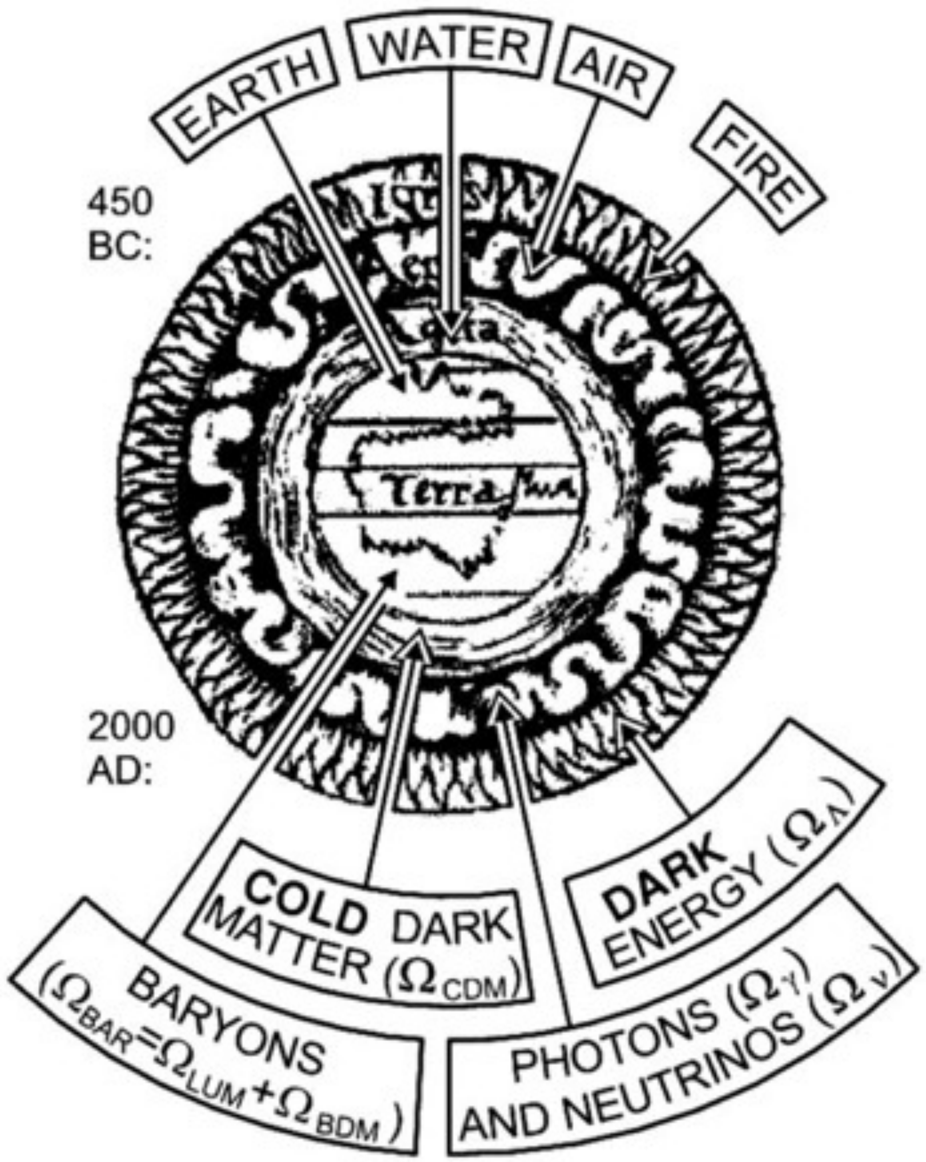
First Dark Matter Search Results from the LUX Detector

Cláudio Silva, LIP/UC Coimbra

on behalf of the LUX collaboration

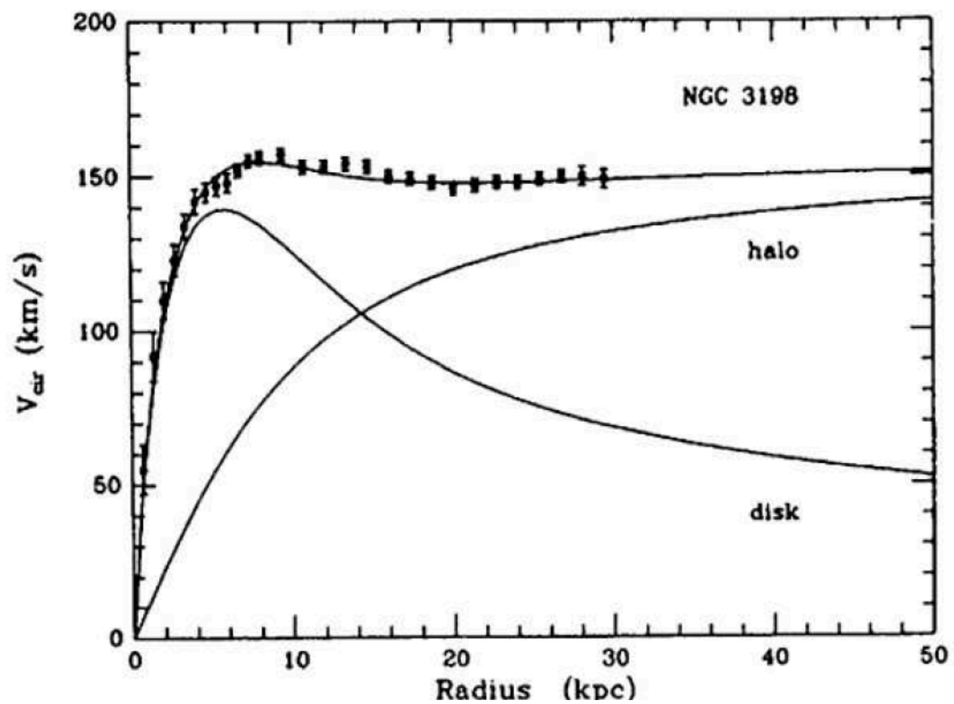
seminar at CPPM, 24 March 2014



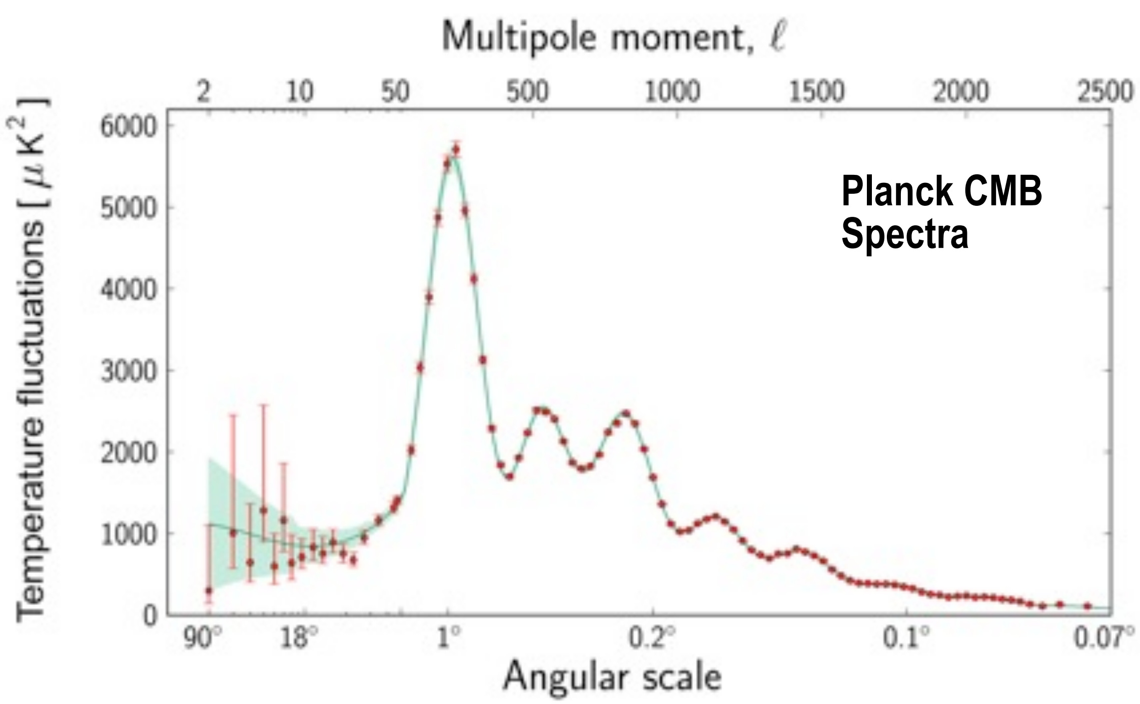
Dark Matter Detection
Brief Introduction

Dark Matter Evidences

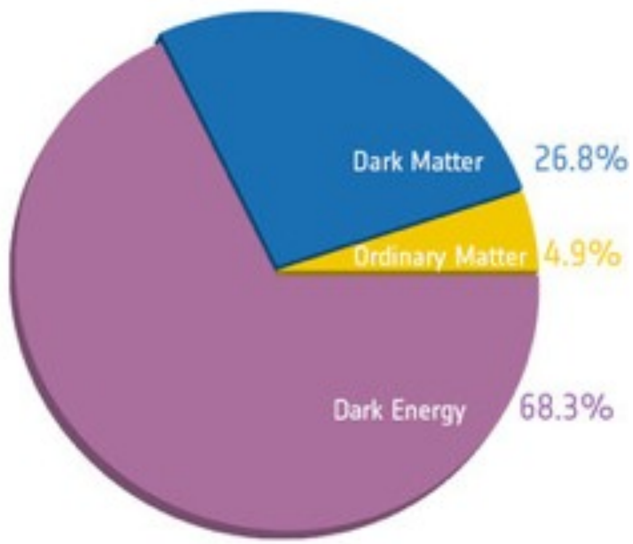
Rotation curve NGC-3198



Bullet-cluster: DM not MOND

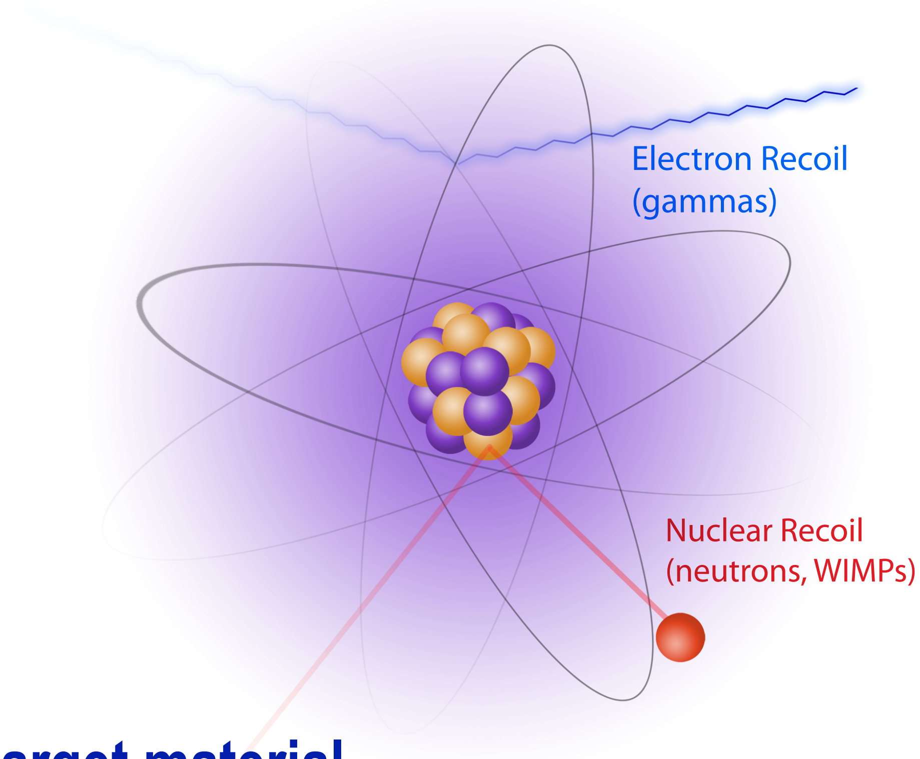


Planck Results



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

Dark Matter – Direct Detection

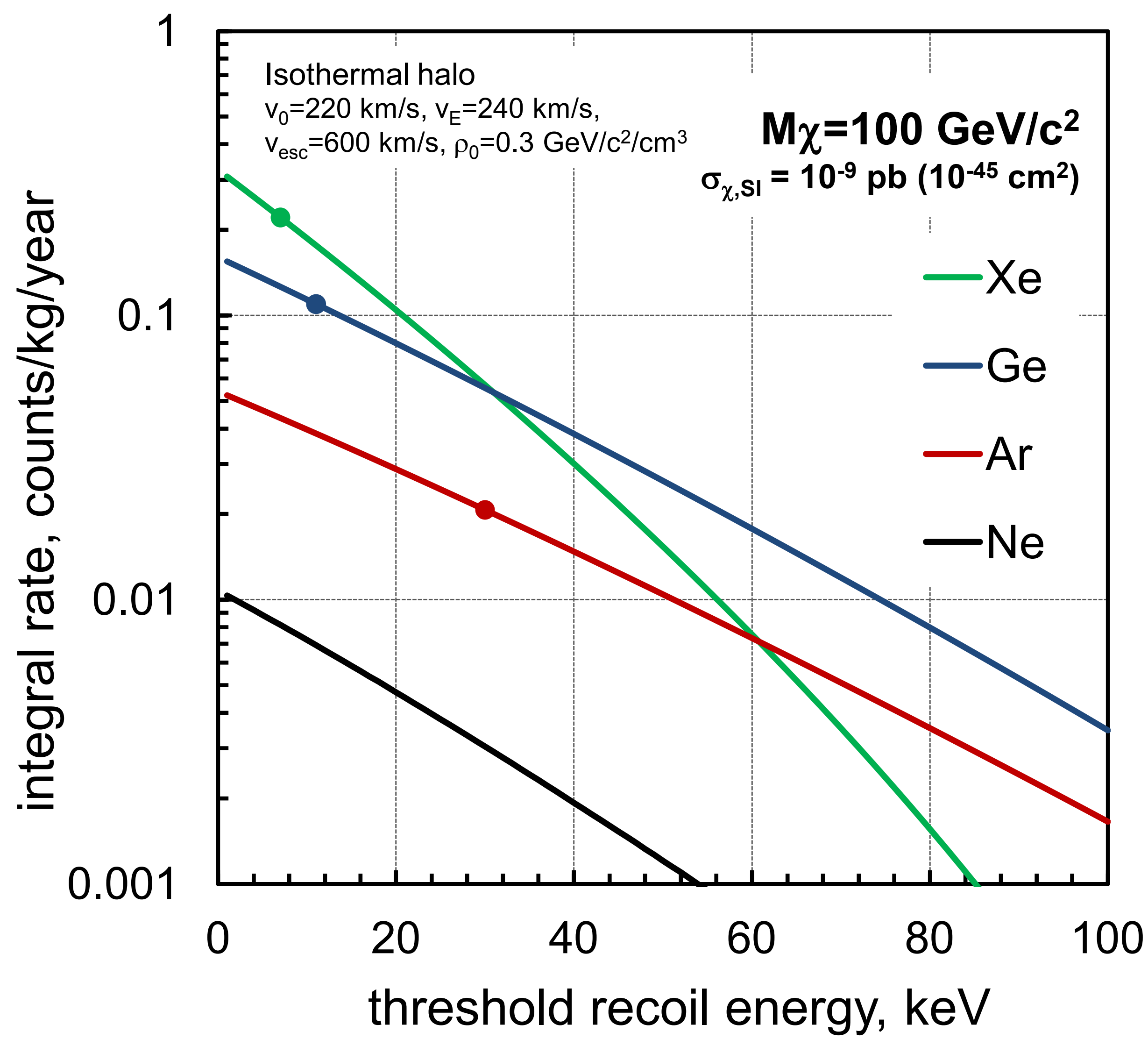


- **Cold Dark Matter Candidates**
  - Axions
  - WIMP's (weakly interative massive particles) are the favoured candidates for cold dark matter:
    - Neutral in most scenarios
    - Requires physics beyond the standard model
  - ... others
- **LUX is a Direct Detection experiment**
  - We look for scattering of galactic WIMPs with the nucleus of the target material.
  - Isothermal model: expect recoil <10 keV requiring detectors with a very low threshold.
- **Weak interaction**
  - Spin dependent cross section
  - Spin independent $\propto A^2$
- **Chalenge backgrounds**
  - Sea level total muon flux: 55.2 m-2·s^{-1} (threshold 300 MeV)
  - Ambient radioactivity: ~100 evts/kg/s
  - Human gamma activity 40K: ~4000 γ/s

Go underground

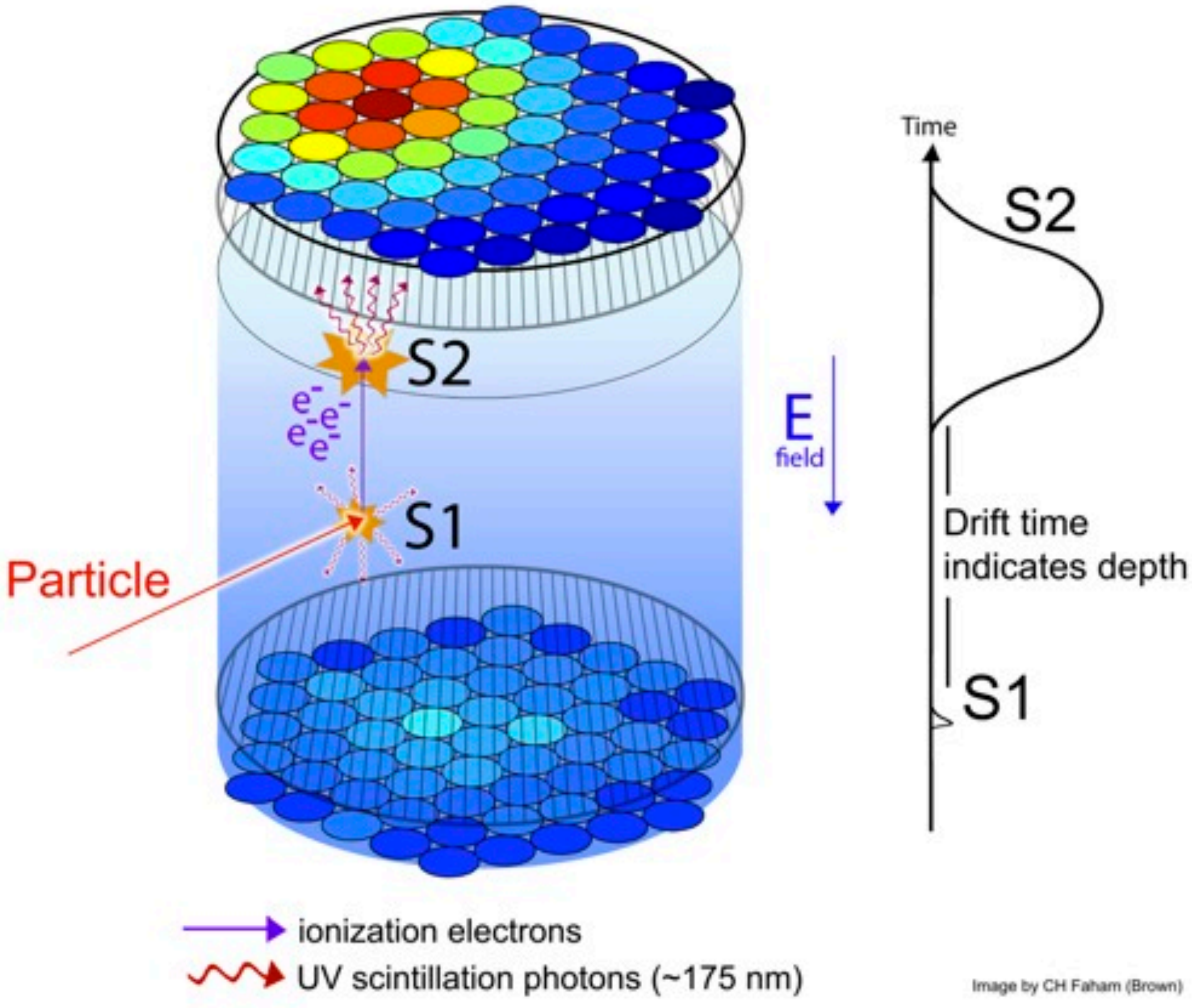
Xenon As a Detector Medium

- **Why xenon?**
  - Spin independent cross section
    - High atomic mass (A=131 g/mol)
  - Spin-dependent isotopes
    - ^{129}Xe 26.4% and ^{131}Xe 21.2%
  - No intrinsic backgrounds
  - Transparent to own scintillation photons
  - Large light output and fast response
  - Long electron drift lengths (~1 m)
  - Self-shielding (using position recons.)
  - Scalable to multi-ton size



- **Recoil energy deposited in:**
  - Light (photons)
    - 178 nm VUV photons
  - Charge (electrons)
  - Heat (not detected).

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.
- S2/S1 used for discrimination
  - WIMPs and neutrons interact with the nucleus ⇒ short, dense tracks
  - γs and e- interact with the atomic electrons ⇒ long, less-dense tracks
  - (S2/S1)γe > (S2/S1)WIMP

LUX Collaboration

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Dongqing Huang	Graduate Student

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Wing H To	Postdoc
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Chang Lee	Graduate Student
Kati Pech	Graduate Student

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Mia Ihm	Graduate Student

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Kareem Kazkaz	Staff Physicist
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James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

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Mongkol Moongweluwan	Graduate Student

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Markus Horn	Postdoc
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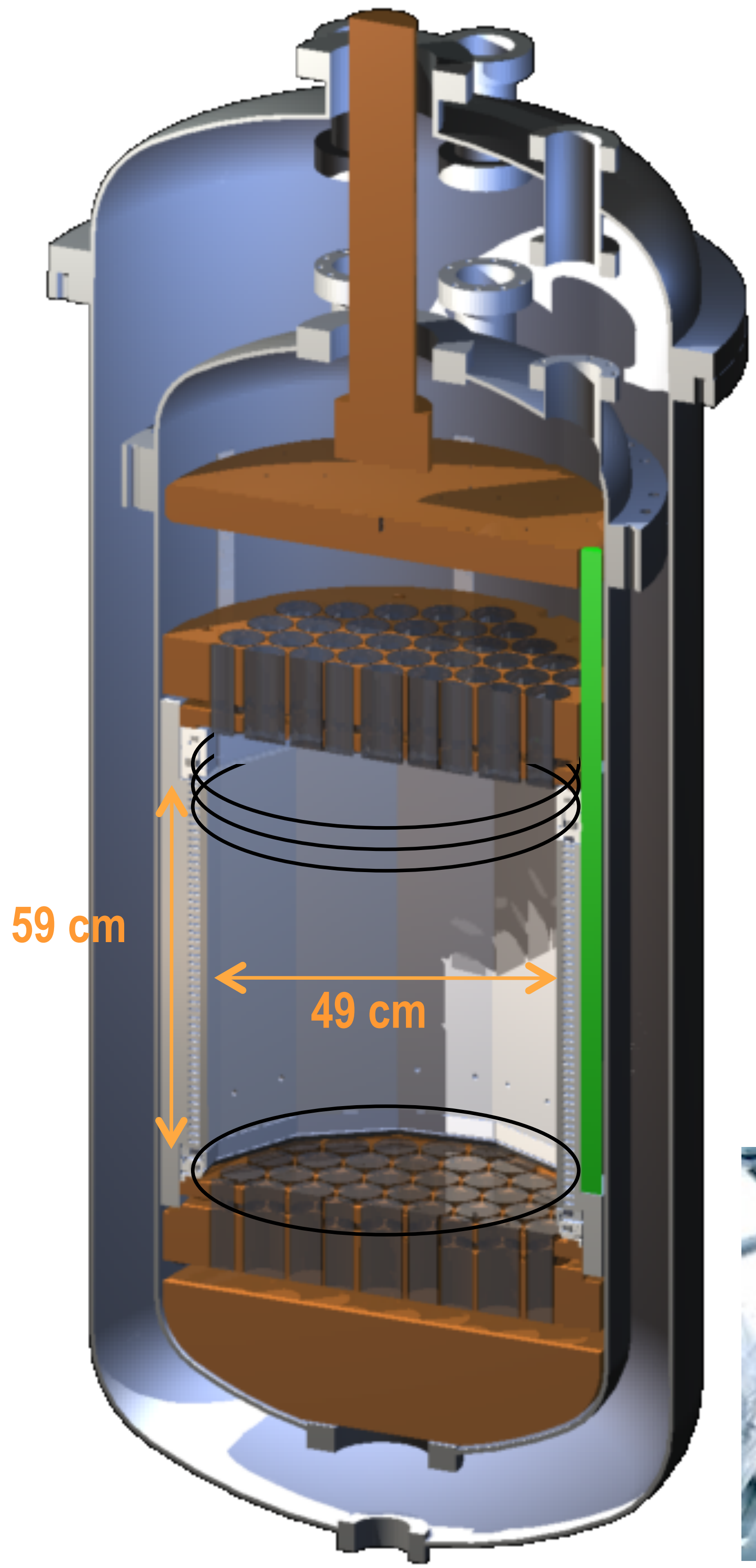
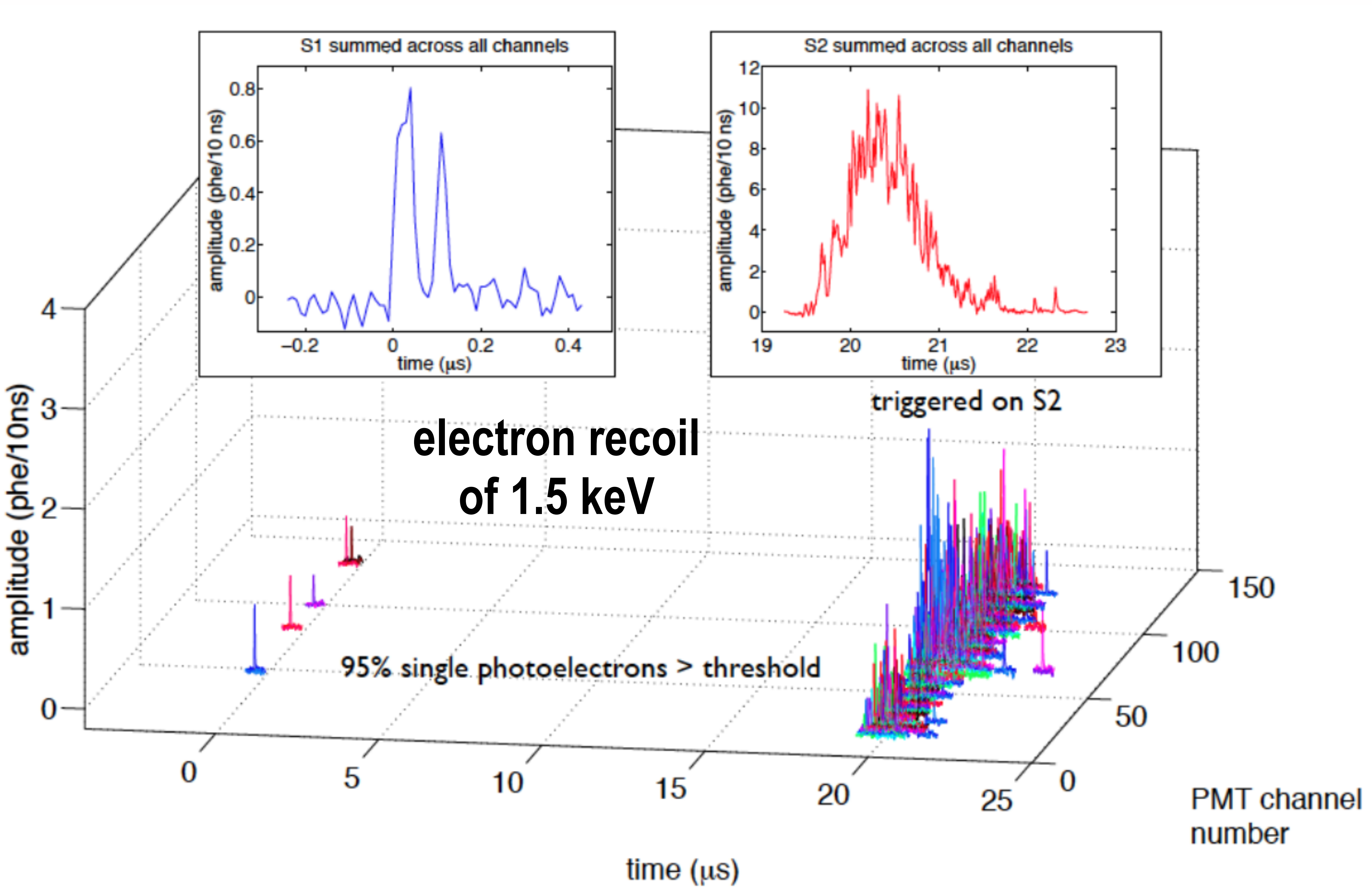
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

THe LUX Detector – Self Shielding



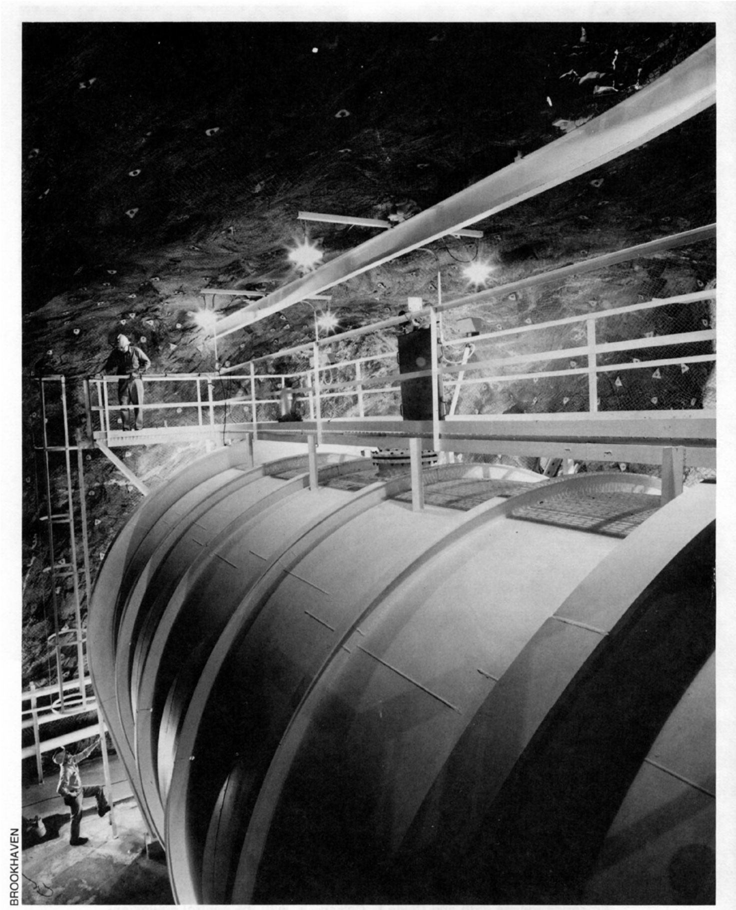
- 370 kg Liquid Xenon Detector (59 cm height, 49 cm diameter) in Gas/liquid fases.
  - 250 kg in the active volume
- Construction materials chosen for low radioactivity: Ti, Cu, PTFE.
  - Screened for radioactivity at SOLO counting facilities and at LBNL.
- 122 ultra low-background PMTs (61 on top, 61 on bottom).
- Active region defined by PTFE (high reflectivity for the VUV light - high light collection).

Typical S1+S2 Event in the LUX detector

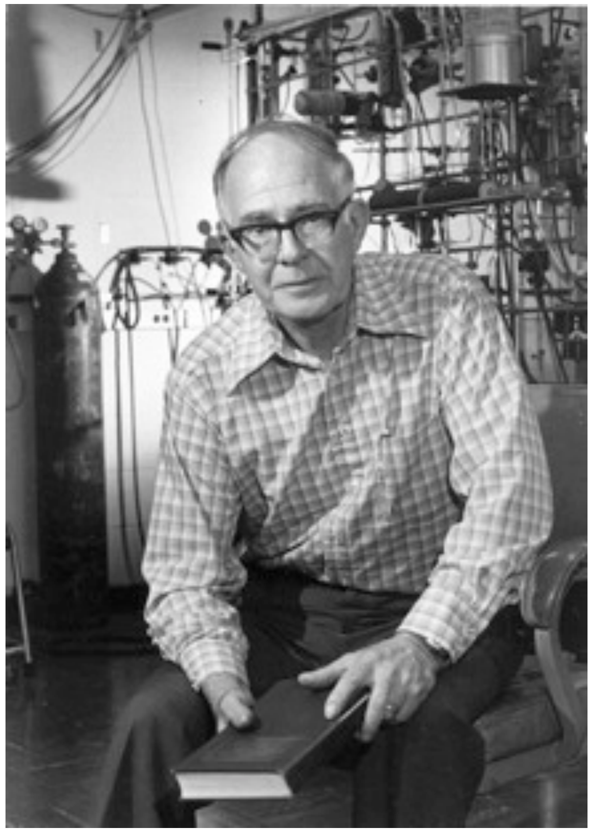


LUX AT SURF

- Sanford Underground Research Facility SURF, Lead, South Dakota, USA.
- Former Home of the Homestake Solar Neutrino Experiment 1970-1994



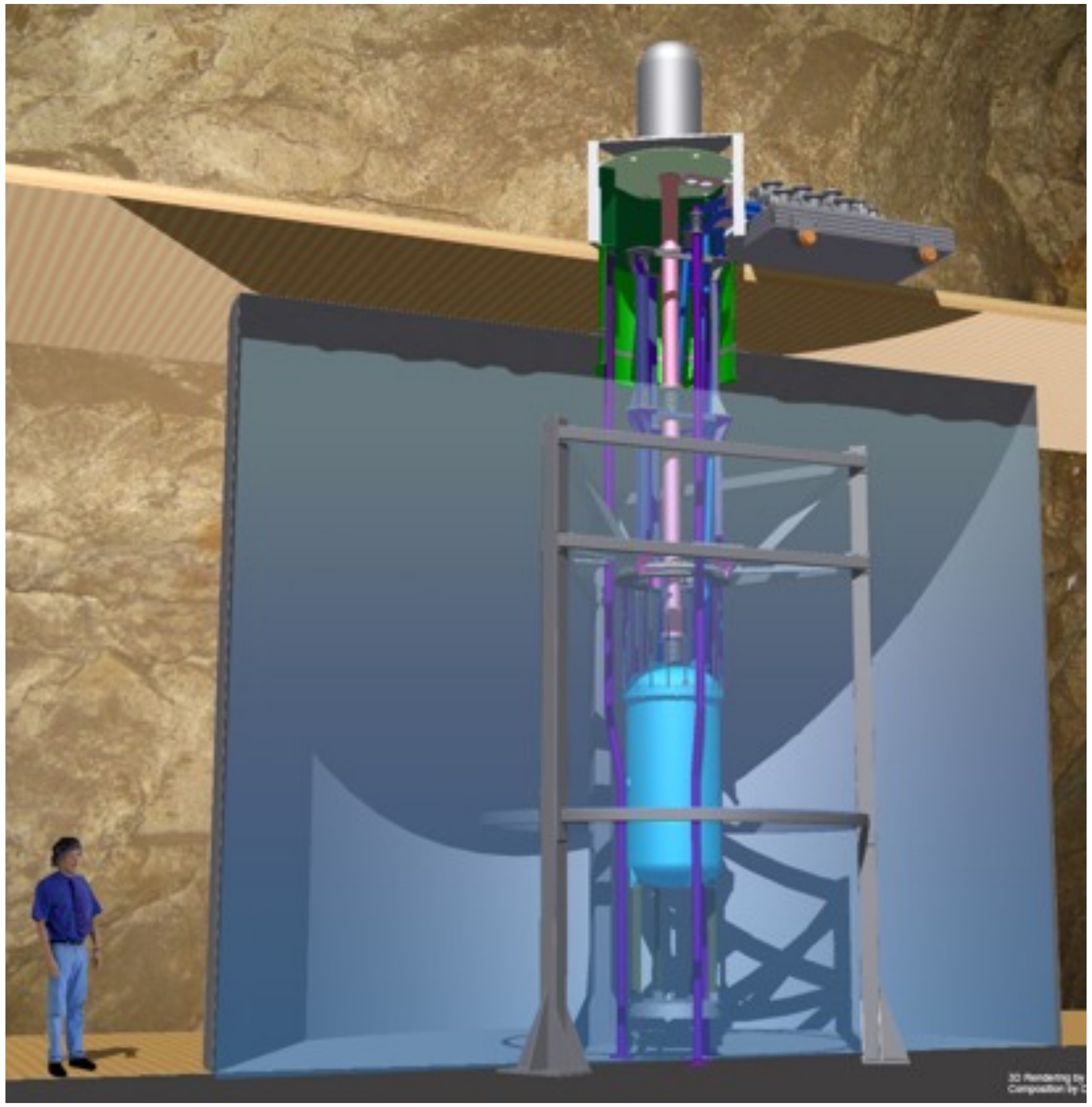
Davis' neutrino detection apparatus one kilometer underground in the Homestake Gold Mine, Lead, South Dakota. The tank contains 400,000 liters of perchloroethylene.

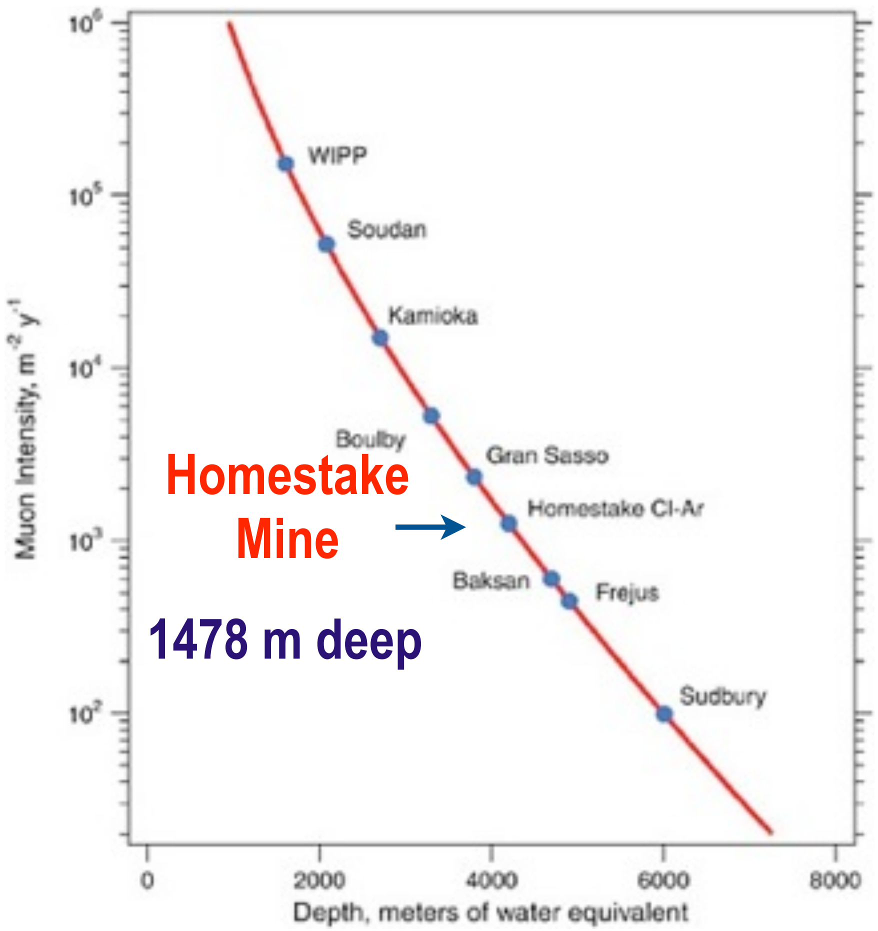


Raymond Davis (Nobelpriset i fysik 2002)

LUX AT SURF

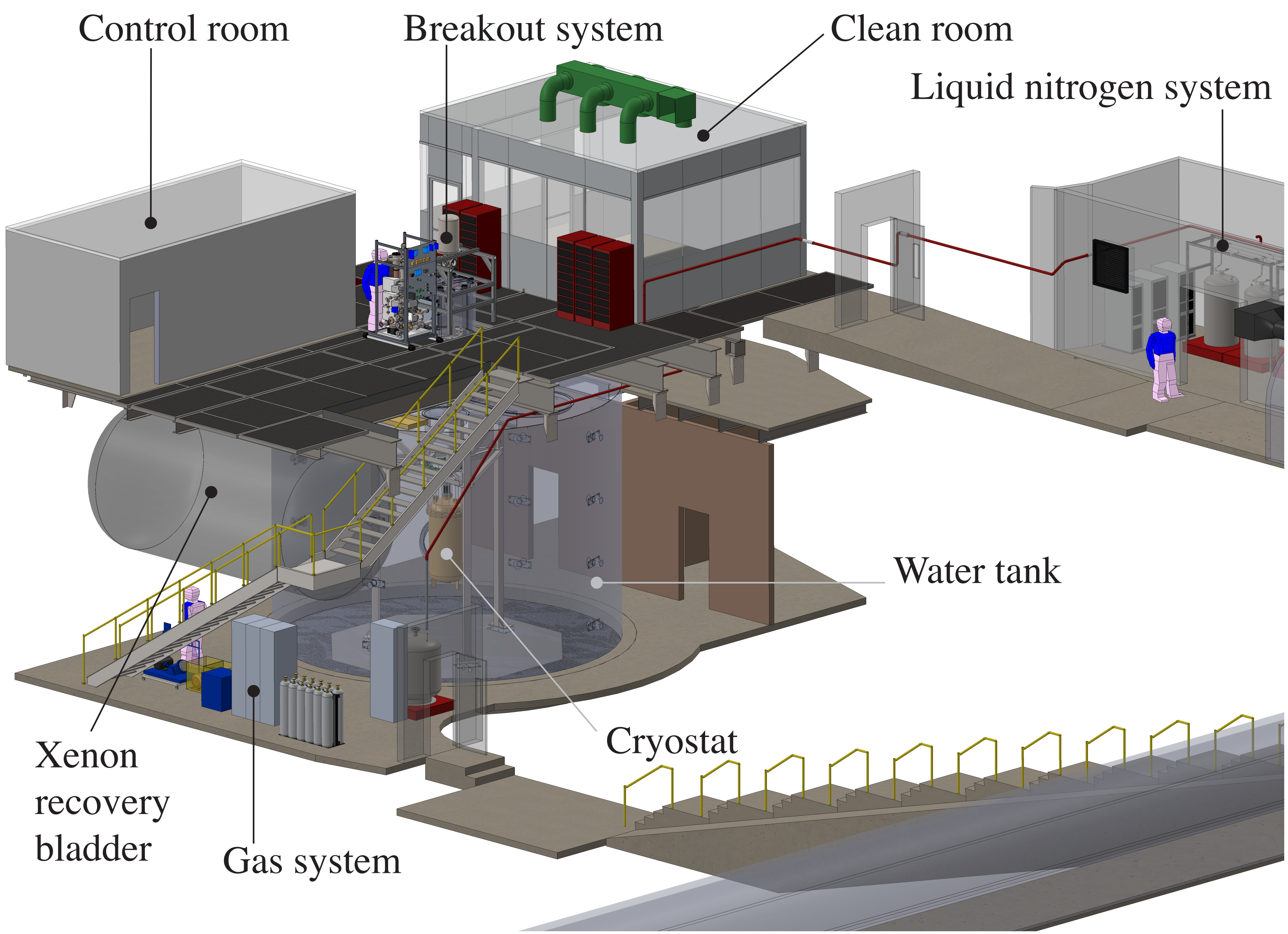
- LUX operates 4850 feet (1478 m) underground at the Sanford Underground Research Facility (SURF), South Dakota, US
- Surrounded by a 7.6 m diameter water shield
- Background dominated by construction materials ...
  - <2 background events per day in the central 118 kg target in the energy window of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

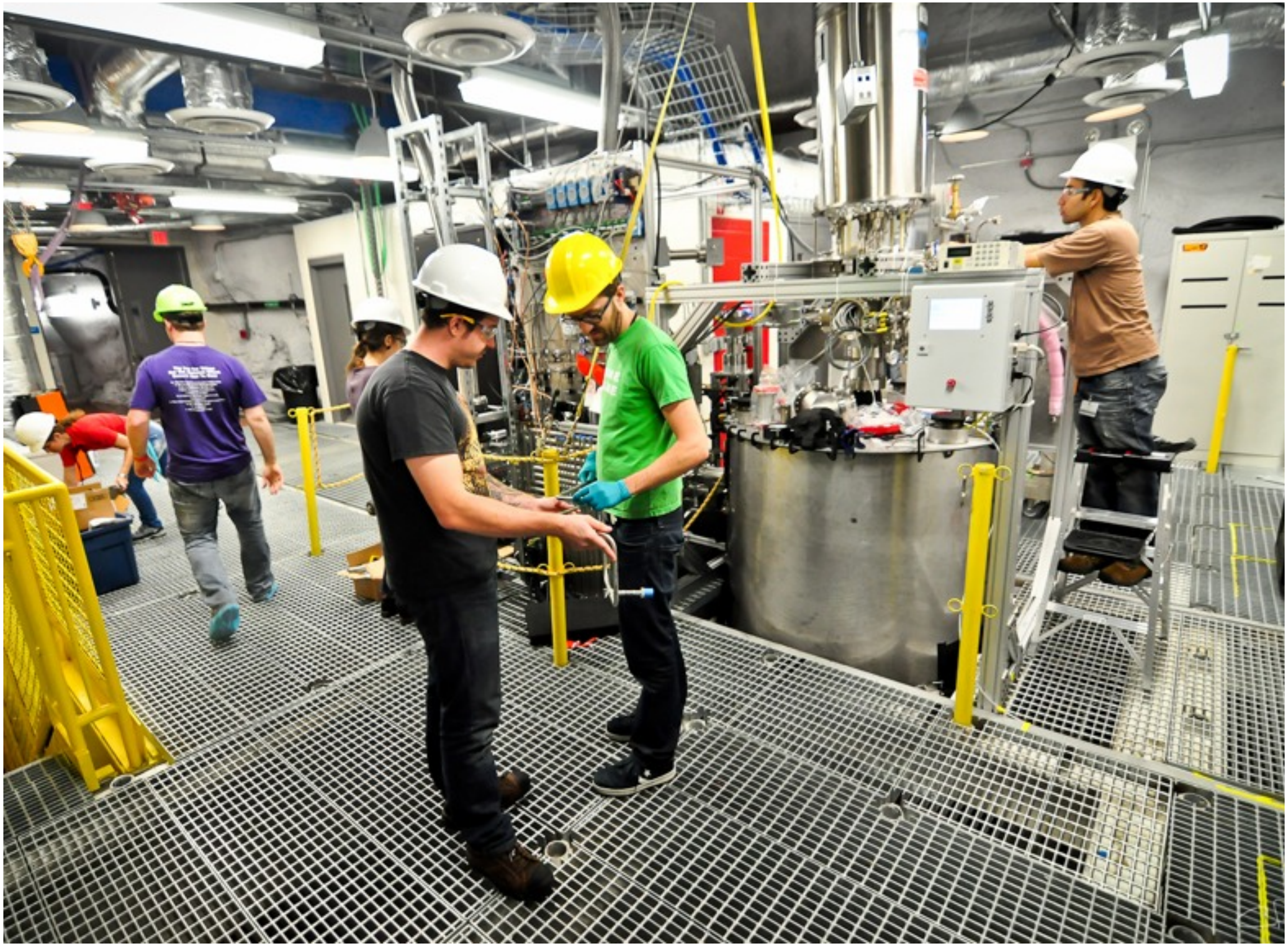




μ flux reduced by x10^{-7}
(compared to sea level)

LUX In the Davis CAMP

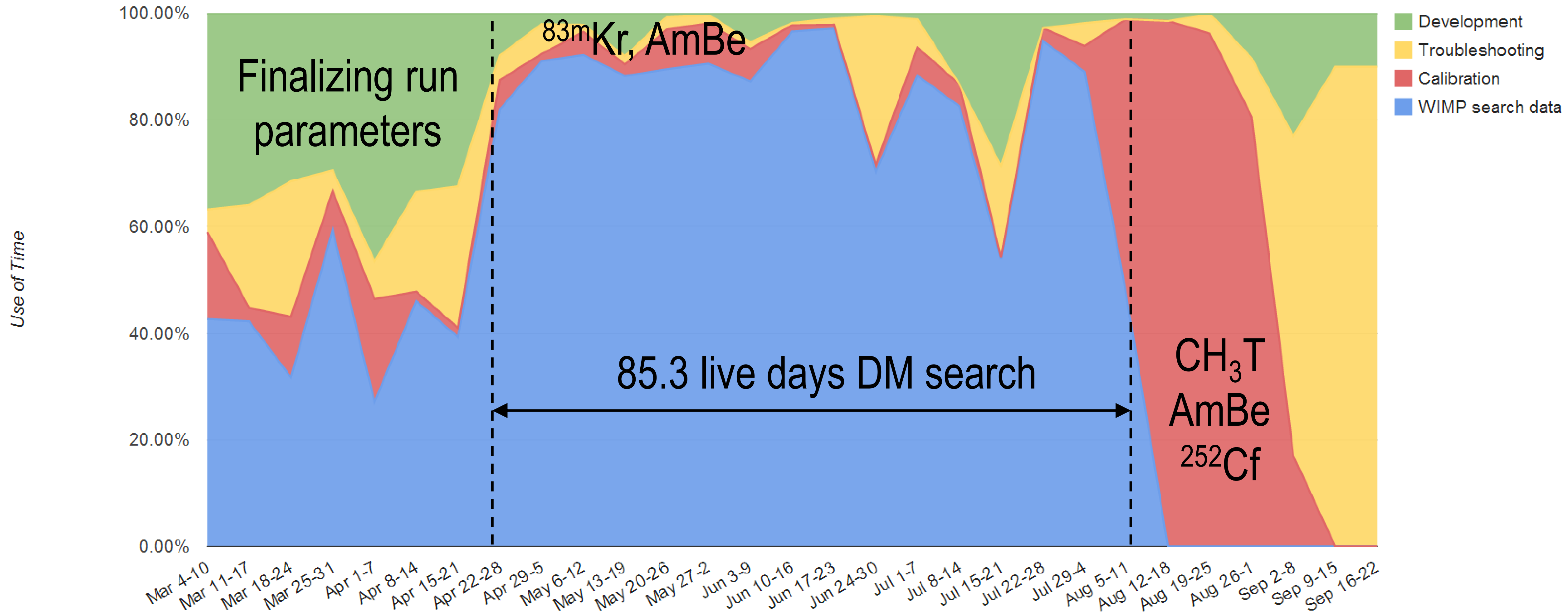




Davis Cavern SURF - Upper Floor, September 2012

LUX in the water tank, September 2012

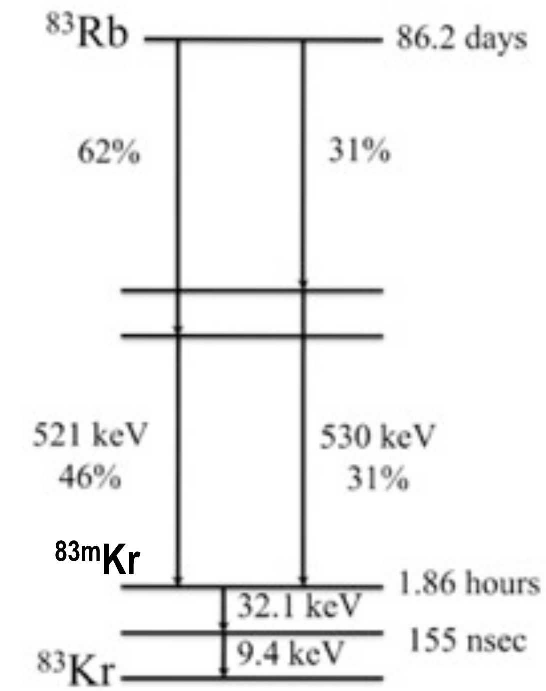
Run 3 data-taking



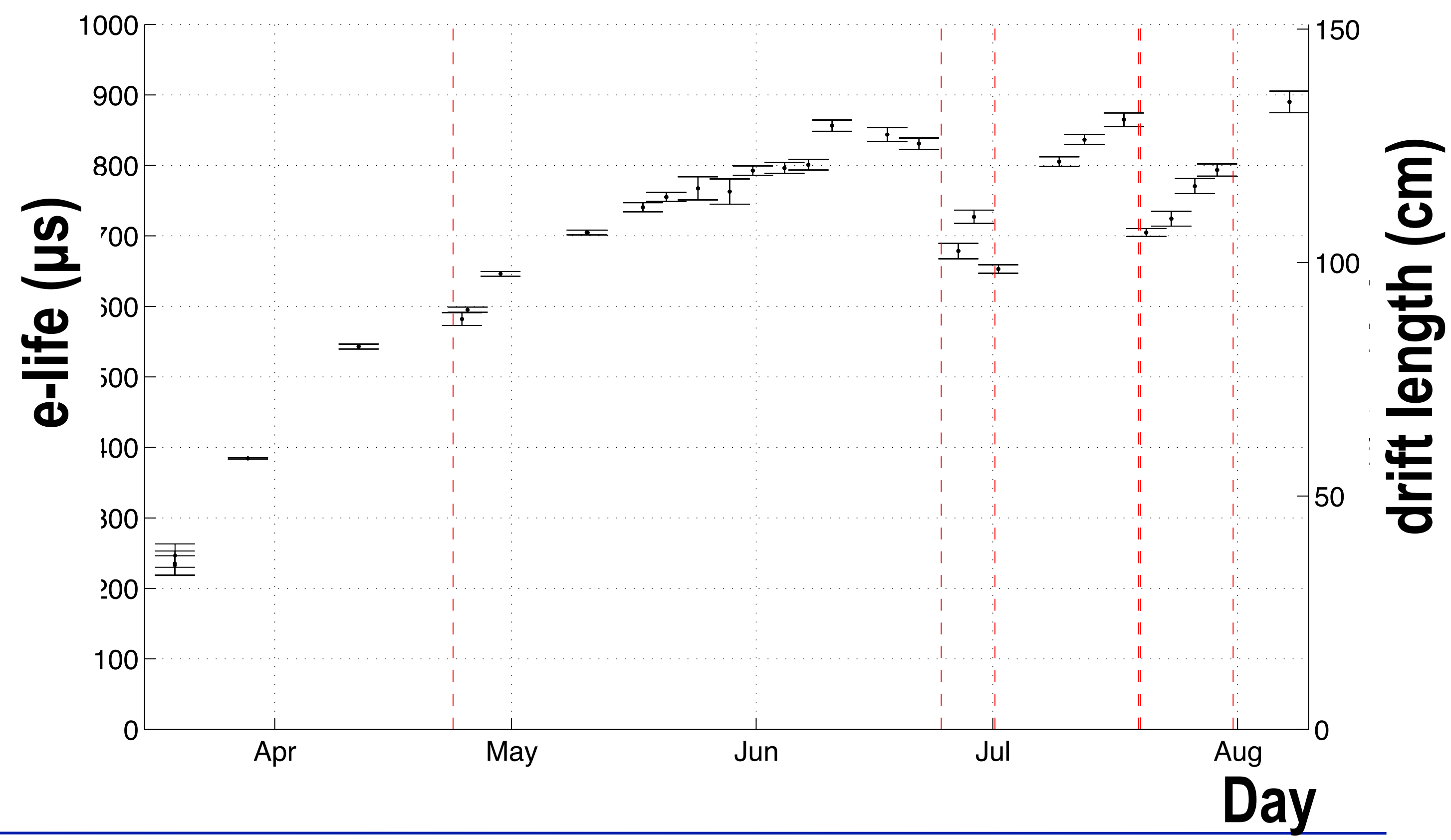
- **Detector cool-down January 2013, Xe condensed mid-February 2013**
- **Data-taking April 21 - August 8, 2013, 85 live days**
  - **>95% data taking efficiency over WIMP search region**
- **Very stable conditions during the run:**
  - **Thermal stability of $\Delta T<0.2$ K, pressure stability $\Delta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

Krypton Calibration

- Xe self-shielding prevents γ's from reaching inner volume
  - Solution: Use internal radioactive sources
- ^{83}Rb produces ^{83m}Kr when it decays; this krypton gas can then be flushed into the LUX gas system to calibrate the detector as a function of position.
- Provides reliable, efficient, homogeneous calibration of both S1 and S2 signals, which then decays away in a few hours, restoring low-background operation.

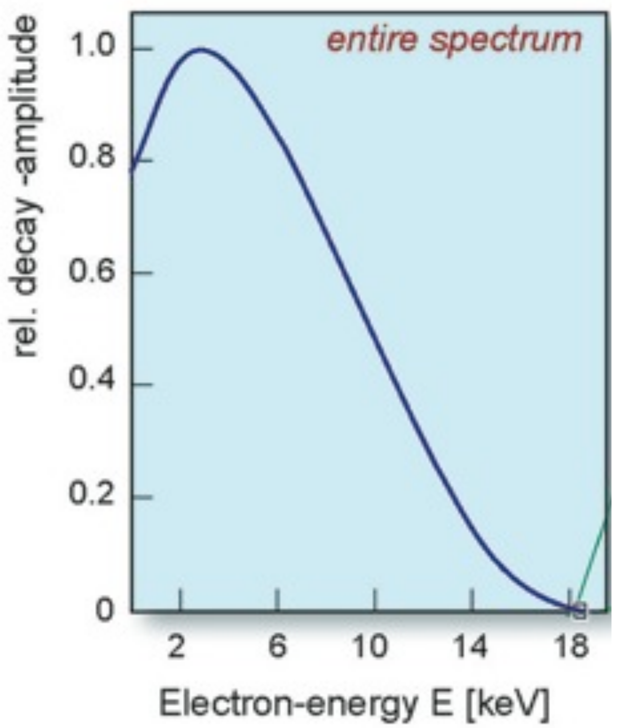


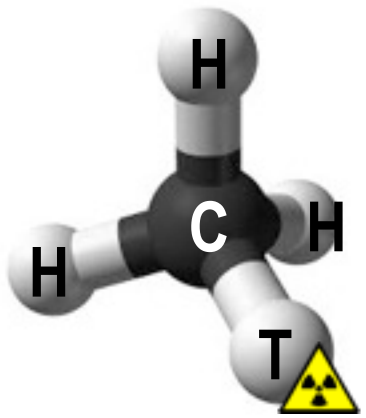
- krypton is used to
  - Correct S1 and S2 with position
  - Electron drift length measurement
    - between 90 and 130 cm during the run.
  - Light detection efficiency: 14%
  - Extraction efficiency: 65%
  - Light response functions for the position reconstruction.

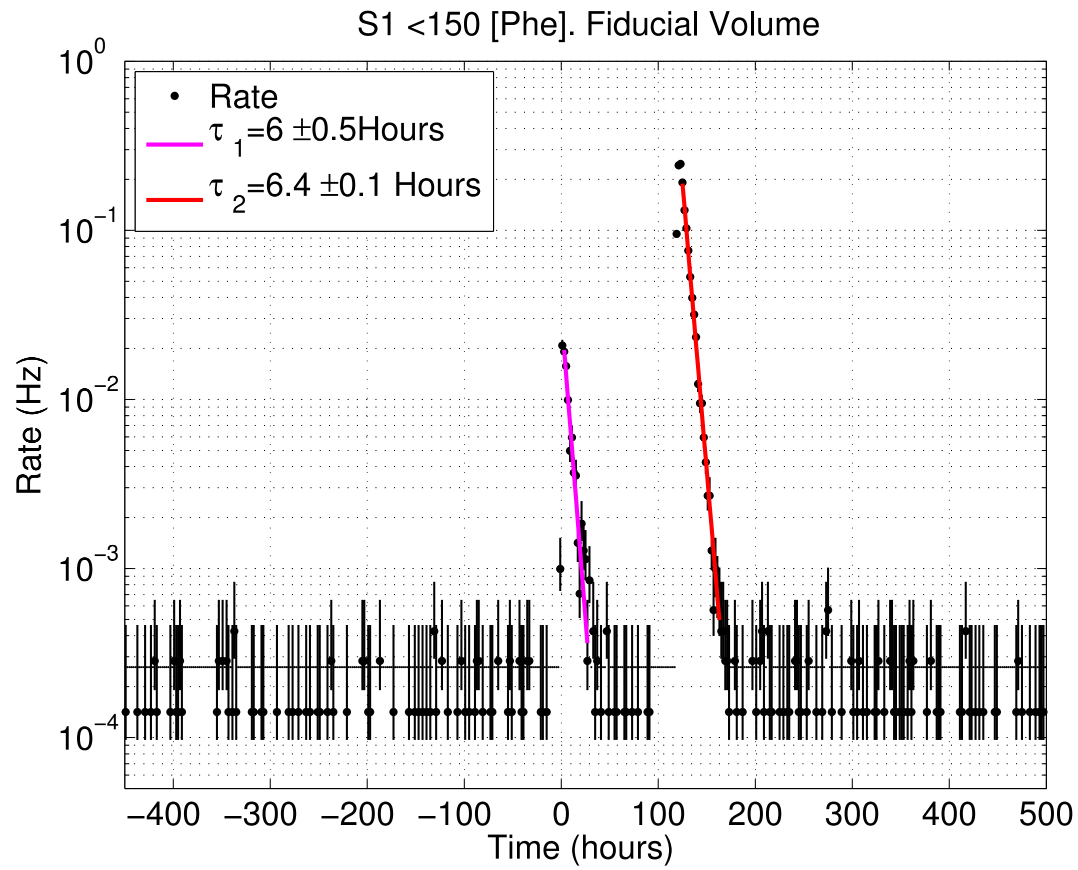


Electronic Recoil Band Calibration

- Tritium source used to calibrate the electronic recoil band.
- 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 a - Long Lifetime
- Tritiated methane was injected in the gas system and removed by the getter.



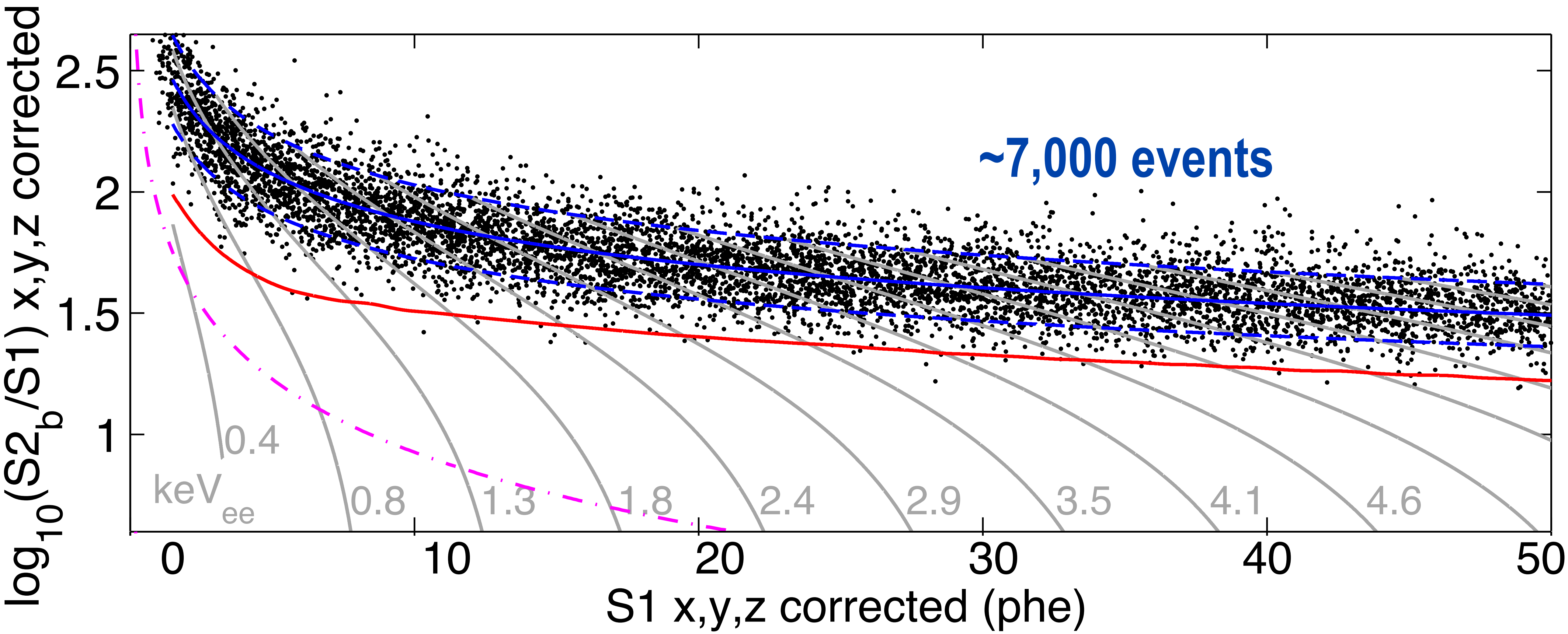




Rate of events with S1 <150 [Phe] in the fiducial volume of the detector. (150 Phe includes the entire tritium beta spectrum).

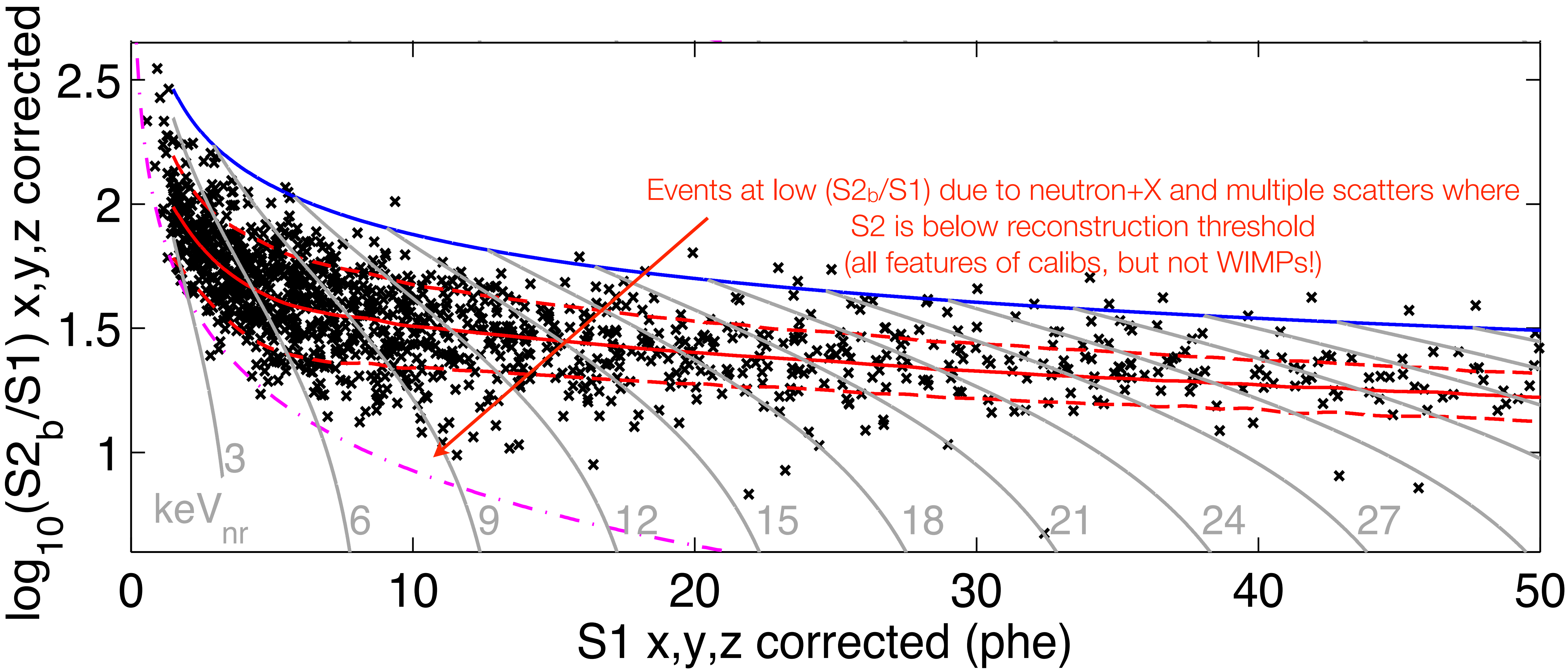
ER Band – Tritium Calibration

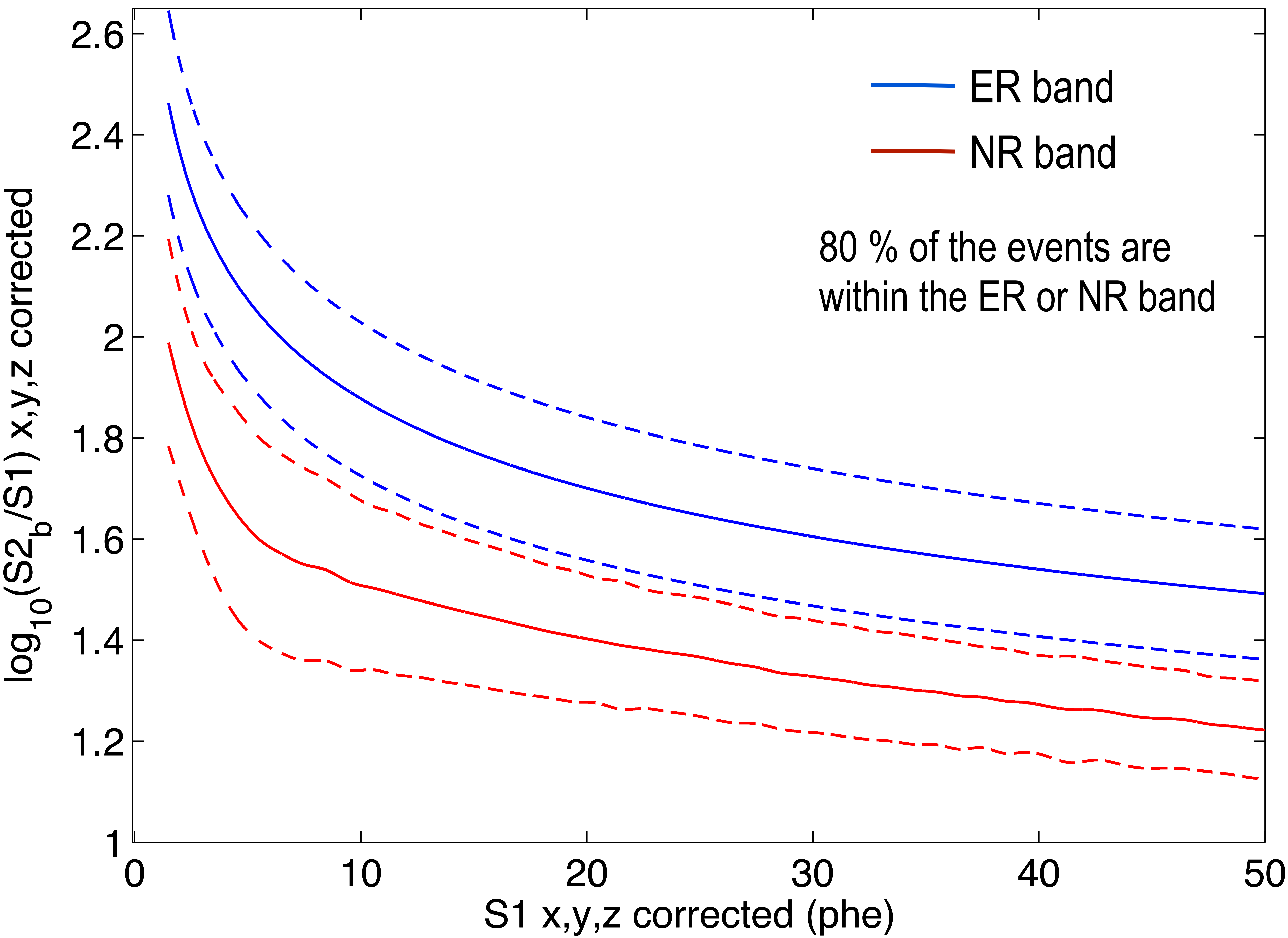
- **Parameterize as Gaussian, with power laws for mean and sigma in 1 phe S1 slices**



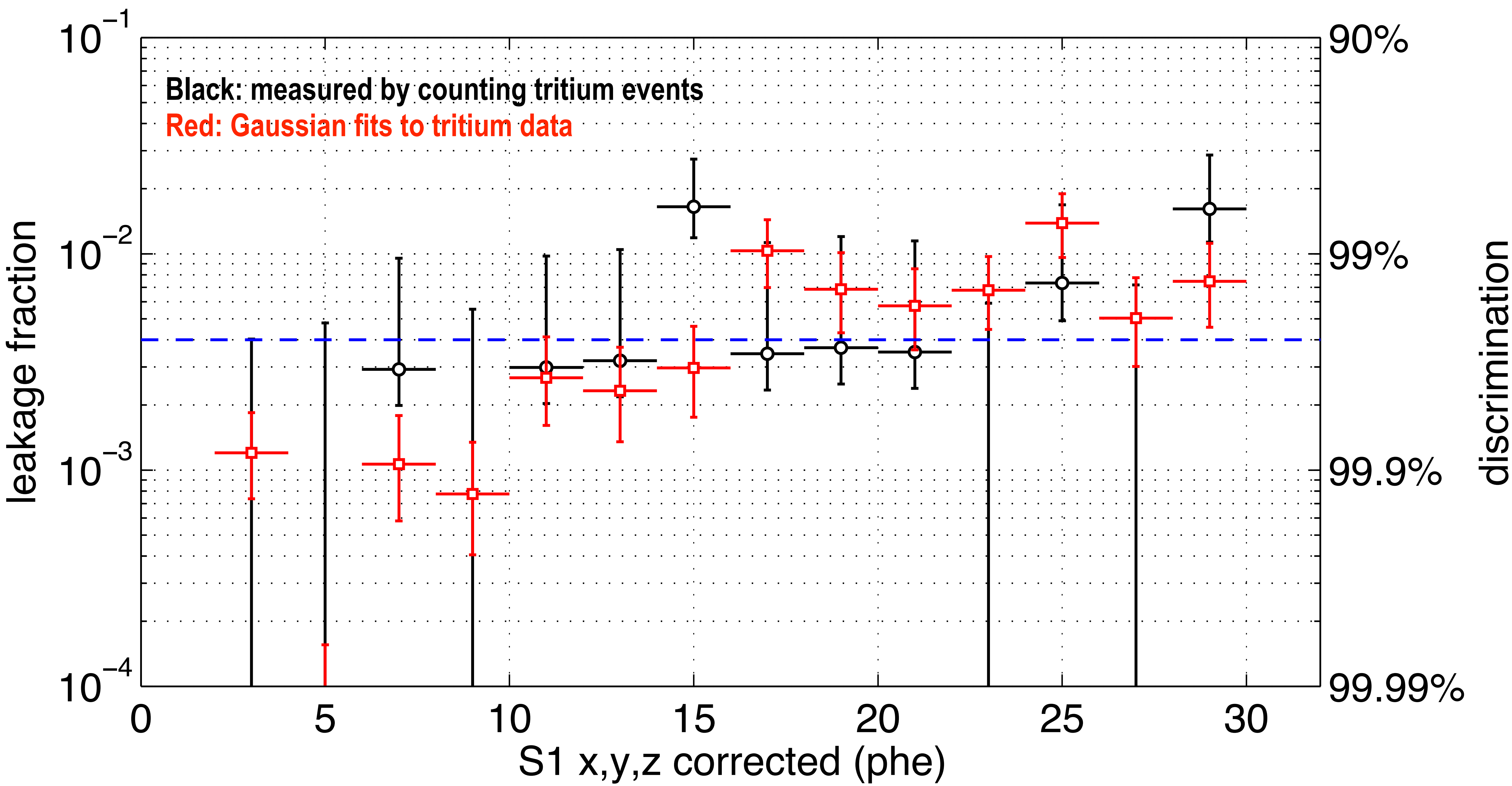
Nuclear Recoil Calibrations

- 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.




ER band
NR band
80 % of the events are within the ER or NR band
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
10
20
30
40
50
S1 x,y,z corrected (phe)
$\log_{10}(S2_b/S1)$ x,y,z corrected

Electron Recoil Discrimination

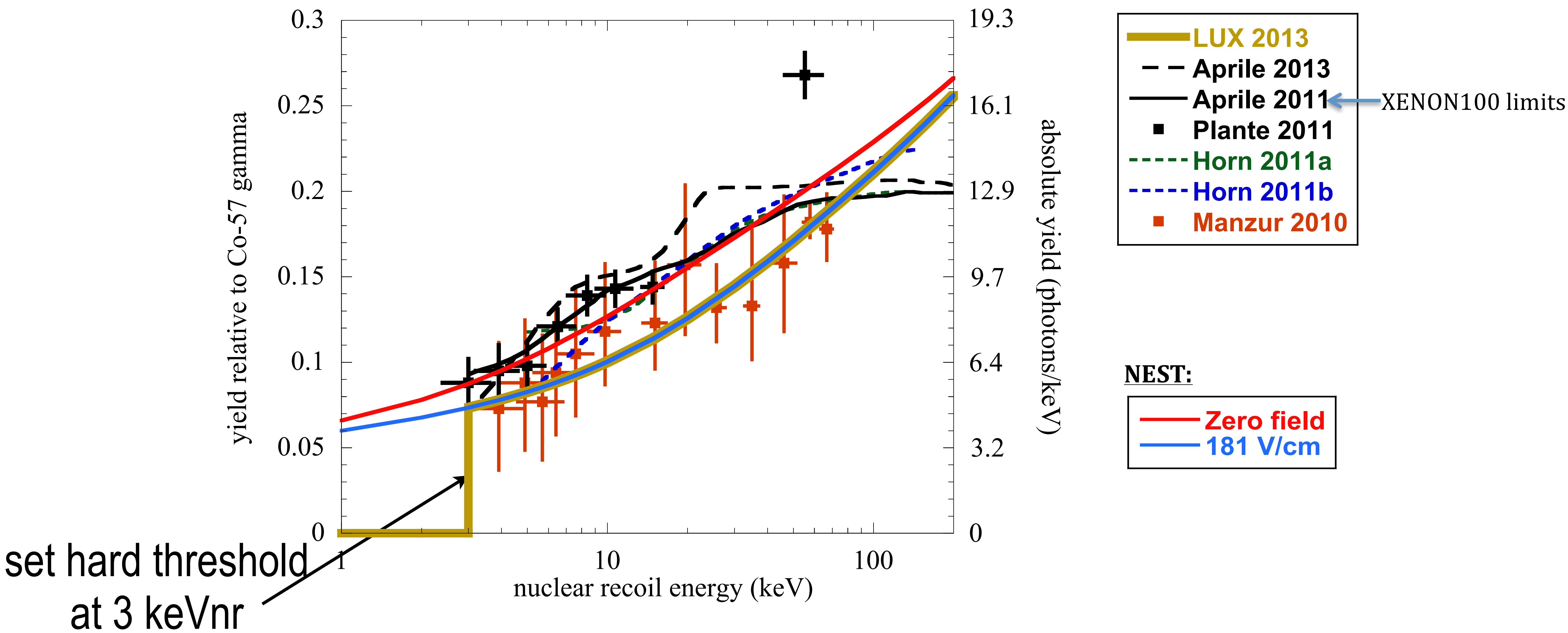


Leakage Fraction: fraction of the events in the ER band that spill over the lower half of the NR band

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

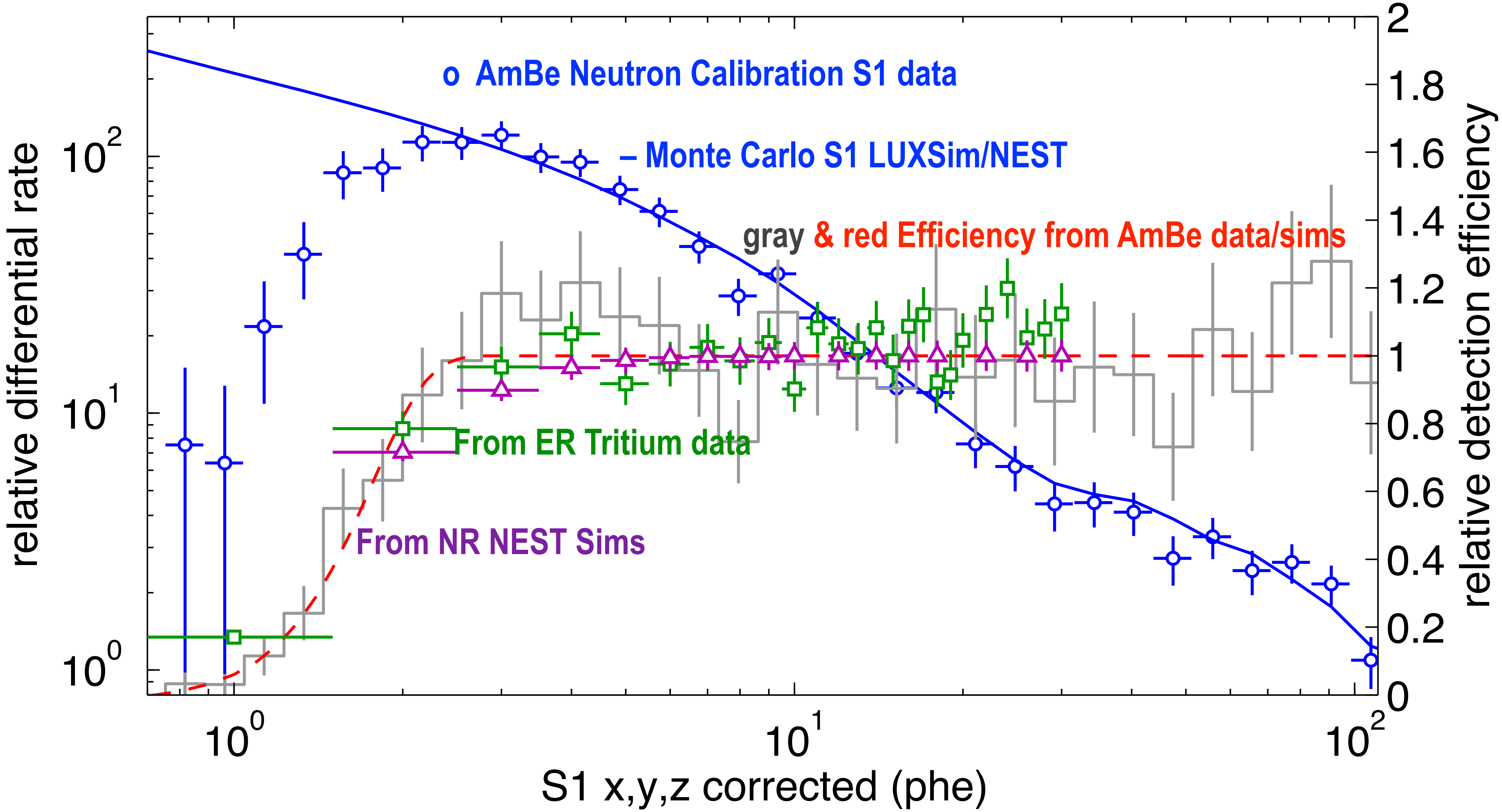
Light Yield

- Modeled using the 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)

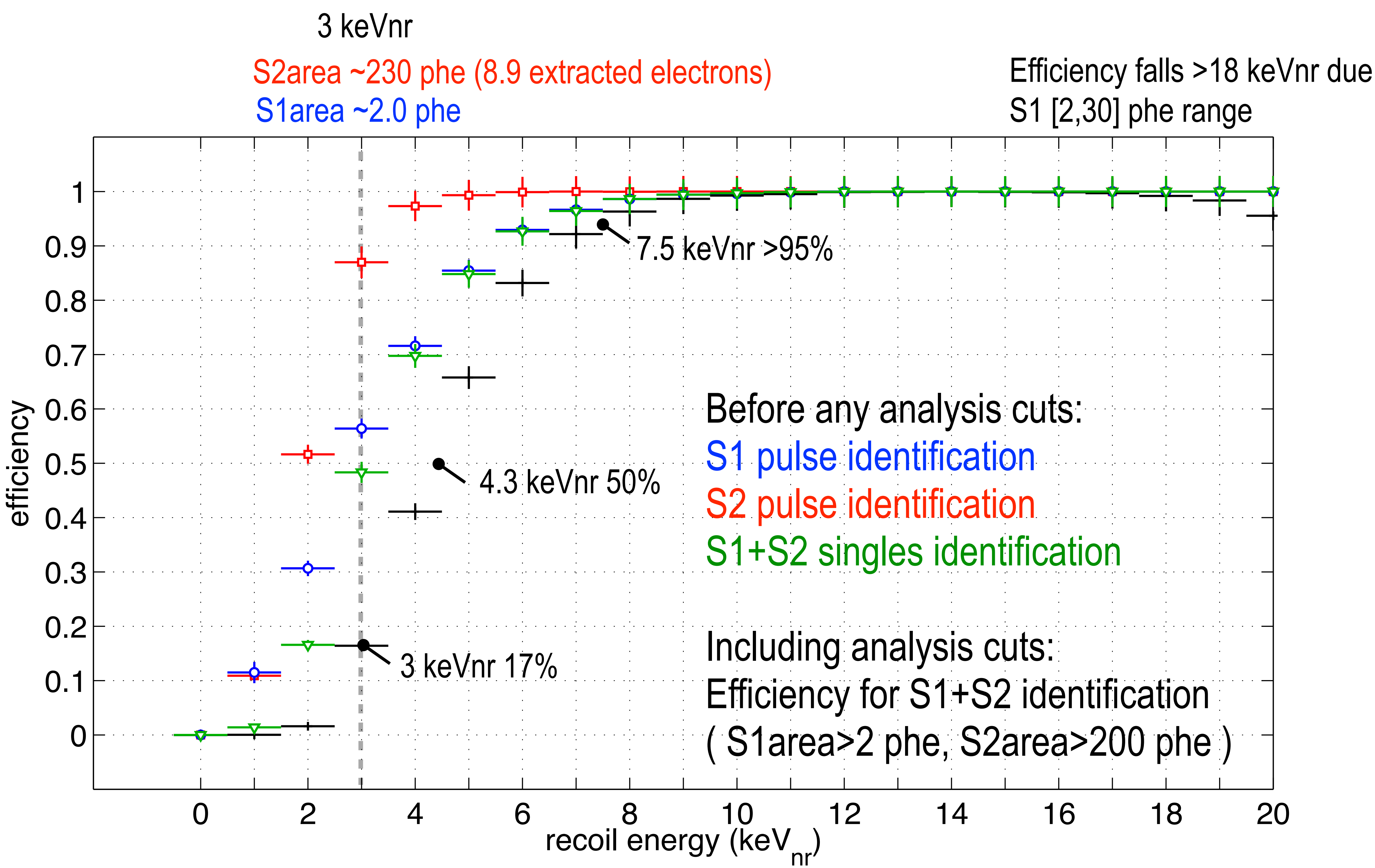


Gold Efficiency For WIMP Detection

- 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.

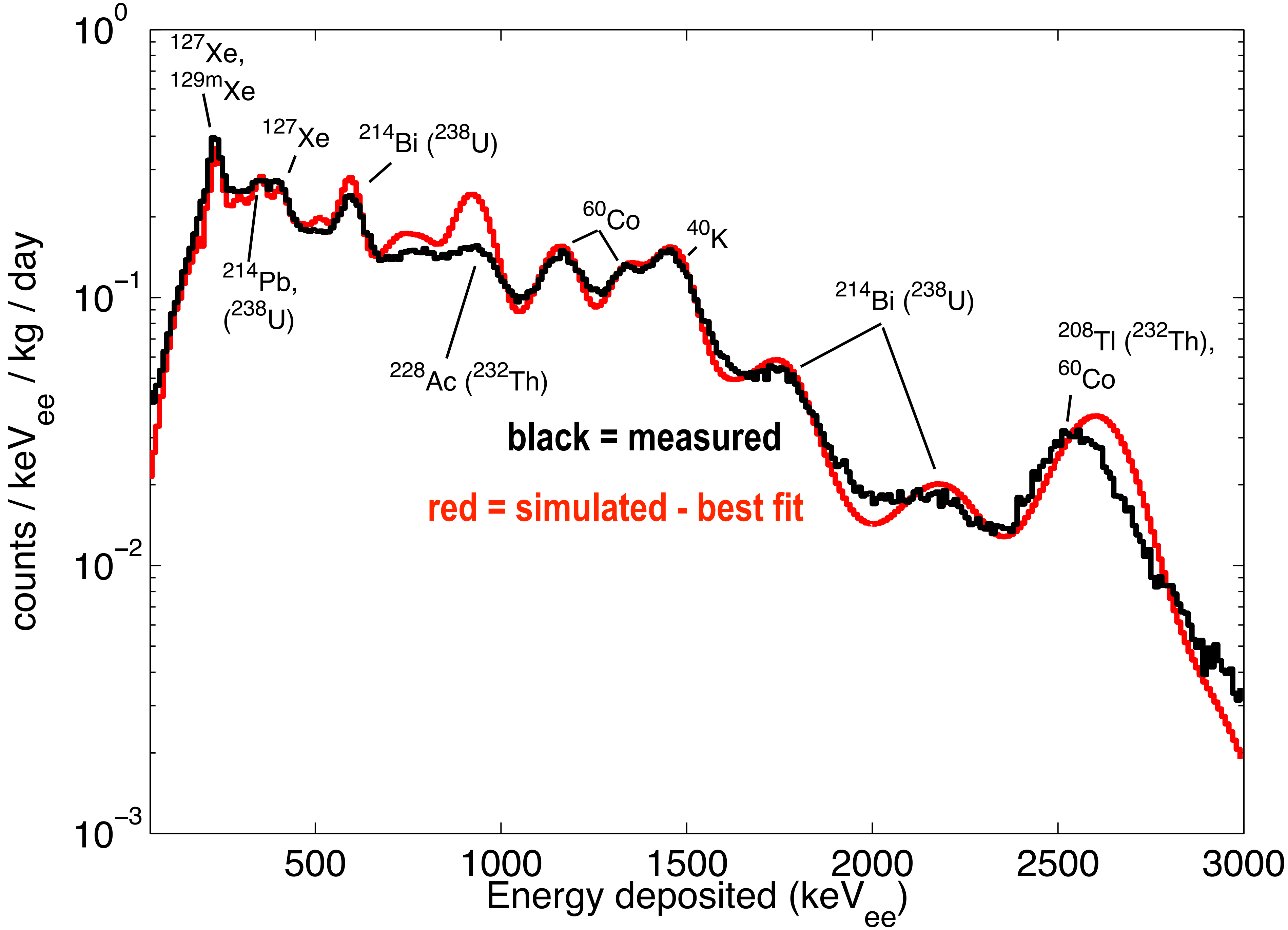


WIMP Detection Efficiency - True Recoil Energy



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

Overall γ Spectrum – high energy

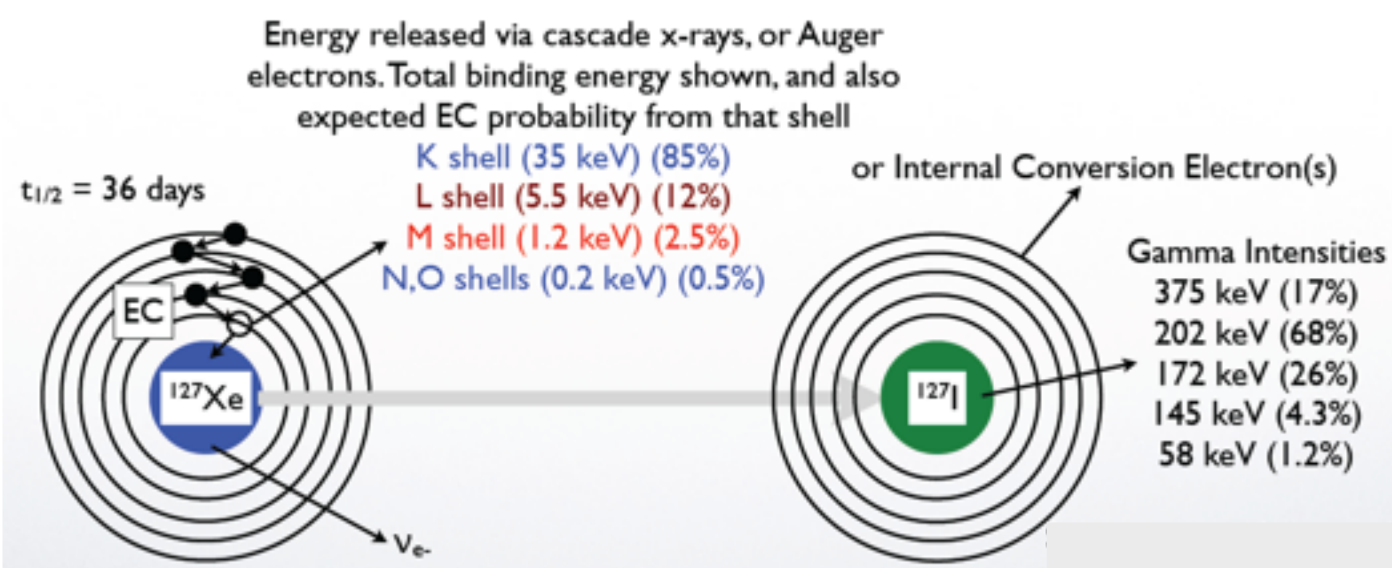


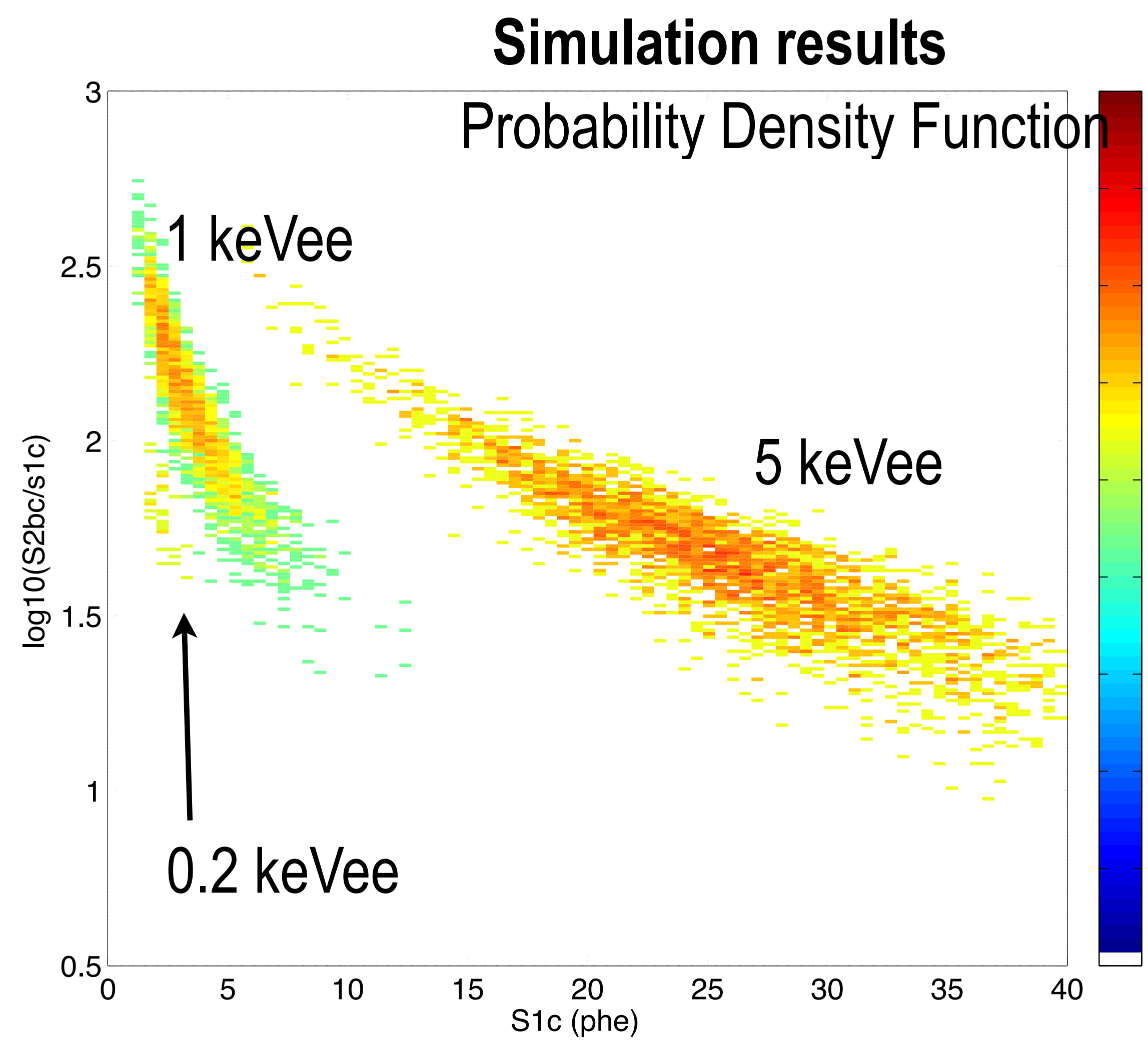
- Full gamma Spectrum , excluding region ±2 cm from top/bottom grids.

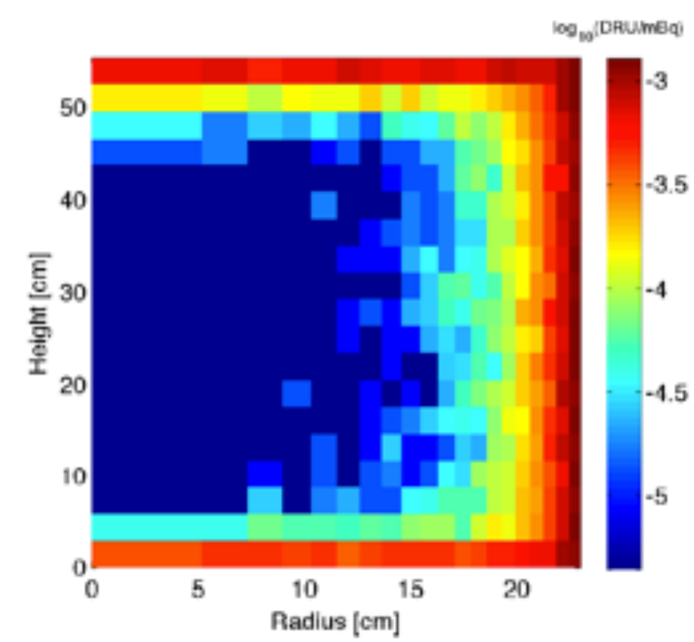
Background From Xe-127

- Electron capture from S-wave orbital:

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

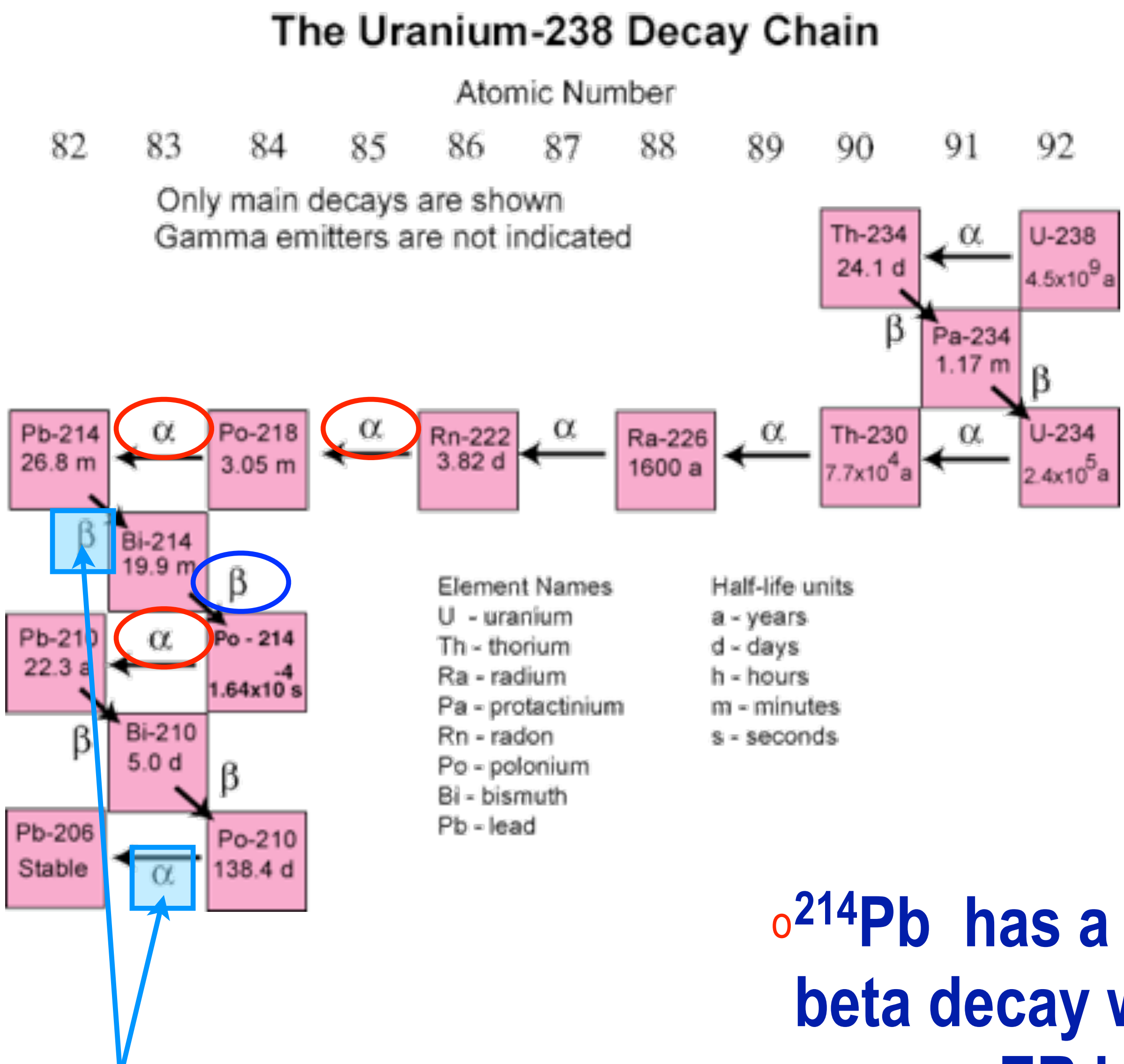


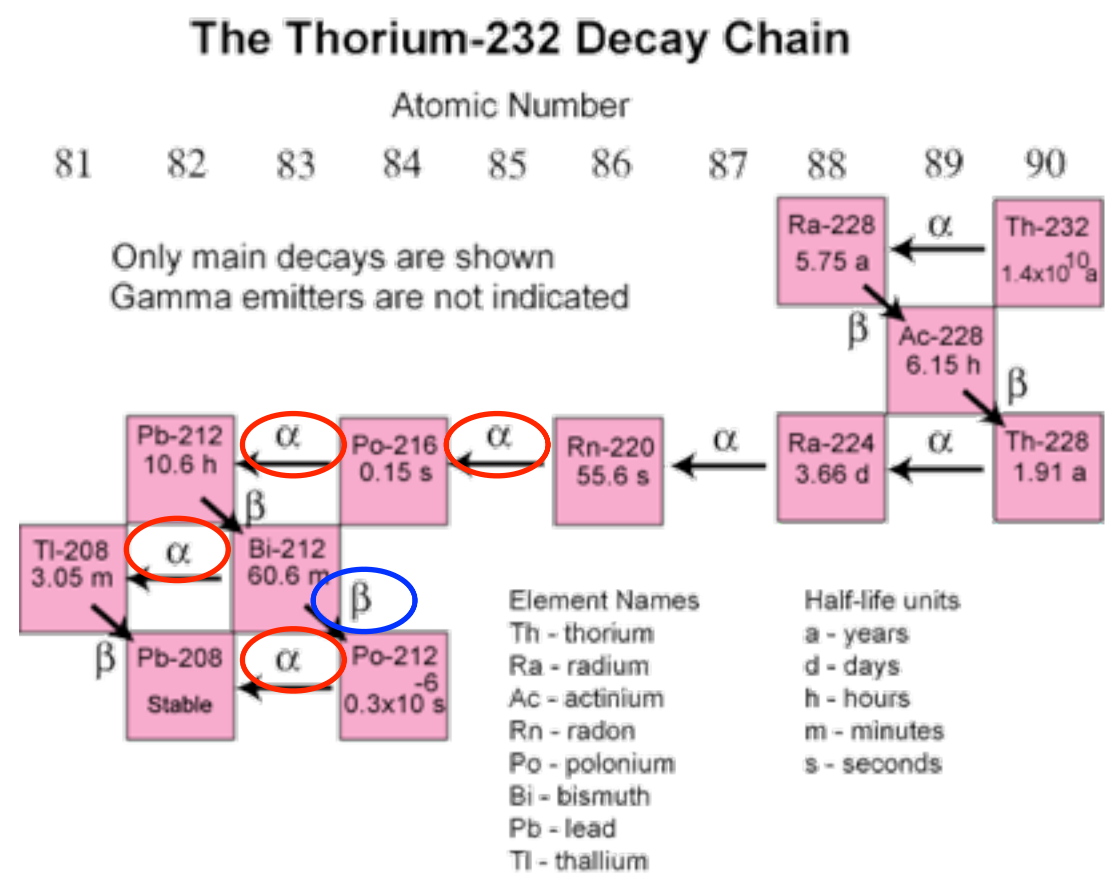




Predict 15 events in WIMP search data

Radon-related backgrounds

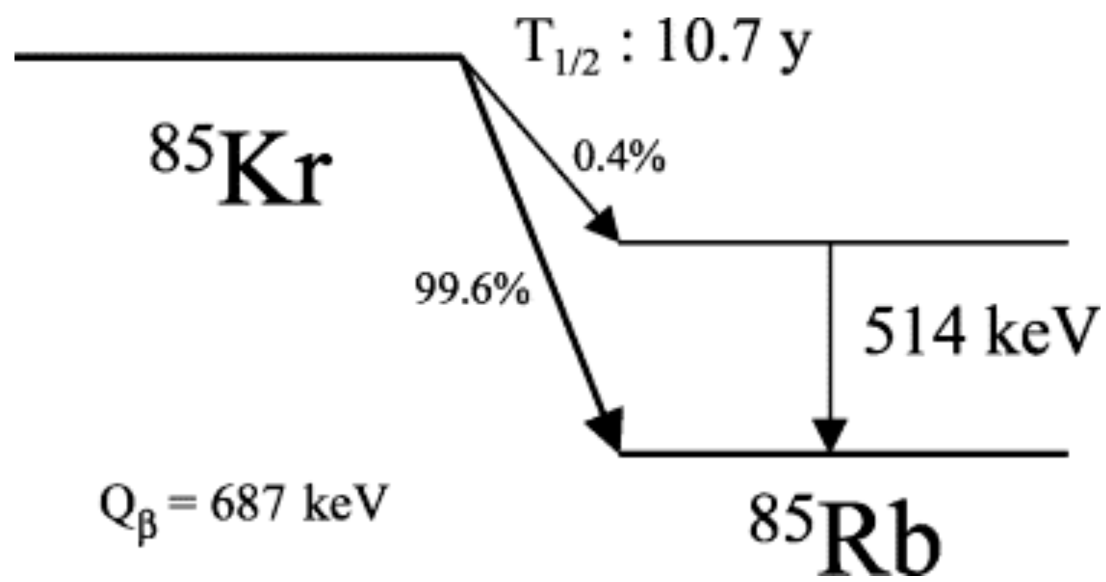




Potential backgrounds in DM search region

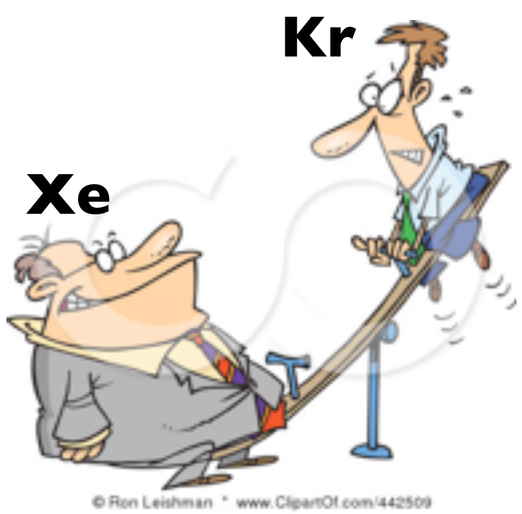
- ^{214}Pb has a half-life of 27 minutes and undergoes “naked” beta decay with 11% probability. This generates a low-energy ER background in the WIMP search region in the fiducial volume.
- ^{214}Bi and ^{212}Bi β decays are vetoed at the 90% level due to the low half-life of heir daughters.

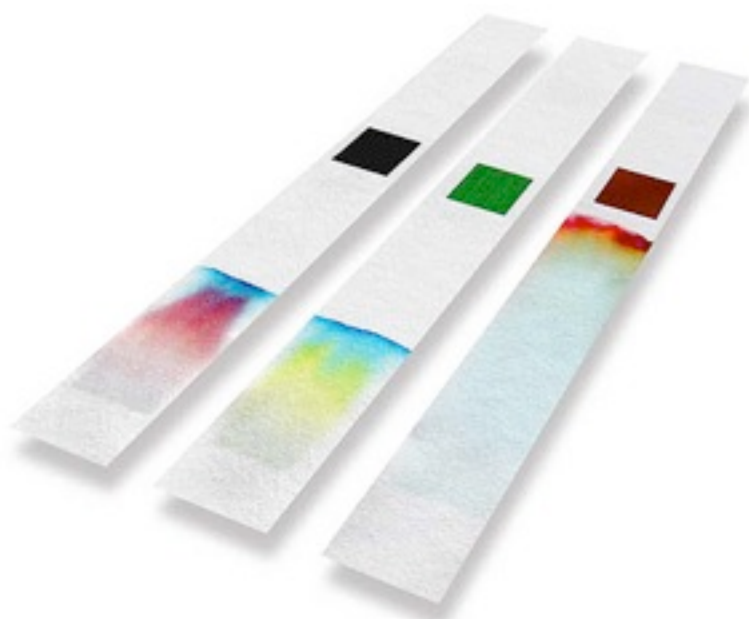
Background From Pb-214/Kr-85

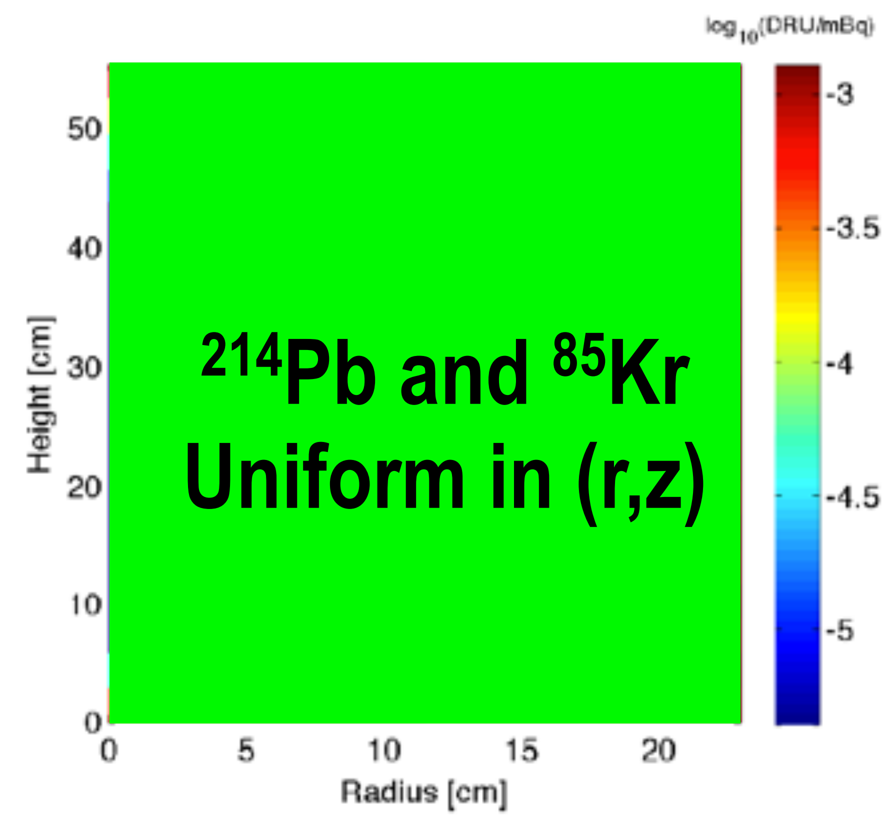


^{85}Kr - beta decay – intrinsic background in liquid Xenon

- Kr concentration reduced from 130 ppb to 3.5 ppt (factor of 30,000) using a chromotographic system developped by the LUX collaboration





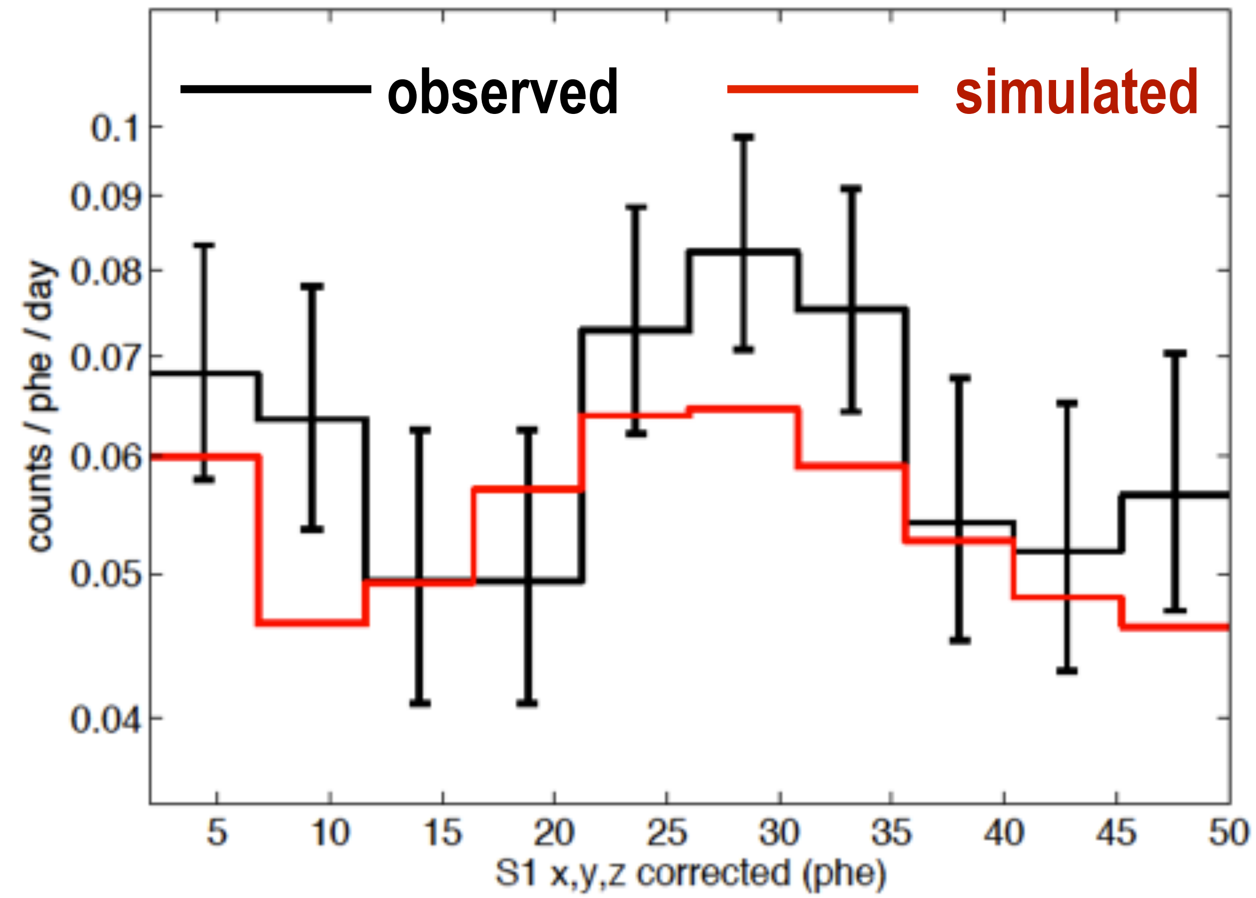


Predict 10 events in WIMP search data

Low Energy Backgrounds

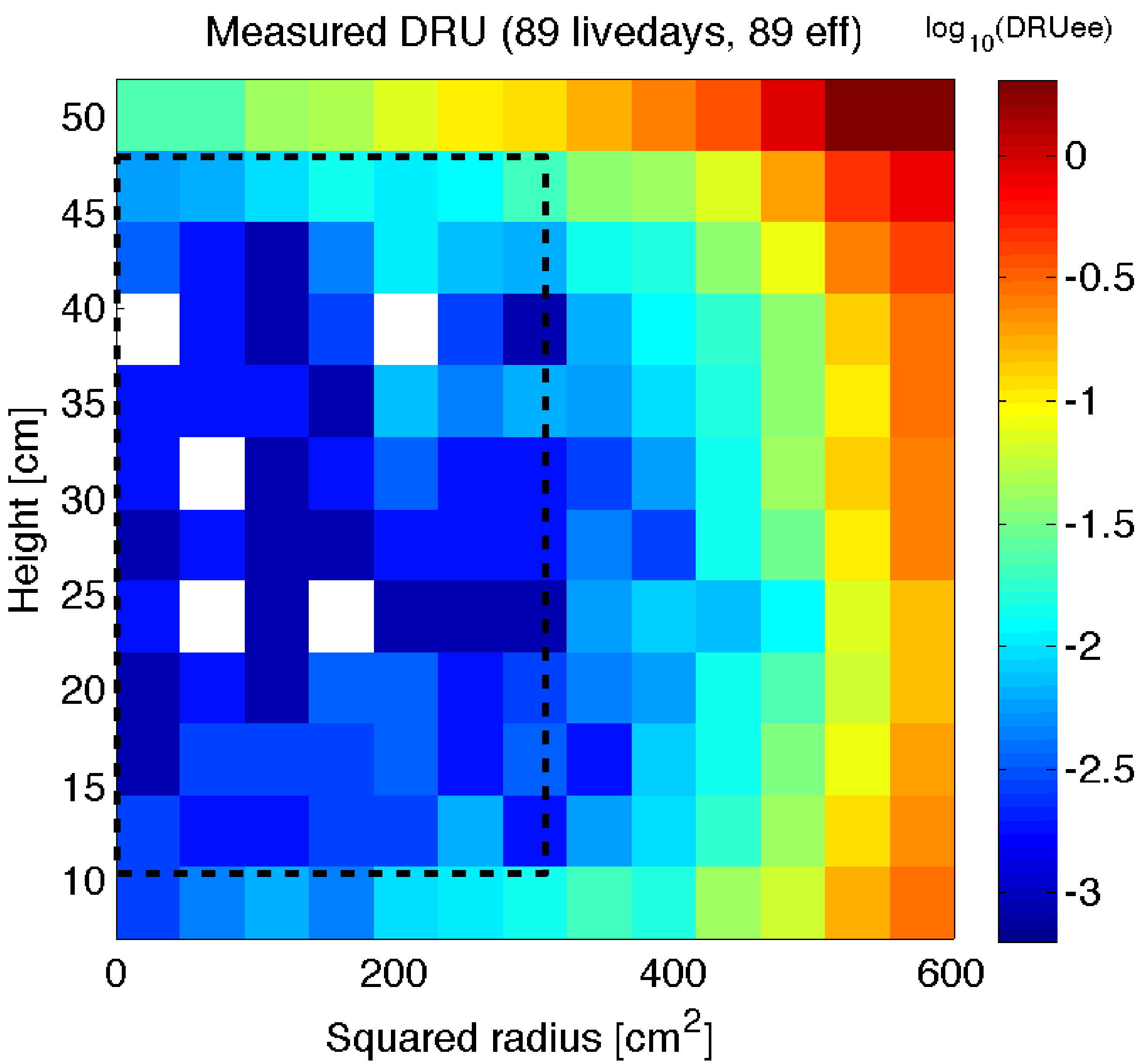
- Monte Carlo predictions of low-energy ER background rates from all significant sources, 118 kg fiducial and 0–8 keVee energy

Background Component	Source	10^{-3} x evts/keVee/kg/day
γ-rays	Internal Components	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{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	$0.17 \pm 0.07_{sys}$
Total Predicted	**Total**	$\mathbf{2.6 \pm 0.2_{stat} \pm 0.4_{sys}}$
Observed	**Total**	$\mathbf{3.6 \pm 0.2_{stat}}$

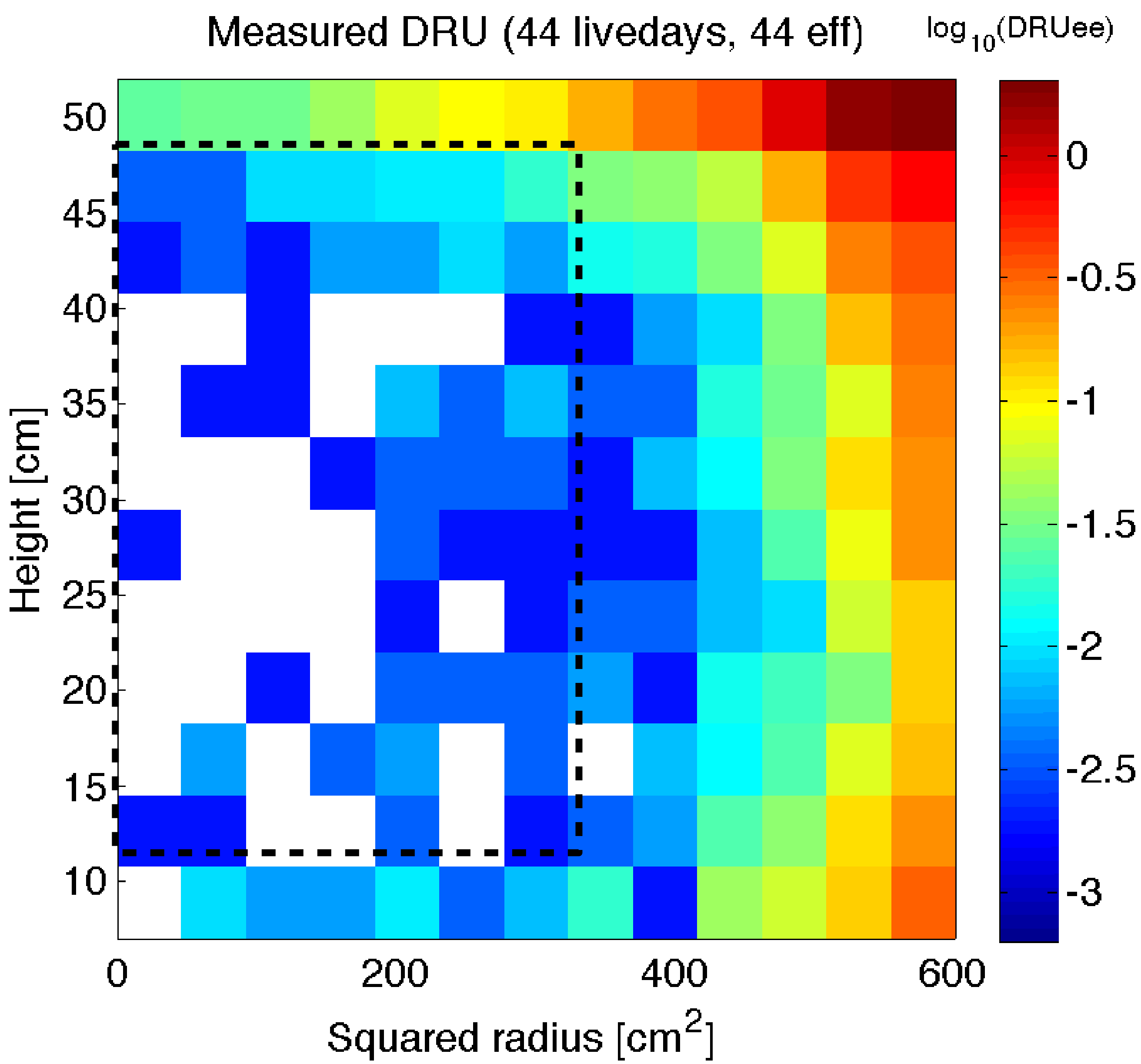


Observed Backgrounds

All the run



Last 44 days



r<18 cm z=7-47 cm

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	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.**
- **Hardware trigger: at least two trig. channels > 8 phe within 2 μs window (16 PMTs per trig. channel)**
  - **> 99% efficient for raw S2 > 200 phe (~8 e^-).**

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

- **Remove periods of live-time when liquid level, gas pressure or grid voltages were out of nominal ranges:**
  - **Less than 1.0 % live-time loss!**

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

- **Exactly 1 S2 and 1 S1 as identified by the pulse finding and classification code:**
  - **Separate S1s from S2s using pulse shape and PMT hit distributions.**
  - **S1s identification includes a two fold PMT coincidence requirement.**

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

- **Accept events with S1 between 2-30 phe (0.9-5.3 keV_{ee}, ~3-25 keV_{nr}):**
  - We impose that at least 2 PMTs are above threshold.
  - 2 phe analysis threshold allows sensitivity down to low WIMP masses. Expected S1 for a 3 keVnr event is 1.94 phe.
  - Upper limit of 30 phe avoids ^{127}Xe 5 keV_{ee} activation.

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

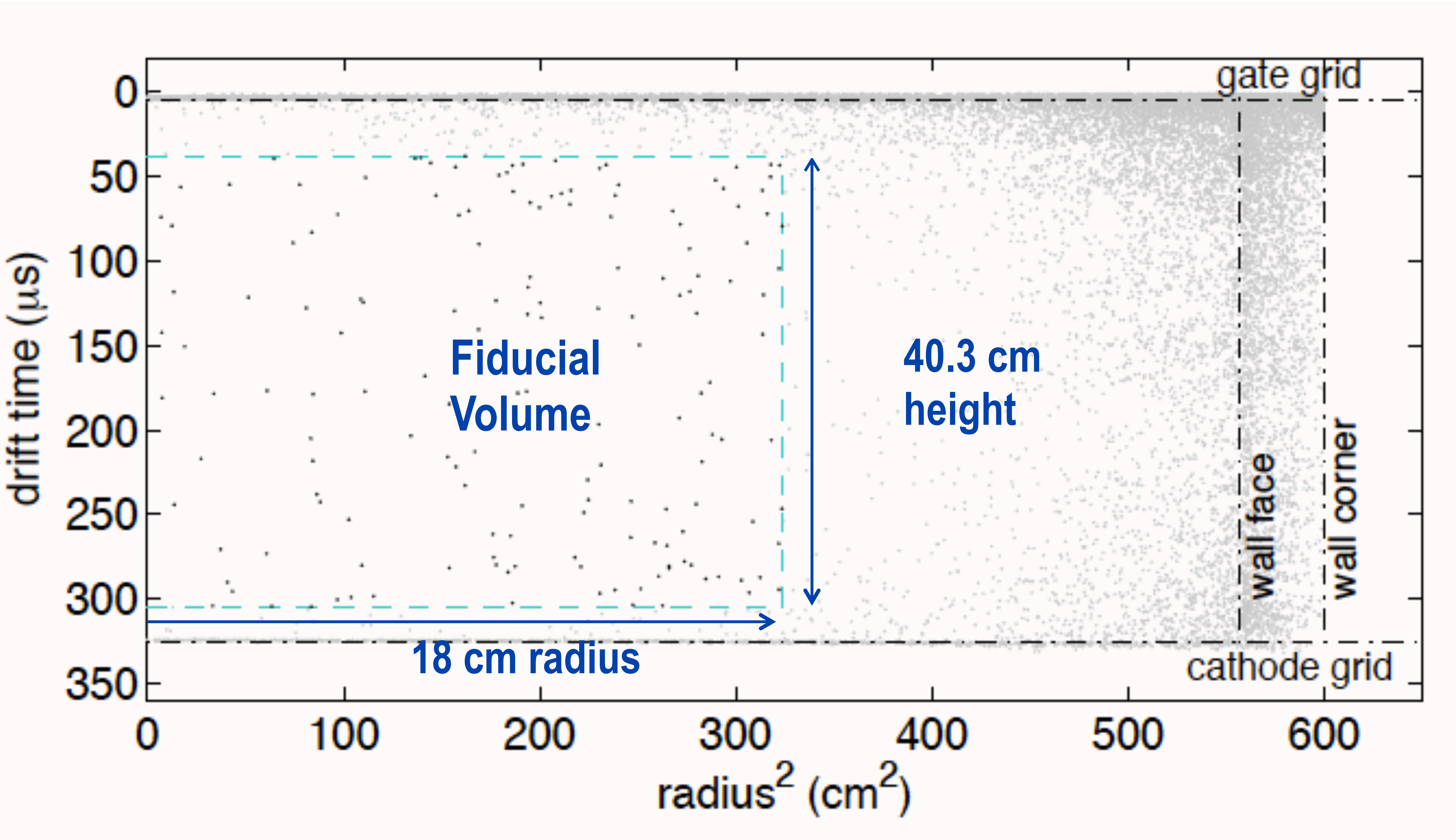
- S2 threshold cuts subdominant to S1:
  - 200 phe ~ 8 single electrons
  - Removes small S2 edge events and single electron events

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

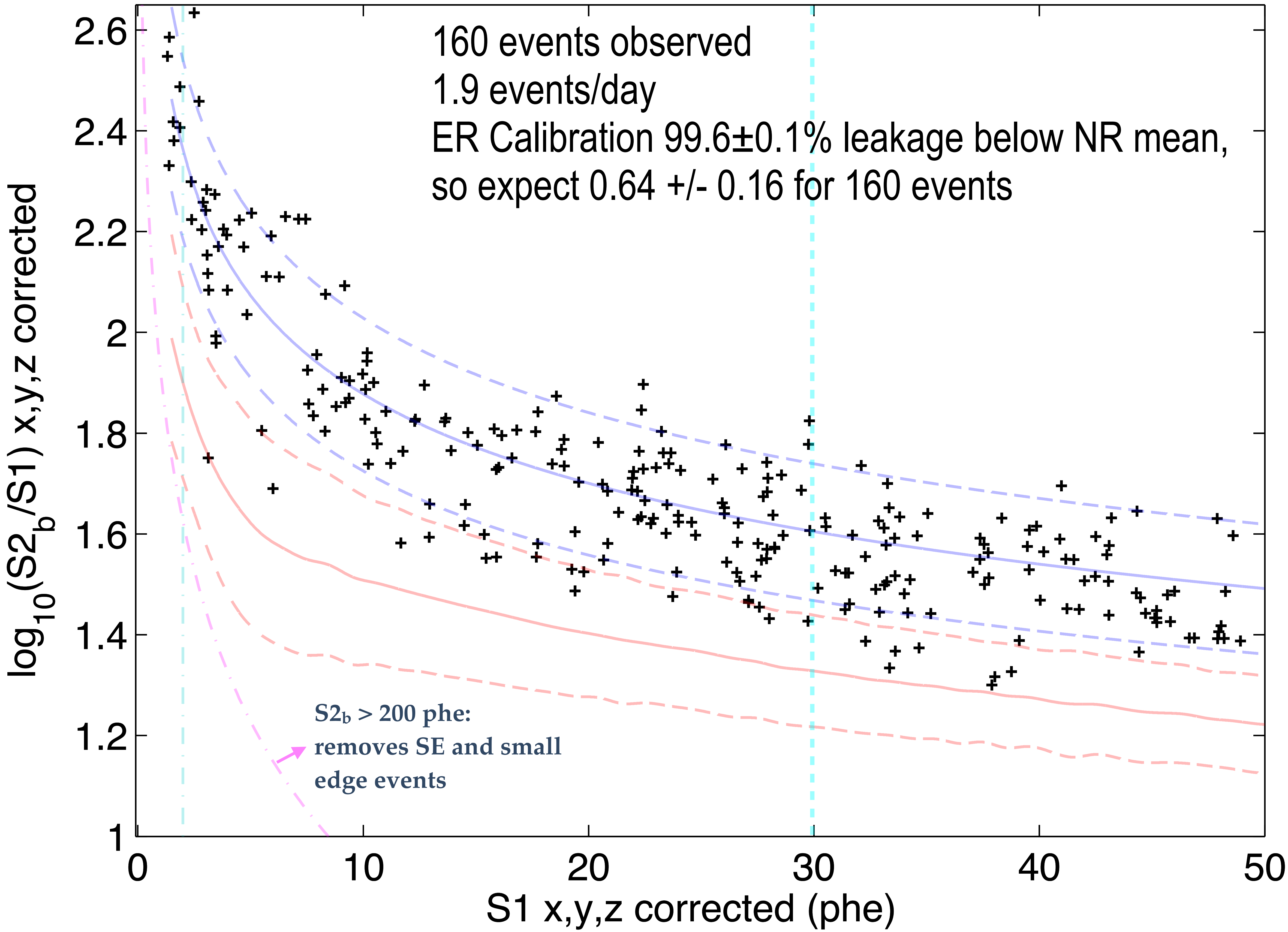
- Require less than 100 phe (< 4 extracted electrons) of additional signal in 1 ms period around S1 and S2 signals:
  - Simple cut to removes additional single electron events in 0.1-1 ms following large S2 signals
  - Only 0.8% hit on live-time

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	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

- **Fiducial Cut: radius < 18 cm, 38<drift time<305 μs, 118.3+-6.5 kg fiducial**
  - Low energy alpha-parent nuclear recoil events generate small S2+S1 events. The radius and drift time cuts were set using population of events which had S1's outside of the WIMP signal search range, but with S2's of a comparable size to lower S1 events in same population. This ensured that position reconstruction for sets were similar, and definition of fiducial was not biased.
  - Cuts also remove corner regions where ER event rates are proportionally very high.



Total mass in the fiducial volume 118 kg


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
S2b > 200 phe:
removes SE and small
edge events
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

Setting the Limit – PRL

- **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.**

Fixed point to test

Nuisance parameters, not fixed

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

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.**

Setting the Limit – the Likelihood

$$\mathcal{L}_{WS} \propto \prod_{i=1}^{\mathcal{N}} \Big[N_s P_s(\boldsymbol{x};\boldsymbol{\sigma},\boldsymbol{\theta_s}) + N_{\text{Compt}} P_{ER}(\boldsymbol{x};\boldsymbol{\theta_{\text{Compt}}})$$

$$+ N_{Xe-127} P_{ER}(\boldsymbol{x};\boldsymbol{\theta_{\text{Xe}-127}}) + N_{\text{Rn}-122} P_{ER}(\boldsymbol{x};\boldsymbol{\theta_{Rn}}) \Big]$$

Discriminant between ER/NR

Energy

Discriminants against external/internal radiation

Observables: **x** = (S1, $\log_{10}$(S2/S1), r, z)

Parameter of interest: N_S

Nuisance parameters: N_{Compt}, $N_{Xe\text{-}127}$, $N_{Rn/Kr\text{-}85}$

Gaussian constrain to within 30% of the predicted rates

Modeling The Signal

from the nuclear band parametrization

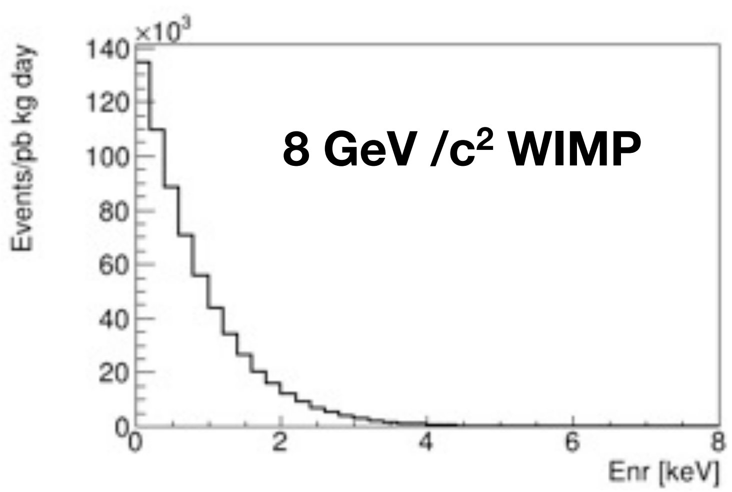
P_s is uniform in r^2 and z

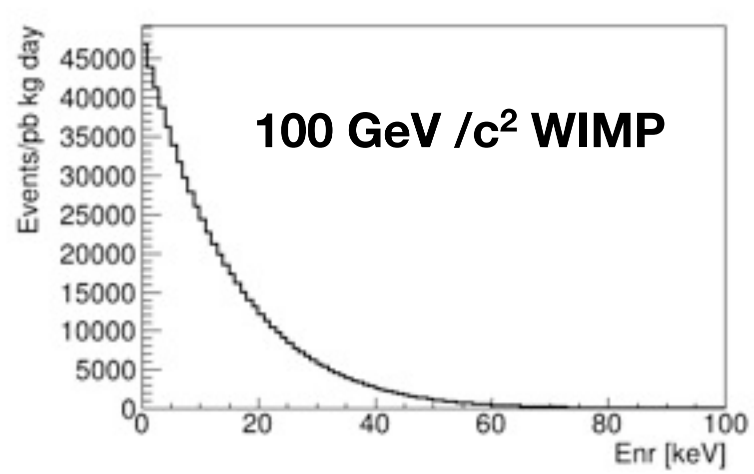
$$P_s(\boldsymbol{x};\boldsymbol{\sigma},\boldsymbol{\theta_s}) = \boxed{P_{NR}(\log_{10}(S2/S1)\,|S1)}\boxed{P_s(E_{NR}(S1))}\boxed{P_s(r)P_s(z)}$$

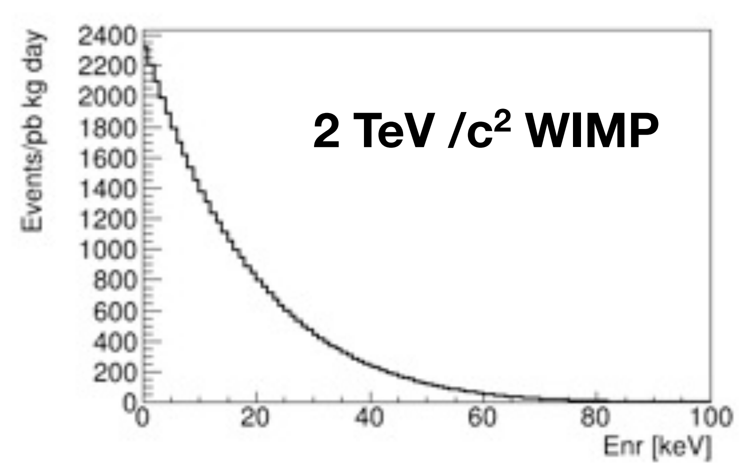
contains the WIMP recoil energy spectrum

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

WIMP spectrum (we used the standard!)

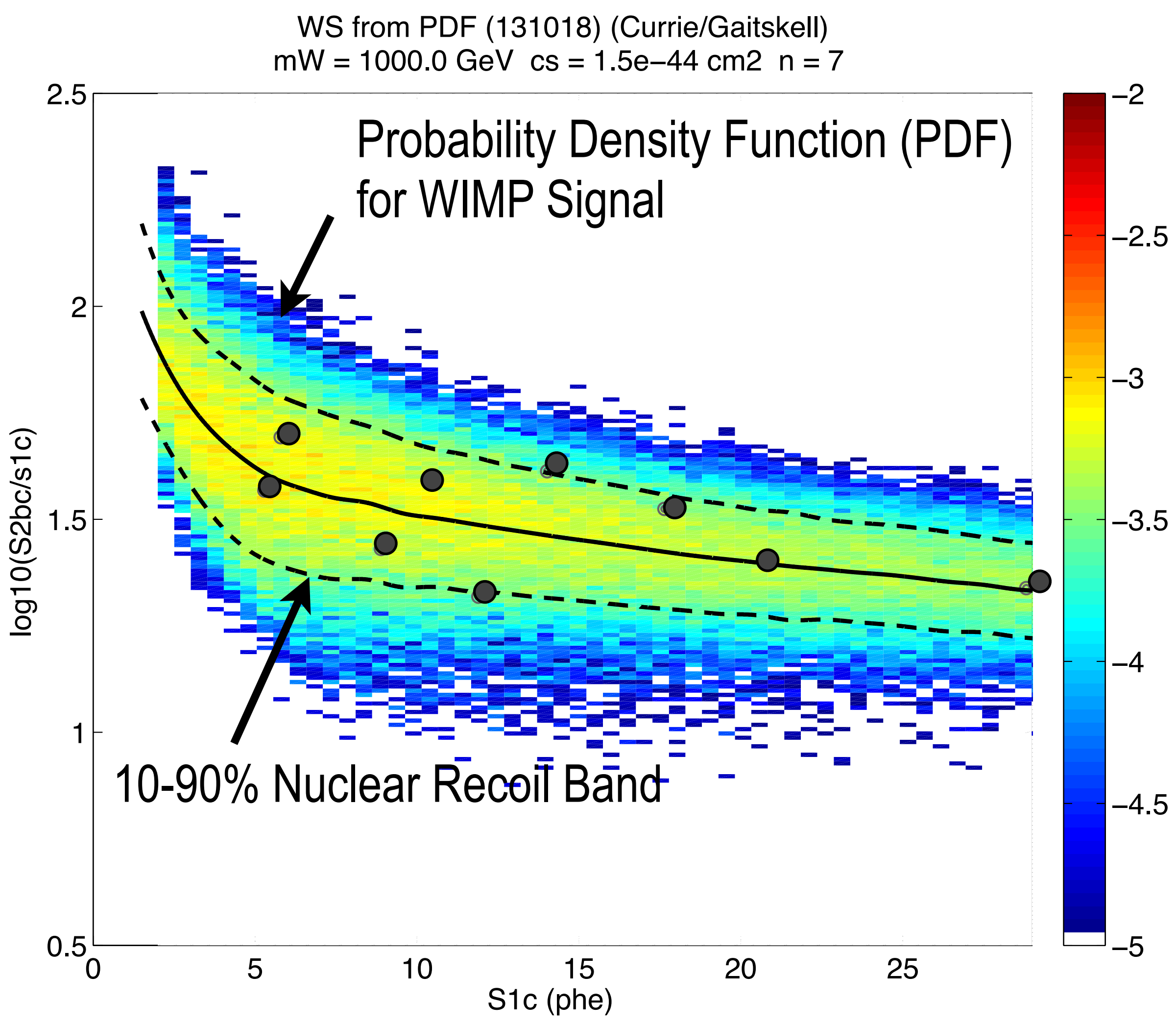


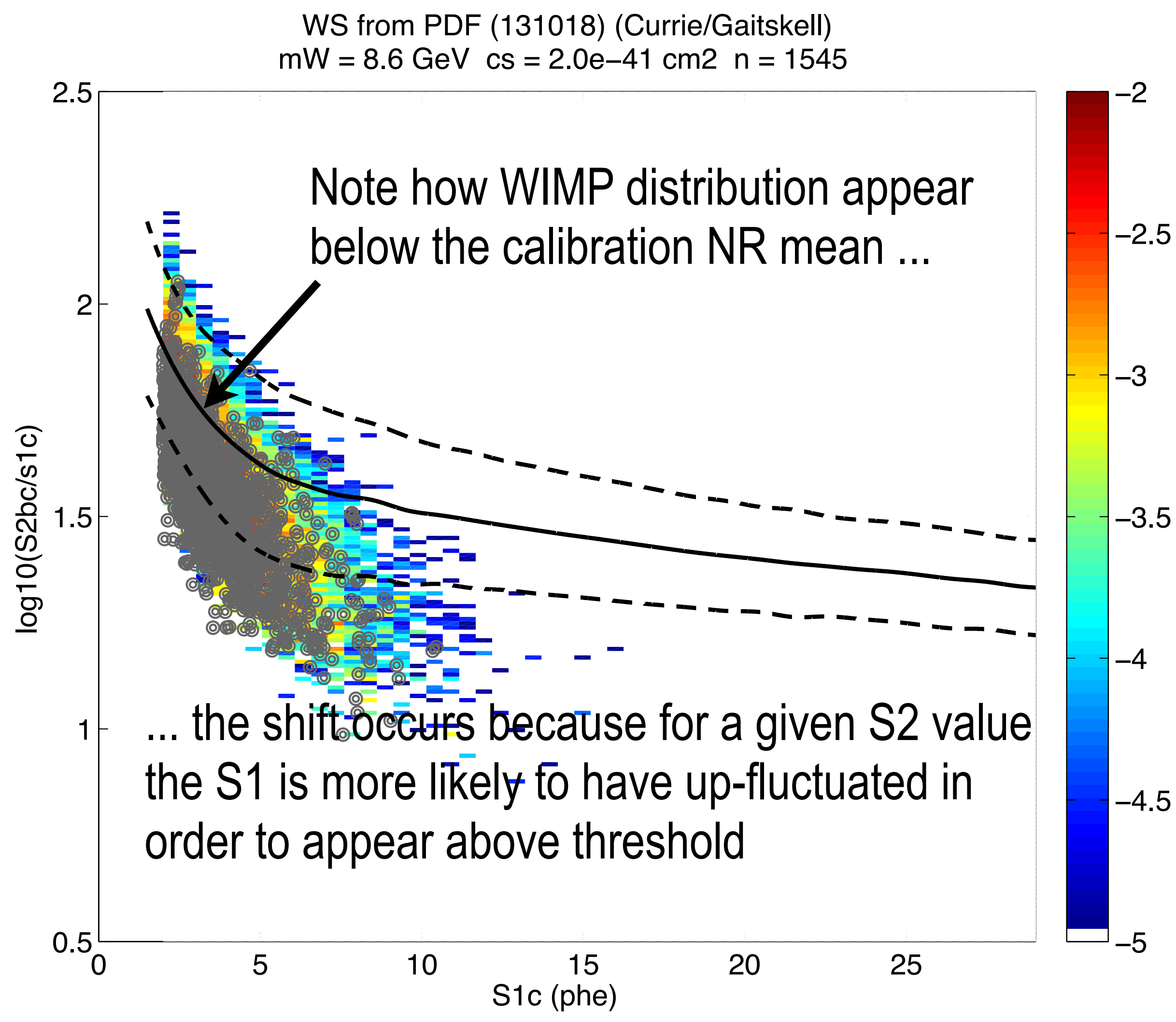




Setting the Limit – The Signal

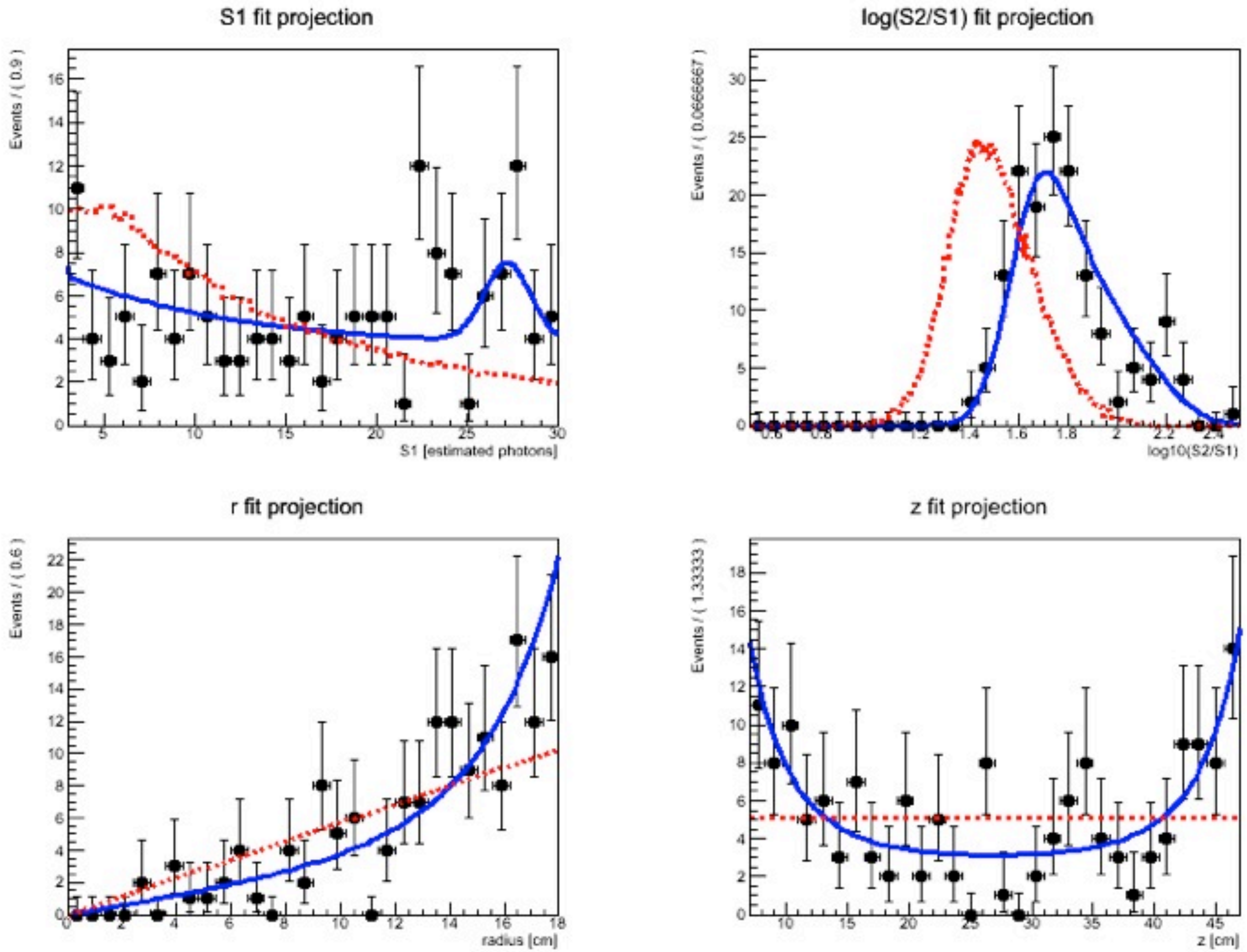
- **For a 1000 GeV WIMP and cross section at the existing XENON100 90% CL Sensitivity 1.9x10^{-44} cm^2**
  - **expect 9 WIMPs in LUX search**
- **For 8.6 GeV WIMP at 2.0×10^{-41} cm^2, CDMS II Si (2012) 90% CL:**
  - **expect 1550 WIMPs in LUX search**





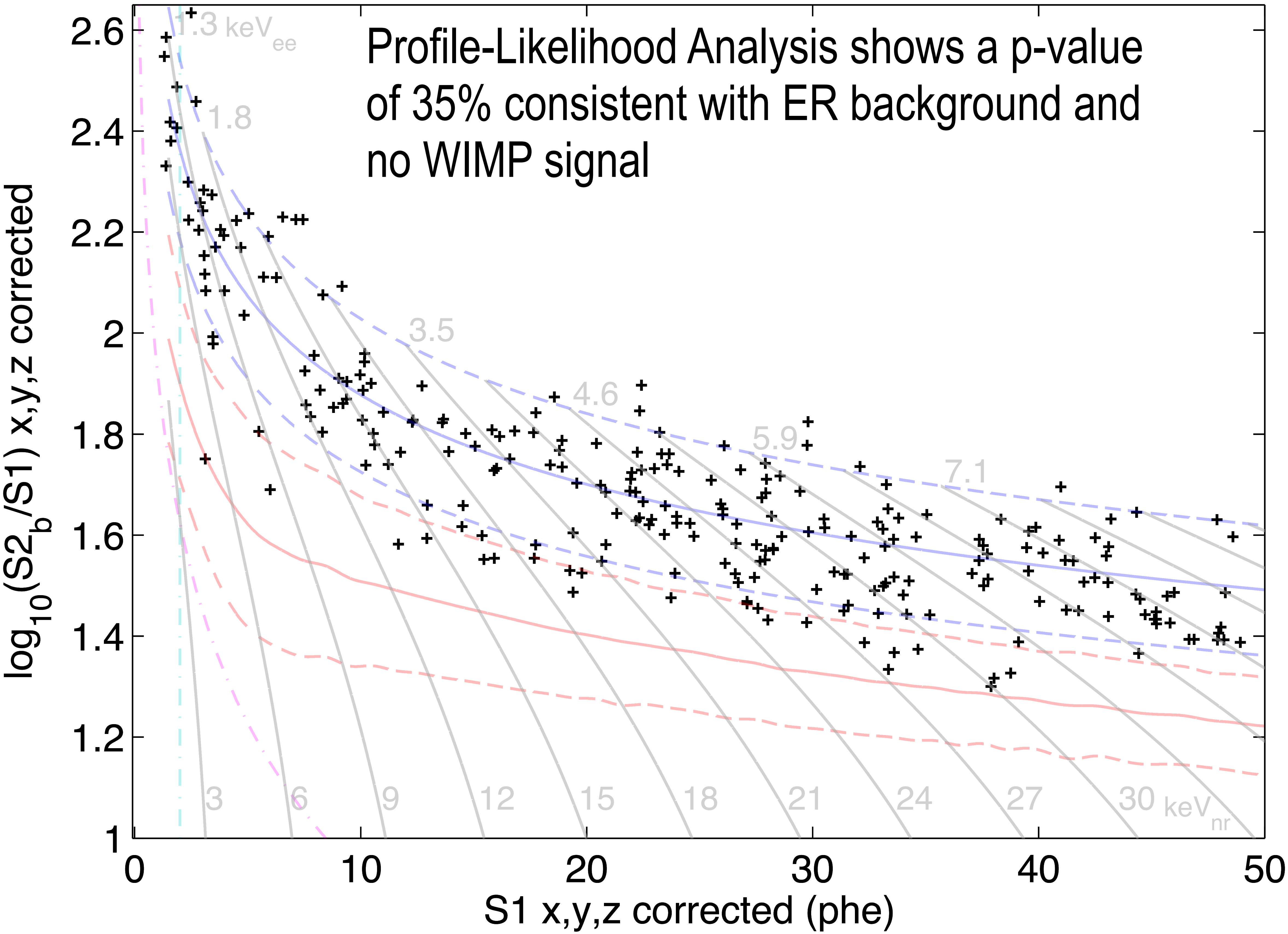
PDF assumes Standard Milky Way Halo parameters as described in Savage, Freese, Gondolo (2006) v_0=220 km/s, v_{escape} = 544 km/s, ρ_0 = 0.3 GeV/c^2, v_{earth} = 245 km/s.

Fit Projections

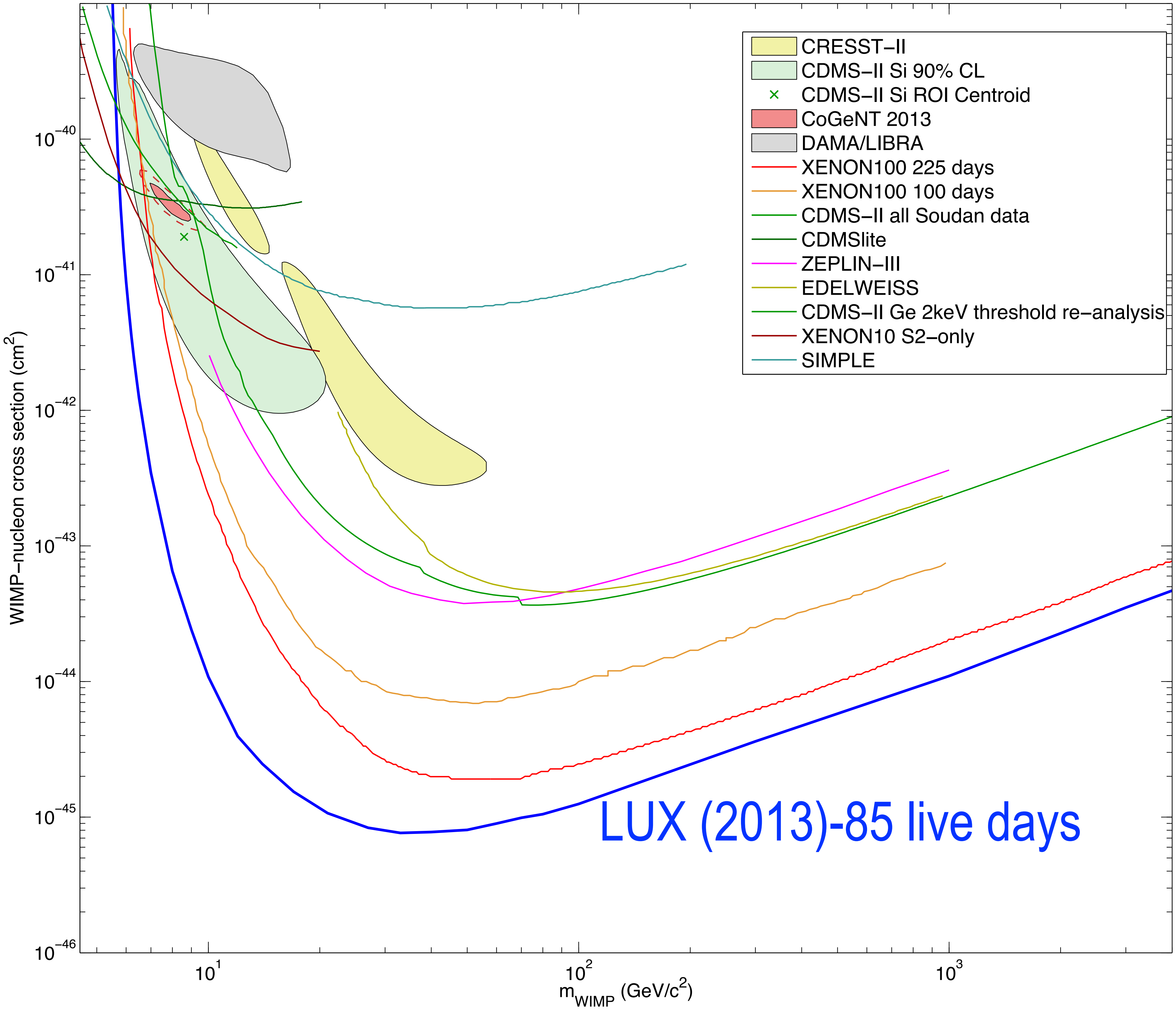


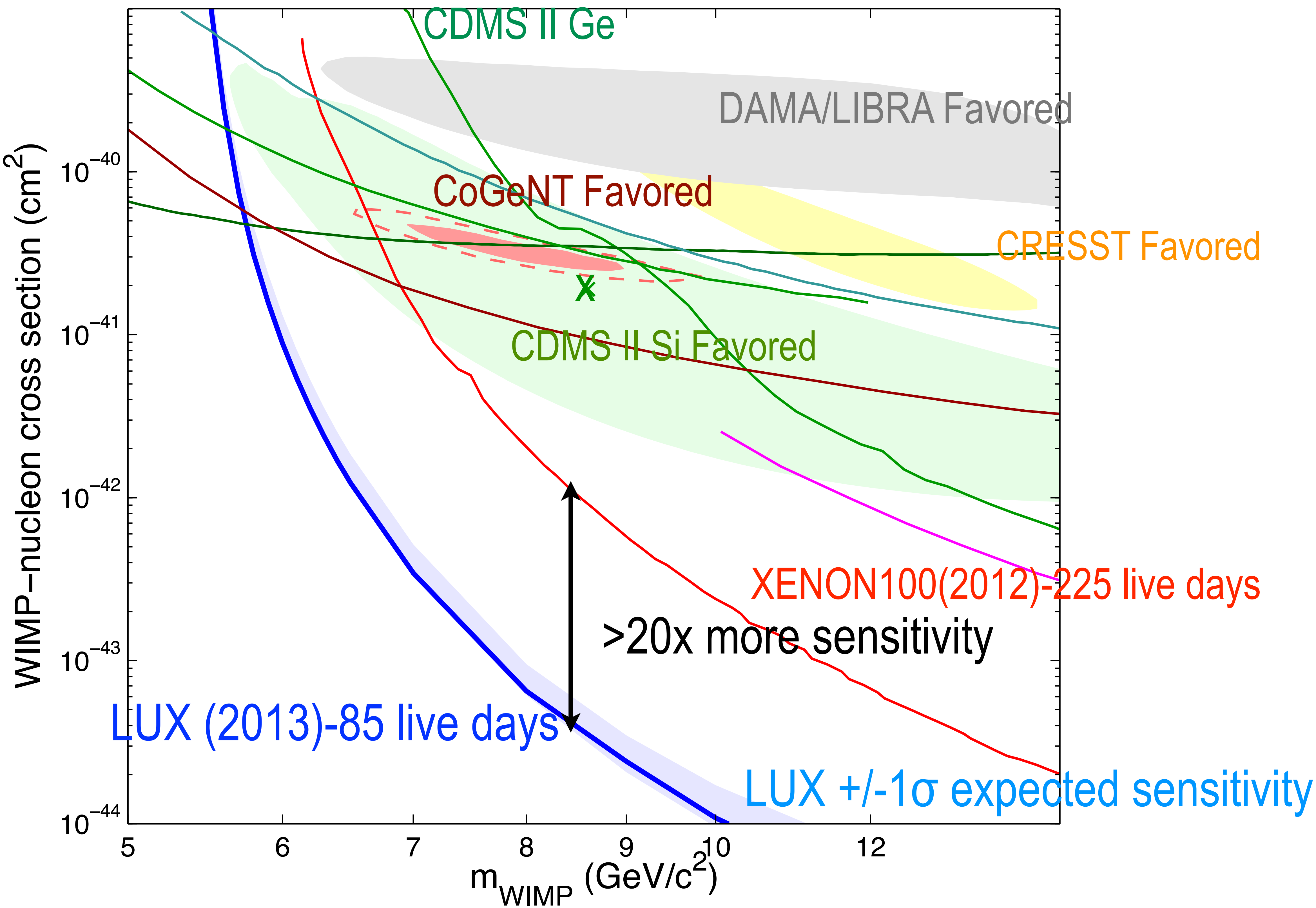
Only background

100 GeV WIMP Signal


Profile-Likelihood Analysis shows a p-value of 35% consistent with ER background and no WIMP signal
1.3 keV$_{ee}$
1.8
3.5
4.6
5.9
7.1
3
6
9
12
15
18
21
24
27
30 keV$_{nr}$
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
10
20
30
40
50
$\log_{10}(S2_b/S1)$ x,y,z corrected
S1 x,y,z corrected (phe)

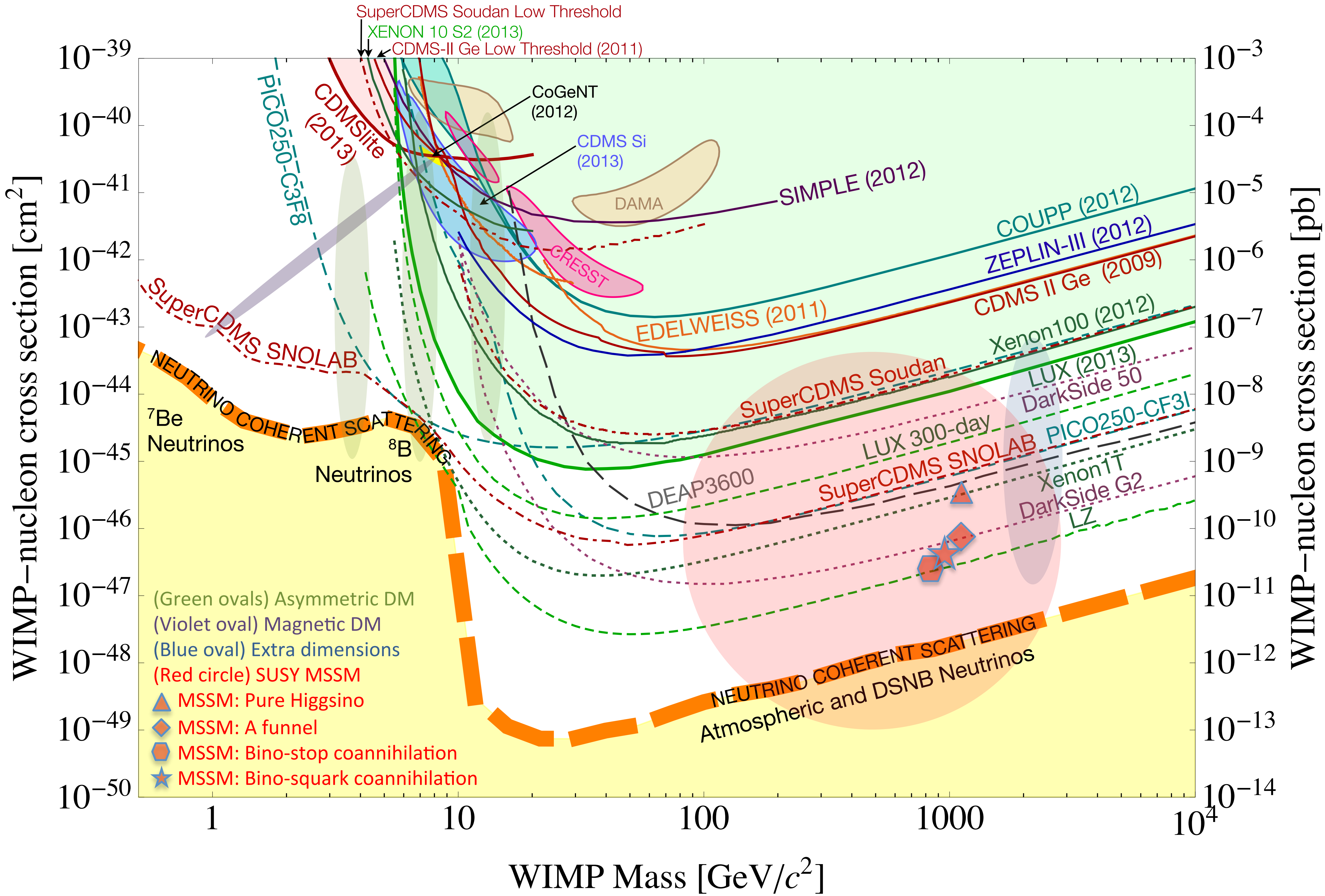
Spin-independent sensitivity plots

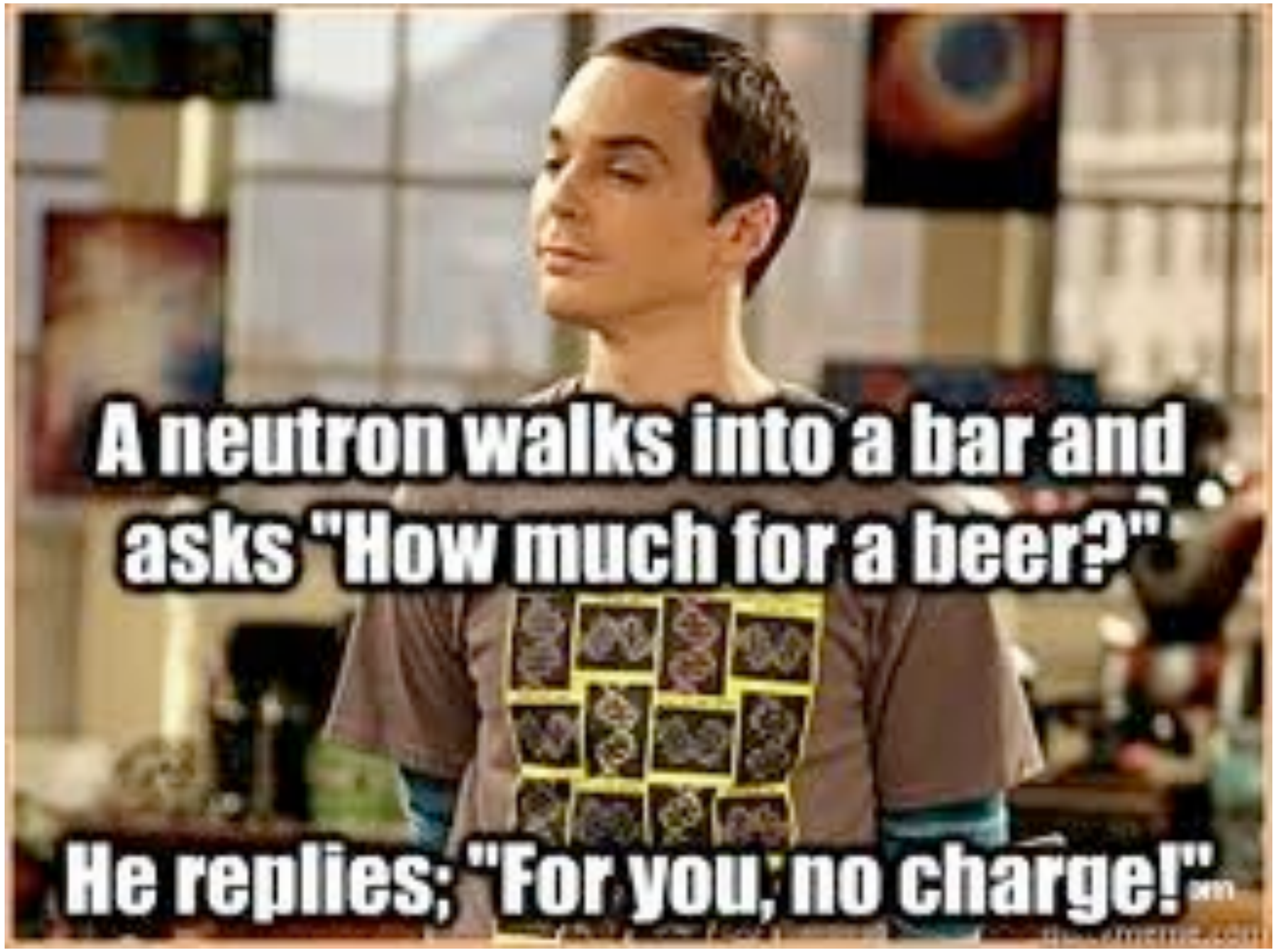




Low-mass WIMPs fully excluded

Current WIMP Cross-section Limits

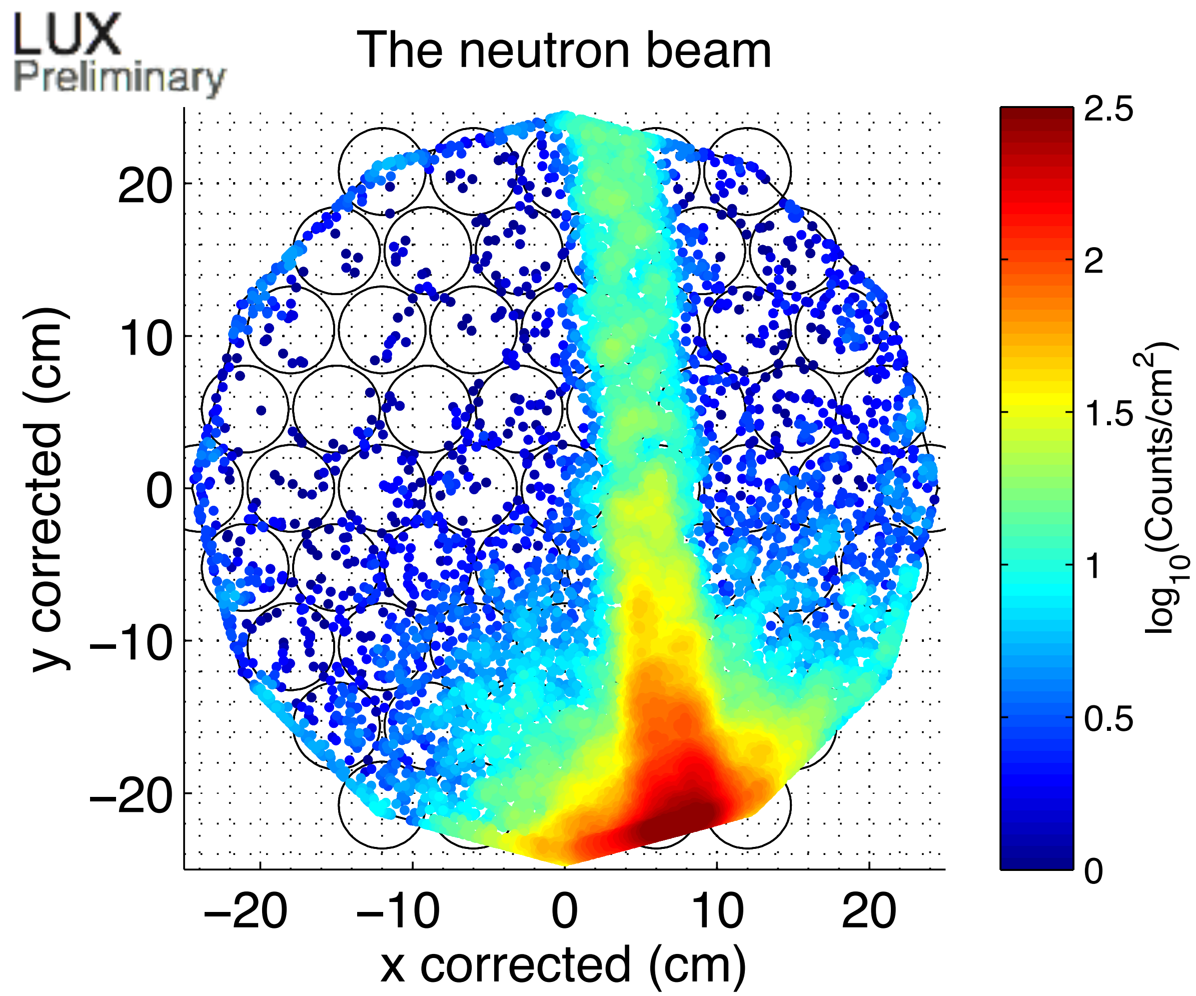


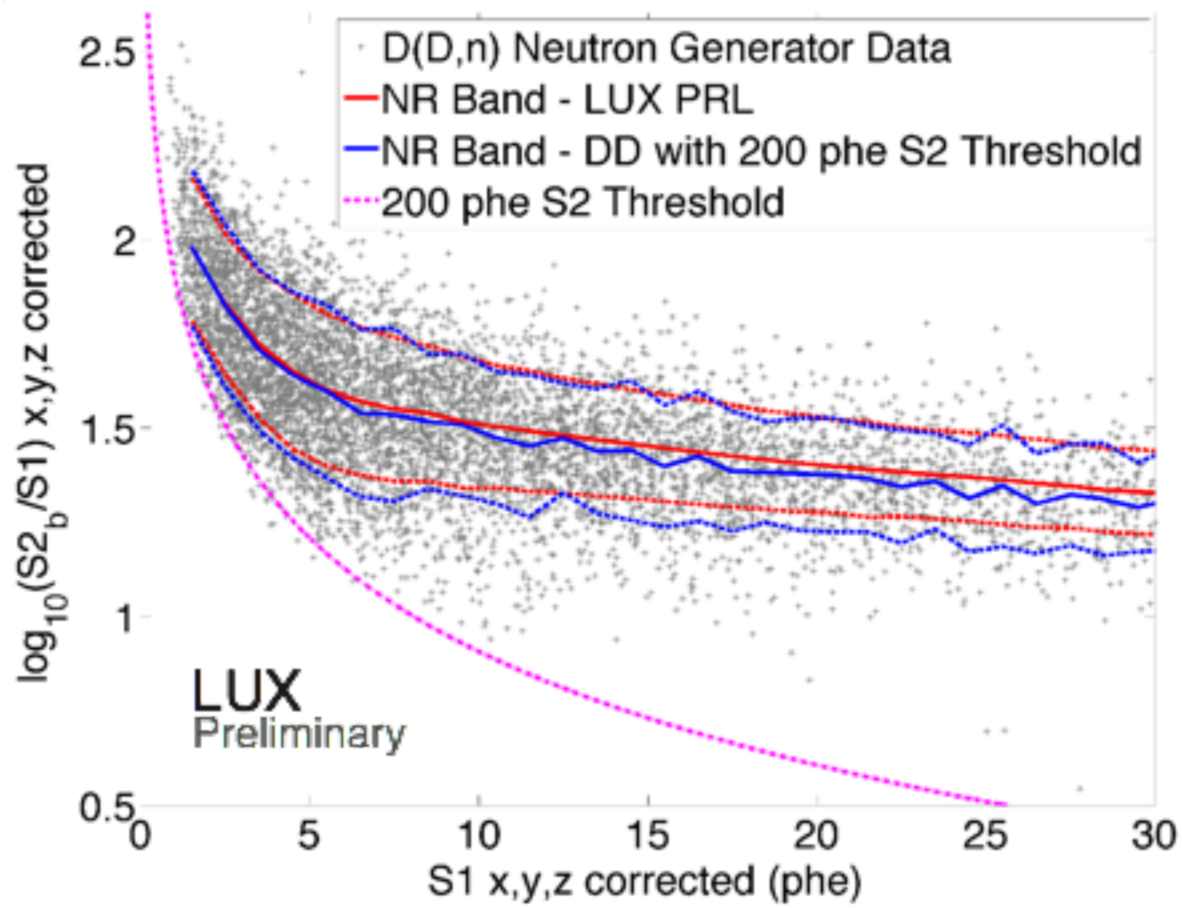


DD Calibrations
(LUX Preliminary Results)

Deuterium-Deuterium Beam Calibrations

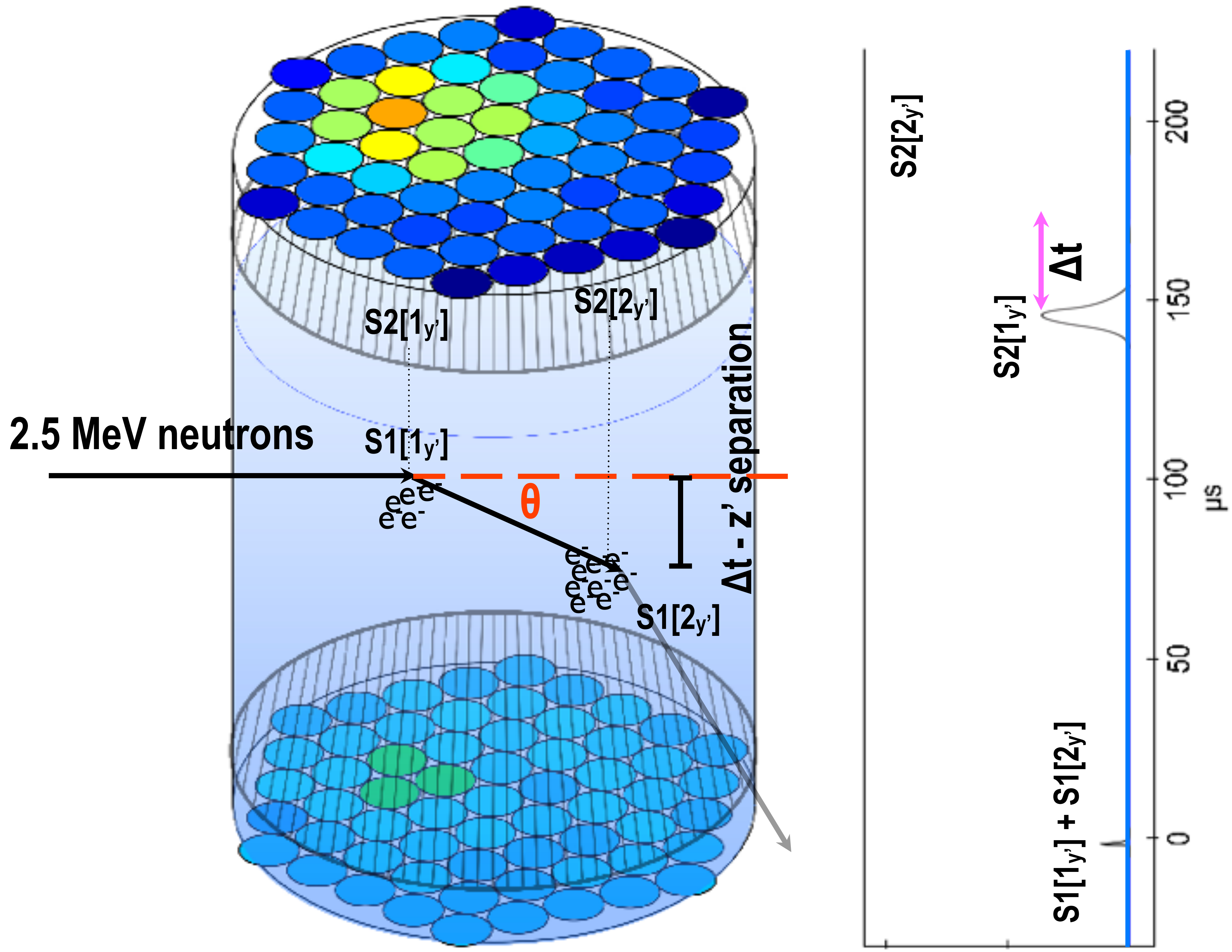
- **Neutron generator/beam pipe assembly aligned 15.5 cm below liquid level in LUX active region to maximize usable single / double scatters**
  - **Beam Energy 2.5 MeV (elastic scattering dominant)**
  - **Beam leveled to ~1 degree**
  - **105.5 live hours of neutron tube data used for analysis**
  - **Complete Geant4 LUXSim + NEST simulation of D-D neutron calibration**





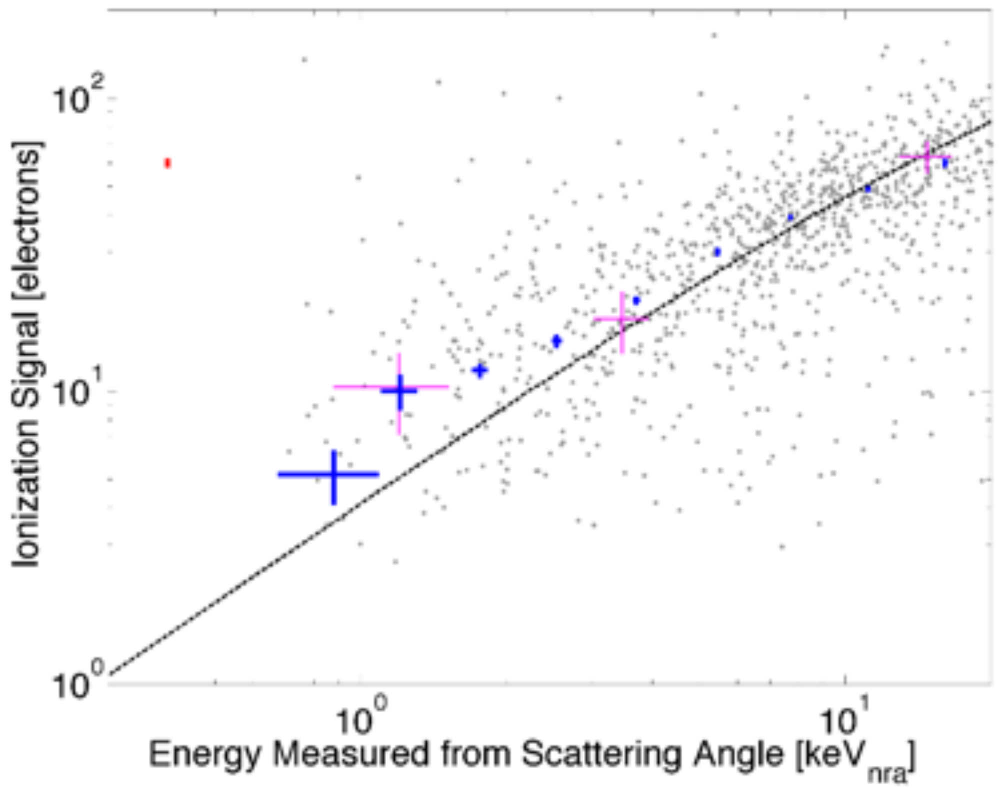
Agrees with NR Band used in LUX 2014 PRL Accepted Dark Matter Result arXiv:1310.8214v2

Deuterium-Deuterium Double-scattering events

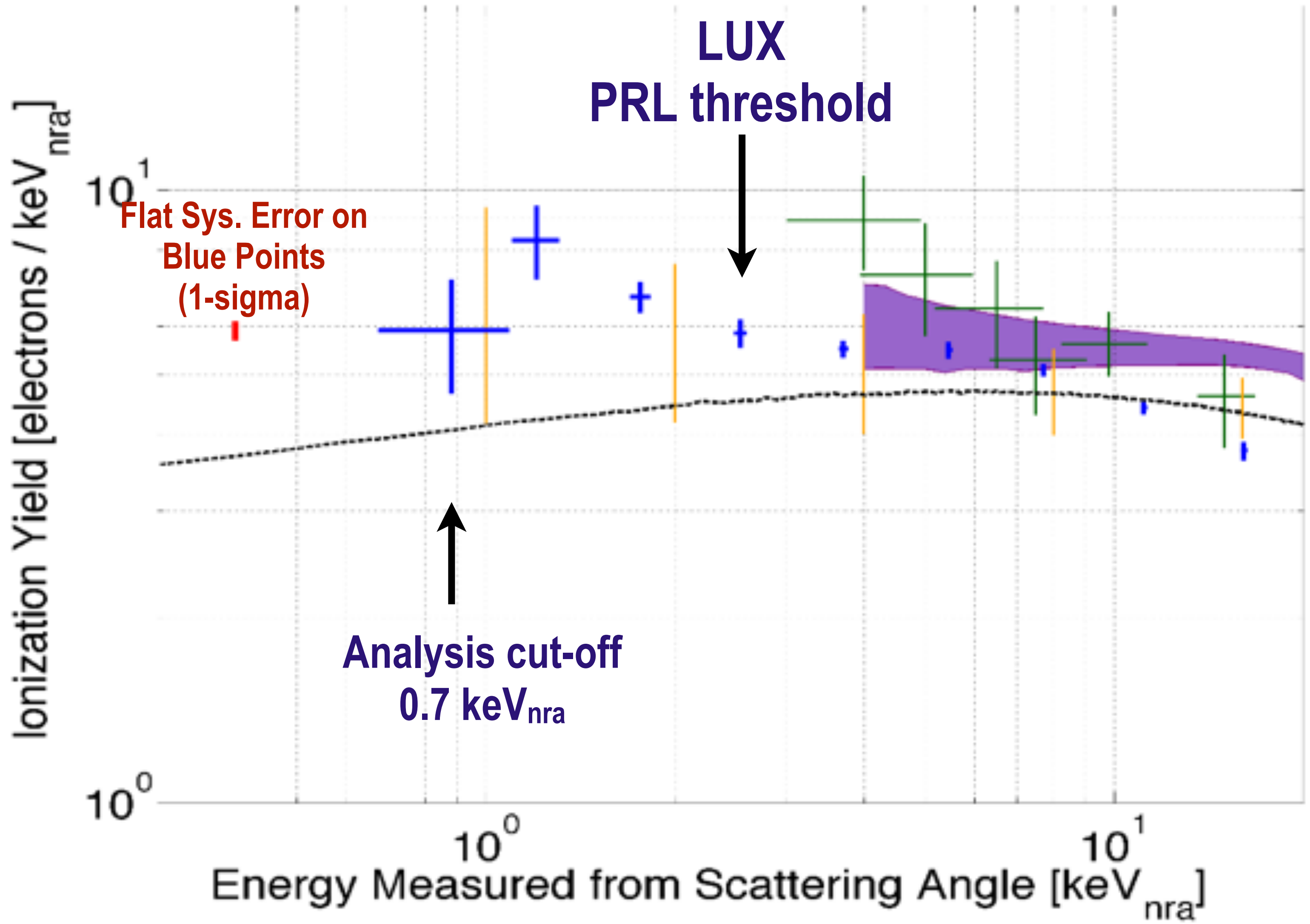


$$E_r = E_n \frac{4 m_n m_{\mathrm{Xe}}}{(m_n + m_{\mathrm{Xe}})^2} \frac{1 - \cos\theta}{2}$$

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)

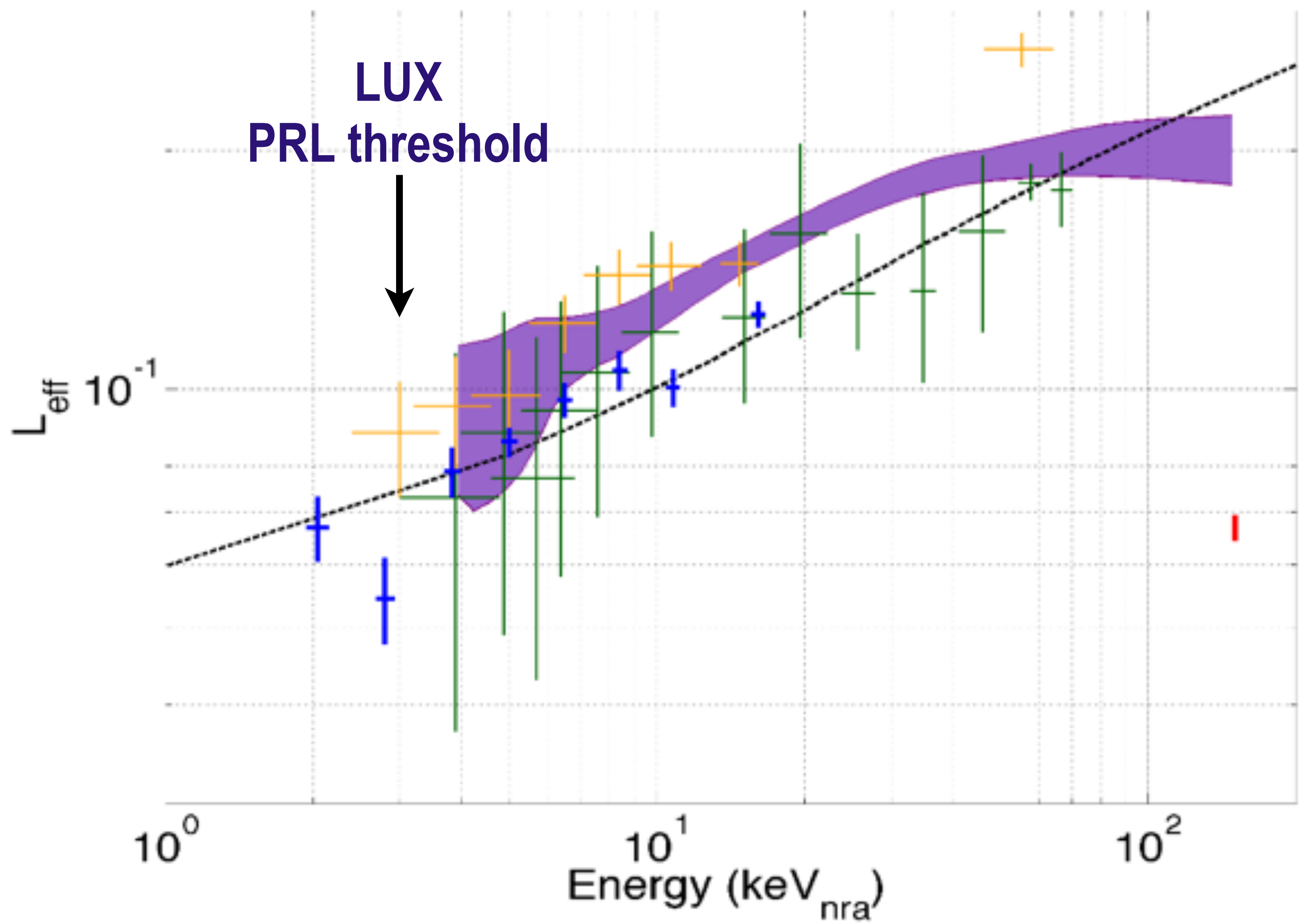
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

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)

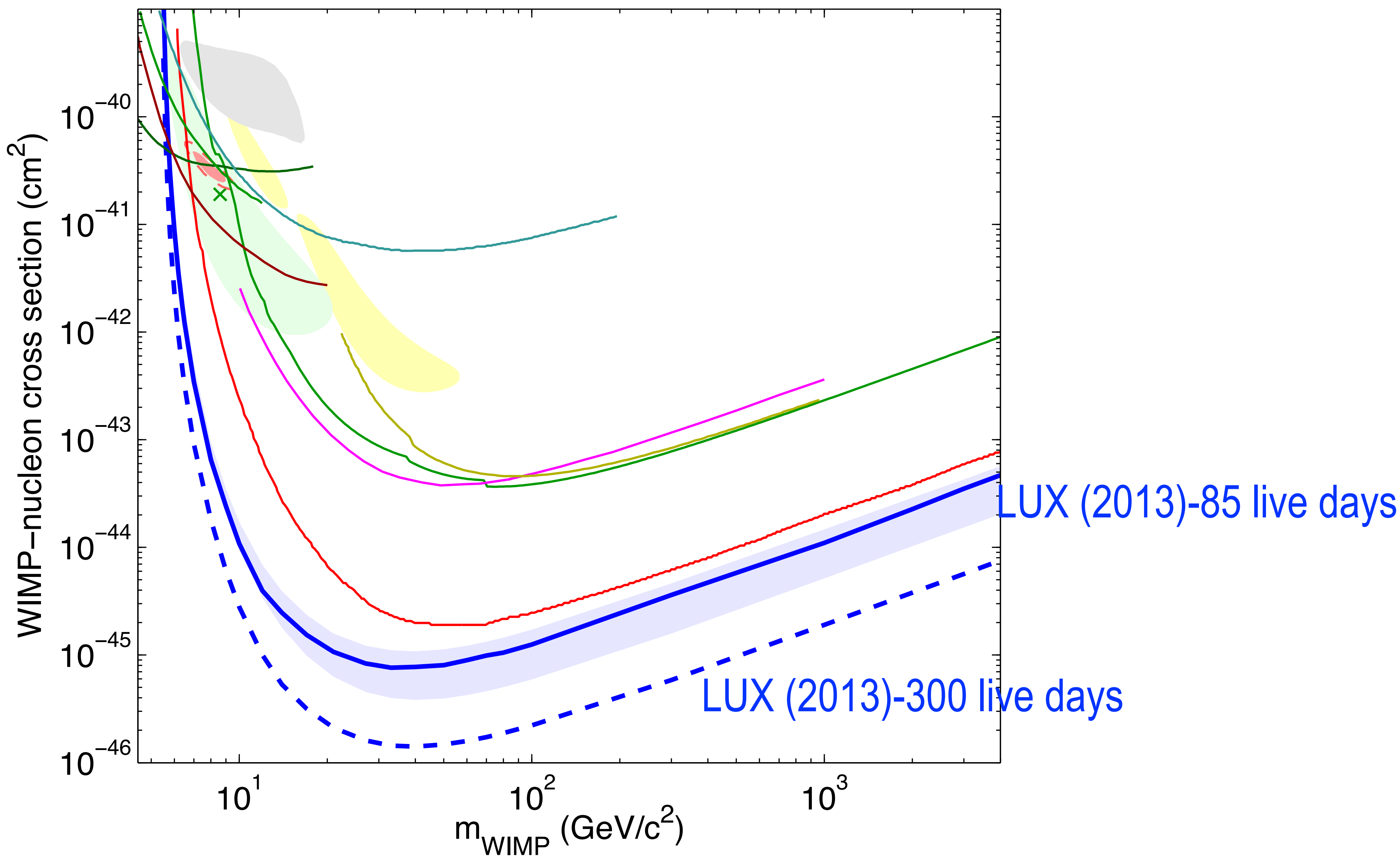
Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)

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

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

Future Plans

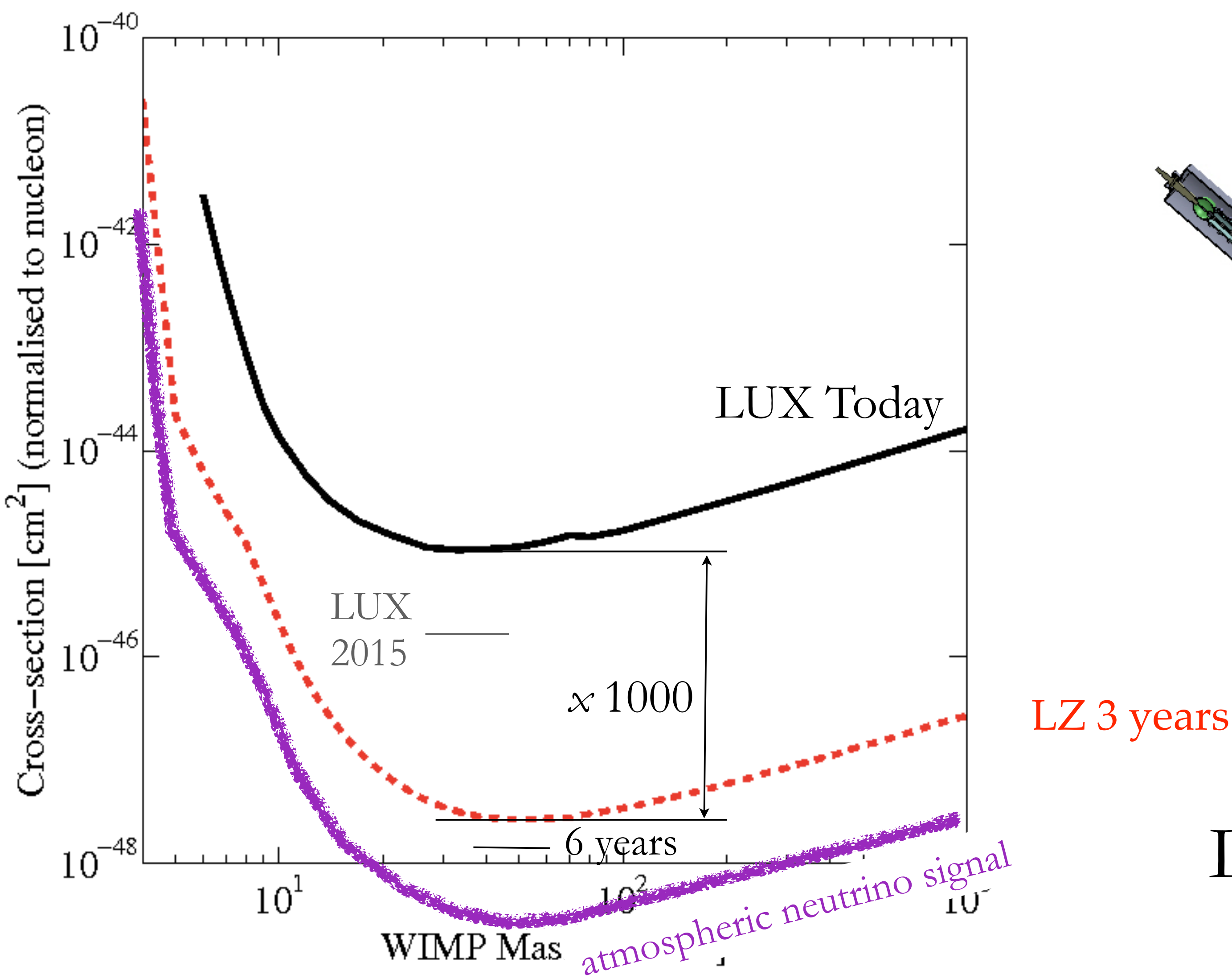
LUX 300 day run



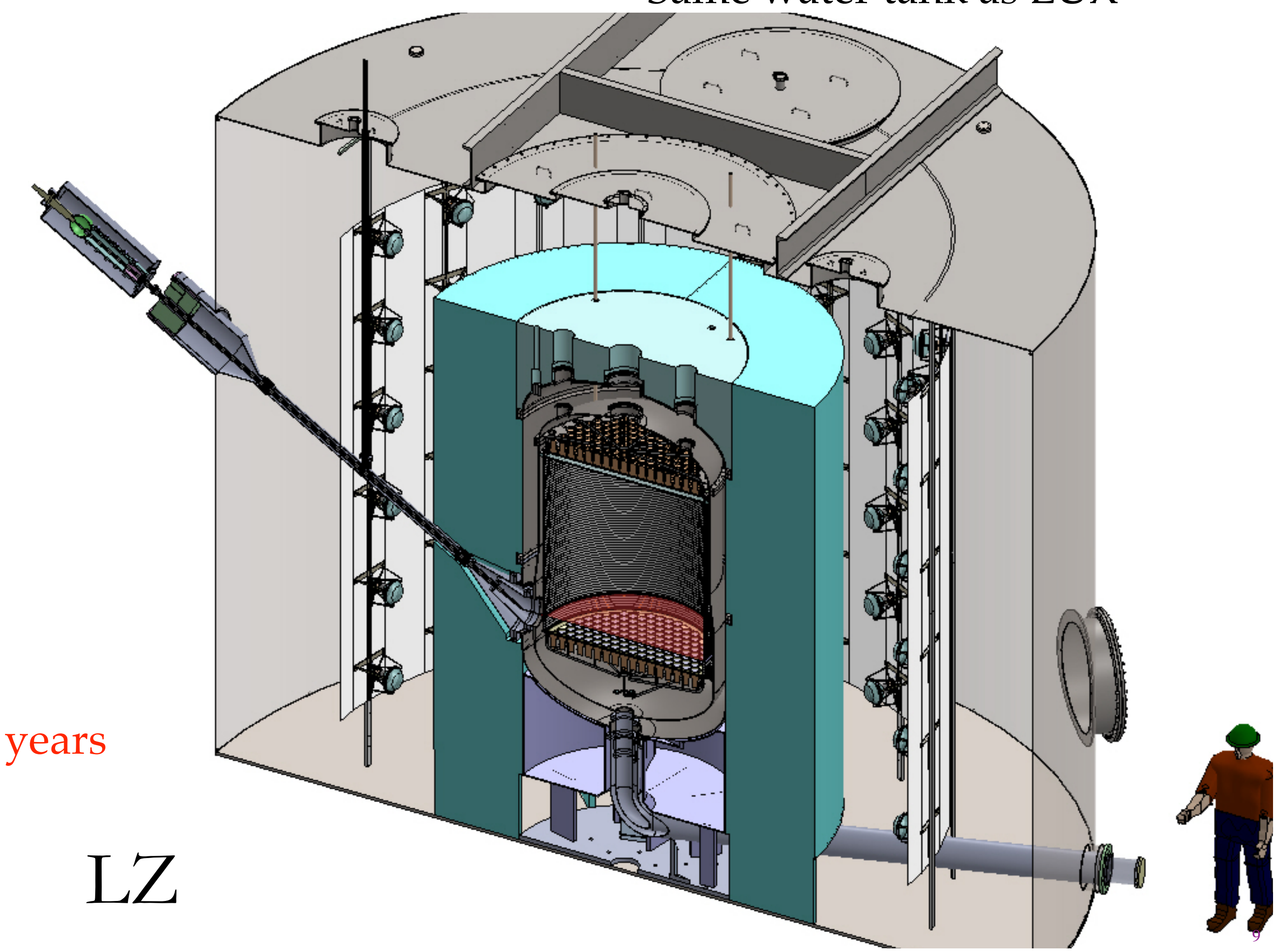
- **300 day run planned for 2014/2015**
  - **Still not background limited and expect factor of ~5 improvement in sensitivity → discovery possible**
  - **Potential for improvements to E fields/calibrations /reconstruction**

Longer term: LUX-ZEPLIN (LZ)

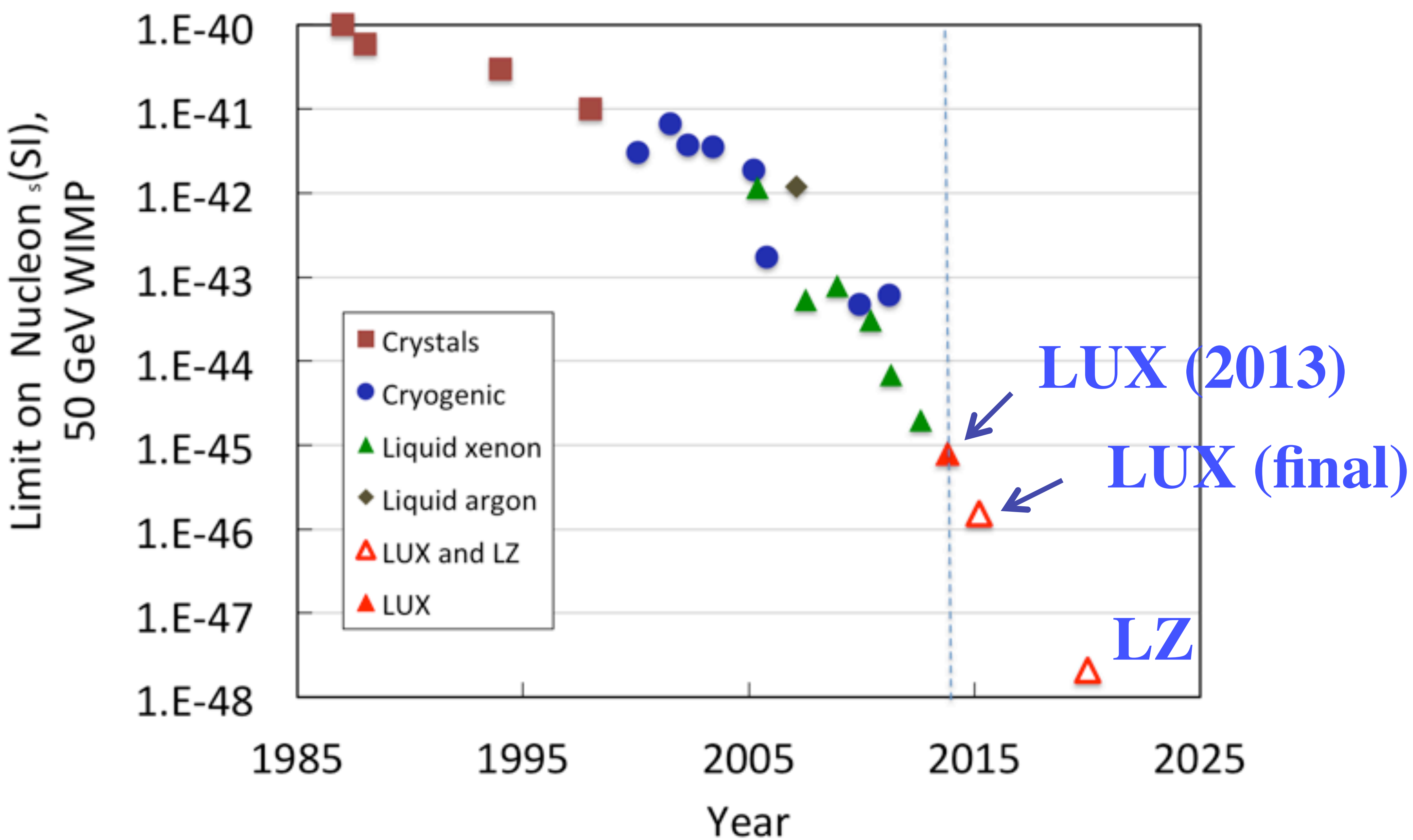
- 20 times LUX Xenon mass, active scintillator veto, Xe purity at sub ppt level
- Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds
- Proposal for US down-select process end of Nov., decision expected Jan 2014
- If approved will be deployed Davis lab 2016+



Same water tank as LUX



Historical Progress in the Limits



CONCLUSIONS

- 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
- Neutron DD Calibrations
- Results published in
  - LUX Main Results PRL 112, 091303 (2014)
  - Radiogenic and Muon-Induced Backgrounds in the LUX (arXiv 1403.1299)