Present status of LUX and LUX-ZEPLIN (LZ) experiments

Isabel Lopes

LIP, Universidade de Coimbra, Portugal

On behalf of LUX and LZ Collaborations

Dark Matter – Cairo, Egypt, 14 -17 December 2015

Outline

1. LUX

- Reminder – what is LUX?
- The October 2013 result
- LUX "Run 4" into 2016
- Calibration and re-analysis effort of 2013 "Run 3" data

2. LUX-ZEPLIN (LZ)

The Basics

WHAT IS LUX?

THE LUX COLLABORATION

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
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
Peter Sorensen	Scientist
Victor Gehman	Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Mia Ihm	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Grp.
Kareem Kazkaz	Staff Physicist
[illegible]nardo	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

SLAC Nation Accelerator Laboratory

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Kim Palladino	Project Scientist
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Wing To	Research Associate
Rosie Bramante	Graduate Student
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
Mark Hanhardt	Support Scientist

Texas A&M

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

University at Albany, SUNY

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Steven Young	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 Manalaysay	Postdoc
Scott Stephenson	Postdoc
Jacob Cutter	Graduate Student
James Morad	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Postdoc
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
Tom Davison	Graduate Student
Maria Francesca Marzioni	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Jon Balajthy	Graduate Student
Richard Knoche	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

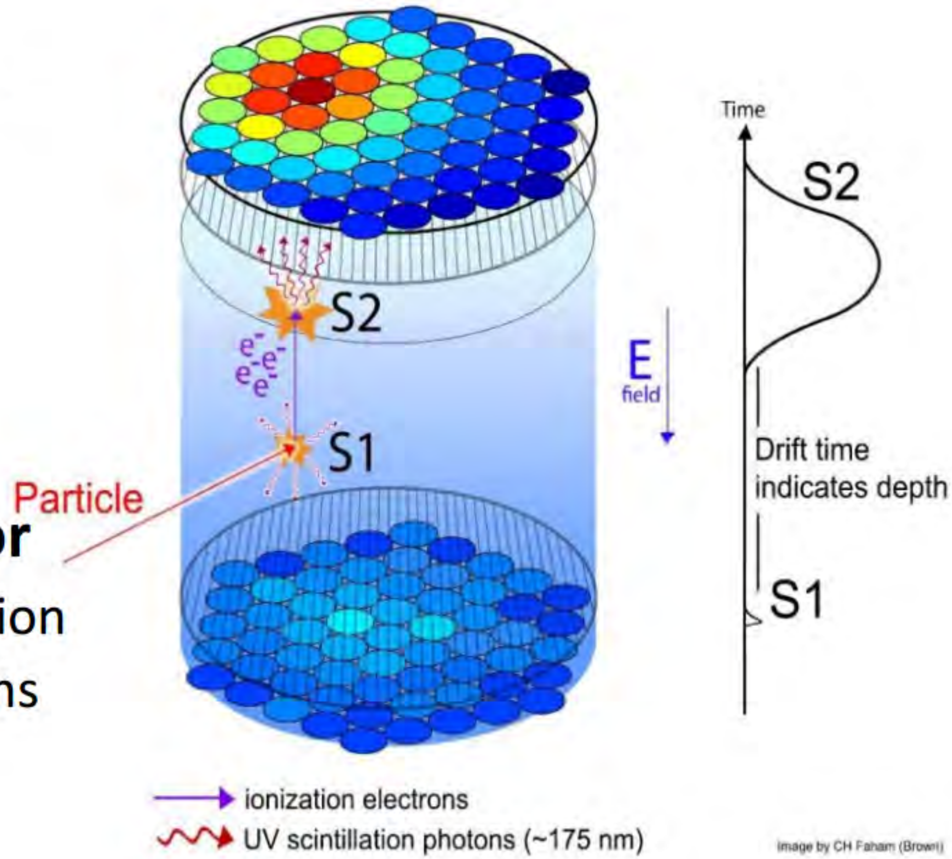
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student

Yale

Daniel McKinsey	PI, Professor
Ethan Bernard	Research Scientist
Markus Horn	Research Scientist
Blair Edwards	Postdoc
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

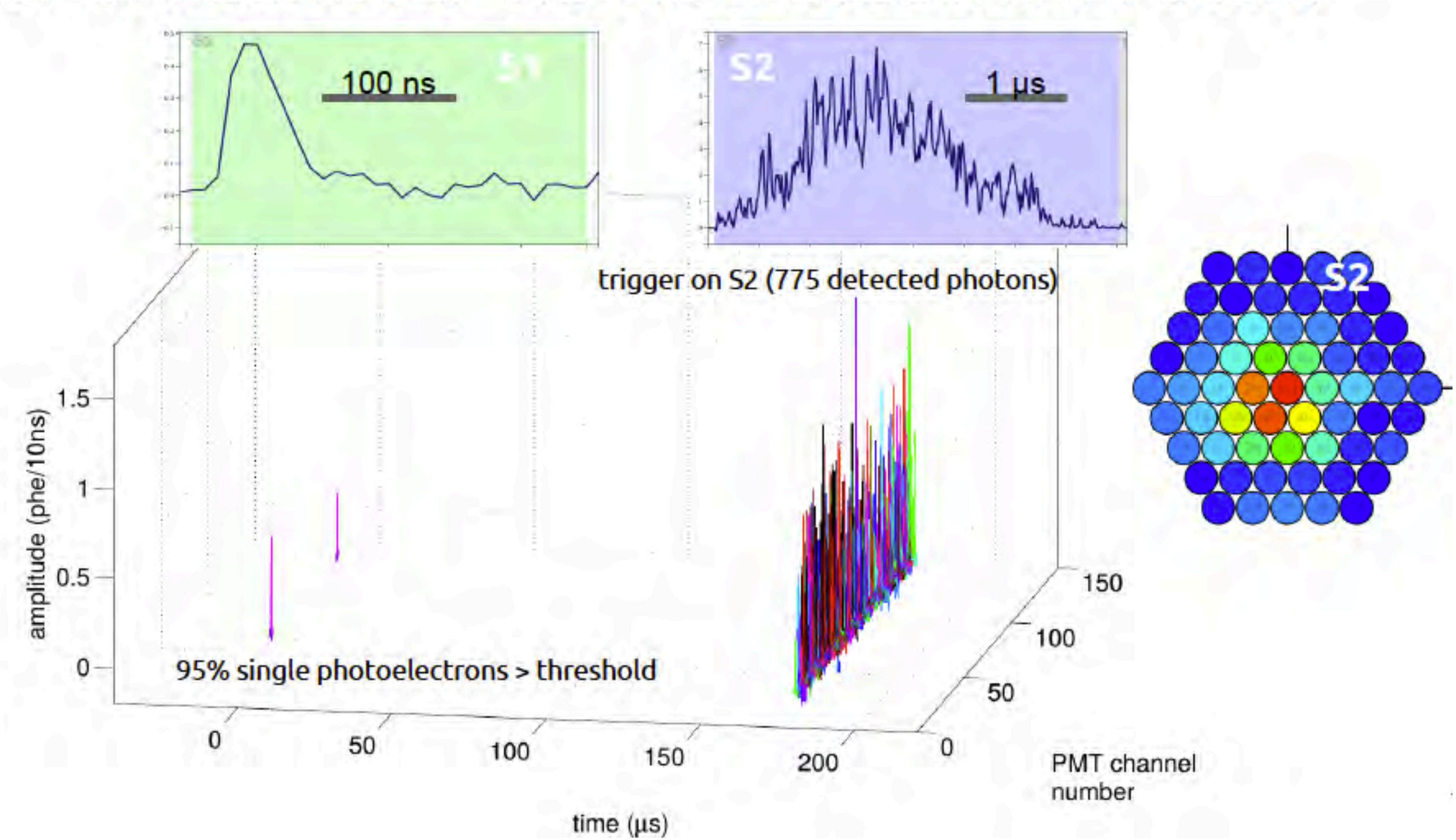
LUX Principle: Two-Phase Xenon TPC

- **S1: LXe is an excellent scintillator**
  - Density: 3 g/cm^3
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~2 keV**
- **S2: Even better ionisation detector**
  - S1+S2 allows mm vertex reconstruction
  - Sensitive to single ionisation electrons
  - **Nuclear recoil threshold <1 keV**



- **And a great WIMP target too**
  - Scalar WIMP-nucleon scattering rate dR/dE~A^2
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity
  - Excellent ionisation threshold: ‘light WIMP’ searches using S2 only
  - No damaging intrinsic backgrounds (^{127}Xe, $^{129m/131m}$Xe, ^{85}Kr, ^{136}Xe)

1.5 keV electron recoil event



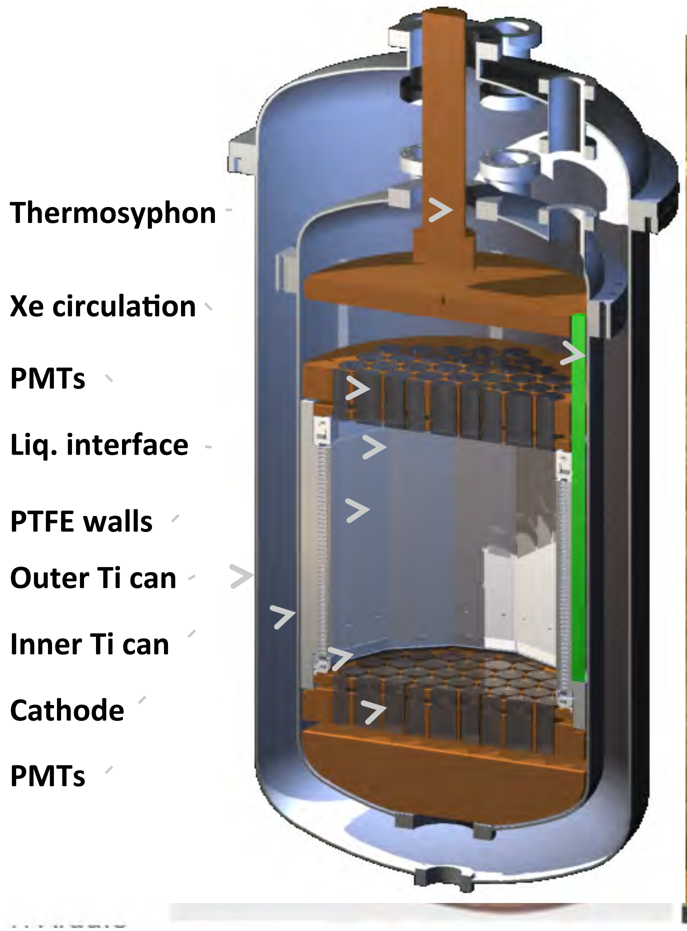
LUX Technology

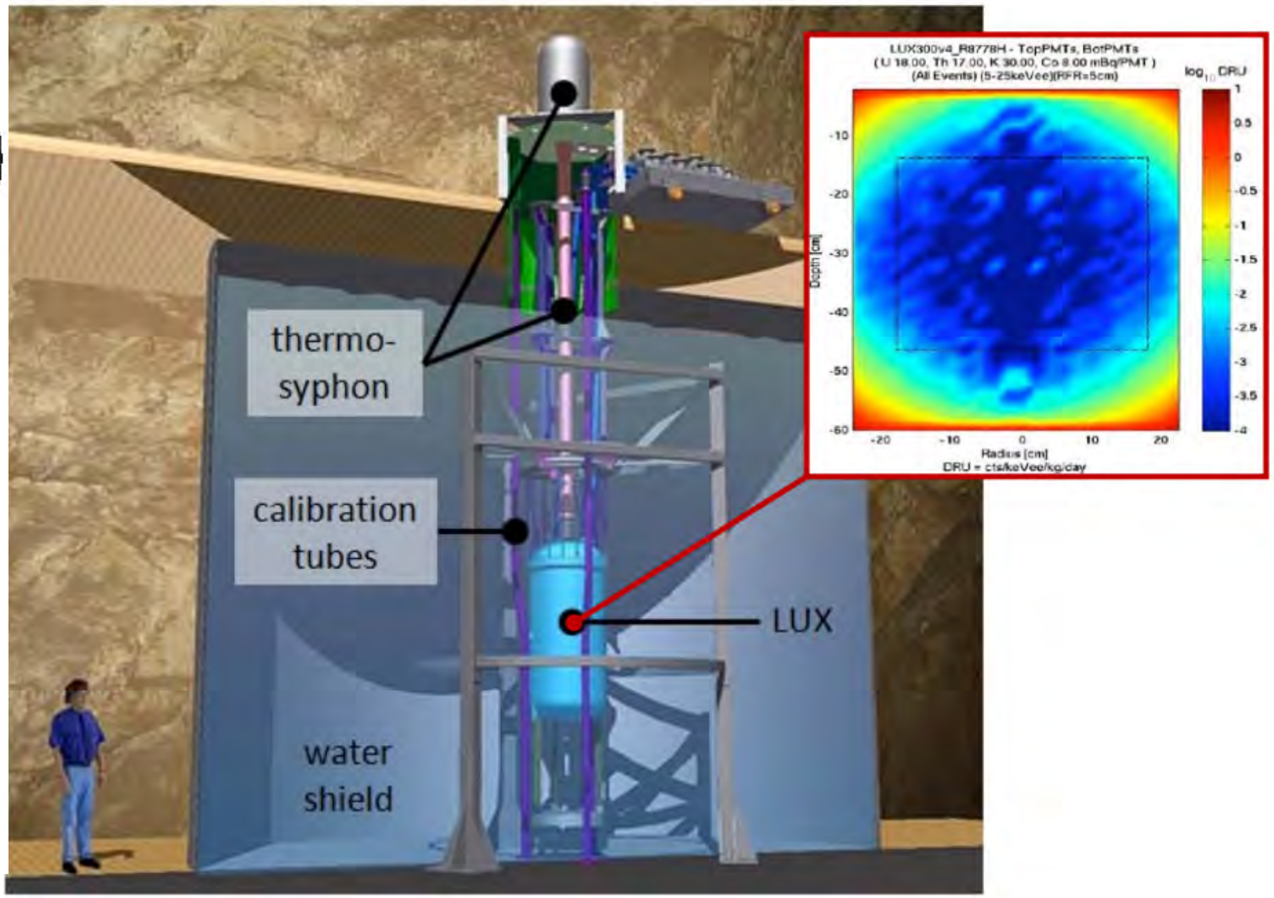
NIM. A 704, 111-126 (2013)
[arXiv:1211.3788]

Not actually used for Run 3

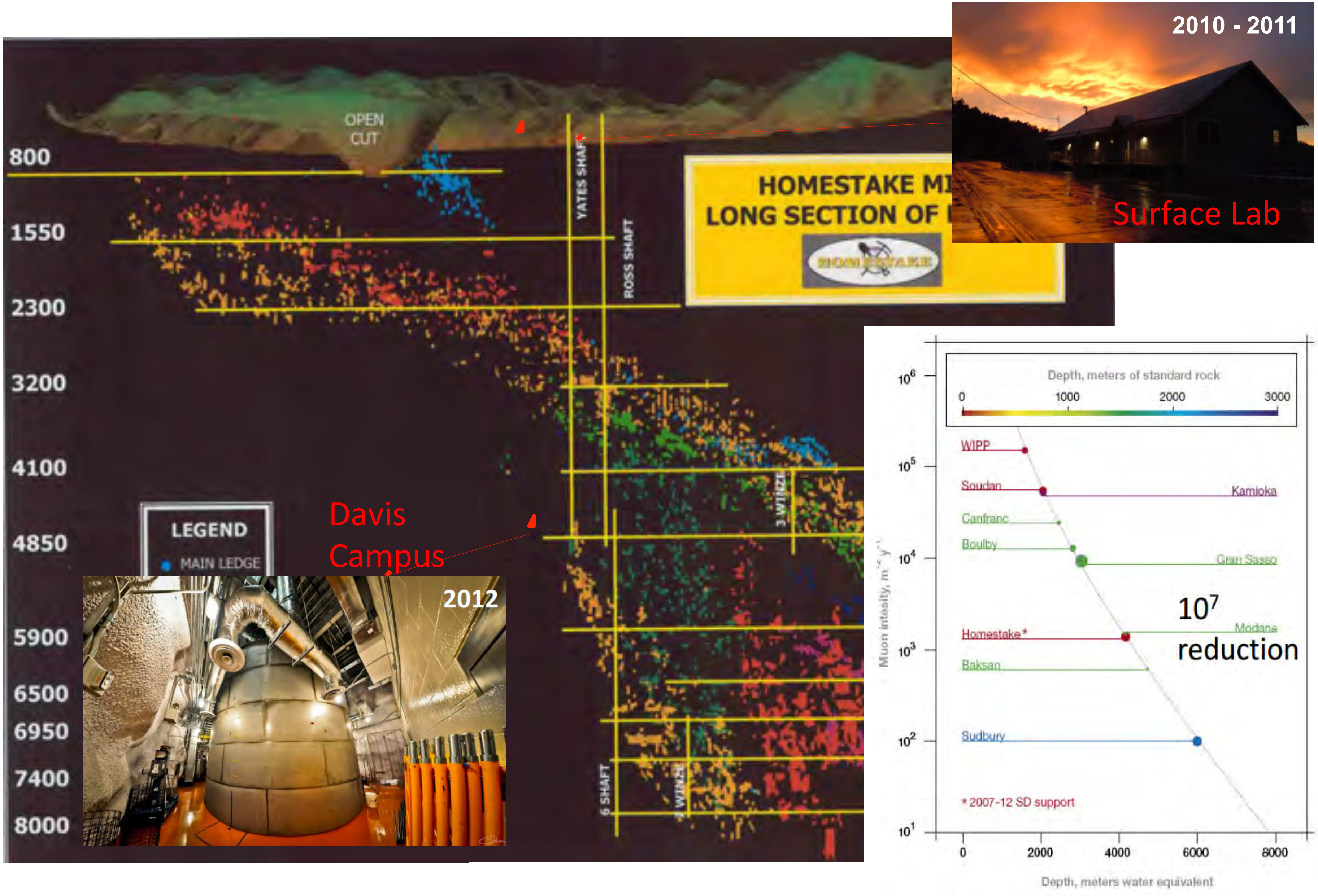
Two-phase xenon detector

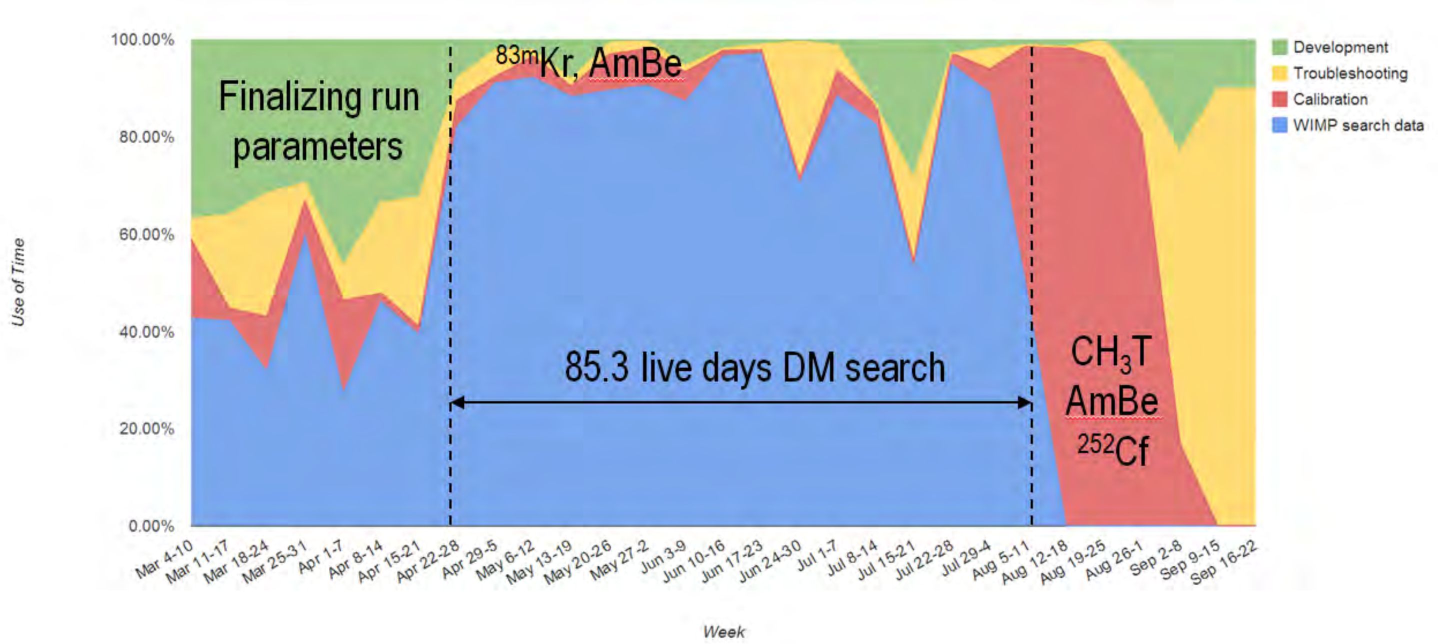
- 250 kg (active) mass of ultrapure liquid xenon (370 kg total)
- S1 and S2 light read out by two arrays of **61** ULB photomultiplier tubes
- Shielded from external radioactivity by ultrapure water (Cerenkov μ detector)





Sanford Lab – Davis Laboratory

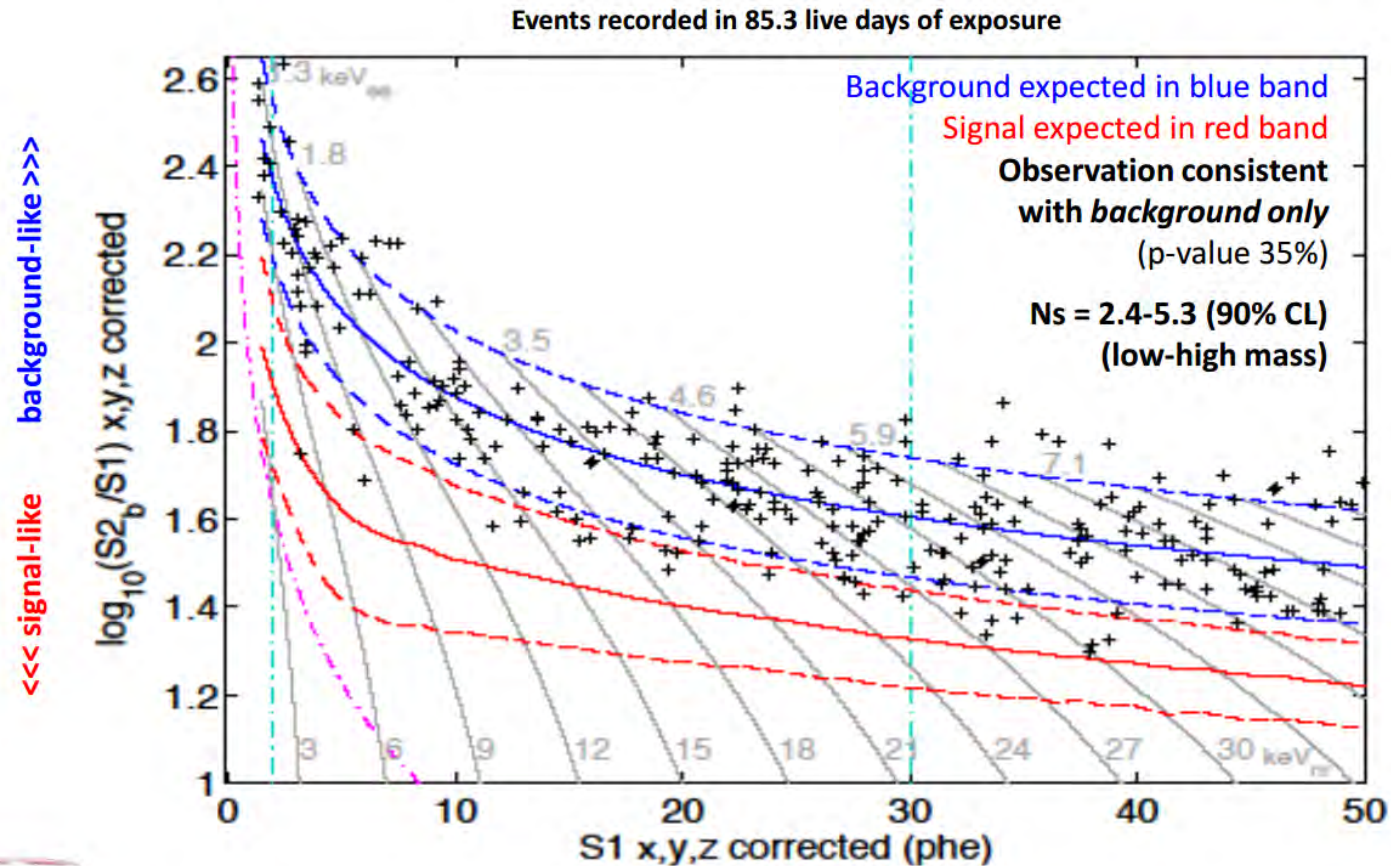




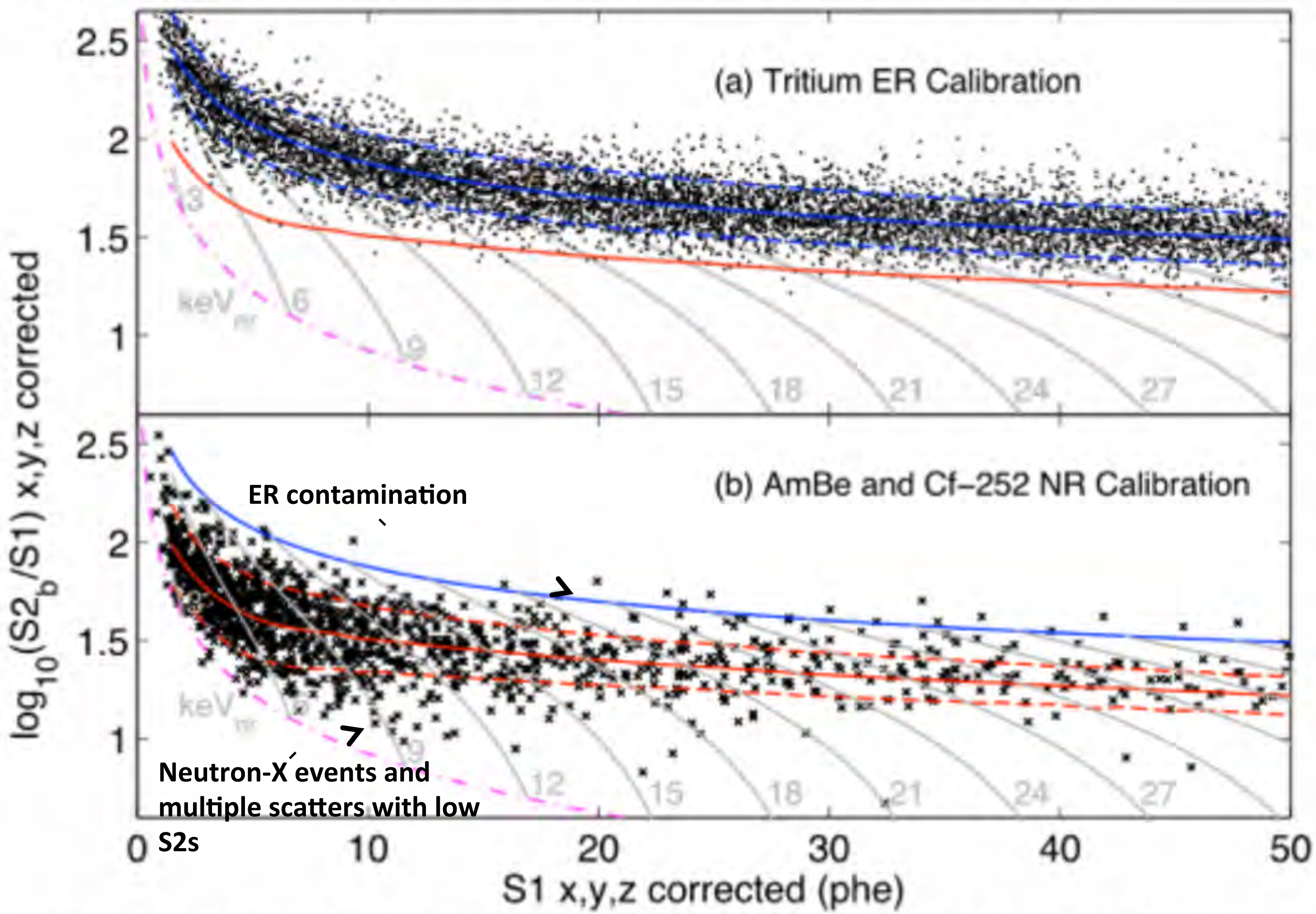
April – August Data

THE LUX 2013 RESULT

LUX WIMP Search, 85.3 live-days, 118 kg

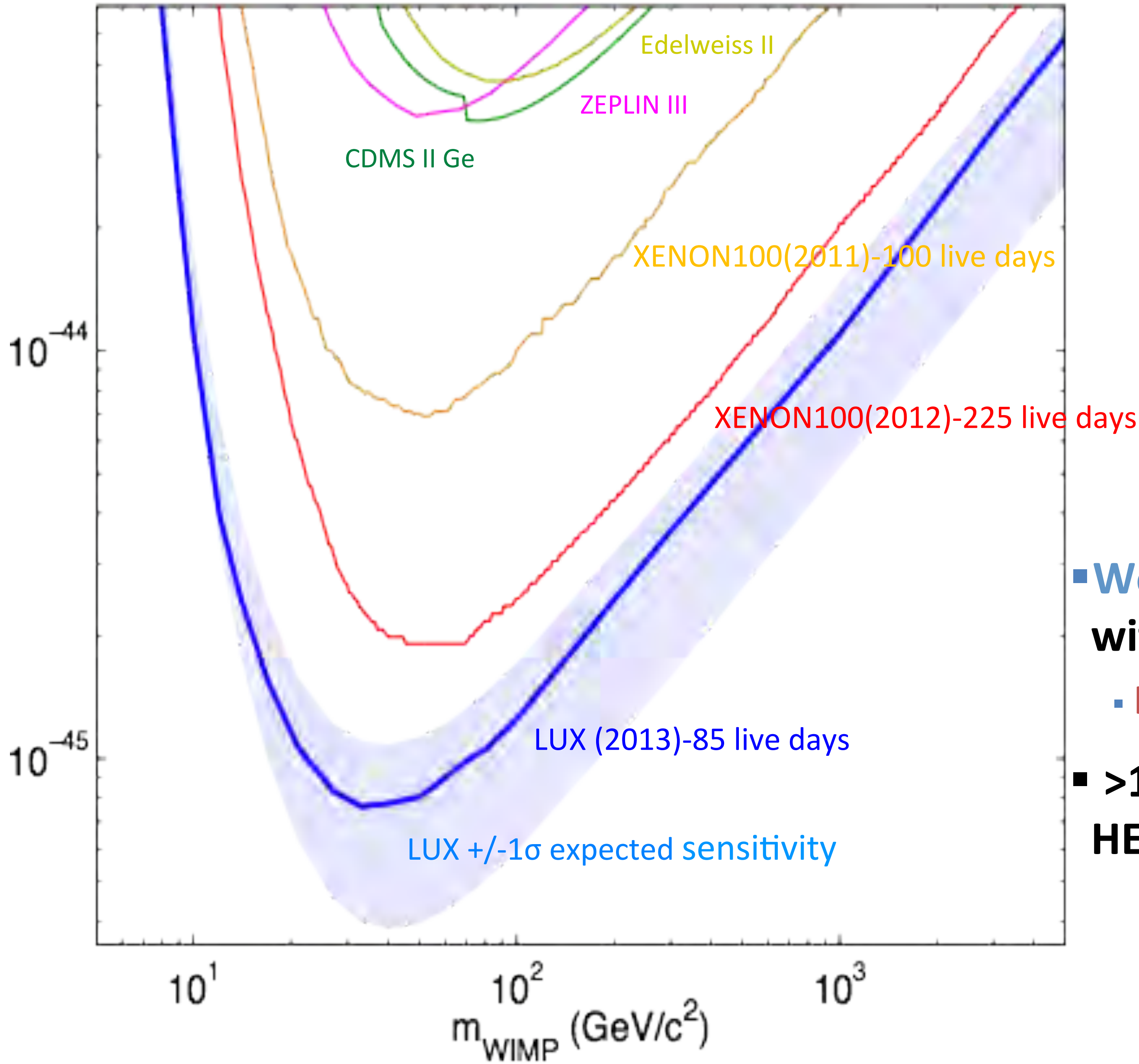


ER and NR Calibration Data



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

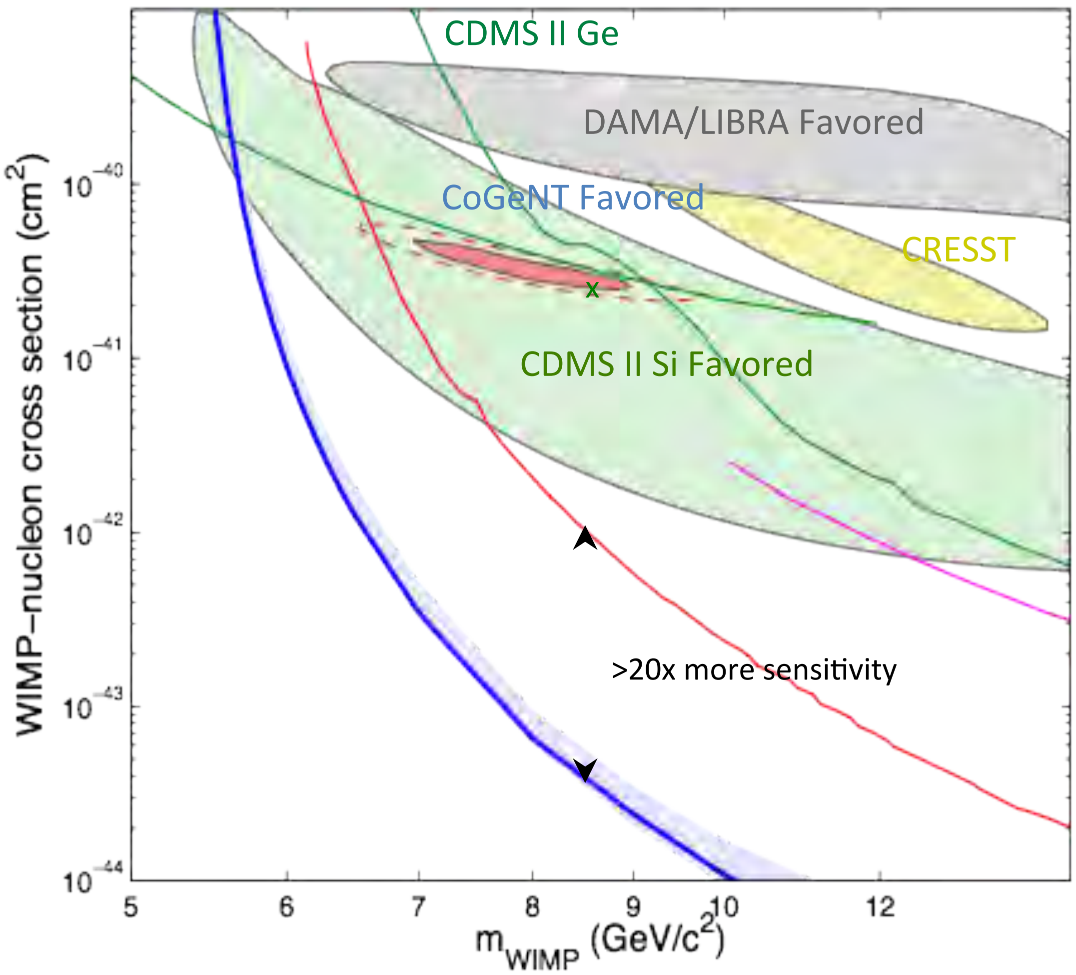
Limit on SI WIMP-nucleon cross-sections



- **World-leading sensitivity, with optimum at 33 GeV/c^2**
  - **Improvement factor x2-3**
- **>1000 citations on Inspire-HEP by Dec 2015**

Limit on SI WIMP-nucleon cross-sections - low mass WIMPs

- **Low-mass regime: several "hints" of WIMP signal strongly disfavored**
- **Dramatic relative improvement in sensitivity due to excellent light collection**



It’s happening

LUX RUN 4 AND ONGOING OPERATIONS

LUX Run 4

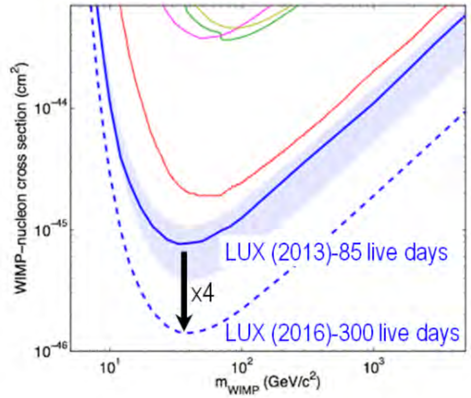
- Before Run 4
  - **End of 2013**: high-stats calibration data with CH_3T and DD neutron sources, for Run 3
  - **First half of 2014**: optimizing grids HV, “conditioning”. Increased extraction field by 17%

- Run 4 **started in Sep 2014** after finalizing new stable run parameters (mainly HV)
  - First: 4 weeks of DD neutron data + 5 days of CH_3T data
  - Accumulated ~250 live-days of WIMP search data so far
  - Second set of DD + CH_3T calibrations in March-April.
  - Aiming for **300 live-days** WS + necessary calibrations before **June 2016**

LUX Run4- Prospects

Expected improvement over 2013 sensitivity: x2 – x4

- One important low-E intrinsic background has disappeared (^{127}Xe)
- Benefit from better background modeling for Profile Likelihood analysis
- Benefit from improved detector response calibration at very low energy



These can also be applied to Run 3 data, now that we have the end-2013 calibration data, have had a year to look at it, and to refine the background model!

More of a good thing

RE-ANALYSIS OF 2013 RUN 3 DATA

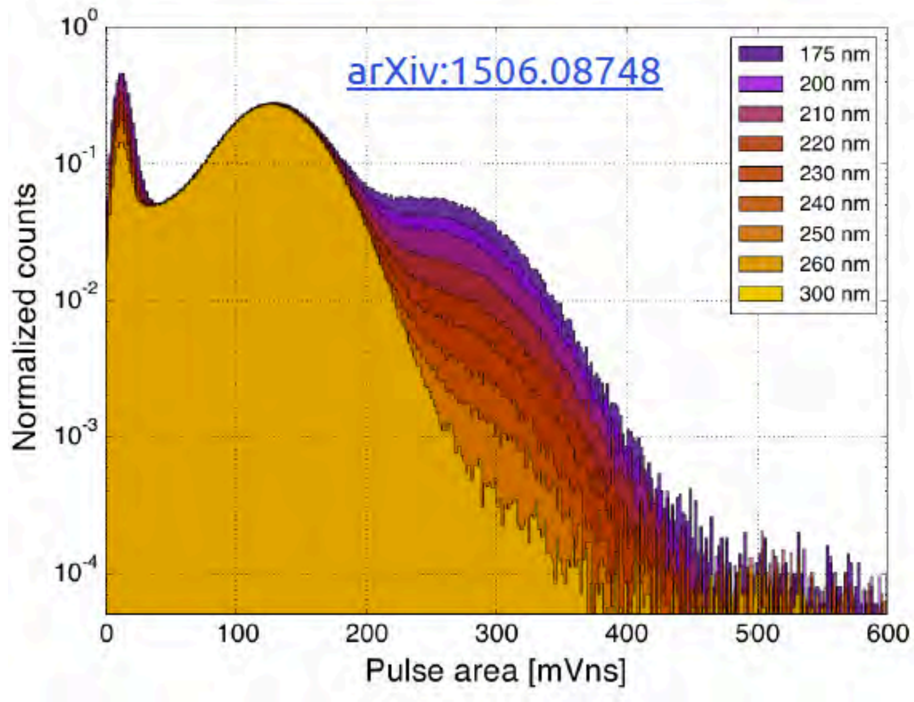
Measuring light

Better estimators for detected photons:

· Removed a bias in baselines

· Photon response calibrated in the VUV (2 phe from 1 photon)

· Digital counting of photons in PMT waveforms (for S1<20 keV)



Event Energy reconstruction

$$E = \frac{1}{L}\left(n_{ph} + n_e\right)W$$

n_{ph}, n_e: photons and electrons leaving the interaction site

L: mean fraction of recoil energy lost to electrons

L=1 for electron recoils; L<1 for nuclear recoils

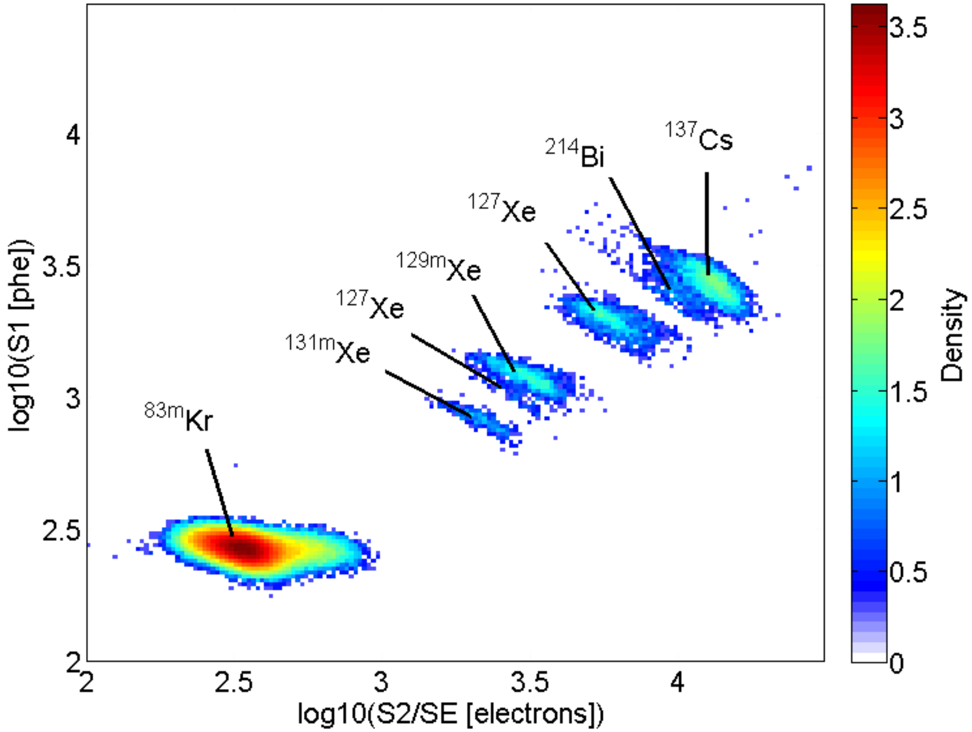
W=13.7 eV T. Shutt et al., Nucl. Phys. Proc. Suppl. 173, 160 (2007).

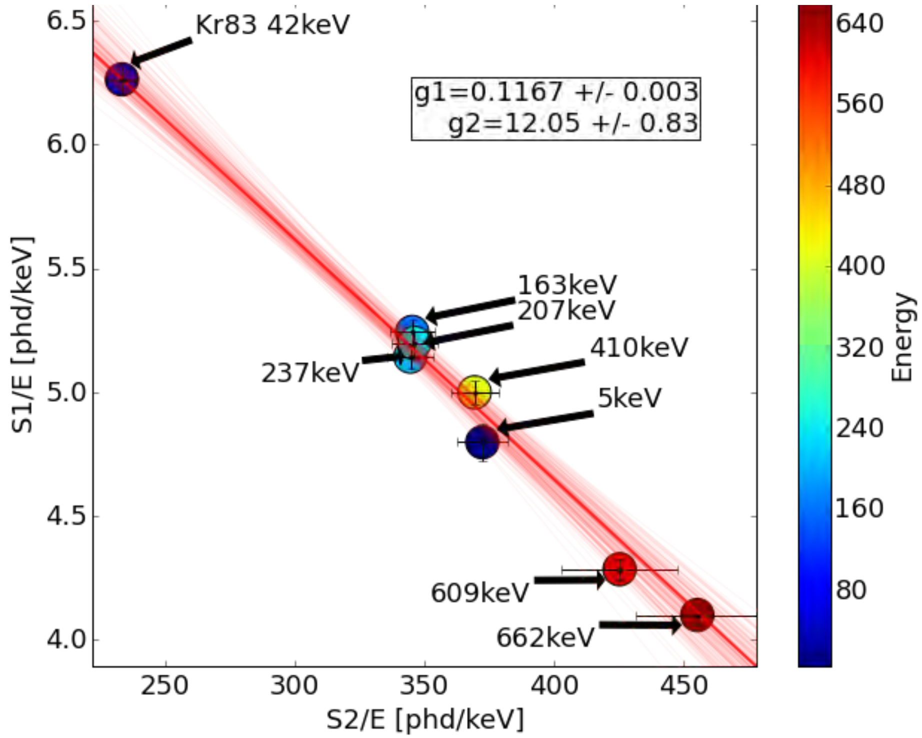
$$\langle S_{1c} \rangle = g_1 n_{ph} \qquad \langle S_{2c} \rangle = g_2 n_e$$

g_1 accounts for light collection efficiency

g_2= electroluminescence per single electron x electron extraction efficiency

g-Factors Determination





- 12% efficiency for the detection of a primary scintillation photon
  - previously 14% quoted
- 49% electron extraction (from 24.66 detected photons/e and g_2=12)
  - previously 65% but g_2=16.0 is what matters

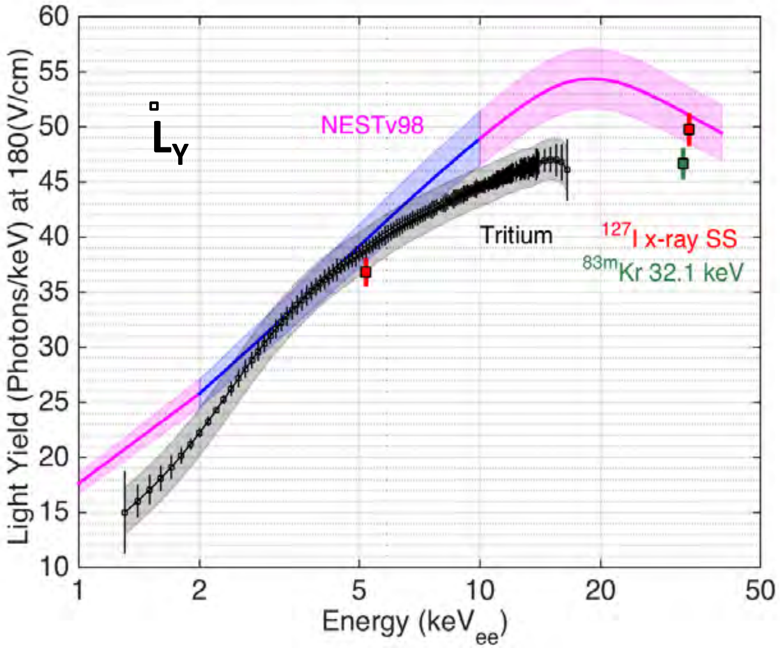
ER Calibration with tritium (0 -18 keV)

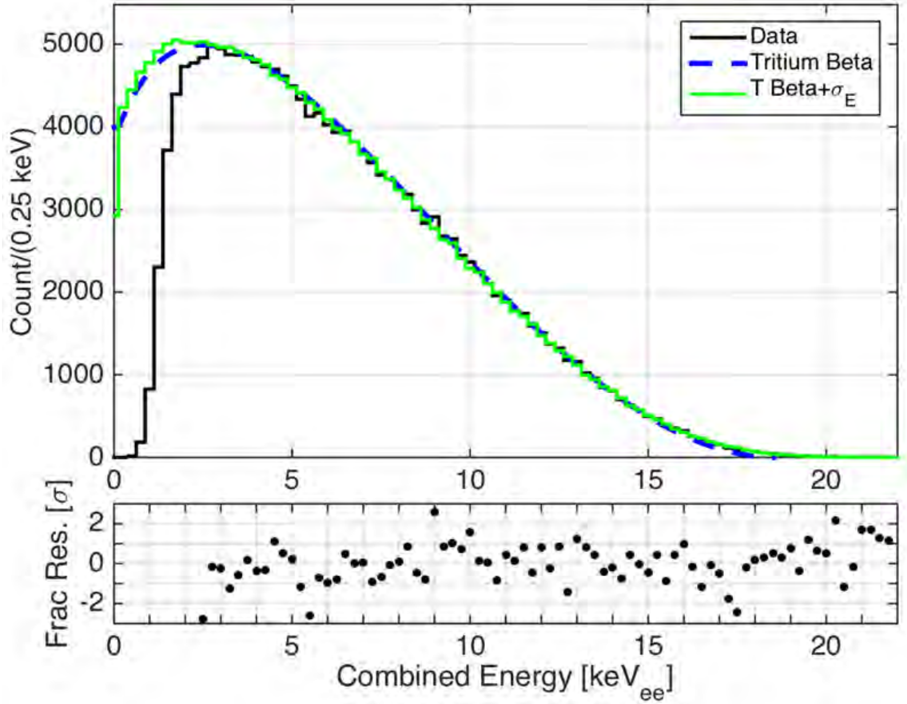
- Injection of CH_3T
- Homogeneous β source, Q = 18 keV
- Demonstrated removal with $\tau < 12$h
- Can take WS data again safely 5 days after 3 Bq injection
- Extract Q_Y and L_Y for electron recoils

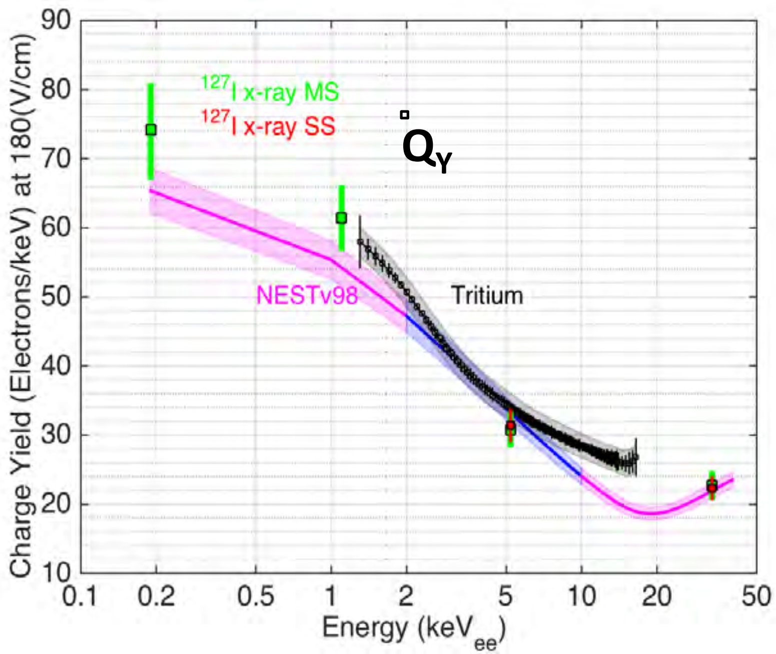
2nd campaign of CH_3T in Dec 2013

- 180 000 events accumulated

Out of the tritium data

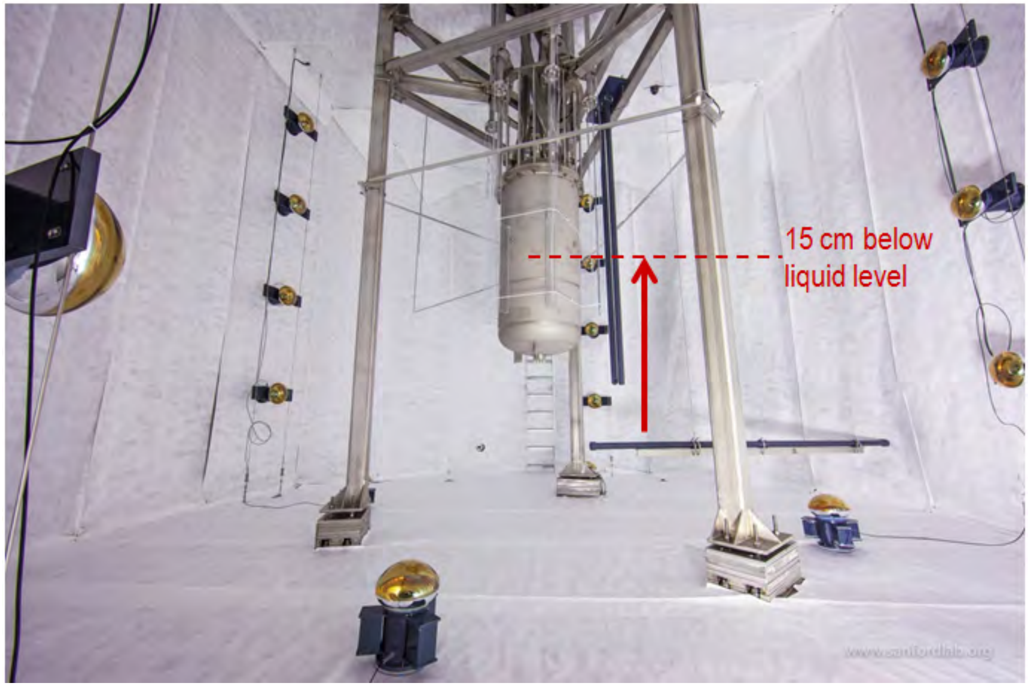


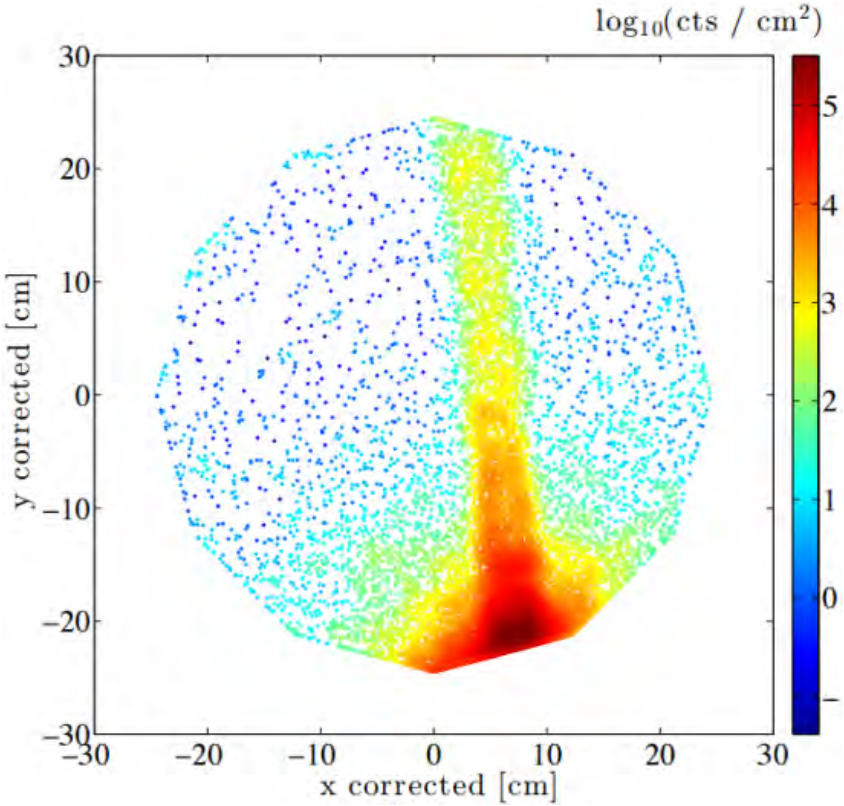




- Powerful support for the combined energy model
- L_y and Q_y for ER measured down to 1.1 keV
- Precise determination of the probability for an ER event to “leak” down into NR S2/S1 region, as a function of S1

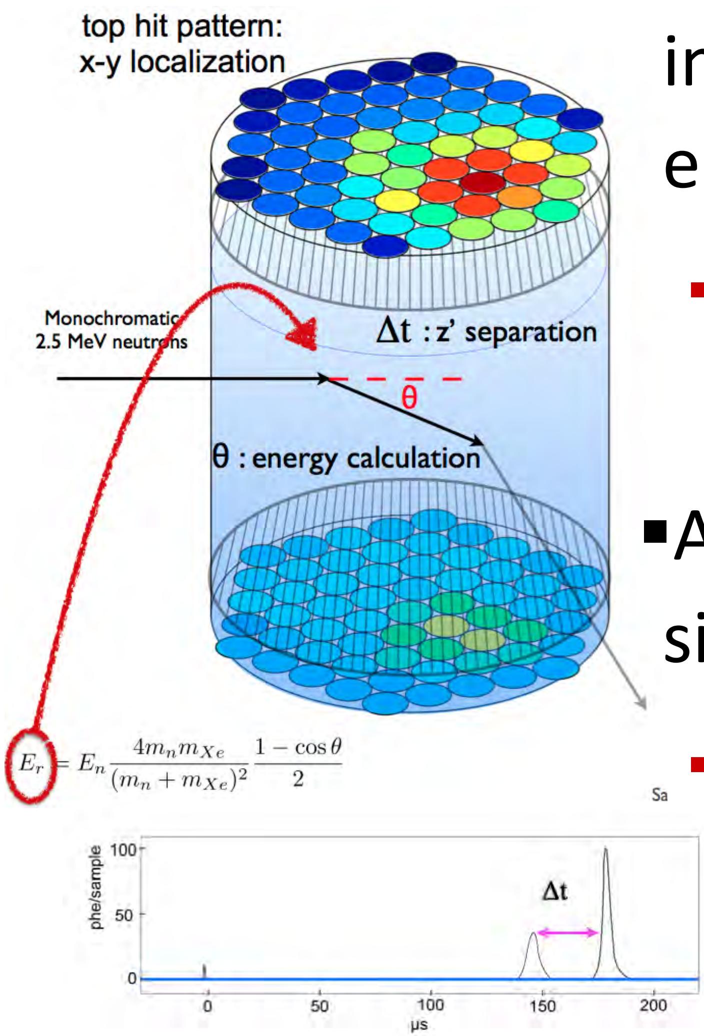
In situ NR Calibration





- D-D neutron generator
- Neutron generator/beam pipe assembly aligned 16 cm below liquid level in LUX active region to maximize usable single / double scatters
- 105 live hours of beam time in Aug 2013

In situ NR Calibration with kinematically - constrained neutron scatters

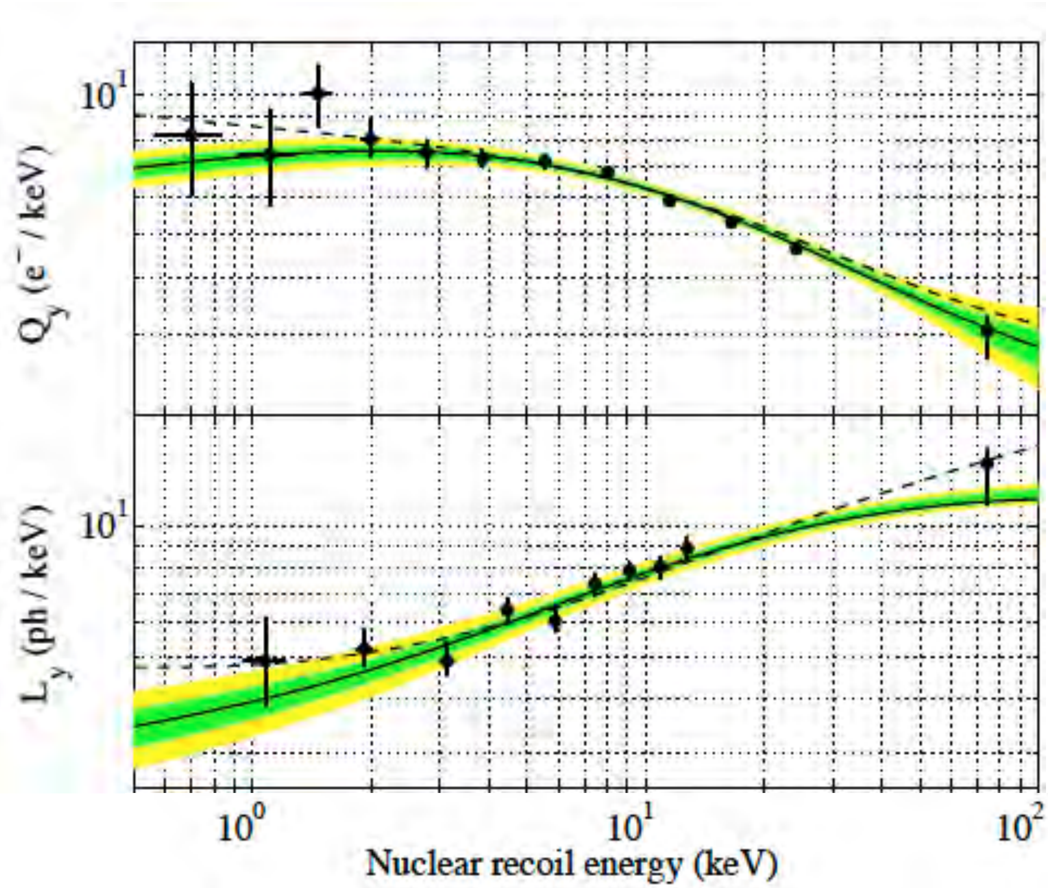


$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1-\cos\theta}{2}$$

- Identify double scatters along beam line inside LUX. Angle θ gives deposited energy.
  - → Absolute calibration of ionization response Q_Y
- Apply ionization scale found above to single scatters
  - → Absolute calibration of scintillation response L_Y

Nuclear Recoil Response

- Data first shown in Feb 2014 with very preliminary analysis.
- Significant effort to refine analysis since then
  - Study of all systematics
  - Optimization of events selection
  - Improved models of ionization and scintillation
- Great progress:
  - Q_Y measured down to 0.7 keVr
  - L_Y measured down to 1.1 keVr



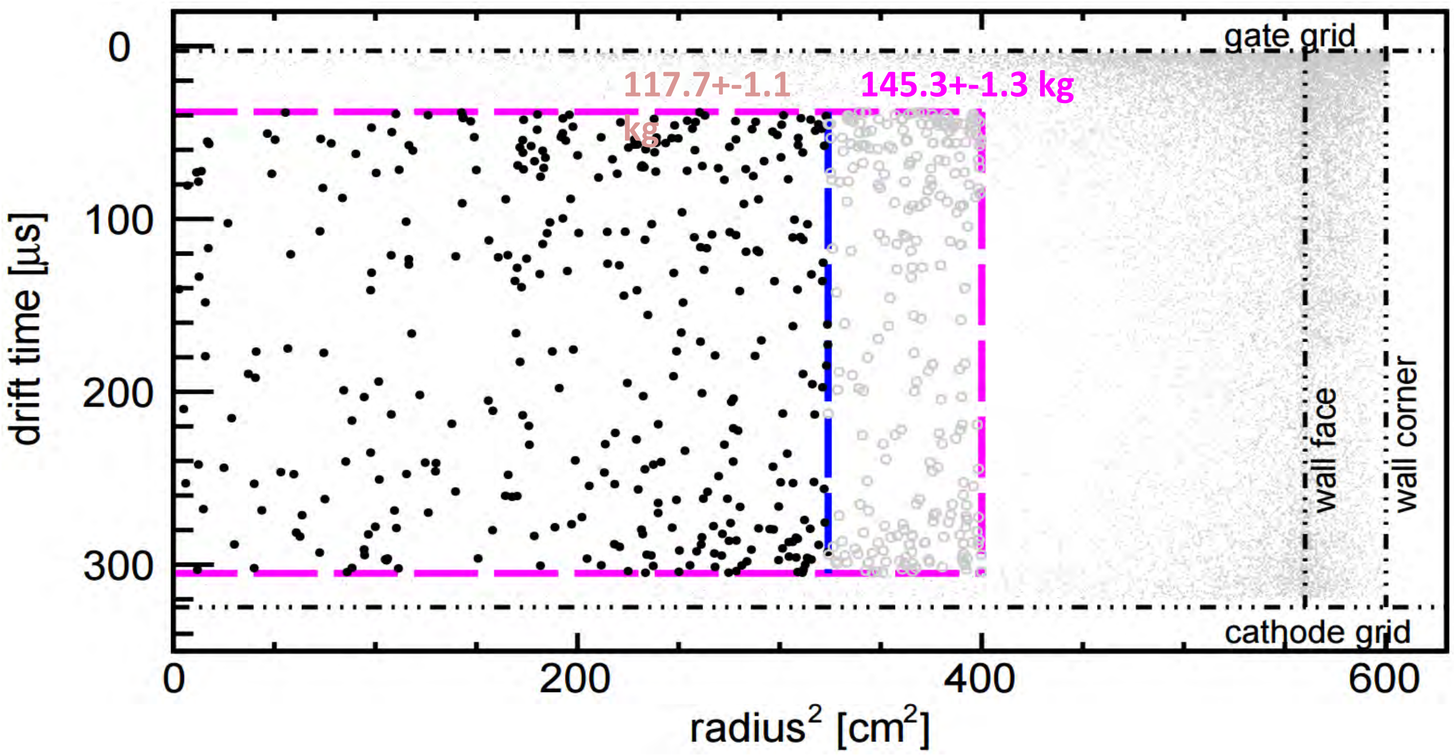
- **Kinematic reach now 3.3 GeV/c² WIMP mass**

What else was Improved?

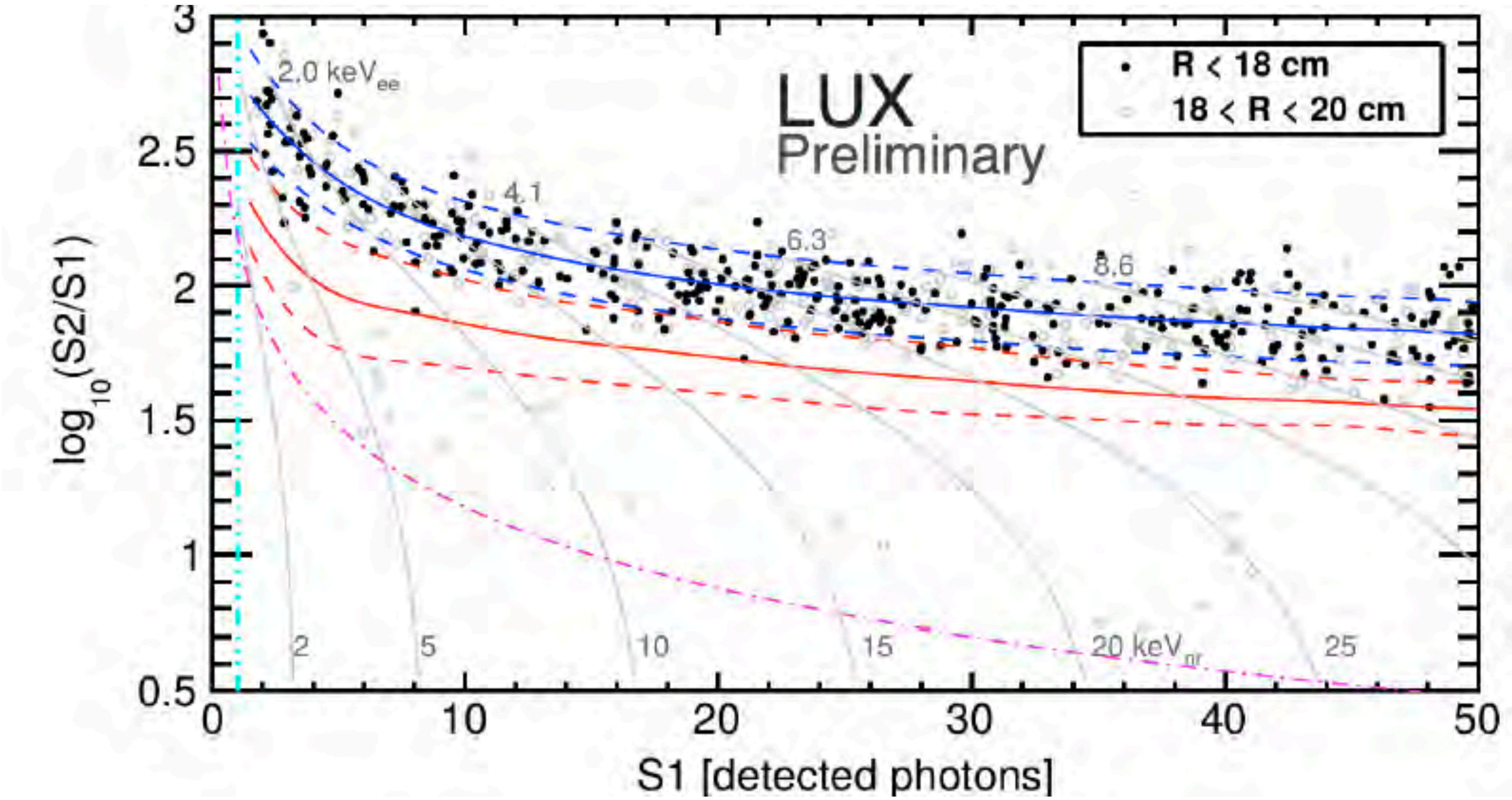
- Update to Background Model
  - Addition of "Wall Events"
    - ^{206}Pb nuclear recoils
    - ^{37}Ar
  - ^{127}Xe naked X-rays included
- Increase of the exposure
  - Increase of fiducial volume (118 kg → 145kg)
  - + 10 days of data
- Updates to position reconstruction algorithm
  - Use of photon counting at very low energy
  - Improvement of LRFs
- Taking into account non-uniformity of electric field
- Use of both top and bottom PMT array to determine S2

Distribution of Backgrounds

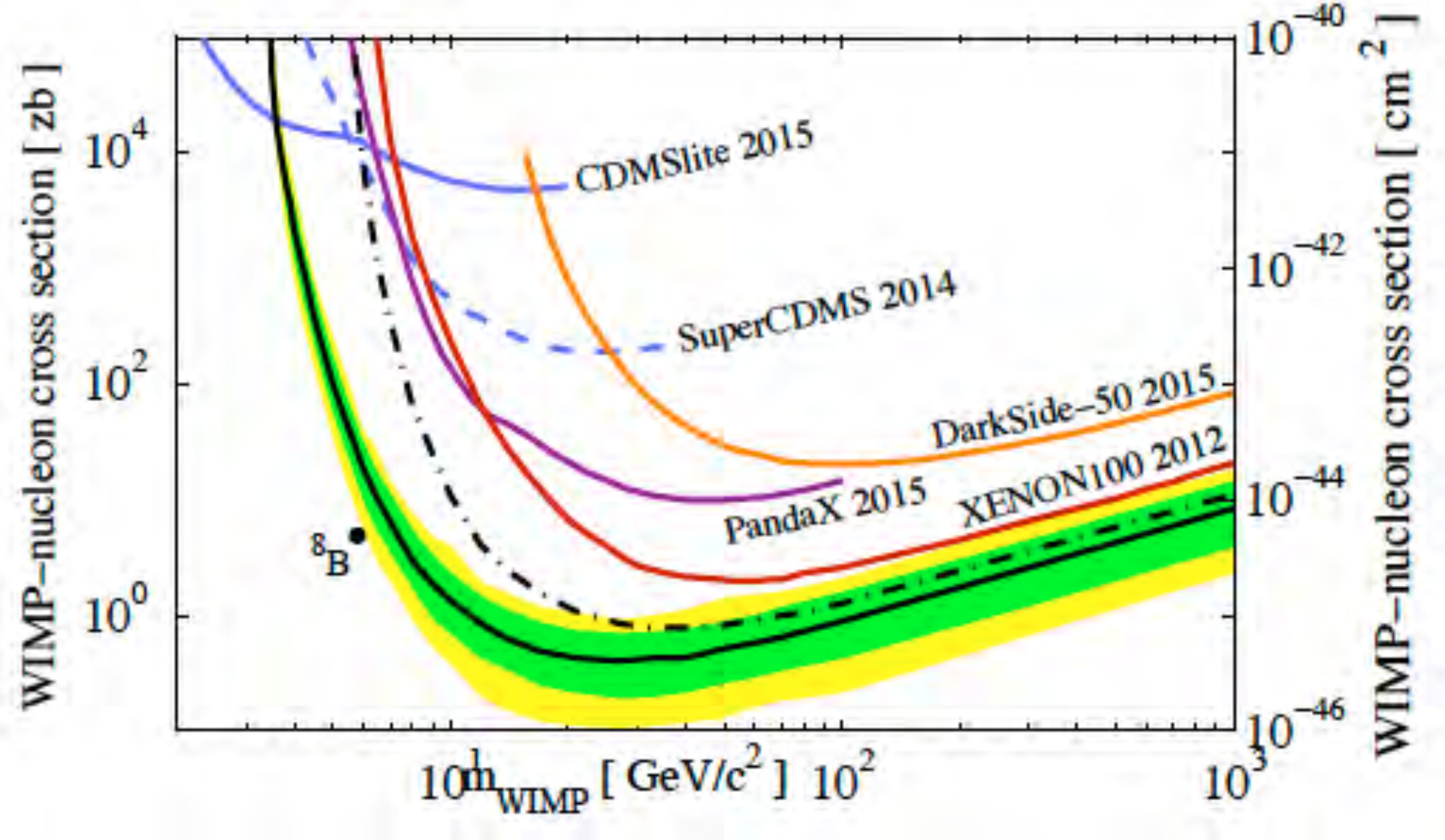
- Measured 3.5 ppt Kr with RGA.
- PMT gamma-rays = biggest background
- 591 surviving events in the fiducial volume No ER v. NR discrimination here: PLR deals with whole distribution.



WIMP-Search Data



Spin-Independent elastic WIMP-nucleon cross section



LUX-ZEPLIN (LZ)

LZ = LUX + ZEPLIN

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)

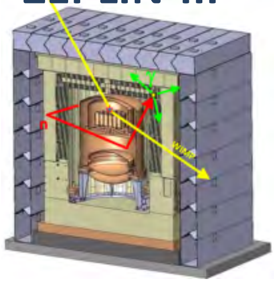
University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
University of California, Berkeley
Brookhaven National Laboratory
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Kavli Institute for Particle Astrophysics & Cosmology
Lawrence Livermore National 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

LZ Timeline

Year	Month	Activity
2012	March	LZ (LUX-ZEPLIN) collaboration formed
	May	First Collaboration Meeting
	September	DOE CD-0 for G2 dark matter experiments
2013	November	LZ R&D report submitted
2014	July	**LZ Project selected in US and UK**
2015	April	DOE CD-1/3a approval, similar in UK Begin long-lead procurements(Xe, PMT, cryostat)
2016	April	DOE CD-2/3b approval, baseline, all fab starts
2017	June	Begin preparations for surface assembly @ SURF
2018	July	Begin underground installation
2019	Feb	Begin commissioning

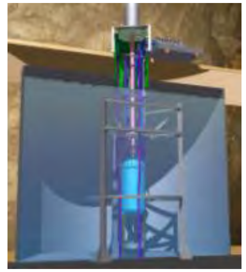
ZEPLIN → LUX → LZ

ZEPLIN-III



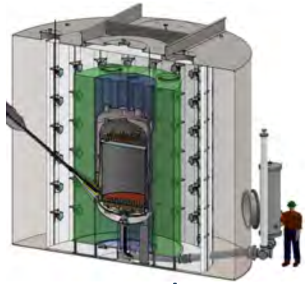
6 kg LXe fid

LUX



100 kg

LZ



5600 kg

Next-generation LXe experiment building on LUX & ZEPLIN programmes

- **Route to detection & study: a progressive programme**
  - **ZEPLIN** pioneered two-phase Xe for WIMP searches (3.9×10^{-8} pb/n)
  - **LUX** is present world leader in sensitivity (7.6×10^{-10} pb/n, and ongoing)
  - **LZ** expected sensitivity: ~2×10^{-12} pb/n with 3-year run
- **Experimental approach: a low risk but aggressive programme**
  - Internal bk-free strategy (self-shielding, modest discrimination assumed)
  - Two-phase Xe technology: high readiness level
  - Some infrastructure inherited from LUX
- **LZ will provide exciting physics opportunities for light & heavy WIMPs (GeV-TeV): since we do not know what BSM physics looks like!**

Scale up ≈ 50 in fiducial mass

LZ

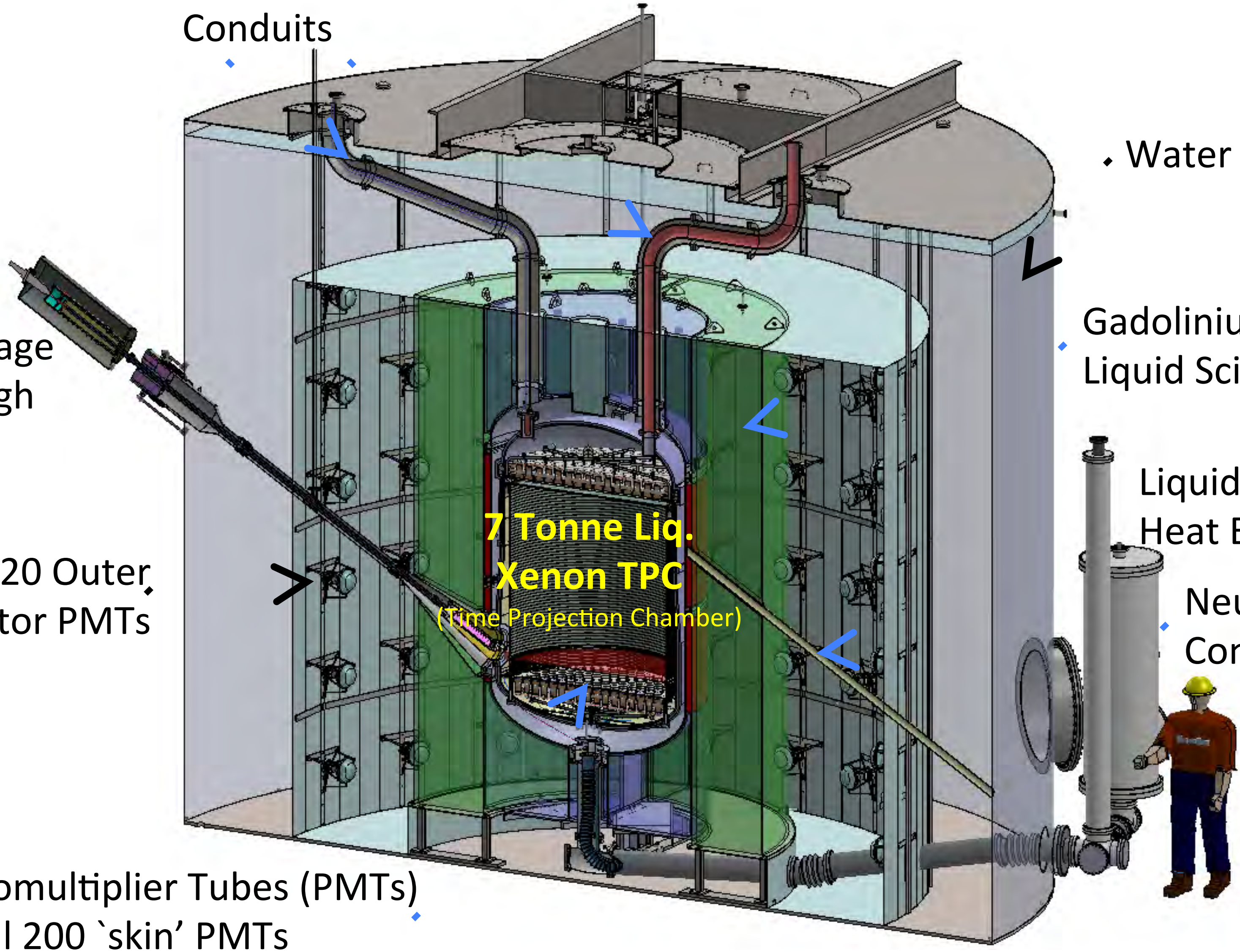
Total mass – 10 T
WIMP Active Mass – 7 T
WIMP Fiducial Mass – 5.6 T

LUX

LUX → LZ

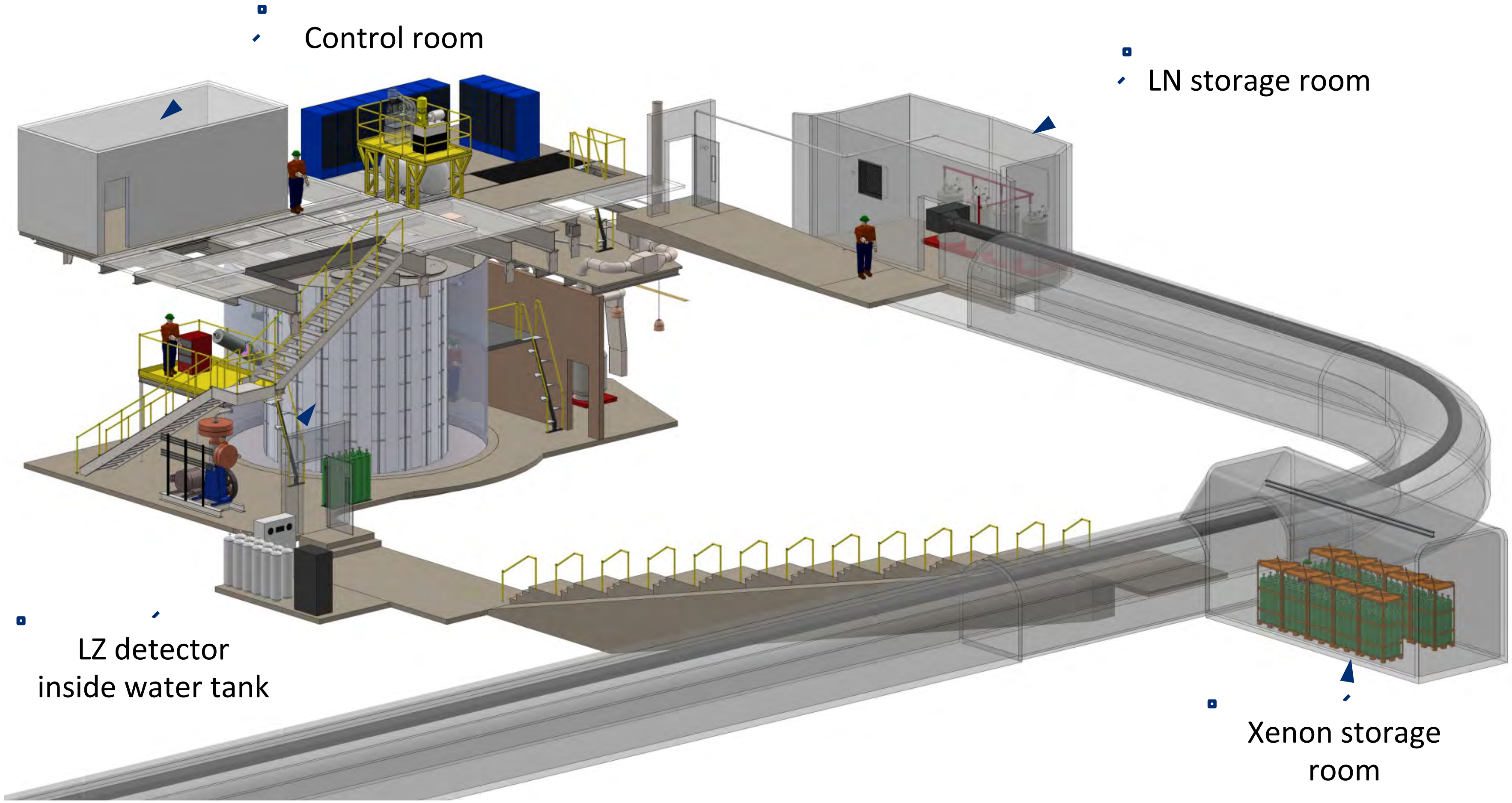
- LUX water shield and an added liquid scintillator active veto.
- Instrumented "skin" region of peripheral xenon as another veto system.
- Unprecedented levels of Kr removal from Xe.
- Radon suppression during construction, assembly and operations.
- Photomultipliers with ultra-low natural radioactivity.

LZ Overview


Instrumentation
Conduits
Water Tank
High Voltage
Feedtrough
Gadolinium Loaded
Liquid Scintillator
Liquid Xenon
Heat Exchanger
7 Tonne Liq.
Xenon TPC
(Time Projection Chamber)
120 Outer
Detector PMTs
Neutron Calib.
Conduit
488 Photomultiplier Tubes (PMTs)
Additional 200 `skin' PMTs

LZ Underground at SURF

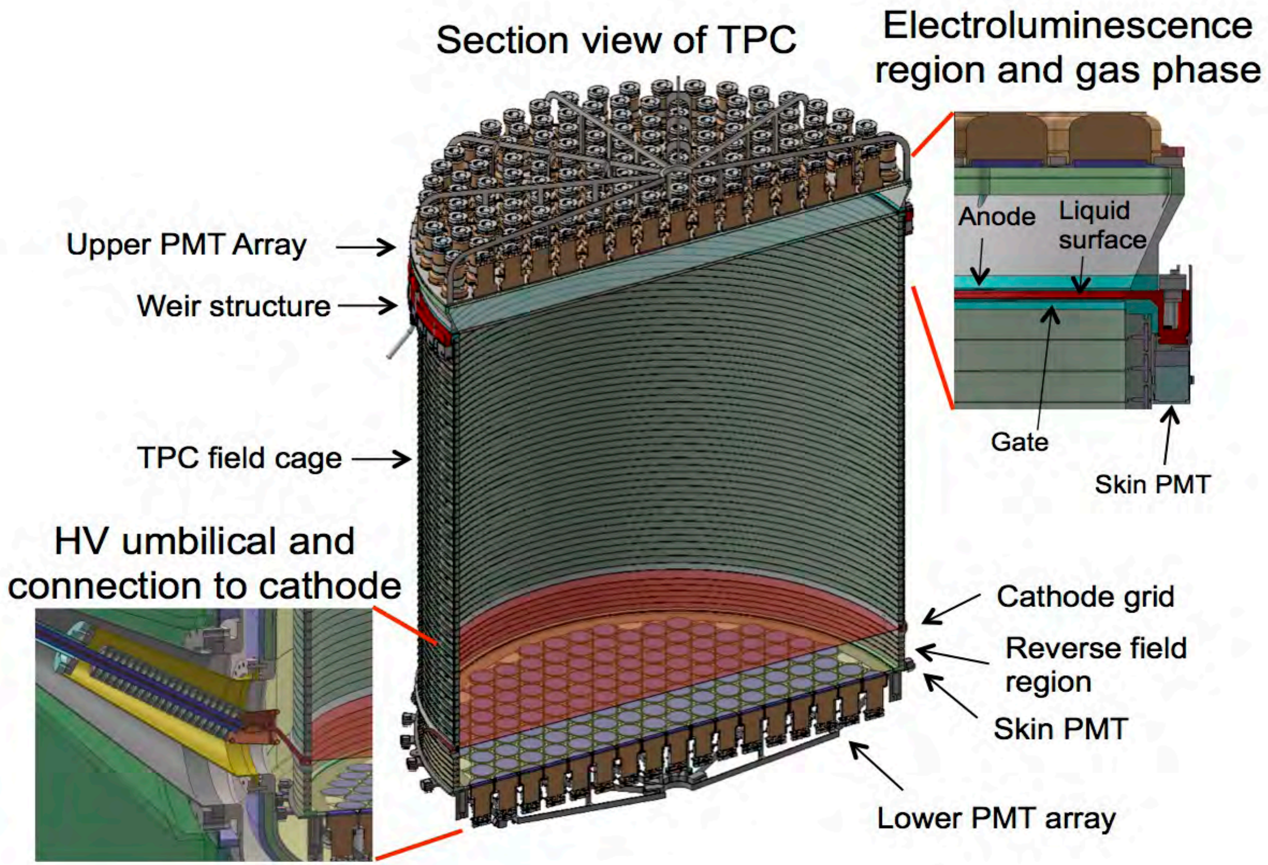
Years of experience at SURF from LUX



Design Status Summary

- Conceptual, and in some cases more advanced design, completed for all aspects of detector
- Conceptual Design Report available as **arXiv:1509.02910**
- Acquisition of Xenon started
- Procurement of PMTs and cryostat started
- Collaboration – wide prototype program underway to guide and validate design
- Backgrounds modeling and validation well underway

THE LZ TPC



- **TPC PARAMETERS**
  - 1.5 m diameter/length (3x LUX)
  - 7 tonne active LXe mass (28x LUX)
  - 2x 241 3-inch PMTs (4x LUX)
  - Highly reflective PTFE field cage
  - 100 kV cathode HV (10x LUX)
  - Electron lifetime 3 ms (3x LUX)

PHYSICS PARAMETERS

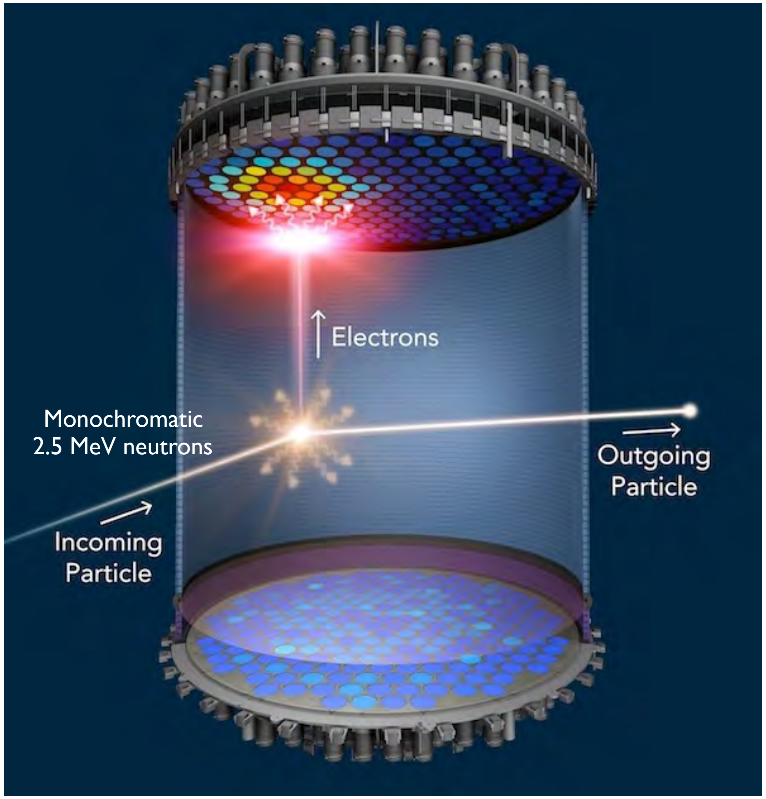
- 5.8 keVr S1 threshold (4.5 keVr LUX)
- 0.7 kV/cm drift field, 99.5% ER/NR disc. (already surpassed in LUX at 0.2 kV/cm)

Xe Detector Prototyping

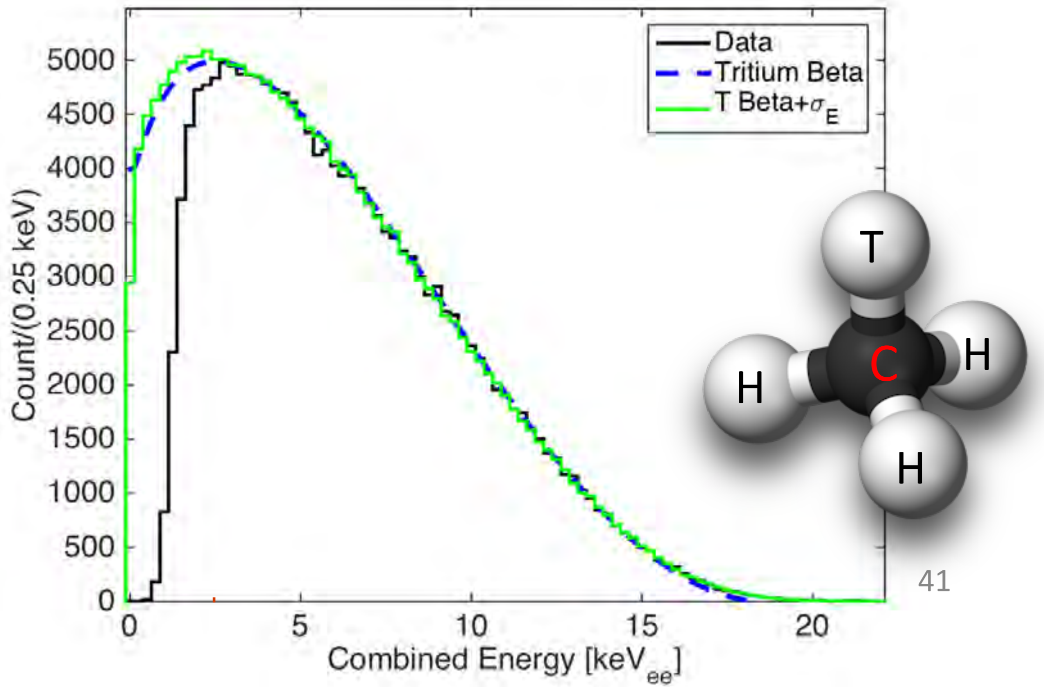
- Extensive program of prototype development underway
- Three general approaches
  - Testing in liquid argon, primarily of HV elements, at Yale and soon at LBNL
  - Design choice and validation in small (few kg) LXe test chambers in many locations: LLNL, Yale-> UC Berkeley, LBNL, U Michigan, UC Davis, Imperial College, MEPhI
  - System test platform at SLAC, Phase I about 100 kg of LXe, TPC prototype testing to begin in few months

LZ Calibrations

- Demonstrated in LUX. Calibrate The Signal and Background Model *in situ.*
- DD Neutron Generator (Nuclear Recoils)
- Tritiated Methane (Electron Recoils)
- Additional Sources e.g. YBe Source for low energy (Nuclear Recoils)



Tritium Beta Spectrum Measured in LUX



Extensive Calibration

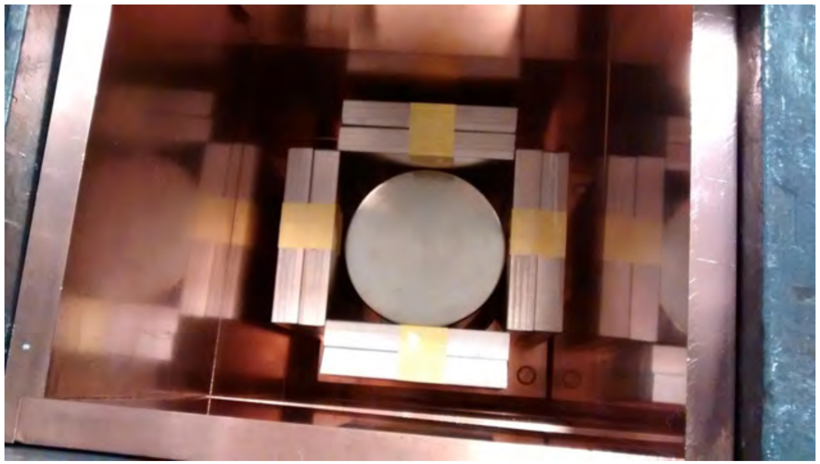
- LUX has led the way to detailed calibrations. LZ will build on this and do more.

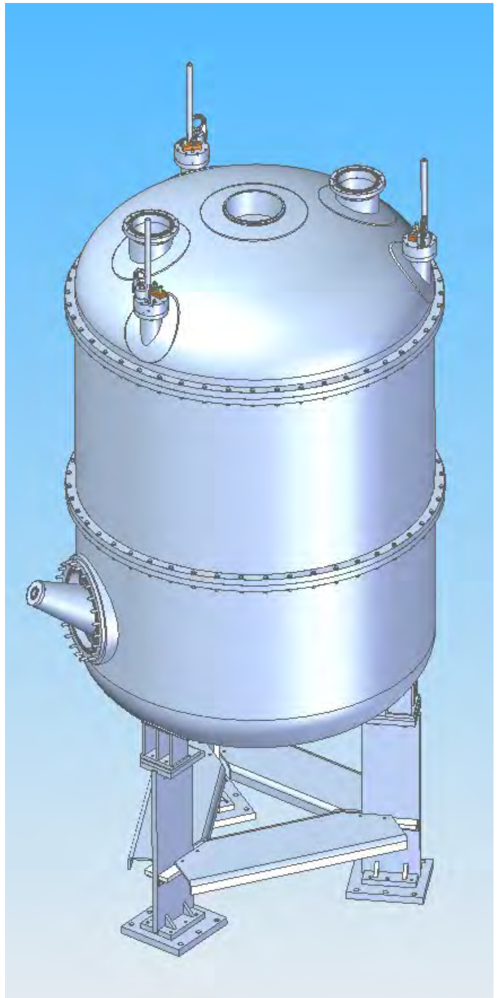
Done in LUX and will be done in LZ	Not done in LUX, but will do in LZ
^{83m}Kr (routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
Tritiated methane (every few months)	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator(upgraded early next year to shorten pulse)	

Cryostat Vessels

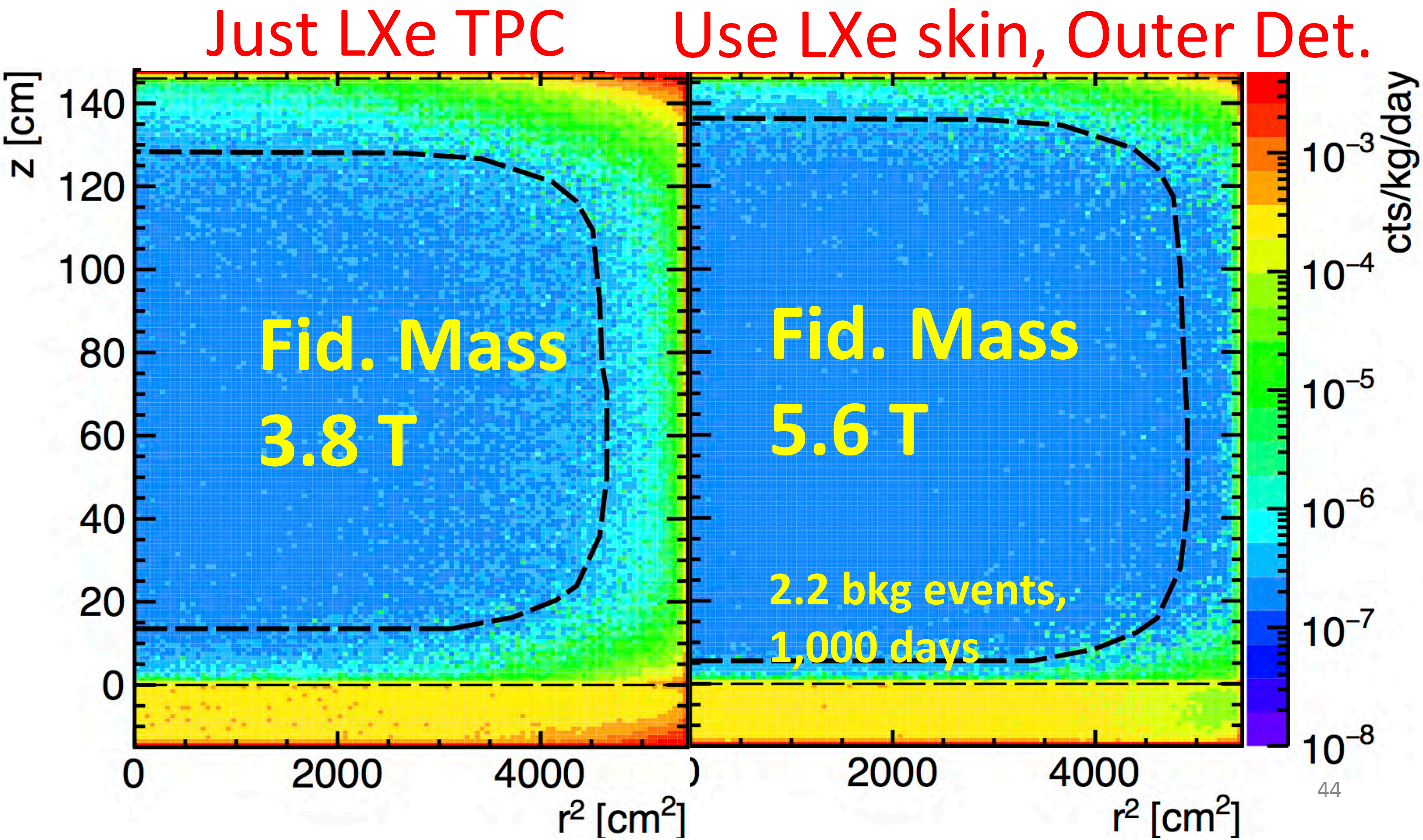
- UK responsibility
- Low background titanium chosen direction

  SS alternative advanced as backup
- Ti slab for all vessels(and other parts) received and assayed
- Contributes < 0.05 NR+ER counts in fiducial volume in 1,000 days after cuts



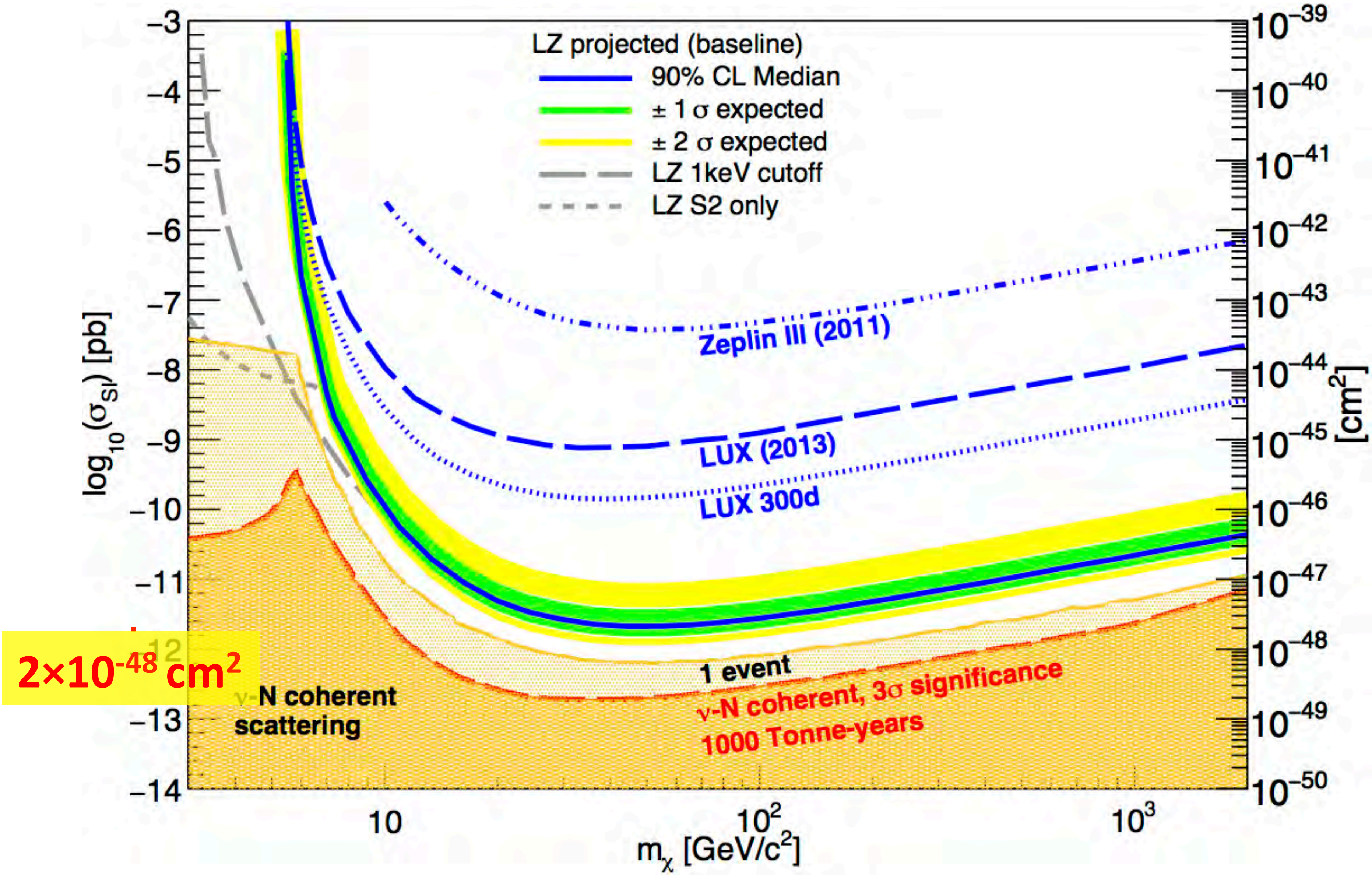


Background Modeled



Projected Sensitivity – Spin Independent

(LZ 5.6 Tonnes, 1000 live days)



Conclusions

- LZ Project well underway, with procurement of Xe, PMTs and cryostat vessels started
- Extensive prototype program underway
- LZ benefits from the excellent LUX calibration techniques and understanding of background
- LZ sensitivity expected to be finally limited by neutrino-induced `background'

Extra Slides

The model

Charge production:

$$n_e = L(E_0) \times \frac{E_0}{W} \left(\frac{1}{1 + N_{ex}/N_i} \right) (1 - r) + C \, \frac{n_{ph}}{f_l} (1 - f_l)$$

Light production:

$$n_{ph} = L(E_0) \times \frac{E_0}{W} \left(1 - \frac{1}{1 + N_{ex}/N_i} (1 - r) \right) \times f_l$$

Five free parameters:

- N_{ex} / N_i
- TIB ($4\,\varsigma$)
- A
- k or α
- C

NR signal loss:

$$L = \frac{k \; g(\epsilon)}{1 + k \; g(\epsilon)} \quad \text{or} \quad \alpha \frac{s_e}{s_e + s_n}$$

Bi-excitonic quenching / ionization:

$$f_l = \frac{1}{1 + A \; s_e}$$

Thomas-Imel recombination:

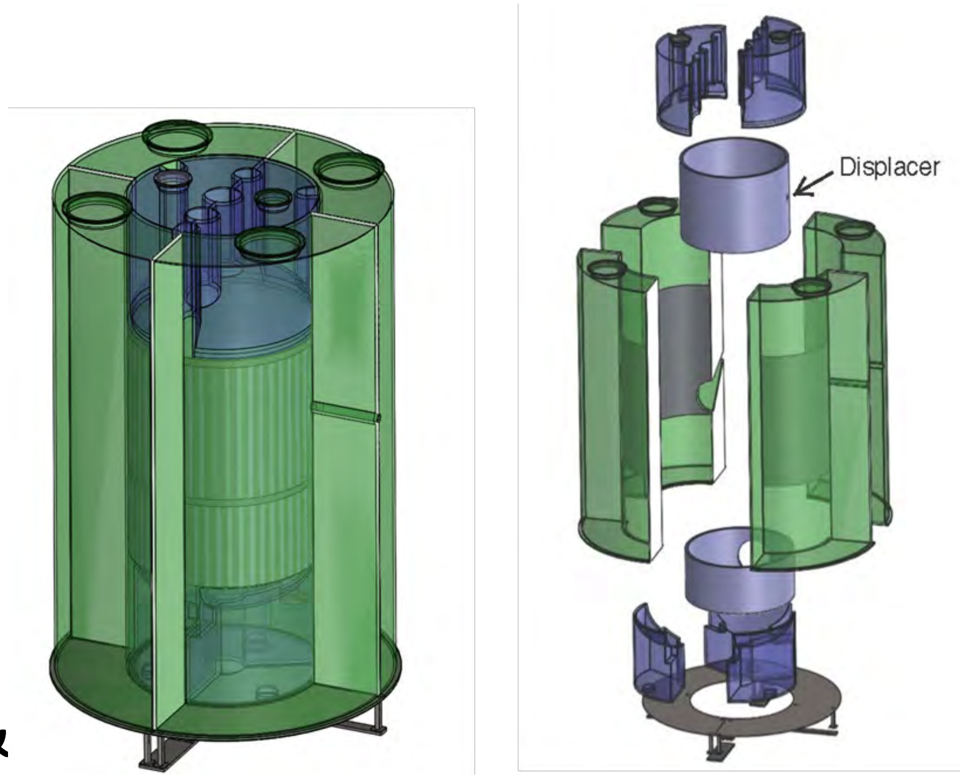
$$r = 1 - \frac{\ln(1 + N_i \, \varsigma)}{N_i \, \varsigma}$$

^{85}Kr Removal and Screening

- Remove Kr to <15 ppq (10^{-15} g/g) using gas chromatography.
- Best LUX batch 200 ppq
- Setting up to process 200 kg/day at SLAC
- Have a sampling program to instantly assay the removal at SLAC and continuously assay in situ

Outer Detector

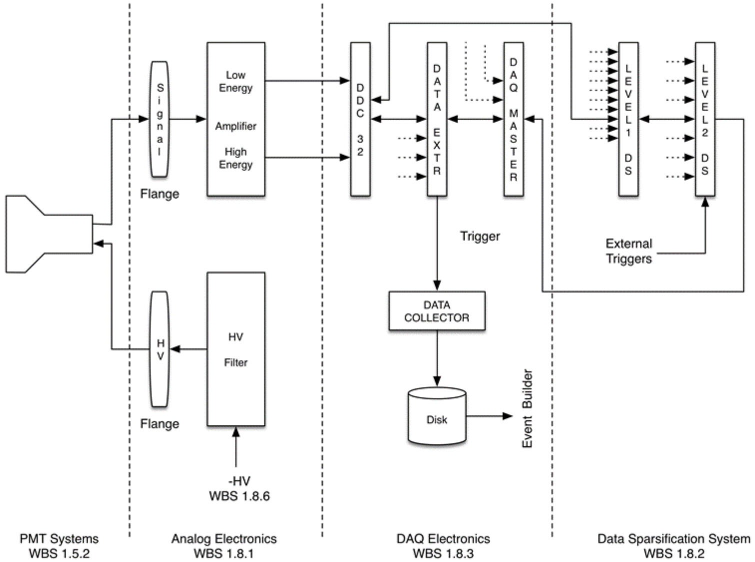
- Essential to utilize most Xe, maximize fiducial volume
- Segmented tanks – installation constraints (shaft, water tank)
- Gadolinium - loaded scintillator, LAB, OK underground
- Daya Bay legacy, scintillator & tanks (and people)
- Advanced conceptual design



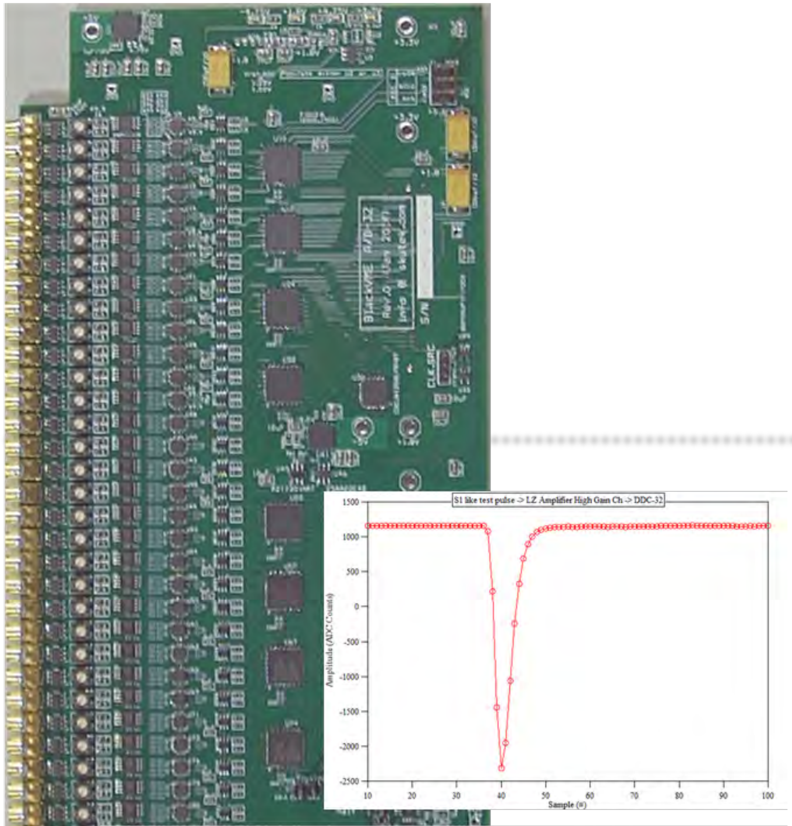
Layout of the LZ outer detector system, which consists of nine acrylic tanks. The largest are the four quarter-tanks on the sides. Two tanks cover the top, and three the bottom. The exploded view on the right shows the displacer cylinders placed between the acrylic vessels and the cryostat.

Electronics/DAQ

- LUX legacy, augmented by experienced new groups (primarily DAQ, controls)
- Prototyping underway, will lead to full – chain test of key elements by end of year



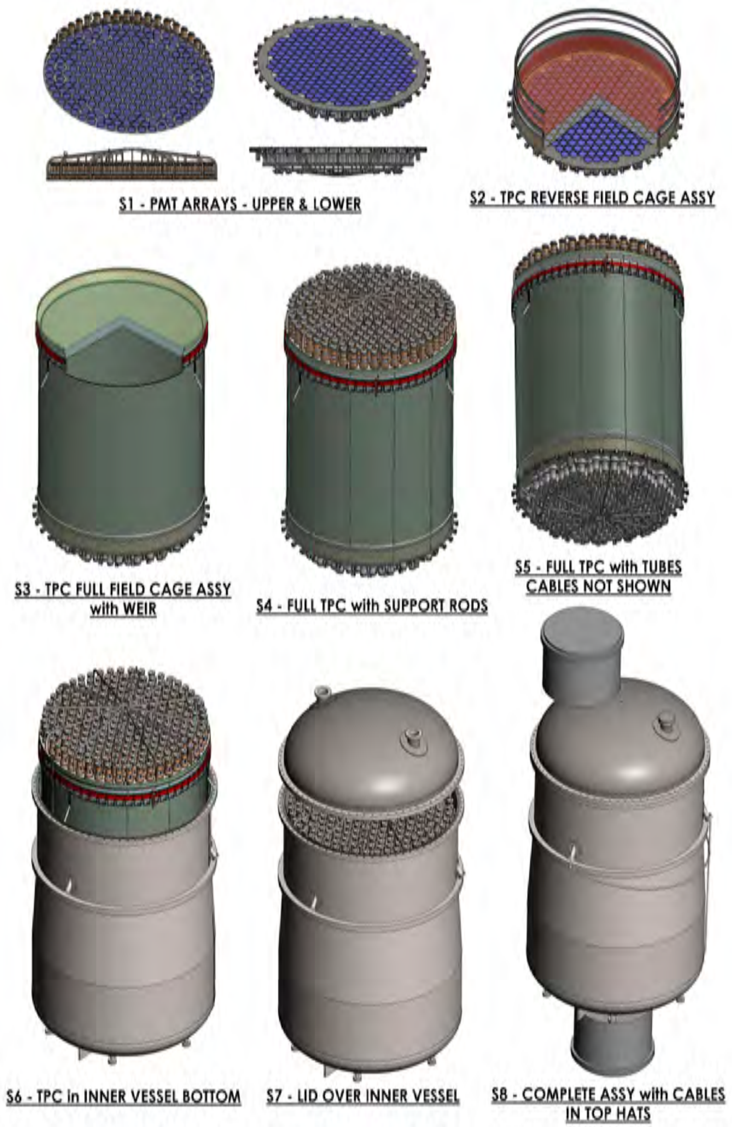
32 channel digitizer prototype

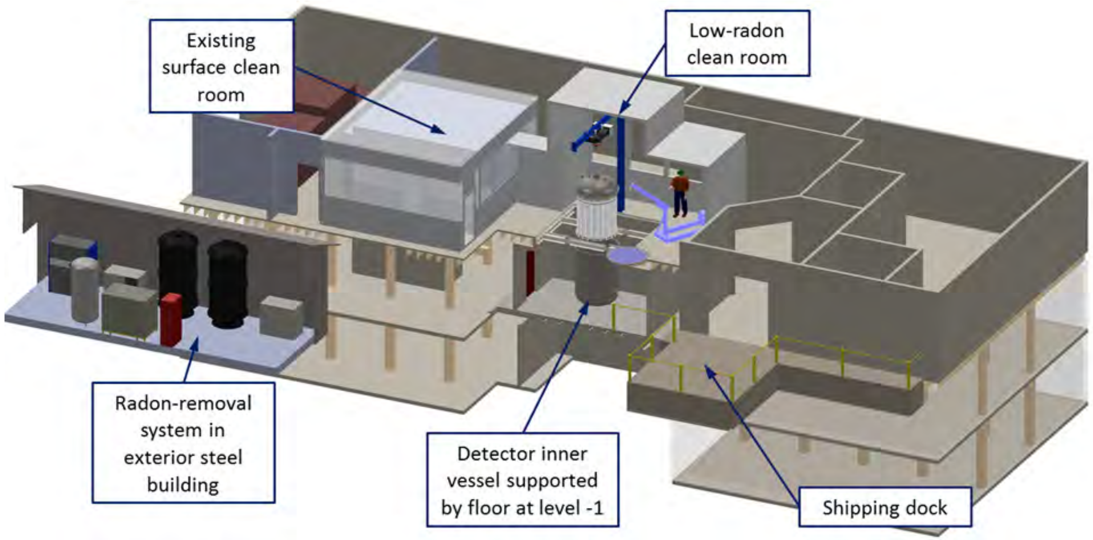


S1 test pulse from the high-gain amplifier output.
Excellent pulse response without ringing or overshoot.

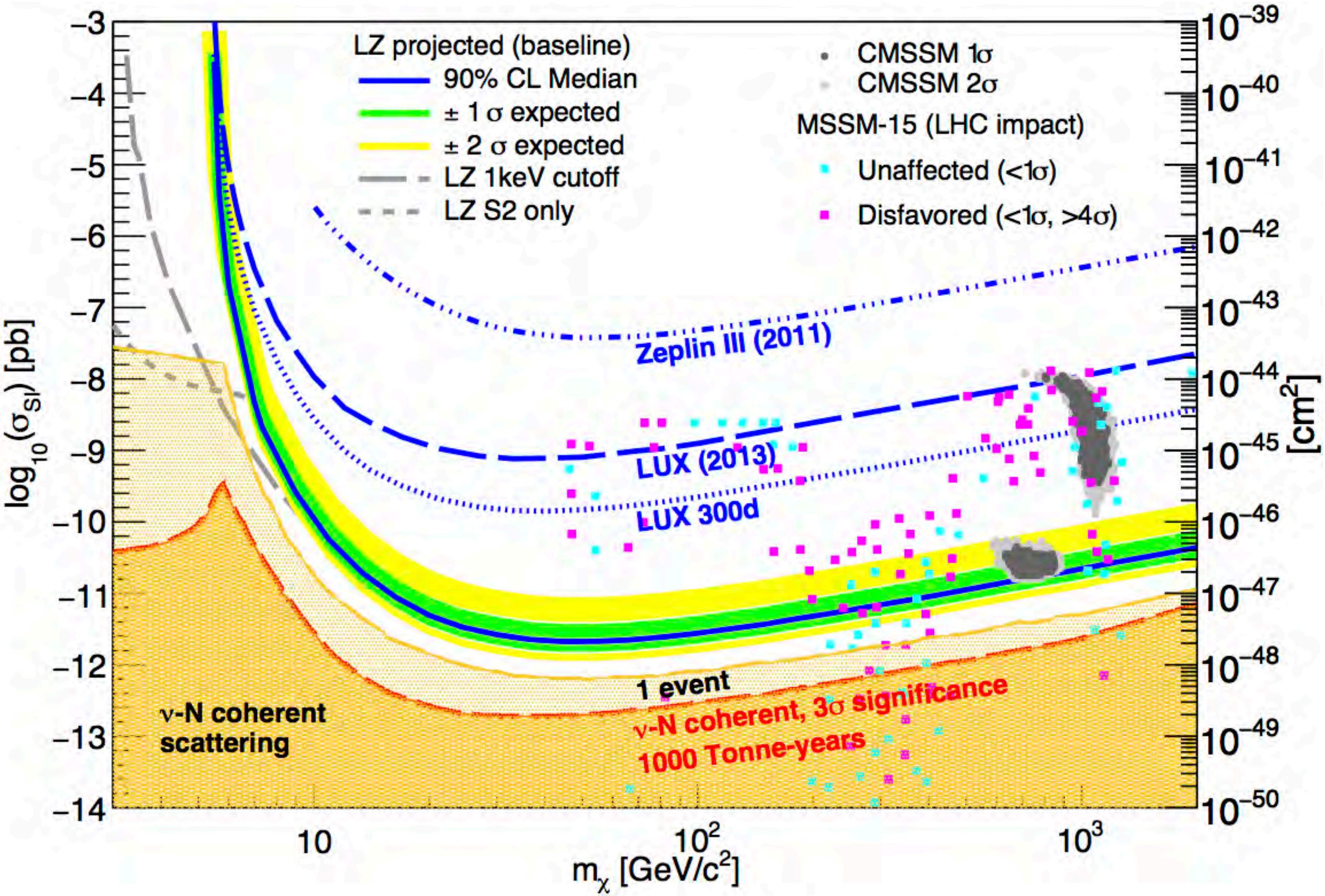
Integration/Installation

- Surface assembly of TPC into inner cryostat
- LUX experience at SURF
- Dedicated on – site infrastructure improvements for LZ. Design started, construction

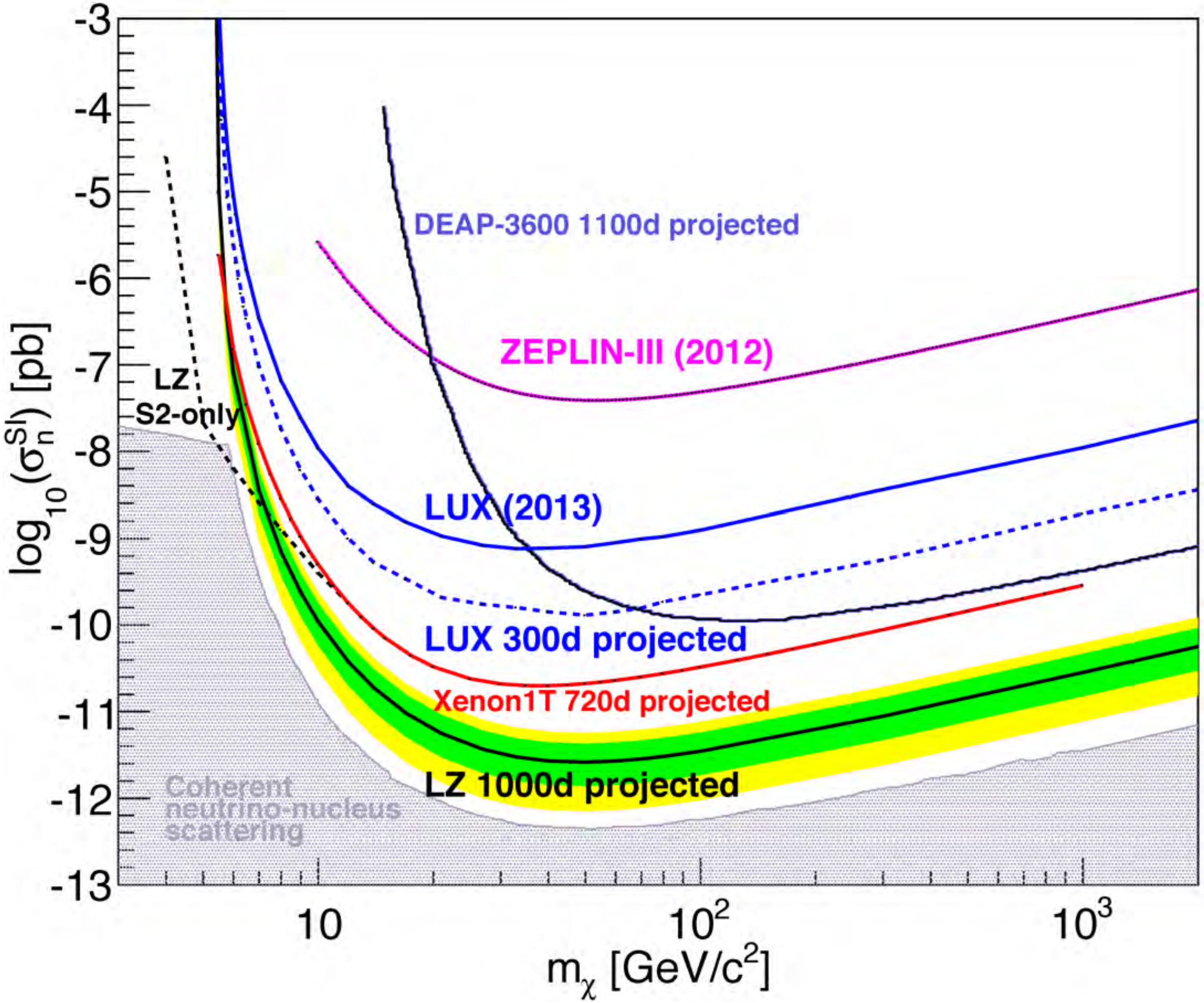




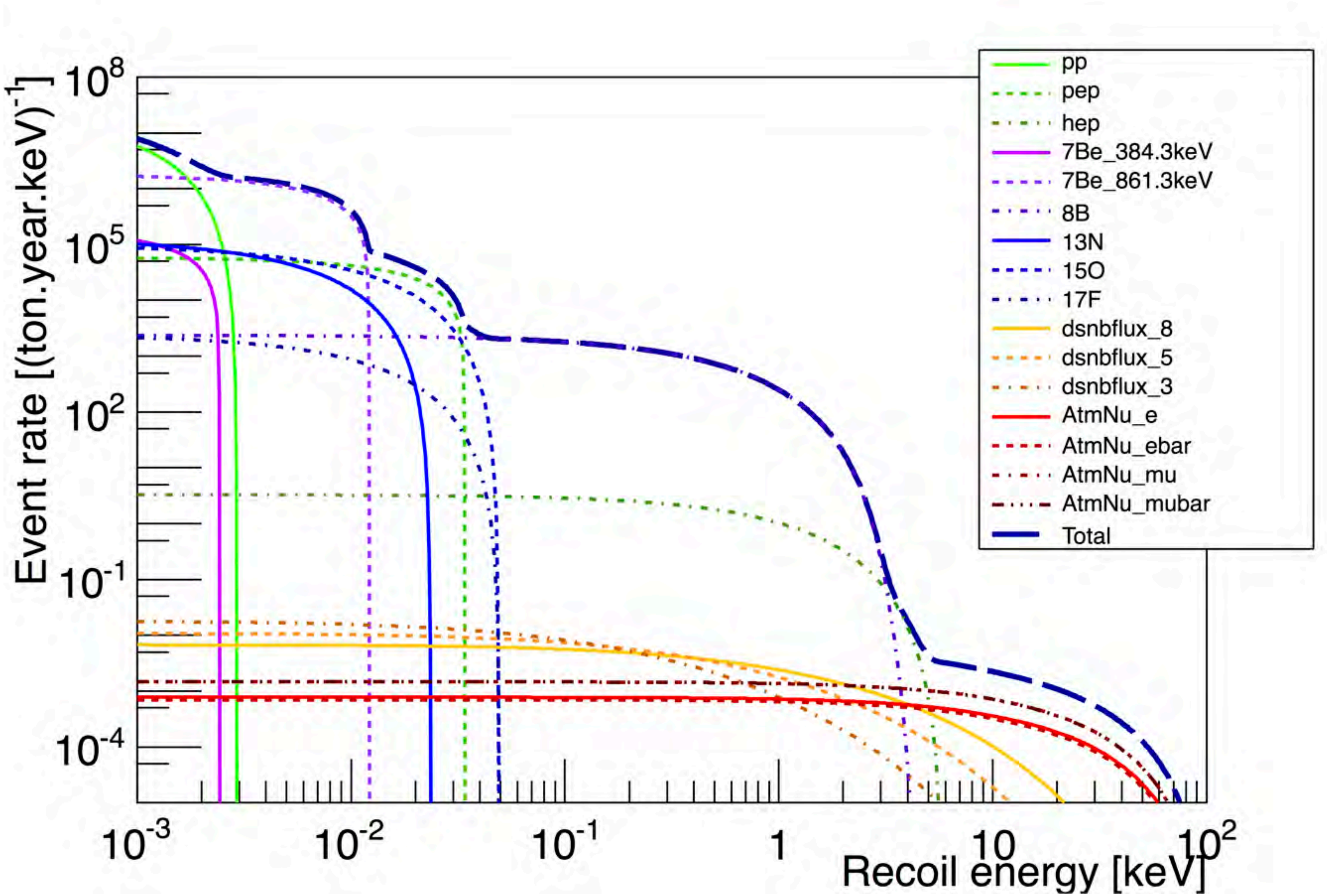
Sensitivity with SUSY Theories



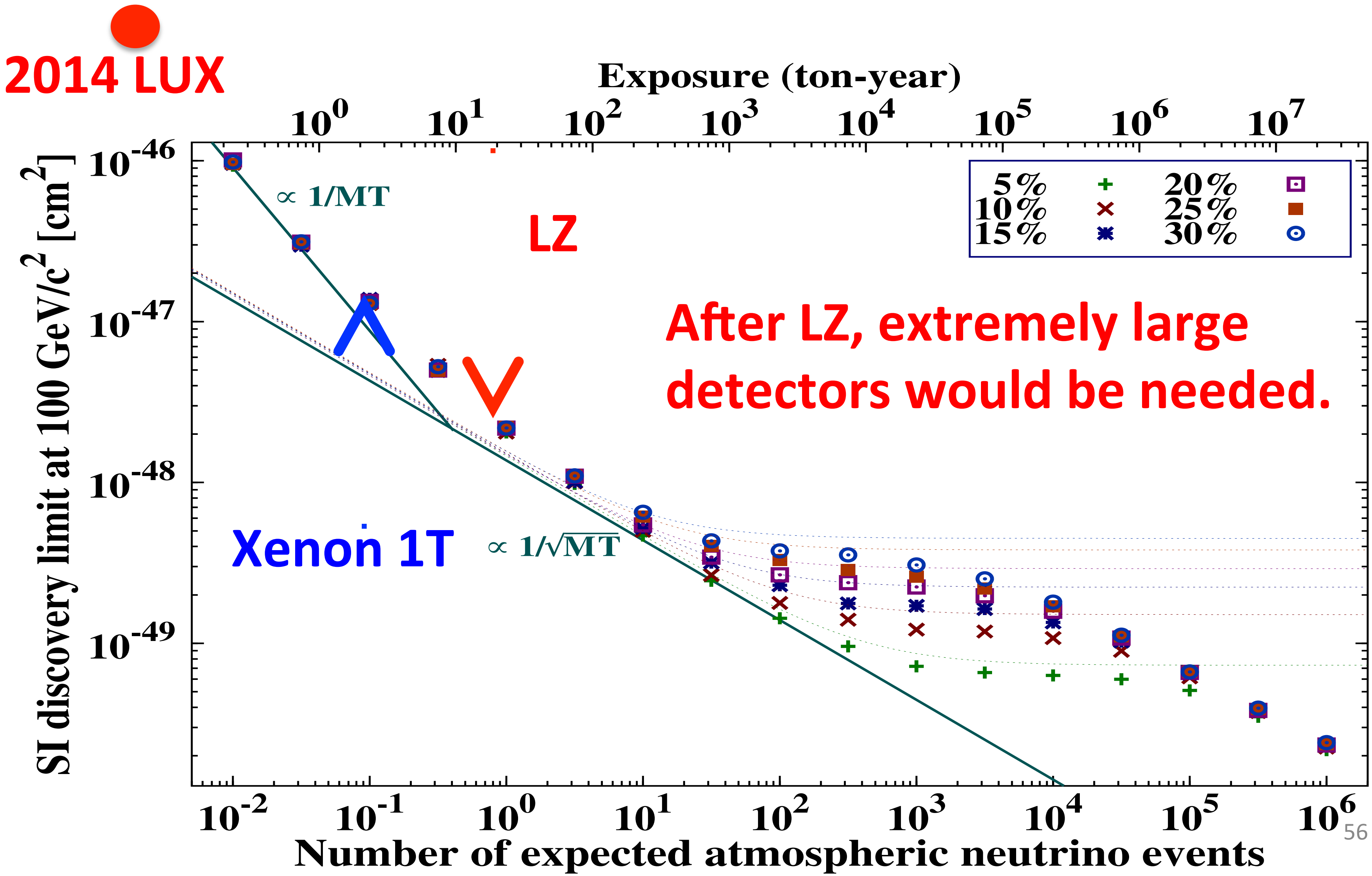
Sensitivity with Competition



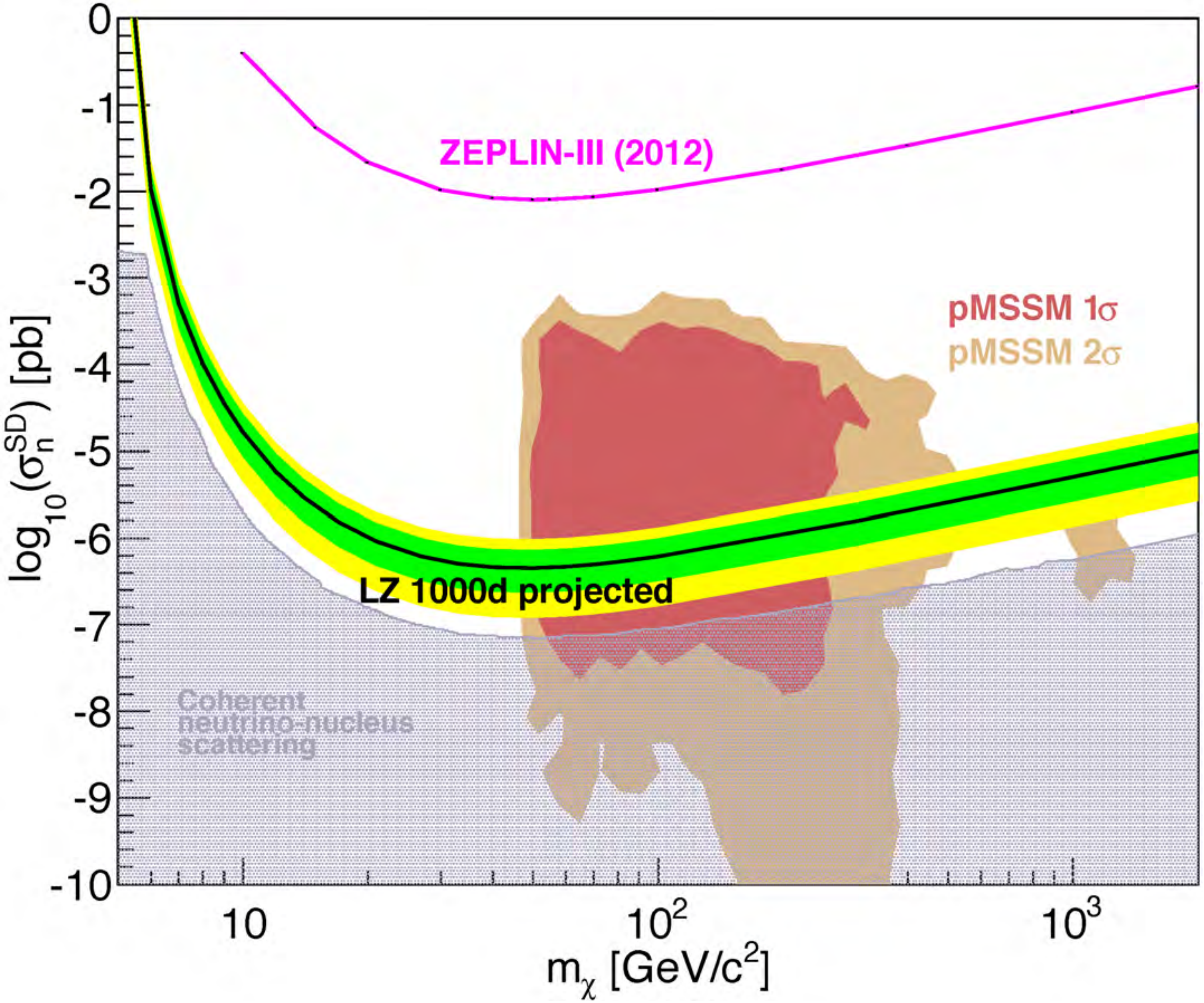
Response of Xe to Neutrinos arXiv:1307:5458



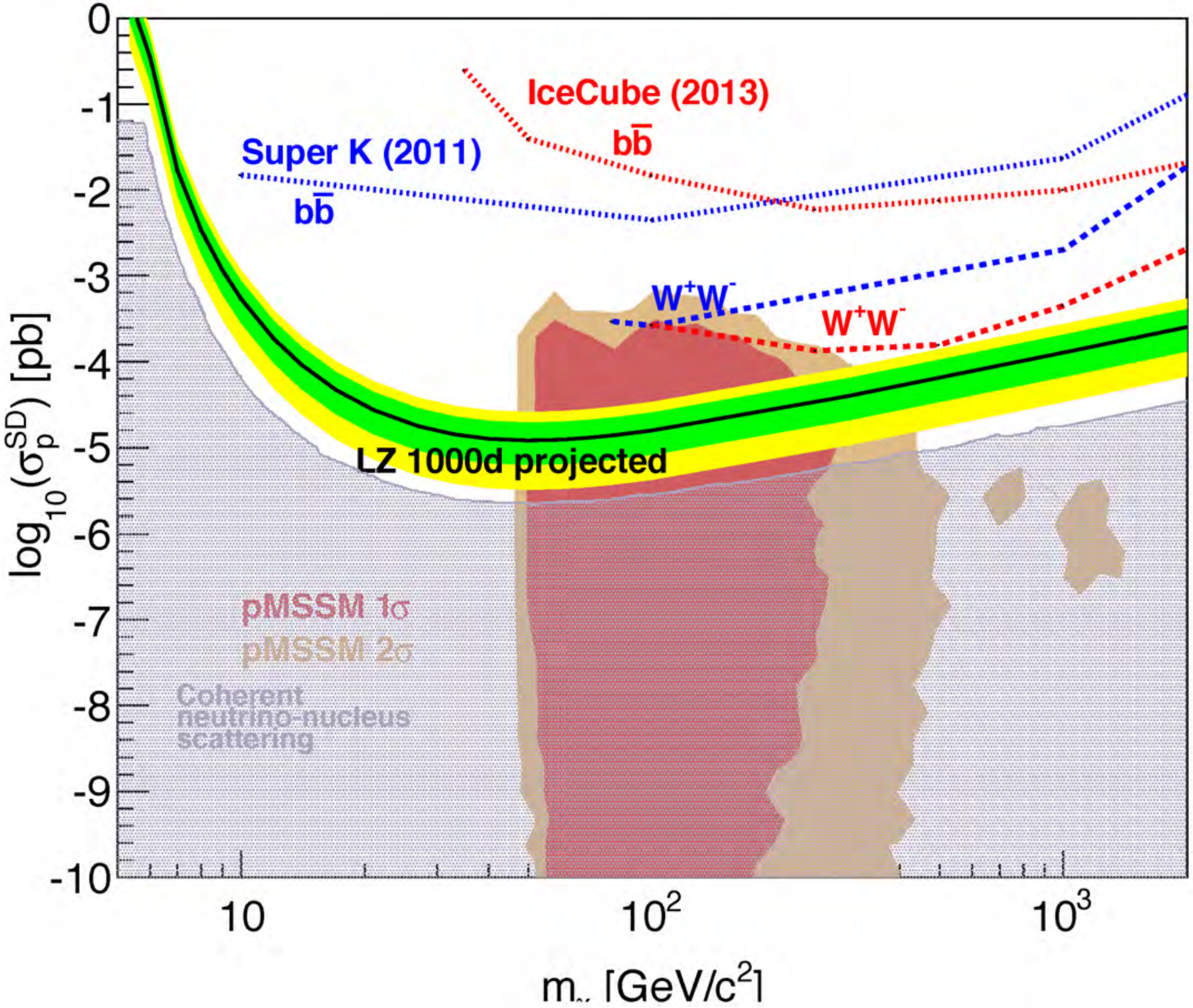
LZ – At the neutrino `knee' arXiv:1408.3581



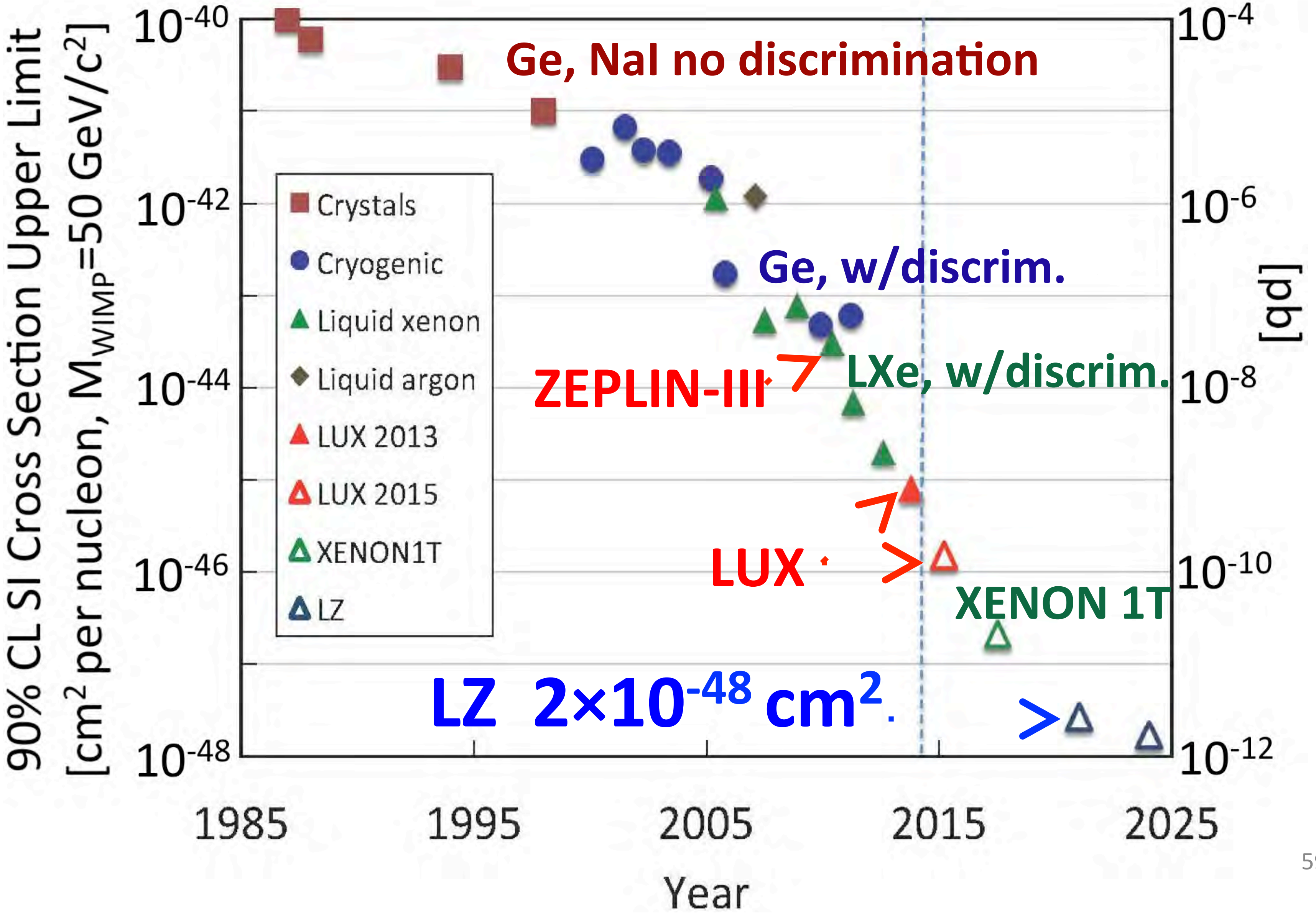
Spin Dependent Neutron



Spin Dependent Proton



Time Evolution



Running Time

- Sensitivity vs. running time.
- 1,000 days is the nominal.
- Baseline backgrounds
- Rapid improvement in sensitivity
- Potential to eventually get to ~ 1 x 10^{-48} cm^2