Dark Matter Searches in LUX

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on behalf of the LUX Collaboration

COSPA-2016

INVESTIGADOR FCT

QUALIFICAR É CRESCER.

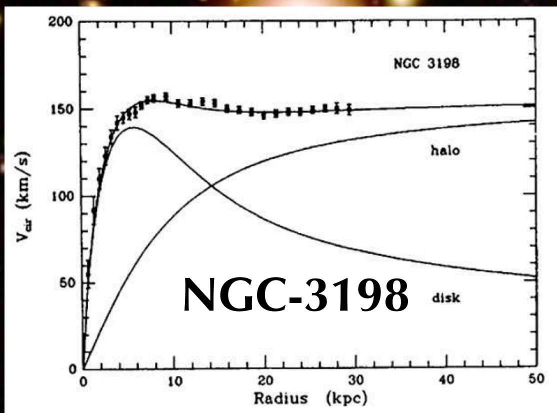
Outline

- The LUX detector - two phase Liquid/ Gas time projection chamber
  - Direct dark matter detection
  - How LUX detector works
- The LUX calibrations (Krypton, DD and Tritium)
- 332 live-days second science run (2014-2016) results
  - LUX backgrounds
  - Main dark matter search analysis
  - Salting
  - LUX dark matter search limits

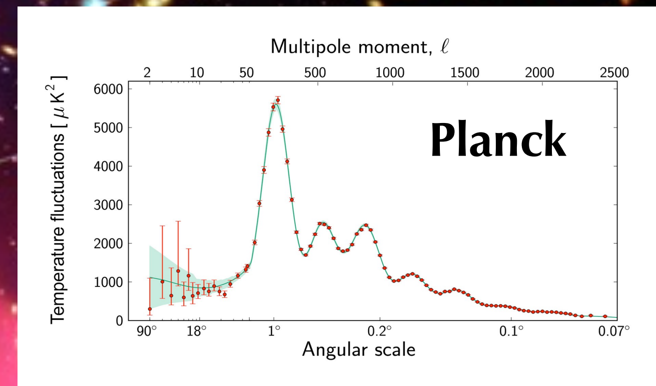
Image: LUX inside the water tank (September 2012)

Dark Matter Evidence

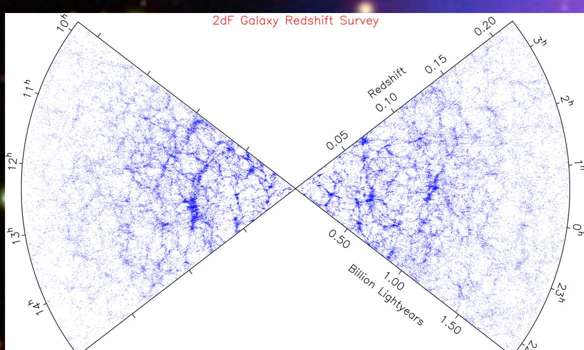
Rotation curves of galaxies



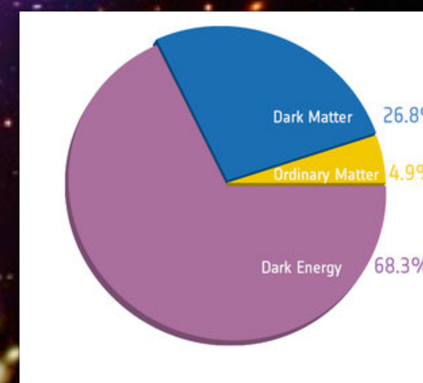
Cosmic Microwave Background



Galaxies Surveys



Gravitational lensing
Bullet Cluster



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

See talk from Paolo Gondolo 9:00 AM tomorrow

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.

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 effective field interaction…**
  - **Isothermal model: expect recoil <10 keV requiring detectors with a very low threshold.**
  - **Challenge backgrounds - (Ambient radioactivity: ~100 evts/kg/s)**
    - **Go underground, passive and active veto, careful selection of materials with very low background**

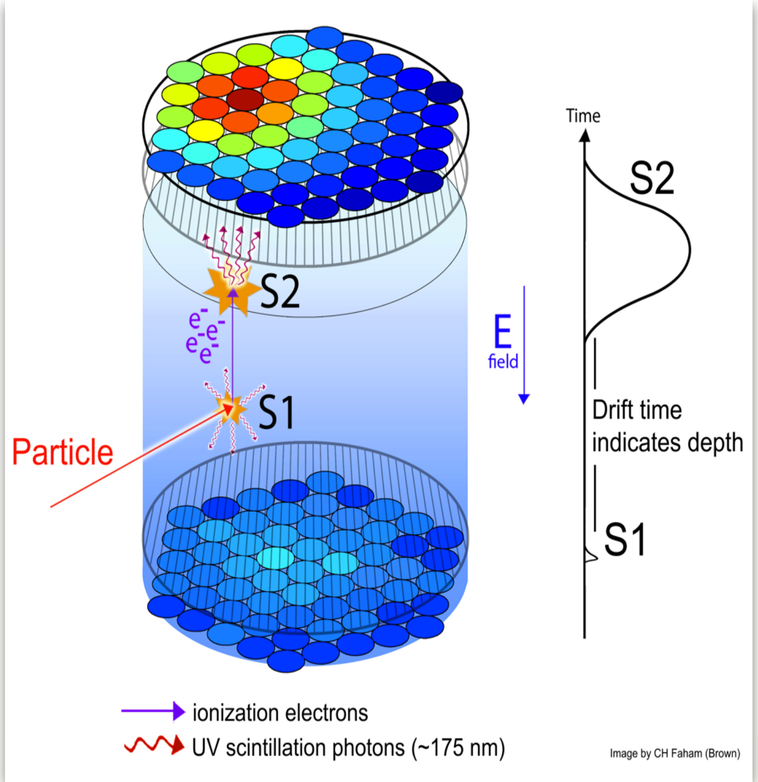
See talk from Manfred Lindner 9:30 AM tomorrow

Indirect Detection

Why a Liquid Xenon TPC?

LUX is a dual phase liquid/gas xenon time projecting chamber (TPC). Why?

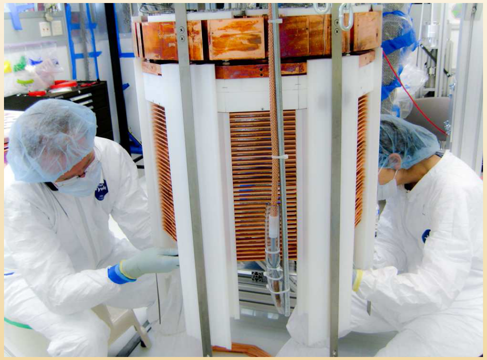
- **Xenon has a high atomic mass (A=131), high density (2.9 g/cm^3), no intrinsic backgrounds and a high light yield.**
- **TPCs are scalable to multi-ton size (see LZ).**
- **Energy depositions produce light and charge**
  - Prompt scintillation (S1)
  - Proportional scintillation (S2): Measurement 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 is used as a discriminator against backgrounds (>99%):**
  - Nuclear Recoil (NR): WIMPs and neutrons interact with nuclei - short, dense tracks
  - Electronic Recoil (ER): axions, γs and e- interact with the electrons - longer, less dense tracks
- **Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity studies.**

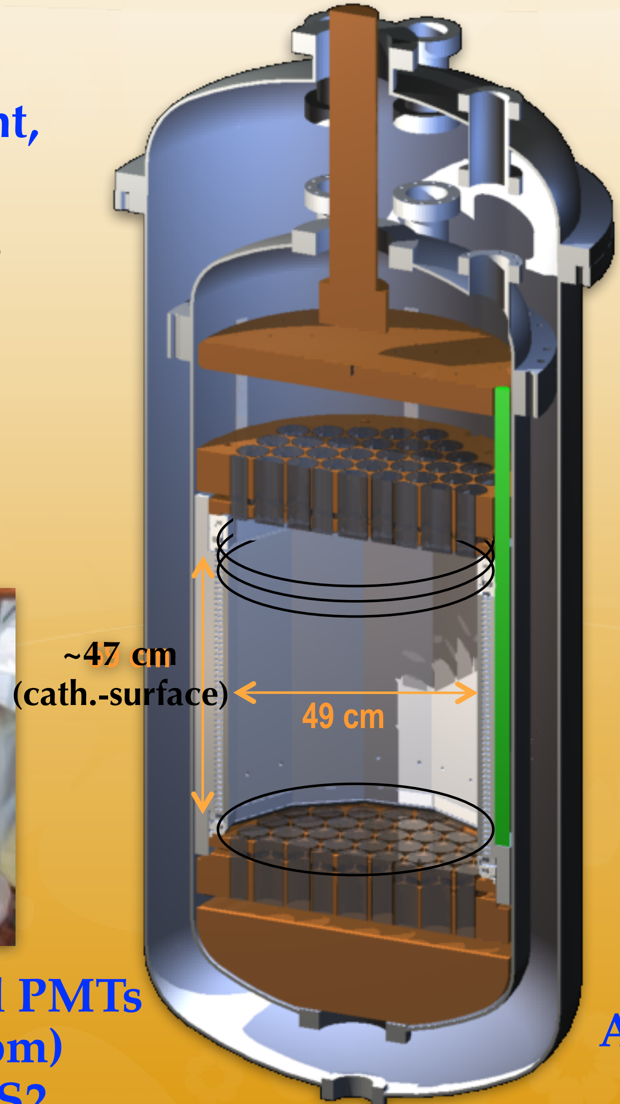
The LUX Experiment

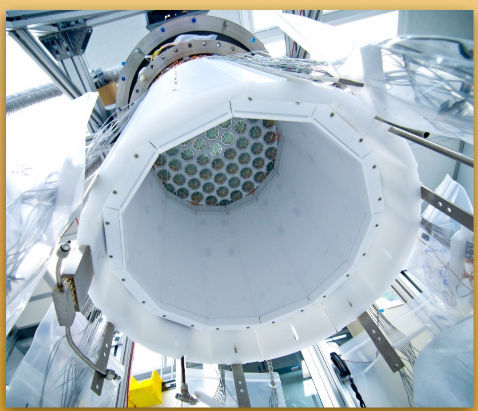
- 370 kg Liquid Xenon Detector (59 cm height, 49 cm diameter)
  - 250 kg in the active region (with field)



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

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



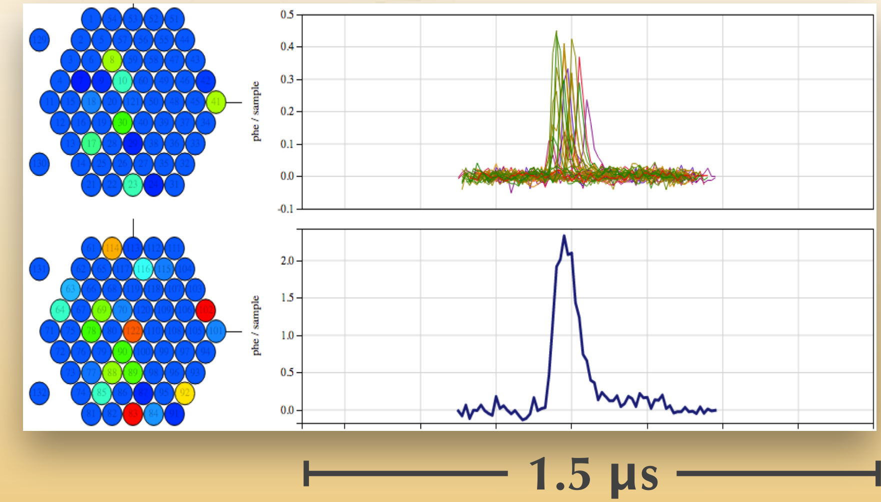


Active region defined by PTFE reflectors (high reflectivity >97%) - high light collection)

Typical LUX Pulses

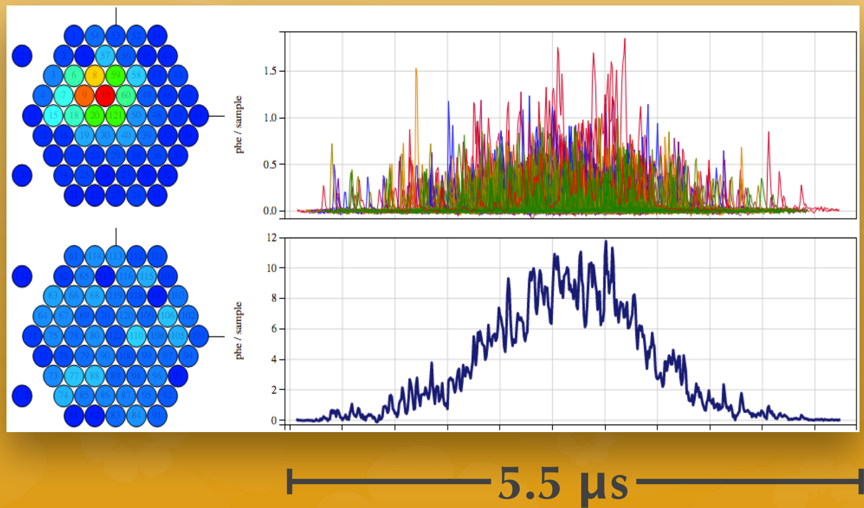
S1 - Prompt scintillation

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

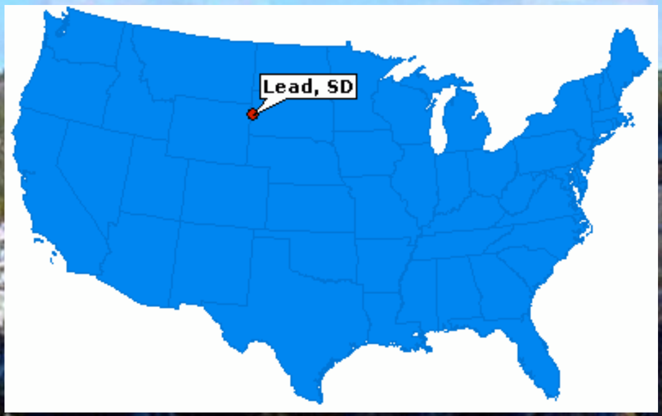


S2 - Electroluminescence

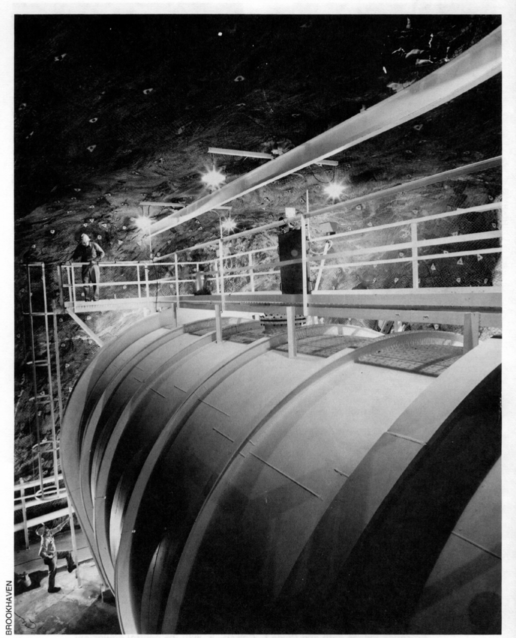
- Near-gaussian pulse shape
  - pulse width depends on the depth
- ~25 phd per extracted electron
- ~57/43% (top/bot.) light in PMTs
- Threshold of 150-200 phd (WIMP-Search)



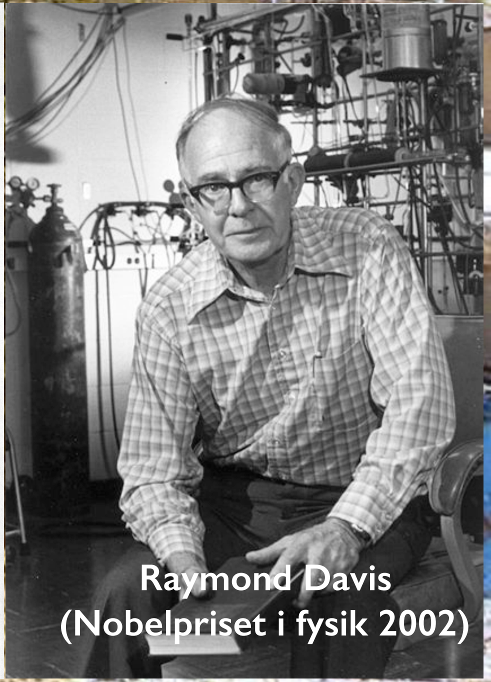
LUX AT SURF (Sanford Underground Research Facility)



- 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.

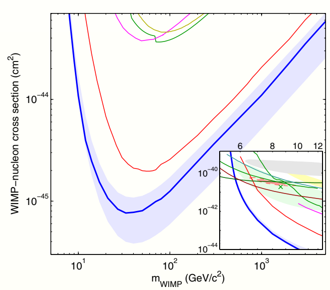


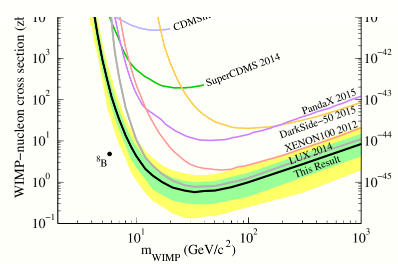
Raymond Davis (Nobelpriset i fysik 2002)

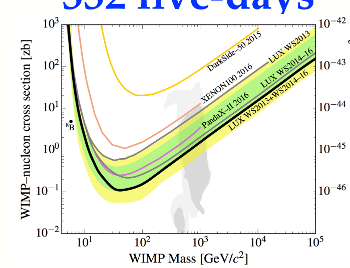
Timeline 2006-2016

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**







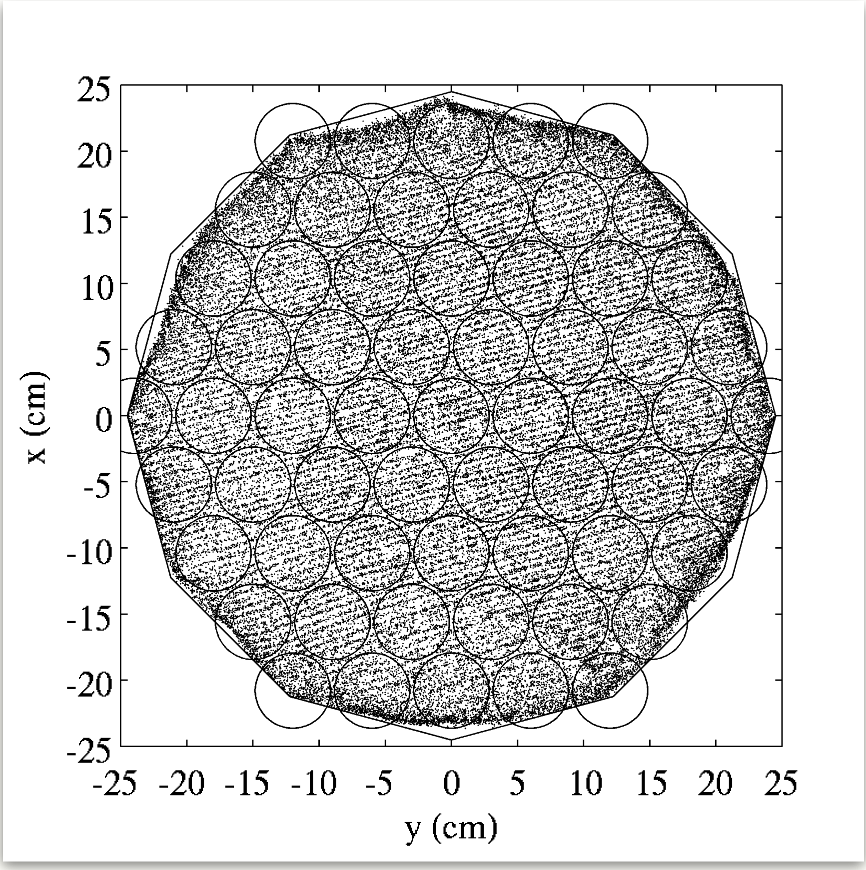
PRL, 112, 091303 2014 **PRL, 116, 161301 2016** **arXiv 1608.07648**

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)

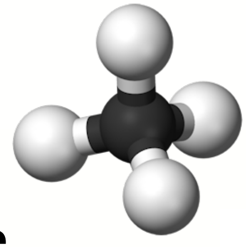
Second Science Run



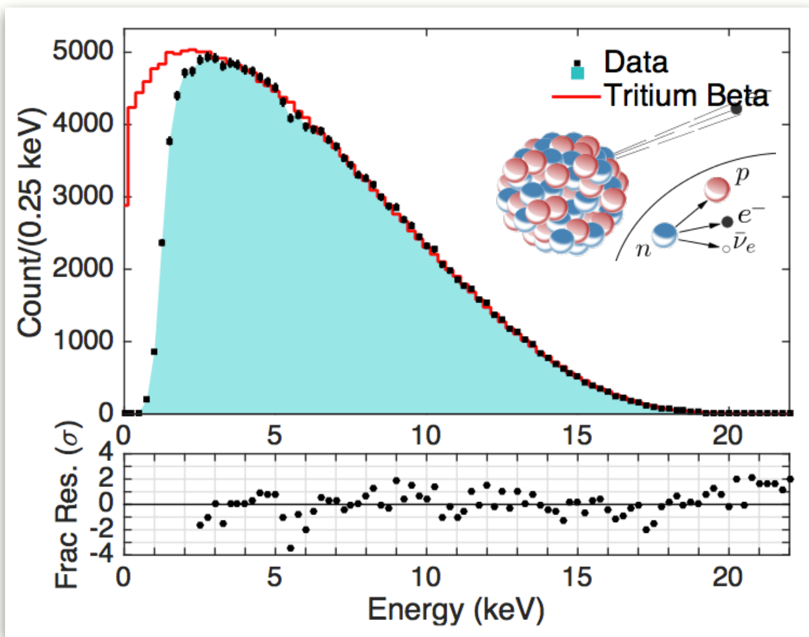
The large difference between the drift field (180 V/cm) and the extraction field (2.8 kV/cm in liquid) causes the the drift field lines to be compressed as they pass through the gate plane; any electrons leaving the drift volume appear only in narrow strips between each pair of gate wires.

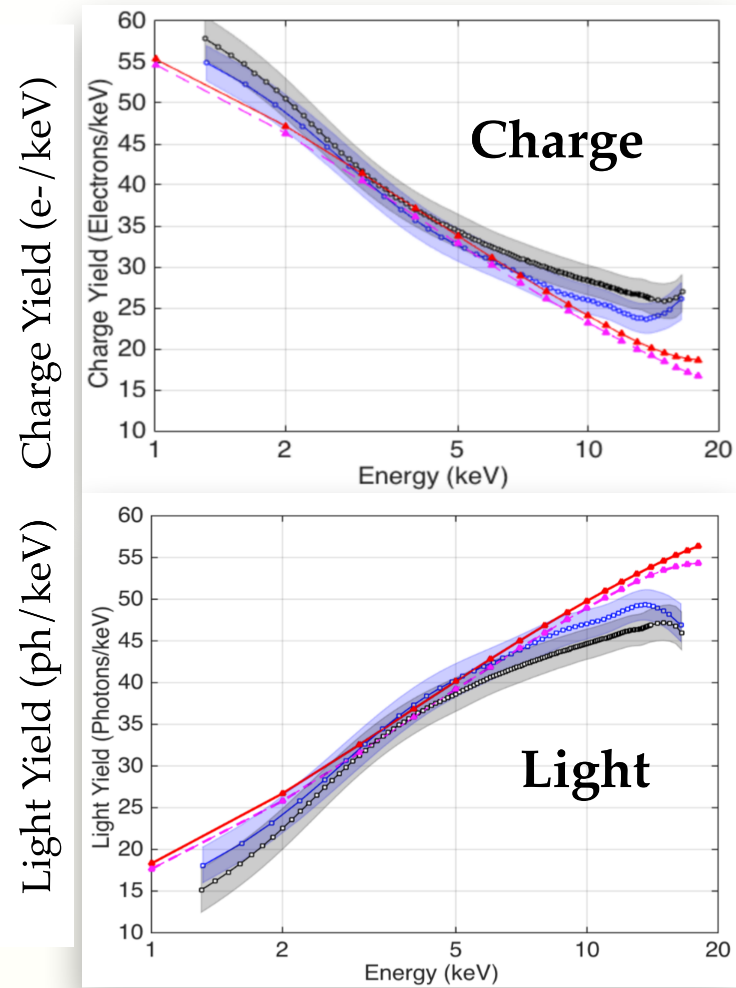
ER Calibrations

- **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 system and removed by the getter.**
- **ER calibrations performed every three months**

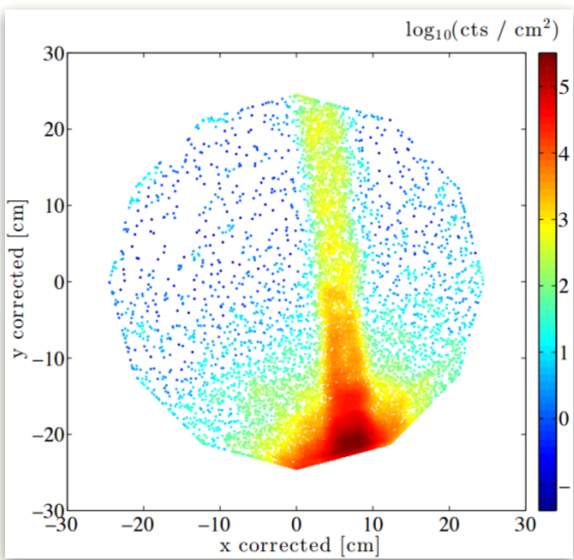


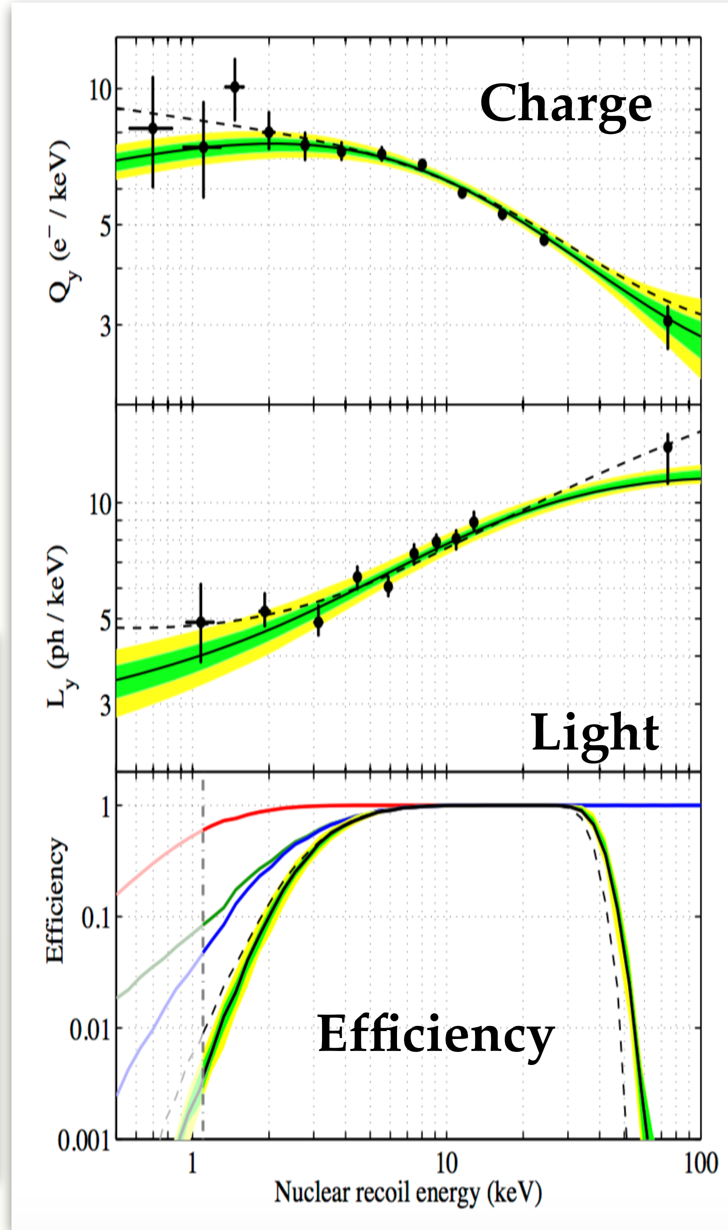


Phys. Rev. D 93, 072009 (2016)

NR Calibration

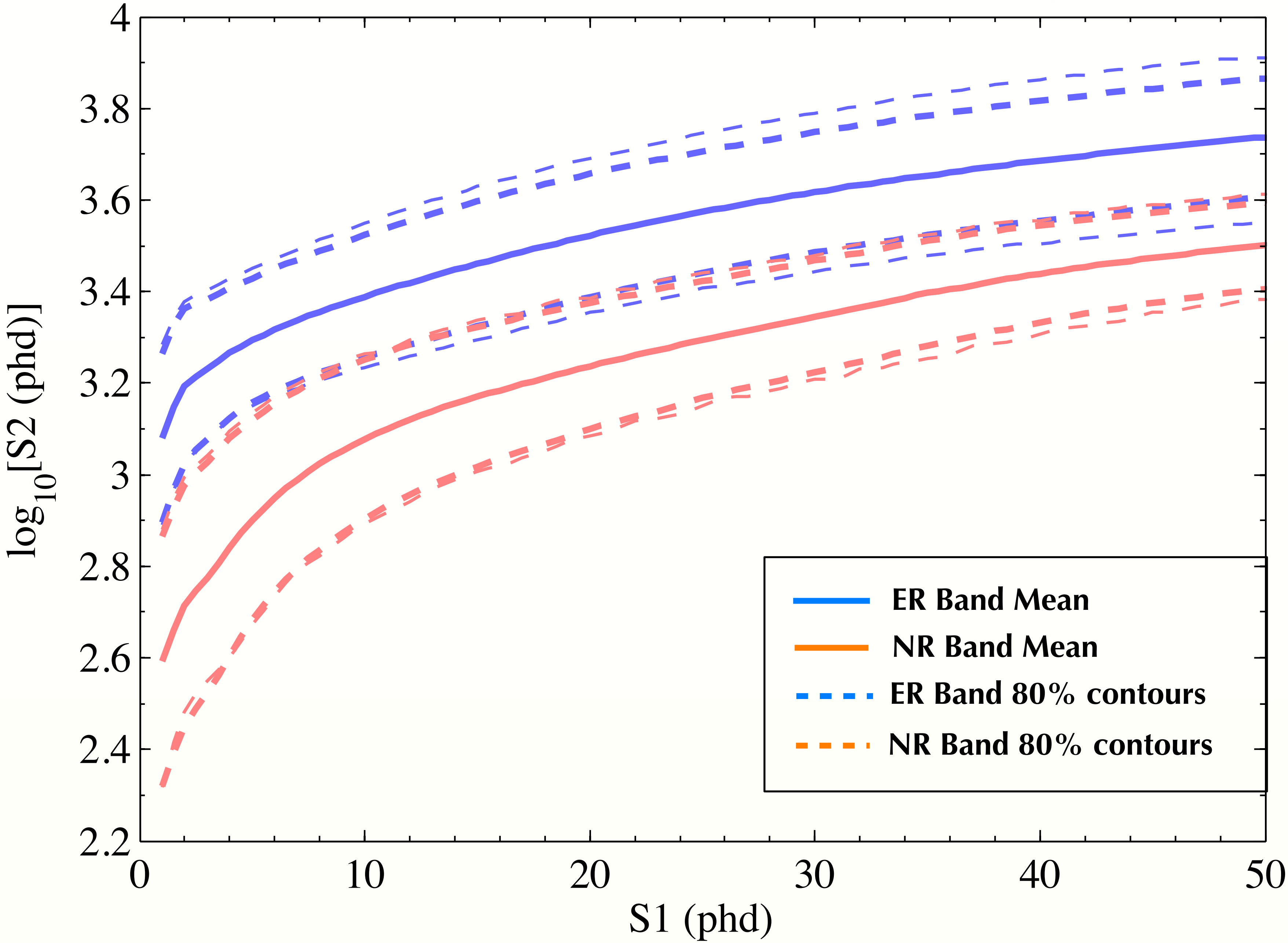
- **Deuterium-Deuterium neutron Generator installed outside LUX water tank**
- **The 2.45 MeV emitted neutrons are collimated to the level of ~1 degree**
- **Two analysis are performed**
  - **Double-scatters - ionization yield Q_y (0.7 to 74 keV_{nr})**
  - **Single-scatters - scintillation yield L_y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



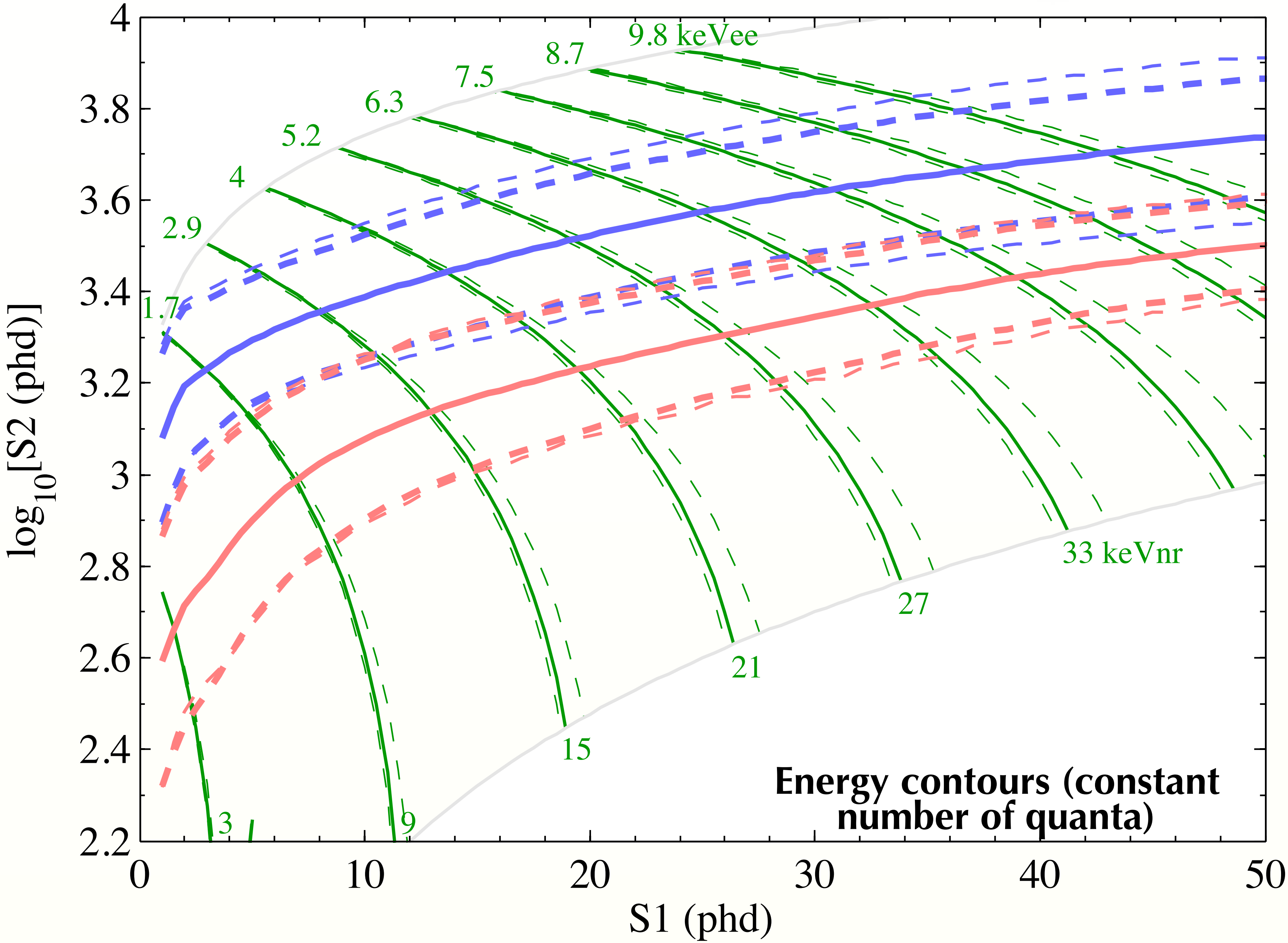


https://arxiv.org/abs/1608.05381

LUX 2014/2016 Detector's Response



LUX 2014/2016 Detector's Response



Estimation of Backgrounds

Background source	Expected number below NR median
External Gamma Rays	1.51±0.19
Internal Betas	1.20±0.06
^{238}U late chain wall back.	8.7±3.5
Accidental S1-S2	0.34±0.10
Solar ^{8}B neutrinos	0.15±0.02

External Gamma Rays, Internal Betas: Bulk volume, but leakage at all energies

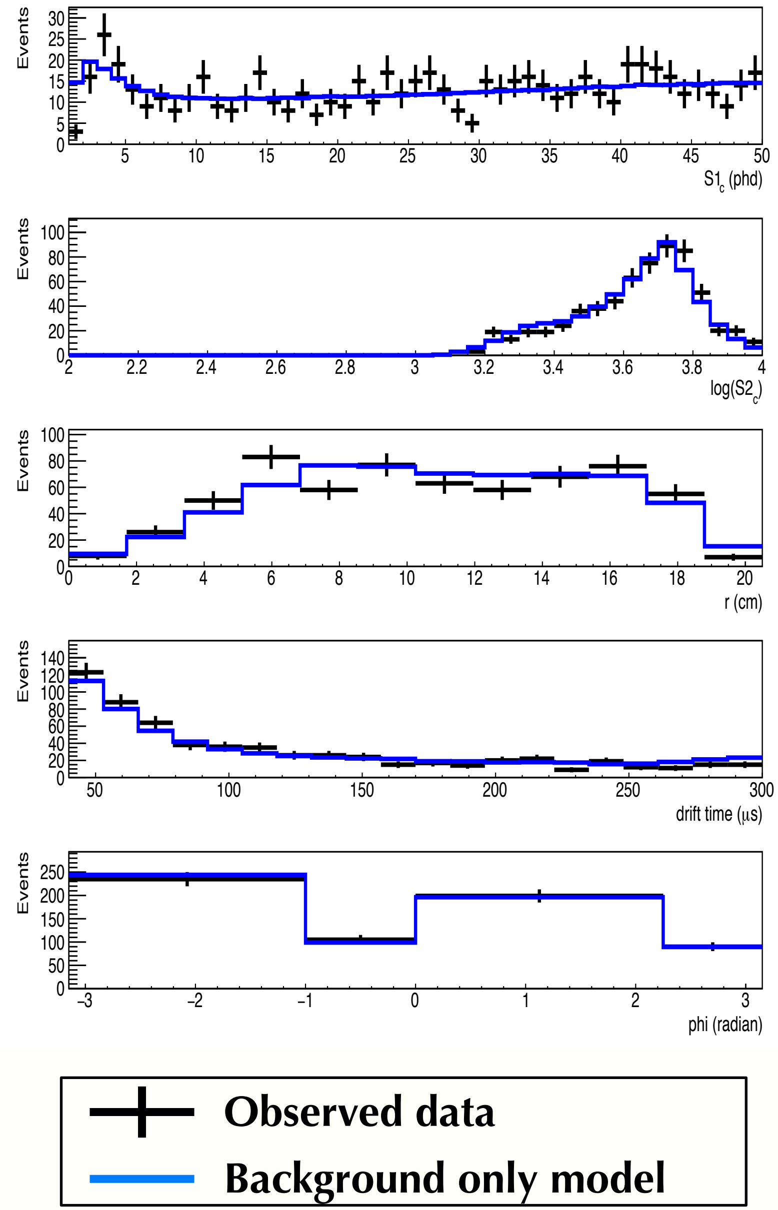
^{238}U late chain wall back.: Low-energy, but confined to the edge of our fiducial volume

Accidental S1-S2, Solar ^{8}B neutrinos: In the bulk volume, low- energy, in the NR band

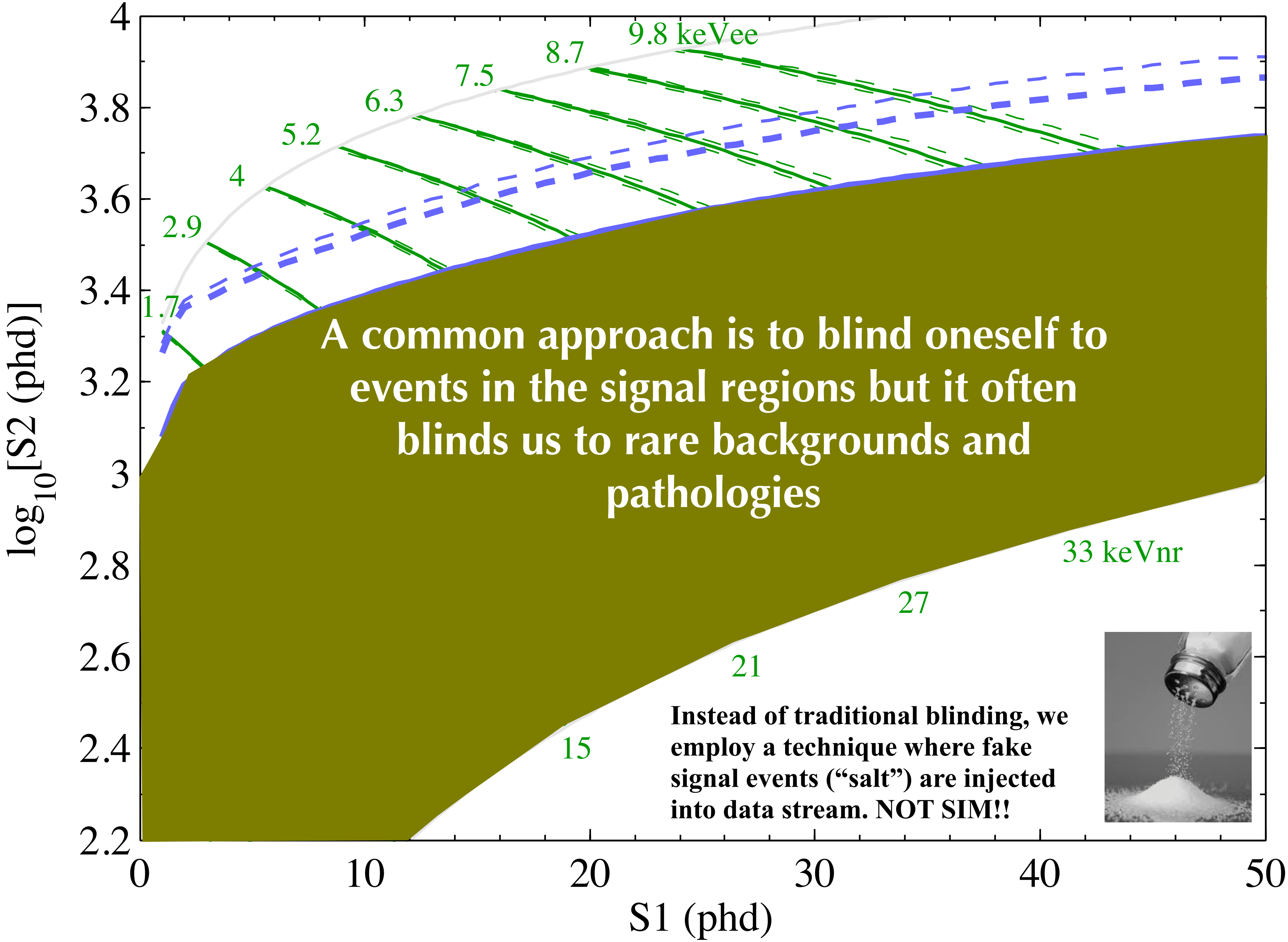
- These figures are figure of merit only. In our analysis we use a **likelihood analysis.**
  - + ~ 0.3 single scatter neutrons, e.g. from (α, n), not included in PLR

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
- The response of the detector (S1 and S2 signals) is modeled with NEST (Noble Element Simulation Technique, http://www.albany.edu/physics/NEST.shtml) with input from our situ calibration data
  - See M. Szydagis 2013 JINST 8 C10003
- 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.



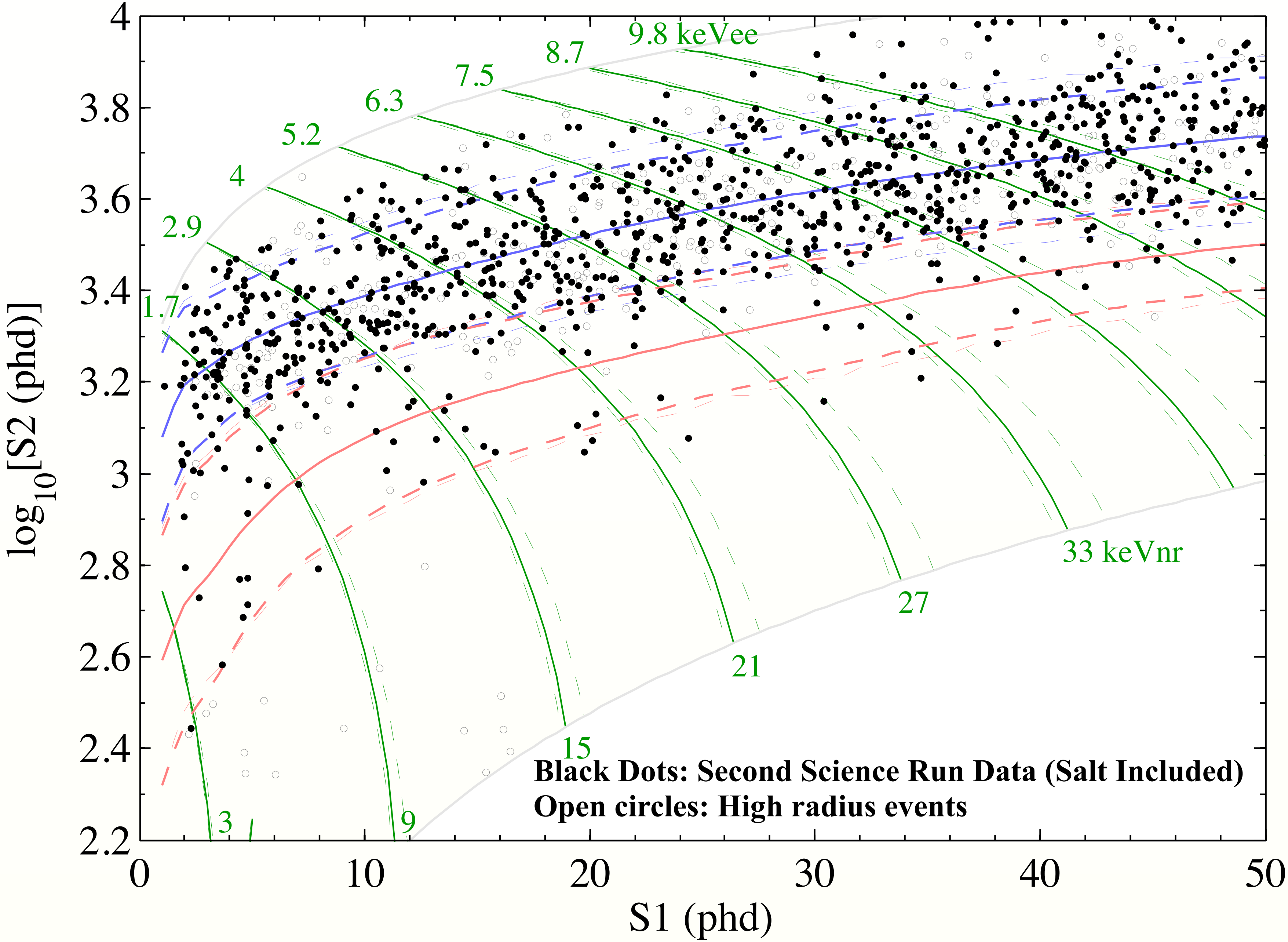
LUX Blind Analysis



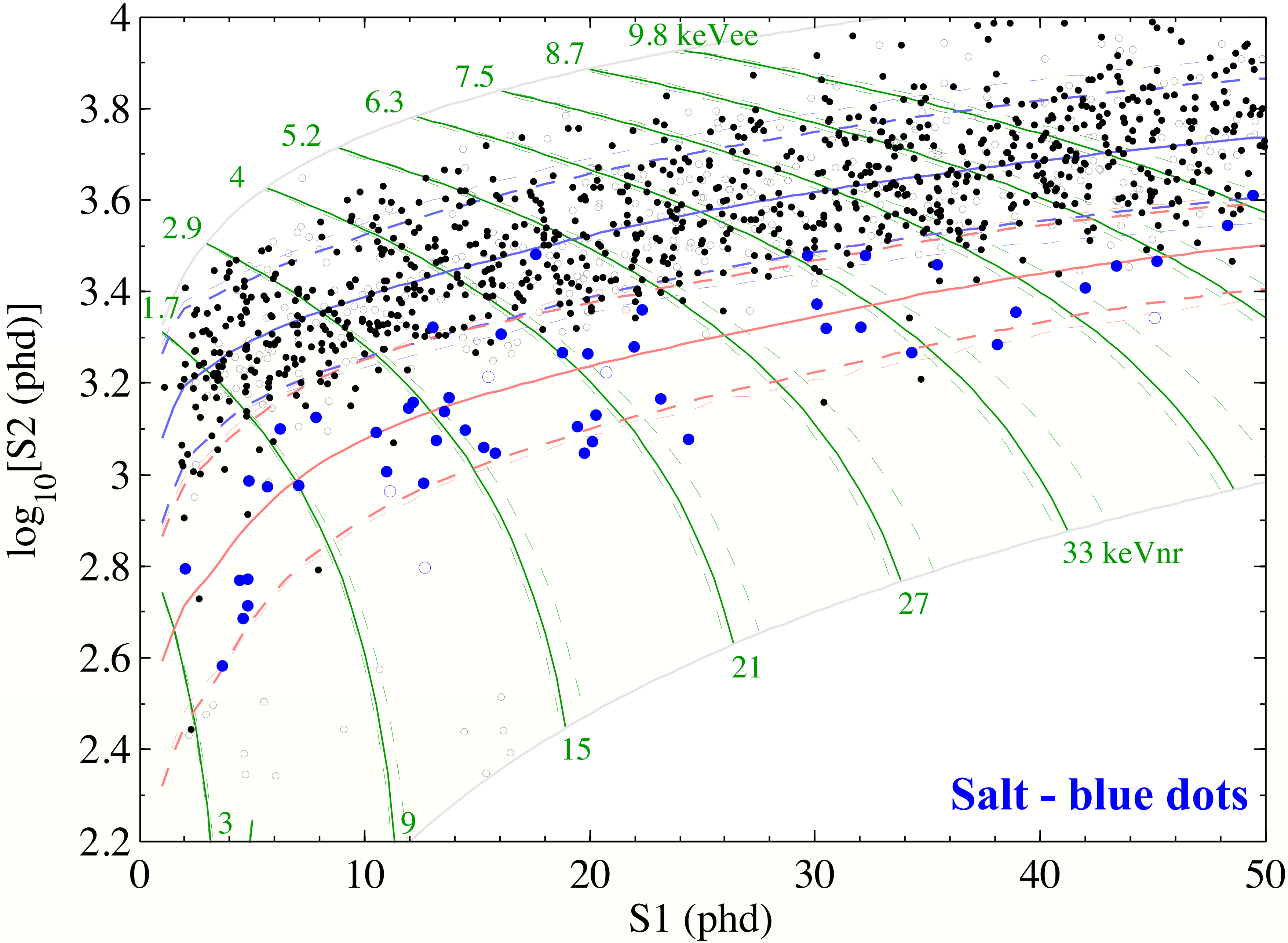
A common approach is to blind oneself to events in the signal regions but it often blinds us to rare backgrounds and pathologies

Instead of traditional blinding, we employ a technique where fake signal events (“salt”) are injected into data stream. NOT SIM!!

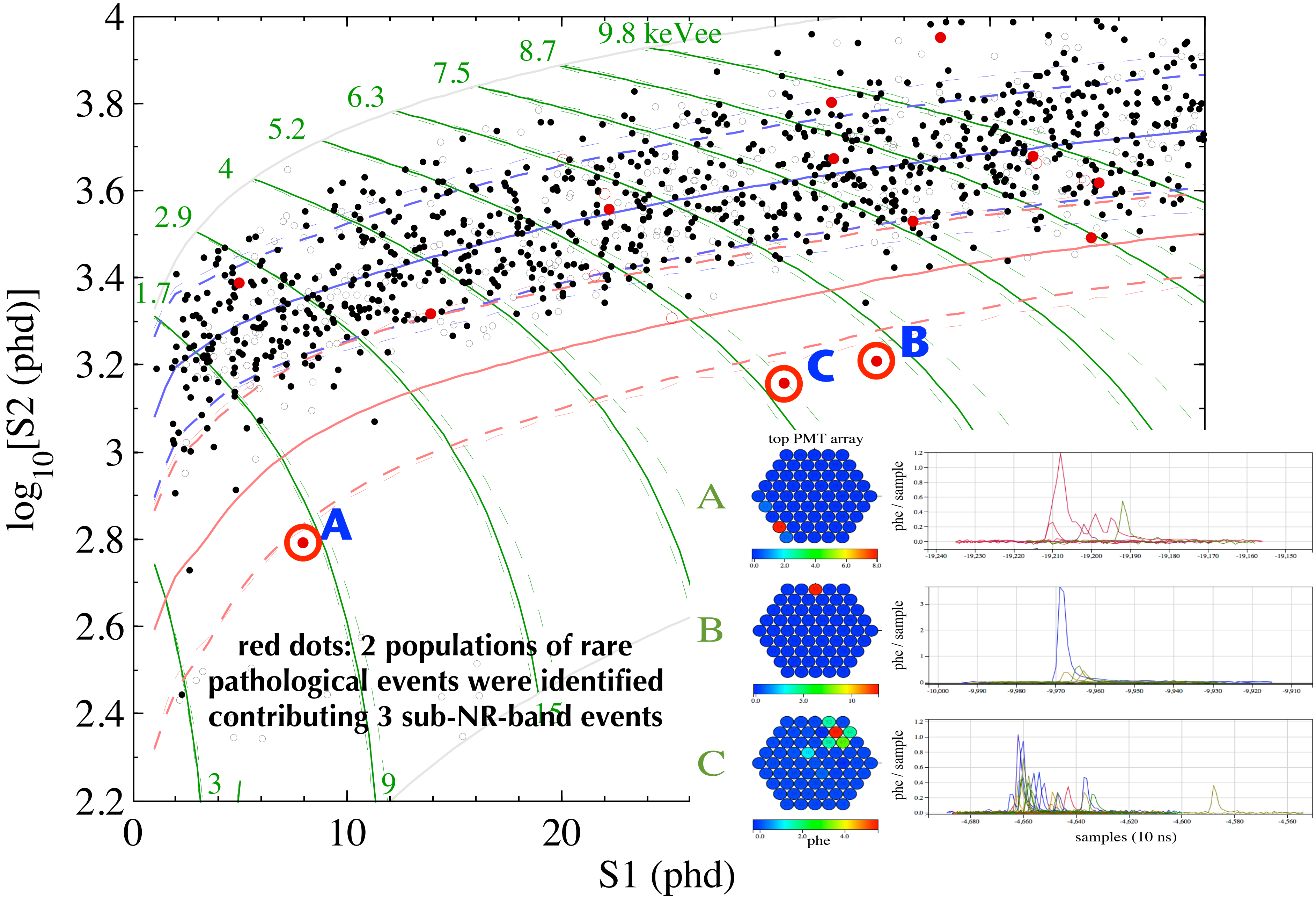
WIMP-search data from 332 live days



WIMP-search data - Salt Identified

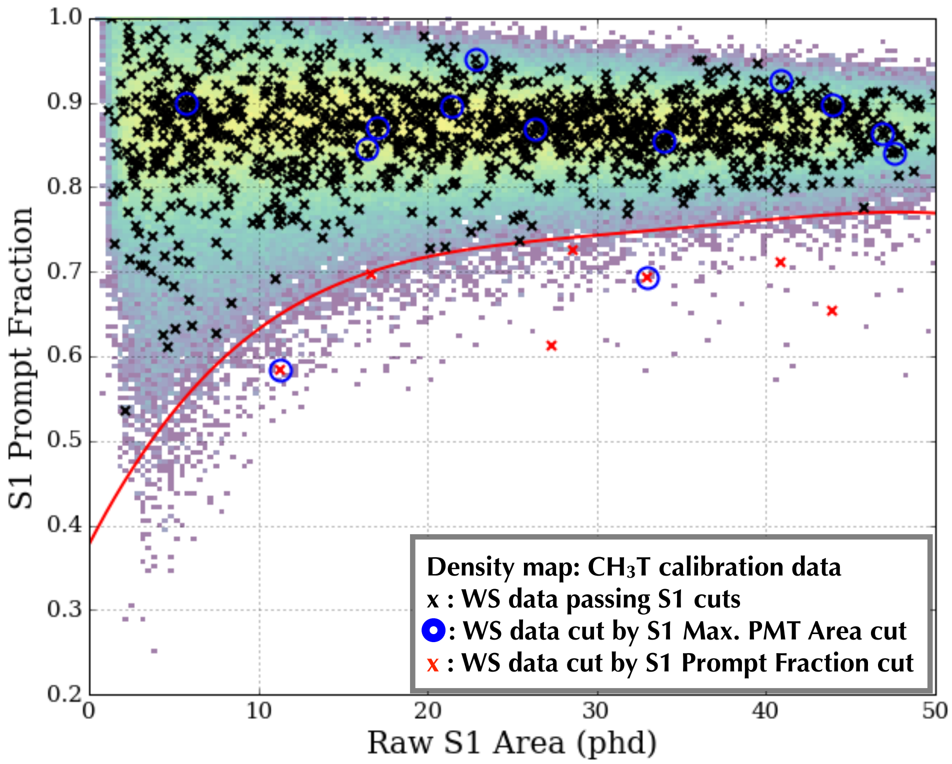


WIMP-search data - Pathological Events

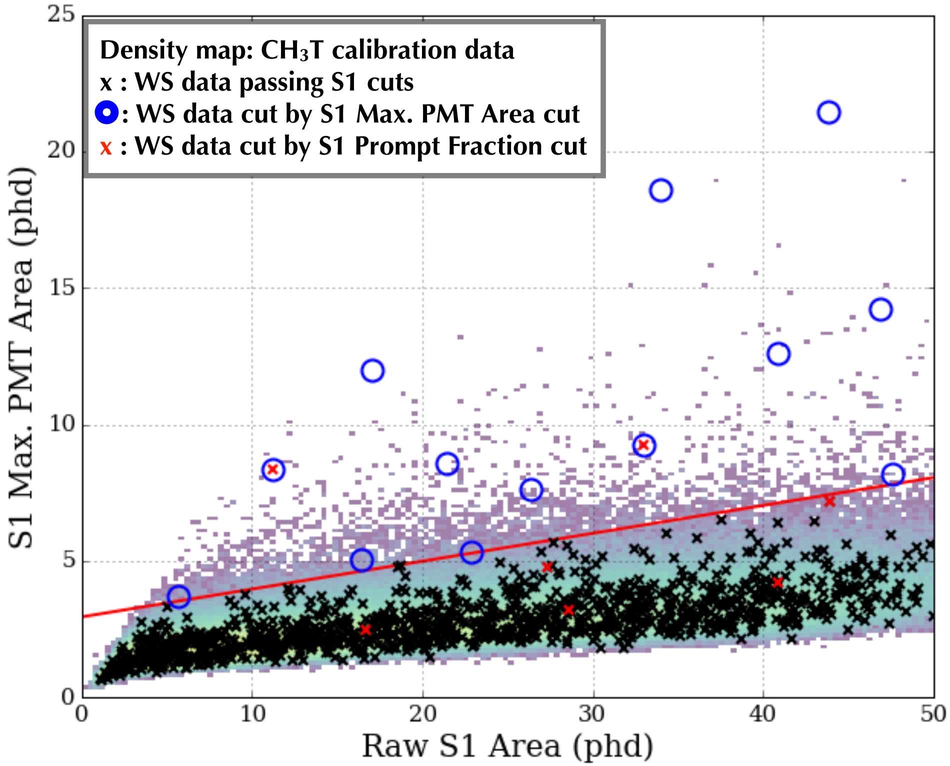


Post-Unsalting Quality Cuts

- 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

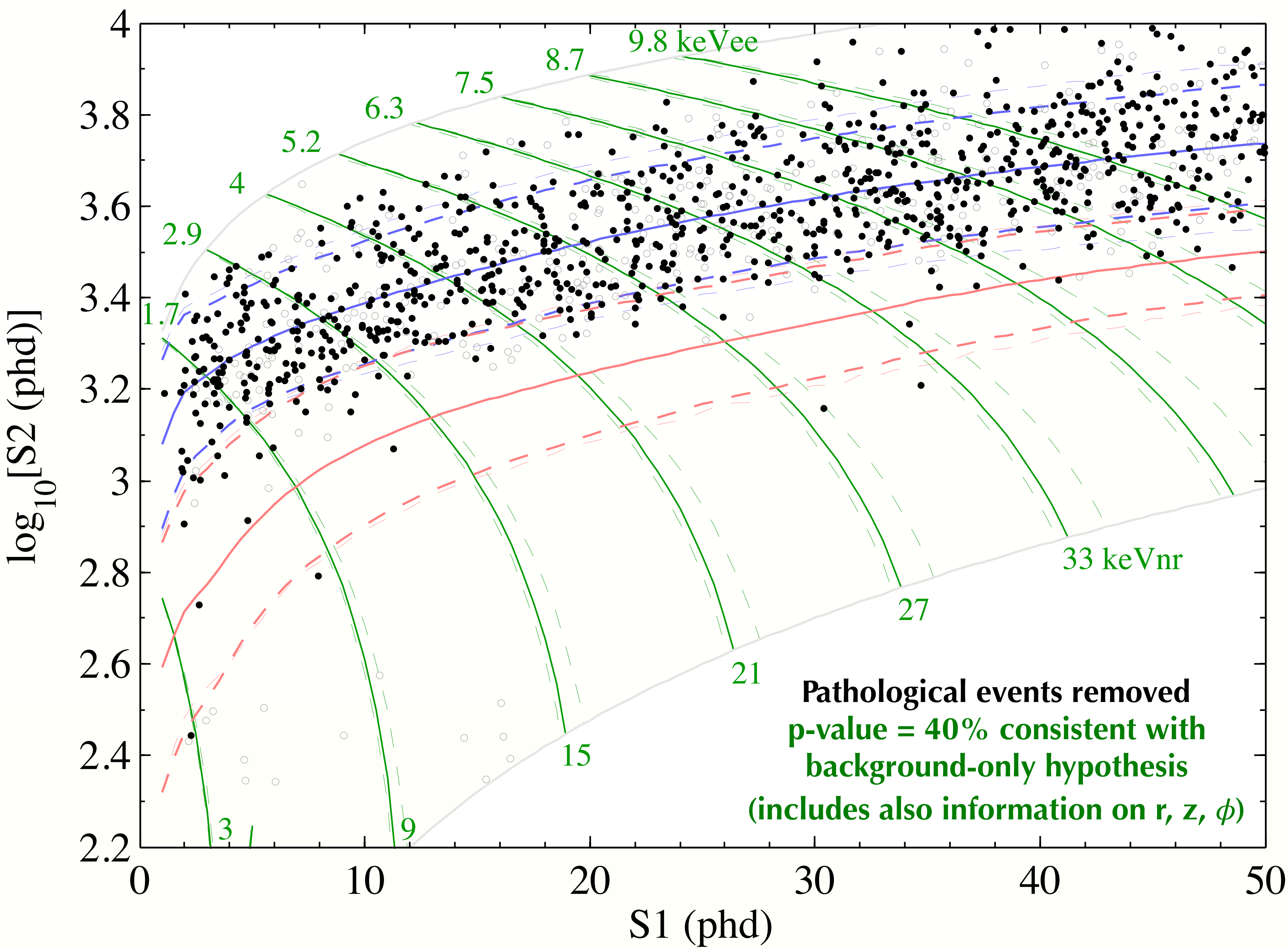


Removes events with S1 that has gas-event-like time structure



Removes events with S1 light overly concentrated in a single PMT

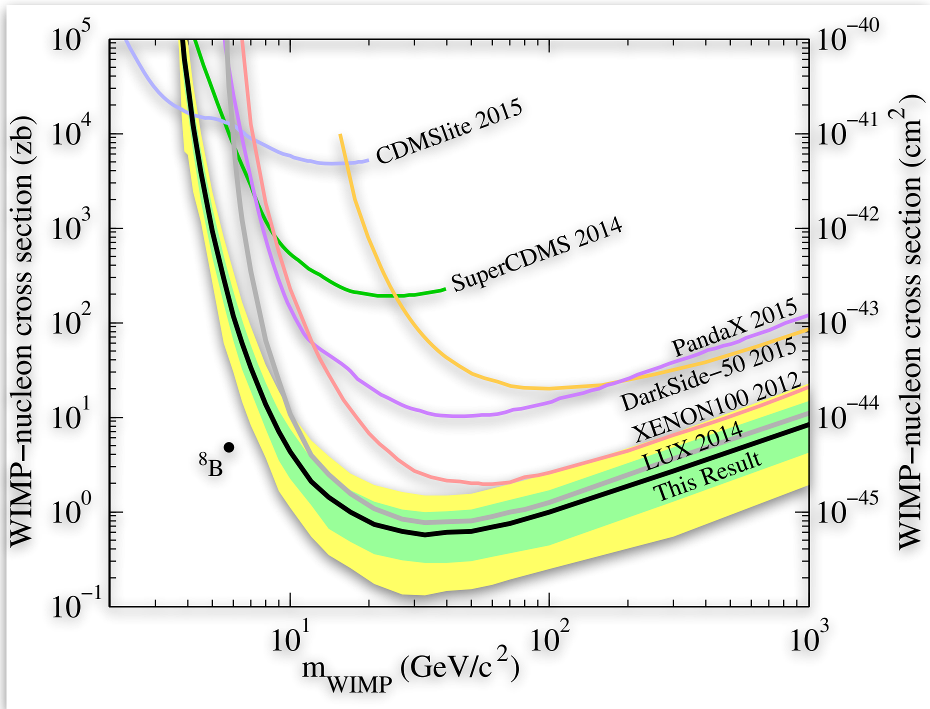
WIMP-search data from 332 live days



FSR Reanalysis - 95 Live Days

Old Limits from the 2015 reanalysis of 2013 data (FSR)

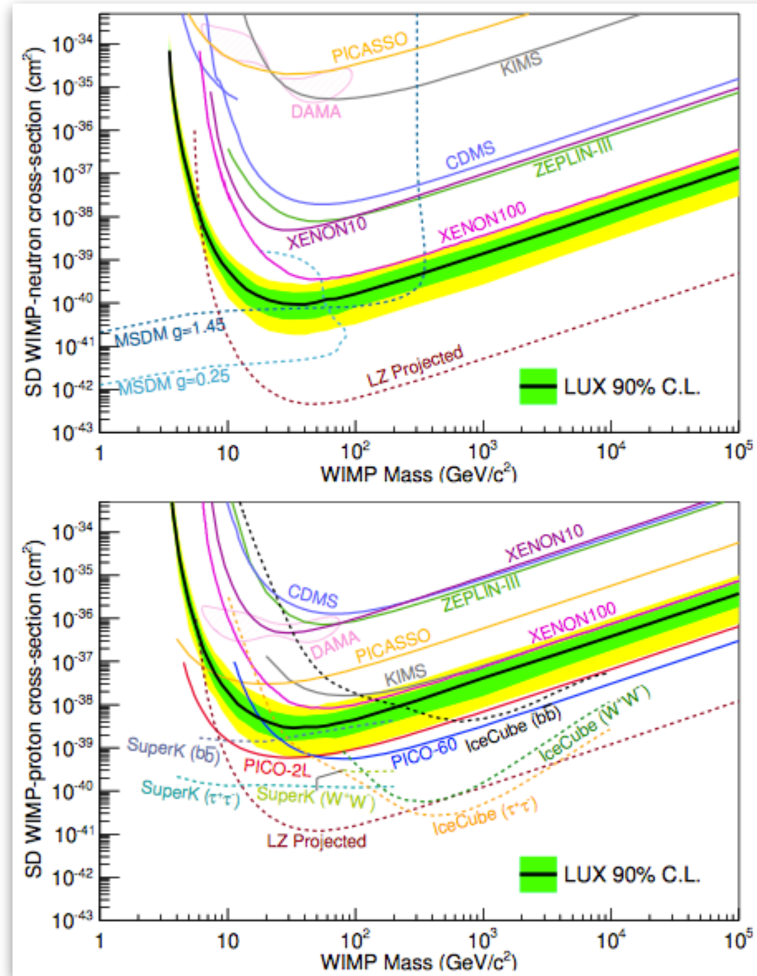
Spin Independent



PRL, 116, 161301 (2016)

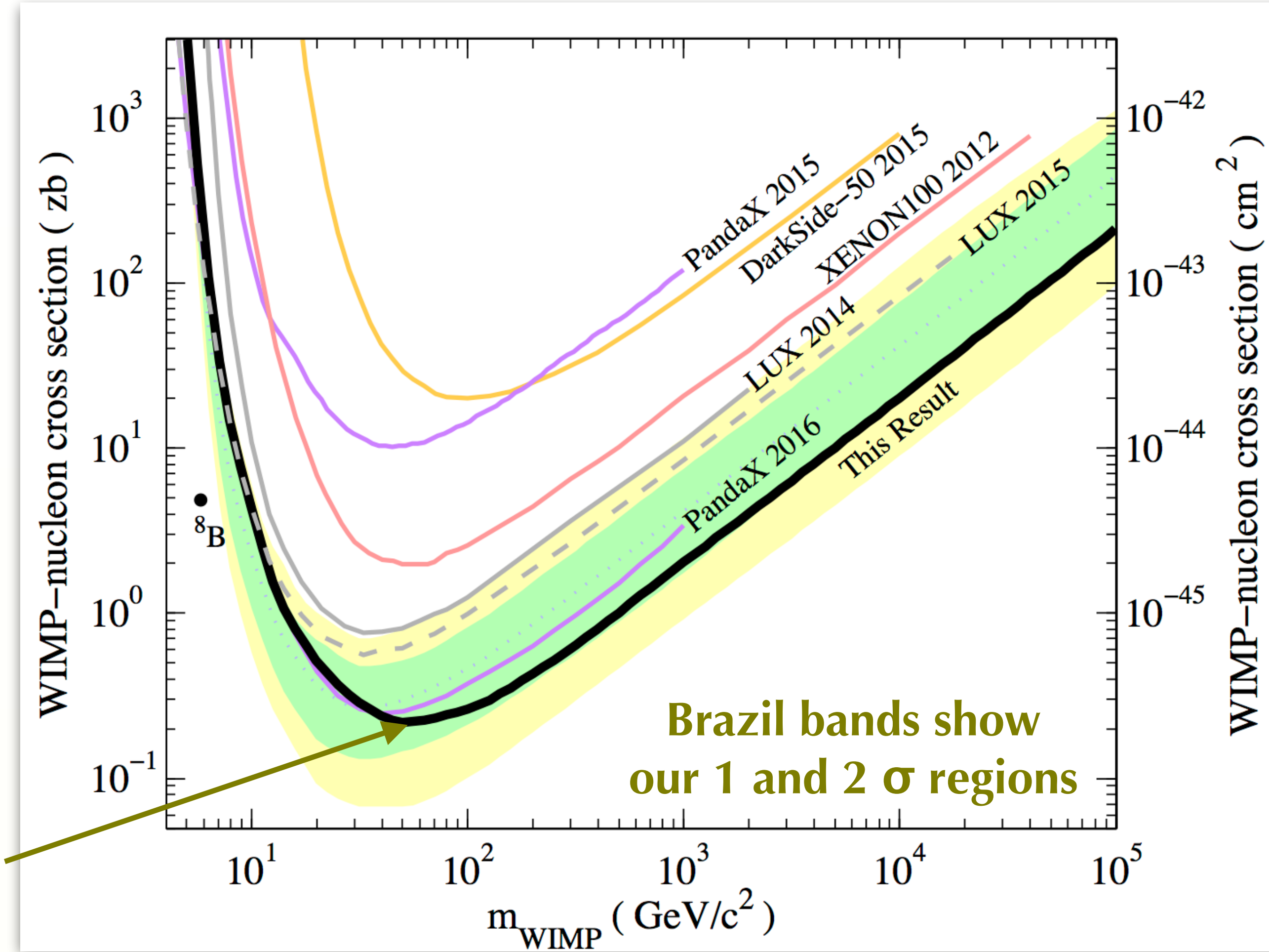
0.60 zeptobarns (at 33 GeV/c²)

Spin Dependent



PRL, 116, 161302 (2016)

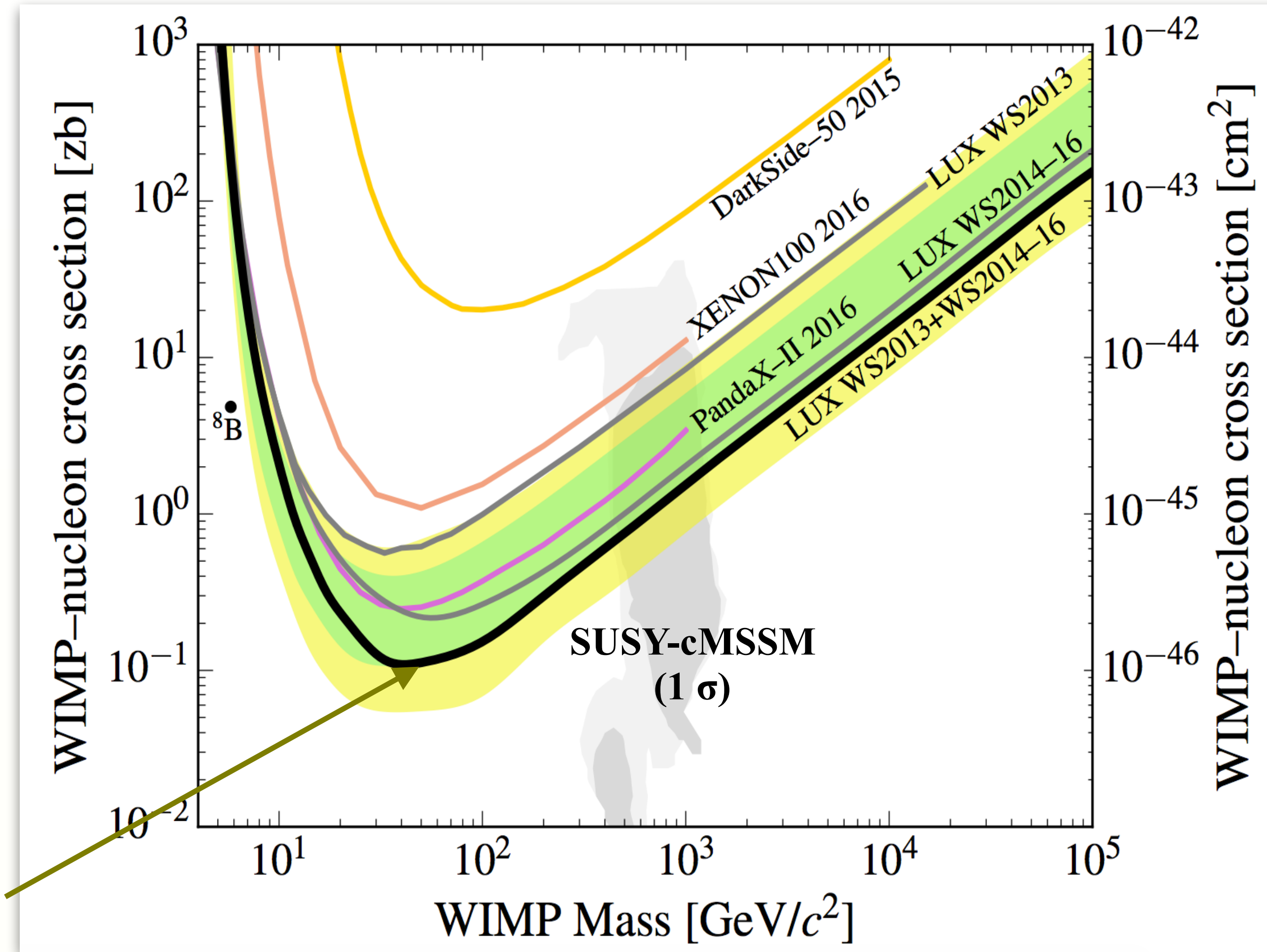
WIMP-nucleon SI Exclusion - SSR



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.**

SI Exclusion - FSR+SSR

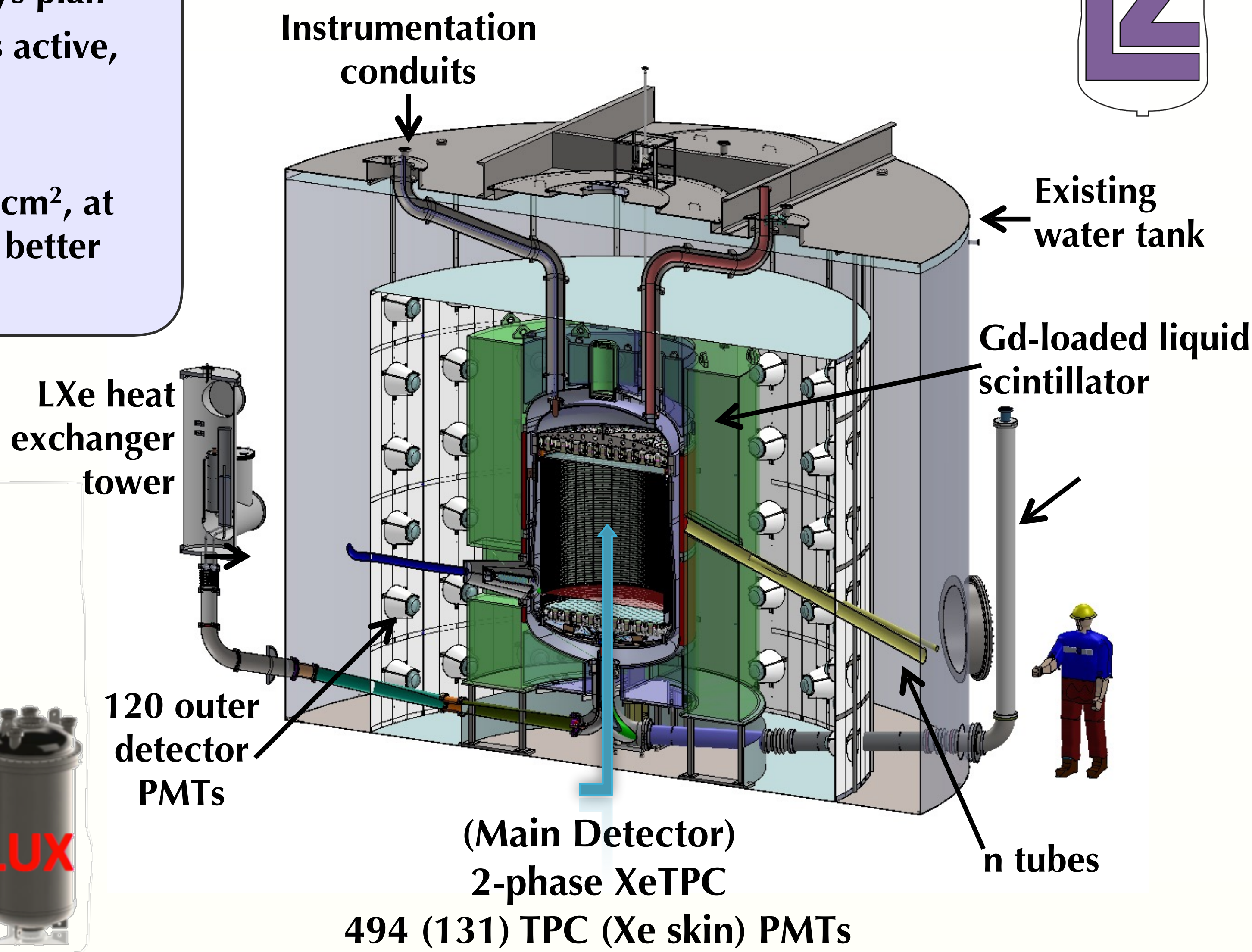


0.11 zeptobarns (at 50 GeV/c²)

- **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: < 2×10^{-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.
- LUX had significant improvements in the calibration of xenon detectors - essential to improve detector's sensitivity.
- 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) at 50 GeV/c2.
- When both runs are combined SI WIMPs are excluded down to 0.11 zeptobarns at 50 GeV/c^2.
- 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
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Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

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Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
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Khadeeja Yazdani	Graduate Student

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Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

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Francisco Neves	Auxiliary Researcher
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Claudio Silva	Postdoc
Paulo Bras	Graduate Student

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Christina Ignarra	Research Associate
Wing To	Research Associate
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Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA / Sanford Lab

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Dana Byram	Support Scientist

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Jack Genovesi	Graduate Student
Steven Young	Graduate Student

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Paul Terman	Graduate Student

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Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
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Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Nicole Larsen	Graduate Student

UC Davis

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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

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Dean White	Engineer
Carmen Carmona	Postdoc
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

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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

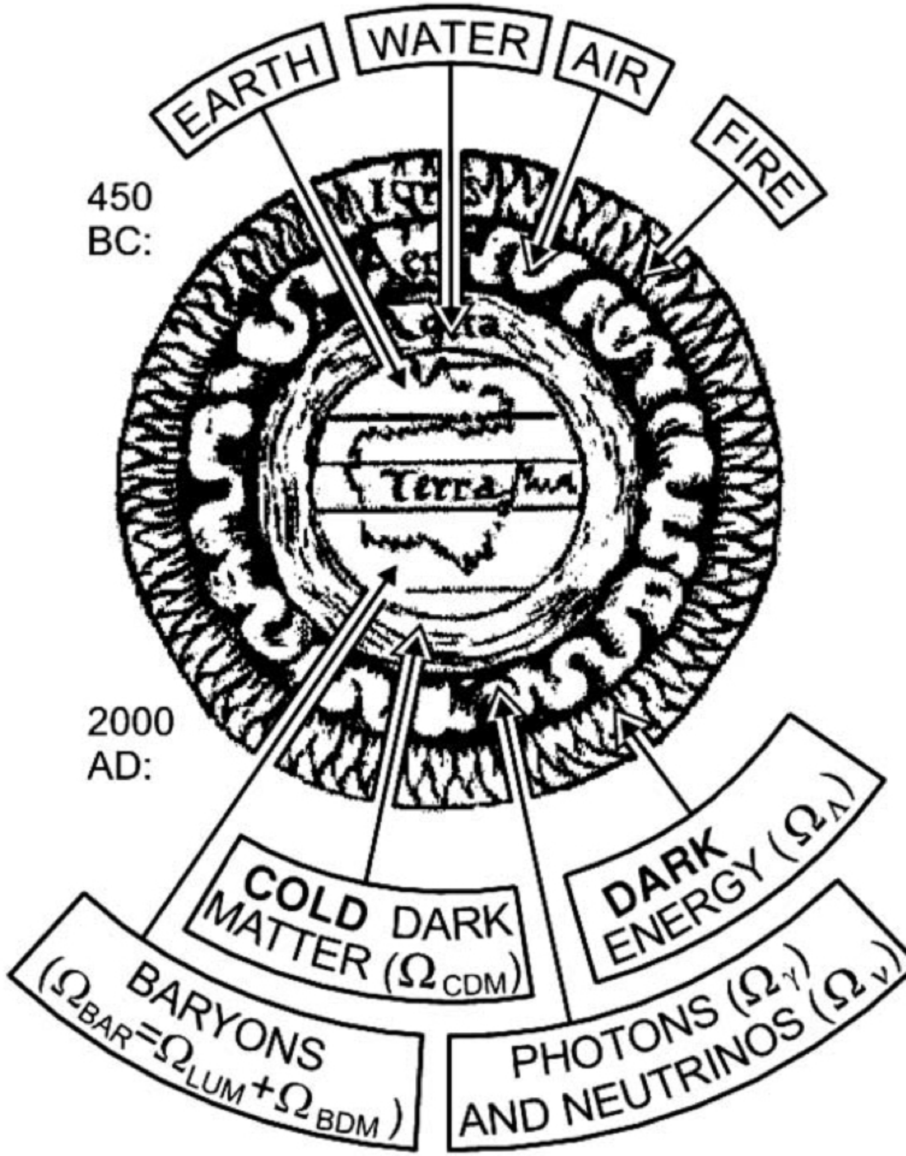
University of South Dakota

Dongming Mei	PI, Professor
Chao Zhang	Postdoc

University of Wisconsin

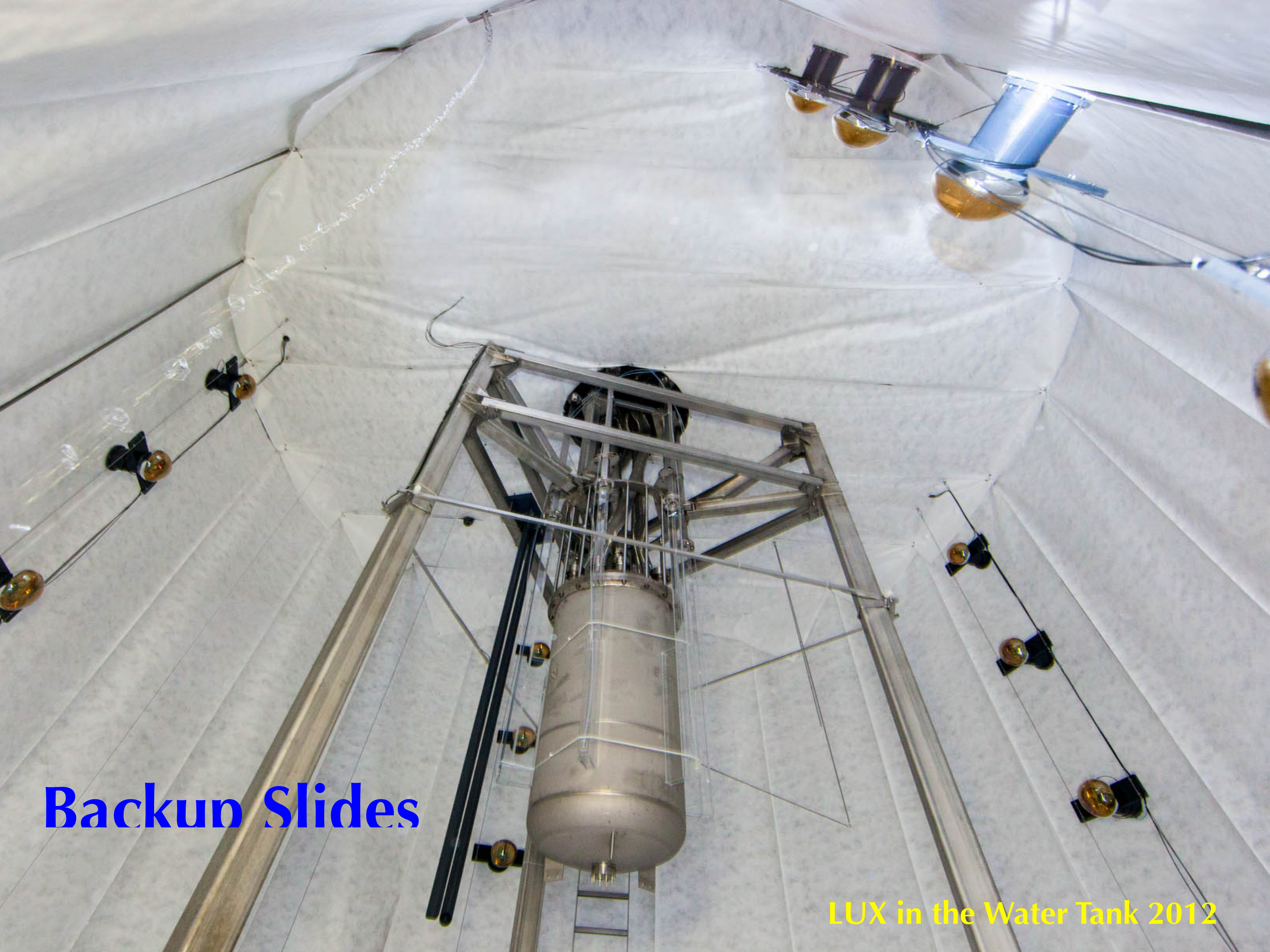
Kimberly Palladino	PI, Asst Professor
Shaun Alsum	Graduate Student


LUX

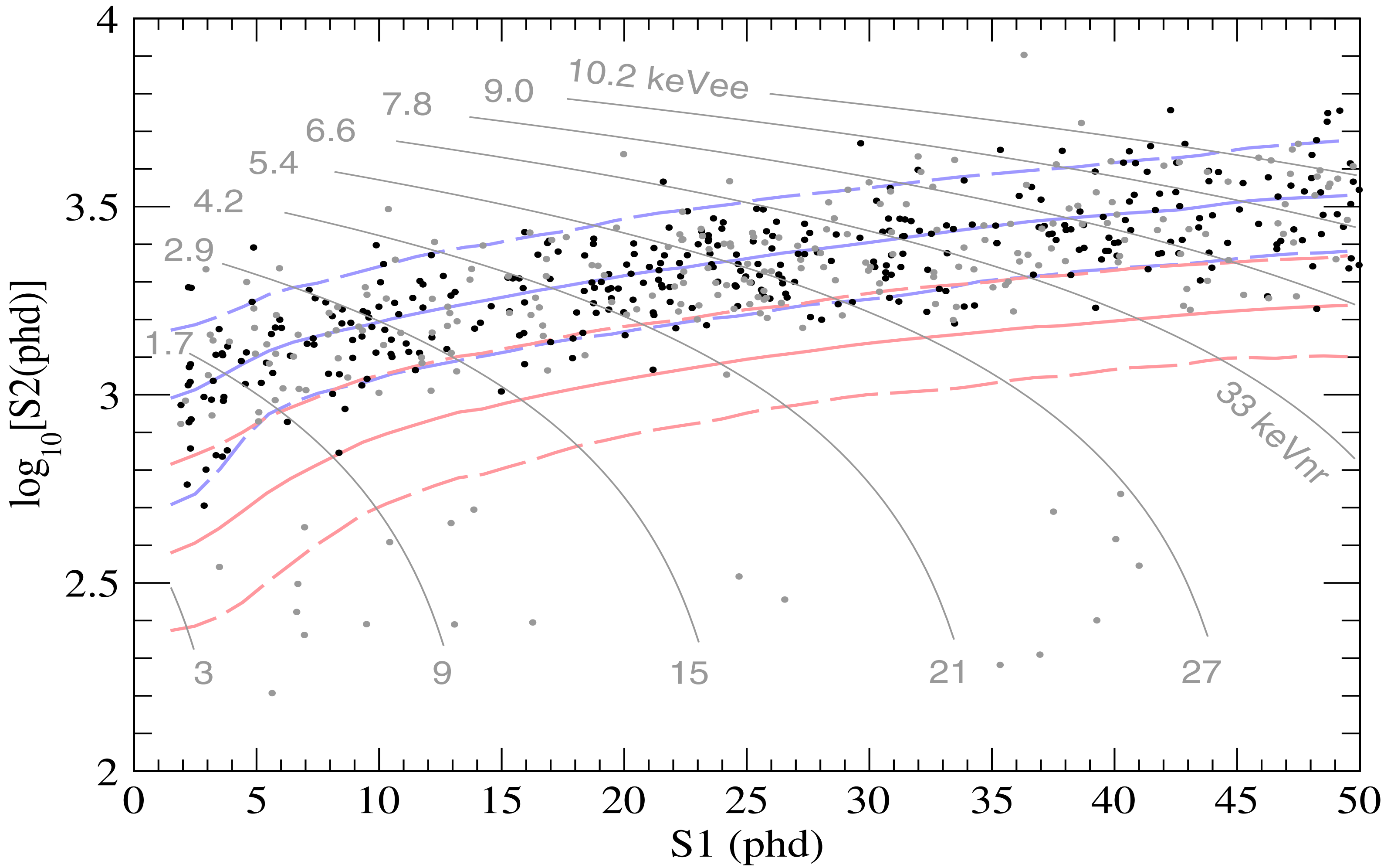


EARTH
WATER
AIR
FIRE
450 BC:
Terra
2000 AD:
COLD DARK MATTER (Ω_{CDM})
DARK ENERGY (Ω_Λ)
BARYONS ($\Omega_{BAR}=\Omega_{LUM}+\Omega_{BDM}$)
PHOTONS (Ω_γ) AND NEUTRINOS (Ω_ν)

THANKS!

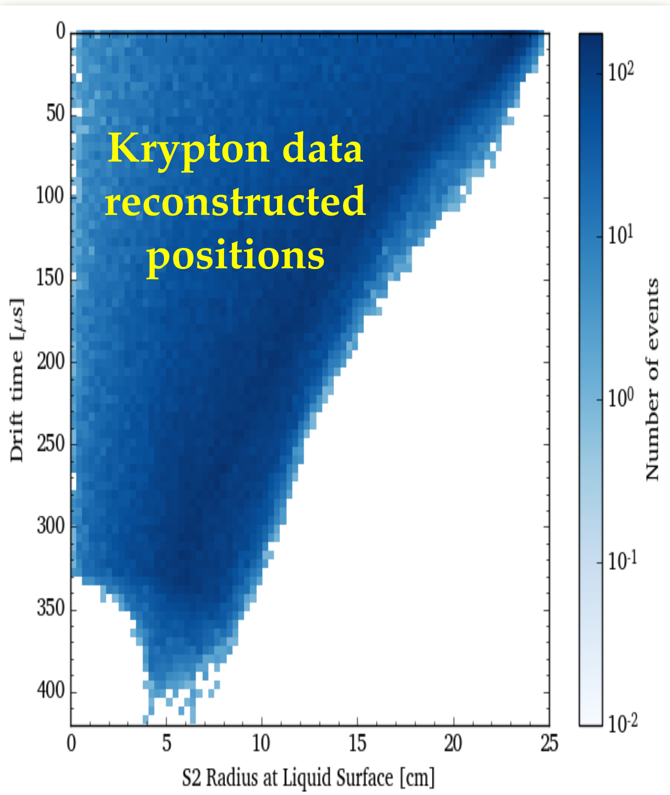

Backup Slides
LUX in the Water Tank 2012

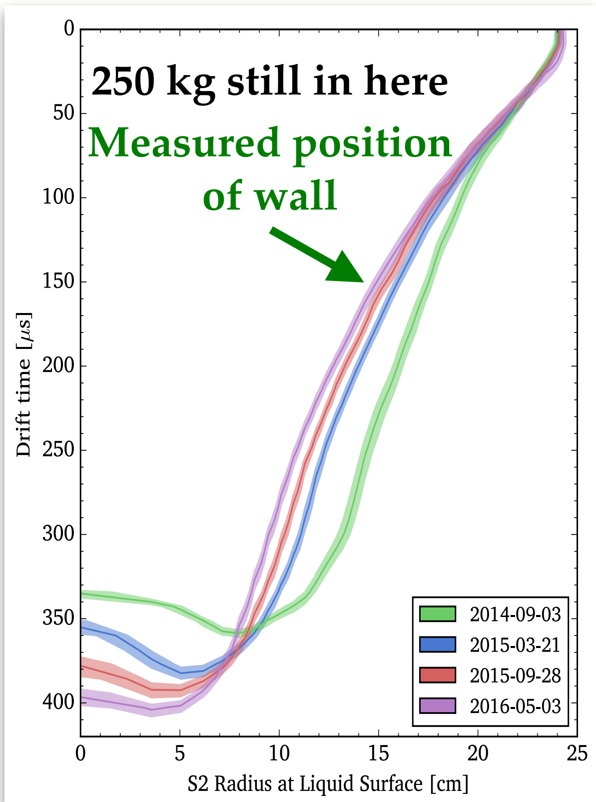
First Science Run Reanalysis

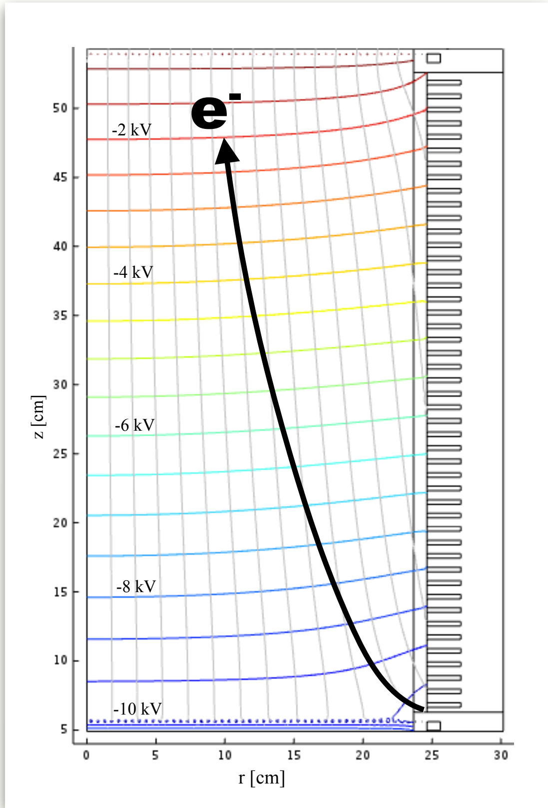


Grid Conditioning

- 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.

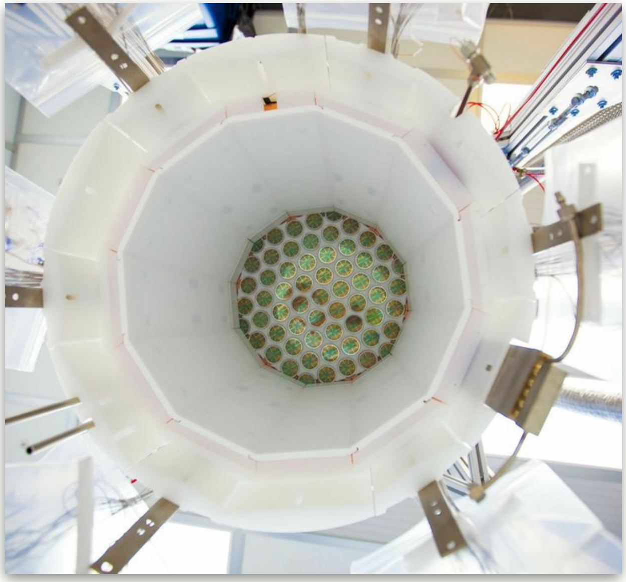


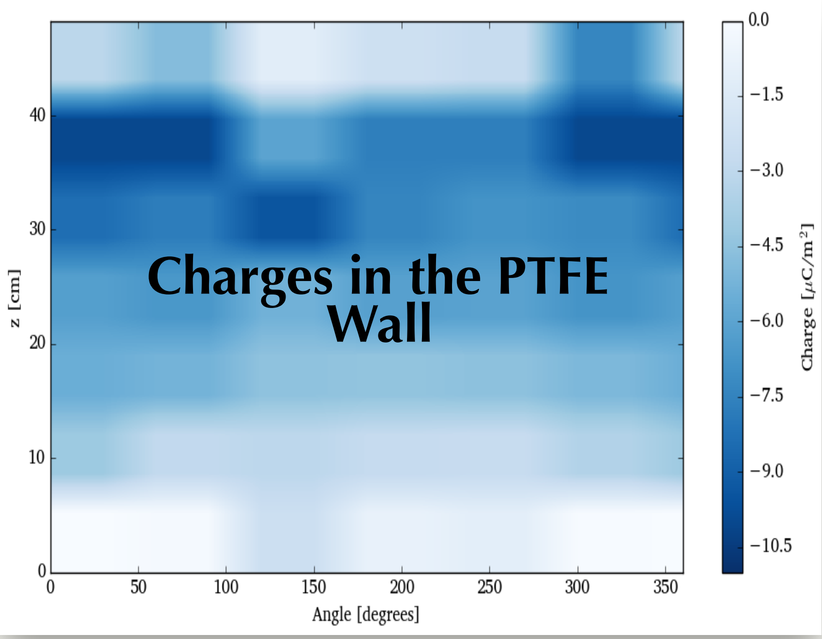


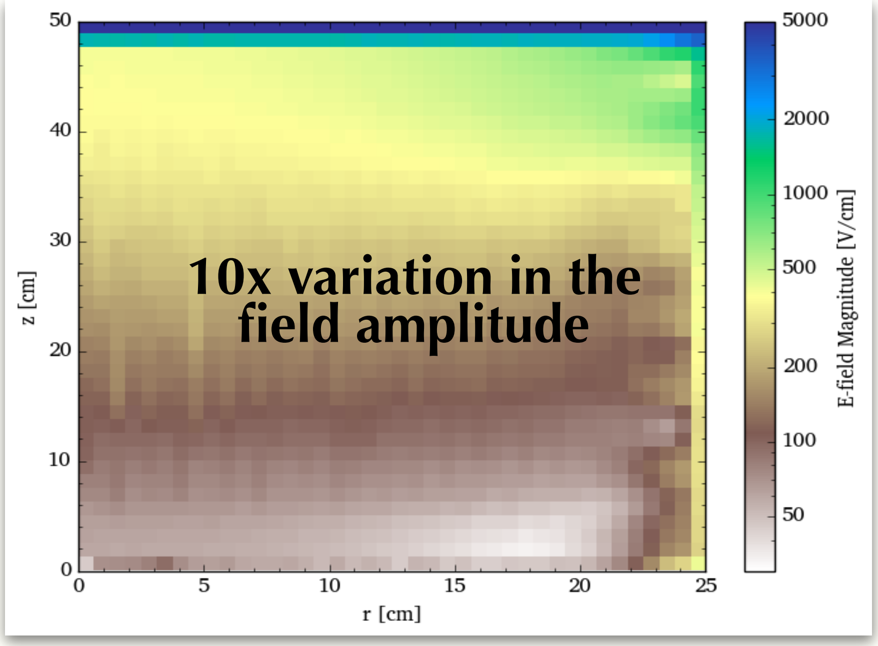


Modeling the Electric Field

- 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/m²) 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

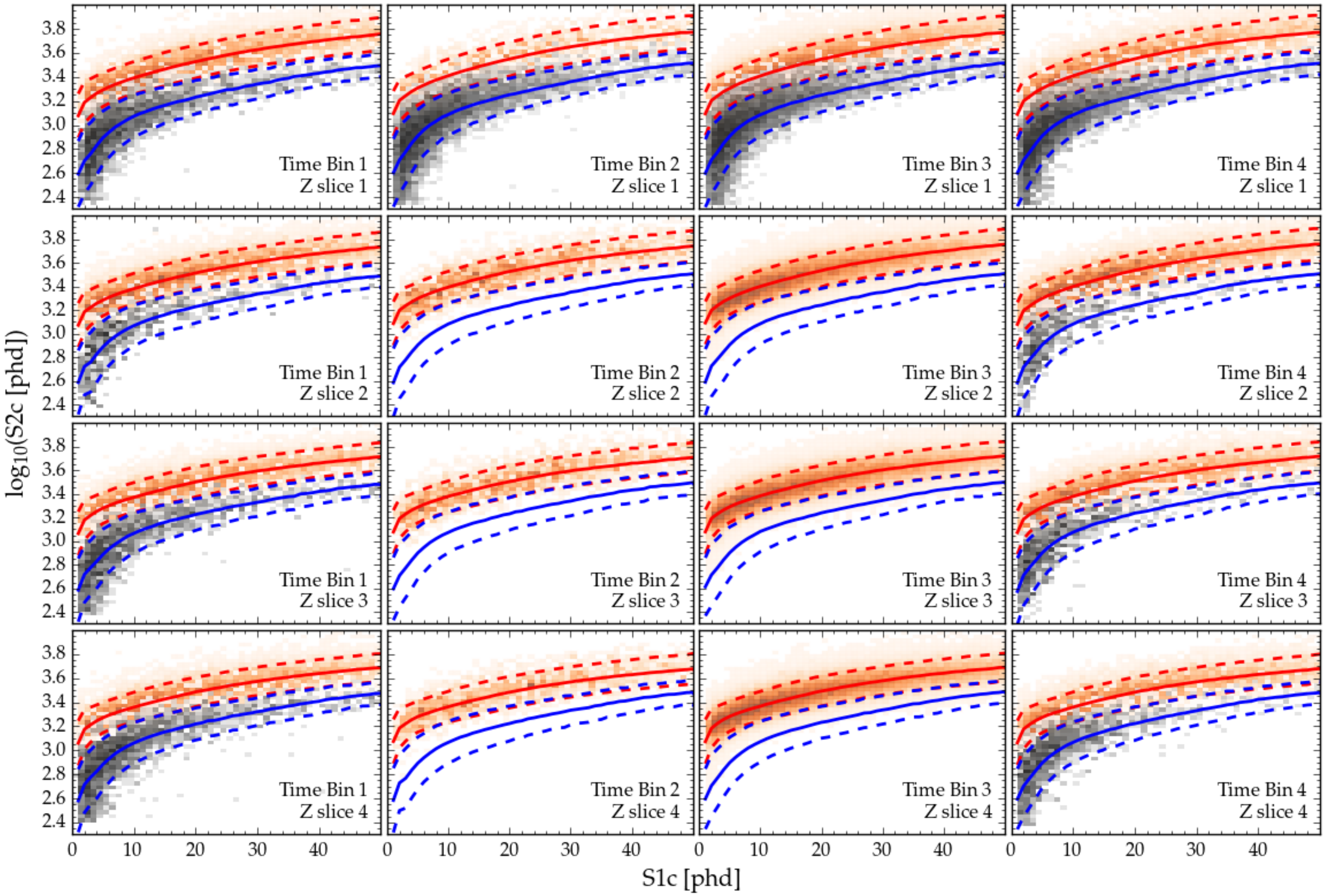
(How to deal with a field that is varying in space and in time?)

- **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)

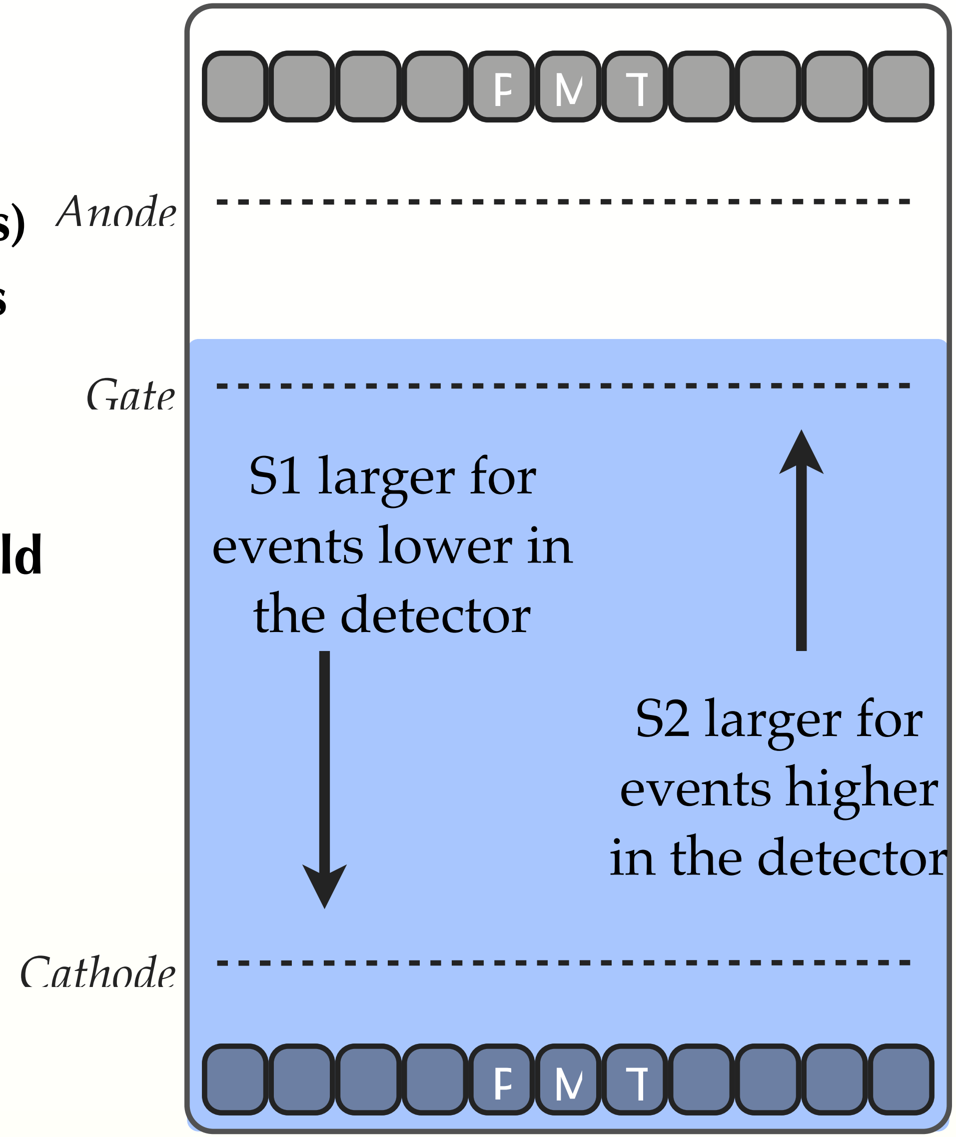
Orange density: DD calibration (NR)

Solid lines:
NEST model,
ER, NR band mean

Dashed lines:
NEST model,
10-90 percentile.

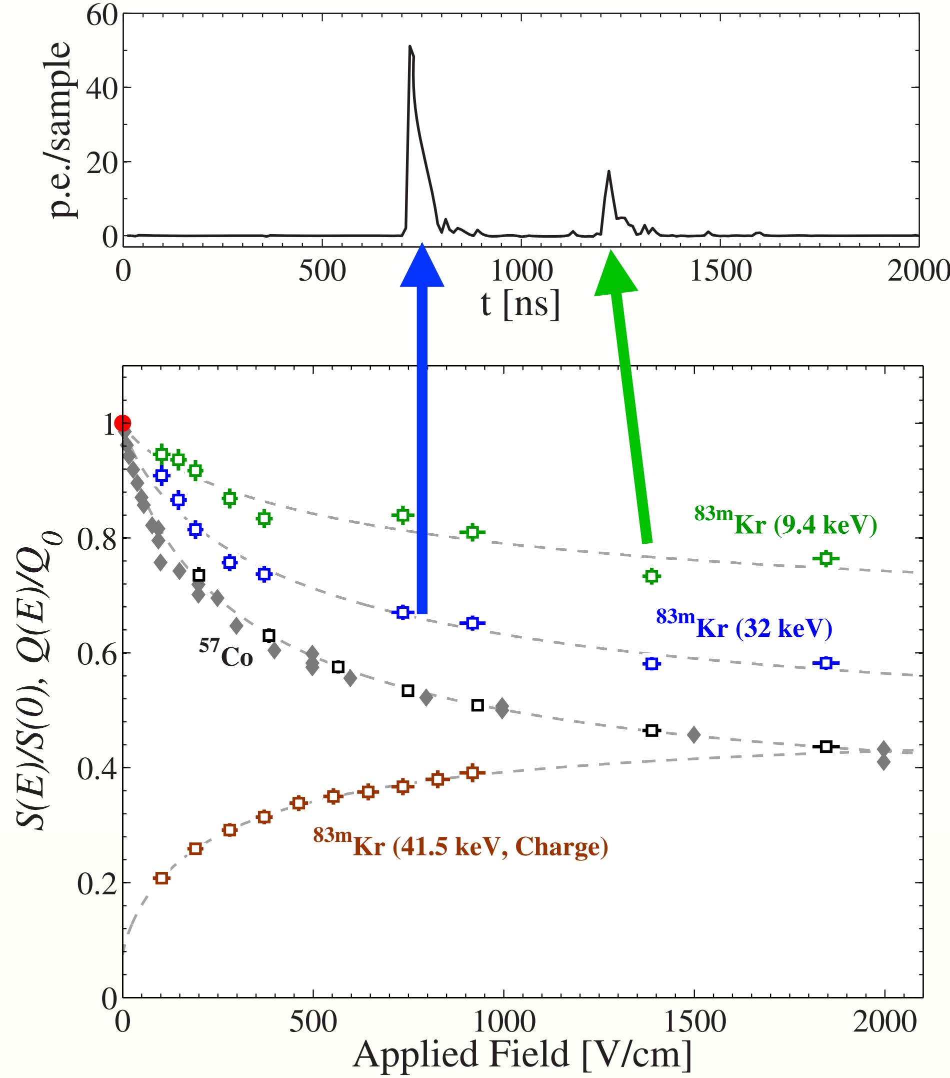
S2/S1 Position Corrections

- 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.



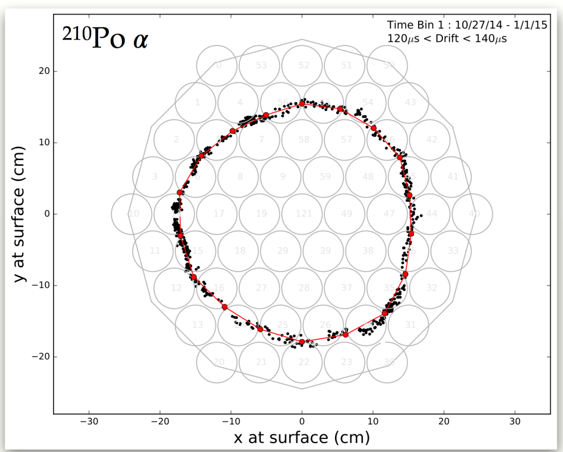
S2/S1 Position Corrections

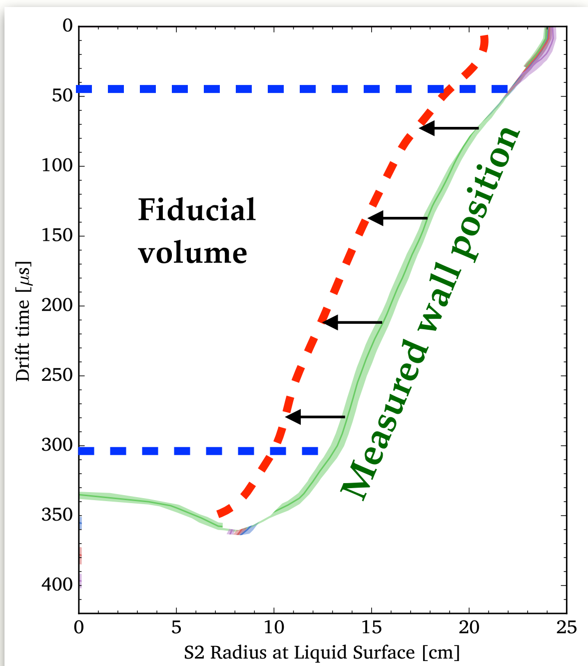
- **Our strategy is:**
  - **Disentangle position effects from field effects;**
  - **Apply a correction to account for position effects only.**
- **^{83m}Kr has two decays close in time. The ratio of the first-to-second S1 pulse area depends on field alone. This allows us to measure the component of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

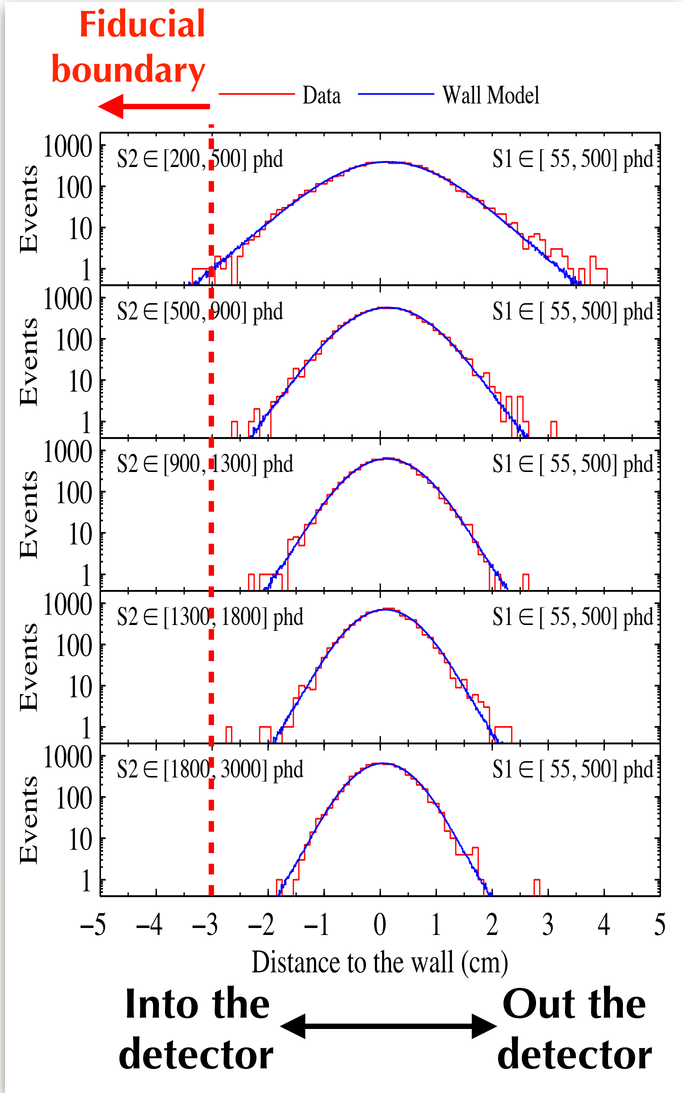


Wall-surface backgrounds

- ^{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.

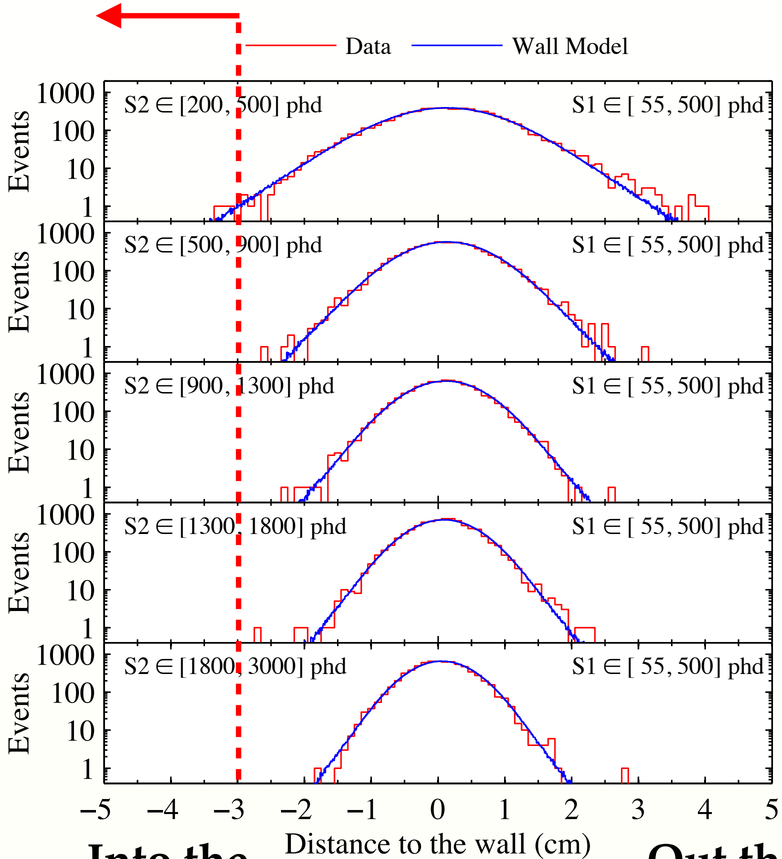






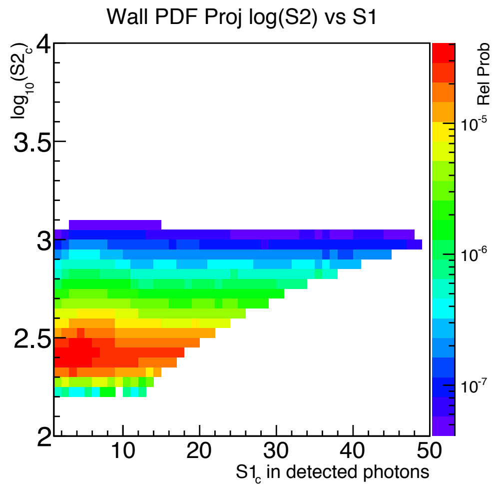
Wall Surface Model

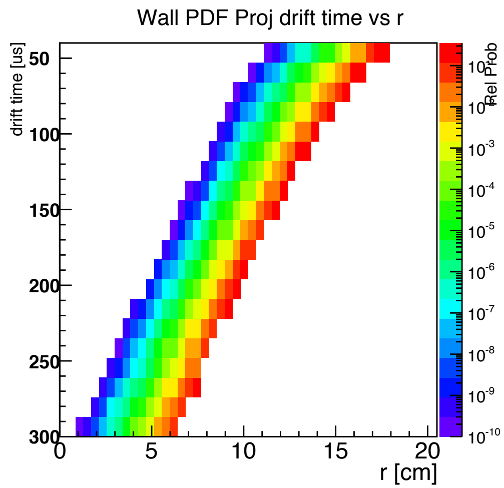
Fiducial boundary



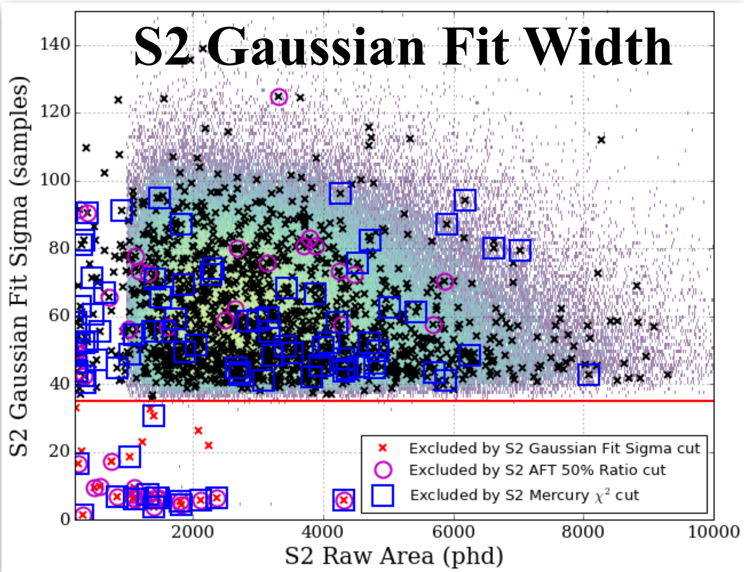
Into the detector ⟷ **Out the detector**

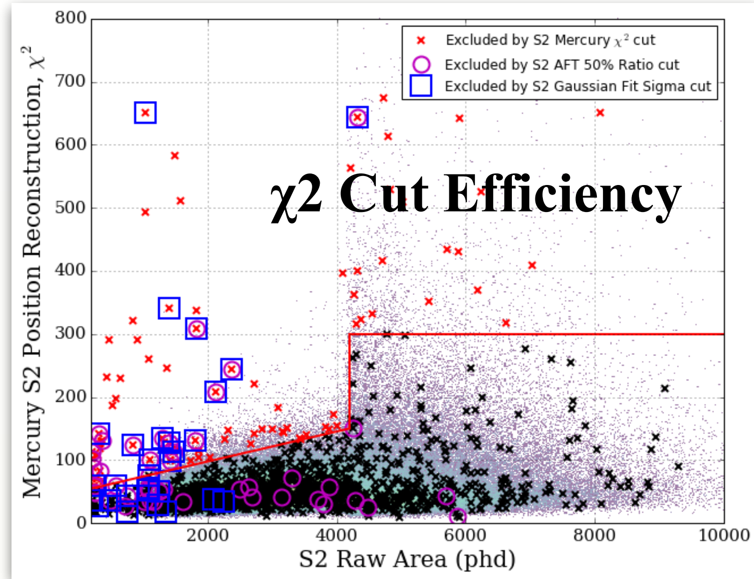
Wall PDFS

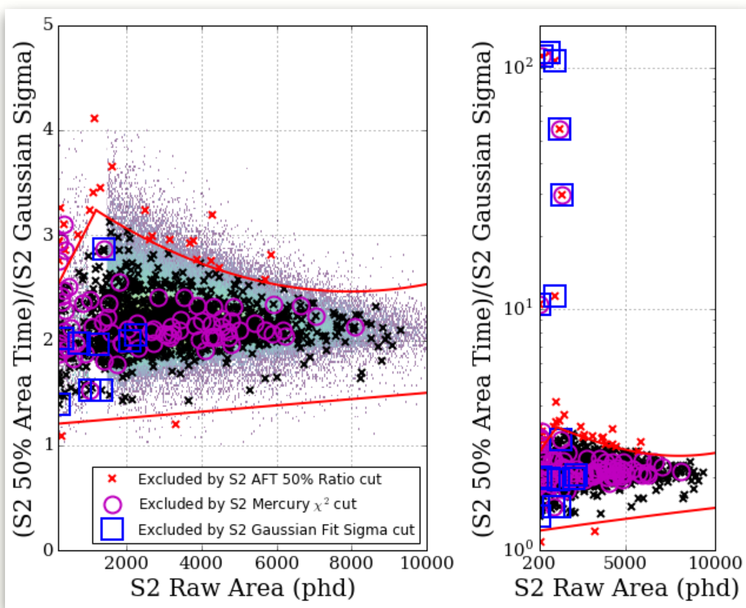


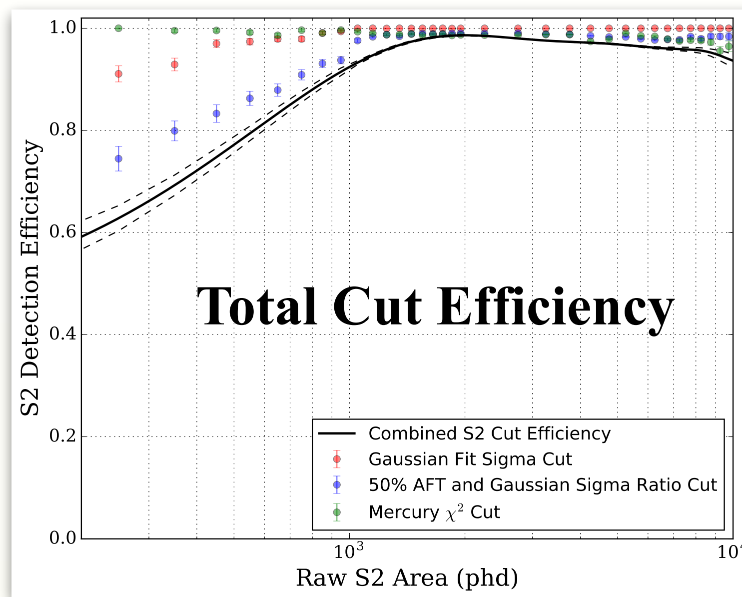


S2 Quality Cuts and Efficiency

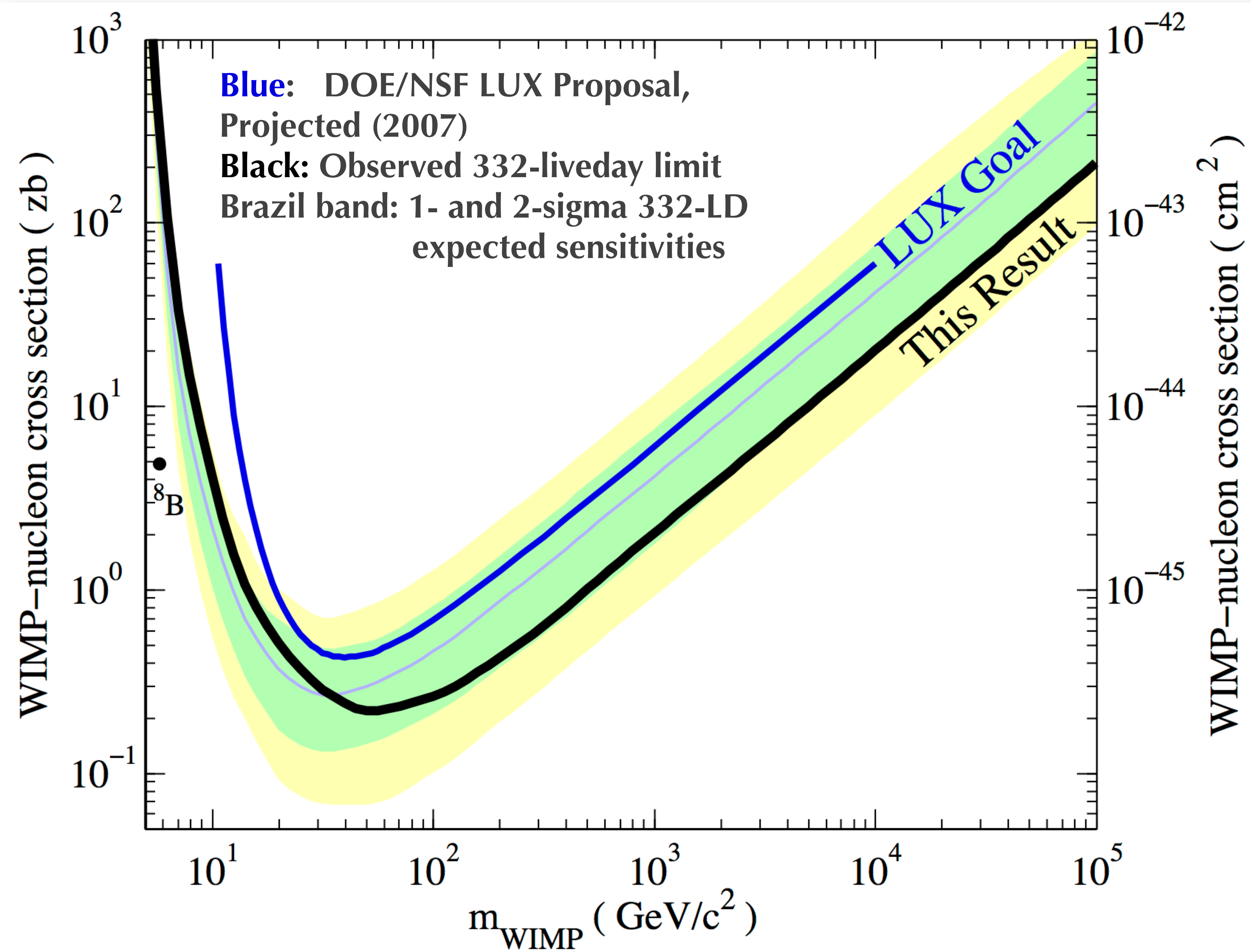






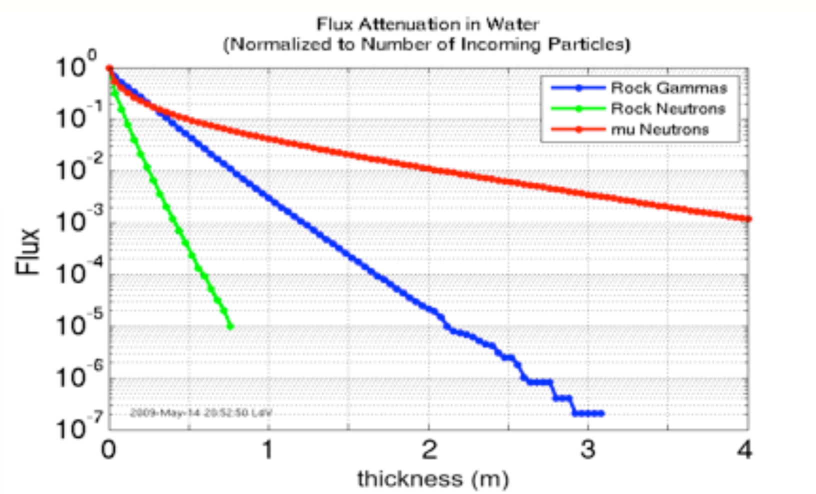


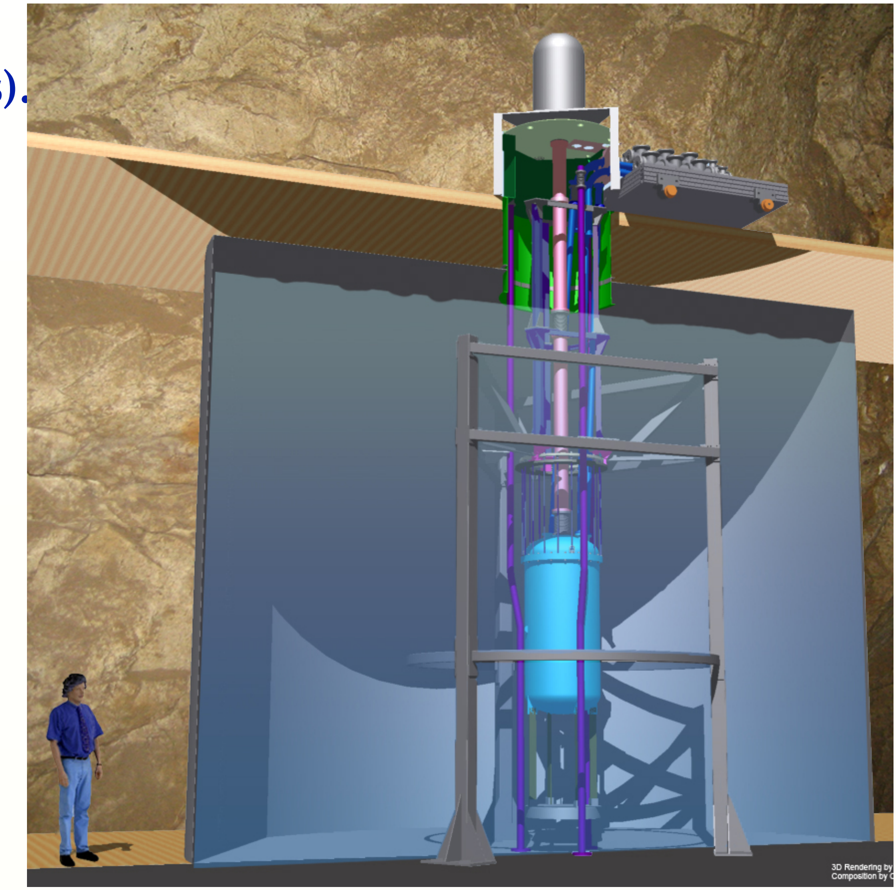
LUX Proposal VS Main Result



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)