# Latest Analyses and Results from the LUX Collaboration

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July 25, 2018
Identification of Dark Matter 2018

*On behalf of the LUX Collaboration*

# Large Underground Xenon (LUX)




4850 ft below the surface

# LUX Timeline

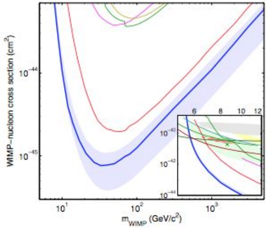
2006: LUX collaboration formed

2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

**WS-2013 (95 live-days)**

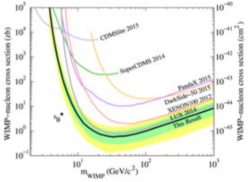
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

**WS-2014/16 (332 live-days)**

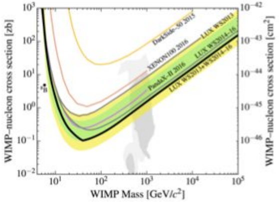
Dec 2015: Re-analysis of WS2013 published



PRL, 116, 161301 (2016)
PRL, 116, 161302 (2016)

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



PRL, 118, 021303 (2017)

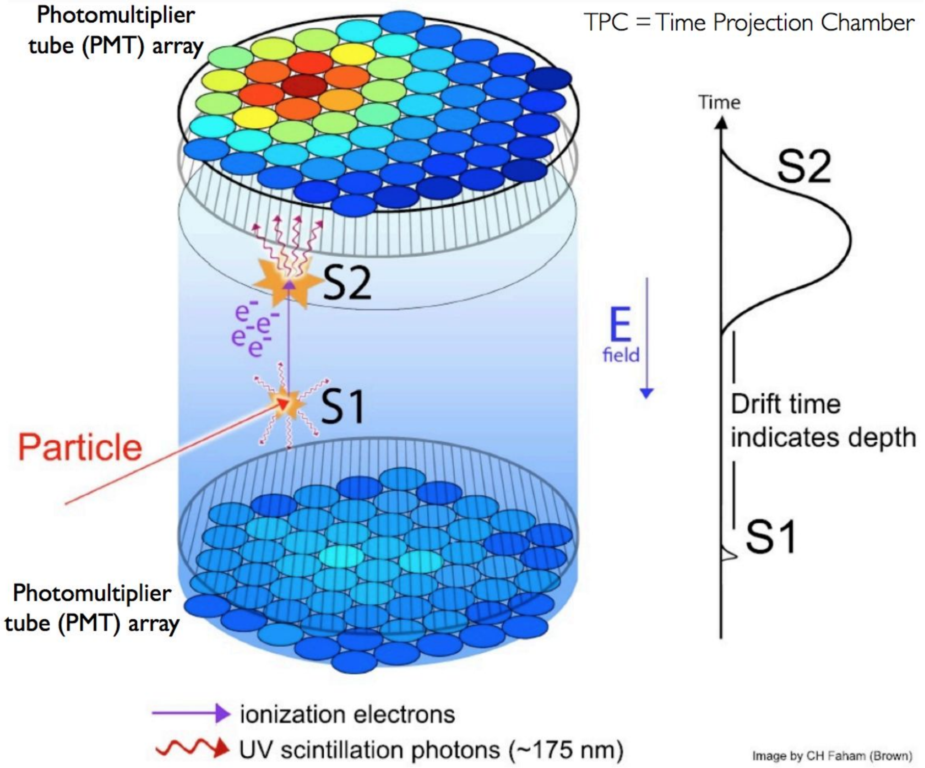
Sept 2016: decommissioning start

June 2017: LUX installed in a museum

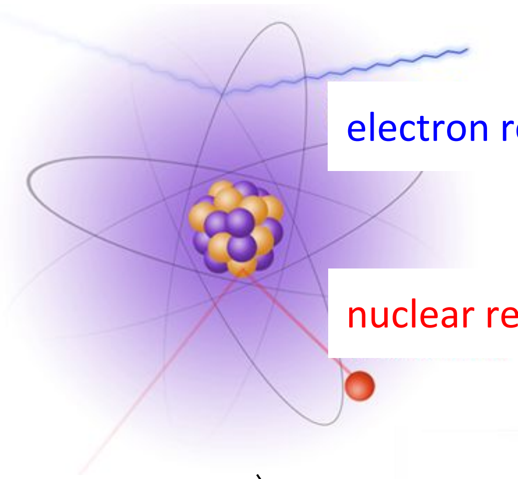
Analysis still ongoing

# The LUX Detector

- Xenon liquid/gas time projection chamber (TPC)
- 250 kg active mass
- Particles deposit energy:
  - S1: excitation signal, prompt scintillation immediately detected by PMTs
  - S2: ionization signal, electrons drifted upward and extracted into the gas phase region to create secondary scintillation
- 3D position reconstruction
  - Z: Δt between S1 and S2
  - X, Y: reconstructed from S2 light pattern
- Multiple scatters rejected with Δt

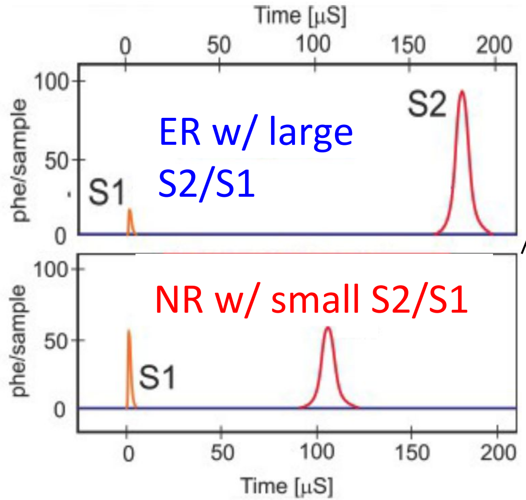


# Electron/Nuclear Recoil Discrimination

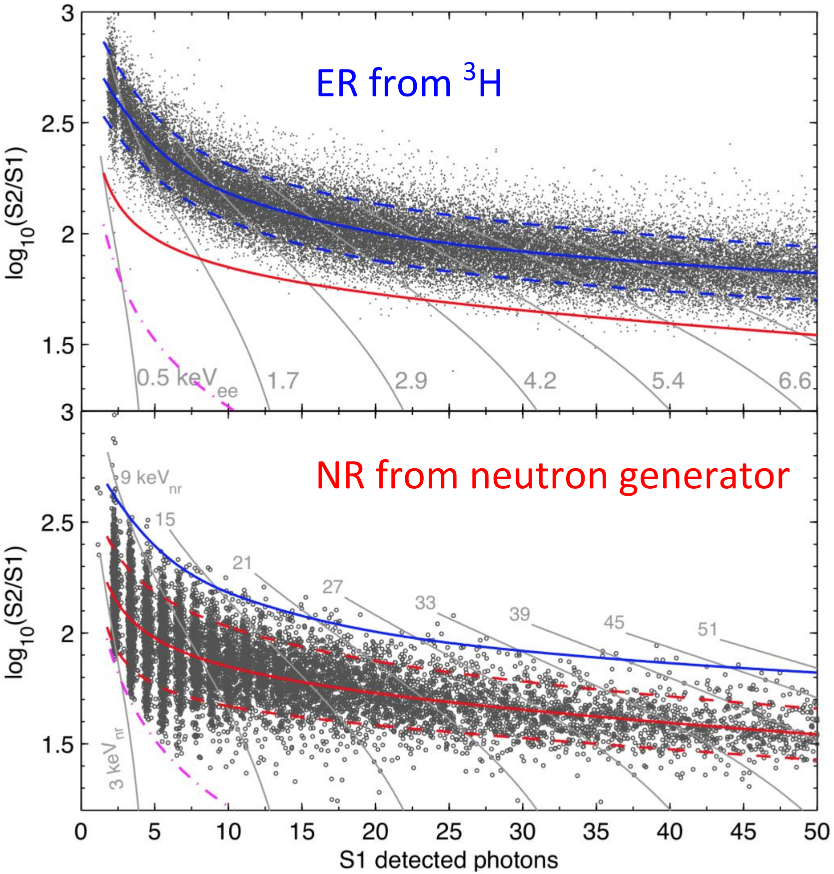


electron recoil (ER) background

nuclear recoil (NR) signal

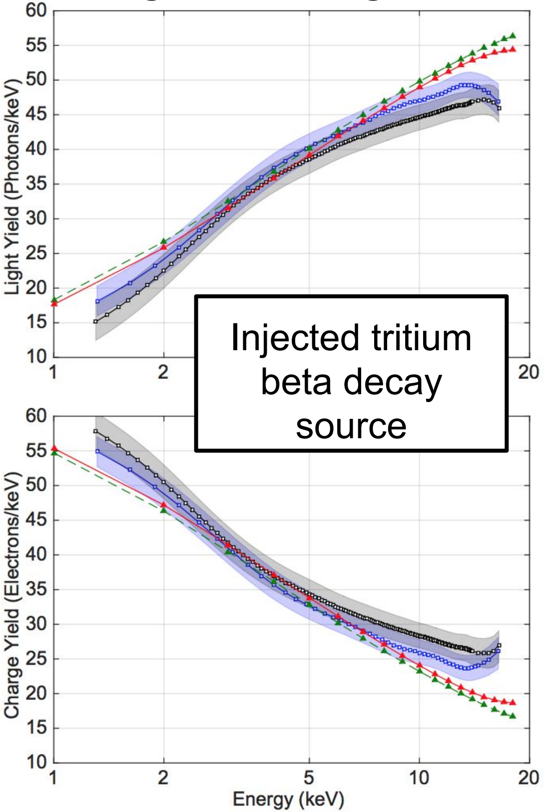



Phys Rev, D 97, 102008, 2018



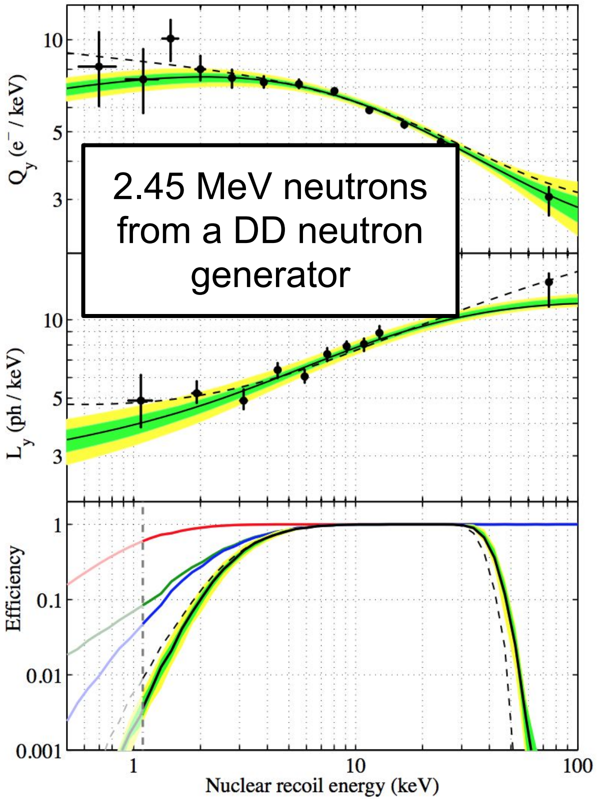
# LUX Calibrations

### ER Light and Charge Yield



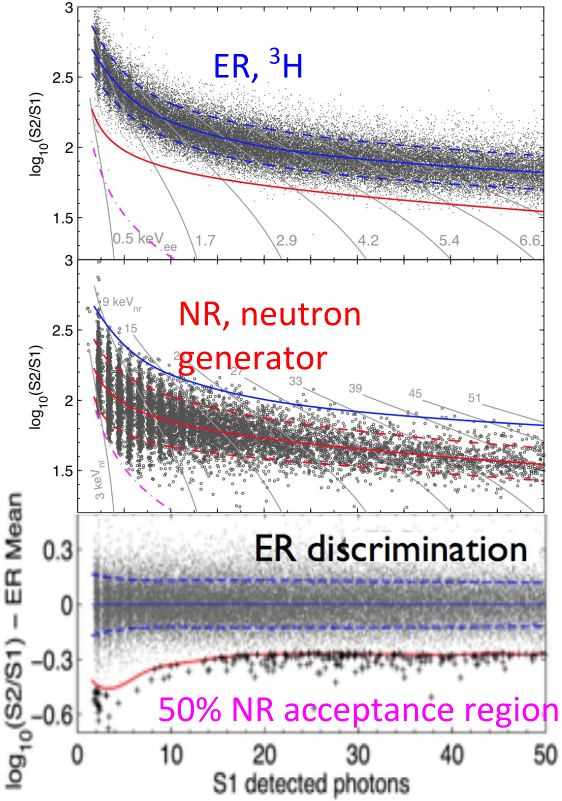

Phys Rev, D 93, 072009, 2016

### NR Light and Charge Yield




Phys Rev Lett, 116, 161301, 2016

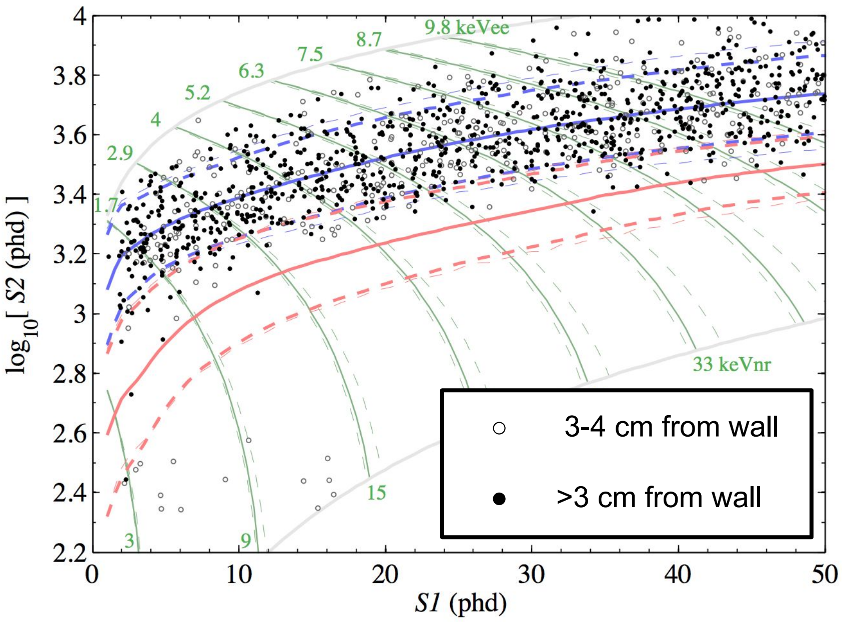
### ER, NR Bands and Leakage Fraction

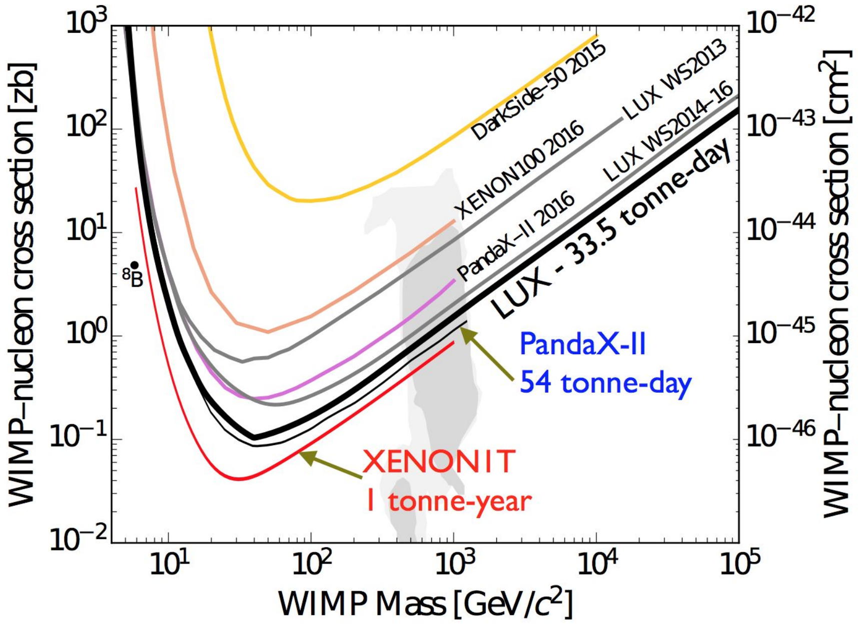



Phys Rev, D 97, 102008, 2018

# Spin Independent Limit

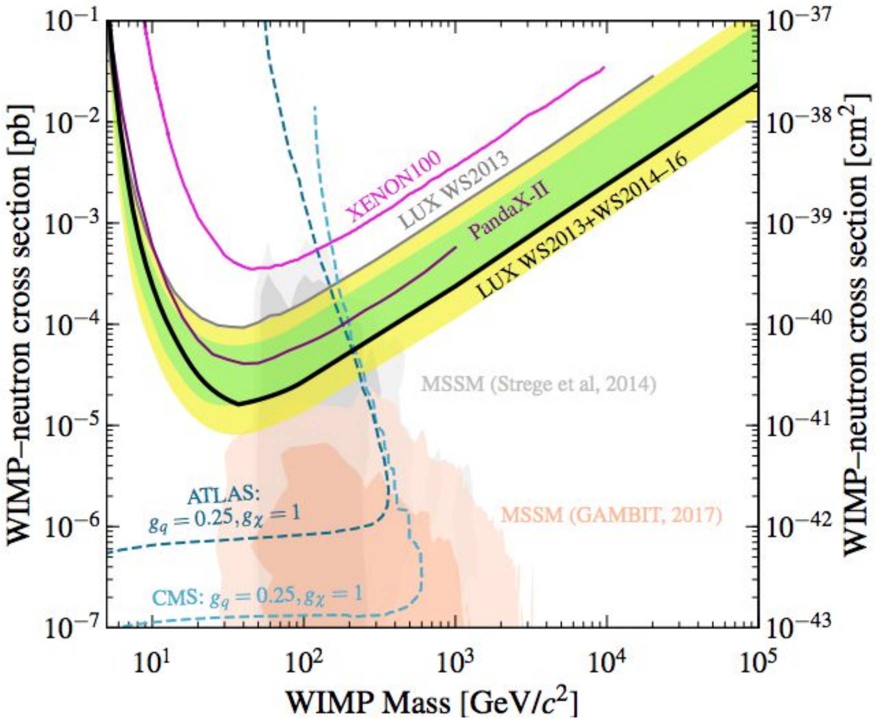
LUX 2017 : 427 live-days: lowest 90% CL exclusion = **0.11 zb at 40 GeV/c** (PRL, 118, 021303, 2017)

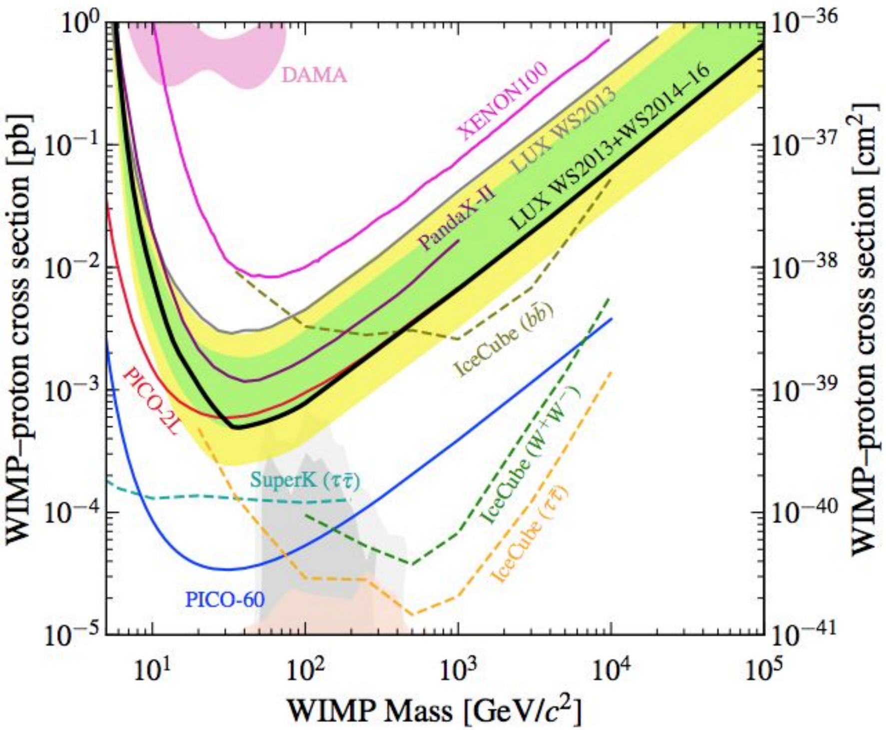



**Summer 2016 result was announced at IDM!**

# Spin-dependent Elastic Cross-section




WS-2013 + WS-2014/16

Phys Rev Lett 118, 251302, 2017

# LUX Analyses Published (2017-2018)

- A search for annual and diurnal electron recoil rate modulations (arXiv:1807.07113)
- LUX Trigger Efficiency (arXiv:1802.07784)
- Liquid xenon scintillation measurements and pulse shape discrimination in the LUX dark matter detector (Phys Rev, D 97, 112002, 2018)
- Position Reconstruction in LUX (J Instrum, Volume 13, Feb 2018, P02001)
- Ultra-Low Energy Calibration of LUX Detector using 127Xe Electron Capture (Phys Rev, D 96, 112011, 2017)
- Kr-83m calibration of the 2013 LUX dark matter search (Phys Rev, D 96, 112009, 2017)
- 3D Modeling of Electric Fields in the LUX Detector (JINST 12, no 11, P11022, 2017)
- First Searches for Axions and Axionlike Particles with the LUX Experiment (Phys Rev Lett 118, 261301, 2017)
- Limits on spin-dependent WIMP-nucleon cross section obtained from the complete LUX exposure (Phys Rev Lett 118, 251302, 2017)
- Signal yields, energy resolution, and recombination fluctuations in liquid xenon (Phys Rev, D 95, 012008,2017)
- Limits on spin-dependent WIMP-nucleon cross section obtained from the complete LUX exposure (Phys Rev Lett 118, 251302 2017)

# LUX Ongoing or Near Finished Analyses

- Effective Field Theory
- Sub-GeV dark matter detection using Bremsstrahlung and Migdal-effect . . Junsong Lin, Tues 15:20
- Lightly ionizing particles
- $^{124}$Xe 2$\nu$ Double Electron Capture
- $^{134}$Xe & $^{136}$Xe 0$\nu\beta\beta$ decay
- Electric field dependence of light yield, charge yield, and recombination fraction and ER/NR discrimination power . . . . . . Vetri Velan, Mon 15:20
- Calibration with $^{14}$C
- Radiogenic backgrounds
- Muon veto performance

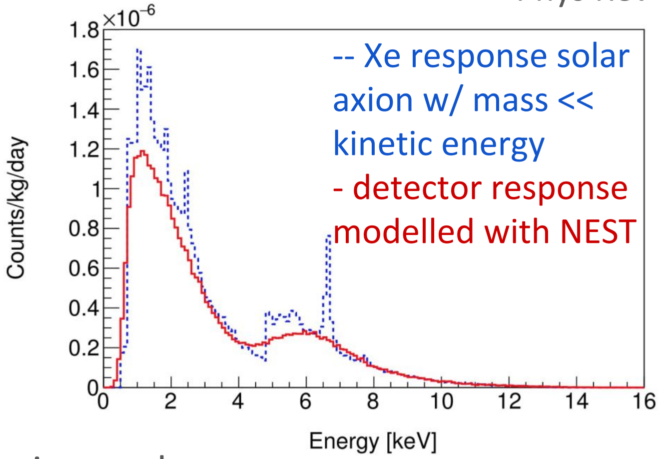
This talk will focus on the topics highlighted in blue

And More!

# Axions & Axion-like Particles

Phys Rev Lett 118, 261301, 2017

**(1)** QCD axions emitted by the sun . . .

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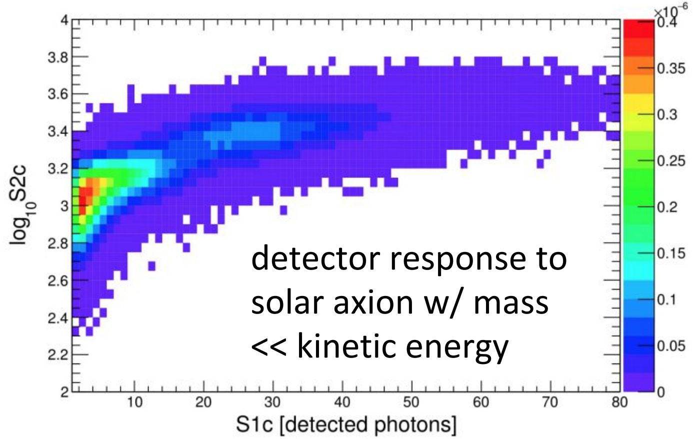
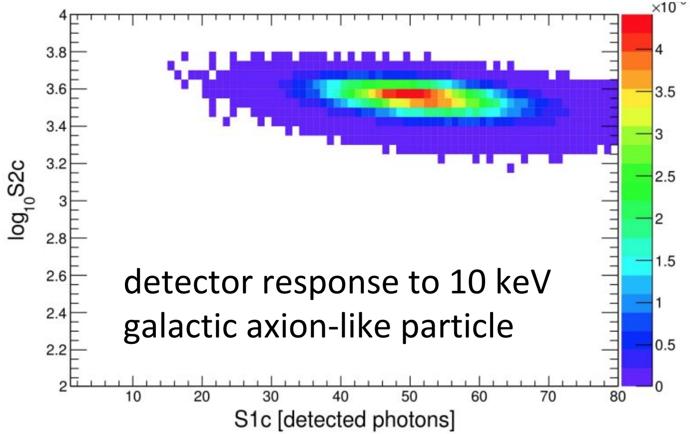



- Peccei-Quinn solution to the strong-CP problem
- WS-2013 data (95 live-days with 118 kg fiducial)
- Axio-electric coupling $g_{Ae}$:

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

**(2)** keV-scale galactic axion-like particles in mass range 1-16 keV/c$^2$ . . .



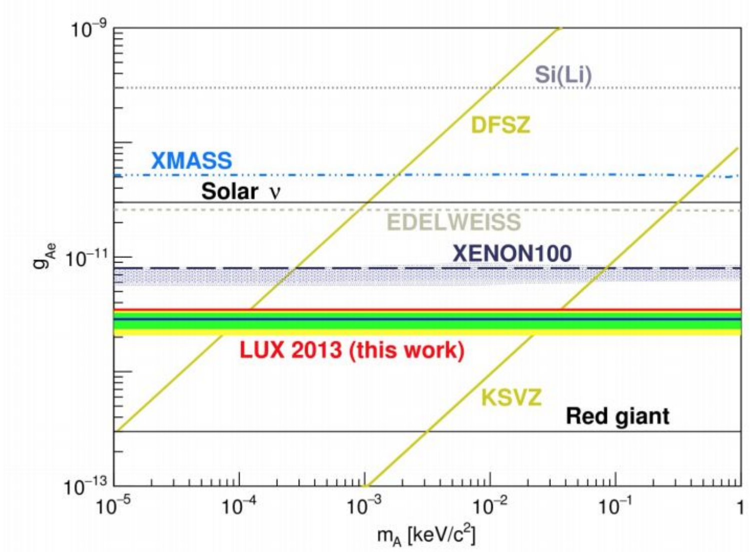
# Axions & Axion-like Particles

Double sided PLR w/ background rates as nuisance parameters ..............

| Parameter | Constraint | Fit value (solar axions) |
|---|---|---|
| Low-$z$-origin $\gamma$ counts | $161 \pm 69$ | $157 \pm 17$ |
| Other $\gamma$ counts | $223 \pm 96$ | $175 \pm 18$ |
| $\beta$ counts | $67 \pm 27$ | $113 \pm 18$ |
| $^{127}$Xe counts | $39 \pm 12$ | $42 \pm 8$ |

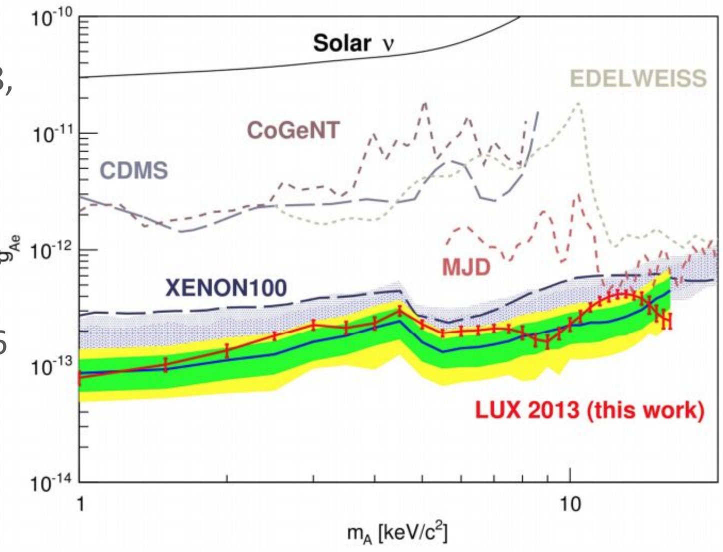
$g_{Ae} < 3.5 \times 10^{-12}$ (90% CL, solar axions)
$m_A < 0.12$ eV/$c^2$ (DFSZ model)
$m_A < 36.6$ eV/$c^2$ (KSVZ model)

$g_{Ae} < 4.2 \times 10^{-13}$ (90% CL, 1-16 keV/$c^2$ ALPs)




Plots are from Phys Rev Lett 118, 261301, 2017

Most recent PandaX-II results from Phys Rev Lett 119, 181806 (2017) have not been included in these plots

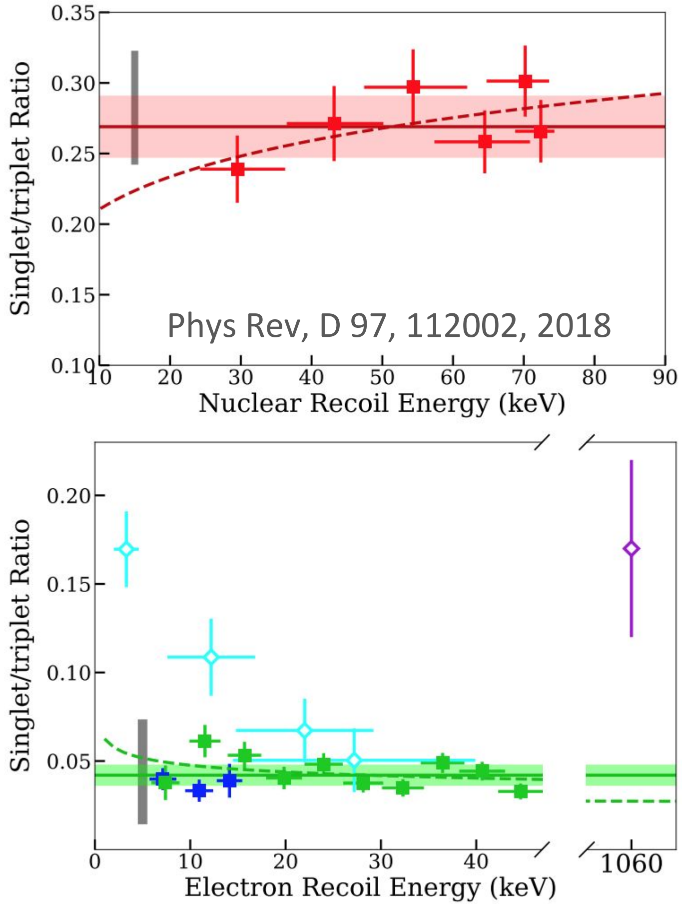


# S1 Pulse Shape Discrimination

- $Xe_2^*$ scintillation
  - Singlet: 2-4 ns
  - Triplet: 21 -28 ns
- Template fitting reconstructs photon detection times
- Analytical model extracts the singlet to triplet ratio for NR below 74 keV and for ER below 46 keV

**LUX**
**E-field = 50 to 400 V/cm**

- DD neutrons
- Tritium
- $^{14}C$
- NR Const Fit = 0.269
- ER Const Fit = 0.042
- NR Exp Fit = $0.15\ E^{0.15}$
- ER Exp Fit = $0.063\ E^{-0.12}$
- NR Const Stat Unc
- ER Const Stat Unc
- Const Sys Unc




**Comparison with Other Experiments**

- XMASS-I at 0 E-field (NIM A, 834, 2016, 192-196)
- $^{207}$Bi IC Source at 4 kV/cm (Phys Rev, B20, 1979, No 8, 3486)

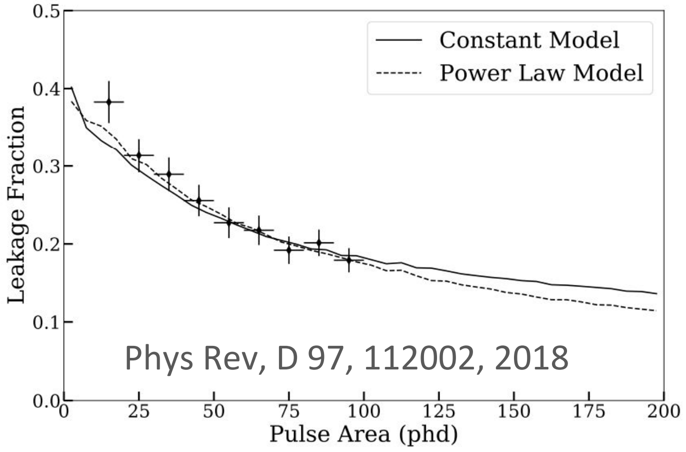
# S1 Pulse Shape Discrimination

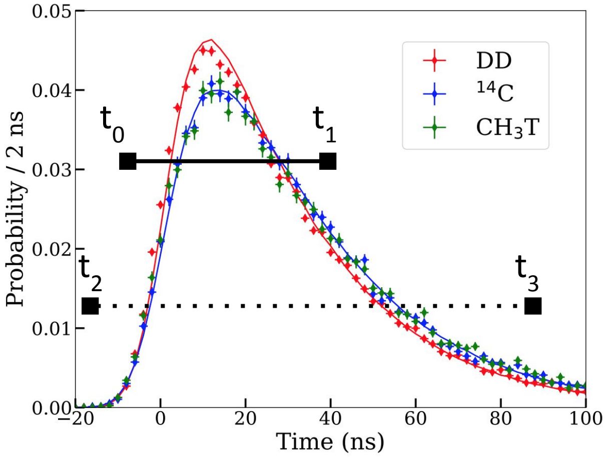
- Prompt fraction discriminator:

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

- Parameters trained to minimize the leakage of ER events into 50% NR acceptance region

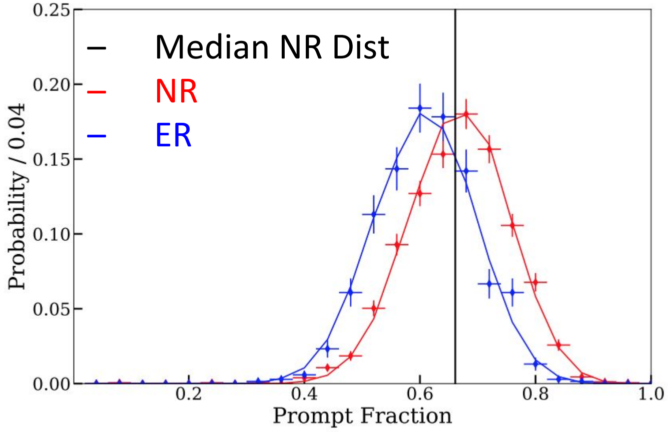
$t_2, t_0, t_1, t_3$ = -14, -8, 32, 134 ns




Average photon detection time spectra 40 - 50 phd (~11-13 $keV_{ee}$)

Normalized prompt fraction distributions 40 - 50 phd

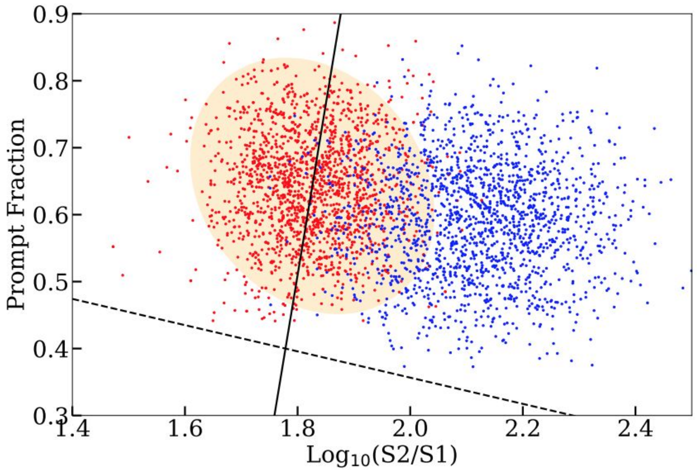


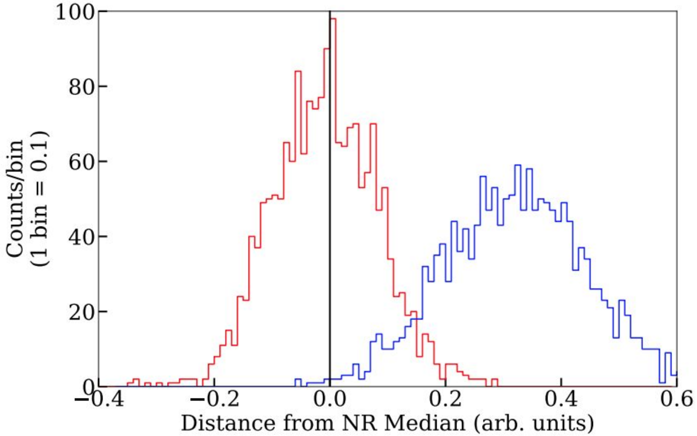
# S1 Pulse Shape Discrimination

- The pulse shape discriminator can be used in conjunction with the charge-to-light ratio ($\log_{10}$(S2/S1)) to develop a 2-D discrimination parameter
- ER leakage over full WS range (0 - 50 phd):
  - **$\log_{10}$(S2/S1): 0.4 ± 0.1 %**
  - **$\log_{10}$(S2/S1) + PS: 0.3 ± 0.1 %**
- ER leakage over range 40 - 50 phd:
  - $\log_{10}$(S2/S1): 0.3 ± 0.2 %
  - $\log_{10}$(S2/S1) + PS: 0.1 ± 0.1 %

**Example: 40 - 50 phd**

– NR
– ER
■ 90% NR Region
– $\log_{10}$(S2/S1) + PS Discriminator
-- Axis Perpendicular to NR Median

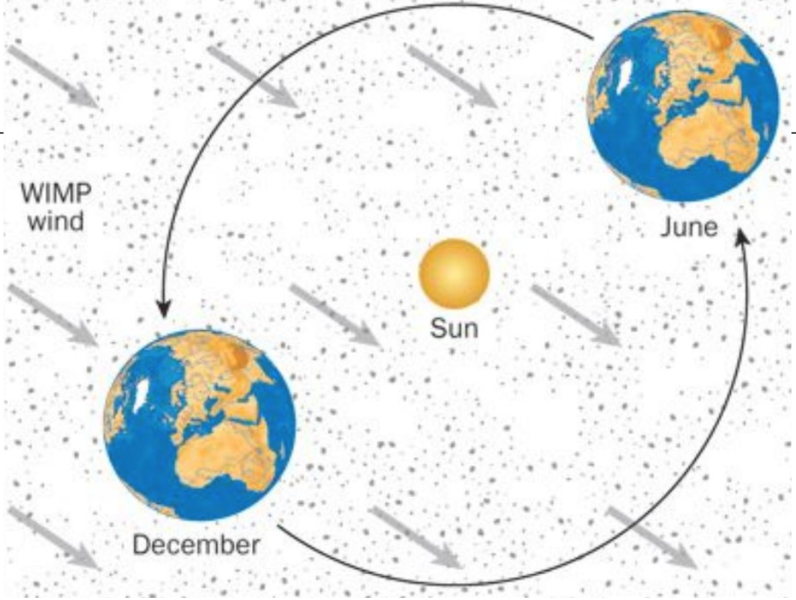


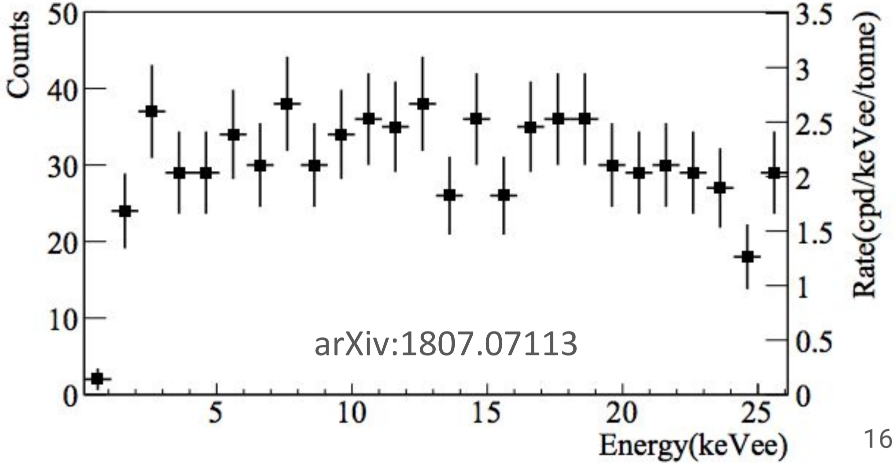




Phys Rev, D 97, 112002, 2018

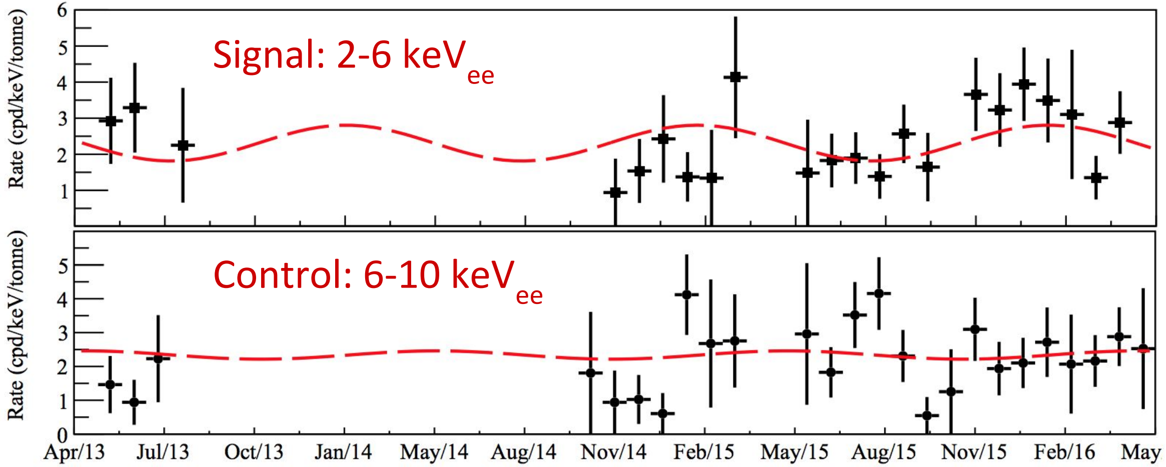
# Annual Modulation

- In many models, dark matter event rate modulates because of Earth's motion about the Sun
- DAMA/LIBRA
  - Modulating w/ highest rate in June
  - For events < 6 keV
- LUX
  - 25 months of WS-2013 + WS-2014/16 data
  - Remove calibration data sets & data from periods of time with unstable slow control parameters (271 remaining live-days)
  - Select small low background fiducial mass of 51.4 kg
  - Select conservative 2 $keV_{ee}$ threshold
  - **2.3 ± 0.21 cpd/$keV_{ee}$/tonne** below 10 $keV_{ee}$



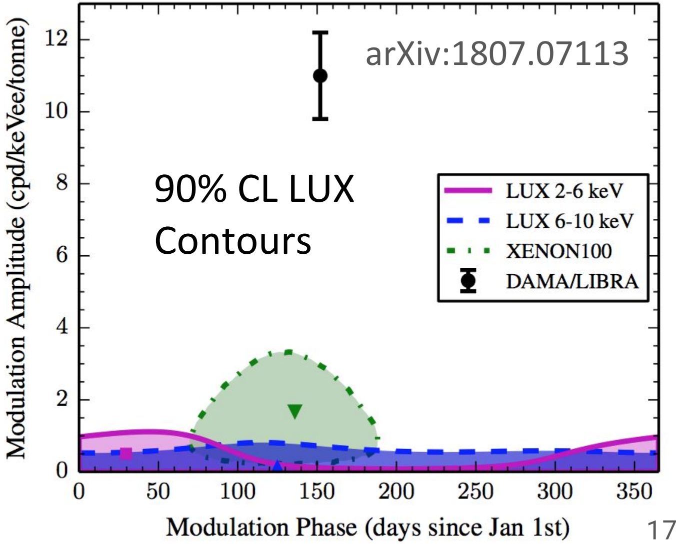



# Annual Modulation




… A = 0.5 ± 0.27 cpd/keV/tonne
φ = 30 ± 35 days since Jan 1st

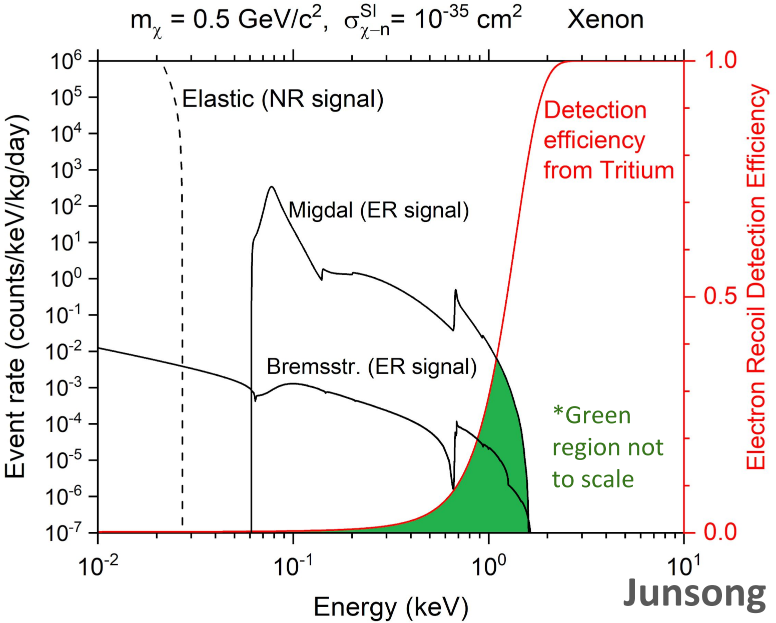
… A = 0.12 ± 0.32 cpd/keV/tonne
φ = 124 ± 113 days since Jan 1st

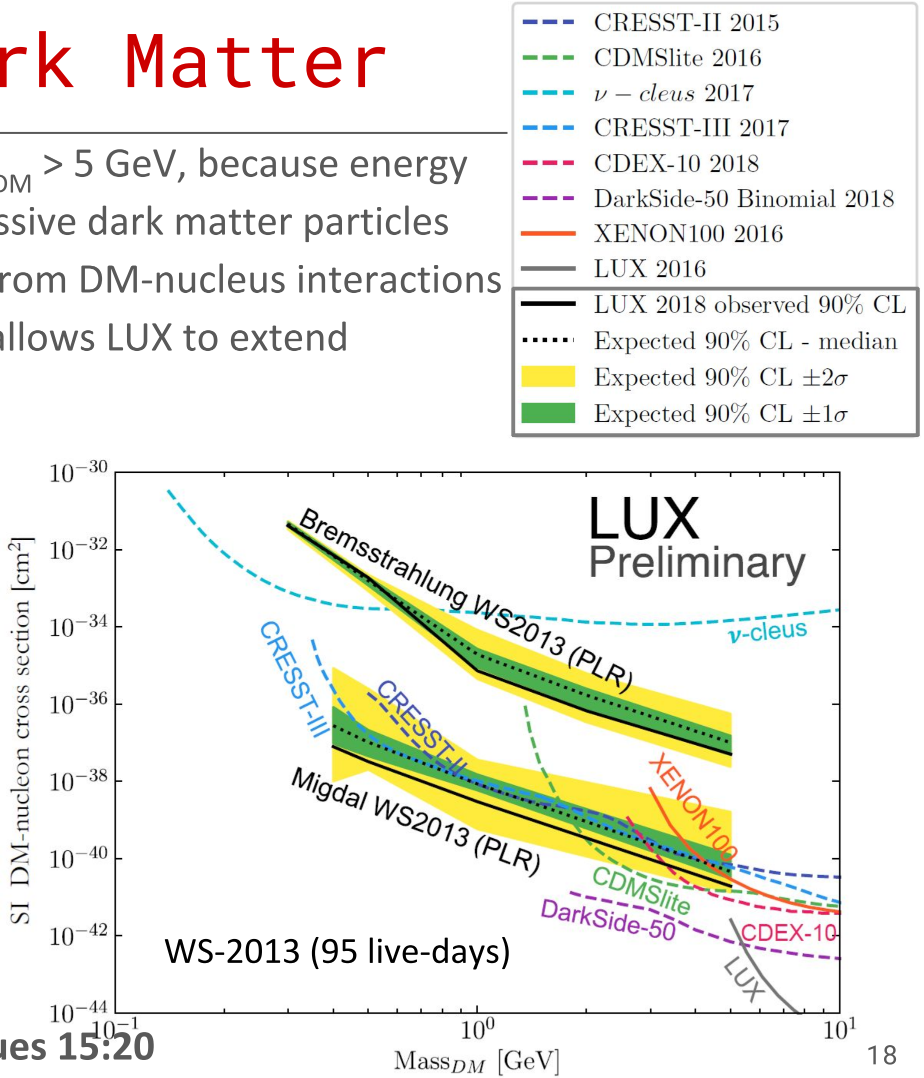



- Signal region for comparison with DAMA/LIBRA
- Control region to assess possible systematic uncertainties
- Fit for amplitude, phase, and constant background using an unbinned maximum likelihood analysis
- No statistically significant annual modulation was observed for energies up to 26 keV$_{ee}$
- 9.2-**σ** tension with DAMA/LIBRA result

# Sub-GeV Dark Matter

- Typical DM-nucleus elastic scattering analysis has $m_{DM} > 5$ GeV, because energy transfer to the xenon nucleus is very low for less massive dark matter particles
- Migdal & Bremsstrahlung are irreducible ER signals from DM-nucleus interactions
- Good detection efficiency for low energy ER events allows LUX to extend sensitivity down to masses of 0.4 GeV



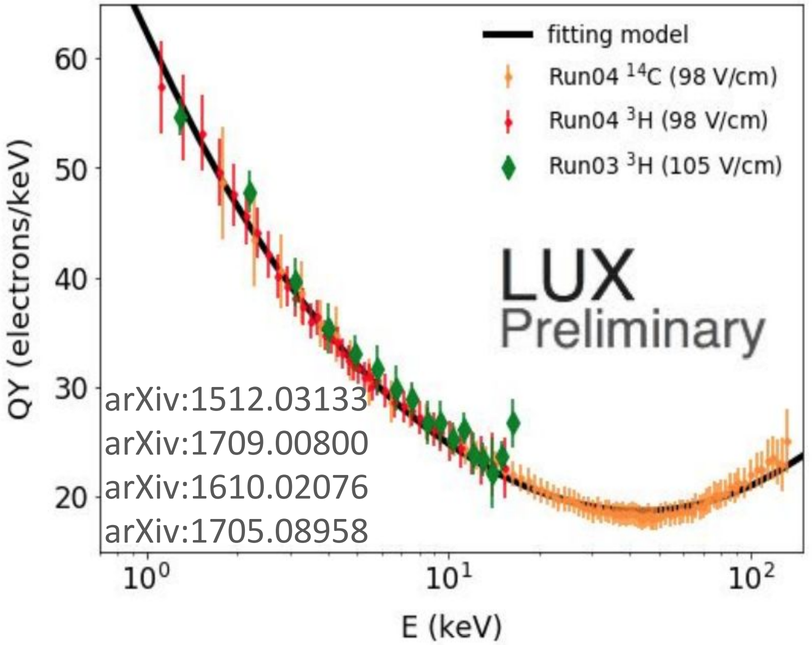




**Junsong Lin, Tues 15:20**

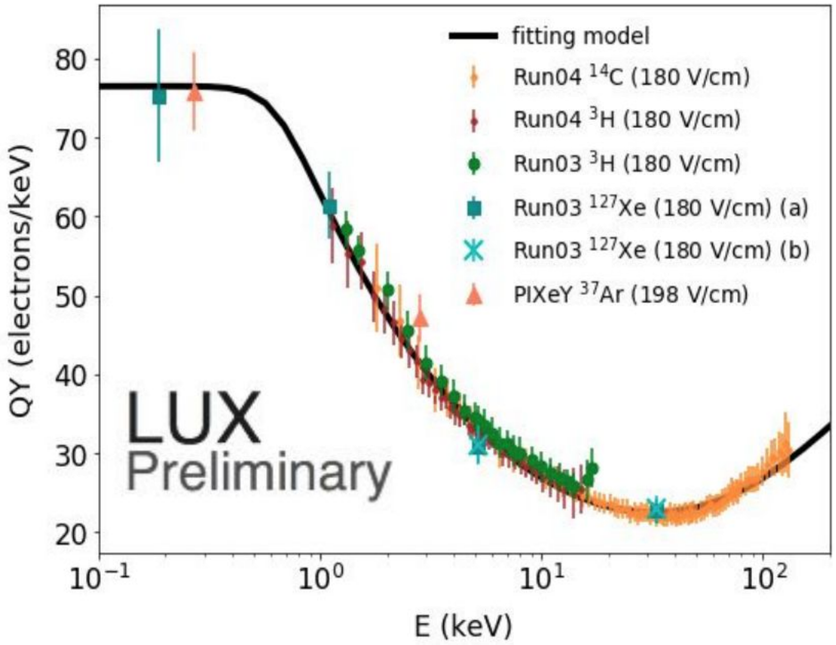
# End of LUX $^{14}C$ Calibration

- Tritiated methane injections: Tritium beta decay Q = 18.6 keV
- $^{14}C$ labelled methane: $^{14}C$ beta decay Q = 156.5 keV
- Below QY results for 100 V/cm and 180 V/cm are shown consistent with previous measurements

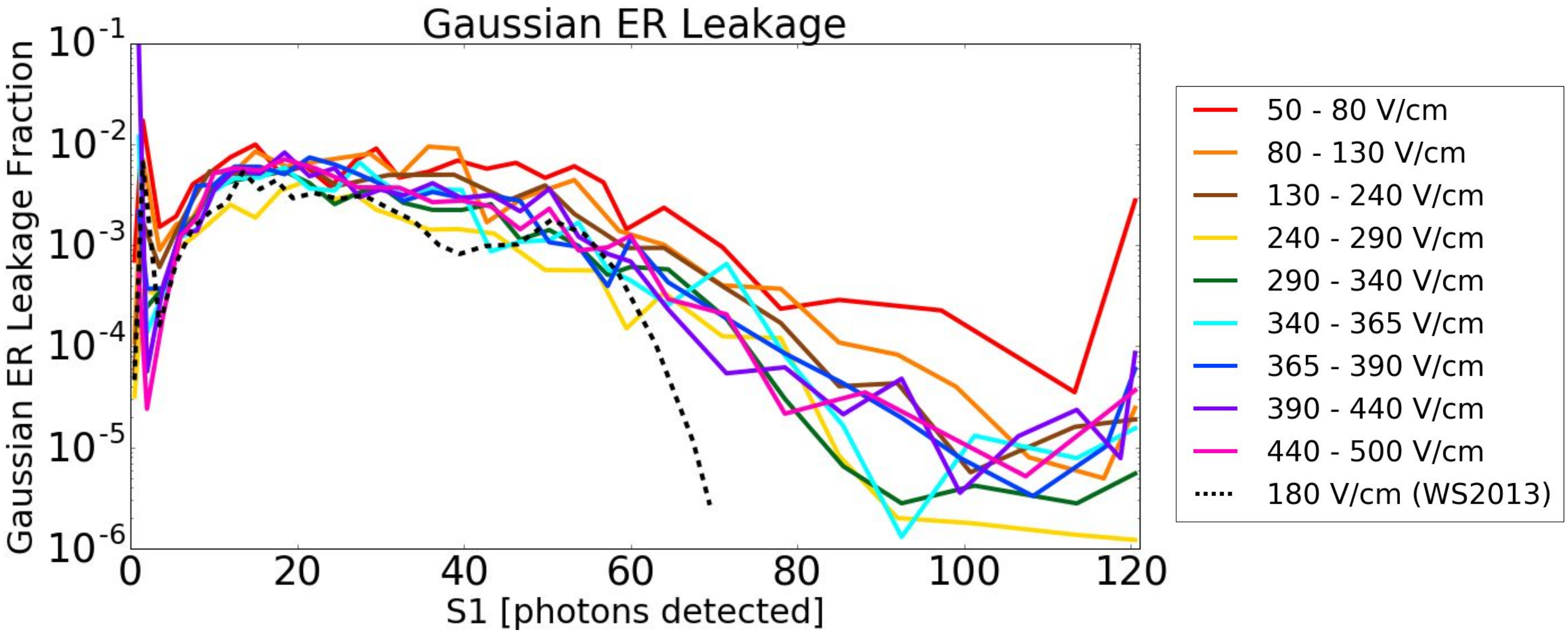
**100 V/cm**




**180 V/cm**



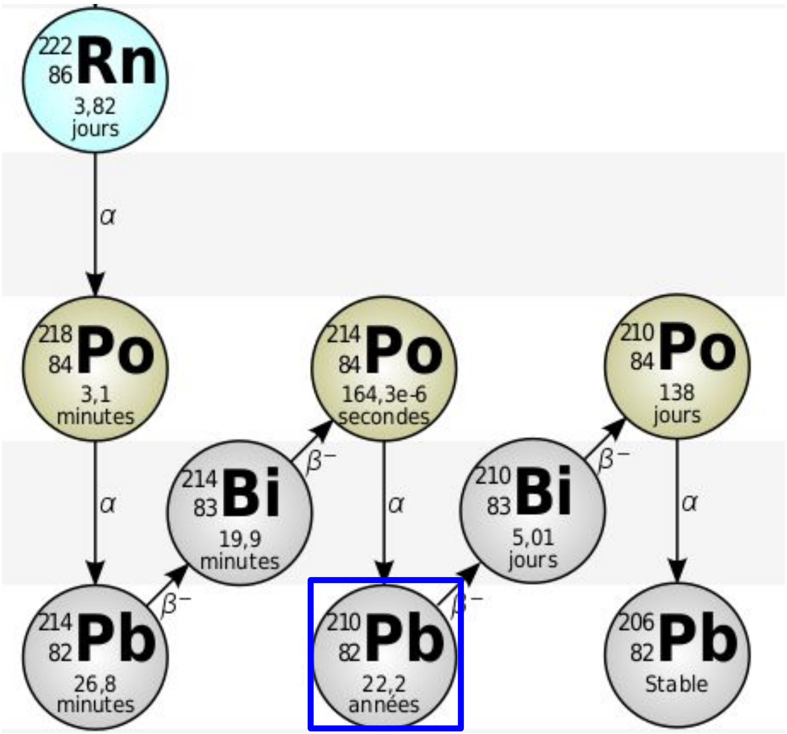
# Electric Field Dependent Discrimination




- In WS-2014/16, throughout the volume of the TPC, E-fields between 50 and 500 V/cm
- This wide range of E-fields can be used to probe ER/NR, charge-to-light discrimination
- **Vetri Velan, Mon 15:20**

# $^{210}Pb$ Backgrounds on Detector

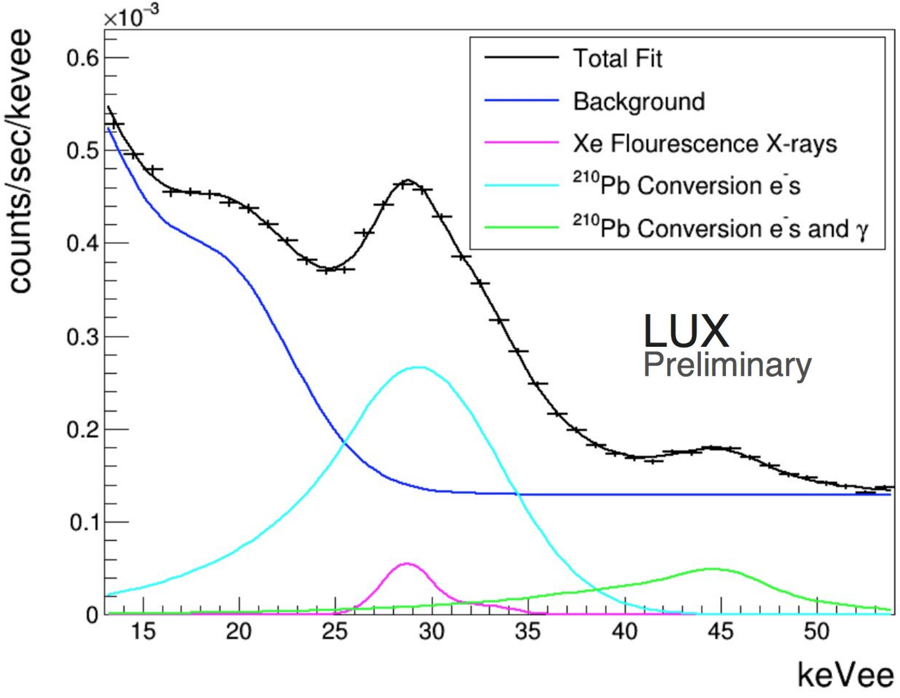
- During construction $^{222}Rn$ progeny plate out on the inner PTFE walls of the detector
- All short lived isotopes decay away leaving $^{210}Pb$, $^{210}Bi$, and $^{210}Po$
- These isotopes can be absorbed off of the walls into the xenon
- This has previously been observed by Kamland[1,2] and Borexino[3], and is of great interest to LUX-ZEPLIN
- **Kate Kamdin Thurs 18:10, "First Evidence for Radon Daughter Solubility in Liquid Xenon"**

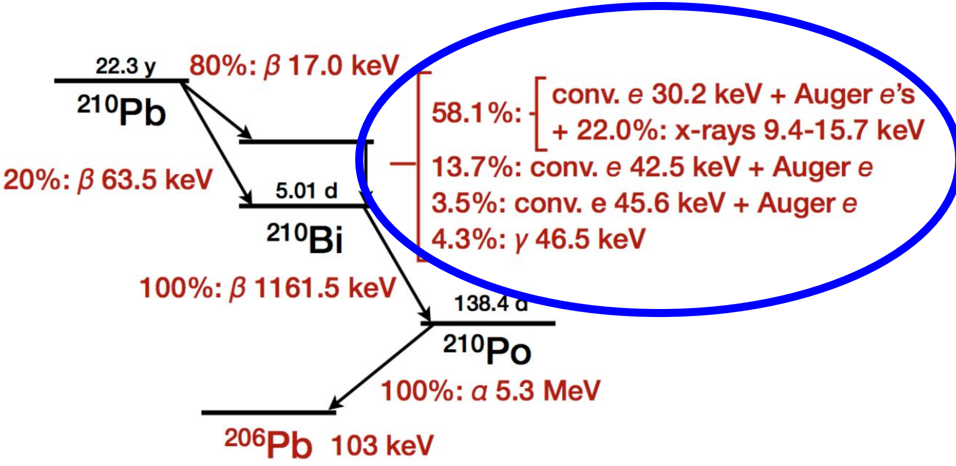



[1]Nuc Part Phys Proc, 265-266, 2015, pp 139-142
[2]Phys Rev, C 92, 055808, 2015
[3]Phys. Rev. D 89,112007, 2014

# Surfaces $^{210}$Pb Surfaces

Data Reconstructed near LUX PTFE Walls



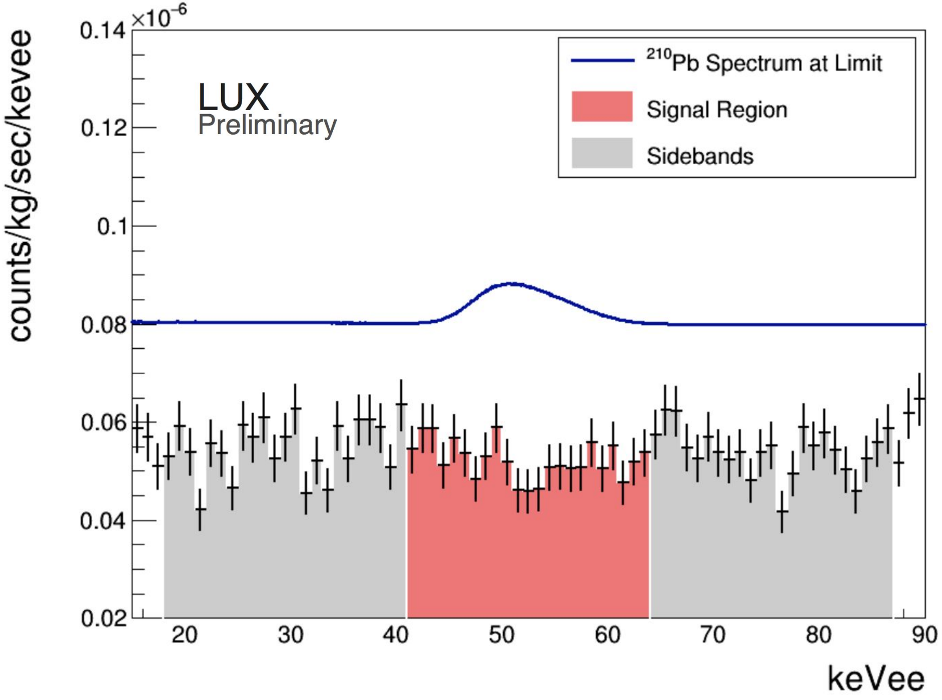

J.Low Temp.Phys. 176 (2014) no.5-6, 959-965

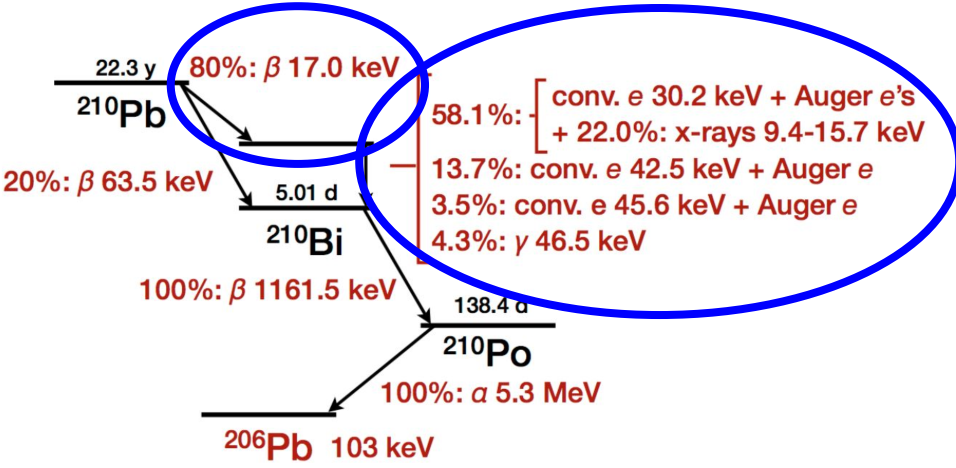
**Activity of $^{210}$Pb on wall in the fiducial volume drift range for WS-2014/16 > 9.6 ± 0.6 mBq**

LUX
Preliminary

# $^{210}$Pb in Liquid Xenon

Data In LUX Fiducial Volume



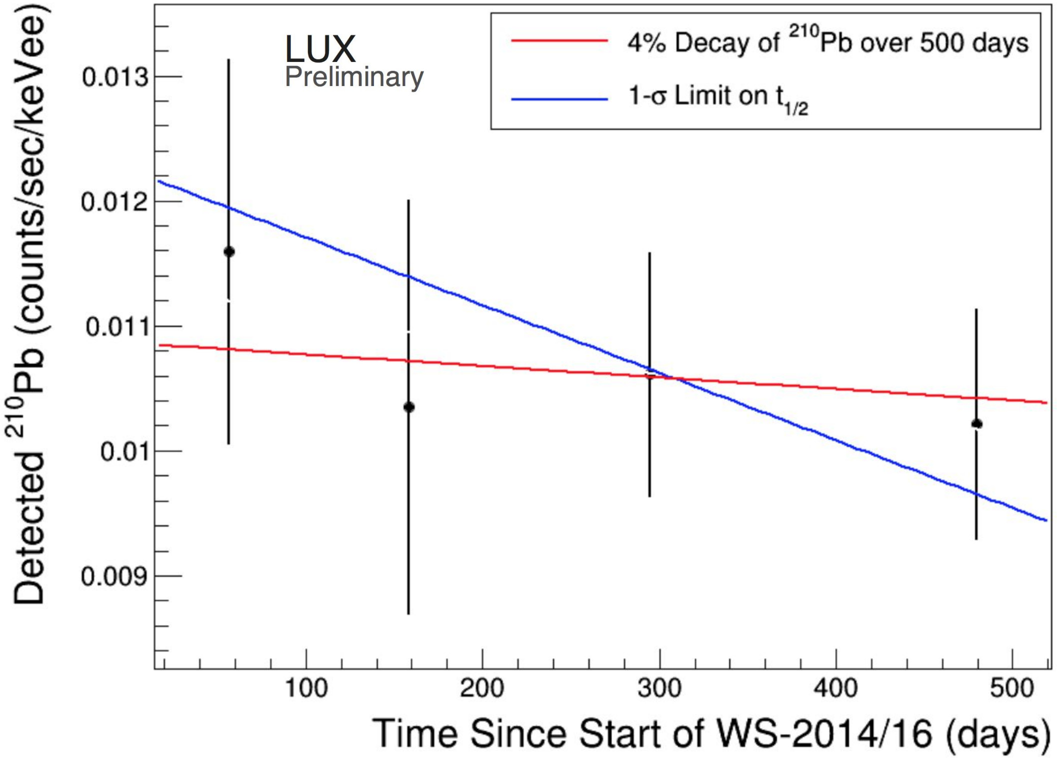




J.Low Temp.Phys. 176 (2014) no.5-6, 959-965

**Activity of $^{210}$Pb in fiducial volume < 0.099 µBq/kg**

LUX
Preliminary

# Leaching of $^{210}$Pb off Surfaces




- Activity of $^{210}$Pb was measured at four times during WS-2014/16
- If there is no leaching, $^{210}$Pb activity will decay by 4% over length of WS-2014/16
- Limit on decay constant for leaching of $^{210}$Pb from detector walls is given as the fit value less 1-**σ**, correcting for 4% $^{210}$Pb decay

**$t_{1/2}$ of $^{210}$Pb leaching off wall > 1.6 x $10^3$ days**

LUX
Preliminary

# Conclusion

- LUX published a limit on the spin independent WIMP-nucleon cross section for the complete exposure in Jan 2017
- Following the SI WIMP limit, LUX has worked on new dark matter analyses, such as:
  - Limits on spin dependent WIMP-nucleon elastic cross section
  - Limits on QCD solar axions and galactic axion-like particles
  - A search for an annual modulation in electron recoil data
  - Preliminary limits on sub-GeV dark matter-nucleus scattering using the Migdal effect and Bremsstrahlung
- LUX is continuing to explore the scope of dark matter models for which xenon time projection chamber detectors are competitive
- LUX is continuing to perform new calibration and analyses of radiogenic backgrounds to best inform future experiments such as LUX-ZEPLIN