Searching for Dark Matter with LUX and LUX-ZEPLIN

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on behalf of the LUX and LZ collaborations

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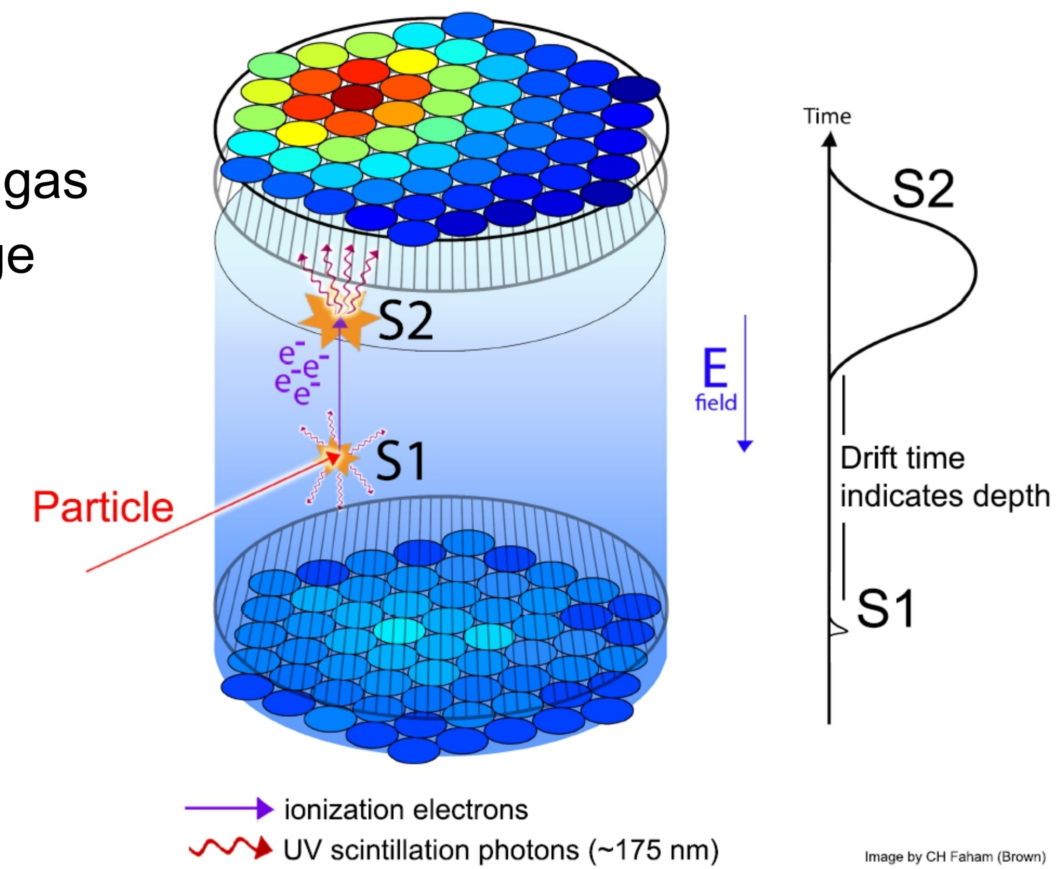
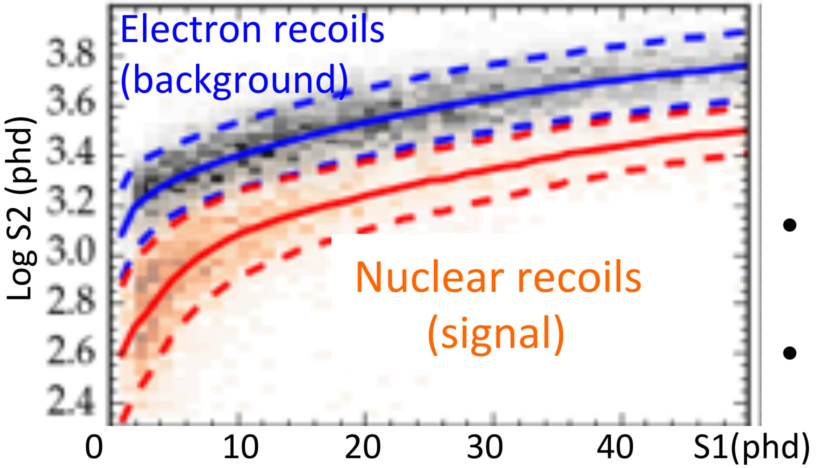
Dual phase xenon TPC (Gas/liquid Xe)

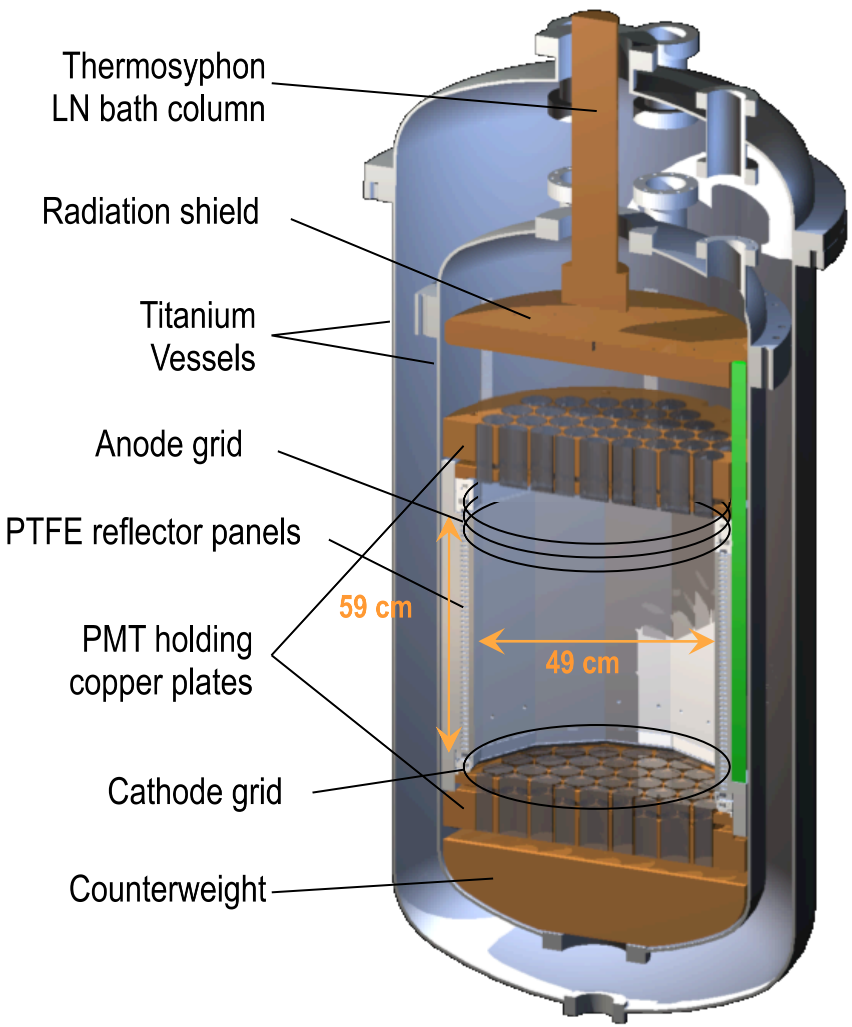
- S1: Primary scintillation
- S2:Proportional scintillation (light emitted by electrons extracted to gas phase) - proportional to the charge
- 3D vertex localization:
- Z from S1 – S2 timing
- X-Y from light pattern in PMT array(s)
- Identification of multiple scatters (via S2 count)





- Only single events (one S1 and one S2) are accepted
- Discrimination based on S2 vs S1

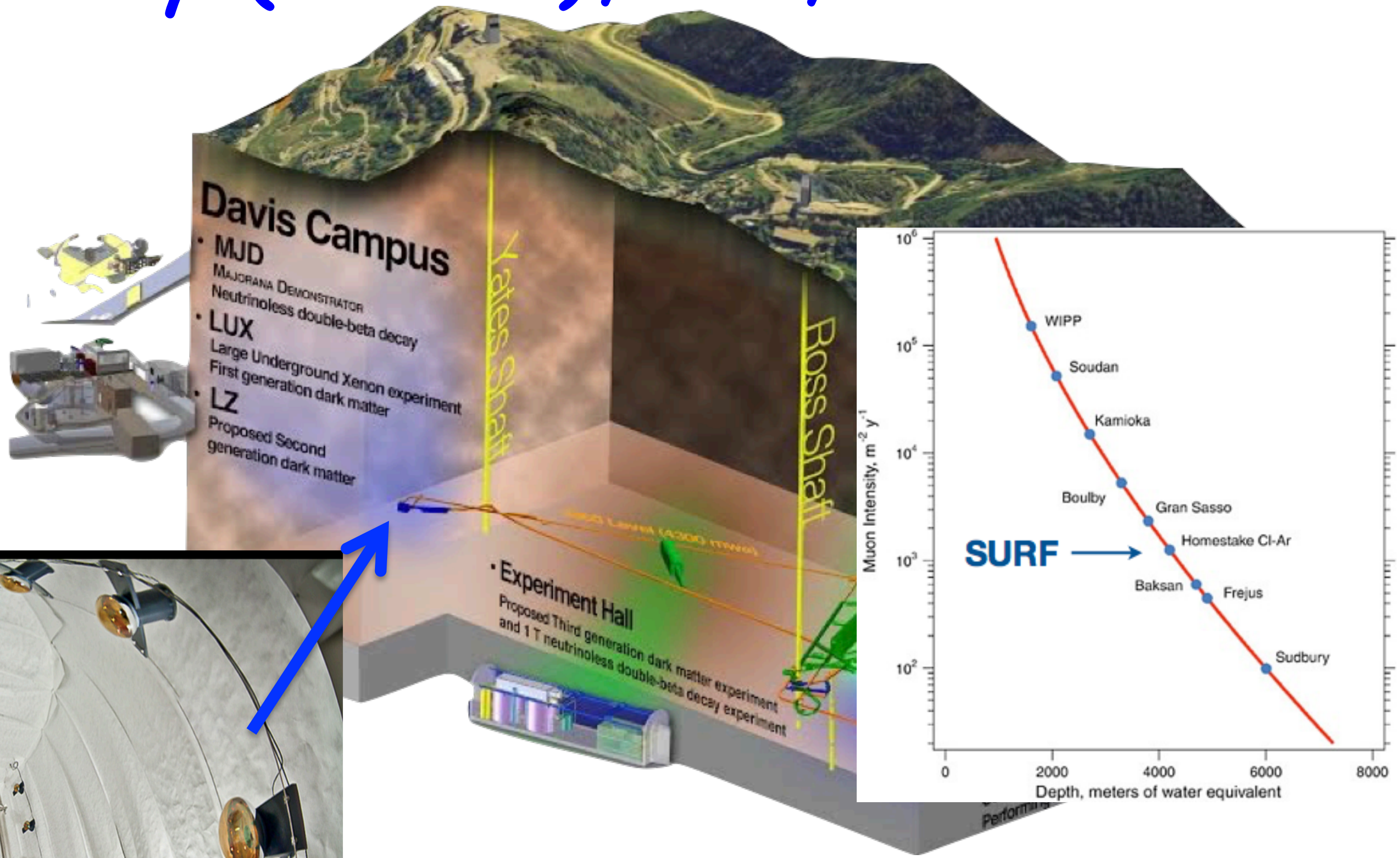
The LUX detector



- Active volume:
  - 250 kg of LXe
  - 48 cm max. drift
- 122 low background(12 mBq/PMT) , high VUV sensitivity PMTs in two arrays
- High reflective (>98%) PTFE walls and PMT trifoils to maximize light collection
- Ultra-low background Ti cryostats (< 0.2 mBq/kg)
- Xenon continuously circulating to maintain purity (~250 kg/day)
- Chromatographic Kr separation (< 4 ppt)

Sanford Underground Research Facility (SURF), SD, USA

The detector and cryostat are inside a ~300 tonne ultra-pure active water tank.



LUX located 1.5 km underground at SURF → cosmic muon rate reduction by ~10^7

LUX Timeline

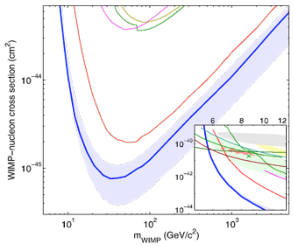
2006: LUX collaboration formed

2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

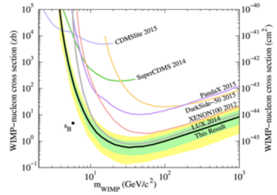
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

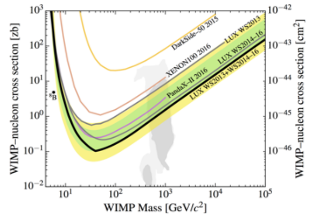
Dec 2015: Re-analysis of WS2013 published



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

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



PRL, 118, 021303 (2017)

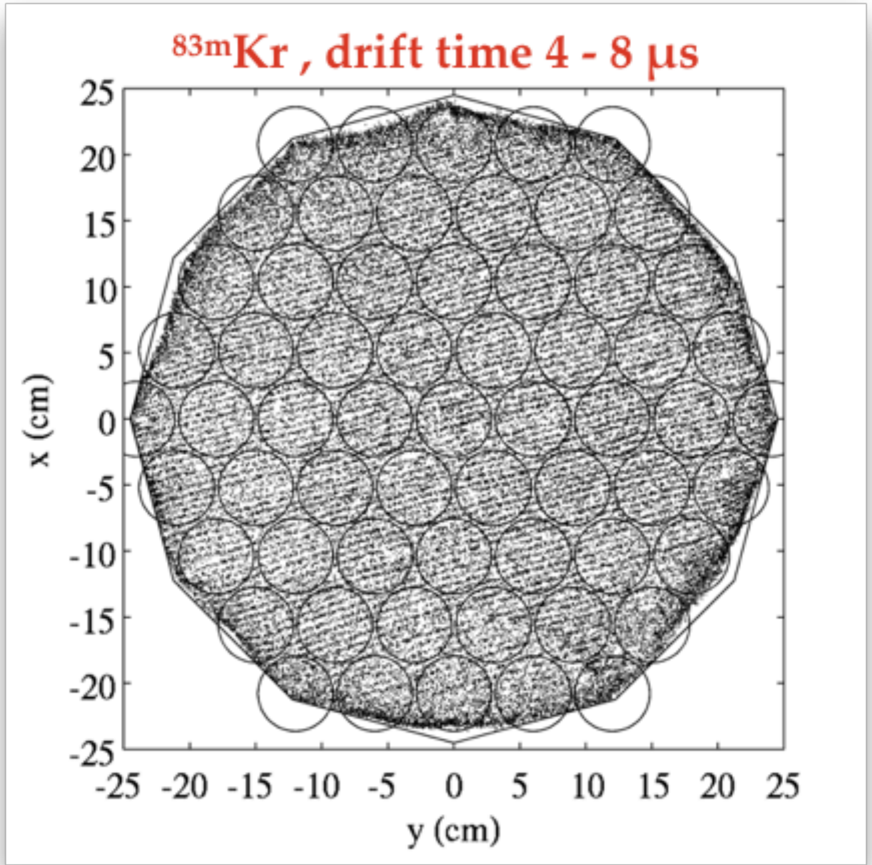
Sept 2016: decommissioning start

Analysis still ongoing

June 2017: LUX installed in a museum

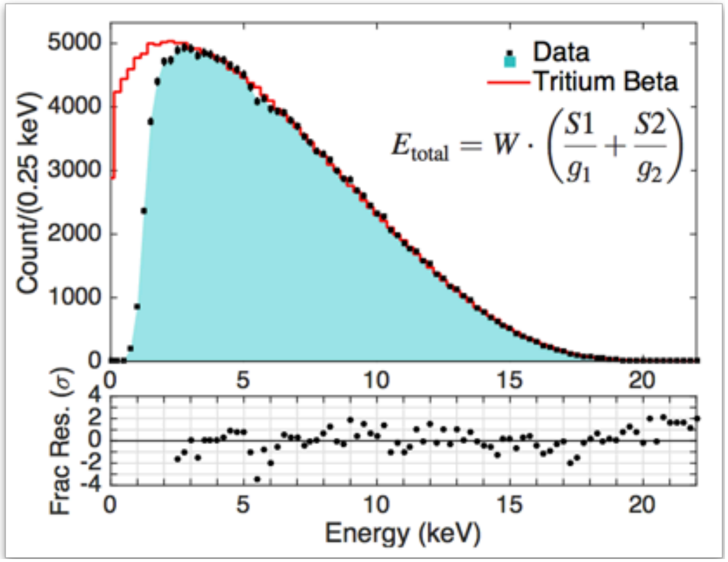
Calibrations — ^{83m}Kr

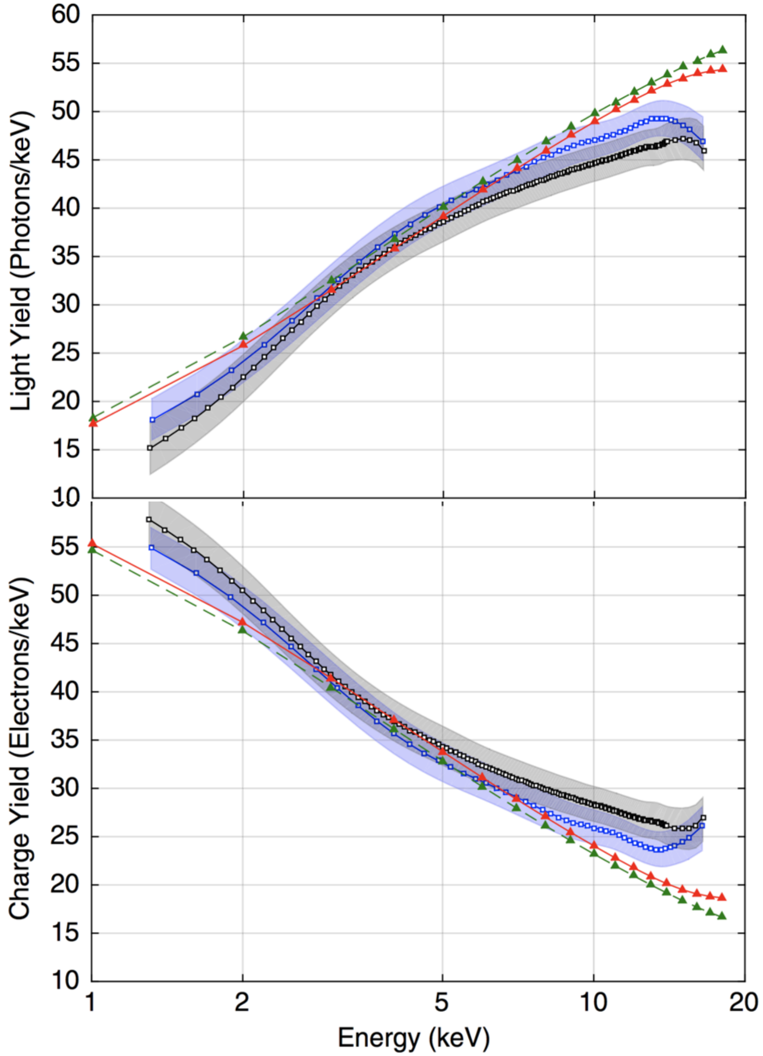
- Injected ~weekly in the gas system
- Quickly mixes in the xenon, **uniform distribution**
- 2 IC electrons in quick succession
  32.2 keV + 9.4 keV ($T_{1/2}$ = 154 ns)
- 1.8 hours half-life
  Clears off the system in a few hours
- **Used weakly for:**
  - Overall stability monitoring
  - Position reconstruction
  - Electron lifetime
  - S1 and S2 position corrections
  - Light collection mapping
  - Electric field modeling



Electron recoil calibration with CH3T

- Tritium β decay (Q= 18.6 keV; <E>=5.9 keV)
- Uniformly distributed
- Every three months
- Long lifetime ($T_{1/2}$=12.3 yr)
- Removal by purification system ($T_{1/2}$ ~ 6 hours)
- Purpose:
  - Determination of the electron recoil (ER) band
  - Absolute calibration of Q_Y and L_Y for ER down to ~1 keVee
  - Detection efficiency vs energy
  - Discrimination vs energy

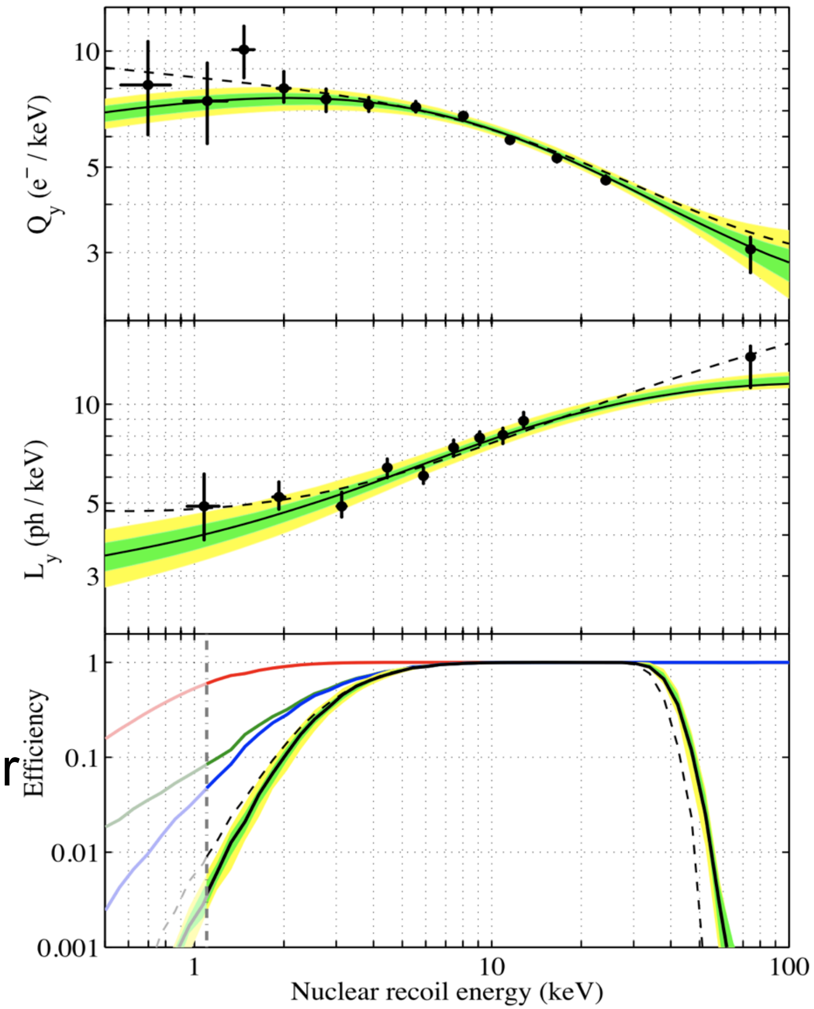




CALIBRATION WITH NEUTRON GENERATOR

- Source: neutrons from DD generator, 2.45 MeV (monoenergetic)
- Geometry: beam collimated by an air-filled pipe in the water tank
- Frequency: quarterly (at different Z's)
- Purpose: determine the nuclear recoil (NR) band

- The energy of NR is calculated from the kinematics of double scatter events
  - Absolute calibration of ionization response Q_Y down to 0.7 keVr
- Once Q_Y is known it can be used to calculate the recoil energy of single scatter events
  - Absolute calibration of scintillation response L_Y down to 1.1 keVr



Backgrounds in 2014-2016 run

Background source	Expected number below NR median *	Comment
External gamma rays	1.51 ± 0.19	Bulk volume, leakage at all energies
Internal betas	1.2 ± 0.06	
Rn plate out (wall background)	8.7 ± 3.5	Low-energy, confined to the edge of fiducial volume **
Accidental S1-S2 coincidences	0.34 ± 0.10	In the bulk volume, low-energy, in the NR band
Solar ^{8}B neutrinos (CNNS)	0.15 ± 0.02	

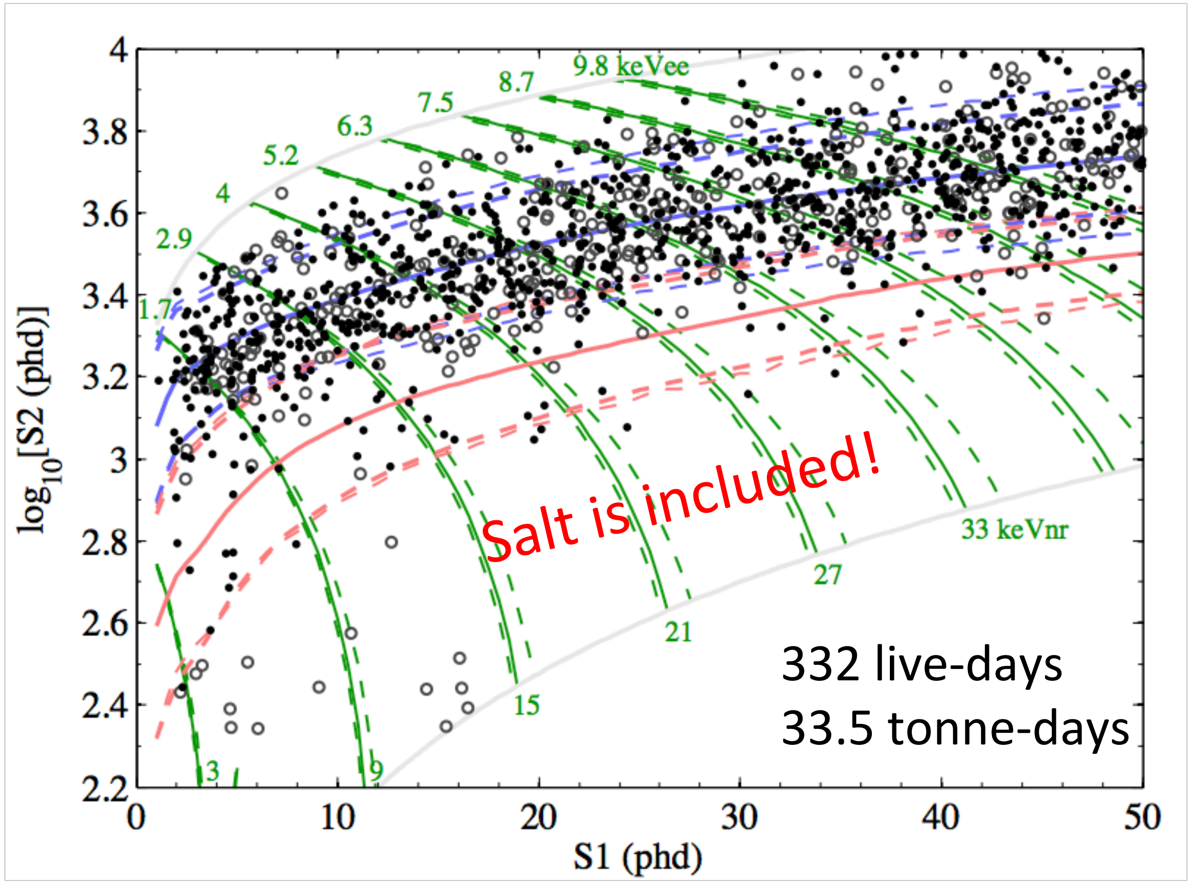
The neutron contribution (0.3 ±0.03) was not included in the PLR

* Figure of merit only as we do likelihood analysis

** Our likelihood analysis includes position information, so these events have low likelihood as signal

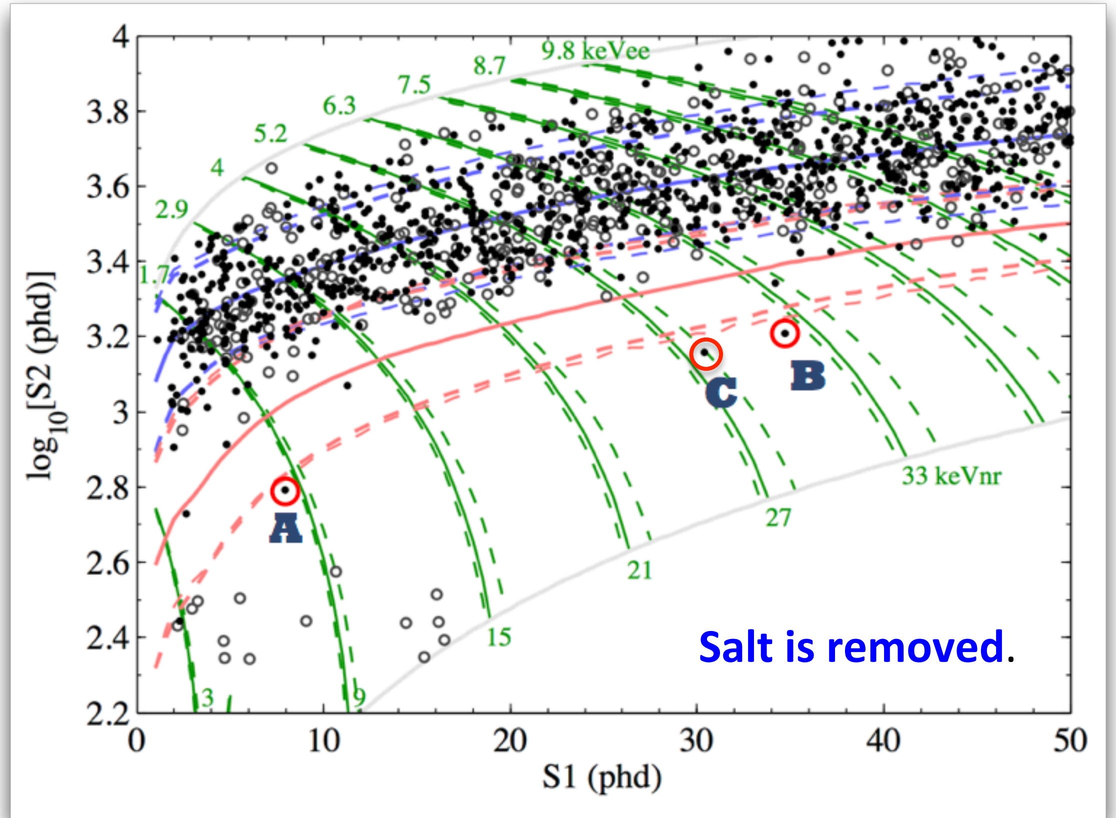
WIMP-Search data + salt

- Instead of blinding, we employ **salting**: fake signal events ("salt") are injected into the data stream.
- Fake events are injected at the level of raw waveforms, and are **built from calibration data** (not simulation).
- Mitigates bias while allowing for scrutinization of individual events.

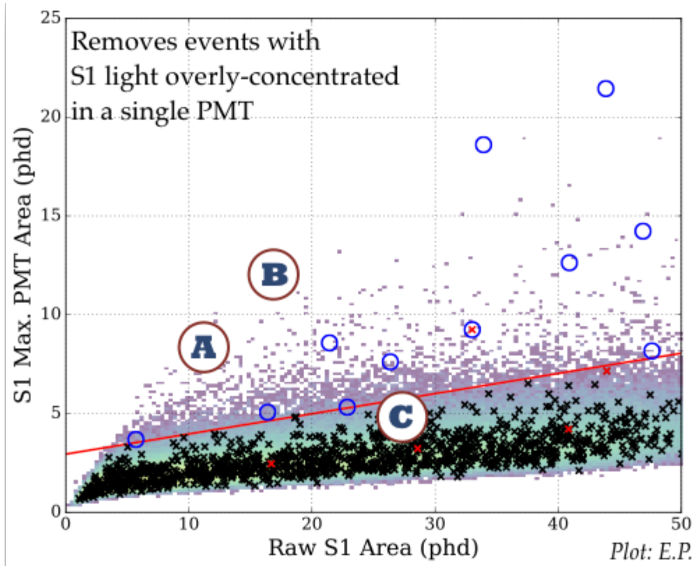


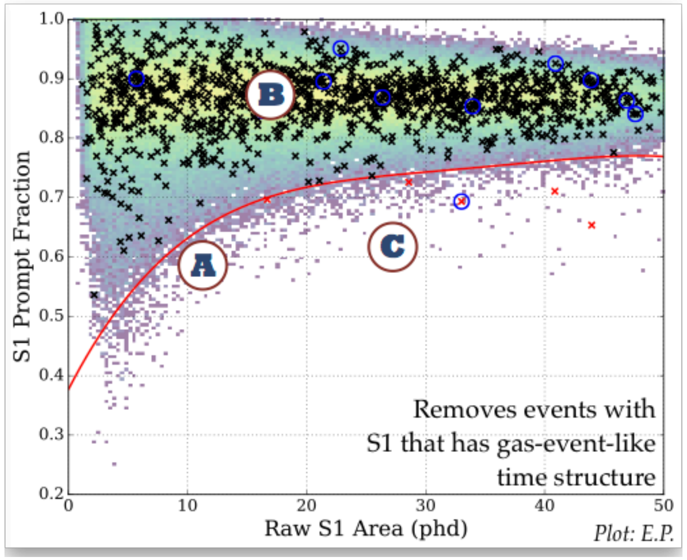
- Black dots: bulk events
- Open: within 1cm of our fiducial boundary
- Salt is not yet identified here.

WIMP-Search data- unsalted



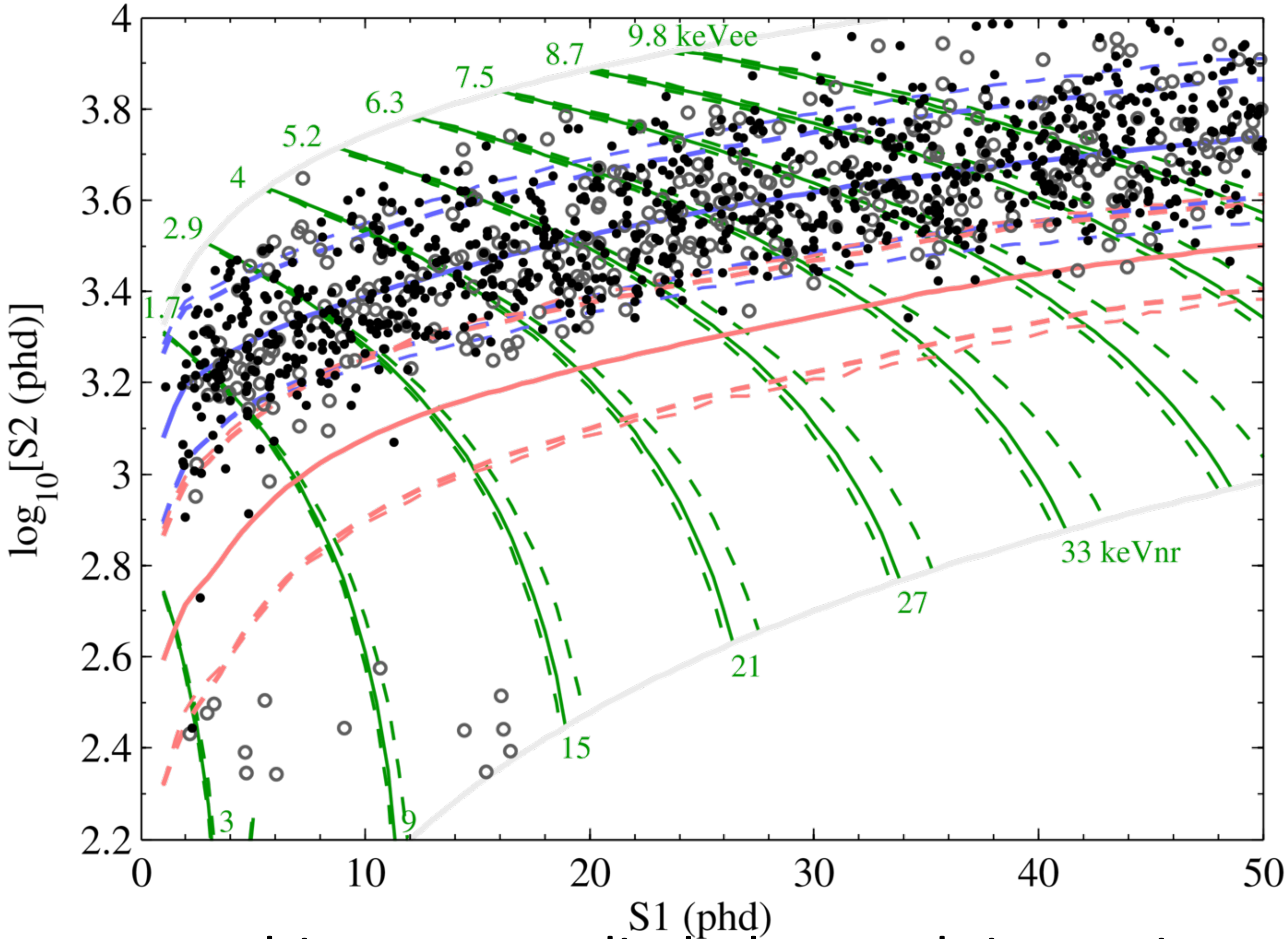
Additional cuts:





- **Events A and B** have ~80% of the light in a single top-edge PMT. Consistent with light leakage from an event outside the TPC.
- **Event C** has time structure consistent with primary scintillation in the gas phase.

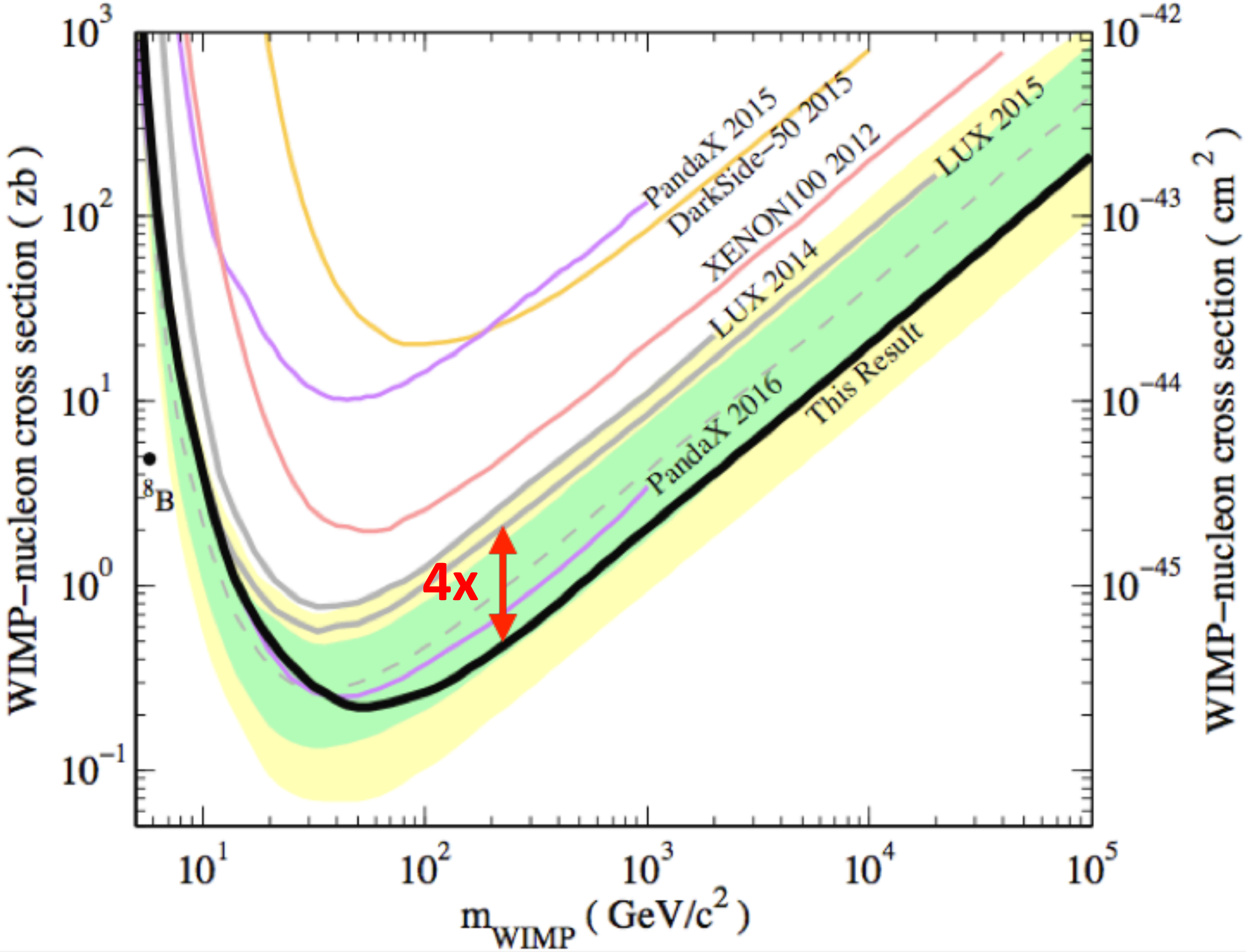
WIMP Search Data



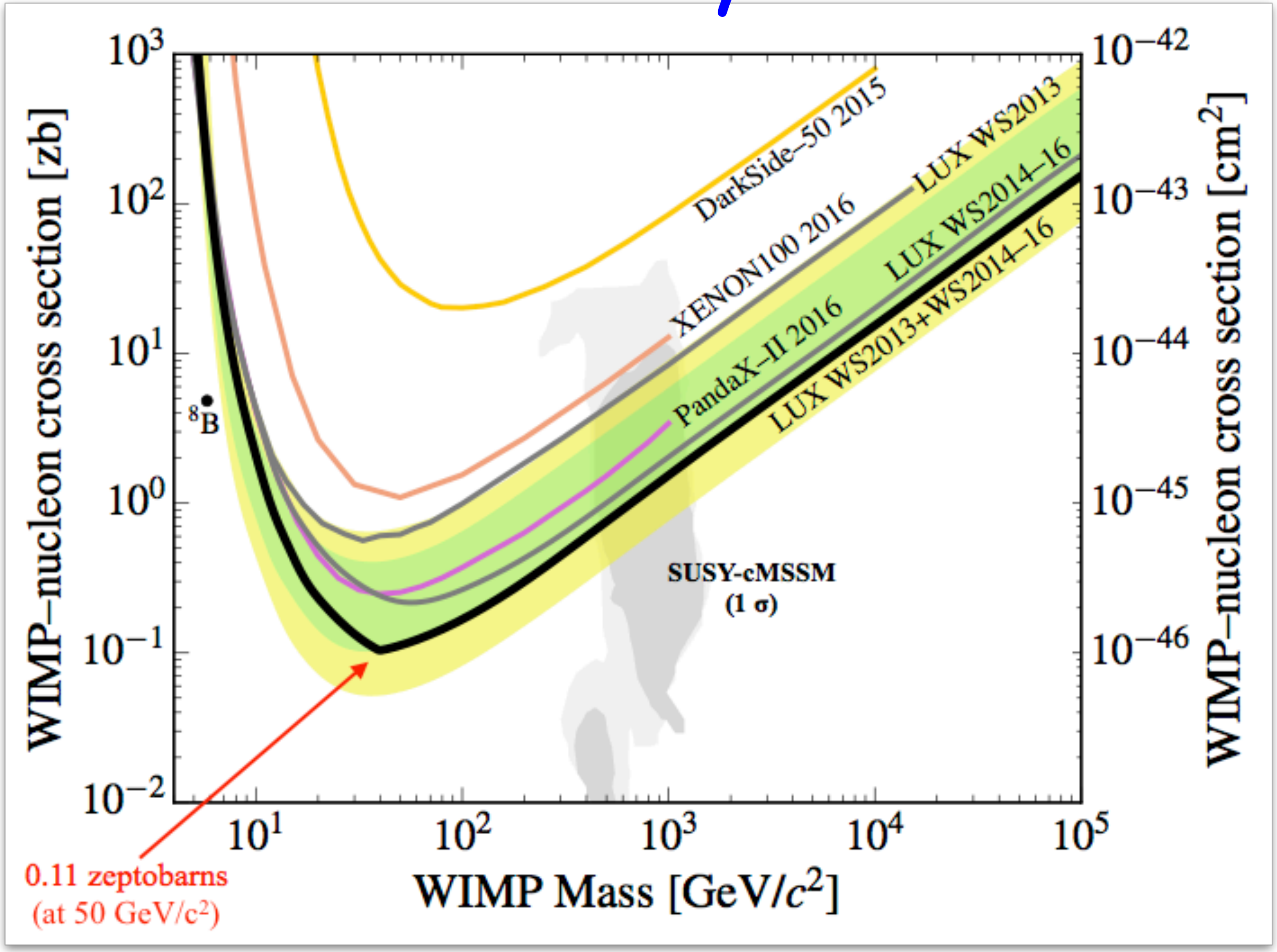
With post-unsalting cuts applied, the result is consistent with **background-only** hypothesis (p-value of 40%)

SI-Exclusion Limit - 332 live-days

- 4x improvement at high mass
- Minimum of 0.22 zb @ 50 GeV
- Brazil bands show 1- and 2-sigma range of sensitivities, based on random BG-only experiments

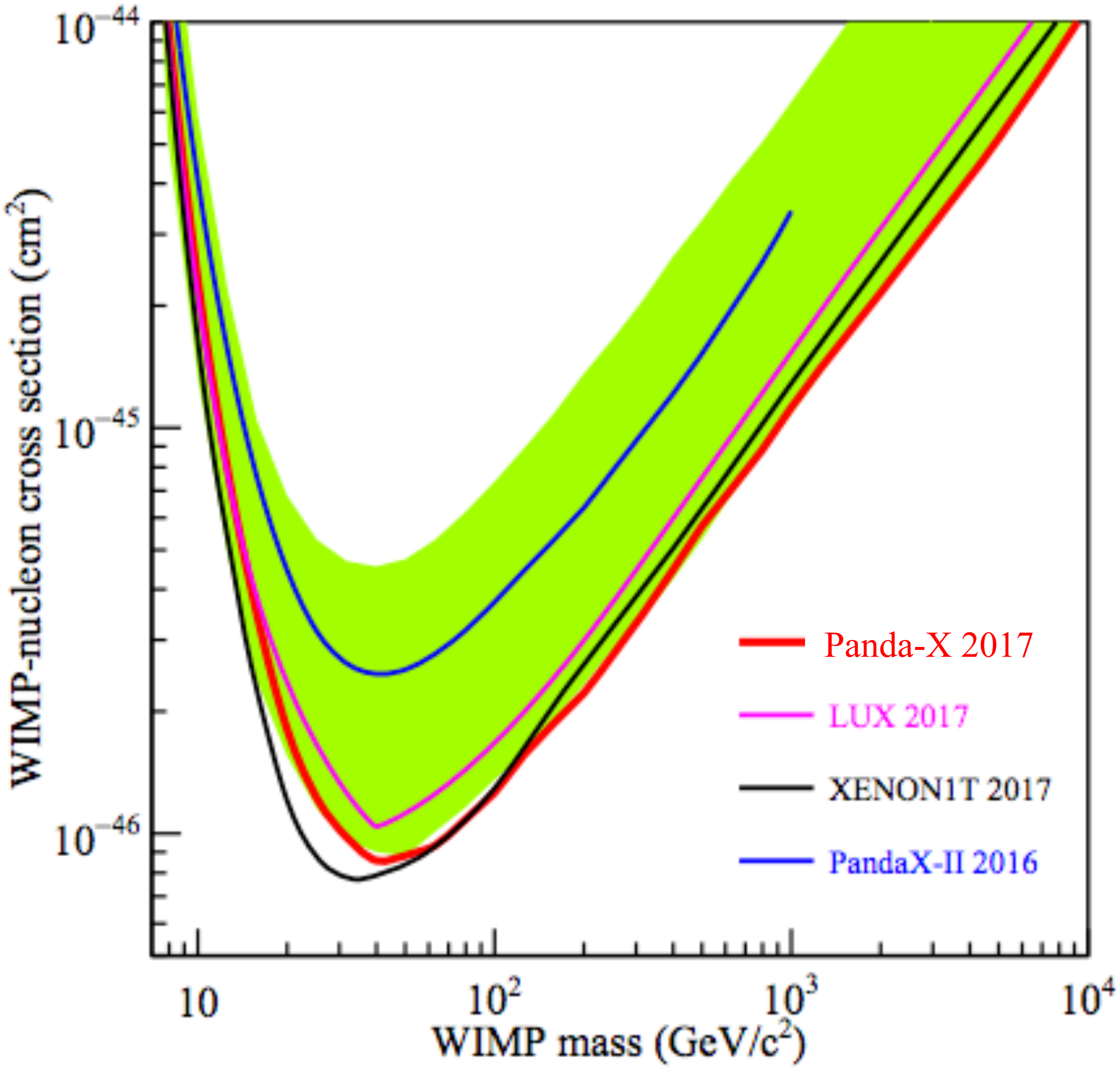


SI-Exclusion Limite – 332+95 live-days



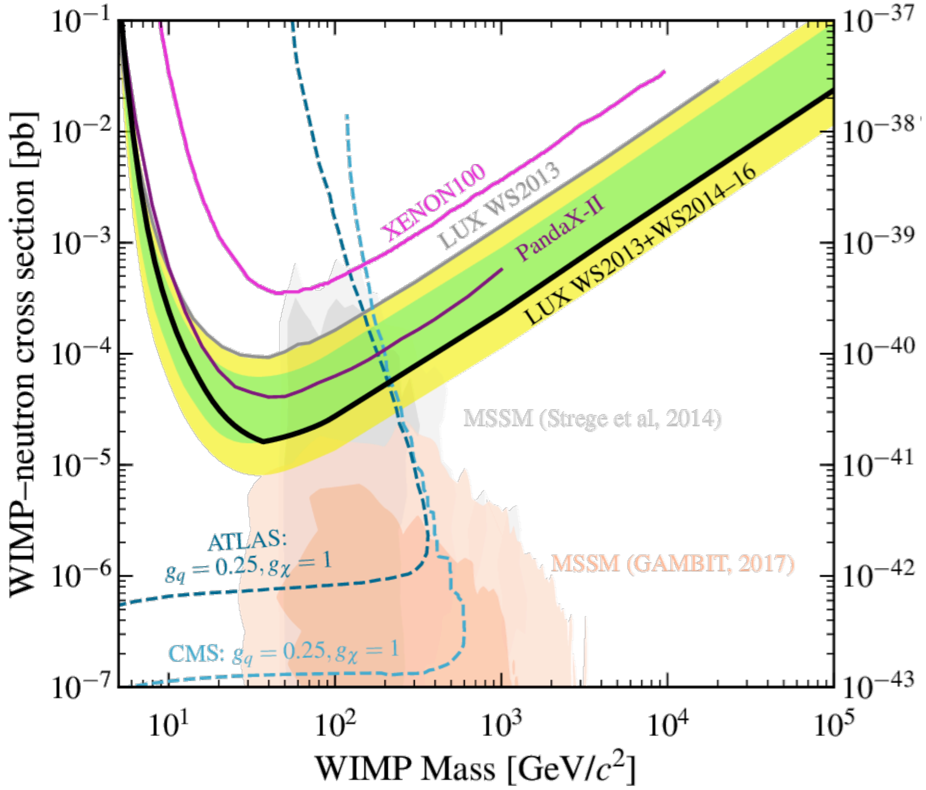
PRL, 118, 21303 (2017)

SI-Exclusion Limit- Present status

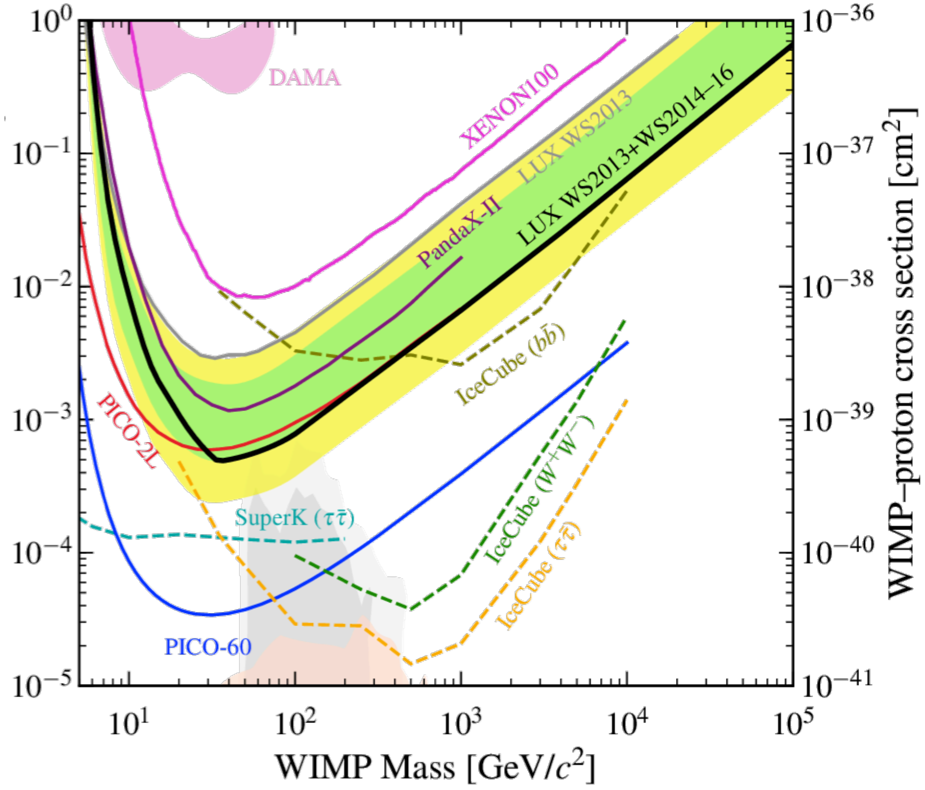


SD-exclusion limits from the whole exposure (95+332 days)

WIMP-neutron



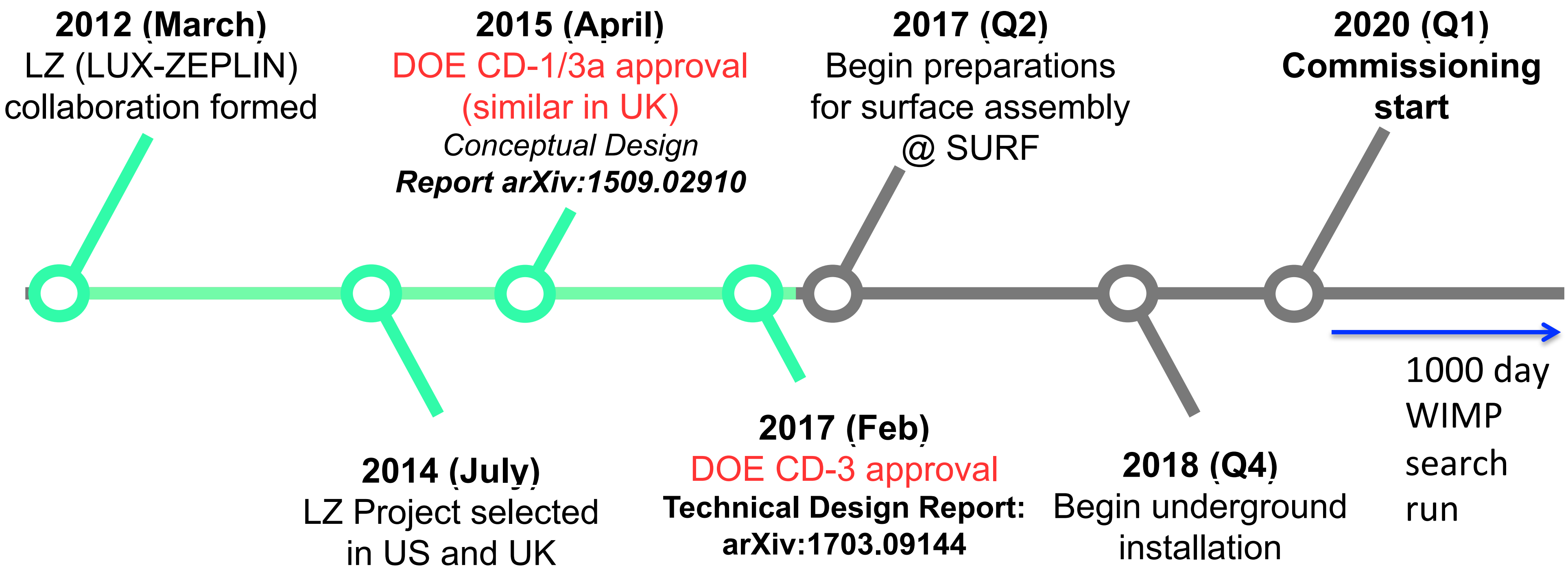
WIMP-proton



LUX → LUX-ZEPLIN (LZ)

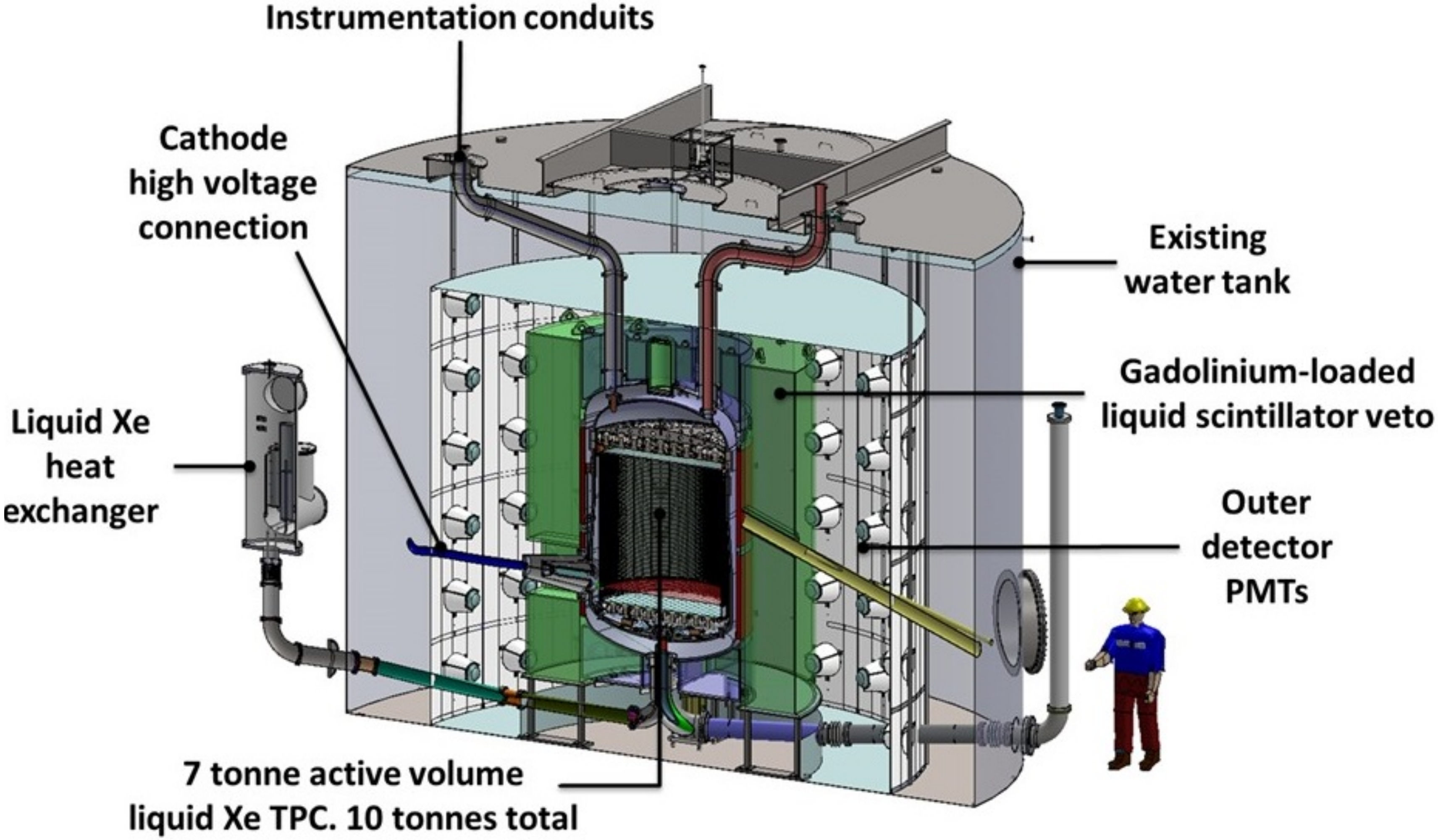
- Total mass increase factor ~30
- LUX water shield and **added liquid scintillator active veto**
- **Instrumented "skin"** region around the TPC field cage as additional veto
- Unprecedented levels of Kr (<15 ppq)
- Radon suppression during construction, assembly & operations
- PMTs with ultra-low natural radioactivity (~mBq)
- Fiducial mass increase factor ~50

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
1000 day WIMP search run

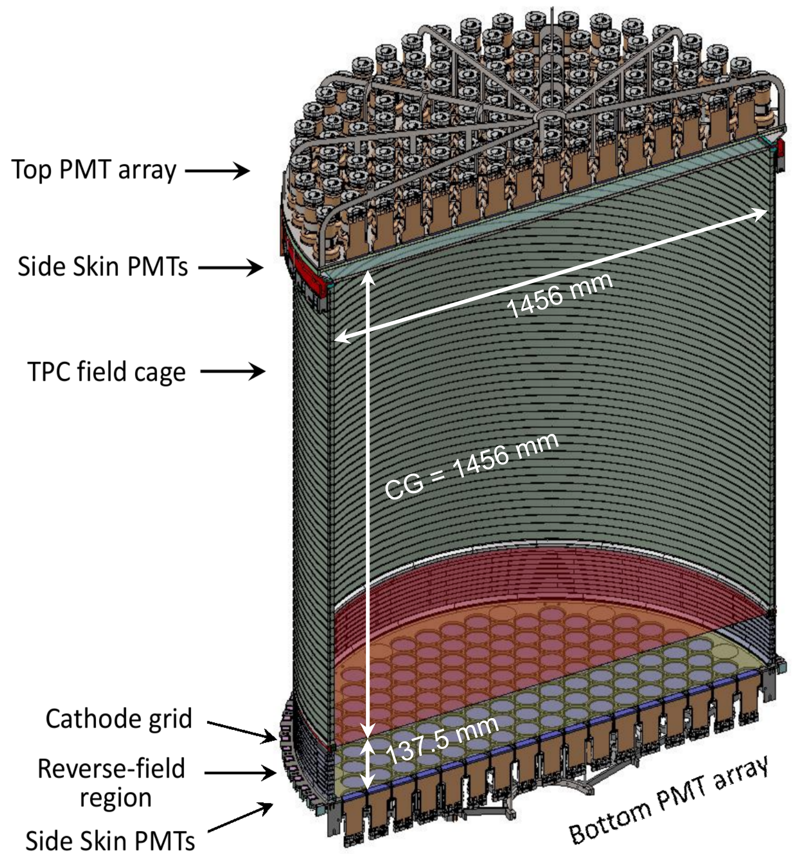
LZ Detector Overview



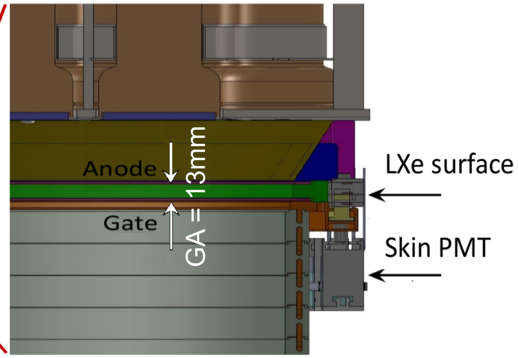
- Will be installed in the same laboratory used for **LUX** and inside the **same water tank**;
- 494 PMTs (in the TPC) acquiring in dual-gain;
- **Instrumented skin** region (additional veto)

LZ TPC

SECTION VIEW OF THE LXE TPC



GAS PHASE AND ELECTROLUMINESCENCE REGION

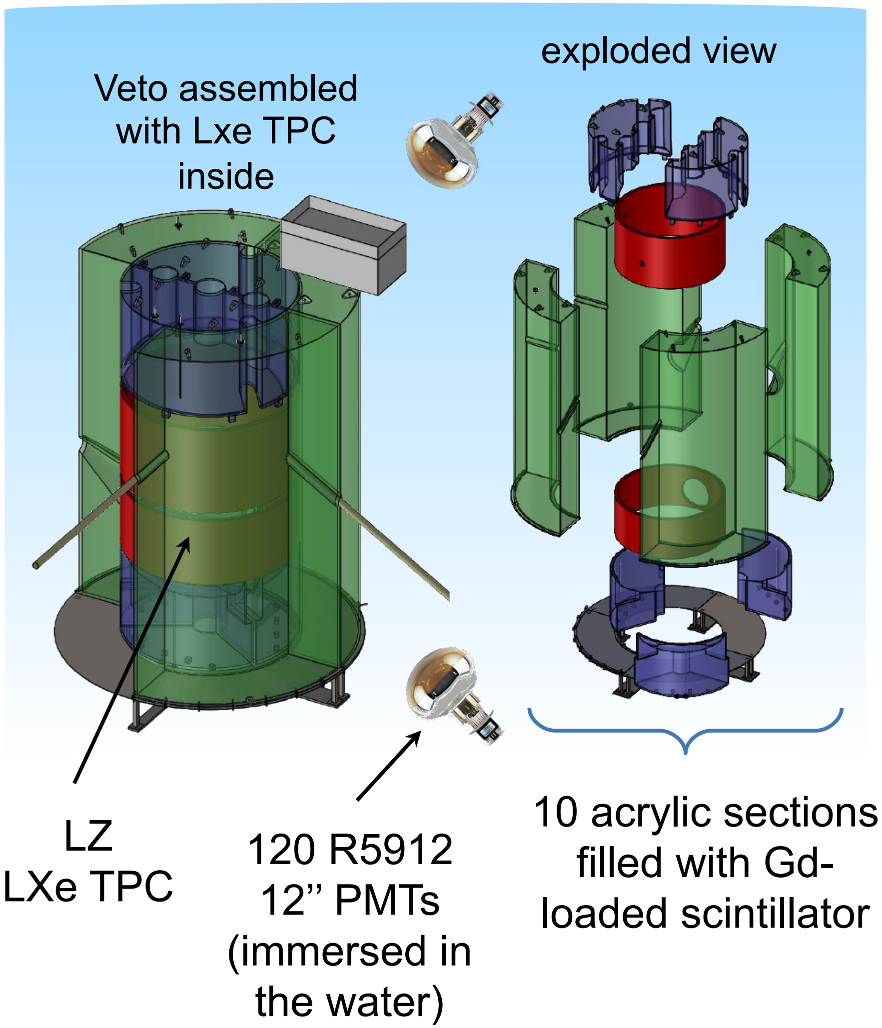


TPC PMTs: 3-inch Hamamatsu R11410 PMT

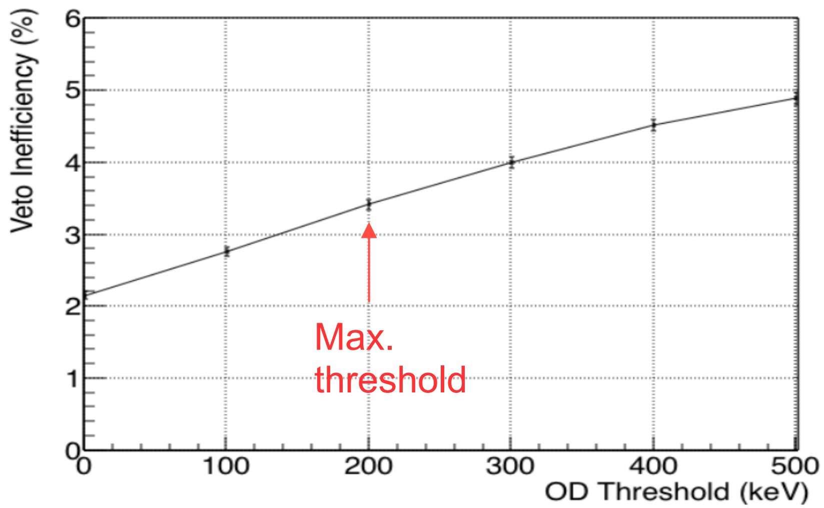
Parameter	Baseline	Goal
Electroluminescence field (kV/cm)	10.2 (8 mm gas)	
Electron extraction probability	95%	99%
TPC drift field (kV/cm)	0.31	0.65
Maximum drift time (μs)	806	665
Longitudinal diffusion (μs)	2.2	2.0
Transverse diffusion (mm)	1.8	1.4
ER/NR discrimination	99.7%	

- **Instrumented "Skin" region optically separated from TPC (180 PMT)**

Outer Detector (OD)

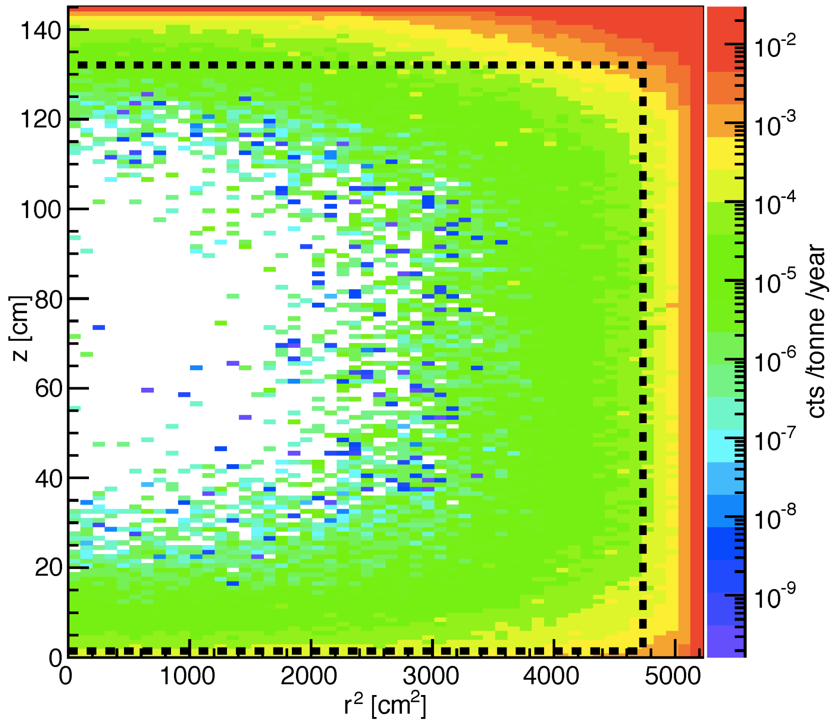


- Gd-loaded liquid scintillator (60 cm thick; 21.5 tons of Linear Alkylbenzene –LAB);
- Immersed in water tank;
- Segmented tanks – installation constraints;
- ~97% efficiency for neutrons.

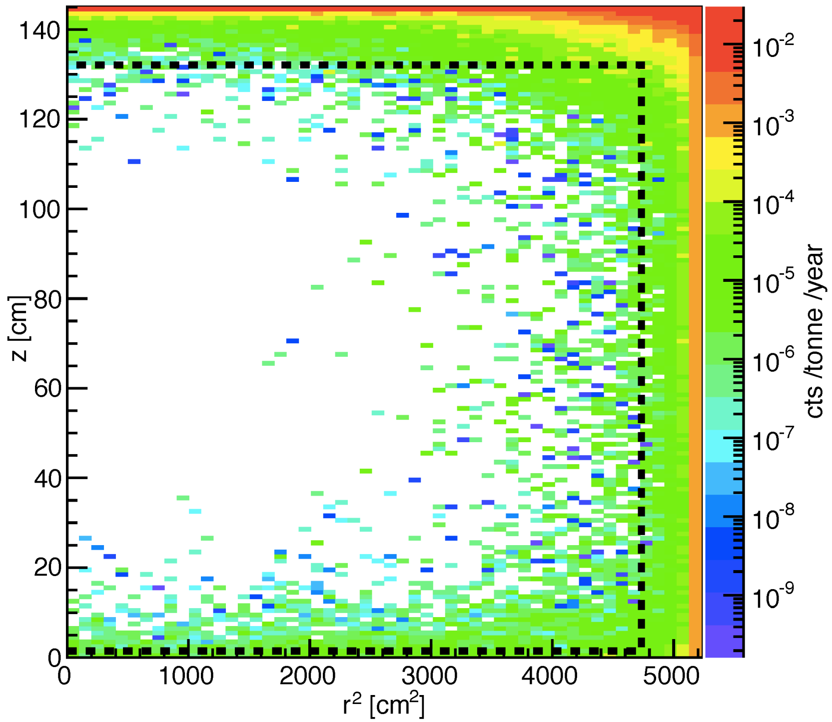


Outer Detector and "Skin"

Single NR scatter in TPC



Vetoed by Gd-LS and "skin"



- NR background plus ER leakage from sources external to the LXe; 6 - 30 keVnr acceptance);
- 50% NR acceptance and 99.5% ER discrimination);
- Addition of OD and "skin" allows to increase fiducial mass from 3.8 to 5.6 ton
- Dotted line shows the boundary of the 5.6 ton fiducial mass

LZ Backgrounds

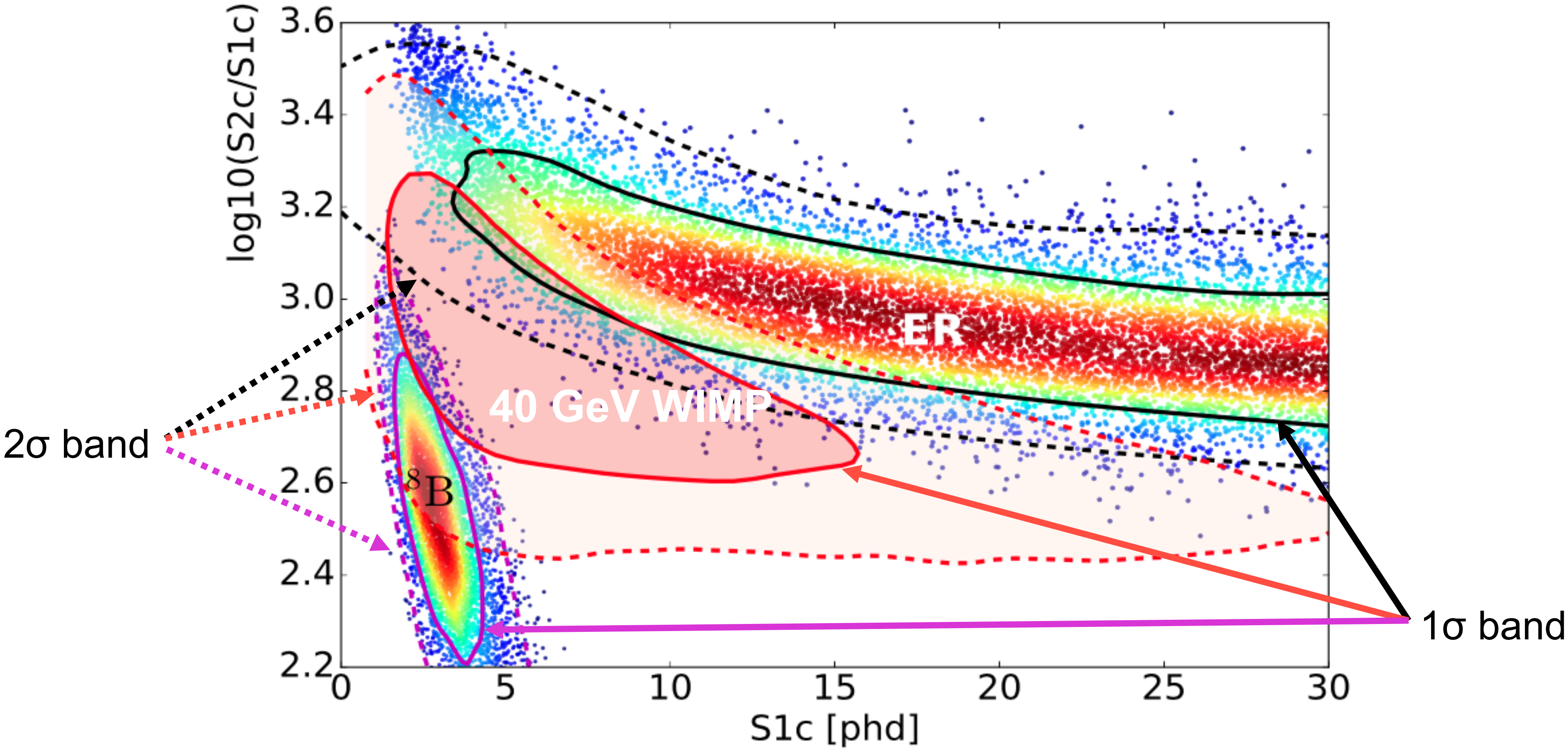
Background source	RE cts	NR cts
Detector components	6.2	0.07
Dispersed radionuclides (Rn, Kr, Ar)	911	–
Laboratory and cosmogenic	4.3	0.06
Fixed surface contamination	0.19	0.37
^{136}Xe 2υββ	67.0	–
Neutrinos (ν-e, ν-A)*	255	0.72
Total	**1240**	**1.22**
Total (99.5% ER desc., 50% NR eff.)	**6.22**	**0.61**
Total ER+NR background events	**6.82**	

* neutrinos events from ^{8}B not included

- Signal-like background events in 1000 live-days with 5.6-tonne fiducial mass: single scatters in ~1.5 - 6.5 keV (6- 30 keVnr),
- Largest contribution comes from **Rn**, followed by **ν-e** solar neutrino scattering and atmospheric **ν-A** scattering;

^{8}B background in LZ

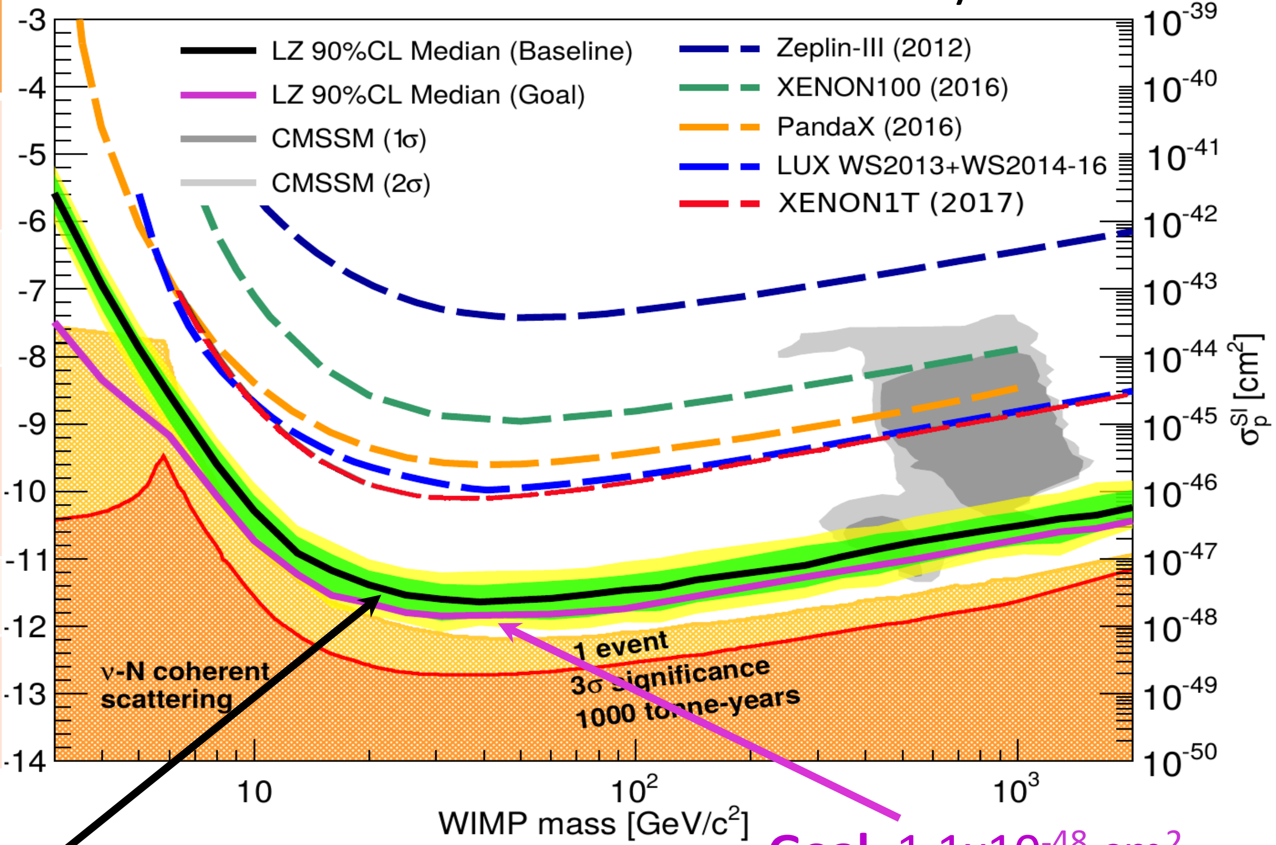
- **With PLR, neutrino background from solar ^{8}B** (7 events for 1000 days & 5.6 tons fiducial mass) **affects low-mass WIMPs only**.
- The statistic shown represent **5x** the expected **ER** background and **500x** the expected **^{8}B** background for the 1000 days run)



Projected Sensitivity - Spin Independent

Detector parameter	Baseline	Goal
Light collection	7.5%	12%
Extraction efficiency	95%	99%
Electron lifetime (μs)	850	2800
N-Fold	3	2
^{222}Rn (mBq in 7 tons)	13.4	0.67

5.6 Tons, 1000 live days
PLR used to estimate the sensitivity



Baseline: 2.3×10^{-48} cm^2 @40 GeV WIMP

Goal: 1.1×10^{-48} cm^2 @ 40 GeV WIMP

Summary

- LUX First Science Run in 2013; Second Science Run 2014-2016. In 2017, Published a new result for the full exposure of **47.5 tonne-days** (427 live-days).
- Improved Spin-Indep. WIMP Sensitivity by **factor 20x** since the state prior to 2013.
- Pioneer DD neutron, tritium and ^{83m}Kr calibrations contributed to improving the acceptance for low mass WIMPs.
- Measured LXe response to electron and nuclear recoils down to sub-keV energies - essential for data analysis of current and future LXe DM detectors
- LUX has taught us a lot for the next generation of dark matter detectors
- The ~50x larger fiducial **mass LZ detector continues on its path** towards commissioning at SURF in the beginning of 2020.

LUX & LZ Collaborations

LUX collaboration

30 institutions

~100 scientists

www.luxdarkmatter.org

LZ collaboration

36 institutions

~250 scientists, engineers and technicians

www.lzdarkmatter.org