First Results from the **LUX** Dark Matter Experiment

At the Sanford Underground Research Facility

Matthew Szydagis, UC Davis,
on behalf of the LUX collaboration

CosPA 2013

The LUX Collaboration

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Collaboration Meeting, UC Davis, October 2013

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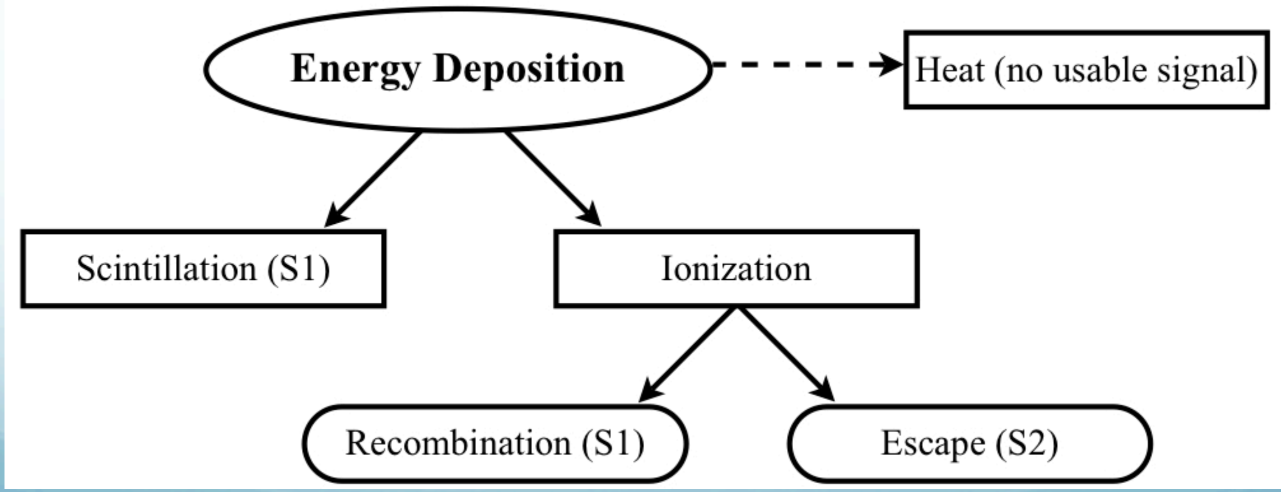
Direct Detection of WIMPs

- Body of evidence extensive for dark matter
  - Best-fit model for explaining the angular power spectrum of the CMB temperature anisotropy
  - Gravitational lensing
  - Large-scale structure observations and simulations
  - Galactic rotation curves
- All these point to a significant non-baryonic, non-relativistic component of matter (~85% of the matter or ~25% of total mass-energy in universe)
- WIMP is one possible candidate, and most searches are geared towards finding WIMPs
- Low-energy nuclear recoil (NR) are expected

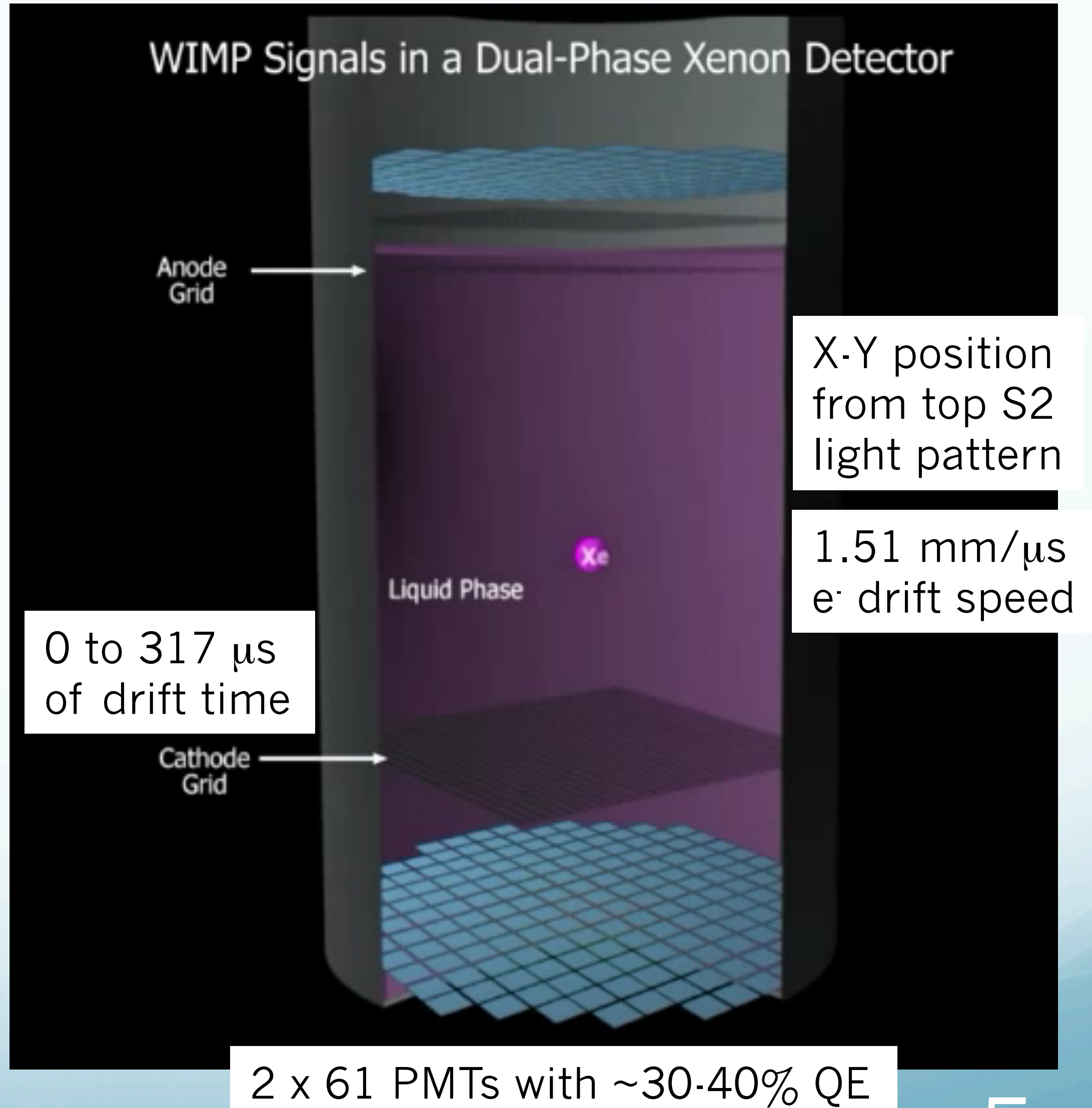
Noble Element Physics

- Energy ≠ S1: energy deposited into 3 channels ("heat" prominent for NR, reducing their S1 & S2)
- Excitation and recombination lead to the S1, while escaping ionization electrons lead to S2
- Scintillation comes from decaying molecules, not atoms. Not absorbed before it can be detected



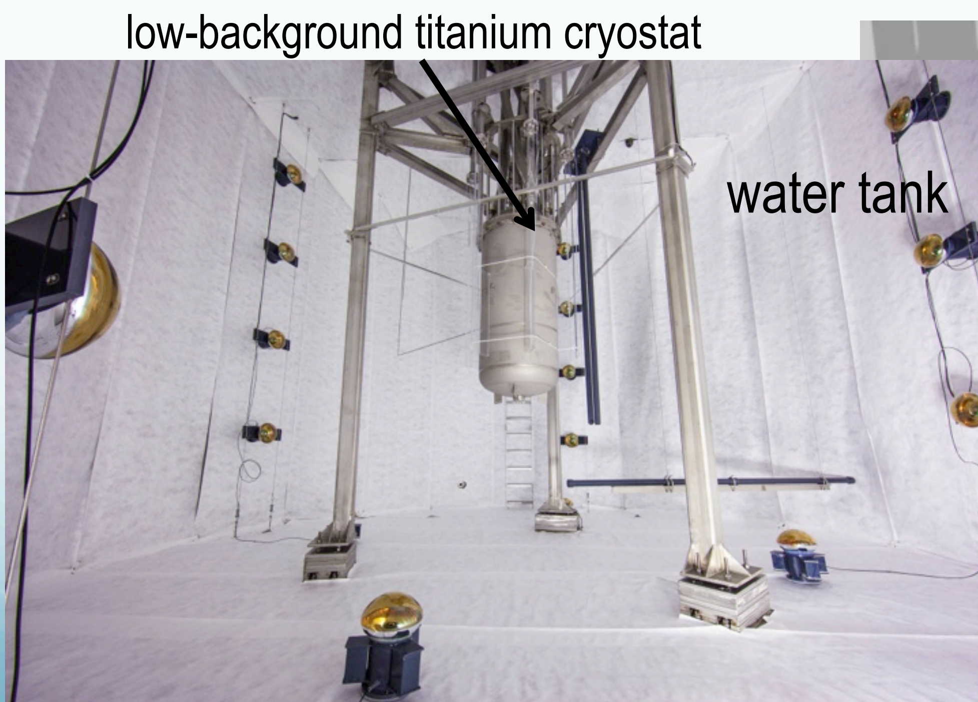
How LUX Works

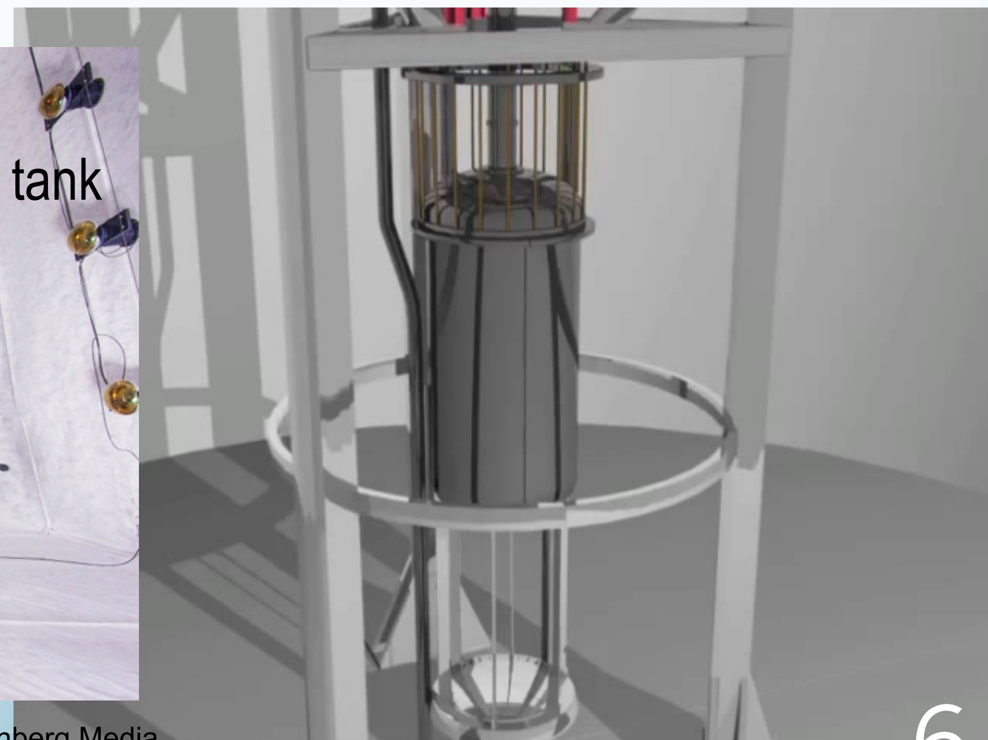
- **L**arge **U**nderground **X**enon experiment
- Two-phase xenon TPC
- The ratio of S2 to S1 forms the heart of the NR vs. ER (electron recoil) discrimination of the backgrounds
- Fiducialization and multiple-scattering rejection powerful: LXe dense, so it is good at self-shielding
- Non-blind analysis but cuts are very simple



Detector: By the Numbers

- 4300 m.w.e. depth at SURF in Lead, South Dakota (old Homestake Au mine)
- 6.1x7.6 m HxD water tank. 370 kg gross/250 active/118 fiducial Xe inside
- 48 cm H (gate to cathode) X 47 cm D active region with 181 V/cm drift field
- Good purity: 87-134 cm e^- m.f.p. over course of run (~500-900 us "lifetime")
- 6.0 kV/cm extraction field (3.1 in LXe) resulting in 65% extraction efficiency
- 200 phe S2 analysis threshold or mean 8 e^-'s (~25 phe/e^-) avoids low-e^- BGs





Animation: Harvard-Smithsonian Center for Astrophysics, Annenberg Media

"Combined" Energy Scale

$$\cancel{E_{\mathrm{nr}} = (S1/L_y)(1/\mathcal{L}_{\mathrm{eff}})(S_{\mathrm{ee}}/S_{\mathrm{nr}})}$$

$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$

W_{LXe} = 13.7 +/- 0.2 eV

- Energy a linear combination of the number of primary photons n_γ and electrons n_e generated
- Photon count equal to S1 phe (XYZ-corrected using 10^6+ Kr83m events) divided by collection efficiency (light collection x PMT QE), and electron count is S2 phe (XYZ-corrected) divided by the product of extraction efficiency and the number of phe per e^-
- Scale calibrated using Xe activation lines, Kr83m, and tritium ($\mathcal{L}$=1 for ER). Hitachi-corrected Lindhard factor assumed for NR (k=0.11 not 0.166) which matches LUX + other general NR data

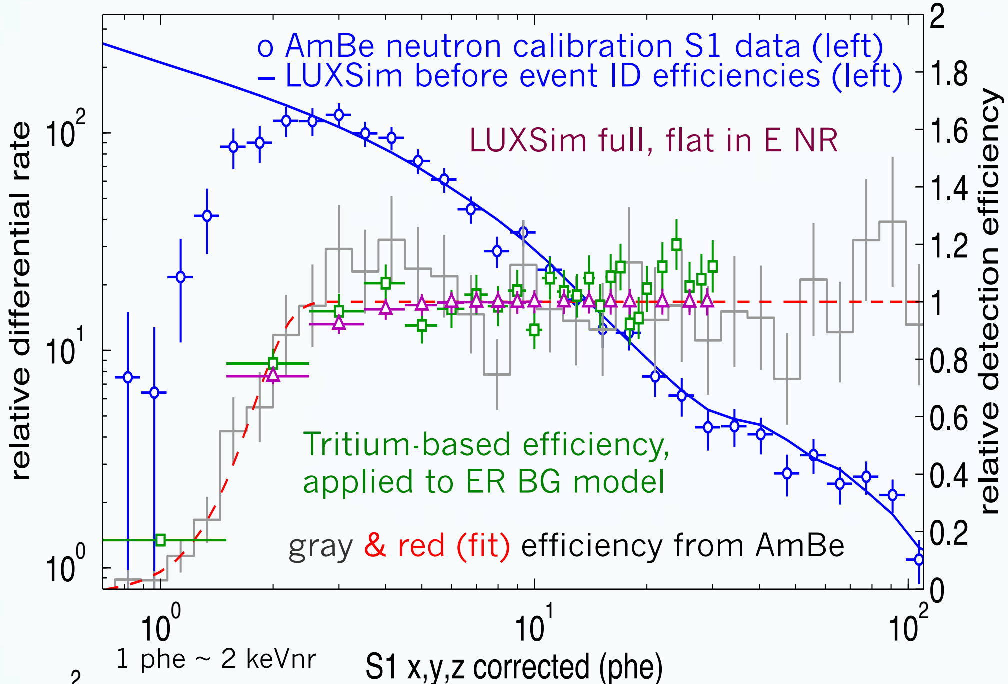
Light Collection

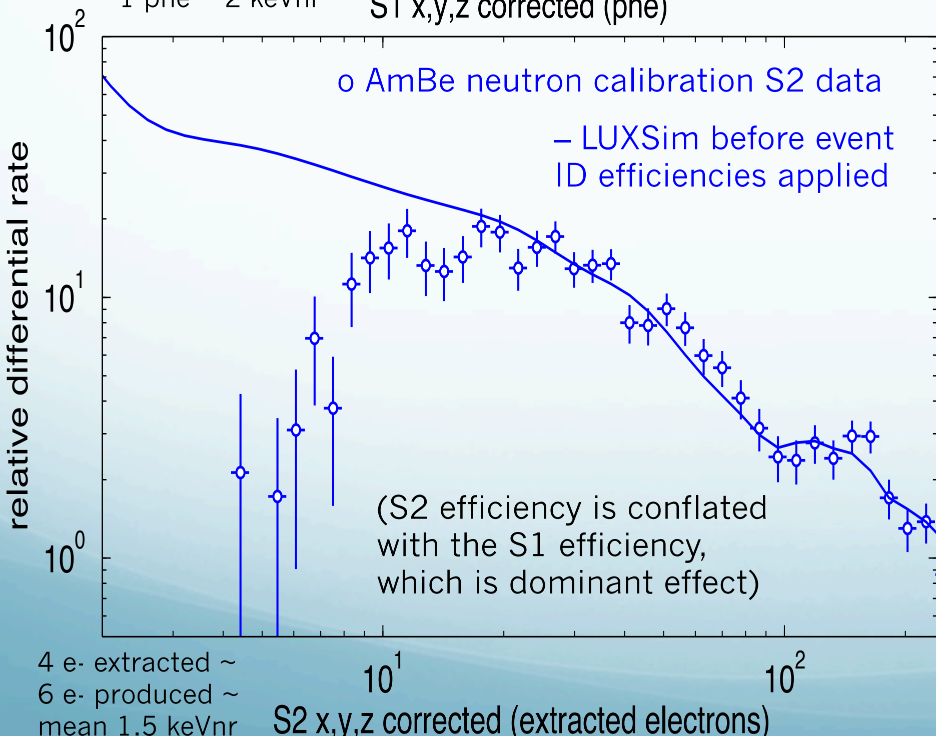
Non-VUV-reflective metallic surfaces covered with Teflon. Estimated zero-field yield at 122 keV of 8.8 phe/keV. Compare to XENON100 which also uses NEST to make the calculation: 2.28 / 0.58 = 3.9 phe/keV, >2x smaller.

XENON100 Co-57 est. yield: 2.28 phe/keV @730 V/cm, with value 0.58 of what it is at 0 V/cm (well-established)

- Field-shaping rings, and spaces between PMTs all covered with PTFE (measurements consistent with >95% reflectivity)
- 14% efficiency for the detection of a primary scintillation photon at the PMTs after journey
  - From center of detector
  - Varies from 11 to 17% between top and bottom
  - Mapped out with Kr83m
  - Total internal reflection causes most light to be in bottom PMT array
  - Cross-checked: different sources, methods

Pulse Finding





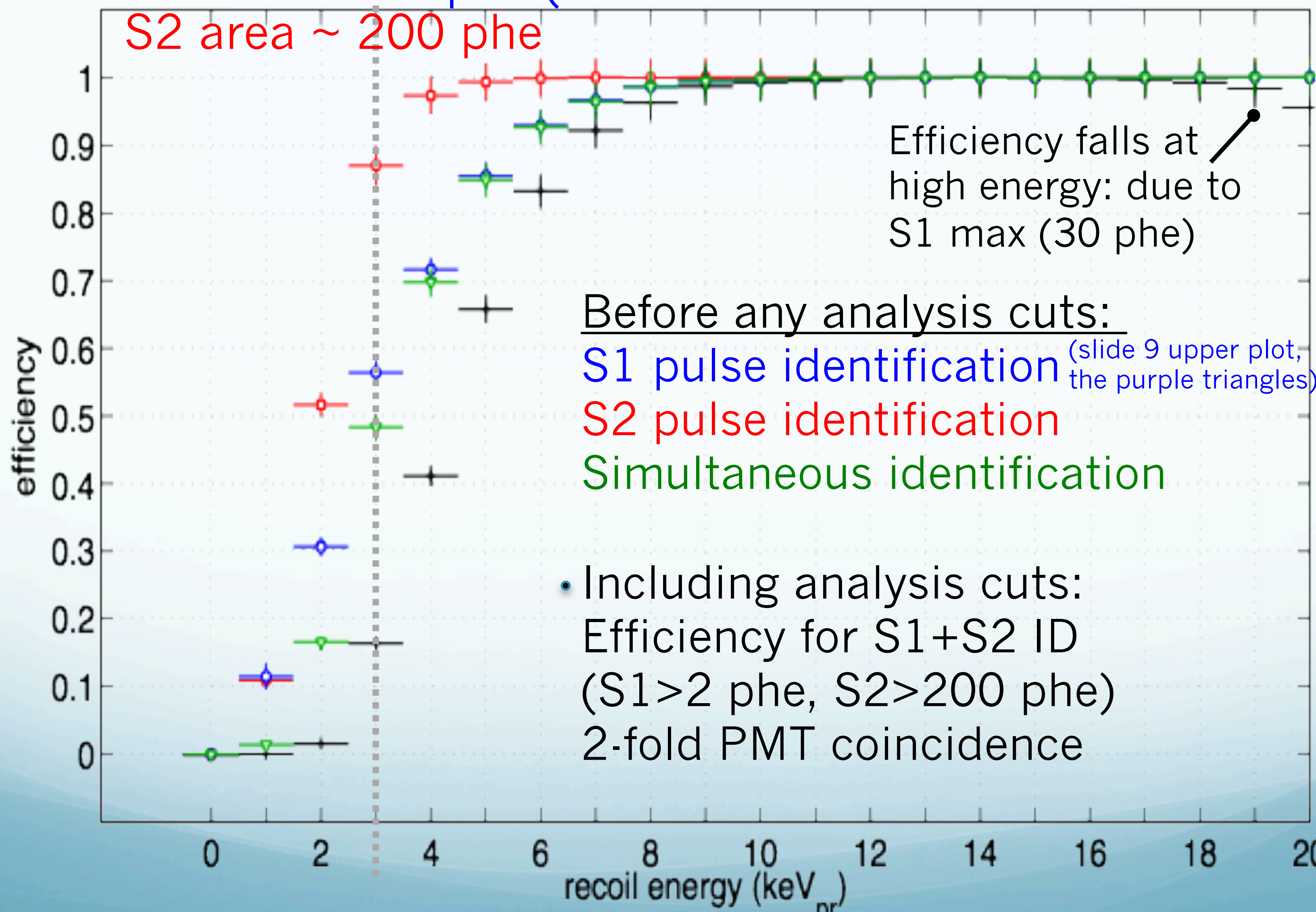
- Studied in great detail
  - AmBe / Cf-252 calibrations, effective at producing low-E NR
  - Tritiated (H-3) methane
  - Full Monte Carlo (processed like real data)
- Excellent agreement observed when assuming NEST light yield and deriving NR efficiency versus looking at efficiency of tritium S1 signal
- Hand-scan estimated absolute efficiency 98% cross-checked against expected number of H-3 injection events

All Pulse Finding Efficiencies

3 keVnr (true, not reconstructed)

S1 area ~ 2.0 phe (no sub-threshold fluctuations assumed)

S2 area ~ 200 phe



Efficiency falls at high energy: due to S1 max (30 phe)

Before any analysis cuts:

S1 pulse identification (slide 9 upper plot, the purple triangles)

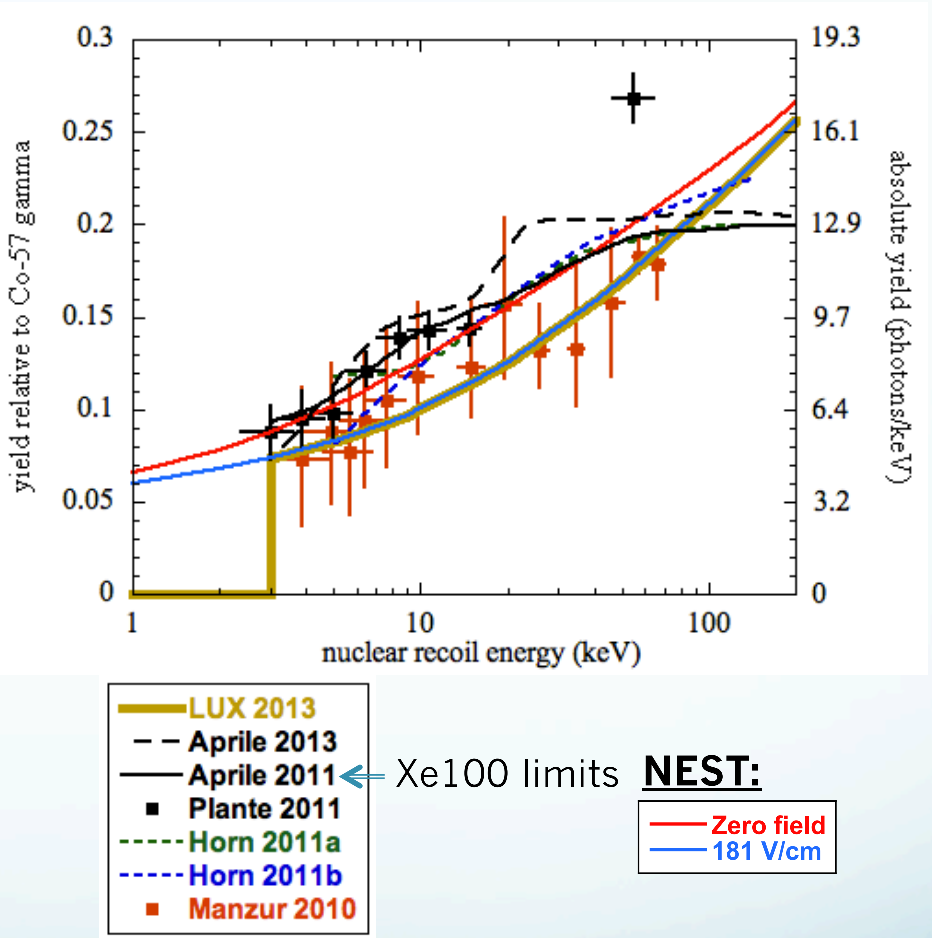
S2 pulse identification

Simultaneous identification

- Including analysis cuts: Efficiency for S1+S2 ID (S1>2 phe, S2>200 phe) 2-fold PMT coincidence

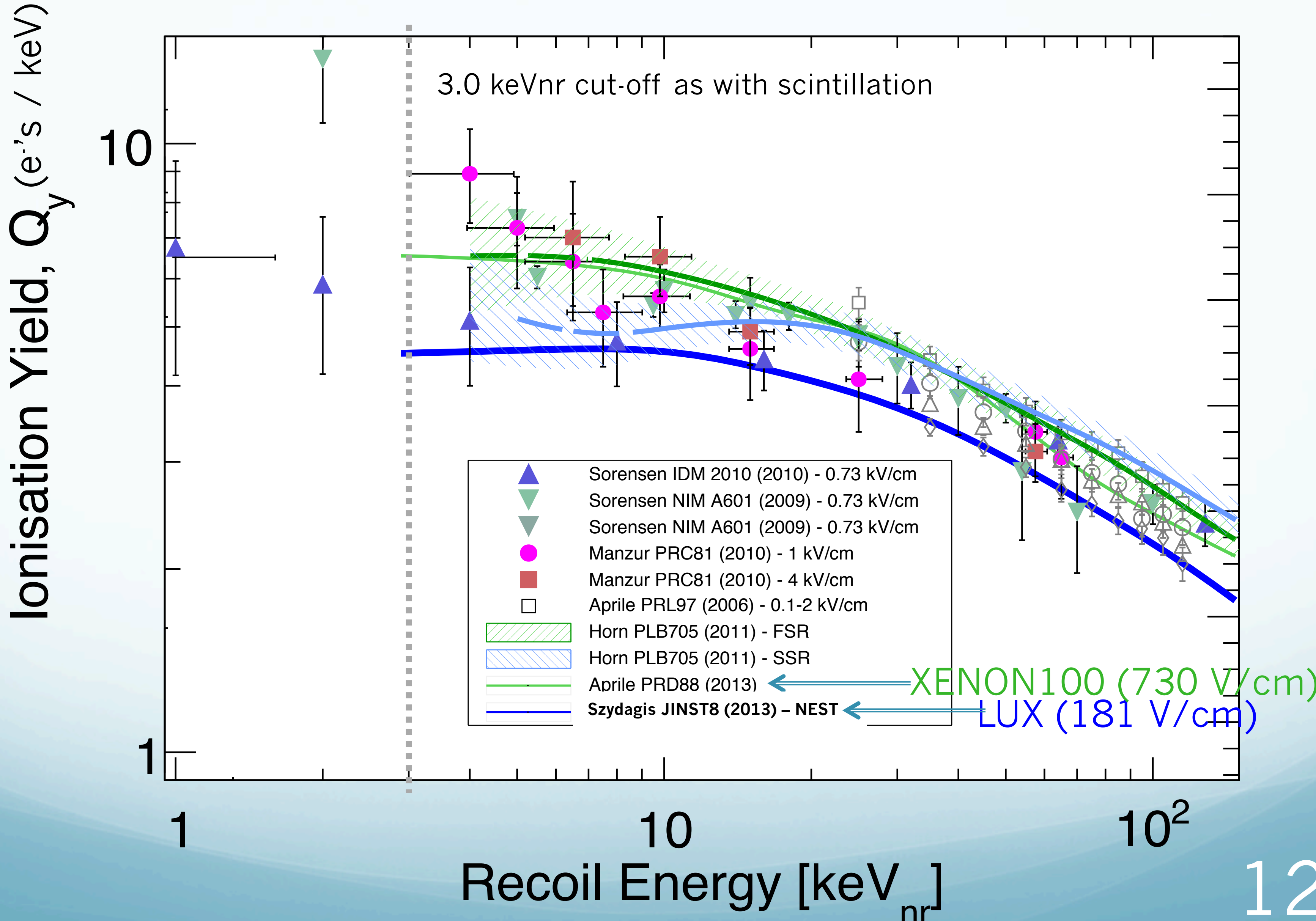
Scintillation Yield

- Modeled using NEST (the **N**oble **E**lement **S**imulation **T**echnique)
  - Based on canon of existing experimental data
  - Includes thesis data of Eric Dahl, from five different fields (60, 522, 876, 1951, 4060 V/cm)
  - Extracted energy-dependent light suppression factors (S_{nr}, S_{ee}) for electric field (at expense of charge via recombination probability)
  - Result is conservative approach (~0.8 of light at 181 V/cm compared to 0 V/cm): compare with past (0.90-0.95 assumed, for much higher fields) and LAr
  - Conservative, but also predictive, and matches LUX data!
- No need to use 63 photons/keV Co-57 zero-field (can't penetrate anyway), and non-linearity in ER yield re-proven by recent Compton scattering results handled



Data taken at non-zero field is translated by those reporting the results, assuming reduction of 0.95 (Aprile 2013, 730 V/cm) or 0.9 (Horn 2011, ~4000 V/cm, from ZEPLIN-III). LUX is 181 V/cm. All other data points actually taken at zero field.

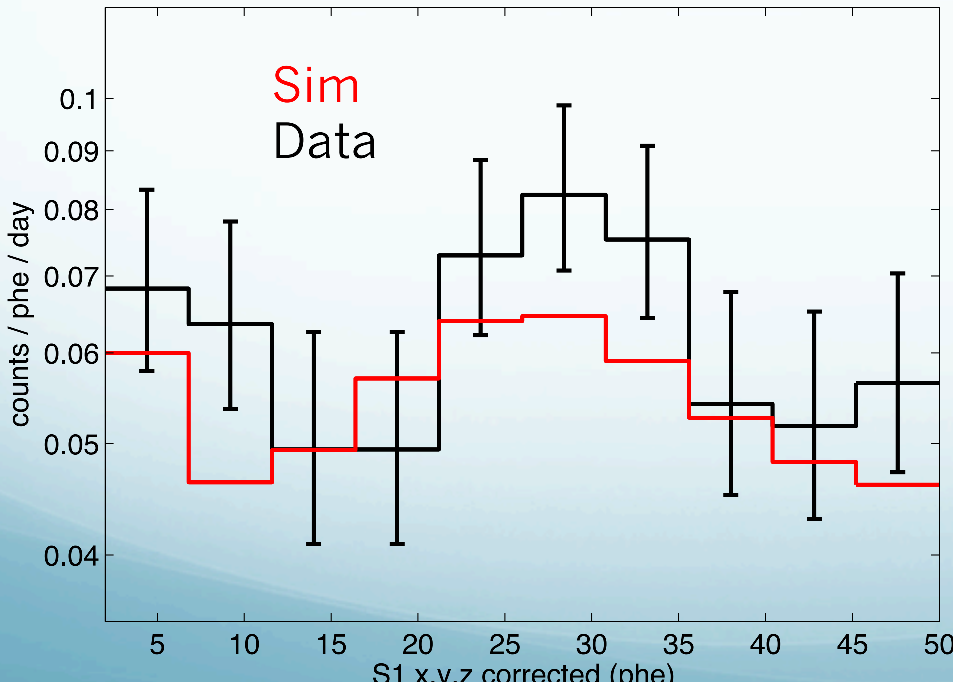
Ionization Yield

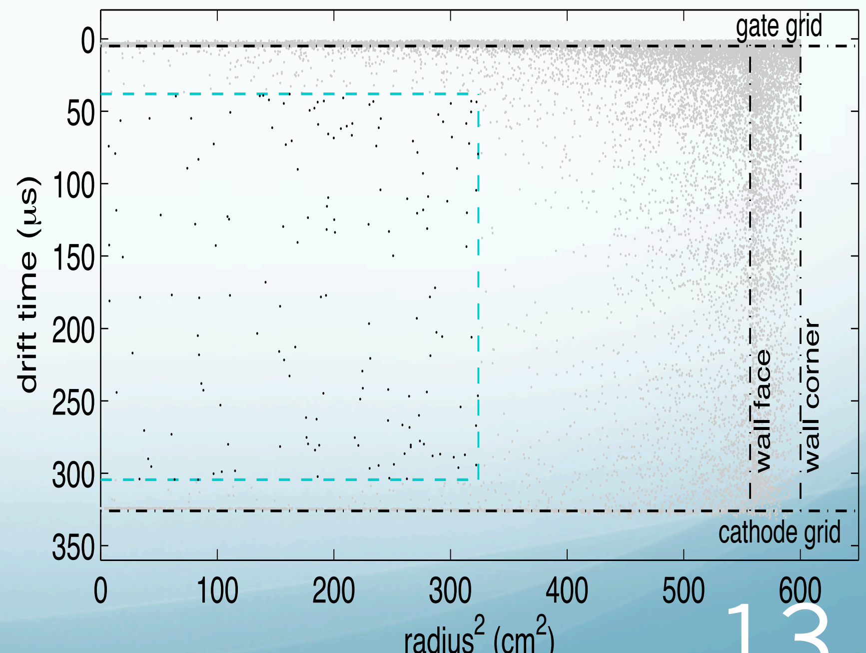


Backgrounds

- $3.1 \pm 0.2 \times 10^{-3}$ counts/(keV-kg-day) in region of interest
- Averaged over April-August WIMP search (85.3 live-days)
- 3.5 ppt Kr (measured)
- Getting better: cosmogenics from surface run decaying away

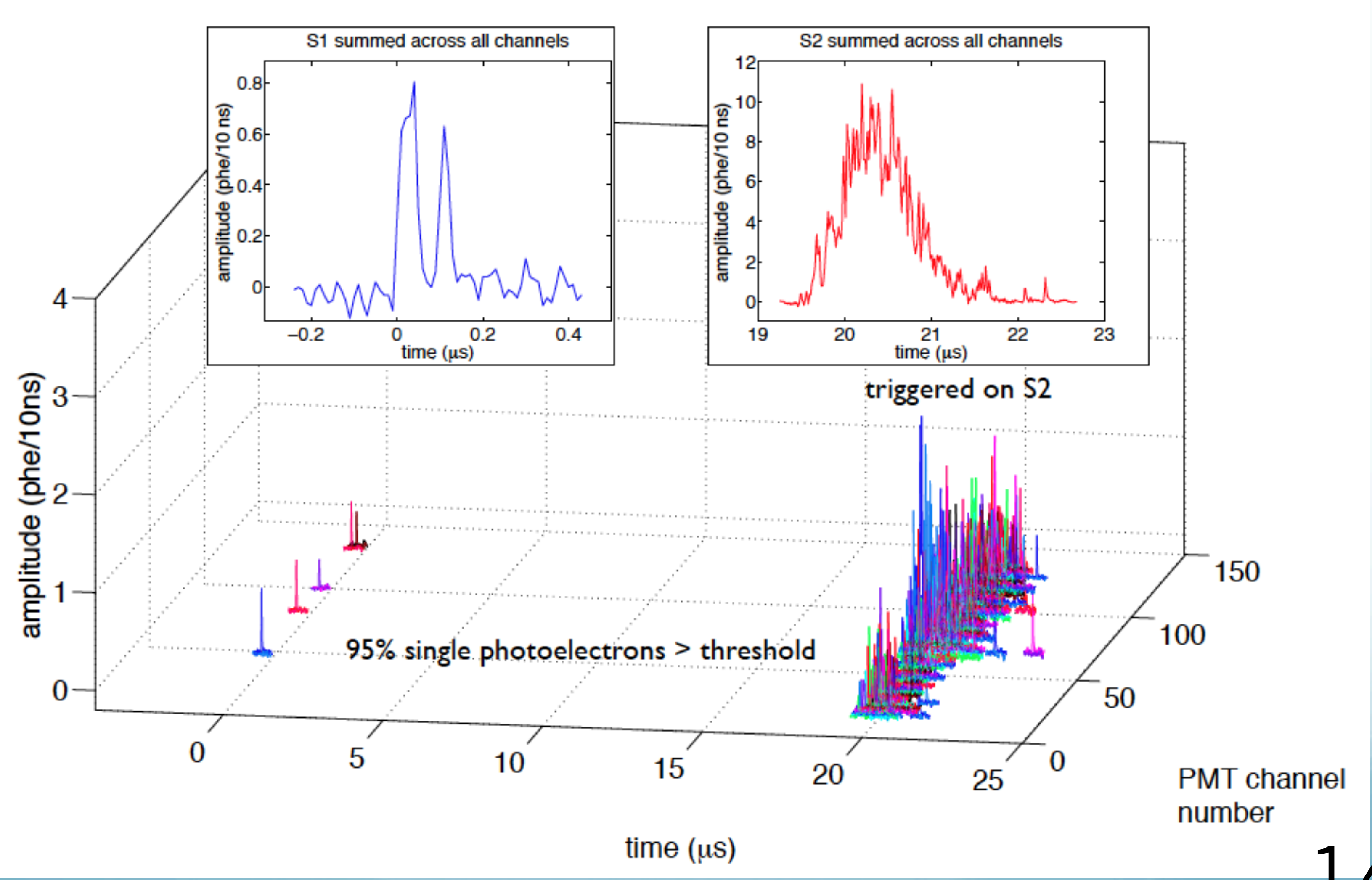
Source	Background rate, mDRU_{ee}
γ-rays	$1.8 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}$
^{127}Xe	$0.5 \pm 0.02_{\text{stat}} \pm 0.1_{\text{sys}}$
^{214}Pb	0.11–0.22 (90% C. L.)
^{85}Kr	$0.13 \pm 0.07_{\text{sys}}$
Total predicted	$2.6 \pm 0.2_{\text{stat}} \pm 0.4_{\text{sys}}$
Total observed	$3.1 \pm 0.2_{\text{stat}}$



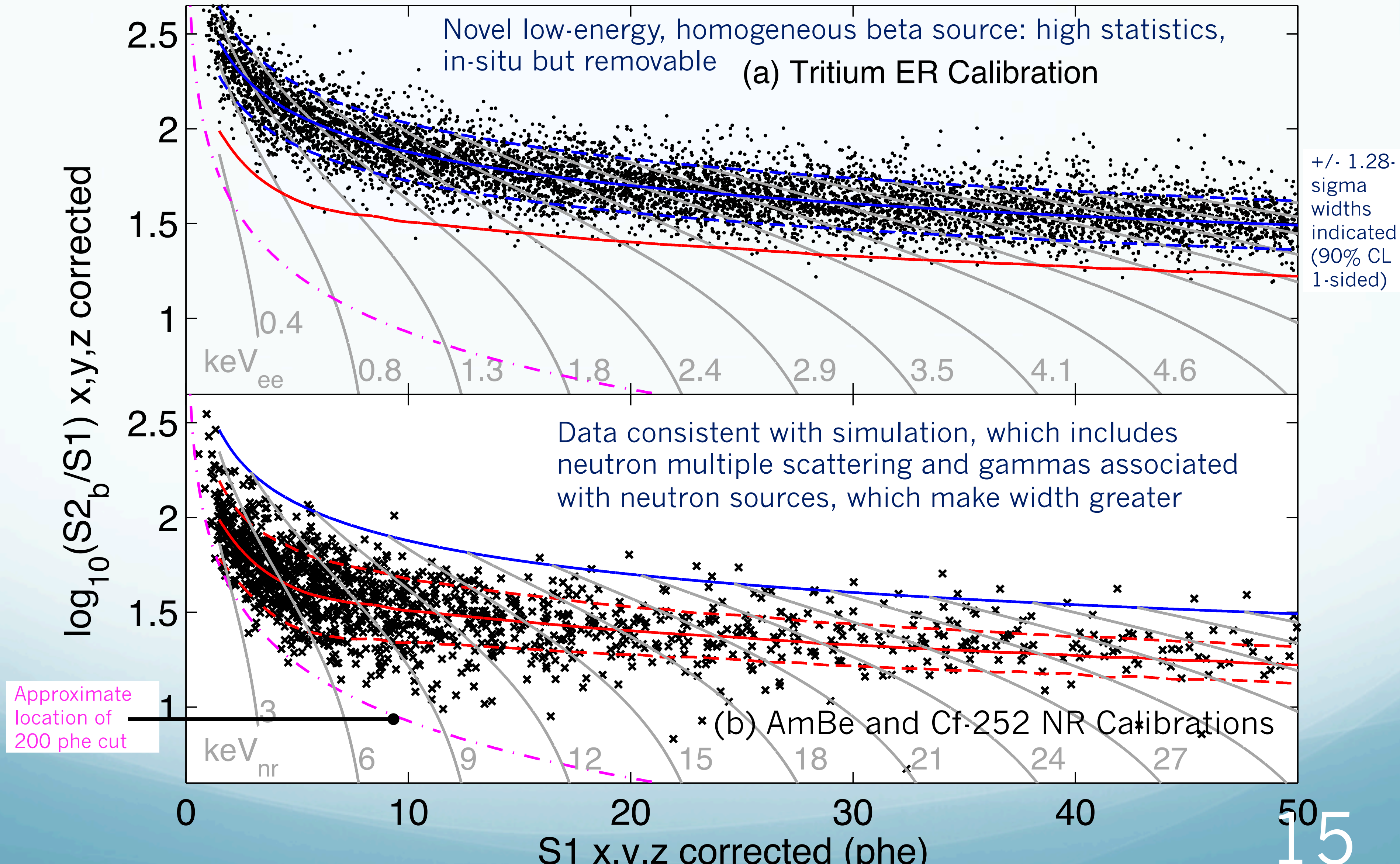


What a Typical Event is Like

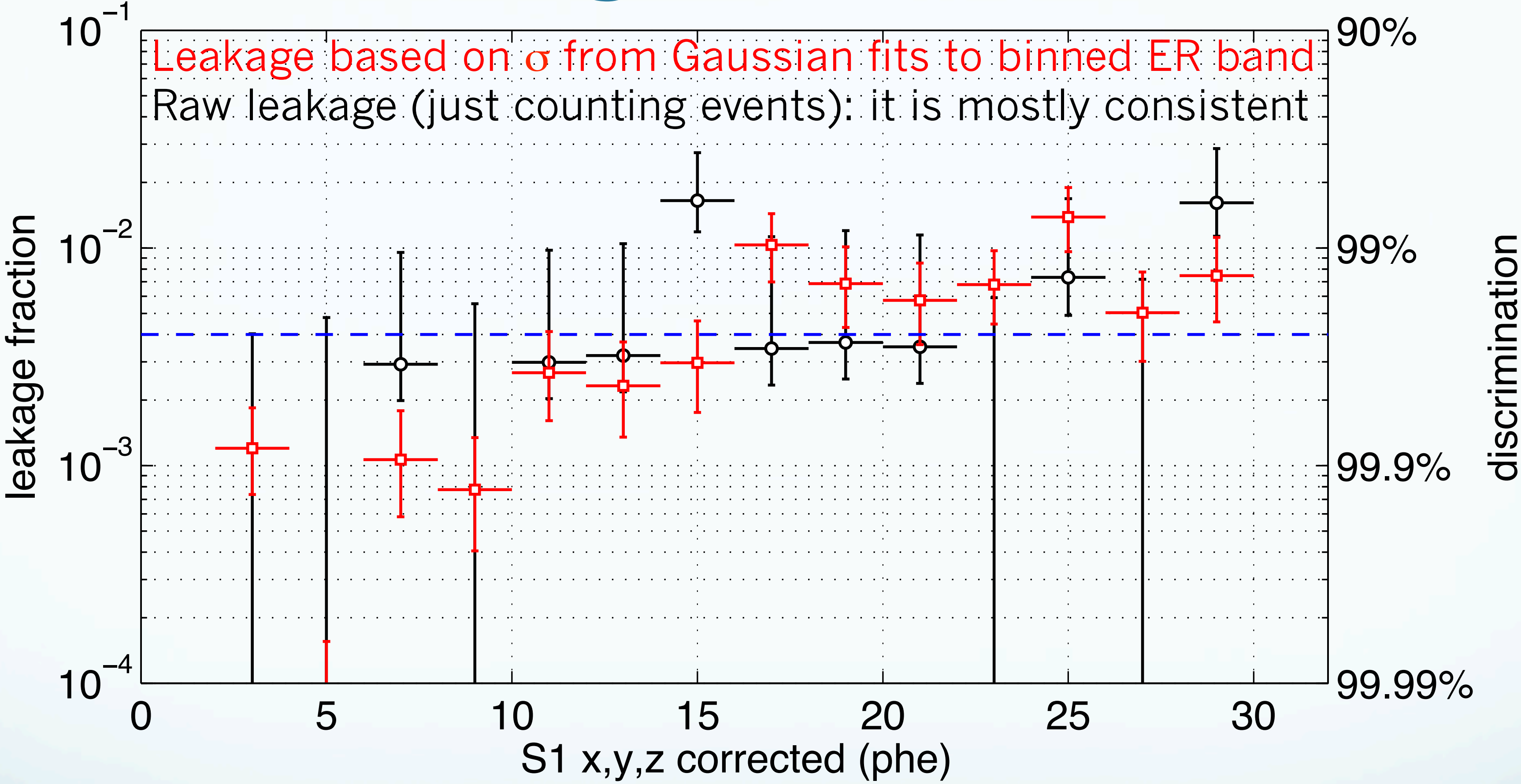
1.5 keVee (combined energy reconstruction) ER event



ER and NR Band Calibrations

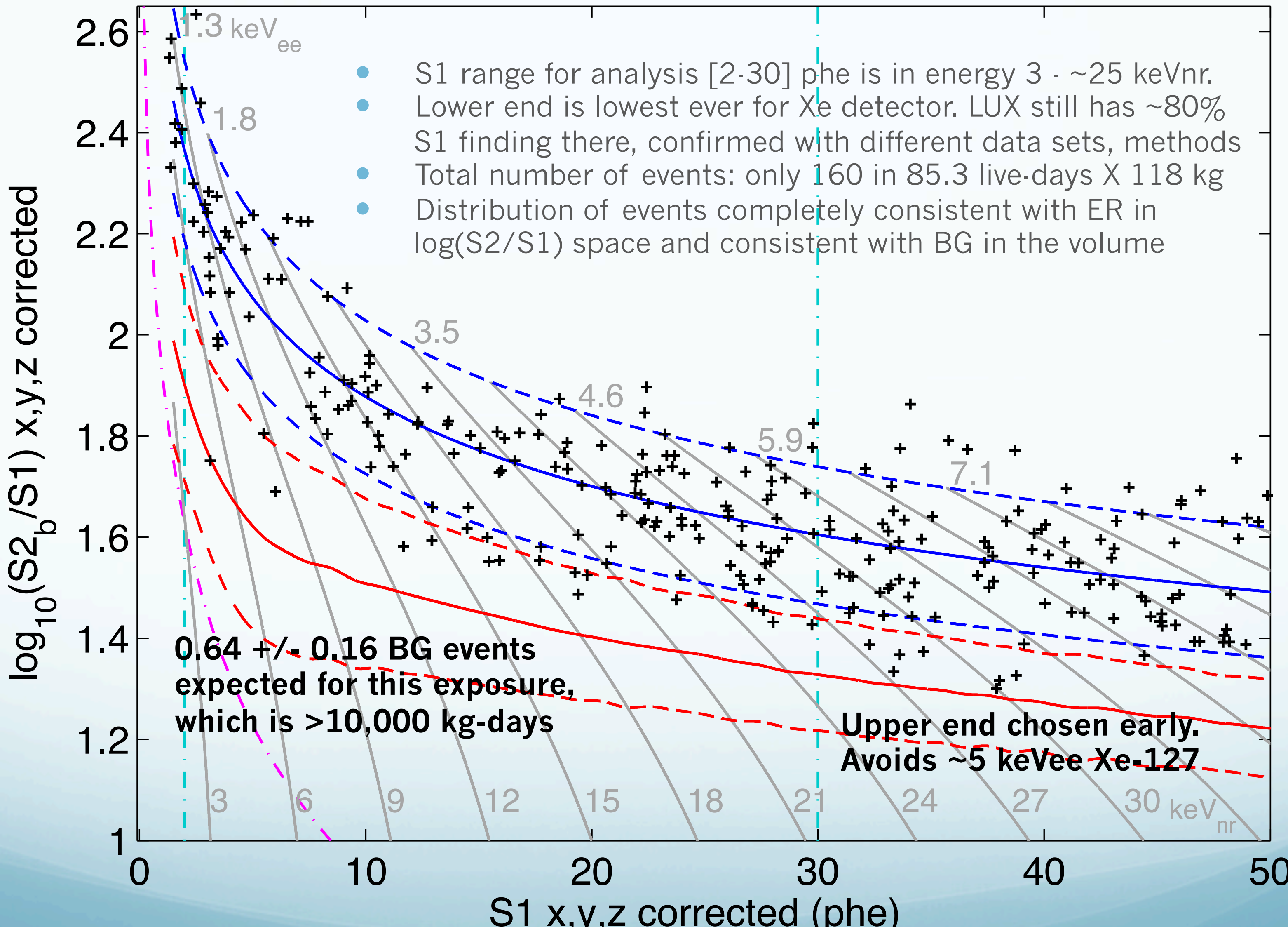


ER Leakage into NR Band

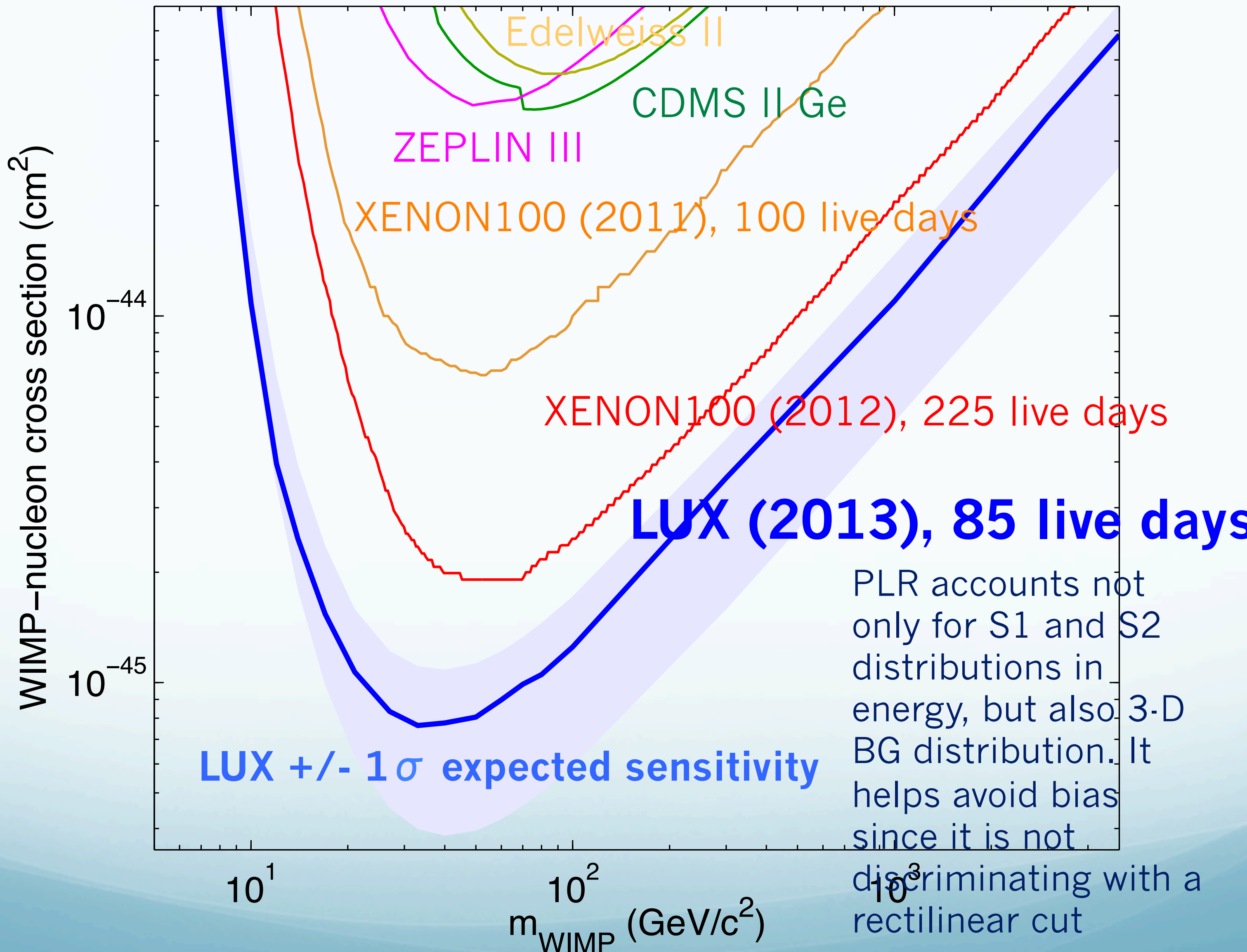


- Mean leakage 0.4 +/- 0.1% (2-30 phe S1 region) accepting all NR events below power law fit to the NR Gaussian mean in slices
- Light collection appears to be as important as field for leakage
- Not used directly in our limit calculation, which is a PLR (Profile Likelihood Ratio) not cut-and-count, but illustrates separation

WIMP Search Result

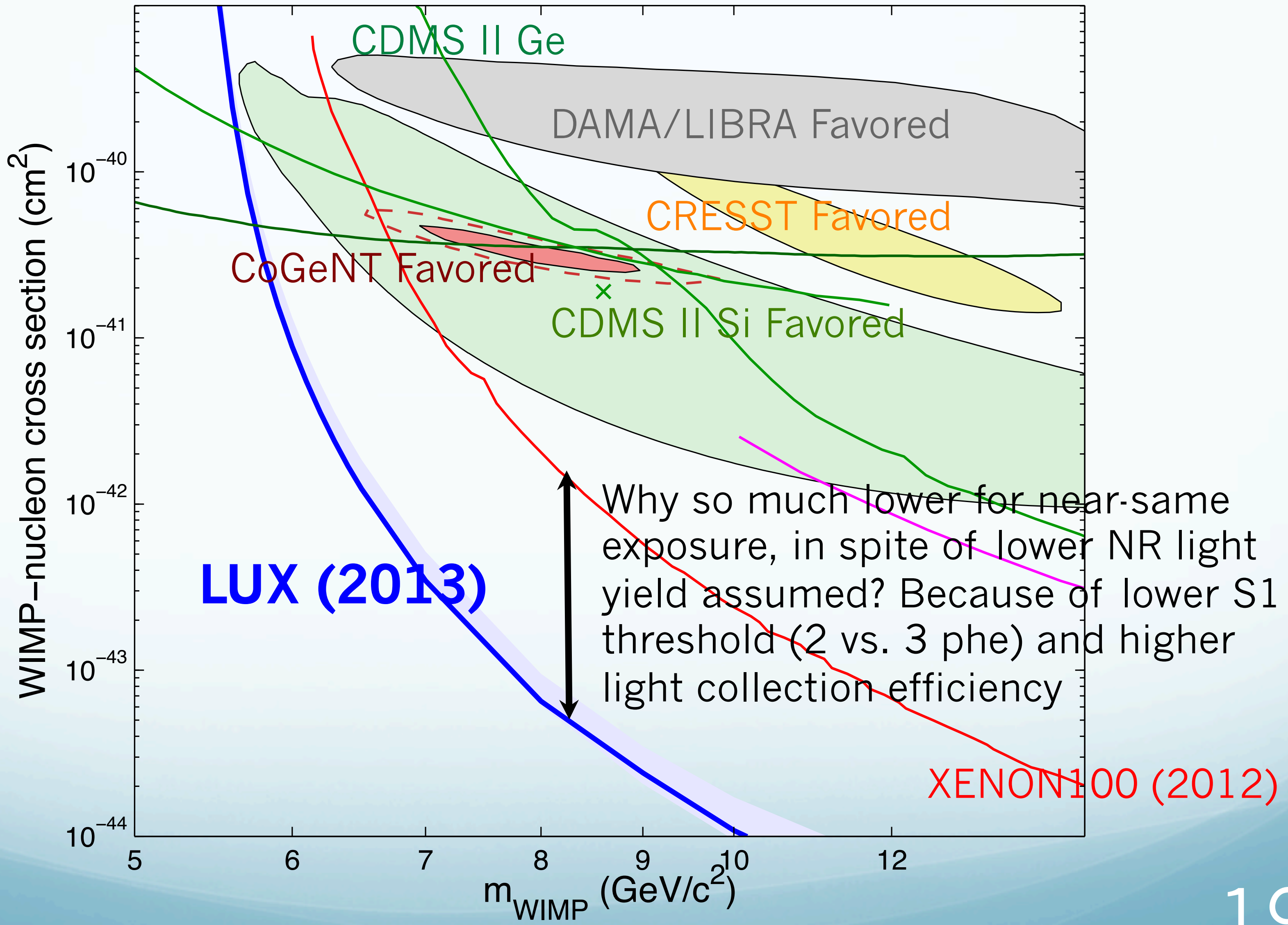


WIMP Dark Matter Limit



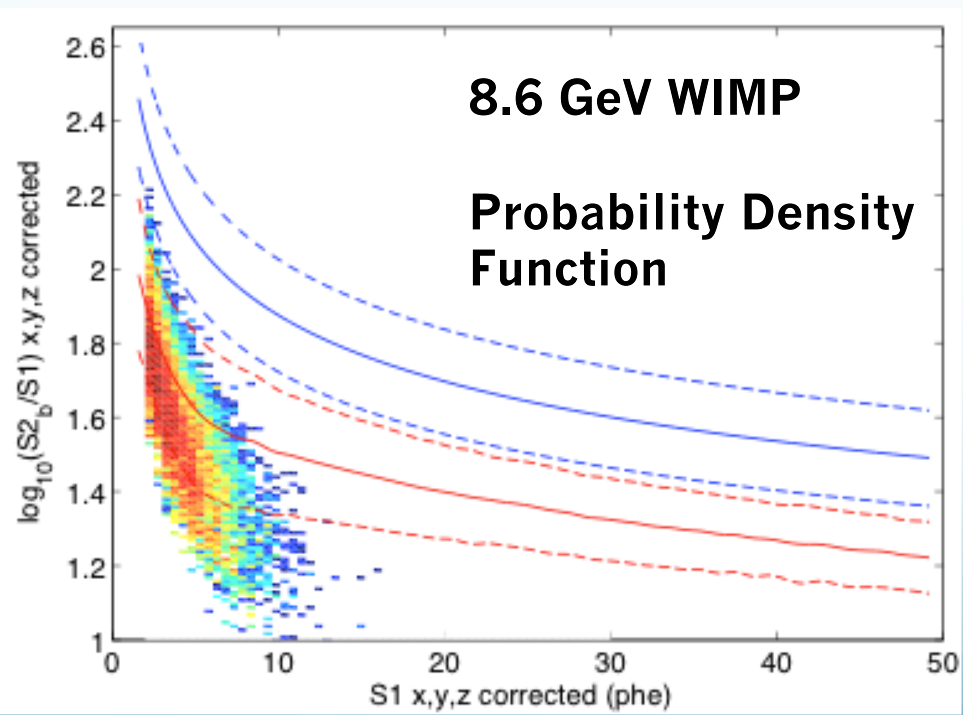
PLR accounts not only for S1 and S2 distributions in energy, but also 3-D BG distribution. It helps avoid bias since it is not discriminating with a rectilinear cut

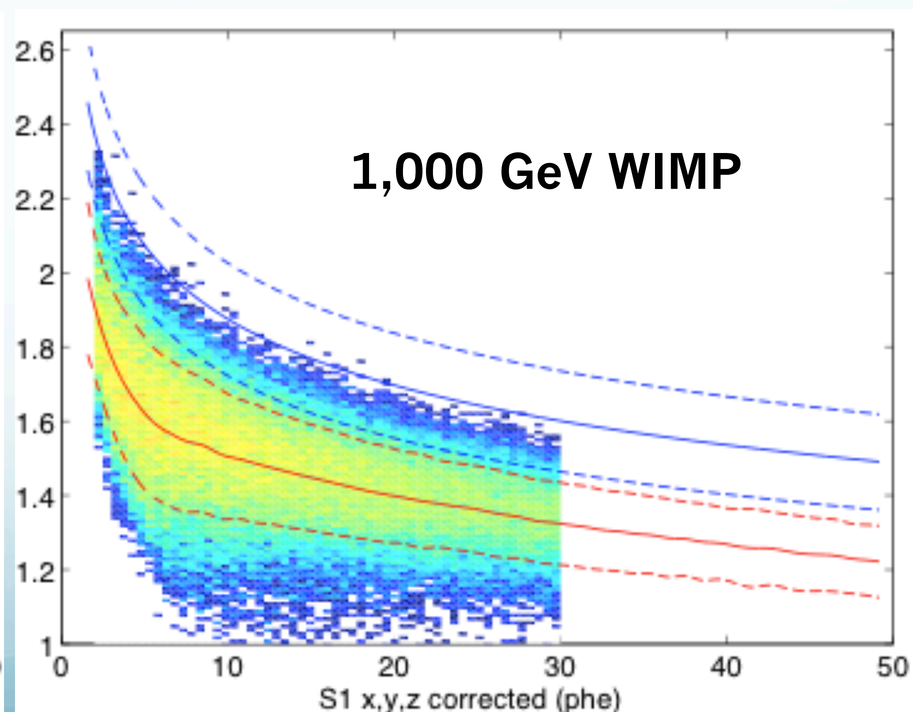
Low-Mass WIMP Region



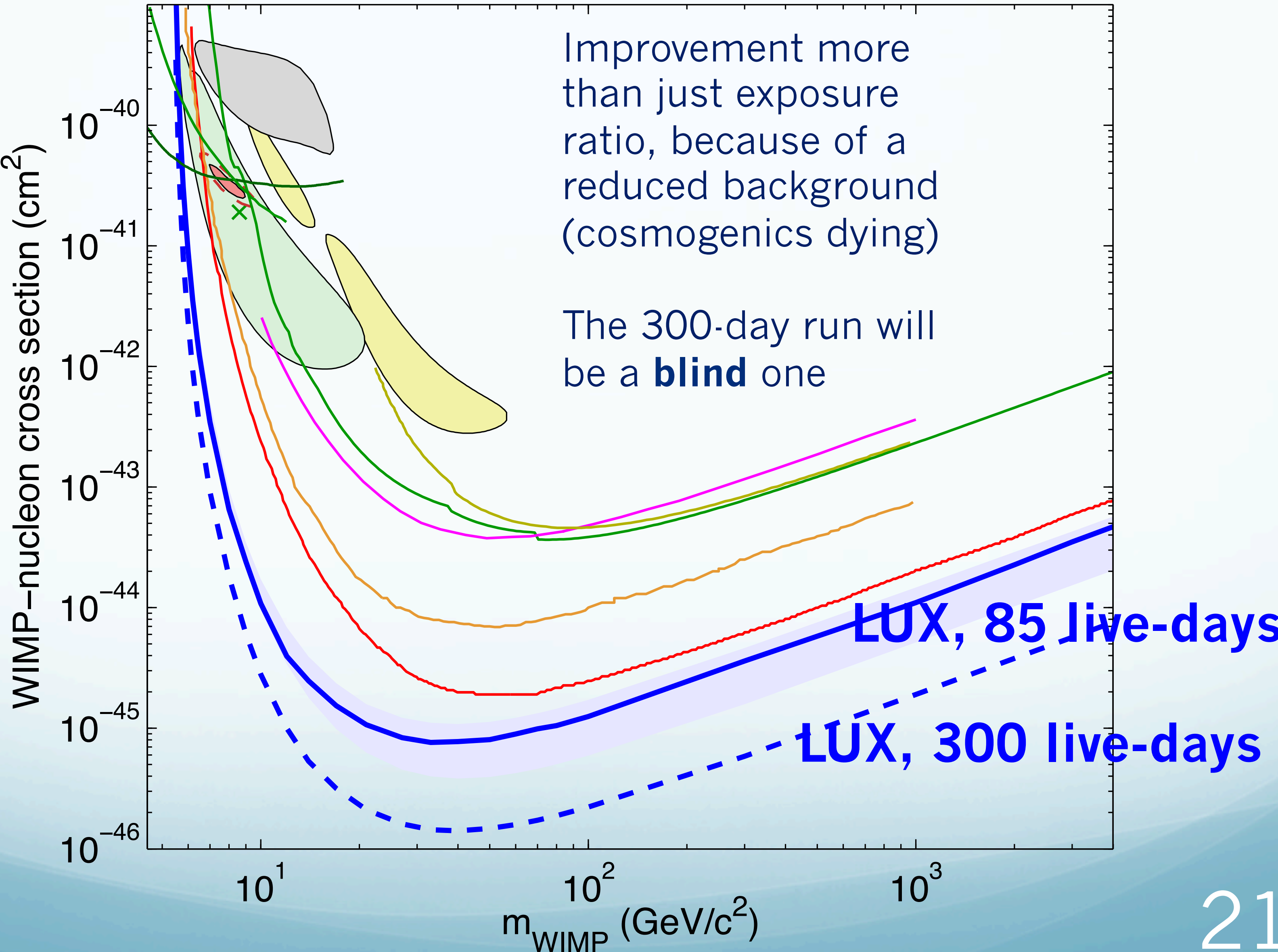
Sensitivity at Different Masses

- Signal model examples for different WIMP masses, which have unique recoil spectra and lack effects applicable only to neutrons
- Lower-mass WIMPs not only produce less energetic recoils but appear lower in log(S2/S1) space: detections would be from upward fluctuations in S1, making them more different from ER
- This is qualitatively true no matter what the yields for NR are!





A Bright Future Anticipated



Improvement more than just exposure ratio, because of a reduced background (cosmogenics dying)

The 300-day run will be a **blind** one

CONCLUSION

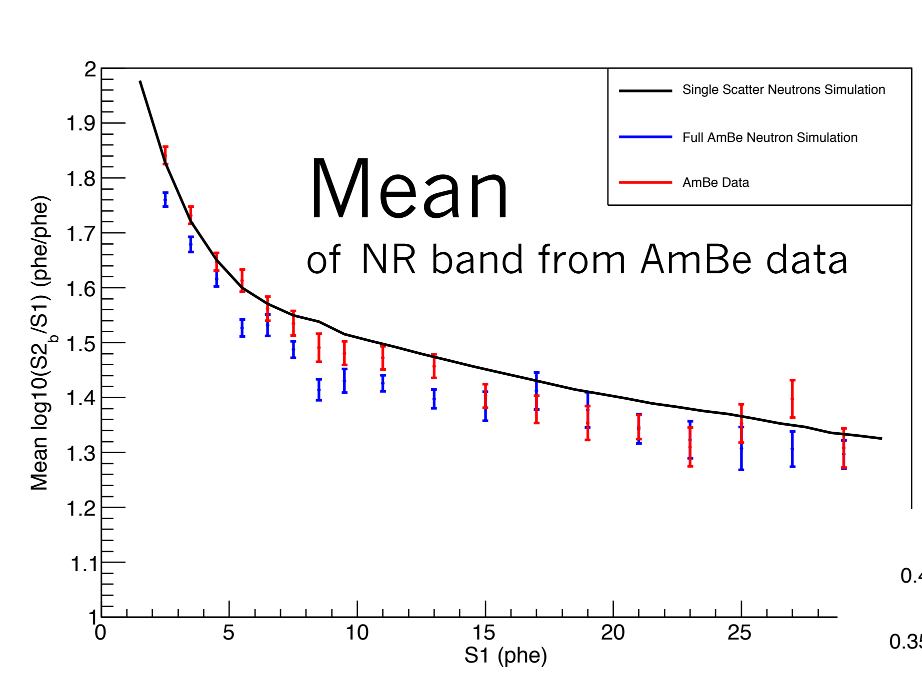
- LUX has most kg-days exposure of any xenon TPC, as well as the lowest energy threshold
- Forged ahead with great internal calibration sources
- Low-energy NR data agree with Monte Carlo, with location of band at LUX field *predicted* (1^{st} time)
- Currently has the most stringent limit on the WIMP-nucleon spin-independent interaction cross-section across a wide range of WIMP masses
- In spite of assumptions more conservative than what have been used in past for Xe detectors (but what we do agrees with our data) result is in conflict with low-mass WIMP interpretations of signals seen in CoGeNT, CDMS, and elsewhere
- Quiet detector with <2 events / day in energy and volume regions of interest, and it's getting quieter

BACKUP MATERIAL

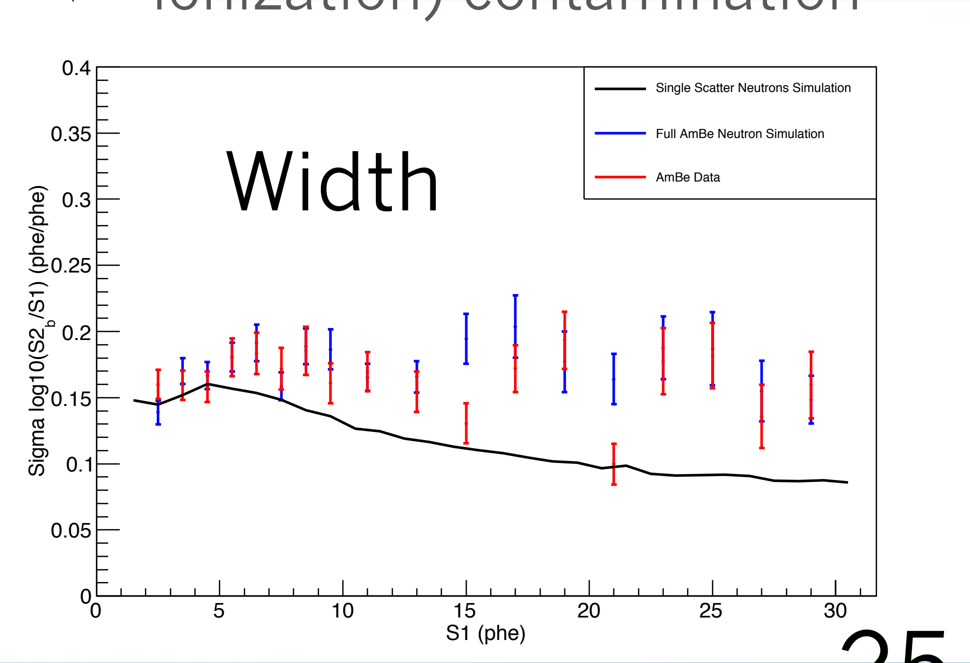
Summary of Events Post-Cuts

Cut	Explanation	Events Remaining
All Triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918,901
Single Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585,686
S1 energy	Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-18 keVnr)	26,824
S2 energy	Accept 200-3300 phe (>8 extracted electrons) Removes single electron / small S2 edge events	20,989
S2 Single Electron Quiet Cut	Cut if >100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)	19,796
Drift Time Cut away from grids	Cutting away from cathode and gate regions, 60 < drift time < 324 us	8731
Fiducial Volume radius and drift cut	Radius < 18 cm, 38 < drift time < 305 us, 118 kg fiducial	160

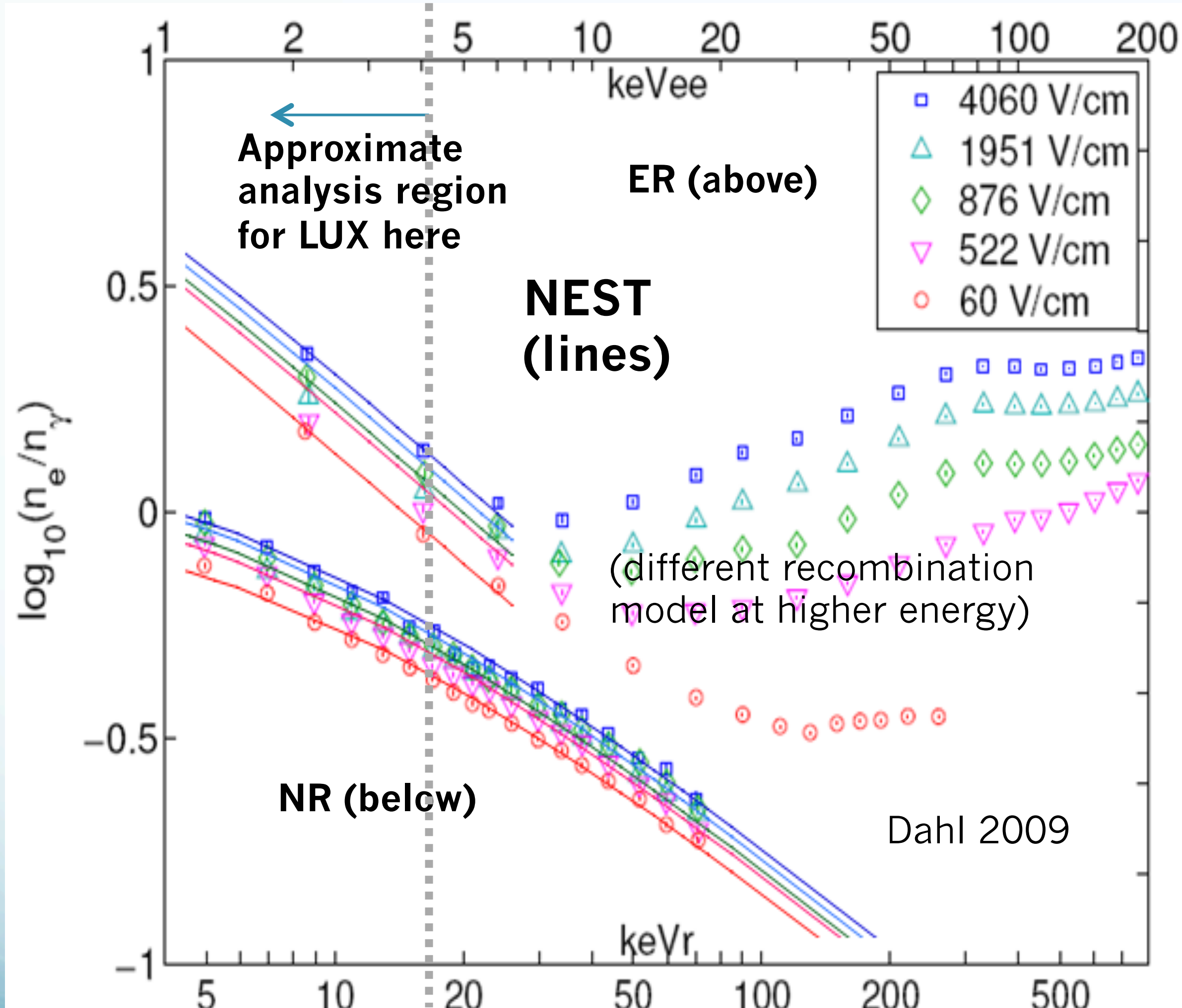
NR Calibration MC Vetting



- Both single-scatter (WIMP-like) and full AmBe simulations use NEST, but AmBe sim includes ER component (Compton scatters) + neutron-X event (multiple-scatter, single-ionization) contamination
- Neutron-only effects shifting band mean and width in well-understood fashion, inapplicable to WIMP scattering. When they're included, there's agreement with data



Electric Field Dependence

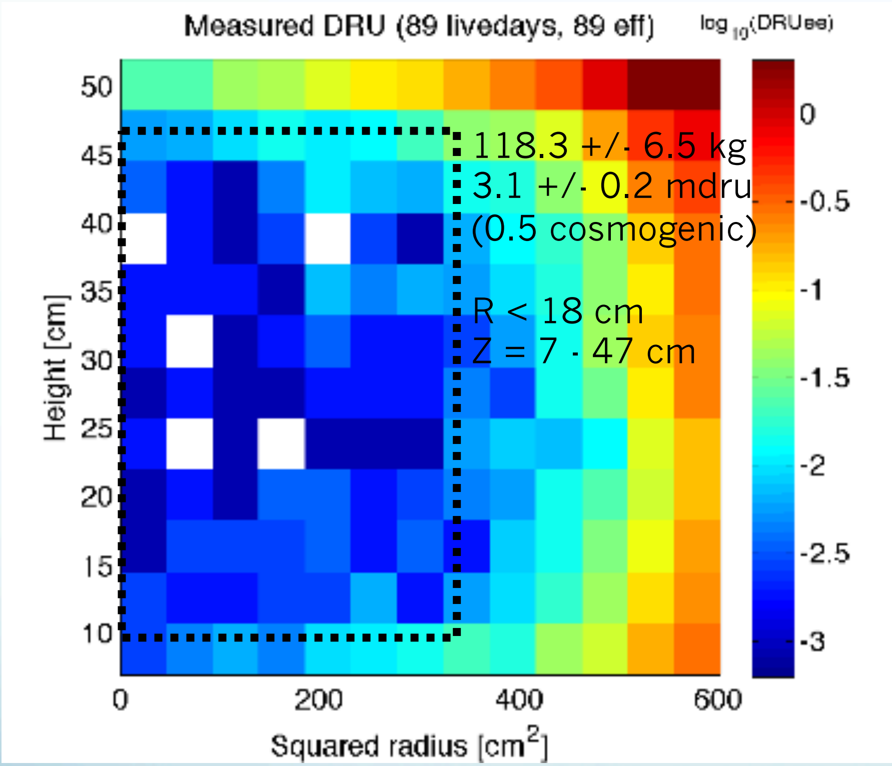


The keVnr energy scale shown here is Dahl's, and assumes an old, flat $\mathcal{L} = 0.25$: using Hitachi, the 5 keVnr point is actually 8.67 and the 70 keVnr point is 85.5 (and this correction has been accounted for in NEST when fitting the data). The keVee scale is still correct

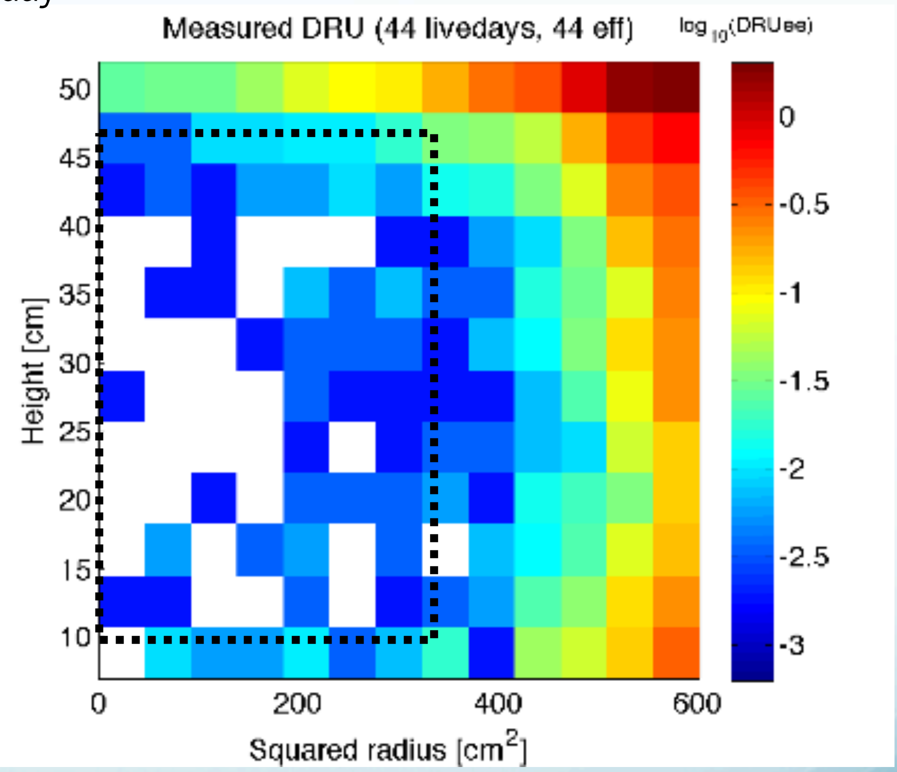
- Data presented in terms of $\log(n_e/n_\gamma)$, converted from log(S2/S1), but keVee scale is (n_e+n_γ)*13.7e-3 keV and so can easily extract n_γ and n_e alone and get their field dependencies
- AmBe and Cf-252 sources, not an angle-tagged neutron scattering measurement, but important thing is *relative* yield is well-established

BG (<5 keVee) Cooling Off

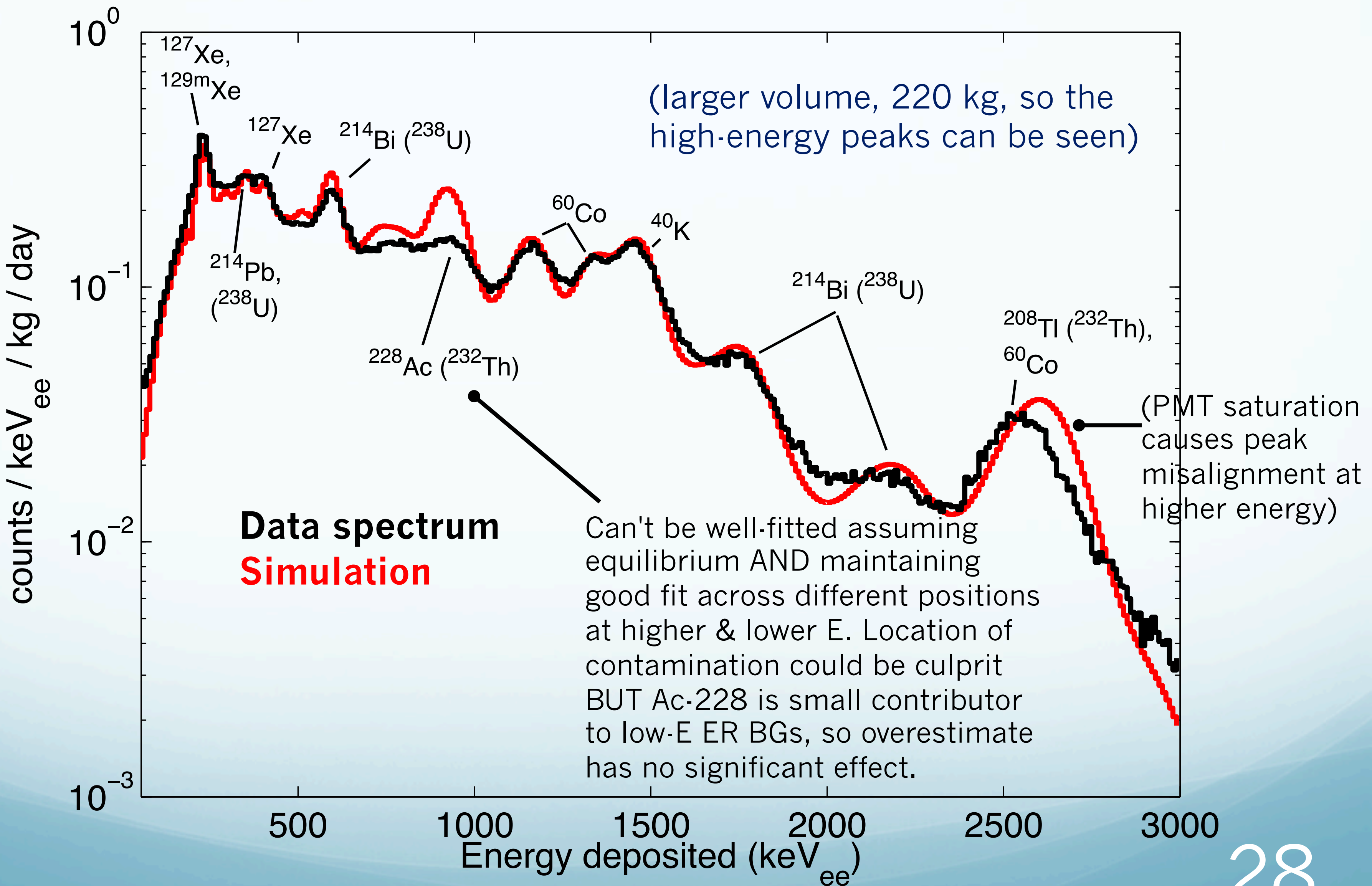
log10
evts/keVee/kg/day



Xe cosmogenic activity cools

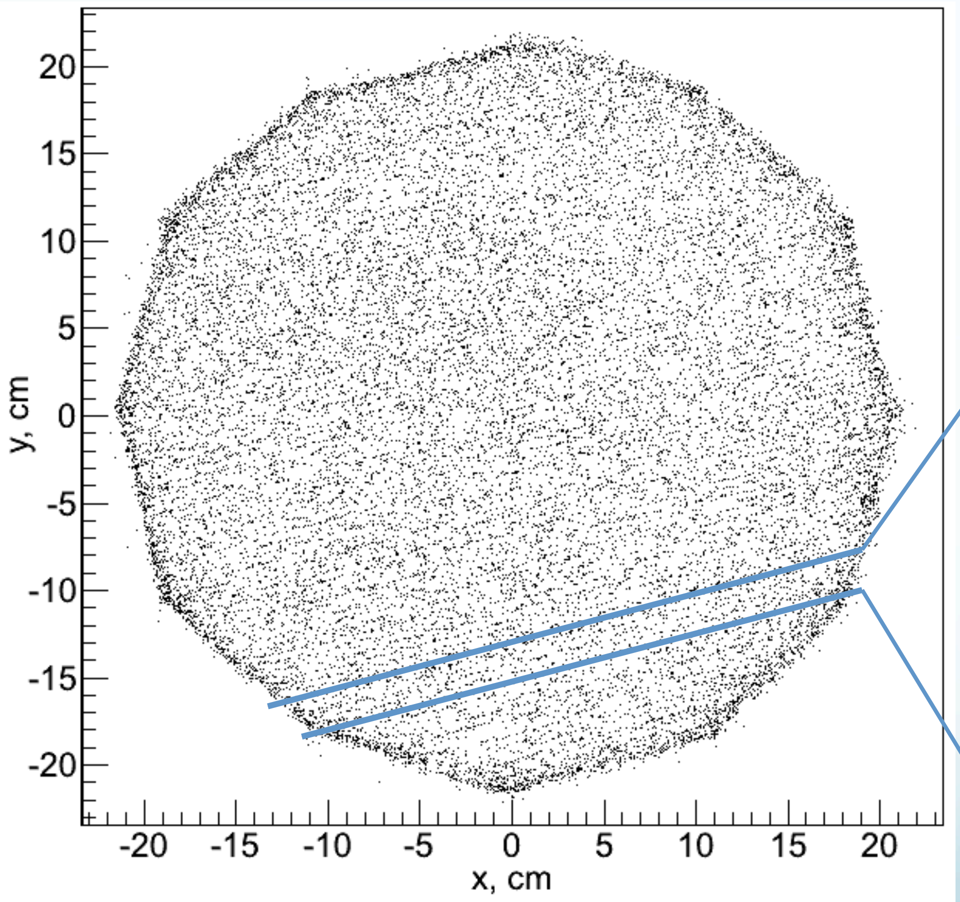


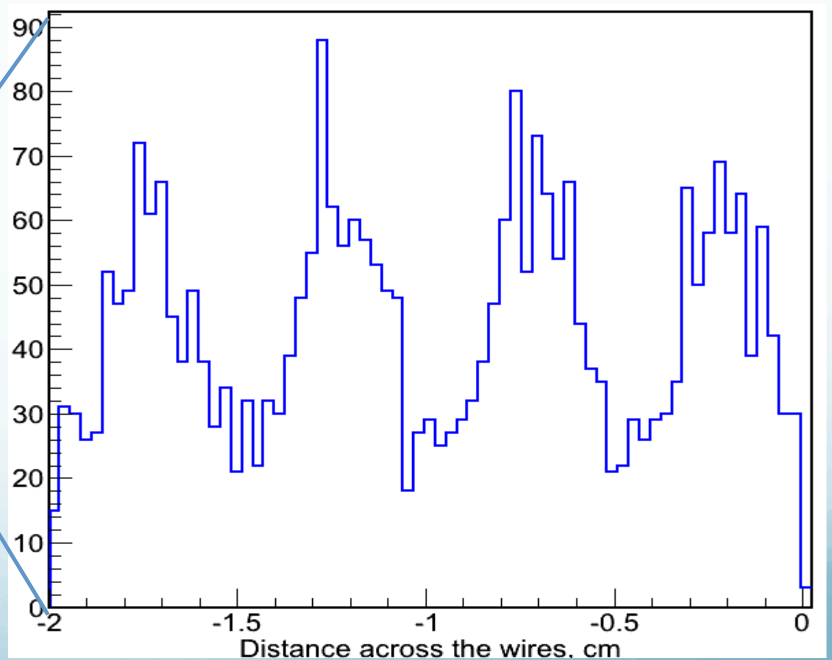
Full Background Model



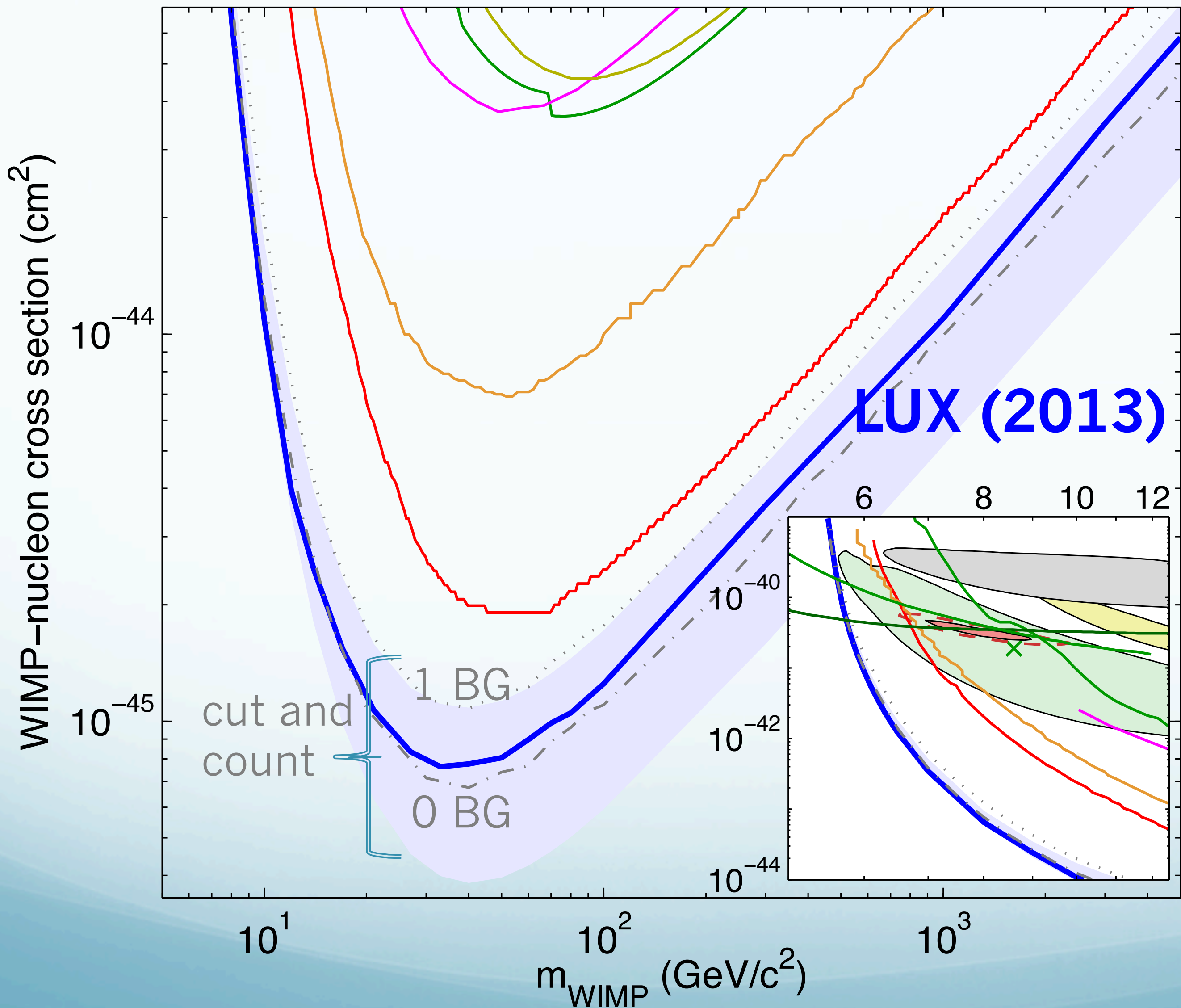
Position Reconstruction

- Iterative approach used to optimize resolution (Mercury, developed by ZEPLIN)
- XY reconstruction of events near the anode grid resolves grid wires with 5 mm pitch





Cut-and-Count Cross Check



- The PLR is well bounded by the 0 and 1 BG event cases, but lies closer to 0 BG, as we would expect
- Feldman-Cousins with 0.64 BG events expected
- PLR takes likelihood of an event being NR into account instead of making binary decision