First results from the LUX Dark Matter Experiment

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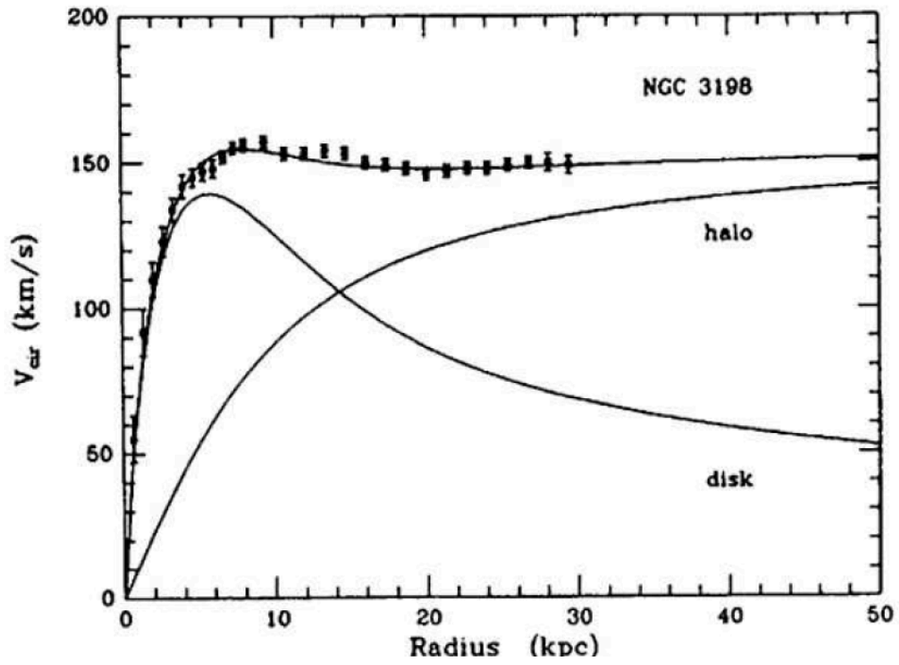
on behalf of the LUX collaboration

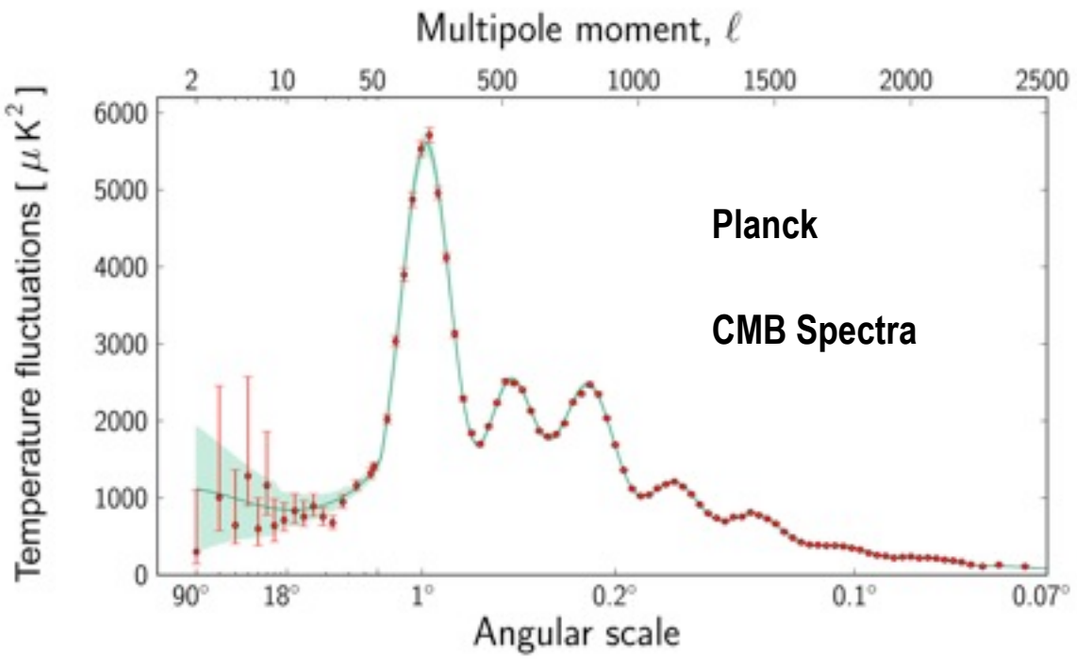
Rencontres de Moriond 2014
Electroweak Session
18th of March 2014

DARK MATTER EVIDENCES

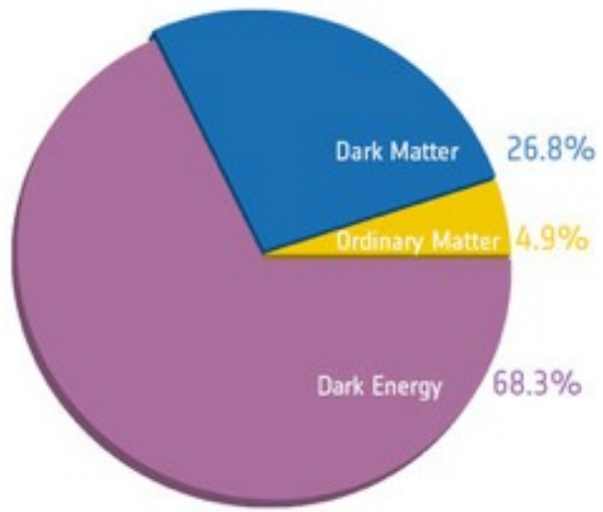
Rotation curve NGC-3198



Bullet-cluster: DM not MOND



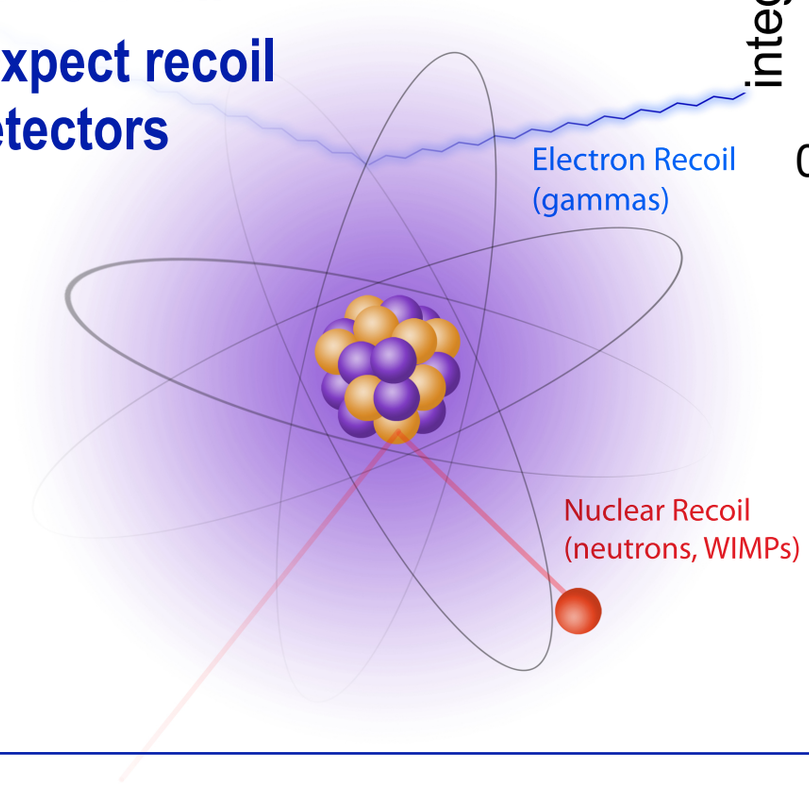
Planck Results



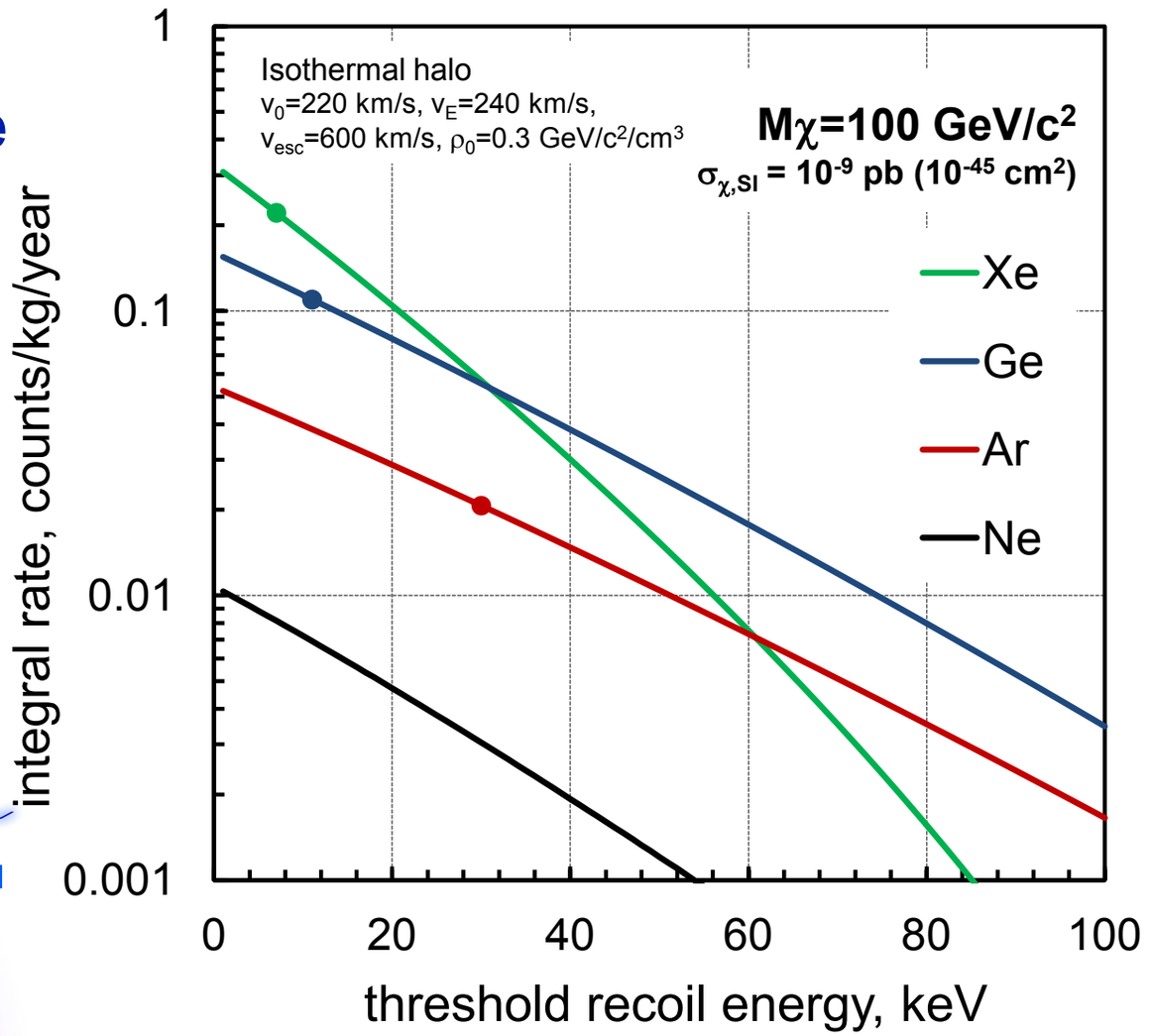
$$\frac{\text{Dark Matter}}{\text{Ordinary Matter}} \approx 5.44 \pm 0.14$$

DARK MATTER - DIRECT DETECTION

- **Cold Dark Matter Candidates**
  - **Axions**
  - **WIMP's (weakly interative massive particles) are the favoured candidates for cold dark matter:**
    - **Neutral in most scenarios**
    - **Requires physics beyond the standard model**
  - **... others**
- **LUX is a Direct Detection experiment**
  - **We look for scattering of galactic WIMPs with the nucleus of the target material.**
  - **Isothermal model: expect recoil <10 keV requiring detectors with a very low threshold.**

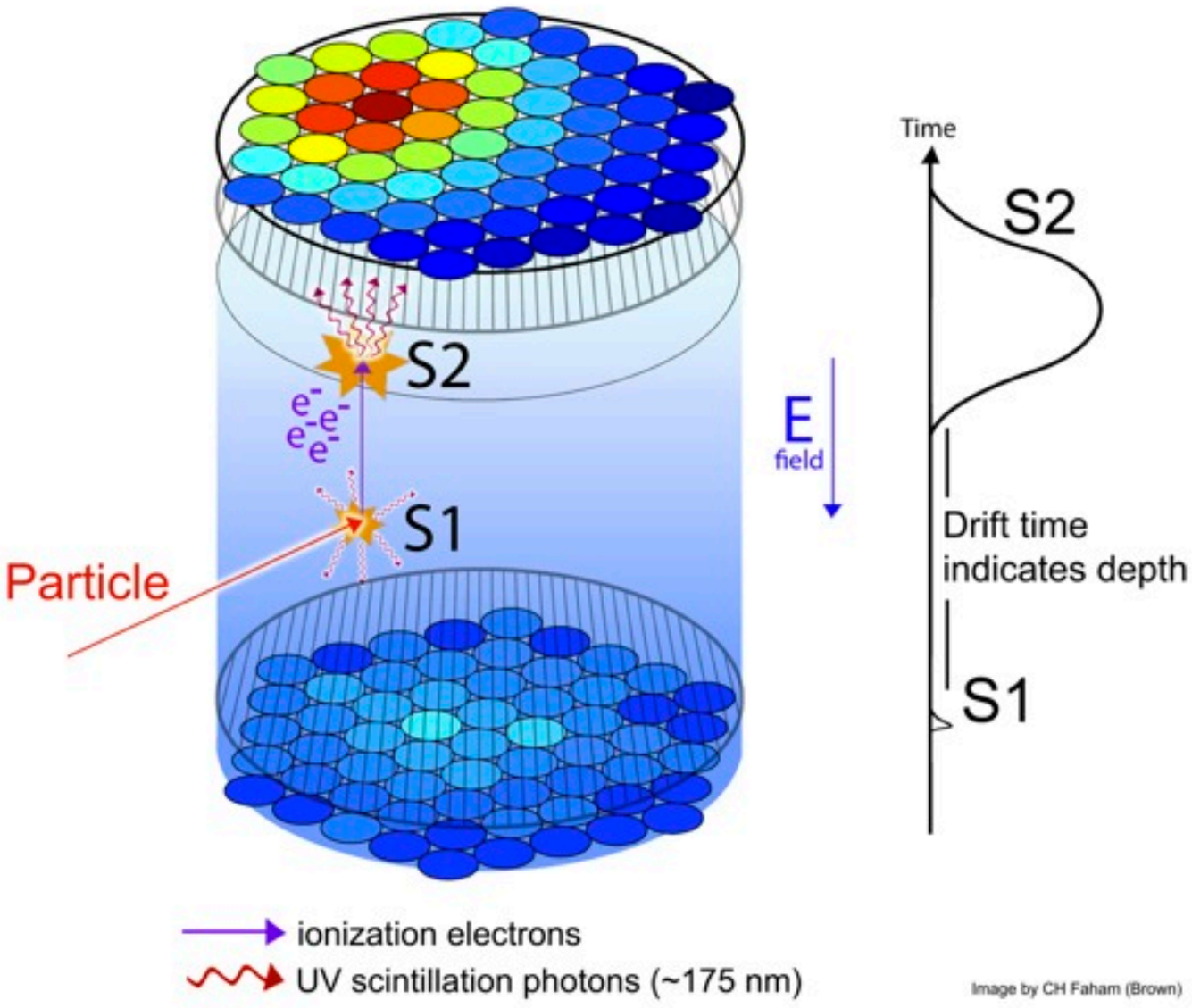


Spin Independent



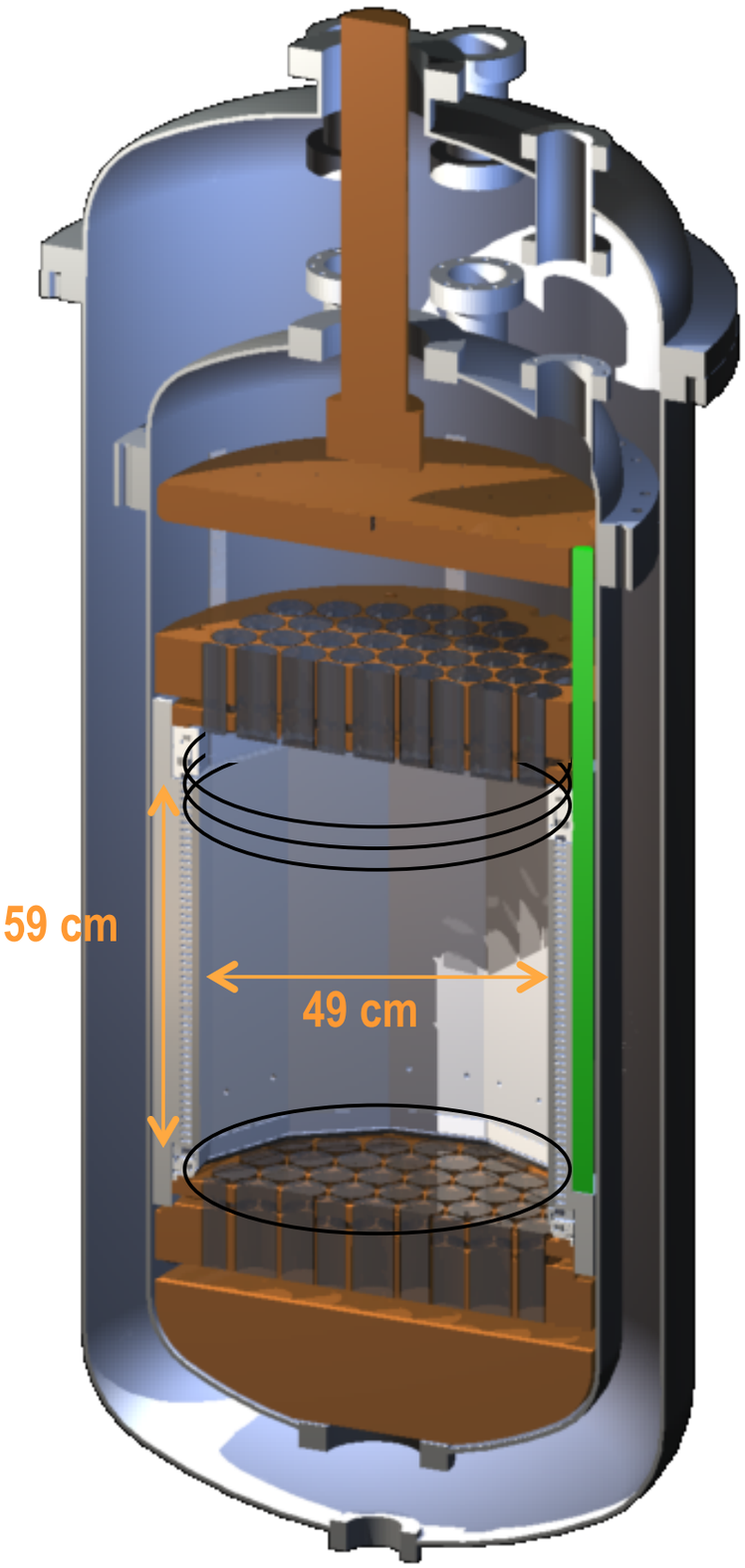
- **Weak interaction**
  - **Spin dependent**
  - **Spin independent** $\sigma \propto A^2$

DOUBLE-PHASE TPC



- **Primary scintillation (S1)**
- **Secondary scintillation signal from electroluminescence after drift (S2)**
- **Position reconstruction**
  - **Z from time difference between S1 and S2 (1.51 mm/μs in LUX for a electric field of 181 V/cm)**
  - **XY reconstructed from light pattern observed in the top array.**
    - **Typical resolution of some mm.**
- **Reject gammas, betas by S2/S1 ratio**
  - **$(S2/S1)_{\gamma,e} > (S2/S1)_{WIMP}$**

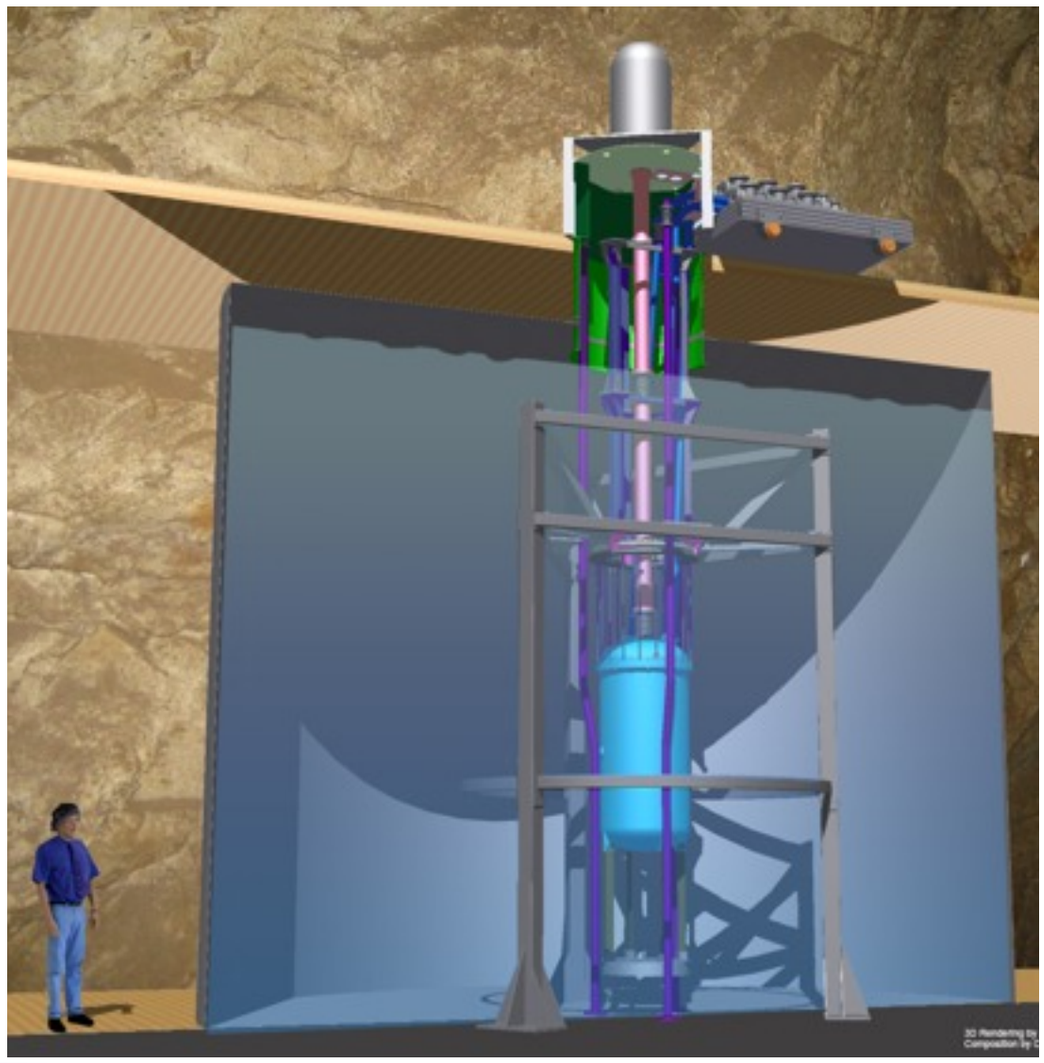
THE LUX DETECTOR

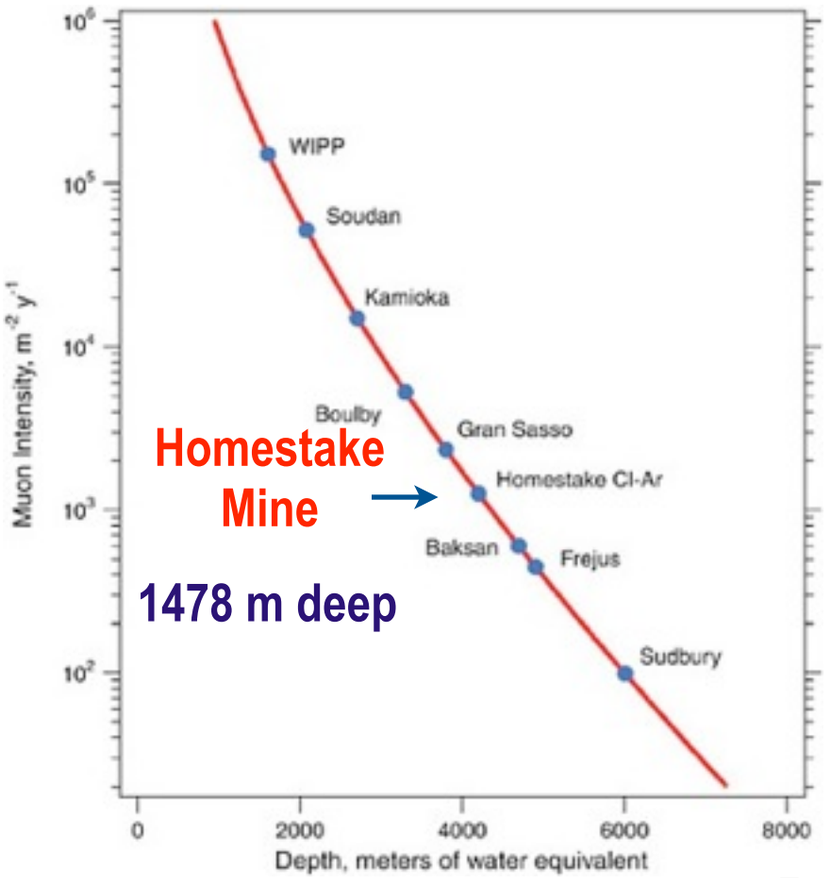


- 370 kg Liquid Xenon Detector (59 cm height, 49 cm diameter) in gas/liquid fases.
  - 250 kg in the active volume
  - 118 kg in the fiducial volume
- Construction materials chosen for low radioactivity: Ti, Cu, PTFE
- Viewed by 122 ultra low-background PMTs
  - 61 on top and 61 on bottom
  - 12 mBq/PMT
- Active region defined by PTFE
  - High reflectivity for the VUV light - high light collection

LUX AT SURF

- LUX operates 4850 feet (1478 m) underground at the Sanford Underground Research Facility (SURF), South Dakota, US
- Surrounded by a 7.6 m diameter water shield
- Background dominated by construction materials ...
  - <2 background events per day in the central 118 kg target in the energy window of interest… and is decreasing.

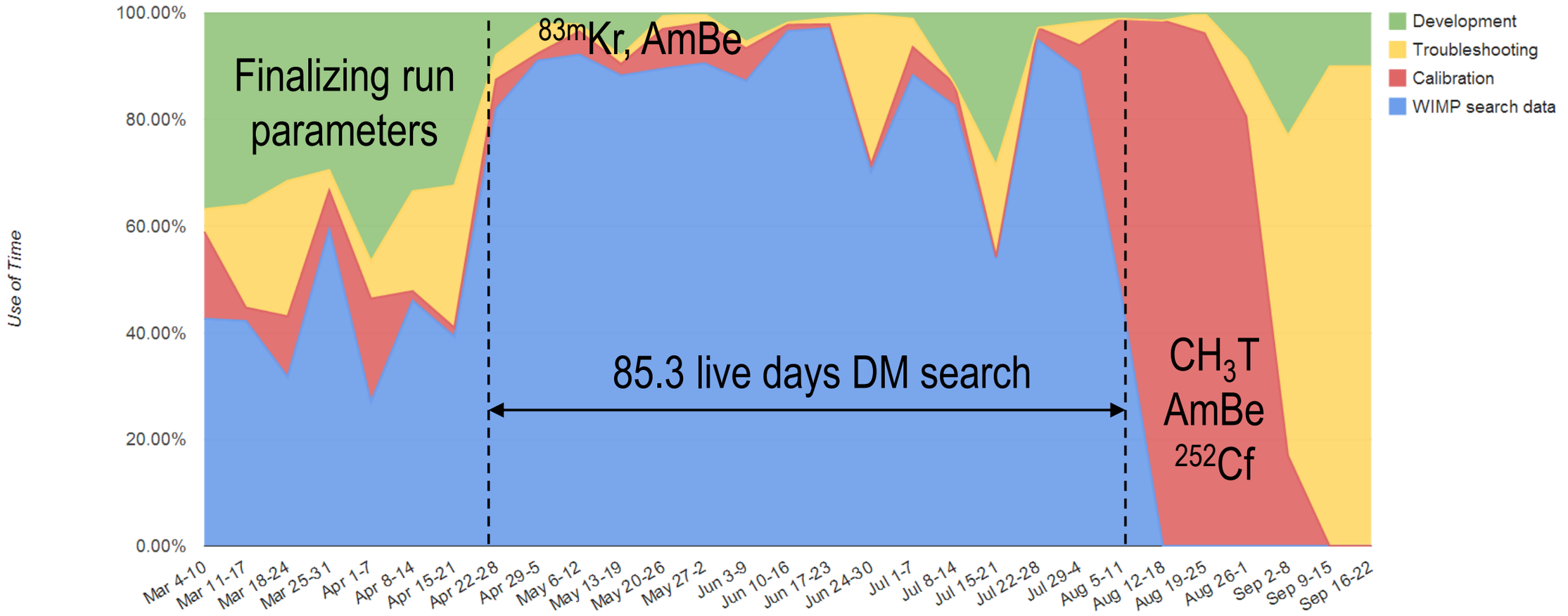




μ flux reduced by x10^{-7} (compared to sea level)

LUX inside the water tank, September 2012

RUN 3 DATA-TAKING



- Detector cool-down January 2013, Xe condensed mid-February 2013
- Data-taking April 21 - August 8, 2013, 85 live days
  - >95% data taking efficiency over WIMP search region
- Very stable conditions during the run:
  - Thermal stability of $\Delta T<0.2$ K, pressure stability $\Delta P/P<1\%$ and liquid level variation <0.2 mm
- ^{83m}Kr and AmBe calibrations throughout, CH_3T after WIMP search (internal calibrations)
- Non-blind analysis

BACKGROUNDS IN LUX AT LOW ENERGY

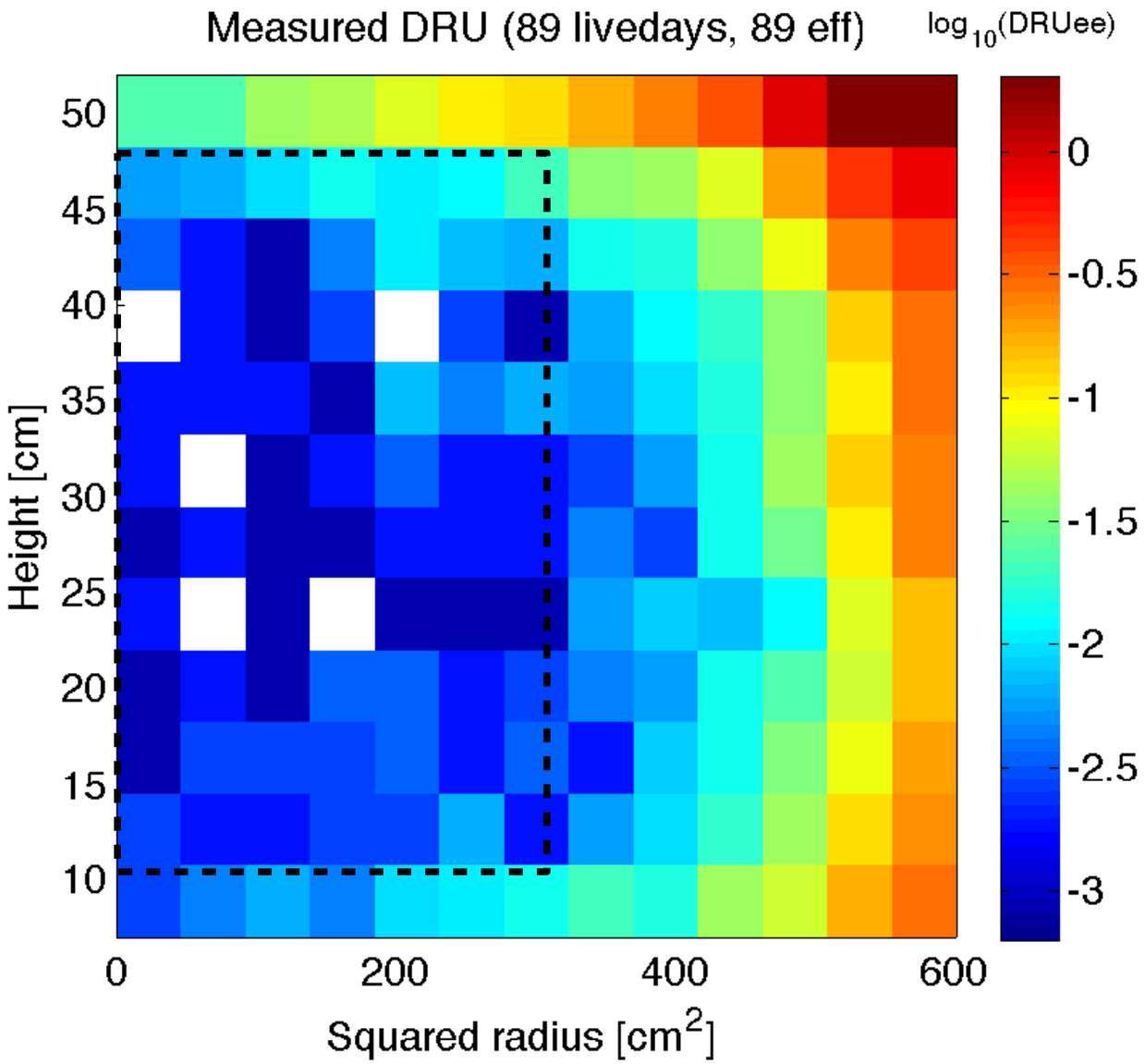
Predicted and measured low-energy background rates in the LUX 118 kg WIMP search fiducial during the 85.3 day run. Rates are averaged over the energy range 0.9–5.3 keVee.

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	$0.11\text{-}0.22_{(90\%\ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.17 \pm 0.10_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.6 \pm 0.3_{stat}$

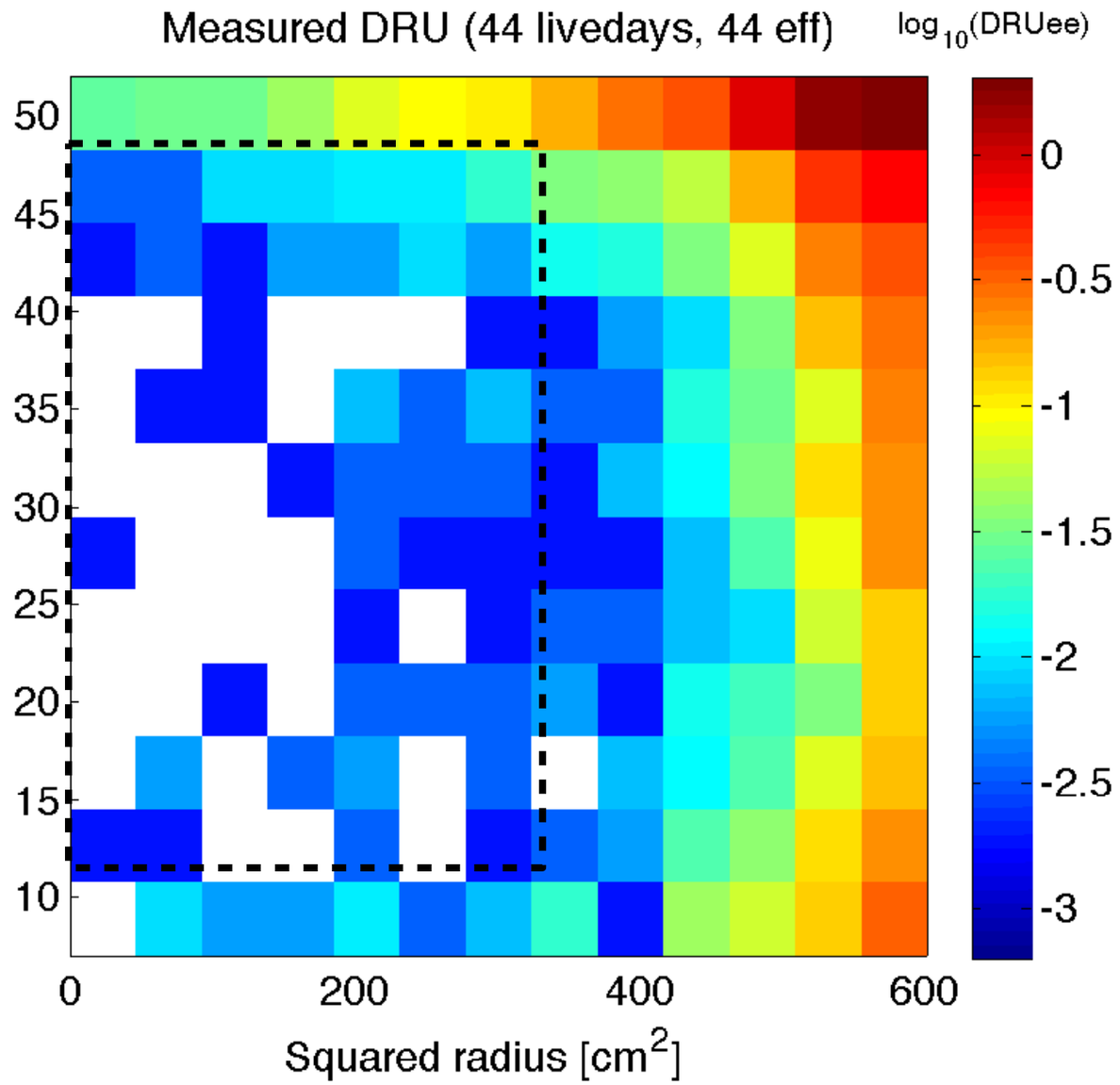
- **Model based on radioactive counting of detector components and simulation.**
  - **Very good agreement with the data**
- **Extremely low backgrounds at low energy**

OBSERVED BACKGROUNDS AT LOW ENERGY

Entire run



Last 44 days

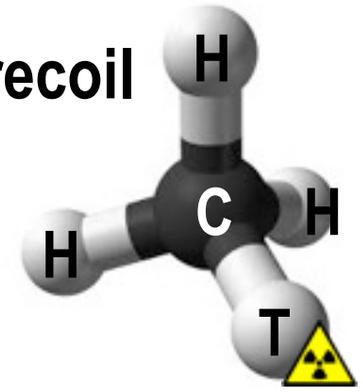


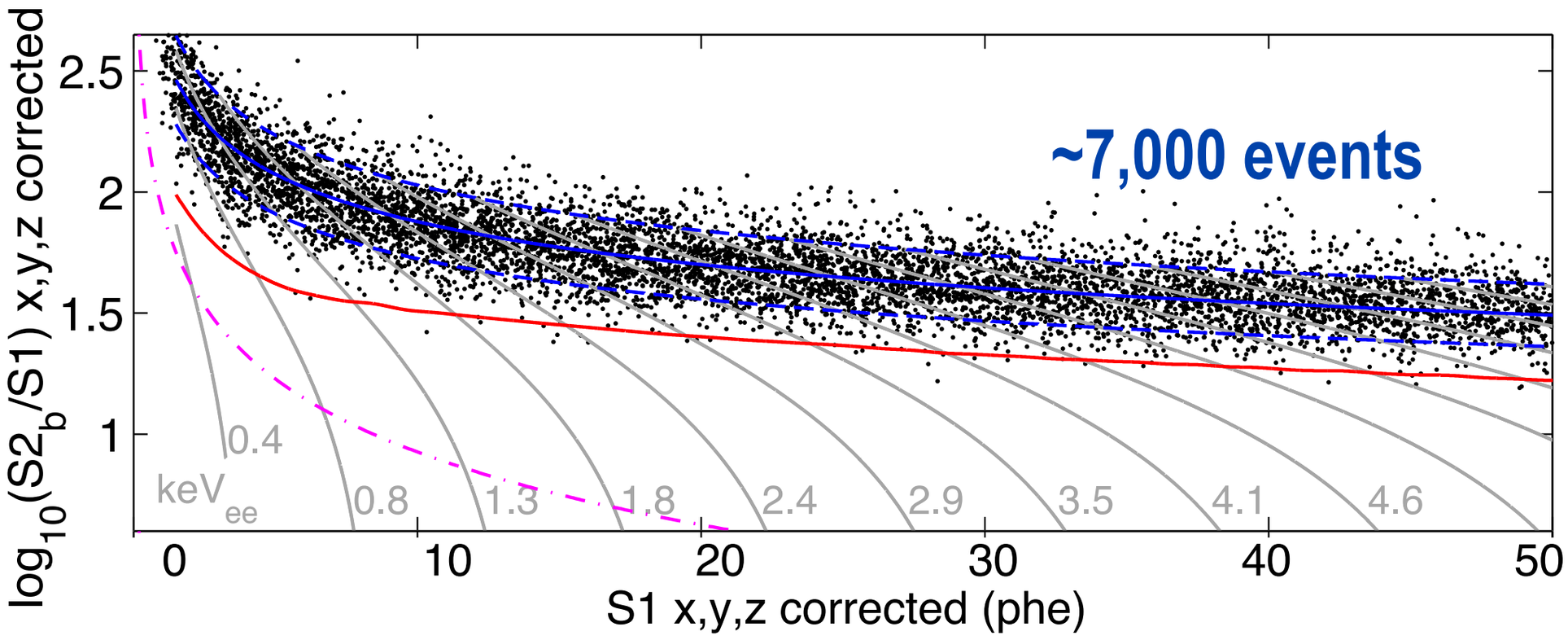
r<18 cm, z=7-47 cm, 0.9–5.3 keVee

1 DRU_{ee} = events/keV_{ee}/kg /day

ELECTRONIC RECOIL CALIB.

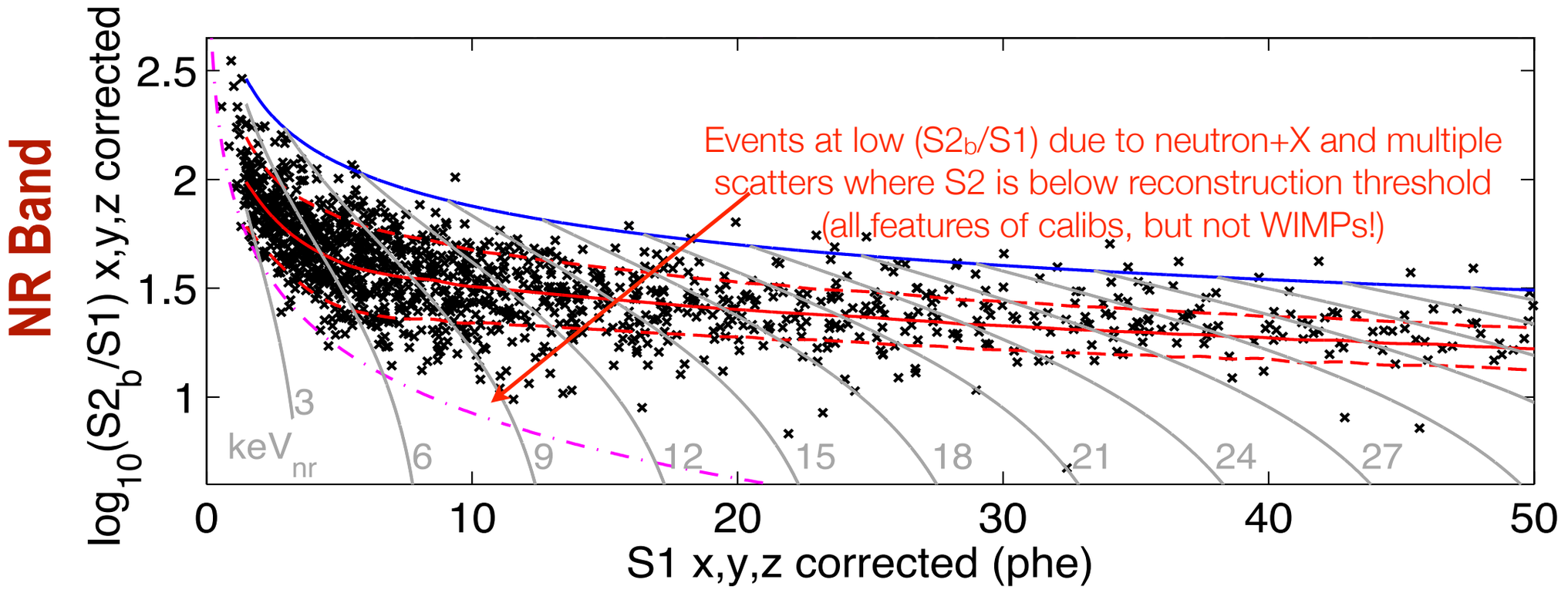
- Xe self-shielding prevents γ's from reaching inner volume
  - Solution: Use internal radioactive sources
- Tritium is an ideal source for determination of the detector's electron recoil band and low energy threshold
  - E(max) - 18.6 keV
  - <E> - 5.9 keV
  - β decay with $T_{(1/2)}$ = 12.6 y - Long Lifetime
- Tritiated methane was injected in the gas system and removed by the getter.





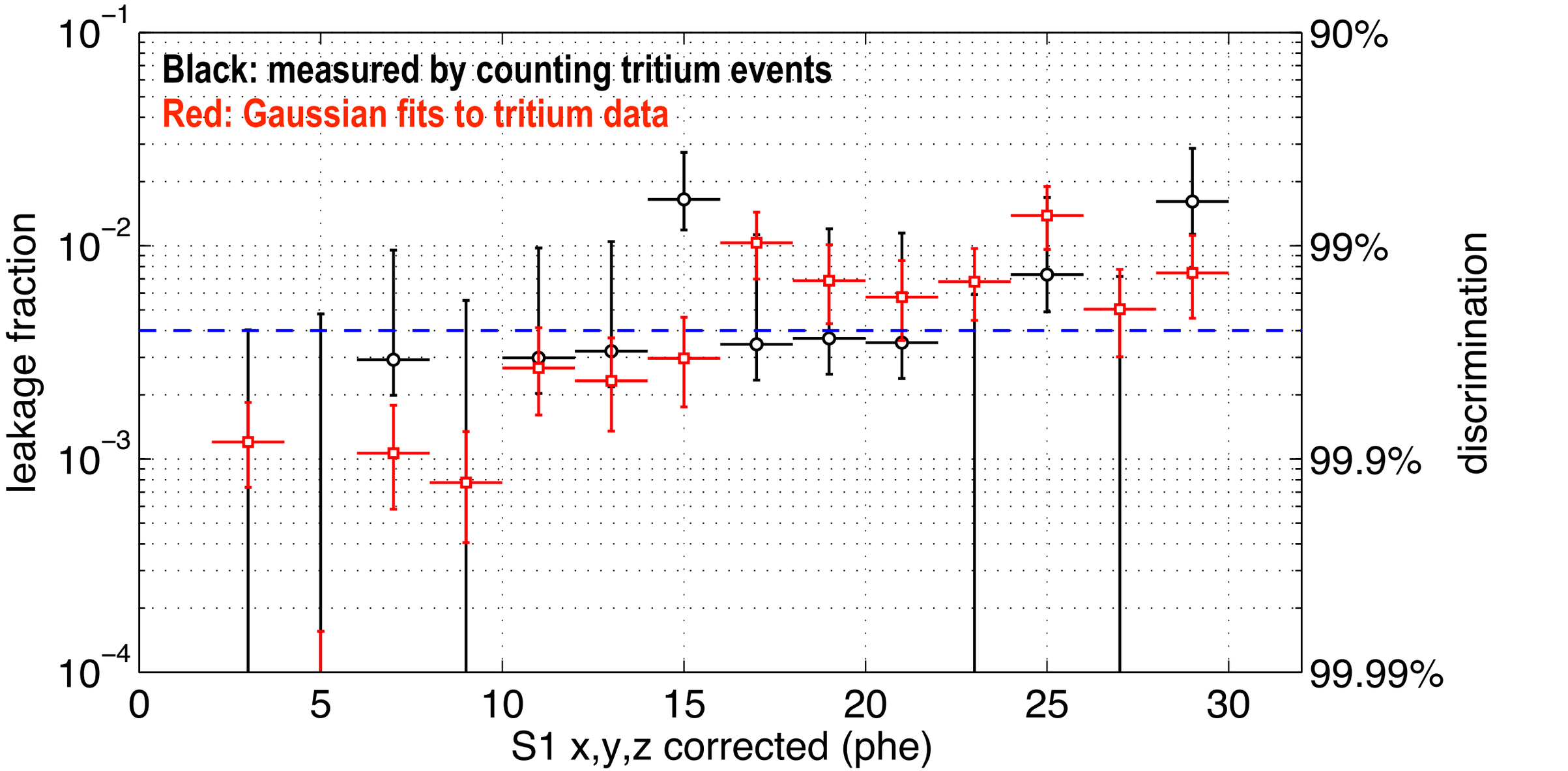
NUCLEAR RECOIL CAL.

- Recoil band defined by **NEST** (Noble Element Simulation Technique) which is based on the canon of existing experimental data
  - (see http://nest.physics.ucdavis.edu and JINST 8, 2013, C10003)
- Confirmed with ^{241}AmBe and ^{252}Cf (external sources)
- GEANT4 + NEST MC was carried out that includes Neutron+X, to allow direct comparison.



ELECTRON RECOIL DISCRIMINATION

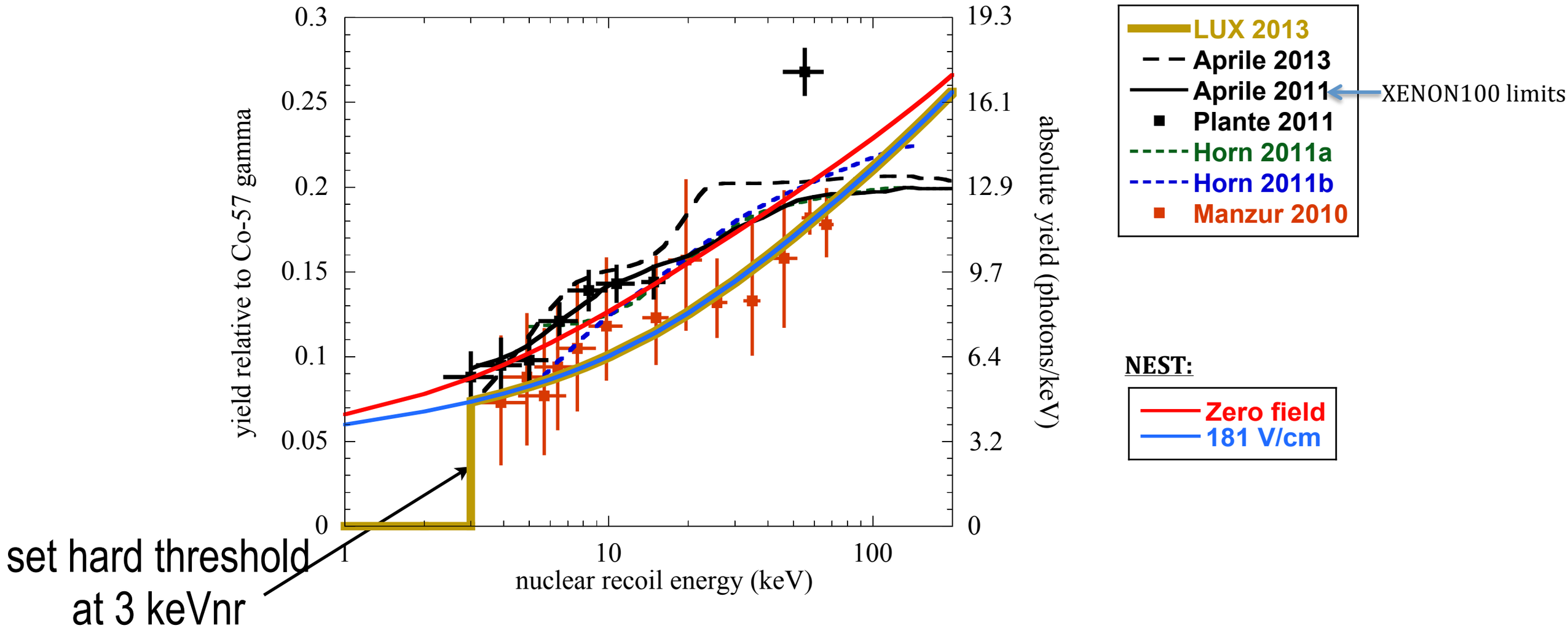
- **Average discrimination from 2-30 S1 photoelectrons measured to be 99.6% (with 50% nuclear recoil acceptance)**



Leakage Fraction: fraction of the events in the ER band that spill over the lower half of the NR band

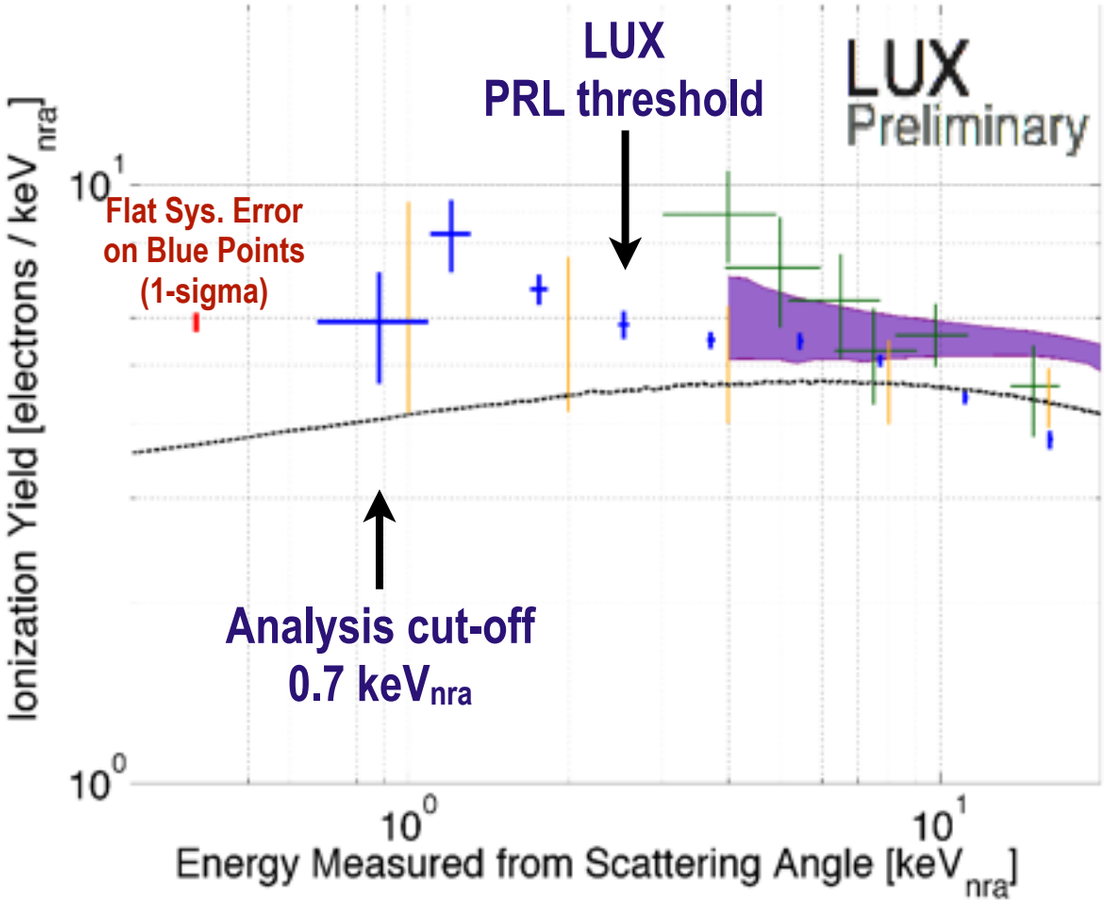
LIGHT YIELD EFFICIENCY

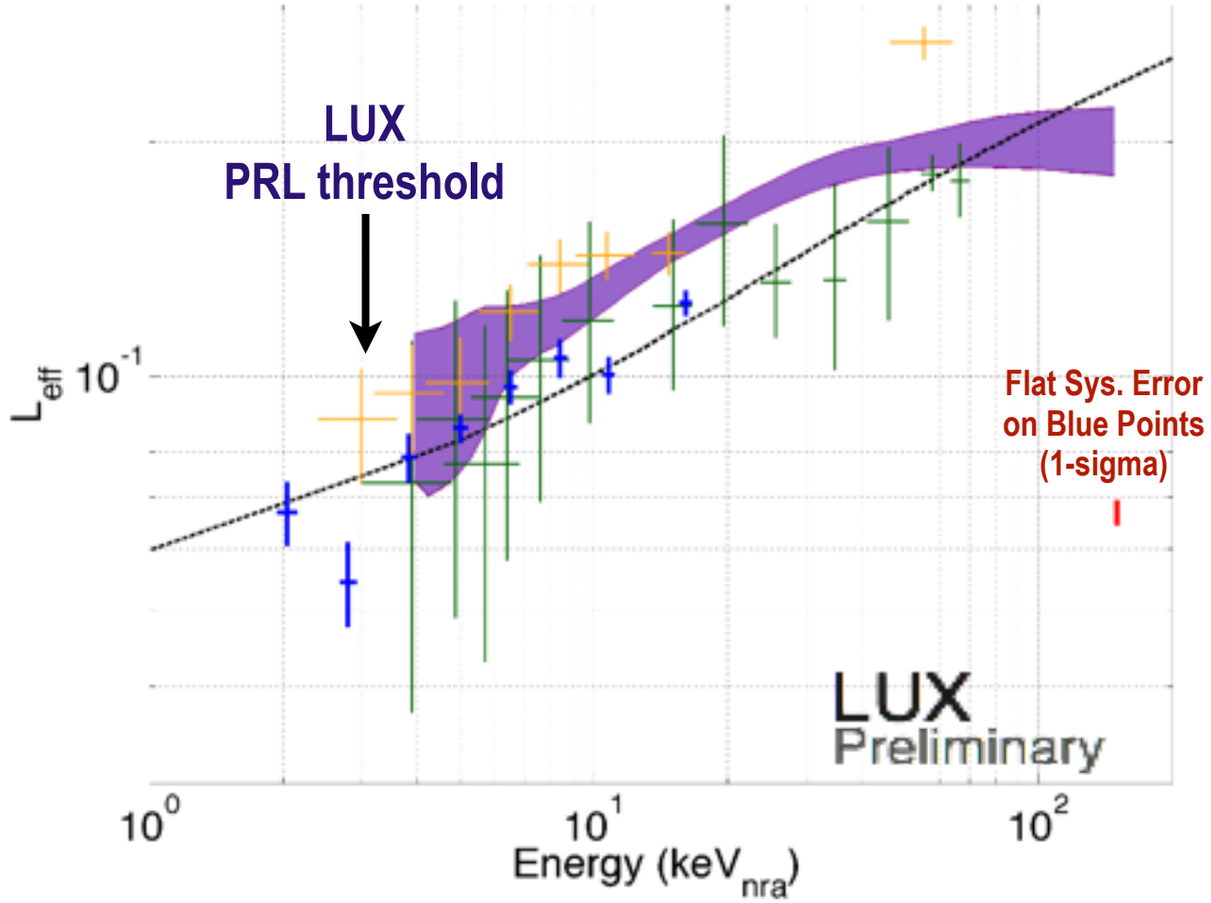
- **Modeled using NEST.**
- **Artificial cutoff in light and charge yields assumed below 3 keV_{nr}. This is to be conservative and it does not represent actual physics.**
- **Includes E field quenching of light signal (77-82% compared to zero field)**



DEUTERIUM-DEUTERIUM BEAM CALIBRATIONS

- **Fall 2013 - Adelphi DD108 Neutron Generator Installed Outside LUX Water Tank**
  - **Beam leveled to ~1 degree**
  - **Double-scatters - ionization yield Q_y (down to 1 keV_{nra})**
  - **Single-scatters - scintillation yield L_{eff} and NR band calibration (down to 2 keV_{nra})**





Blue Crosses - LUX Measured at 181 V/cm

Green Crosses - Manzur 2010; 1 kV/cm for Q_y and 0 V/cm for L_{eff}

Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm

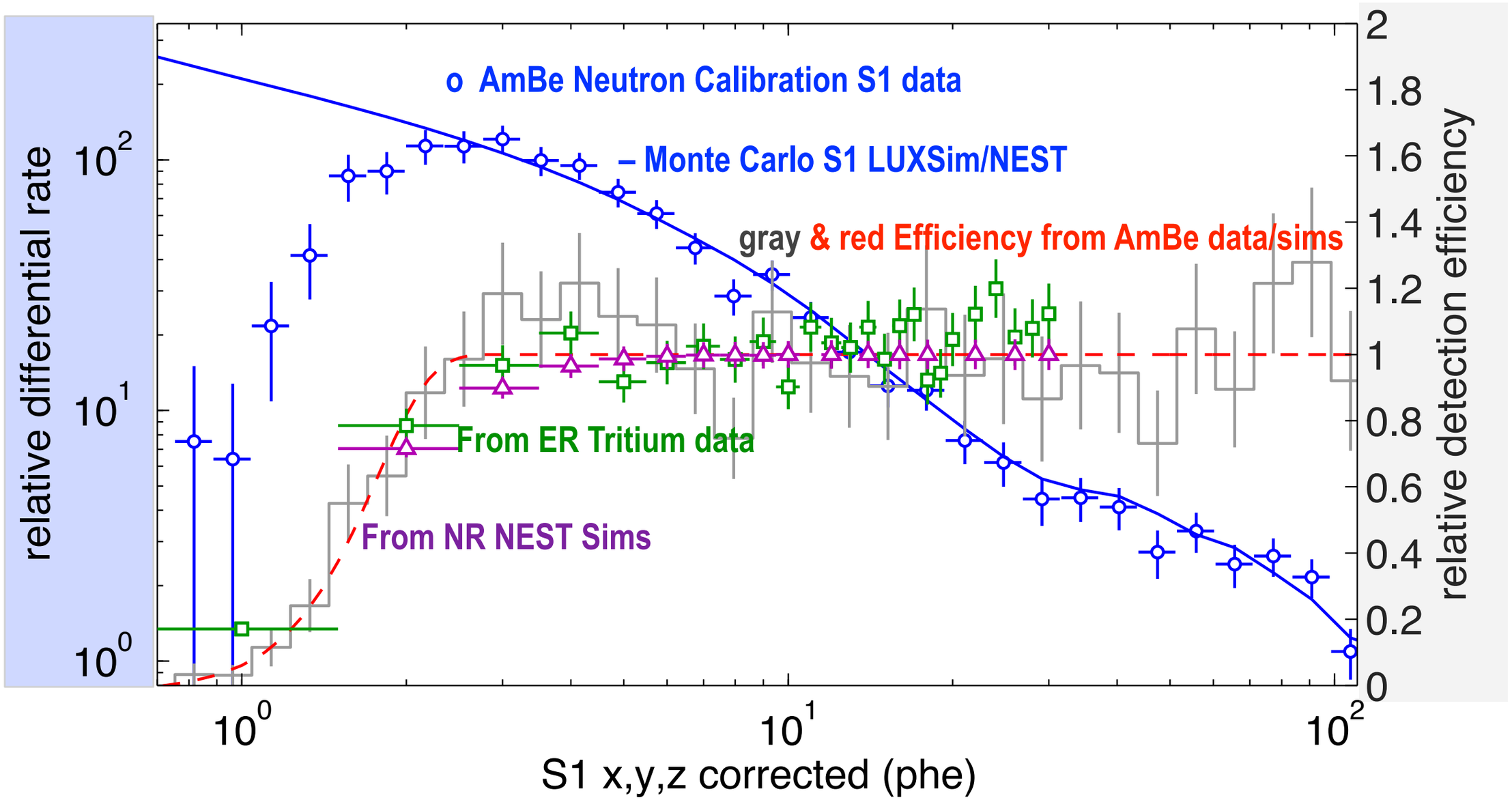
Orange Lines - Sorensen IDM 2010; 0.73 kV/cm for Q_y and 0 V/cm for L_{eff}

Black Dashed Line - NEST Predictions at 181 V/cm

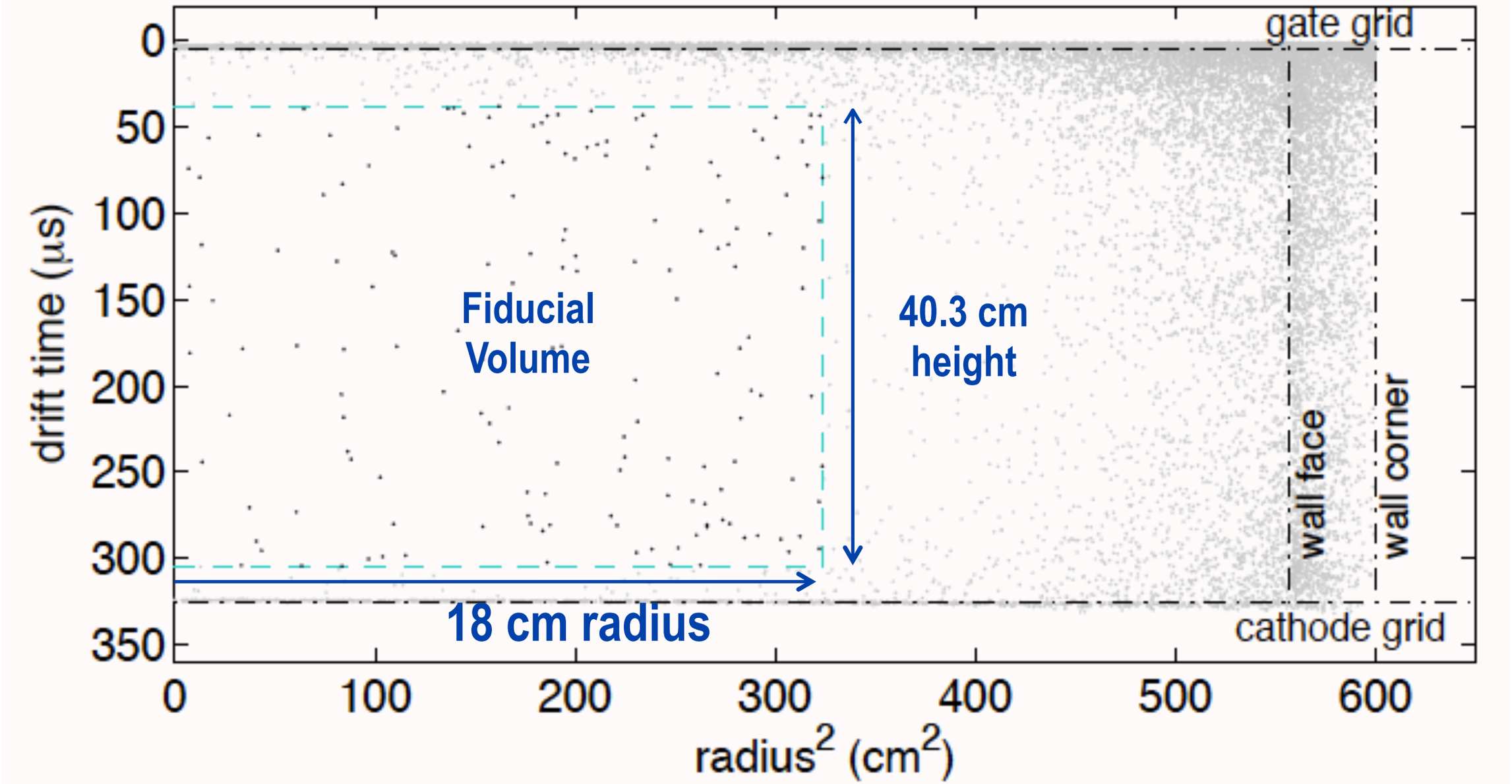
These results were not used in the science run data analysis

LUX GOLD EFFICIENCY FOR WIMP DETECTION

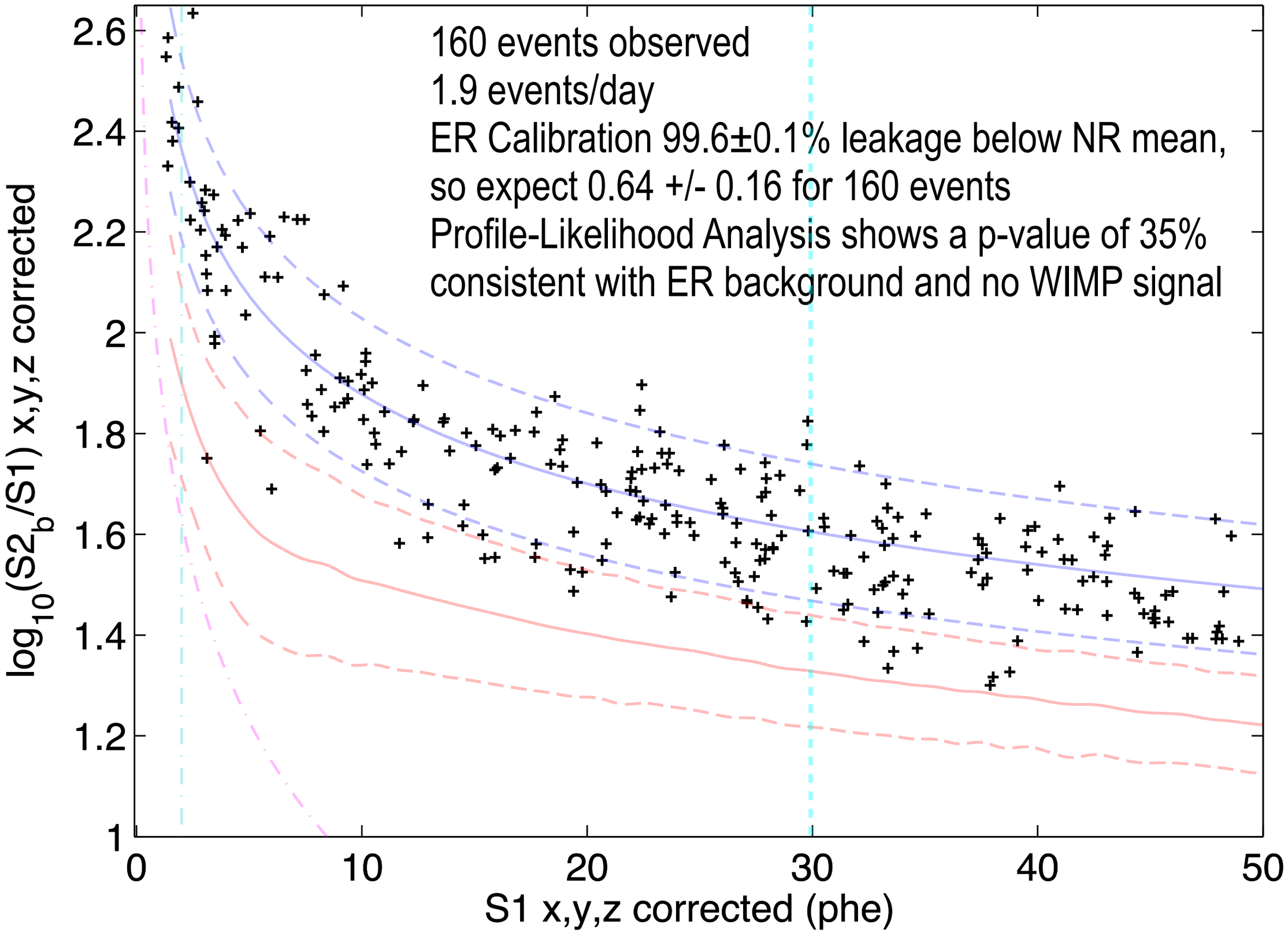
- **Cumulative efficiency of: finding the S2 pulse, finding the S1 pulse, and finding (only) one of each in a given event.**
- **Studied using calibration with neutrons (^{241}AmBe e ^{252}Cf) tritium calibration and a full MC simulation of low energy nuclear recoils.**



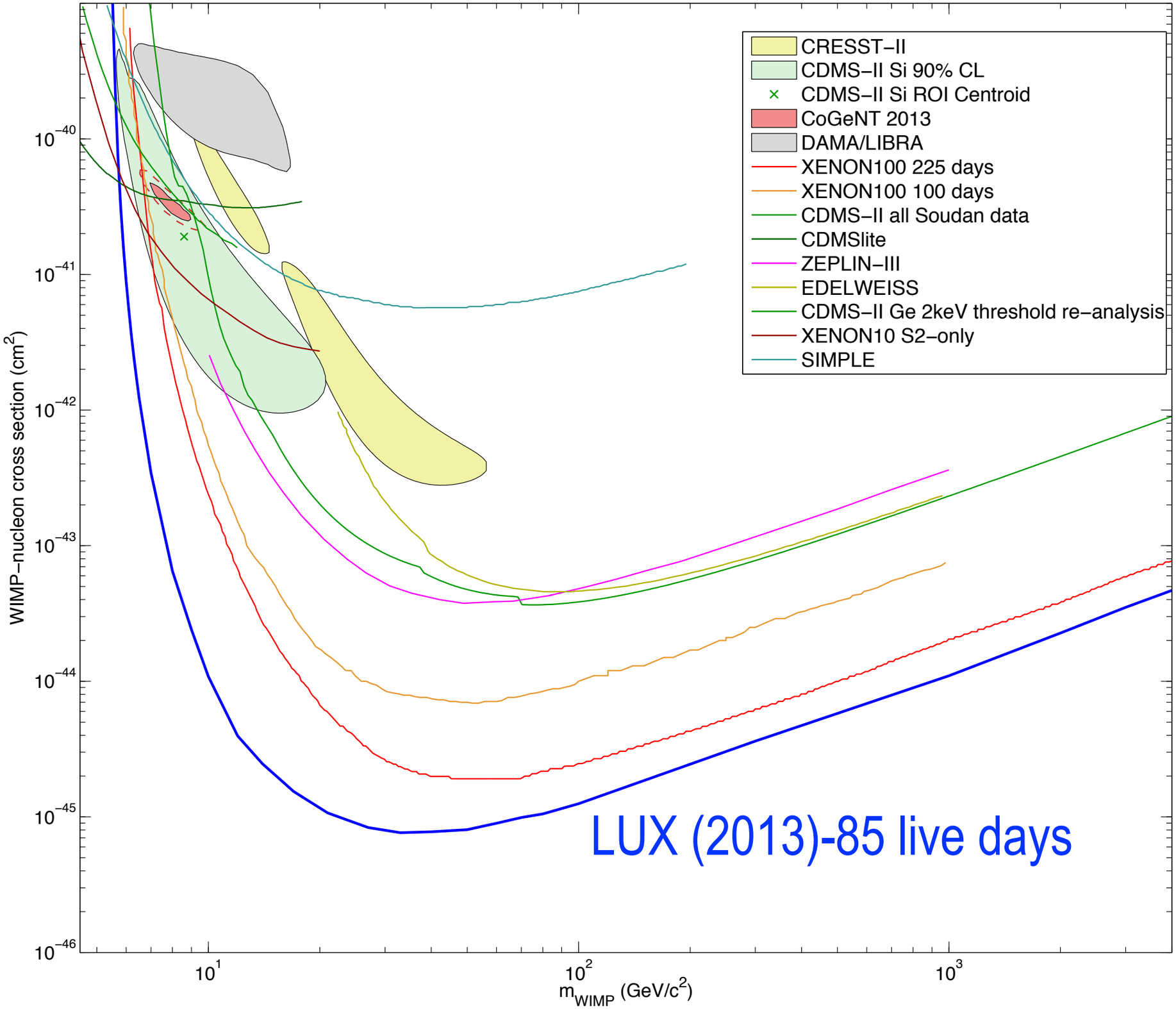
SPACIAL DISTRIBUTION OF THE GOLD EVENTS

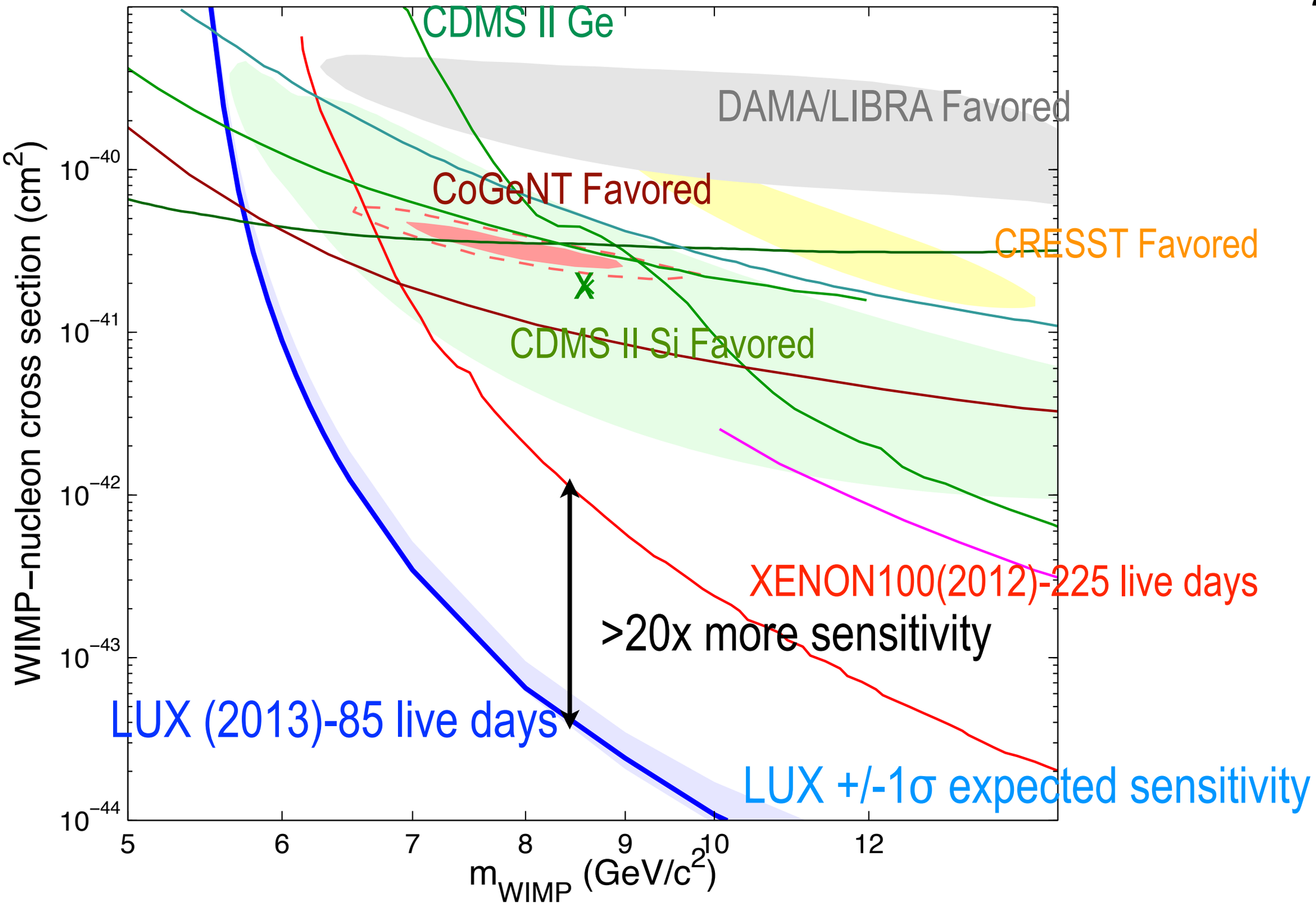


- Single scatters (1 S1 + 1 S2) , S1 Yield 2-30 phe and S2 Yield 200-3300 phe
- Fiducial Cut: radius < 18 cm, 38<drift time<305 μs, 118.3+-6.5 kg fiducial


160 events observed
1.9 events/day
ER Calibration 99.6±0.1% leakage below NR mean,
so expect 0.64 +/- 0.16 for 160 events
Profile-Likelihood Analysis shows a p-value of 35%
consistent with ER background and no WIMP signal
log10(S2b/S1) x,y,z corrected
S1 x,y,z corrected (phe)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
10
20
30
40
50

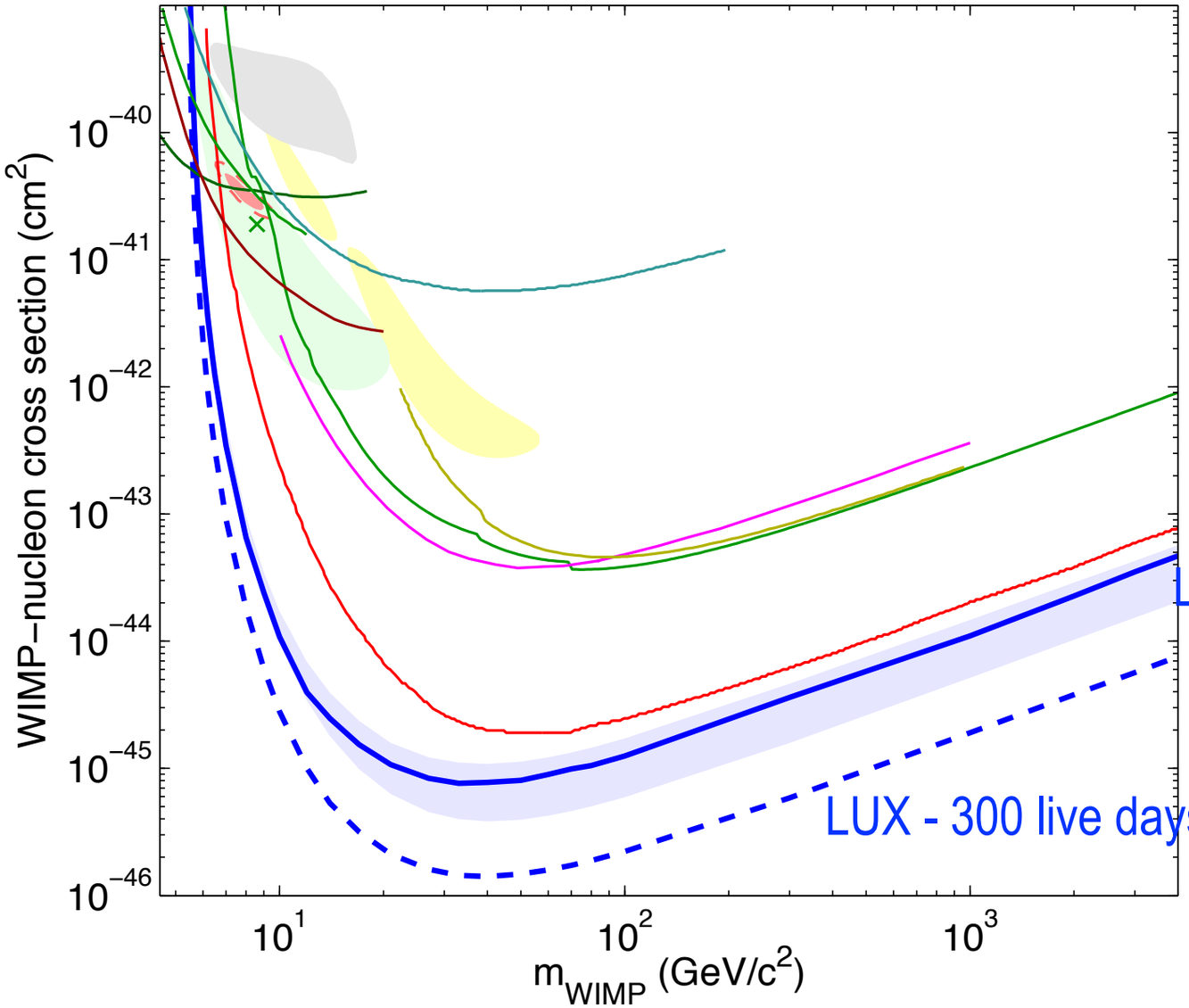
SPIN-INDEPENDENT SENSITIVITY





Favoured regions for low-mass WIMPs excluded

LUX 300 DAY RUN

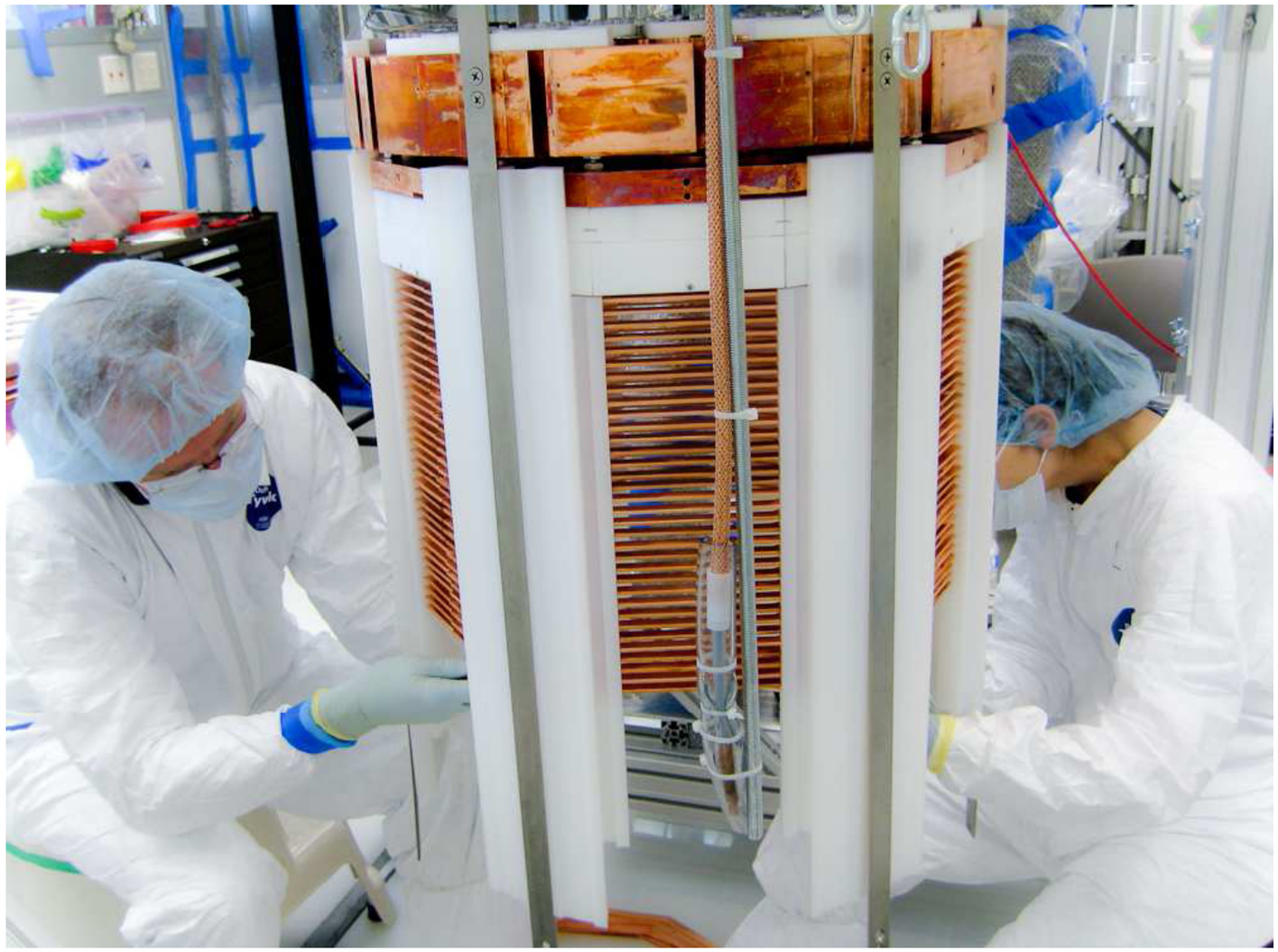


- **300 day run planned for 2014/2015**
  - **Still not background limited and expect factor of ~5 improvement in sensitivity → discovery possible**
  - **Potential for improvements to E fields/calibrations /reconstruction**

CONCLUSION

- **LUX has made a WIMP Search run of 86 live-days and released the analysis within 9 months of first cooling in Davis Lab**
  - **Backgrounds as expected, inner fiducial ER rate <2 events/day in region of interest**
  - **Major advances in calibration techniques including ^{83m}Kr and Tritiated-CH_4 injected directly into Xe target**
  - **Very low energy threshold achieved 3 keV_{nr} with no ambiguous/leakage events**
  - **ER rejection shown to be 99.6+/-0.1% in energy range of interest**
- **Intermediate and High Mass WIMPs**
  - **Extended sensitivity over existing experiments by x3 at 35 GeV and x2 at 1000 GeV**
- **Low Mass WIMP Favored Hypotheses ruled out**
  - **LUX WIMP Sensitivity 20x better**
  - **LUX does not observe 6-10 GeV WIMPs favored by earlier experiments**
- **Results published in**
  - **LUX Main Results PRL 112, 091303 (2014)**
  - **Radiogenic and Muon-Induced Backgrounds in the LUX Dark Matter Detector (arXiv 1403.1299)**


UC DAVIS CONFERENCE CENTER
Thanks!



Backup Slides

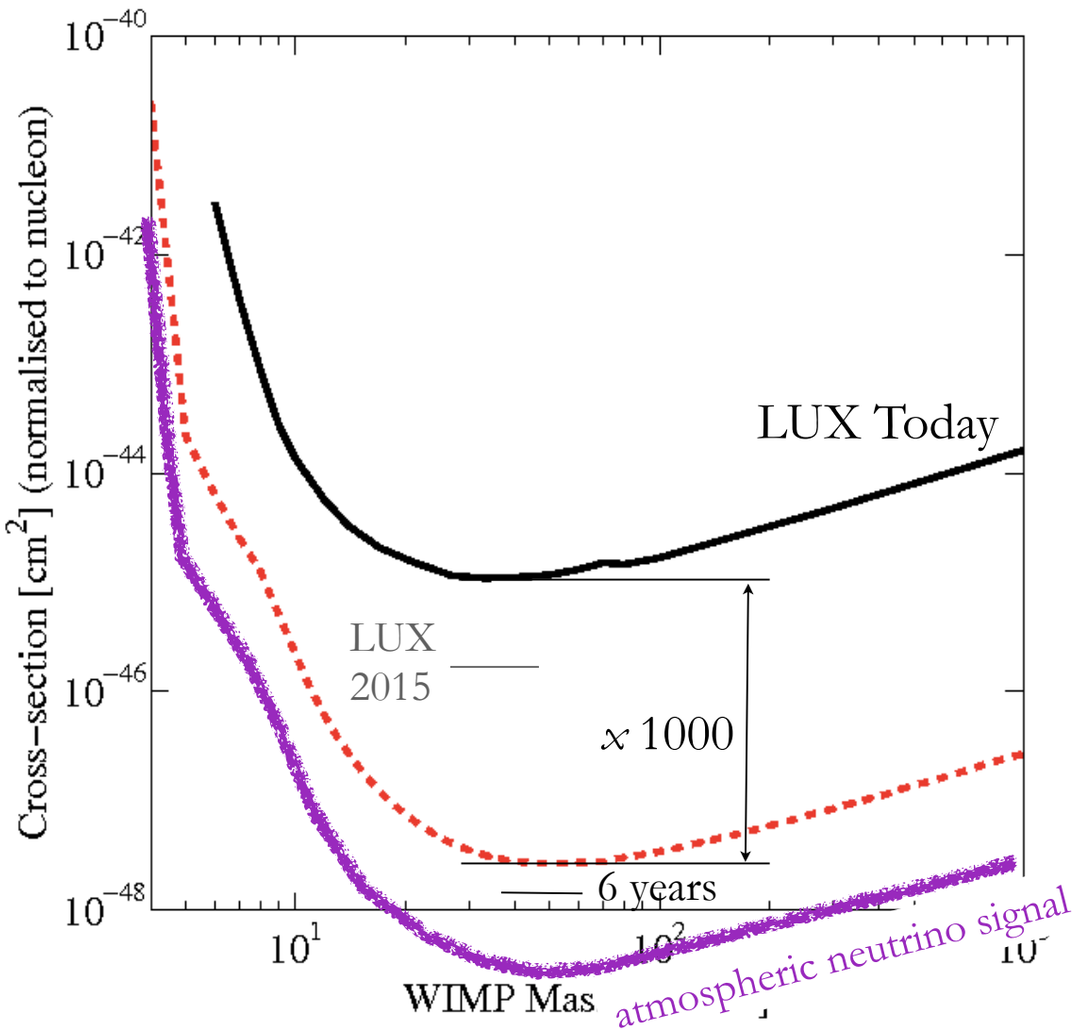
RUN 3 EVENT SELECTION AND CUTS

Cut	Events Remaining
All Triggers	83,673,413
Detector Stability	82,918,904
Single Scatterer (1 S1 + 1 S2)	6,585,686
S1 Yield 2-30 phe (0.9-5.3 keVee, ~3-25 keVnr)	26,824
S2 Yield 200-3300 phe (200 phe ~ 8 single electrons)	20,989
Single Electron Background	19,796
Fiducial Volume (radius < 18 cm, 38<drift time<305 μs, 118.3+-6.5 kg fiducial)	160

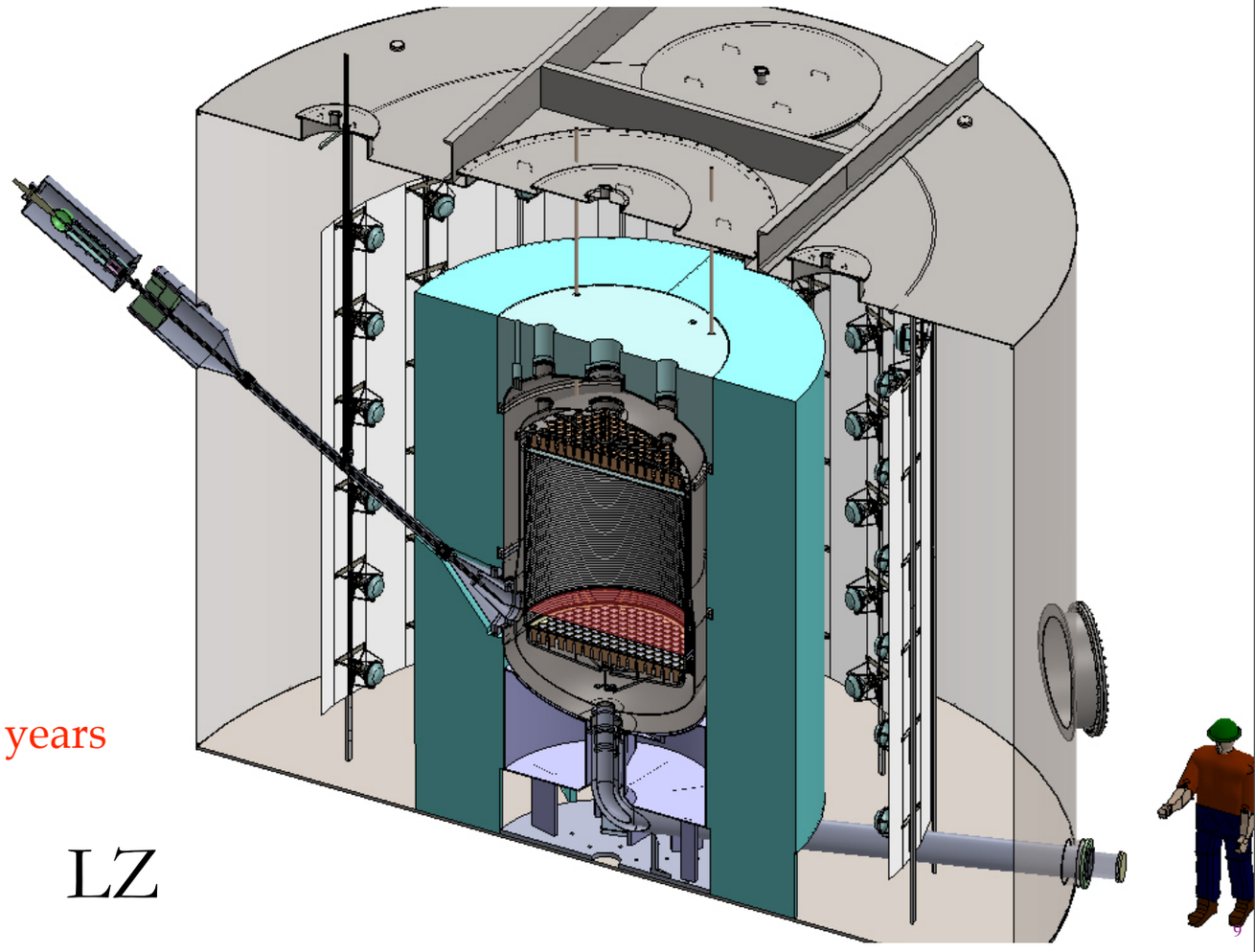
- We aimed to apply minimum set of cuts in order to reduce any tuning of event cuts/acceptance.
- The cut list is very short.

LONGER TERM: LUX-ZEPLIN (LZ)

- **20 times LUX Xenon mass, active scintillator veto, Xe purity at sub ppt level**
- **Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds**
- **If approved will be deployed Davis lab 2017+**



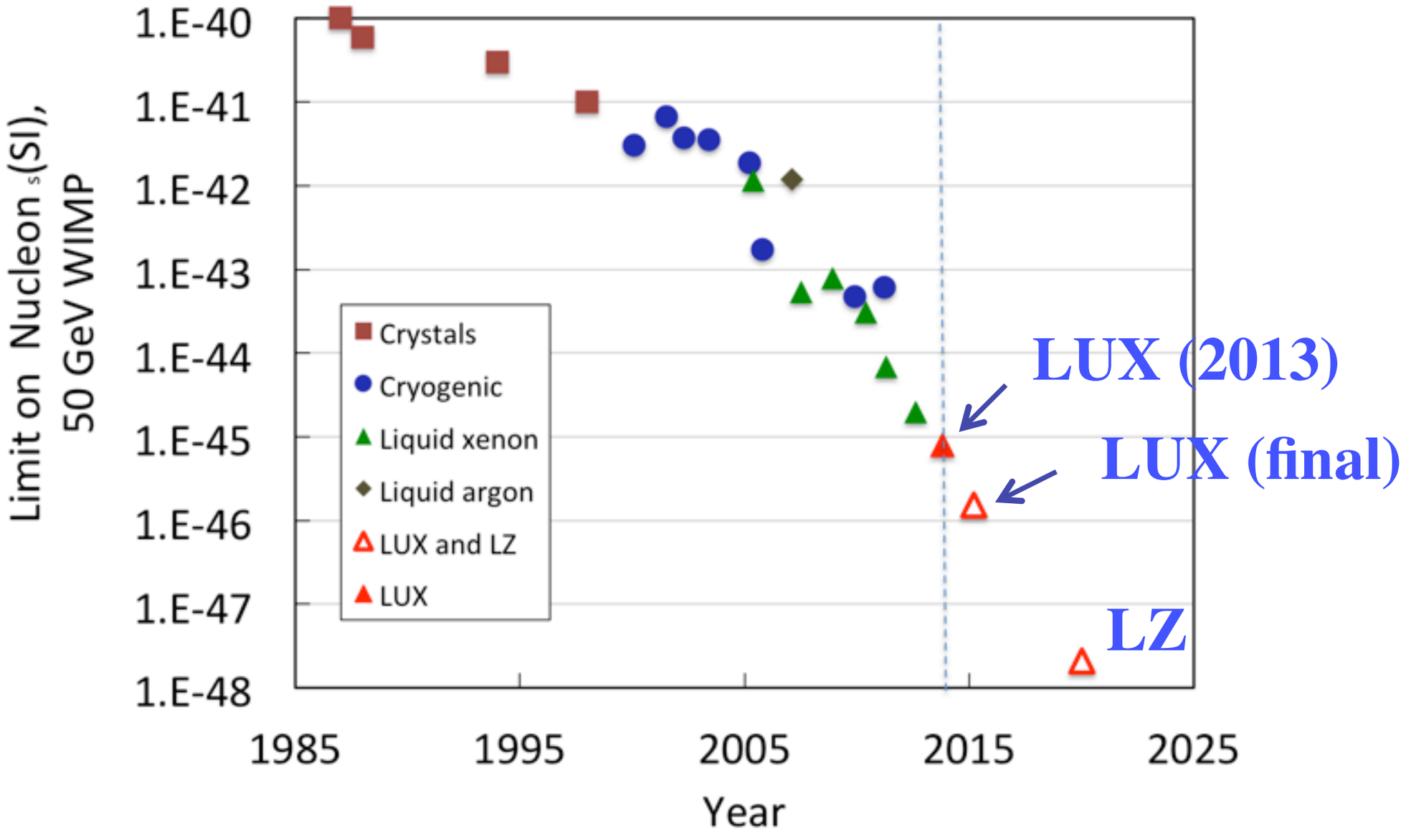
Same water tank as LUX



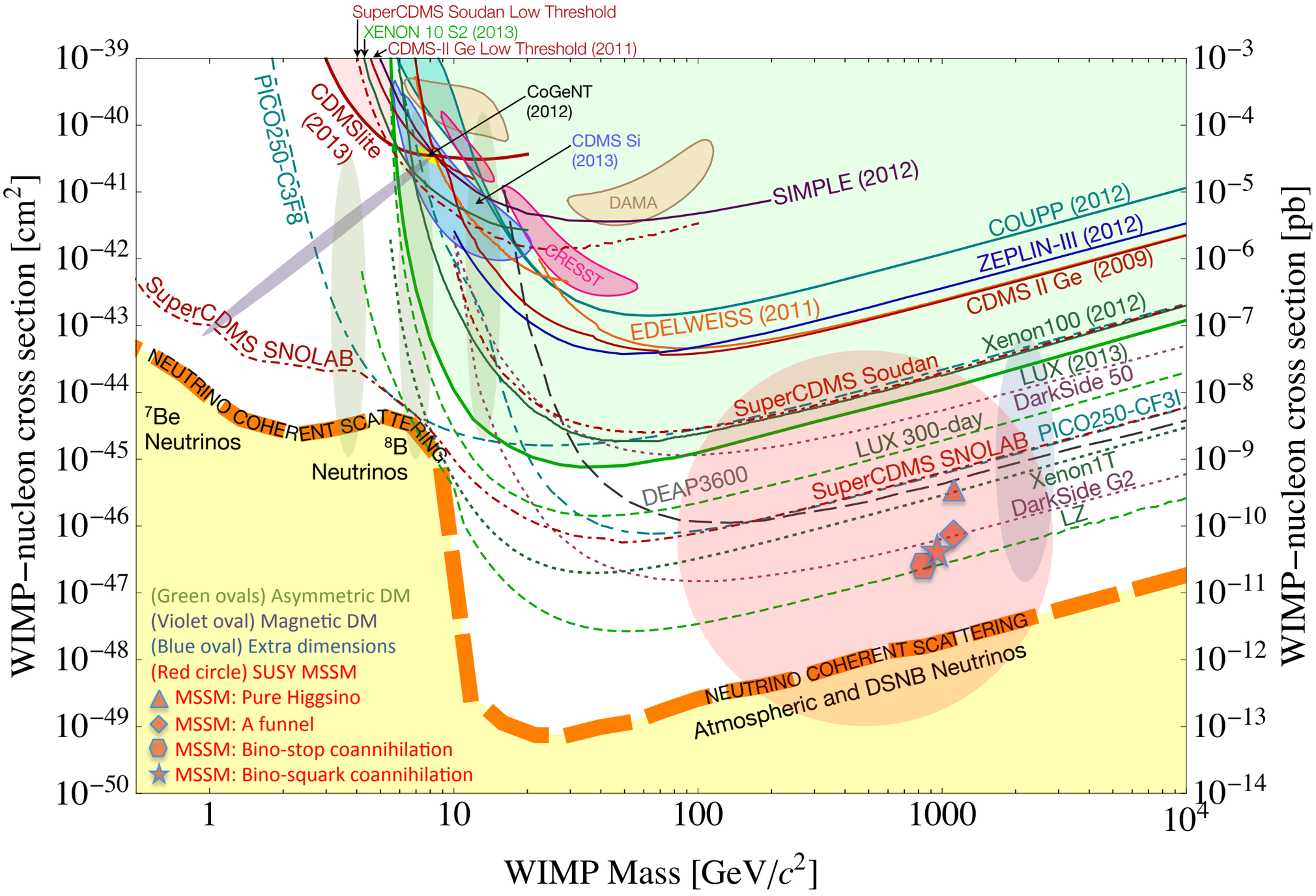
LZ 3 years

LZ

HISTORICAL PROGRESS IN THE LIMITS



CURRENT WIMP CROSS-SECTION LIMITS



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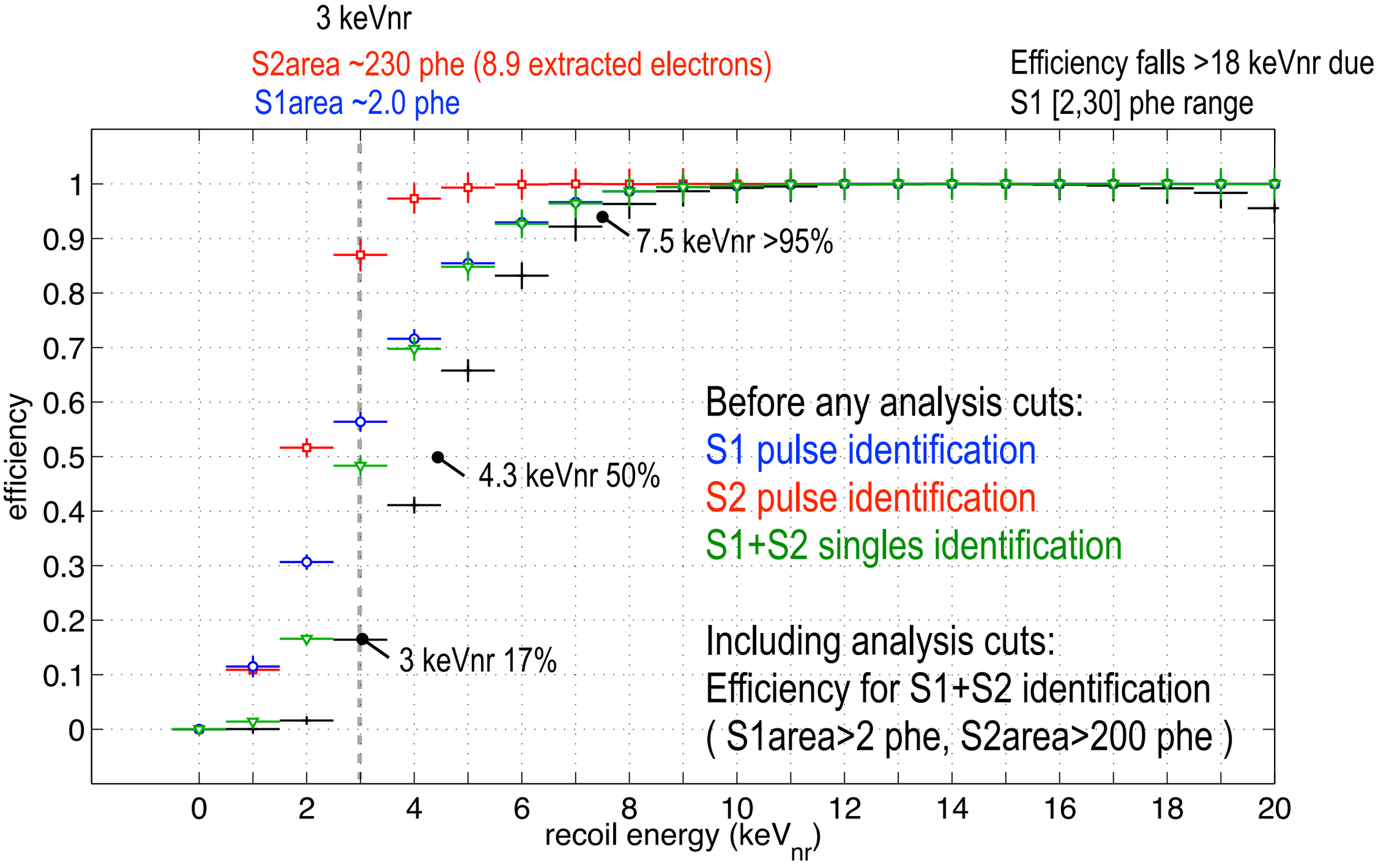
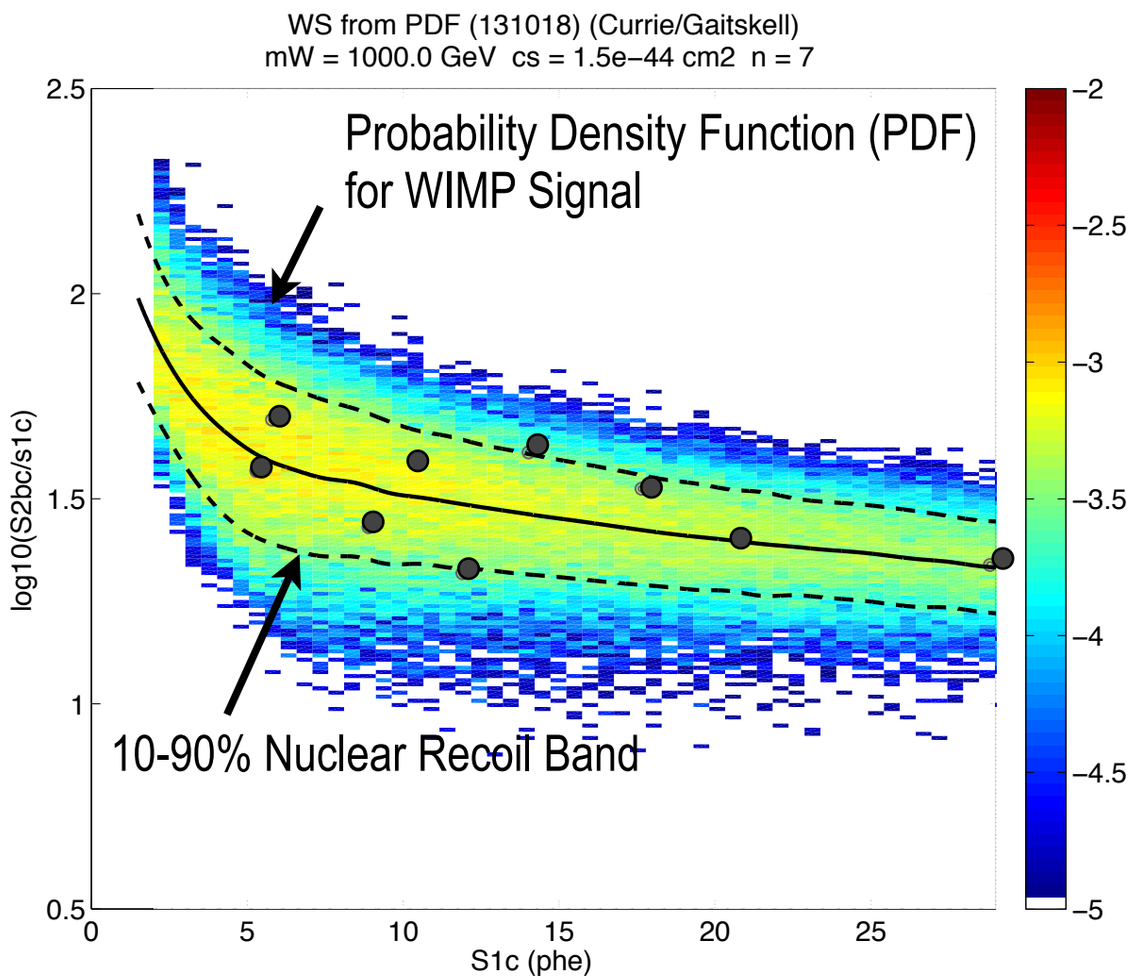
WIMP DETECTION EFFICIENCY - TRUE RECOIL ENERGY

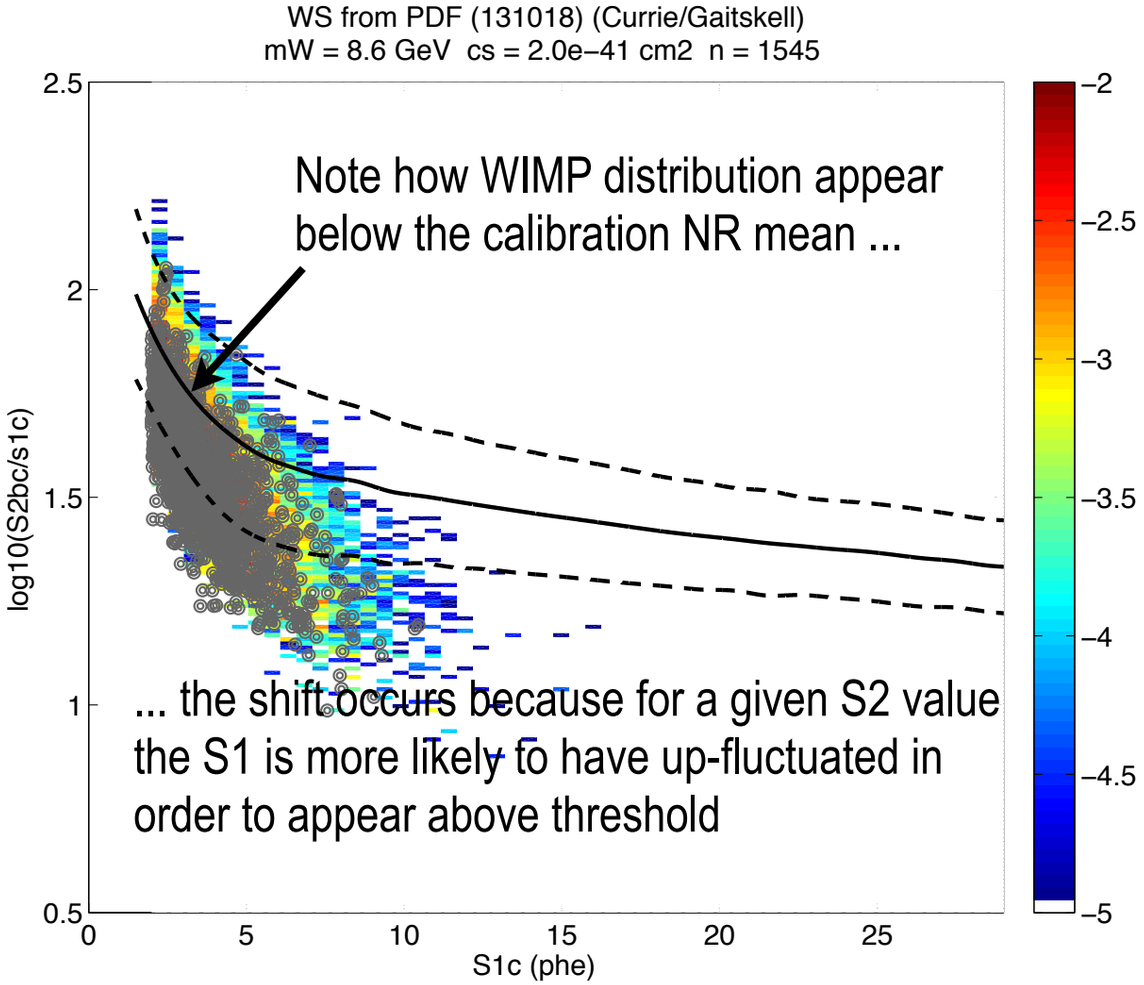


True Recoil Energy equivalence based on LUX 2013 Neutron Calibration/NEST Model

SIMULATED RESPONSE FOR HYPOTHETICAL WIMP SIGNALS

- **For a 1000 GeV WIMP and cross section at the existing XENON100 90% CL Sensitivity 1.9×10^{-44} cm^2**
  - **expect 9 WIMPs in LUX search**
- **For 8.6 GeV WIMP at 2.0×10^{-41} cm^2, CDMS II Si (2012) 90% CL:**
  - **expect 1550 WIMPs in LUX search**

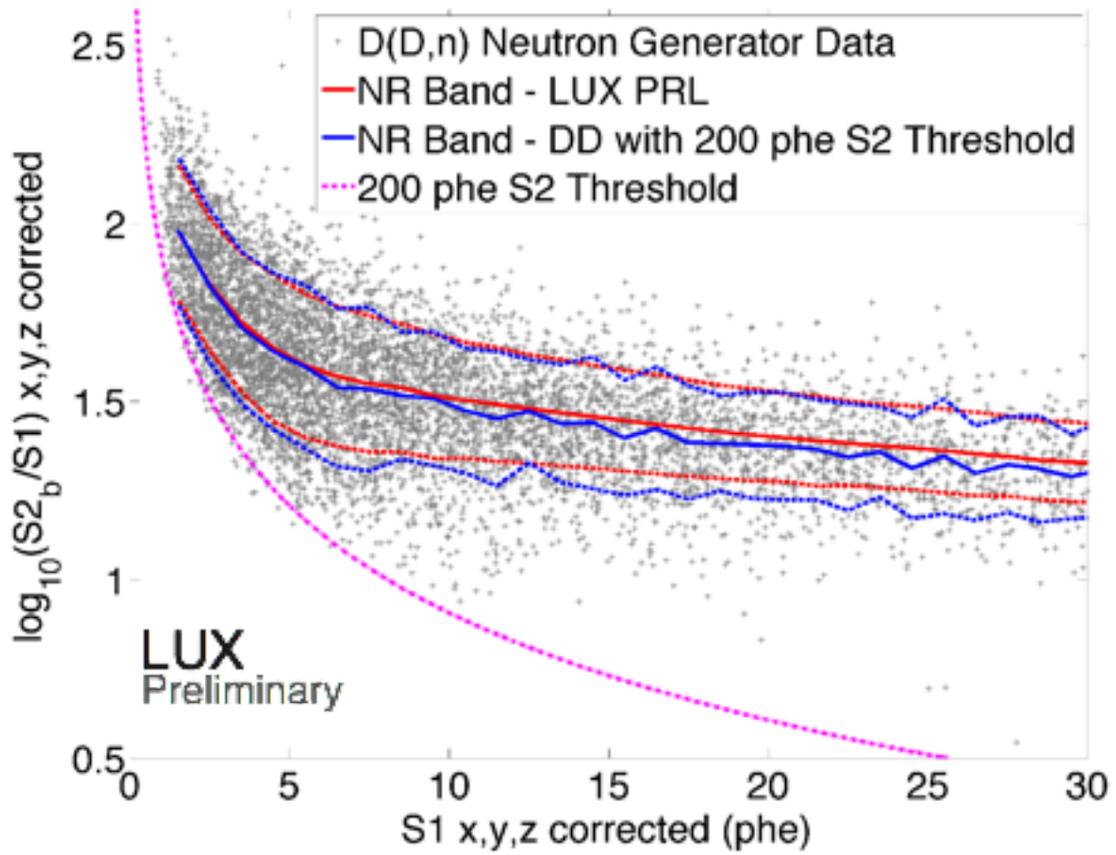




PDF assumes Standard Milky Way Halo parameters as described in Savage, Freese, Gondolo (2006) v_0=220 km/s, v_{escape} = 544 km/s, ρ_0 = 0.3 GeV/c^2, v_{earth} = 245 km/s.

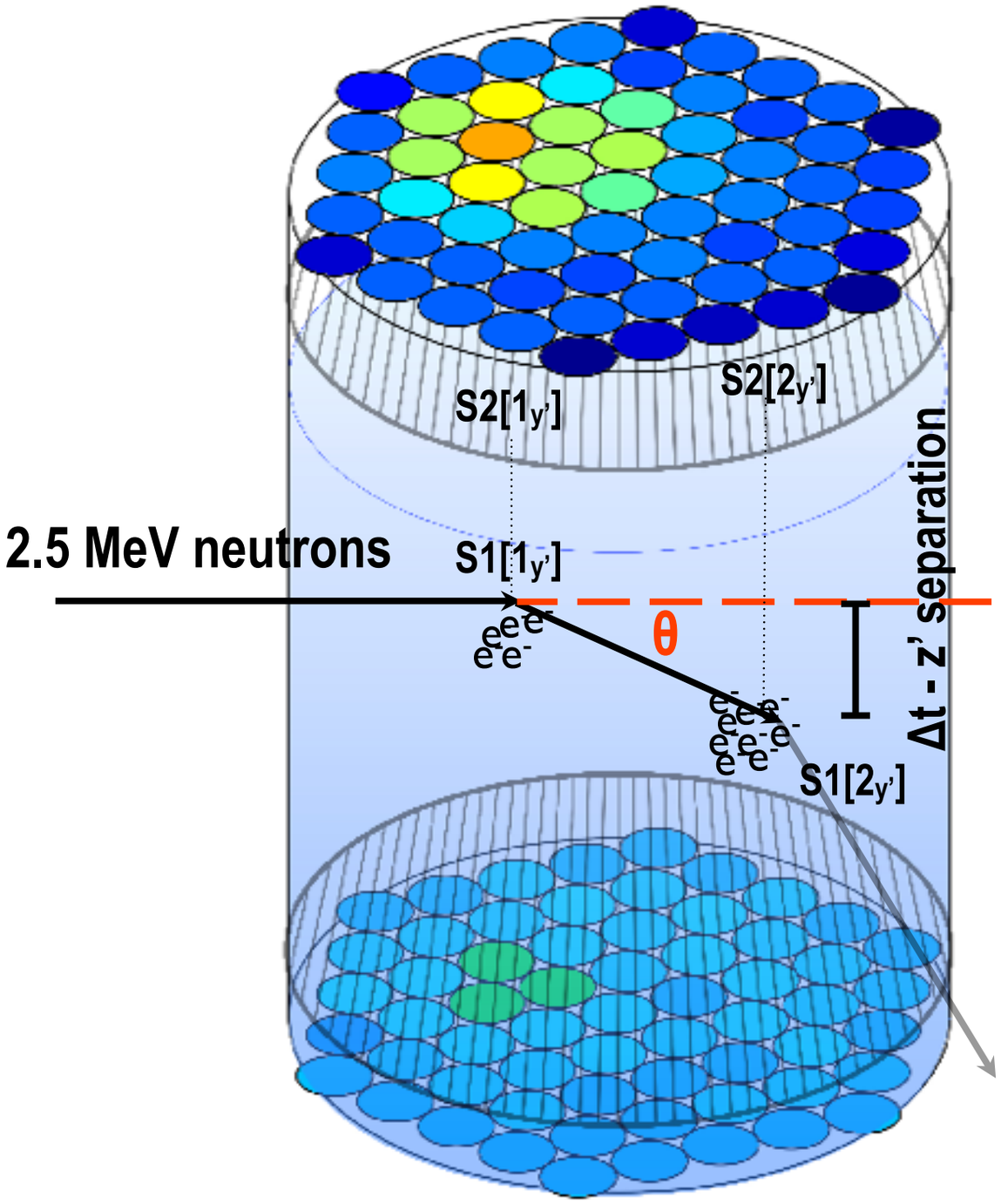
DEUTERIUM-DEUTERIUM BEAM CALIBRATIONS

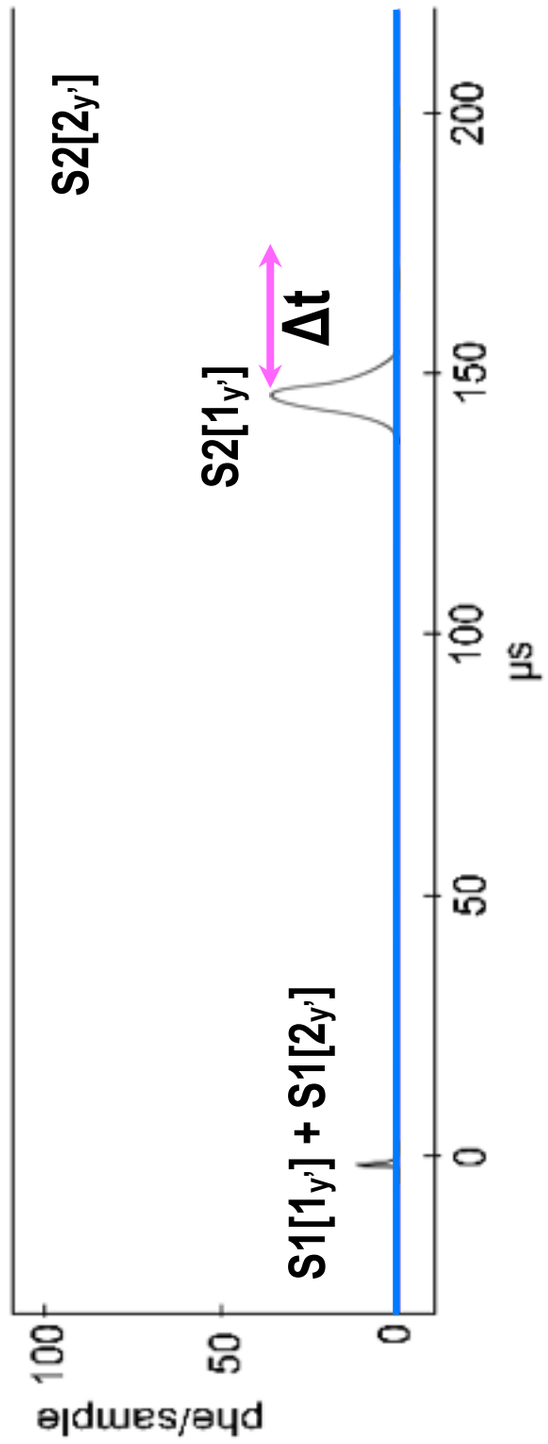
- **Neutron generator/beam pipe assembly aligned 15.5 cm below liquid level in LUX active region to maximize usable single / double scatters**
  - **Beam leveled to ~1 degree**
  - **105.5 live hours of neutron tube data used for analysis**
  - **Complete Geant4 LUXSim + NEST simulation of D-D neutron calibration**



Agrees with NR Band used in LUX 2014 PRL Accepted Dark Matter Result arXiv:1310.8214v2

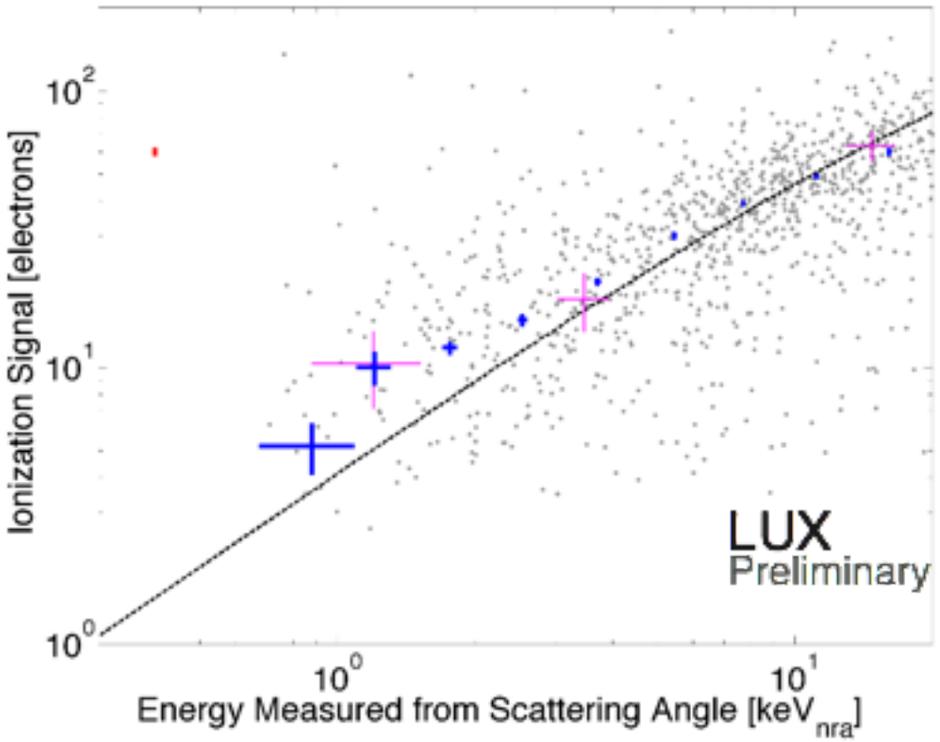
DEUTERIUM-DEUTERIUM BEAM CALIBRATIONS



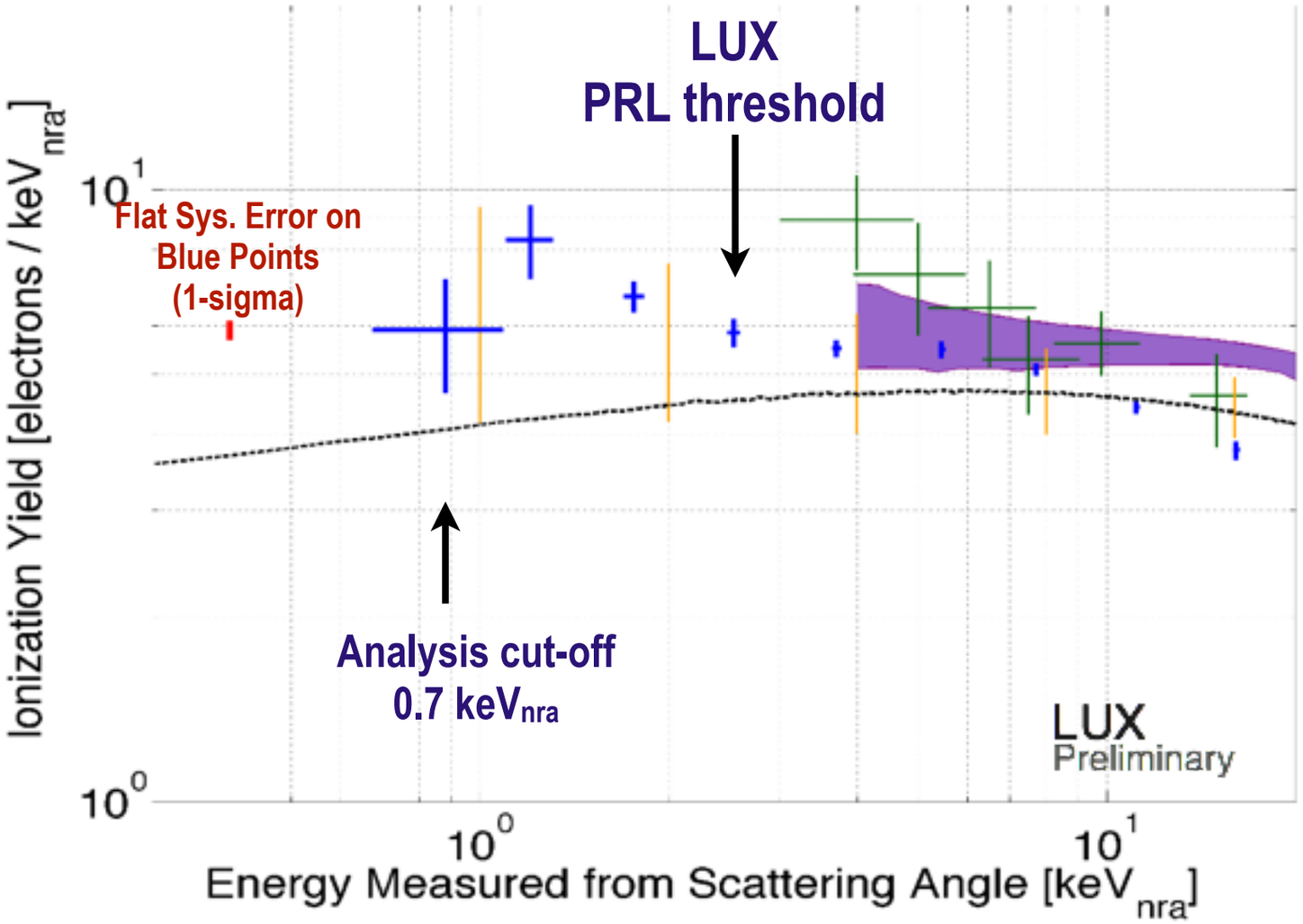


$$E_r = E_n \frac{4 m_n m_{\mathrm{Xe}}}{\left(m_n + m_{\mathrm{Xe}}\right)^2} \frac{1 - \cos\theta}{2}$$

DEUTERIUM-DEUTERIUM IONIZATION YIELD



- **Reconstruct number of electrons at interaction site by matching ionization signal model with observed event distribution using binned maximum-likelihood**
- **Systematics associated with threshold correction discussed in extra slides**
- **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.**



Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)

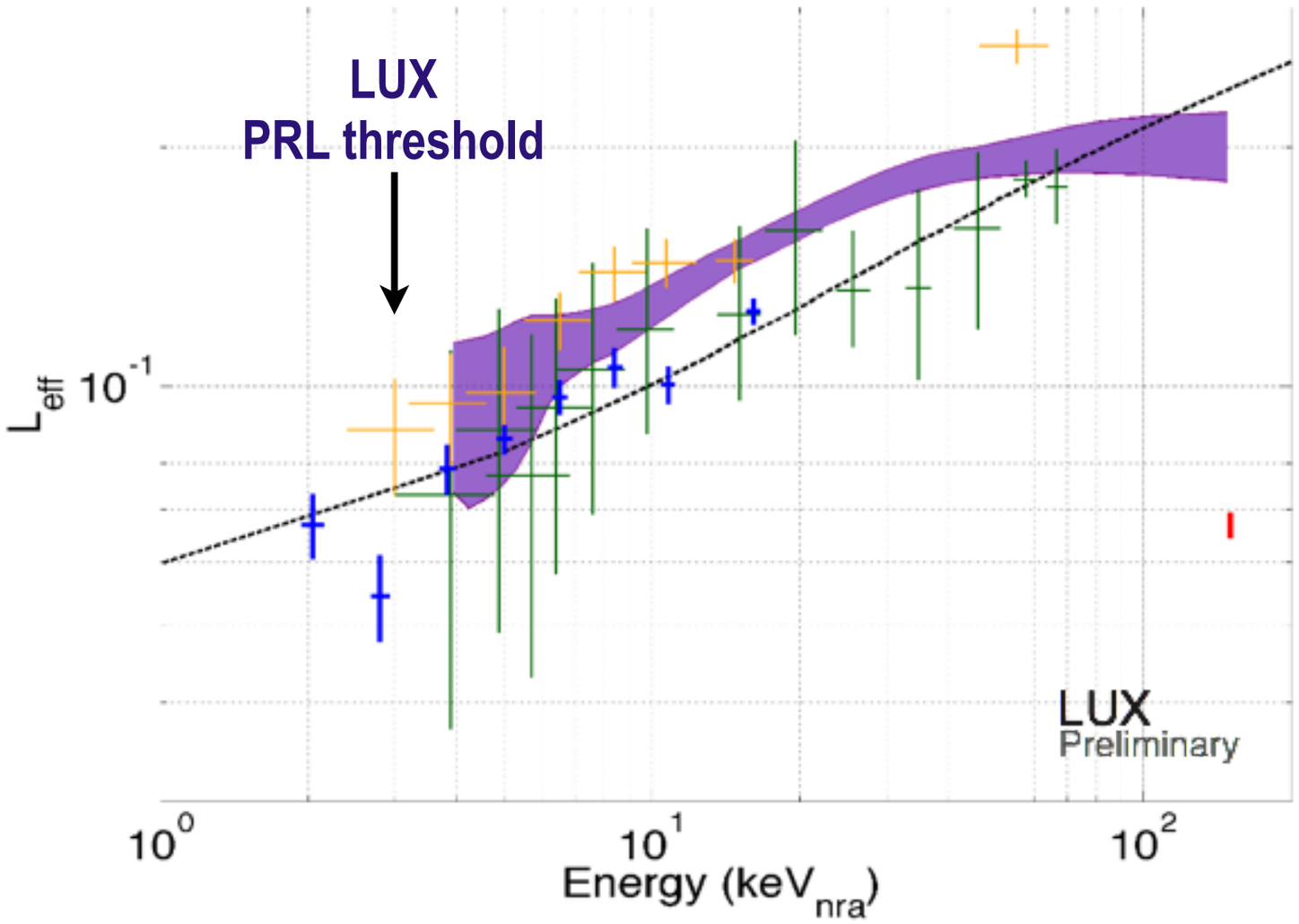
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

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

DEUTERIUM-DEUTERIUM SCINTILLATION YIELD

- 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
- First bin conservatively begins at 50 phe S2bc to avoid spurious single electron coincidence
- LUX Leff values currently reported at 181 V/cm as opposed to the traditional zero field value.
- Energy scale defined using LUX measured Qy
- X error bars representative of error on mean of population in bin



Blue Crosses - LUX Measured L_{eff}; reported at 181 V/cm (absolute energy scale)

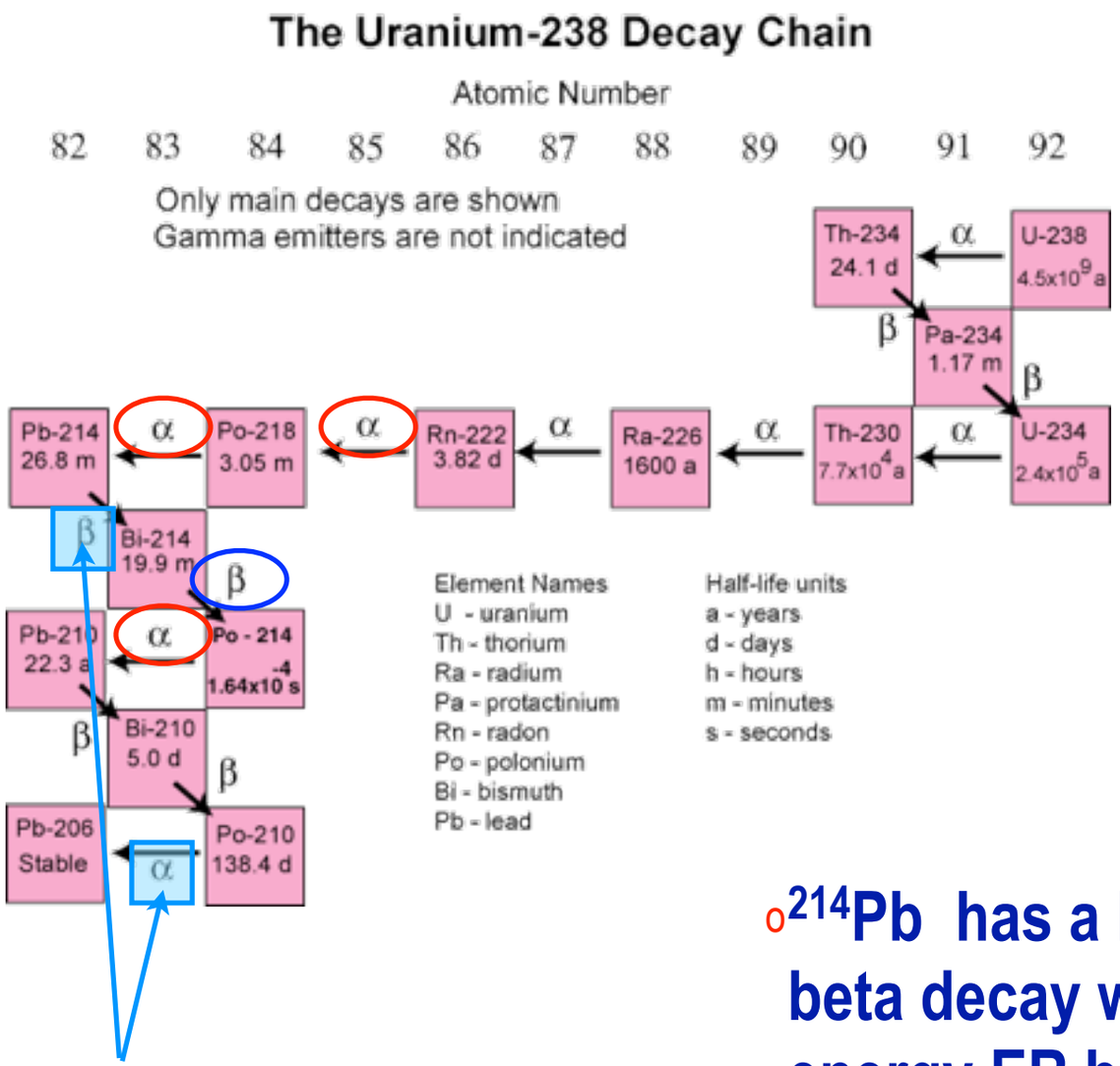
Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)

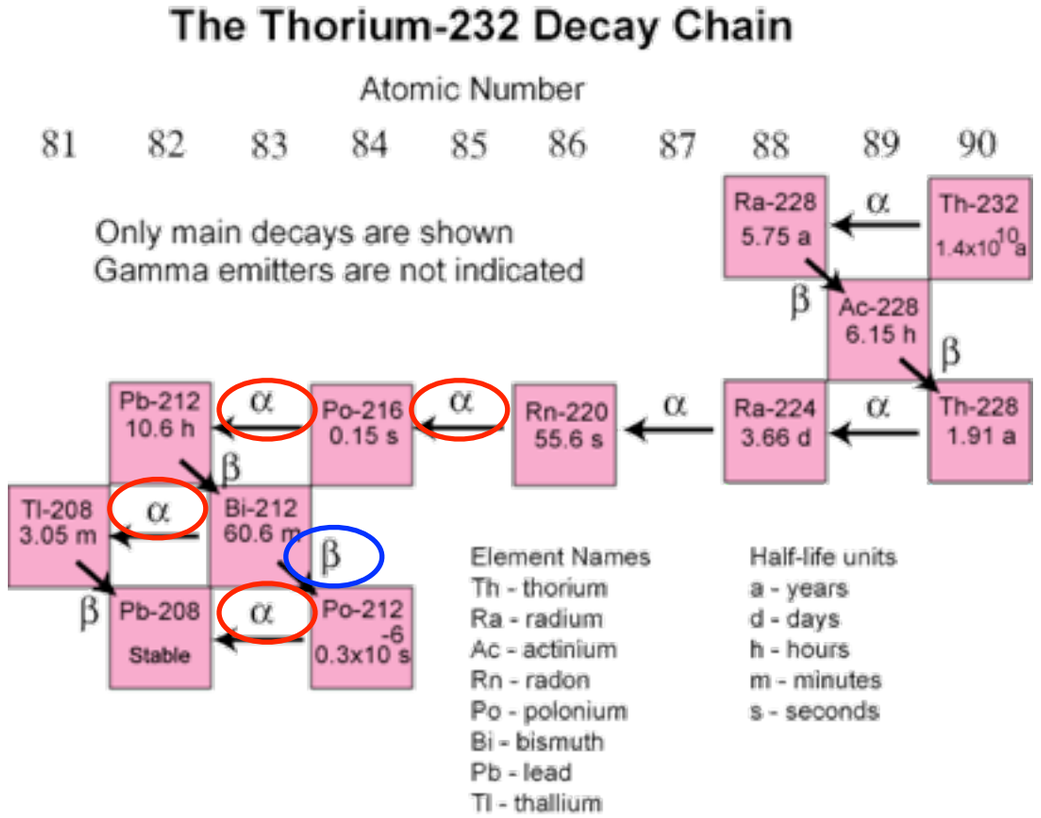
Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)

Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)

Black Dashed Line - Szydagis et al. (NEST) Predicted Scintillation Yield at 181 V/cm

RN-RELATED BACKGROUNDS





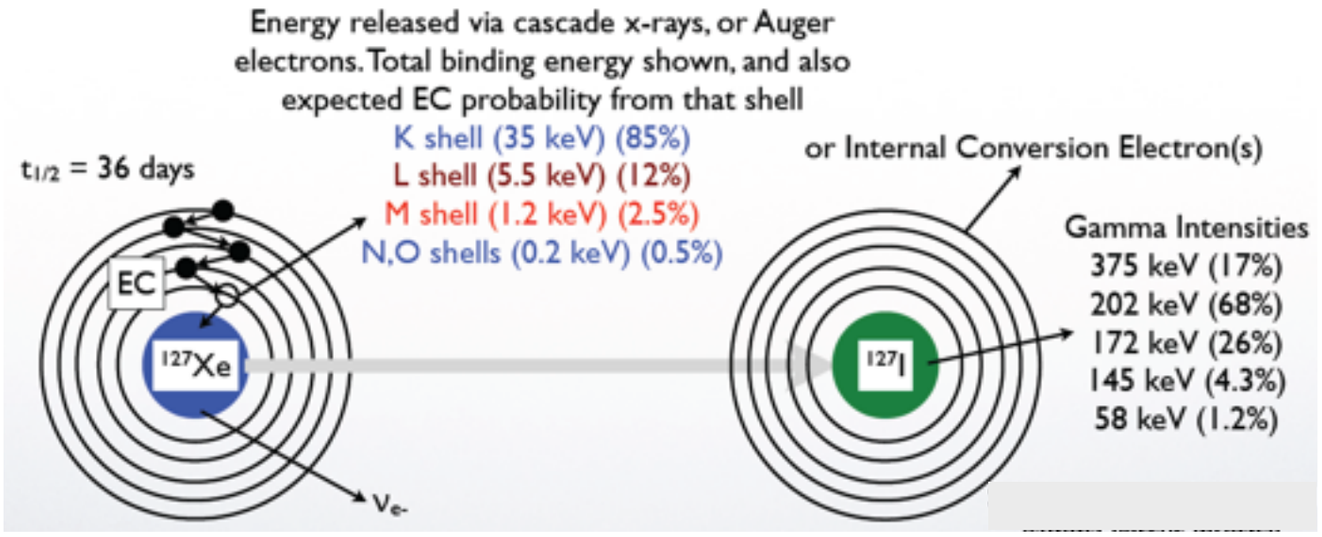
Potential backgrounds in DM search region

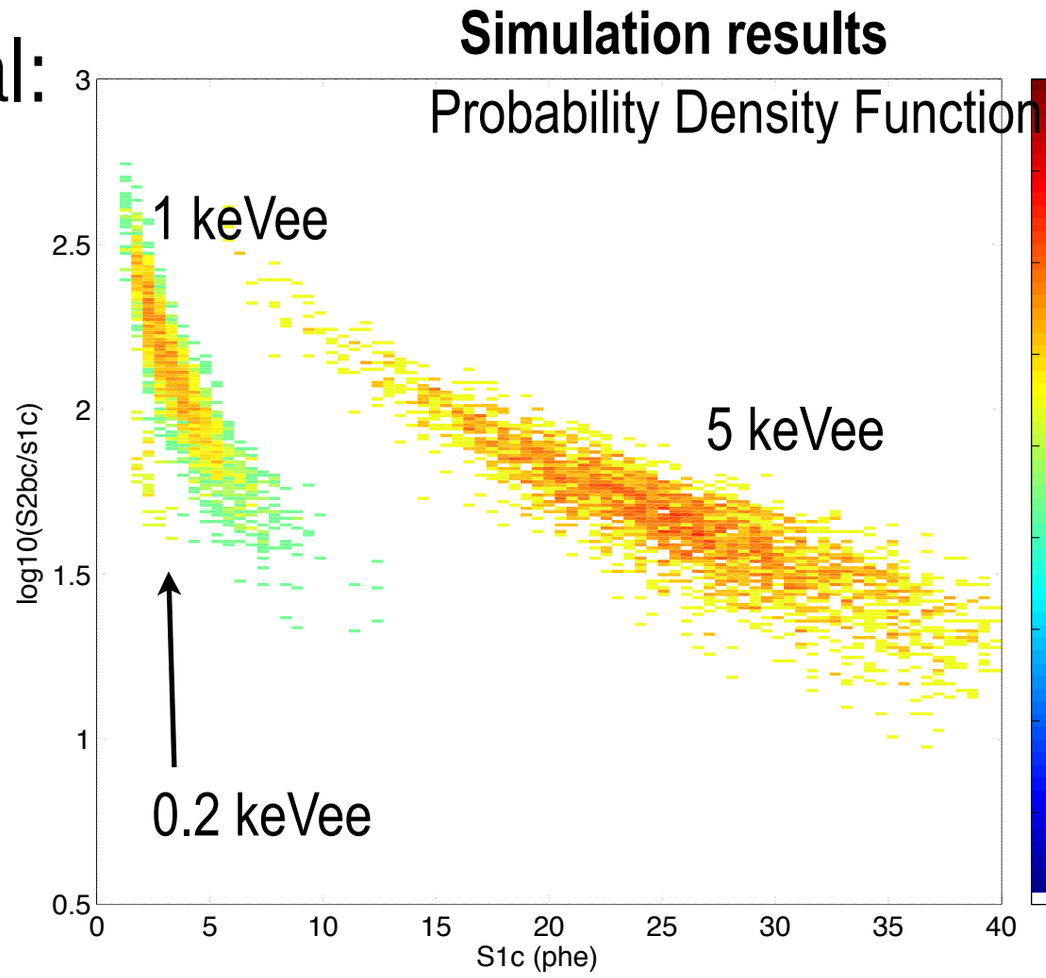
- ^{214}Pb has a half-life of 27 minutes and undergoes "naked" beta decay with 11% probability. This generates a low-energy ER background in the WIMP search region in the fiducial volume.
- ^{214}Bi and ^{212}Bi β decays are vetoed at the 90% level due to the low half-life of heir daughters.

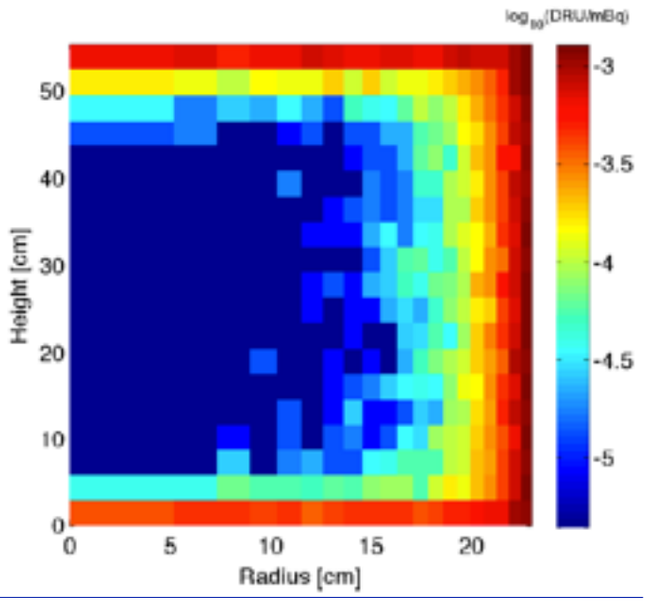
BACKGROUND FROM XE-127

- Electron capture from S-wave orbital:

$$p + e^- \rightarrow n + \nu_e$$



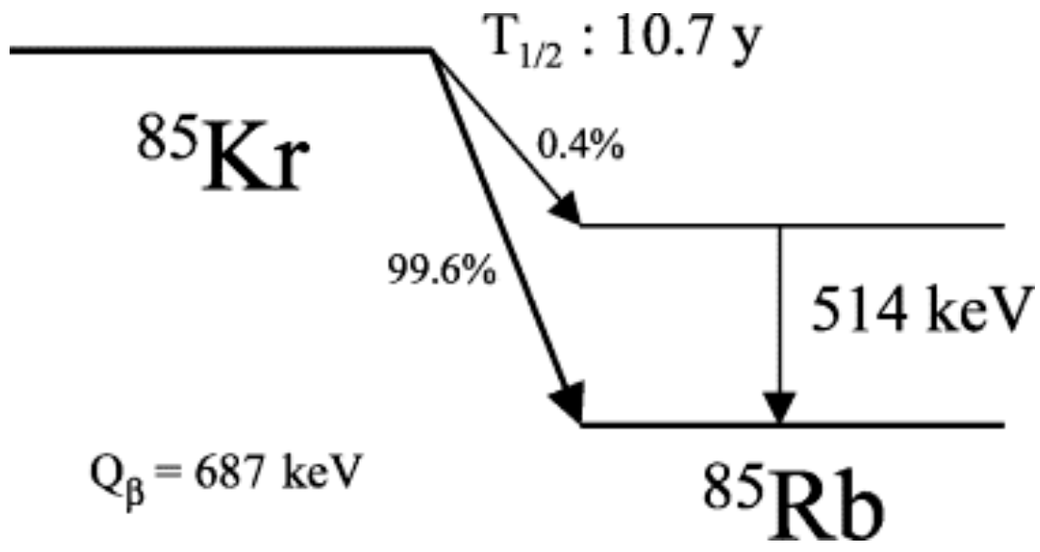




Predict 15 events in WIMP search data

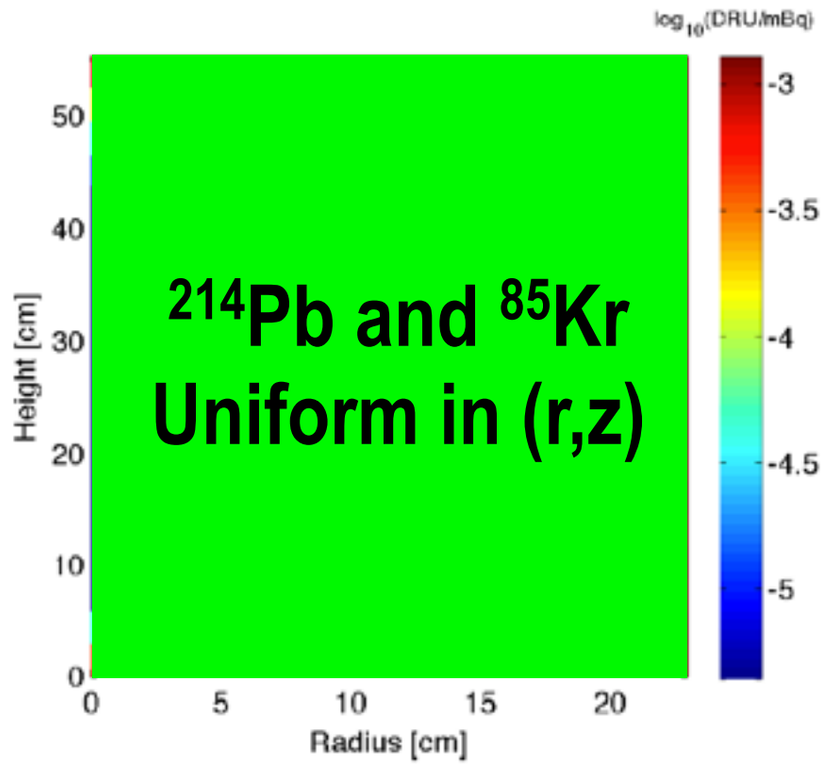
BACKGROUND FROM PB-214/KR-85

- **^{85}Kr - beta decay – intrinsic background in liquid X**
- **Kr concentration reduced from 130 ppb to 3.5 ppt (factor of 30000) using a chromotographic system developped by the LUX collaboration**



^{214}Pb (from ^{238}U chain) has a half-life of 27 minutes and undergoes a beta decay. This generates a low-energy ER background in the WIMP search region.

Predict 10 events in WIMP search data



SETTING THE LIMIT

- **Use of Profile Likelihood Ratio (PLR)**
  - **we don't have to draw acceptance boxes avoiding potential bias in data analysis from selecting regions in S1,S2 signal-space.**

$$q_\sigma \equiv -2\log\left[\frac{\mathcal{L}\left(\sigma_{\text{test}}, \hat{\hat{\boldsymbol{\theta}}}\right)}{\mathcal{L}\left(\hat{\sigma}, \hat{\boldsymbol{\theta}}\right)}\right]$$

Fixed point to test

Nuisance parameters, not fixed

Value of maximum likelihood

- **Generate pseudo-experiments for σ_{test}, compare the value of test statistic in data with the value of $q_{\sigma,i}$ from each pseudo-experiment and from that get the p-value.**

MODELING THE SIGNAL

from the nuclear band parametrization

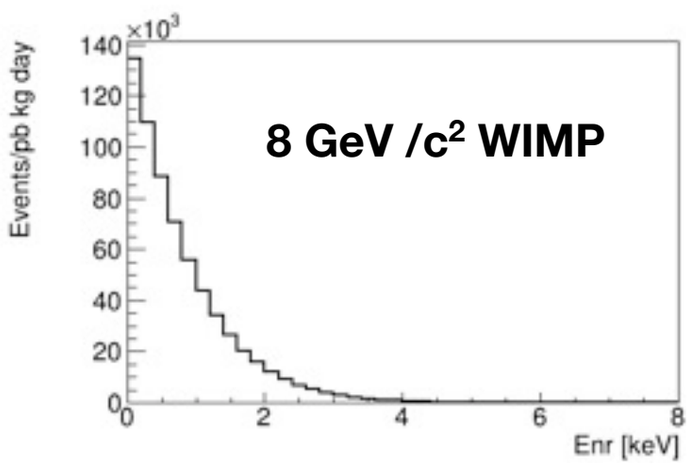
P_s is uniform in r^2 and z

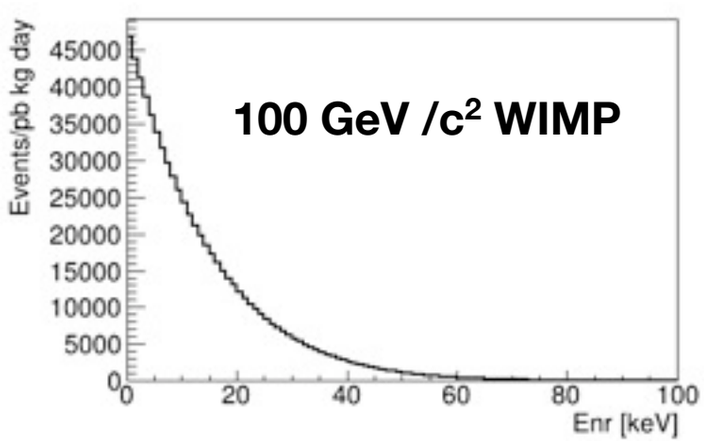
$$P_s(\boldsymbol{x};\boldsymbol{\sigma},\boldsymbol{\theta_s}) = P_{NR}(\log_{10}(S2/S1)\,|S1)\,P_s(E_{NR}(S1))\,P_s(r)P_s(z)$$

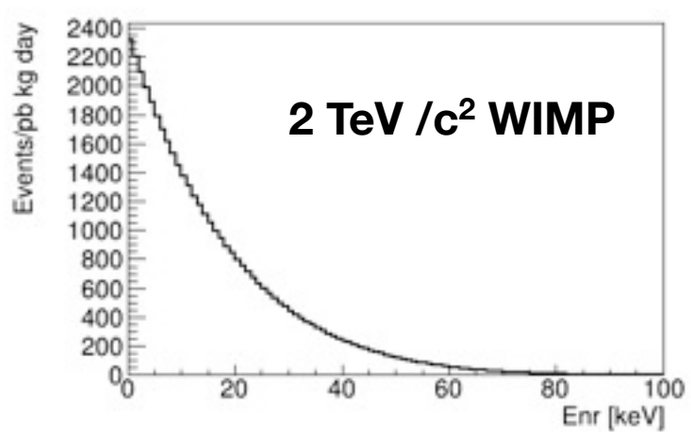
contains the WIMP recoil energy spectrum

$$P_s(E_{NR}(S1)) = \varepsilon(S1)\frac{dR}{dE_{NR}}(\sigma_{\mathrm{WIMP}}, m_{\mathrm{WIMP}}, \boldsymbol{\theta}_s)\frac{dE_{NR}}{dS1}$$

WIMP spectrum (we used the standard!)

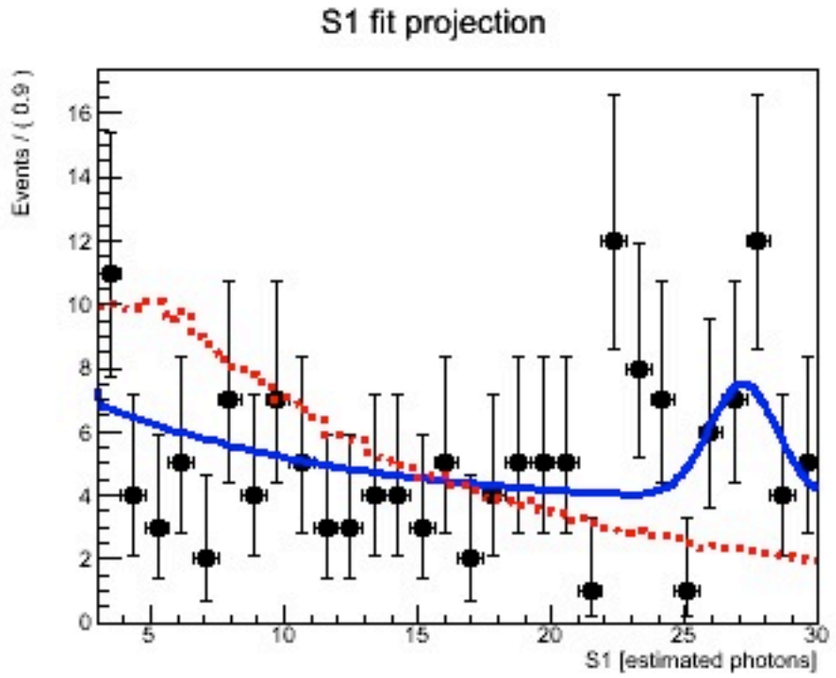


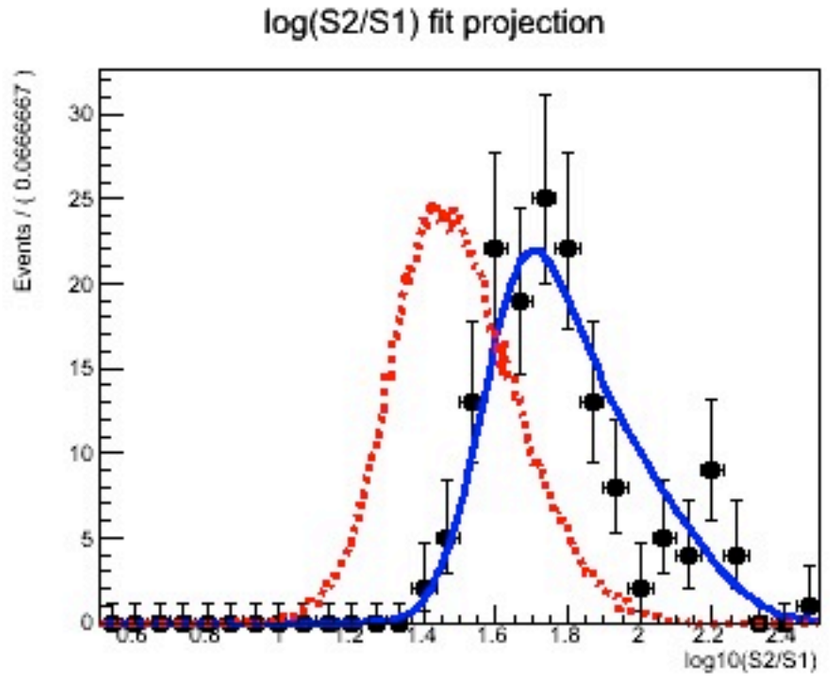


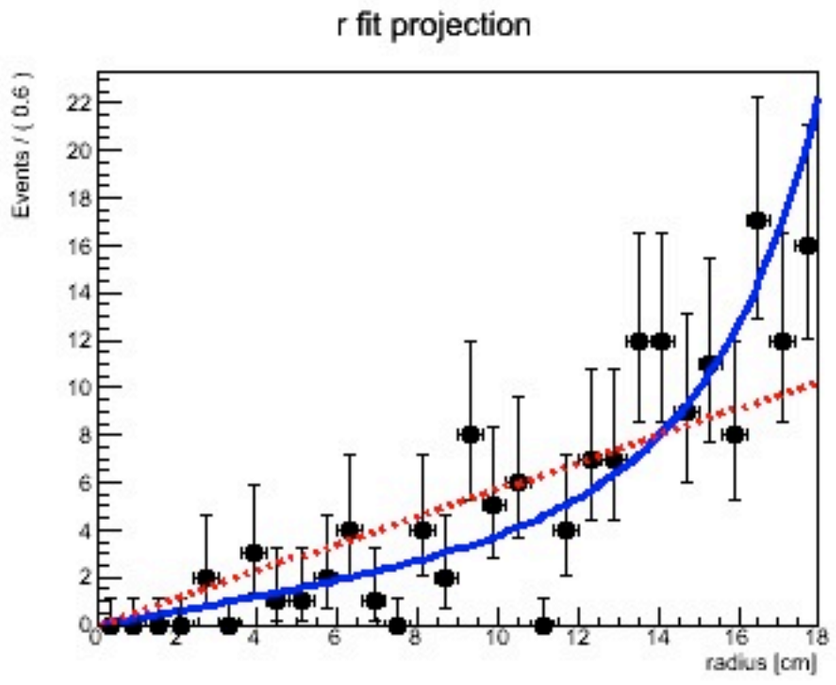


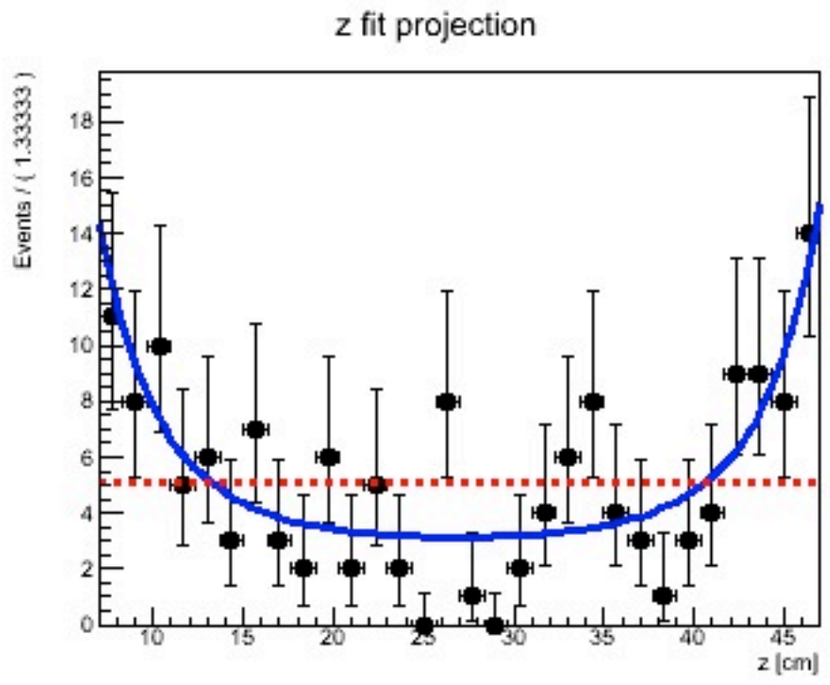
FIT PROJECTIONS

100 GeV WIMP Signal









DISCUSSION

- **Data Analysis and Blinding Discussion**
  - The Xe Target inner fiducial volume is very simple, it sits inside a larger volume of Xe with only a "virtual" surface dividing them
  - Modeling of extrinsic and intrinsic background signals in large monolithic Xe volume has low systematics
  - No blinding was imposed for the first WIMP data analysis
  - We aimed to apply minimum set of cuts in order to reduce any tuning of event cuts/acceptance.
  - The cuts list is very short ...
  - Fiducial Volume was selected based on requirement to keep low energy events from grid and teflon surface out of WS data. Primarily alpha-decay events.
  - Low energy alpha-parent nuclear recoil events generate small S2 + S1 events. Studies position reconstruction resolution. Tested using data outside WIMP search S1 energy range. This ensured that position reconstruction for sets were similar, and definition of fiducial was not biased.
  - Use of Profile Likelihood Ratio (PLR) analysis means we don't have to draw acceptance boxes
  - This avoids potential bias in data analysis from selecting regions in S1,S2 signal-space
  - Inputs for Profile Likelihood Ratio analysis were developed using high statistics in situ calibrations, with some simulations to cross check