Direct Dark Matter Searches with LUX

Cláudio Silva on behalf of the LUX Collaboration

Rencontres de Moriond, La Thuile, Italia, 20th March 2017

Very High Energy Phenomena in the Universe

Snow in Summer - Location of the Sanford Underground Laboratory (and LUX)

INVESTIGADOR FCT

QUALIFICAR É CRESCER.

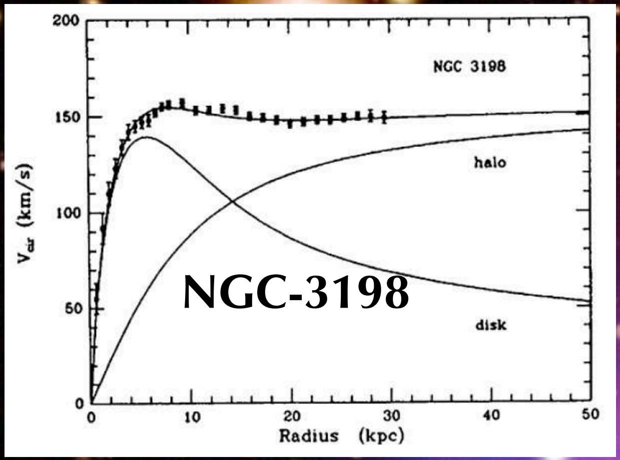
Outline

- The LUX detector - two phase Liquid/Gas xenon time projection chamber
  - Direct dark matter detection
  - How LUX detector works
- The LUX calibrations
  - Krypton (^{83m}Kr);
  - Neutron recoils: D-D
  - Electron recoils: ^{3}H
- 332 live-days second science run (2014-2016) results
  - LUX backgrounds
  - Main dark matter search analysis
    - Spin independent
    - Spin dependent (NEW!)

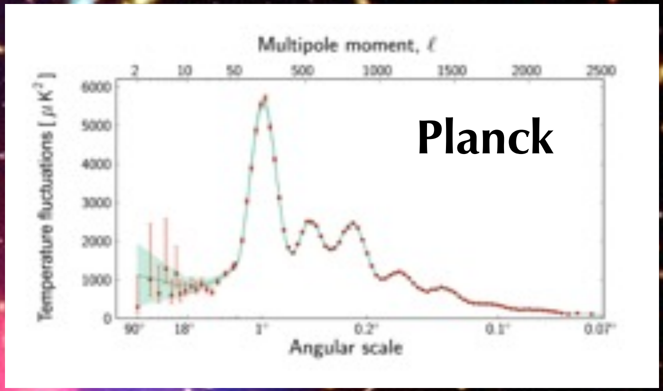
Image: LUX inside the water tank (September 2012)

Dark Matter Evidence

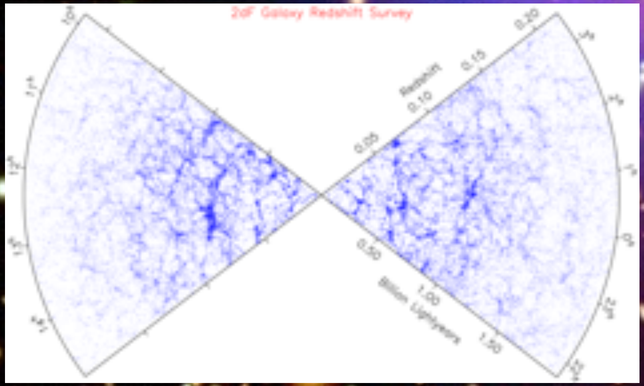
Rotation curves of galaxies



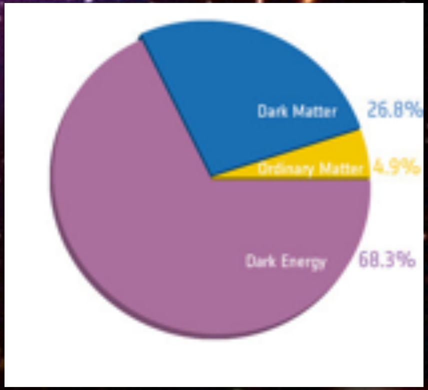
Cosmic Microwave Background



Galaxies Surveys



Gravitational lensing
Bullet Cluster

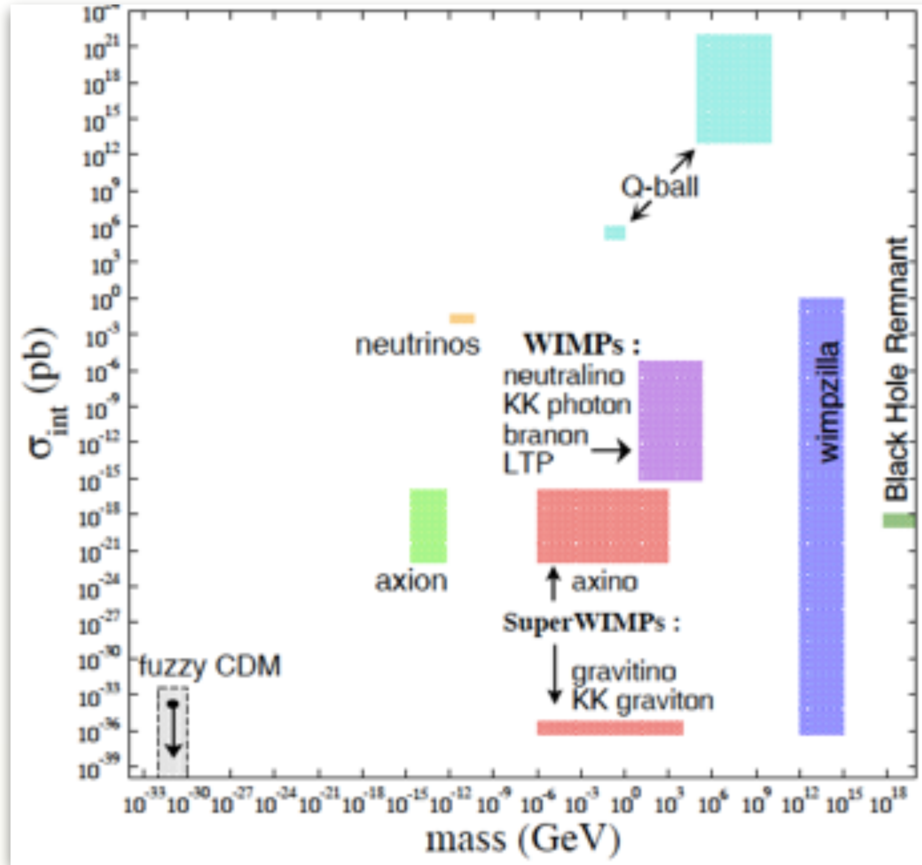


$$\frac{\text{Dark Matter}}{\text{Ordinary Matter}} \approx 5.44 \pm 0.14$$

Background figure:
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.

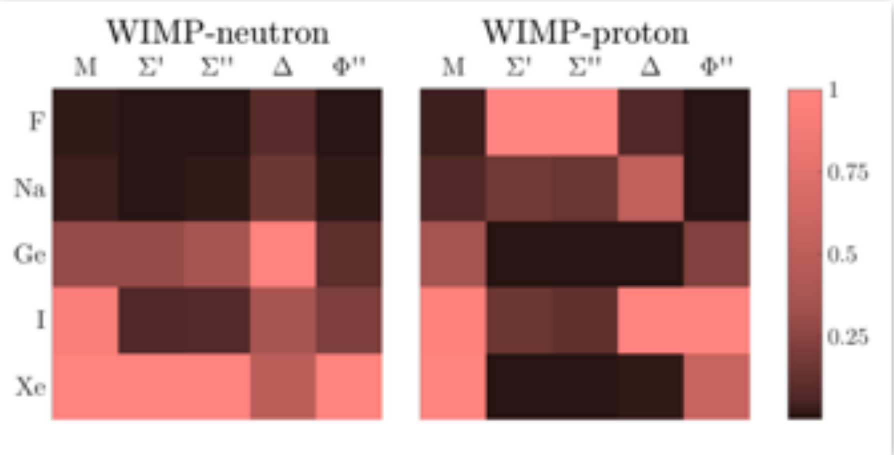
Cold Dark Matter Particle Candidates

- **WIMPs (weakly interactive massive particles):**
  - **Stable and neutral in most scenarios;**
  - **Solves the Gauge Hierarchy Problem**
  - **WIMP Miracle (density from freeze out)**
  - **Physics beyond the standard model:**
    - Super-symmetry - neutralino
- **Axions (solution to the strong CP problem - Peccei-Quinn solution)**
- **And many, many others…**
  - **superWIMPs, light gravitinos, branons, Sterile Neutrinos, Kaluza-Klein bosons …**



Dark Matter Detection

- **LUX is a Direct Detection exp.**
  - Galactic WIMPs scatter with nucleus of the target
    - Spin independent (M) - proport. to A^2
    - Spin dependent interaction (Σ' and Σ'')
    - Other effective field interactions…
  - Axions are detected through axioelectric effect
- **Challenges**
  - Isothermal model: expect recoil <10 keV requiring detectors with a very low threshold.
  - Challenge backgrounds
    - Go underground, passive and active veto, careful selection of materials with very low background, discriminate nuclear recoils from electron recoils

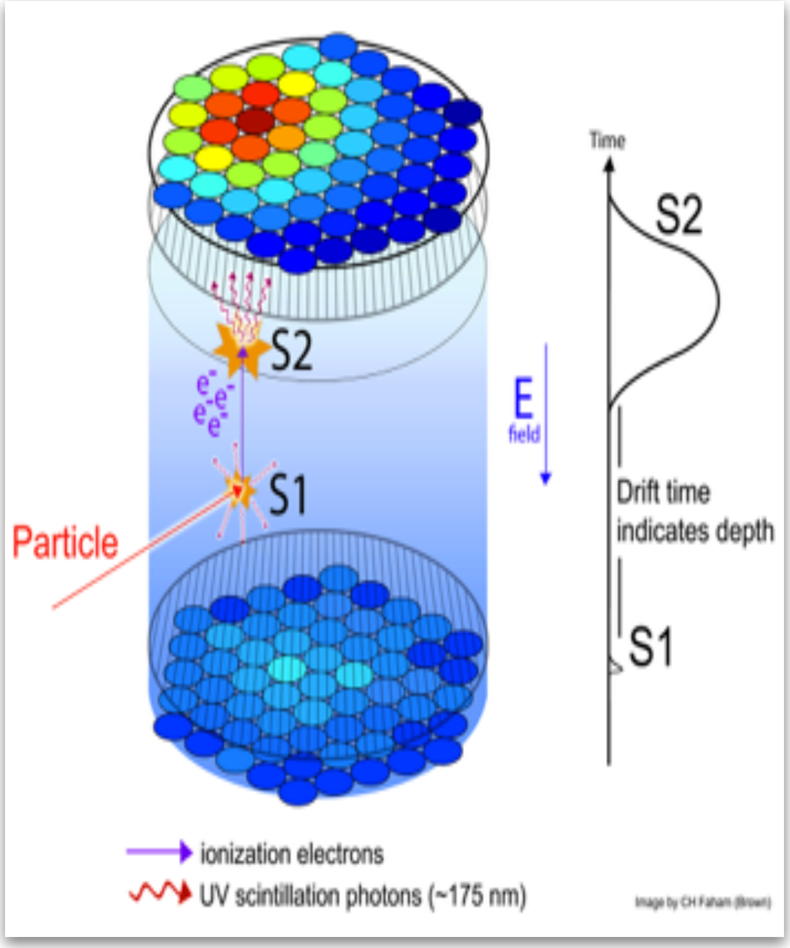


Why Xenon as a Target Nucleus

- Good for most EFT interactions
  - High atomic mass (A=131)
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enhance spin-dependent sensitivity studies
- High density (2.9 g/cm^3)
- High light yield
- No intrinsic backgrounds

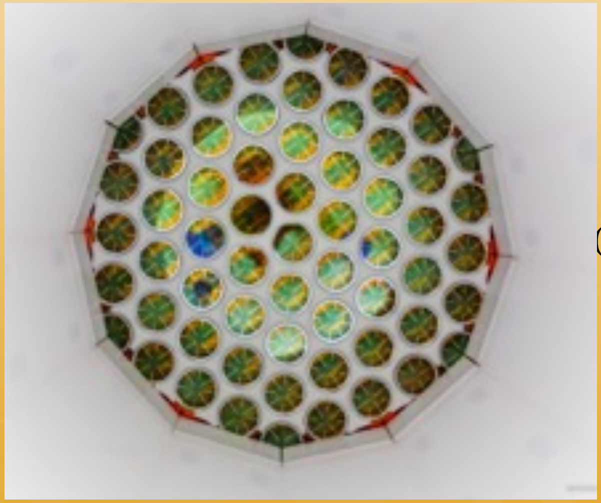
Liq. Xenon Time Projecting Chamber

- **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 (S2/S1) is 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**
- **TPCs are scalable with improvement of performance**

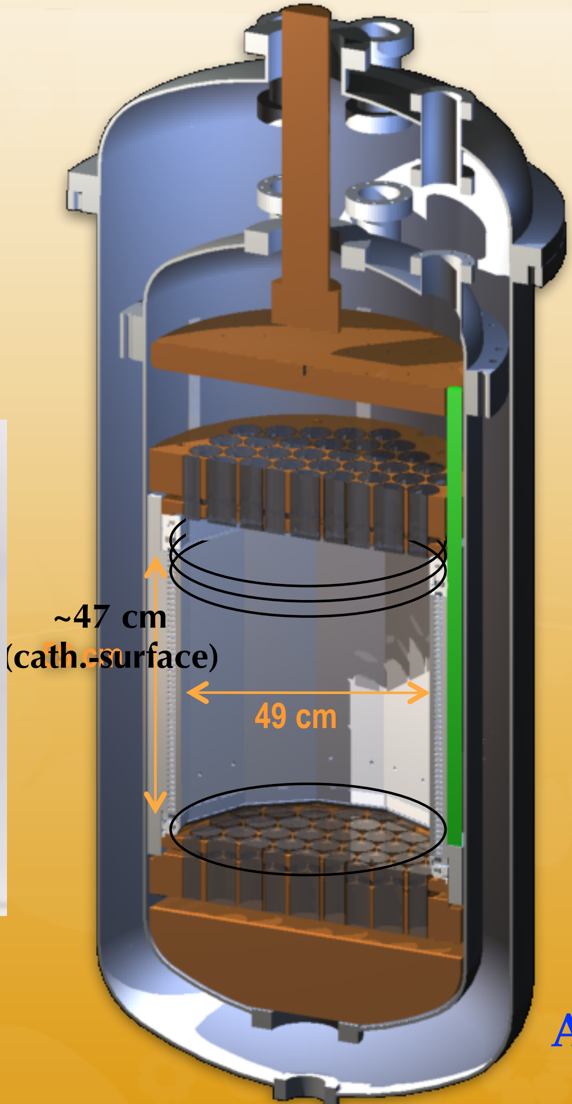


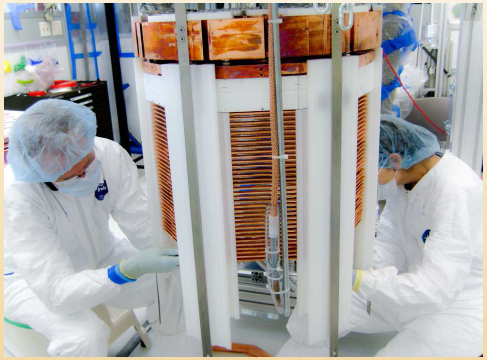
The LUX Experiment

- 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





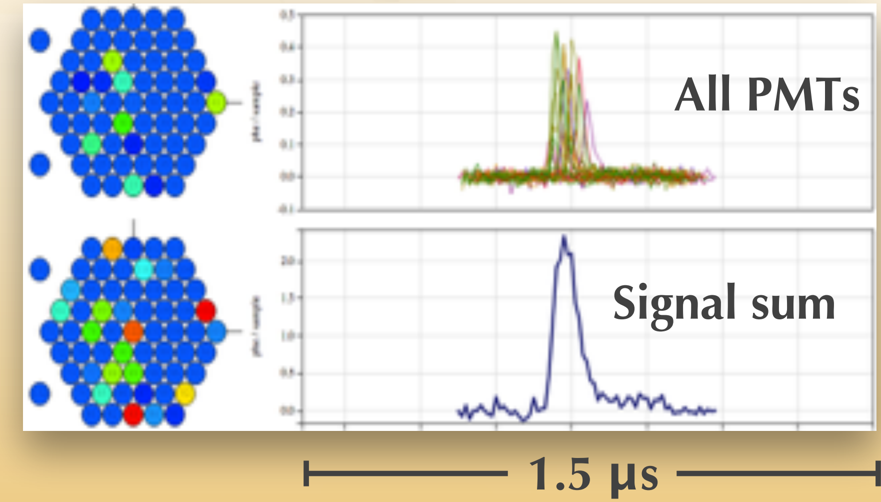
Construction materials chosen for low radioactivity (Ti, Cu, PTFE)

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

Typical LUX Pulses

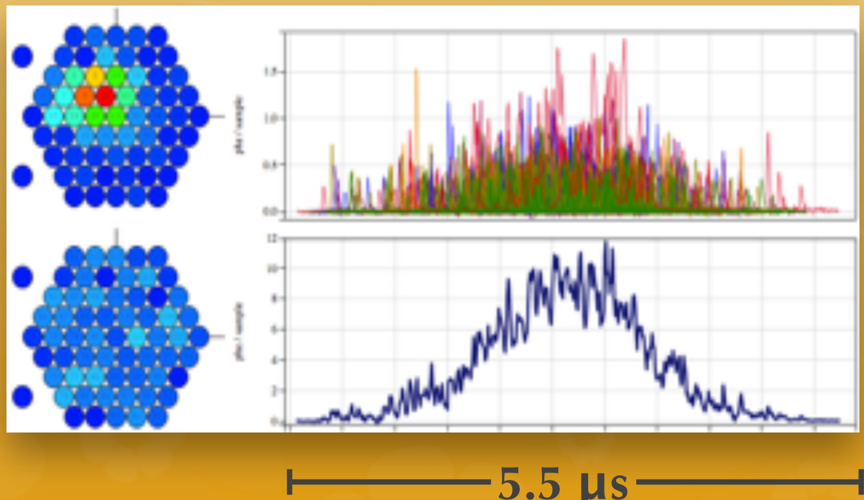
S1 - Prompt scintillation

- Sharp rise with a exponential decay
  - Pulse FWHM: ~100 ns
- ~60-90% of light in bottom PMTs
  - Ratio depends on the depth of the event
- Threshold of 2 detected photons



S2 - Electroluminescence

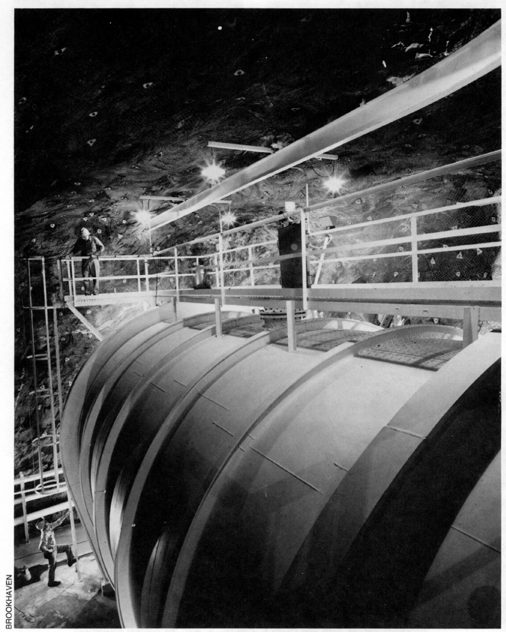
- Near-gaussian pulse shape
  - pulse width depends on the depth (z)
- ~57/43% (top/bot.) light in PMTs
- ~25 phd per extracted electron
- Threshold of 200 phd (WIMP-Search)



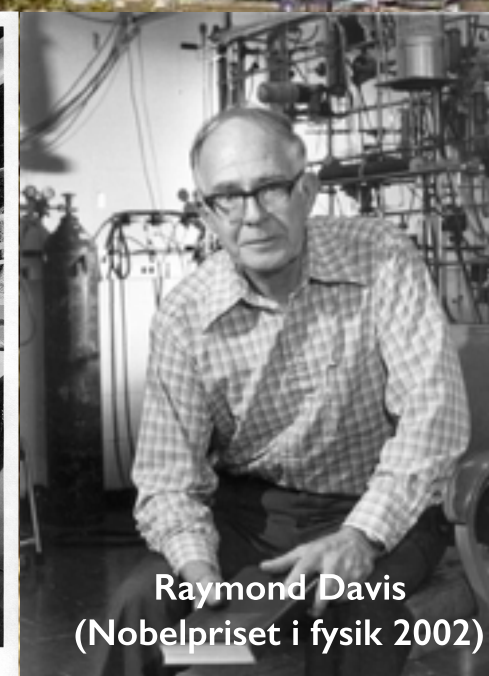
Phd stands for detected photons

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)

The LUX collaboration

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SD Mines

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Steven Young	Graduate Student

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Paul Terman	Graduate Student

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Timeline 2006-2016

Two main scientific 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

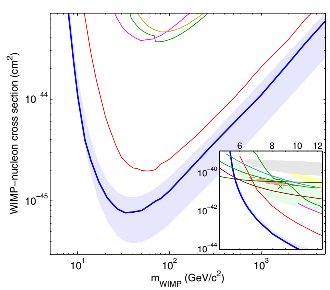
2014 (Sep): Second Science Run (SSR) Starts

2015 (Dec): 3-month run reanalysis posted

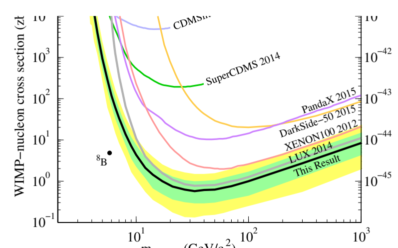
2016 (May): SSR finished - 332 live-days

2016 (Jul): SSR results released 332 live-days

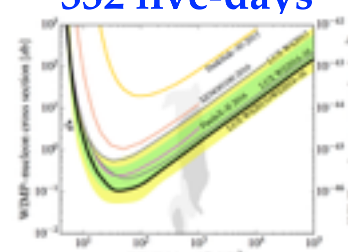
2016 (Sep): LUX decommission



PRL, 112, 091303 2014



PRL, 116, 161301 2016
PRL, 116, 161302 2016



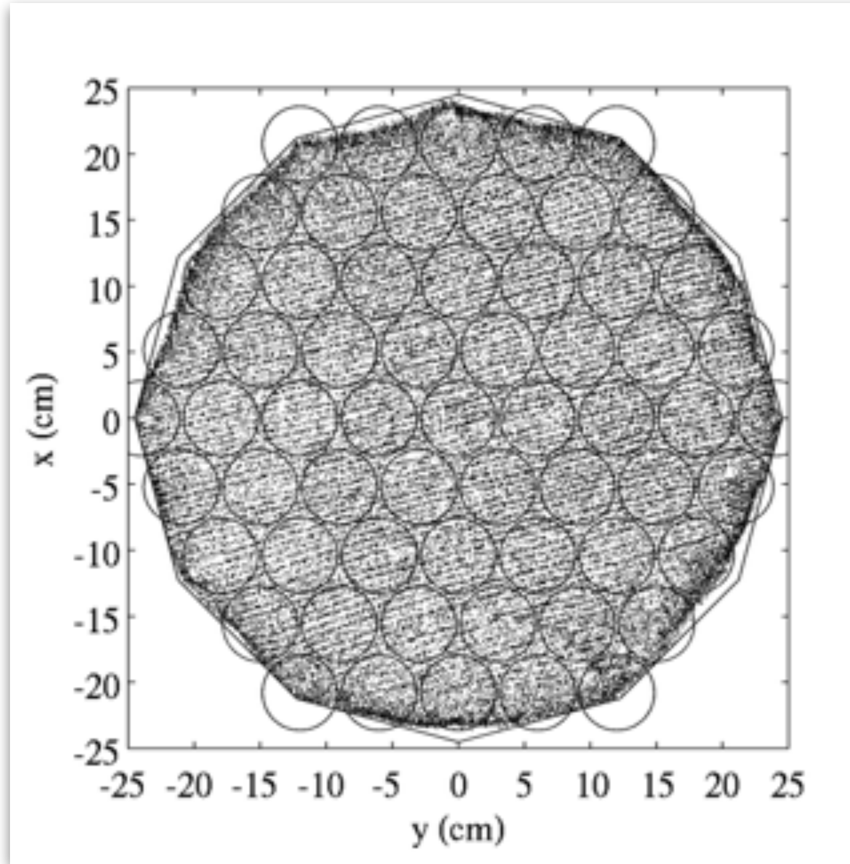
PRL, 118, 021303, 2017

Krypton Calibrations

- ^{83m}Kr injected in the gas system and decaying 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)

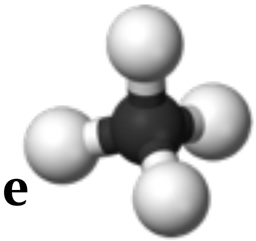
Second Science Run

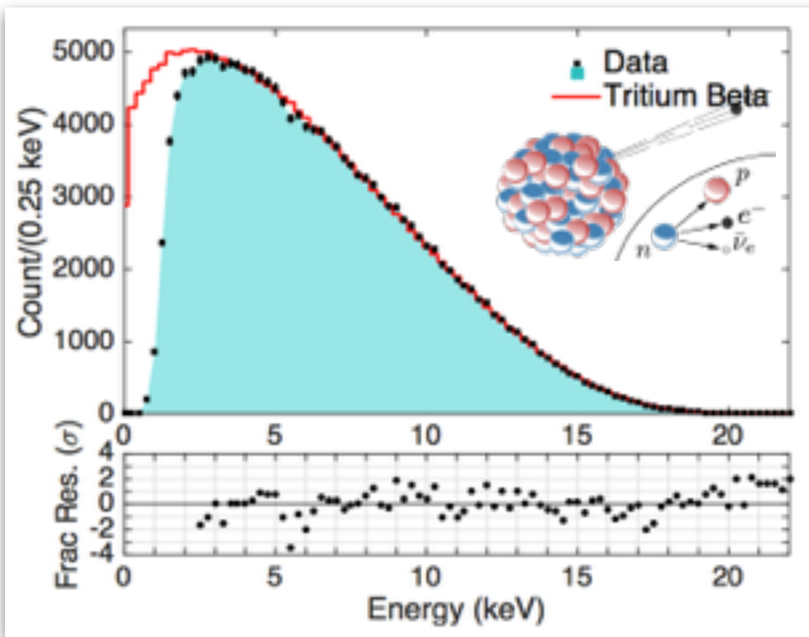


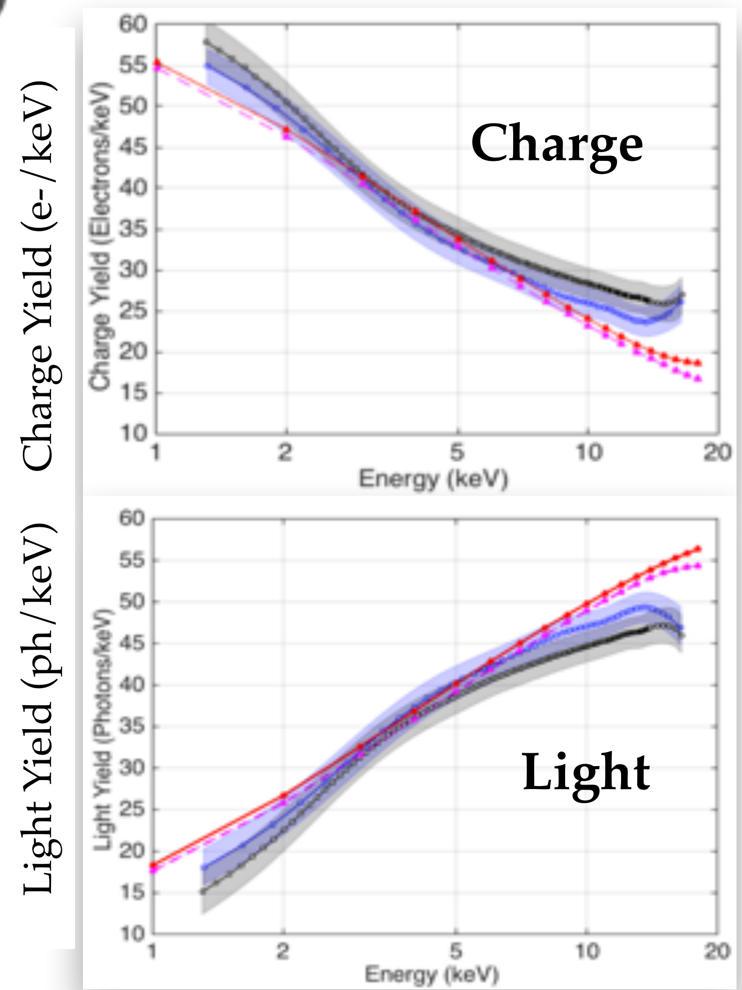
The large difference between the drift field (180 V/cm) and the extraction field (2.8 kV/cm in liquid) causes the the drift field lines to be compressed as they pass through the gate plane; any electrons leaving the drift volume appear only in narrow strips between each pair of gate wires.

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



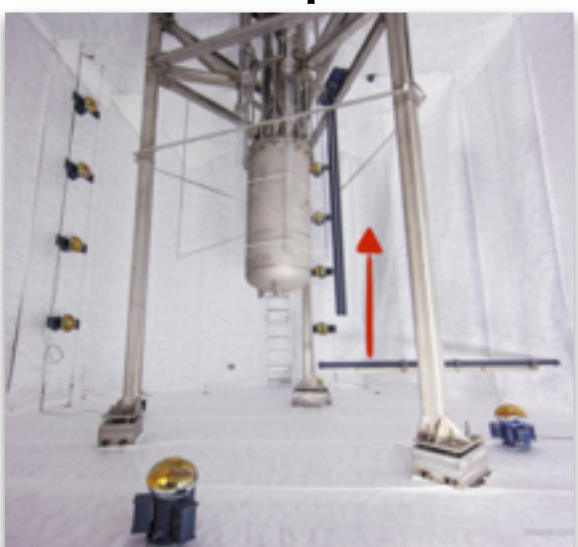


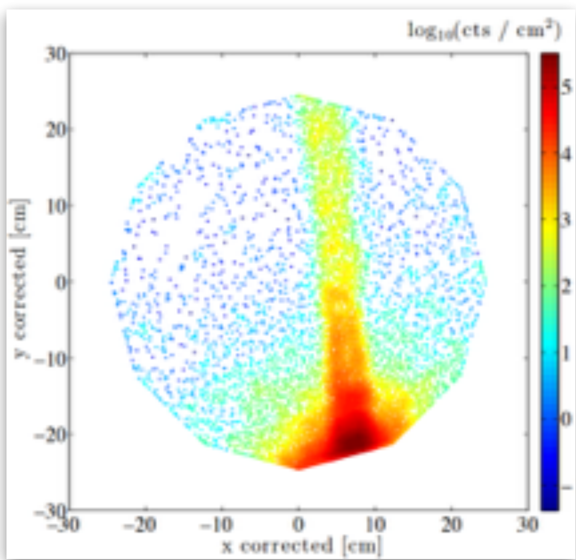


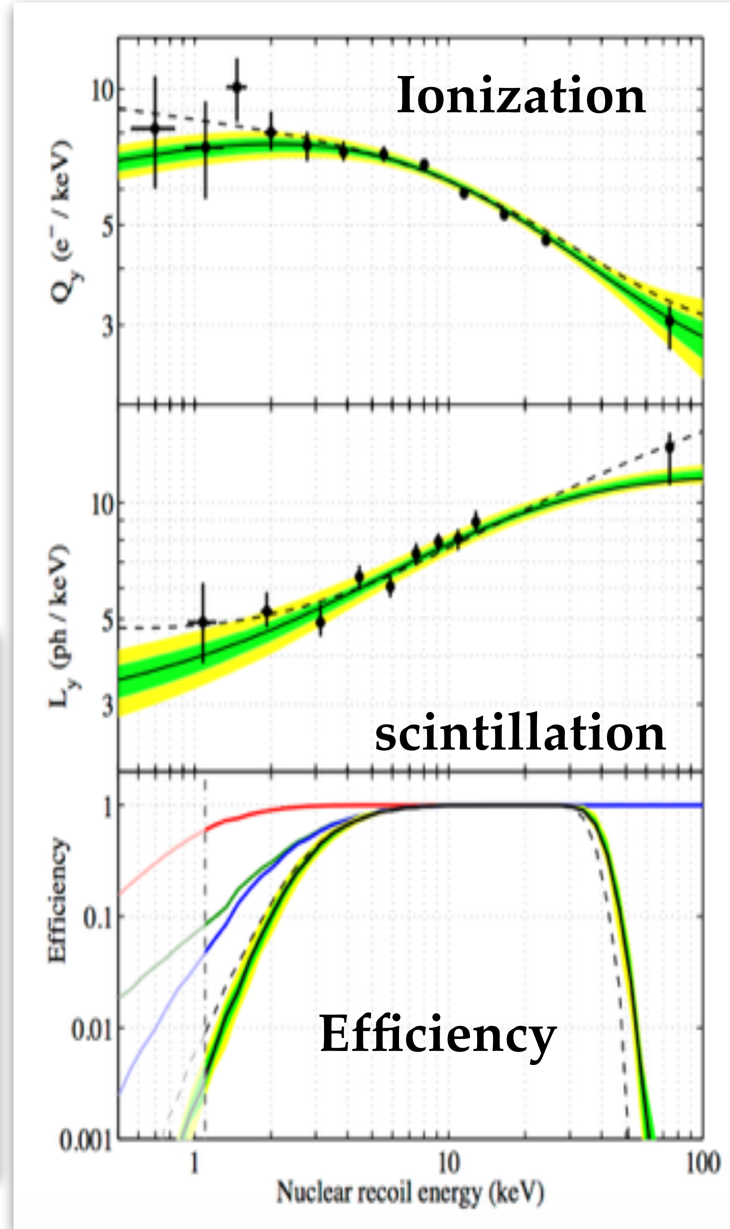
Phys. Rev. D 93, 072009 (2016)

NR Calibrations

- 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})
- NR calibrations every three months and at different depths.

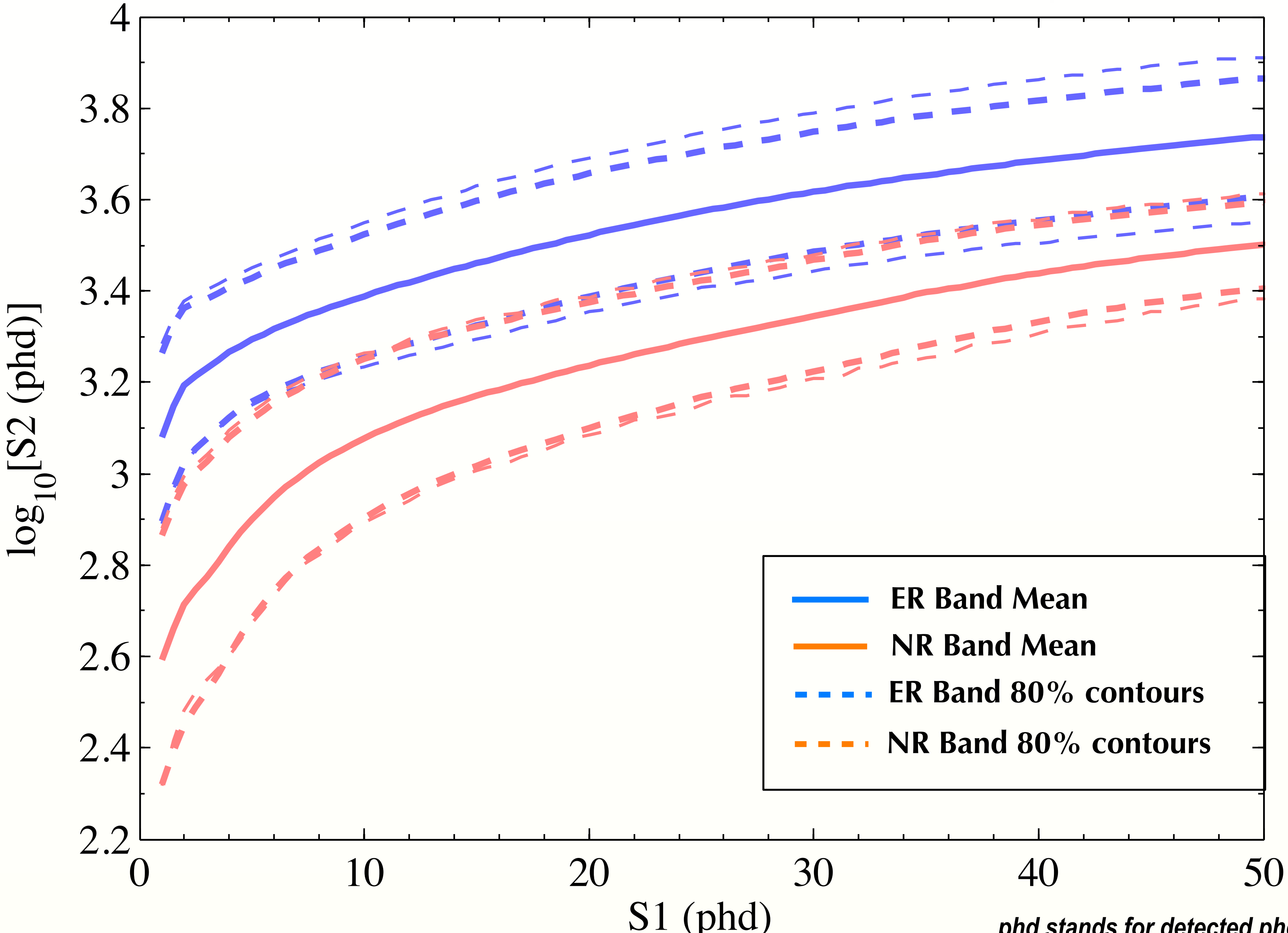






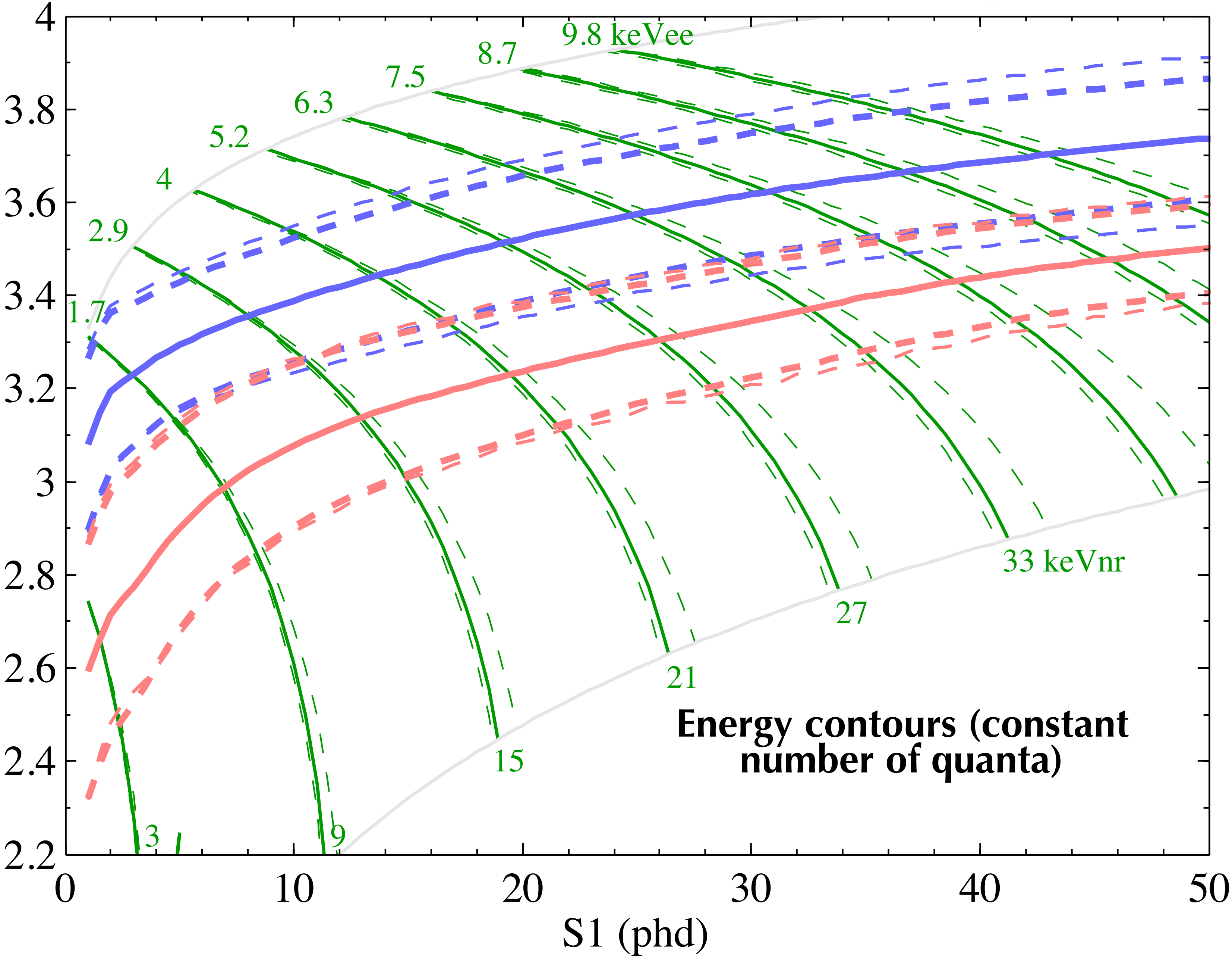
https://arxiv.org/abs/1608.05381

LUX 2014/2016 Detector's Response

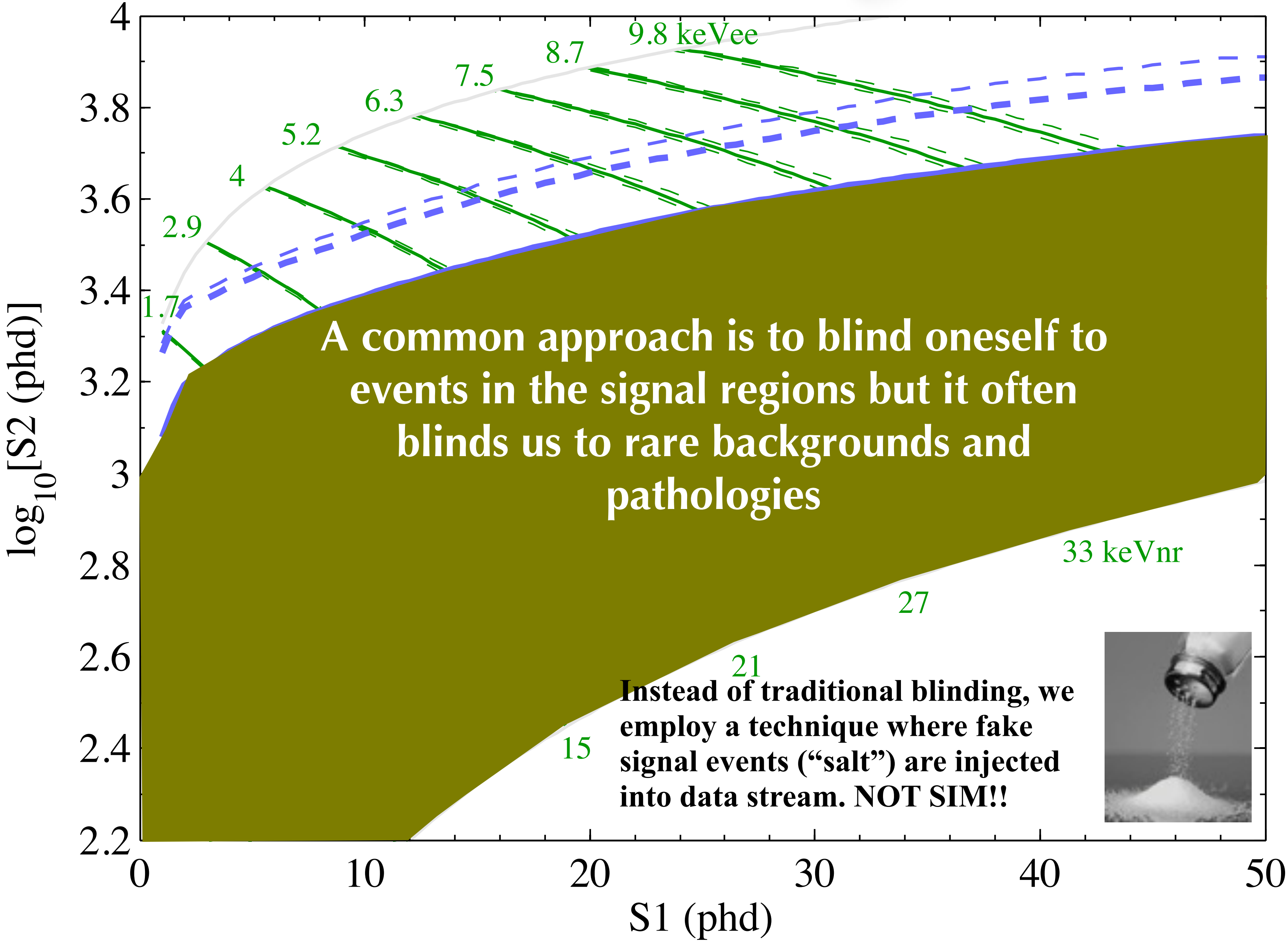


phd stands for detected photons

LUX 2014/2016 Detector's Response



LUX Salting

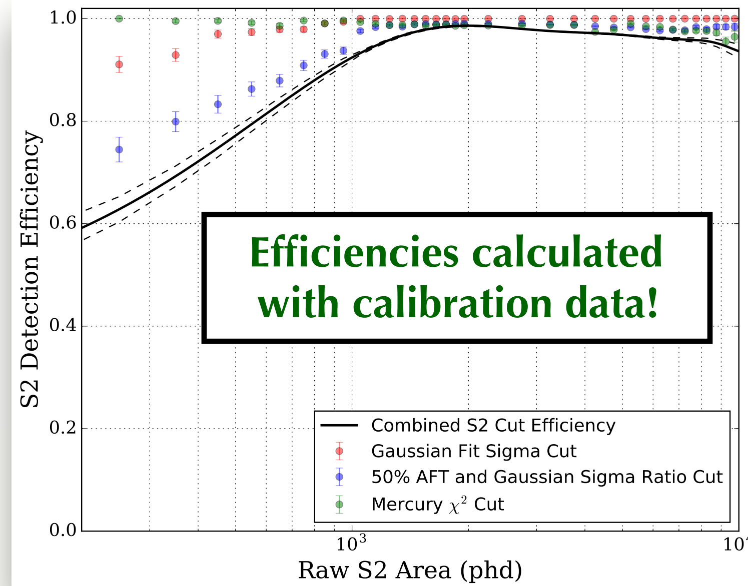


A common approach is to blind oneself to events in the signal regions but it often blinds us to rare backgrounds and pathologies

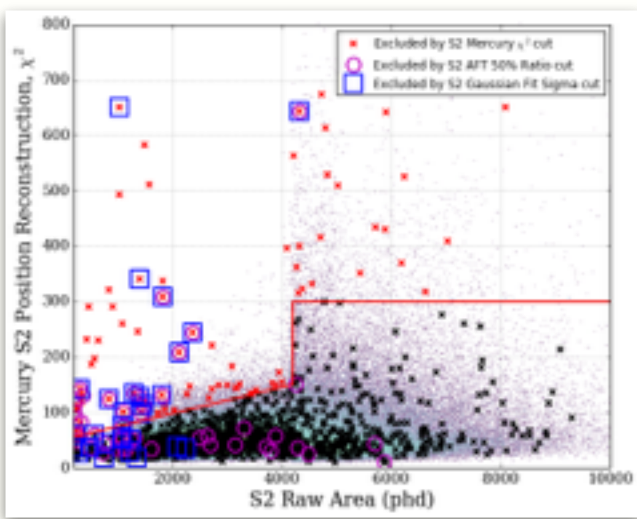
Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIM!!

S2 Quality Cuts and Efficiency

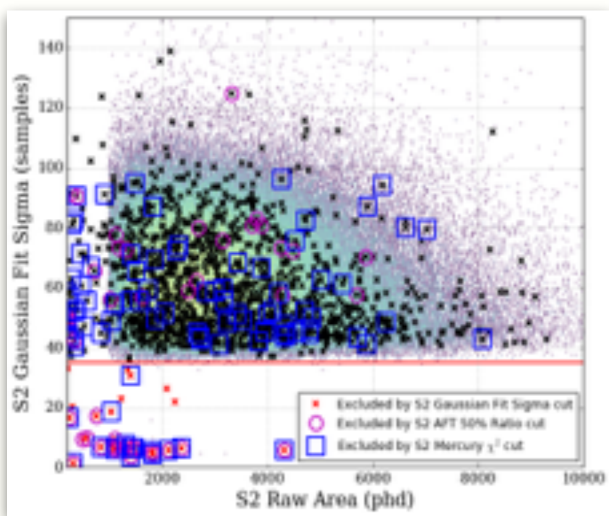
- **After single-scatter event selection (1 S1 + 1 S2), fiducializing, and cutting out periods of detector instability, few pathologies remain. These pathologies are targeted applying cuts to the S2:**
  - **Position reconstruction χ^2 cut analysis the PMT hit pattern. It removes single-electron pile-up, additional multiple scatters (*x,y* separated) and PMT after-pulsing.**
  - **S2 waveform cuts to remove misclassified gas events and merged S2s from multiple scatters (z separated).**



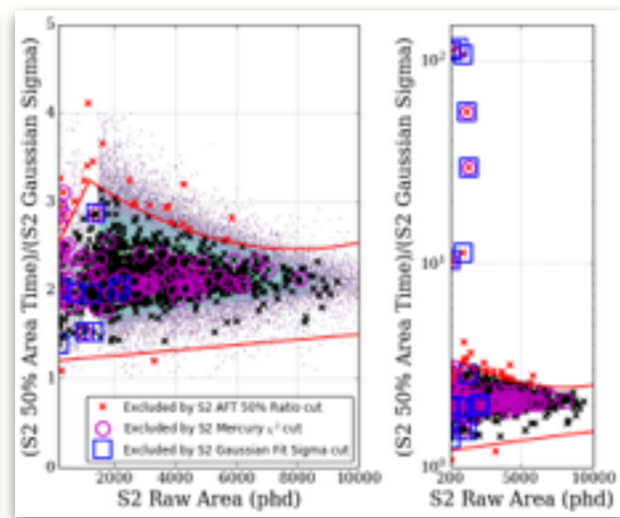
Position Reconstruction χ2 Cut



S2 Gaussian Fit Width



S2 Gaussian Sigma Cut



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

Bulk volume, but leakage at all energies

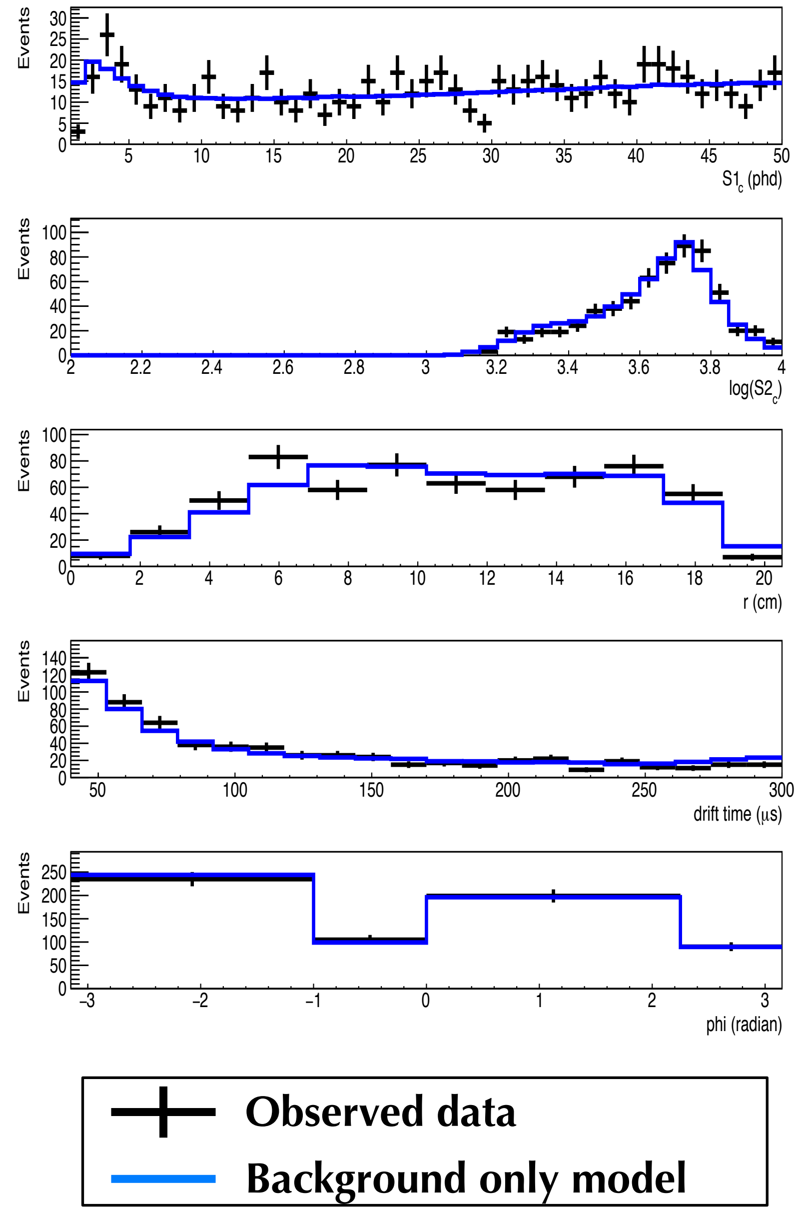
Low-energy, but confined to the edge of our fiducial volume

In the bulk volume, low-energy, in the NR band

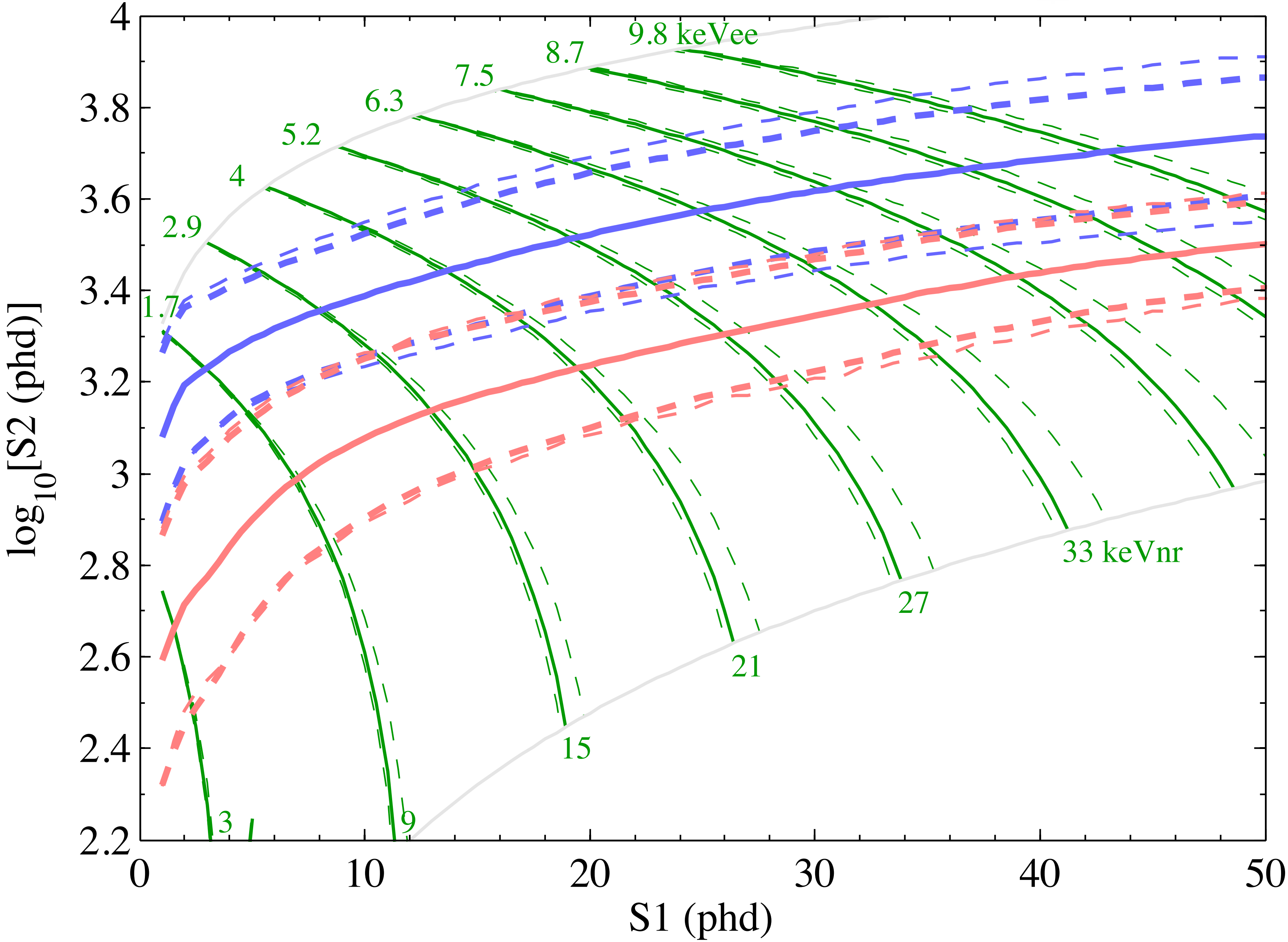
- These figures are figure of merit only. In our analysis we use a likelihood analysis.
  - + ~ 0.3 single scatter neutrons, e.g. from (α, n), not included in PLR

LUX Likelihood Analysis

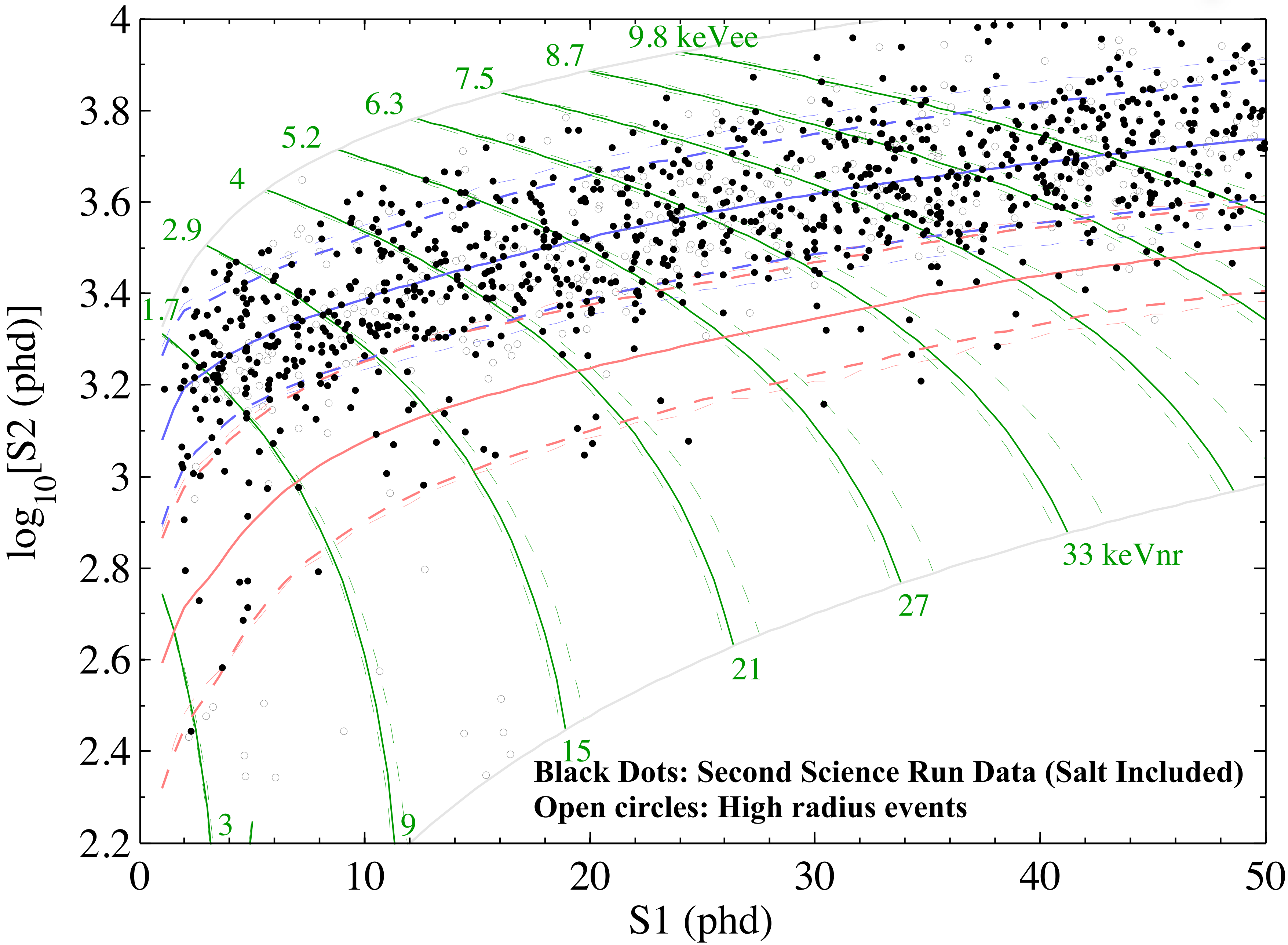
- A profile-likelihood test (PRL) was implemented to compare the models with the observed data
- 5 un-binned PLR dimensions
  - z/drift time, r, ϕ, S1 and $\log_{10}$(S2)
- 1 binned PLR dimension:
  - Event date
- Detector's response (S1,S2) modeled with NEST (Noble Element Simulation Technique) with 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.



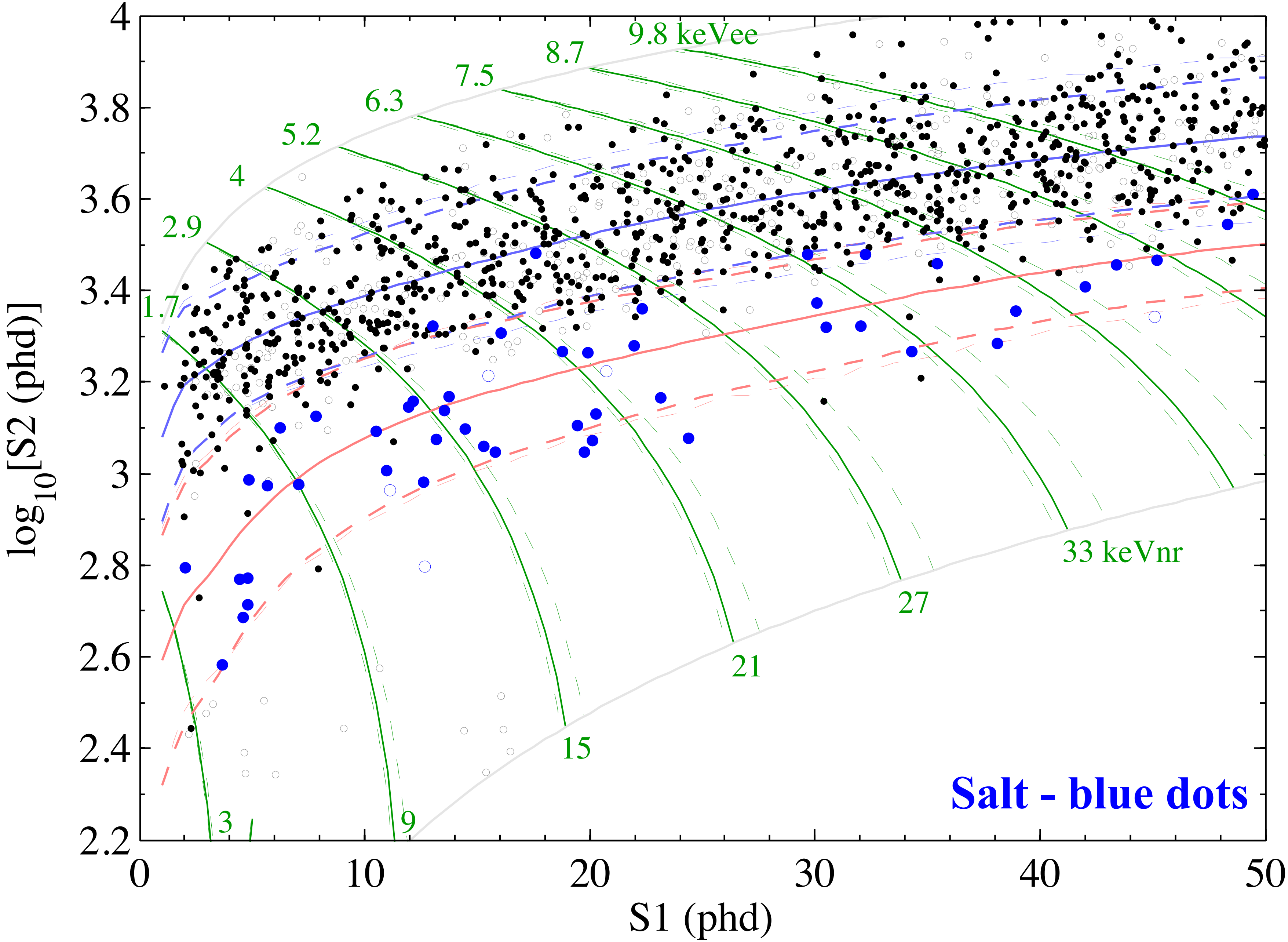
LUX 2014/2016 Detector's Response



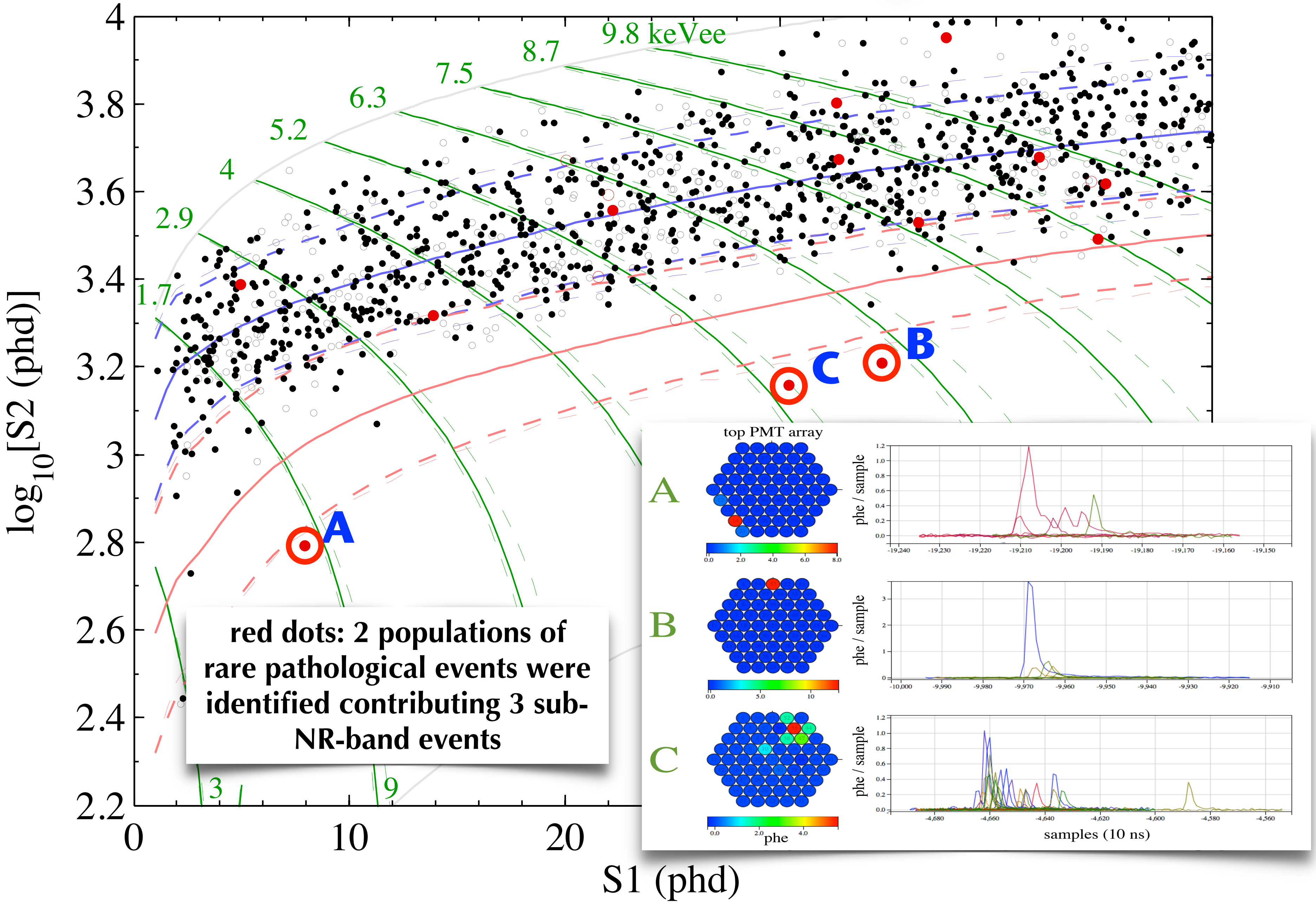
WIMP-search data from 332 live days



WIMP-search data - Salt Identified

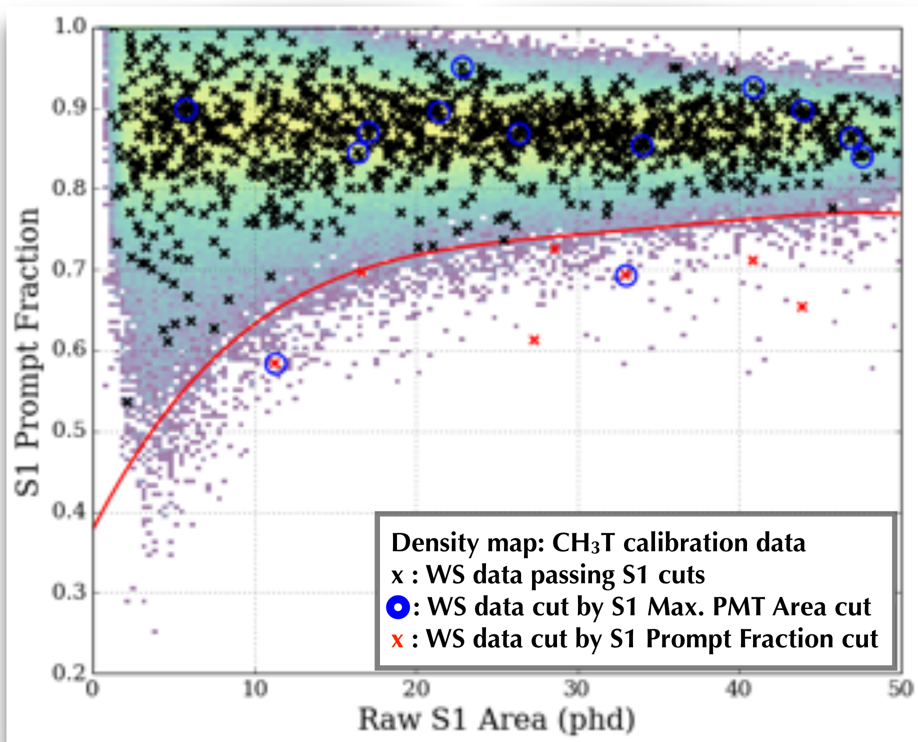


WIMP-search data - Pathological Events

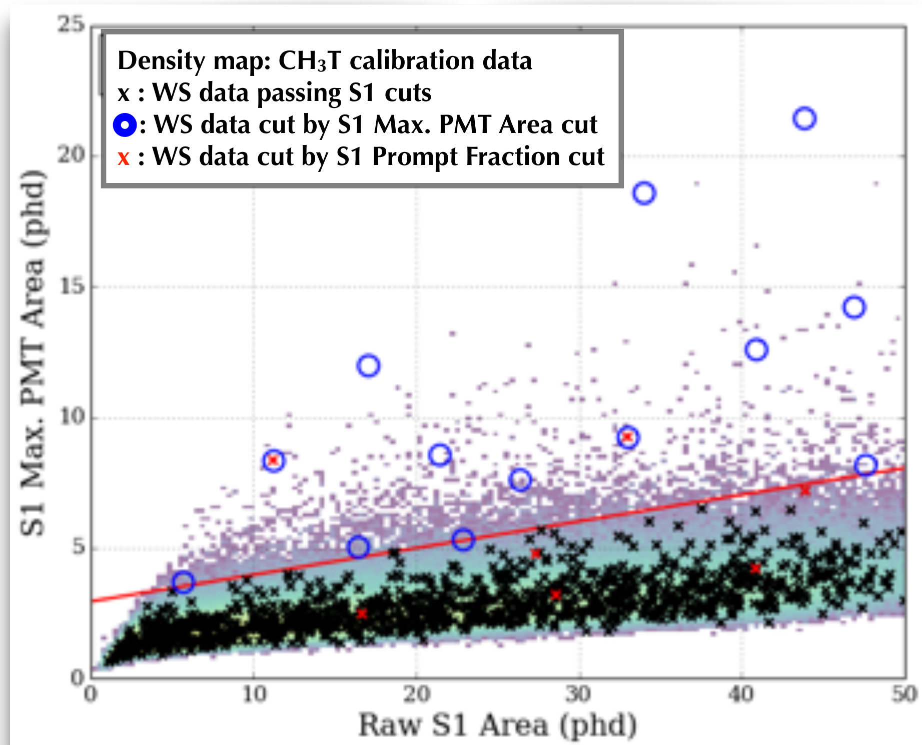


Post-Unsalting Quality Cuts

- 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

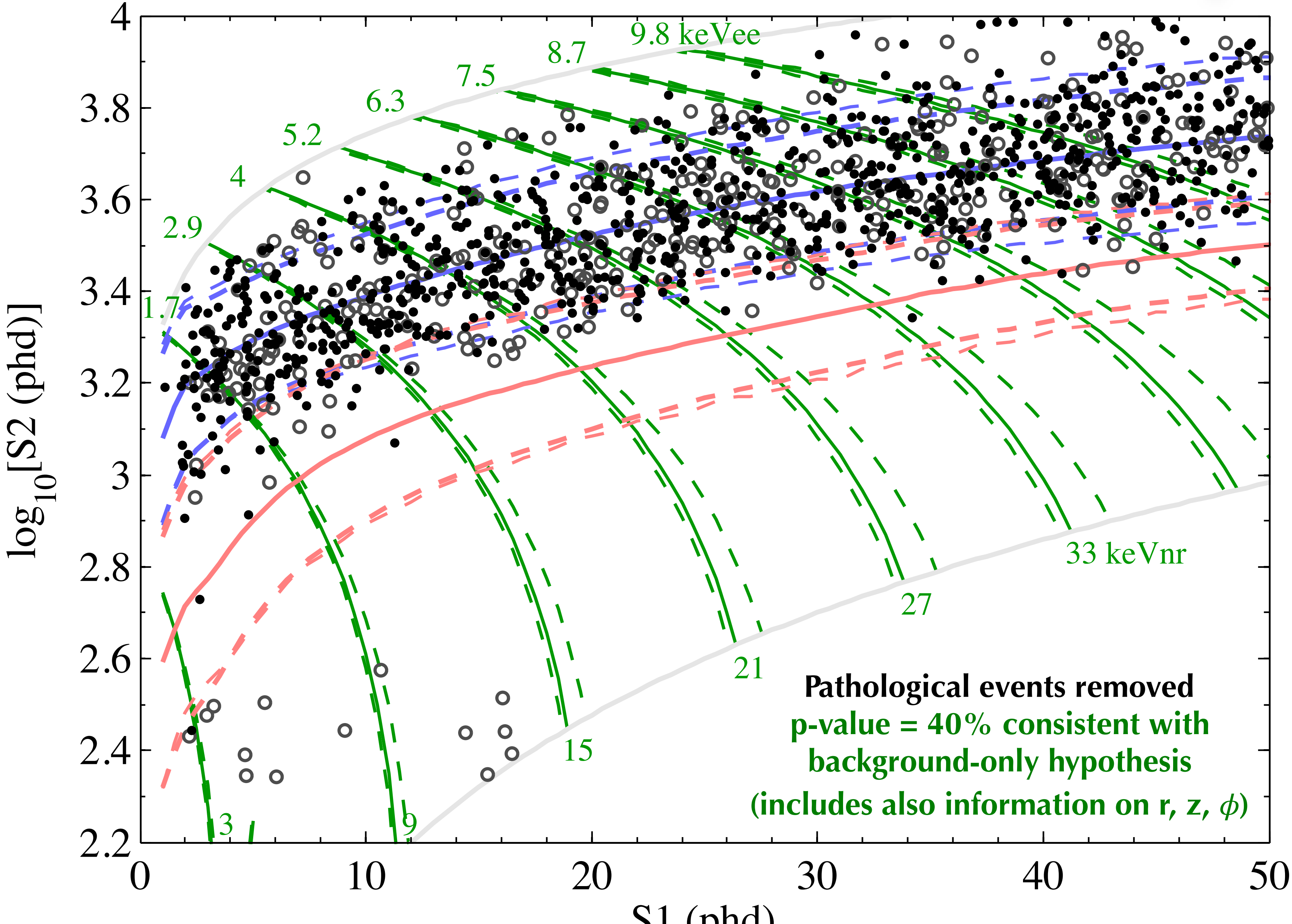


Removes events with S1 that has gas-event-like time structure

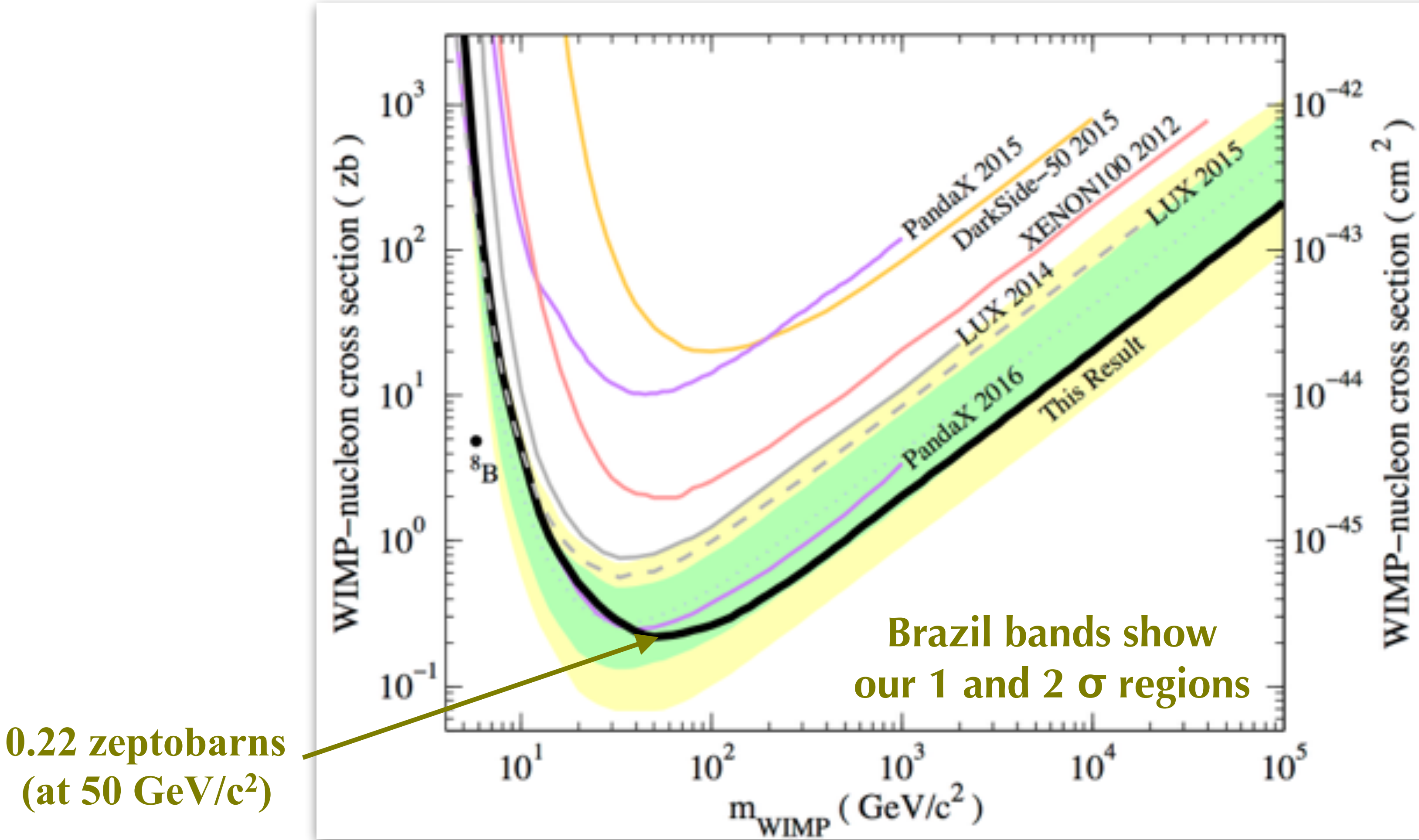


Removes events with S1 light overly concentrated in a single PMT

WIMP-search data from 332 live days

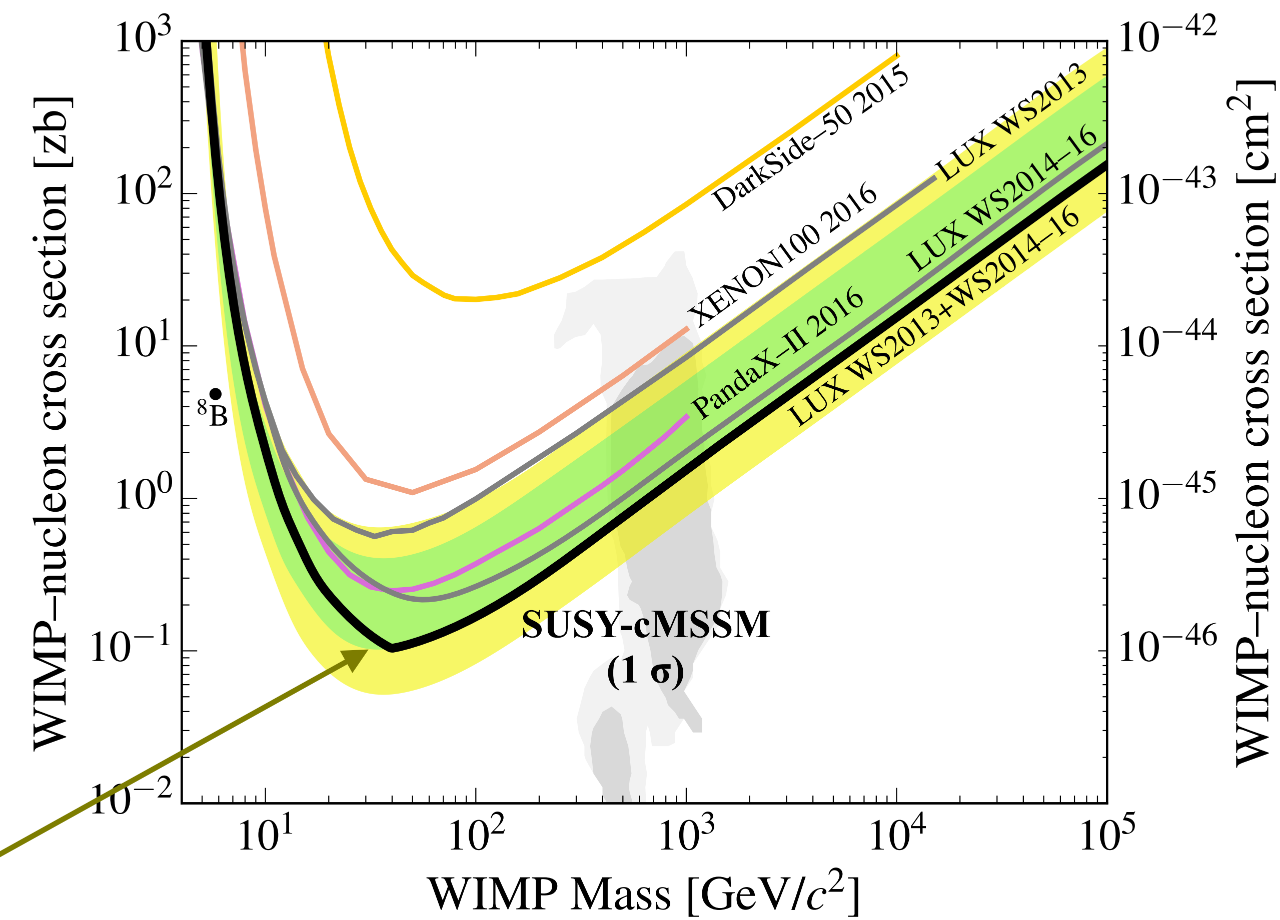


WIMP-nucleon SI Exclusion - SSR



- **We observed an improvement of a factor of four for high WIMP masses compared with the results from the first science run (PRL, 116, 161301 (2016)).**

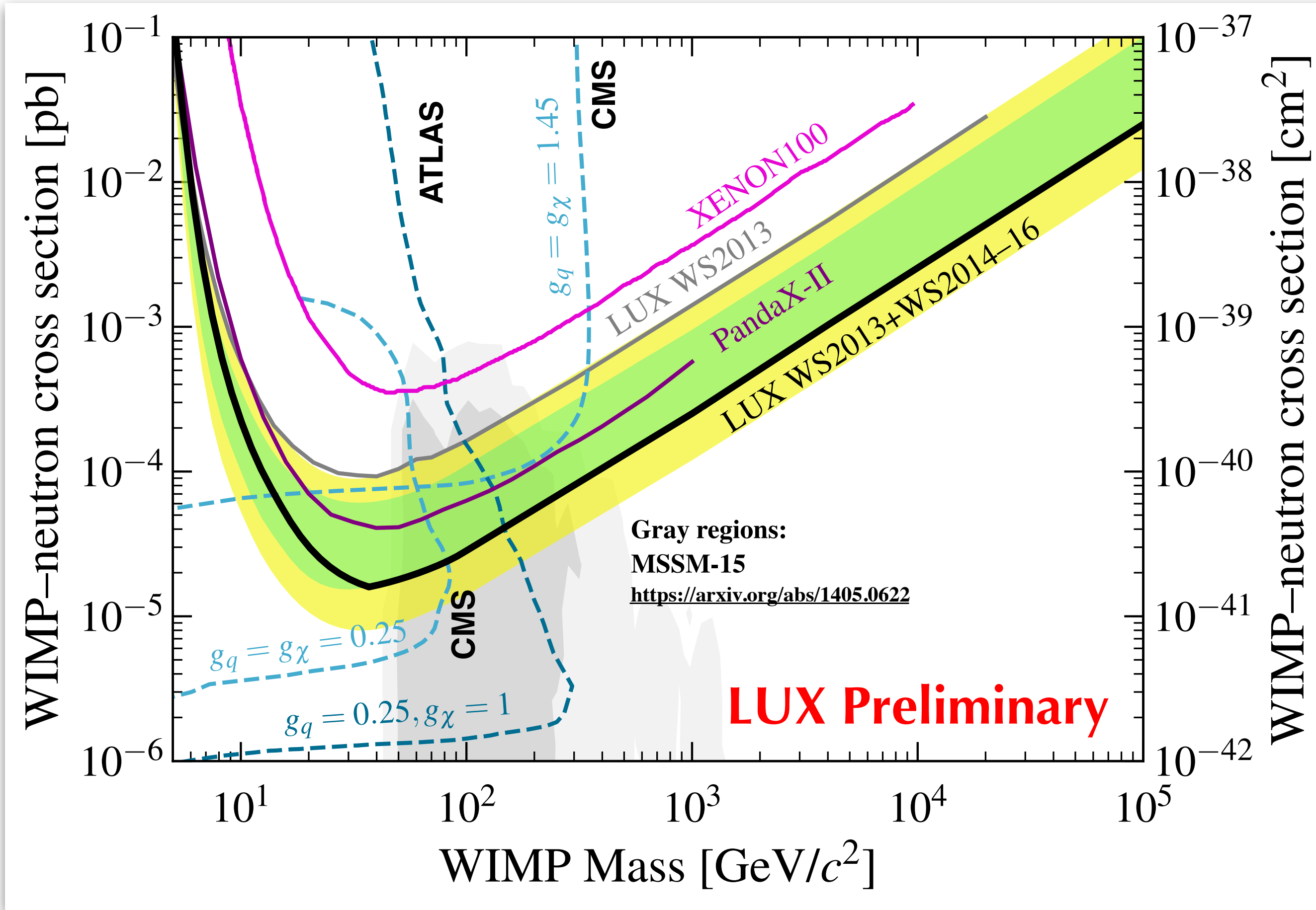
SI Exclusion - FSR+SSR



0.11 zeptobarns (at 50 GeV/c^2)

- **Both LUX Runs Combined**
  - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.118.021303
- **LUX now excludes significant portions of the 1-sigma regions for WIMPs favored by certain supersymmetric models.**

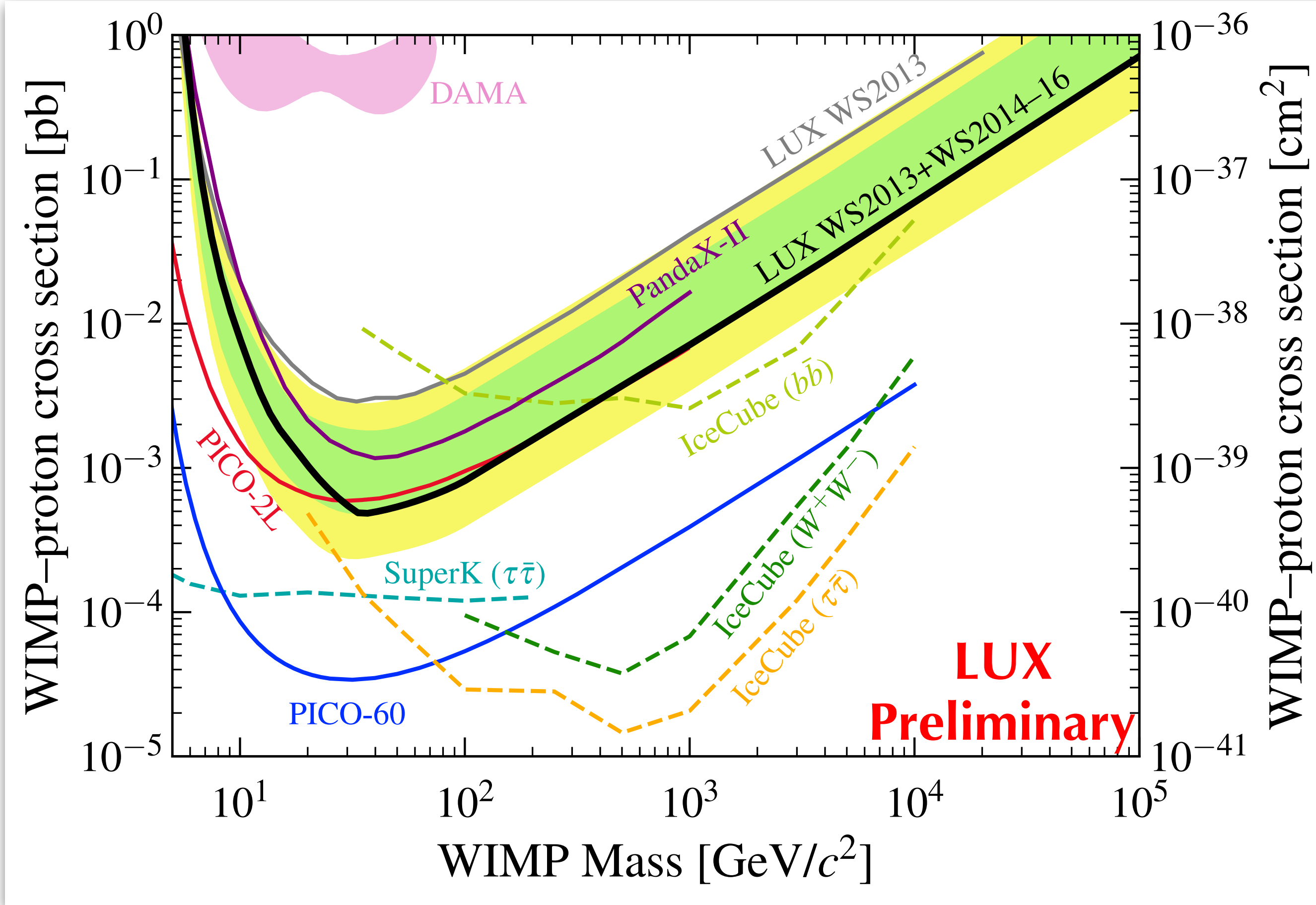
Spin-Dependent Neutrons (FSR+SSR)



1.6×10^{-41} cm^2 (at 35 GeV/c^2)

- **Both runs combined**
- **We observed an improvement of a factor of six compared with the results from the first science run (PRL, 116, 161302 (2016)).**

Spin-Dependent Protons (FSR+SSR)

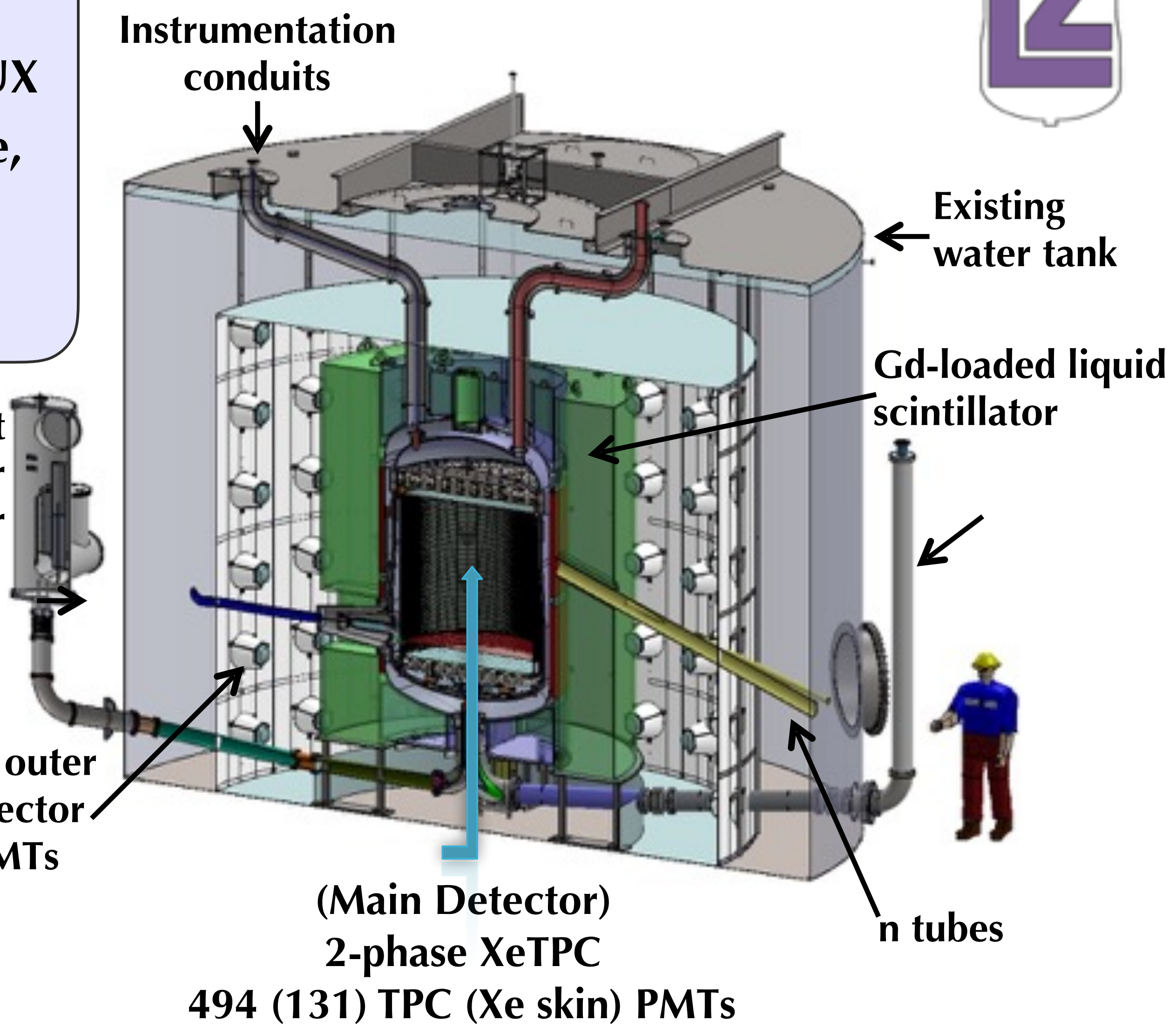


5×10^{-40} cm^2 (at 35 GeV/c^2)

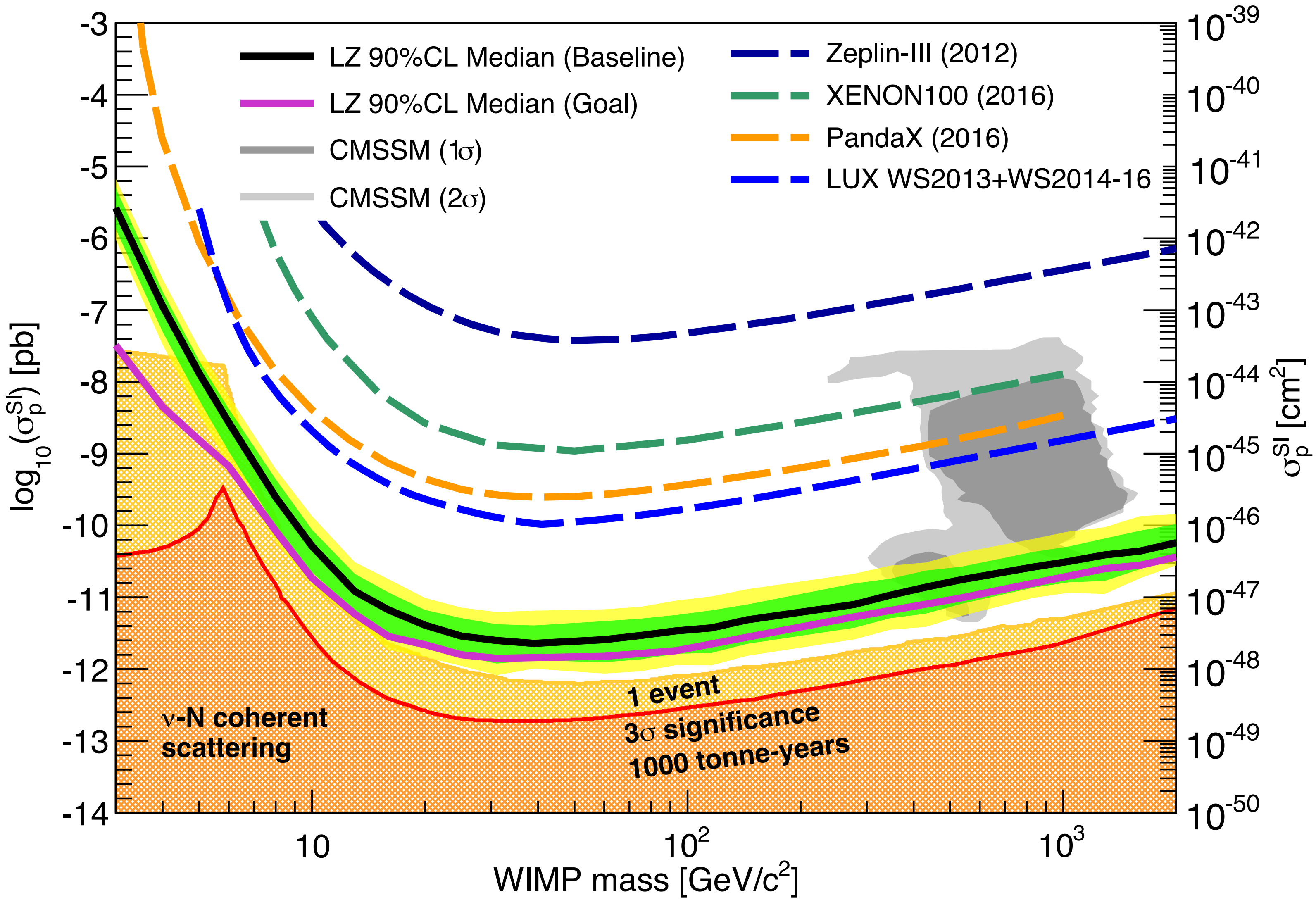
- **We observed an improvement of a factor of six compared with the results from the first science run - (PRL, 116, 161302 (2016))**

The LUX-ZEPLIN Experiment

- Turning on by 2020 with 1,000 initial live-days plan
- In the same location of LUX
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto system



The LUX-ZEPLIN Experiment

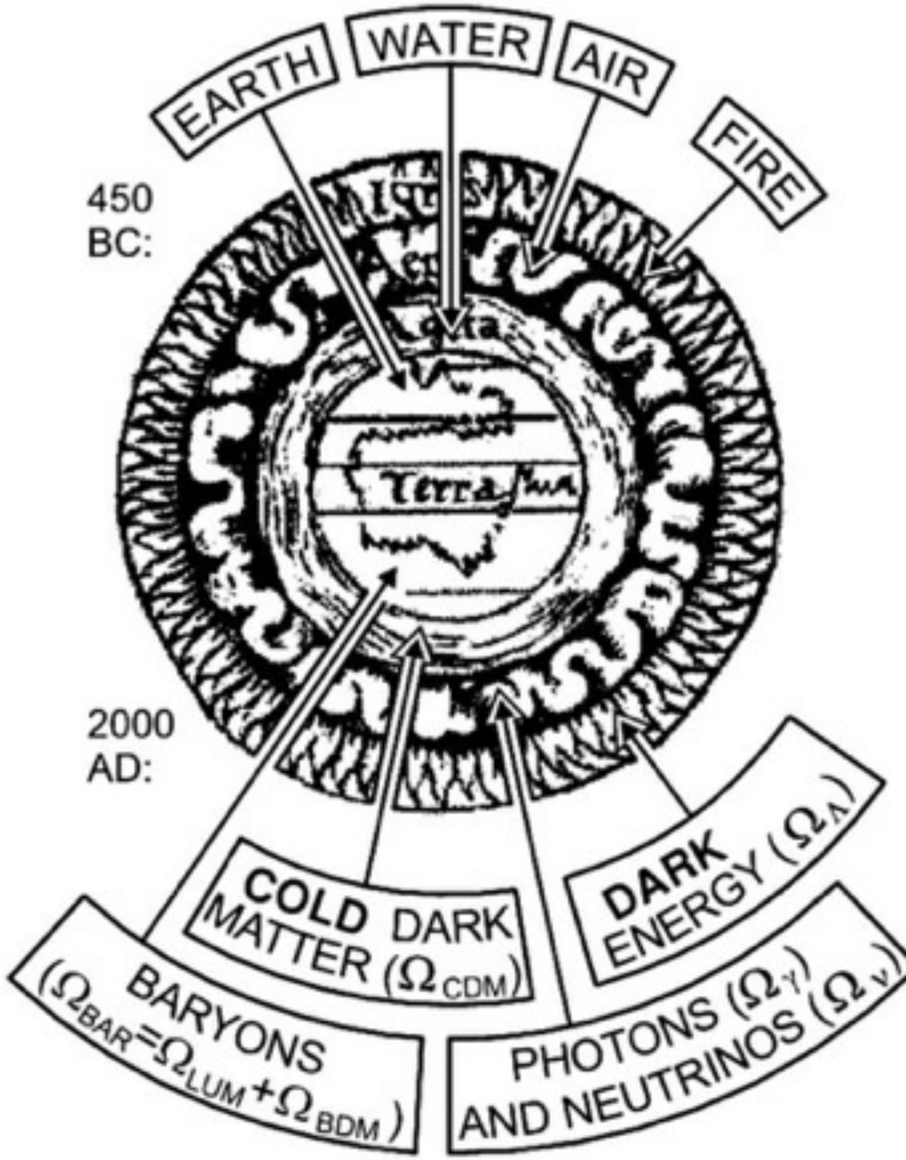


(LZ 5.6 Tonnes, 1000 live days)

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 (2.2×10^{-46} cm^2) at 50 GeV/c^2.**
- **When both runs are combined SI WIMPs are excluded down to 0.11 zeptobarns at 50 GeV/c^2.**
- **Spin-Dependent results show a cross section of 1.6×10^{-41} cm^2(at 35 GeV/c^2) for neutrons (most sensitive constraint to date) and a cross section 5×10^{-40} cm^2(at 35 GeV/c^2) for protons.**
- **Results available on:**
  - **http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.118.021303**
- **More analysis forthcoming**
  - **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).**

Thanks!
Obrigado!

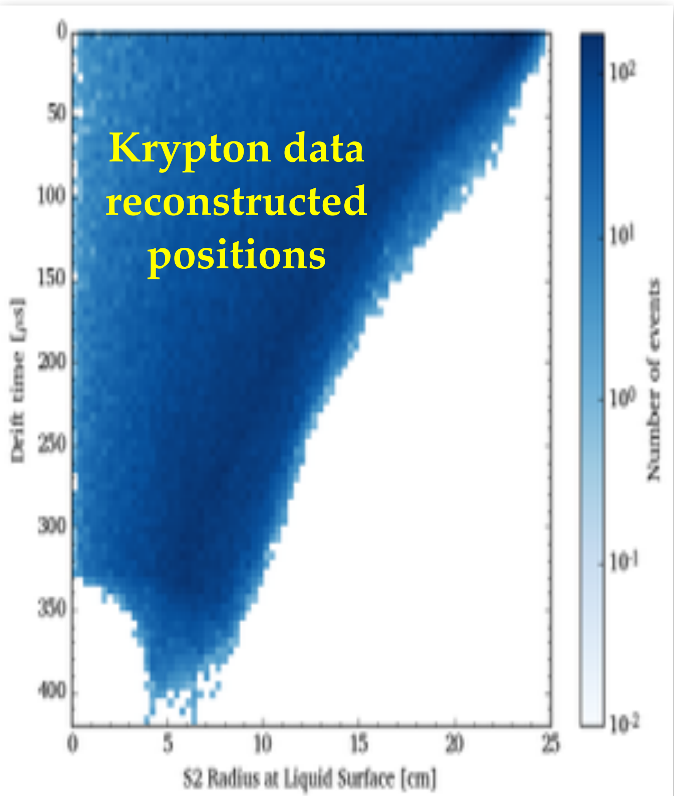


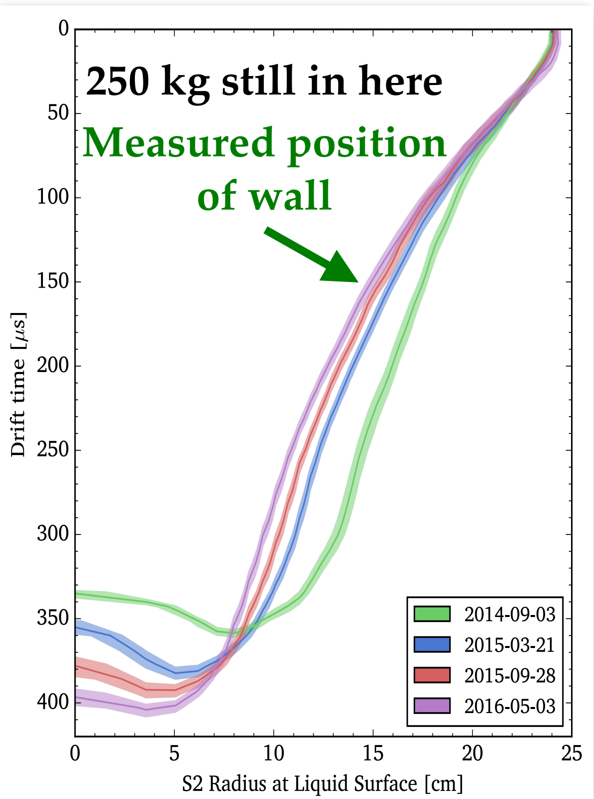
Backup Slides

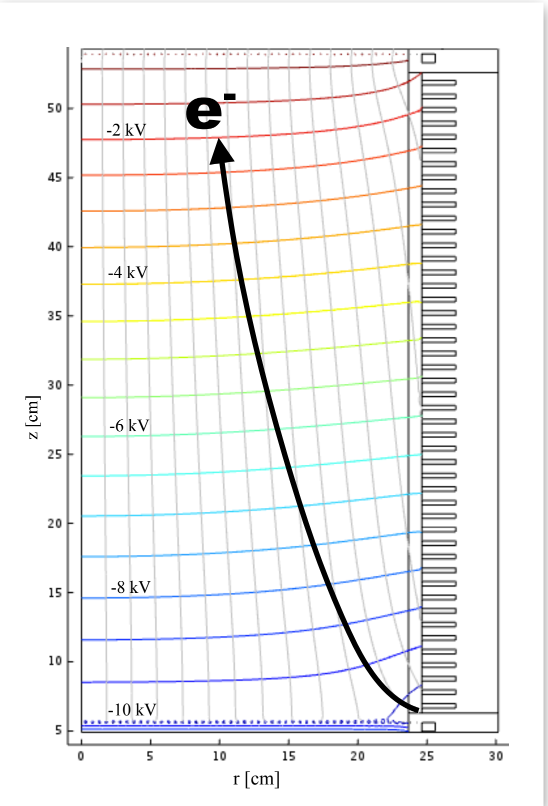
LUX in the Water Tank 2012

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.

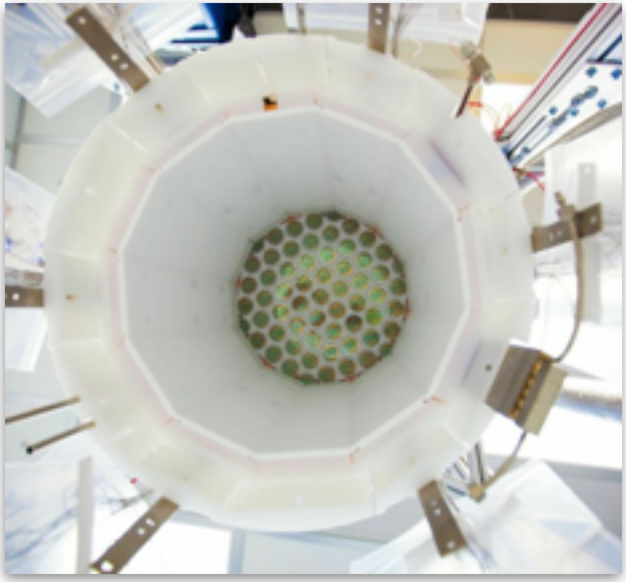


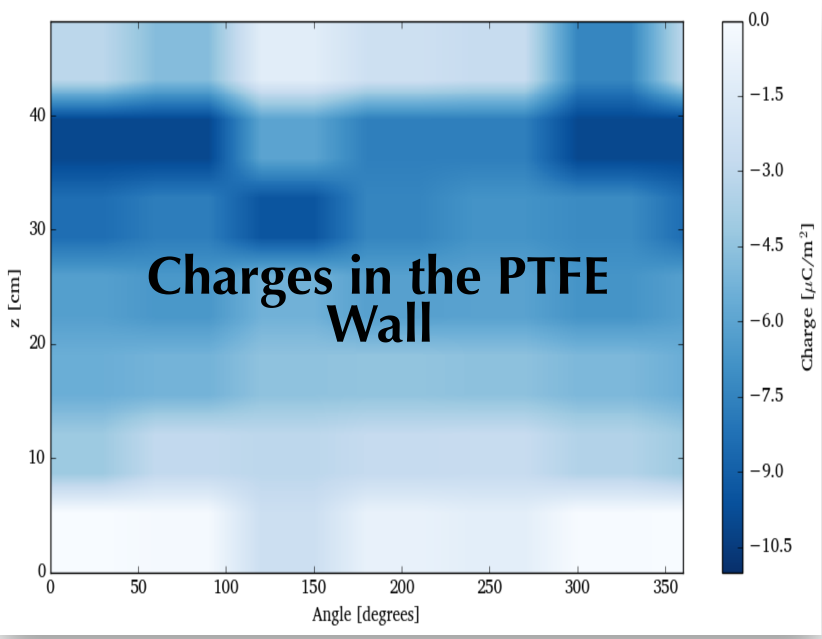


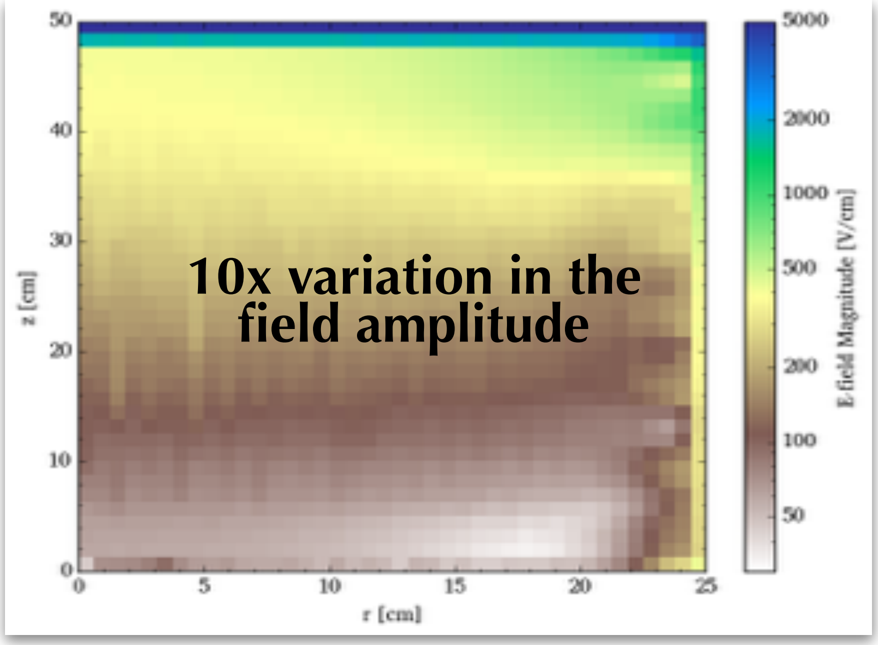


Modeling the Electric Field

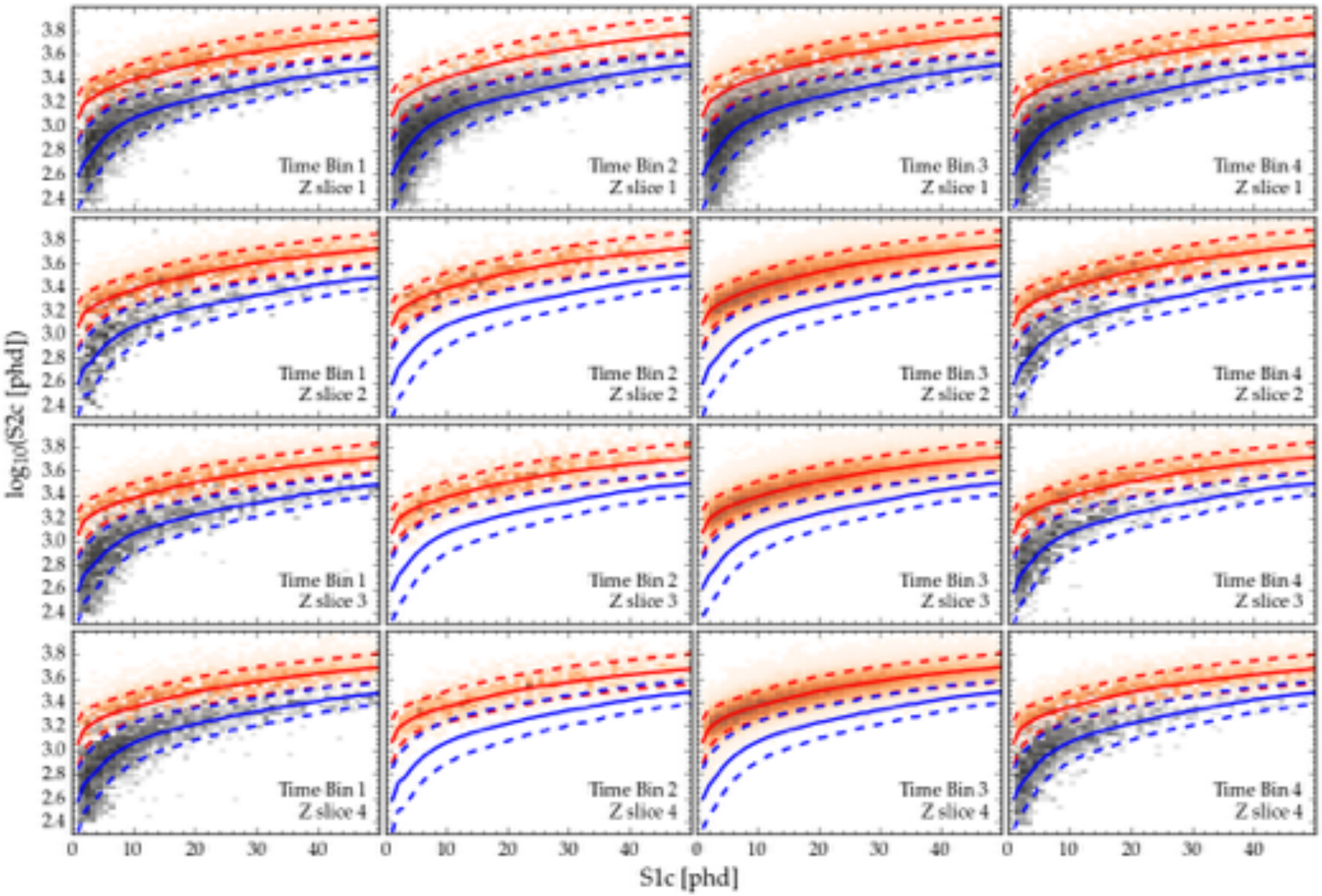
- **A Fully 3-D model is constructed in the COMSOL Multiphysics® FEM software to compute the electric field in the active region of LUX**
- **The observed radial field is consistent with a build up of negative charge (0 to -10 μC/m²) on the PTFE walls.**
- **Charges are added to the walls to produce the radial field that best produces the observed distribution of ^{83m}Kr decays.**







Dealing with the Fields



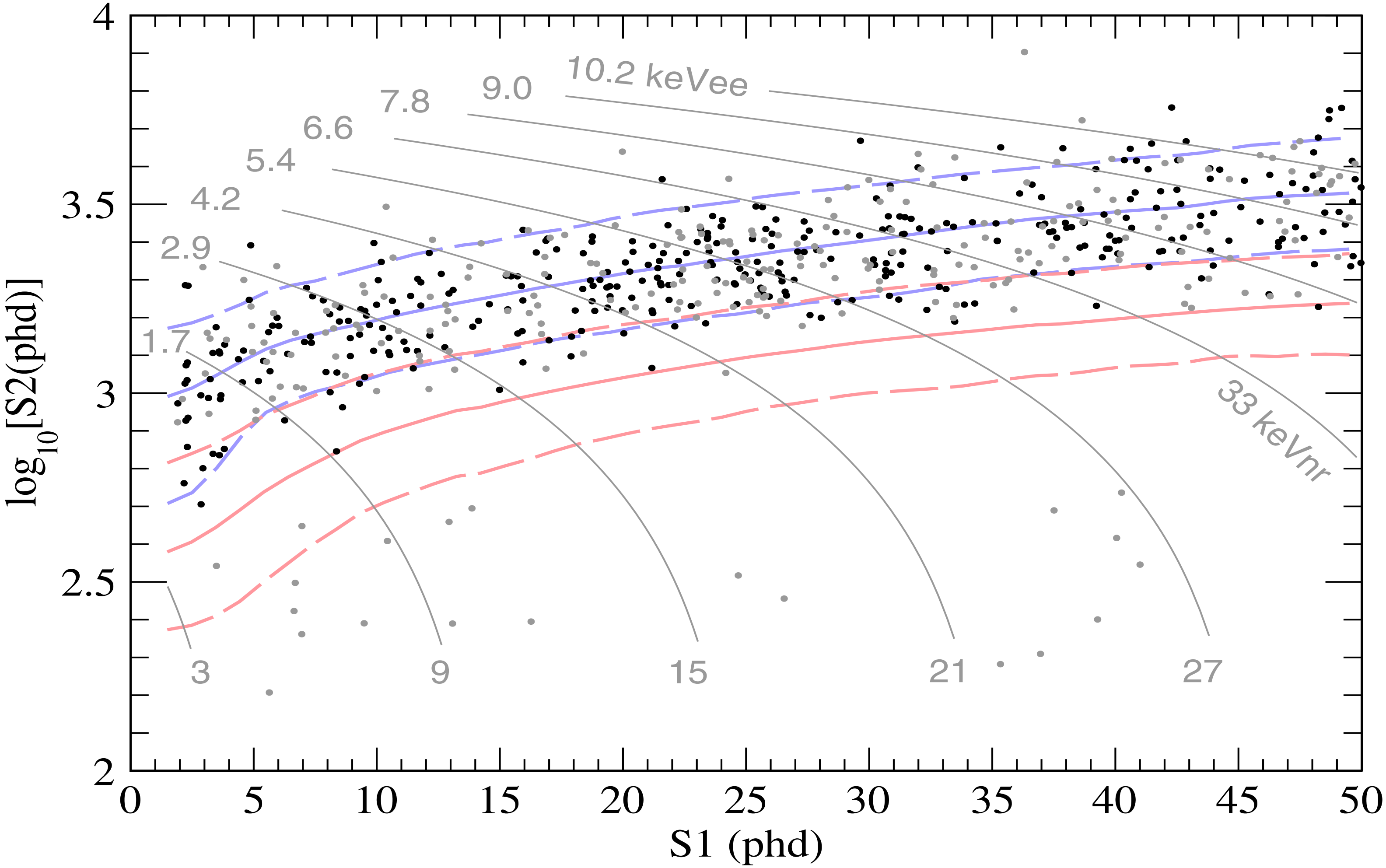
Gray density: CH_3T calibration (ER)

Orange density: DD calibration (NR)

Solid lines:
NEST model,
ER, NR band mean

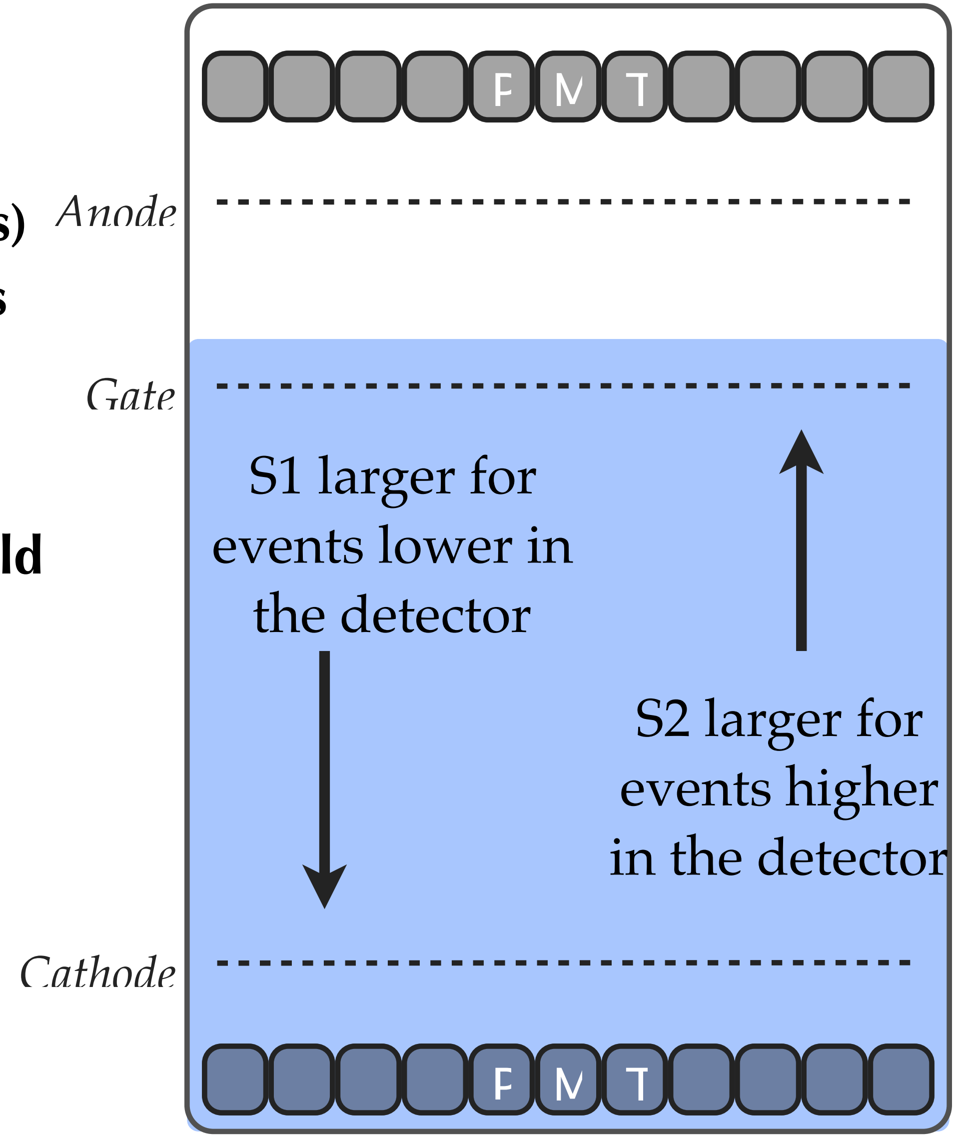
Dashed lines:
NEST model,
10-90 percentile.

First Science Run Reanalysis



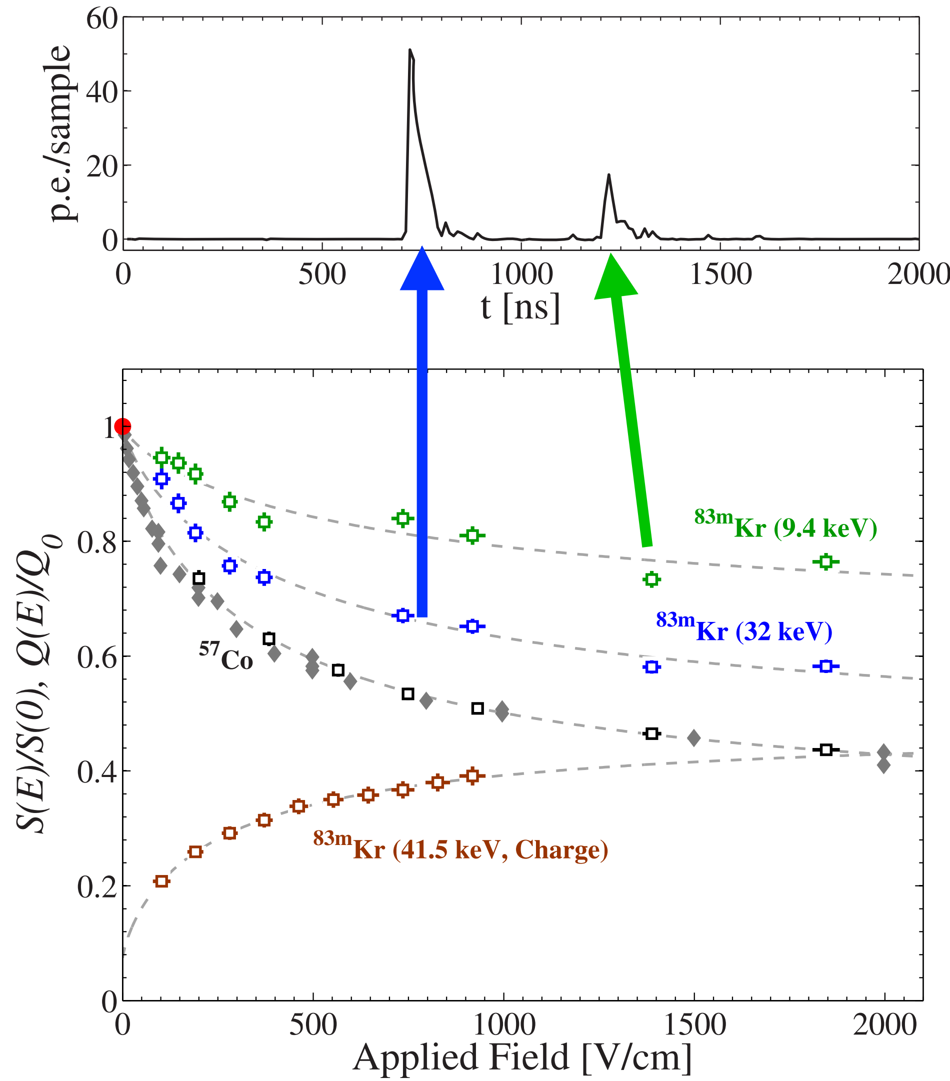
S2/S1 Position Corrections

- **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.**



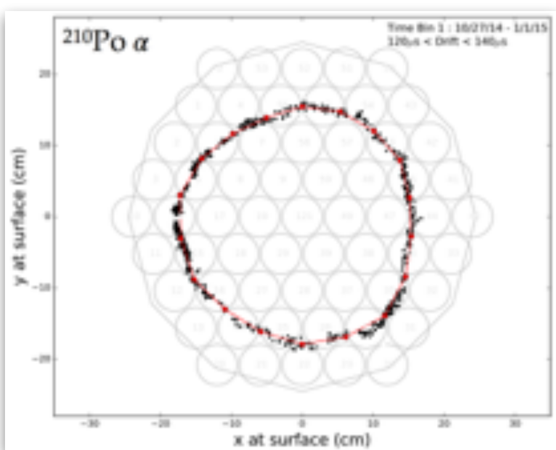
S2/S1 Position Corrections

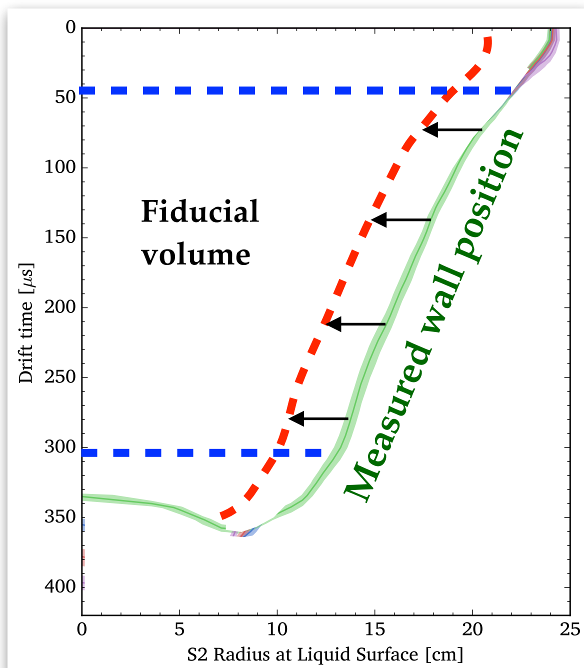
- **Our strategy is:**
  - **Disentangle position effects from field effects;**
  - **Apply a correction to account for position effects only.**
- **^{83m}Kr has two decays close in time. The ratio of the first-to-second S1 pulse area depends on field alone. This allows us to measure the component of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

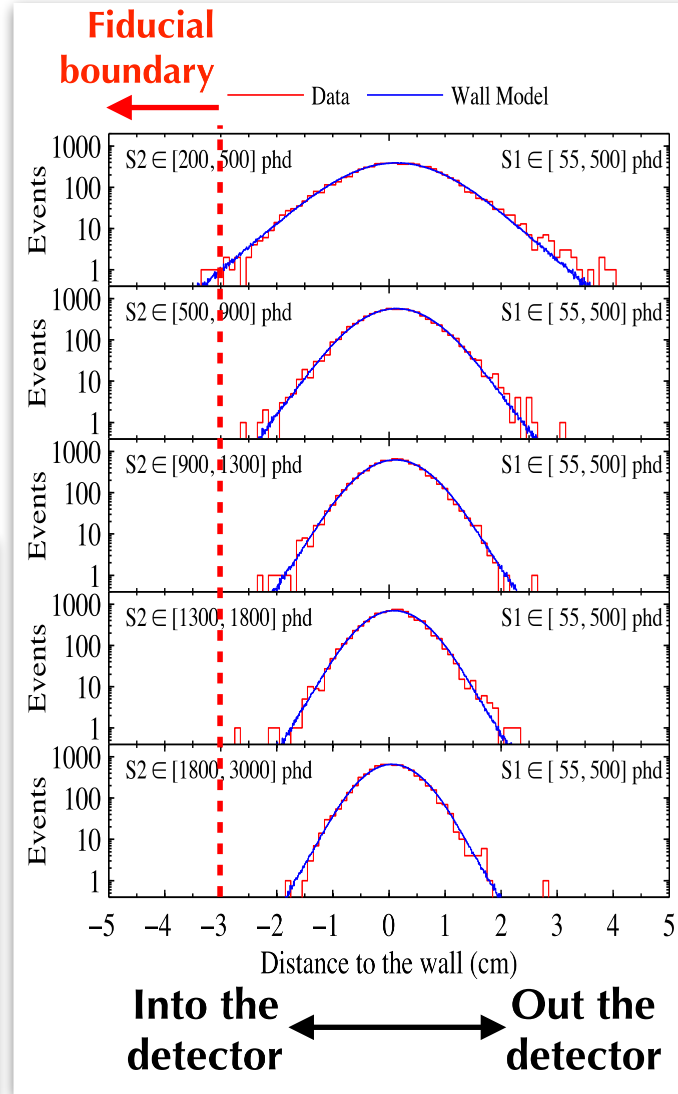


Wall-surface backgrounds

- ^{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

How to predict the number of wall events leaking into fiducial volume?

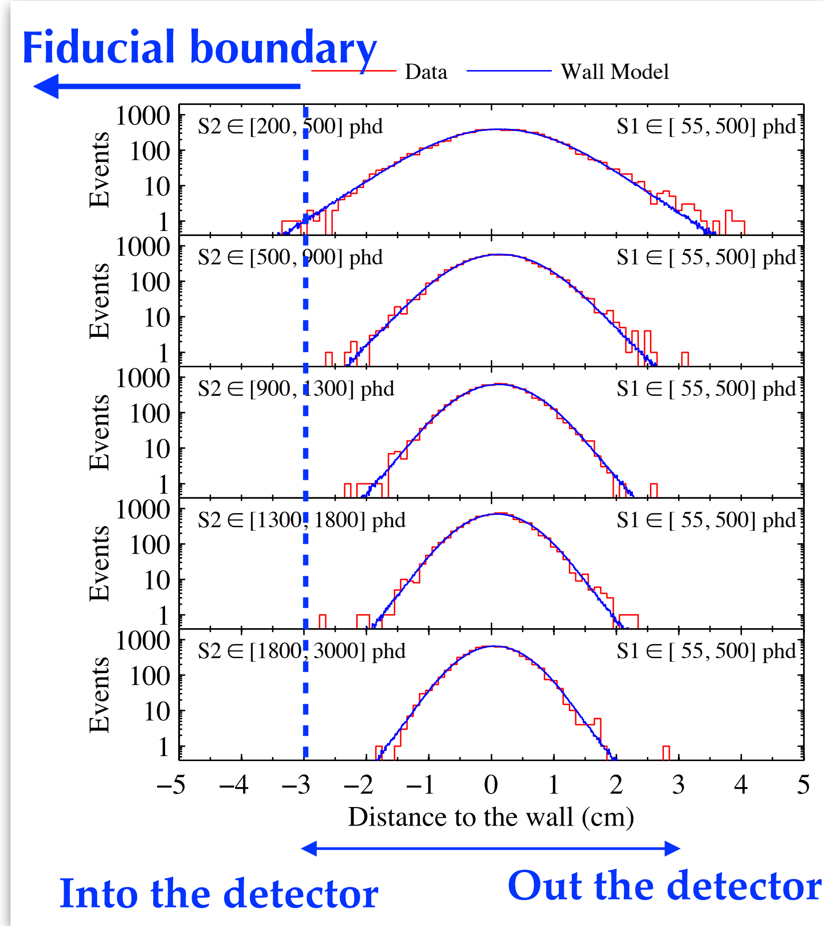
$$P_{\text{wall}} = \boxed{N\left(S1, S2, \phi, z, DB\right)} * \boxed{P_r\left(S2_{\text{raw}}, d_{\text{wall}}\right)}$$

Number of Events **Radial Model**

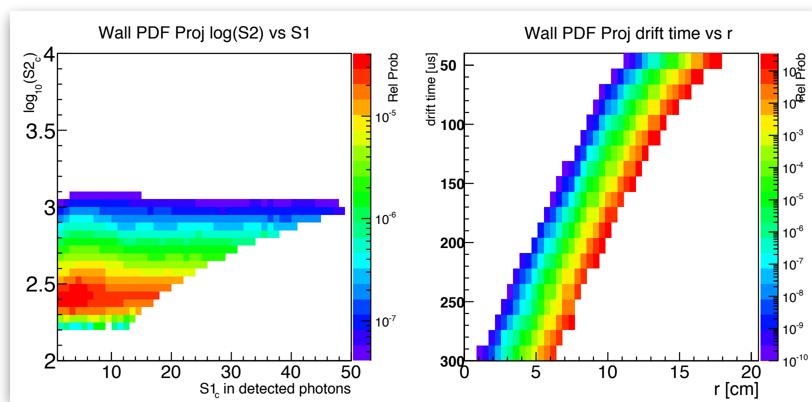
- **Leakage depends on the number of events, *N*, and how they distribute around the wall, P_r.**
- **To get N we used our WIMP search data, but with the radial position of the events larger than the radial position of the wall - events leaking towards the wall.**
- **To get P_r our strategy is:**
  - **Describe the events as function of the ratio between the distance to the wall and the uncertainty called pulls g**

$$g = \frac{d_{\text{Wall}}}{\sigma_r}$$

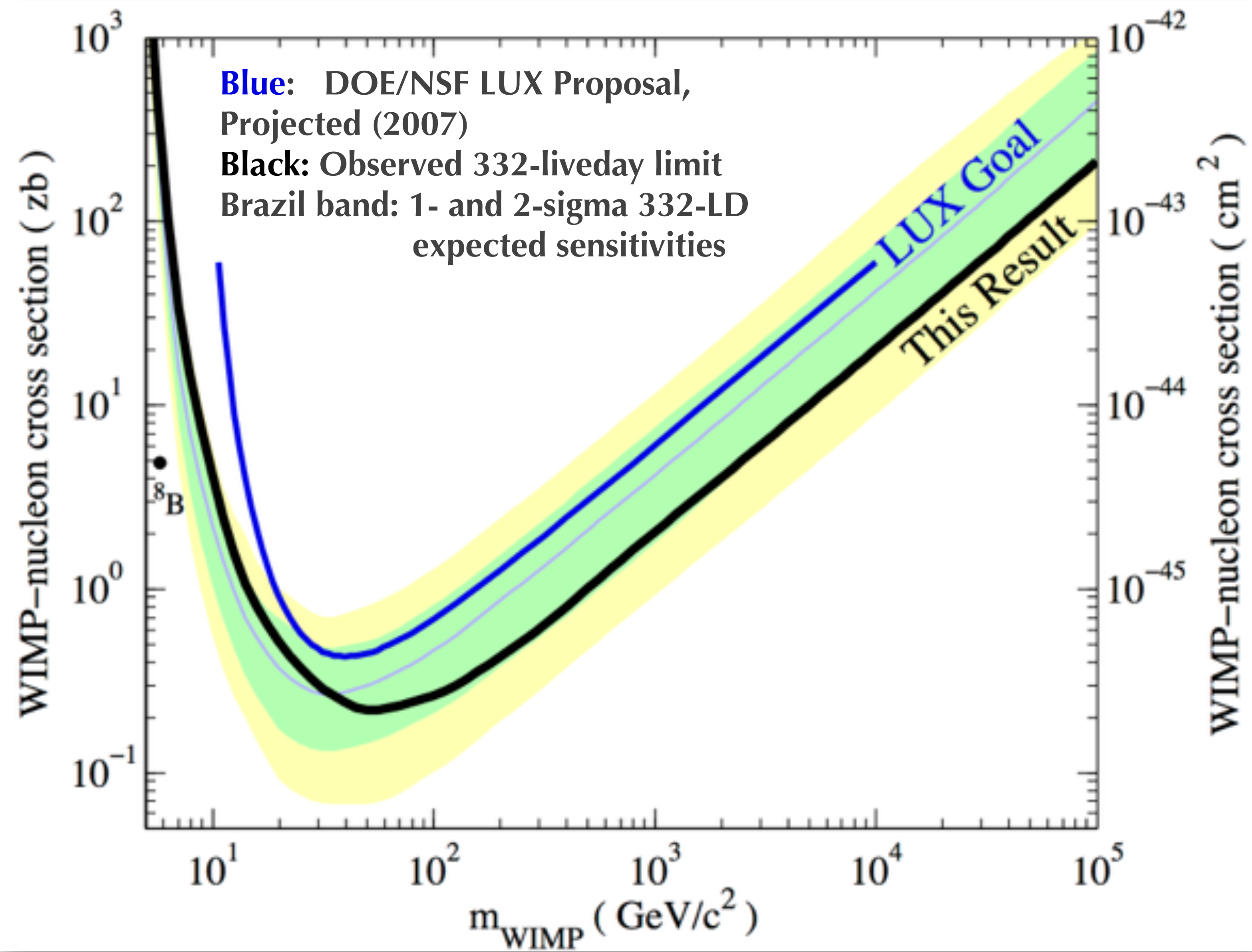
  - **Use the data with S1>50 phd to get systematics.**



Wall PDFS

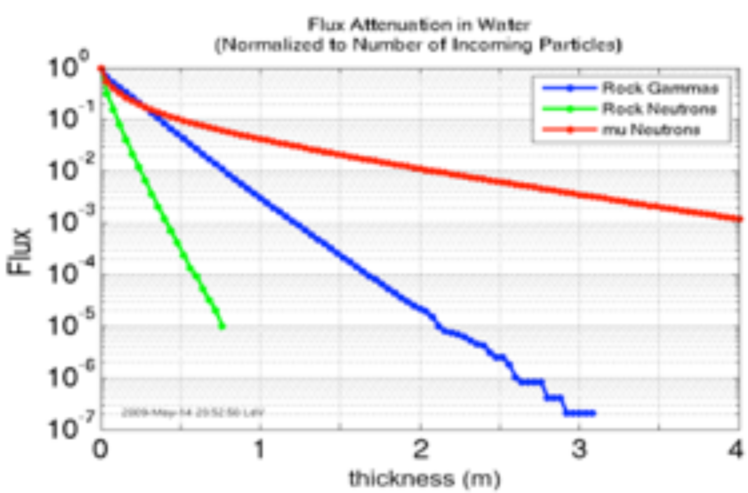


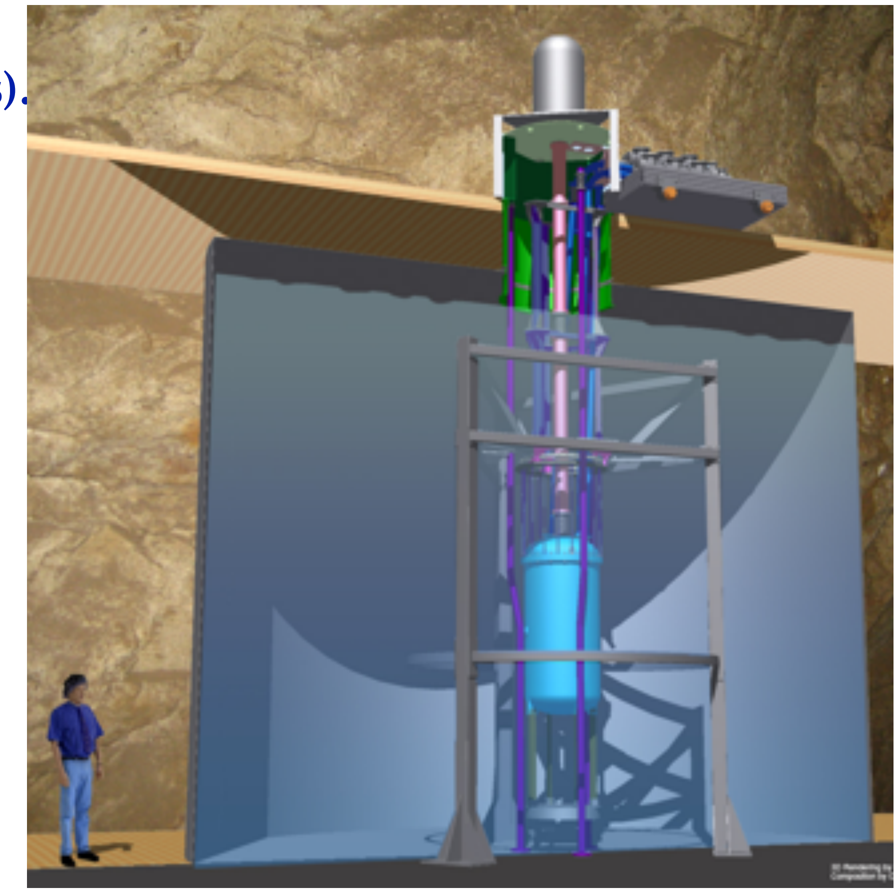
LUX Proposal VS Main Result



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)