Recent results from the LUX experiment and progress towards the LZ experiment

Adam Bernstein, Rare Event Detection Group Leader, Physics and Life Sciences Directorate,
Lawrence Livermore National Laboratory
On behalf of the LUX collaboration
May 2016

International Symposium on revealing the history of the universe with underground particle and nuclear research 2016

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Outline

- Introduction to LUX, the Large Underground Xenon detector and collaboration
- What is new since our last limit publication in 2013 ?
- Next steps for LUX
- LZ status and plans

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Graduate Student

Imperial College London

Henrique Araujo	PI, Reader
Tim Sumner	Professor
Alastair Currie	Postdoc
Adam Bailey	Graduate Student
Khadeeja Yazdani	Graduate Student

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Michael Witherell	Lab Director
Simon Fiorucci	Scientist
Peter Sorensen	Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Mia Ihm	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Group
Kareem Kazkaz	Staff Physicist
Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc
Paulo Bras	Graduate Student

SLAC Nation Accelerator Laboratory

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Kim Palladino	Project Scientist
Tomasz Biesiadzinski	Research Scientist
Christina Ignarra	Research Scientist
Wing H To	Research Scientist
Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD School of Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA

David Taylor	Project Engineer
Markus Horn	Research Scientist
Mark Hanhardt	Support Scientist

UNY at Albany

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Sean Fallon	Graduate Student
Steven Young	Graduate Student

Texas A&M

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Britt Hollbrook	Senior Engineer
John Thmpson	Development Engineer
Dave Herner	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalasay	Postdoc
Scott Stephenson	Postdoc
James Moard	Graduate Student
Sergey Uvarov	Graduate Student
Jacob Cutter	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Project Scientist
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer
Sally Shaw	Graduate Student

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc
Maria Francesca Marzioni	Graduate Student
Tom Davison	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Richard Knoche	Graduate Student
Jon Balajthy	Graduate Student

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Mongkol Moongweluwan	Graduate Student

University of South Dakota

Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student

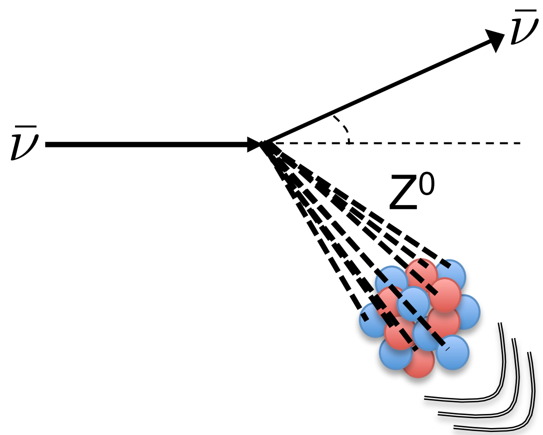
Yale → University of California Berkeley

Daniel McKinsey	PI, Professor
Ethan Bernard	Research Scientist
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student

Two coherent scattering processes on nuclei

- Coherent Elastic Neutrino Nucleus Scattering (fast, light)

$$\bar{\nu} + Xe \rightarrow \bar{\nu} + Xe$$

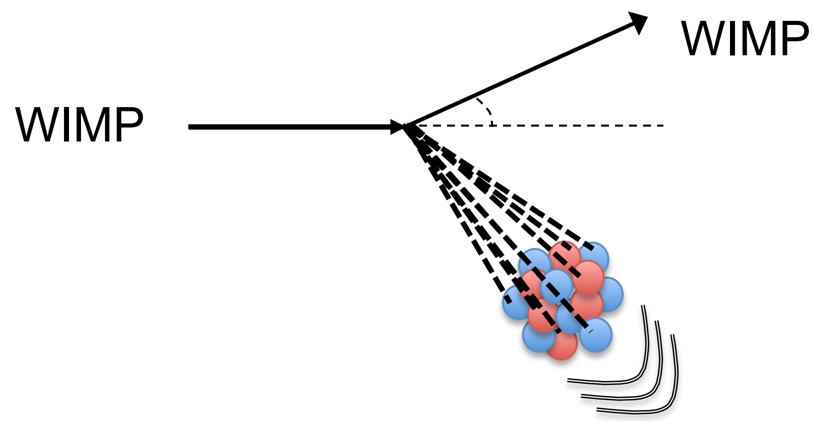


$\lambda \sim$ a few fm $E_{\bar{\nu}} \sim 1 - 50$ MeV

M = ~ 1 meV

- Weakly Interacting Massive Particle Scattering (slow, heavy)

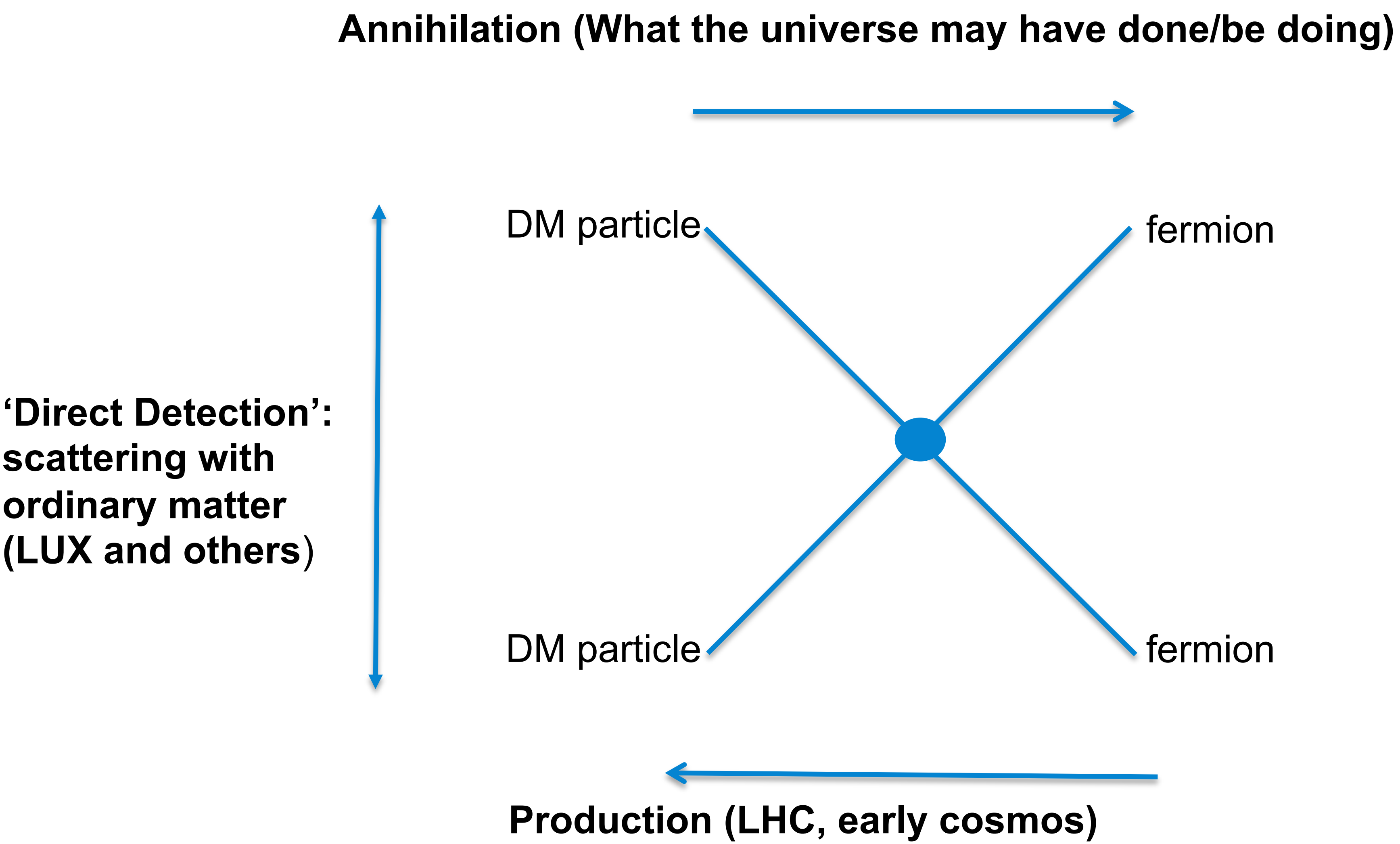
$$WIMP + Xe \rightarrow WIMP + Xe$$



$\lambda \sim$ a few fm

M = 100 GeV (e.g.)

WIMP interactions with ordinary matter



WIMP 'Direct Detection' Using Atoms

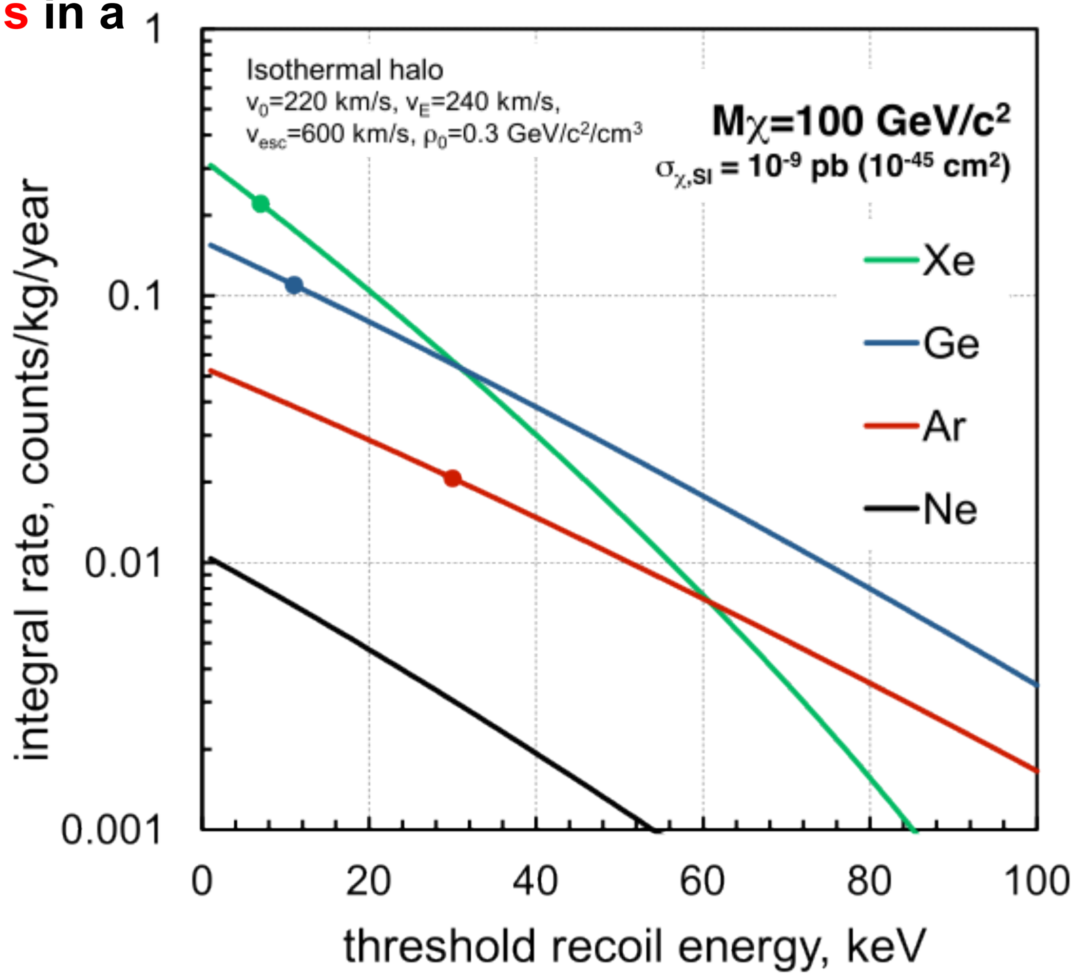
Look for **anomalous nuclear recoils** **in a low-background detector.**

$\text{Rate} = N \rho \sigma \langle v \rangle$.

$\sigma \sim A^2 \rightarrow$ **due to coherence**

100 GeV WIMP recoil energy

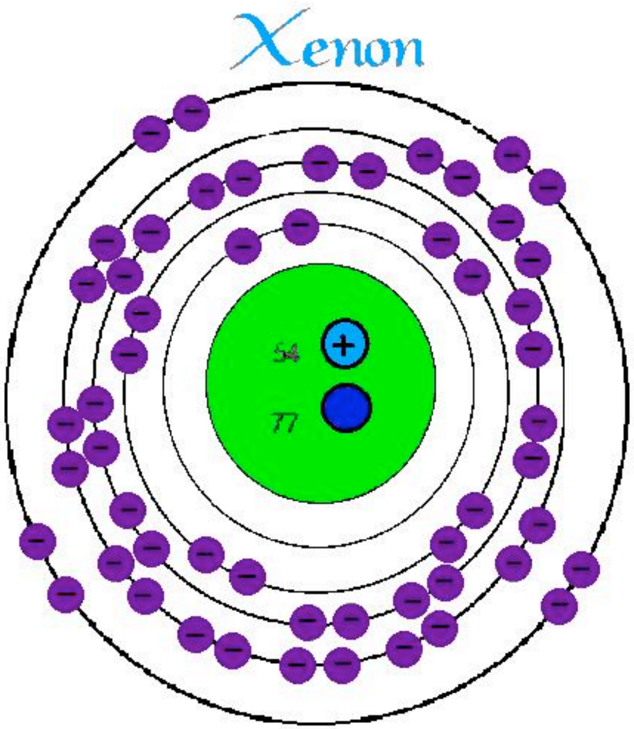
$E_R \approx \frac{1}{2} m_{Xe} c^2 \beta^2 \approx 30$ keV



General requirements:

- Deep underground laboratory
- Low energy threshold
- Low radioactivity
- Gamma ray rejection
- Neutron shielding
- Scalability
- Patience
- Obsessiveness

The appeal of xenon for dark matter search



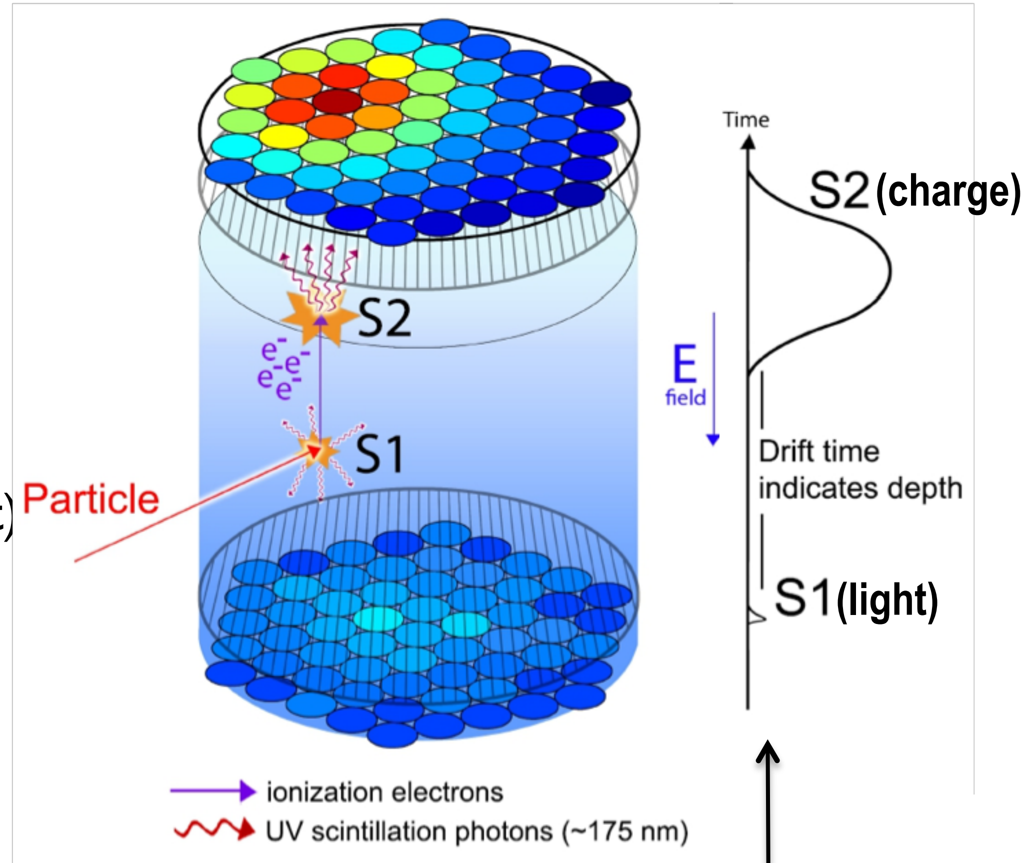
- ✓ A = 132 – enhanced WIMP interaction probability due to coherence (A^2)
- ✓ Density = 3 g/cc – self-shielding/**fiducialization** for unwanted gammas
- ✓ High scintillation and ionization yield – natural, no dopants
- ✓ No long lived radioactive isotopes
- ✓ **ratio of scintillation and ionization is different for E&M v. nuclear recoils**
- ✓ High purity attainable → long e- drift lengths
- ✓ 'Easy' cryogenics with liquid nitrogen or mechanical cooling

Dual-phase noble liquid Time Projection Chambers

- primary or **S1** scintillation
  (prompt photons generated in liquid
  start the TPC clock)

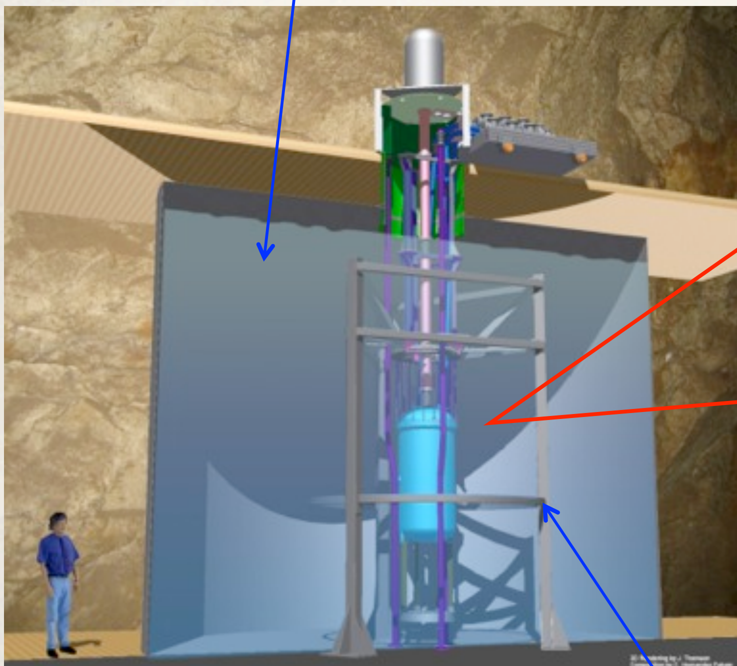
  and:

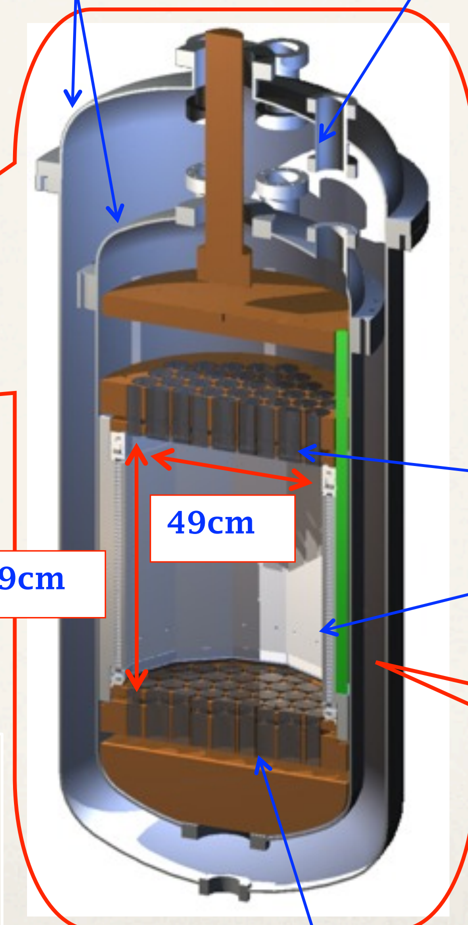
  secondary or **S2** scintillation
  (delayed electrons, each converted
  to hundreds of photons in gas blanket)
- Good electron drift properties
- Large self-shielded target mass
- 3-D signal localization to ~1 mm
- Powerful discrimination between
  nuclear and electromagnetic recoils

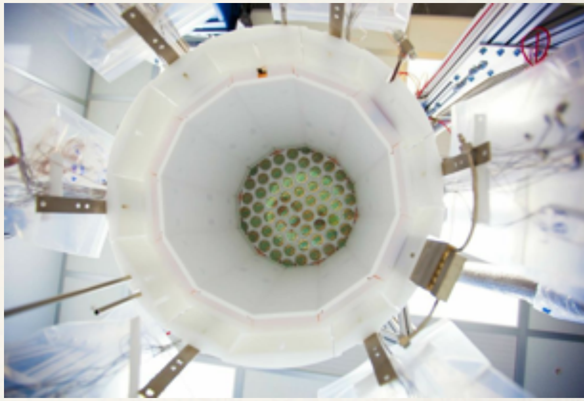


S1/S2 ratio differs for nuclear/E&M recoils

Introduction to the LUX Detector

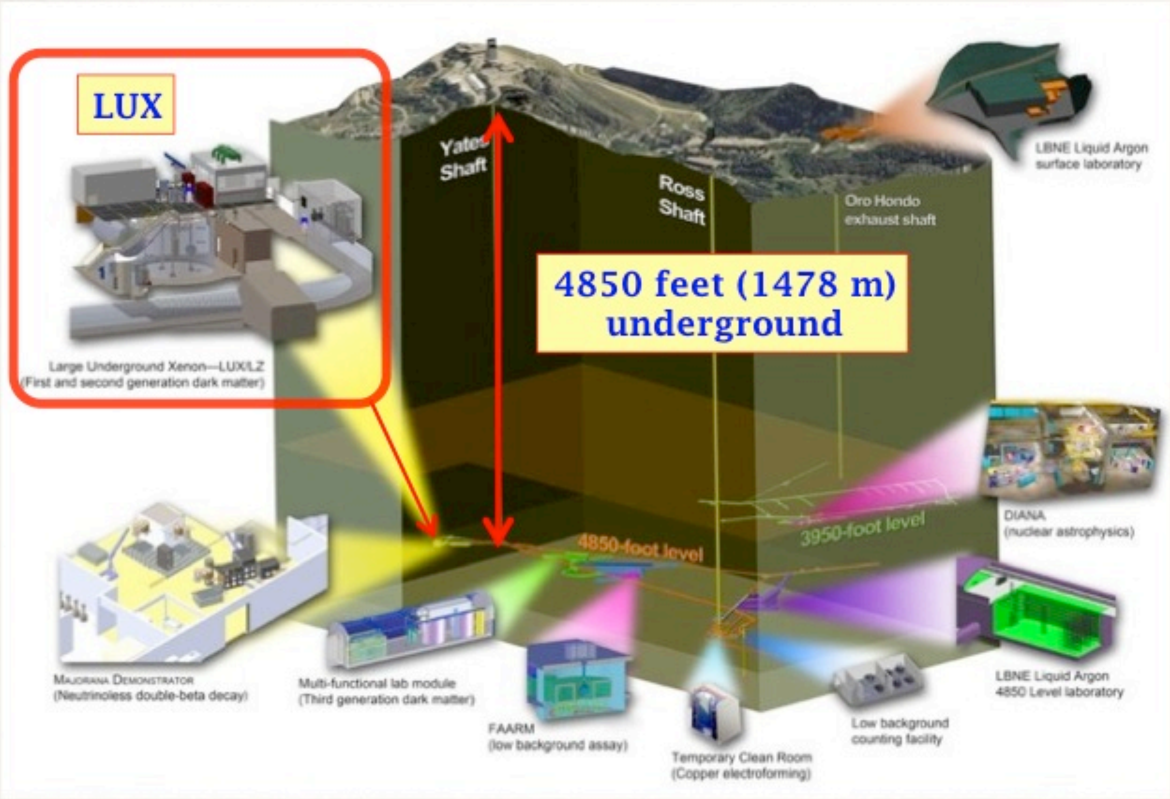


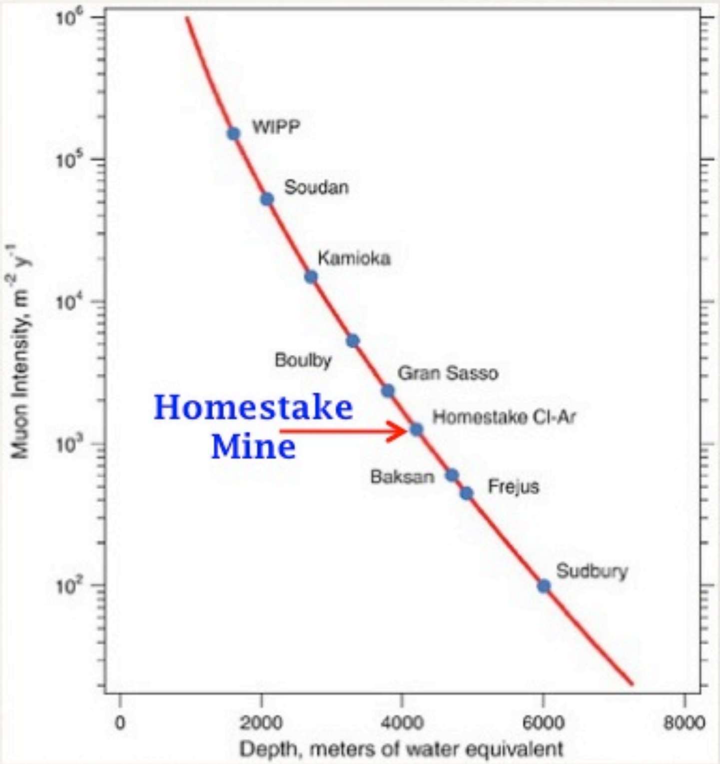




- 370 kg Lxe, 145 kg fiducial (latest)
- 122 PMTS (QE ~30% @ 175nm
- Low radioactivity materials
- \> 1 kW cooling power from thremosyphons
- 70,000 gallons of DI water
- Rn content <100 mBq/m^3

LUX is buried 1.5 km underground in the Sanford Underground Research Facility – also the future home of LZ





$55.2\ m^{-2} \cdot sec^{-1} \rightarrow 10^{-5}\ m^{-2} \cdot sec^{-1}$

~10^7 fold muon flux suppression

LUX’s Laboratory at SURF

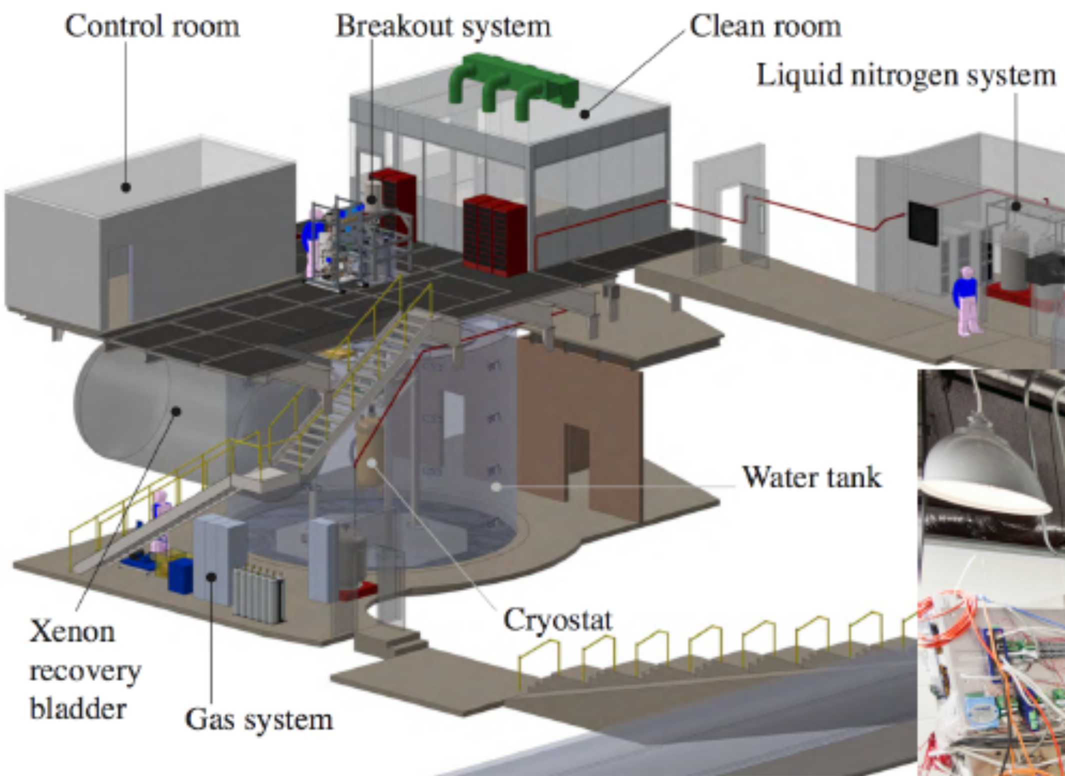
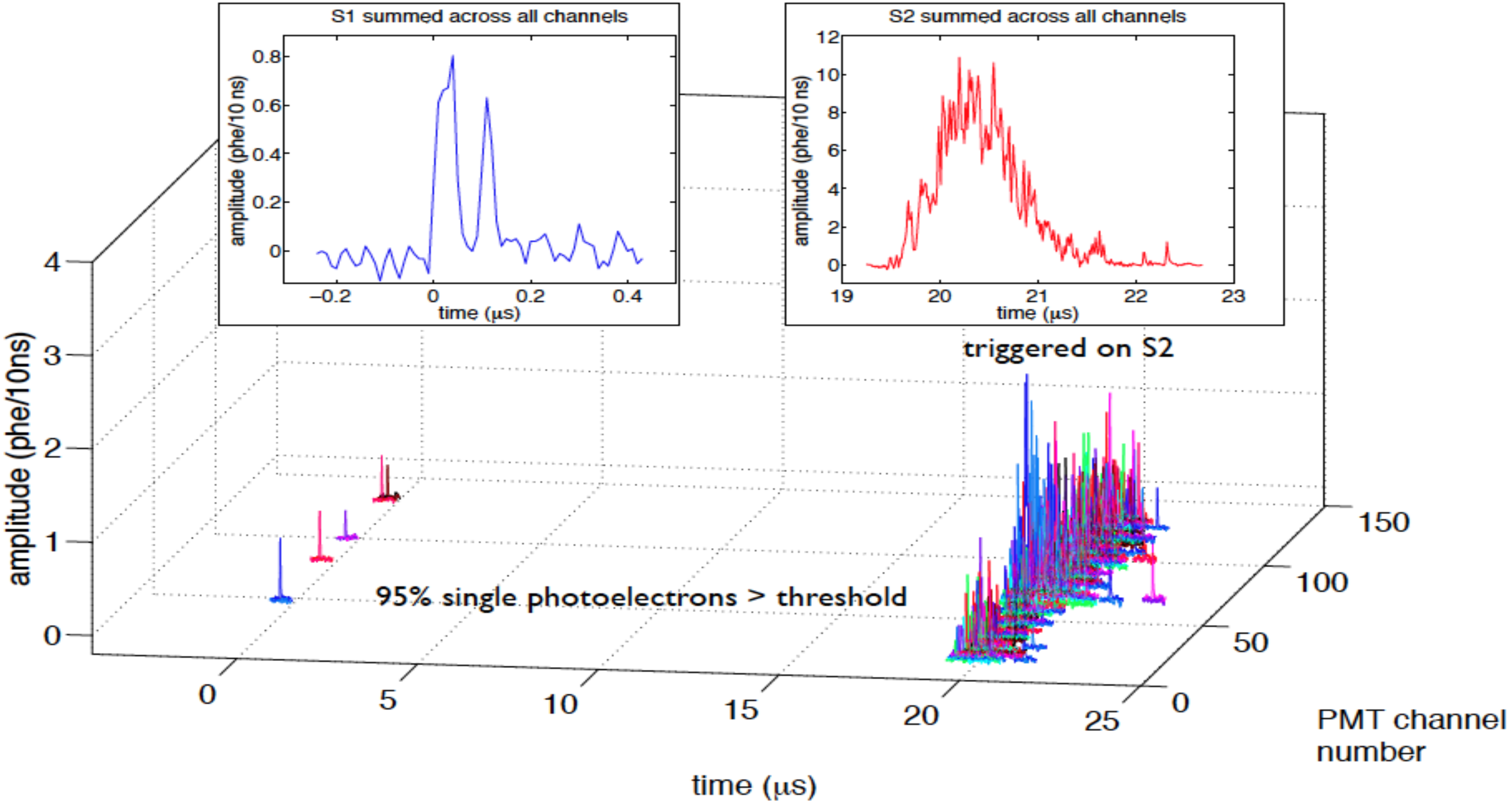


Figure 16: Rendering of the layout of the Davis Laboratory.

arXiv:1211.3788

A typical candidate event in LUX

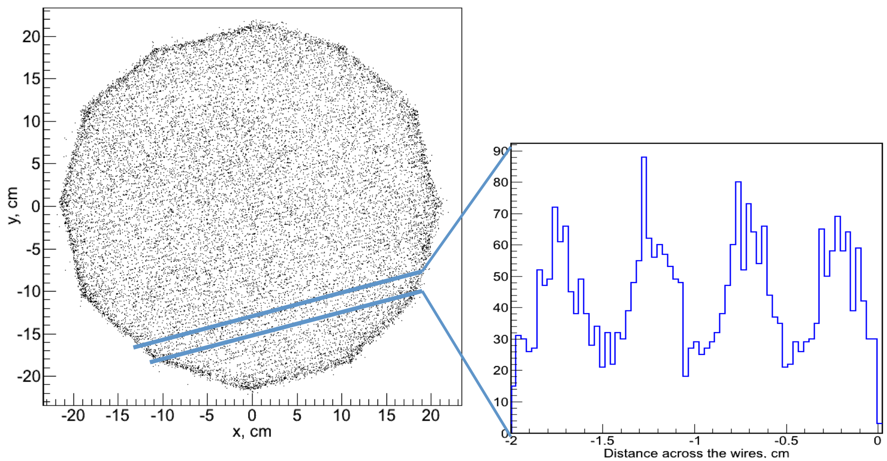


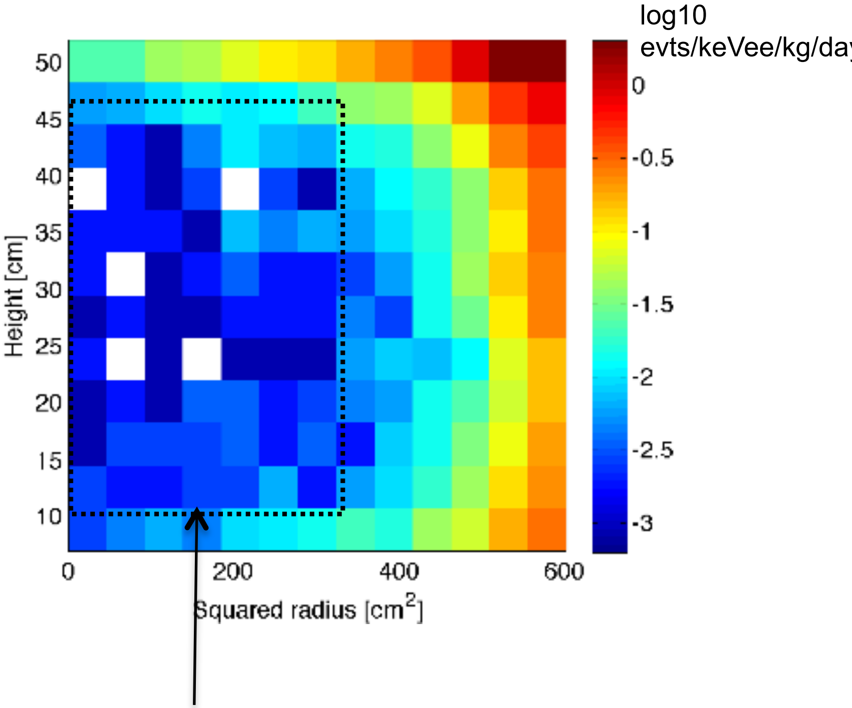
Excellent 3-D position reconstruction leads to a well defined and quiet fiducial volume

Z position is determined by the time between S1 and S2 (electron drift speed of 1.5 mm/microsecond)

X-Y position is determined by fitting the S2 hit pattern relative to measured light response functions

Reconstruction of XY from events near the anode grid resolves grid wires with 5 mm pitch.





LUX fiducial volume (from first analysis)

What's new with LUX and LZ

In the last few months:

- Spin **Independent** WIMP limits with 10^3 better sensitivity at low mass then our previous world record (PRL.116.161301)

- Spin **Dependent** WIMP limits – also the most sensitive in the world – for neutrons, and competitive for protons (PRL.116.161302)

Coming up:

- Completed 300 day LUX acquisition– 3x more data – analysis in progress
- Completion of major external review of the LZ design 'CD-2'

Around the corner

- The bittersweet LUX decommissioning this fall !
- Preparations for LZ at the Sanford Laboratory

We've re-analyzed (more or less) the same data : why did our results improve ?

- high statistics electron recoil calibration with tritium source (PRD.93.072009)
- new *in situ* neutron recoil calibrations lower our energy cutoff for accepting events:
  3 keV → 1 keV
- Improved understanding of recombination and electromagnetic energy scale

The work of our energetic and bright cadre of post-docs and students is on display at the APS April 2016 meeting www.aps.org/meetings/april/

Electromagenetic recoil (ER) calibration with tritiated-methane

170,000 events

Well known distribution

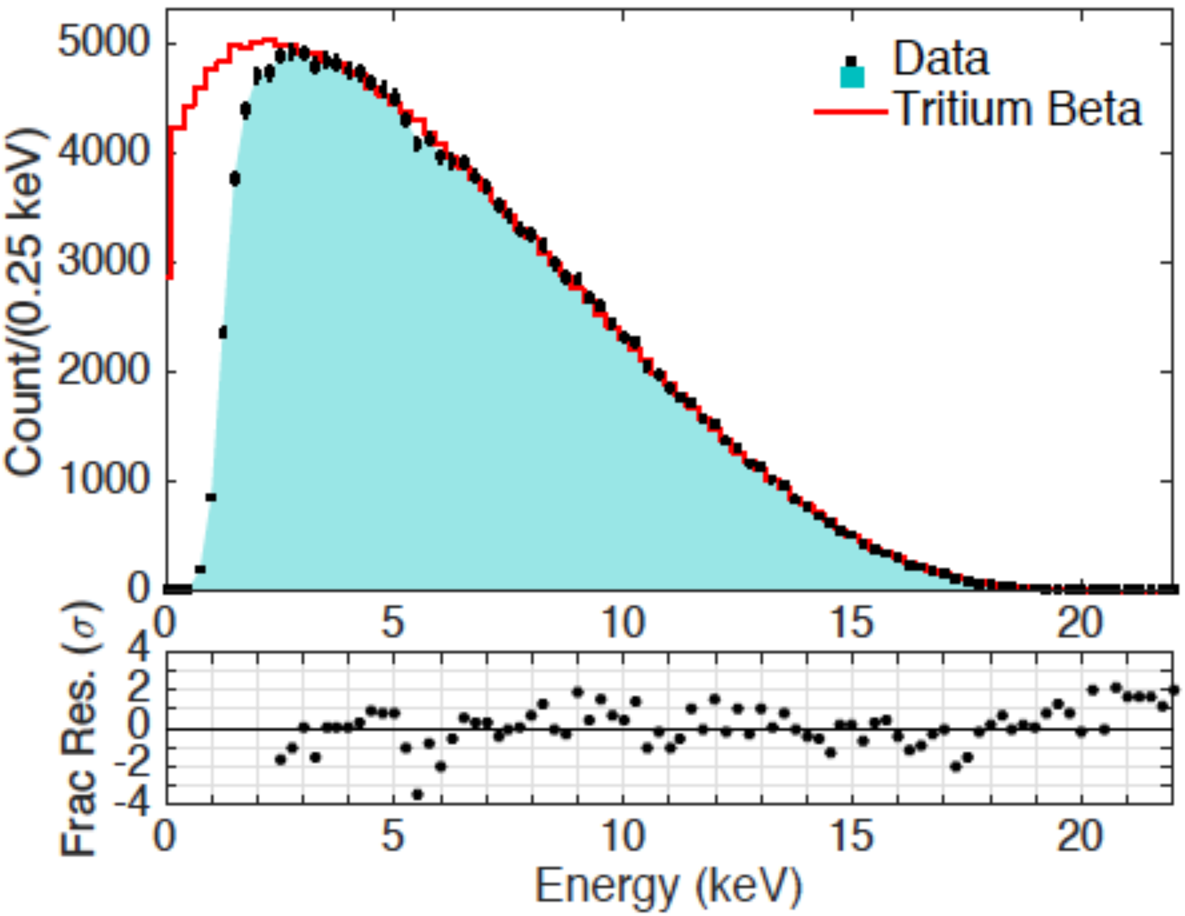
Spans the WIMP search region

Uniform throughout xenon volume – permits calibration at detector center

Response persists even at 1 keV

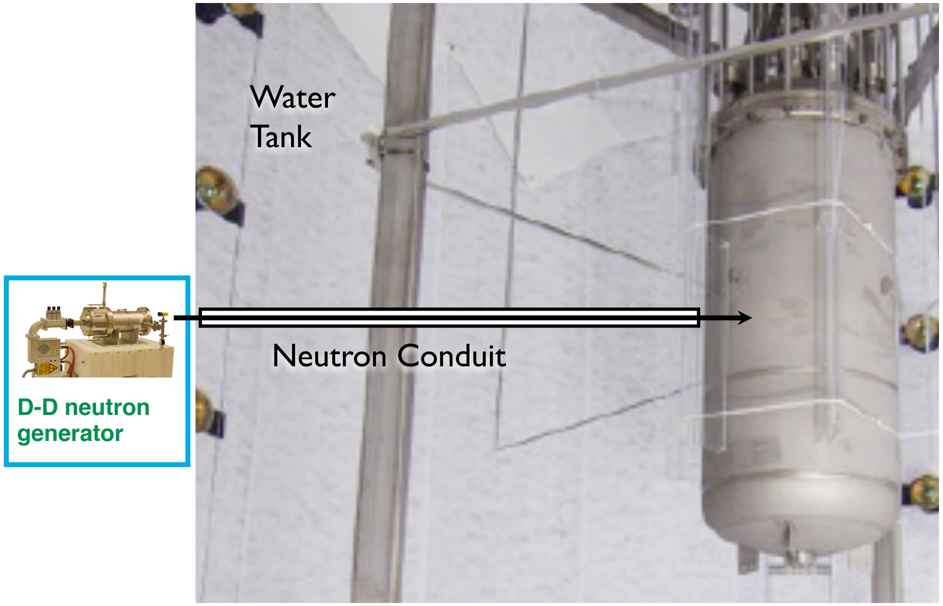
Improved measurement of ER charge/light yields compared to previous LUX analysis

Completely removed in ~6 hours

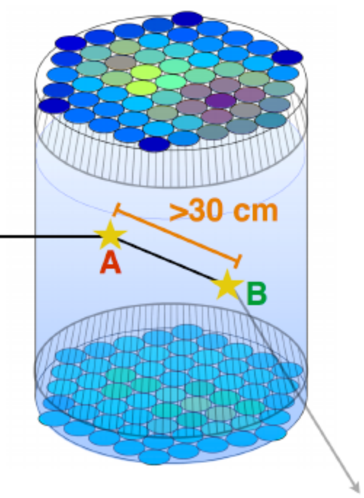


We've performed an *in situ* nuclear recoil calibration with a D-D neutron source

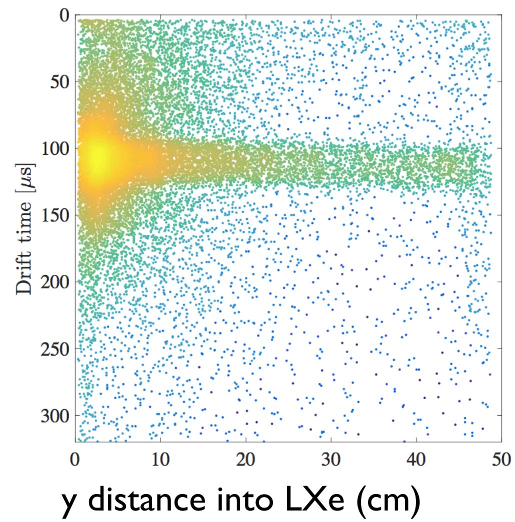
- 2.45 MeV mono-energetic neutron beam
- Neutrons collimated by an air-filled pipe
- Double scatters events permit reconstruction of incident neutron energy
- Paper in preparation



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



Z distance (height) in detector

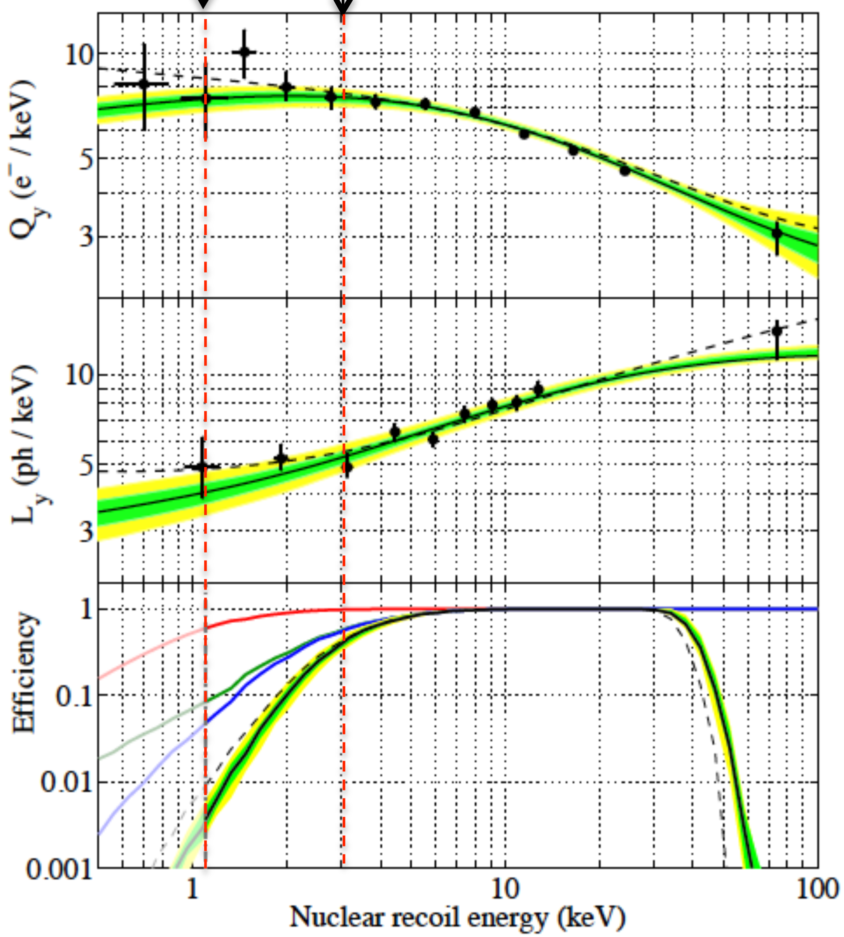


Absolute measurements of charge and photons per keV for nuclear recoils, down to ~1 keV

New signal cutoff @ 1.1 keV

Old signal cutoff 3.3 keV

(below which we conservatively assumed zero yield)



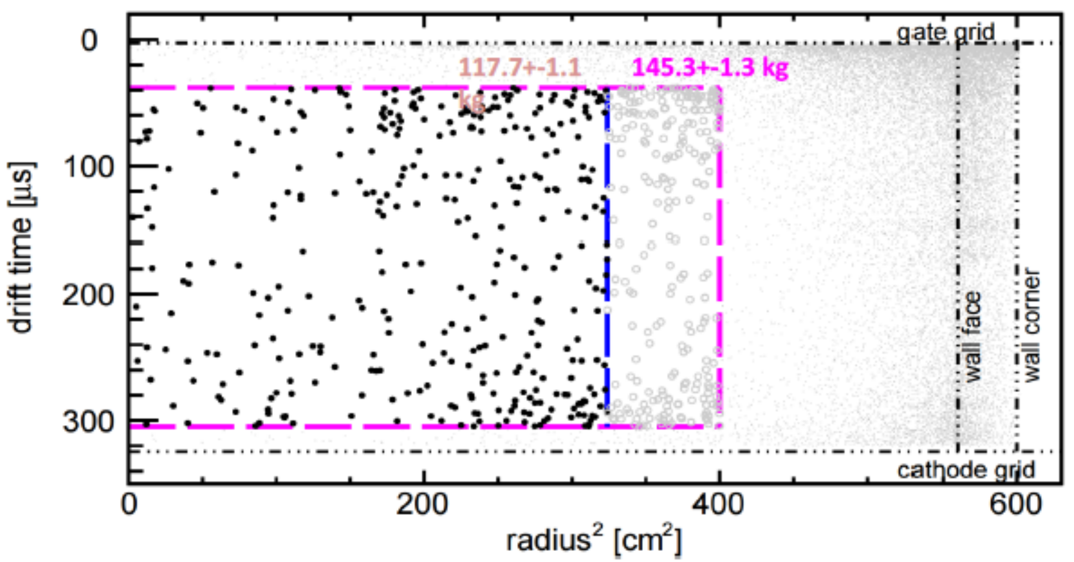
efficiencies

- S2
- S1
- S1 +S2
- S1+S2 > thresholds

Yield measurements below 3 keV allow a us to remove the hard cut at 3.3 keV, improving our acceptance

Event candidates for the updated analysis

145 kg fiducial vol. (was 117)
95 live days (was 85)

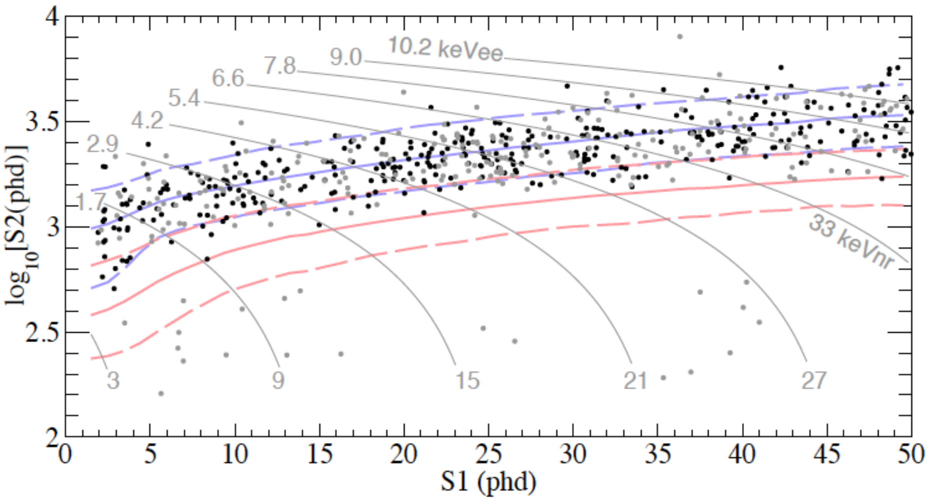


● < 18 cm events
○ ● > 18 cm events

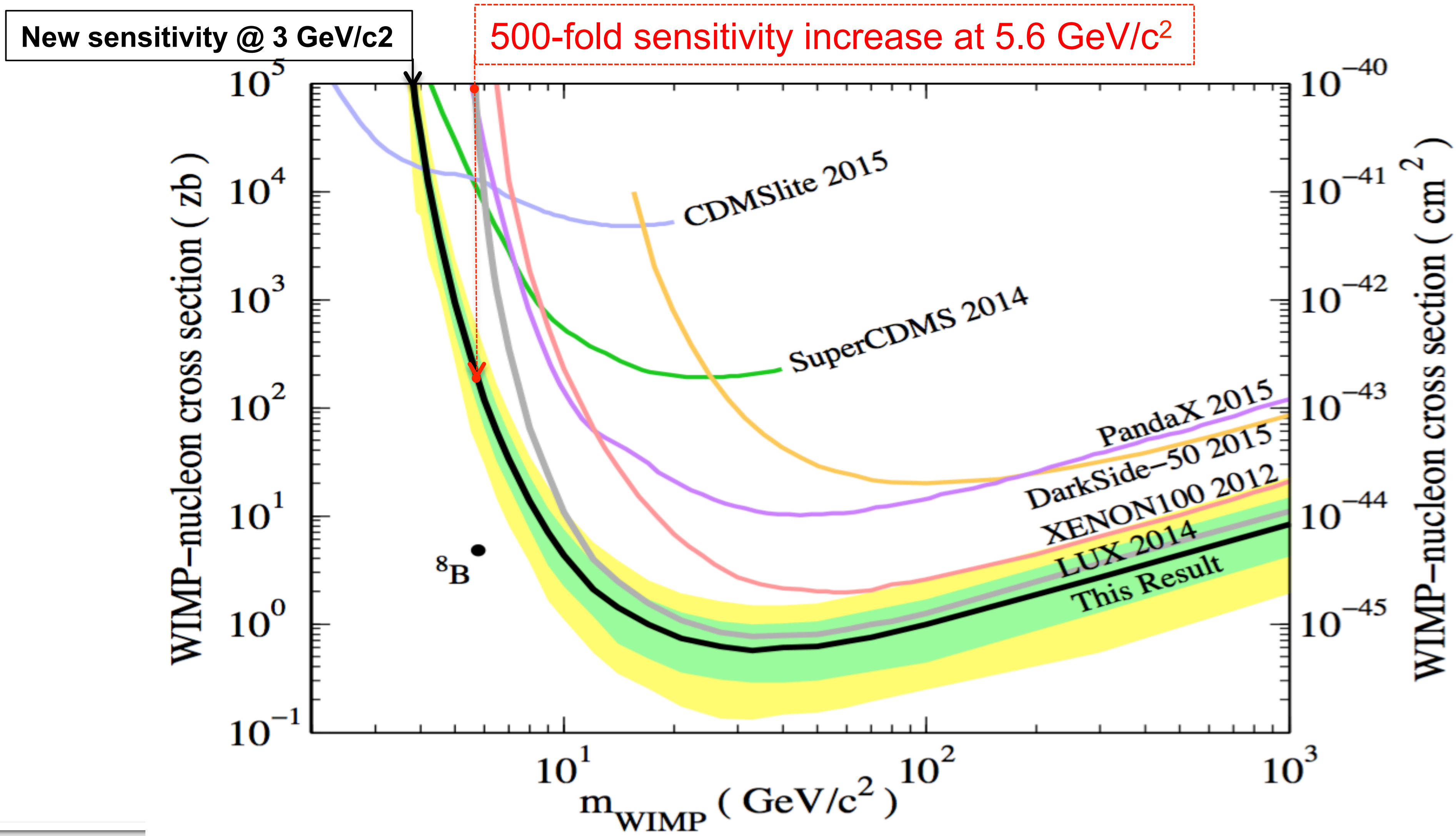
10/50/90 percentile for

Uniform-in energy electromagnetic recoils

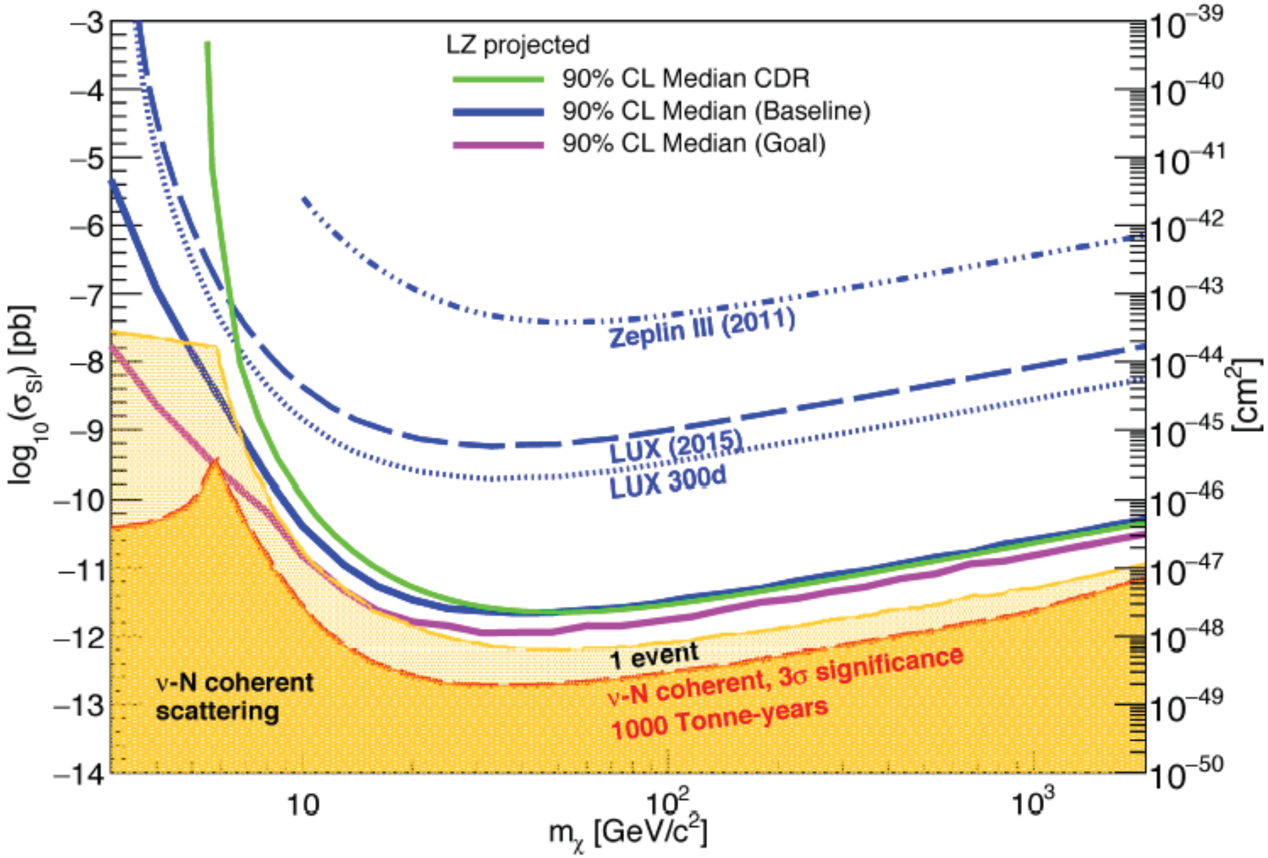
Hypothetical 50 GeV/c² WIMP



The increased acceptance improves sensitivity at low masses



Coherent scatter will appear in the LZ WIMP search detector – provided thresholds are low enough

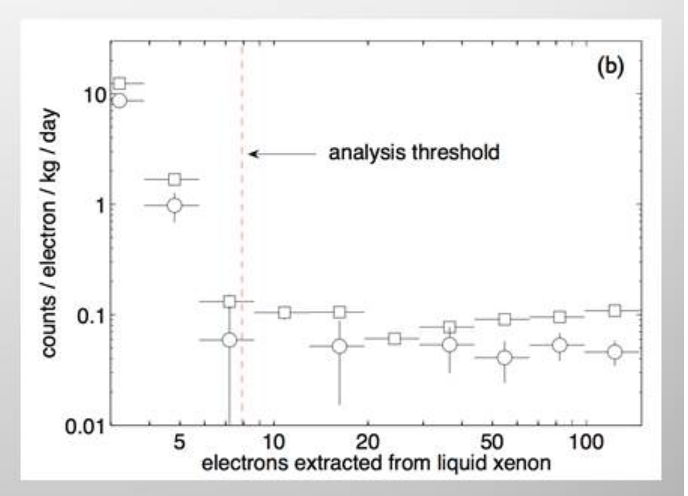


For light-mass (5-10 GeV) WIMPS, the “floor” for non-directional detectors like LZ comes from **Boron-8 solar neutrinos**

LUX as a laboratory to study future detectors

Few-electron backgrounds from all sources may limit our sensitivity to the lowest recoil energies/lightest mass WIMPS – and solar coherent neutrinos

LUX helps provides insight into their origin

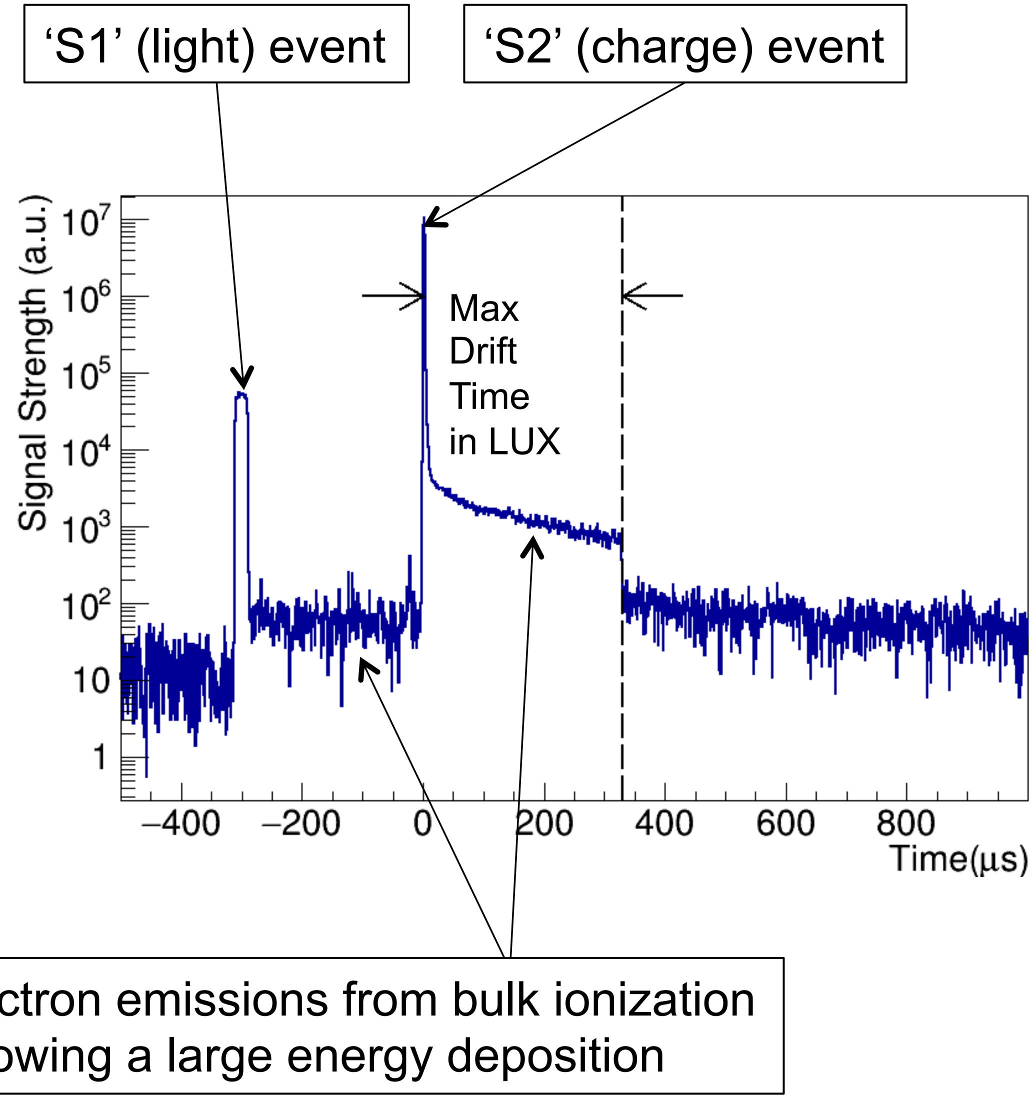


Xenon10 S2-only analysis, arXiv:1011.6439

Rising background at few e- seen in XENON-10 and in surface detectors

In LUX, photo-ionization in the bulk liquid can be time-correlated with a prior scintillation or ionization event

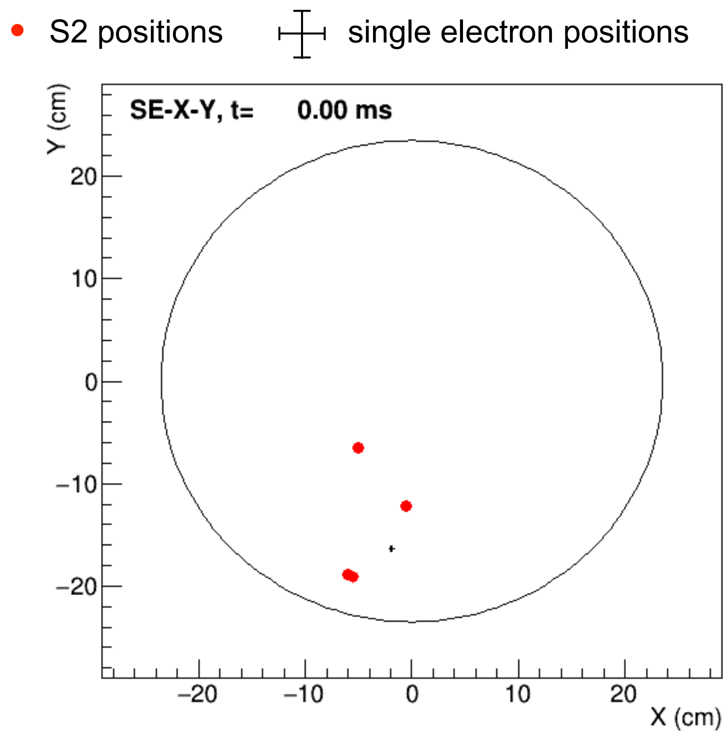
- Xe scintillation light can ionize impurities in the bulk liquid
- Produced by both scintillation (S1) and ionization (S2) light
- Time delay up to full drift time in the detector



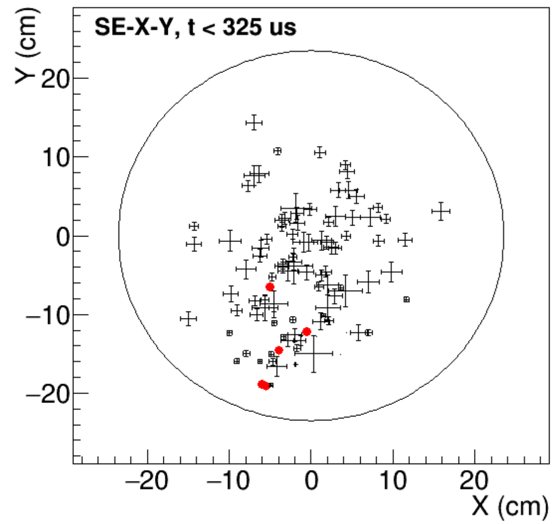
LUX shows evidence for both photoionization of bulk impurities, and release of electrons at the gas-liquid boundary

Different X-Y position patterns can be identified for different stages of electron emission:

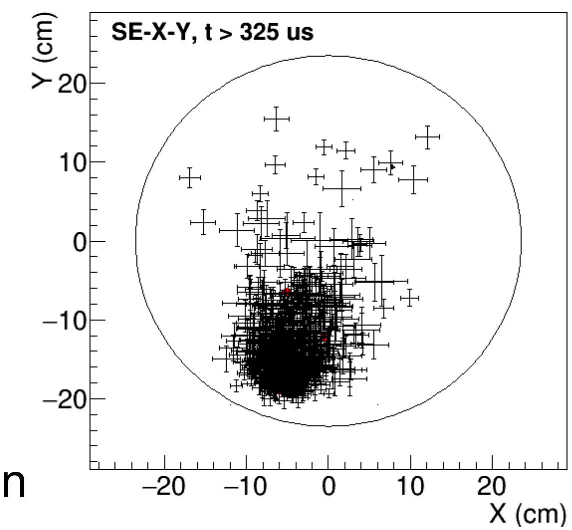
- Prompt electron emissions from bulk photoionization
- Delayed electrons emissions from liquid surface



Top-down (X-Y) view of single electron distribution



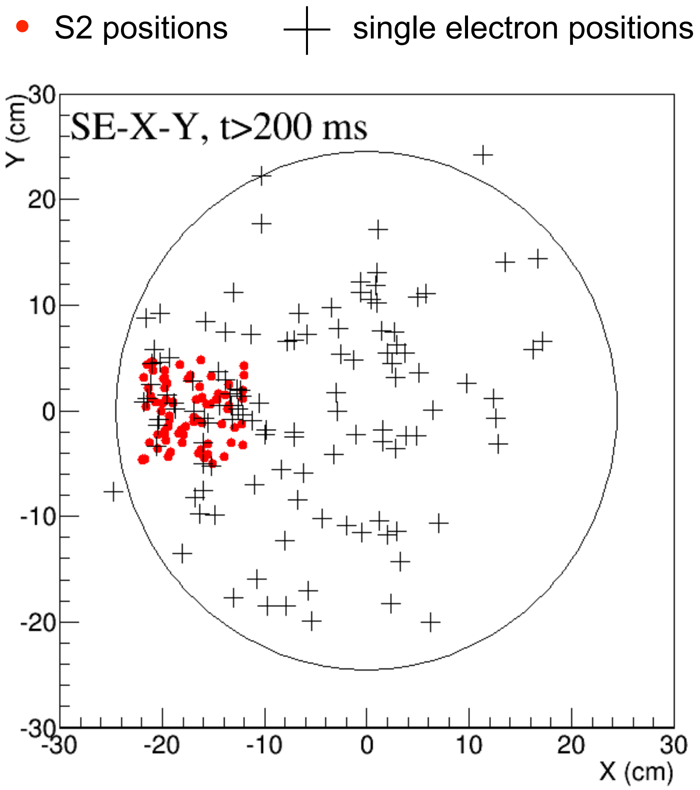
Time correlated prompt events (bulk)



Position correlated delayed events (surface)

Some emissions are neither time nor space correlated with prior energy depositions

The distribution of few-electron events 200 ms after small, isolated energy depositions is <u>not</u> highly space or time correlated with a prior event.



These backgrounds are consistent with Malter-like ion-assisted emission from cathode – and other noise sources

Summary of study of the origin of LUX few-electron backgrounds

- Background electron emission limits the sensitivity of Xe (and Ar) TPCs at very low energy depositions
- Several sources have been identified with the LUX detector
  - Photo-ionization electrons dominate shortly after light signals
  - Delayed electron emissions at the S2 location dominate long after energy depositions – emissions from liquid surface

Ion trapping on grids or walls may also contribute – these mechanisms are under active study

LZ collaboration and schedule

32 institutions currently

=US (23) + UK(8)+PT(1)+RU(1)

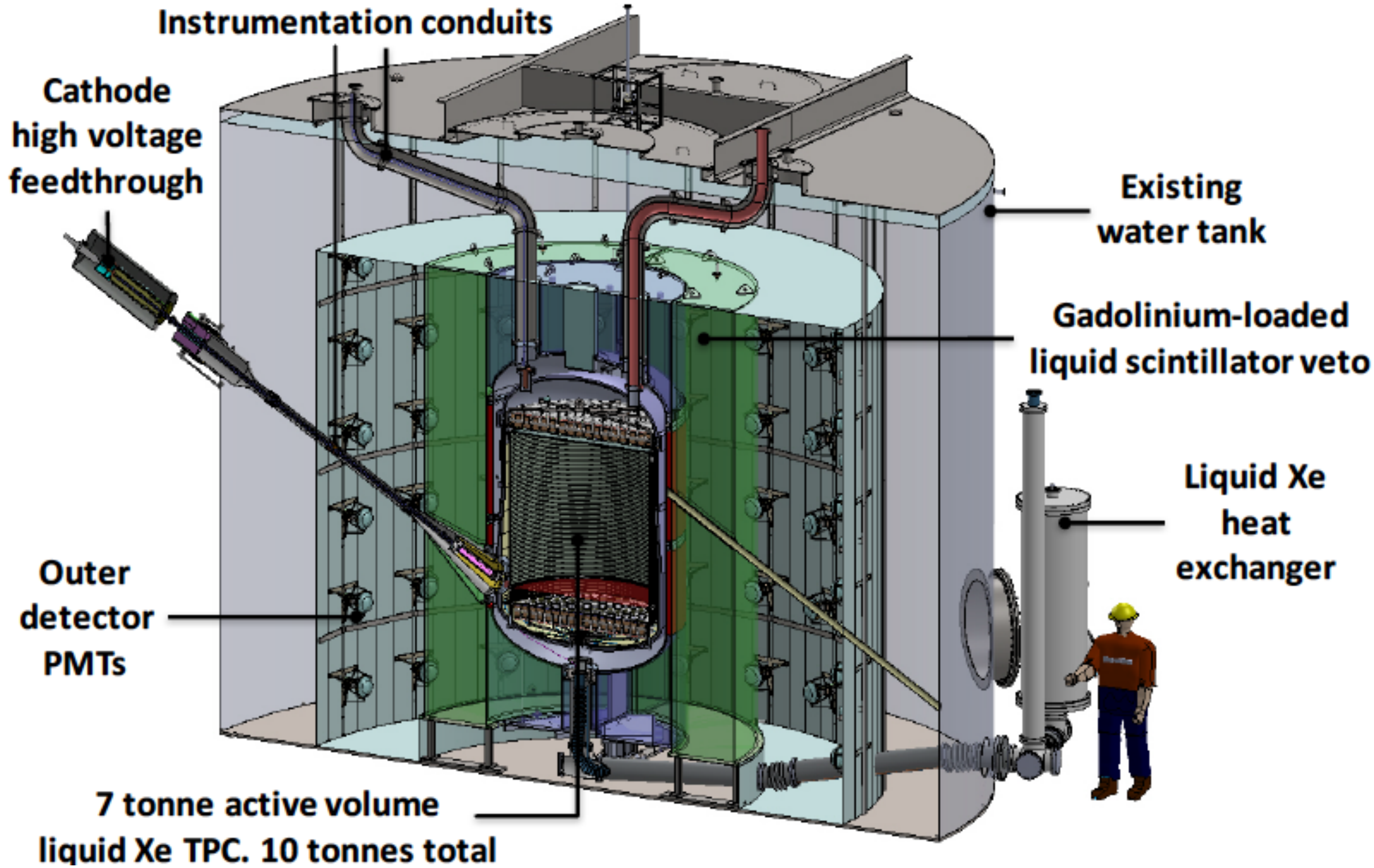
About **190 people**

LIP Coimbra (Portugal)
MEPhI (Russia)
Edinburgh University (UK)
University of Liverpool (UK)
Imperial College London (UK)
University College London (UK)
University of Oxford (UK)
STFC Rutherford Appleton Laboratories (UK)
Shanghai Jiao Tong University (China)
University of Sheffield (UK)

University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
University of California, Berkeley
Brookhaven National Laboratory
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Kavli Institute for Particle Astrophysics & Cosmology
Lawrence Livermore National Laboratory
University of Maryland
University of Michigan
Northwestern University
University of Rochester
University of California, Santa Barbara
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University
University of Wisconsin
Yale University

Year	Milestone
2012	Collaboration formed
2014	LZ project selected in the UK and as a Generation 2 DM experiment in the US
2015	DOE ‘CD-1’ approval (April)
2016	DOE ‘CD-2’ approval (April)
2017	Prep for surface assembly at SURF
2018	Begin underground installation
2019	Commissioning starts

The LZ design



Summary

- LUX has published a new PRL with a ~500x better limit on light mass (5.2 GeV/c^2) WIMP –and additional sensitivity down to ~3.3 GeV/c^2
- LUX remains the world's most sensitive direct dark matter search detector for spin-independent and neutron-channel spin dependent WIMPS
- DD neutron, tritium and other calibrations all contributed to improving our acceptance for low mass WIMPS
- LUX has nearly completed an acquisition of 300 days of live data, compared to 95 in the current data set
- LUX teaches us about noise sources and light/charge yields for the next generation of dark matter (and coherent scatter) detectors
- The ~50x larger fiducial mass LZ detector continues on its path towards deployment at the Homestake Mine in the coming years