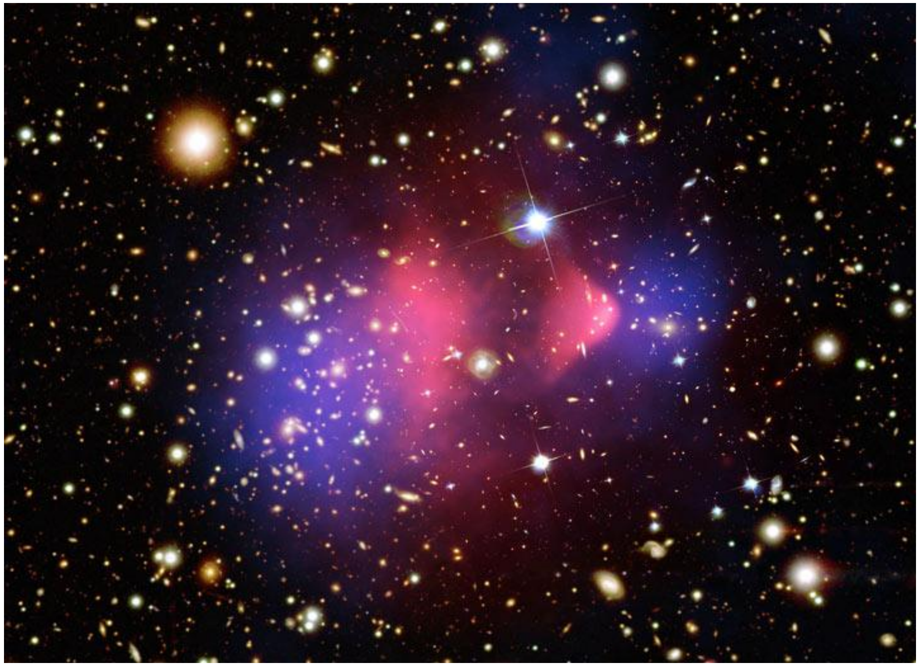
U Mass Lowell Colloquium – September 19th, 2012

Dark Matter in the Black Hills
The Why and How of the LUX experiment

www.luxdarkmatter.org

Since 1933, we have had strong evidence that a large fraction of the mass of the Universe is hidden to us. Today, after decades of efforts both theoretical and observational, this "Dark Matter enigma" remains one of Physics' hottest topics. In this talk I will attempt to cover the basics of Dark Matter physics and what makes the case for its existence so compelling. We will then review the various ways in which one can detect it, before focusing in particular on the LUX experiment, a liquid xenon detector currently being operated at the Sanford Underground Laboratory in Lead, South Dakota.

S. Fiorucci – Brown University

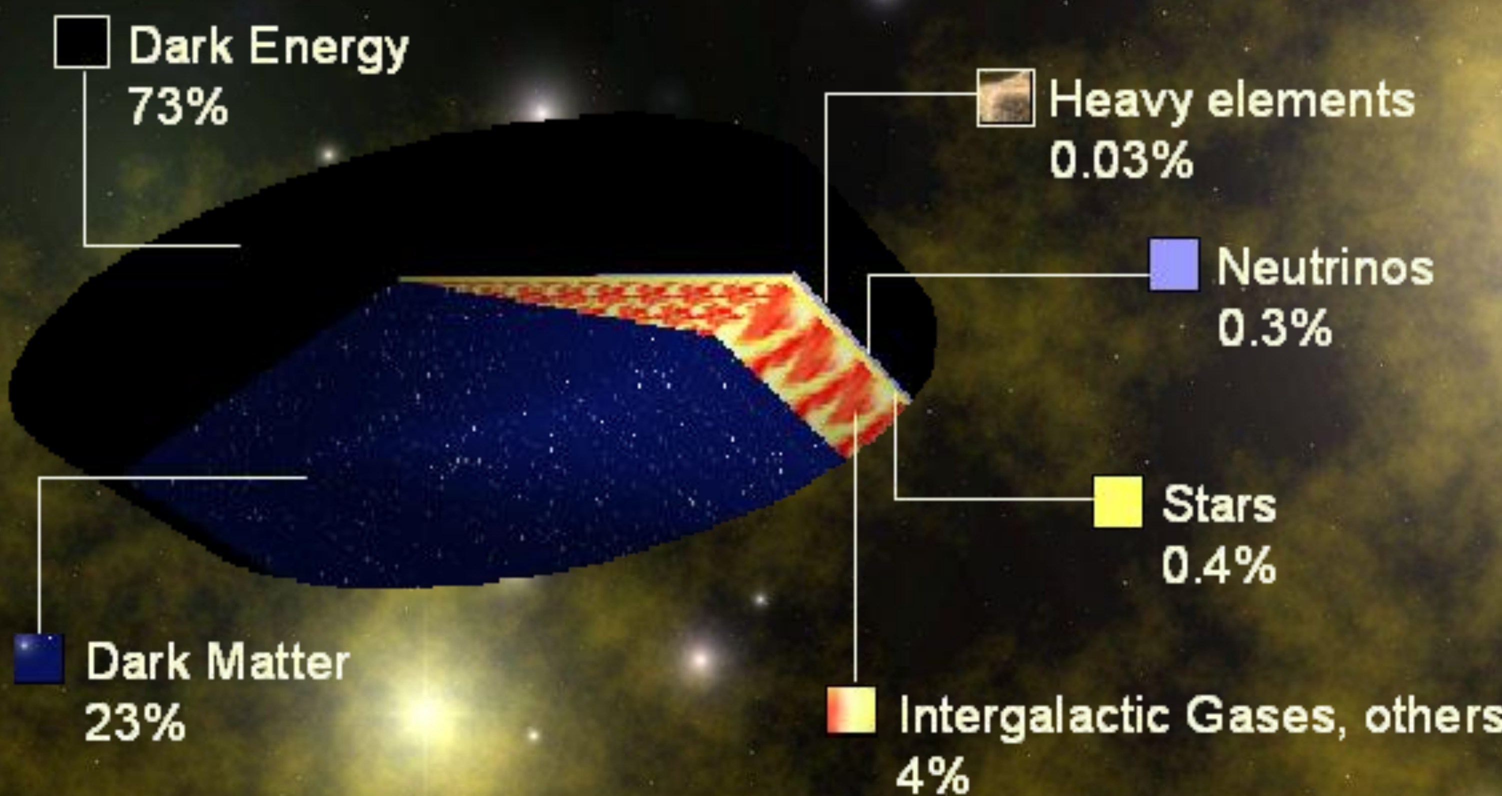


The bullet cluster, or dark matter caught with its pants down

Cosmic Matters

The Case for Dark Matter

What is the Universe made of ?

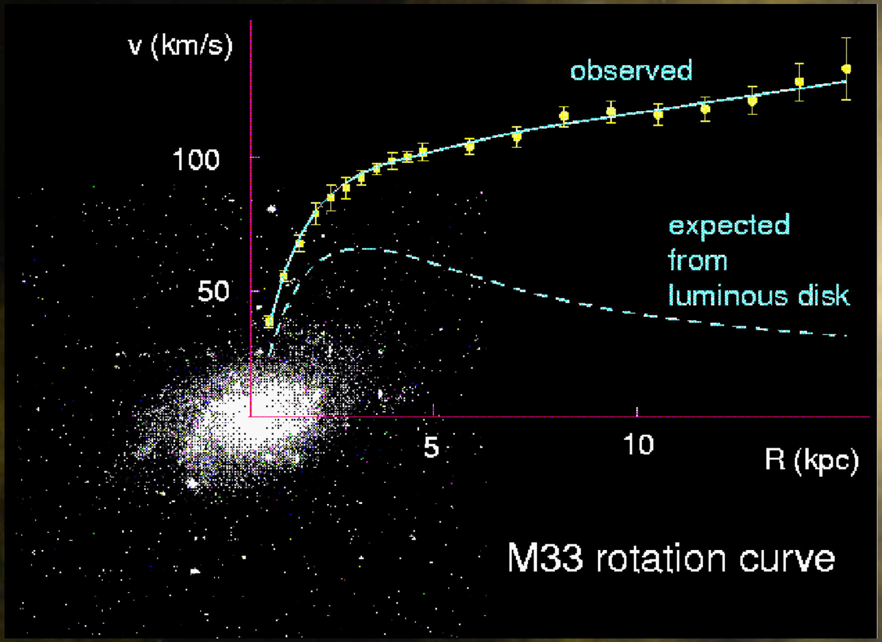


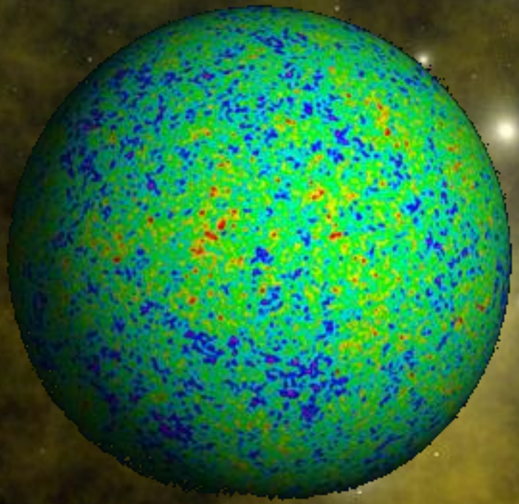
Observational Evidence

(at the galactic level)

• **First evidence**: 1933 F. Zwicky (initially with galaxies clusters)

Stars radial velocities dictated by gravitation laws **do not match** observation
→ **It is as if a large, unseen mass exists in the galaxy**





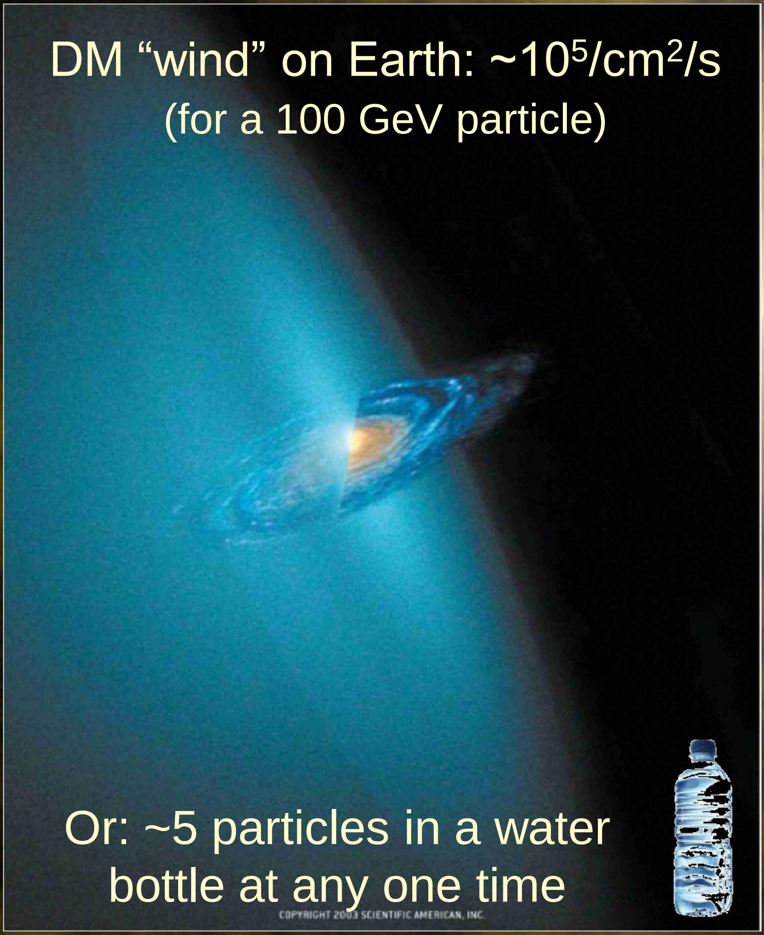
• Since then, more clues:
- Cosmological Microwave Background (CMB) puts constraining limits on each component of the universe
- Dark Matter needed to explain the formation of large cosmic structures

Just Invisible Regular Matter ?

- Could it just be matter we simply cannot see?
  For instance: giant planets, interstellar gas clouds, tiny neutron stars, black holes…
- Those have been looked for in the past two decades, most notably through **gravitational lensing**
- **Can explain at most 5%** of the missing mass
  → **Not nearly enough!**

Galactic Dark Matter Halo

- **Basic idea**: each galaxy is surrounded by a homogeneous (?) cloud of massive, neutral, very weakly interacting particles, with a total mass ~5x of everything else
- Such a particle is generically called a **WIMP**, its exact nature remaining to be determined
- Halo's properties dictated by observations
  → We know how much total mass there is, and we can make educated guesses on the velocities distribution, particle mass, etc… with <u>large (x3-100 !) uncertainties</u>
- Massive neutrino already eliminated

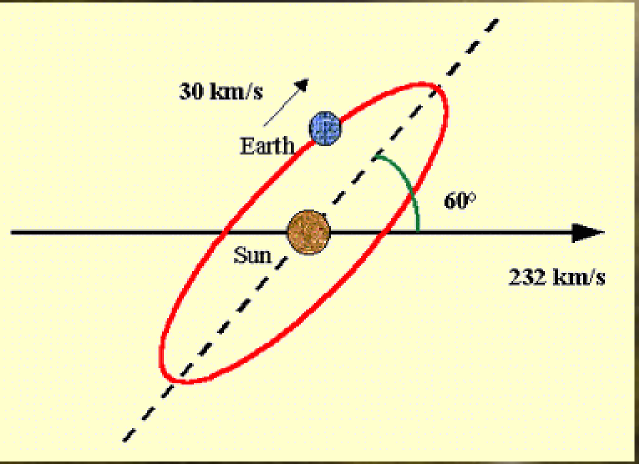


Beyond the Standard Model

→ **Example: the Neutralino:** $\chi = \alpha\tilde{\gamma} + \beta\tilde{Z} + \gamma\tilde{H}_1^0 + \delta\tilde{H}_2^0$

Lightest Supersymetric Particle (LSP) and its own antiparticle

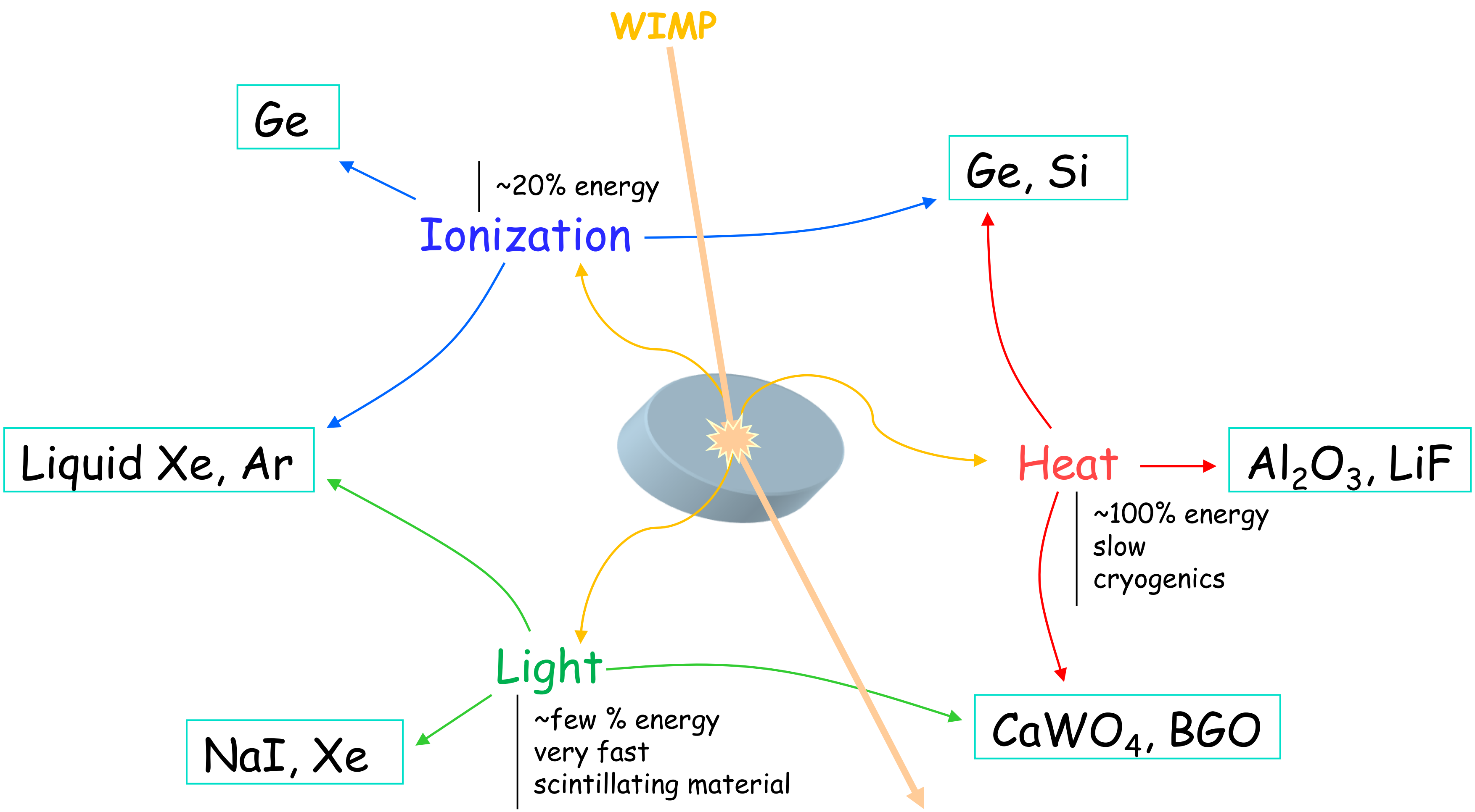
- **Indirect detection:**
  - Detection of WIMP annihilation products
- **Direct detection:**
  - WIMP scattering on nuclei
- **Production at accelerators**
- **Possible Signatures:**
  - Nuclear vs electronic recoil
  - Recoil energy spectrum shape
  - Directionality of interactions (earth, sun)
  - Annual flux modulation
  - Diurnal direction modulation
  - No multiple interactions
  - Consistency between targets of different natures



Needle in a Haystack

Direct Detection of Dark Matter

Direct Detection Possibilities



Many International Efforts

Background Challenges

- Search sensitivity (low energy region <<100 keV)
  - Current Experimental Limit < 1 event /kg /year
  - Goal < 1 event /tonne /year
- Activity of typical Human?
  - ~10 kBq (10^4 decays per second, 10^9 decays per day)
- Environmental Gamma Activity
  - Unshielded 10^7 evt/kg/day (all values integrated 0–100 keV)
  - This can be easily reduced to ~10^2 evt/kg/day using 25 cm of Pb
- Main technique to date: nuclear vs electron recoil discrimination
  - This is how CDMS II experiment went from 10^2 -> 10^{-1} evts/kg/day)
- Moving below this
  - Reduction in External Gammas: e.g. High Purity Water Shield 4m gives <<1 evt/kg/day
  - Gammas from Internal components - goal intrinsic U/Th contamination toward ppt (10^{-12} g/g) levels
  - Detector Target can exploit self shielding for inner fiducial if intrinsic radiopurity is good
- Environmental Neutron Activity / Cosmic Rays => Go DEEP
  - (α,n) from rock 0.1 cm^{-2} day^{-1}
  - Since <8 MeV use standard moderators (e.g. polyethylene, or water, 0.1x flux per 10 cm)
  - Cosmic Ray muons generate high energy neutrons 50 MeV - 3 GeV which are tough to moderate
  - Need for depth (DUSEL) - surface muon 1/hand/s, Homestake 4850 ft 1/hand/month

Eliminating Possibilities

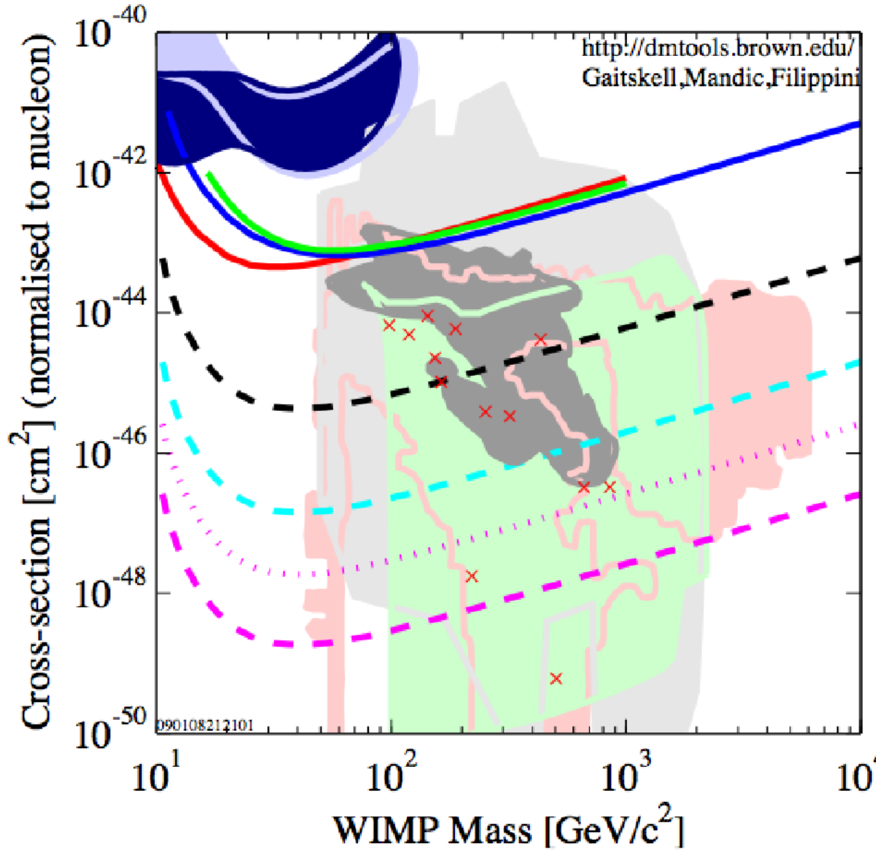
- Strategy for the past decade:
  - improve detector sensitivity
  - reduce background

  in order to have a chance to see interactions from WIMPs predicted by supersymetric models

- Today: we reach into the first optimistic models, with detector masses ~hundreds of kg

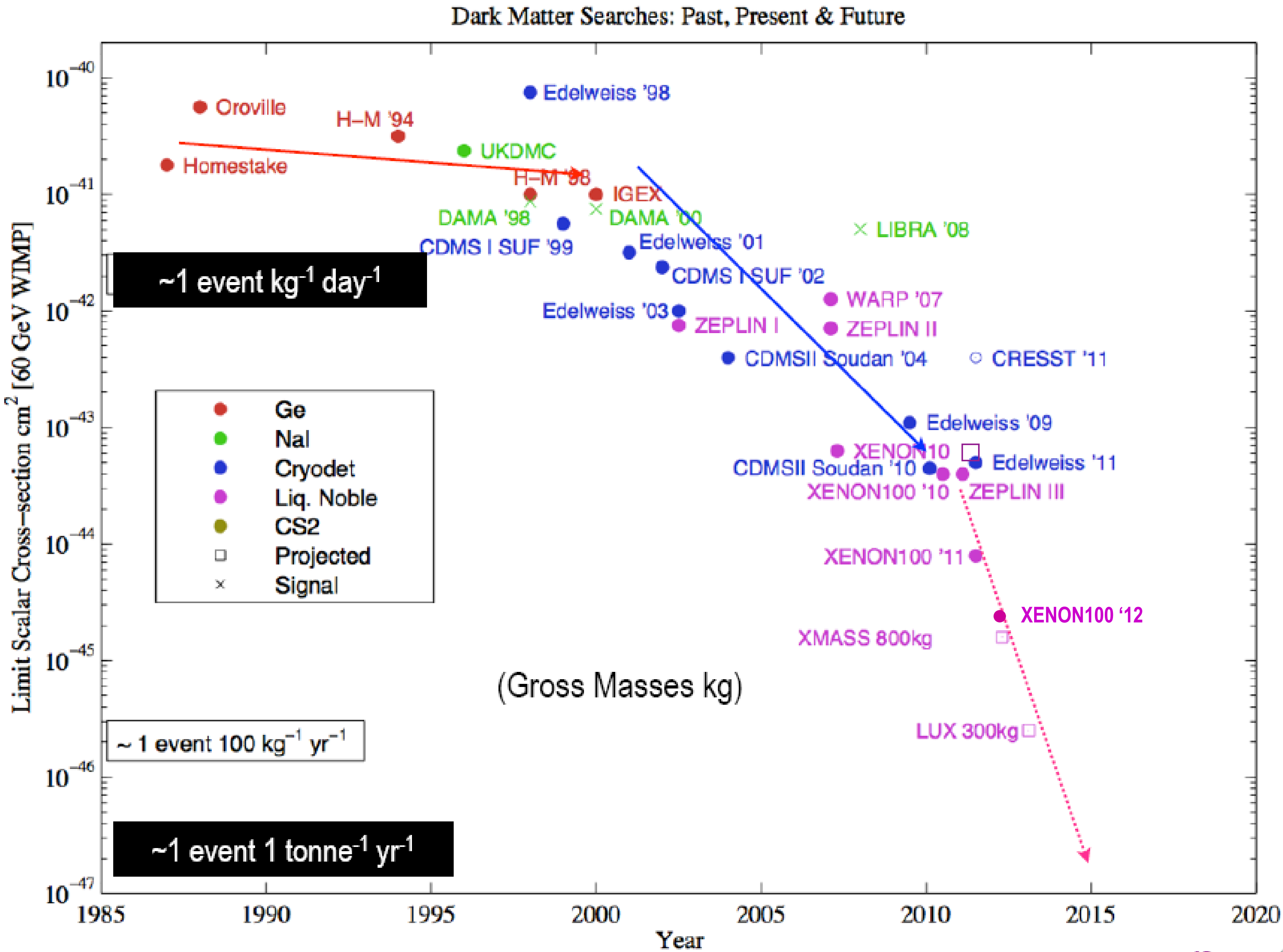
  <u>We still see nothing!</u>

- Eventually: we will need multi-ton detectors. Within 10 years, the search for Dark Matter will be over



And if we find nothing…?

Dark Matter Direct Searches – Timeline



Really just a bucket of xenon

The LUX Experiment

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
Carlos Hernandez Faham	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Mike Dragowsky	Research Associate Professor
Tom Coffey	Research Associate
Carmen Carmona	Postdoc
Karen Gibson	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student
Tim Ivancic	Graduate Student

Imperial College London

Henrique Araujo	PI, Senior Lecturer
Tim Sumner	Professor
Alastair Currie	Postdoc

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Victor Gehman	Scientist
David Taylor	Engineer
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

Texas A&M

James White	PI, Professor
Robert Webb	Professor
Rachel Mannino	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Robert Svoboda	Professor
Richard Lander	Professor
Britt Hollbrook	Senior Engineer
John Thomson	Senior Machinist
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

UC Santa Barbara

Harry Nelson	PI, Professor
Mike Witherell	Professor
Dean White	Engineer
Susanne Kyre	Engineer
Curt Nehrkorn	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer

University of Edinburgh

Alex Murphy	PI, Reader
James Dobson	Postdoc
Lea Reichhart	Graduate student

University of Maryland

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

Collaboration Meeting, UCSB March 2012

University of Rochester

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

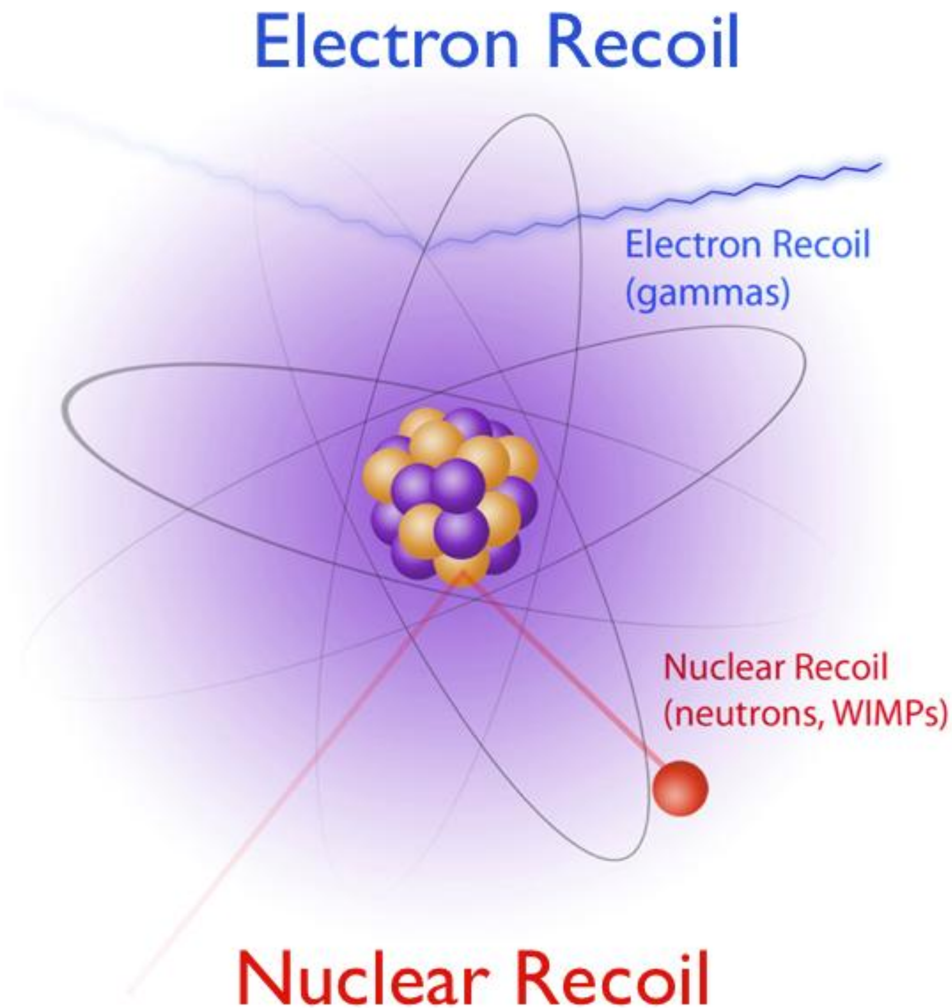
University of South Dakota

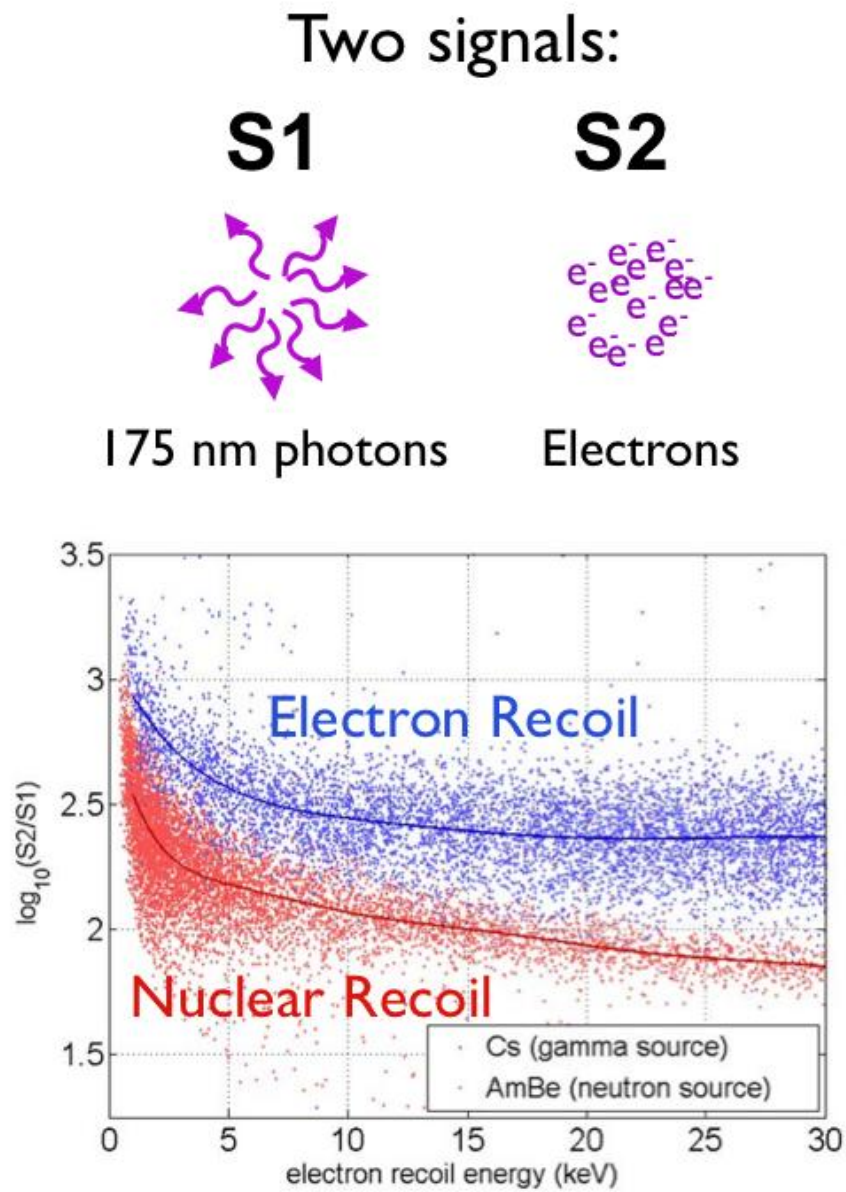
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Dana Byram	Graduate Student
Chris Chiller	Graduate Student
Angela Chiller	Graduate Student

Yale

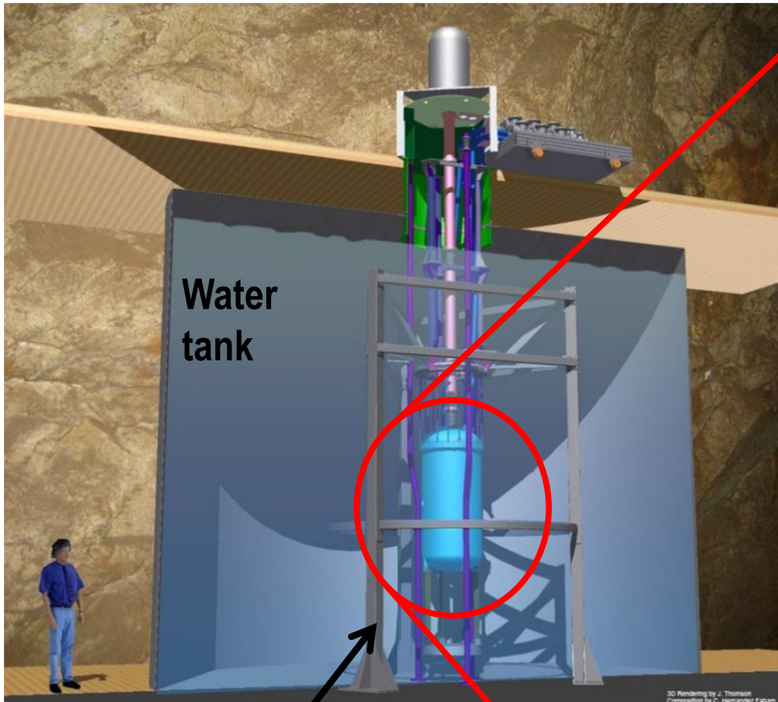
Daniel McKinsey	PI, Professor
Peter Parker	Professor
James Nikkel	Research Scientist
Sidney Cahn	Lecturer/Research Scientist
Alexey Lyashenko	Postdoc
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease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

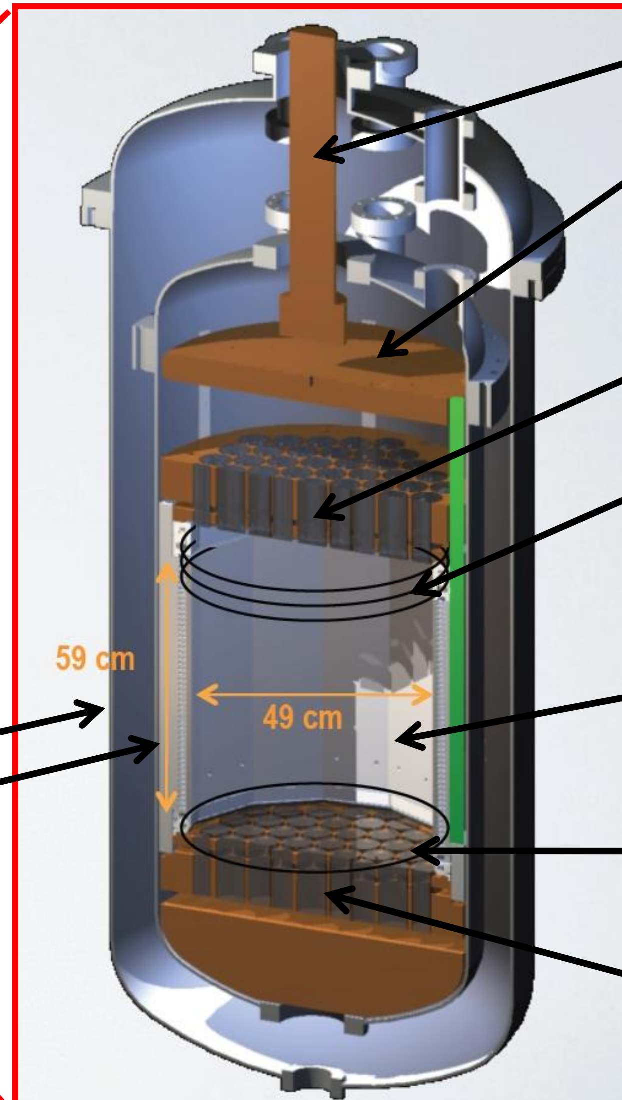
Dark Matter Interaction with Xenon





The LUX Experiment

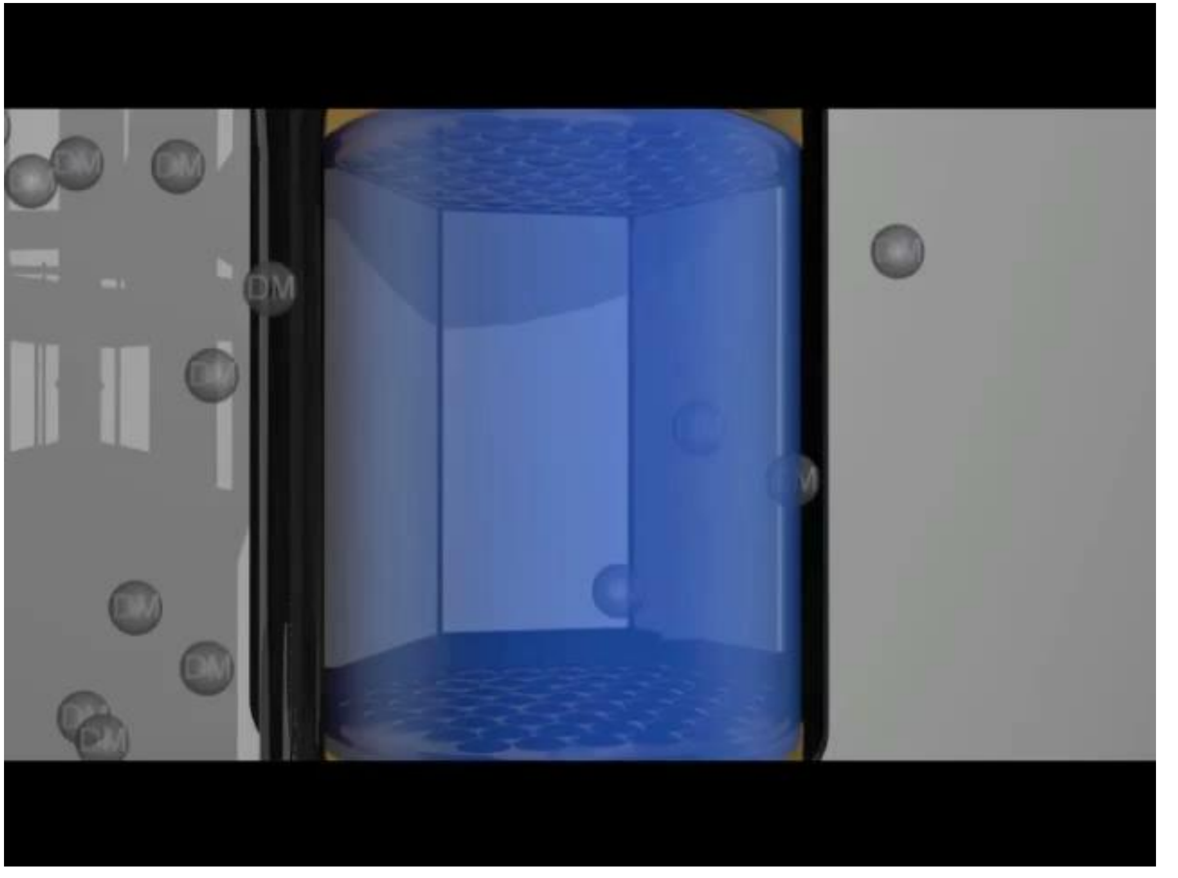


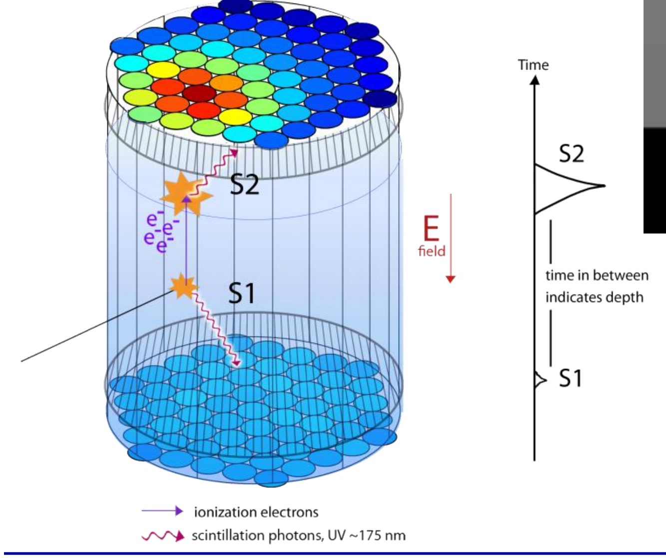


- 370 kg xenon
  - 300 kg active region
  - 100 kg fiducial
- 122 PMTs 2” round
- Low-background Ti cryostat

LUX Design – Dual Phase Xenon TPC

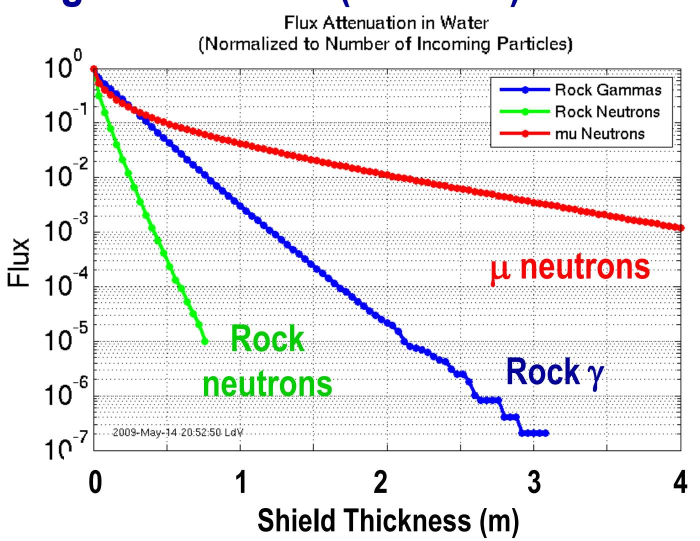
- Can measure single electrons and photons
- Charge yield reduced for nuclear recoils
- Excellent 3D imaging
  - Reject multiple scatters
  - Eliminate edge events to take advantage of Xe self shielding

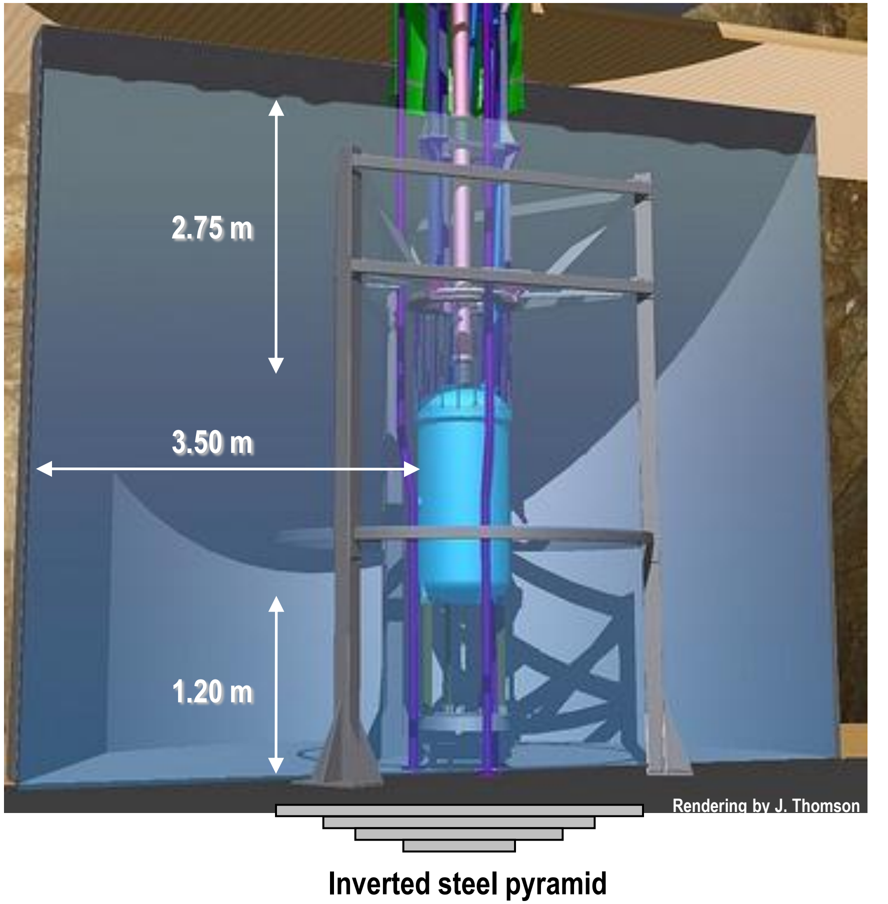




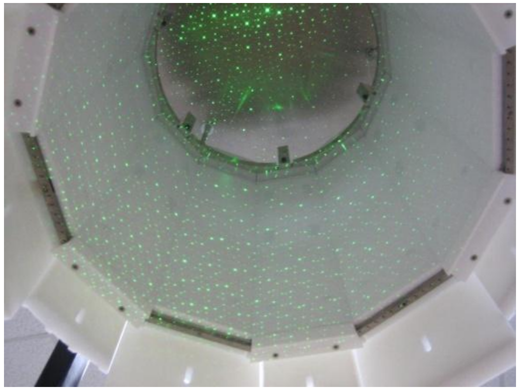
LUX Design – Water Tank

- 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: $\sim 10^{-9}$
  - High-E neutrons (>10 MeV): $\sim 10^{-3}$

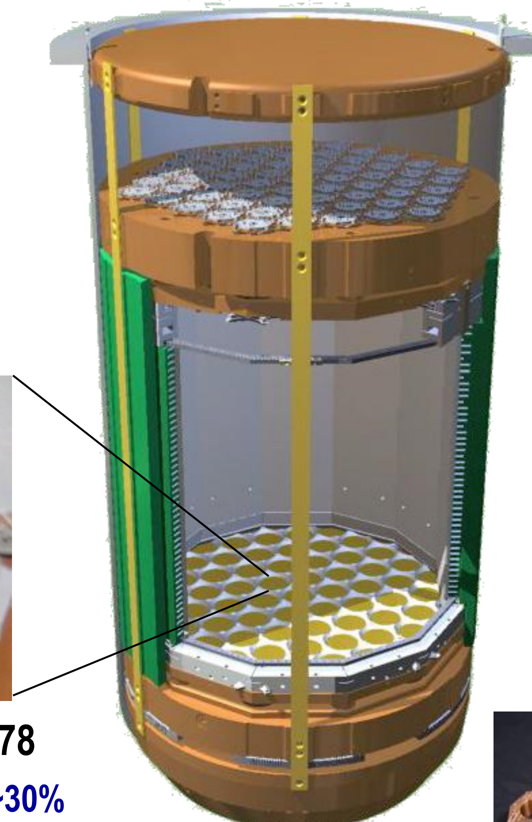


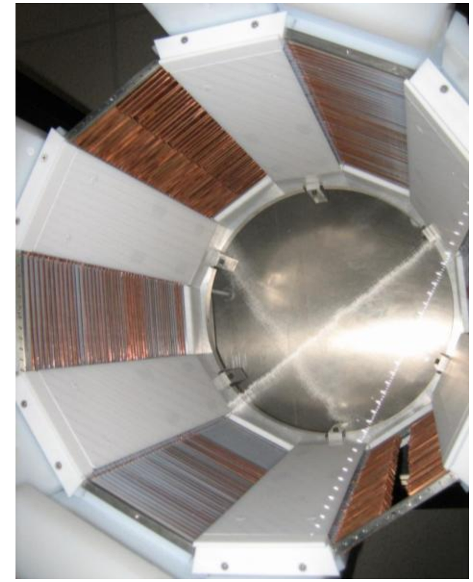


LUX Design – Internals



- 5 HV Grids total, in place and tested





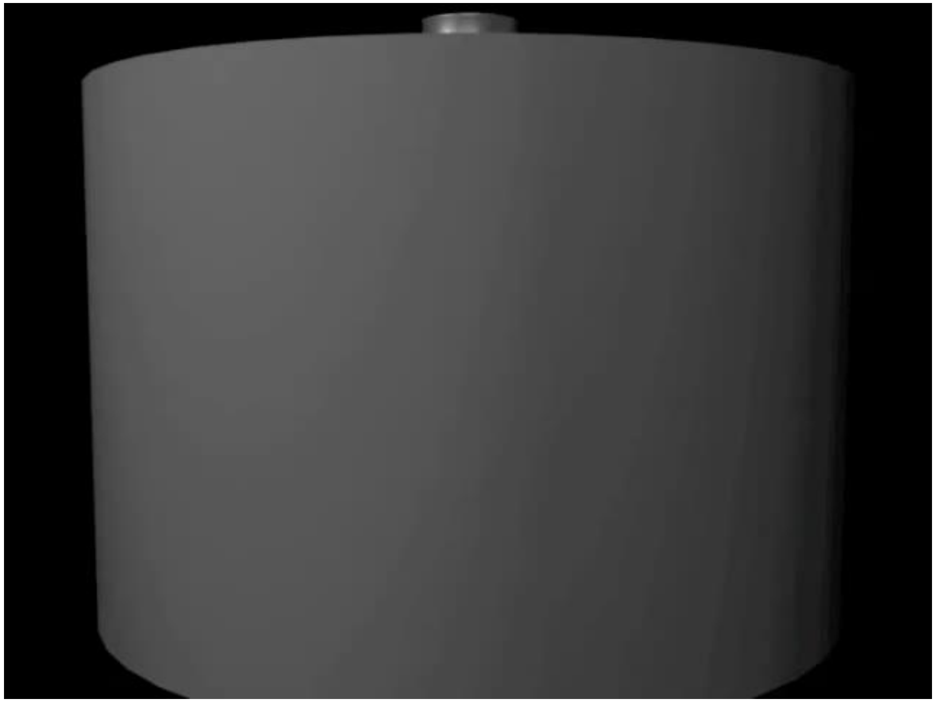
- Dodecagonal field cage + PTFE reflector panels

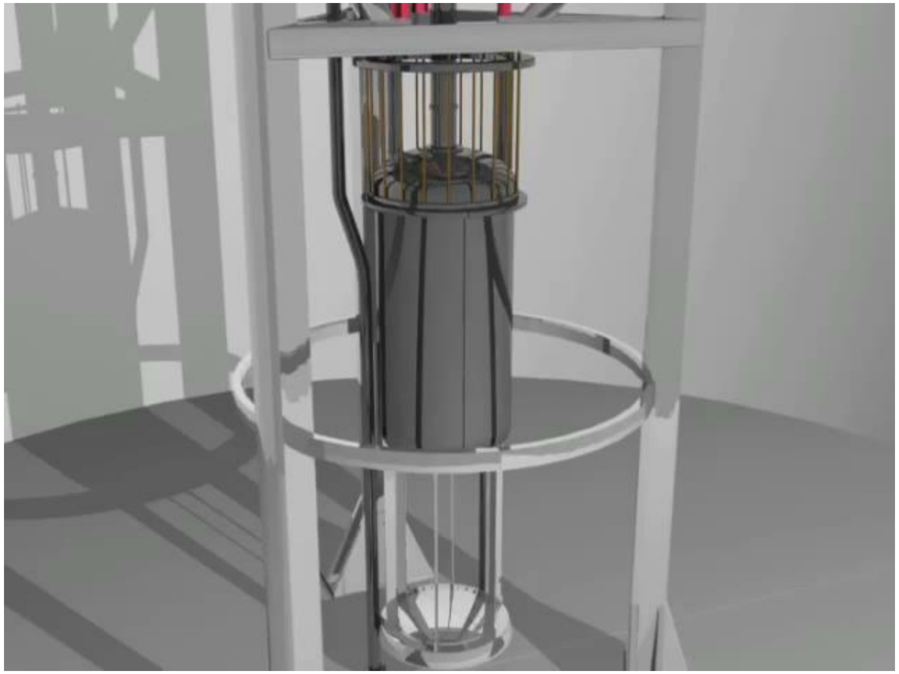
- 122 2" PMT R8778
  - 175 nm, QE > ~30%
  - U/Th ~10/2 mBq/PMT
  - All tested in LUX 0.1 program

First assembly completed at Sanford Surface Lab: Spring 2010 – Jan 2011

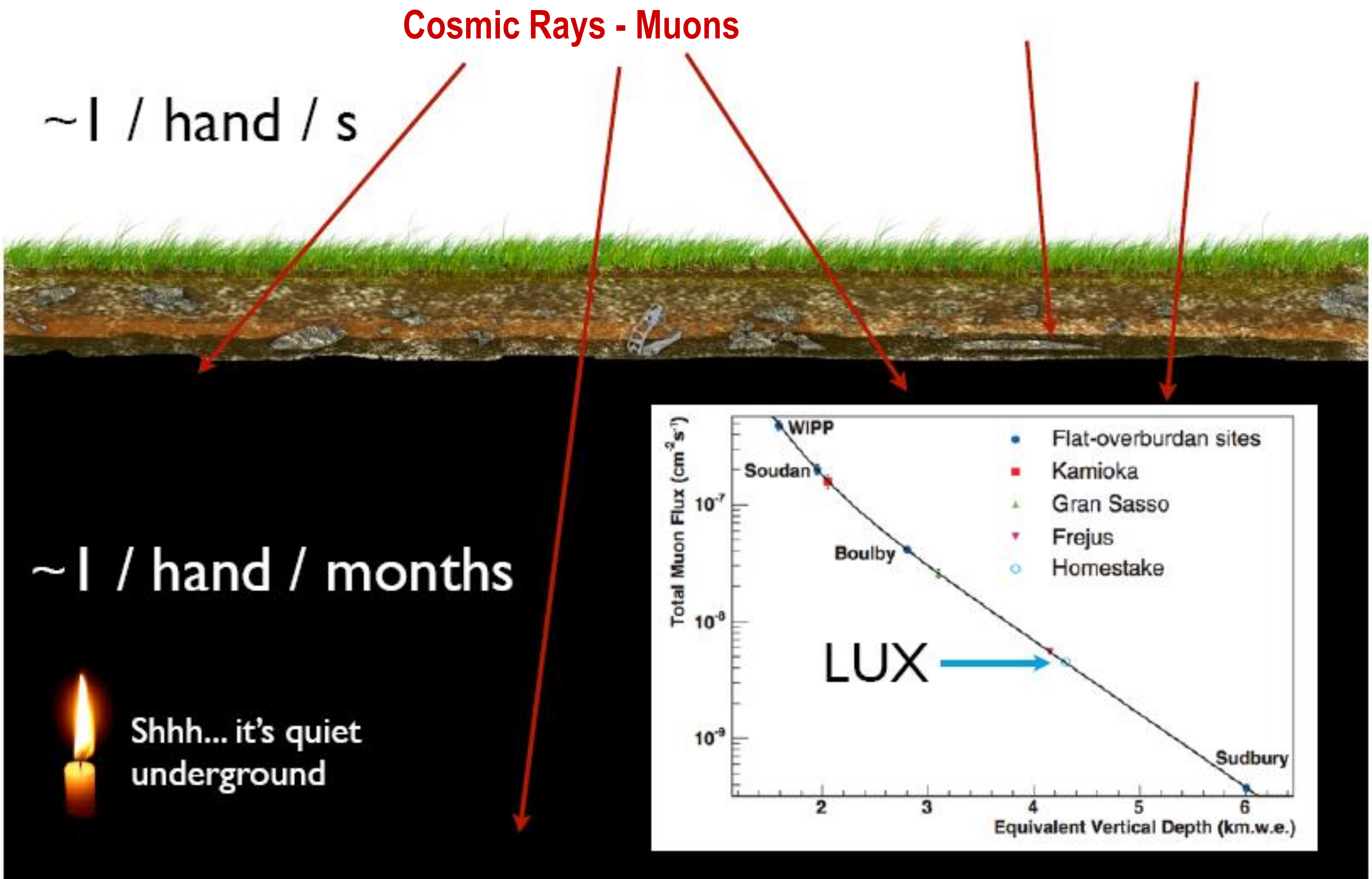
- Copper PMT holding plate

LUX detector – Animated

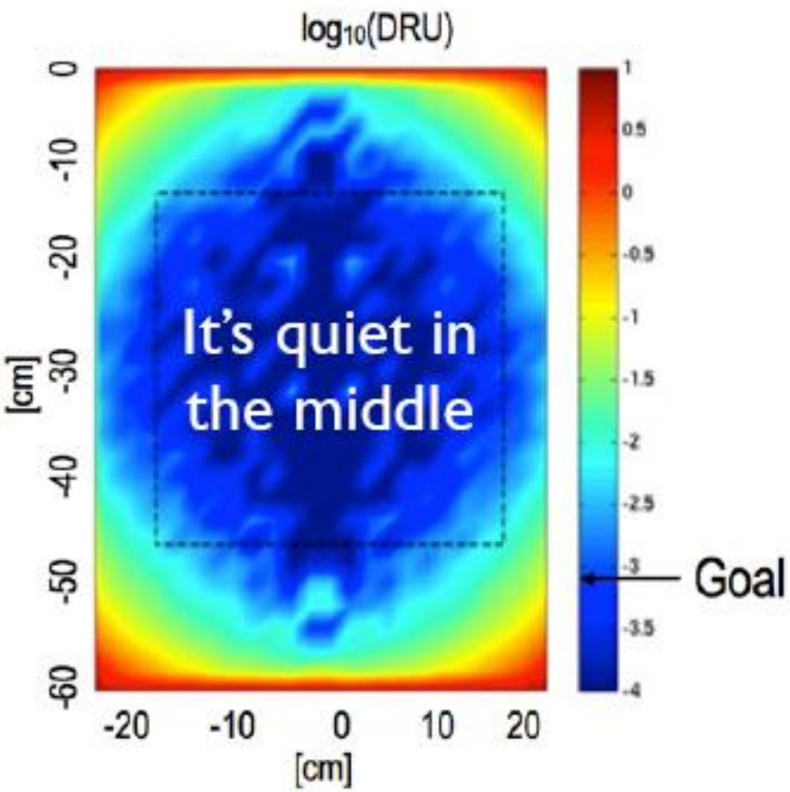


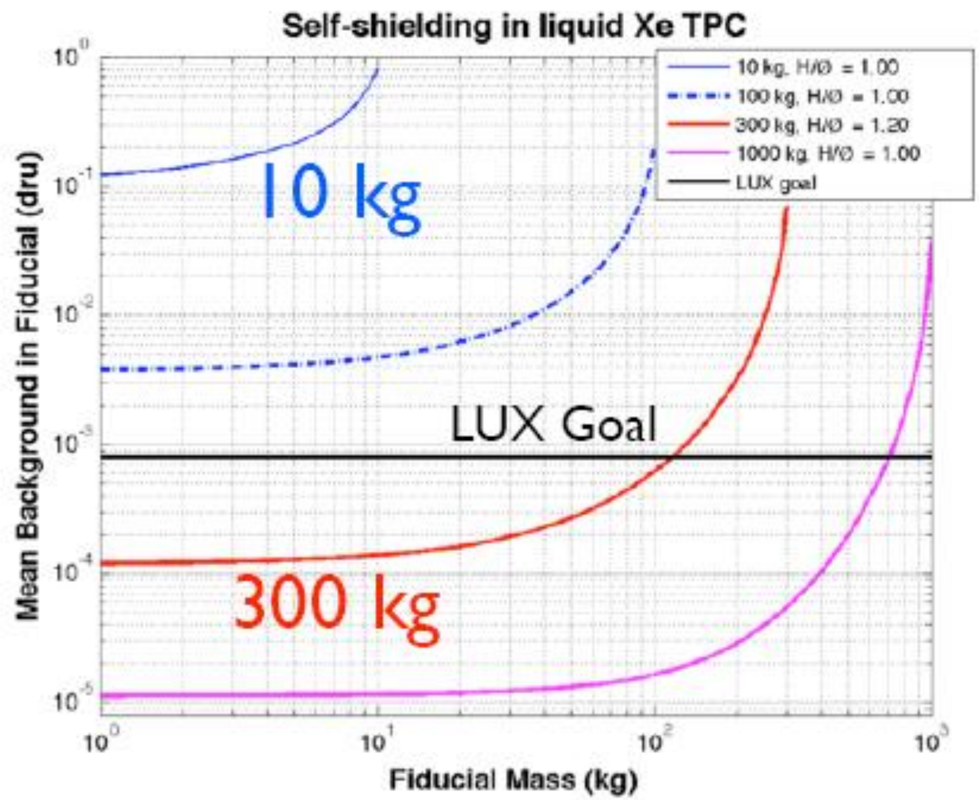


LUX Design – Deep Underground Operation



LUX Design – Self-shielding

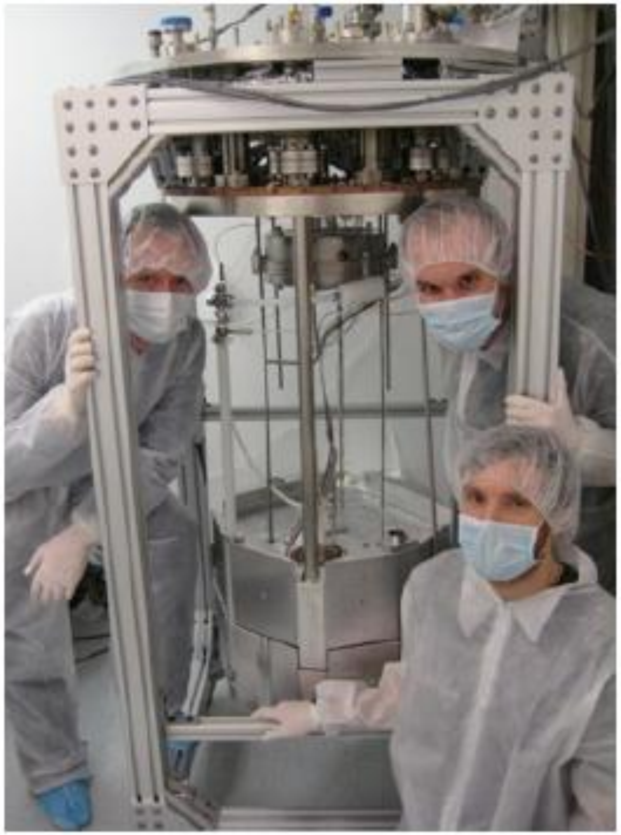




- LXe is a dense target at 3 g/cm^3
- Self-shielding allows this technology to greatly benefit from scaling up

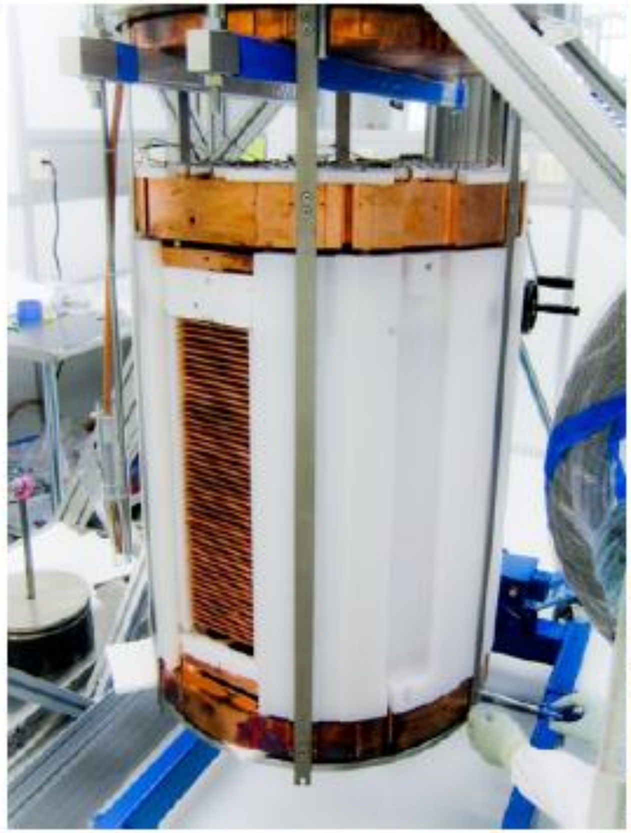
The LUX Program

LUX0.1 - CWRU



2007 – 2009

LUX - Surface



2010 – 2011

LUX - Underground

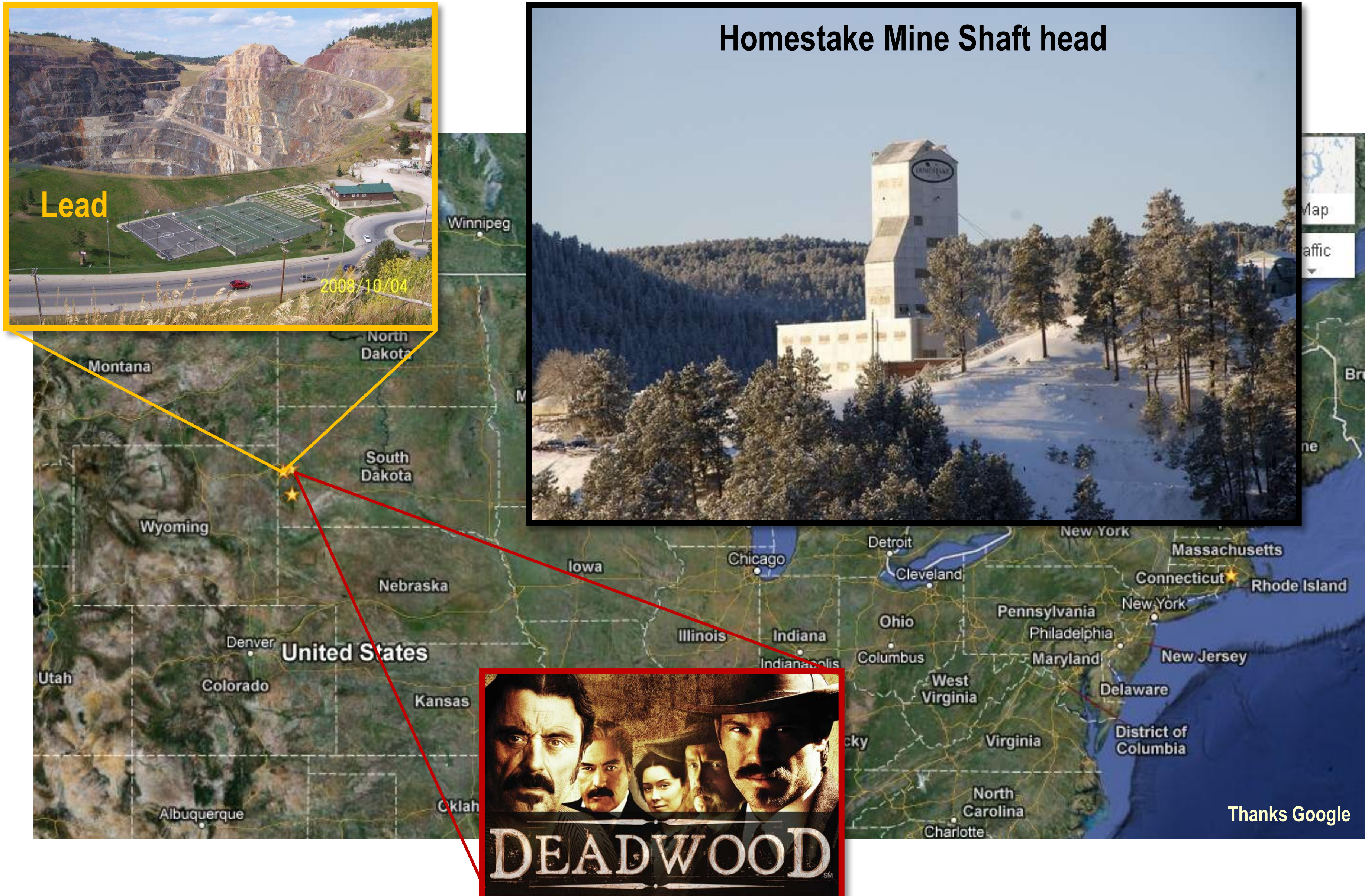
2012+

The Sanford Surface Laboratory, place of Wonders

Running before it jumps

The LUX Experiment: Surface Operations

The Sanford Laboratory at Homestake



Sanford Lab – Surface Facility

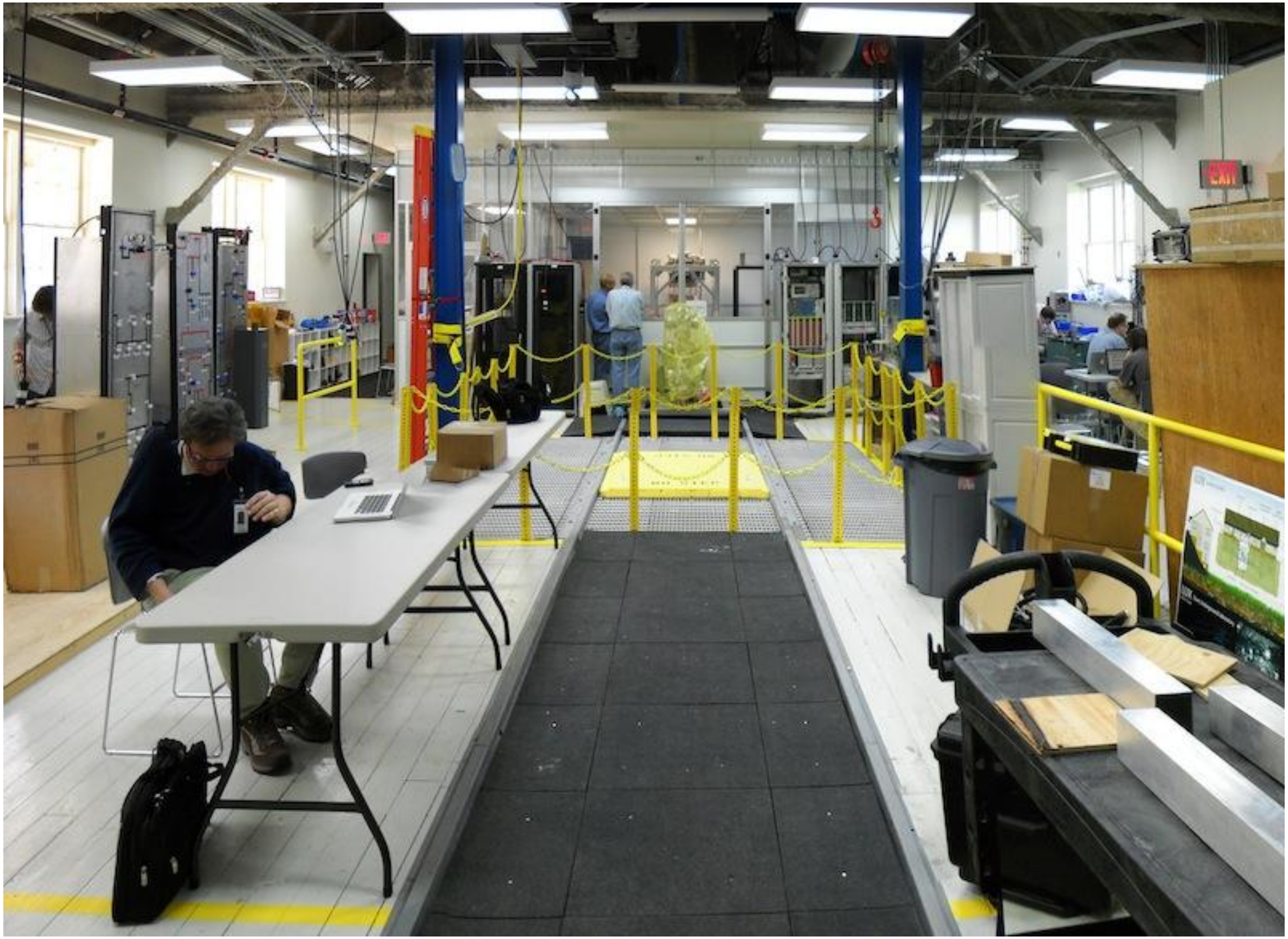
- Full-scale test of LUX deployment
  - Liq/gas system
  - PMT testing
  - DAQ testing
  - S1 trigger efficiency
  - Xe purity

- 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: S2 gating, reduced PMT gain
- LUX detector integration on site since November 2009
  - Completed two "Runs" in June 2011, and November 2011 – February 2012
  - Started dismantling to go underground at end of May 2012

"Warehouse" – June 2009

“Warehouse” – November 2009

Surface Lab – September 2010



Surface Lab – August 2010 to February 2011

Surface Lab – March 2011

Black Hills Pioneer

- **EXIT 10 BID AWARDED** PG. 3
- **SPARTANS TOP STURGIS** PG. 26

Friday, March 4, 2011 Vol. 135 #227 50 cents www.bhpioneer.com

Lab experiment reaches milestone

Researchers from the University of California at Davis, watch as the LUX dark matter detector is lowered into a water tank at the surface laboratory at the Sanford Underground Laboratory in Lead.
Photo by Matt Kapust/Sanford Underground Laboratory

Outdoor market coming to Lead

Lead Live! set for summer months

By Mark VanGerpen
Black Hills Pioneer

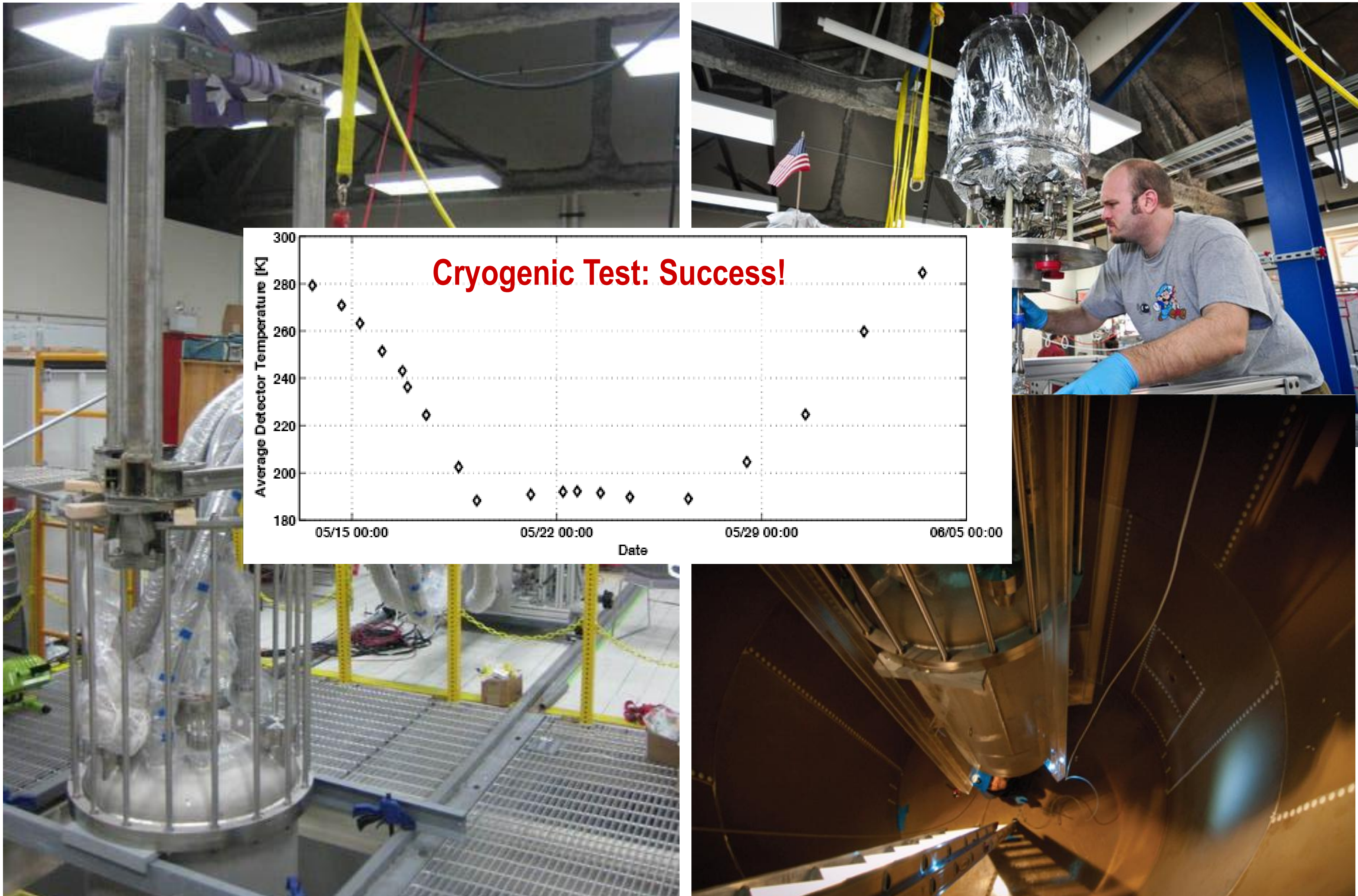
LEAD — In addition to ongoing efforts in Lead to revitalize the city's downtown business district, several members of the community have pulled together to organize an outdoor market on Main Street this summer.

Lead resident Chris Coolidge said the market, coined "Lead Live!", will be a family-oriented, recurring event throughout the summer, and will give

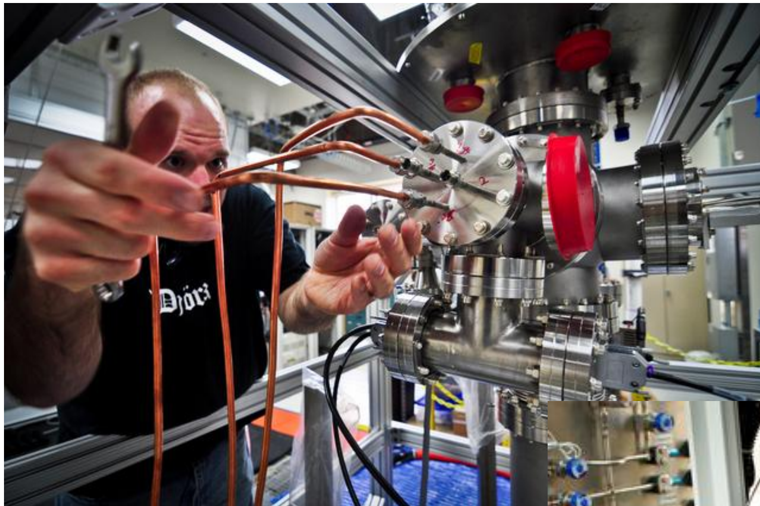
See LEAD LIVE – Page 31

Budget forecast

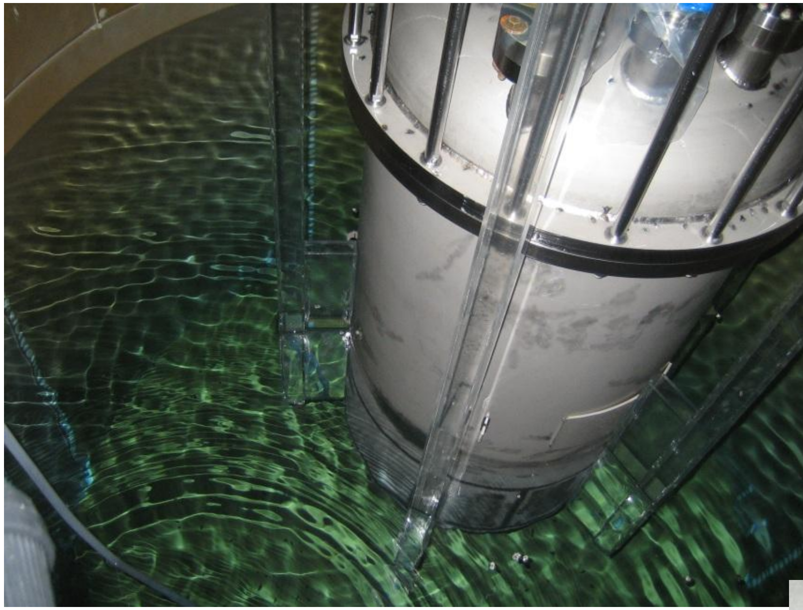
Surface Lab – May 2011 : Run 1



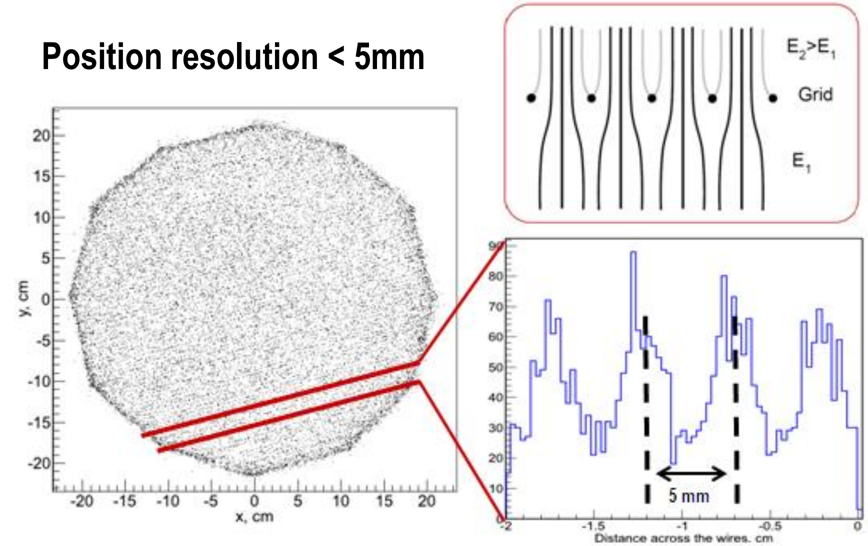
Surface Lab – July to October 2011

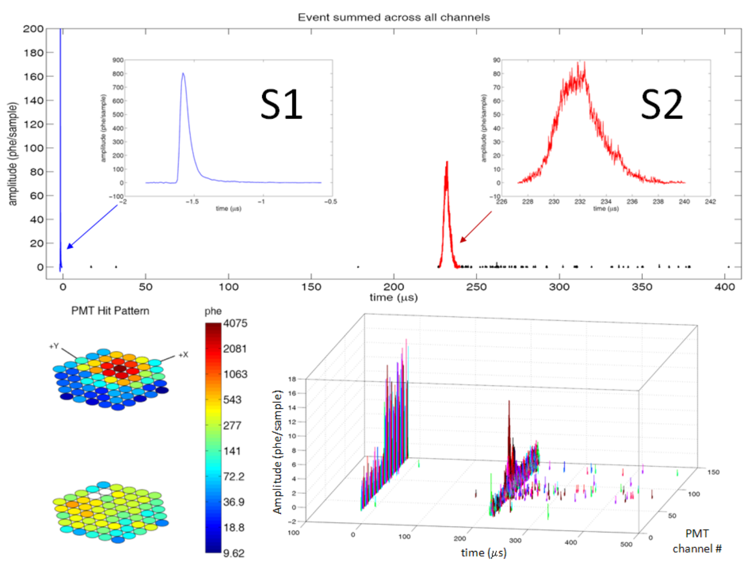


Surface Lab – October 2011 to February 2012 : Run 2

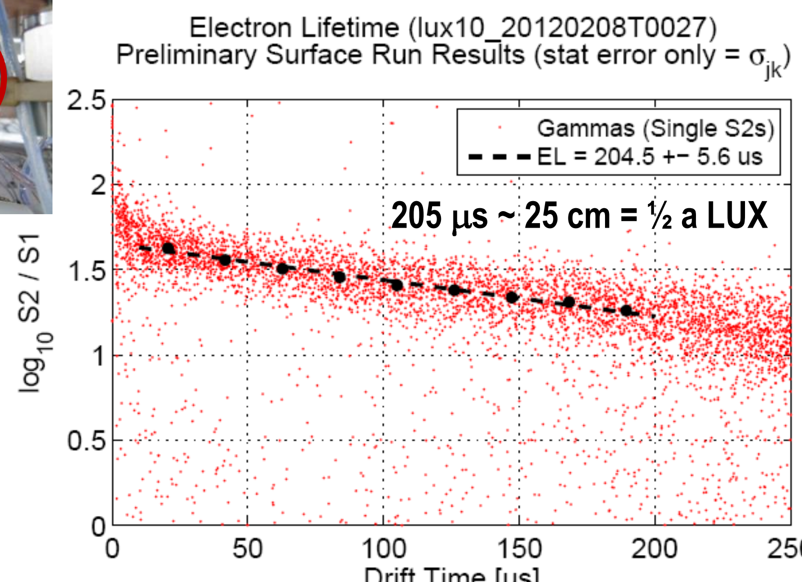


Position resolution < 5mm





Leak!



LUX Run 2 Summary

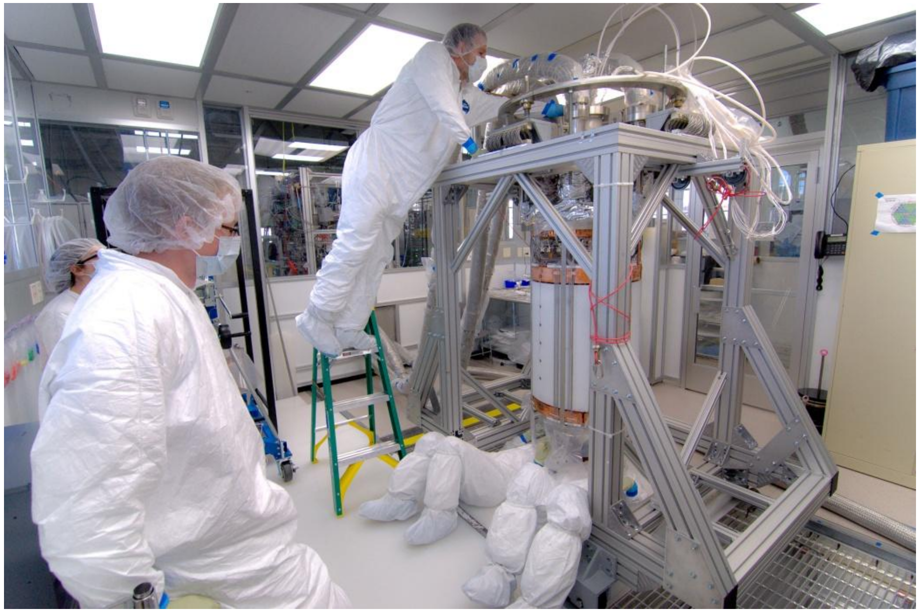
- **List of major achievements already communicated to the World by February 2012**

✓ 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

- **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

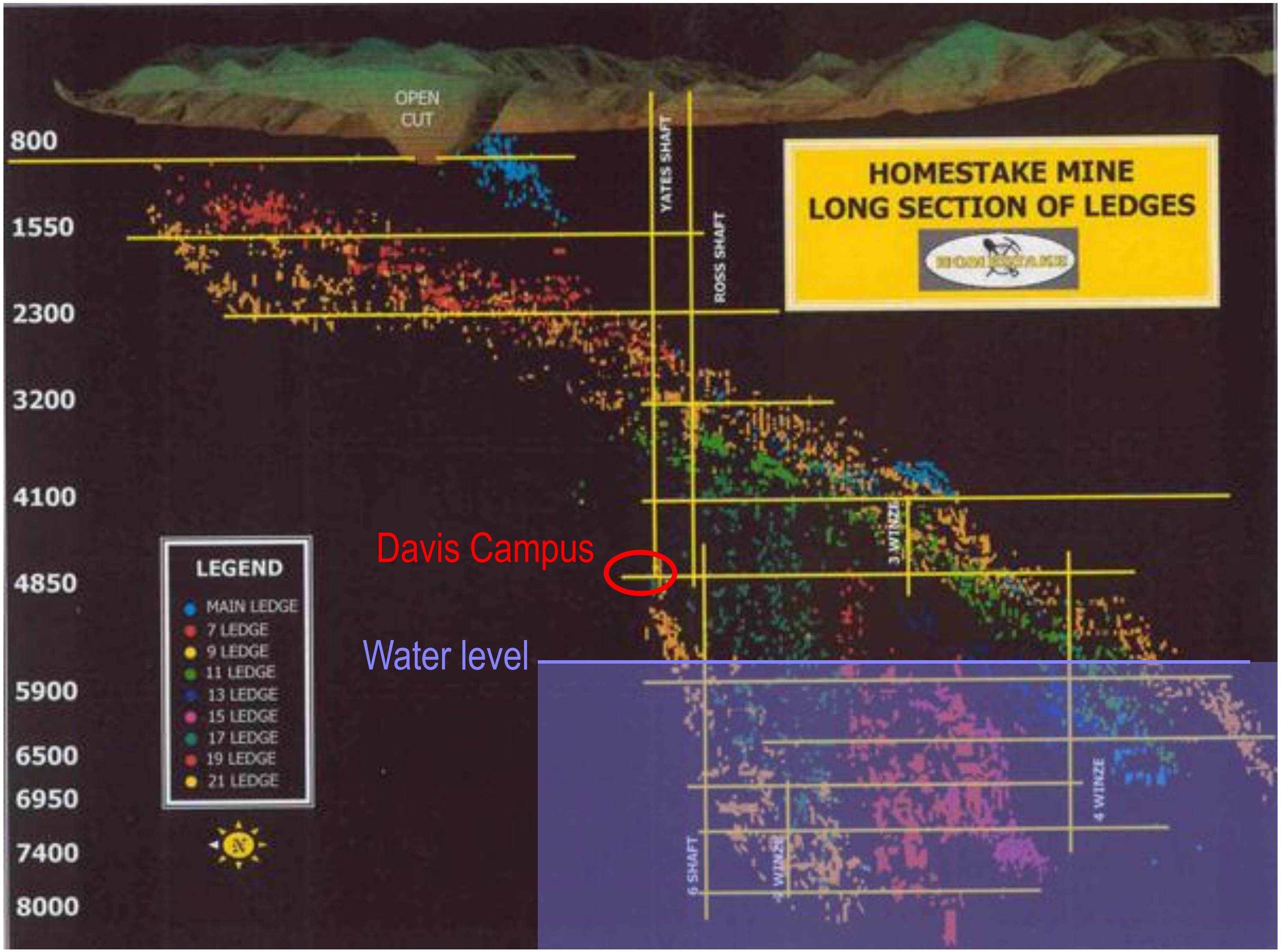


Access Tunnel to the Davis Underground Laboratory, Dec 2011

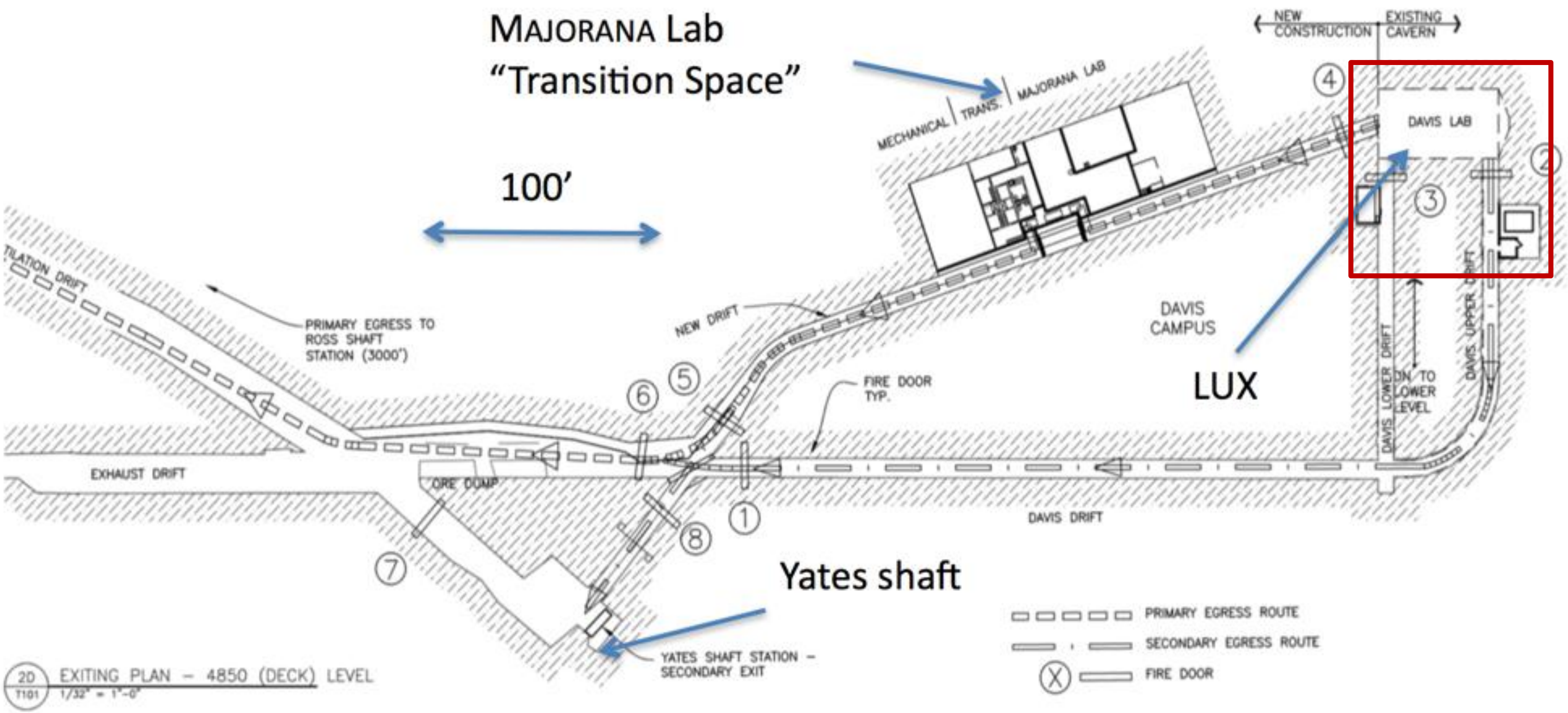
Boldly going where no detector has gone before

The LUX Experiment: Underground

Sanford Lab – Davis Laboratory



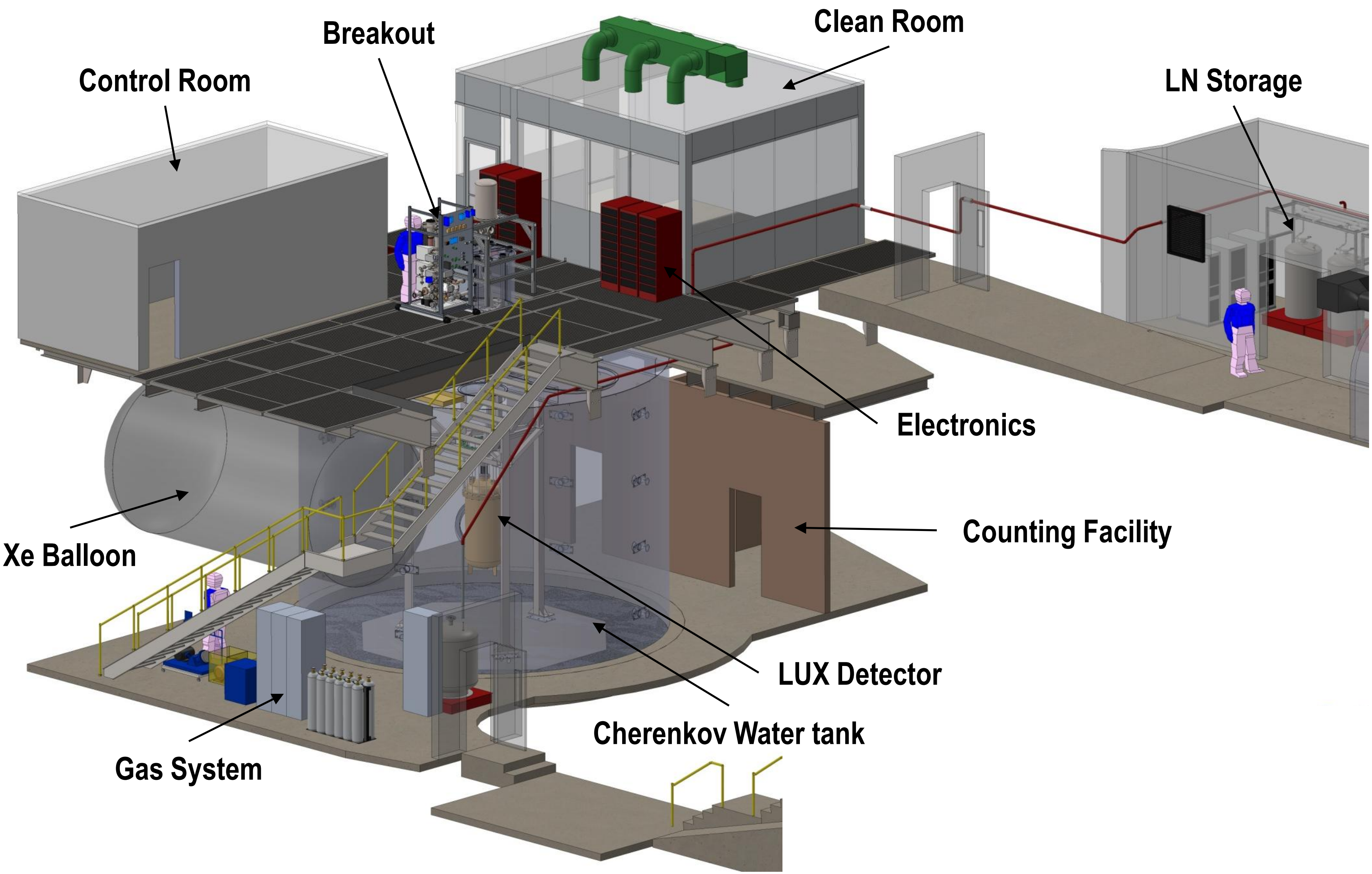
Sanford Lab – Davis Laboratory



Davis Campus, 4850' level, near Yates shaft

Was flooded until May 2009!

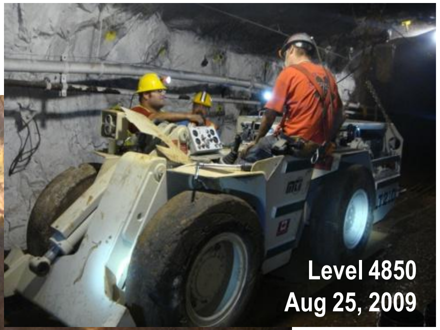
Sanford Lab – Davis Laboratory



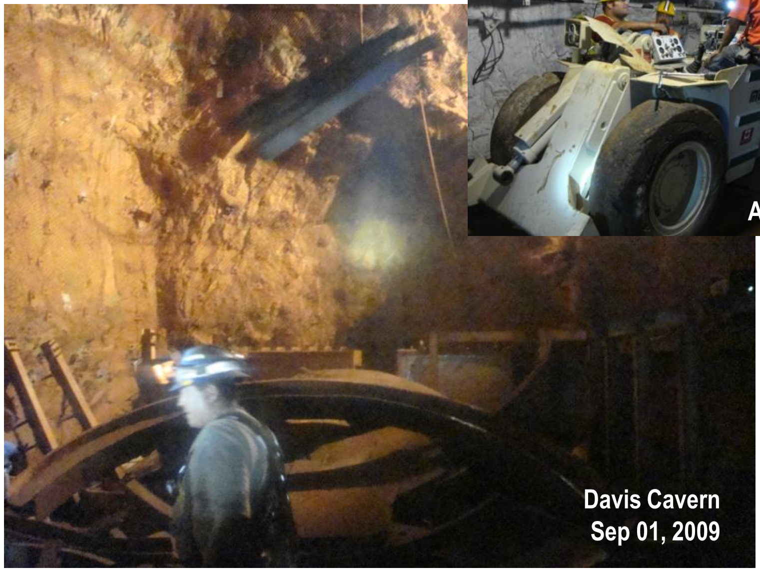
Davis Campus – Construction Schedule

- May 2009 : 4850 ft level dewatered
- Aug 31 2009: Began excavation of new drift
- Sep 10 2009: Steel structures removal complete
- Nov 15 2009: Detailed Construction Docs complete
- Jul 2010: Excavation complete
- Feb 2011: Outfitting Documents complete
- Jun 2011: Begin Lab outfitting
- Jun 2012: Lab ready


Davis Cavern
Aug 20, 2009


Level 4850
Aug 25, 2009


Davis Cavern
Aug 24, 2009


Davis Cavern
Sep 01, 2009

Davis Laboratory – February 2011

Transition Area

Davis Cavern

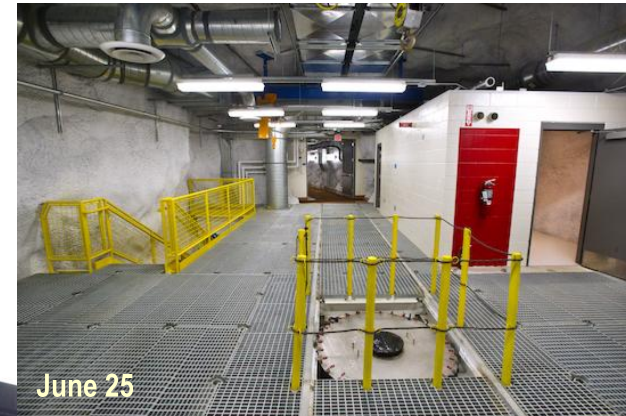
Davis Campus – December 2011

Davis Campus – February 2012

Davis Campus – Summer 2012

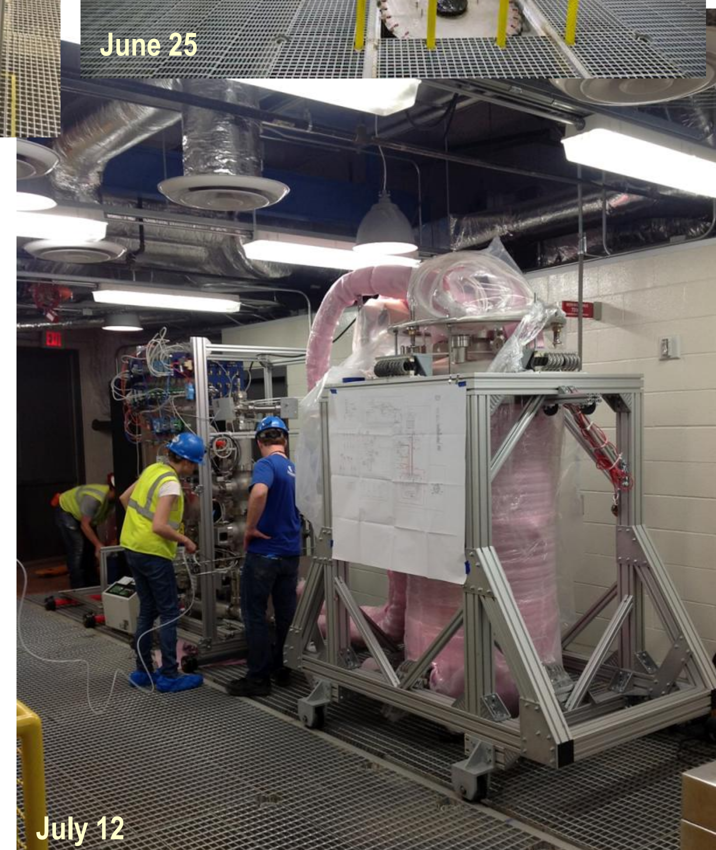
June 15

July 6



June 25

June 29



July 12

August 25

Davis Campus – September 2012

LUX – Underground Program (1)

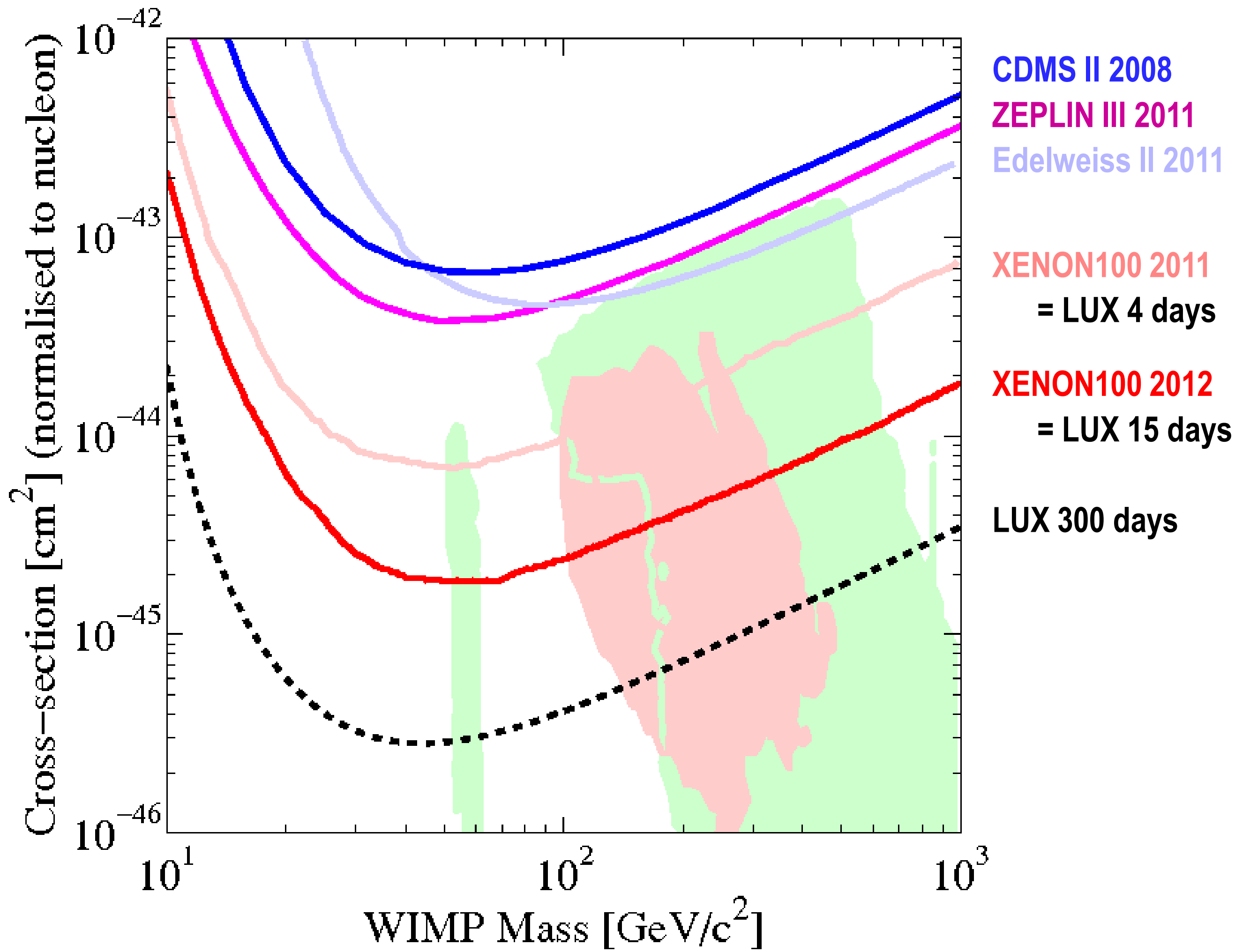
- February 2012: End of Operations at Surface Lab
  - Start relocating equipment by June 15
  - Detector transported July 11
- June 2012: Davis beneficial occupancy. Installation ~ 3 months
  - Bring in subsystems: gas system, Xe storage, electronics…
  - Bring in detector + breakout cart
  - Fill water tank and start water circulation system
  - Meanwhile: Purify the xenon at CWRU (Kr removal)
- September 2012: LUX detector installed underground
  - ~6 weeks for all systems check-outs
  - ~5 weeks for cool down and condensing xenon, start circulation
  - ~3 weeks to reach acceptable Xe purity and stable operation
- January 2013: Start of Science Run

LUX – Underground Program (2)

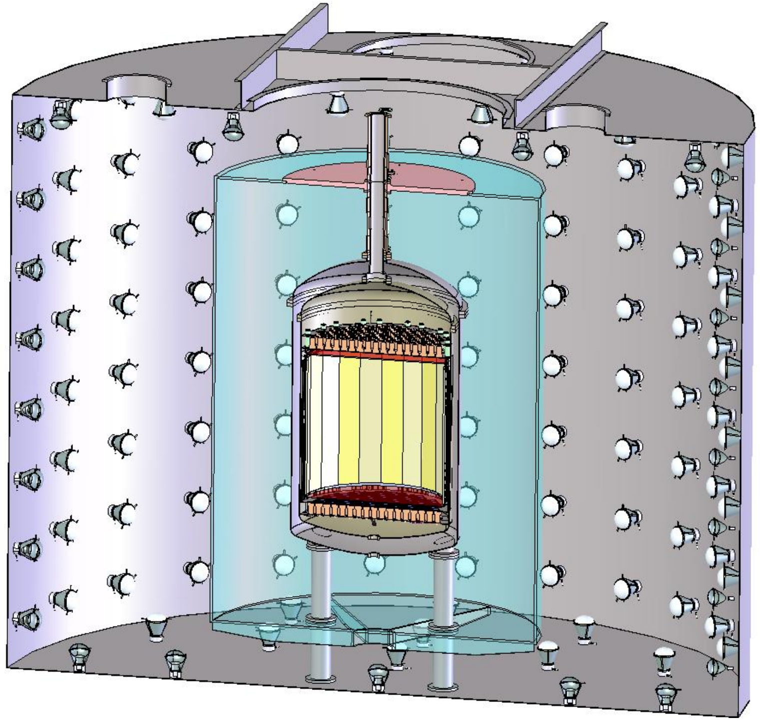
- **January 2013: Start of Science Run**
  - **1 month to first data release**
    - **In ~15 days of low-background data, we match the current best WIMP sensitivity**
  - **Intermediary result: 60 live days**
    - **Refine analysis and cuts, efficiencies**
    - **Improve current best sensitivity by x2 – x3 (dep. on background)**
  - **Science goal = 300 live days of low-background data**

    + a few live weeks of calibration data (neutron + gamma)
- **February 2014: Earliest possible date for end of LUX campaign**
  - **We will certainly have enough interesting additional data to take for several months after the 300 live days**
- **Keep taking data until LZ detector is ready to be built underground.**

LUX WIMP Sensitivity Goal



And if that is not enough…?

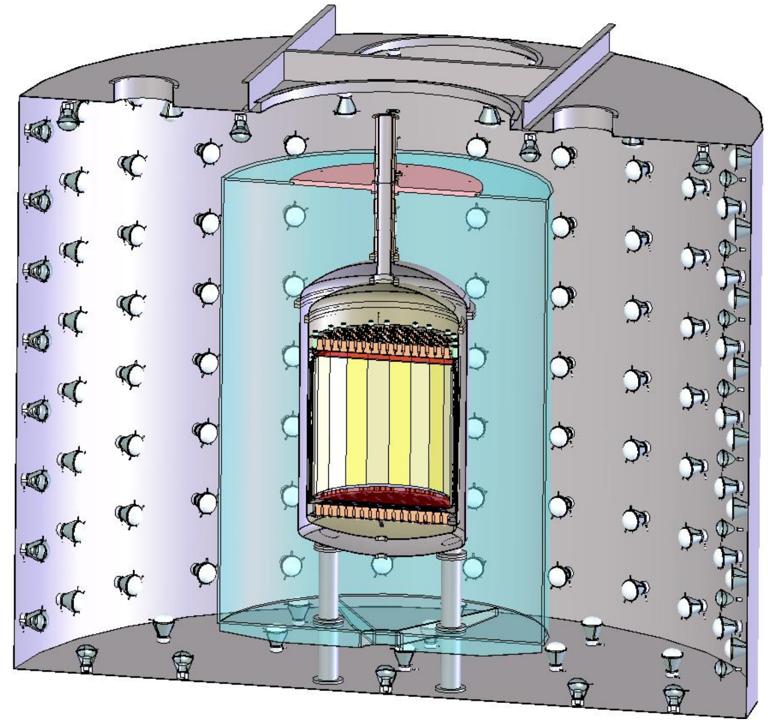


The endgame is near

Next: The LZ Program

LZ Program – Overview

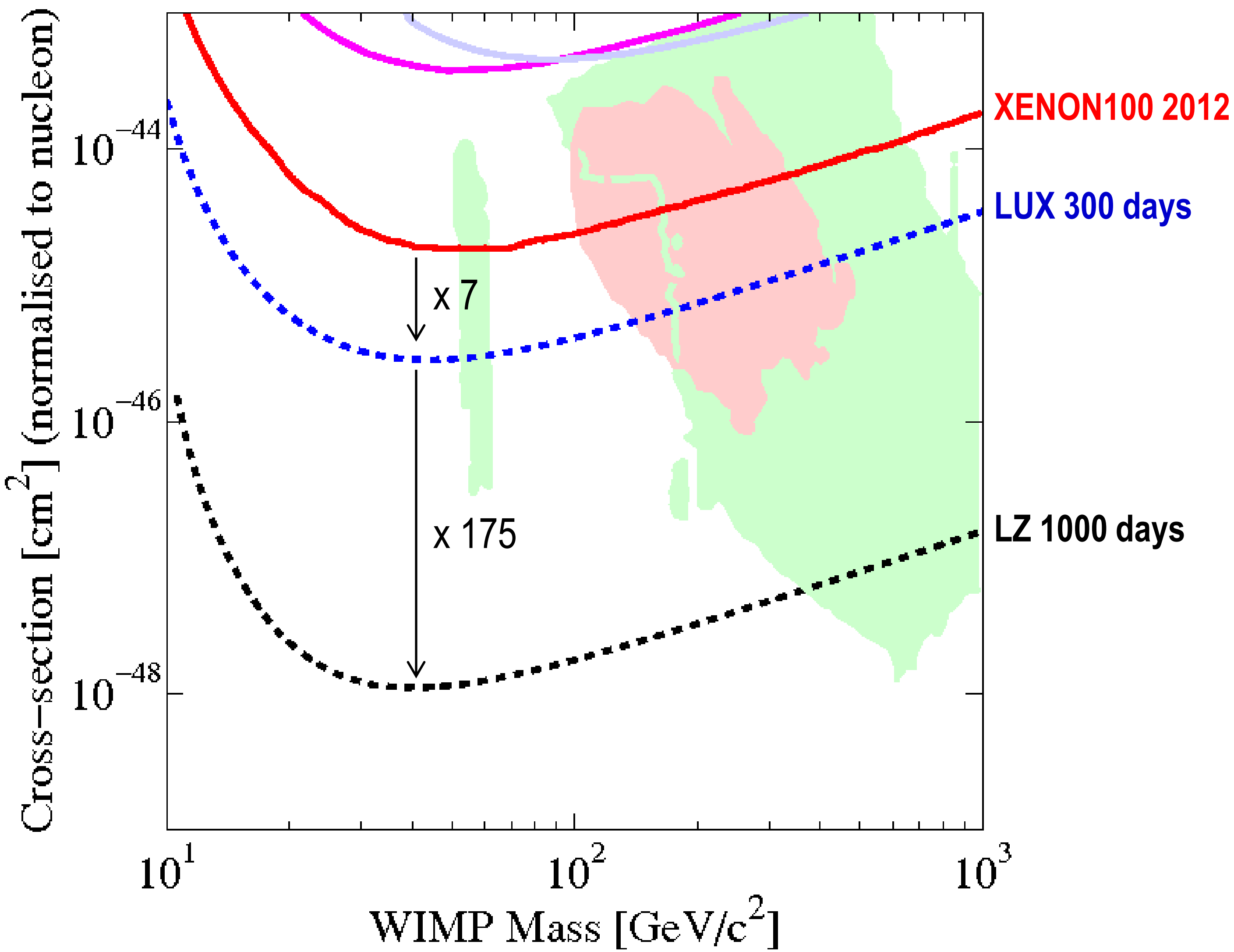
- Born from the joining of LUX and ZEPLIN
- Construction 2014-2016
- Run 2016- 2019 (…?)
- New features compared to LUX
  - Increased Xe mass : 7t total, 5t fiducial
  - 482 3" PMTs at ~1 mBq radioactivity level
  - Liquid Scintillator shield/veto
  - Instrumented « dead » Xe space
  - Improved Cherenkov veto coverage



LZ uses the same water tank as LUX in the Davis Lab

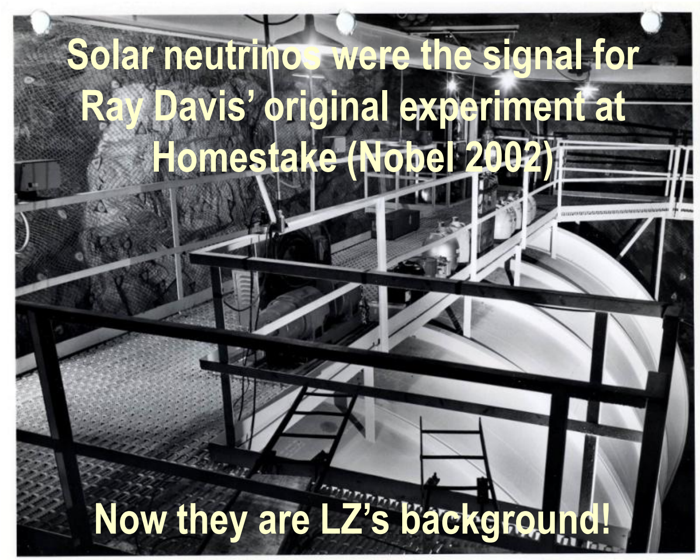
- ...That’s it. Progress in sensitivity comes chiefly with:
  - Increasing the Xe mass
  - Scaling up existing LUX technology
  - Xe self-shielding is driving the background rates down dramatically
- R&D effort ramping up since 2011, Project Management through LBNL

LZ Program – WIMP Sensitivity Reach

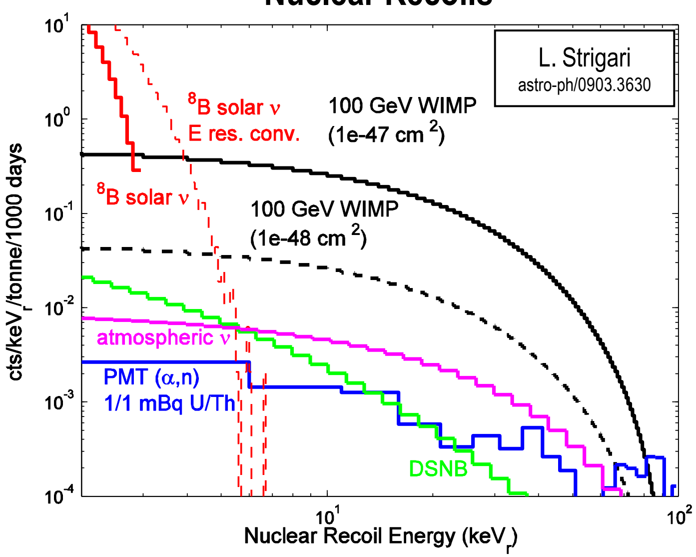


LZ, ultimate Dark Matter instrument?

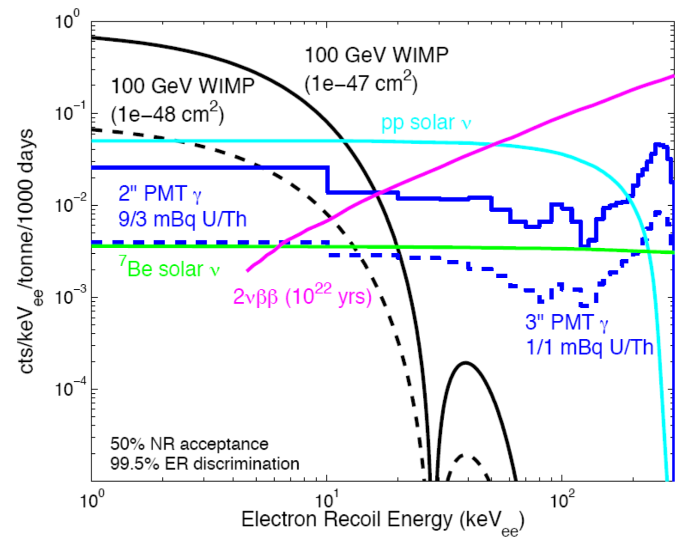
- Electron Recoil signal limited by p-p solar neutrinos
  - Subdominant with current background rejection
- Nuclear Recoil background: coherent neutrino scattering
  - ^{8}B solar neutrinos
  - Atmospheric neutrinos
  - Diffuse cosmic supernova background
- LZ reaches this fundamental limit for direct WIMP searches



Nuclear Recoils



Electron Recoils




This is what particle physicists look like 1 mile underground

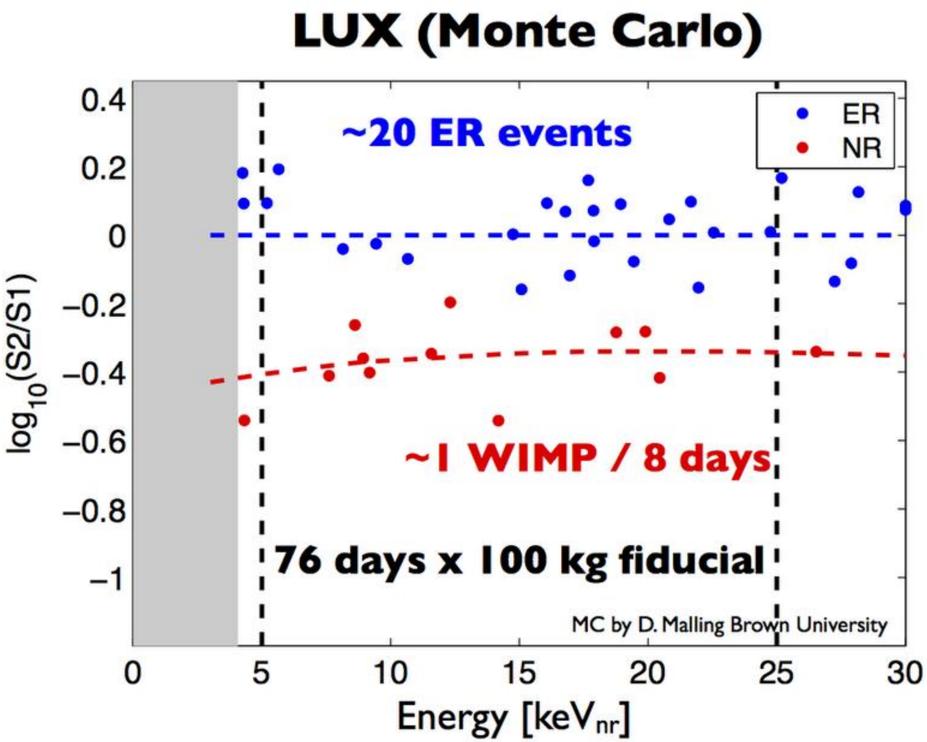
If you have remained awake and in the room until now,

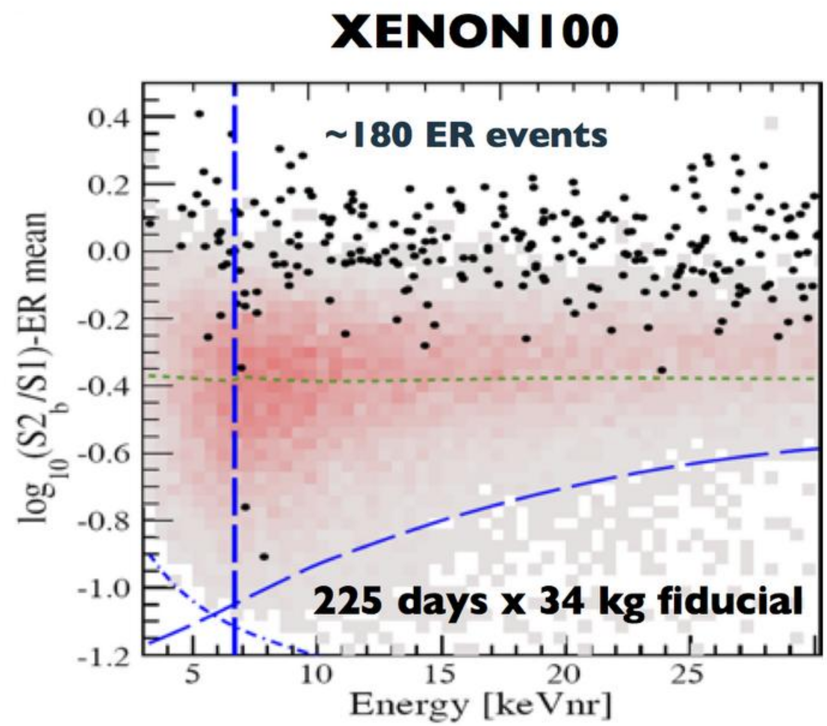
Thank you!

Because this was not long enough already…

Additional Slides

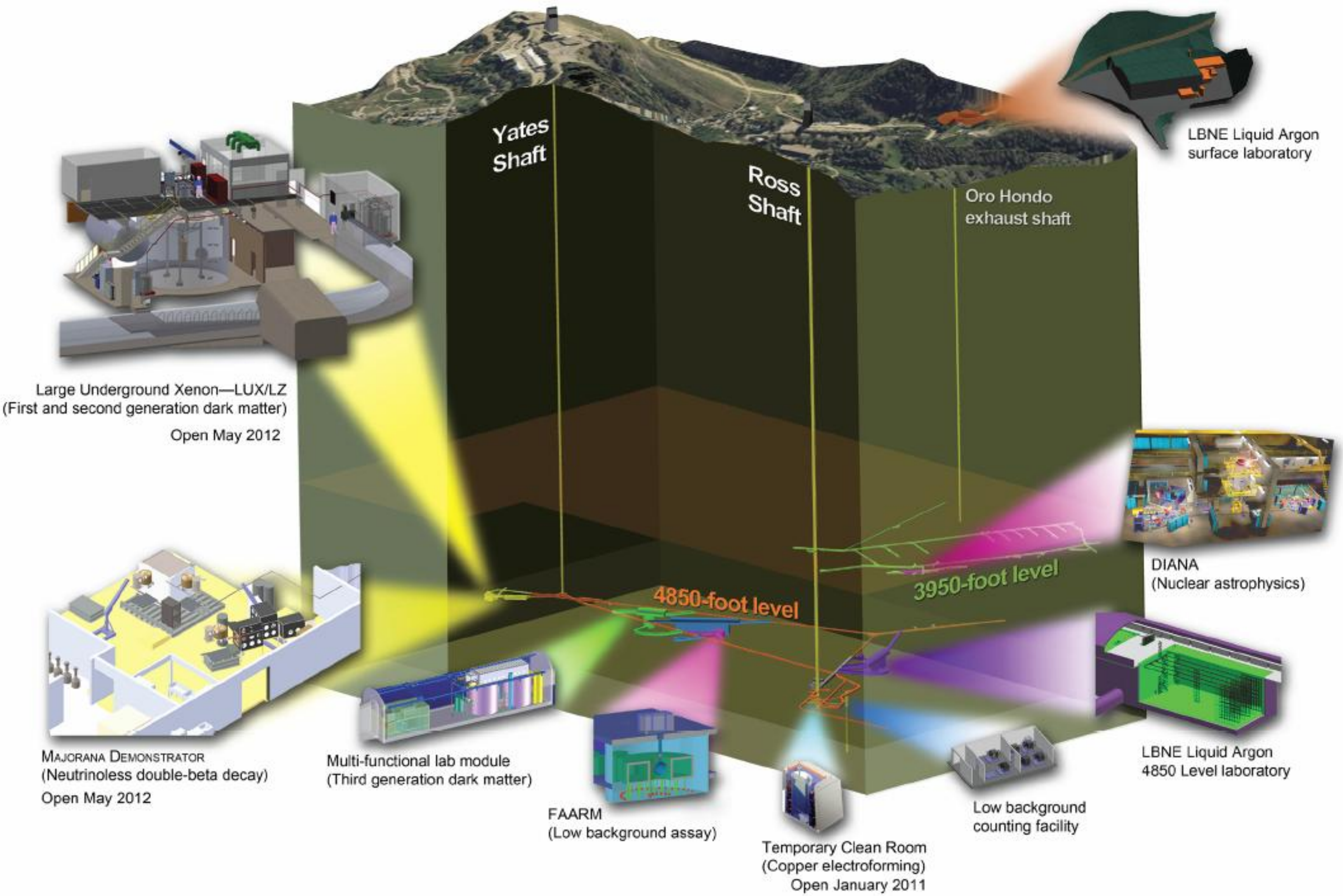
LUX – XENON100 Comparison





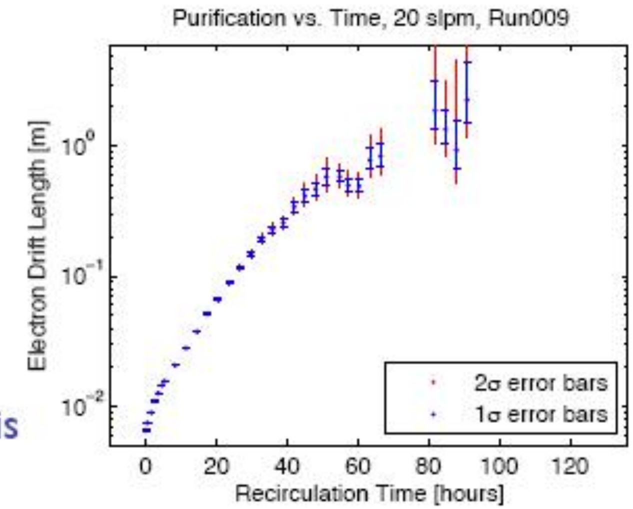
Comparison of LUX and XENON100 data for the same exposure of 7600 kg.d, from the latest XENON100 result (July 2012). LUX data is simulated from known radioactive background components. The WIMP signal in red corresponds to a 100 GeV/c^2 WIMP with a cross-section at the current best sensitivity limit of 2.5 10^{-45} cm^2. The ER background is one order of magnitude lower, allowing for a clearer detection signal or a stronger limit.

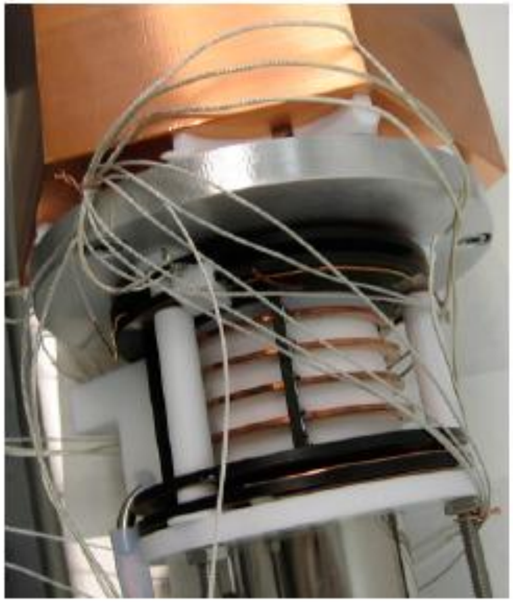
Future of Sanford Lab

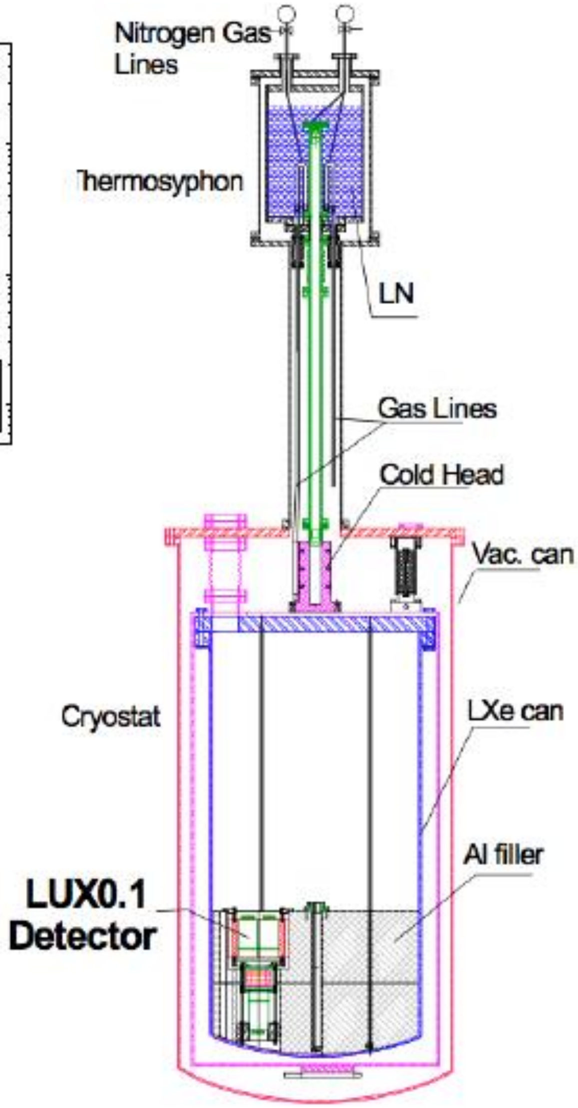


LUX 0.1 2007-2009

- Full integration of all LUX subsystems
- 60kg xenon
- 4 PMTs
- Thermosyphon
- Gas handling, circulation
- Electronics chain, DAQ, analysis
- Full test of LUX personnel (postdocs and graduate students)







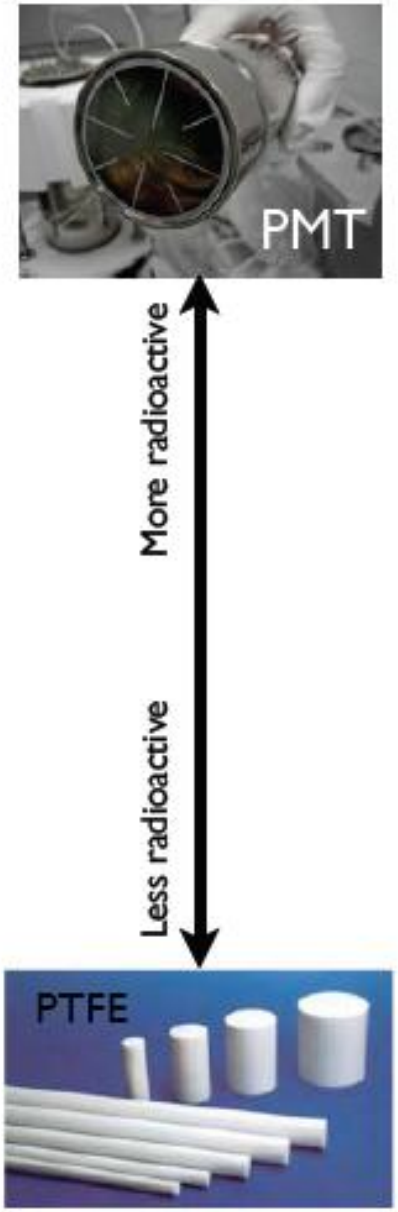
LUX Design – Low-radioactivity

- PMTs
  - 10/2/65 mBq/PMT (U/Th/K) and 2 n/year/PMT
  - However, multiply by x122 and consider the fact that they are right next to the active region...
  - They are the dominant source of internal background
  - In 30,000 kg-days, in fiducial region and in 5-25 keV$_r$, all PMTs would contribute:
    - 0.5 gamma events
    - 0.1 neutron events

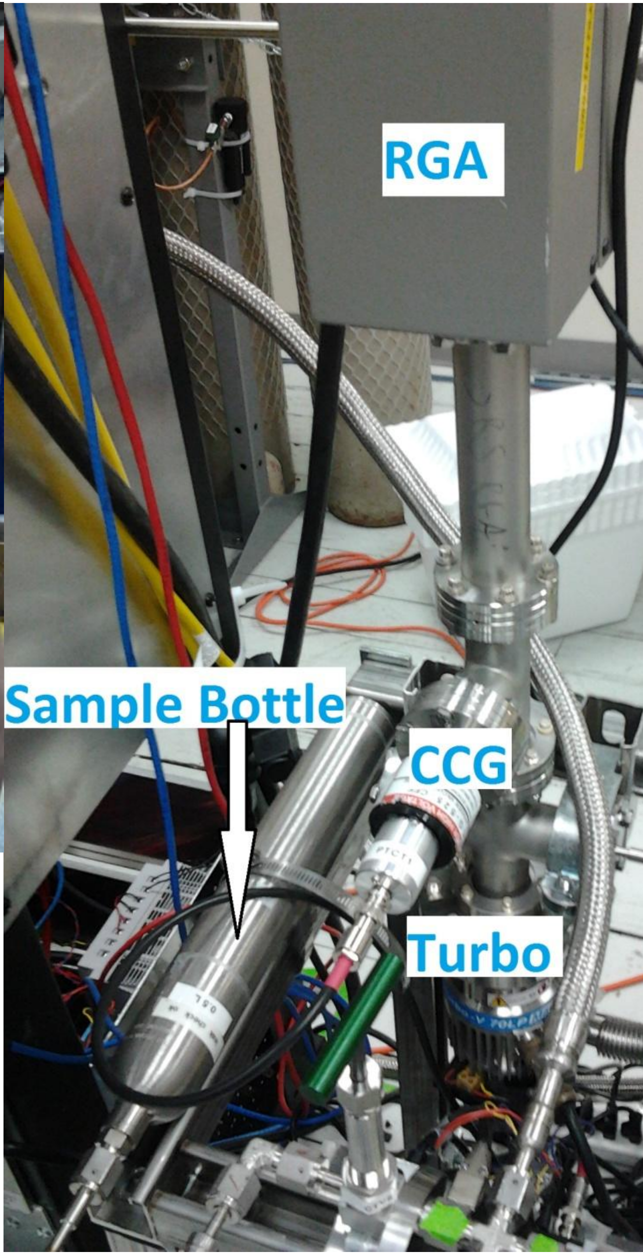
- Titanium Cryostat
  - Very low radioactivity: <0.4 mBq/kg U+Th
  - Largely subdominant

- Rn
  - Cleanroom reduces levels to < 40 Bq/m^3.
  - Minimize exposure, increase airflow

- Kr
  - Present in commercial Xe at ppm level. Reduced to <2 ppt with charcoal column separation



Circulation, Sampling and Storage



Circulation at 35 SLPM through purifier by diaphragm pump

In-situ xenon sample RGA analysis[1] sensitivity:
0.7 ppb O_2 mol / mol
0.5 ppt Kr mol / mol

1) A. Dobi et al., NIM-A, Vol. 675, 40-46 (2012) [arXiv:1109.1046]

LUX – Surface Program

- June 2011: Run 01 (3 weeks)
  - Using Ar gas, 20 PMTs, deploy in water tank
  - Run 01 goals: test all cryogenic systems, DAQ
- July - October 2011: Upgrades for full system
  - Install all PMTs (in clean room), finish plumbing, wire all DAQ
- November 2011 – February 2012: Run 02
  - Run 02 goals:
    - Confirm all systems ready for underground
    - Get first data on light collection, xenon purity

Great success
8 phe/keV

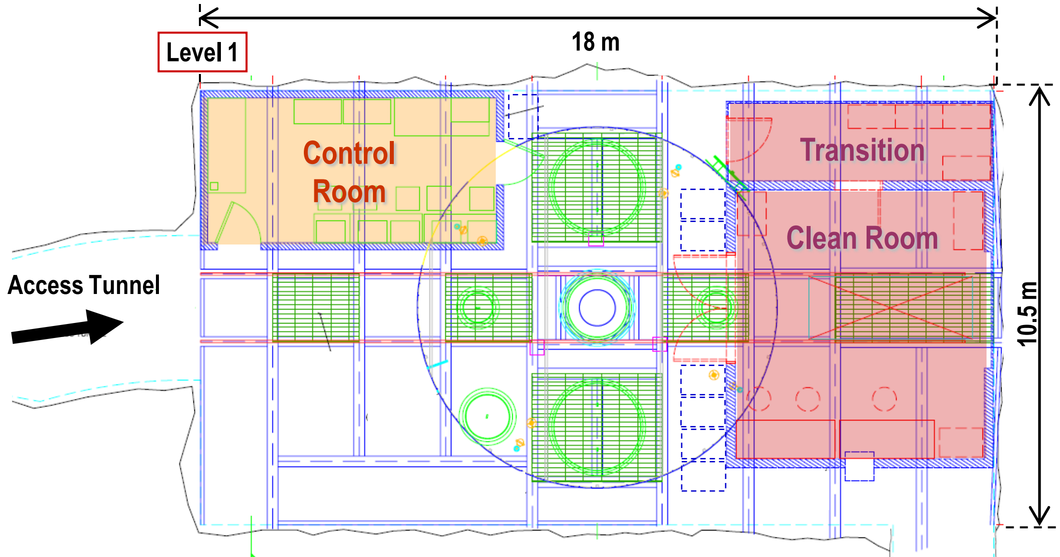
Limited by leak in
internal plumbing;
Still promising

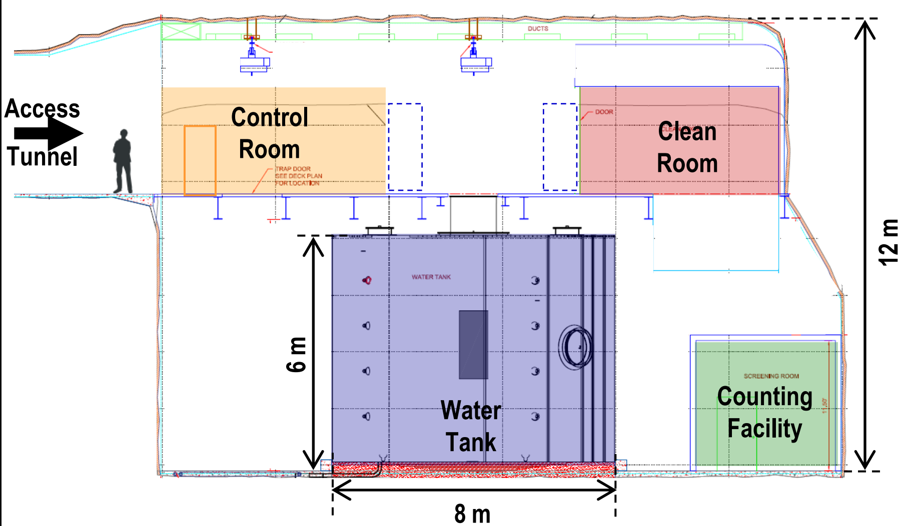
- March – July 2012: Last Upgrades and Fixes
  - Start moving equipment underground as early as March 30th
  - Move detector itself July 11, 2012

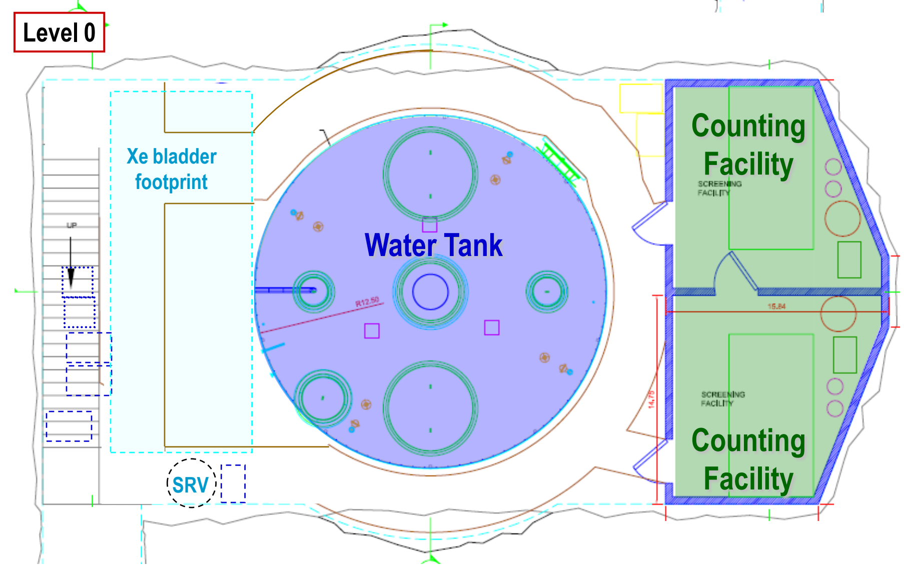
Sanford Lab – Davis Laboratory

The Davis Laboratory @ Homestake

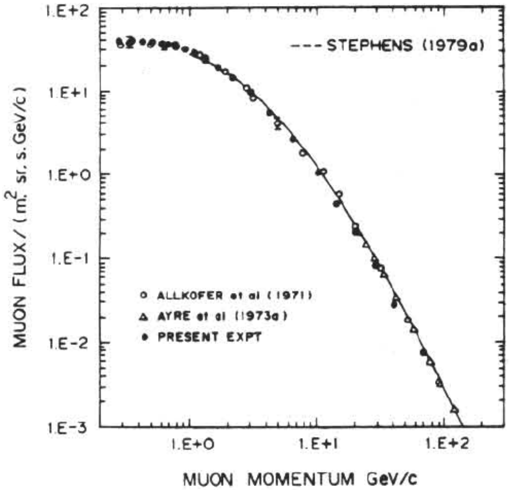
- Left: N-S vertical cross-section
- Top right: Plan view, level 1
- Bottom right: Plan view, Level 0

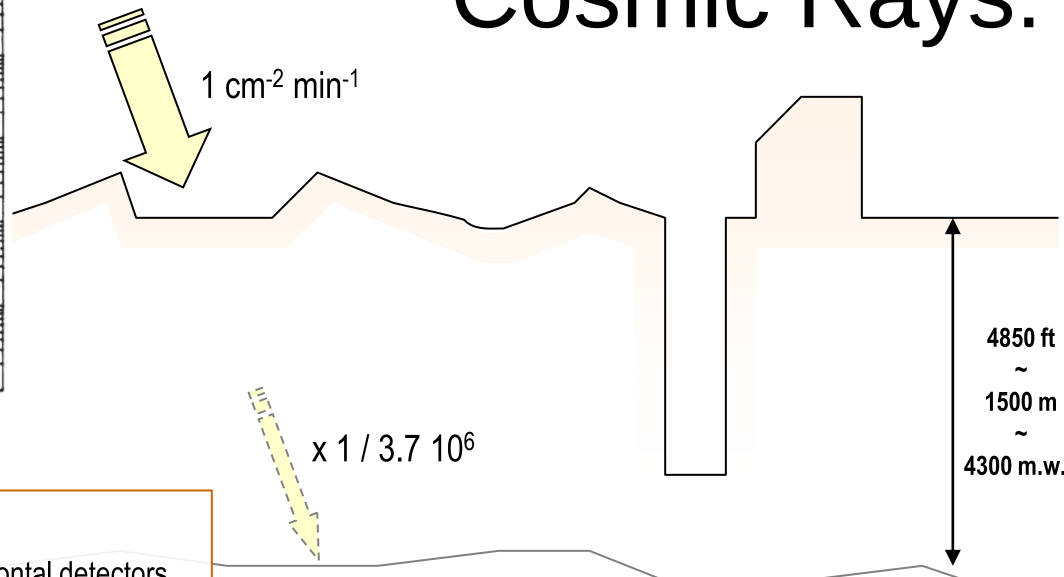




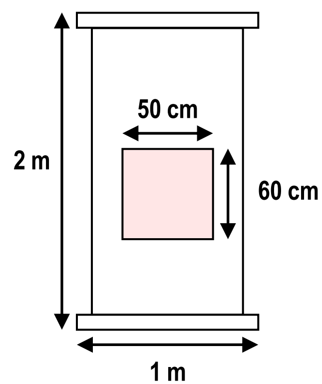


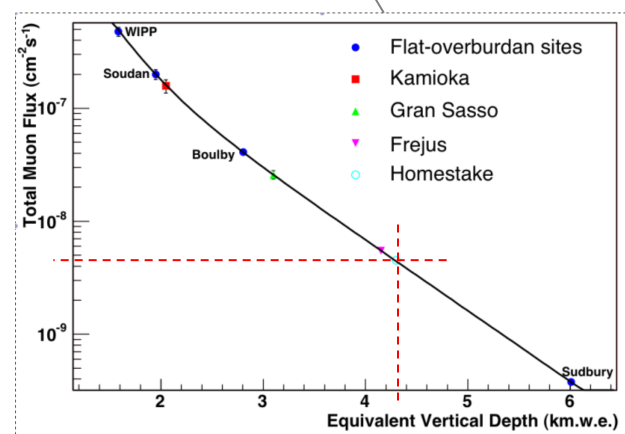
Cosmic Rays: Muons





- At sea level:
  - Flux ~ 1 cm^{-2} min^{-1} for horizontal detectors
  - E_{avg} ~ 4 GeV
- At Homestake 4850L:
  - Total flux divided by factor 3.7 10^6
  - E_{avg} ~ 320 GeV





Ref: Mei & Hime astro-ph/0512125

Internal Background Sources

- Screening of all internals and close materials
- Main Dangers
  - Cryostat (largest unshielded mass 325 kg)
  - PMTs and PMT bases (closest to Xe)
  - Xenon contamination