LZ: The Why and the How

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SURF Annual User Association General Meeting

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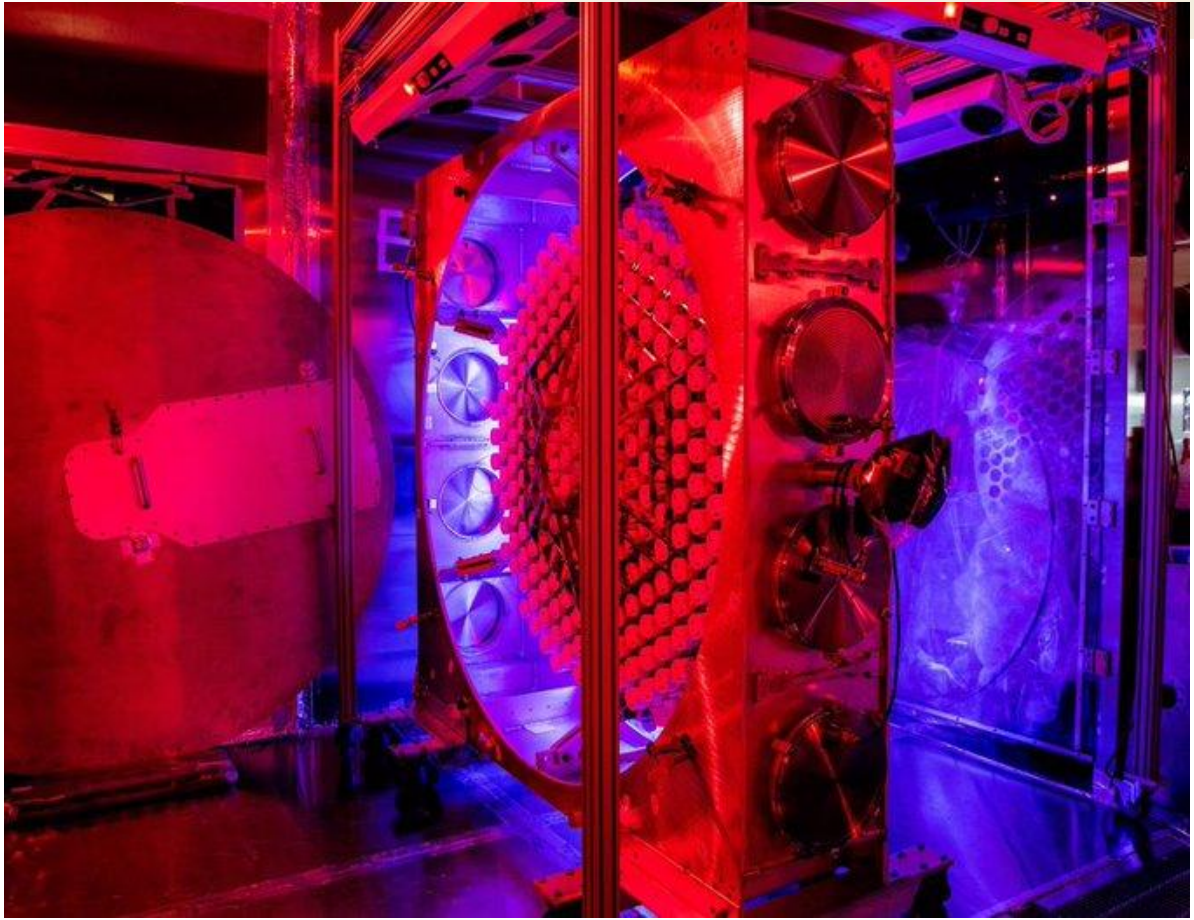
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline



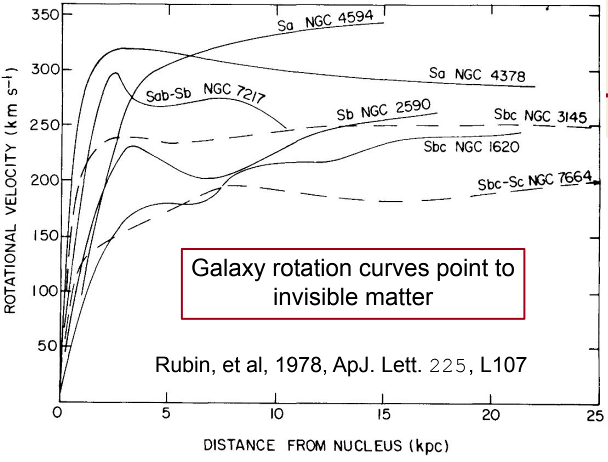
Dark matter and how to find it

Overview of LZ & Assembly

- Detector as a whole
- TPC, cleanliness & backgrounds
- Skin Detector
- Outer Detector & effects of the veto
- Circulation and cryogenics

LZ science reach

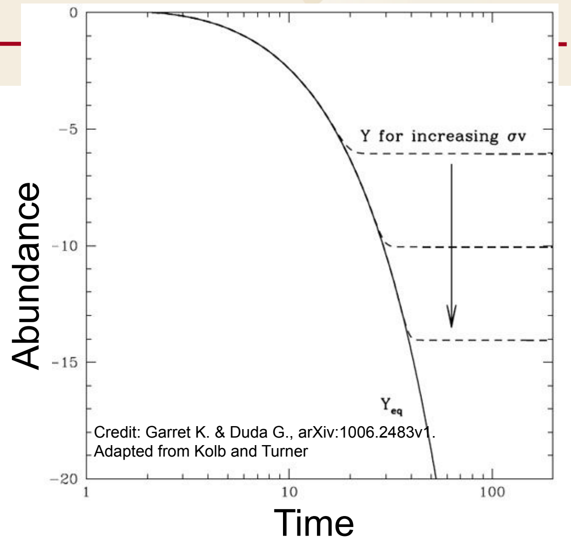
Motivation for Dark Matter and WIMPs



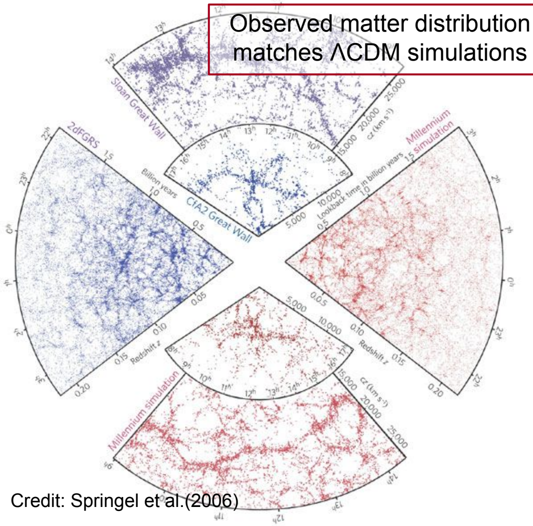
Galaxy rotation curves point to invisible matter

Rubin, et al, 1978, ApJ. Lett. 225, L107

- Dark matter interacts gravitationally, but not electromagnetically
- Could it be a particle?

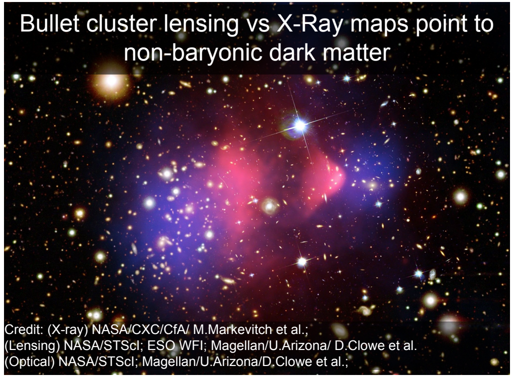


Credit: Garret K. & Duda G., arXiv:1006.2483v1. Adapted from Kolb and Turner



Observed matter distribution matches ΛCDM simulations

Credit: Springel et al.(2006)



Bullet cluster lensing vs X-Ray maps point to non-baryonic dark matter

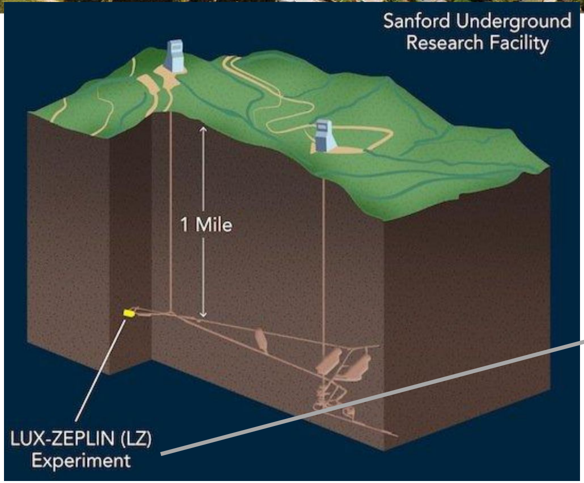
Credit: (X-ray) NASA/CXC/CfA/ M.Markevitch et al.; (Lensing) NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. (Optical) NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

- **WIMPs: Weakly interacting massive particles**
- Attractive candidate for dark matter
  - ~100 GeV mass "natural" for weak scale interaction
- WIMP search detectors like LZ are ALSO sensitive to lower and higher mass weakly interacting particles as well as other interaction types

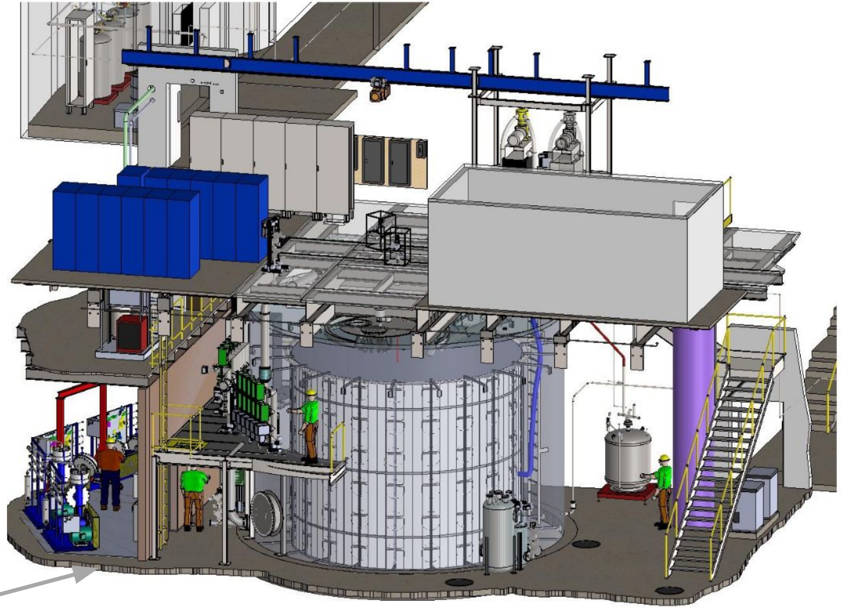
SANFORD UNDERGROUND RESEARCH FACILITY

A view of SURF and the Black Hills it's situated in

- 4300 m.w.e. overburden
- 4850 level (~1 mile underground)
- Muon flux reduced by O(1e7)

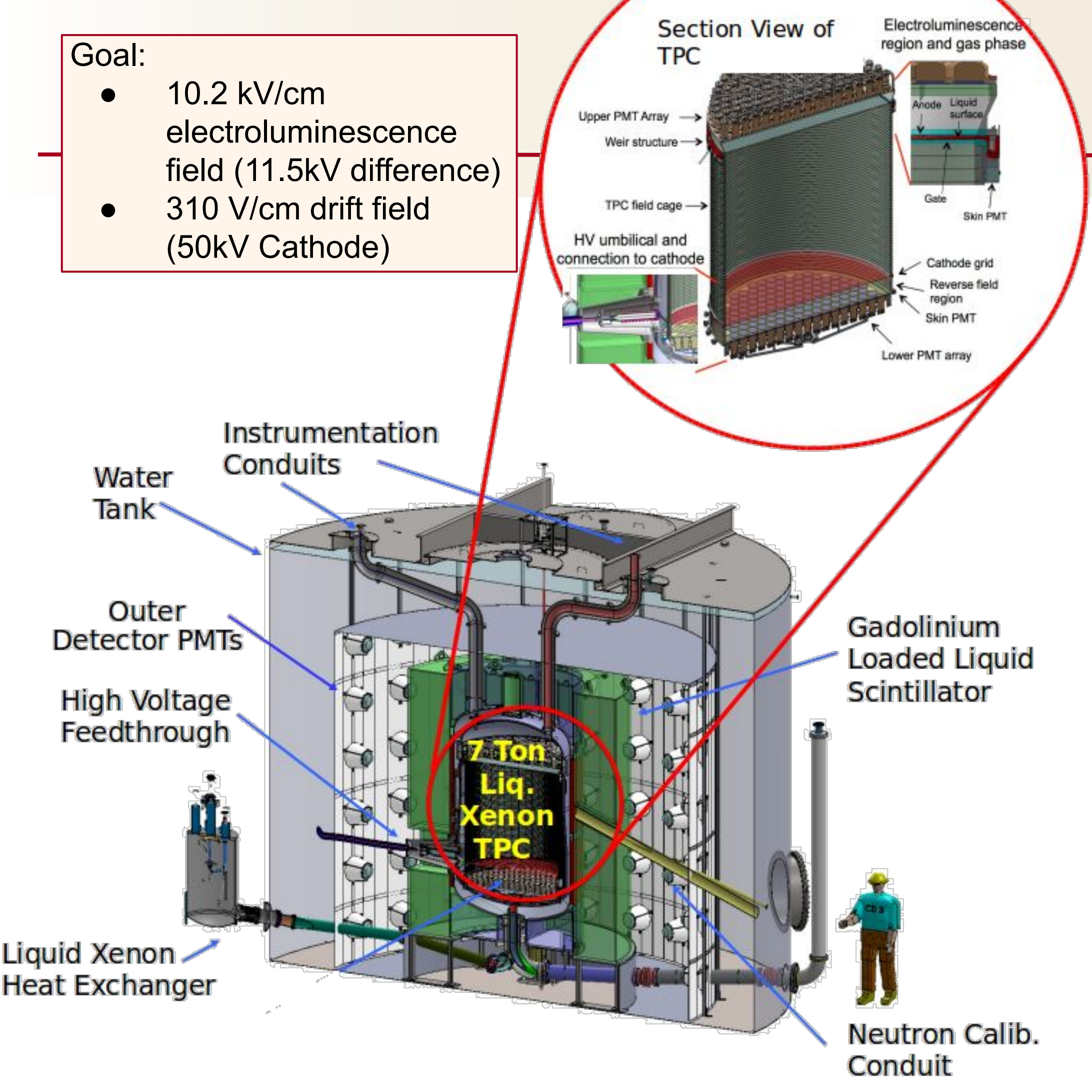


The Davis Cavern



LZ Detector

Goal:
- 10.2 kV/cm electroluminescence field (11.5kV difference)
- 310 V/cm drift field (50kV Cathode)

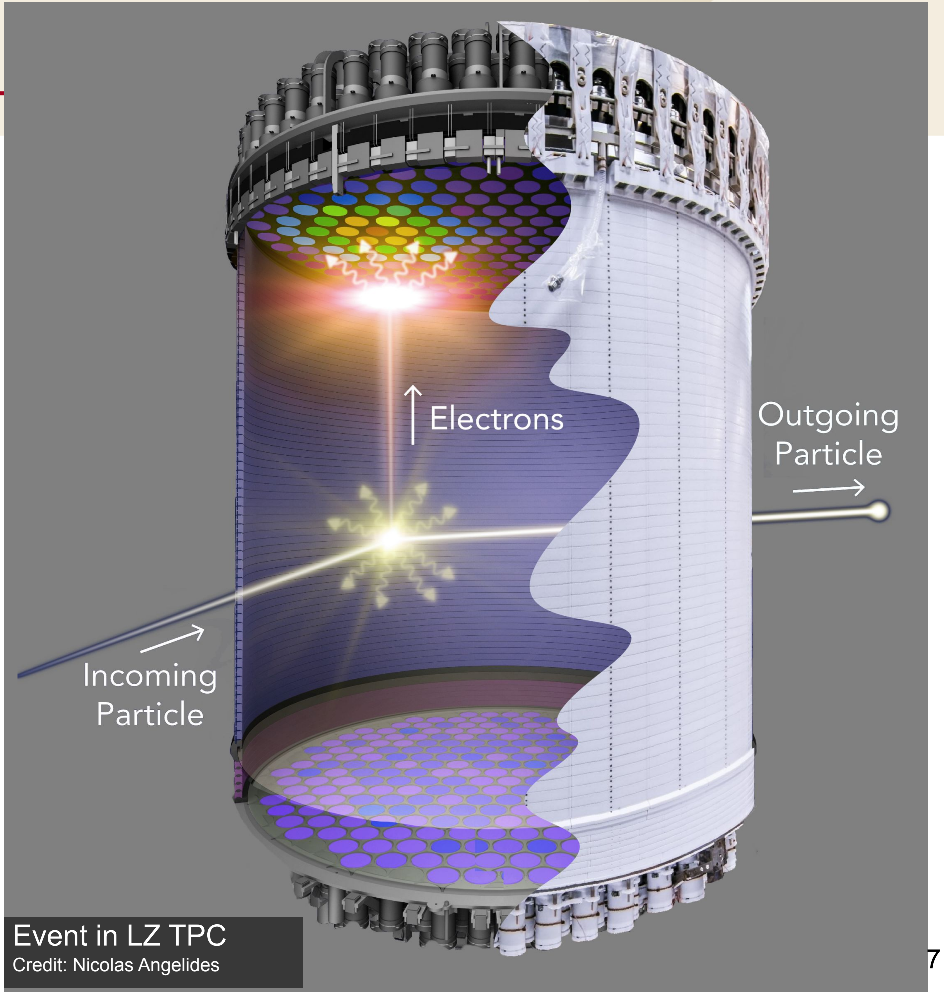


- 10 tonnes of Xe total
    - 7 tonnes active, 5.6 tonnes fiducial
    - 1.5 m diameter, 1.5 m height active region
- 494 3” PMTs in TPC
- Titanium inner cryostat vessel (ICV) and outer cryostat vessel (OCV)
- Veto system: Xe skin and outer detector
- Gas circulation/purification system
- Internal and external calibration, electron recoils (ER) and nuclear recoils (NR)

The TPC, Skin and ICV

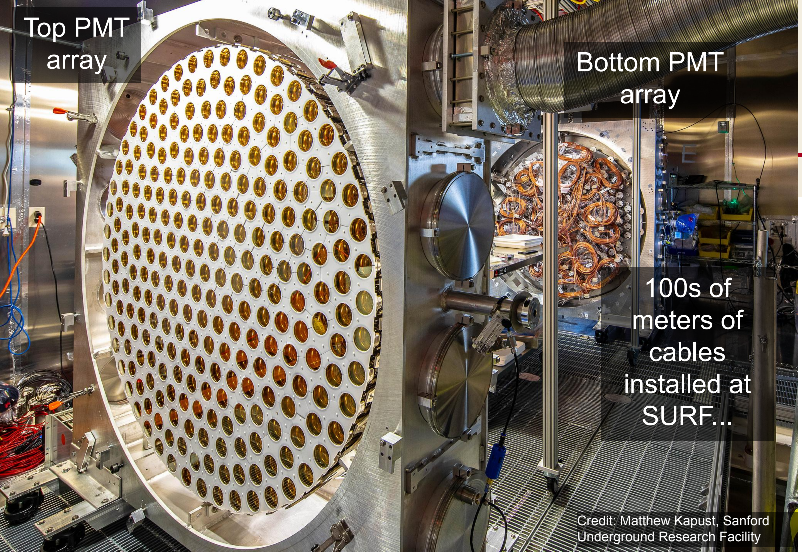
Time Projection Chamber - TPC

- At its heart, LZ contains a dual-phase TPC
  - Particle collision→light (S1) + electrons
    - Reflective structure (PTFE) + PMT arrays collect light
  - Electrons are drifted and extracted in a field cage→electroluminescence (S2)
    - Electrons move in a field generated by electrode grids
  - 3D position reconstruction
    - Top PMT array localizes S2s
- Strengths of Xe TPCs
  - Self-shielding
  - BG discrimination
    - Electron recoils (ER) vs Nuclear recoils (NR)



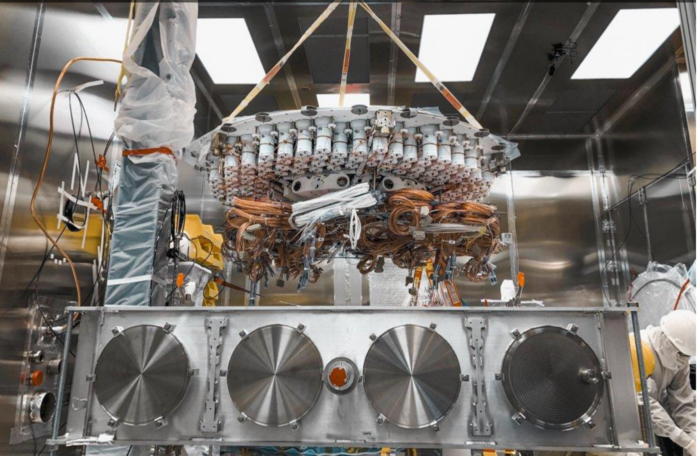
Event in LZ TPC
Credit: Nicolas Angelides

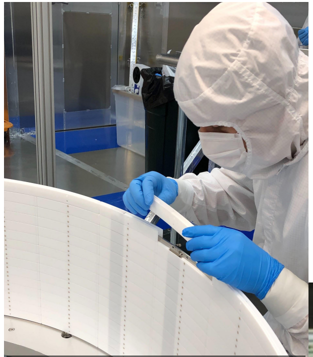
Constructing the TPC



Credit: Matthew Kapust, Sanford Underground Research Facility

Taking out the bottom array (including bottom skin structure) out of its PALACE

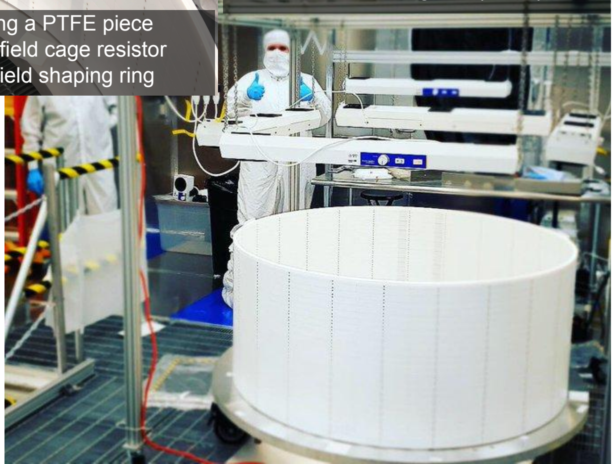




Installing a PTFE piece over a field cage resistor and a field shaping ring

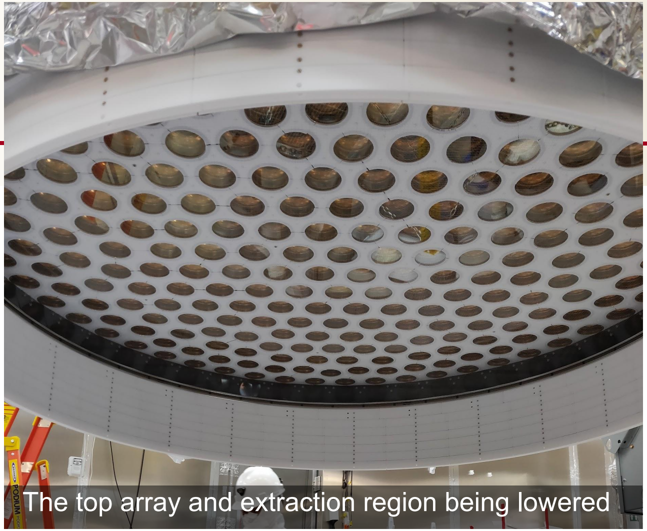
Gate grid entering the SAL cleanroom

Field cage construction: the forward field region (FFR)



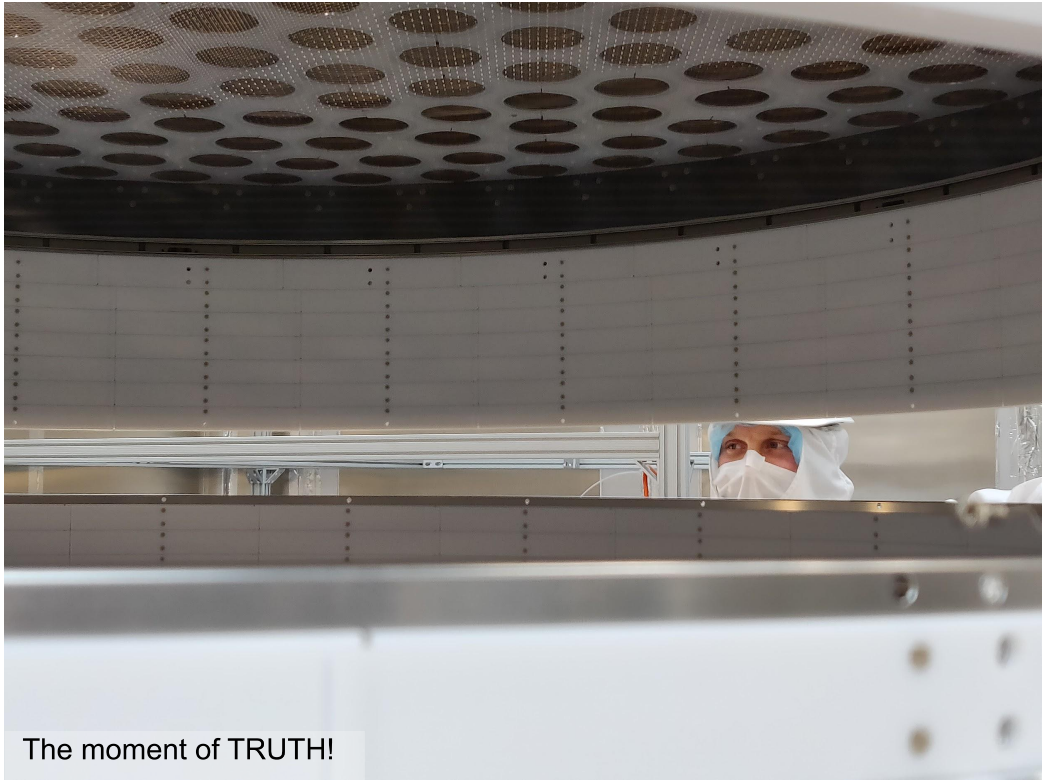
- Subcomponents constructed at multiple institutions
- Assembled at the surface assembly lab

Putting the whole thing together



The top array and extraction region being lowered

Inside the TPC: made sure we took the photo safely and cleanly



The moment of TRUTH!

Complete TPC (+ Looking for dust)

The completed TPC

Credit: Nick Hubbard, Sanford Underground Research Facility

Complete assembly dust examination under UV light

Background Controls

Materials:

- Screened ALL detector materials
- Selected radiopure materials
- Rn emmanation of components and of the integrated detector

Xe Contaminants:

- Removal of ^{85}Kr and ^{39}Ar (along with the Kr) from Xe
- Rn addressed by material selection AND inline radon removal system

Construction/Integration:

- Control dust deposition + remedial cleaning
- Reduce Rn plate-out

Others:

- Shield against cosmogenics and external radiation
- Prevent charge emission due to HV

PTFE components before and after remedial cleaning under UV examination

EPJ C, 80, 1044 (2020)

Astroparticle Physics, 96, 1-10 (2017)

LZ Background Model

Assuming 5.6 tonne fiducial mass, 1000 live-days and veto

Energy range:

- 1.5 - 6.5 keV for ERs
- 6 - 30 keV for NRs

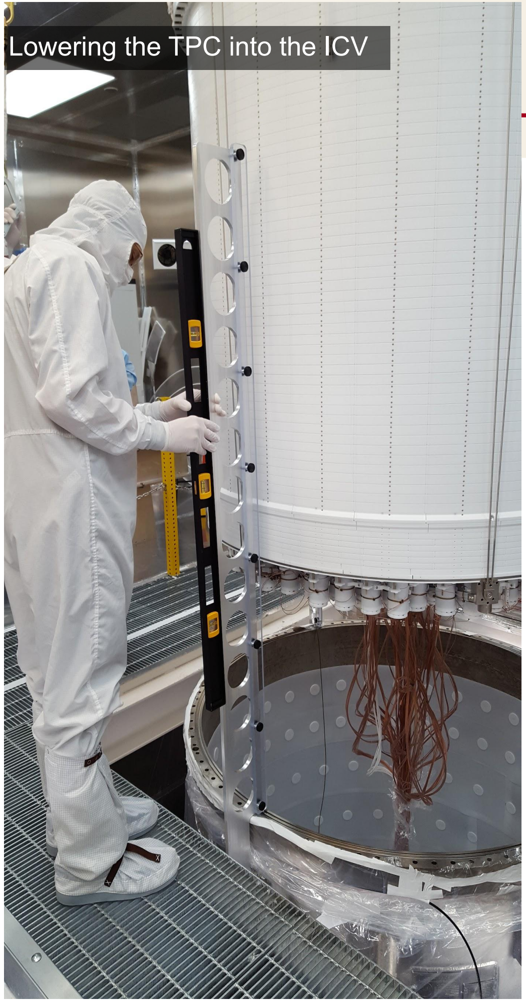
Total background expected is 6.18 events

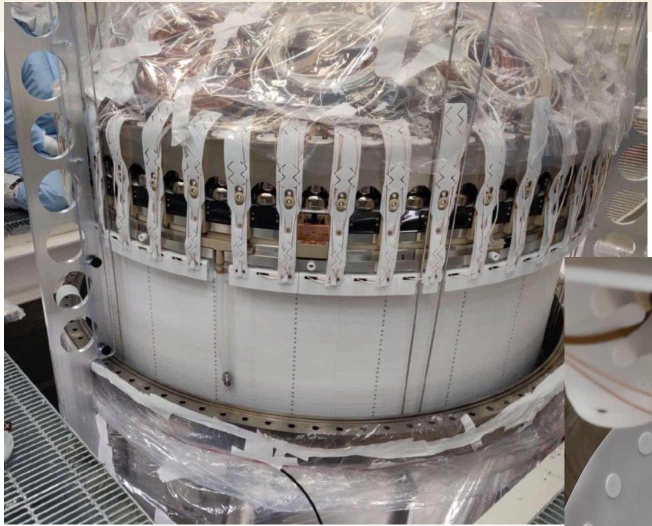
(LZ is NOT a cut and count experiment though…)

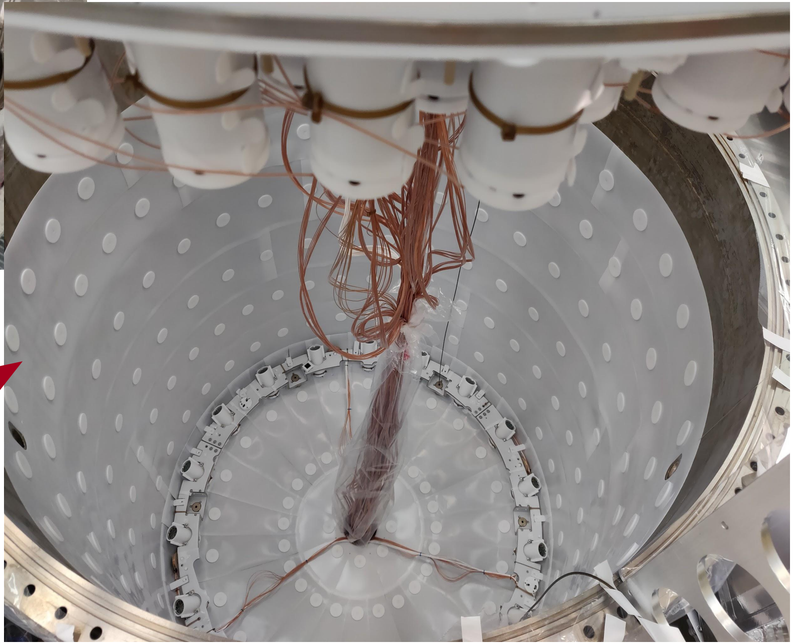
Background Source	ERs	NRs
Detector Components	9	0.07
Surface Contamination	40	0.39
Xenon Contaminants (Rn, Kr, Ar)	819	0
Laboratory and Cosmogenics	5	0.06
Physics (2β decay, neutrinos*) *Not including 8B and hep coherent scatters	258	0.51
Total	1131	1.03
Total (with discrimination and NR efficiency)	5.66	0.52

Final Integration at the Surface

Inserting the TPC into the inner cryostat (ICV)







Inside of the ICV lined with PTFE. Ring of PMTs at the bottom observe the skin

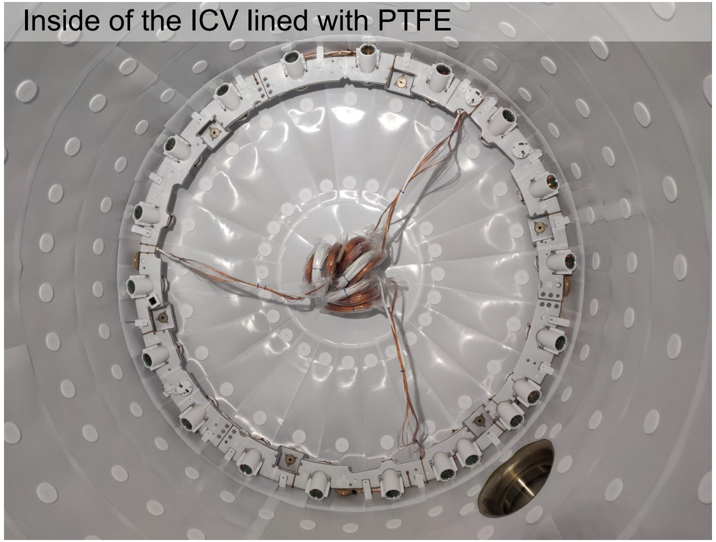
Speaking of the skin...

… Xe Skin

Light Detection outside of the TPC -> VETO!

- 2 tonnes of Xe around and underneath the TPC
- 131 PMTs
- PTFE lined
- Veto TPC with coincident γ-rays with > 95% efficiency expected

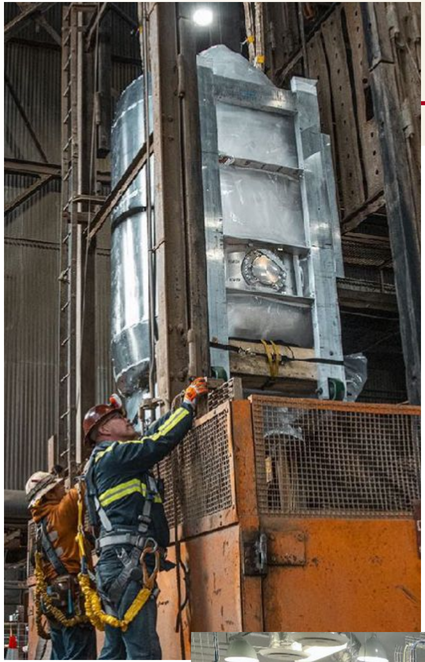
Installing bottom side skin PMTs



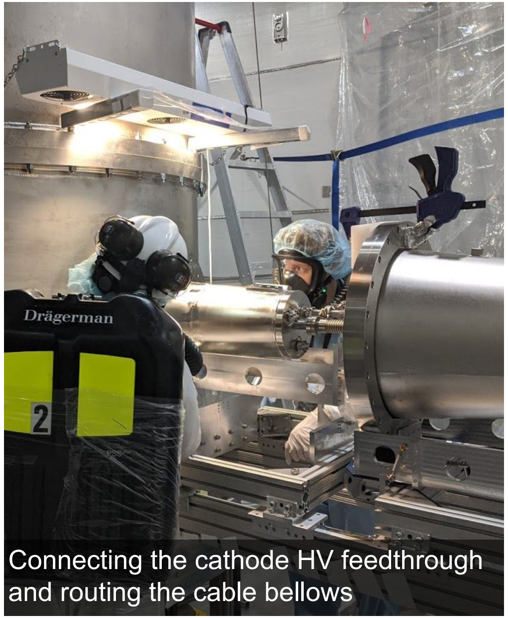
Inside of the ICV lined with PTFE

Top skin PMTs on upper PTFE field cage layers

Heading Underground and Outfitting There



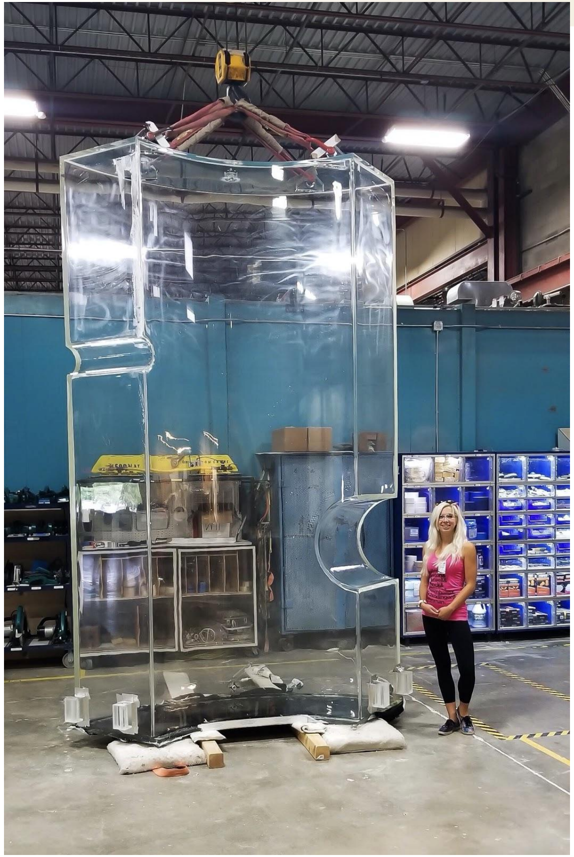
ICV, wrapped in insulation, entering the OCV



Connecting the cathode HV feedthrough and routing the cable bellows

The Outer Detector

Outer Detector



Outer Detector (OD)

- 17 tonnes Gd-loaded liquid scintillator observed by PMTs
  - In 10 acrylic vessels
- Veto TPC with coincident γ-rays and neutrons
  - ~8 MeV γ-rays from thermal neutron capture

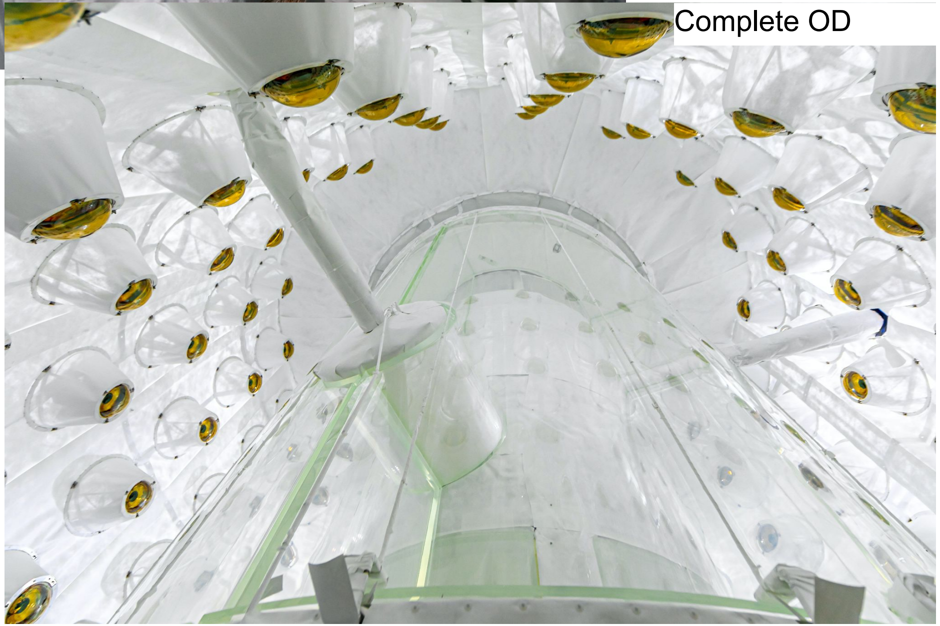
OD acrylic vessels surrounding the ICV inside of the water tank

Test fit of OD PMT models

Outer Detector

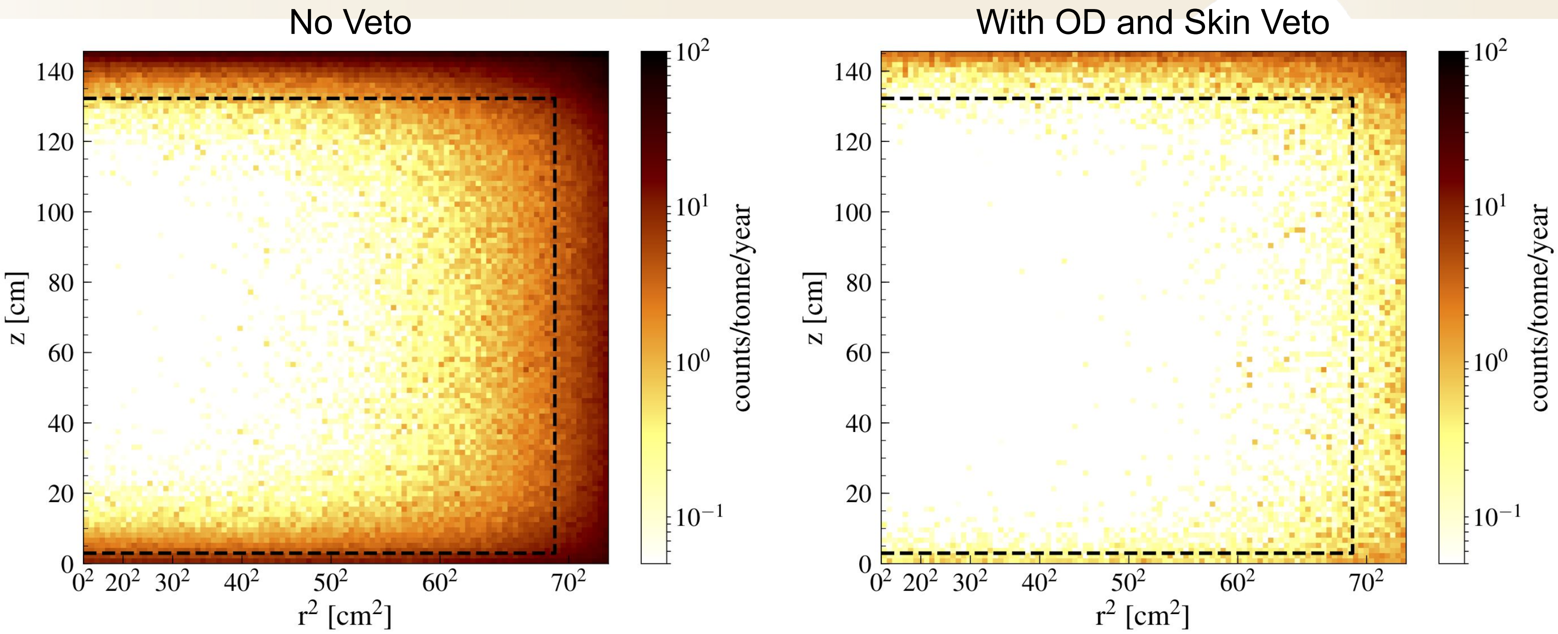
- 120 PMTs
- All of this surrounded by a water shield
- 40 optical fiber injection points for calibration
  - Also using radioactive sources for calibration


Installing PMTs and tyvek reflectors


Complete OD


OD scintillator tanks around the ICV with DD calibration conduit visible

Effects of the Skin & OD Veto



3.2 tonnes →5.6 tonnes fiducial

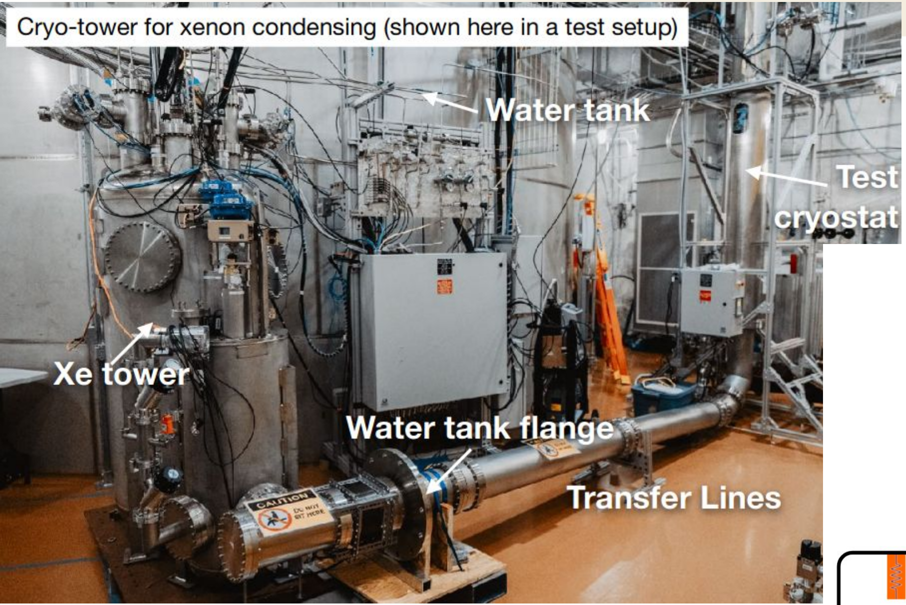
80% of the active volume

Phys. Rev. D 101, 052002 (2020)

Xe Circulation System and Cryogenics

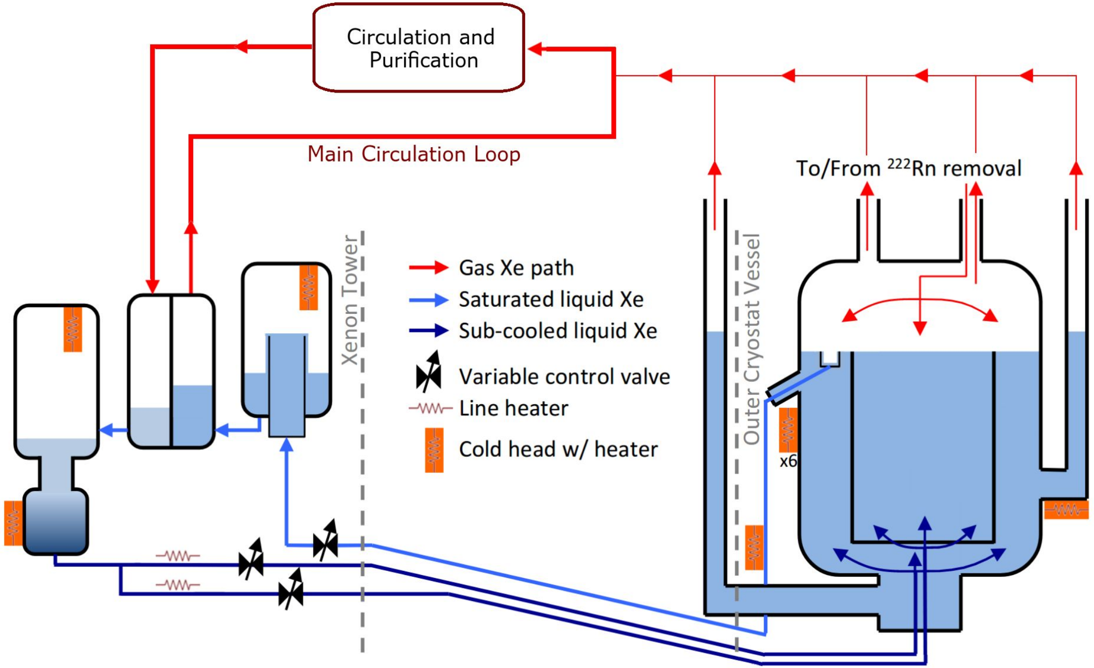
The rarely-mentioned workhorse of the experiment

LZ Xenon Handling



Plastic outgassing poisons Xe →constant purification needed at 500 L/minute (gas)

Small in-line radon removal system to help mitigate our main background

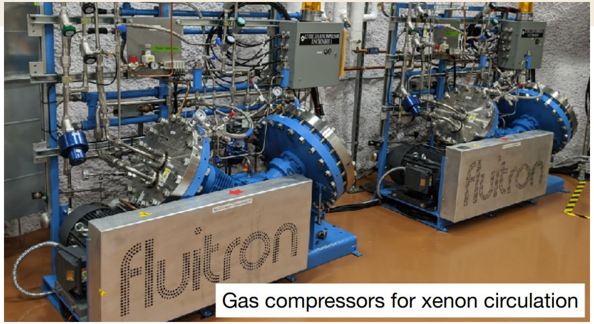


Circulation test (above) commissioned (and debugged) the Xe handling system early

Cryo, Xe Storage and Source Injection


Cryogenic systems for xenon cooling

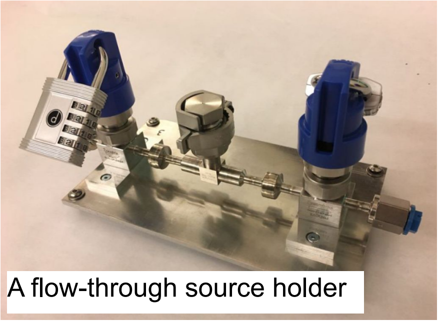
Cryocoolers (now have two) regenerating liquid nitrogen, LN, used to cool the detector. We also use LN delivered from the surface (Thank you SURF!)



Gas compressors for xenon circulation

A pair of large compressors used to circulate Xe. Another pair is used to recover Xe into the storage packs (below) that initially brought cleaned Xe to SURF. Recovery systems utilize backup generators in case of major failures.

We inject radioactive compounds into the Xe stream to calibrate the LZ TPC and skin internally


A flow-through source holder


Xenon storage in underground alcove at SURF

What will LZ do?

LZ Sensitivity: Simulated Data

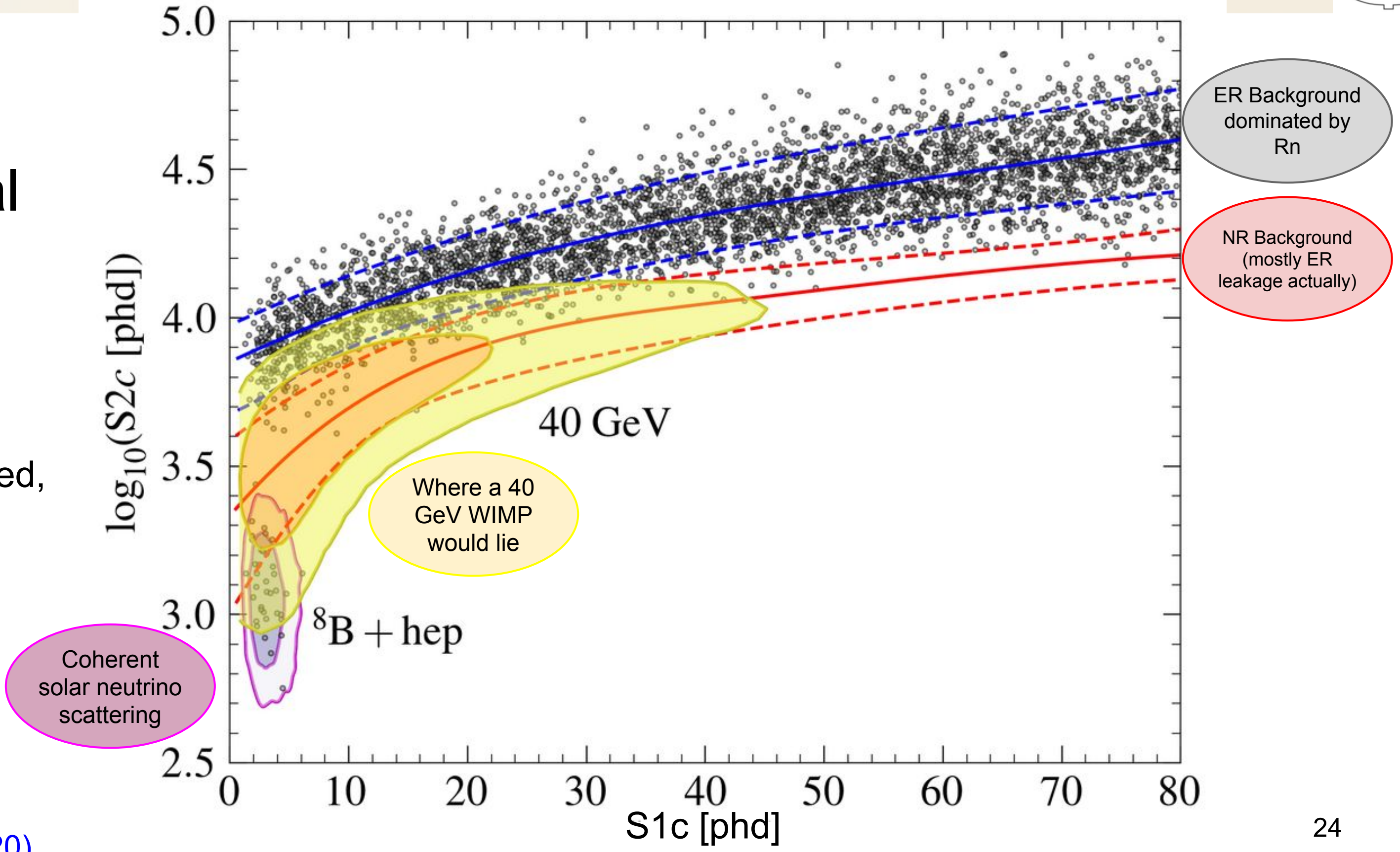
1000 live days

5.6 tonne fiducial mass

As a reminder:

S1c -> initial light, corrected, in photons

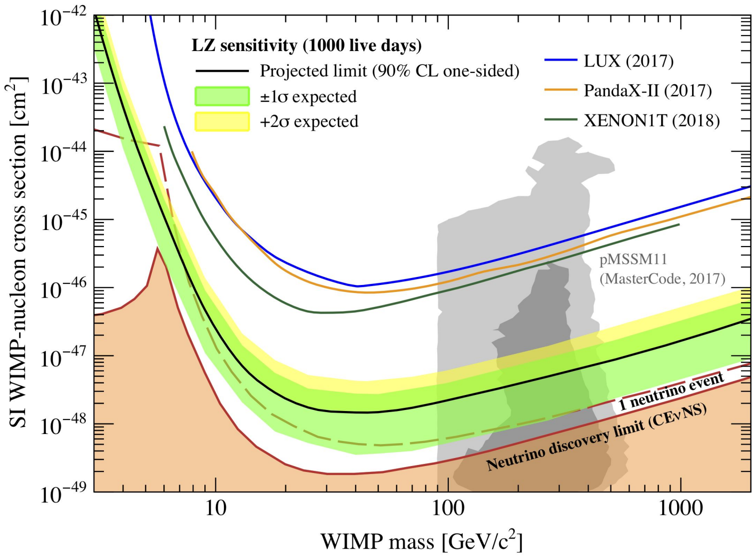
S2c -> ionized charge converted to photons and corrected



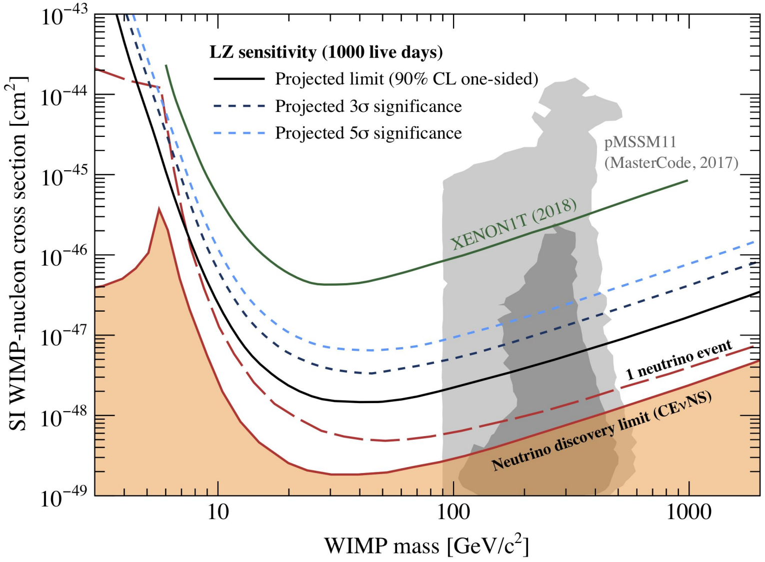
Phys. Rev. D 101, 052002 (2020)

LZ Sensitivity: Limits and Discovery Potential

Expected Limits



Discovery Potential



- 90% CL minimum of 1.4 x 10-48 cm^2 at 40 GeV
- And a REAL chance of a discovery

And more…
0νββ, Axions+ALPs, Low mass dark matter and more!

Acknowledgements

@lzdarkmatter

https://lz.lbl.gov/

LZ (LUX-ZEPLIN) Collaboration

34 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

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Conclusion

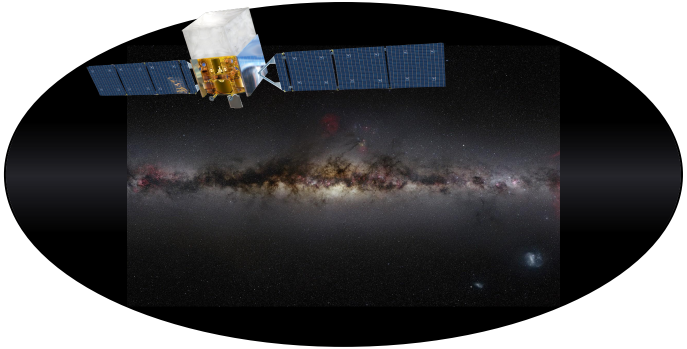
- LZ uses proven technology to investigate WIMP dark matter and more
- Construction is complete (sort off) and commissioning is underway
- Detector cold and operating with Xe gas
- First science data expected this year

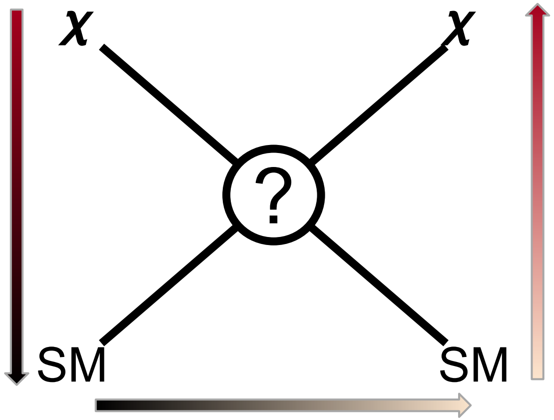
Stay tuned for some great science!

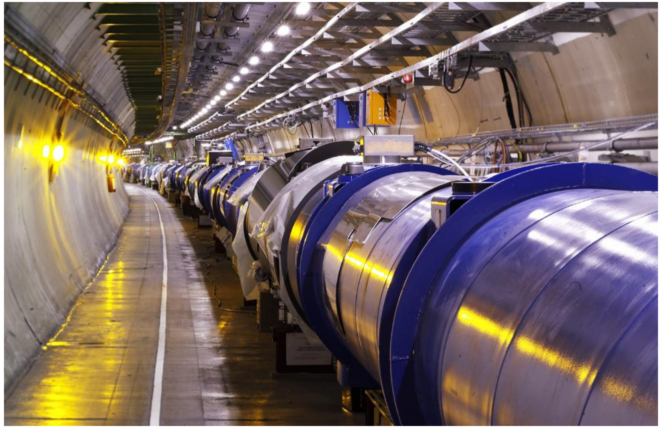
Thank You!

Backup

How Do We Look For Dark Matter?







Indirect Detection:
Can look for gamma rays and/or particles resulting from DM annihilation

Direct Detection:
Can look for DM and standard model particles scattering

Different targets possible, using different technologies…

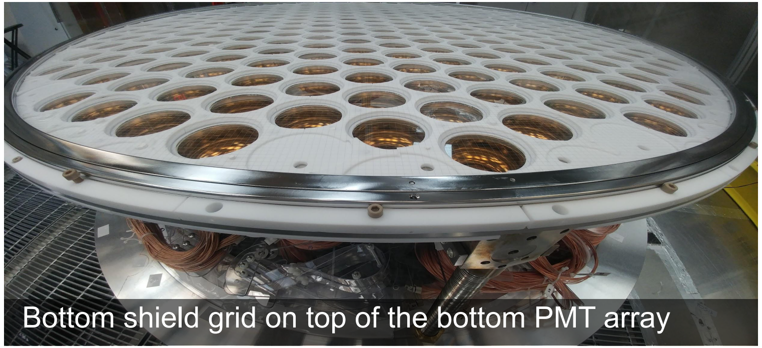
Liquid Xenon well matched to weak scale particles

Missing Energy:
Can look for missing energy that went into producing DM particles

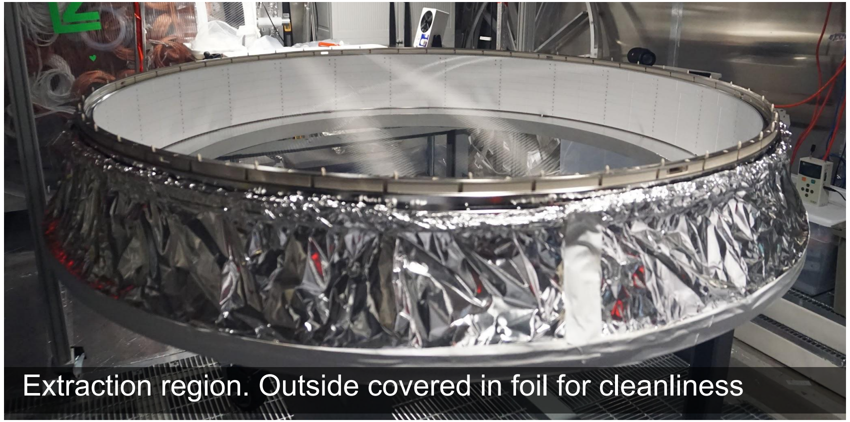
Reverse Field And Extraction Region Construction

- Constructing the RFR on top of the bottom array
- Extraction region constructed on top FFR layers

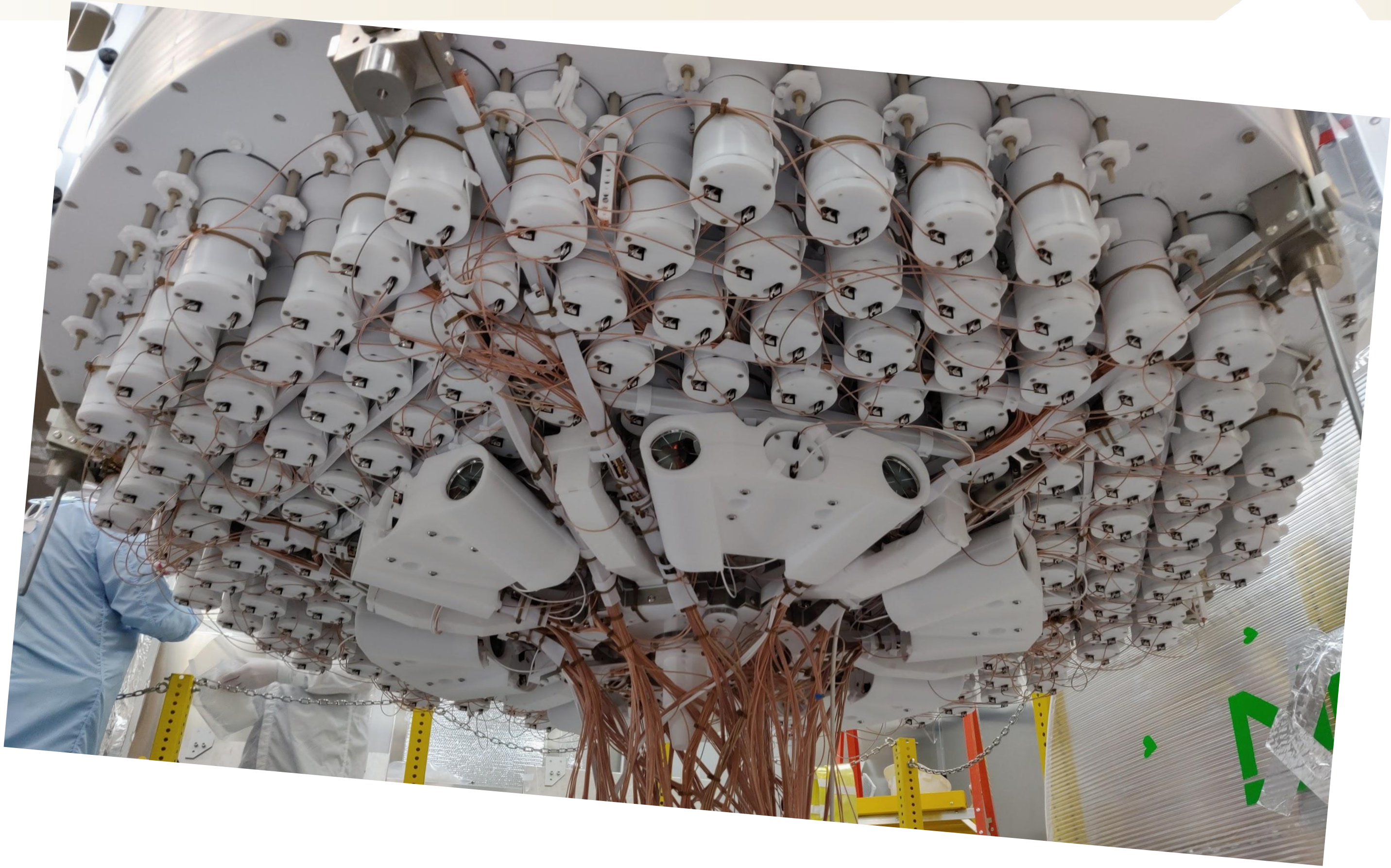

Gate grid, manufactured at SLAC, entering the SAL cleanroom


Bottom shield grid on top of the bottom PMT array

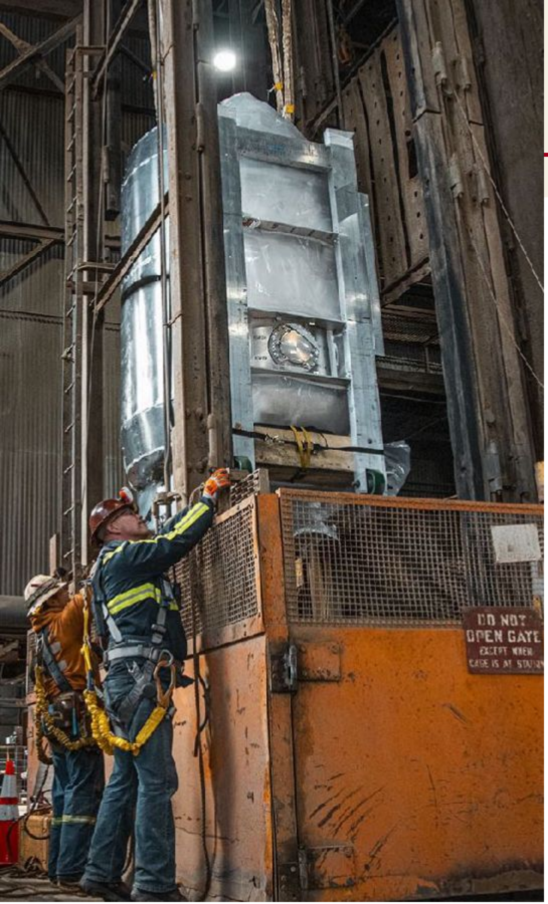

LZ RFR with bottom grid and cathode grids installed


Extraction region. Outside covered in foil for cleanliness

Bottom Array Dome Region



Detector heading Underground

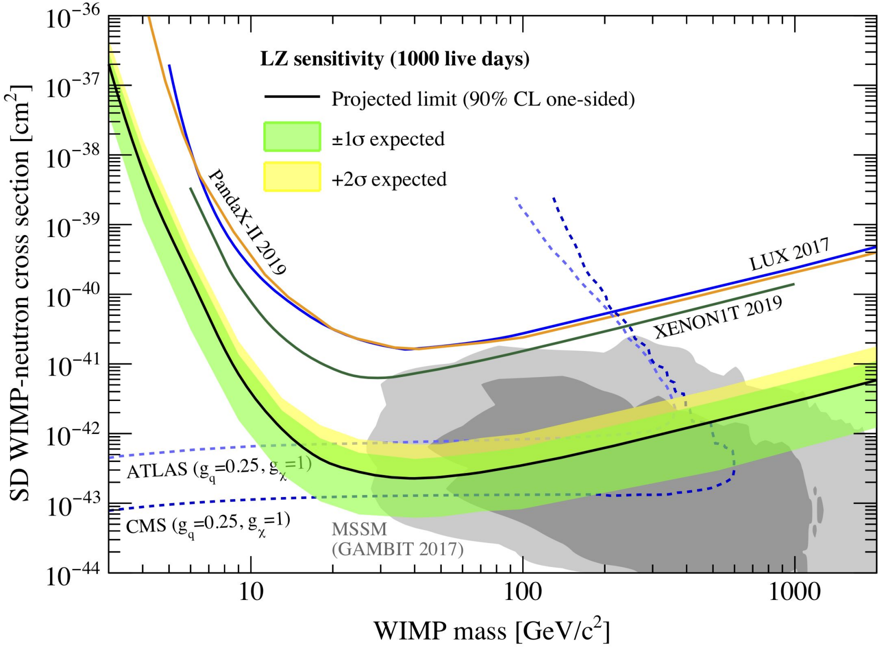


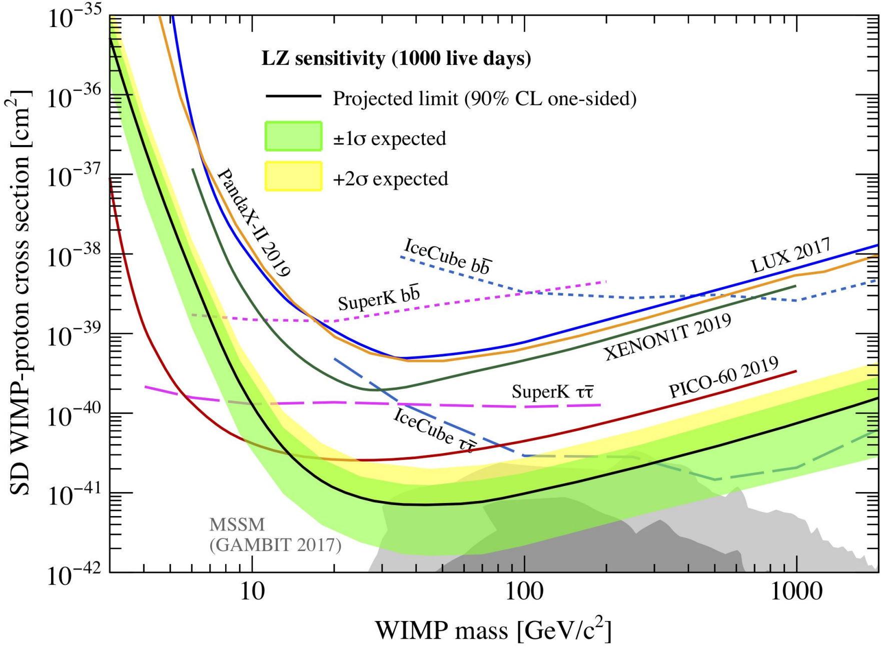
Outfitting Underground

ICV, wrapped in insulation, entering the OCV

Connecting the cathode HV feedthrough and routing the cable bellows

Spin Dependent Projections





Estimated backgrounds from all significant sources in the LZ 1000 day WIMP search exposure. Counts are for a region of interest relevant to a 40 GeV/c^2 WIMP: approximately 1.5–6.5 keV for ERs and 6–30 keV for NRs; and after application of the single scatter, skin, and OD veto, and 5.6-tonne fiducial volume cuts. Mass-weighted average activities are shown for composite materials, and the ^{238}U and ^{232}Th chains are split into contributions from early and late chain, with the latter defined as those coming from isotopes below and including ^{226}Ra and ^{224}Ra, respectively.

		$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K			
Background source	Mass (kg)	mBq/kg						n/yr	ER (cts)	NR (cts)
Detector components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								Subtotal	9	0.07
Surface contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									⋯	0.05
^{210}Bi mobility (0.1 μBq/kg LXe)									40.0	⋯
Ion misreconstruction (50 nBq/cm^2)									⋯	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									⋯	0.12
								Subtotal	40	0.39
Xenon contaminants										
^{222}Rn (1.8 μBq/kg)									681	⋯
^{220}Rn (0.09 μBq/kg)									111	⋯
^{nat}Kr (0.015 ppt g/g)									24.5	⋯
^{nat}Ar (0.45 ppb g/g)									2.5	⋯
								Subtotal	819	0
Laboratory and cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									⋯	0.06
Cosmogenic activation									0.2	⋯
								Subtotal	5	0.06
Physics										
^{136}Xe $2\nu\beta\beta$									67	⋯
Solar neutrinos: $pp + {}^7$Be $+ {}^{13}$N, ^{8}B $+ hep$									191	0*
Diffuse supernova neutrinos (DSN)									⋯	0.05
Atmospheric neutrinos (Atm)									⋯	0.46
								Subtotal	258	0.51
Total									1131	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.66	0.52
Sum of ER and NR in LZ for 1000 days, 5.6-tonne FV, with all analysis cuts									6.18	

*NR events from solar neutrinos will be concentrated at very low energies; we expect none above the 6 keV NR threshold used here.

Calibration sources

A: internal injection

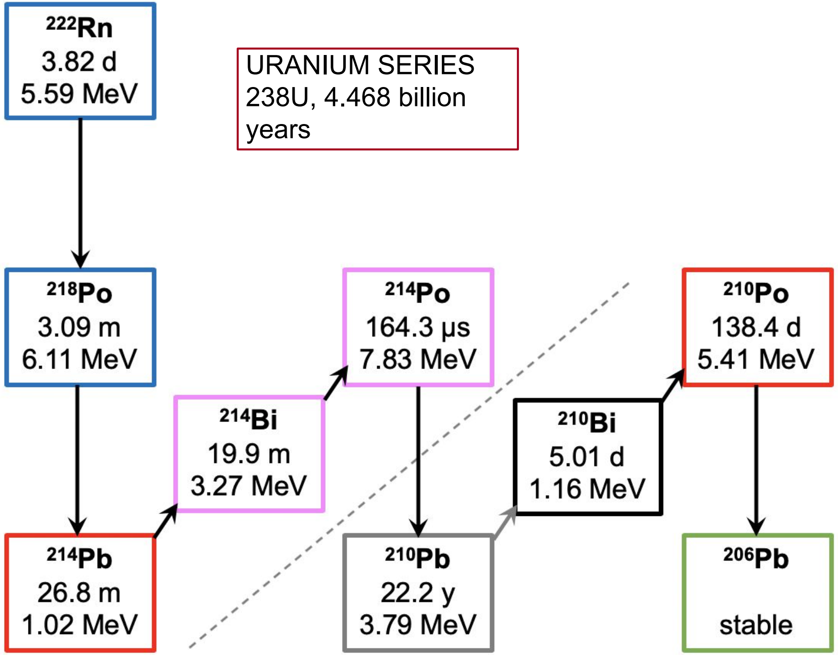
B: side tube deployment, 3 tubes at any height

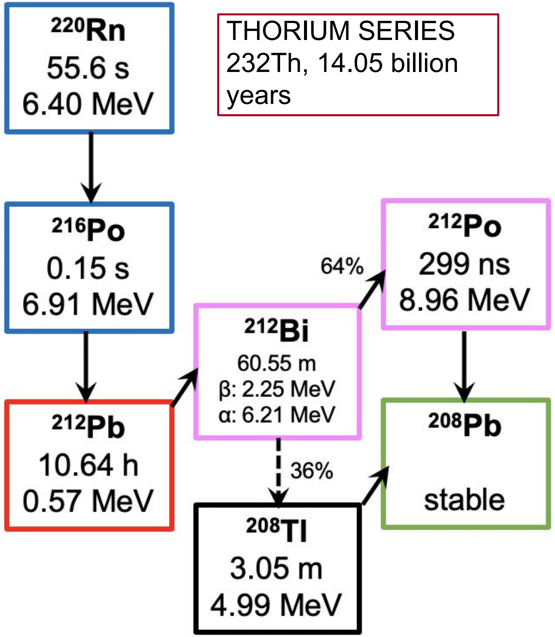
C: photo-neutron sources, on top of the OCV

D: DD neutrons

	Nuclide	Type	Energy [keV]	$\tau_{1/2}$
A	^{83m}Kr	γ	32.1 , 9.4	1.83 h
	^{131m}Xe	γ	164	11.8 d
	^{220}Rn	α, β, γ	various	10.6 h
	^{3}H	β	18.6 endpoint	12.5 y
	^{14}C	β	156 endpoint	5730 y
B	^{241}AmLi	(α,n)	1500 endpoint $^{(a)}$	432 y
	^{252}Cf	n	Watt spectrum	2.65 y
	^{241}AmBe	(α,n)	11,000 endpoint	432 y
	^{57}Co	γ	122	0.74 y
	^{228}Th	γ	2615	1.91 y
	^{22}Na	γ	511,1275	2.61 y
	^{60}Co	γ	1173 , 1333	5.27 y
	^{133}Ba	γ	356	10.5 y
	^{54}Mn	γ	835	312 d
C	^{88}YBe	(γ,n)	152	107 d
	^{124}SbBe	(γ,n)	22.5	60.2 d
	^{205}BiBe	(γ,n)	88.5	15.3 d
	^{206}BiBe	(γ,n)	47	6.24 d
D	DD	n	2450	–
	D Ref.	n	272 $\rightarrow$ 400	–

Radon Chains

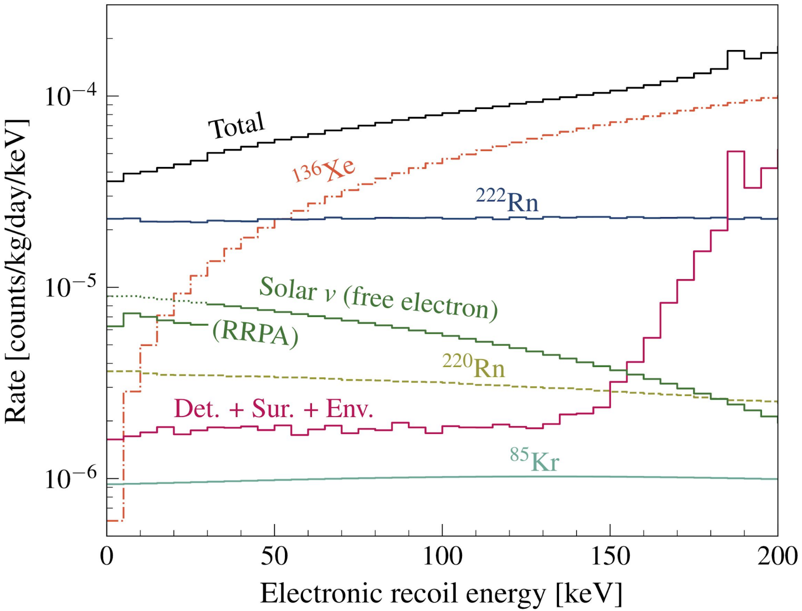


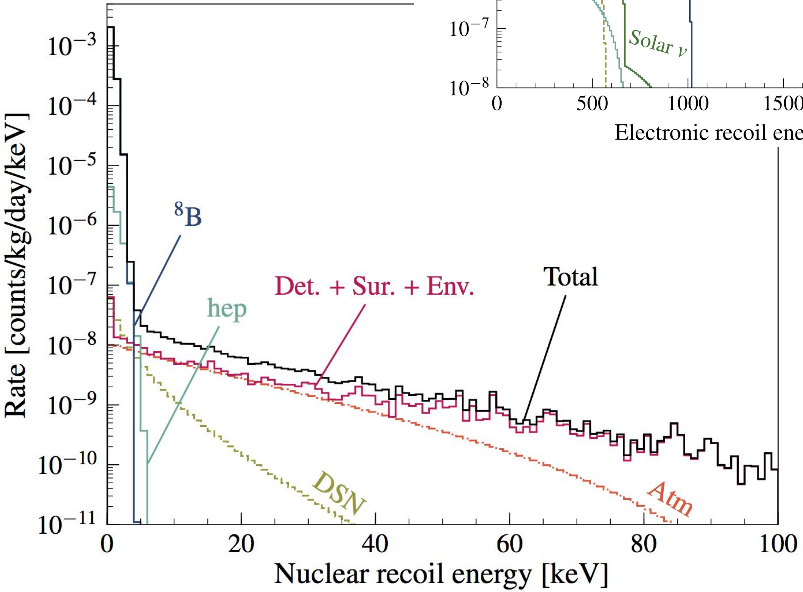


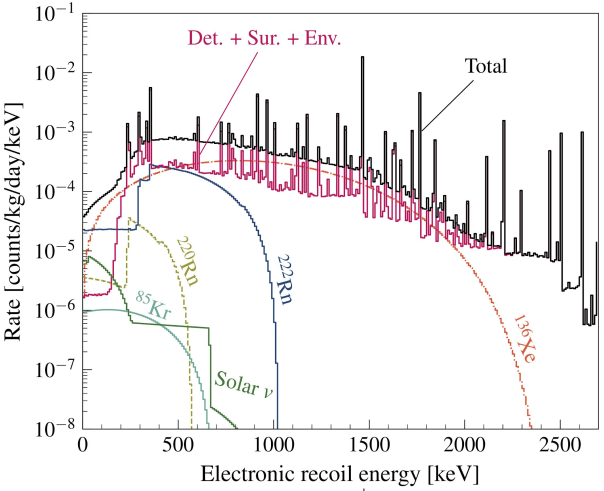
- **Pb-214** naked beta is biggest background concern in LZ
- **Pb-210** implants
- **Po-210** forms wall background

- Whole chain decays away in ~days

What the LZ Background Looks like



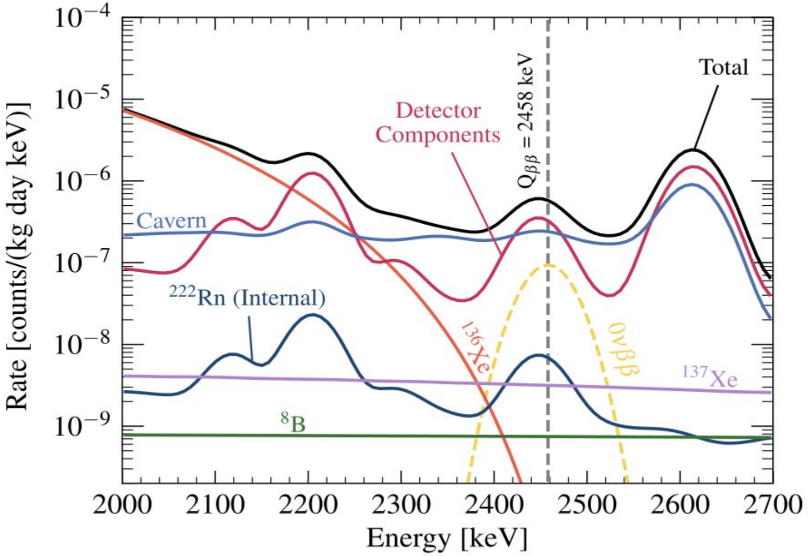


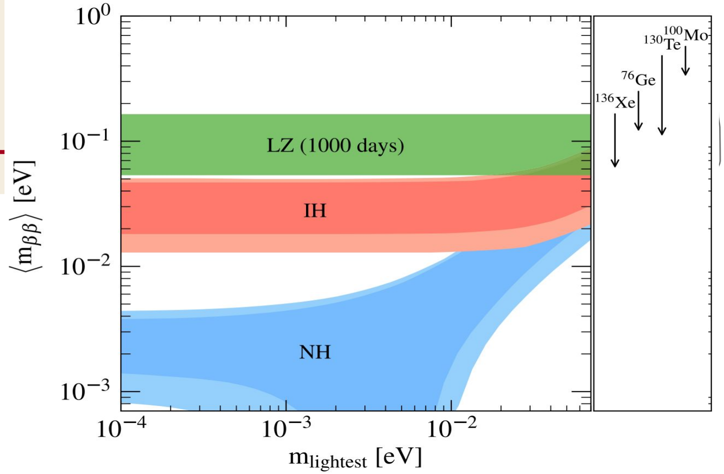


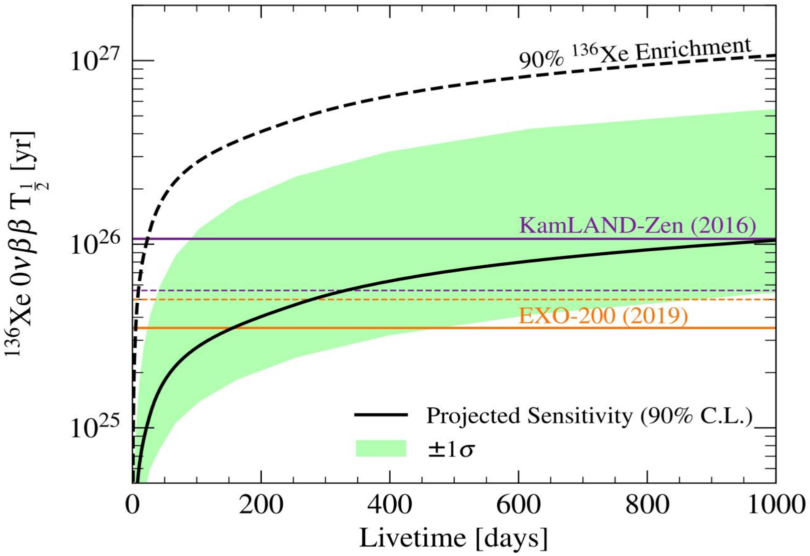
[Phys. Rev. D 101, 052002 (2020)](https://doi.org/10.1103/PhysRevD.101.052002)

Phys. Rev. C 102, 014602 (2020)

0νββ







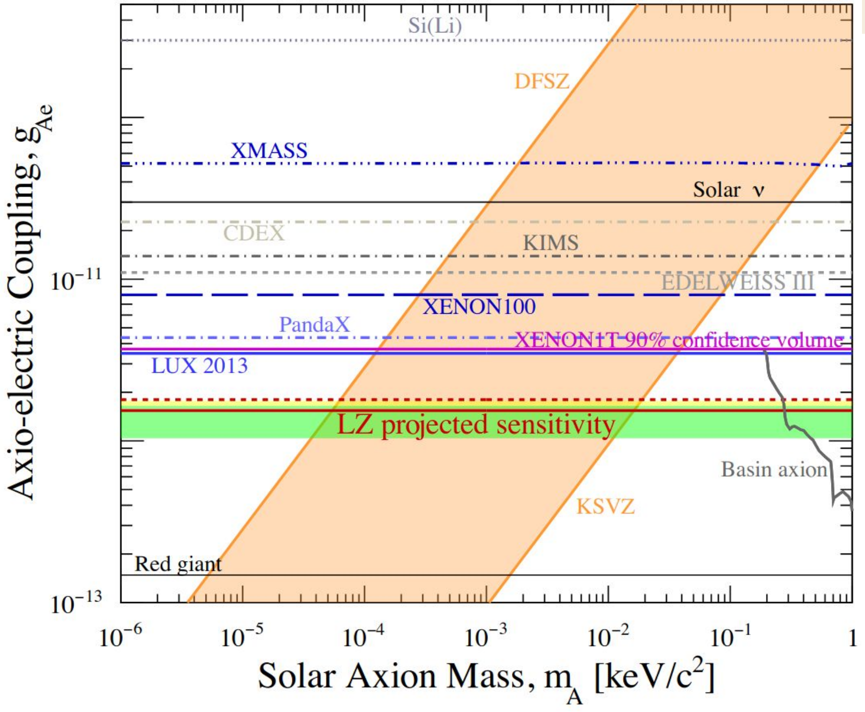
136Xe Q value is 2458keV

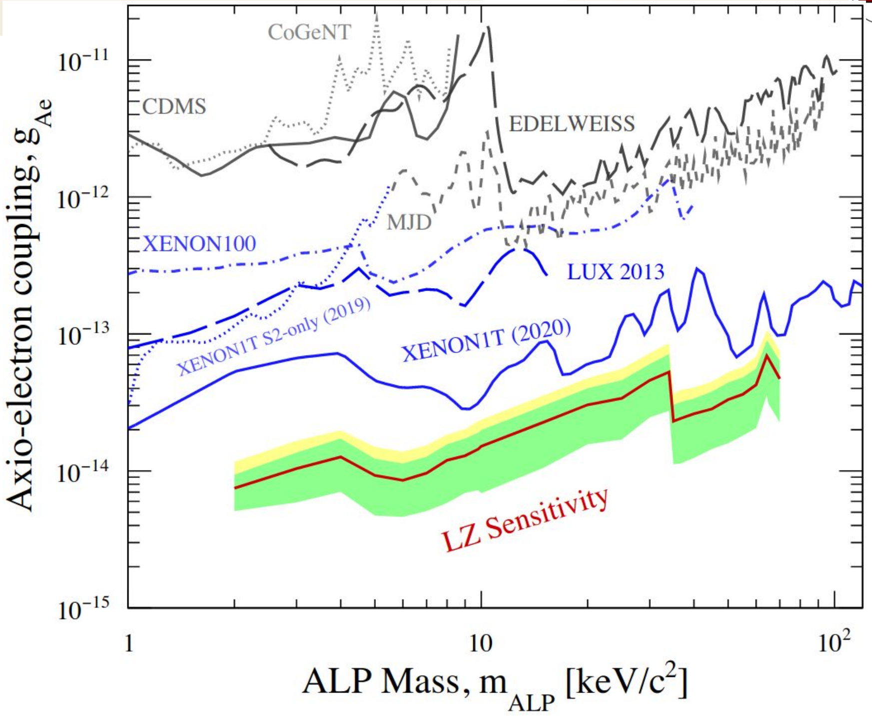
1% energy resolution at Q

T ½ 90% C.L. > 1e26 years

1000 live days and inner 1 tonne fiducial

Axions + ALPs

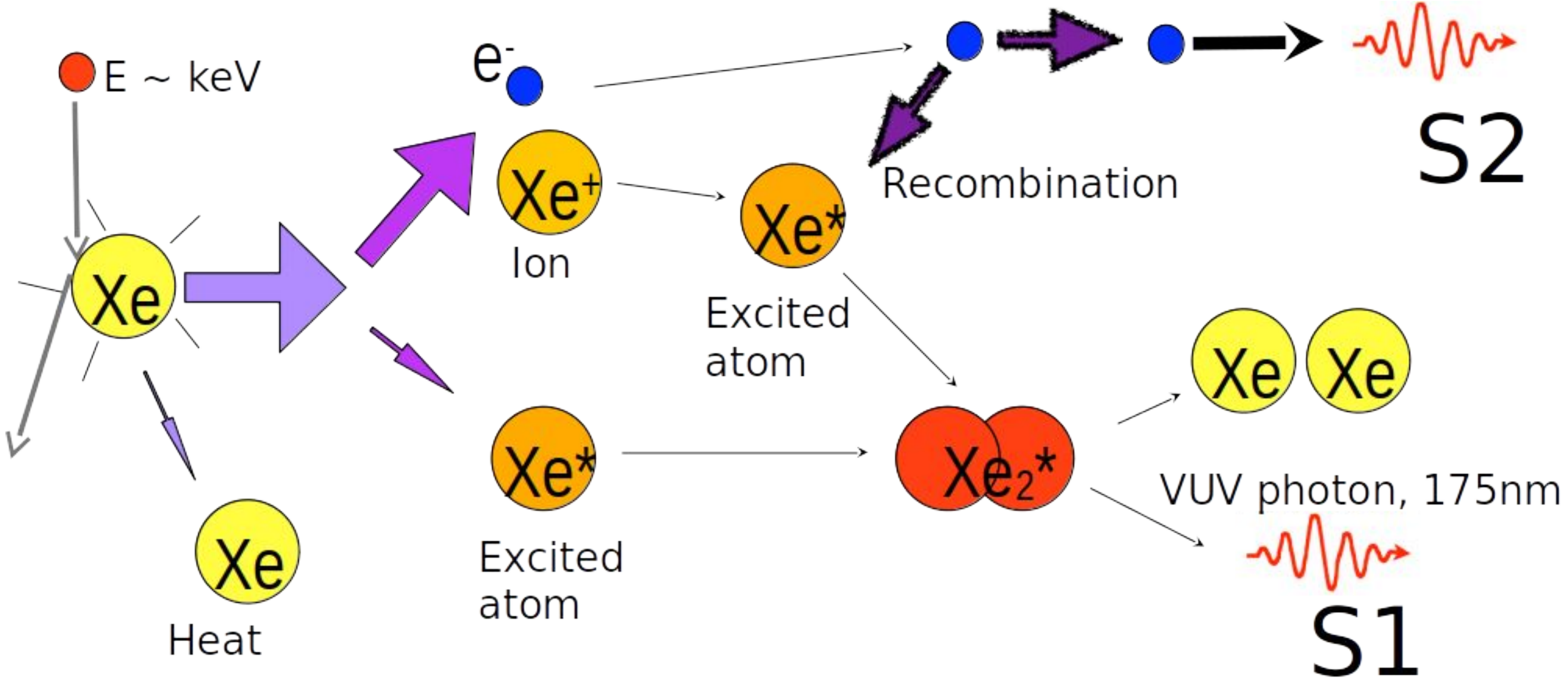




Sensitive to electron recoils from many types of new physics including

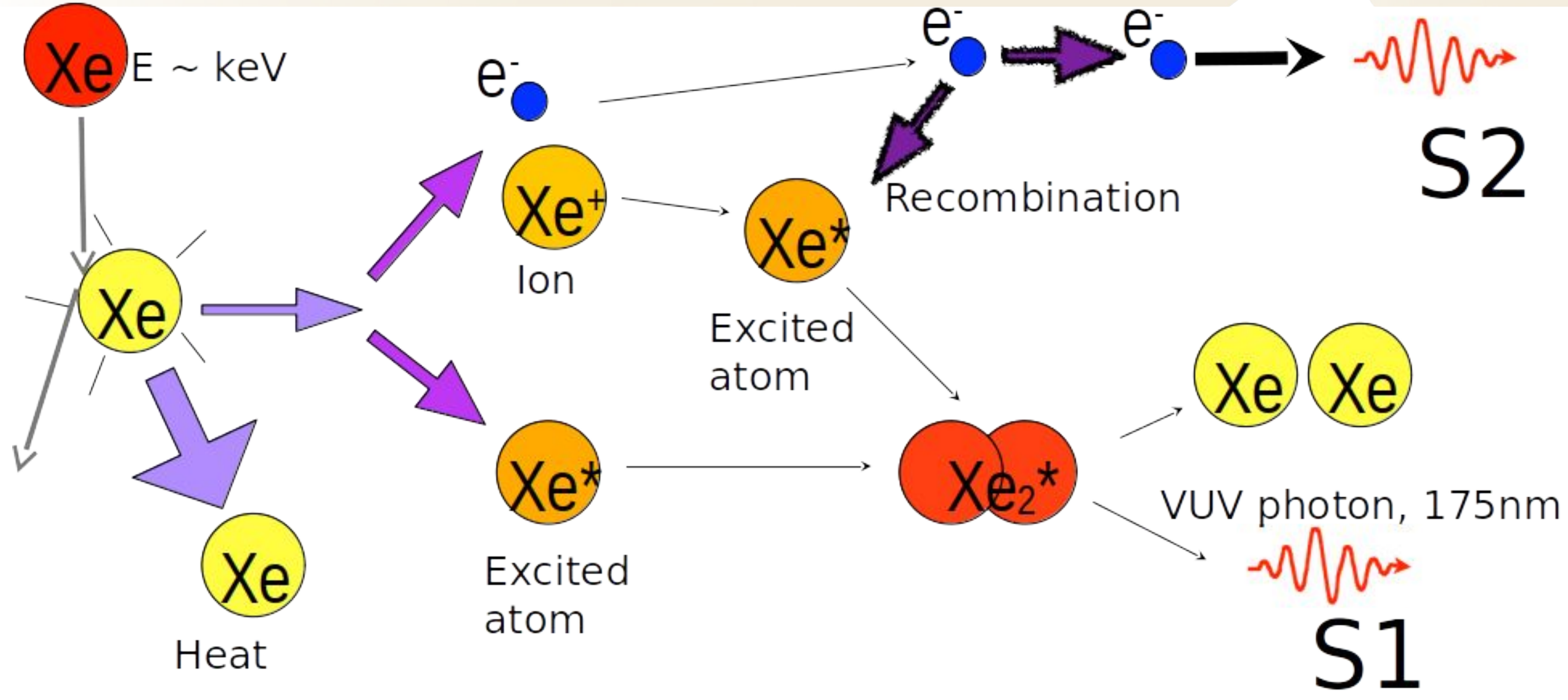
Neutrino magnetic moment, Solar axions (axio-electric effect), Axion like particles

Paper in prep



Electron Recoils

Figure: Gibson/Shutt



Nuclear Recoils

Figure: Gibson/Shutt