Dark Matter in the Black Hills
The LUX Experiment at SURF

First Results from October 2013
and a few more things that have happened since then

LUX

www.luxdarkmatter.org

Simple as we can, but no simpler

The LUX Experiment

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Karen Gibson	Postdoc
Tomasz Biesiadzinski	Postdoc
Wing H To	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student

Imperial College London

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

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Carlos Hernandez Faham	Postdoc
Victor Gehman	Scientist
Mia Ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Group
Dennis Carr	Mechanical Technician
Kareem Kazkaz	Staff Physicist
Peter Sorensen	Staff Physicist
John Bower	Engineer

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Luiz de Viveiros	Postdoc
Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

SD School of Mines

Xinhua Bai	PI, Professor
Tyler Liebsch	Graduate Student
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
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Bob Svoboda	Professor
Richard Lander	Professor
Britt Holbrook	Senior Engineer
John Thomson	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Postdoc
Matthew Szydagis	Postdoc
Richard Ott	Postdoc
Jeremy Mock	Graduate Student
James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Dean White	Engineer
Susanne Kyre	Engineer
Carmen Carmona	Postdoc
Curt Nehrkorn	Graduate Student
Scott Haselschwardt	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer
Lea Reichhart	Postdoc

Collaboration Meeting, Sanford Lab, April 2013

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc

University of Maryland

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

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	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
Dana Byram	*Now at SDSTA

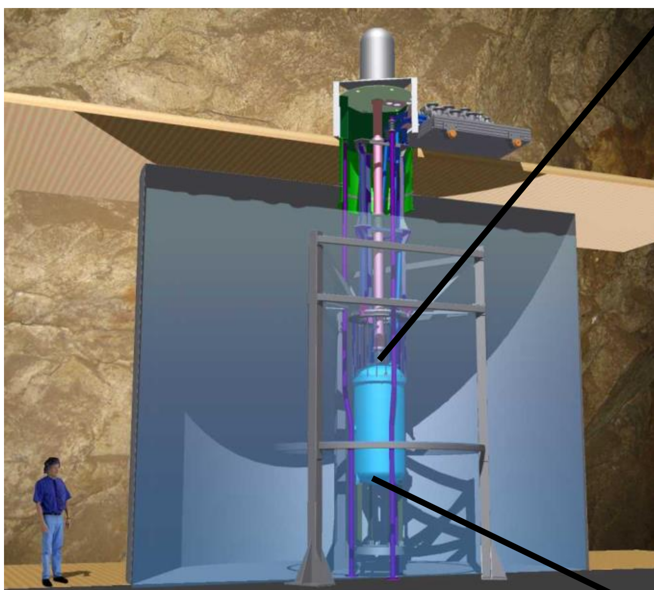
Yale

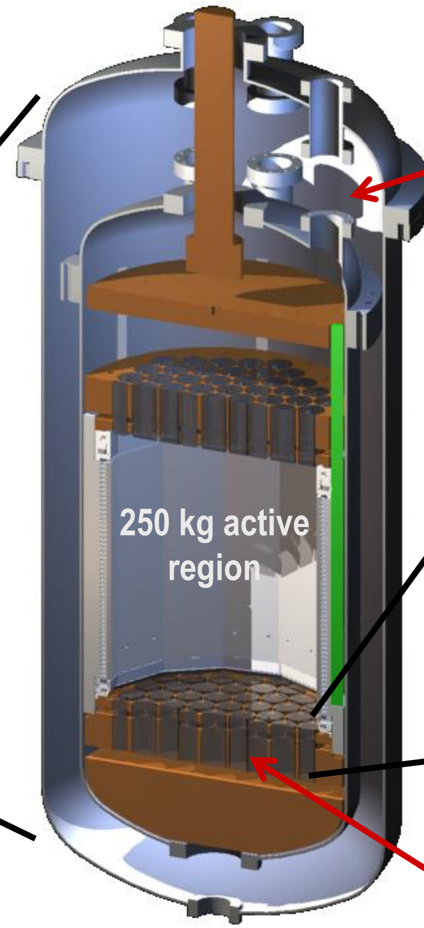
Daniel McKinsey	PI, Professor
Peter Parker	Professor
Sidney Cahn	Lecturer/Research Scientist
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

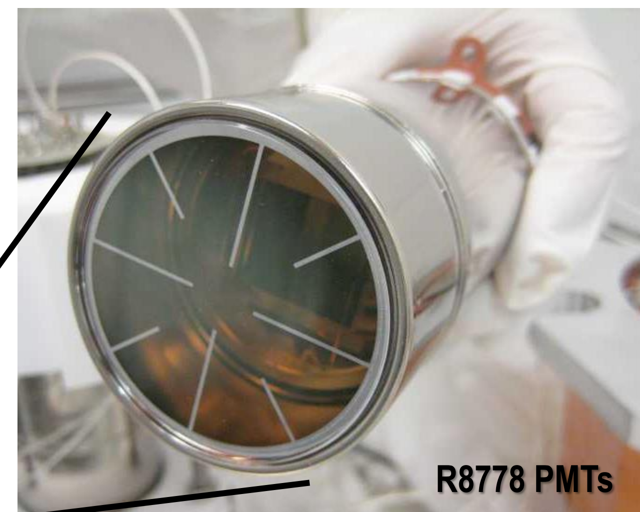
The LUX Detector

- **L**arge **U**nderground **X**enon
- **370kg Liquid Xe** Detector (active volume: 49 cm height, 49 cm diameter)
- **122 PMTs** (Hamamatsu R8778, ø = 5 cm)
  61 on top, 61 on bottom
- Low-background Ti Cryostat
- Water tank shielding

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

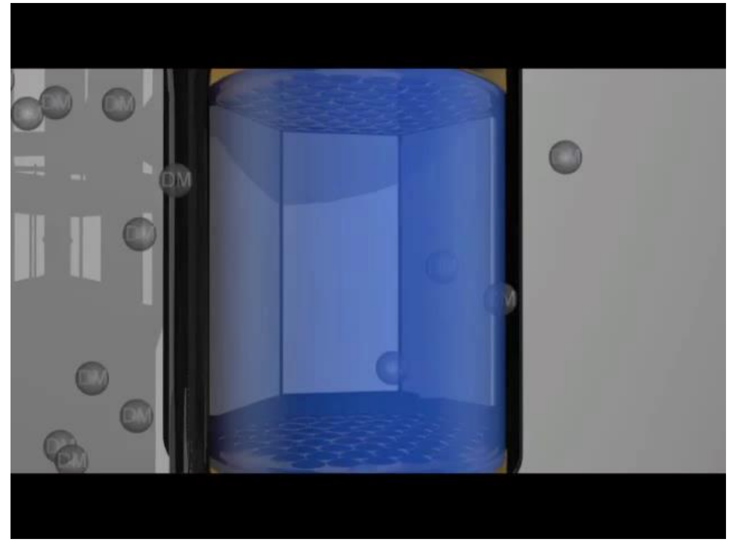


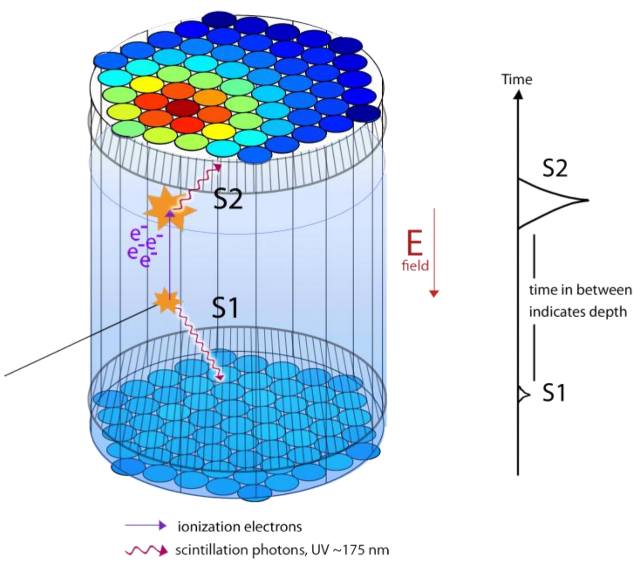




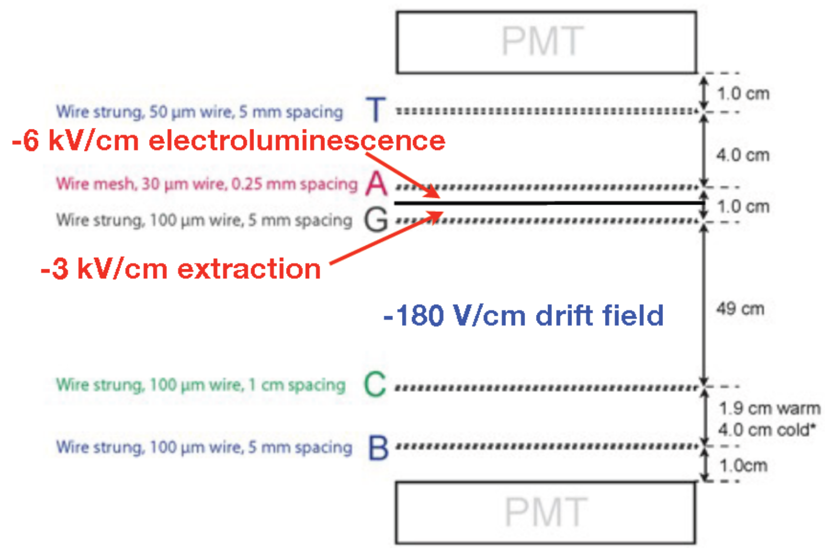
LUX Design – Dual Phase Xenon TPC

- **Can measure single electrons and photons**
- **Charge yield reduced for nuclear recoils**
- **Excellent 3D imaging**
  - **Reject multiple scatters**
  - **Eliminate edge events to take advantage of Xe self shielding**



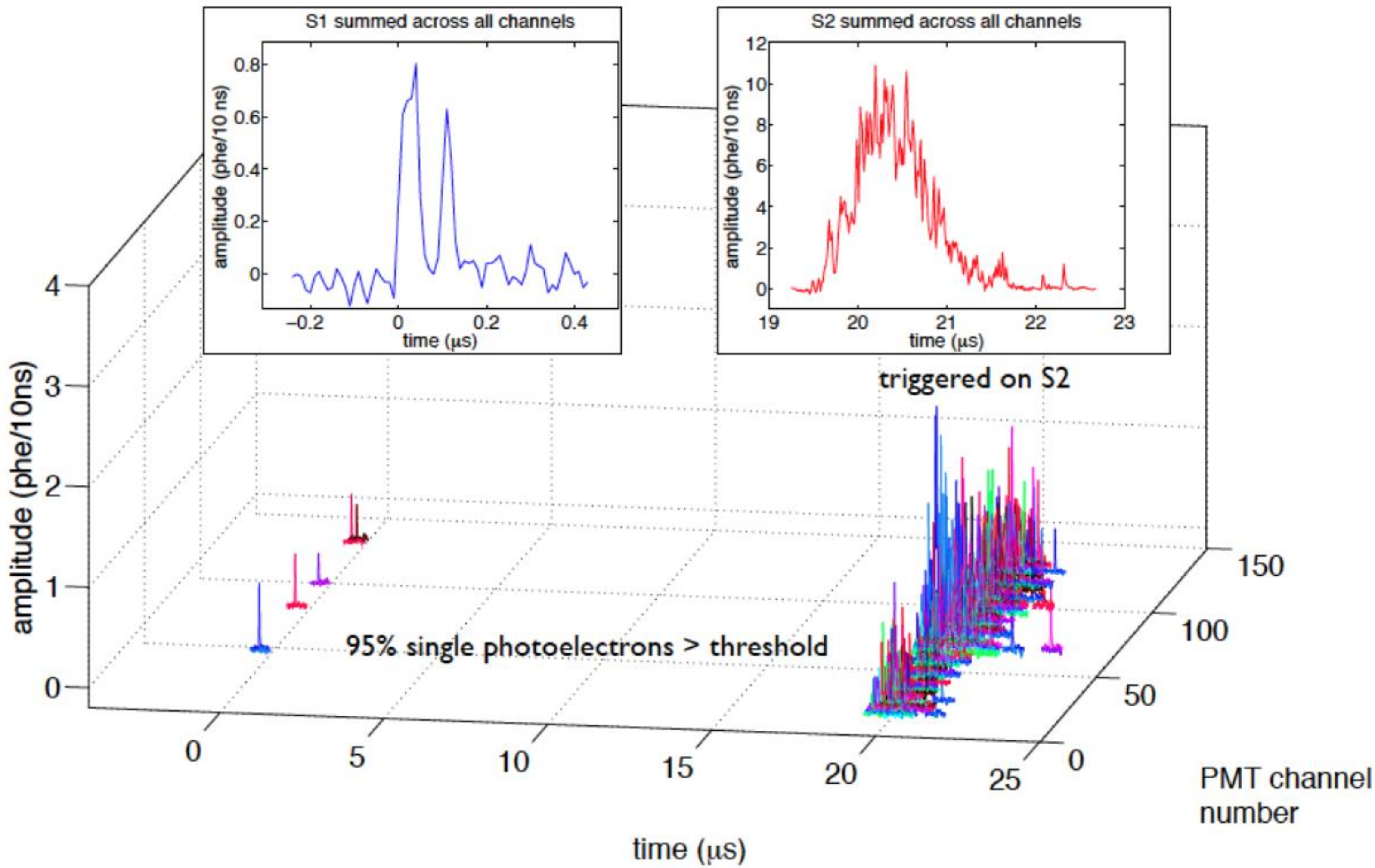


The LUX Detector Grid Configuration

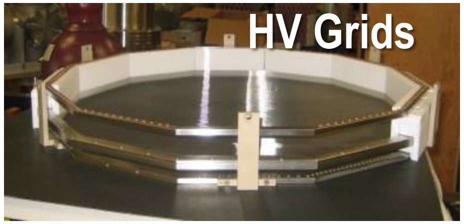


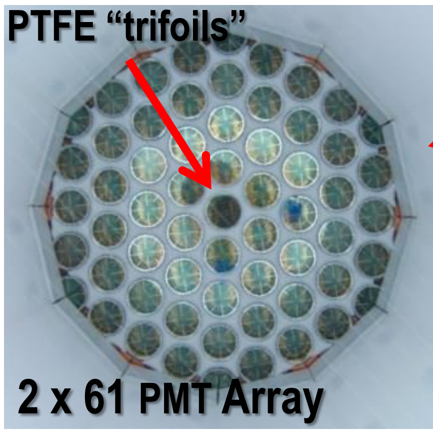
Typical Event in LUX

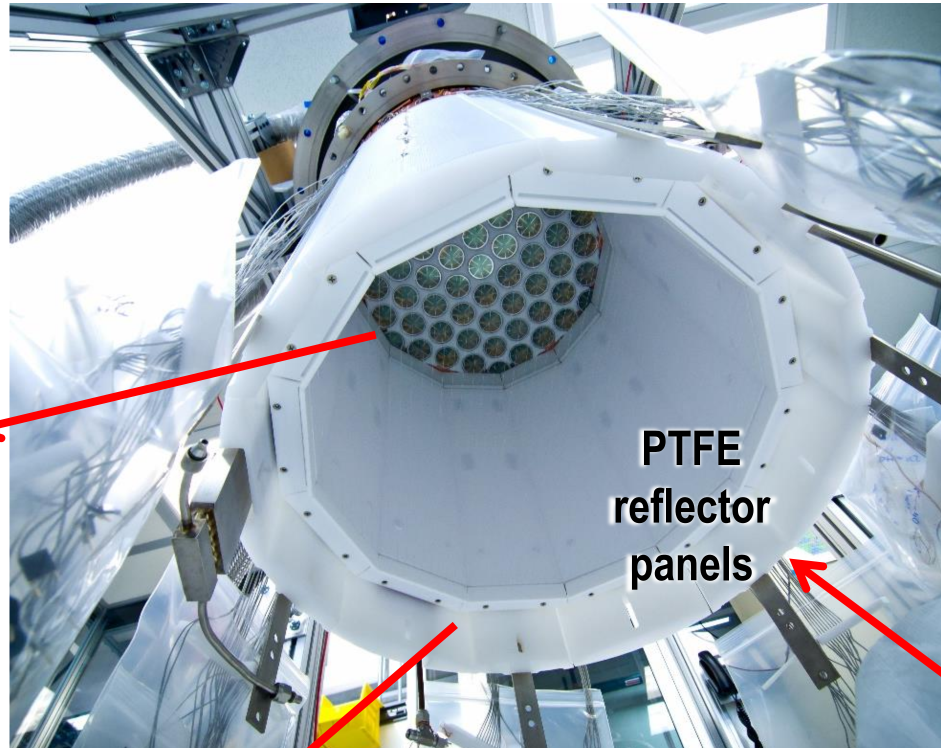
~ 1.5 keV gamma



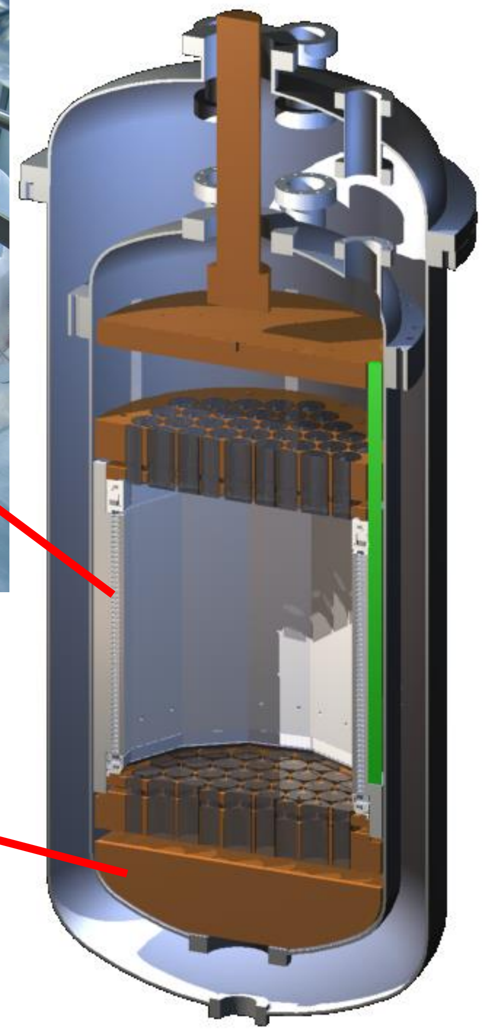
LUX Design – Internals





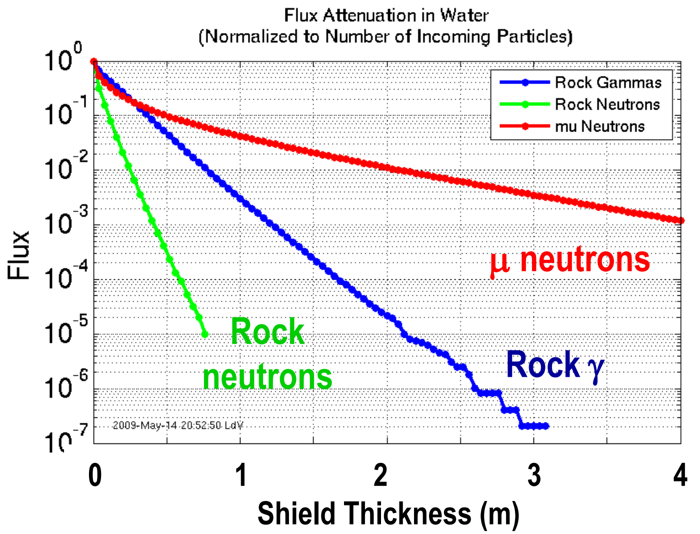


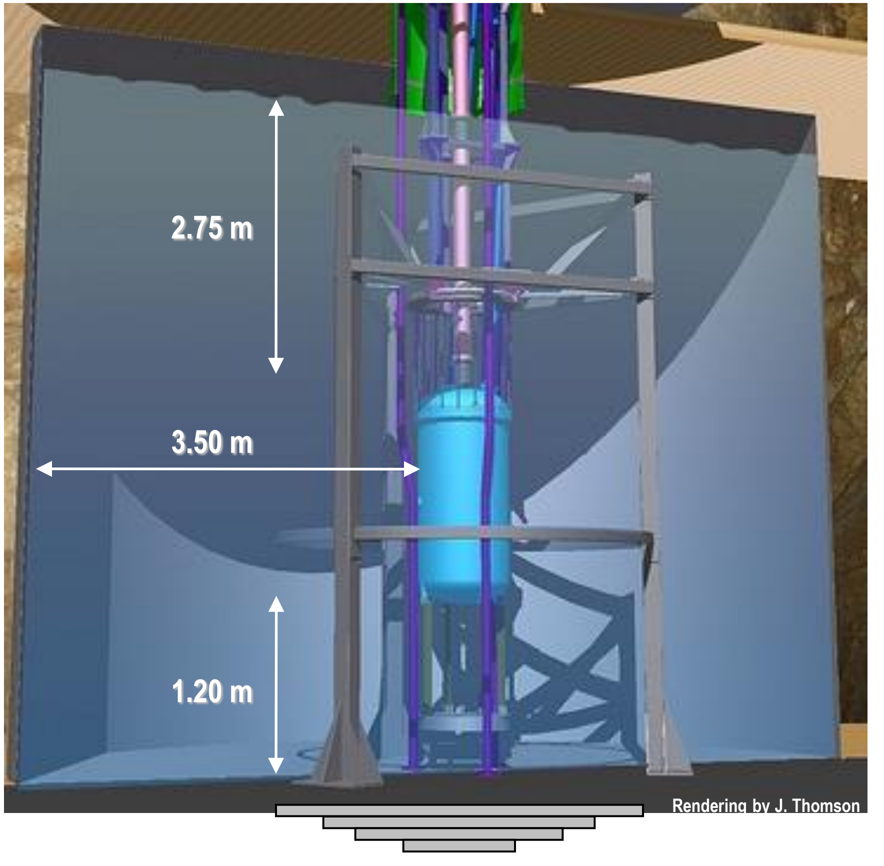
Active region defined by PTFE slabs (high reflectivity for Xe scintillation light)



LUX Design – Water Tank

- Water Tank: d = 8 m, h = 6 m
  - 300 tonnes, 3.5 m thickness on the sides
  - Inverted steel pyramid (20 tonnes) under tank to increase shielding top/bottom
- Cherenkov muon veto
- Ultra-low background facility
  - Gamma event rate reduction: ~10^{-9}
  - High-E neutrons (>10 MeV): ~10^{-3}





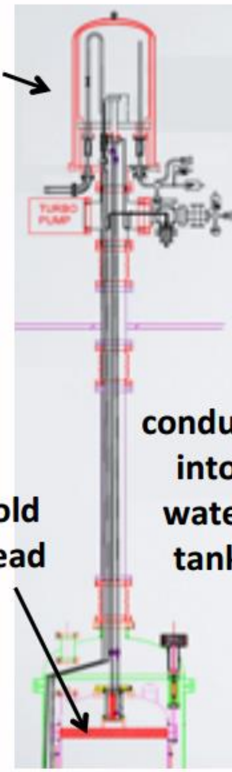
Inverted steel pyramid

LUX Design – Supporting Systems

Xenon gas handling and sampling

Cathode HV feedthrough

Thermosyphon cryogenics



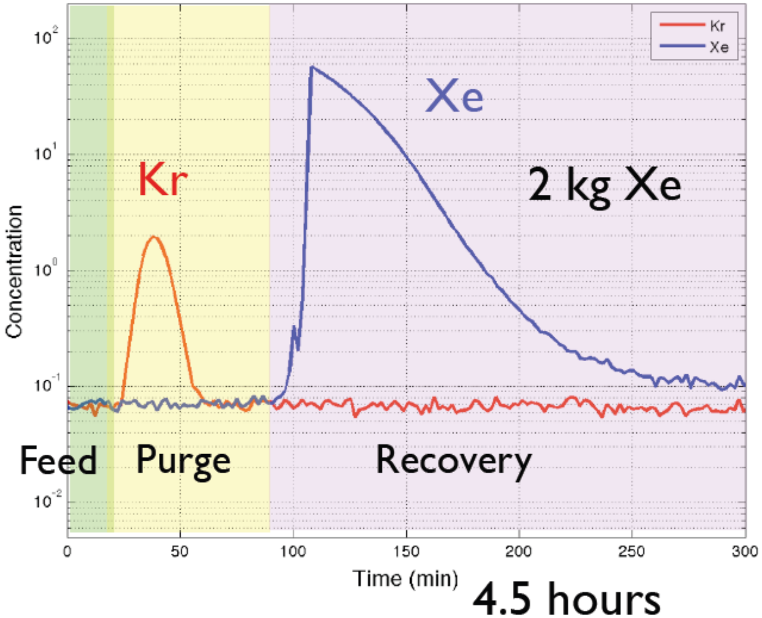
LUX Thermosyphon

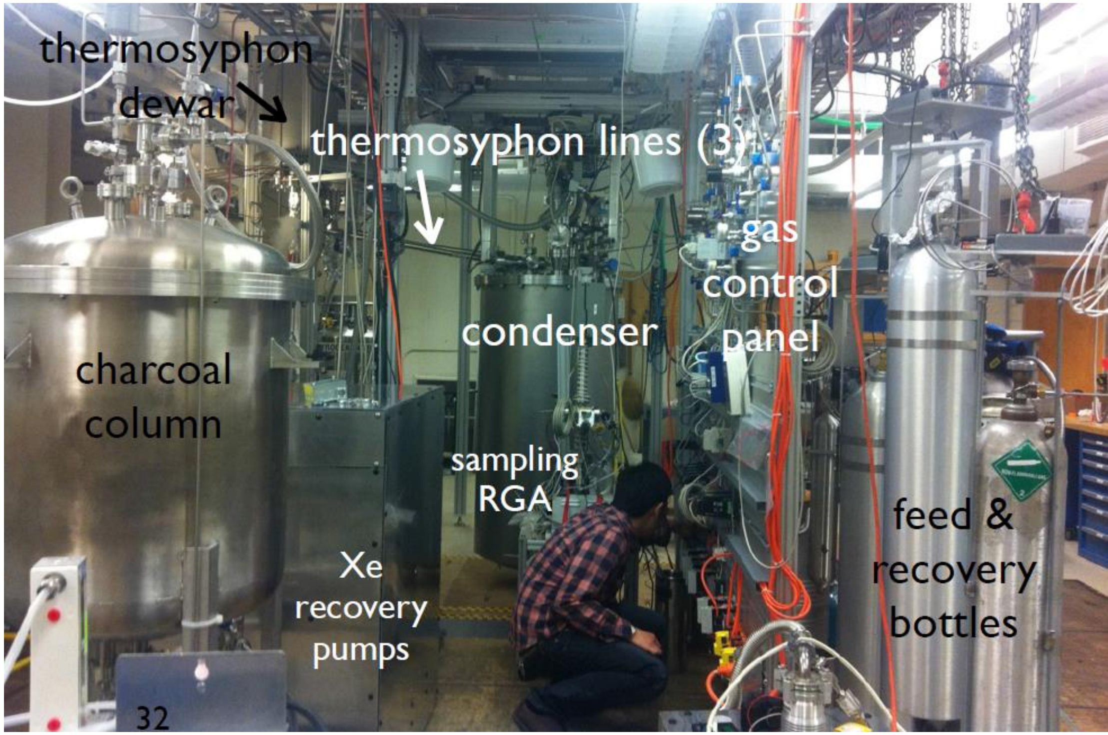
Xe storage and recovery

LUX Krypton Removal System

arXiv:1103.2714

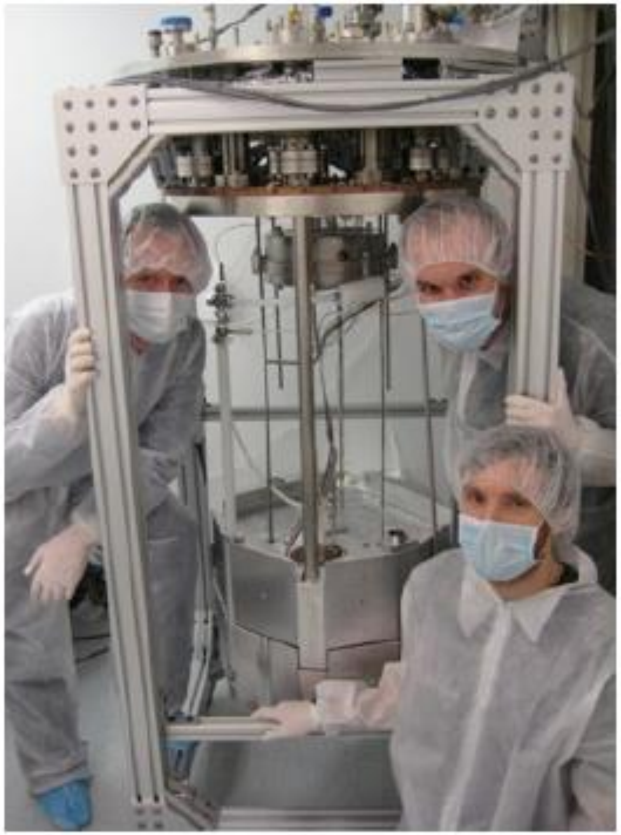
- ^{85}Kr - beta decay – intrinsic background in liquid Xe
  - Research grade Xenon: ~100 ppb Kr => 10^4 - 10^5 reduction needed
- August 2012 - January 2013: Kr removal at dedicated facility
  - Chromatographic separation system
- Kr concentration reduced from 130 ppb to 3.5 ± 1 ppt, (factor of 35000)
  - 1 ppt is achievable, working on sub-ppt (useful for next-generation detectors)





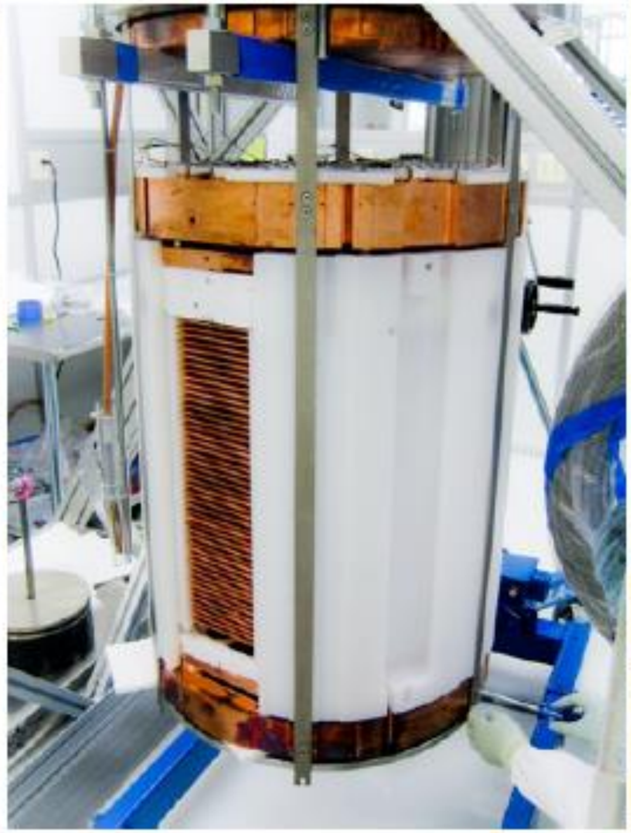
The LUX Program

LUX0.1 - CWRU



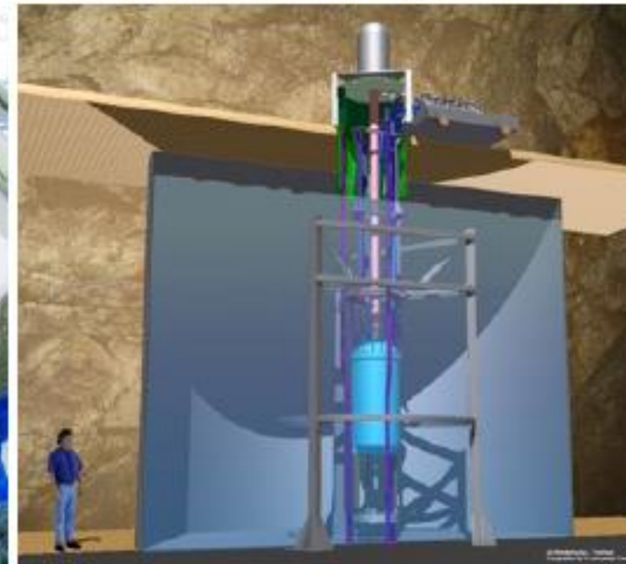
2007 – 2009

LUX - Surface



2010 – 2011

LUX - Underground



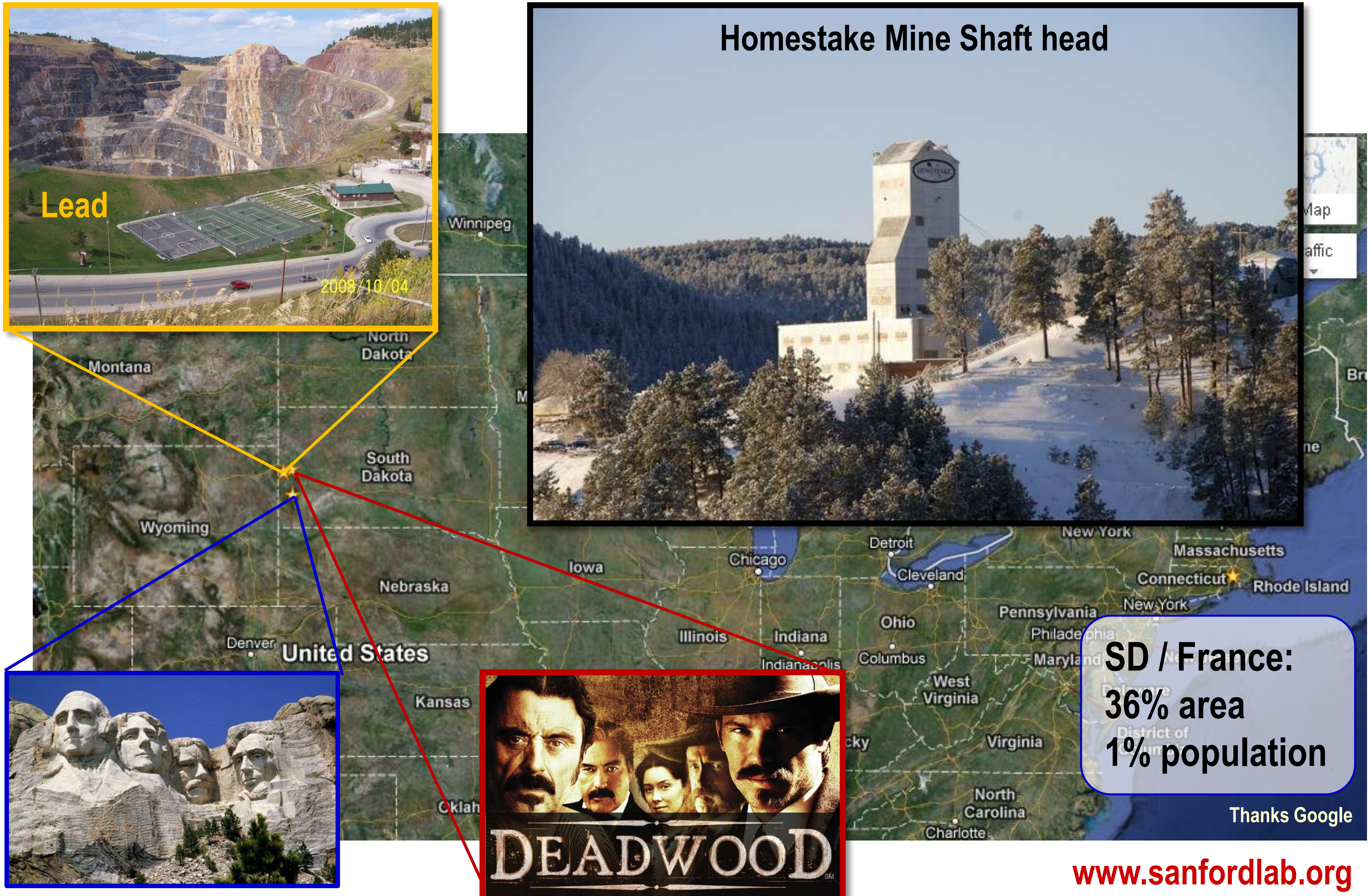
2012+

The Sanford Surface Laboratory, place of Wonders

Running before it jumps

The LUX Experiment: SURF-ace Operations

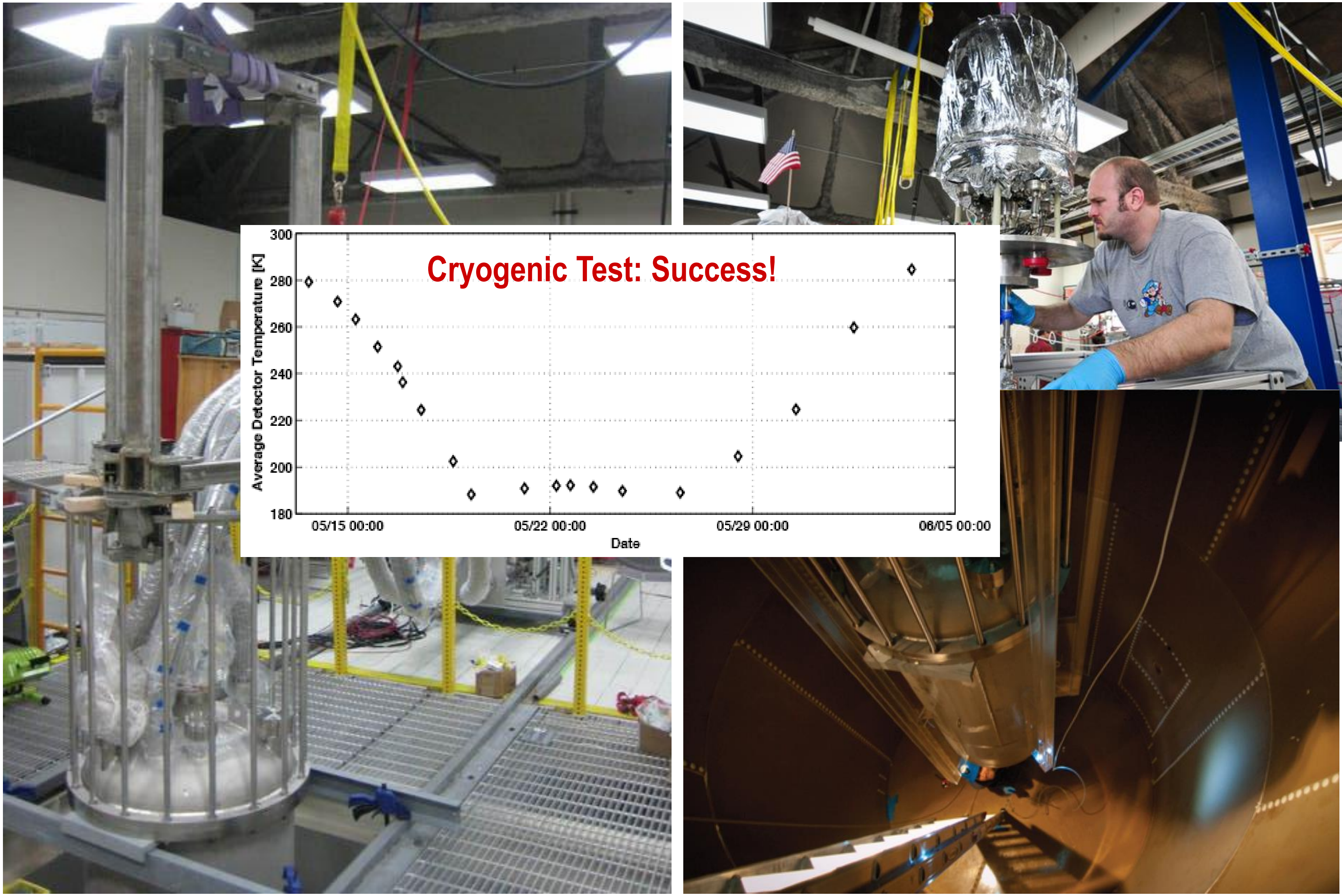
The Sanford Laboratory at Homestake



www.sanfordlab.org

Surface Lab – August 2010 to February 2011

Surface Lab – May 2011 : Run 1



LUX Run 2 Summary

- **List of major achievements already communicated to the World by February 2012**

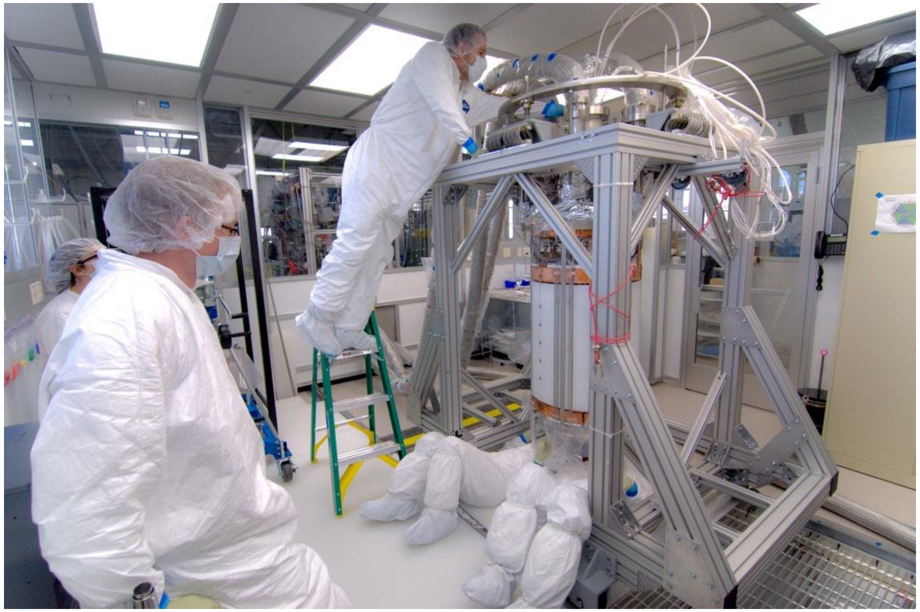
  - ✓ Deployed into water tank shield
  - ✓ Stable cryogenic control for ~100 days of running
  - ✓ Purification at 35 SLPM
  - ✓ Heat exchanger efficiency > 98%; < 5 W heat load at 300 kg/day
  - ✓ In-situ xenon purity analysis
  - ✓ Working PMTs, Trigger, DAQ
  - ✓ Excellent light collection (8 phe / keV in center)
  - ✓ Drift field to 120 V / cm (limited by electroluminescence on grid)
  - ✓ Recovered xenon to storage vessel by cryopumping

Paper: arXiv:1210.4569

- **To which one can add:** **Working slow-control and alarm system, working muon veto, emergency storage system in place, working calibration system (external and internal), reviewed and tested operating and assembly procedures, no (work related) injuries over 17 months and > 38,500 total work hours…**

- **Negative points:**
  - **Leak in condenser line limited purification capability (easily fixed)**
  - **One PMT base stopped working (out of 122; now fixed)**
  - **Used ~20-30 kg more Xenon to fill detector than anticipated (we have a lot to spare now)**
  - **Drift field limited by flaws on Cathode grid wires (now replaced and tested)**
  - **Did not find Dark Matter (neither did anyone else)**

Surface Lab – March to July 2012

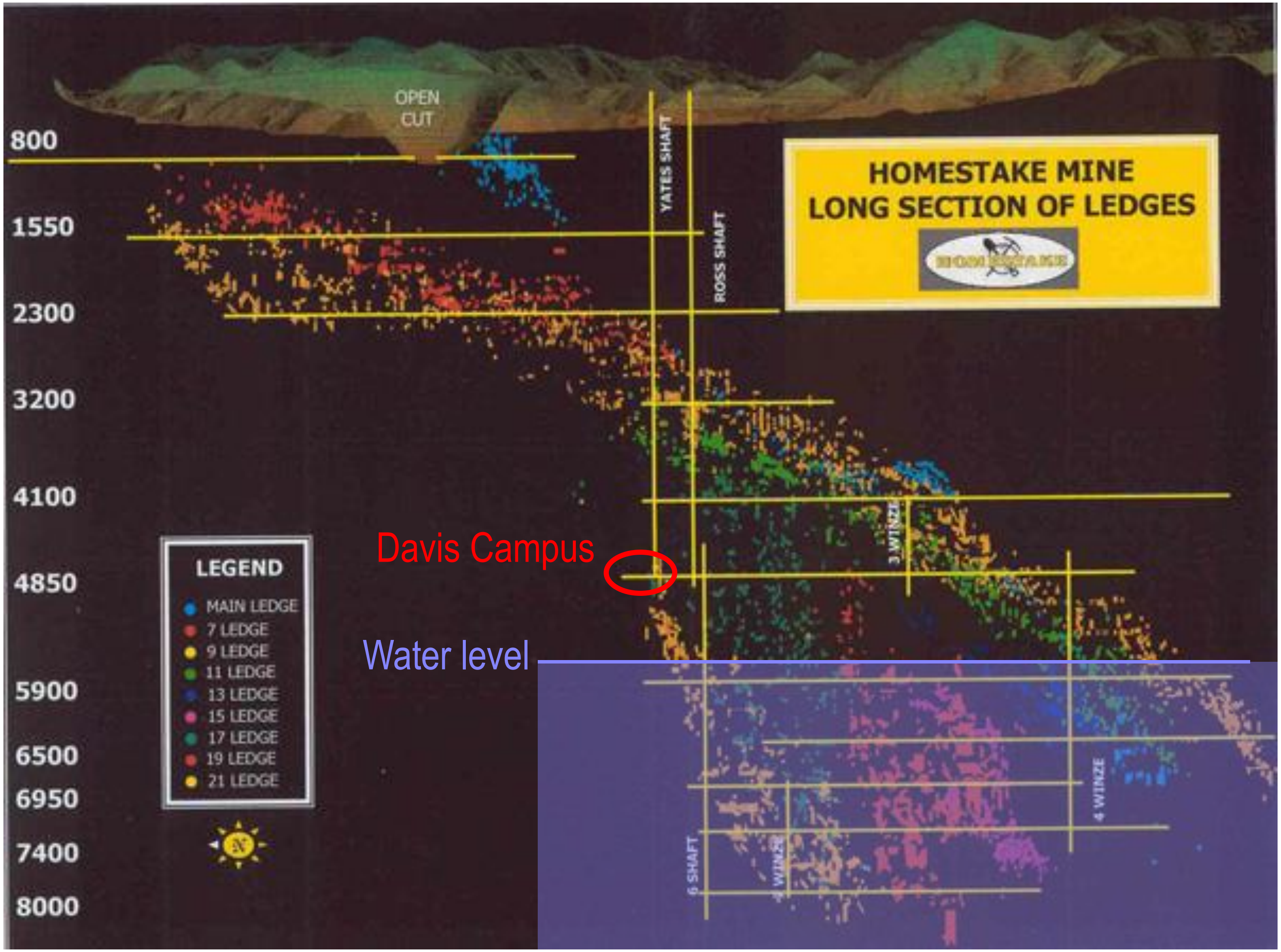


Access Tunnel to the Davis Underground Laboratory, Dec 2011

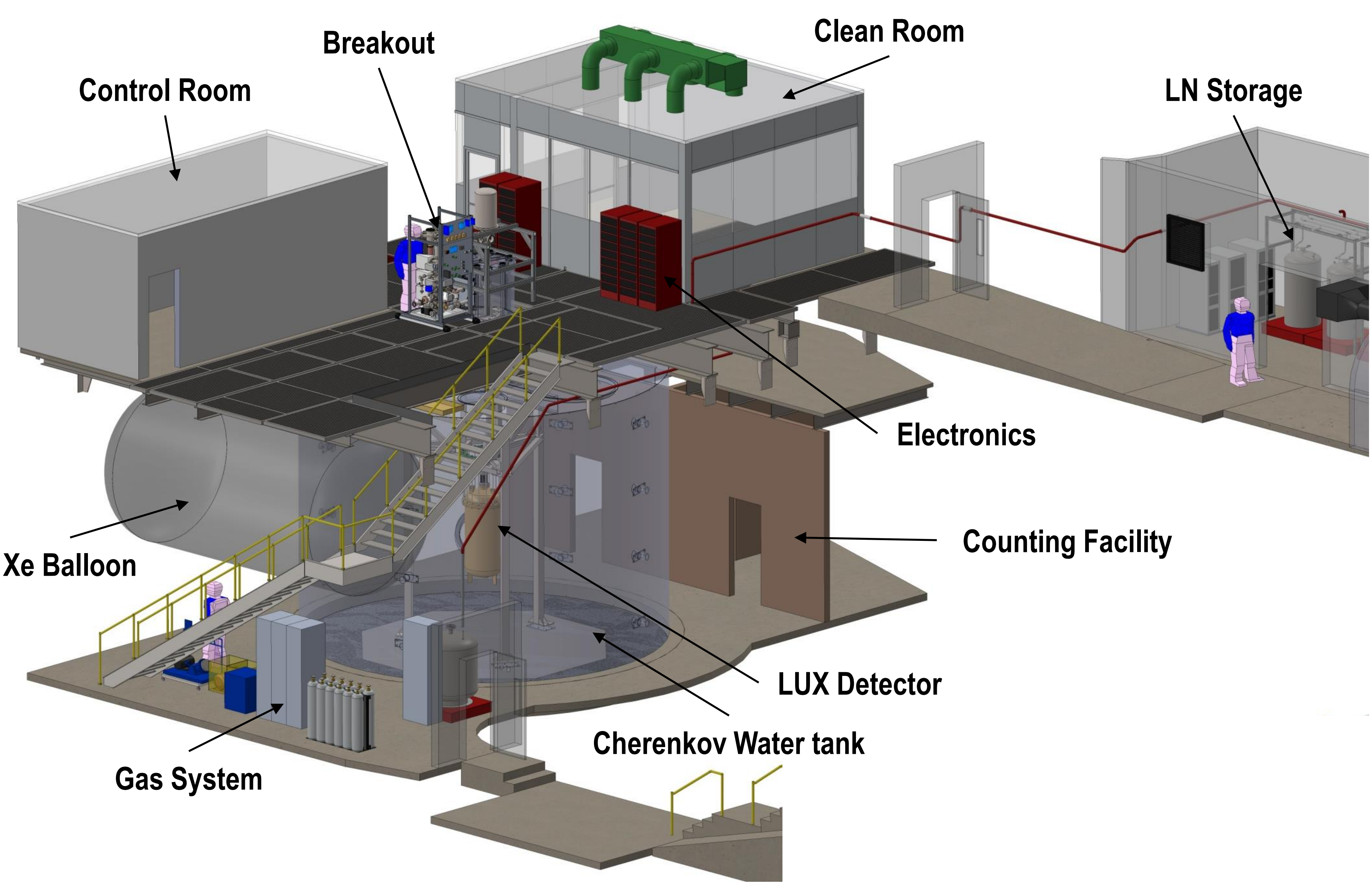
Boldly going where no detector has gone before

The LUX Experiment: Underground

Sanford Lab – Davis Laboratory



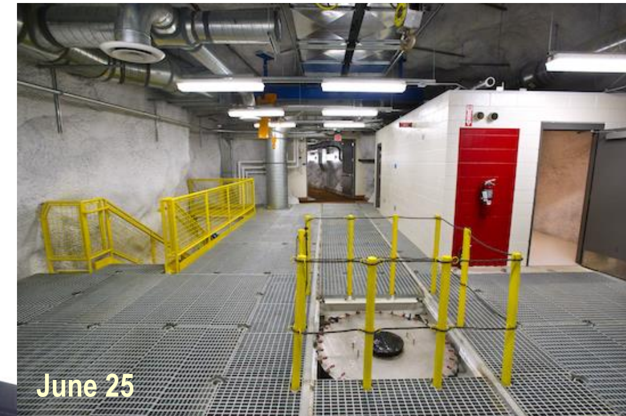
Sanford Lab – Davis Laboratory



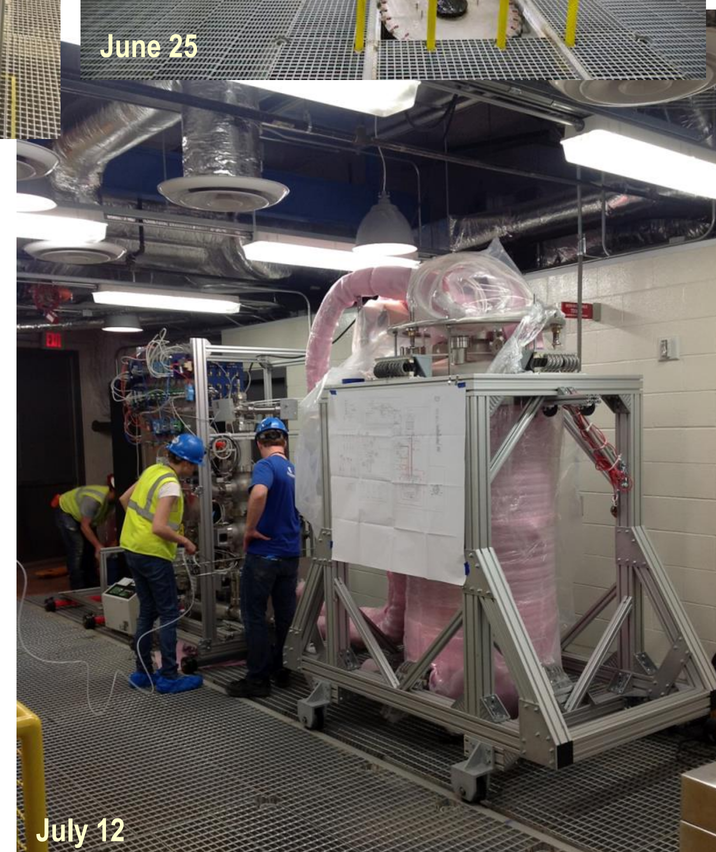
Davis Campus – Summer 2012


June 15


July 6


June 25


June 29


July 12

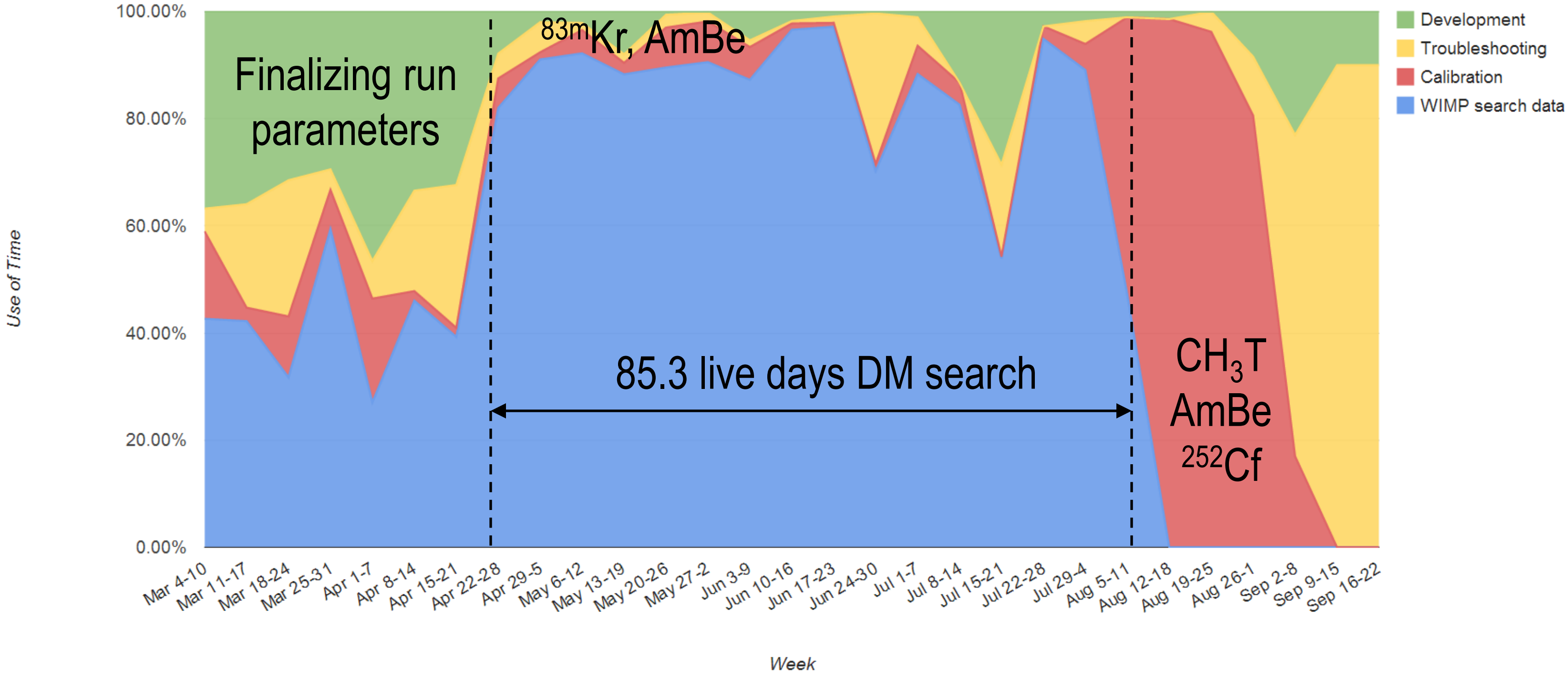

August 25

Davis Campus – September 2012

Now for the main event

LUX Run 3: Dark Matter Search

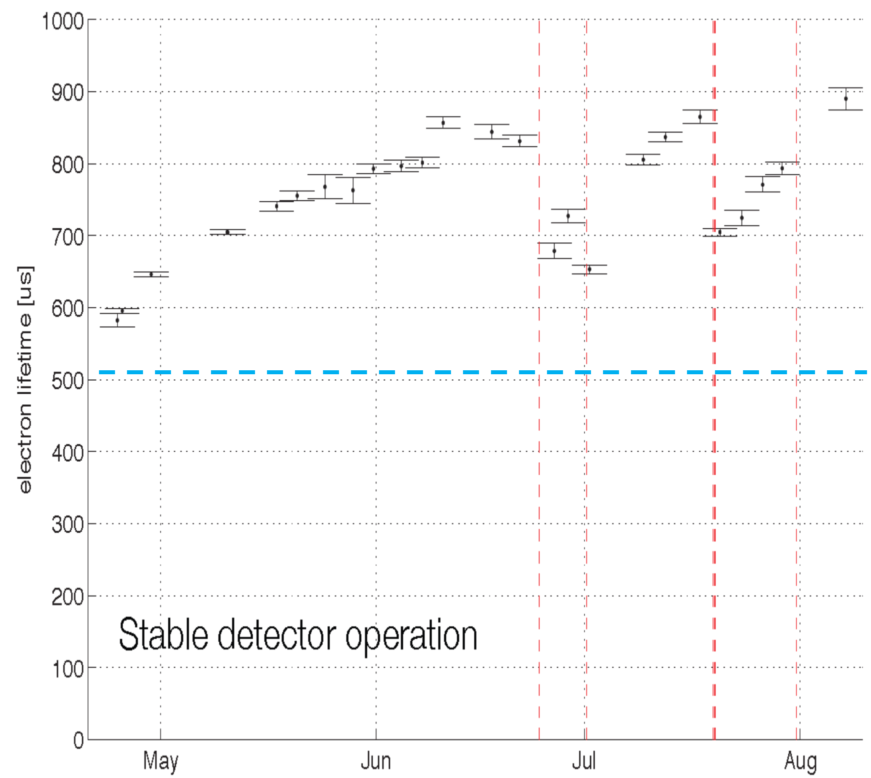
LUX Run 3: Some Statistics



- **Detector cool-down January 2013, Xe condensed mid-February 2013**
- **95% Data taking efficiency during WIMP search period (minus storms)**
- **Waited until after WS data before precision CH_3T calibration**

Run Parameters Overview

- **Xenon Purity: electron drift length 87 – 135 cm during Run 3**
  - Circulation at 250 kg / day
  - Monitored weekly using ^{83m}Kr data
- **Light collection efficiency: 14%**
  - Incl. geometry and PMT QE
  - ^{83m}Kr data provides 3D corrections
- **Drift field: 181 V/cm**
  - Drift speed 1.51 ± 0.01 mm / μs
  - ER discrimination 99.6%
- **Electron extraction efficiency: 65%**

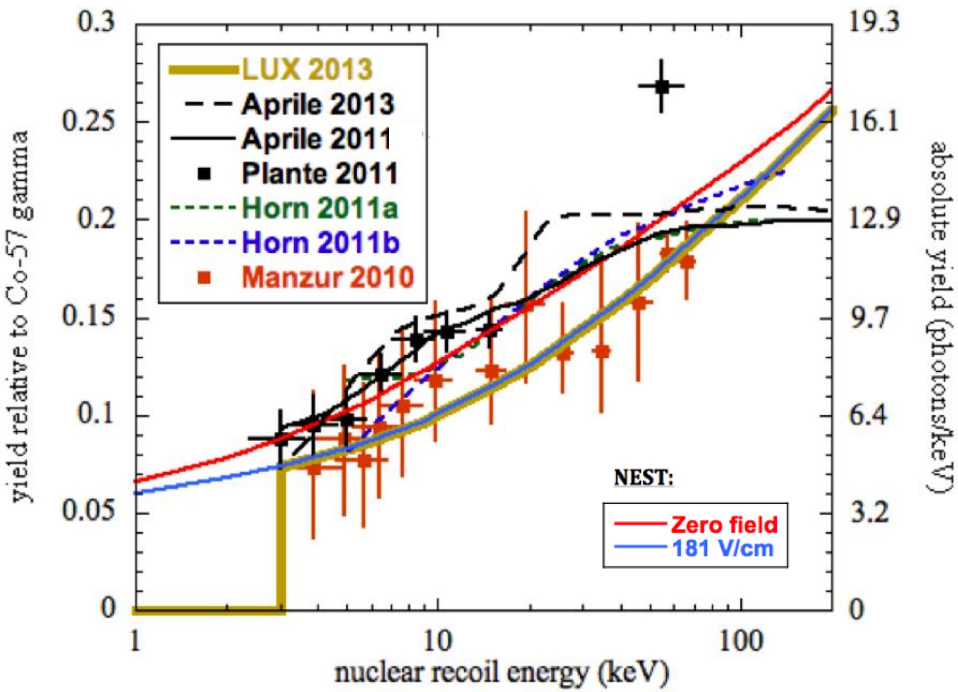


- **Fiducial mass: 118.3 ± 6.5 kg**
  - Defined by edges α background
  - Measured with homogeneous ER calibration data… ^{83m}Kr, again!

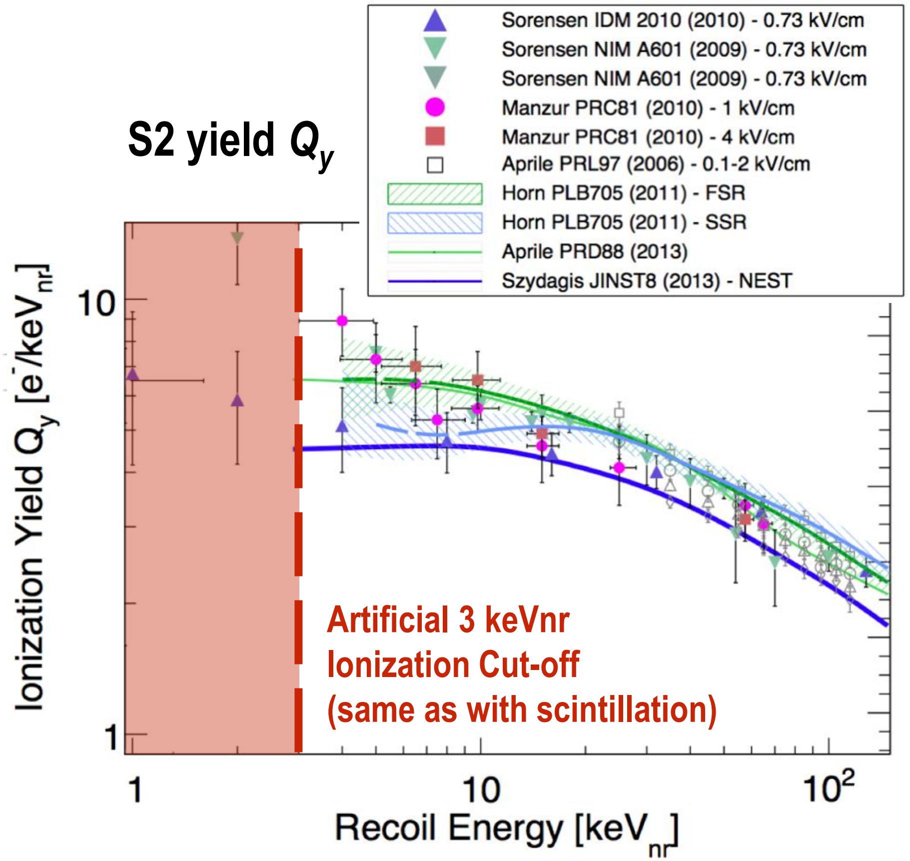
Light and Charge Yields

- Modeled Using Noble Element Simulation Technique (NEST) - arxiv:1106.1613
- NEST based on canon of existing experimental data.
- **Artificial cutoff** in light and charge yields assumed **below 3 keVnr**, to be conservative.
- Includes predicted electric field quenching of light signal, to 77-82% of the zero field light yield

S1 Light yield L_{eff}

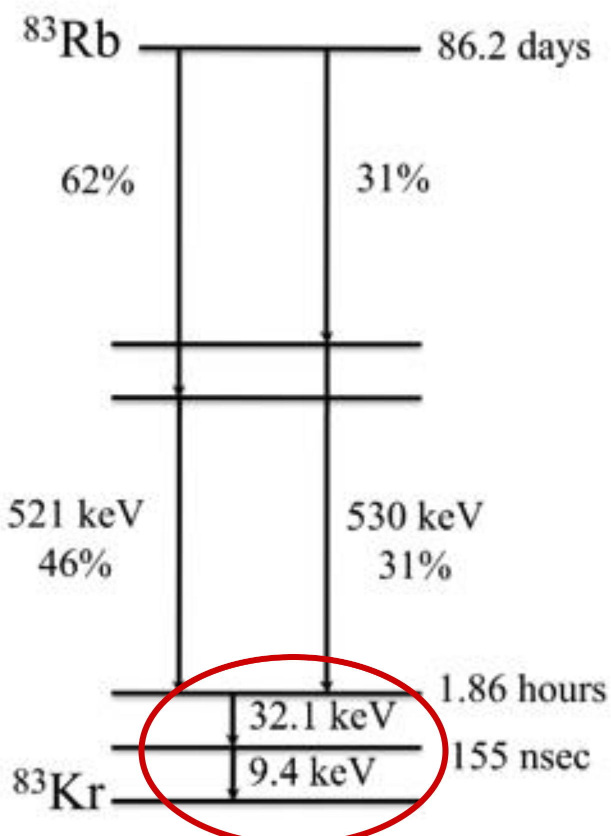


S2 yield Q_y



LUX Calibrations – ^{83m}Kr

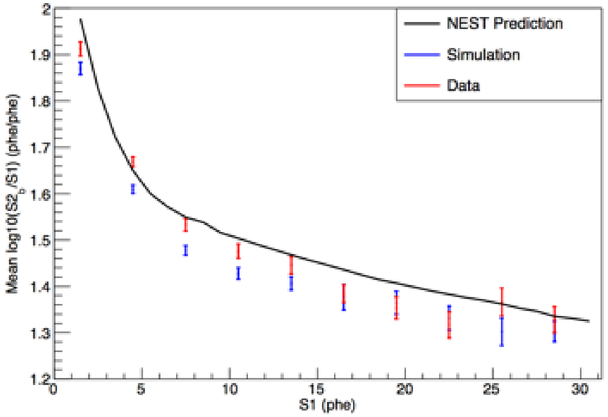
- ^{83}Rb produces ^{83m}Kr when it decays; this krypton gas can then be flushed into the LUX gas system to calibrate the detector as a function of position.
- Provides reliable, efficient, homogeneous calibration of both S1 and S2 signals, which then decays away in a few hours, restoring low-background operation.

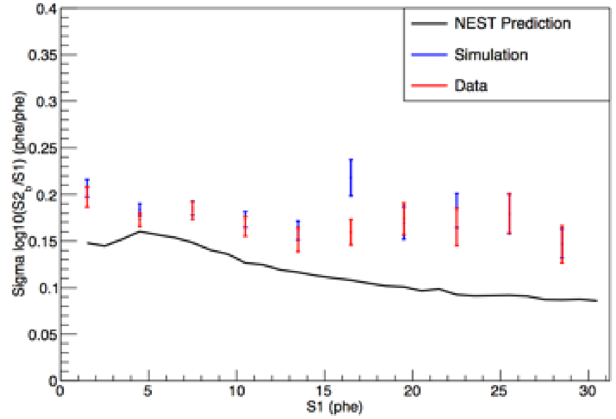


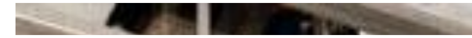
- **Bonus: tomography of Xe flow**

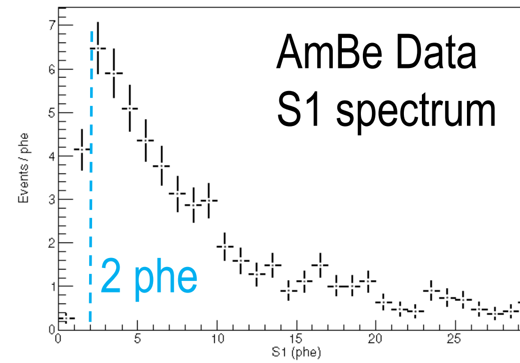
^{83m}Kr source (^{83}Rb infused into zeolite, within xenon gas plumbing)

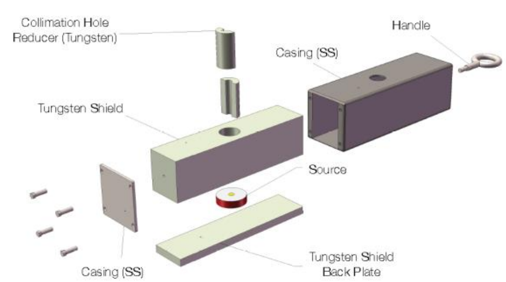
LUX Calibrations – AmBe and ^{252}Cf







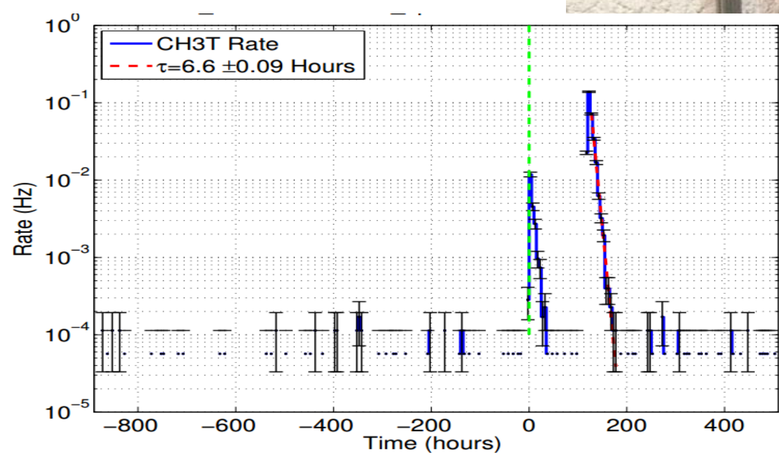




- **Above plots show comparisons between simulation (blue), the NEST prediction (black), and data for the mean and width of the nuclear recoil band from AmBe calibrations**
- **The mean and width are different in the calibrations because the data contain ER contamination and neutron-X events, which are modeled well by the simulation**

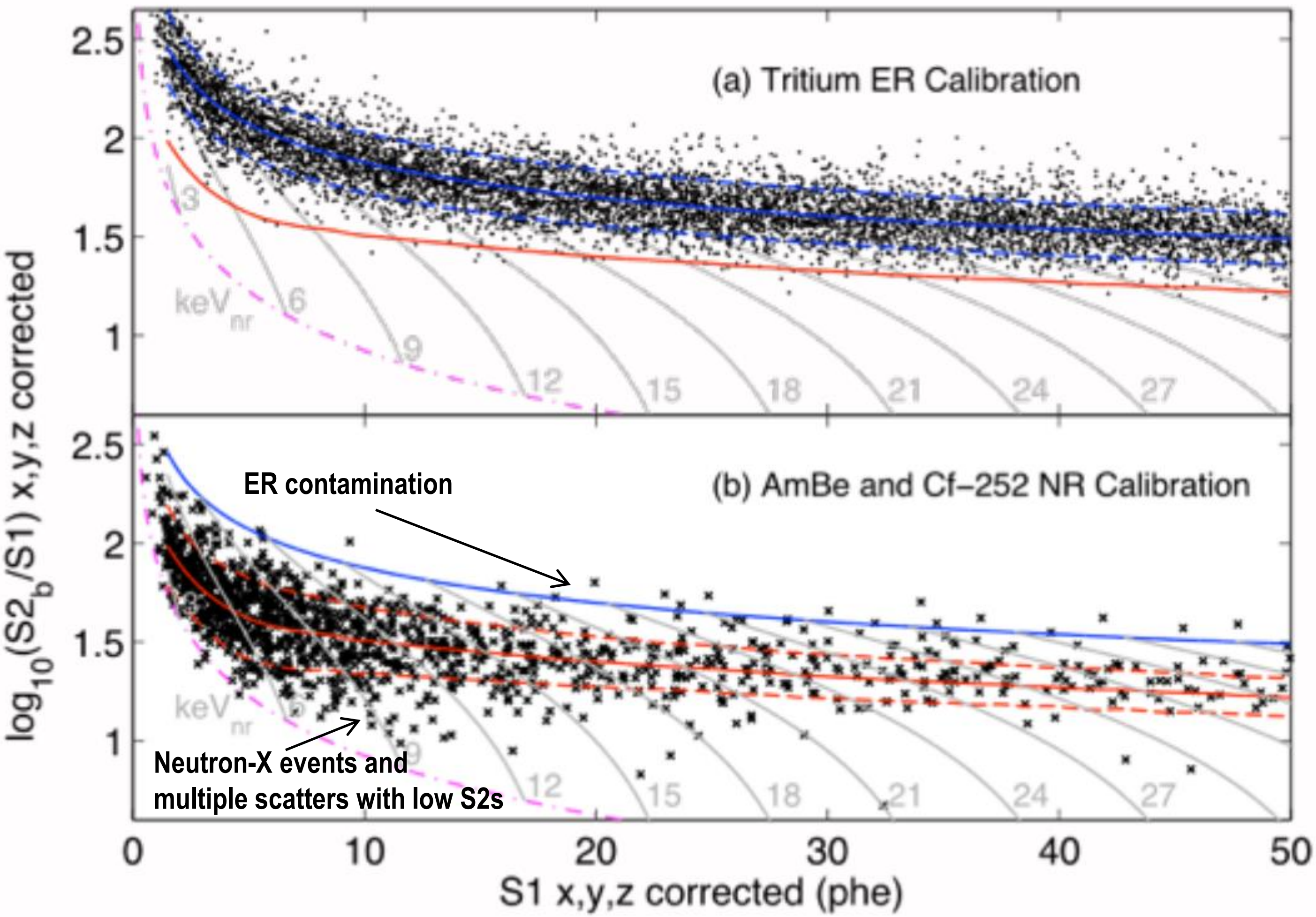
LUX Calibrations – CH_3T

- **LUX uses tritiated methane, doped into the detector, to accurately calibrate the efficiency of background rejection.**
- **This beta source (endpoint energy 18 keV) allows electron recoil S2/S1 band calibration with unprecedented accuracy**
- **The tritiated methane is then fully removed by circulating the xenon through the getter**
- **This was tested first with natural methane injection, and monitored with our in-line xenon sampling system**
- **Dedicated paper coming**



ER and NR Calibration Data

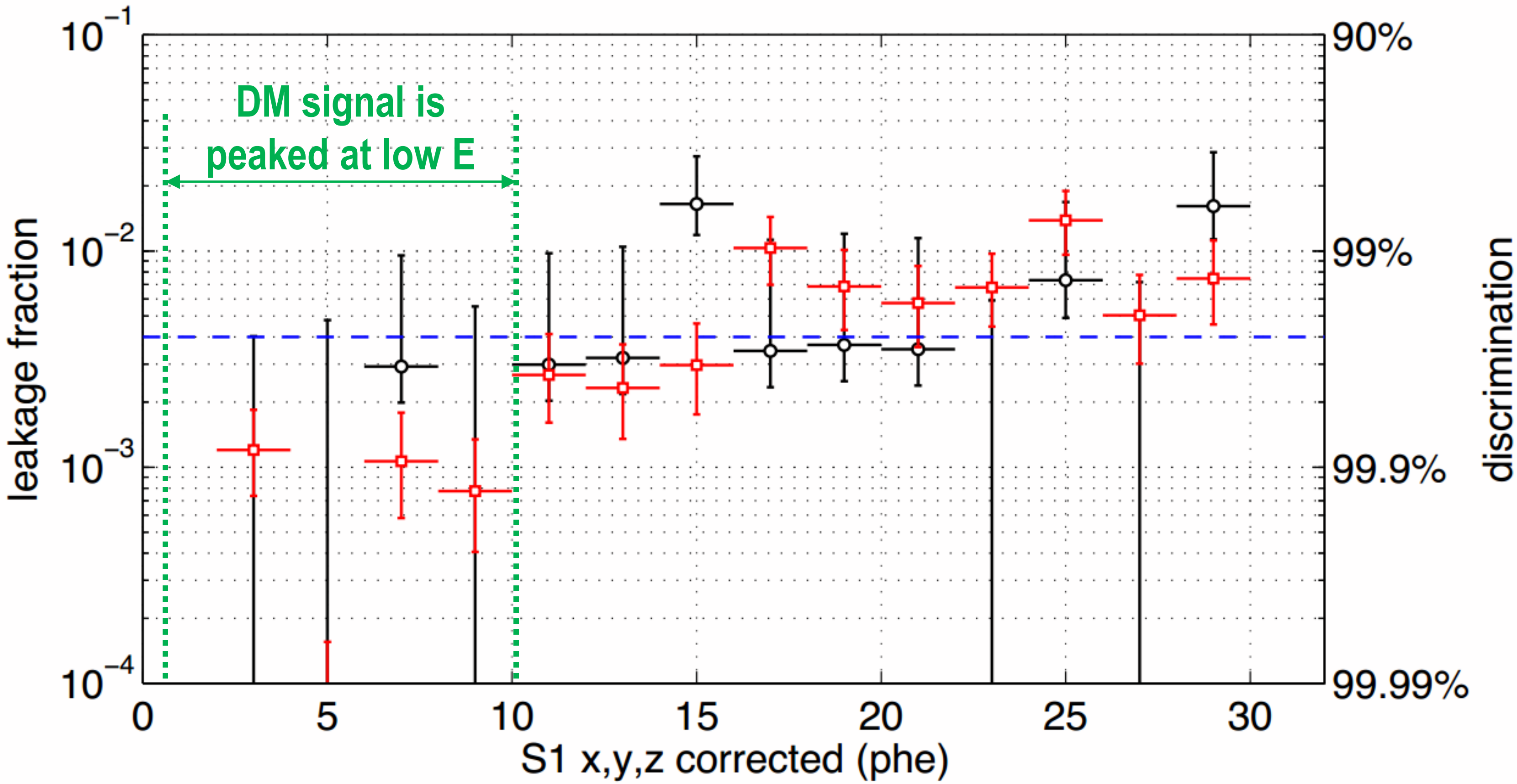
Tritium provides very high statistics electron recoil calibration (200 events/phe)
Neutron calibration is consistent with NEST + simulations



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

ER Discrimination

Average discrimination from 2-30 S1 photoelectrons measured to be 99.6% (with 50% nuclear recoil acceptance)

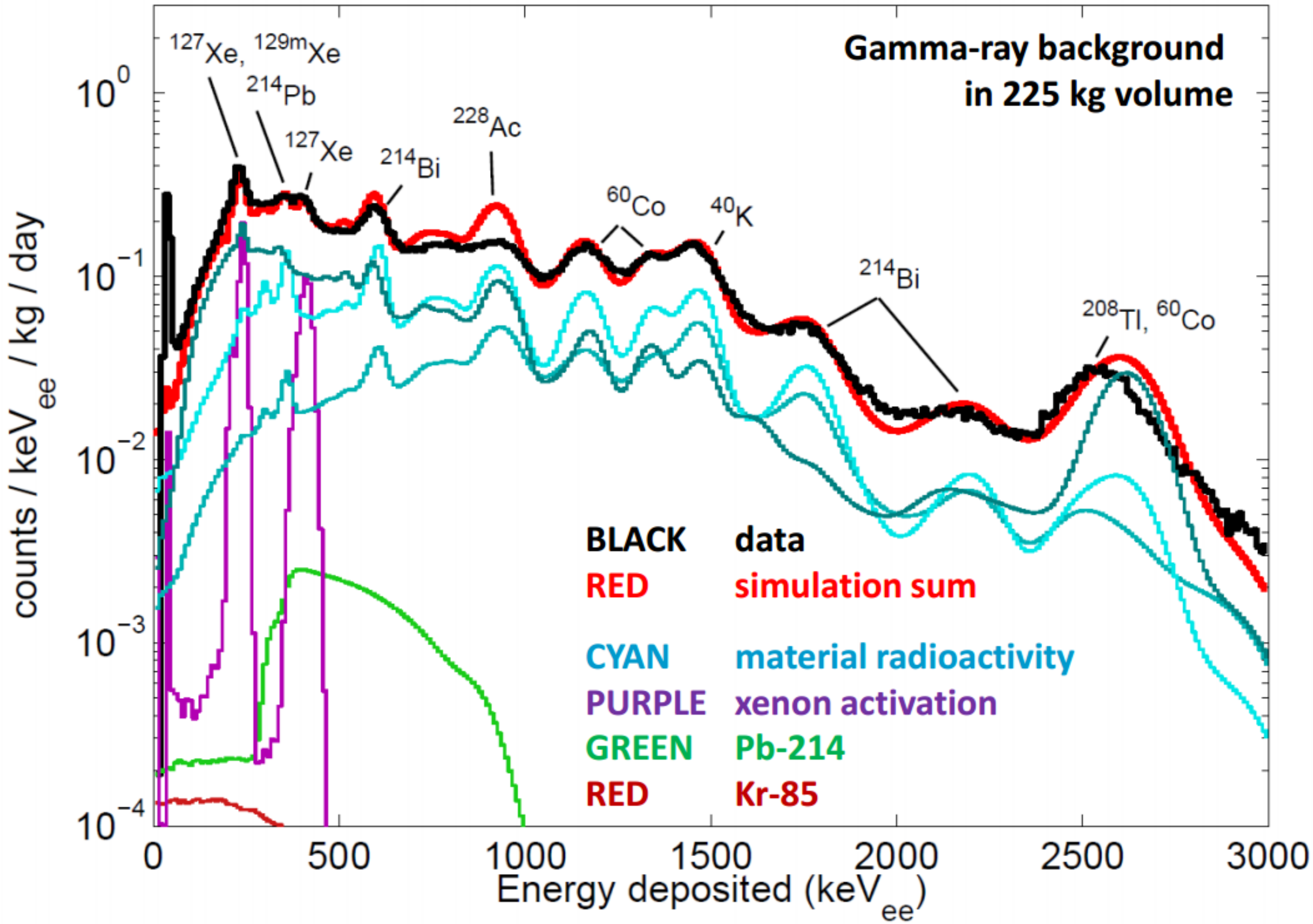


Black circles show leakage from counting events from the dataset

Red circles show projections of Gaussian fits below the nuclear recoil band mean

LUX Run 3 – Background Levels

- Full gamma spectrum, excluding region ±2 cm from top/bottom grids



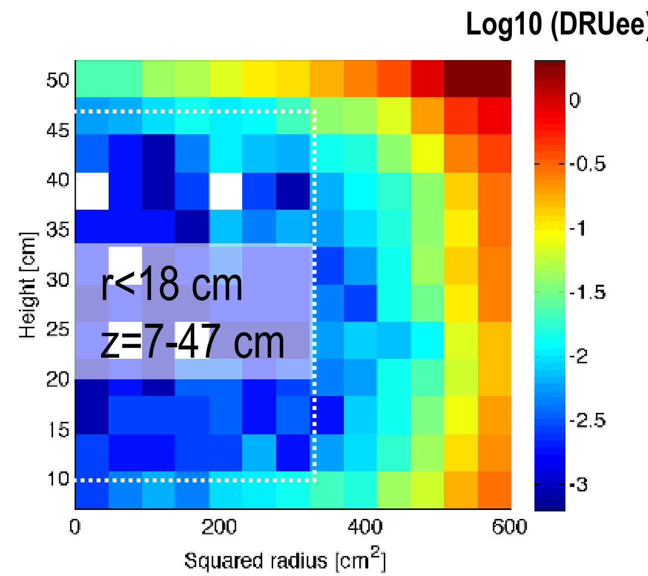
LUX Run 3 – Background Levels

Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-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 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	^{222}Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{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	$3.1 \pm 0.2_{stat}$

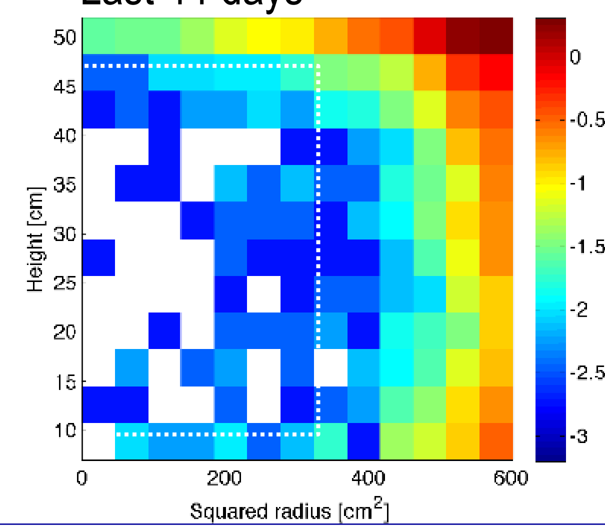
- **Neutron background negligible (exp 0.06 evt)**
- **Dedicated publication is now available:**

arXiv:1403.1299

ER < 5 keVee in 118 kg



Last 44 days

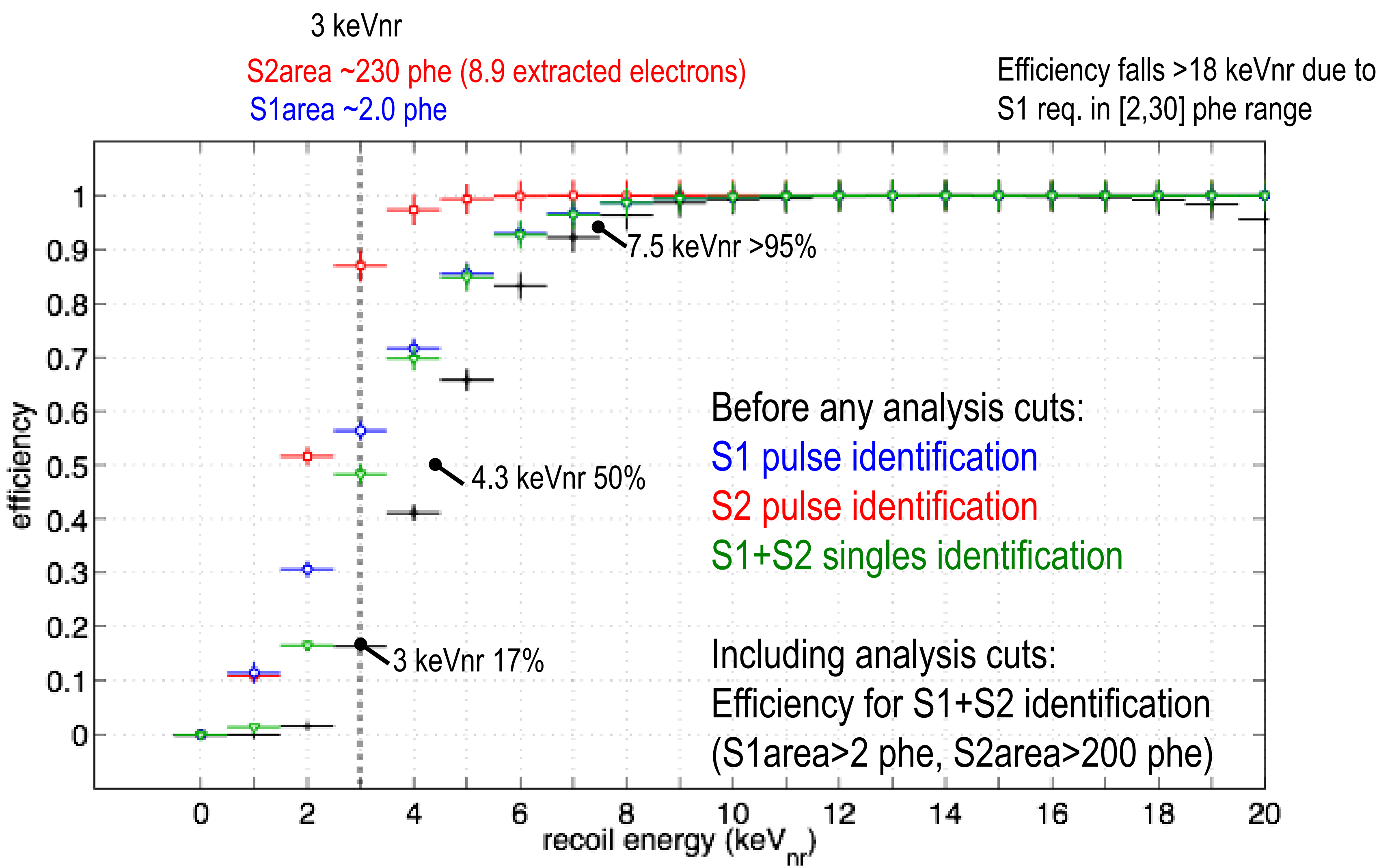


LUX Run 3 – Data Selection

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 (R,Z)t cut	Radius < 18 cm, 38 < drift time < 305 us, 118 kg fiducial	160

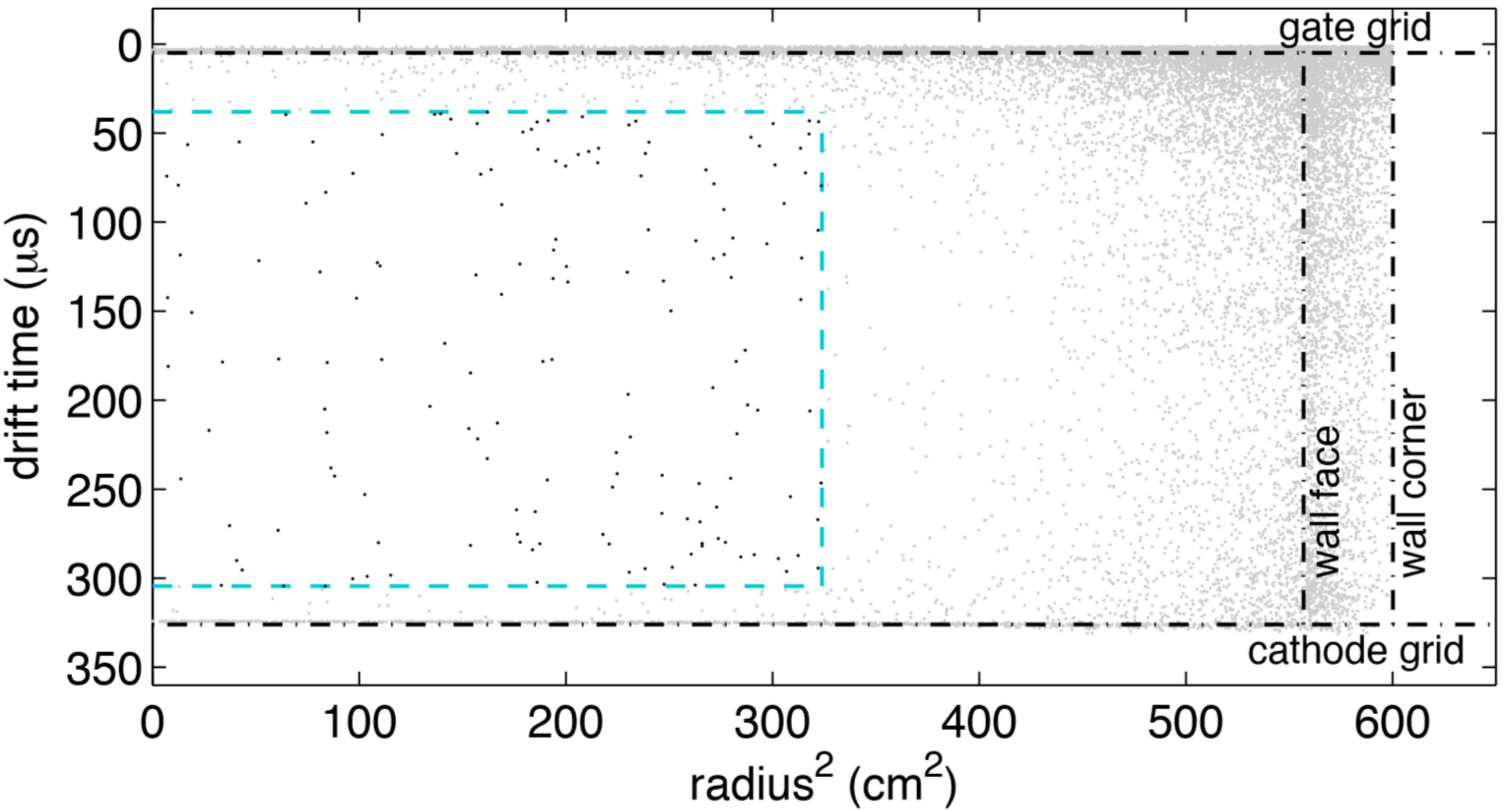
- **Simple, obvious cuts**
- **No “tuning” beyond selecting a threshold, higher energy cutoff, fiducial volume**
- **PLR analysis not so sensitive to how may events are “in the box”**

LUX Run 3 – NR Detection Efficiency

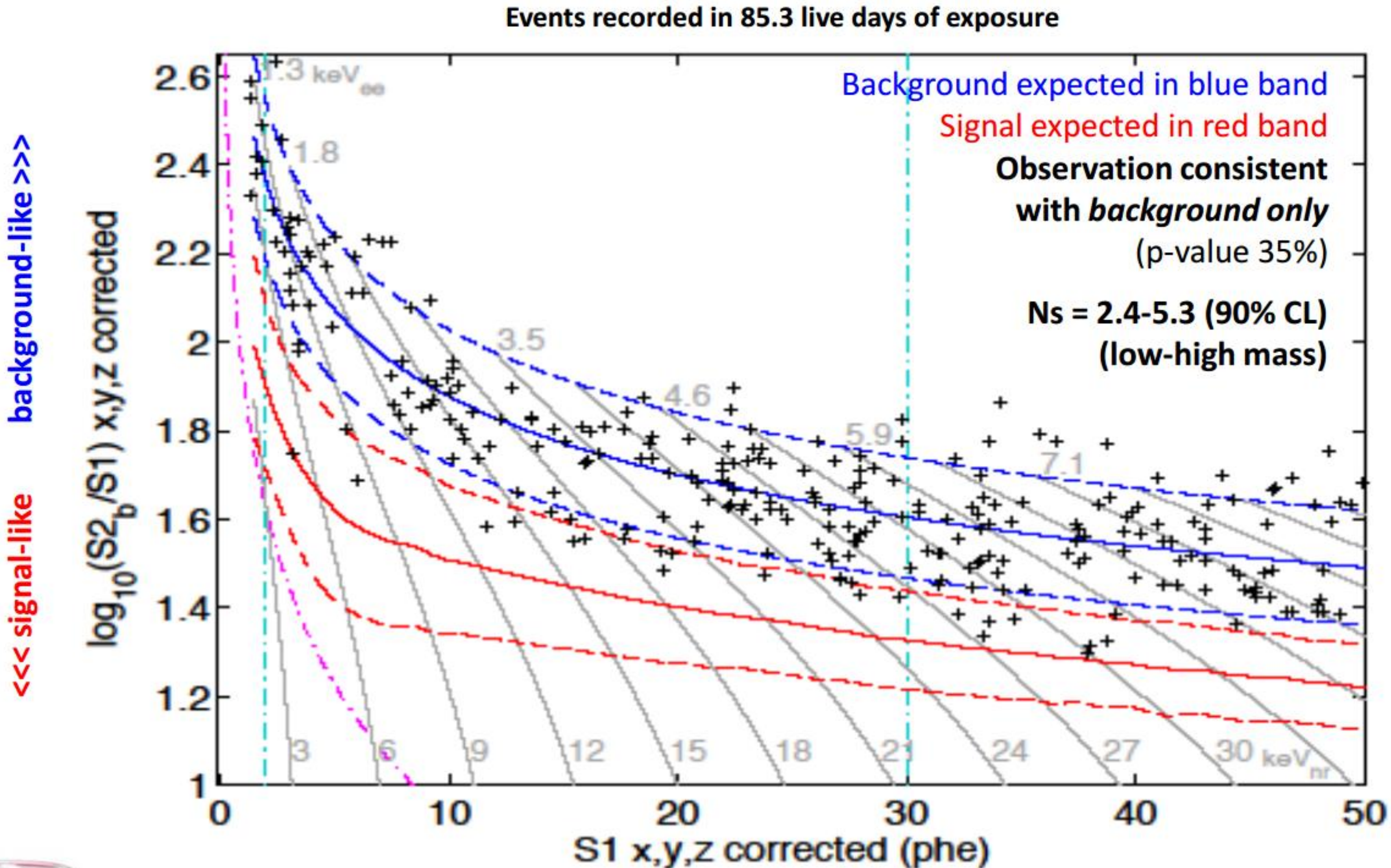


True Recoil Energy equivalence based on LUX 2013 Neutron Calibration/NEST Model

LUX WIMP Search, 85.3 live-days, 118 kg



LUX WIMP Search, 85.3 live-days, 118 kg



The Economist

"Absence of evidence, or evidence of absence?"

New York Times

"Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly"

Profile Likelihood Ratio (PLR) Analysis

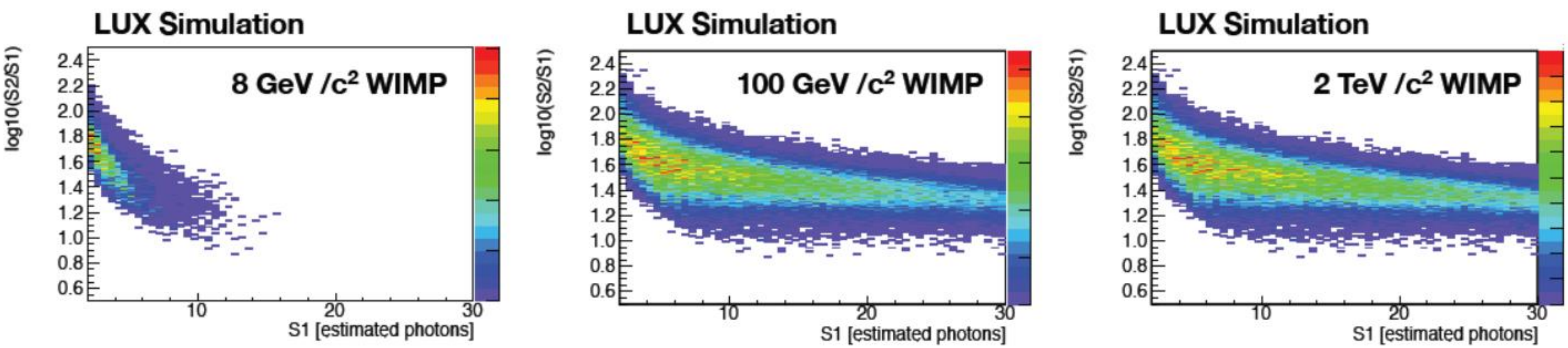
$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} \Big(N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}}) + N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}}) + N_{Rn} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Rn}}) \Big)$$

Observables: **x** = (S1, $\log_{10}$(S2/S1), r, z)

Parameter of interest: N_s

Nuisance parameters: N_{Compt}, N_{Xe-127}, $N_{Rn,Kr-85}$

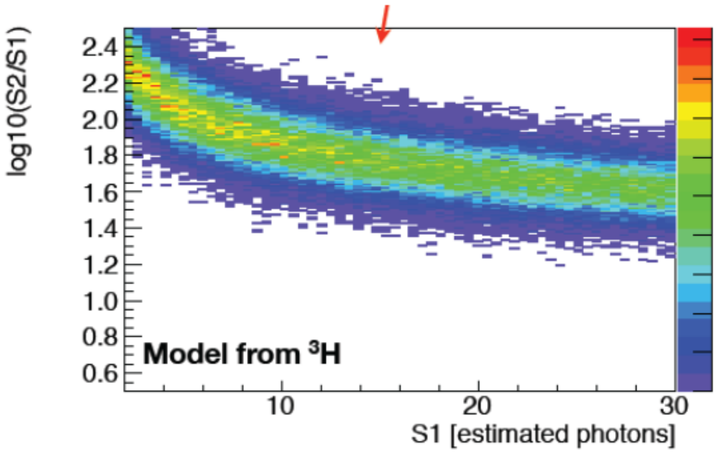
SIGNAL MODEL: simulated 2D PDFs including resolution/efficiencies; uniform in (r^2,z)

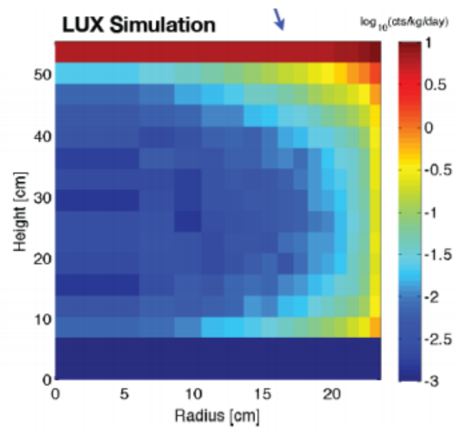


PLR: Nuisance Parameters Distributions

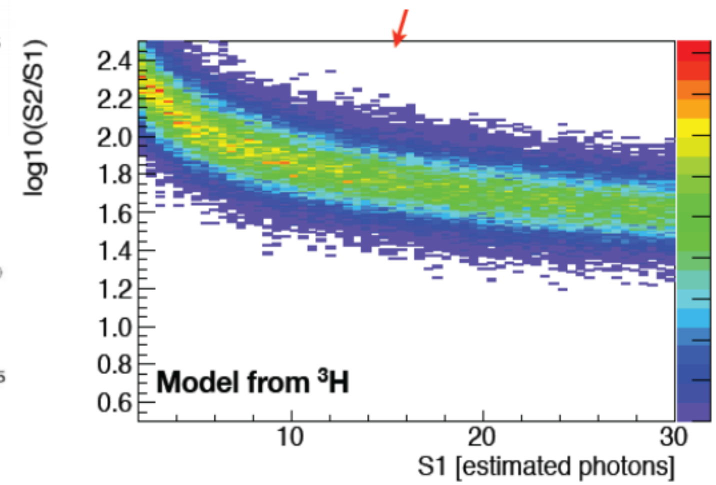
BACKGROUND MODELS: simulated 2D PDFs including resolution/efficiencies

External radioactivity (Compton-scattered gammas)

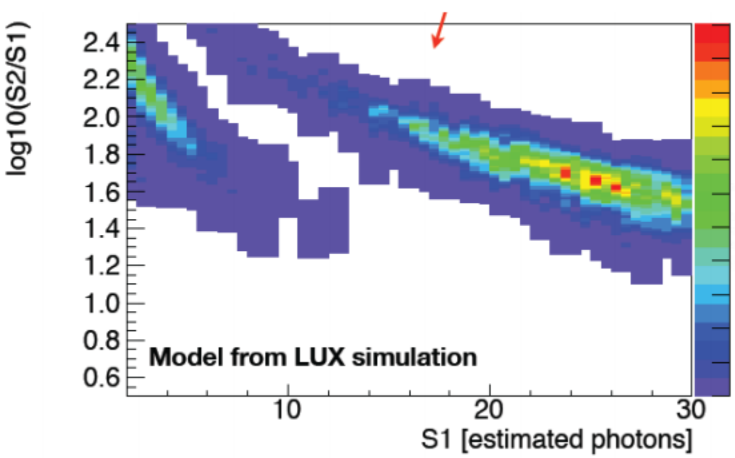


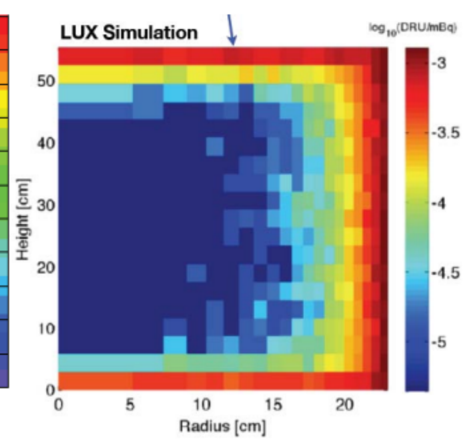


Pb-214/Kr-85
Uniform in Eee and space



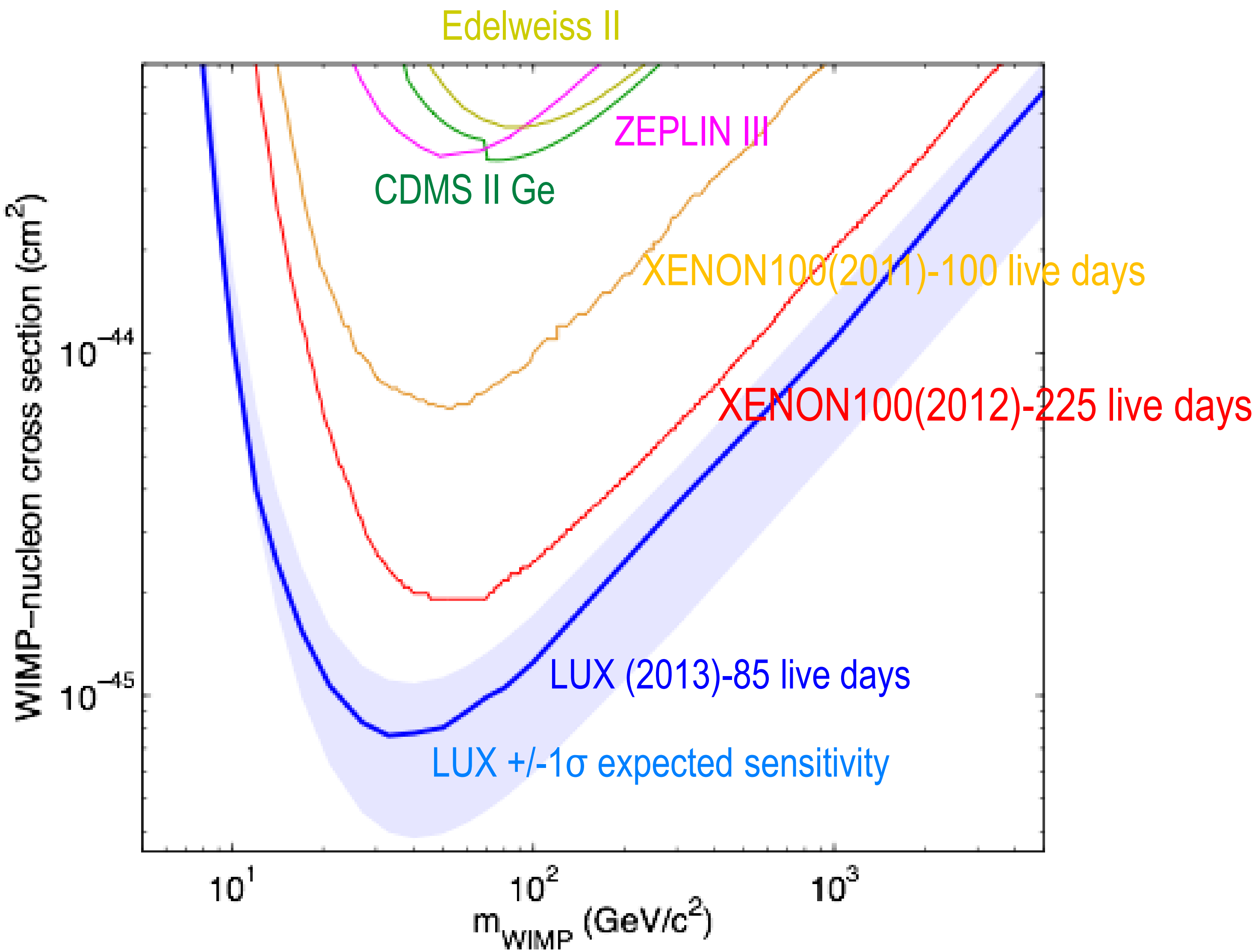
Xe-127 atomic cascade with HE gamma escape





LUX Run 3 – Spin Independent Sensitivity

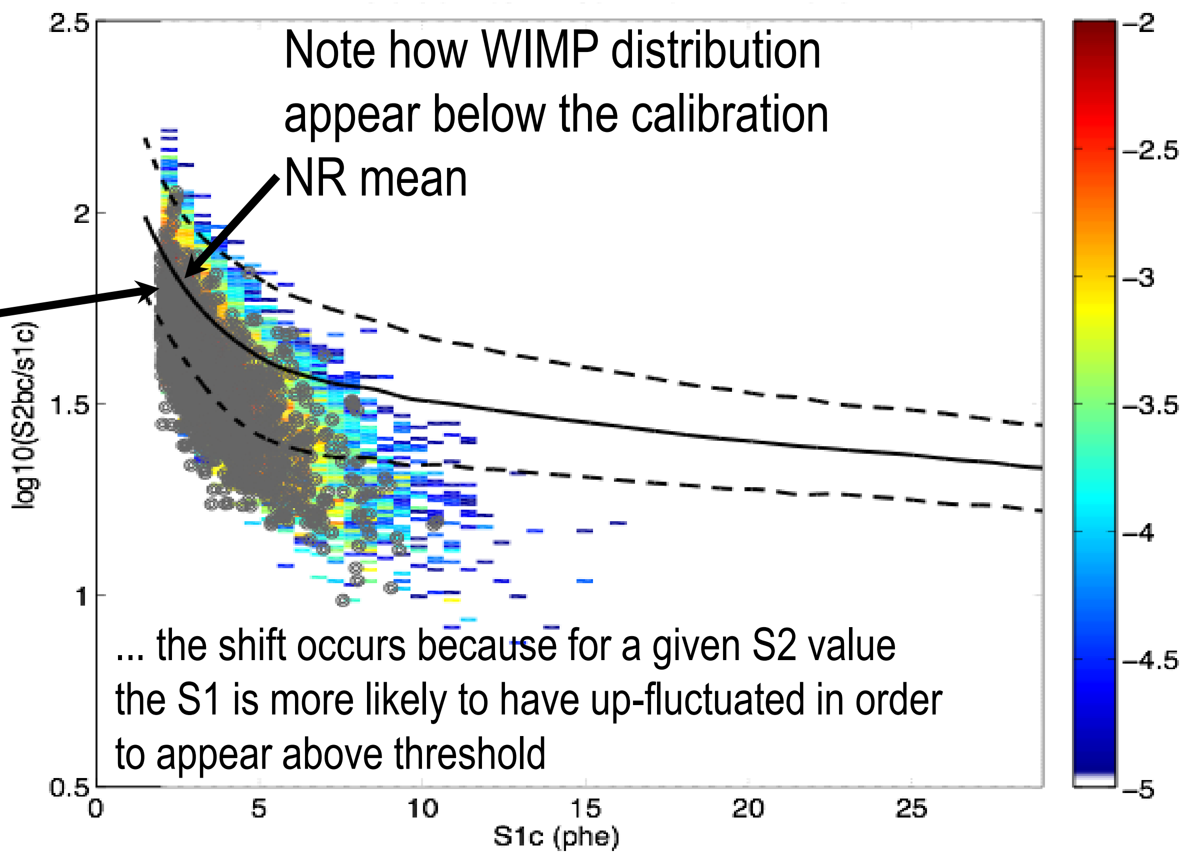
- Deviation of 1σ in detection efficiency shifts the limit by 5%



So how about those light WIMPs?

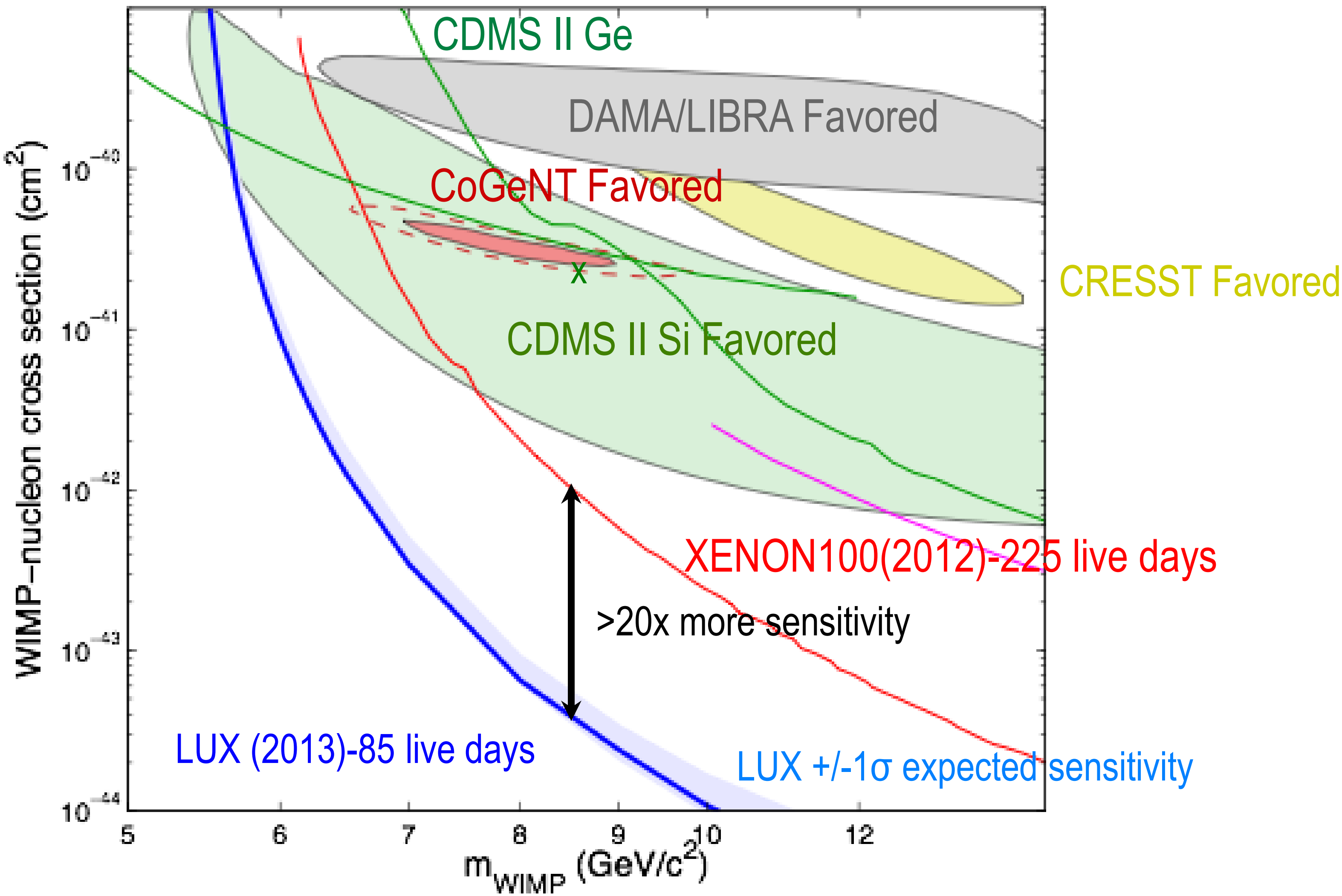
- At a mass of 8.6 GeV and cross section favored by CDMS II Si (2012) $\sigma = 2.0\ 10^{-41}\ cm^2$ – Expect ~1500 WIMPs in LUX Run 3

Conservatively assume no signal generated for recoils < 3 keVnr to reflect lowest energy for which NR calibration is available.



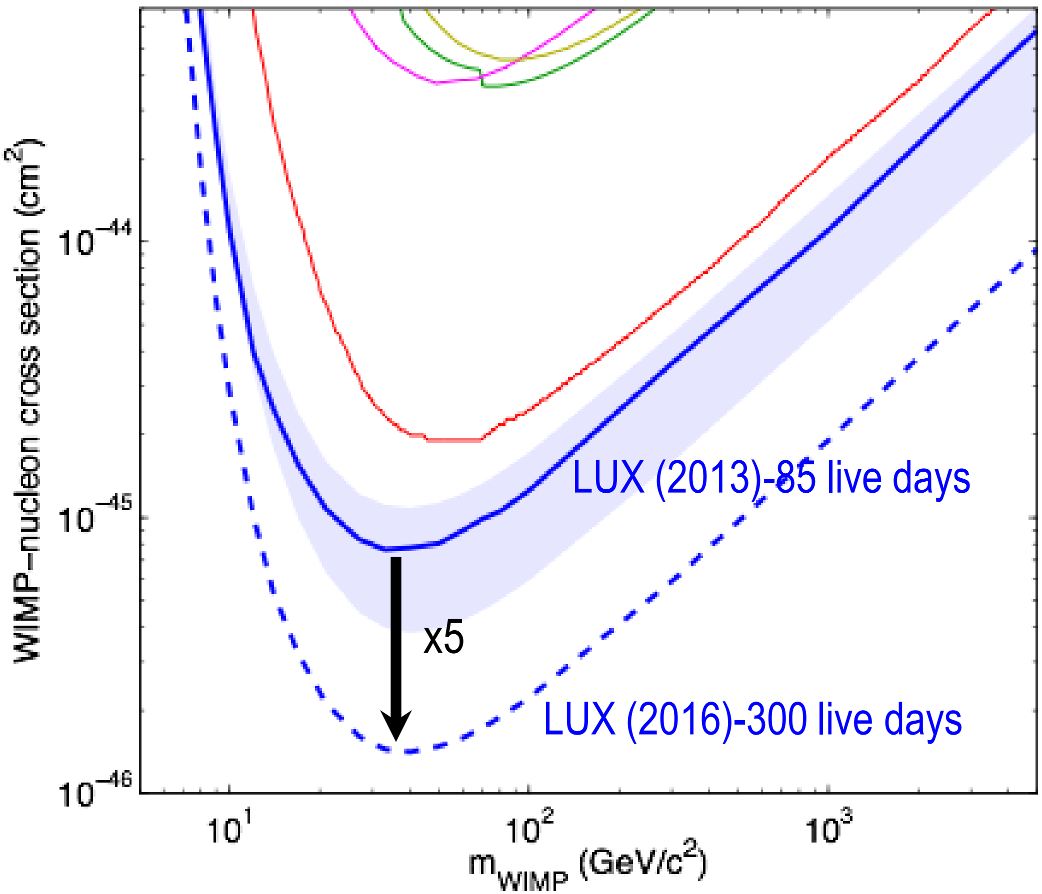
- The shift in the WIMP PDF downwards improves the effective ER event leakage fraction

LUX Run 3 – Low Mass WIMPs Sensitivity



Projected LUX 300 day WIMP Search Run

- Wrap up post-Run3 items until Summer 2014
  - Increased calibration stats
  - Measure NR response
  - Looking at improving E-fields
- We intend to run LUX for a new run of 300 days in 2014/15
  - Extending sensitivity by another factor ~5
  - Discovery still possible
- LZ 20x increase in target mass
  - If approved, plans to be deployed in Davis Lab in 2016+



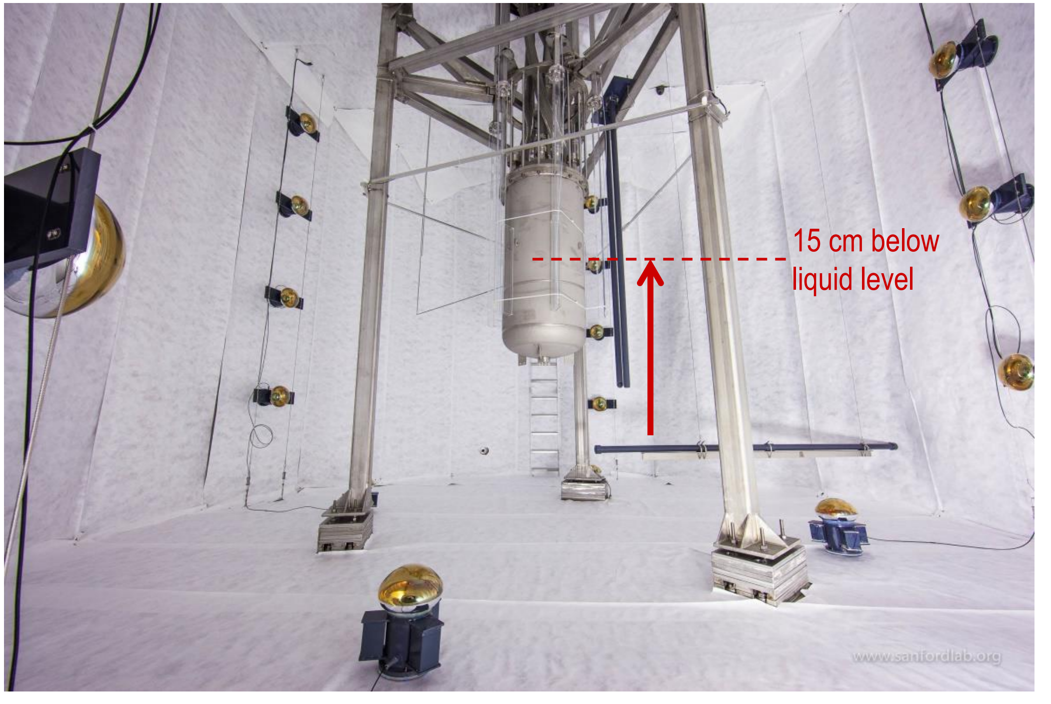
Life after Run 3 (and before Run 4)

Since then, what?

Precision NR Response Calibration for LXe

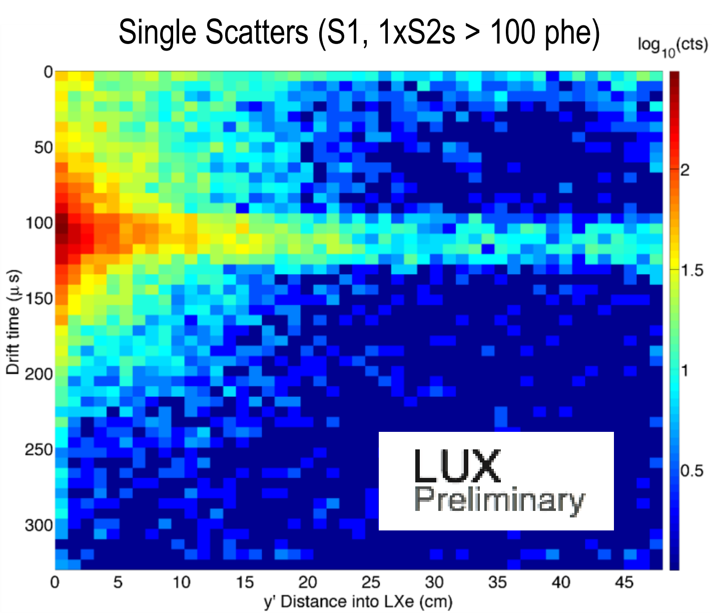
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

- Use a mono-energetic source of neutrons at 2.45 MeV
- Collimate them with a 3 m tube of air through water
- Identify double scatters along beam line inside LUX. Angle gives deposited energy.
  - → Absolute calibration of ionization response
- Apply ionization scale found above to single scatters
  - → Absolute calibration of scintillation response

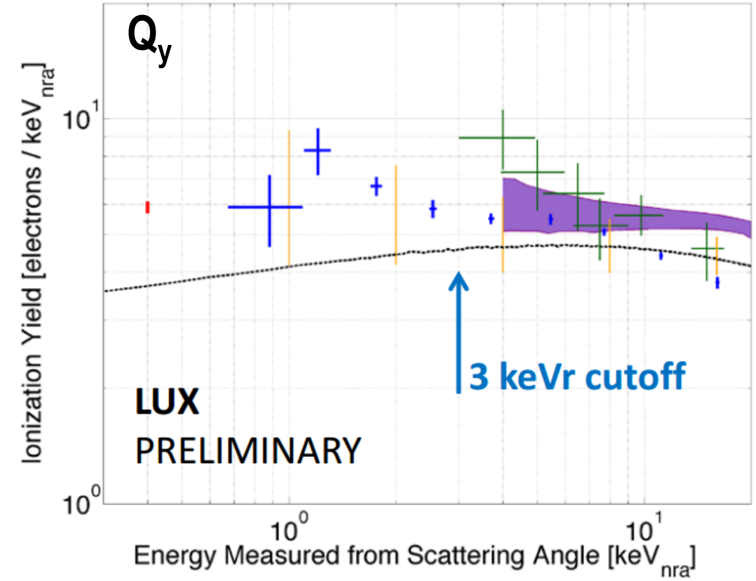


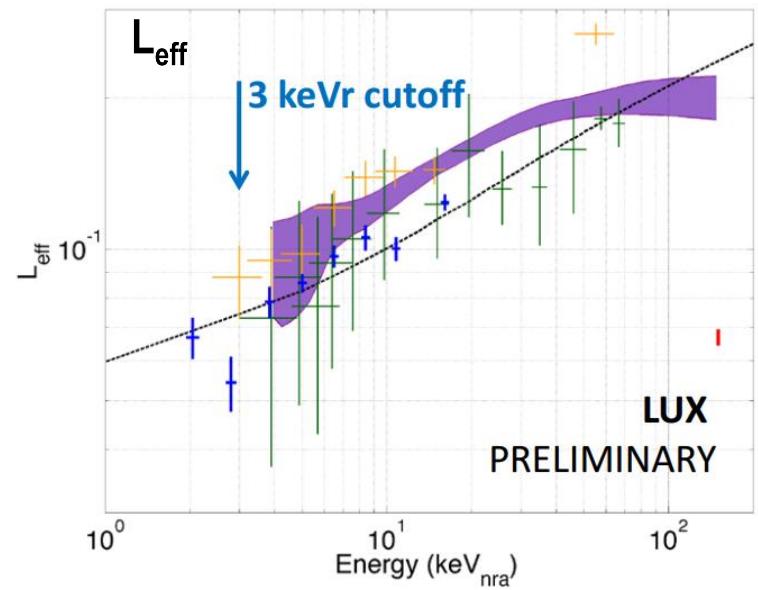
DD Neutron Generator – Result (preliminary!)

- 105 live hours of beam time accumulated
- Analysis still ongoing
  - Improve MC stats and accuracy
  - Push energy threshold down
  - Refine understanding of systematics
- Dedicated publication will be forthcoming
- Direct implications for sensitivity of Run 3!



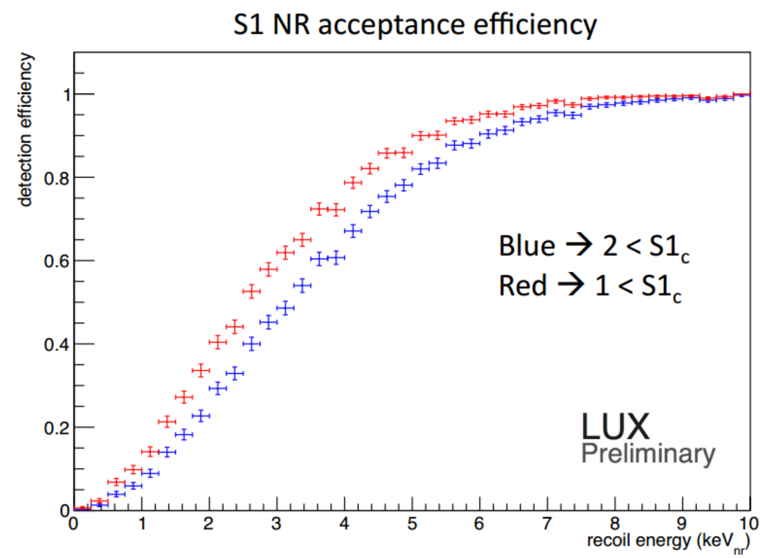
Compare to slide 26

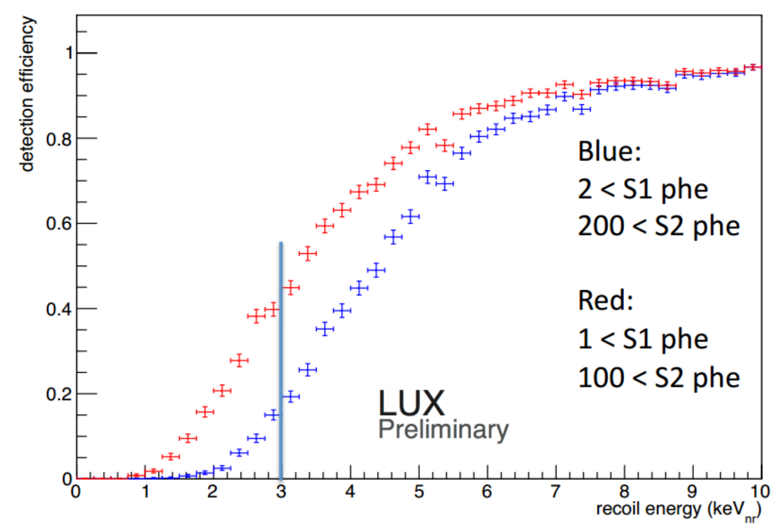




Further Exploring very-low Energies

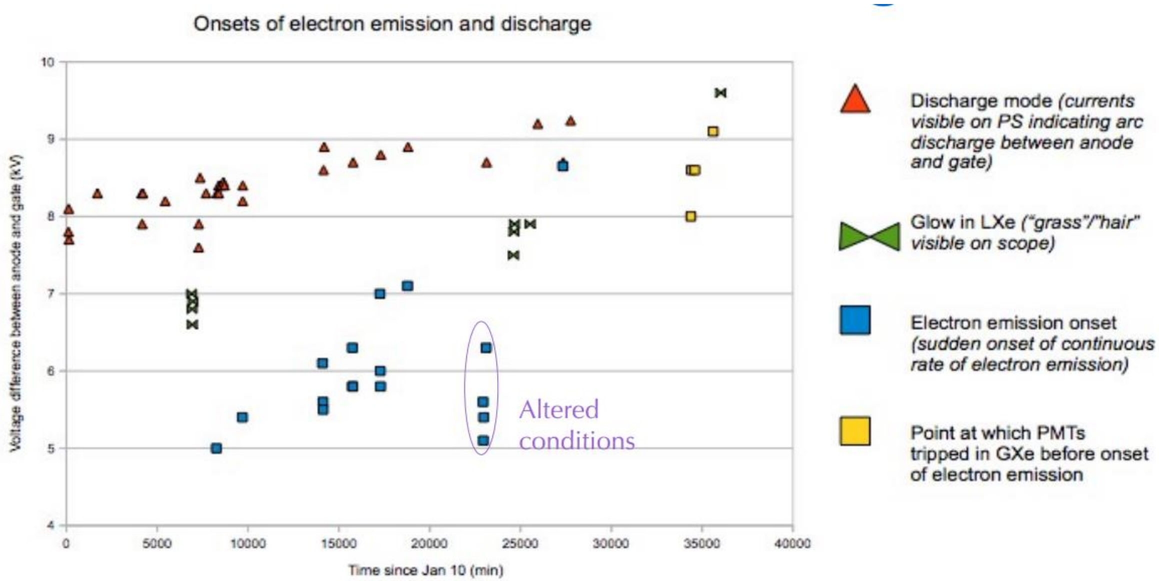
- Simply applying new Leff and Qy to existing analysis already provides significant improvement below 10 GeV
  - As much as possible we want to explore all options for a "new" Run3 result together instead of piecemeal
- With DD neutron data in hand, we can be more confident about exploring data below current analysis thresholds
  - Results from simulated data shown at APS:
- Also looking at S2-only analysis, similar to what was done in Xenon10
  - Challenges: fiducialization, single-e background
  - Progress on algorithms also presented at APS





Grids HV Conditioning

- Fields achieved during Run 3 were sufficient, but we can do better
  - Drift field – 181 V/cm. Discrimination ~99.6%. Higher field may get even better (?)
  - Gas extraction field – 6 kV/cm. Efficiency 65%, can definitely get better.
  - Both limited by electroluminescence
- Conditioning = continuously apply high voltage, watch current on grids, glow patterns, electron emission…
- In this mode since January 2014. Campaign reaching its end.
  - Some hints of progress
  - Will know for sure when cool down and condense again
  - A few more details presented at APS meeting



Result paper published in PRL 112.091303
http://arxiv.org/abs/1310.8214

Instrument paper NIM A 704 111-126 (2013)
http://arxiv.org/abs/1211.3788

Backgrounds paper submitted to Astropart. Phys.
http://arxiv.org/abs/1403.1299

Several LUX theses now available on luxdarkmatter.org

Run 4 to start first half of 2014. Expect more exciting results in the future!

Thank you!

Because this was not long enough already…

Additional Slides

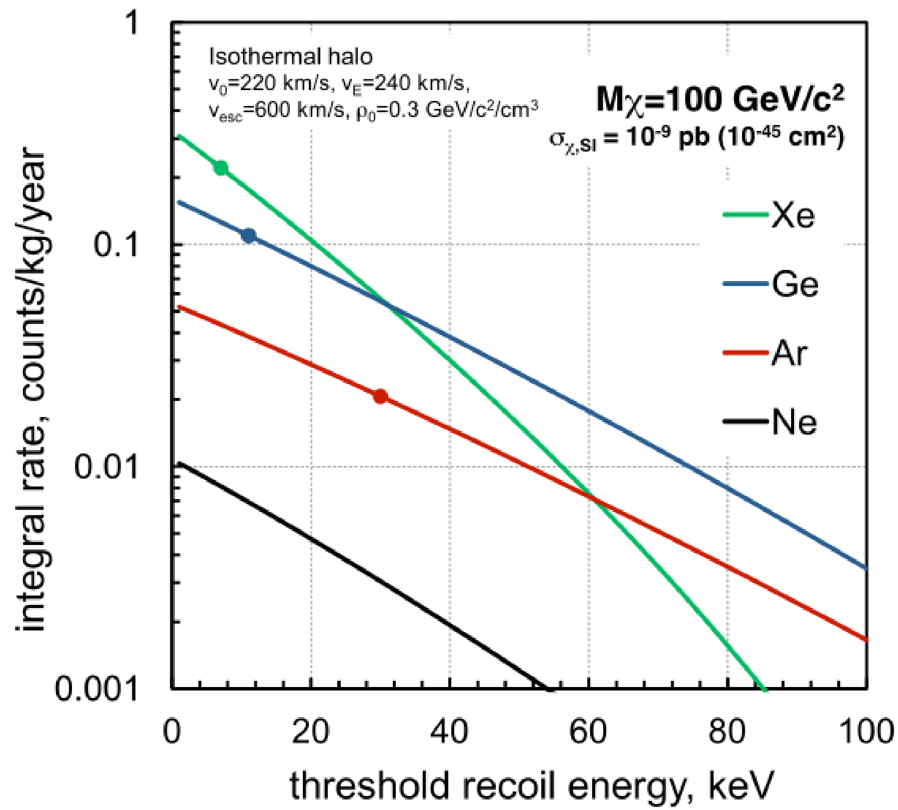
WIMP Direct Detection

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

$R = N \rangle \int \langle v \rangle$.   From $\langle v \rangle$ = 220 km/s, get order of 10 keV deposited.

Requirements:

- **Low radioactivity**
- **Low energy threshold**
- **Gamma ray rejection**
- **Scalability**
- **Deep underground laboratory**



Sanford Lab – Surface Facility

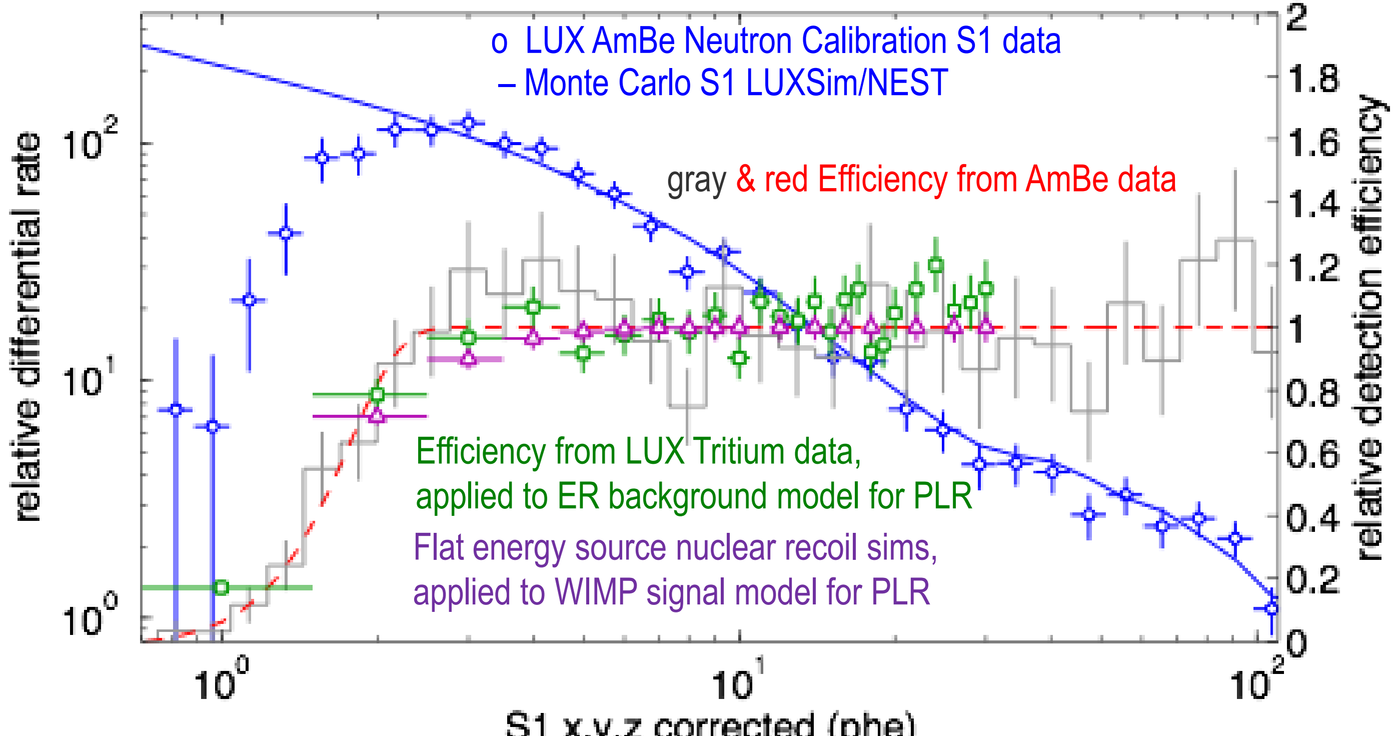
- Full-scale test of LUX deployment
  - Liq/gas system
  - PMT testing
  - DAQ testing
  - S1 trigger efficiency
  - Xe purity

- Exact duplicate of the underground layout for all major systems
- 1 m thick water shield designed to allow limited real data taking, even at the surface
  - Expected Gamma rate ~70 Hz, Neutron rate ~30 Hz, Muon rate ~50 Hz
  - Natural detector limit: 175 Hz (PMT gain stability, < 10% event overlap)
  - Requires reduced PMT gains
- LUX detector integration on site November 2009 – July 2012
  - Completed two "Runs" in June 2011, and November 2011 – February 2012
  - Started dismantling to go underground at end of May 2012

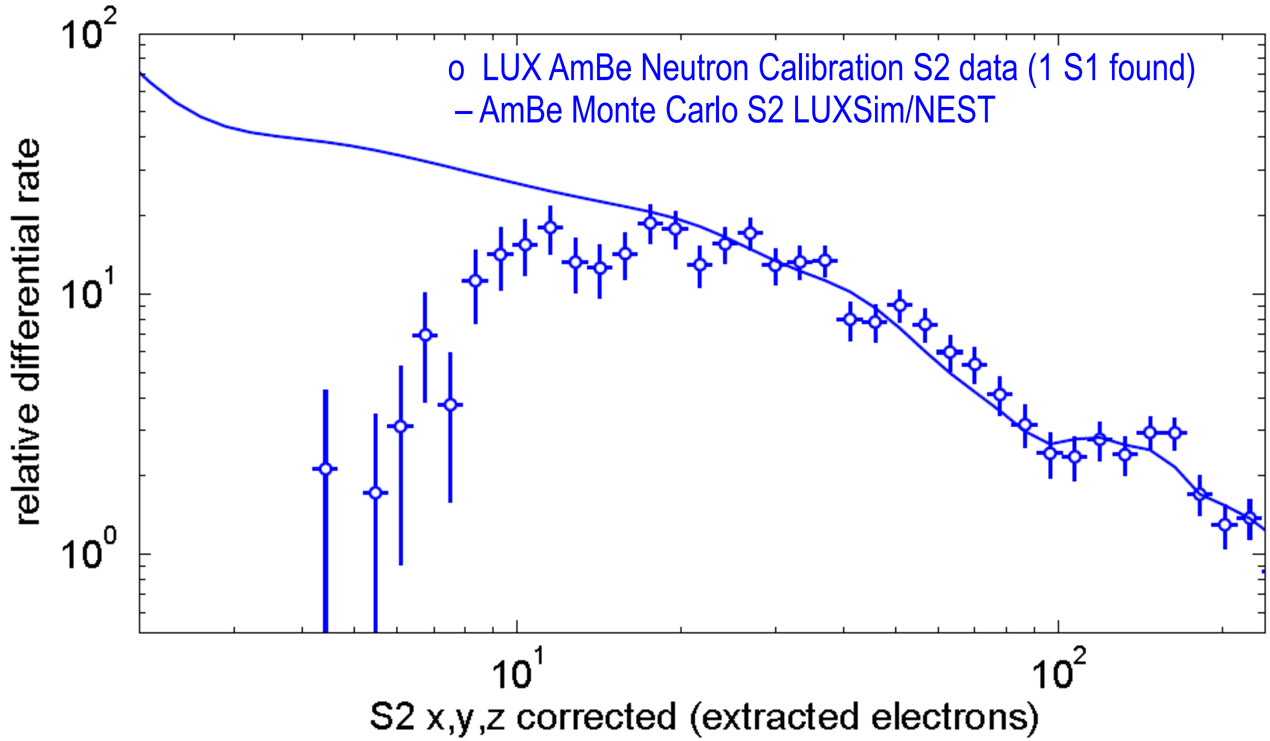
Surface Lab – July to October 2011

LUX Run 3 – S1 Efficiency

- S1 efficiency was studied in detail using:
  - AmBe NR calibration
  - Tritiated-Methane calibration
  - LED calibration
  - Full Monte Carlo of NR events (S1+S2 processed by same analysis chain)
- Overall efficiency is dominated by S1 efficiency, compared to S2 efficiency



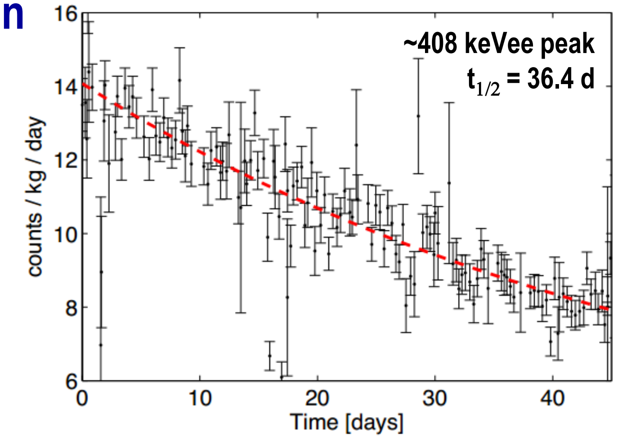
LUX Run 3 – S2 Efficiency

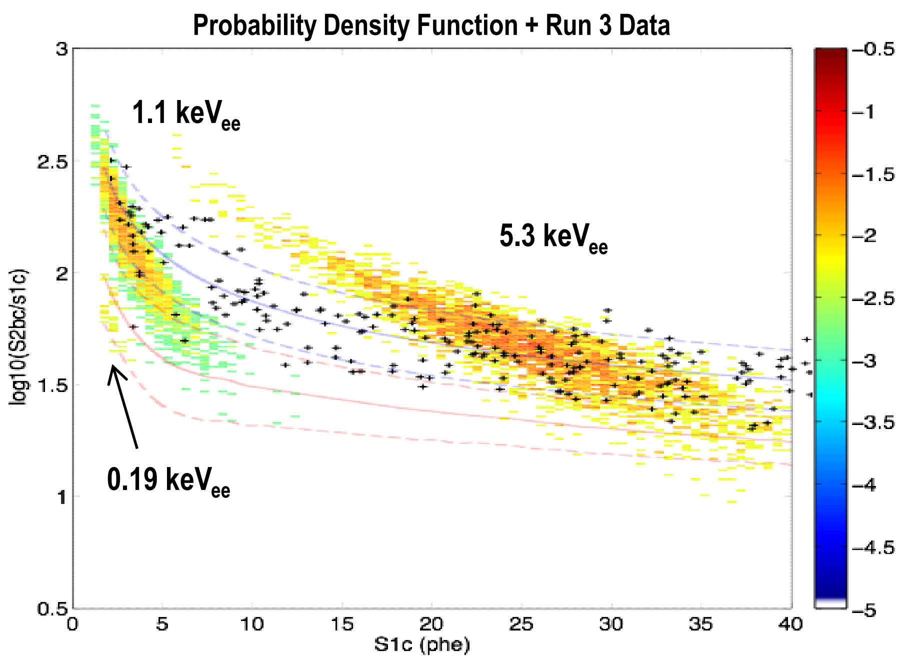


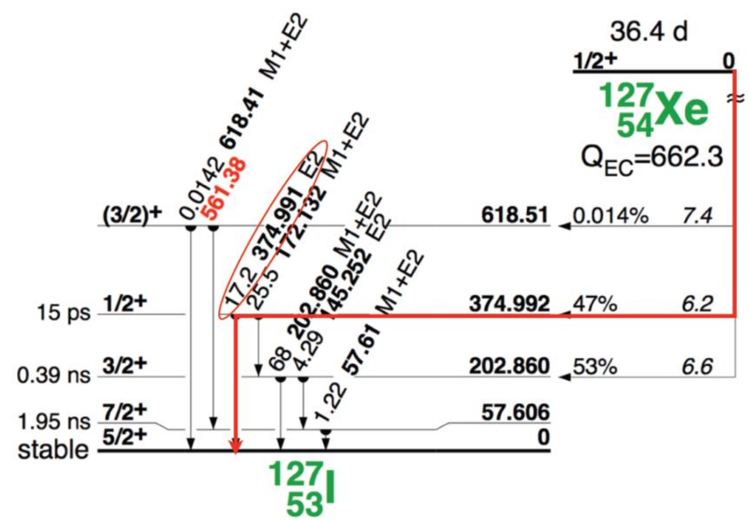
- Good agreement above ~20 electrons
- Below that the S2 efficiency is affected by S1 detection efficiency
- This is why choice of 200 phe S2 threshold (~8 e-) has minimal impact on analysis

Contribution from Intrinsic Sources: ^{127}Xe

- **Isotope of interest for WIMP search = ^{127}Xe**
  - **EC decay with gammas 203 or 375 keV, possibility to escape the active volume.**
  - **X-ray / Auger emission corresponding to ^{127}I levels: 33.2 keV_{ee} (K), 5.3 (L), 1.1 (M), 0.19 (N)**
  - **Depth-dependent background profile; data follows prediction**
  - **Contribution modeled as a nuisance in the PLR analysis**
  - **Accounts for 0.5 $mDRU_{ee}$ (avg) in WIMP ROI over Run 3**
  - **It will have disappeared for Run 4**







Uranium and Thorium Chains