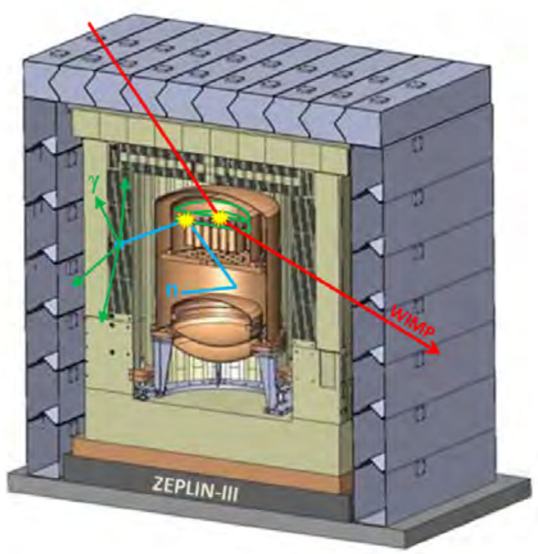
The LZ Dark Matter Experiment

Luiz de Viveiros
Penn State University

LUX + ZEPLIN = LZ

ZEPLIN-III

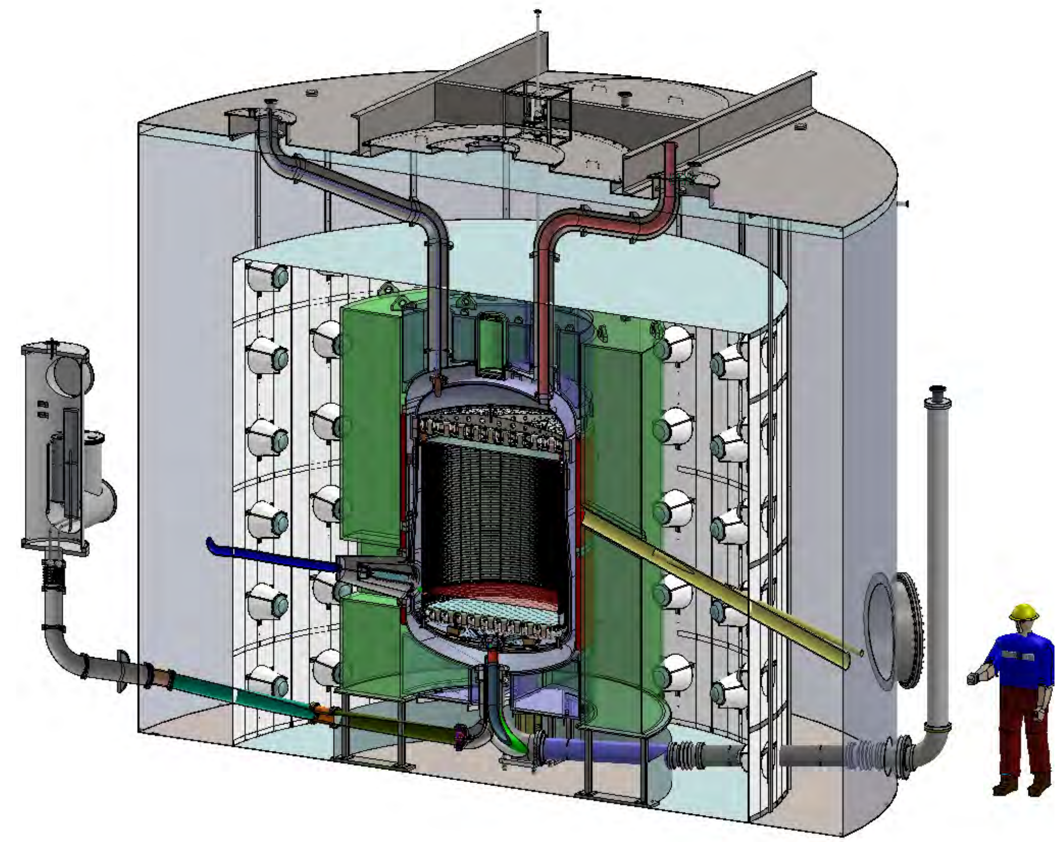


ZEPLIN pioneered WIMP-search with 2-phase Xe.
6 kg LXe fiducial,
3.9×10^{-33} cm^2

LUX

Most sensitive WIMP detector.
100 kg LXe fiducial,
1.1×10^{-46} cm^2

LZ

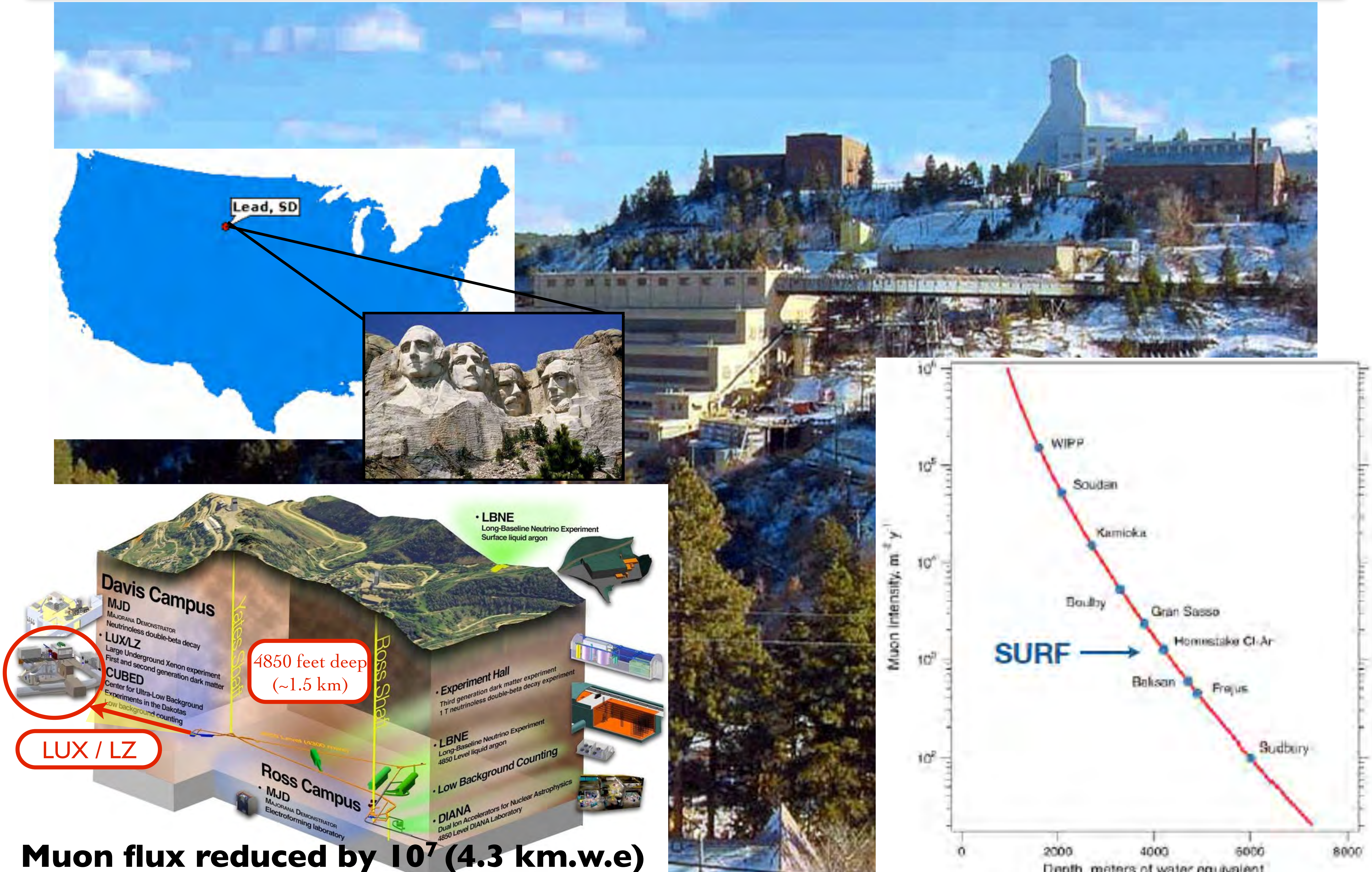


Scale-up using demonstrated technology and experience.
5600 kg LXe fiducial

THE LZ COLLABORATION

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

SANFORD UNDERGROUND RESEARCH FACILITY (SURF) IN LEAD, SD



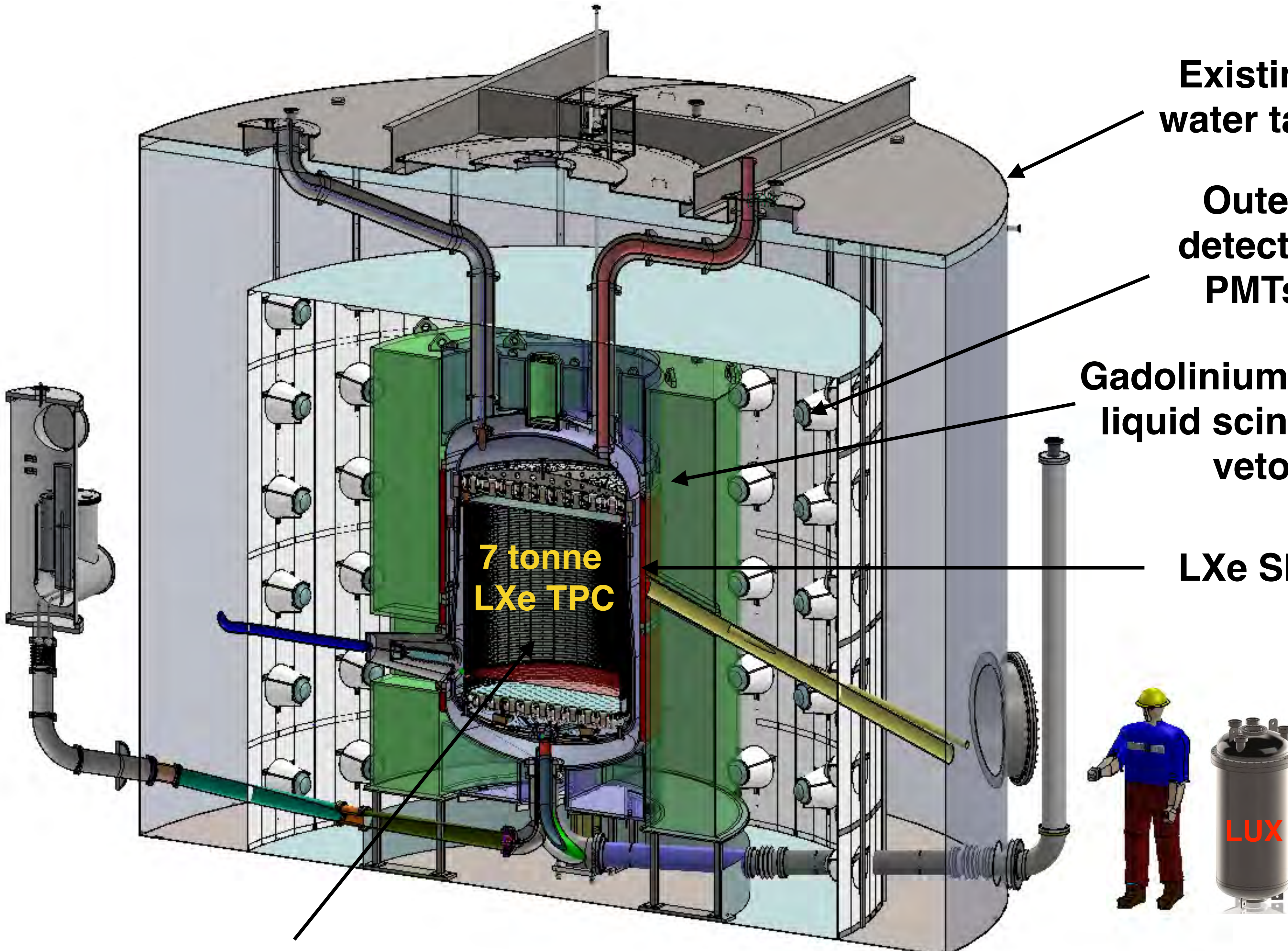
Muon flux reduced by 10^7 (4.3 km.w.e)

LZ: Go Big or Go Home

- Linear size: 3x LUX
- Total Mass: 10 T (x27 LUX)
- Active mass: 7 T (x28 LUX)
- Fiducial mass: 5.6 T (~x40 LUX)
- Sensitivity: x50-x100 LUX

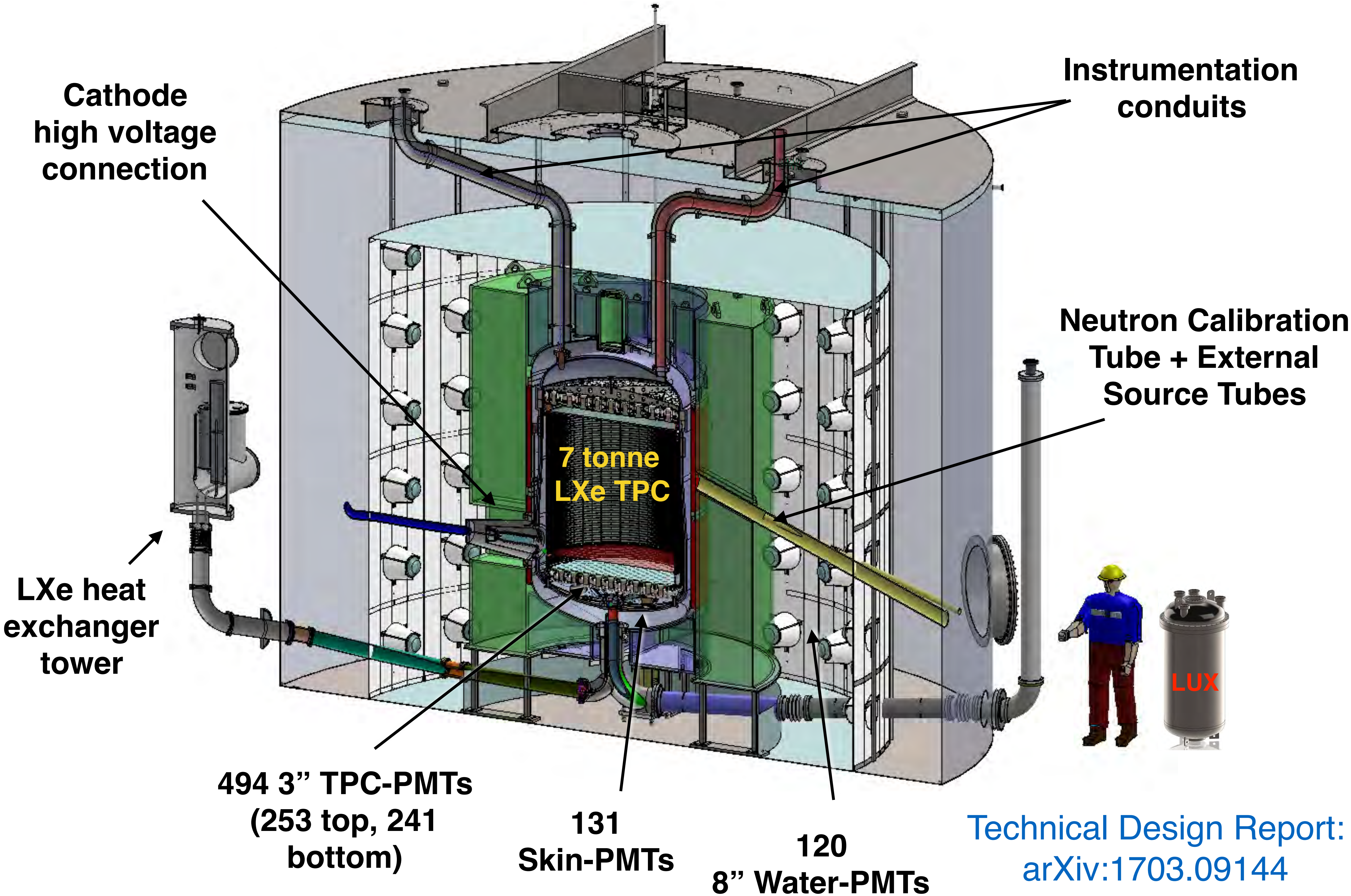
LZ Design Overview (1)

- 3-component veto system:
  - Water tank from LUX
  - Gd-loaded scintillator
  - Instrumented LXe Skin



Technical Design Report: arXiv:1703.09144

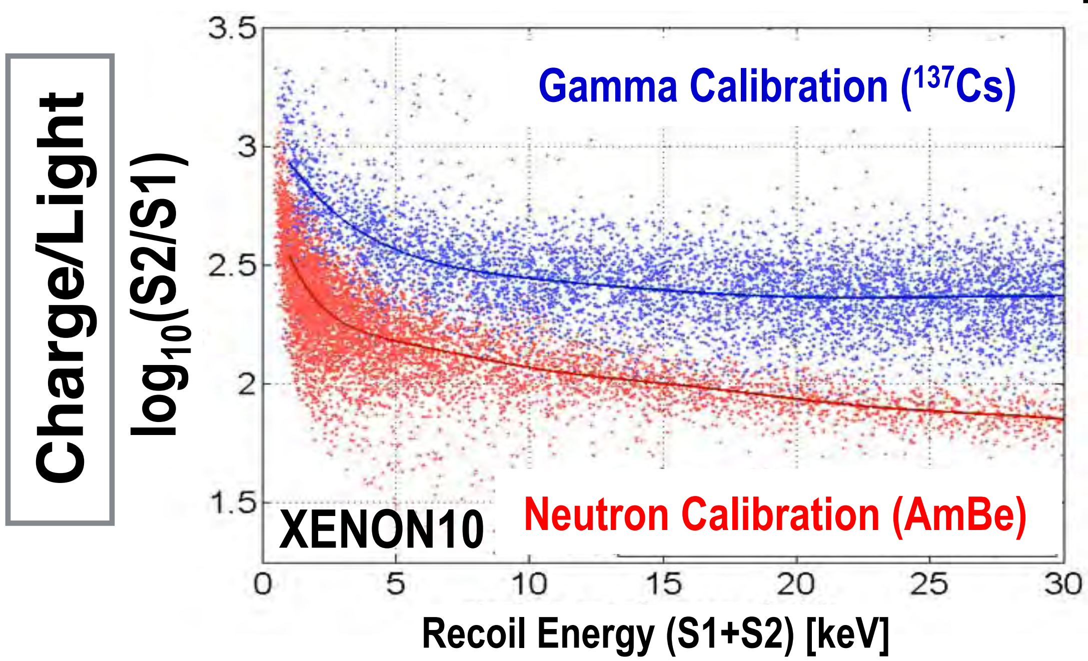
LZ Design Overview (2)

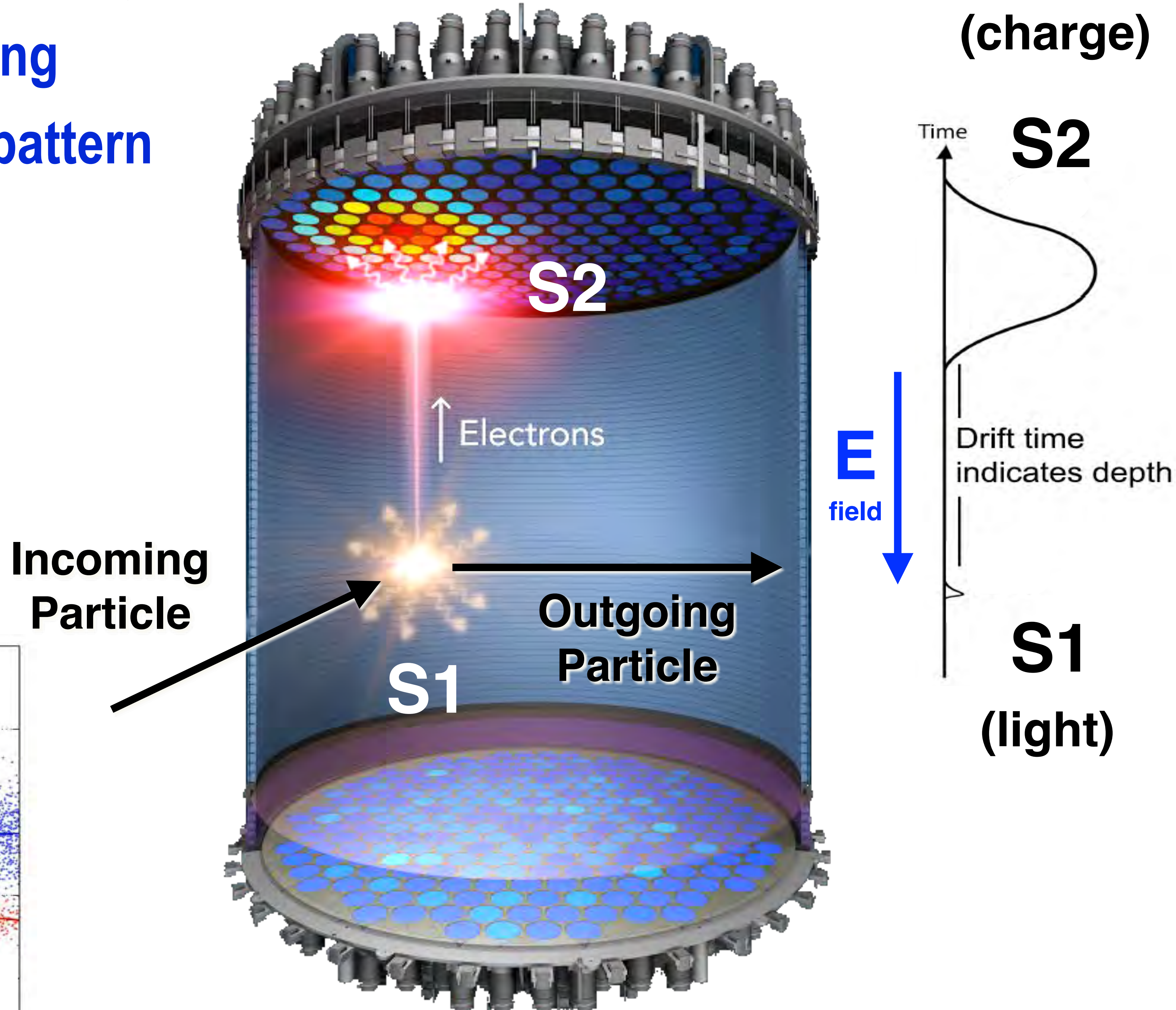


Technical Design Report: arXiv:1703.09144

Dual Phase Xenon TPC

- **Excellent 3D imaging capability**
  - Z position from S1 - S2 timing
  - XY positions from S2 light pattern
- **Charge / Light Ratio => Signal vs Background discrimination**

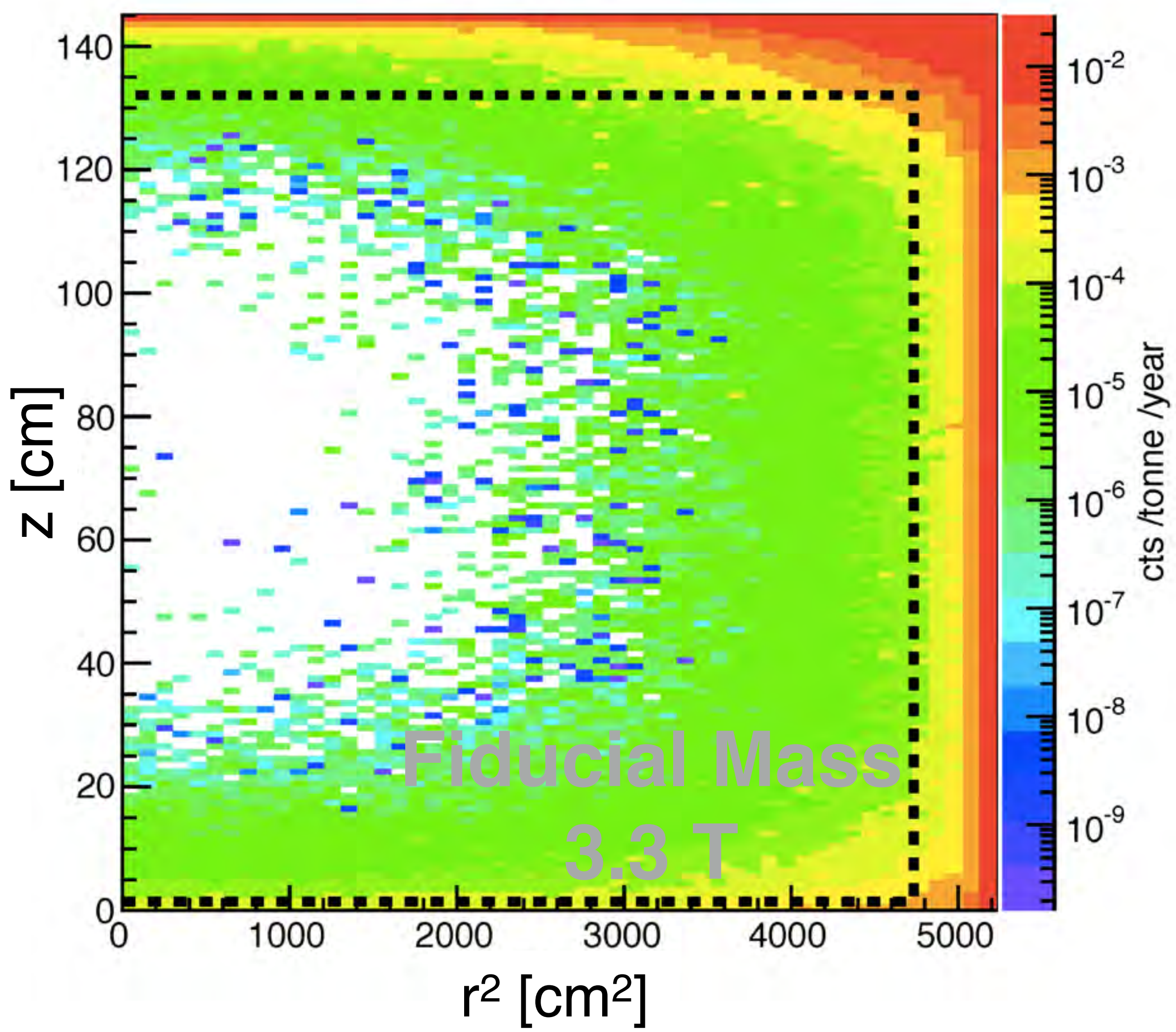


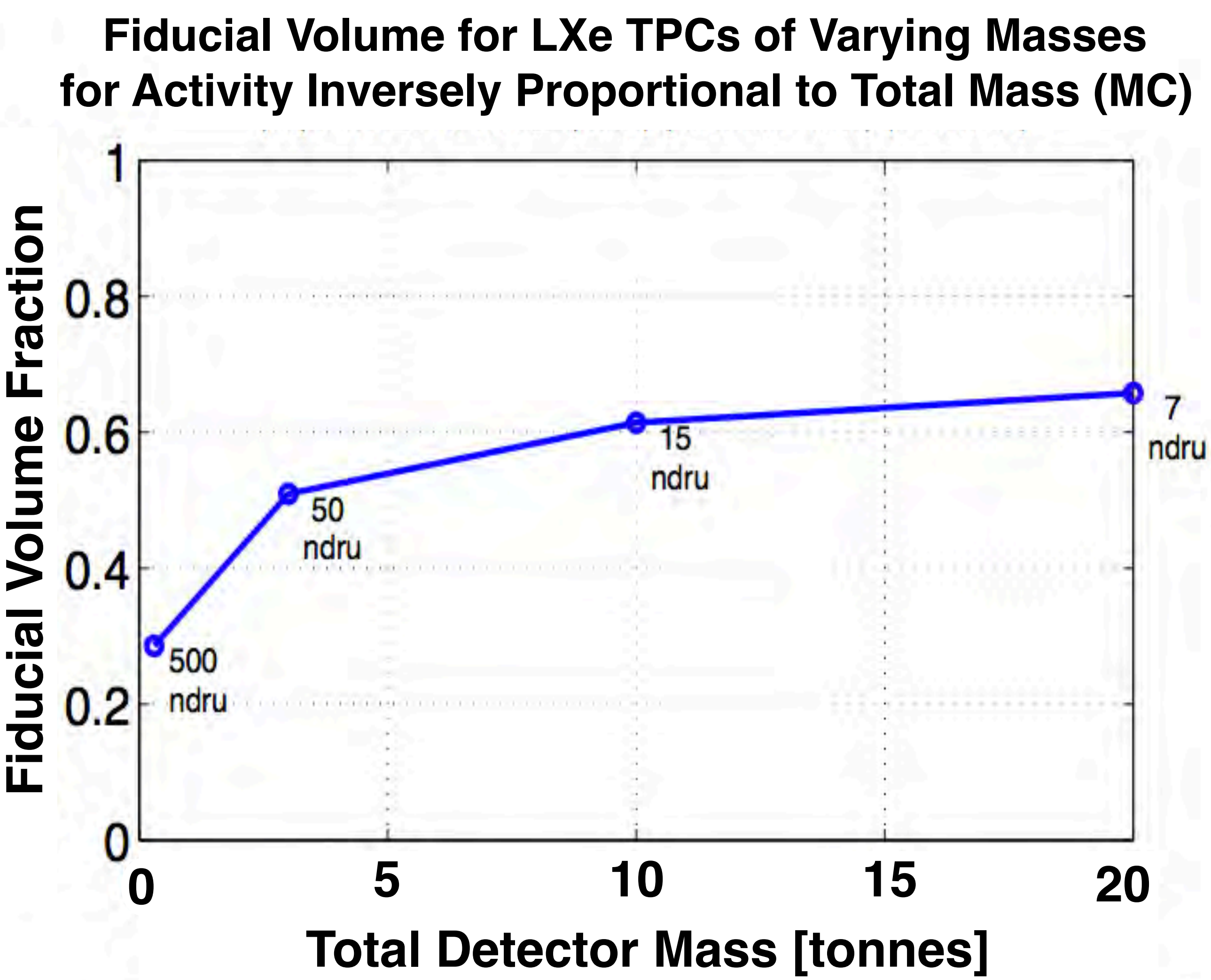


How to maximize the WIMP target mass?

- Fiducial volume => low backgrounds

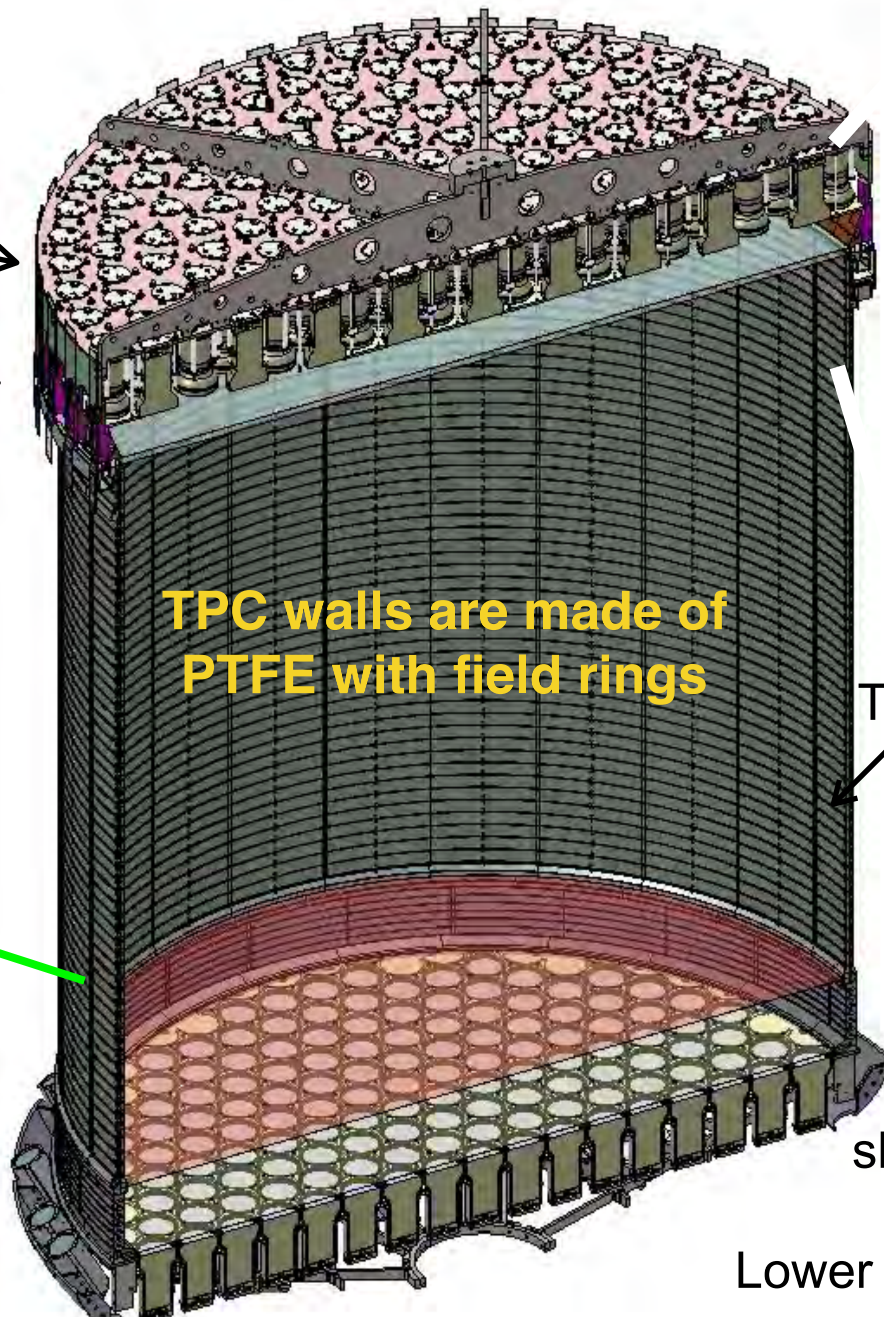
Xe-TPC only

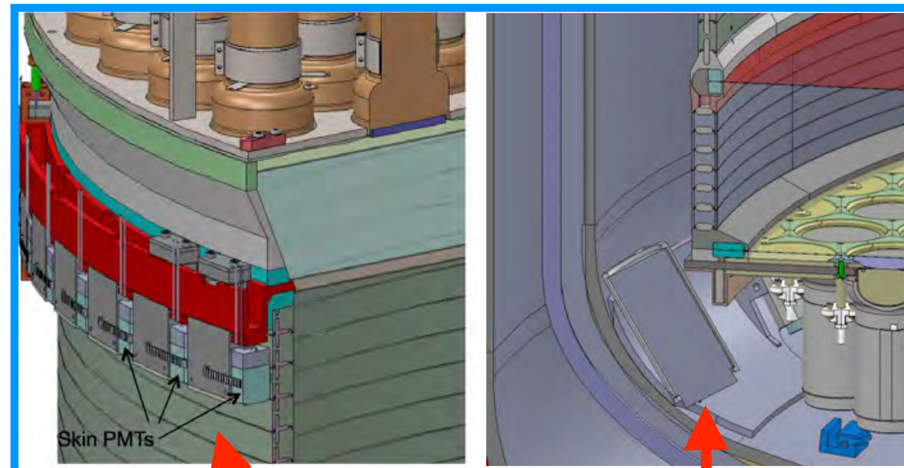


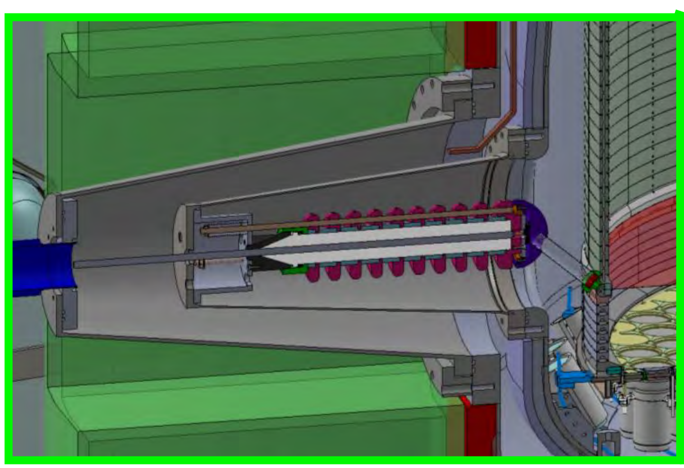


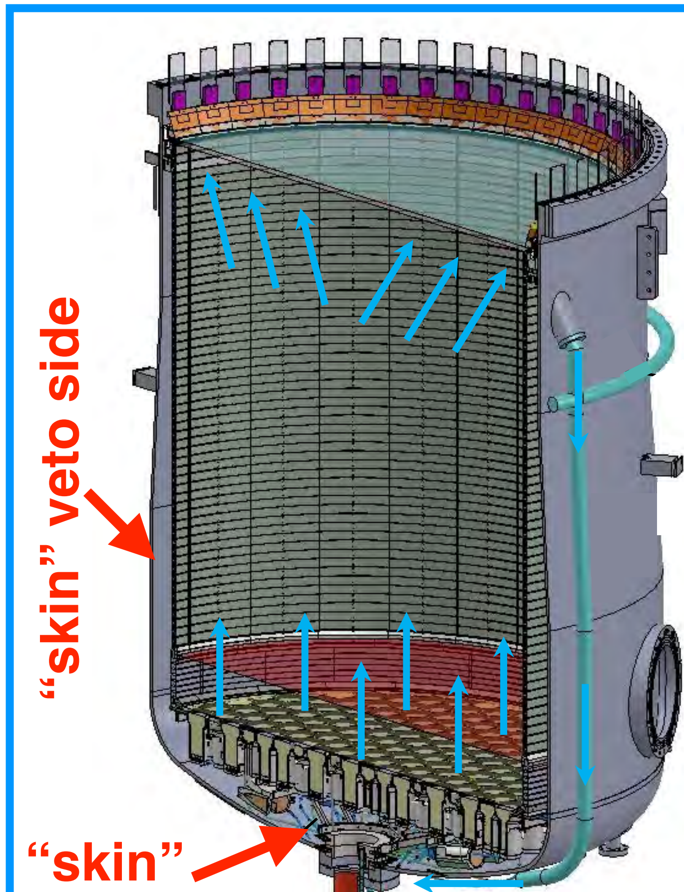
Xenon “Skin” veto

Effective height & diameter both ~1.46 m



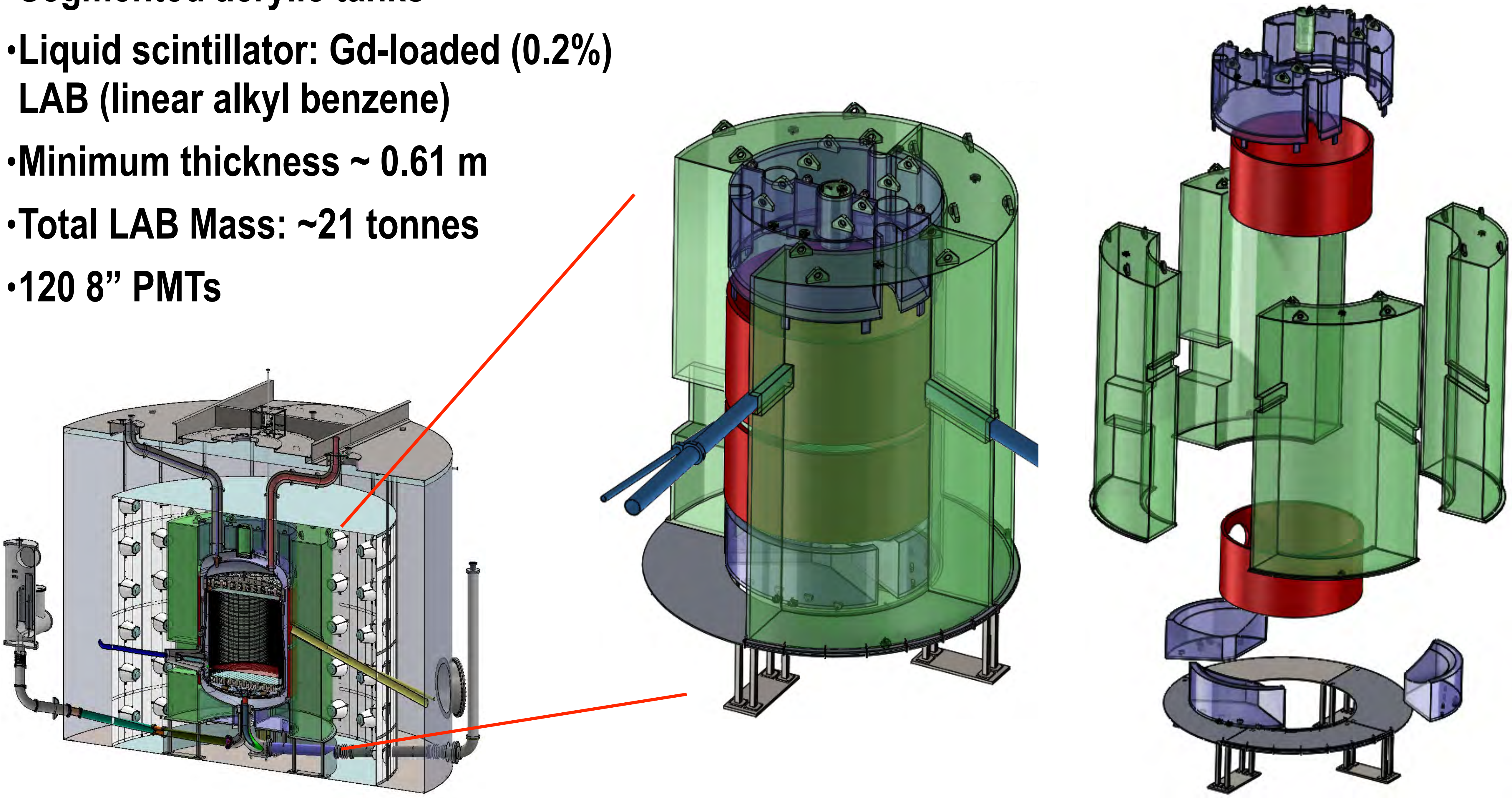






OUTER DETECTOR: GAMMA/NEUTRON VETO SYSTEM

- Suppression of neutron-induced nuclear recoil rate → maximize fiducial volume.
- Segmented acrylic tanks
- Liquid scintillator: Gd-loaded (0.2%) LAB (linear alkyl benzene)
- Minimum thickness ~ 0.61 m
- Total LAB Mass: ~21 tonnes
- 120 8” PMTs



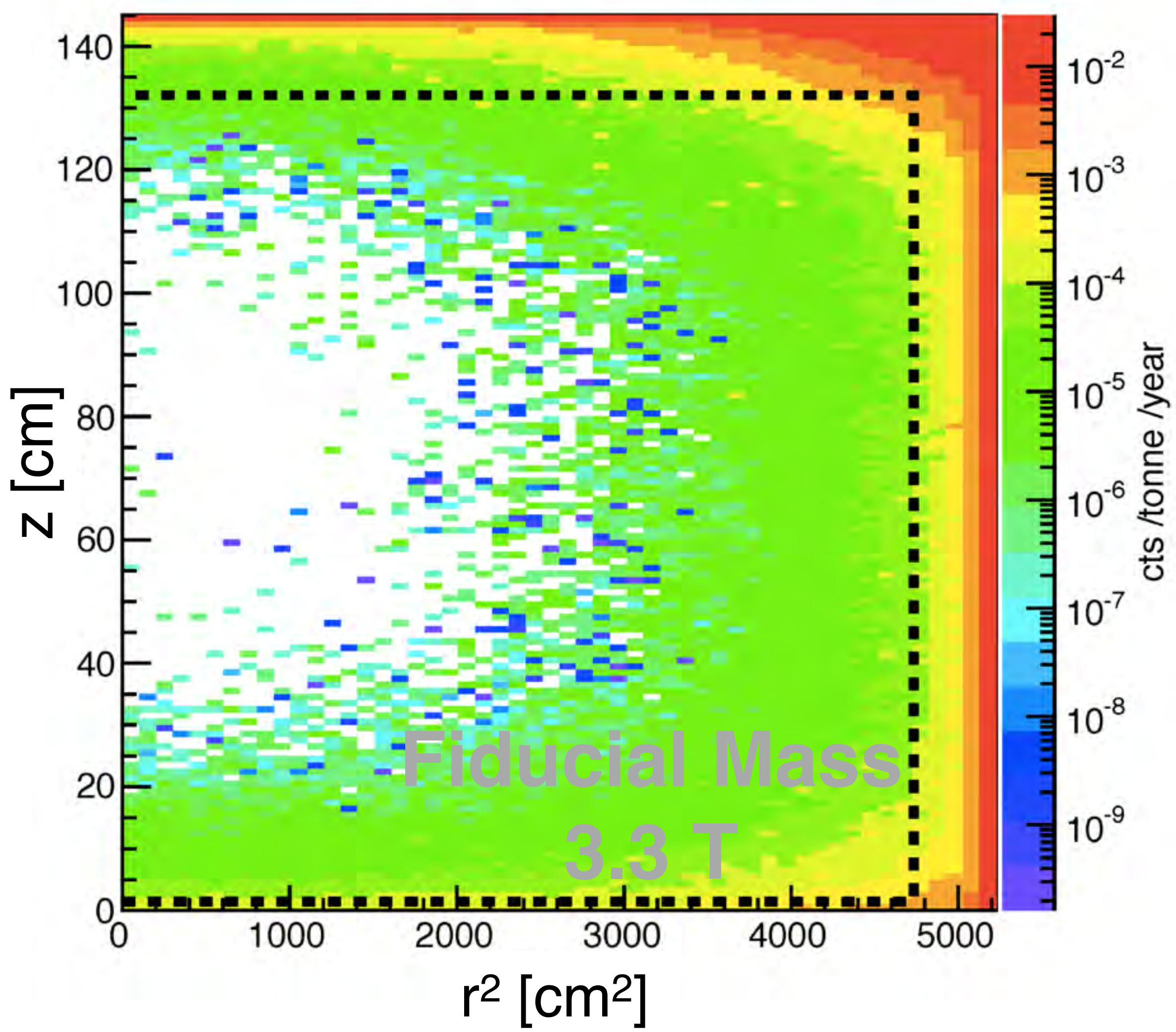
- Daya Bay legacy: scintillator, tanks, and people!

How to maximize the WIMP target mass?

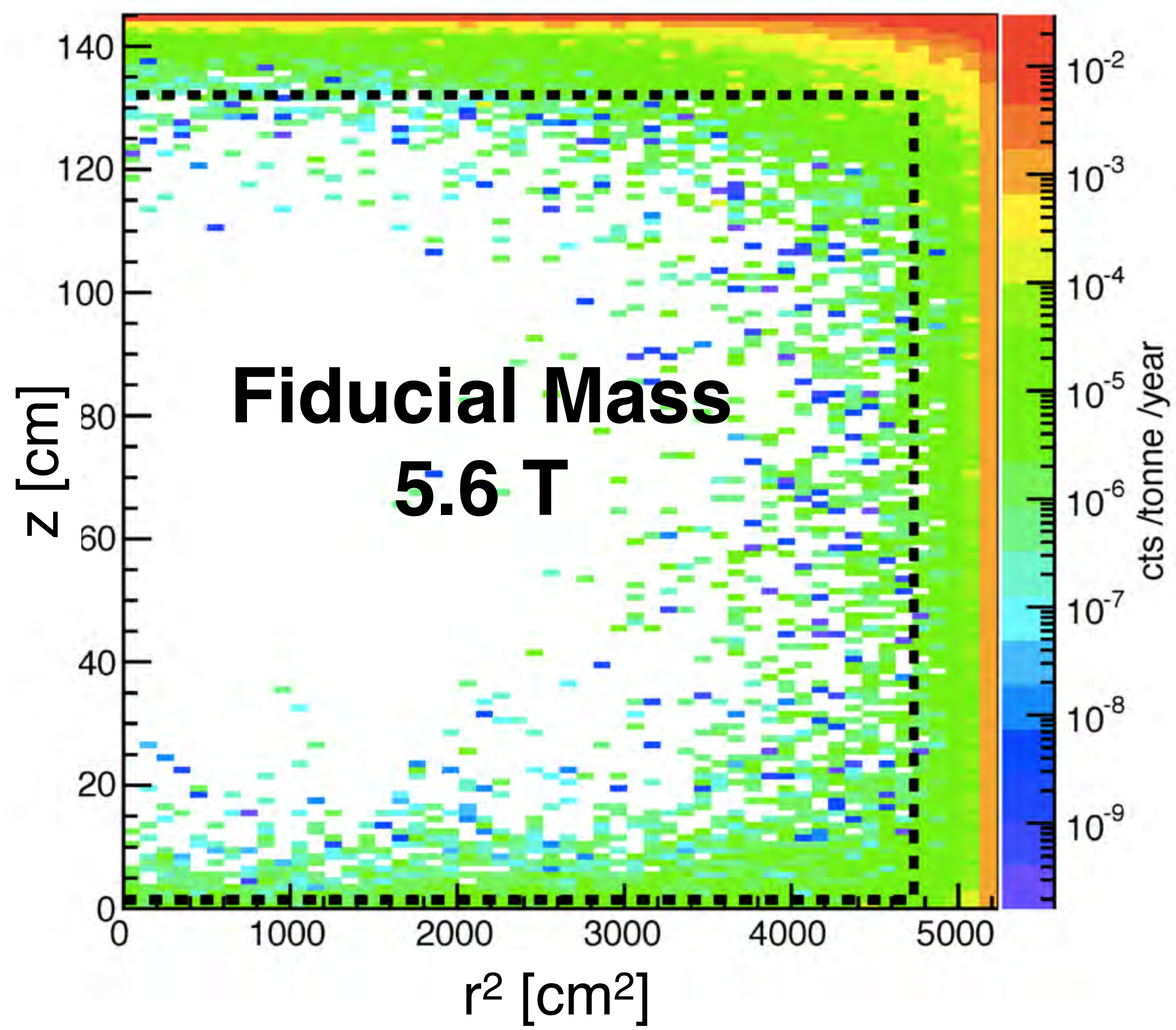
- Three-component veto system:
  - Water tank
  - Xenon "skin"
  - Gd-loaded scintillator

Tag neutrons and gammas → in situ monitoring of residual backgrounds!!!

Xe-TPC only



TPC + skin + Gd-scint.



EXPECTED BACKGROUNDS FOR 5.6 T FIDUCIAL - 1000 DAYS (1)

- **Radon is the dominant background!**

Intrinsic Contamination Backgrounds	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rej.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	40.5	Y	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	Y	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.82	15.41	81.83	1.46	0.013
R11410 PMT Bases *	2.8	Y	545.95	76.25	31.72	30.54	2.33	82.56	48.20	0.39	0.005
R8778 2" PMTs	6.1	Y	137.50	59.38	16.88	16.88	16.25	412.50	52.80	0.13	0.008
R8520 Skin 1" PMTs	2.2	Y	60.50	5.19	4.75	4.75	24.20	332.76	4.60	0.02	0.001
R8520 Skin PMT Bases *	0.3	Y	765.90	79.14	38.12	34.59	3.40	128.23	6.84	0.01	0.001
PMT Cabling	103.5	Y	29.83	1.47	3.31	3.15	0.65	33.14	2.65	1.43	0.000
TPC PTFE	193.0	N	0.02	0.02	0.03	0.03	0.00	0.12	23.64	0.06	0.009
Grid Wires	0.75	N	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	Y	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	Y	5.41	0.09	0.28	0.23	0.00	0.54	10.83	0.23	0.004
TPC Sensors	0.90	Y	21.09	13.51	22.89	14.15	0.50	26.29	24.77	0.01	0.002
TPC Thermometers	0.06	Y	335.50	90.46	38.48	25.02	7.26	3 359	1.49	0.05	0.000
Xe Recirculation Tubing	15.1	Y	0.79	0.18	0.23	0.330	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	1.9	2.0	0.5	0.6	1.4	1.2	4.9	0.04	0.001
HX and PMT Conduits	199.6	Y	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2406.1	N	1.59	0.11	0.29	0.25	0.07	0.56	123.70	0.63	0.013
Cryostat Seals	33.7	Y	73.91	26.22	3.22	4.24	10.03	69.12	38.78	0.45	0.002
Cryostat Insulation	23.8	Y	18.91	18.91	3.45	3.45	1.97	51.65	69.83	0.43	0.007
Cryostat Teflon Liner	67.0	N	0.02	0.02	0.03	0.03	0.00	0.12	8.21	0.00	0.001
Outer Detector Tanks	3199.3	Y	0.16	0.39	0.02	0.06	0.04	5.36	77.96	0.45	0.001
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0	534	7 587	0.01	0.000
Outer Detector PMT Supports	770.0	N	1.20	0.27	0.33	0.49	1.60	0.40	14.30	0.00	0.000
222Rn (2.0 µBq/kg)										722	-
220Rn (0.1 µBq/kg)										122	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 µBq/kg)										40.0	-
Laboratory and Cosmogenics										4.8	0.06
Fixed Surface Contamination										0.19	0.37
Subtotal (Non-ν counts)										**922**	**0.50**
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
Subtotal (Physics backgrounds)										322	0.72
Total										1 240	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)										6.22	0.61
										6.83	

Expected backgrounds for 5.6 T fiducial - 1000 days (2)

- **Radon is the dominant background!**

Intrinsic Contamination Backgrounds	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rel.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	40.5	Y	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	Y	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.82	15.41	81.83	1.46	0.013
R11410 PMT Bases *	2.8	Y	545.95	76.25	31.72	30.54	2.33	82.56	48.20	0.39	0.005
R8778 2" PMTs	6.1	Y	137.50	59.38	16.88	16.88	16.25	412.50	52.80	0.13	0.008
R8520 Skin 1" PMTs	2.2	Y	60.50	5.19	4.75	4.75	24.20	332.76	4.60	0.02	0.001
R8520 Skin PMT Bases *	0.3	Y	765.90	79.14	38.12	34.59	3.40	128.23	6.84	0.01	0.001
PMT Cabling	103.5	Y	29.83	1.47	3.31	3.15	0.65	33.14	2.65	1.43	0.000
TPC PTFE	193.0	N	0.02	0.02	0.03	0.03	0.00	0.12	23.64	0.06	0.009
Grid Wires	0.75	N	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	Y	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	Y	5.41	0.09	0.28	0.23	0.00	0.54	10.83	0.23	0.004
TPC Sensors	0.90	Y	21.09	13.51	22.89	14.15	0.50	26.29	24.77	0.01	0.002
TPC Thermometers	0.06	Y	335.50	90.46	38.48	25.02	7.26	3 359	1.49	0.05	0.000
Xe Recirculation Tubing	15.1	Y	0.79	0.18	0.23	0.330	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	1.9	2.0	0.5	0.6	1.4	1.2	4.9	0.04	0.001
HX and PMT Conduits	199.6	Y	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2406.1	N	1.59	0.11	0.29	0.25	0.07	0.56	123.70	0.63	0.013
Cryostat Seals	33.7	Y	73.91	26.22	3.22	4.24	10.03	69.12	38.78	0.45	0.002
Cryostat Insulation	23.8	Y	18.91	18.91	3.45	3.45	1.97	51.65	69.83	0.43	0.007
Cryostat Teflon Liner	67.0	N	0.02	0.02	0.03	0.03	0.00	0.12	8.21	0.00	0.001
Outer Detector Tanks	3199.3	Y	0.16	0.39	0.02	0.06	0.04	5.36	77.96	0.45	0.001
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0	534	7 587	0.01	0.000
Outer Detector PMT Supports	770.0	N	1.20	0.27	0.33	0.49	1.60	0.40	14.30	0.00	0.000
222Rn (2.0 μBq/kg)										722	-
220Rn (0.1 μBq/kg)										122	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 μBq/kg)										40.0	-
Laboratory and Cosmogenics										4.8	0.06
Fixed Surface Contamination										0.19	0.37
Subtotal (Non-ν counts)										**922**	**0.50**
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
Subtotal (Physics backgrounds)										322	0.72
Total										1 240	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)										6.22	0.61
										6.83	

RN EMANATION

- Rn (and Kr) - dominant internal radioactive background
- Emanates from most materials
- 2 μBq/kq requirement, 0.1 μBq/kq goal
- Four separate measurements systems, ~0.1 mBq sensitivity
- Main assembly laboratory at SURF will have reduced radon air system

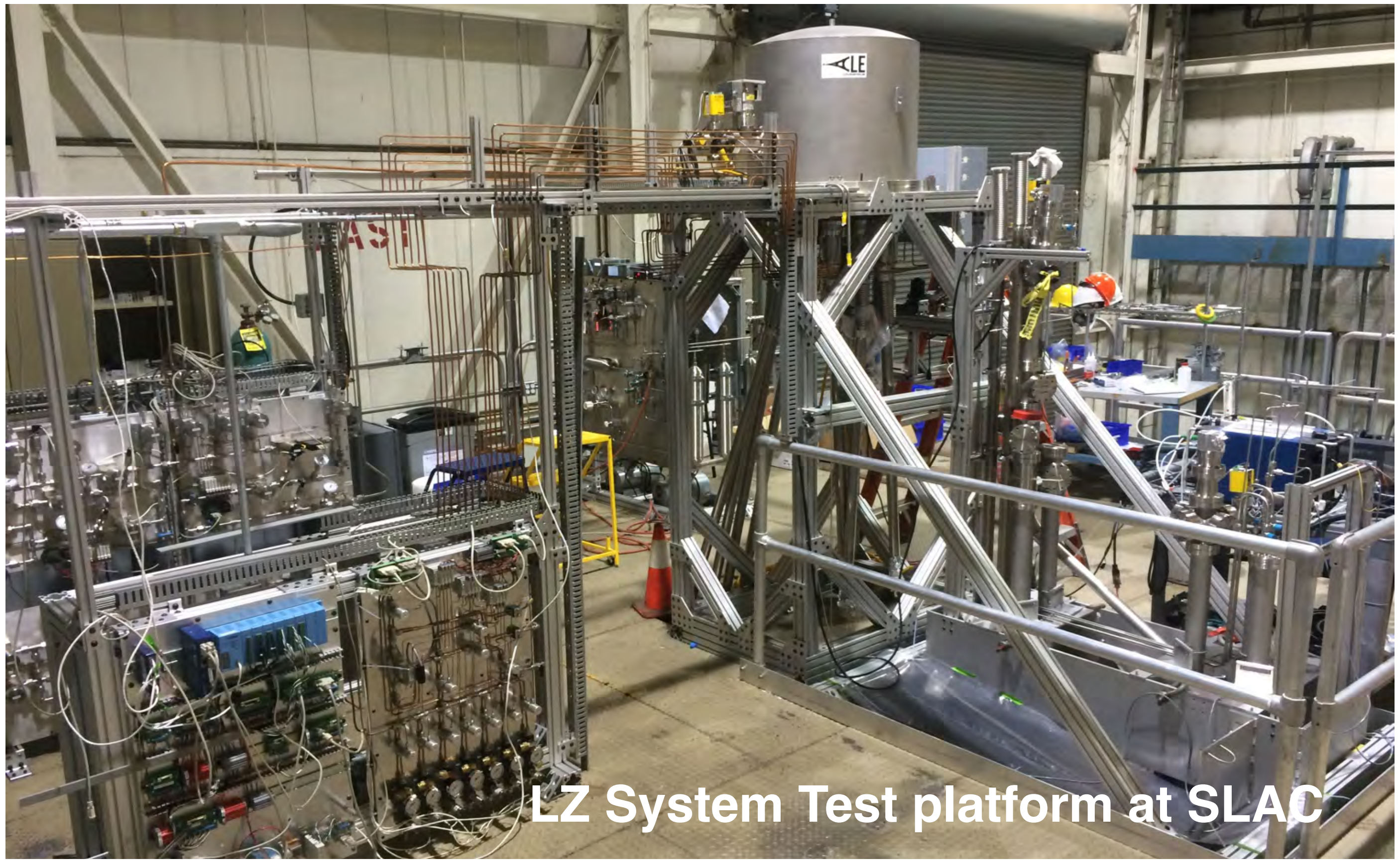
Performance Drivers

- Performance requirements
  - Baseline: Fully expect these to be met
  - Goals: What we are aiming for

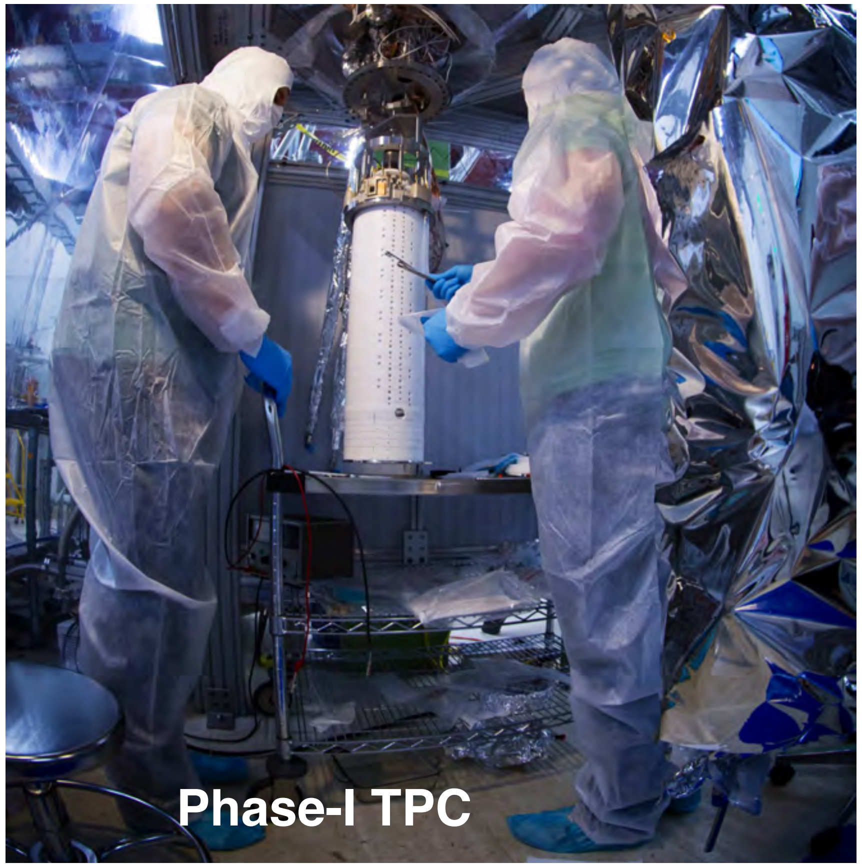
	Achieved in LUX (current best)	LZ Baseline	LZ Goal
^{222}Rn (μBq/kg)	~30 (~3 in EXO-200)	2	0.1
Drift Field (V/cm)	180 V/cm (667 V/cm Panda-X)	310	650
Electron lifetime (μs)	> 1000	850	2800
Light Collection	0.12	0.075	0.12
Single phe efficiency	0.95	0.9	1.0
N-fold coincidence	2	3	2

DETECTOR PROTOTYPING

- Extensive prototyping program:
  - Testing in liquid argon, primarily of HV elements at LBNL
  - System test platform at SLAC
    - Phase I Ongoing: ~100 kg of LXe TPC; grids and fields R&D; circulation system testing; software development.
    - Phase II: Large Xe gas vessel; full scale grids.



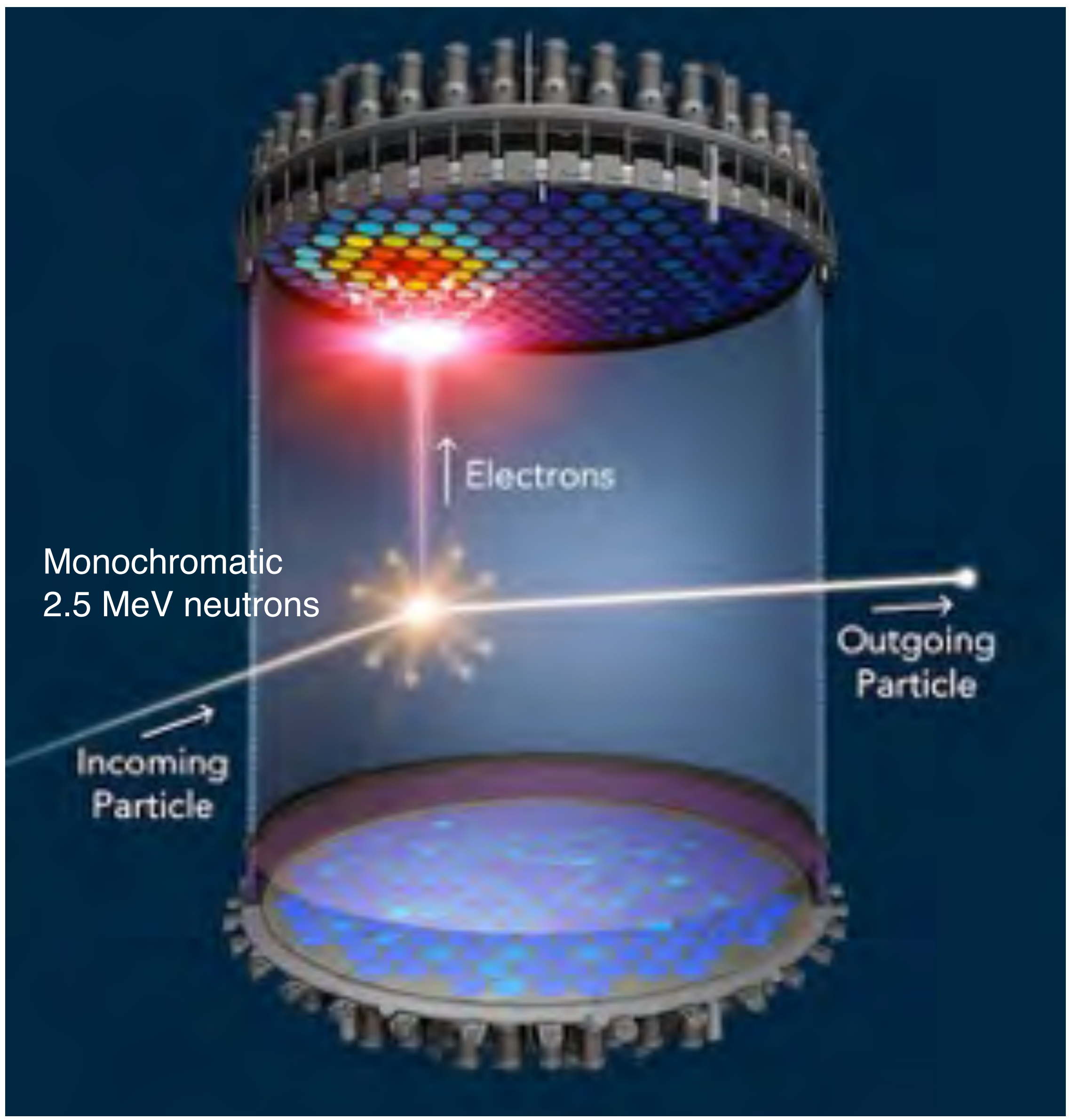
LZ System Test platform at SLAC



Phase-I TPC

EXTENSIVE CALIBRATIONS

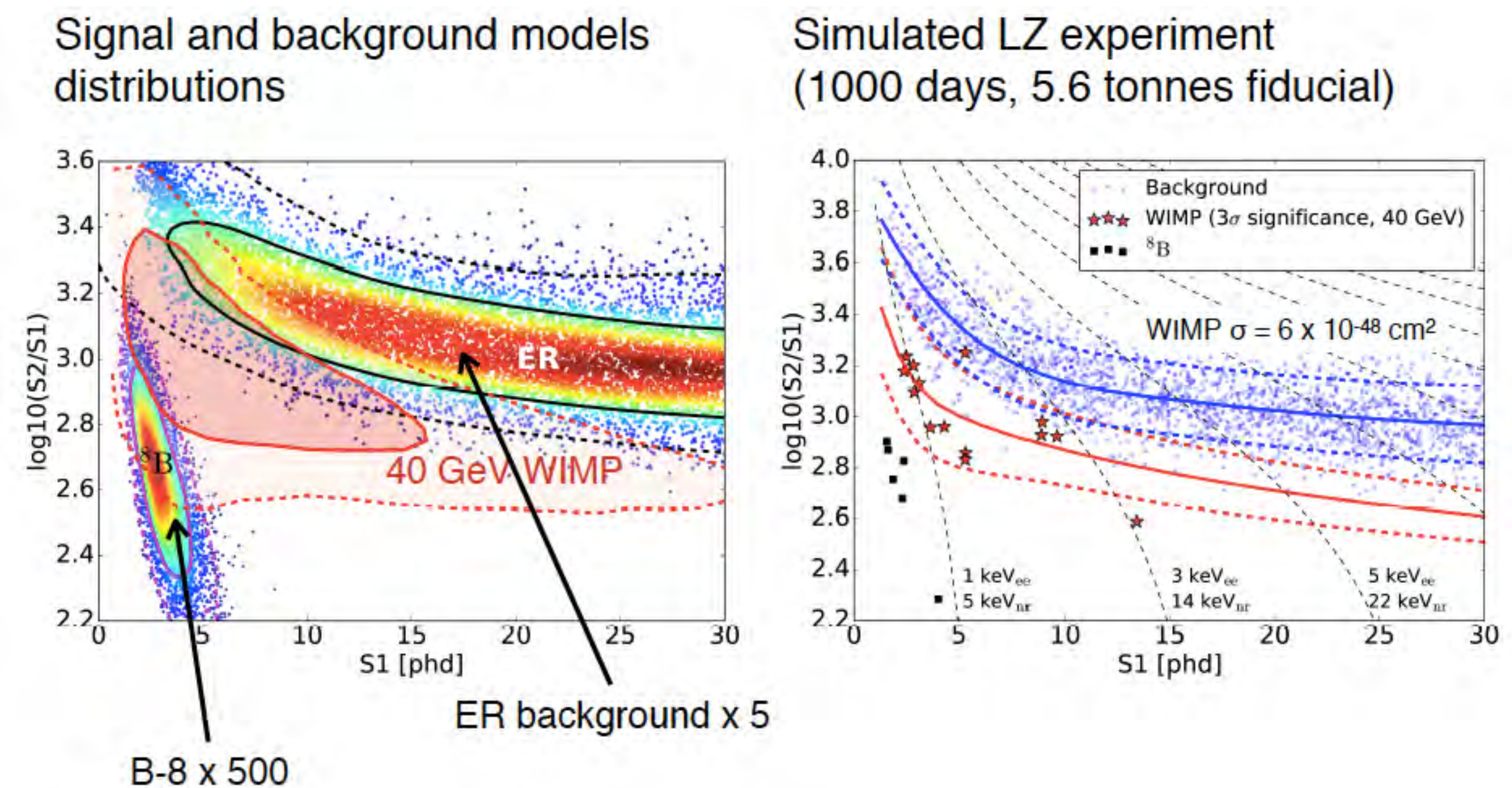
- Challenge for ton-scale detectors: Self-shielding complicates matters.
  Solution: injected sources!
- LUX has led the way to detailed calibrations. LZ will build on this and do more.



Done in LUX, will be done in LZ	Not done in LUX, but will do in LZ
^{83m}Kr	Inject activated Xe (^{131m}Xe)
Tritiated methane	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator (upgraded soon to shorten pulse)	

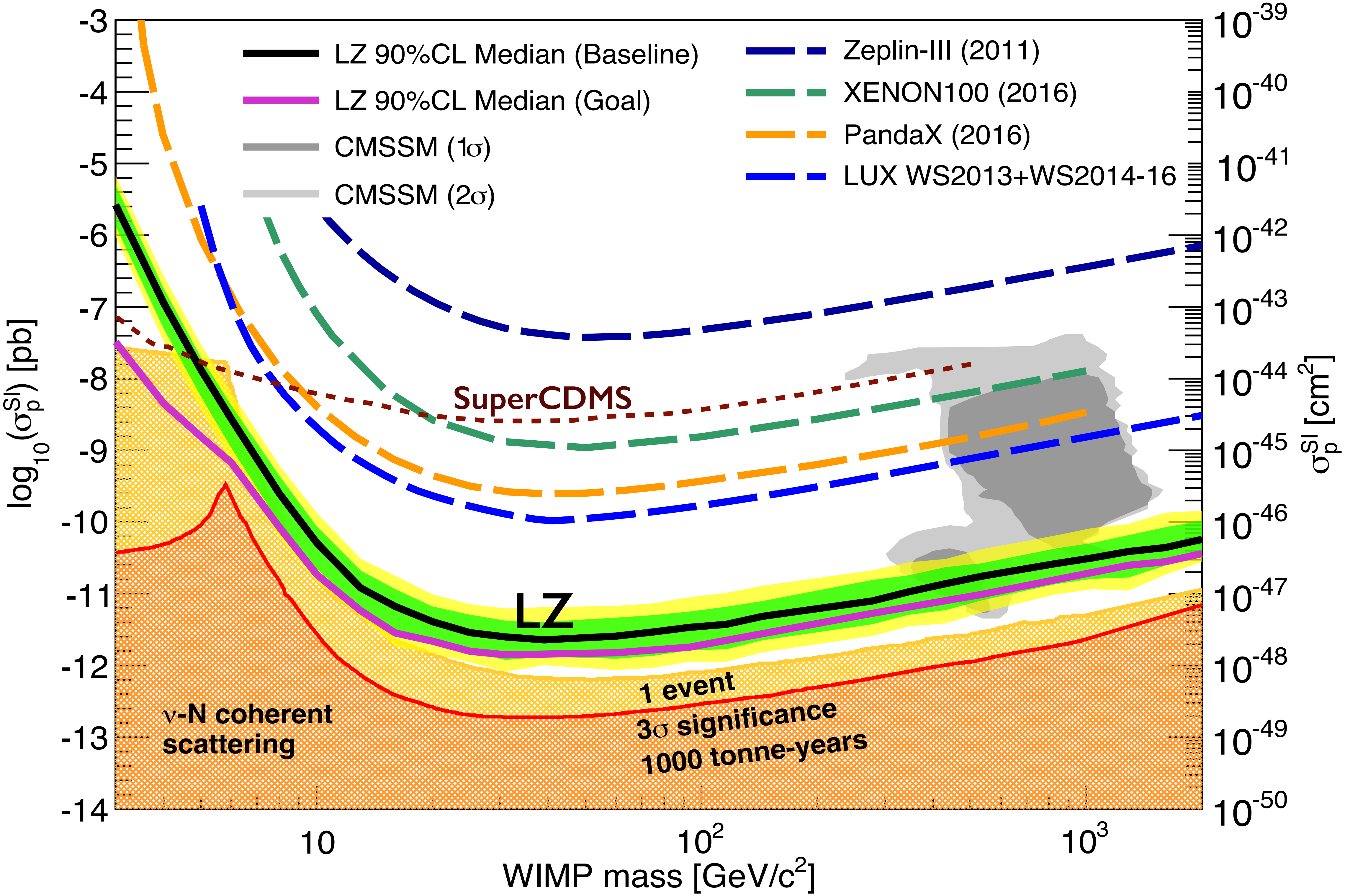
Signal and Background

- Advanced analysis procedure PDFs for PLR



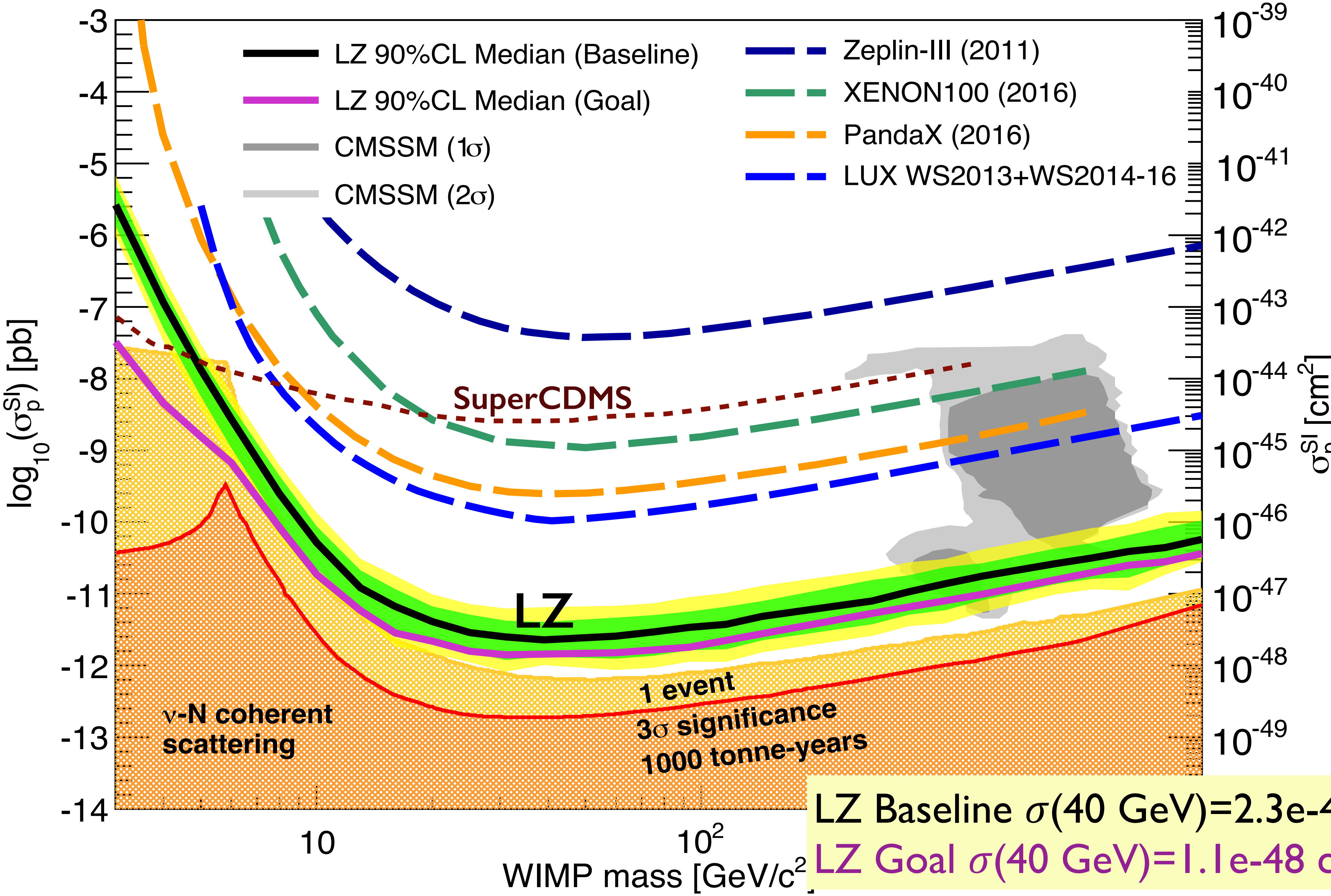
PROJECTED SENSITIVITY - SPIN INDEPENDENT

- The 'ultimate' direct Dark Matter detector: Approaches coherent neutrino scattering background! (LZ 5.6 T, 1000 live days)



Projected Sensitivity - Spin Independent

- The 'ultimate' direct Dark Matter detector: Approaches coherent neutrino scattering background! (LZ 5.6 T, 1000 live days)



LZ Baseline σ(40 GeV)=2.3e-48 cm^2

LZ Goal σ(40 GeV)=1.1e-48 cm^2

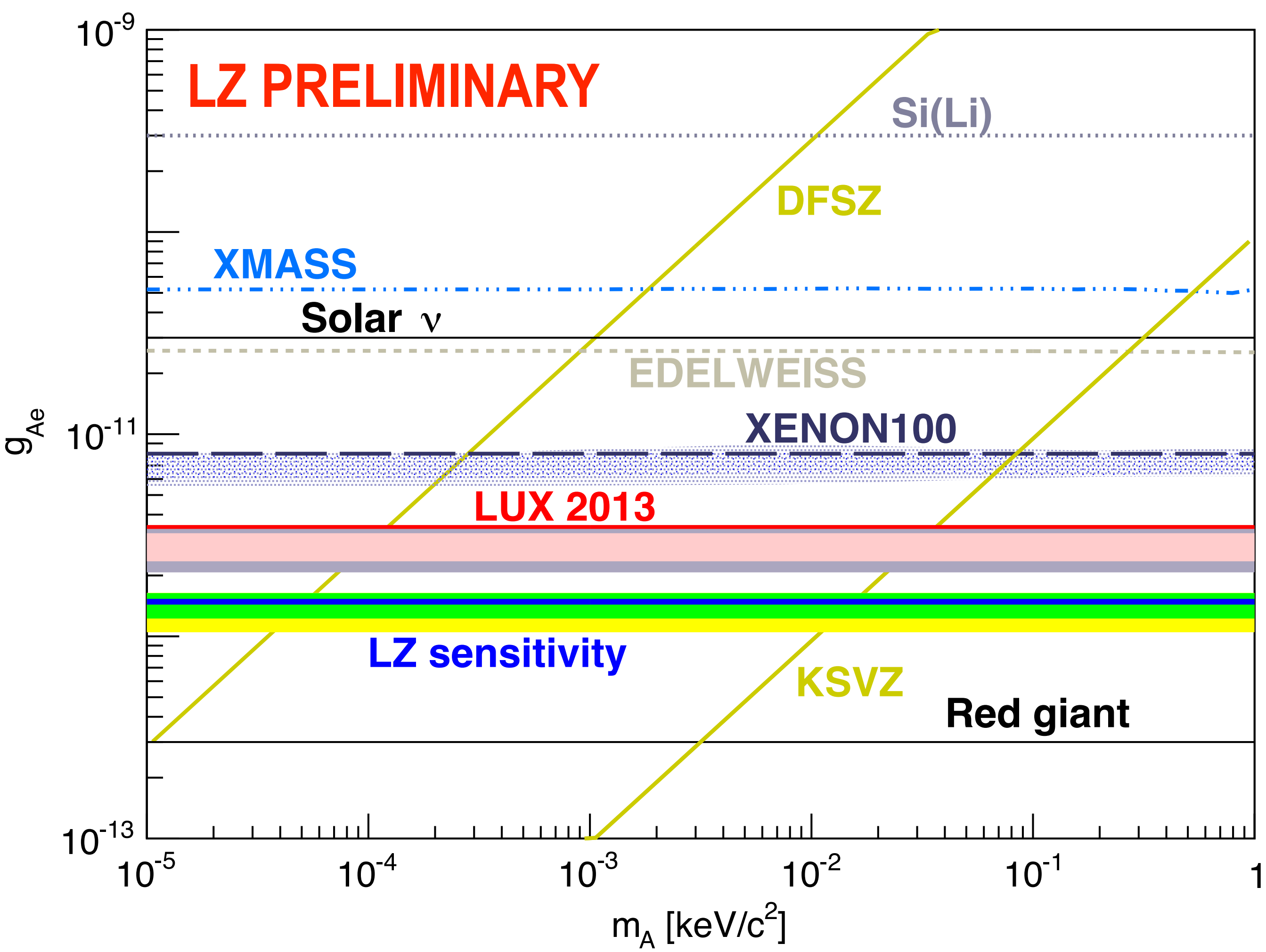
Other physics with LZ

- **LZ high sensitivity and low backgrounds open the door to a host of measurements other than WIMPs. For instance, neutrinos are not just newly relevant background, they become an interesting signal on their own!**

	Dark Matter	Neutrinos
Nuclear Recoils	• **WIMPs** • Low Mass WIMPs (S2-only analysis)	• **Coherent Neutrino-Nucleus Scattering (CNNS) of Solar and Nearby Supernova Neutrinos**
Electron Recoils	• **Axions** • Electrophilic WIMPs	• **Solar Neutrinos** • **Double Beta Decays** • Neutrino Magnetic Moment • Sterile Neutrinos (requires source; after LZ science run)

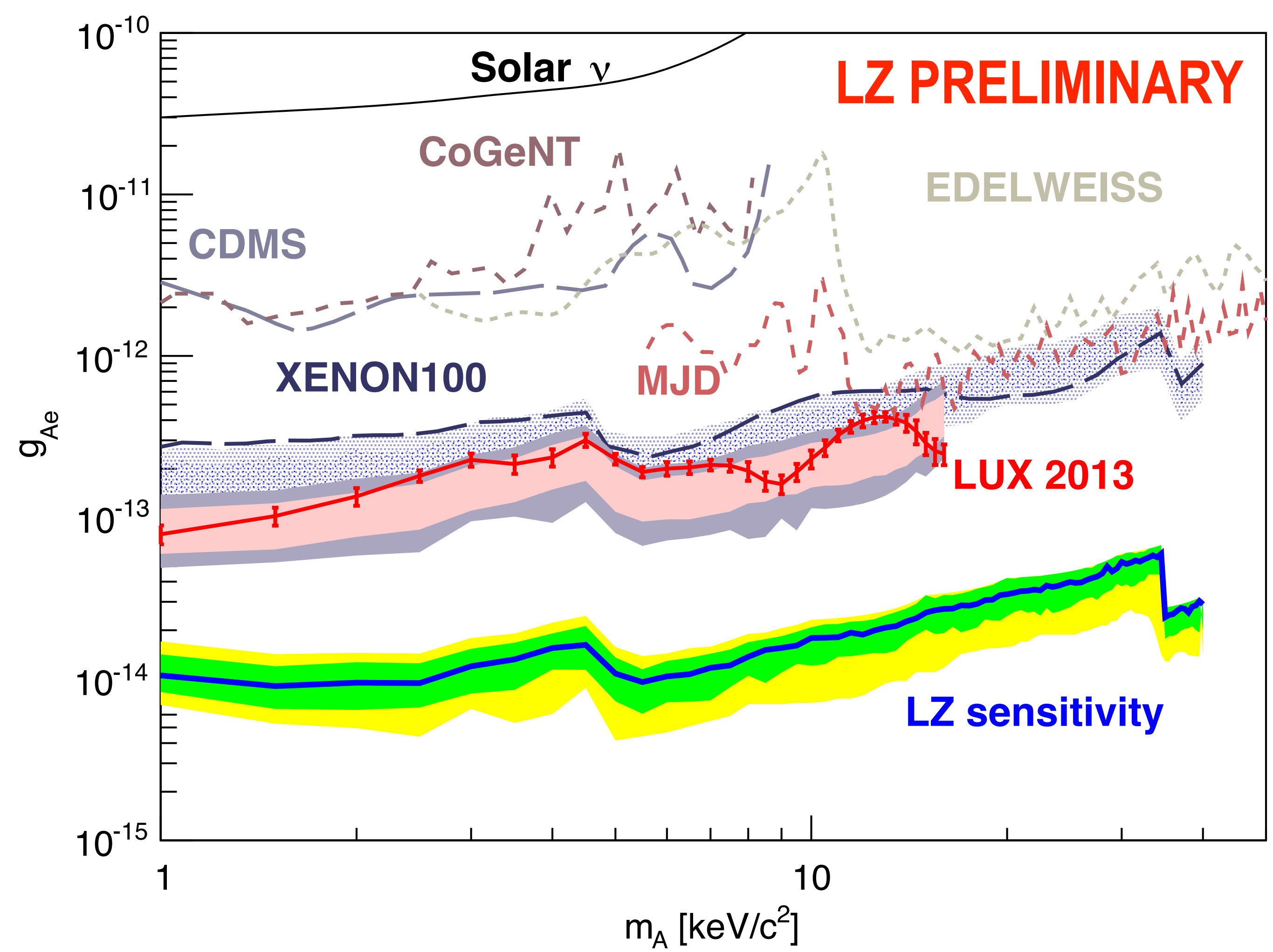
Axions and ALPs

- "Axioelectric" effect - ER energies ≲ few keV
  - Spectrum peaks at particle mass
- 1000 live-days, 5.6 ton fiducial mass



Solar ALPs

excludes $g_{Ae} > 1.5\times10^{-12}$ (90% CL)

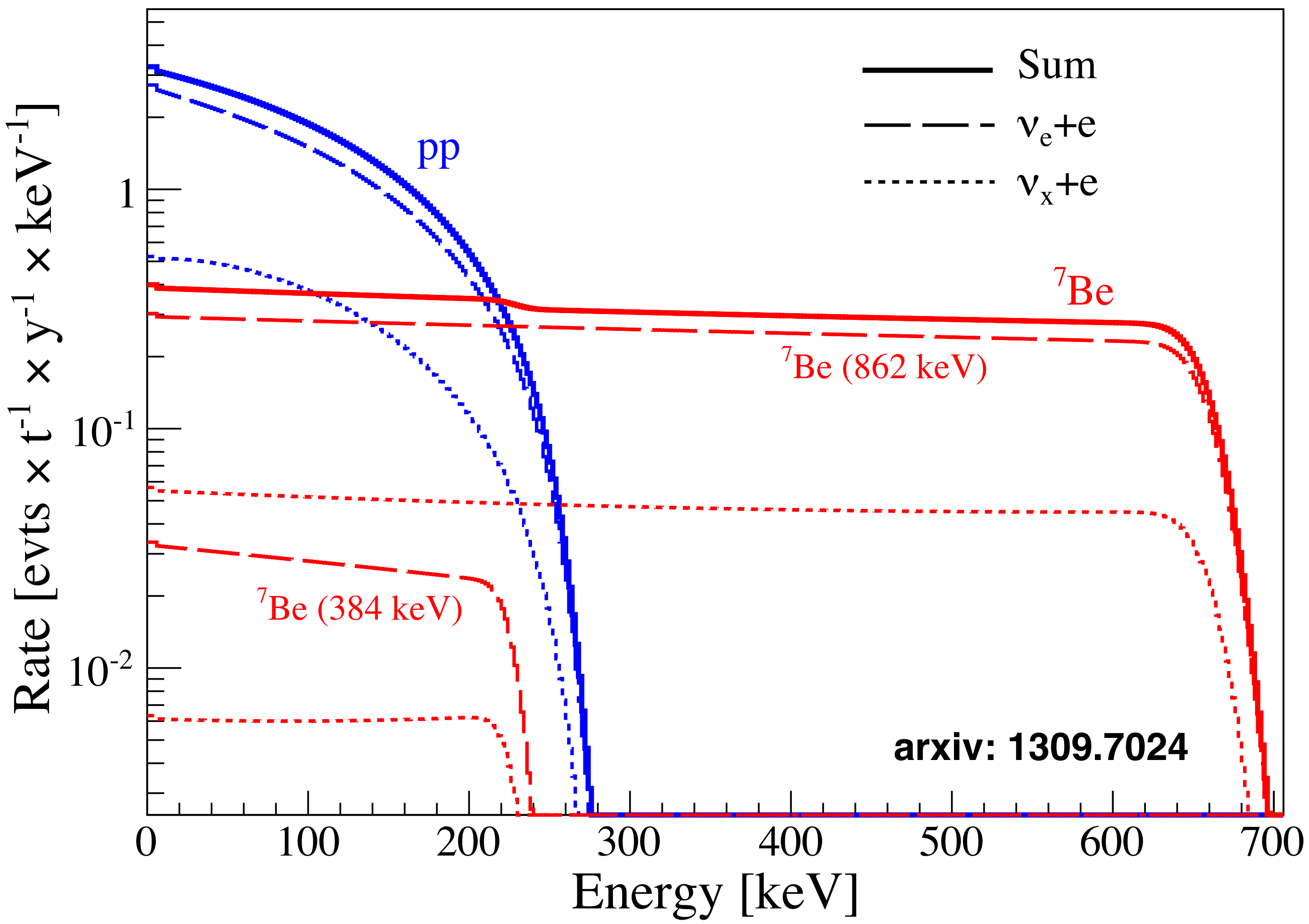


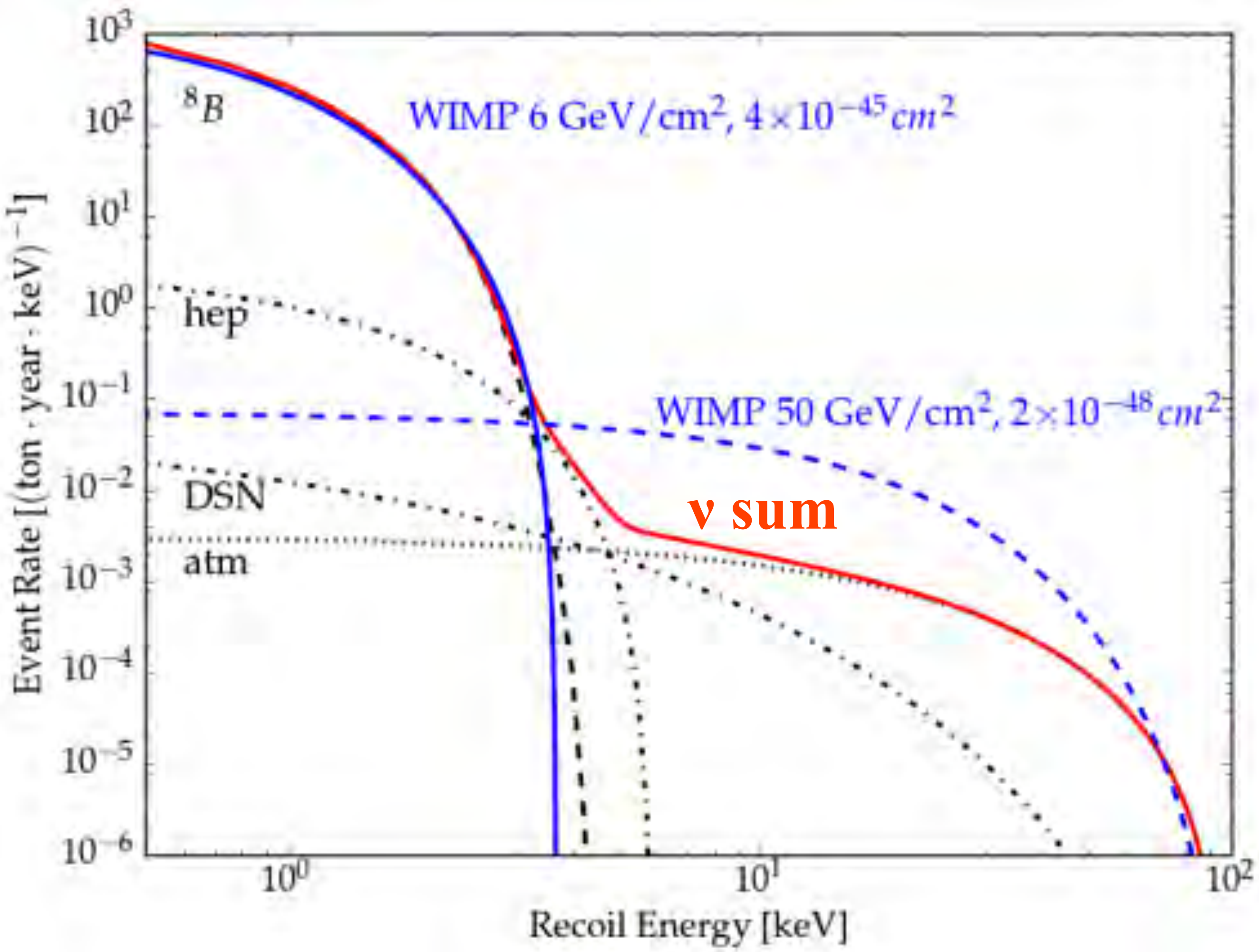
Galactic (Dark Matter) ALPs

excludes $g_{Ae} > 5.9\times10^{-14}$ (90% CL) across the mass range 1-40 keV/c^2

Neutrinos

- Double Beta Decay
  - $0\nu\beta\beta$: 7 tonnes active LXe → 630 kg of ^{136}Xe (9% natural abundance)
  - $2\nu\beta\beta$: ~70 events WIMP Search Energy Range 1.5-6.5 keVee
- Solar pp neutrinos
  - Detected via electron elastic scattering
  - Test of solar models, neutrino models
  - ~250 solar pp events
- Coherent Neutrino-Nucleus Scattering (CNNS): Nuclear Recoils
  - 8B Recoils mimic low mass WIMPs
  - Expect ~7 8B events and 0.5 events from others
  - DSN and atmospheric neutrinos will become the dominant background for experiments beyond LZ.





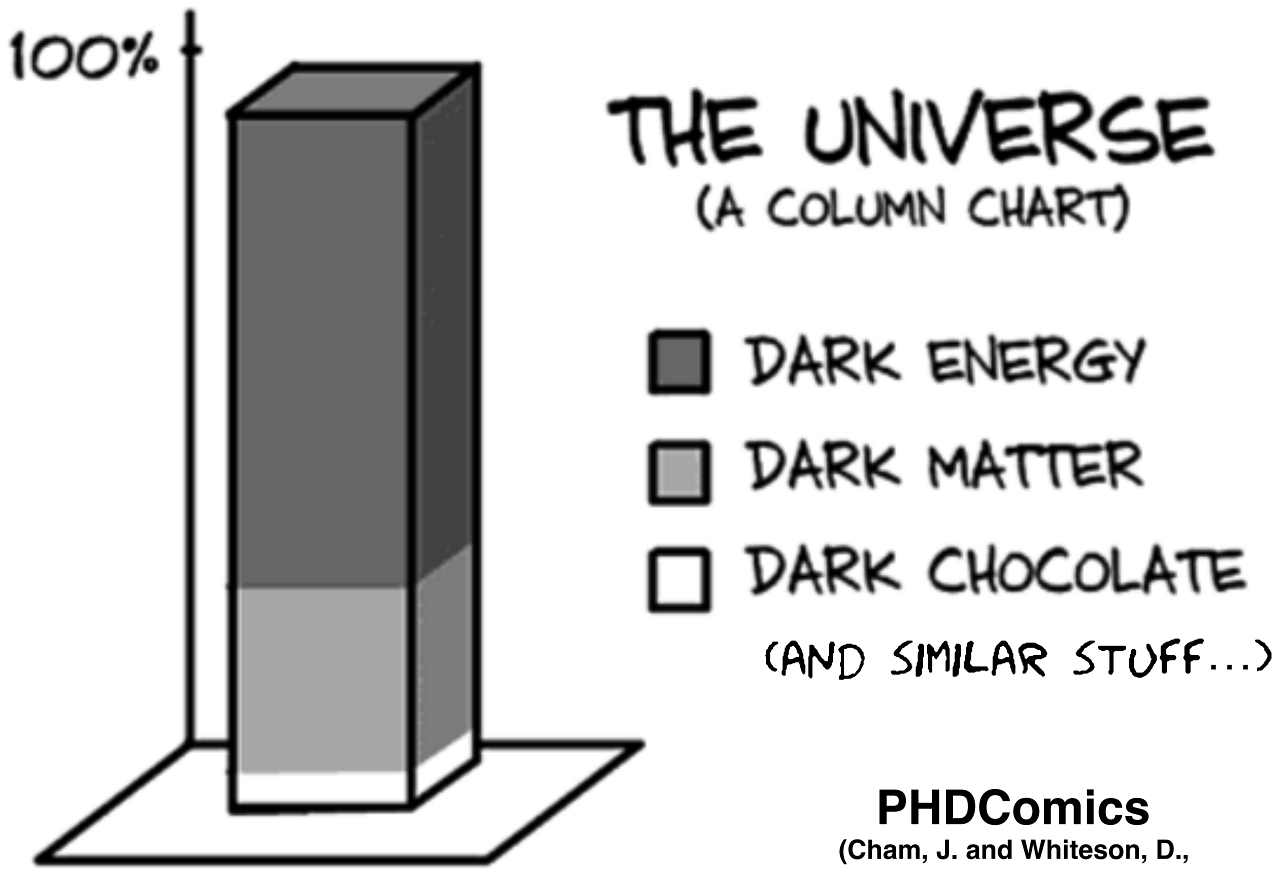
LZ Timeline

Year	Month	Activity
2012	March September	LZ (LUX-ZEPLIN) collaboration formed DOE CD-0 for G2 dark matter experiments
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
2017	February	DOE CD-3 approval, fabrication start
2017	March	LUX removed from underground
2017	August	Begin preparations for surface assembly @ SURF
2018	June	Begin underground installation
2019		Underground installation
2020	April	Start operations
2025+		Planning on 5+ years of operations

Conclusion

- LZ benefits from excellent LUX understanding of backgrounds and calibration techniques
- Project well underway, with extensive prototype program ongoing and imminent start of construction
- Will explore significant fraction of available phase space:
  - Baseline WIMP sensitivity: 2.3×10^{-48} cm^2 @ 40 GeV/c^2 and approaching neutrino floor
- Non-WIMP physics reach

THANK YOU!



PHDComics
(Cham, J. and Whiteson, D., "We Have No Idea", 2017)