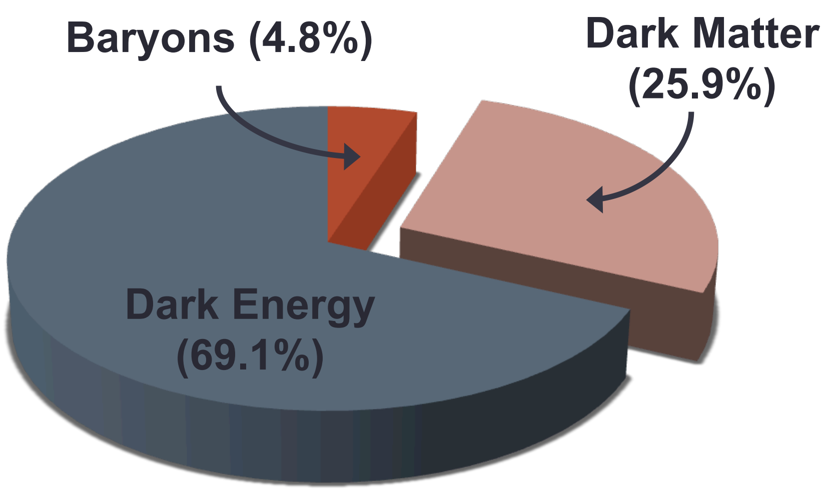
Improved Limits from the Large Underground Xenon Dark Matter Experiment

KICP Colloquium
Nicole A. Larsen
17 February 2016

Dark Matter



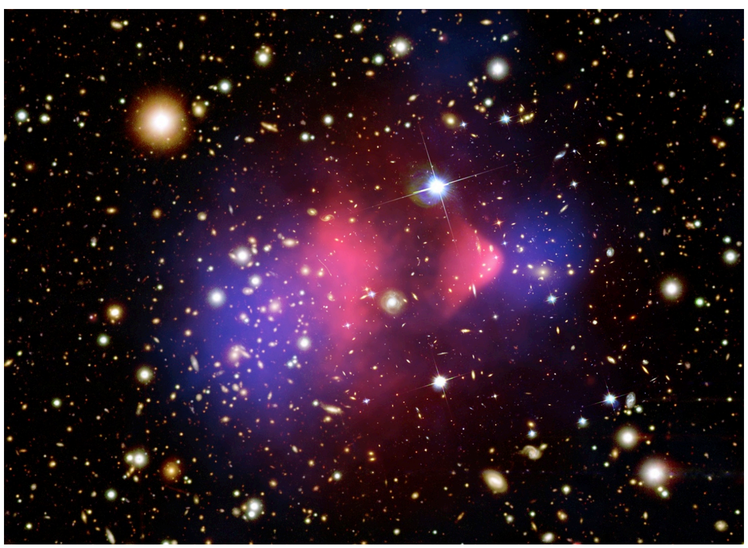


Image from http://apod.nasa.gov/

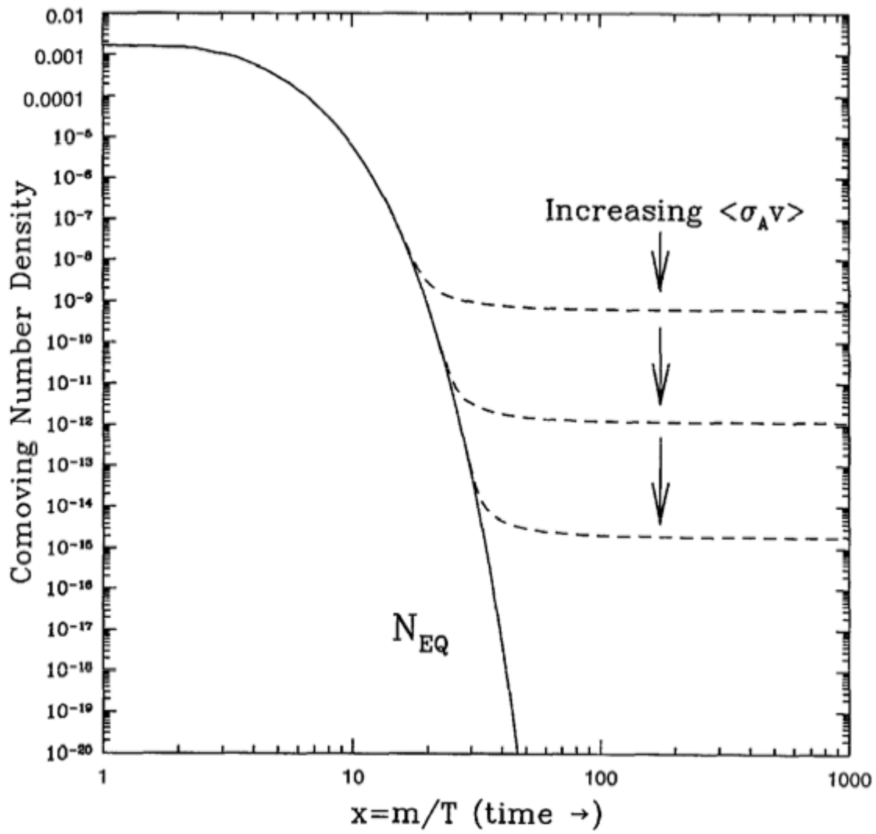
- Exerts a gravitational influence
- Interacts only weakly with normal matter
- Electrically neutral
- Stable
- Nonrelativistic freeze-out
- Requires beyond Standard Model physics
- WIMPs are a favored candidate (but there are alternatives)
- Evidence comes from:
  - Galactic rotation curves
  - Gravitational lensing
  - CMB/BAO
  - BBN

The WIMP Hypothesis

- **WIMP = "Weakly Interacting Massive Particle"**
- **Initially in thermal/chemical equilibrium with photons, electrons, baryons:**

$$\chi\chi \longleftrightarrow \text{SM SM}$$

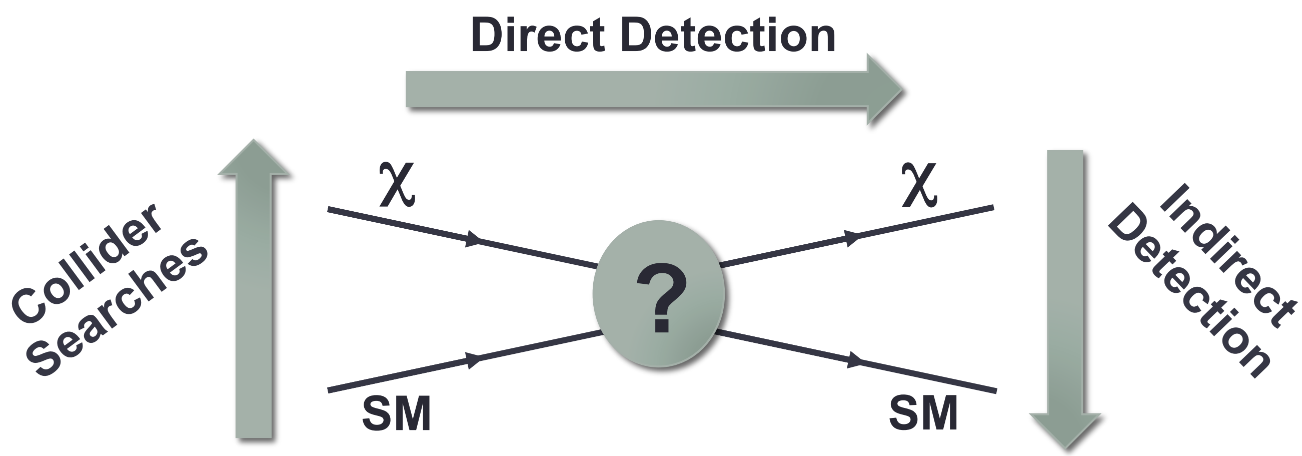
- **Freeze-out occurs as interaction rate drops below the universe's expansion rate**



WIMP mass $m_\chi \sim 100$ GeV/c^2 and $\sigma \sim$ weak-scale coupling yield exactly the observed relic abundance!

- **WIMPs arise naturally in many extensions to the Standard Model (SUSY…)**

Three Different Detection Strategies



- **Direct Detection**: As the Earth travels through the galactic dark matter halo, look for a flux of ambient WIMPs scattering off a Standard Model particle in the laboratory
- **Indirect Detection**: Look for Standard Model final-state particles such as gammas or neutrinos resulting from dark matter annihilations/decays.
- **Collider Searches**: Look for the production of non-Standard-Model particles in high-energy collisions of Standard Model particles.

Direct Detection

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_A} \int_{v>v_{min}} v f(\vec{v}) \frac{d\sigma}{dE_R} d^3v$$

Differential event rate wrt recoil energy (events/keV/kg/day)

Differential cross-section

Average over WIMP velocity distribution

- **WIMP-nucleon recoil spectrum is approximately a decaying exponential**
- **f(v) depends on halo model: typically Maxwellian truncated at galactic escape velocity (544 km/s) and account for Earth's motion through galaxy (220 km/s + annual modulation)**
- **Local dark matter density also depends on halo model: $\rho_0 \sim 0.3$ GeV/cm^3**

$$\frac{d\sigma}{dE_R} = \frac{m_A}{2\pi v^2} |\mathcal{M}|^2$$

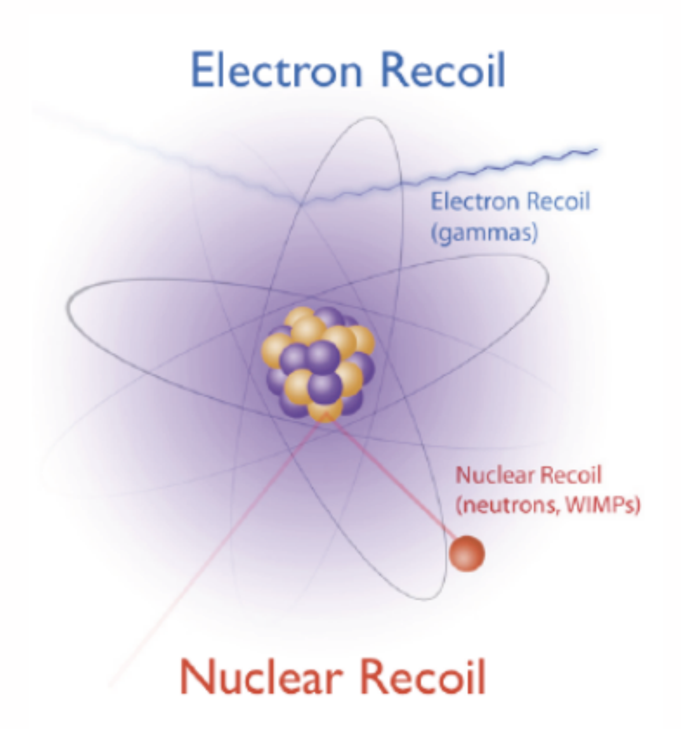
FERMI'S GOLDEN RULE

Scattering amplitude $|M|^2$ contains all the particle physics:

$|M|^2 \sim A^2 F^2(q)$ for SI interactions
$|M|^2 \sim (J+1/J) \langle S_p \rangle F^2(q)$ for SD interactions

Form factor $F^2(q)$ contains all the nuclear physics

Direct Detection



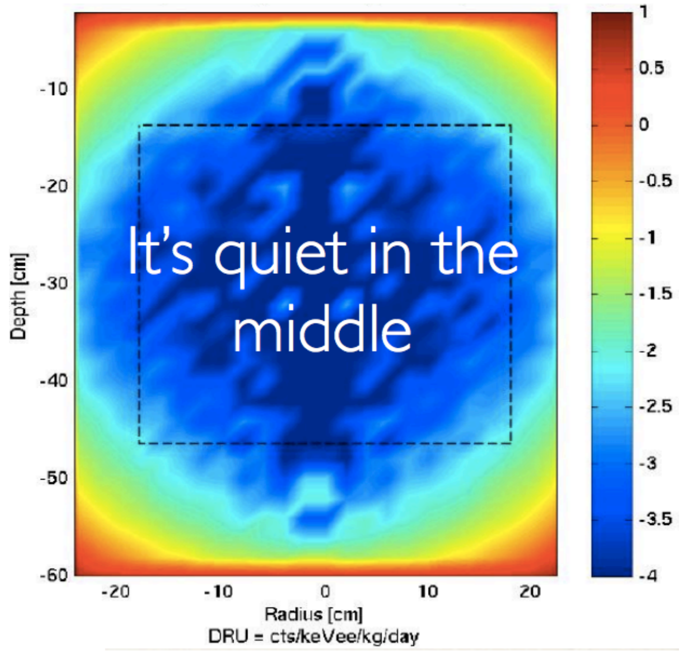
- WIMPs scatter elastically off nuclei
  - Recoil energies O(10 keV)
  - Expect <1 WIMP event/kg/year
- Neutrons also scatter off of nuclei; indistinguishable background
- Gammas and electrons scatter off atomic electrons

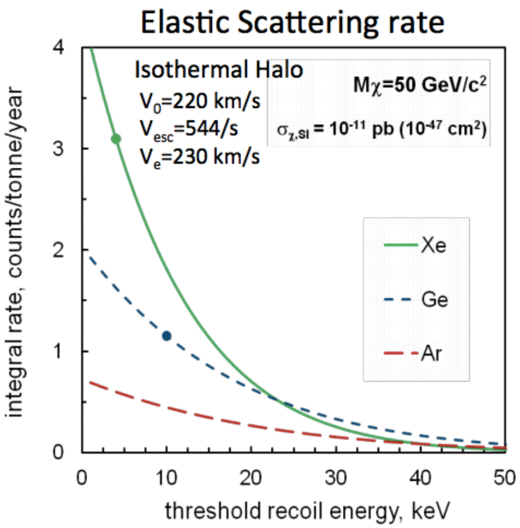
- Energy from scatters is typically deposited into one or more of three different channels:
  - Phonons
  - Scintillation
  - Ionization

LUX and other two-phase noble liquid detectors

Xenon as a Direct Detection Target

- **High density (3 g/cm^3) and high atomic mass (A = 131 g/mol)**
- **Scintillates brightly in the near-UV (178 nm) with fast (ns) response time**
- **Excellent ionization threshold and long electron drift lengths (~1 m)**
- **Odd isotopes => spin-dependent sensitivity.**

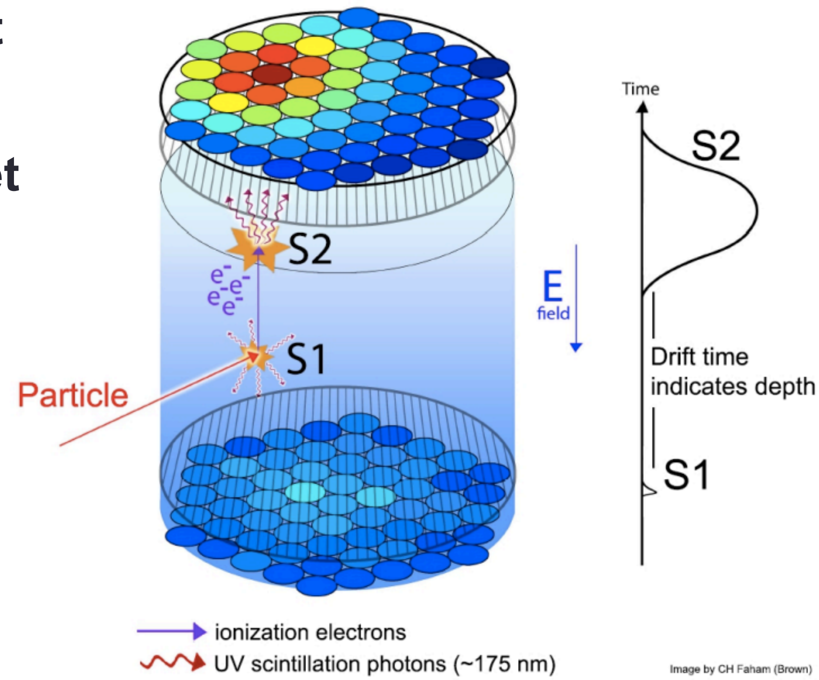




- **No long-lived intrinsic backgrounds**
- **Scalable to multi-ton size**
- **Self-shielding possible with 3D reconstruction**

Dual-Phase TPCs: Principle of Operation

- The target is cooled to condensation point => liquid topped by a thin layer of gas.
- An incident particle excites/ionizes a target atom which scintillates ("primary" or "S1" light).
- Ionization electrons produced are drifted upwards by an applied electric field and extracted into the gas phase, where they scintillate again ("proportional" or "S2" light).



3D imaging possible:

Timing between the S1 and S2 pulses yields z-position

PMT hit patterns yield xy-position

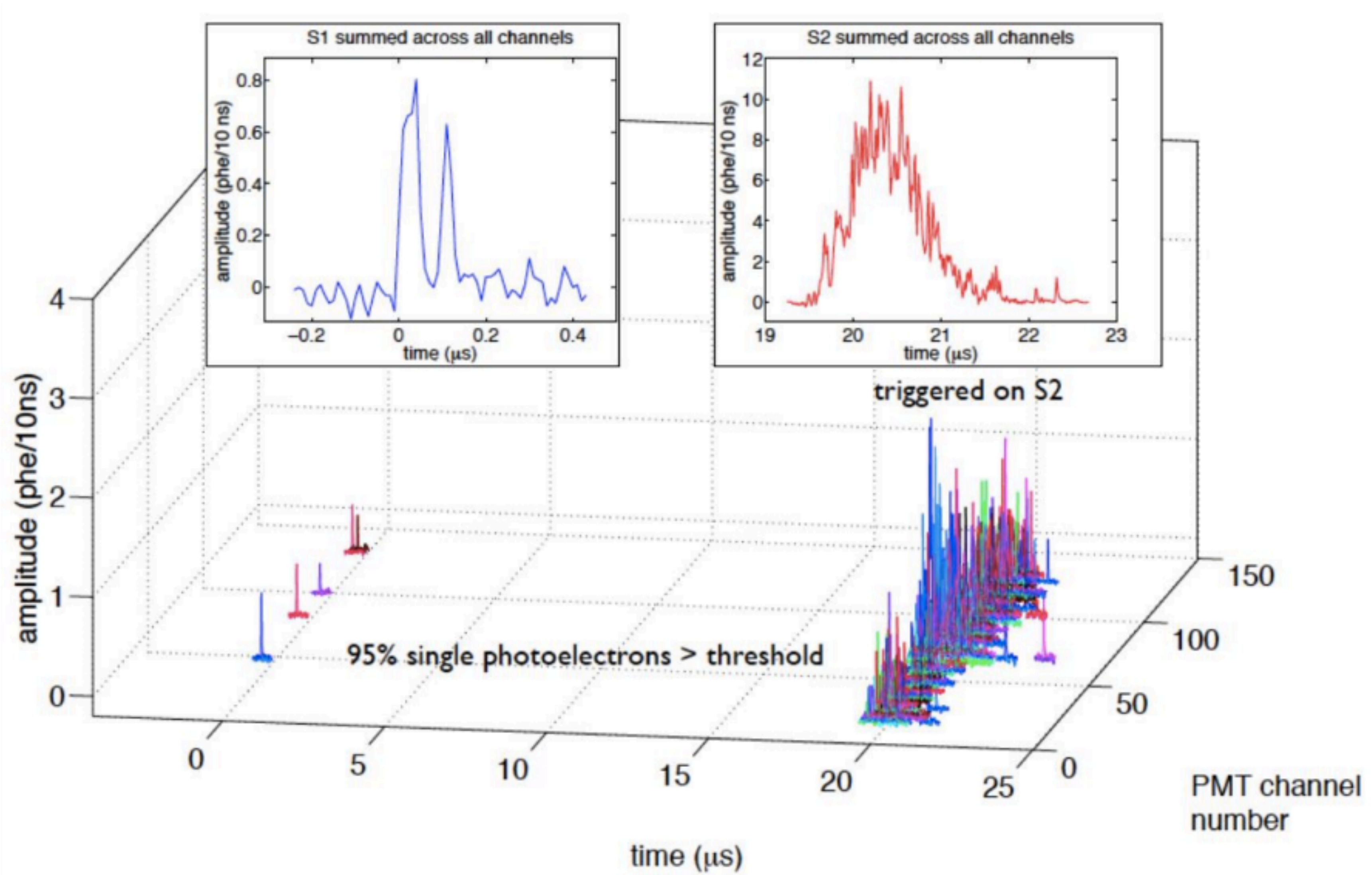
ER/NR discrimination possible:

Nuclear recoils produce dense tracks

Electron recoils produce less-dense tracks

=> $(S2/S1)_{\gamma} >> (S2/S1)_{neutron}$

A Typical Event: 1.5 keV Gamma



The LUX Collaboration

Brown

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Khadeeja Yazdani	Graduate Student

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Kevin Lesko	Senior Scientist
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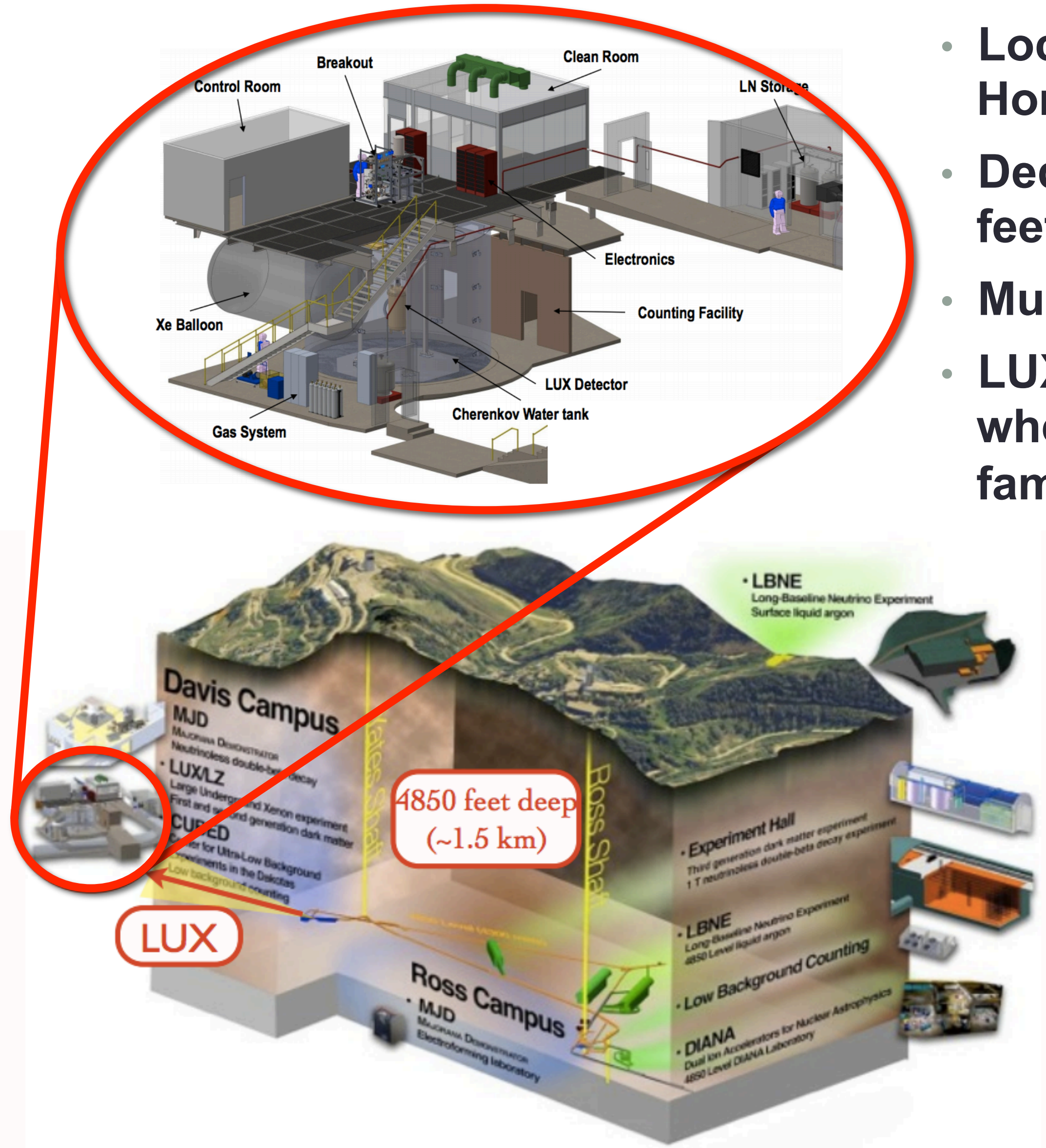
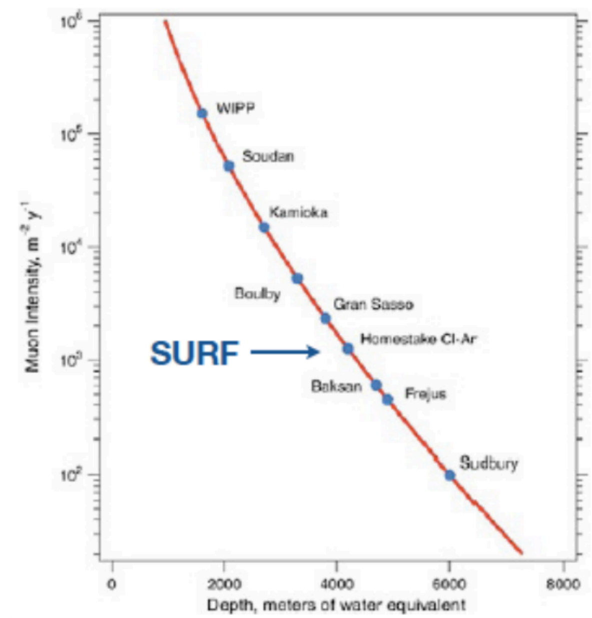
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student

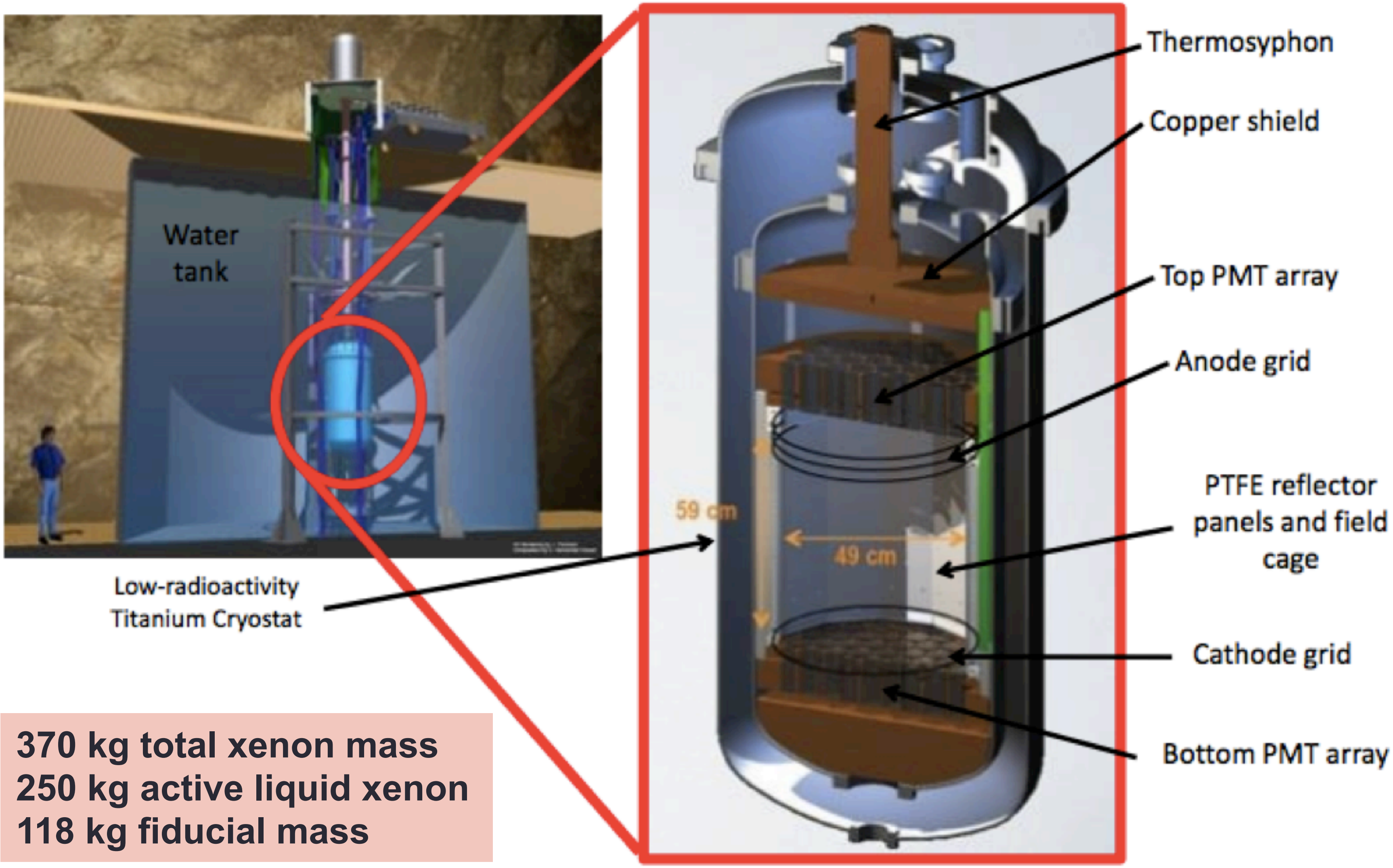
The Sanford Underground Research Facility

- Located in Lead, SD at the old Homestake gold mine
- Dedicated laboratory located 4850 feet underground (4300 m.w.e.)
- Muon flux reduced by a factor of 10^7
- LUX is located in the Davis Cavern, where Ray Davis performed his famous solar neutrino experiment.





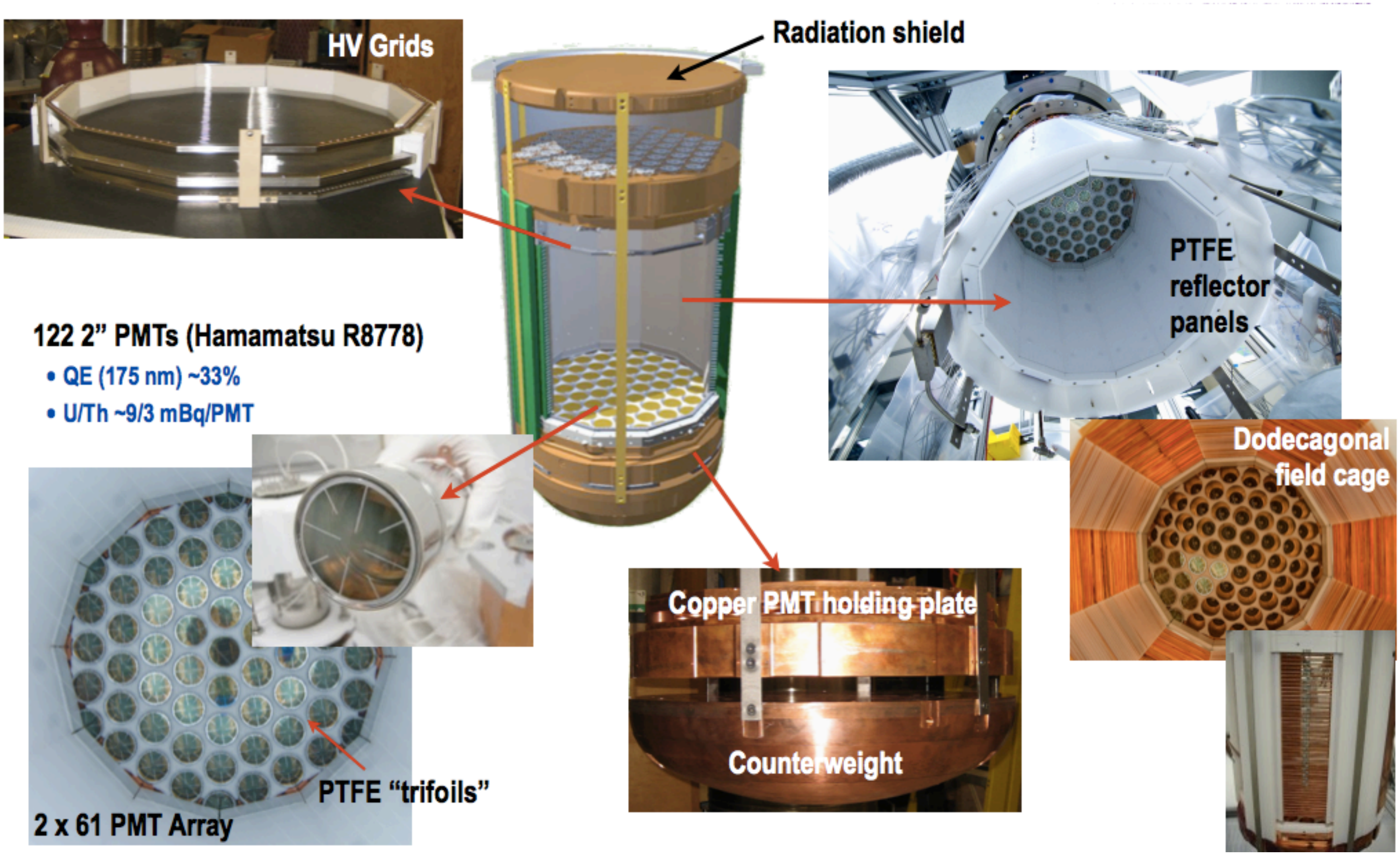
The Large Underground Xenon Experiment



370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

LUX instrument paper: NIM A 704 11-126(2013) (arXiv:1211.3788)

LUX Internals

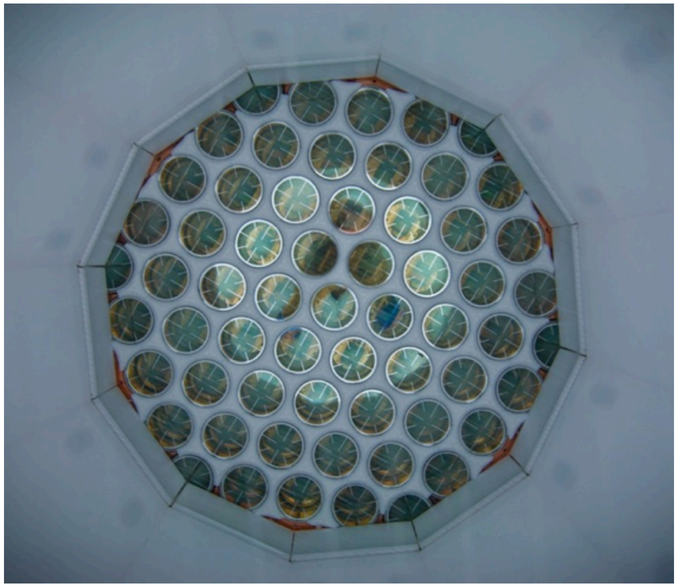


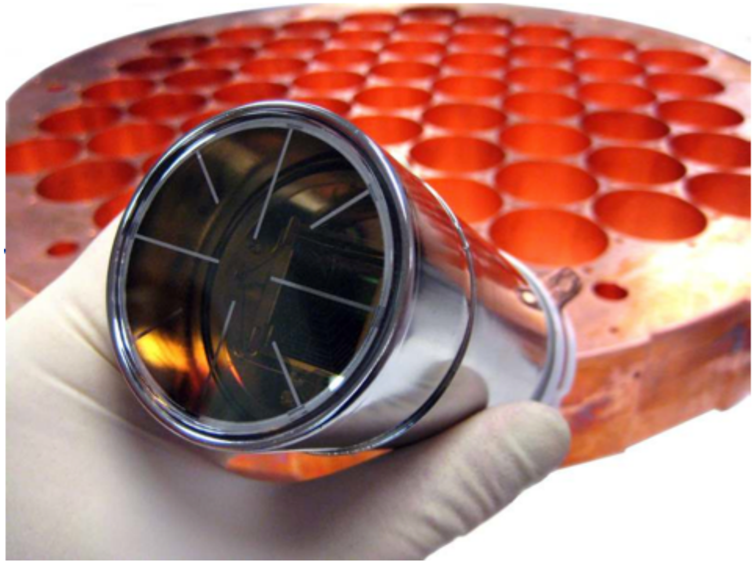
122 2" PMTs (Hamamatsu R8778)

- QE (175 nm) ~33%
- U/Th ~9/3 mBq/PMT

LUX PMTs

- **Extremely low radioactivity**
  - **< 9.5 mBq ^{238}U / PMT**
  - **< 2.7 mBq ^{232}Th / PMT**
  - **< 66 mBq ^{40}K / PMT**
- **33% quantum efficiency; 90% collection efficiency**
- **Gain = 3.3e6**
- **2" diameter provides high surface area coverage**
- **Efficient detection of 175-nm light**
- **Operates in the LXe temperature range (165 - 180 K)**





LUX Circulation, Cryogenics, and Purity

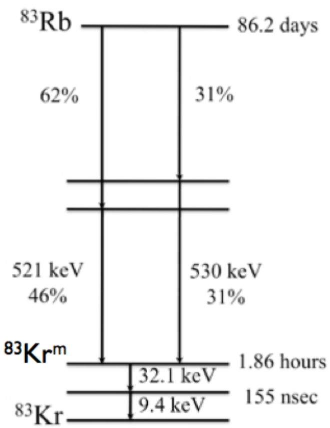
- **SAES MonoTorr PS4 heated zirconium getter removes electron-capturing impurities such as O_2 and N_2**
- **>250 kg/day of xenon is pumped out of the active volume, through the getter, and back (limited only by MAWP of KNF circulation pumps)**
- **In situ sampling system monitors xenon purity**
  - **Sensitive to 0.7 ppb O_2 and 0.5 ppt Kr**

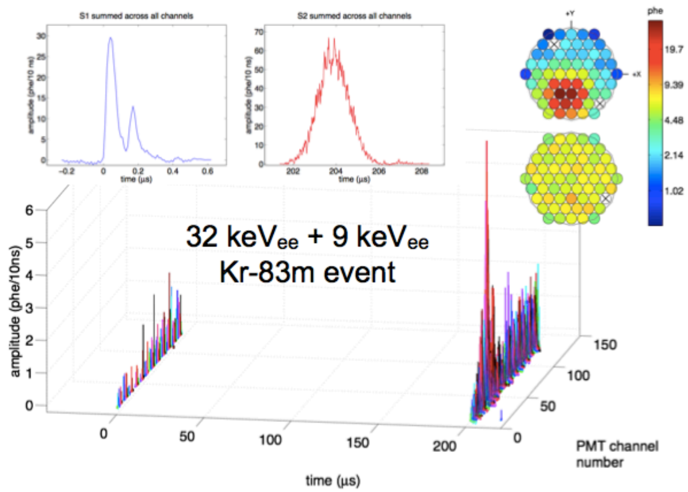
Xenon handling and purification systems

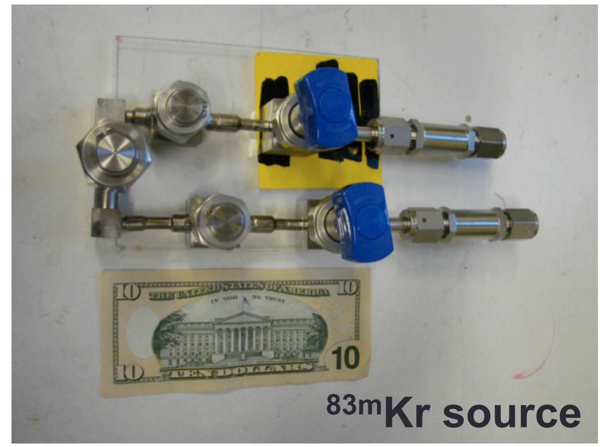
- **LN-based themosyphons produce up to ~200 W cooling power, and three heat exchangers in the circulation path reduce cooling power requirement by 98%**

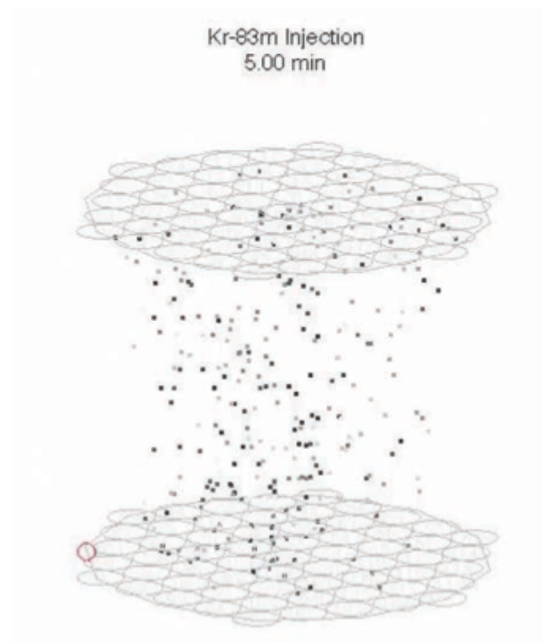
Detector pressure stable to within 1% and temperature to within 0.2 K during normal operations

LUX Calibrations – ^{83m}Kr Injection



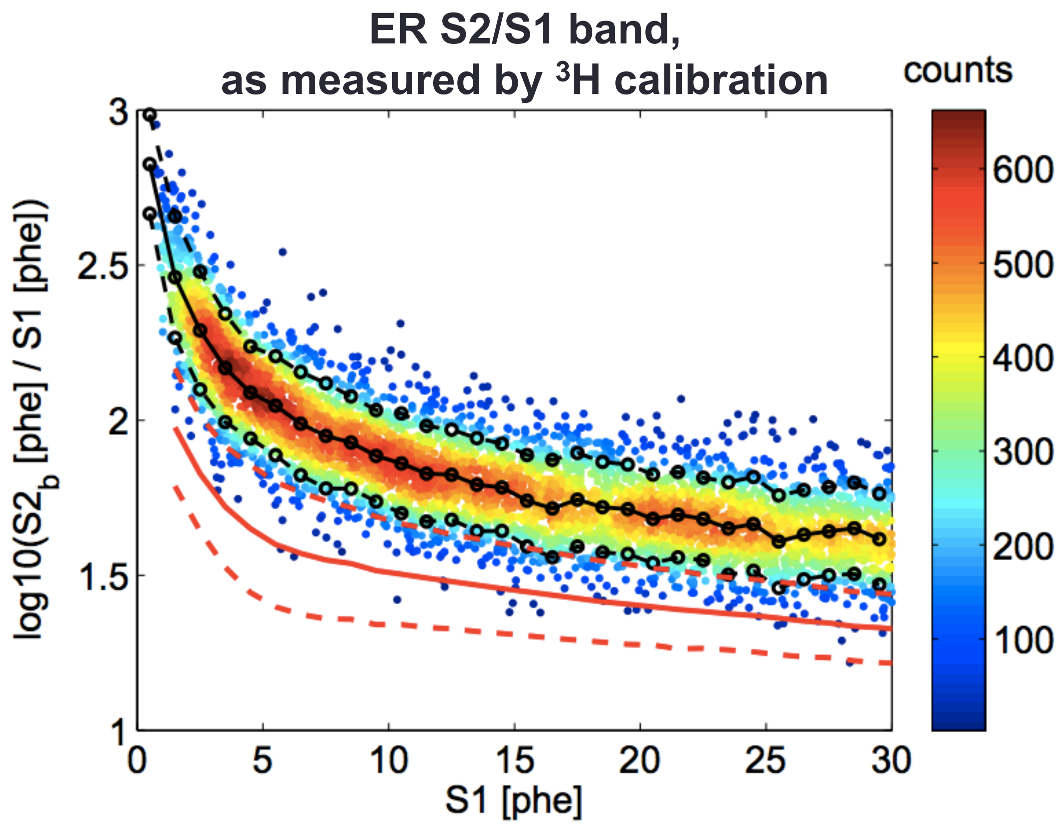






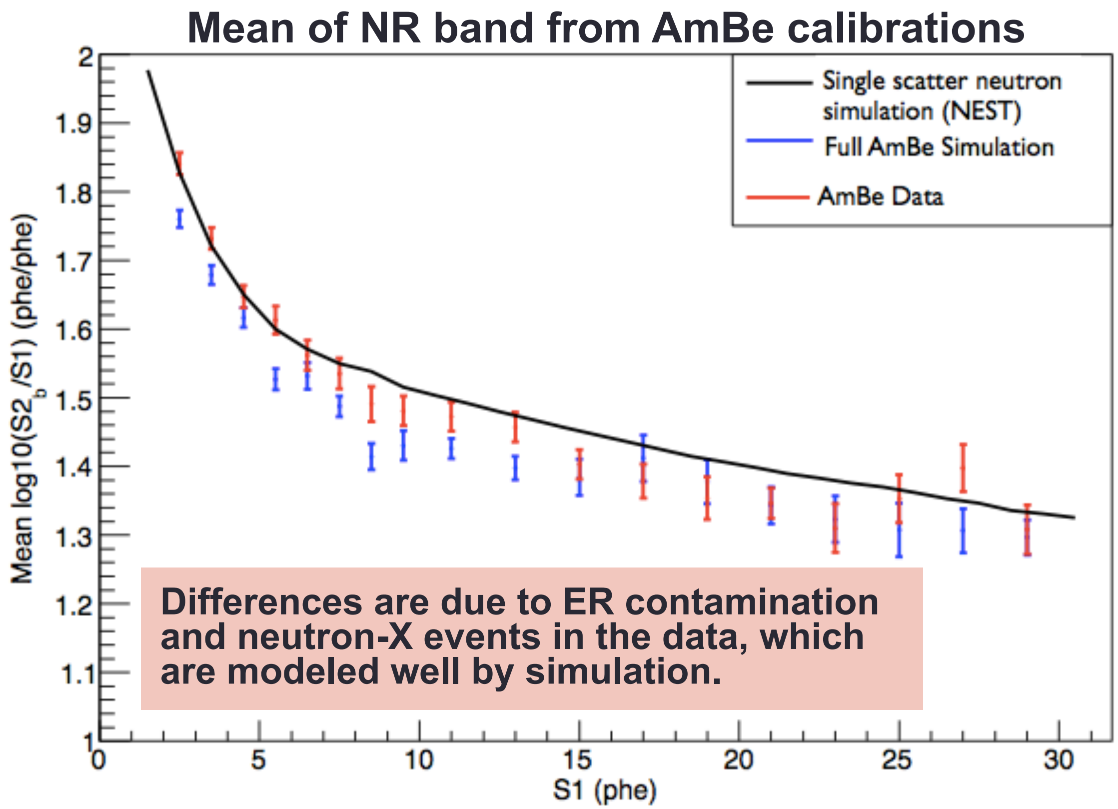
- ^{83}Rb decays to ^{83m}Kr, which is flushed directly into the xenon circulation path and decays away on a few-hour timescale.
- Used for:
  - Determination of fiducial volume
  - Position-based S1 and S2 corrections
  - Measurement of electron lifetime (~1 injection/week)
- Bonus: tomography of xenon flow

LUX Calibrations – CH_3T Injection



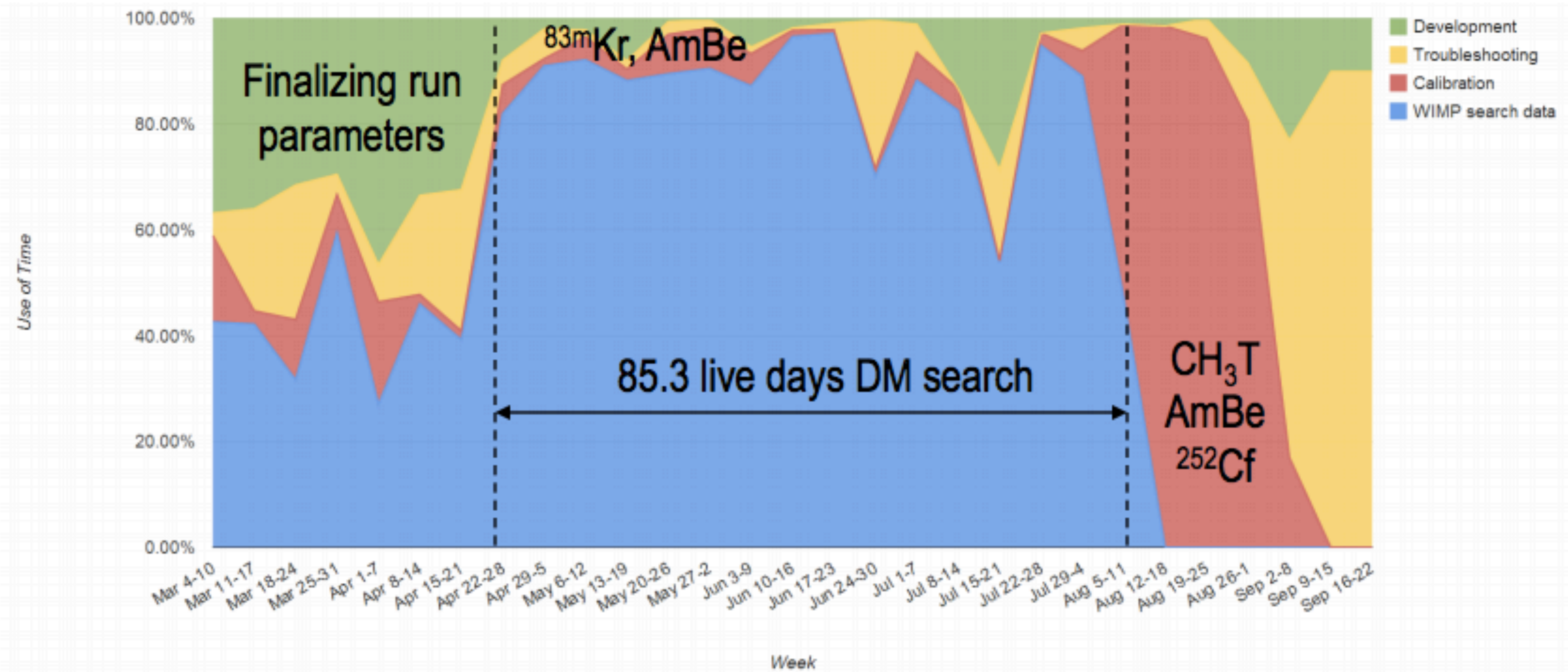
- Tritiated methane doped directly into the xenon is used to calibrate electron recoil band with very high statistics down to very low energies.
  - Beta source with 18 keV endpoint energy and 12-year half-life
  - Tritiated methane can be fully removed by circulating xenon through the getter, with ~ few hour time constant

LUX Calibrations – AmBe and ^{252}Cf



- Six acrylic source tubes allow for deployment of sources external to the LUX cryostat (must overcome self-shielding)
- AmBe and ^{252}Cf used for NR calibrations

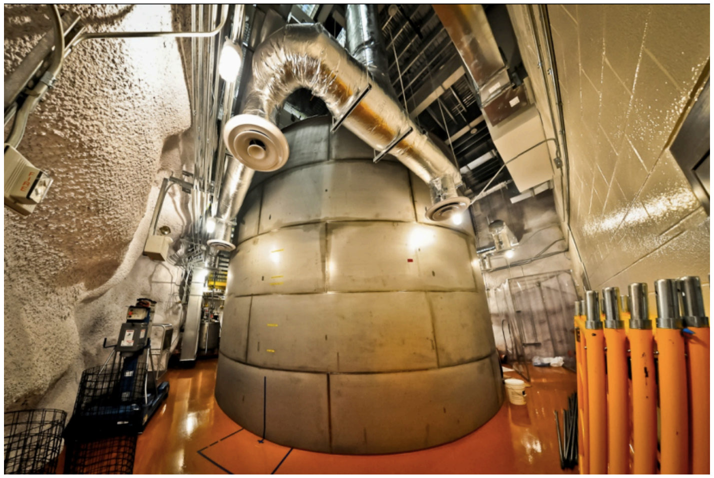
LUX First Underground Run - Overview



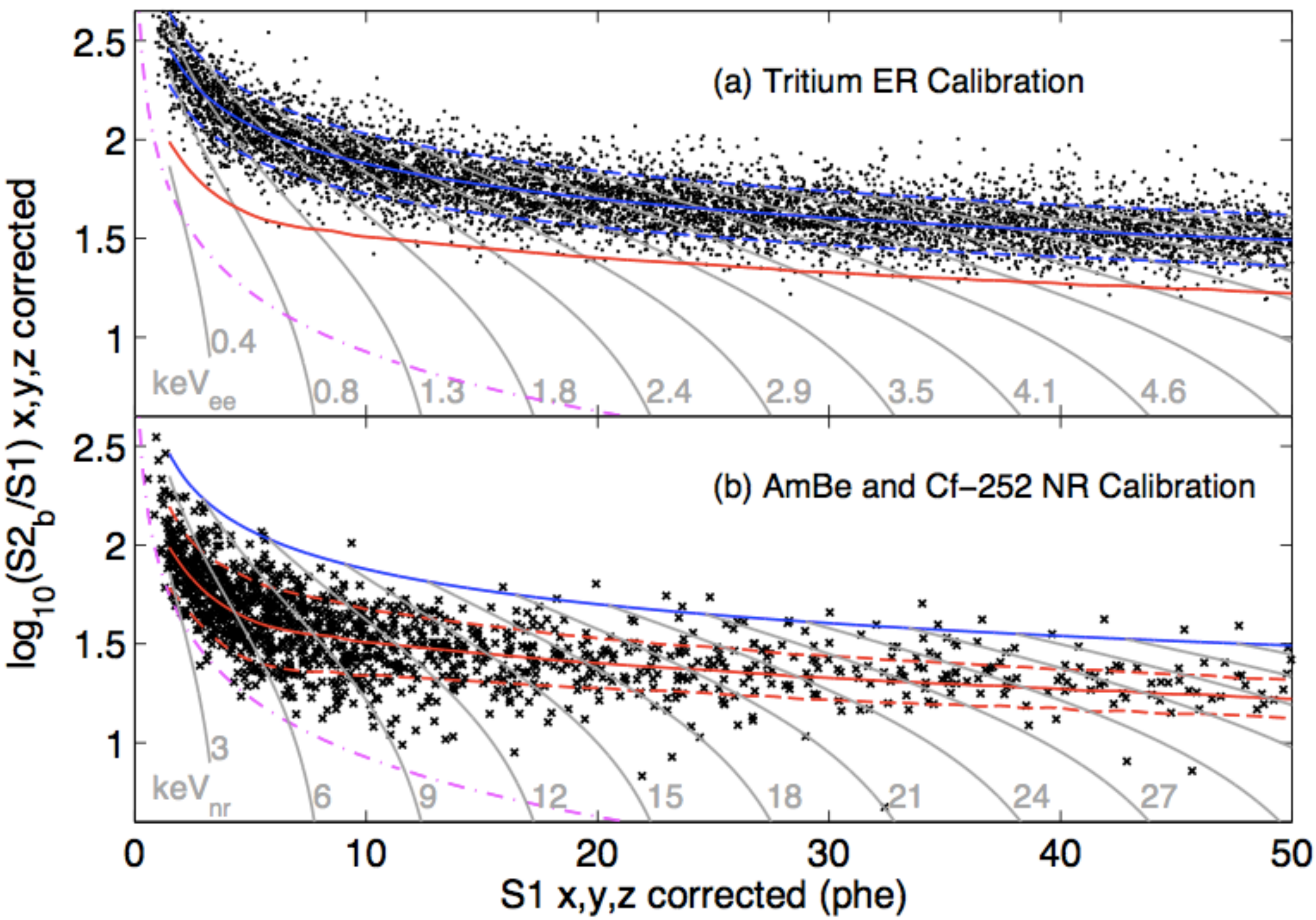
- Detector cool-down January 2013; xenon condensed mid-February 2013; WIMP-search data collected from April to August 2013.
- Overall 95% data-taking efficiency during the WIMP search period
- Total: 85.3 live-days of WIMP-search data collected

LUX First Underground Run - Highlights

- Xenon purity: electron drift length 87-135 cm
  - Monitored weekly using ^{83m}Kr injections
- Drift field: 181 V/cm (speed 1.5 mm/μs) with 99.6% ER discrimination
- Light collection efficiency: 14% (includes detector geometry and PMT QE; 3D corrections provided by ^{83m}Kr calibrations)
- Fiducial mass: 118.3 +/- 6.5 kg
  - Selection based on α events from grids and Teflon
- WIMP-search window: ~3-25 keV_{nr}



Electron Recoil Discrimination in LUX



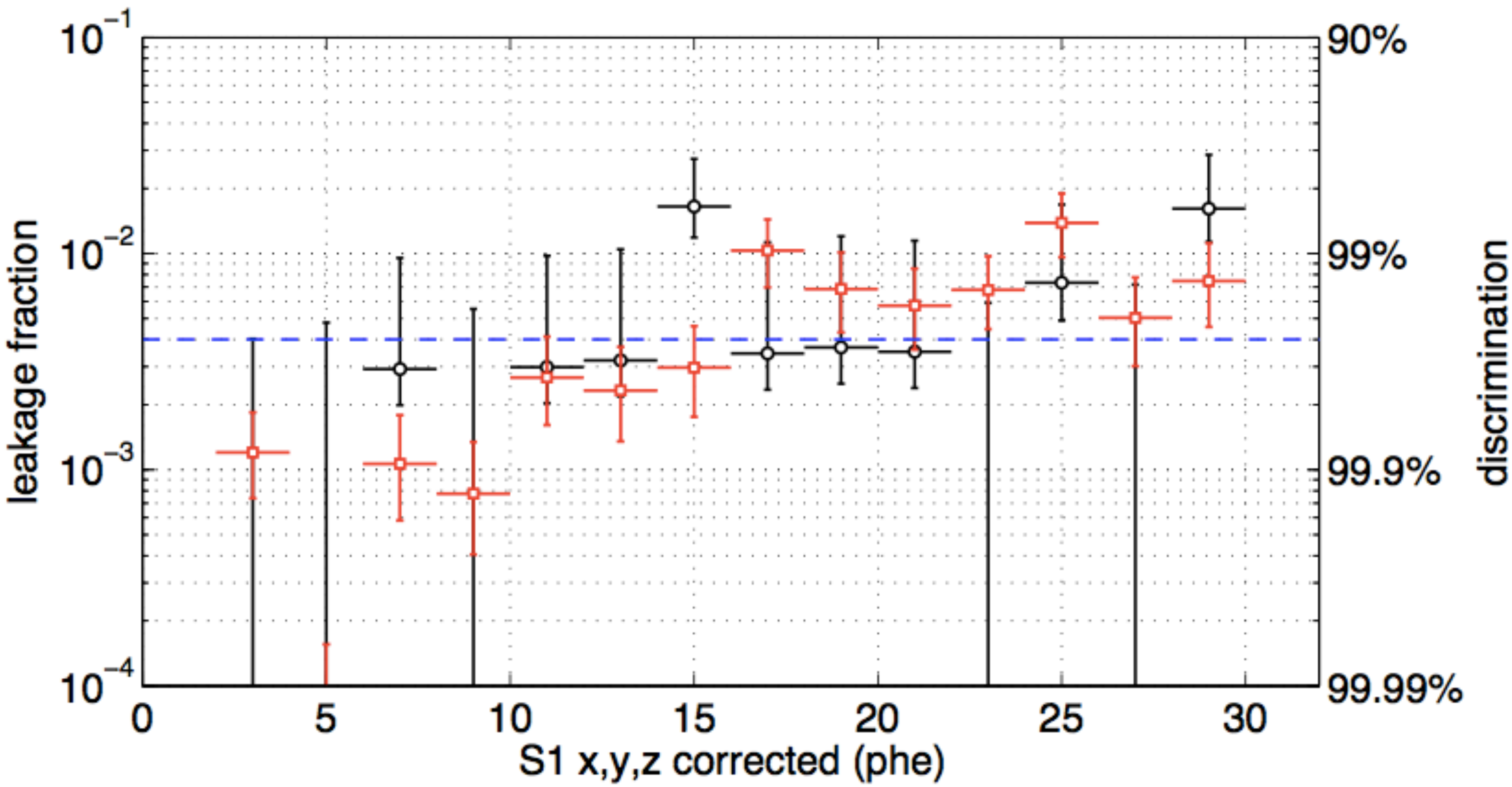
Red = mean of nuclear recoil band

Blue = mean of electron recoil band

Gray contours indicate constant energies using an S1-S2 combined energy scale

Average ER discrimination (with 50% NR acceptance): 99.6 %

Electron Recoil Discrimination in LUX



Black: leakage from counting events from the dataset
Red: projections of Gaussian fits below the nuclear recoil band mean

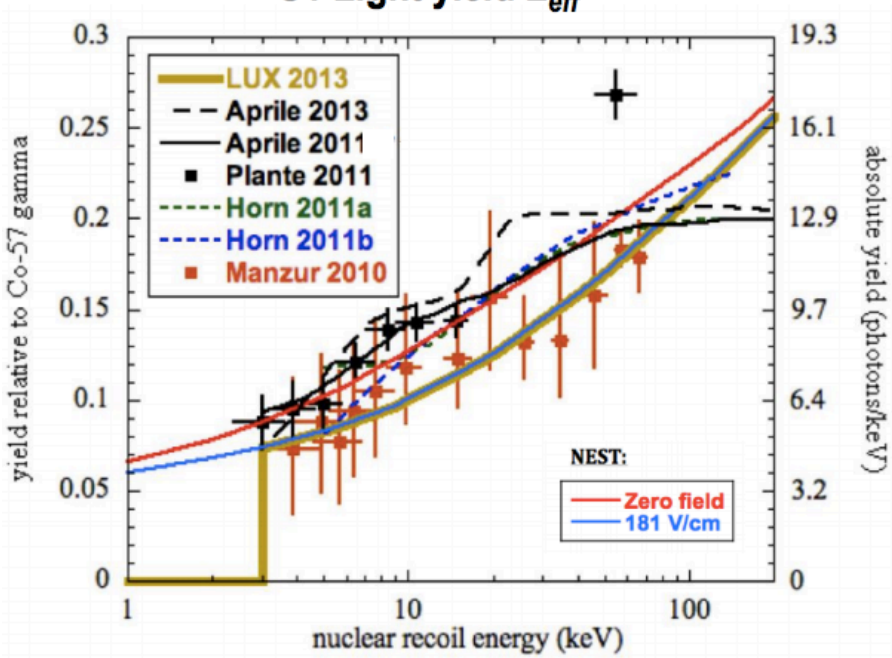
Average ER discrimination (with 50% NR acceptance): 99.6 %

Charge and Light Yield in LUX

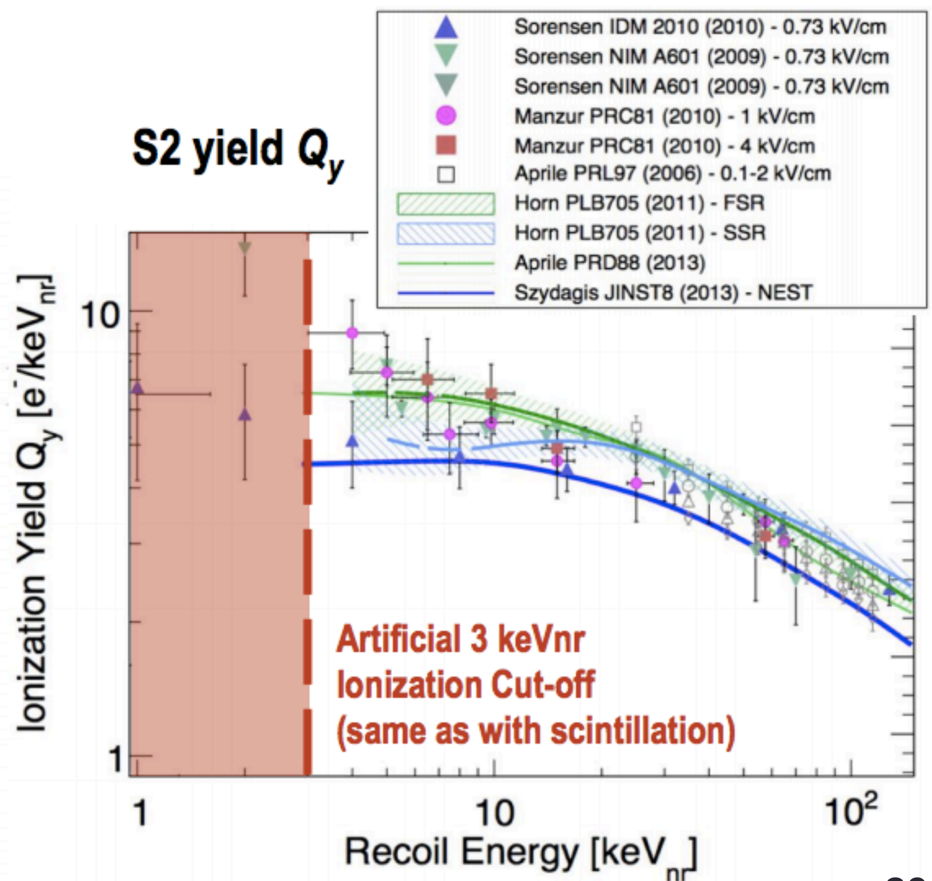
- **Modeled using the Noble Element Simulation Technique (NEST), based on canon of existing data**
- **Artificial cutoff below 3 keV$_{nr}$, to be conservative**

NEST Paper: arXiv:1106.1613

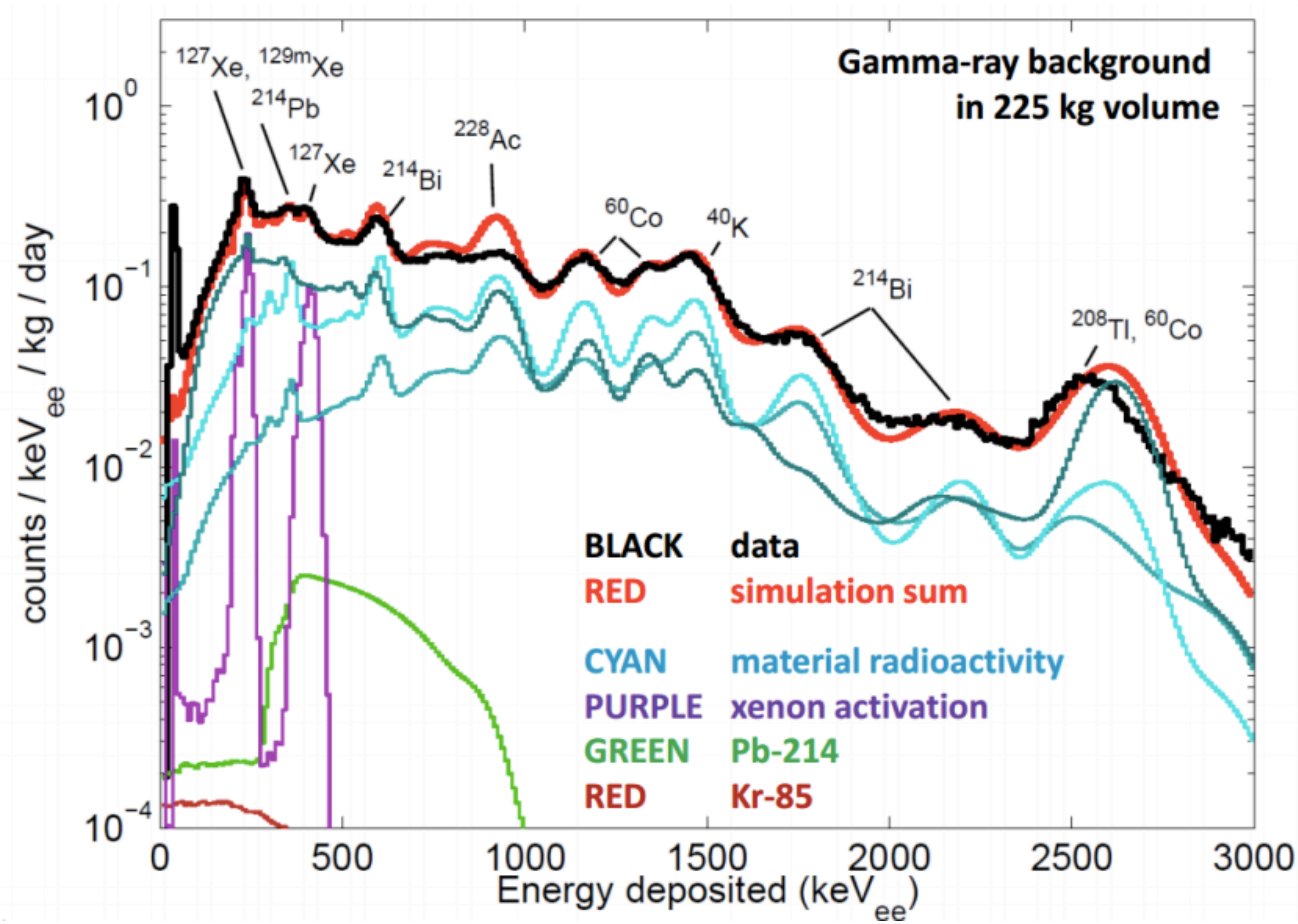
S1 Light yield L_{eff}



S2 yield Q_y

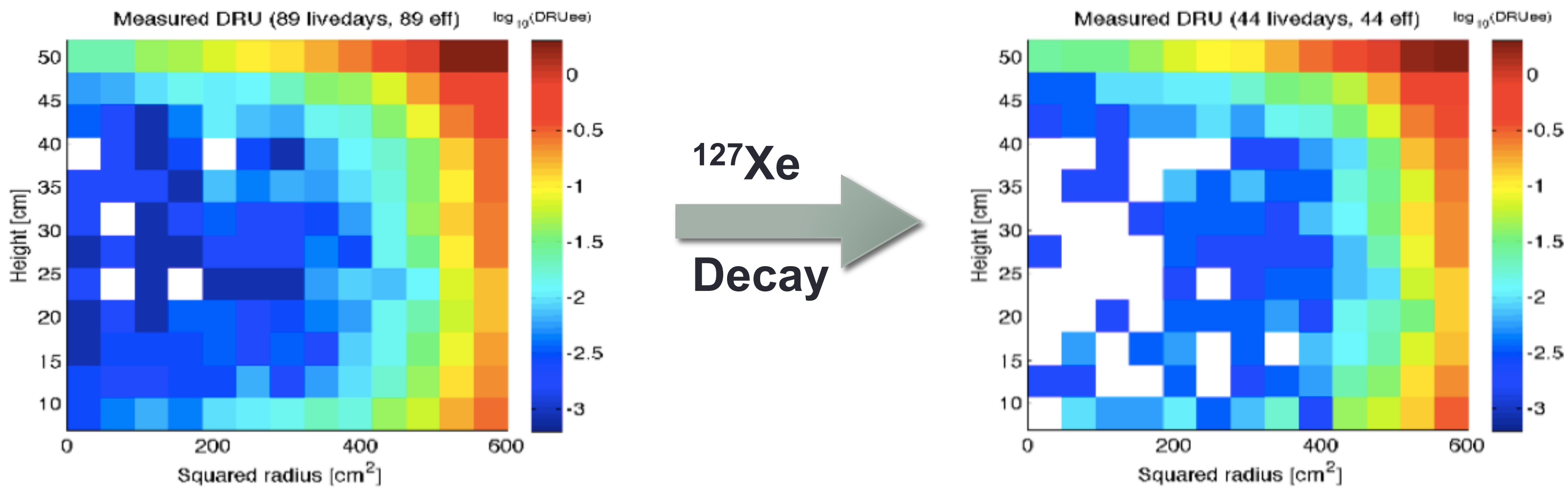


Backgrounds in LUX



Full gamma spectrum, excluding region ±2 cm from the grids

Backgrounds in LUX



Background Component	Source	10^{-3} x events/keVee/kg/day
γ-rays	Internal Components, including PMTs (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4-day half-life)	Cosmogenic (0.87 to 0.28 during run)	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	^{222}Rn	0.11-0.22 (90%-CL)
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.17 \pm 0.1_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.1 \pm 0.2_{stat}$

LUX backgrounds paper: arXiv:1403.1299

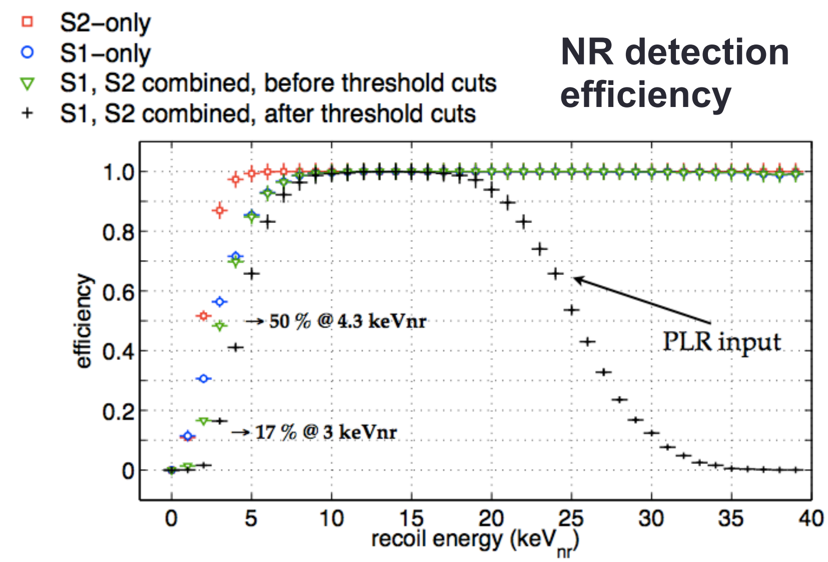
Event Selection and Cuts

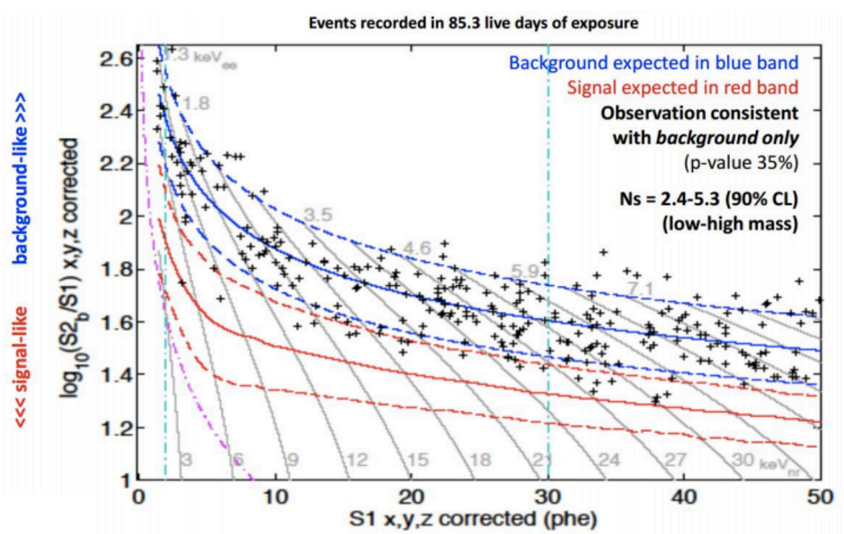
Cut	Explanation	Events Remaining
All Triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918,901
Single Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585,686
S1 energy	Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-18 keVnr)	26,824
S2 energy	Accept 200-3300 phe (>8 extracted electrons) Removes single electron / small S2 edge events	20,989
S2 Single Electron Quiet Cut	Cut if >100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)	19,796
Drift Time Cut away from grids	Cutting away from cathode and gate regions, 60 < drift time < 324 us	8731
Fiducial Volume radius and drift cut	Radius < 18 cm, 38 < drift time < 305 us, 118 kg fiducial	160

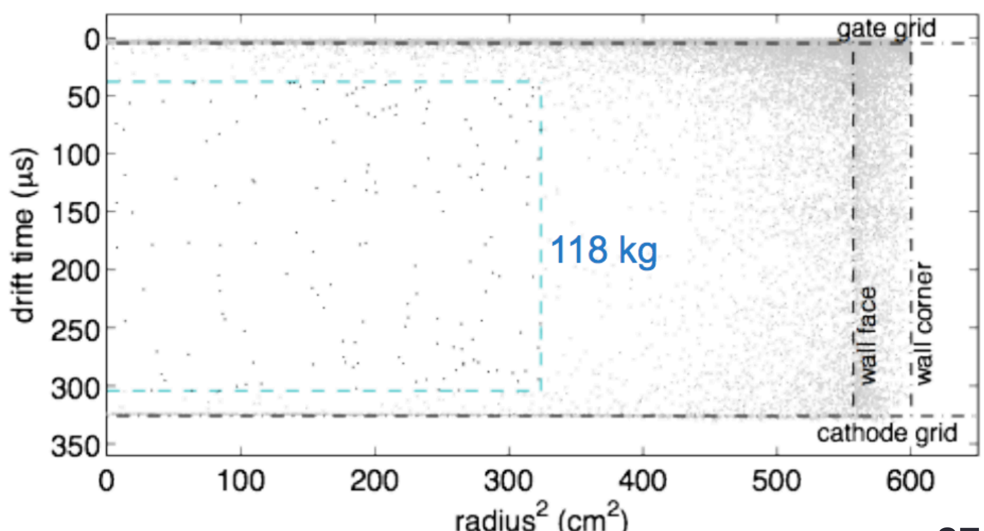
Only simple, obvious cuts – no tuning beyond selecting a threshold, high energy cutoff, and fiducial volume.

The LUX First WIMP-Search Result

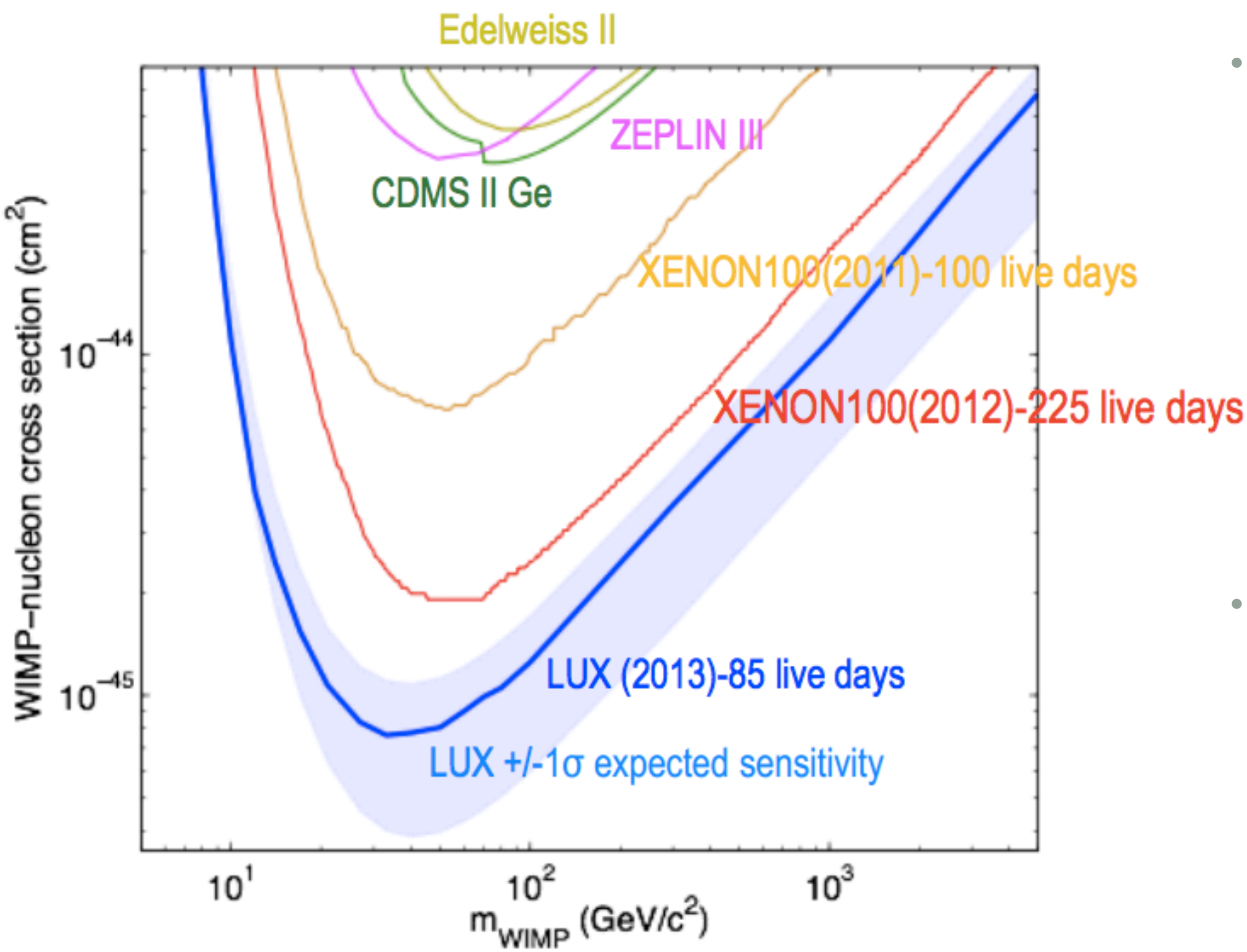
- **After all selection cuts, 160 candidate events left in the fiducial volume**
- **Distribution is consistent with electron recoil background and no WIMP signal with a p-value of 0.35 from Profile-Likelihood Ratio Analysis with incorporated background models, detector effects, and efficiencies**







The LUX First WIMP-Search Result



- **World's best limit on spin-independent WIMP-nucleon elastic scattering cross section:**

7.6×10^{-46} cm^2
for 33-GeV WIMPs

- **Ruled out the possible low-mass WIMP signals reported by DAMA, CoGeNT, and CDMS-II Si**

LUX 2013 result: PRL.112.091303 (arXiv:1310.8214)

The LUX First WIMP-Search Result And Beyond...

Improved WIMP scattering limits from the LUX experiment

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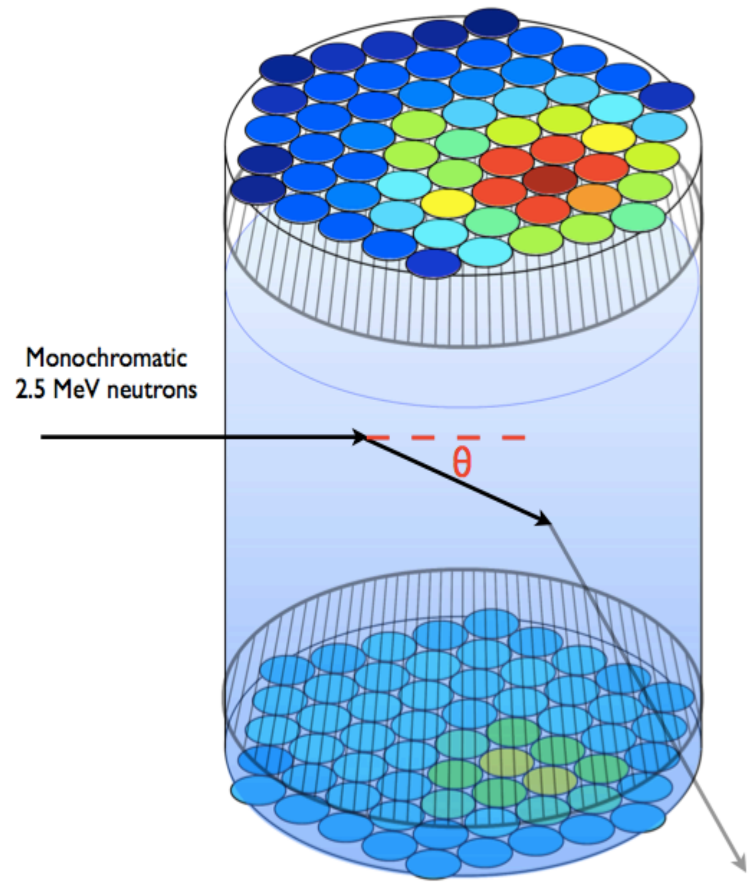
(LUX Collaboration)

LUX 2015 reanalysis paper: arXiv:1512.03506

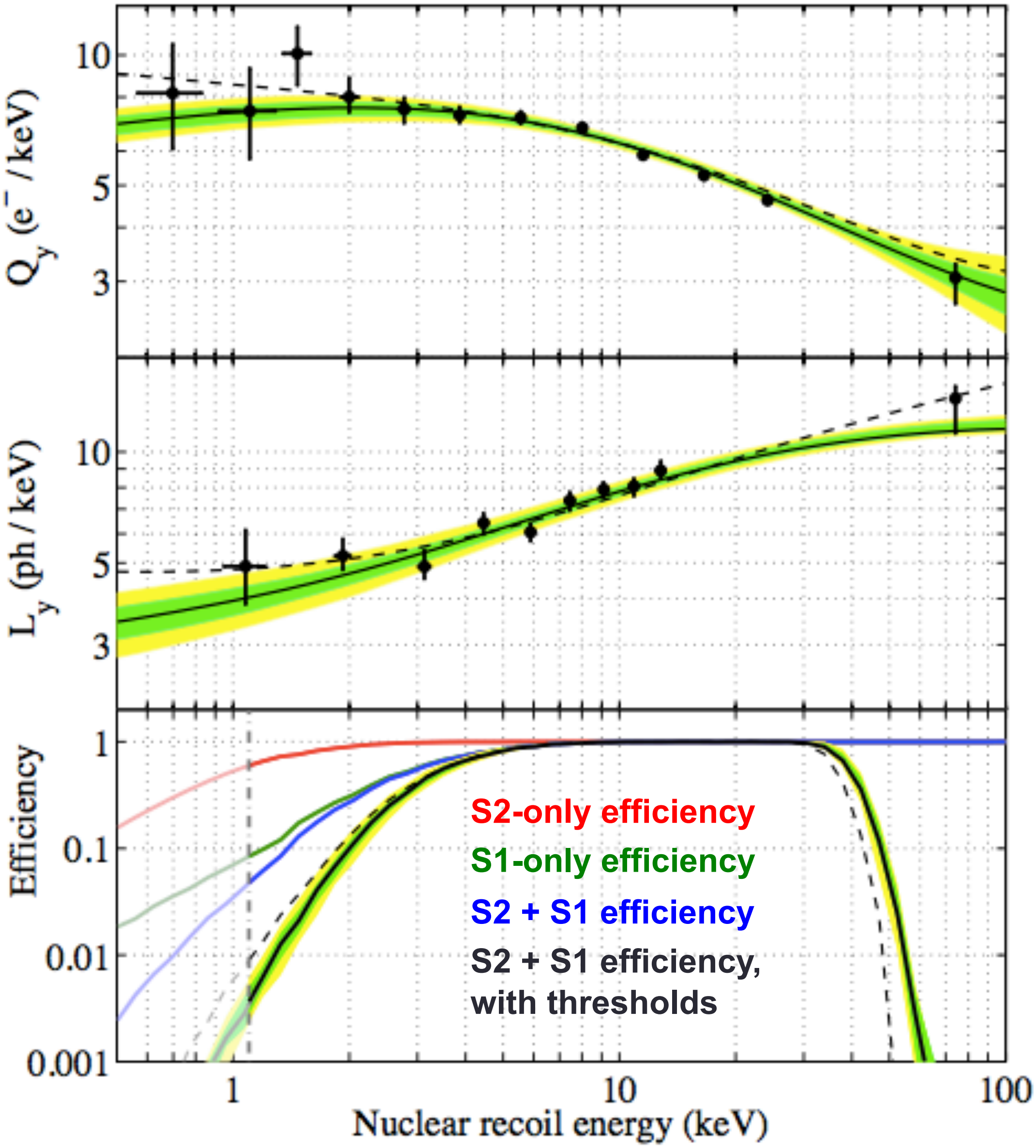
New NR Calibrations

- Adelphi DD108 deuterium-deuterium fusion source deployed adjacent to the water tank produces a 2.45 MeV mono-energetic neutron beam
- Neutrons collimated by an air-filled PVC pipe extending into the water tank 16 cm below the xenon liquid surface
- Select double-scatters, then recoil energy can be precisely determined from kinematics
- 107 live-hours of NR events acquired (~ 1×10^8 neutrons/sec)



$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

New NR Calibrations



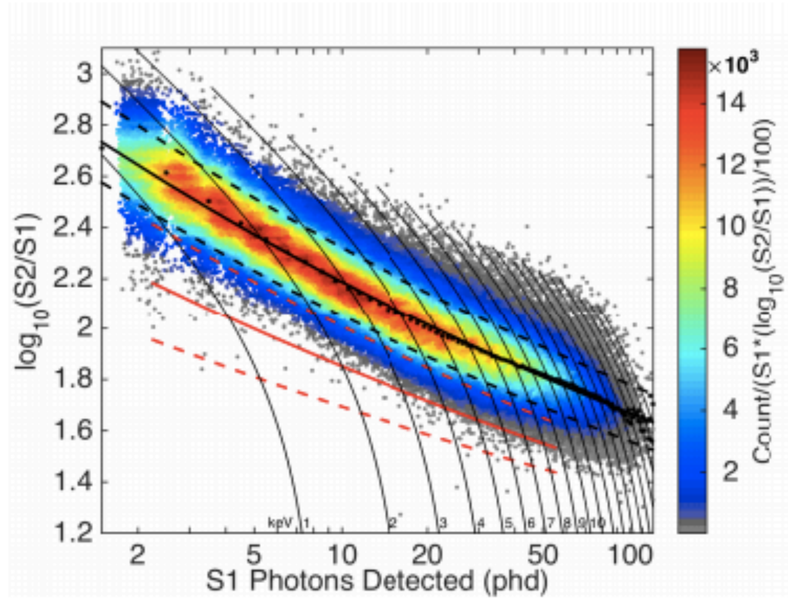
- Charge yield (top) and light yield (middle) measured for the first time for low-energy nuclear recoils in xenon below 3 keV_{nr} (0.7 keV_{nr} up to 75 keV_{nr})

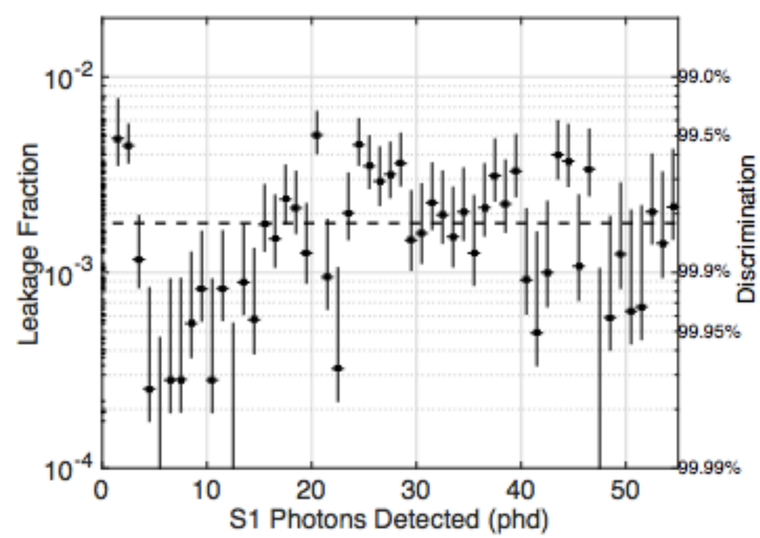
New lower energy threshold: 1.1 keV_{nr}

Extended Tritium Calibrations

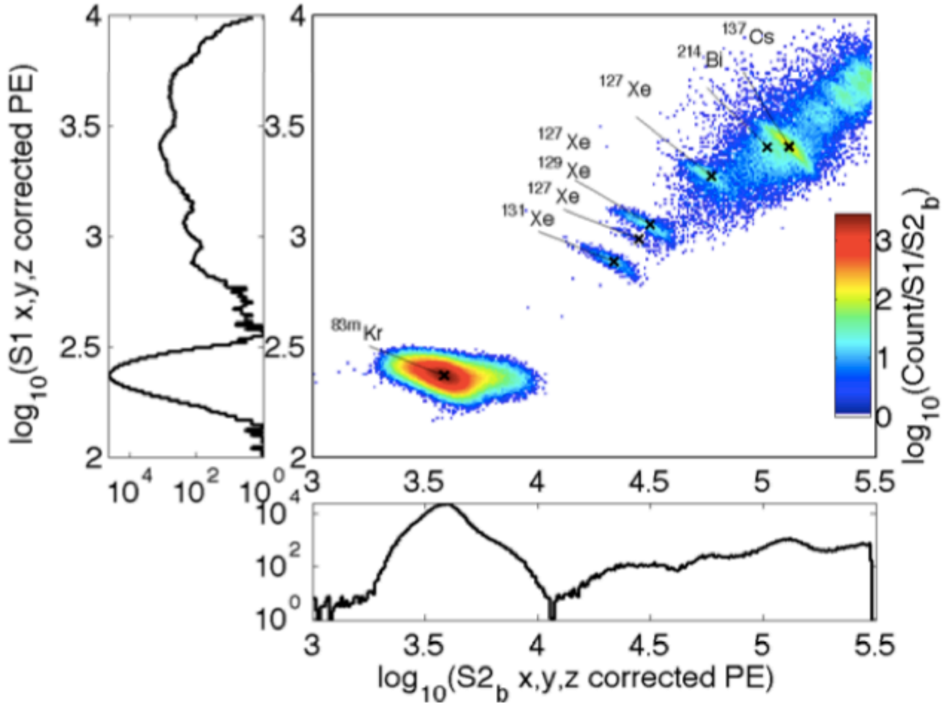
- In December 2013 10 Bq of CH_3T injected into the xenon
  - 17000 events in the fiducial volume
  - Compare to 800 mBq used for 2013 result
- Precise measurement of light and charge yield for low-energy ER events
- Width of ER band characterized in terms of detector resolution and event-by-event fluctuations
- ER/NR discrimination measured to be 99.81% ± 0.02% (stat) ± 0.1% (sys)

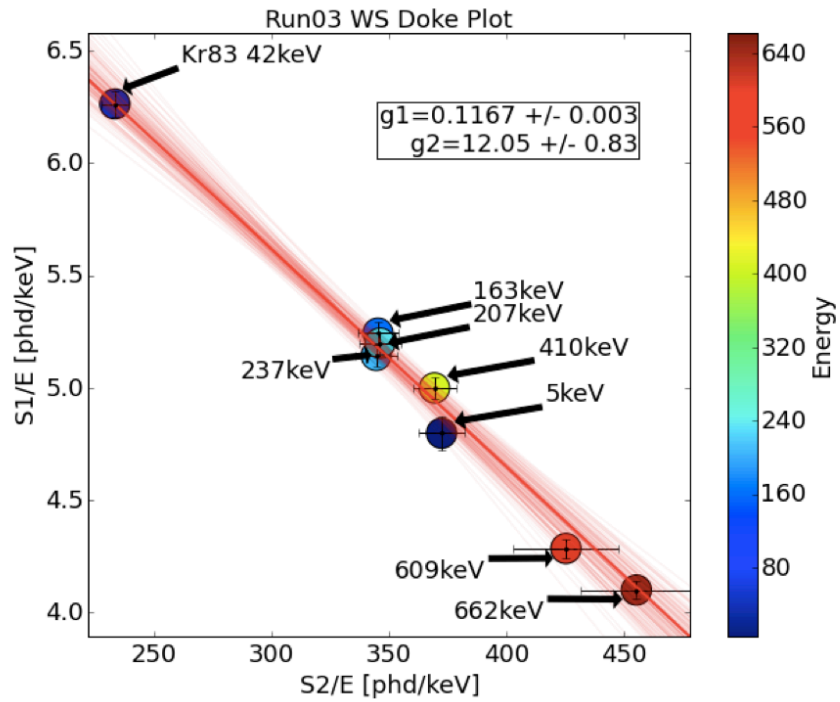
LUX 2015 tritium paper: arXiv:1512.03133





Energy Calibration





- **Detector-specific gain factors g1 = 0.117 ± 0.003 phd/photon and g2 = 12.1 ± 0.8 phd/electron are measured in situ**
  - **“Doke plot”: Fit a line to datasets from mono-energetic ER sources in S1/E vs. S2/E space**
  - **W = 13.7 eV/quantum in xenon**

$$E = \frac{1}{\mathcal{L}(E)}\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right) W$$

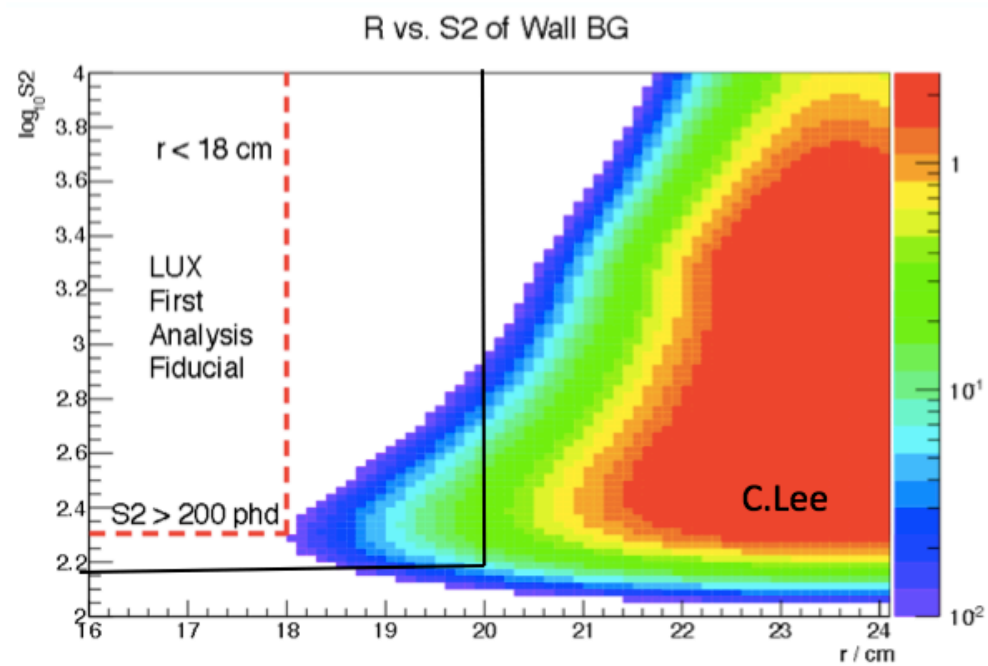
Improvements to Event Reconstruction

- **Noise artifact removed from PMT pulse areas**
- **Single-electron and small-S1 events used to calculate single photon area**
  - **Removes systematics from previous calibration using pulsed LEDs**
  - **“Spike counting” improves resolution for small pulses**
- **Double-photoelectron emission characterized and taken into account**

  Paper by LBNL group, 2015: arXiv:1506.08748
- **Both PMT arrays used to estimate S2 size**
  - **Compare to bottom-only for 2013 analysis**
- **Effects of electric field non-uniformity near detector edges corrected using ^{83m}Kr data**

Improvements to Background Model

- **Predominant background: low-energy ER from detector components + contaminants (^{85}Kr, Rn-daughters) in the xenon**
- **Asymmetric modeling of backgrounds from top and bottom of detector**
- **Wall events (e.g. ^{222}Rn - ^{206}Pb) modeled using low-S2 sidebands, accounting for incomplete charge collection**



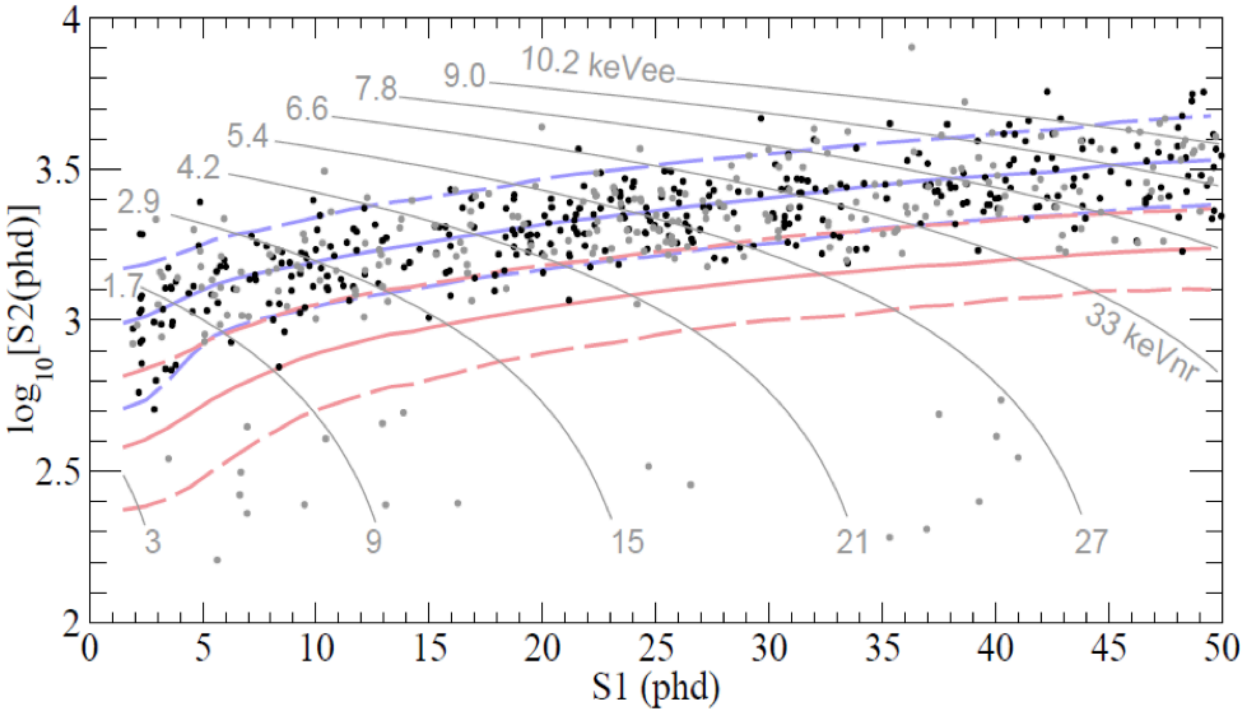
- **Subdominant backgrounds, not included in the model:**
  - **Expected neutron background using revised cuts: 0.08 ± 0.01 NR events**
  - **S1 + S2 coincidence: 1.1 total events**
  - **^{8}B solar neutrino scattering: 0.10 total events**

Increased Fiducial Size and Detector Exposure

- Additional 10 live-days of data incorporated into analysis
- Expanded fiducial volume enabled by modeling of background wall events
  - 2013: radius = 18 cm, fiducial mass = 118 kg
  - 2015: radius = 20 cm, fiducial mass = 145 kg

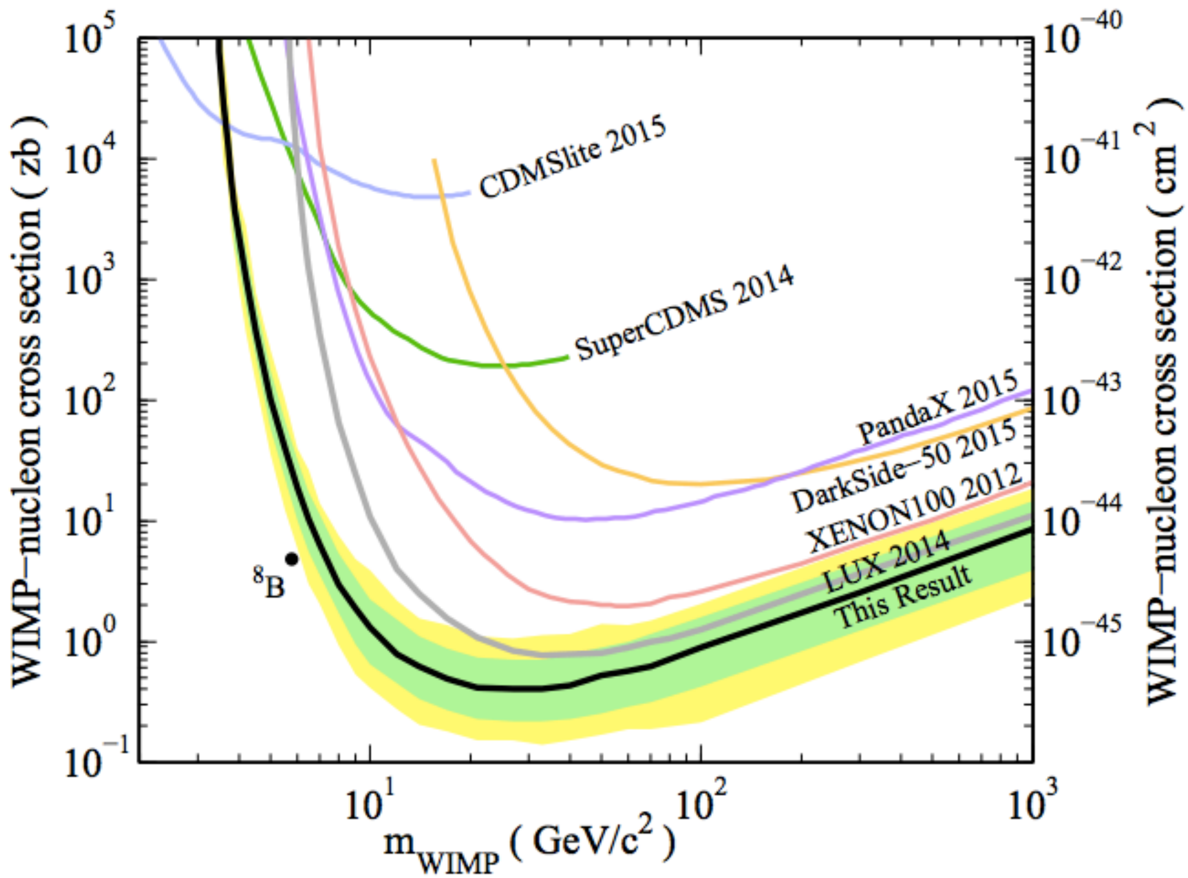
Overall 40% increase in detector exposure

- Allowed range of S1 and S2 sizes: 1 phd < S1 < 50 phd, S2 > 150 phd



591 events observed;
589 events predicted by background model

LUX 2015 WIMP-nucleon Interaction Limit



- **Improved sensitivity to low-mass WIMPs over LUX 2013 result**
  - **Minimum kinematically-accessible mass 3.3 GeV (compare to 5.2 GeV)**
- **23% improvement in limit for high-mass WIMPs**

New minimum spin-independent cross section limit:

4 X 10^{-46} cm^2 for 33-GeV WIMPs

Summary

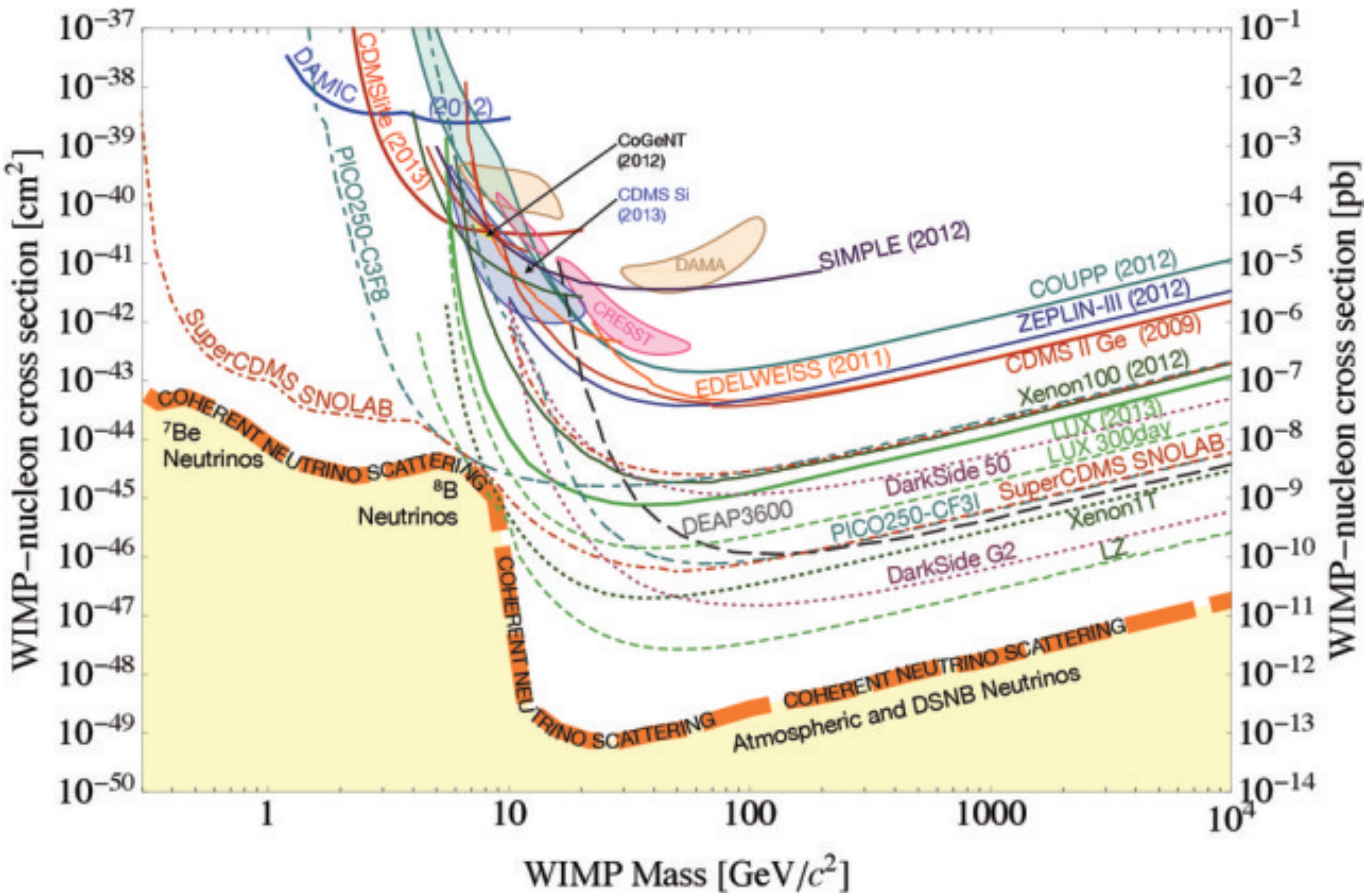
- In 2013, LUX set a world-leading limit on spin-independent WIMP-nucleon interactions
- In December 2015, a reanalysis of the LUX 2013 WIMP search dataset was released
  - Incorporated a new NR calibration using a beam of mono-energetic neutrons from DD source and additional high-statistics ER tritium calibrations, allowing thresholds to be lowered to 1.1 keV_{nr}
  - Modeling of wall events enabled the use of an extended 145-kg fiducial volume
  - Improved single-photoelectron calibrations and event reconstruction algorithms
  - Extra 10 live-days of data taken after the tritium calibrations

Overall 23% improvement of spin-independent cross section limit for high mass WIMPs, and even more significant improvement for low-mass WIMPs

Future Outlook

- This year, LUX is undergoing an extended 300-day WIMP search run
  - Blind analysis via “salting”
  - 4x increase in detector exposure, with additional D-D and CH_3T calibrations
  - Radioactive xenon backgrounds no longer relevant
  - Improvements in electric field and background modeling
  - Better handling of PLR nuisance parameters to allow more variation at low energies
  - Potential for discovery!
- Next up: the LZ (LUX-ZEPLIN) experiment
  - 5600-kg fiducial volume with liquid scintillator veto and instrumented xenon “skin”
  - Deployment at the Davis Campus of SURF starting in 2017
  - Will reach the ultimate sensitivity limit: that of solar neutrino coherent scattering!

The Big Picture…



From the Snowmass CF1 2013 Report: arxiv:1310.8327v2

Stay tuned for more results!

- **Spin-dependent, effective field theory, S2-only, solar neutrinos, axions…**

N. Larsen Dissertation

Spin-dependent limit just released: arXiv:1602.0348

First spin-dependent WIMP-nucleon cross section limits from the LUX experiment

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Thank you!