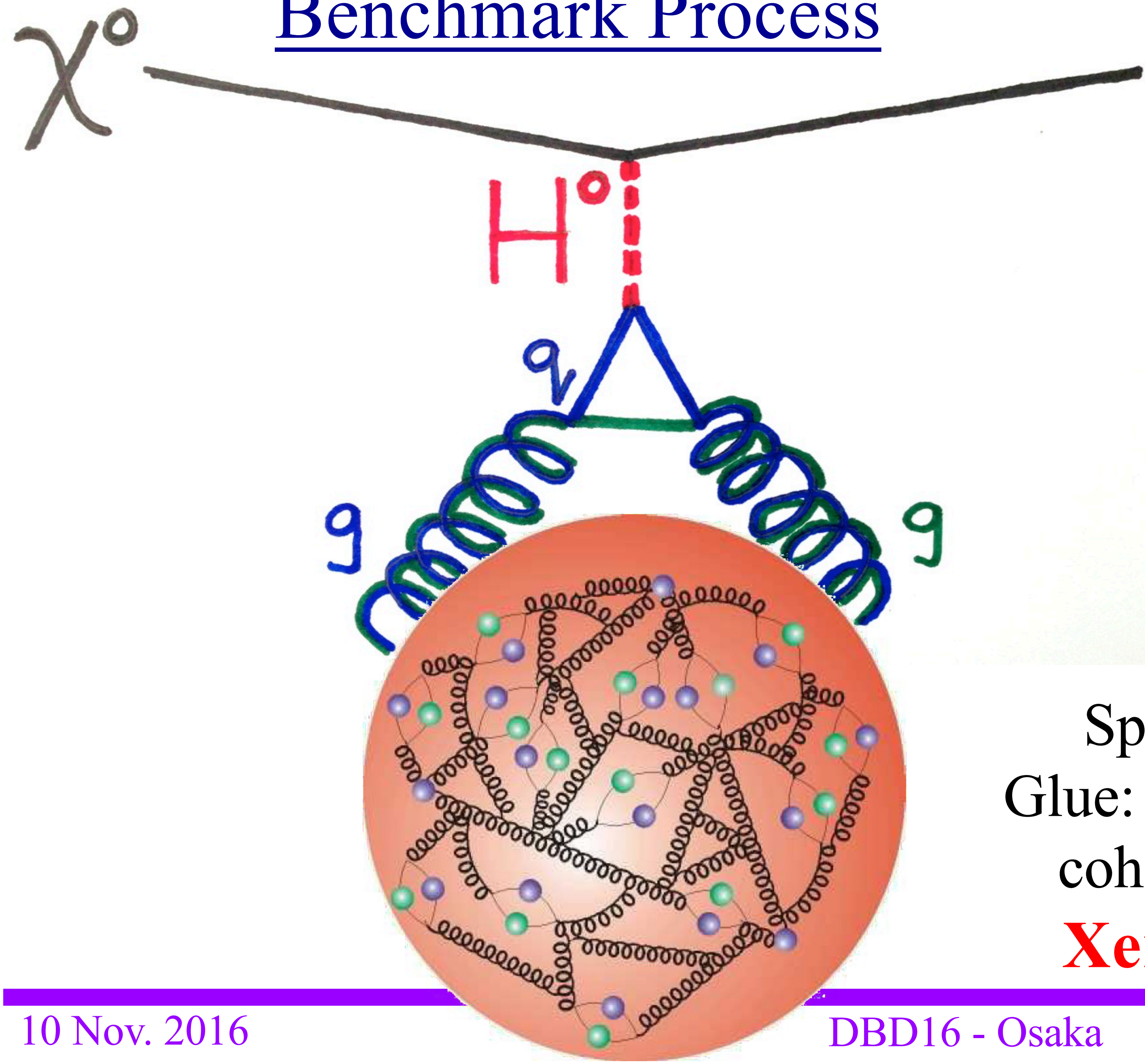
Dark Matter: LUX and LZ

Harry Nelson / LUX, LZ & UCSB

DBD16 at Osaka

November 10, 2016

Benchmark Process



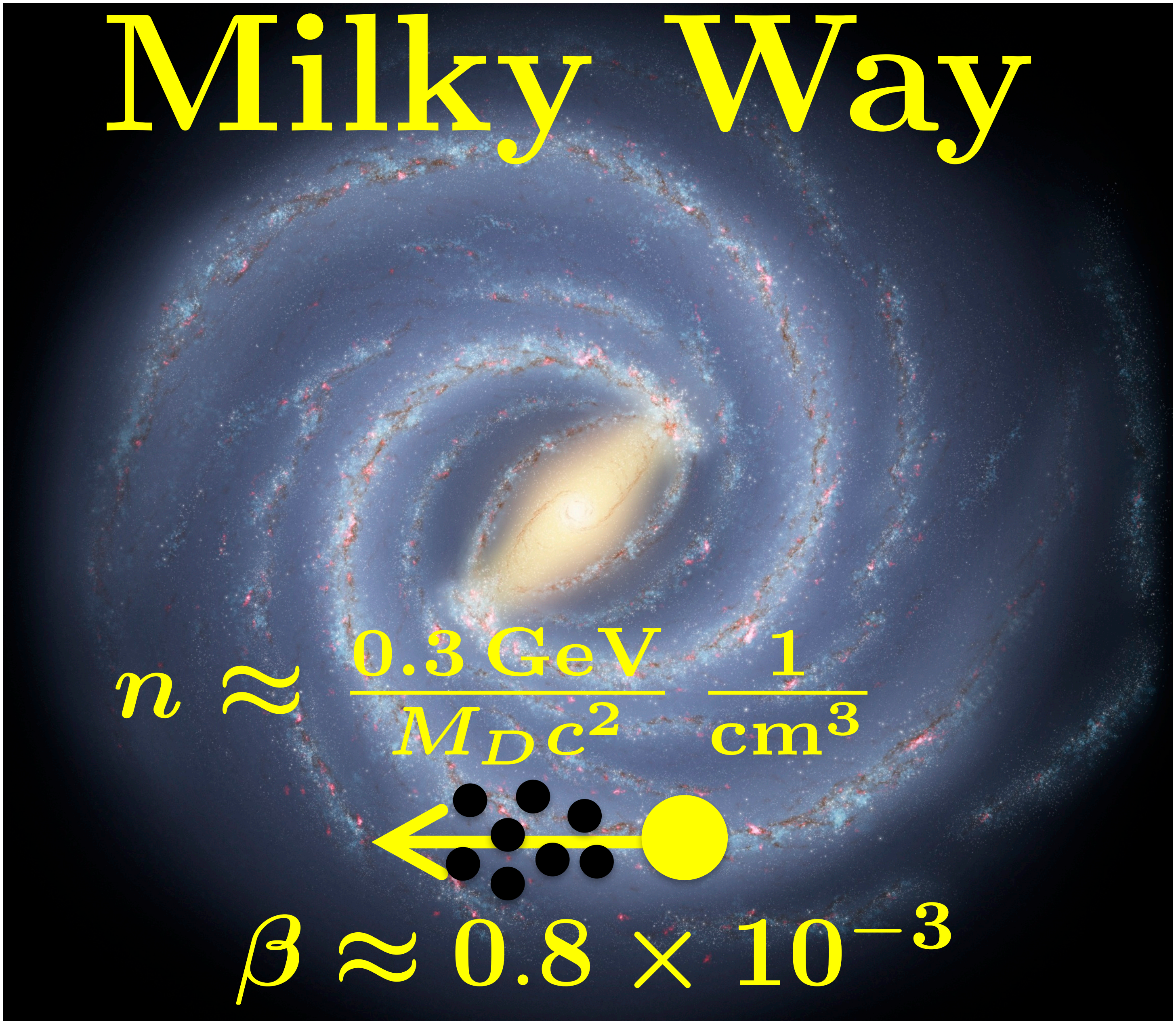
Spin-Independent
Glue: n/p indifferent,
coherent, $\sigma \approx A^{(2-4)}$

Xenon: A ≈ 131

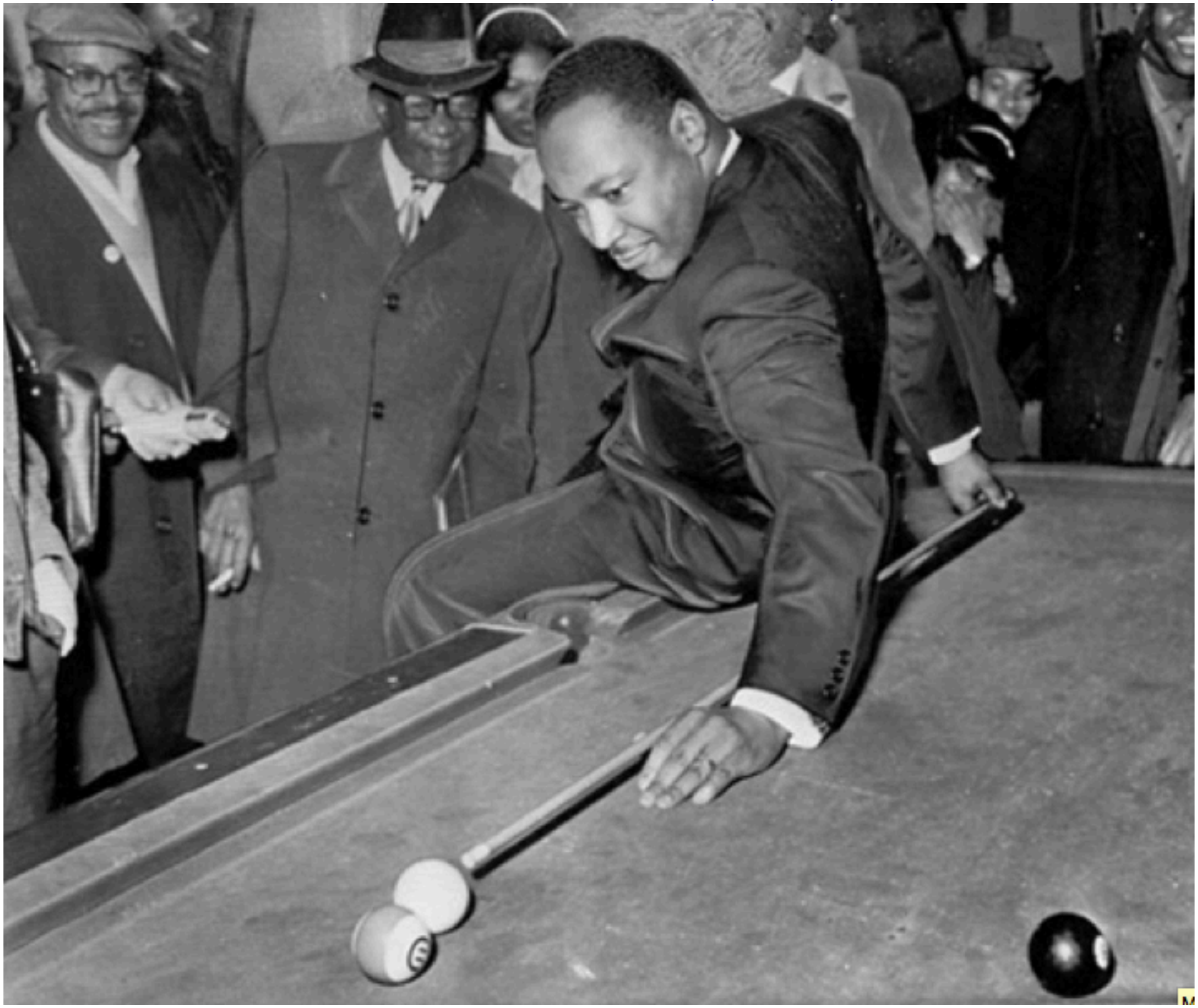
Xenon

- Dense Liquid
- Natural Scintillator
- Long lived radioisotopes are 2νββ decays, very long half lives
- 9 `stable' isotopes
- 2 with unpaired neutron

^{A}Z	$\tau_{1/2}$ or f	J^{p}
^{122}Xe	20 h	0^+
^{123}Xe	2.1 h	$(1/2)^+$
^{124}Xe	0.10 %	0^+
^{125}Xe	17 h	$(1/2)^+$
^{126}Xe	0.09 %	0^+
^{127}Xe	**36 d**	**$(1/2)^+$**
^{128}Xe	1.91 %	0^+
^{129}Xe	**26.4 %**	**$(1/2)^+$**
^{130}Xe	4.1 %	0^+
^{131}Xe	**21.2 %**	**$(3/2)^+$**
^{132}Xe	26.9 %	0^+
^{133}Xe	5.2 d	$(3/2)^+$
^{134}Xe	10.4 %	0^+
^{135}Xe	9.1 h	$(3/2)^+$
^{136}Xe	8.9 % (2.2×10^{21} y)	0^+


Milky Way
$n \approx \frac{0.3\,\mathrm{GeV}}{M_D c^2} \frac{1}{\mathrm{cm}^3}$
$\beta \approx 0.8 \times 10^{-3}$

Signal: Nuclear Recoils (NR) from WIMPs



Lead, South Dakota

Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank

LUX/LZ Here

LUX in Santa Barbara

The LUX collaboration

Berkeley Lab / UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Michael Witherell	Lab Director
Peter Sorensen	Scientist
Simon Fiorucci	Project Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Brown University

Richard Gaitskell	PI, Professor
Samuel Chung	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Postdoc

University of Edinburgh, UK

Alex Murphy	PI, Professor
Paolo Beltrame	Research Fellow
Tom Davison	Graduate Student
Maria F. Marzioni	Graduate Student

Imperial College London, UK

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

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Grp.
Kareem Kazkaz	Staff Physicist
Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

LIP Coimbra, Portugal

Isabel Lopes	PI, Professor
Jose Pinto da	Assistant Professor
Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc
Paulo Bras	Graduate Student

SLAC Stanford (CWRU)

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Wing To	Research Associate
Rosie Bramante	Graduate Student
Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA / Sanford Lab

David Taylor	Project Engineer
Markus Horn	Research Scientist
Dana Byram	Support Scientist

University at Albany

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Sean Fallon	Graduate Student
Jack Genovesi	Graduate Student
Steven Young	Graduate Student

Texas A&M University

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

UC Berkeley (Yale)

Daniel McKinsey	PI, Professor
Ethan Bernard	Project Scientist
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Nicole Larsen	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Britt Hollbrook	Senior Engineer
John Thomson	Development
Dave Hemer	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Project Scientist
Jacob Cutter	Graduate Student
James Morad	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

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

University College London, UK

Chamkaur Ghag	PI, Lecturer
James Dobson	Postdoc
Sally Shaw	Graduate Student

University of Maryland

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

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Diktat Koyuncu	Graduate Student
M. Moongweluwan	Graduate Student
Jun Yin	Graduate Student

University of South Dakota

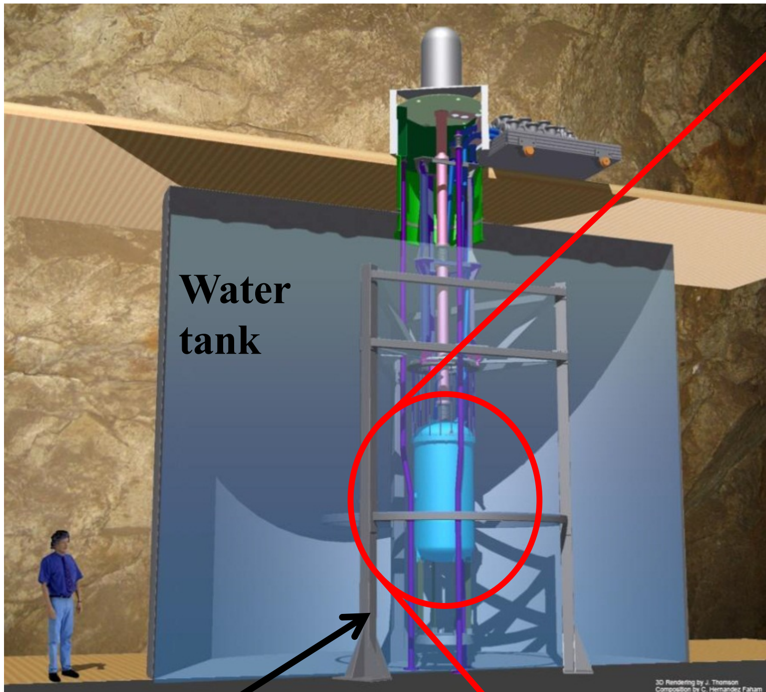
Dongming Mei	PI, Professor
Chao Zhang	Postdoc

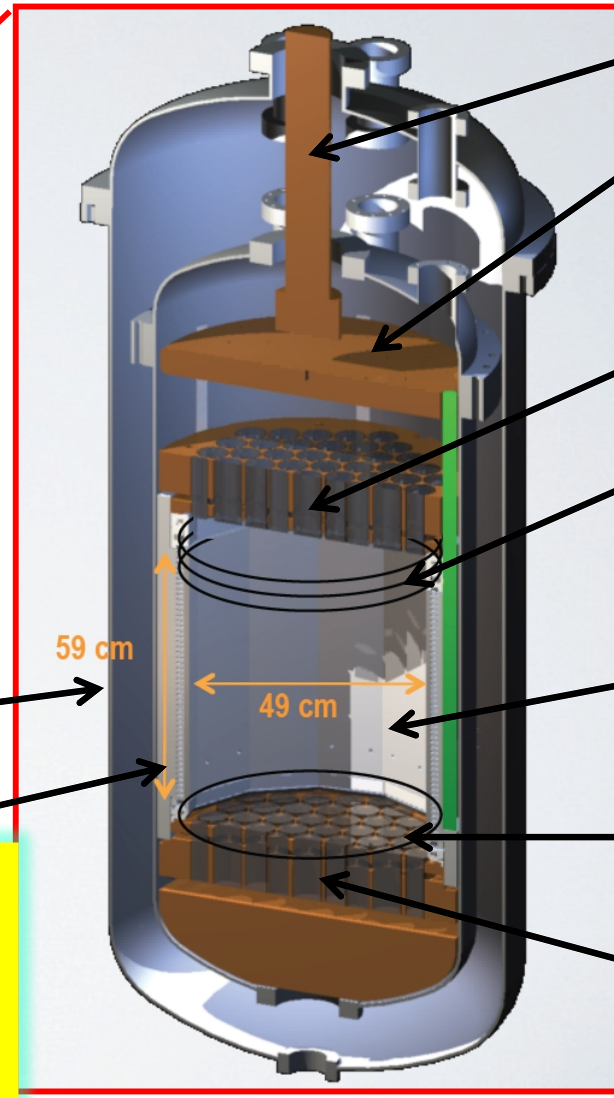
University of Wisconsin

Kimberly Palladino	PI, Asst Professor
Shaun Alsum	Graduate Student

LUX Installed (Fall 2012)

In the tank and detailed cross section



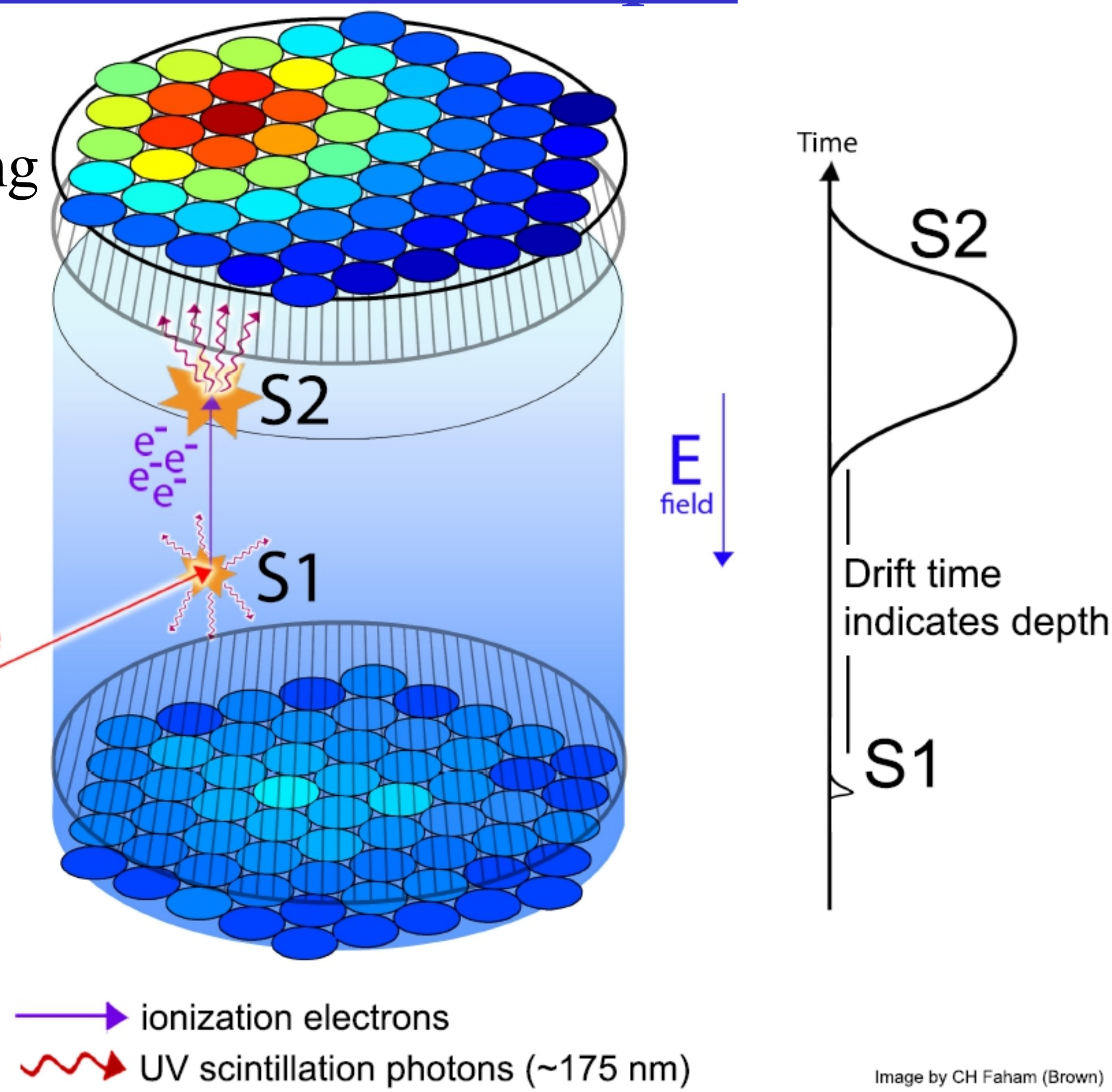


- **370 kg xenon**
  - **250 kg active region**
  - **≈100 kg fiducial mass**

Liquid Xenon TPC Principle

Z position from S1 – S2 timing

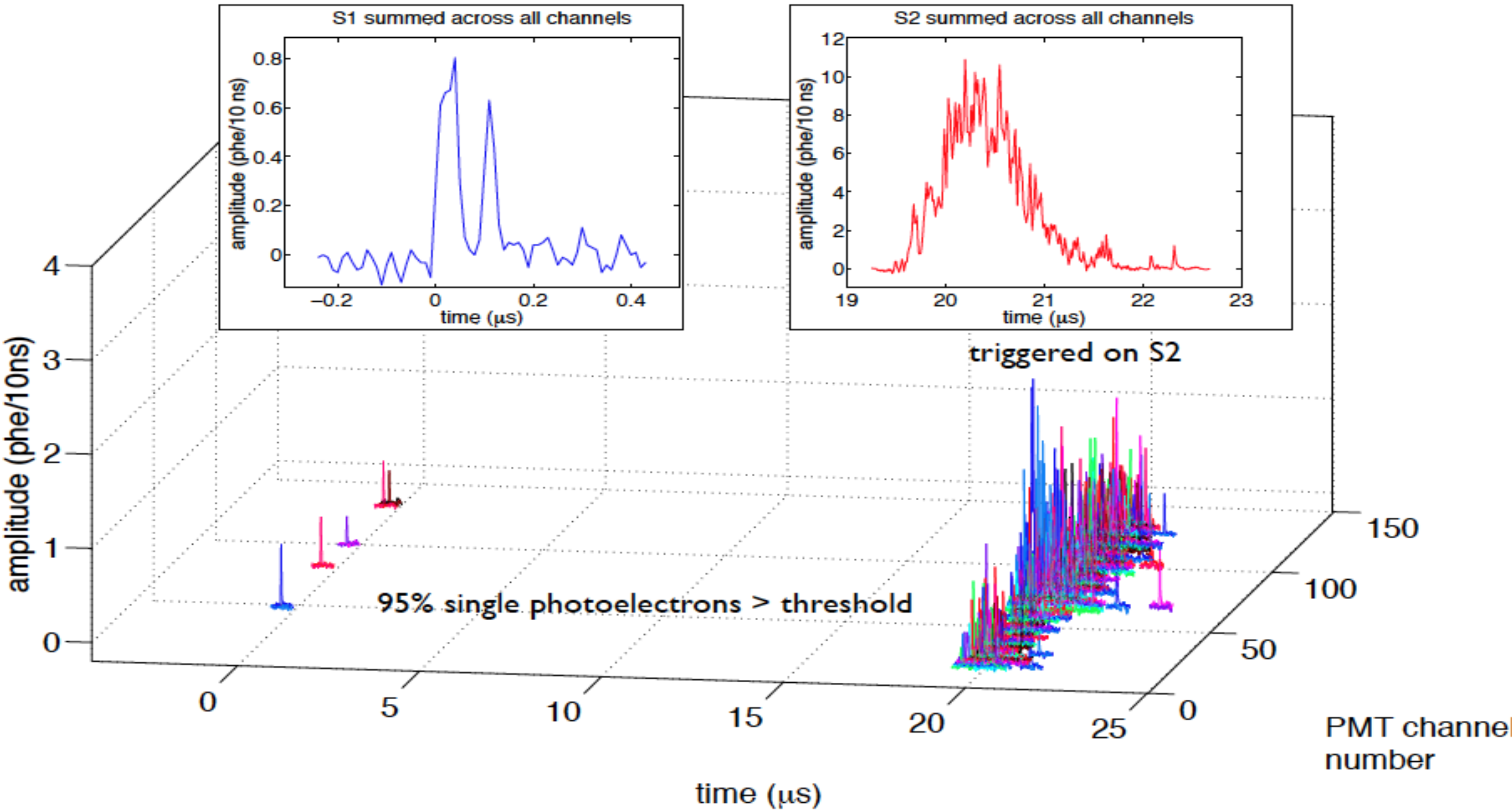
X-Y positions from S2 light pattern



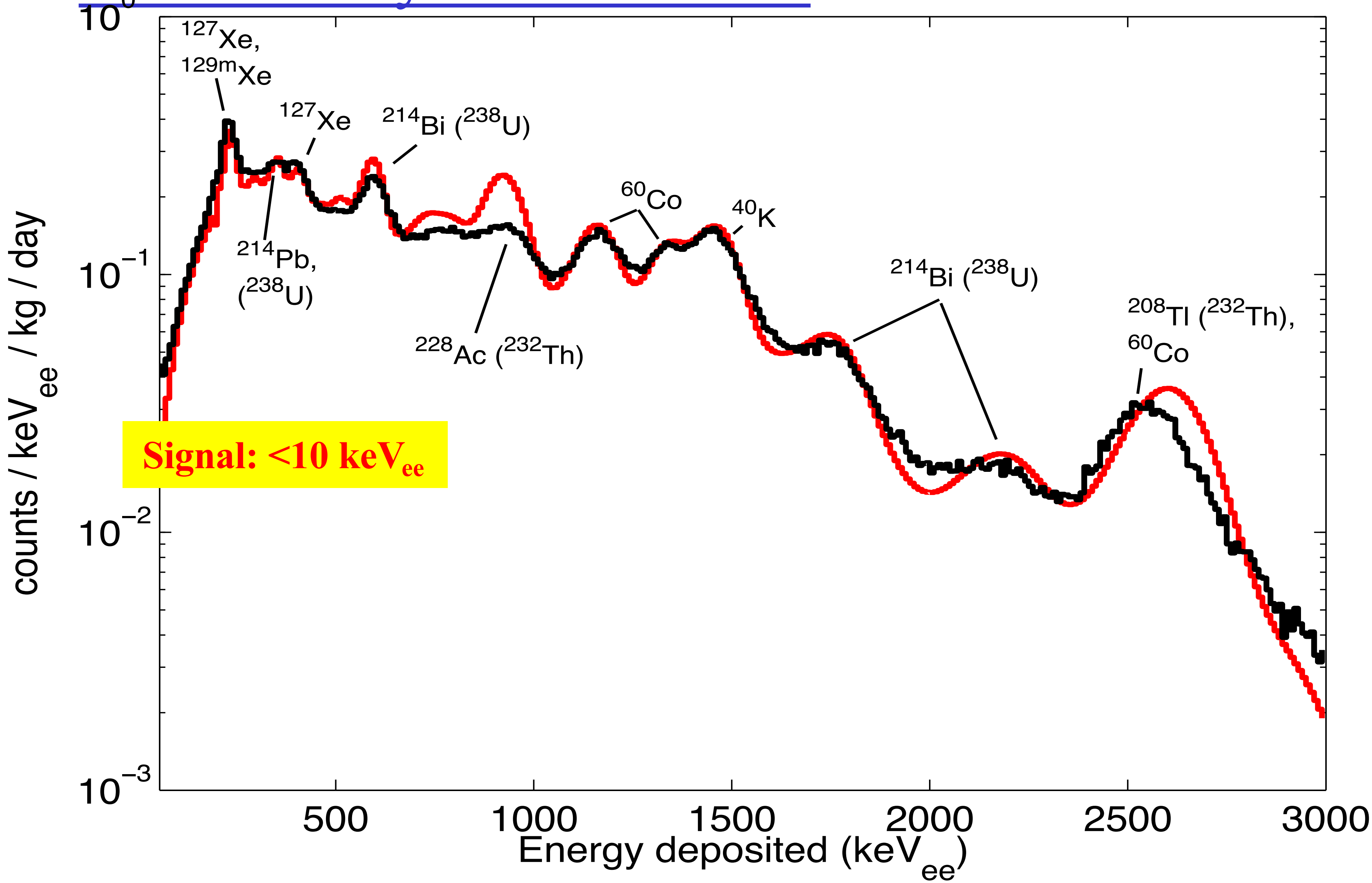
Reject gammas (Electron Recoils) by charge (S2) to light (S1) ratio.

Baseline > 99.5% rejection.

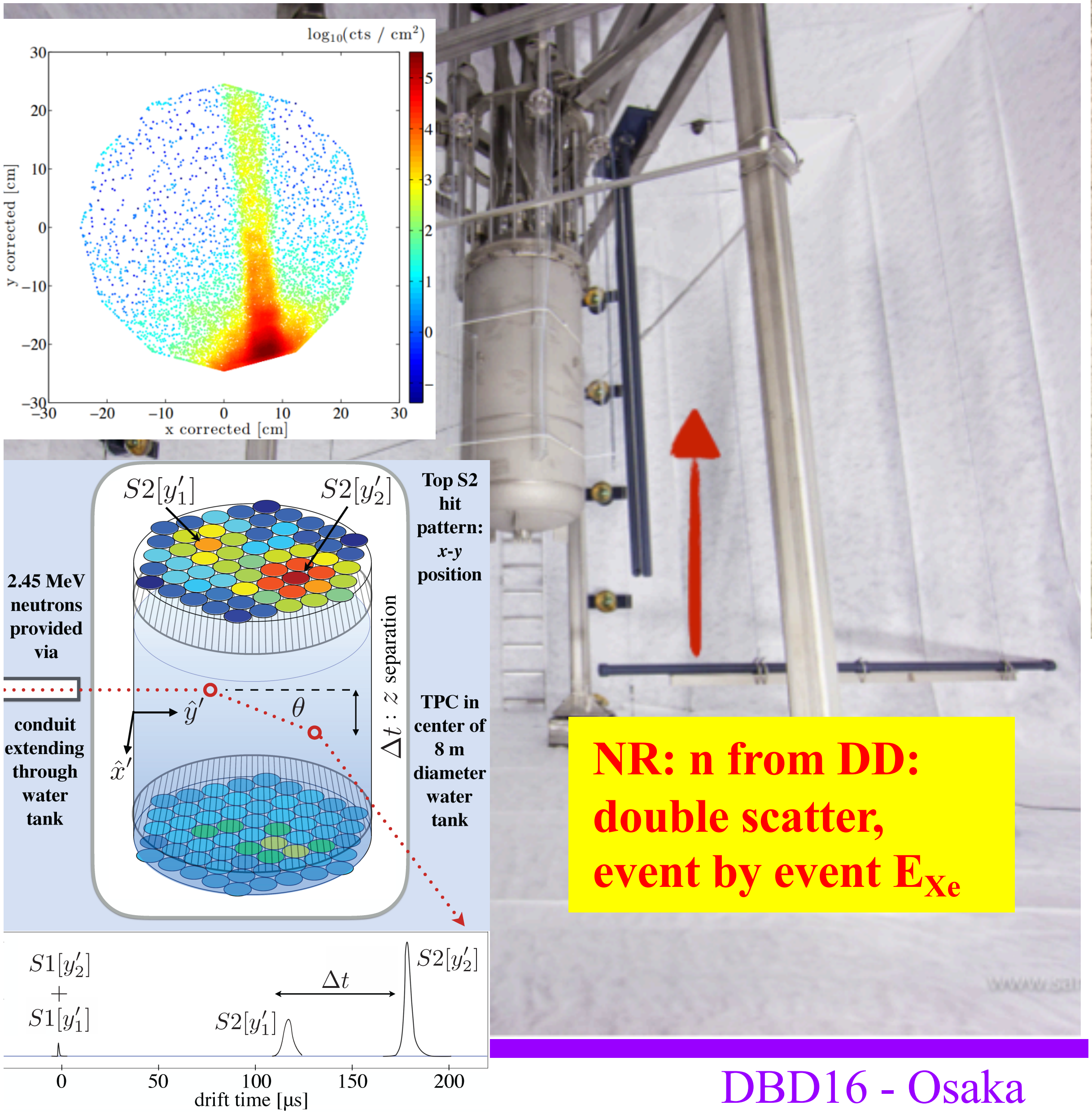
Typical Event in LUX



Gamma Ray Environment

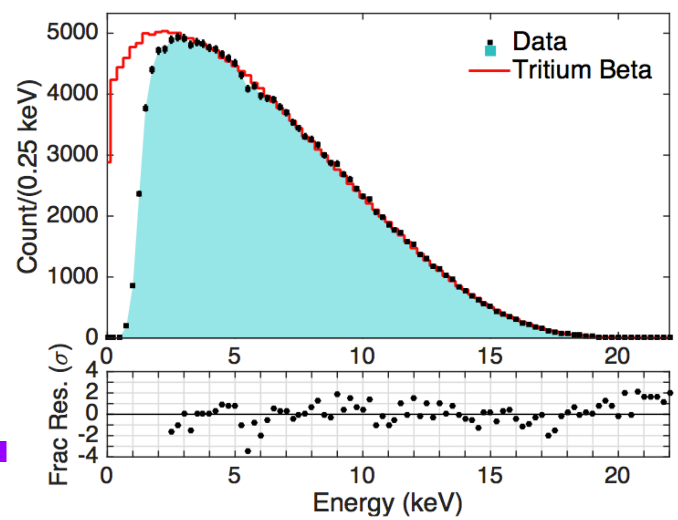


Calibration

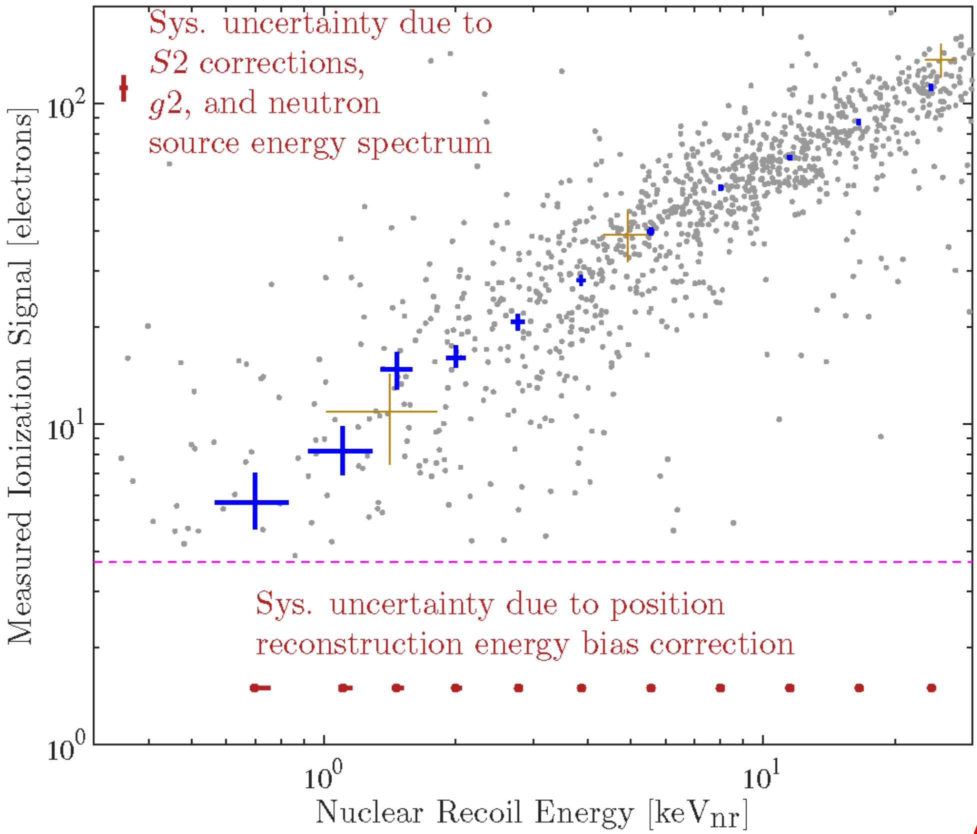


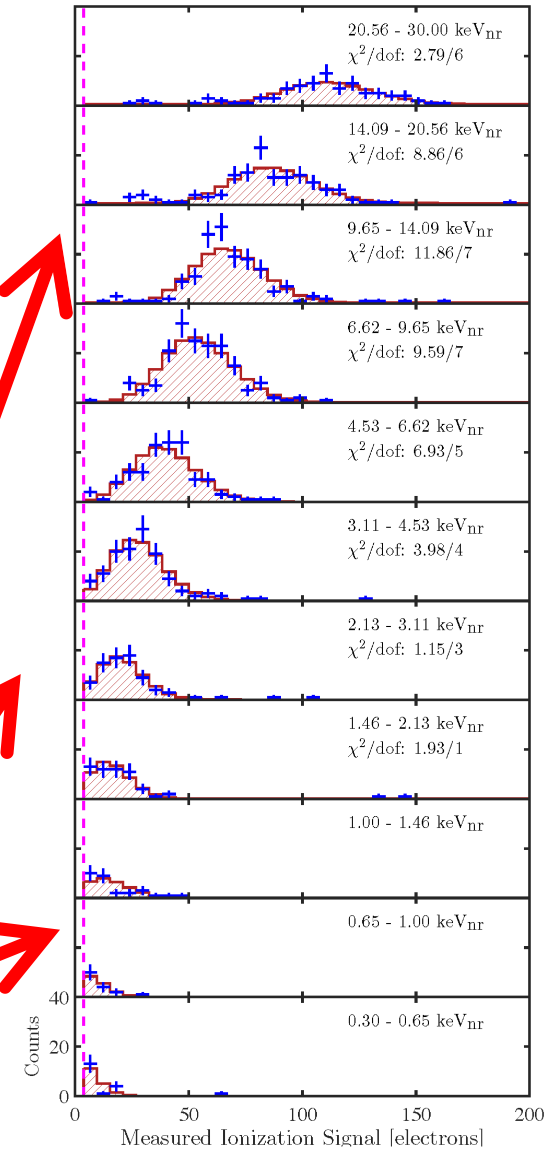
NR: n from DD: double scatter, event by event E_{Xe}

ER: T=^{3}H in CH_3T



Double Scatter Neutrons – Ionization for NR

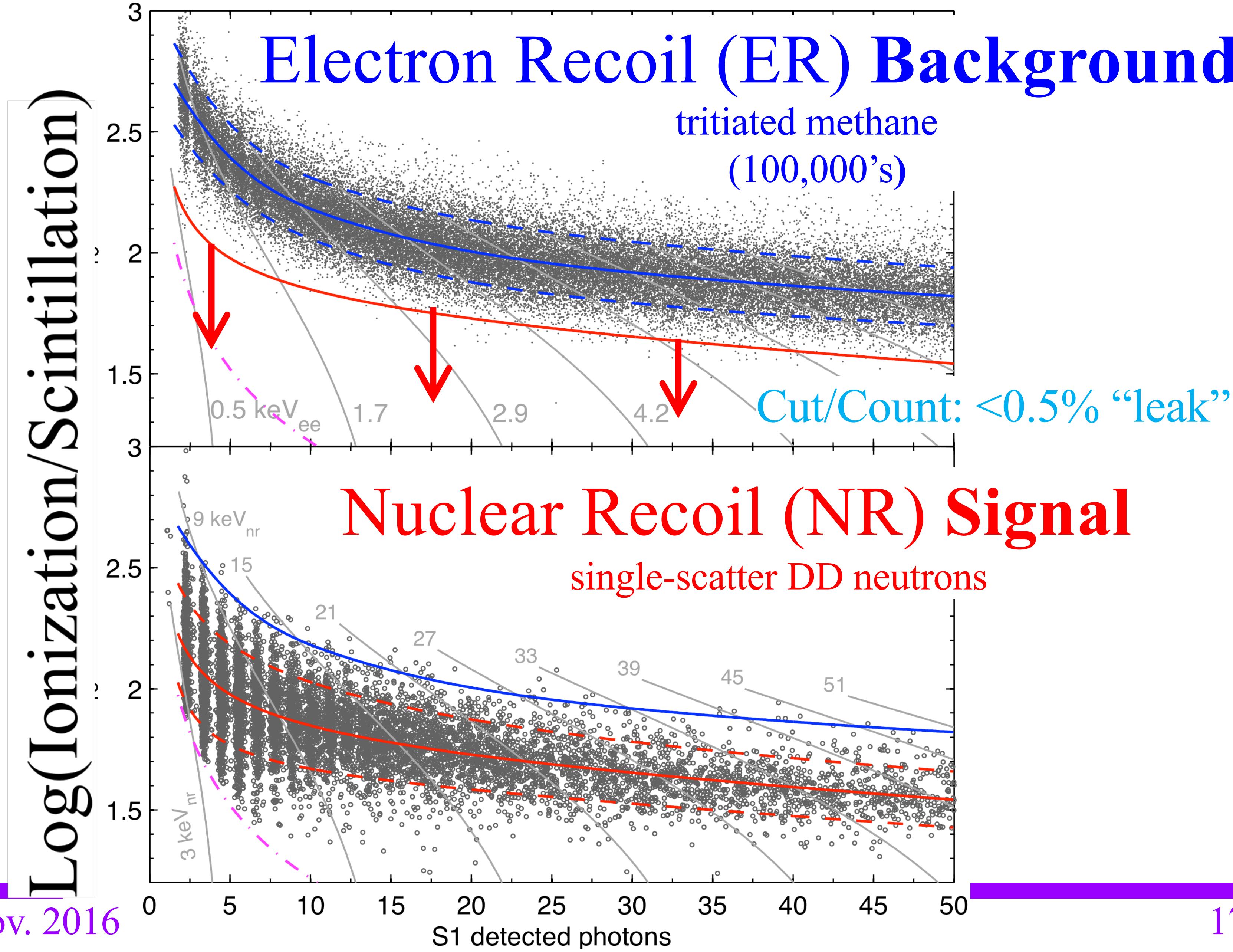




Energy from kinematics

Slices in energy

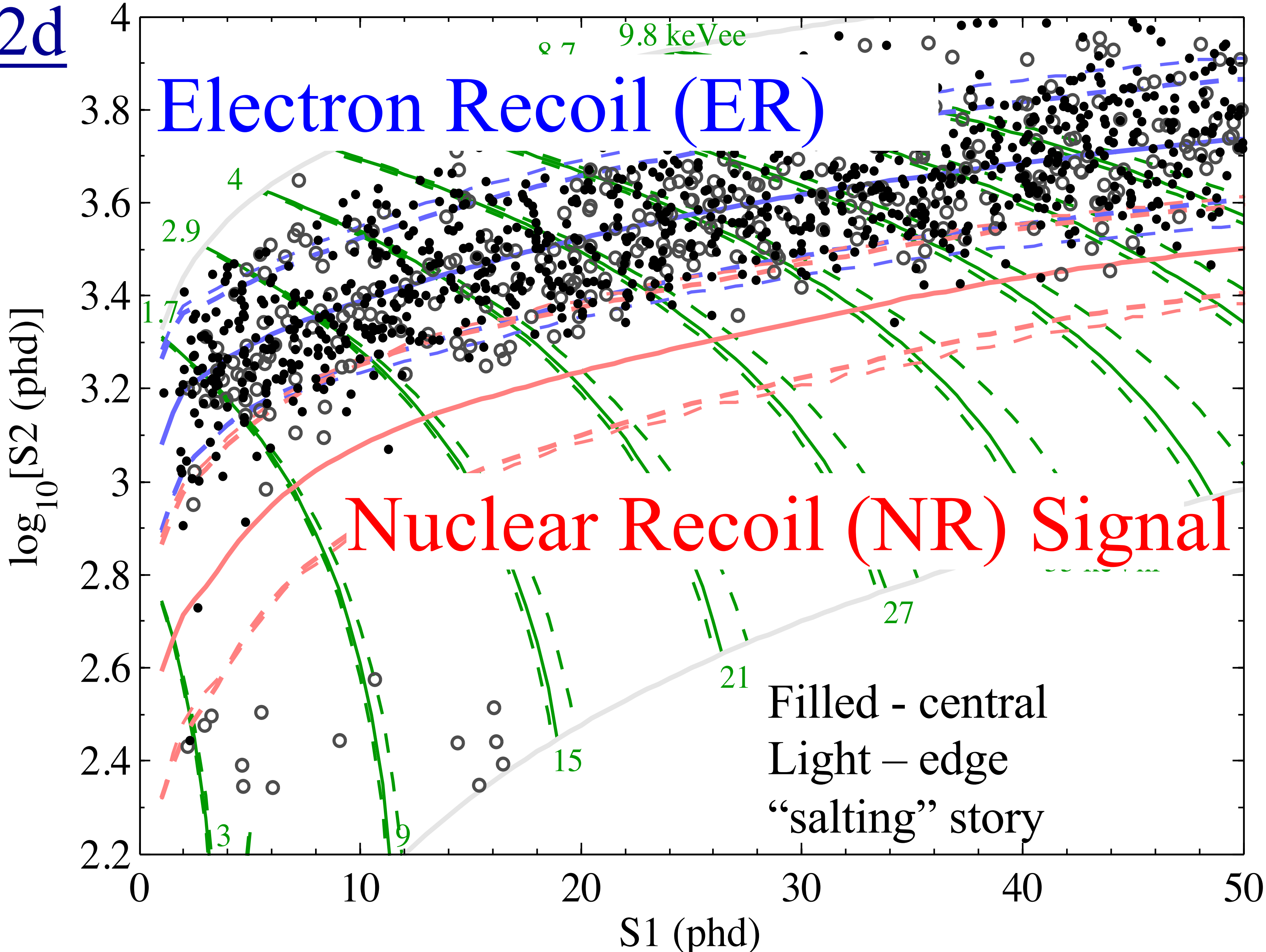
High Statistics LUX Calibrations



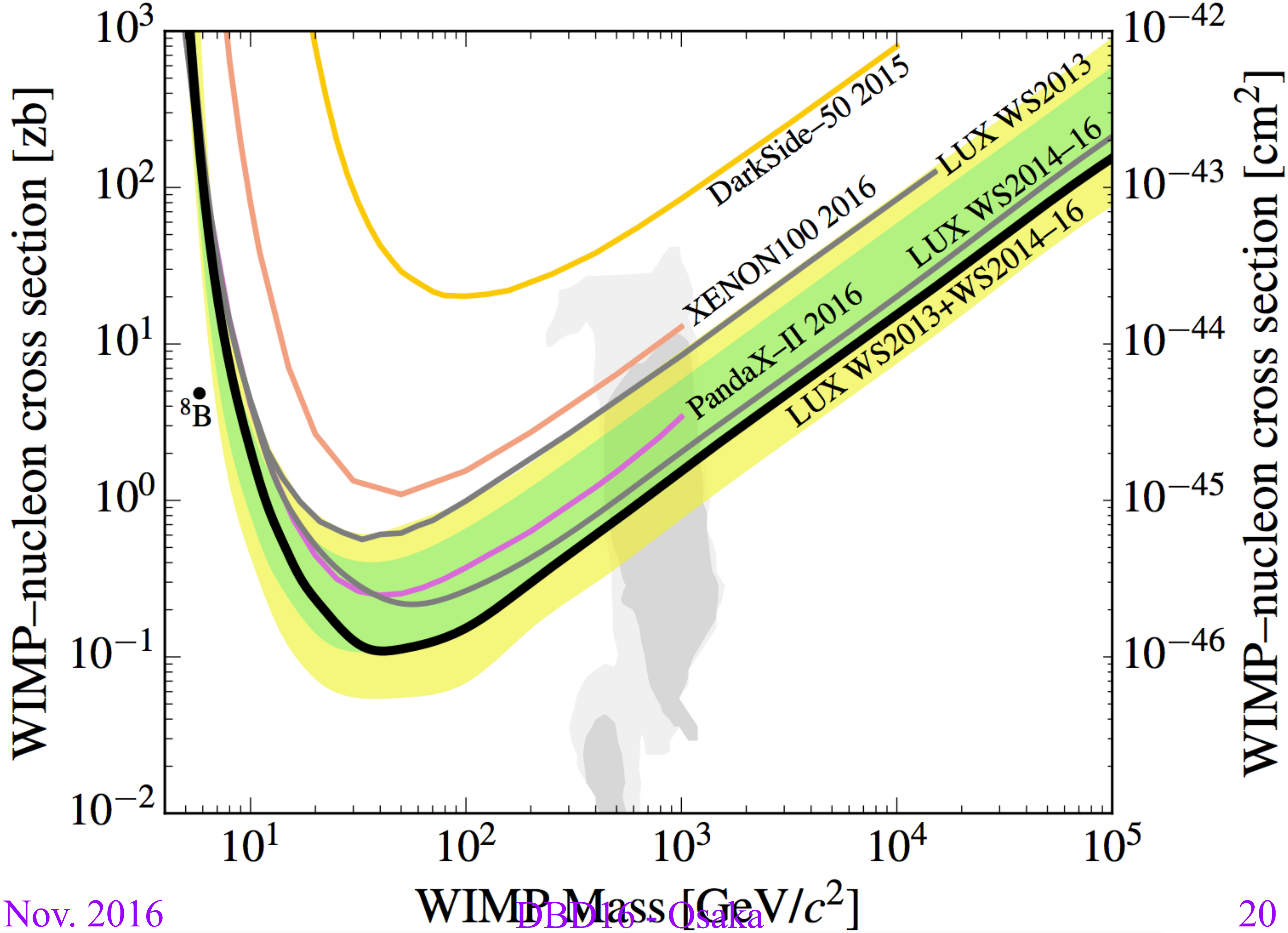
LUX WIMP Search Data Guide

- WS2013 run: 95 live days
  - First result, published 2014
  - Improved with calibrations: published 2016
    - Low mass WIMPs
- WS2014-16 run: 332 live days
  - Calibrate drifts in the detector
  - Raw data here
- Show combined limit curve

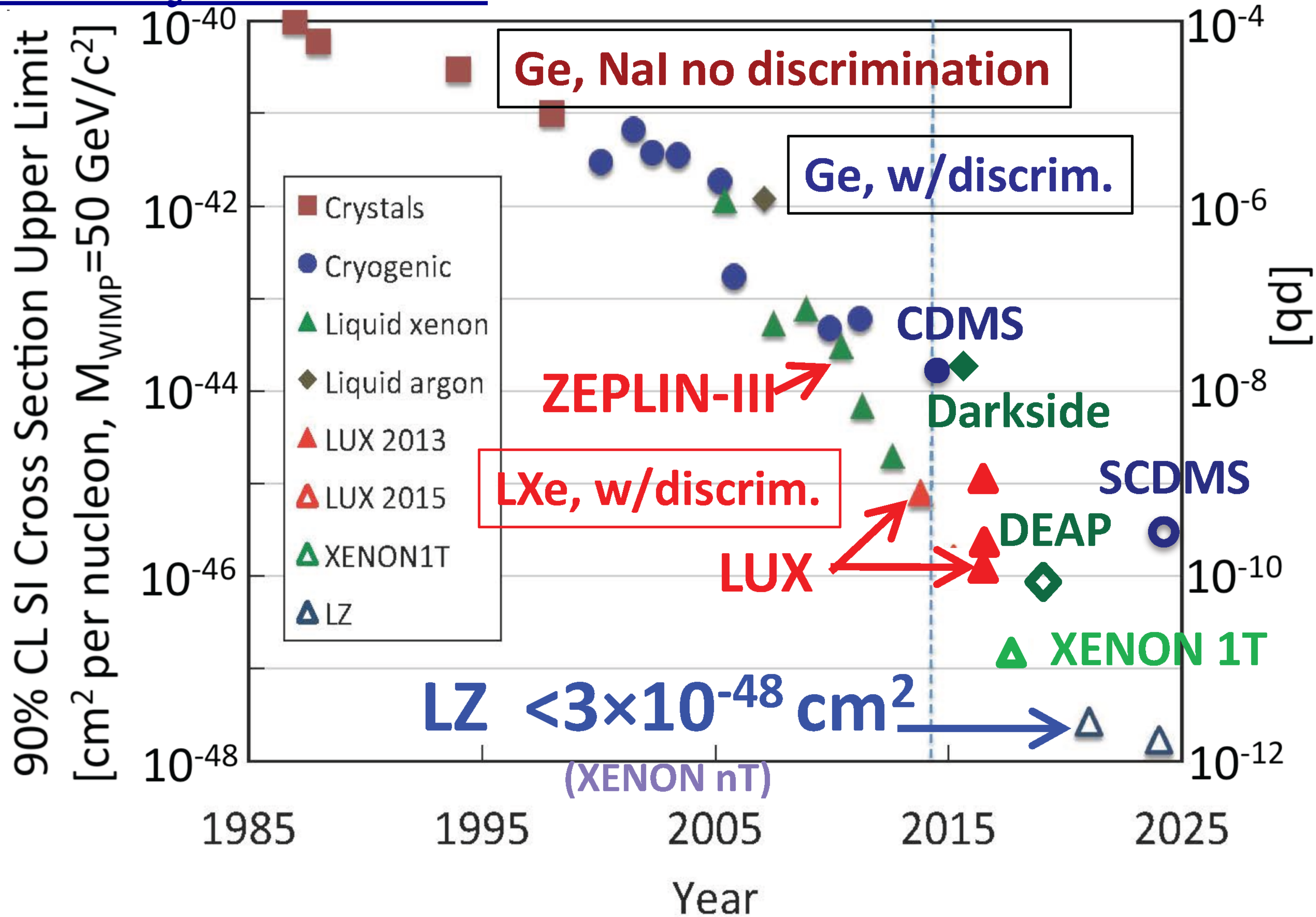
332d


Electron Recoil (ER)
Nuclear Recoil (NR) Signal
9.8 keVee
4
2.9
1.7
3
9
15
21
27
Filled - central
Light – edge
"salting" story
log10[S2 (phd)]
S1 (phd)
0
10
20
30
40
50
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4

Combined Limit Curve



History & Future



LZ= LUX + ZEPLIN

37 Institutions, 217 People

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

Black Hills State University
Brookhaven National Laboratory (BNL)
Brown University
Fermi National Accelerator Laboratory (FNAL)
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Northwestern University
Pennsylvania State University
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority (SDSTA)
STFC Rutherford Appleton Laboratory (RAL)
Texas A&M University
University at Albany (SUNY)
University of Alabama
University of California (UC), Berkeley
University of California (UC), Davis
University of California (UC), Santa Barbara
University of Maryland
University of Massachusetts

University of Michigan
University of Rochester
University of South Dakota
University of Wisconsin-Madison
Washington University in St. Louis
Yale University

At Oxford, August 2016

LZ 7 t LXe active – fits in LUX Water Tank

LZ

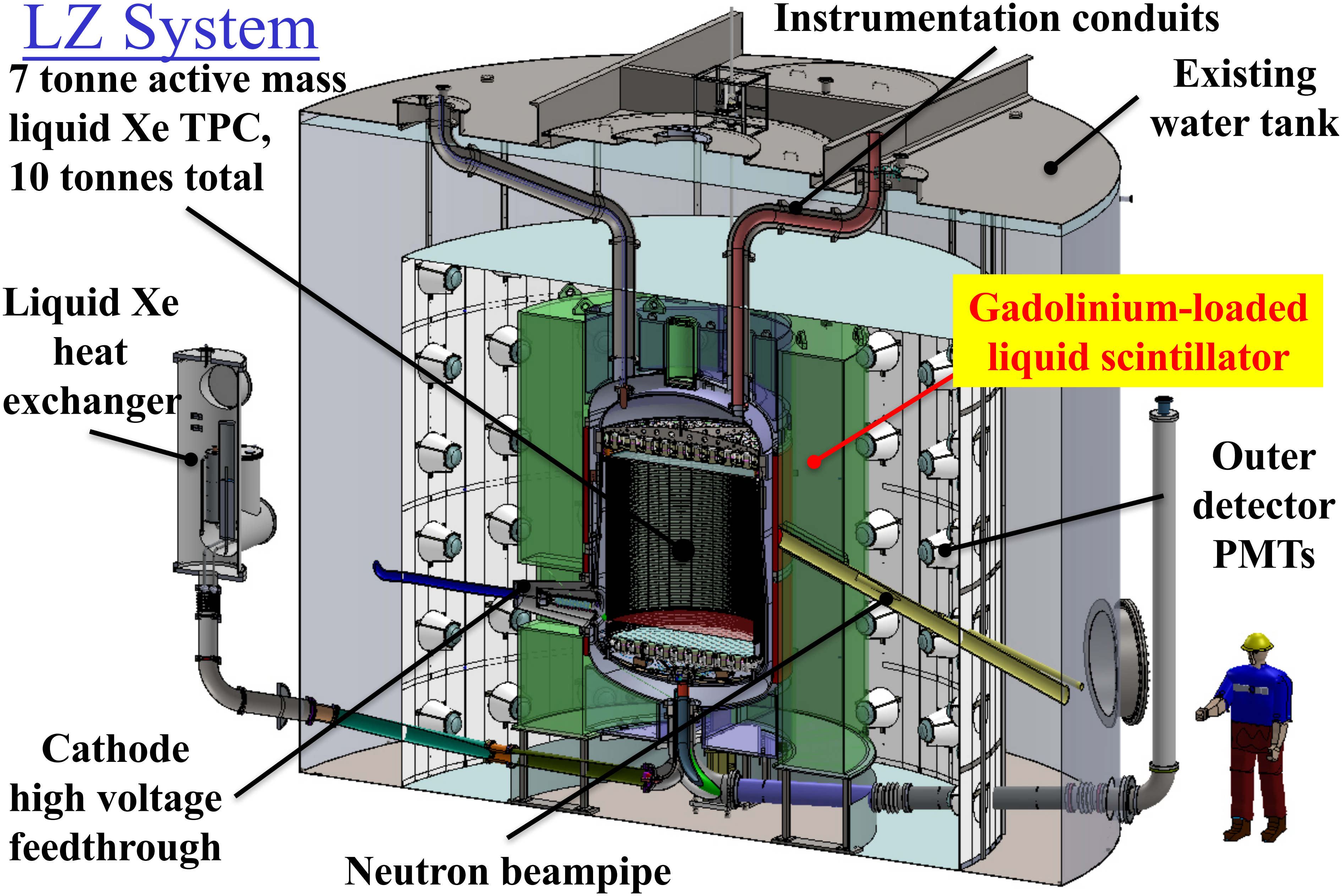
Passed DOE CD-1, CD-2, partially CD-3;

Complete CD-3 expected Jan. `17

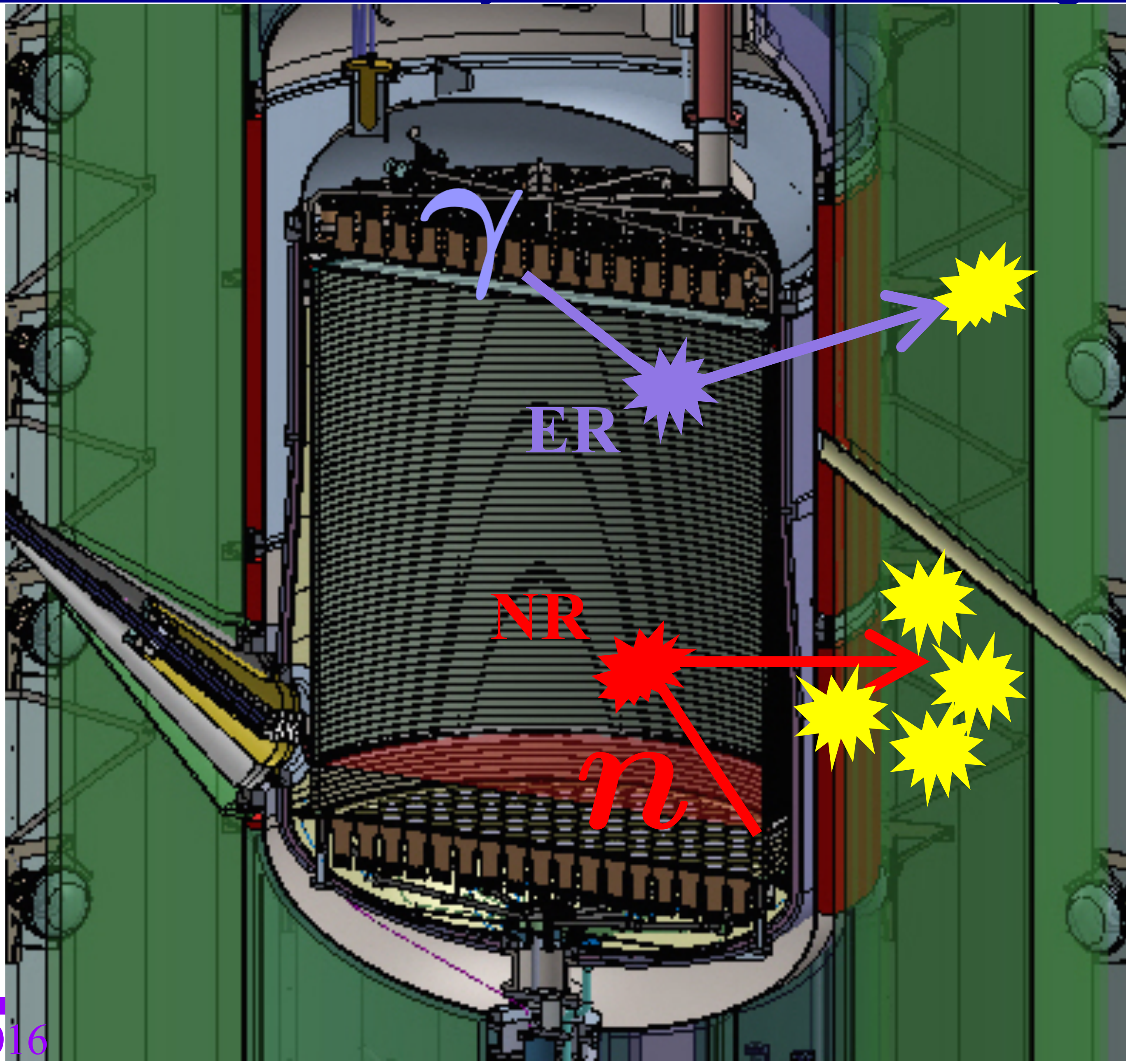
Operations: Apr. `20

LUX

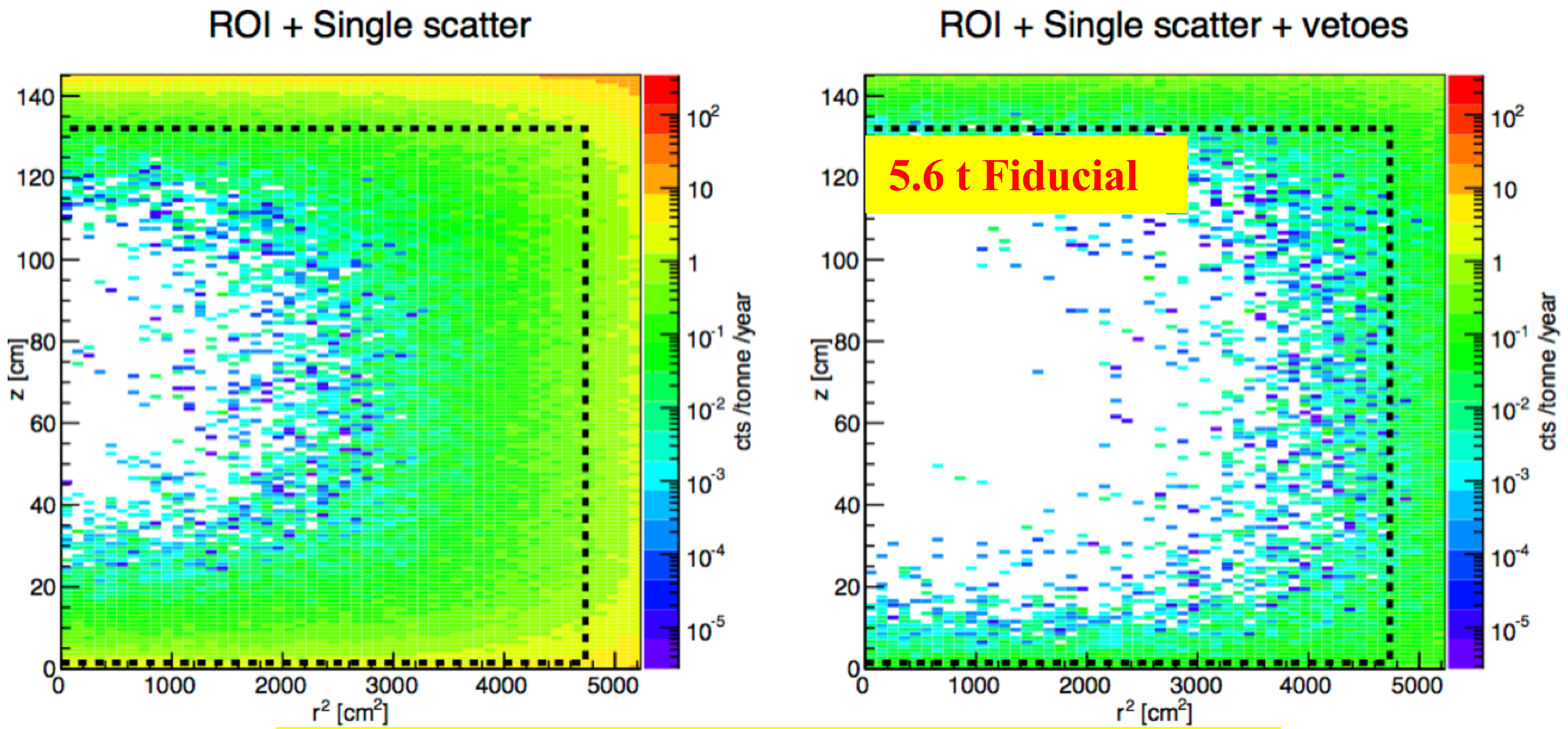
LZ System


7 tonne active mass liquid Xe TPC, 10 tonnes total
Instrumentation conduits
Existing water tank
Liquid Xe heat exchanger
Gadolinium-loaded liquid scintillator
Outer detector PMTs
Cathode high voltage feedthrough
Neutron beampipe

Background from Nearby Material – LXe Edges



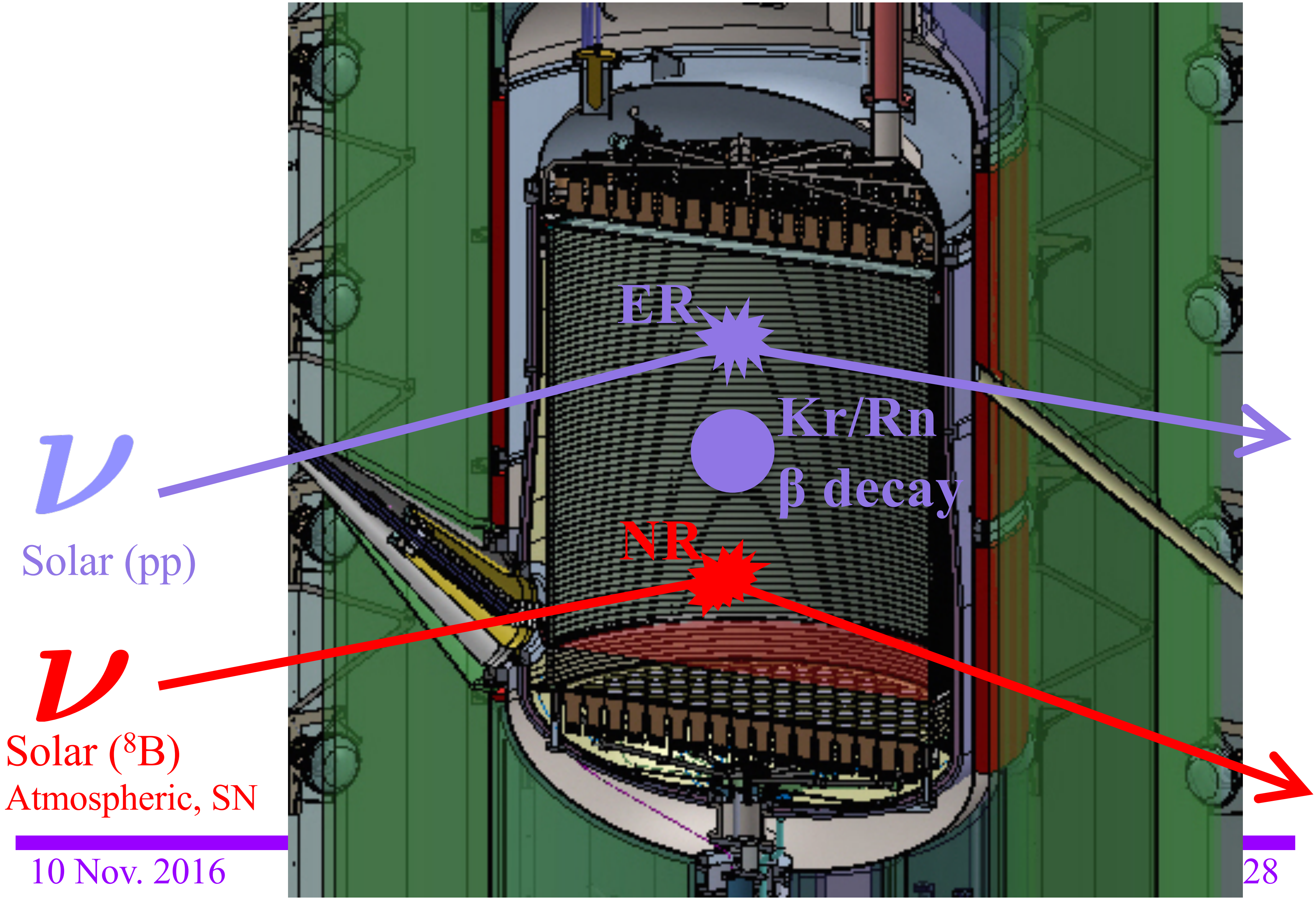
Impact of the Outer Detector



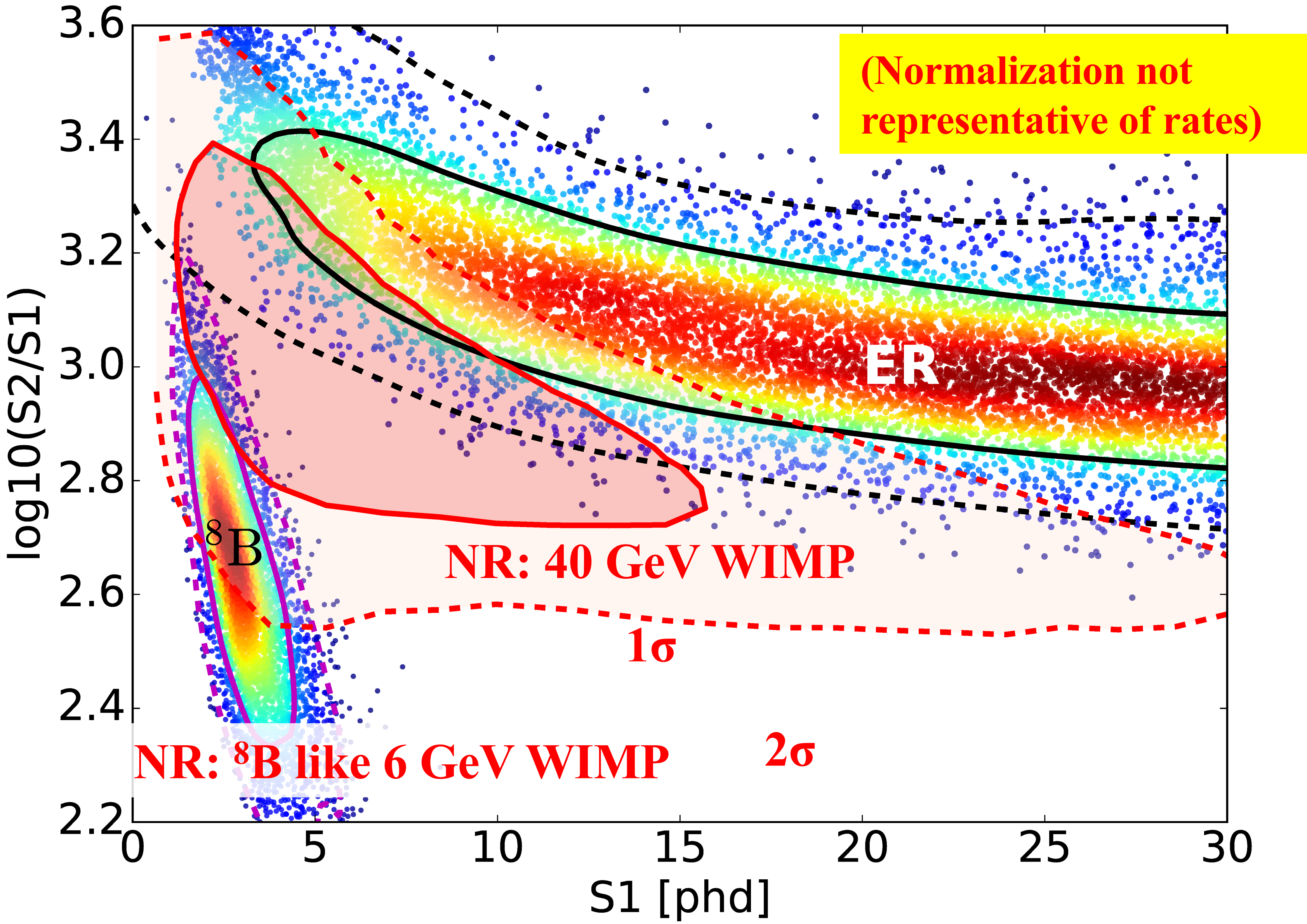
Fiducial mass fraction: from ≈50% to ≈80%

In case of a suspected signal, the Outer Detector provides cross checks on backgrounds

Backgrounds – Uniform Through LXe Volume



LZ Simulation - shapes crucial



NR Background Tallies – 1000 days, 5.6 t

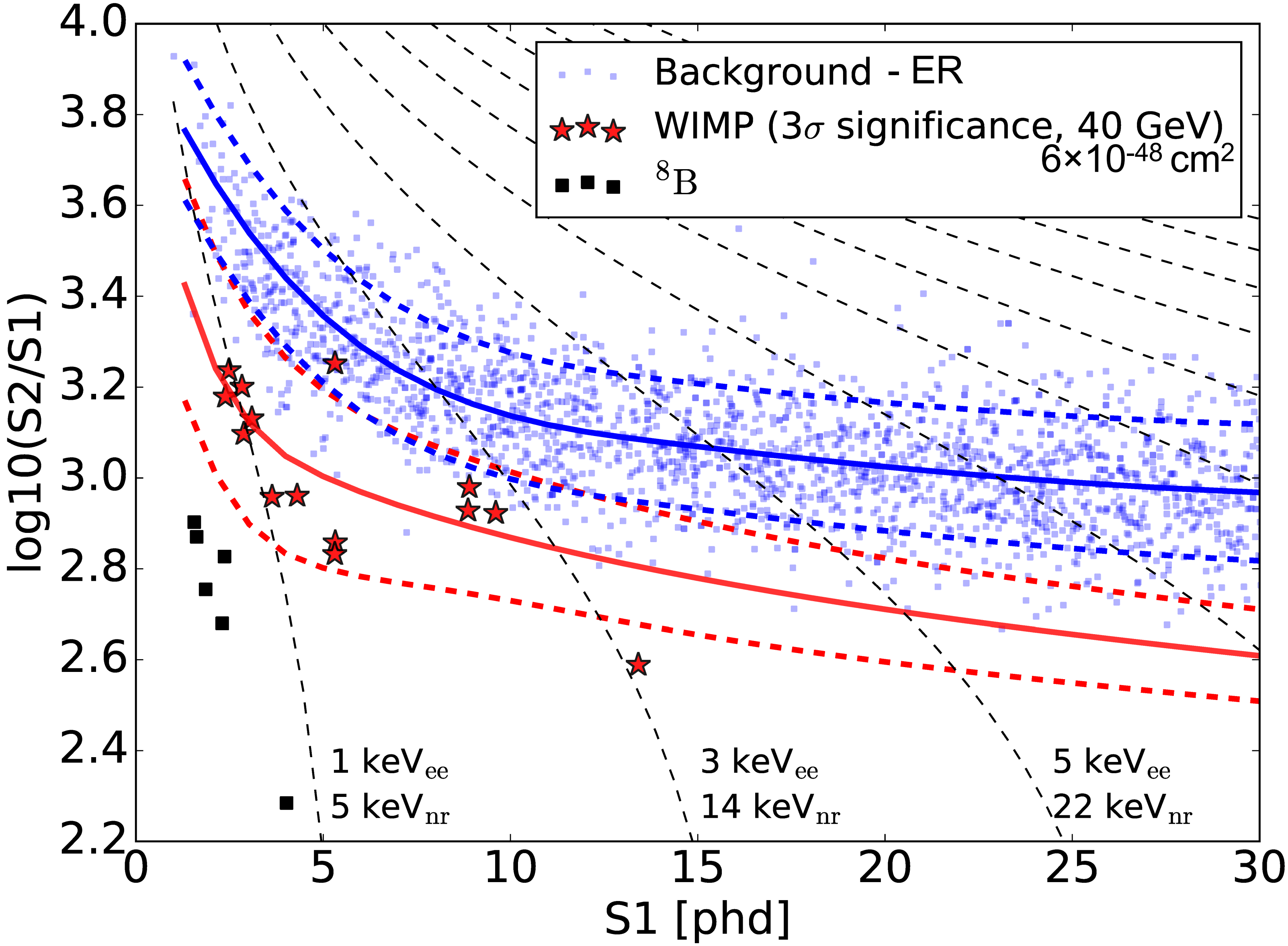
- ^{8}B Nuclear Recoils – like 6 GeV WIMP
  - Sensitive to low threshold detector response
  - ≈7 (baseline) to ≈300 (goal)
- Other nuclear recoils
  - ≈0.5 nearby material, strong spatial dependence
    - dominant: dust!
  - ≈0.7 due to neutrinos, uniform in LXe
    - dominant: atmospheric

ER Background Tallies – 1000 days, 5.6 t

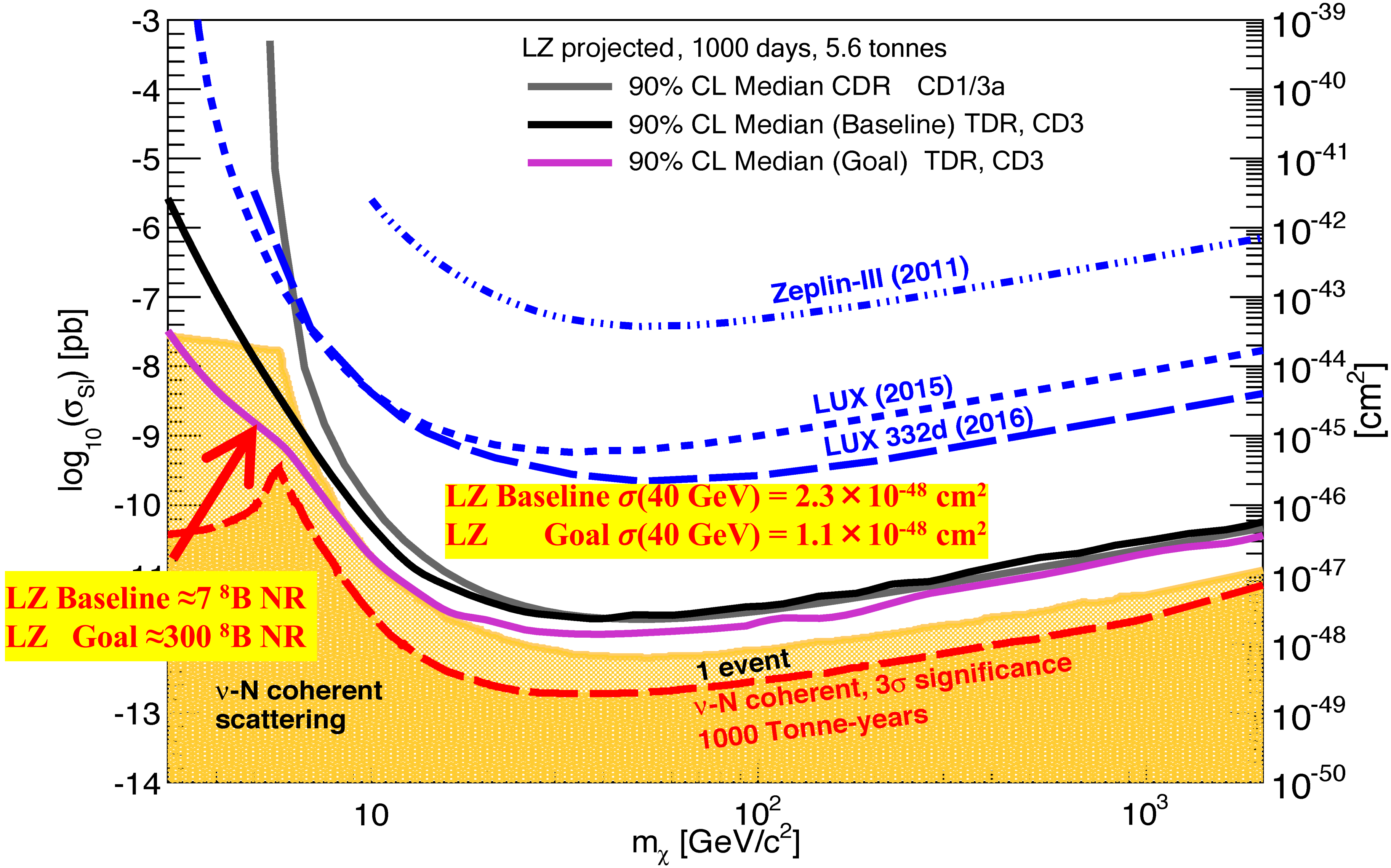
- pp solar ≈ 255
- ^{136}Xe $2\nu\beta\beta$ ≈ 67 (very low energy)
- Nearby material ≈ 11 (strong spatial dependence in LXe)

- Internal Radioactive Gases, uniform in LXe
  - 72 (goal) to ≈1000 (baseline)
  - Dominantly ^{222}Radon emanation
  - Vigorous screening program

Baseline Simulation 1000 days, 5.6 t



Projected Sensitivity (Spin Independent)

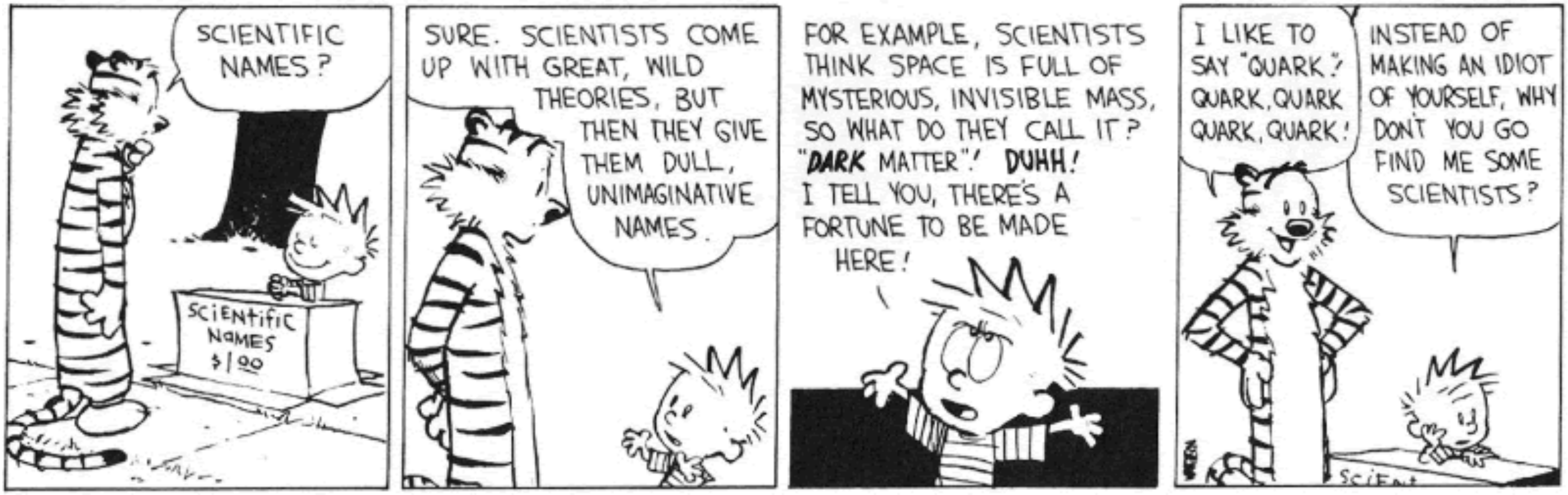


^{136}Xe 0νββ – 1000 days, 5.6 t in LZ

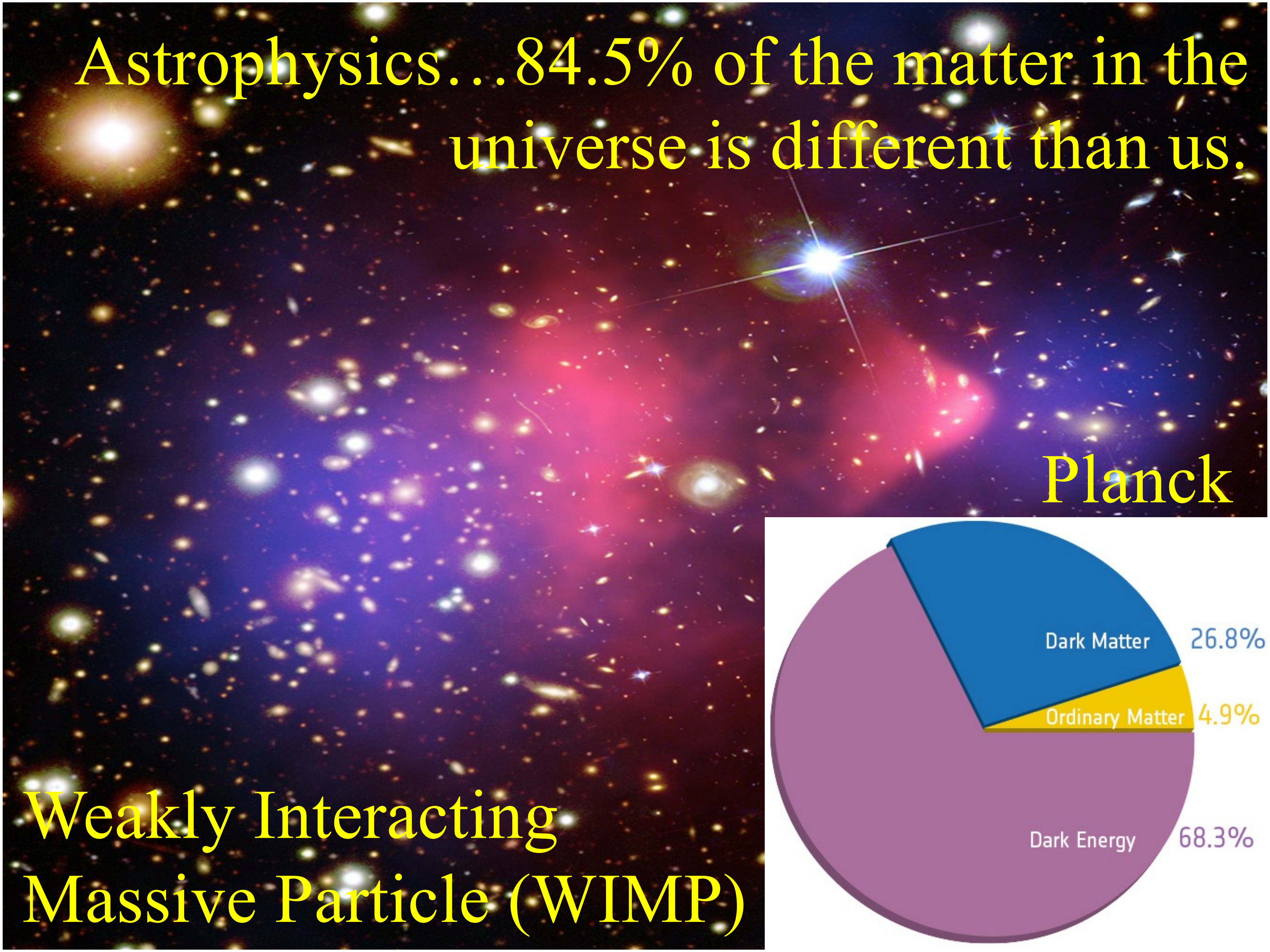
- Challenges
  - Experiment optimized for 1.5-10 keV_{ee}
  - More shielding of ^{208}Tl, ^{214}Pb gammas needed
  - Power of spatial shape, Bragg ID, etc..
- Preliminary estimates... ≈ 1t fiducial
  - Unenriched… ≈ 10^{26} y
  - 90% ^{136}Xe… ≈ 10^{27} y
- If a WIMP signal emerges, change the isotopic abundance Xe target, to understand WIMP interaction with nuclei

Summary

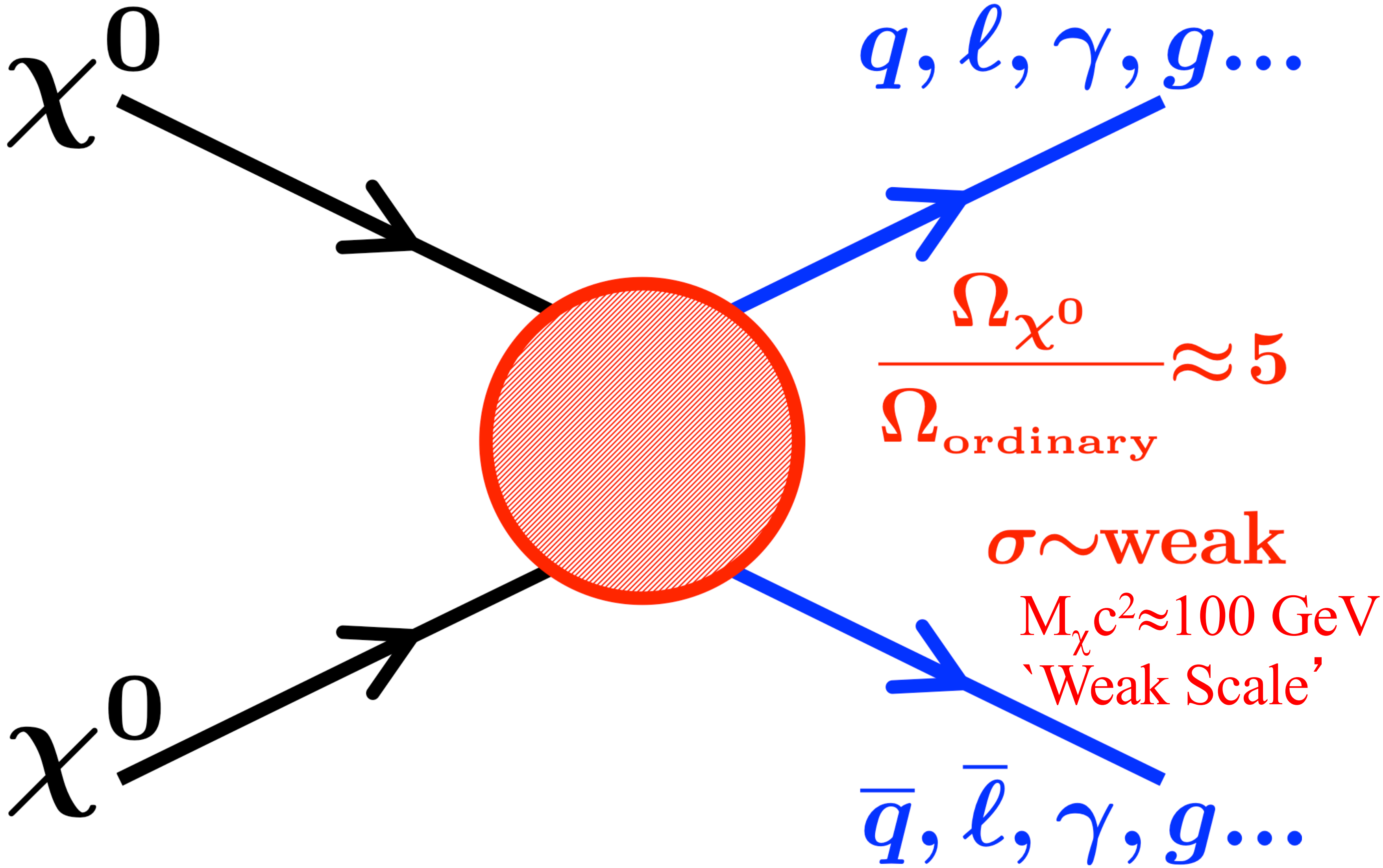
- 2-phase liquid xenon TPCs push the frontier of WIMP sensitivity, and LUX led the way for a few years
- LUX has substantially advanced the art of calibration
- LZ will operate in April 2020 and is projected to achieve best spin independent sensitivity better than 3×10^{-48}cm^2, and start to see irreducible neutrino background


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

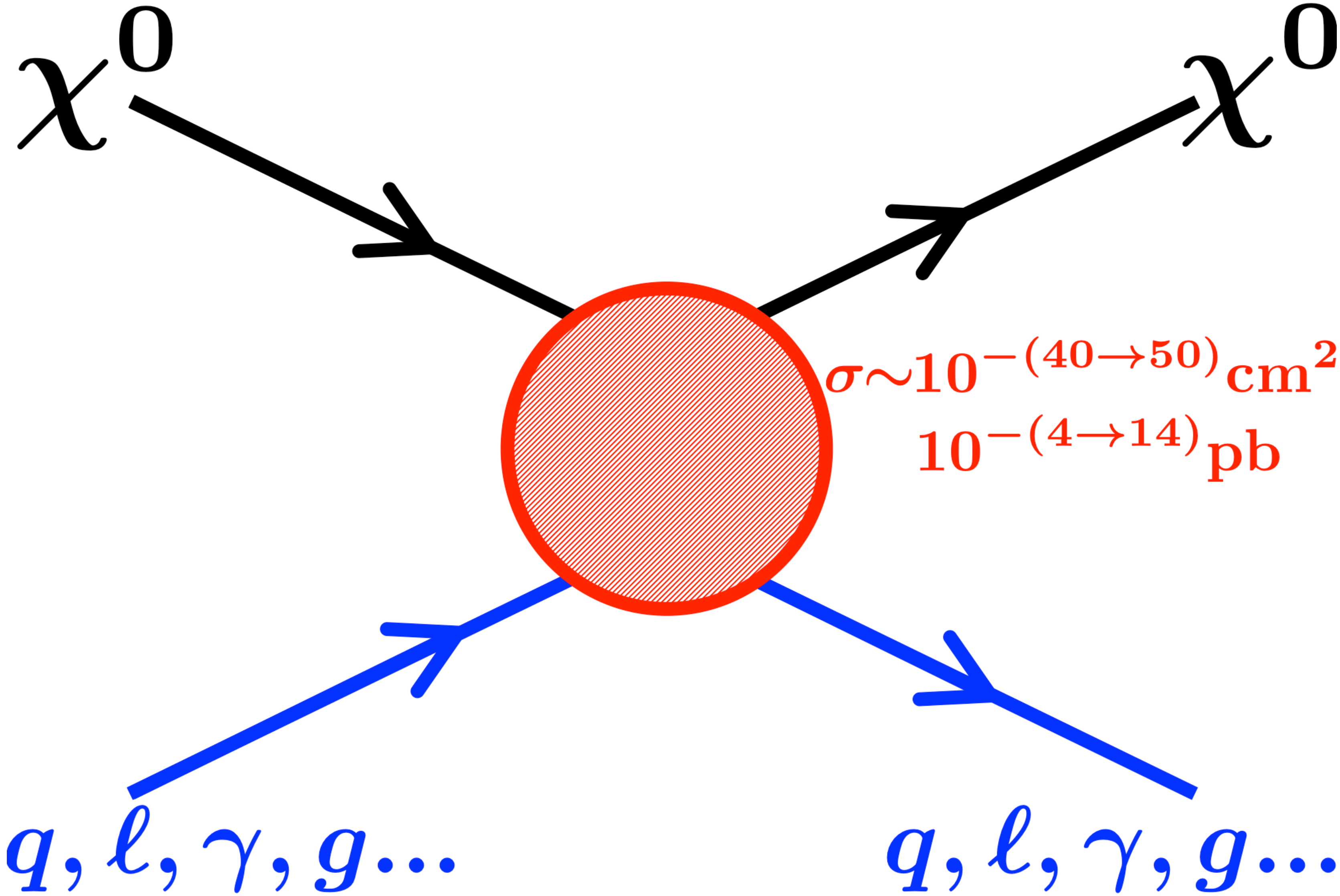
THANKS!


Astrophysics…84.5% of the matter in the universe is different than us.
Planck
Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%
Weakly Interacting Massive Particle (WIMP)

The WIMP


χ^0
χ^0
$q, \ell, \gamma, g...$
$\bar{q}, \bar{\ell}, \gamma, g...$
$\frac{\Omega_{\chi^0}}{\Omega_{ordinary}} \approx 5$
σ~weak
$M_\chi c^2 \approx 100$ GeV
`Weak Scale'

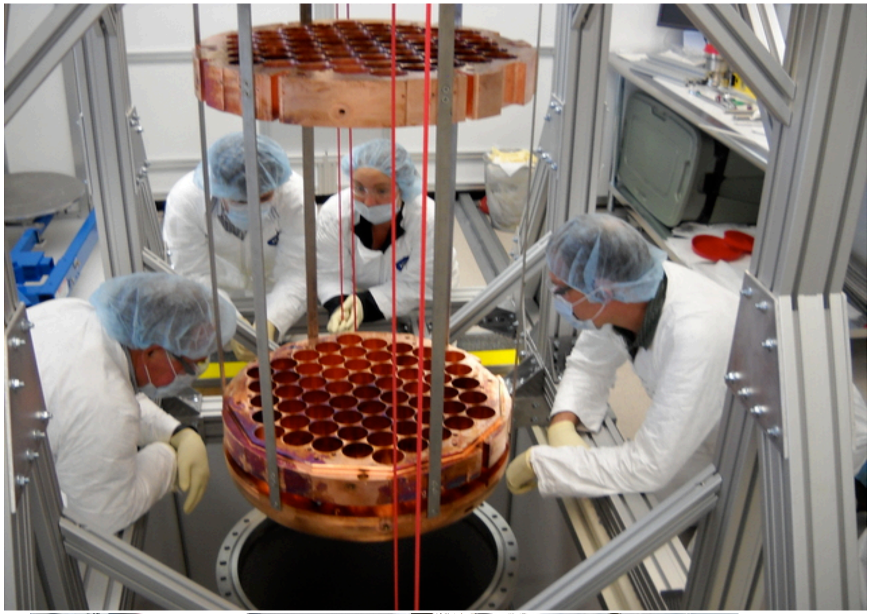
Direct Detection

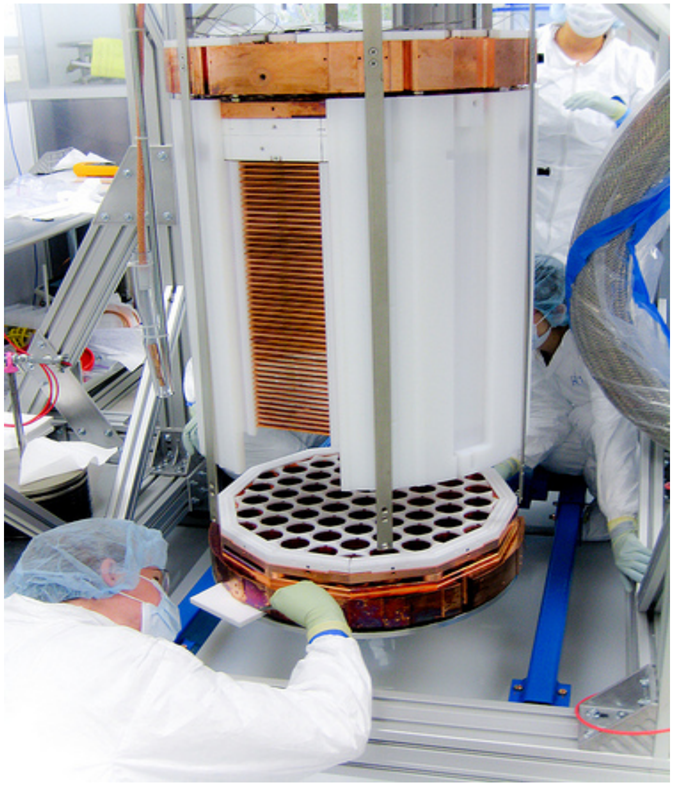


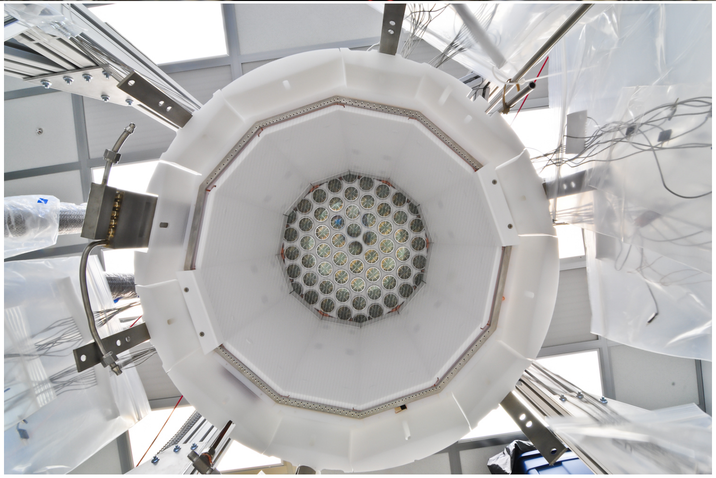
Comparison of Nobles

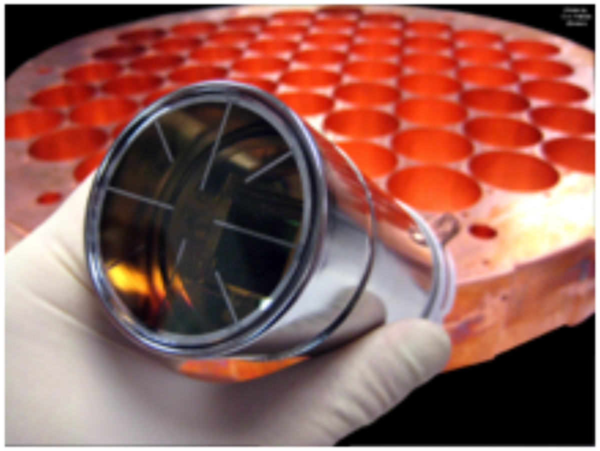
Element	A (nat)	Atm (ppmv)	bp (K)	Sc. E. (eV)	Density (gm/cm^3)	Comments
Helium	4.00	5.2	4.2	16	0.13	Great Pulse Shape Disc
Neon	20.2	18	27	16	1.2	"
Argon	39.9	9300	87	9.8	1.4	"
Krypton	83.8	1.1	121	8.3	2.4	^{85}Kr (Reactors)
Xenon	131.3	0.09	165	7.1	3.1	Lower energy scint/lumi
Radon	≈222	10^{-19}	211		4.4	Emanation afflicts above

LUX being built

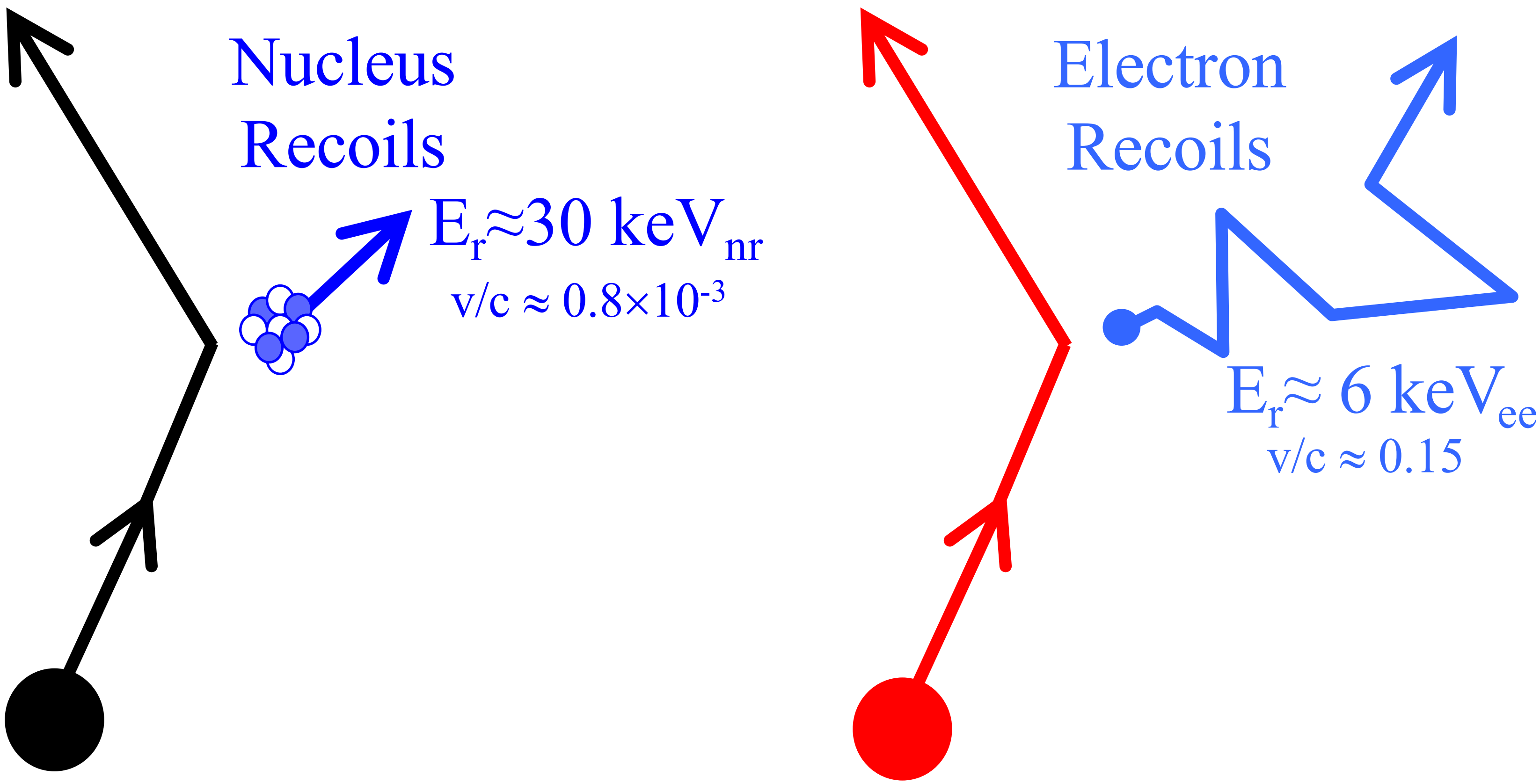








Signal and Background

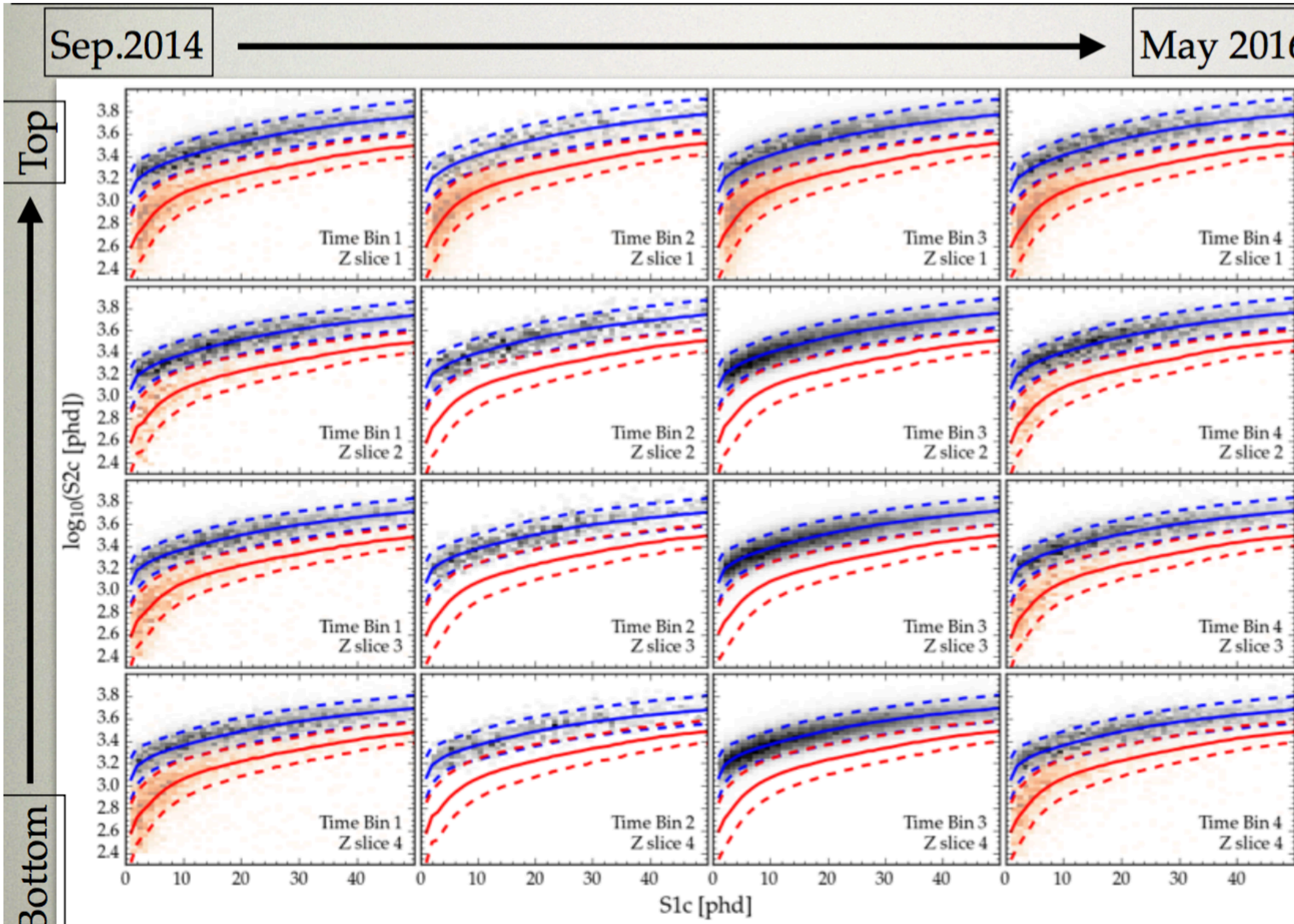


χ^0 (calibrate: neutron)

γ, e^- (calibrate: tritium injection)

Discrimination – detector's ability to distinguish these

Solution: Time / Space Bins



Gray density: CH_3T calibration (ER)

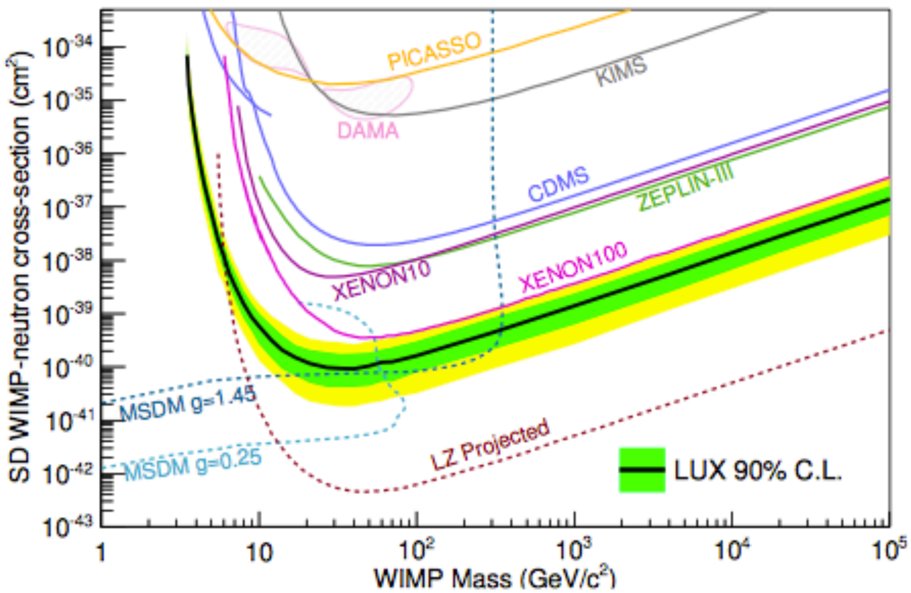
Orange density: DD calibration (NR)

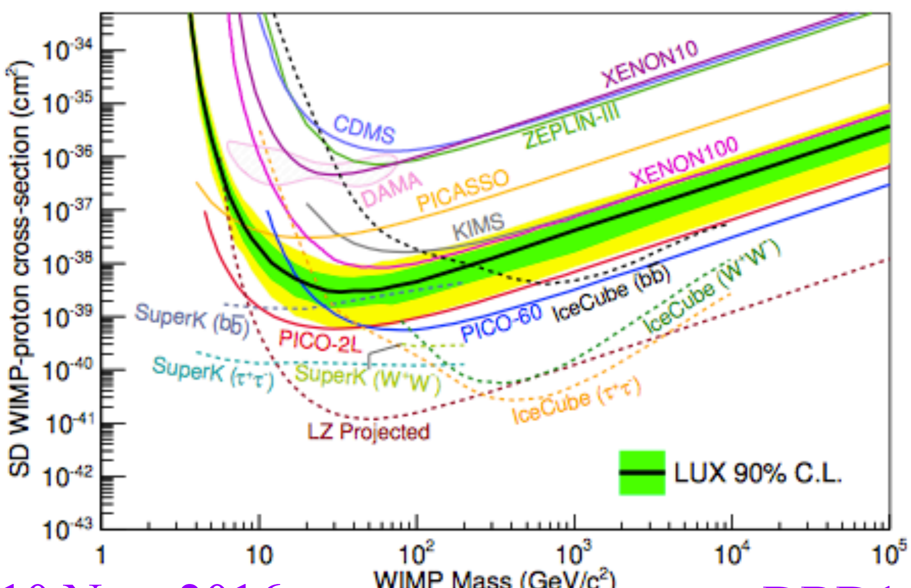
Solid lines: NEST model, band mean.

Dashed lines: NEST model, 10-90 percentile.

4 event date bins X 4 z-slices = 16 ‘segments’

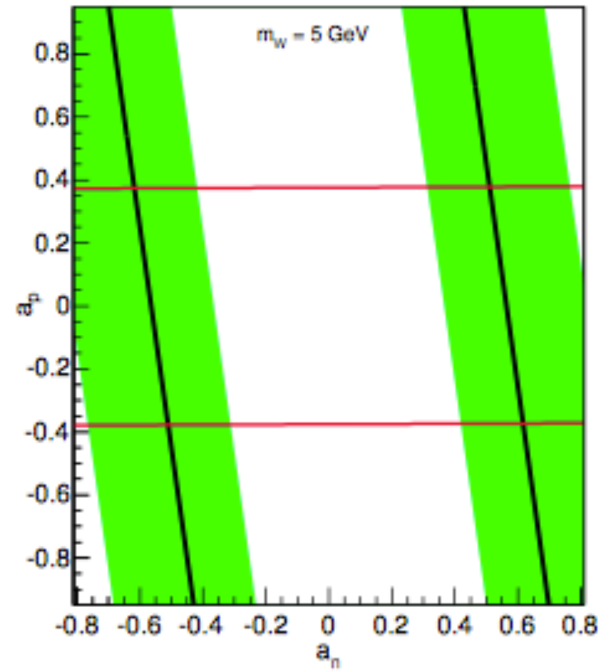
SD Exclusion

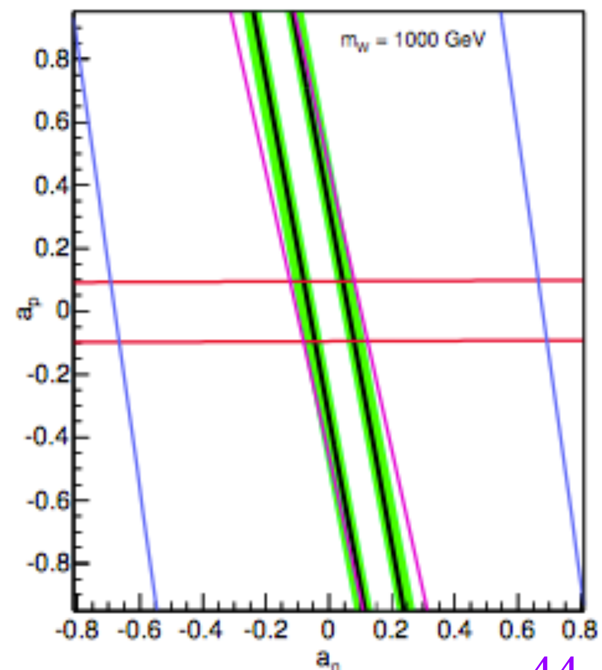




NOTE: This is still the old run. Still needs to be updated with the 1 year's worth of new data

Xenon is the *best* element for neutron coupling (while fluorine is best for protons)





Fiducial Mass Fraction

Experiment	Active Mass (kg)	Fiducial Mass (kg)	F/A (%)	Best Sensitivity (cm^2)	Livetime (y)	Year
Xenon 10	13.9	5.4	39	4.5×10^{-44}	0.16	2008
Zeplin III	12.6	5.6	44	4×10^{-44}	0.73	2012
Xenon 100	66	34	51	2×10^{-45}	0.61	2013
LUX	248	118	48	7.6×10^{-46}	0.26	2015
LUX	248	100	40	2×10^{-46}	0.90	2016
DEAP-3600	3600	1000	28	1×10^{-46}	3	2017
Xenon 1T	2000	1160	58	2×10^{-47}	2	2018
LZ	7000	5600	80	3×10^{-48}	3	2021

Fiducial mass fraction: from ≈50% to ≈80%

In case of a suspected signal, the Outer Detector provides cross checks on backgrounds

Backgrounds (5.6 t, 1000 live-days) (I)

Source	ER	NR
Atmospheric neutrinos	-	0.5
HEP solar neutrinos	-	0.2
Diffuse solar neutrinos	-	0.05
pp+^{7}Be+^{13}N solar neutrinos	255	
^{136}Xe 2νββ	67	
Subtotal Physics (Uniform in LXe fiducial)	**322**	**0.7**

Fixed Internal Surface Contamination	0.2	0.4
Laboratory Walls, Cosmogenics	4.3	0.07
R11410 3” PMTs	1.5	0.01
PMT Cabling	1.4	-
Cryostat Vessel	0.6	0.01
20 other components	3 (27%)	0.05 (10%)
Subtotal External Backgrounds (Non-Uniform in LXe fiducial)	**11**	**0.5**
Subtotal	**333**	**1.2**

Backgrounds (5.6 t, 1000 live-days) (II)

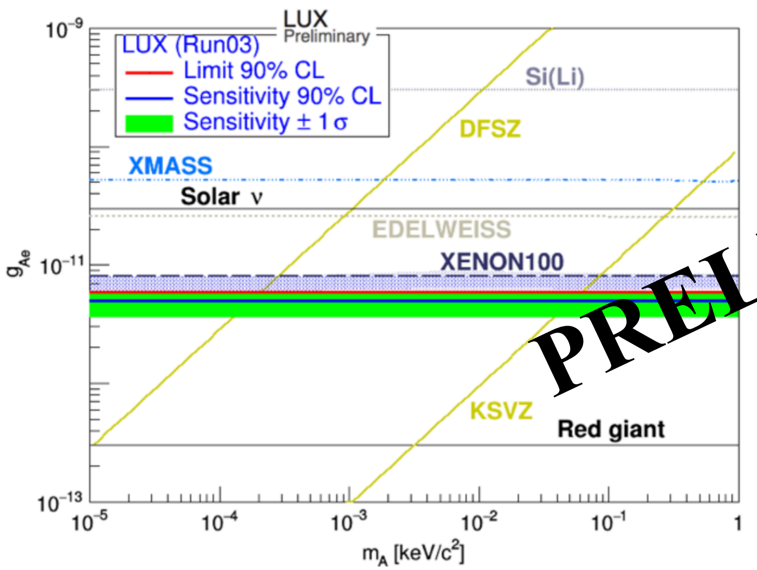
Source	**ER**	**NR**
Subtotal Previous Page	**333**	**1.2**
	ER (Baseline / Goal)	
^{222}Radon – (2 / 0.1) µBq/kg	722 / 36	
^{nat}Krypton (0.075 / 0.015) ppt g/g	125 / 25	
^{220}Radon aka Thoron – (0.1 / 0.005) µBq/kg	122 / 6	
^{210}Bismuth (0.1 / 0.005) µBq/kg	40 / 2	
^{nat}Argon (0.45) ppb g/g	2.5	
Subtotal Internal Backgrounds (Uniform in LXe fiducial)	**1012 / 72**	
Total	**1344 / 405**	**1.2**
Efficiency below median of NR band	0.005	0.5
Total below median of NR band	**6.7 / 2**	**0.6**

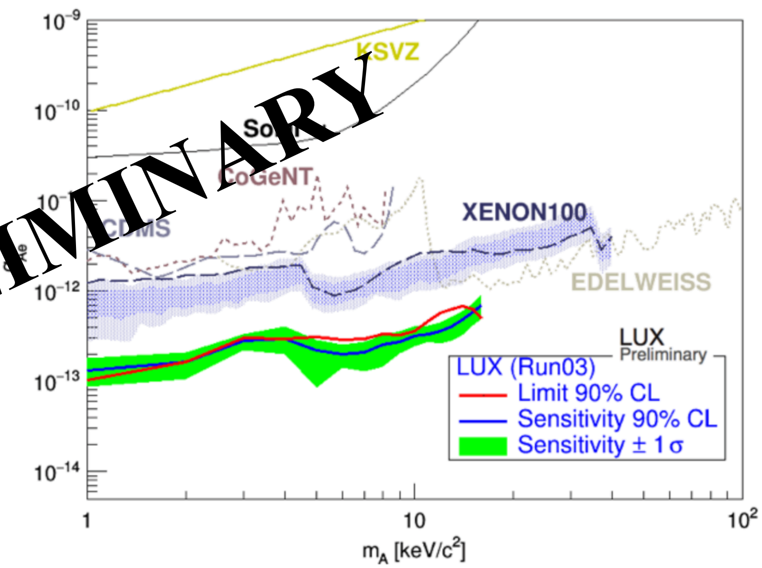
Radon Budget Estimate (Preliminary)

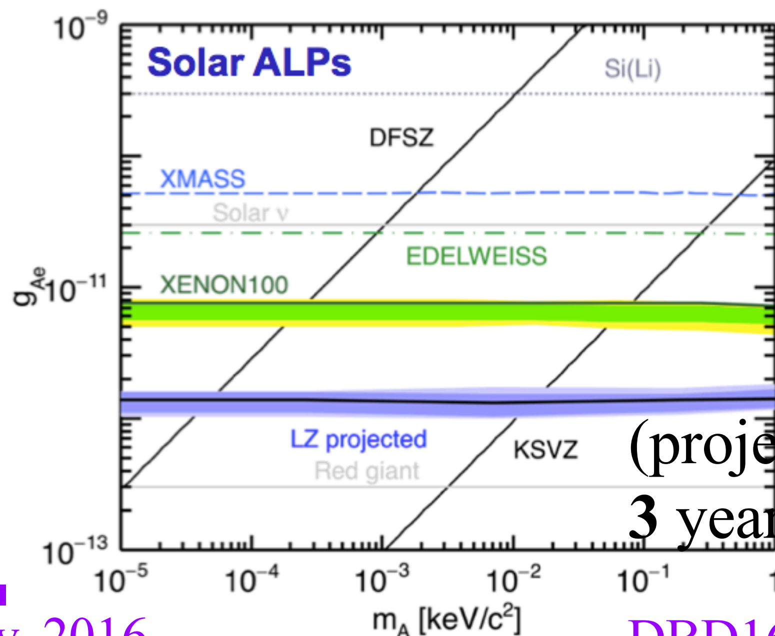
- To aid planning of assay schedule, identify areas likely to need mitigation
  - Added Xe gas mitigation system to reduce by 90%
- Estimates based on most comparable measurements
  - Some upper limits
  - Measured at room temperature but most cold * in LZ
    - Corrected only (conservatively) for capacitors, PMT cabling
- Dust
- Total 18.3 mBq
  - On track to achieve requirements

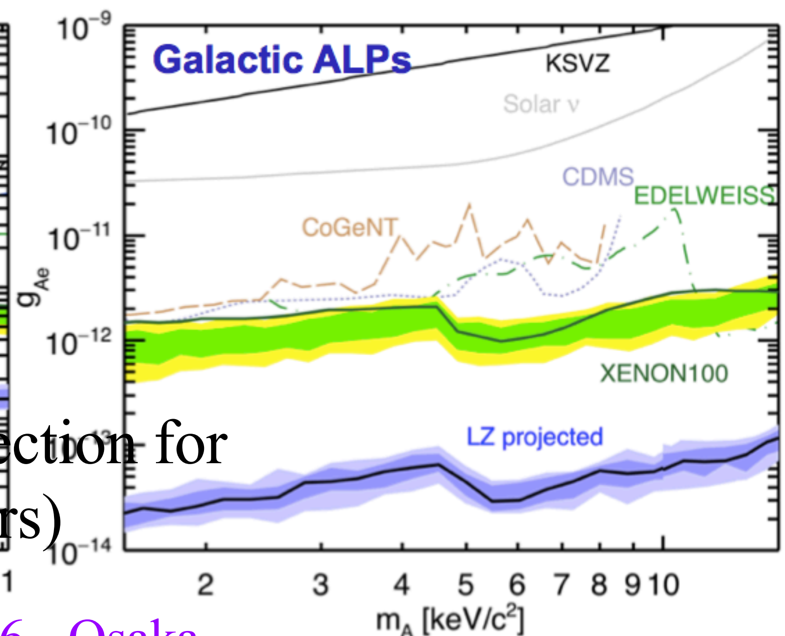
Material	Component(s)	Quantity	Unit	Requirement (mBq)	Estimate (mBq)	Screening Quantity
Al_2O_3 resistor	PMT Bases	9790	#	0.66	0.86*	3,650
$BaTiO_3$ capacitor	PMT Bases	3010	#	0.66	0.015*	100,000
Cirlex	PMT Bases	6000	cm^2	0.11	0.45*	668
Titanium	Cryostat, PMT Mounts, Field Rings, Grid Supports	412,000	cm^2	1.70	0.41	550
PTFE	Reflectors, HV Umbilical	840,000	cm^2	0.66	<1.3*	205,000
PMT Cabling†	PMT Cabling	17,000	m	0.55	0.09	3,000
PMT Feedthrough†	PMT HV Flange	122	#	0.11	0.49	5
PMT Feedthrough†	Signal Flange	88	#	0.11	<0.24	5
Steel Conduit†	Cabling Conduit	100,000	cm^2	0.22	0.055	100,000
R11410 PMT	R11410 PMT	488	#	1.10	1.26	488
R8520 PMT	R8520 PMT	180	#	0.55	0.30	180
Polyethylene	HV Umbilical	4200	cm^2	0.11	0.10	42,000
Tin-coated copper	HV Umbilical	11,000	cm^2	0.11	0.002	110,000
Tivar	HV Umbilical	3894	cm^2	0.22	0.004*	20,000
Acetal	HV Umbilical	195	cm^2	0.11	0.0002*	2000
Copper	HV Umbilical	39	cm^2	0.11	0.000007	400
Epoxy	HV Umbilical	1000	cm^2	0.11	0.0001*	10,000
Steel	Cryostat Seals, Xe Recirculation	135,000	cm^2	0.77	0.104	135,000
Recirculation Pump	Xe Recirculation	1	#	0.22	0.1	1
Purification Getter	Xe Recirculation	2.5	kg	1.10	1.34	2.5
Transducers & Valves	Xe Recirculation	30	#	0.44	0.17	30
Welds	Recirculation System, Cryostat	32.3	m	0.22	0.58	18.3
Dust				10.0	10.0	
Total				**20.0**	**18.3**	

Axions (LUX 95 days, and LZ)









(projection for
3 years)