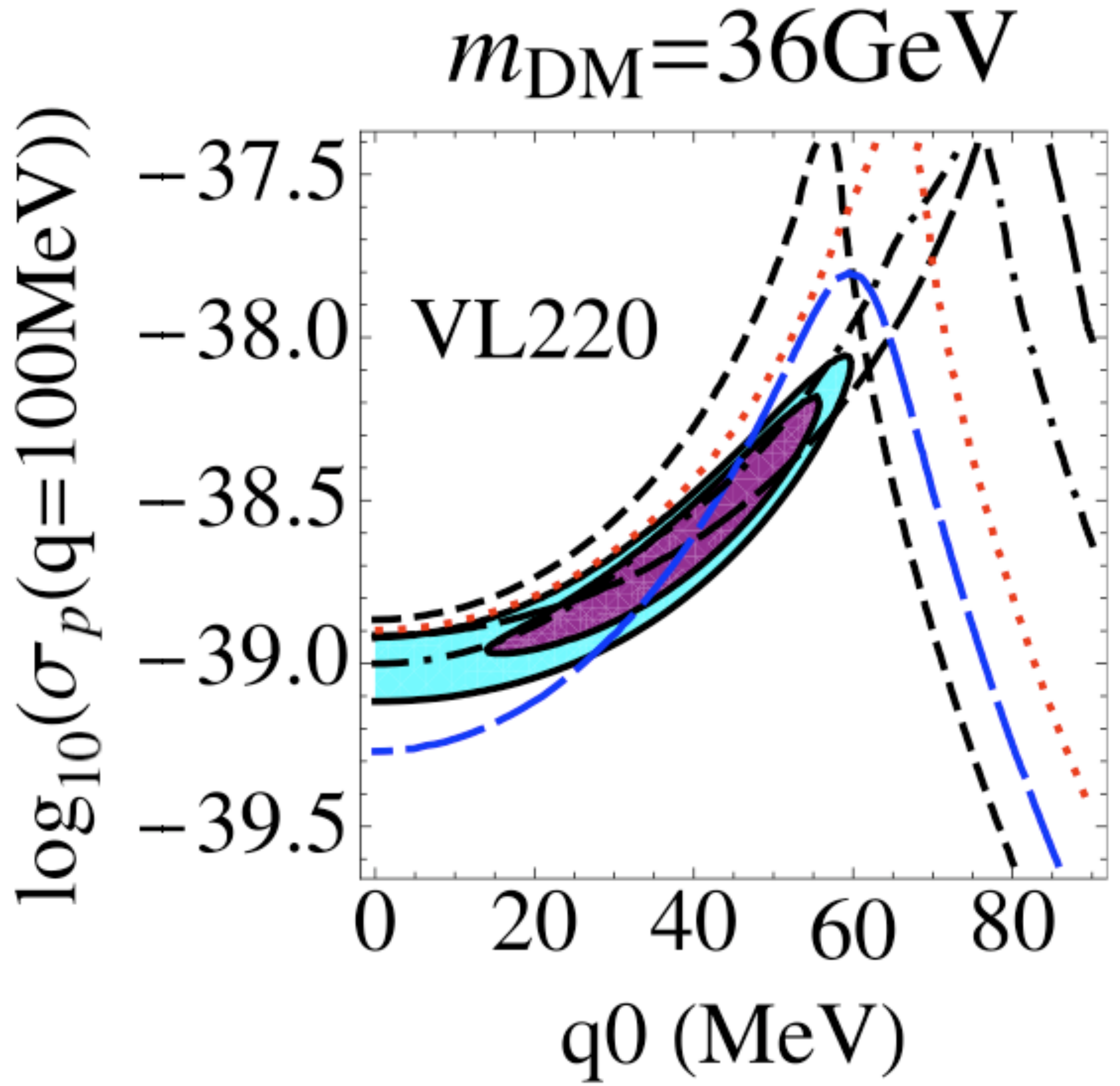


Thanks

Momentum-dependent interactions

arxiv:0908.2991

3 gauge boson model: some parameter space remaining



lower-mass dark matter with DM streams and/or channeling

PHYSICAL REVIEW D **79**, 115011 (2009)

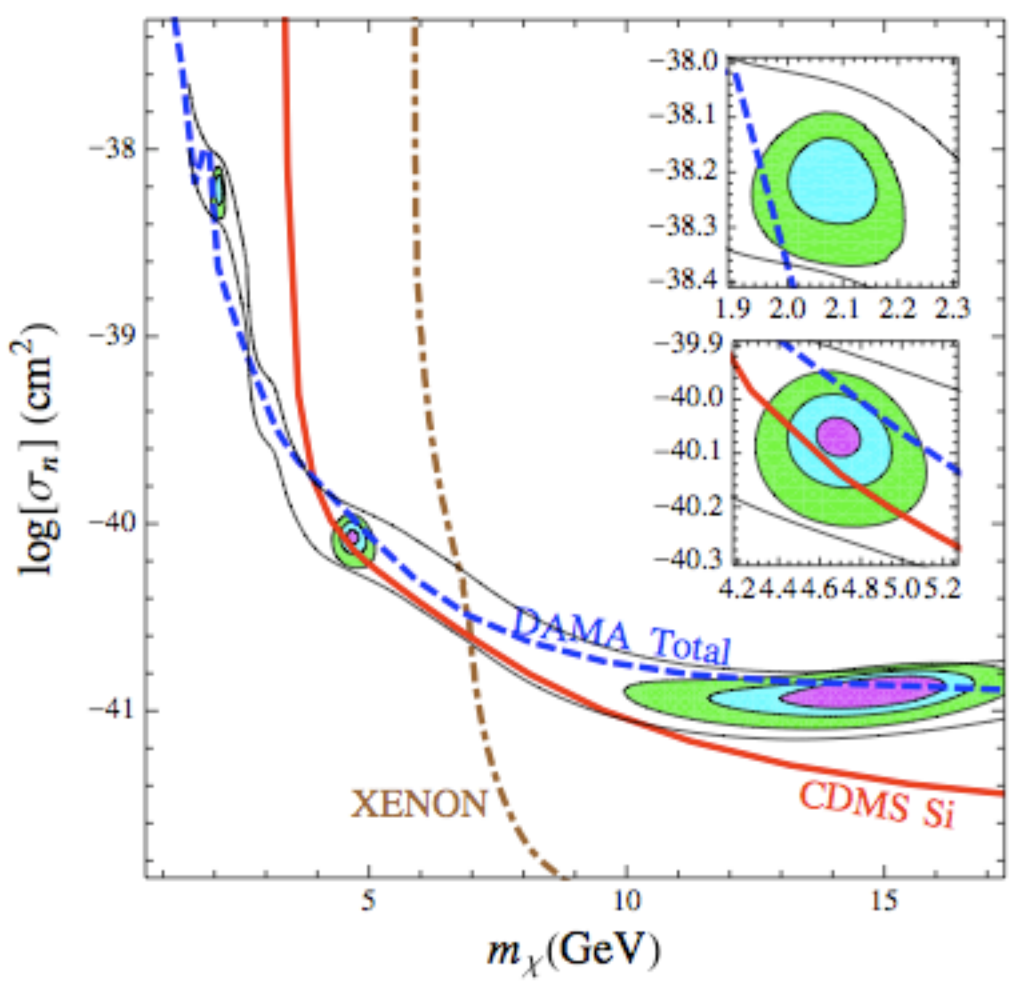


FIG. 3 (color online). Similar to Fig. 1, but incorporating a stream of DM, with $v_{str} = 900$ km/s, and $\sigma_{str} = 20$ km/s. Insets: magnification of parameter space near 2 and 4 GeV. The 2 GeV relies on both channeling and the stream; the 4 GeV region arises from unchanneled events from the stream.

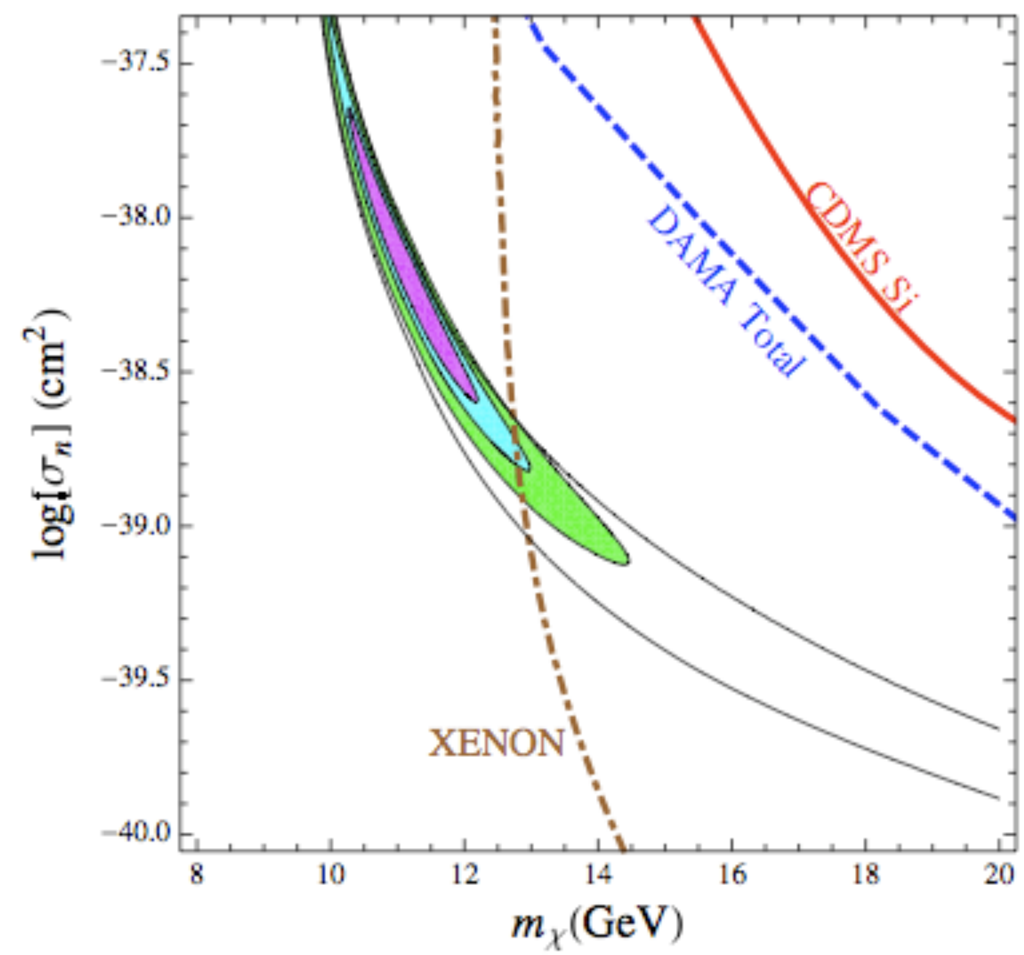
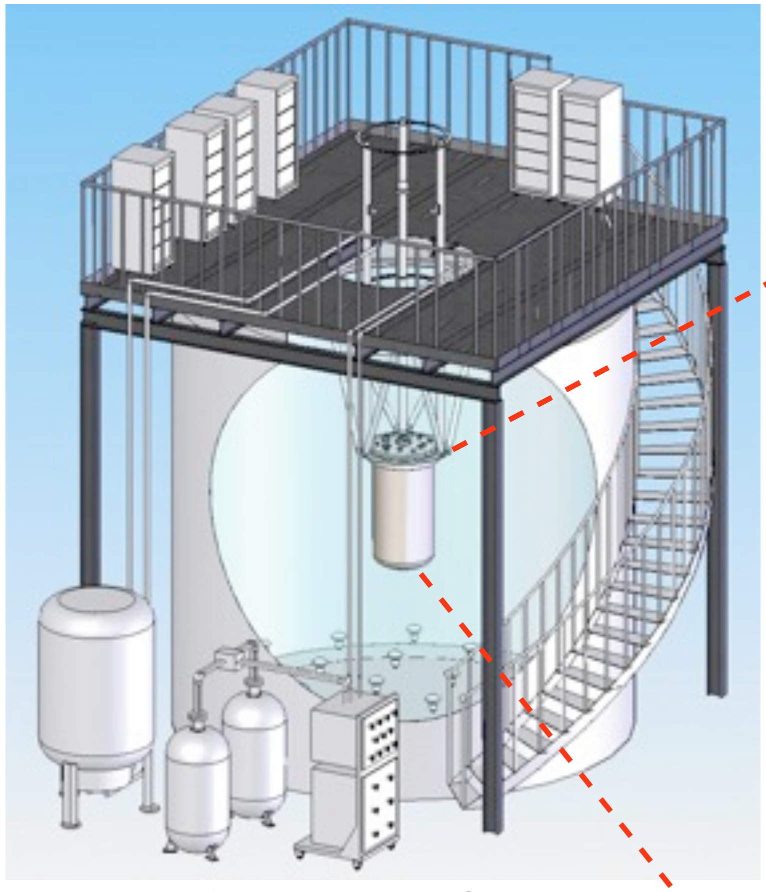


FIG. 4 (color online). Similar to Fig. 1, but including only inelastic scatterings, with $\delta = 35$ keV.

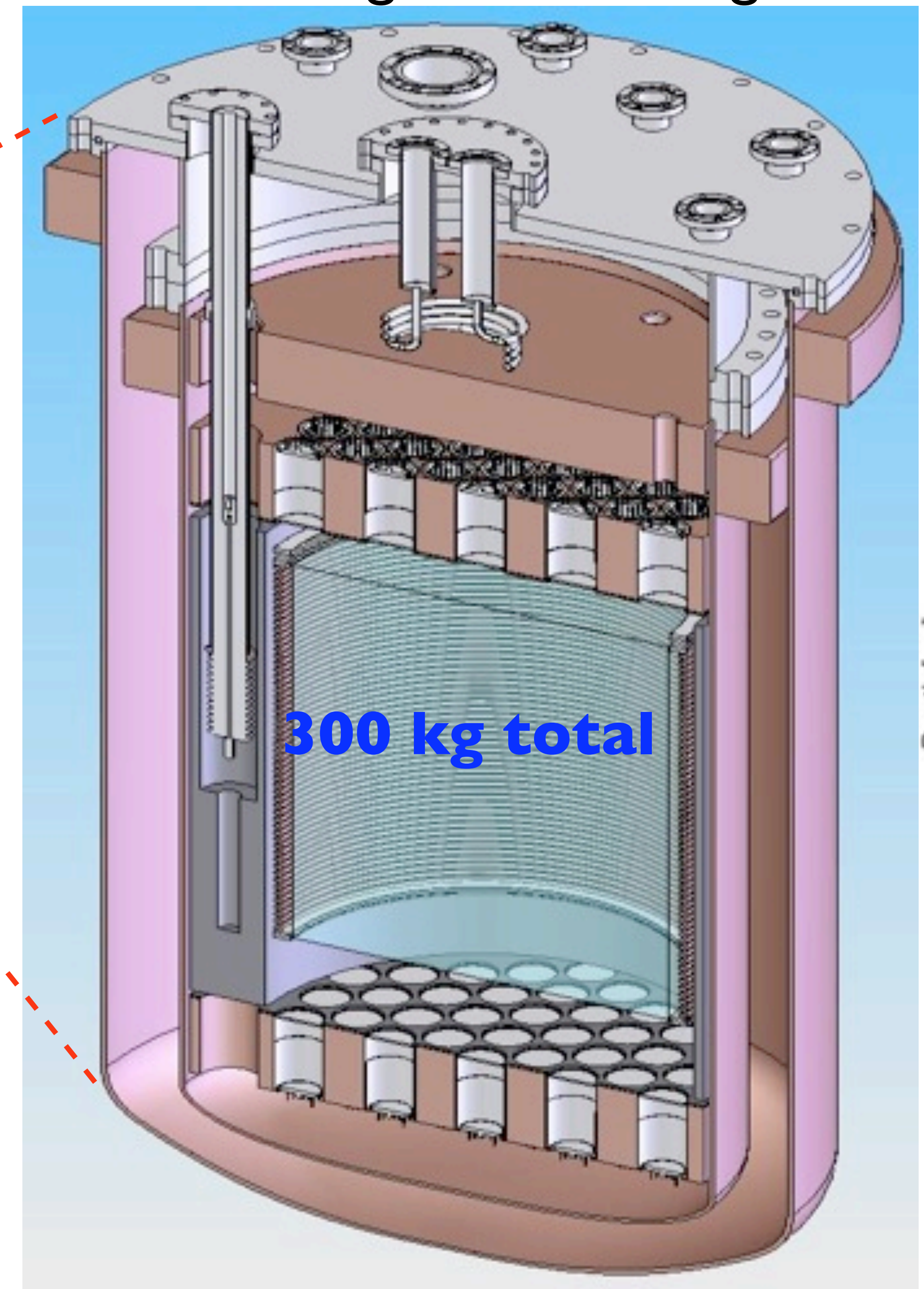
XENON10 progeny

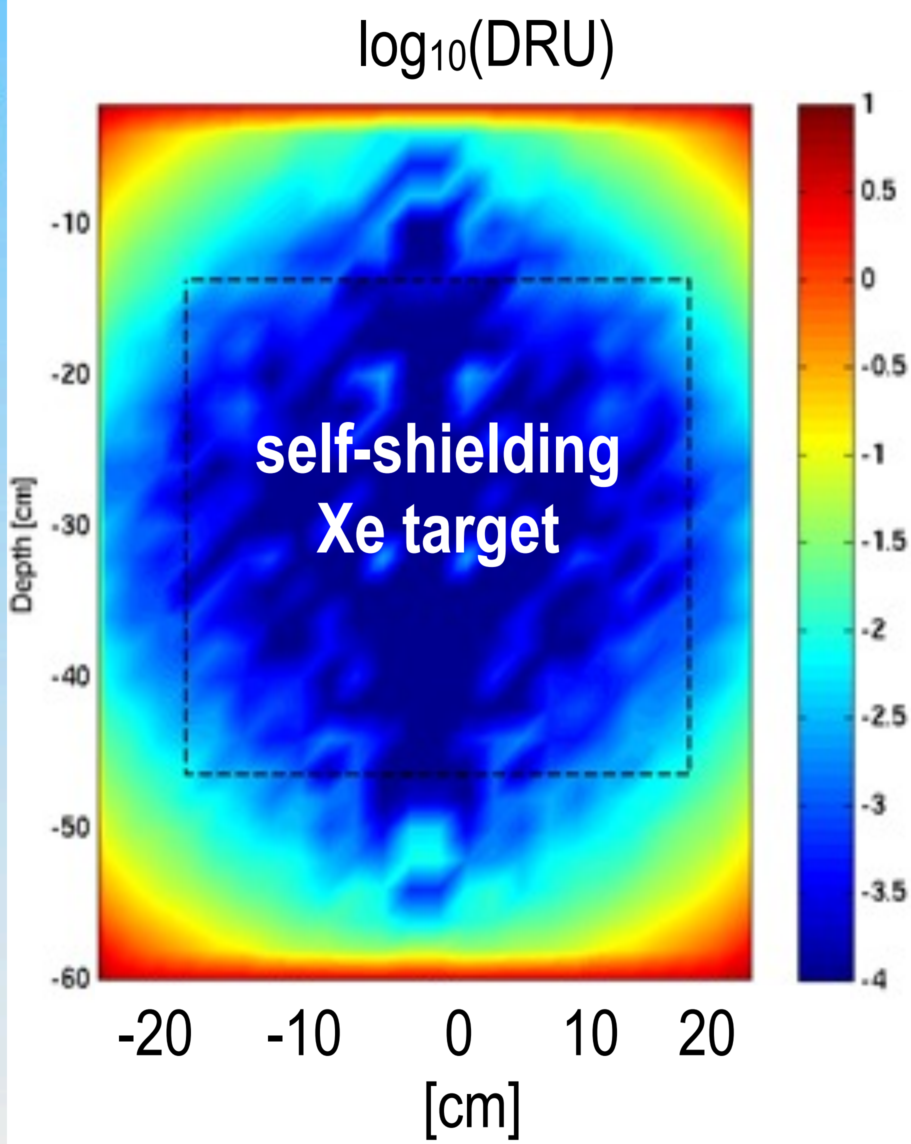
LUX (100 kg target), installation at DUSEL, Homestake Gold Mine, South Dakota

xenon target: 60 cm height, 50 cm diam.



6 m diam. H_2O shield





Nature's sense of humor (?)