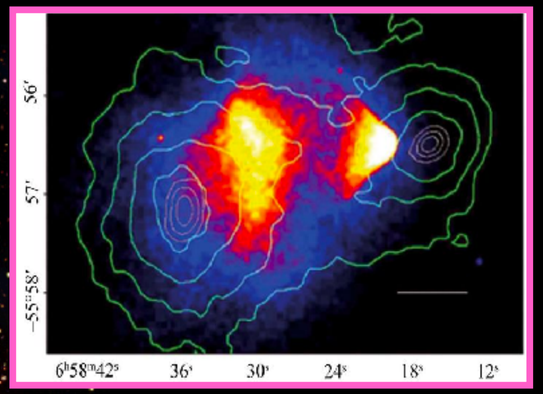
WIMP Hunting in the Black Hills: the LZ Dark Matter Experiment

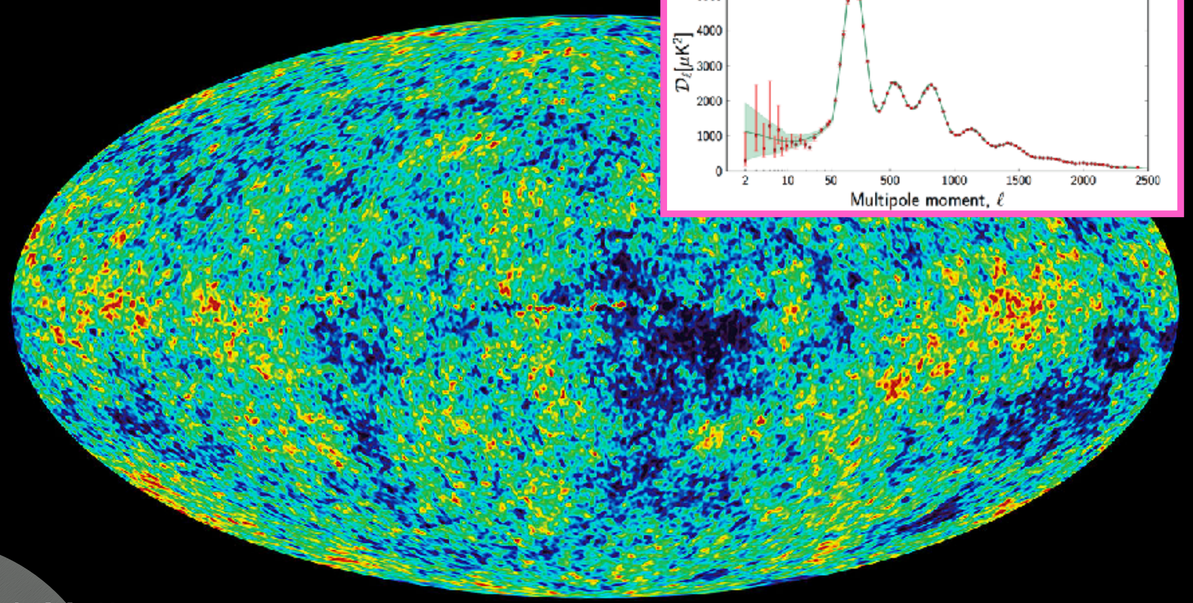
Dr. Sally Shaw - sally@physics.ucsb.edu

Rising Stars in Experimental Particle Physics 2021

Dark Matter

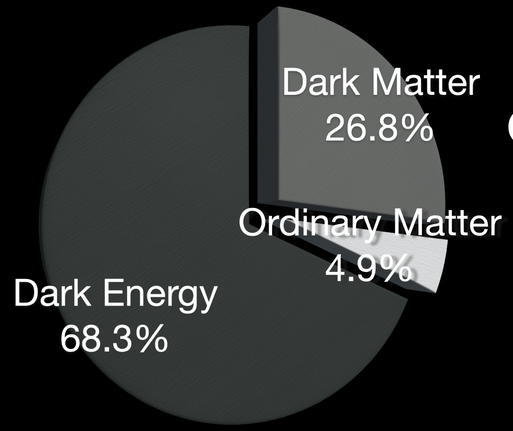
Dark Matter





Bullet Cluster

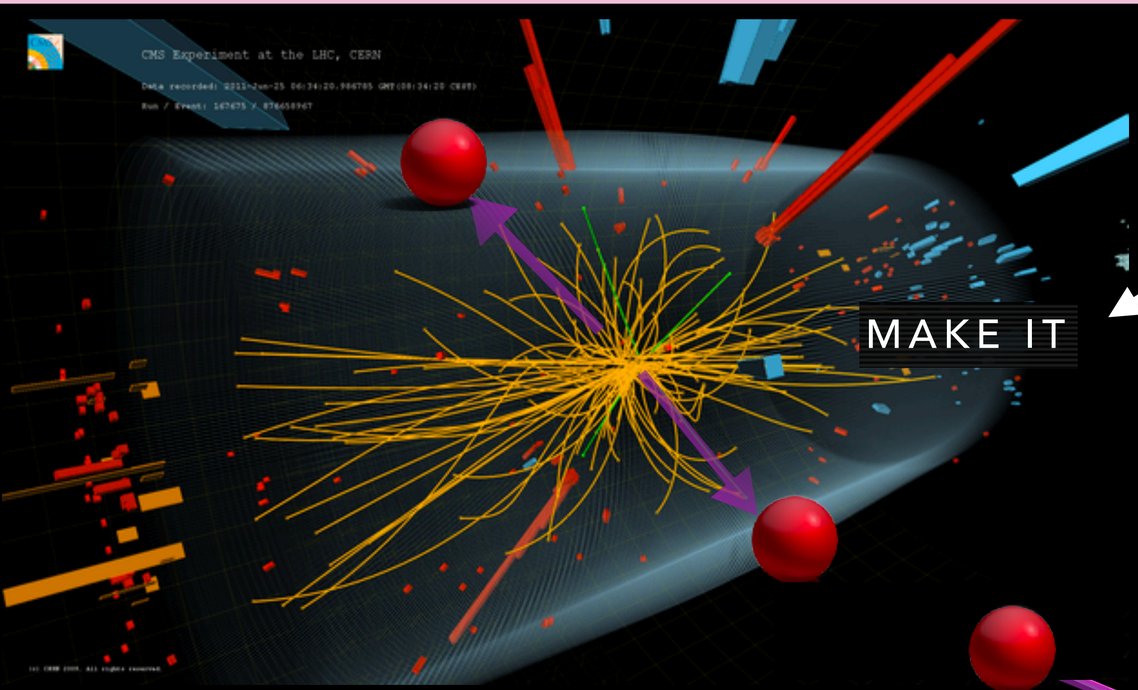
- Gravitational lensing measurements suggest two cores of non-interacting heavy material → two galaxy clusters collided
- Mass from lensing is distributed differently to the mass from electromagnetic radiation → this mass is “dark”



Cosmic Microwave Background

- Relic radiation from after recombination ~379,000 years ago, now measured as a thermal radiation of 2.7 K
- Distribution of anisotropies gives us information on the dark matter energy density of the universe

Dark Matter Detection

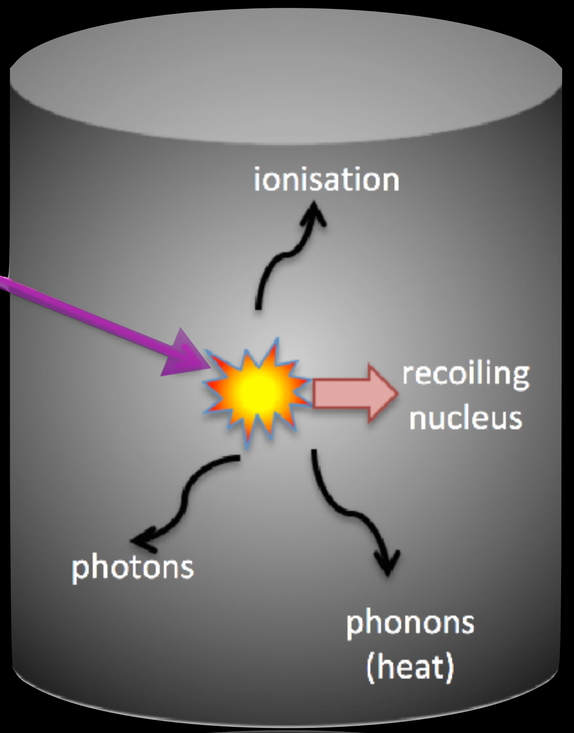


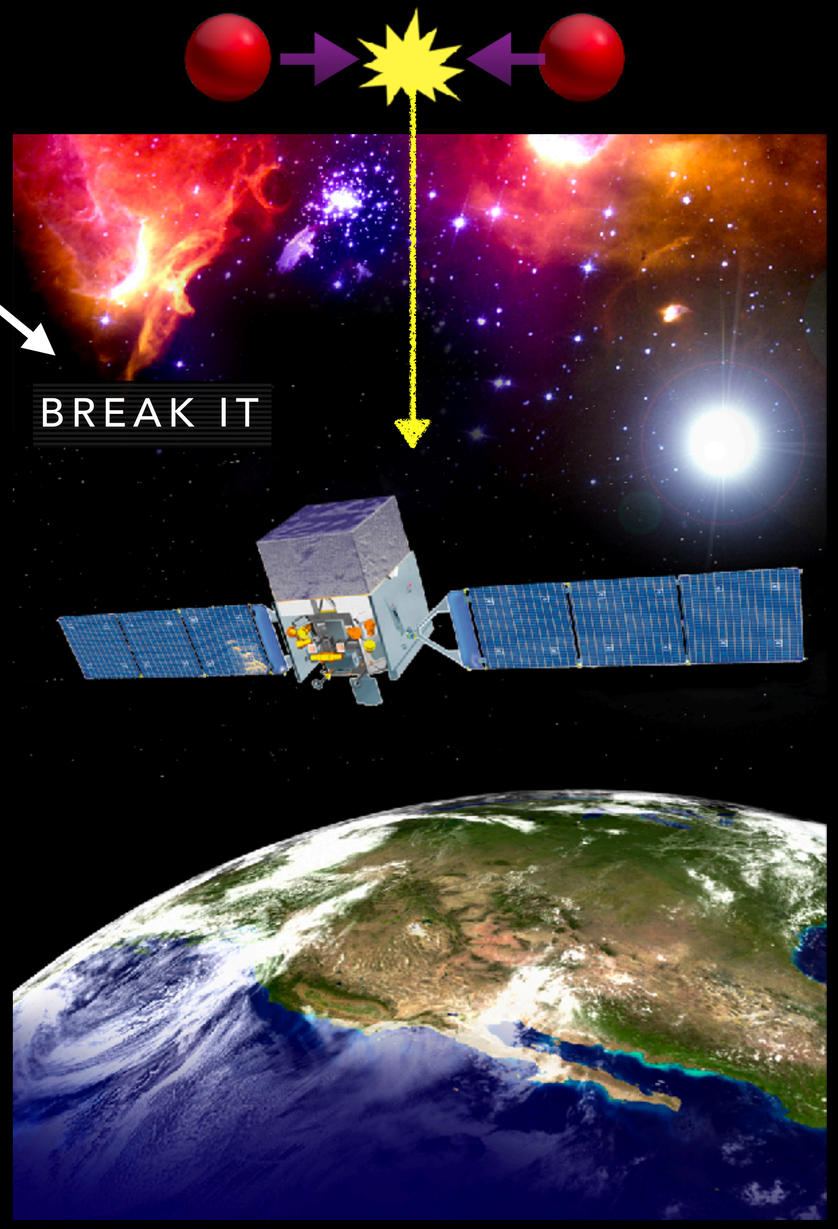
3 ways to detect Weakly Interacting Massive Particles (WIMPs)

MAKE IT

SHAKE IT

BREAK IT



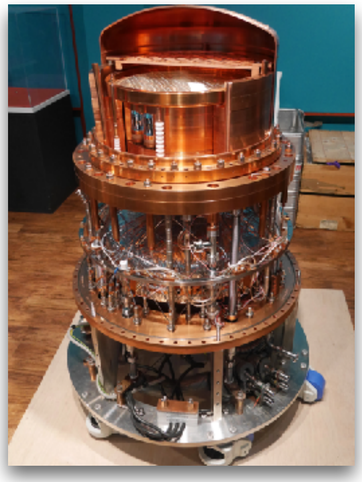


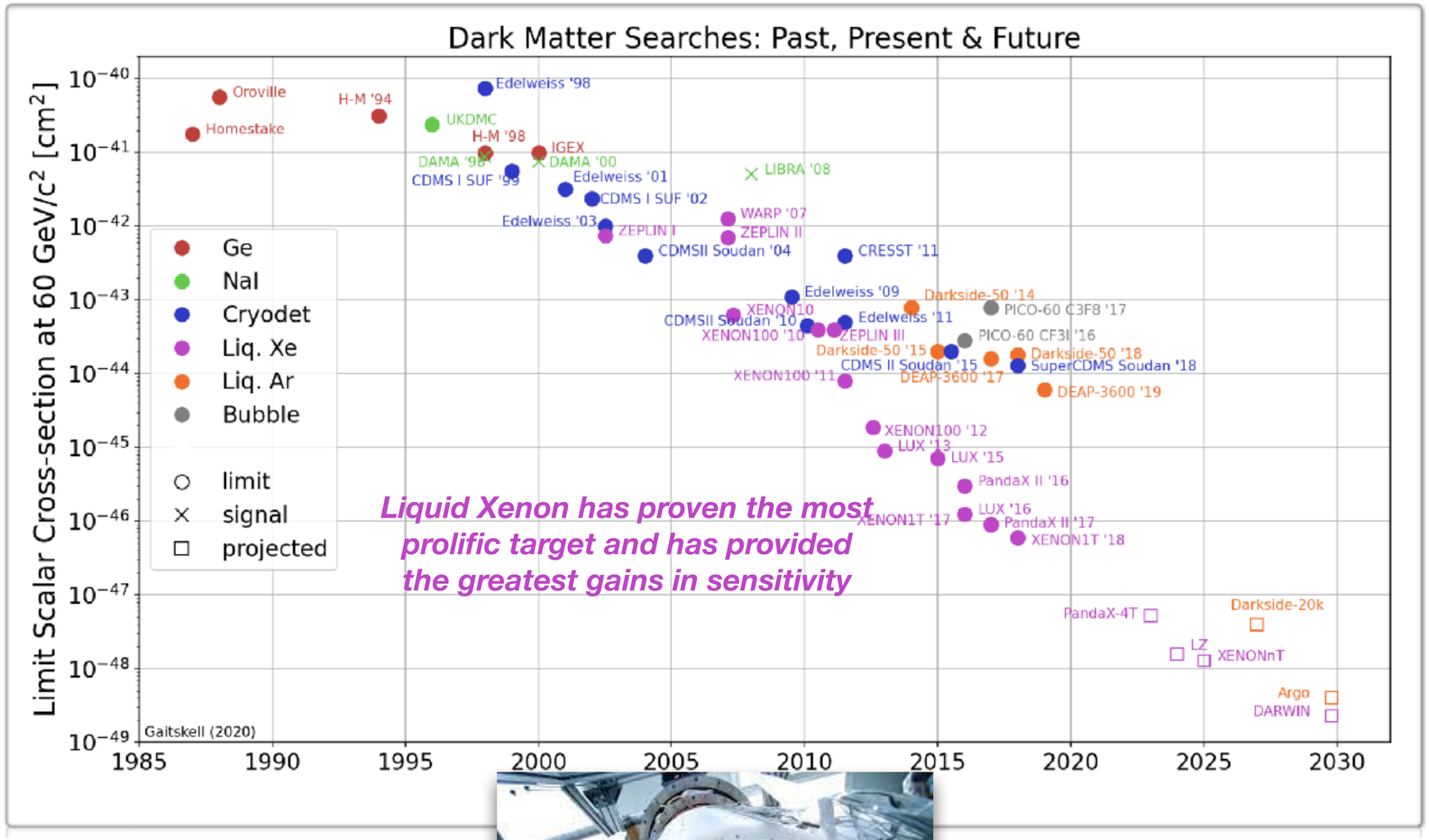
WIMP Hypothesis:

- Dark matter is a **heavy, neutral particle** that does not (observably) interact electromagnetically
- Its relic density can be achieved through particles **annihilating with cross sections on the weak scale** → weakly interacting massive particles

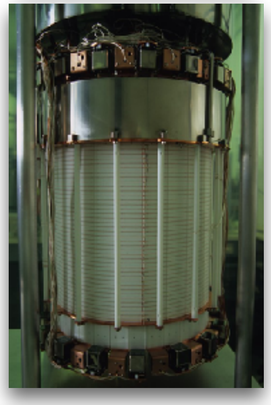
Direct Detection

There has been a global effect since the 80s to build bigger, more sensitive targets for direct dark matter detection





Liquid Xenon has proven the most prolific target and has provided the greatest gains in sensitivity



ZEPLIN I,II,III

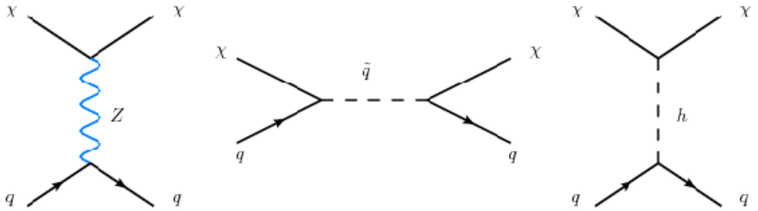
LUX

XENON10, 100, 1T

Direct Detection

Expected signal: a Xe **nuclear recoil**

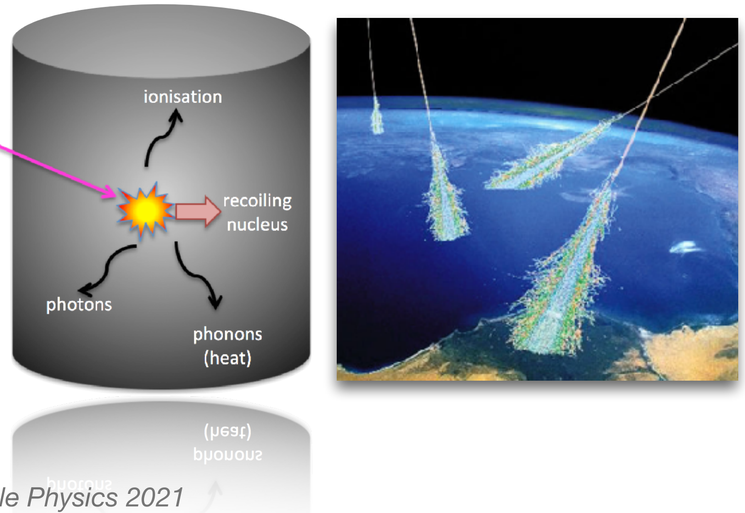
WIMP-nucleon scattering:
- Spin Independent: scalar, coherent across nucleus, $\sigma \propto A^2$
- Spin Dependent: axial vector, needs unpaired nucleon



detector exposure | particle/nuclear physics | astrophysics

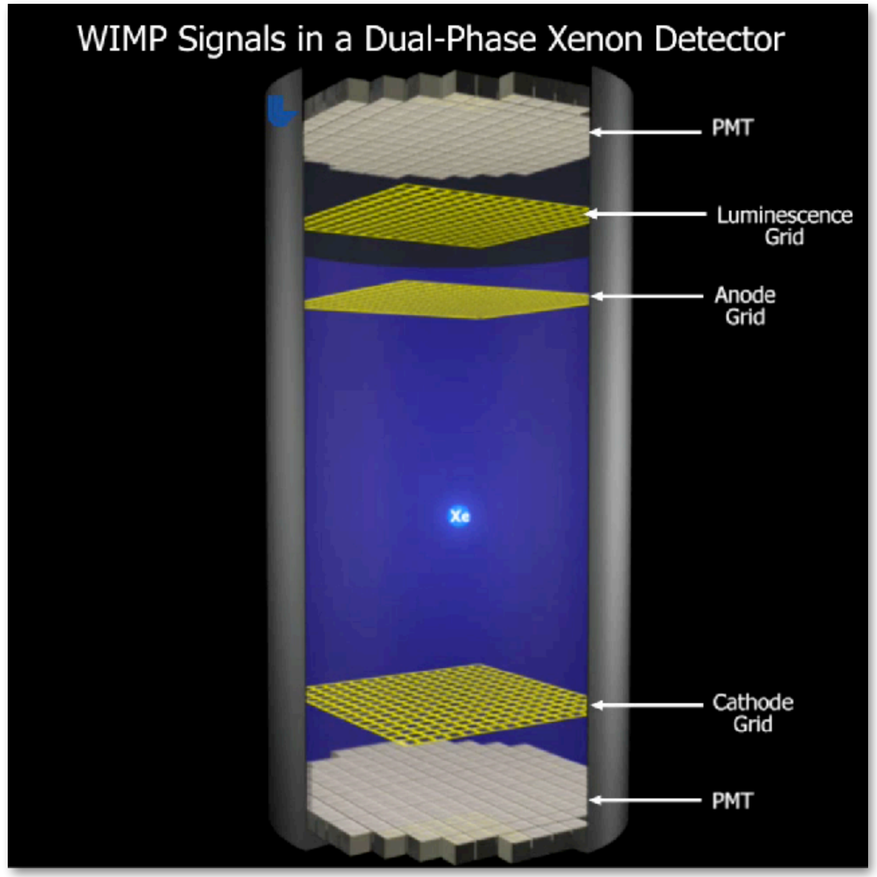
$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{2m_\chi \mu_{\chi N}} \sigma_0 F^2(E_R) \int_{v_{min}} \frac{f(\bar{v})}{v} d^3v$$

*Need a medium that produces something **detectable** after a nuclear recoil, and if possible a way to discriminate between signal (DM) and background (γ,e-,n)*



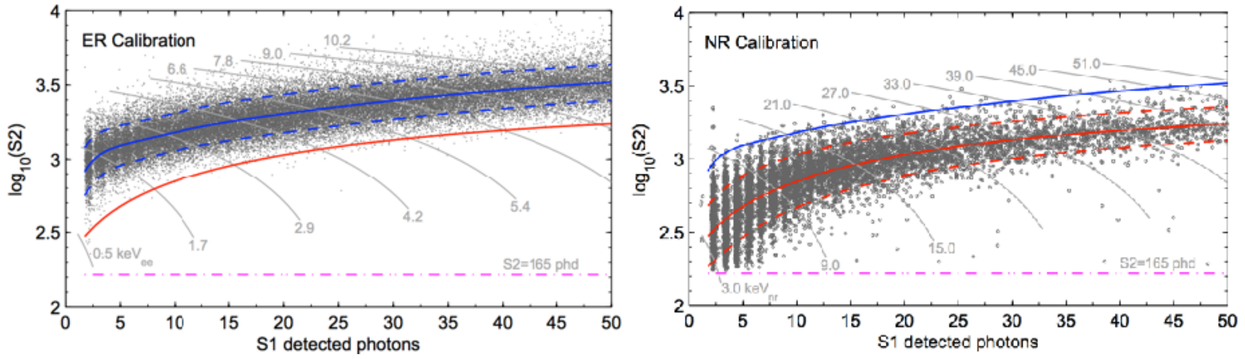
*Need a **low background** environment, well shielded from cosmic rays and with minimal radioactivity*

Why Xenon?
- **High atomic mass**: spin-independent cross section enhanced by A^2 dependence for scattering
- Has **unpaired nucleons** (^{129}Xe, ^{131}Xe) for sensitivity to spin-independent scattering
- Dense, excellent **self-shielding** properties
- Intrinsically **radiopure**

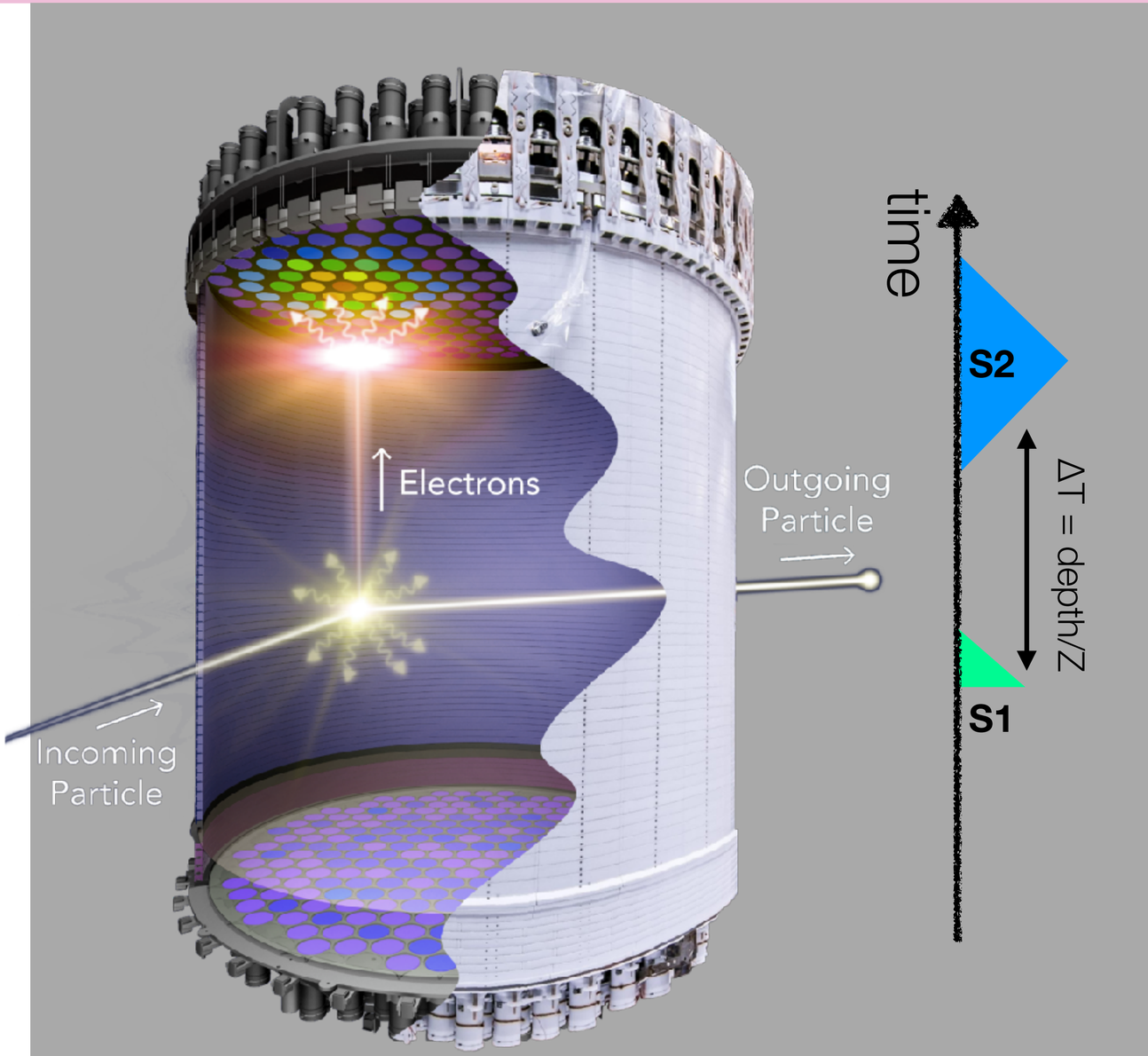


Direct Detection with Dual-Phase LXe TPCs

- Primary signal is **nuclear recoil** of a xenon atom. Most backgrounds are electron recoils.
- Two signals: scintillation (S1) in LXe and ionisation (S2) in GXe
  - ER/NR **discrimination** from ratio of S1 and S2 signals



  - 3D position reconstruction - XY from PMT array, Z from Δt between S1 and S2



The LZ Collaboration

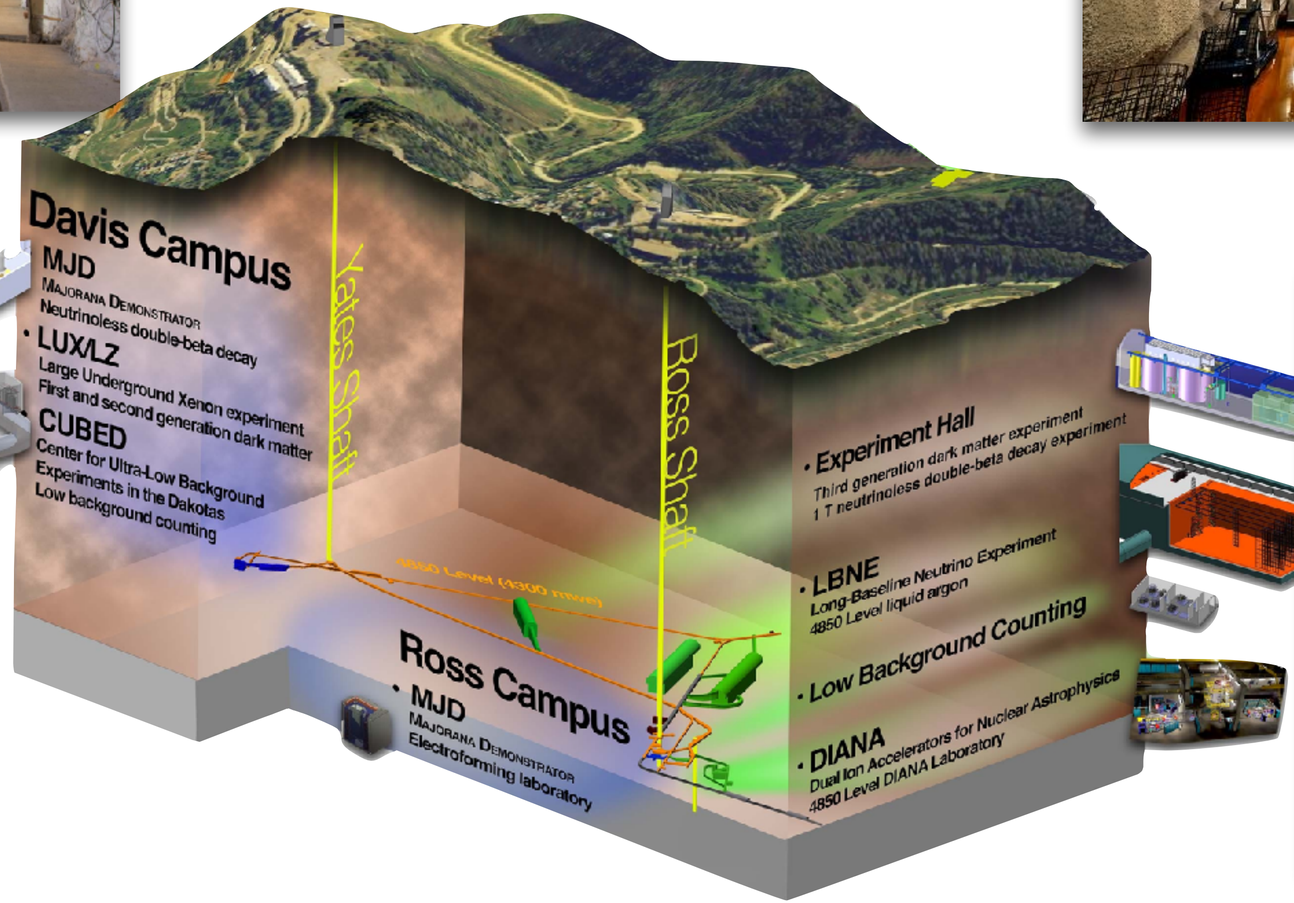
1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
8) University of Bristol (UK)
9) University of Edinburgh (UK)
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)

38 institutions across the US, UK, Portugal and South Korea

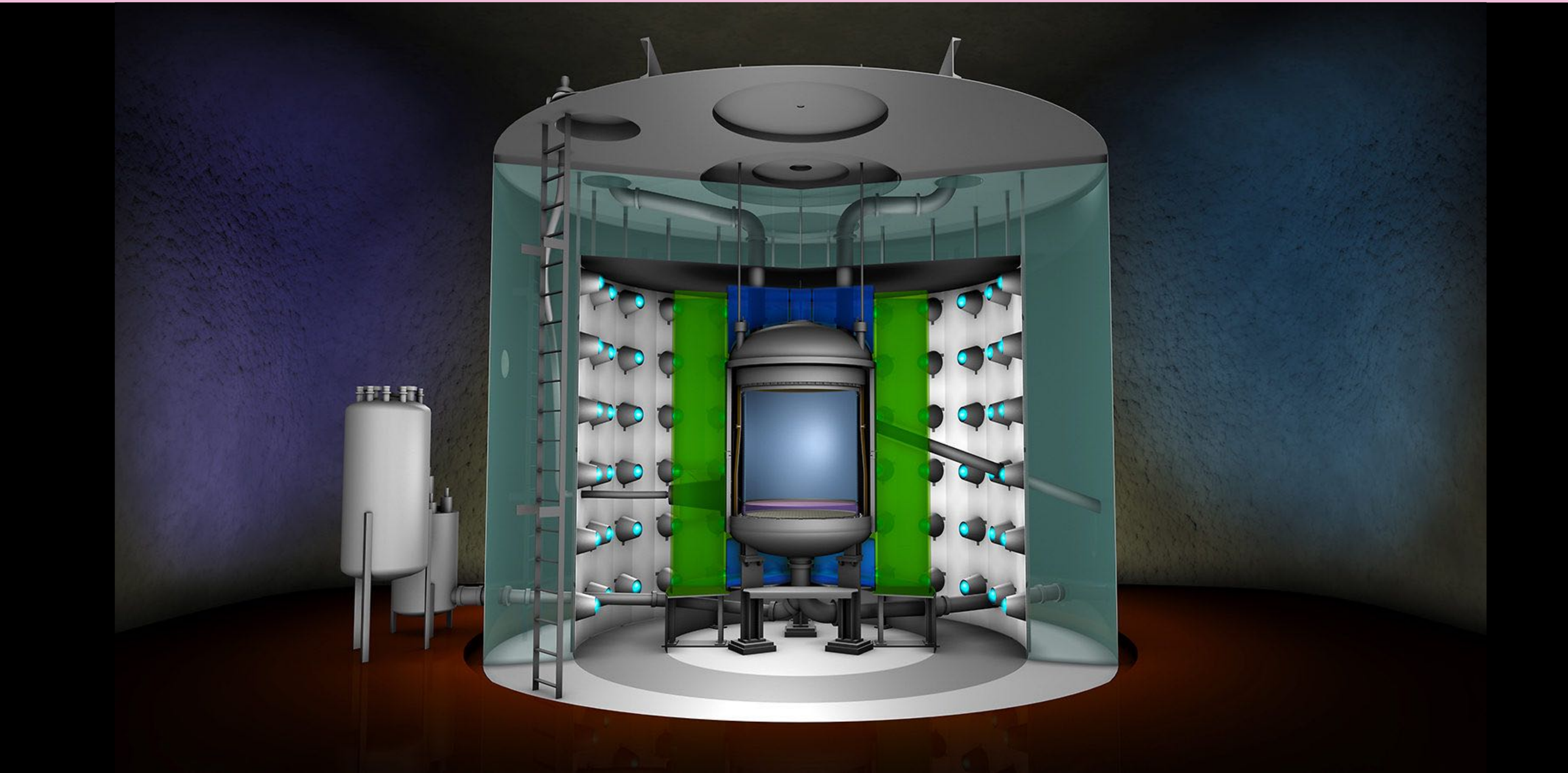
250 scientists, engineers, and technicians

The Sanford Underground Research Facility

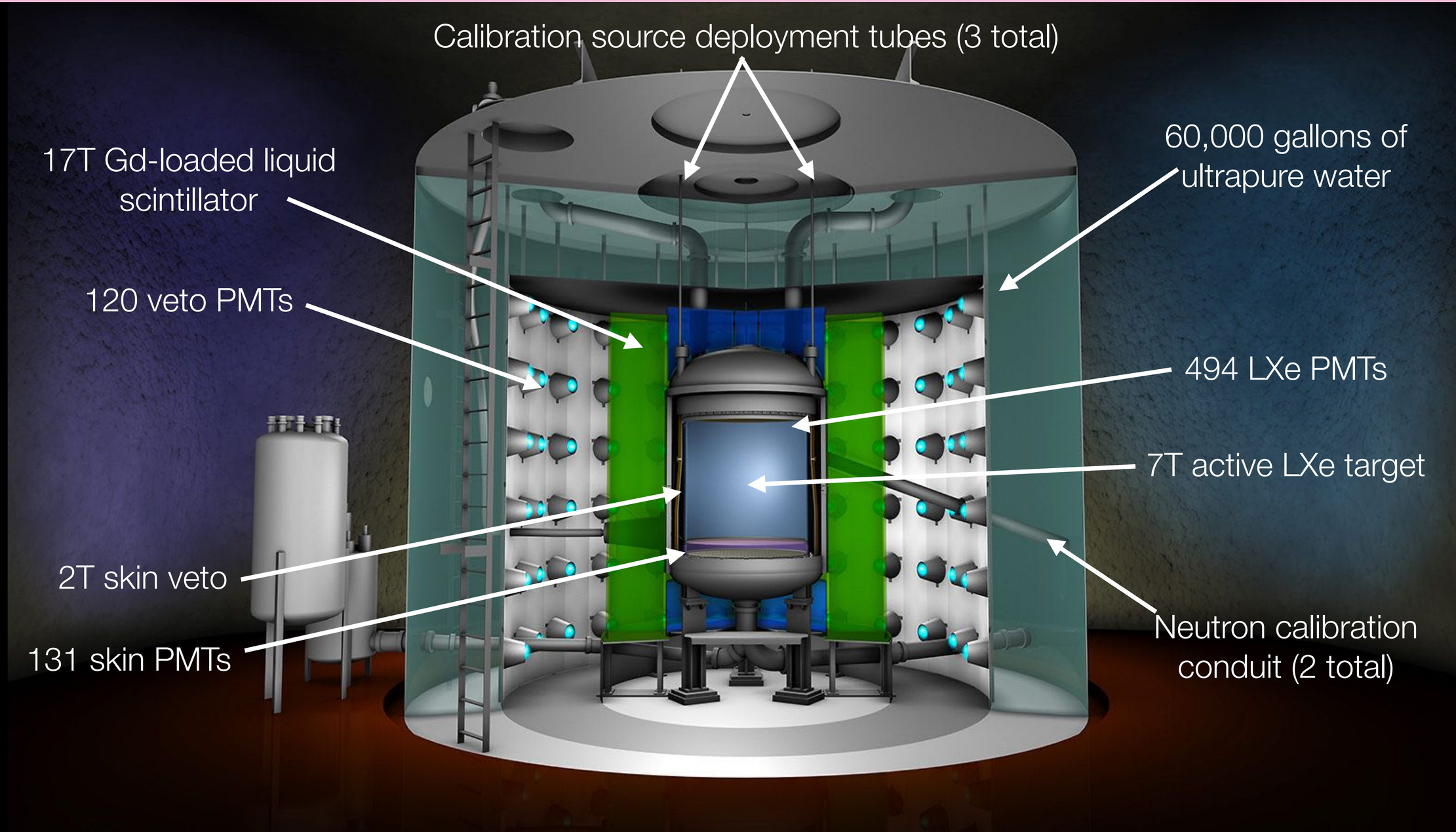
Sanford
Underground Research Facility



The LZ Detector



The LZ Detector



“Sally for Scale”

LZ Acrylic Vessel **LUX Outer Cryostat** **LZ Outer Cryostat**

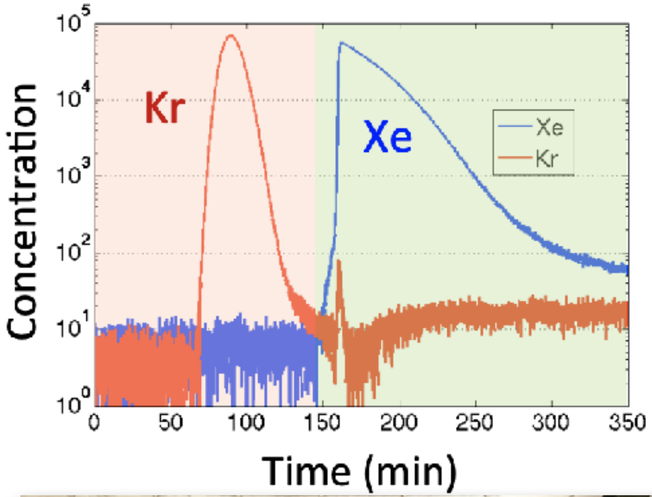
* I am 5’2"
/ 160 cm

Xenon

10T total Xenon, undegoes:

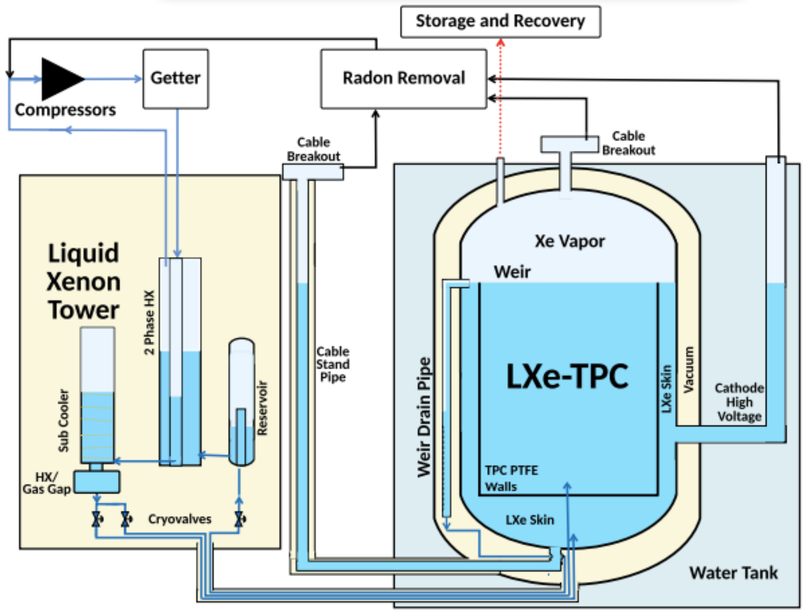
- Krypton removal at SLAC*
  - **Gas charcoal chromatography**
  - Goal: < 300 ppq ^{nat}Kr/Xe
- Online purification of GXe
  - **Hot zirconium getter** removes electronegative impurities
  - Full 10T purified every 2.4 days
- Radon removal
  - Inline radon removal system uses **activated carbon trap**, 10x reduction of radon in 1 pass

* see talk by D. Ames, Friday at 11am
The LZ Krypton Removal Chromatography System



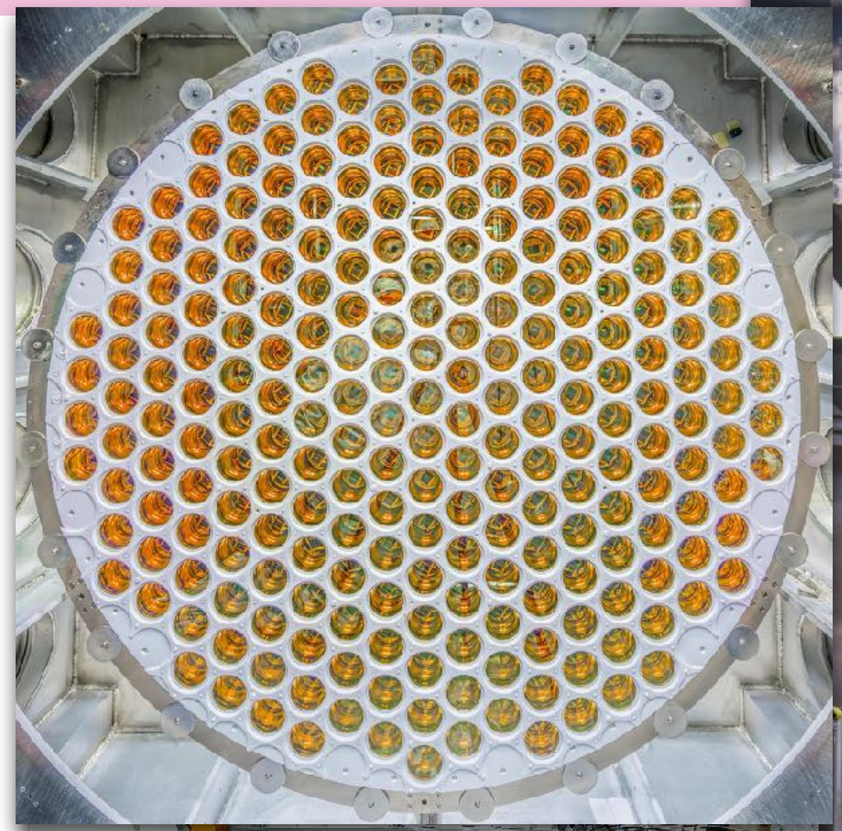

Krypton removal system at SLAC

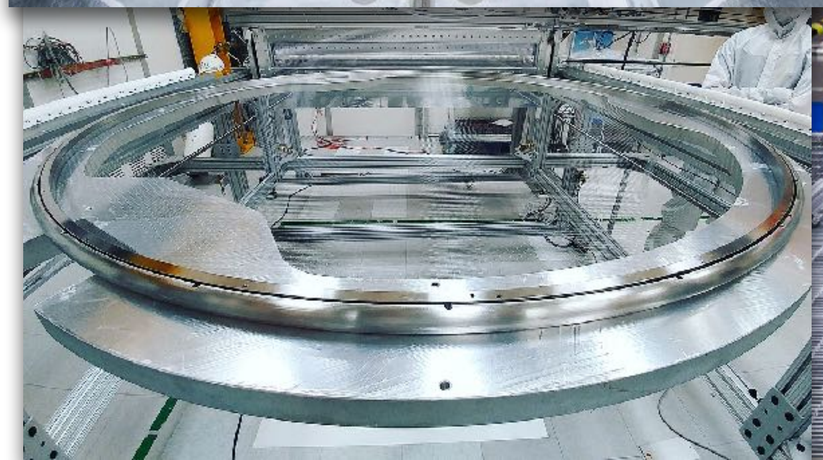
Radon reduction system at SURF

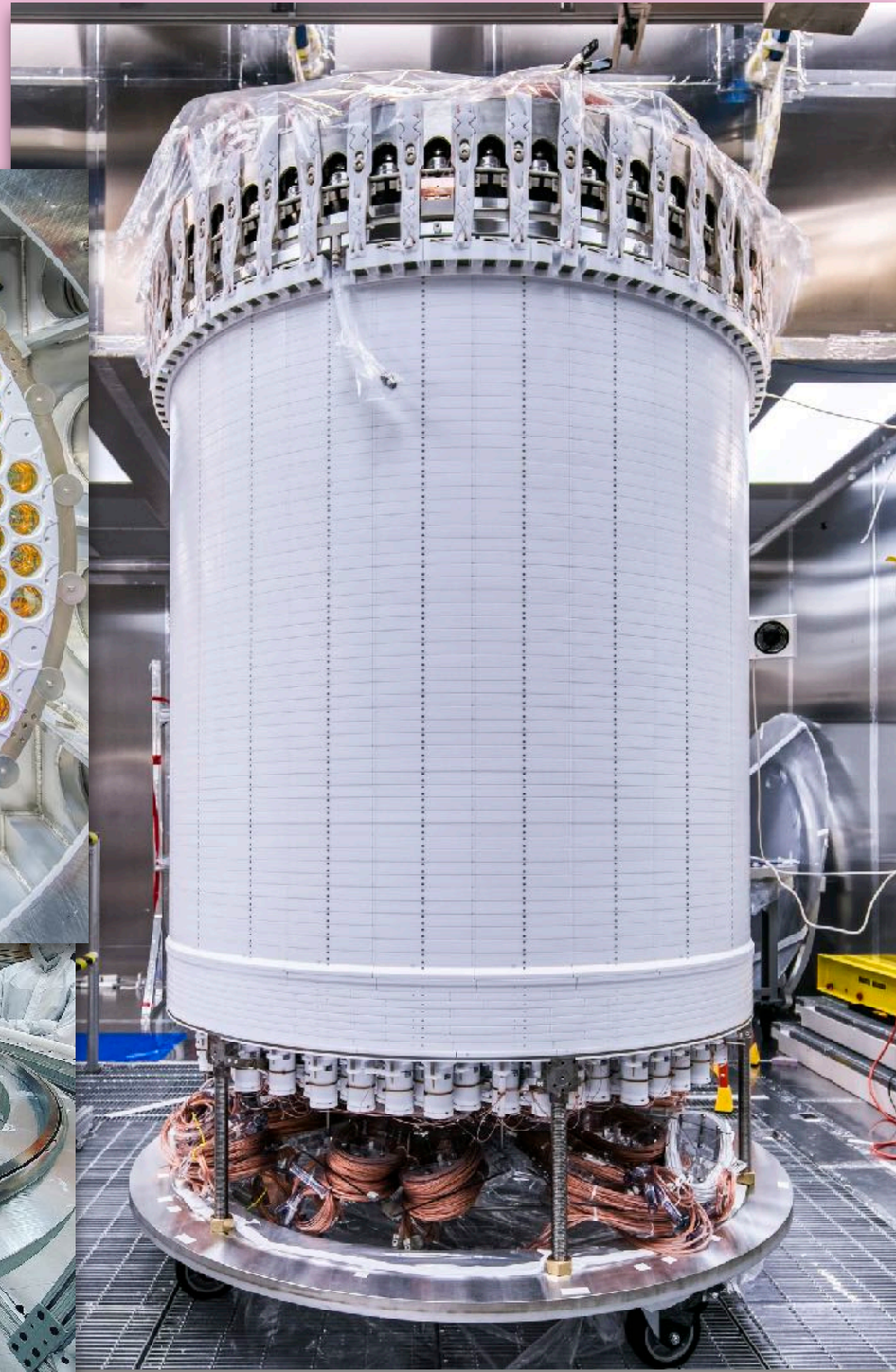


Time Projection Chamber

- 2 PMT arrays of Hamamatsu R11410-20 PMTs (494 total)
- 4 electrodes/grids woven on specialized looms and **passivated** to reduce e- emission*
- 57 field rings embedded in reflective PTFE → **310V/cm drift field**
- TPC completed August 2019
- Inserted into ICV at surface assembly lab



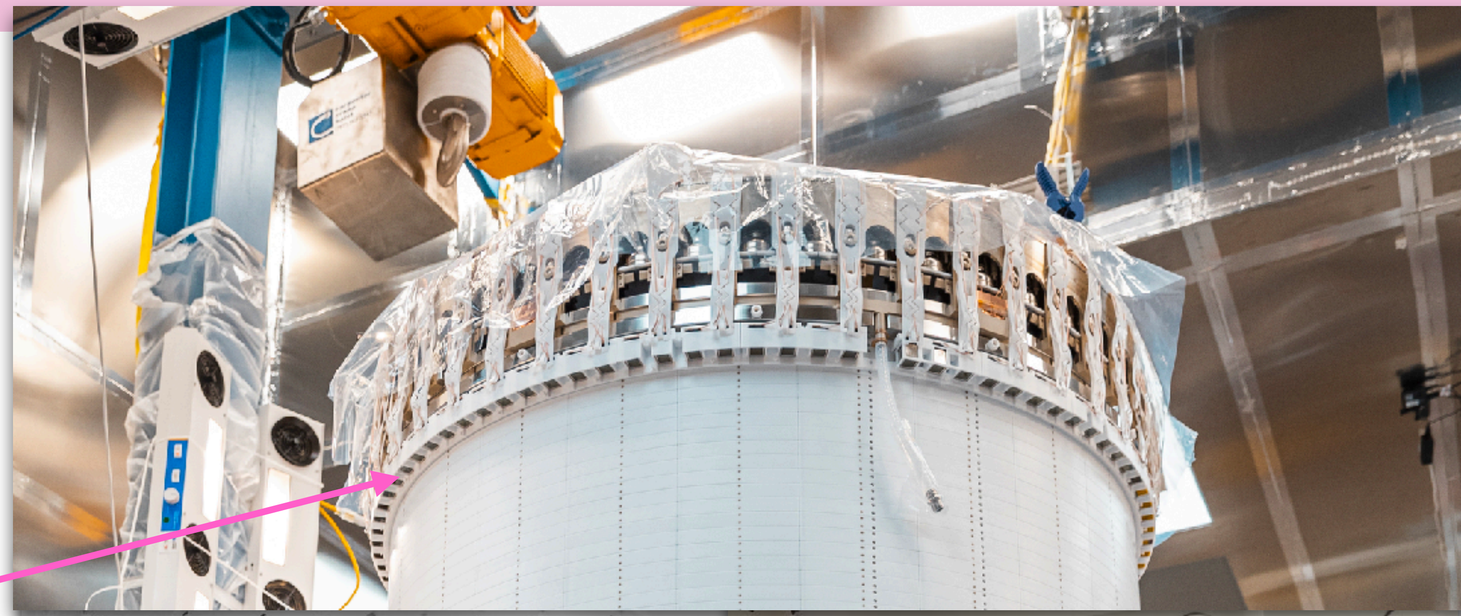


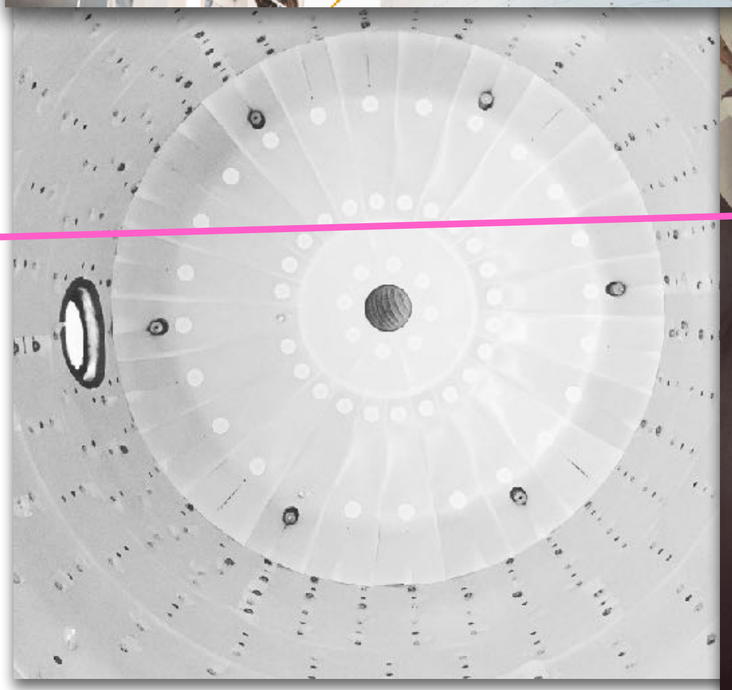


* see talk by R. Linehan, Thurs at 8am
Understanding the impact of high voltage electrodes on low-energy dark matter searches with the LZ dual phase xenon TPC

Liquid Xenon Skin Detector

- 2T of active xenon between the ICV and the TPC field cage
  - Optically isolated from TPC
  - 93 1” R8520 PMTs in ice cube trays at the top
  - 20 side + 18 dome 2” R11410 PMTs at the bottom
- Expected to be **>95% efficient** at tagging γ-rays





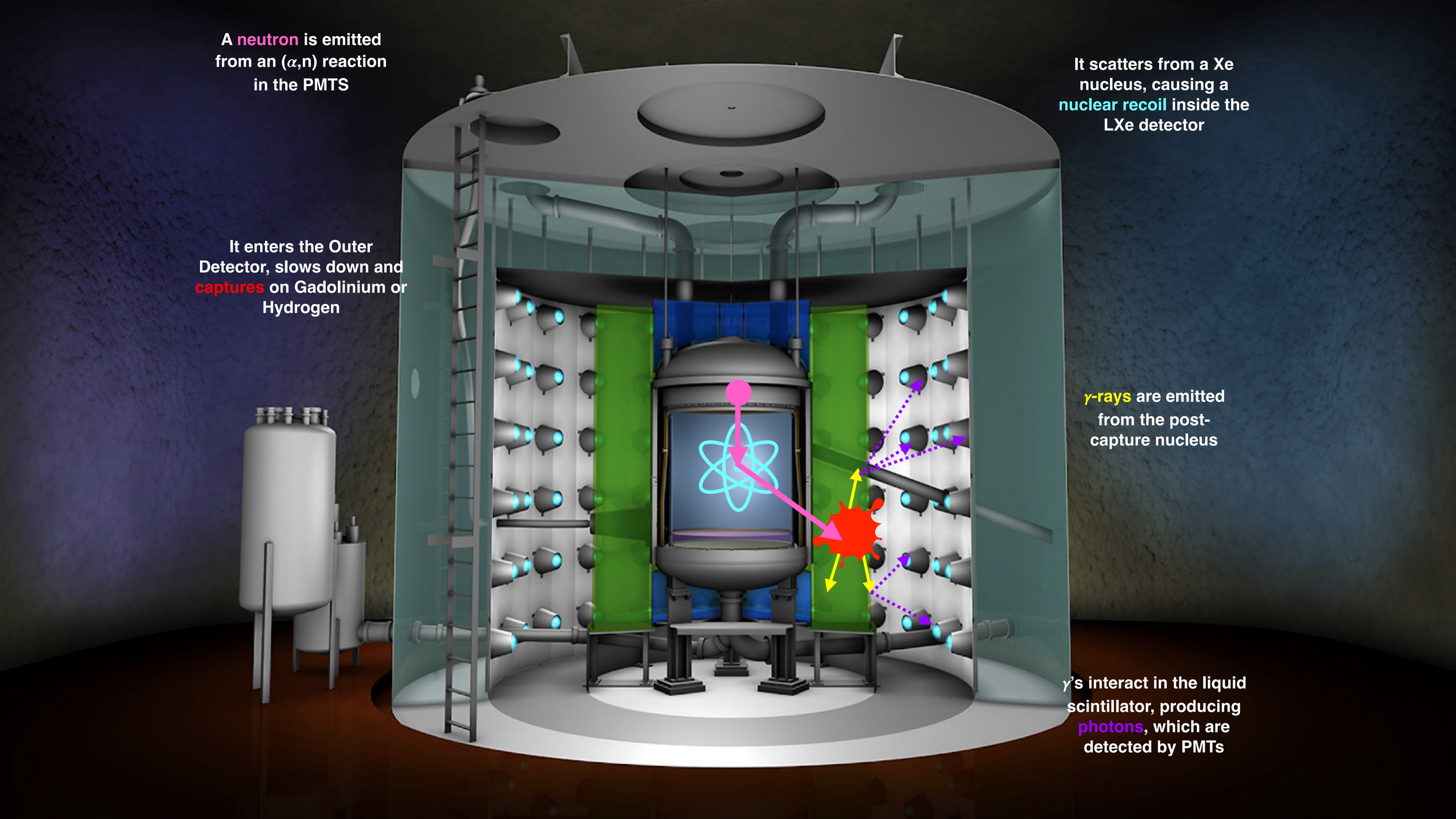
Titanium Vessels

ICV at the Surface Assembly Lab

ICV being lowered into OCV

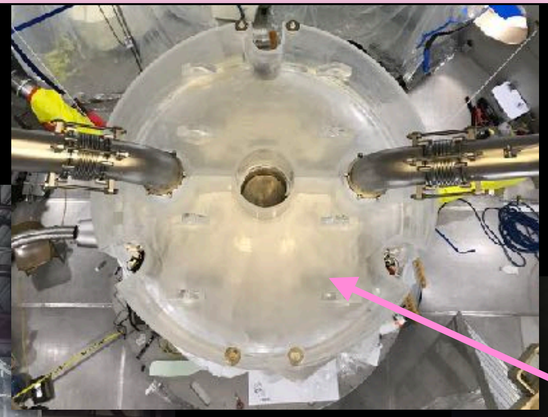
ICV and OCV in place in water tank

Inner vessel installed in the water tank
December 2019


A neutron is emitted from an (α,n) reaction in the PMTS
It enters the Outer Detector, slows down and captures on Gadolinium or Hydrogen
It scatters from a Xe nucleus, causing a nuclear recoil inside the LXe detector
γ-rays are emitted from the post-capture nucleus
γ's interact in the liquid scintillator, producing photons, which are detected by PMTs

Outer Detector

2 top vessels

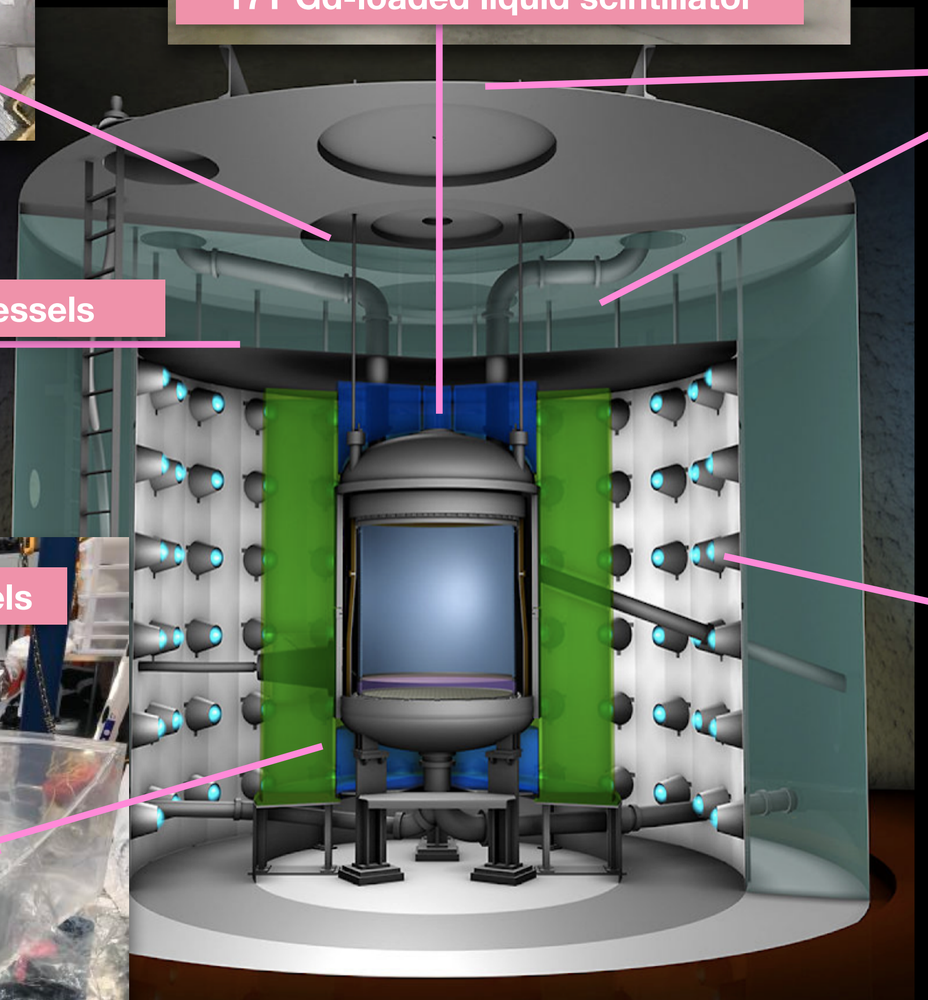


10 segmented acrylic vessels

3 side vessels

3 bottom vessels

17T Gd-loaded liquid scintillator



GdLS Filling System

120 8” PMTs

Outer Detector Installation

Side vessel lowering into water tank

Post-acrylic cleaning yoga

All acrylic vessels in place!

PMT and tyvek installation

Top tank fill system installation

OD construction completed spring 2021

Cleanliness and Background Mitigation

- **Detector materials**
  - Radio-assay campaign
  - gamma-screening
  - ICPMS
  - NAA
- **Rn emanation**
  - Four Rn emanation screening sites
  - Two portable Rn assay panels
  - Target Rn activity: 2 μBq/kg
- **Rn daughters and dust on surfaces**
  - TPC assembly in Rn-reduced cleanroom
  - Dust < 500 ng/cm^3 on all LXe contact surfaces
  - Rn-daughter plate-out on TPC walls < 0.5 mBq/m^2
- **Xenon contaminants**
  - ^{85}Kr, ^{39}Ar
  - Charcoal chromatography @ SLAC
  - Final natKr/Xe <300 ppq
- **Cosmogenics and externals**
  - 4300 m.w.e. underground
  - Instrumented Xe skin region
  - GdLS outer detector
  - High purity water shield


Cleanliness protocols!


HPGe screening at Boulby

Radon reduction system at SURF


Charcoal chromatography columns at SLAC

Backgrounds

ER Backgrounds:

- γ-rays & β-decays from ^{238}U, ^{232}Th chains
- ^{60}Co, ^{40}K
- Xenon lines
- ^{222}Rn, ^{220}Rn and ^{85}Kr in the LXe

NR Backgrounds

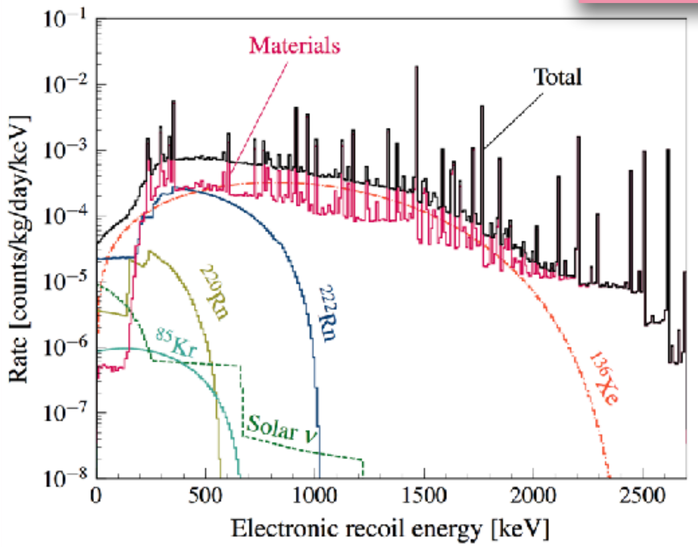
- Neutrons from (α,n) & spontaneous fission in detector components
- ^{8}B solar neutrinos
- Wall background (mis-reconstructed ion recoils)

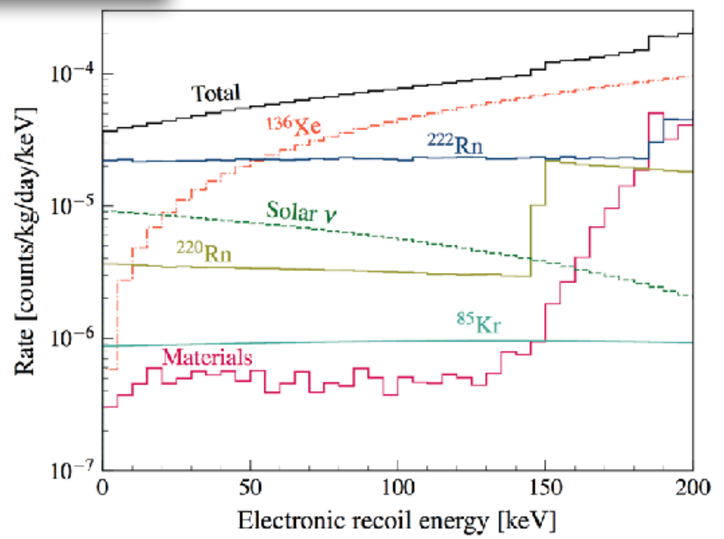
Key for reducing background:

- Fiducialisation (self-shielding)
- Single scatter cuts
- Energy cuts
- Dual veto system (skin and OD)

OD reduces NR backgrounds and allows maximal fiducial volume

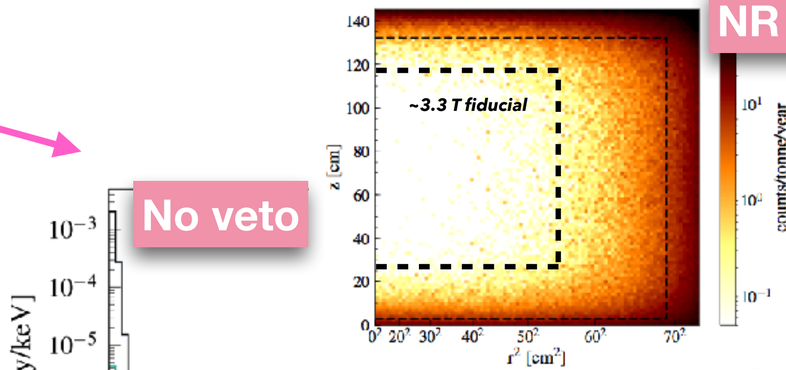
ER backgrounds



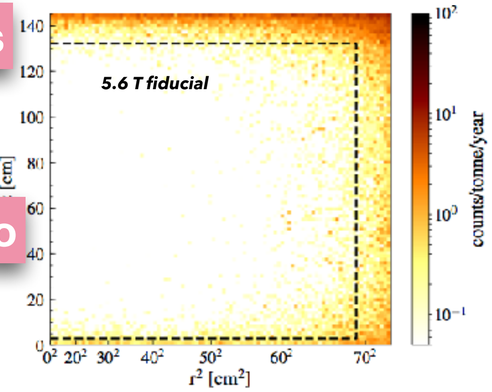


NR backgrounds

No veto

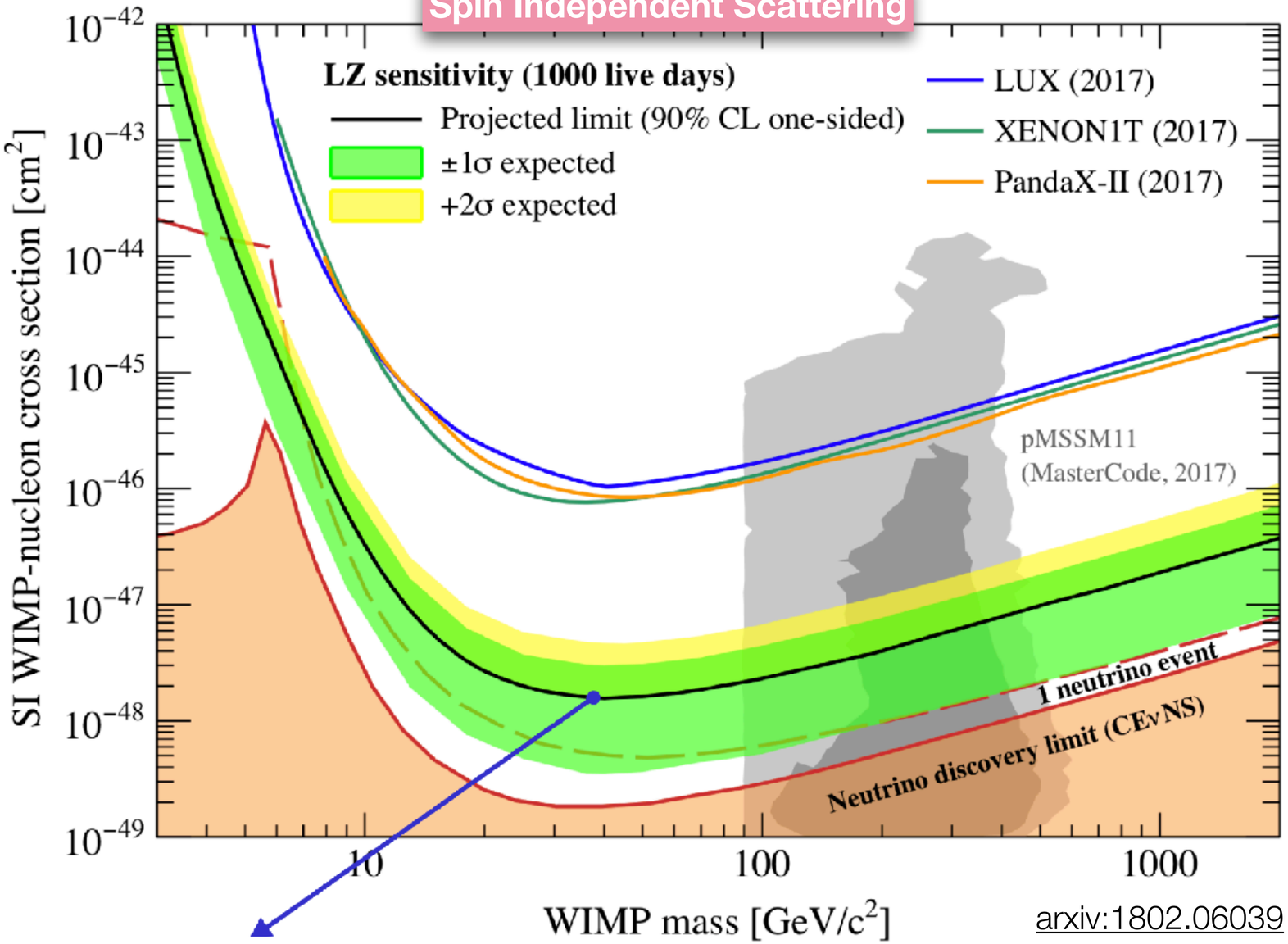


With veto



LZ Sensitivity Projections

Spin Independent Scattering

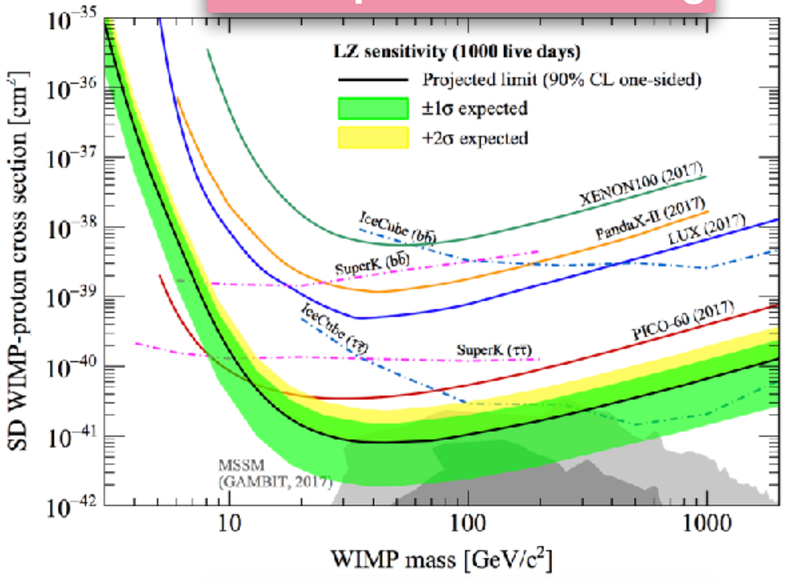


1.4 x 10⁻⁴⁸ cm² @ 40 GeV/c²

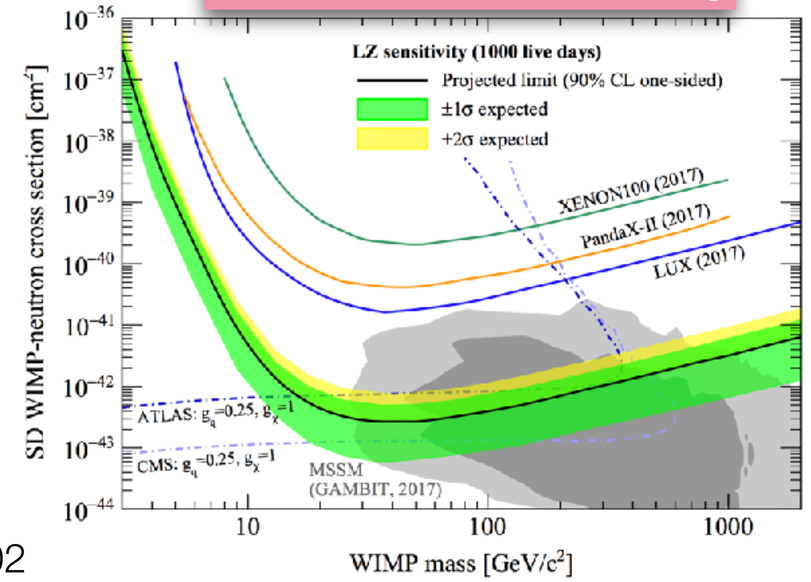
arxiv:1802.06039

Phys. Rev. D **101**, 052002

WIMP-proton scattering



WIMP-neutron scattering



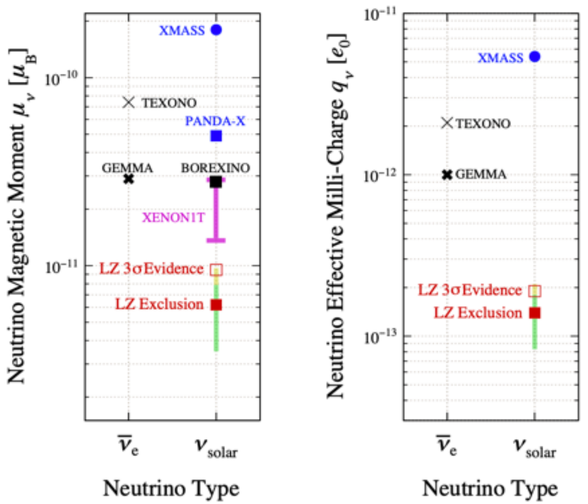
LZ Physics Reach

LZ physics reach extends beyond vanilla WIMPs:

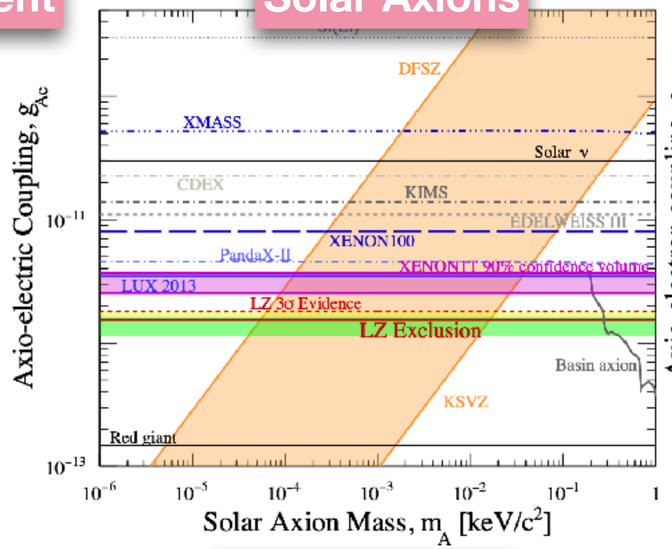
- Solar axions
- Axion-like particles (ALPs)
- 2νββ of ^{134}Xe with competitive sensitivity to 0νββ
- Enhanced sensitivity to low mass DM through Migdal effect
- Leptophilic dark matter
- Neutrino magnetic moment
- Mirror dark matter

arxiv:2102.11740
arxiv:2104.13374

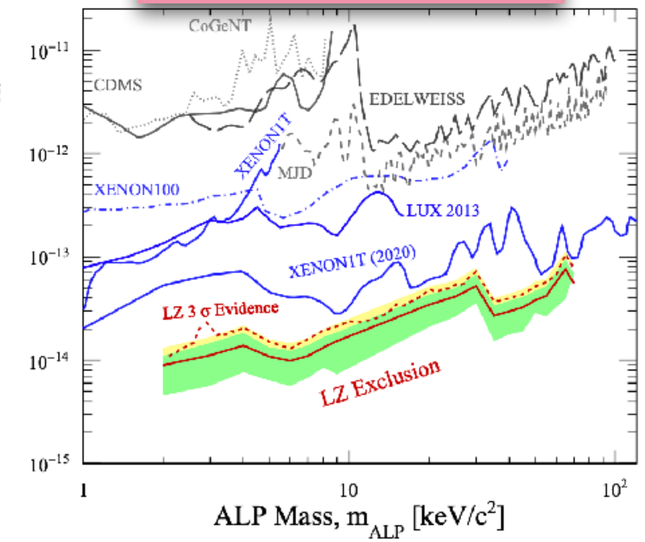
Neutrino magnetic moment



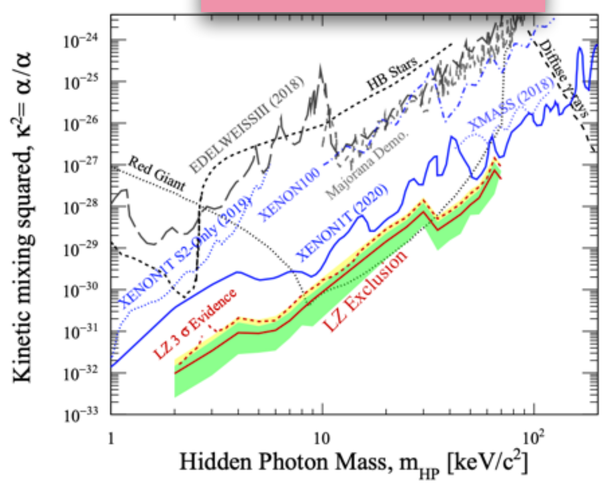
Solar Axions



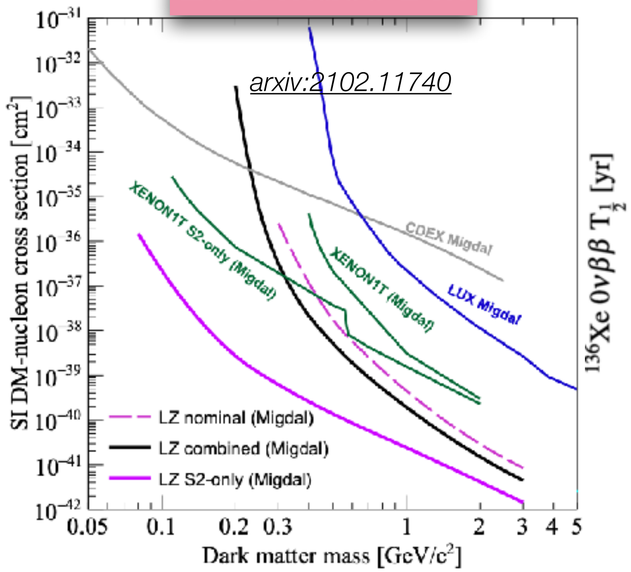
Axion-Like Particles



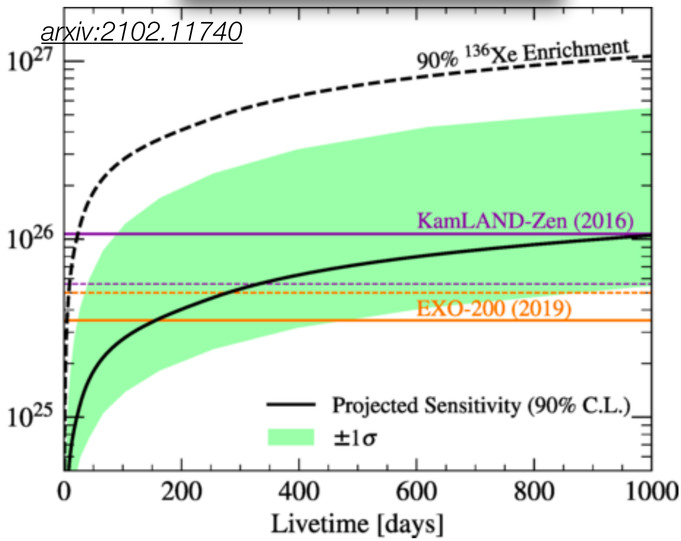
Hidden Photons



Low mass DM



134Xe 0νββ decay



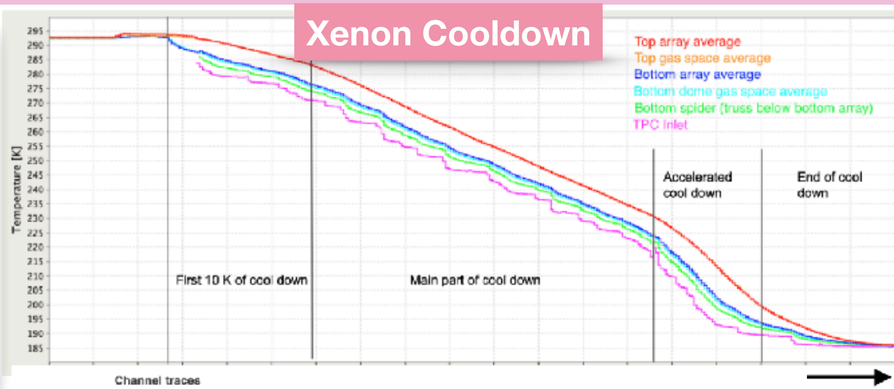
Commissioning

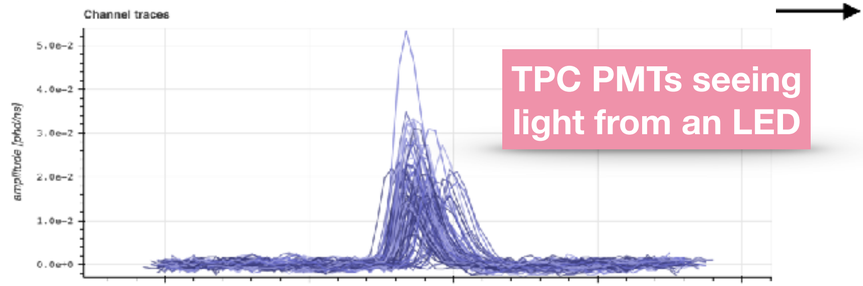
Xenon:

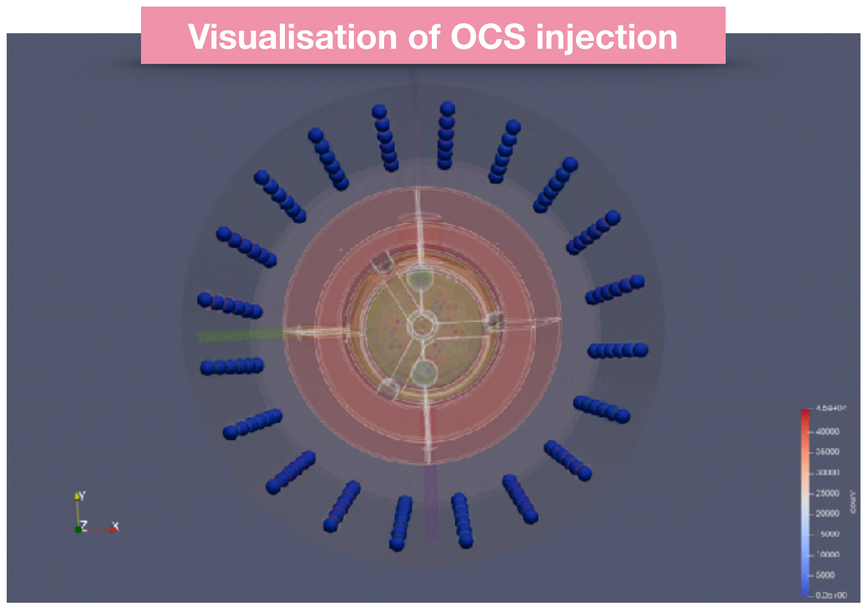
- Circulation test completed last year with test cryostat underground
- Achieved designed gas circulation rate of 500 slpm
- TPC has been cooled down to ~185 K

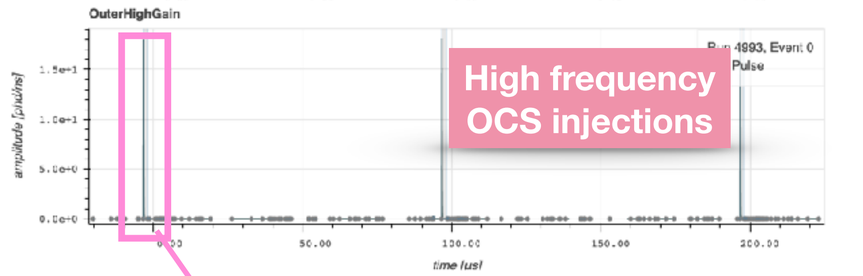
PMTs:

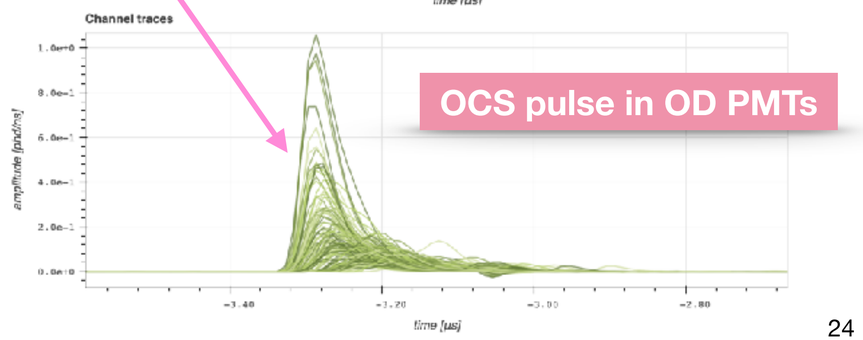
- Fully tested and characterized with LEDs calibration in all three detectors
- OD OCS system fully characterized
  - arxiv:2102.06281











LZ construction is complete!

- We have cold xenon, all PMTs have been tested with LEDs
- Physics data taking this year
- Expected **40x improvement** in sensitivity on current limits, also sensitive to non-WIMP physics
- **2022 will be an exciting year!**

Thanks!

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- Royal Holloway University of London
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- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
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- 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
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- University of Wisconsin, Madison

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UKRI Science and Technology Facilities Council

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