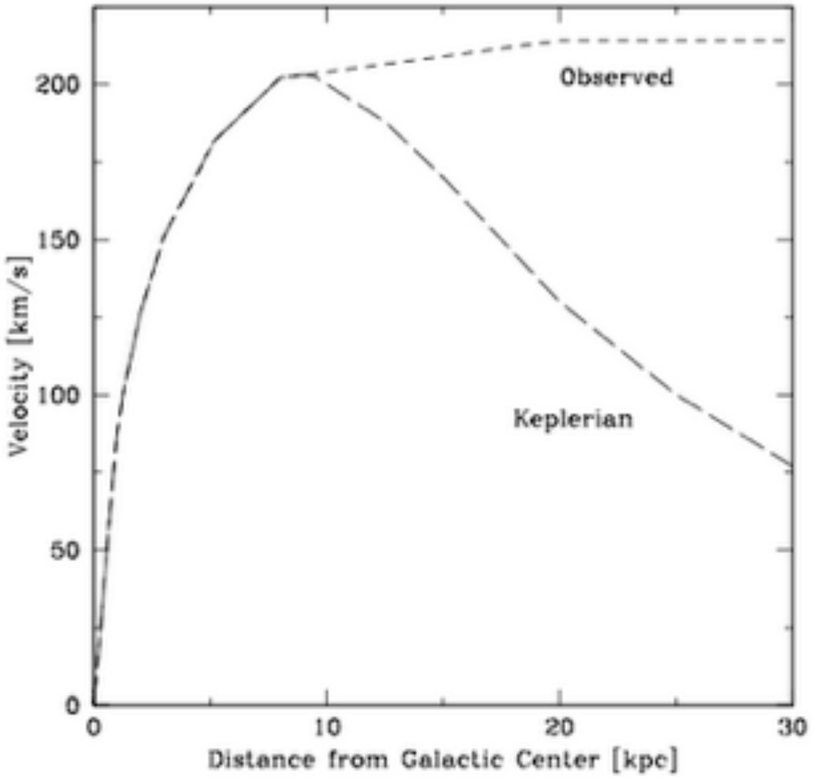
The LZ Dark Matter Experiment

Dark Matter

- First suggested by Fritz Zwicky in the 1930 while studying the Coma Cluster
- Later studied by Vera Rubin in the 1970's
- At large radii within galaxy clusters, the rotational velocity of galaxies within the cluster does not go to zero
- The explanation: there is extra mass that neither absorbed nor emitted light, referred to as dark matter

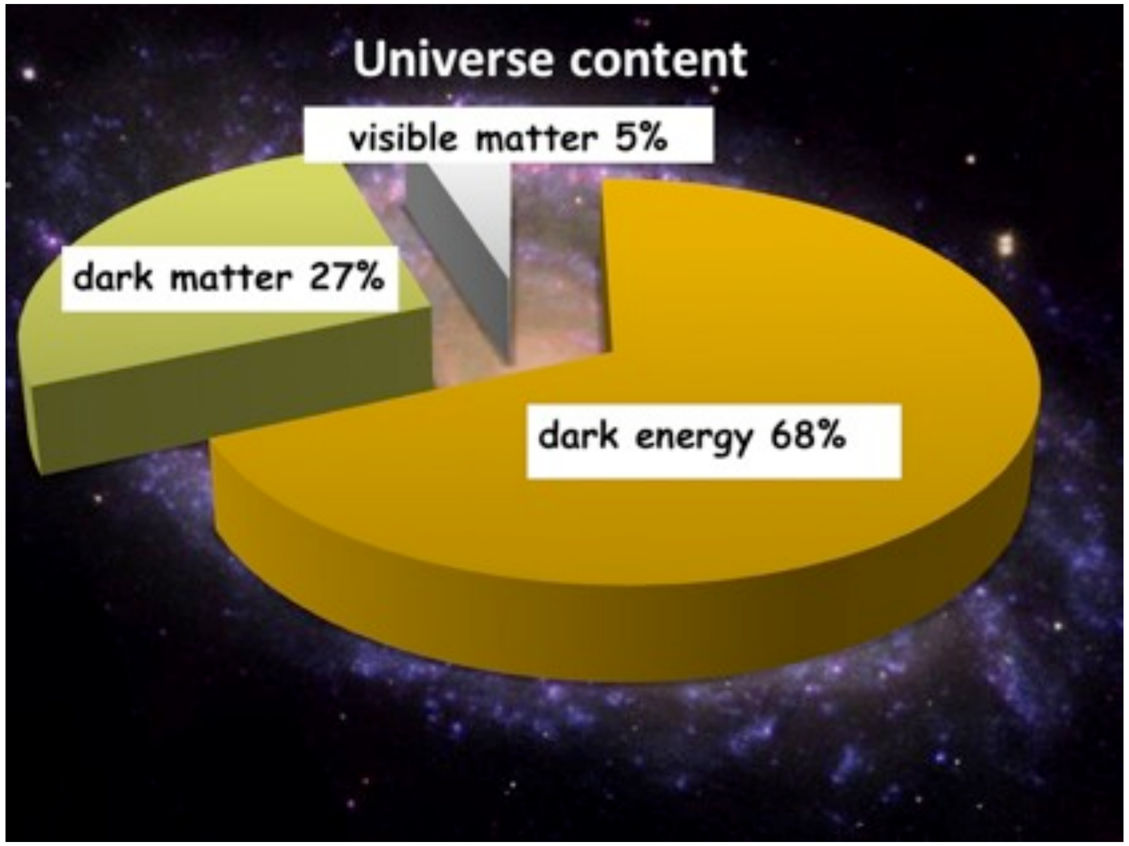
Fritz Zwicky

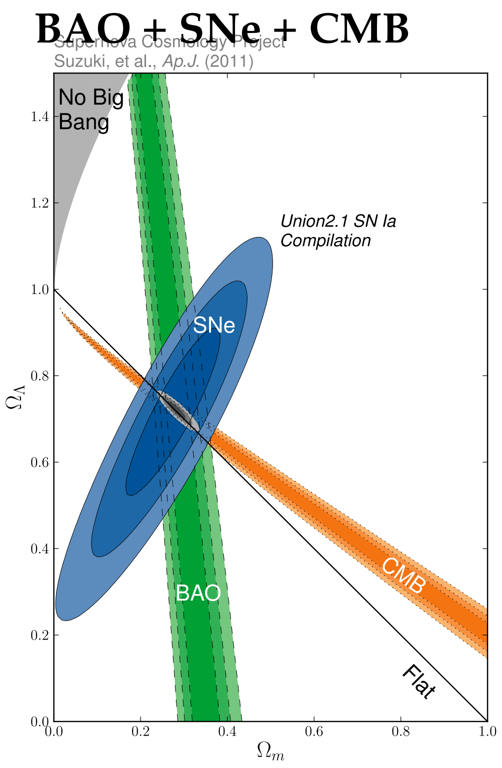
Rotation curves of galaxies

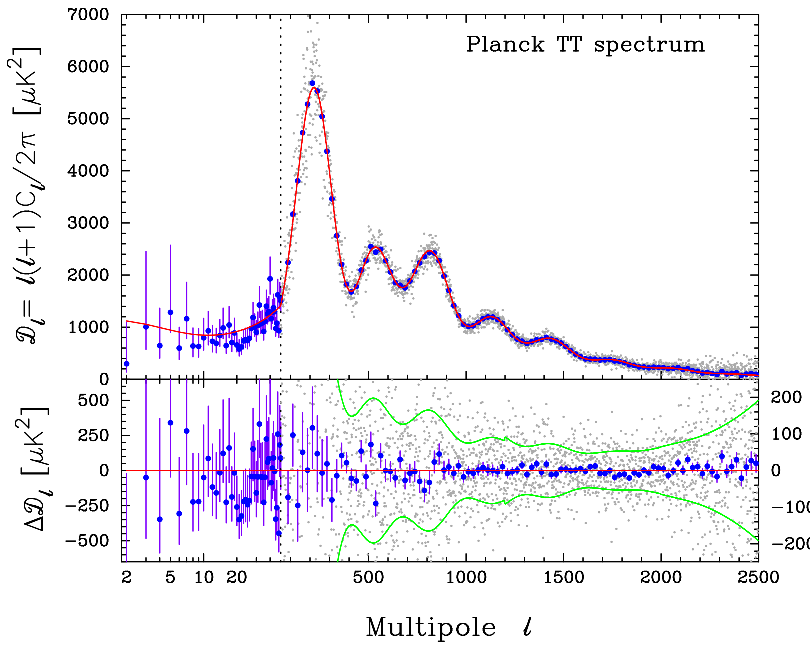


Growing Evidence

Galactic rotation curves, BAO, CMB, gravitational lensing, and other measurements point to 27% of the universe being composed on non-baryonic dark matter







The Bullet Cluster

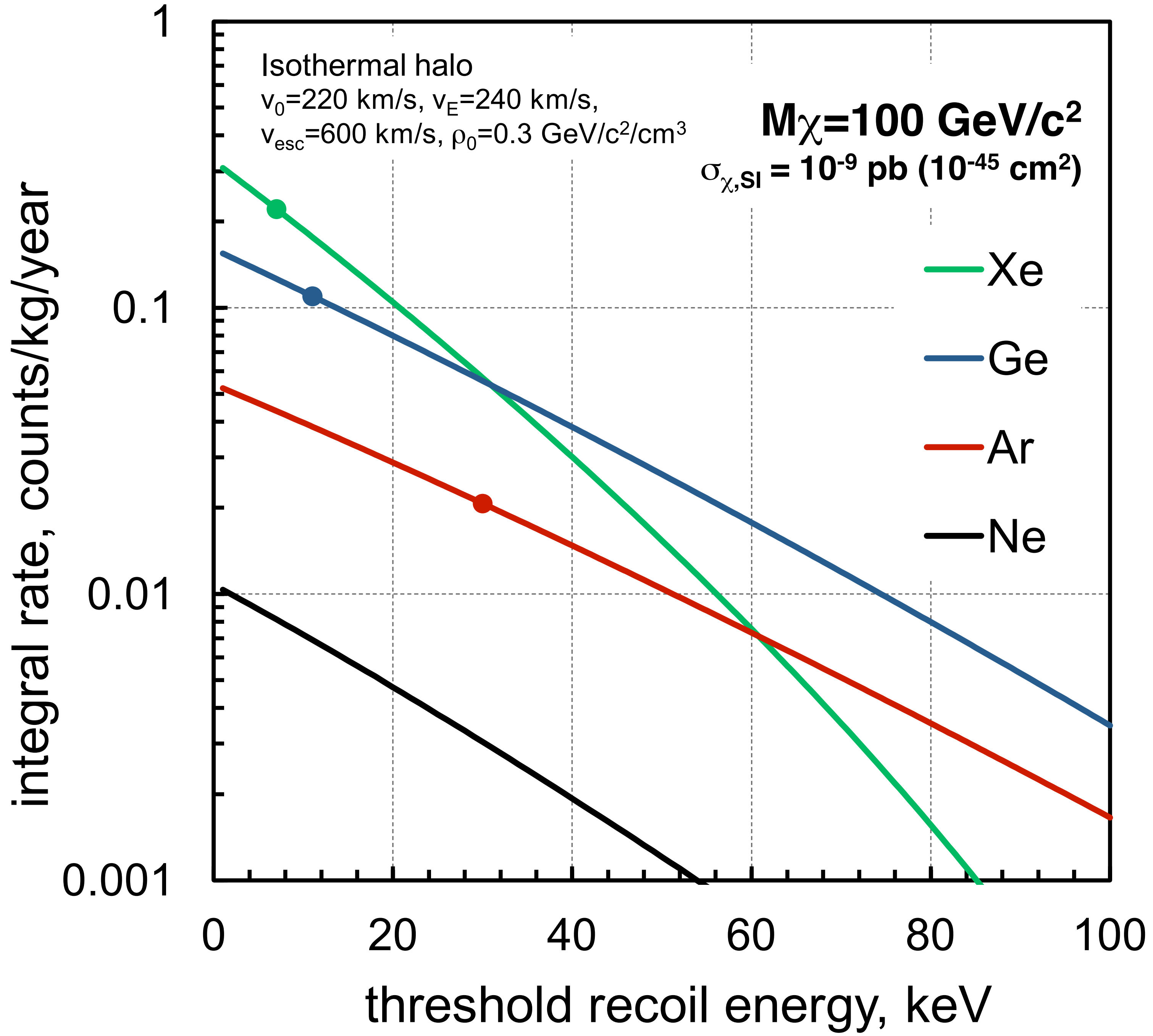
- Above: image of two galaxies passing through each other, showing the hot gas (red) and center-of-mass from gravitational lensing (blue)
- Strongest evidence to data that dark matter phenomenon is not due to Modified Newtonian Dynamics

Weakly Interacting Massive Particles

- Weakly Interacting Massive Particles (WIMPs) are a leading candidate dark matter particle
- Only interact with baryonic matter through the weak force => very hard to detect!
- WIMPs, if they exist, could make up ALL the dark matter (this is known as the WIMP Miracle)
- Require physics beyond the standard model, typically either super symmetry or extra dimensions

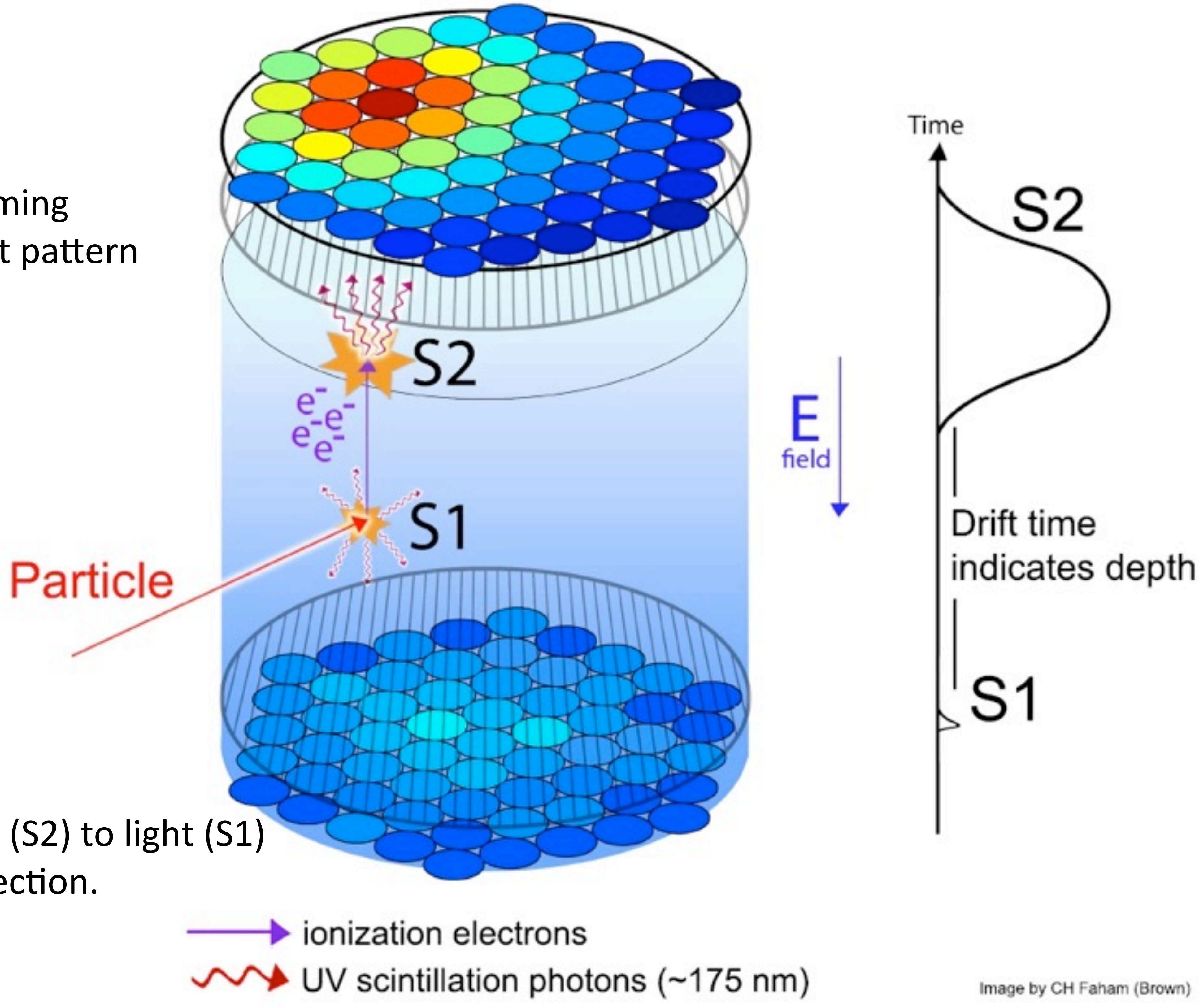
WIMP Direct Detection

- Look for anomalous number of low-energy events in a large detector
- Requires low energy threshold (10's of keV or lower!)
- Requires separating nuclear recoils (WIMP-like) from electron recoils (gamma-like)
- LUX looked for 1 event in ~100 kg in 85 days, for reference that's less than
  - A banana (~10 decays/s)
  - A bicycle tire (.3 decays/s)
  - A liter of air outdoors (~1 decay/min.)
- LZ aims for 1000X better than this!



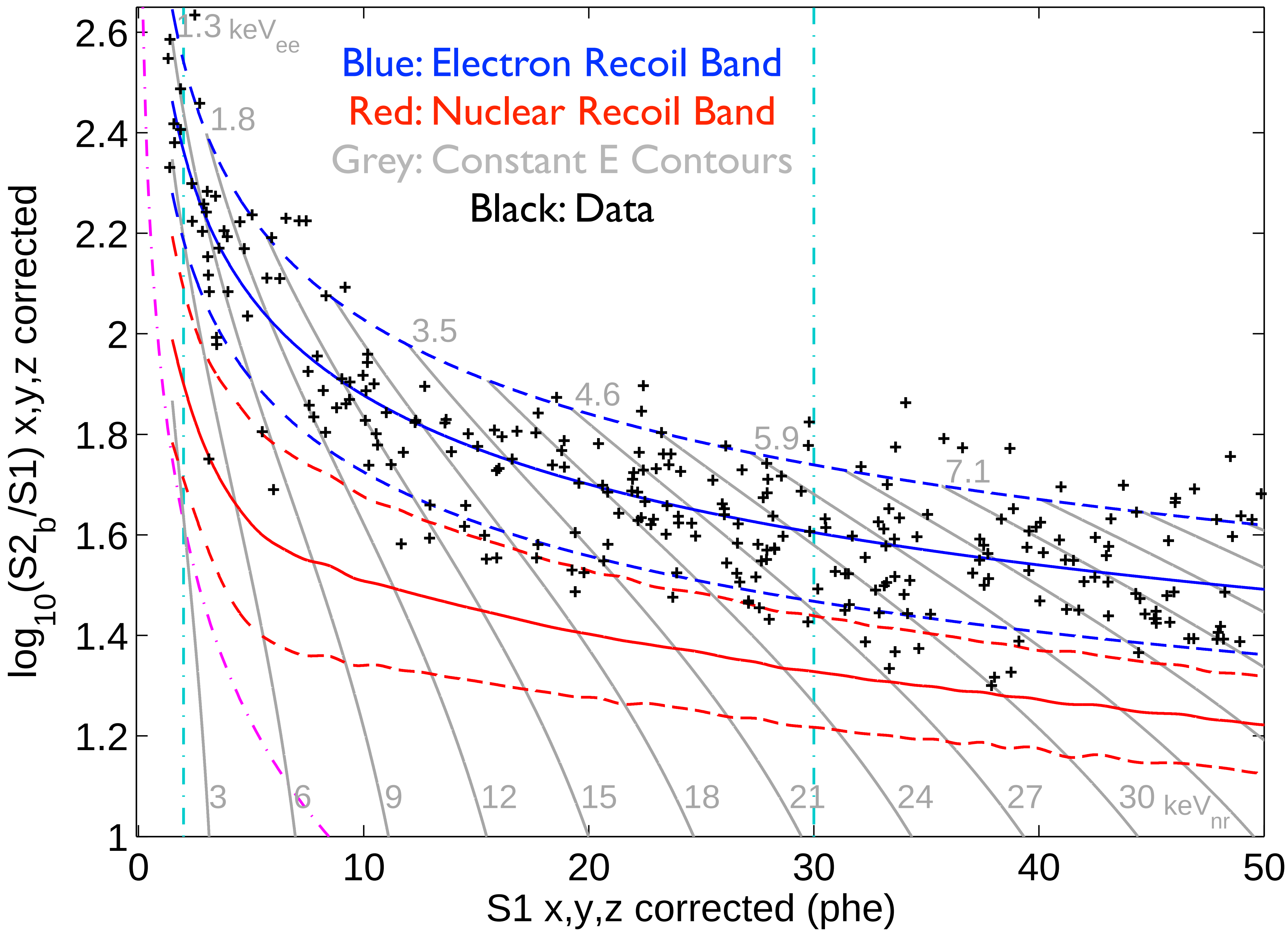
Liquid Xenon TPC Principle

Z position from S1 – S2 timing
X-Y positions from S2 light pattern



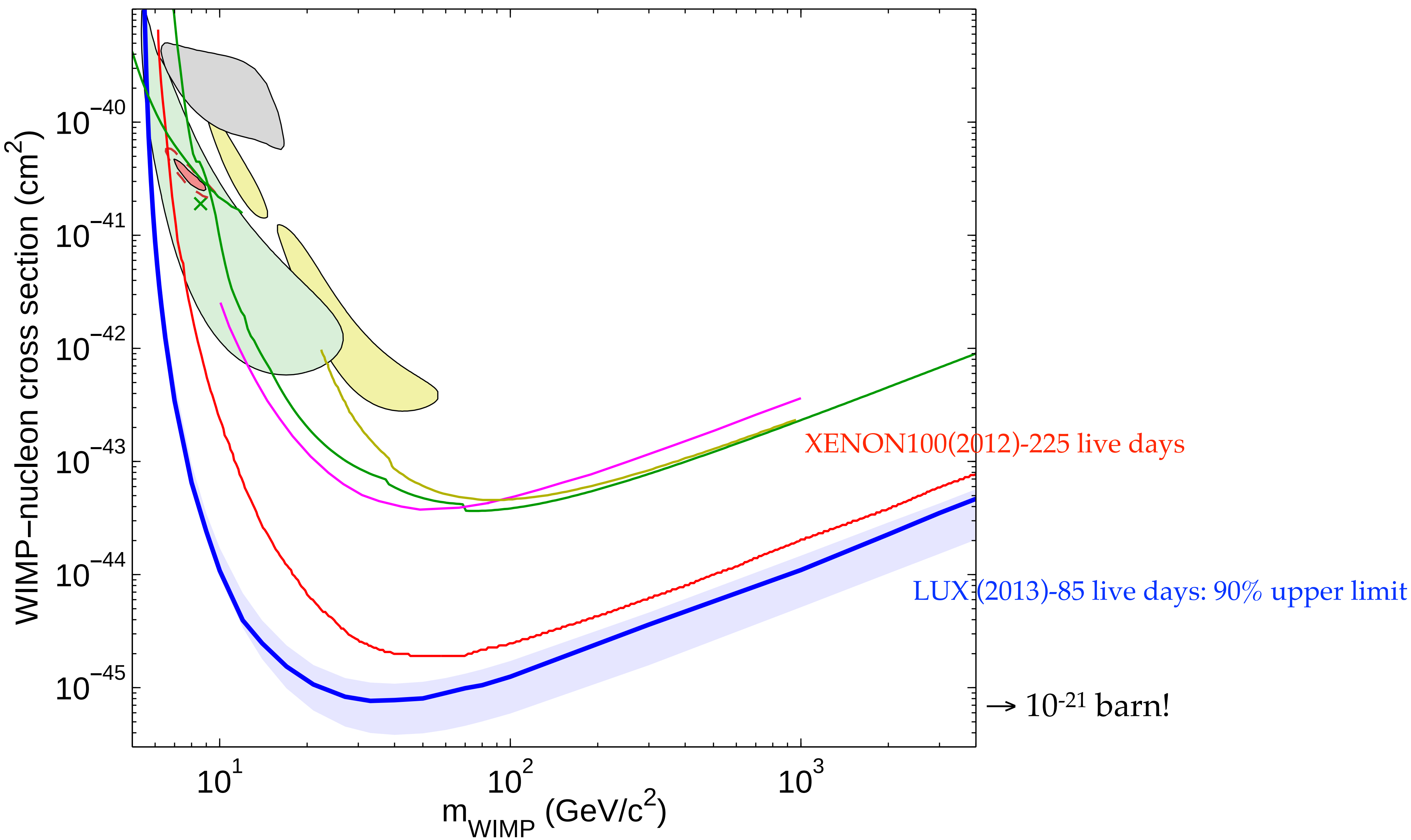
Reject gammas by charge (S2) to light (S1) ratio. Expect > 99.5% rejection.

LUX WIMP Search

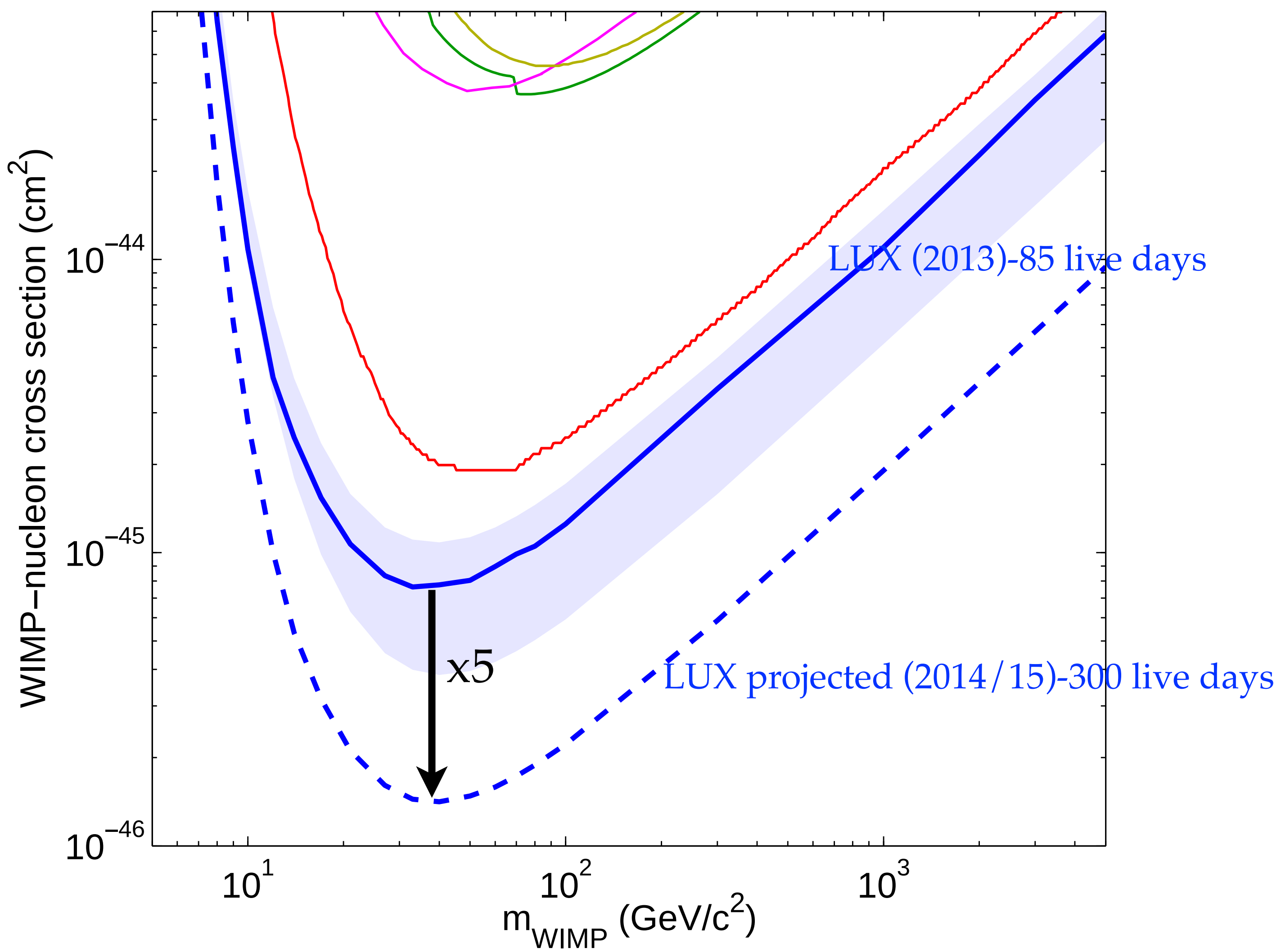


- 160 events observed in fiducial volume between 2 and 30 phe S1
- 99.6% electron recoil (ER) discrimination with 50% acceptance for nuclear recoils (NR)

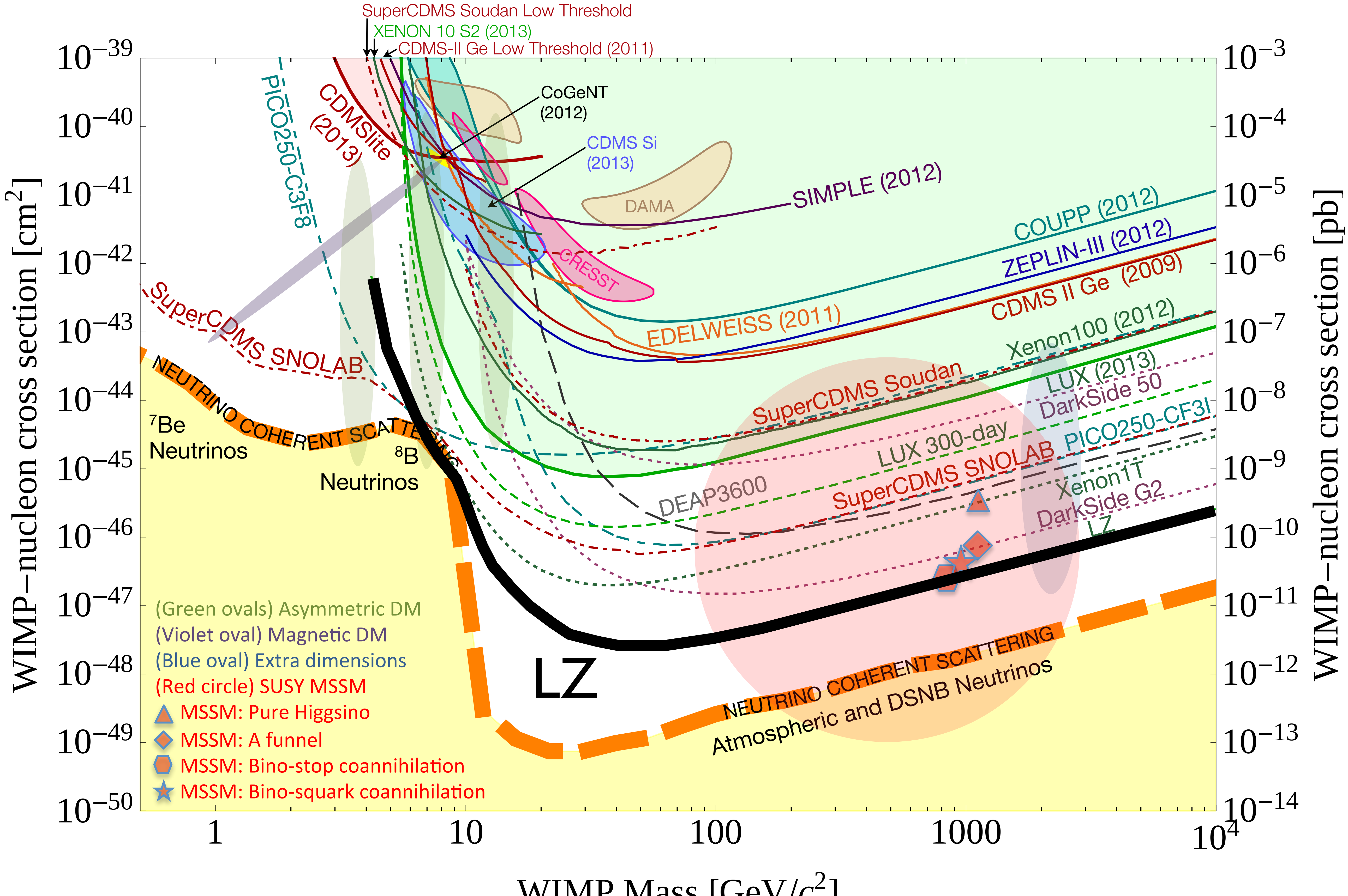
Spin-independent WIMP Limits



Improving Sensitivity



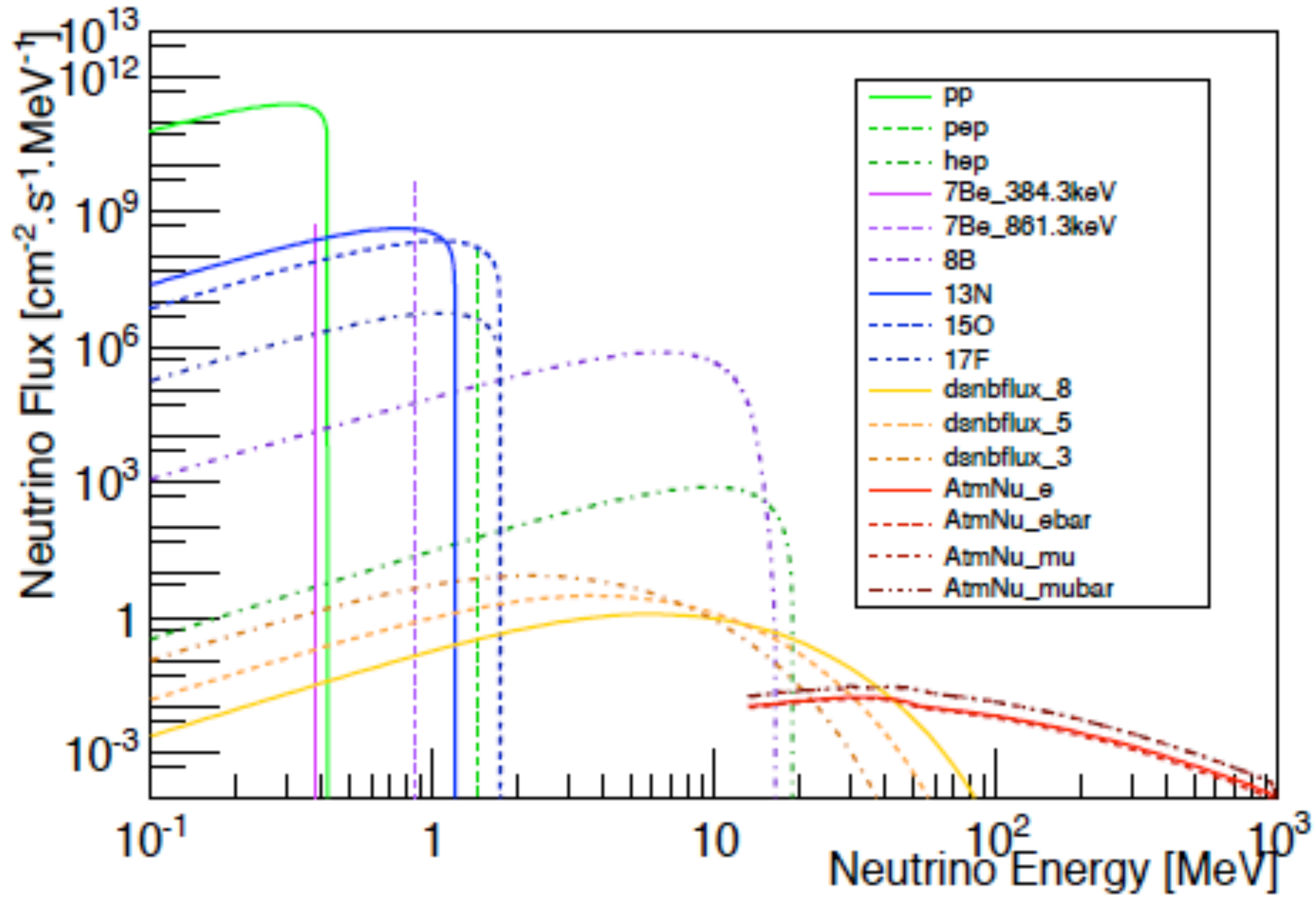
- 300 day run planned for 2014-2015
- Still not background limited
- Expect a factor of 5 improvement in sensitivity!



- Lots of parameter space still to explore
- Dashed orange band represents fundamental neutrino background

Neutrino Backgrounds

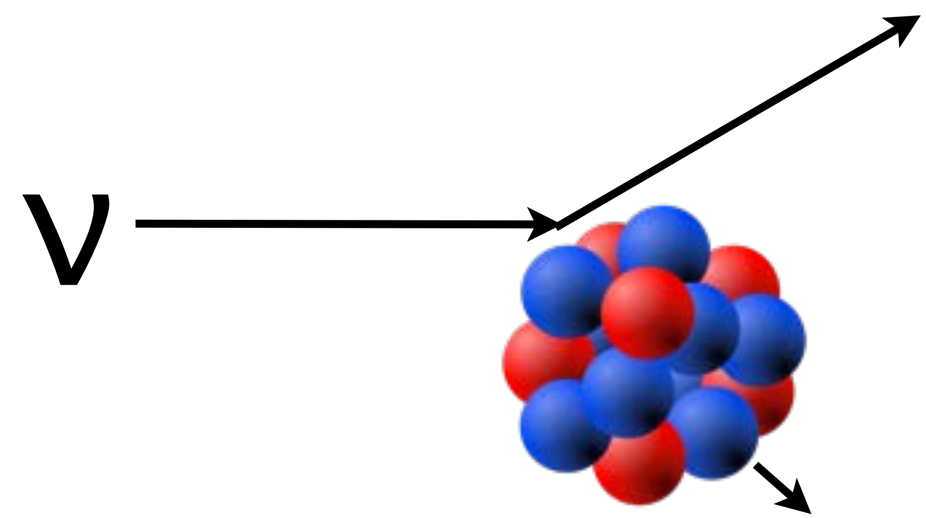
- At some point, neutrino backgrounds become significant in dark matter searches
- Although the flux of solar neutrinos is high, they're mostly at low-energy
  - This is why they only matter for light WIMPs (> 10 GeV)

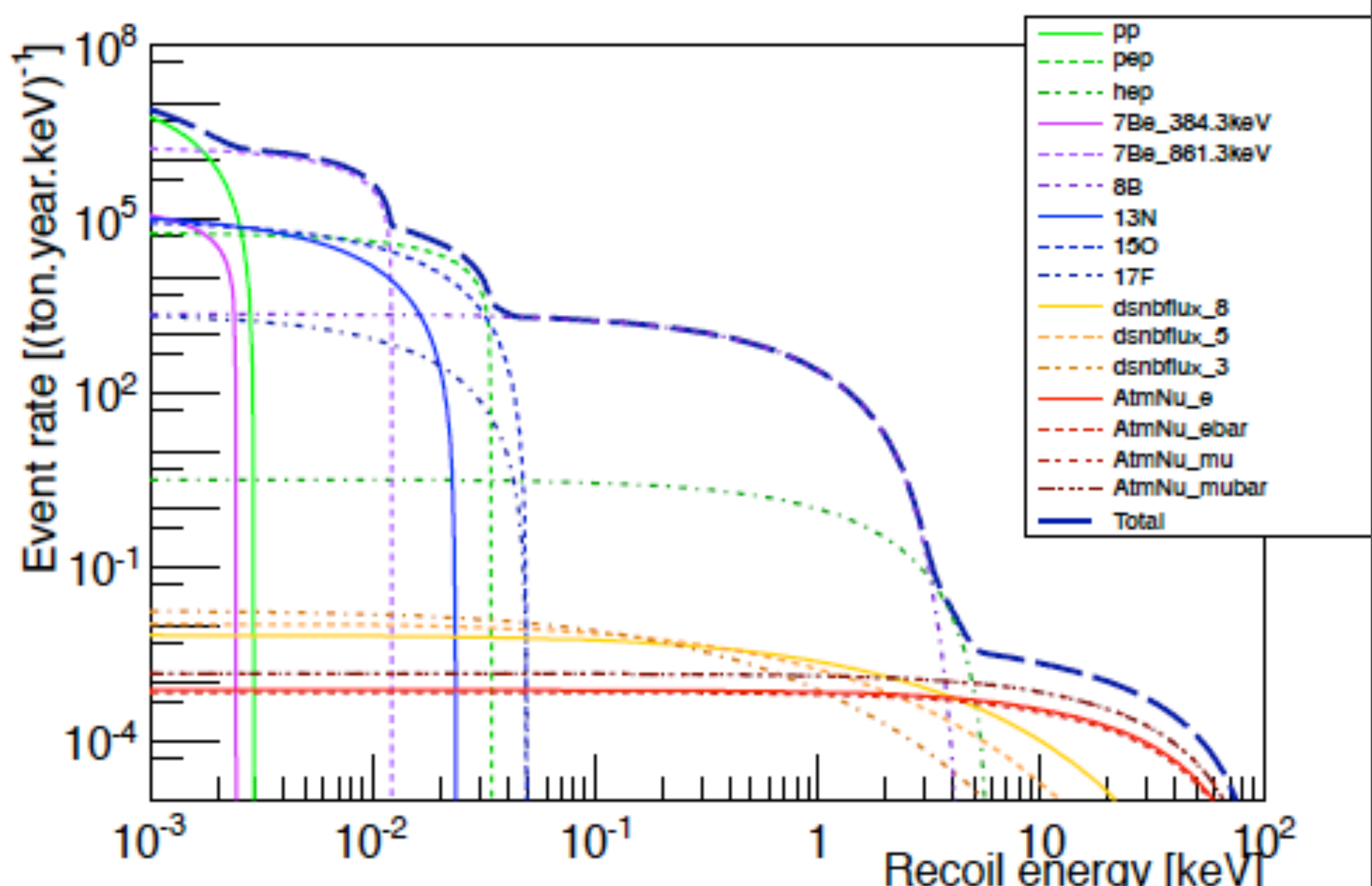


Plot taken from Billard et. al, arXiv:1307.5458v3

Neutrino Backgrounds (NR)

- Coherent neutrino scattering: neutrino scatters off nucleus as one object (for E_ν < 50 MeV)
  - Indistinguishable from event-by-event from WIMPs
- Not a problem for LZ above 4 keVnr
- ^{8}B neutrinos could be a background in low-threshold analyses

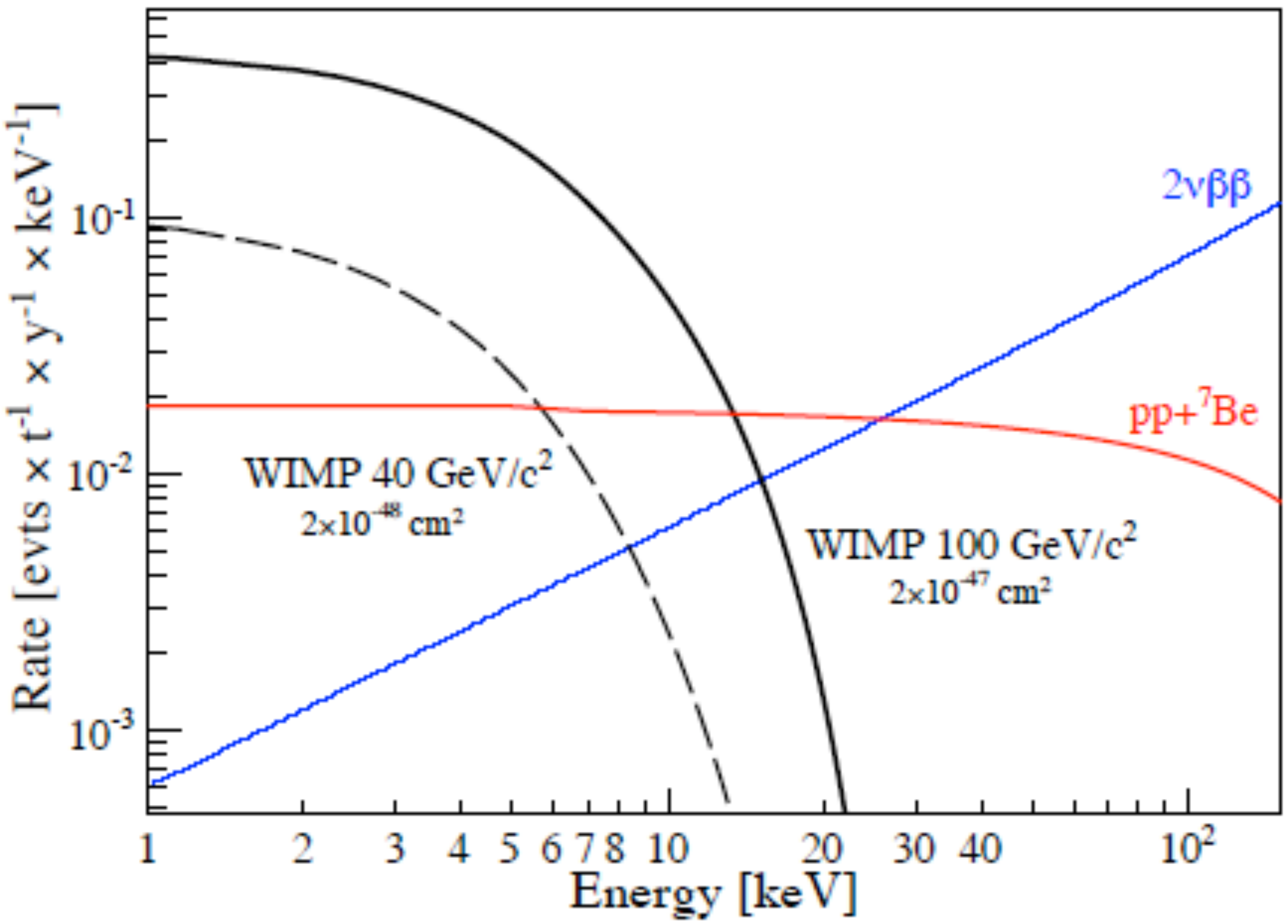




Plot taken from Billard et. al, arXiv:1307.5458v3

Neutrino Backgrounds (ER)

- In Xe, can reject ~99.5% of ER while keeping 50% of NR
- Imagine a
  - 5 ton detector
  - ~5 keVee window
  - 3 years of operation
  - => ~1 irreducible background event
  - (unless ER discrimination can be improved...)



Plot taken from Baudis et. al, arXiv: 1309.7024v2, assumes 99.5% rejection of electron recoils

Union of LUX and ZEPLIN + others

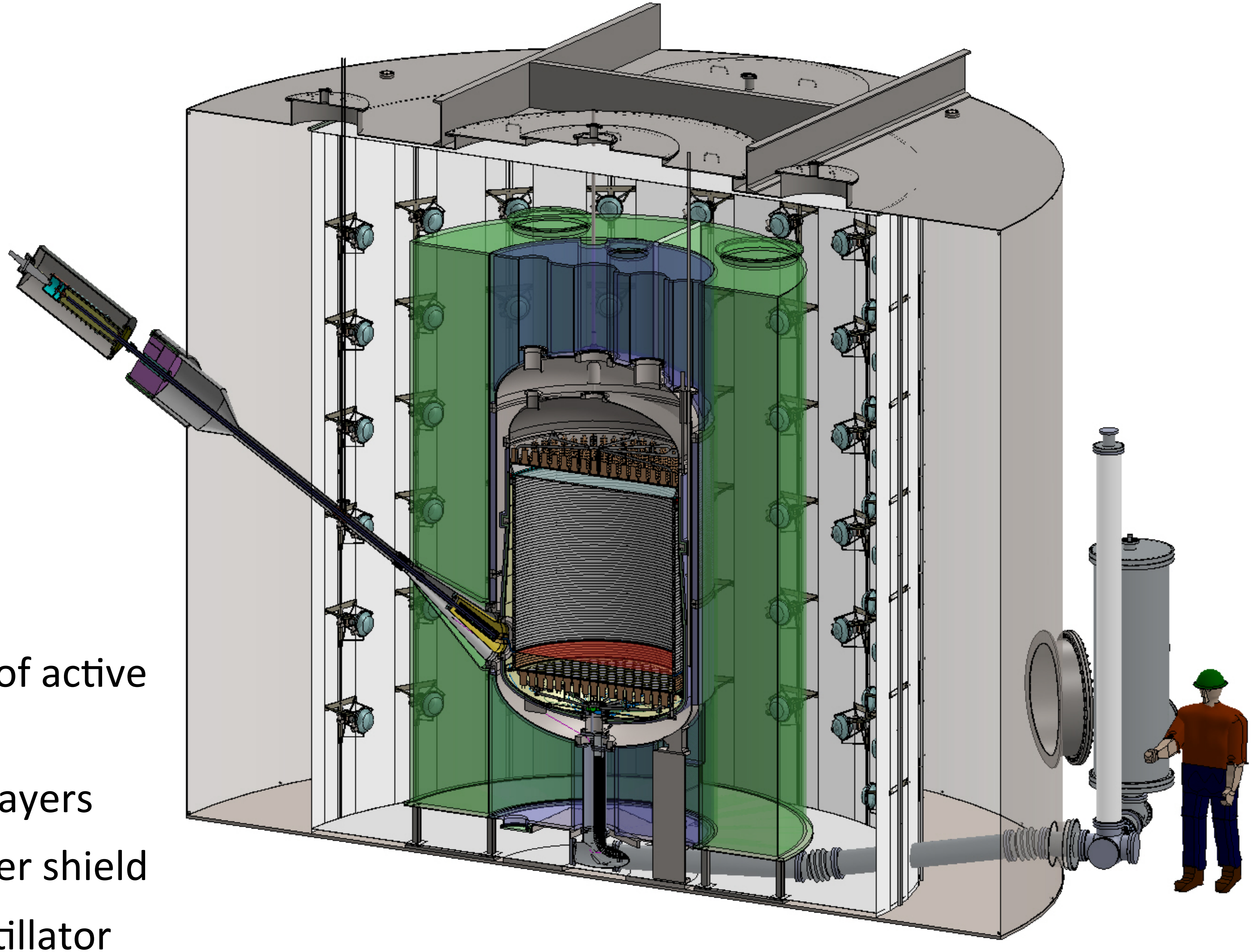
Brookhaven National Laboratory
Brown University
Case Western Reserve University
LBNL/UC, Berkeley
Lawrence Livermore Lab
SLAC
SD School of Mines & Technology
SD Science and Technology Authority
Texas A&M University
University of Alabama
UC, Davis
UC, Santa Barbara
University of Maryland
University of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

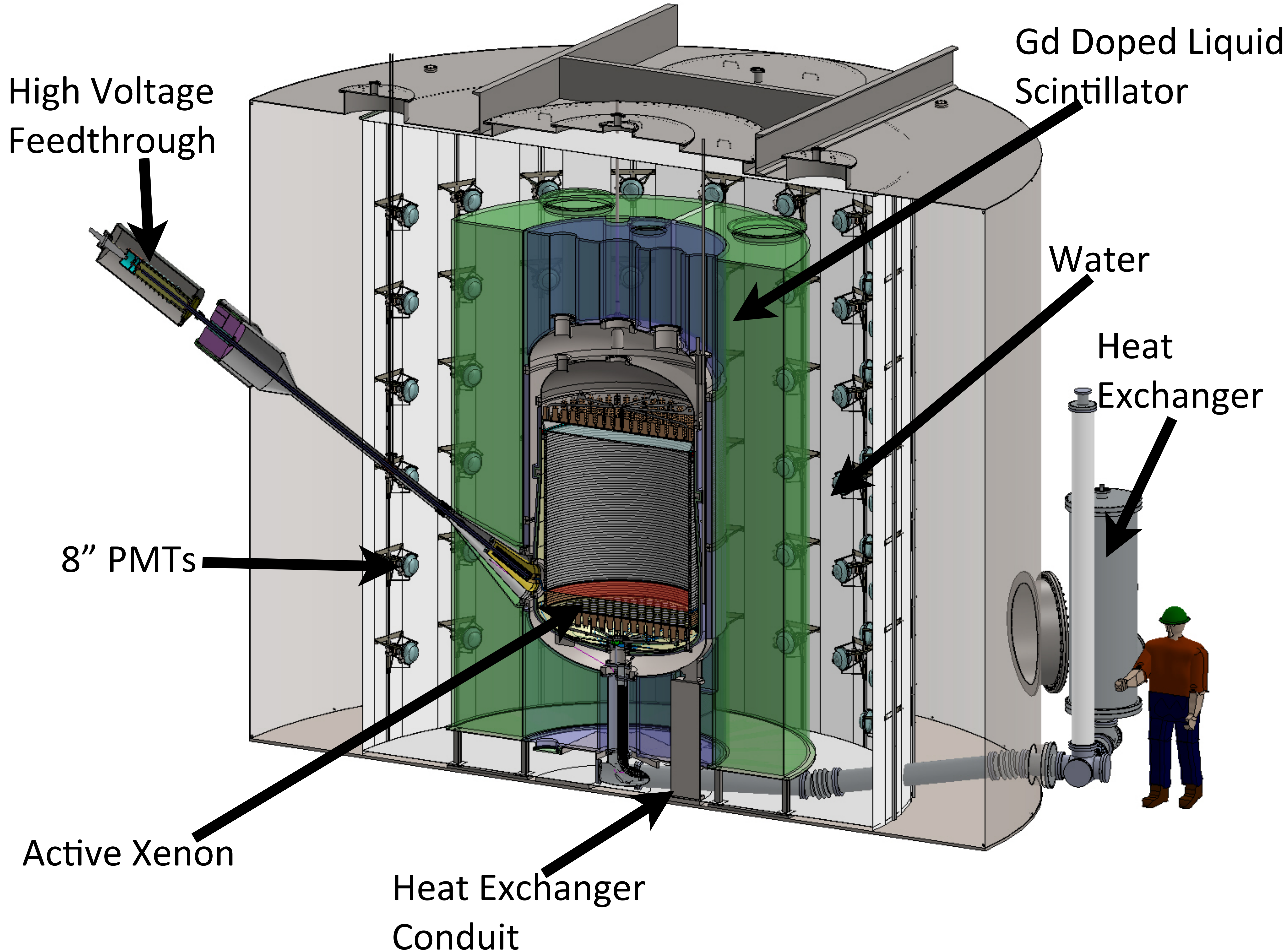
18 US and 9 European institutions

Sanford Underground Research Facility

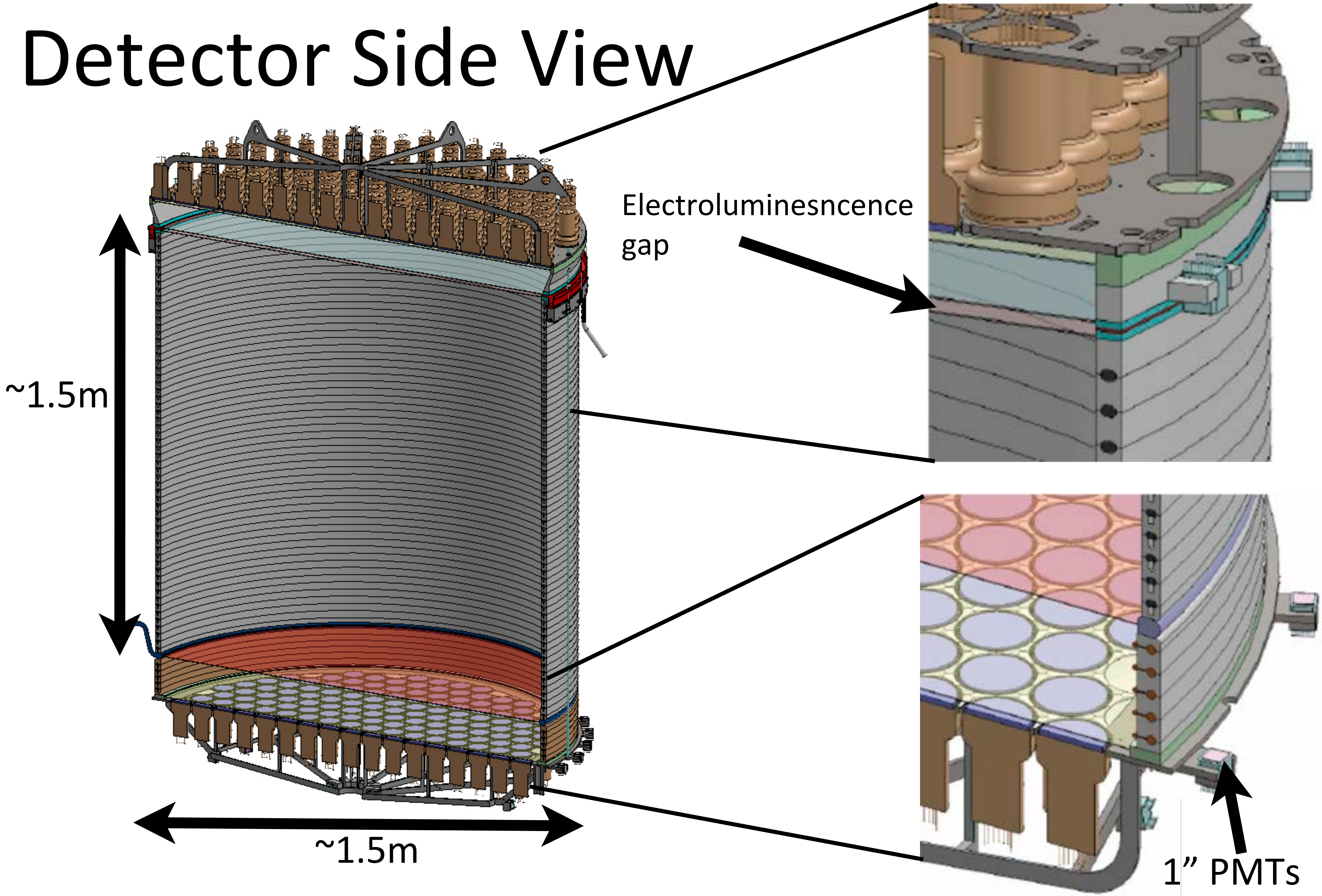
Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank



- 7 tons of active xenon
- Three layers
  - Water shield
  - Scintillator
  - Xenon (active and skin)

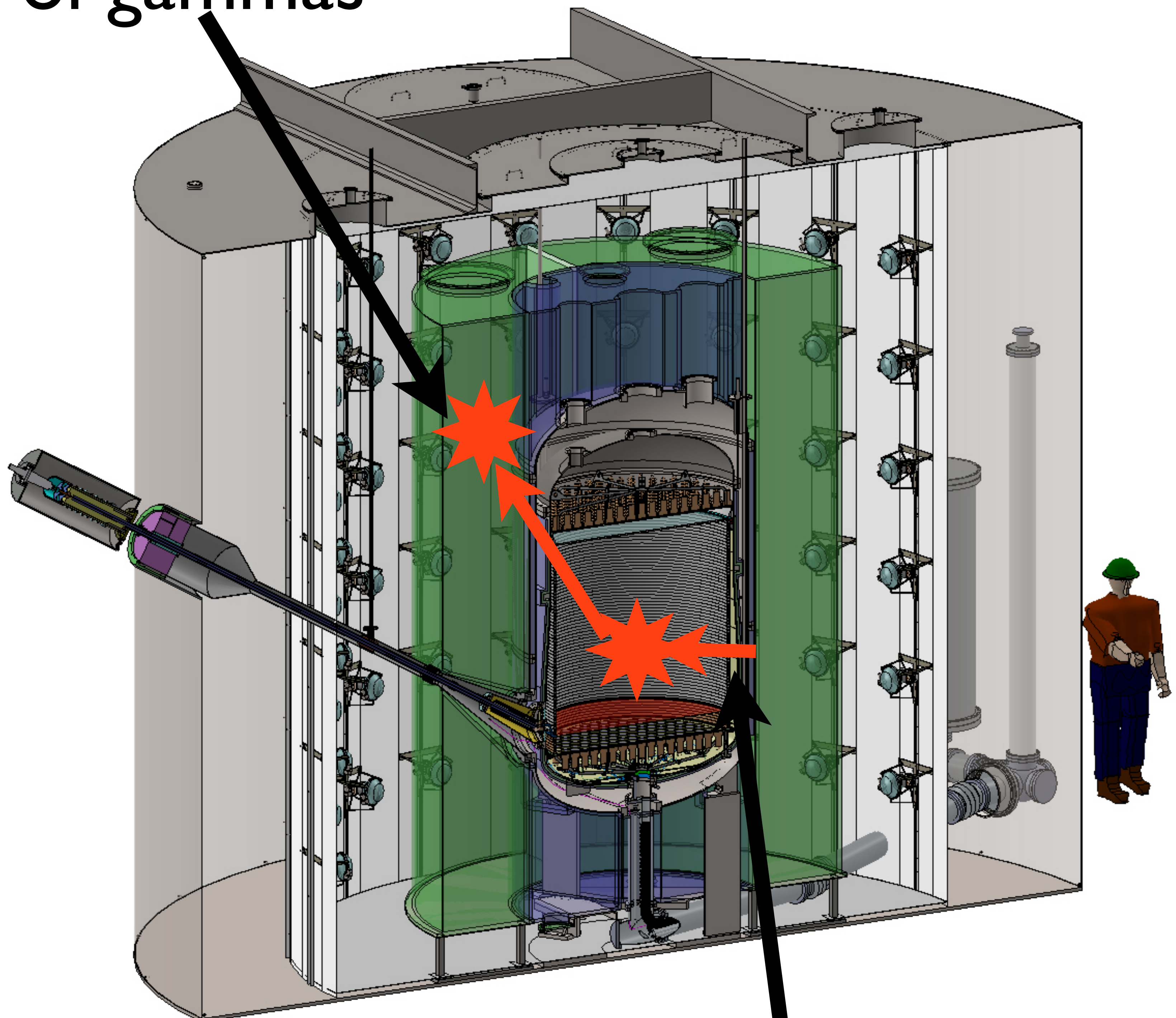

High Voltage Feedthrough
Gd Doped Liquid Scintillator
Water
Heat Exchanger
8” PMTs
Active Xenon
Heat Exchanger Conduit

Detector Side View

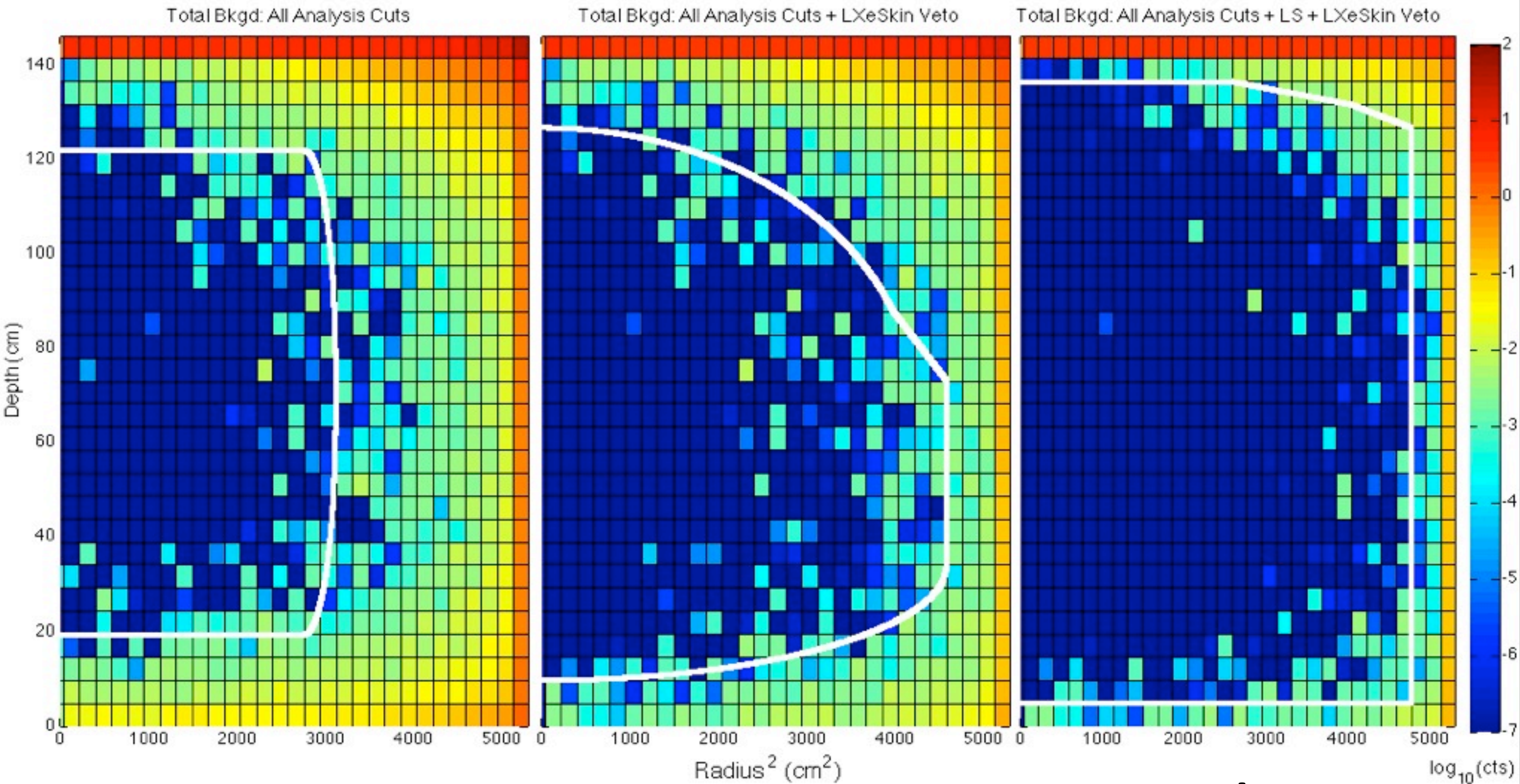


PMTs in xenon skin help to tag external backgrounds!

- Gd-doped linear akyl benzene (LAB) used for tagging outgoing neutrons
- ^{155}Gd and ^{157}Gd have particularly high neutron capture cross sections
- Result of capture: 8 MeV gamma cascade
  - Very clear signature!



Fiducial Volume and Vetoes

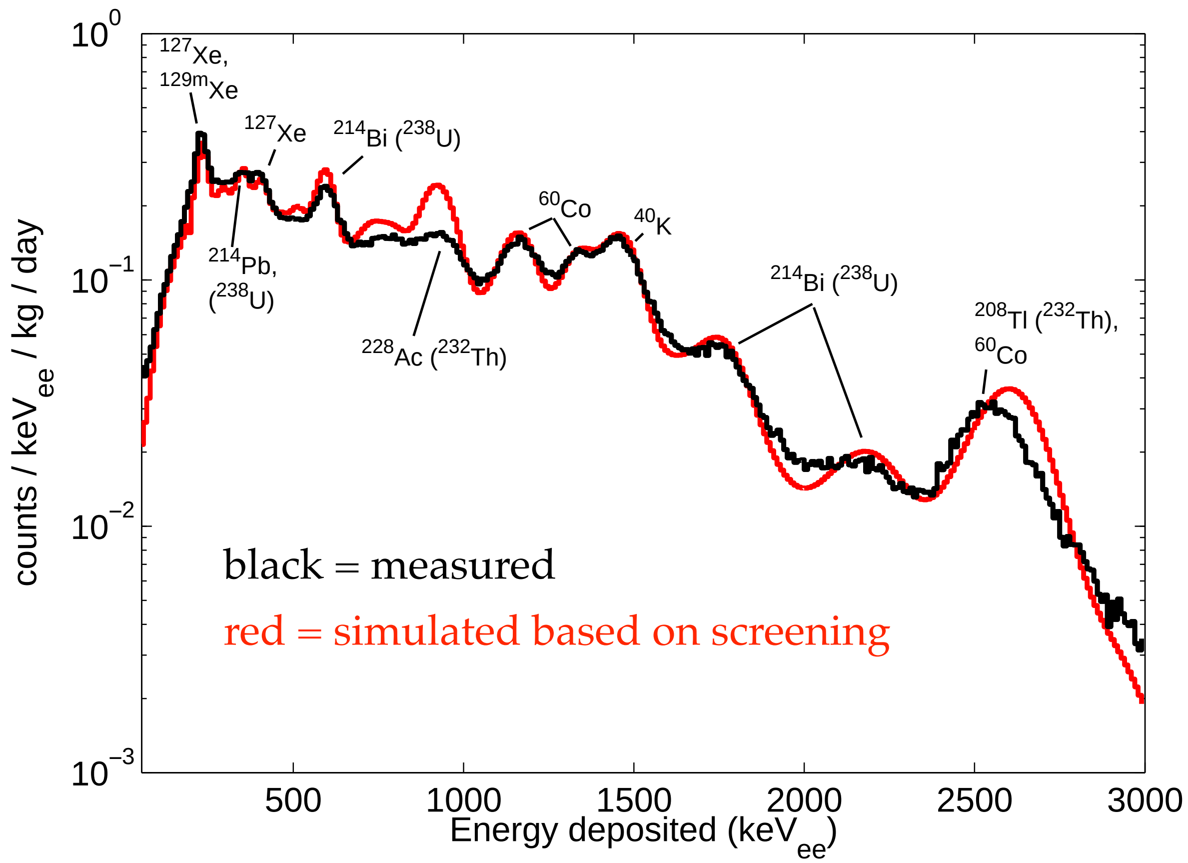


2.8 Tons

Skin Veto
4.1 Tons

+ Gd-LAB
5.6 Tons

LUX Background Model



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	0.11-0.22$_{(90\%\ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.1 \pm 0.2_{stat}$

- There backgrounds are all reducible:
  - Gamma-rays come mainly from PMTs => get lower radioactivity PMTs
    - Can also take advantage of xenon self-shielding
  - ^{127}Xe is a cosmogenic with a 36.4 day half-life => decays away with time underground
  - Reduce ^{85}Kr using chromatography

Estimated LZ Background

ER NR

Item	^{238}U	^{232}Th	^{40}K	ER Counts	NR Counts
Ti 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)
PTFE panels	0.01 mBq/kg	0.002 mBq/kg	0.06 mBq/kg	(0.002) 0.002 (0.01)	(0.0006) 0.0009 (0.004)
3" PMT	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)
Extra-TPC Subtotal				(11) 14 (40)	(0.05) 0.10 (0.35)
Kr + Rn				46	
Neutrinos				234	0.61
Totals	Raw			(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			**(1.79) 1.83 (2.04)**	

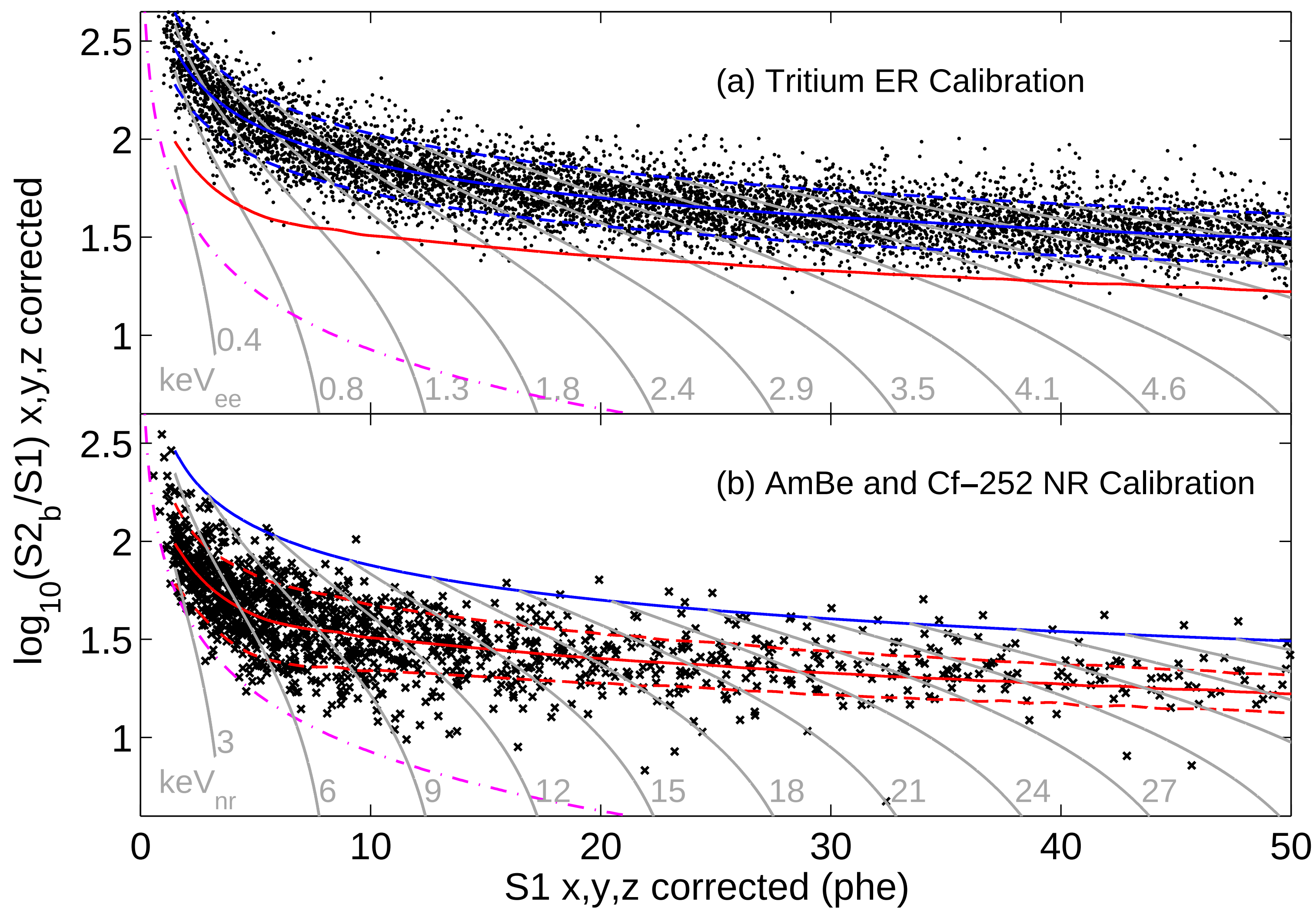
Estimated LZ Background

All numbers approximate! ER NR

Item	^{238}U	^{232}Th	^{40}K	ER Counts	NR Counts
Ti cryostat	1 mBq/kg	1 mBq/kg	2 mBq/kg	2	0
PTFE Panels	.01 mBq/kg	.001 mBq/kg	.1 mBq/kg	0	0
3" PMTs	3 mBq/kg	3 mBq/kg	30 mBq/kg	10	0
Other (TPC)	Various	Various	Various	5	0
TPC Total				15	0
Kr + Rn				50	0
Neutrinos				250	0.5
Totals			Raw	332	0.5
ER Reject	99.5%	NR Accept	50%	~2	0.25
			Combined	~2	

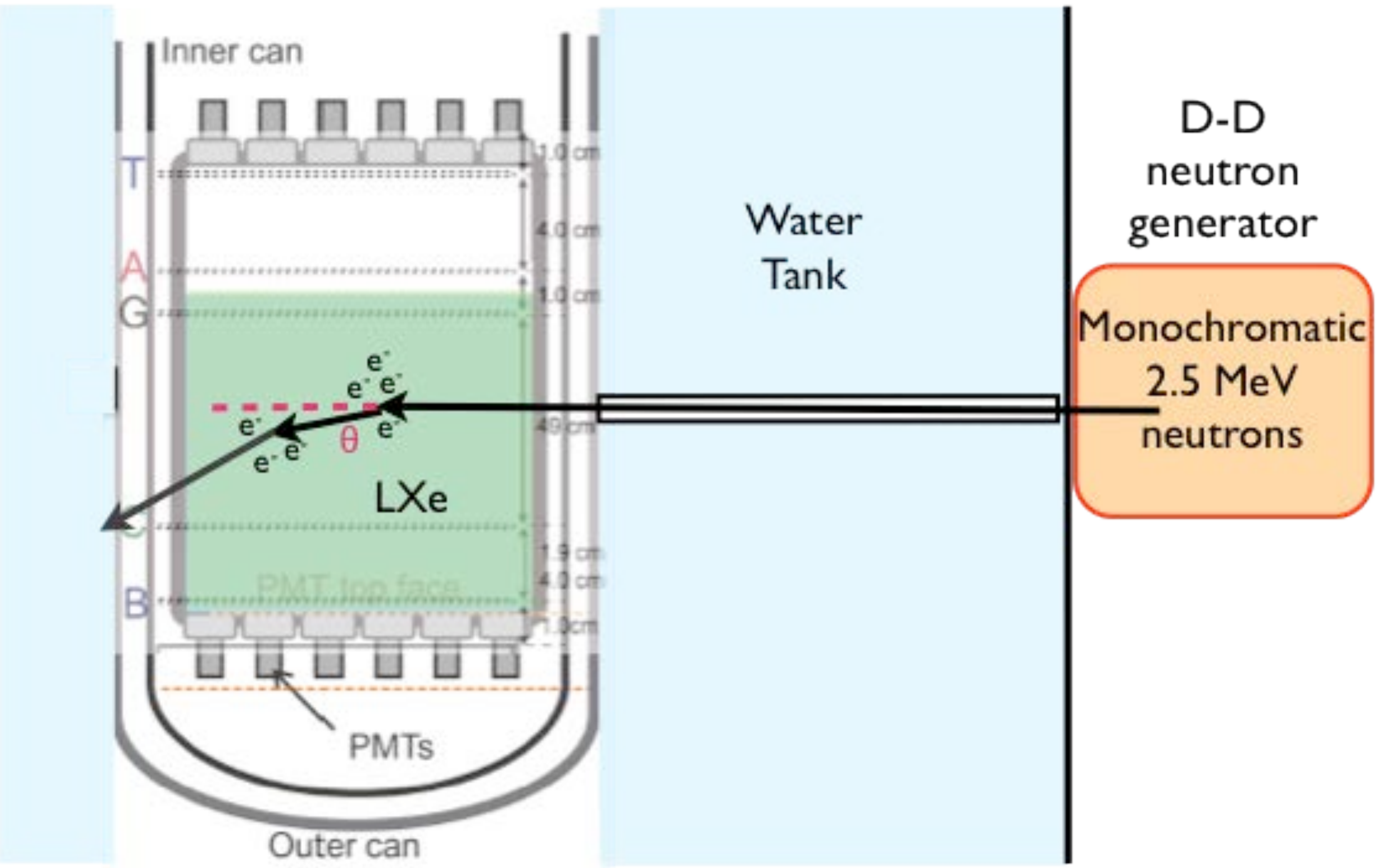
Calibrating LZ

- Plot: LUX ER and NR calibrations using tritium and external neutron sources
- How will this be done in LZ?
    - Tritium source was perfect, no need to change it!
    - There are improvements one could make to neutron calibrations
        - DD source (already done in LUX)
        - YBe source
        - AmLi source

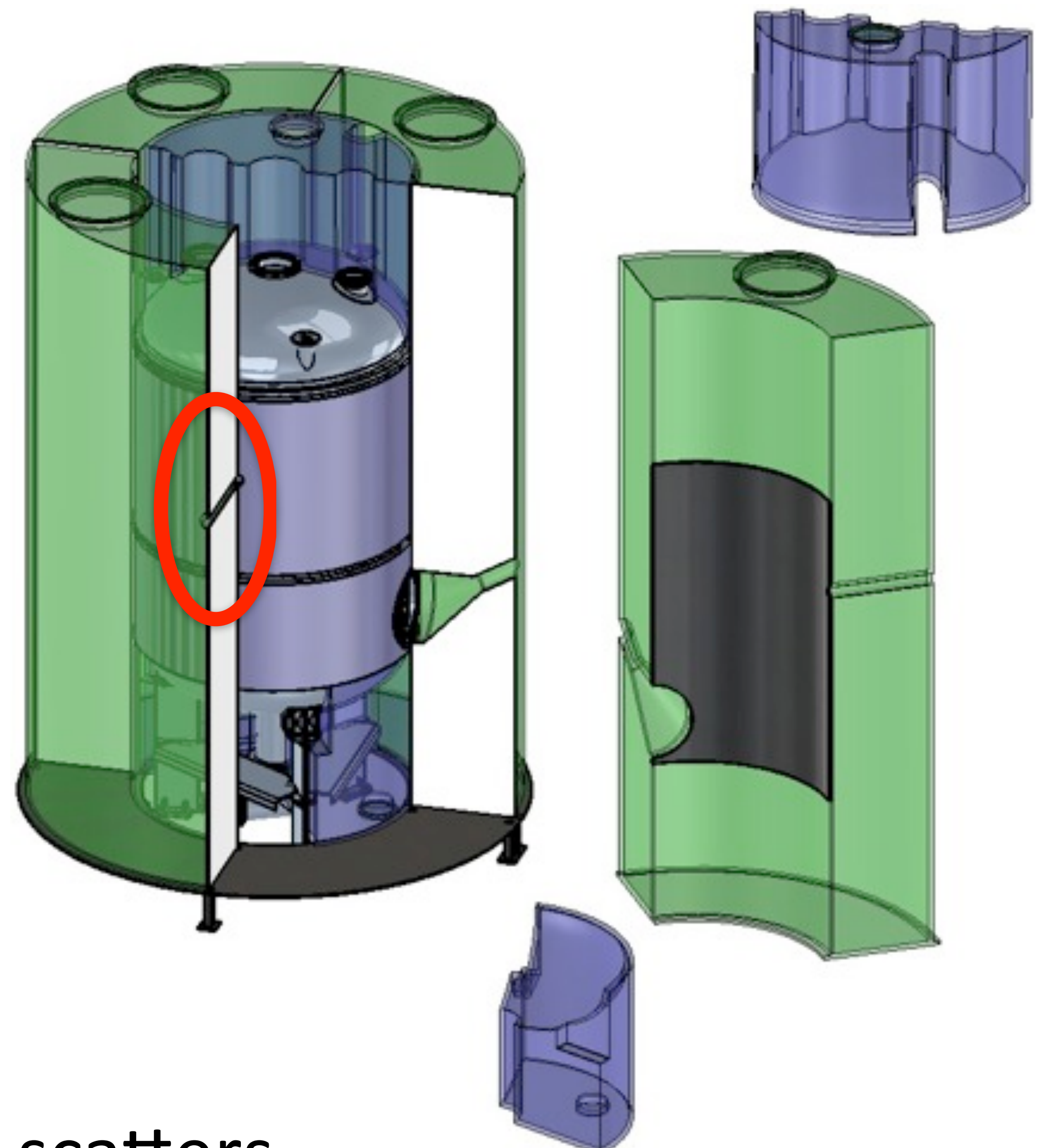


Monoenergetic, Collimated Neutrons

LUX



LZ



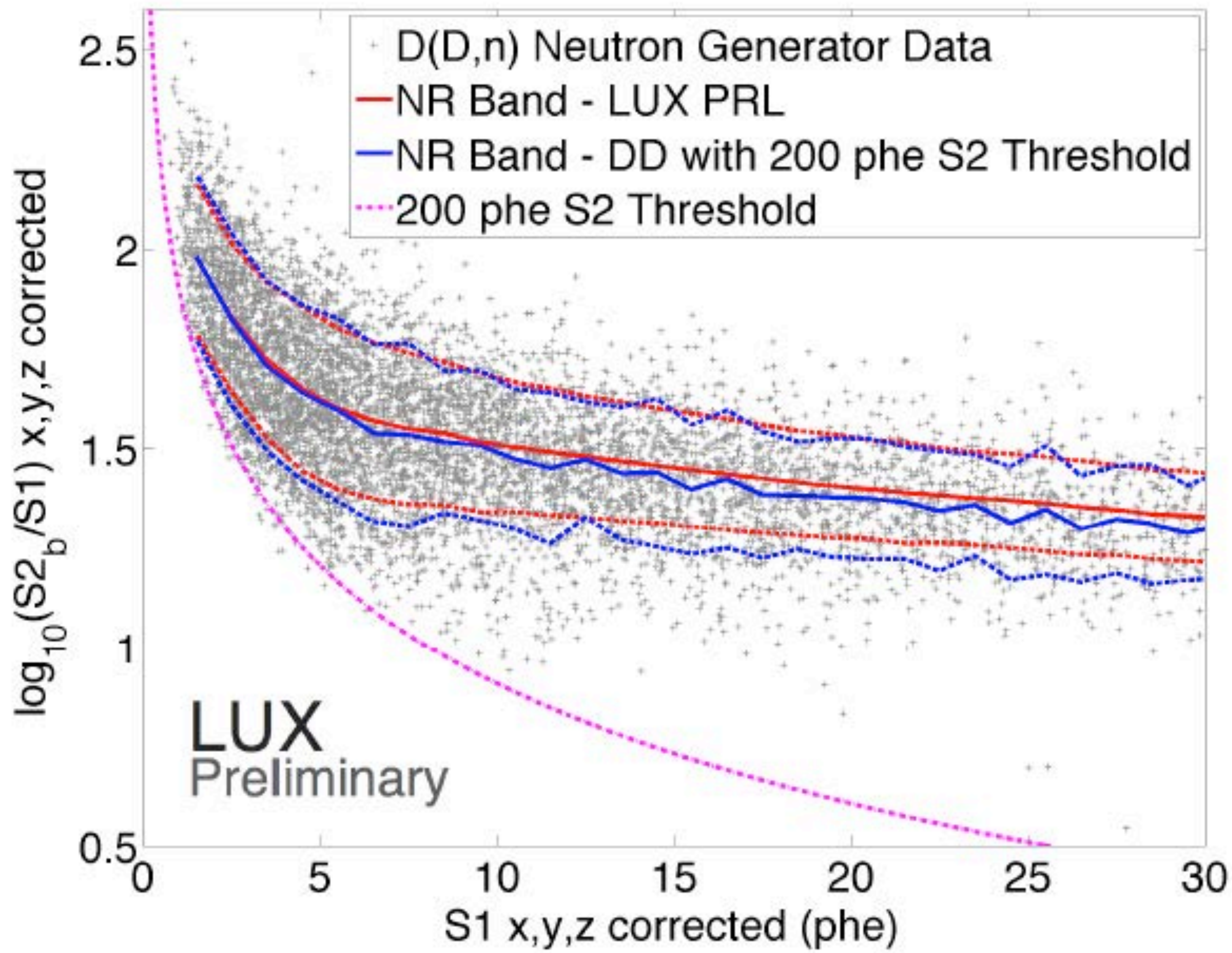
Double scatter, n energy gives E_r

Two S2's… calibrate S2

Transfer S2 calibration to S1 with single scatters

DD Neutron Calibrations

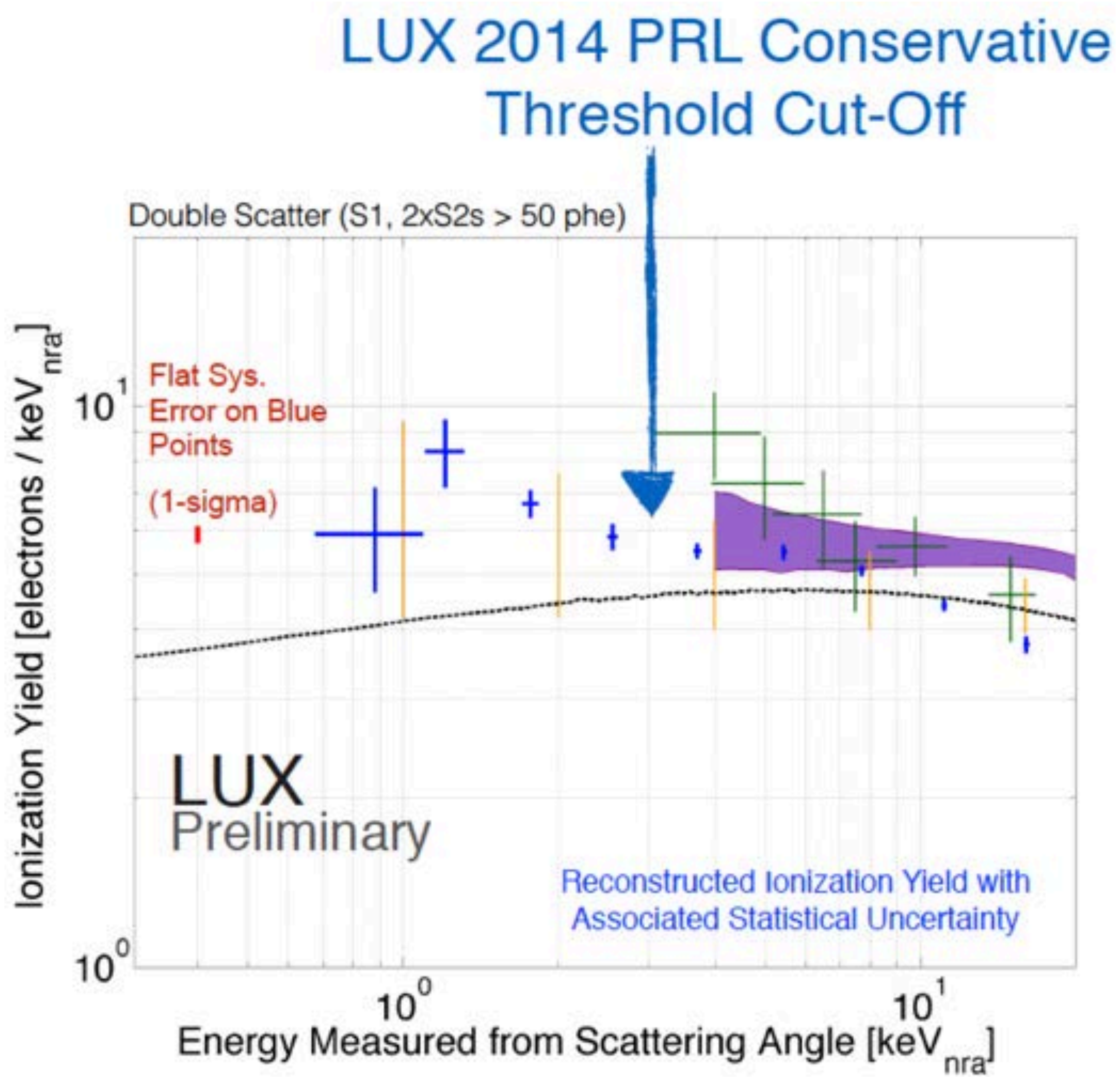
- DD gives a very clean calibration of the nuclear recoil reponse



Ionization (S2)

- Systematic error of 7% from threshold correction for (lowest energy) 0.7-1.0 keVnra bin
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency.
- Current analysis cut-off at 0.7 keV_{nra}

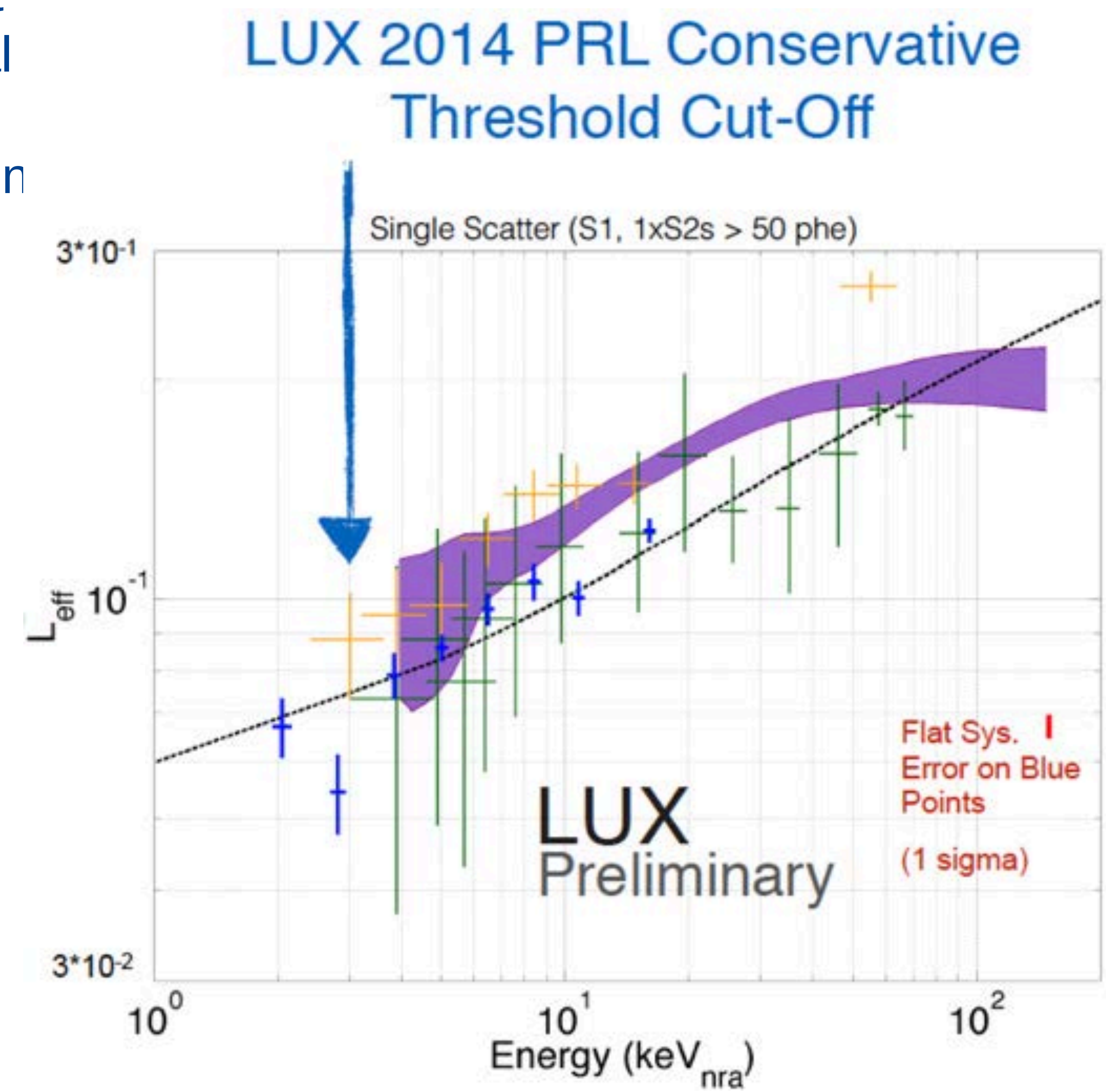
Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)
Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)
Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm



Scintillation (S1)

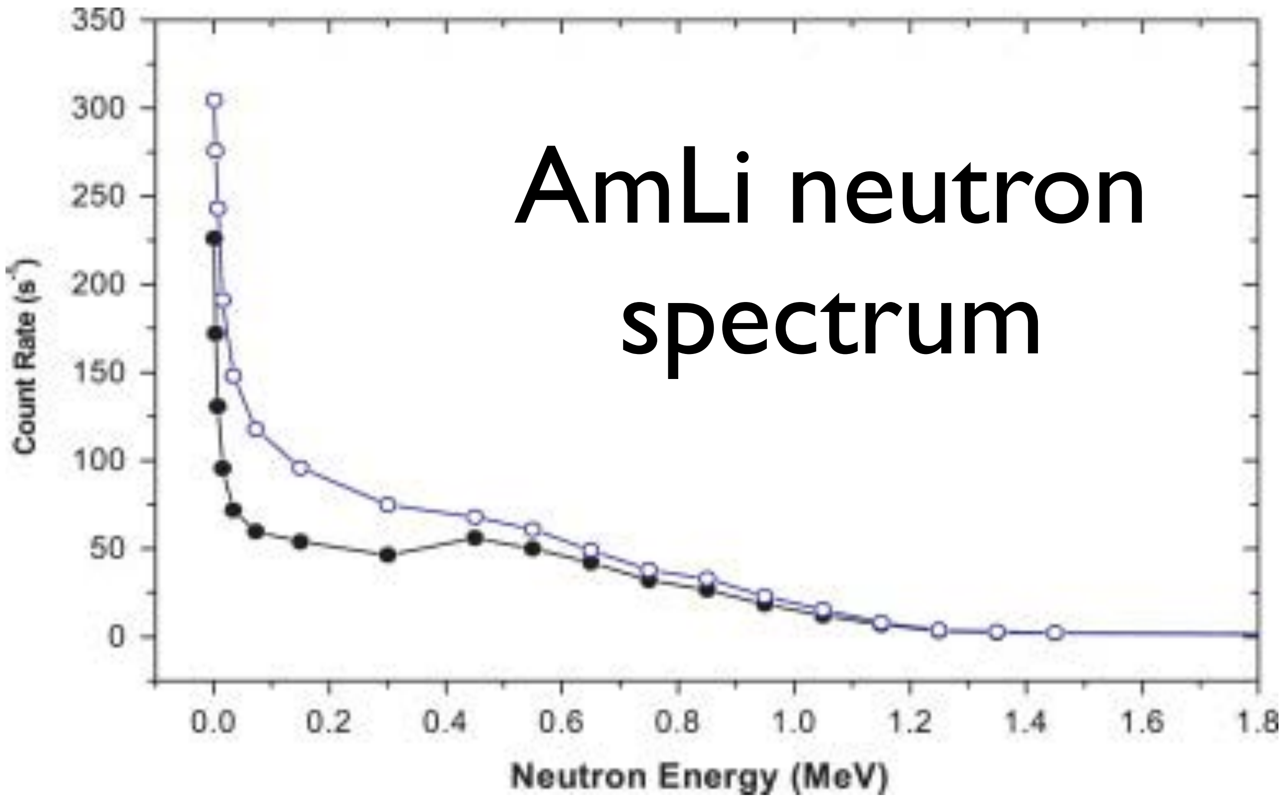
- LUX Leff values currently reported at 181 V/cm as opposed to the traditional zero field value.
- X error bars representative of error on mean of population in bin
- Energy scale defined using LUX measured Qy
- Method can be extended below existing 2 keV_{nra} point

Blue Crosses - LUX Measured Leff; reported at 181 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)
Purple Band - Horn Combined Zeplin III FSR/ SSR; 3.6 kV/cm, rescaled to 0 V/ cm (energy scale from best fit MC)
Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)
Black Dashed Line - Szydagis et al (NEST) Predicted Scintillation Yield at 181 V/cm



NR Endpoints

- DD: mono-energetic 2.45 MeV neutrons => ~75 keVnr end point in Xe
- AmLi: broadband (α,n) source between 0-1.5 MeV (plot) => ~40 keVnr end point in Xe
- YBe: 152 keV mono-energetic (γ,n) source => 4.5 keVnr end point in Xe



Plot taken from Tagziria and Looman, Appl. Radiat. Isot. 70 (2012) pp. 2395-2402

Baseline plan

Under consideration

Electric Field

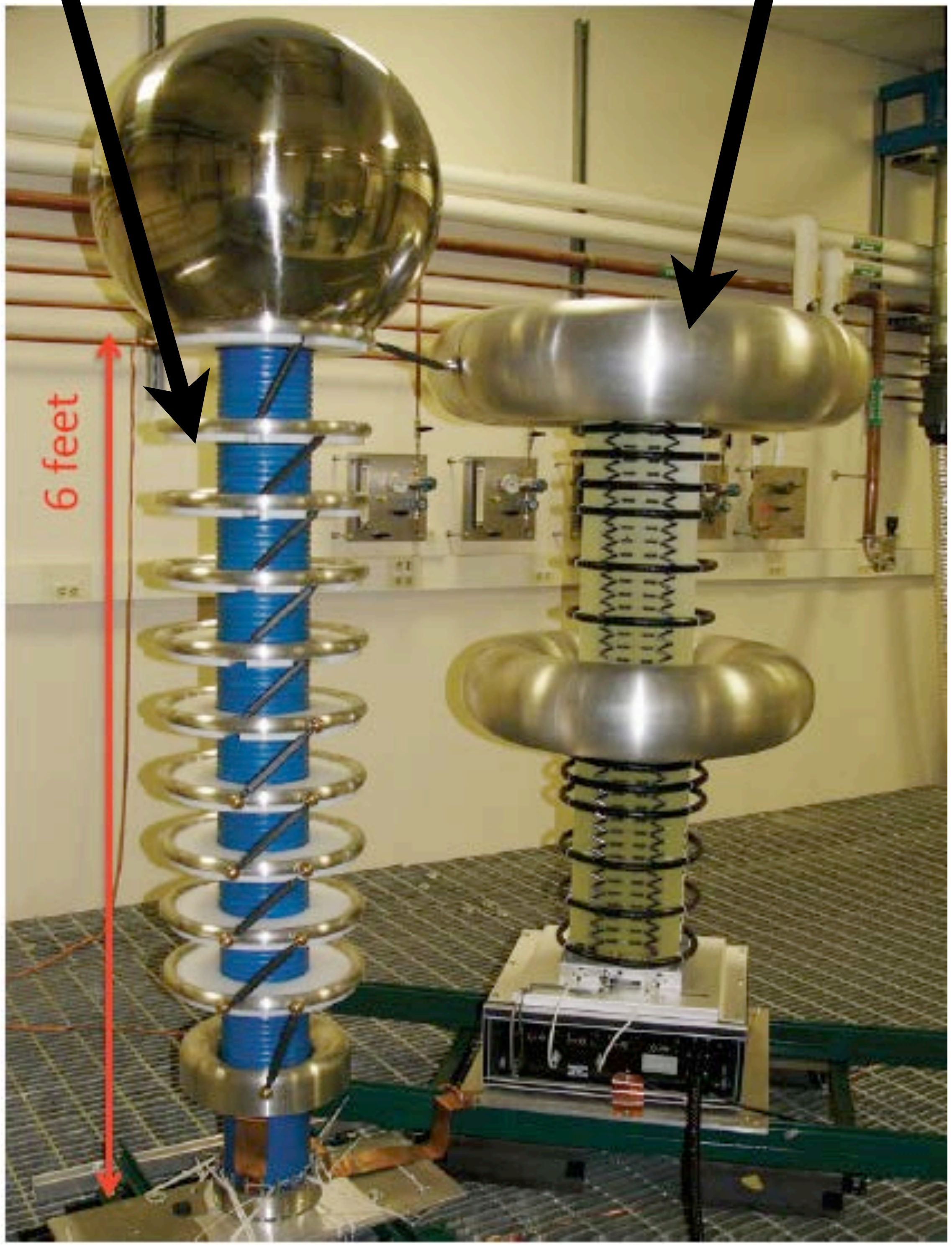
Experiment	Drift Length	Cathode Voltage	Electric Field	ER Reject
EXO-200	20 cm	-8 kV	376 V/cm	N/A
XENON100	30 cm	-16 kV	533 V/cm	99.75%*
ZEPLINIII (1st Science Run)	3.6 cm	-10 kV	3900 V/cm	99.98%
LUX	50 cm	-10 kV	181 V/cm	99.6%
LZ Goal	130 cm	-100 kV	770 V/cm	TBD

- Some examples of high voltages achieved in xenon time projection chambers
- Highest voltage so far (in absolute value): 16 kV
- LZ has 3X the drift distance of LUX => need high voltage for the same field
- So the saying goes, "They don't pay you to plug yourself" but...

* >50% NR Acceptance!

Yale High Voltage R&D

- Epoxy poured feedthrough
- Feedthrough tested up to -200 kV (not in Ar)
- Used for tests of high voltage in LAr

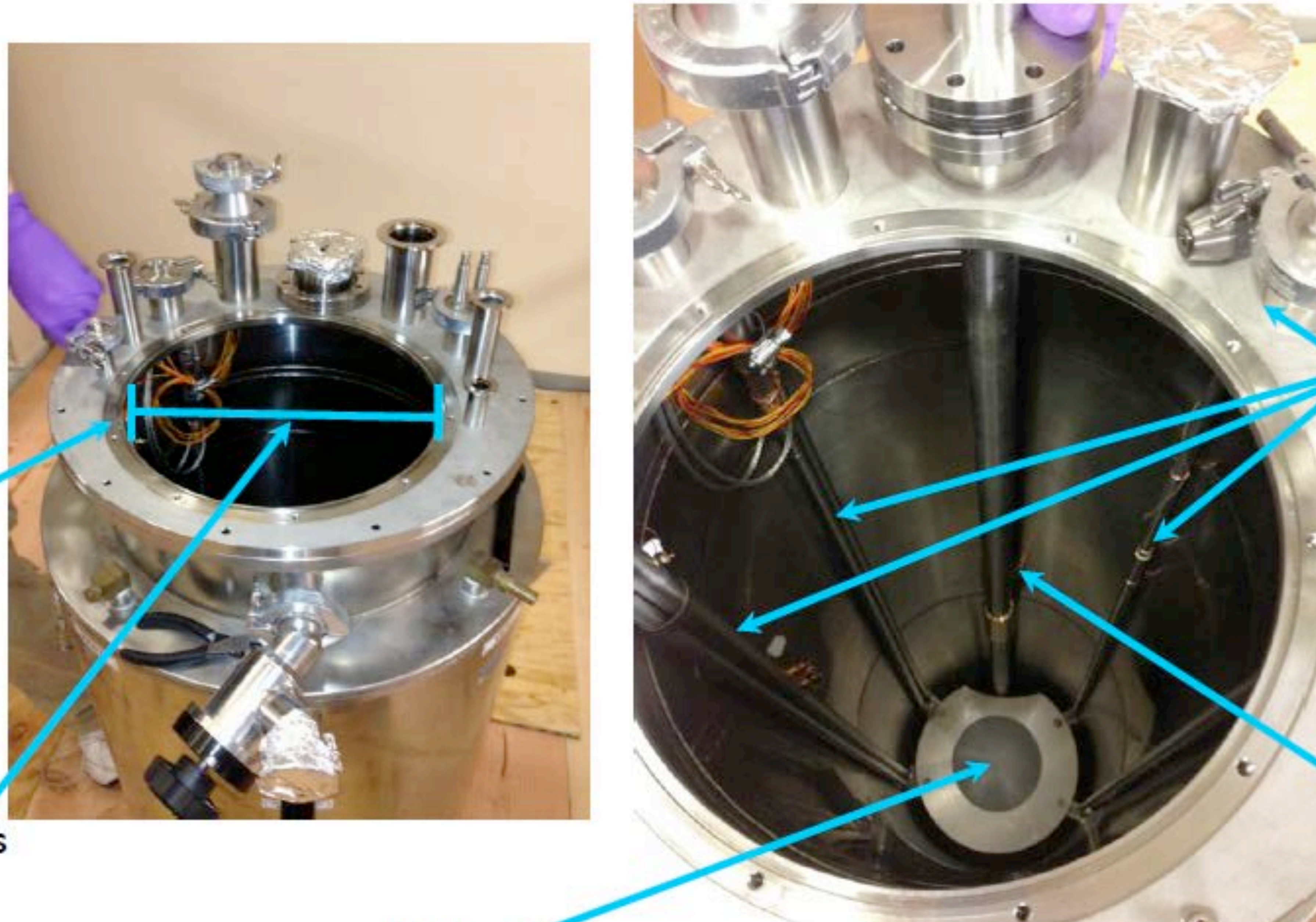


High Voltage in LAr

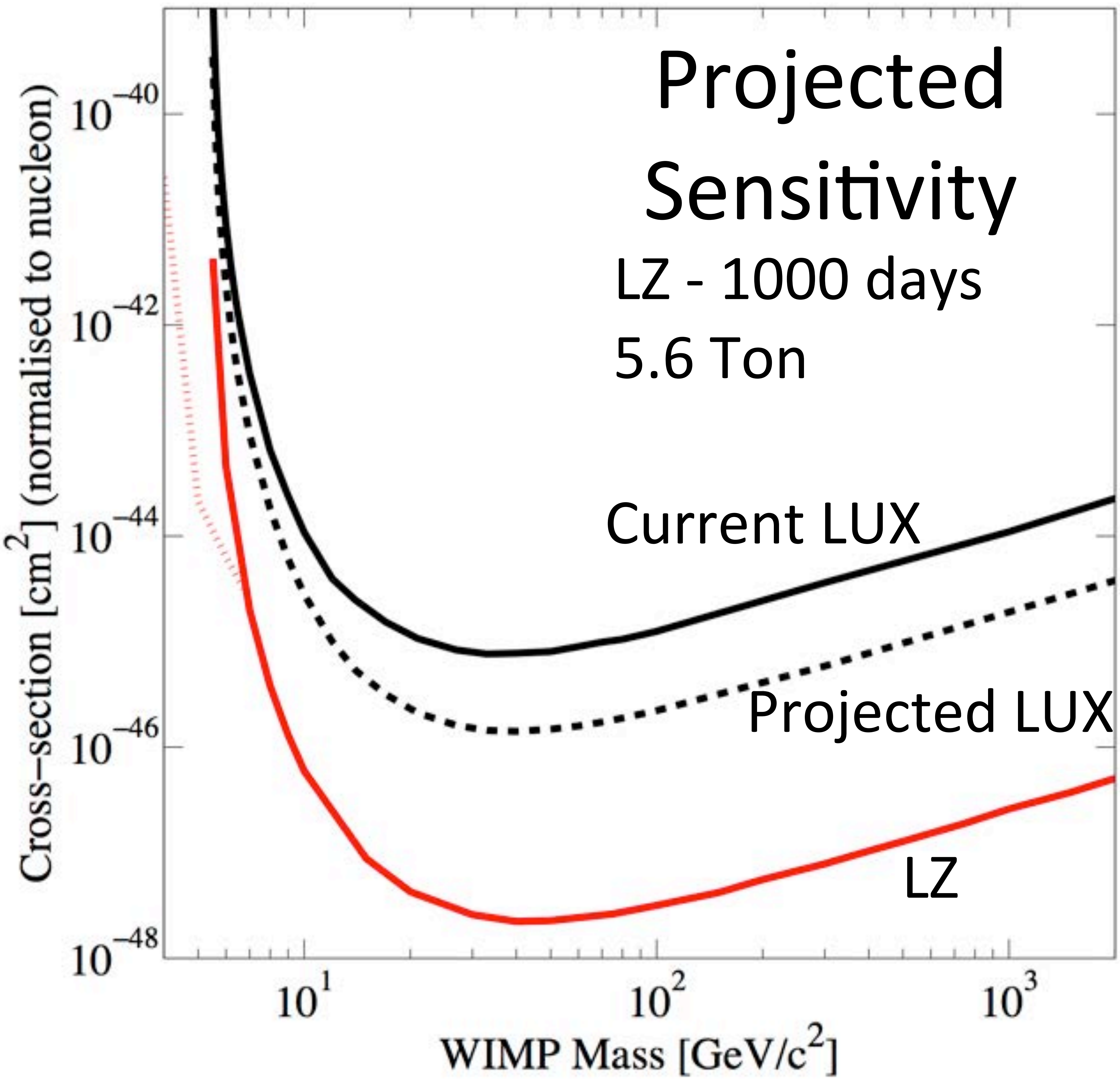
HV
Cable

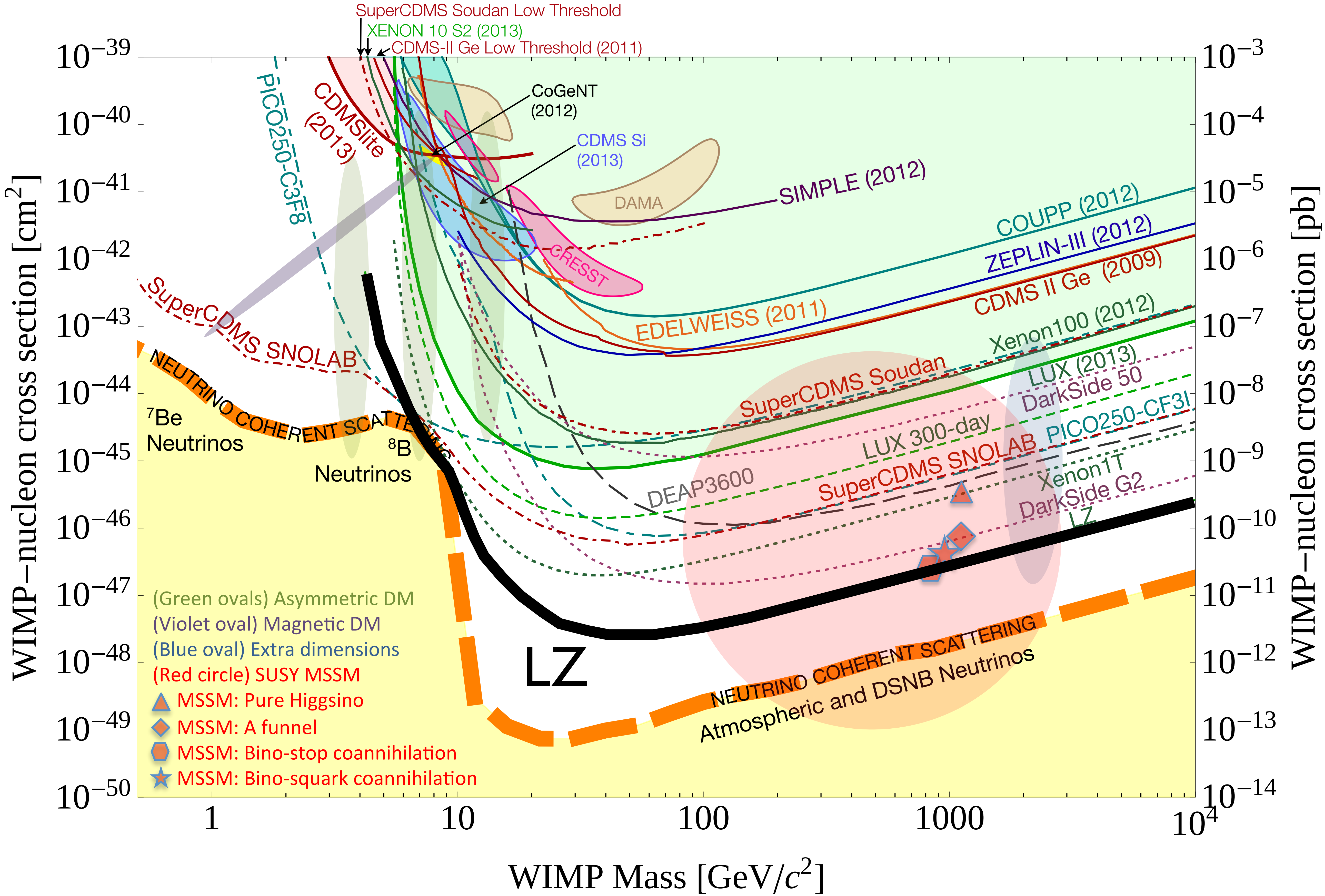
~200L
LAr
Dewar

LAr Test Dewar



- PMT for viewing light related to HV discharge or glow
- Setup is designed for option to purify argon while running: removing electronegatives could affect HV


Projected Sensitivity
LZ - 1000 days
5.6 Ton
Current LUX
Projected LUX
LZ
Cross-section [cm^2] (normalised to nucleon)
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^1
10^2
10^3
WIMP Mass [GeV/c^2]



- Lots of parameter space still to explore
- Dashed orange band represents fundamental neutrino background

Summary

- LZ aims to improve on the sensitivity of LUX by > 100X
- Building on LUX experience from for neutron and tritium calibrations
- LZ is start construction some time soon after LUX is complete!