Who Has Seen the WIMP? Neither You Nor I.

Daniel McKinsey
LUX Co-Spokesperson
UC Berkeley and LBNL

Neutrino seminar
Fermilab
March 24, 2016

Who has seen the wind?
Neither I nor you.
But when the leaves hang trembling
The wind is passing through.

Who has seen the wind?
Neither you nor I.
But when the trees bow down their heads
The wind is passing by.

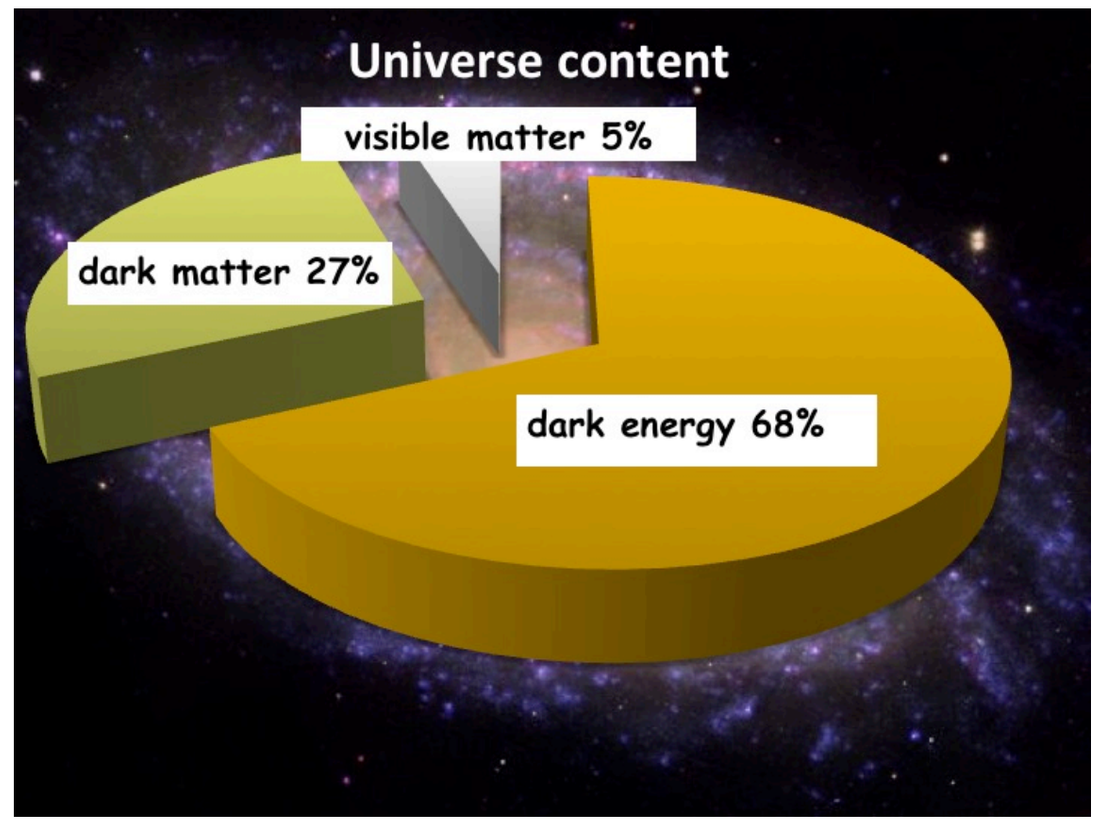
by Christina Rossetti, 1830-1894

Composition of the Universe

The Higgs particle has been discovered, the last piece of the Standard Model.

But as successful as it has been, the Standard Model describes only 5% of the universe. The remaining 95% is in the form of dark energy and dark matter, whose fundamental nature is almost completely unknown.

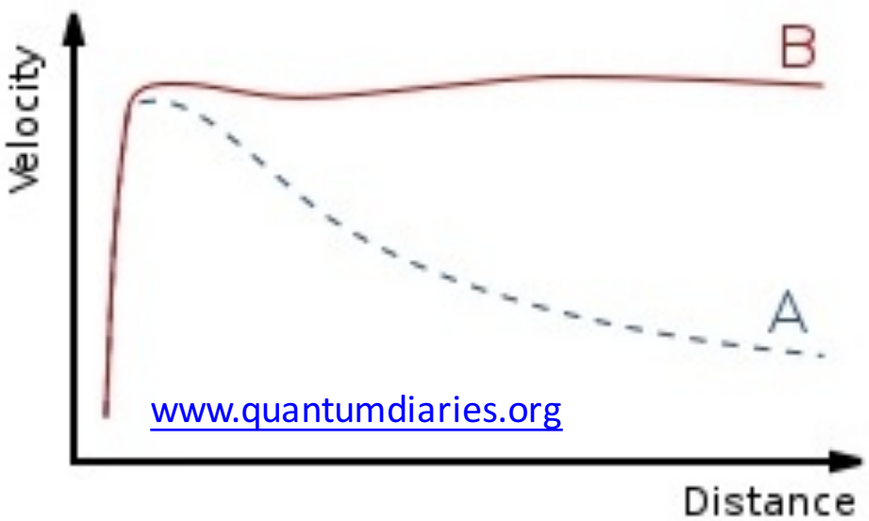
Image: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



www.quantumdiaries.org

Evidence for Dark Matter

Galaxy rotation curves



The cosmic microwave background

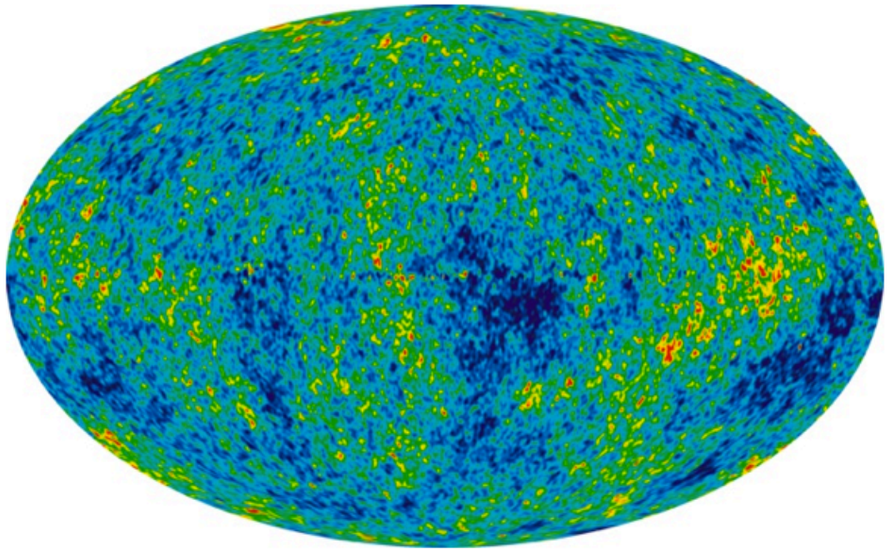


Image: ESA and the Planck collaboration

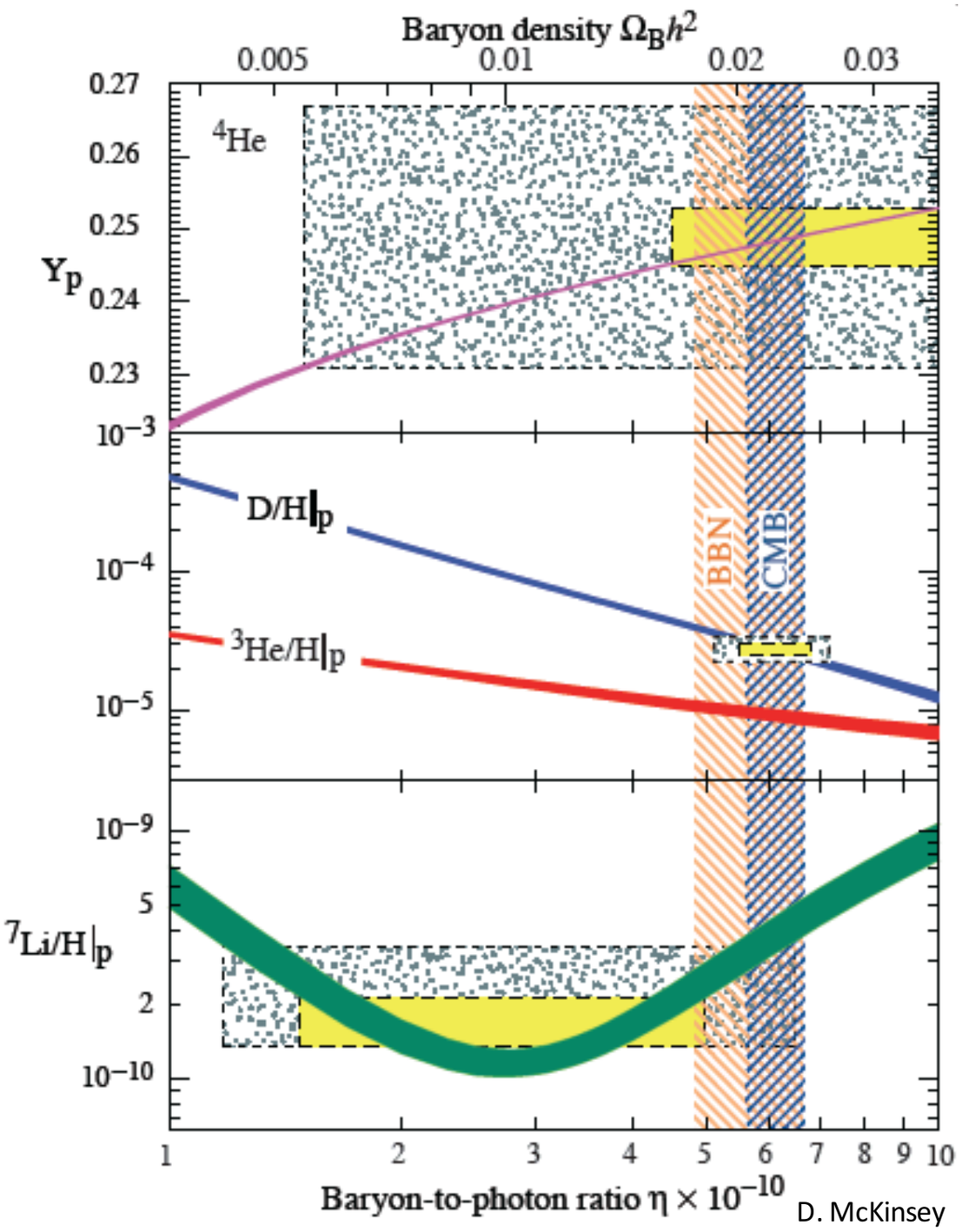
Gravitational lensing

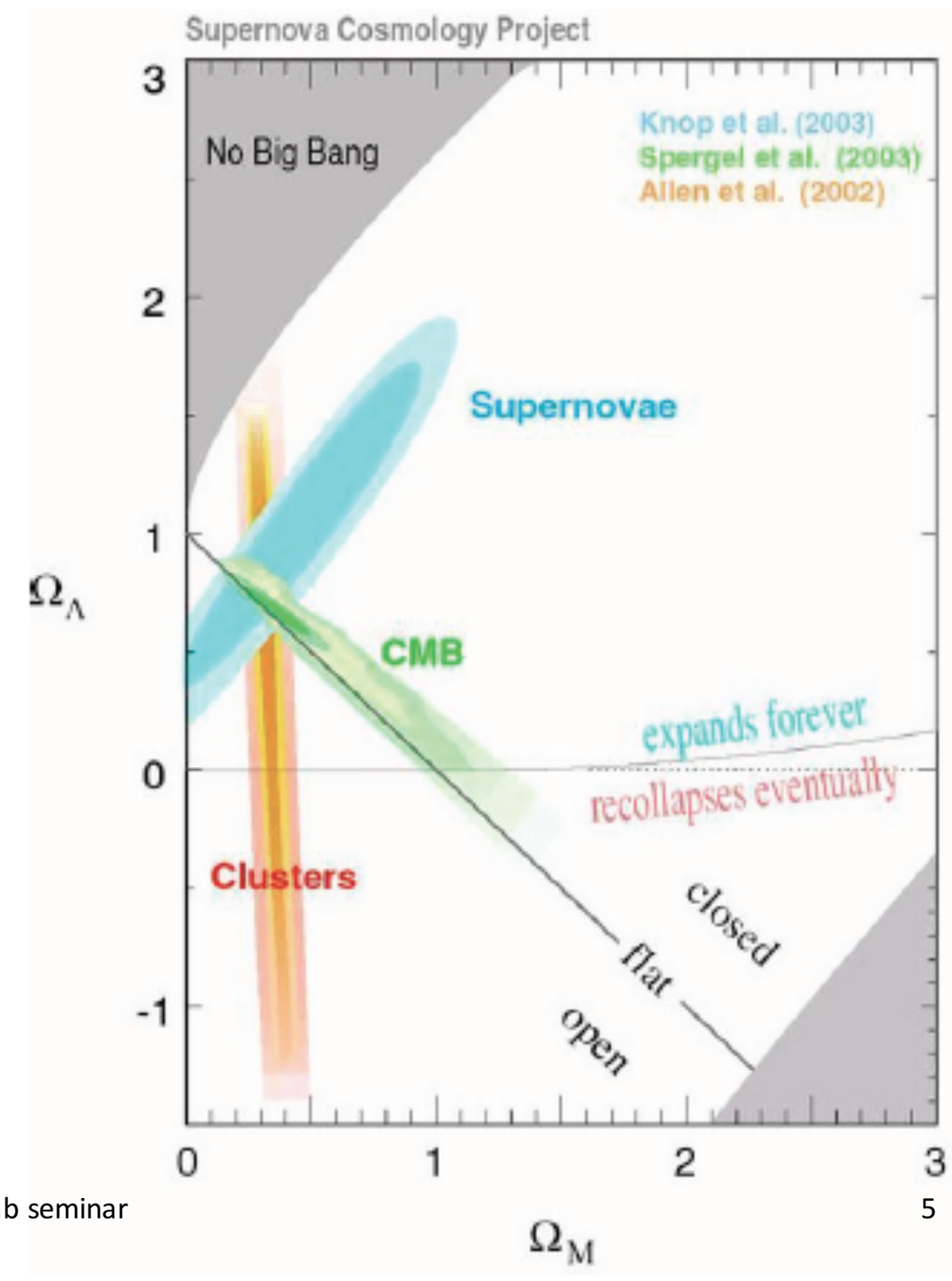
Colley, Turner, Tyson, and NASA

- 27% of the energy composition of the universe
- Properties:
- Stable and electrically neutral
- Non-baryonic
- Non-relativistic
- Estimated local density: $0.3 \pm 0.1 \mathrm{GeV \cdot cm^{-3}}$
- Candidates: WIMPs, axions, dark photons,...

Evidence for Dark Matter

Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.





Weakly Interacting Massive Particles (WIMPs)

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

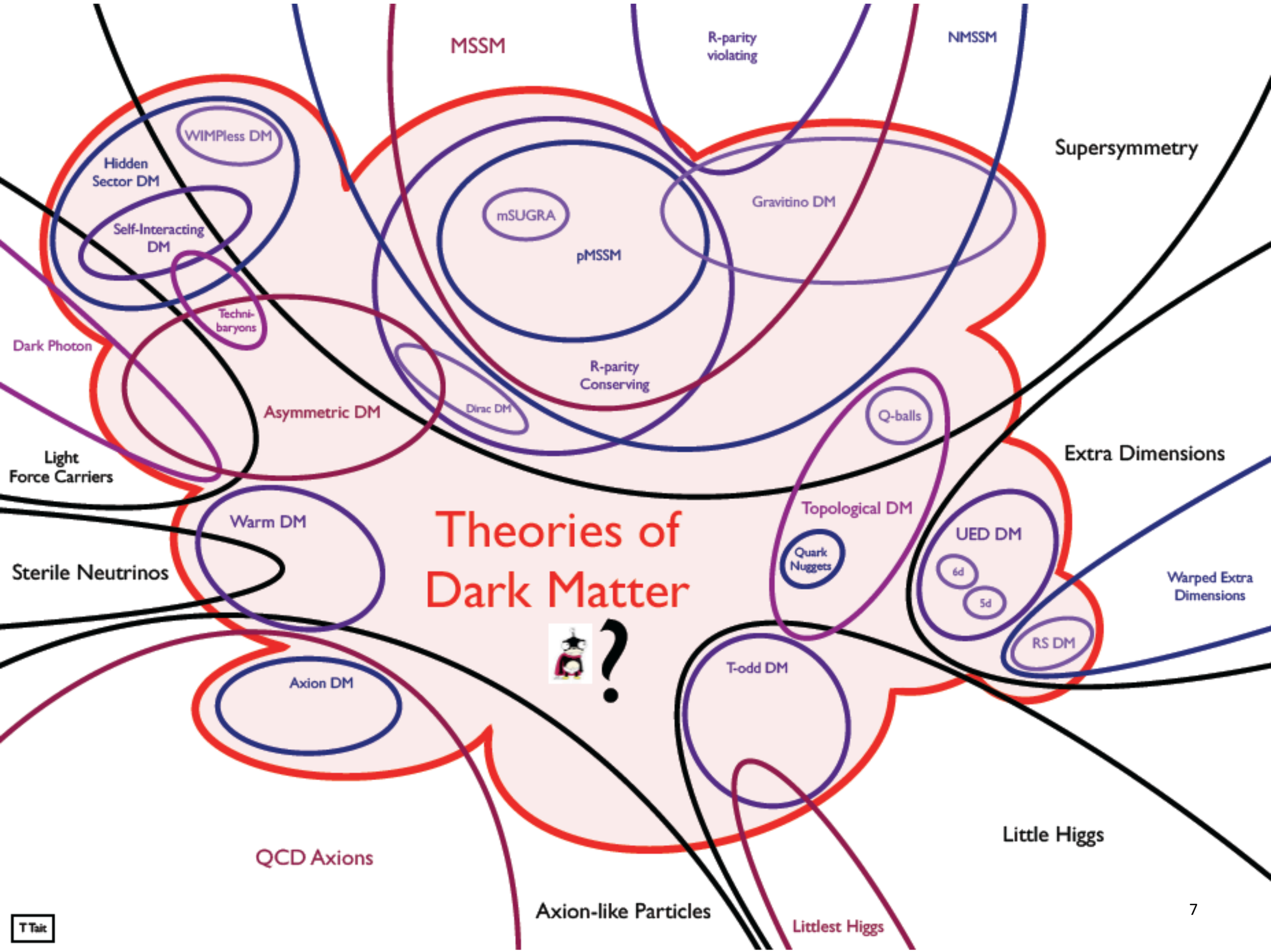
- Formed in massive amounts in the Big Bang.
- Non-relativistic freeze-out. Decouples from ordinary matter.
- Would exist today at densities of about $1000/m^3$.

Supersymmetry provides a natural candidate – the neutralino.

- Lowest mass superposition of photino, zino, higgsino
- Mass range from the proton mass to thousands of times the proton mass.
- Wide range of cross-sections with ordinary matter, from 10^{-40} to 10^{-50} cm^2.
- Charge neutral and stable!

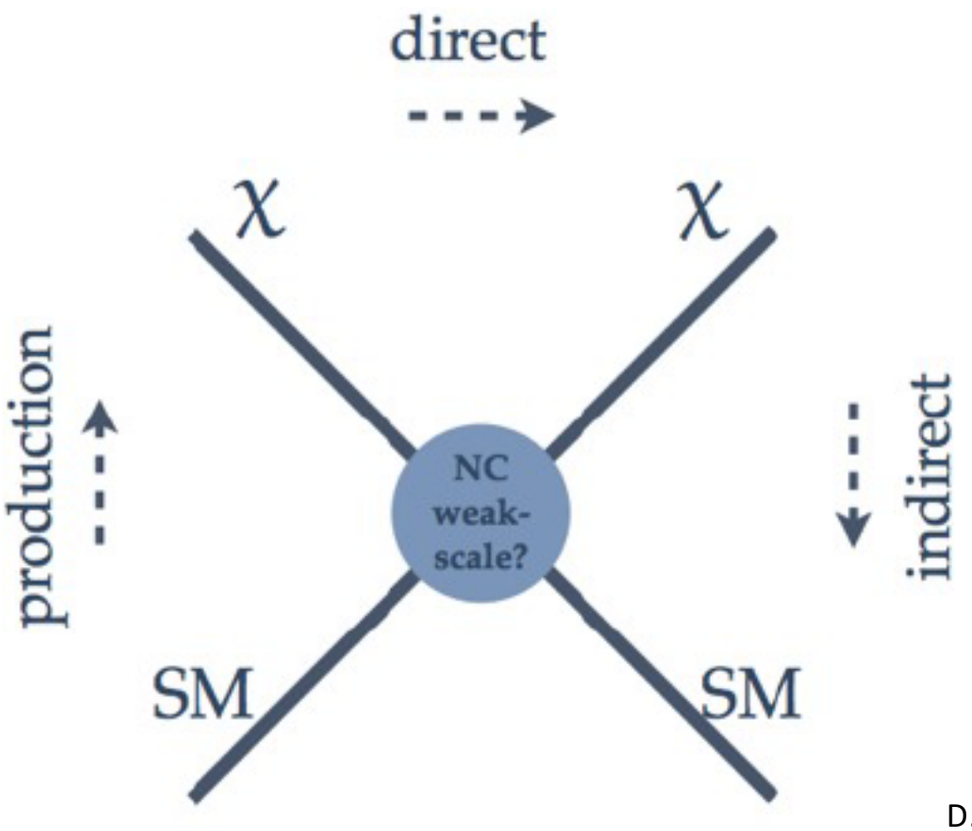
Universal Extra Dimensions: predicts stable Kaluza-Klein (KK) particles

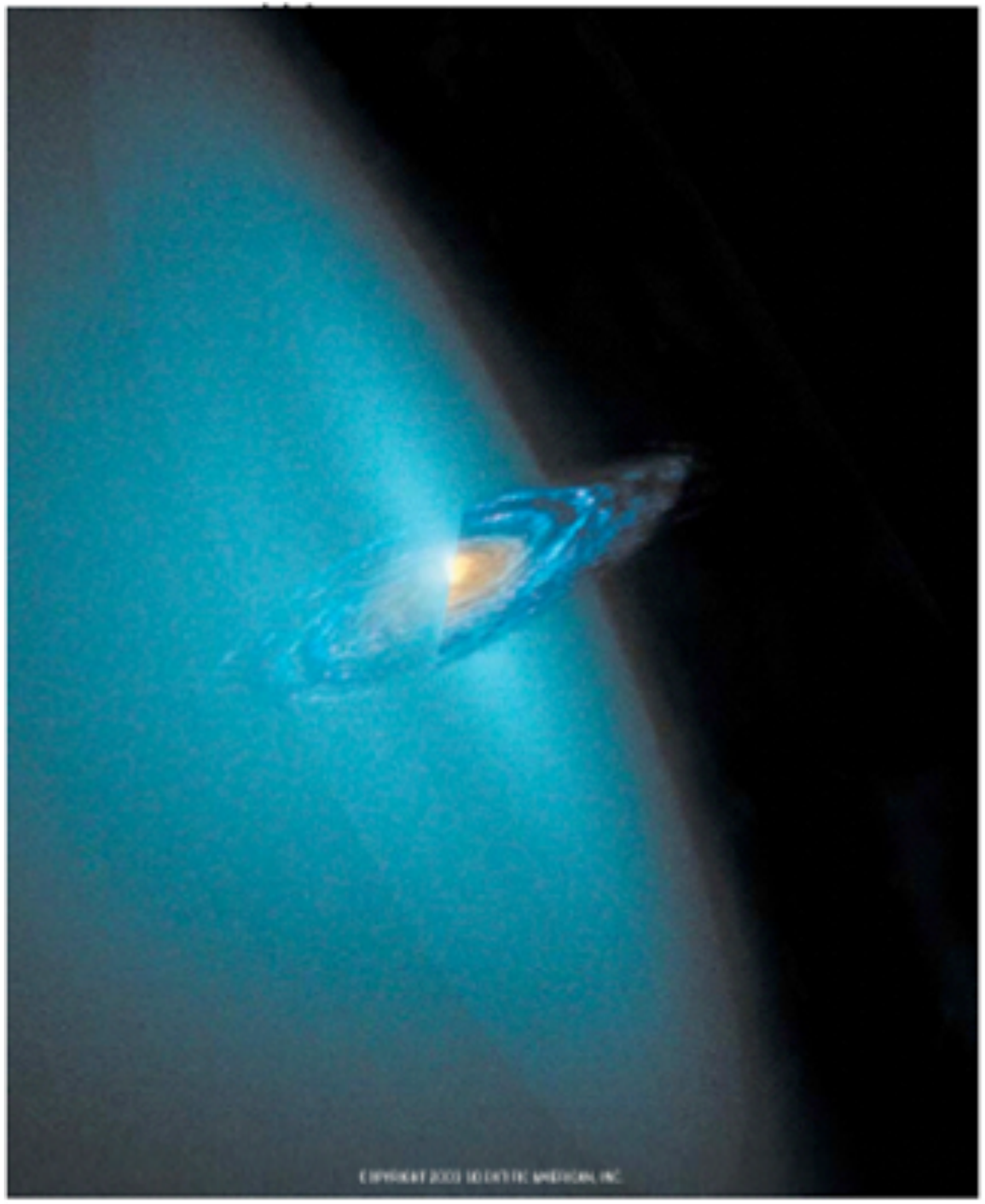
- Similar direct detection properties as neutralino
- Distinguishable from neutralinos at accelerators


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
mSUGRA
pMSSM
Gravitino DM
R-parity Conserving
Dirac DM
Asymmetric DM
Q-balls
Extra Dimensions
Light Force Carriers
Warm DM
Theories of Dark Matter
Topological DM
Quark Nuggets
UED DM
6d
5d
Warped Extra Dimensions
Sterile Neutrinos
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

A dark matter halo surrounds and fills every galaxy, including the Milky Way

- Density at Earth: ~ 300 m_{proton} / liter
- If m_{WIMP} = 100 GeV, then 3 WIMPs / liter (!)
- Typical orbital velocity = 230 km/sec
  - = 1/1000 speed of light
- deBroglie wavelength is larger than nucleus:
  - coherent scalar scattering on ordinary nuclear matter
  - cross section ~ A^2
- Rate << 1 event/kg/(1000 days)





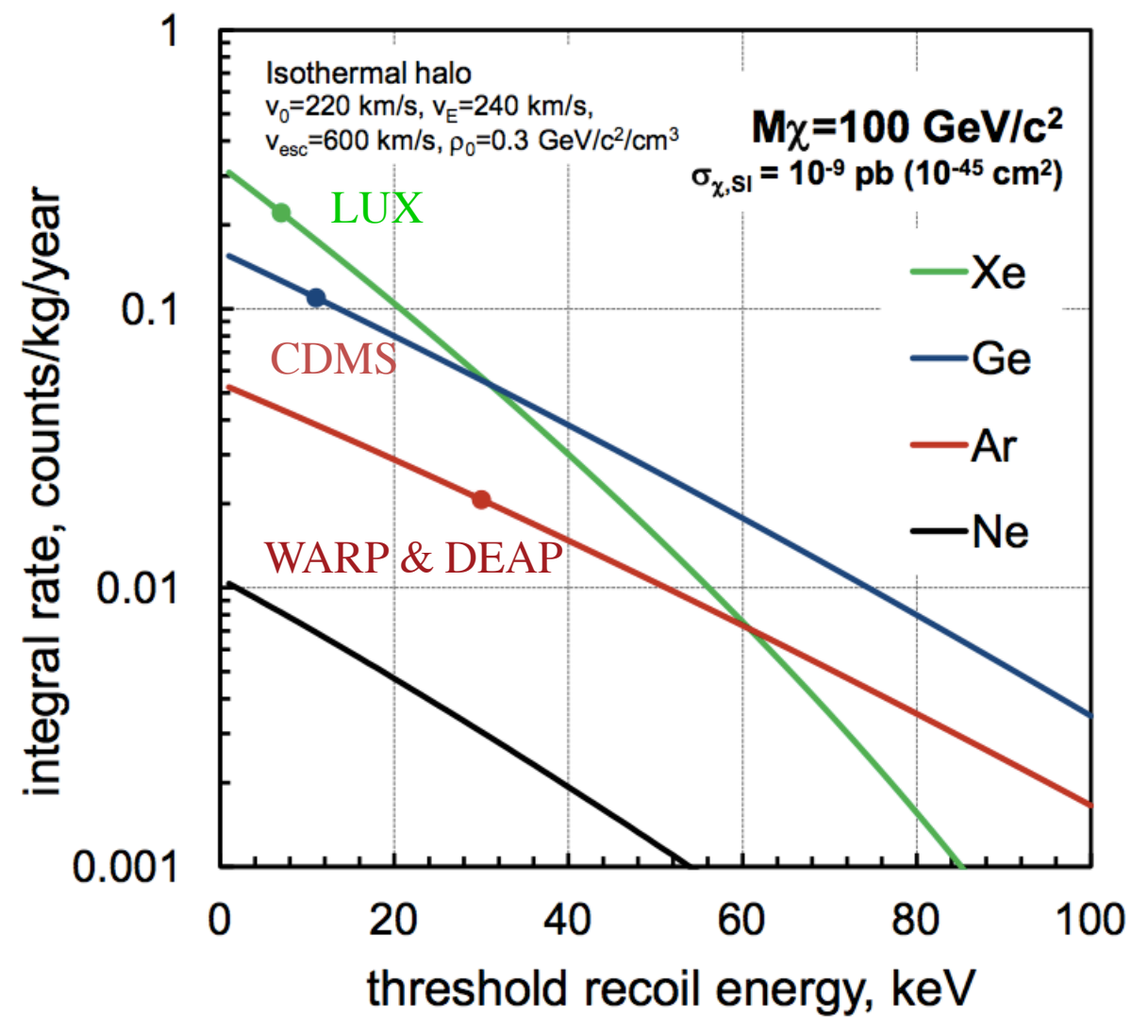
WIMP Direct Detection

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

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

Requirements:

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



The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

The LUX Collaboration

Brown

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

Case Western

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

Imperial College London

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

Lawrence Berkeley + UC Berkeley

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

Lawrence Livermore

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

LIP Coimbra

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

SD School of Mines

Xinhua Bai	PI, Professor
Tyler Liebsch	Graduate Student
Doug Tiedt	Graduate Student

SDSTA

David Taylor	Project Engineer
Mark Hanhardt	Support Scientist

Texas A&M

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

UC Davis

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

UC Santa Barbara

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

University College London

Chamkaur Ghag	PI, Lecturer
Lea Reichhart	Postdoc

Collaboration Meeting, Sanford Lab, April 2013

University of Edinburgh

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

University of Maryland

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

University of Rochester

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

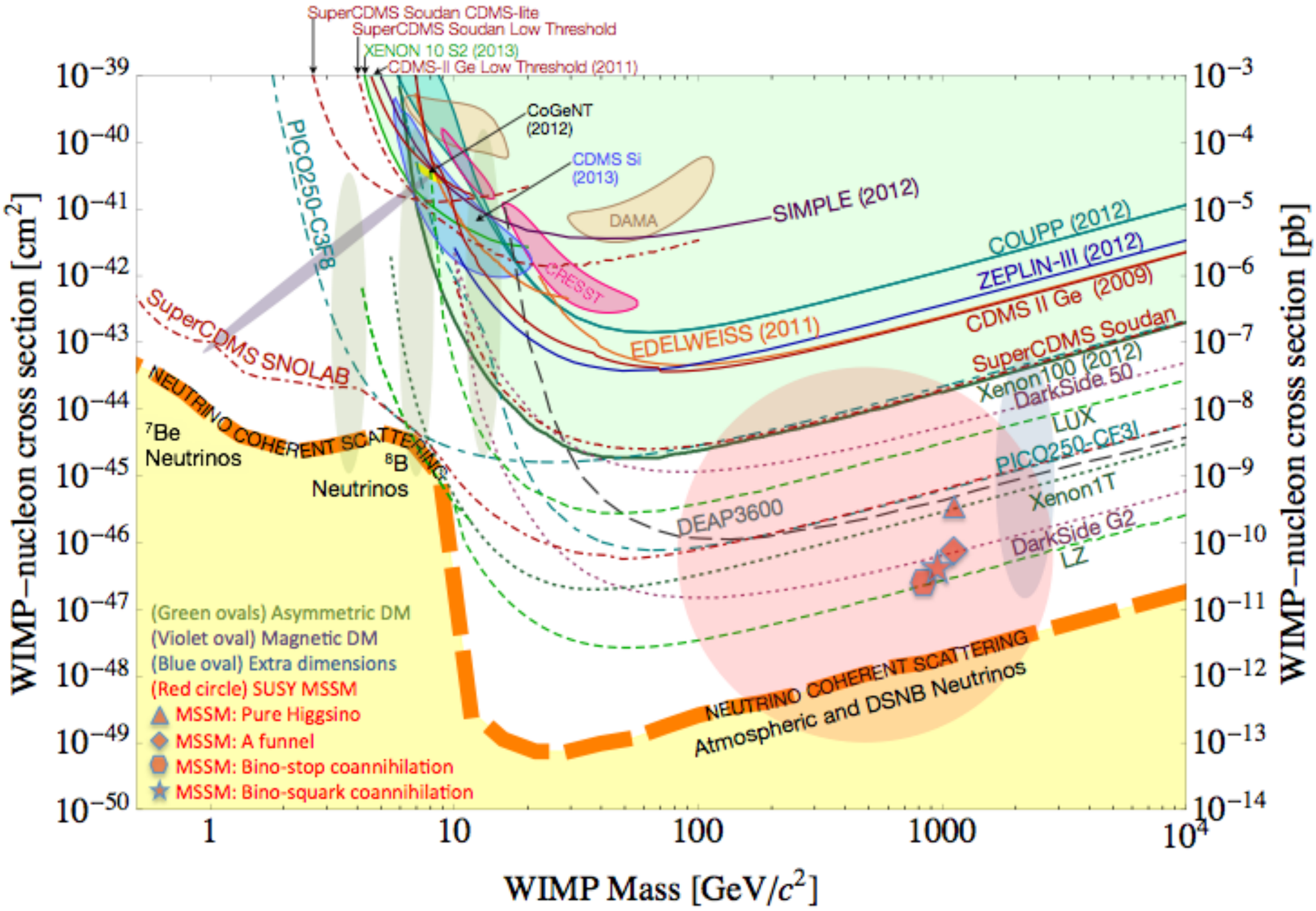
University of South Dakota

Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

Yale -> UC Berkeley

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

WIMP Cross-section Limits in 2013

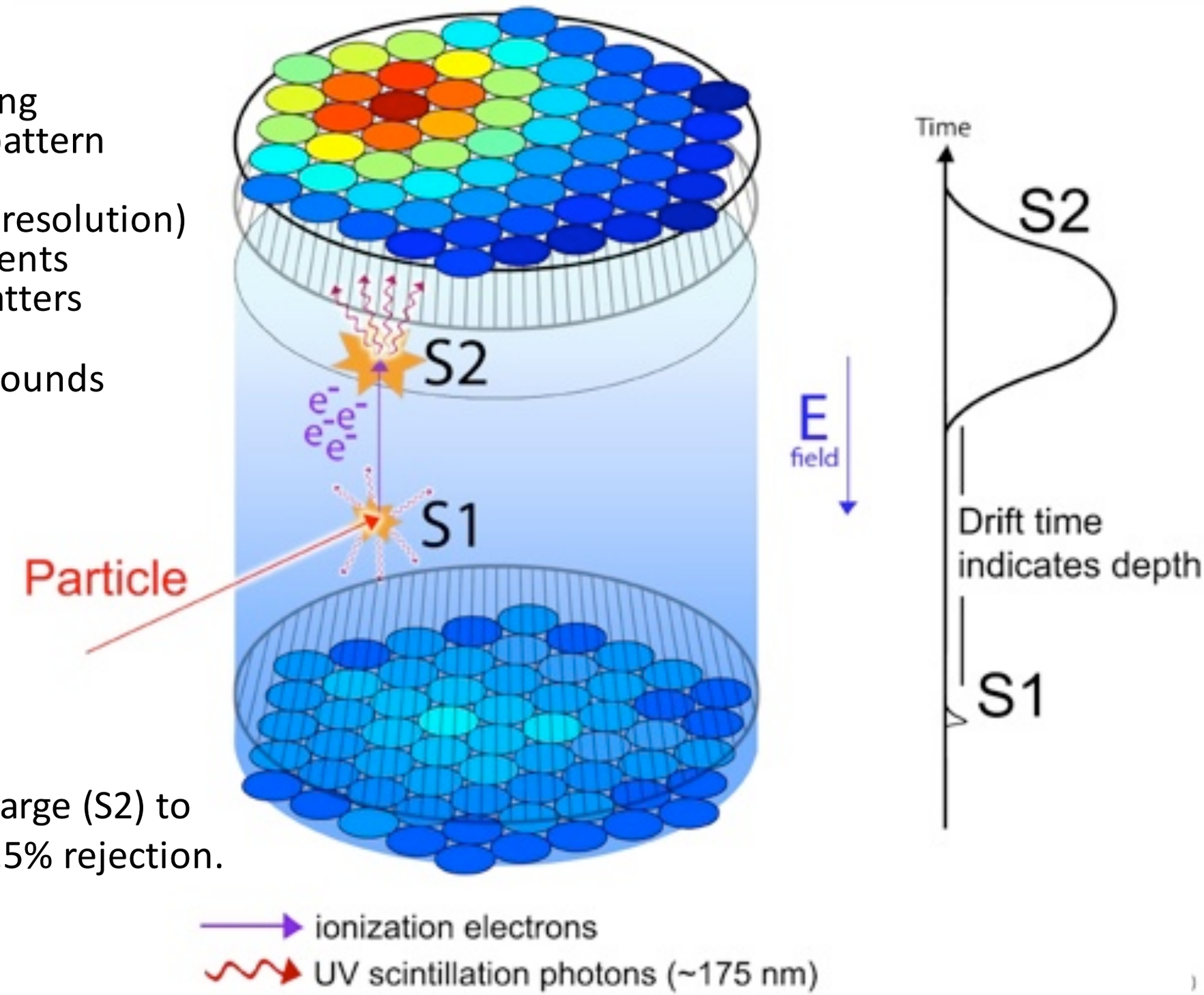


Two-phase Xenon WIMP Detectors

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

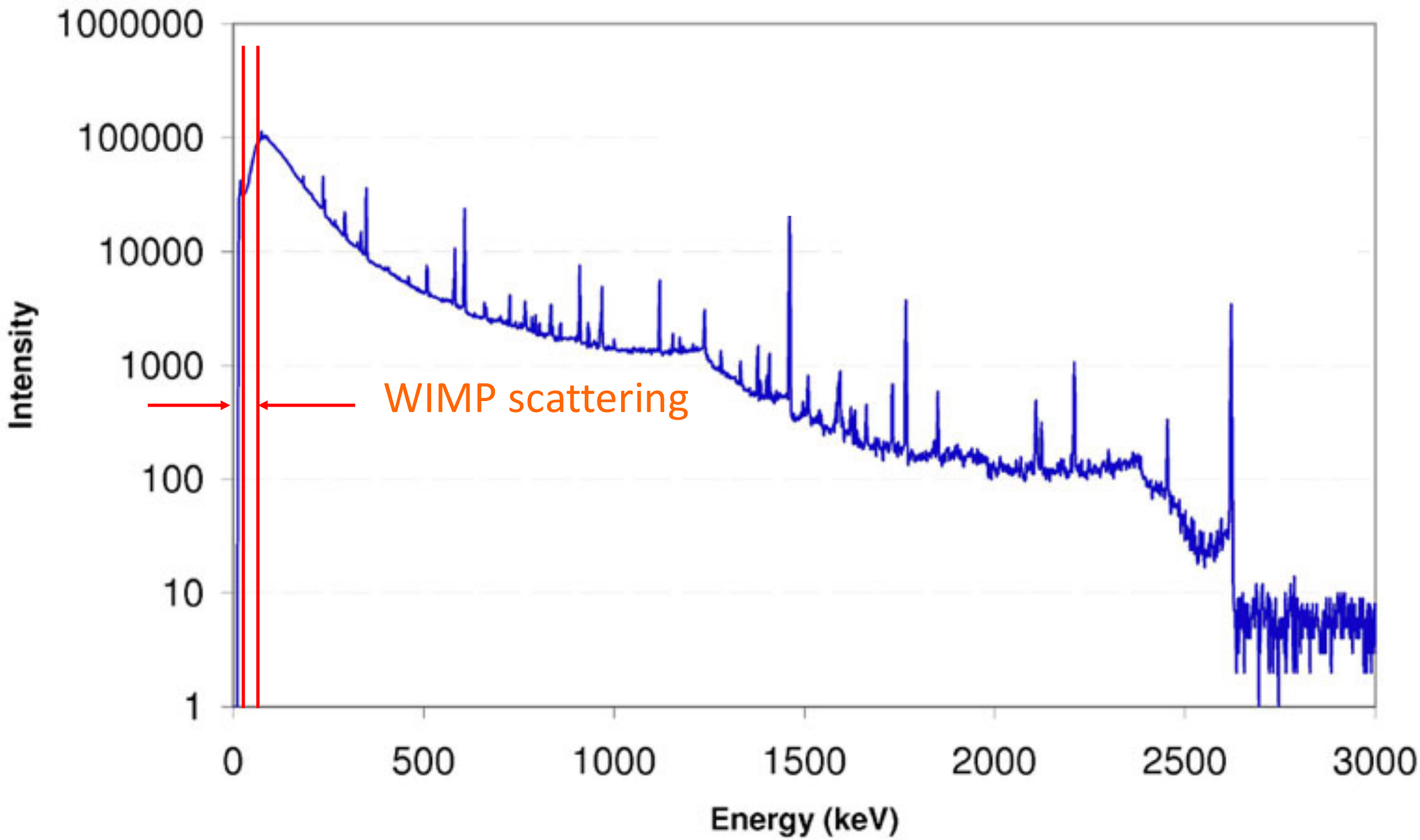
Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds reduced by self-shielding



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

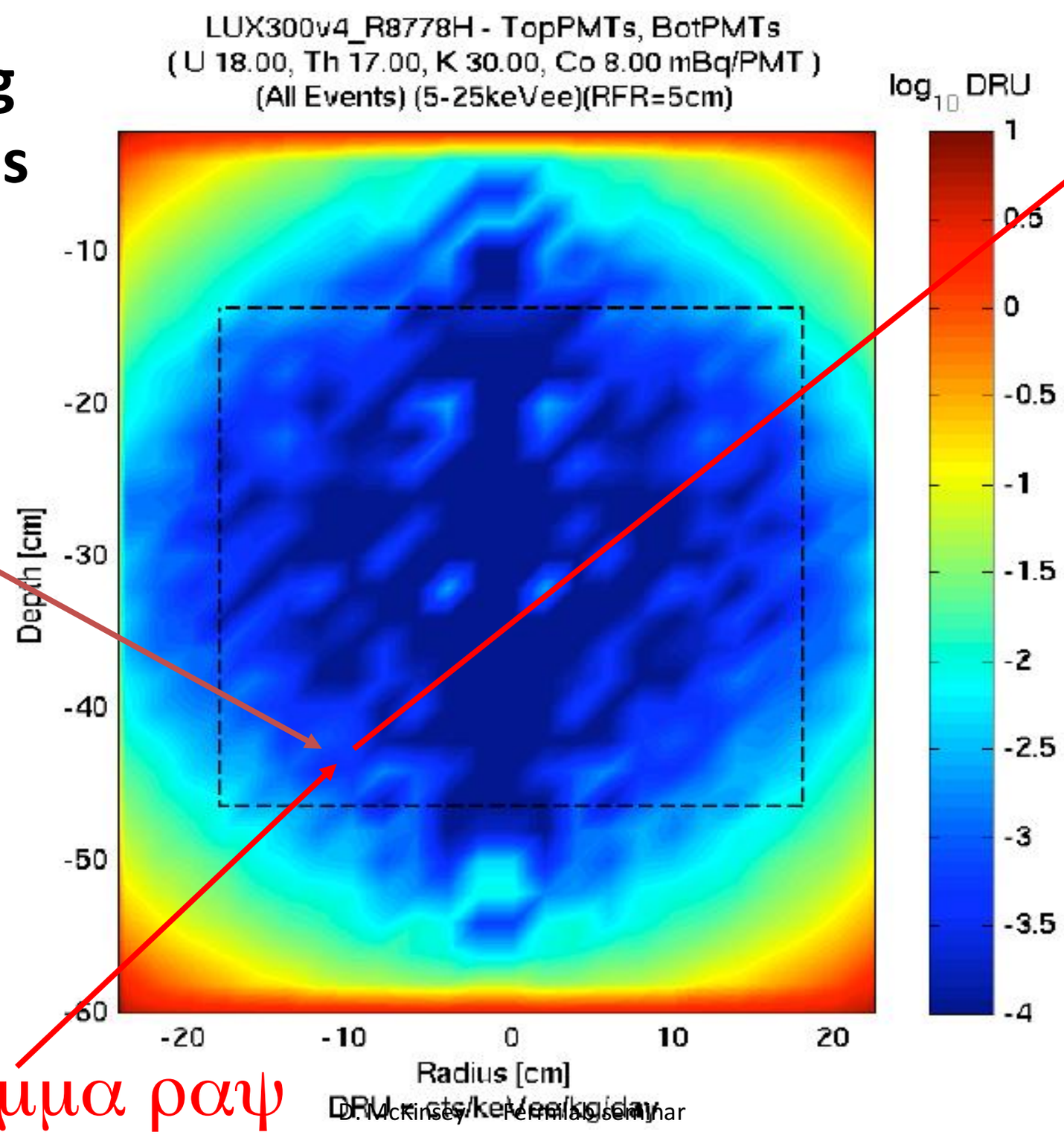
Ordinary radioactive decay here on earth



Kinematics alone provides strong rejection

Self-shielding is what makes LUX work

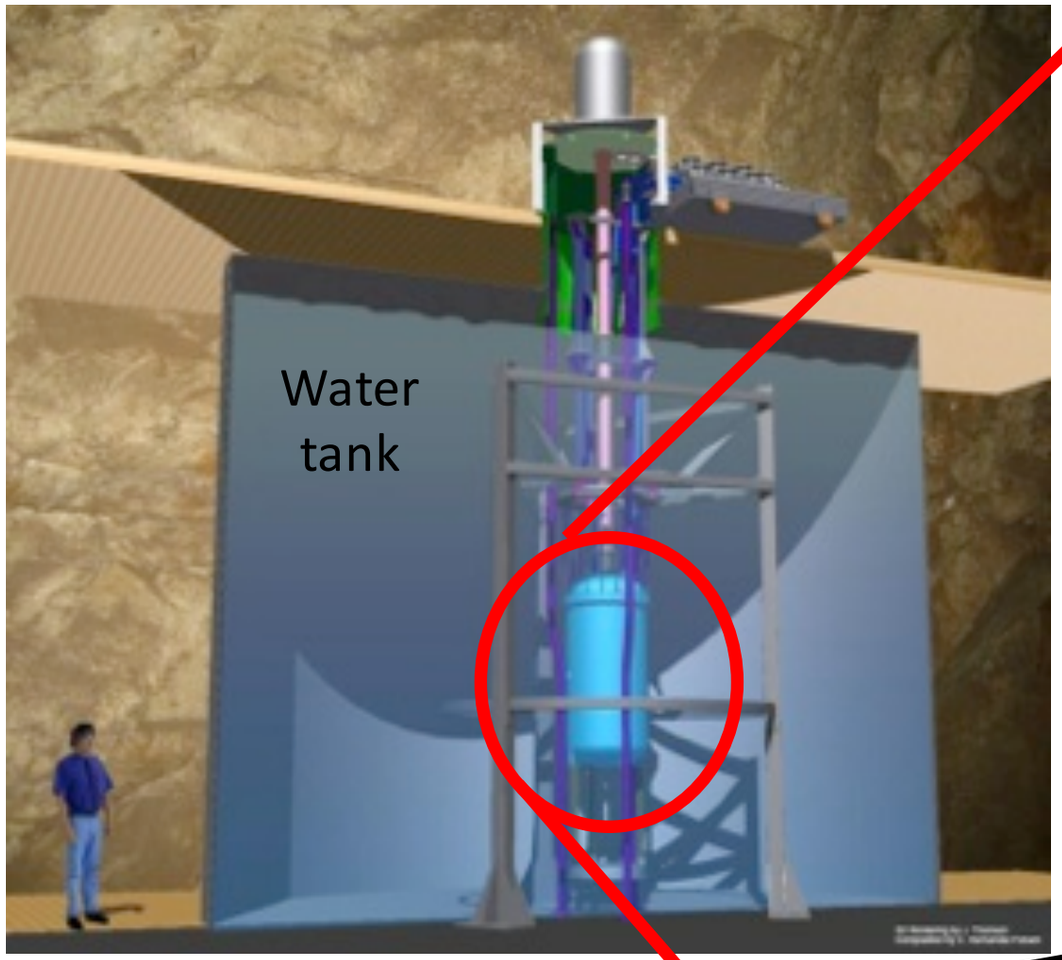
~ keV deposition

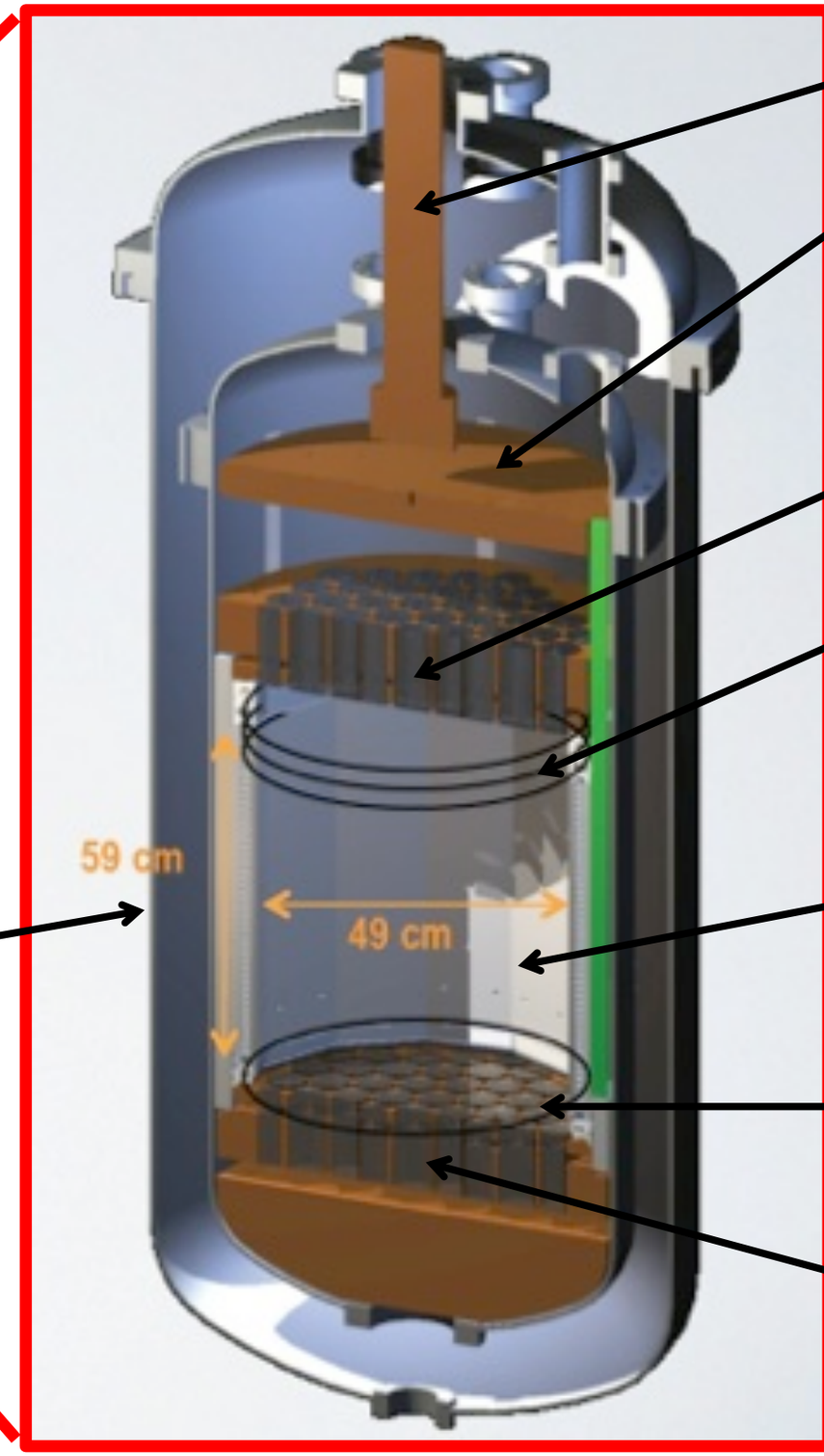


Must cross full volume without interacting again

~ MeV γαμμα ραψ

The LUX Detector





Thermosyphon

Copper shield

Top PMT array

Anode grid

PTFE reflector panels and field cage

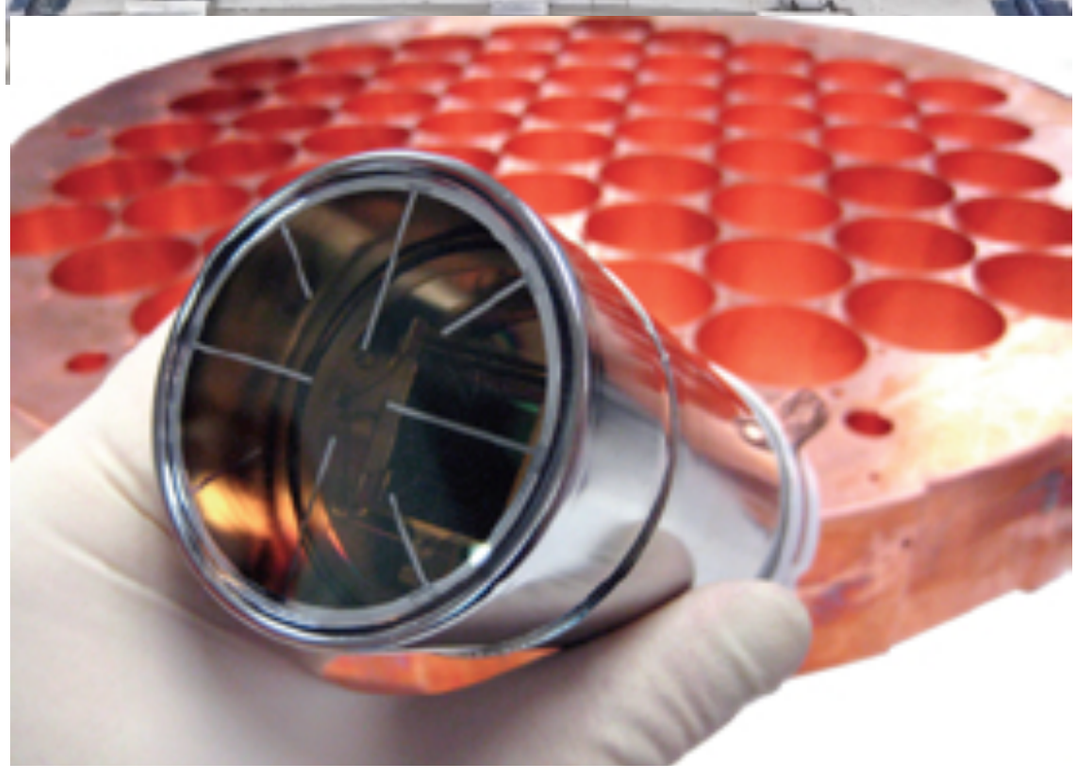
Cathode grid

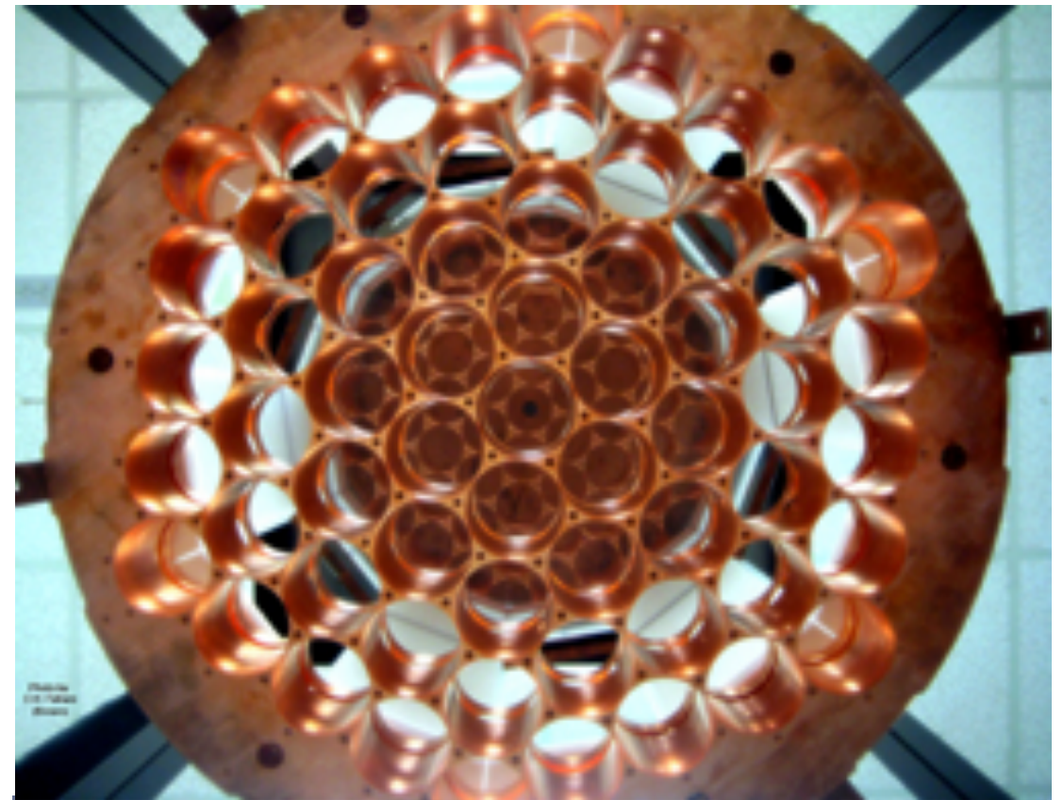
Bottom PMT array

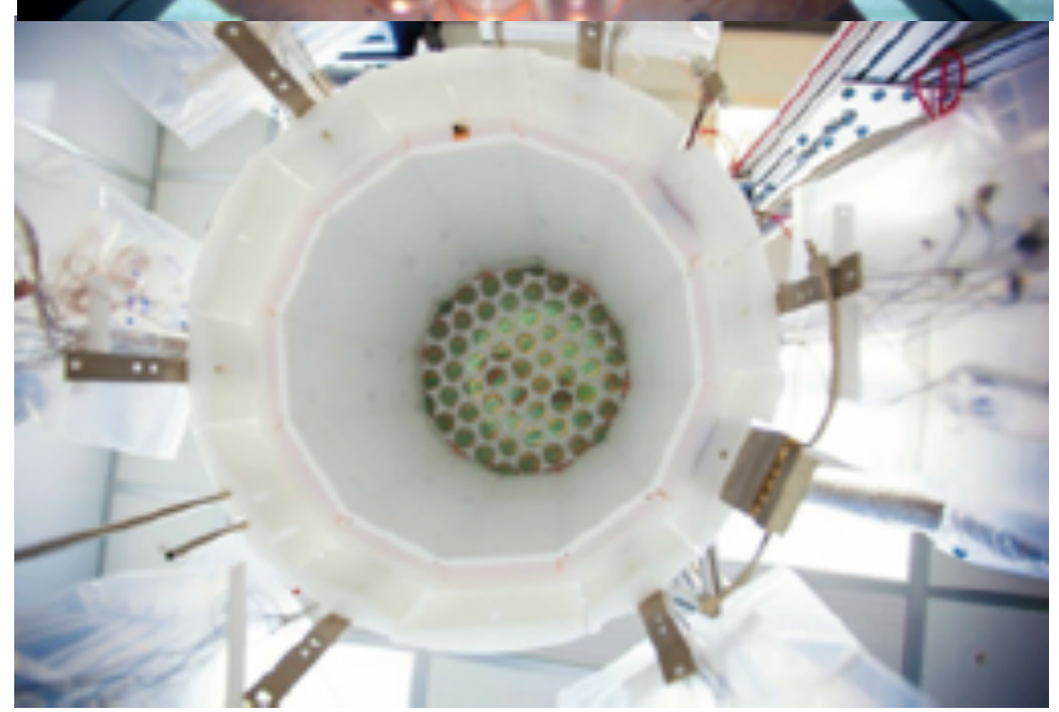
Low-radioactivity Titanium Cryostat

370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

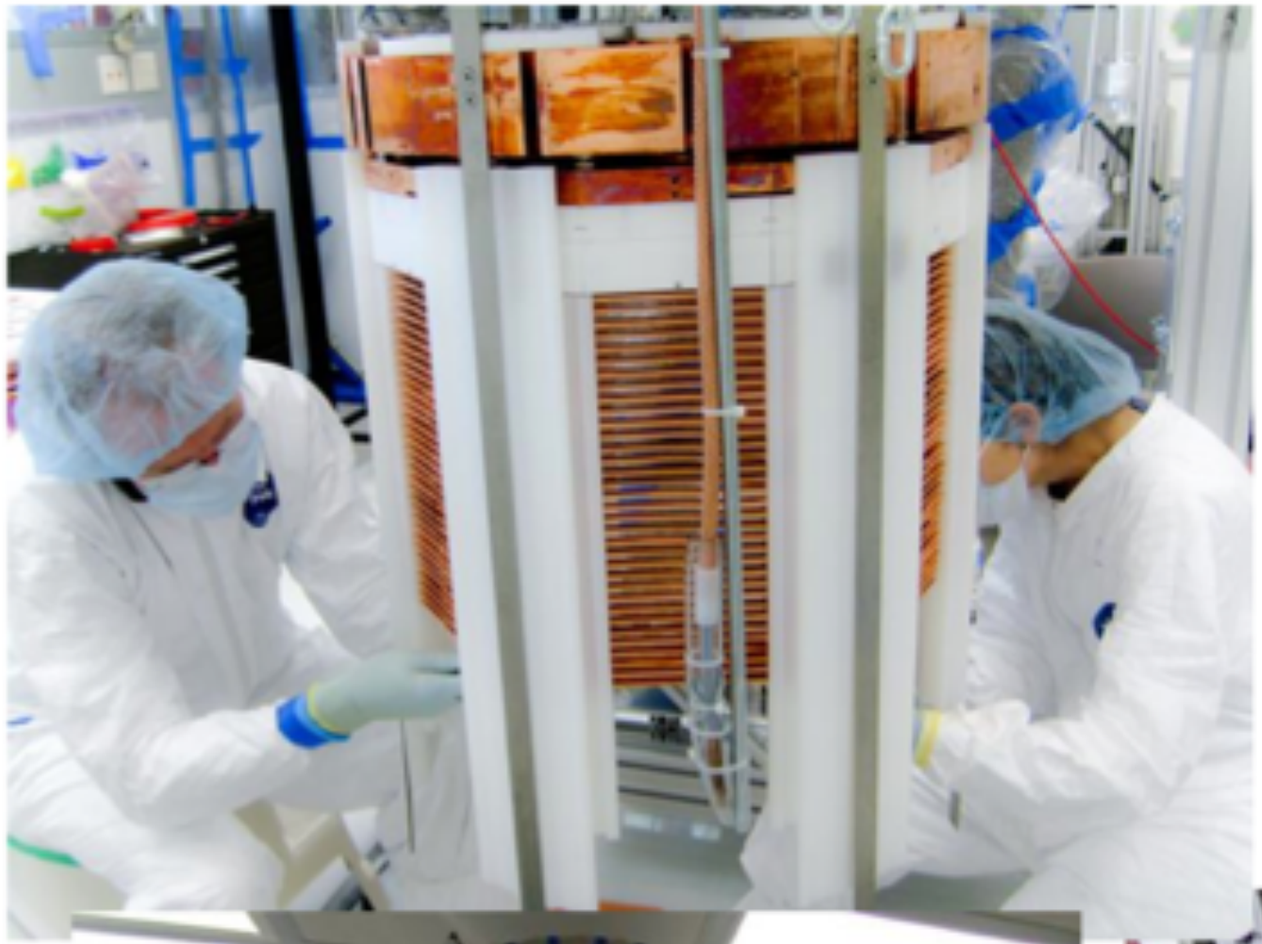
LUX – the Instrument

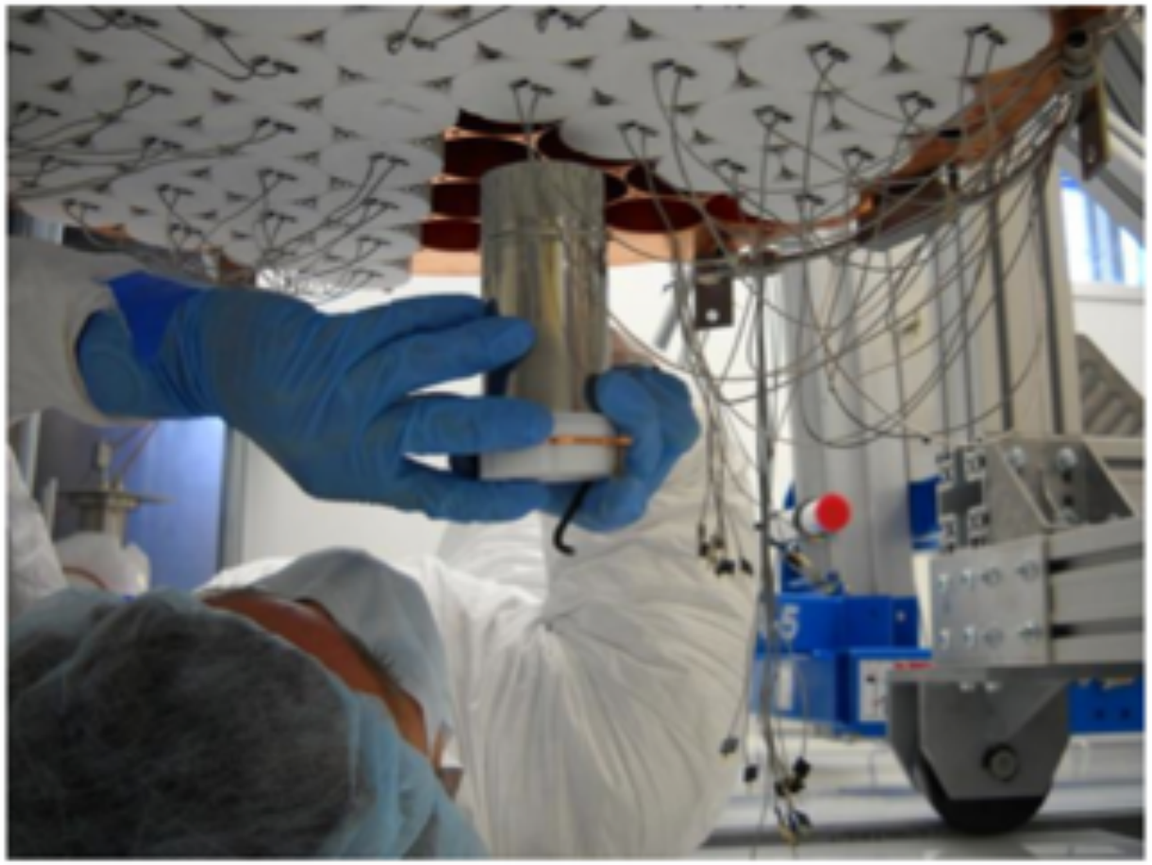






LUX Construction

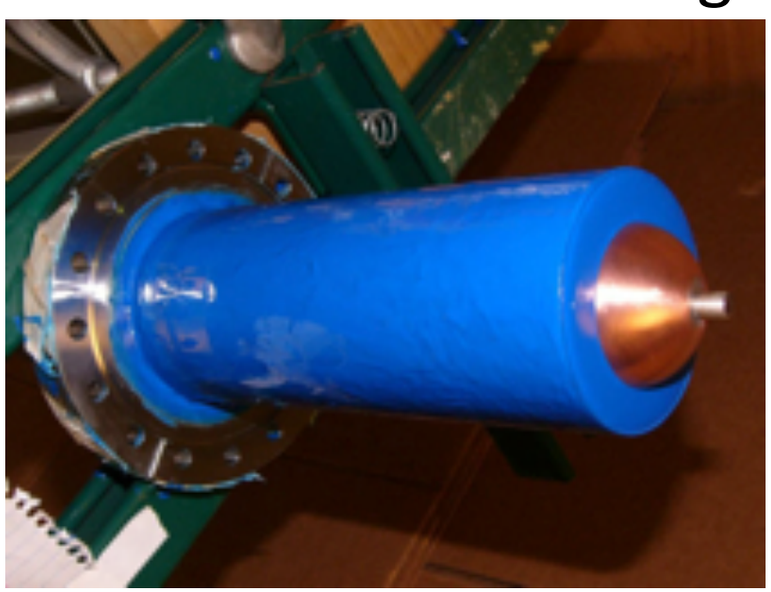




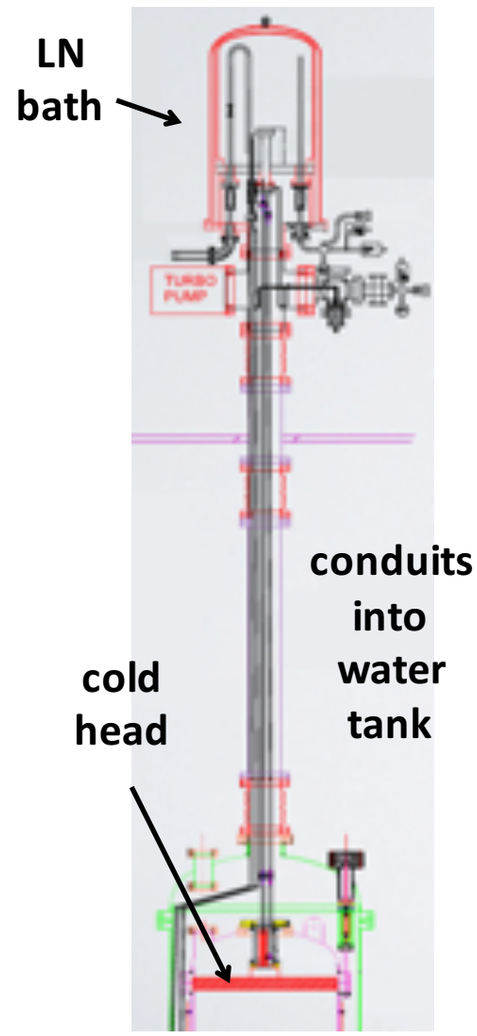
LUX – Supporting Systems

Xenon gas handling and sampling

Cathode HV feedthrough



Thermosyphon cryogenics



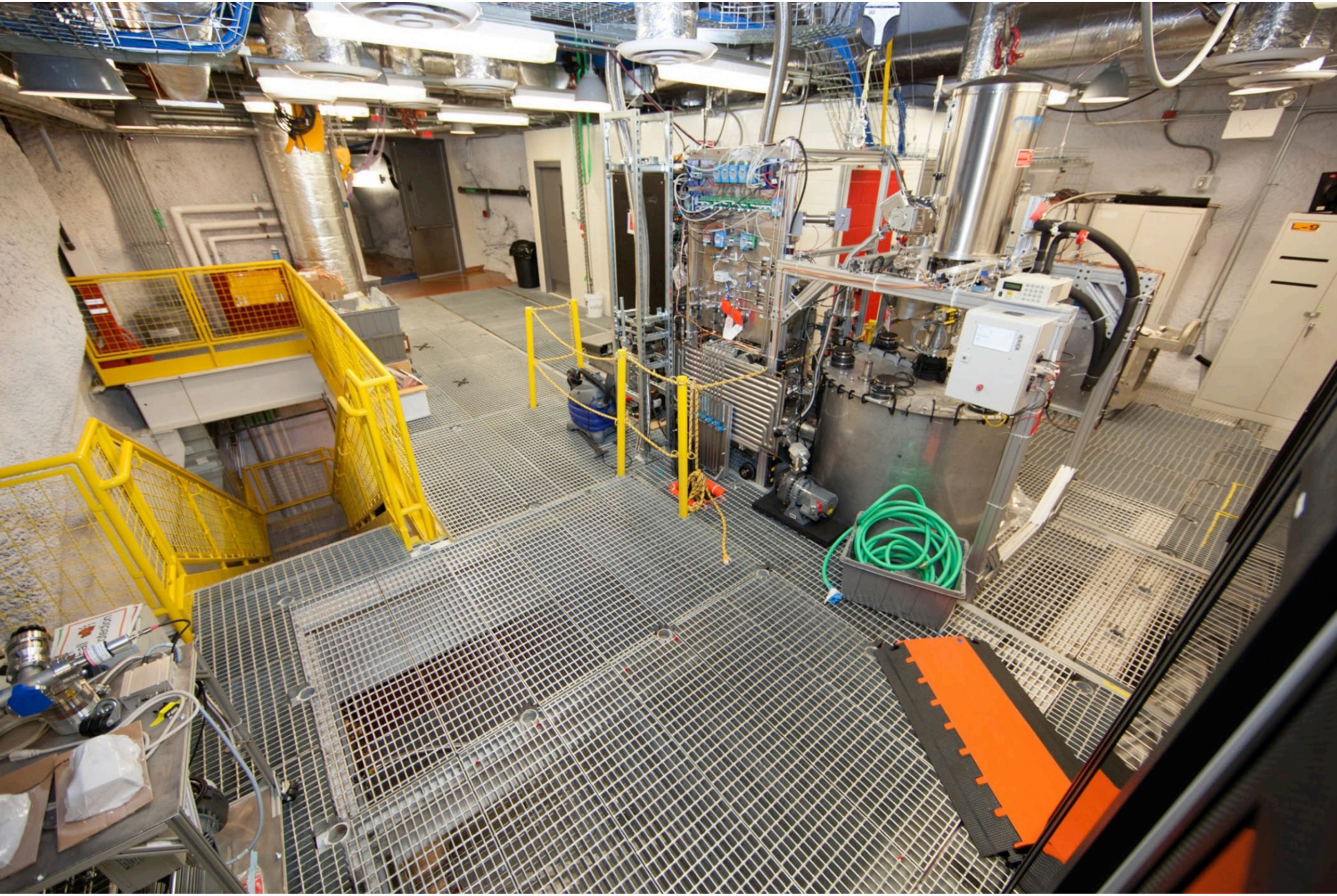
LUX Thermosyphon

Xe storage and recovery

The New Sanford Underground Research Facility

Old Homestake Mine (Hearst)
Now SURF (Sanford Underground Research Facility)
4850' underground

South Dakota



LUX installed in its water tank shield, a mile underground at SURF

LUX Timeline

LUX funded in 2008 by DOE and NSF

Above-ground laboratory completed at SURF in 2011

LUX assembled; above-ground commissioning runs completed

Underground laboratory completed at SURF in 2012.

LUX moves underground in July to its new home in the Davis cavern.

Detector cooldown and gas phase testing completed early February 2013

Xenon condensation completed mid February 2013

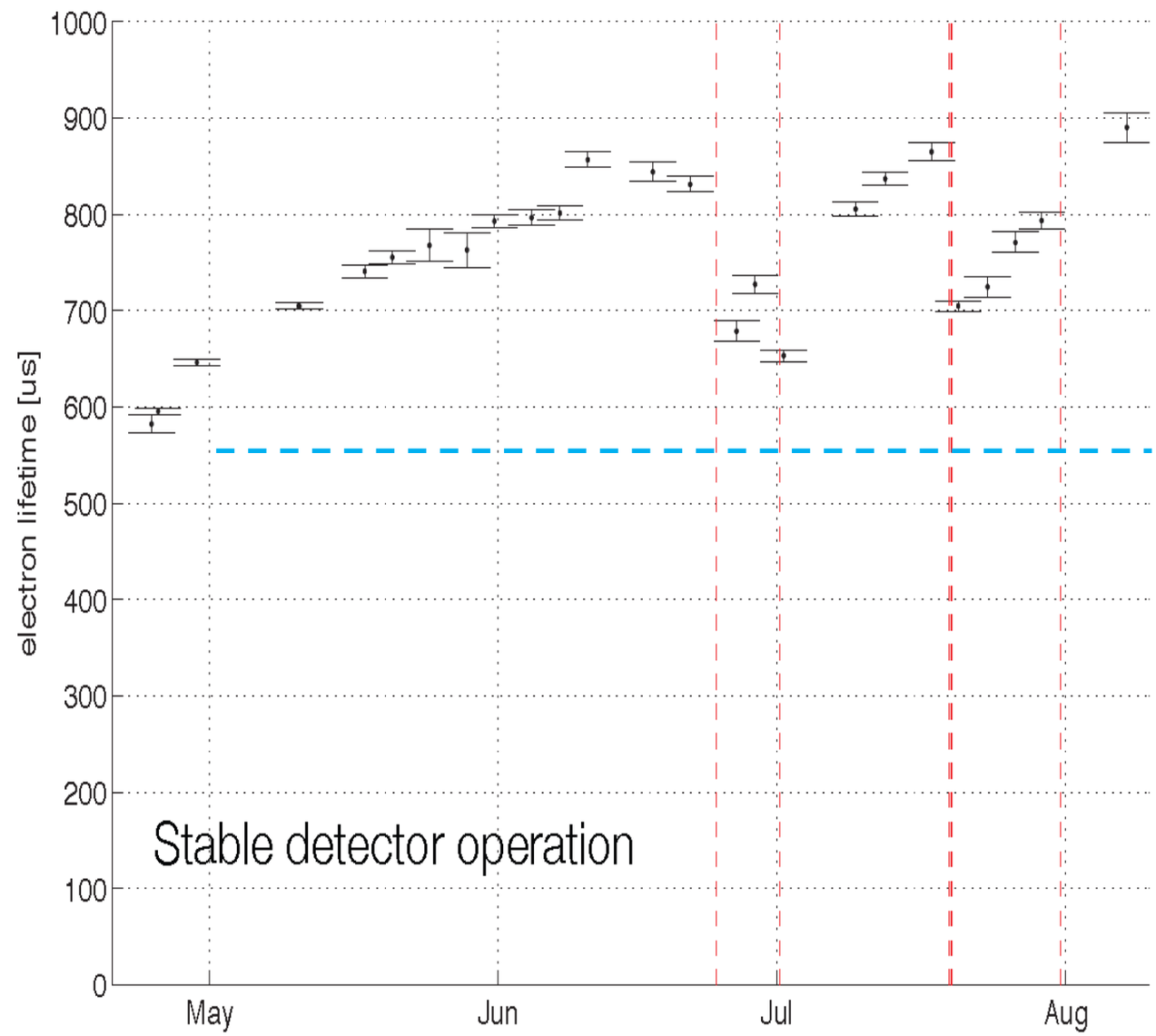
Detector commissioning completed April 2013

Initial (3-month) WIMP search. First results presented October 2013!

Full year-long WIMP search began in 2014. Result in 2016.

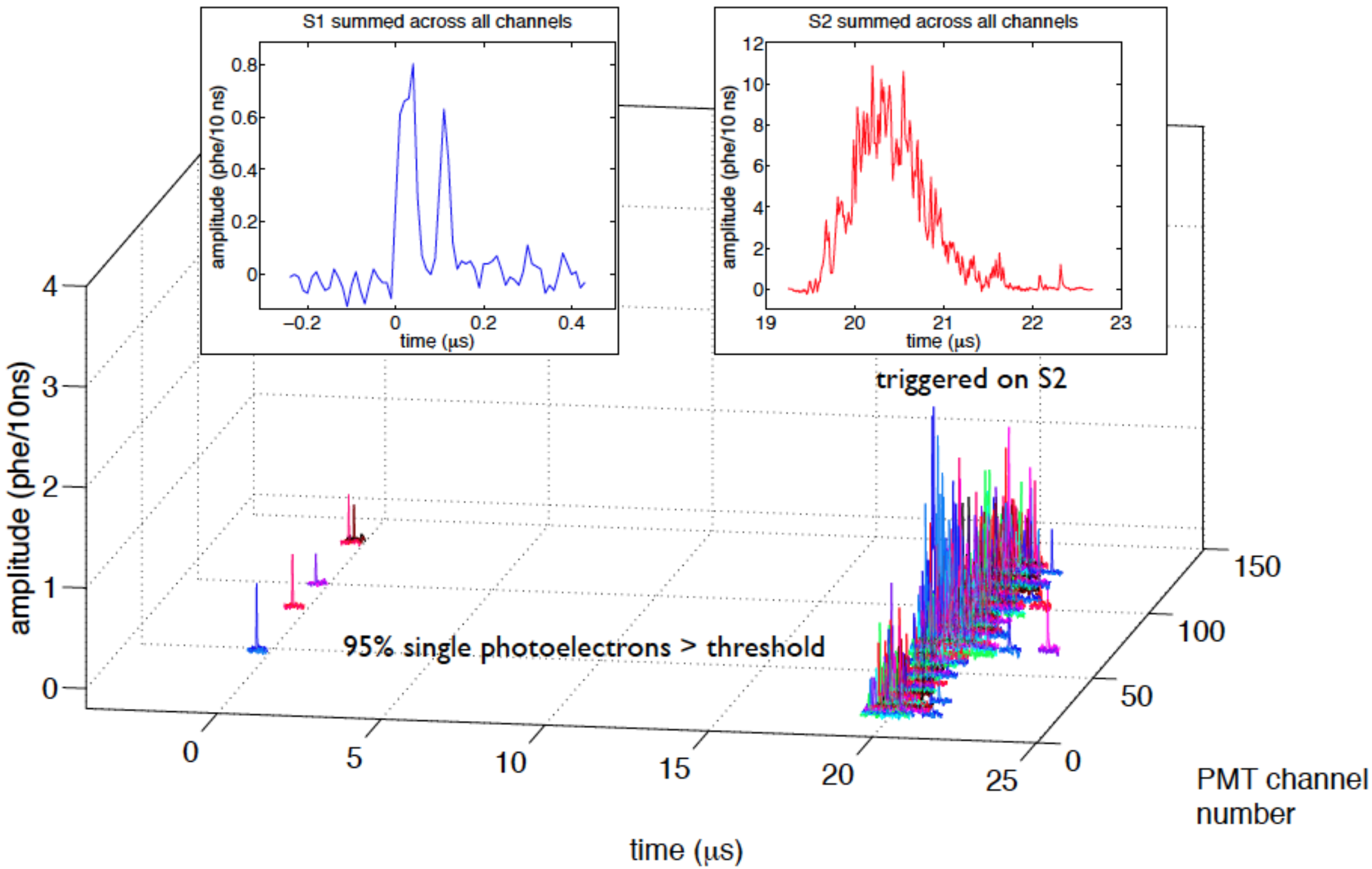
LUX - Run Parameters Overview

- Xenon Purity: electron drift length 87 – 135 cm during Run 3
  - Circulation at 250 kg / day
  - Monitored weekly using ^{83m}Kr data
- Light collection efficiency: 14%
  - Incl. geometry and PMT QE
  - ^{83m}Kr data provides 3D corrections
- Drift field: 181 V/cm
  - Drift speed 1.51 ± 0.01 mm / ms
  - ER discrimination 99.6%
- Electron extraction efficiency: 64%
- Fiducial mass: 118.3 ± 6.5 kg
  - Defined by background from edges
  - Measured with homogeneous ER calibration data… ^{83m}Kr, again!



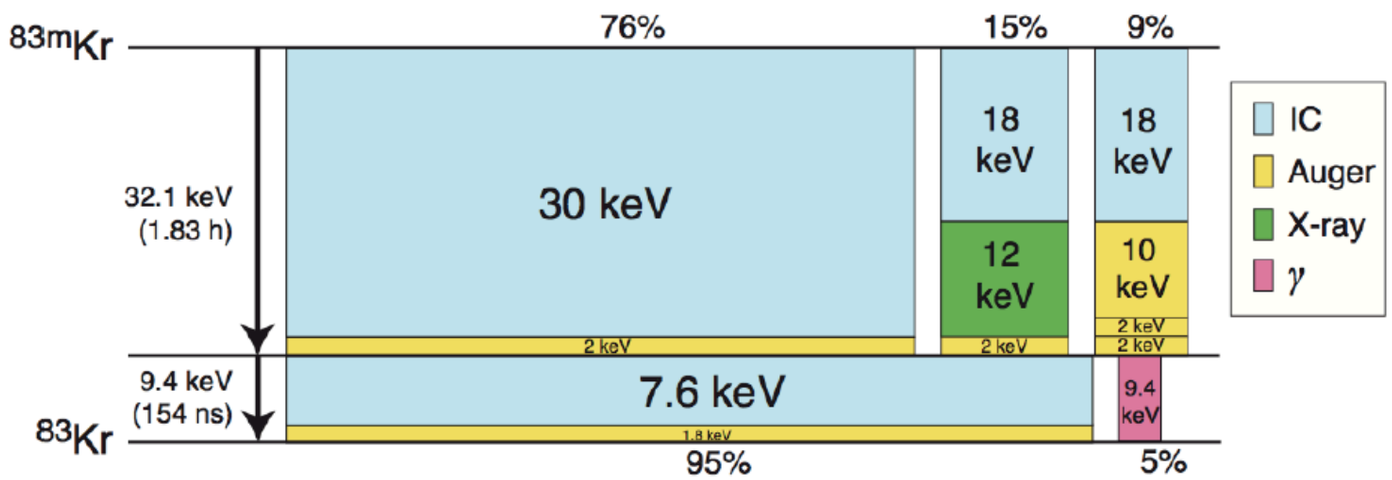
Typical Event in LUX

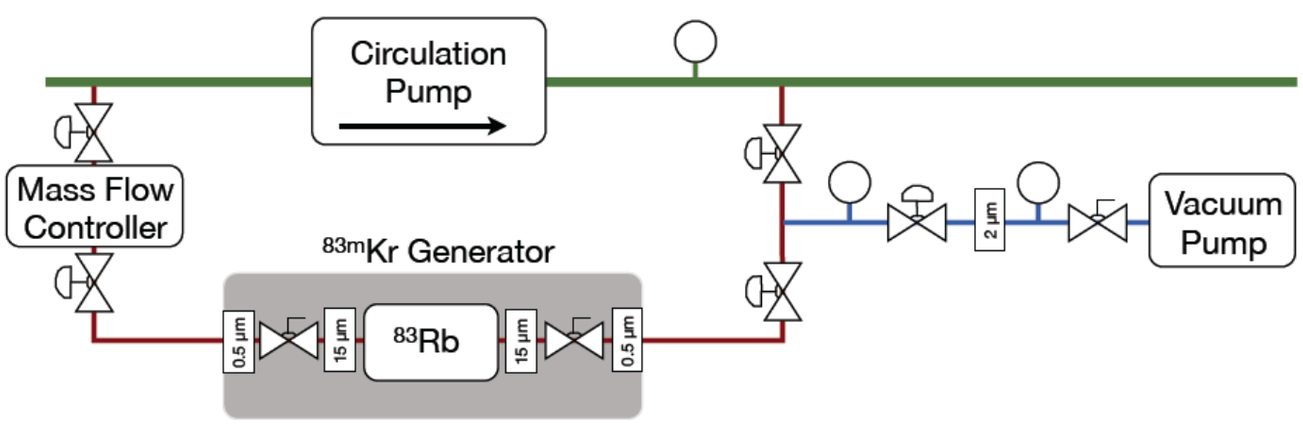
1.5 keV gamma ray scattering event



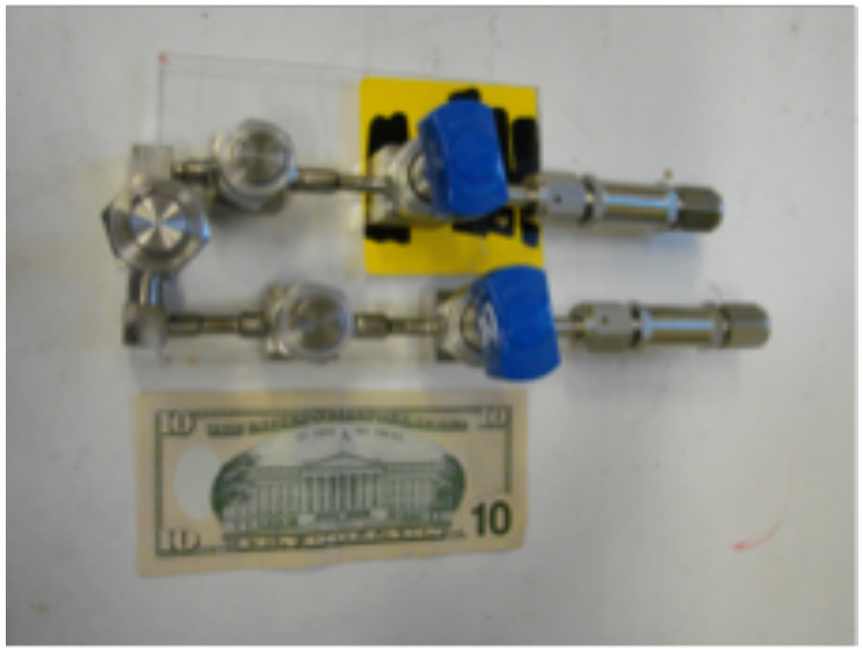
Kr-83m Calibration

- Rb-83 produces Kr-83m when it decays; this krypton gas can then be flushed into the LUX gas system to calibrate the detector as a function of position.
- Provides reliable, efficient, homogeneous calibration of both S1 and S2 signals, which then decays away in a few hours, restoring low-background operation.
- First used in liquid nobles by the McKinsey group:
  - see L. Kastens et al, Phys. Rev. C **80**, 045809 (2009) and Journal of Instrumentation **5**, P05006 (2010).

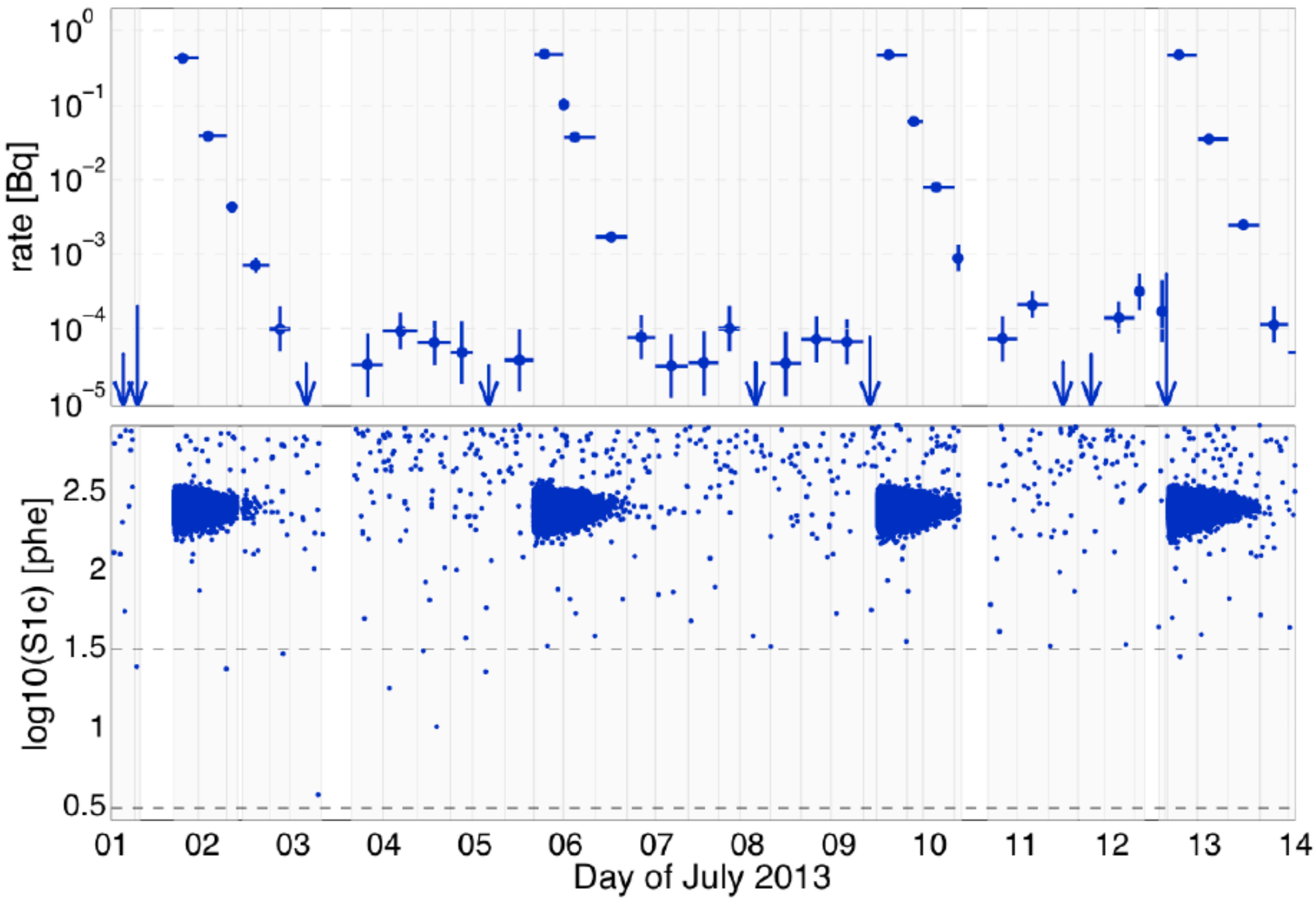




Kr-83m source (Rb-83 coated on charcoal, within xenon gas plumbing)



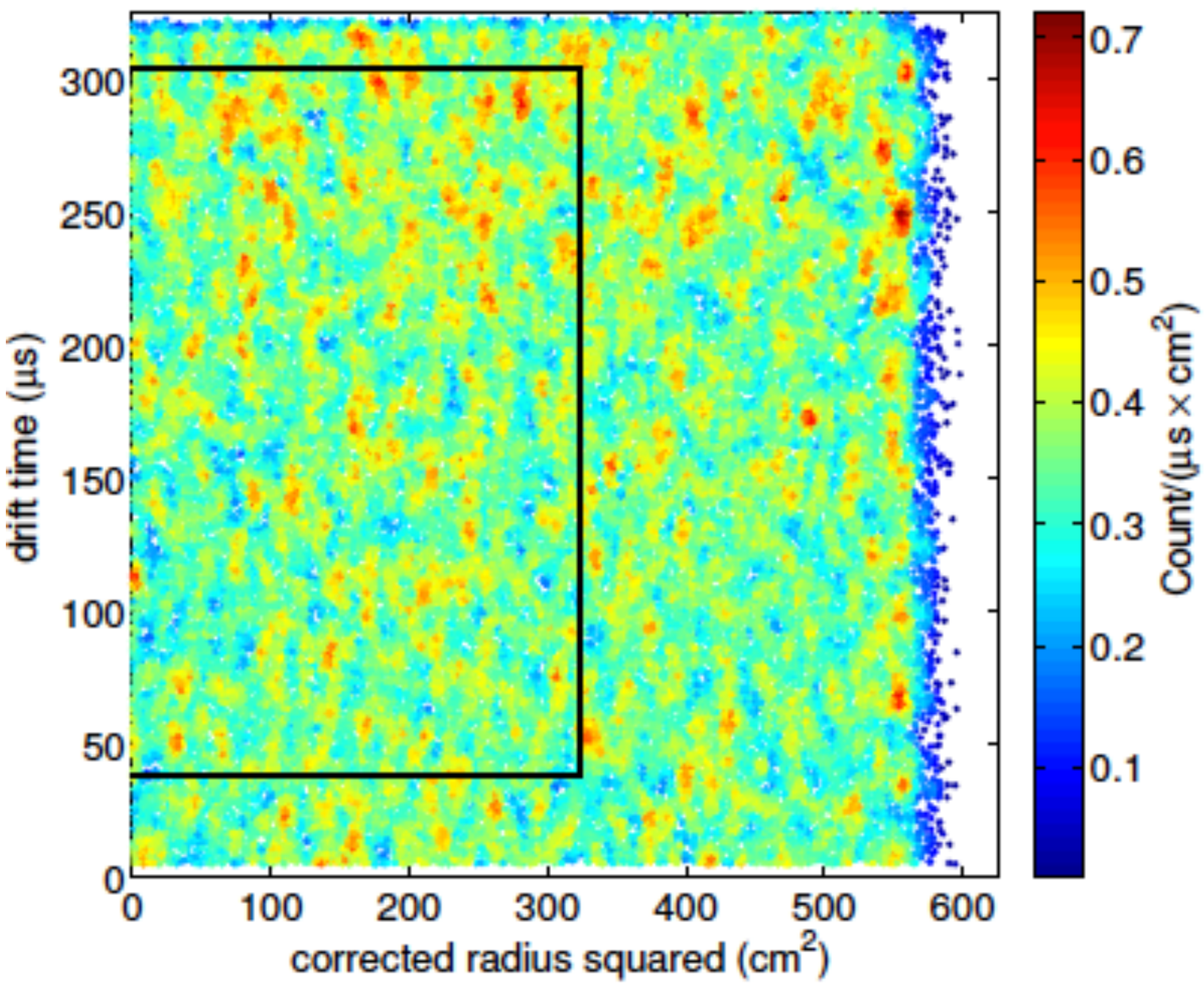
Repeated, frequent use of Kr-83m



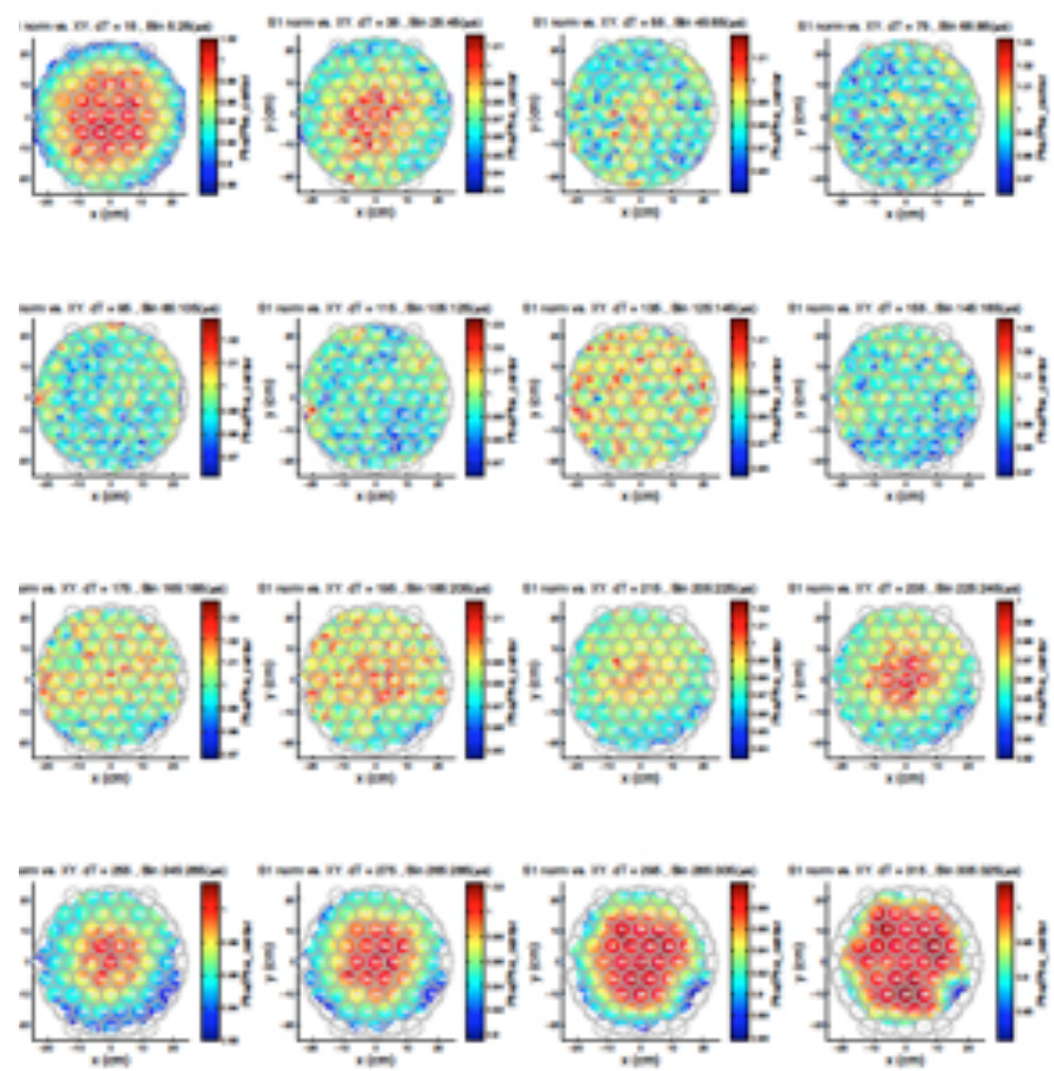
Kr-83m Calibration

- Over 1 million Kr-83m events, spread uniformly through the detector.

Fiducial volume determination

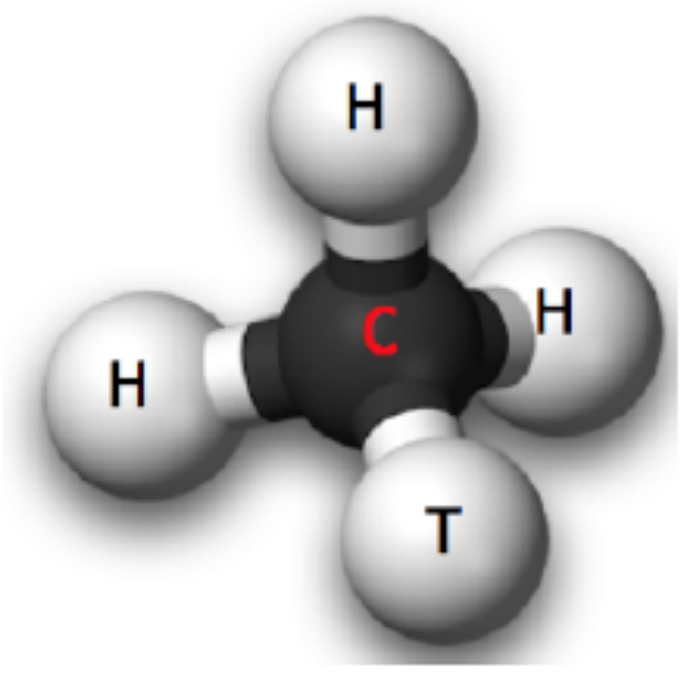


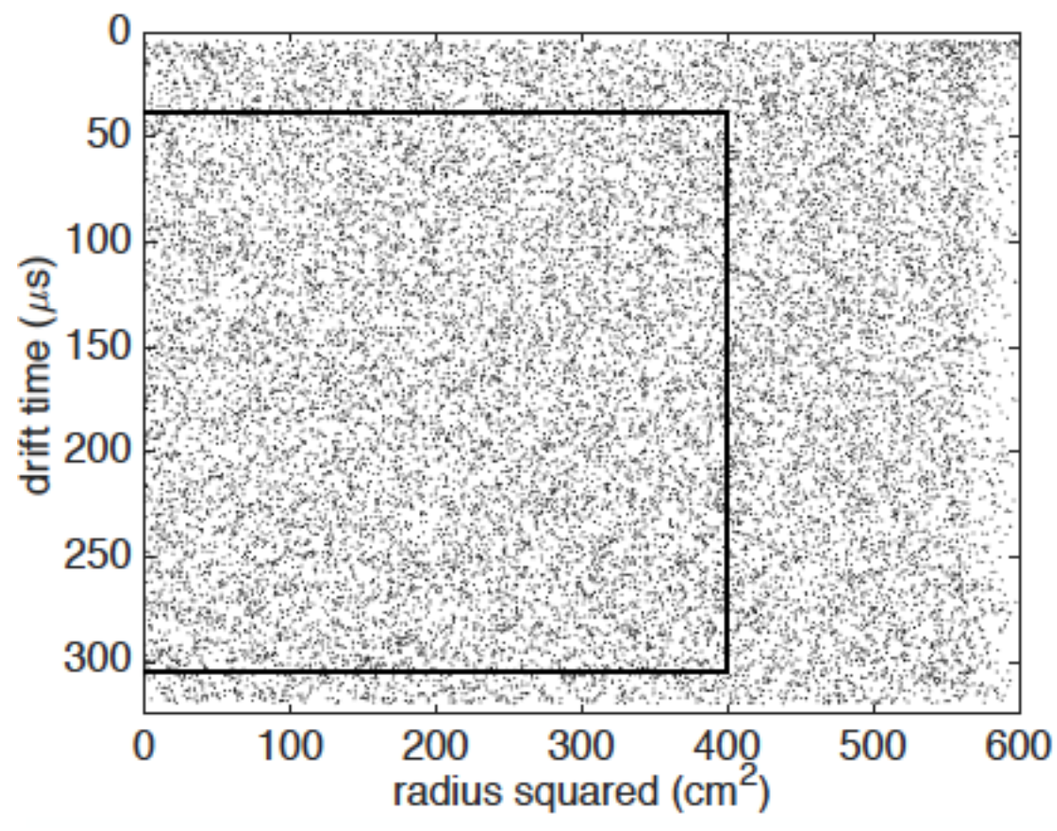
Position-based S1 corrections



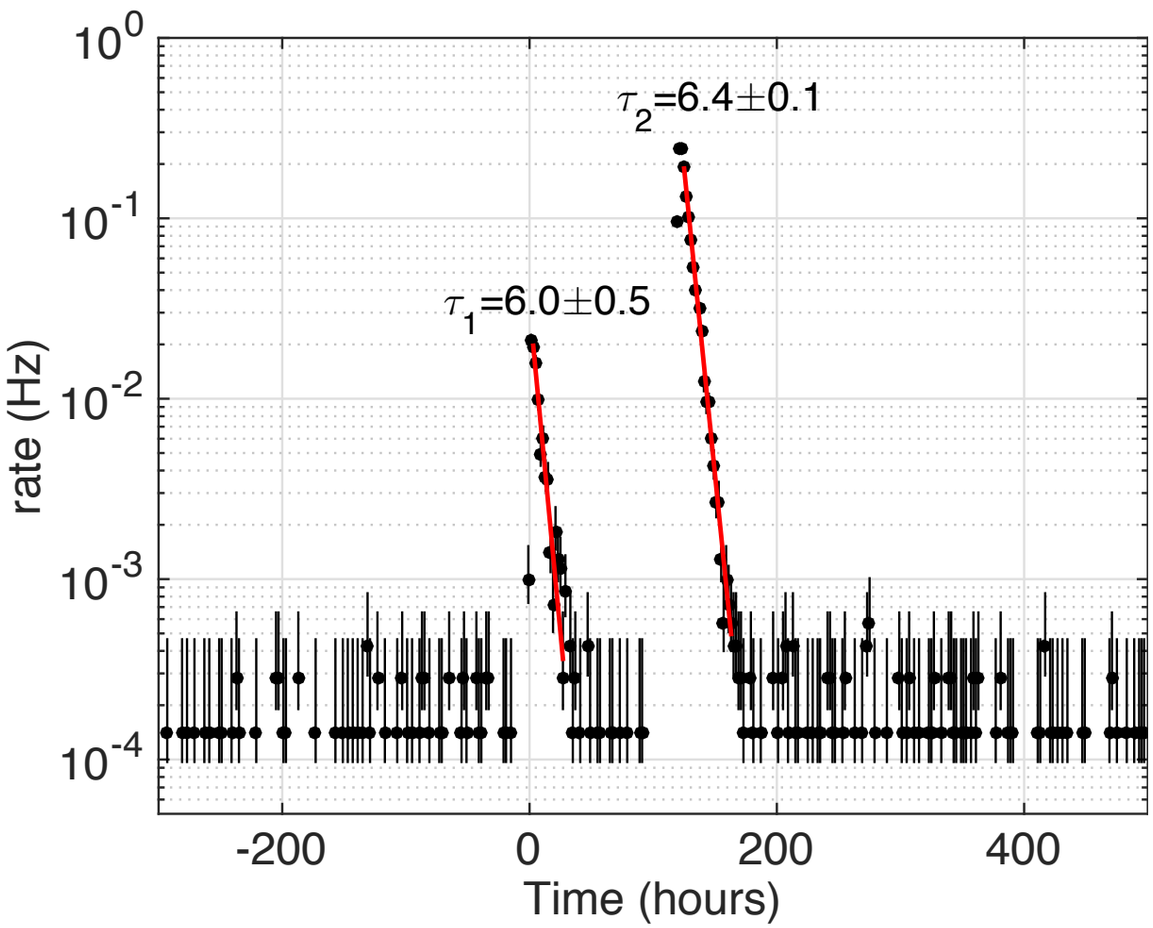
Tritiated Methane Calibration

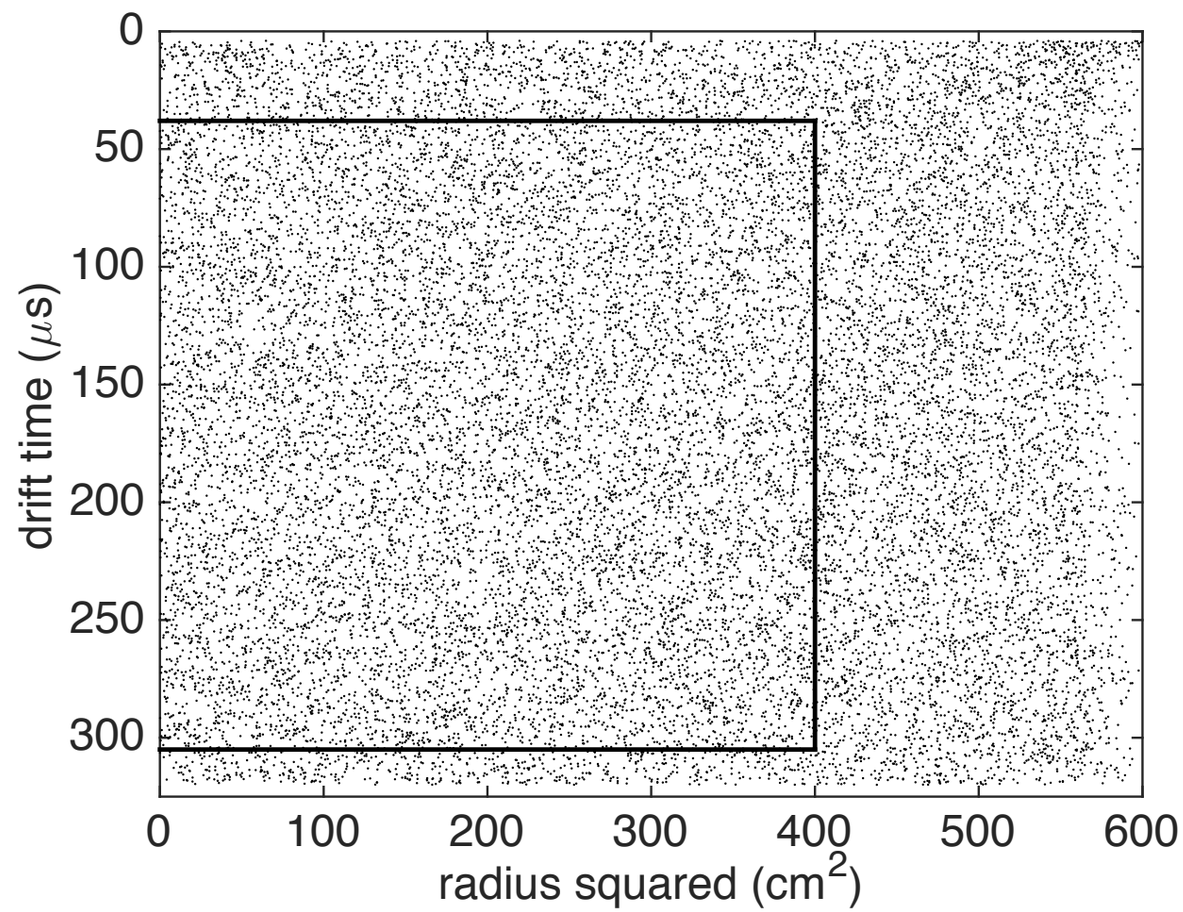
- LUX uses tritiated methane, doped into the detector, to accurately calibrate the efficiency of background rejection.
- This beta source (endpoint energy 18 keV) allows electron recoil S2/S1 band calibration with unprecedented accuracy
- The tritiated methane is then fully removed by circulating the xenon through the getter
- Parametrization of the electron recoil band from the high-statistics tritiated methane data is then used to characterize the background model.



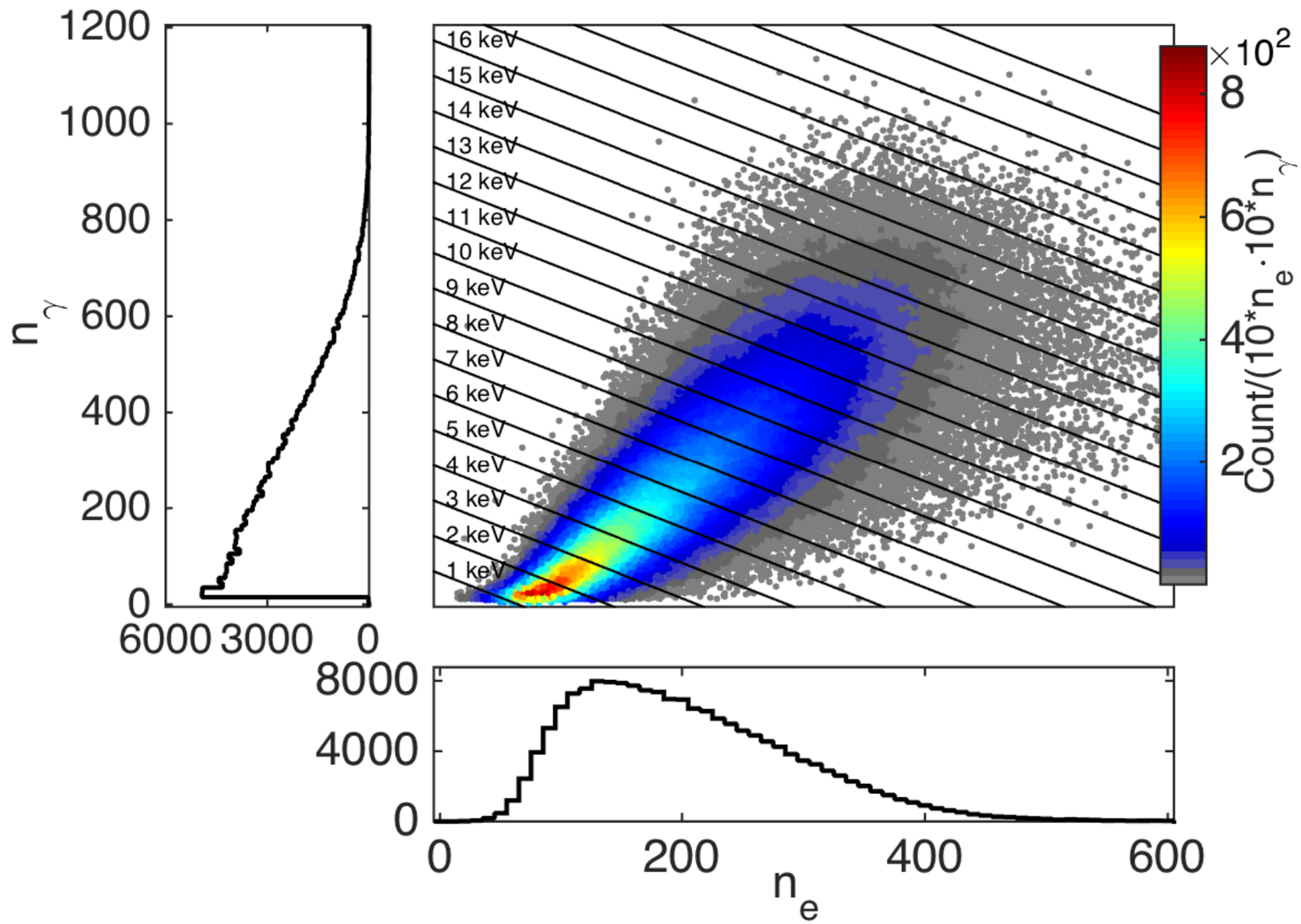


Tritiated Methane injection



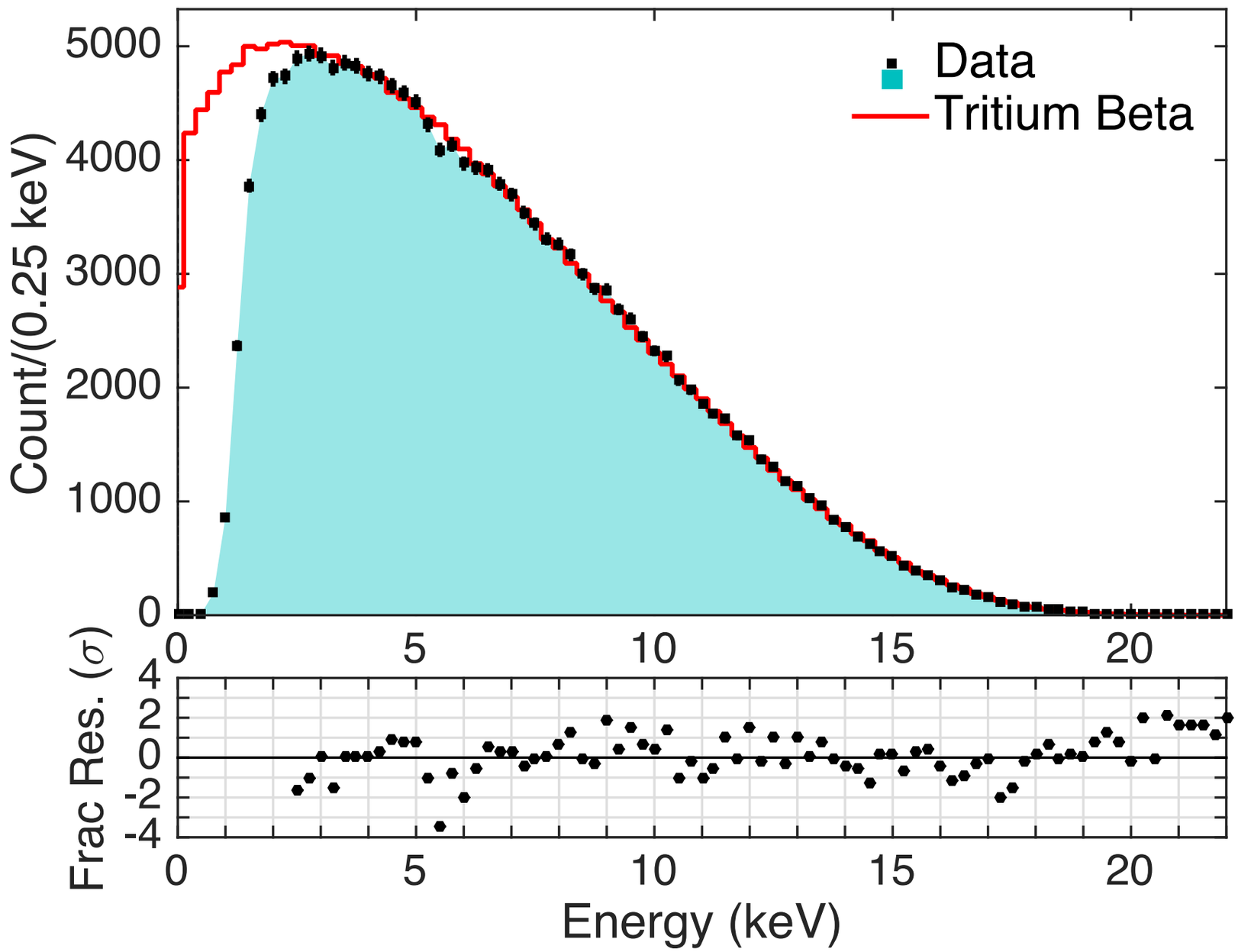


Tritium beta decay measured in both light and charge



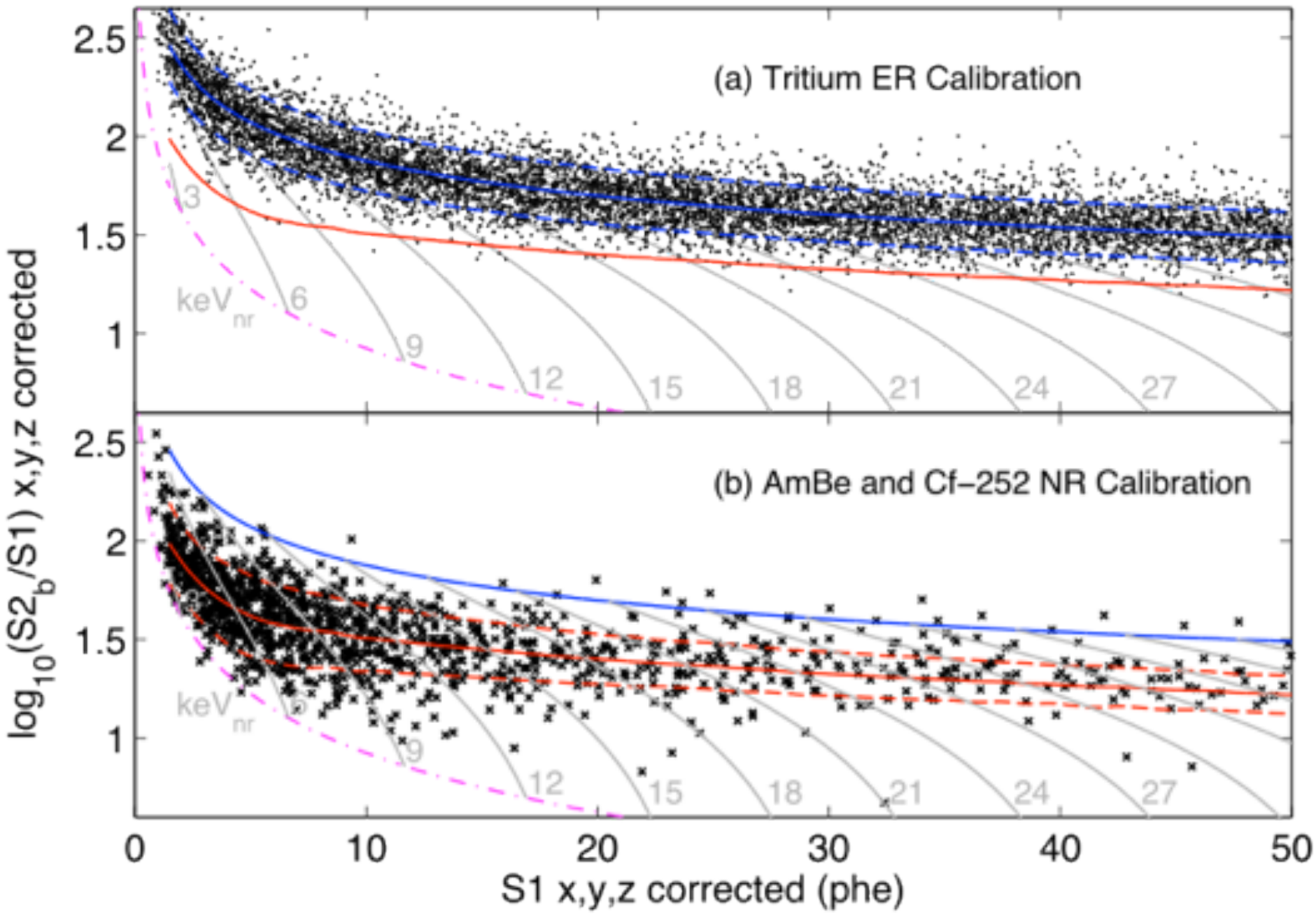
Tritium combined energy spectrum

$$E = W(n_\gamma + n_e) = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$



Electron Recoil and Nuclear Recoil Bands

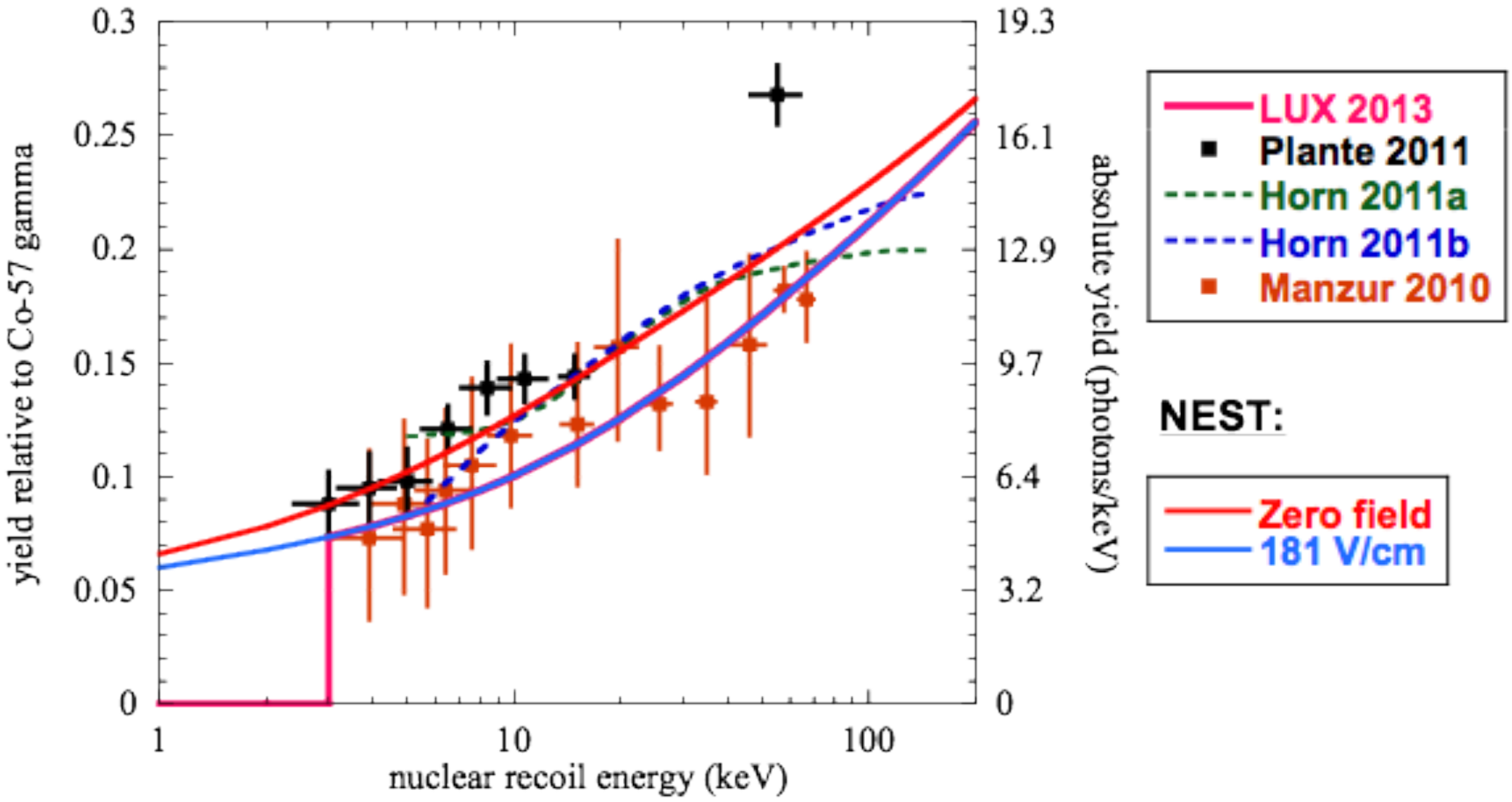
Tritium provides very high statistics electron recoil calibration (200 events/phe)
Neutron calibration is consistent with NEST + simulations



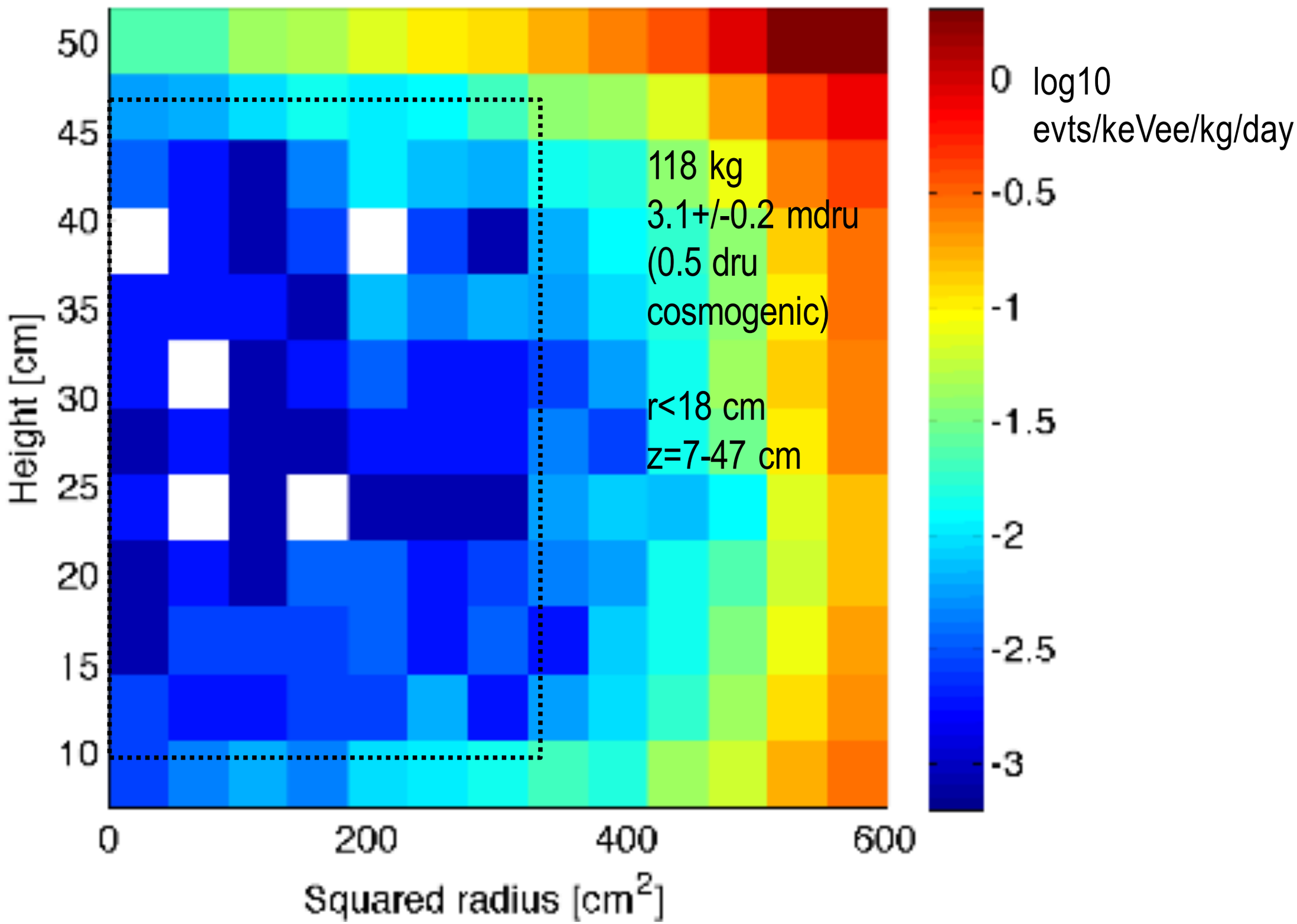
Gray contours indicate constant energies using a S1-S2 combined energy scale

Light and Charge Yields in LUX

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

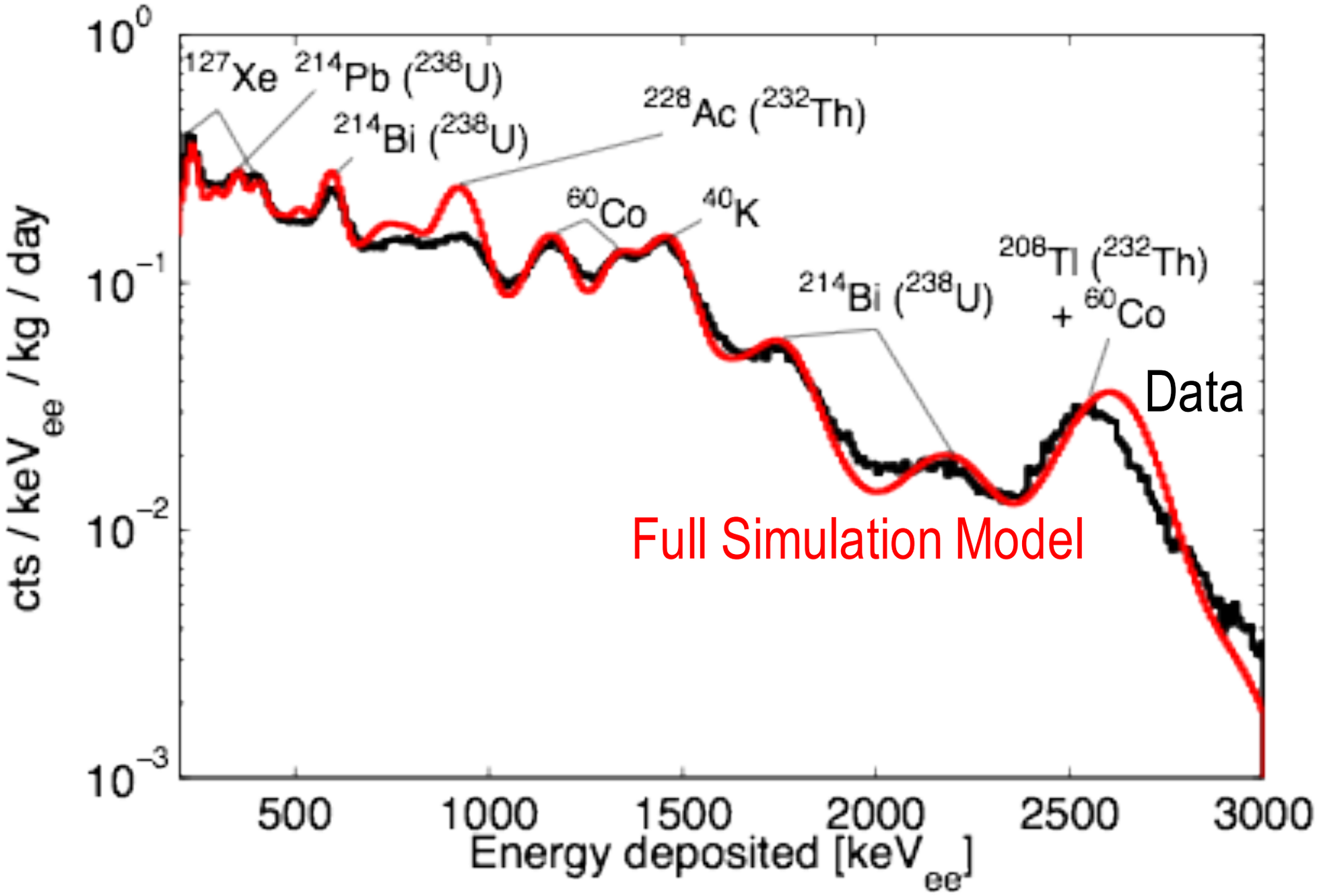


Total Electron Recoil Event Rate <5 keVee



LUX High Energy Gamma Background in 220 kg

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



Background Summary for 118 kg Fiducial

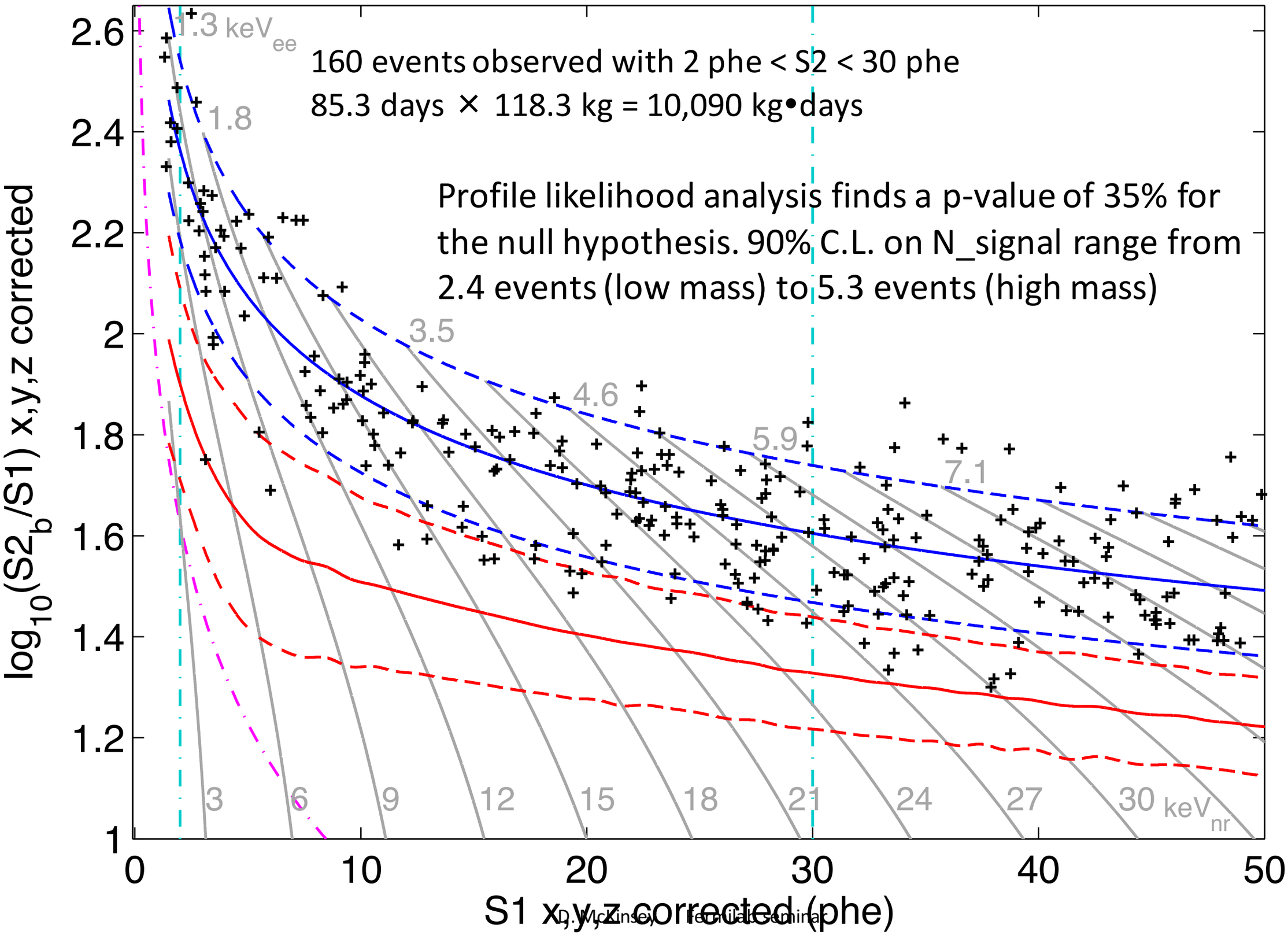
- Average levels over period April-August WIMP Search Run

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	0.11-0.22(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	$3.1 \pm 0.2_{stat}$

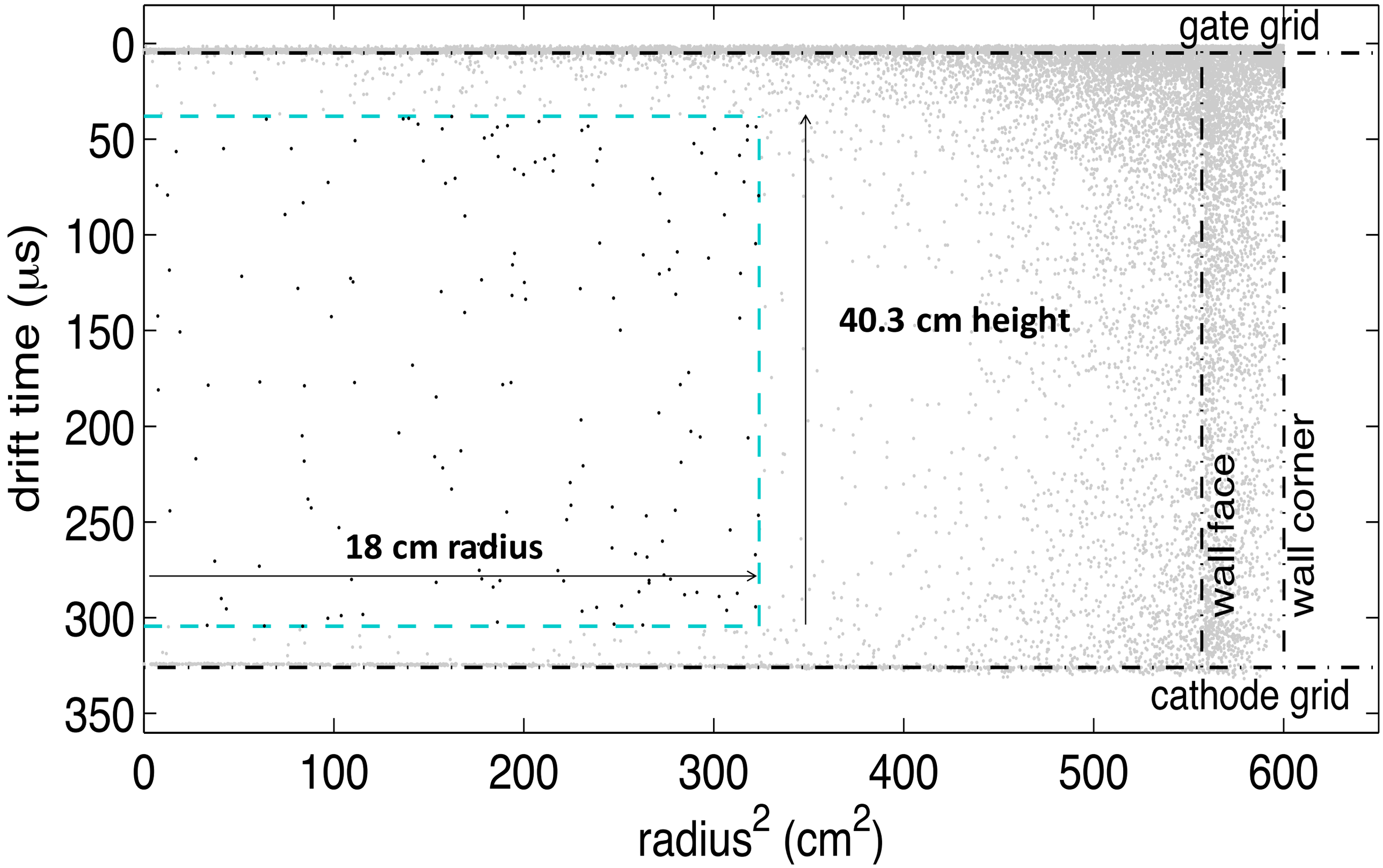
Event & Cuts Summary: 85 live days

Cut	Explanation	Events Remaining
All Triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918,901
Single Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585,686
S1 energy	Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-25 keVnr)	26,824
S2 energy	Accept 200-3300 phe (>8 extracted electrons) Removes single electron / small S2 edge events	20,989
S2 Single Electron Quiet Cut	Cut if >100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)	19,796
Drift Time Cut away from grids	Cutting away from cathode and gate regions, 60 < drift time < 324 us	8731
Fiducial Volume radius and drift cut	Radius < 18 cm, 38 < drift time < 305 us, 118 kg fiducial	160

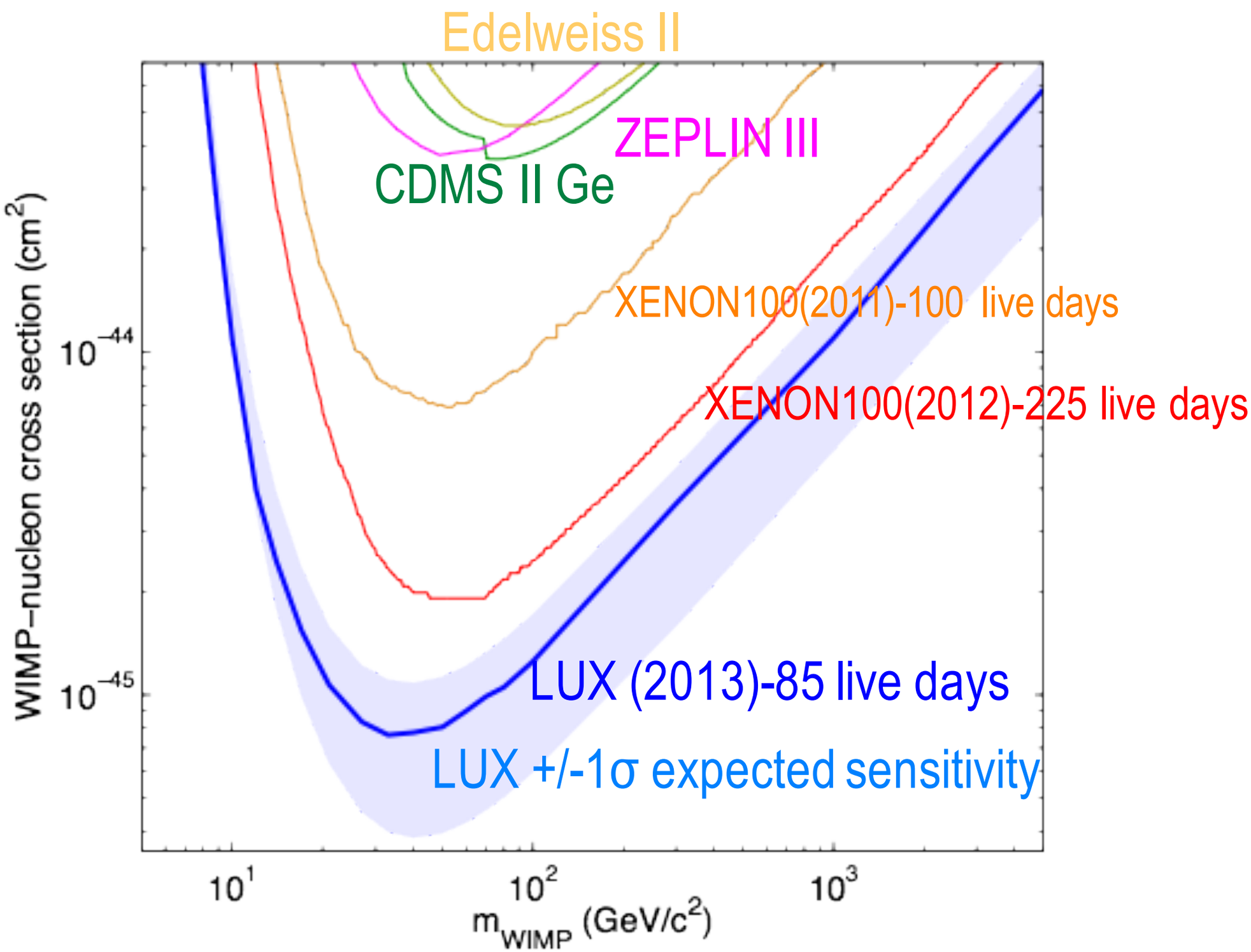
LUX WIMP search data



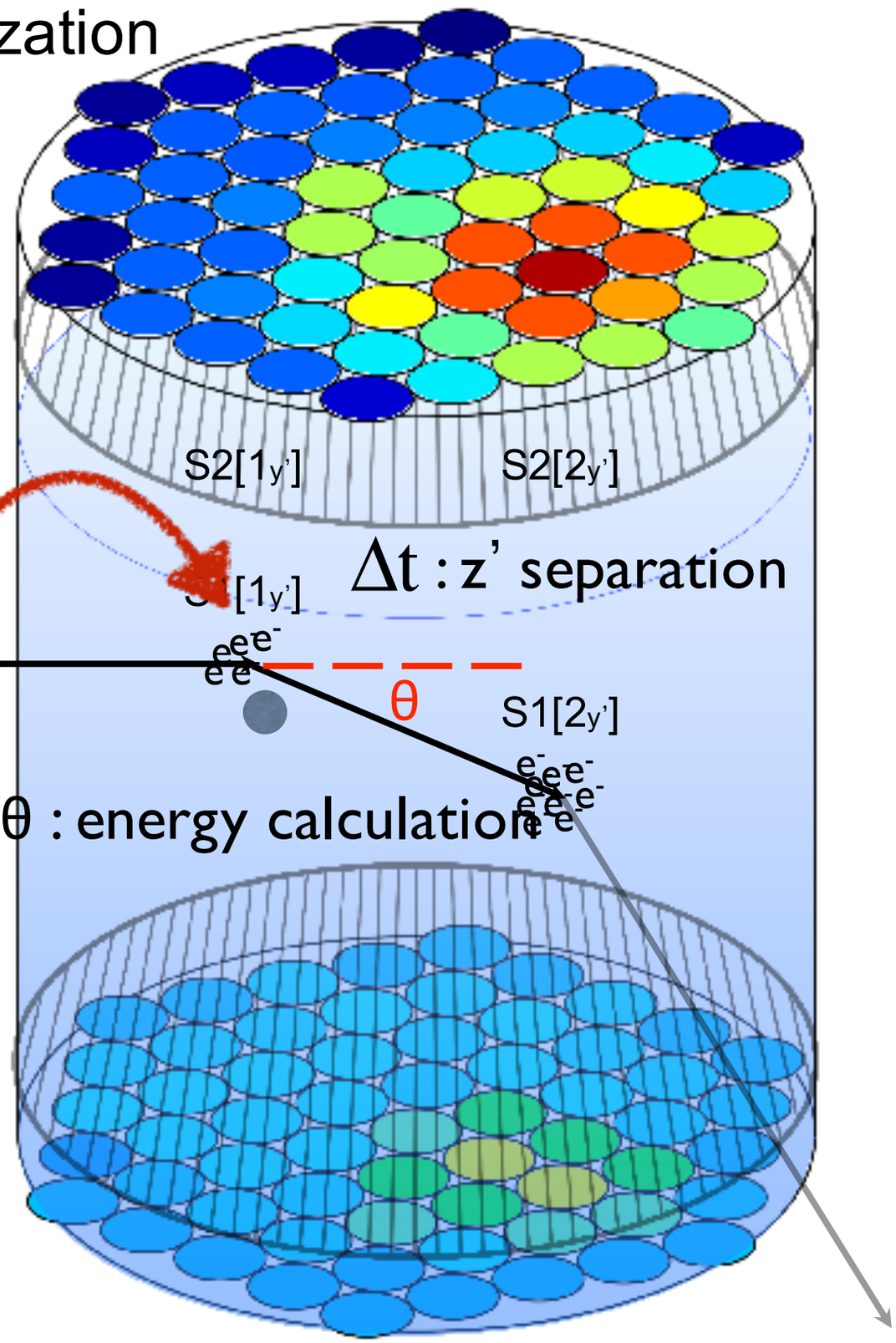
Fiducial Mass Cut – 118 kg



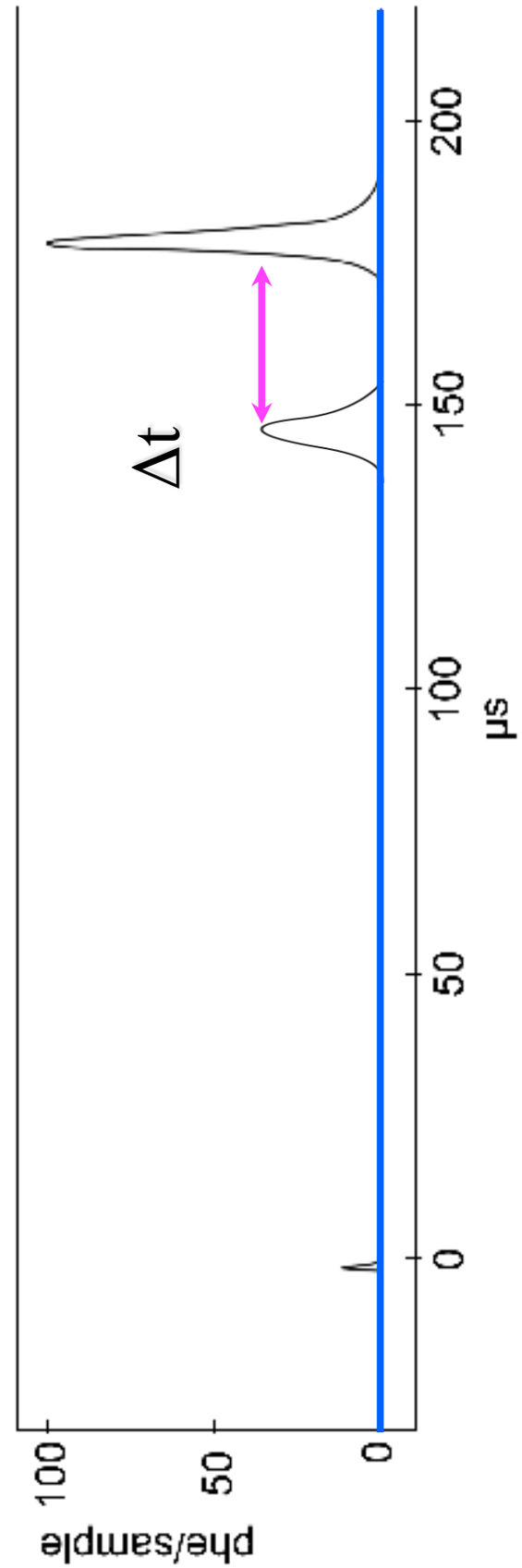
Spin Independent Sensitivity Plots



top hit pattern:
x-y localization

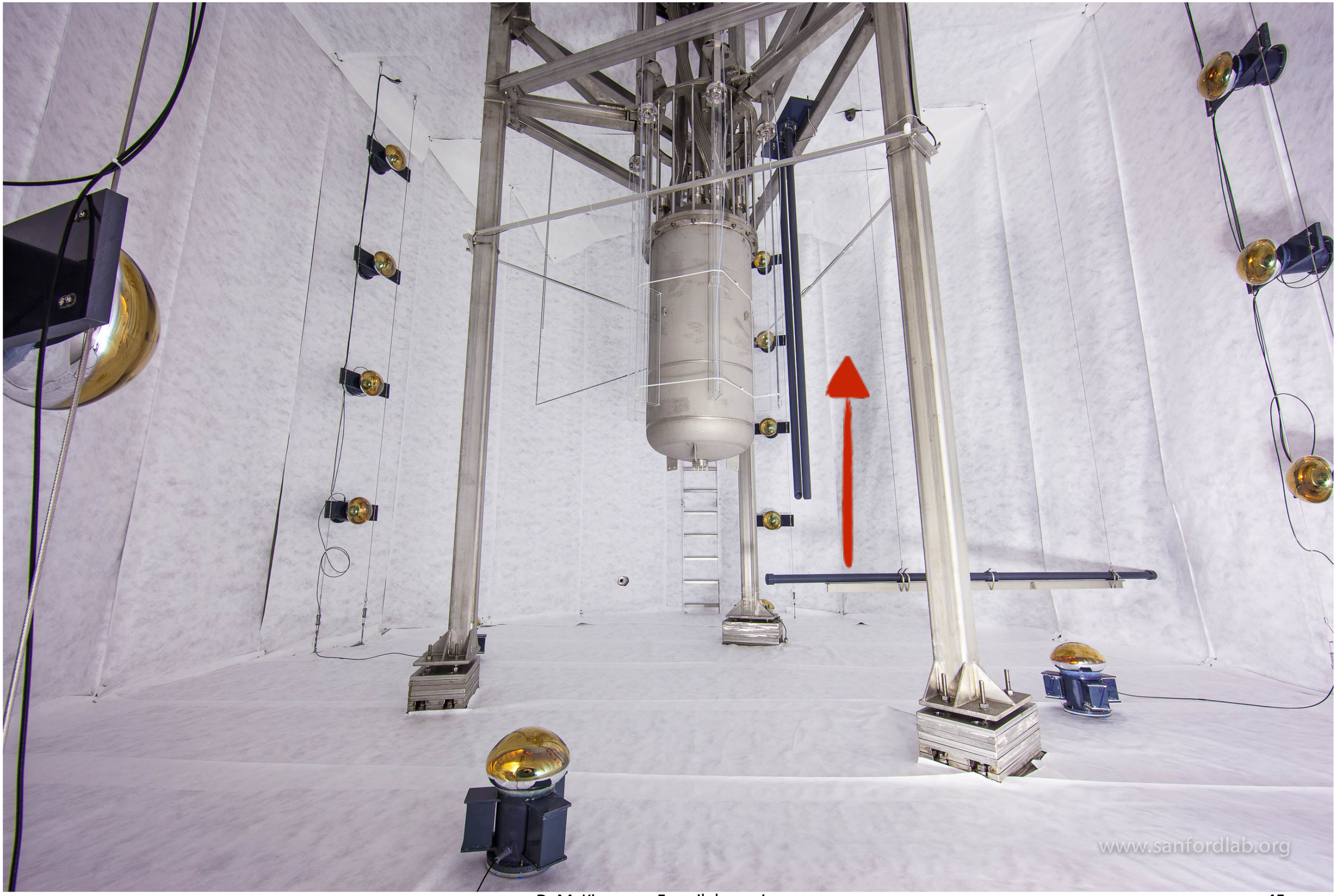


Monochromatic
2.5 MeV neutrons

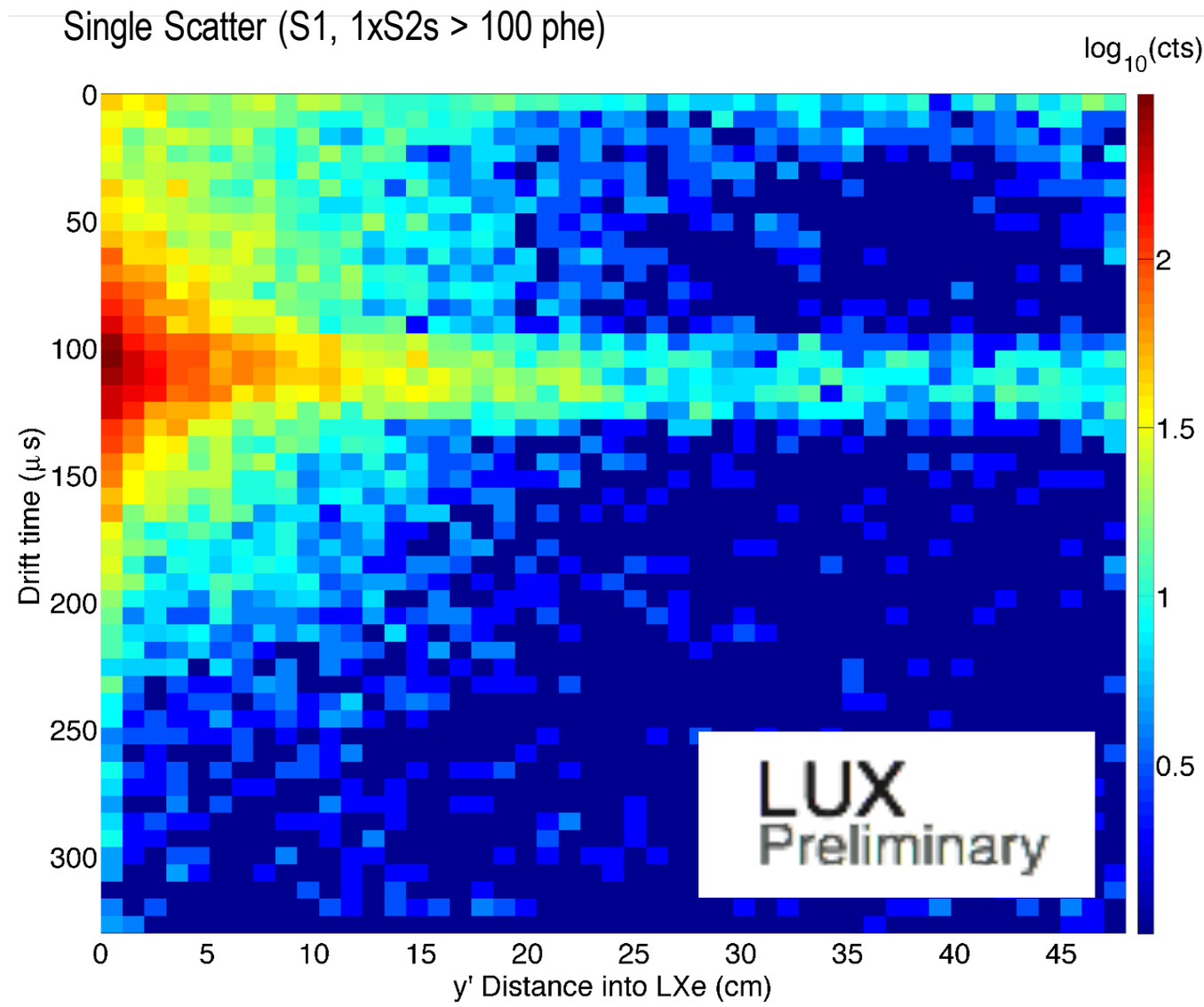


$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Neutron Conduit Installed in the LUX Water Tank - Fall 2012



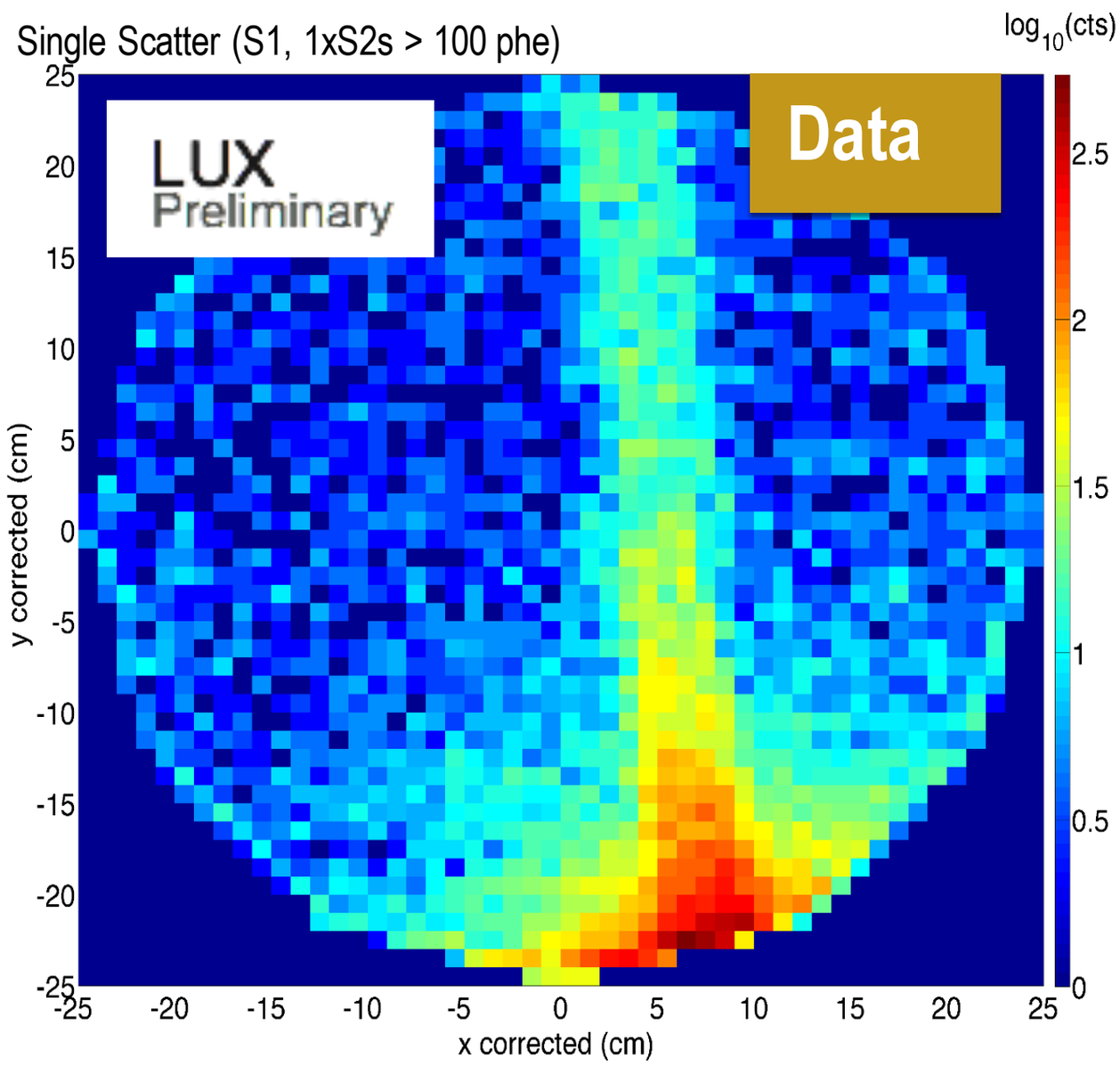
Adelphi DD108 Neutron Generator Installed Outside LUX Water Tank - Fall 2013

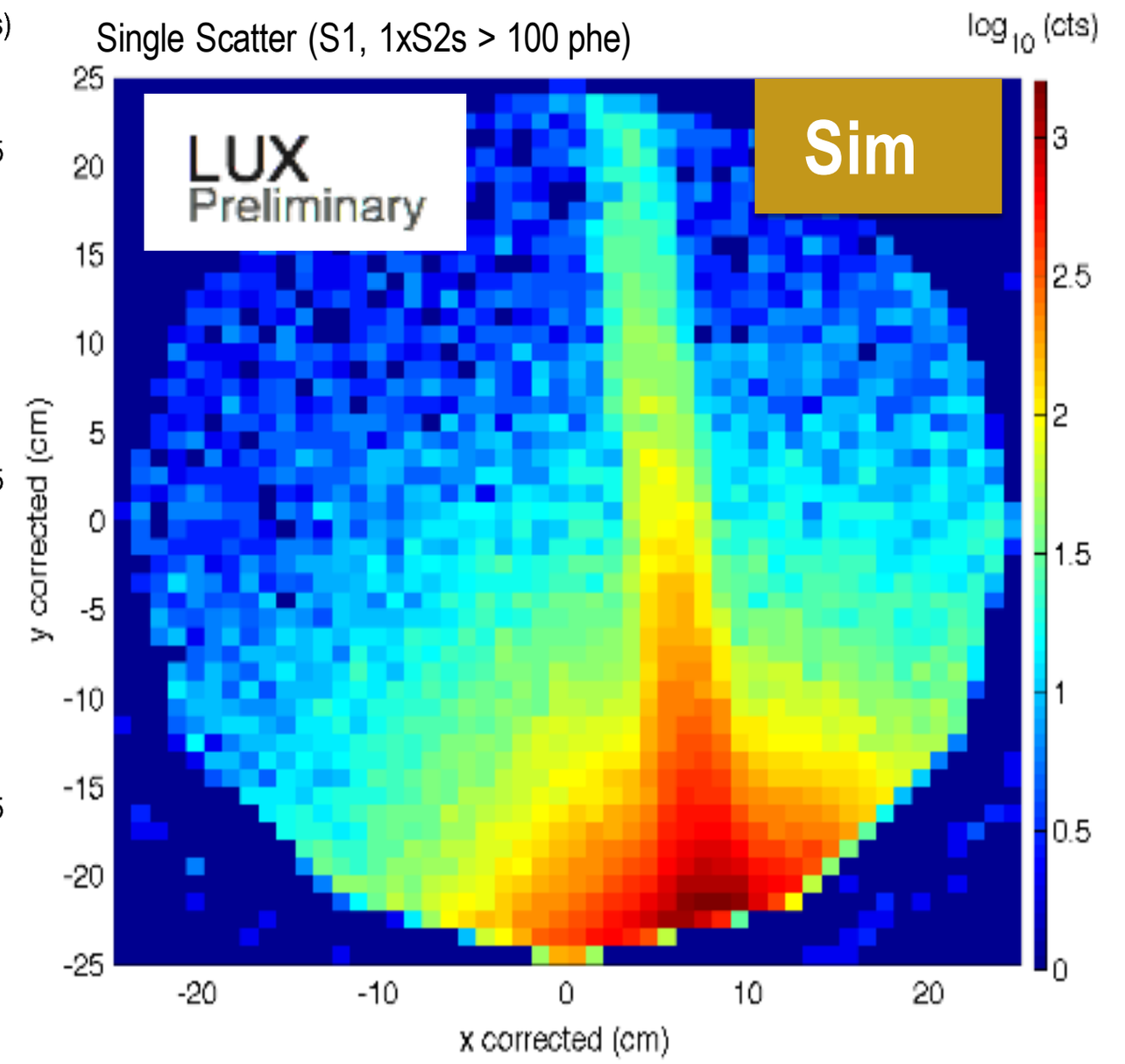


- Neutron generator/beam pipe assembly aligned 15.5 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 105.5 live hours of neutron tube data used for analysis

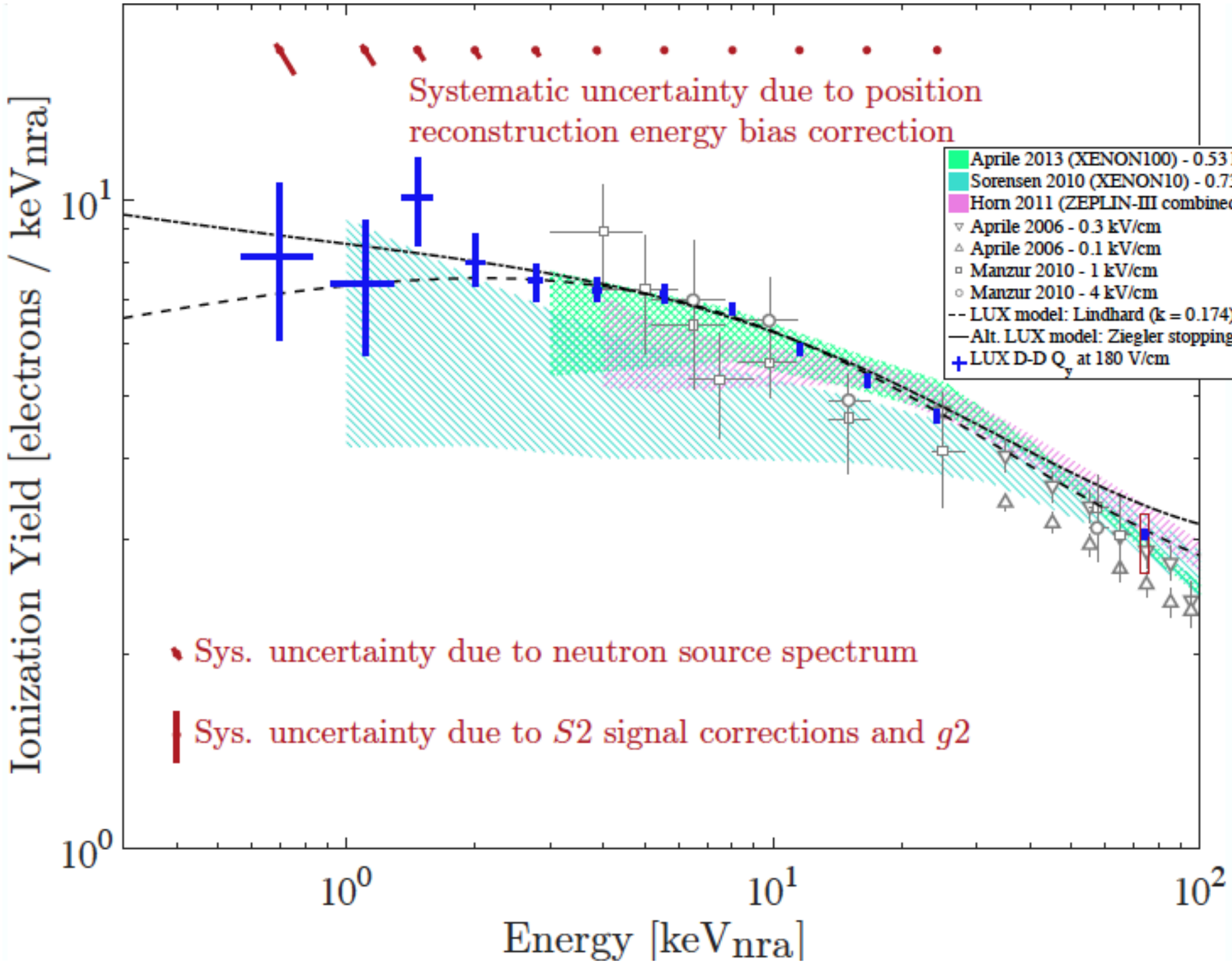
Reconstructed Neutron Beam Event X-Y Positions

Complete Geant4 LUXSim + NEST simulation of D-D neutron calibration

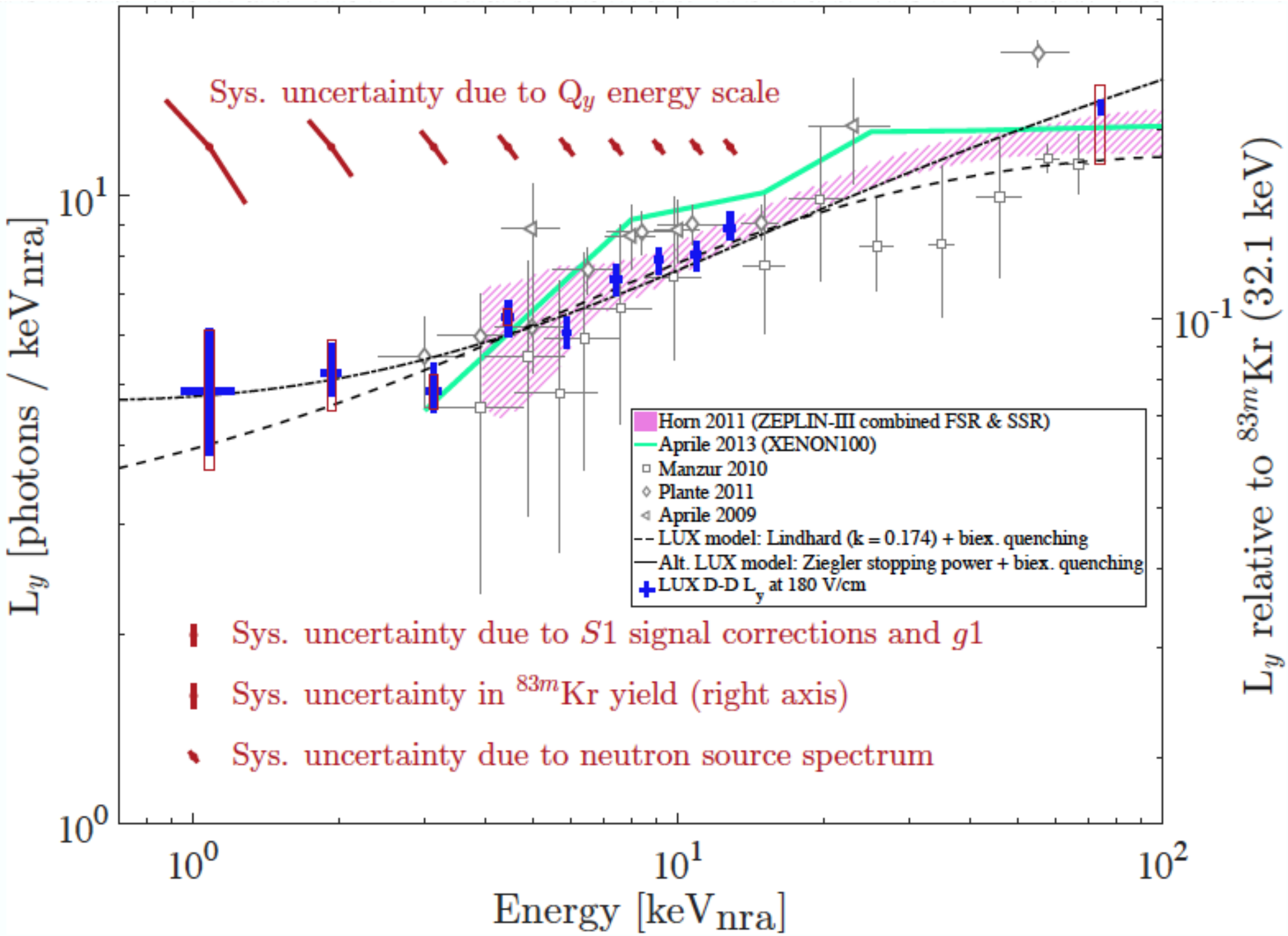




Nuclear Recoil Charge Yield Absolutely Measured Down to 0.7 keV in LUX



Nuclear Recoil Light Yield Measured in LUX Using Absolute Energy Scale, Down to 1.08 keV

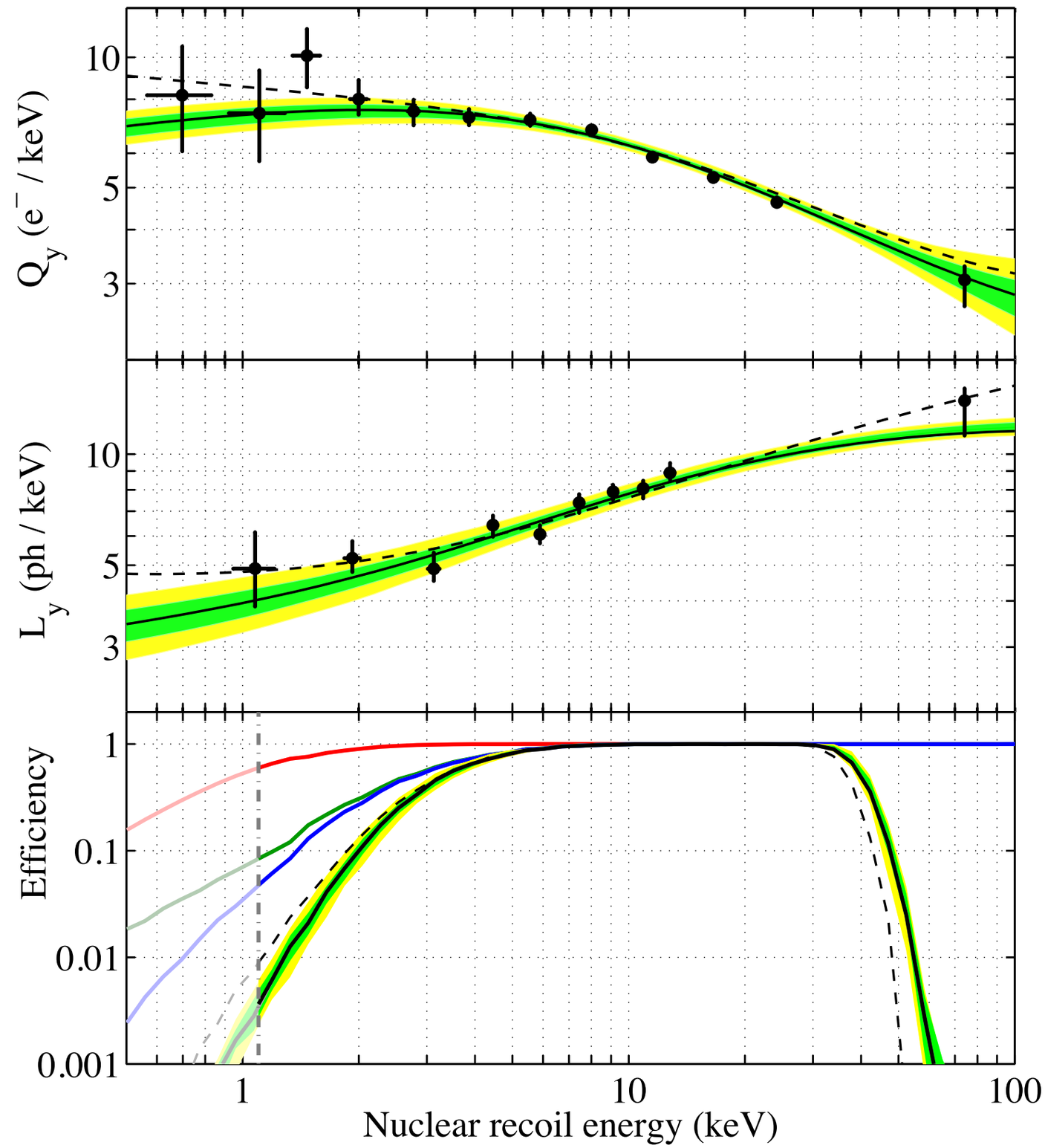


Charge and Light Yields for Nuclear Recoils, Measured Using DD Neutron Calibration in LUX

Charge Yield

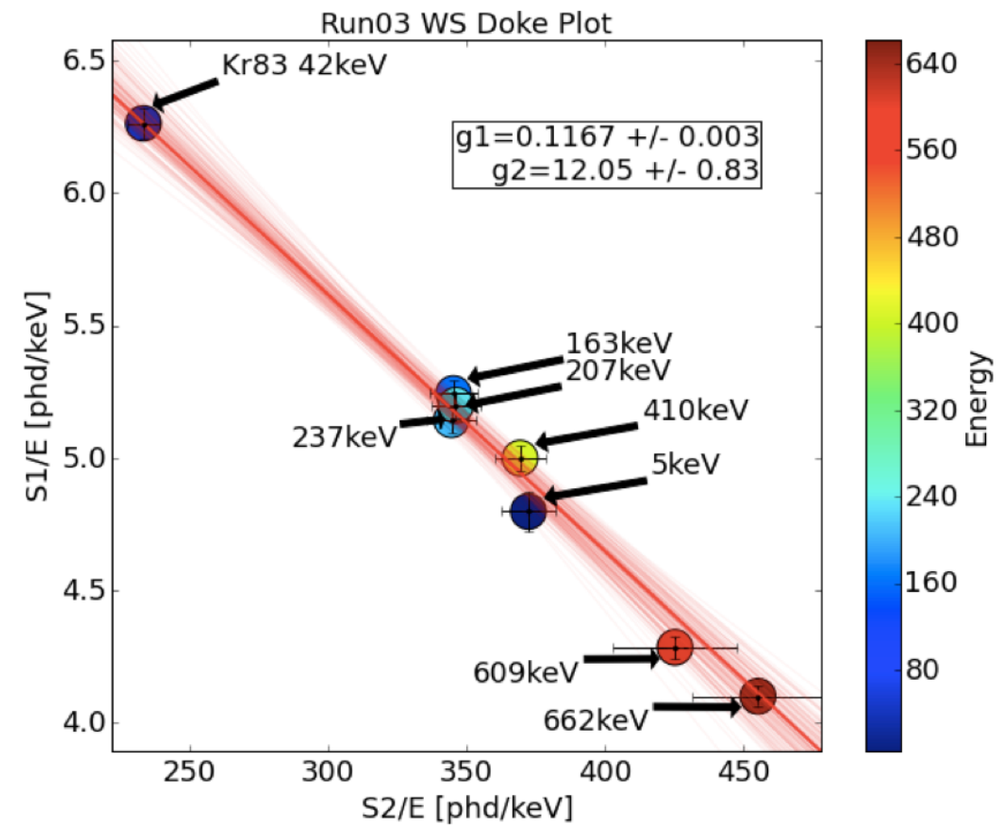
Light Yield

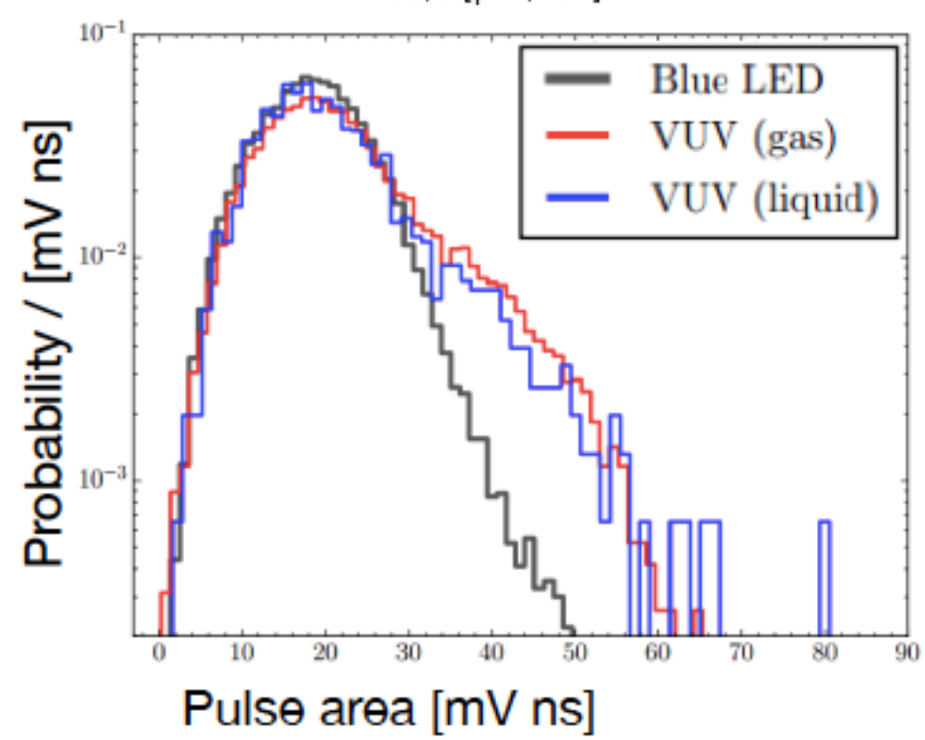
WIMP signal efficiency



Improvements in 2015 Reanalysis

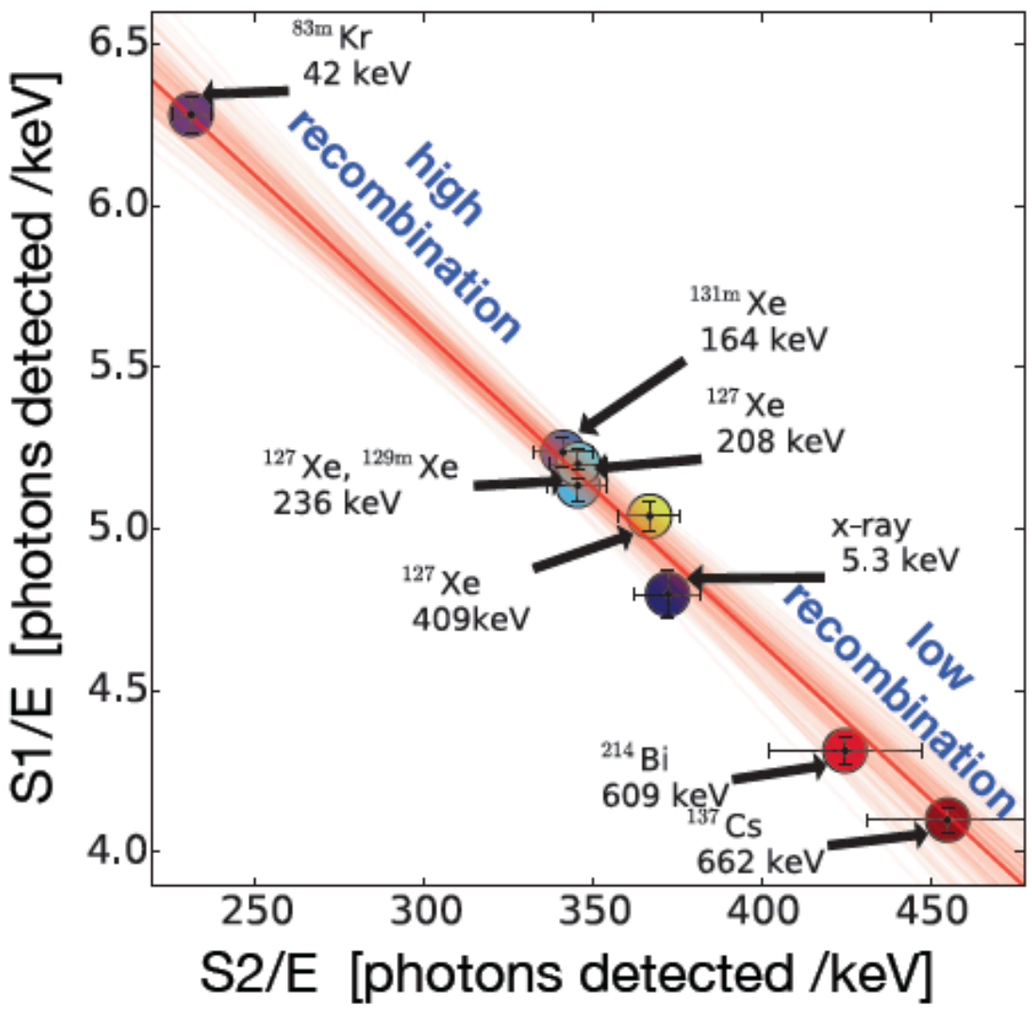
- New algorithm:S1 is 'photons detected' instead of total S1 area. At lowest energies, simply an integer count of PMT hits.
- Better Energy Calibration: detector-specific gain factors g1 = 0.117 ± 0.003 phd/photon and g2 = 12.1 ± 0.8 phd/electron are measured in situ
- Both PMT arrays used to estimate S2 size (compare to bottom-only for 2013 analysis).
- Improvements to the gamma-ray background model to better reproduce ER spatial distribution.
- New NR Calibration, with a new lower energy threshold of 1.1 keV_{nr}
- Calibrated likelihood of 2 phe from 1 VUV photon, in situ (~20%)
- Effects of electric field non-uniformity near detector edges corrected using ^{83m}Kr data





Precise Detector Efficiencies and Gains

'Doke plot' analysis:
Electron recoils all start with the same [excitation:ionization] ratio.
Energy-dependent recombination **then moves quanta from one category to the other, 1-to-1.**
We leverage this 1-to-1 correspondence of quanta**, and fit for signal-per-quanta**.



$$S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g_1}{W}$$

$$S2/E = \frac{n_e}{(n_\gamma + n_e)} \times \frac{g_2}{W}$$

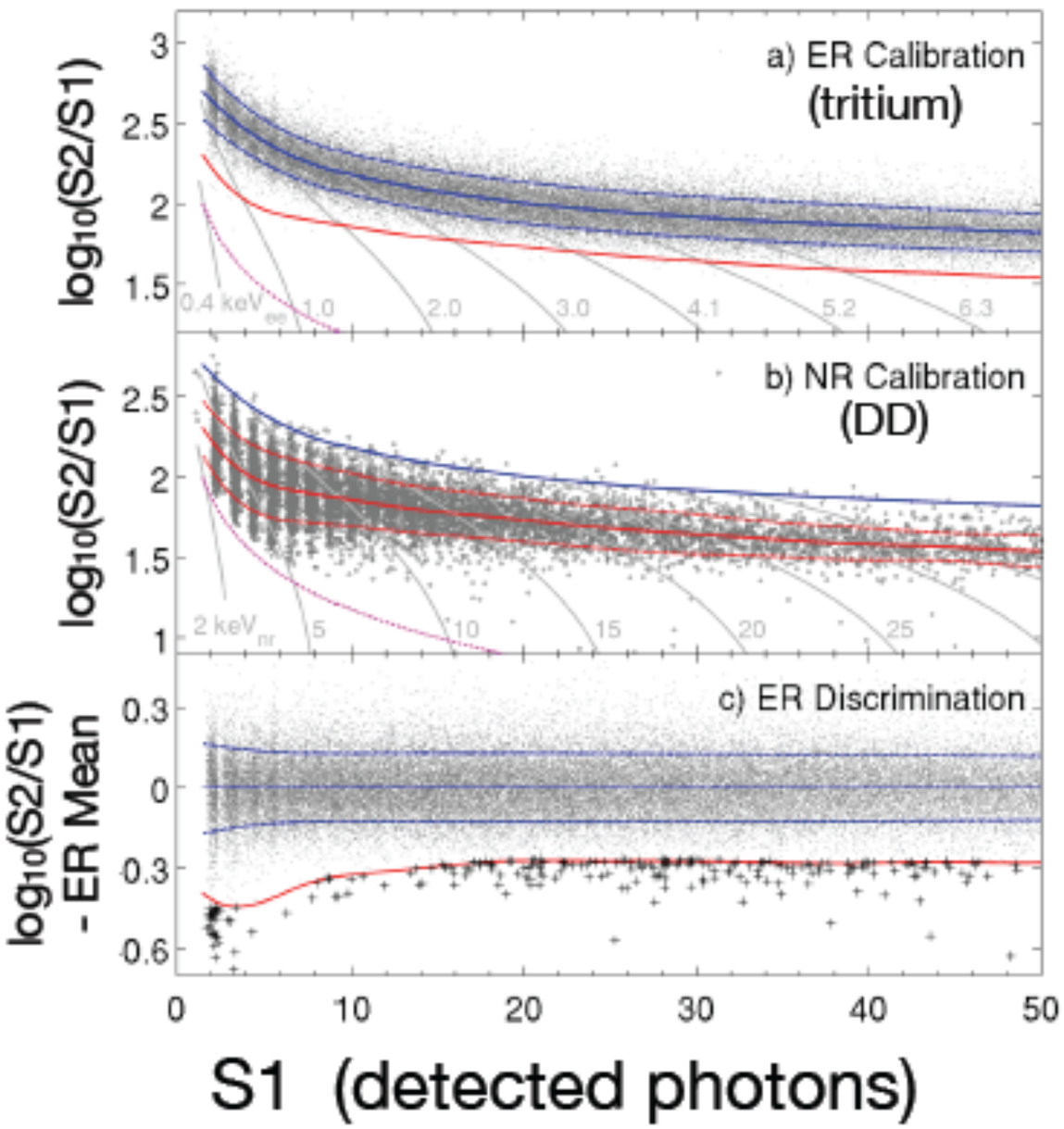
$$W = 13.7\text{eV}$$

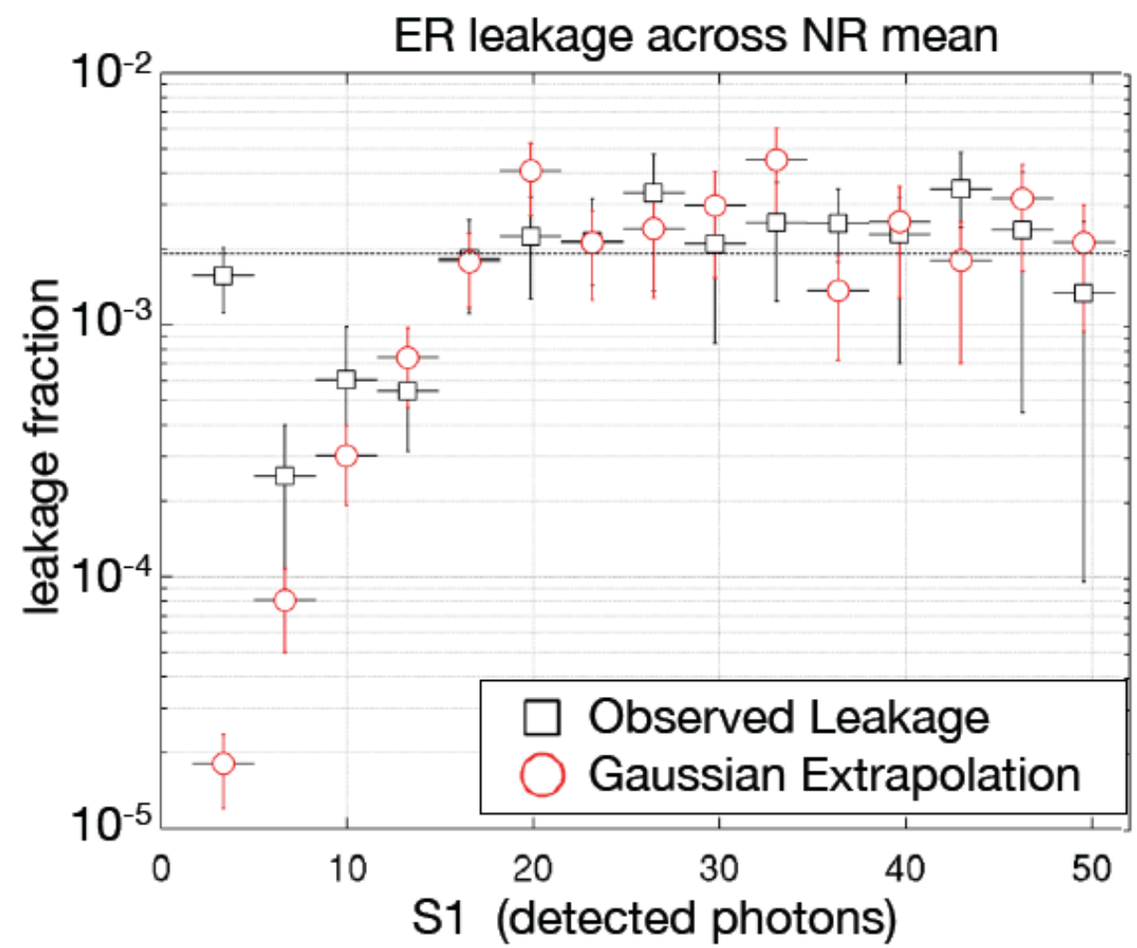
$$\left(\frac{S1}{E}\right) = \left(\frac{g_1}{W}\right) - \left(\frac{S2}{E}\right)\left(\frac{g_1}{g_2}\right)$$

result:

$$\langle S1 \rangle\ [\text{phd}] = [0.1167 \pm 0.003]\ n_\gamma$$
$$\langle S2 \rangle\ [\text{phd}] = [12.05 \pm 0.83]\ n_e$$

Electron Recoil / Nuclear Recoil Discrimination

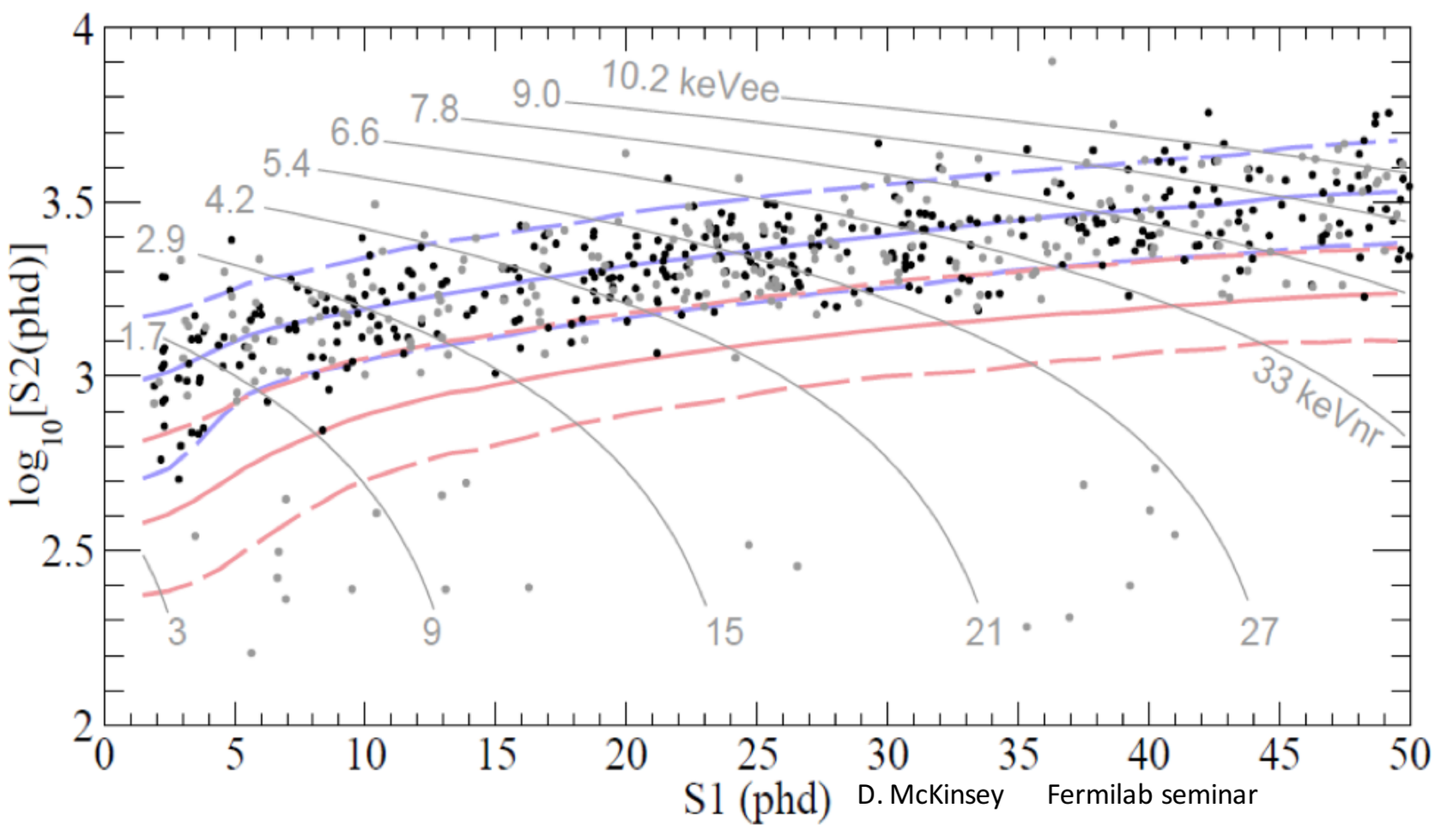




Increased Fiducial Size and Detector Exposure

- Additional 10 live-days of data incorporated into analysis
- Expanded fiducial volume enabled by modeling of background wall events
  - 2013: radius = 18 cm, fiducial mass = 118 kg
  - 2015: radius = 20 cm, fiducial mass = 145 kg

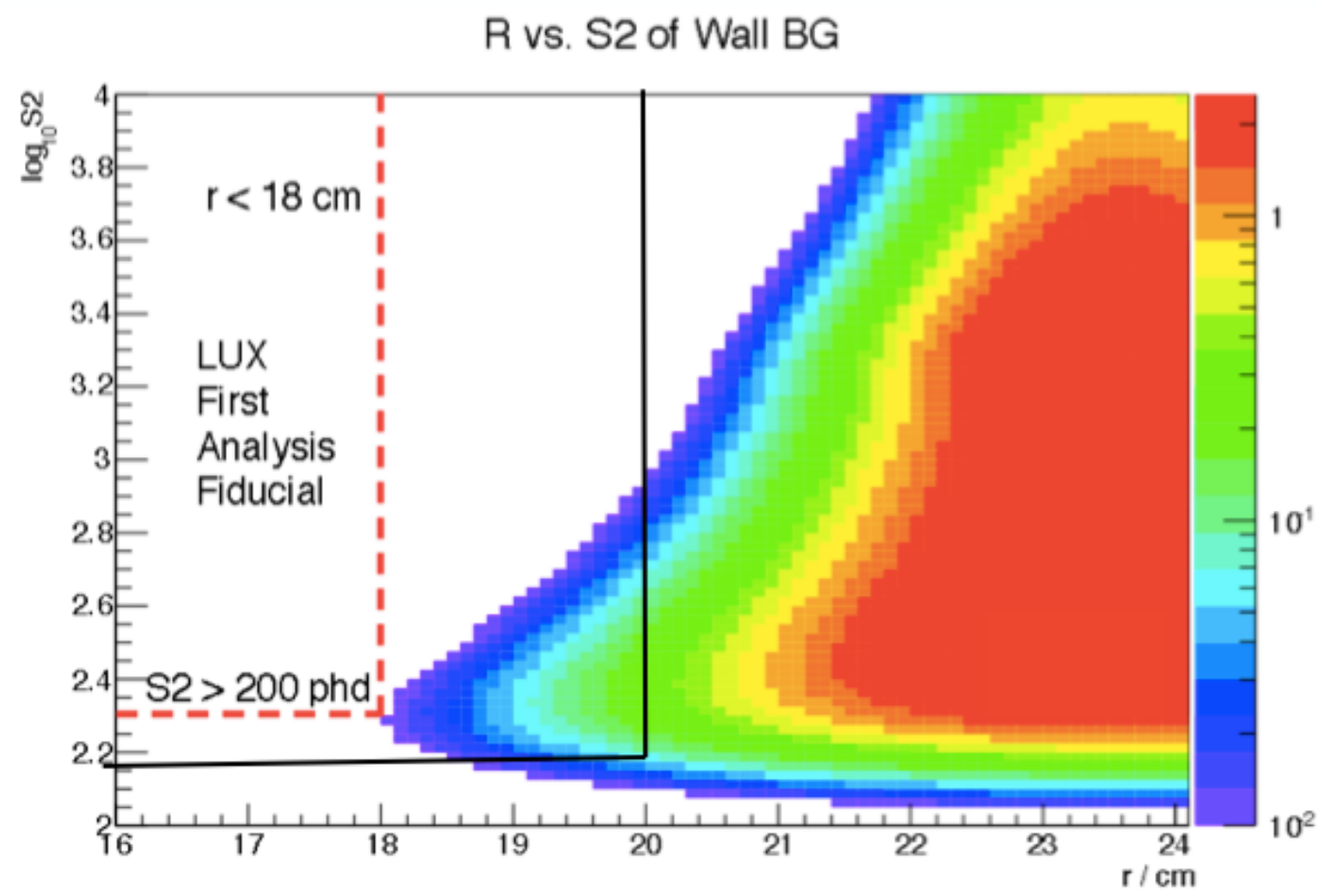
  } Overall 40% increase in detector exposure
- Allowed range of S1 and S2 sizes: 1 phd < S1 < 50 phd, S2 > 150 phd



591 events observed;
589 events predicted by background model

Improvements to Background Model

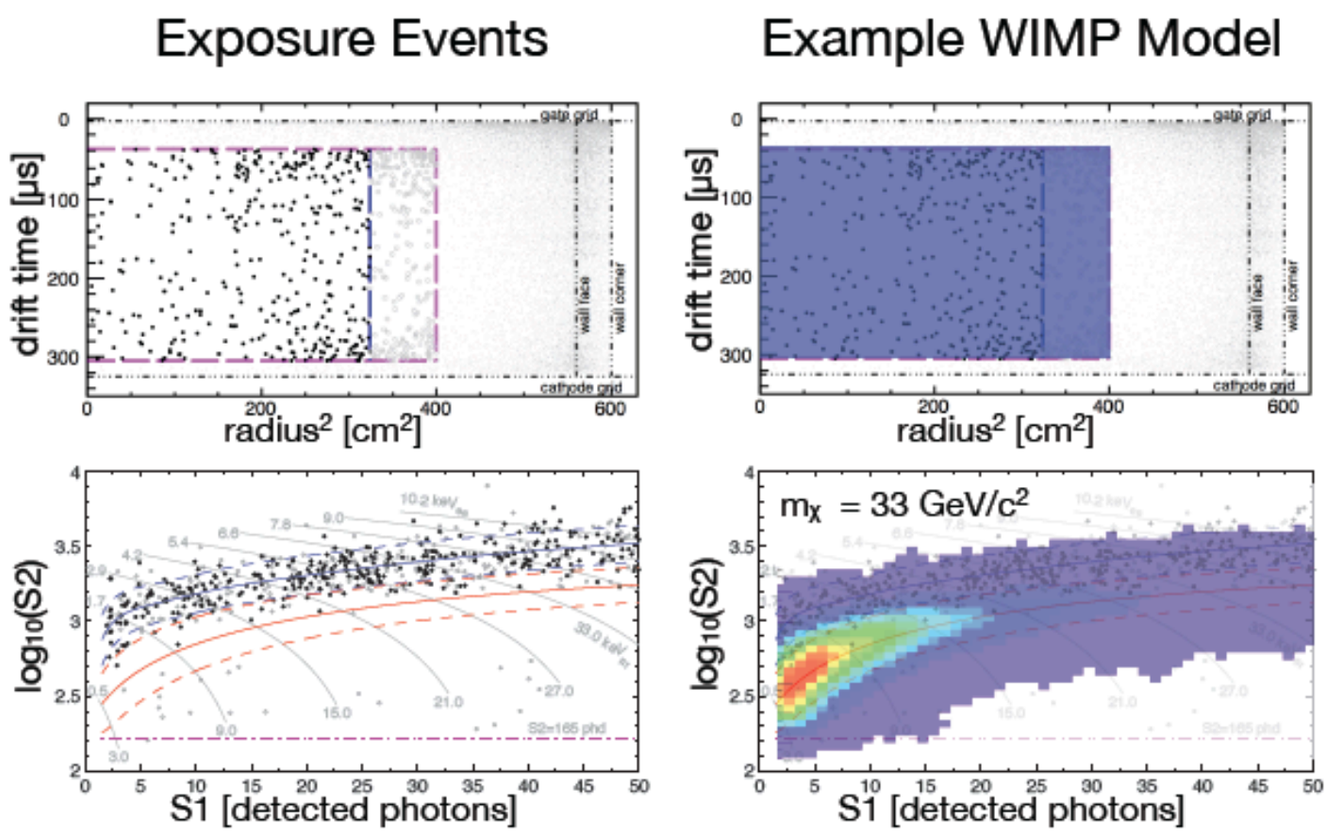
- Predominant background: low-energy ER from detector components + contaminants (^{85}Kr, Rn-daughters) in the Xe
- Two main improvements:
  - More detailed modeling of detector construction components
  - Wall events (e.g. ^{222}Rn - ^{206}Pb absorbed into PTFE) empirically modeled



- Subdominant backgrounds, not included in the model:
  - Expected neutron background using revised cuts: 0.08 ± 0.01 NR events
  - S1 + S2 coincidence: 1.1 total events
  - ^{8}B solar neutrino scattering: 0.10 total events

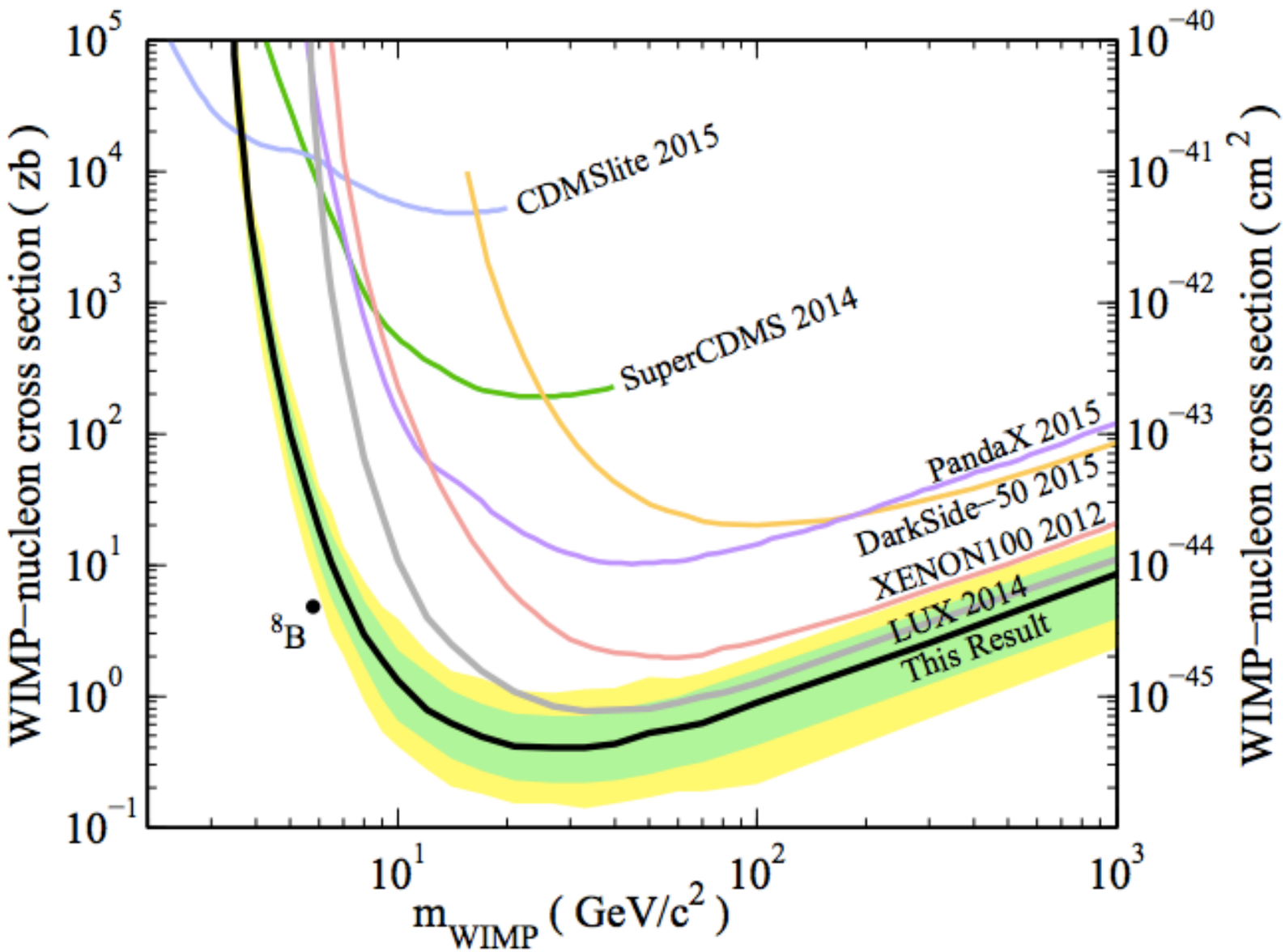
Profile Likelihood Ratio in [r, z, S1, logS2]

- Both ER and NR response is precisely calibrated, so PLR model uncertainties are small.
- Dominant detector response uncertainties included,
  but have minimal effect on limits (<20% at all masses)



	Parameter	Constraint	Fit value
	Lindhard k	0.174 ± 0.006	-
	S2 gain ratio: $g_{2,\mathrm{DD}}/g_{2,\mathrm{WS}}$	0.94 ± 0.04	-
background rates	Low-z-origin γ counts: $\mu_{\gamma,\mathrm{bottom}}$	172 ± 74	165 ± 16
	Other γ counts: $\mu_{\gamma,\mathrm{rest}}$	247 ± 106	228 ± 19
	β counts: μ_β	55 ± 22	84 ± 15
	^{127}Xe counts: $\mu_{\mathrm{Xe\text{-}127}}$	91 ± 27	78 ± 12
	^{37}Ar counts: $\mu_{\mathrm{Ar\text{-}37}}$	-	12 ± 8
	Wall counts: μ_{wall}	24 ± 7	22 ± 4

LUX 2015 WIMP-Nucleon Interaction Limit



- Improved sensitivity to low-mass WIMPs over LUX 2013 result
  - Minimum kinematically-accessible mass 3.3 GeV (compare to 5.2 GeV)
- 23% improvement in limit for high-mass WIMPs

New minimum spin-independent cross section limit:
6 X 10^{-46} cm^2 (0.6 zb) for 33-GeV WIMPs
LUX 2015 reanalysis paper: arXiv:1512.03506

LUX-ZEPLIN

LZ = LUX + ZEPLIN

University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
University of California, Berkeley
Brookhaven National Laboratory
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Kavli Institute for Particle Astrophysics & Cosmology
Lawrence Livermore National Laboratory
University of Maryland
University of Michigan
Northwestern University
University of Rochester
University of California, Santa Barbara
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University
University of Wisconsin
Yale University

32 institutions currently
About 200 people

Center for Underground Physics (Korea)
LIP Coimbra (Portugal)
MEPhI (Russia)
Edinburgh University (UK)
University of Liverpool (UK)
Imperial College London (UK)
University College London (UK)
University of Oxford (UK)
STFC Rutherford Appleton and Daresbury Laboratories (UK)
University of Sheffield (UK)

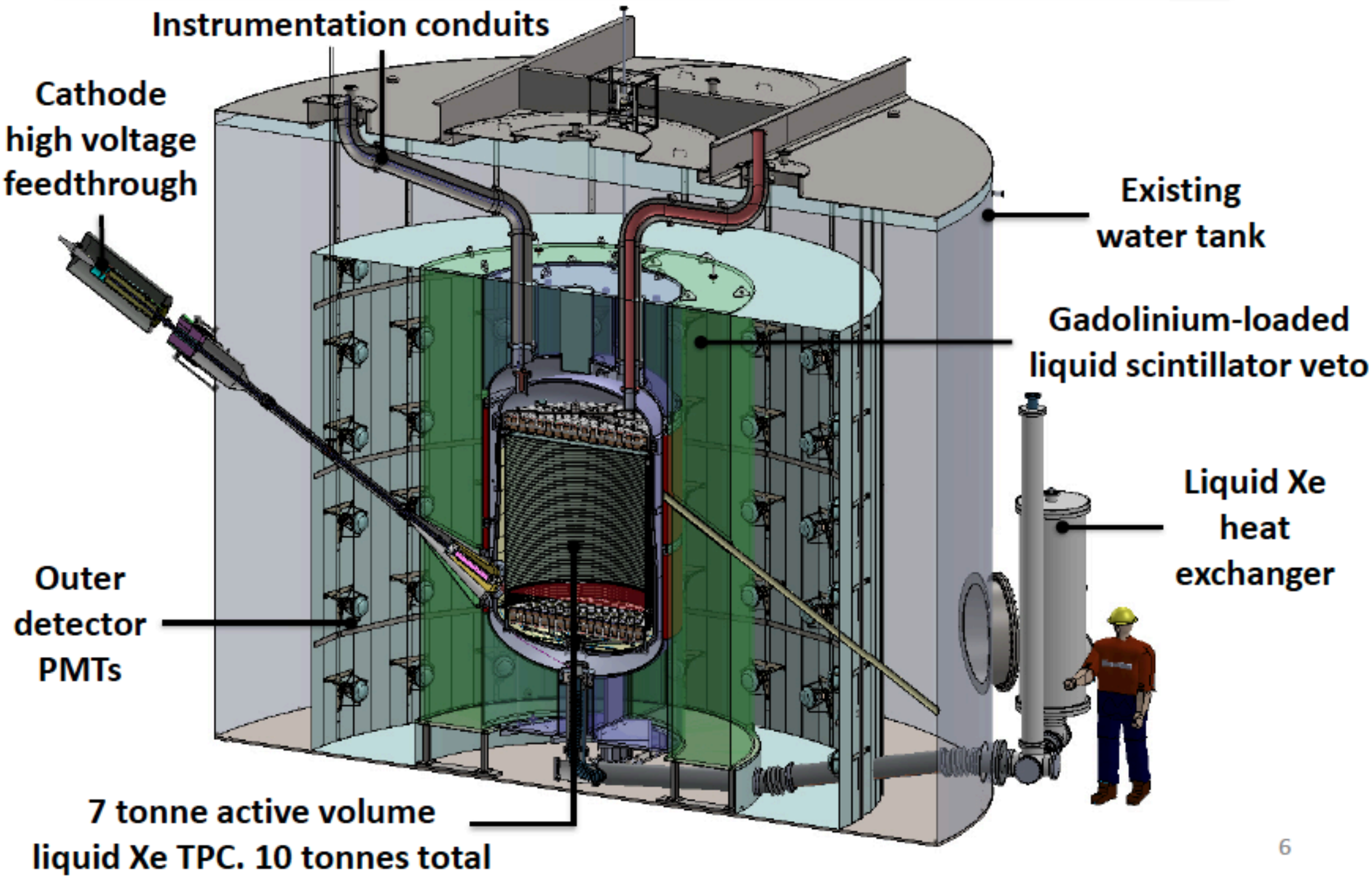
Scale Up ≈ 50 in Fiducial Mass

LZ

Total mass – 10 T
WIMP Active Mass – 7 T
WIMP Fiducial Mass – 5.6 T

LUX

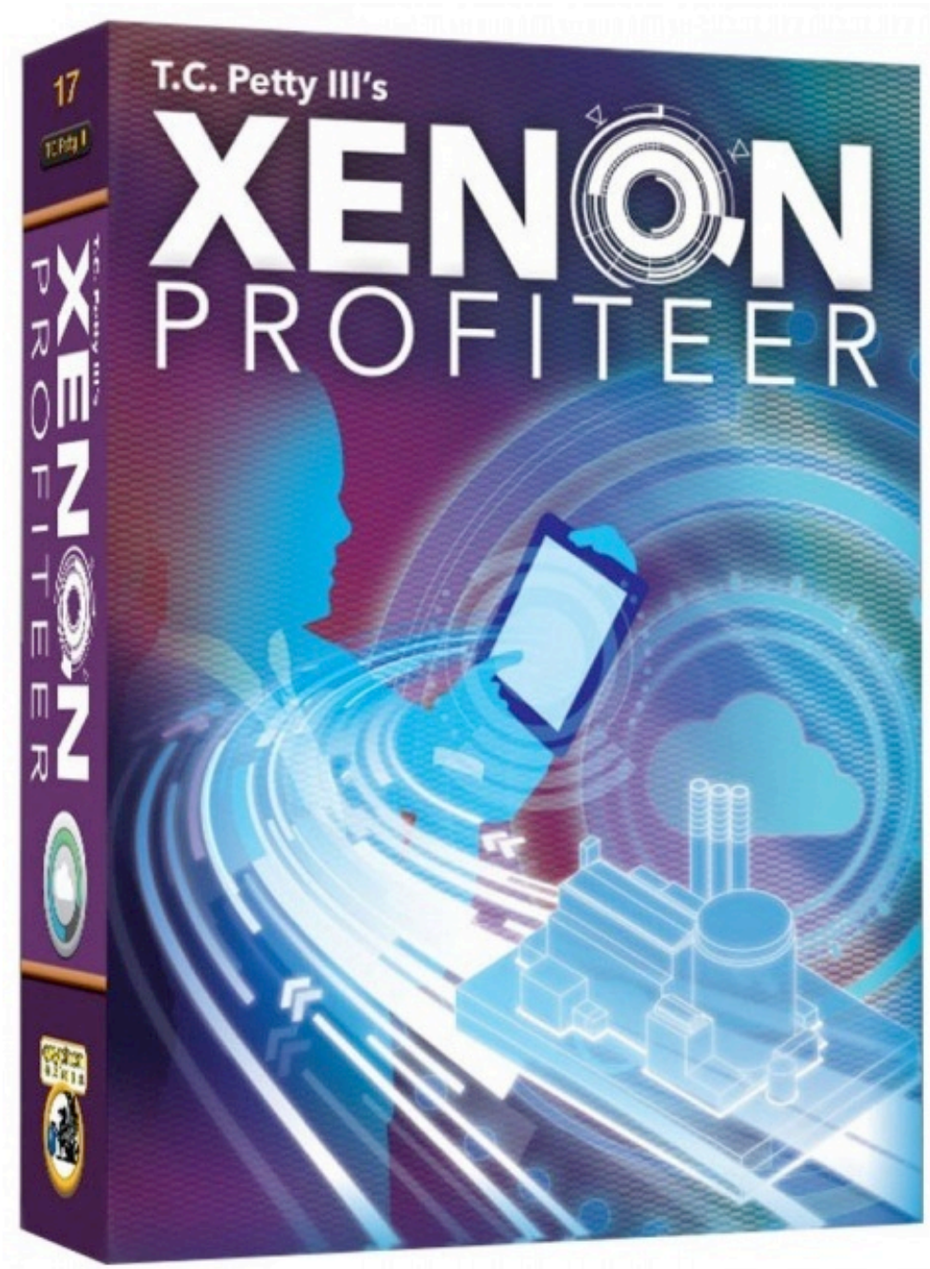
LZ Detector Overview



6

“In Xenon Profiteer, you use your entrepreneurial spirit and an Air Separation facility to isolate valuable Xenon and make a profit.”

“***Xenon Profiteer*** is a highly thematic, deck-deconstruction, euro game for 2-4 entrepreneurs in which each player takes control of their own Air Separation Facility and distills Xenon from their Systems to complete lucrative contracts. You will also physically expand your facility by building upgrades, pipelines, and acquiring new contracts and connecting them to your Center Console.”



Gryphon and Eagle Games

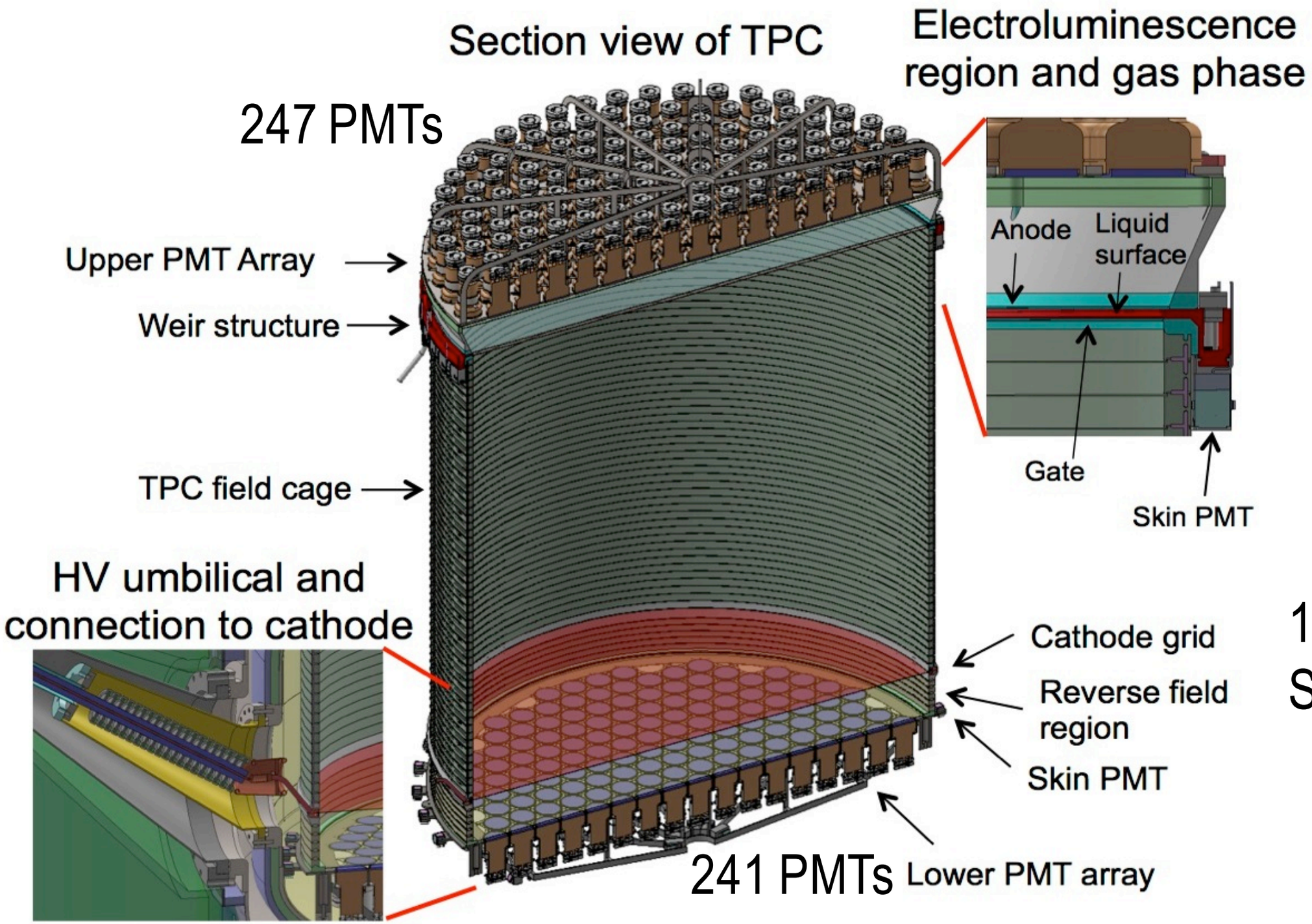
Key Design Points

- 7 active tonnes of LXe can yield 2 x 10^{-48} cm^2 sensitivity in about three years of running
- 5.6 tonne fiducial volume, 1000 days
- Requires all detector systems working together
  - Xe detector with good light collection, reasonable background rejection (ER discrimination) and good signal detection efficiency
  - Sophisticated veto system: skin (outside active Xe region) + scintillator/water allows maximum fiducial volume to be obtained, maximizes use of Xe and substantially increases reliability of background measurements
  - Control backgrounds, both internal (within the Xe) and external from detector components/environment

Design Status Summary

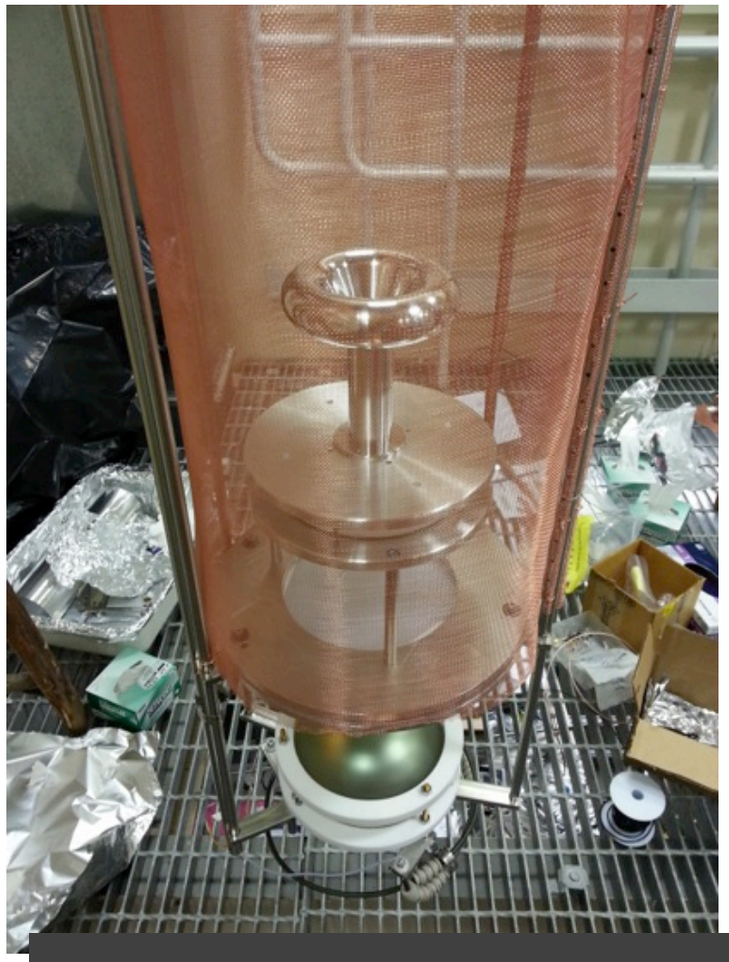
- Conceptual, and in some cases more advanced design, completed for all aspects of detector
- Conceptual Design Report can be viewed on arXiv
- Acquisition of Xenon started
- Procurement of PMTs and cryostat started
- Collaboration – wide prototype program underway to guide and validate design
- Backgrounds modeling and validation well underway

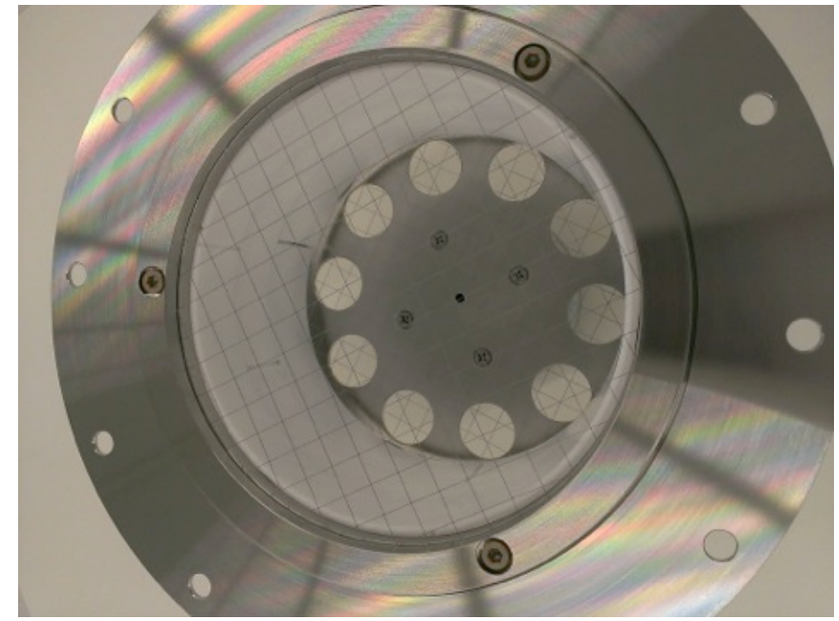
Xe TPC Detector



180 total Skin PMT

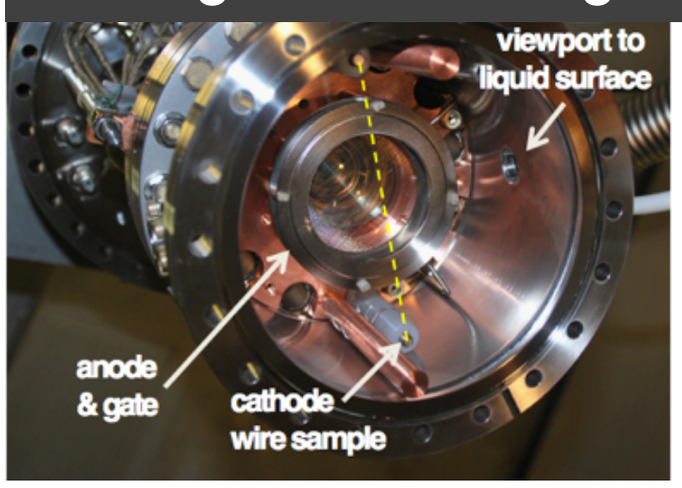
High Voltage Studies





Prototype of highest E-field region tested in LAr

Wire grid tests ongoing



- LZ cathode nominal operating goal: 100 kV (~ 700 V/cm)
- Feedthrough prototype tested to 200 kV
- Prototype TPC for 100 kg LXe system being tested at SLAC
- HV prototyping expanding at Berkeley
- Wire electron emission studies at Imperial

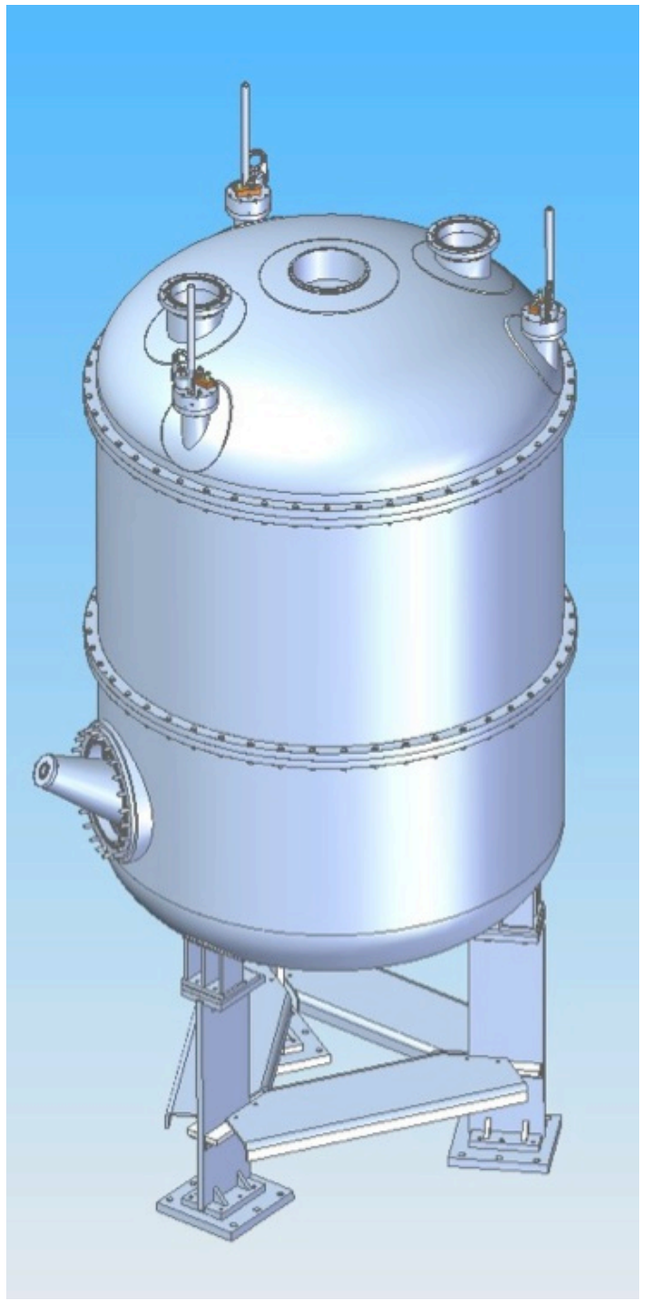
Extensive Calibration

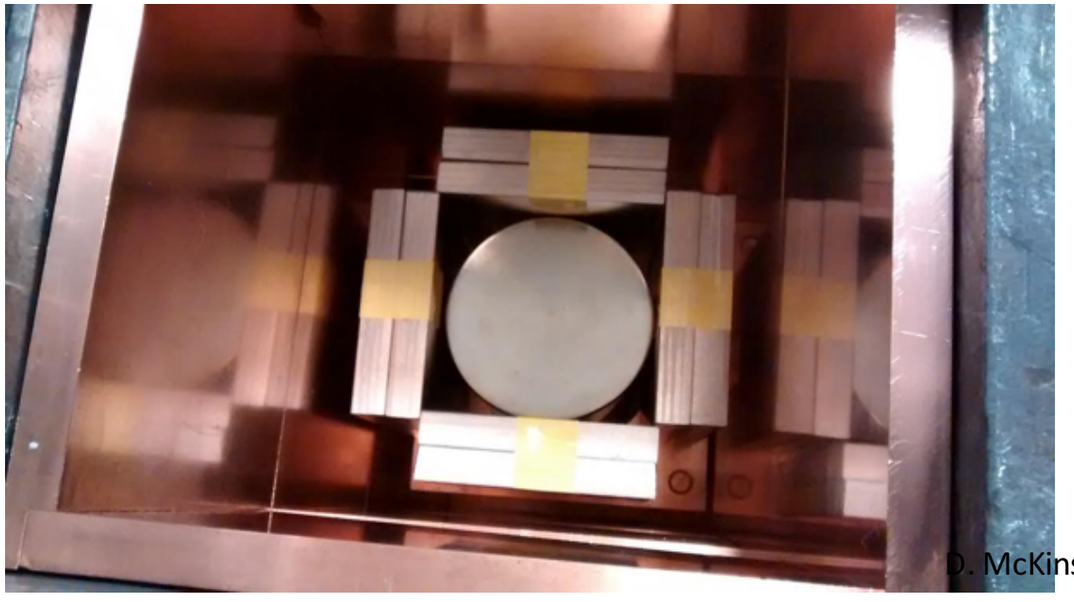
- LUX has led the way to detailed calibrations. LZ will build on this and do more.

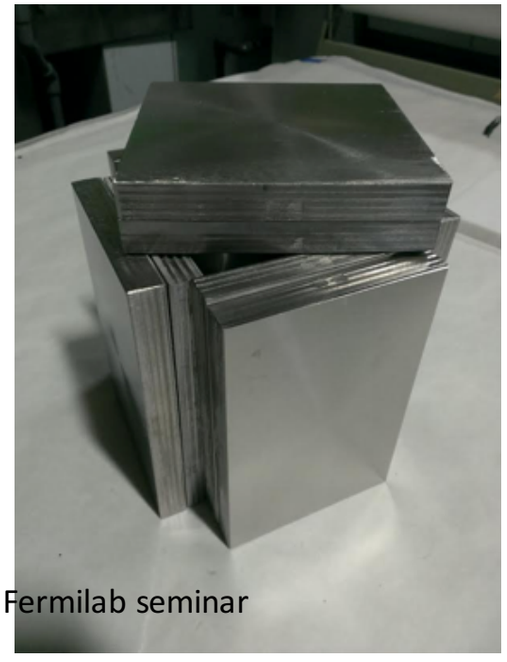
Done in LUX and will be done in LZ	Not done in LUX, but will do in LZ
^{83m}Kr (routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
Tritiated methane (every few months)	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator(upgraded early next year to shorten pulse)	

Cryostat Vessels

- UK responsibility
- Low background Ti chosen as cryostat material
- 5-ton Ti slab for all vessels (and other parts) received and assayed
- Contributes < 0.05 NR+ER counts in fiducial volume in 1,000 days after cuts



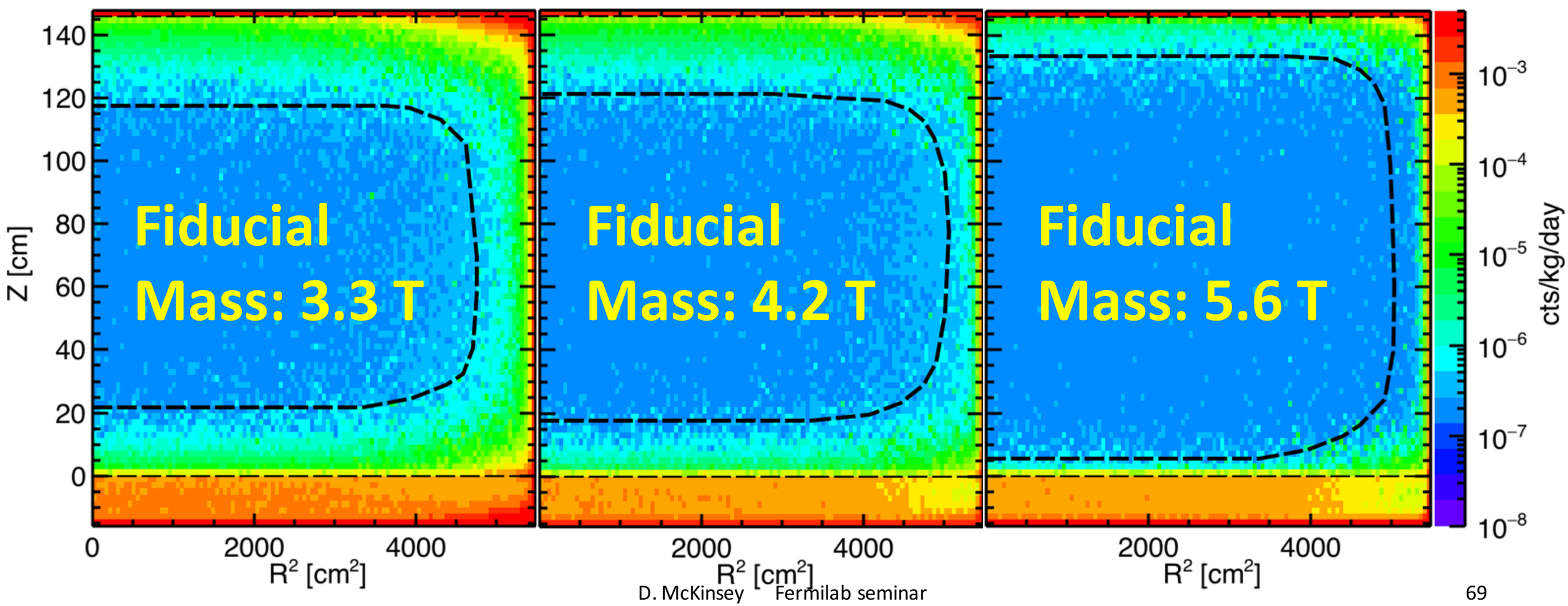




How to maximize the WIMP target mass?

- Two-component outer detector:
  - 0.75 m thick Gd-loaded scintillator
  - instrumented Xenon "skin"
  - tag neutrons and gammas

***in-situ* monitoring of residual backgrounds!!!**

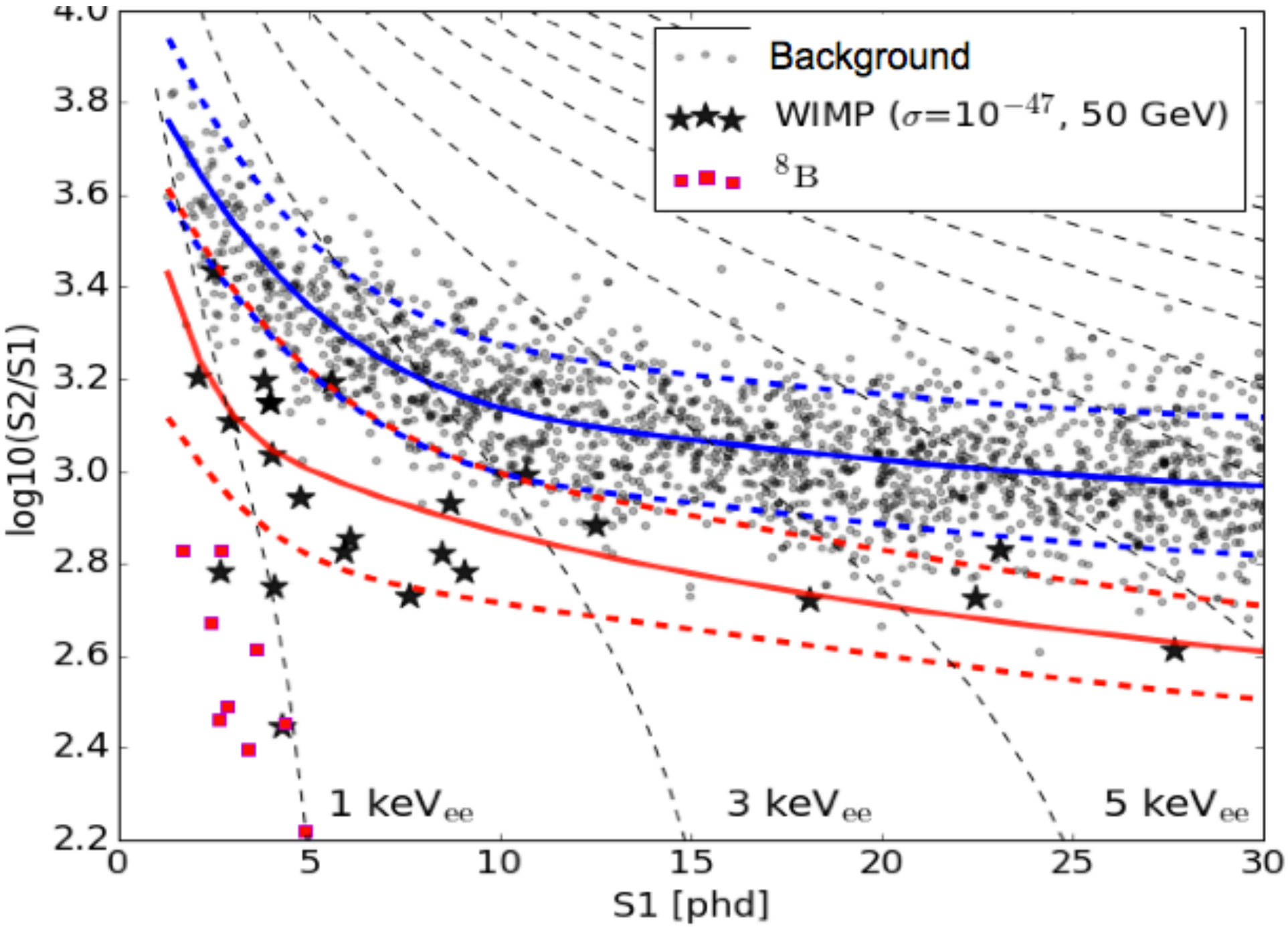


LZ Projected Backgrounds

Expected backgrounds for 5.6 T fiducial - 1,000 days

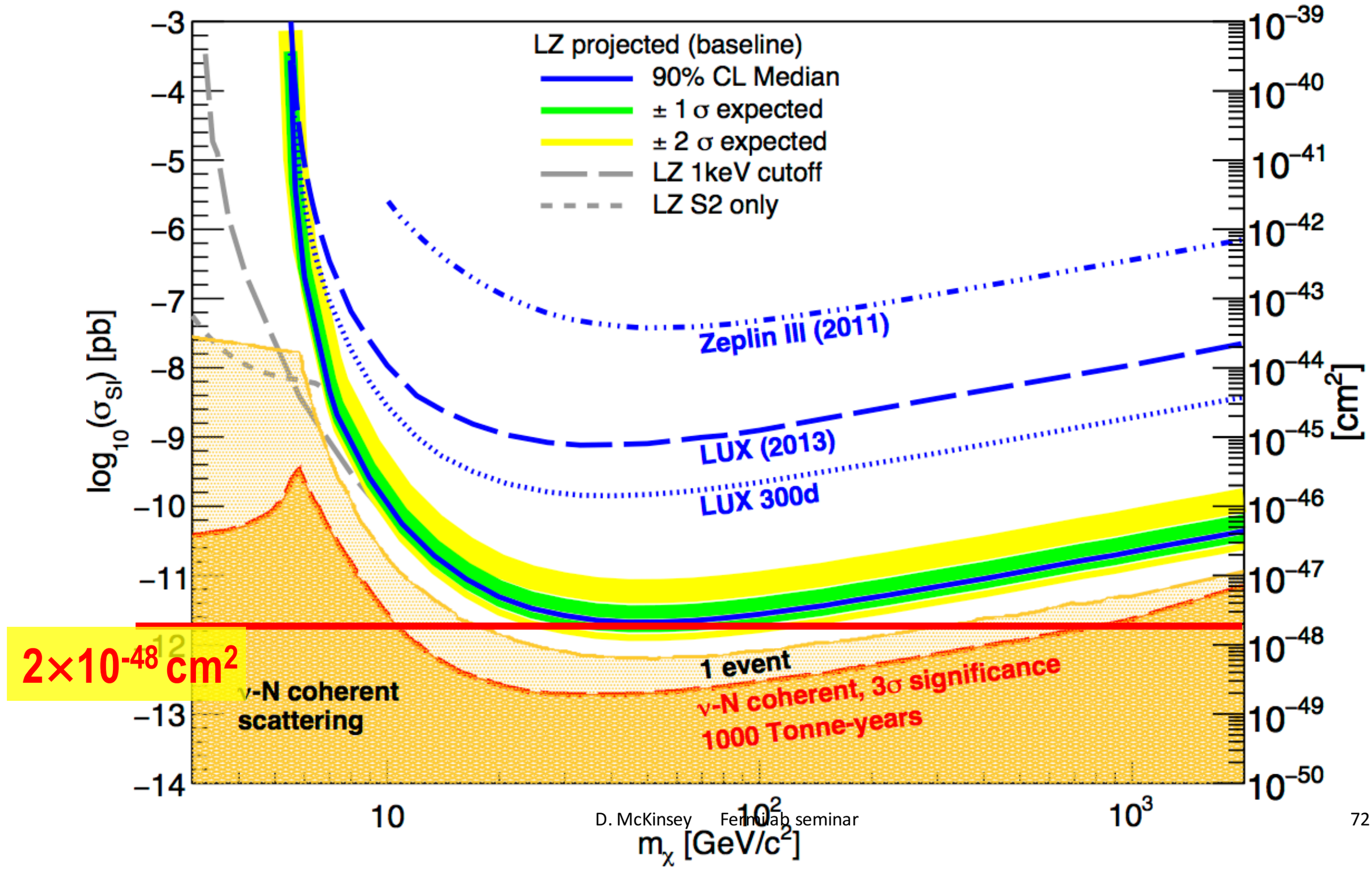
Item	Mass kg	U mBq/kg	Th mBq/kg	^{60}Co mBq/kg	^{40}K mBq/kg	n/yr	ER cts (ER)	NR cts (NR)
R11410 PMTs	93.7	2.7	2.0	3.9	62.1	373	1.24	0.20
R11410 bases	2.7	74.6	29.1	3.6	109.2	77	0.17	0.03
Cryostat vessels	2,140	0.09	0.23	≈0	0.54	213	0.86	0.02
OD PMTs	122	1,507	1,065	≈0	3,900	20,850	0.08	0.02
Other components	-	-	-	-	-	602	9.5	0.05
Total components							11.9	0.32
Dispersed radionuclides (Rn, Kr, Ar)							54.8	-
^{136}Xe 2νββ							53.8	-
Neutrinos (ν-e, ν-A)							271	0.5
Total events							391.5	0.82
WIMP background events (99.5% ER discrimination, 50% NR acceptance)							1.96	0.41
Total ER+NR background events							2.37	

Example LZ Exposure

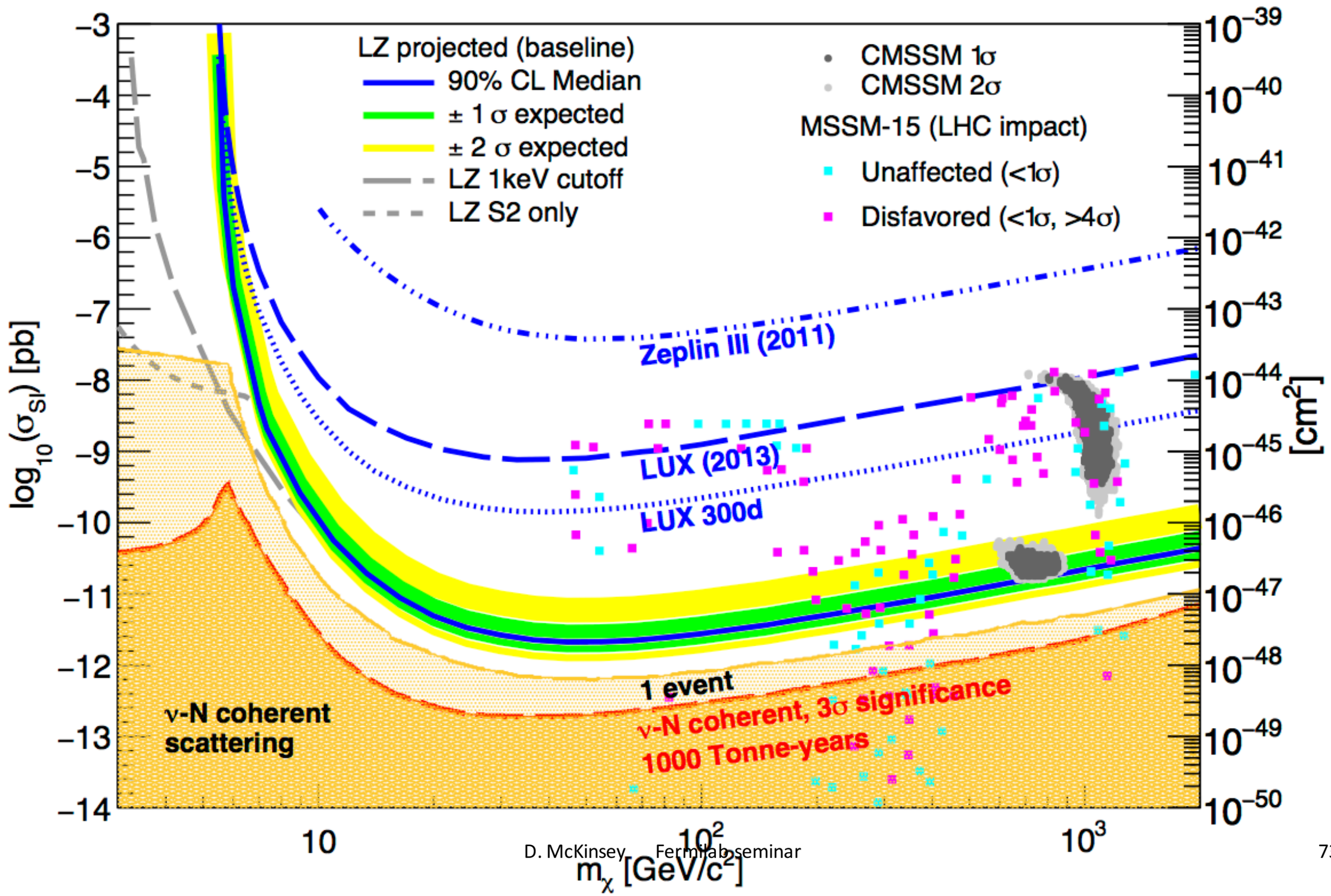


Projected Sensitivity – Spin Independent

(LZ 5.6 Tonnes, 1000 live days, 6 keV_{nr} analysis threshold)



Sensitivity with SUSY Theories

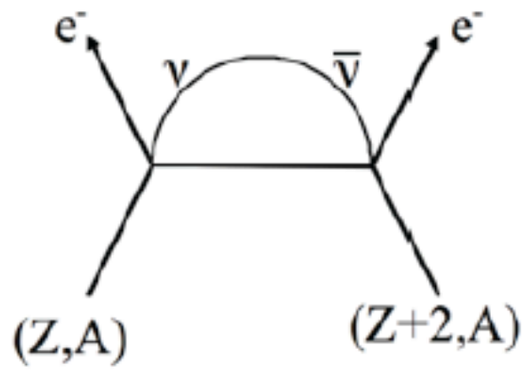


Neutrino Physics with LZ

- Neutrinoless Double Beta Decay of ^{136}Xe
  - Use self-shielding to reduce gamma-ray backgrounds in a 1-2 tonne fiducial mass
  - Projected sensitivity: 90% confidence level $T^{0\varpi}_{1/2}$ of 2 x 10^{26} years
  - Enriching the Xe target could increase this to ~ 2 x 10^{27} years
  - Current limit is 2.6 x 10^{25} years (preliminary) from KamLAND-Zen

- External Neutrino Physics
  - Solar neutrinos
    - Expect about 850 pp neutrino events between 1.5 and 20 keV_{ee}
  - Supernova neutrinos
    - Via flavor-blind coherent neutrino-nucleus scattering
    - For a 10 kpc SN, LZ would see about 50 events with energy > 6 keV_{nr} and 100 events > 3 keV_{nr}
  - Sterile neutrinos
    - Could use a 5 MCi ^{51}Cr source near LZ
    - Excellent position reconstruction for better source normalization, higher sterile neutrino masses.
  - Neutrino magnetic moment
    - Sensitivity near astrophysical limit of 2 x 10^{-12} Bohr magnetons.

What is 0νββ?



$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e-$

2νββ

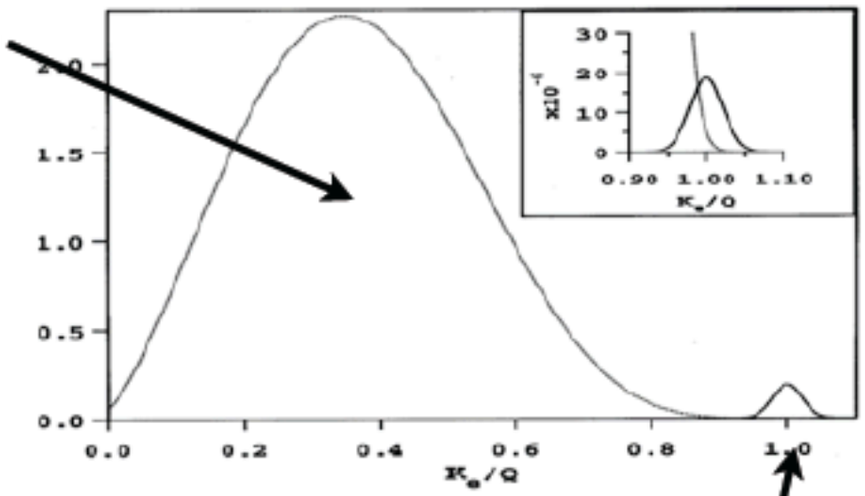


Figure from Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

0νββ

- Happens only if the ν_e is its own anti-particle (Majorana particle)
- Discovery implies
  - existence of Majorana particles
  - lepton number violation
  - B-L violation
- **Signal: mono-energetic, single site peak at 2458 keV**

Keys to Sensitivity

- **Large mass of isotope**
  - To measure > 10^{25} year half-life, need > 10^{25} particles
- **Low-background at Q-value**
  - Signal is small compared to typical ambient radioactivity
- **Energy resolution at Q-value**
- **Multiple scatter rejection**
  - Main backgrounds are gamma which prefer to Compton scatter or pair-produce

$0\nu\beta\beta$ In LZ

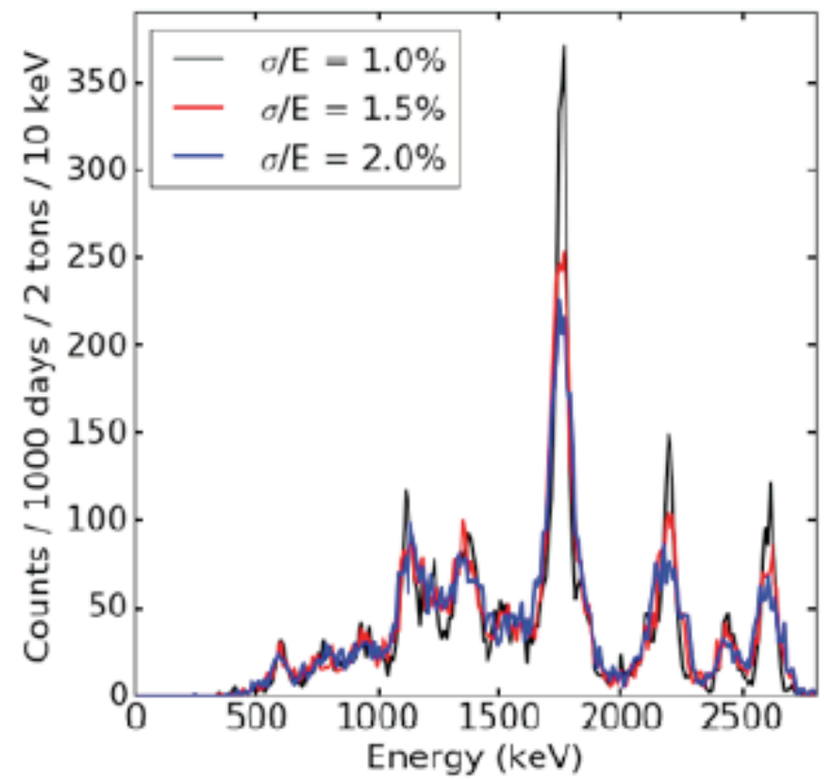
- 7 tons of active xenon => 620 kg ^{136}Xe (8.9% of natural Xe)
- Very low backgrounds
- Low-gain DAQ channel for dynamic range
- Use tight fiducial cut ($\geq$ 2 tons) to reduce backgrounds
- Xe TPCs have strong multiple scatter rejection capabilities (Compton scatters and pair-production dominate for > 1 MeV gammas)
- Punchline: with **NO ADDITIONAL UPGRADES** LZ can be a competitive search for $0\nu\beta\beta$

Energy Resolution (σ/E)

- EXO-200 experiment: 1.5% (@ 2.458 MeV, noise dominated)
- PiXeY detector: 0.8% (@ 2.615 MeV)
- MiX detector: 1.0% (@ 1.33 MeV)
- LZ Requirement R-150004: 2.0% @ 2.5 MeV

Backgrounds

- Main background comes from Xe vessels and insulation
- Background from from vessel dominate
- Table is for 2-ton exposure, ± 2 σ window for 1000 days
  - **NOT** using optimized fiducial volume

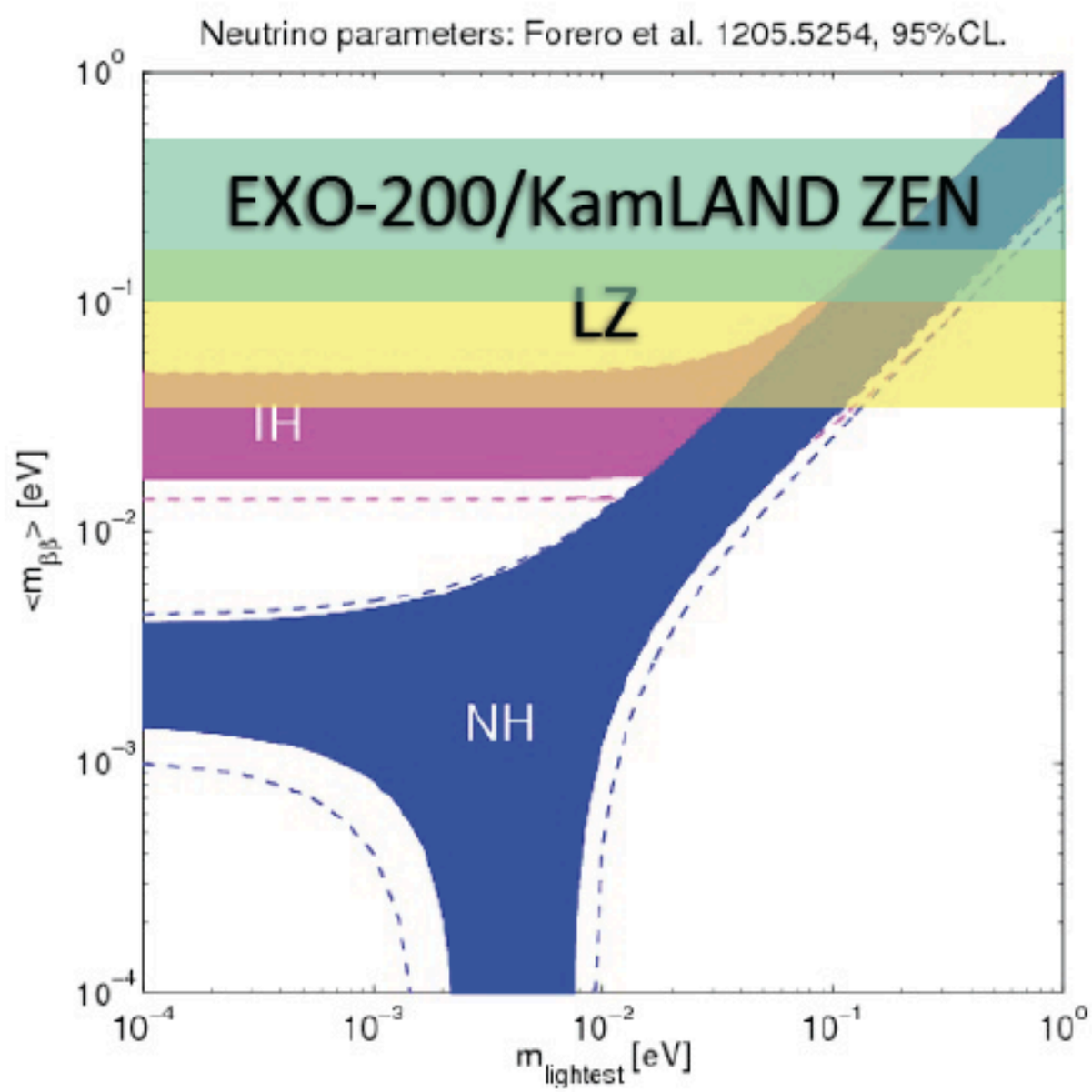


Item	1.0% σ/E	1.5% σ/E	2.0% σ/E
TPC PMTs	< .01	0.05	0.18
Skin PMTs	< .01	0.02	0.02
Xe Vessels	2.5	2.7	3.2
Vessel Seals	< .01	< .01	0.03

Sensitivity

σ/E	1.0%	1.5%	2.0%
Half-life	4.0 X 10^{26} years	2.5 X 10^{26} years	1.8 X 10^{26} years
Neutrino mass	35-110 meV	45-140 meV	60-160 meV

Limits based on Feldman-Cousins cut-and-count analysis on an optimized fiducial volume (for each scenario)



LZ Timeline (latest following budget reprofiling)

Year	Month	Activity
2012	March	LZ (LUX-ZEPLIN) collaboration formed
	May	First Collaboration Meeting
	September	DOE CD-0 for G2 dark matter experiments
2013	November	LZ R&D report submitted
2014	July	LZ Project selected in US and UK
2015	April	DOE CD-1/3a approval, similar in UK
		Begin long-lead procurements(Xe, PMT, cryostat)
2016	April	DOE CD-2/3b approval, baseline, all fab starts
2017	June	Begin preparations for surface assembly @ SURF
2018	July	Begin underground installation
2020	Jan	Cooldown/start of commissioning

Conclusions

- LXe is the pre-eminent target for WIMPs of mass > 4 GeV.
- New LUX analysis reaches a 90% exclusion limit of **6×10^{-46} cm^2**
- The LXe 2-phase approach benefits from continued improvements in calibration techniques and understanding of background.
- The LZ Project is well underway, with procurement of Xe, PMTs and cryostat vessels started
- LZ commissioning to begin in 2019
- Extensive prototype program underway
- LZ sensitivity expected to reach **$1\text{-}2\times10^{-48}$ cm^2**

Who has seen the WIMP?

Neither I nor you.

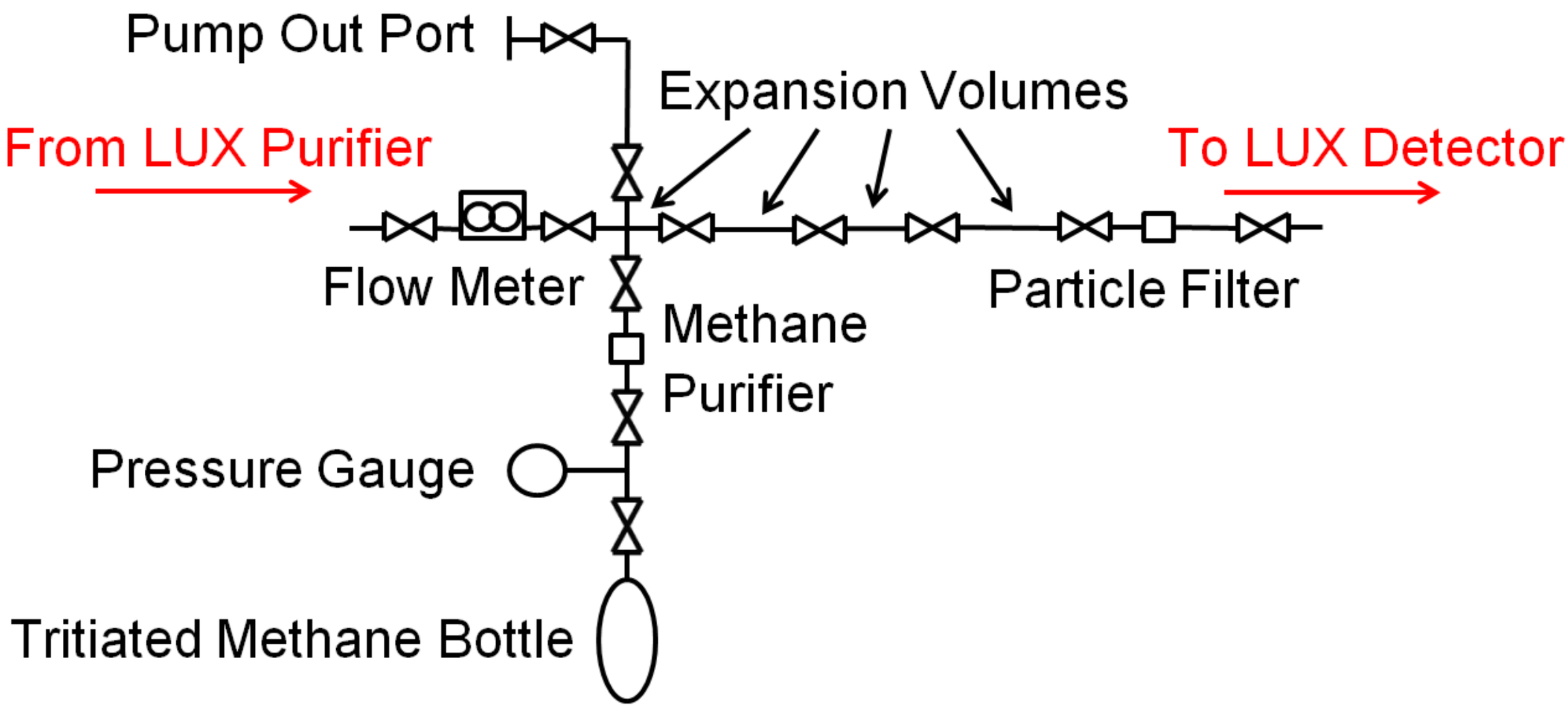
But when the liquid xenon flashes in the time projection chamber

Dark Matter is passing through.

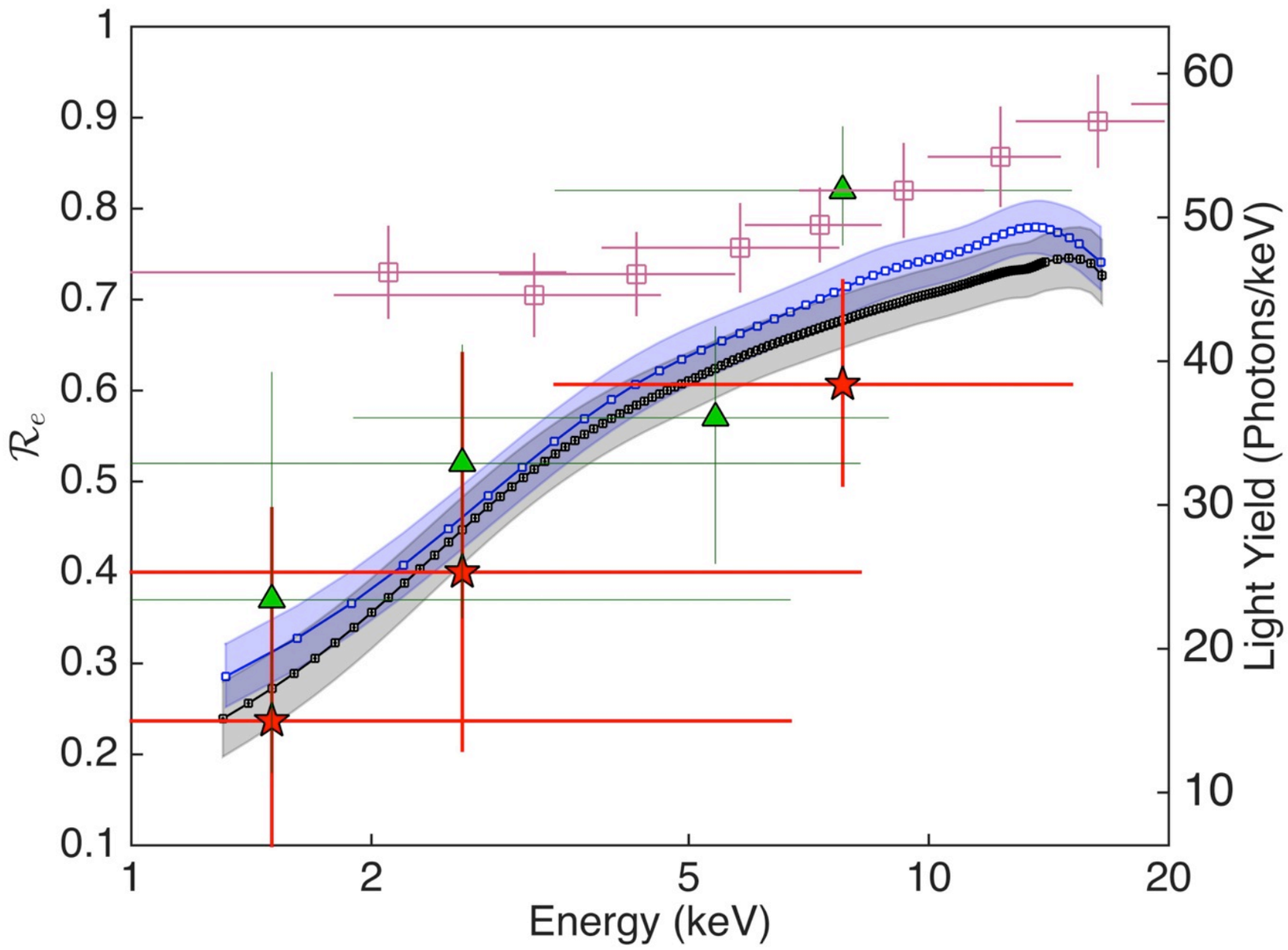
DM and Eva Allan

(with apologies to Christina Rossetti)

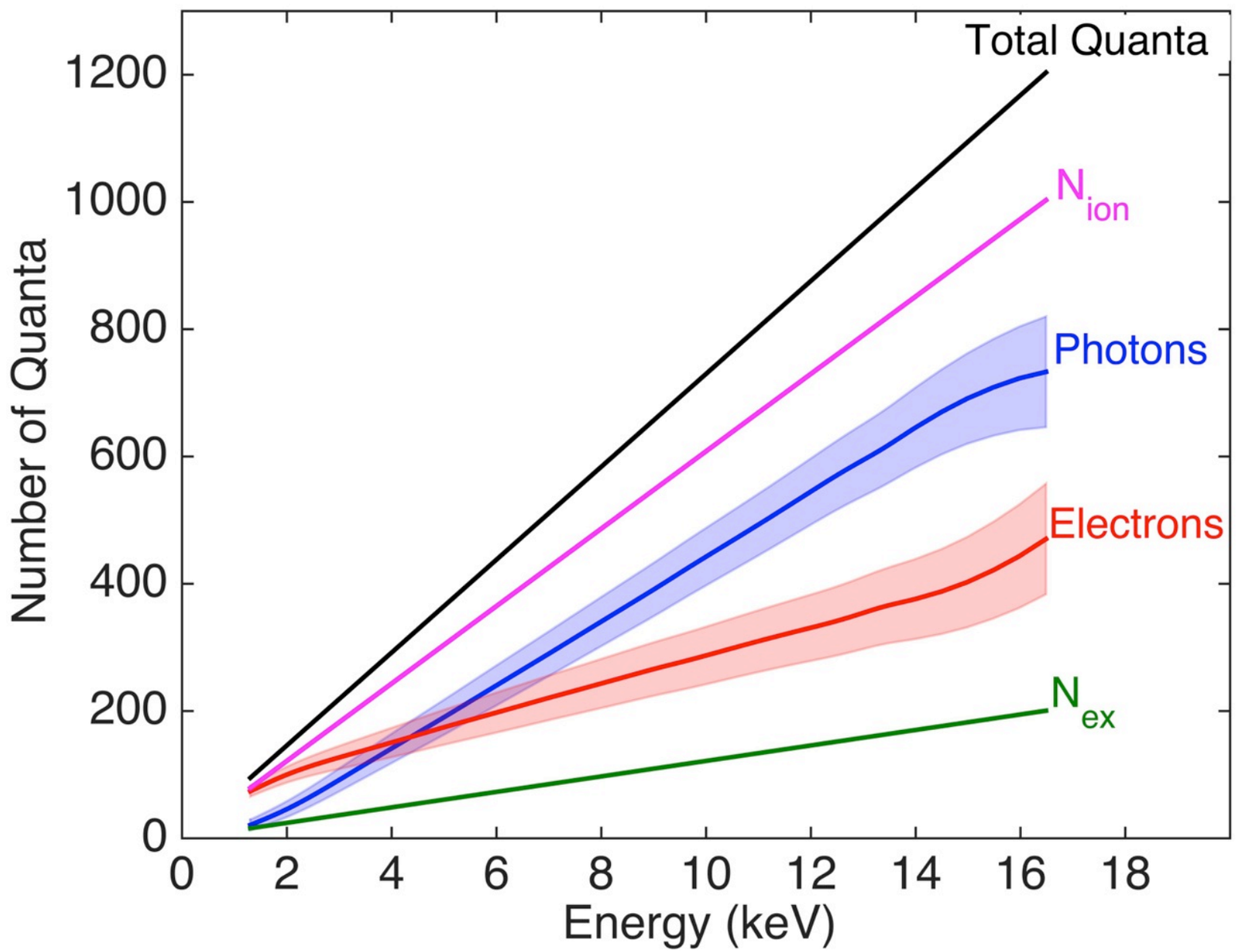
Tritiated Methane injection system



Recombination and Light Yield

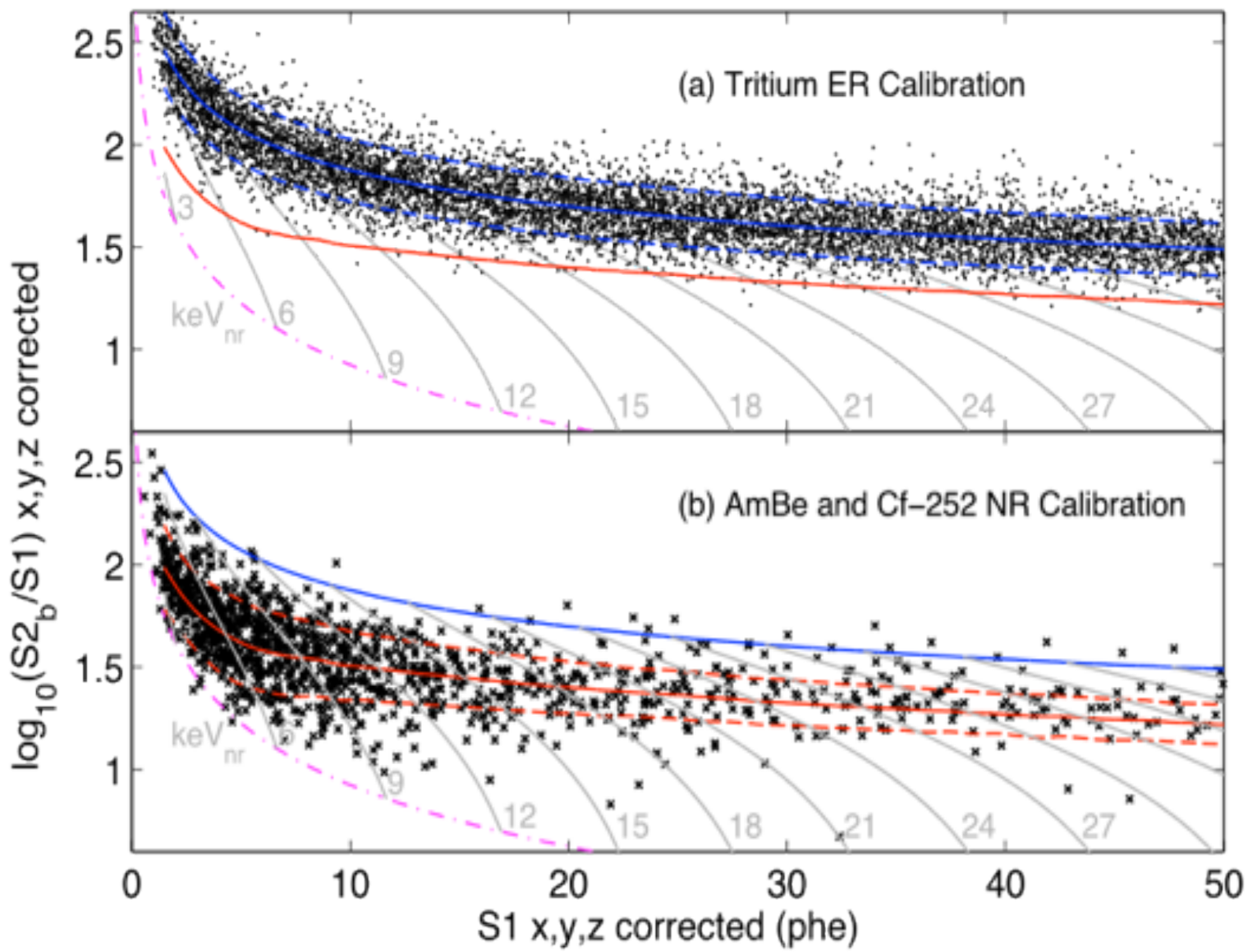


Total Quanta (electrons +photons) for electron recoils in LXe

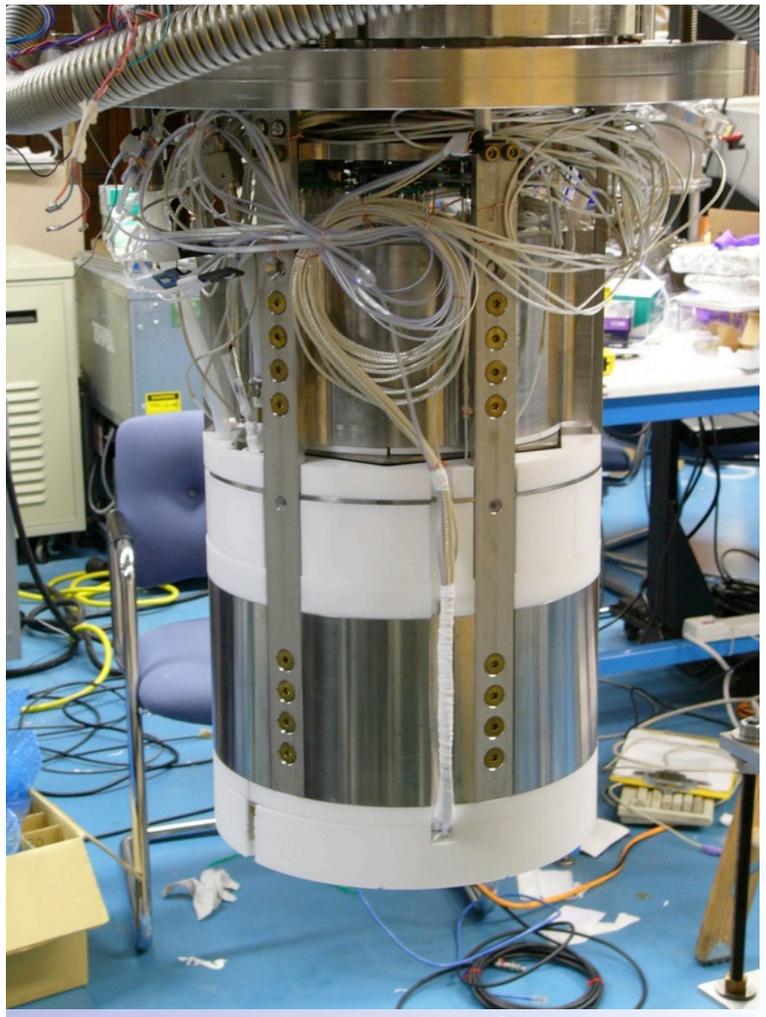


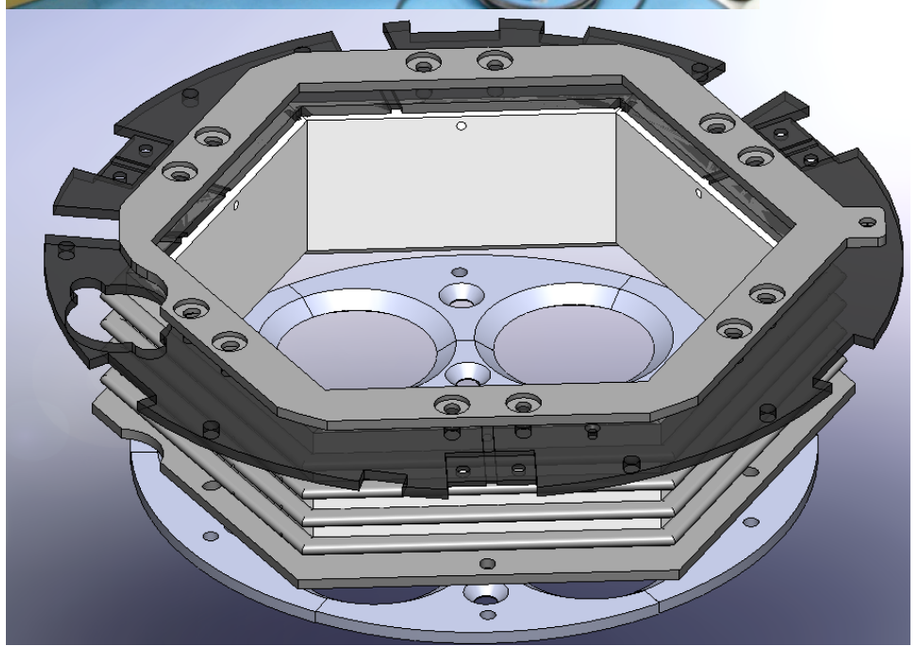
Why High Cathode Voltage?

- Higher cathode voltage means higher drift field, and more charge extracted from tracks.
- Higher drift field means better electron recoil discrimination, by suppressing recombination and thereby better isolating the ionization/atomic excitation ratio, which is different for electron and nuclear recoils.
- In LUX we see 99.6% discrimination at 181/cm.
- Higher drift field is expected to improve discrimination, reducing backgrounds from pp-solar neutrinos, Kr-85, Rn daughters, and gamma rays.

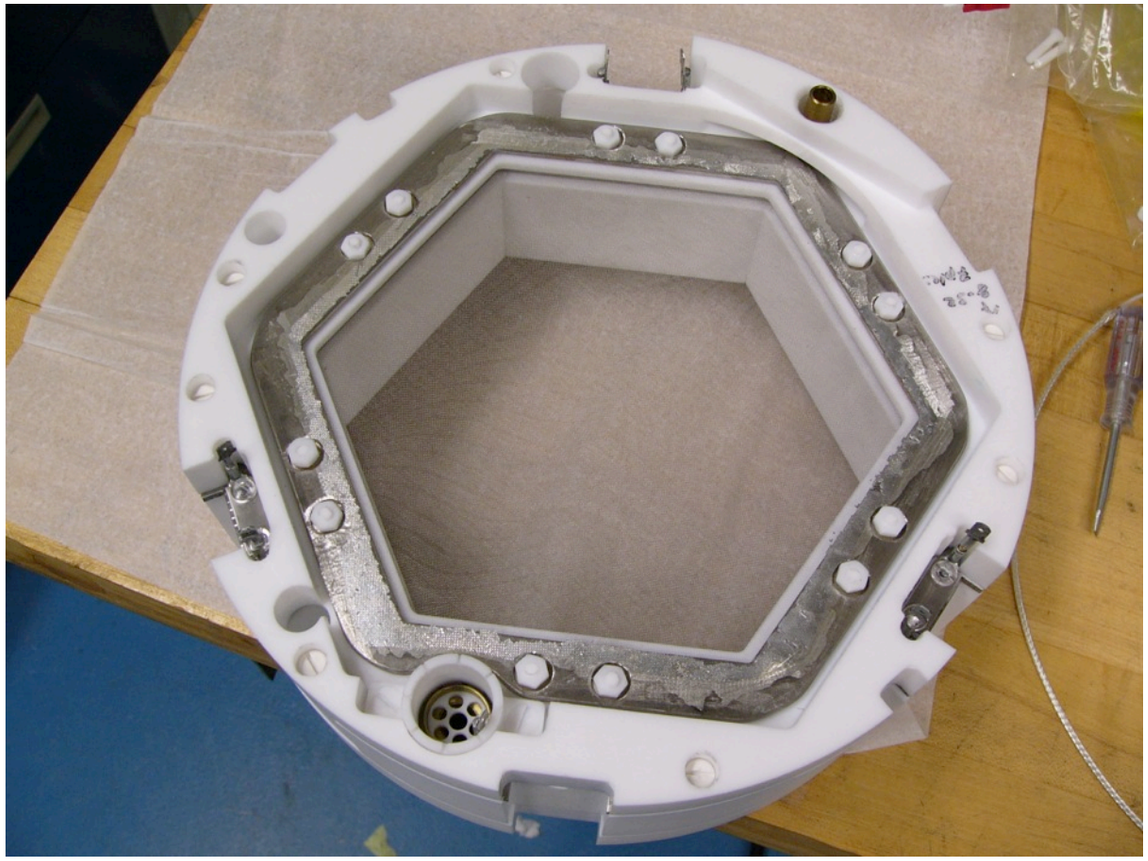


PIXeY – Particle Identification in Xenon at Yale

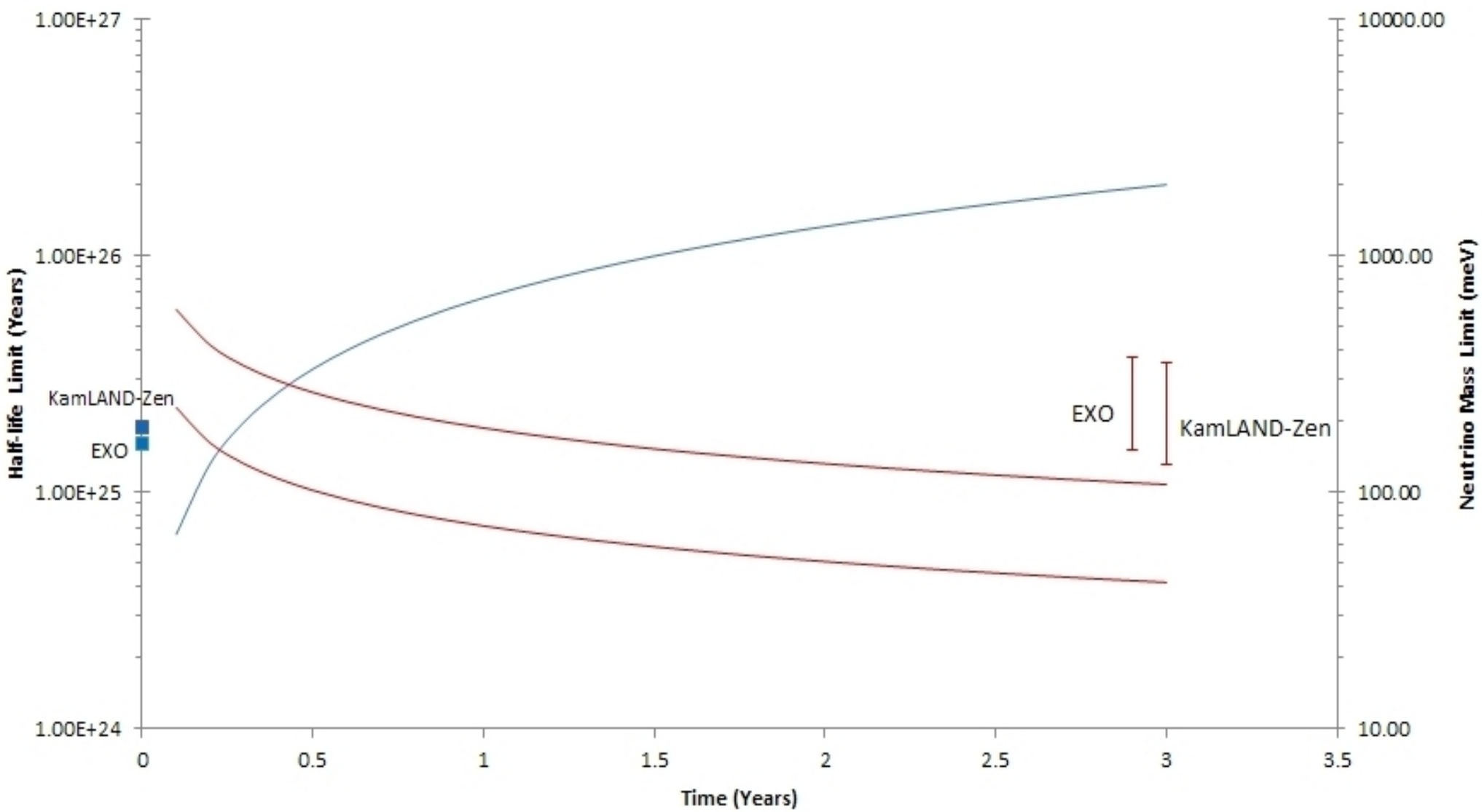




- Currently supported by DHS Academic Research Instrumentation program: $400k/year.
- Two-phase Xe detector; 4 kg active xenon volume.
- Designed for optimal light collection and strong drift field.
- Currently operating at Yale.
- R&D platform for studying
  - Gamma-neutron (a.k.a. beta-WIMP) discrimination
  - Energy resolution (relevant for neutrinoless DBD)
  - Calibration with gaseous sources
  - Gamma ray imaging



LZ Expected Performance Over 3 years



- After 3 years of operation, half-life limit is 1.99 x 10^{26} years

Conclusion

- LUX has made a WIMP Search run of 86 live-days and released the analysis + PRL submission within 9 months of first cooling in Davis Lab
  - Backgrounds as expected, inner fiducial ER rate <2 events/day in region of interest
  - Major advances in calibration techniques including ^{83m}Kr and Tritiated-CH_4 injected directly into Xe target
  - Very low energy threshold achieved 3 keVnr with no ambiguous/leakage events
  - ER rejection shown to be 99.6+/-0.1% in energy range of interest

- Intermediate and High Mass WIMPs
  - Extended sensitivity over existing experiments by x3 at 35 GeV and x2 at 1000 GeV

- Low Mass WIMP Favored Hypotheses ruled out
  - LUX WIMP Sensitivity 20x better than XENON100
  - LUX does not observe 6-10 GeV WIMPs hinted at by earlier experiments

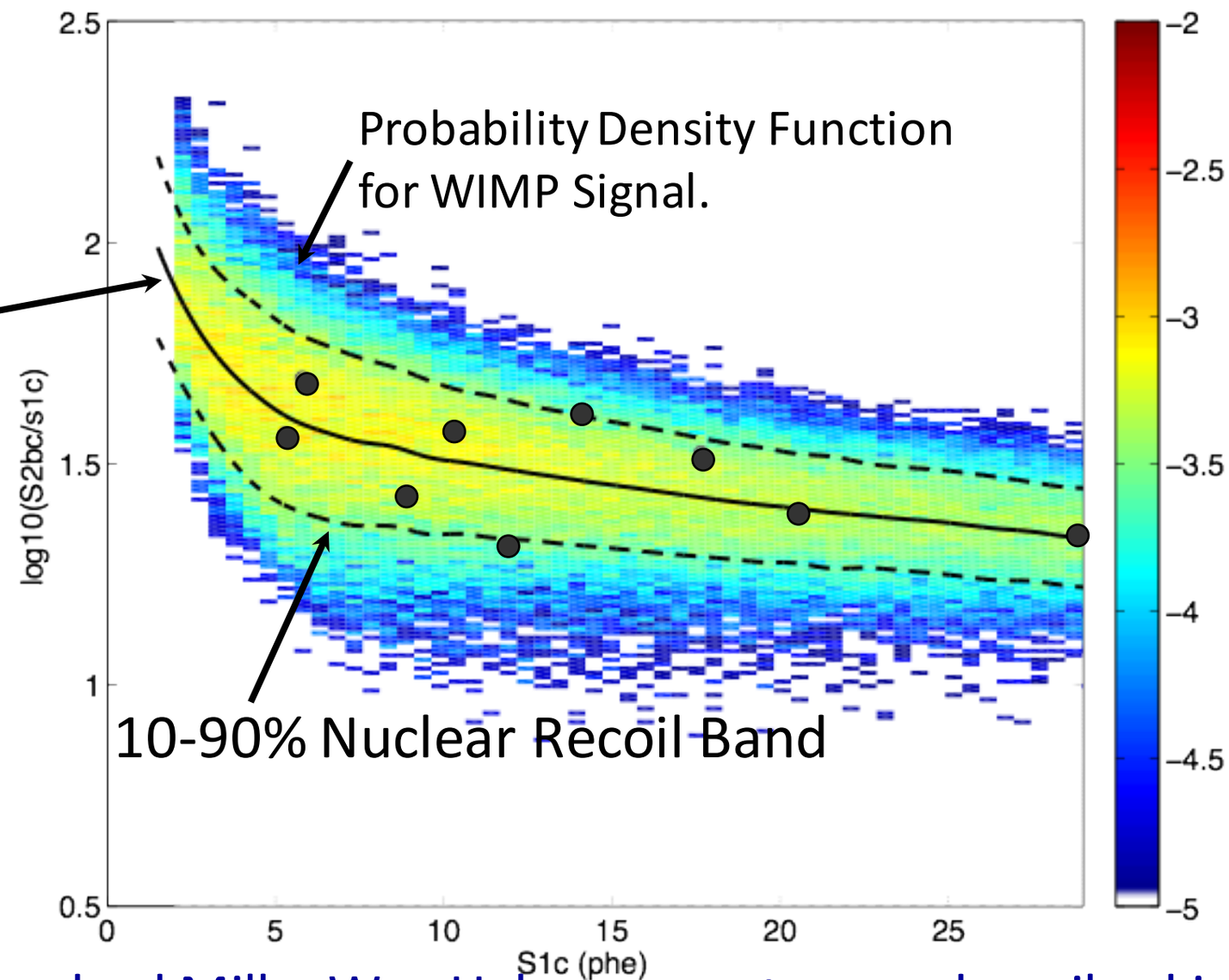
- More LUX analyses underway or under consideration
  - In situ calibration using a monoenergetic neutron beam
  - Improved limits at low WIMP mass, using new calibration data
  - Impact of LUX data on other WIMP interaction models (spin-dependent, plus larger set of operators)
  - Solar and galactic axion searches
  - Neutrino magnetic moment search
  - Etc… (anything that benefits from low background + low threshold)

- The LZ Detector is being designed
  - Projected sensitivity 1000 times better than LUX
  - Will replace LUX in the Davis cavern water tank

Simulated WIMP Signals for 85 days, 118 kg

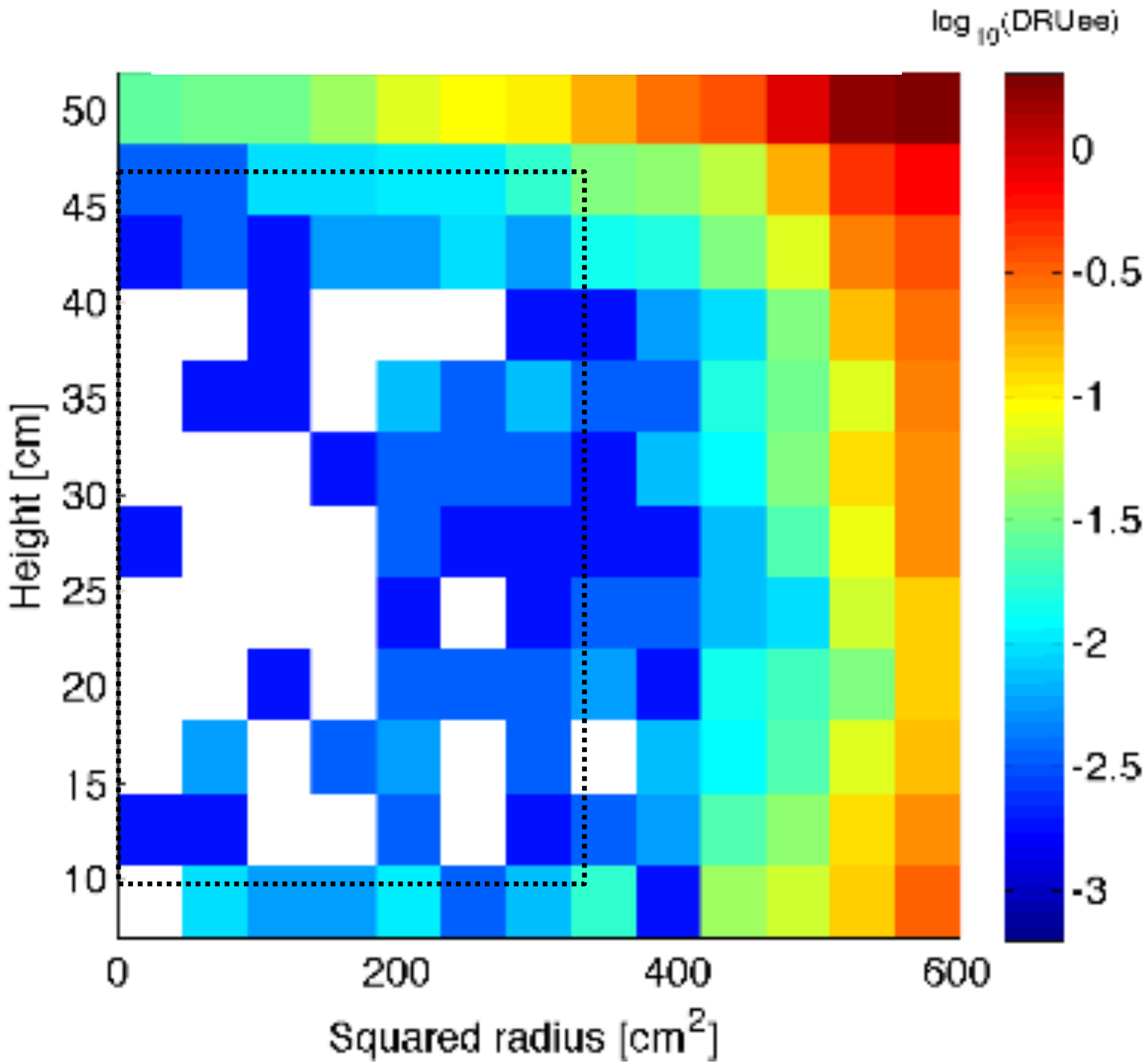
- Pick a mass of 1000 GeV and cross section at the existing XENON100 90% CL Sensitivity 1.9 x 10^{-44} cm^2 - Would expect 9 WIMPs in LUX Search

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



- PDF assumes Standard Milky Way Halo parameters as described in Savage, Freese, Gondolo (2006) v_0=220 km/s, v_{escape} = 544 km/s, ρ_0 = 0.3 GeV/c^2, v_{earth} = 245 km/s

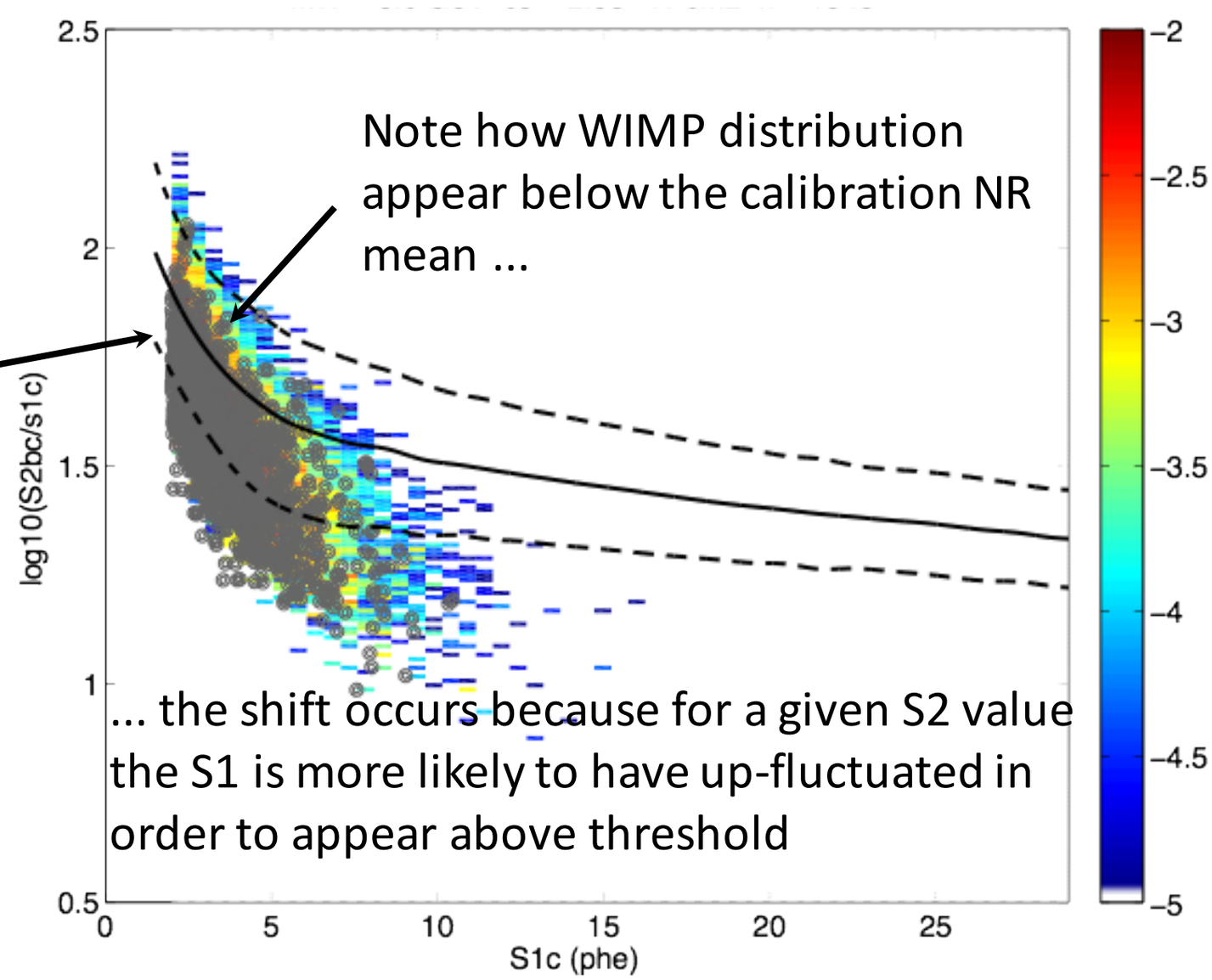
And it continues to get quieter - Xe Cosmogenic Activity cools (rate in 44 days)



Simulated WIMP Signals for 85 days, 118 kg

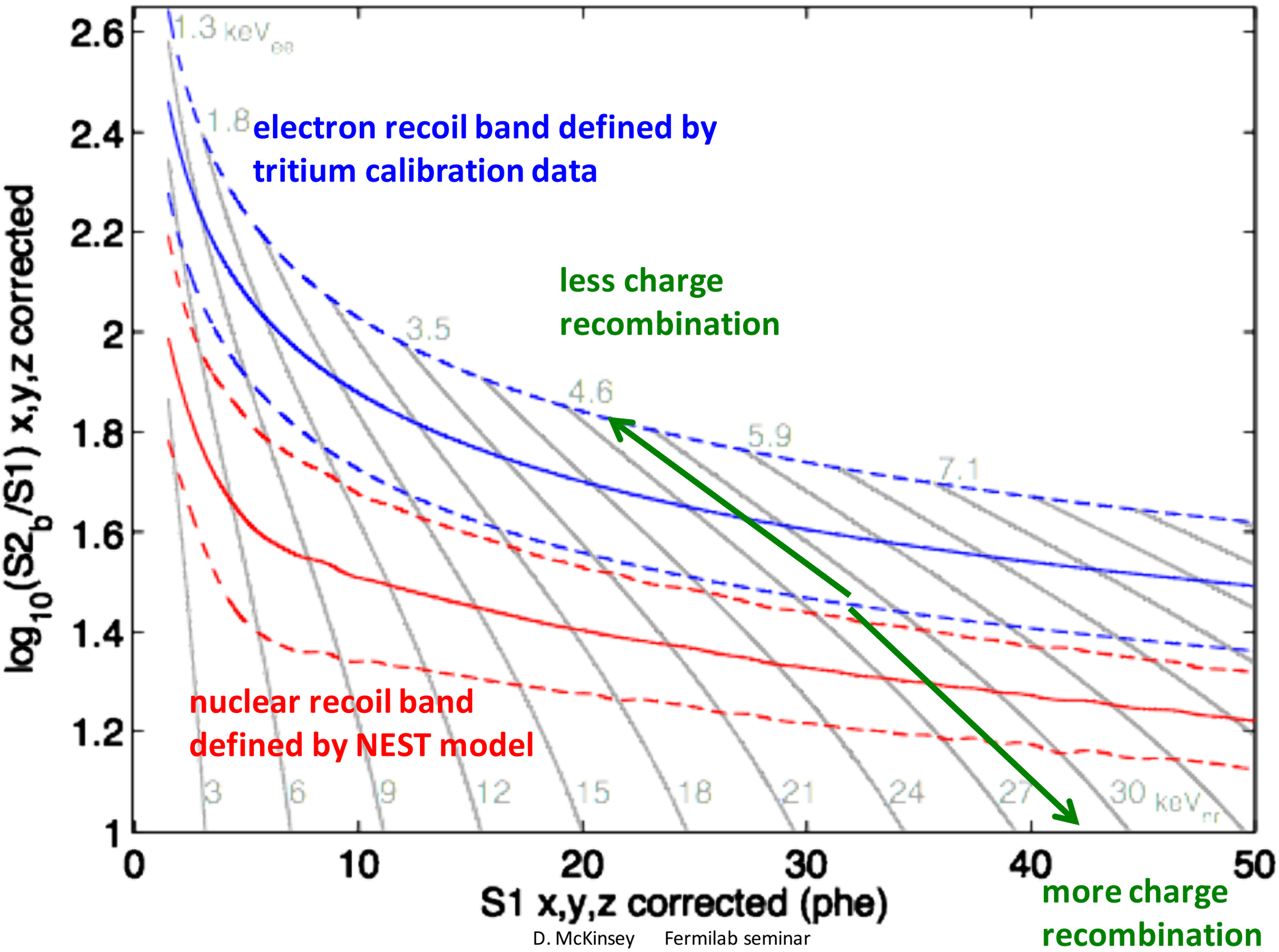
- At a mass of 8.6 GeV and cross section favored CDMS II Si (2012) cross section 2.0 x 10^{-41} cm^2 - Expect 1550 WIMPs in LUX Search

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

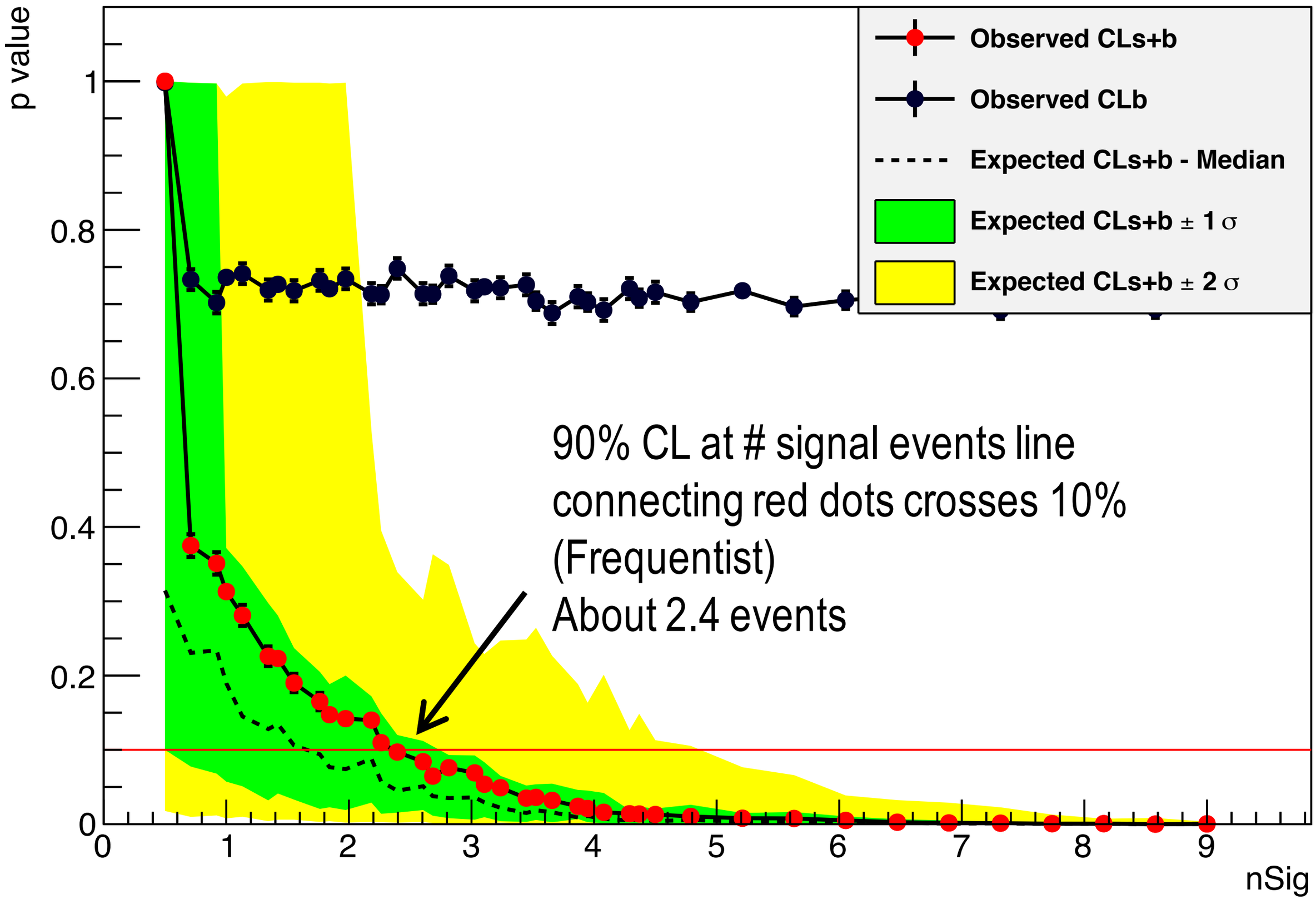


- The shift in the WIMP PDF downwards improves the effective ER event leakage fraction

LUX keV_{ee} and keV_{nr} energy scales

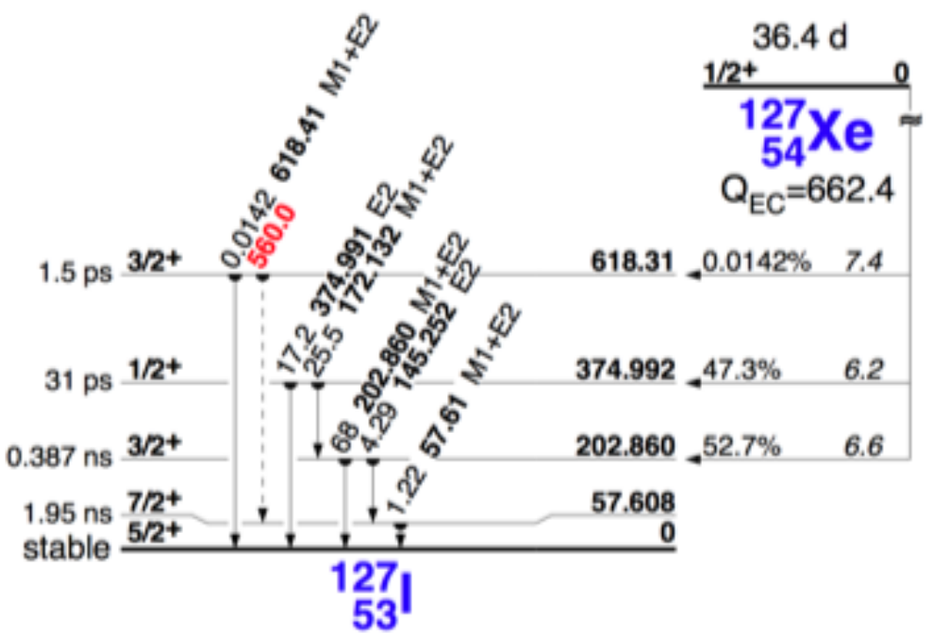


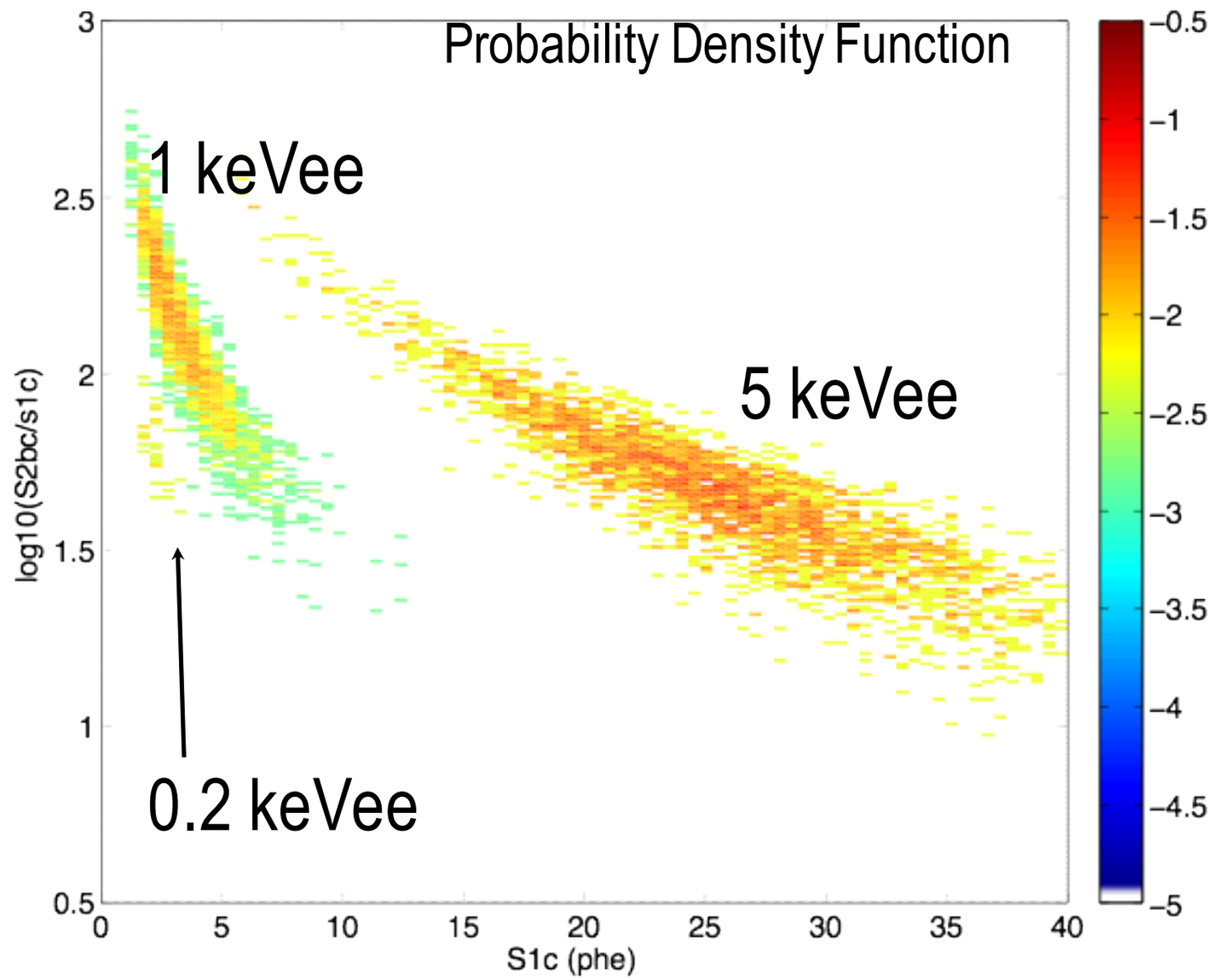
WIMP Mass 7 GeV Limit



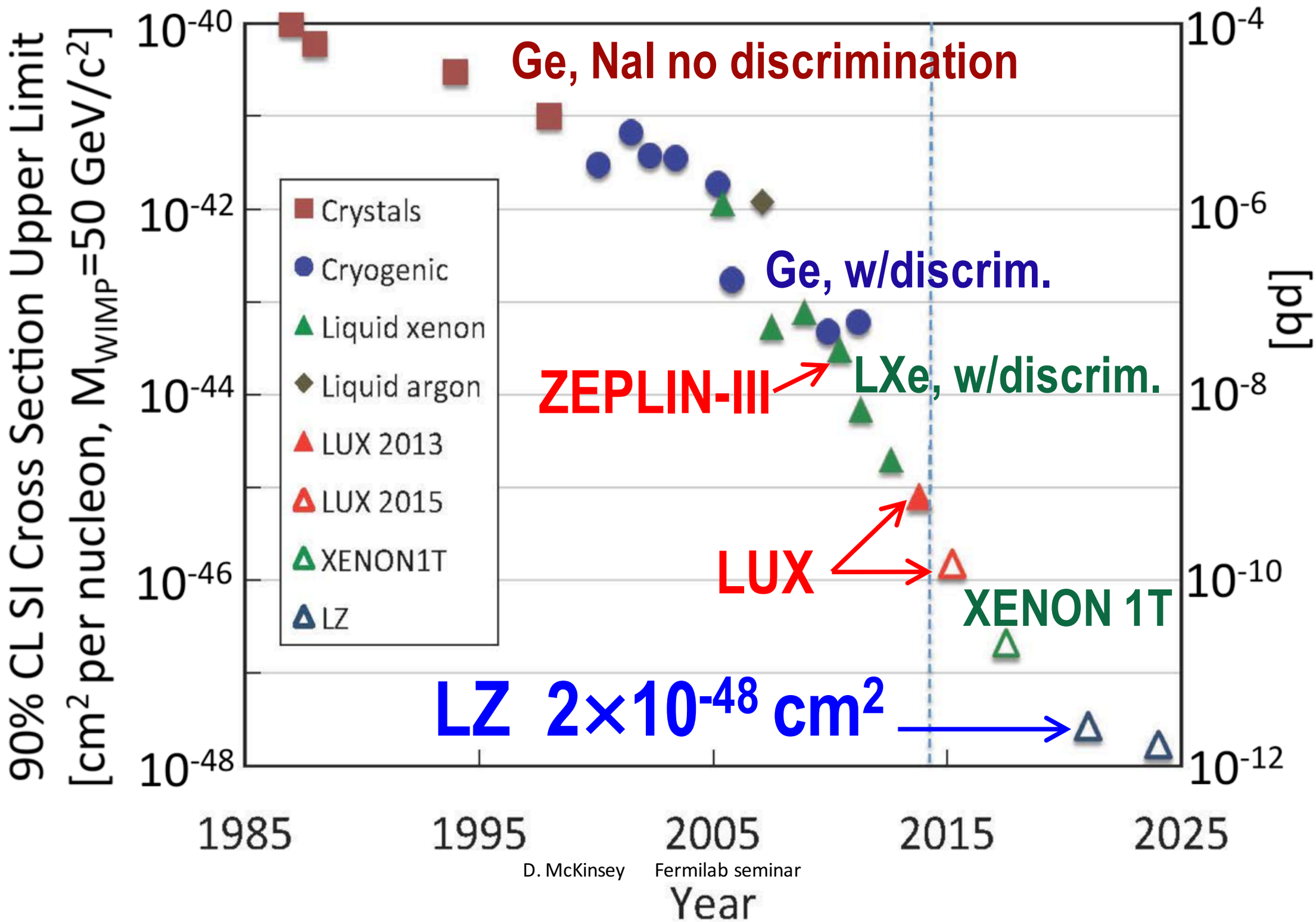
127Xe Electron Capture - Simulation

- x-ray line emission in center of detector following full escape of gamma associated with nuclear excited state





Time Evolution



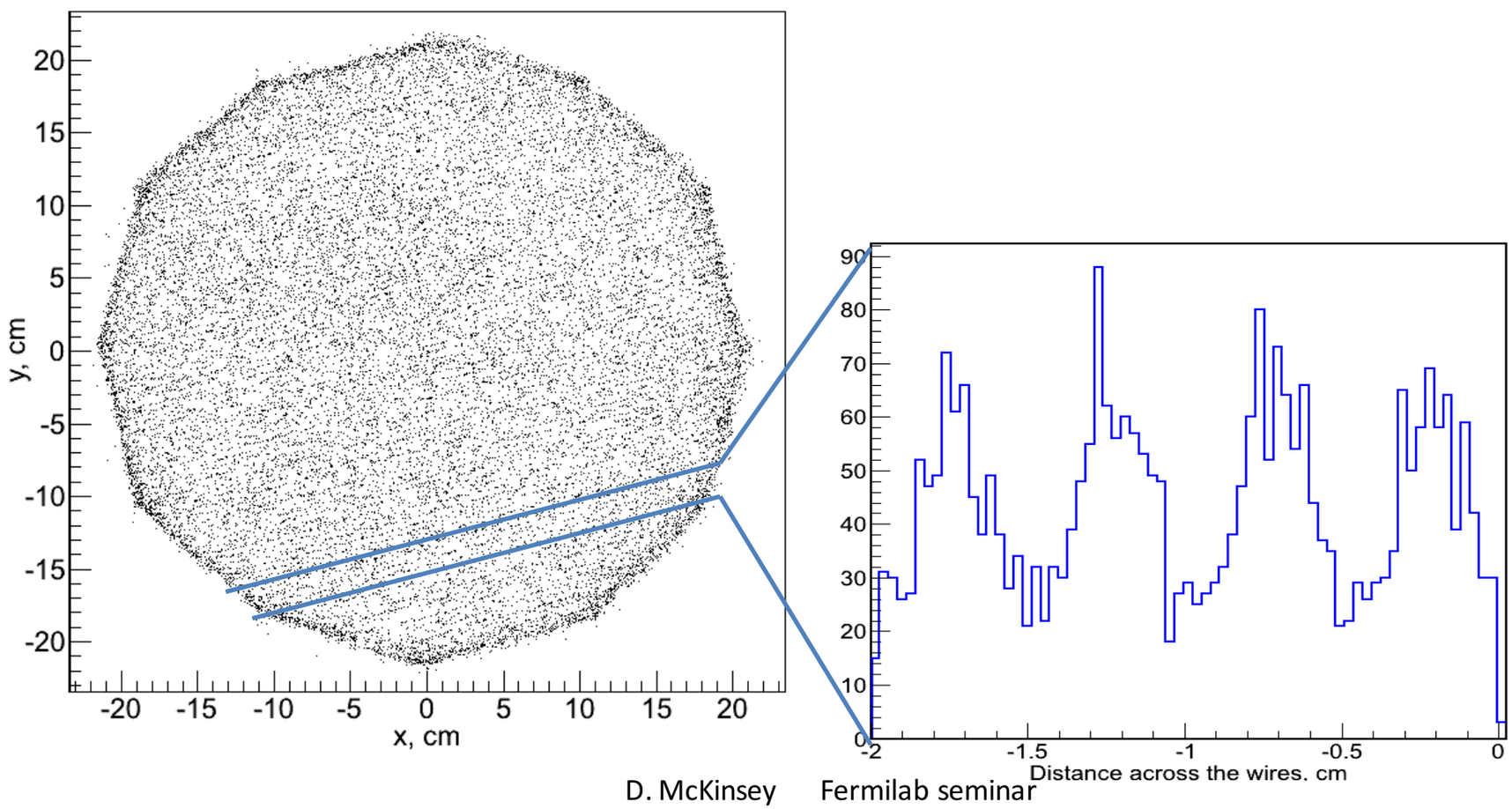
XYZ Position Reconstruction

Z coordinate is determined by the time between S1 and S2
(electron drift speed of 1.51 mm/microsecond)

Light Response Functions (LRFs) are found by iteratively fitting the distribution
of S2 signal for each PMT.

XY position is determined by fitting the S2 hit pattern relative to the LRFs.

Reconstruction of XY from alpha events near the anode grid resolves grid wires with 5 mm pitch.



LUX WIMP Search Summary
(or, how did you spend your summer?)

- April 21 - August 8, 2013 - 110 calendar days
  - 85.3 live days of WIMP Search
  - 118.3+/-6.5 kg fiducial mass

- Calibrations
  - Frequent injected ^{83m}Kr calibration to correct for any S1 or S2 gain shifts
  - AmBe&Cf calibrations+Sims to define NR band
  - Injected Tritiated Methane defines full ER band at all relevant energies

- Efficiency
  - Efficiency for WIMP event detection was studied using data from calibration sets using multiple techniques and all were all shown to be consistent with one another

LUX WIMP Search Summary /2

- Data Analysis and Blinding

  - The Xe Target inner fiducial volume is very simple, it sits inside a larger volume of Xe with only a "virtual" surface dividing them
    - Modeling of extrinsic and intrinsic background signals in large monolithic Xe volume has low systematics

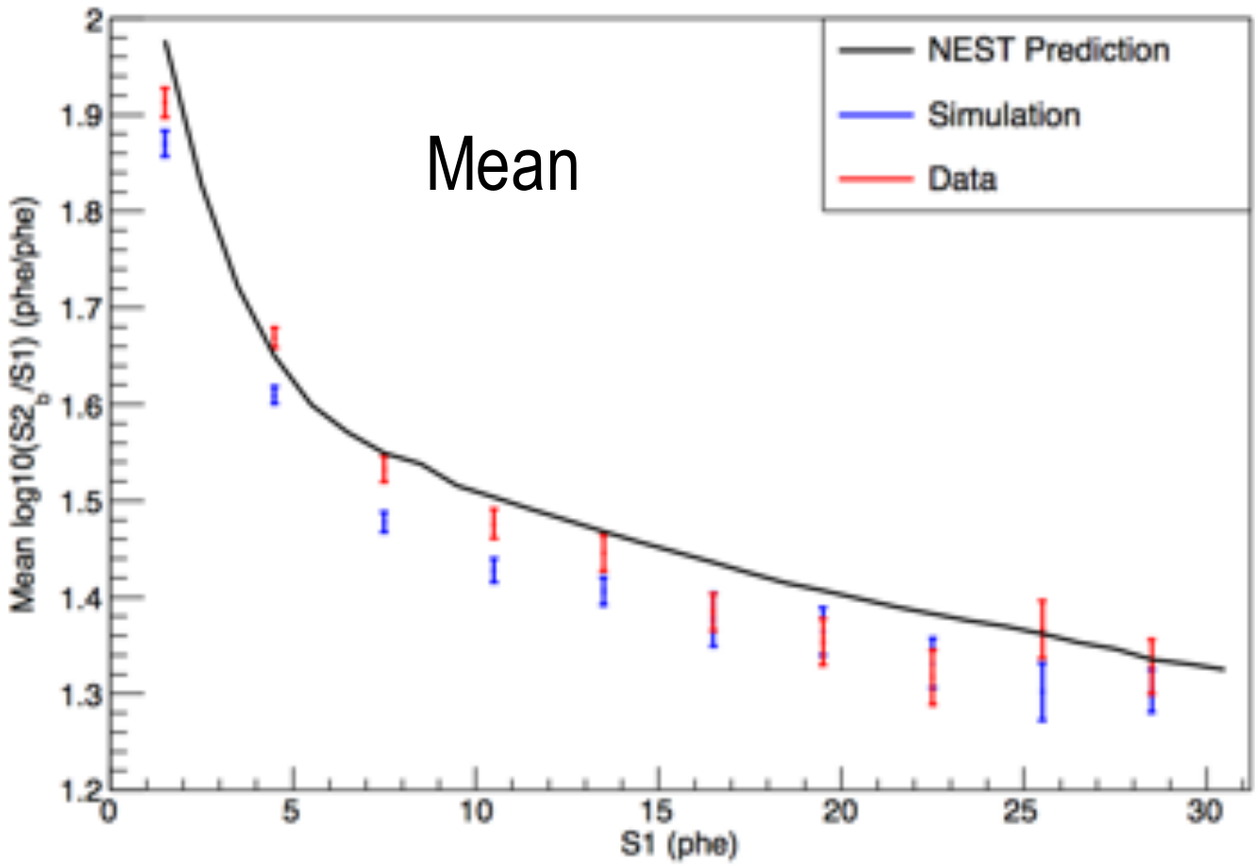
  - No blinding was imposed for the first WIMP data analysis
    - We aimed to apply minimum set of cuts in order to reduce any tuning of event cuts/acceptance.
    - The cuts list is very short ...

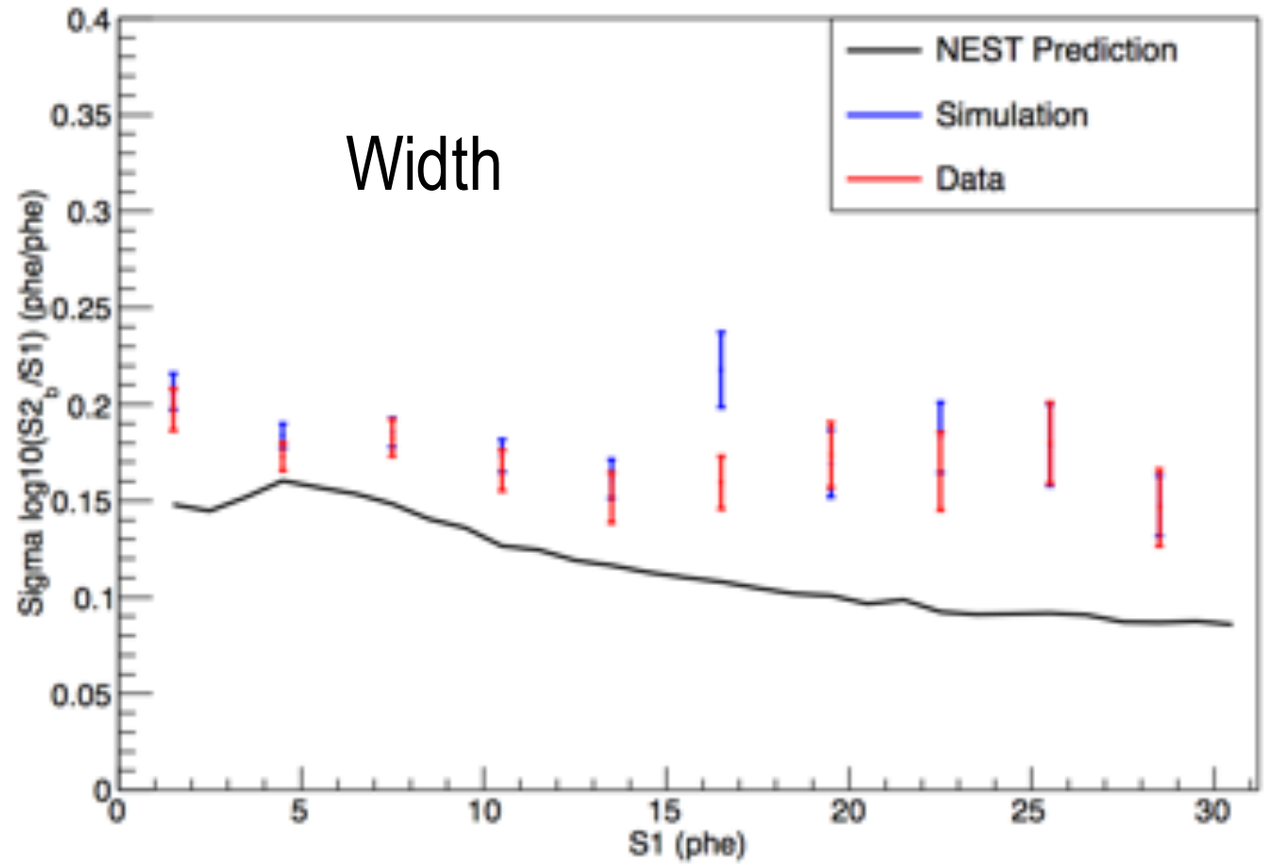
  - Fiducial Volume was selected based on requirement to keep low energy events from grid and teflon surface out of WS data. Primarily alpha-decay events.
    - Low energy alpha-parent nuclear recoil events generate small S2 + S1 events. Studies position reconstruction resolution. Tested using data outside WIMP search S1 energy range. This ensured that position reconstruction for sets were similar, and definition of fiducial was not biased.

  - Use of Profile Likelihood Ratio (PLR) analysis means we don't have to draw acceptance boxes
    - This avoids potential bias in data analysis from selecting regions in S1,S2 signal-space

  - Inputs for Profile Likelihood Ratio analysis were developed using high statistics in situ calibrations, with some simulations to cross check

NR Calibrations

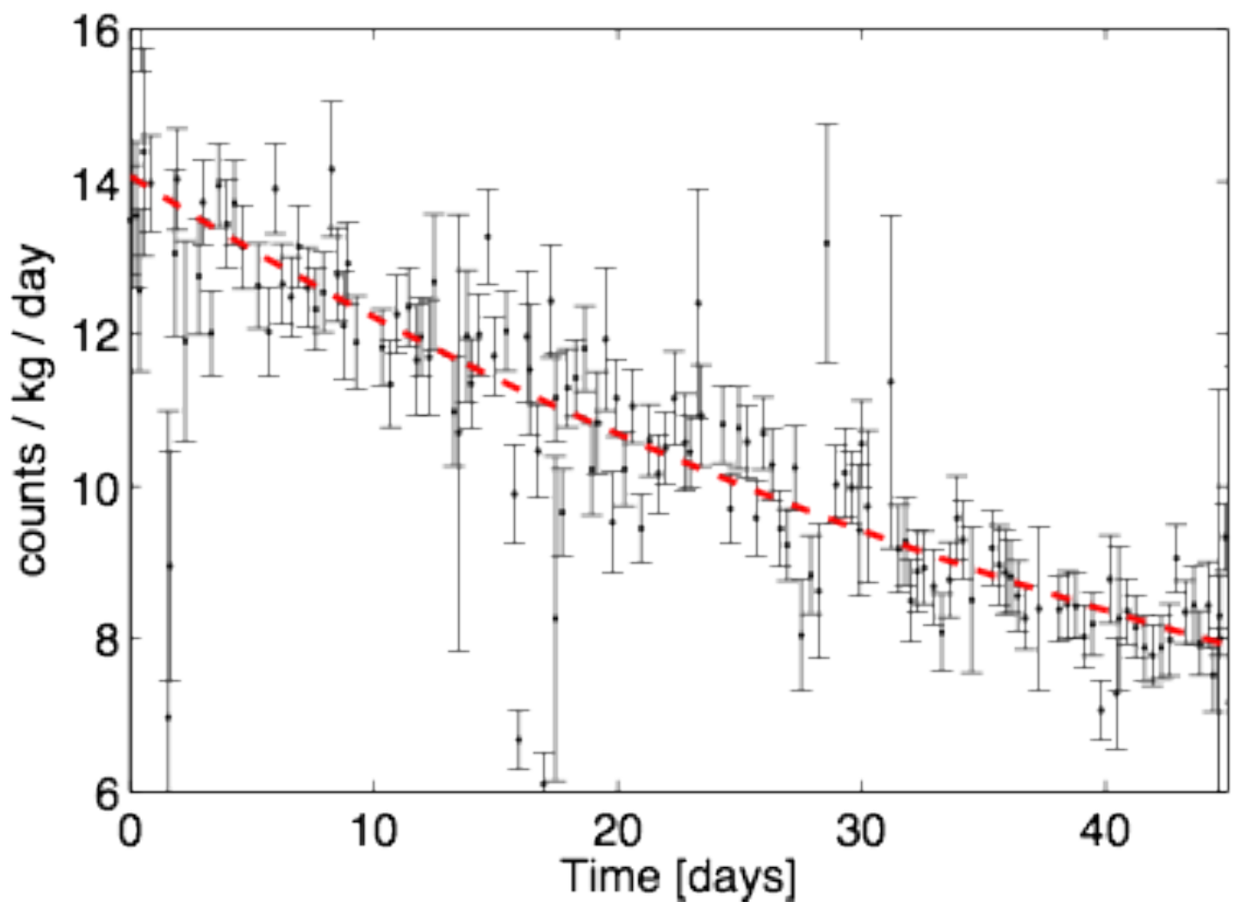




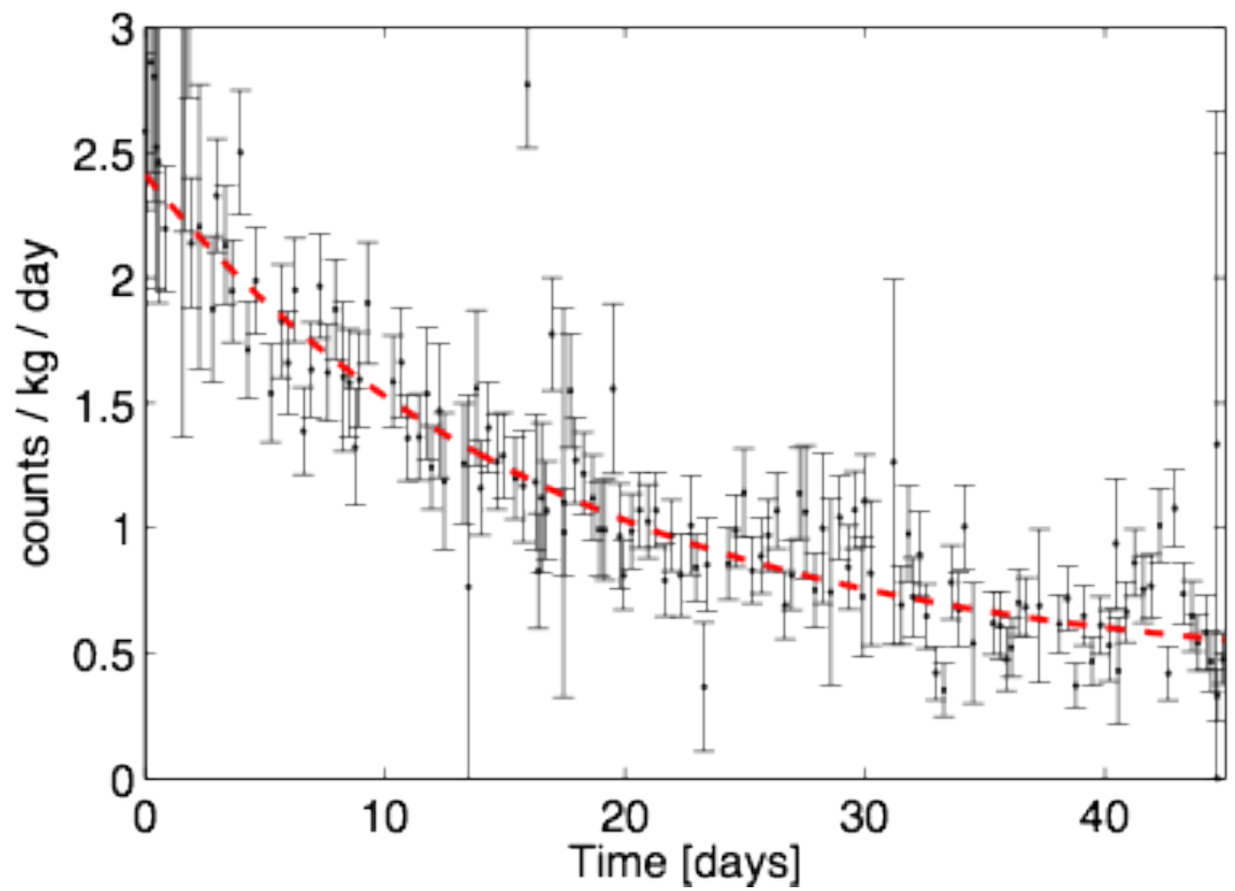
- Above plots show comparisons between simulation (blue), the NEST prediction (black), and data for the mean and width of the nuclear recoil band from AmBe calibrations
- The mean and width are different in the calibrations because the data contain ER contamination and neutron-X events, which are modeled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

Cosmogenic Isotopes Decaying

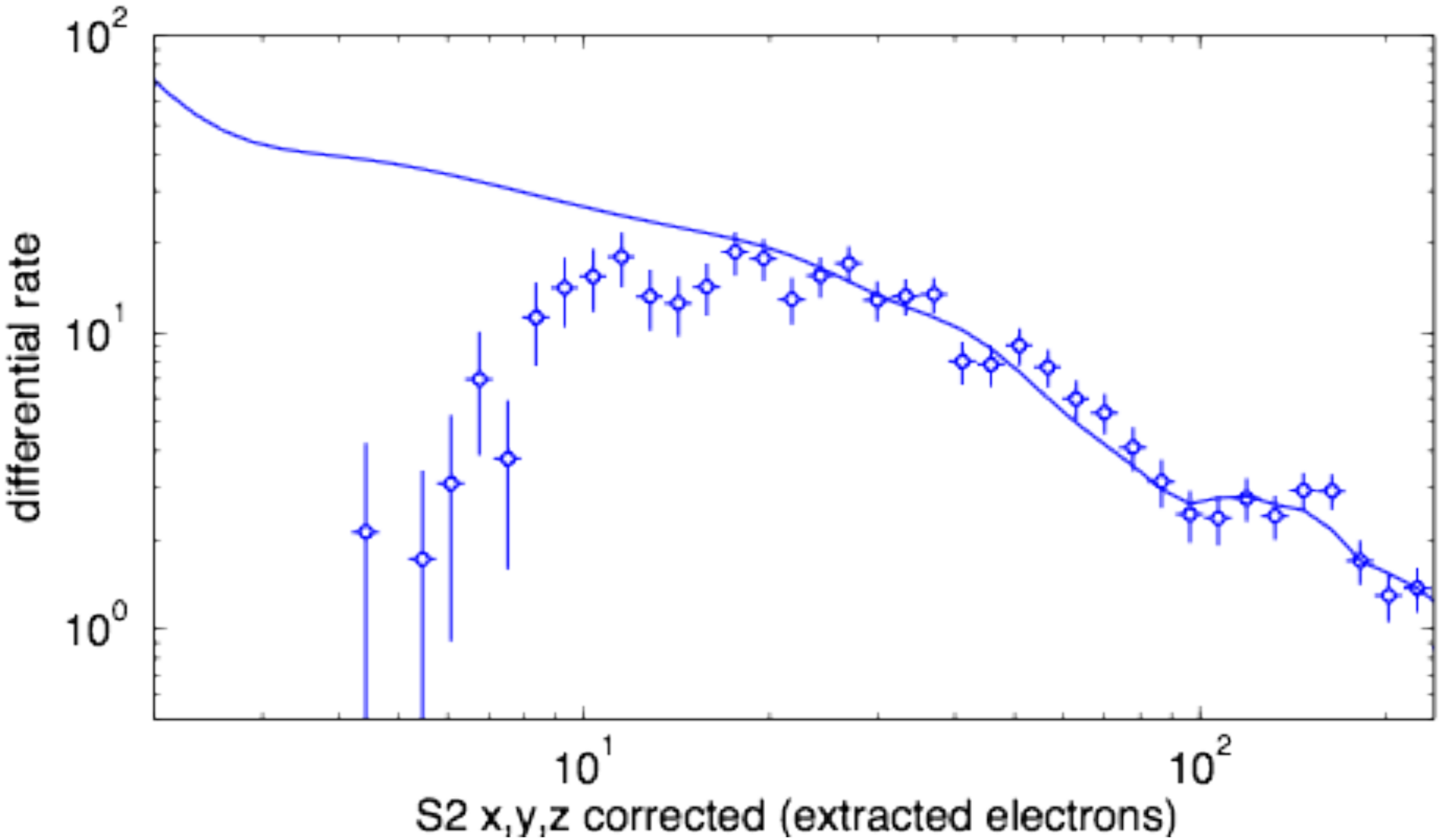
- 127Xe Decay vs Time

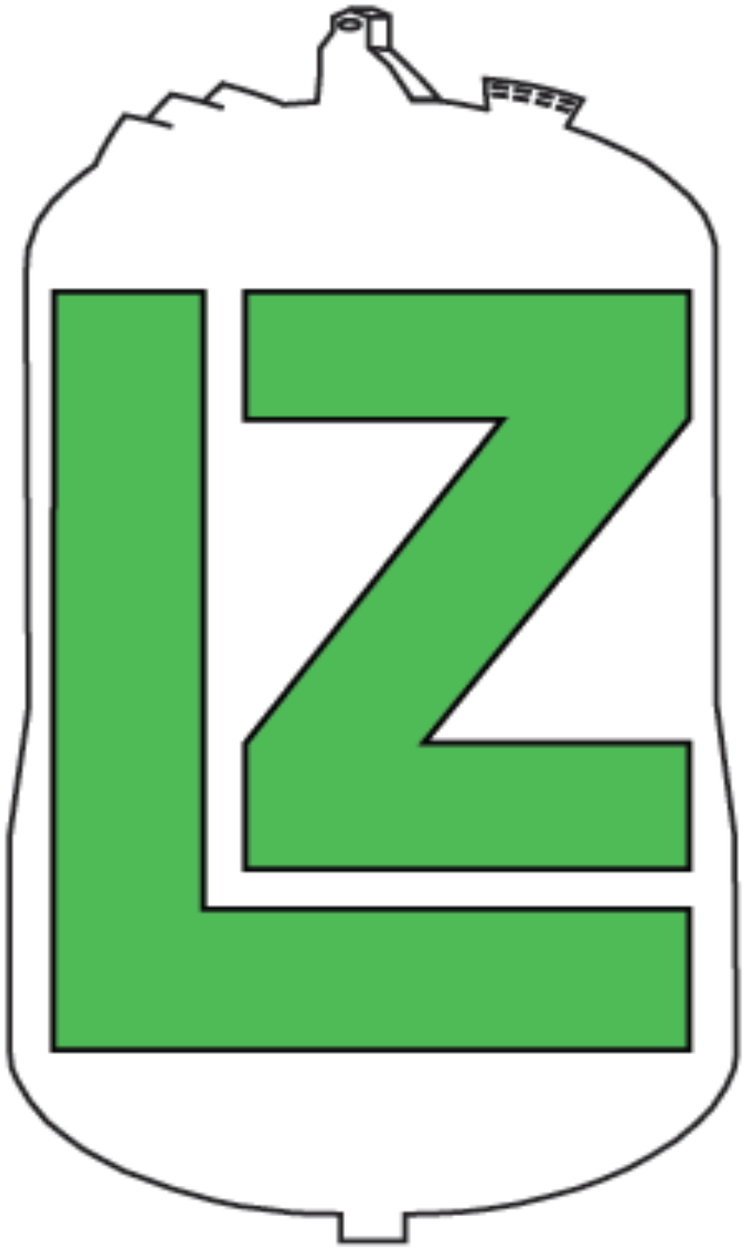


131mXe Decay vs Time



AmBe S2 Calibration

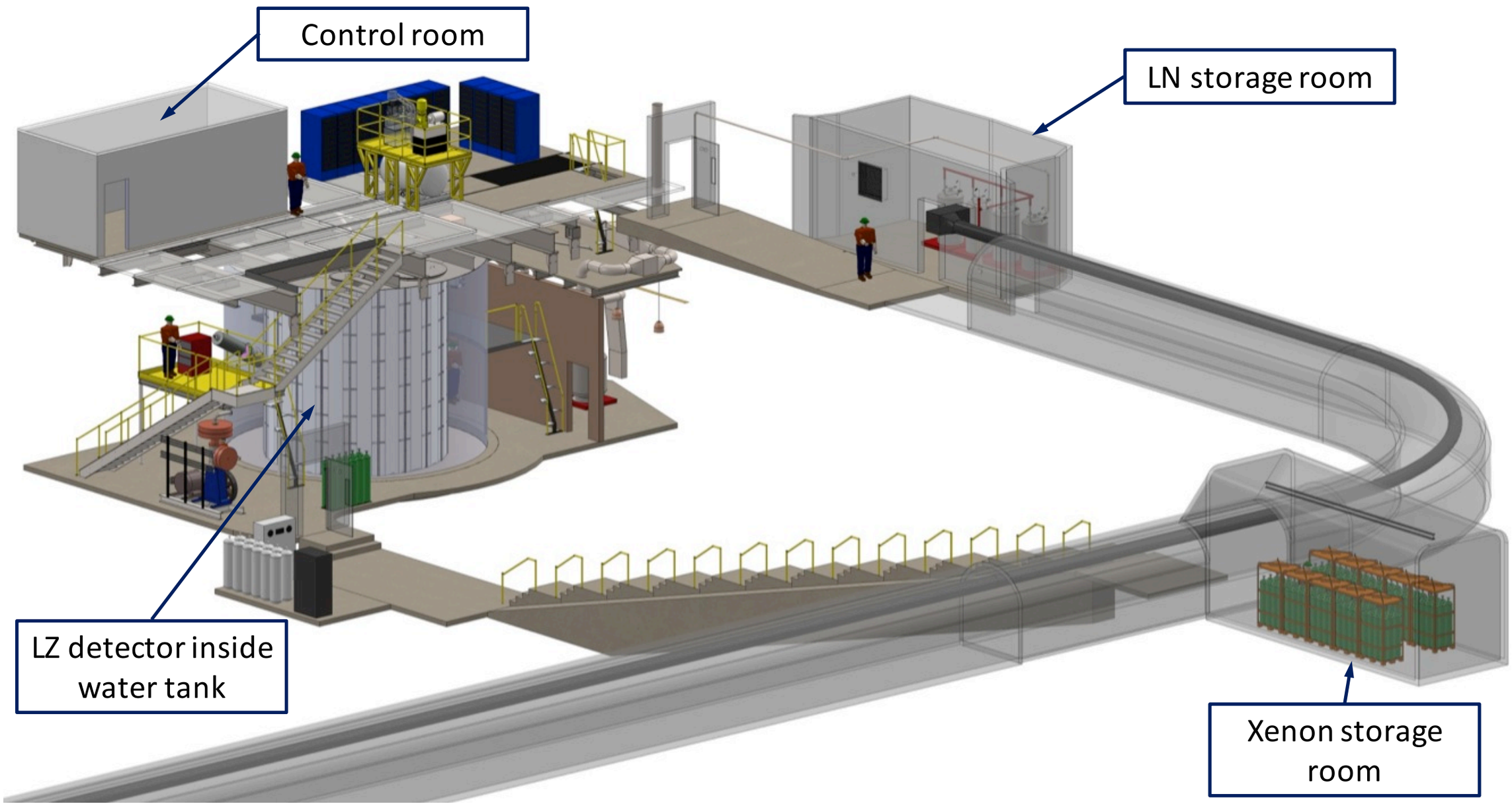




Extra Slides

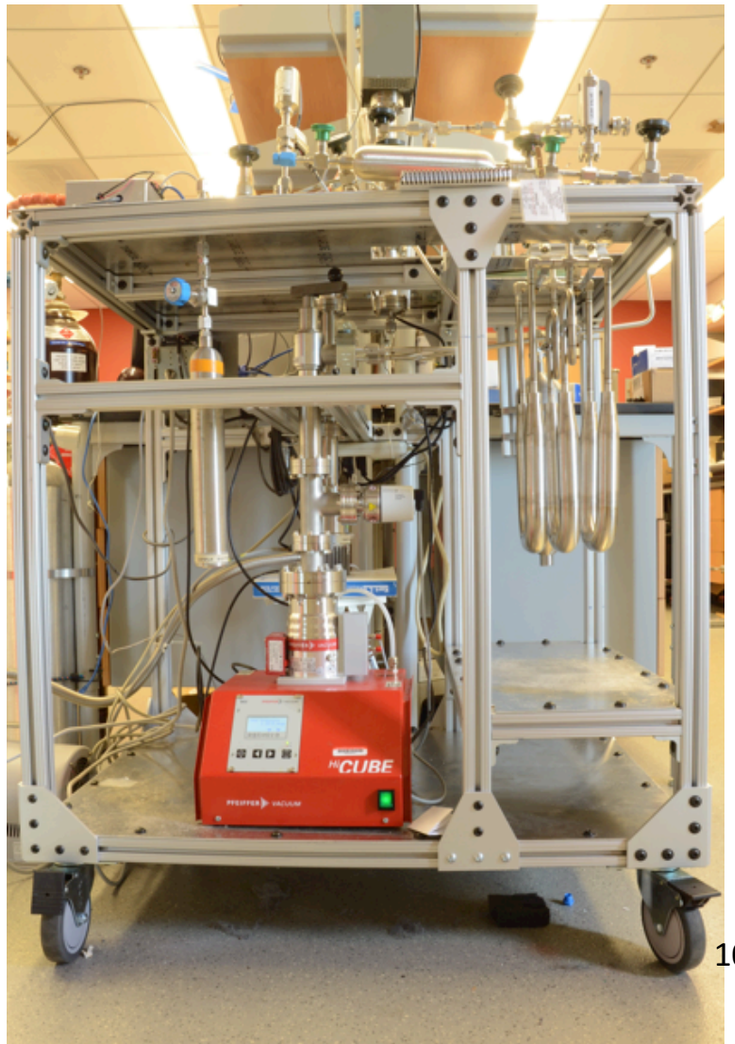
LZ Underground at SURF

Years of experience at SURF from LUX



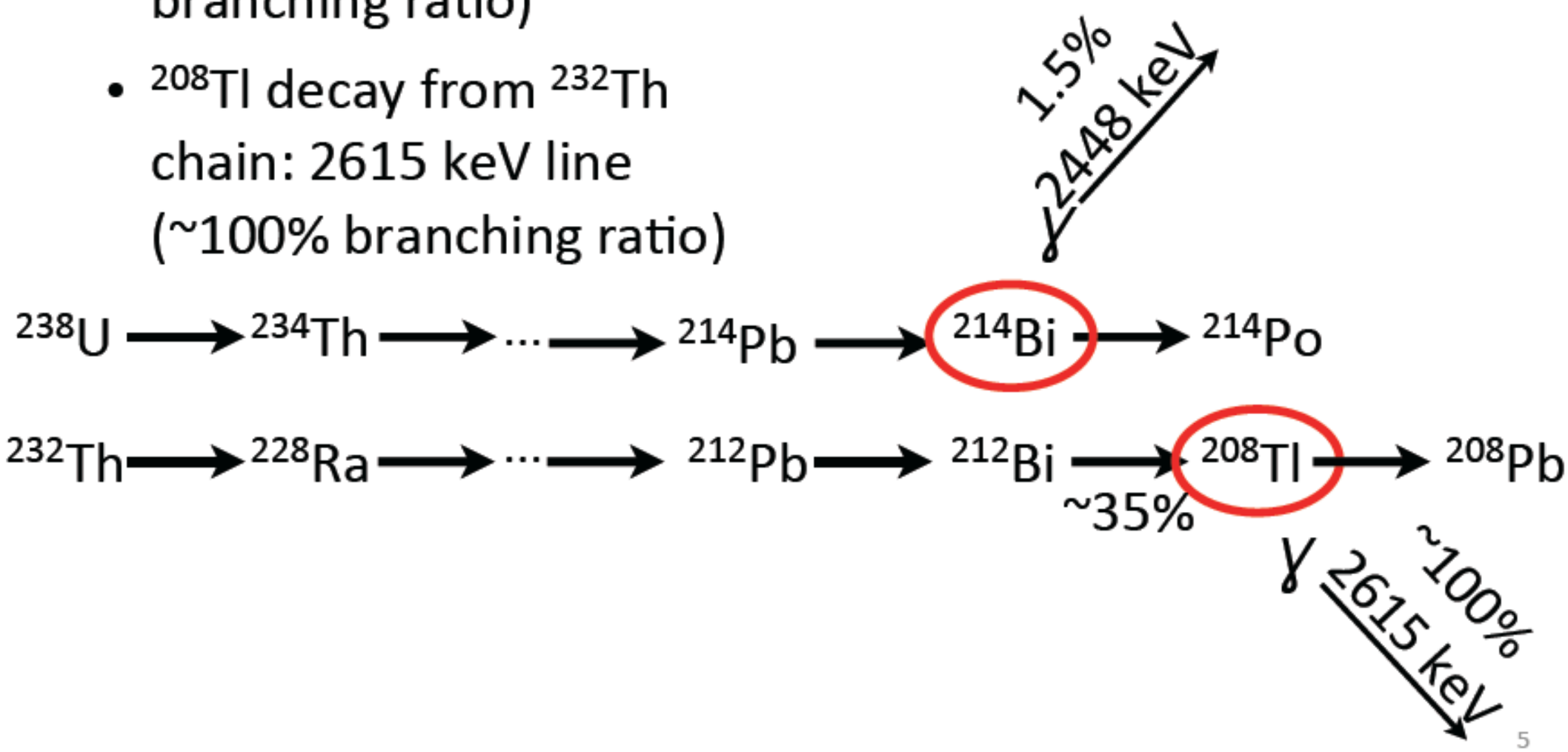
^{85}Kr Removal and Screening

- Remove Kr to <15 ppq (10^{-15} g/g) using gas chromatography.
- Best LUX batch 200 ppq
- Setting up to process 200 kg/day at SLAC
- Have a sampling program to instantly assay the removal at SLAC and continuously assay in situ



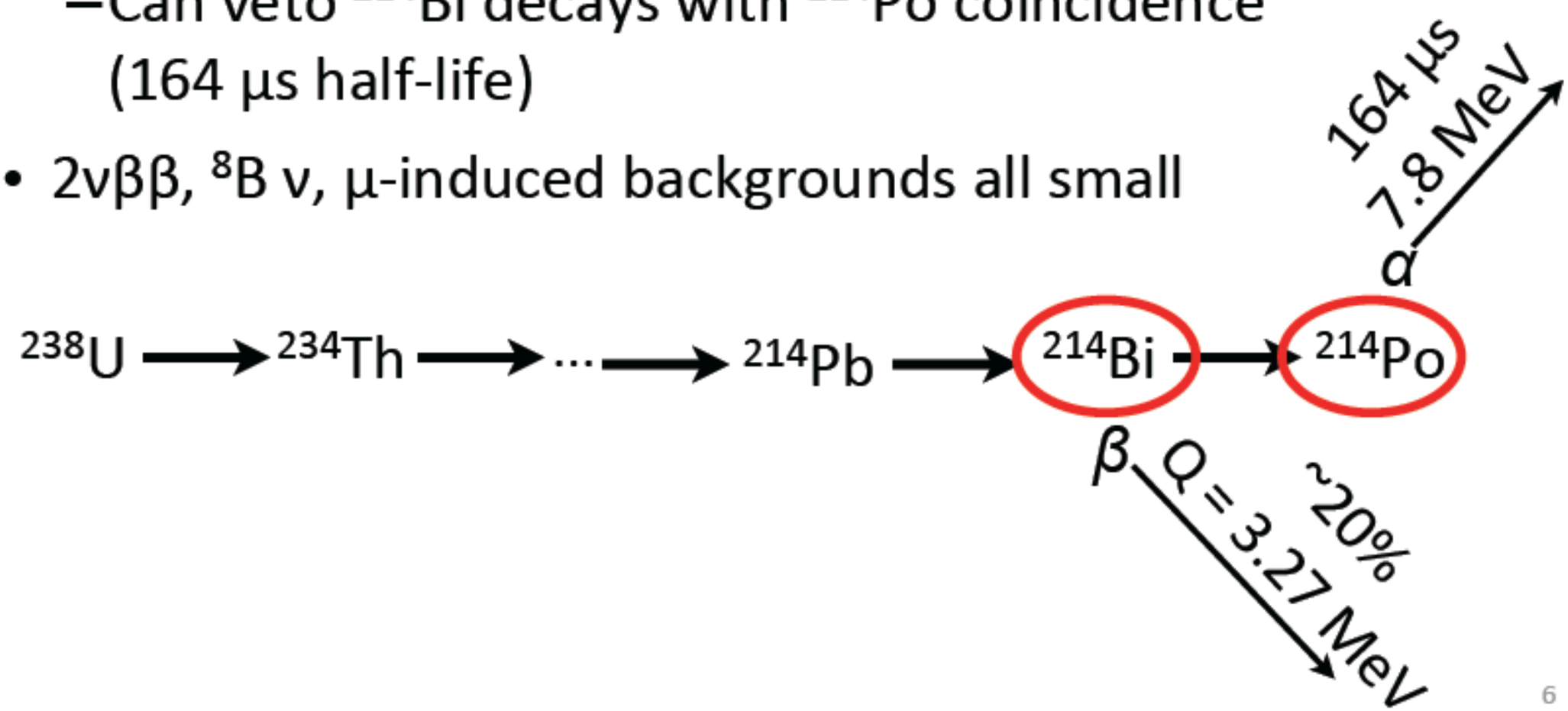
Backgrounds Near 2458 keV

- ^{214}Bi from ^{238}U chain: one line at 2448 keV (1.5% branching ratio)
- ^{208}Tl decay from ^{232}Th chain: 2615 keV line (~100% branching ratio)



Important Backgrounds

- Internal radon not a concern:
  - 2448 keV line comes with a beta => self-vetoing
  - Can veto ^{214}Bi decays with ^{214}Po coincidence (164 μs half-life)
- 2νββ, ^{8}B ν, μ-induced backgrounds all small



6

Xe Detector PMTs

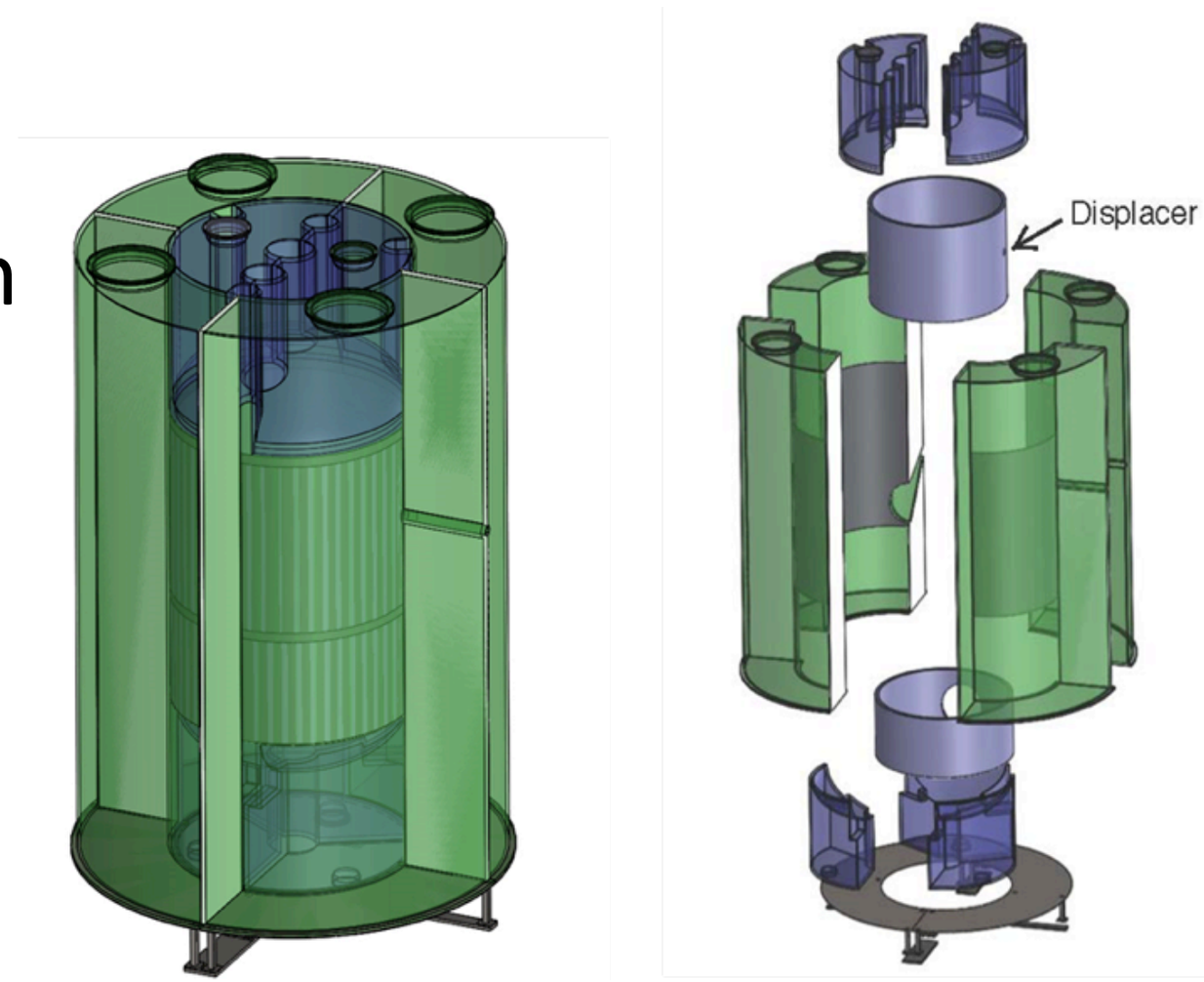
- R11410-22 3” PMTs for TPC region
  - Extensive development program, 50 tubes in hand, benefit from similar development for XENON, PANDA-X and RED
  - Materials ordered and radioassays started prior to fabrication.
  - First production tubes early 2016.
  - Joint US and UK effort
- R8520-406 1” for skin region
  - Considering using 2” or 3” for bottom dome region, recycle tubes from older detectors

Xe Detector Prototyping

- Extensive program of prototype development underway
- Three general approaches
  - Testing in liquid argon, primarily of HV elements, at Yale and soon at LBNL
  - Design choice and validation in small (few kg) LXe test chambers in many locations: LLNL, Yale-> UC Berkeley, LBNL, U Michigan, UC Davis, Imperial College, MEPhI
  - System test platform at SLAC, Phase I about 100 kg of LXe, TPC prototype testing to begin in few months

Outer Detector

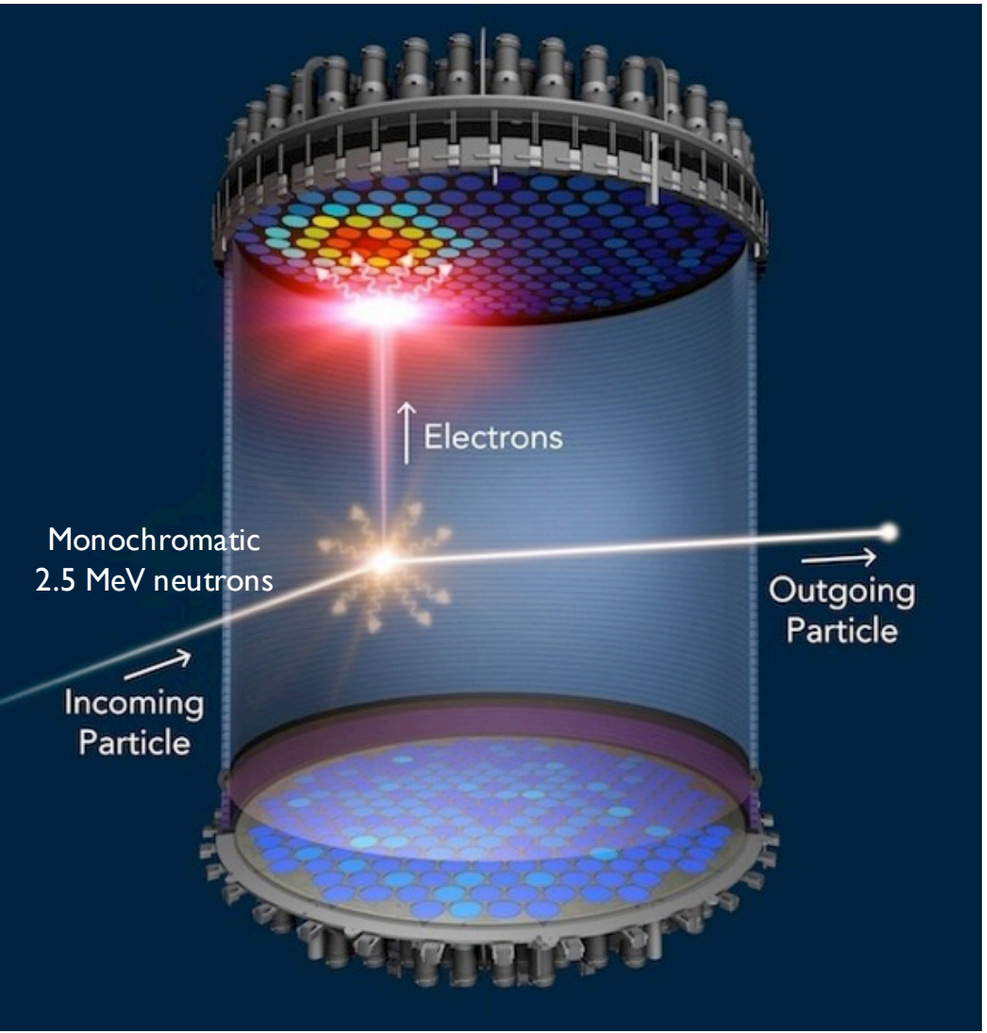
- Essential to utilize most Xe, maximize fiducial volume
- Segmented tanks – installation constraints (shaft, water tank)
- Gadolinium - loaded scintillator, LAB, OK underground
- Daya Bay legacy, scintillator & tanks (and people)
- Advanced conceptual design

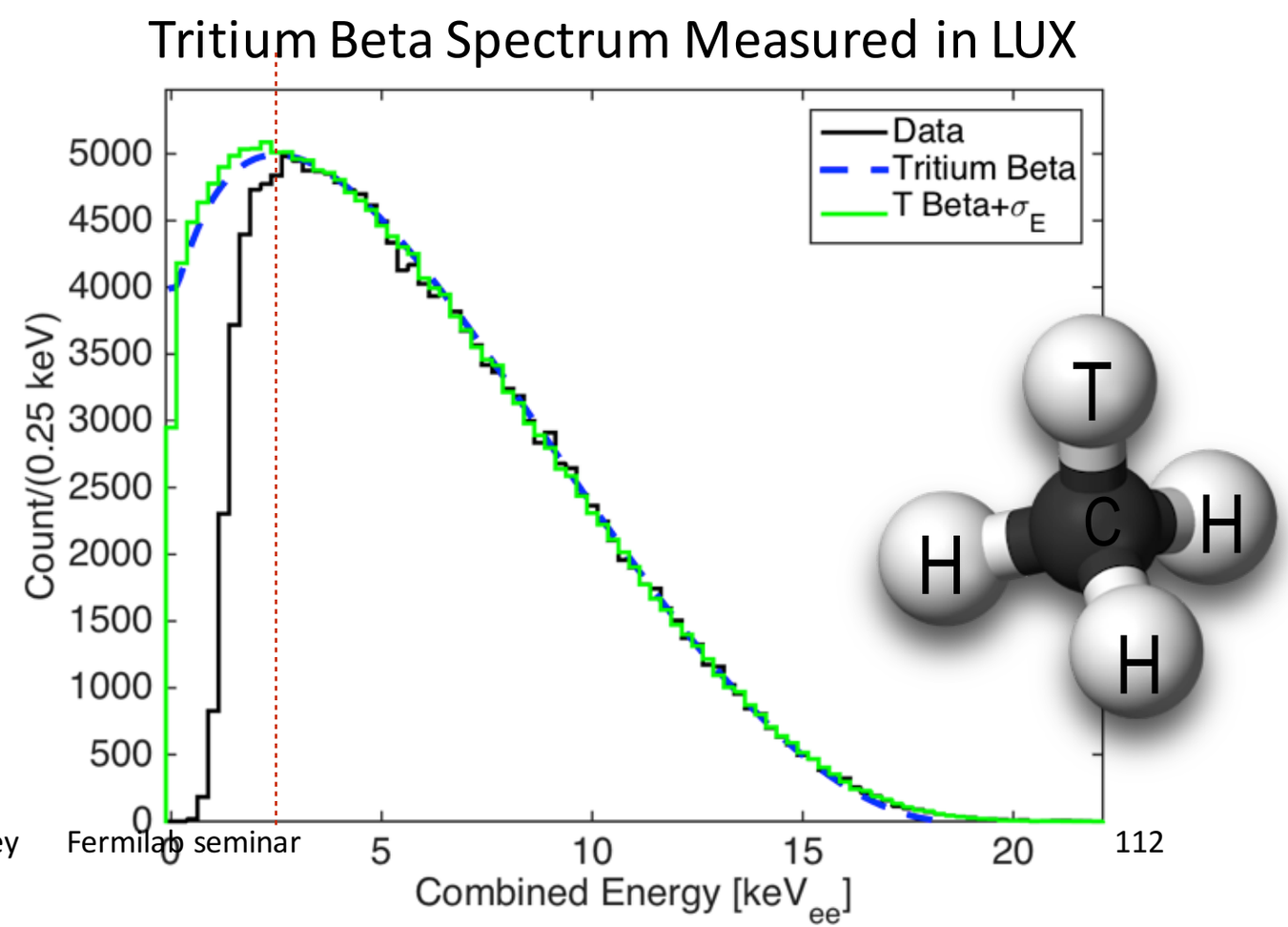


Layout of the LZ outer detector system, which consists of nine acrylic tanks. The largest are the four quarter-tanks on the sides. Two tanks cover the top, and three the bottom. The exploded view on the right shows the displacer cylinders placed between the acrylic vessels and the cryostat.

LZ Calibrations

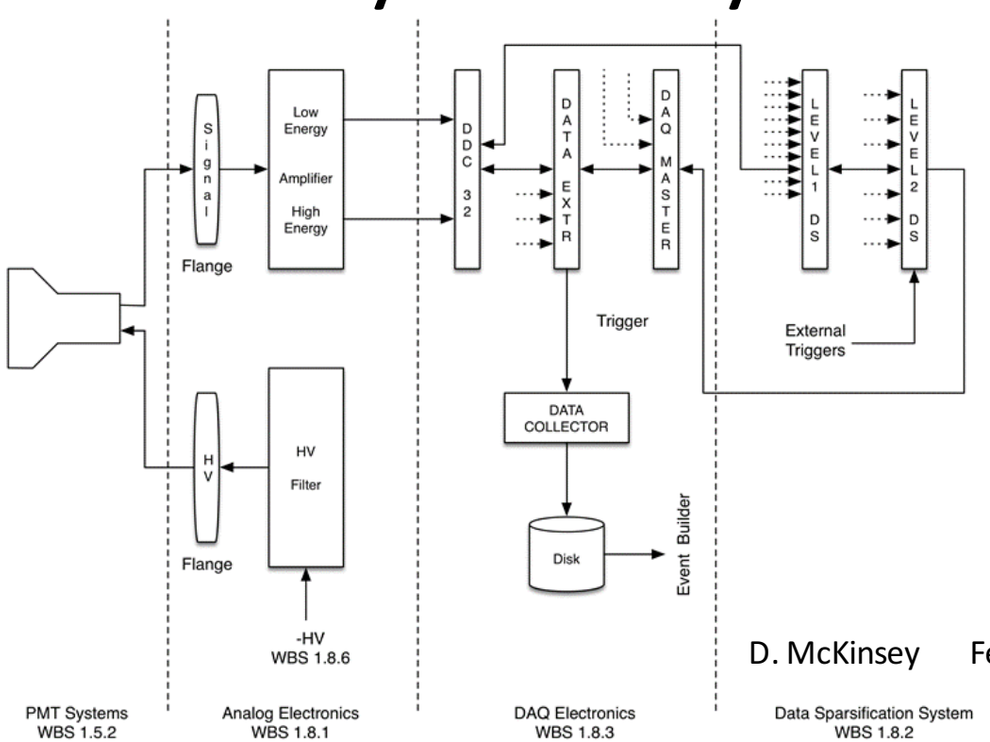
- Demonstrated in LUX. Calibrate The Signal and Background Model *in situ.*
- DD Neutron Generator (Nuclear Recoils)
- Tritiated Methane (Electron Recoils)
- Additional Sources e.g. YBe Source for low energy (Nuclear Recoils)



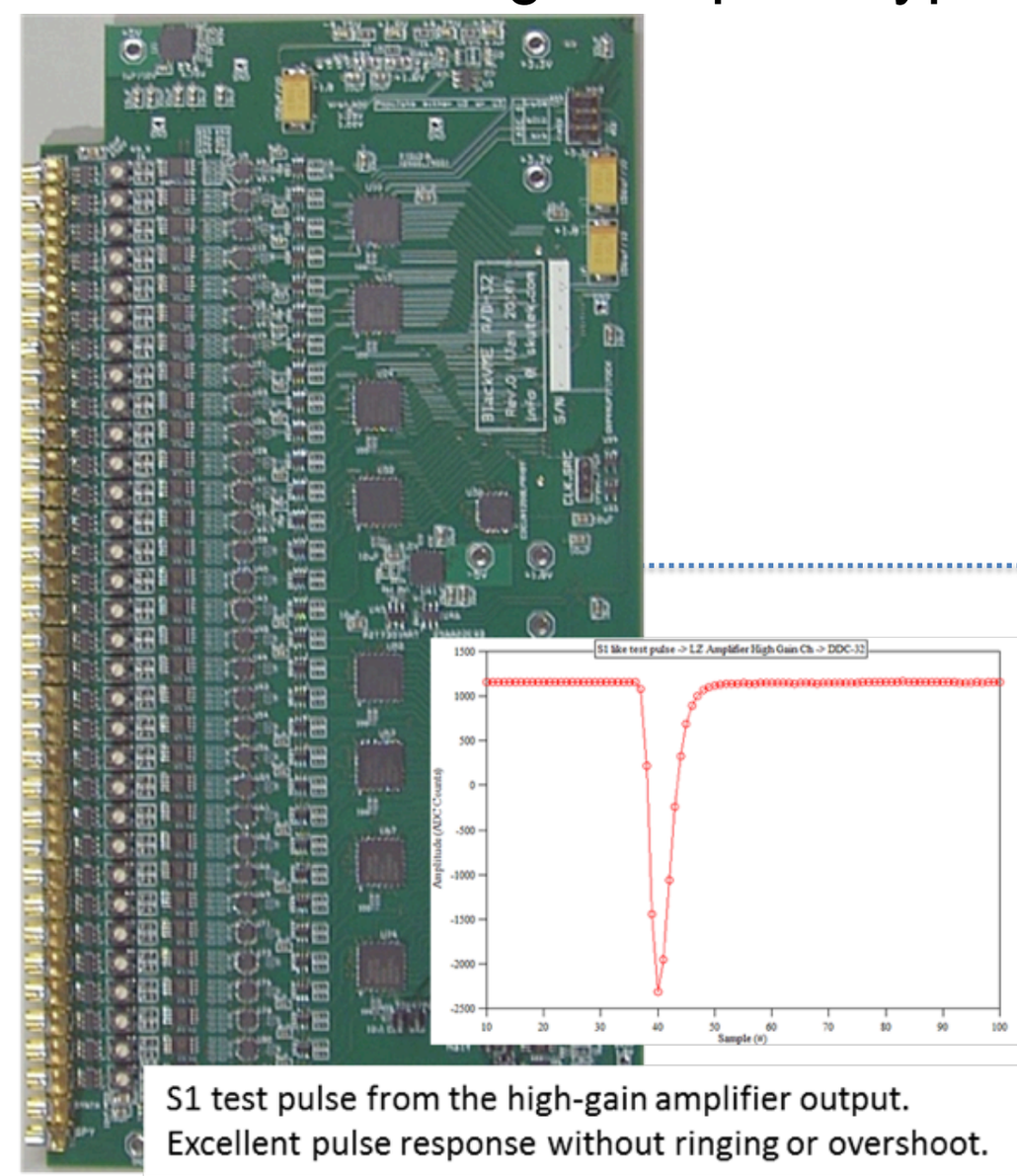


Electronics/DAQ

- LUX legacy, augmented by experienced new groups (primarily DAQ, controls)
- Prototyping underway, will lead to full – chain test of key elements by end of year

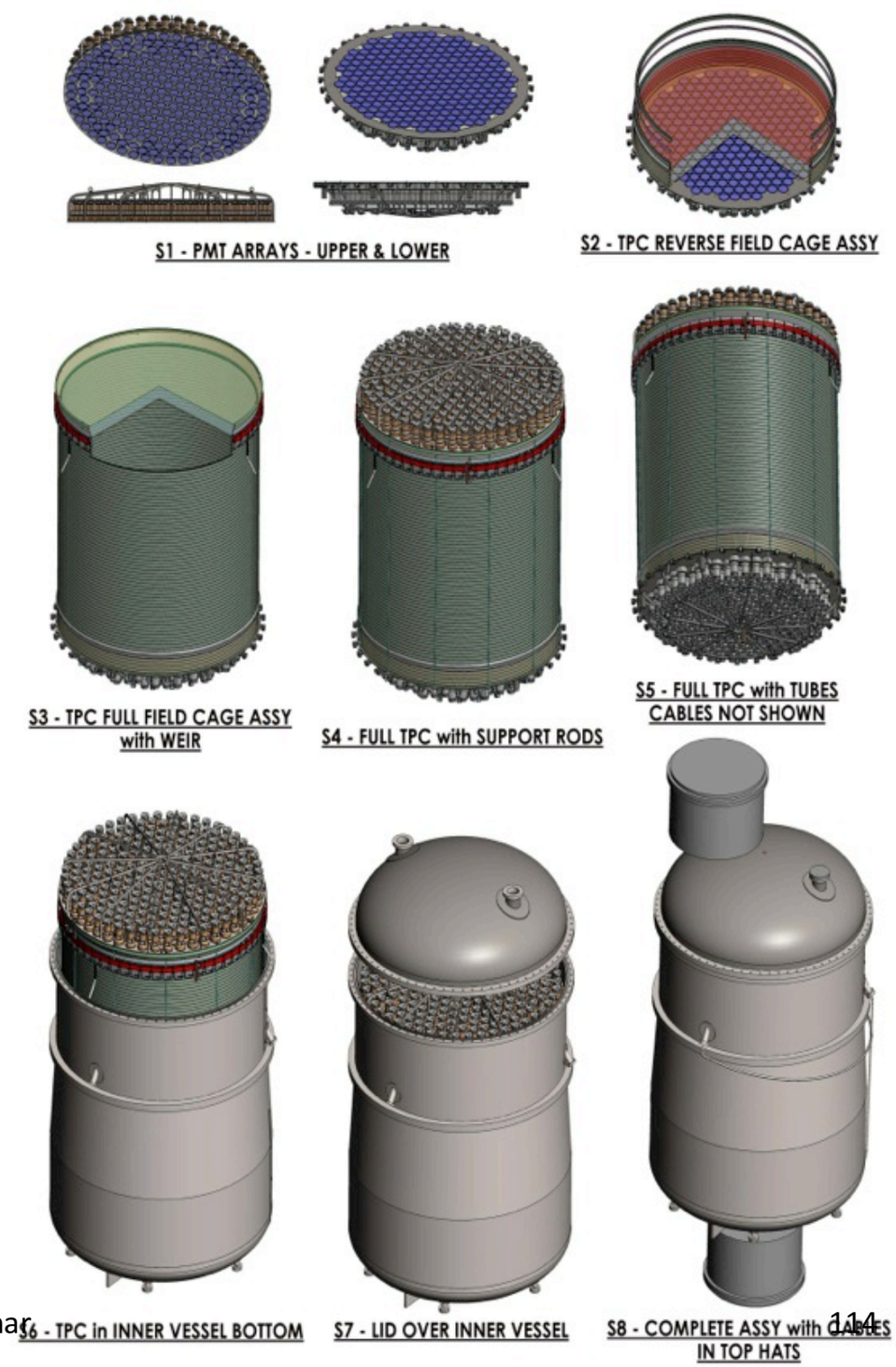


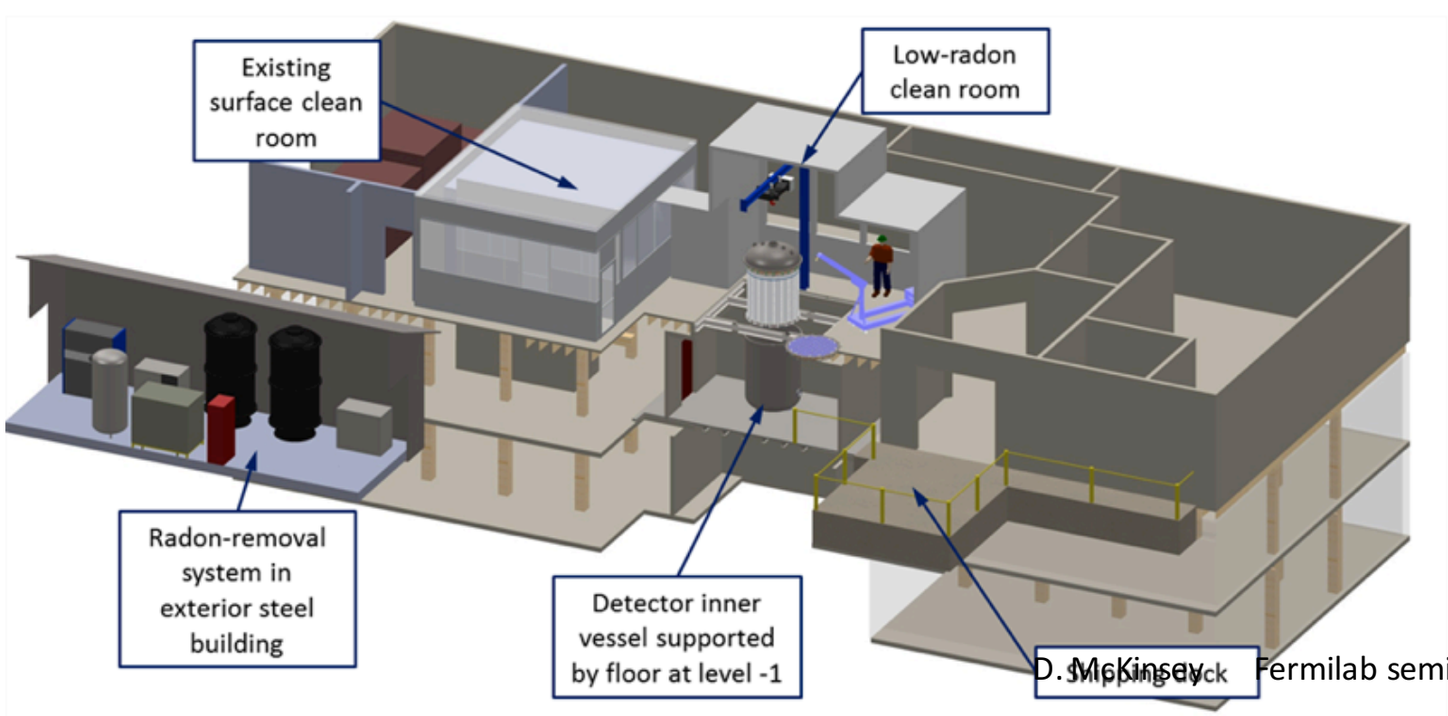
32 channel digitizer prototype



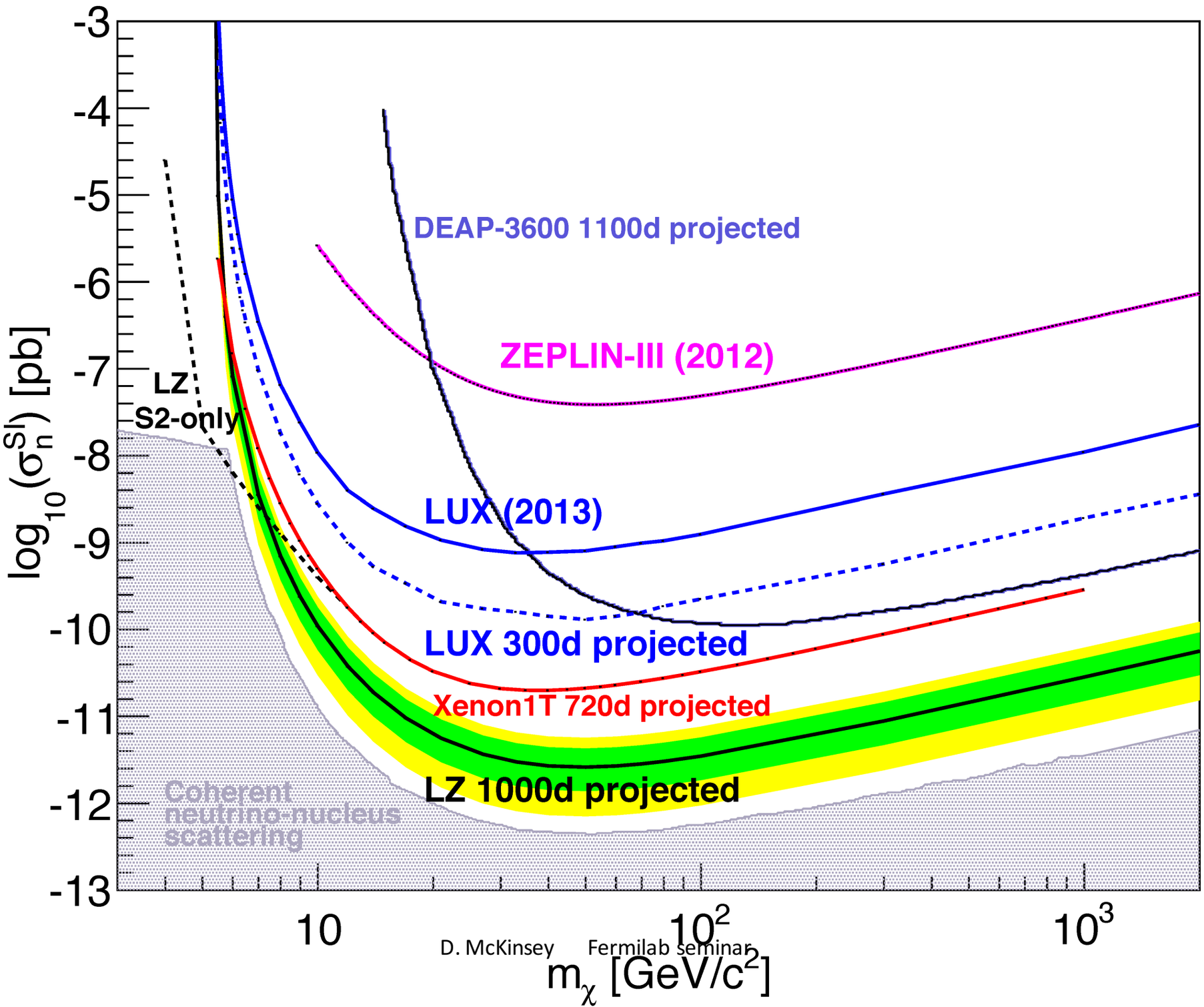
Integration/Installation

- Surface assembly of TPC into inner cryostat
- LUX experience at SURF
- Dedicated on – site infrastructure improvements for LZ. Design started, construction

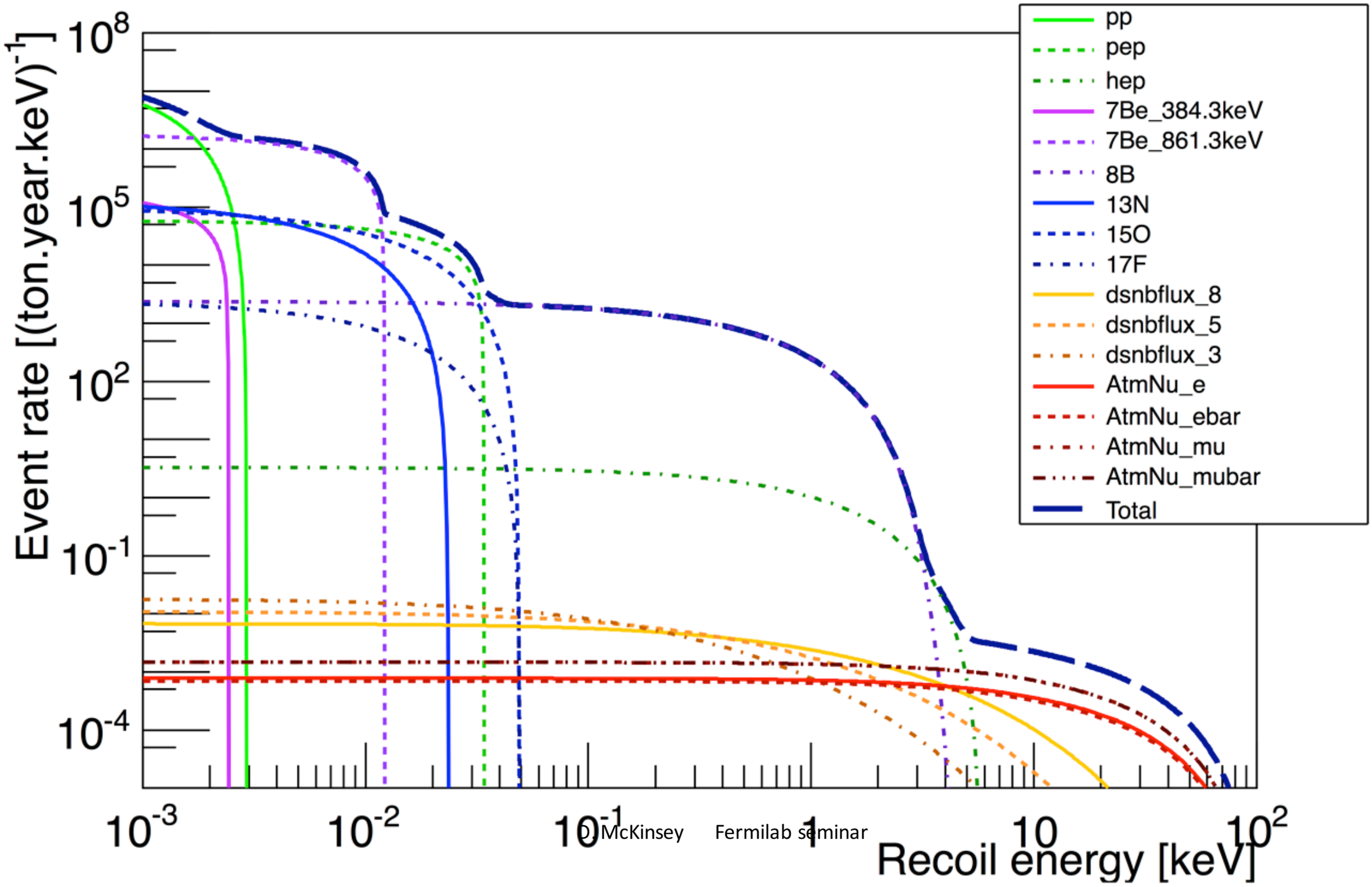




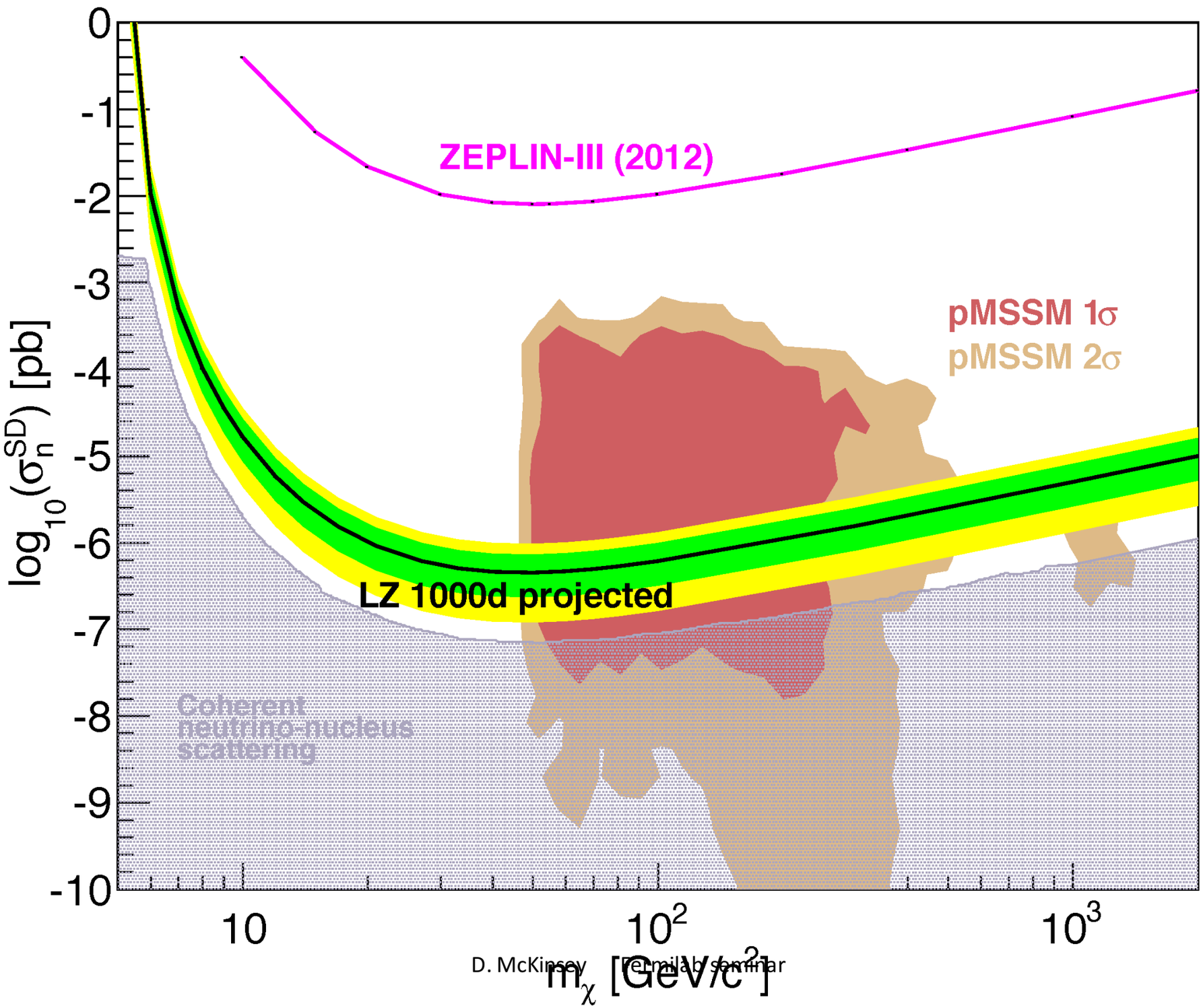
Sensitivity with Competition



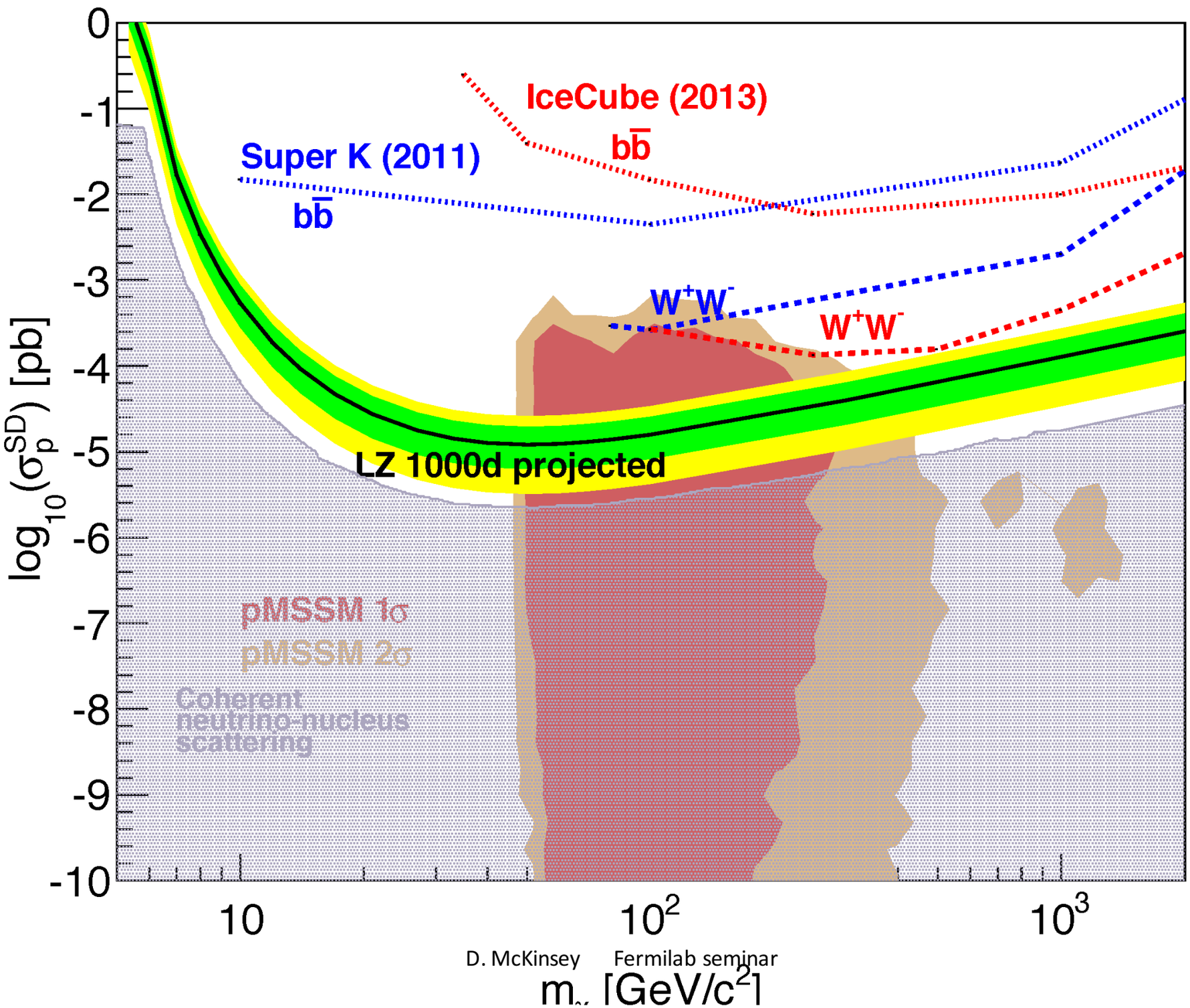
Response of Xe to Neutrinos arXiv:1307:5458



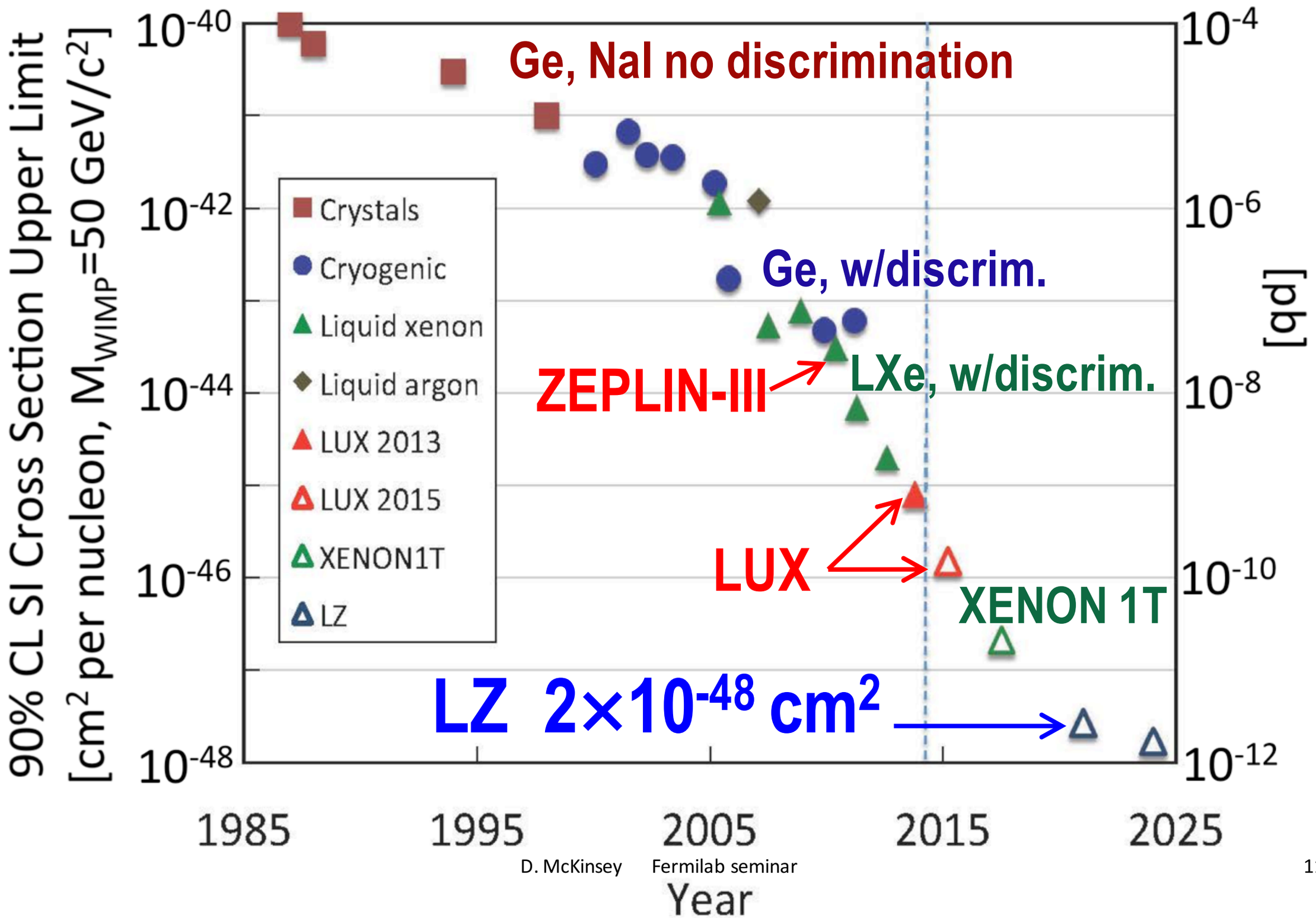
Spin Dependent Neutron

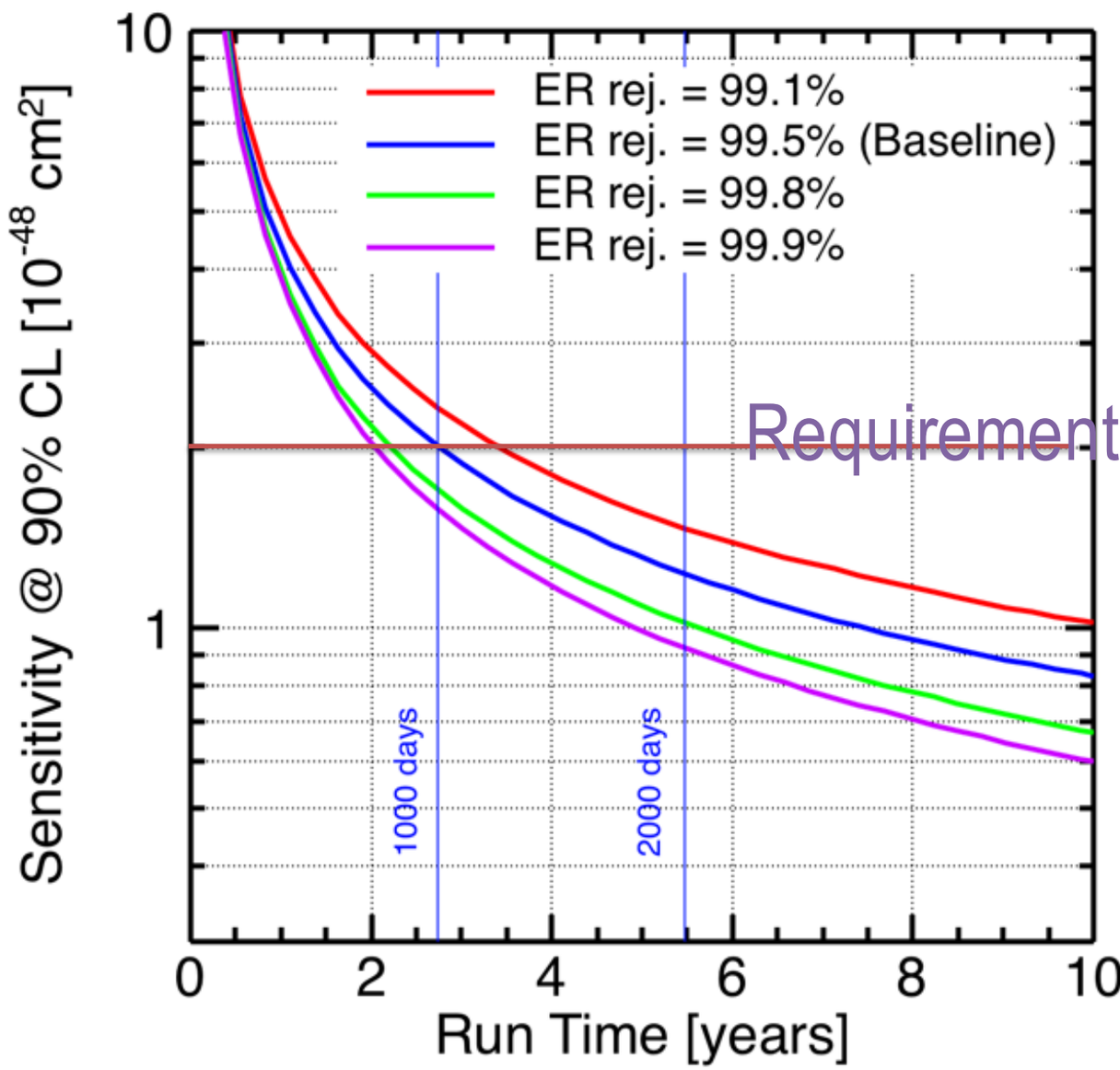


Spin Dependent Proton



Time Evolution



Running Time

- Sensitivity vs. running time.
- 1,000 days is the nominal.
- Baseline backgrounds
- Rapid improvement in sensitivity
- Potential to eventually get to ~ 1 x 10^{-48} cm^2