The LUX/LZ Experiments

F. Neves on behalf of the LUX and LZ collaborations

Patras 2018, 18-22 June

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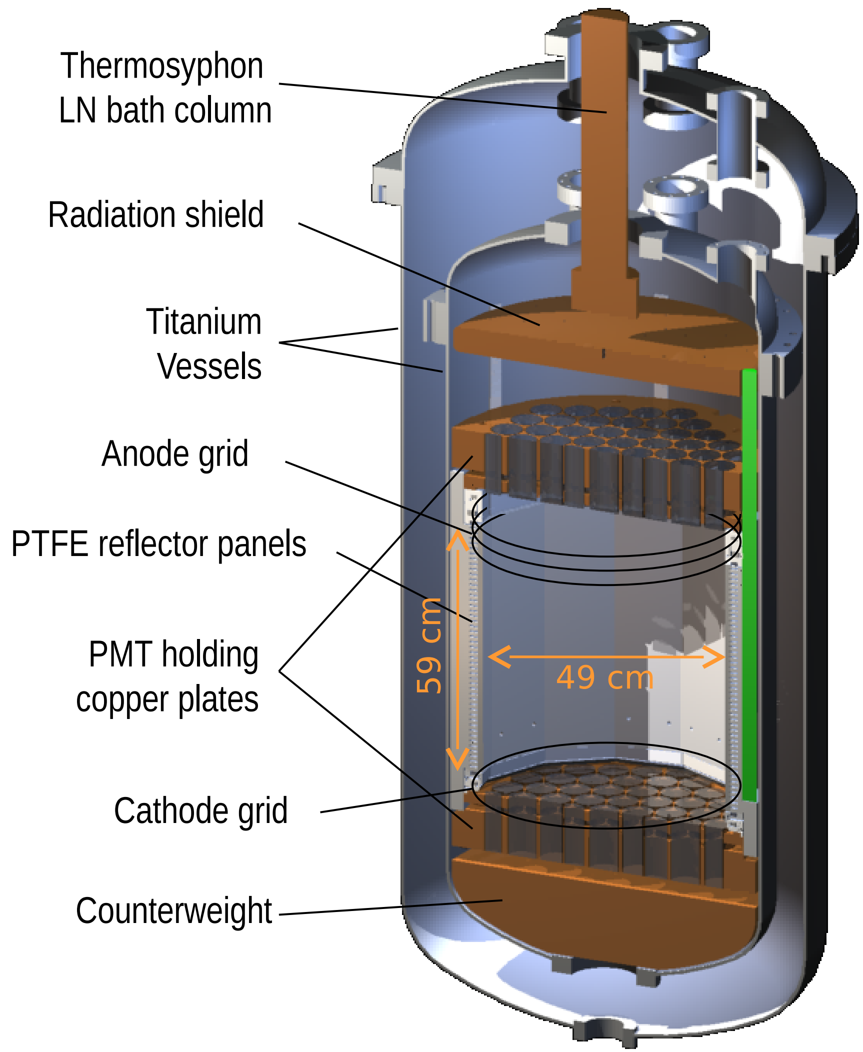
PTDC/FIS-NUC/1525/2014

Outline

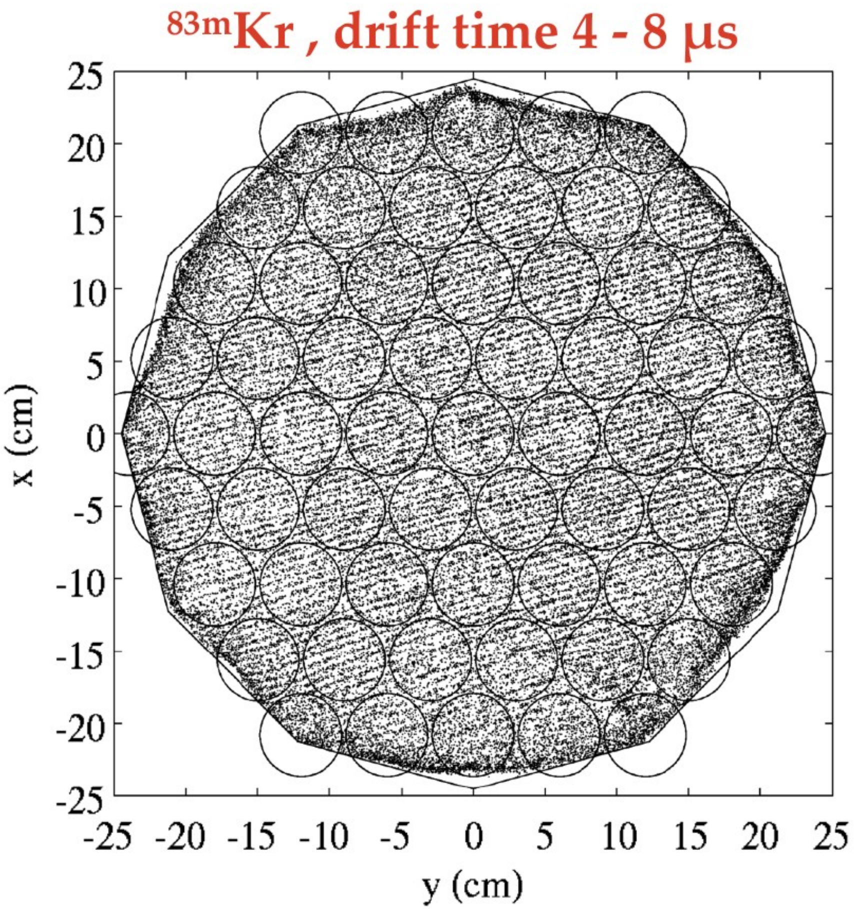
- LUX detector
  - Overview;
  - ER/NR calibrations;
  - Backgrounds;
  - WIMP search results;
  - Axions/ALPs search results;
  - Results from new (re)analysis pos-decommissioning.
- LZ Detector
  - Overview;
  - Calibrations;
  - Backgrounds
  - Sensitivity to WIMPs
  - Sensitivity to Axions/ALPs
  - Sensitivity to other physics.

LUX detector: overview



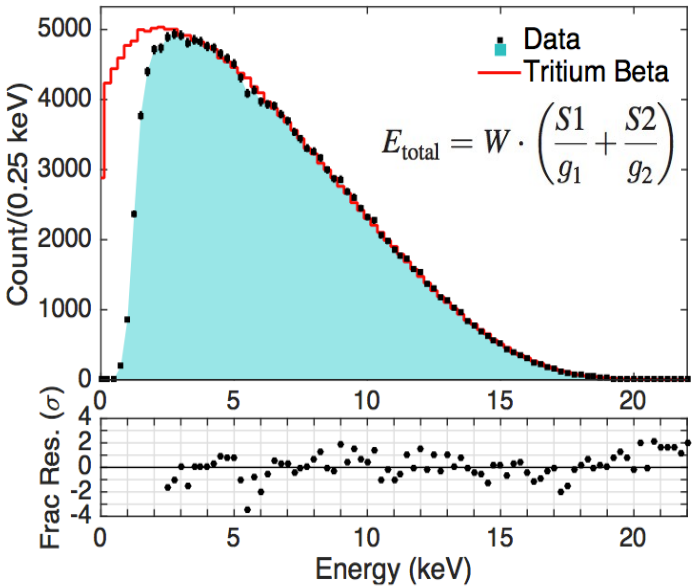
- **61 top + 61 bottom PMTs** viewing ~250 kg of xenon in the active region (~120 kg fiducial);
- **Ultra low background** PMTs (12 mBq/PMT);
- Titanium cryostat (<0.2 mBq/kg);
- Internal copper shield;
- Active region defined by **PTFE** slabs (high reflectivity for xenon scintillation light: >95%);
- Maximum drift time: 50 cm;
- Xenon continuously recirculated to maintain purity (~250 kg/day)
- Chromatographic separation reduced Kr content to ~4 ppt.
- Inside 300 tonne water tank: all external backgrounds subdominant.

Calibrations (ER): ^{83m}Kr

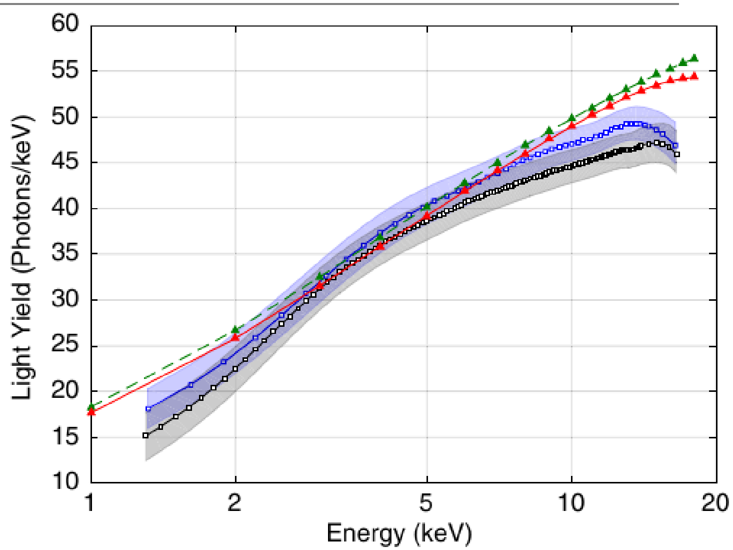


- ^{83m}**Kr** was **injected** ~weekly into the detector to **characterize detector response** and **monitor stability**;
- Quickly mixes in the xenon, producing an **uniform distribution** of events;
- 2 IT gammas in quick succession;
  - 32.2 keV + 9.4 keV ($T_{1/2}$ = 154 ns)
  - **Mono energetic** for our standard analysis
- 1.8 hours half-life
  - Clears the system in a few hours
- Used for:
  - Overall stability monitoring;
  - Position reconstruction;
  - Electron lifetime;
  - S1 and S2 position corrections;
  - Electric field modeling.

Calibrations (ER): Tritium

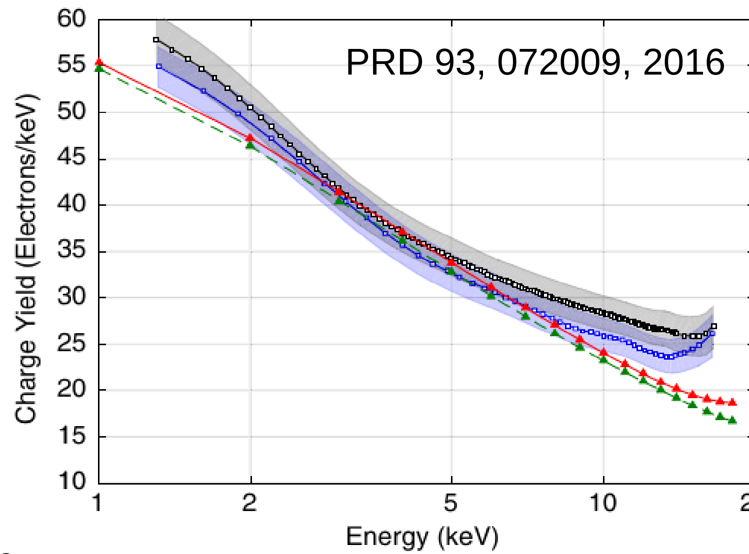


- Tritium (CH_3T) has a low energy β decay:
  - Q = 18.6 keV, <E> = 5.9 keV:
  - **overlaps with the energy ROI for WIMPs**;
  - ideal to study the response of the detector to electron recoils;
- **used to determine the ER band**;
- Long half-life (12.3 yr):
  - CH_3T removed by purity system (T1/2 ~6 hours);
- Injected every three months.

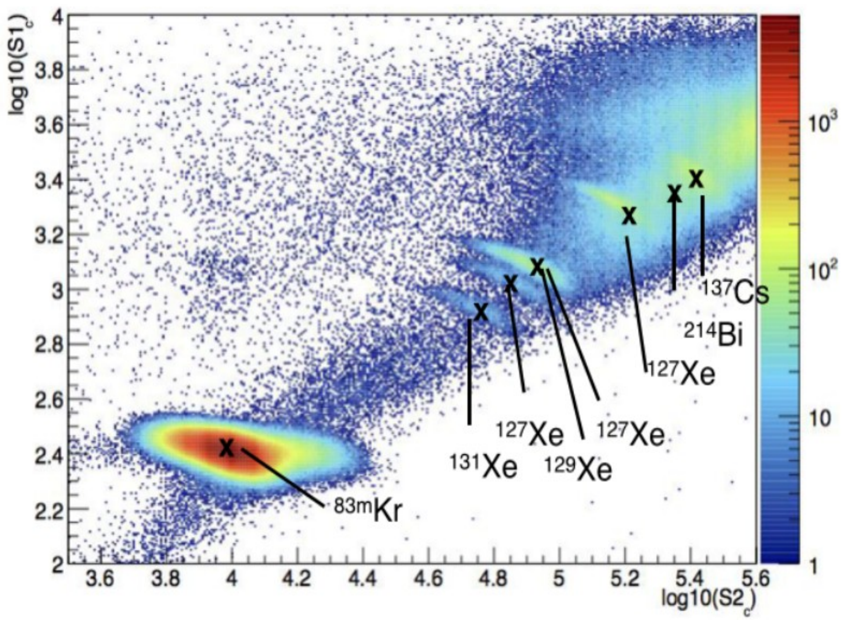


LUX data:
■ 180 V/cm
■ 105 V/cm

NEST v0.98:
▲ 180 V/vm
▲ 105 V/vm



Calibrations (ER): all available



Compilation of LUX line source calibration data:

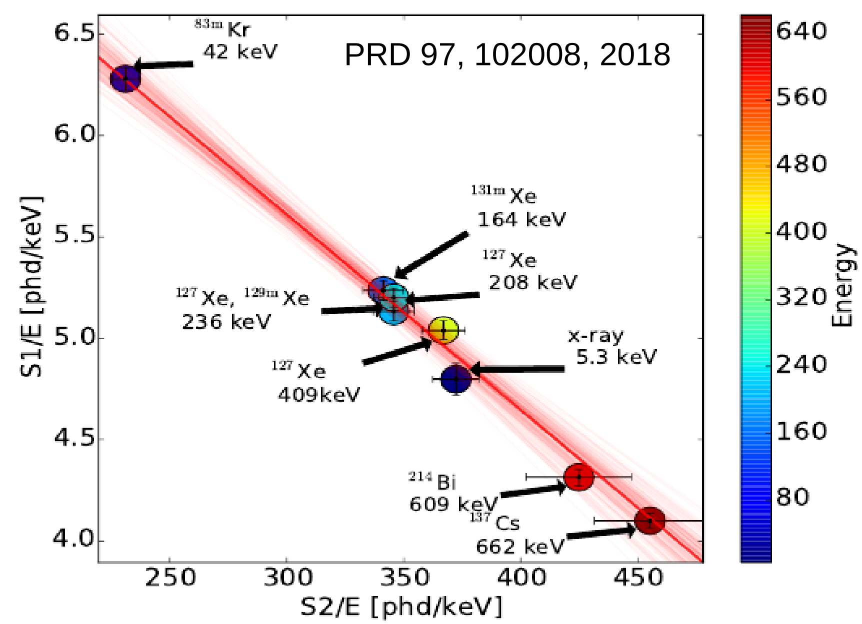
- ^{83m}Kr and ^{137}Cs data were collected during dedicated calibration runs;
- All other lines were present in the low background WIMP search data:
  - ^{127}Xe, ^{129}Xe and ^{131}Xe are of cosmogenic origin and were only present early in Run 3.

Extracted $\mathbf{g_1}$ and $\mathbf{g_2}$ in the energy range from **5.3 keV** (X-ray from ^{127}Xe) to **662 keV** (γ from ^{137}Cs):

$$E_{\text{total}} = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right),$$

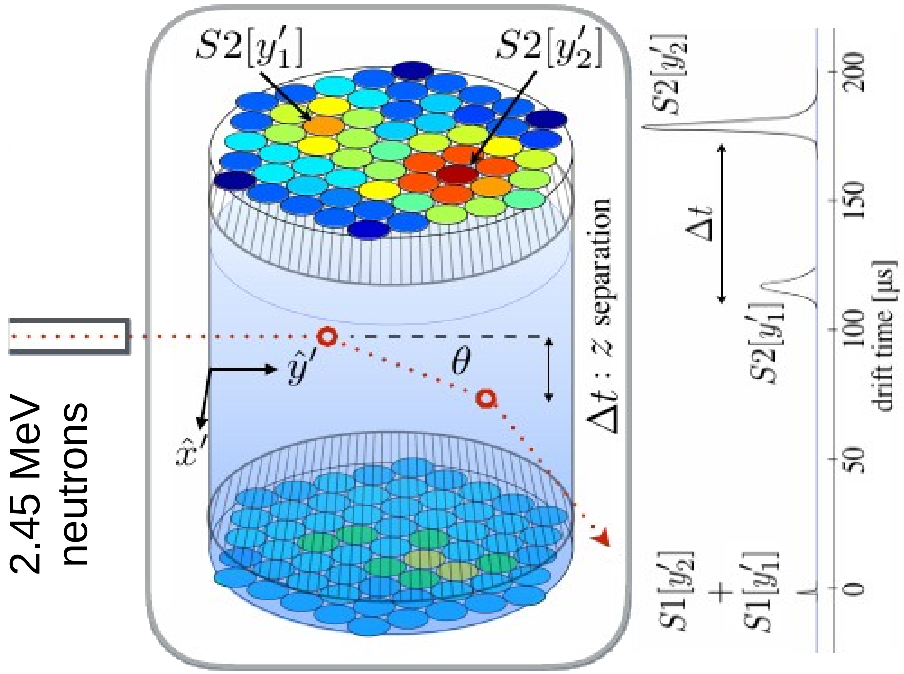
$\mathbf{g_1 = 0.117 \pm 0.003}$

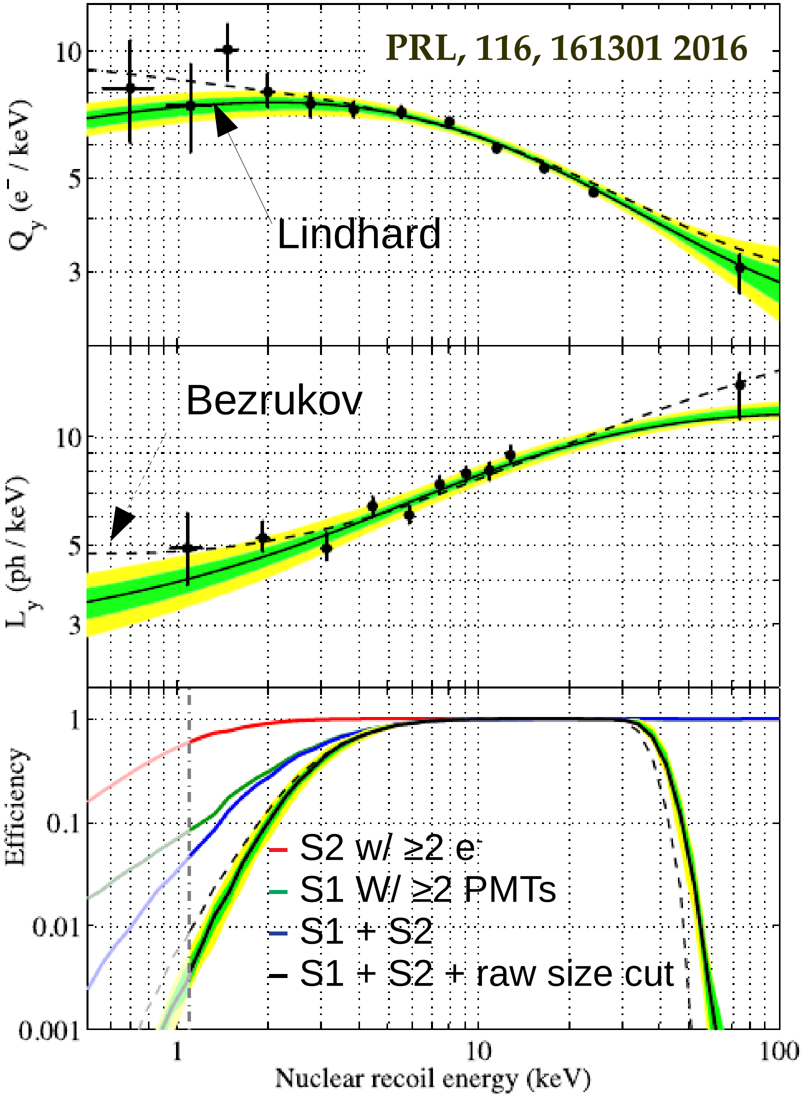
$\mathbf{g_2 = 12.1 \pm 0.8}$



Calibration (NR): DD

- DD neutron generator (2.45 MeV) outside water tank
- NR calibrations every 3 months (different levels);
- Double-scatters used for $\mathbf{Q_y}$ analysis (**0.7 - 74 keV**);
- Single-scatters used for $\mathbf{L_y}$ analysis and **NR band characterization** (**1.1 - 74 keV**).





LUX Backgrounds

Best fit parameters for the various **background populations** in the correspondent WS2013 and WS2015-16 **PLR analysis**:

- Unlike the WS2013, ^{127}Xe and ^{37}Ar are no longer present in the WS2015-16 run
- After WS2015-26, updating the **background model at higher energies** (EFT analysis).

Background source	WS2013	WS2015-16
gamma rays	228 ± 19	590 ± 34
Internal betas	84 ± 15	499 ± 39
^{127}Xe	78 ± 12	–
^{37}Ar	12 ± 8	–
Rn plate out (wall background)	22 ± 4	12 ± 3
Accidental S1-S2 coincidences	~1.1	0.34 ± 0.10
Solar ^{8}B neutrinos (CNNS)	~0.1	0.16 ± 0.03
neutrons	0.08 ± 0.01	~0.3

In the bulk, leakage at all energies in the NR band

Low energy but low likelihood because limited to the edge of the detector (PLR uses position information)

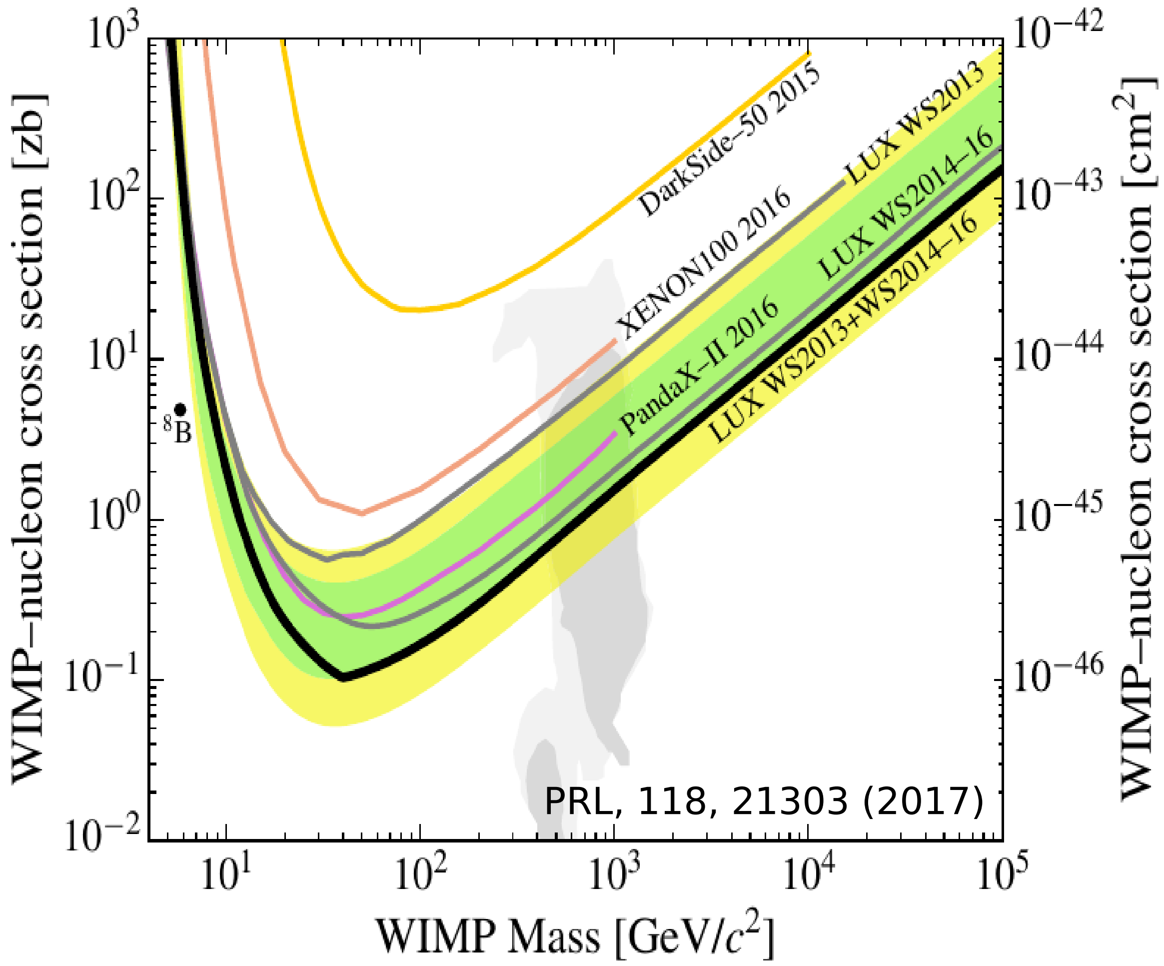
In the bulk, at low energy in the NR band

Not Included in PLR

PRL, 116, 161301 2016 **PRL, 118, 21303 (2017)**

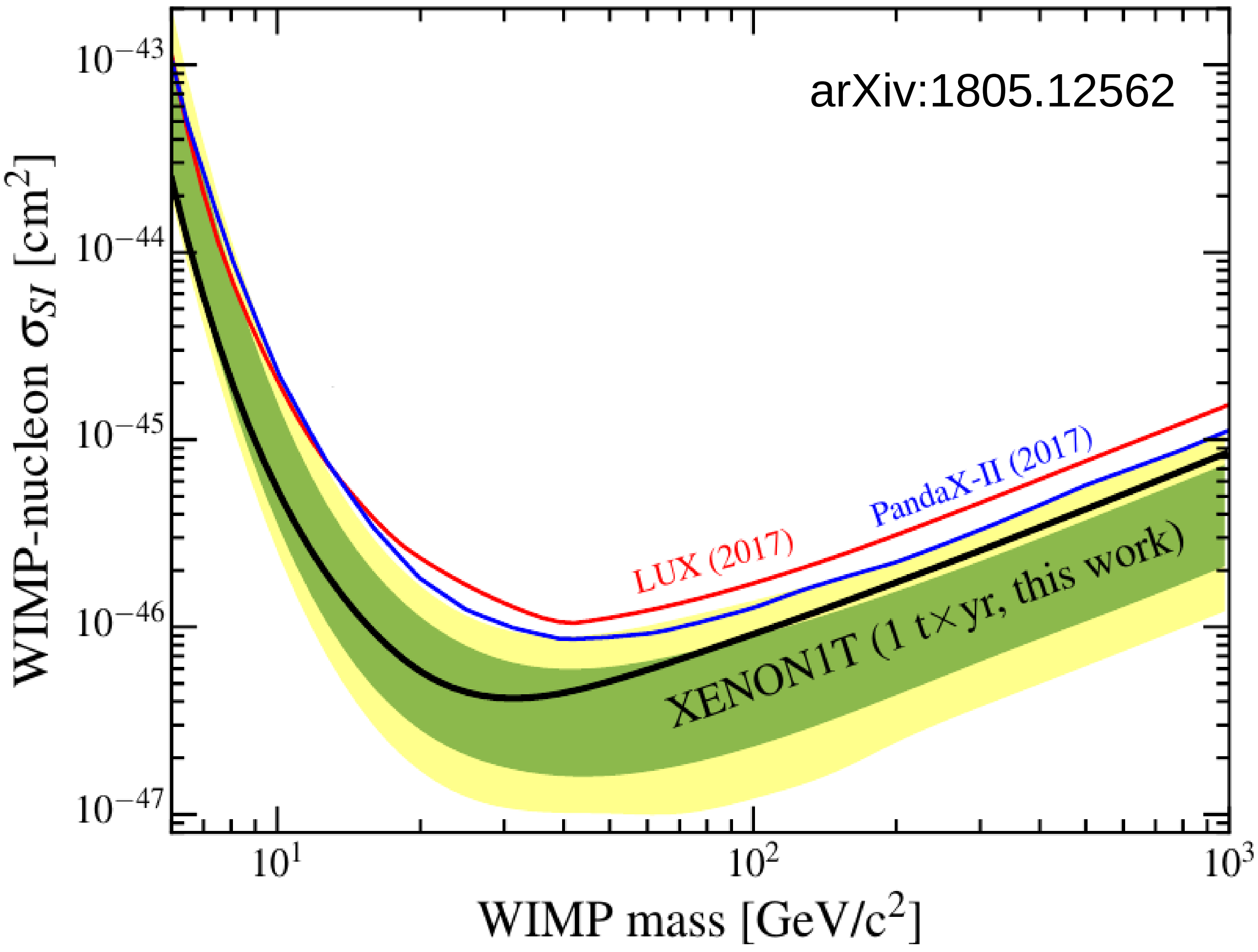
The SI Limit (combined)

WIMP-nucleon Spin-Independent (SI) exclusion limit (PLR analysis) of **1.1 x 10^{-46} cm^2** at **50 GeV c^{-2}** using the combined exposure of **3.35 x 10^4 kg.day** from 2 WIMP Search runs:



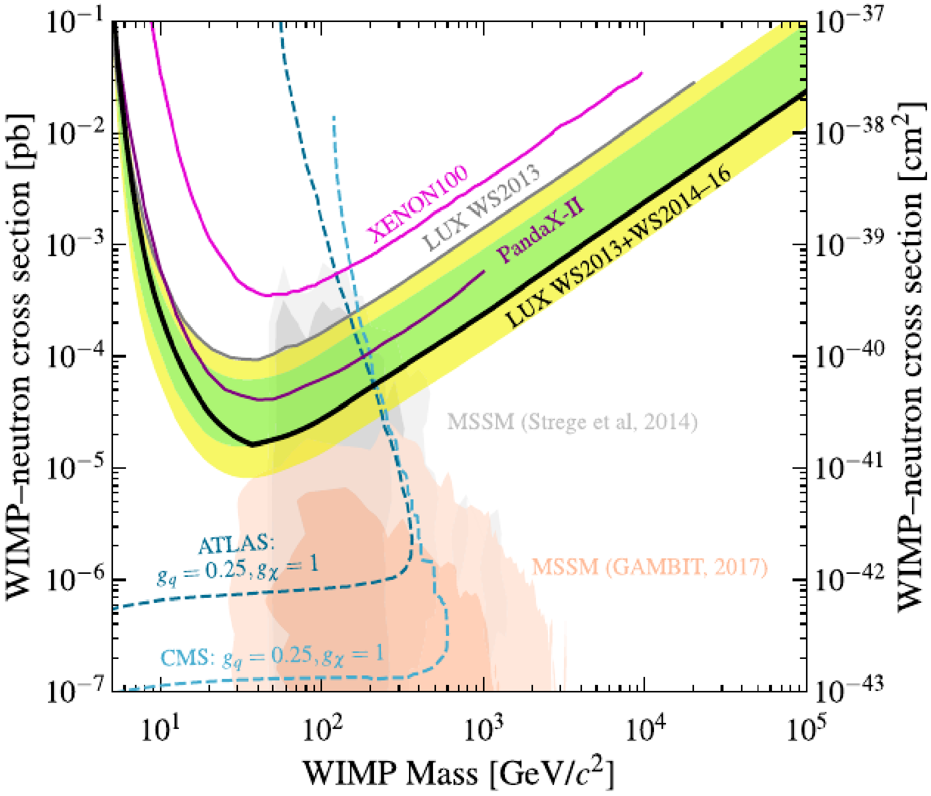
- **WS2013**: 95 live-days;
- **Calibrations** campaign, including new DD (n) and Tritium (β);
- **Grids *conditioning*** campaign
  - New operation voltages;
  - Improved electron extraction efficiency to (73±4)%;
- **Calibrations** campaign at the new operation conditions;
- **WS2015-16**: 332 live-days;
- **Calibrations** campaign, including new calibration sources;

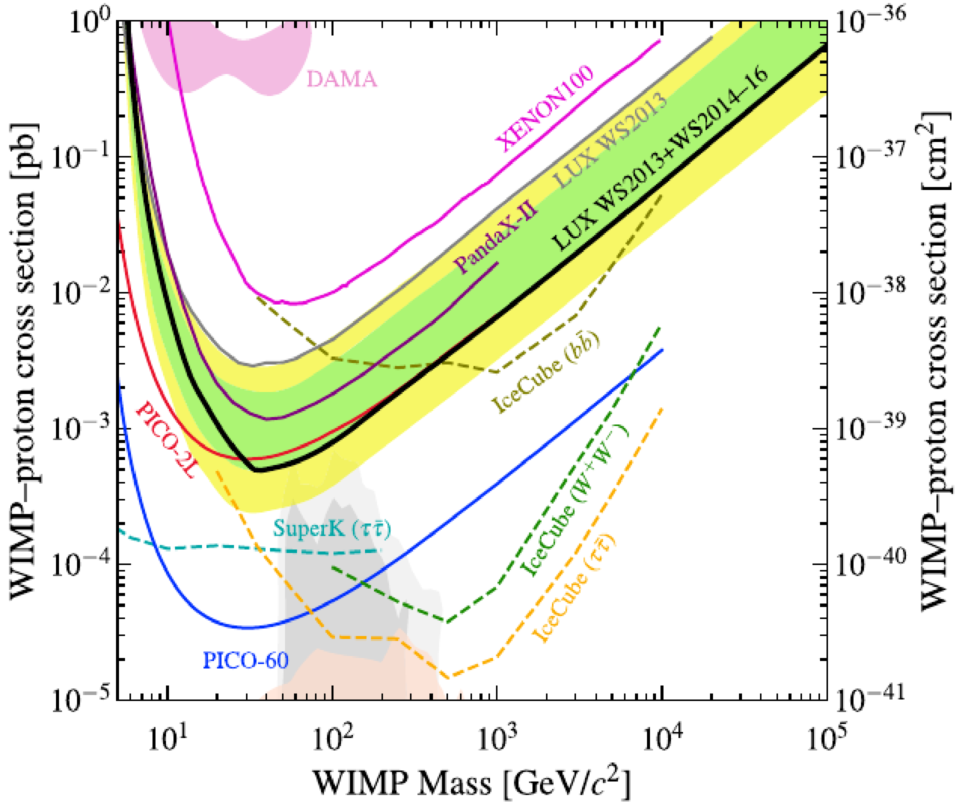
(Very) recent results from XENON-1T



The SD Limit (combined)

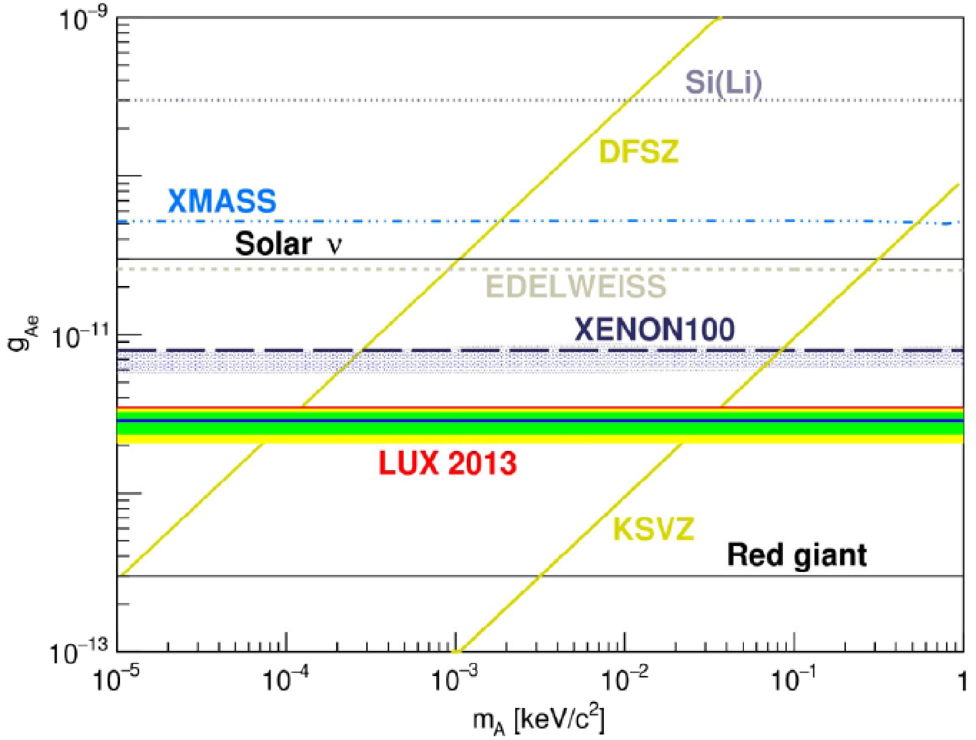
WIMP-nucleon Spin-Dependent (SD) exclusion limit (PLR analysis) of σ_n = **1.6 x 10^{-41} cm^2** and σ_p **= 5 x 10^{-40} cm^2 at 35 GeV c^{-2}** using the combined exposure of the 2 WIMP Search runs (SW2013, WS2015-16).



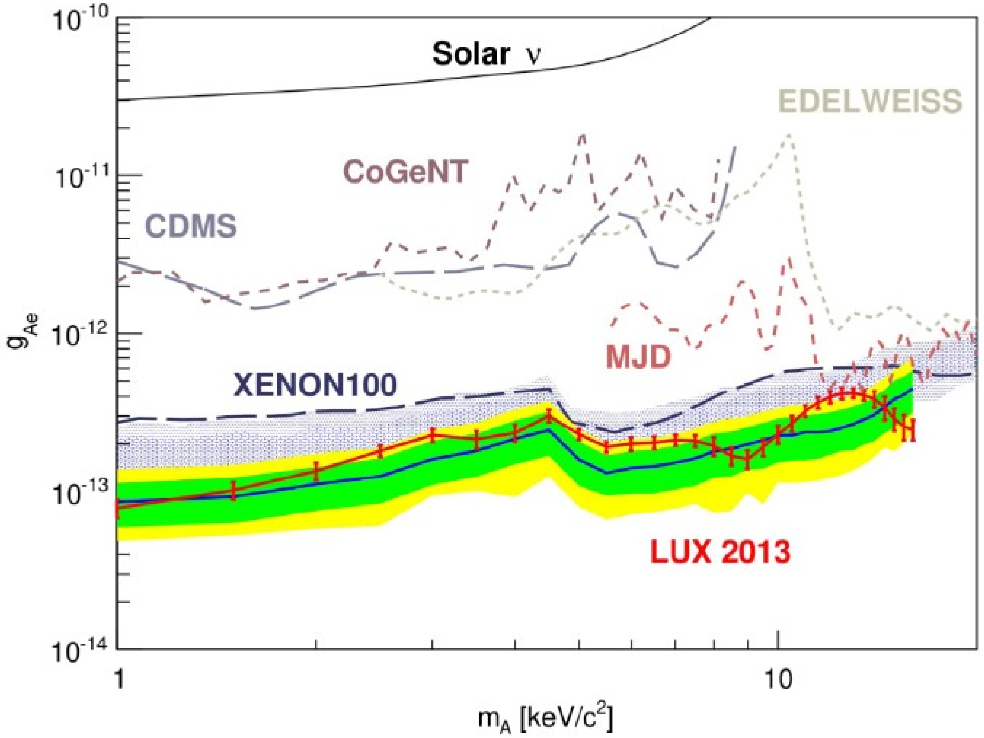


Limits for Axions and ALPs

Axions



ALPs

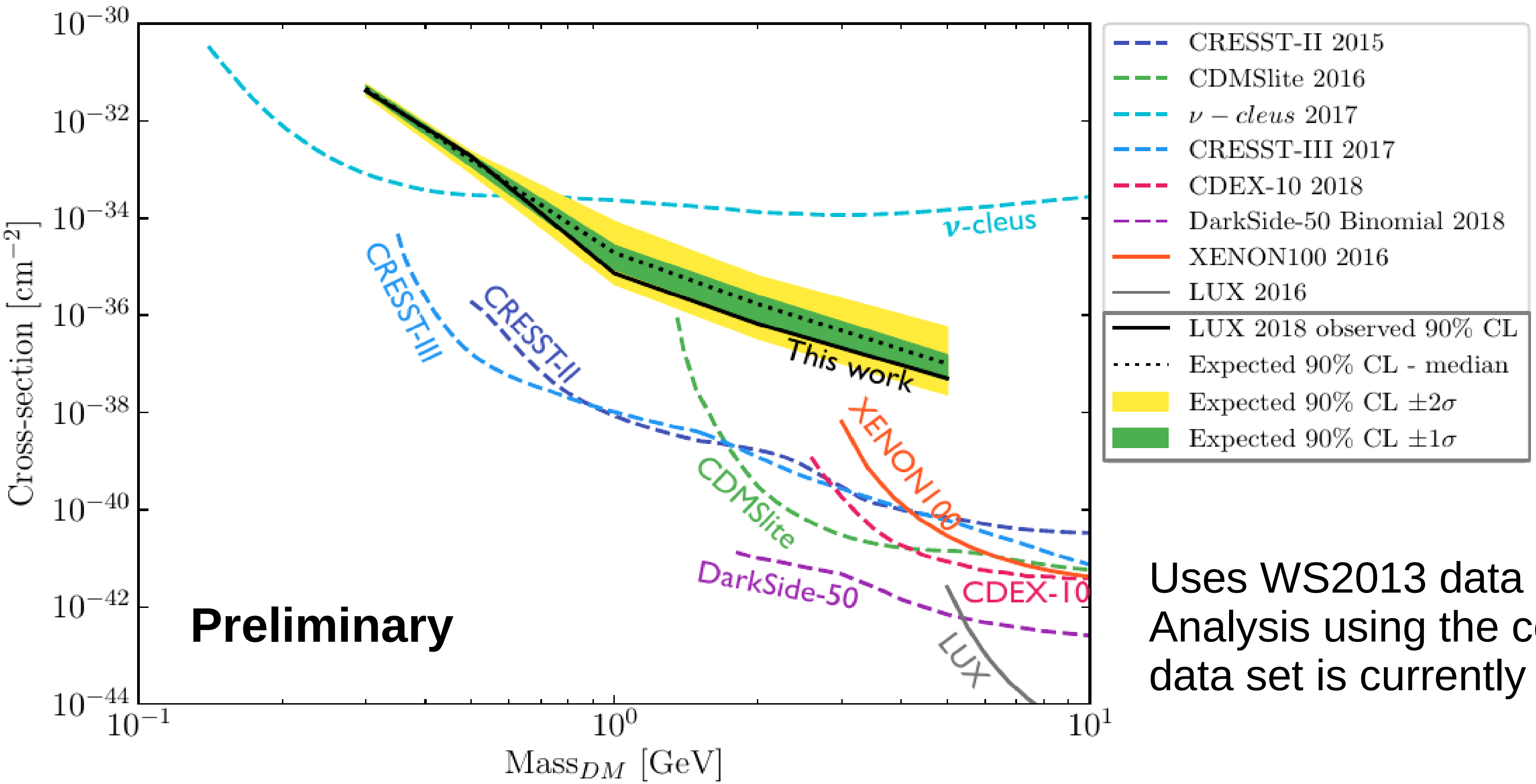


- LUX (2013) excludes $\mathbf{g_{Ae} > 3.5 \times 10^{-12}}$ (90% CL)
  - $\mathbf{m_A > 0.12\ eV/c^2}$ (DFSZ model)
  - $\mathbf{m_A > 36.6\ eV/c^2}$ (KSVZ model)
- LUX (2013) excludes $\mathbf{g_{Ae} > 4.2 \times 10^{-13}}$ (90% CL) across the range **1-16 keV/c²** in ALP mass

PRL 118, 261301 (2017)

Post WS2015-16:
Sub-GeV WIMP sensitivity

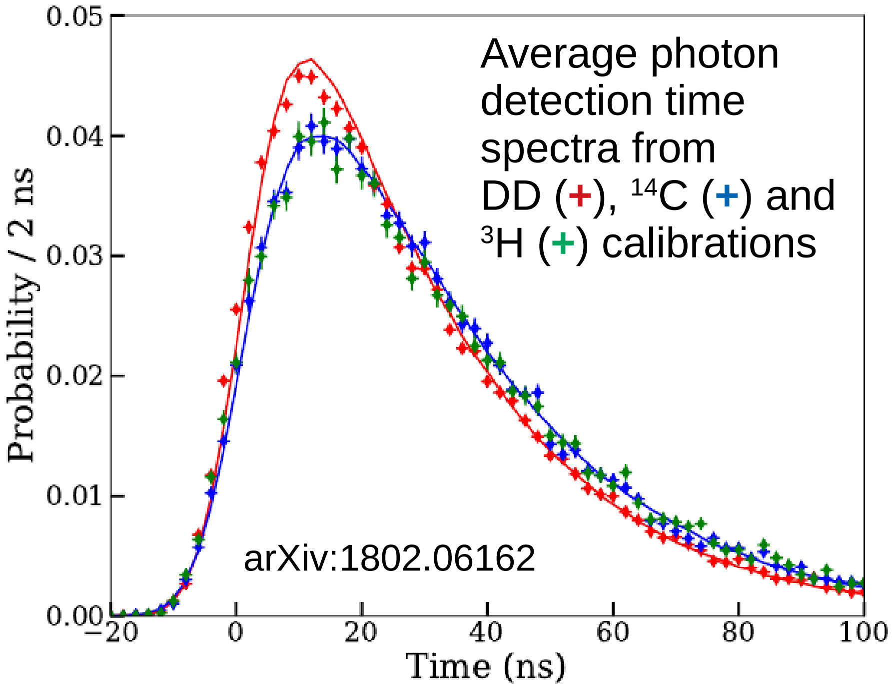
- WIMP-nucleon interaction, but **electron recoil** signal (PRL 118, 031803 2017):
  - Emission of a **Bremsstrahlung photon** from a polarized xenon atom;
  - Gain access to low energy NR interactions by looking for this ER signature;
  - Improved detection efficiency (ER have lower threshold then NR);
  - **LUX gain sensitivity to ~ 0.3 GeV WIMPs !**



Uses WS2013 data only.
Analysis using the complete data set is currently underway!

Pos-WS2015-16: Pulse shape ER/NR discrimination

- Developed a template-fitting method to **reconstruct the detection times of photons.** The model for the photon detection time takes into account:
  - The properties of the **xenon scintillation** (i.e. singlet and triplet emission);
  - Photon **optical transport** (e.g. reflection at the PTFE walls, etc);
  - **Electronics response** (e.g. photoelectrons transit time, cables delay);



Simulated NR/ER time spectra using best fit parameters: DD (▬), ^{14}C (▬) and ^{3}H (▬)

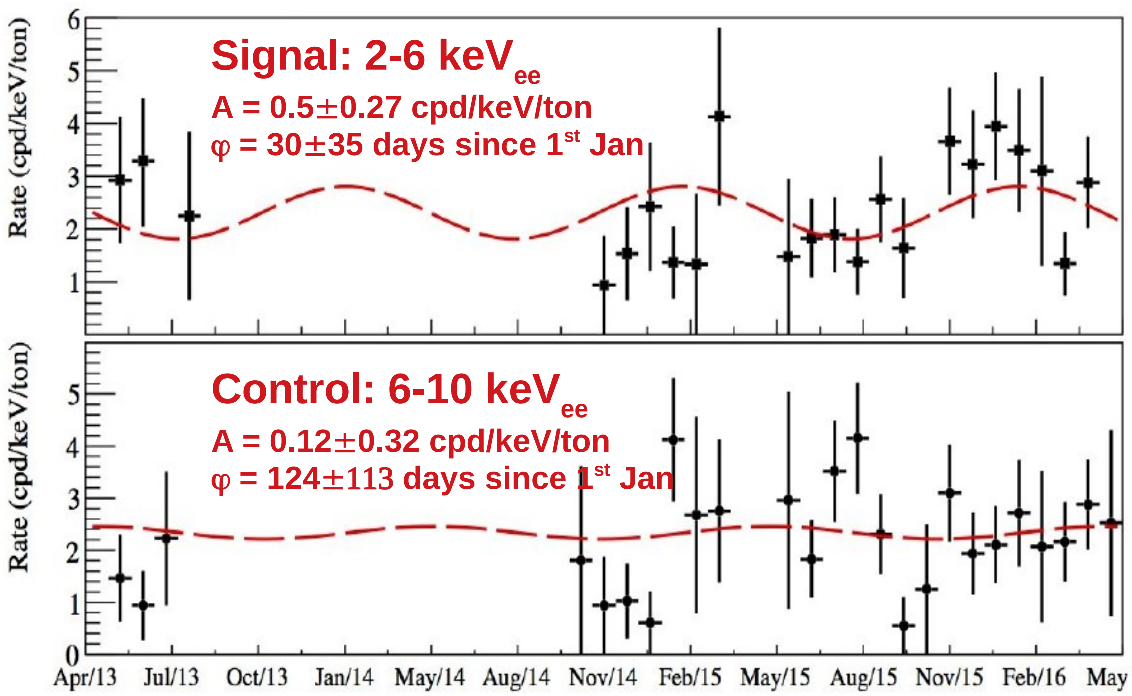
- singlet-to-triplet scintillation ratio for ER (<46 keV): 0.042 ± 0.006
- **1st-ever** measurement of the **NR singlet-to-triplet ratio** (Er < 74 keV): **0.269 ± 0.022**
- The model was used to optimize a **prompt fraction discrimination** parameter:

For the WS2013 and WS2014-16, the **ER leakage**, measured using the log(S2/S1) discriminator, is **0.4 ± 0.1%** and reduces to **0.3 ± 0.1 %, when also using the pulse discriminator.**

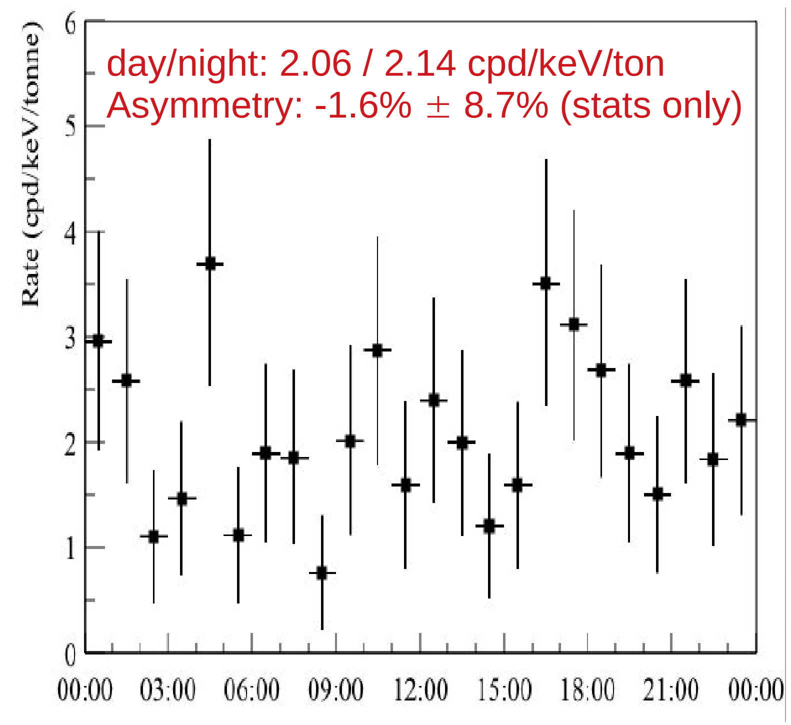
Pos-WS2015-16: Annual / Diurnal modulation

- **No significant annual or diurnal modulation** features are identified;
- LUX result consists of the world's **most sensitive** modulation searches so far;

Annual (Preliminary)



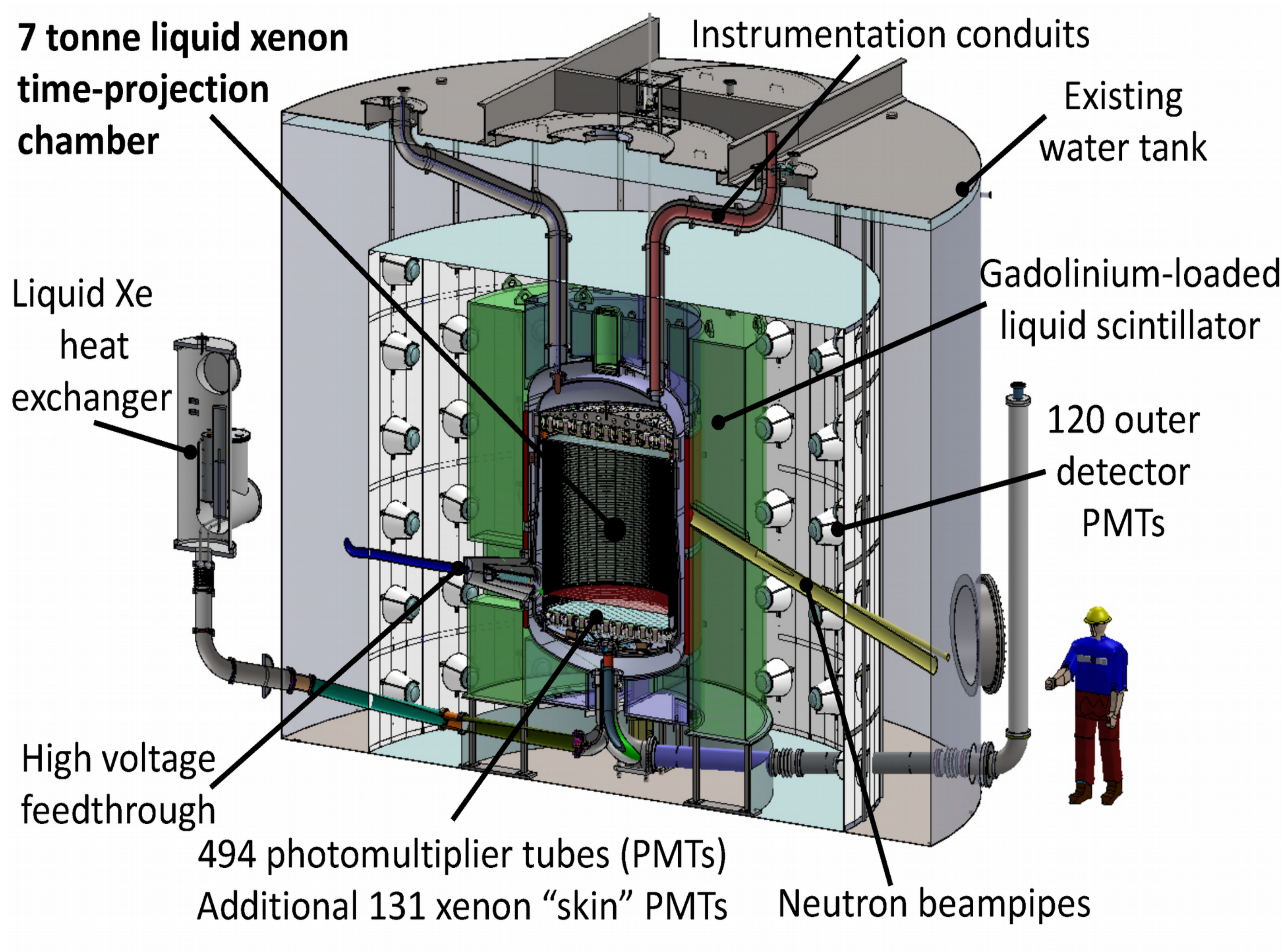
Diurnal (Preliminary)



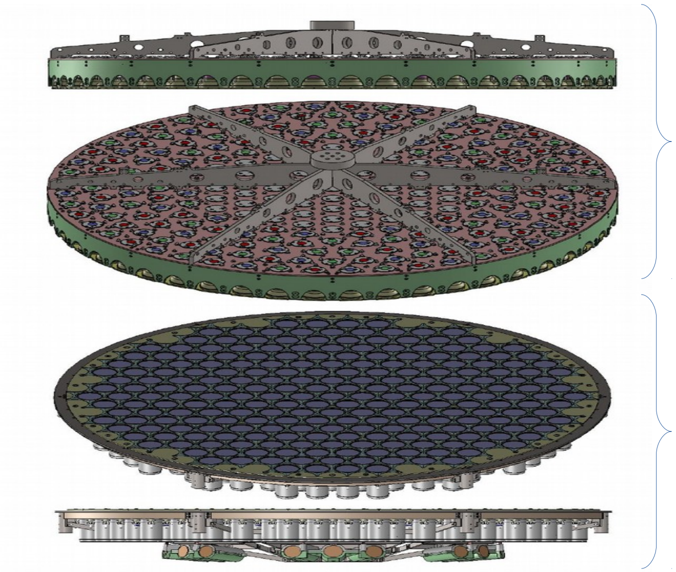
- ~2 cpd/keV/tonne, **40x lower than DAMA**;
- Best fits using unbinned extended maximum likelihood;
- Control region event can be fully explained as background.

The LZ Detector details

- 10 tonnes of LXe:
  - 7 ton active;
  - **5.6 fiducial**;
- Will be installed in the same laboratory used for **LUX** and inside the **same water tank**;
- 494 PMTs (in the TPC) acquired in dual-gain;
- Gadolinium-loaded liquid scintillator veto;
- Instrumented skin region (additional veto)



The LZ Detector: light collection



TOP PMT array
241 3'' PMTs arranged in a hexagonal configuration

Bottom PMT array
253 3'' PMTs arranged in a hexagonal-circular configuration to maximize light collection

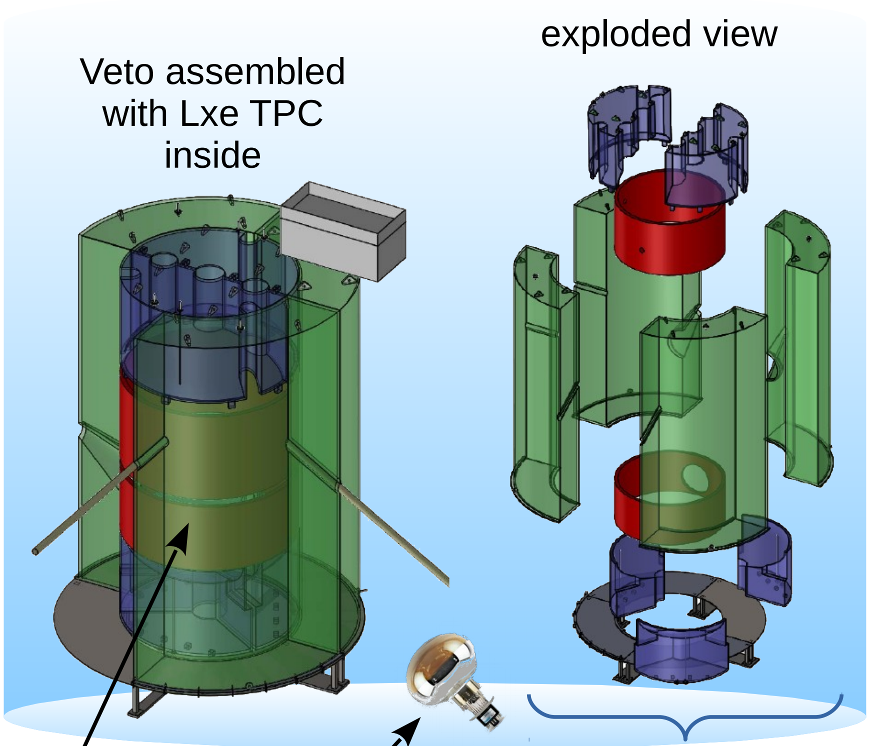
3-inch Hamamatsu R11410 PMT

Property	Baseline	Optimistic
PTFE reflectivity - liquid	95%	97%
PTFE reflectivity - gas	80%	85%
Average PMT QE	25%	28%
Grid reflectivity (liquid and gas)	20%	40%
Absorption length in liquid (m)	30	100
FV-averaged S1 PDE (α_1)	8.5%	13.3%

	Diffuse + Specular model (DS)		
	A	n_{PTFE}	BHR
807NX	0.961 (>0.955)	1.73	0.961 (>0.955)
NXT85	0.975 (>0.973)	1.8	0.975 (>0.973)
LUX	0.978 (>0.975)	1.79	0.978 (>0.975)

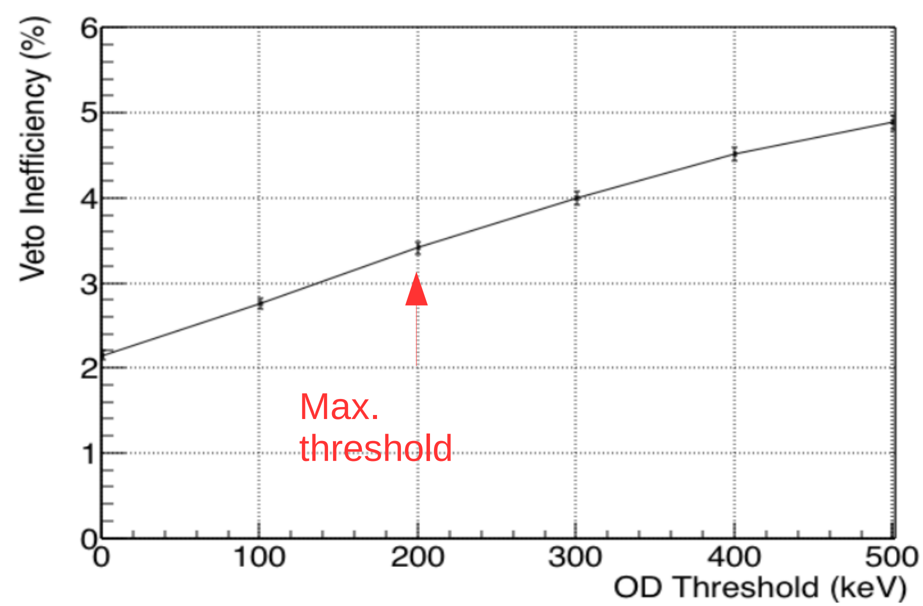
BHR – **B**i-**H**emispherical **R**eflectance.
A – **A**lbedo.

The LZ Outer Detectors



3 independent outer detectors (vetos), for γ with energies in the few MeV range and neutrons from (α,n) reactions or created by cosmic-ray interactions:

- The instrumented "skin" of LXe outside the LXe TPC;
- Gd-loaded liquid scintillator (LAB) acrylic sections;
  - 7% light collection efficiency (130 PE @ 1MeV).
- Surrounding water tank (muon veto);



The LZ Detector: calibration

- A rigorous calibration is mandatory for an unambiguous claim of direct detection of any hypothetical dark matter candidate:

Baseline Calibration sources:

Isotope	What	Purpose	Deployment
Tritium	β, Q = 18.6 KeV	ER band	Internal
^{83m}Kr ^{131m}Xe	β/γ, 32.1KeV and 9.4 KeV γ, 164keV	TPC (x,y,z), Xe skin	Internal
^{220}Rn	α's, various	Xenon skin	internal
AmLi	(α,n)	NR band	CSD
^{252}Cf	Spontaneous fission	NR efficiency	CSD
^{57}Co ^{228}Th ^{22}Na	γ, 122 keV γ, 2.615 MeV, etc 511 keV	Energy scale, TPC, OD sync	CSD
^{88}YBe ^{205}BiBe ^{206}BiBe	n, 152 keV n, 88.5 keV n, 47 keV	Low energy NR response	External
DD	n, 2.450 keV n, 272 keV	NR light and charge yields	External

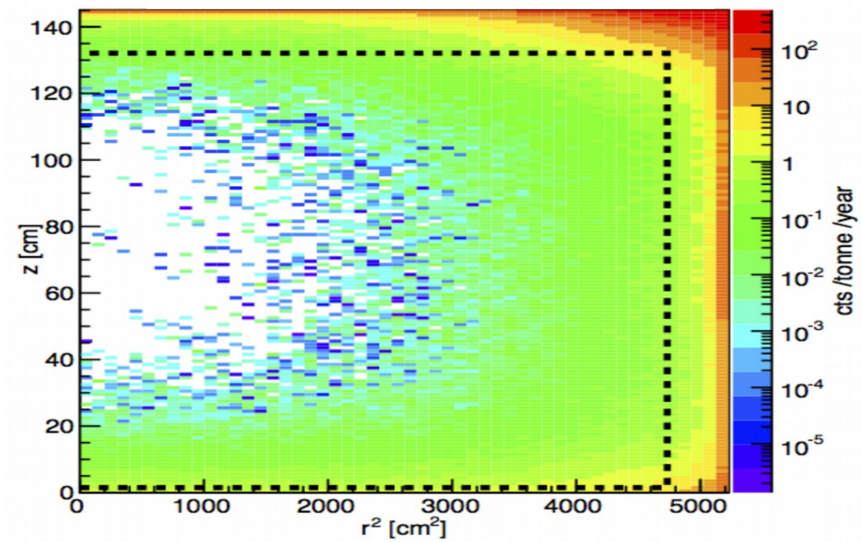
LZ backgrounds

Background source	RE cts	NR cts
Detector components	9	0.07
Dispersed radionuclides (Rn, Kr, Ar)	816	–
Laboratory and cosmogenic	5	0.06
Surface contamination and dust	40	0.39
^{136}Xe $2\upsilon\beta\beta$	67.0	–
Neutrinos (υ-e, υ-A)	255	0.72
Total	**1192**	**1.03**
Total (99.5% ER desc., 50% NR eff.)	**5.96**	**0.51**
Total ER+NR background events	**6.48**	

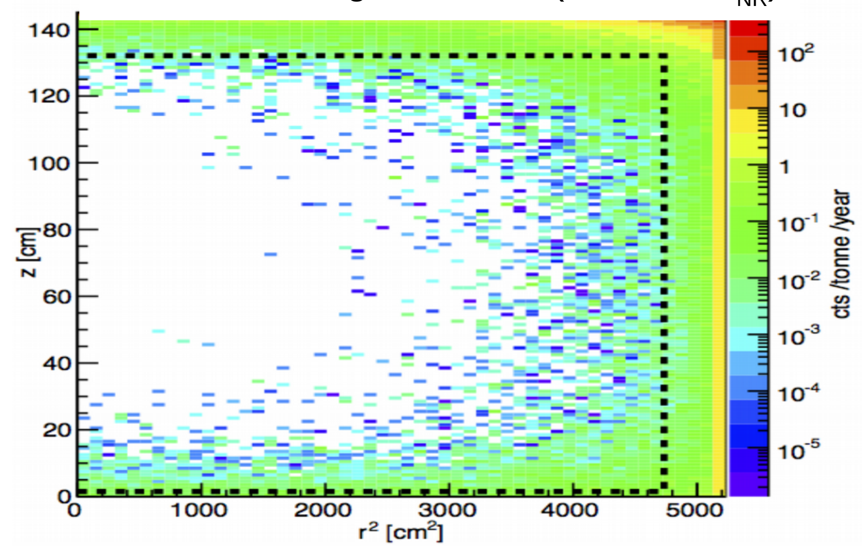
signal-like background events in 1000 live-days

- Largest contribution comes from **Rn**, Followed by **ν-e** solar neutrino scattering and atmospheric **ν-A** scattering;

NR + ER leakage (6 - 30 keV_{NR})

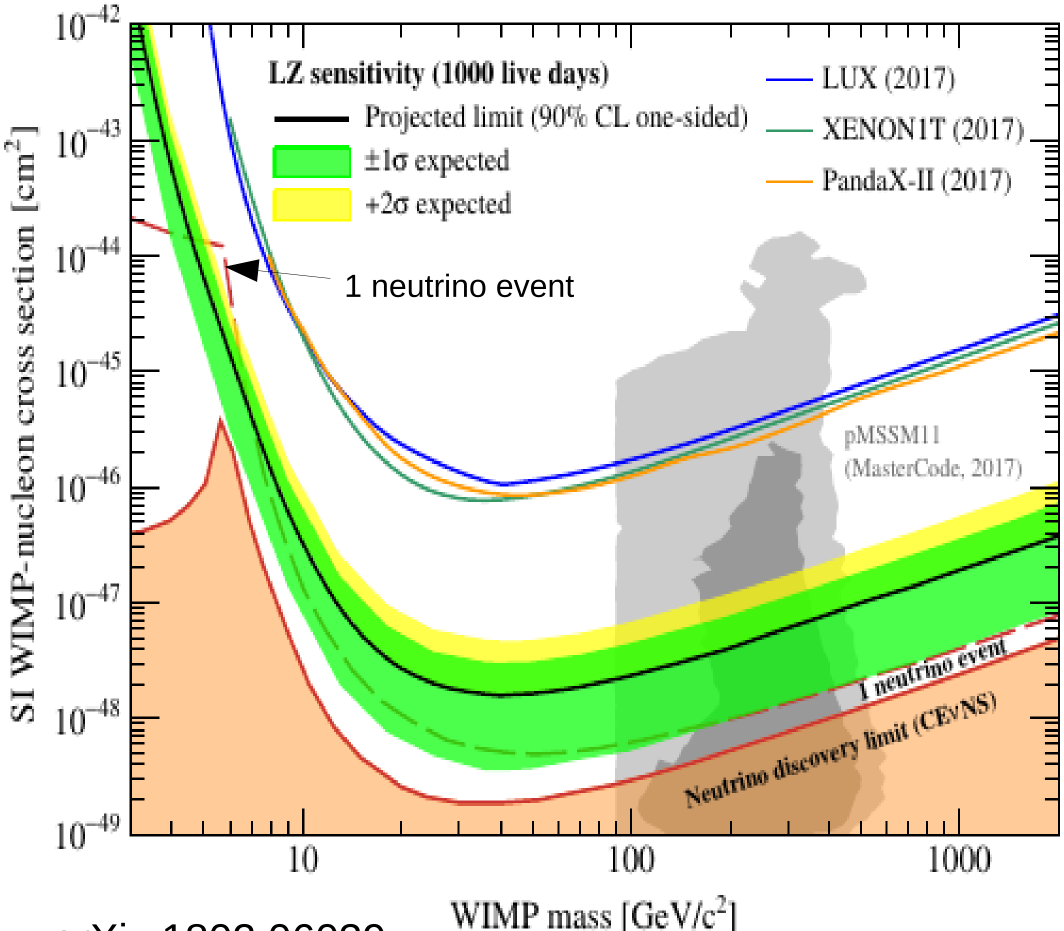


NR + ER leakage + vetoes (6 - 30 keV_{NR})



LZ sensitivity to WIMPs (SI)

WIMP-nucleon Spin-Independent (SI) exclusion limit (PLR analysis) of **1.6×10^{-48} cm²** at **40 GeV c⁻²** for **1000 days run and 5.6 tonne** fiducial mass:



arXiv:1802.06039

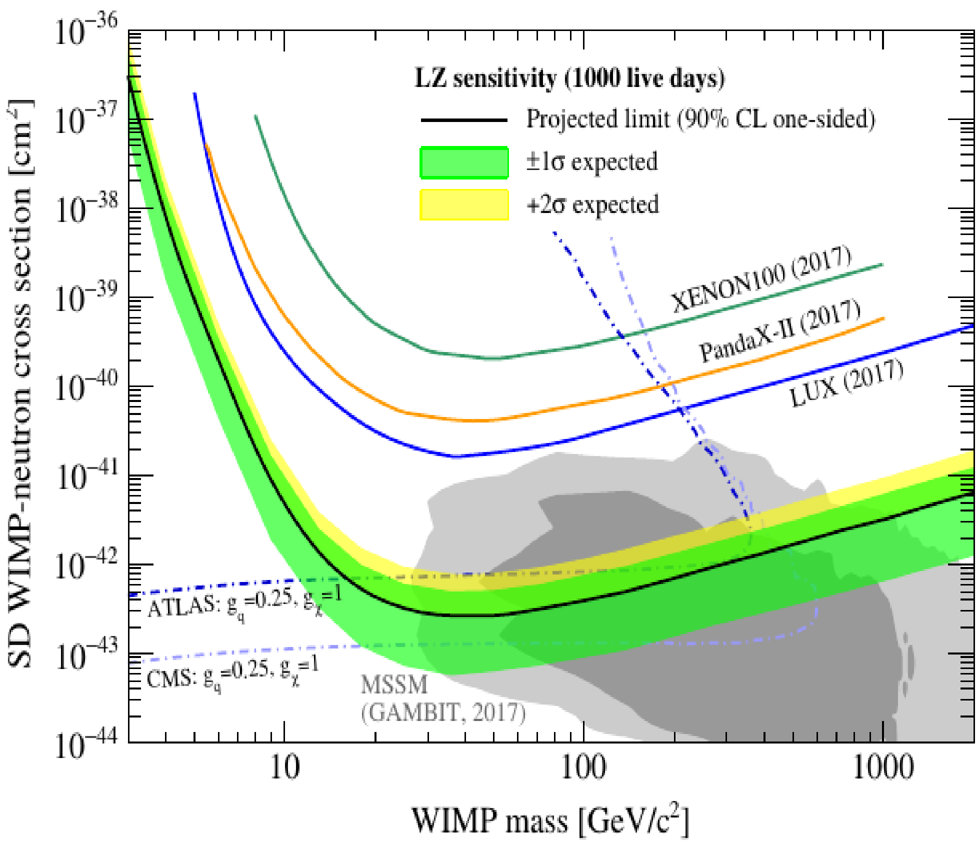
MC detector parameters

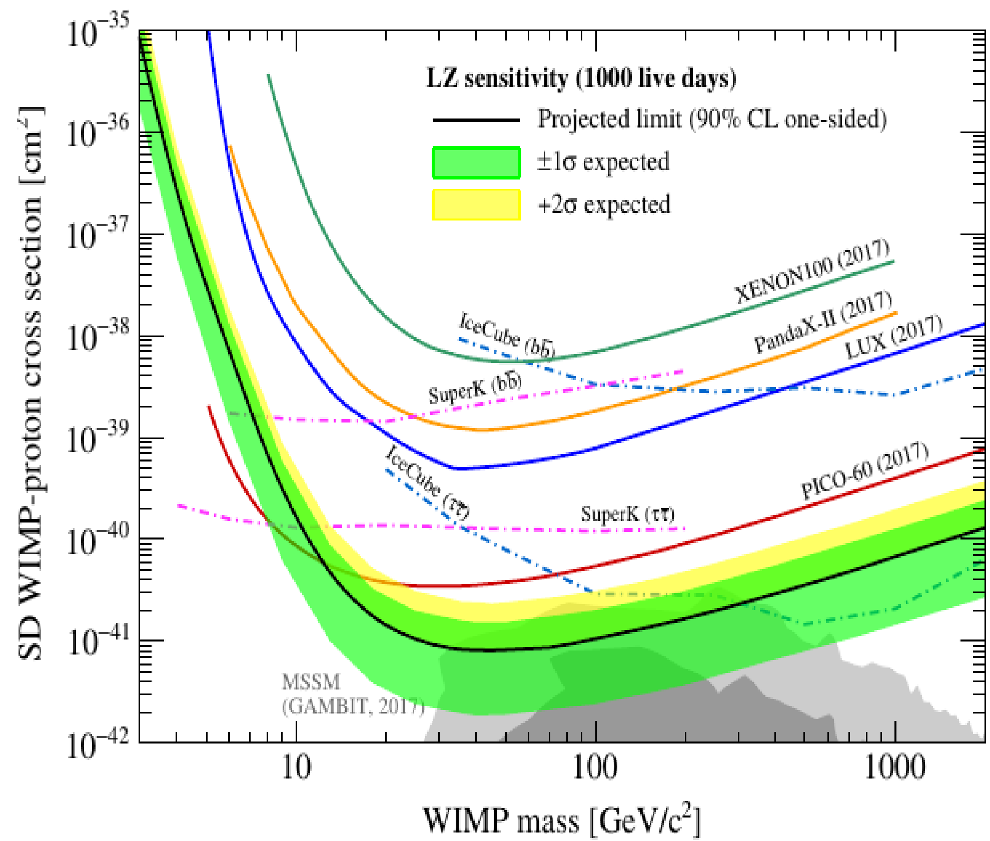
Photon detection efficiency (PDE)	
PDE in liquid (g_1) [phd/ph]	0.119
PDE in gas ($g_{1,gas}$) [phd/ph]	0.102
Single electron size [phd]	83
Eff. Charge gain (g_2) [phd/e]	79
PTFE-LXe reflectivity	0.977
LXe Photon absorption length [m]	100
PMT efficiency at 175 nm	0.269
Other key parameters	
Single phe trigger efficiency	0.95
Single phe relative width	0.38
S1 coincidence level	3-fold
S2 electron extraction efficiency	0.95
Drift field [Vcm^{-1}]	310
Electron lifetime [μs]	850

LZ sensitivity to WIMPs (SD)

WIMP-nucleon Spin-Dependent (SD) exclusion limit (PLR analysis) of **σ_n = 2.7 x 10^{-43} cm^2** and **σ_p = 8.1 x 10^{-42} cm^2 at 40 GeV c^{-2}** for a run of **1000 days and 5.6 tonne** fiducial mass.

arXiv:1802.06039



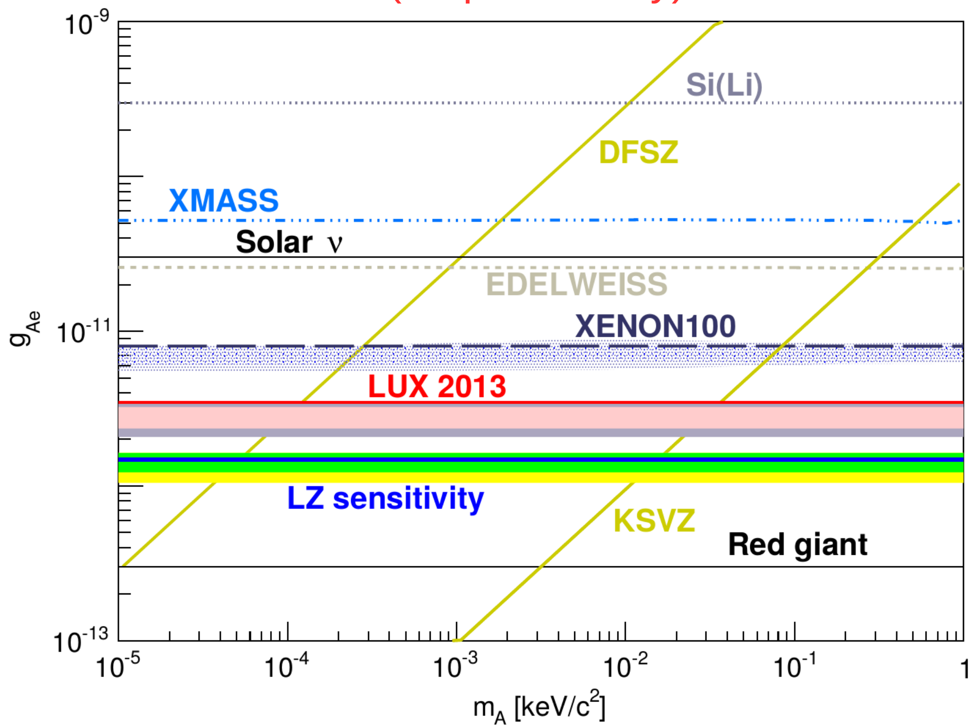


LZ sensitivity to Axions and ALPs

For **1000 live-days, 5.6 ton** fiducial mass
(LZ Baseline assumptions)

Axions

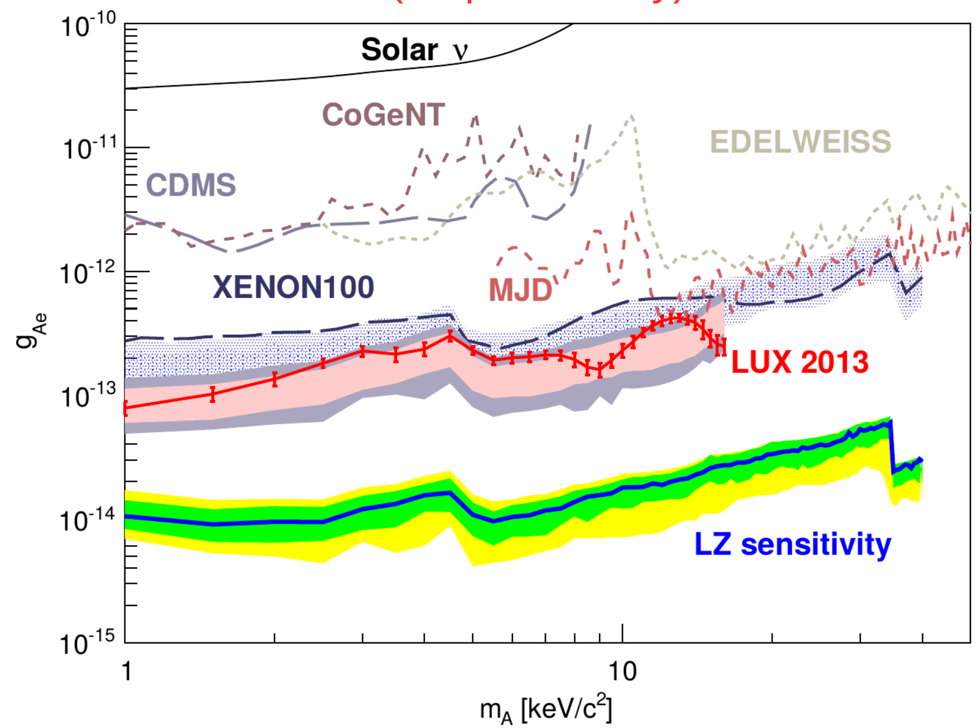
(LZ preliminary)



Excludes $\mathbf{g_{Ae} > 1.5 \times 10^{-12}}$ (90% CL)

ALPs

(LZ preliminary)



Excludes $\mathbf{g_{Ae} \gtrsim 1 \times 10^{-14}}$ (90% CL) across the mass range 1-40 keV.c^{-2}

LZ Sensitivity to: other physics...

- **Elastic Scattering of Solar Neutrinos**:
  - Expected **838 pp events**, **69 events from ^{7}Be** and **<10 from ^{13}N** (E_ν<220 keV) in the **1.5 to 20 keVee** window (LZ will be sensitive to neutrinos energies significantly lower than SAGE or BOREXINO);
- **Coherent Nuclear Scattering of Solar Neutrinos:**
  - Expected **7 events from ^{8}B** neutrinos (W/ a signal very similar to a 6 GeV WIMP);
- **Neutrino Magnetic Moment:**
  - The LZ ~1 keV energy threshold suggests an increase in sensitivity of ~1 order of magnitude relative to the upper limit of $5.4\times10^{-11}\mu_B$ set by BOREXINO;
- **Neutrinoless Double Beta Decay:**
  - LZ has the potential to a sensitivity limit on the 0νββ half-life of ^{136}Xe of 0.74×10^{26} y, 90% C.L. (the current half-live limit is 1.07×10^{26} y set by KamLAND-Zen);
- **Sterile Neutrinos (*not part of the main scientific goal*):**
  - The excellent spatial resolution of the LZ TPC allows the spatial pattern of electron neutrino oscillation into a sterile neutrino from a 5 MCi ^{51}Cr electron neutrino source to be detected.
- **Electrophilic WIMPs**:
  - Axial-vector WIMP-electron scattering **$\sigma_{We}\geq6\times10^{-38}$ cm^2** (w/ background subtraction). (The interpretation of the DAMA excess implies a $\sigma_{We}=2\times10^{-32}$ cm^2 @ M_W=50 GeV/c^2).
- …

The LZ collaboration

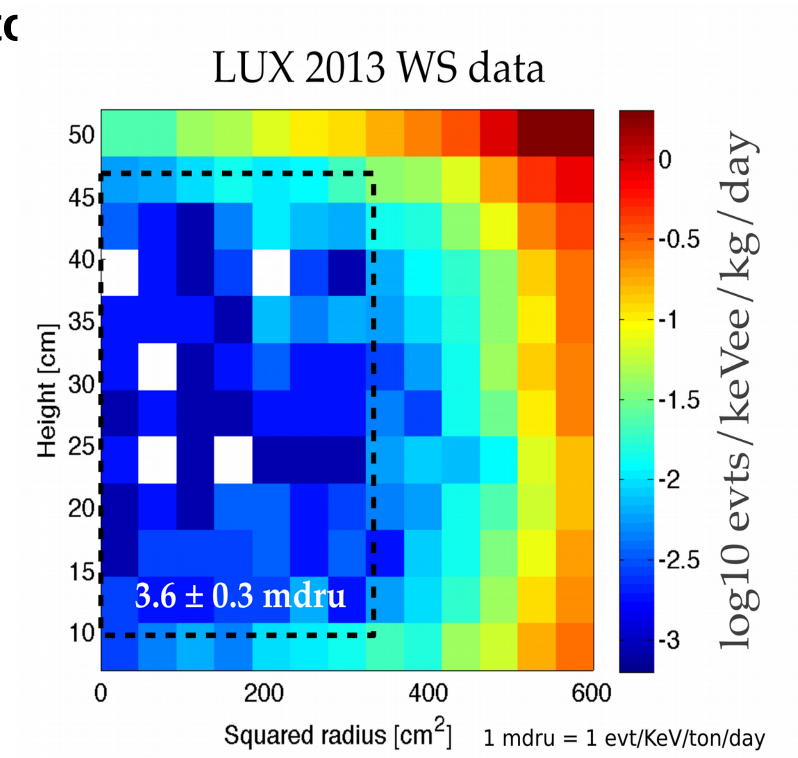
36 institutions – 250 scientists, engineers, and technicians

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) STFC Rutherford Appleton Lab (UK)
6) University College London (UK)
7) University of Bristol (UK)
8) University of Edinburgh (UK)
9) University of Liverpool (UK)
10) University of Oxford (UK)
11) University of Sheffield (UK)
12) Black Hill State University (US)
13) Brookhaven National Lab (US)
14) Brown University (US)
15) Fermi National Accelerator Lab (US)
16) Lawrence Berkeley National Lab (US)
17) Lawrence Livermore National Lab (US)
18) Northwestern University (US)
19) Pennsylvania State University (US)
20) SLAC National Accelerator Lab (US)
21) South Dakota School of Mines and Technology (US)
22) South Dakota Science and Technology Authority (US)
23) Texas A&M University (US)
24) University at Albany (US)
25) University of Alabama (US)
26) University of California, Berkeley (US)
27) University of California, Davis (US)
28) University of California, Santa Barbara (US)
29) University of Maryland (US)
30) University of Massachusetts (US)
31) University of Michigan (US)
32) University of Rochester (US)
33) University of South Dakota (US)
34) University of Wisconsin – Madison (US)
35) Washington University in St. Louis (US)
36) Yale University (US)

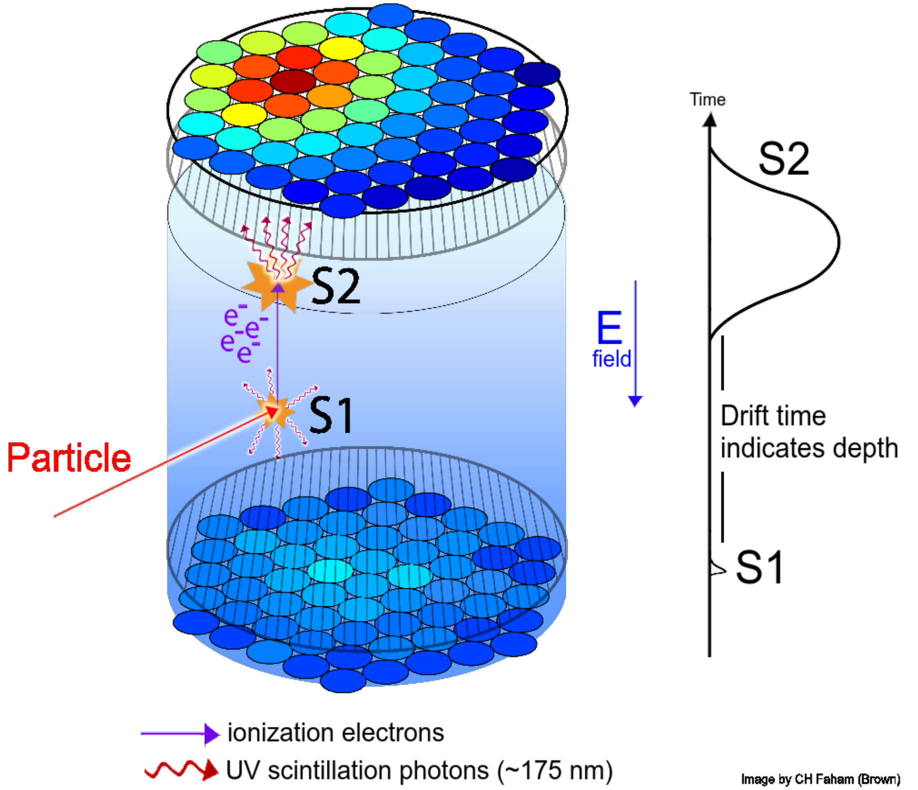
Extra Slides

Xenon as a WIMP target

- **High density** (2.9 *g/cm³*): manageable detector volumes ($R_{WIMP} \lesssim 10^{-5}$ *event/kg/day*);
- **High atomic number** (*A~131*): good for *spin-independent* interactions; plus *spin-dependent* sensitivity (~1/2 odd isotopes in natural xenon);
- Allows **easy/affordable scalability** to ton-level detectors (**LZ**, XENON-nT);
- Allows **self- shielding** by selection of an **inner fiducial volume** while using the (instrumented) **outer *skin* volume as a veto**
- Natural xenon has **no long-lived radioactive isotopes**; plus Kr contamination can be easily reduced to ppt level;
- **Low energy threshold** (*~1 keVee*);
- **Nuclear recoil vs e⁻/γ-ray discrimination** by simultaneous detection of *prompt scintillation* and *charge* drift away of the interaction site by an electric field;

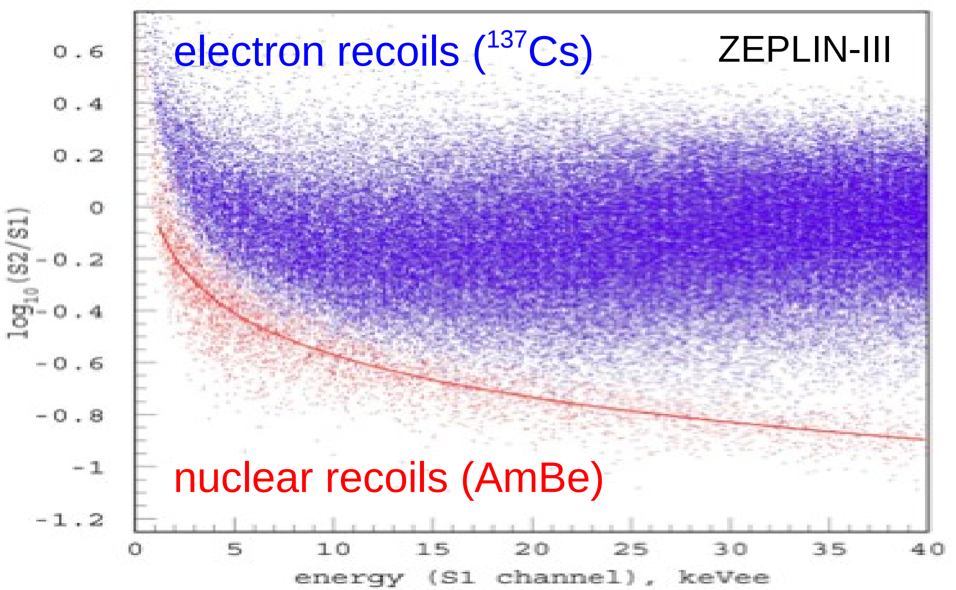


Liquid Xenon TPC

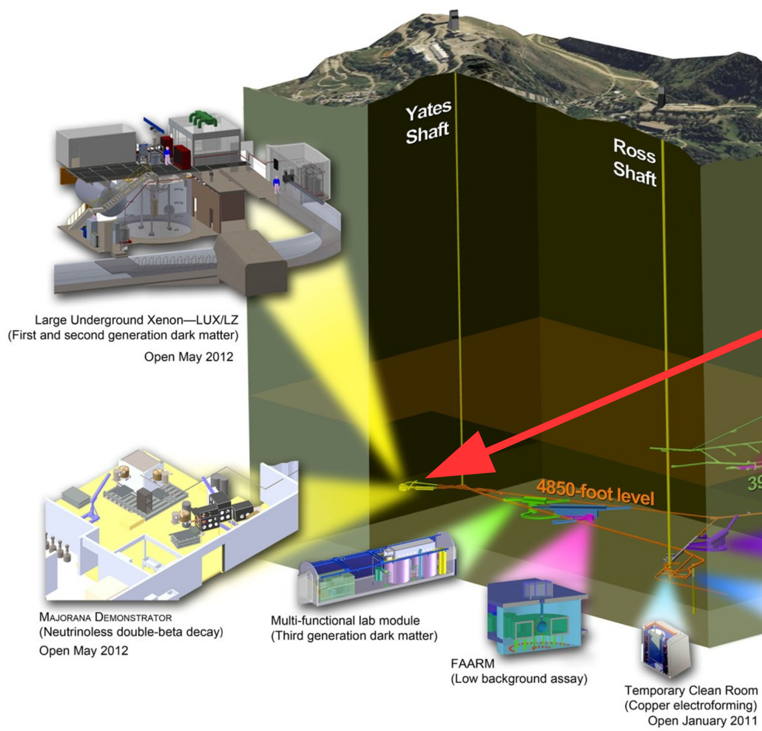


- **(x,y) position reconstruction**: from the S2 light pattern;
- **Depth of interaction (z)**: e^- drift time in the liquid (time difference between S2 and S1);

- **Prompt scintillation (S1).**
- **Proportional scintillation (S2)**: measurement of the e^- charge extracted from the liquid to the gas.
- **S2/S1** depends on the ionising particle (nuclear/electron recoil): **99.7% ER/NR rejection** @ 50% NR acceptance**.**



Sanford UG Research Lab



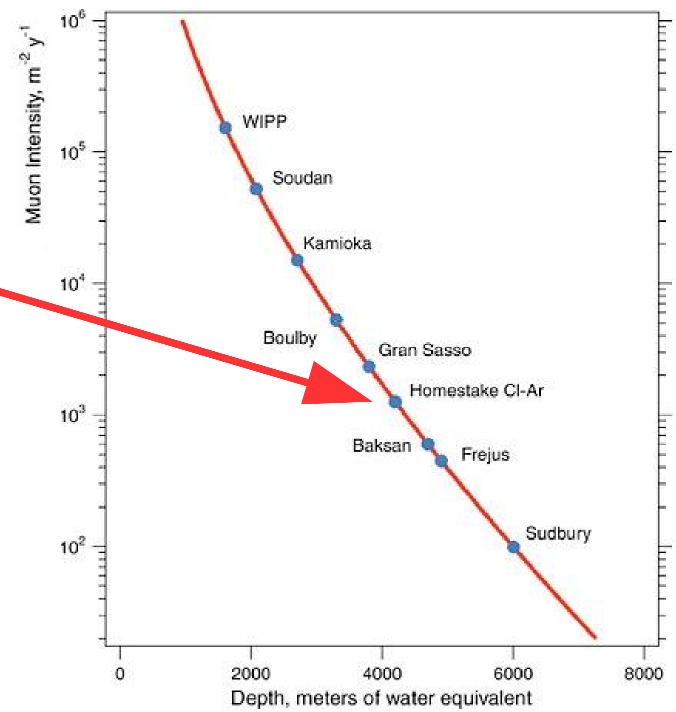
SURF

4850 feet deep

(1478 m)

Muon reduced by 10^7

(4.3 km w.e)



LUX timeline

2008: LUX funded (DOE+NSF)

2013 (Apr): First science run starts

2014 (Sep): 332-day run started!

2016 (May): Run finished

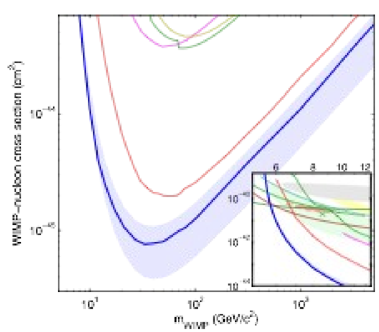
2016 (Sep): Decommis. starts

Analysis still ongoing

2006: LUX collab. formed

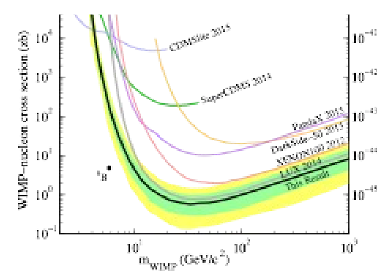
2012 (Jul): UG lab complete, LUX moves UG

2013 (Nov): First results (3 months) reported



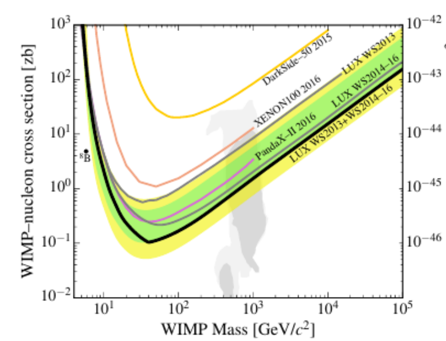
PRL, 112, 091303 2014

2015 (Dec.) 3-month run reanalysis posted



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

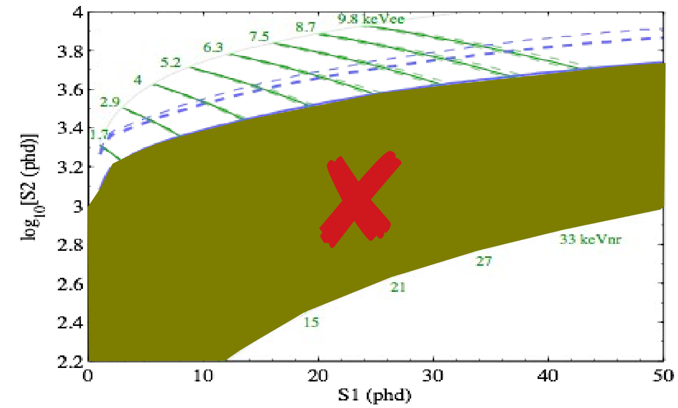
2016 (July): 332 day results announced

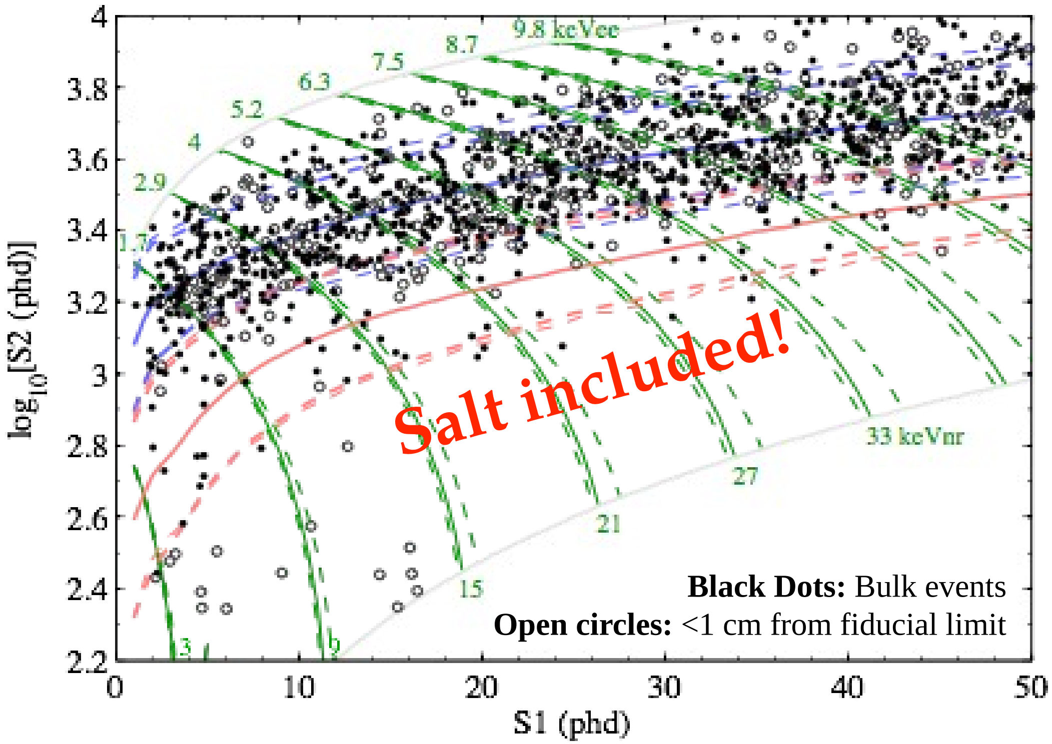


PRL 118, 021303 2017
PRL 118, 251302 2017

Salting the WIMP search data

- Traditional *blind* analysis hides the signal region completely;
- Very often one is also *blind* to **rare backgrounds** or **event pathologies** not taken into consideration in the analysis;





- LUX employ a technique where **fake signal events** – ***salt*** **– are injected into the data stream**;
  - *Salt* events are built using true S1s and S2s and not simulated events!
- Salt events supply an **unbiased tool** to extract analysis/cuts **efficiencies**.

Run4: 332 live-days, 33.5 tonne-days

LZ timeline

2012 (March)
LZ (LUX-ZEPLIN) collaboration formed

2014 (July)
LZ Project selected in US and UK

2015 (April)
DOE CD-1/3a approval (similar in UK)
Conceptual Design Report arXiv:1509.02910

2017 (Feb)
DOE CD-3 approval
Technical Design Report: arXiv:1703.09144

2017 (Q2)
Begin preparations for surface assembly @ SURF

2018 (Q4)
Begin underground installation

2020 (Q1)
Commissioning start

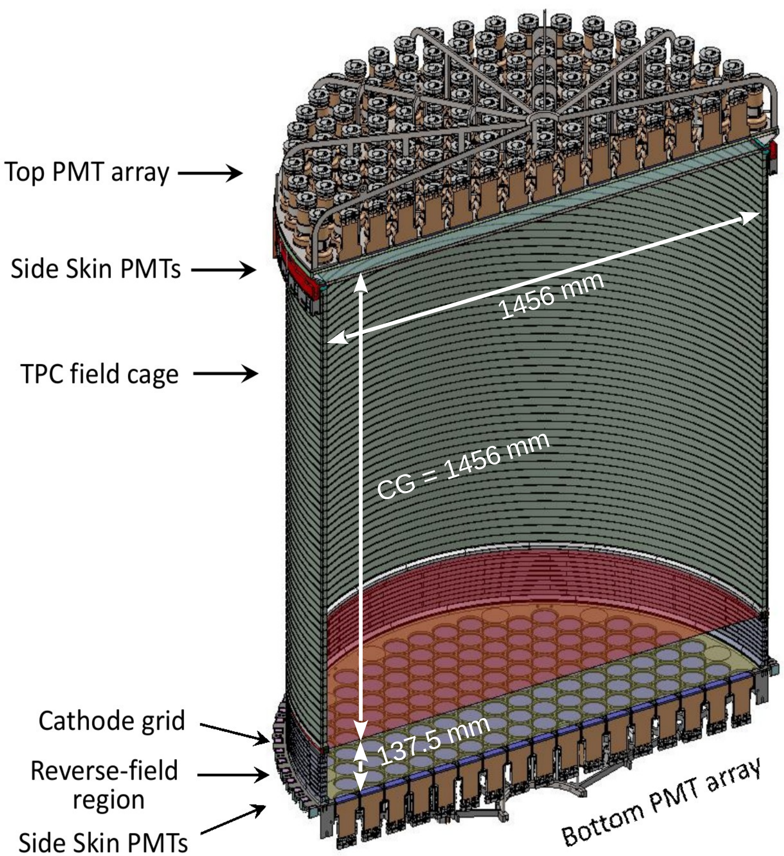
Main milestones (top) and long term production tasks (right)

- final design
- materials screening
- xenon procurement
- PMTs procurement and test
- Gd-LS production

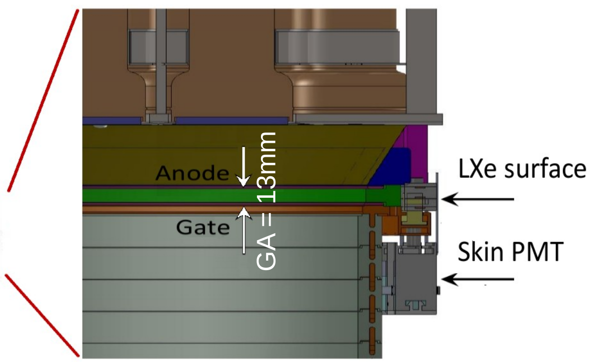
1000 days WIMP search run!

The LZ Detector: LXe TPC

SECTION VIEW OF THE LXE TPC

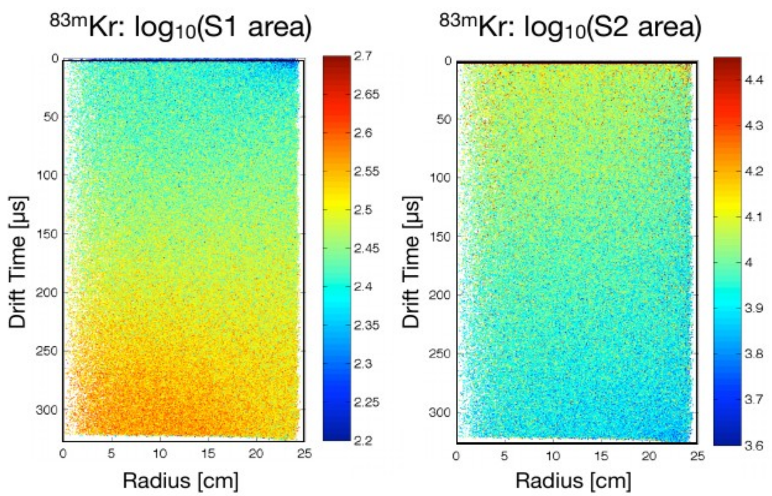


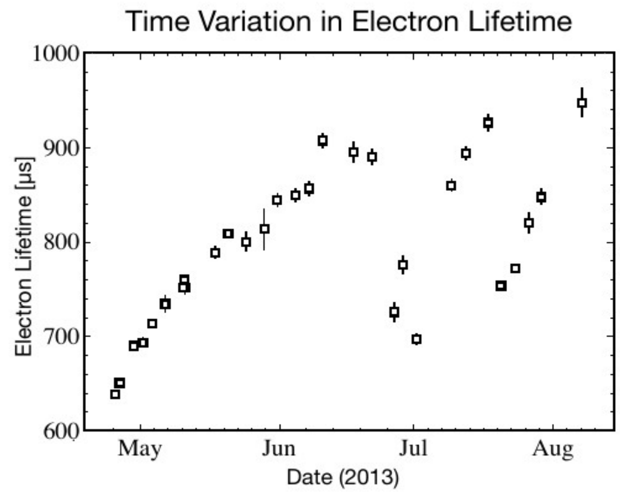
GAS PHASE AND ELECTROLUMINESCENCE REGION



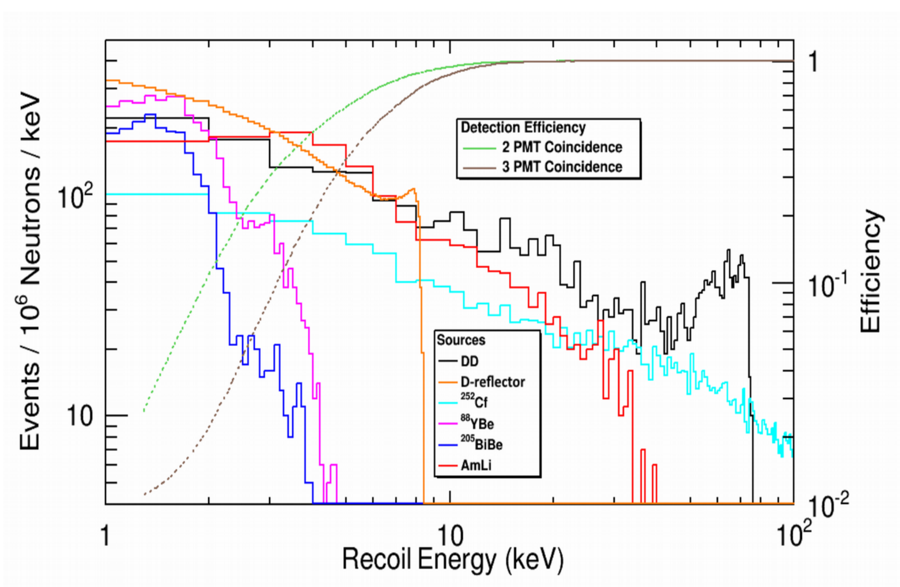
Parameter	Baseline	Goal
Electroluminescence field (kV/cm)	10.2 (8 mm gas)	
Electron extraction probability	95%	99%
TPC drift field (kV/cm)	0.31	0.65
Electron drift velocity (mm/μs)	1.8	2.2
Maximum drift time (μs)	806	665
Longitudinal diffusion (μs)	2.2	2.0
Transverse diffusion (mm)	1.8	1.4
ER/NR discrimination	99.7%	

The LZ Detector: calibration

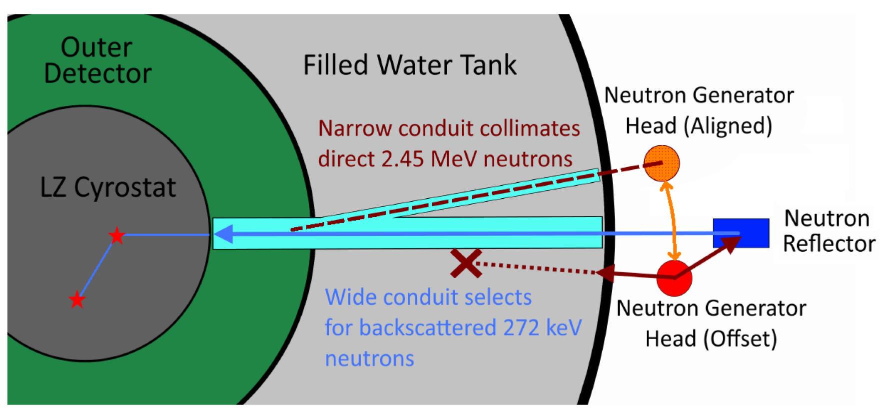




S1 and S2 (x,y,z) dependence (left) and electron lifetime (right), measured from S2(Z), using **LUX ^{83m}Kr calib. data**



Energy spectra (left) covered by the neutron calibrations and schematic representation of the setup for the DD calibration



^{8}B Background in LZ

- Using PLR, neutrino background from solar ^{8}B + HEP:
  - Only significant for low-mass WIMPs only ($\lesssim$ 20 GeV/c^2):
  - MC correspondent to a 1000 days run with 5.6 tonne fiducial mass.