First results from the LUX Dark Matter Experiment

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DESY, Hamburg, Germany
December 17, 2013

Evidence for Dark Matter

Galaxy rotation curves

The cosmic microwave background

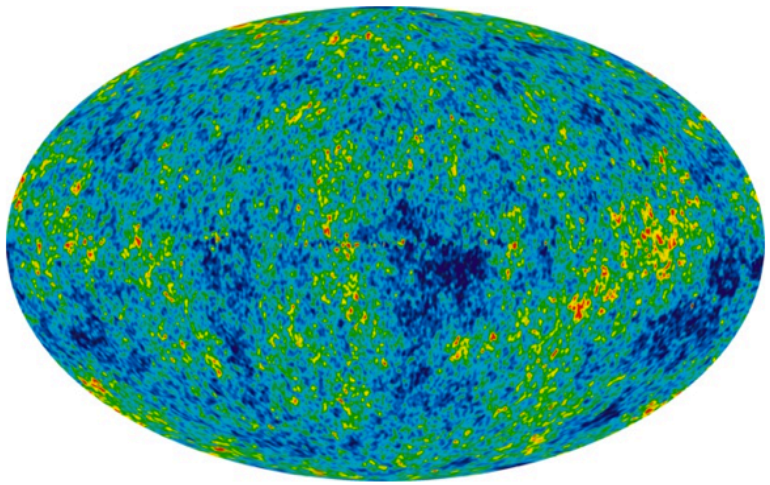
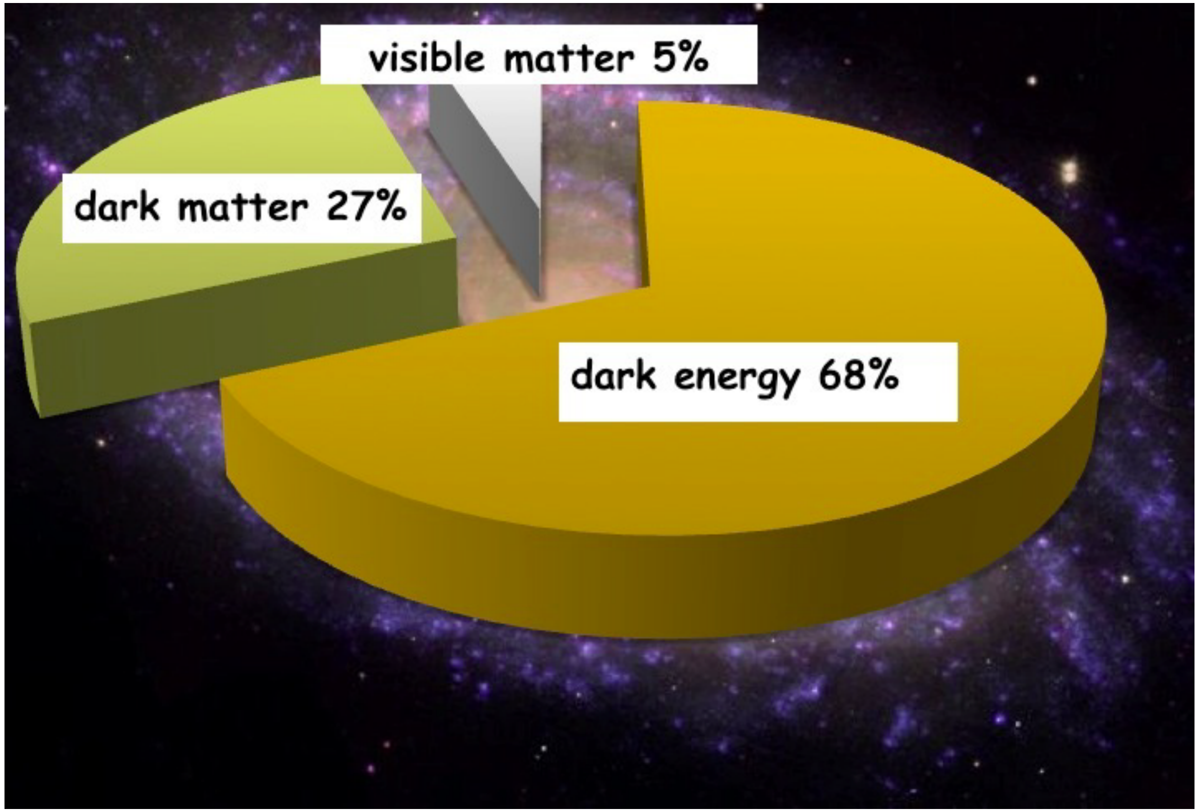


Image: ESA and the Planck collaboration

Gravitational lensing

Colley, Turner, Tyson, and NASA

Composition of the Universe



$$\frac{\textbf{Dark Matter}}{\textbf{Ordinary Matter}} \approx \mathbf{5.44 \pm 0.14}$$

Weakly Interacting Massive Particles (WIMPs)

A new particle that only very weakly interacts with ordinary matter could form **Cold Dark Matter**

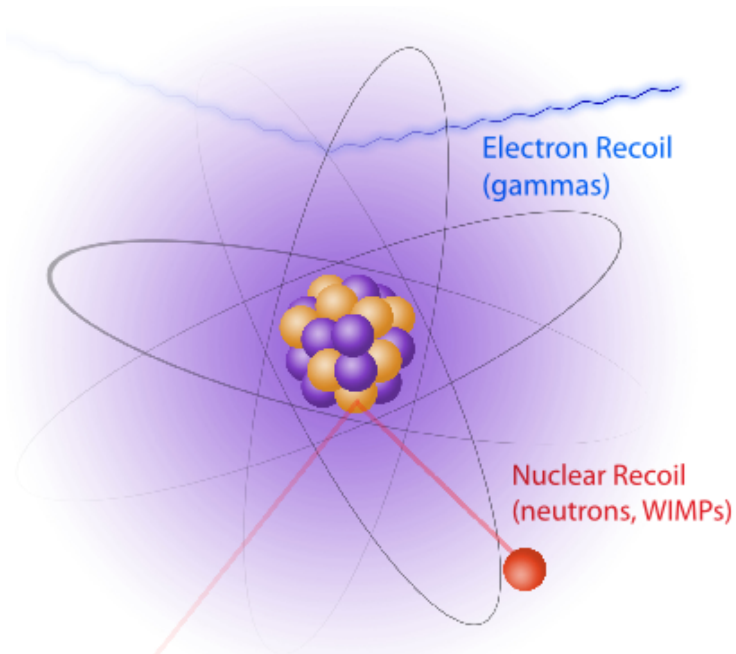
- Formed in massive amounts in the Big Bang.
- Non-relativistic freeze-out. Decouples from ordinary matter.
- Would exist today at densities of about $1000/m^3$.

Supersymmetry provides a natural candidate – the **neutralino**

- Mass range: ~ 1 GeV – 1 TeV
- Wide range of cross-sections with ordinary matter: 10^{-40} - 10^{-50} cm^2.
- Charge neutral and stable

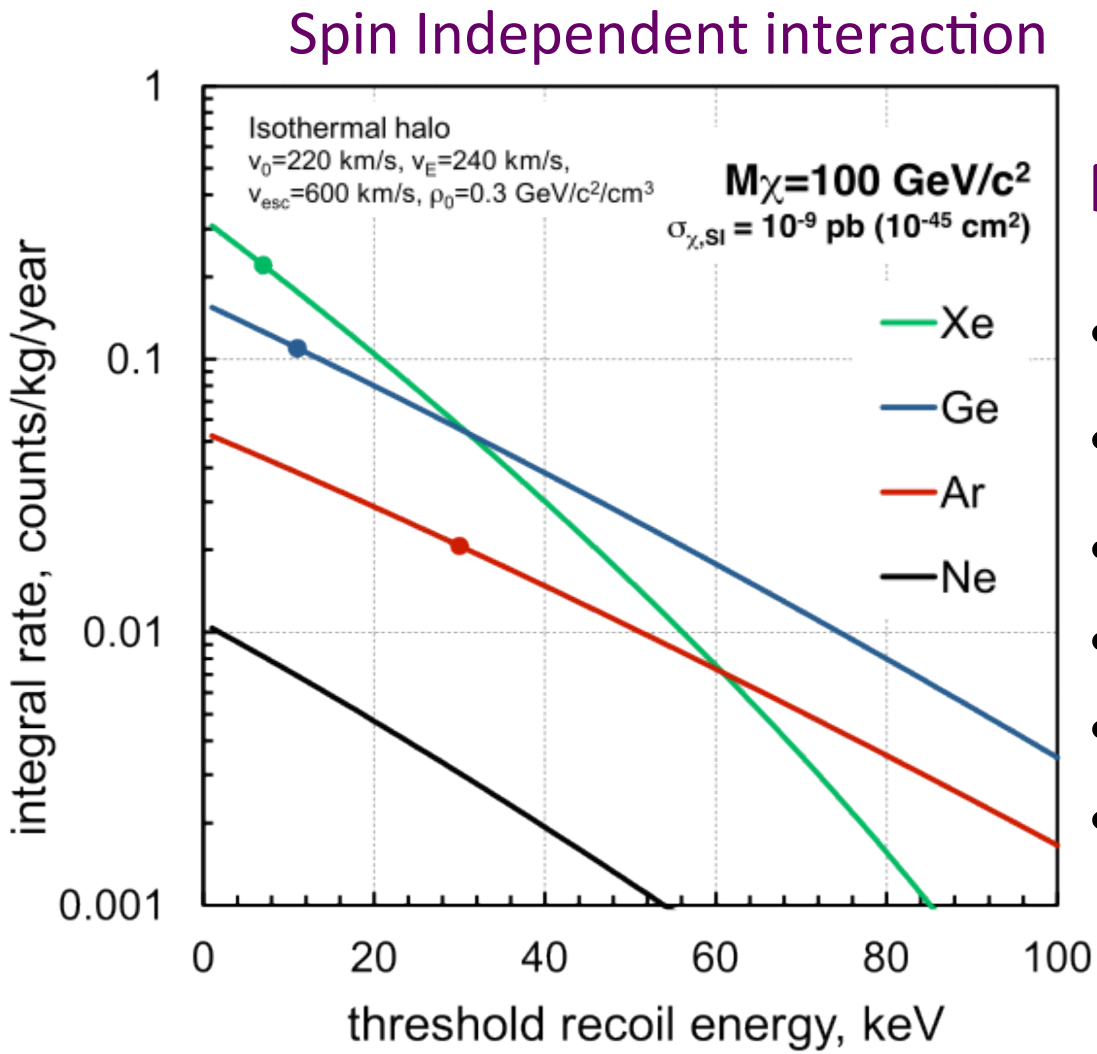
Direct Detection of Galactic WIMPs

Elastic scattering of galactic WIMPs with the nucleus of the target material.



- WIMP speed ~220 km/s
  → expect recoil energy <10 keV
- Expect < 1 event/kg/year
- Spin-independent cross section $\propto A^2$
- Spin-dependent interation ($J \neq 0$)

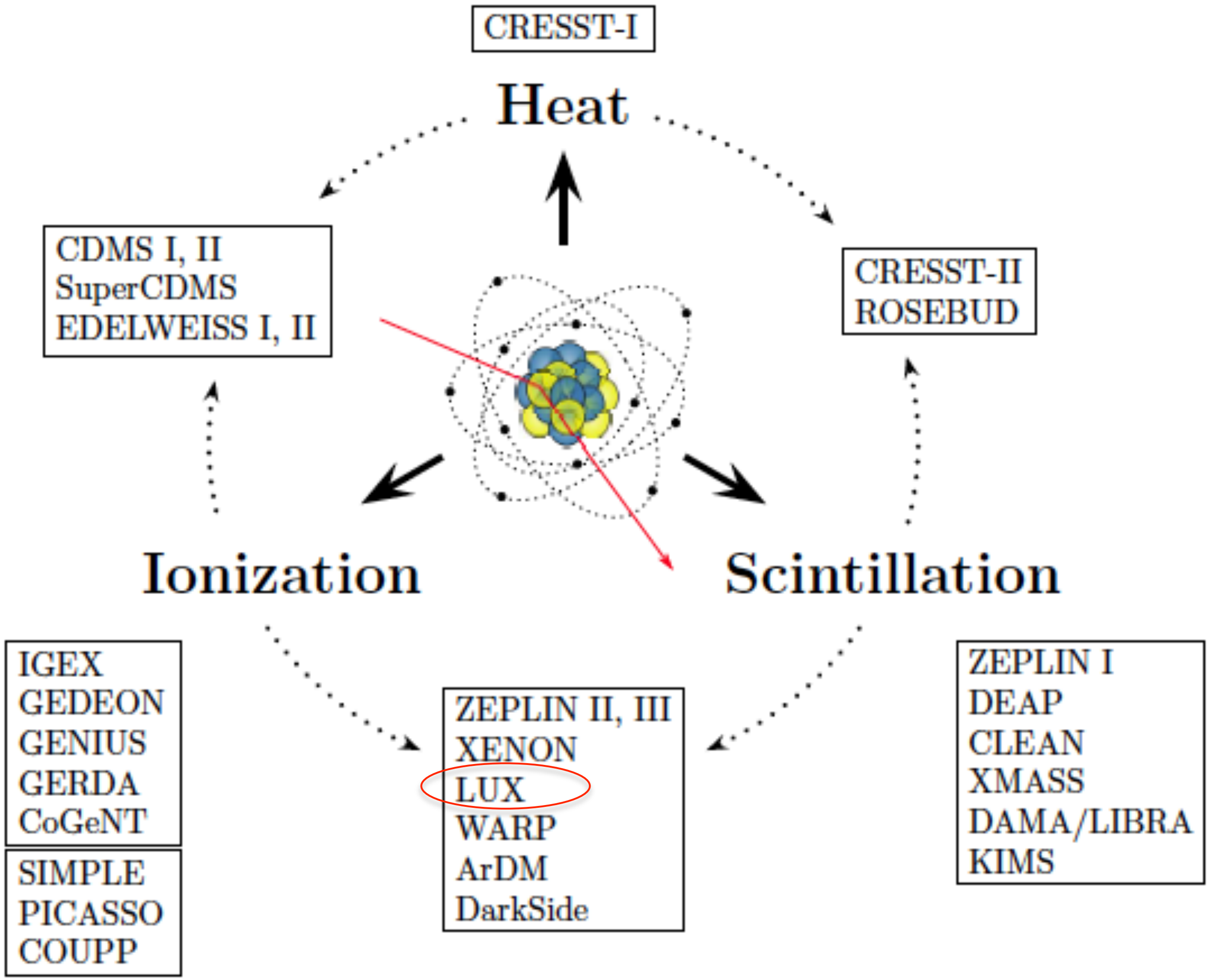
Direct Detection of Galactic WIMPs



Requirements:

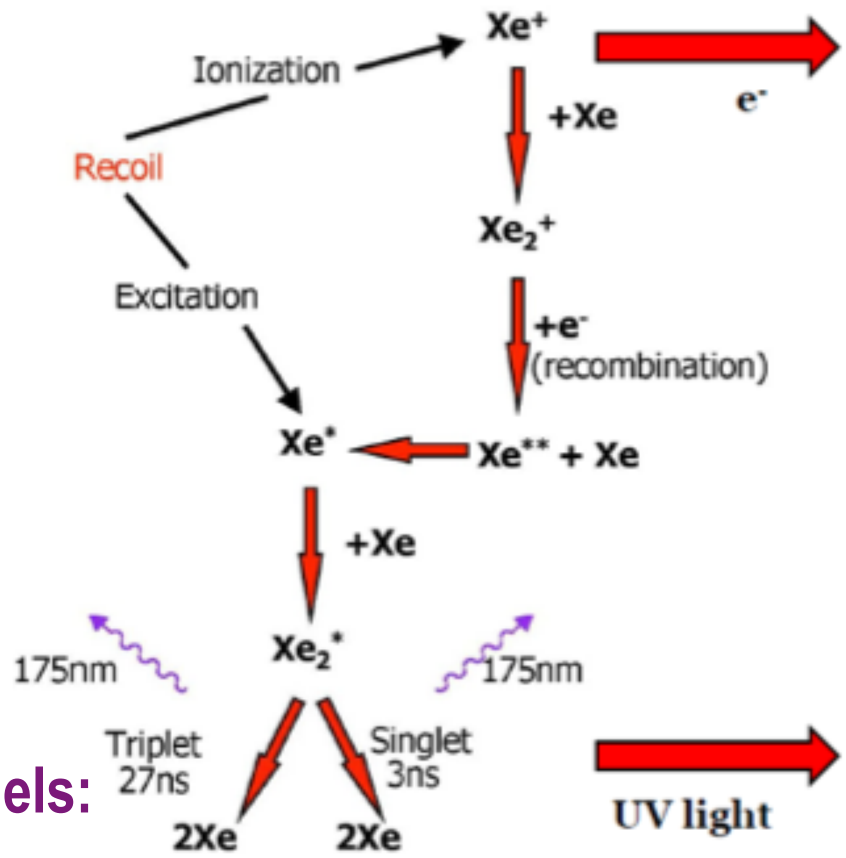
- Low energy threshold
- Large mass
- Low radioactivity
- Deep underground lab
- Gamma ray rejection
- Scalability

Direct Detection Techniques



Why xenon for WIMP detection?

- High atomic mass (A=131 g/mol)
- Relatively high density (2.9 g/cm3)
- Spin-dependent sensitive isotopes
- Large light output and fast response
- Long electron drift lengths (~1 m)
- No intrinsic backgrounds
- Self-shielding (using position recons.)
- Scalable to multi-ton size

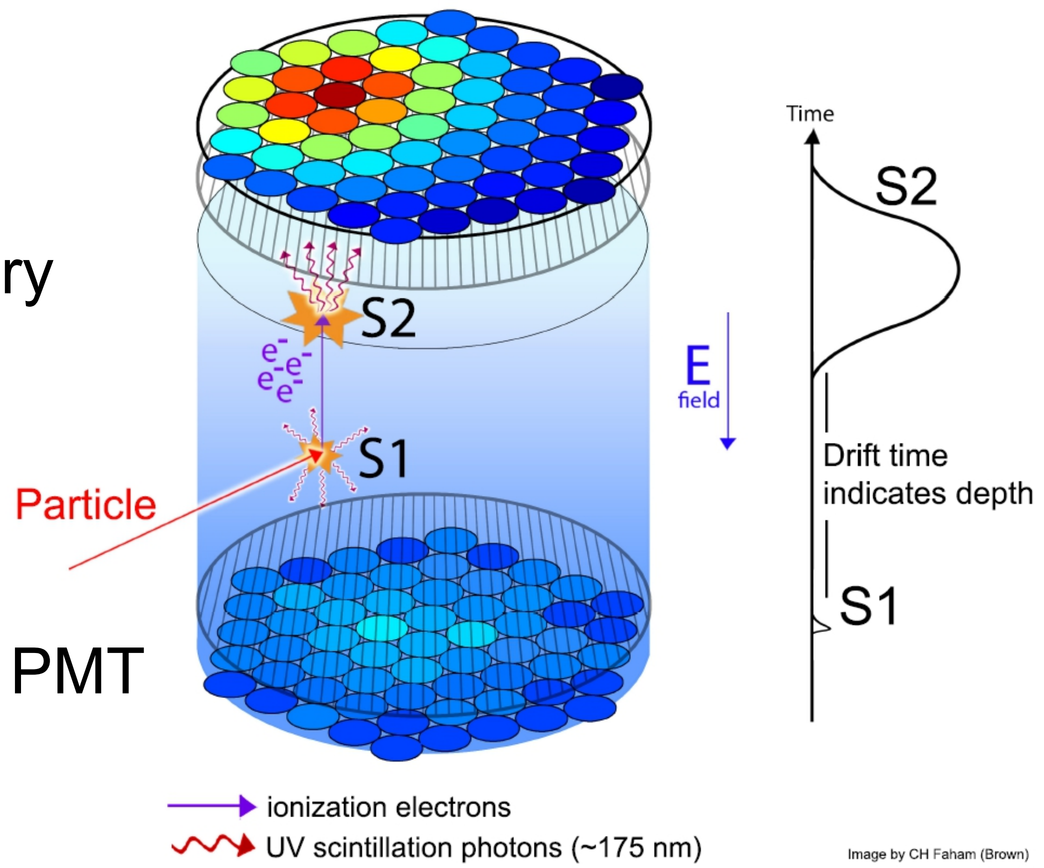


- **Recoil energy deposited in two channels:**
  - **Light**
  - **Charge**

Dual phase xenon TPC

Gas and Liquid Xe

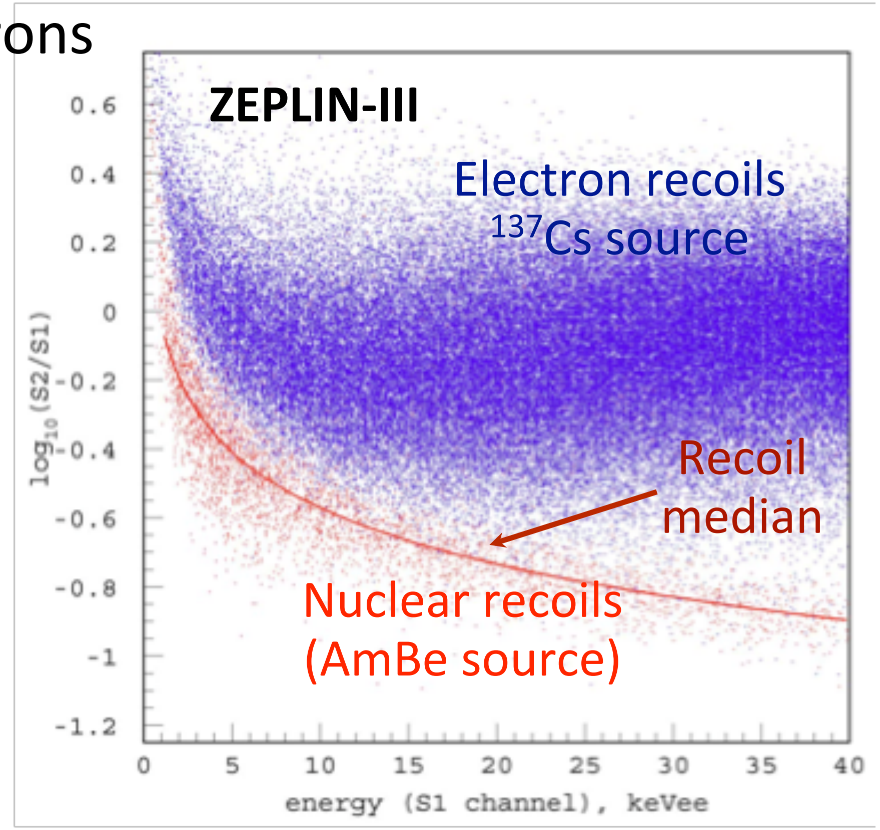
- Primary scintillation (S1)
- Electrons produce secondary scintilation(S2) in the gas
- 3D imaging
  - Z from S1 – S2 timing
  - X-Y from light pattern in PMT array(s)



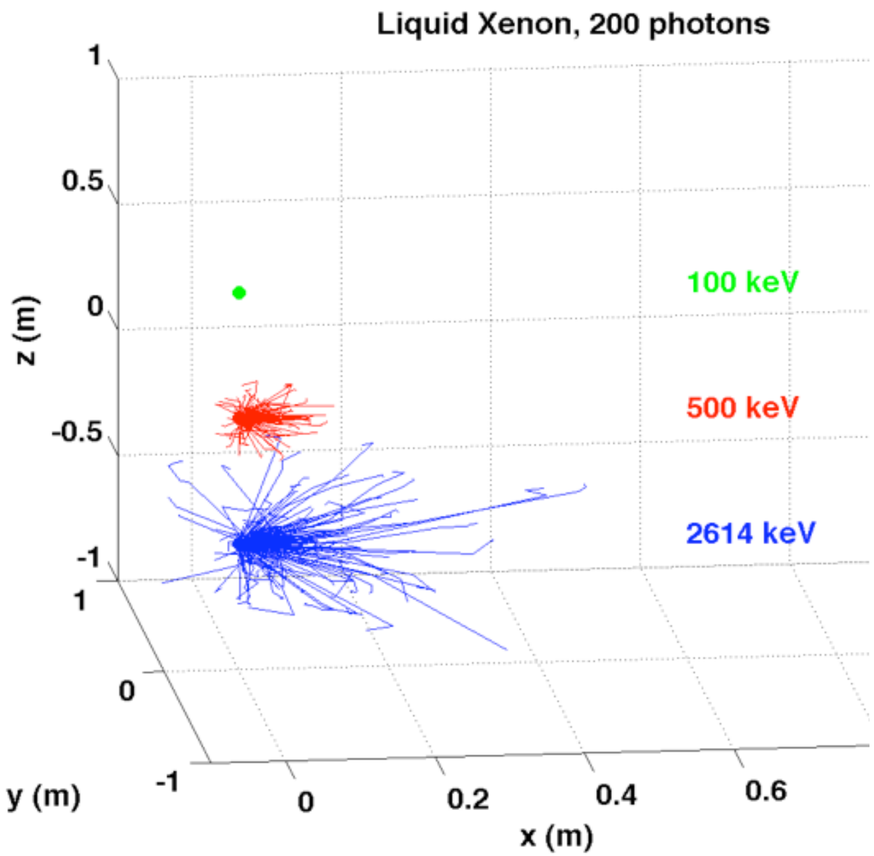
Dual phase xenon TPC: electron/nuclear recoil discrimination

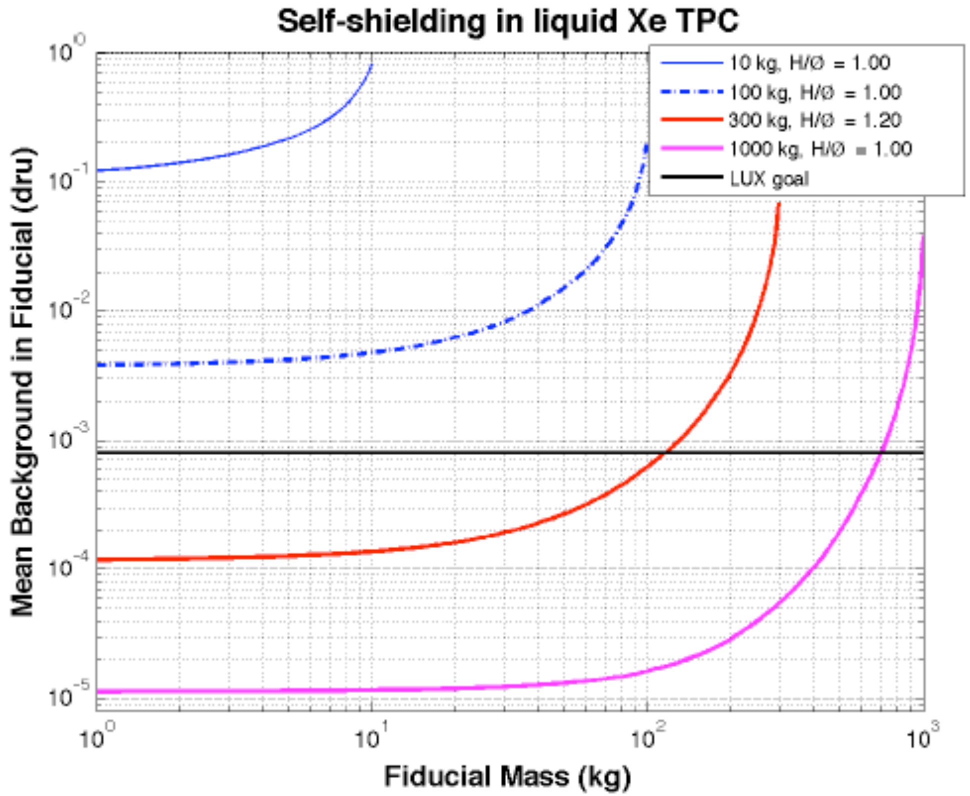
- WIMPs and neutrons interact with nucleus ⇒ short, dense tracks
- γs and e$^-$ interact with atomic electrons ⇒ long, less-dense tracks
- S2/S1 used for discrimination

$(S2/S1)_{\gamma e} > (S2/S1)_{WIMP}$



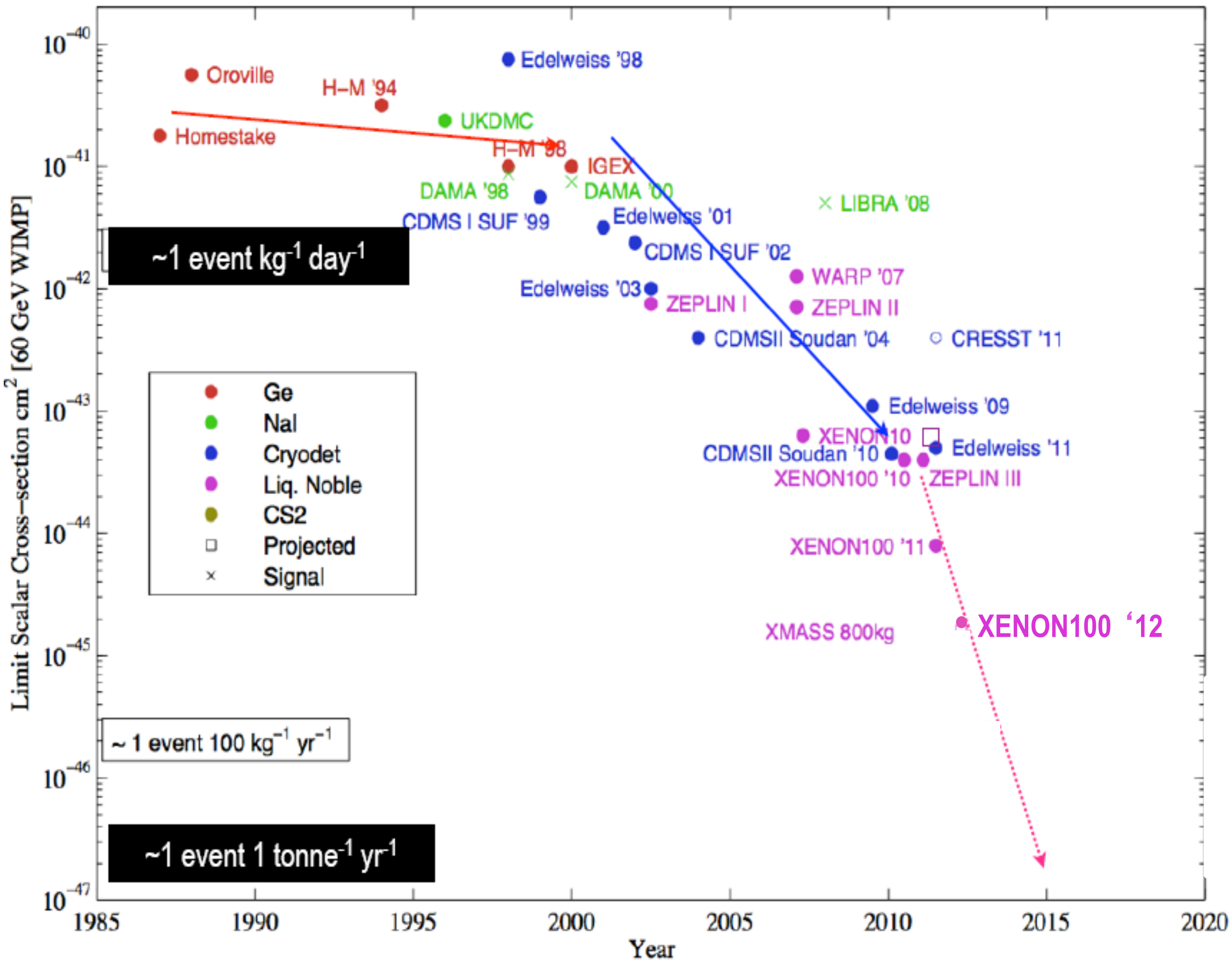
Liquid xenon self-shielding



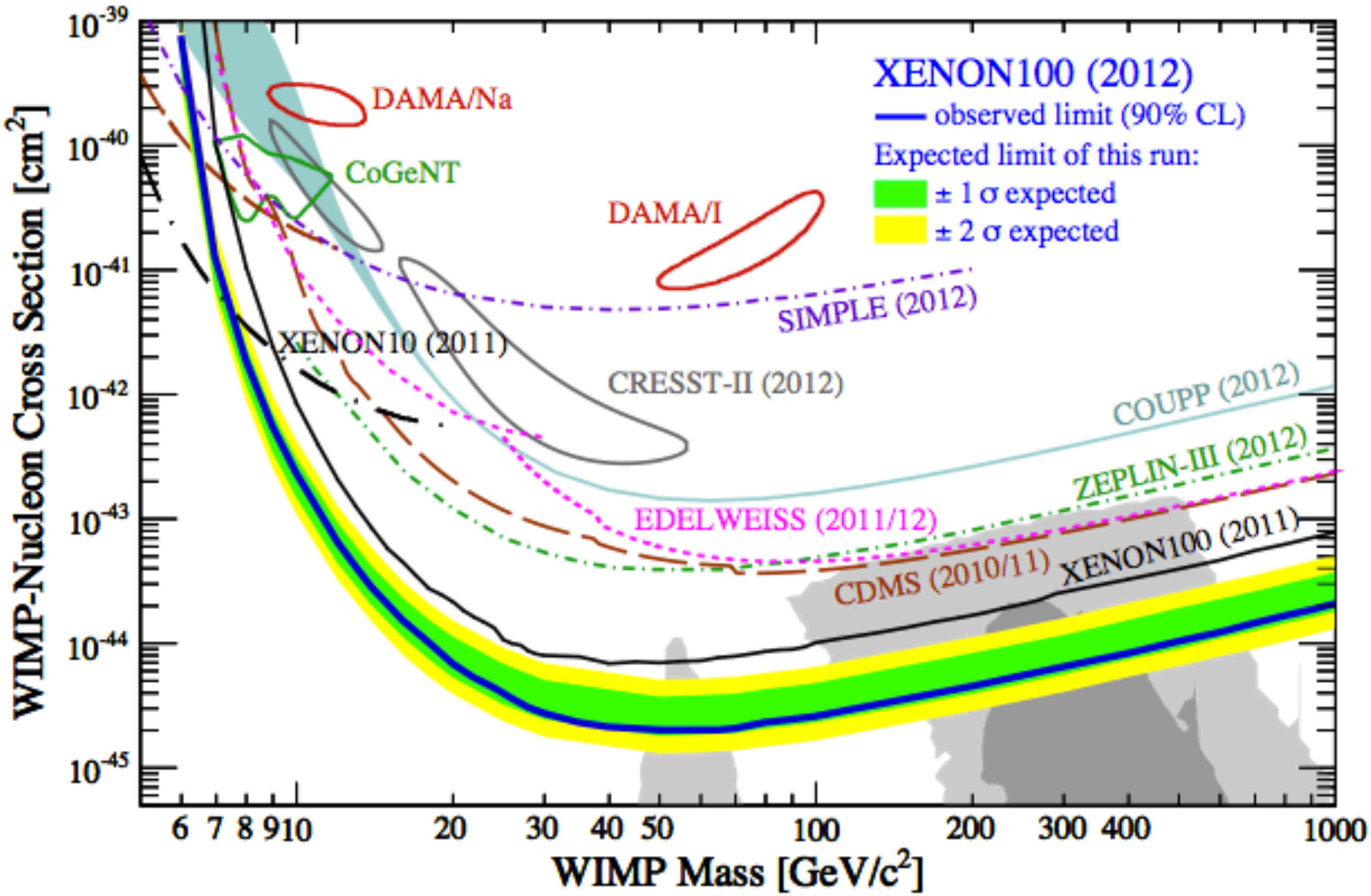


Make use of self-shielding to reduce external and internal backgrounds

Dark Matter Searches

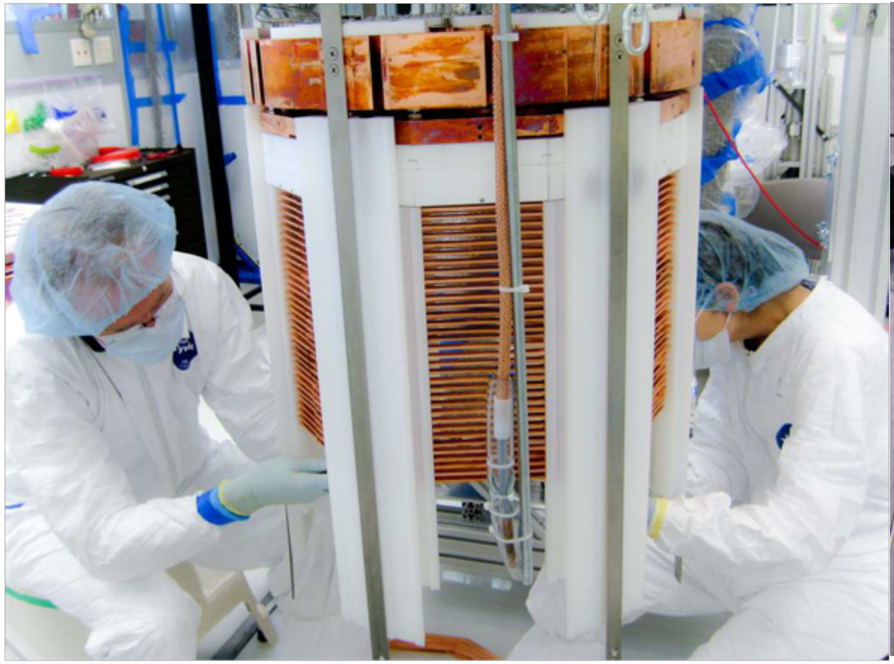


WIMP Search Status



The Large Underground Xenon (LUX) experiment

The worlds largest dual-phase xenon time-projection chamber



The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
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David Malling	Graduate Student
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Kareem Kazkaz	Staff Physicist
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Collaboration Meeting, Sanford Lab, April 2013

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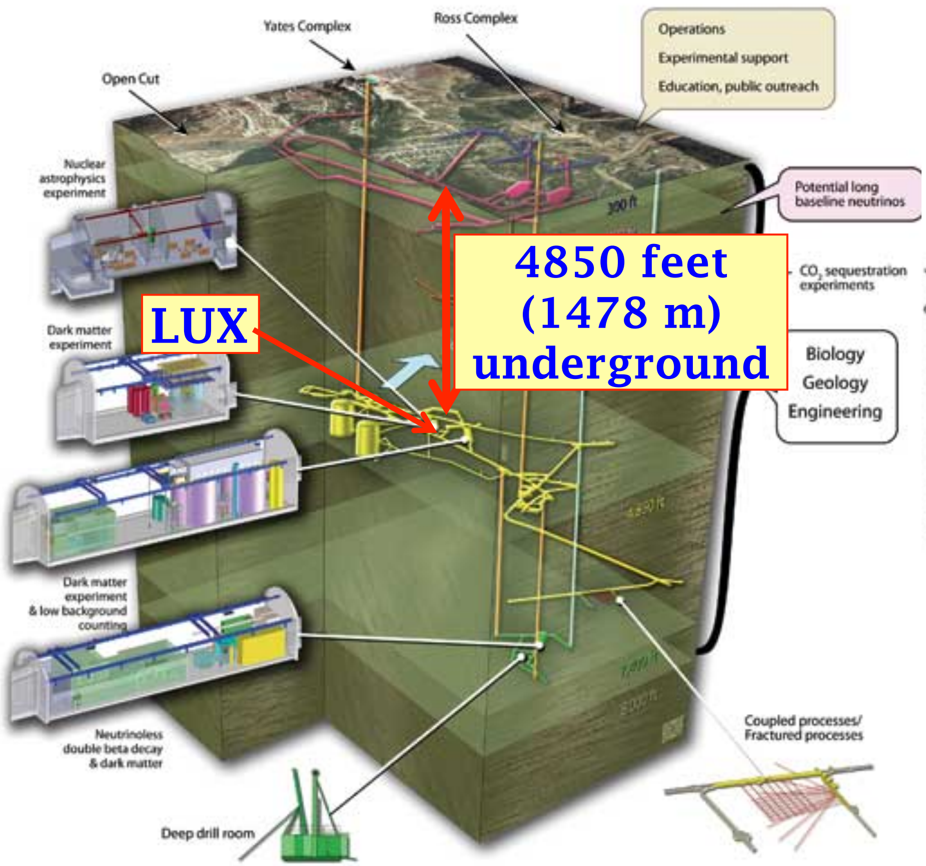
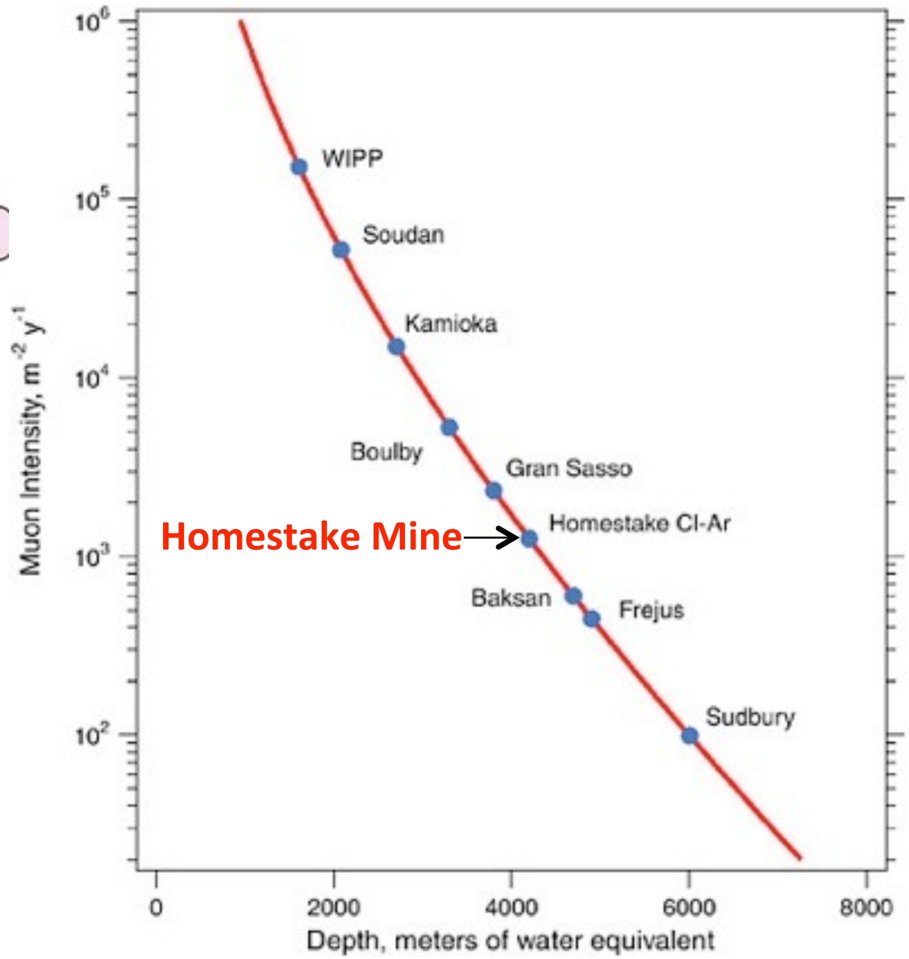
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

LUX at SURF

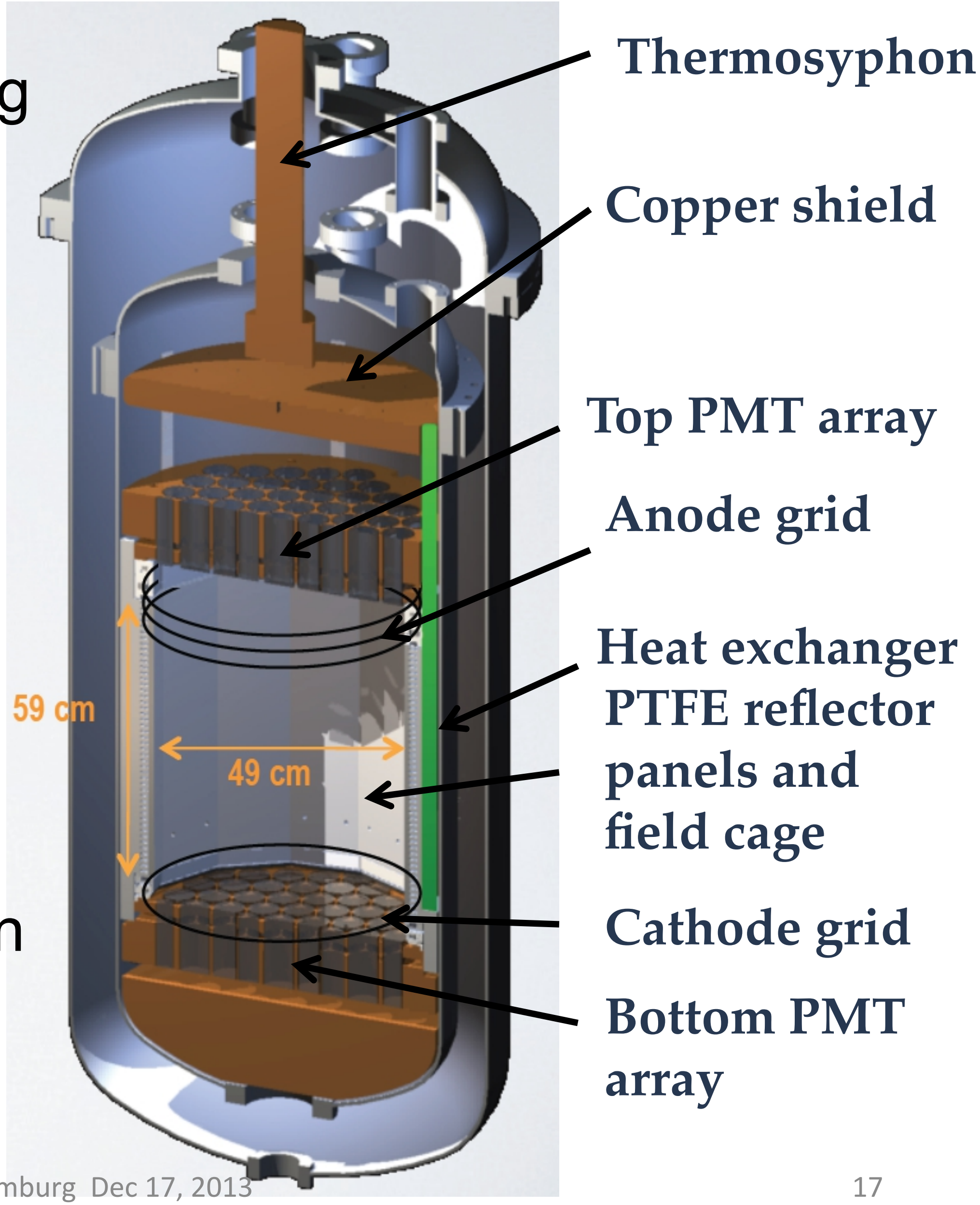
- Sanford Underground Research Facility (SURF) at Homestake Mine (SD, USA)
- ~1.5 km deep (4300 m.w.e.): **μ flux reduced x 10^{-7} compared to sea level → $10^{-5} m^{-2} s^{-1}$**



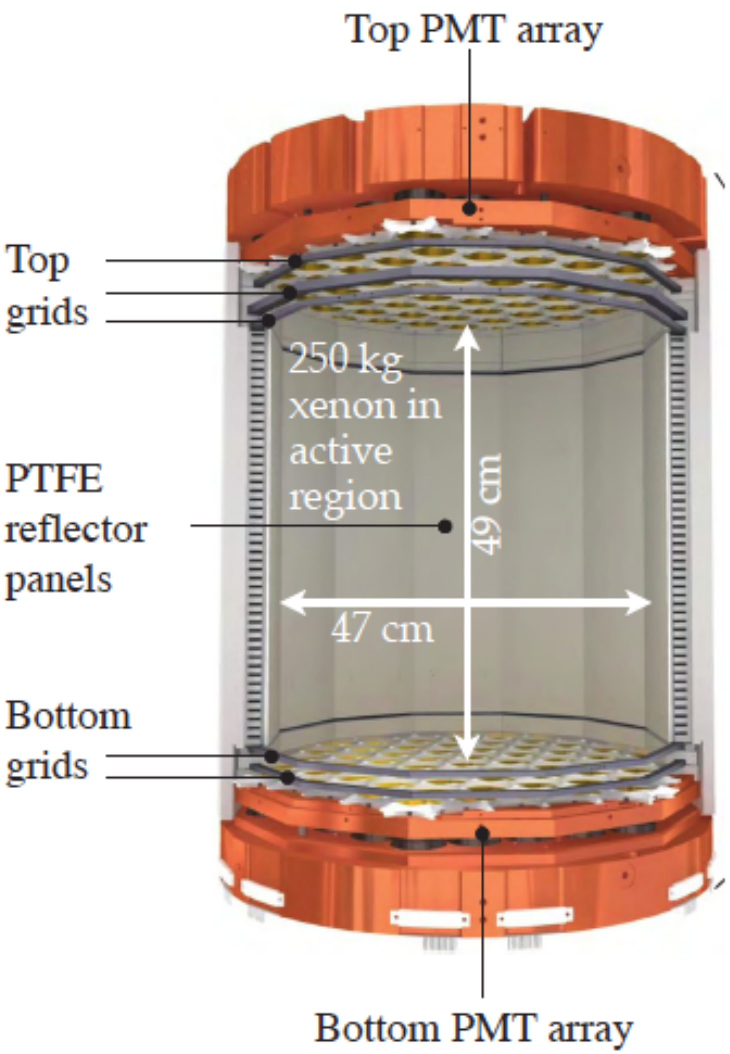


LUX Detector

- 370 kg xenon detector (250 kg active region)
- Active region defined by 12 PTFE slabs (high reflectivity for Xe scintillation light)
- 122 Ultra low background PMTs
- Titanium cryostat (<0.2 mBq/kg)
- High flow plumbing and heat exchanger for rapid circulation (35 SLPM) through external purifier

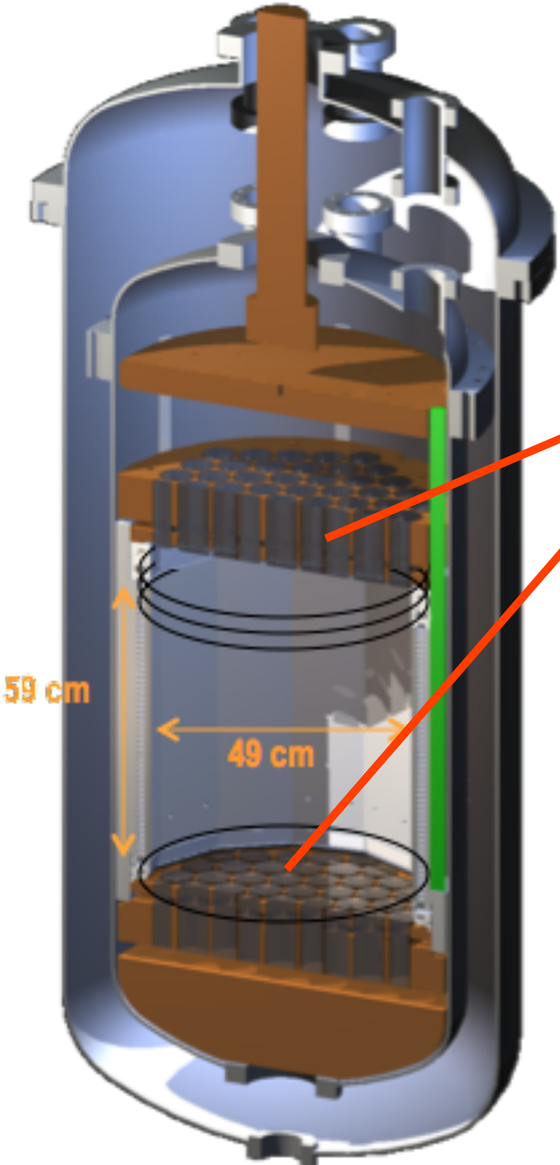


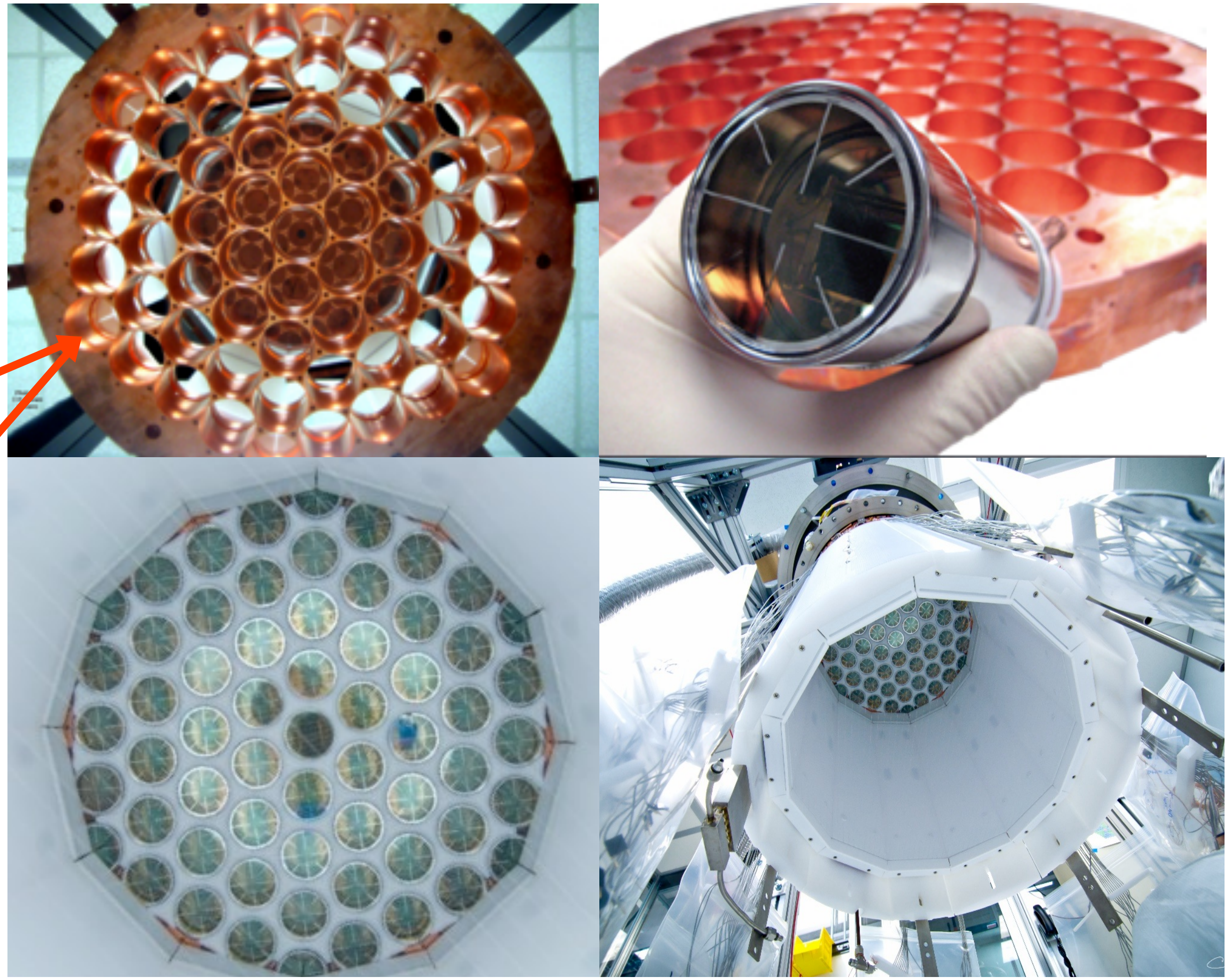
LUX active region



LUX Detector

122 ultra low-background PMTs (2 x 61)





Active region defined by PTFE (high reflectivity for the VUV light - high light collection)

Screening of materials

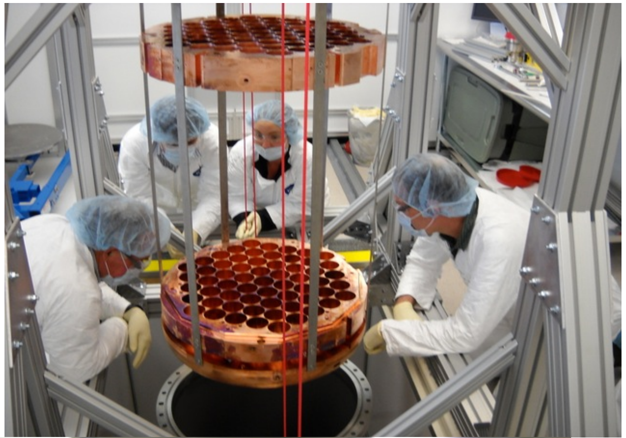
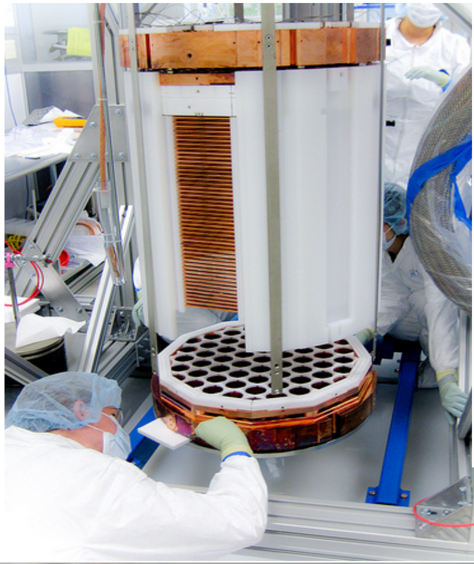
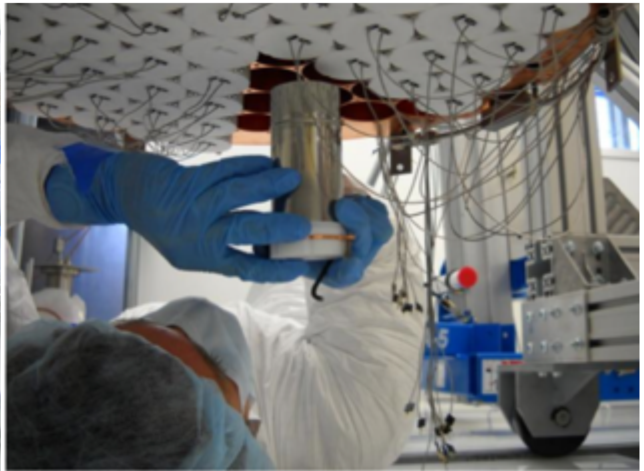
	Unit	Screening Result				
		U238	Th232	Co60	K40	Sc46
PMTs	mBq/PMT	9.5±0.6	2.7±0.3	2.6±0.1	66±2	
Ti	mBq/kg	<0.18	<0.25			4.4±0.3*
Cu	mBq/kg			2.1±0.19*		
PTFE	mBq/kg	<3	<1			
HDPE	mBq/kg	<0.5	<0.35			
Stainless steel**	mBq/kg			19±1		

**Type 304 stainless steel used in electric field grids

*Cosmogenic equilibrium at 1 mile above SL; decays below ground

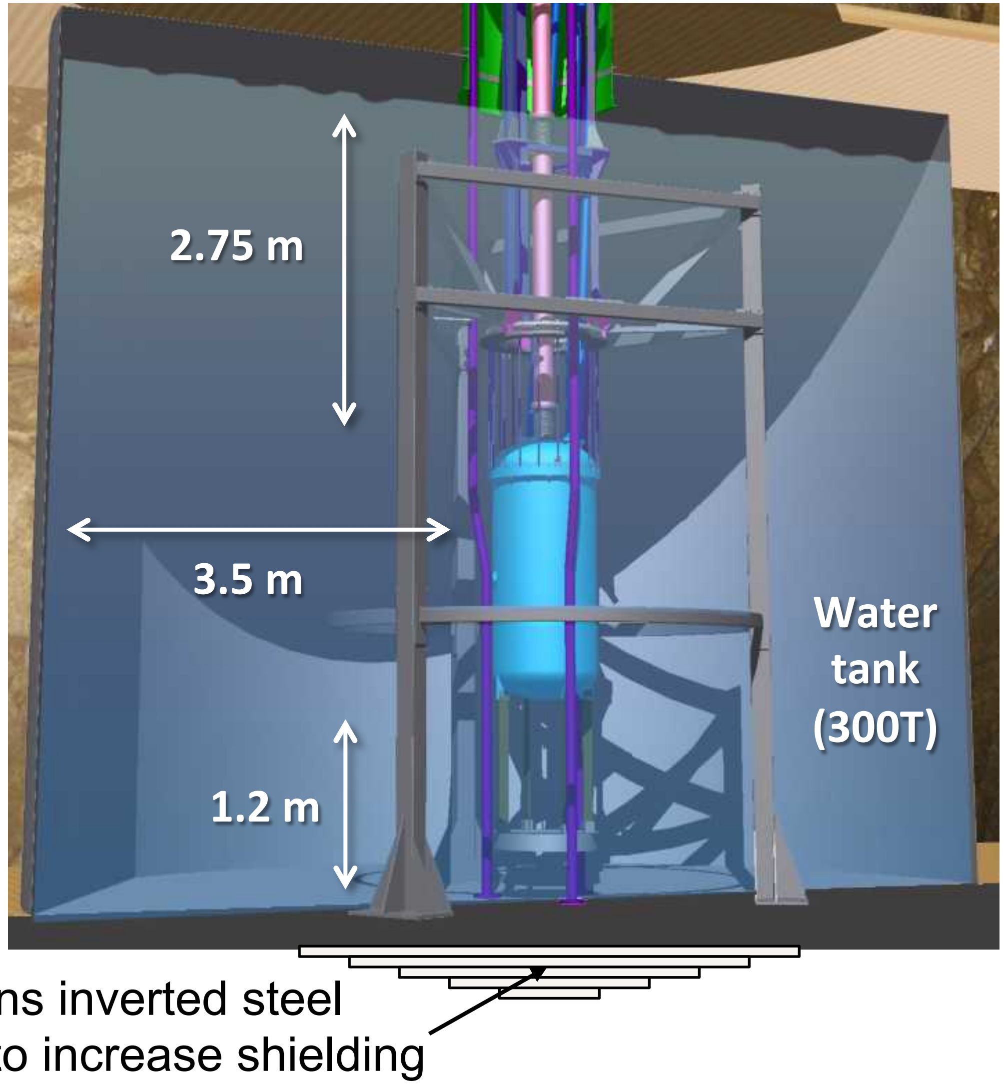
Assembling the Detector

The detector was assembled during the year of 2011.

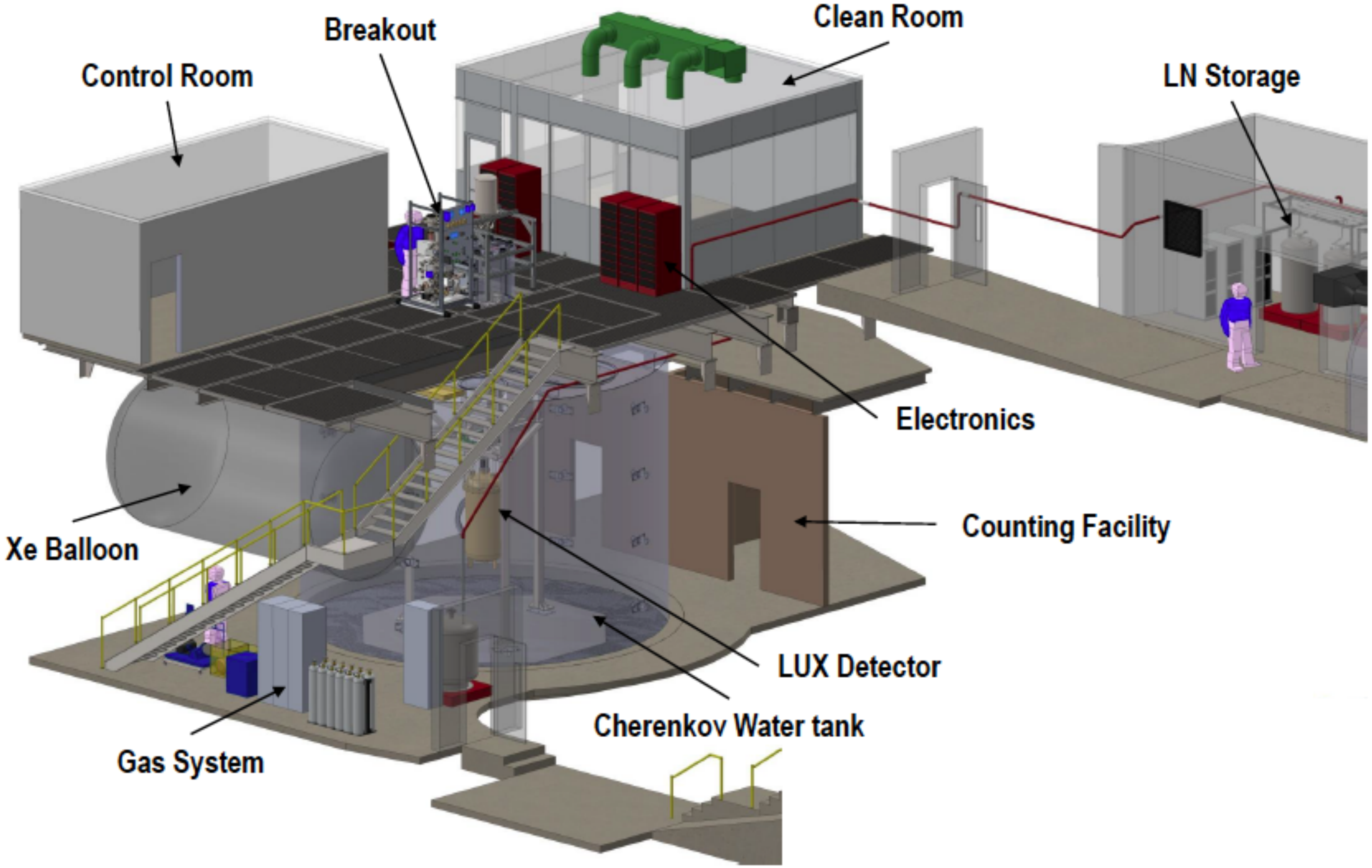

LUX water tank

- Water tank: ø = 8 m, h = 6 m
- Passive shielding
- Muon active veto: 20 PMTs (ø = 10”)



Water tank

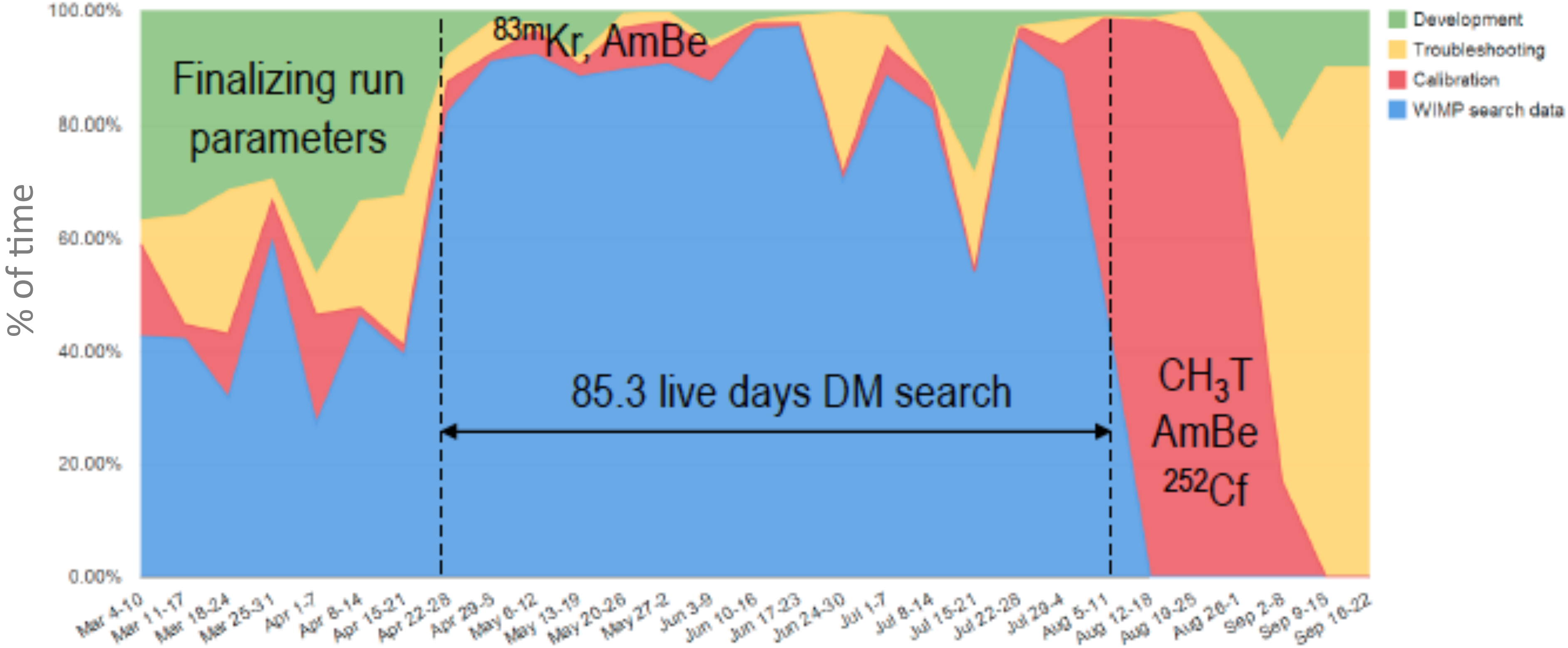
LUX in the Davis Cavern



First dark matter results from LUX

118 kg and 85.3 days of live-time data

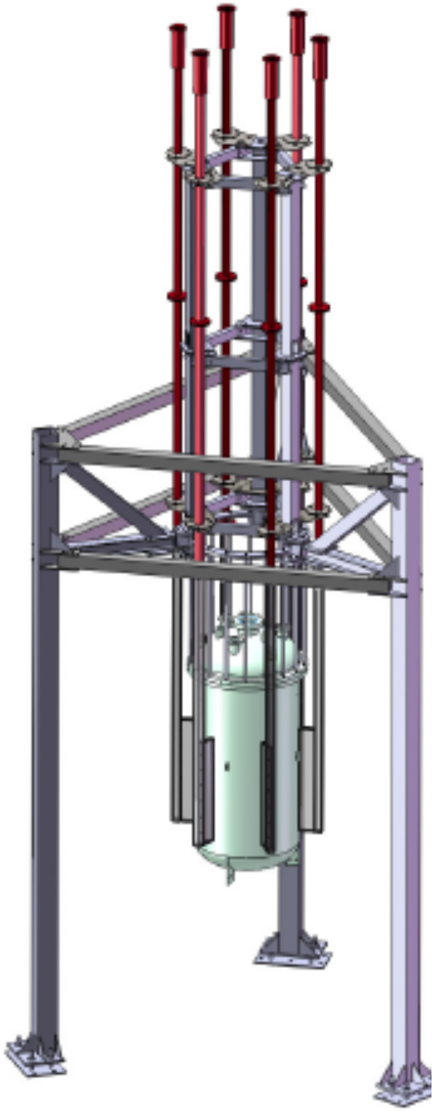
Data taking

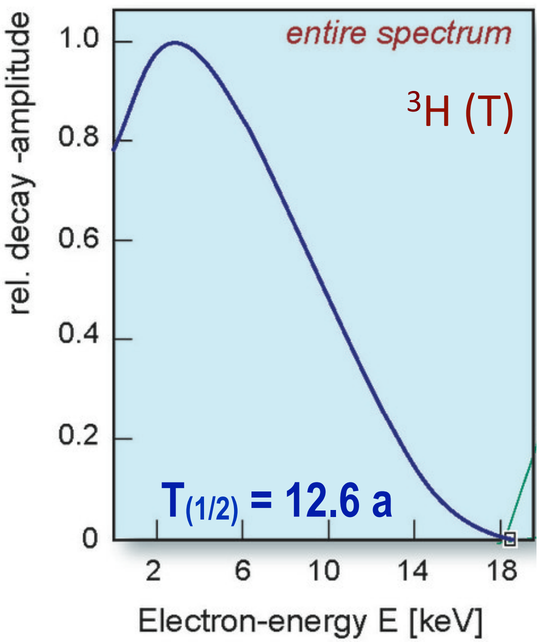


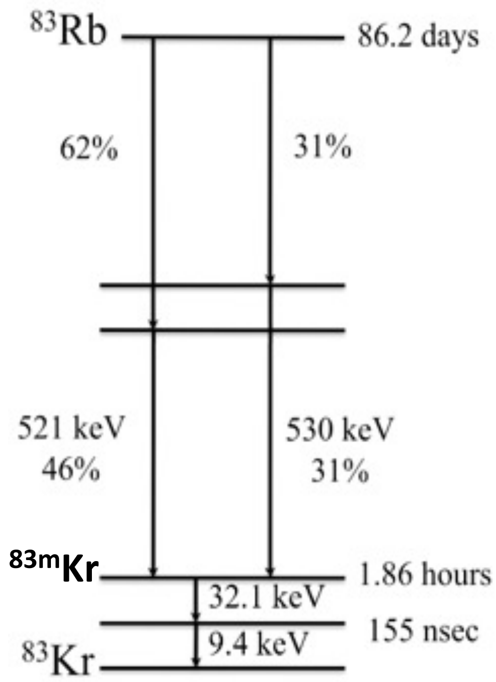
- LUX moves underground in July 2012
- Detector cool-down January 2013, Xe condensed mid-February 2013
- Kr and AmBe calibrations throughout, CH_3T after WIMP search

Calibration

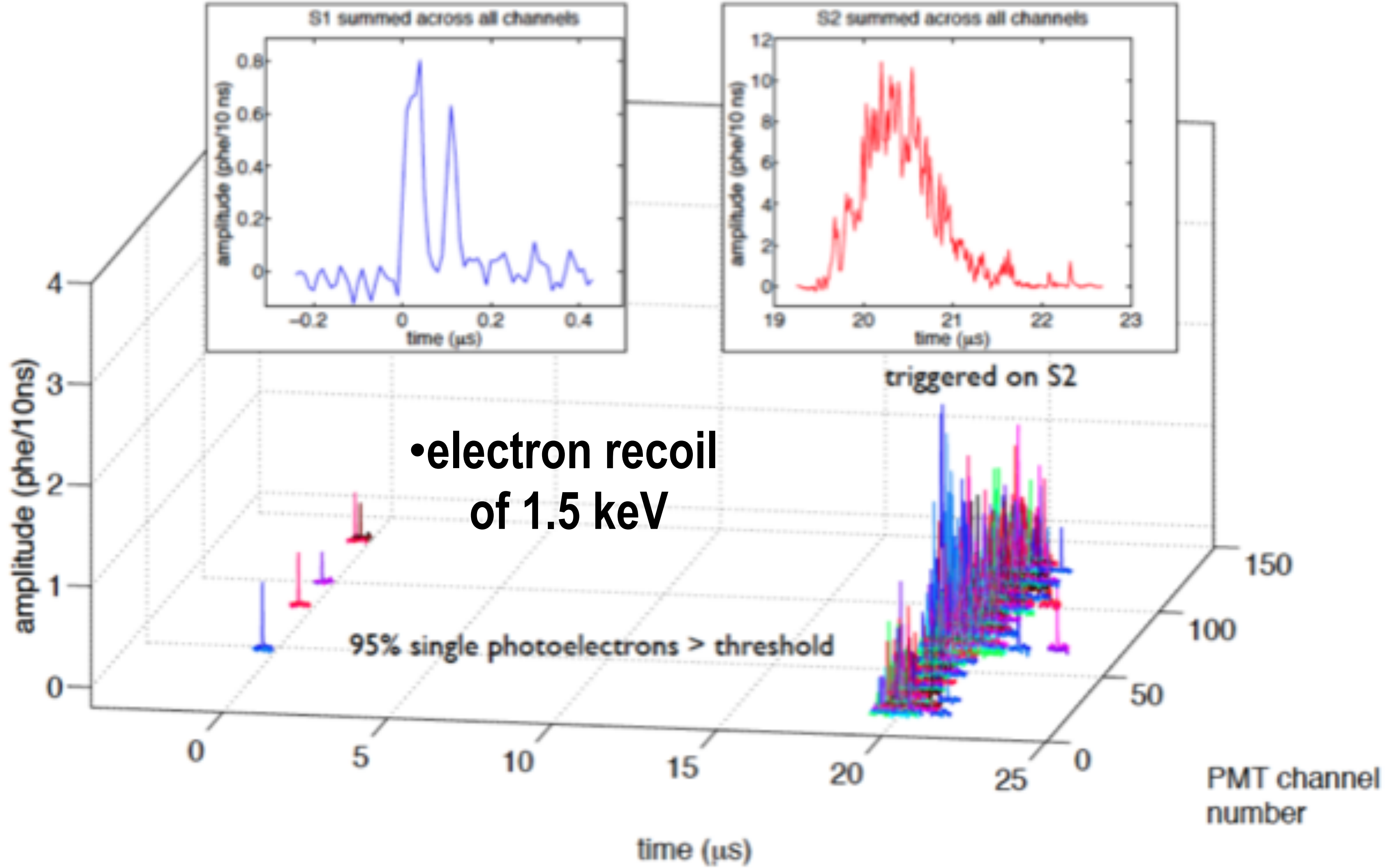
- **External souces via source tubes**:
  - AmBe and ^{252}Cf low energy neutrons
    - validating NR models and detector sim, NR eff.
- **Internal sources injected into circulation system**
  - ^{83m}Kr : half live: 1.8 hours; 32.1+9.4 keV
    - Weekly purity, XYZ maps and light detection efficiency
  - CH_3T: low energy β (end point 18.6 keV)
    - High stats, uniformly distributed
    - ER band, ER acceptance



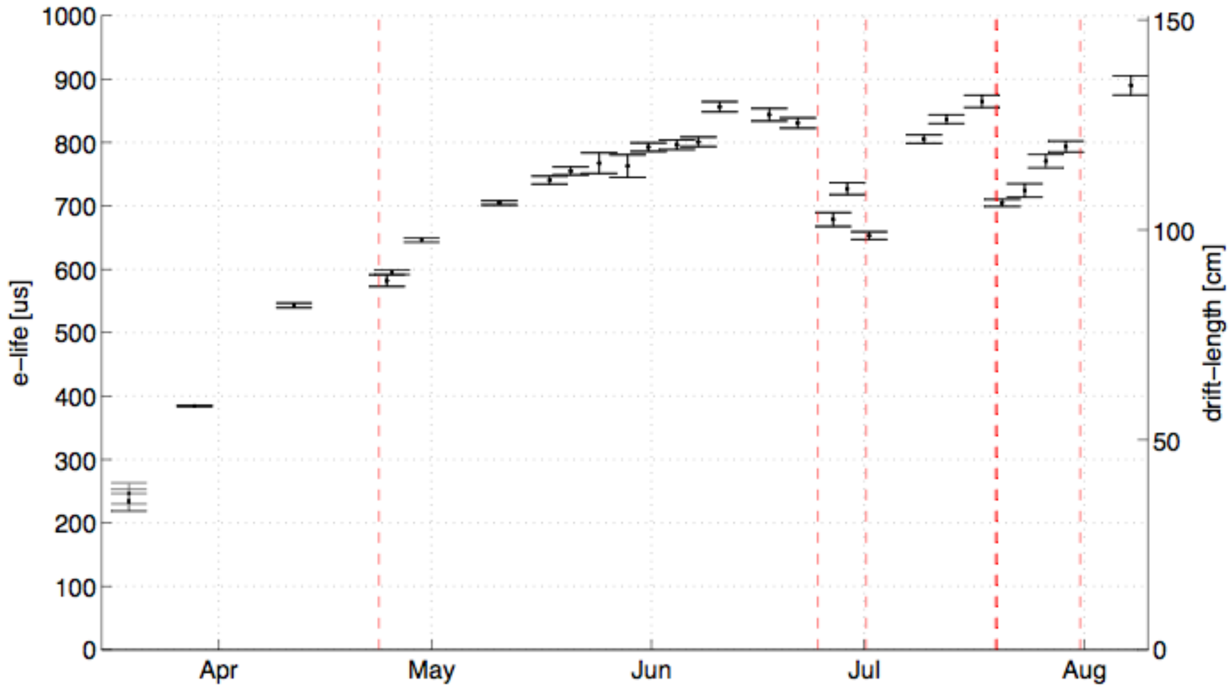




Example of LUX event



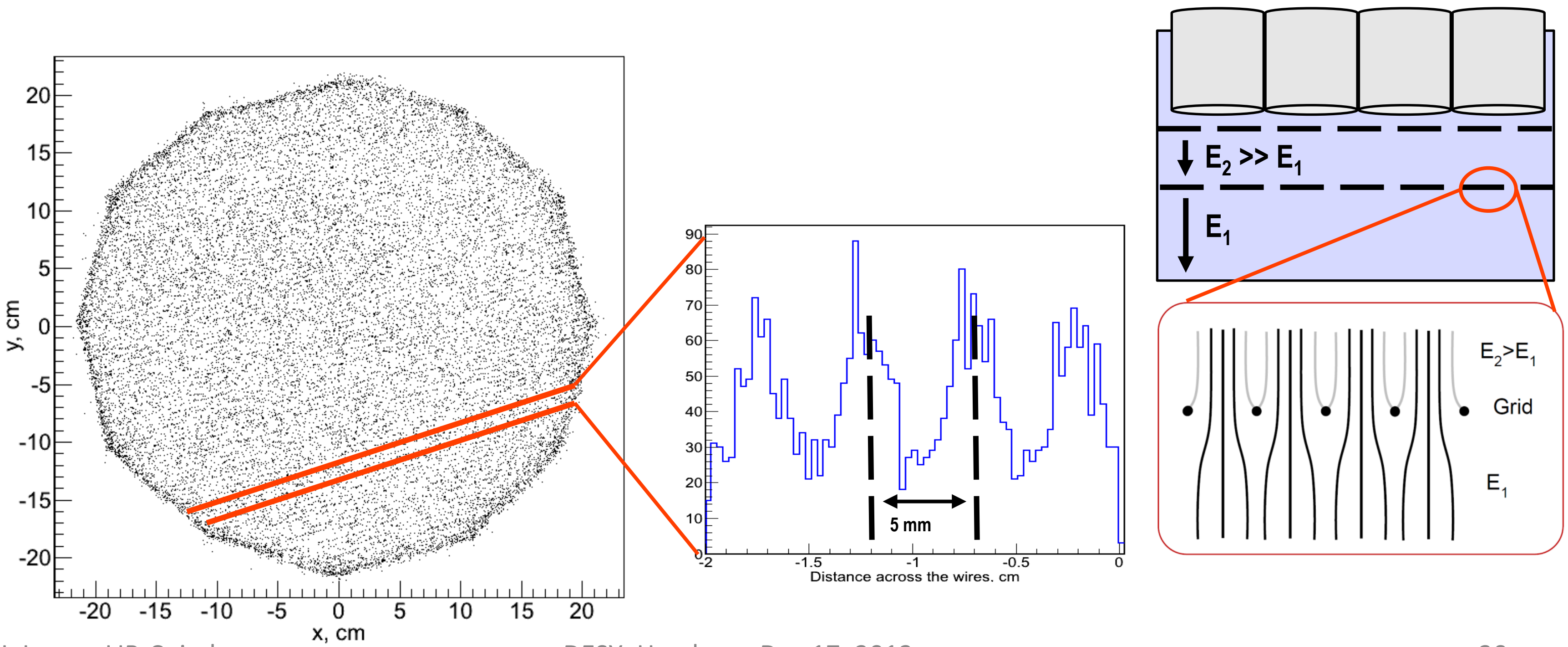
Detector Performance



- Electron drift length between 90 and 130 cm
- Light detection efficiency of 14%
- 65% electron extraction efficiency

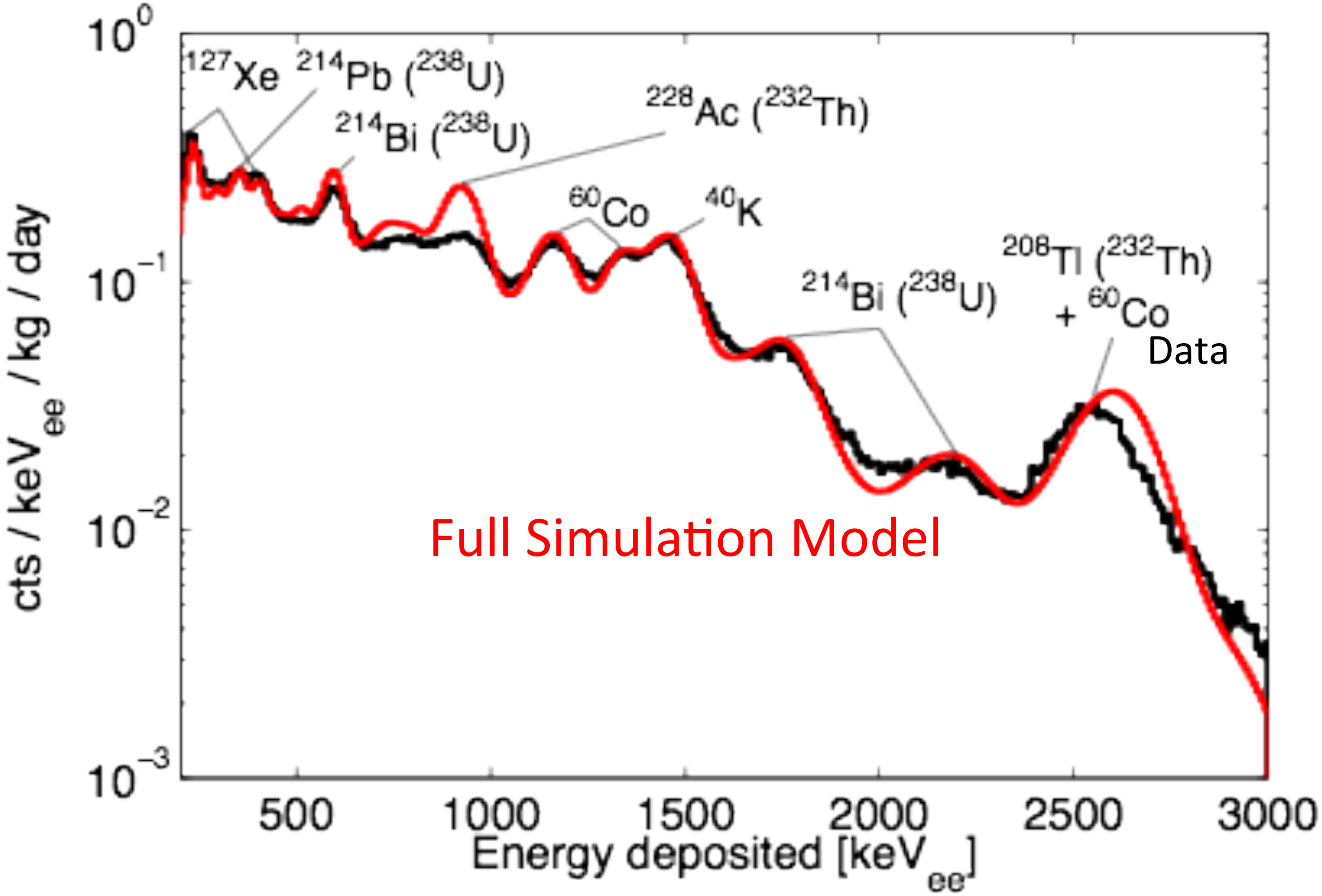
Position reconstruction

- Drift time (1.51 mm/μs @ 181V/cm) for Z-position
- XY from Mercury position reconstruction algorithm (developed for ZEPLIN-III, arXiv: 1112.1481v1)
- Obtained by fitting the S2 PMT hit pattern with LRFs from internal calibrations



LUX High Energy Gamma Background

- Full gamma Spectrum, excluding region ±2 cm from top/bottom grids (in 220 kg)



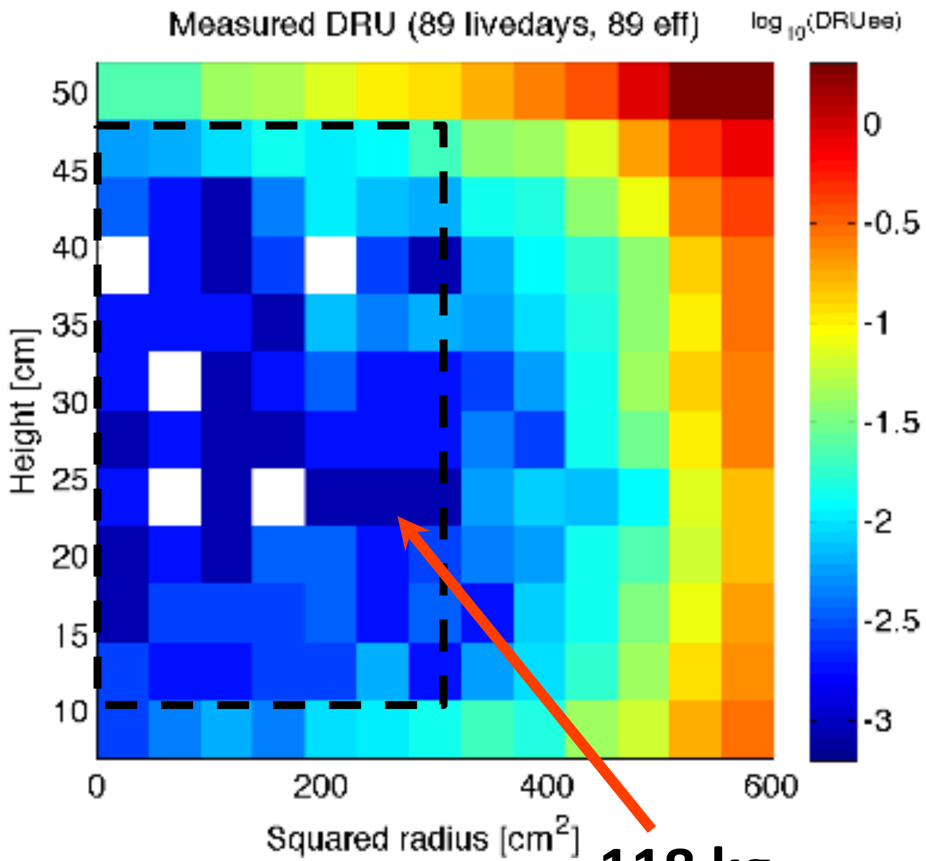
LUX Low Energy ER Background

Monte Carlo predictions of low-energy ER background rates from all significant sources, 118 kg fiducial and 0–8 keVee energy

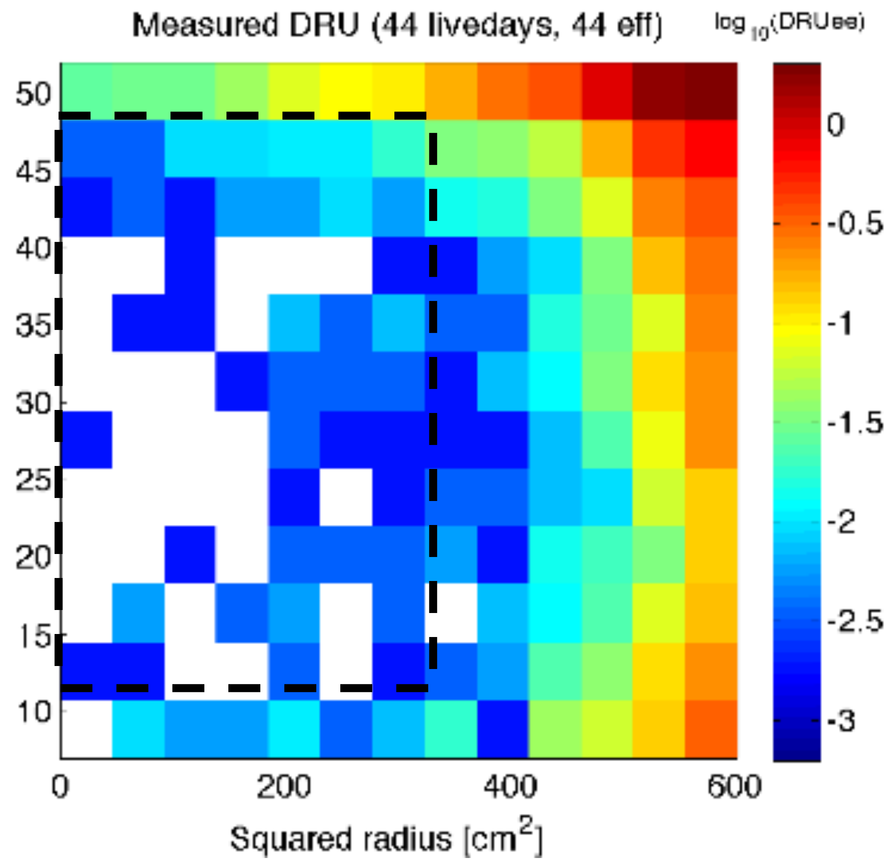
Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	222Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5±1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	**Total**	$\mathbf{2.6 \pm 0.2_{stat} \pm 0.4_{sys}}$
Observed	**Total**	$\mathbf{3.1 \pm 0.2_{stat}}$

Observed Backgrounds

All the run



Last 44 days



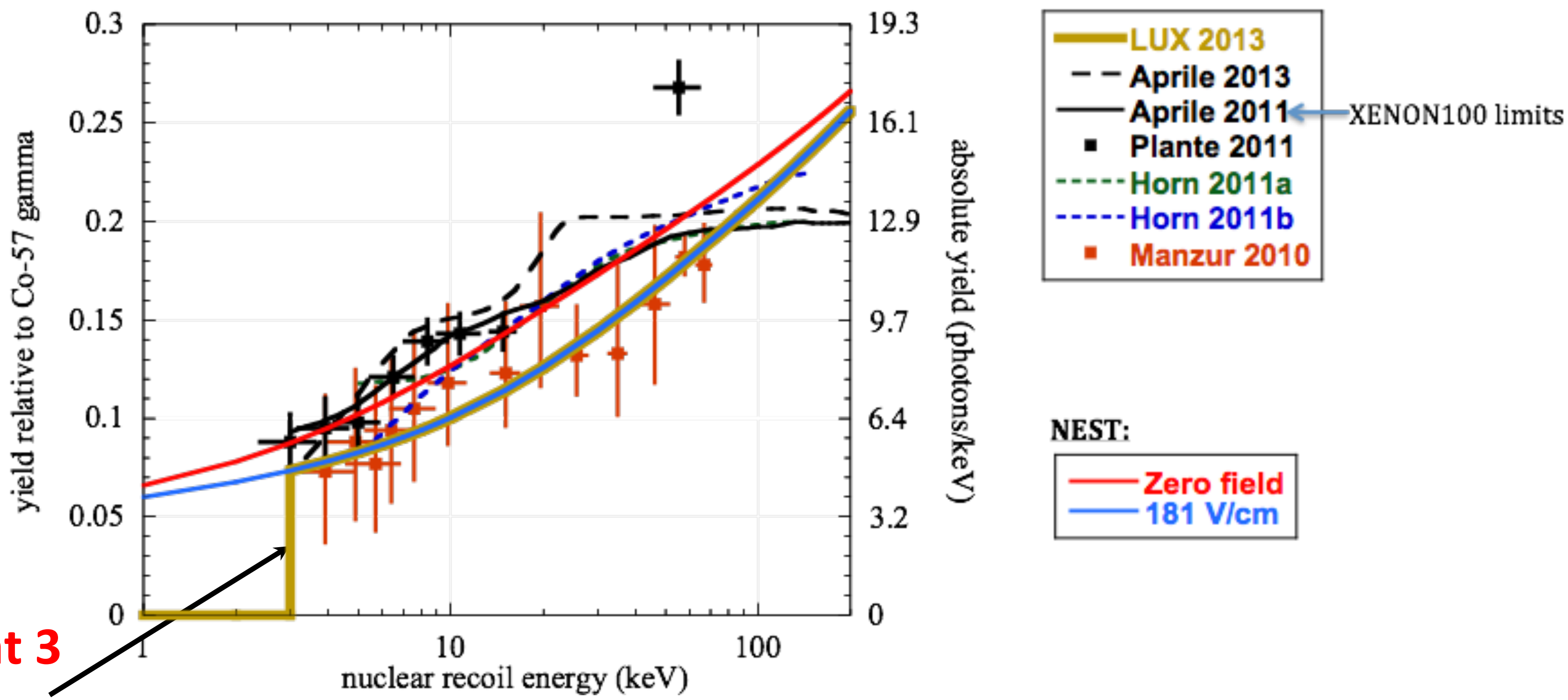
118 kg

3.1 ± 0.2 mdru

r < 18 cm ; 7 < z < 47 cm

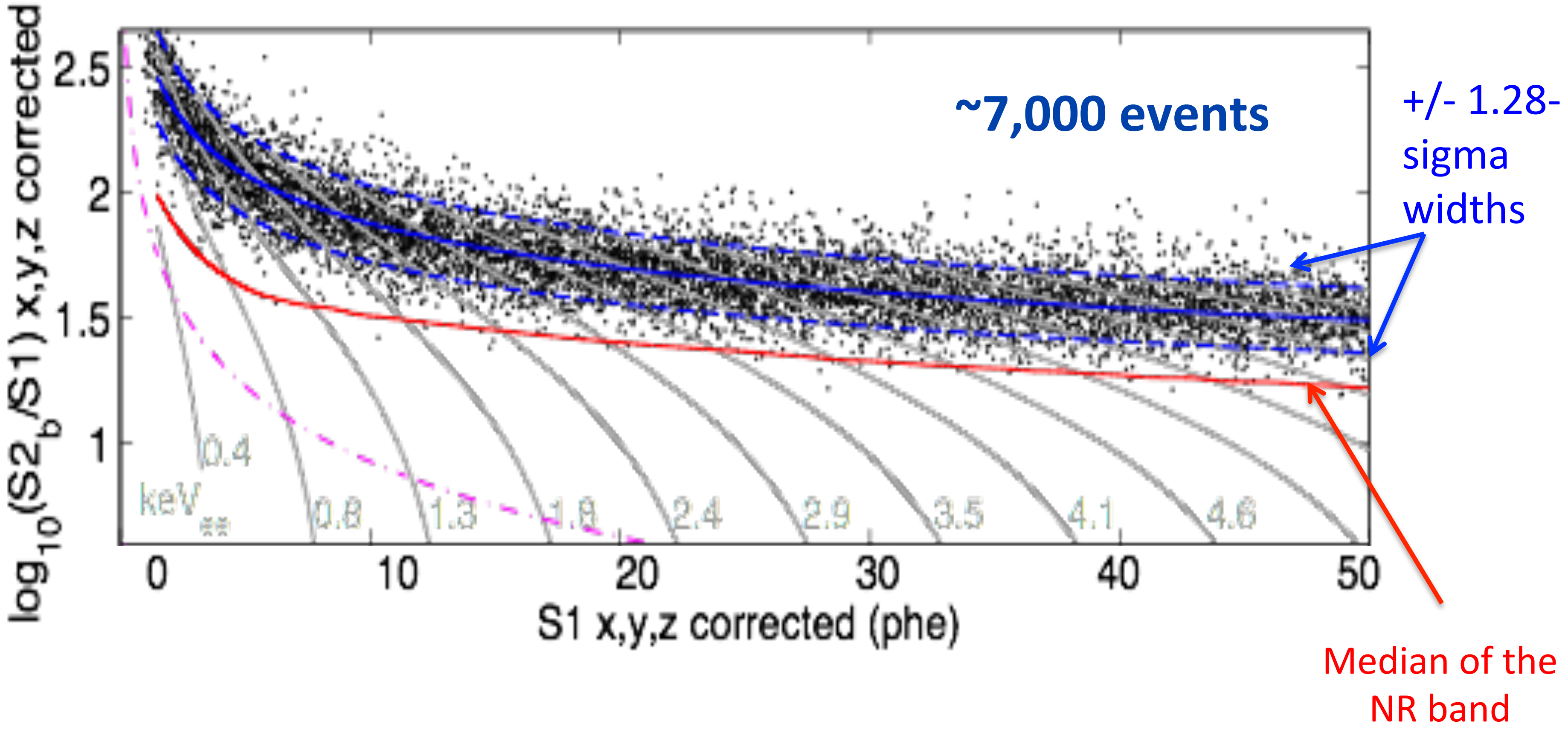
NR Calibration in energy

- Modeled using NEST (Noble Element Simulation Technique).
- Artificial cutoff in light and charge yields assumed below 3 keV_{nr} . This is to be conservative and it does not represent actual physics.
- Includes E field quenching of light signal (77-82% compared to zero field)



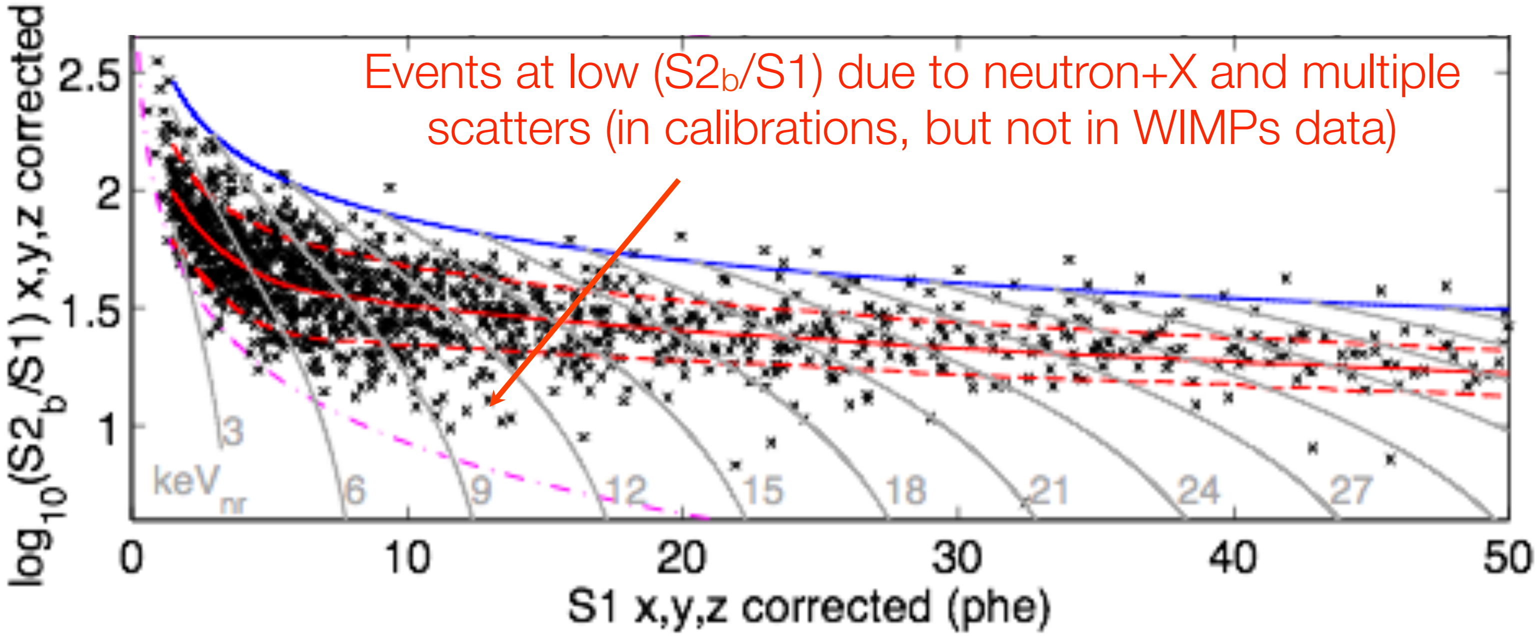
set hard threshold at 3 keVnr

ER Band - Tritium Calibration



Gray contours: constant energy curves using a combination of S1 and S2

Neutron Calibrations

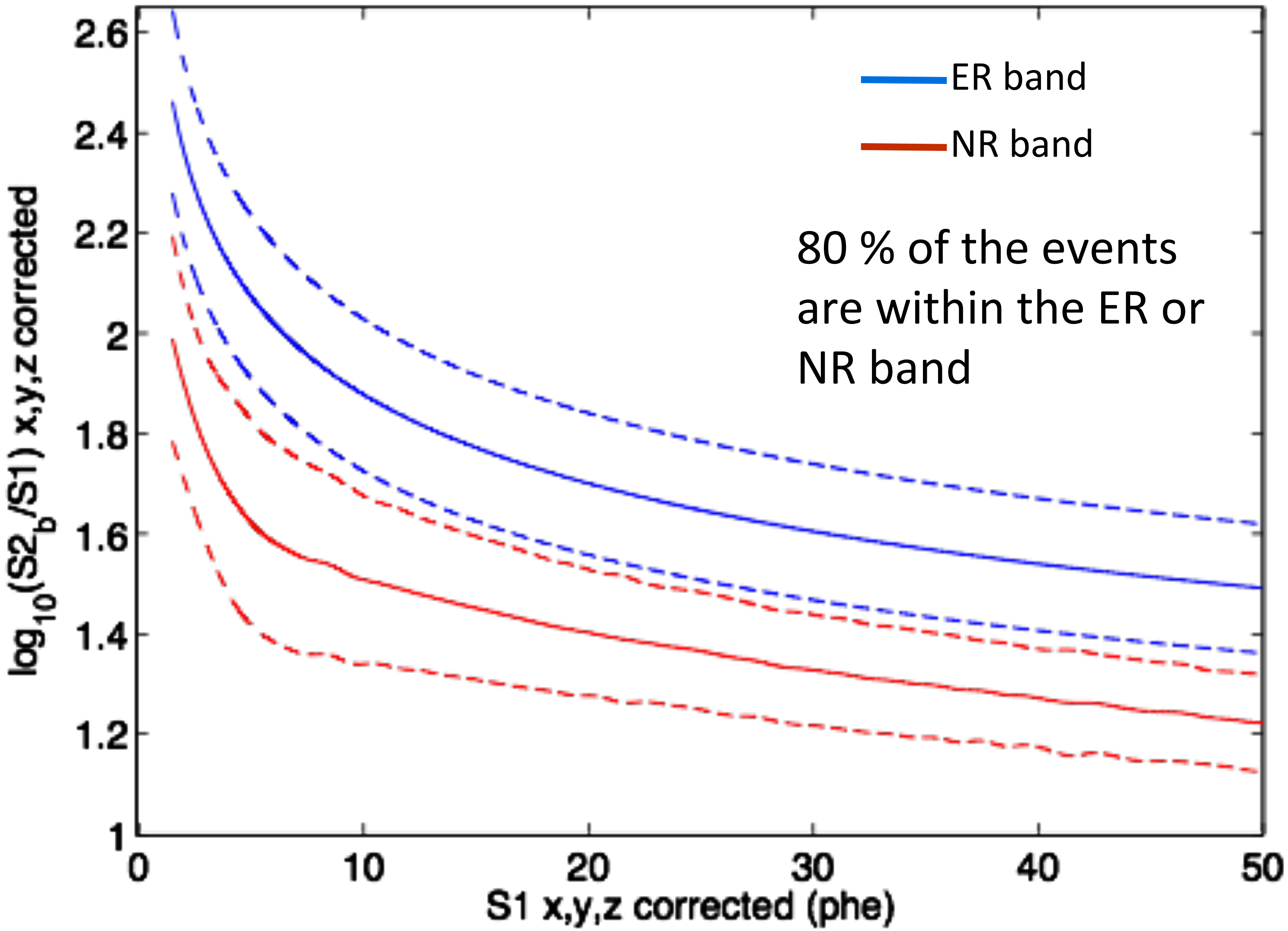


•Obtained with ^{241}AmBe and ^{252}Cf.

•The results are consistent with NEST (Noble Element Simulation Technique (see http://nest.physics.ucdavis.edu).

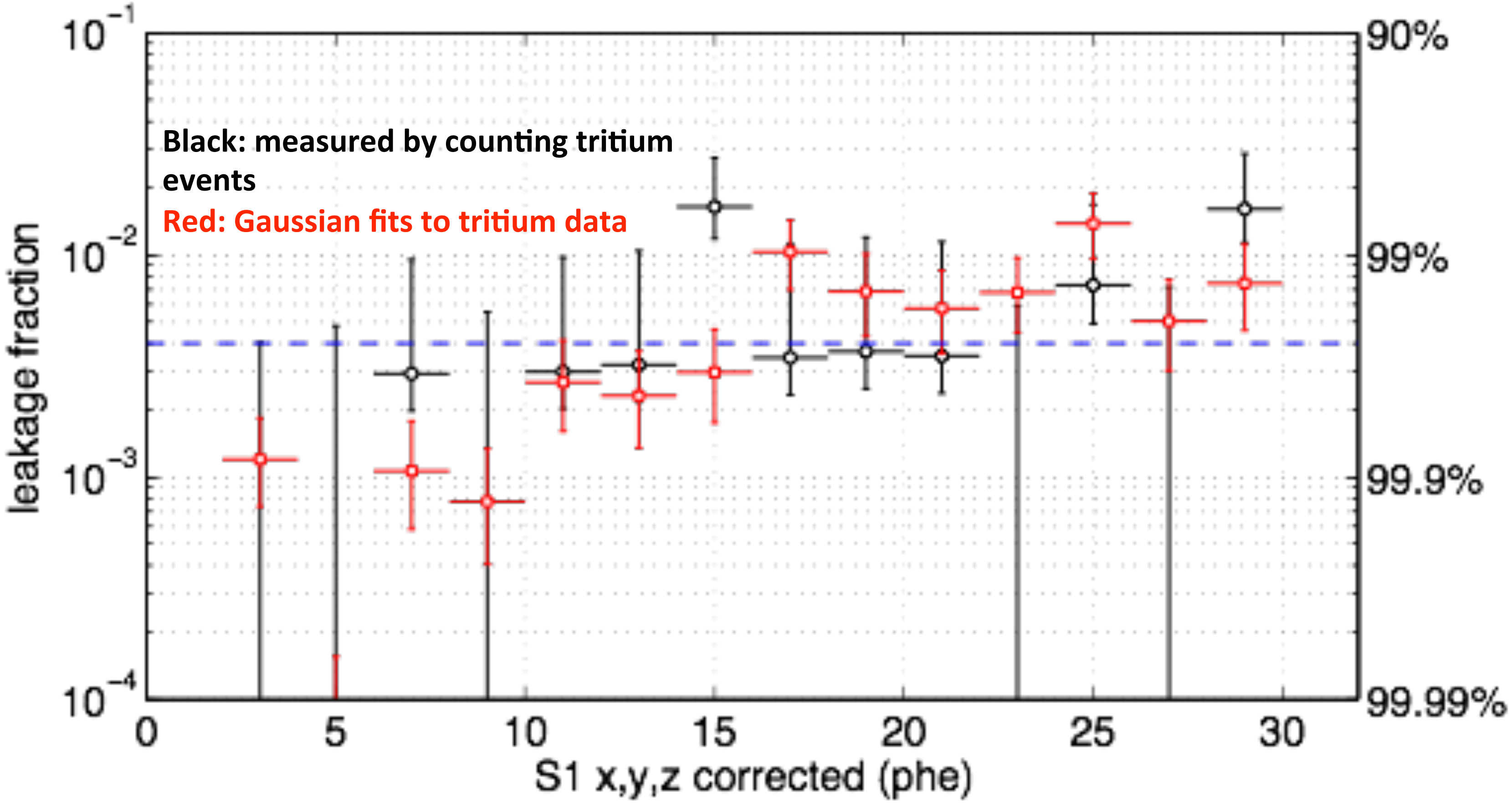
•Simulation results include Neutron+X and multiple scatters to allow direct comparison with calibration data (but not present in WIMP data)

ER and NR bands



Discrimination

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



Leakage Fraction: fraction of the events in the ER band that spill over the lower half of the NR band

Run 3 event selection and cuts

Cut	Events Remaining
All Triggers	**83,673,413**
Detector Stability	82,918,904
Single Scatterer (1 S1 + 1 S2)	6,585,686
S1 Yield 2-30 phe	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	160

- Non-blind analysis
- Minimum number of cuts
- Hardware trigger: at least two trigger channels with > 8 phe within 2 μs window (16 PMTs per trigger channel)

  > 99% efficient for raw S2 > 200 phe (~8 e^-)

Run 3 event selection and cuts

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- Remove periods of live-time when liquid level, gas pressure or grid voltages were out of nominal ranges:

  - Less than 1.0 % live-time loss

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- Exactly **one** S2 and **one** S1 as identified by the pulse finding and classification code:

- Separate S1s from S2s using pulse shape and PMT hit distributions.
- S1s identification includes a two fold PMT coincidence requirement.

Run 3 event selection and cuts

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- Accept events with S1 between 2-30 phe (0.9-5.3 keV_{ee}, ~3-25 keV_{nr}):
  - We impose that at least 2 PMTs are above threshold.
  - 2 phe analysis threshold allows sensitivity down to low WIMP masses.
  - Upper limit avoids ^{127}Xe 5 keV_{ee} activation.

Run 3 event selection and cuts

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Single Electron Background	19,796
Fiducial Volume	160

S2 threshold cuts subdominant to S1:

- 200 phe ~ 8 single electrons
- Removes small S2 edge events and single electron events

Run 3 event selection and cuts

Cut	Events Remaining
All Triggers	83,673,413
Detector Stability	82,918,904
Single Scatterer (1 S1 + 1 S2)	6,585,686
S1 Yield 2-30 phe	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	**19,796**
Fiducial Volume	160

Require less than 100 phe (< 4 extracted electrons) of any additional signal in 1 ms period around S1 and S2 signals:

- Simple cut to remove additional single electron events in 0.1-1 ms following large S2 signals
- Only 0.8% hit on live-time

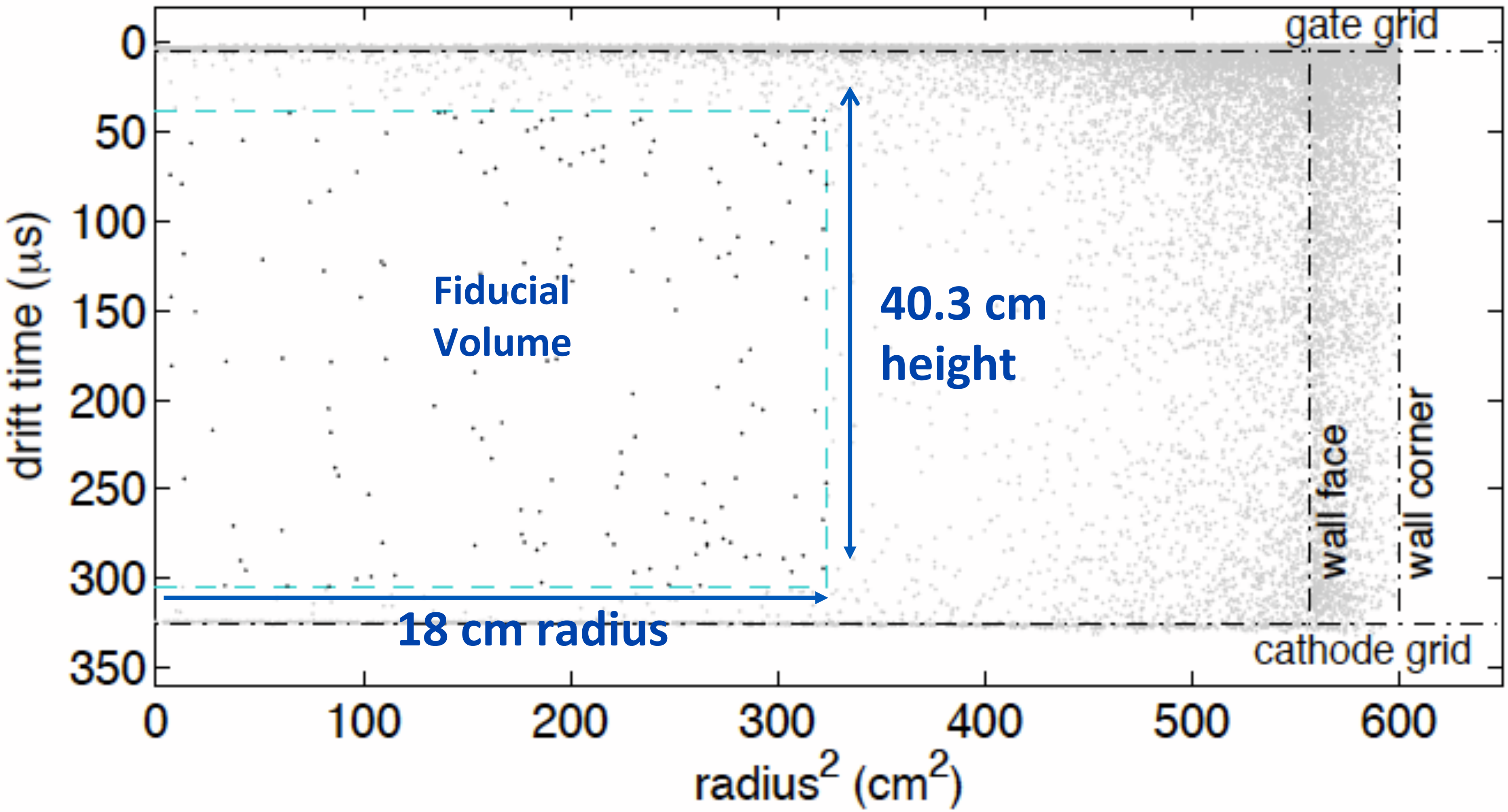
Run 3 event selection and cuts

Cut	Events Remaining
All Triggers	83,673,413
Detector Stability	82,918,904
Single Scatterer (1 S1 + 1 S2)	6,585,686
S1 Yield 2-30 phe	26,824
S2 Yield 200-3300 phe	20,989
Single Electron Background	19,796
Fiducial Volume	**160**

- Fiducial Cuts :
  - Reconstructed radius **< 18 cm**,
  - **38 < drift time < 305 μs** (320 μs is max drift time)
- Cuts define a 118.3 ± 6.5 kg fiducial volume

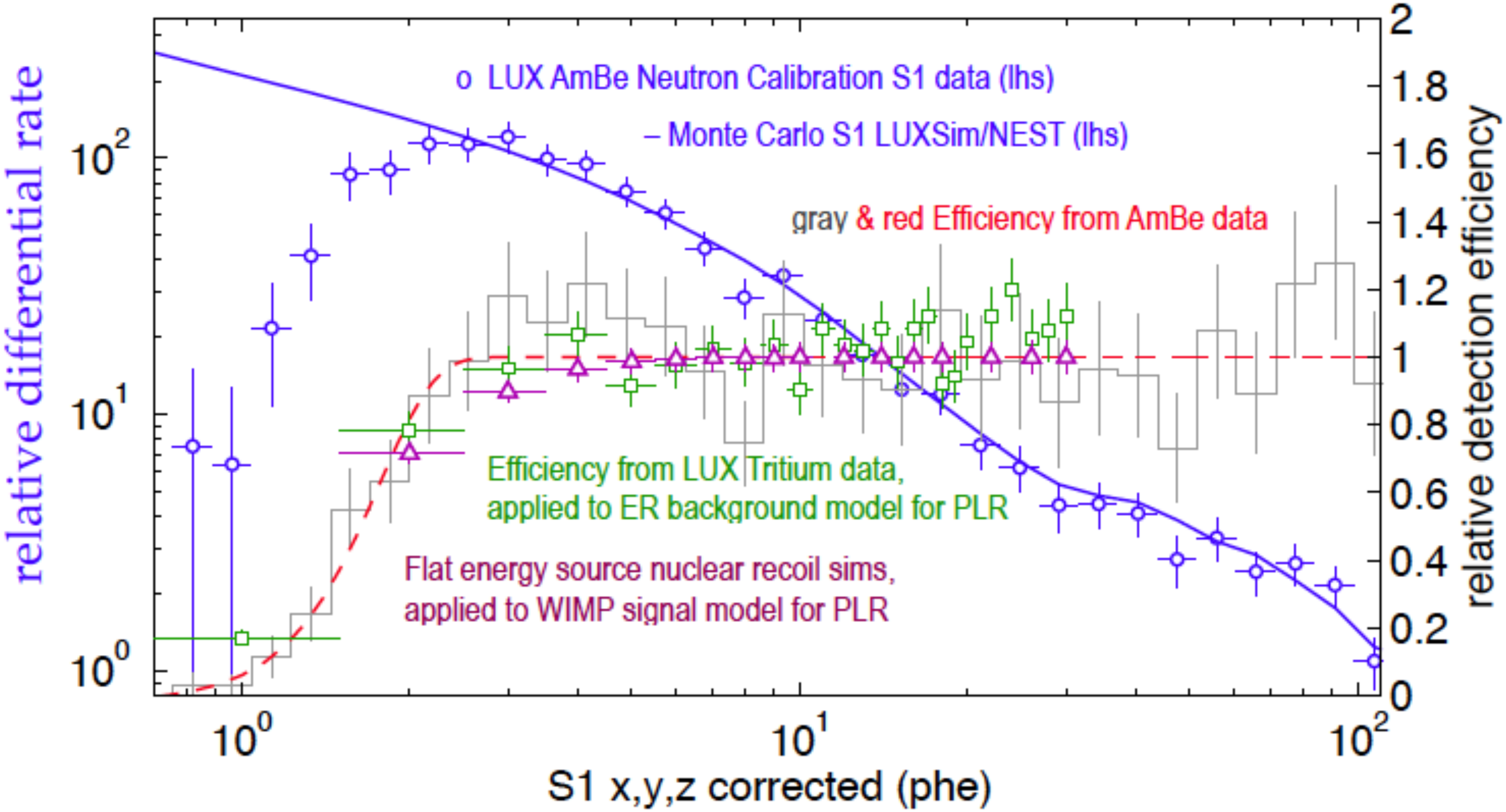
LUX WIMP search data

After all selection cuts: 160 candidate events in fiducial volume



Golden efficiency

- Cumulative efficiency of finding the S2 and the S1 pulses in events having one S2 and one S1 only.
- Using AmBe, Tritium, and full MC simulations

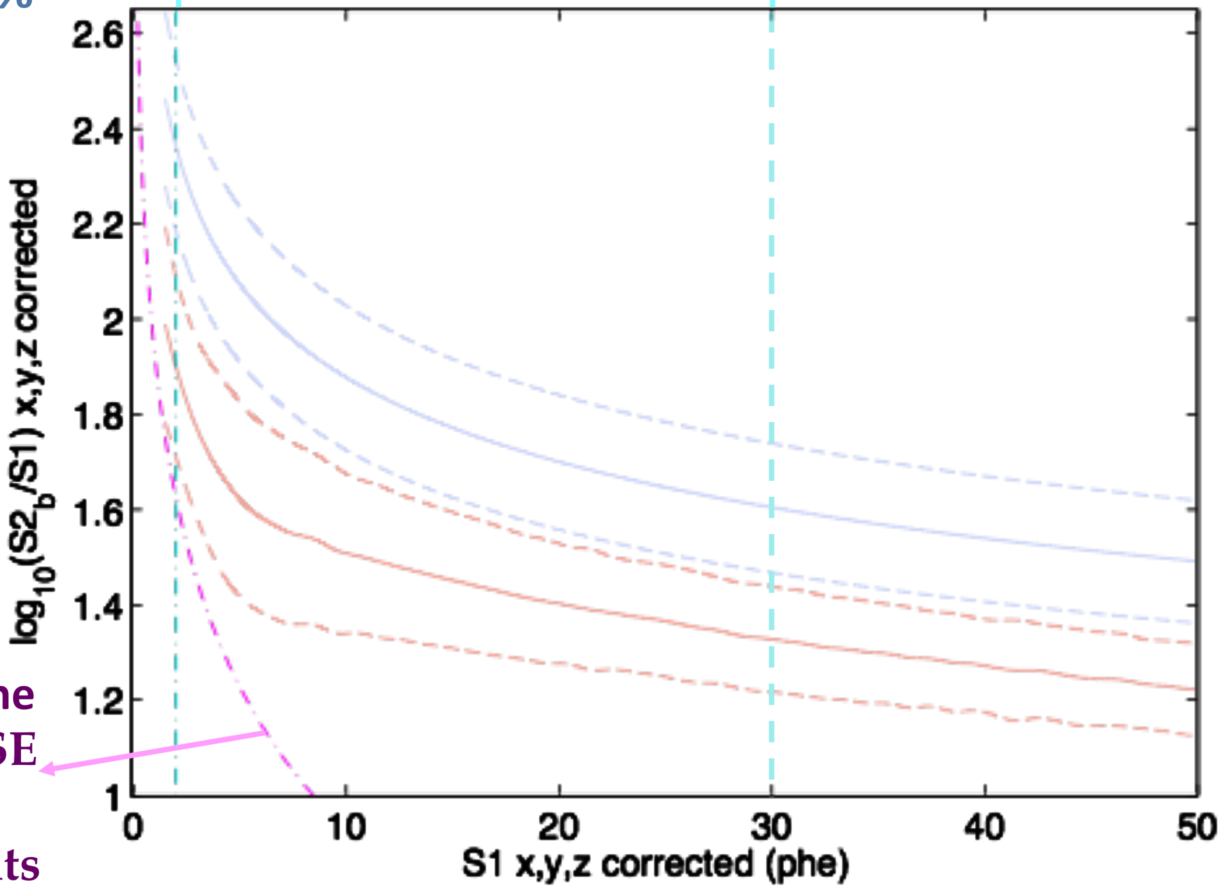


WIMP search data – discrimination

conservative S1 pulse identification > 50%

avoid ^{127}Xe 5 keVee activation

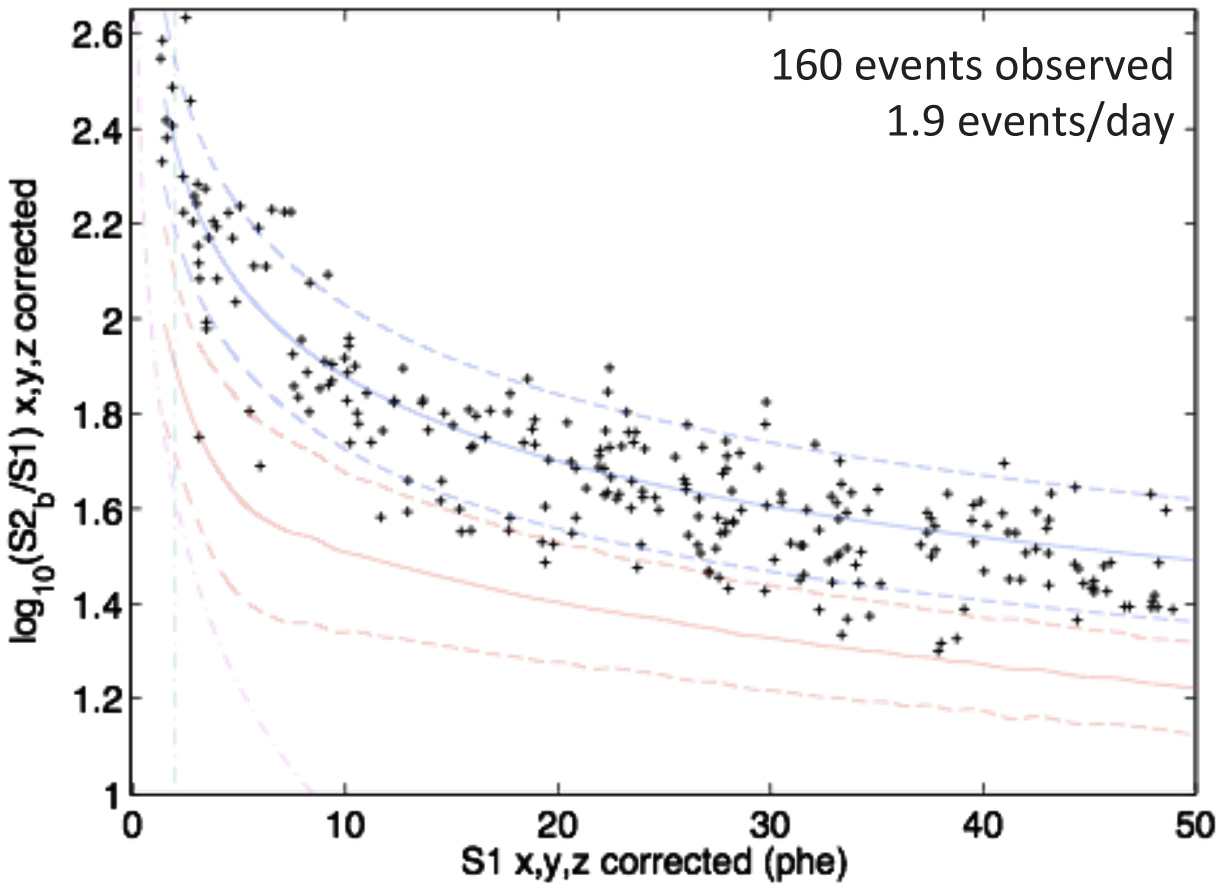
2 < S1 < 30 phe



S2 > 200 phe removes SE and small edge events

WIMP search data

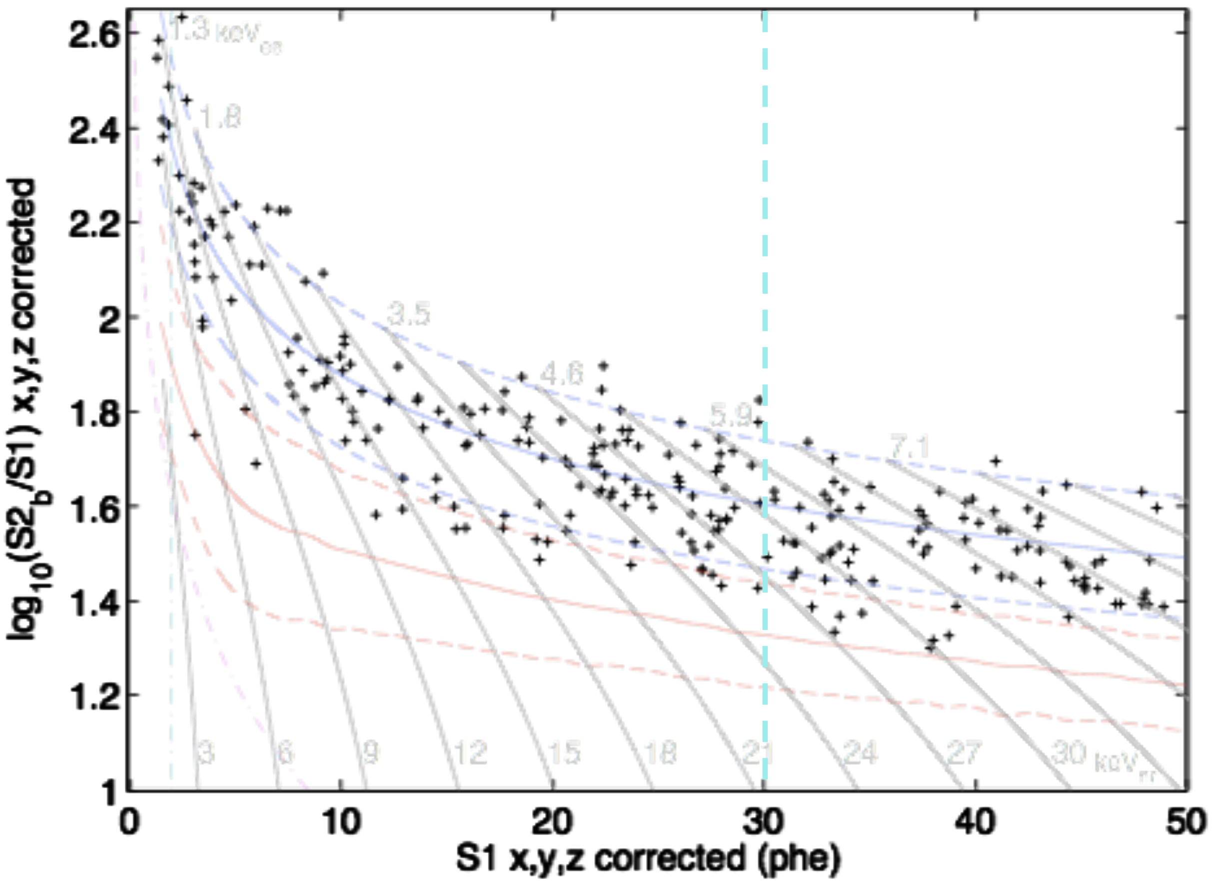
99.6 ± 0.1 % leakage below NR mean, so expect 0.64 ± 0.16



WIMP search data

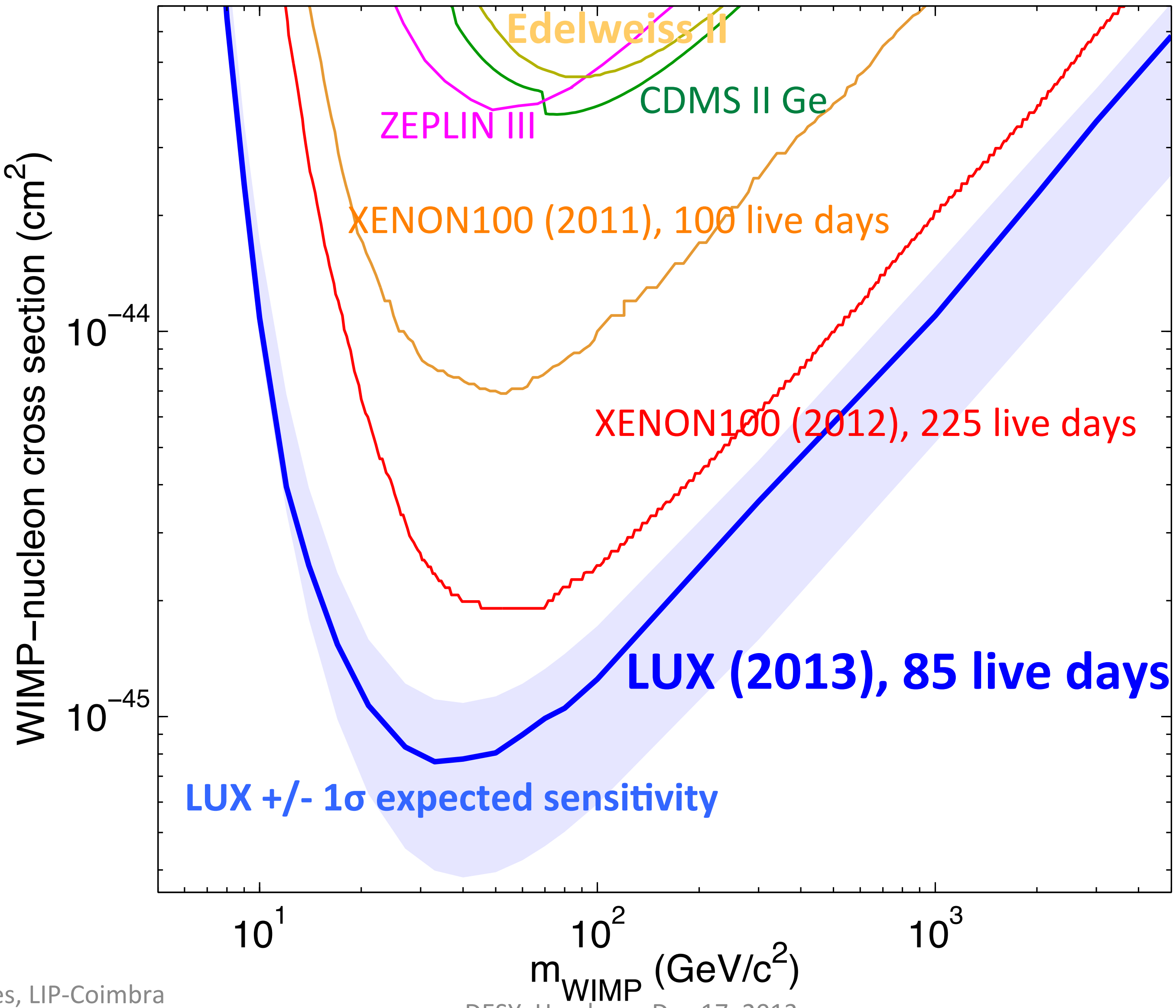
Distribution is consistent with ER background and **no WIMP signal;**

p-value of 0.35 (100 GeV WIMP) from Profile-Likelihood Analysis

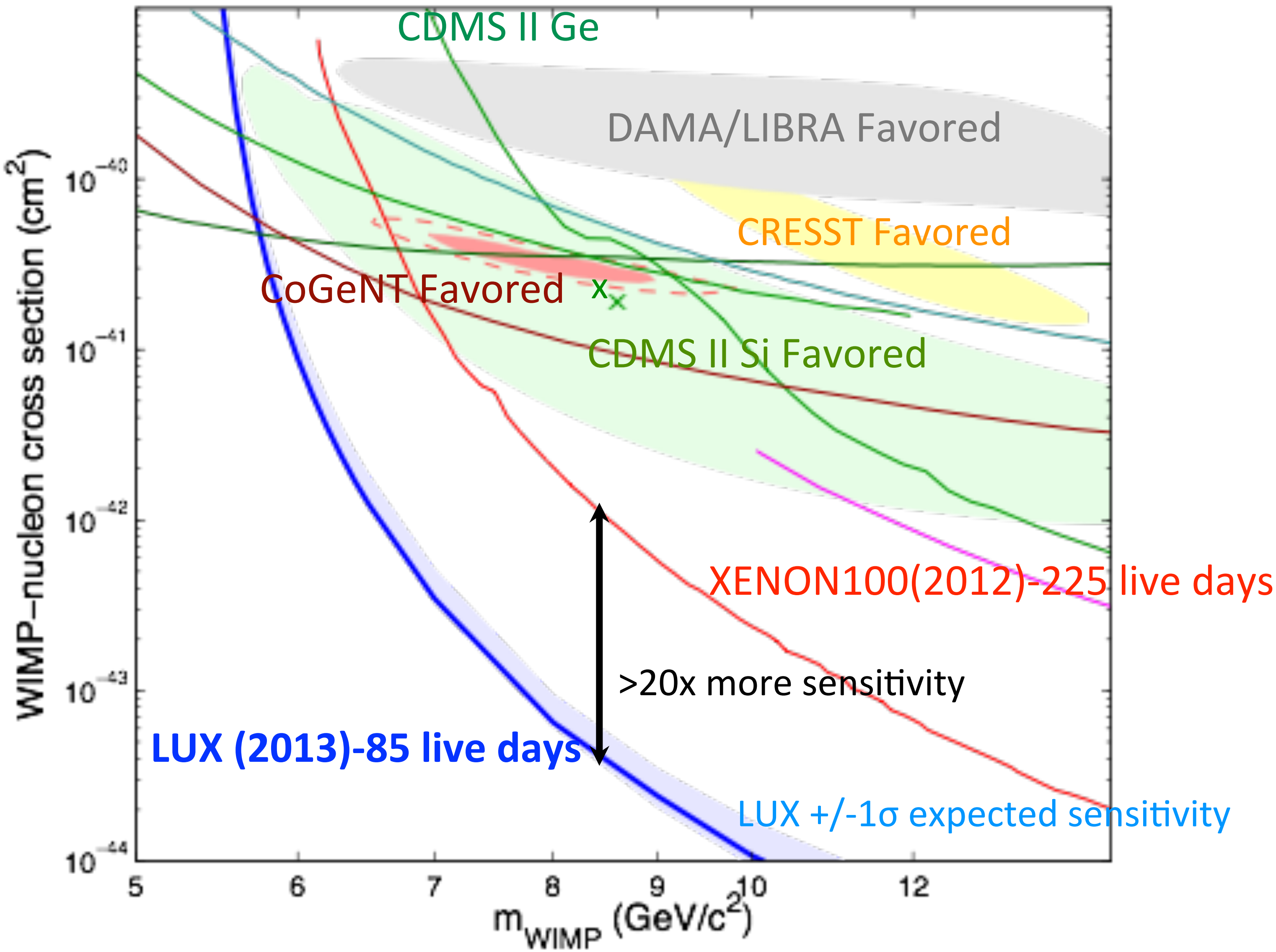


Spin-independent limit

Upper limit @ 33 GeV/c^2 is 7.6×10^{-46} cm^2 → first sub-zeptobarn WIMP detector!



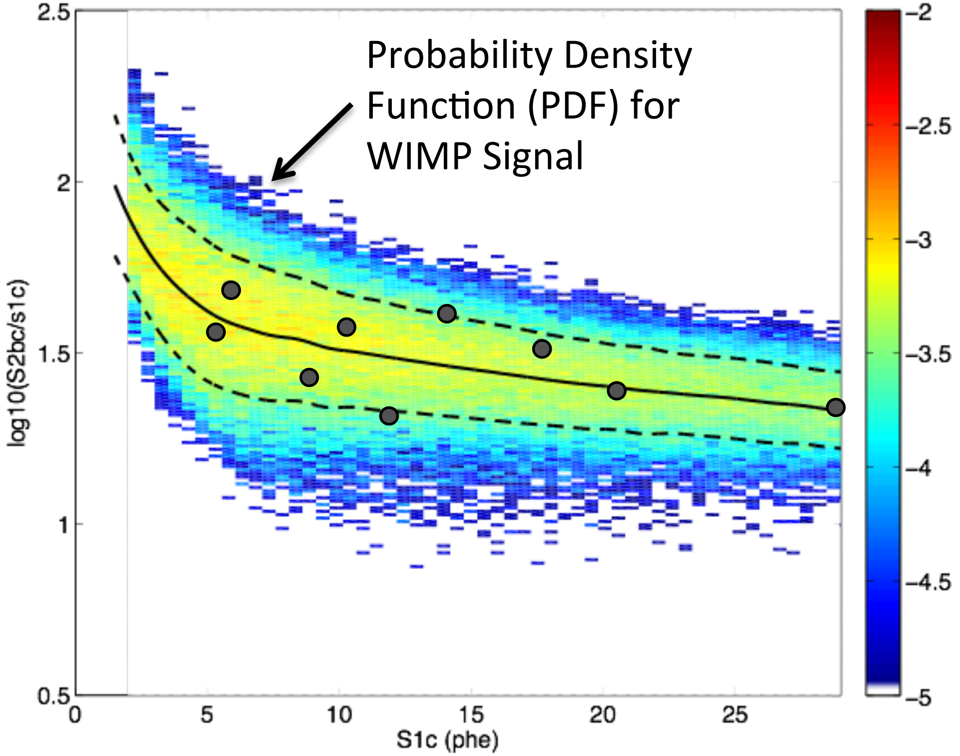
Low mass WIMP excluded



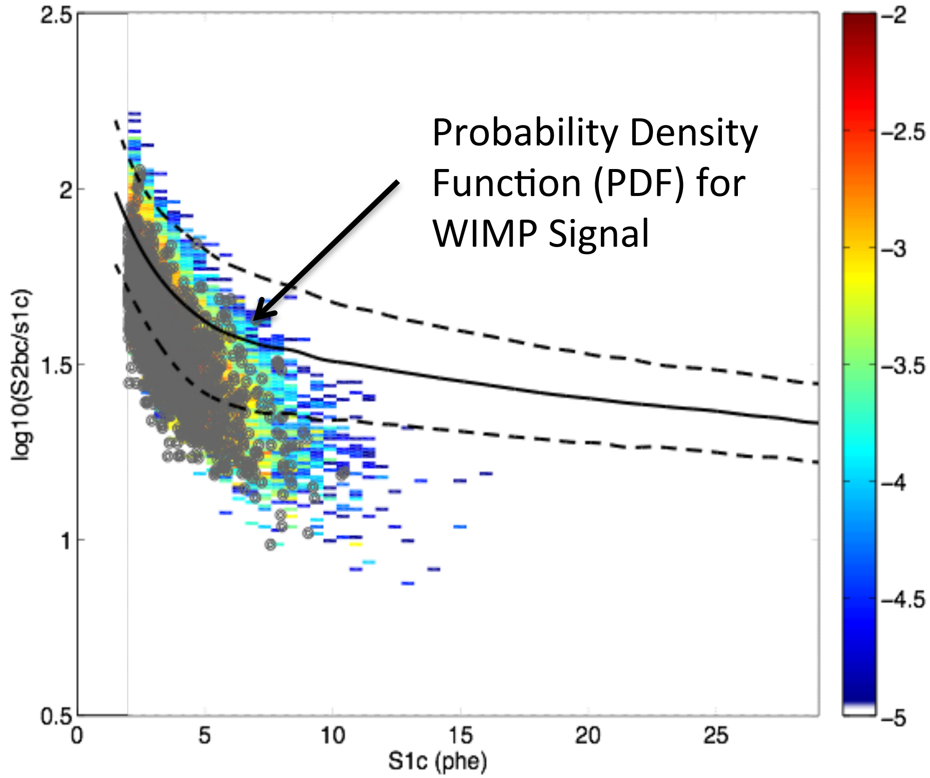
Simulated response to WIMPs

For a 1 TeV WIMP @ 1.9 x 10^{-44} cm^2 (XENON100 90% CL)

➡ **expect 9 WIMPs in this run**

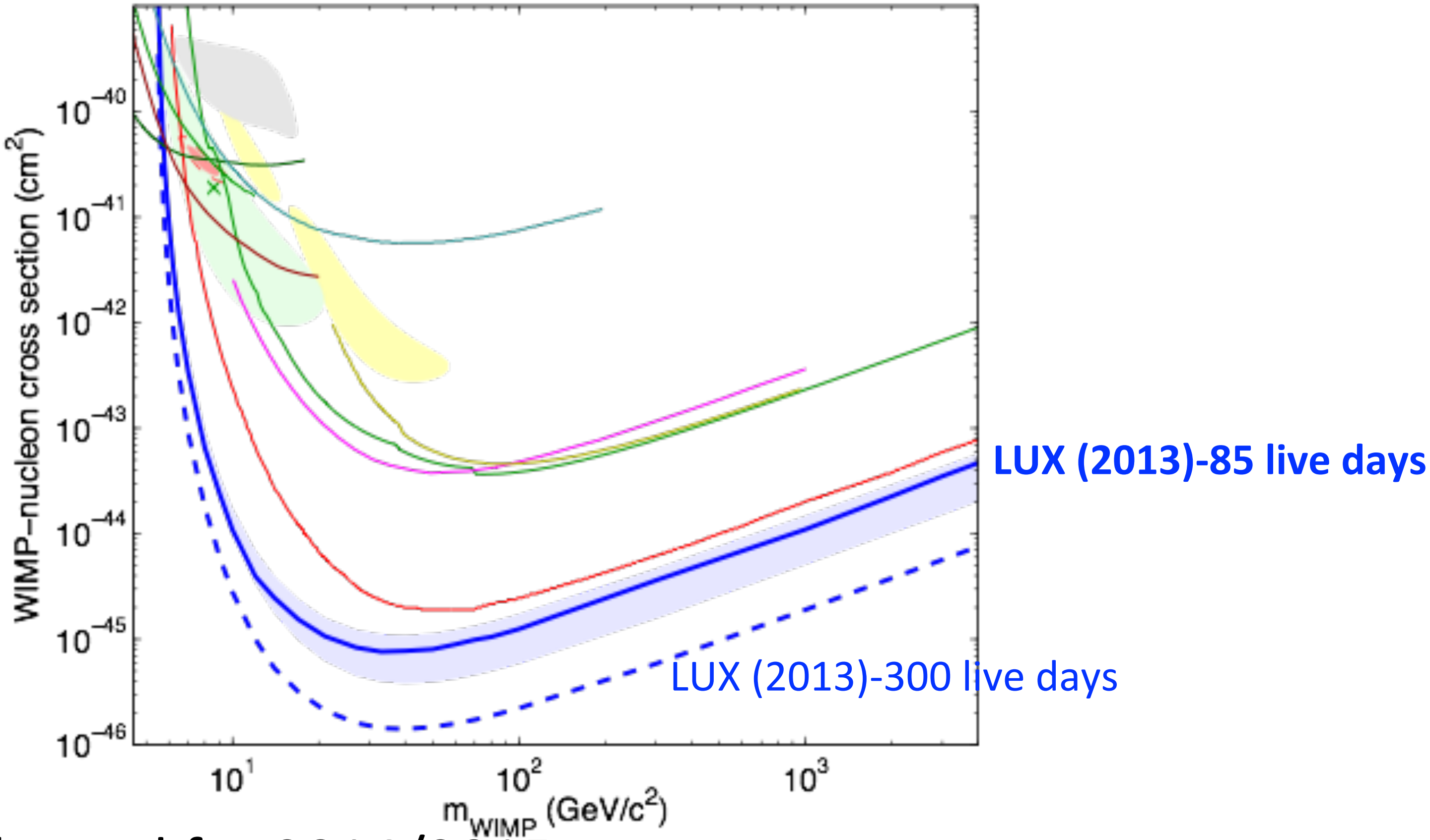


For 8.6 GeV WIMPs @ 2.0 x 10^{-41} cm^2 CDMS II Si (2012) 90% CL



PDF assumes Standard Milky Way Halo parameters v_0=220 km/s, v_{escape} = 544 km/s, ρ_0 = 0.3 GeV/c^2, v_{earth} = 245 km/s.

What's next: LUX 300 day run

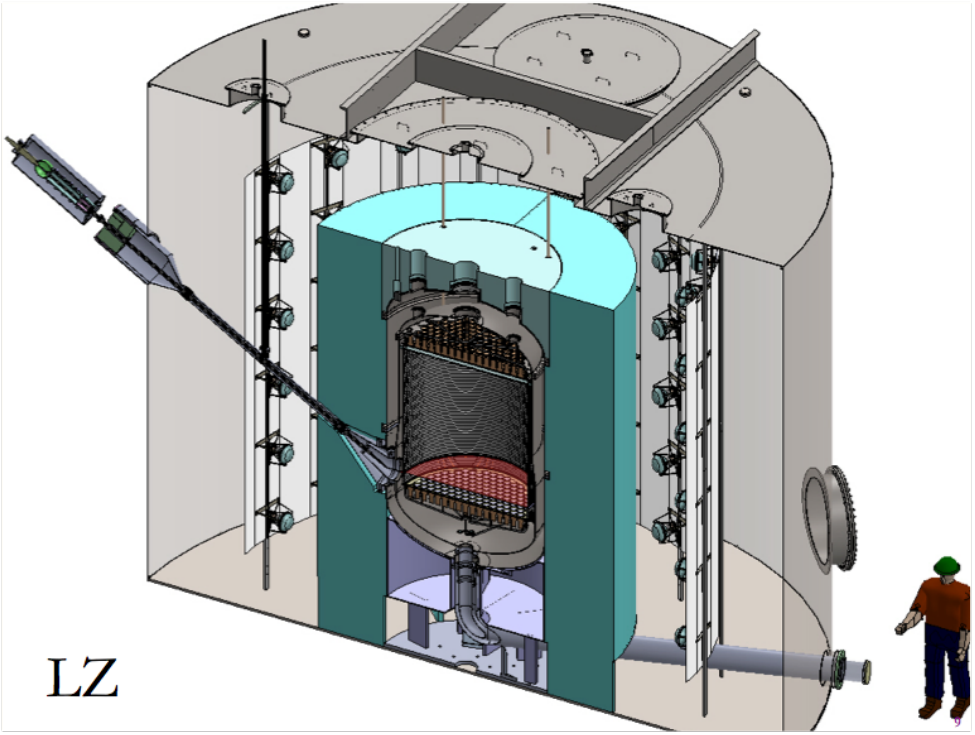


- 300 day run planned for 2014/2015
- Cosmogenic cool-down plus further improvements (E-fields, calib., …)
- Still not background limited and expect factor of ~5 improvement in sensitivity → **discovery possible**

Longer term: LUX-ZEPLIN (LZ)

- 20 times LUX Xenon mass, active scintillator veto, Xe purity at sub ppt level
- Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds

Same water tank as LUX



Onwards and downwards

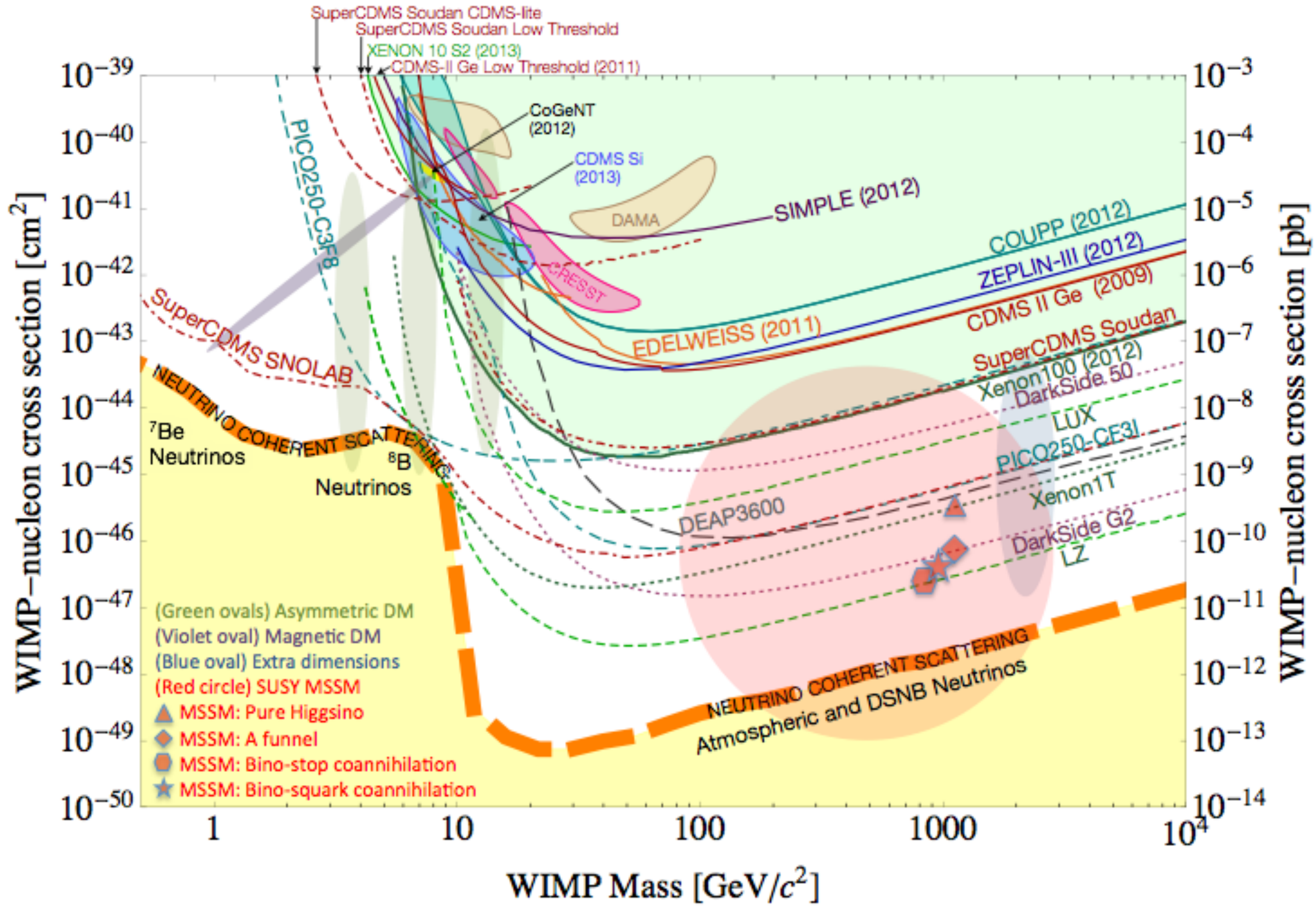
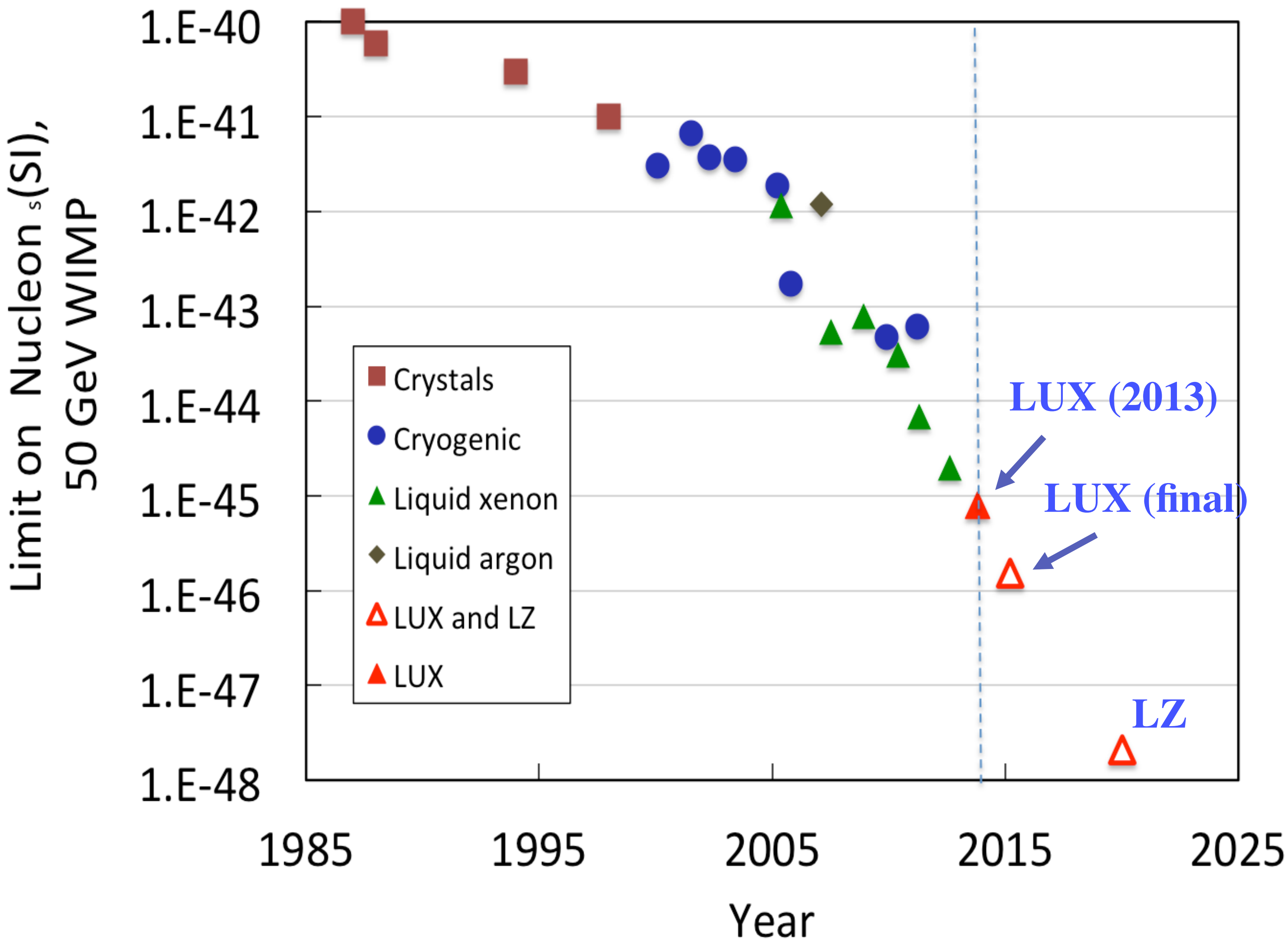
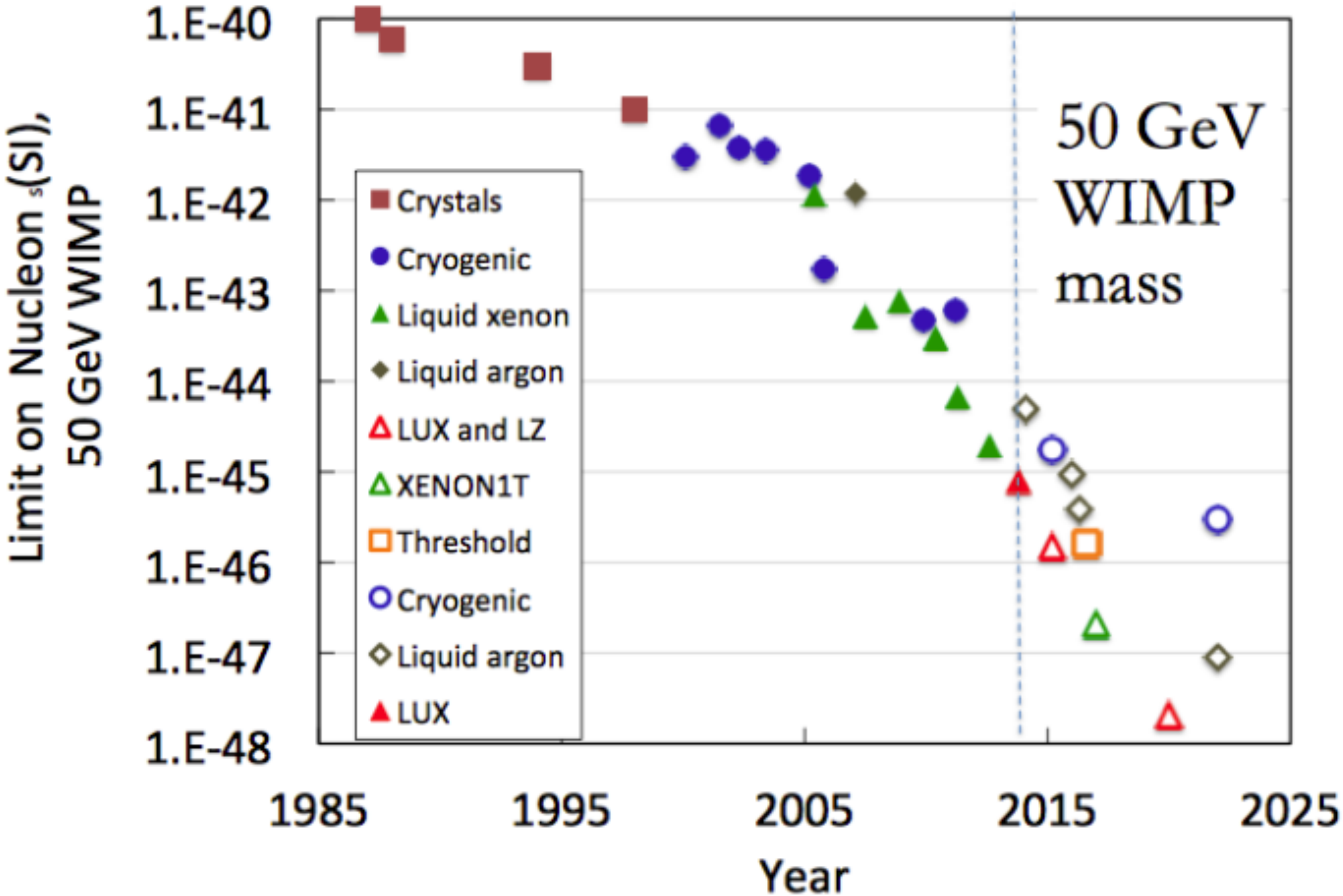


Figure from SNOMASS CF1 WIMP Dark Matter Detection summary

LZ projections

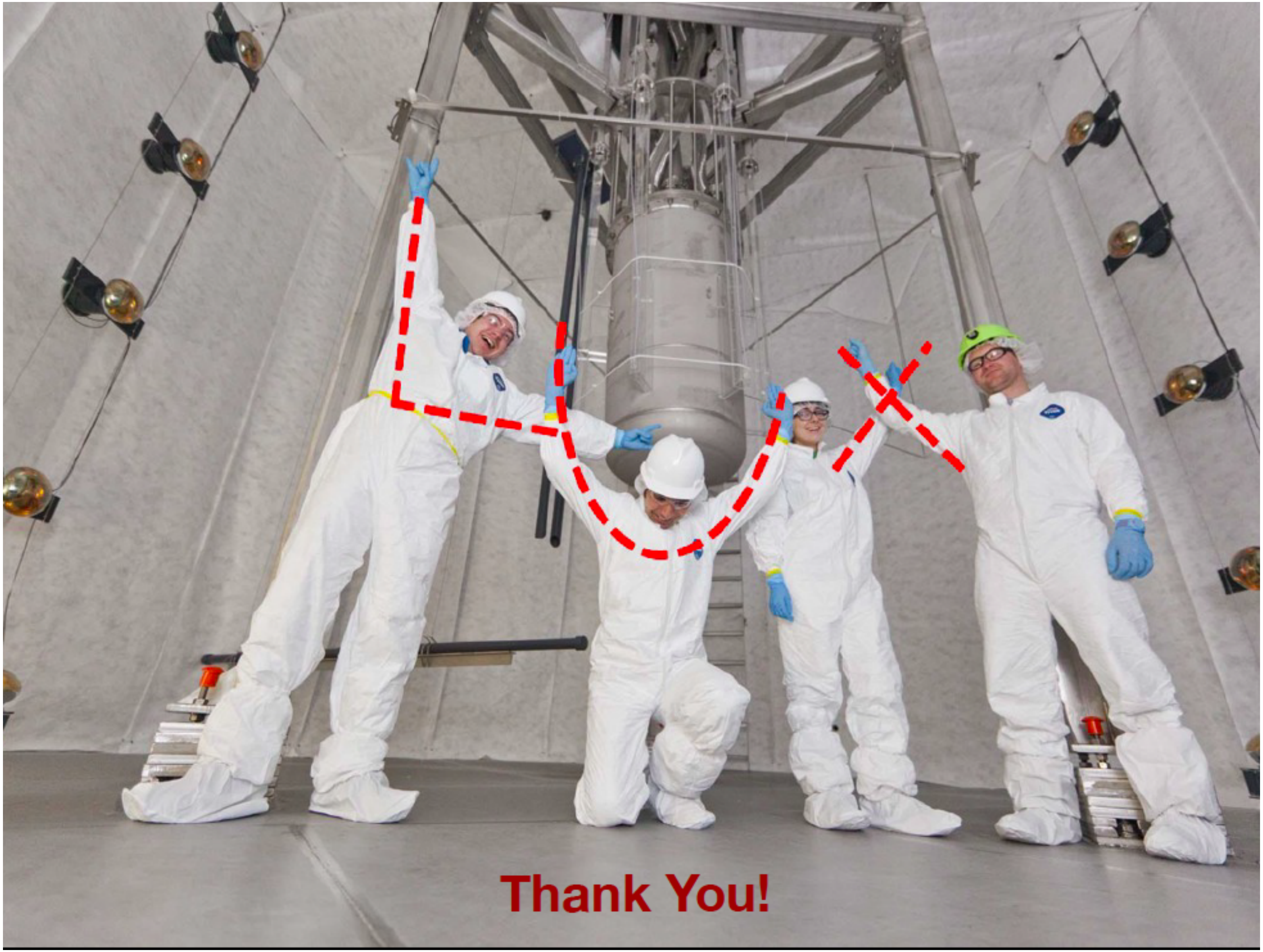


LUX and other "G2" projections



Summary

- **LUX has made a WIMP Search run of 85.3 live-days:**
  - Major advances in calibration techniques including ^{83m}Kr and Tritiated-CH_4 injected directly into Xe target
  - Very low energy threshold achieved : 3 keV_{nr}
  - ER rejection of 99.6+/-0.1% in energy range of interest
- **Results at Intermediate and High Mass WIMPs**
  - 7.6×10^{-46} cm^2 @ 33GeV/c^2 (90% CL)
  - Extended sensitivity over existing experiments by x3 at ~35 GeV and x2 at ~ 1000 GeV
- **Results at Low Mass WIMP**
  - LUX WIMP Sensitivity 20x better
  - LUX does not observe 6-10 GeV WIMPs favored by earlier experiments


Thank You!

Spare slides

NR acceptance

3 keVnr
S2area ~200 phe (8 e)
S1area ~2 phe

Efficiency falls >18 keVnr
due S1 [2,30] phe range