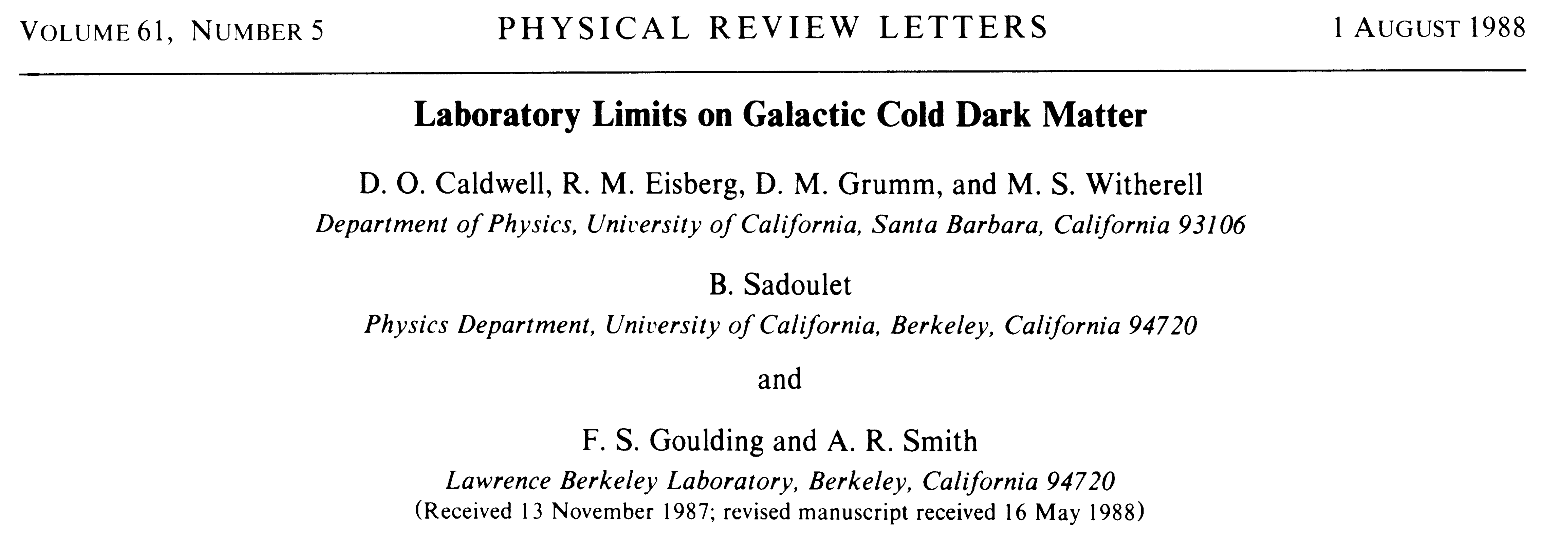
The campaign to observe dark matter using large Xenon detectors.

Michael Witherell
UC Santa Barbara
INPA Dark Matter Workshop
May 8, 2014

In 1988 UCSB-UCB-LBNL published the second non-observation of dark matter.



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Laboratory Limits on Galactic Cold Dark Matter

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(Received 13 November 1987; revised manuscript received 16 May 1988)

"However, when it was decided to look for dark matter, we found that there was a rapidly rising background below about 400 keV. This was due to the presence of about half a gram of In, which undergoes a 486-keV β decay with a half-life of $4\text{x}10^{14}$yr! When the In was removed from one detector, the background for that detector became flat down to about 14 keV at a level of 0.5 counts/keV/kg/day, except for some x-ray peaks."

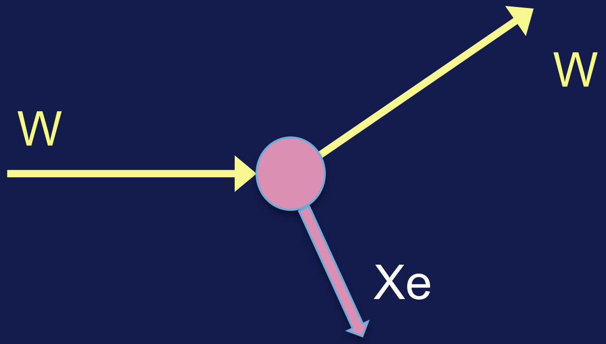
Present experiments achieve about 0.5×10^{-4} in these units. The goal is 10^{-6}.

What do we know about the local dark matter?

- The energy density is about 0.3 GeV/cm^3.
- The DM particles have a broad velocity distribution relative to the earth with a characteristic velocity of about 220 km/s.
- No particle in the Standard Model fits.
  - The mass of the particles is unknown.
- The frequency of dark matter particle scatters in normal matter is no more than a few events per 100 kg per year.

How might we see dark matter?

- A weakly interacting massive particle (WIMP) scatters from a xenon nucleus

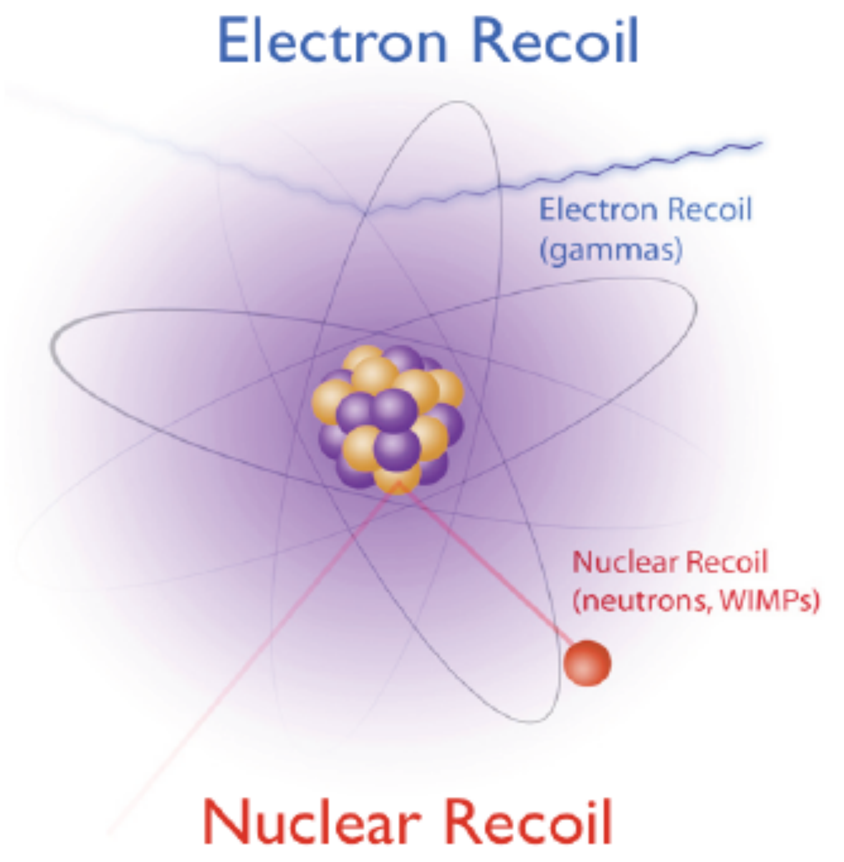


- The xenon nucleus recoils with a small amount of energy (~5 keV). Then it escapes.

Strategy for direct detection

WIMP scatters elastically from the entire nucleus.

- Dominant γ and β create electron recoils (ER).
- Neutrons produce nuclear recoils (NR), but scatter more than once.



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Reducing background radiation

- Minimize radioactive impurities
  - Uranium and Thorium chains; especially Radon.
  - Krypton-81 in Xenon, Argon-39 in Argon.
- Reduce cosmogenic activity
  - Go deep to reduce rate of muons.
  - Keep xenon underground before operation.
- Shield from external activity
  - Pure water
- Neutrons are particularly dangerous, because they look more like WIMPs.

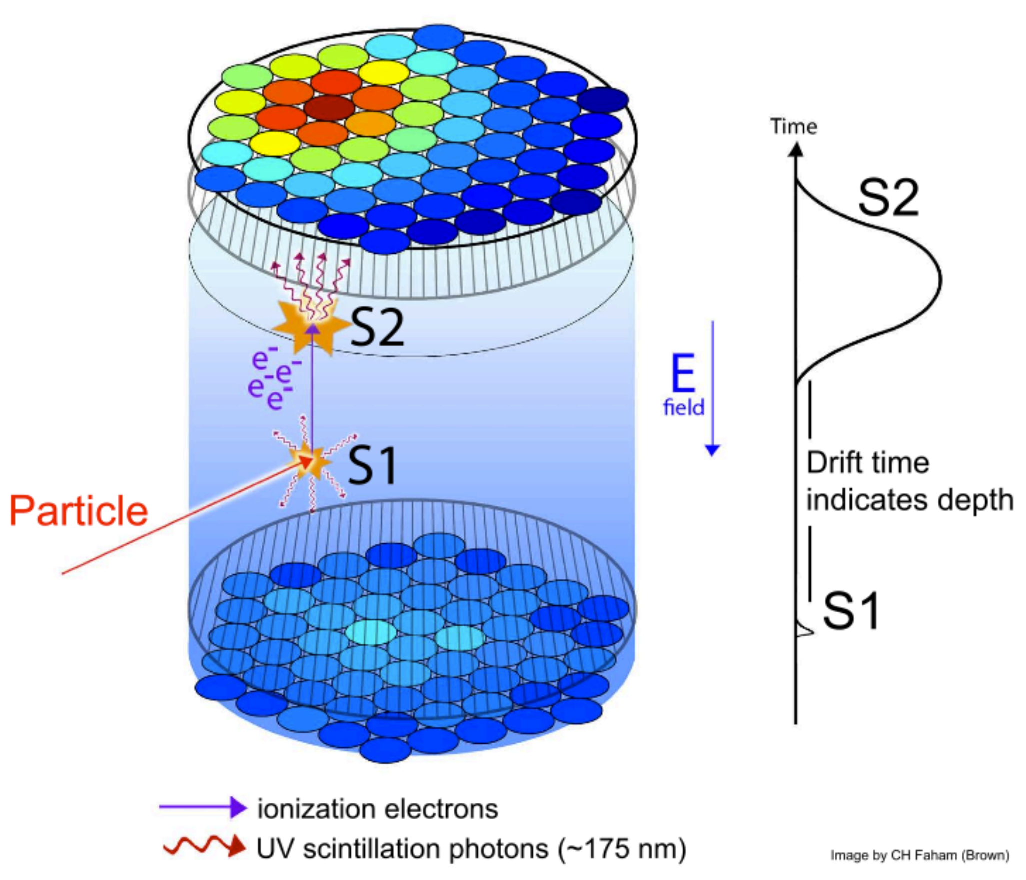
Why use liquid xenon to see dark matter?

Liquid Xenon scintillates brightly at vacuum ultraviolet wavelengths, and is transparent to its own light. And it shields itself from radioactivity coming from the edges.

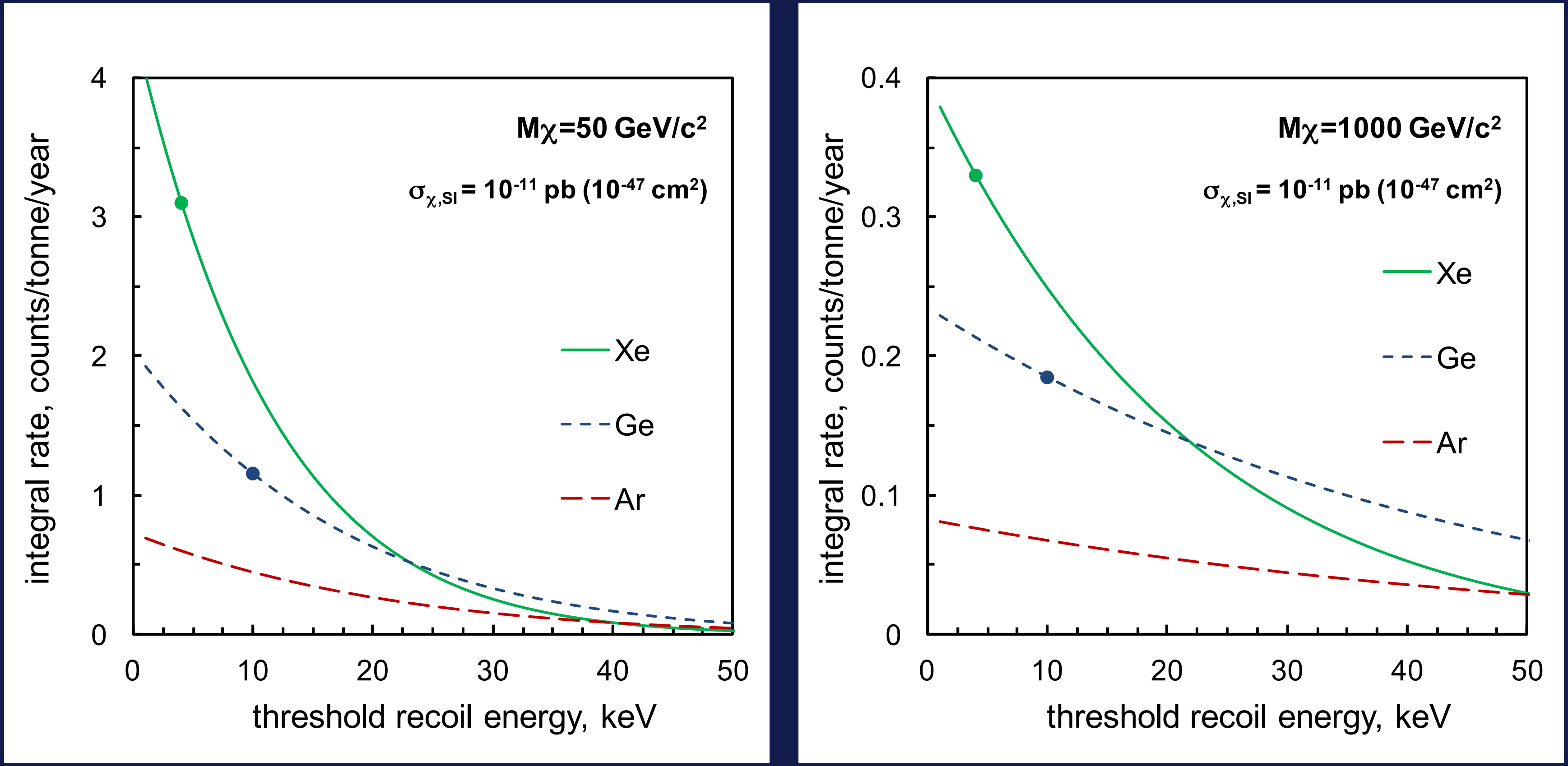
S1 light is direct scintillation.
S2 light counts ionization electrons, is delayed.

Purified xenon can be kept very low in background. Krypton can be removed before operation.

Because of self-shielding, the center of a large xenon detector is very, very quiet.
=> Internal calibrations!



Sensitivity per tonne



The combination of low threshold and high mass makes xenon particularly sensitive per tonne over a wide range of WIMP masses

The LUX Collaboration

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Collaboration Meeting, Sanford Lab, April 2013

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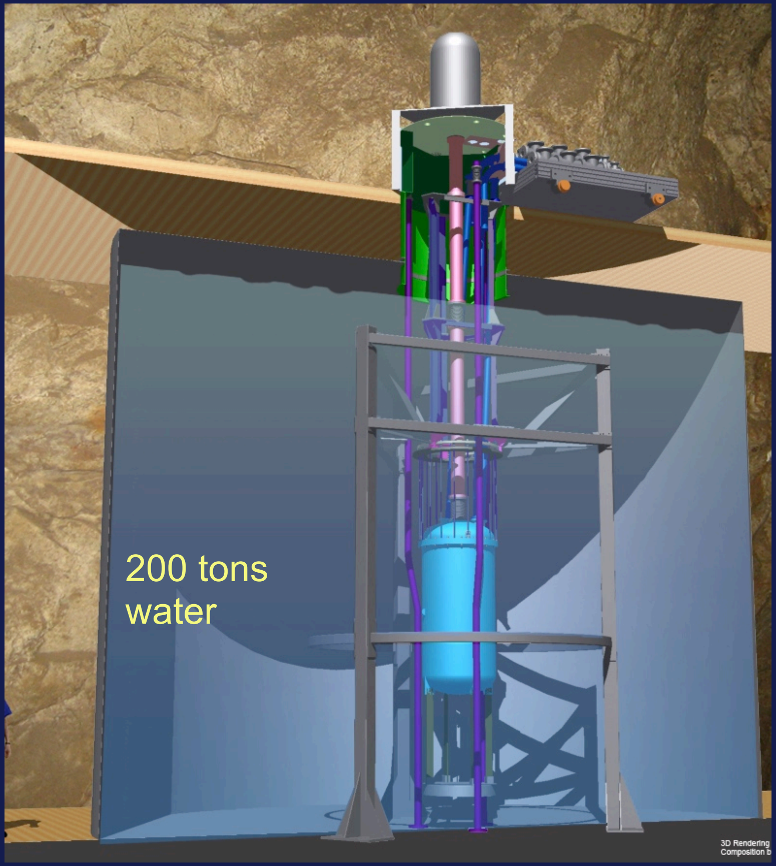
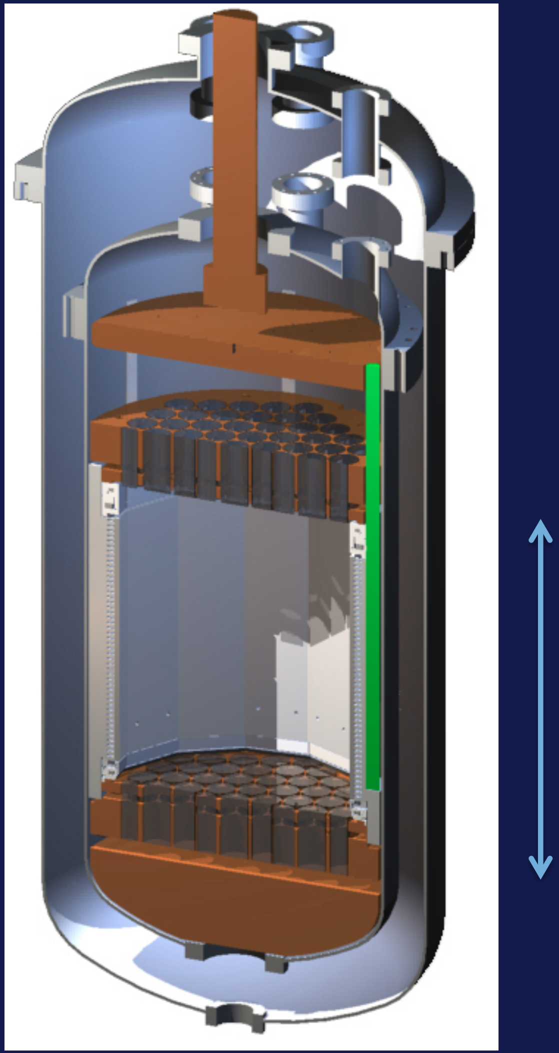
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

Sanford Underground Research Facility

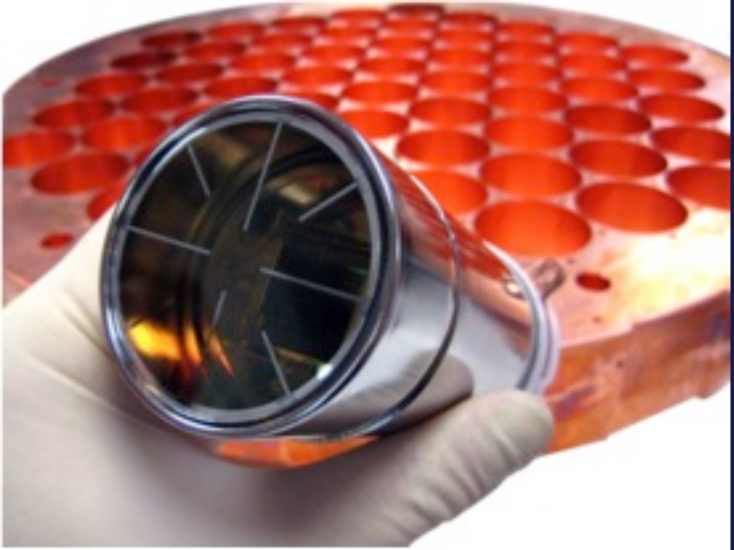
The LUX experiment

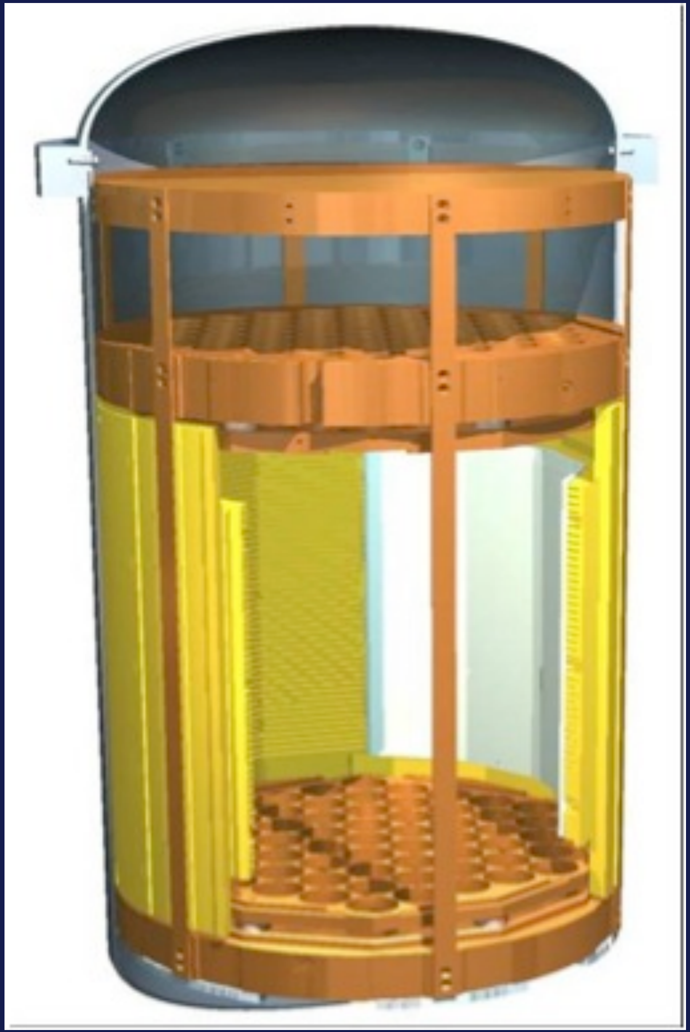


250 kg of active xenon in a titanium vessel
122 photomultiplier tubes


50 cm
or 20"

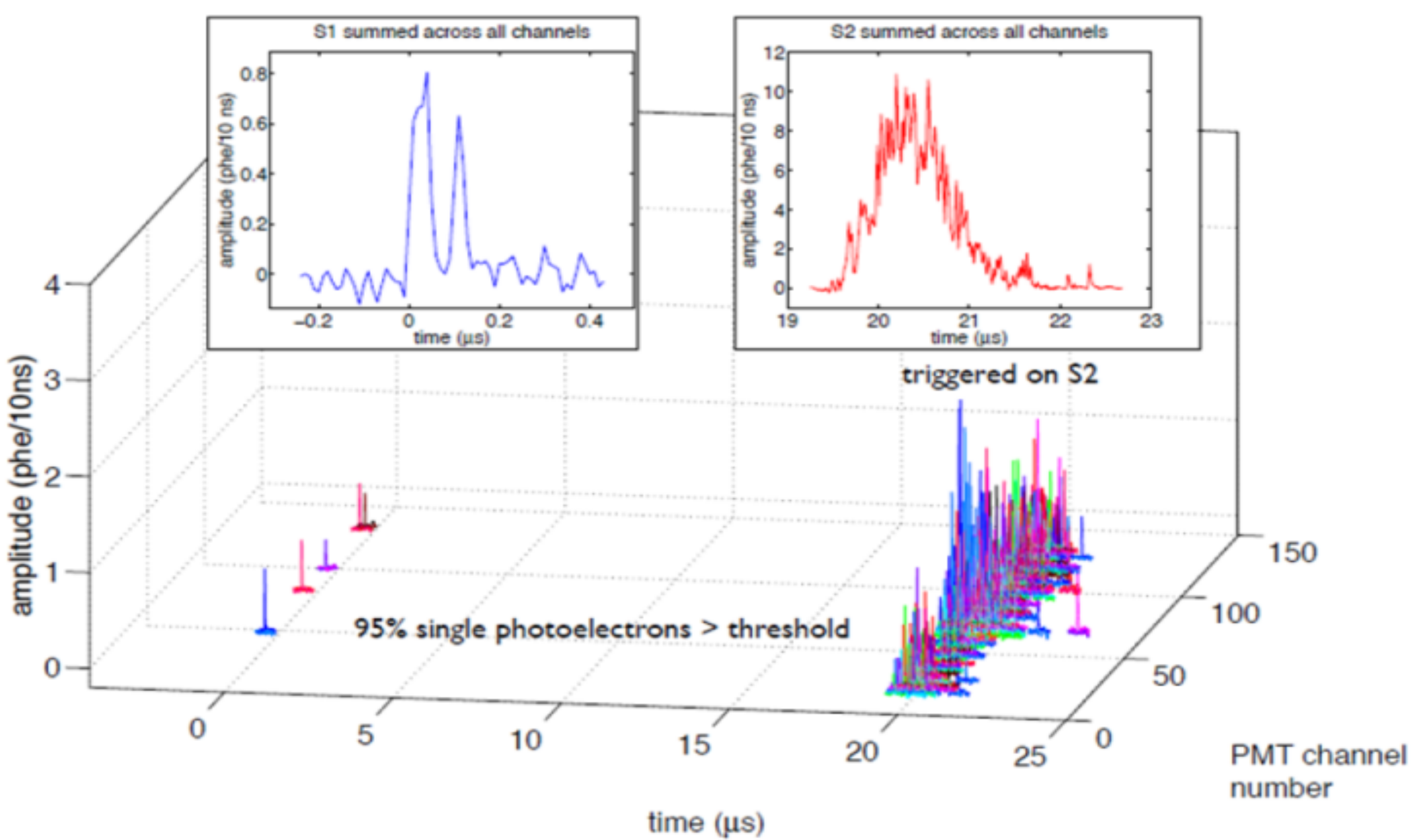
The time projection chamber





- The LUX TPC is a cylinder of liquid xenon (~50 cm h, ~48 cm d).
- Thermosyphons passively cool xenon, operting from a liquid nitrogen reservoir.
- A vertical electric field forces the freed electrons into the gas volume.
- 122 photomultiplier tubes (above) detect the UV scintillation light

Sensitivity to low energy deposits



- 1.5 keV electron recoil interaction
  - 5-fold coincidence for S1
  - Larger S2 signal, delayed by 20 microseconds

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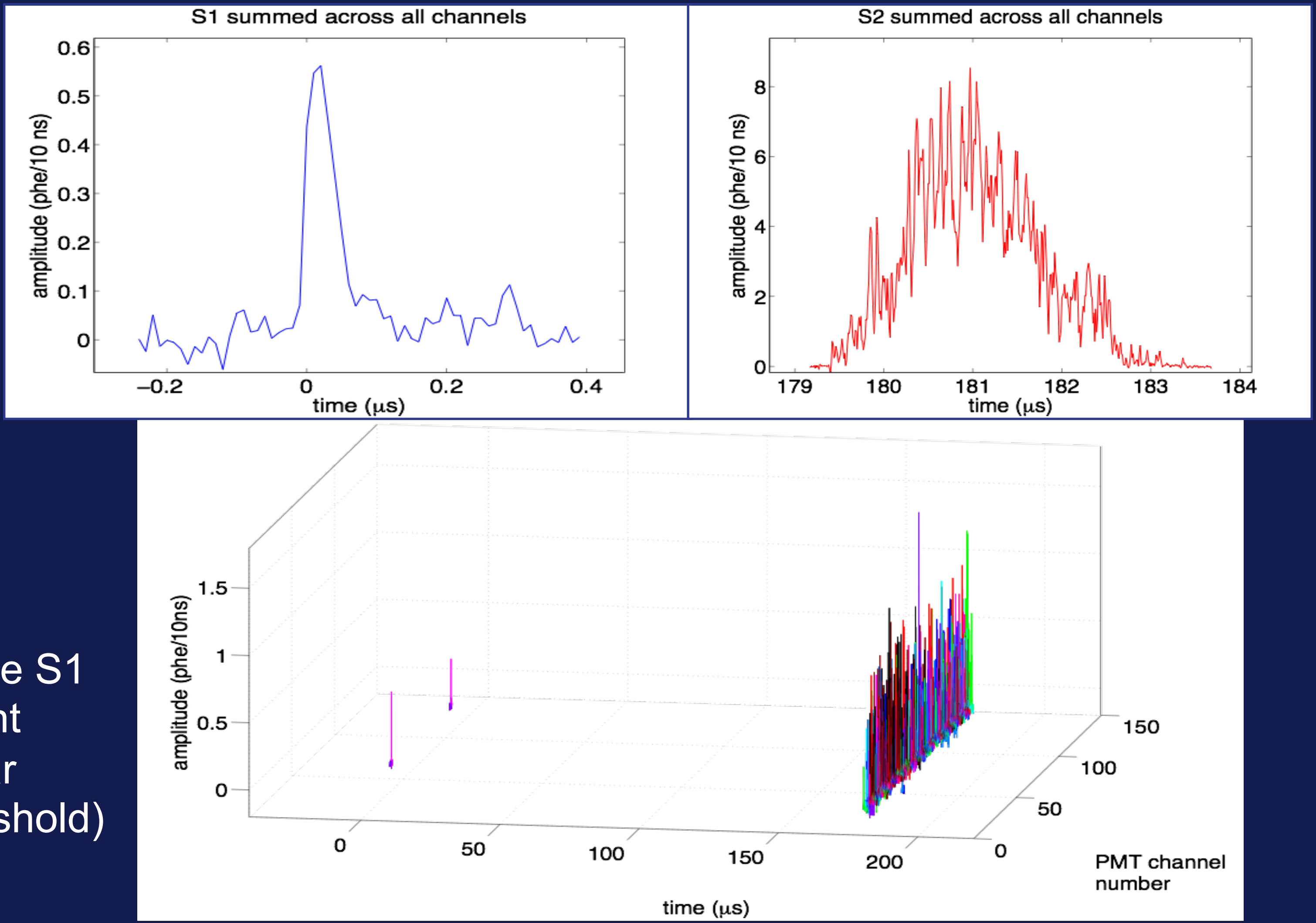
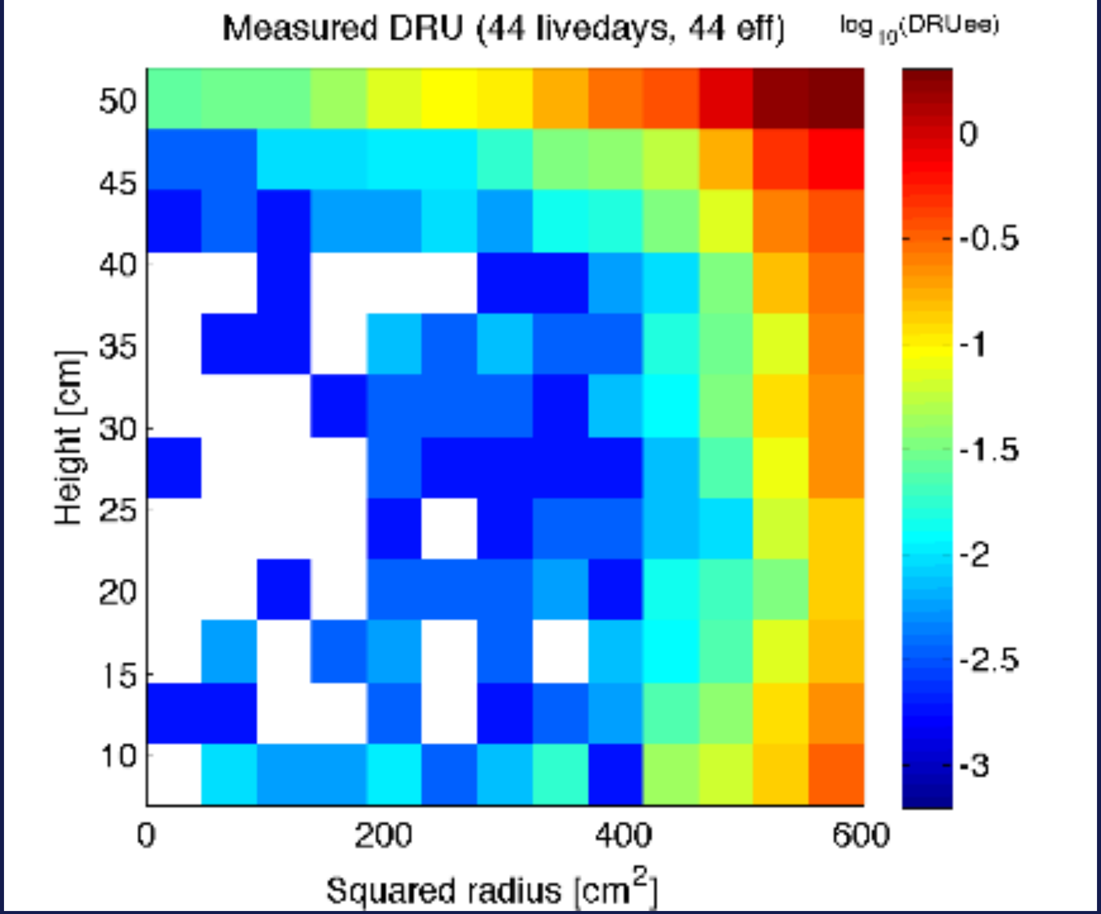
Right at threshold



2 phe S1 event (near threshold)

Xenon shields itself.

log10
evts/keVee/kg/day



- The center of the detector is very quiet.
    - 118 kg fiducial mass
- And it continues to get quieter as cosmogenic activity cools (^{127}Xe)
- How can we calibrate the response in the center?

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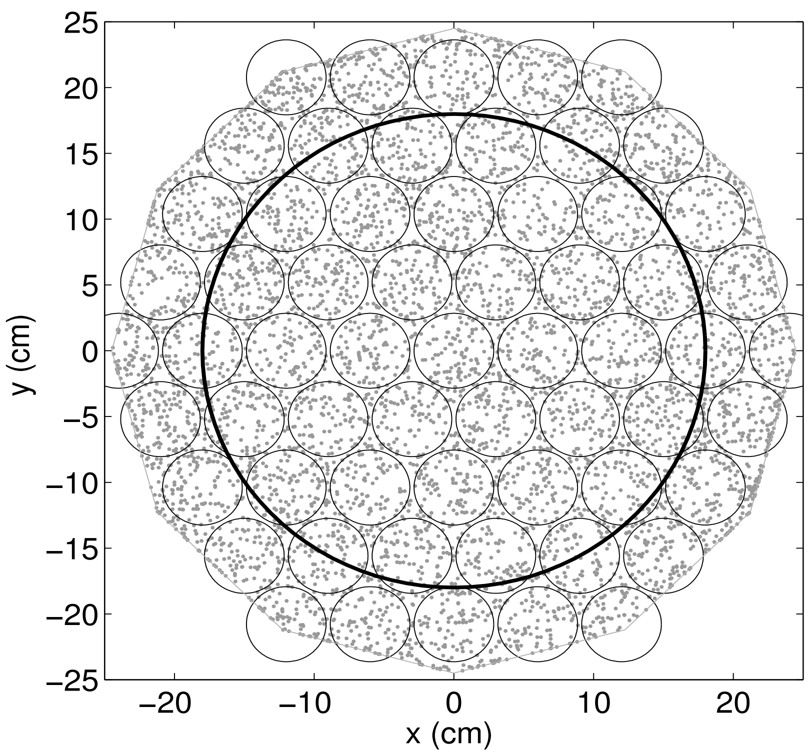
Internal tritium calibration

Tritium beta decay has an endpoint energy of 18.6 keV, ideal for calibrating the WIMP energy region.

LUX developed a method of injecting CH_3T into the xenon, taking calibration data, and removing the methane.

LUX also injected ^{83m}Kr weekly to determine the free electron lifetime and the 3-d correction to photon detection efficiency.

(9.4 and 32.1 keV deposits)



XY distribution of tritium events. Circle at r=18cm.

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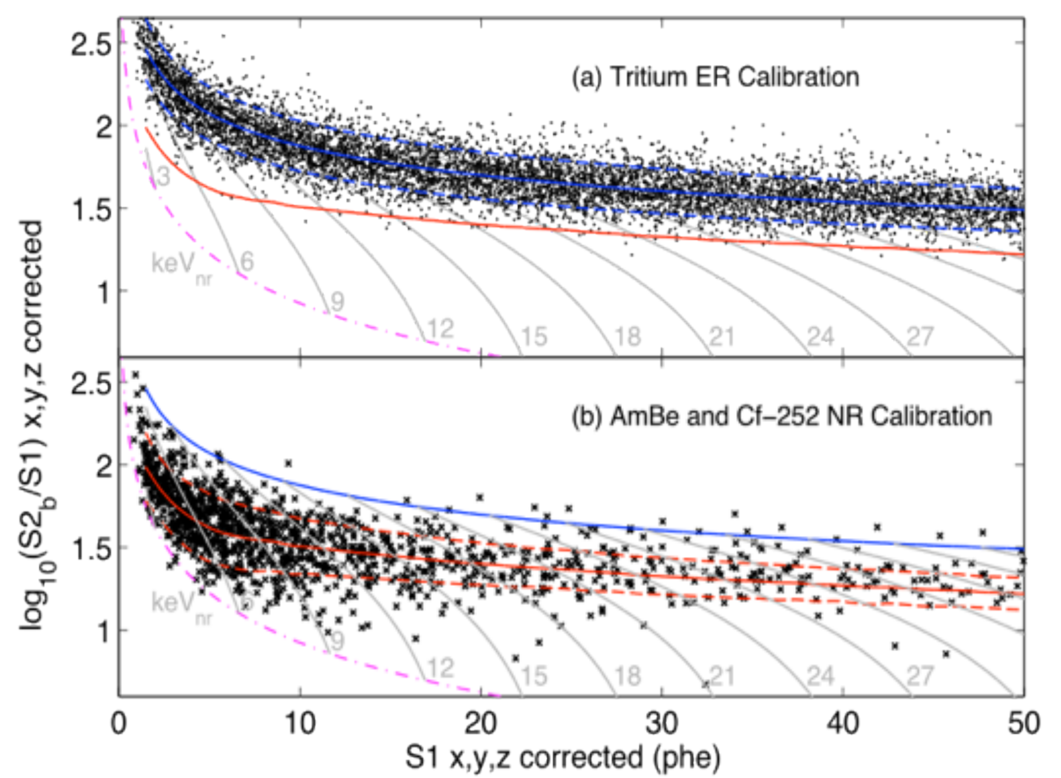
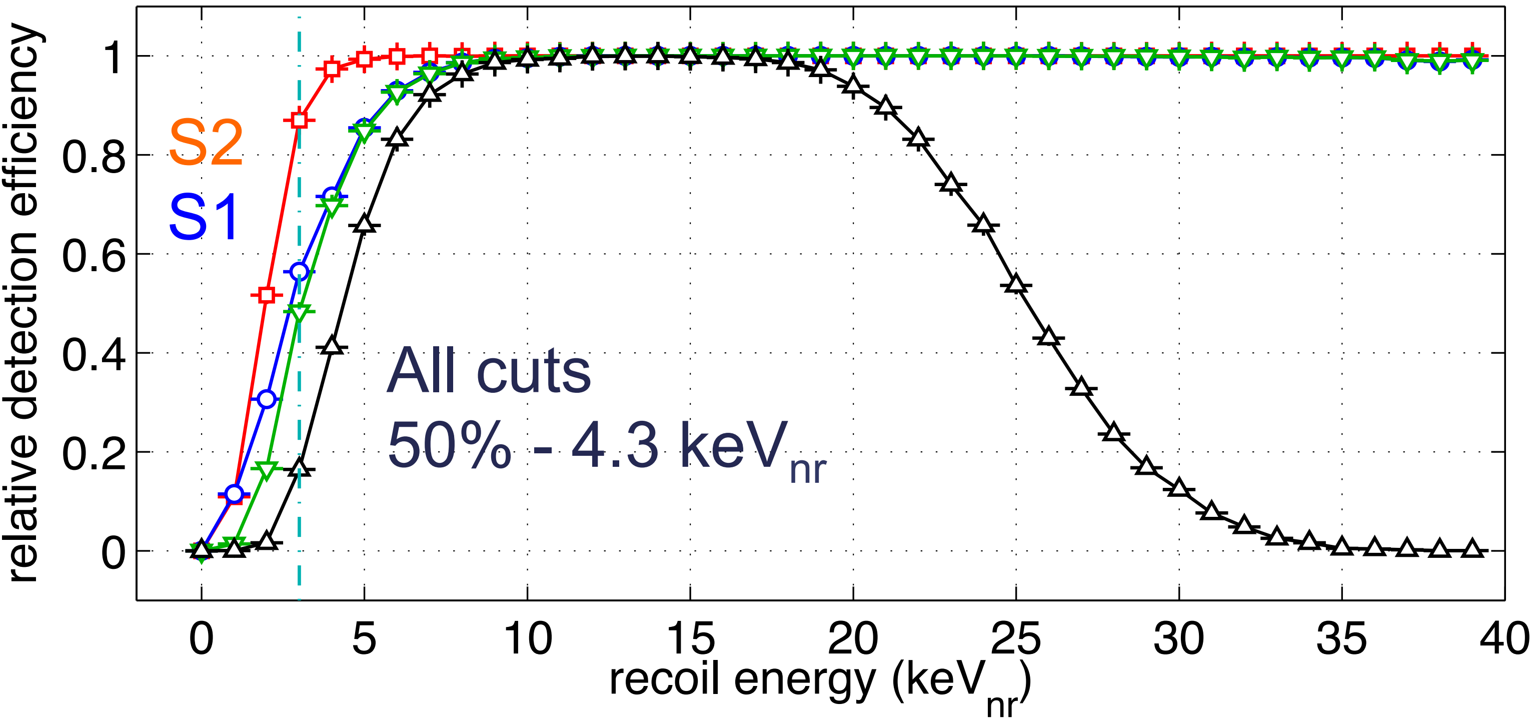
Electron and Nuclear Recoil Bands



ER background rejected by 250x in region of interest

Efficiency for WIMP Detection

- Universal S1, S2 efficiencies
  - AmBe NR calibration
  - Tritiated methane calibration
  - Mono-energetic neutron source



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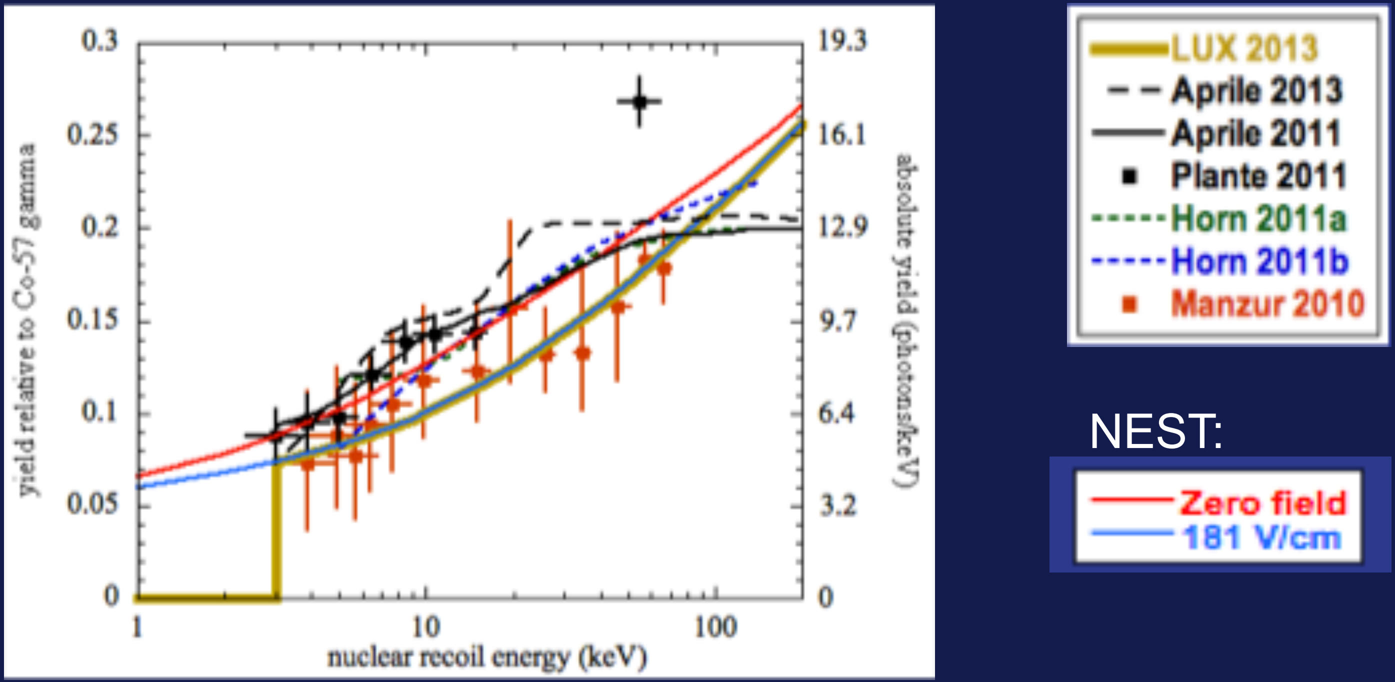
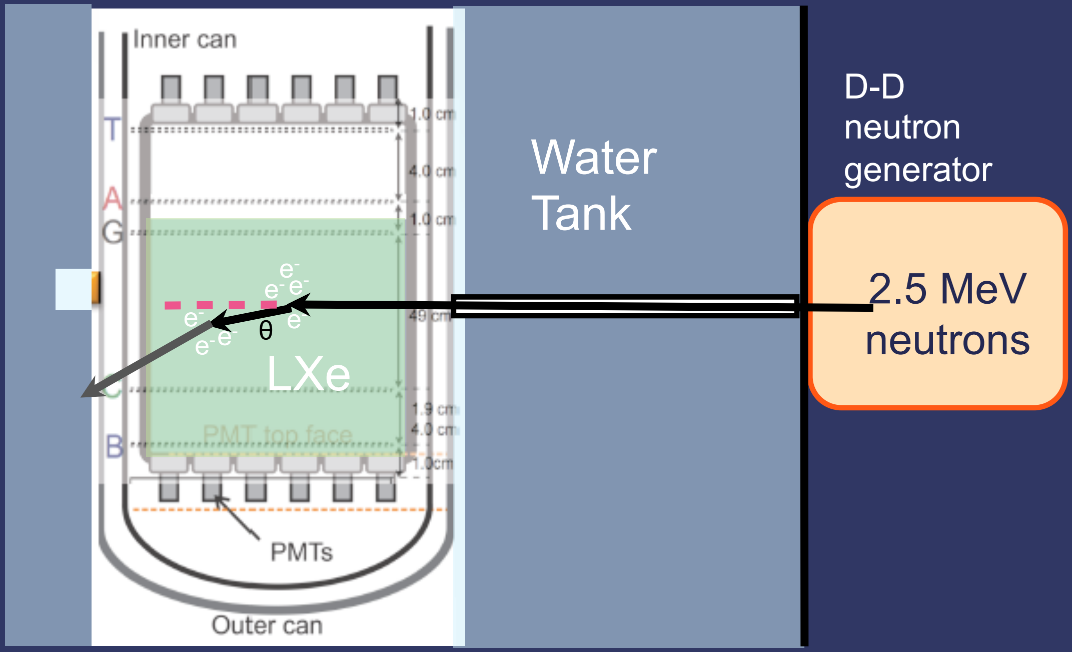
Light and charge yields in LUX

- Light and charge yields modeled fully (NEST)
  - NEST consistent with all experimental data
- Includes effect of E-field, 77-82% of light yield w/ zero light
- To be very conservative, for the initial analysis we assumed no charge or light below 3 keVnr, which we know is wrong.



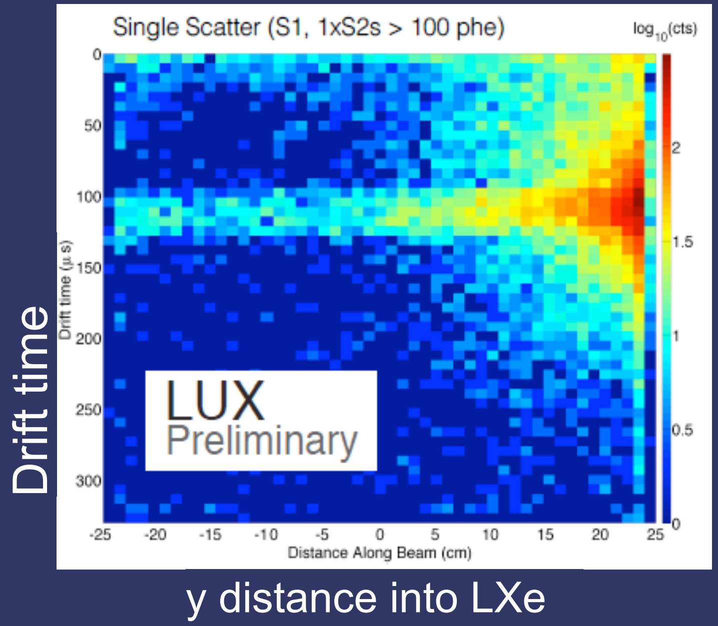
Calibration with monoenergetic, collimated neutrons



Water Tank

D-D neutron generator

2.5 MeV neutrons



Drift time

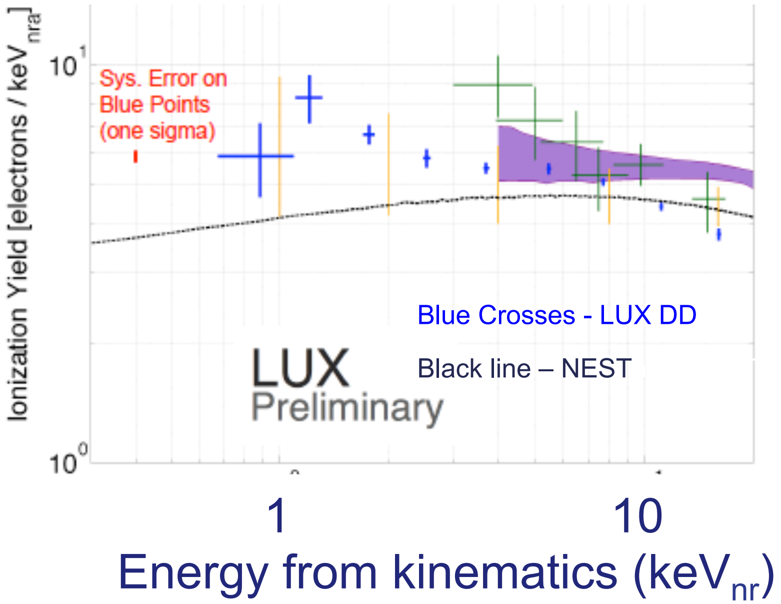
y distance into LXe

Double scatter: angle gives E_{recoil}
Calibrate charge output S2.
Then use single scatters to calibrate light output S1.

In-situ measurement of nuclear recoil events

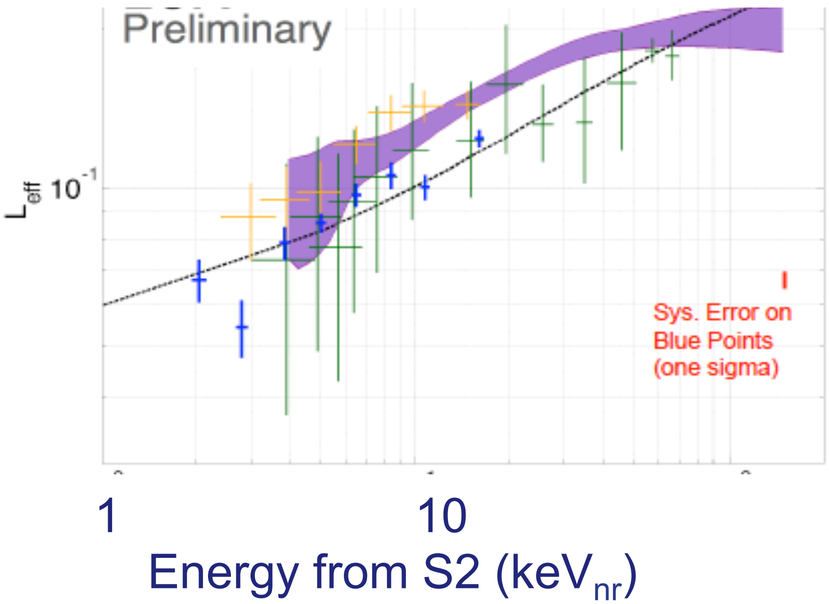
S2 – Ionization

(double scatters)



S1 – scintillation

(single scatters)



Qualitative result:

- Current LUX 2014 PRL is indeed overconservative.
- Light & charge yields continuous below 3 keV.
- Close to NEST simulation.

Updated result coming this fall with lower threshold

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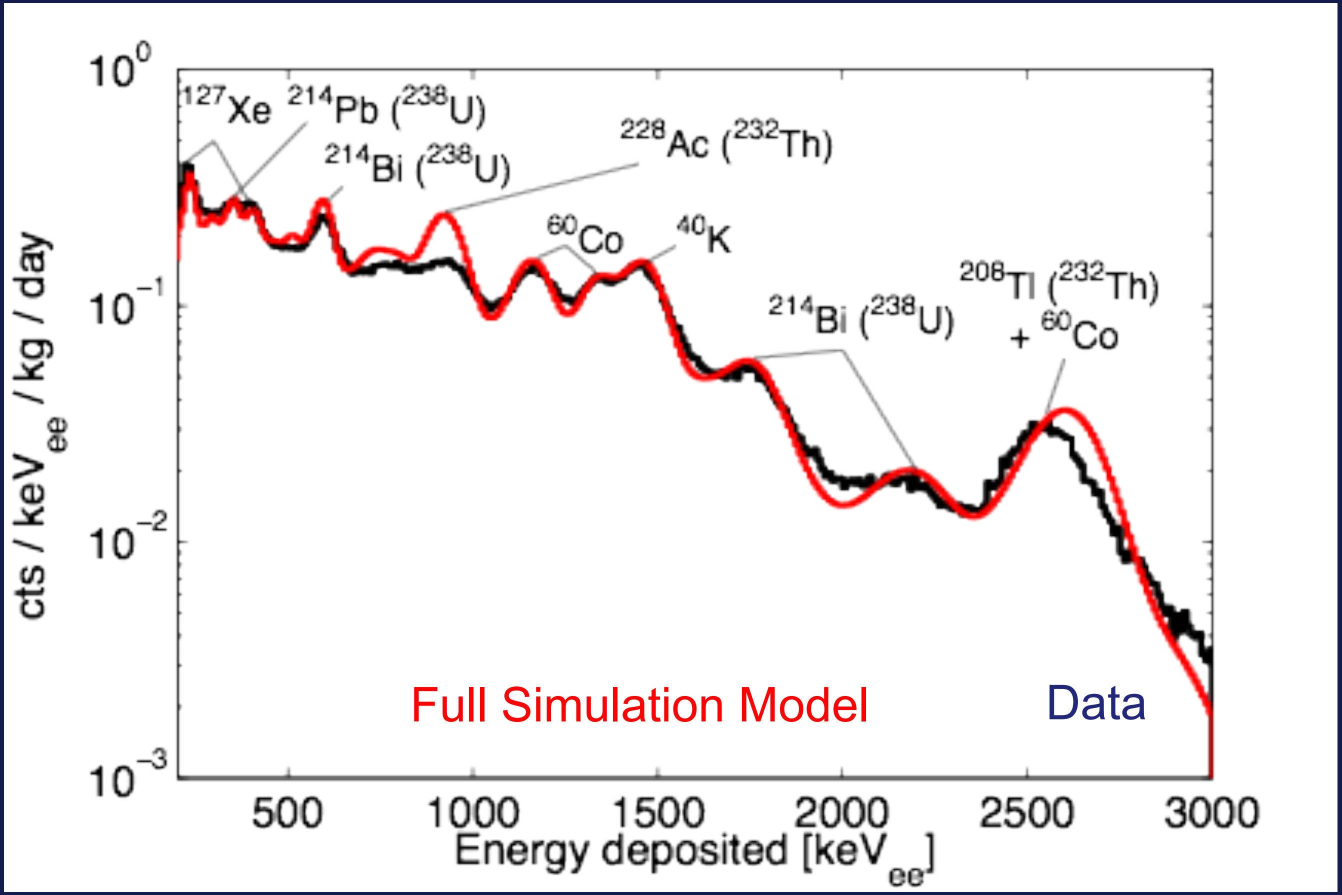
External backgrounds are understood.



Background in 1-10 keV$_{ee}$ range can be predicted reliably because of this understanding.

Background Summary for 118 kg Fiducial

- Average levels over period 2013 WIMP Search Run

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

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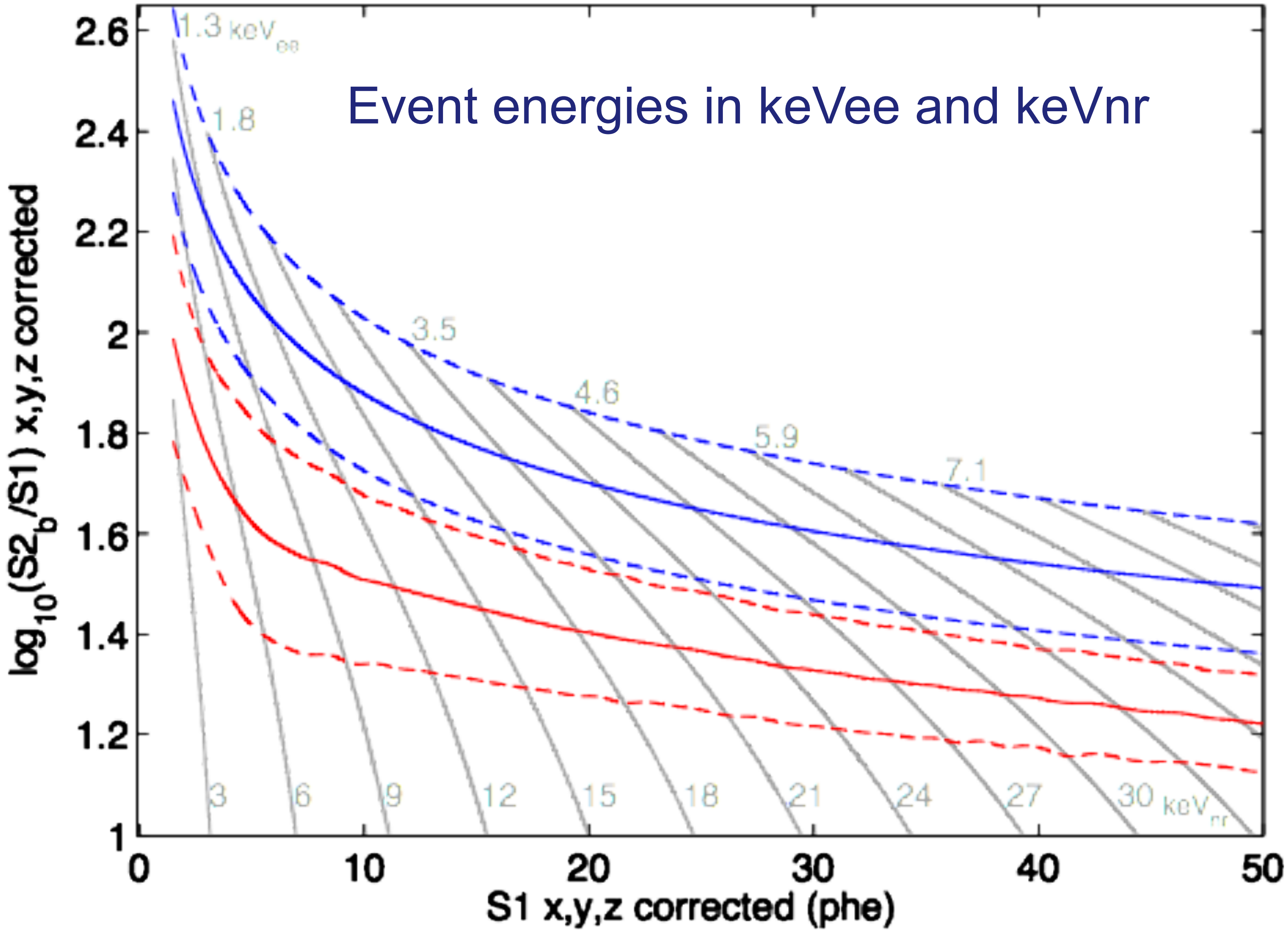
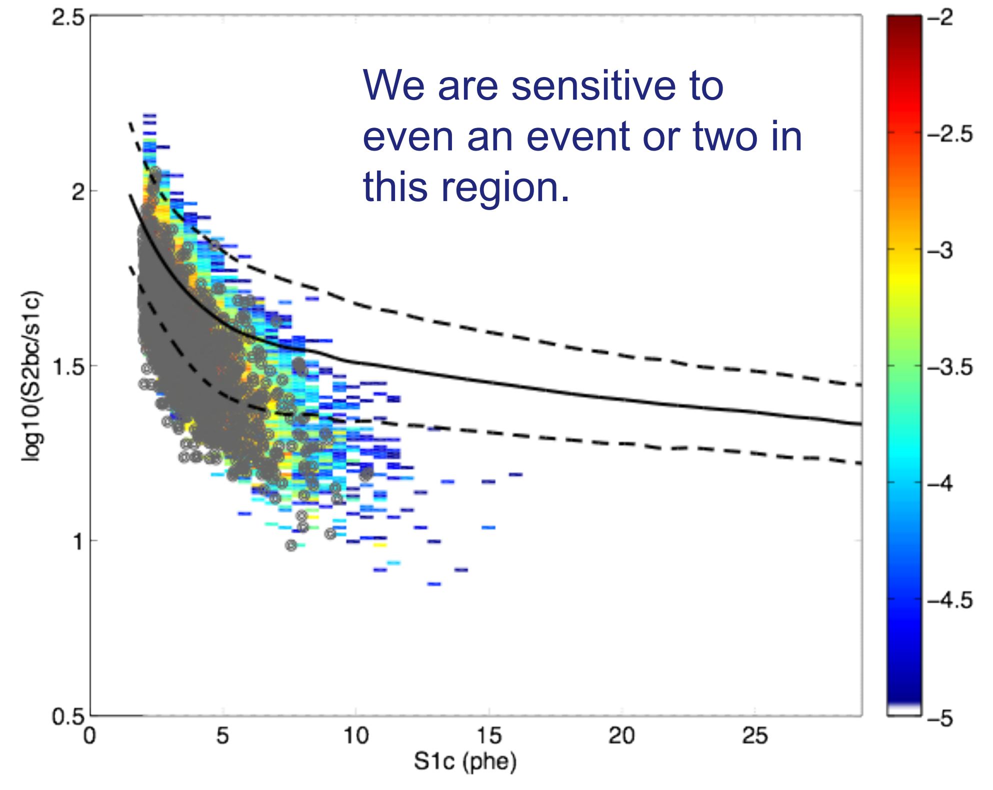
LUX WIMP Search, 85 live-days, 118 kg


Event energies in keVee and keVnr

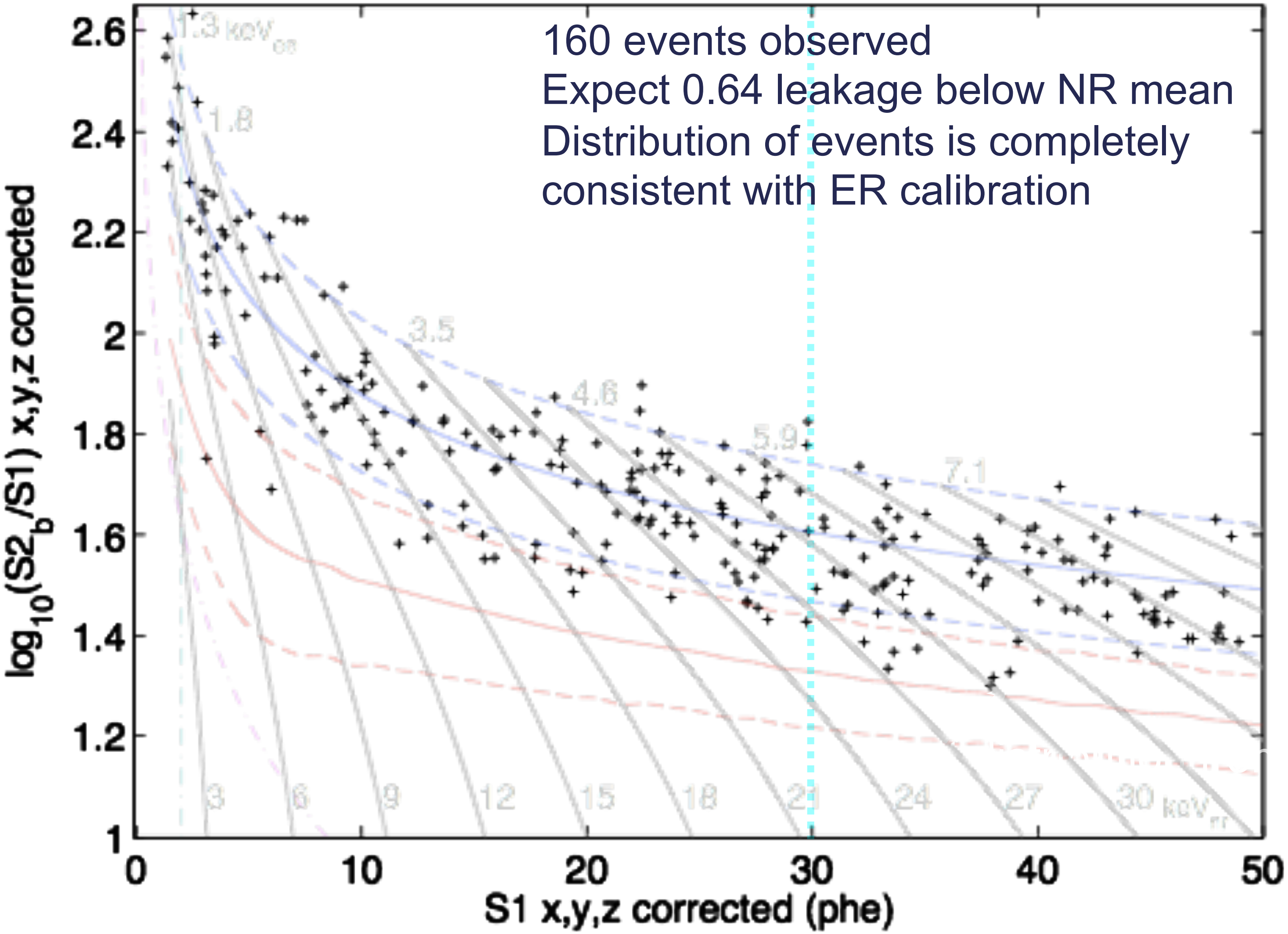
Low-mass WIMPs

- CDMS-Si found 3 events consistent with a mass of 8.6 GeV and a scalar cross section of 2×10^{-41}cm^2.
- This would produce 1550 WIMPs observed in LUX.



We are sensitive to even an event or two in this region.

LUX WIMP Search, 85 live-days, 118 kg



160 events observed
Expect 0.64 leakage below NR mean
Distribution of events is completely
consistent with ER calibration

Spin Independent Sensitivity Plots

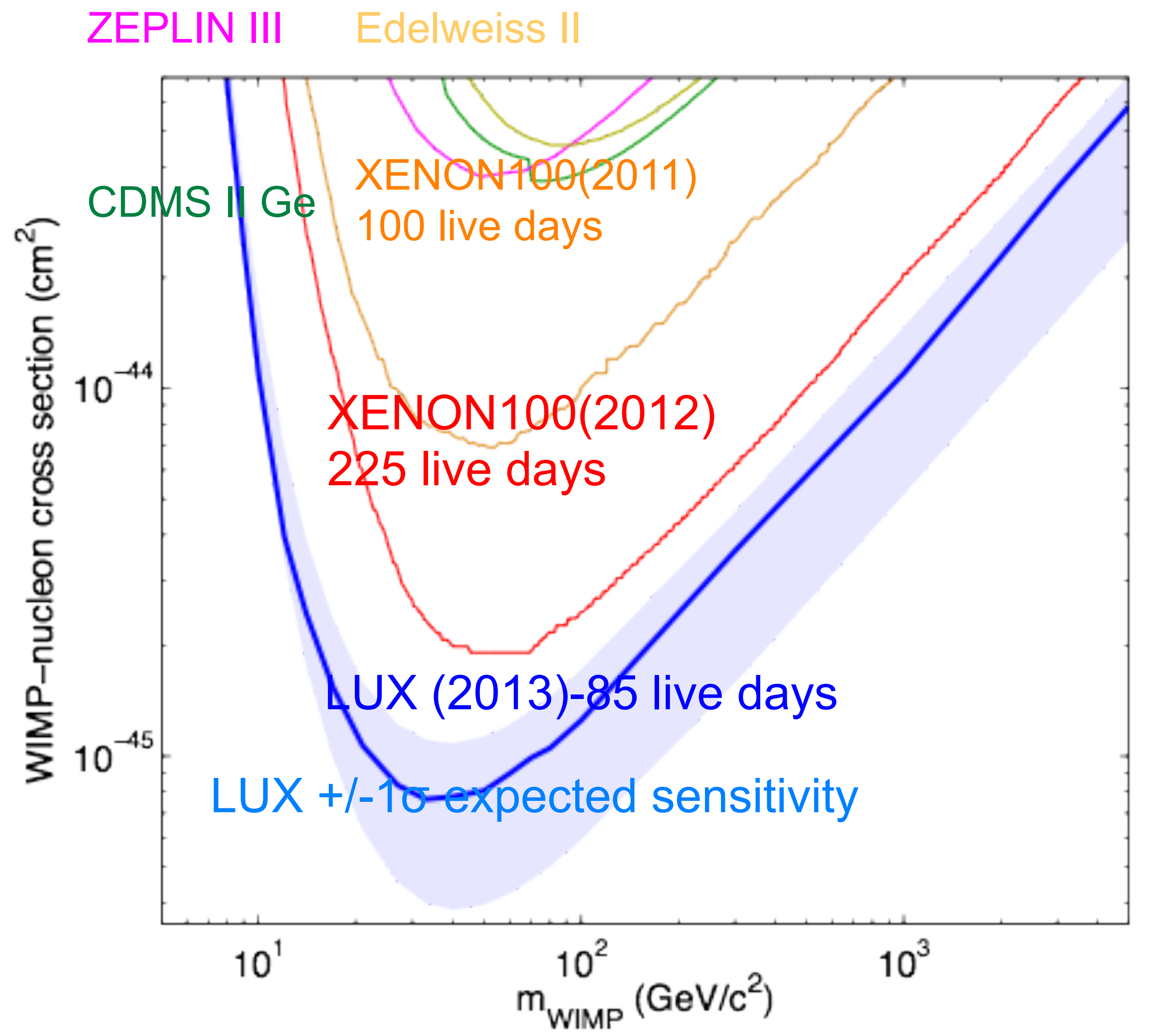
Fall 2014:

Reanalysis of 85 day run using calibration with monoenergetic 2.5 MeV neutrons.

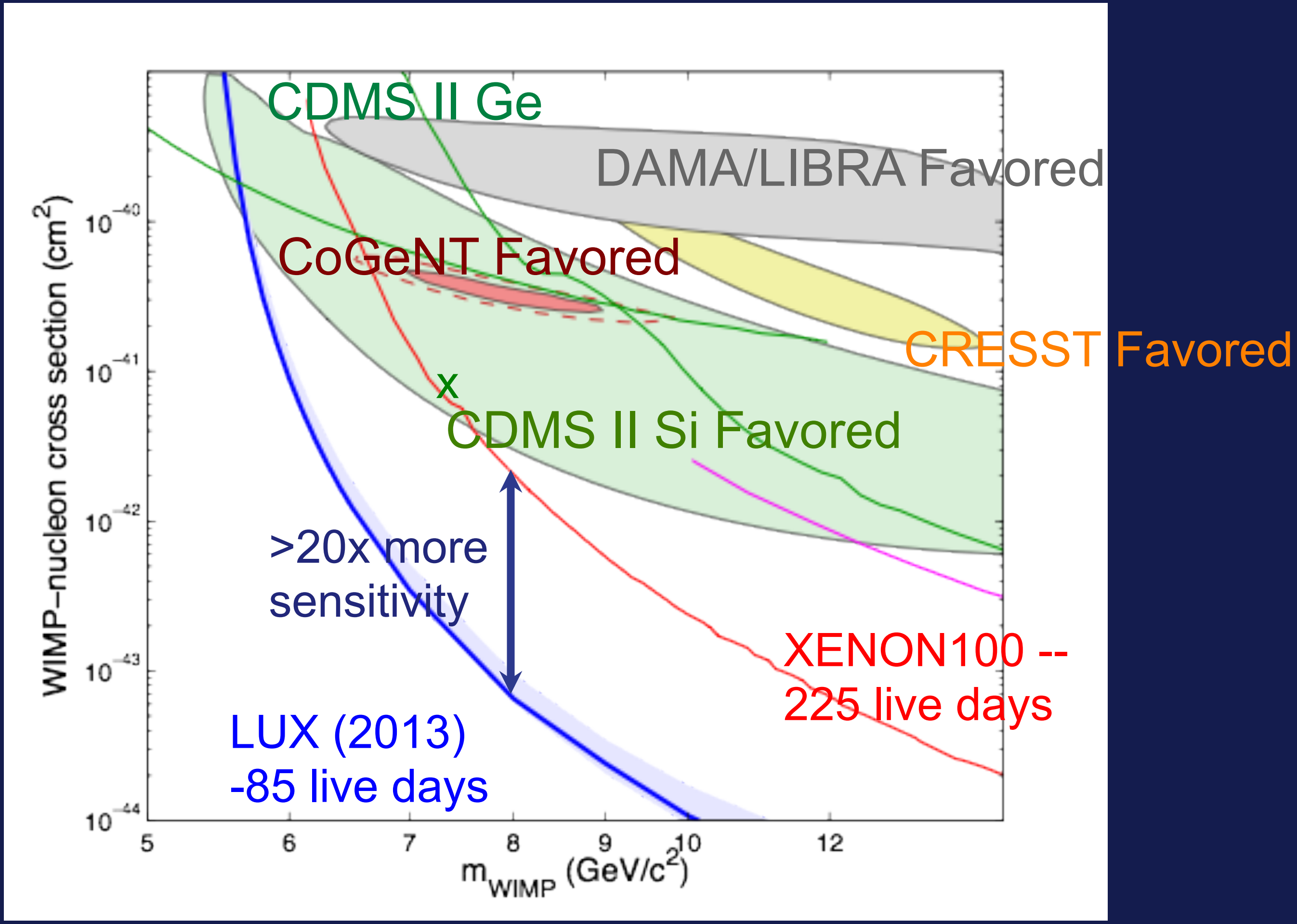
2014-15:

1-year WIMP run.

Extend sensitivity by ~5x from reanalyzed 85-day result.



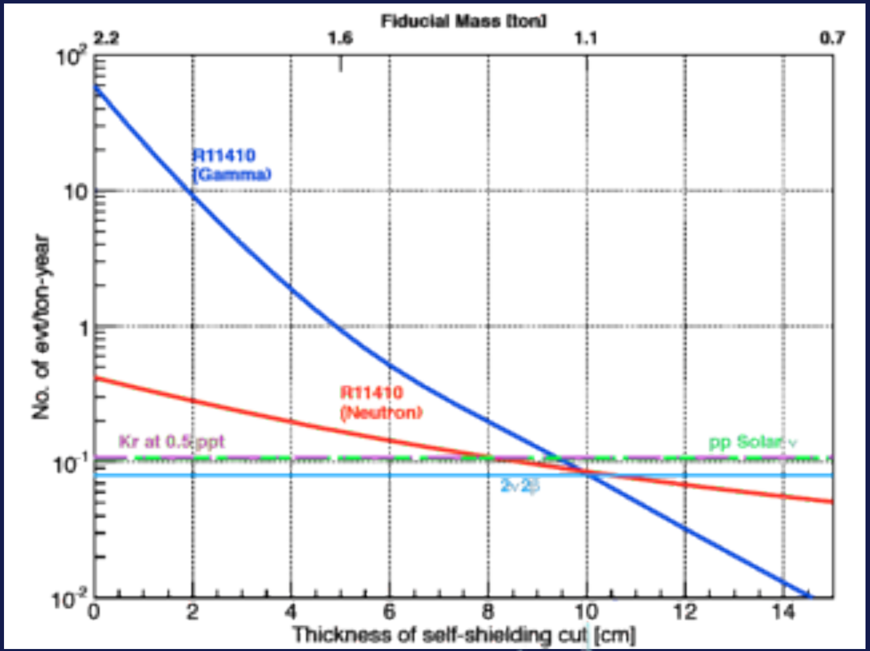
Low Mass WIMPs

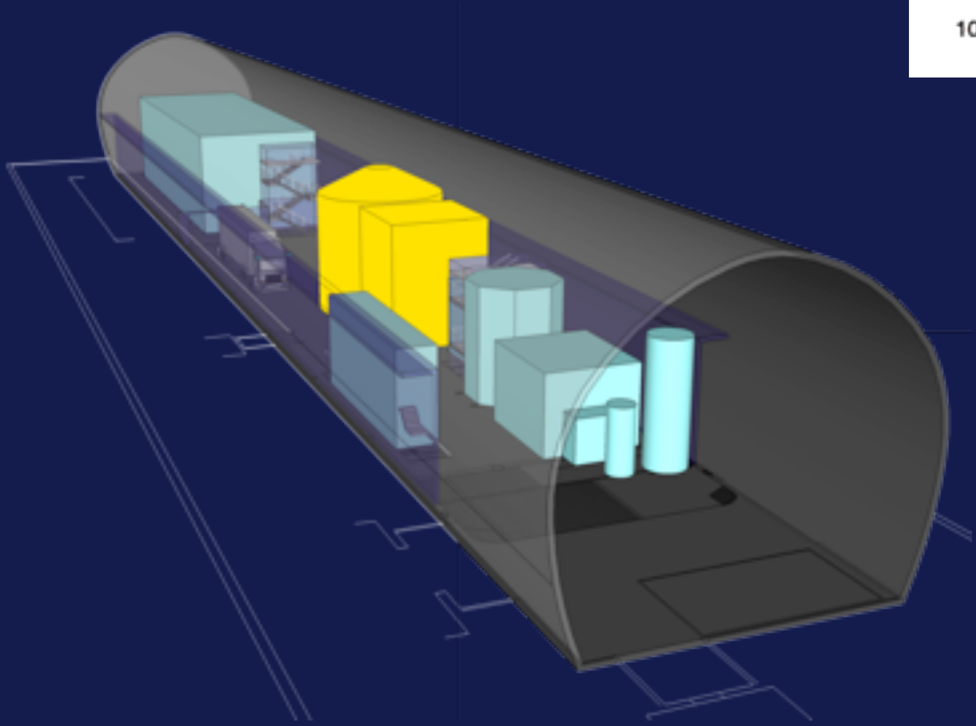


Taking dd generator calibration into account will reduce limits significantly in this range.

XENON1T

- construction under way
- in 10m diameter water tank
- at Gran Sasso
- 1 ton fiducial xenon target
- 3.5 ton total
- external backgrounds reduced to neutrino-induced signal level



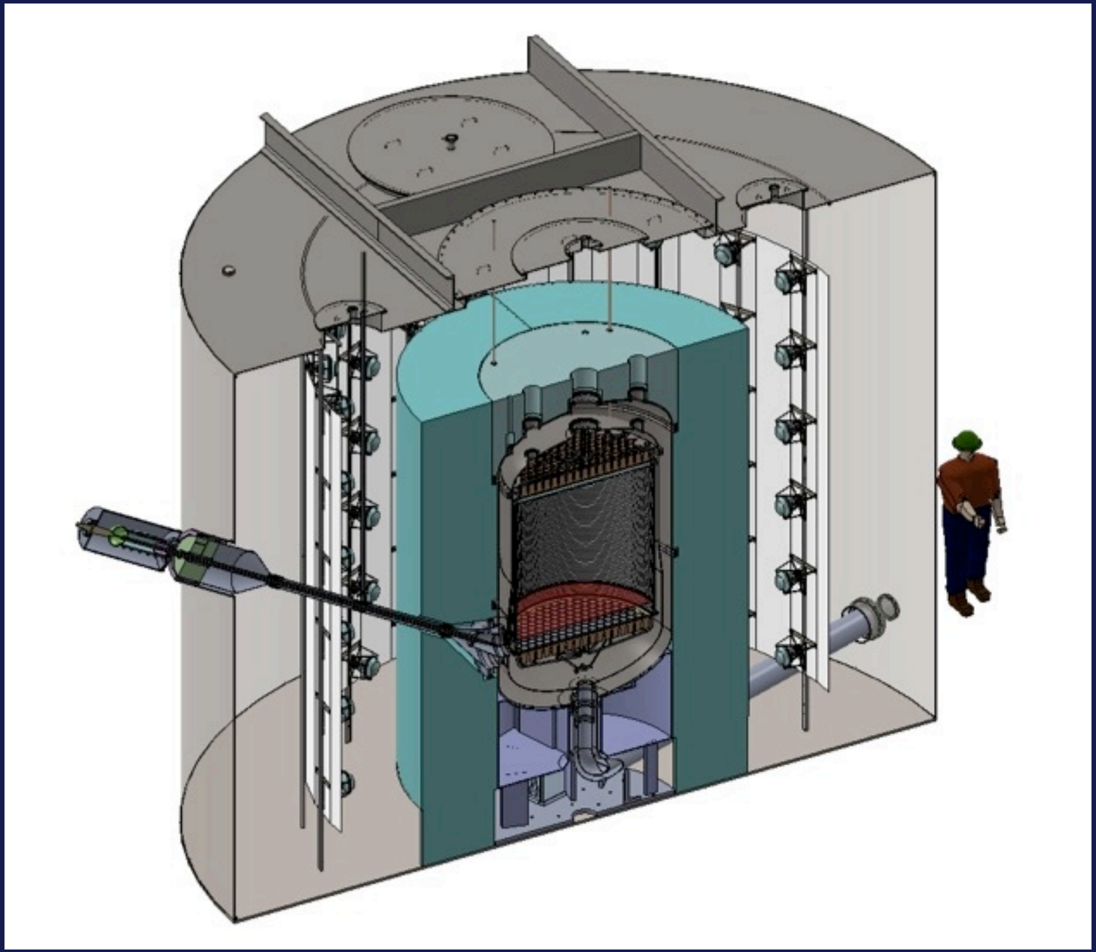


(location between ICARUS and WARP)

Lux-Zeplin (LZ): A large xenon experiment

The Xenon TPC approach scales very well to a much larger detector – LZ.

- 5.6 tons fiducial = 48x LUX
- 25-ton tank of Gd-LAB scintillator to measure and veto external backgrounds
- Fits in existing water tank in the Davis laboratory



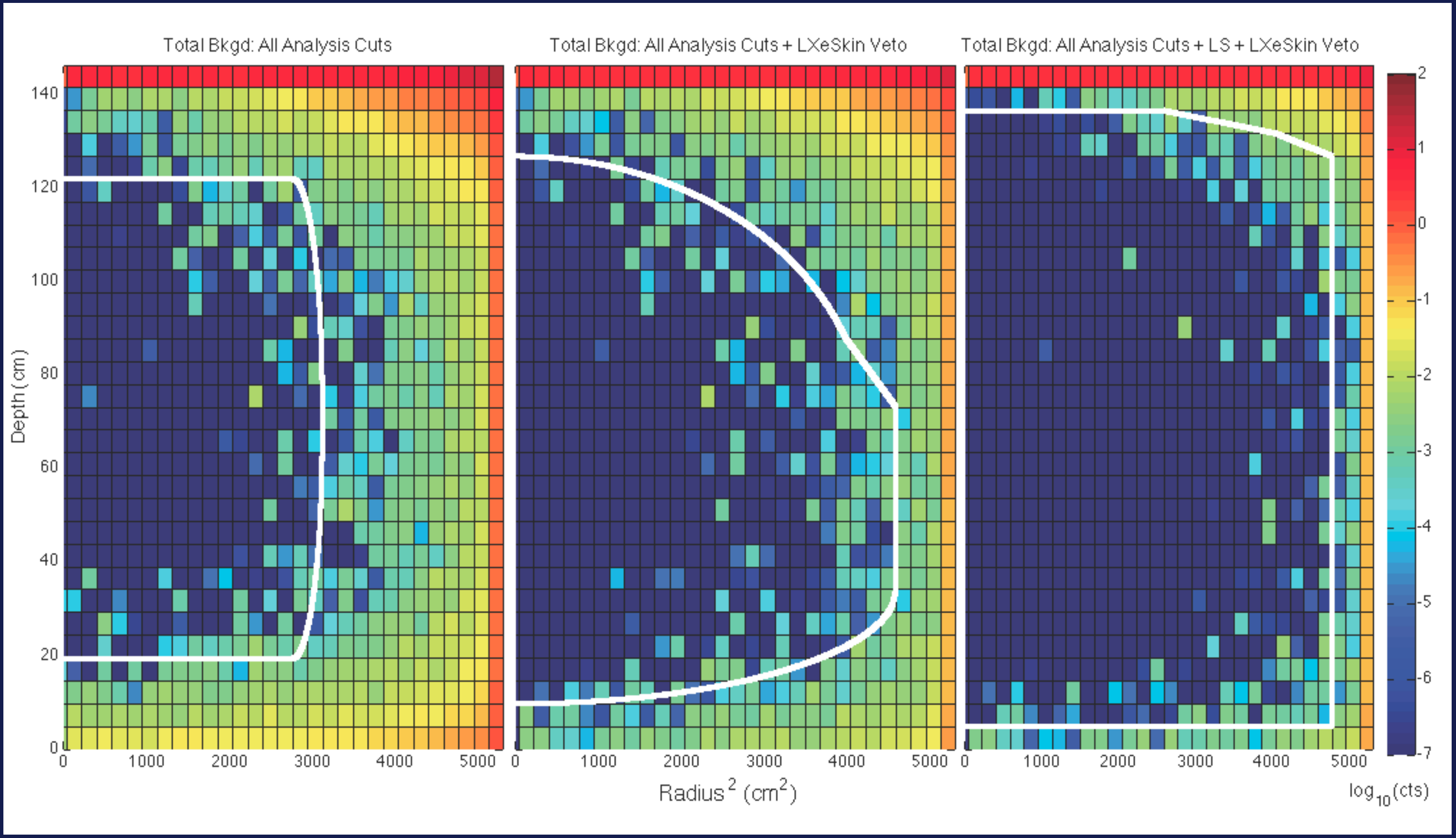
Union of LUX and ZEPLIN + others

- Brookhaven National Laboratory
- Brown University
- Case Western Reserve University
- LBNL/UC, Berkeley
- Lawrence Livermore Lab
- SLAC
- SD School of Mines & Technology
- SD Science and Technology Authority
- Texas A&M University
- University of Alabama
- UC, Davis
- UC, Santa Barbara
- University of Maryland
- University of Rochester
- University of South Dakota
- University of Wisconsin
- Washington University
- Yale University

- University College London
- University of Oxford
- University of Sheffield
- Edinburgh University
- Imperial College London
- LIP-Coimbra
- MEPHI, Moscow
- STFC Rutherford Appleton Laboratory
- STFC Daresbury Laboratory

18 US and 9 European institutions

Effect of LZ Outer detector



no veto
2.8 tonne

Xe skin
4.1 tonne

Gd-LAB +skin
5.6 tonne

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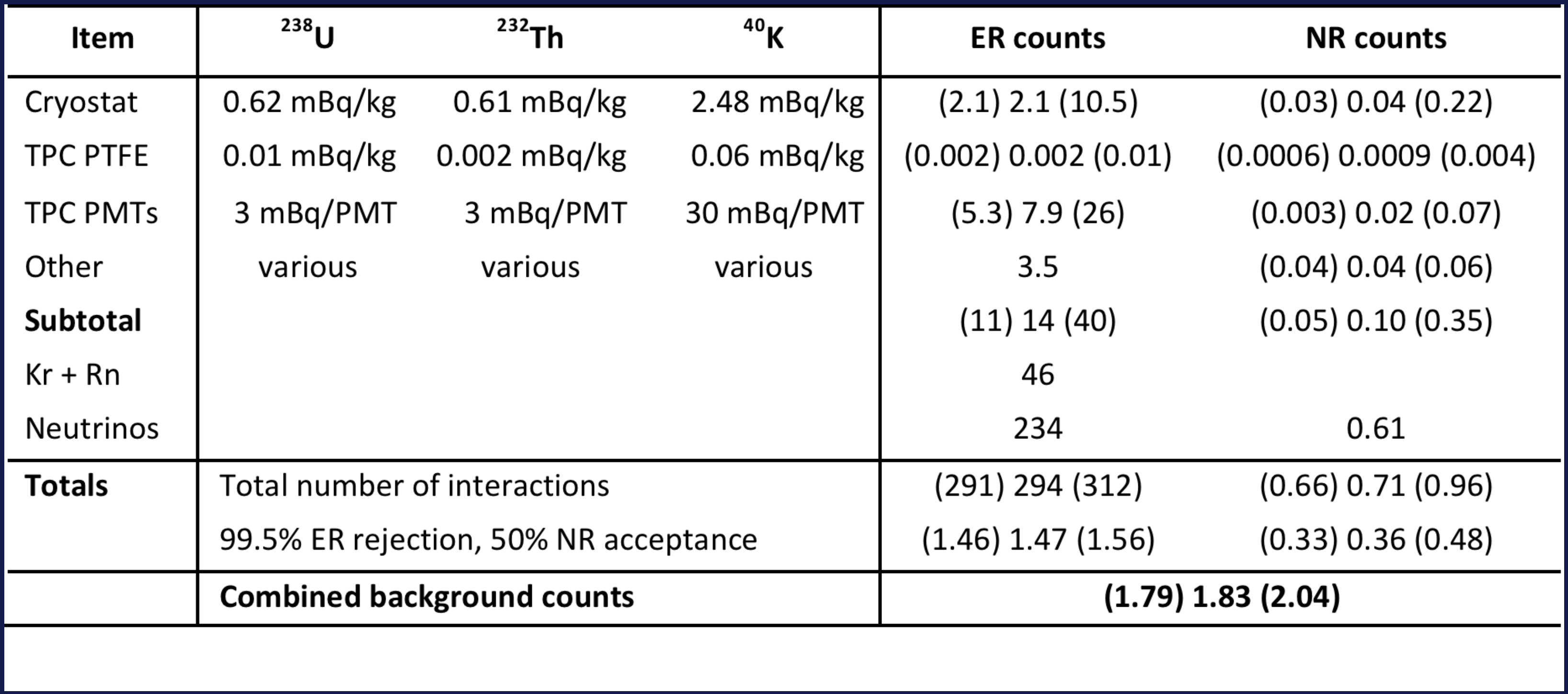
Backgrounds in LZ



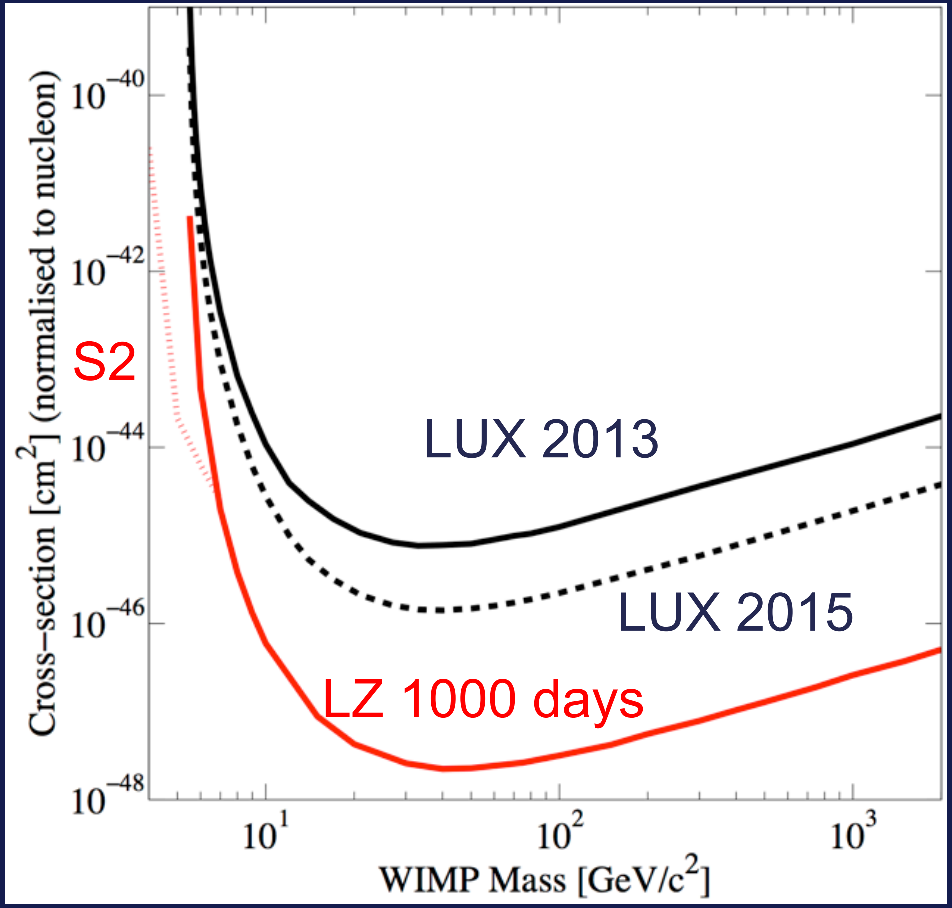
Item	^{238}U	^{232}Th	^{40}K	ER counts	NR counts
Cryostat	0.62 mBq/kg	0.61 mBq/kg	2.48 mBq/kg	(2.1) 2.1 (10.5)	(0.03) 0.04 (0.22)
TPC PTFE	0.01 mBq/kg	0.002 mBq/kg	0.06 mBq/kg	(0.002) 0.002 (0.01)	(0.0006) 0.0009 (0.004)
TPC PMTs	3 mBq/PMT	3 mBq/PMT	30 mBq/PMT	(5.3) 7.9 (26)	(0.003) 0.02 (0.07)
Other	various	various	various	3.5	(0.04) 0.04 (0.06)
Subtotal				(11) 14 (40)	(0.05) 0.10 (0.35)
Kr + Rn				46	
Neutrinos				234	0.61
Totals	Total number of interactions			(291) 294 (312)	(0.66) 0.71 (0.96)
	99.5% ER rejection, 50% NR acceptance			(1.46) 1.47 (1.56)	(0.33) 0.36 (0.48)
	Combined background counts			**(1.79) 1.83 (2.04)**	

- Backgrounds expected in LZ for 1000 live days, 6.5 tonne fiducial mass.
  - (best estimate) baseline (pessimistic)
- Similar model predicted LUX background well.

LZ Sensitivity

- The LZ experiment will have a sensitivity capable of seeing WIMPS with sensitivity ~500x better than today.

- Neutrino coherent scattering will be the largest source of background.



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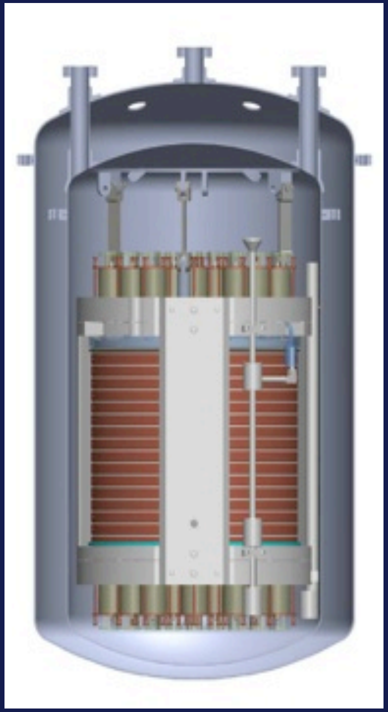
Argon experiment: DarkSide

- DarkSide 50 is being commisioned in LNGS
- Background feature specific to Argon is cosmogenic ^{39}Ar, $t_{1/2}$= 269 y, β with 565 keV endpoint.
  - 10^{10} decays/ton-year from natural Ar
- Rejection comes from
  - Pulse shape discrimination
  - Operating w/ threshold of ~50 keV_{nr}
  - Ionization/phonons for 2-phase Ar
  - Acquiring Argon depleted in ^{39}Ar

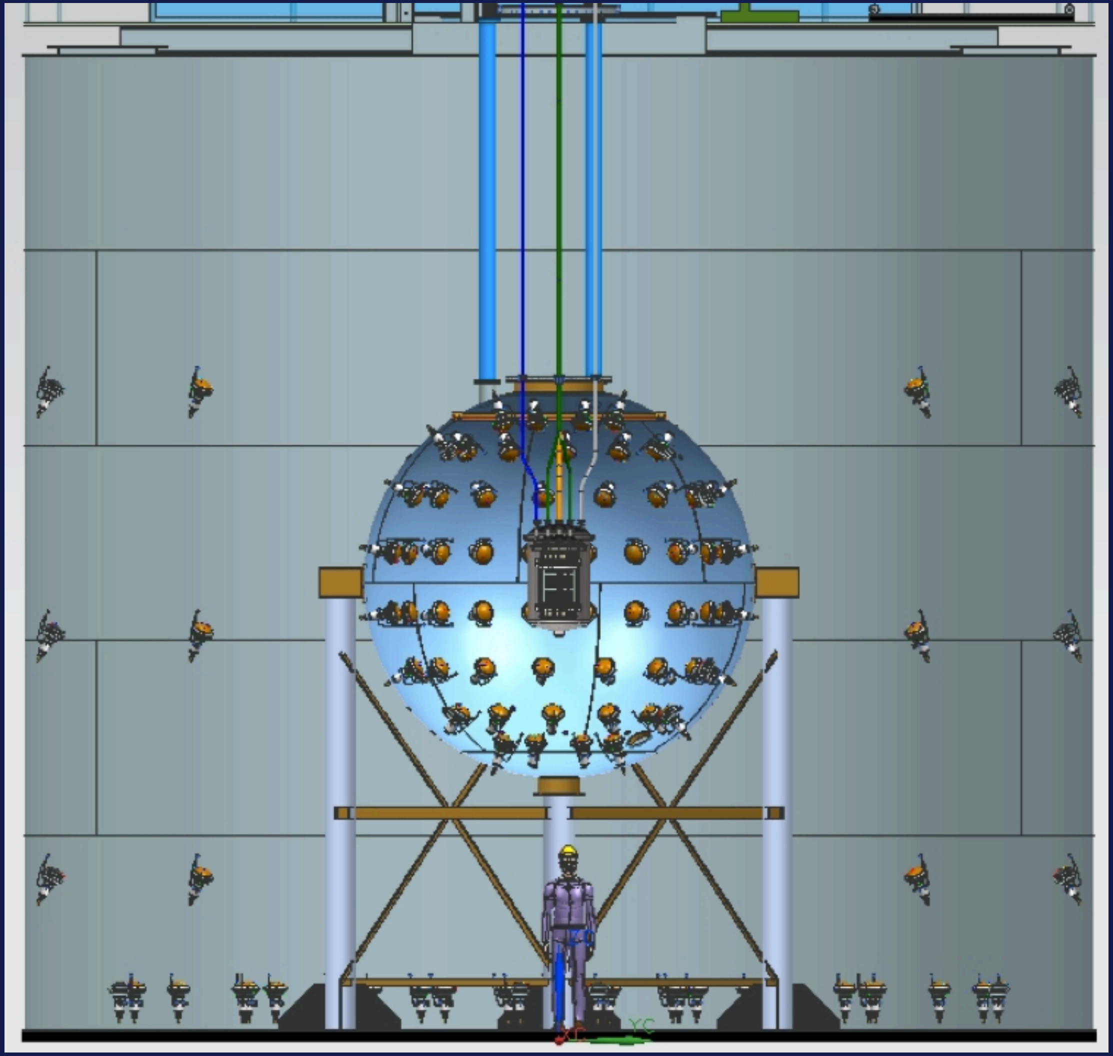
DarkSide 50 in LNGS



DS-50 TPC in cryostat

P. Meyers, Princeton

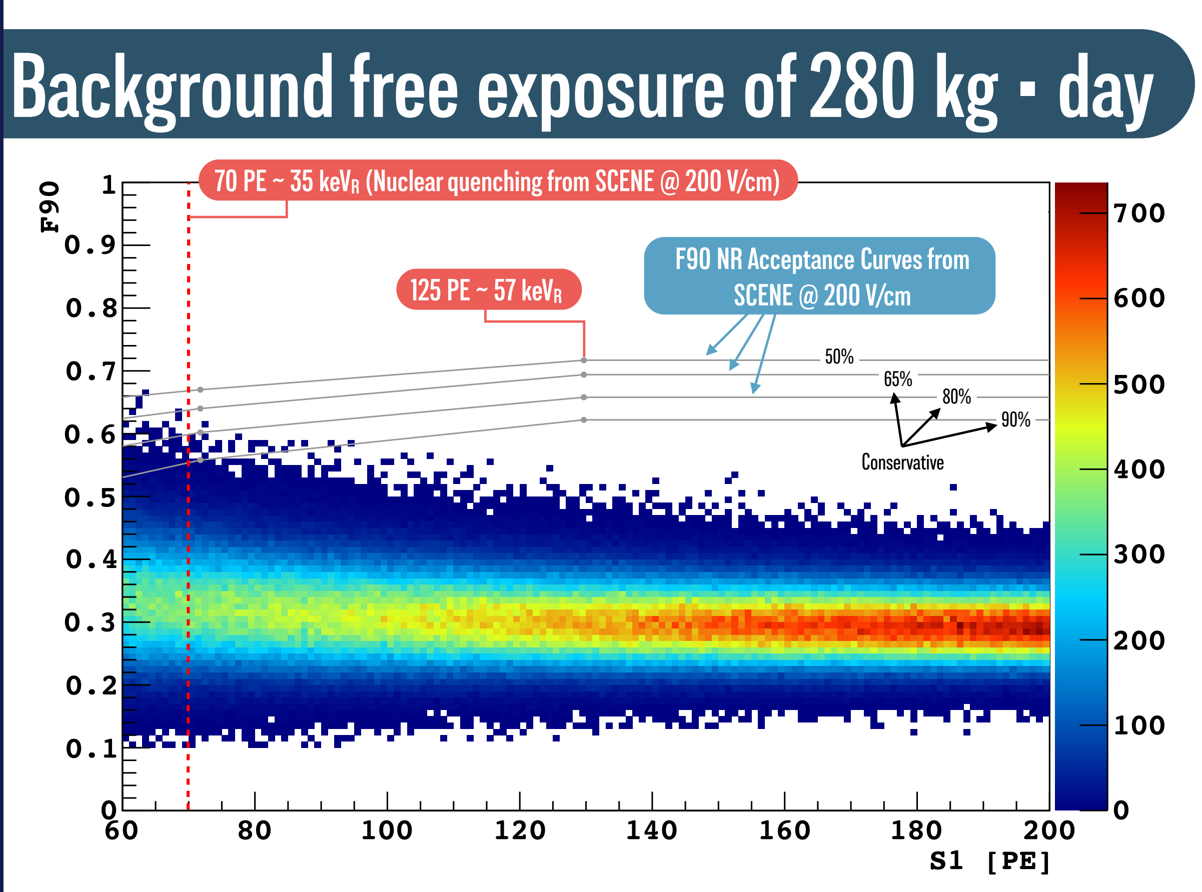
DS-50 commissioning underway; switching to underground argon for 3-year run



DS-50 Cryostat in 4-m Neutron Veto in 11-m Water Tank

New result from DarkSide-50

F90 =
fraction of
light detected
in first 90 ns.



Background free exposure of 280 kg · day

70 PE ~ 35 keV_R (Nuclear quenching from SCENE @ 200 V/cm)

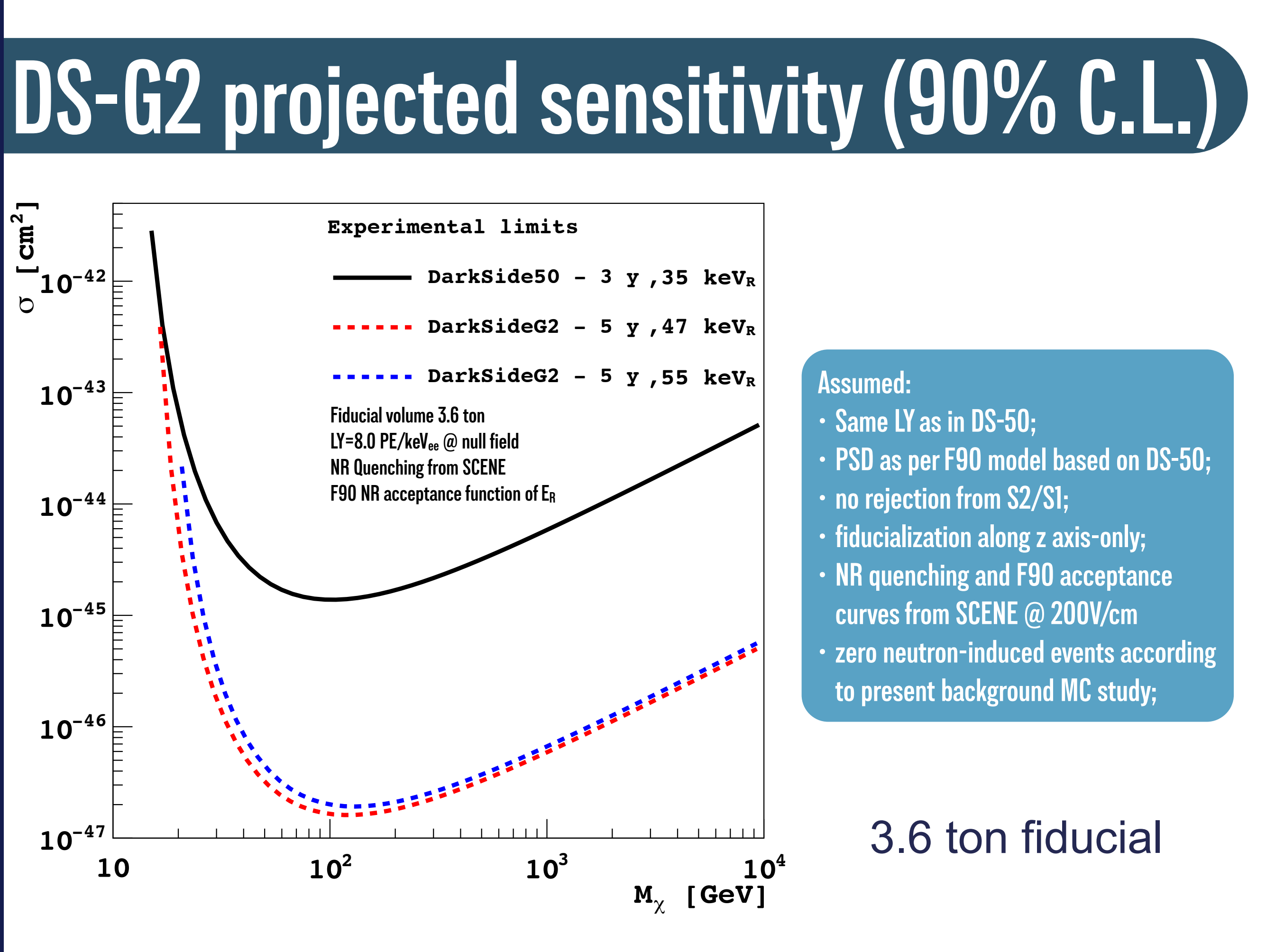
125 PE ~ 57 keV_R

F90 NR Acceptance Curves from SCENE @ 200 V/cm

Luca Grandi
DM2014
UCLA

Pulse-shape discrimination (PSD) + z-fiducialization can suppress background for 2.6 years of DS-50 w/ UAr, using a threshold of 35-50 $keV_{nr.}$

DarkSide G2 projected sensitivity



DS-G2 projected sensitivity (90% C.L.)

Assumed:

- Same LY as in DS-50;
- PSD as per F90 model based on DS-50;
- no rejection from S2/S1;
- fiducialization along z axis-only;
- NR quenching and F90 acceptance curves from SCENE @ 200V/cm
- zero neutron-induced events according to present background MC study;

3.6 ton fiducial

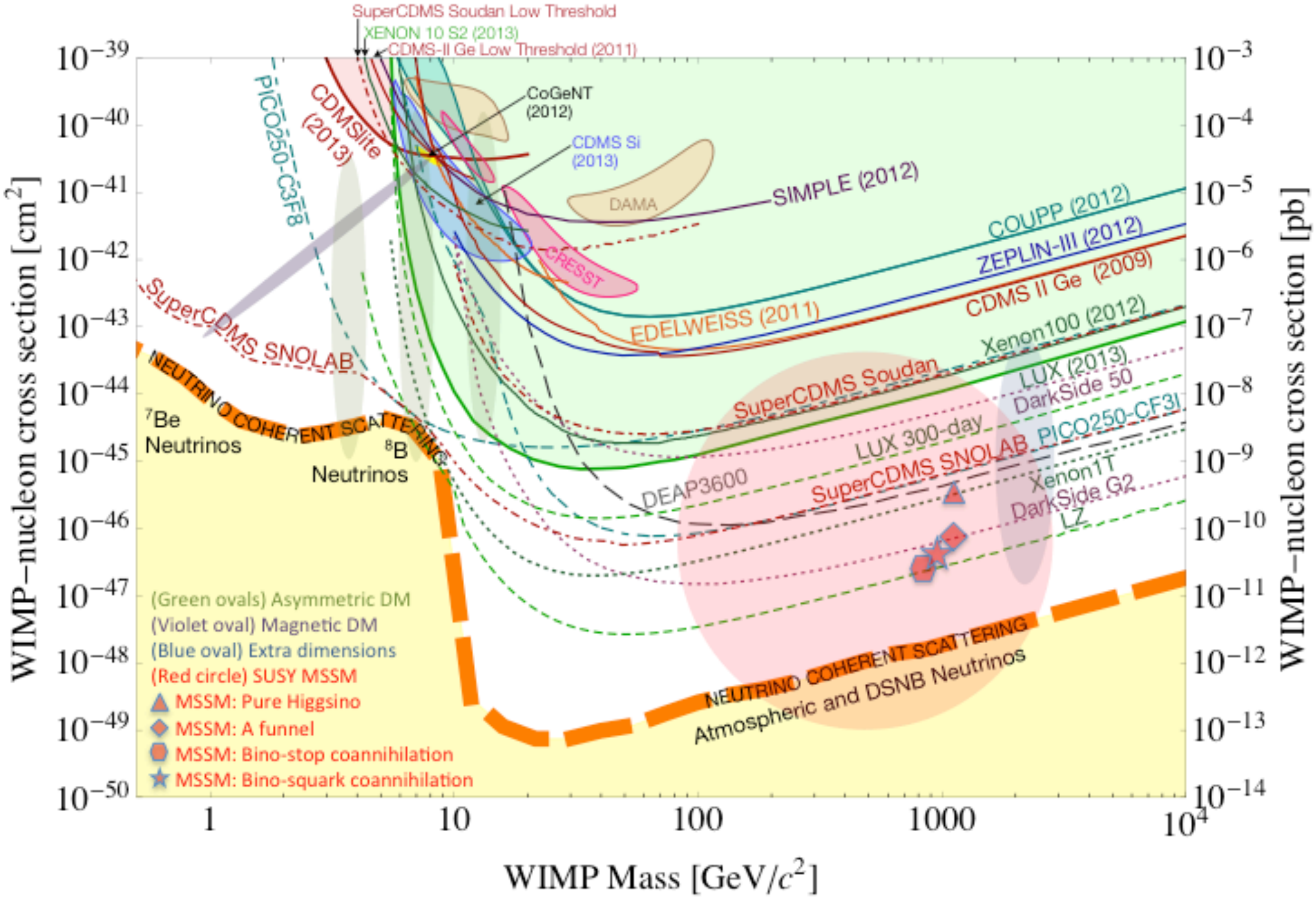
DarkSide Future

DArkSIDE-50

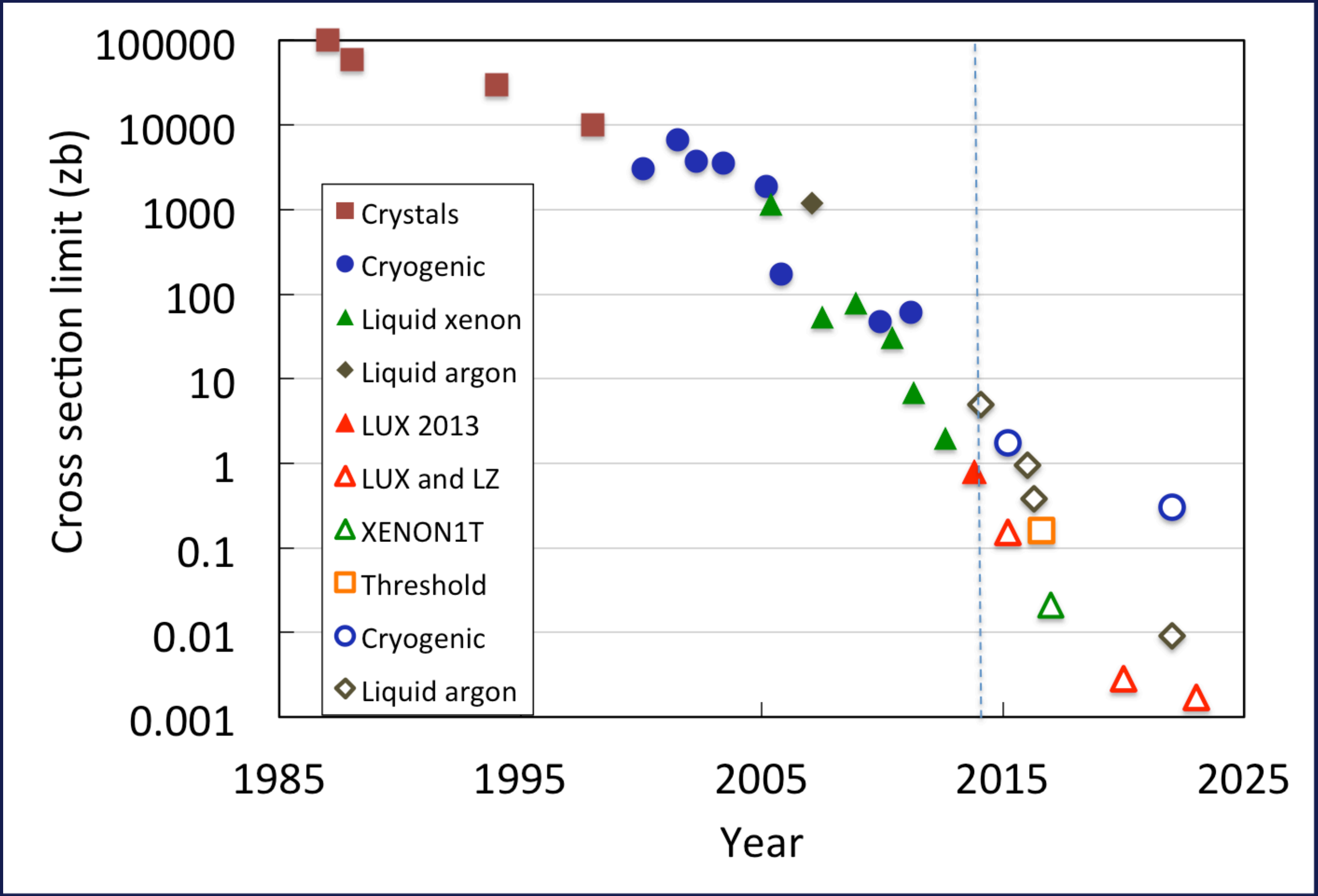
- DS-50 detector is running @ LNGS since Oct. 13;
    - *LAr TPC successfully commissioned;*
    - *Vetoes (designed to host DS-G2) successfully commissioned;*
    - *Scheduled to use Borexino distillation plant to separate PC from TMB and insert the new TMB with low ^{14}C content ;*
- Demonstrated PSD performance needed to reject the expected background from ^{39}Ar (at the level of present upper limit) in 2.6 years of DS-50;
- Plan to calibrate DS-50 and to further study PSD until June when we will switch to UAr and to WIMP search mode;
- DS-50 results extrapolated conservatively to DS-G2 indicate the possibility of running for 5 years ^{39}Ar-free.

UCSB

Survey of Cross-section limits



Rapid progress



Sensitivity to 50 GeV WIMP over time

What would represent a convincing discovery of dark matter interactions?

- We would measure all the sources of background in the xenon.
  - external backgrounds in outer layer, Xe skin, and Gd-LAB outer detector.
  - radon and krypton in central xenon.
- We would determine the background with full WIMP cuts with small systematic error.
- We would see a few events, inconsistent with the measured background level.

Conclusions

- We know we live in a sea of dark matter.
- We do not know what constitutes dark matter, however.
- If the WIMP hypothesis of dark matter is correct, we have a good chance of observing its interactions with normal matter in the laboratory over the next several years.