Dark Matter Searches in LUX

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on behalf of the LUX Collaboration

COSPA-2016

For internal Reviewers

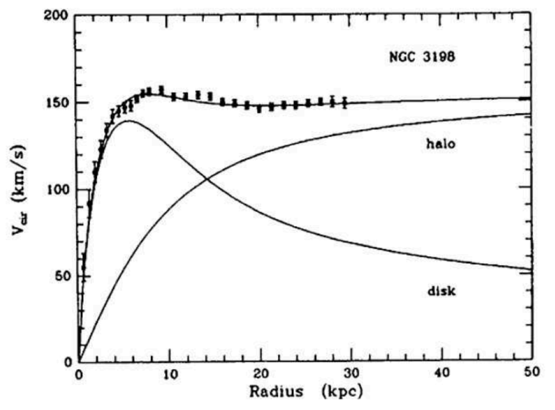
- The presentation is for COSPA-2016
  - 13th International Symposium on Cosmology and Particle Astrophysics
- The talk will be next Monday 28th of November at 14:00 and is 20 minutes long
  - It will actually be on Sunday 27th at 8PM MST or Monday 28th 3AM (Lisbon time)
  - https://indico.cern.ch/event/491882/timetable/
- Relied heavily on the presentations from Aaron, Matthew and Evan (thanks to them!)

OUTLINE

- The LUX detector - two phase Xe detector
  - Direct dark matter detection
  - How LUX detector works (Liquid Xenon time projection chamber)
- The LUX calibrations (Krypton, DD and Tritium)
- 332 live-days second science run results
  - LUX backgrounds
  - Main WIMP search analysis
  - LUX WIMP search limits

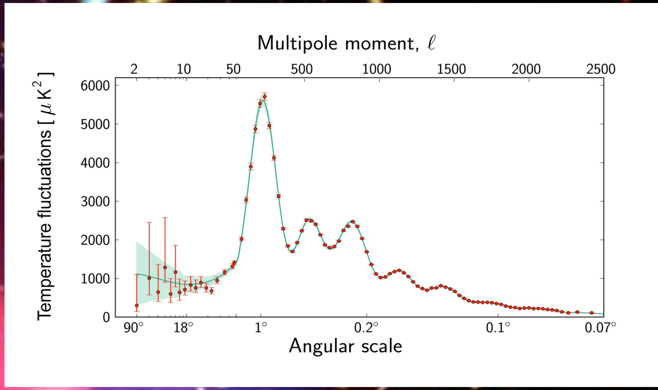
Dark Matter Evidence

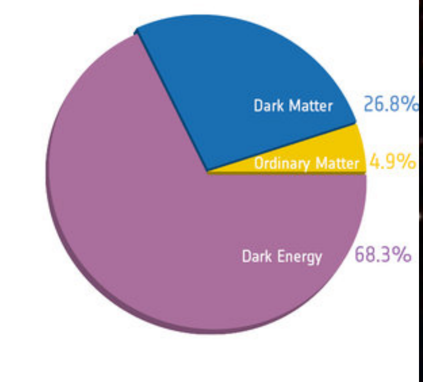
Rotation curve NGC-3198



Bullet-cluster:

Planck CMB Spectra





Bullet Cluster

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

X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.

See talk from Paolo Gondolo 9:00 AM tomorrow

Dark Matter Detection

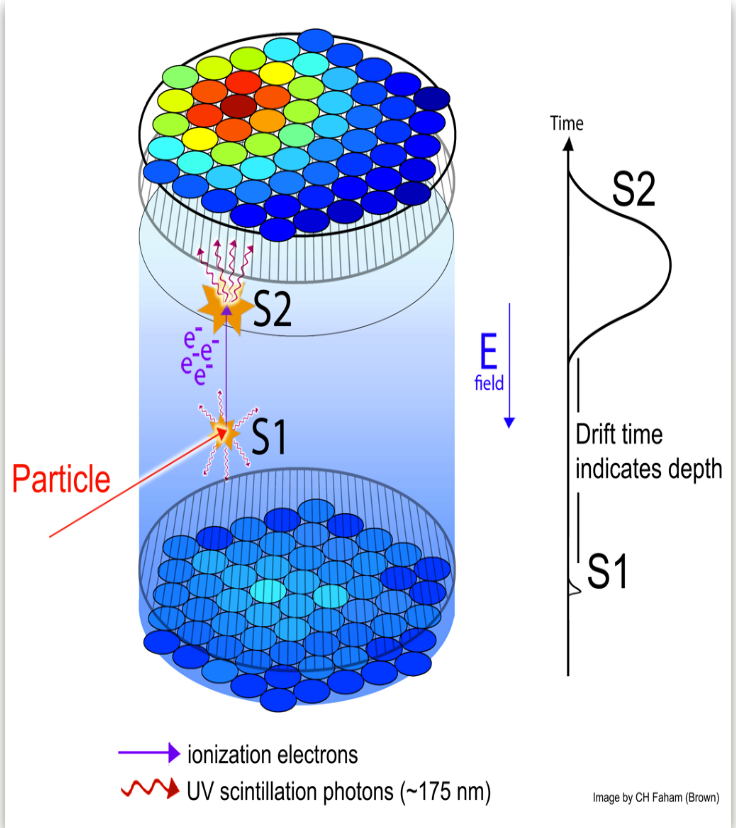
- **Cold Dark Matter Candidates**
  - **WIMP's (weakly interactive massive particles):**
    - **Neutral in most scenarios**
    - **Requires physics beyond the standard model**
  - **Axions (solution to the strong CP violation problem)**
  - **... others**
- **LUX is a Direct Detection experiment**
  - **We look for scattering of galactic WIMPs with the nucleus of the target material.**
    - **Spin dependent interaction**
    - **Spin independent interaction** $\sigma \propto A^2$
    - **Other…**
  - **Isothermal model: expect recoil <10 keV requiring detectors with a very low threshold.**

Indirect Detection

See talk from Manfred Lindner 9:30 AM tomorrow

Why a Liquid Xenon Time Projecting Chamber?

- Xenon has a high atomic mass (A=131), high density (2.9 g/cm^3) and no intrinsic backgrounds.
- Liquid Xenon TPCs are scalable to multi-ton size.
- Energy depositions produce light and charge- two detectable channels:
  - Prompt scintillation (S1)
  - Proportional scintillation (S2): Measurement of the electrons extracted from the liquid to the gas
- 3D Position Reconstruction
  - Depth obtained from the time difference between S1 and S2 - called here drift time
  - XY reconstructed from the S2 light pattern

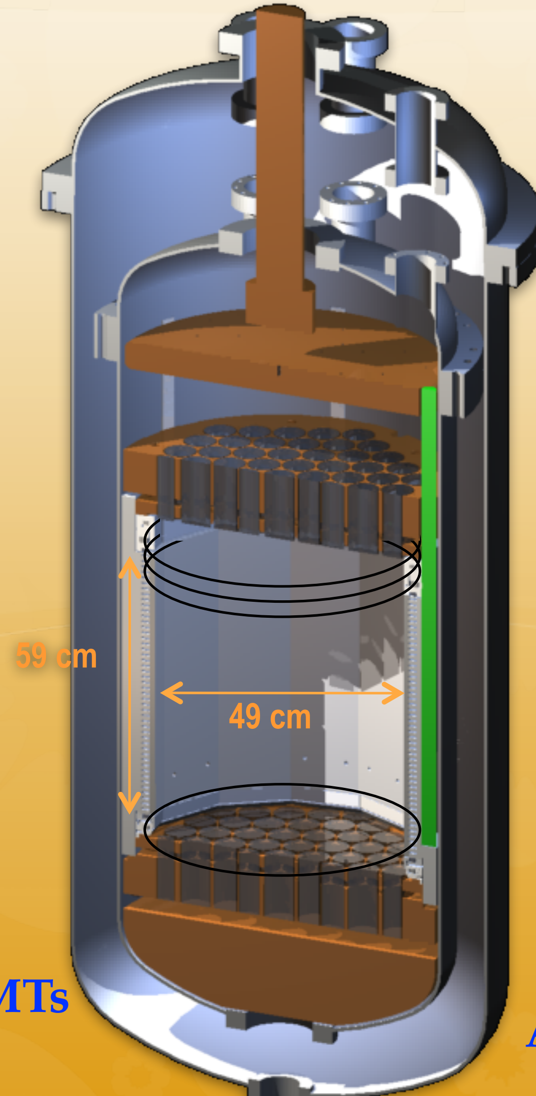


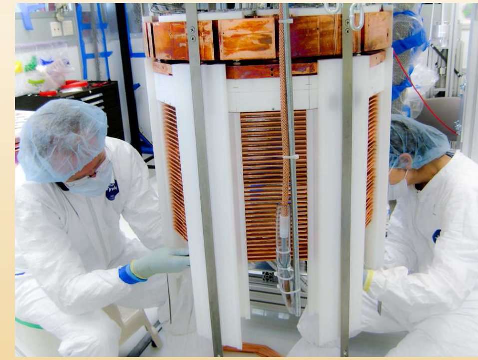
- Ratio of charge to light gives is used as a discriminator against backgrounds (>99%):
  - NR Recoil: WIMPs and neutrons interact with nuclei - short, dense tracks
  - ER Recoil: axions, γs and e- interact with the atomic electrons - longer, less dense tracks
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe, 47.6% natural abun.) enable spin-dependent sensitivity studies.

The LUX Experiment

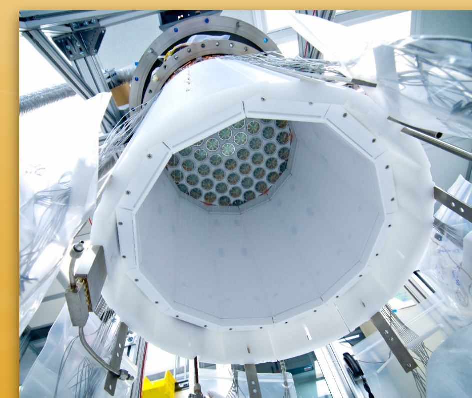
- 370 kg Liquid Xenon Detector (59 cm height, 49 cm diameter)
  - 250 kg in the active region (with field)

122 ultra low-background PMTs (61 on top, 61 on bottom) observe both S1 and S2





Construction materials chosen for low radioactivity (Ti, Cu, PTFE)

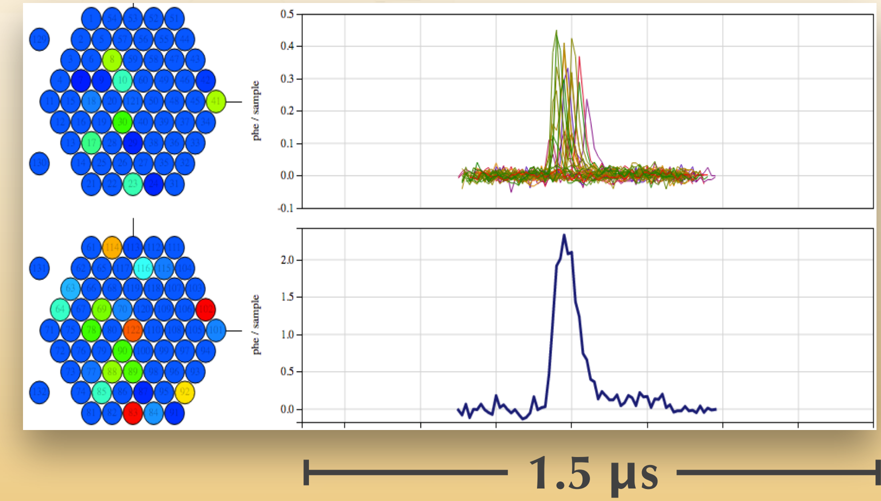


Active region defined by PTFE reflectors (high reflectivity >97%) - high light collection)

Typical LUX Pulses

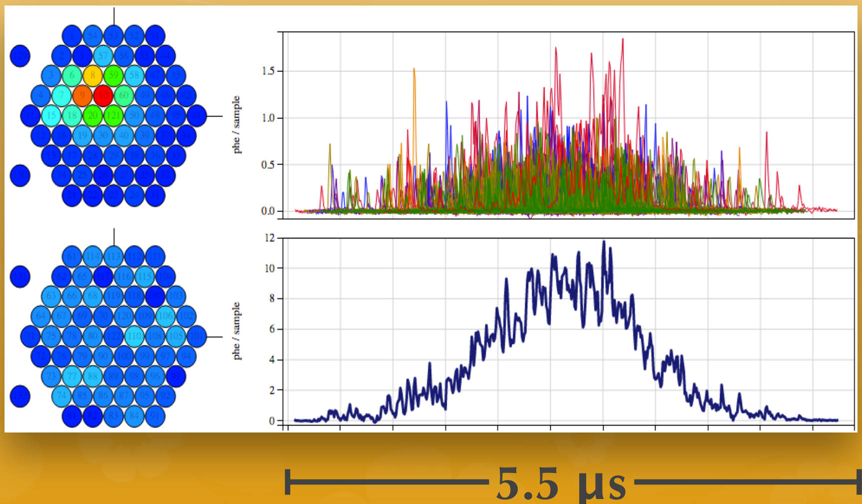
S1 - Prompt scintillation

- ~60-90% of light in bottom PMTs
  - Ratio depends on the depth of the event
- Sharp rise with a exponential decay
  - Pulse FWHM: ~100 ns
  - S1 area: 1-50 phd for WIMP search
- Threshold of 2 detected photons

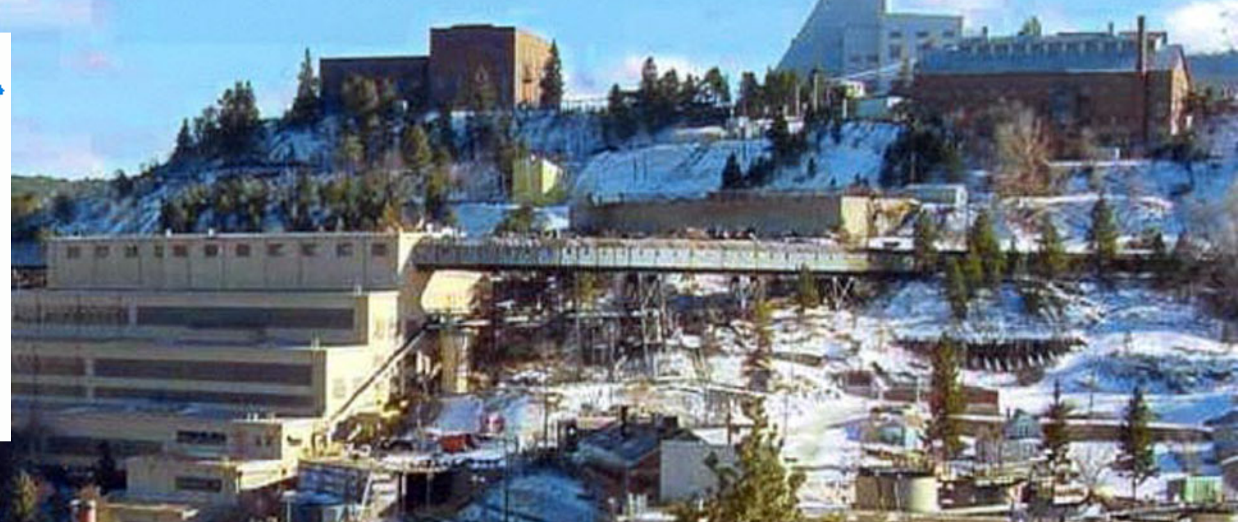


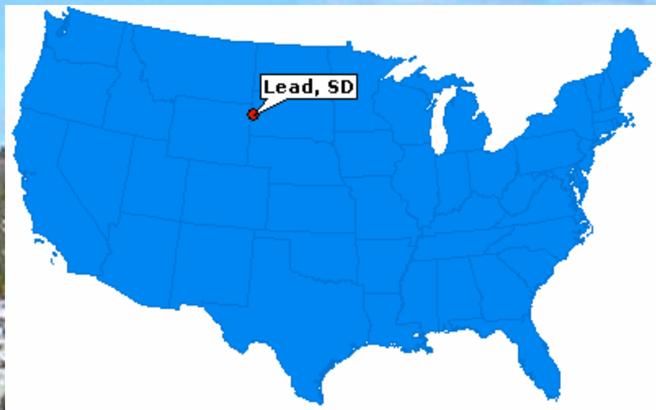
S2 - Electroluminescence

- ~25 phd per extracted electron
- ~57/43% (top/bot.) light in PMTs
- Near-gaussian pulse shape
  - pulse width depends on the depth
- Threshold of 150-200 phd (WIMP-Search)



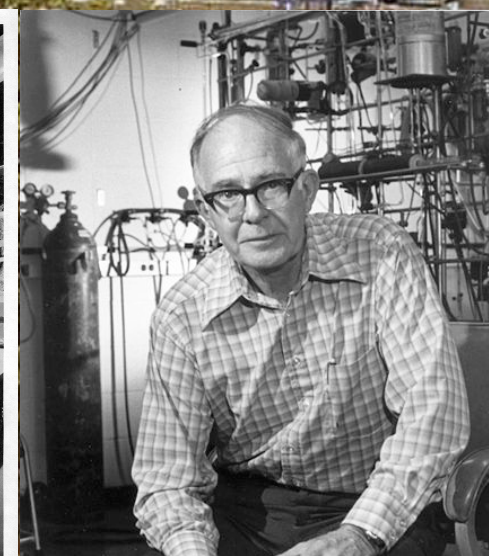
LUX AT SURF
(Sanford Underground Research Facility)





- Sanford Underground Research Facility Lead, South Dakota, USA.
- Former Home of the Homestake Solar Neutrino Experiment 1970-1994
- 1478 m deep (4300 m.w.e.)
- μ flux reduced x10^{-7} compared to sea level)

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 Timeline 2006-2016

Two main WIMP search runs

First Science Run (FSR): 2013/04-2013/09, 95 live-days

Second Science Run (SSR): 2014/09-2016/09, 332 live-days

2006: LUX Collab. Formed

2008: LUX funded (DOE+NSF)

2012 (Jul): LUX moves underground

2013 (Apr): First Science Run (FSR) Starts

2013 (Nov): First Science Run Results Reported

2014 (Jan): Grid Conditioning

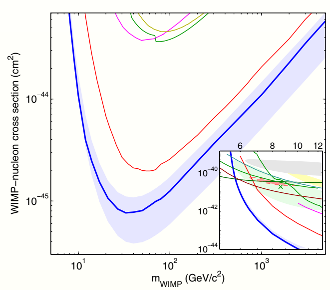
2014 (Sep): Second Science Run (SSR) Starts

2015 (Dec): 3-month run reanalysis posted

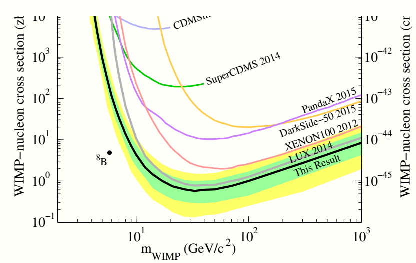
2016 (May): SSR Finished - 332 live-days

2016 (Jul): SSR Results Released 332 live-days

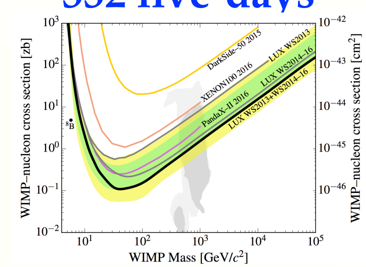
2016 (Sep): LUX decommission



PRL, 112, 091303 2014



PRL, 116, 161301 2016



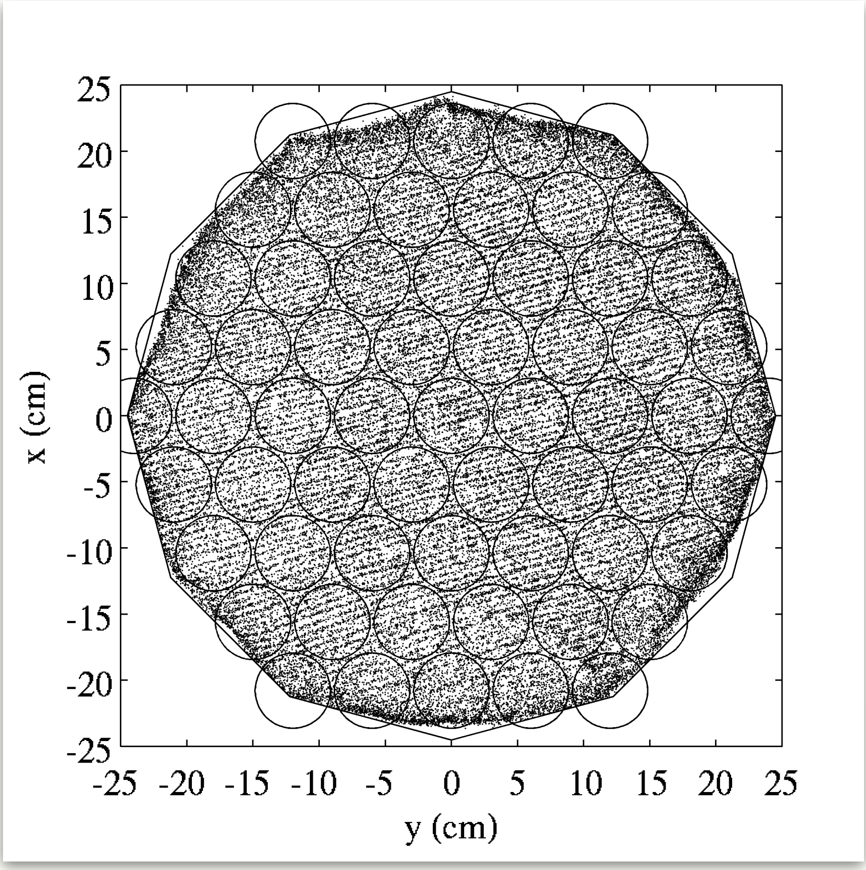
arXiv 1608.07648

Krypton Calibrations

- ^{83m}Kr is an internal source. It is injected in the gas system and decays uniformly inside the detector
  - ^{83m}Kr emits two gamma rays $E_{\gamma,1}$ = 32.2 keV ($T_{1/2}$ = 1.83 h) and $E_{\gamma,2}$ = 9.4 keV ($T_{1/2}$ = 154 ns)
  - 1 to 2 times a week
- ^{83m}Kr used to
  - Develop S1 and S2 position corrections: both S1 and S2 pulses depend on the location of the event due to geometrical light collection and electronegative impurities.
  - Map variations of the electric field in the detector
  - Develop and test the position reconstruction: krypton data is used to get the light response functions (LRFs)of the PMTs. These functions are found by iteratively fitting the distribution of S2 signal for each PMT.

Krypton data ^{83m}Kr (Drift Time 4 - 8 μs)

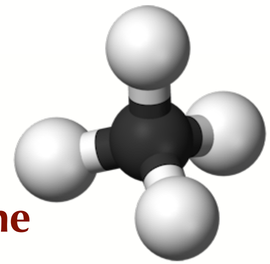
Second Science Run



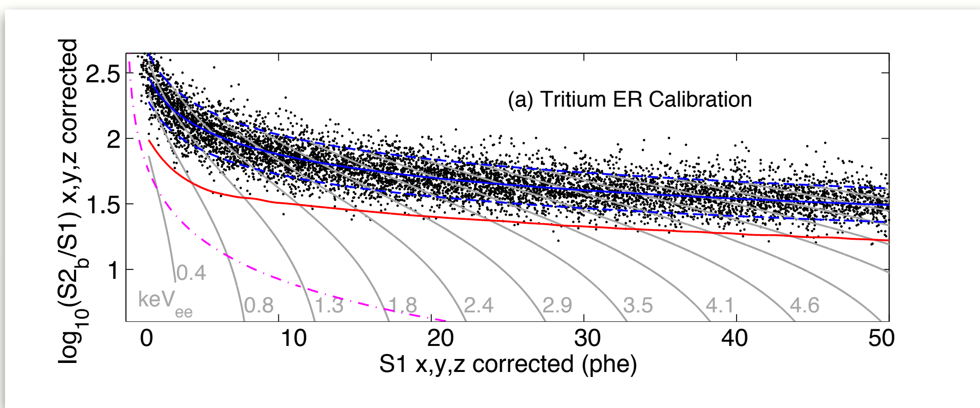
The large difference between the drift field (180 V/cm) and the extraction field (2.8 kV/cm in liquid) causes the the drift field lines to be compressed as they pass through the gate plane; any electrons leaving the drift volume appear only in narrow strips between each pair of gate wires.

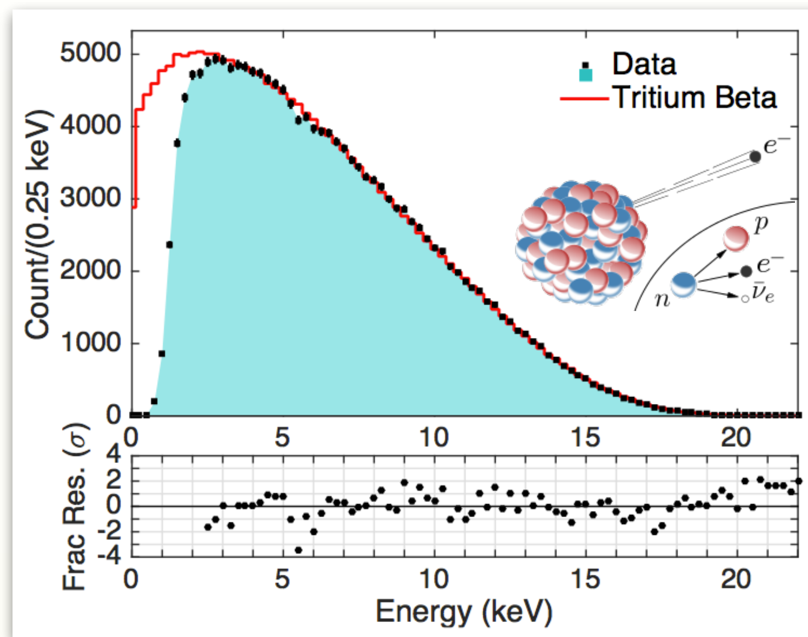
ER Calibrations

- **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.**
- **Tritium calibrations performed every three months during the SSR**

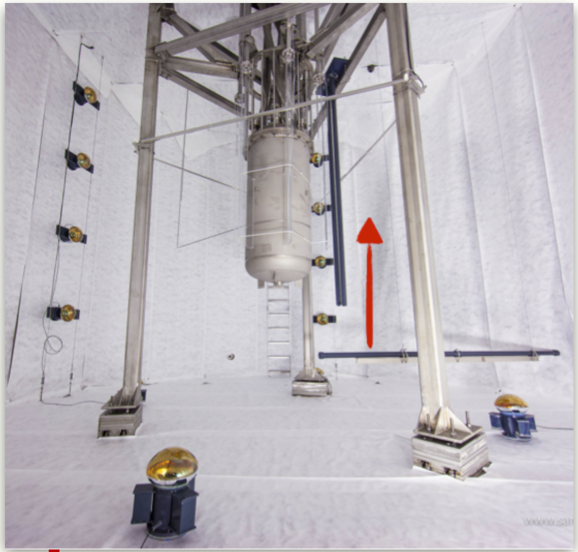


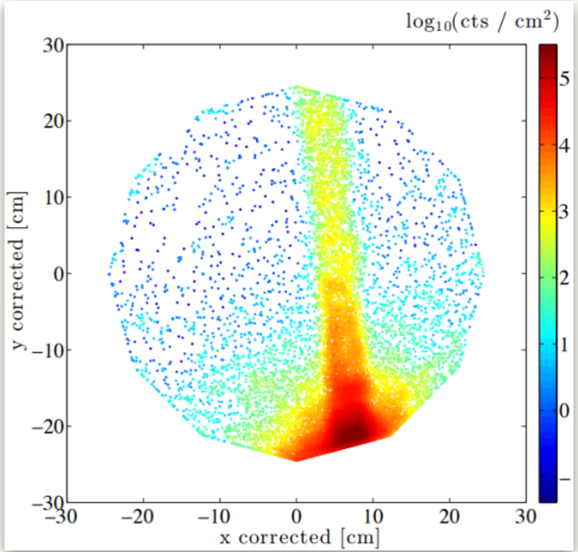


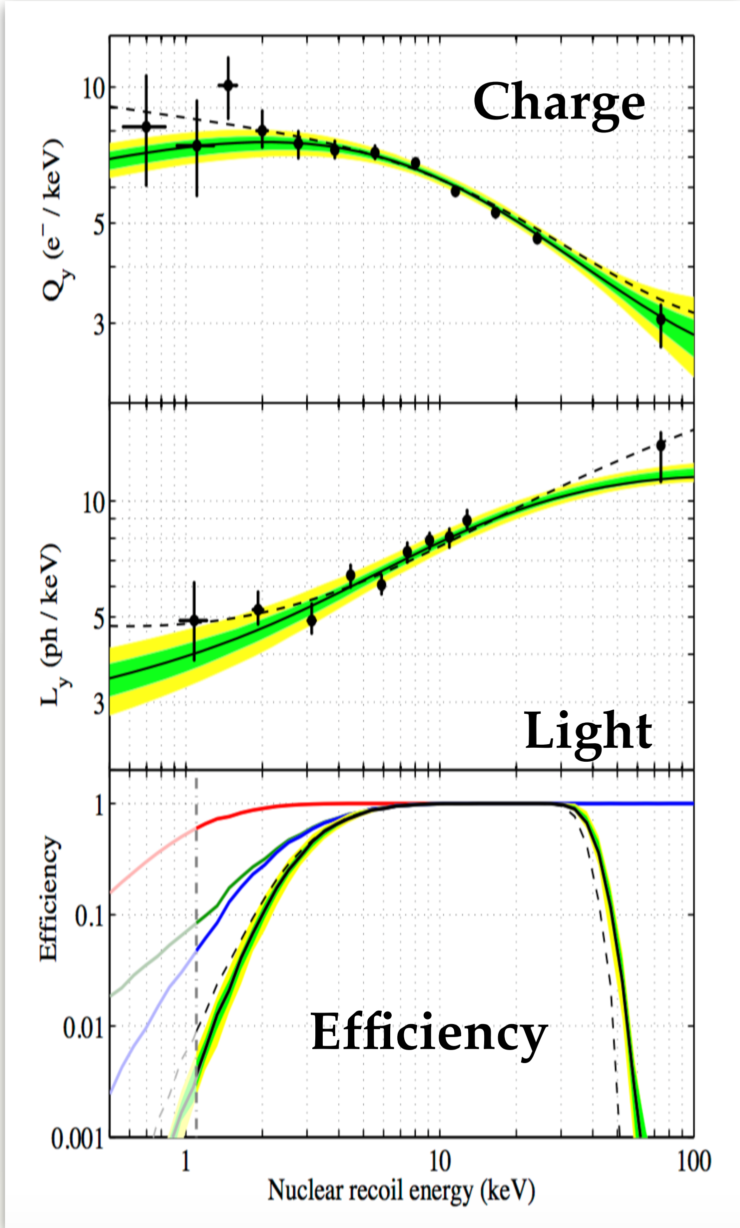
Phys. Rev. D 93, 072009 (2016)

NR Calibration

- Deuterium-Deuterium neutron Generator installed outside LUX water tank
- The 2.45 MeV emitted neutrons are collimated to the level of ~1 degree
- Two analysis are performed
  - Double-scatters - ionization yield Q_y (0.7 to 74 keV_{nr})
  - Single-scatters - scintillation yield L_y and NR band calibration (1.1 to 74 keV_{nr})
- Calibrations every three months and at different depths during the SSR







https://arxiv.org/abs/1608.05381

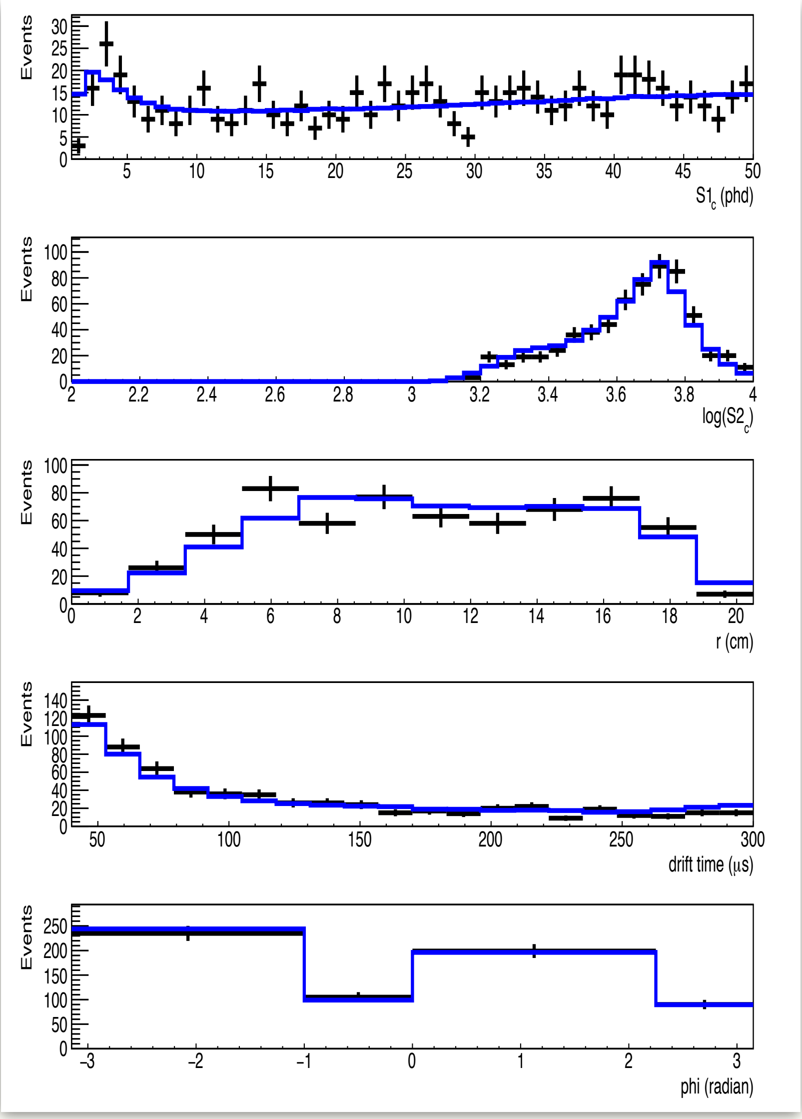
Estimation of Backgrounds

Background source	Expected number below NR median	
External Gamma Rays	1.51±0.19	Bulk volume, but leakage at all energies
Internal Betas	1.20±0.06	
^{238}U late chain wall back.	8.7±3.5	Low-energy, but confined to the edge of our fiducial volume
Accidental S1-S2	0.34±0.10	In the bulk volume, low- energy, in the NR band
Solar ^{8}B neutrinos	0.15±0.02	

- These figures are figure of merit only. In our analysis we use a likelihood analysis.
  - + ~ 0.3 single scatter neutrons, e.g. from (α, n), not included in PLR

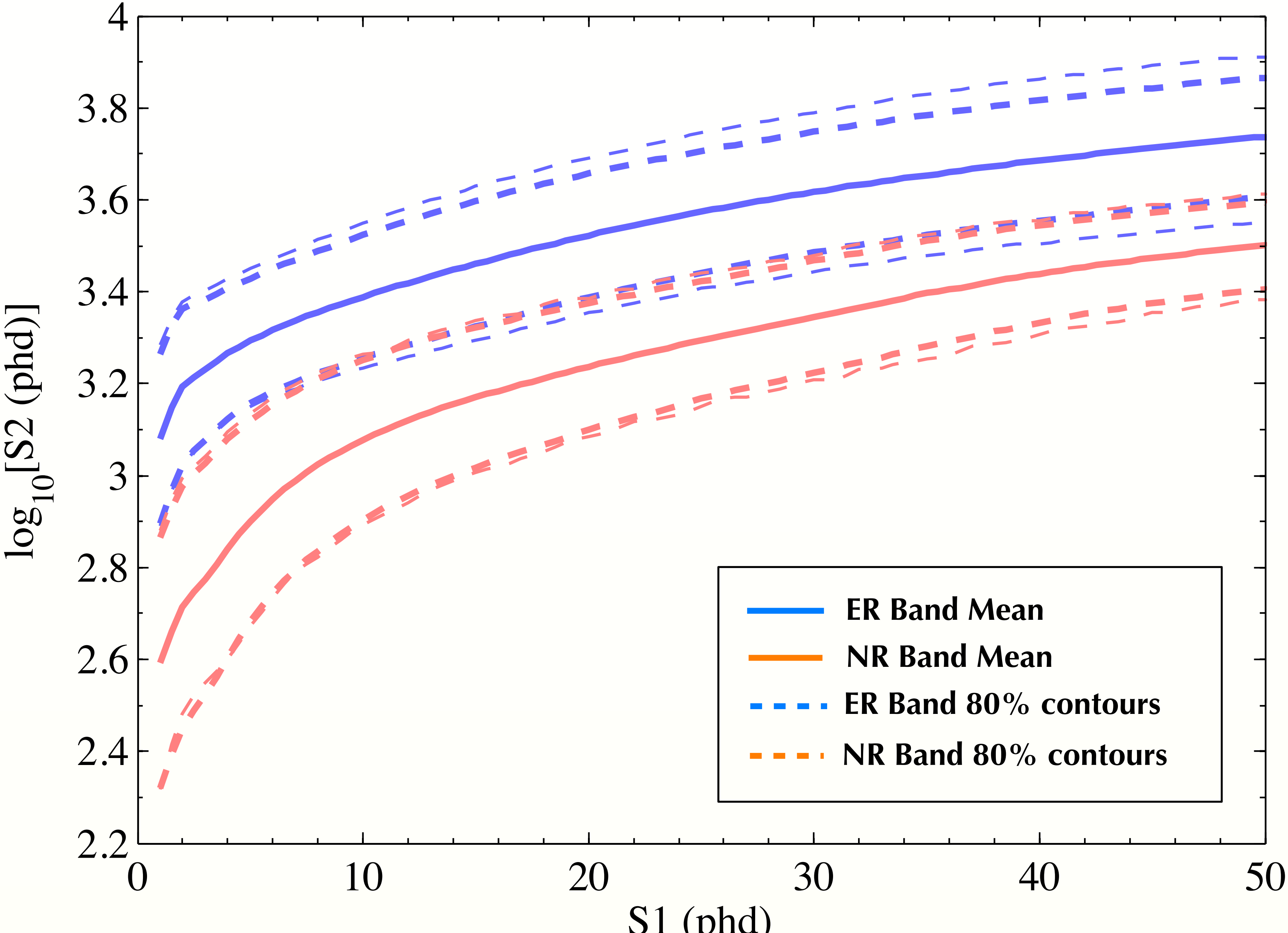
LUX Likelihood Analysis

- A profile-likelihood test (PRL) was implemented to compare the models with the observed data
- 5 un-binned PLR dimensions
  - z/drift time, r, ϕ, S1 and $\log_{10}$(S2)
- 1 binned PLR dimension:
  - Event date
- Data in the upper-half of the ER band were compared to the model (plot at right) to assess goodness of fit.
- Good agreement with background-only model, p-value >0.6 for each projection.
- S1 and S2 are modelled with NEST (Noble Element Simulation Technique, NEST, http://www.albany.edu/physics/NEST.shtml) and based on our in situ calibration data
- NEST is "tuned" to each by varying the applied field until we see a match between model and calibration data.

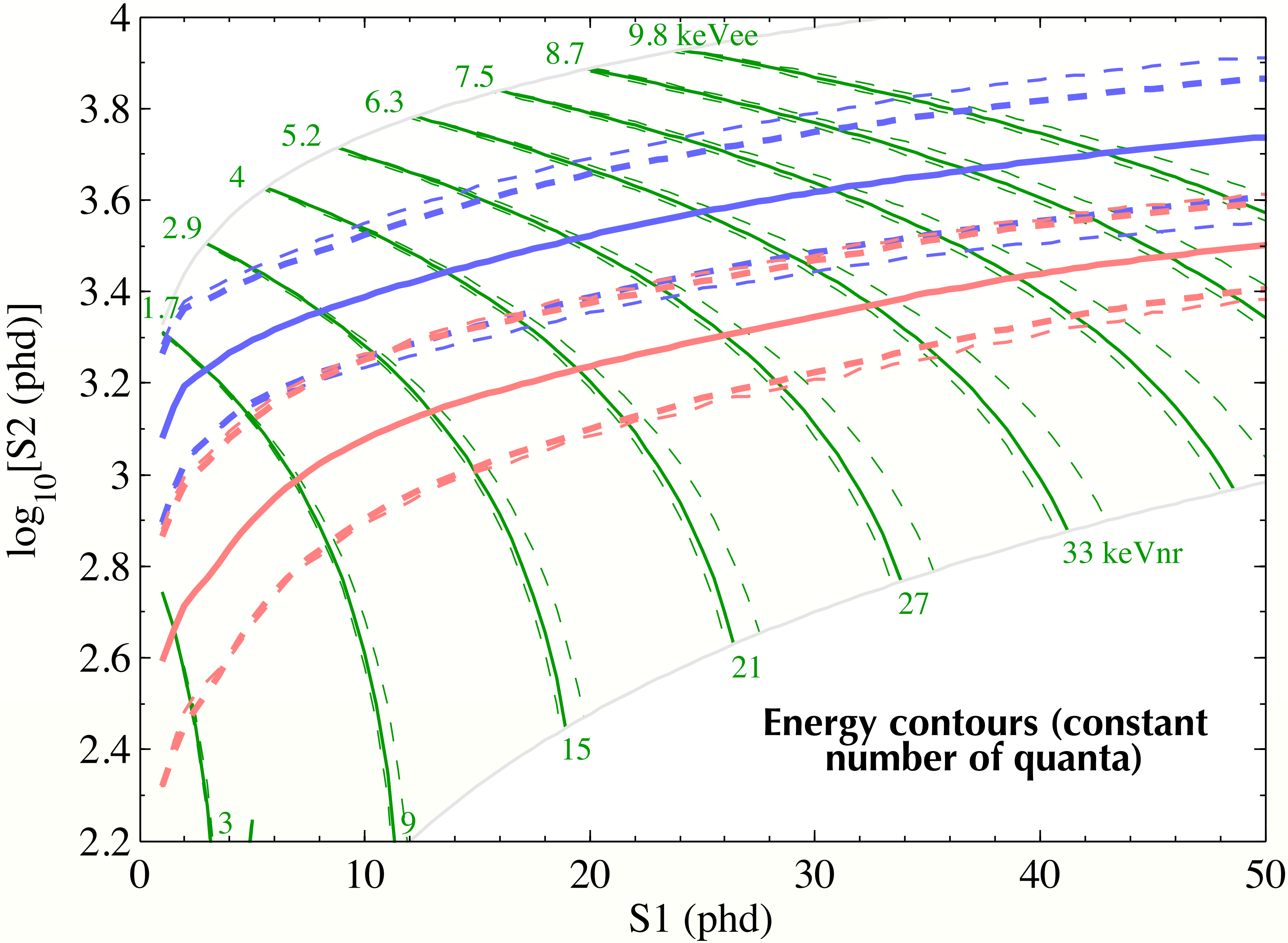


M. Szydagis 2013 JINST 8 C10003 and J. Mock 2014, JINST 9 T04002

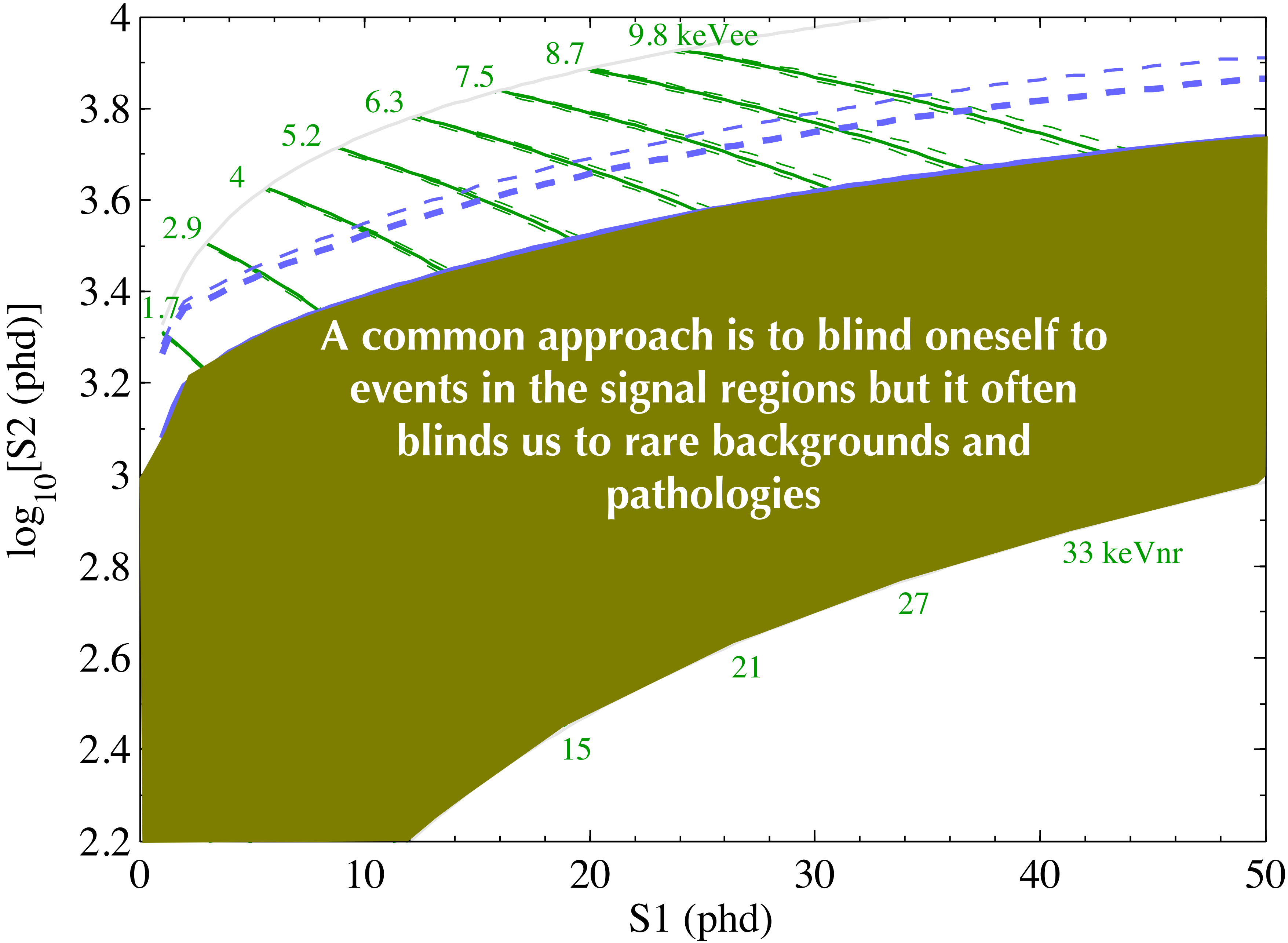
Taking a Look at the Dark Matter Search Data



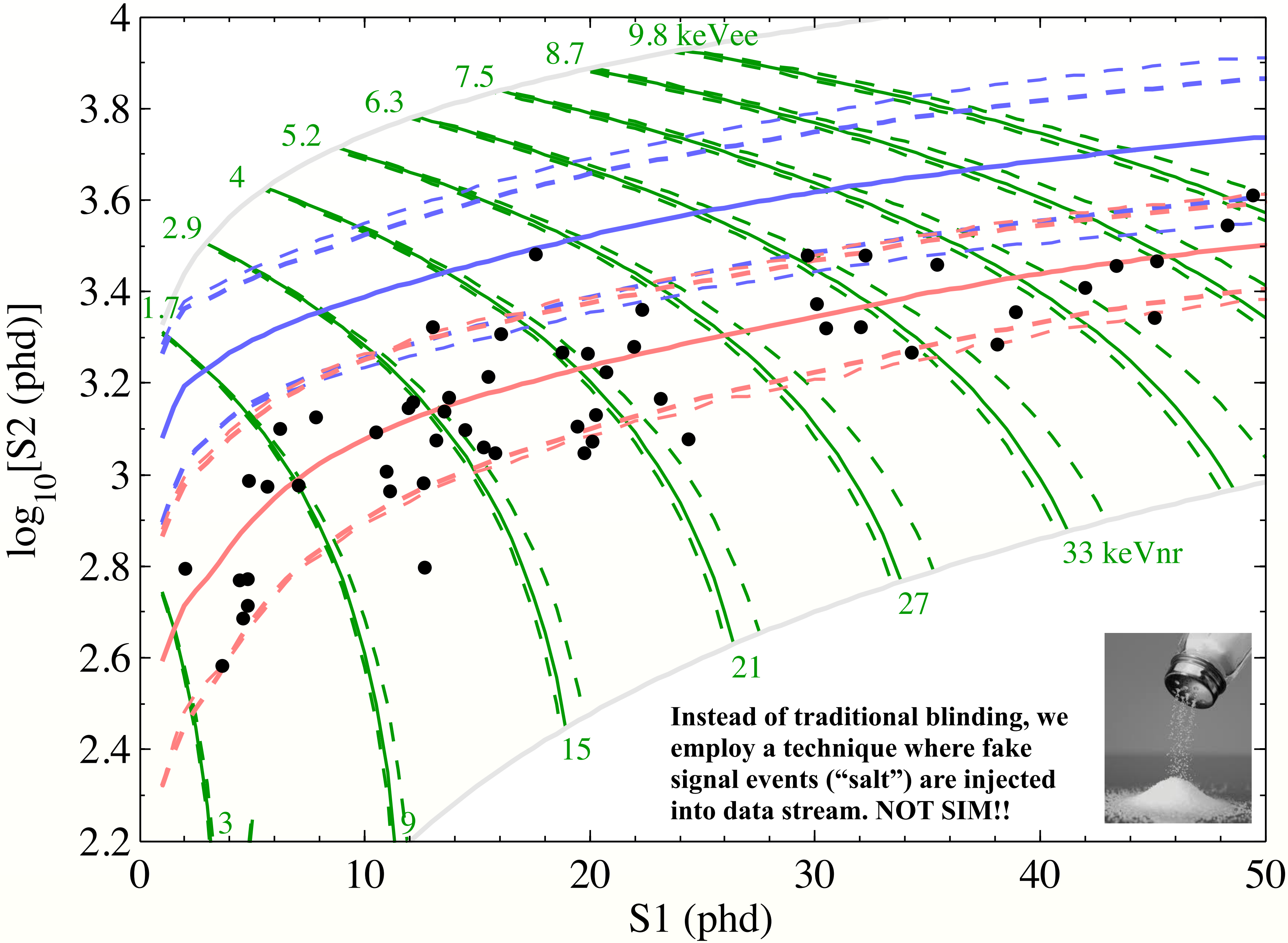
LUX 2014/2016 Detector's Response



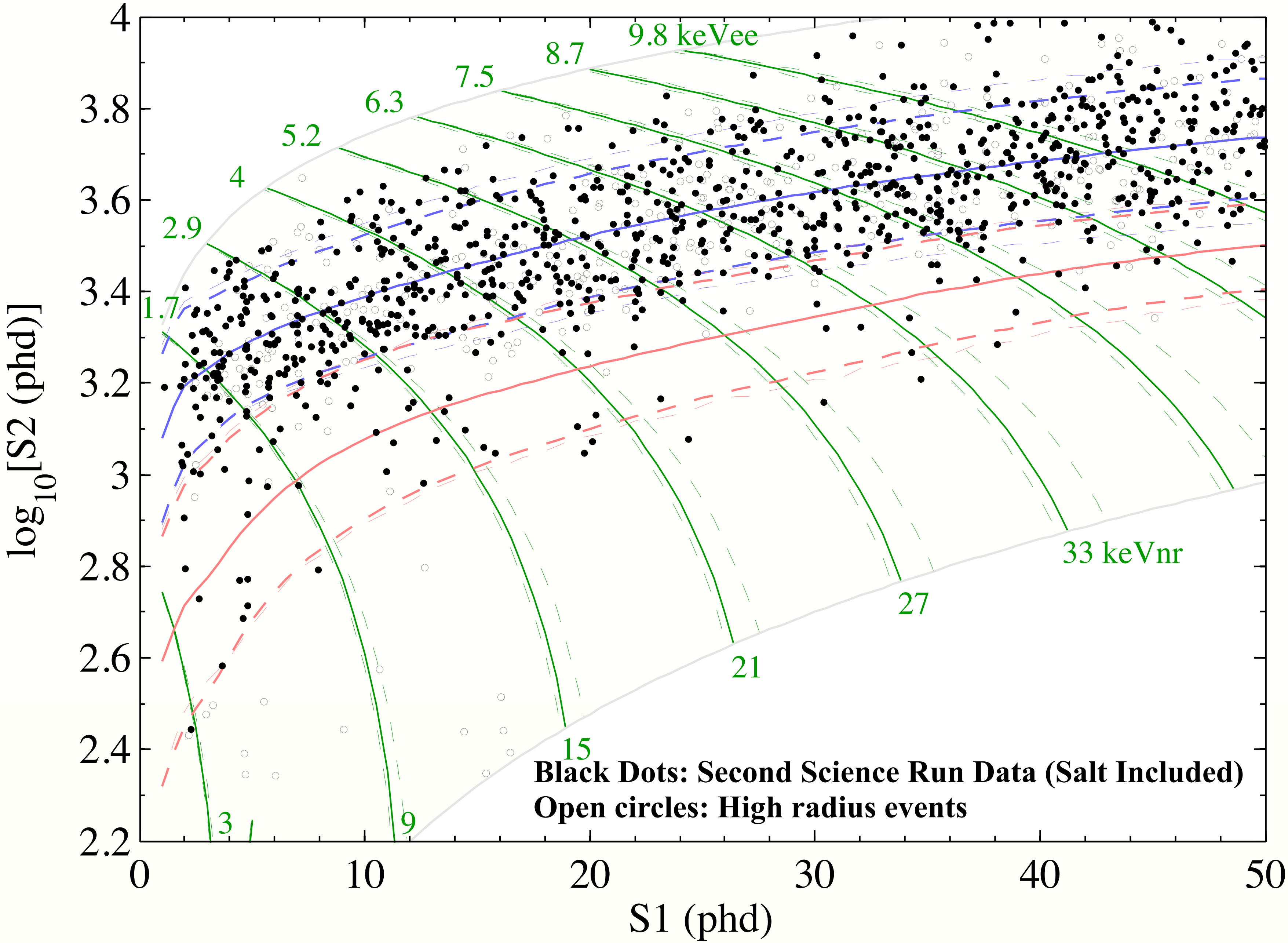
LUX Blind Analysis



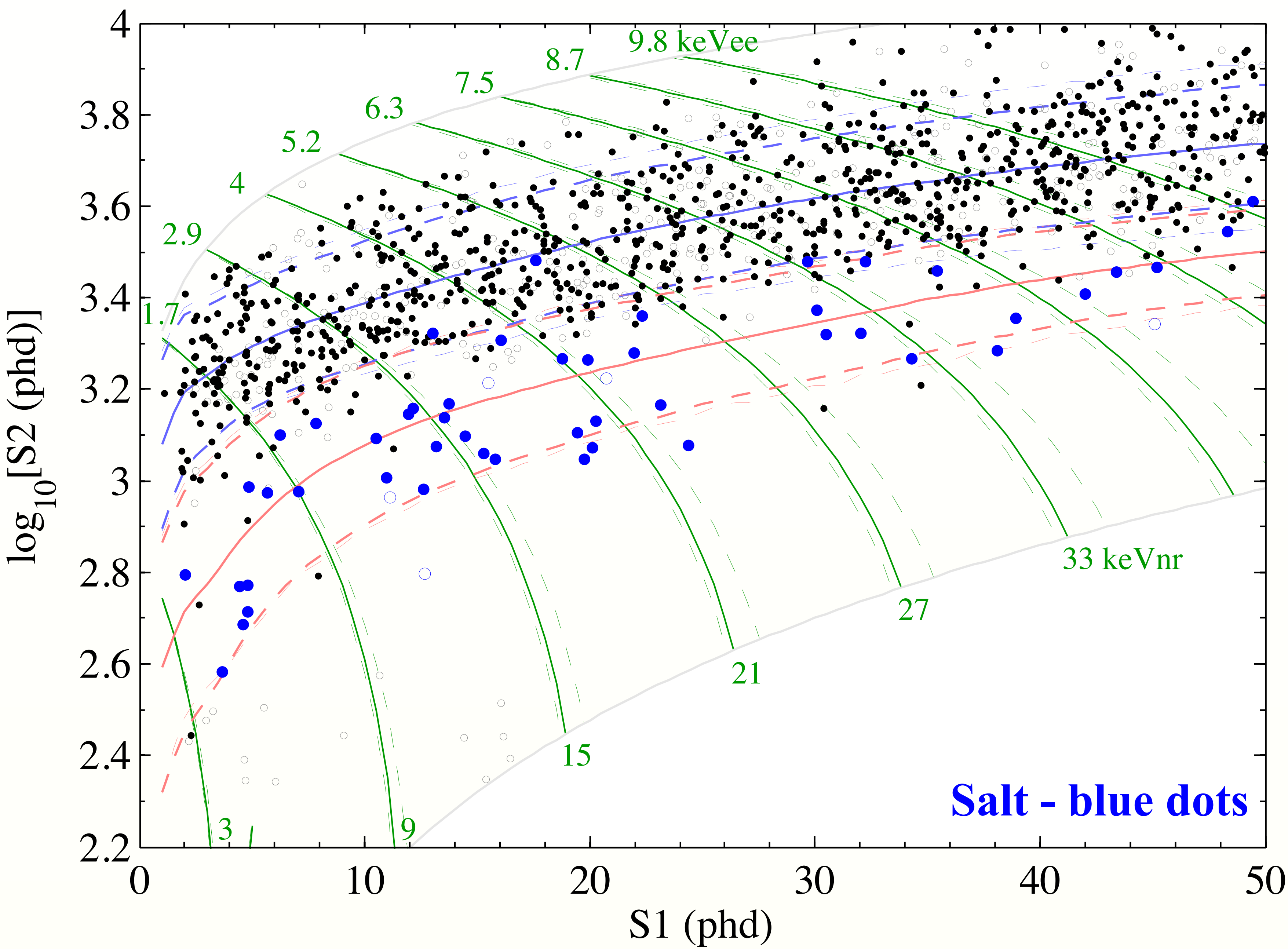
LUX Salting


9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
3
9
15
21
27
33 keVnr
log10[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50
Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIM!!

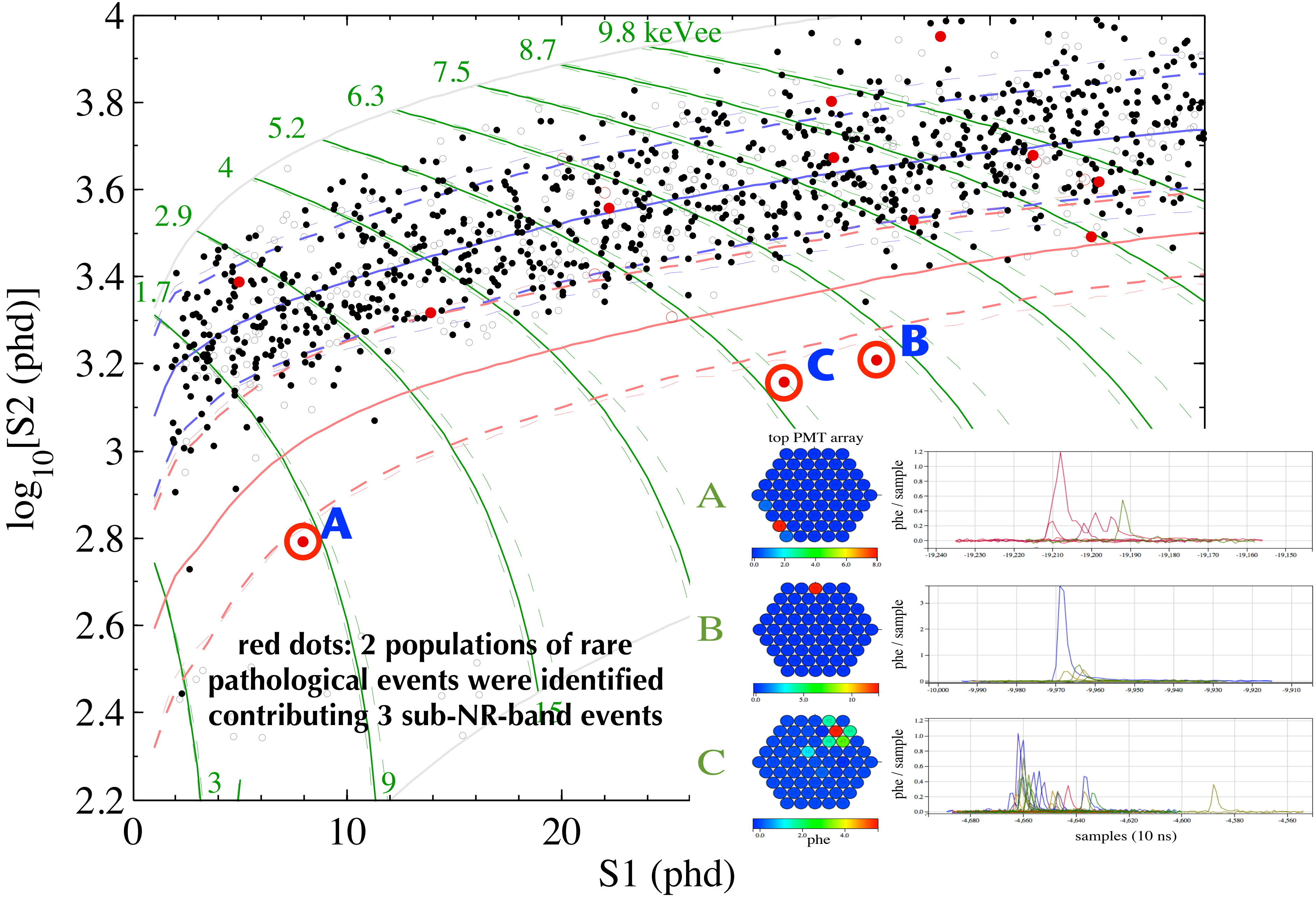
WIMP-search data from 332 live days



WIMP-search data - Salt Identified

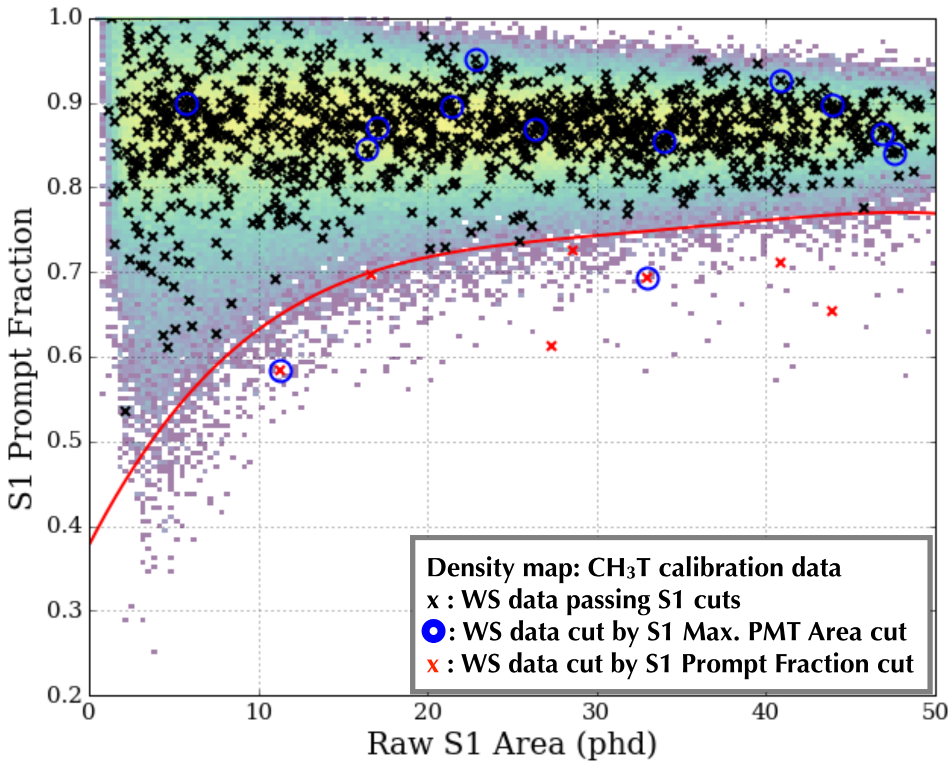


WIMP-search data - Pathological Events

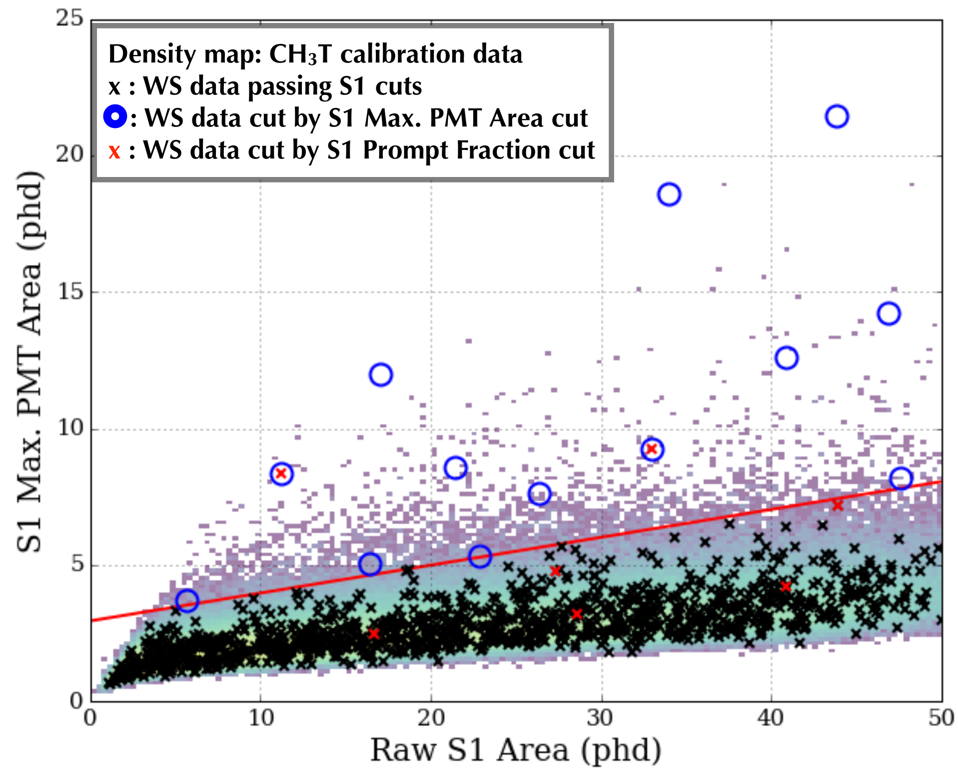


Post-Unsalting Quality Cuts

- **Two additional cuts on the S1 pulse were implemented.**
- **Flat signal acceptance of 98.5% when both cuts are applied to the DD and Tritium data**

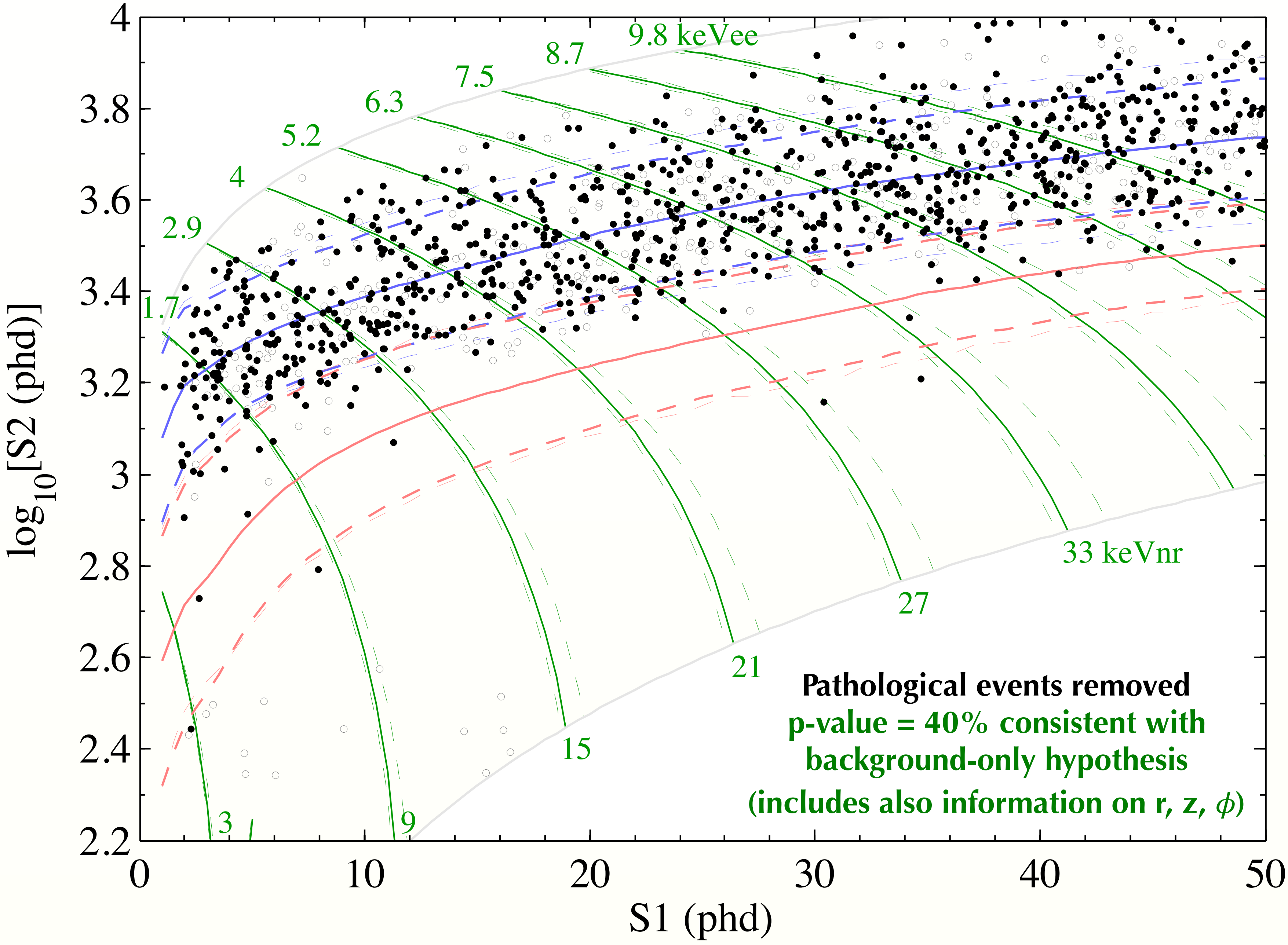


Removes events with S1 that has gas-event-like time structure



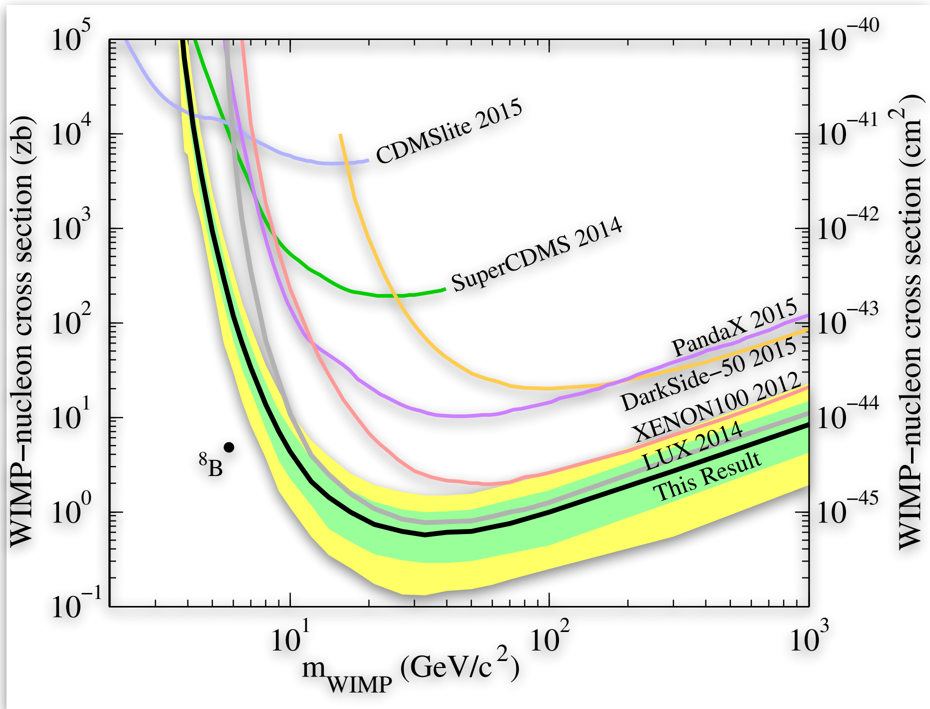
Removes events with S1 light overly concentrated in a single PMT

WIMP-search data from 332 live days



FSR Reanalysis - 95 Live Days

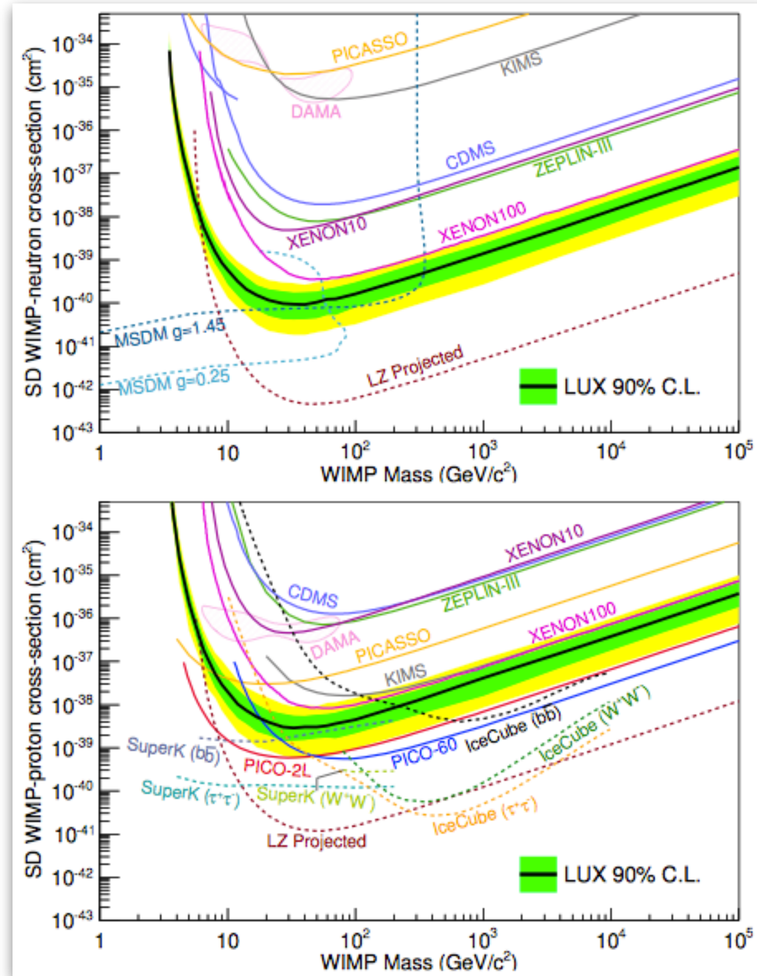
Spin Independent



PRL, 116, 161301 (2016)

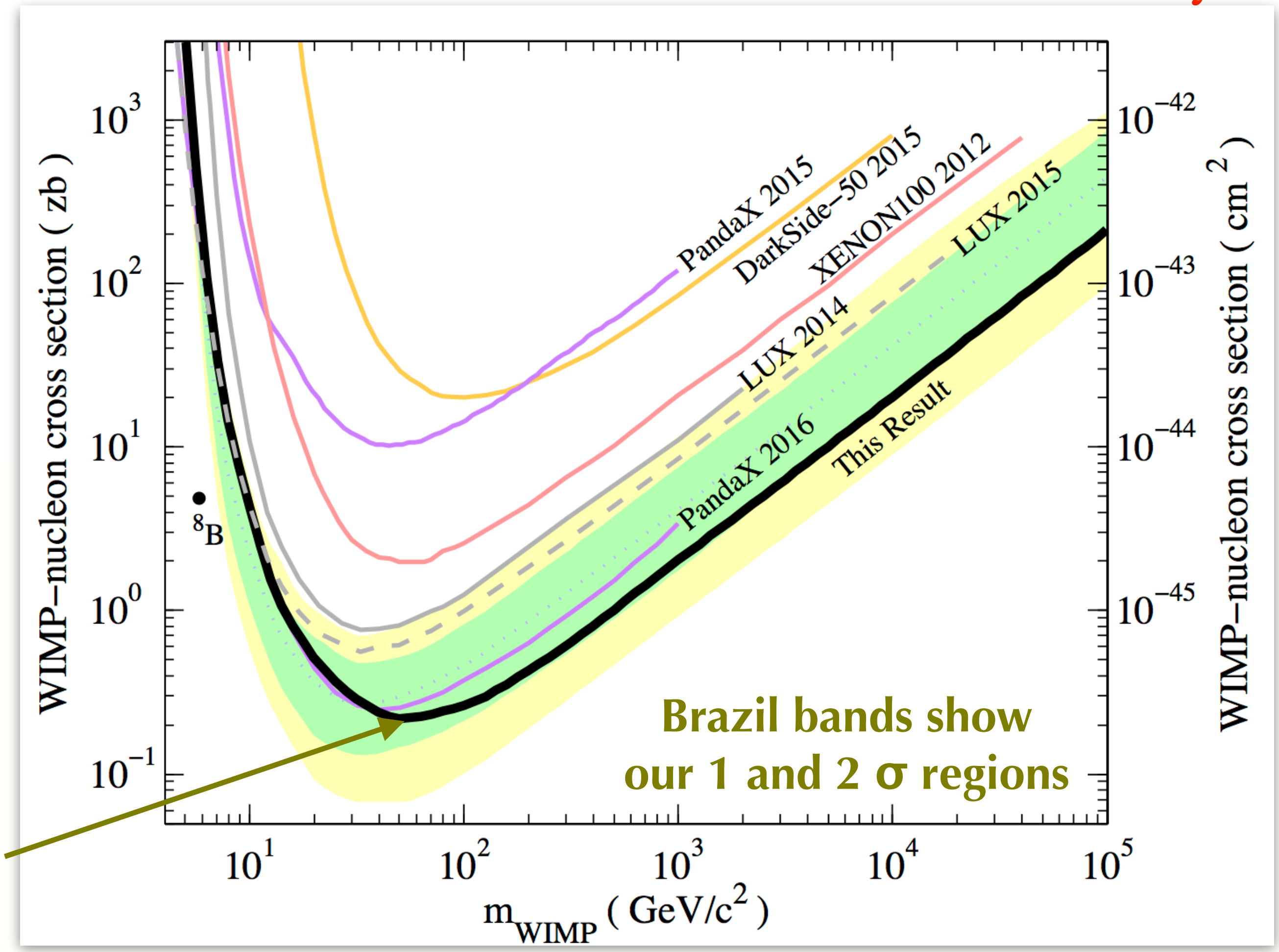
0.60 zeptobarns
(at 33 GeV/c^2)

Spin Dependent



PRL, 116, 161302 (2016)

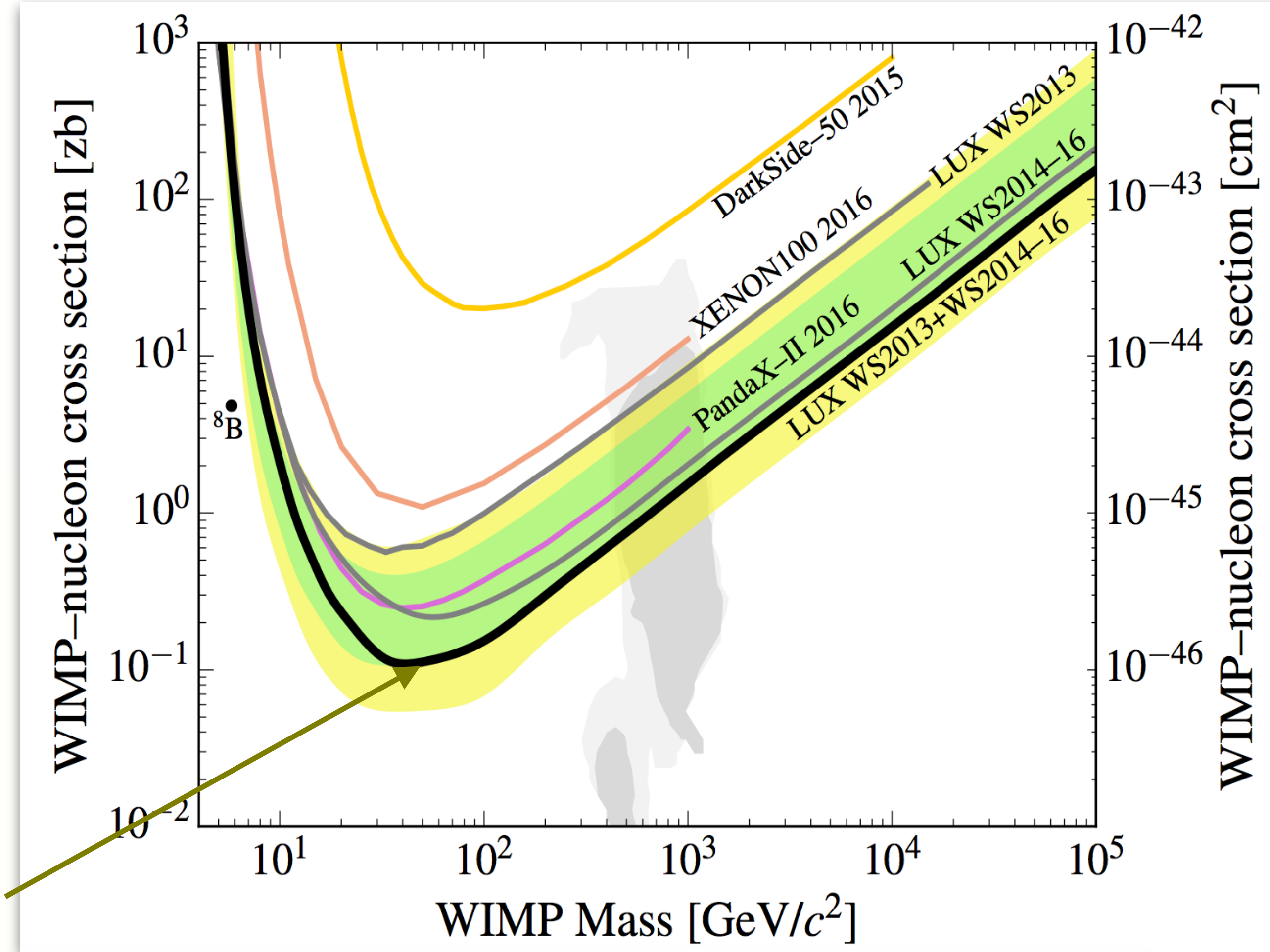
WIMP-nucleon SI Exclusion - SSR 332 days



0.22 zeptobarns (at 50 GeV/c²)

- **We observed an improvement of a factor of four compared with the results from the first science run.**

WIMP-nucleon SI Exclusion - FSR+SSR

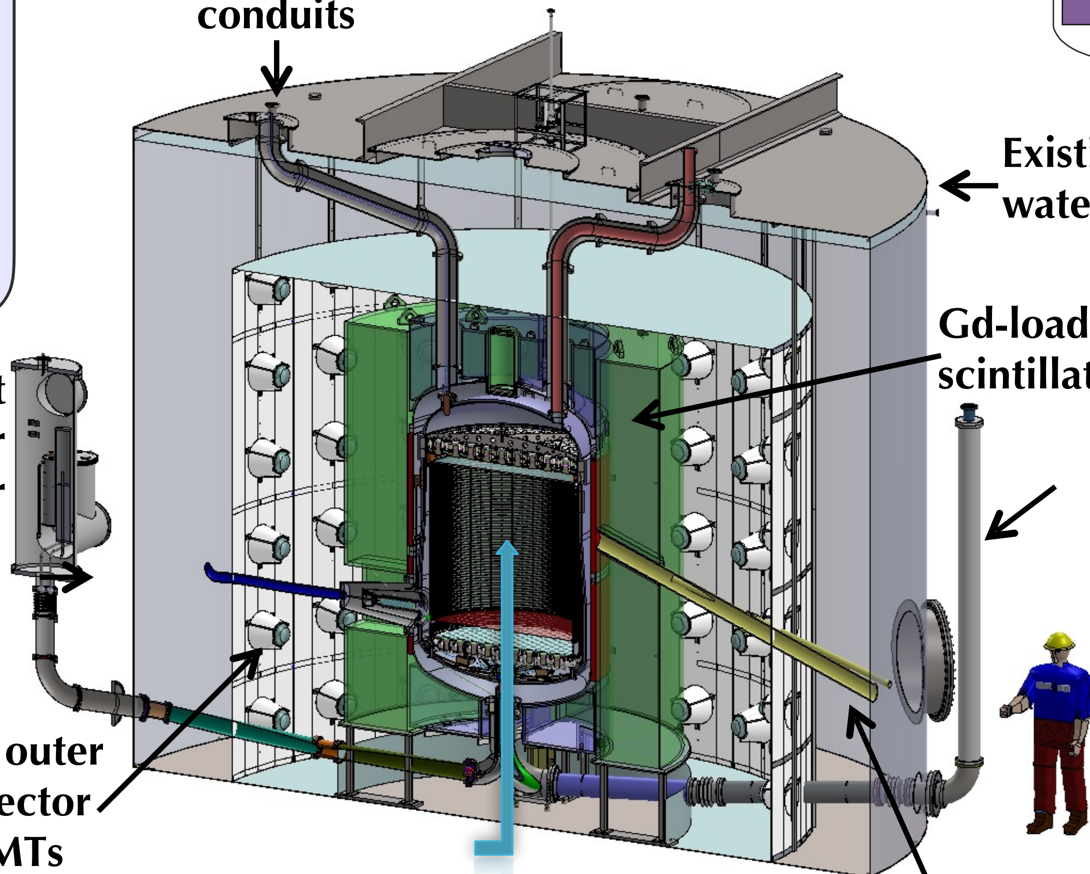


0.11 zeptobarns (at 50 GeV/c^2)

- **Both LUX Runs Combined**
  - https://arxiv.org/abs/1608.07648
- **LUX now excludes significant portions of the 1-sigma regions for WIMPs favored by certain supersymmetric models.**

The LUX-ZEPLIN Experiment

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: $< 2 \times 10^{-48}$ cm^2, at 40 GeV ~100 times better than LUX



Conclusions

- LUX has since 2013 the world-leading result in the dark-matter research.
- The LUX's 332 live-day search, cutting into un-probed parameter space. Excluding SI WIMPs down to 0.22 zeptobarns (2.2x10^{-46} cm^2).
- LUX had significant improvements in the calibration of xenon detectors - essential to improve detector's sensitivity.
- When both runs are combined SI WIMPs are excluded down to 0.11 zeptobarns.
- Results available on:
  - https://arxiv.org/pdf/1608.07648v2.pdf
- More analysis forthcoming
  - Spin-dependent, axion searches/ALP, effective field theory, neutrino less double beta decay, additional calibrations etc.
- Onwards and downwards: LUX-ZEPLIN (LZ) experiment under construction, 7 tonne active mass (2020).

The LUX collaboration

Berkeley Lab / UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Michael Witherell	Lab Director
Peter Sorensen	Scientist
Simon Fiorucci	Project Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Brown University

Richard Gaitskell	PI, Professor
Samuel Chung	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Postdoc

University of Edinburgh, UK

Alex Murphy	PI, Professor
Paolo Beltrame	Research Fellow
Tom Davison	Graduate Student
Maria F. Marzioni	Graduate Student

Imperial College London, UK

Henrique Araujo	PI, Reader
Tim Sumner	Professor
Alastair Currie	Postdoc
Adam Bailey	Graduate Student
Khadeeja Yazdani	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Grp.
Kareem Kazkaz	Staff Physicist
Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

LIP Coimbra, Portugal

Isabel Lopes	PI, Professor
Jose Pinto da	Assistant Professor
Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc
Paulo Bras	Graduate Student

SLAC Stanford (CWRU)

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Wing To	Research Associate
Rosie Bramante	Graduate Student
Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA / Sanford Lab

David Taylor	Project Engineer
Markus Horn	Research Scientist
Dana Byram	Support Scientist

University at Albany

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Sean Fallon	Graduate Student
Jack Genovesi	Graduate Student
Steven Young	Graduate Student

Texas A&M University

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

UC Berkeley (Yale)

Daniel McKinsey	PI, Professor
Ethan Bernard	Project Scientist
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Nicole Larsen	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Britt Hollbrook	Senior Engineer
John Thomson	Development
Dave Hemer	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Project Scientist
Jacob Cutter	Graduate Student
James Morad	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Postdoc
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

University College London, UK

Chamkaur Ghag	PI, Lecturer
James Dobson	Postdoc
Sally Shaw	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Jon Balajthy	Graduate Student
Richard Knoche	Graduate Student

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Diktat Koyuncu	Graduate Student
M. Moongweluwan	Graduate Student
Jun Yin	Graduate Student

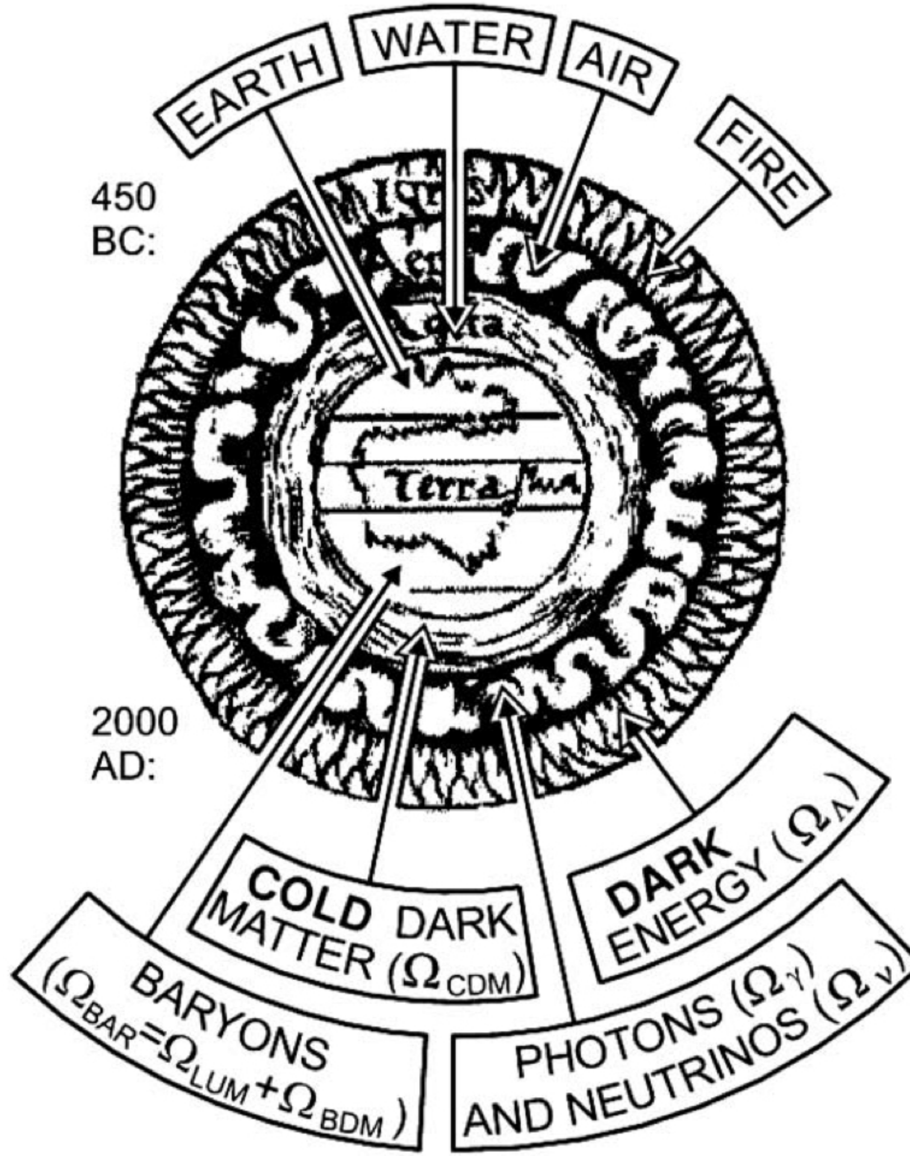
University of South Dakota

Dongming Mei	PI, Professor
Chao Zhang	Postdoc

University of Wisconsin

Kimberly Palladino	PI, Asst Professor
Shaun Alsum	Graduate Student

LUX



EARTH
WATER
AIR
FIRE
450 BC:
Terra
2000 AD:
COLD DARK MATTER (Ω_{CDM})
DARK ENERGY (Ω_{Λ})
BARYONS ($\Omega_{BAR}=\Omega_{LUM}+\Omega_{BDM}$)
PHOTONS (Ω_{γ}) AND NEUTRINOS (Ω_{ν})

THANKS!


Backup Slides
LUX in the Water Tank 2012

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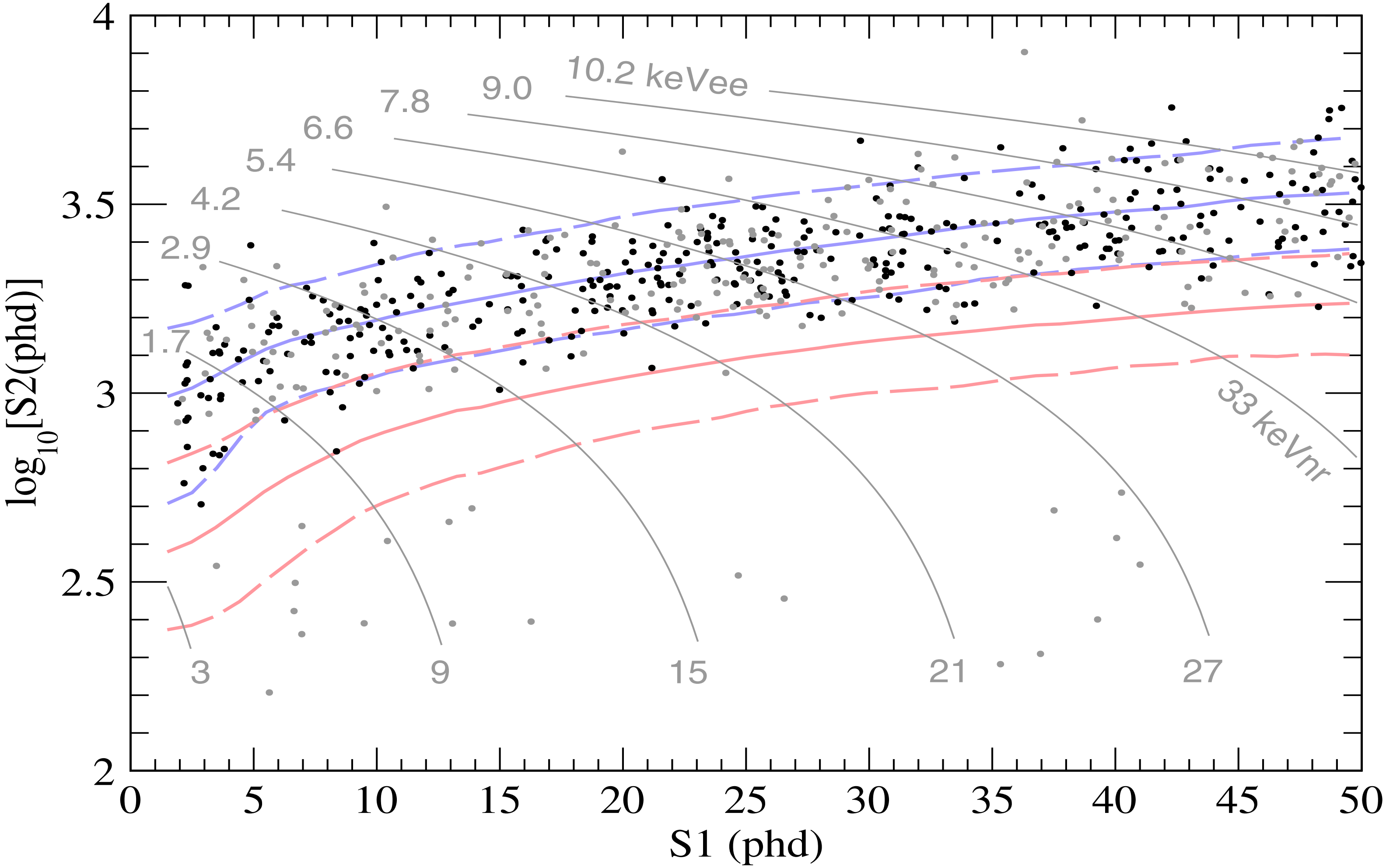
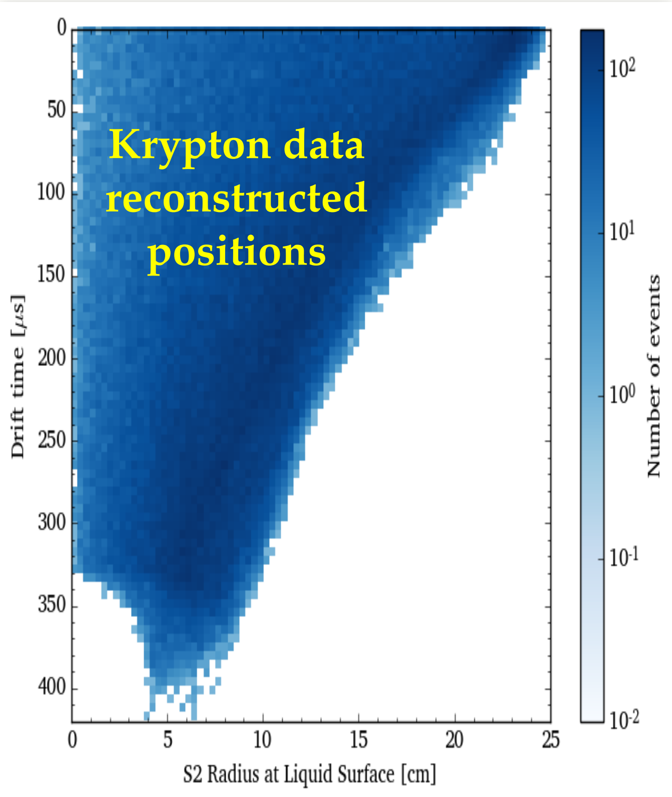
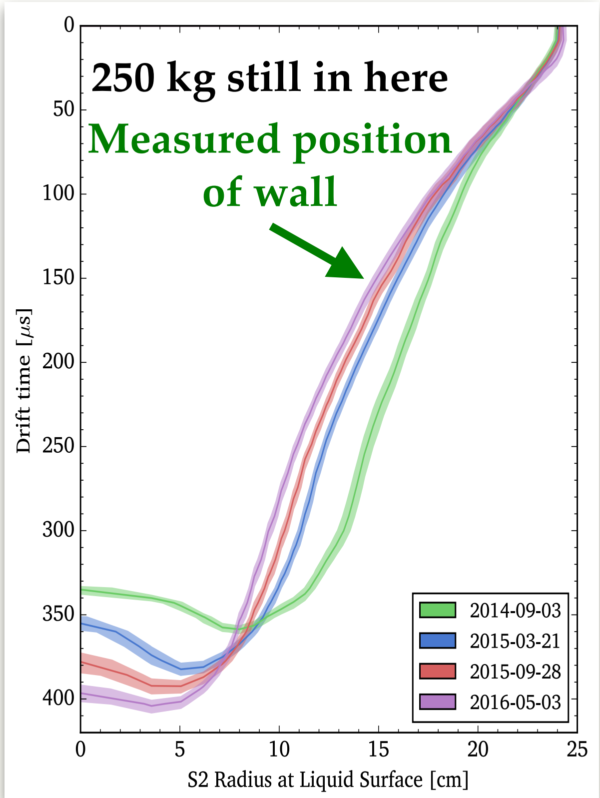
First Science Run Reanalysis

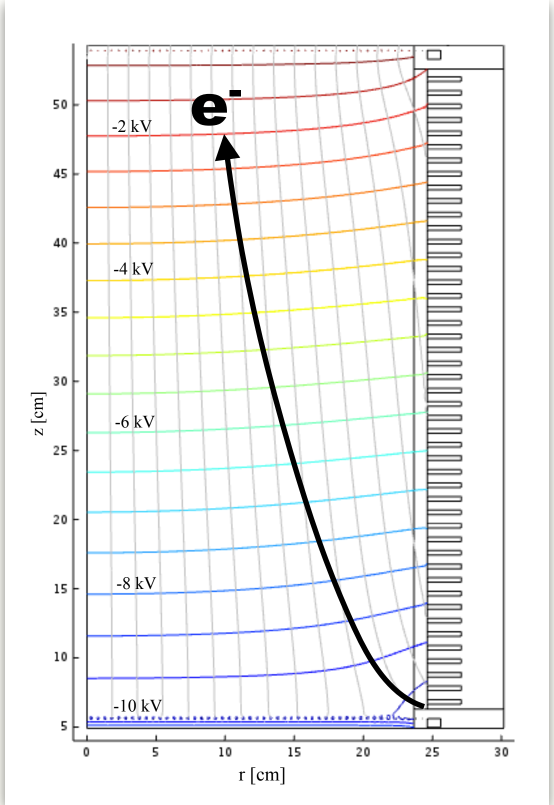


Grid Conditioning

- Results from the first science run featured a 48.9% electron extraction efficiency.
- During the first half 2014 the voltage of the grids was raised for an extended period of time until significant current is drawn. The main objective was to burn any dust or asperities present in the grids.
- After the grid conditioning the electron extraction efficiency increased to >70%.
- …but upon refilling we observed a large radial component in the drift field.
- Moreover the effect of the radial field is time dependent increasing along the run.

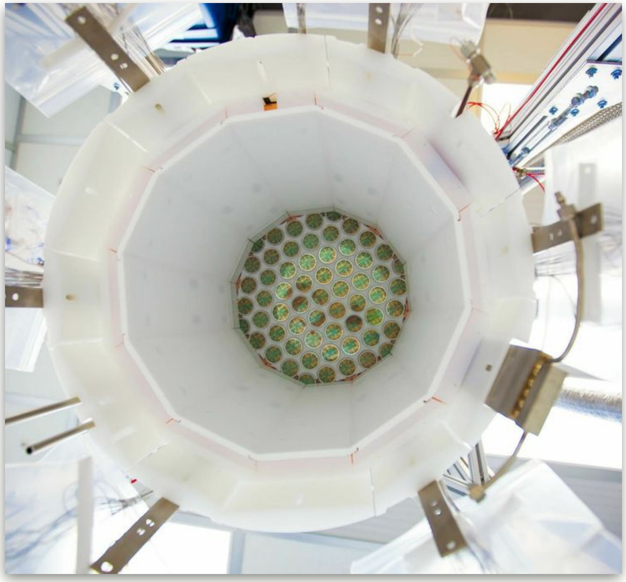


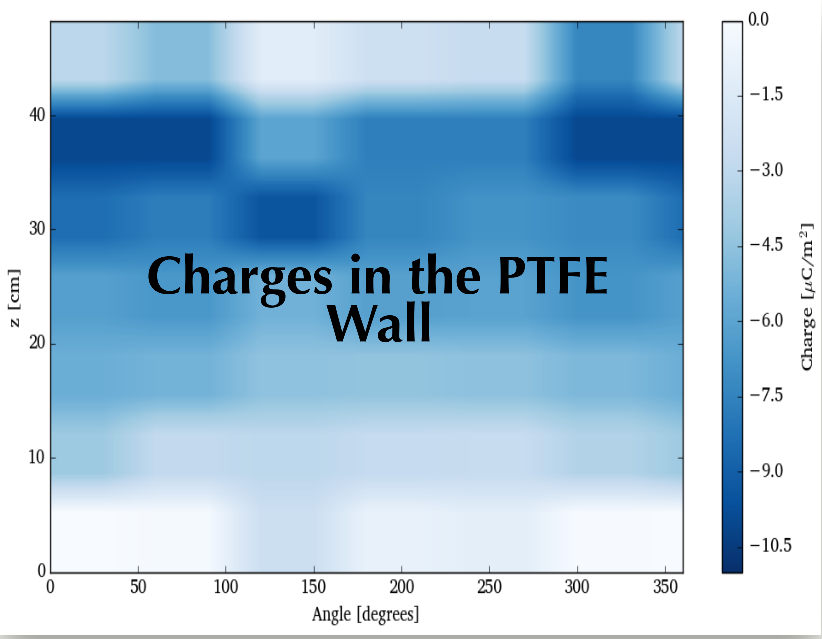


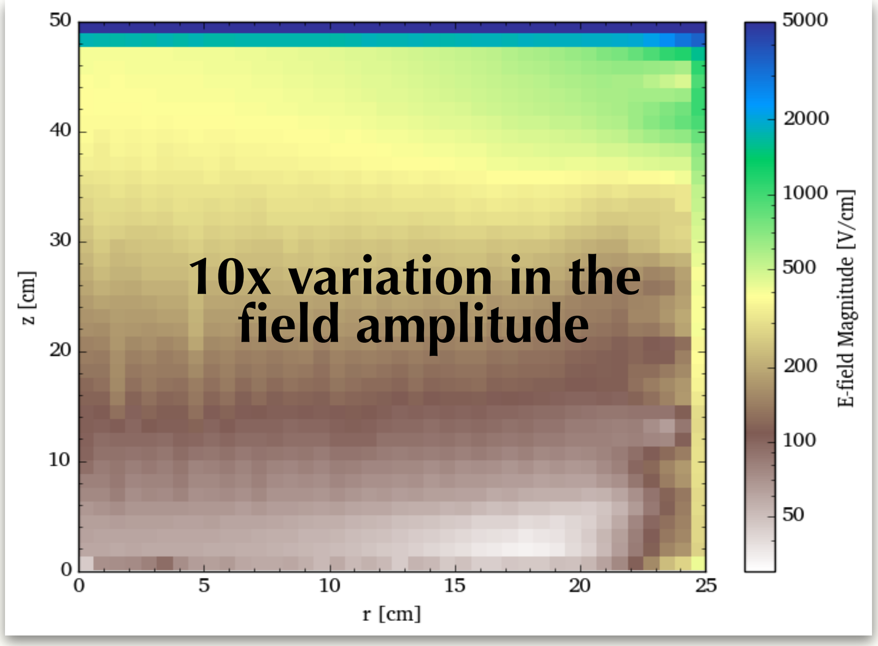


Modeling the Electric Field

- A Fully 3-D model is constructed in the COMSOL Multiphysics® FEM software to compute the electric field in the active region of LUX
- The observed radial field is consistent with a build up of negative charge (0 to -10 μC/m^2) on the PTFE walls.
- Charges are added to the walls to produce the radial field that best produces the observed distribution of ^{83m}Kr decays.







Dealing with the Fields

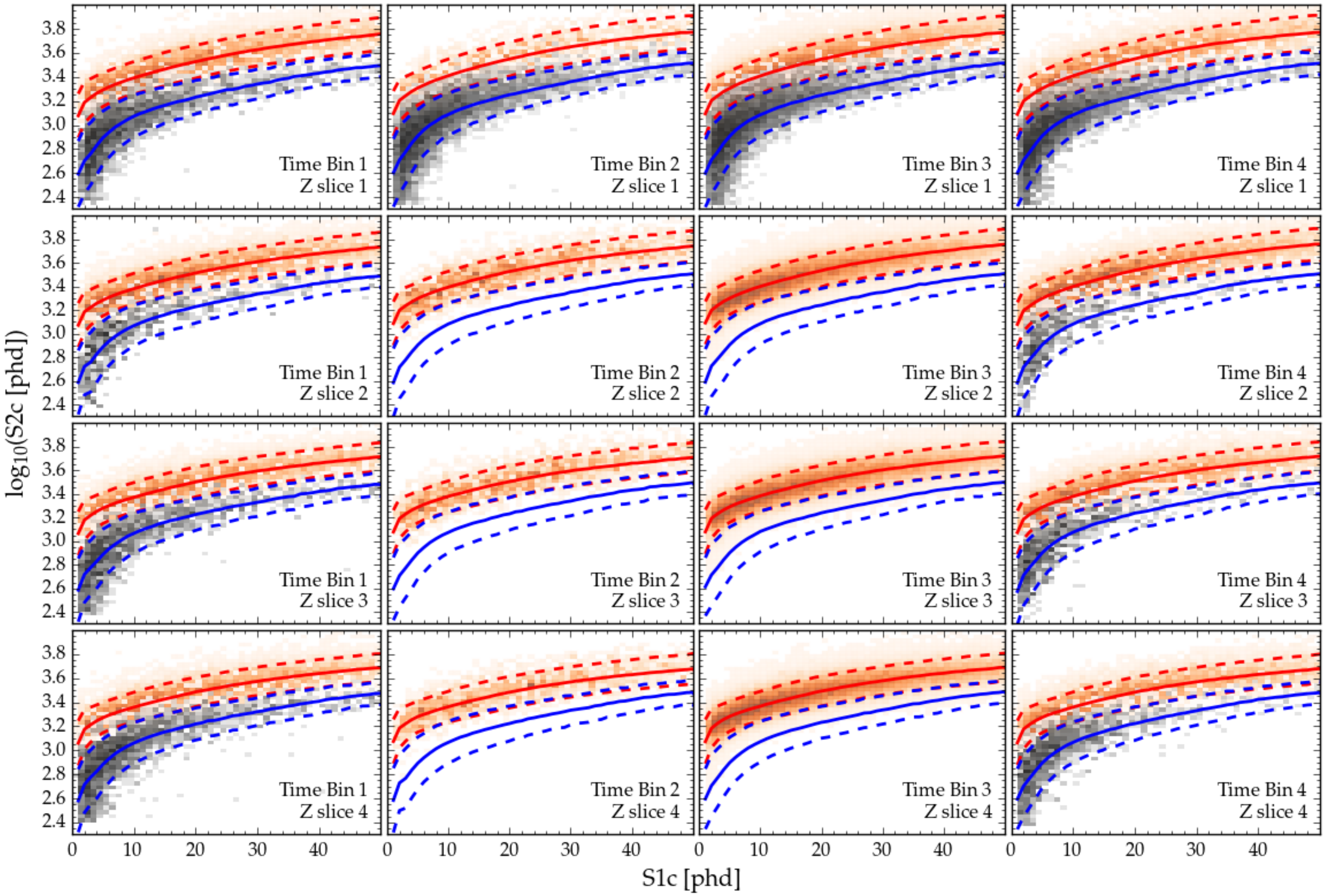
(How to deal with a field that is varying in space and in time?)

- **Detector's volume sliced in *M* time bins and *N z* slices**
- **In each of the *MxN* segments, we assume a uniform detector model for both ER and NR response.**
- **^{83m}Kr is used to compute the fiducial volume in each segment**
- **We found that 4 date bins and 4 z-slices captured the variation with sufficient calibration statistics. The data bins used were:**
  - **Data-bin 1 (2014.09.09-2014.12.31): 46.8 live-days → 105.4±5.3 kg fiducial mass**
  - **Data-bin 2 (2015.01.01-2015.03.31): 46.7 live-days → 107.2±5.4 kg**
  - **Data-bin 3 (2015.04.01-2015.09.30): 91.6 live-days → 99.2±5.0 kg**
  - **Data-bin 4 (2015.10.01-2016.05.03): 146.9 live-days → 98.4±4.9 kg**
- **We effectively have 16 independent detectors**
- **For each detector S1 and S2 are modelled with NEST (Noble Element Simulation Technique, NEST, *http://www.albany.edu/physics/NEST.shtml*)**
- **NEST is "tuned" to each of the 16 detectors by varying the applied field until we see a match between model and calibration data.**

→ **M. Szydagis 2013 JINST 8 C10003 and J. Mock 2014, JINST 9 T04002**

NEST

Dealing with the Fields



Gray density: CH_3T calibration (ER)

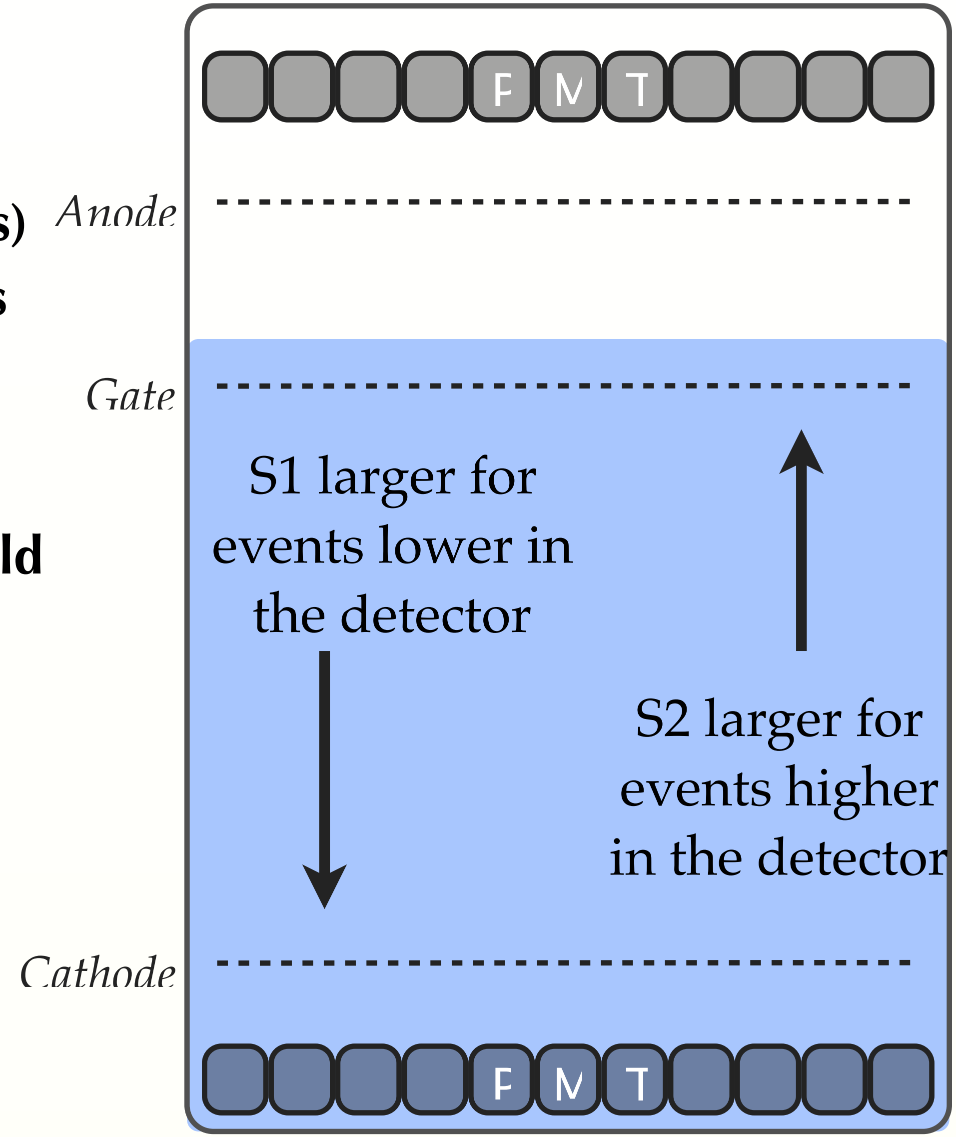
Orange density: DD calibration (NR)

Solid lines:
NEST model,
ER, NR band mean

Dashed lines:
NEST model,
10-90 percentile.

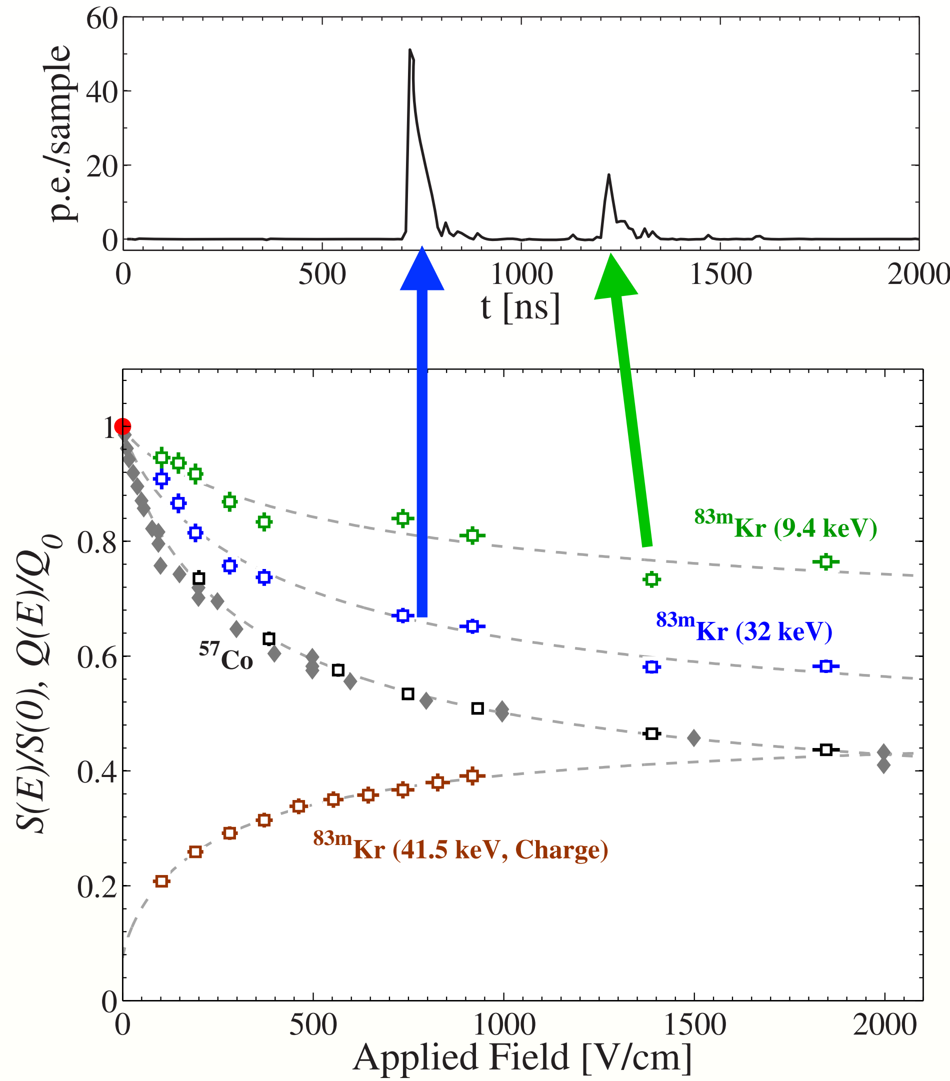
S2/S1 Position Corrections

- Size of the S1 depends on the location of the event (due to geometrical light collection), and S2 (due electronegative impurities)
- On the FSR the correction factors for both S1 and S2 were obtained by flat fielding a mono-energetic source ^{83m}Kr.
- However, a spatially varying E-field ALSO affects S1 and S2 sizes, but differently for every particle type and energy.



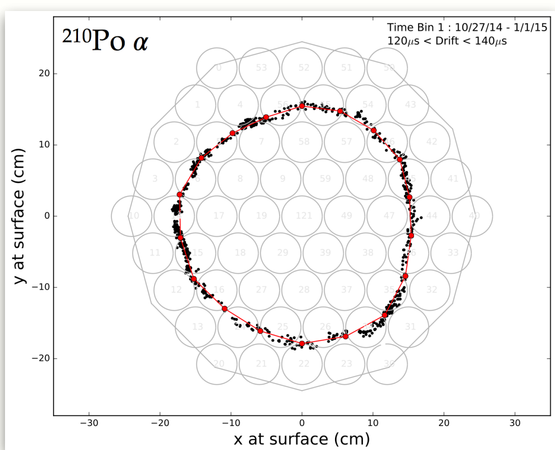
S2/S1 Position Corrections

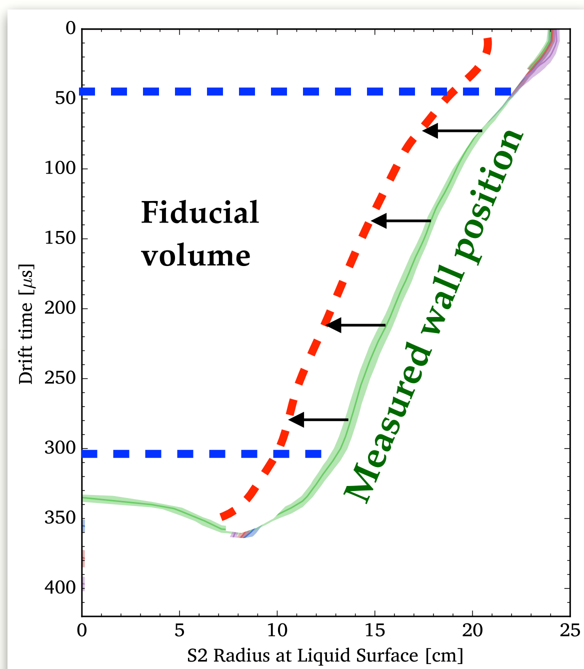
- **Our strategy is:**
  - **Disentangle position effects from field effects;**
  - **Apply a correction to account for position effects only.**
- **^{83m}Kr has two decays close in time. The ratio of the first-to-second S1 pulse area depends on field alone. This allows us to measure the component of variation due to applied field alone.**

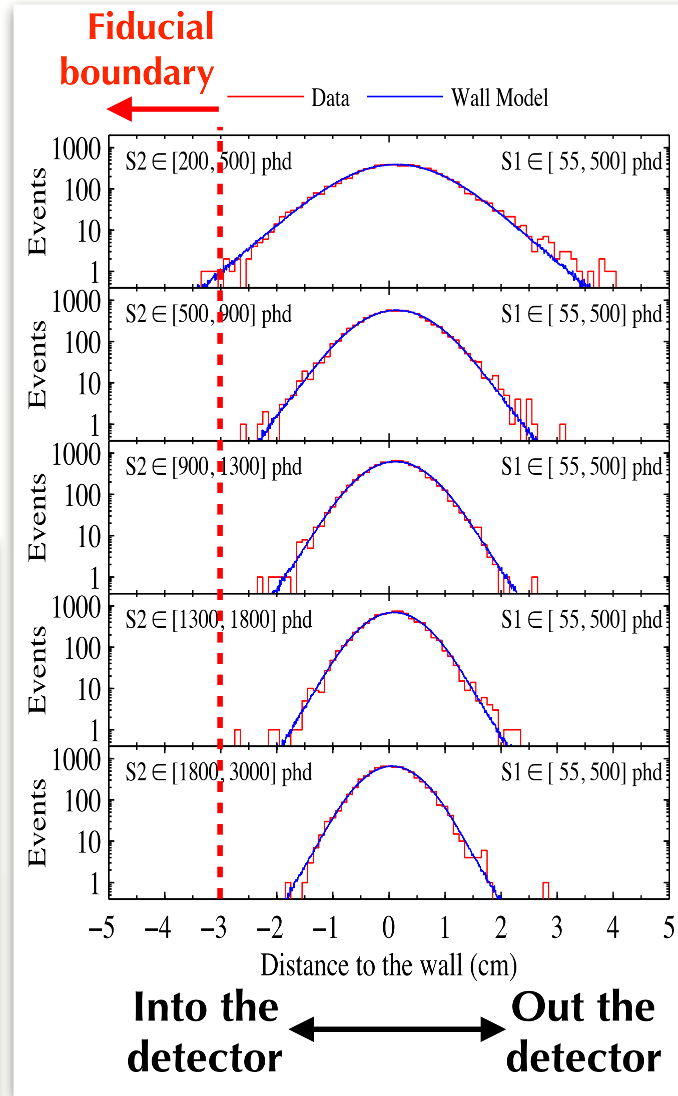


Wall-surface backgrounds

- ^{238}U late chain plate-out on PTFE surfaces survives as ^{210}Pb and its daughters (mainly ^{210}Bi and ^{210}Po).
- Betas and ^{206}Pb recoils travel negligible distance, but they can be reconstructed some distance from the wall as a result of position resolution (especially for small S2s).
- These sources can be used to define the position of the wall in measured coordinates, for the 4 data bins and any combination of drift-time and ϕ.
- The boundary of the fiducial volume is defined at 3 cm from the observed wall in S2 space and for a drift time between 50 and 300 μs.

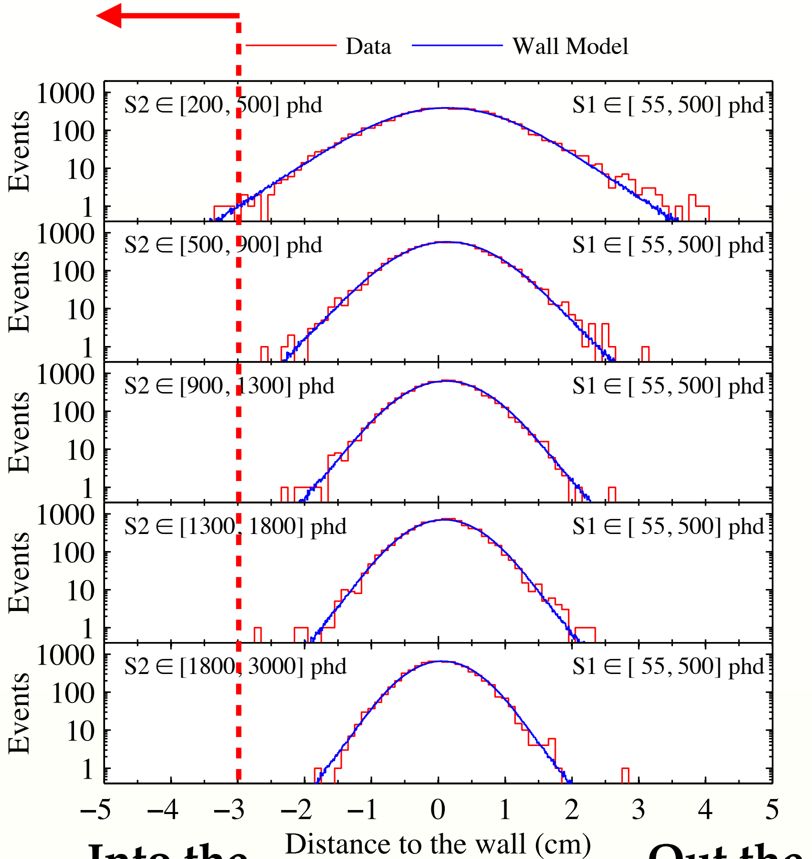






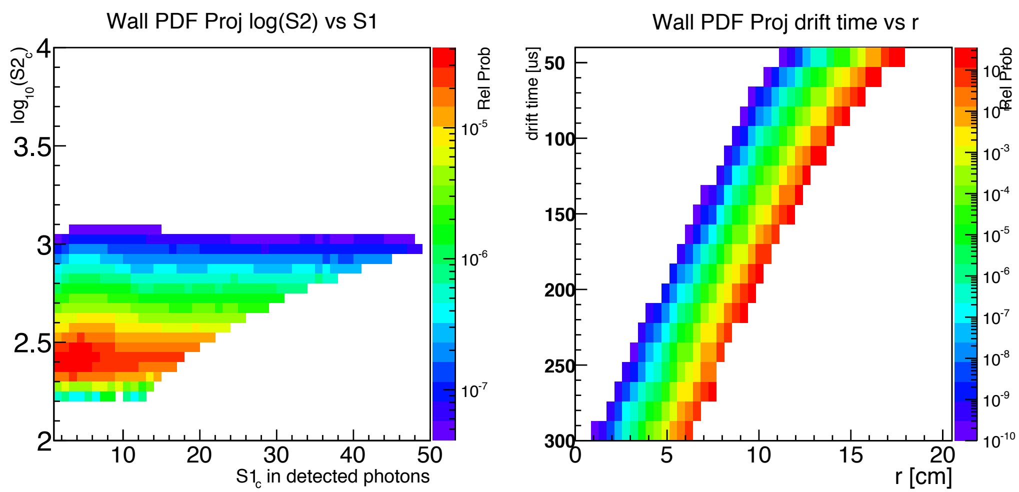
Wall Surface Model

Fiducial boundary

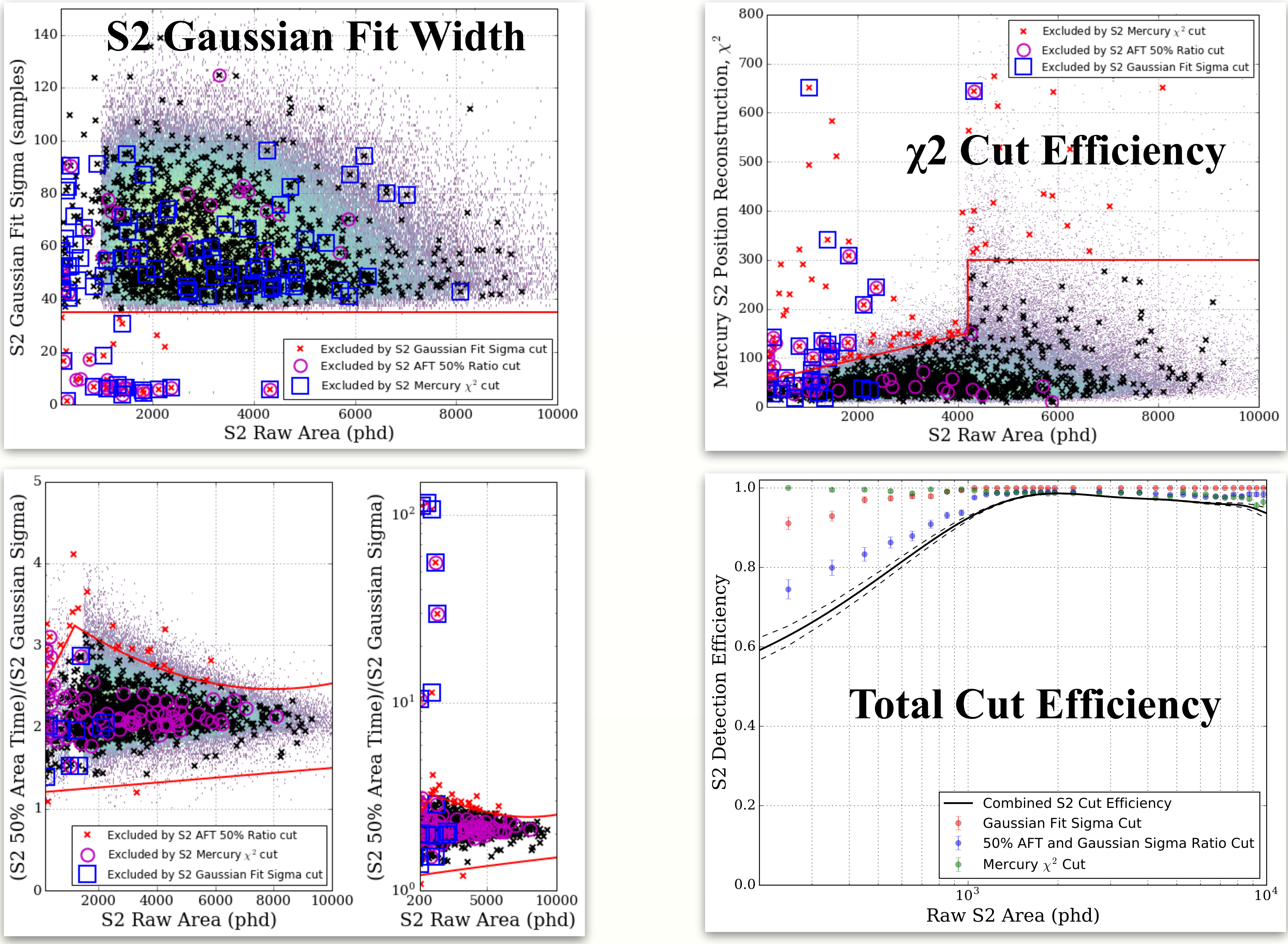


Into the detector ⟷ **Out the detector**

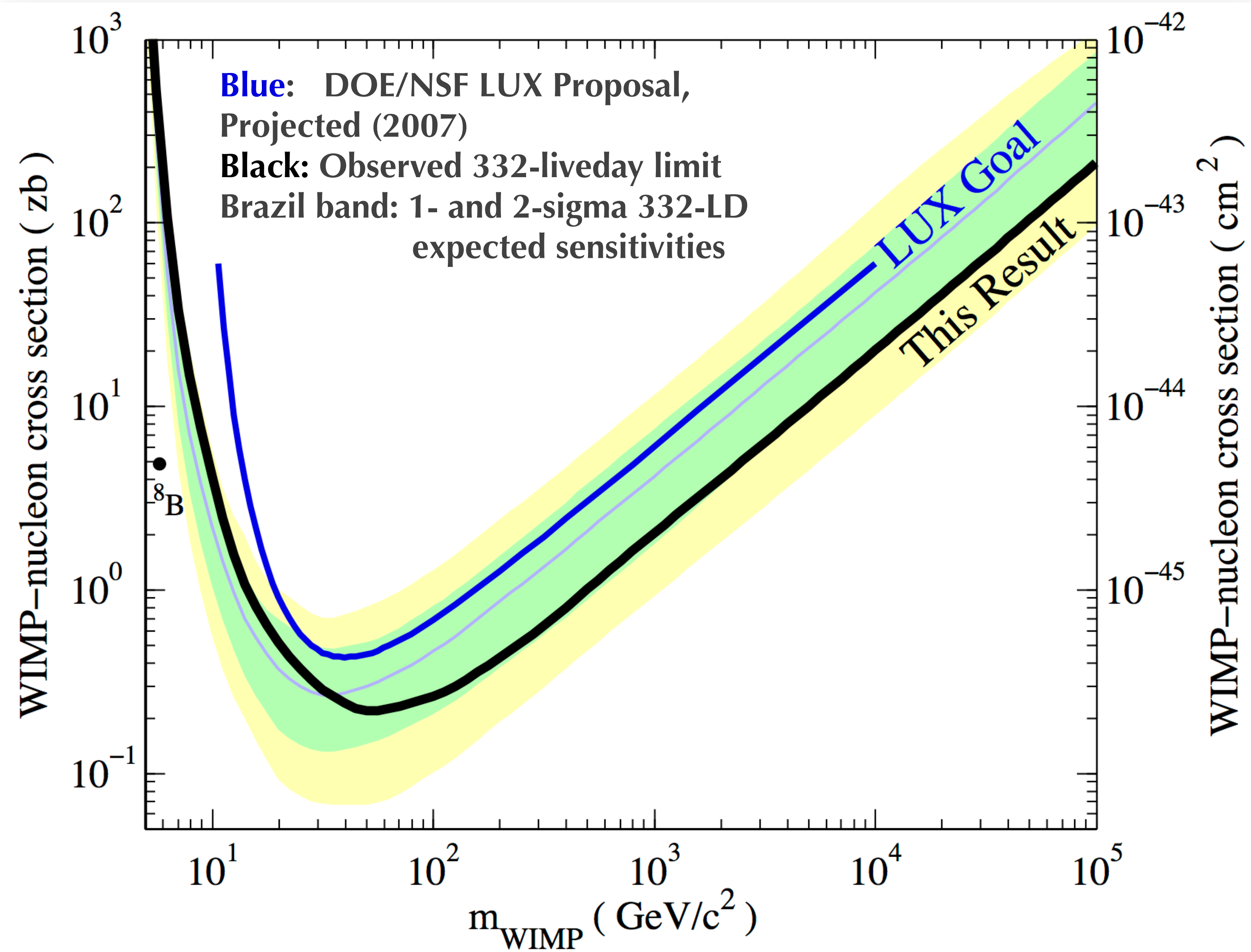
Wall PDFS



S2 Quality Cuts and Efficiency

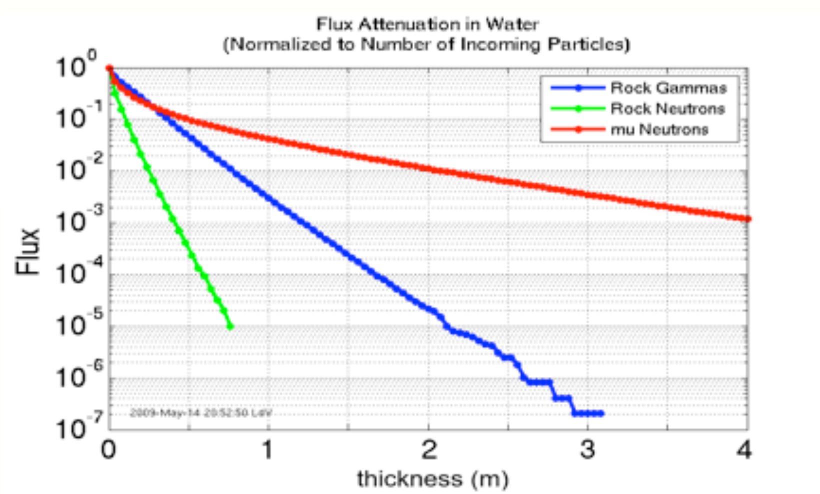


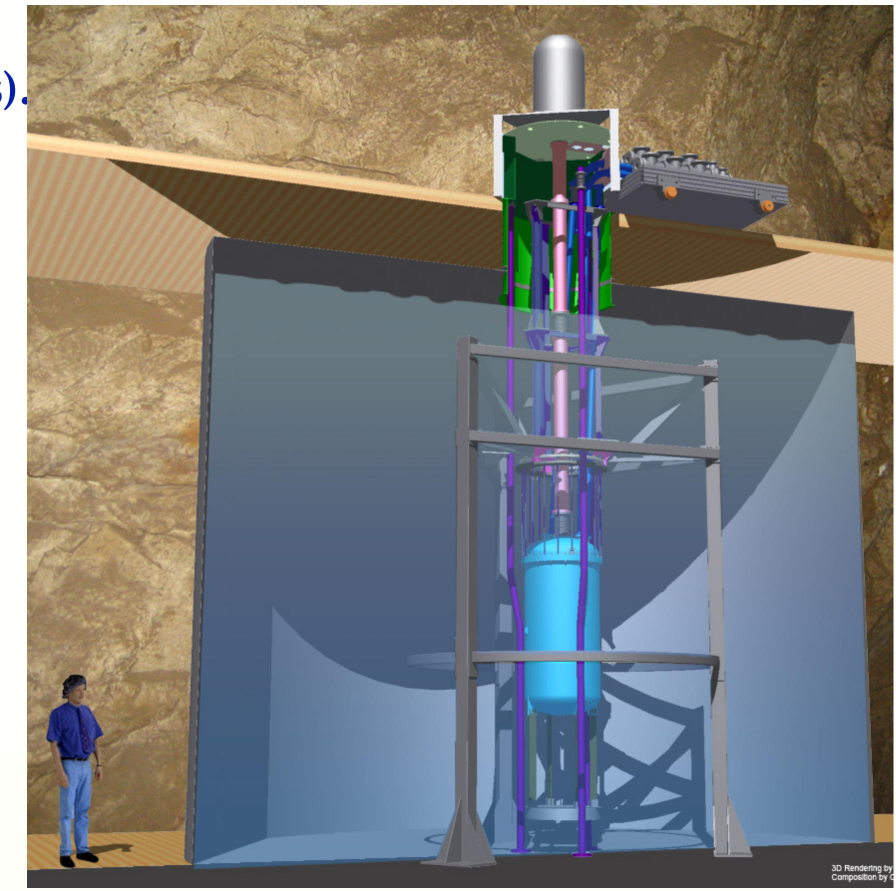
LUX Proposal VS Main Result



The Water Shield

- **Water Tank: ø = 8 m, h = 6 m (300 tonnes)**
- **Cherenkov based active shielding**
  - **Dimensions: ø = 8 m, h = 6 m (300 tonnes).**
  - **Muon active veto: 20 PMTs Ø10″.**
- **Ultra-low Background**
  - **γ suppression: x10^{-9}**
  - **Neutron sup. (E_n >10 MeV ~10^{-3} and E_n <10 MeV >10^{-9}).**





Krypton Removal

- ^{85}Kr - beta decay – intrinsic background in liquid Xe
  - ^{85}Kr: 0.687 MeV β, 10 yr half-life
  - Research grade Xenon: ~100 ppb Kr => 10^4 - 10^5 reduction needed
- August 2012 - January 2013: Kr removal at Case Western Reserve University
  - Chromatographic separation system
  - Kr lighter & less polarisable than Xe. Kr bonds weaker, travels faster through charcoal and pure xenon is left behind.
- Kr concentration reduced from 130 ppb to 4 ppt, (factor of 30000)
  - 1 ppt achievable (useful for next-generation detectors)