


Latest results from the LUX Dark Matter Experiment

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on behalf of the LUX Collaboration

DSU workshop, Annecy, France, 25th June 2018

INVESTIGADOR FCT

QUALIFICAR É CRESCER.

Outline

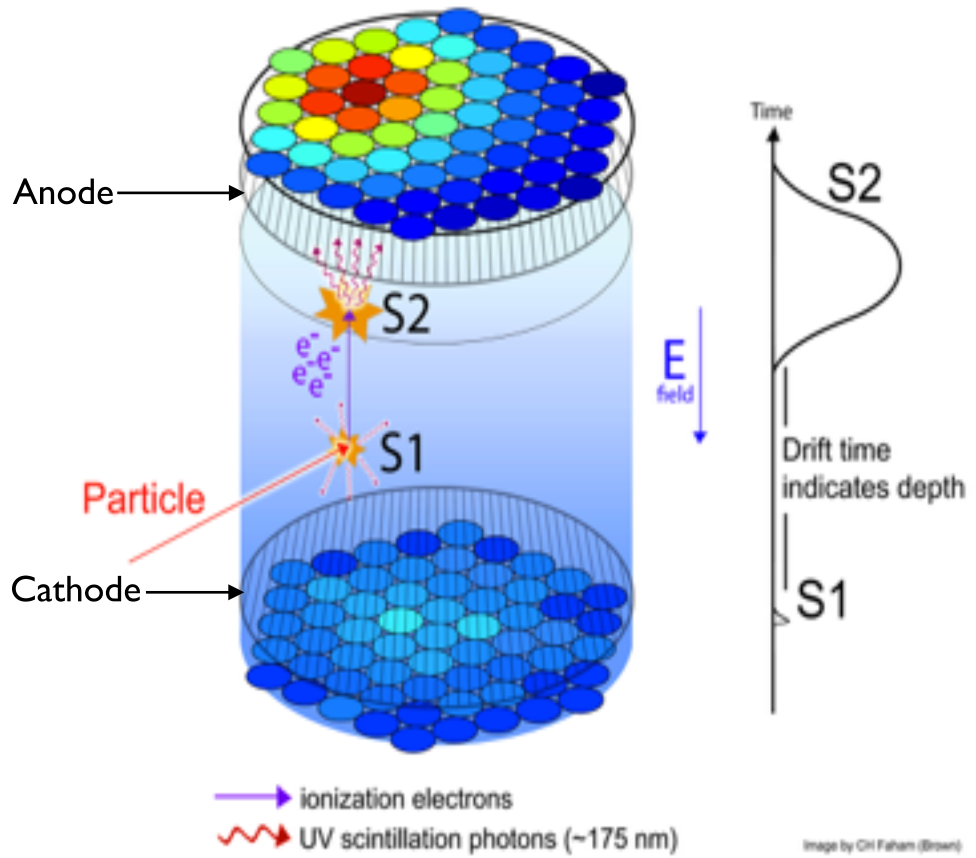
- The LUX detector
- Spin-dependent and spin-independent WIMP interaction - full exposure.
- New calibrations
  - ^{14}C yields
  - Pulse shape discrimination
- New rare searches results
  - Axions and Axion-like-particles
  - ER annual and diurnal modulation
  - Sub-GeV DM searches
- The LZ detector

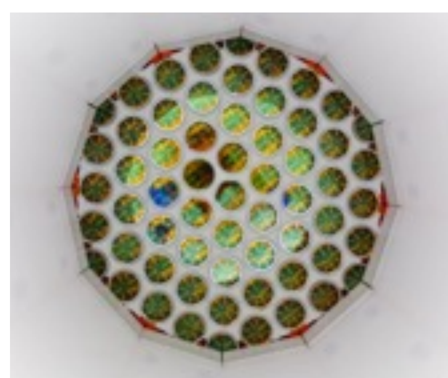
Image: LUX inside the water tank (September 2012)

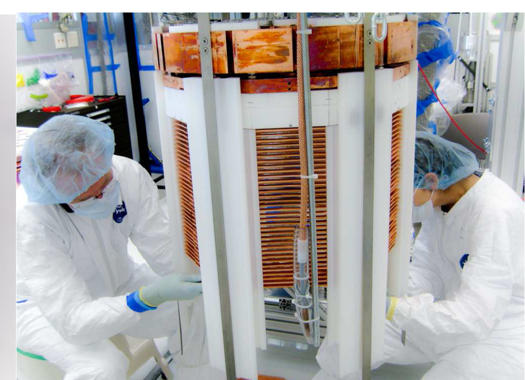
LUX Time Projection Chamber

- LUX is a liquid/gas time projecting chamber (TPC):
  - 370 kg of liquid LXe - 250 kg in the active region (~47 cm height, ~⌀49 cm).
- Energy depositions produce light and charge:
  - **S1 signal** Light ⇒ Prompt scintillation
  - **S2 signal** Charge ⇒ Proportional scintillation

  122 PMTs (61 on top, 61 on bottom) observe both S1 and S2.
- 3D Position Reconstruction
  - Depth (z) ⇒ time difference between S1 and S2 (drift time)
  - xy ⇒ reconstructed from the S2 light pattern.

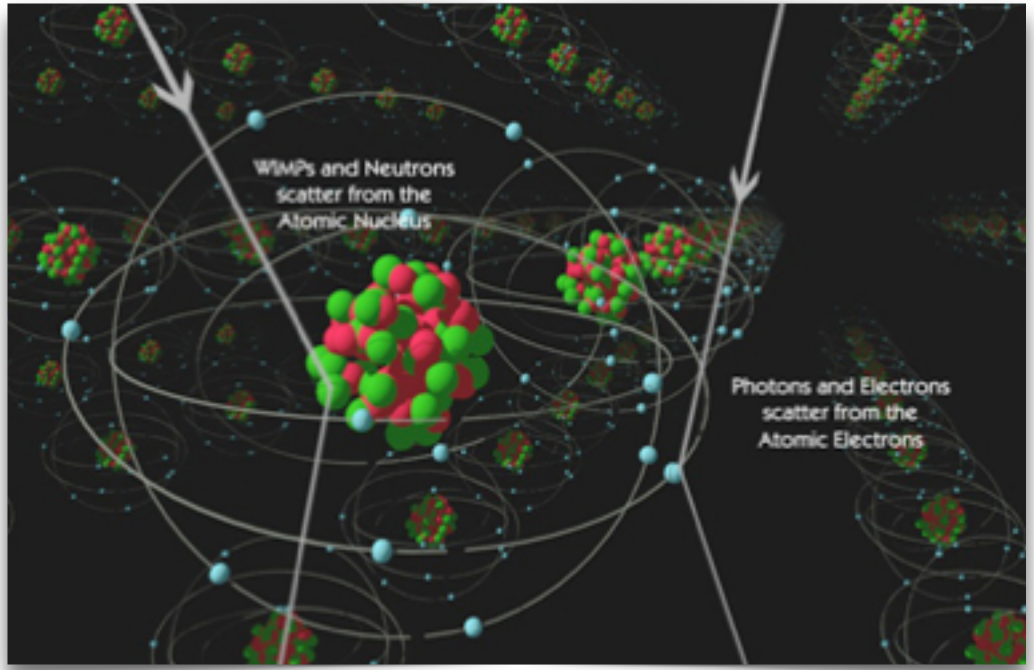


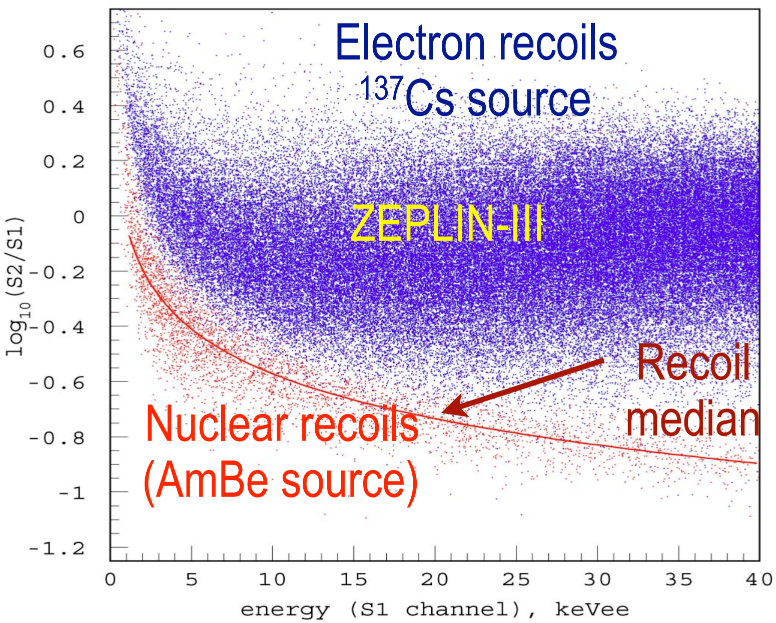




Liquid Xenon TPC

- Ratio of charge to light is used as a discriminator against backgrounds (>99%):
  - ELECTRONIC RECOIL (ER): γs and e- interact with the electrons ⇒ high ionization to scintillation ratio
  - NUCLEAR RECOIL (NR): WIMPs and neutrons interact with nuclei ⇒ lower ionization to scintillation ratio
- Quenching processes are different between NR and ER





LUX Timeline

2006: LUX coll. formed

2012 (Jul): LUX moves underground

2013 (Apr): First Science Run WS2013 starts

2013 (Nov): WS2013 results reported (85 live-days)

2014 (Sep): Second Science Run (WS2014–16) Starts

2015 (Dec): WS2013 reanalysis posted (95 live-days)

2016 (May): WS2014-16 run finishes

2016 (May-Aug): Final calibrations

2016 (Jul): WS2014-16 results released (332 live-days)

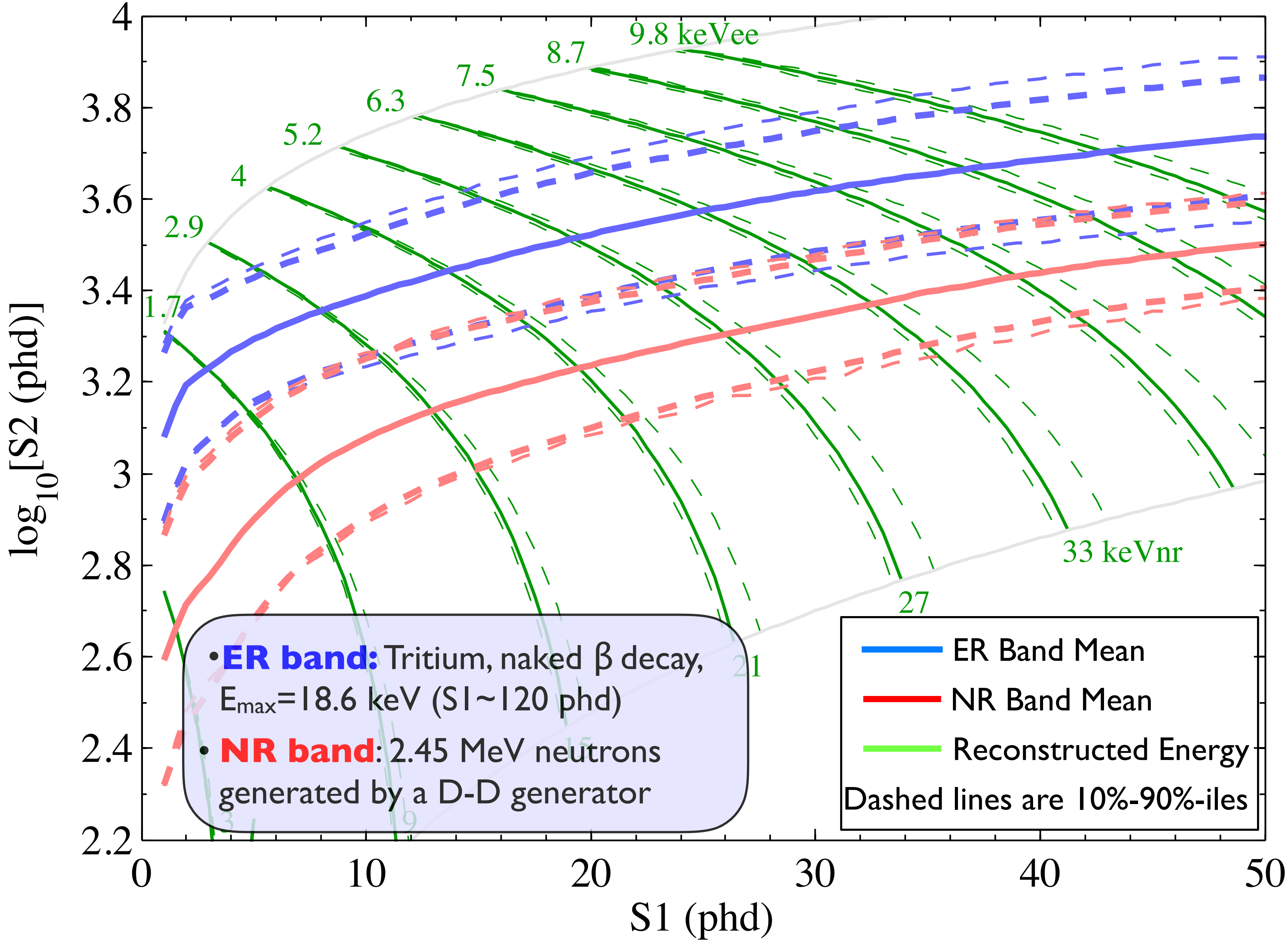
2016 (Sep): LUX Decommission

Analysis of the collected data continues!

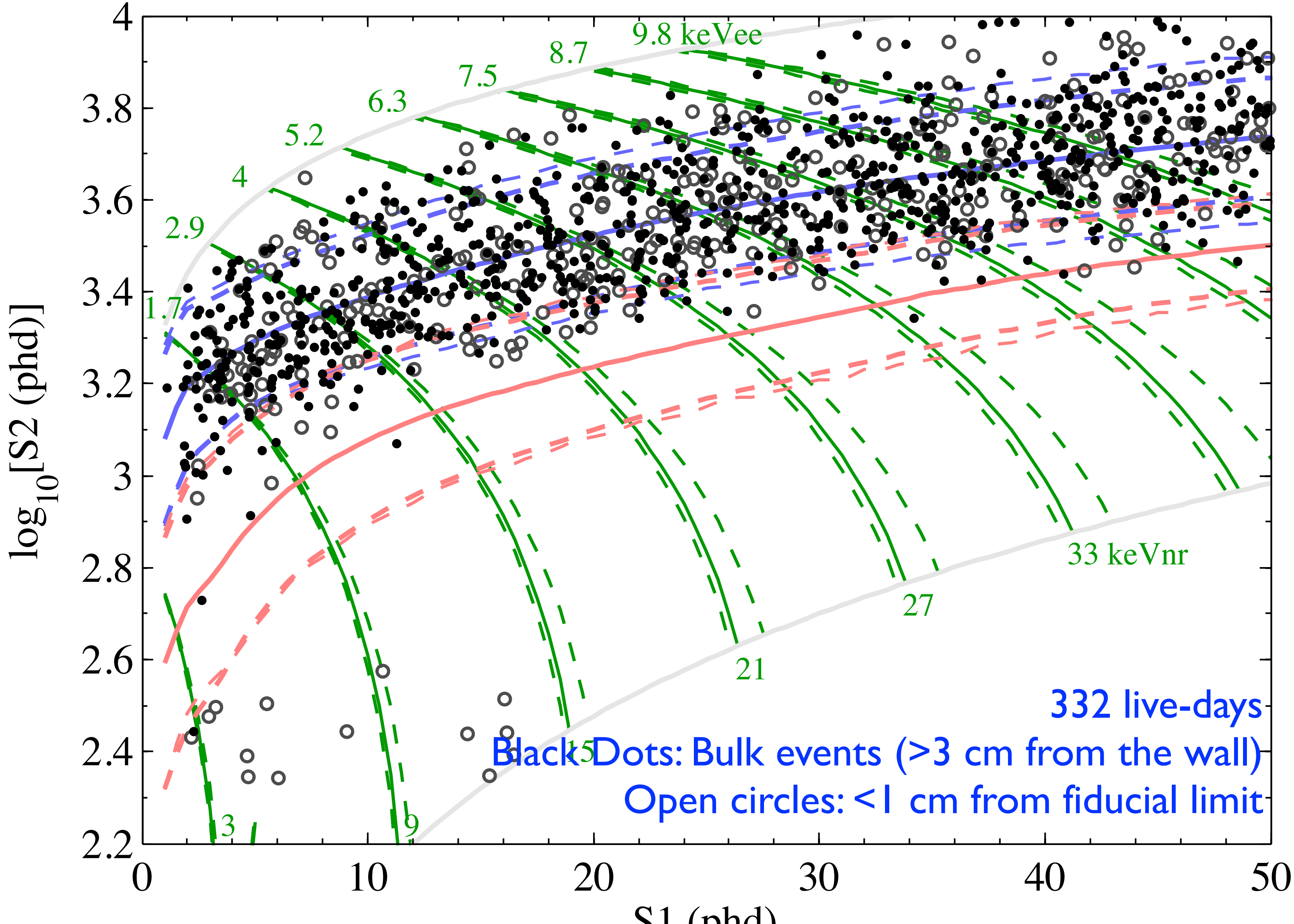
2017 (Jun): LUX in a museum

Two main scientific runs:
WS2013: 2013/04–2013/09, 95 live-days
WS2014–16: 2014/09–2016/05, 332 live-days

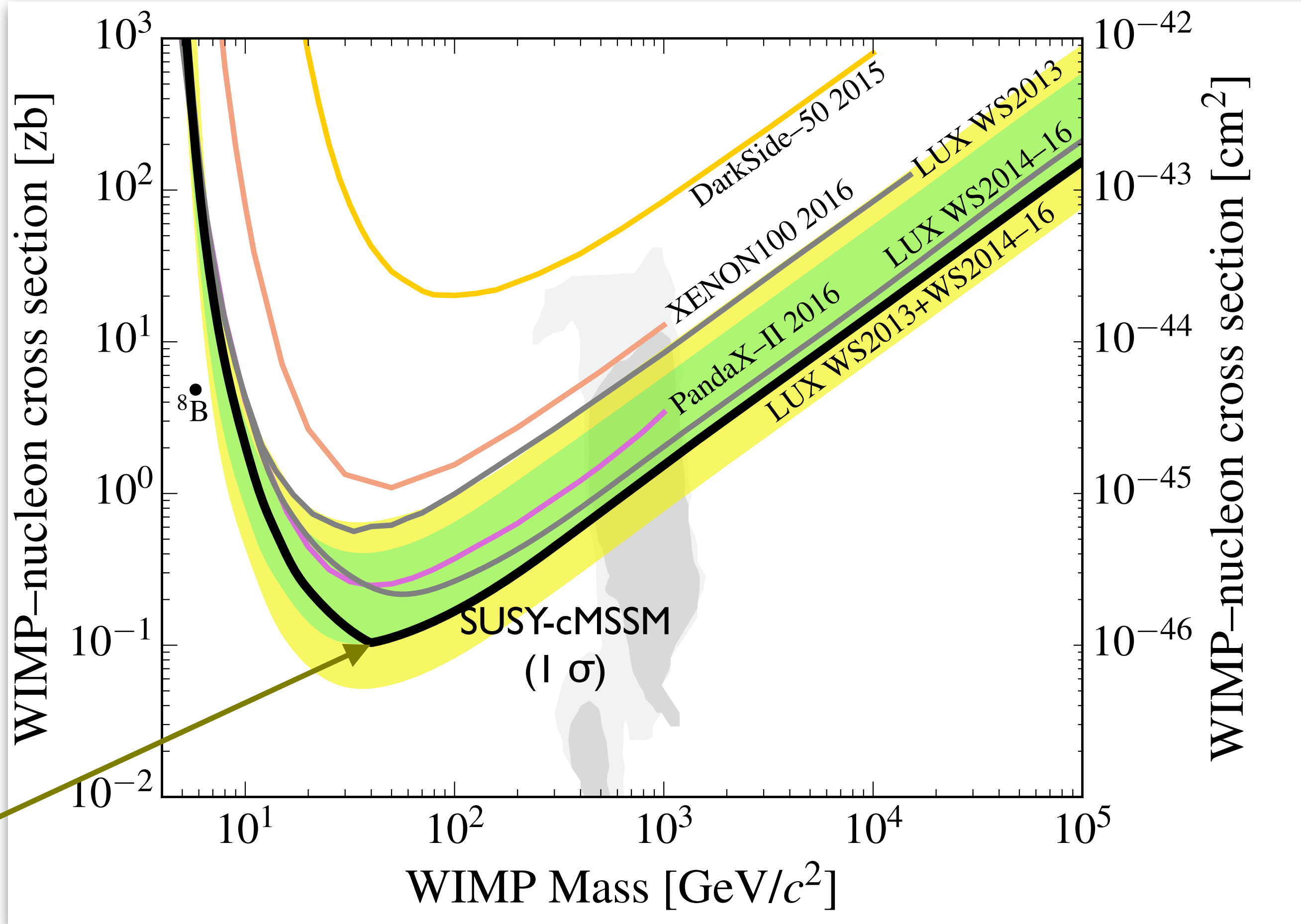
WS2014-16 Detector Response



WIMP-search data WS2014-16



Spin-Independent - WS2013+WS2014-16



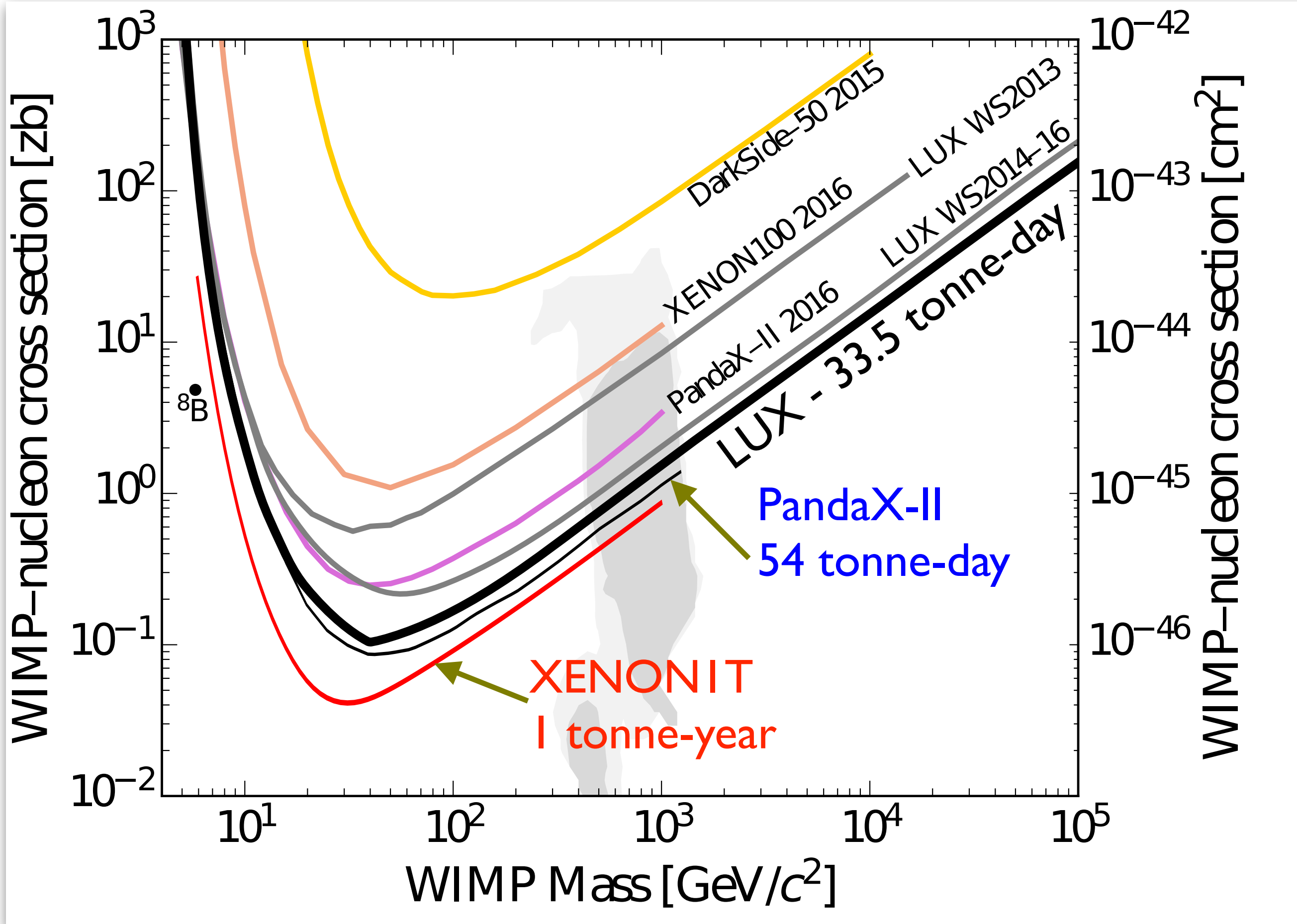
0.11 zeptobarns (at 50 GeV/c^2)

- Both Runs Combined, 95+332 live-days, 33.5 tonne-days
  - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.118.021303

PRL, 118, 021303, 2017

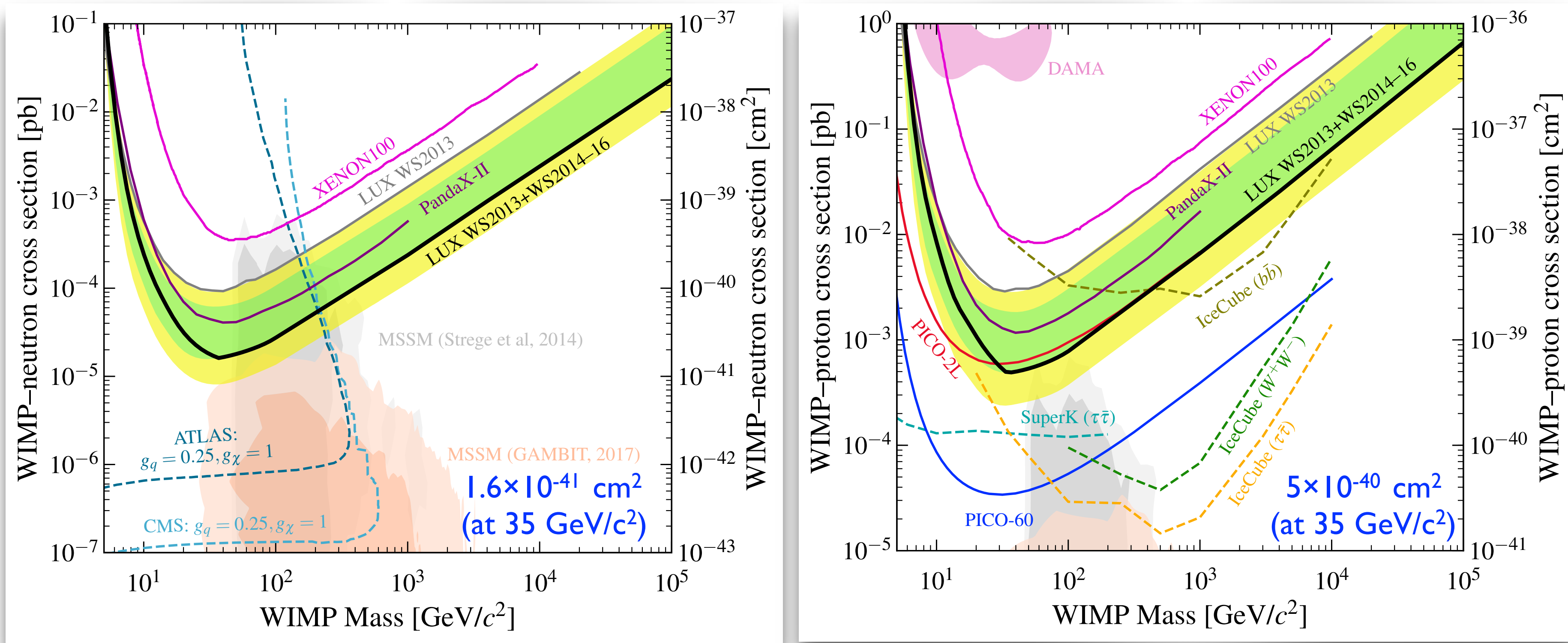
Spin-Independent - WS2013+WS2014-16

See Ranny Budnik talk, tomorrow at 9 a.m.



- PandaX-II - acquired between 2016 and 2017 (77.1 live-days) - PRL 119, 181302
  - Lowest 90% C.L. exclusion - 0.086 zeptobarns at 40 GeV/c
- XENON1T - acquired between 2016-2018 (278.8 live-days) - arXiv1805.12562
  - Lowest 90% C.L. exclusion - 0.041 zeptobarns at 30 GeV/c

Spin-Dependent - WS2013+WS2014-16



- 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).

PRL 118, 251302, 2017

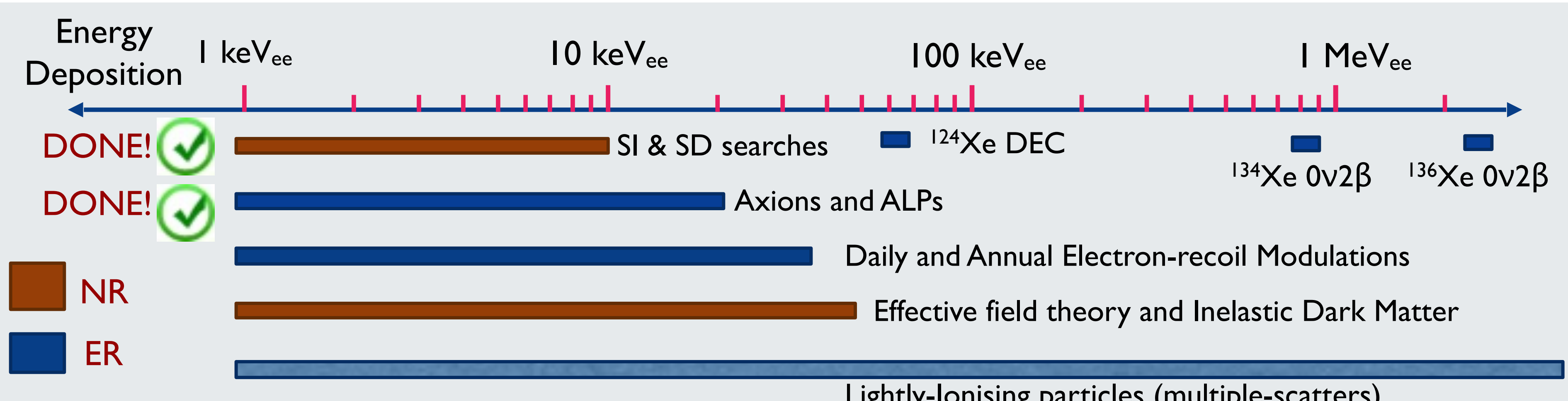
LUX post-run objectives

Towards multi-tonne liquid xenon TPCs

I. Understand the response of the detector for different particle types, energy deposition, electric field, etc
   1. Wide range of calibration sources available: following the primary WIMP-search run (Run04), a series of calibrations were performed (^{14}C, ^{3}H, ^{43m}Kr, ^{222}Rn, …).
   2. Access to different electric fields in the detector: the drift field in the detector changes between 40 V/cm and 400 V/cm.

II. Understand in detail the backgrounds of the detector

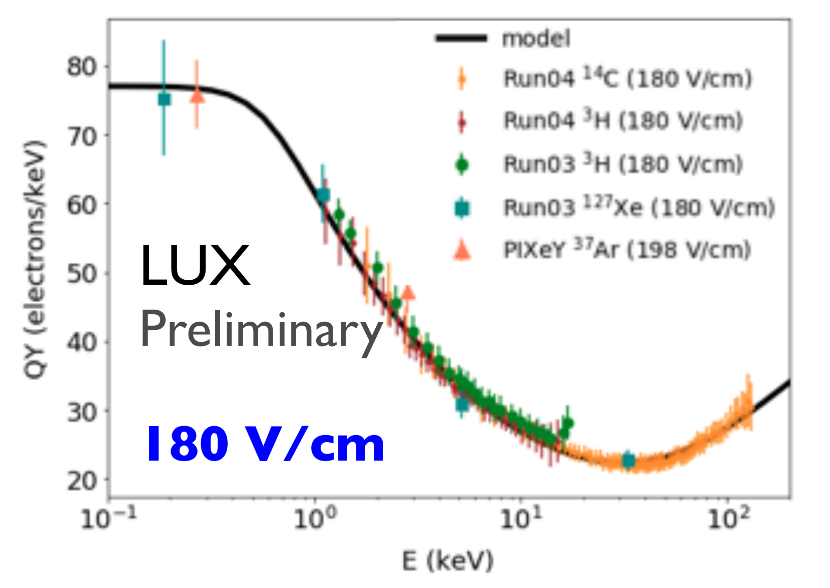
III. Look for other possible signals:
   1. Dark matter: EFT, Inelastic DM, Axions, Axions, etc…
   2. Neutrino physics: $0\nu2\beta$ decays, ν magnetic moment, CEνNS, etc..

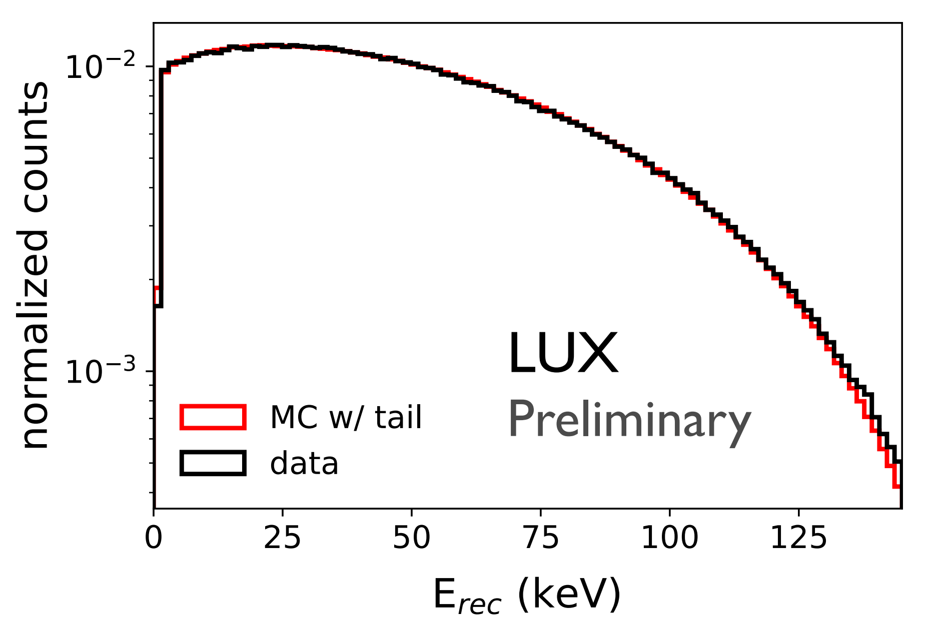


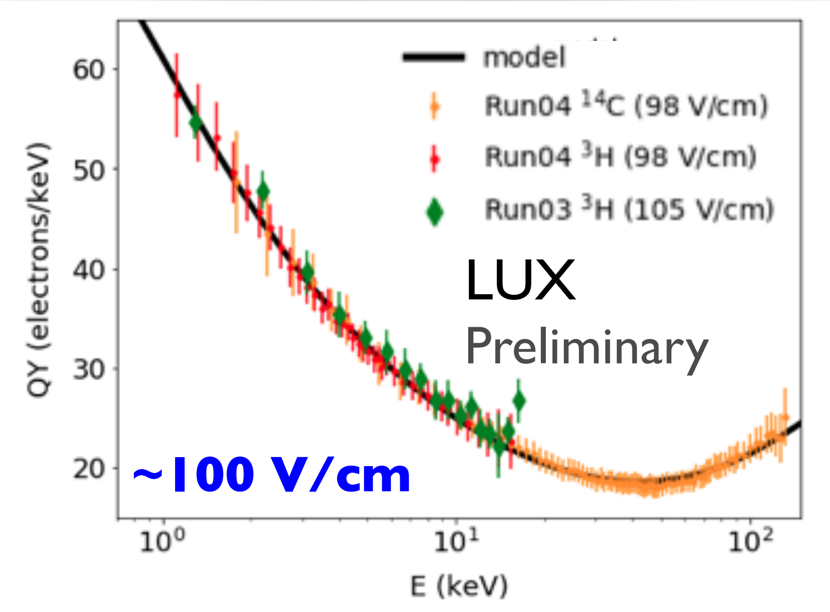
(Not all possible analysis are shown and not representative of our current analysis effort)

ER Calibrations - ^{14}C source

- ^{14}C β calibration
  - E_{max} = 156.5 keV, $T_{1/2}$ = 5,730 a
- Light yield, charge yield, and recombination probability estimated for different energies and fields
  - Field bins ranging from 40 V/cm until 490 V/cm
- Detector resolution taken into account





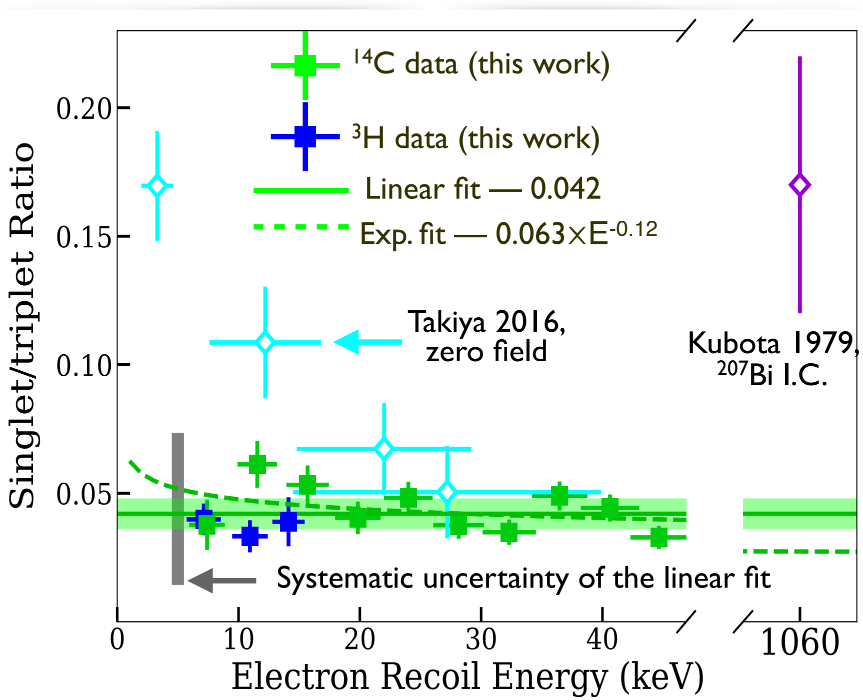


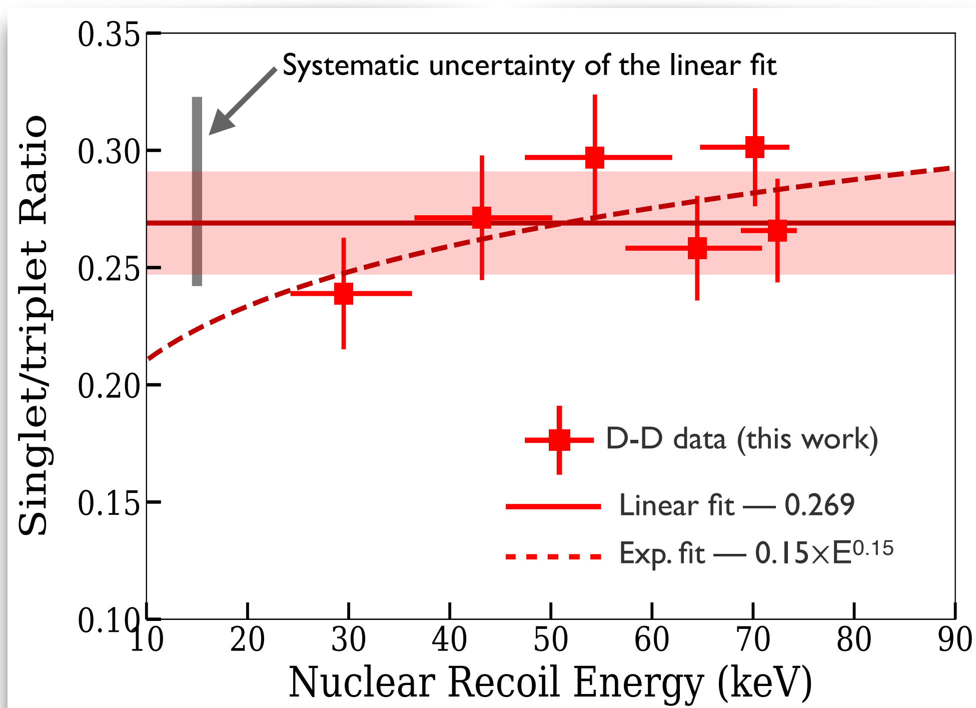
S1 Pulse Shape Calibrations

- Xenon scintillation originates from two excited molecular states with decay times
  - Singlet state - 4 ns
  - Triplet state - 24 ns

→ **Singlet-to-triplet ratio is different for electron recoil (ER) and nuclear recoil (NR).**

- Measurement of the scintillation timing characteristics of liquid xenon using a template-fitting method to reconstruct the detection times of photons:
  - measurement of the singlet-to-triplet scintillation ratio for ER and NR (first ever)





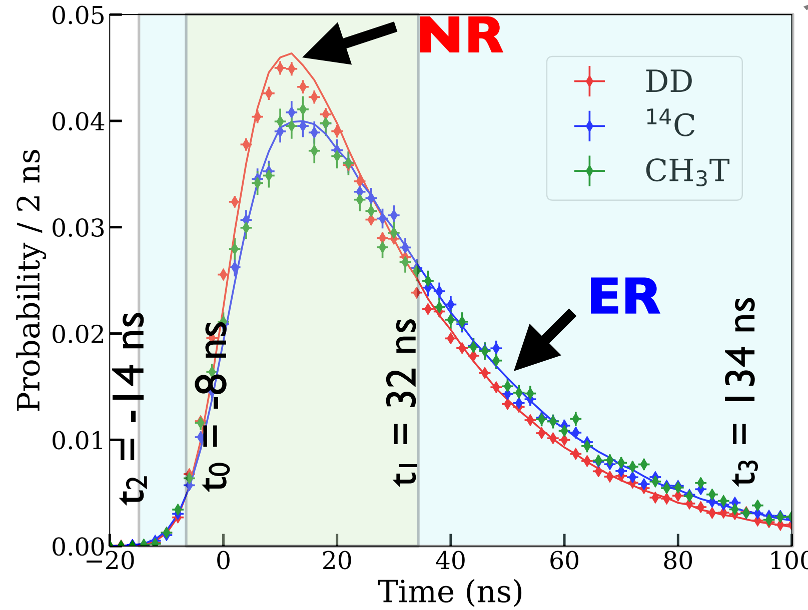
S1 Pulse Shape

- NR/ER discrimination using the S1 prompt fraction defined as

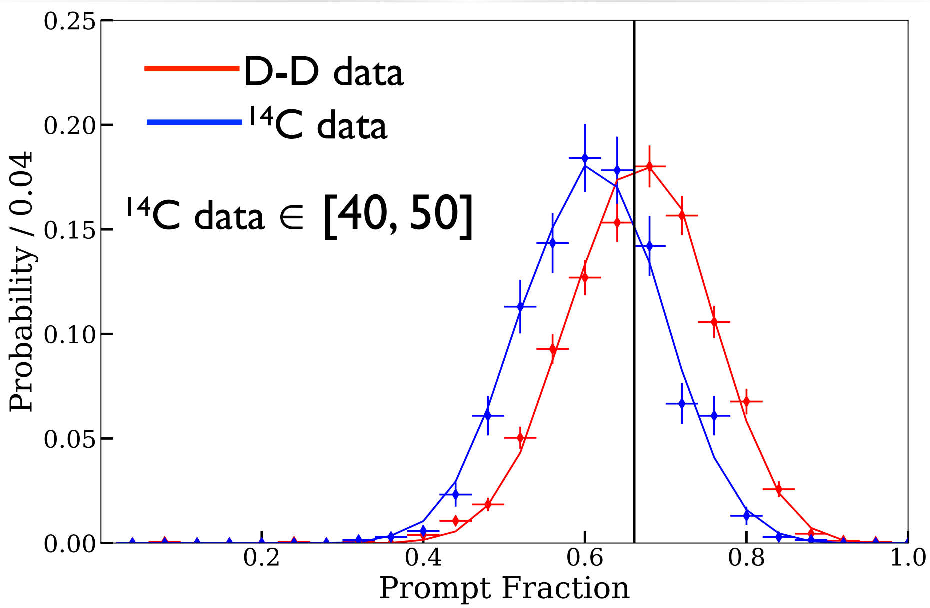
$$\mathrm{PF} = \frac{\int_{t0}^{t1} \mathrm{S1}(t)dt}{\int_{t2}^{t3} \mathrm{S1}(t)dt} = \frac{\sum \text{Prompt Photons}}{\sum \text{Total Photons}}$$

$t_{0\text{-}3}$, variables are allowed to vary independently to minimize the leakage of ER events into the 50% NR acceptance region.

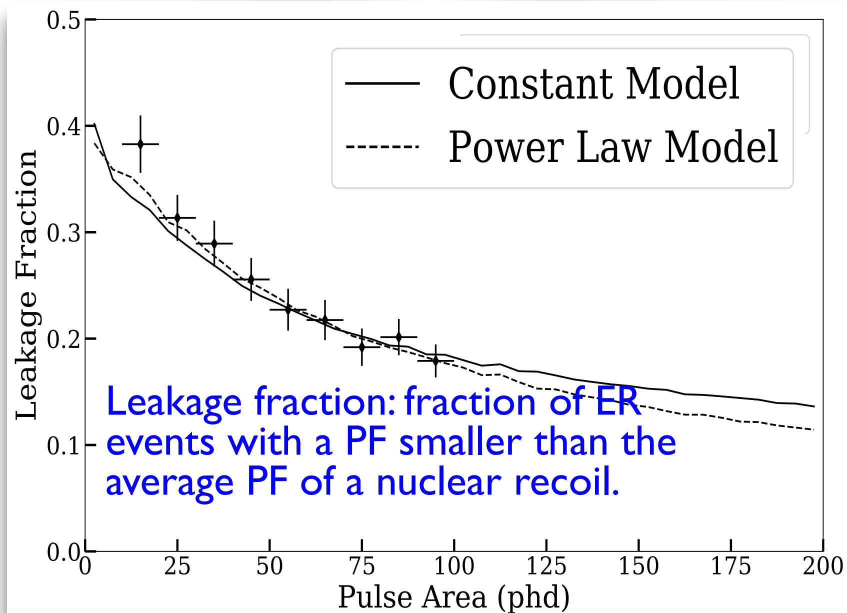
See more in PRD 97, 112002 (2018)!



Top: Average photon detection time spectra for events with pulse area between 40–50 phd.



Top: PF distribution



Top: Fraction of ER events that leak into the NR region.

Axions and Axion-like Particles

- The axion field provides a dynamical solution to the strong CP violation.
- Two sources of axions studied - I) axions from the sun and II) ALPs slowly moving within our Galaxy.
- They couple with electrons, via the axio-electric effect

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

g_{Ae} measures the coupling between axions and electrons.

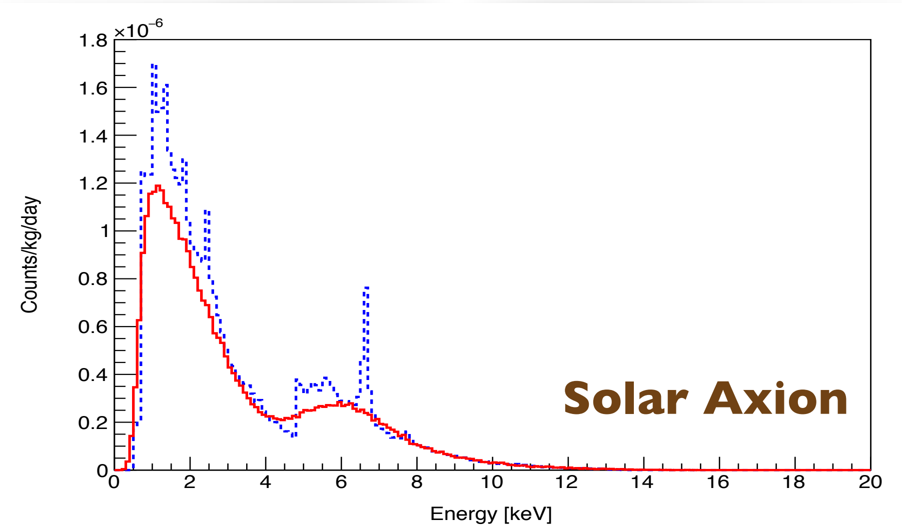


Figure: Solar axion spectral shape: product of solar axion flux [JCAP 12, 008 (2013)] and photo- electric cross section on xenon.

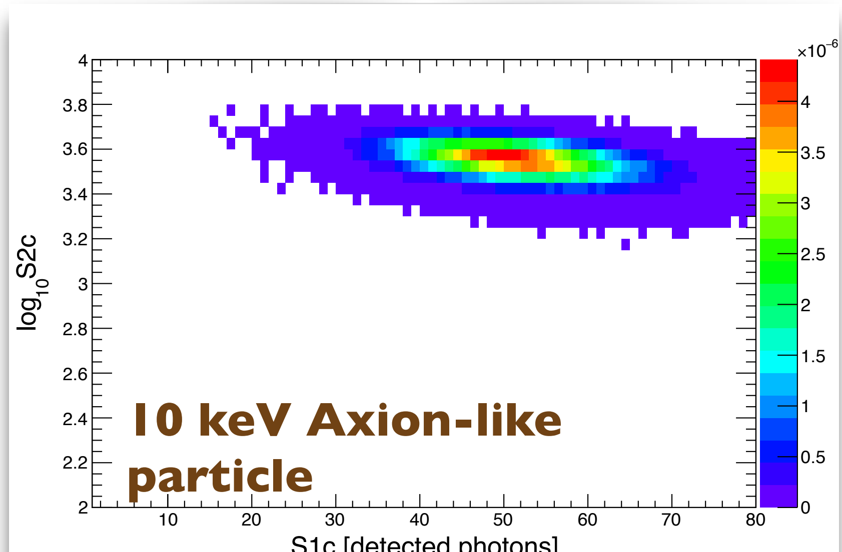
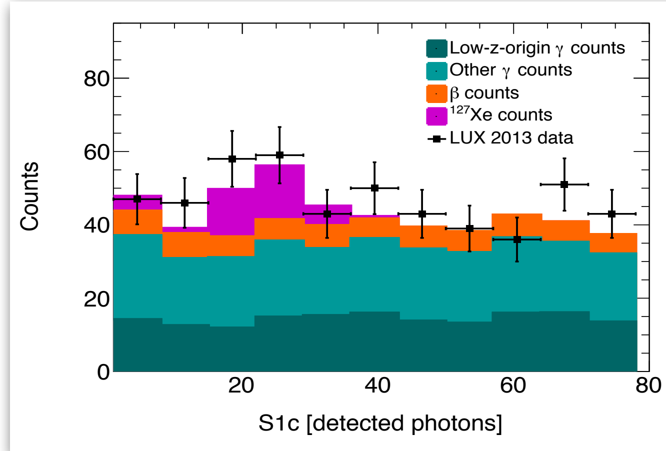
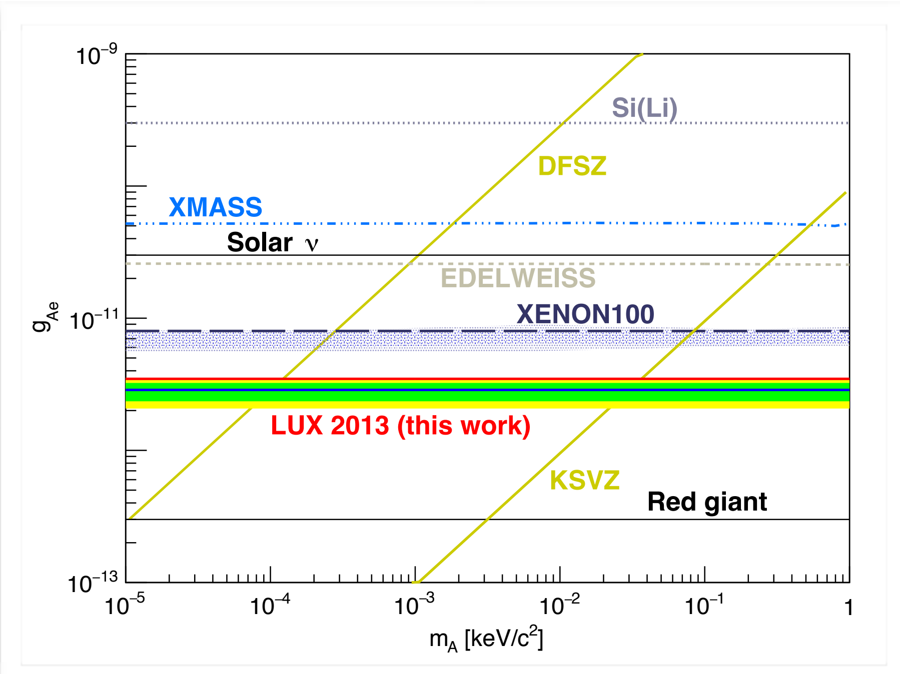


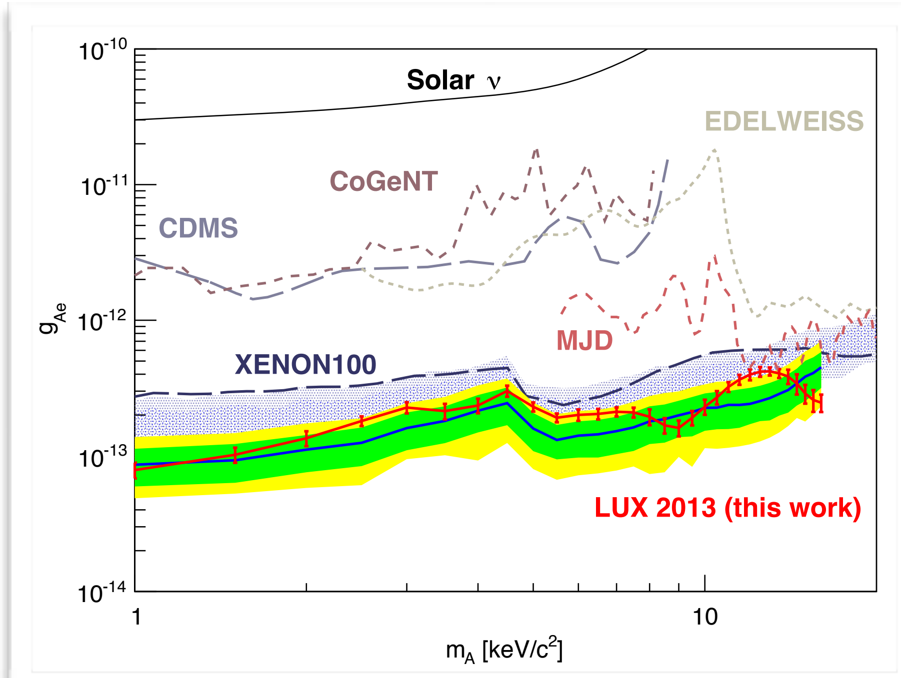
Figure: Detector response for a 10 keV ALP. Axio-electric absorption leads to electron recoils with kinetic energy equal to the ALP mass: sharp spectral feature, smeared by energy resolution.

Axions and Axion-like Particles

- WS2013 data: 95 live-days, 118 kg fiducial.
- Standard PLR analysis sets a two-sided limit on g_{Ae}, having the BG rates as nuisance parameters.







$g_{Ae} > 3.5\times10^{-12}$ (90% CL)

$m_A > 0.12$ eV/c² (DFSZ model)

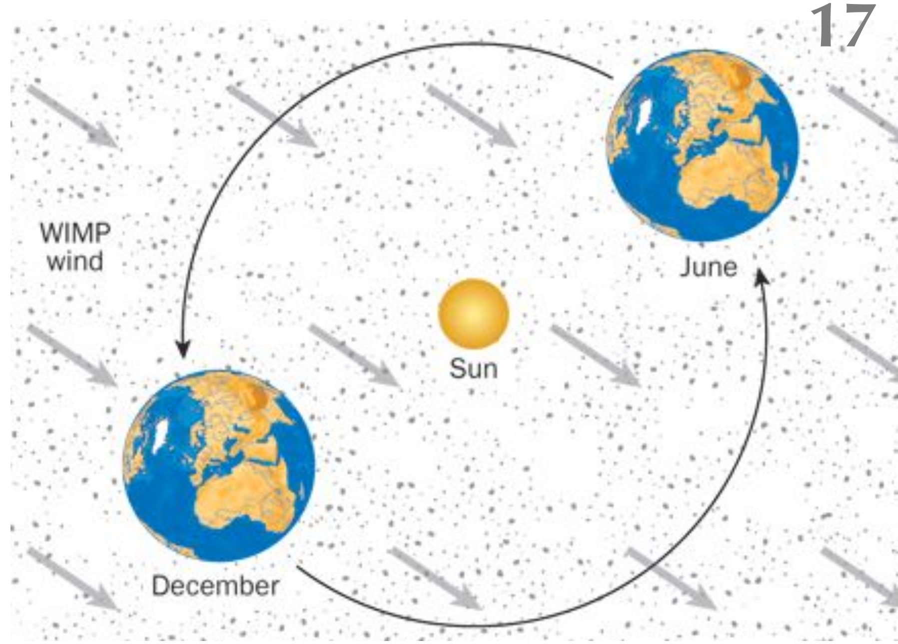
$m_A > 36.6$ eV/c² (KSVZ model)

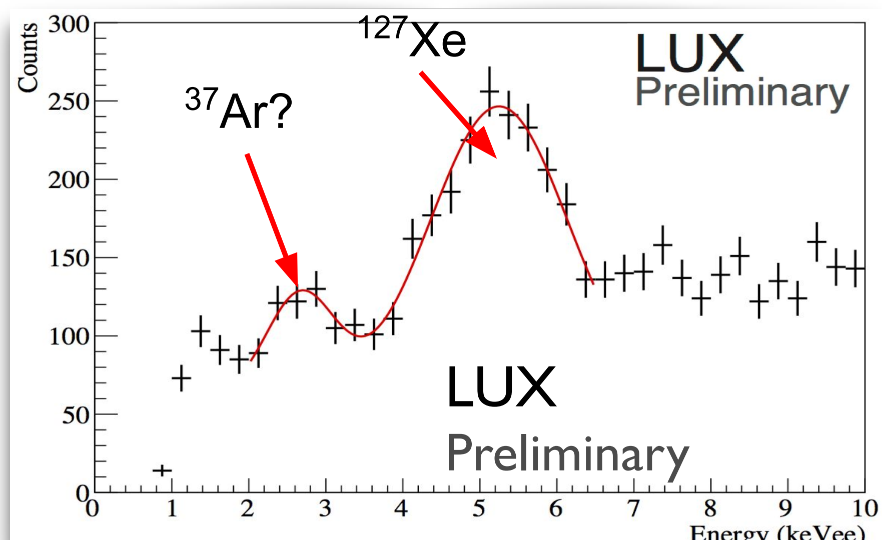
$g_{Ae} > 4.2\times10^{-13}$ (90% CL)

(across the range 1-16 keV)

ER Modulations

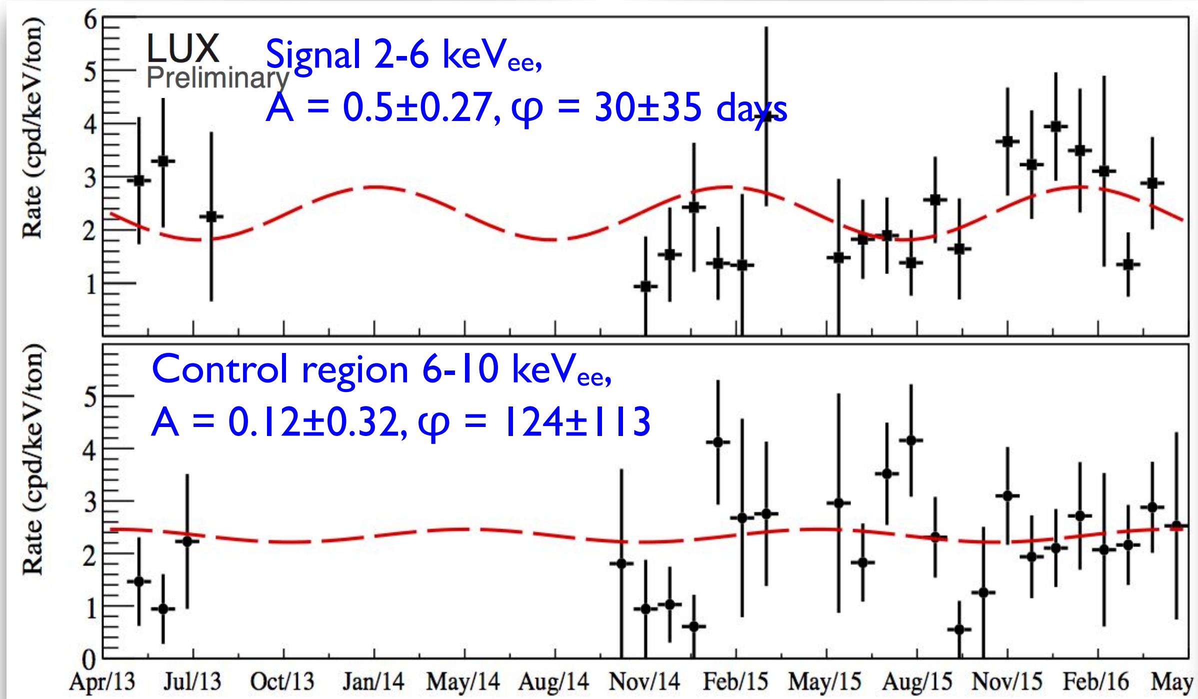
- DM interaction rate in an Earth-based experiment is expected to modulate due to the motion of the Earth around the sun.
- LUX Electron-recoil data:
  - Low background rate ~3 counts/keV/tonne
  - Modest rate excess at 3 keV - maybe explained by ^{37}Ar.
  - Electron recoil events uniformly distributed in the volume.
- Analysis:
  - WS2013 and WS2014-16 (2 calendar years)
  - Using innermost volume (51.4 kg)
  - Remove periods of data with unstable slow control parameter (temperature, pressure and liquid level), during and after calibrations, low liquid xenon purity - **271 live-days.**

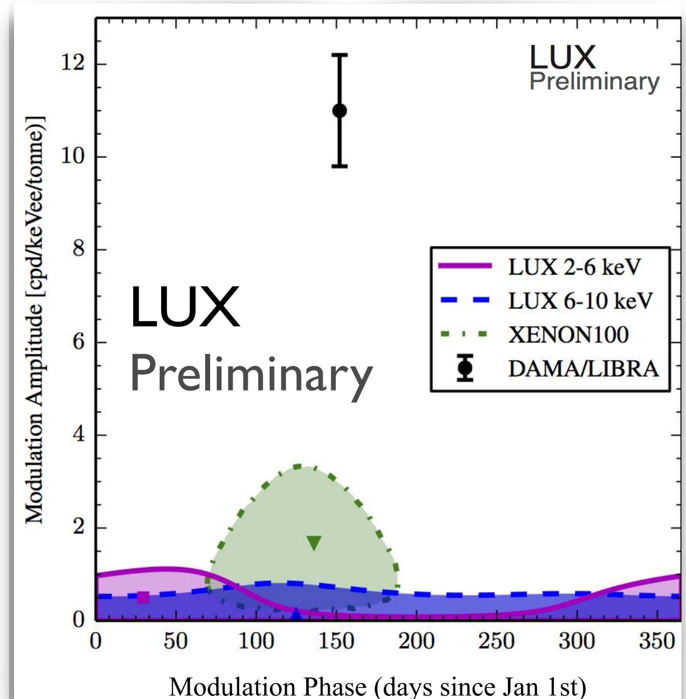




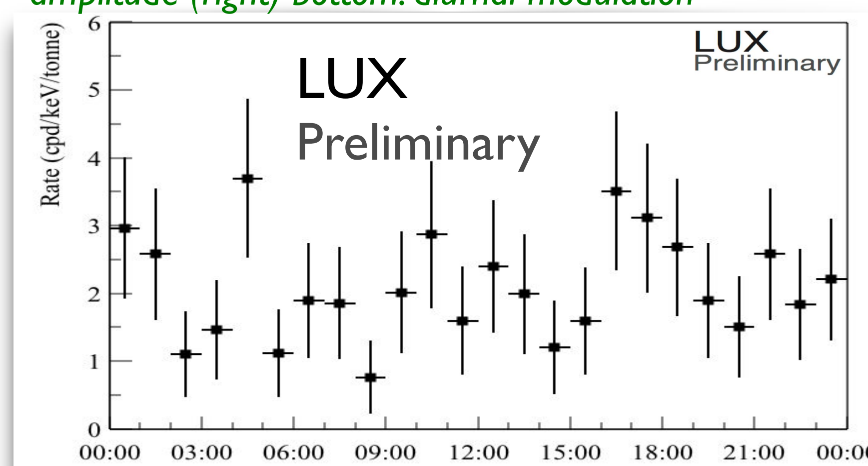
(top) Low energy spectrum observed in LUX WS

Annual and Diurnal Modulation





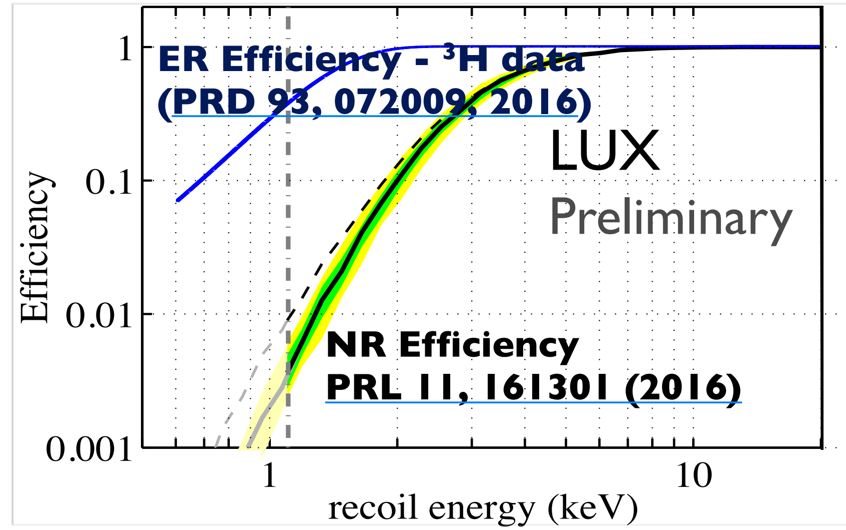
Top plots: annual modulation, rate (left) and modulation amplitude (right) bottom: diurnal modulation

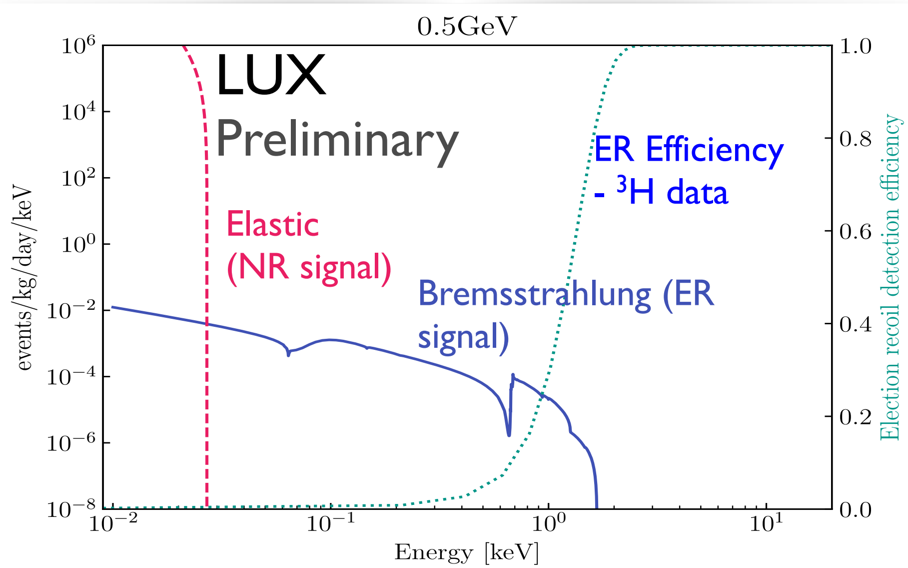


- ~2 cpd/keV/tonne - 40x lower than DAMA;
- Best fits using unbinned extended maximum likelihood;
- Day/night rates
  - 2.06 / 2.14 cpd/keV/tonne (asymmetry factor of -1.6±8.7%)
- Next →look to other energy bins.

Sub-GeV DM

- The light yield for a nuclear recoil is practically 0 below 1.1 keV — can only look for $m_{DM} \gtrsim 5$GeV.
- LUX is more sensitive to lower energies of electron recoils (50% energy threshold):
  - Nuclear recoils = 3.3 keV
  - Electron recoils = 1.2 keV

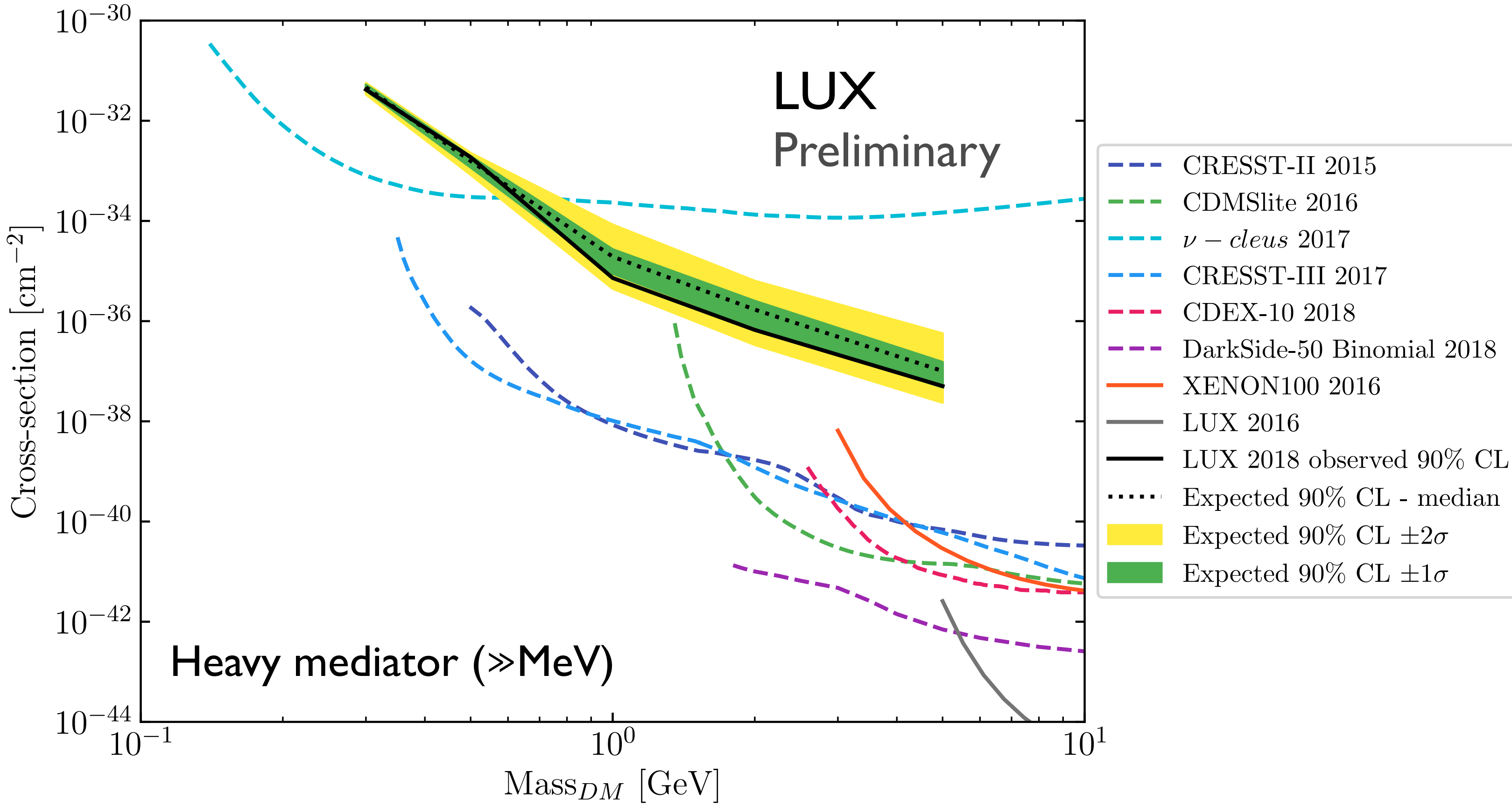




Top: Scattering rates for 0.5 GeV DM

- LUX can detect sub-GeV DM via Bremsstrahlung
  - Emission of a photon from a xenon atom — nuclear interaction, but electron recoil signal.
- Using the same data set and background model of the WS2013 data (except that we are looking for signal in the electron recoil band).

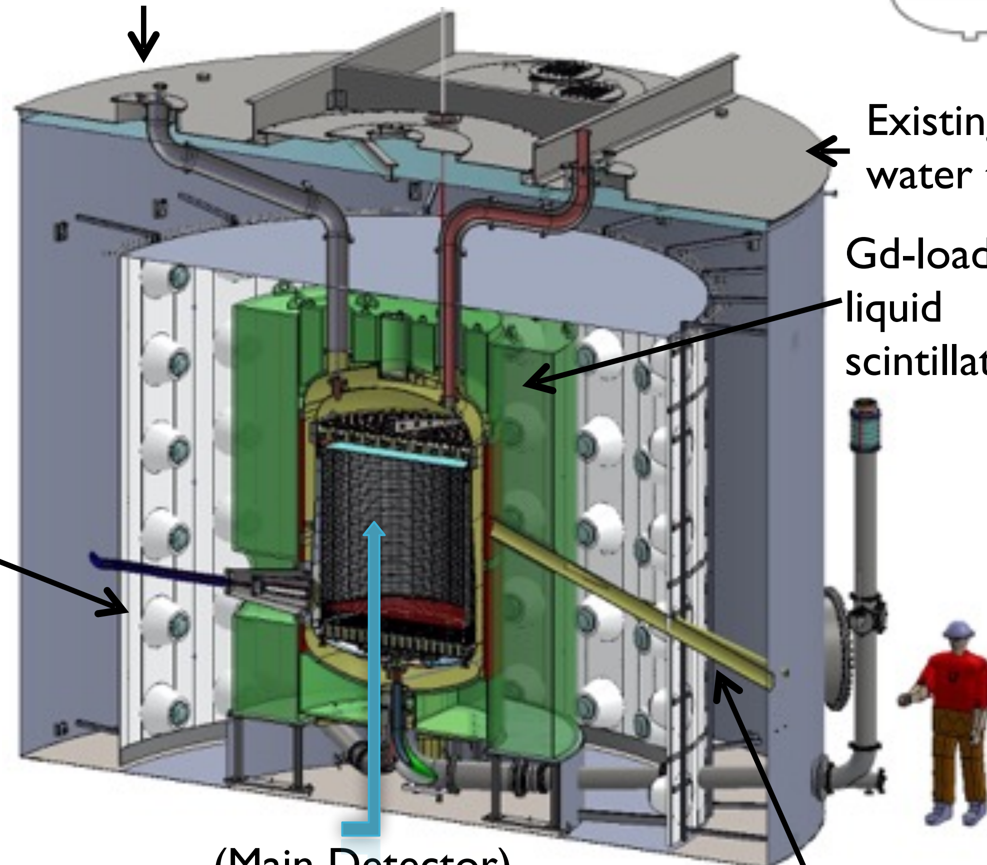
Sub-GeV DM



Limit for 95 live-days of data (WS2013, 13.8 tonne·day exposure).
Limit from the complete LUX exposure is forthcoming.

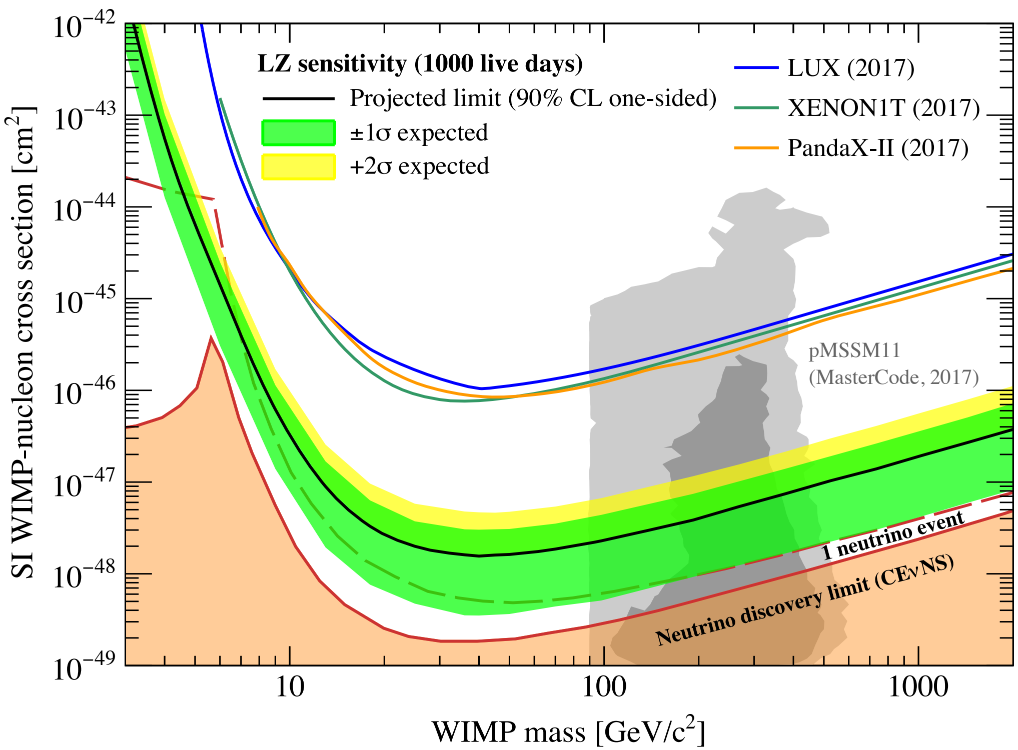
The LUX-ZEPLIN Experiment

- 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

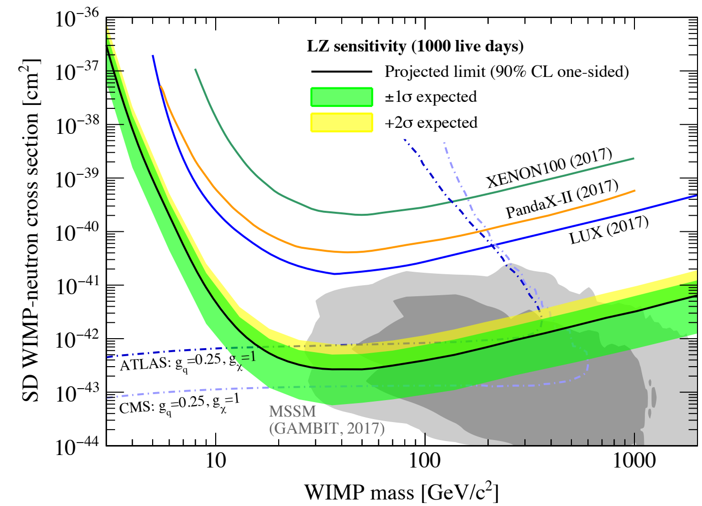


The LUX-ZEPLIN Sensitivity

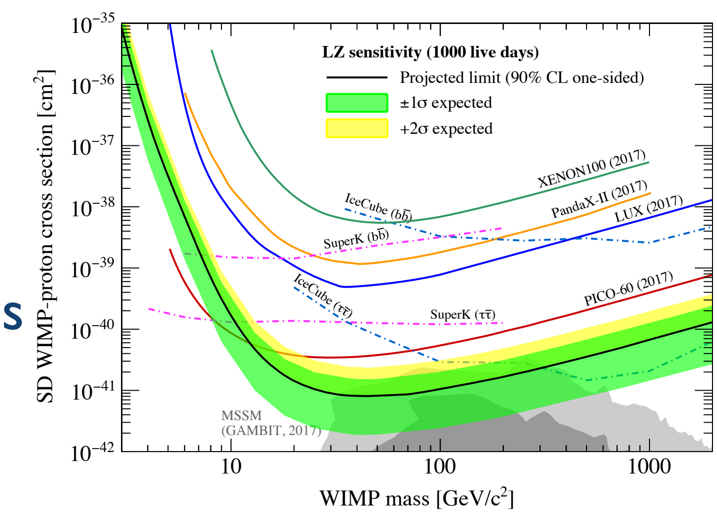
SI WIMP-nucleon elastic scattering



SD WIMP-neutron cross section



SD WIMP-proton cross section



Sensitivity for 1,000 live days and a 5.6 tonnes

Paper on arXiv: Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment

arXiv 1802.06039

Conclusions

- The LUX spin-independent WIMP limit led the field for 3 years (2013-2016). Only recently are the larger XeTPCs catching up.
- Significant improvements in the calibration of xenon detectors:
  - LUX yields, efficiencies, and fields well calibrated, simulated, and understood;
  - New pulse shape discrimination presented.
- And is still producing new physics results:
  - No annual or the diurnal modulation observed in the ER signal.
  - and more results in the back-up slides!
- More analysis forthcoming
  - Effective field theory, double electron capture, neutrinoless double beta decay, more calibrations etc.
- Onwards and downwards: LUX-ZEPLIN (LZ) experiment under construction, 7 tonne active mass (2020).

LUX collaboration

Berkeley Lab / UC Berkeley

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Adam Bailey	Ex-Graduate Student
Khadeeja Yazdani	Ex-Graduate Student
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Paulo Bras	Graduate Student

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Jack Genovesi	Research Assistant

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Junsong Lin	Postdoc
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Lucie Tvrznikova	Graduate Student
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Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student
Dean White	Engineer
Susanne Kyre	Engineer

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David Woodward	Research Associate
Peter Rossiter	Graduate Student

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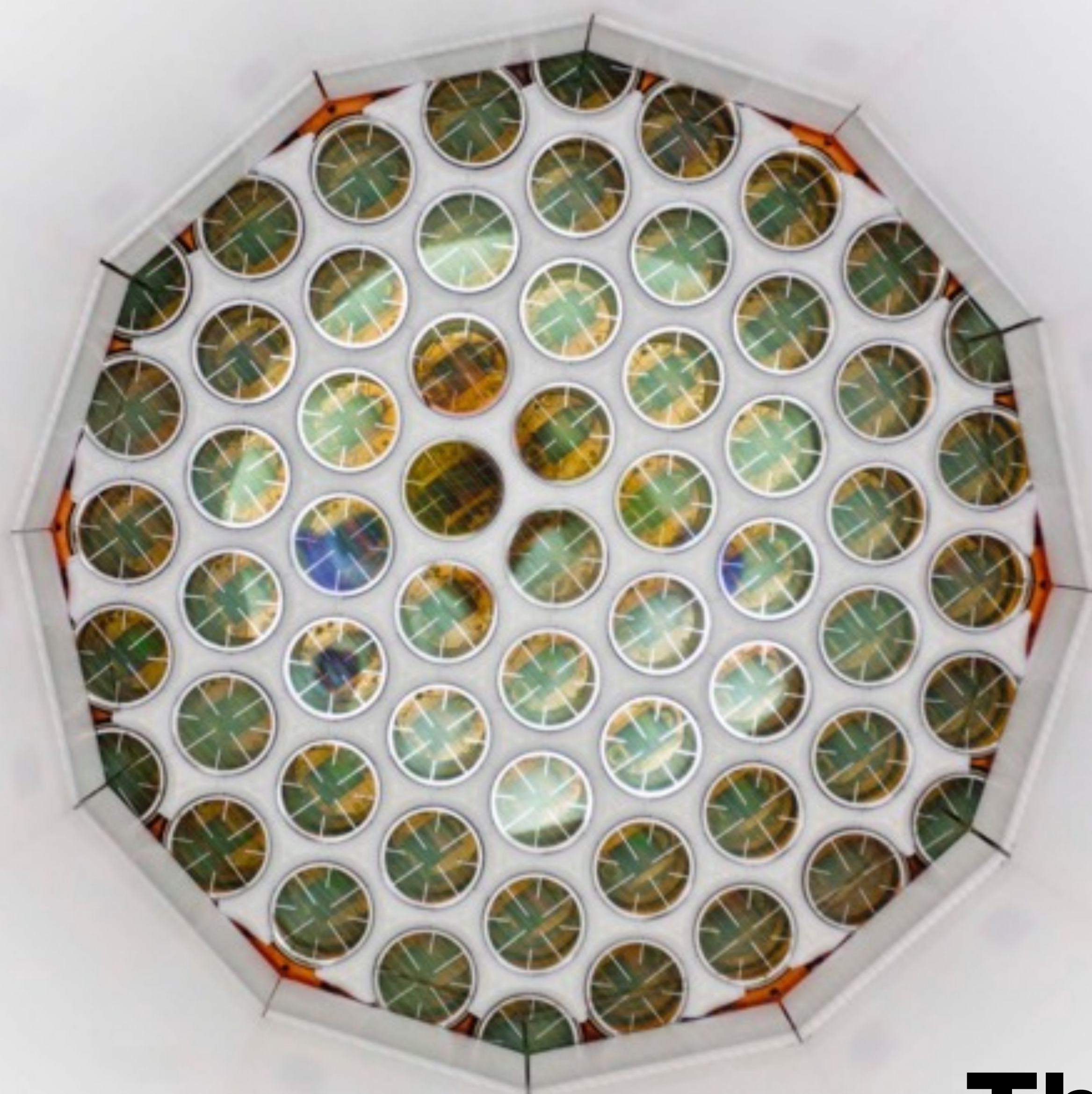
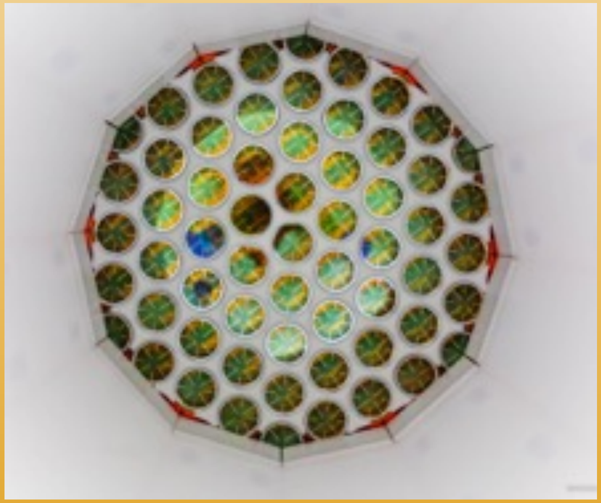
Dongming Mei	PI, Professor



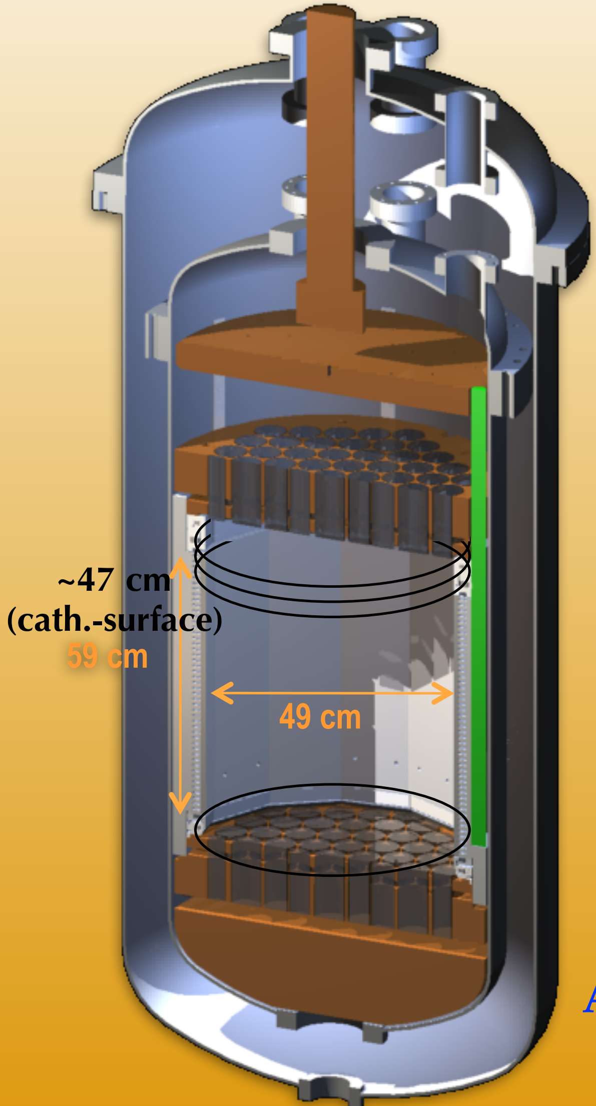
Thanks!

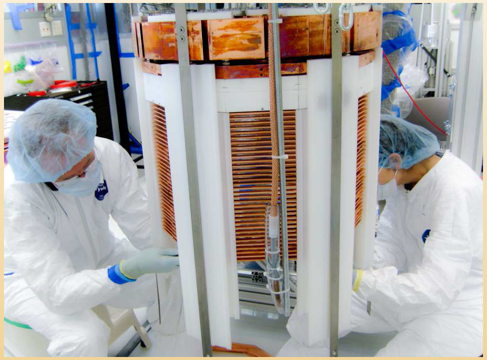
The LUX Experiment

- 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



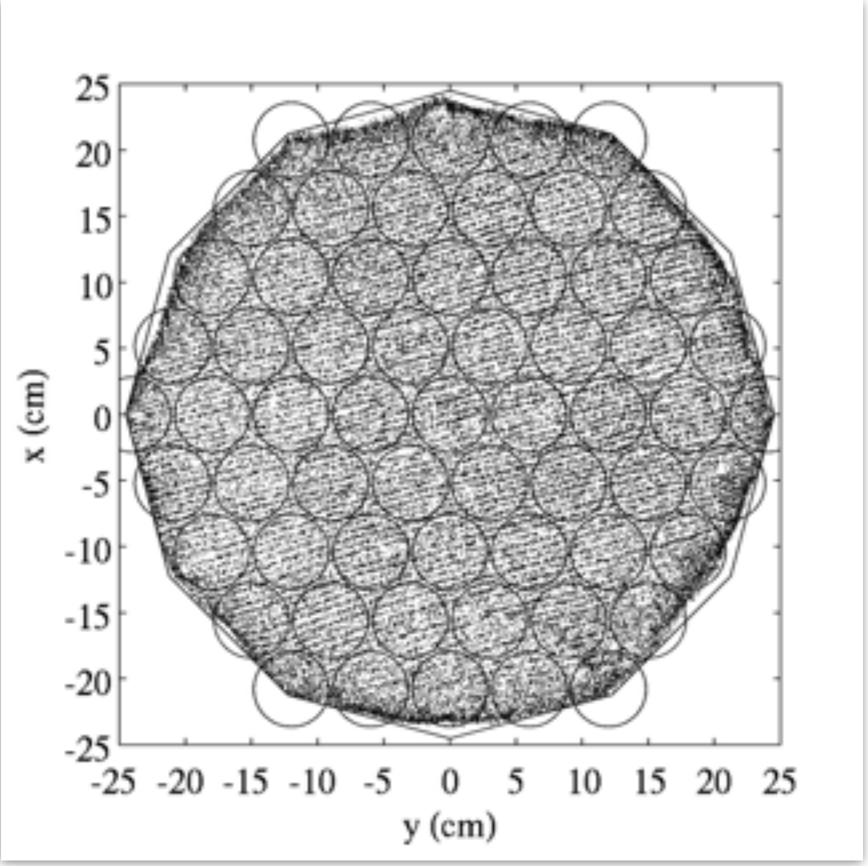


Construction materials chosen for low radioactivity (Ti, Cu, PTFE)

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

^{83m}Kr monitors detector performance

- ^{83m}Kr injected in the gas system and decaying uniformly inside the detector. It decays by emitting 2 internal conversion electrons
  - 32.2 keV ($T_{1/2}$ = 1.83 h) followed by 9.4 keV ($T_{1/2}$ = 154 ns) (Mono-energetic for our analyses)
  - see **PRD 96, 112009**
- ^{83m}Kr used for:
  - Overall stability monitoring
  - 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 - see **JINST 12 P11022**
  - Develop and test the position reconstruction - see **JINST 13 P02001**



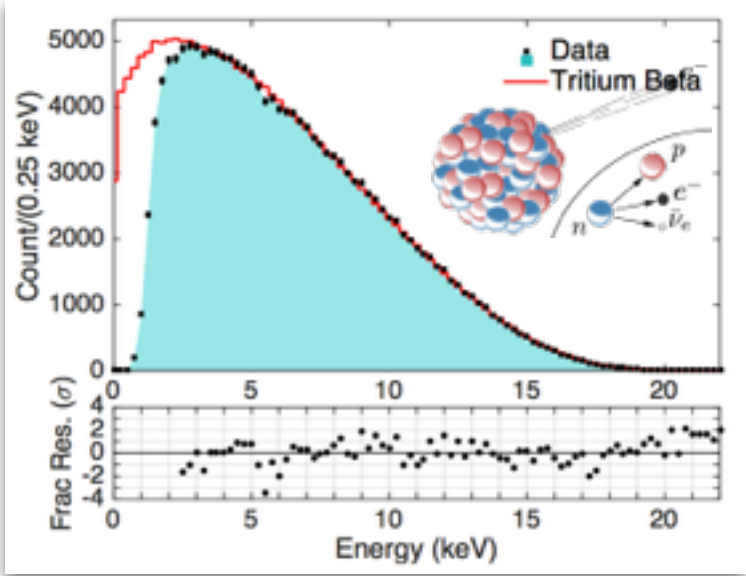
^{83m}Kr data (Drift Time 4 - 8 μs), SSR

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 creating the strip pattern observed in this figure.

^{3}H and D-D calibrate the detector response

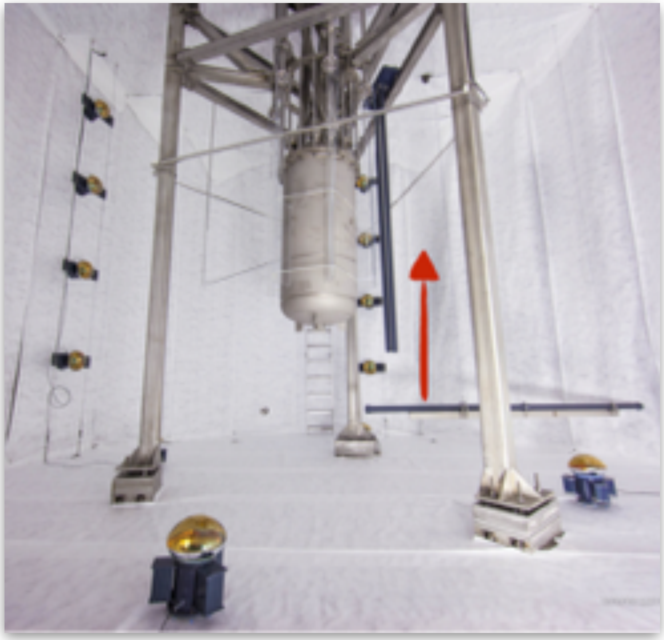
- **ER Calibrations:** Tritium, naked β decay
  - E_{max}=18.6 keV (S1~120 phd), $T_{1/2}$ =12.32 a.
  - Tritiated methane injected in the gas system and removed by the getter ($T_{1/2}$ ~ 6 h).
  - ER band calculation (right) and absolute calibration of Q_Y and L_Y for ER down to ~1 keVee.

PRD 93, 072009, 2016



- **NR Calibrations**: 2.45 MeV neutrons
  - Generated by a D-D generator placed outside the detector and collimated by an air-filled pipe.
  - Performed quarterly at different z's.
  - Neutrons scatter elastically with the nucleus
    - Double-scatters - ionization yield Q_y
    - Single-scatters - scintillation yield L_y and NR band calibration.

arXiv:1608.05381



Backgrounds in WS2014–16

Background source	Expected number below NR median
External Gamma Rays	1.51±0.19
Internal Betas	1.20±0.06
Rn plate out (wall back.)	8.7±3.5
Accidental S1-S2	0.34±0.10
Solar ^{8}B neutrinos (CEνNS)	0.15±0.02

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

Rn plate out: Low-energy, but confined to the edge of our fiducial volume†

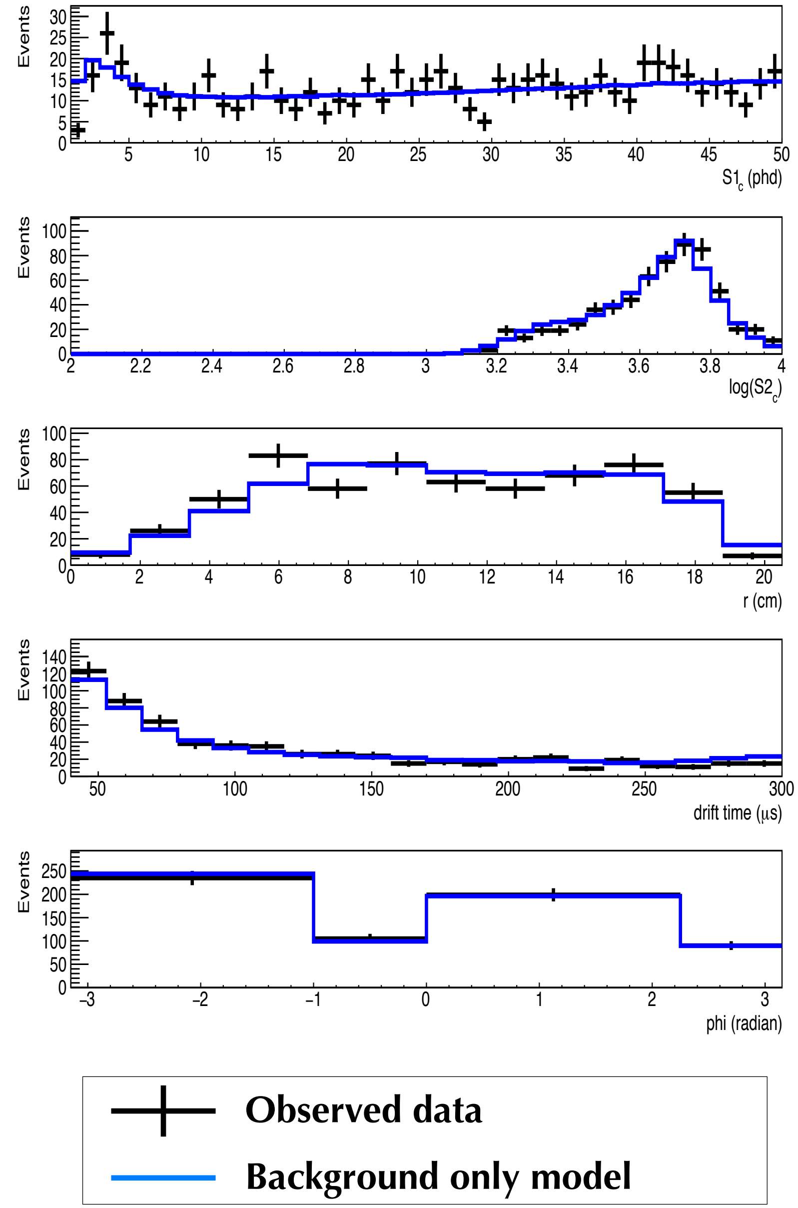
Accidental S1-S2 and Solar ^{8}B neutrinos: In the bulk volume, low- energy, in the NR band

- 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

† - Our likelihood analysis includes position information, so these events have low likelihood as signal.

LUX Likelihood Analysis

- A profile-likelihood test (PLR) 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.



^3H and D-D calibrate the detector response

ER and NR bands

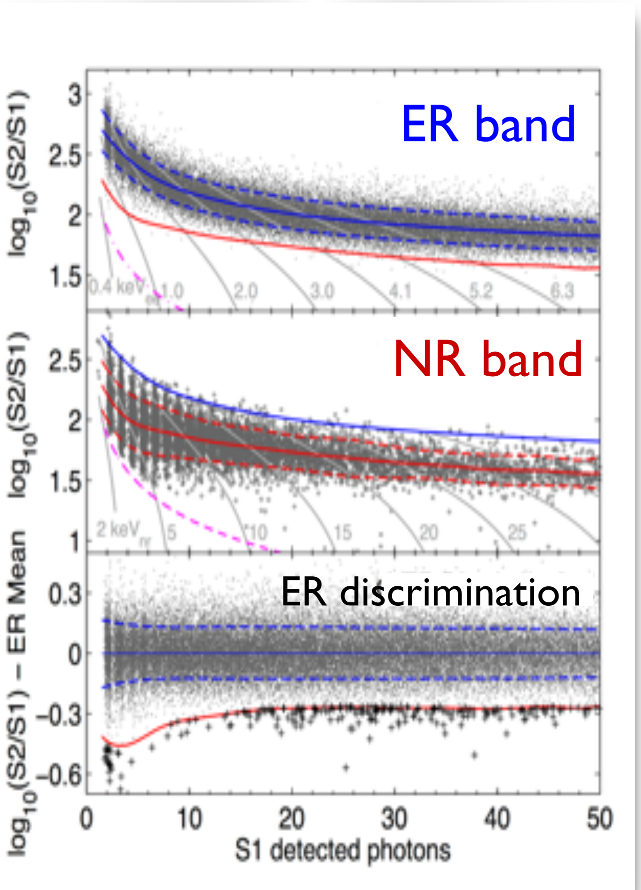
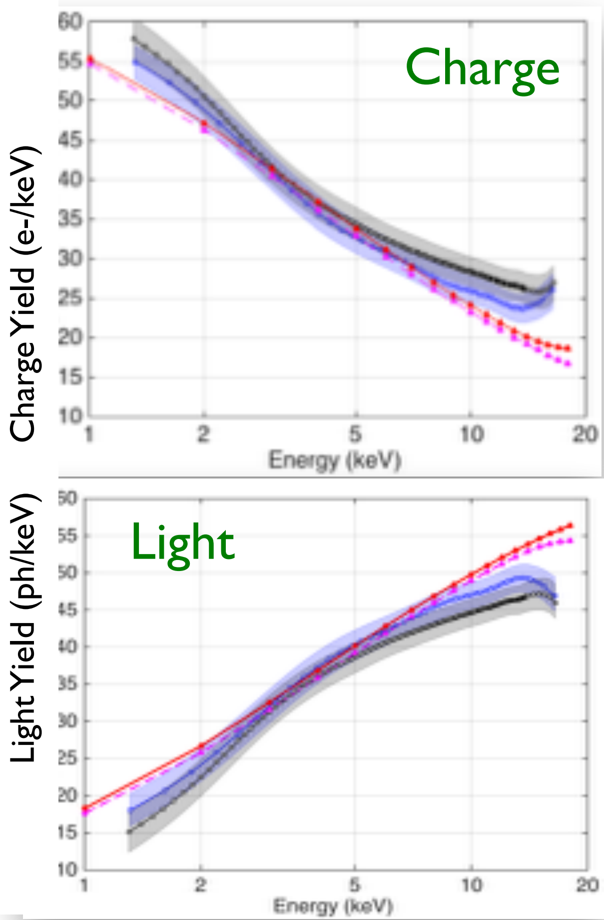


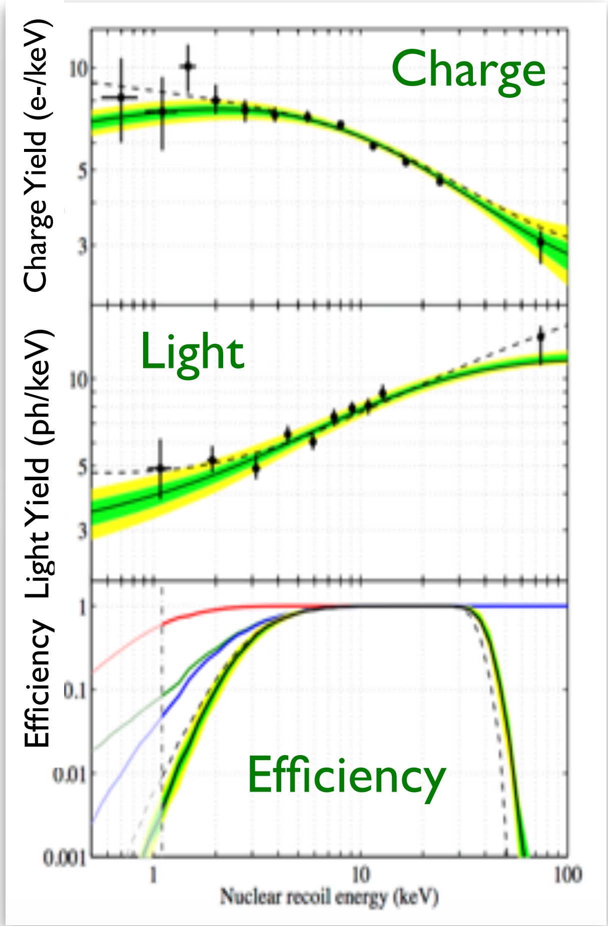
Figure: NR and ER calibration
(PRD, 95, 012008, 2017)

ER Light and Charge yields



PRD 93, 072009, 2016

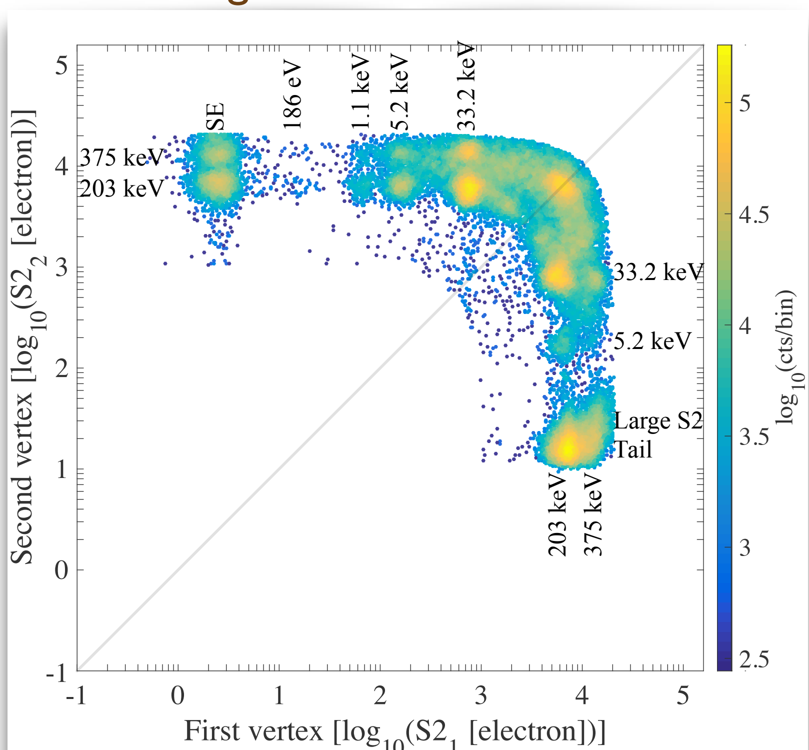
NR Light and Charge yields

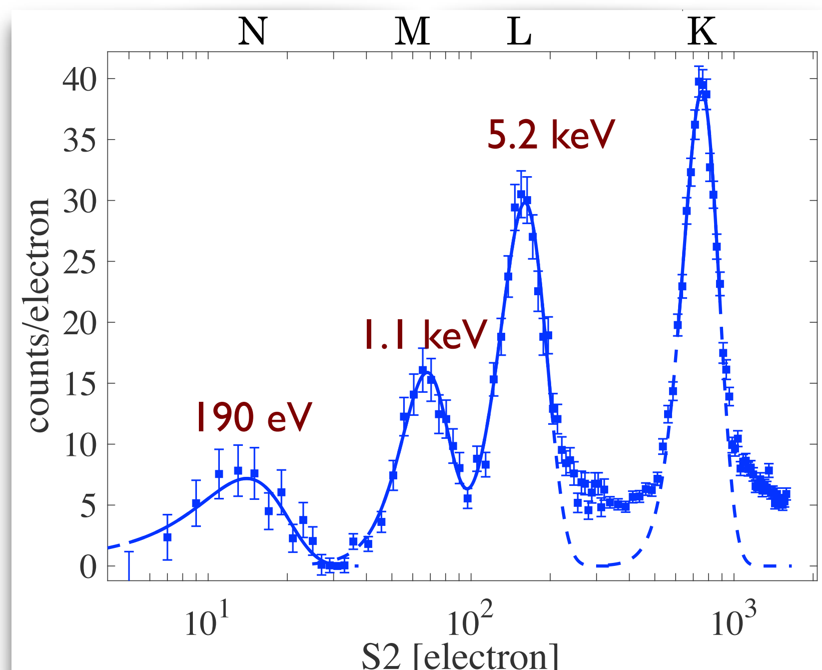


arXiv:1608.05381

ER Calibration - ^{127}Xe

- The ^{127}Xe radioisotope is present in the WS2013 data due to cosmogenic activation of the xenon during its time on the surface.
  - 36.4 days of half-life, ^{127}Xe initial activity of 490 ± 95 µBq/kg
  - Decays to an excited state of ^{127}I via electron capture (EC). With a ~62% probably, the decay of the excited state is via a single γ-ray emission (203 keV or 375 keV).
  - The vacancy resulting from the electron capture is subsequently filled with an electron from a higher level via emission of cascade X-rays or Auger electrons.



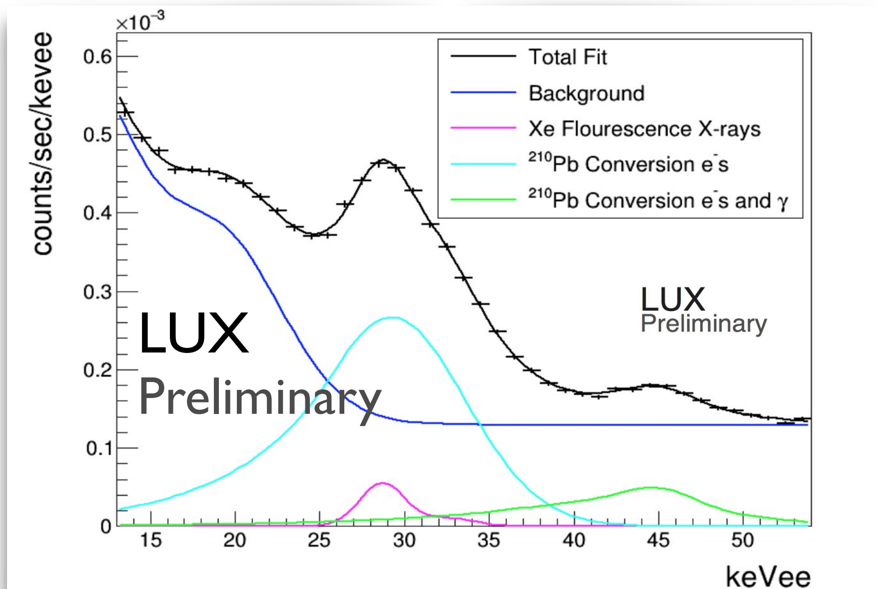


PRD, 96, 112011, 2017

Backgrounds - ^{210}Pb decay

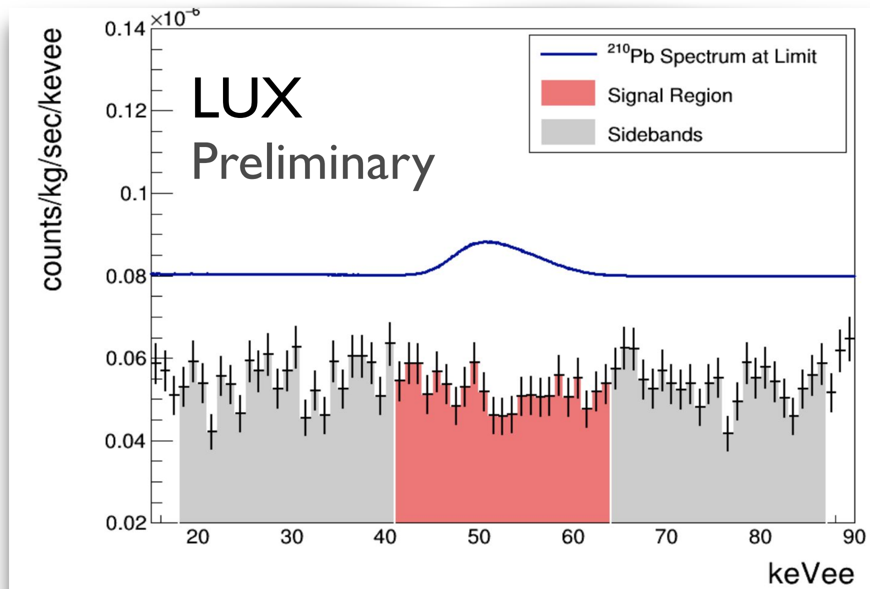
- During construction ^{222}Rn progeny plate out on the inner PTFE walls.
- All short lived isotopes decay away leaving ^{210}Pb, ^{210}Bi, and ^{210}Po.
- These isotopes can be absorbed off of the walls into the xenon.

^{210}Pb in the walls



Measured activity is
>5.7±0.4 mBq/cm^2
(WS2014-16 data)

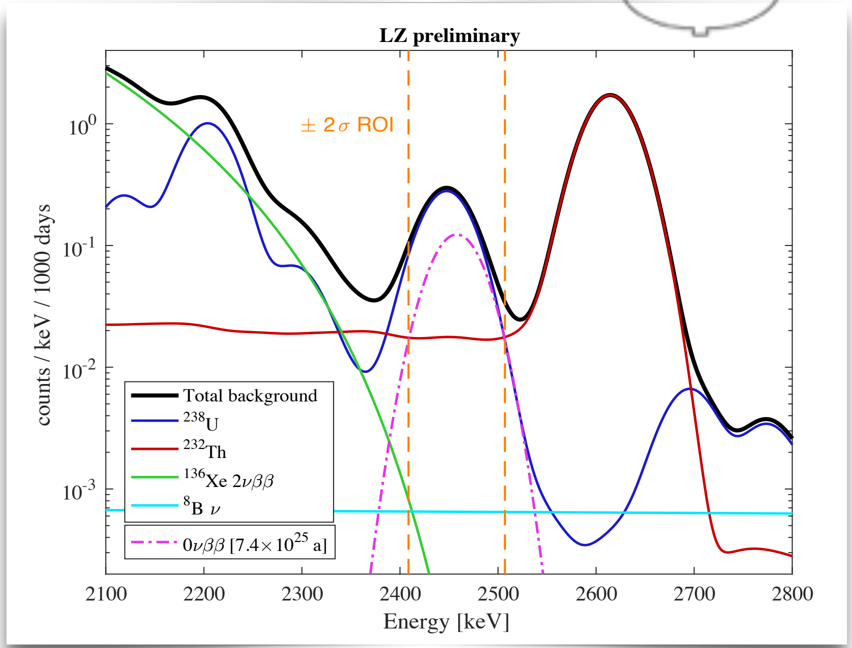
^{210}Pb in the fiducial volume
r<20 cm, at ~4 cm from the wall



Measured activity is
<0.1 μBq/kg (WS2013)

LZ Sensitivity to other physics

- Axions and Axion-like searches:
  - Axions: $g_{Ae}>1.5\times10^{-12}$ (90% C.L.).
  - Axion-like particles: $g_{Ae}>1.5\times10^{-12}$ (90% C.L.)
- Neutrinoless Double Beta Decay:
  - Two isotopes available ^{134}Xe and ^{136}Xe.
  - Preliminary sensitivity studies show a limit on the $0\nu\beta\beta$ half-life of ^{136}Xe (90% C.L.).
- Elastic Scattering of Solar Neutrinos:
  - Expected 838 pp events, 69 events from ^{7}Be from ^{13}N (E_ν<220 keV) in the 1.5 to window.



Background spectra for ^{136}Xe $0\nu2\beta$
Sensitivity limit $T_{1/2}$ ($0\nu2\beta$) >0.74×1026 a (90% C.L.).

- Neutrino Magnetic Moment (μ_ν):
  - The LZ ~1 keV energy threshold suggests an increase in sensitivity of ~1 order of magnitude relative to the upper limit of 5.4×10^{-11} μ_B set by BOREXINO.
- Coherent Nuclear Scattering of Solar Neutrinos (CEνNS):
  - Expected 7 events from ^{8}B neutrinos (with a signal very similar to a 6 GeV WIMP).