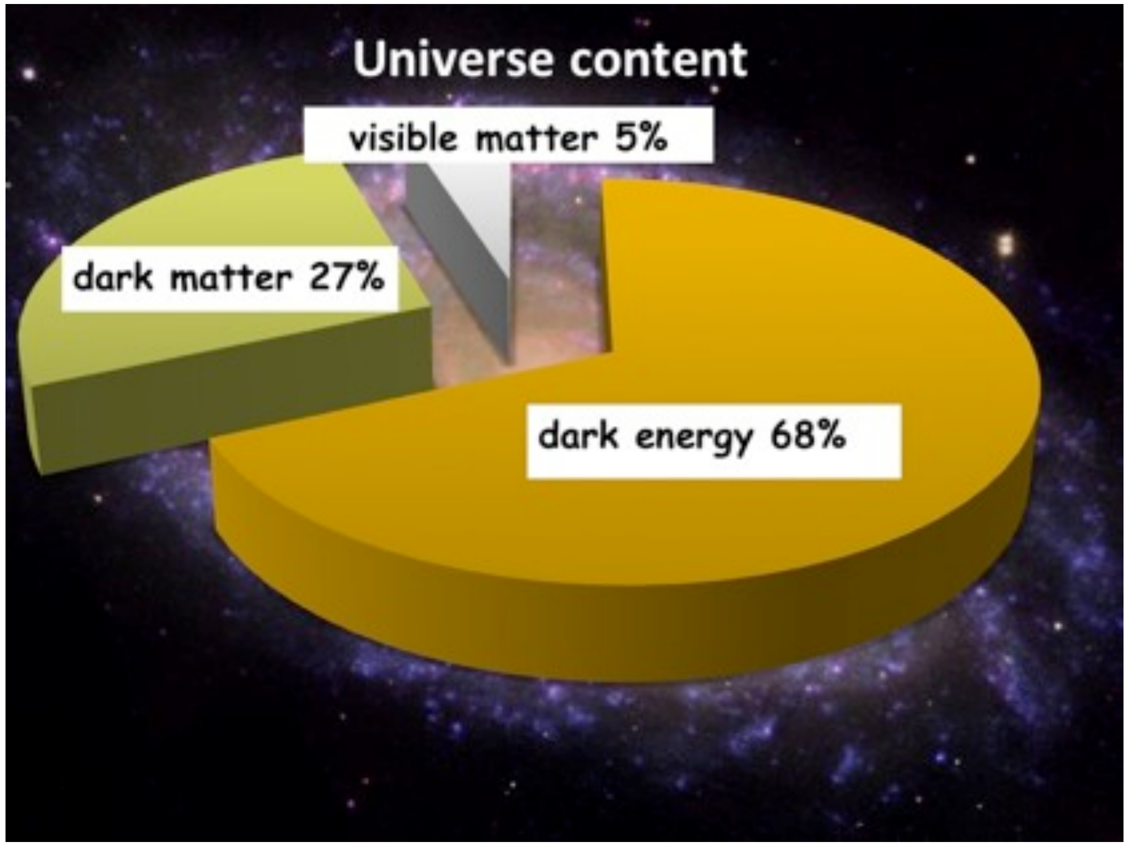
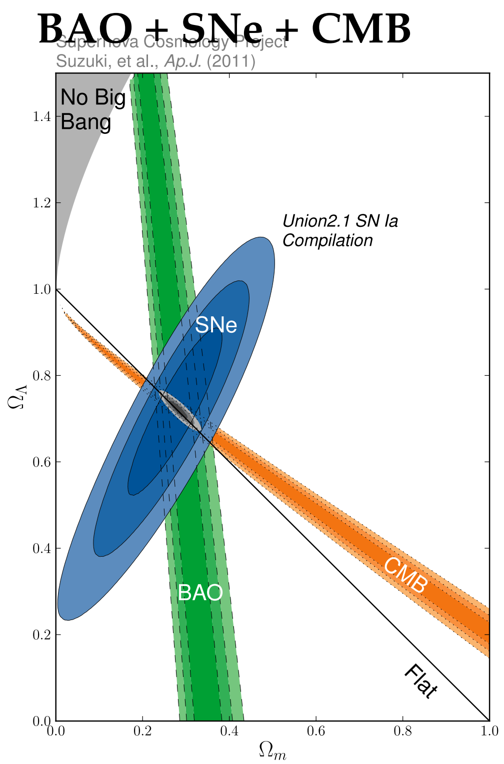
Recent Results from the Large Underground Xenon Experiment (LUX)

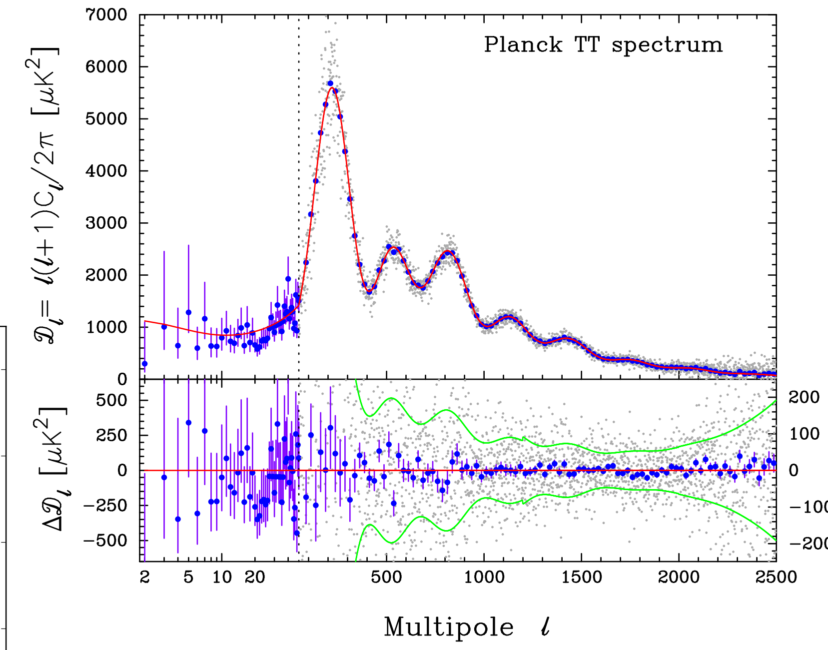
Kevin O'Sullivan
Yale University

Dark Matter

Galactic rotation curves, BAO, CMB, gravitational lensing, and other measurements point to 27% of the universe being composed on non-baryonic dark matter

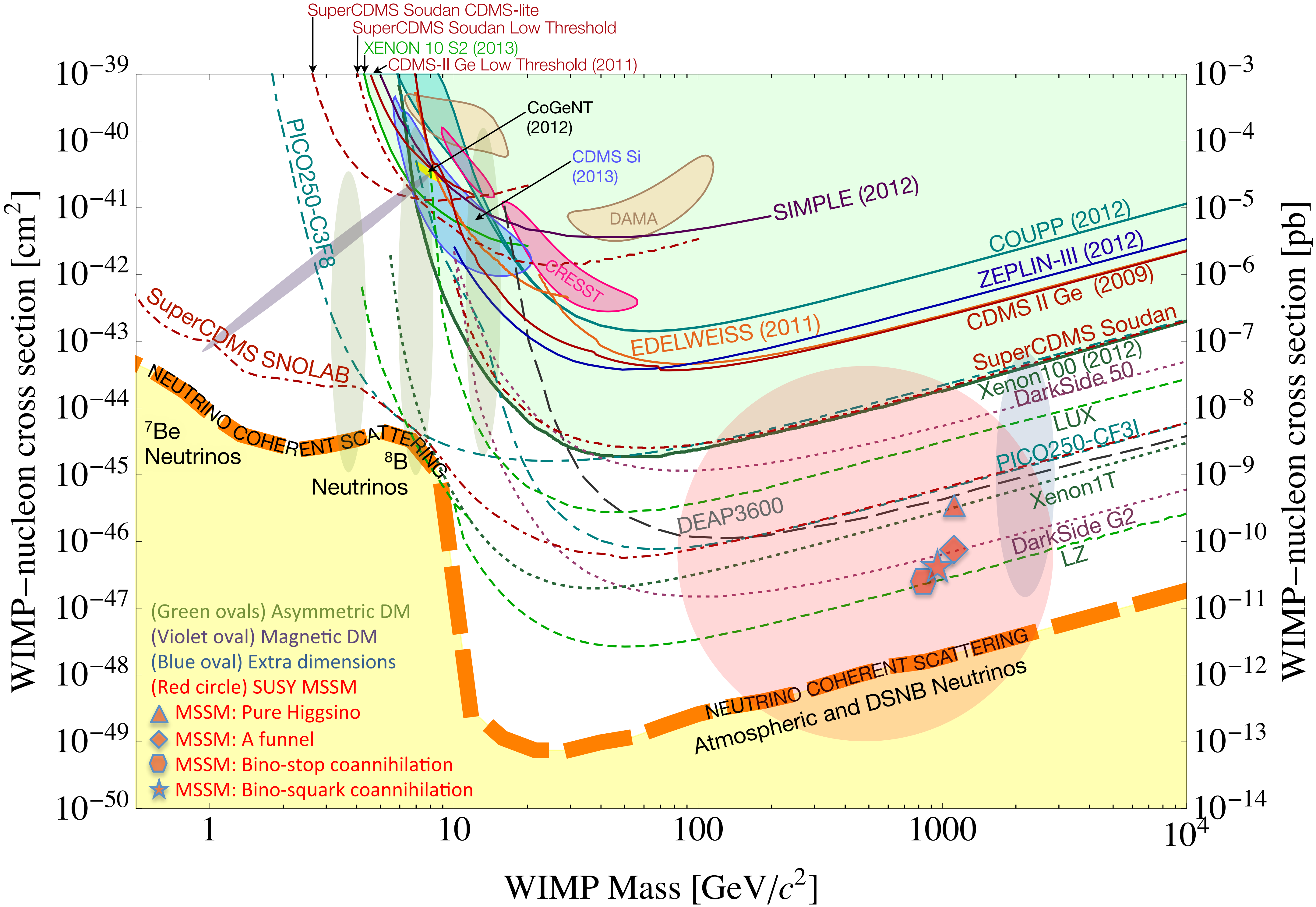






Weakly Interacting Massive Particles

- Weakly Interacting Massive Particles (WIMPs) are a leading candidate dark matter particle
- Only interact with baryonic matter through the weak force => very hard to detect!
- WIMPs, if they exist, could make up ALL the dark matter (this is known as the WIMP Miracle)
- Require physics beyond the standard model, typically either super symmetry or extra dimensions



- Pre-LUX limits on WIMP dark matter (solid lines), favored regions (shaded ovals), and sensitivities of proposed experiments (dashed lines)
- Green region is excluded by existing experiments
- LUX goal: get backgrounds down to 1 event / 100 kg / year!

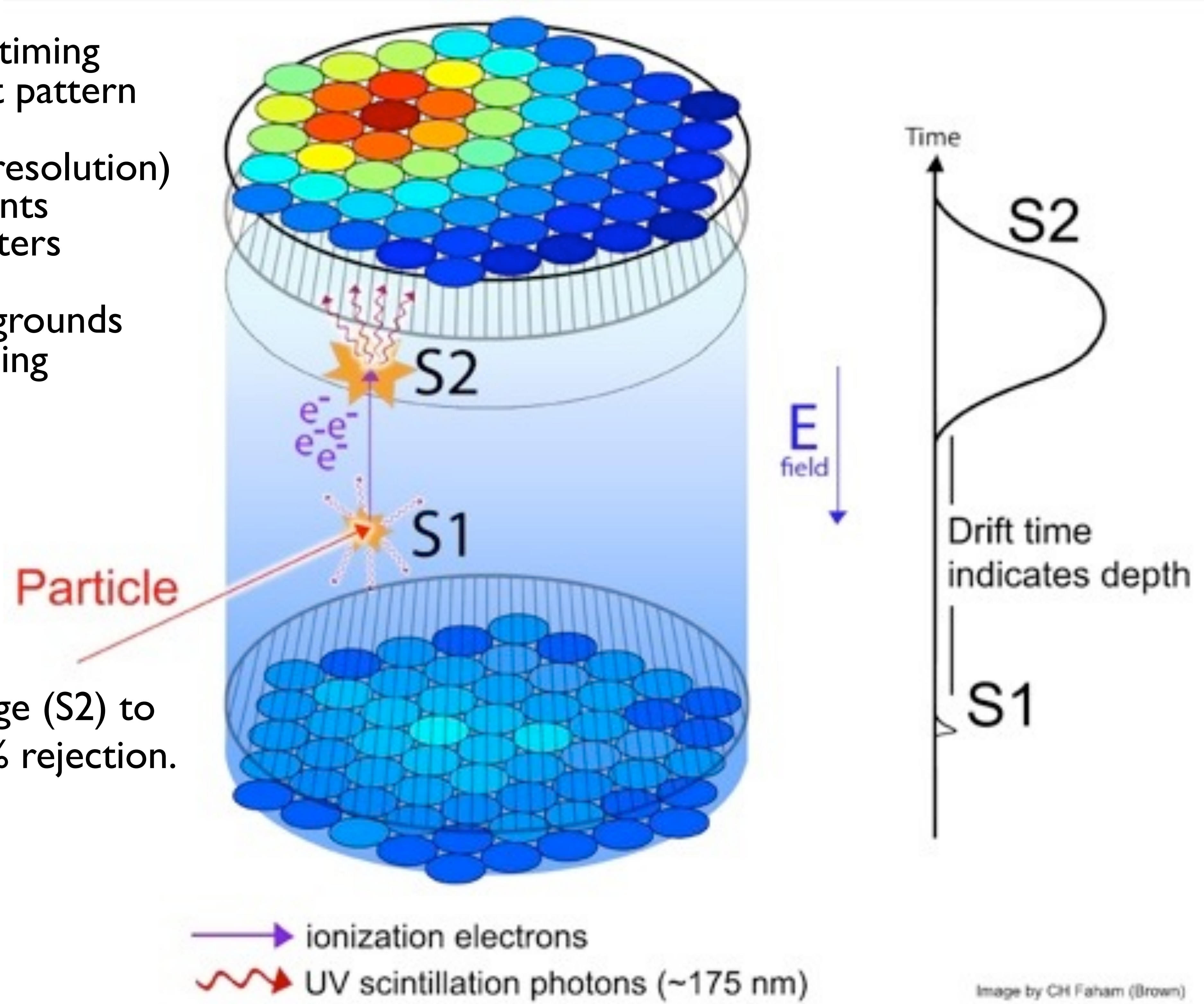
Two-Phase Xe Detectors

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds reduced by self-shielding

Reject gammas, betas by charge (S2) to light (S1) ratio. Expect > 99.5% rejection.



The LUX Collaboration

Brown

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Sergey Uvarov	Graduate Student
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Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
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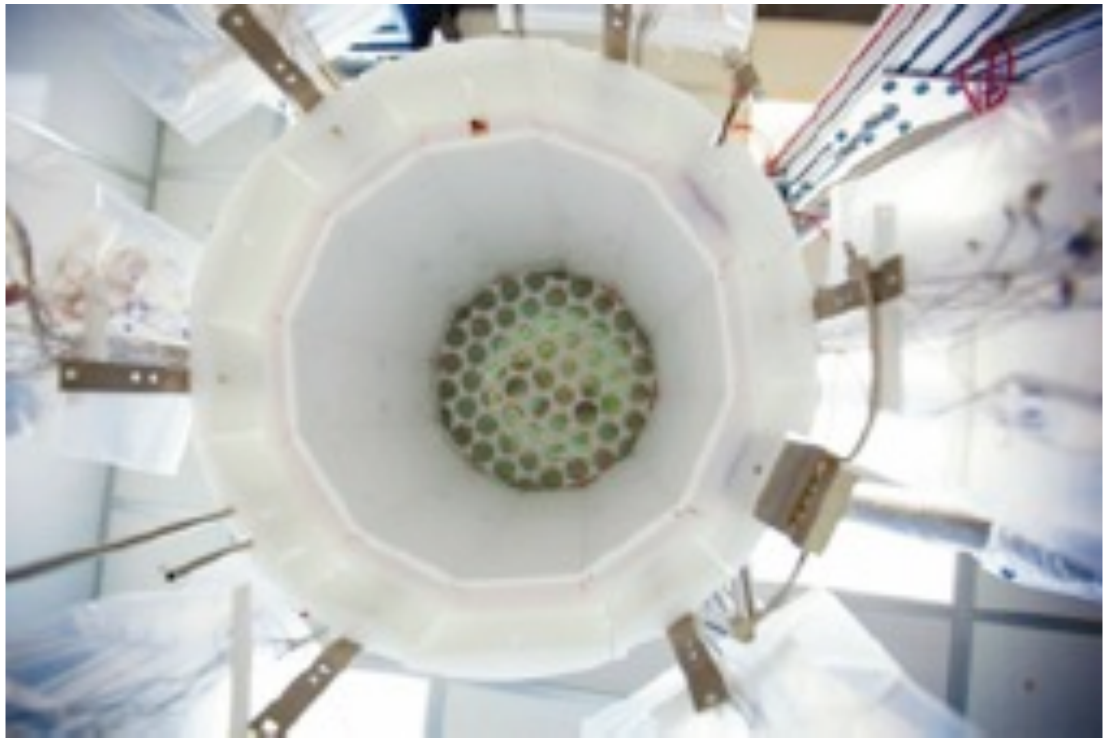
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

Detector Construction

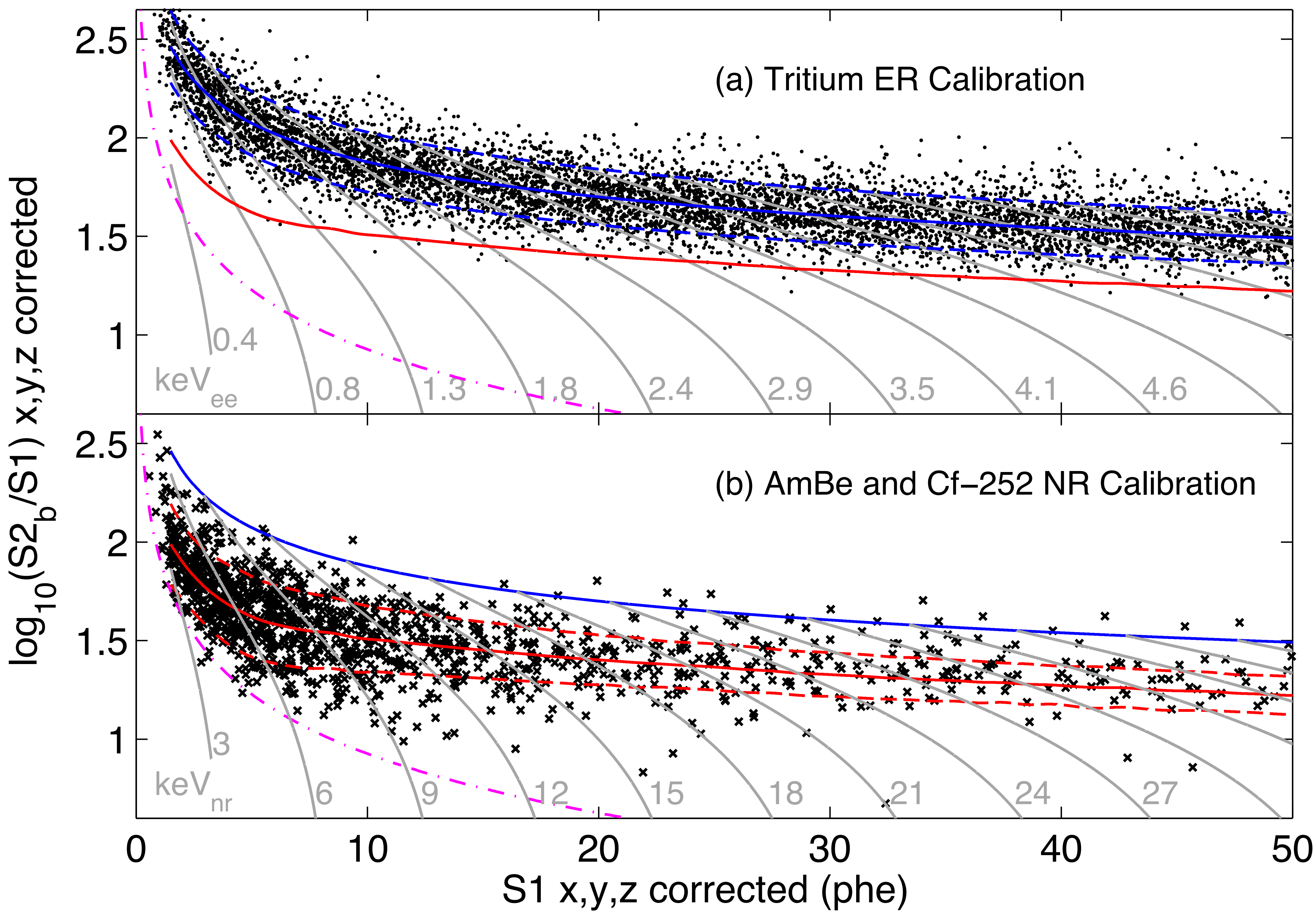
LUX operates 4850 feet (1480 m) underground at the Sanford Underground Research Facility (SURF)

LUX Inside Water Tank



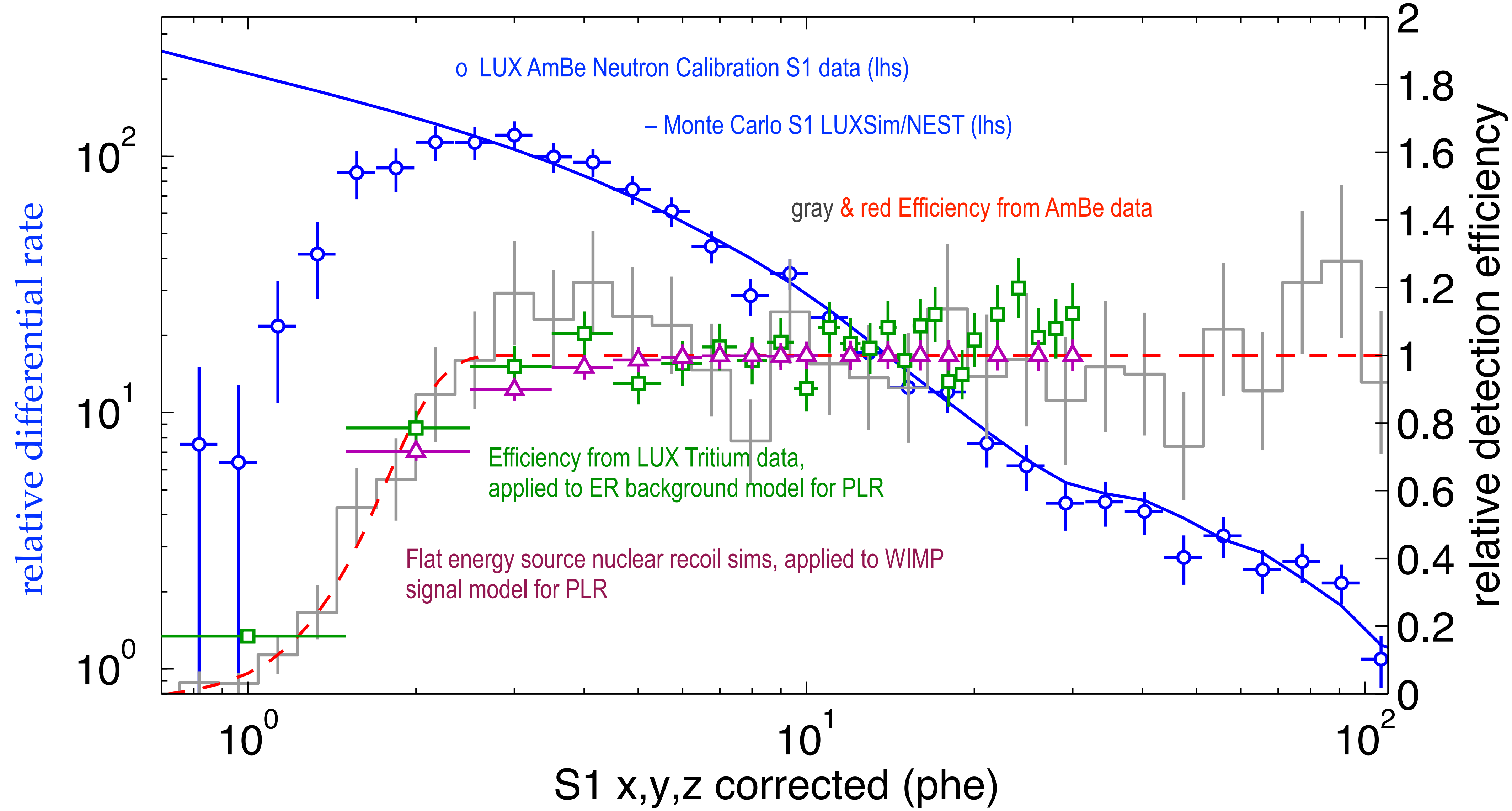
LUX Internals

Electron Recoil Discrimination



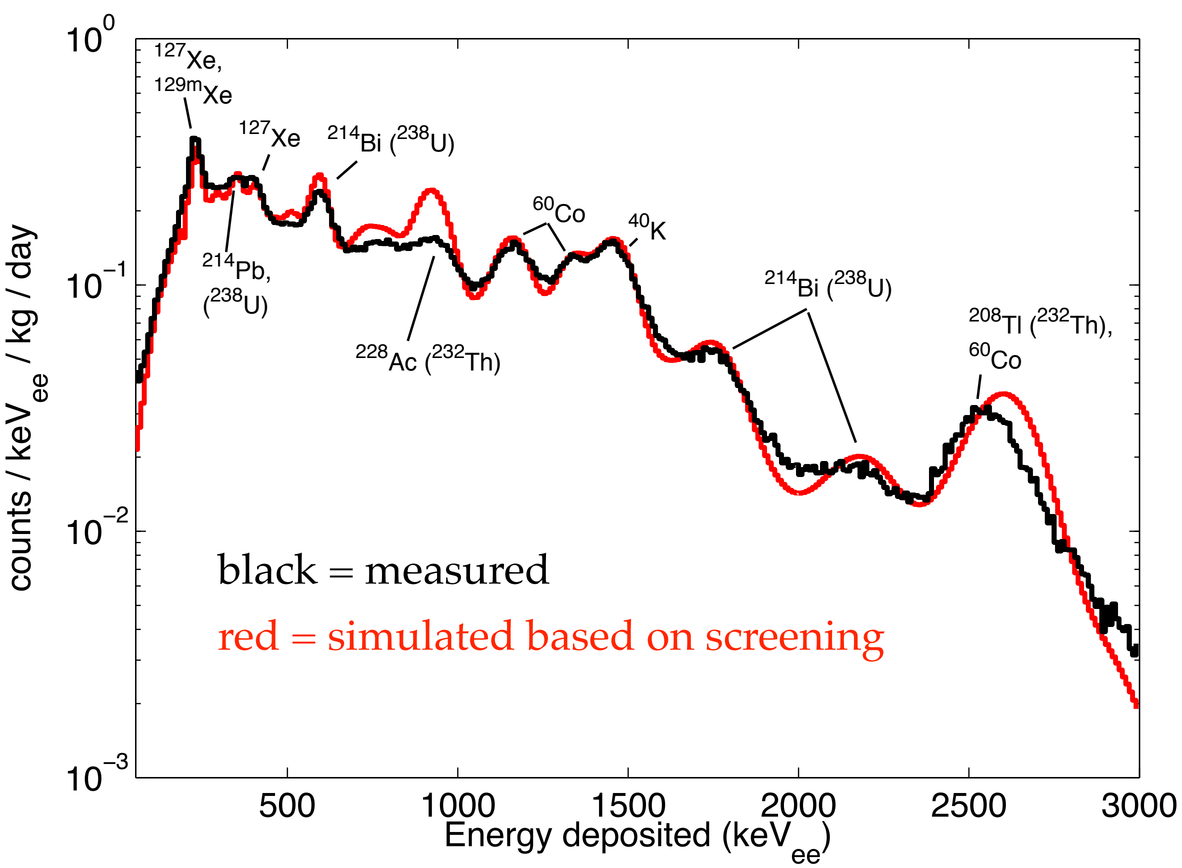
- LUX uses the difference in S2/S1 ratio of nuclear recoils (WIMP-like) to discriminate against electron recoils (gammas and internal betas)

Detection Efficiency



- Three different methods used to determine LUX detection efficiency versus S1
- All three in agreement!
- 80% efficient at 2 phe threshold

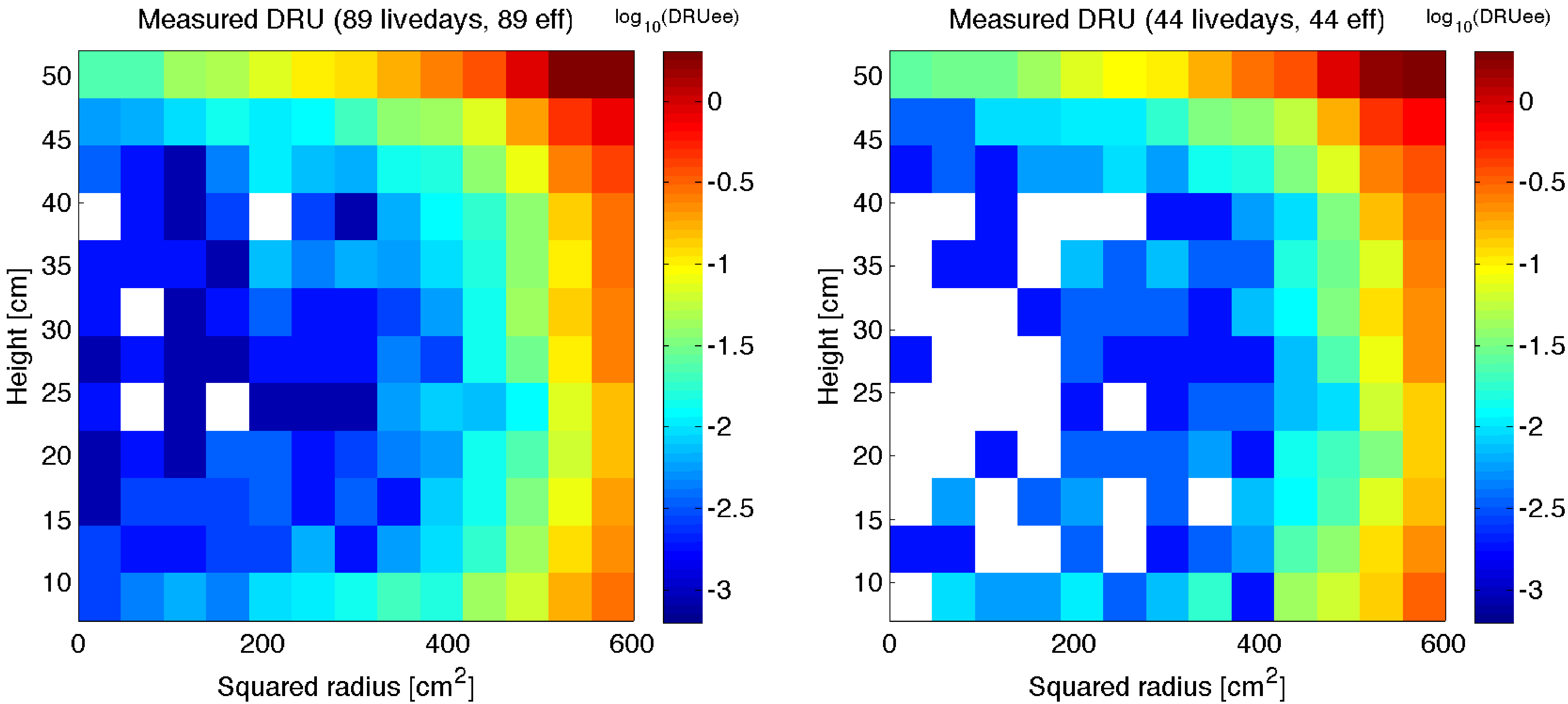
LUX Background Model



Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	^{222}Rn	0.11-0.22$_{(90\% \ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.1 \pm 0.2_{stat}$

- Model based on radioactive counting of detector components and simulation
- Very good agreement with data
- Extremely low backgrounds at low energies

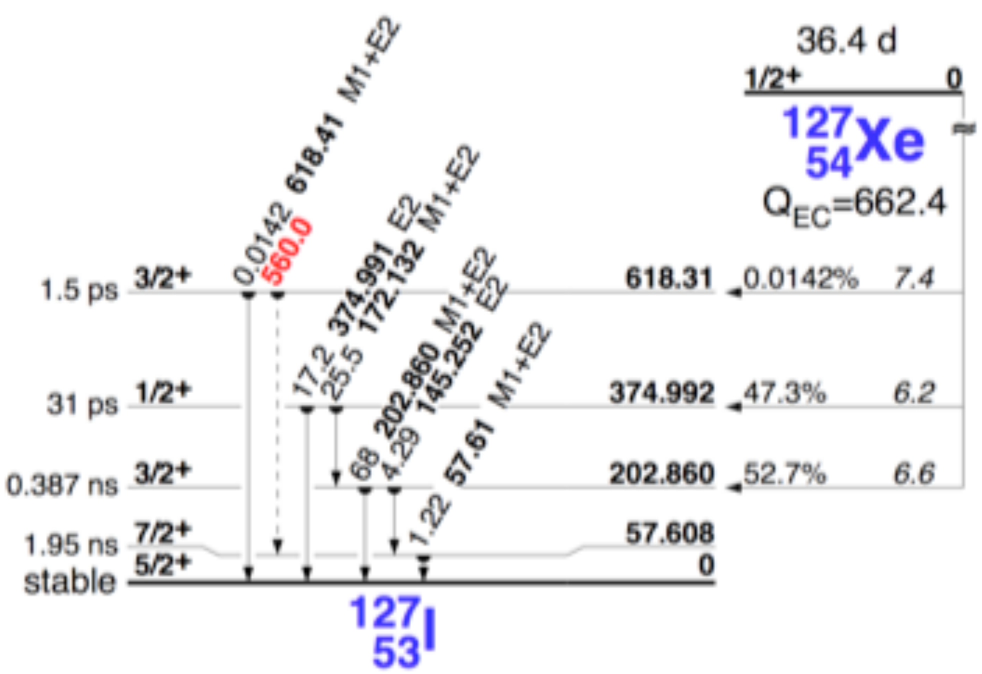
Fiducialization

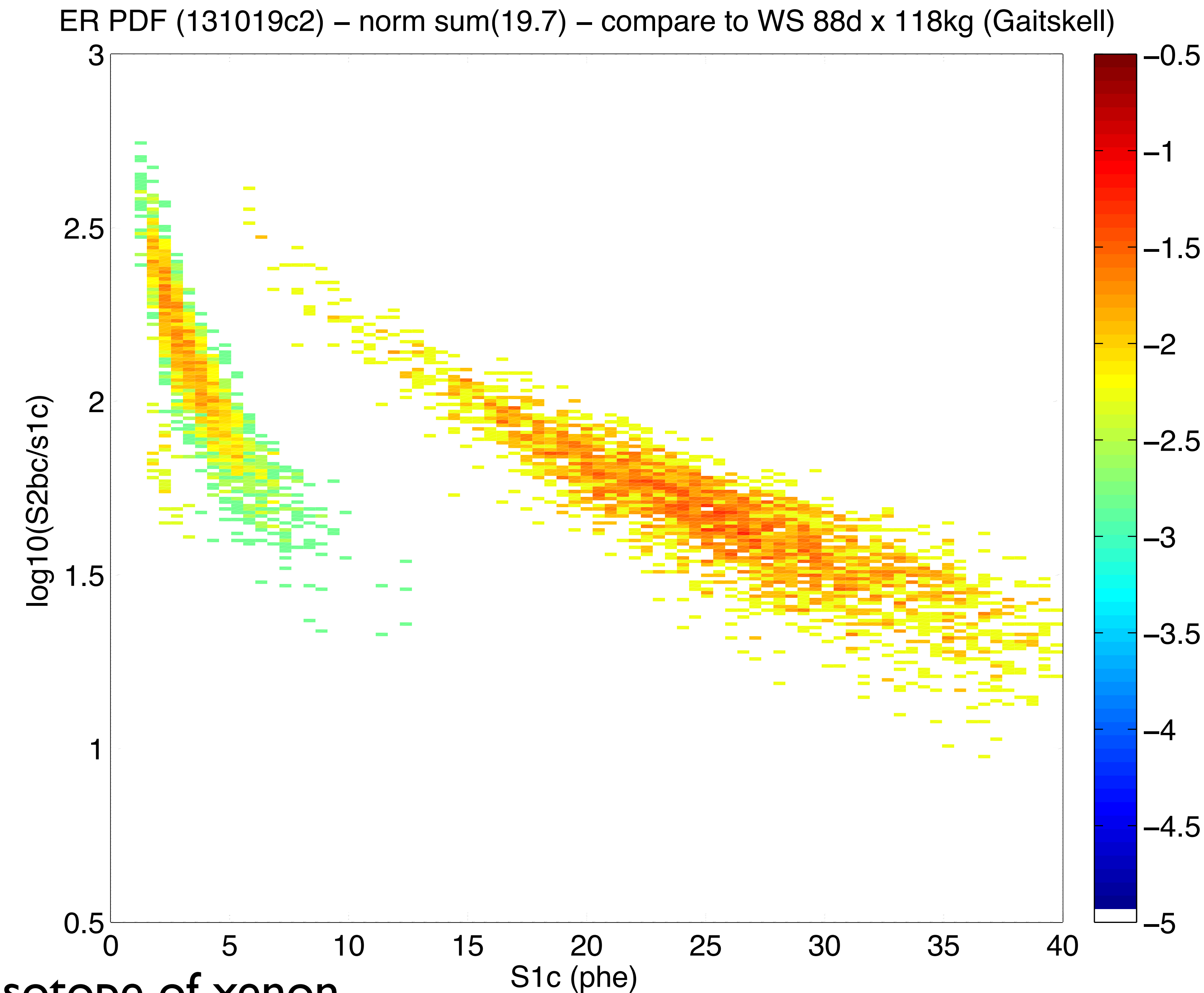


- Xenon is self-shielding: using only the inner xenon reduces backgrounds from external gammas

- Background is dropping: notice lower backgrounds in the second half of the WIMP search run (right plot) as opposed to the entire run (left plot)

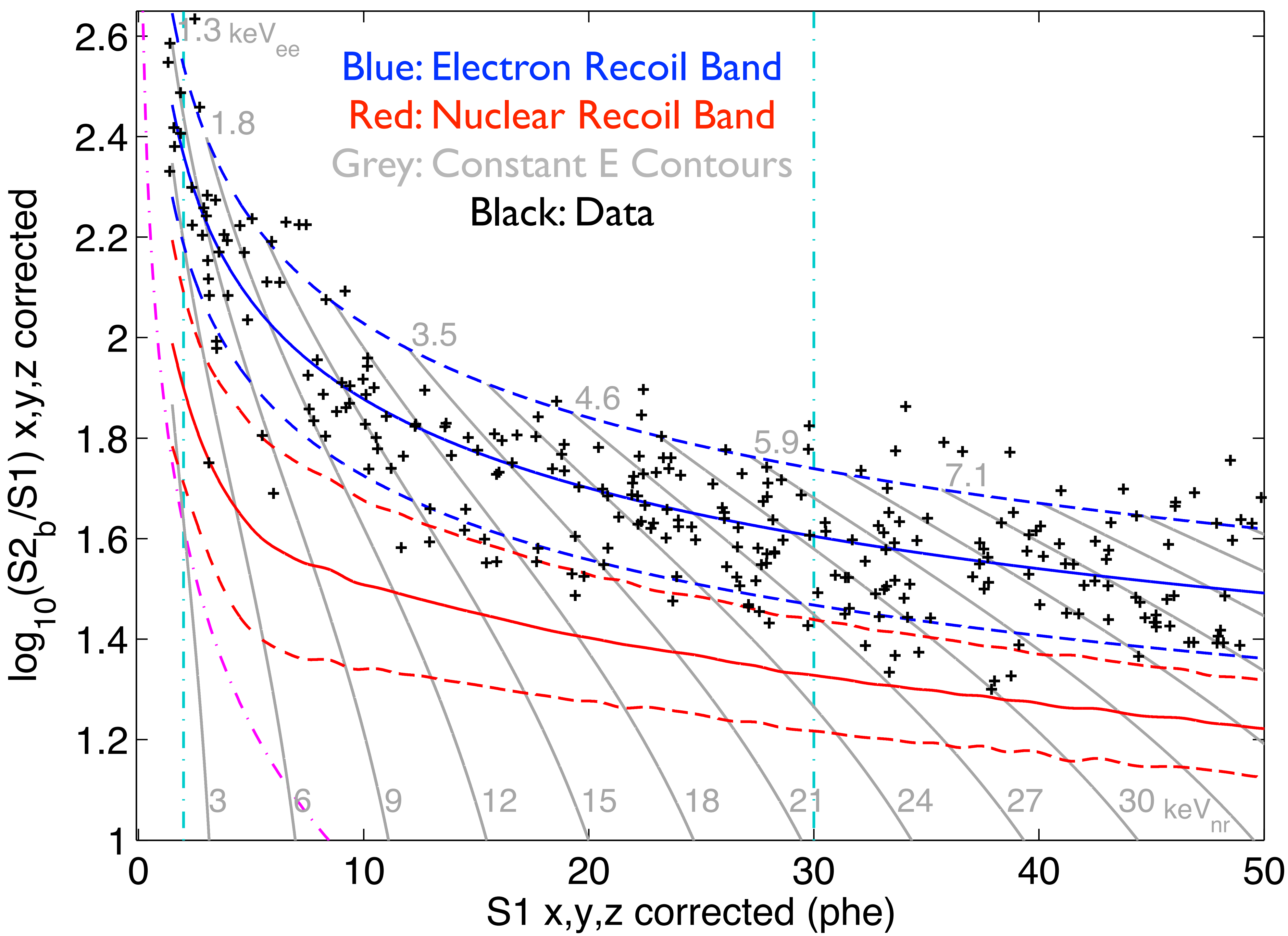
^{127}Xe Background





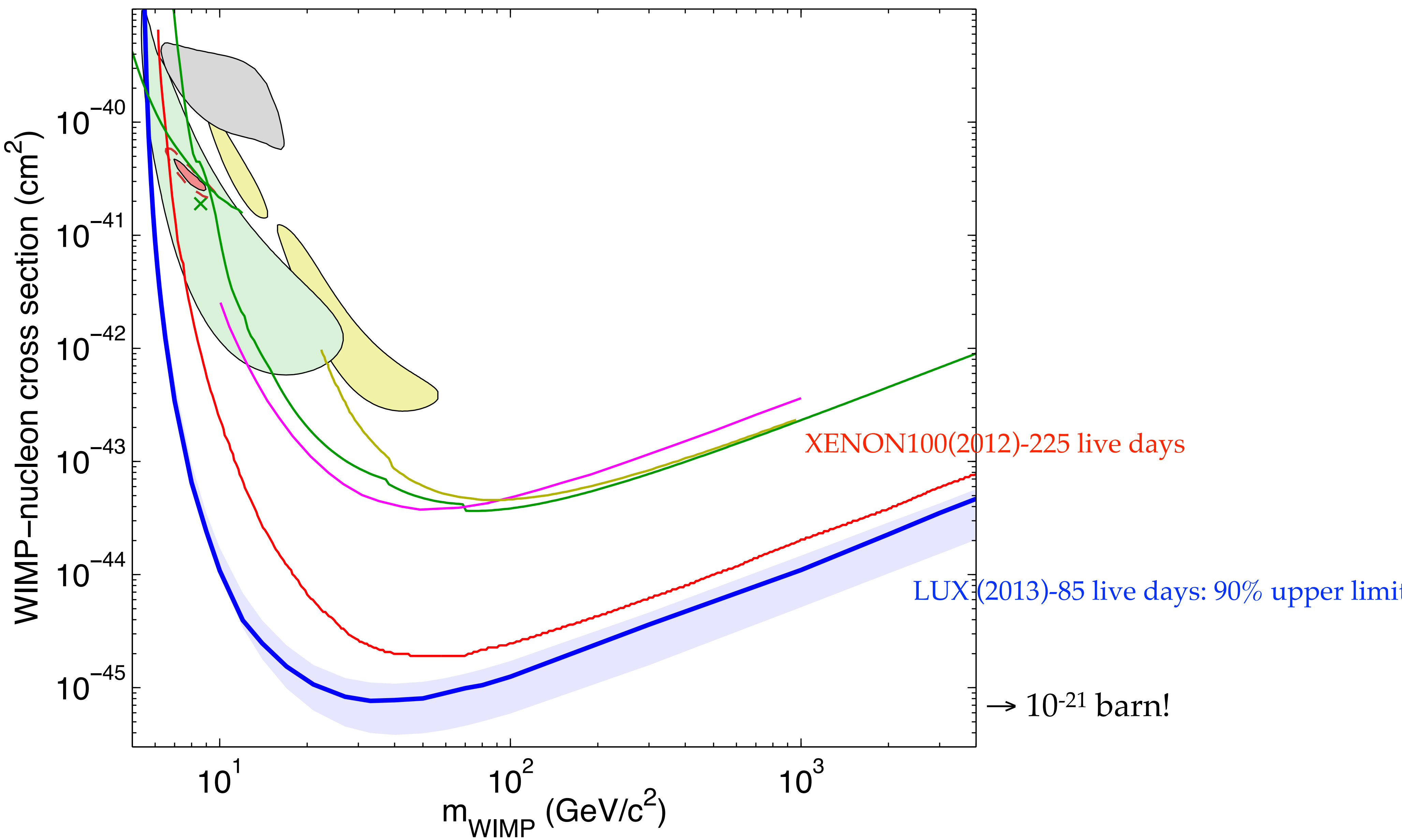
- Cosmogenically activated isotope of xenon
- Gives off low-energy x-rays: .2 keVee, 1 keVee, and 5 keVee which become a background when accompanying gammas escape
- Decays away with a 36.4 day half-life

WIMP Search Data

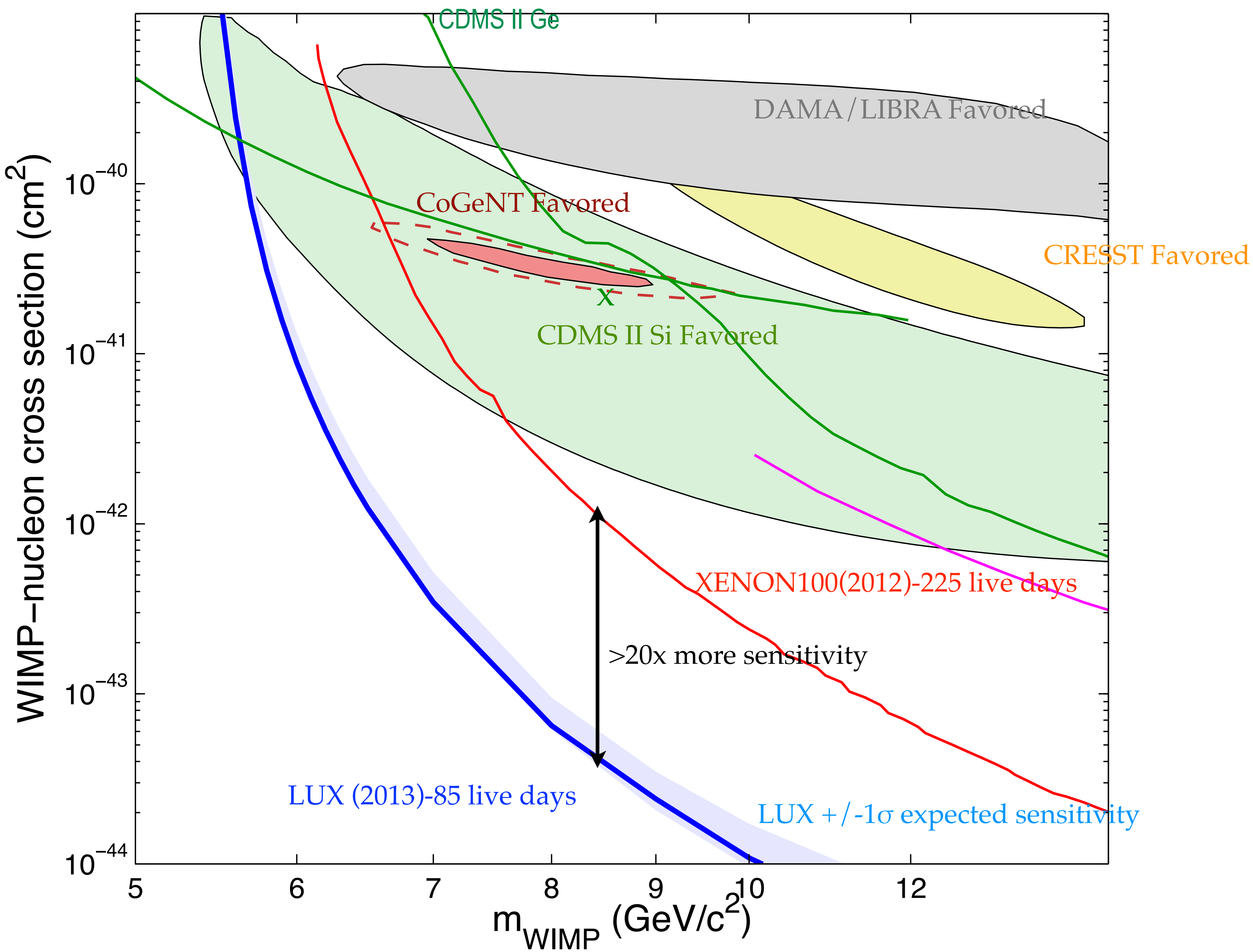


- 160 events observed in fiducial volume between 2 and 30 phe S1

Spin-independent WIMP Limits

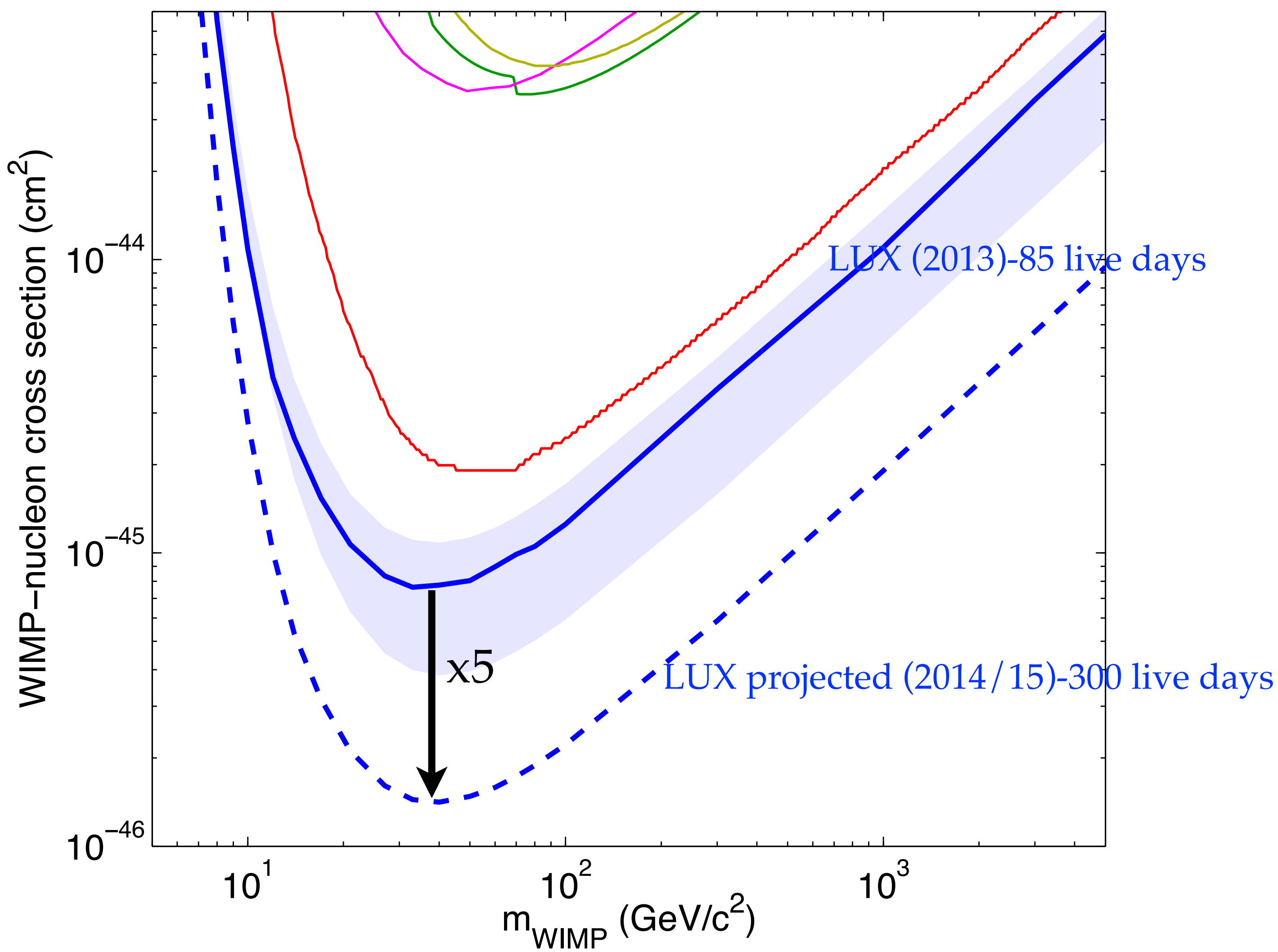


Low-Mass Limit



- LUX data is inconsistent with putative signals from CoGeNT and CDMS II Si

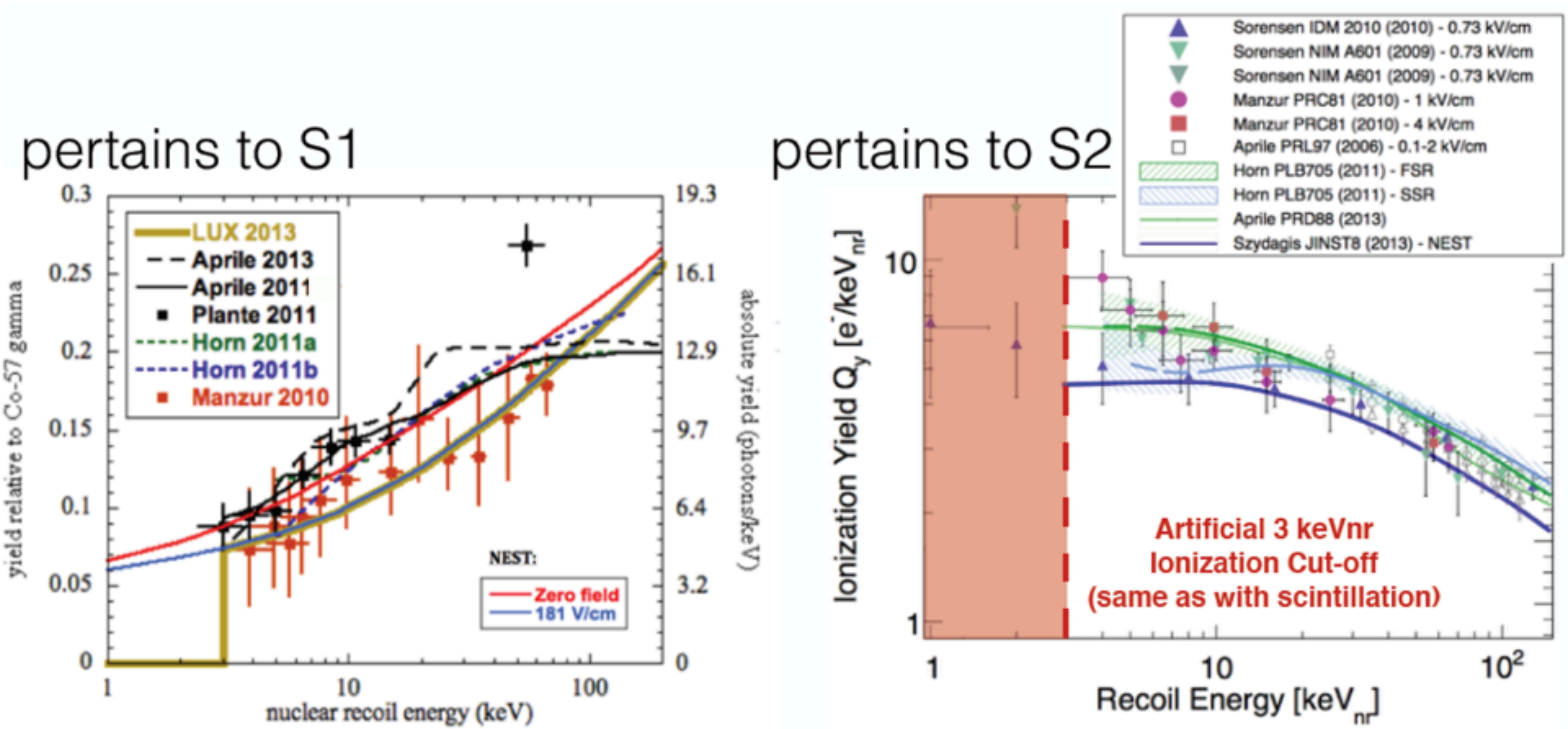
Improving Sensitivity



- 300 day run planned for 2014-2015
- Still not background limited
- Expect a factor of 5 improvement in sensitivity!

Deuterium-Deuterium Beam Calibrations

Response for Nuclear Recoils

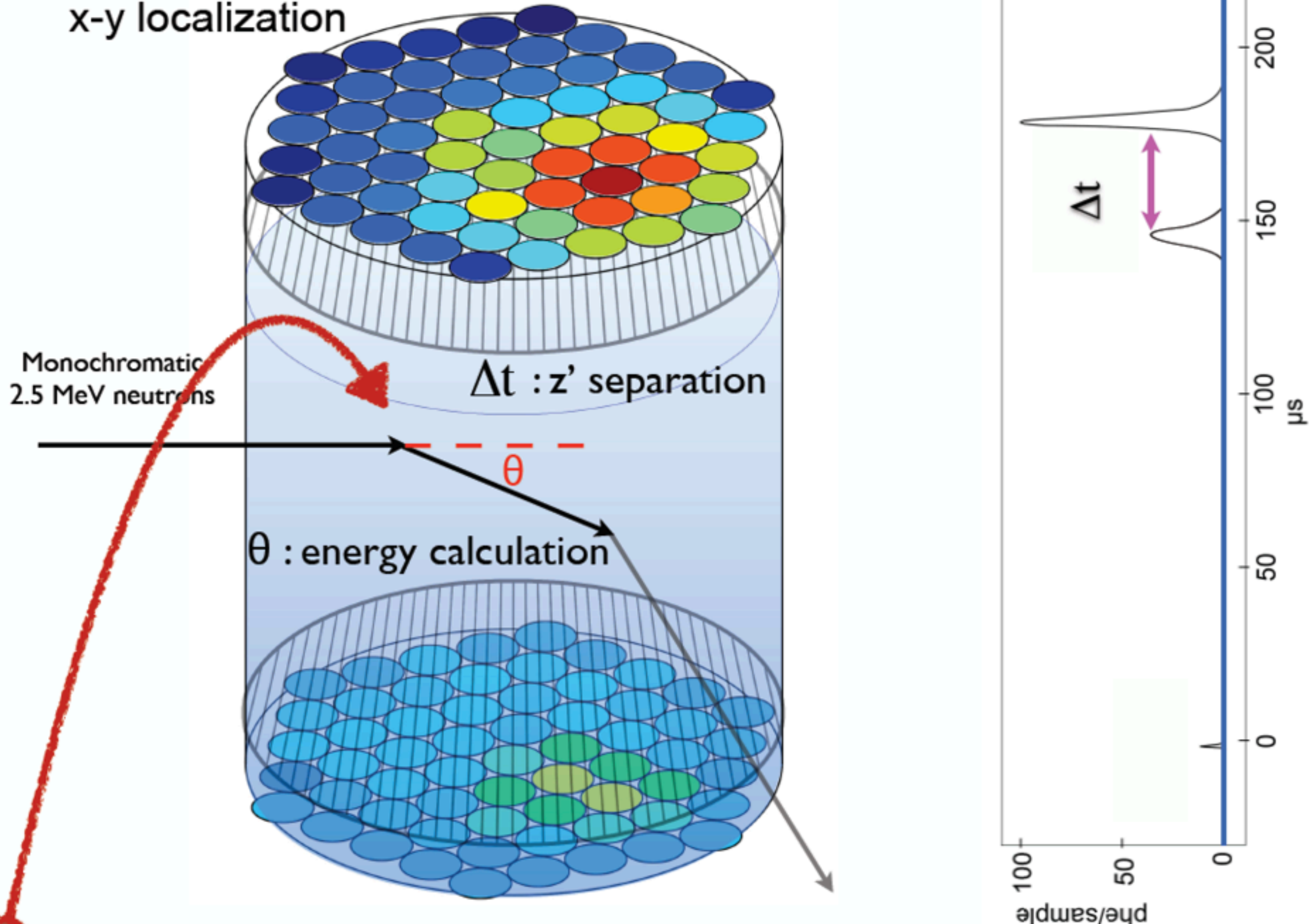


Leff

Qy

- LUX makes the conservative assumption that nuclear recoils below 3 keV$_{nr}$ produce no response in xenon
- Studying these properties of xenon further would allow us to extend our limit to lower masses

top hit pattern:
x-y localization

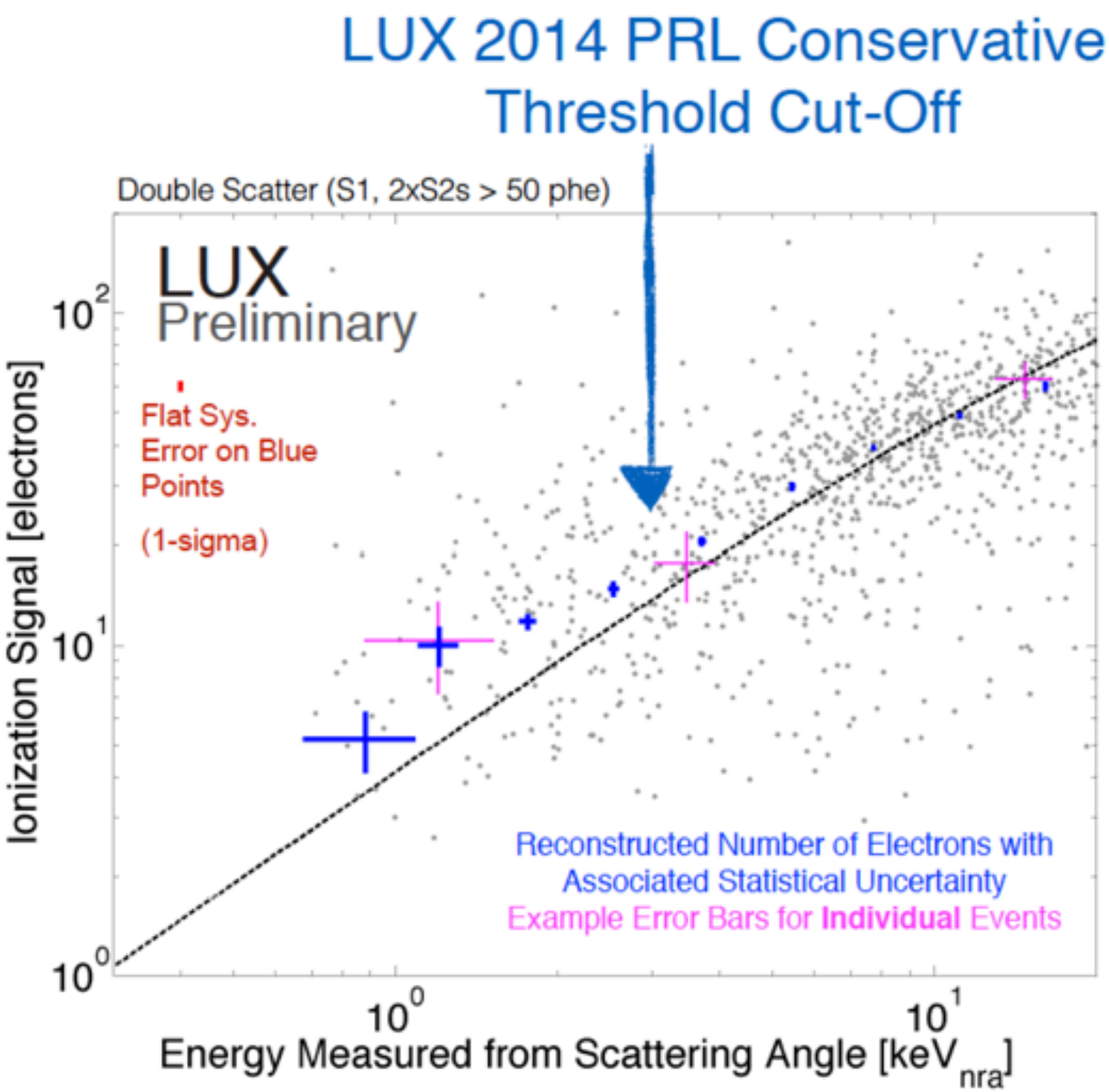


$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Samuel Chan, Carlos Faham for the LUX Collaboration

Ionization (S2)

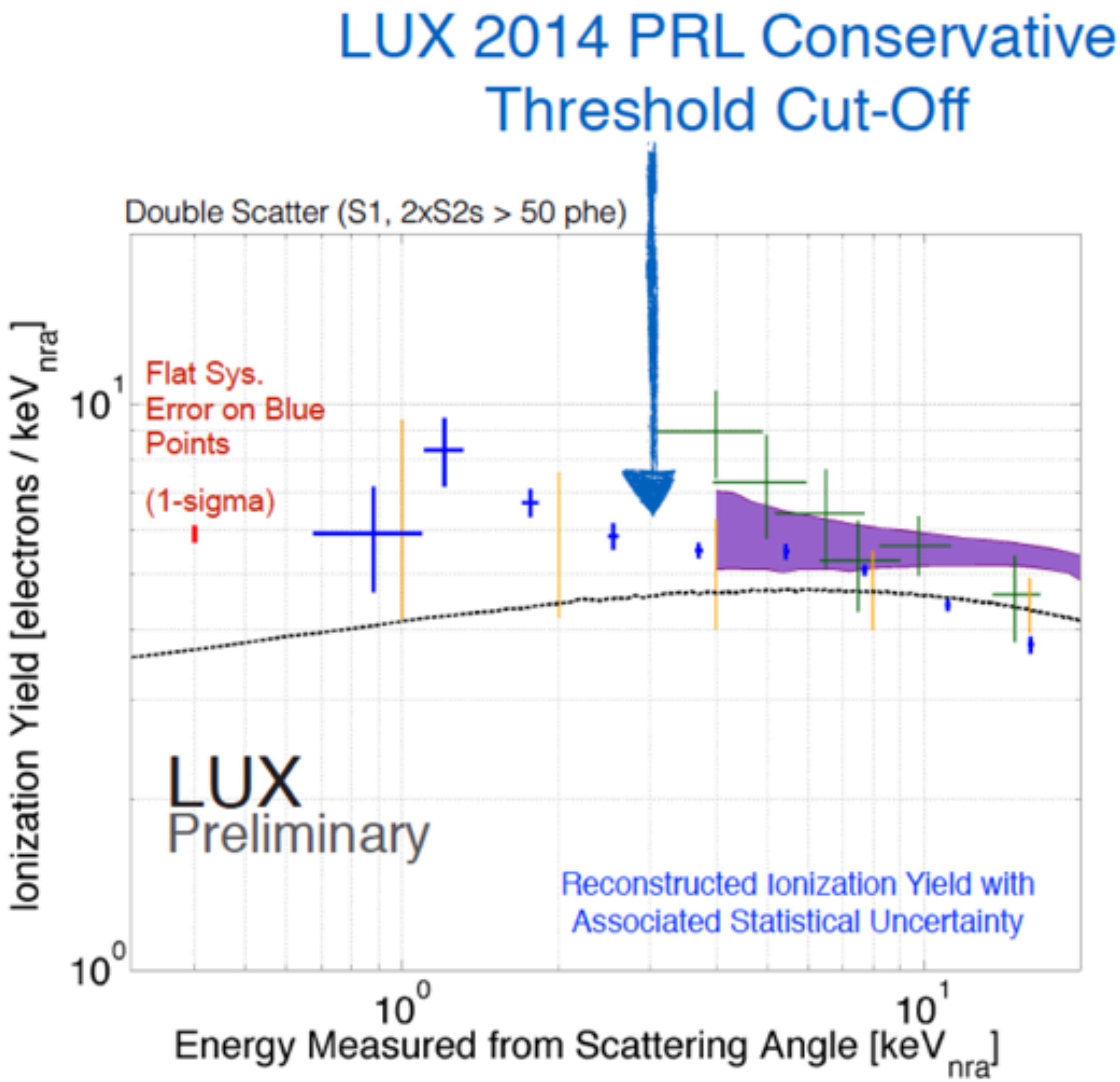
• Reconstruct number of electrons at interaction site by matching ionization signal model with observed event distribution using binned maximum-likelihood
• Systematic error of 7% from threshold correction for (lowest energy) 0.7-1.0 keV_{nra} bin
• Red systematic error bar shows common
scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency.
• Lowest event energy included for analysis is 0.7 keV_{nra}



Grey Points - Individual double scatter events
Magenta Crosses - Error bars for individual event from best 10% from each bin
Blue Crosses - Reconstructed number of electrons at interaction site accounting for threshold effects in signal analysis
Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Signal at 181 V/cm

Ionization (S2)

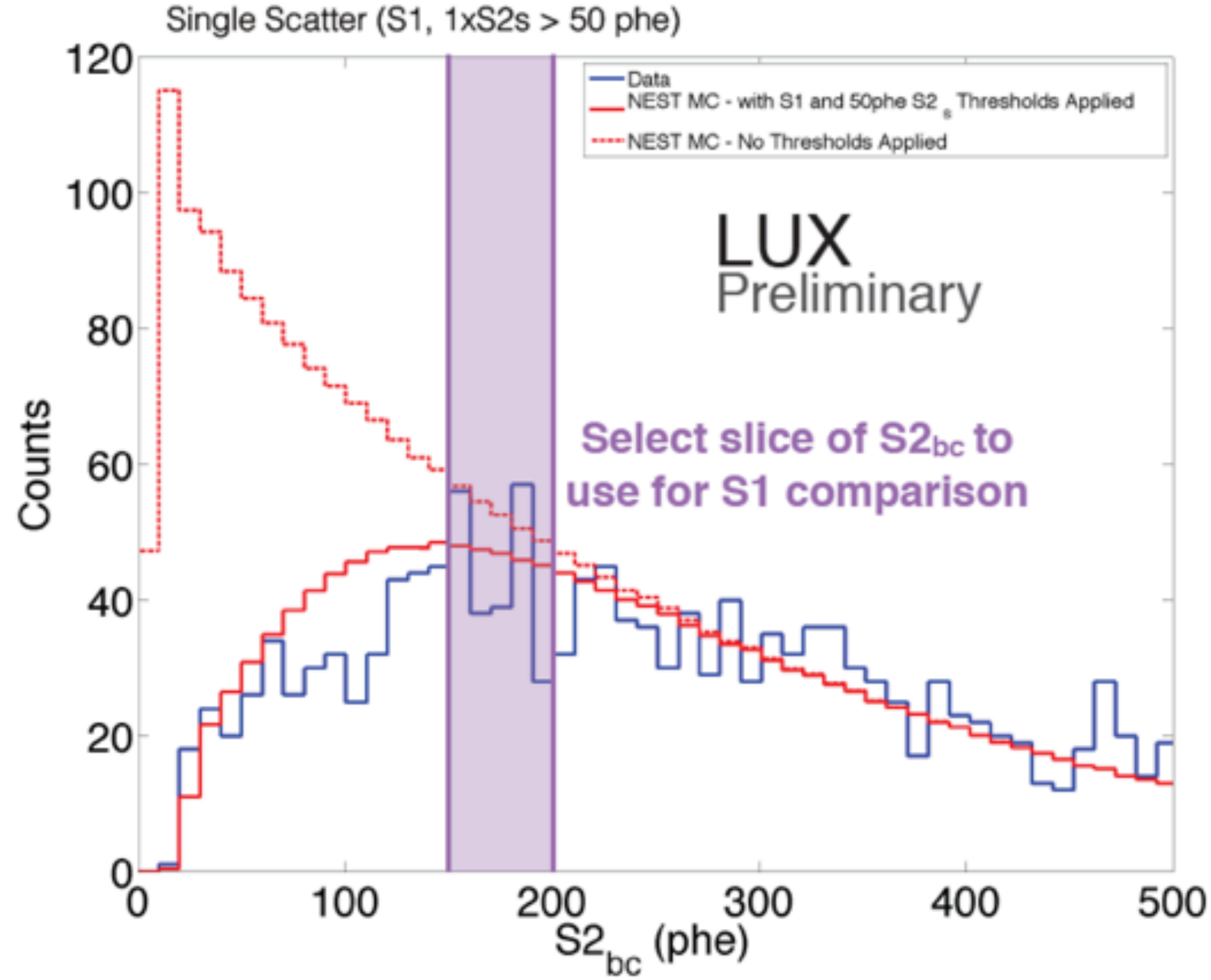
- Systematic error of 7% from threshold correction for (lowest energy) 0.7-1.0 keVnra bin
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency.
- Current analysis cut-off at 0.7 keV_{nra}



Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)
Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)
Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm

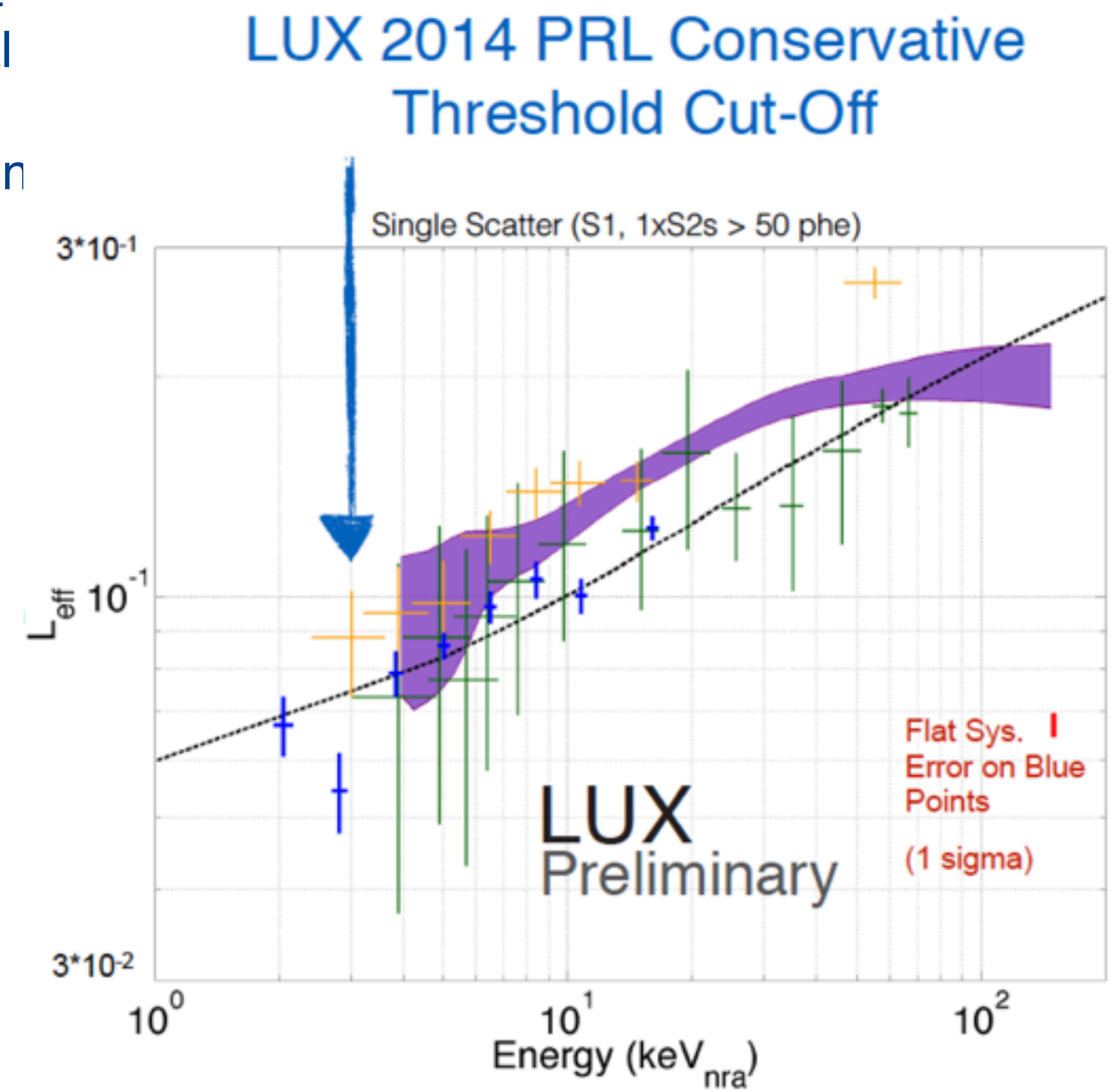
Scintillation (S1)

- Use single scatters with suitable selection criteria
- NEST based MC used to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Normalized from 200 - 400 phe (6.5-13.5 keV_{nra})
- First bin conservatively begins at 50 phe $S2_{bc}$ to avoid spurious single electron coincidence



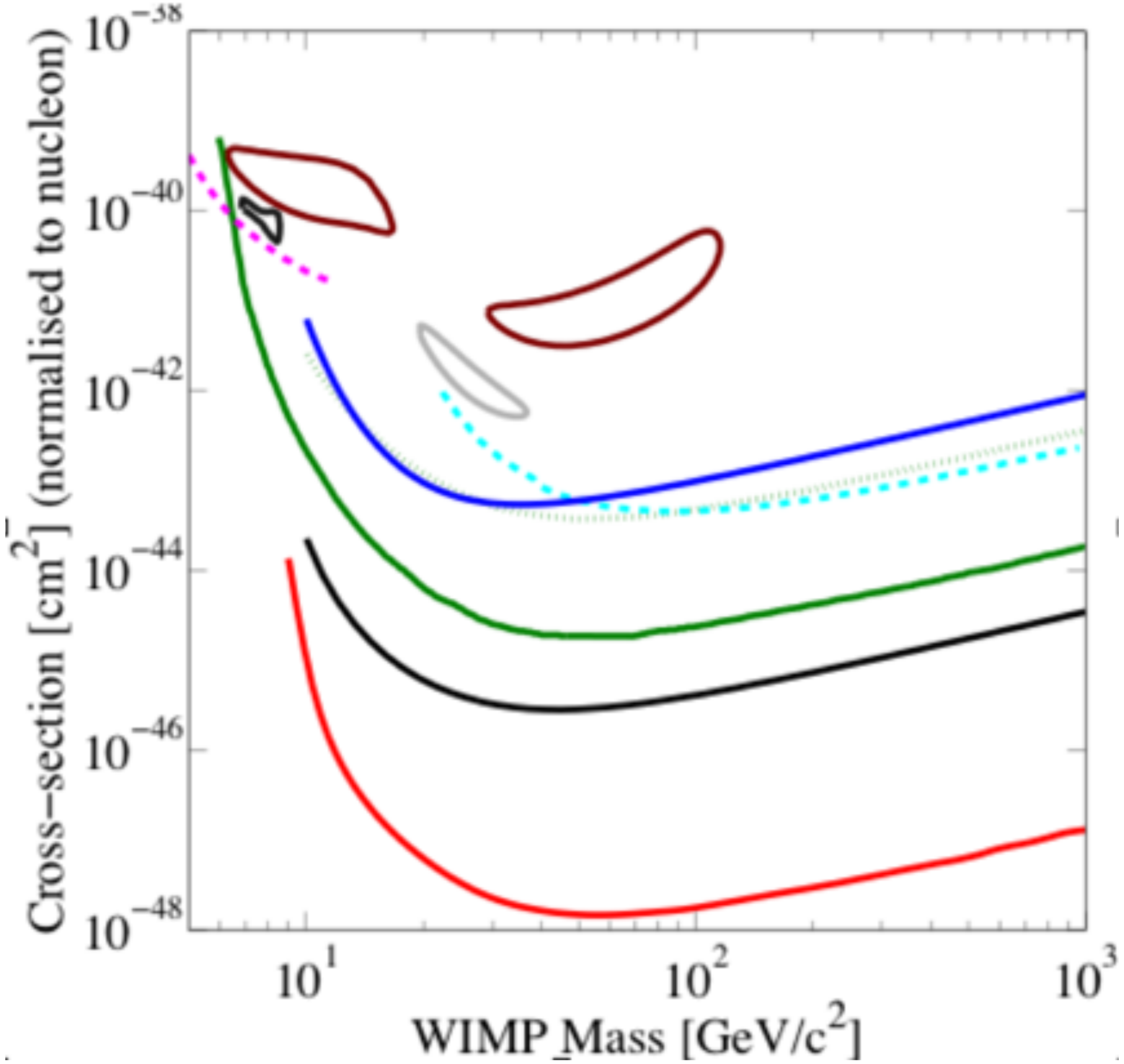
Scintillation (S1)

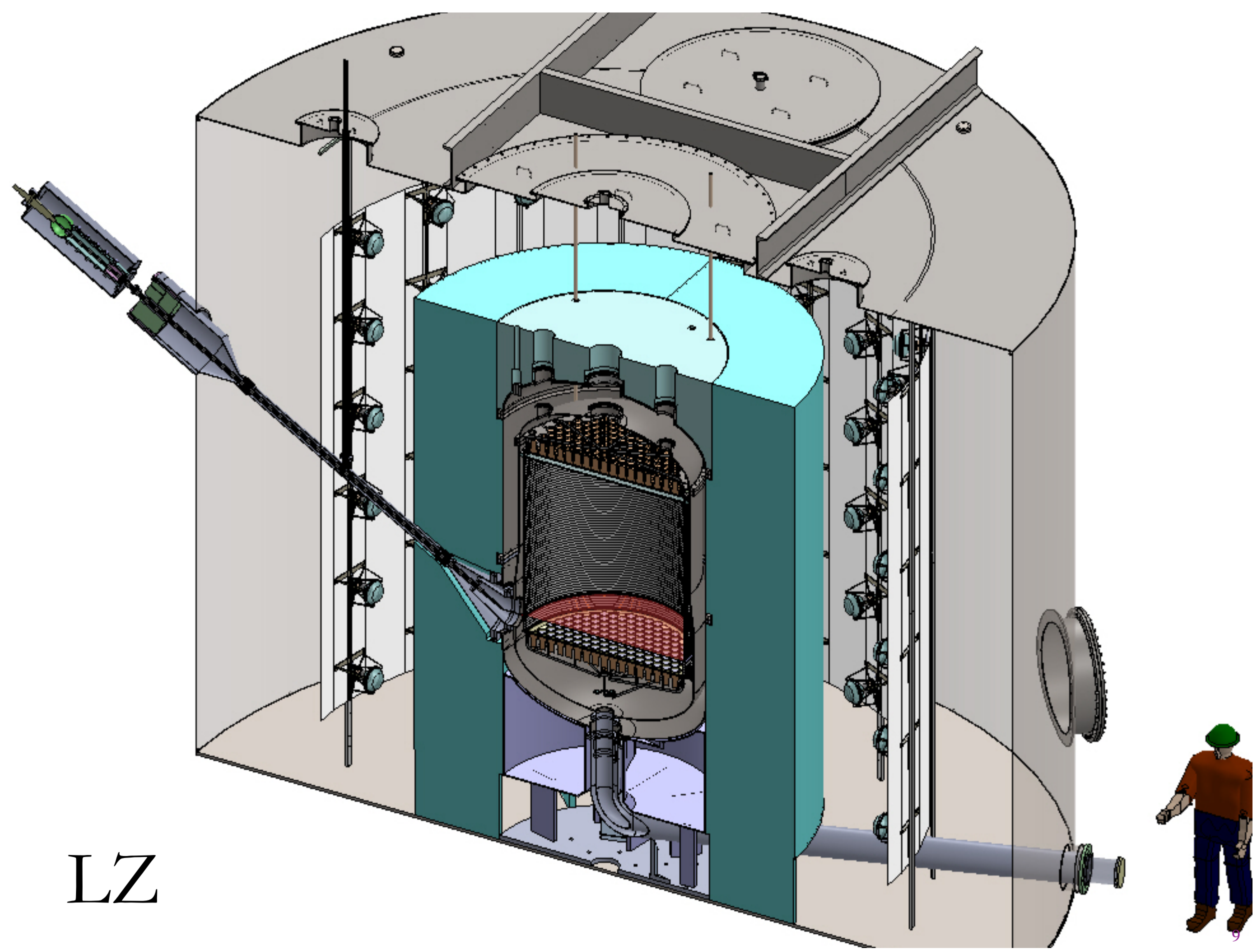
• LUX Leff values currently reported at 181 V/cm as opposed to the traditional zero field value.
• X error bars representative of error on mean of population in bin
• Energy scale defined using LUX measured Qy
• Method can be extended below existing 2 keV_{nra} point



Blue Crosses - LUX Measured Leff; reported at 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)
Purple Band - Horn Combined Zeplin III FSR/ SSR; 3.6 kV/cm, rescaled to 0 V/ cm (energy scale from best fit MC)
Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)
Black Dashed Line - Szydagis et al (NEST) Predicted Scintillation Yield at 181 V/cm

LUX-ZEPLIN (LZ)





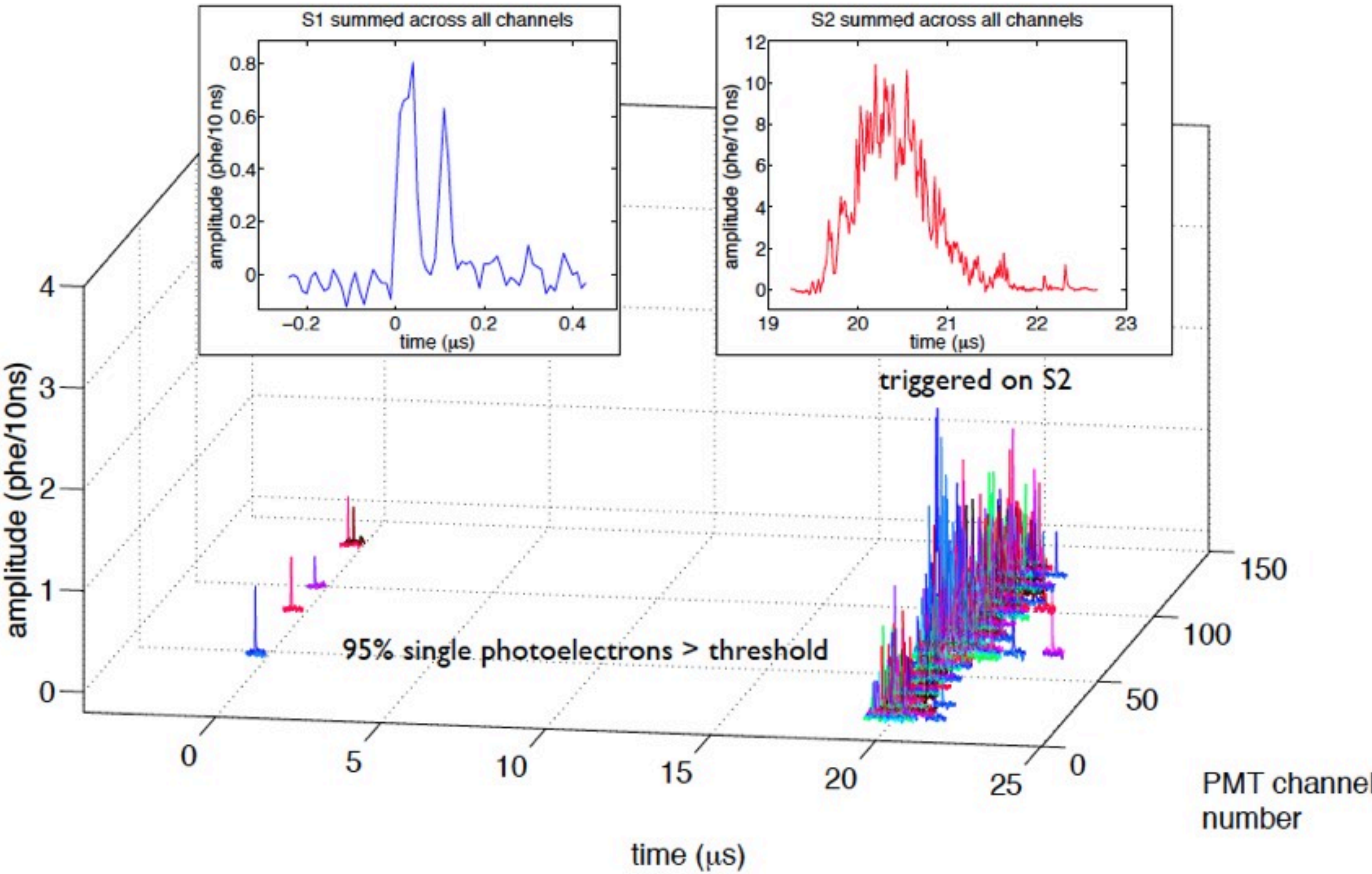
- 20X larger volume
- Lower backgrounds from PMTs
- Planned to run for 3 years

Summary

- LUX now has the most sensitive WIMP search in the world, including at low masses
  - Result is inconsistent with putative low mass WIMP signals
- Expect 5X improvement in sensitivity in next run
- Improved understanding of low-energy response
  - Opens the possibility to push limit to lower WIMP masses
- Thank you for your attention!

Back Up Slides

A 1.5 keV γ Scatter



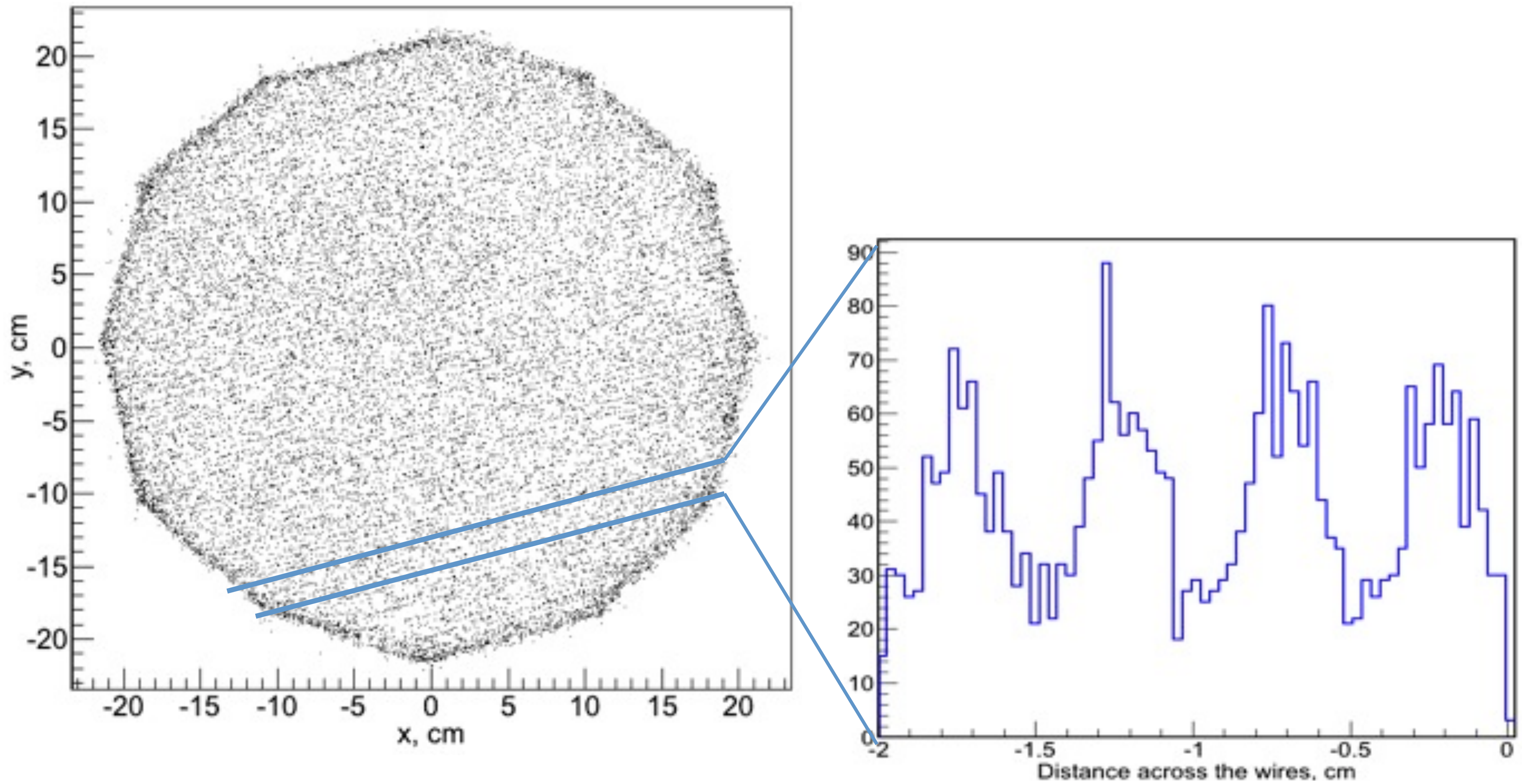
Position Reconstruction

Z coordinate is determined by the time between S1 and S2 (electron drift speed of 1.51 mm/microsecond)

Light Response Functions (LRFs) are found by iteratively fitting the distribution of S2 signal for each PMT.

XY position is determined by fitting the S2 hit pattern relative to the LRFs.

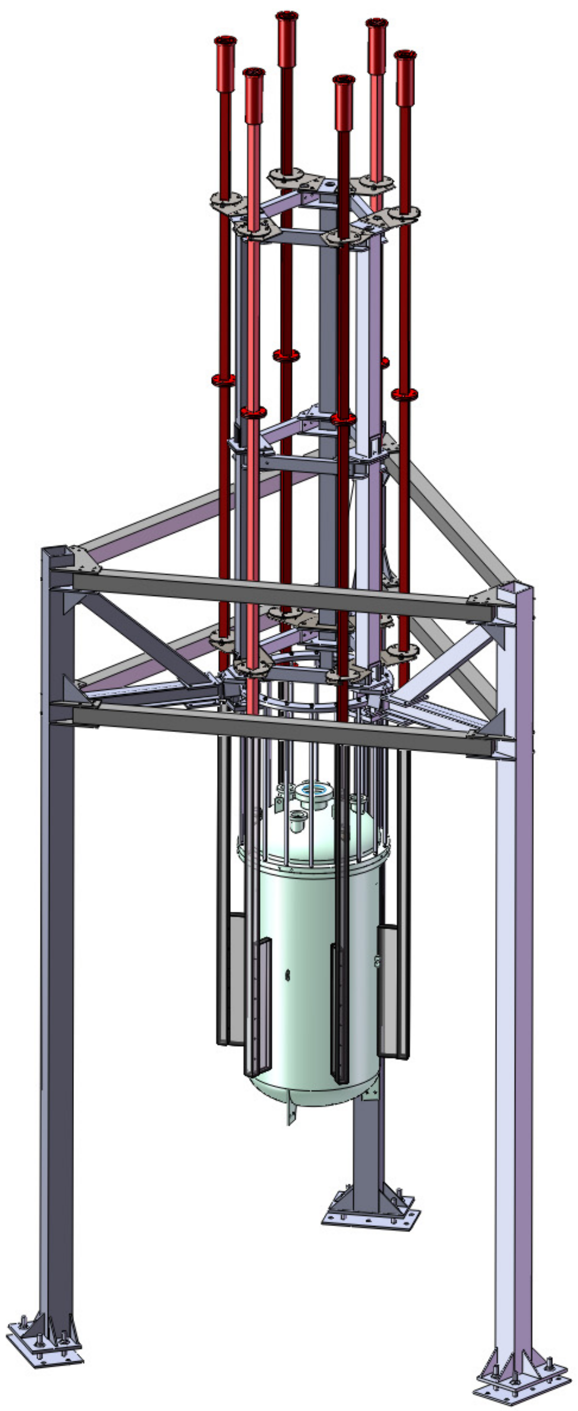
Reconstruction of XY from events near the anode grid resolves grid wires with 5 mm pitch.



Events and Cuts

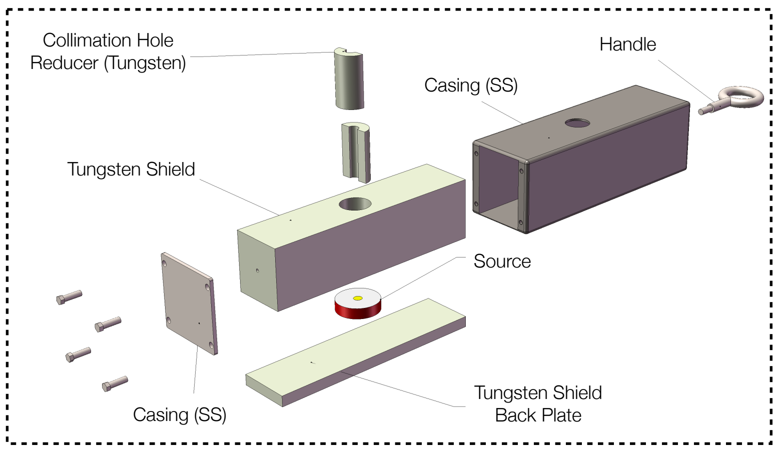
Cut	Explanation	Events Remaining
All Triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918,901
Single Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585,686
S1 energy	Accept 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

Detector Calibrations



- External neutron sources: AmBe (α,n) and ^{252}Cf (spontaneous fission)
- Internal beta sources:
  - 83mKr: 1.8 hr. half-life, produces two mono-energetic betas at 32.1 and 9.4 keV
    - Excellent for studying position dependence of detector response
  - Tritiated methane: beta with 18.6 keV end point for calibrating electron recoil response to low energies

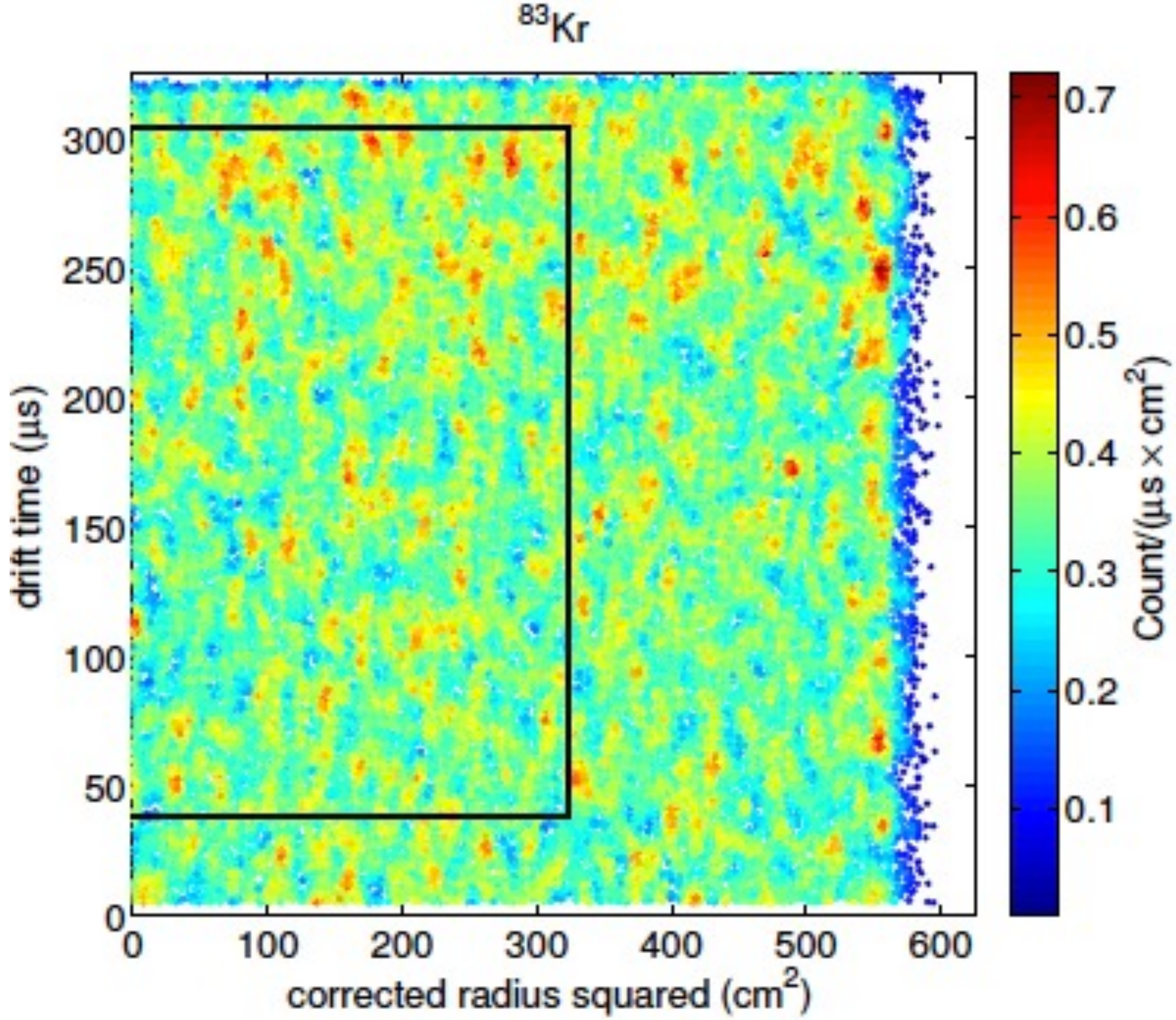
external source holder



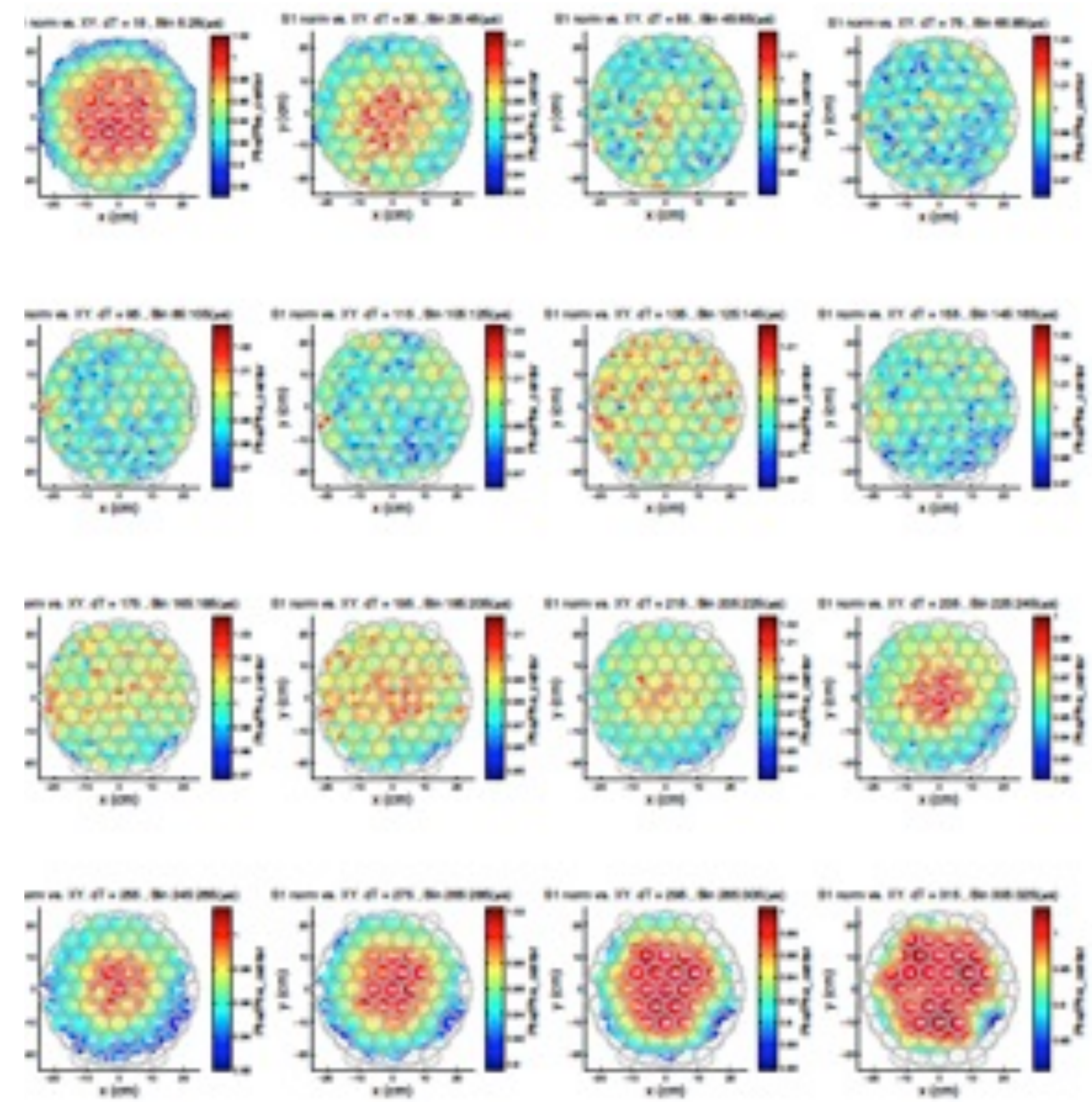
^{83}Rb coated charcoal plumbed into gas system → ^{83m}Kr

^{83m}Kr Calibrations

Fiducial volume determination

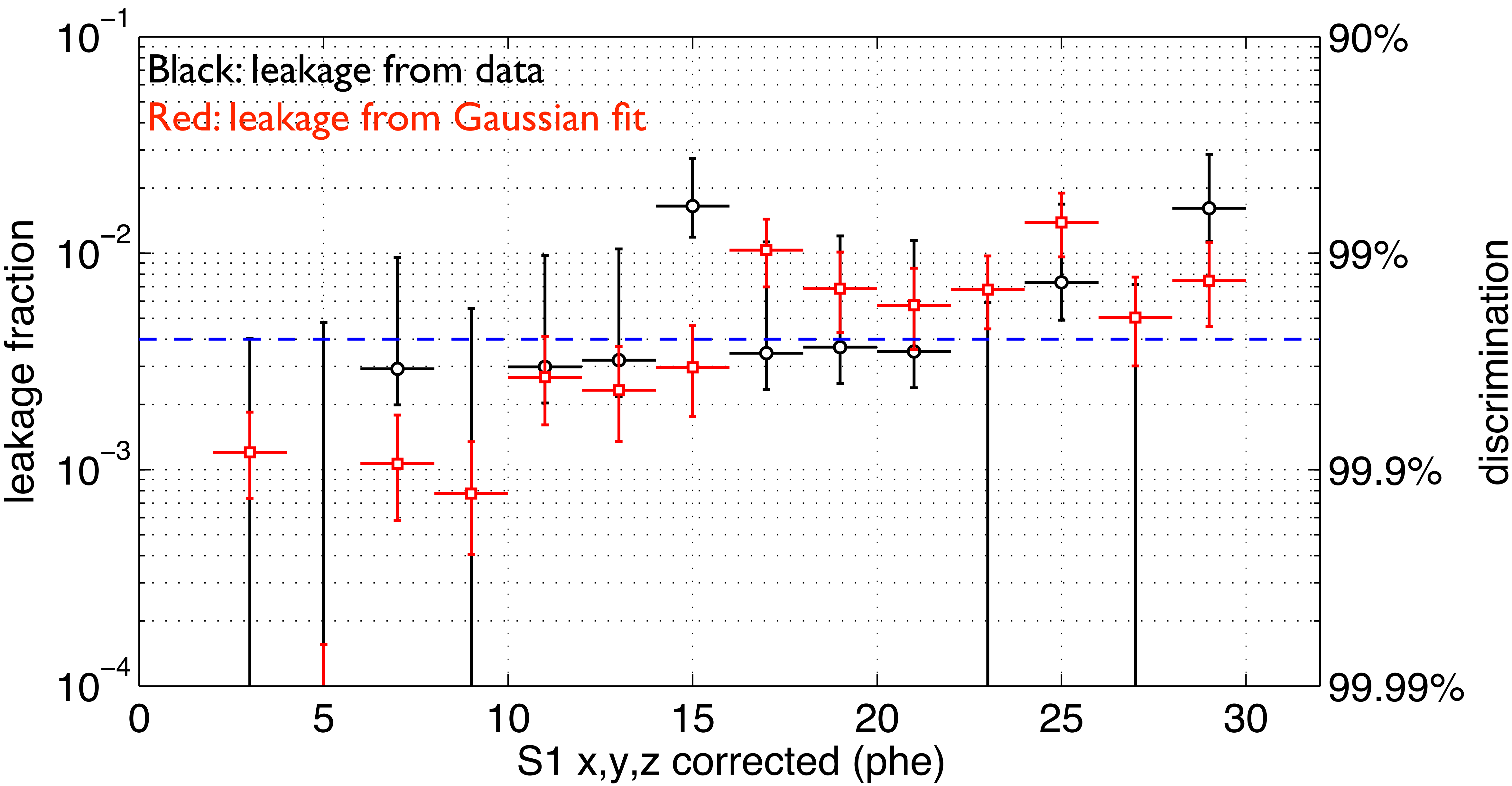


Position-based S1 corrections



- 83mKr produces two mono-chromatic betas/x-rays uniformly through the detector volume => great source for calibration position dependence of detector response!

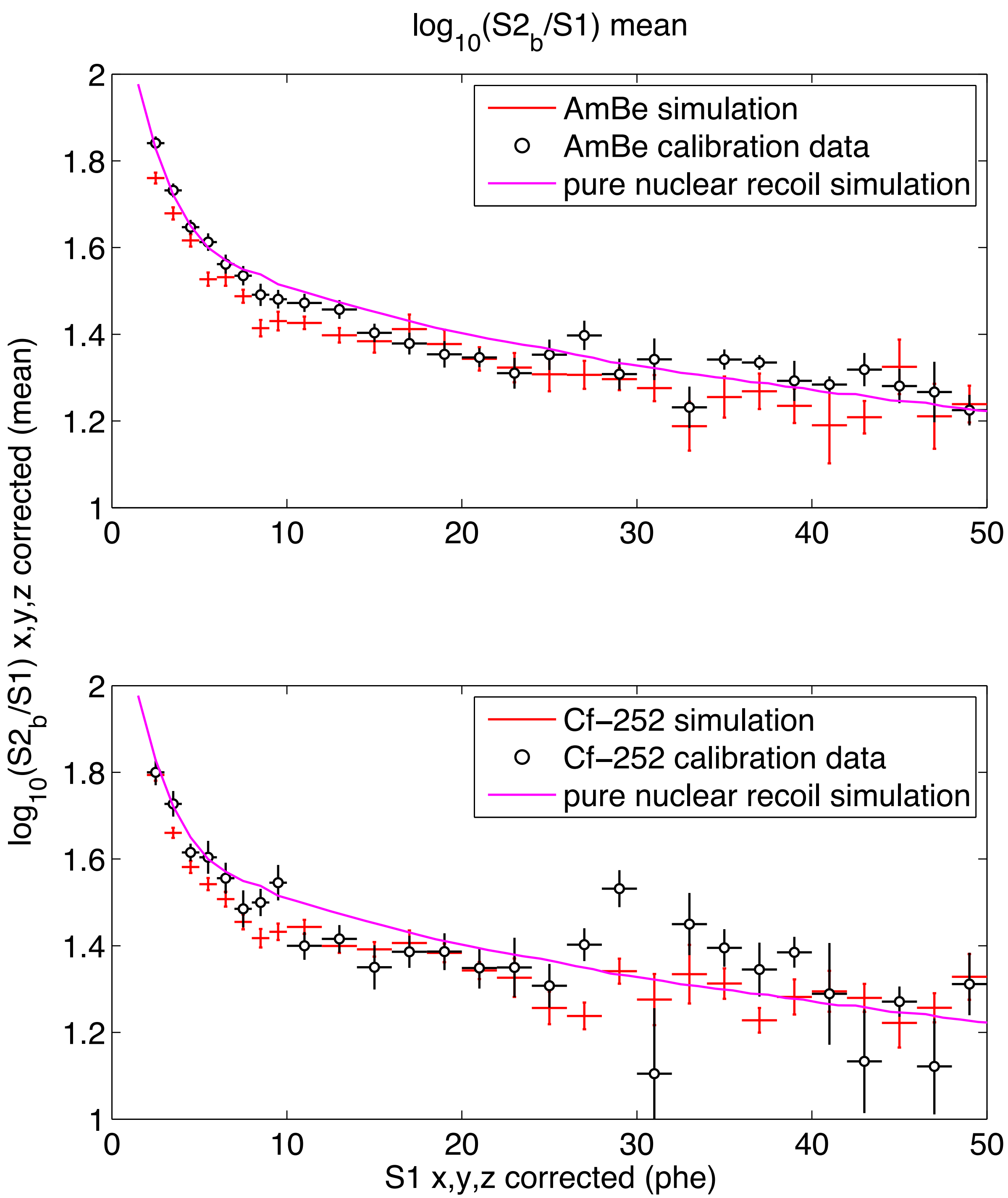
Electron Recoil Leakage



- Fraction of electron recoil events below nuclear recoil mean (50% acceptance) versus S1
- Average of 99.6% electron recoil discrimination with 50% nuclear recoil acceptance

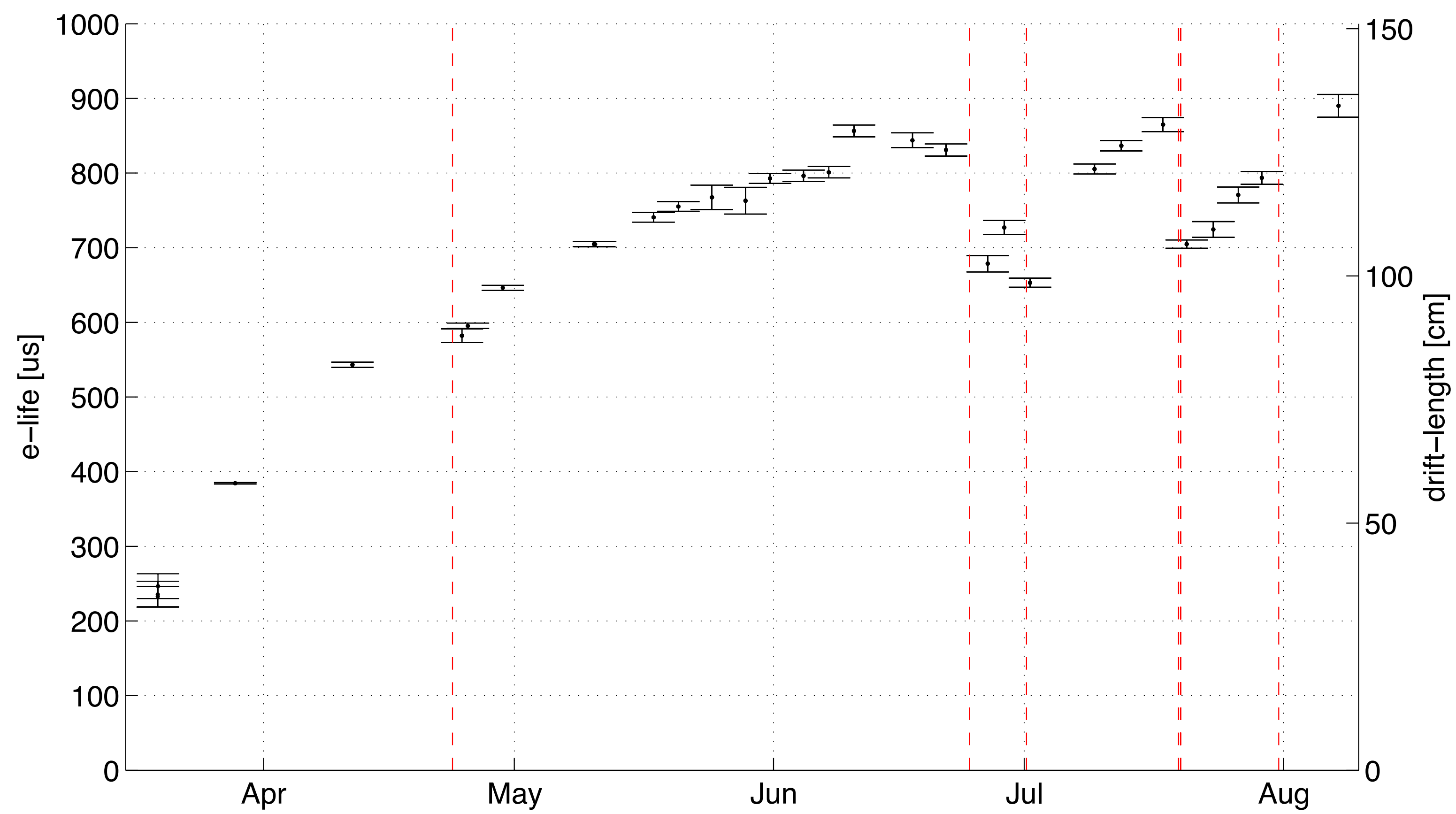
Nuclear Recoil Calibrations

- Comparison of nuclear recoil band mean in data and simulation
- Notice width and mean are different from pure (single scatter) nuclear recoil simulations
  - Real data is affected by gamma contamination and misidentified multiple scatters

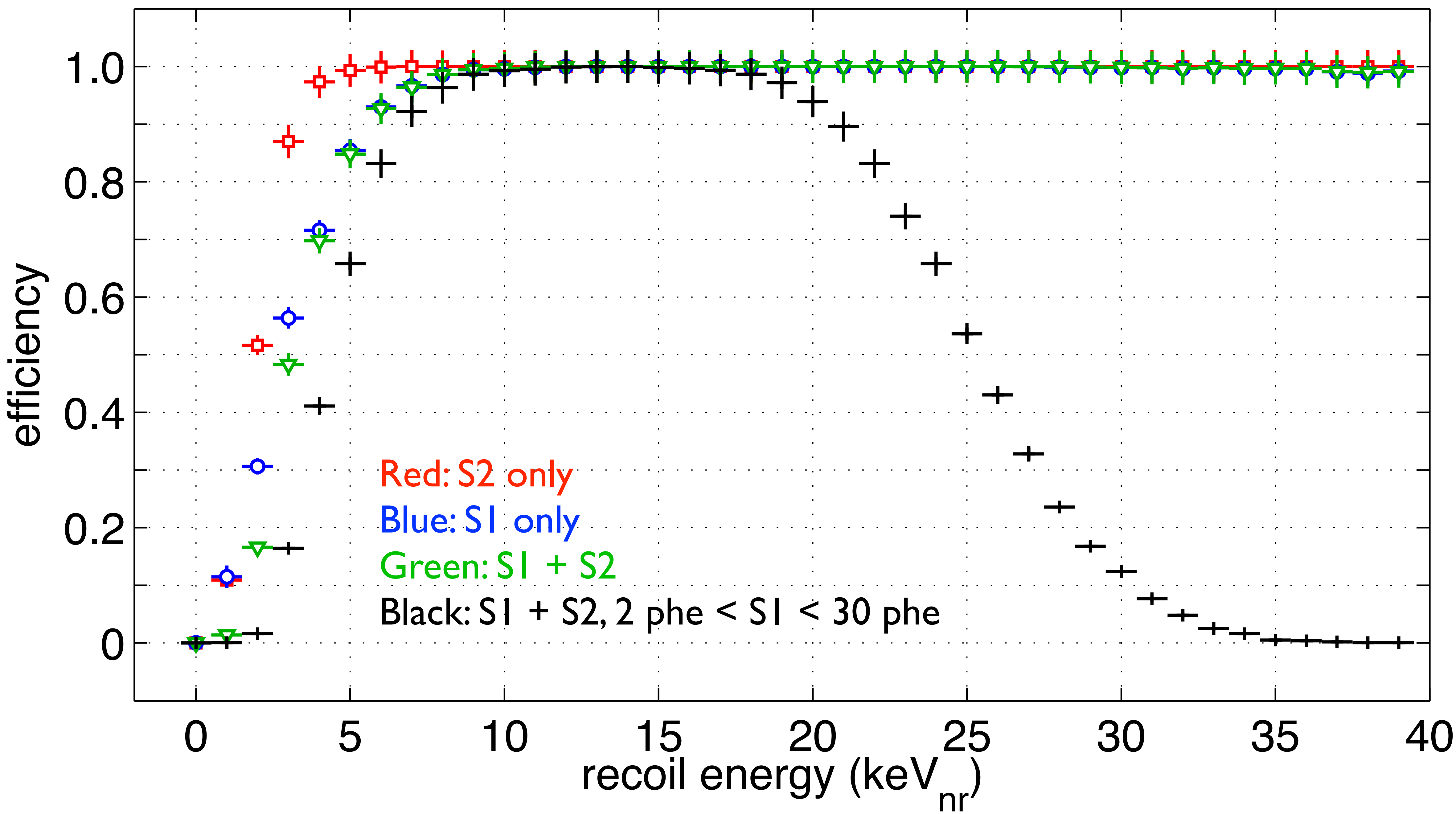


Electron Lifetime

- Xenon circulated through purification system at 27 SLPM
- Electron lifetime measured using ^{83m}Kr betas
- Was between 87 ± 9 and 134 ± 15 cm during WIMP search (LUX drift length: ~50 cm)



Acceptance Used in WIMP Search Analysis



Profile Likelihood Analysis

$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}})$$

$$+ N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}}) + N_{Rn} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Rn}})$$

WIMP signal PDF:
- WIMP dE/dR for given mass
- efficiency from validated NR sims
- N_s is parameter of interest

Backgrounds as nuisance parameters:
- detector efficiencies included
- 30% uncertainty on overall rate

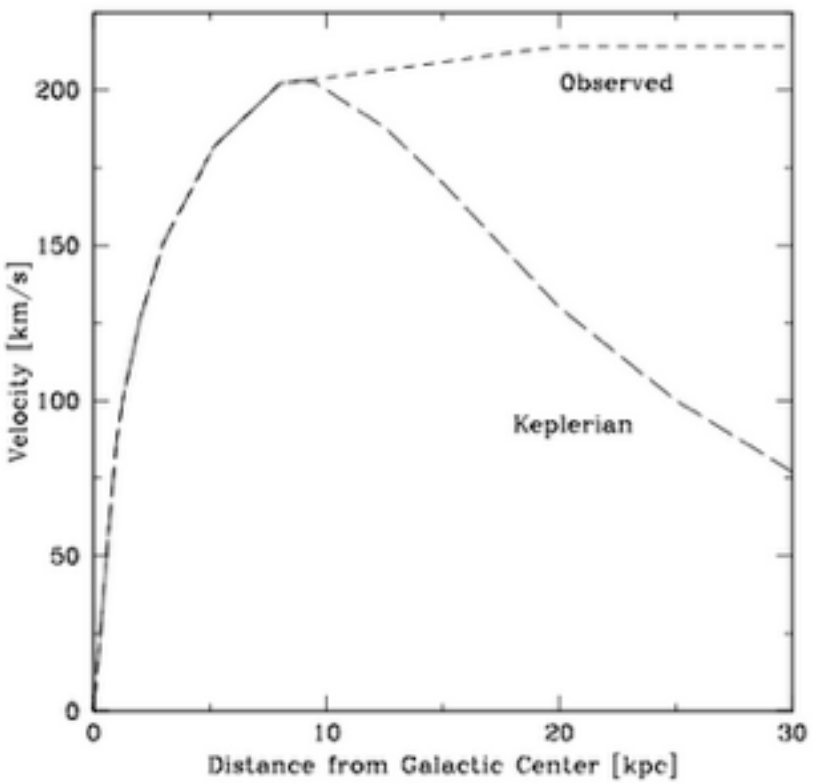
The Bullet Cluster

- Above: image of two galaxies passing through each other, showing the hot gas (red) and center-of-mass from gravitational lensing (blue)
- Strongest evidence to data that dark matter phenomenon is not due to Modified Newtonian Dynamics

Dark Matter

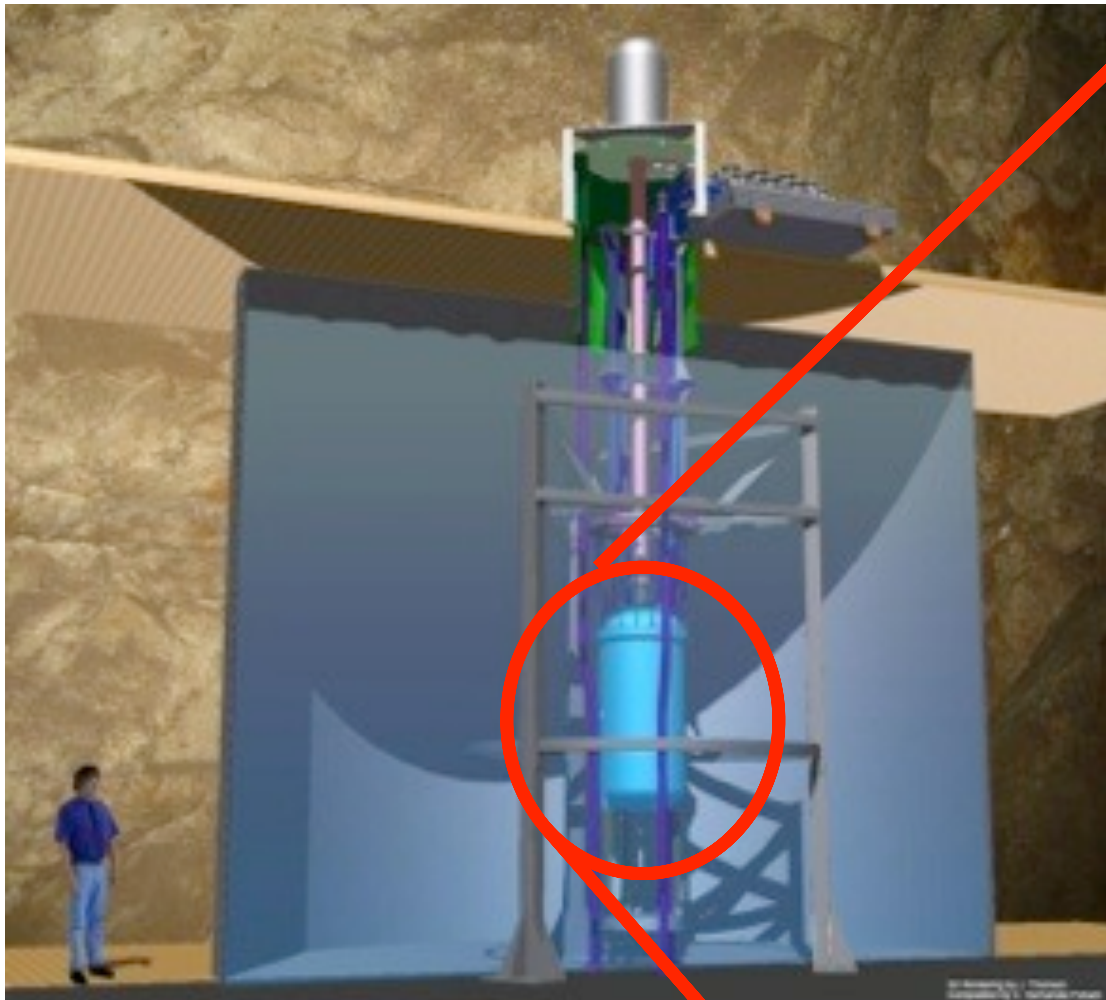
Fritz Zwicky

Rotation curves of galaxies

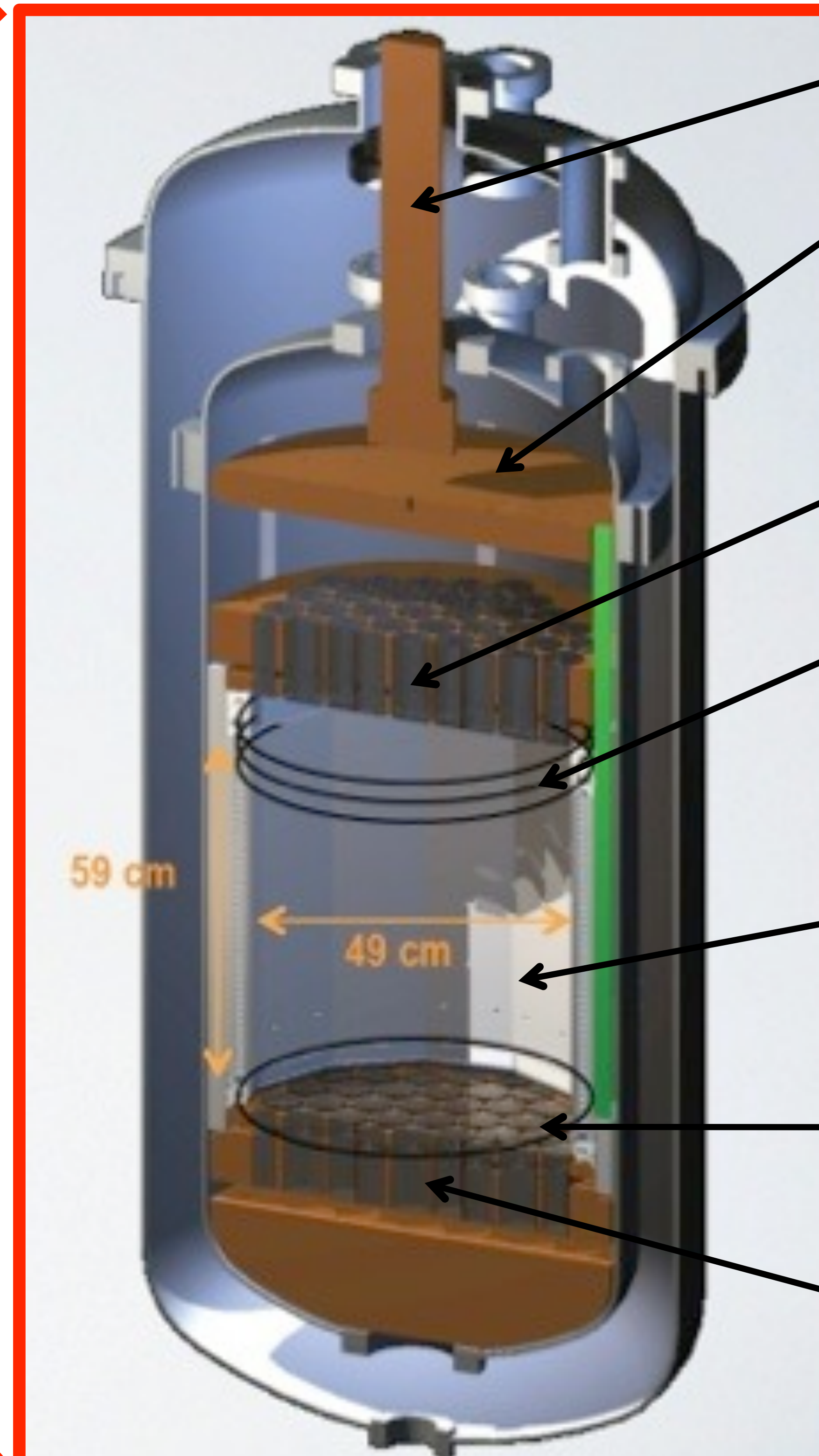


- First suggested by Fritz Zwicky in the 1930 while studying the Coma Cluster
- Later studied by Vera Rubin in the 1970's
- At large radii within galaxy clusters, the rotational velocity of galaxies within the cluster does not go to zero
- The explanation: there is extra mass that neither absorbed nor emitted light, referred to as dark matter

The LUX Detector



Low-radioactivity
Titanium Cryostat



370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

Detector Construction