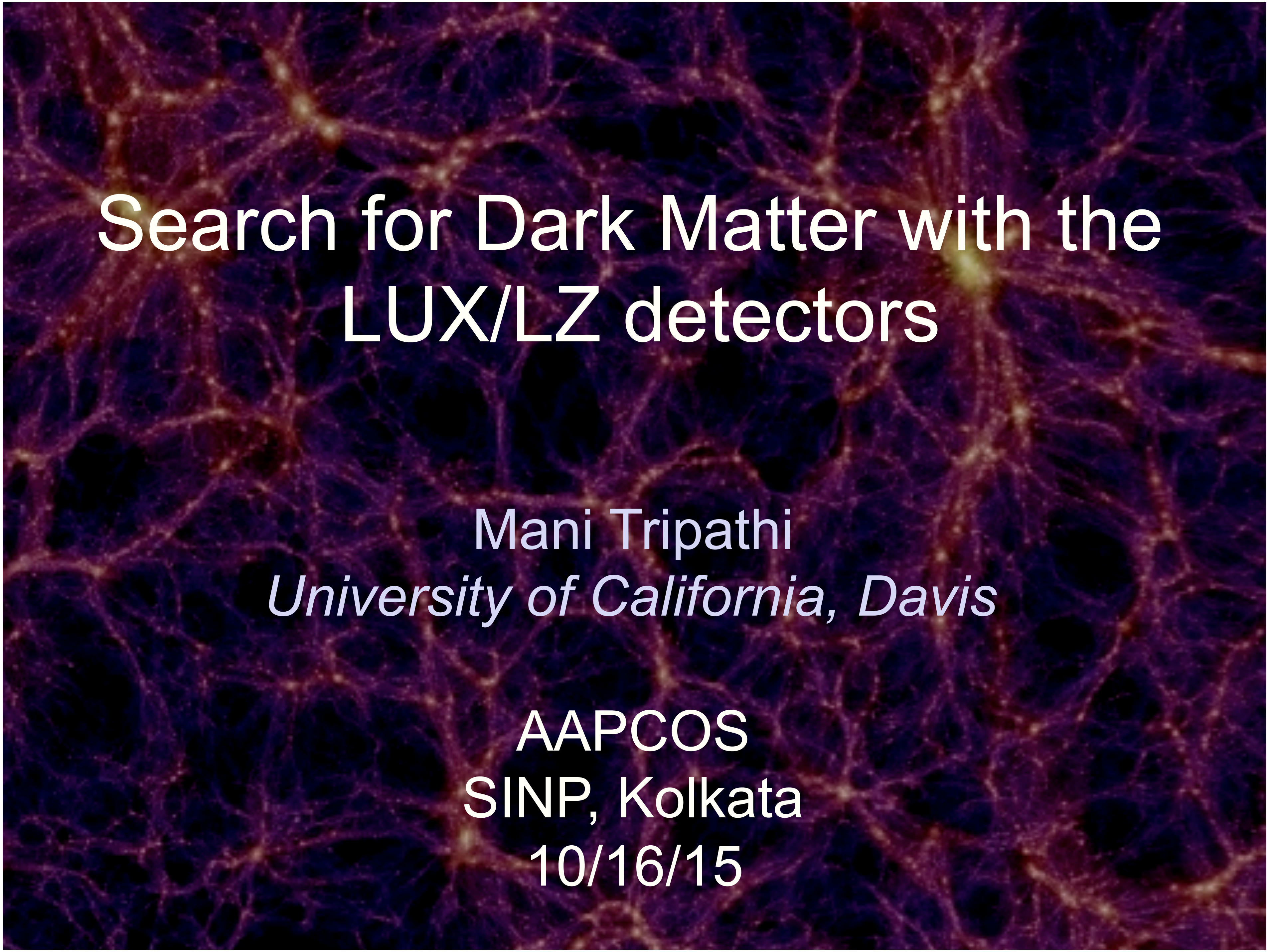


Search for Dark Matter with the LUX/LZ detectors

Mani Tripathi
University of California, Davis

AAPCOS
SINP, Kolkata
10/16/15

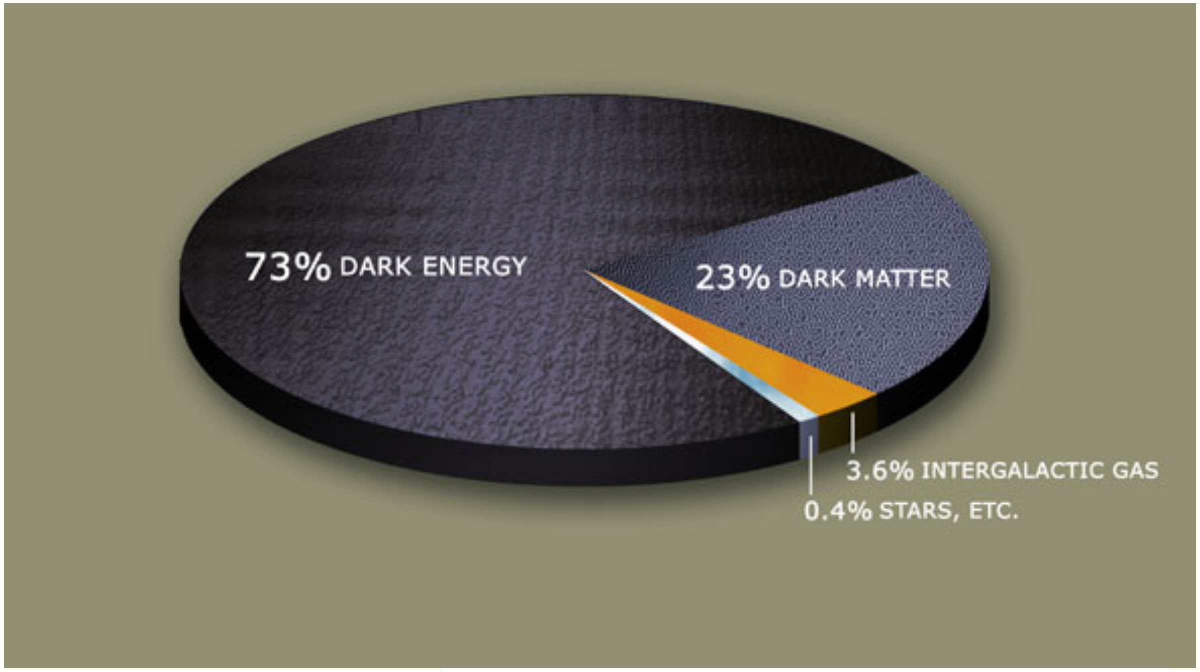
Outline

1. The Dark Matter problem
2. Direct detection of DM in a laboratory
3. Two-phase Xenon Time Projection Chambers
4. Updated calibrations of the LUX detector
5. The future: LZ program

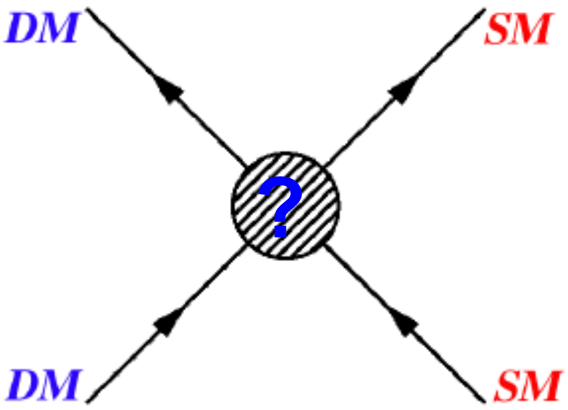
The Dark Matter Problem

A good problem to have. There is a known effect looking for an answer … as opposed to a known solution looking for an experimental effect.

A real challenge for experimentalists to study this known energy density.



- Postulate 1: DM is a particle.
- Postulate 2: DM and SM particles interact with some force that is very weak but <u>much</u> stronger than gravity.

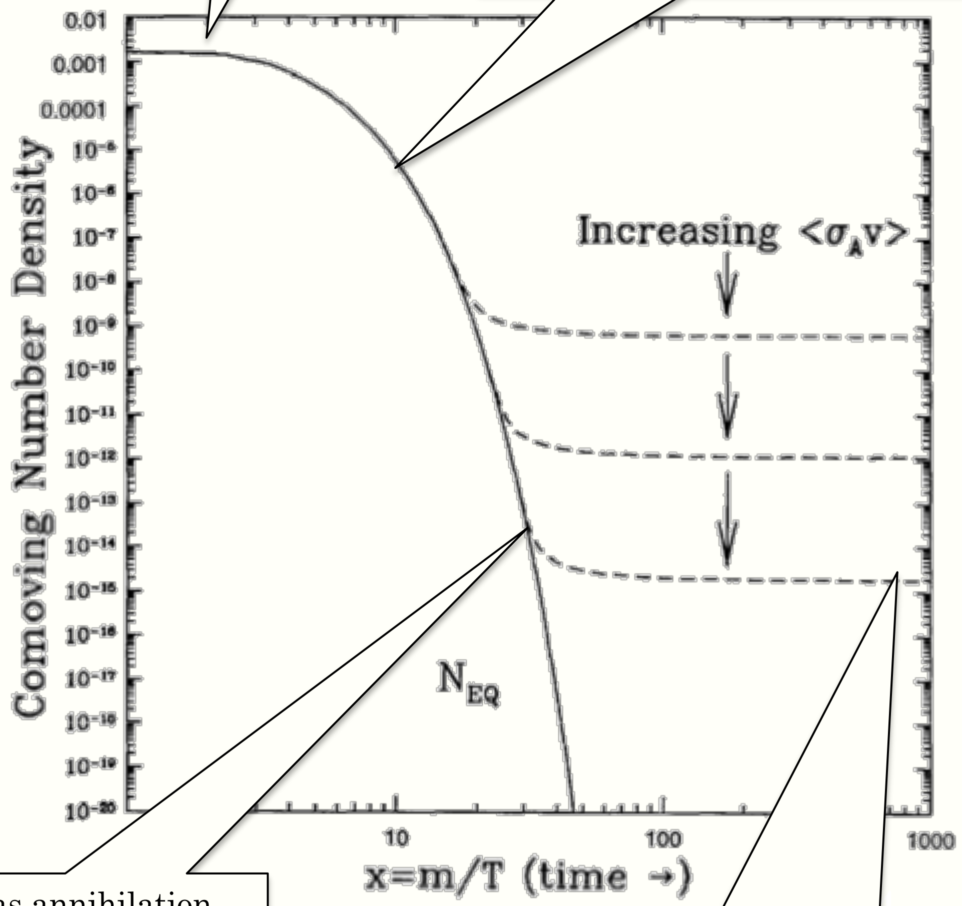


WIMP Miracle

A happy coincidence implied that new physics at the TeV scale with appropriately weak cross section leads to a dark matter relic (with a new quantum number preventing decay).

$$\Omega_x h^2 = \frac{3\cdot 10^{-27}\, cm^3 / s}{\langle \sigma_A v \rangle} \approx 0.12$$

$$\Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$



1. Flat region. Constant density. Equal production and annihilation.
$n_{eq} \sim T^3$

2. Exponential suppression as temperature falls below mass of dark matter particle.

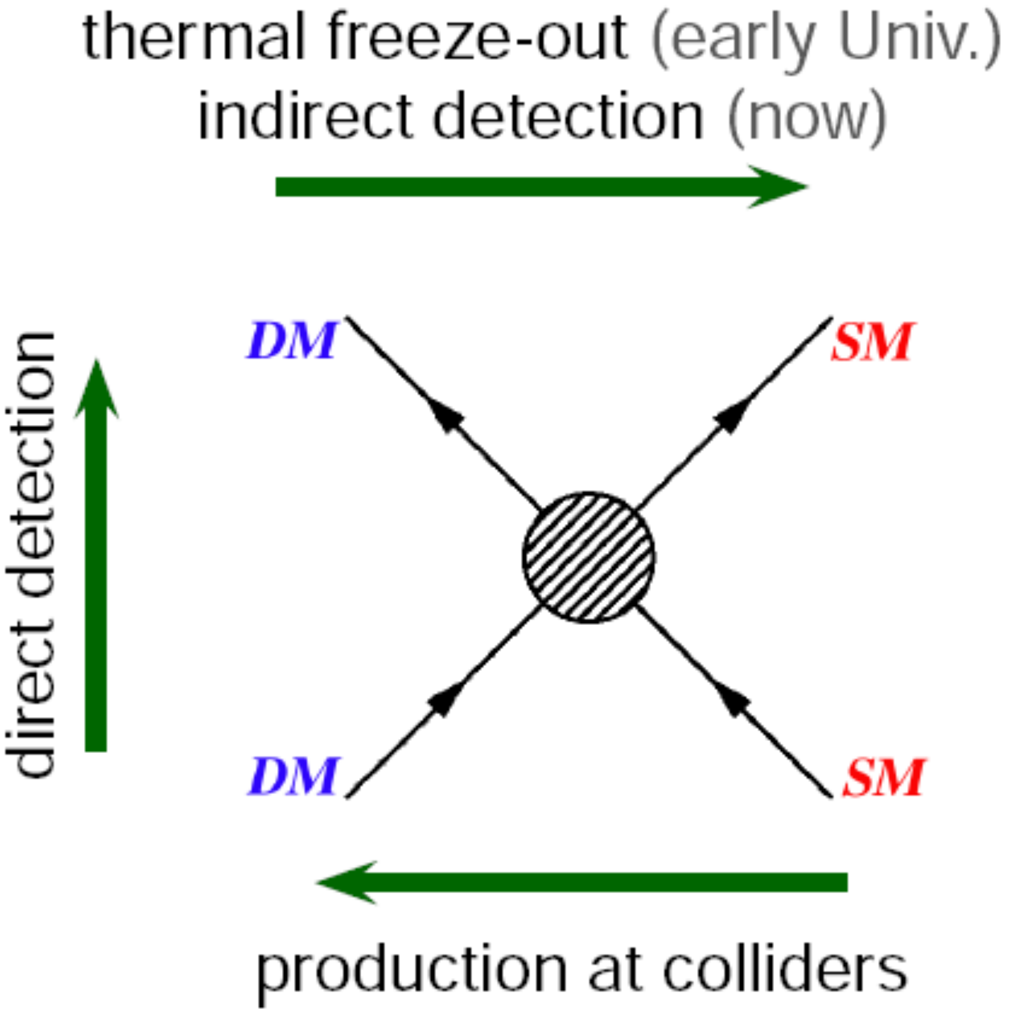
$n_{eq} \sim (m/T)^{3/2} e^{-m/T}$

3. Turn over as annihilation rate decreases, becoming smaller than the expansion rate.

4. Relic abundance remains. Larger cross-sections keep annihilations occurring for longer.

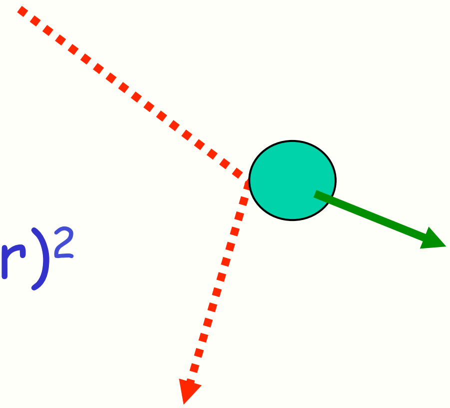
Detection Techniques

- Three major categories of investigations.
- Important to maintain the theoretical connection between these approaches.



Direct Detection

Basic goal: search for nuclear recoil from DM elastic scattering.



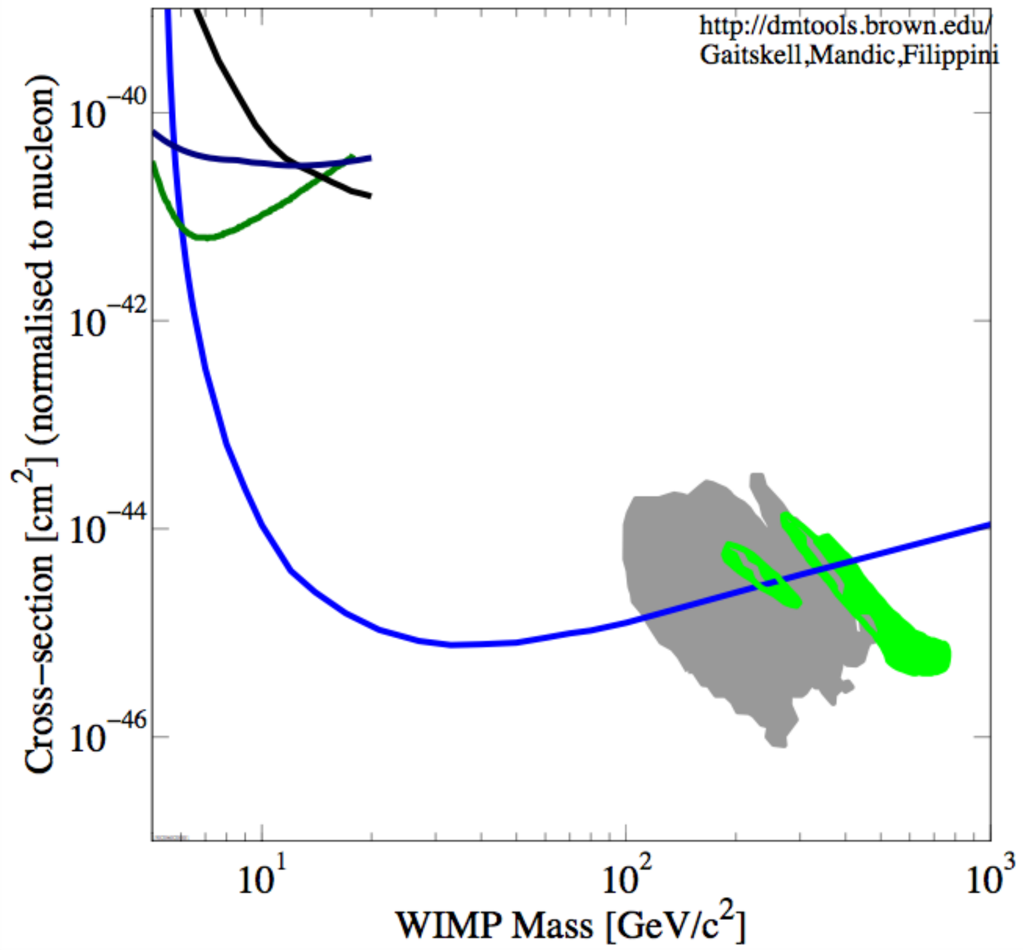
Simple dynamics. Cross section α (form factor)^2

Spin-independent: Nucleon form factor gives rise to A^2 enhancement due to coherence.

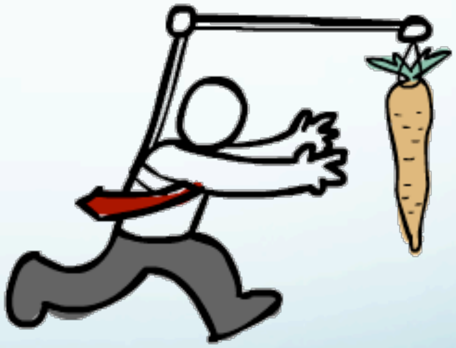
The dependence on q^2 is also contained in the form-factors.

Spin-dependent: Form factor depends on nuclear spin. No coherence enhancement.

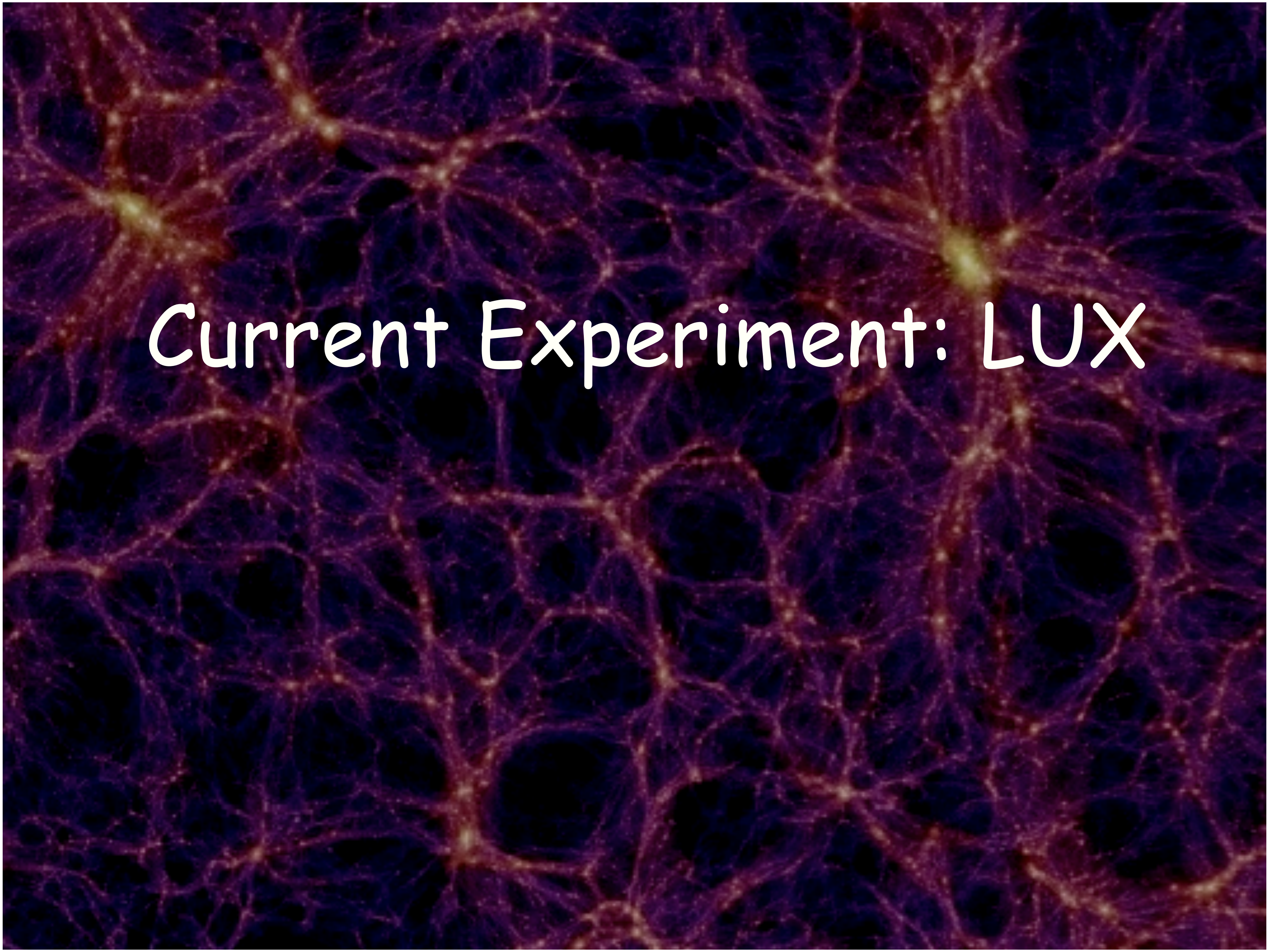
Time Progression of Sensitivity



Years 2000-2013



Animation courtesy of Aaron Manalaysay, UC Davis



Current Experiment: 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
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

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

Collaboration Meeting, Lead, June 2015

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

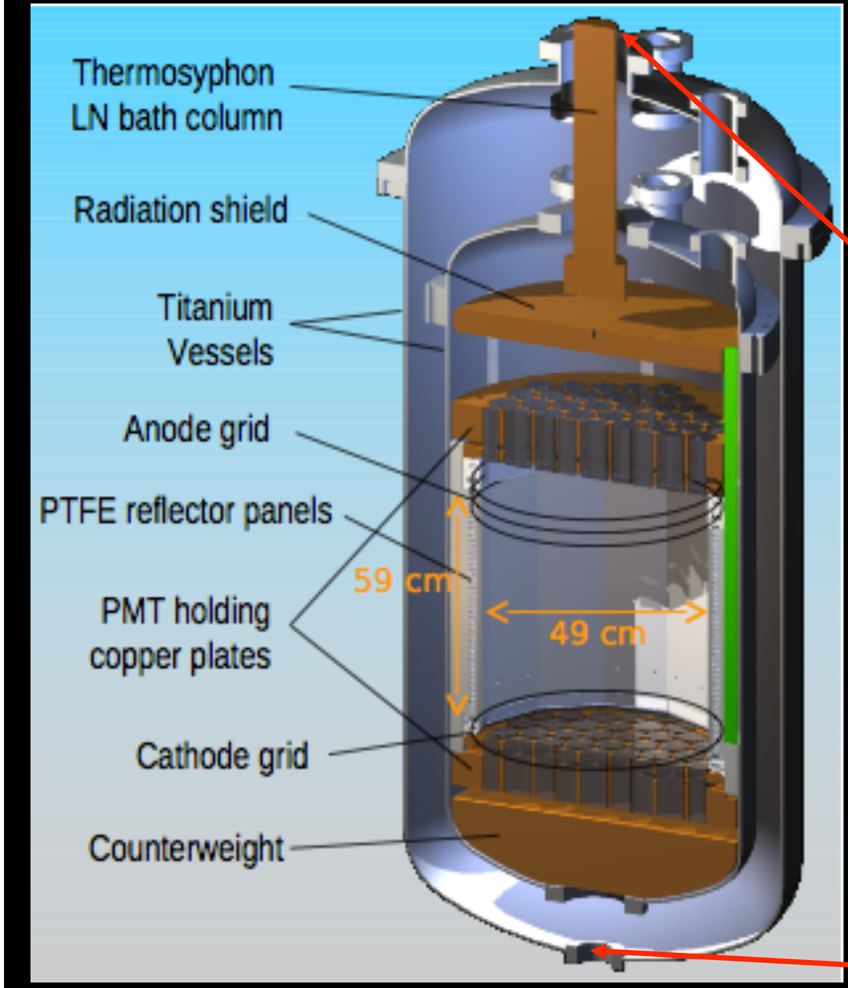
University of South Dakota

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

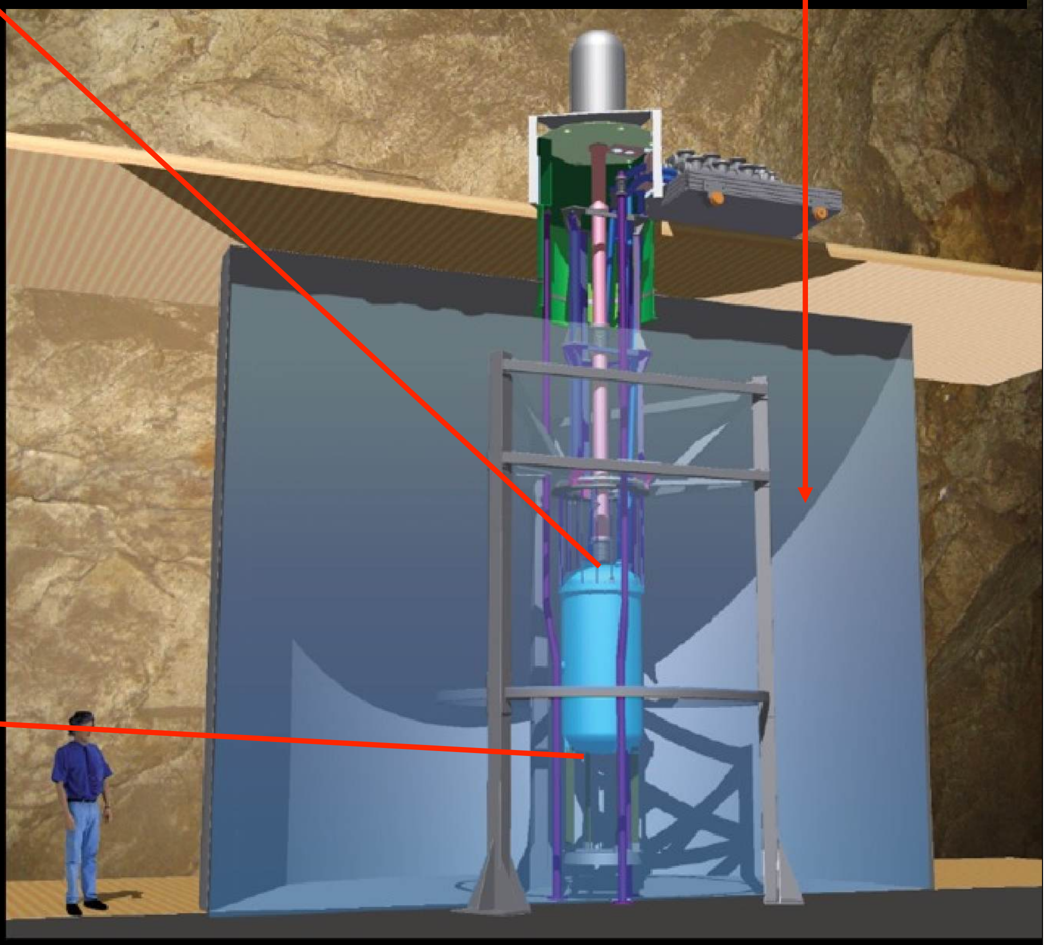
Yale

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

The LUX detector



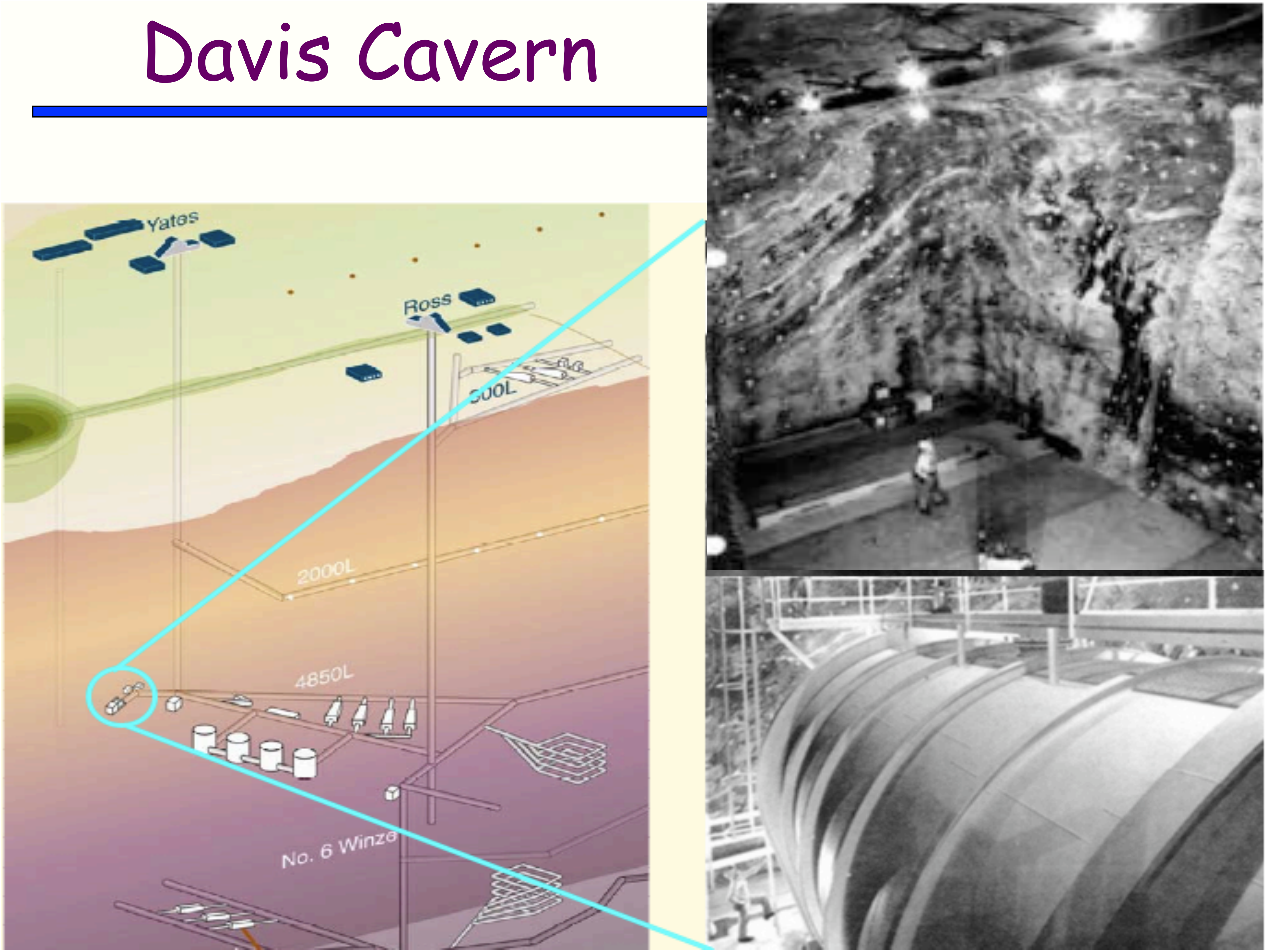
- ~ 7m diameter Water Cerenkov Shield.
- 48 cm H (gate to cathode) X 47 cm D active region with 181 V/cm drift field



•250 kg (active), 118 kg (fiducial) of Lxe

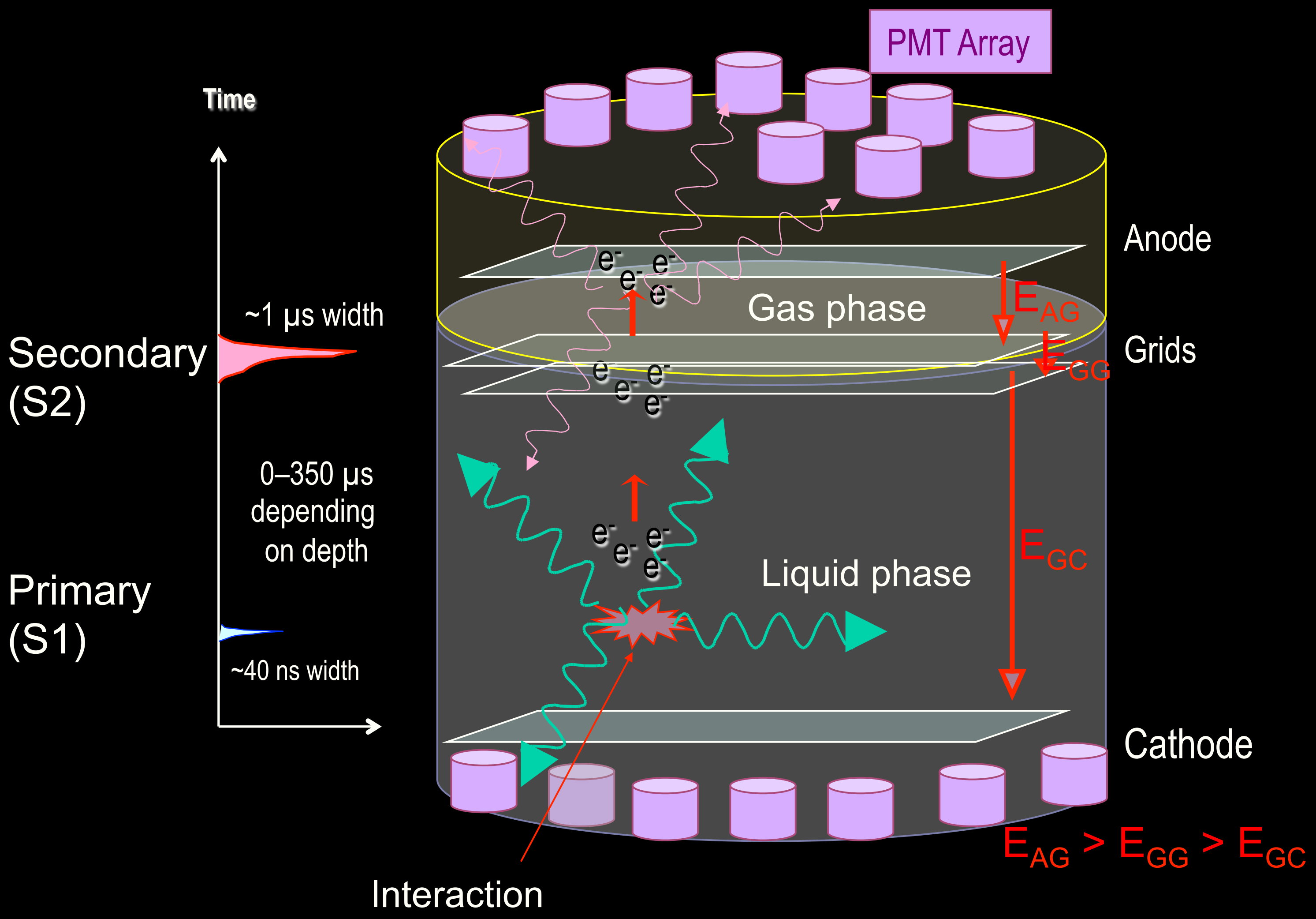
•122 photomultiplier tubes (top plus bottom)

Davis Cavern



Commissioned in 2012
First results in 2013

Two Signal Technique



Why Xenon?

Nobel element => Inert. Can be purified via gettering techniques.

No long-lived radio-isotopes. Metastable istopes useful in calibration.

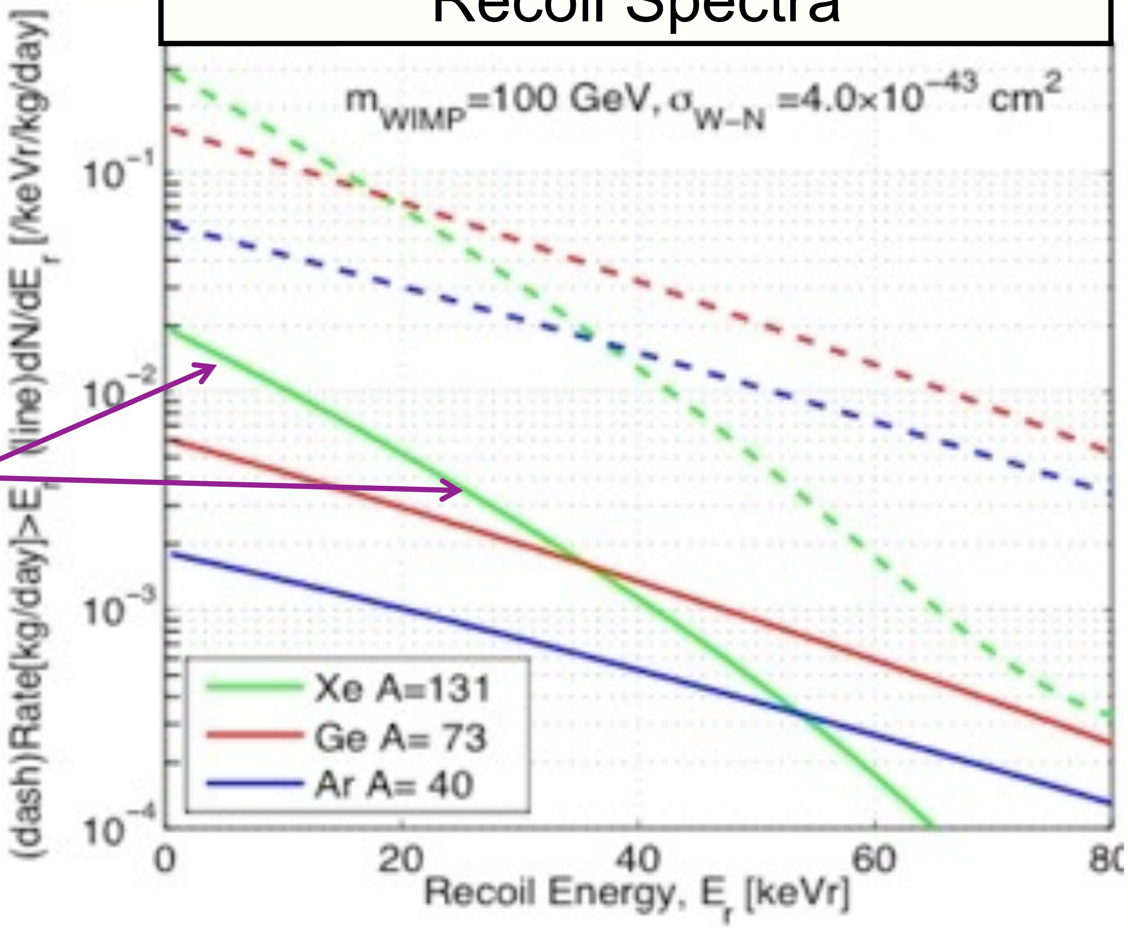
High density (~3g/cm^3)
=> Powerful self-shielding.

High A (131) => Large elastic σ

Higher Sensitivity in the range 5 keV < E < 25 keV.

Long electron drift lengths (few m) => scalable

Efficient scintillator



Recoil Spectra

Background Suppression

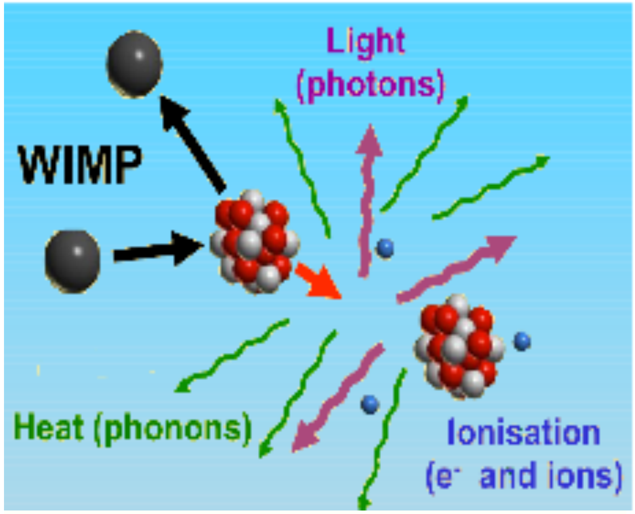
A large suppression of backgrounds required:

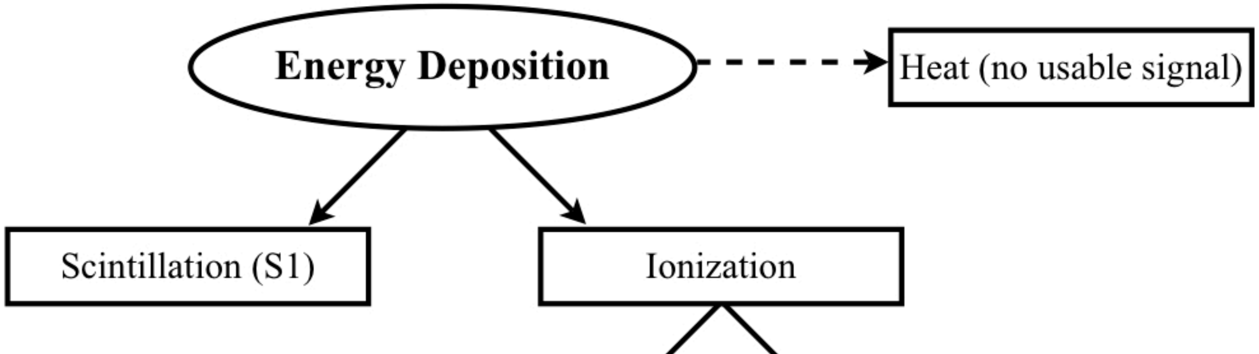
1. Gamma induced electron recoils. Discrimination is based on measuring two characteristic signals from the recoil. The discriminant employed is log (S2/S1) as a function of S1

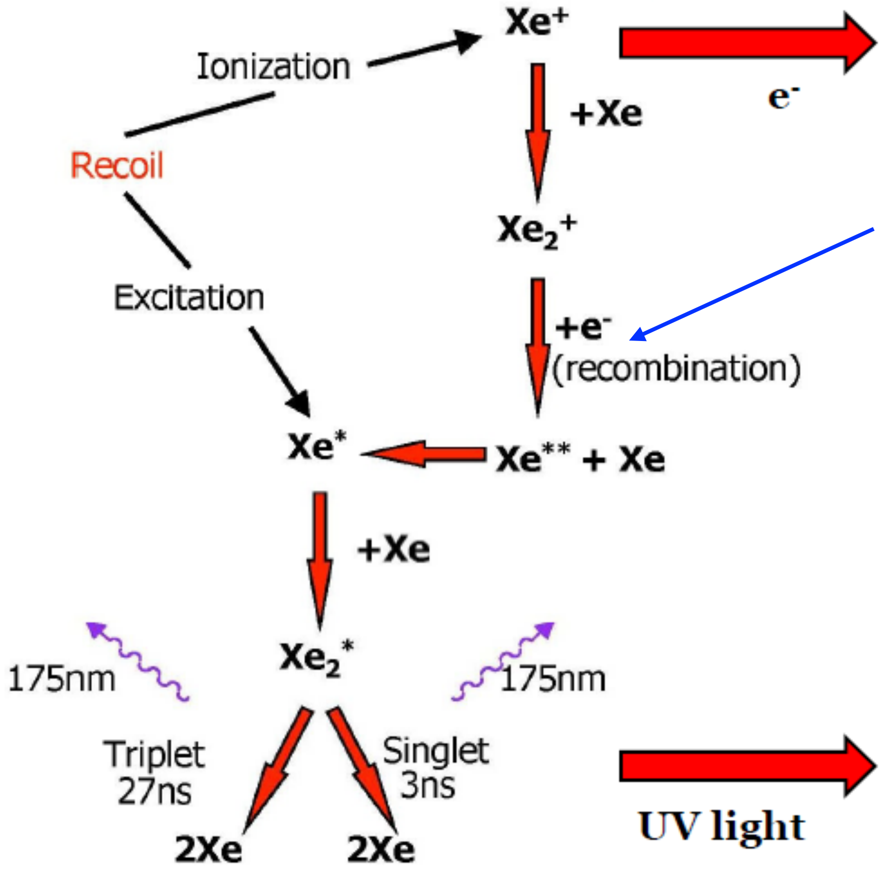
2. Neutron induced nuclear recoils. Neutrons need to be eliminated:

- Deep underground deployment
- Use of ultra-low radioactivity materials and components
- Large external shield (e.g., water)
- Active veto (e.g., gadolinium doped liquid scintillator)
- Double scatters (DM does not)

Scintillation process in LXe







Difference in in recombination efficiency is exploited to discriminate between electron and nuclear recoils.

Xenon is transparent to its own scintillation light !

Figure of merit derived from plots of:

Log (charge escaping recombination/ total primary light produced)

Physics Handled by NEST

- **N**oble **E**lement **S**imulation **T**echnique is a a data-driven model explaining the scintillation and ionization yields of noble elements as a function of particle type, electric field, and *dE/dx* or energy
- Provides a full-fledged Monte Carlo (in Geant4) with
  - Mean yields: light and charge, and photons/electron
  - Energy resolution: key in discriminating background
  - Pulse shapes: S1 and S2, including single electrons
- The wealth of data on noble elements was combed and all of the physics learned combined

M. Szydagis et al., JINST 8 (2013) C10003. arxiv:1307.6601
M. Szydagis et al., JINST 6 (2011) P10002. arxiv:1106.1613
J. Mock et al., Submitted to JINST (2013). arxiv:1310.1117

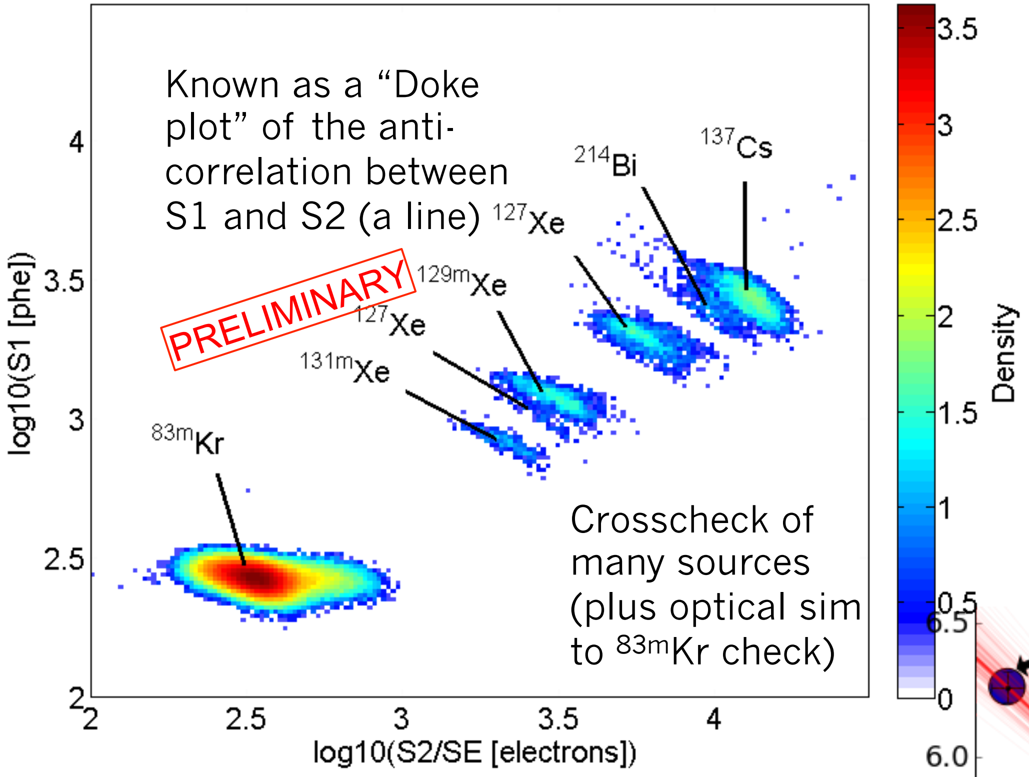
Event Energy Reconstruction

$$\begin{aligned} \text{Energy} &= [\ N_{ph} + N_{e-}\ ] * W \\ &= [\ (\ S1 / g_1\ ) + (\ S2 / g_2\ )\ ] * 13.7e\text{-}3 \text{ keV(ee)} \end{aligned}$$

- g_1 is an overall efficiency, mapped out with Kr83m
- g_2 accounts for electron extraction efficiency and number of photons detected per extracted electron

- NR has factor $L < 1$ accounting for fewer overall quanta (not just S1 photons) being generated due to NR being more effective making more NR (i.e. heat)

New Calculation of the g-Factors

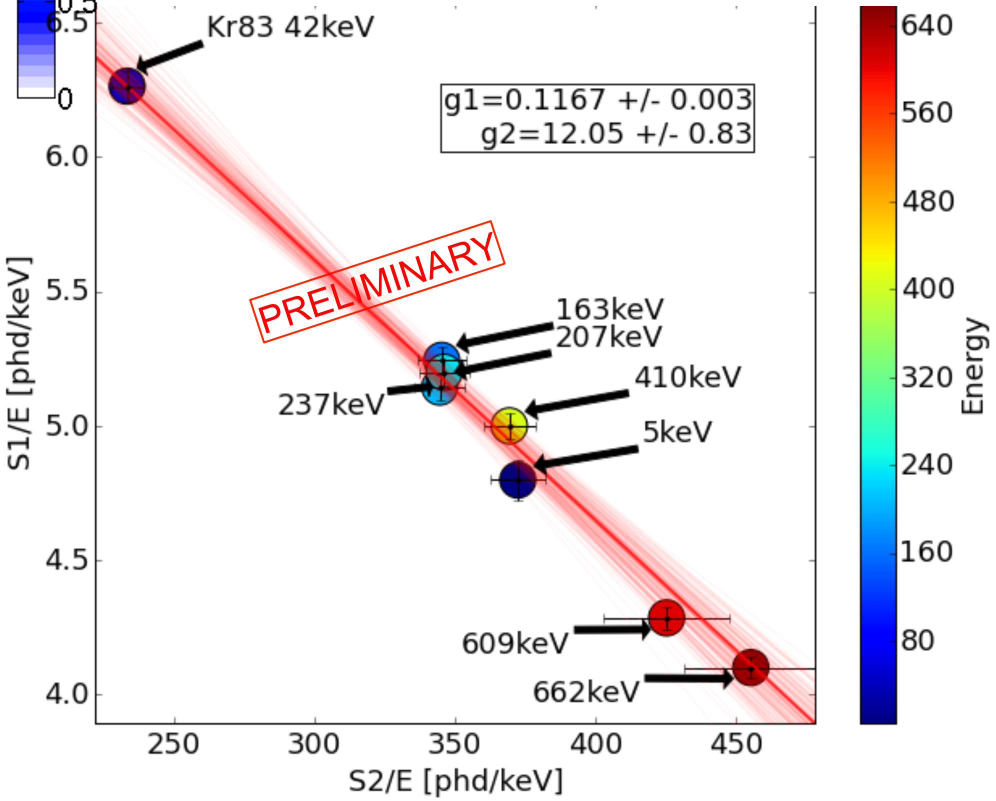


Known as a "Doke plot" of the anti-correlation between S1 and S2 (a line)

Crosscheck of many sources (plus optical sim to ^{83m}Kr check)

12% efficiency for the detection of a primary scintillation photon

Previously 14% quoted



$g1=0.1167$ +/- 0.003
$g2=12.05$ +/- 0.83

49% extraction, coupled with 24.66 detected photons per single electron to make "g_2"

Previously 65%, but it is product of absolute yield with is what matters

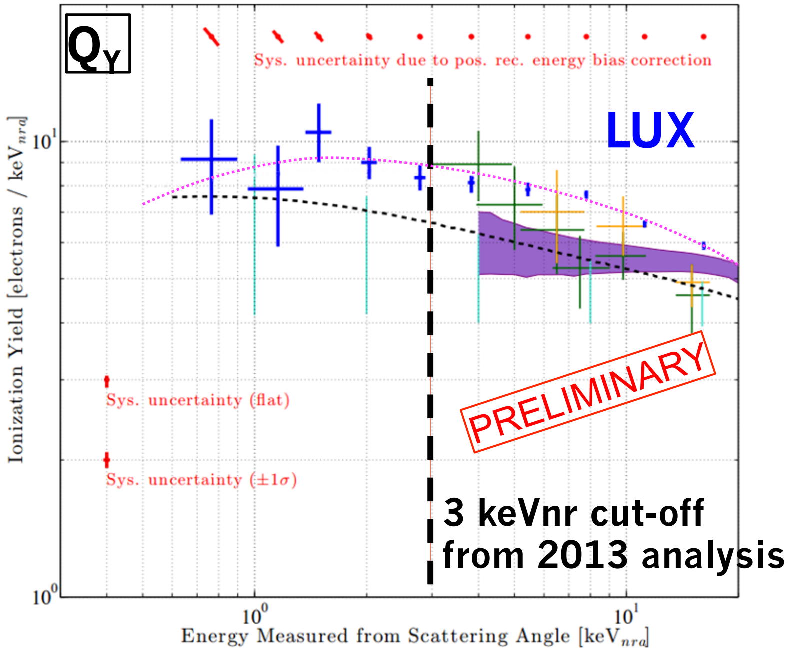
NR Charge and Light Yields

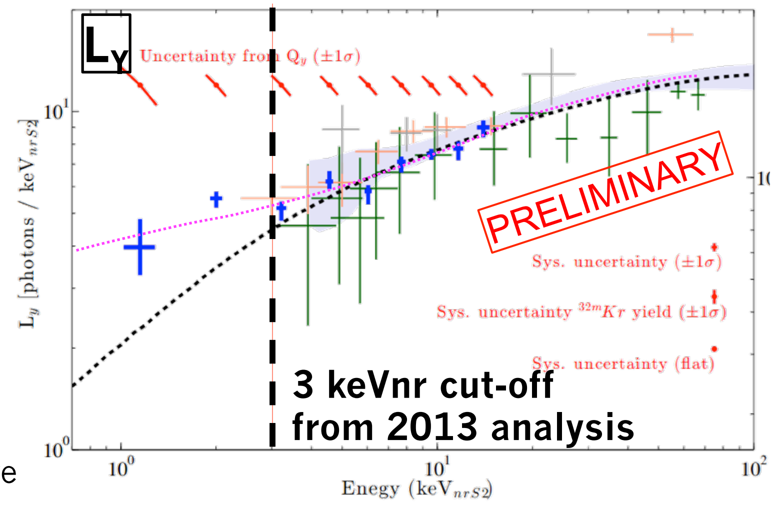
- *in situ* measurements

- No longer relying on LUX AmBe, ^{252}Cf, or modeling from old data, or extrapolating from results of small test chambers.
- *Charge yield* Measured down to ~0.8 keVnr. (Previous low 4 keV)

- Data from Deuterium-Deuterium neutron gun. Use S2 to identify double scatters. Determine energy deposition from scattering angle. For S1, S2-derived energy scale.
- *Light yield* measured down to ~1.2 keVnr. (Previous low 3 keV)

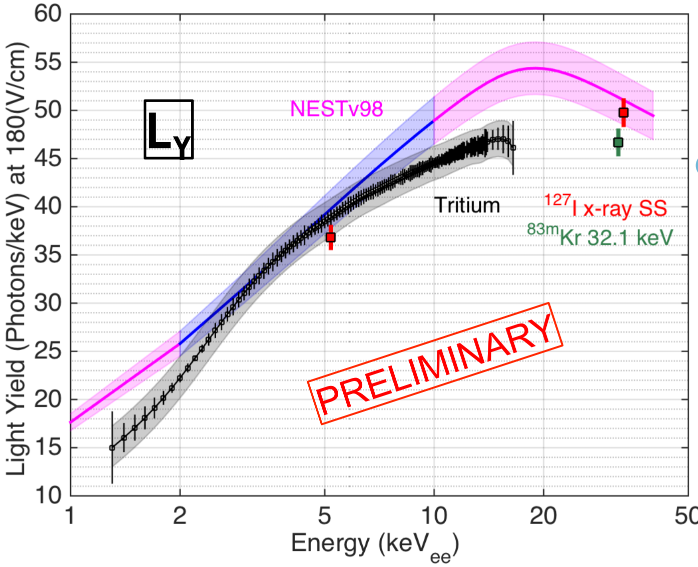
- New modeling

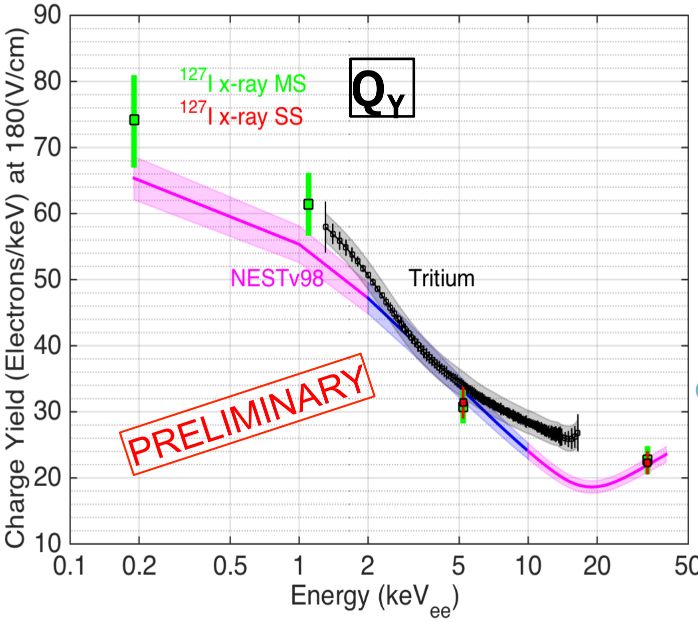




------ NEST 1.0 still too conservative
------ Modified NEST for re-analysis

Same scrutiny for ER

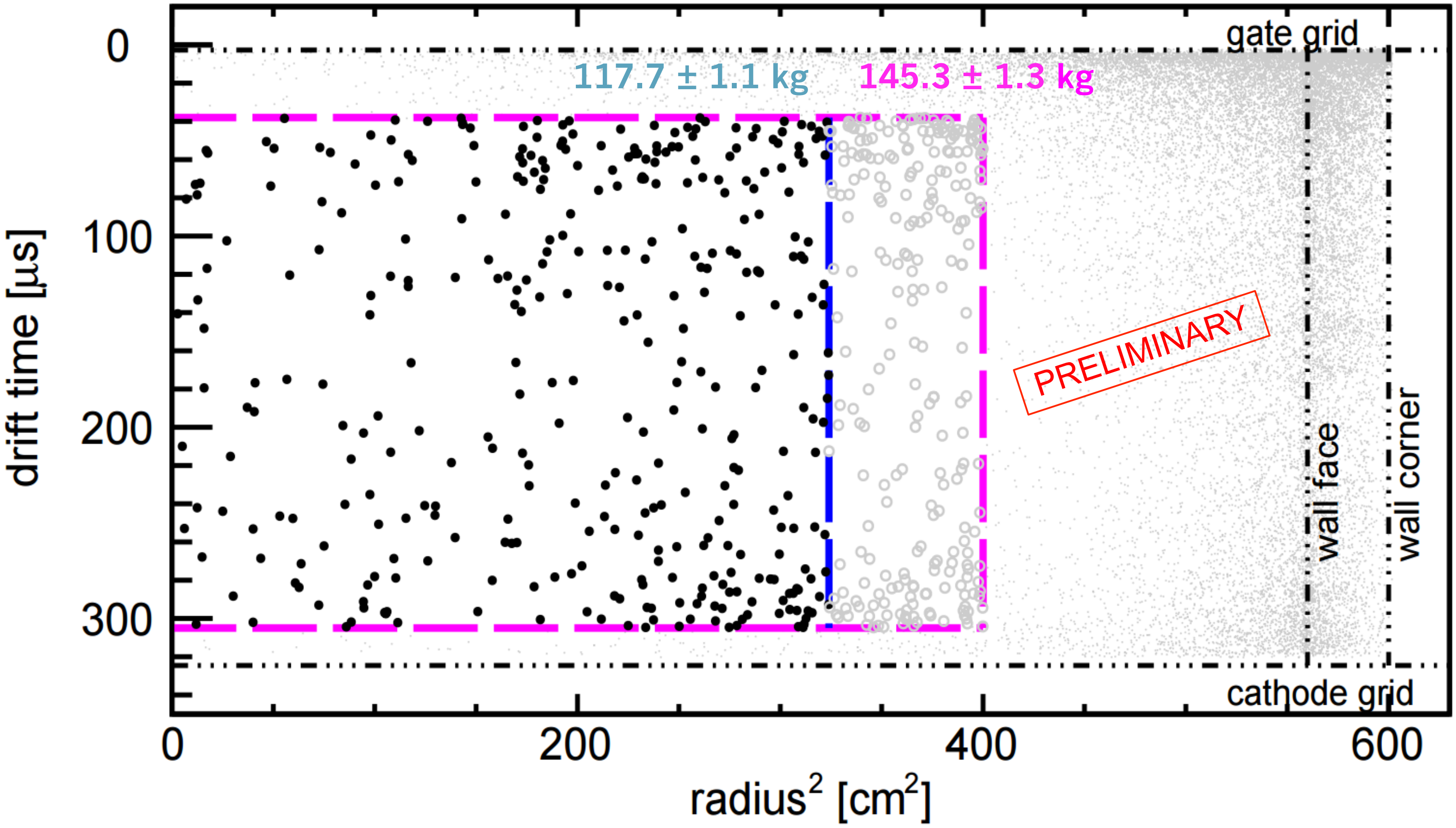




- Internally-deployed tritium source provides ER from 0 to 18 keVee
  - LUX measurably efficient at 1 keV!
- Improved stats over calibration in first LUX result, running longer
  - High statistics provide very precise determination of probability for an ER event to “leak” down into NR S2/S1 region, as a function of S1
  - This ER provides us with both light and its charge yield too
- Because uniformly distributed, used with ^{83m}Kr for good, accurate measure of the fiducial volume

Distribution of Backgrounds

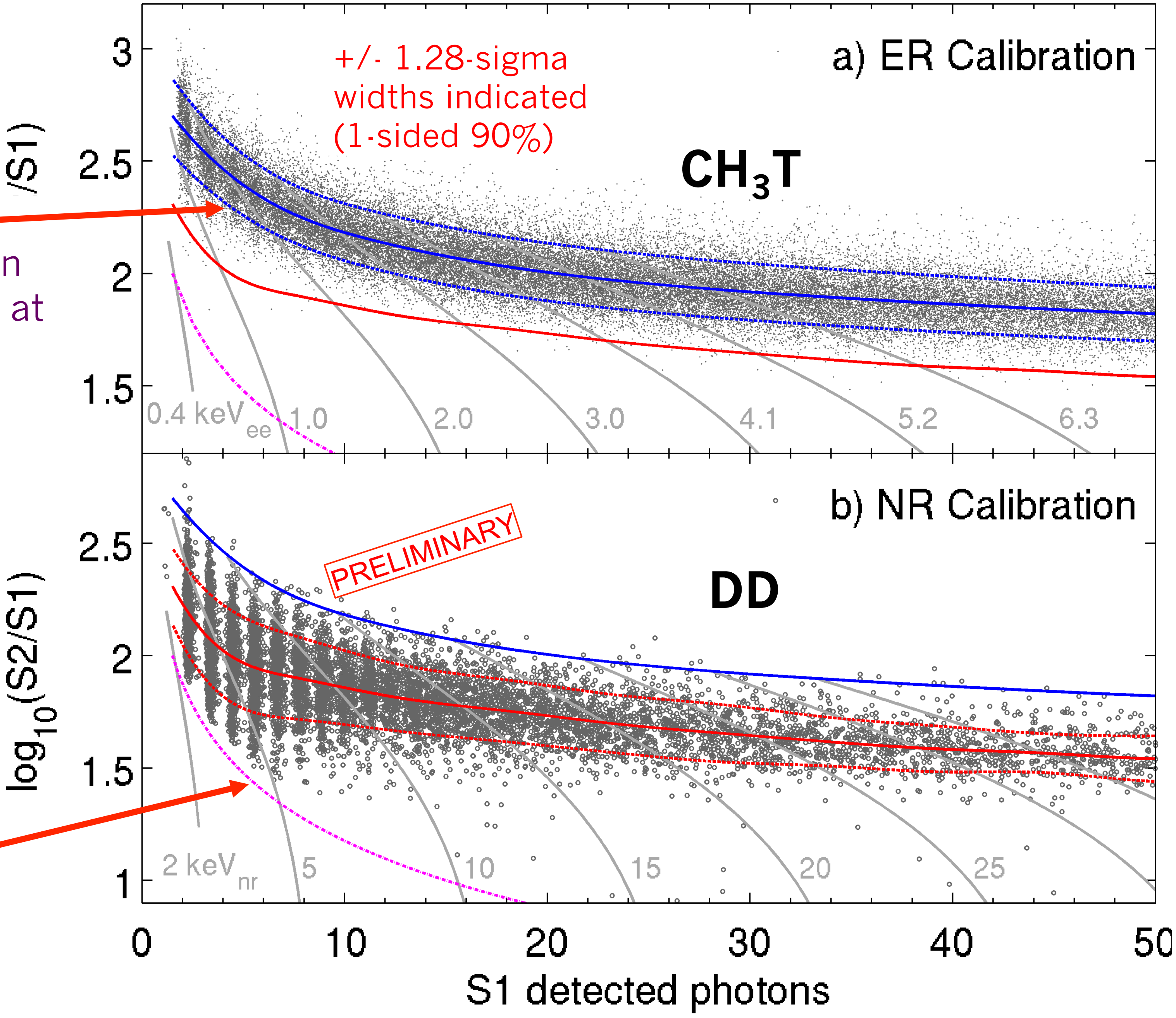
- 3.6 +/- 0.3 x 10^{-3} single scatters/(keV-kg-day) in low-energy regime
  - Measured 3.5 ppt Kr with RGA. PMT gamma-rays = biggest background
  - Cosmogenics from surface run have decayed away (Xe131m, Xe129m)
  - Potential fiducial mass increase (was 118 kg in 2013)



The "Bands"

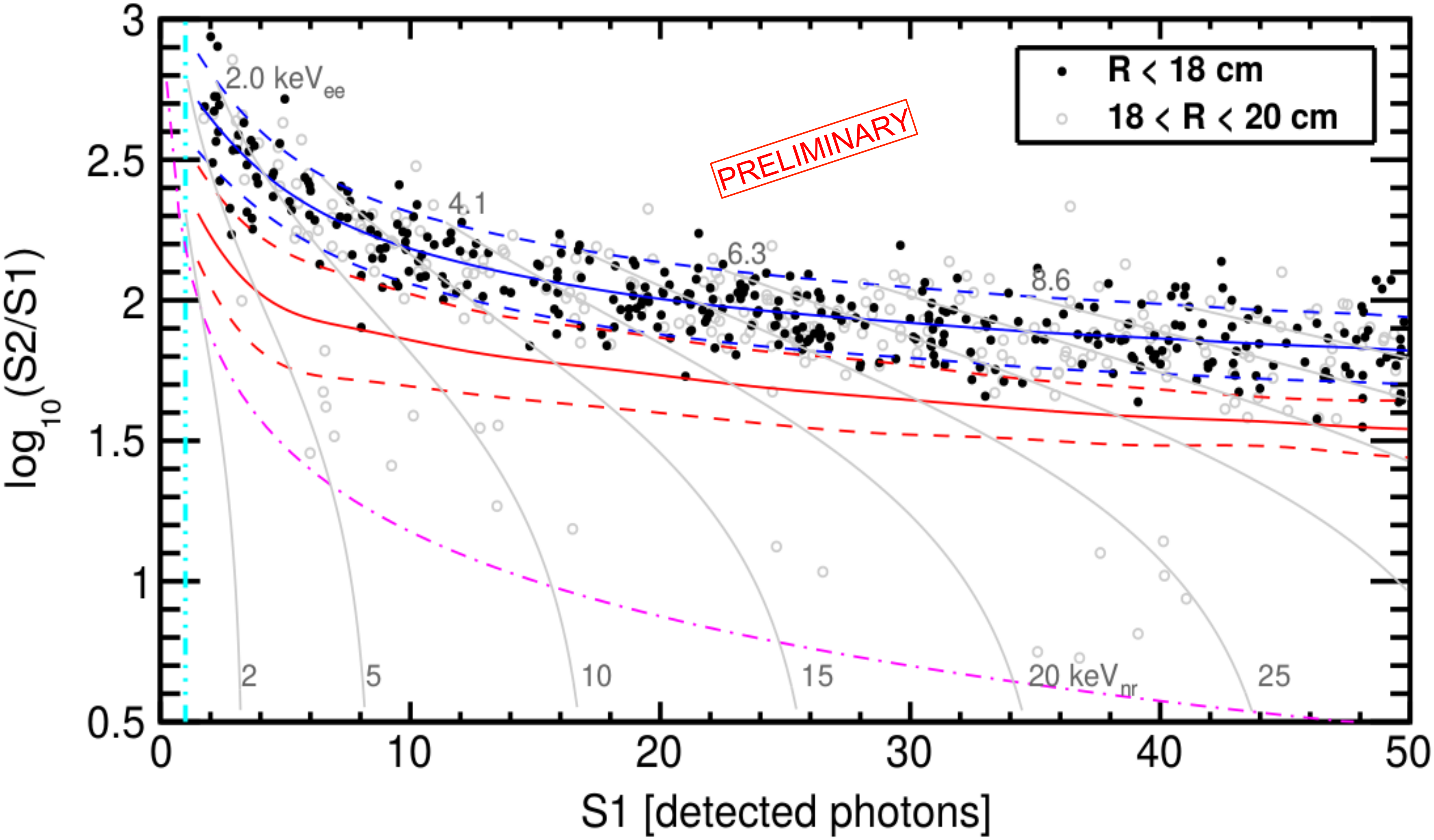
New: DIGITAL individual photon counting, useful at low energies

Approximate location of 165 phd cut, lowered from 200 previous (8 => 6 e⁻'s)



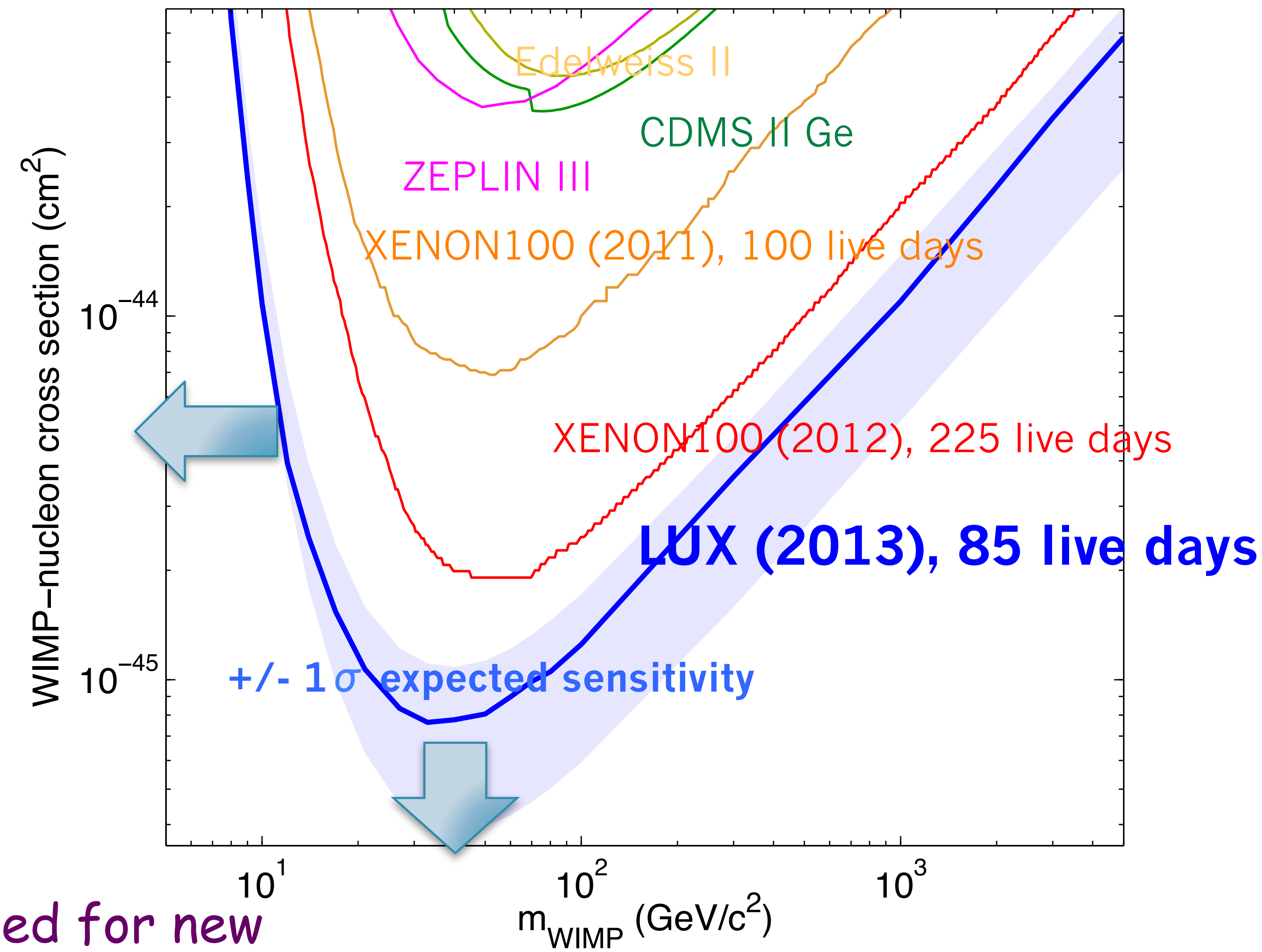
S1 and S2 are both position-corrected using Kr

Updated WIMP Search Data



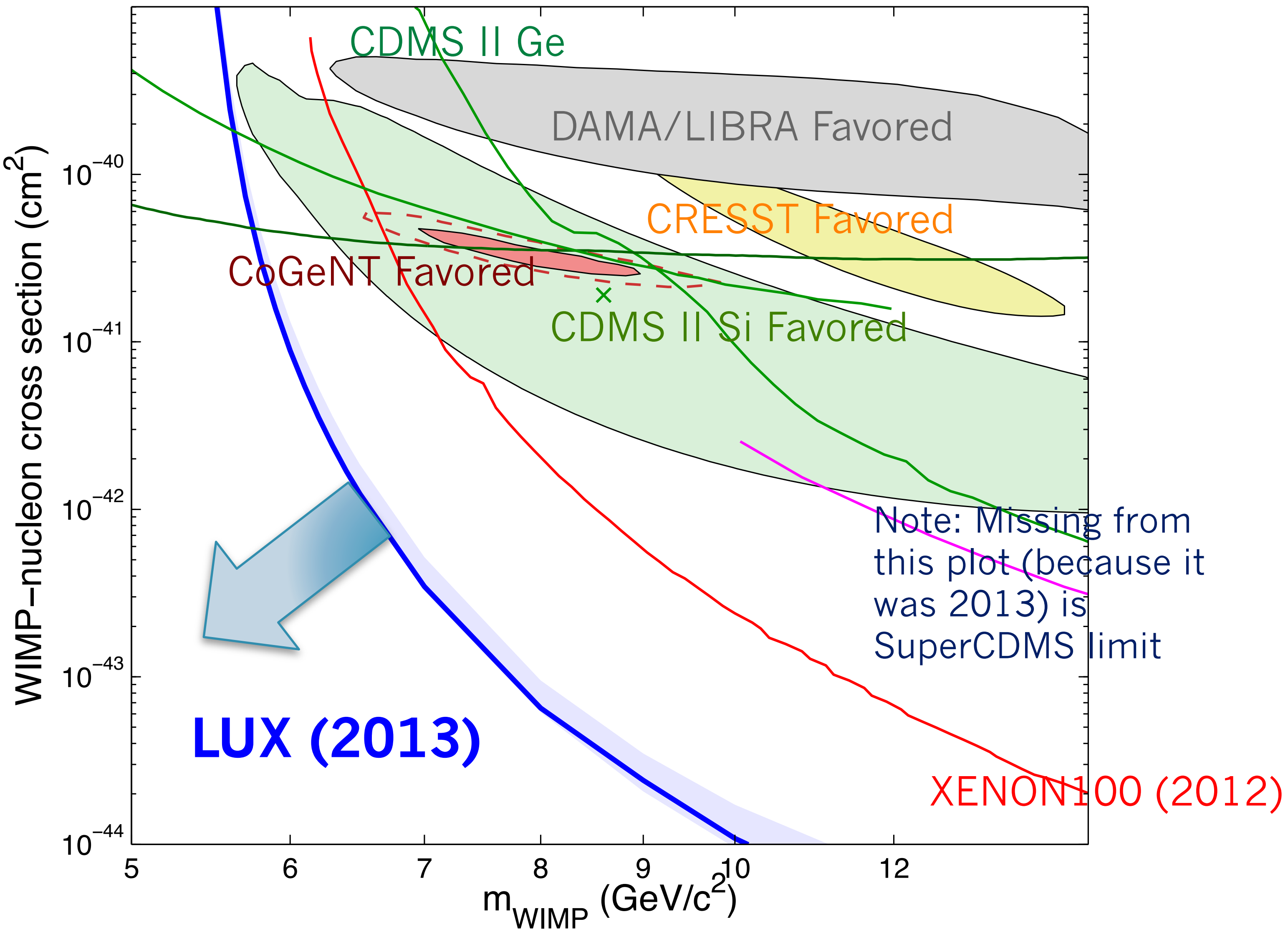
A Profile Likelihood Ratio (not cut-and-count) method uses all events.

WIMP Dark Matter Limit



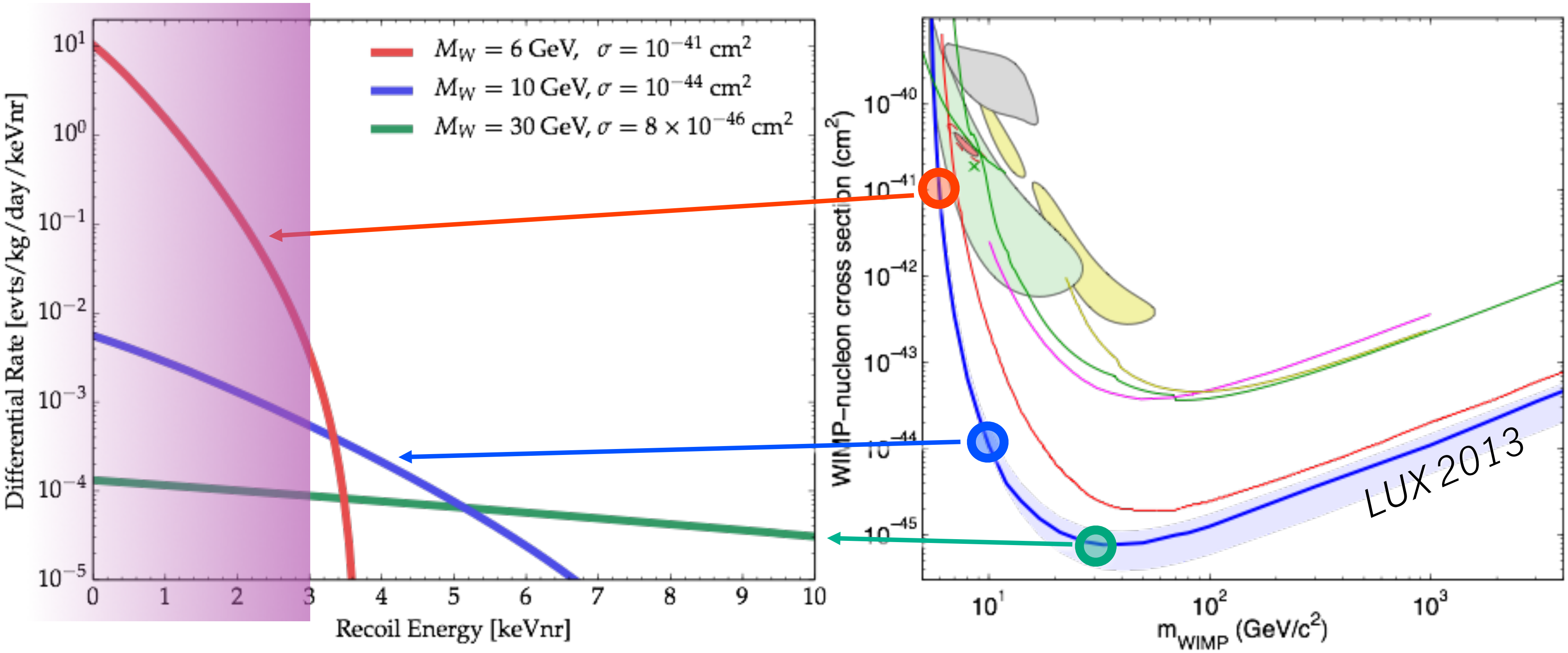
Stay tuned for new results later this year.

LUX Low-Mass Sensitivity



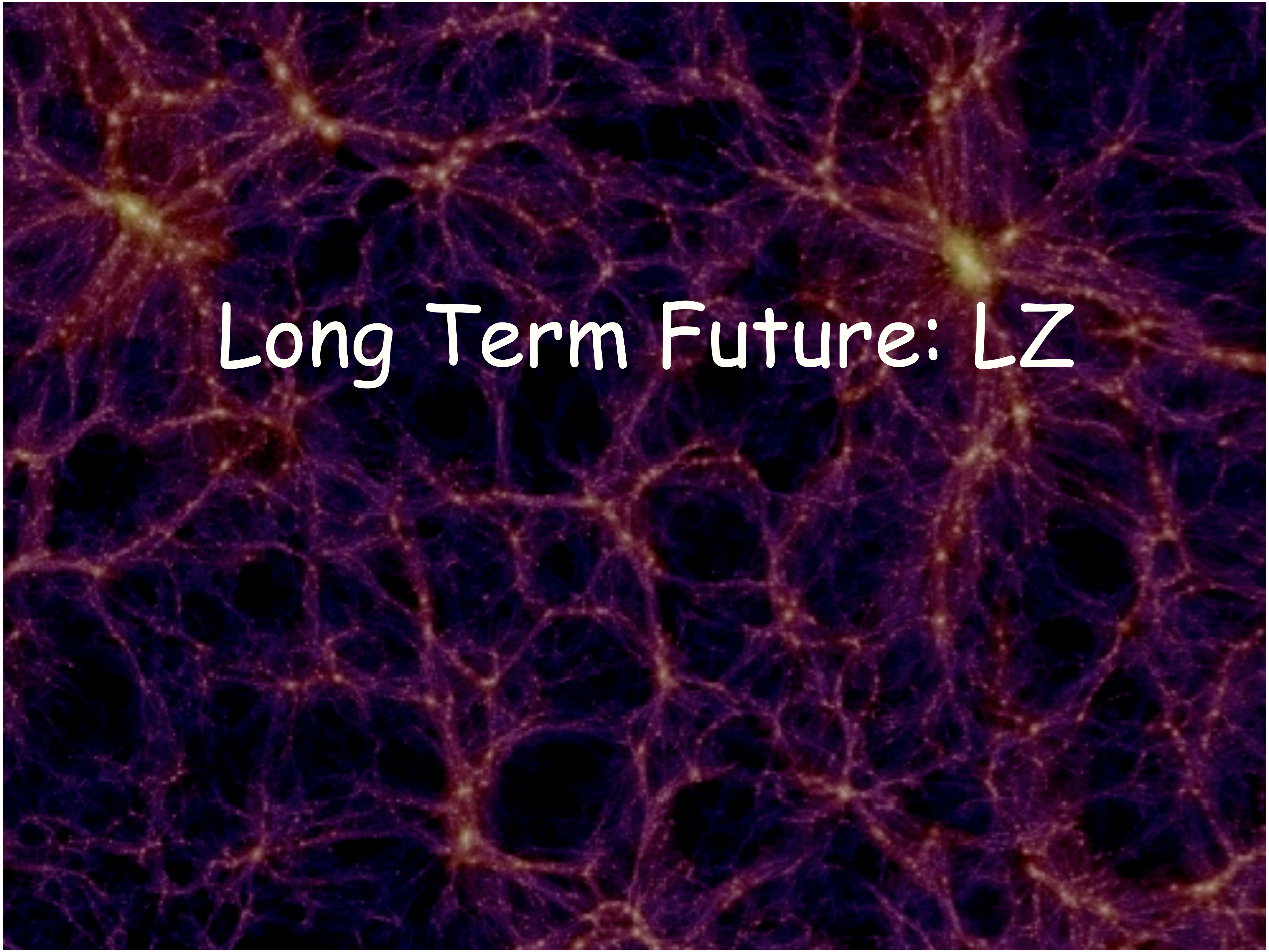
Note: Missing from this plot (because it was 2013) is SuperCDMS limit

Another Look at Light WIMPs



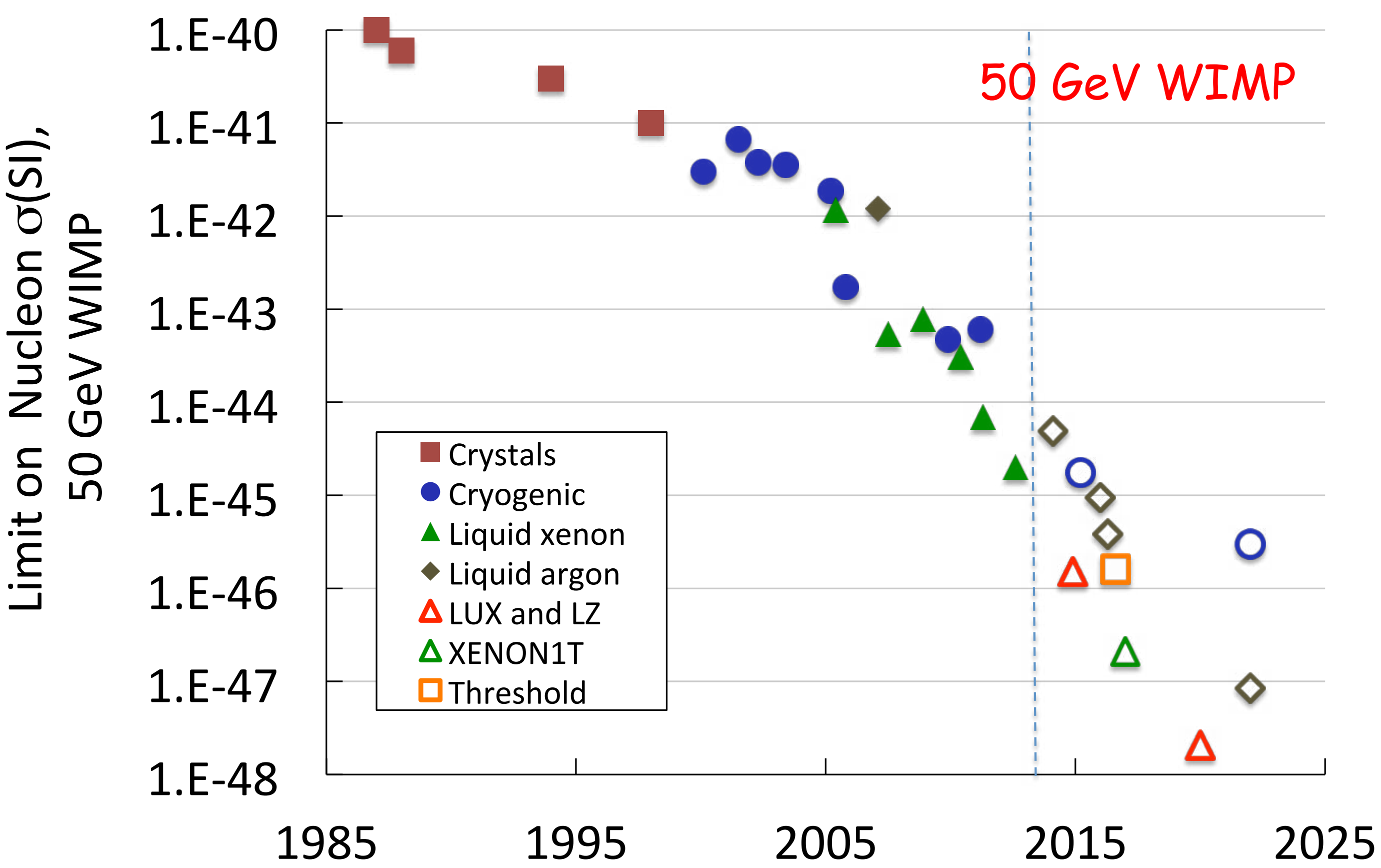
LUX 2013 upper limits assumed NO SENSITIVITY to recoils below 3 keVnr. This was not an *analysis* threshold, but an artificial one, a hard cut-off

For example, decreasing this response cutoff from 3 keV to 1 keV provides access to a factor of 1000* more signal at M = 6 GeV/c^2.

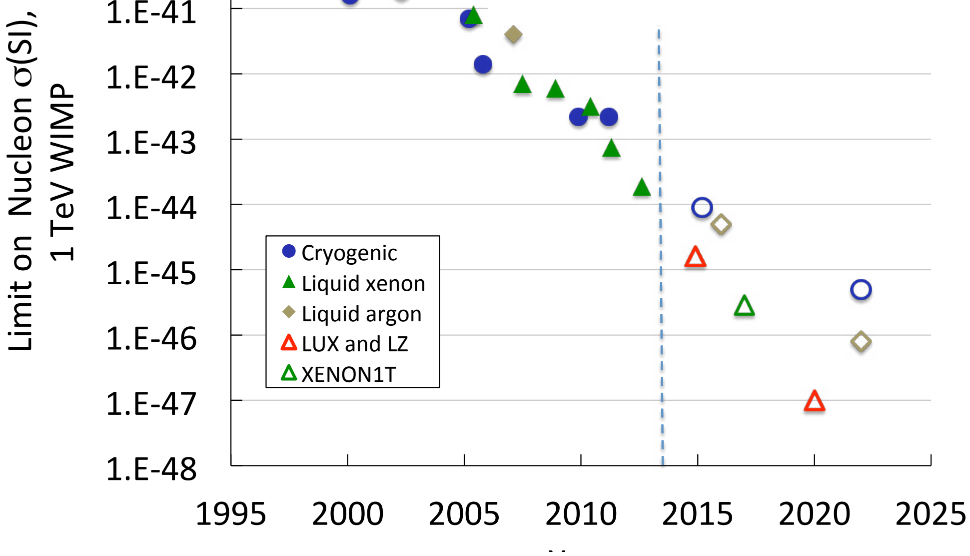


Long Term Future: LZ

A compact history of WIMP Searches



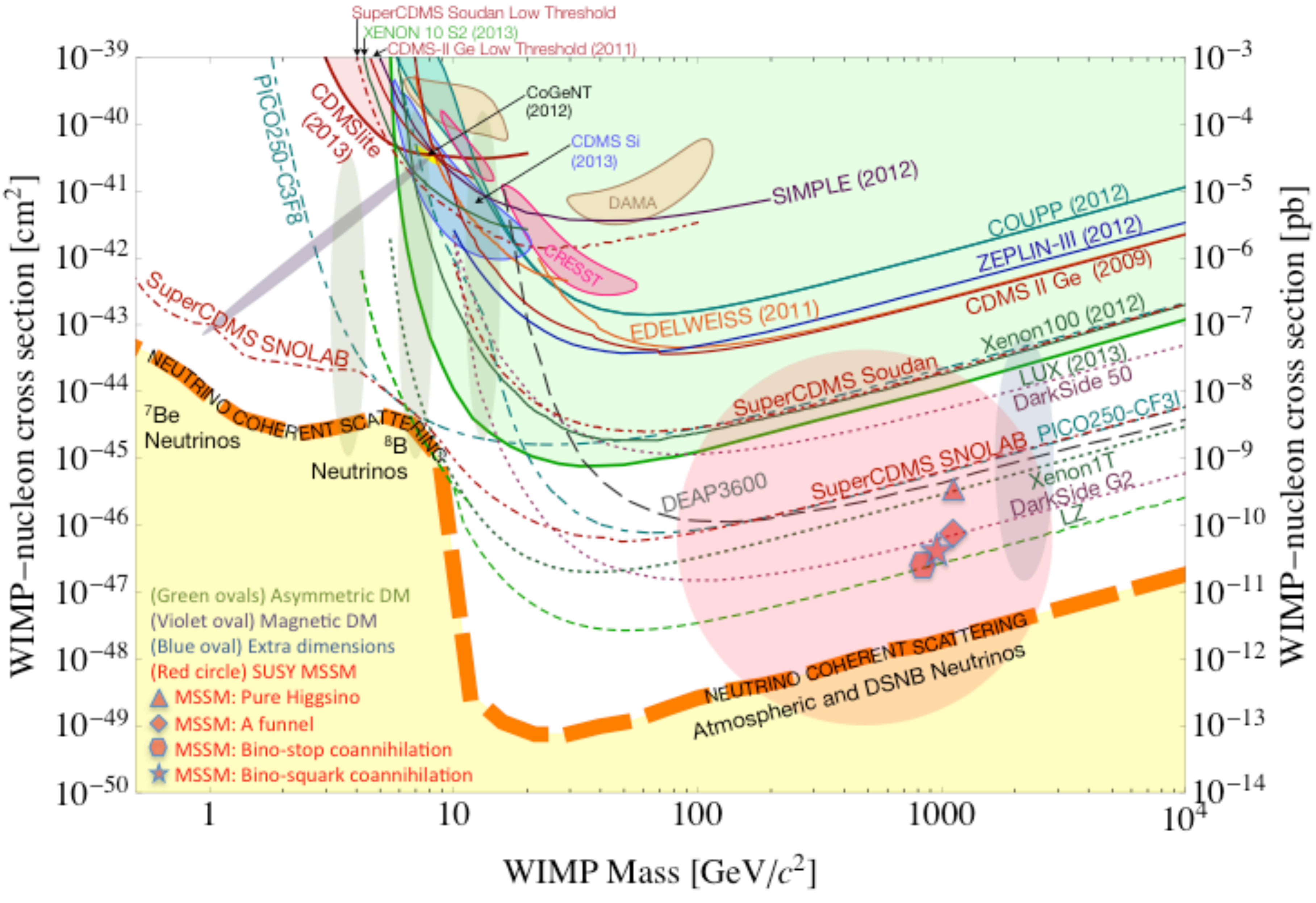
1 TeV WIMP



LZ is poised to possibly provide an end-point to this saga … hopefully by discovering WIMPs or, by ruling out most of the theoretical <u>and</u> experimentally accessible landscape.

Plots compiled by
Mike Witherell, UCSB

Snowmass Projections



LZ = LUX + ZEPLIN

32 institutions currently
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 Meeting at U. of Alabama

LZ: Evolution of LUX and ZEPLIN

Building on experiences gained in both programs, the proposed new experiment will utilize the LUX infrastructure at the Sanford Underground Research Facility to mount a state-of-the-art detector. Highlighted features include:

- 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.
- Cryogenics and Xe purification systems made external to the main detector in a unique design.
- Fully digital deadtime-less data acquisition and trigger system.

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

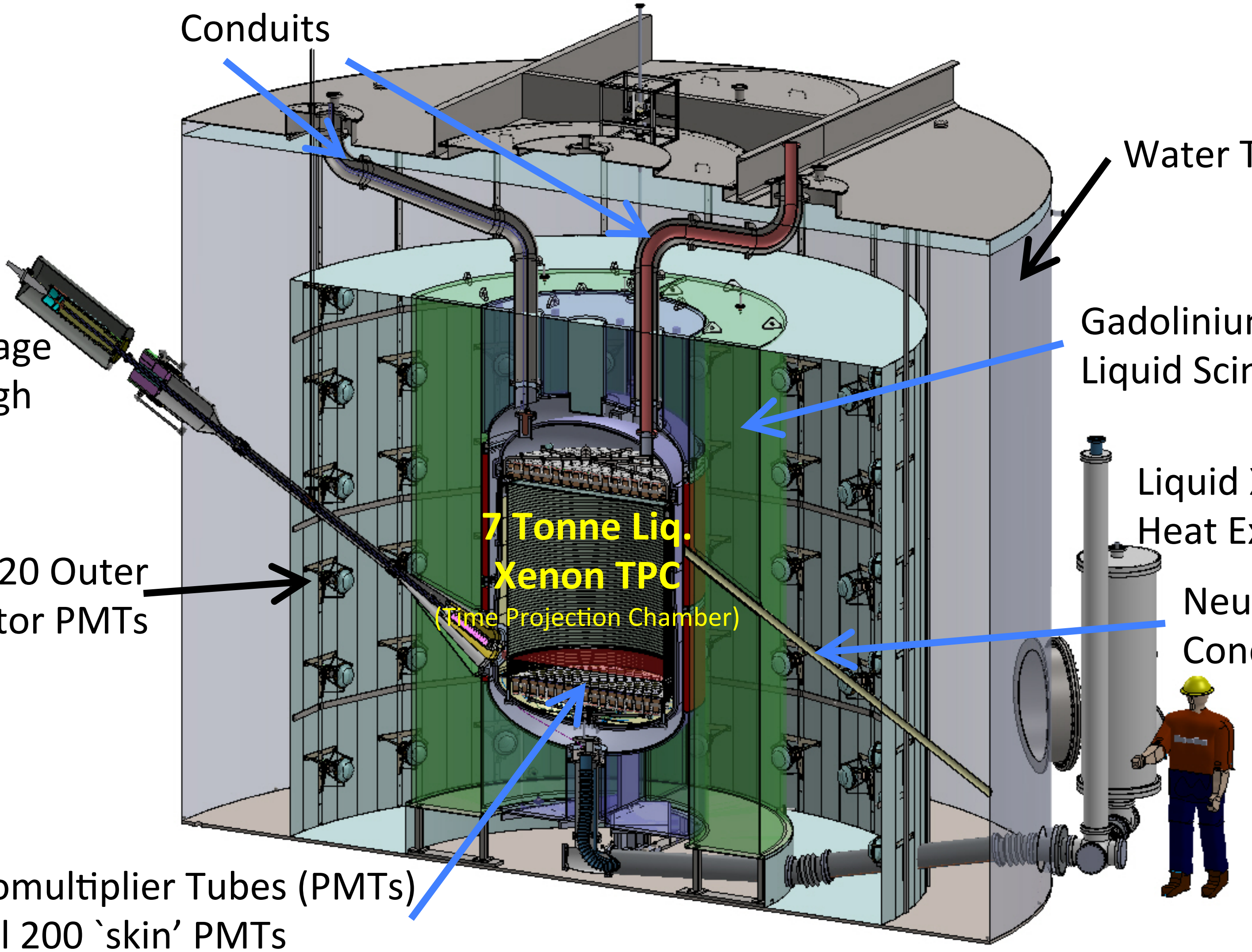
Scale Up ≈50 in Fiducial Mass

LZ

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

LUX

LZ Overview



Instrumentation
Conduits

Water Tank

High Voltage
Feedtrough

Gadolinium Loaded
Liquid Scintillator

Liquid Xenon
Heat Exchanger

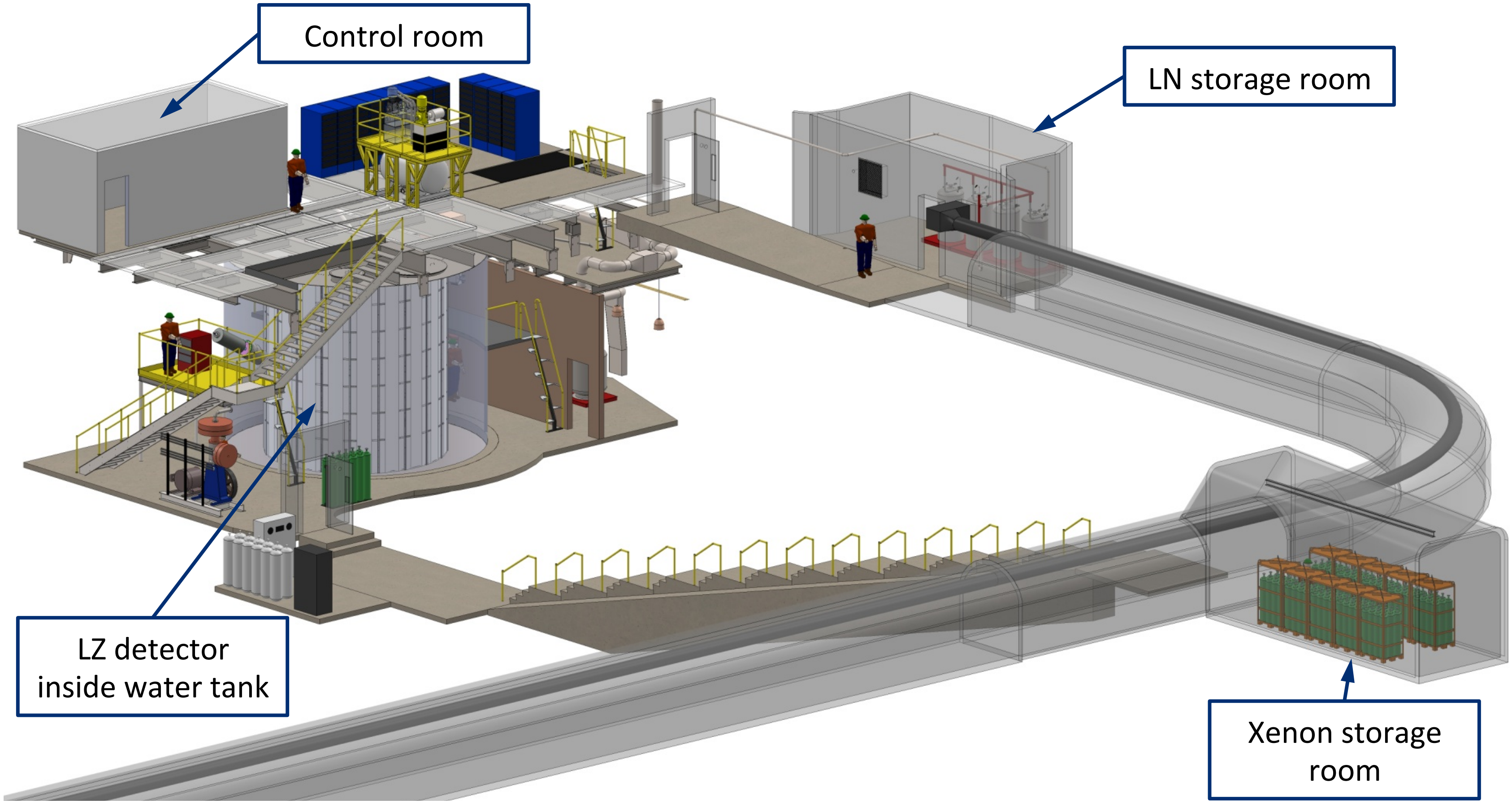
120 Outer
Detector PMTs

Neutron Calib.
Conduit

488 Photomultiplier Tubes (PMTs)
Additional 200 `skin' PMTs

LZ Underground at SURF

Years of experience at SURF from LUX



Control room

LN storage room

LZ detector
inside water tank

Xenon storage
room

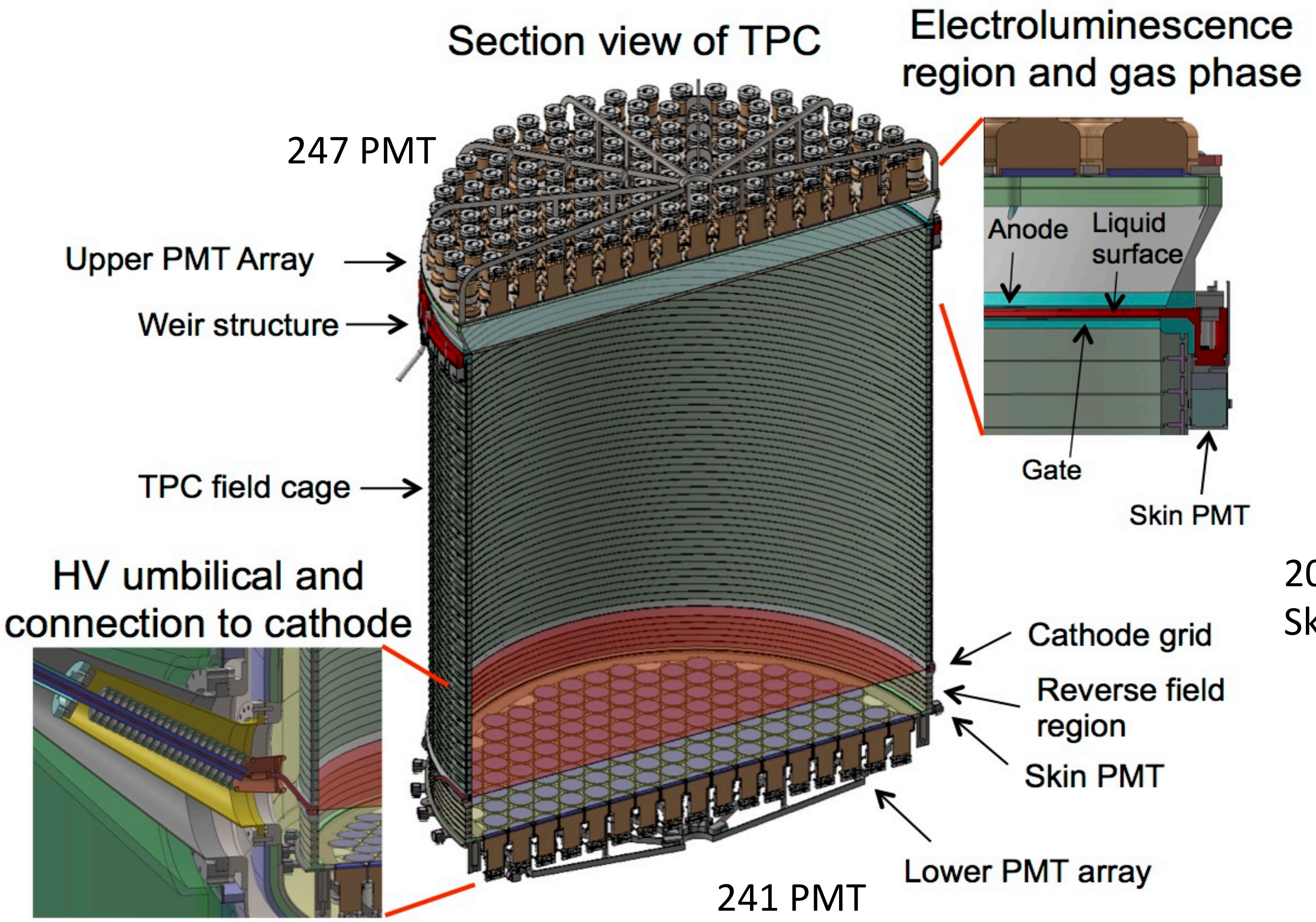
Key Design Points

- ✓ 7 active tonnes of LXe can yield 2 x 10^{-48} cm^2 sensitivity in about three years of running
- ✓ 5.6 tonne fiducial volume, 1000 days
- ✓ Requires all detector systems working together
    - ◆ Xe detector with good light collection, reasonable background rejection (ER discrimination) and good signal detection efficiency
    - ◆ Sophisticated veto system: skin (outside active Xe region) + scintillator/water allows maximum fiducial volume to be obtained, maximizes use of Xe and substantially increases reliability of background measurements
    - ◆ Control backgrounds, both internal (within the Xe) and external from detector components/environment

Design Status Summary

- Conceptual, and in some cases more advanced design, completed for all aspects of detector
- Conceptual Design Report about to appear on arXiv
- 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

Xe TPC Detector



247 PMT

241 PMT

200 total
Skin PMT

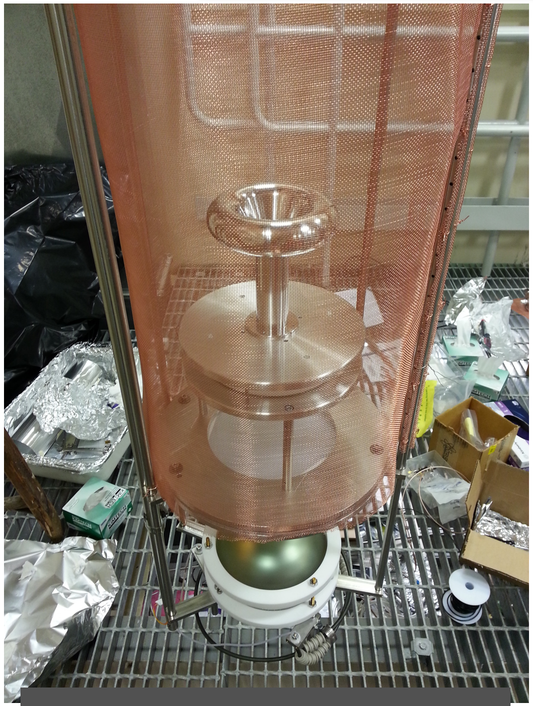
Xe Detector PMTs

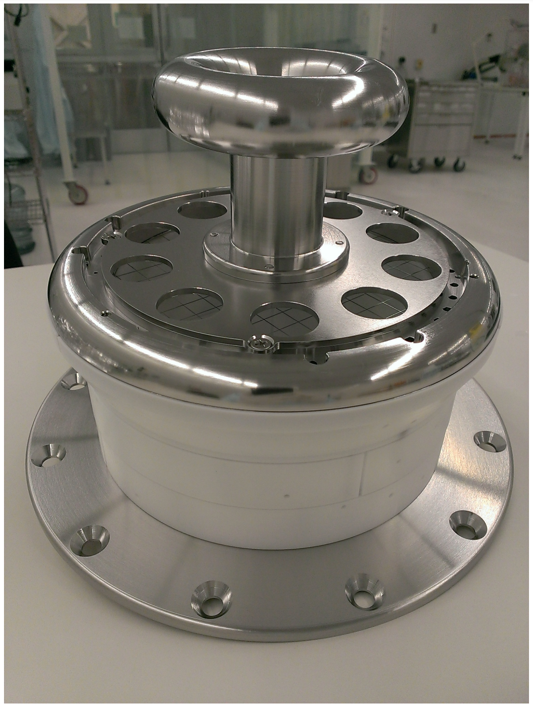
- R11410-22 3” PMTs for TPC region
  - Extensive development program, 50 tubes in hand, benefit from similar development for XENON, PANDA-X and RED
  - Materials ordered and radioassays started prior to fabrication.
  - First production tubes early 2016.
  - Joint US and UK effort
- R8520-406 1” for skin region
  - Considering using 2” or 3” for bottom dome region, recycle tubes from older detectors

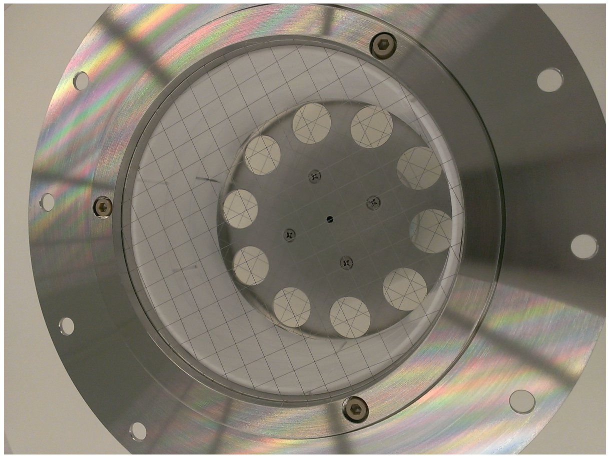
Xe Detector Prototyping

- 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

High Voltage Studies

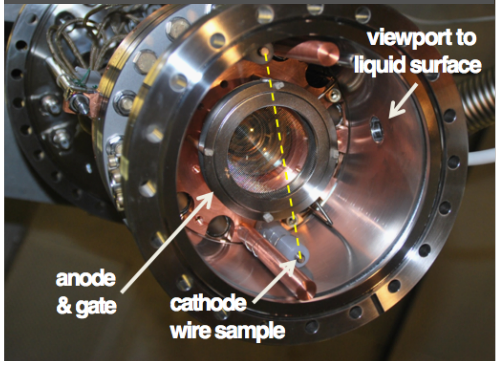






Prototype of highest E-field region tested in LAr

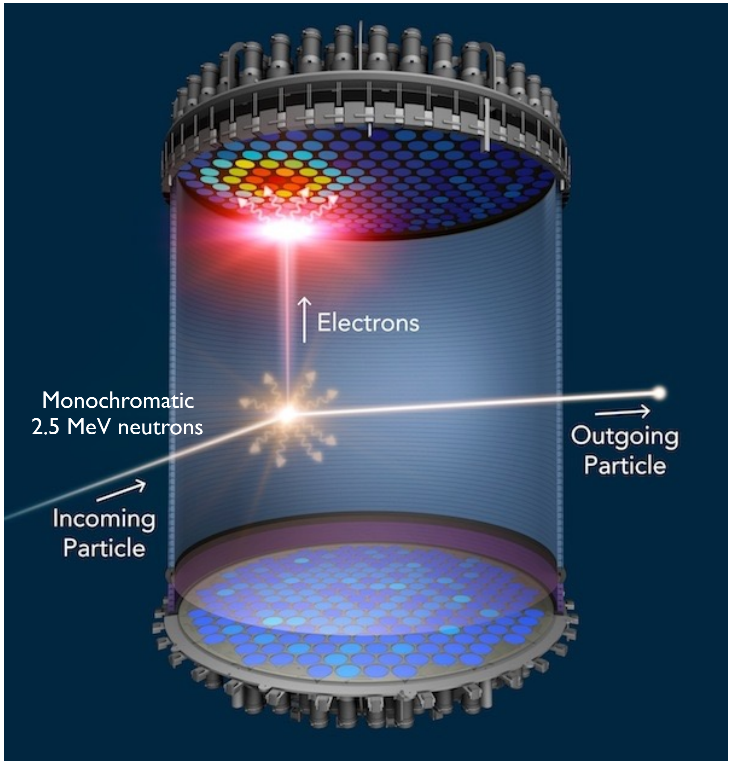
Wire grid tests ongoing

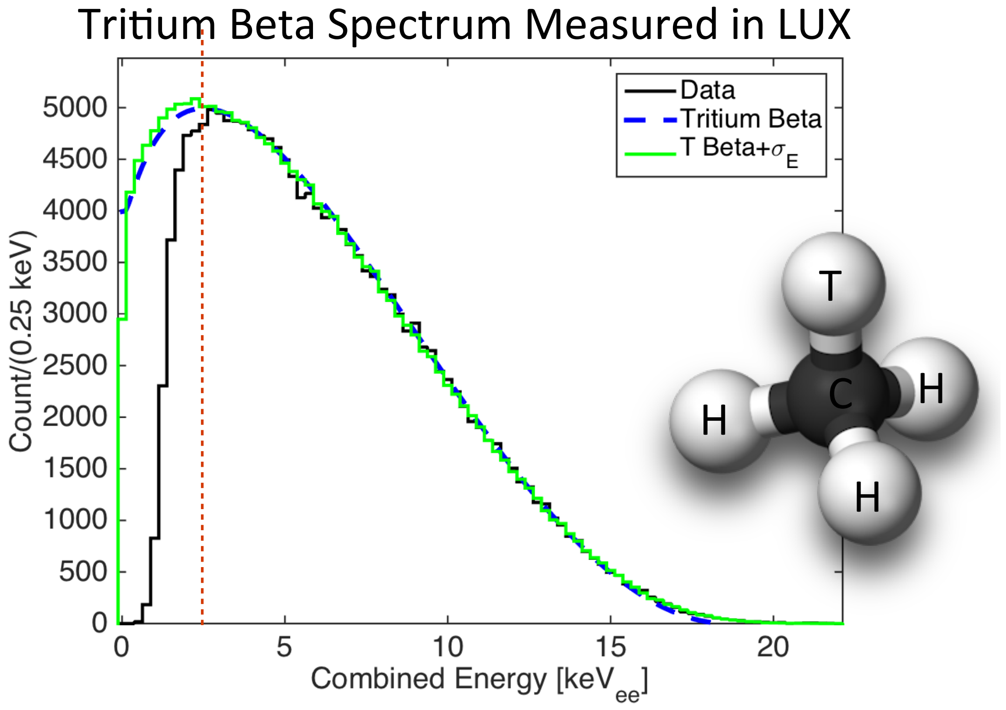


- ✦ Cathode voltage design goal: 200 kV (provides margin)
- ✦ LZ nominal operating goal: 100 kV (~700 V/cm)
- ✦ Feedthrough prototype tested to 200 kV
- ✦ Prototype TPC for 100 kg LXe system fabrication starting
- ✦ HV prototyping expanding at Berkeley

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

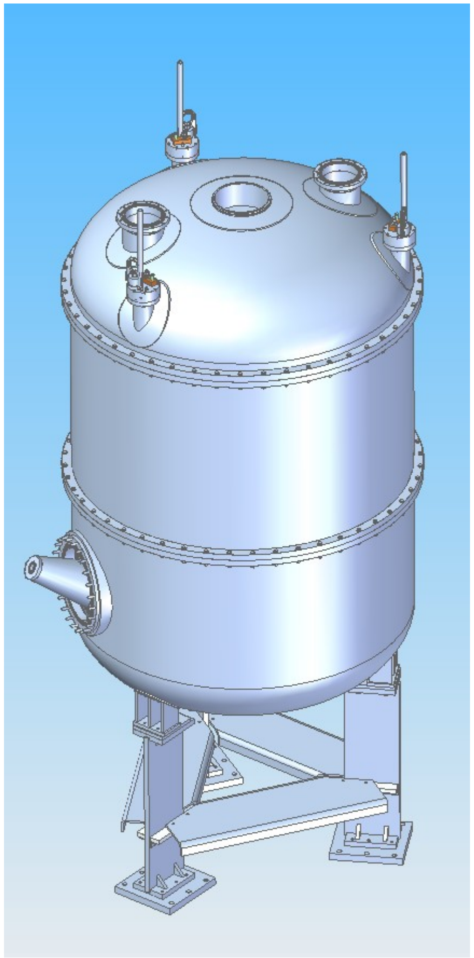
✦ LUX has led the way to detailed calibrations. LZ will build on this and do more.

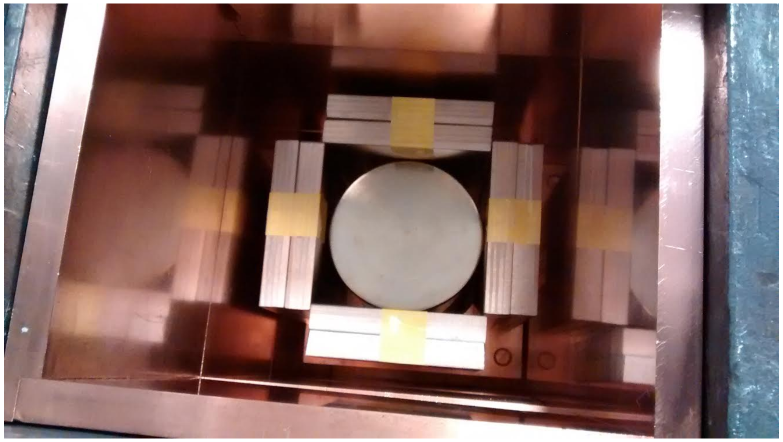
Done in LUX and will be done in LZ	**Not done in LUX, but will do in LZ**
^{83m}Kr (routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
Tritiated methane (every few months)	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator(upgraded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

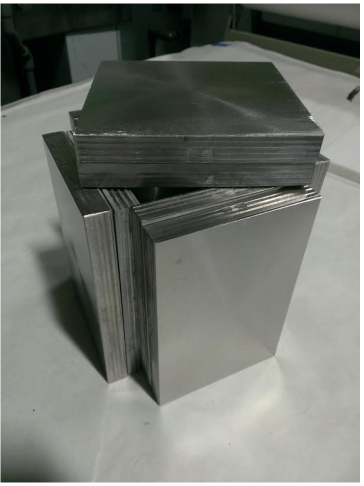
Cryostat Vessels

- 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

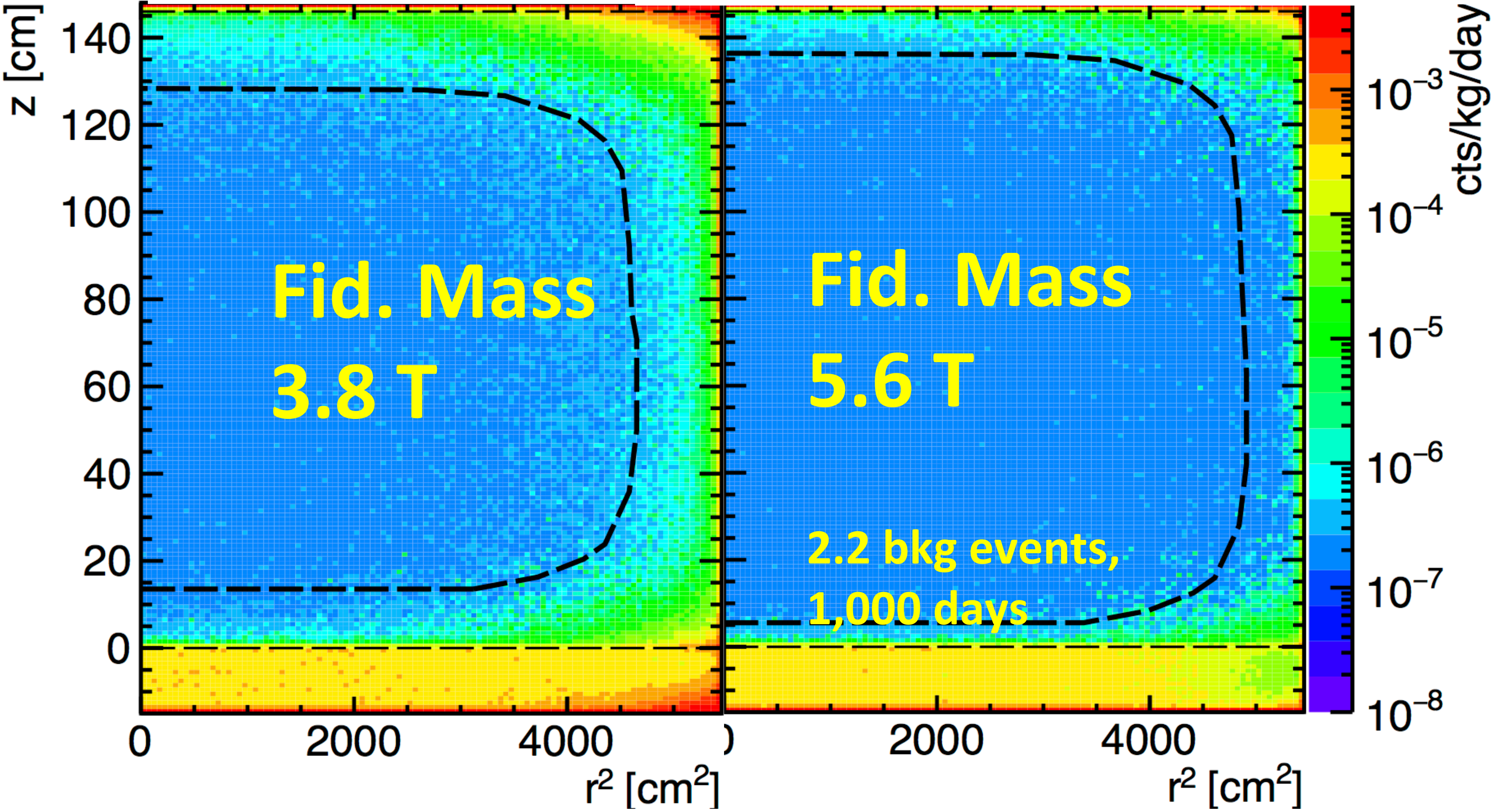






Background Modeled

Just LXe TPC
Use LXe skin, Outer Det.



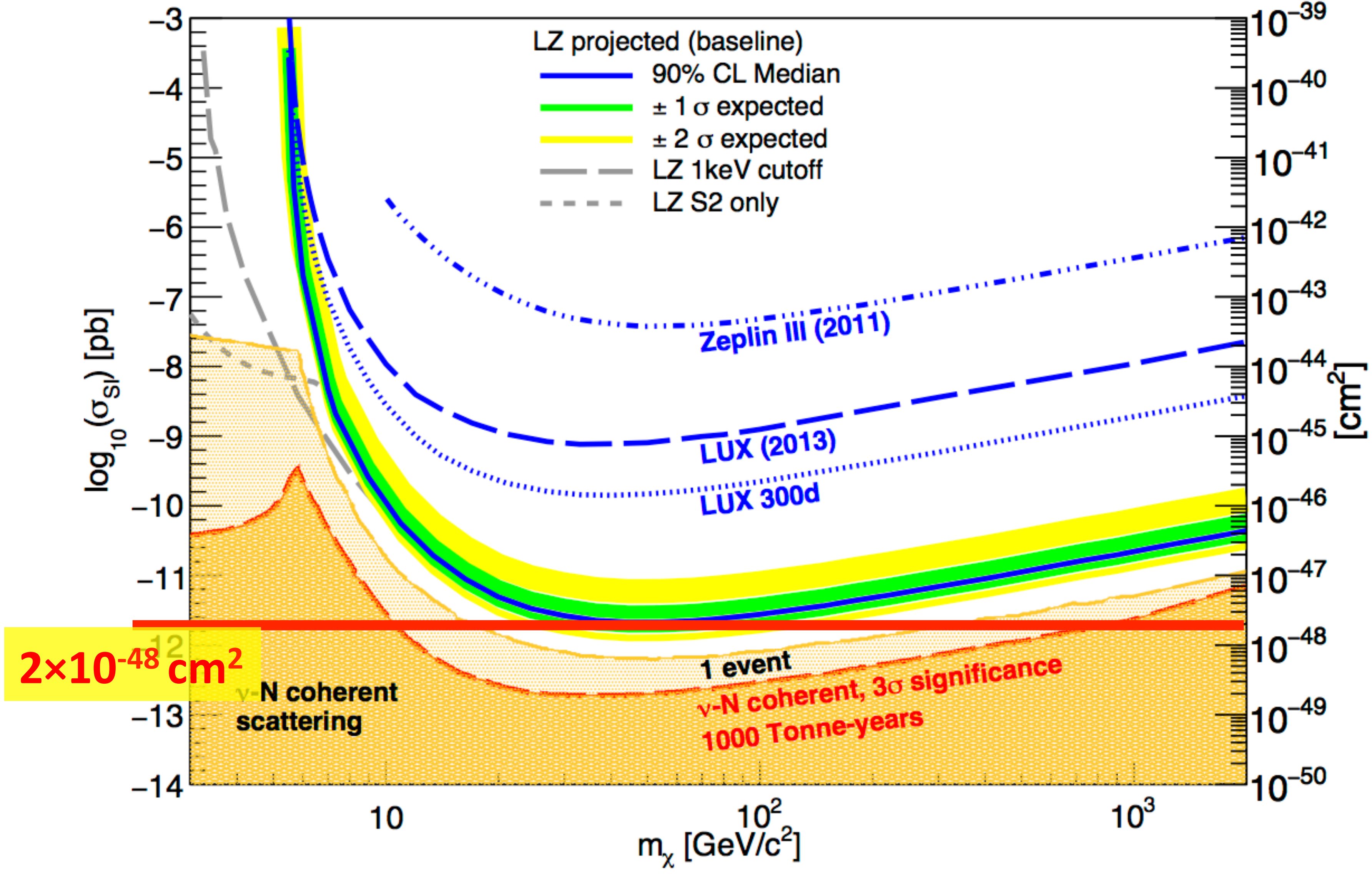
Fid. Mass
3.8 T

Fid. Mass
5.6 T

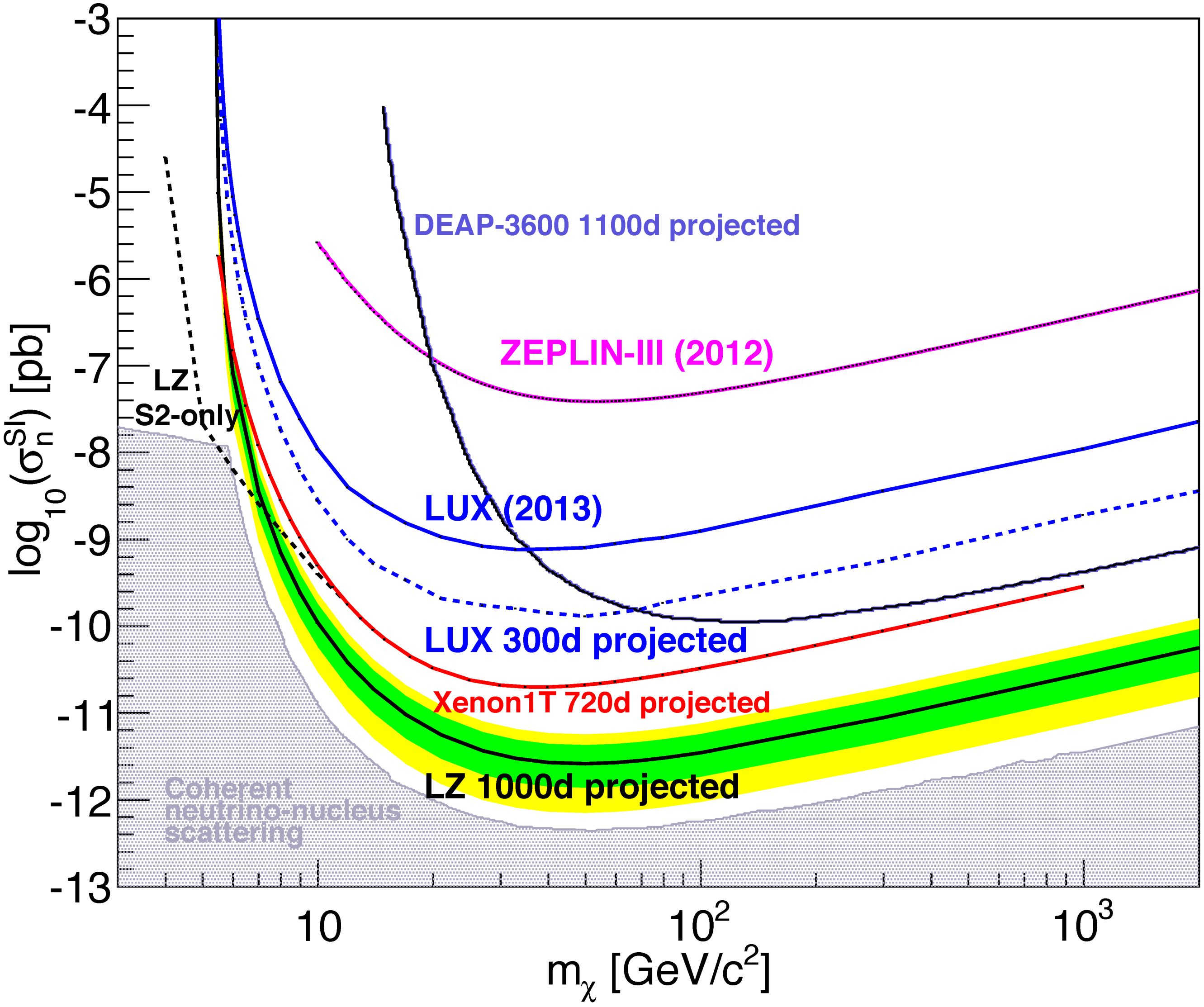
2.2 bkg events,
1,000 days

Projected Sensitivity – Spin Independent

(LZ 5.6 Tonnes, 1000 live days)



Sensitivity with Competition



Summary

- LUX has the largest kg-days exposure of any xenon TPC, as well as the lowest energy threshold
- Pioneering work with internal calibration sources. Low-energy NR data agree with MC.
- LUX has provided the most stringent limit on the WIMP-nucleon spin-independent interaction cross-section.
- LUX result is in conflict with low-mass WIMP interpretations of signals seen in CoGeNT, CDMS, and elsewhere
- LZ holds the promise to be the ultimate WIMP search experiment. Limited by neutrino-induced `background'
- LZ Project well underway. Procurement of Xe, PMTs and cryostat vessels started. Extensive prototype program.
- LZ benefits from the excellent LUX calibration techniques and understanding of background

Waiting for the Jackpot