PERSPECTIVES FOR DIRECT DARK MATTER SEARCHES WITH LUX ZEPLIN

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for the LZ collaboration

STFC/Rutherford Appleton Laboratory (UK)

Collider Physics and the Cosmos, 9-13 October 2017, Arcetri, Florence , Italy

Direct Dark Matter Searches: LZ

- Direct detection experiments
    - Overview of direct detection experiments
    - Reach and limitations
- LZ detector - design
    - Principle of DM detection in LZ
    - Outer Detector
    - Time Projection Chamber
- LZ control & operation
    - Detector calibration
    - Background control
- Conclusions & outlook

Direct detection DM experiments

SNOLab
DEAP/CLEAN
Picasso
COUPP

Boulby
ZEPLIN
DRIFT

YangYang
KIMS

Homestake
LUX

Modane
EDELWEISS

Kamioka
XMASS
Newage

Soudan
SuperCDMS
CoGeNT

Canfranc
ArDM
Rosebud
ANAIS

Gran Sasso
XENON
CRESST
DAMA/LIBRA
DarkSide
WARP

Jinping
Panda-X
CDEX

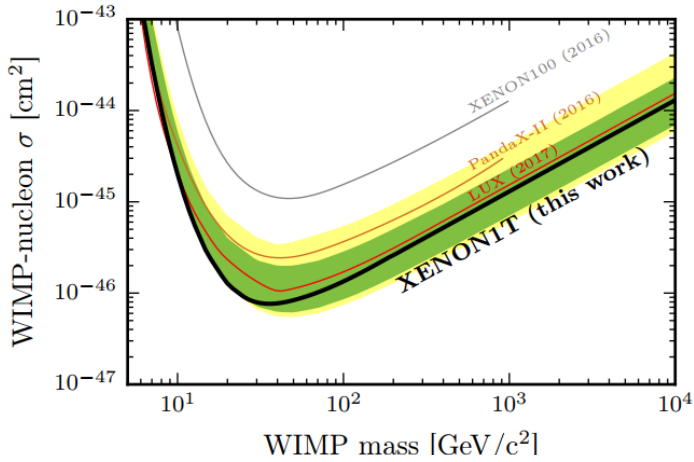
South Pole
DM Ice

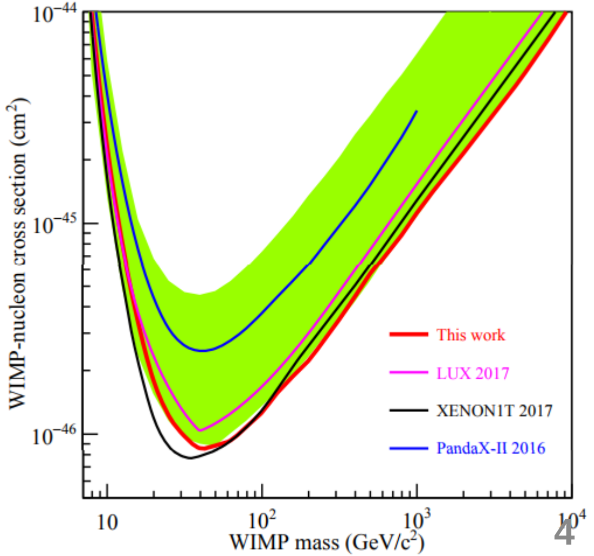
Recent DD DM results

- LUX – see later slide
- Xenon-1T
  - 34 days of exposure
  - 5.4×10^4 kg day exposure
  - Electronic background 1.9×10^{-4} evt/kg/day/keV$_{ee}$
  - 90% C.L exclusion at 7.7×10^{-47} cm^2 for 35 GeV/c^2 WIMPS
  - Most stringent upper limit > 10 GeV/c^2 (10-99 GeV/c^2 post Panda-II)

  arXiv:1705.06655
- PandaX-II
  - 77 days of new exposure (80d in 2016)
  - 5.4×10^4 kg day exposure
  - Background 0.8×10^{-3} evt/kg/day (×25 improvement)
  - 90% C.L exclusion at 8.6×10^{-47} cm^2 for 40 GeV/c^2 WIMPS
  - Most stringent upper limit > 100 GeV/c^2

  arXiv:1708.06917





Recent DD DM results

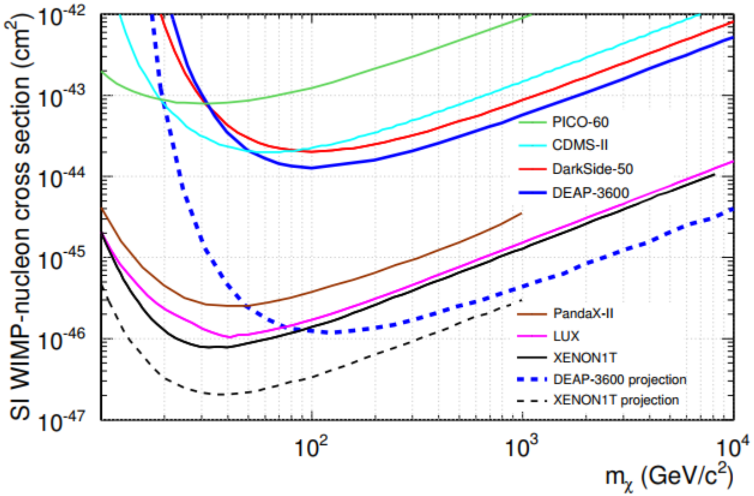
- DEAP3600 LAr
    - 4.4 days of exposure
    - 9.9×10^{3} kg day exposure
    - Electronic background 1.2×10^{-7} evt 16-33 keV_{ee}
    - 90% C.L. exclusion at 1.2×10^{-44} cm^2 for 100 GeV/c^2 WIMPS

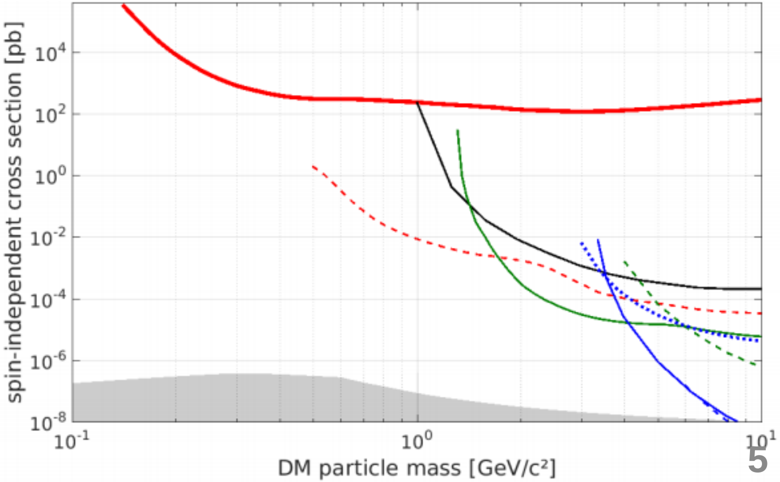
arXiv:1707.08042

- CRESST-III
    - 0.5 gr sapphire detector
    - High (above ground) background
    - Extends the region of DD DM searches down to 140 MeV/c^2

arXiv:1707.06749

- Reanalyses from SuperCDMS and CDMS-lite
    - Advanced sensitivity ~ Gev/c^2 masses

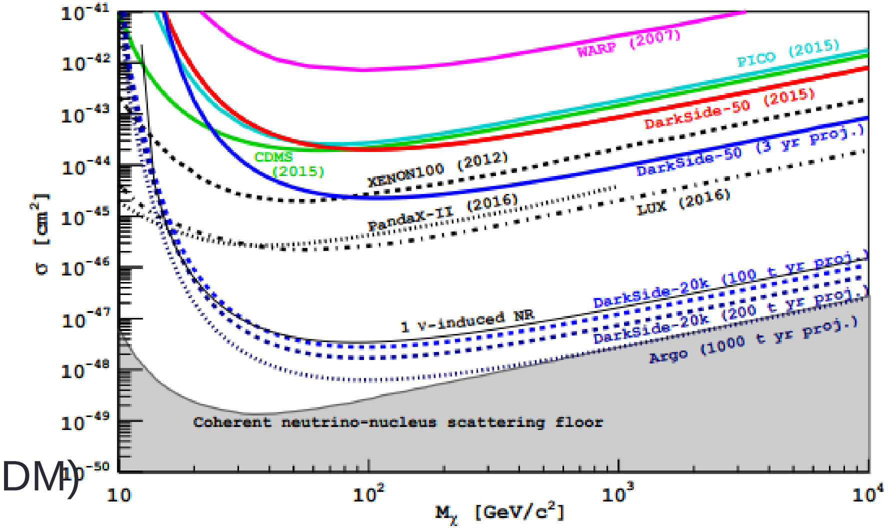




future DD DM projects & aspirations

- LUX-Zeplin
- Xenon-nT
- PandaX-nT at CJPL (4 tonnes initially)
- DEAP3600 long dataset
- Darkside50 (have >500 live days already)
- Darkside-20k (DEAP, MiniCLEAN,Darkside and ArDM)

arXiv:1707.08145



Pushing the 10^{-48} cm^2 limit…

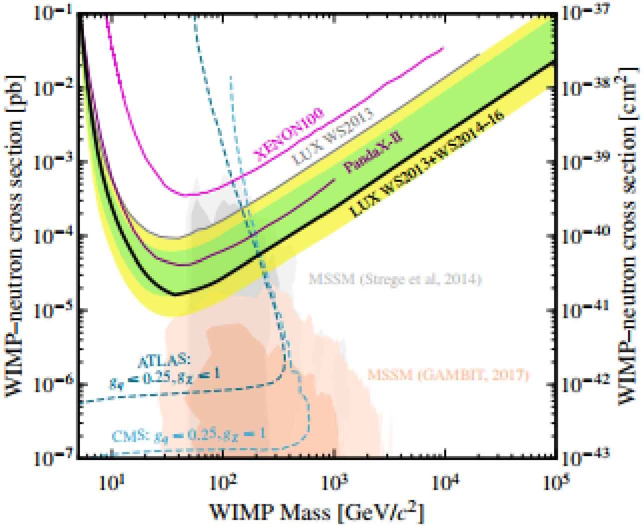
WIMP-nucleon & neutrino-nucleus interactions

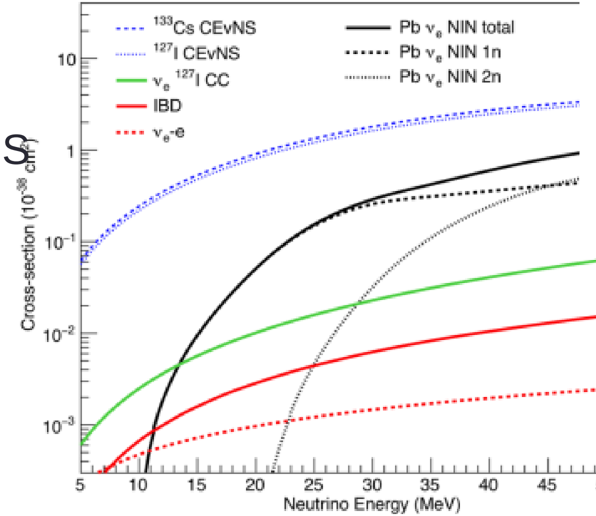
- PICO-60 WIMP – proton
  - 90% C.L. on WIMP-neutron $\sigma_p=3.4\times10^{-41}$ cm^2 at 30 GeV/c^2
  - 1167 kg day exposure

  arXiv:1702.07666
- LUX WIMP – neutron
  - 90% C.L. on WIMP-neutron $\sigma_n=1.6\times10^{-41}$ cm^2 at 35 GeV/c^2

  arXiv:1705.03380
- Coherent
  - 14.6kg CsI scintillator @ SNS
  - 6.7σ C.L. observation

  Science 03 Aug 2017: eaao0990



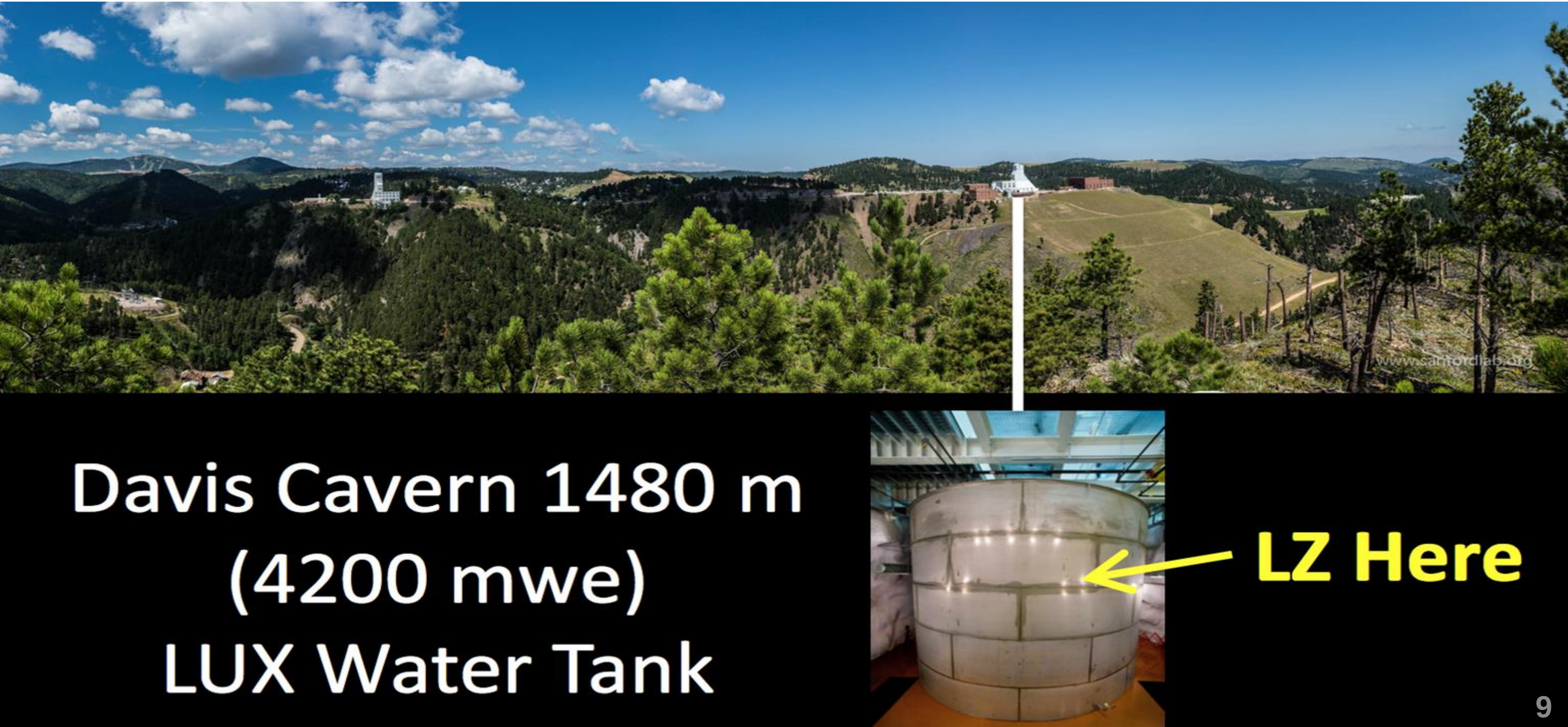


LZ collaboration, September 2017

38 institutions, 250 scientists, engineers, and technicians

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
8) University of Bristol (UK)
9) University of Edinburgh (UK)
10) University of Liverpool (UK)
11) University of Oxford (UK)
12) University of Sheffield (UK)
13) Black Hill State University (US)
14) Brandeis University (US)
15) Brookhaven National Lab (US)
16) Brown University (US)
17) Fermi National Accelerator Lab (US)
18) Lawrence Berkeley National Lab (US)
19) Lawrence Livermore National Lab (US)
20) Northwestern University (US)
21) Pennsylvania State University (US)
22) SLAC National Accelerator Lab (US)
23) South Dakota School of Mines and Technology (US)
24) South Dakota Science and Technology Authority (US)
25) Texas A&M University (US)
26) University at Albany (US)
27) University of Alabama (US)
28) University of California, Berkeley (US)
29) University of California, Davis (US)
30) University of California, Santa Barbara (US)
31) University of Maryland (US)
32) University of Massachusetts (US)
33) University of Michigan (US)
34) University of Rochester (US)
35) University of South Dakota (US)
36) University of Wisconsin – Madison (US)
37) Washington University in St. Louis (US)
38) Yale University (US)

Sanford Underground Research Facility



Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank

LZ Here

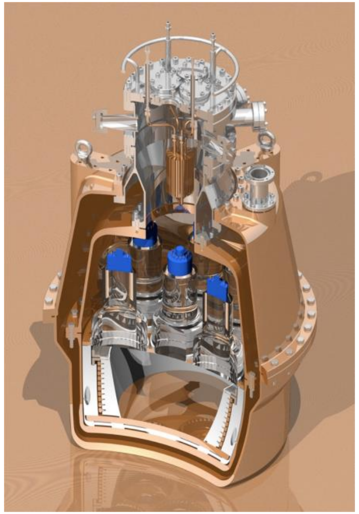
ZonEd Proportional scintillation in LIquid Noble gases

ZEPLIN pioneered WIMP-search with double-phase LXe:

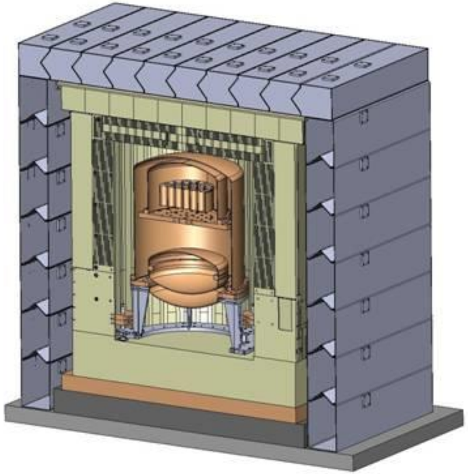
- 12 kg LXe, operated at BOULBY UK
- 90% C.L. exclusion at 3.9×10^{-44} cm^2 for 50 GeV/c^2 WIMPS

arXiv:1110.4769

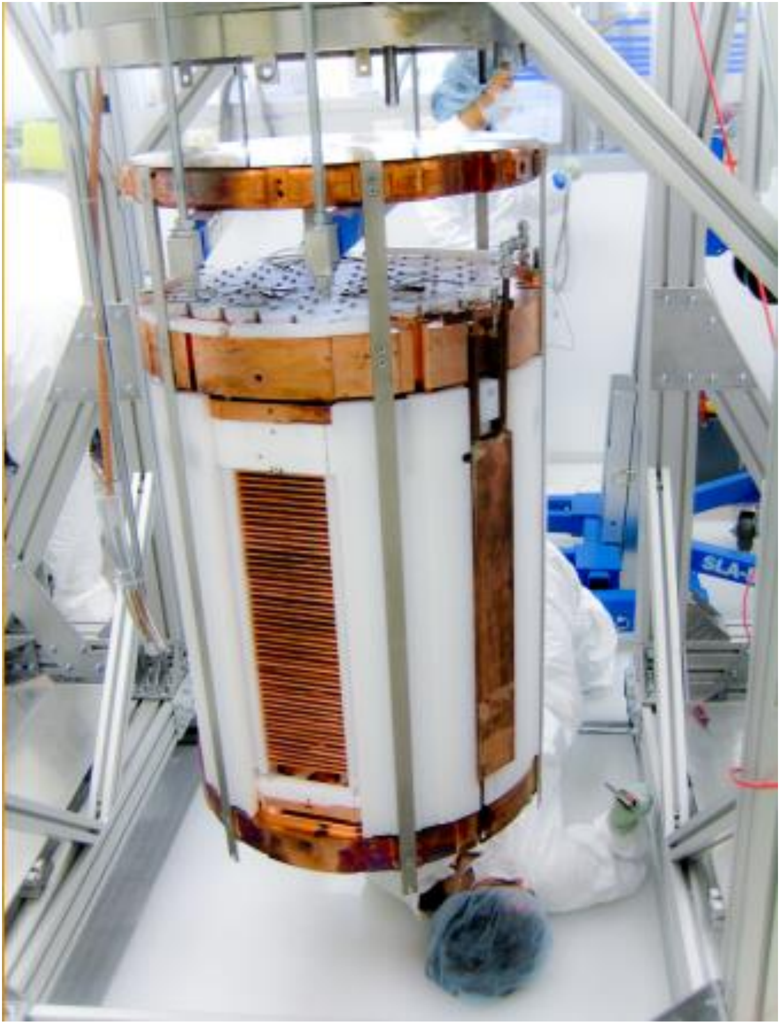
Zeplin-I (single phase)



Zeplin-II (double phase)



Zeplin-III (double phase, high field)

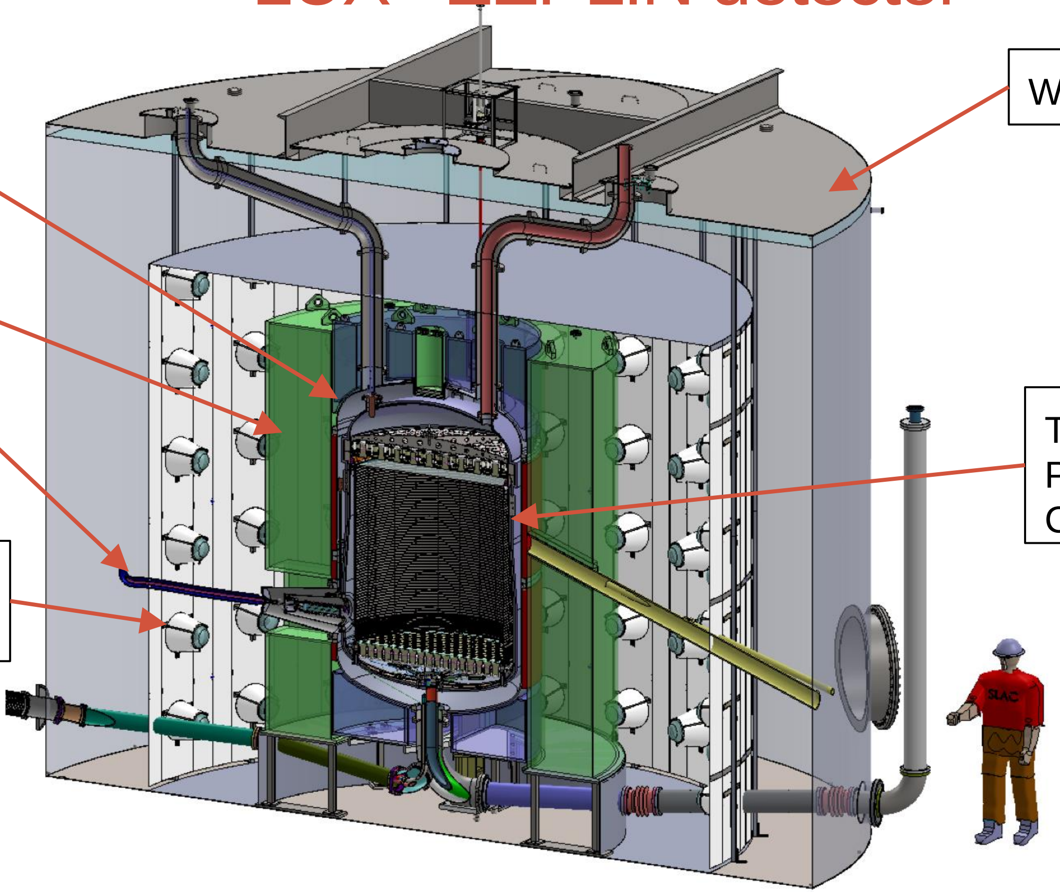


Large Underground Xenon (LUX) experiment

- 250 kg active mass
- 3.4×10^4 kg day exposure
- 90% C.L exclusion at 1.1×10^{-46} cm^2 for 50 GeV/c^2 WIMPS (combined datasets)
- Pioneering dispersed Kr & T calibration sources

arXiv:1608.07648

LUX - ZEPLIN detector



Water tank

Ti cryostat

Gd-loaded Scintillator

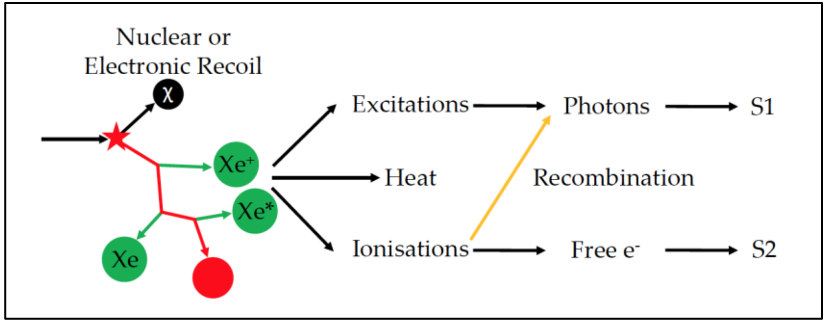
HV connection

Time Projection Chamber

Veto Photomultipliers

Central region 5600 kg fiducial

S1 and S2 signal



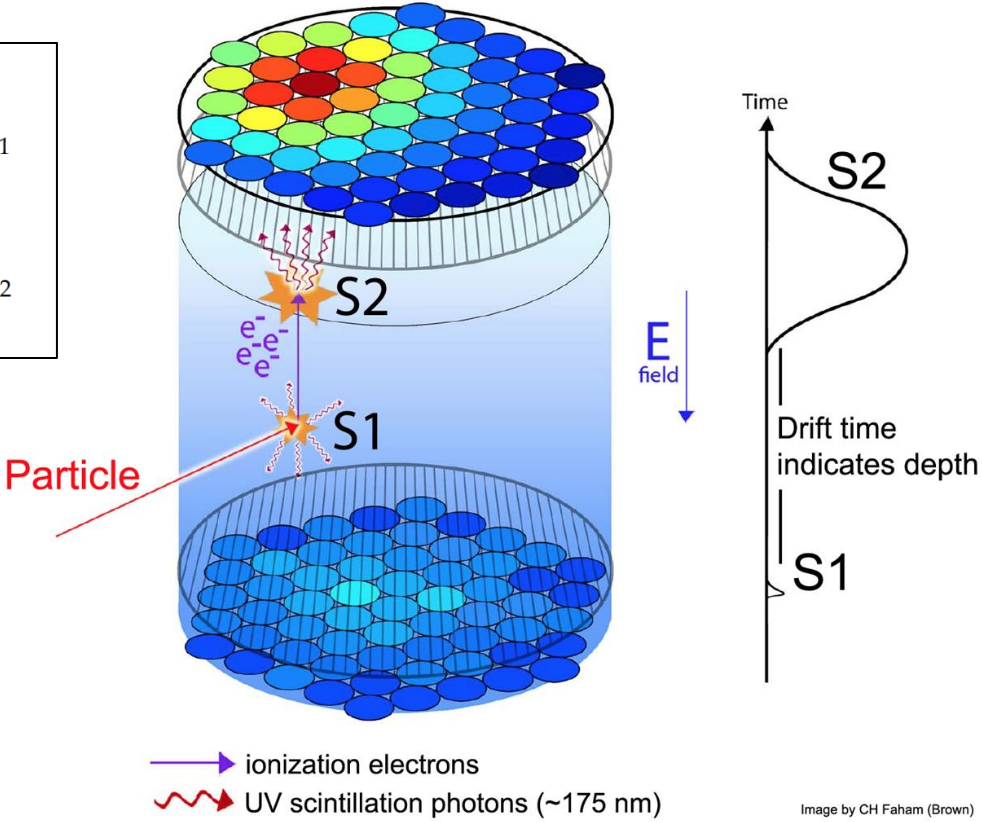


Image by CH Faham (Brown)

- Single photon and electron sensitivity
- Z position from S1-S2 timing
- X-Y position from S2 signal pattern
- ER/NR discrimination by charge to light ratio (S2/S1)

Background reduction

- Photomultipliers of ultra-low natural radioactivity
- Low background titanium cryostat
- LUX water shield and an added gadolinium-loaded scintillator active veto
- Instrumented “skin” region of peripheral xenon as another veto system
- Radon suppression during construction, assembly and operations
- Ultra-low levels of Kr in Xe

Source of backgrounds

Item	ER cts	NR cts
Detector Components	6.2	0.07
Disperse radionuclides (Rn, Kr, Ar)	911	-
Laboratory and cosmogenic	4.3	0.06
Fixed surface contamination	0.19	0.37
^{136}Xe 2$\nu\beta\beta$	67	-
Neutrinos (ν-e, ν-A)	255	0.72
Total	1244	1.22

Performance drivers

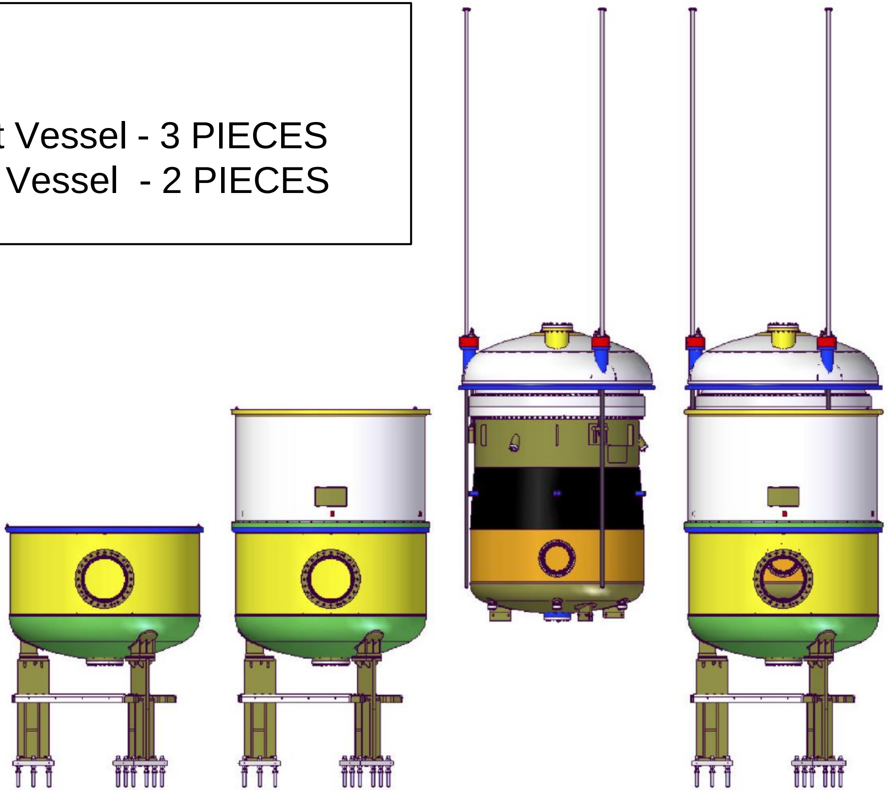
Detector Parameter	Reduced	Baseline	Goal
Light collection (PDE)	0.05	0.075	0.12
Drift field (V/cm)	160	310	650
Electron lifetime (μs)	850	850	2800
PMT phe detection	0.8	0.9	1.0
N-fold trigger coincidence	4	3	2
^{222}Rn (mBq in active region)	13.4	13.4	0.67
Live days	1000	1000	1000

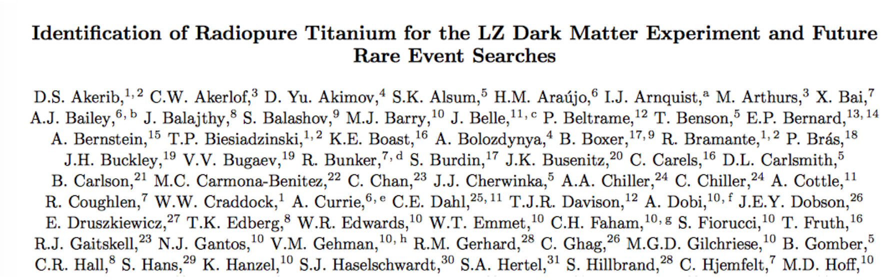
Titanium cryostat

CALIBRATION TUBES

CRYOSTAT :

Outer Cryostat Vessel - 3 PIECES
Inner Cryostat Vessel - 2 PIECES





Identification of Radiopure Titanium for the LZ Dark Matter Experiment and Future Rare Event Searches

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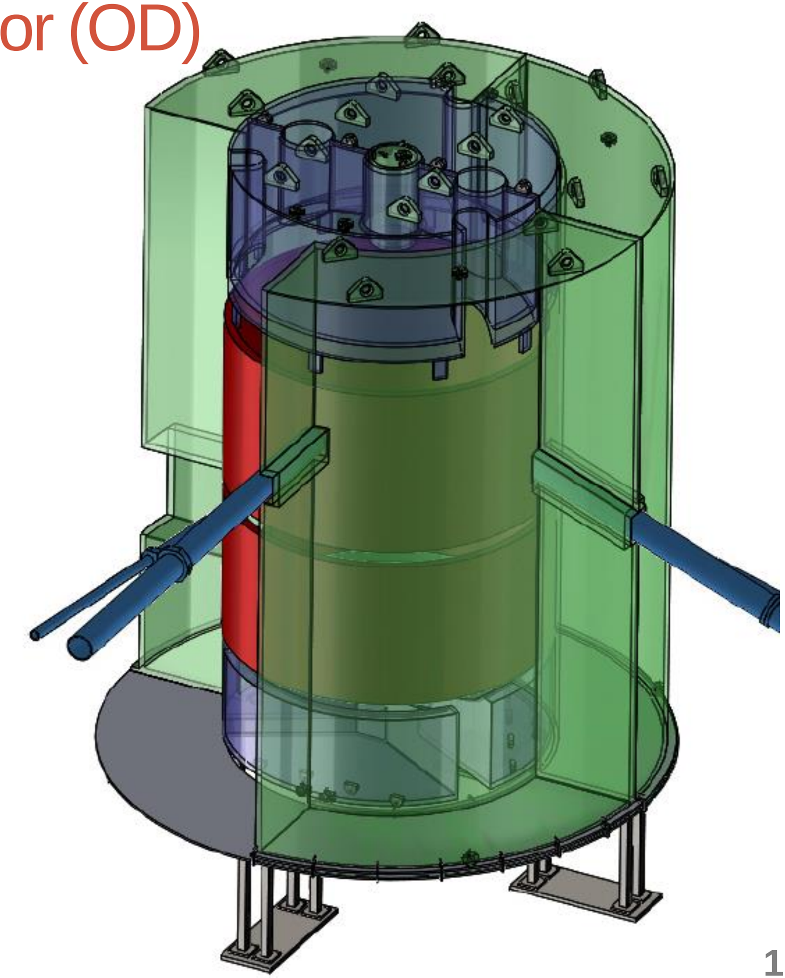
The Outer Detector (OD)

- Essential to utilise most Xe, maximise fiducial volume
- Hermetic measurement of penetrating background
- Segmented tanks – installation constraints (shaft, water tank)
- 60 cm thick, 21.5 of Gd loaded liquid scintillator
- 97% efficiency for neutrons
- Daya bay legacy, scintillator & tanks (and people)

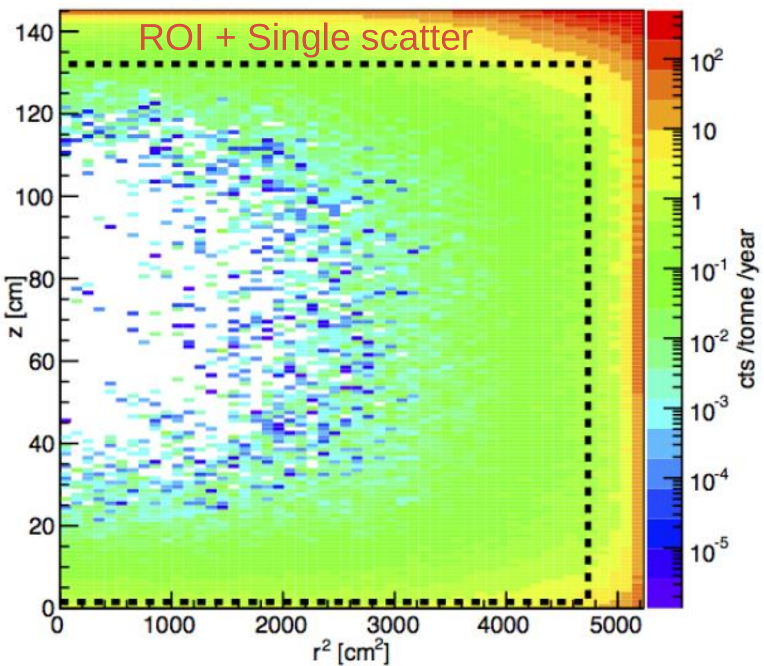


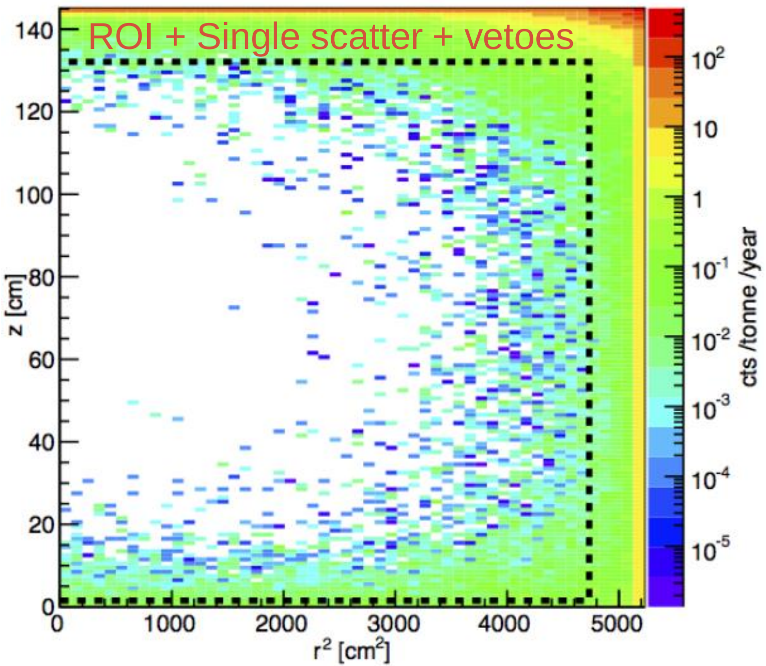
Background Rejection: defining the fiducial mass

- ROI from bottom, side, top:

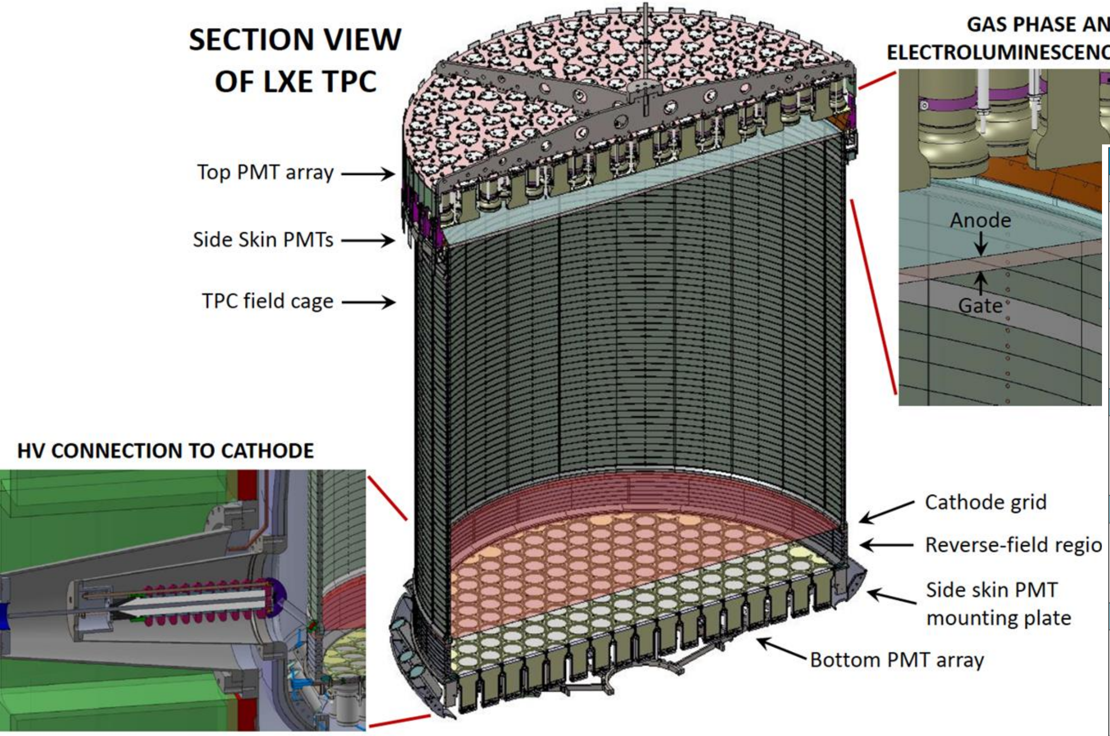
  1.5cm (cathode), 4cm (wall),
  13.5cm (gate grid)

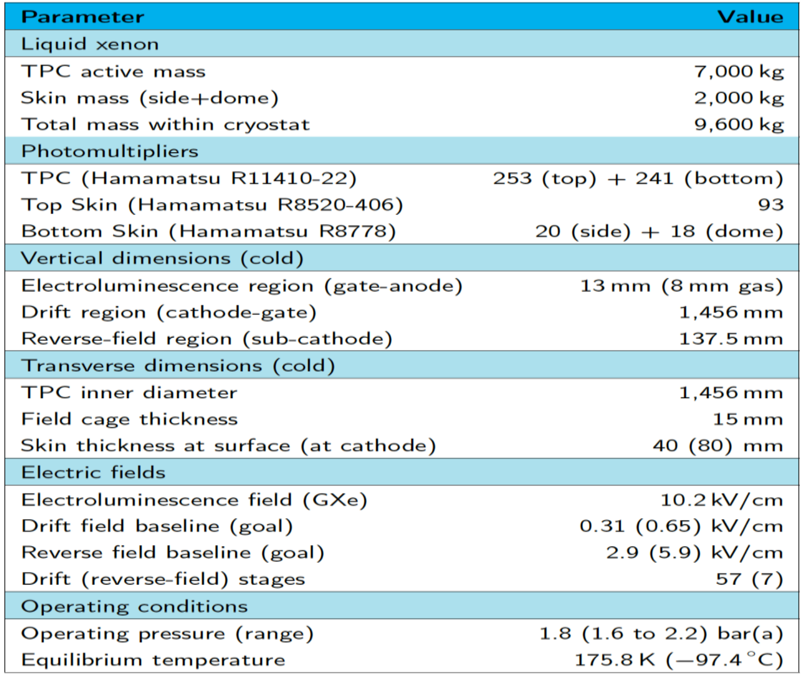
- Increases effective fiducial mass from 3.8T → 5.6T
- Skin veto + OD, Internal backgrounds now dominate





Time Projection Chamber

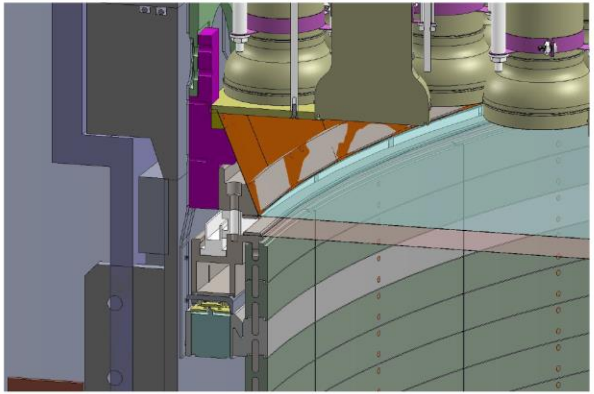


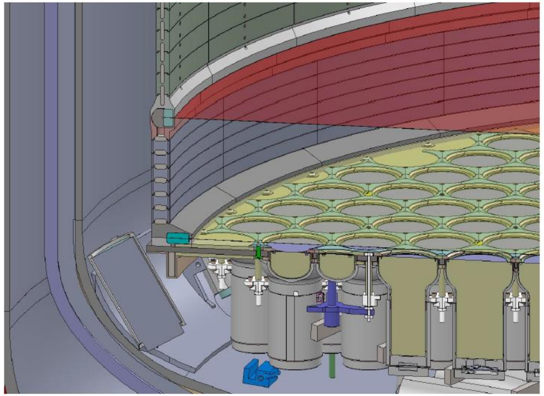


Parameter	Value
Liquid xenon	
TPC active mass	7,000 kg
Skin mass (side+dome)	2,000 kg
Total mass within cryostat	9,600 kg
Photomultipliers	
TPC (Hamamatsu R11410-22)	253 (top) + 241 (bottom)
Top Skin (Hamamatsu R8520-406)	93
Bottom Skin (Hamamatsu R8778)	20 (side) + 18 (dome)
Vertical dimensions (cold)	
Electroluminescence region (gate-anode)	13 mm (8 mm gas)
Drift region (cathode-gate)	1,456 mm
Reverse-field region (sub-cathode)	137.5 mm
Transverse dimensions (cold)	
TPC inner diameter	1,456 mm
Field cage thickness	15 mm
Skin thickness at surface (at cathode)	40 (80) mm
Electric fields	
Electroluminescence field (GXe)	10.2 kV/cm
Drift field baseline (goal)	0.31 (0.65) kV/cm
Reverse field baseline (goal)	2.9 (5.9) kV/cm
Drift (reverse-field) stages	57 (7)
Operating conditions	
Operating pressure (range)	1.8 (1.6 to 2.2) bar(a)
Equilibrium temperature	175.8 K (−97.4 °C)

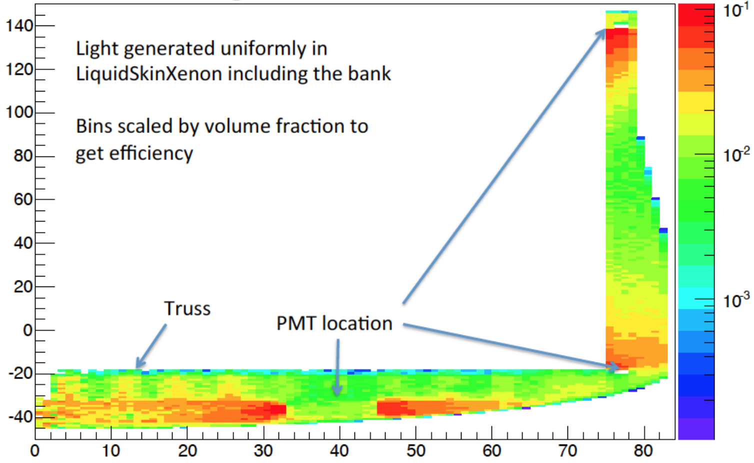
Skin region

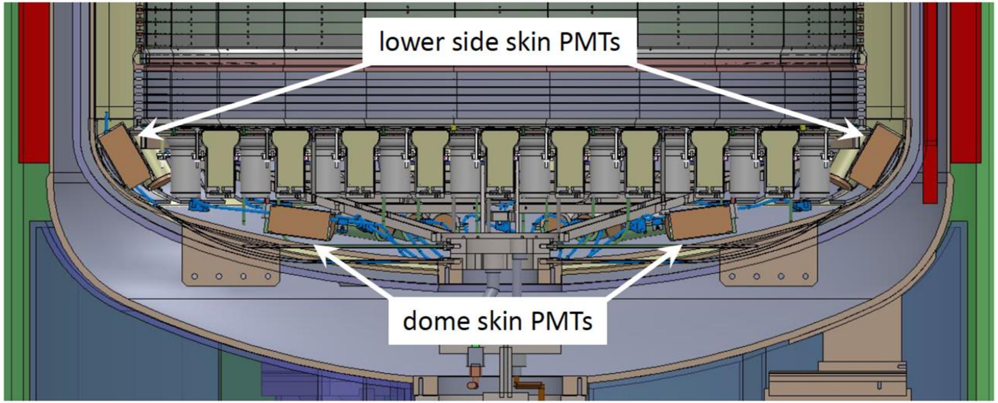
Acts as veto system together with the Outer Detector



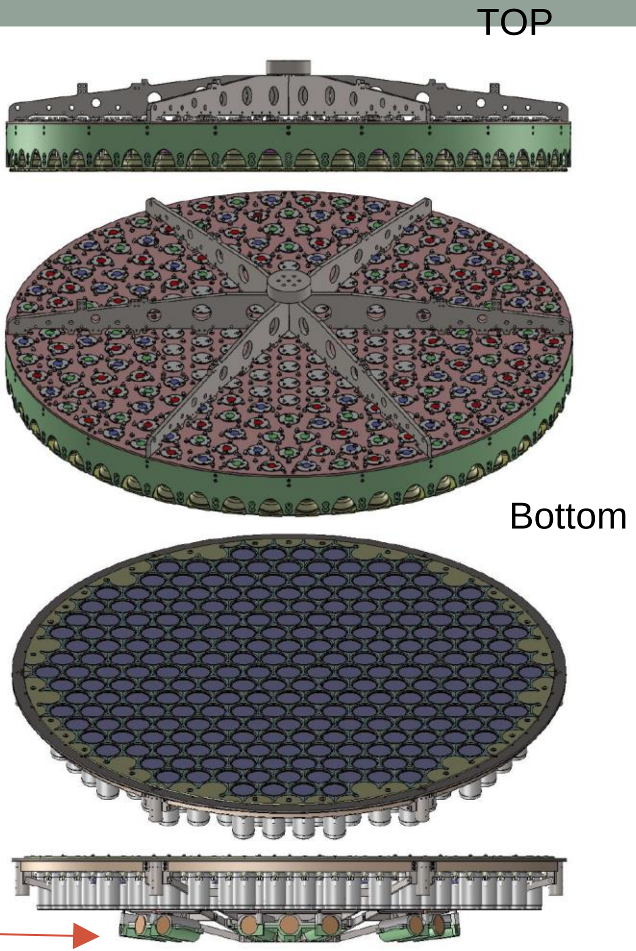


Light collection





Photomultipliers



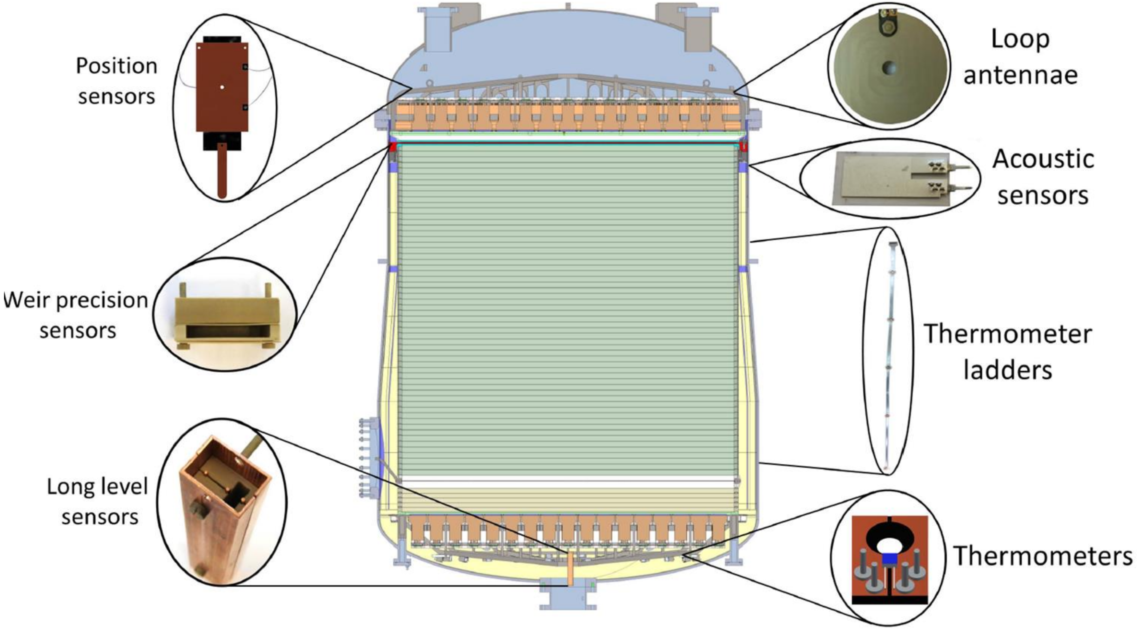
Top: 253 pmts

Bottom: 241 pmts

Skin: 93 pmts

Dome skin: 20 (side) + 18 (dome)

Sensors



Sensor	Number	Location
Thermometers	101	66 in Xe space, 35 in vacuum space
Weir Precision Sensors	6	Surface level
Long Level Sensors	4	Surface level, dome skin
Position Sensors	6	On top PMT truss
Loop Antennae	8	On PMT trusses and near HV feedthrough
Acoustic Sensor	8	Attached to ICV outer wall

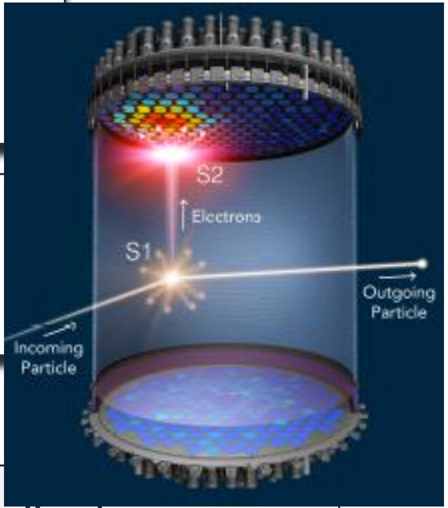
Calibrations

Basic questions about registered event

- How did the particle interact?
- How much energy did it deposit?

Scintillation photons - S1

Ionised electrons - S2



Need to know the spatial & temporal response of the detector

Variation in the (*x*,*y*,*z*) response of S1 and the (*x*,*y*) response of S2 ← Detector geometry, light collection, …

Variation in (*z*,*t*) response of S2 ← Xenon purity changes, …

Calibration sources

Isotope	What	Purpose	Deployment
Tritium	beta, $Q = 18.6\,\text{keV}$	ER band	Internal
$^{83\text{m}}$Kr	beta/gamma, 32.1 keV and 9.4 keV	TPC (x,y,z)	Internal
$^{131\text{m}}$Xe	164 keV γ	TPC (x,y,z), Xe skin	Internal
^{220}Rn	various α's	xenon skin	Internal
AmLi	(α,n)	NR band	CSD
^{252}Cf	spontaneous fission	NR efficiency	CSD
^{57}Co	122 keV γ	Xe skin threshold	CSD
^{228}Th	2.615 MeV γ, various others	OD energy scale	CSD
^{22}Na	back-to-back 511 keV γ's	TPC and OD sync	CSD
^{88}Y Be	152 keV neutron	low-energy NR response	External
^{205}Bi Be	88.5 keV neutron	low-energy NR response	External
^{206}Bi Be	47 keV neutron	low-energy NR response	External
DD	2,450 keV neutron	NR light and charge yields	External
DD	272 keV neutron	NR light and charge yields	External

External Radioisotope sources (gamma)

Calibration Source Deployment (CSD) gamma sources

- ^{228}**Th**: 2.615 MeV
- ^{57}**Co**: 122 keV
- ^{22}**Na**, 511 keV back-to-back

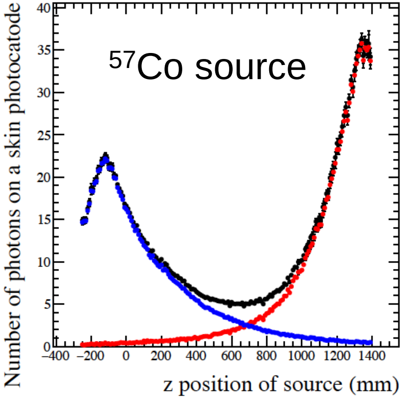
Higher energy backgrounds

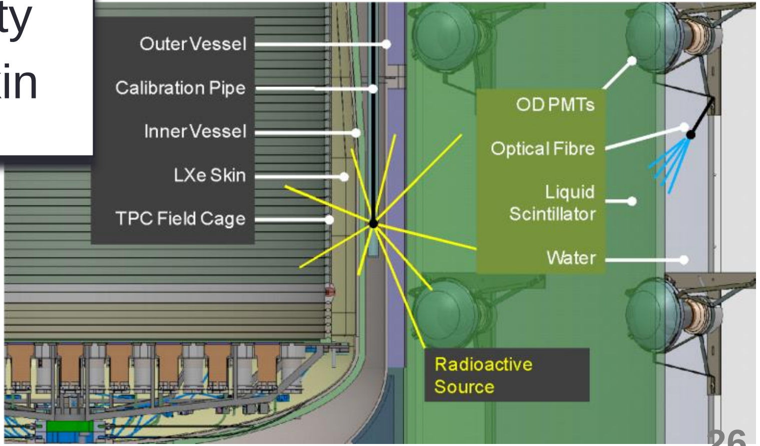
Edge of TPC

Outer detector calibration

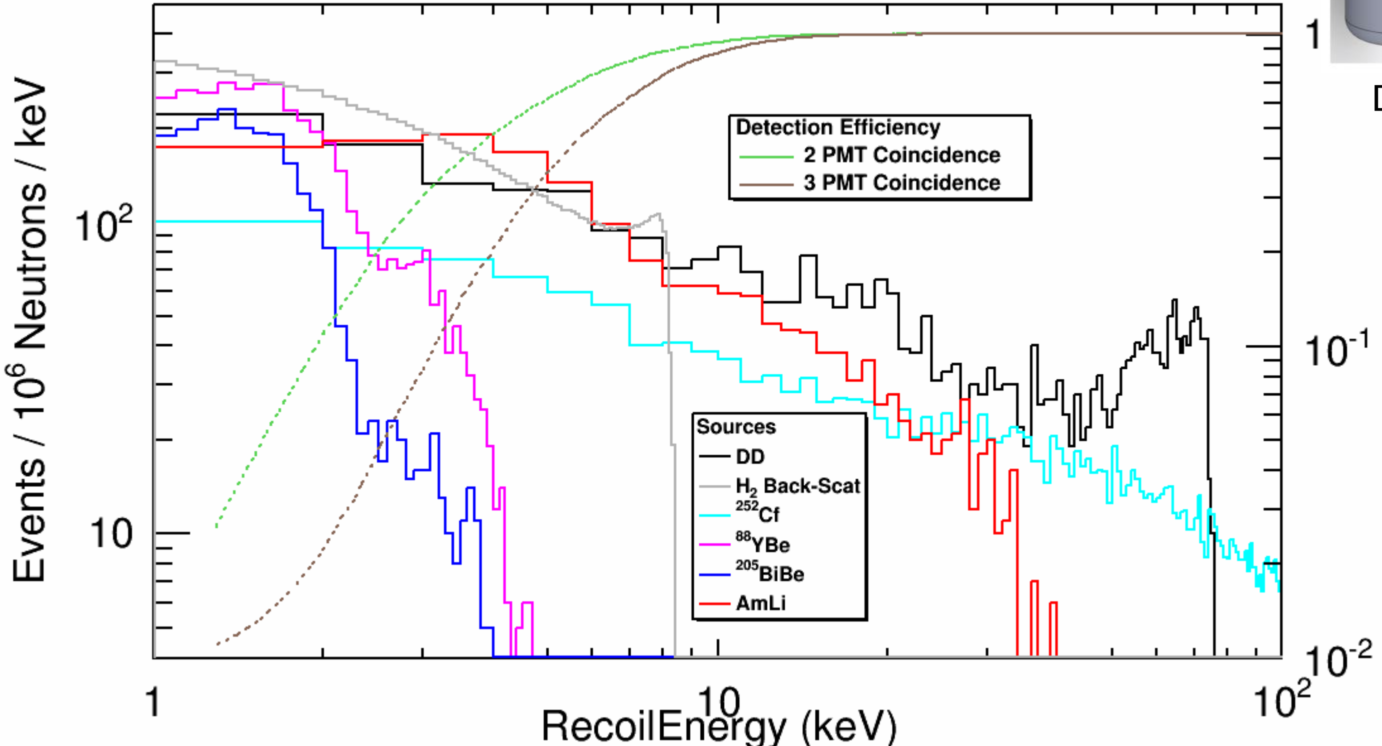
Xe skin

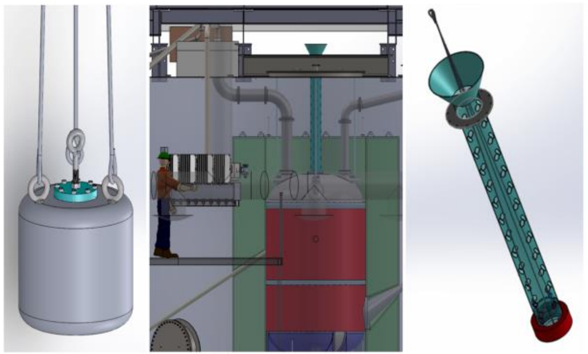
Timing synchronicity outer detector & skin





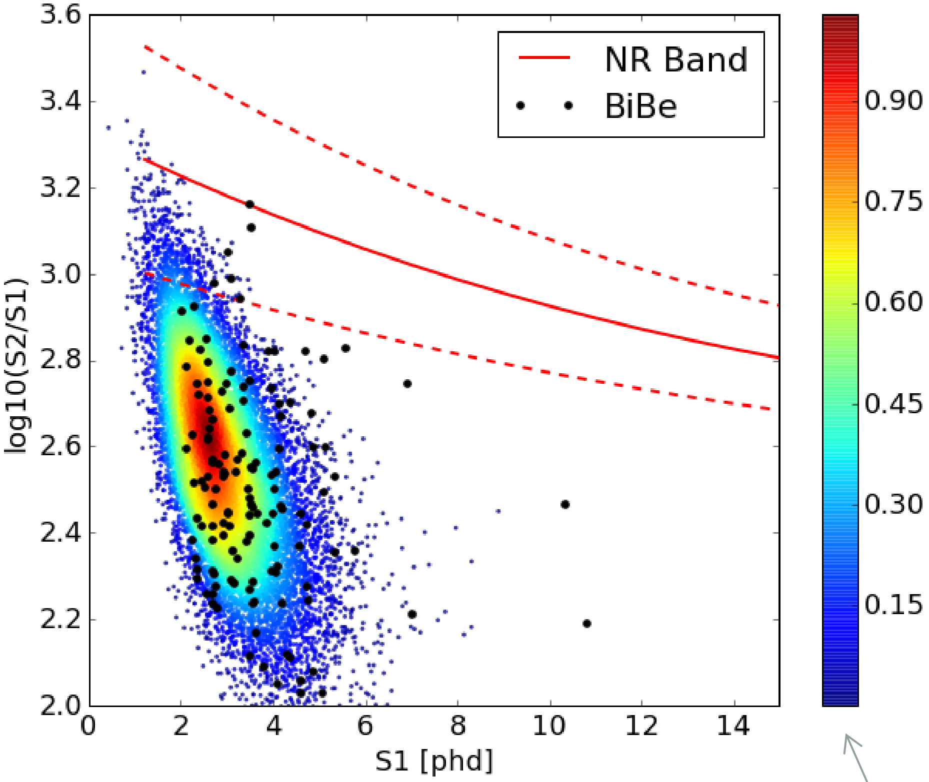
Neutron Calibration Sources

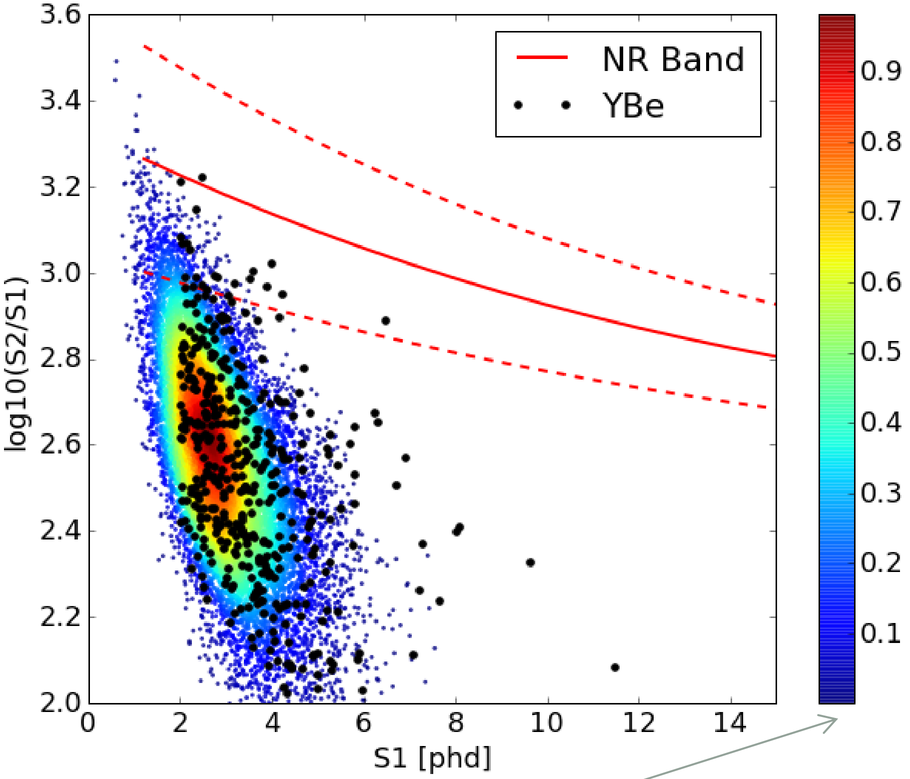




Deployment of the YBe source

Neutrino vs neutron scatters





^{8}B solar neutrino coherent scatters

Material screening

WIMP-nucleon cross section at 2.3×10^{-48} cm^2 within 1000 days of data taking and 5600 kg require:

- electron recoil (ER) background from non-astrophysical sources : 37×10^{-6} events/keV/kg/day (37 μdru)
- nuclear recoil (NR) background must also be low, with ~ 1 count in the exposure.

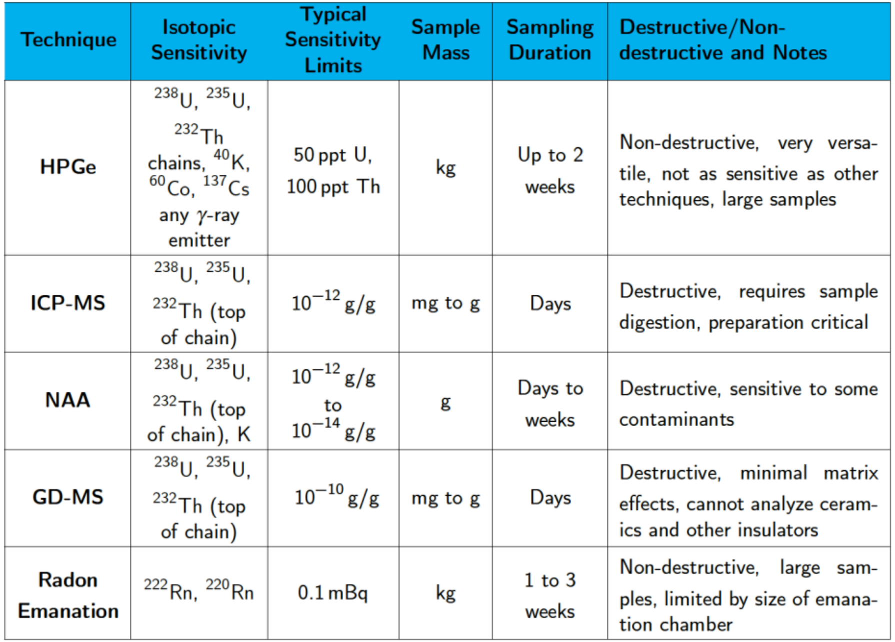
Monitoring and control of the background:

1. Material screening in components selection with more stringent requirements 0.4 NR and < 1 μdru in ER
2. Direct measurements of radon emanation from construction material for maximum activity of 10 mBq

   (throughout of LXe)
3. Removal of radioactive elements in LXe to below 1 μdru

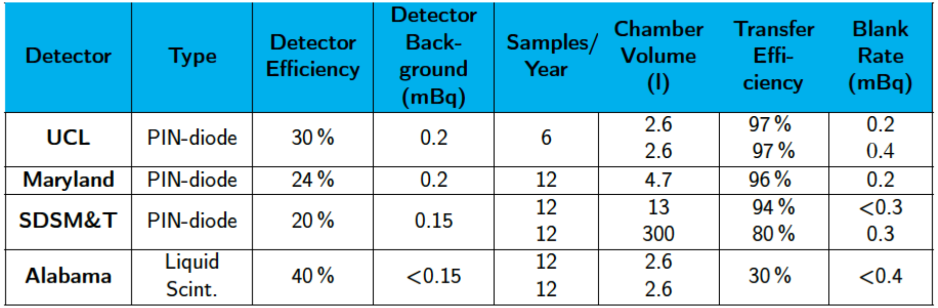
Material screening techniques and facilities

Screening Techniques



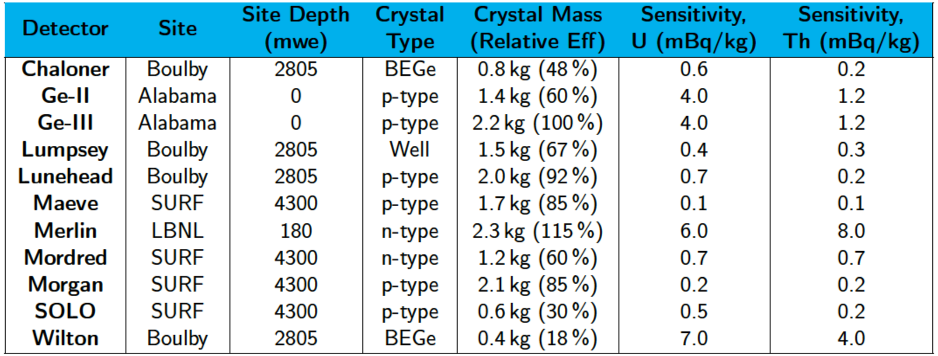
Technique	Isotopic Sensitivity	Typical Sensitivity Limits	Sample Mass	Sampling Duration	Destructive/Non-destructive and Notes
HPGe	^{238}U, ^{235}U, ^{232}Th chains, ^{40}K, ^{60}Co, ^{137}Cs any γ-ray emitter	50 ppt U, 100 ppt Th	kg	Up to 2 weeks	Non-destructive, very versatile, not as sensitive as other techniques, large samples
ICP-MS	^{238}U, ^{235}U, ^{232}Th (top of chain)	10^{-12} g/g	mg to g	Days	Destructive, requires sample digestion, preparation critical
NAA	^{238}U, ^{235}U, ^{232}Th (top of chain), K	10^{-12} g/g to 10^{-14} g/g	g	Days to weeks	Destructive, sensitive to some contaminants
GD-MS	^{238}U, ^{235}U, ^{232}Th (top of chain)	10^{-10} g/g	mg to g	Days	Destructive, minimal matrix effects, cannot analyze ceramics and other insulators
Radon Emanation	^{222}Rn, ^{220}Rn	0.1 mBq	kg	1 to 3 weeks	Non-destructive, large samples, limited by size of emanation chamber

Rn emanation facilities



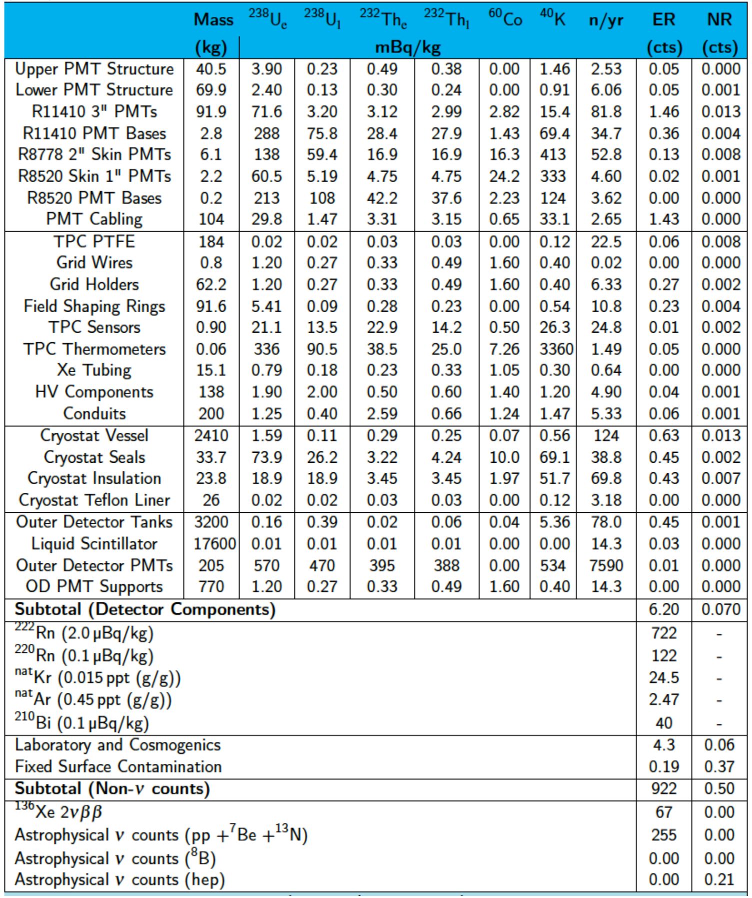
Detector	Type	Detector Efficiency	Detector Back-ground (mBq)	Samples/ Year	Chamber Volume (l)	Transfer Efficiency	Blank Rate (mBq)
UCL	PIN-diode	30 %	0.2	6	2.6 2.6	97 % 97 %	0.2 0.4
Maryland	PIN-diode	24 %	0.2	12	4.7	96 %	0.2
SDSM&T	PIN-diode	20 %	0.15	12 12	13 300	94 % 80 %	<0.3 0.3
Alabama	Liquid Scint.	40 %	<0.15	12 12	2.6 2.6	30 %	<0.4

Gamma screening facilities

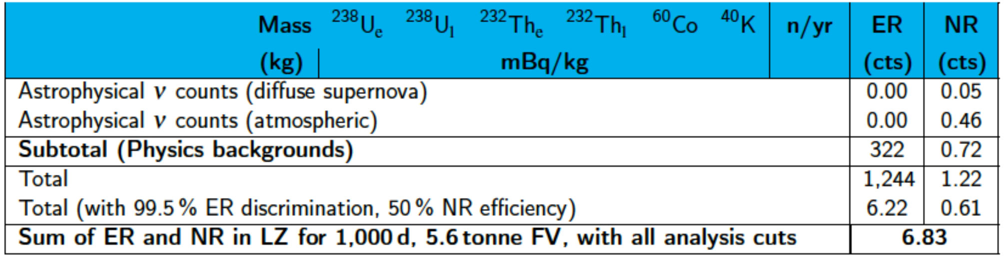


Detector	Site	Site Depth (mwe)	Crystal Type	Crystal Mass (Relative Eff)	Sensitivity, U (mBq/kg)	Sensitivity, Th (mBq/kg)
Chaloner	Boulby	2805	BEGe	0.8 kg (48 %)	0.6	0.2
Ge-II	Alabama	0	p-type	1.4 kg (60 %)	4.0	1.2
Ge-III	Alabama	0	p-type	2.2 kg (100 %)	4.0	1.2
Lumpsey	Boulby	2805	Well	1.5 kg (67 %)	0.4	0.3
Lunehead	Boulby	2805	p-type	2.0 kg (92 %)	0.7	0.2
Maeve	SURF	4300	p-type	1.7 kg (85 %)	0.1	0.1
Merlin	LBNL	180	n-type	2.3 kg (115 %)	6.0	8.0
Mordred	SURF	4300	n-type	1.2 kg (60 %)	0.7	0.7
Morgan	SURF	4300	p-type	2.1 kg (85 %)	0.2	0.2
SOLO	SURF	4300	p-type	0.6 kg (30 %)	0.5	0.2
Wilton	Boulby	2805	BEGe	0.4 kg (18 %)	7.0	4.0

Estimated background

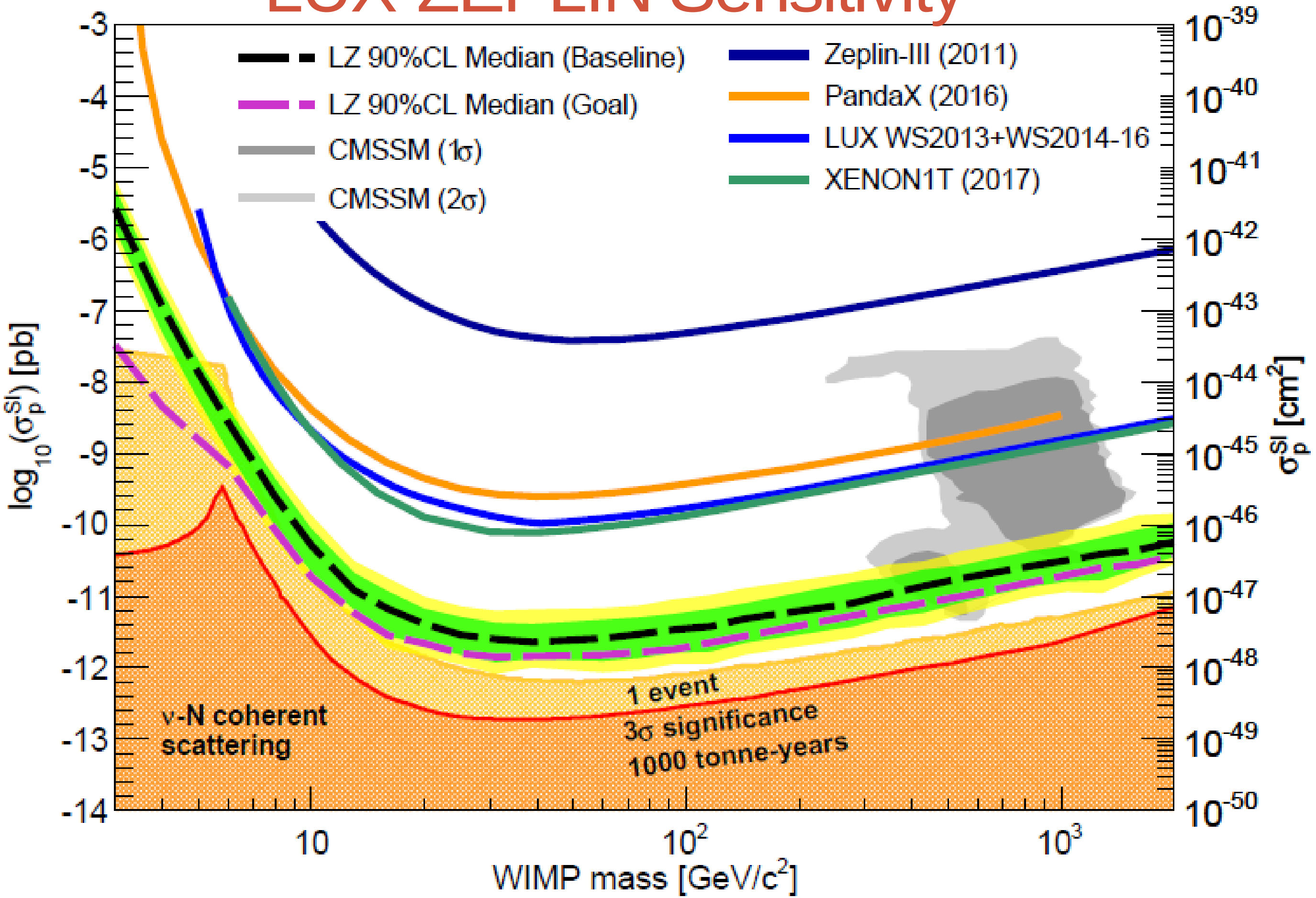


	Mass	^{238}U$_e$	^{238}U$_l$	^{232}Th$_e$	^{232}Th$_l$	^{60}Co	^{40}K	n/yr	ER	NR
	(kg)	mBq/kg							(cts)	(cts)
Upper PMT Structure	40.5	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	71.6	3.20	3.12	2.99	2.82	15.4	81.8	1.46	0.013
R11410 PMT Bases	2.8	288	75.8	28.4	27.9	1.43	69.4	34.7	0.36	0.004
R8778 2" Skin PMTs	6.1	138	59.4	16.9	16.9	16.3	413	52.8	0.13	0.008
R8520 Skin 1" PMTs	2.2	60.5	5.19	4.75	4.75	24.2	333	4.60	0.02	0.001
R8520 PMT Bases	0.2	213	108	42.2	37.6	2.23	124	3.62	0.00	0.000
PMT Cabling	104	29.8	1.47	3.31	3.15	0.65	33.1	2.65	1.43	0.000
TPC PTFE	184	0.02	0.02	0.03	0.03	0.00	0.12	22.5	0.06	0.008
Grid Wires	0.8	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	5.41	0.09	0.28	0.23	0.00	0.54	10.8	0.23	0.004
TPC Sensors	0.90	21.1	13.5	22.9	14.2	0.50	26.3	24.8	0.01	0.002
TPC Thermometers	0.06	336	90.5	38.5	25.0	7.26	3360	1.49	0.05	0.000
Xe Tubing	15.1	0.79	0.18	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Components	138	1.90	2.00	0.50	0.60	1.40	1.20	4.90	0.04	0.001
Conduits	200	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2410	1.59	0.11	0.29	0.25	0.07	0.56	124	0.63	0.013
Cryostat Seals	33.7	73.9	26.2	3.22	4.24	10.0	69.1	38.8	0.45	0.002
Cryostat Insulation	23.8	18.9	18.9	3.45	3.45	1.97	51.7	69.8	0.43	0.007
Cryostat Teflon Liner	26	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	3200	0.16	0.39	0.02	0.06	0.04	5.36	78.0	0.45	0.001
Liquid Scintillator	17600	0.01	0.01	0.01	0.01	0.00	0.00	14.3	0.03	0.000
Outer Detector PMTs	205	570	470	395	388	0.00	534	7590	0.01	0.000
OD PMT Supports	770	1.20	0.27	0.33	0.49	1.60	0.40	14.3	0.00	0.000
Subtotal (Detector Components)									6.20	0.070
^{222}Rn (2.0 μBq/kg)									722	-
^{220}Rn (0.1 μBq/kg)									122	-
^{nat}Kr (0.015 ppt (g/g))									24.5	-
^{nat}Ar (0.45 ppt (g/g))									2.47	-
^{210}Bi (0.1 μBq/kg)									40	-
Laboratory and Cosmogenics									4.3	0.06
Fixed Surface Contamination									0.19	0.37
Subtotal (Non-ν counts)									922	0.50
^{136}Xe $2\nu\beta\beta$									67	0.00
Astrophysical ν counts (pp + ^{7}Be + ^{13}N)									255	0.00
Astrophysical ν counts (^{8}B)									0.00	0.00
Astrophysical ν counts (hep)									0.00	0.21



	Mass	^{238}U$_e$	^{238}U$_l$	^{232}Th$_e$	^{232}Th$_l$	^{60}Co	^{40}K	n/yr	ER	NR
	(kg)	mBq/kg							(cts)	(cts)
Astrophysical ν counts (diffuse supernova)									0.00	0.05
Astrophysical ν counts (atmospheric)									0.00	0.46
Subtotal (Physics backgrounds)									322	0.72
Total									1,244	1.22
Total (with 99.5 % ER discrimination, 50 % NR efficiency)									6.22	0.61
Sum of ER and NR in LZ for 1,000 d, 5.6 tonne FV, with all analysis cuts									6.83	

LUX-ZEPLIN Sensitivity



LUX-ZEPLIN timeline

Year	Month	Activity
2012	March	LZ (LUX-ZEPLIN) collaboration formed
2014	July	LZ Project selected in US and UK
2015	April	DOE CD-1/3a approval, similar in the UK Conceptual Design Report arXiv: 1509.02910
2017	February	DOE CD-2/3b approval Technical Design Report arXiv: 1703.09144
2017	March	LUX removed from underground
2017	June	Begin preparations for surface assembly at SURF
2018	July	Begin underground installation
2019	Late	Begin commissioning
2020+		Planning on 5+ years of operation

Conclusions

- Direct Detection Dark Matter searches operating world-wide & producing new results at a high pace
- LZ sensitivity to 2.3×10^{-48} cm^2 at 40 GeV expected with a fiducial mass of 5600 kg with 1000 days of exposure
- LUX-ZEPLIN – On track to take data from 2020