LZ: A Second Generation Direct Dark Matter Search

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LEPP-3
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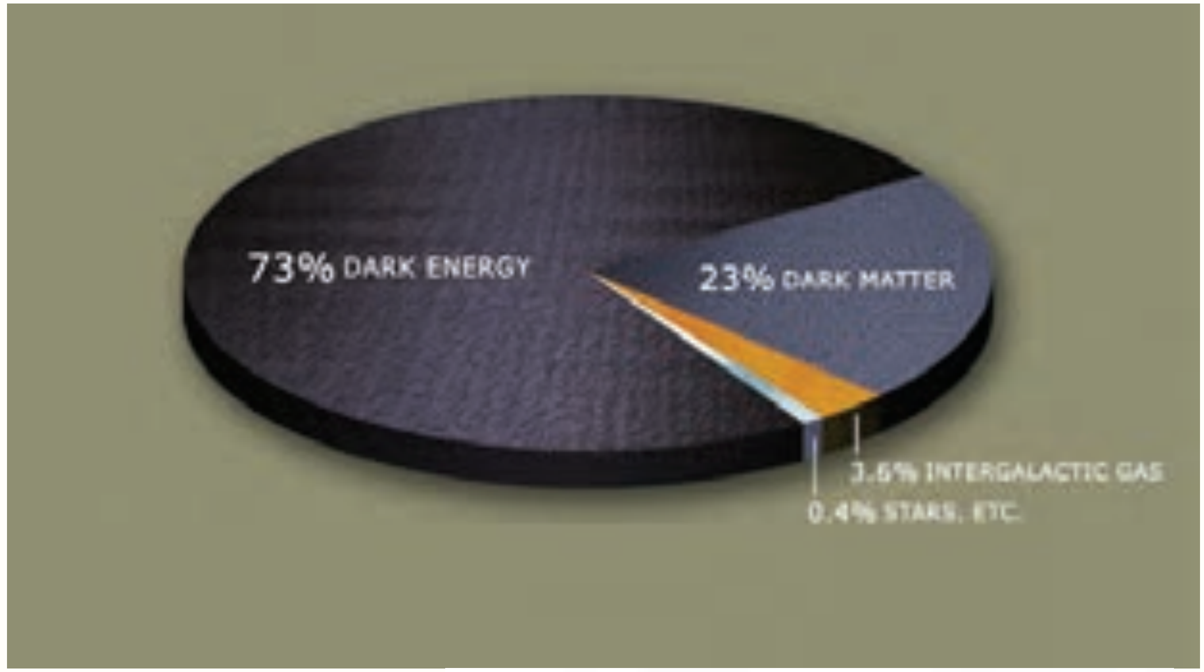
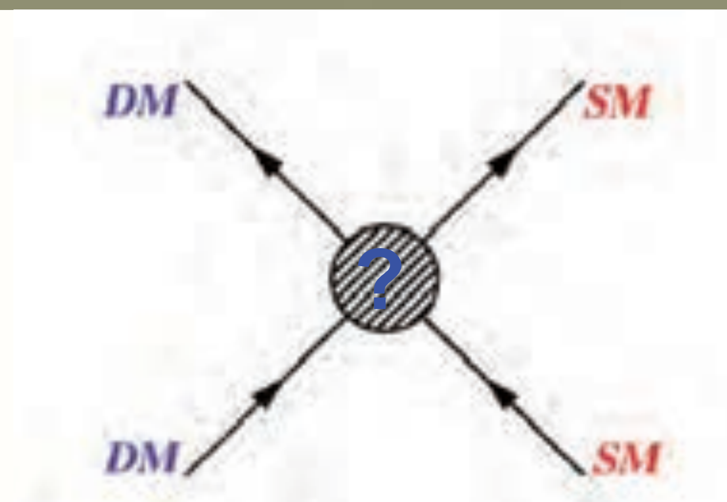
The Dark Matter Problem

A good problem to have. There is a known effect looking for an answer … as opposed to a known solution looking for an experimental effect.

A real challenge for experimentalists to study this known energy density.

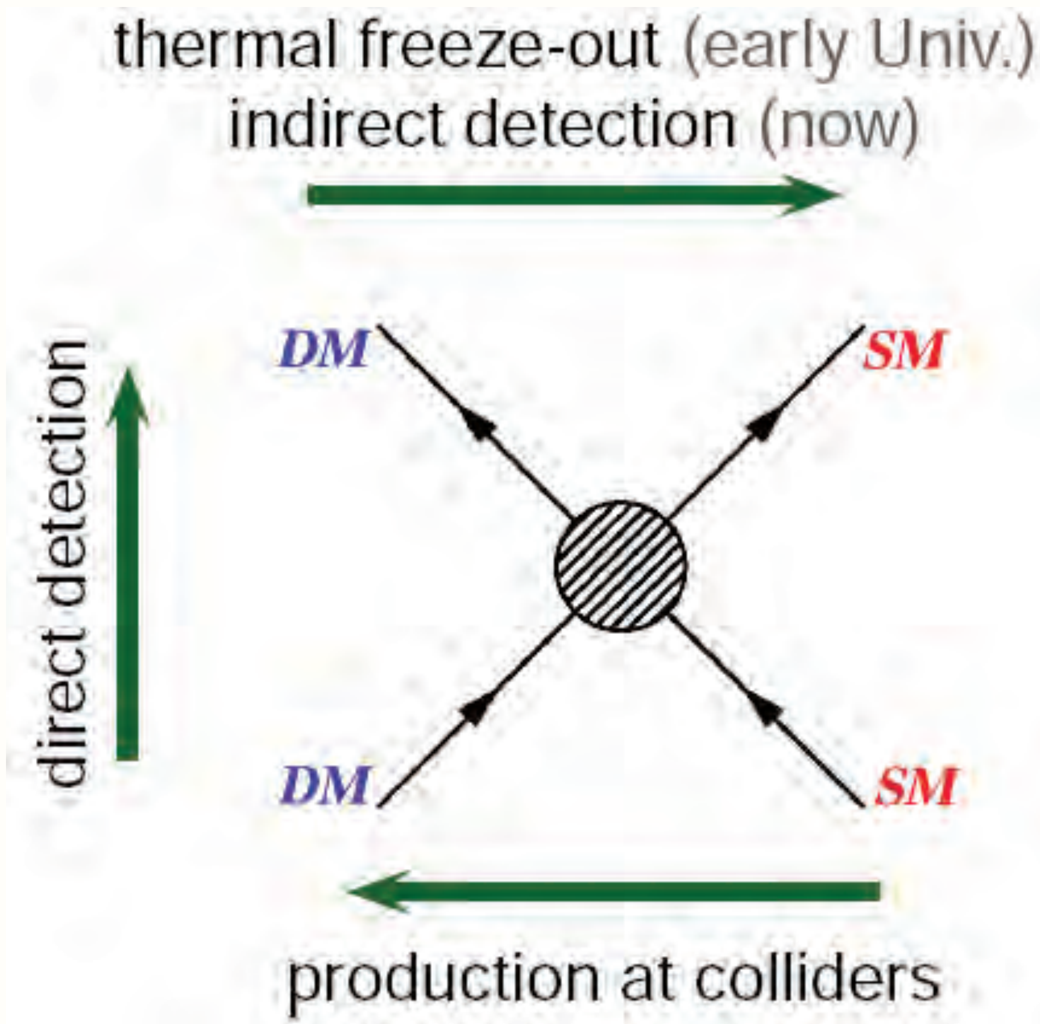


- Postulate 1: DM is a particle.
- Postulate 2: DM and SM particles interact with some force that is very weak but <u>much</u> stronger than gravity.



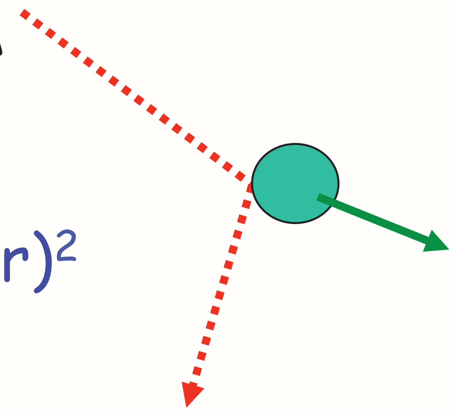
Detection Techniques

- Three major categories of investigations.
- Important to maintain the theoretical connection between these approaches.



Direct Detection

Basic goal: search for nuclear recoil from DM elastic scattering.



Simple dynamics. Cross section α (form factor)^2

Spin-independent: Nucleon form factor gives rise to A^2 enhancement due to coherence.

The dependence on q^2 is also contained in the form-factors.

Spin-dependent: Form factor depends on nuclear spin. No coherence enhancement.

WIMP Miracle

A happy coincidence implied that new physics at the TeV scale with appropriately weak cross section leads to a dark matter relic (with a new quantum number preventing decay).

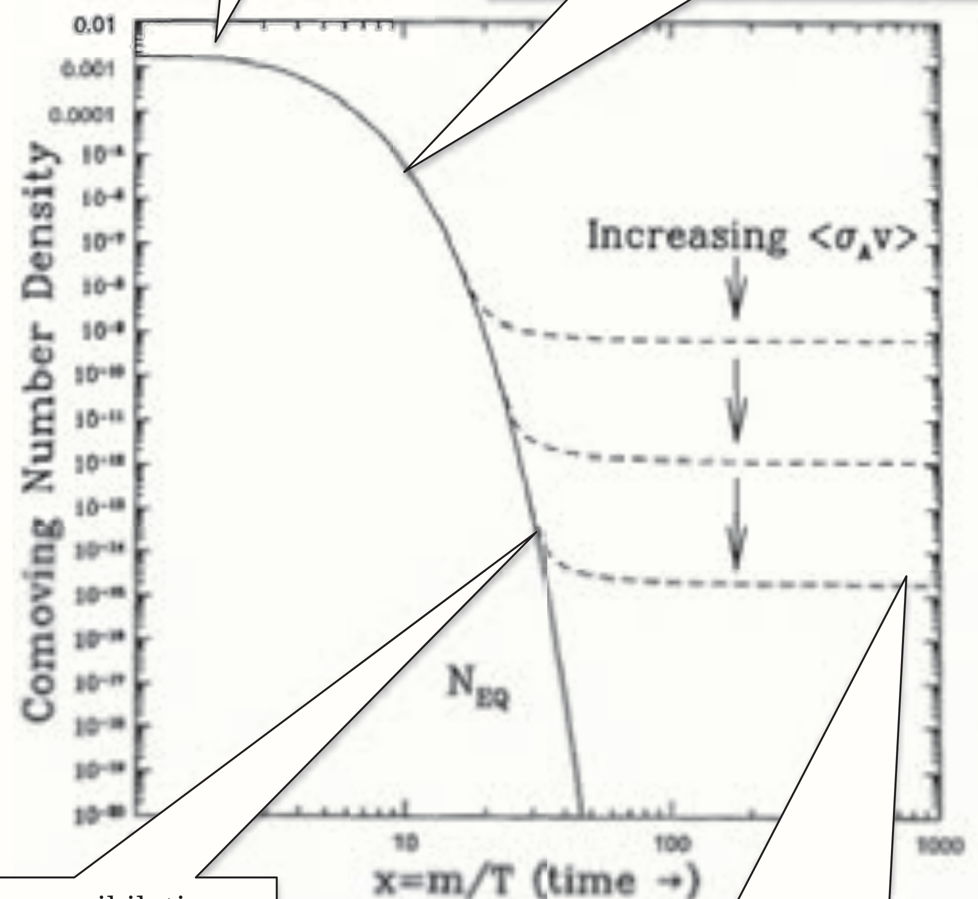
$$\Omega_x h^2 = \frac{3 \cdot 10^{-27}\, cm^3 / s}{\langle \sigma_A v \rangle} \approx 0.12$$

$$\Rightarrow \sigma_A \approx \frac{\alpha^2}{M^2_{EW}}$$

1. Flat region. Constant density. Equal production and annihilation. $n_{eq} \sim T^3$

2. Exponential suppression as temperature falls below mass of dark matter particle.

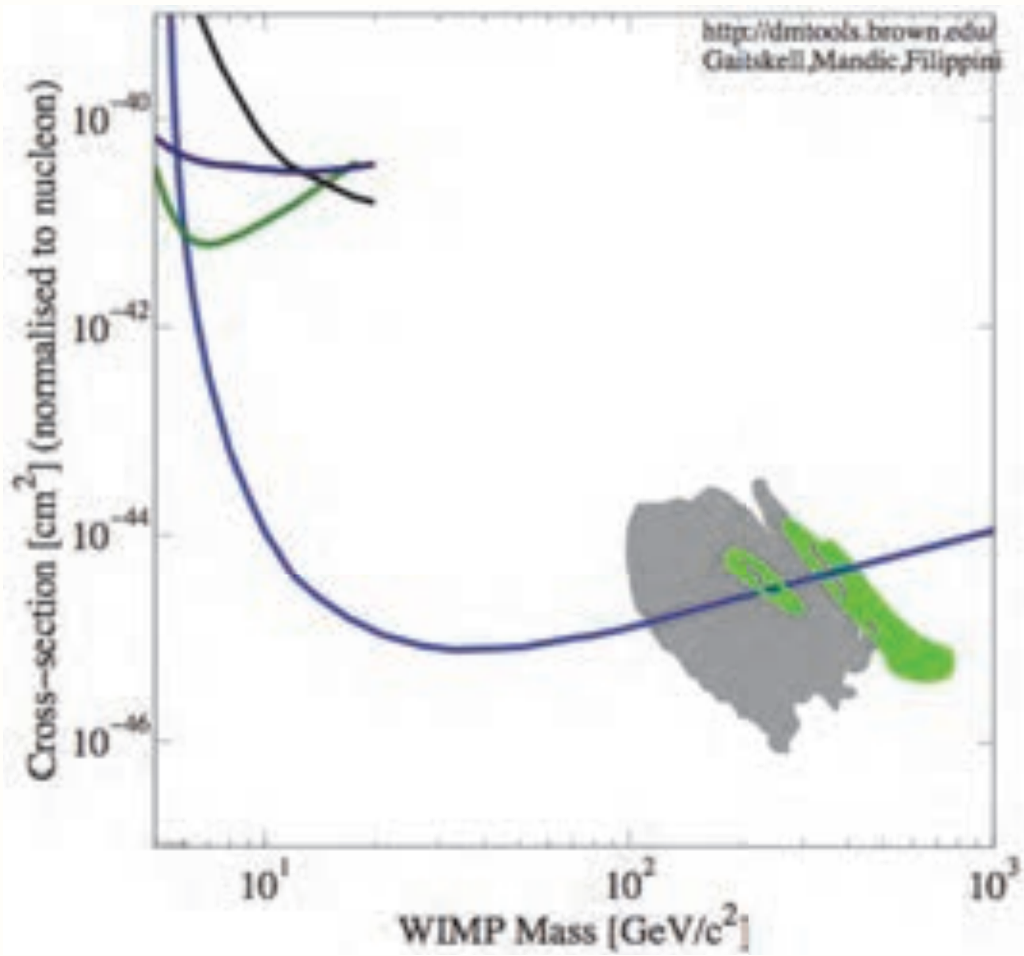
$n_{eq} \sim (m/T)^{3/2}\, e^{-m/T}$



3. Turn over as annihilation rate decreases, becoming smaller than the expansion rate.

4. Relic abundance remains. Larger cross-sections keep annihilations occurring for longer.

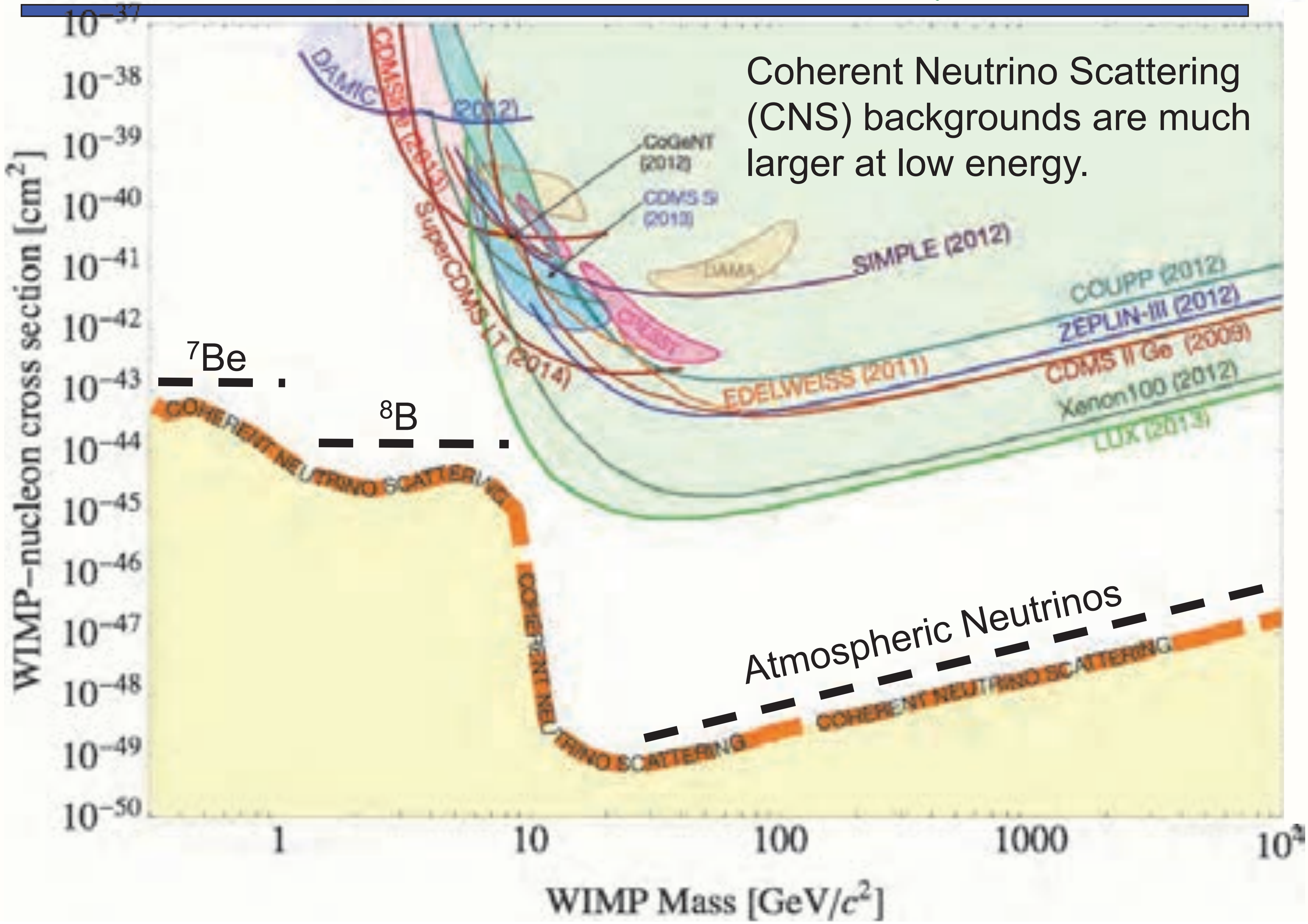
Time Progression of Sensitivity



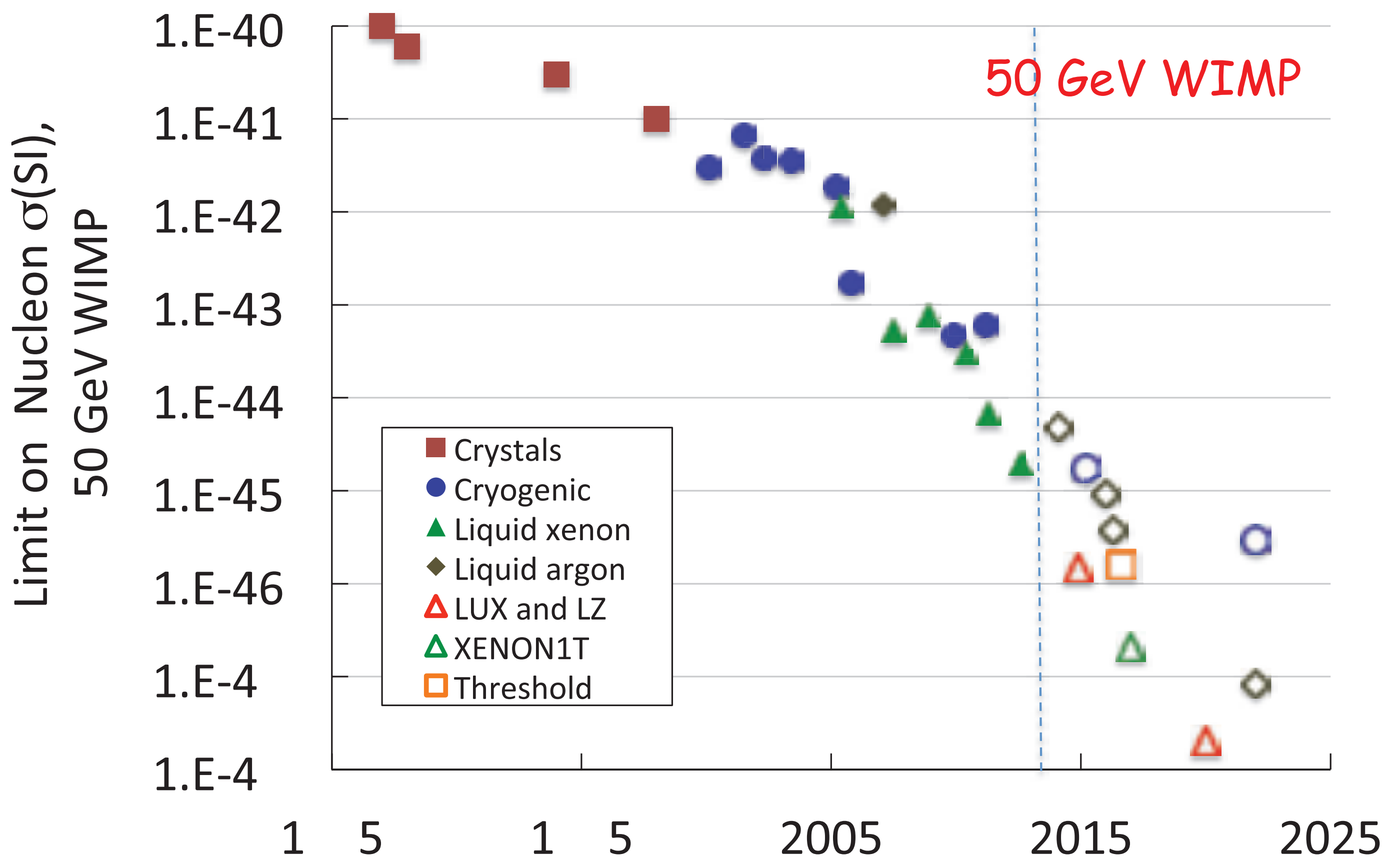
Years 2000-2013

Animation courtesy of Aaron Manalaysay, UC Davis

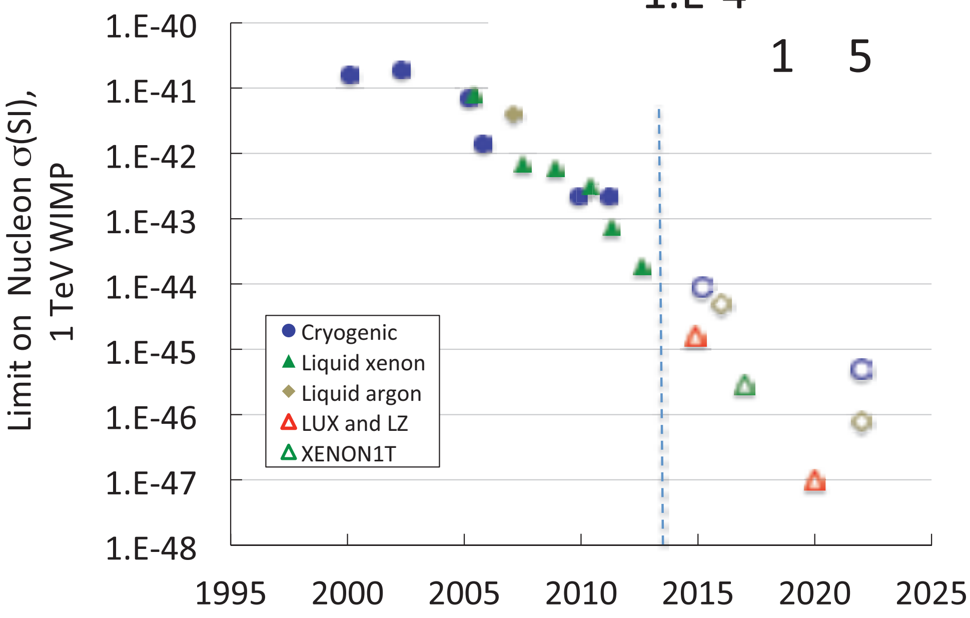
Where we are today



A compact history of WIMP Searches



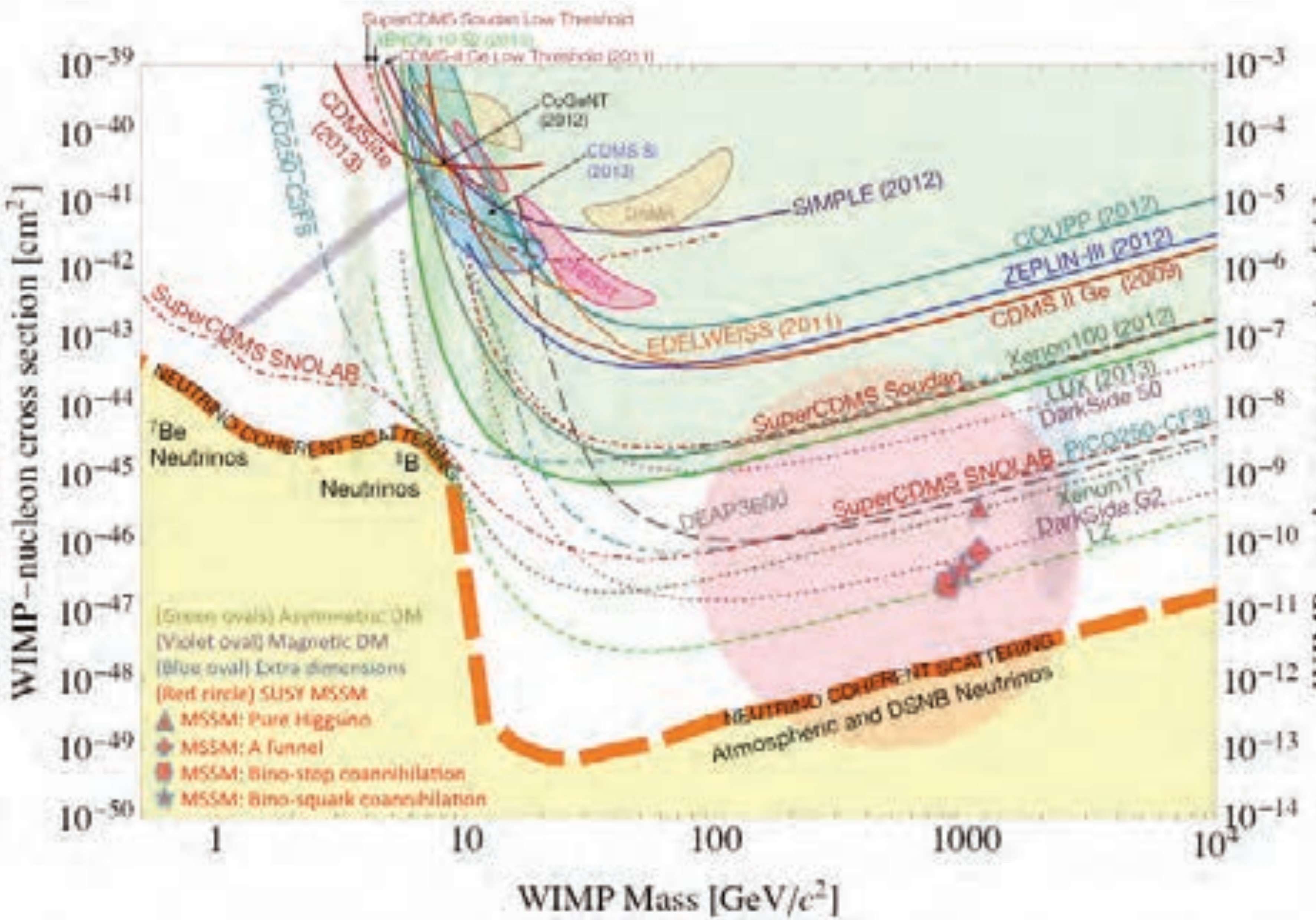
1 TeV WIMP



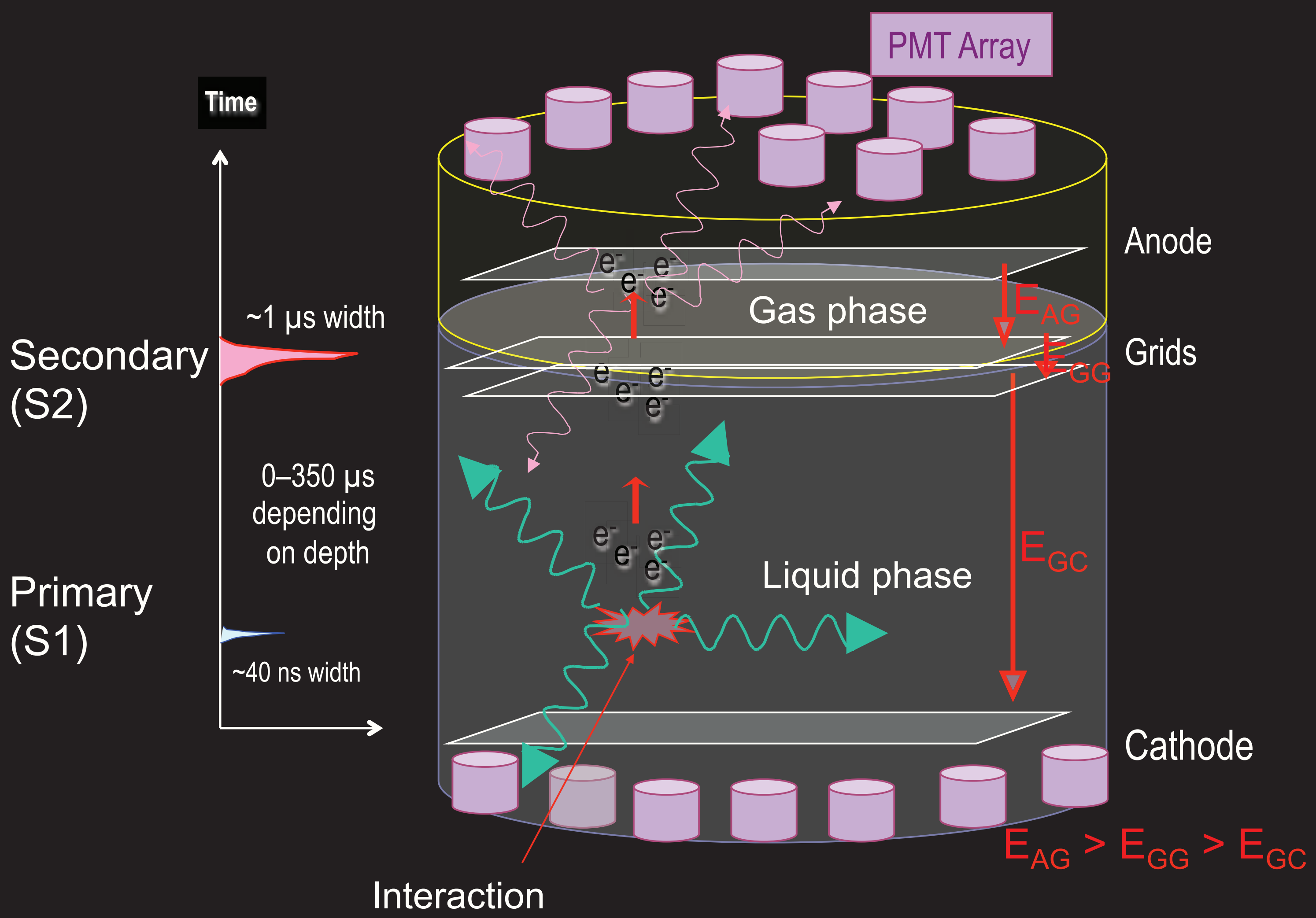
LZ is poised to possibly provide an end-point to this saga … hopefully by discovering WIMPs or, by ruling out most of the theoretical <u>and</u> experimentally accessible landscape.

Plots compiled by Mike Witherell, UCSB

Snowmass Projections



Two-phase XE TPC: Two Signal Technique



Why Xenon?

Nobel element => Inert. Can be purified via gettering techniques.

No long-lived radio-isotopes. Metastable istopes useful in calibration.

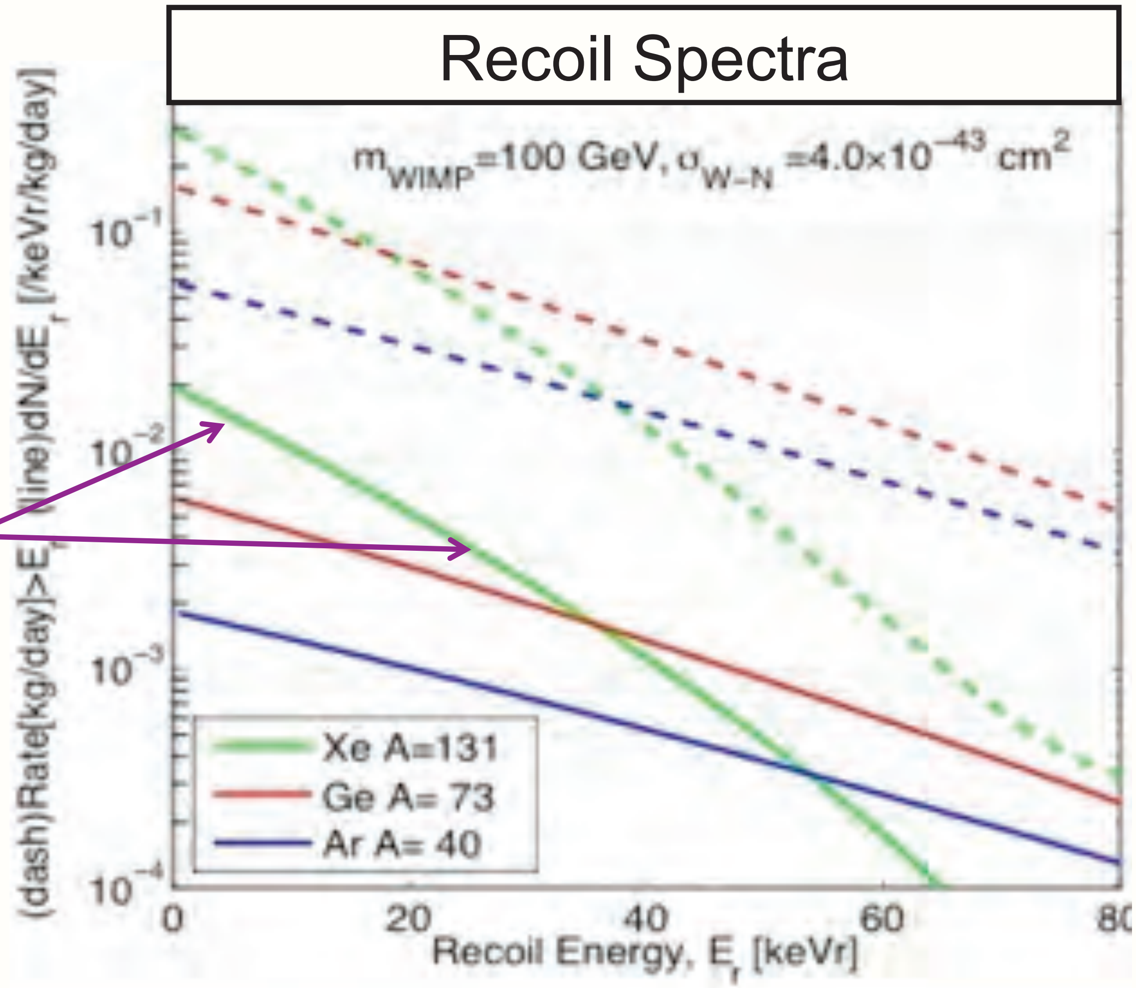
High density (~$3 g/cm^3$)
=> Powerful self-shielding.

High A (131) => Large elastic σ

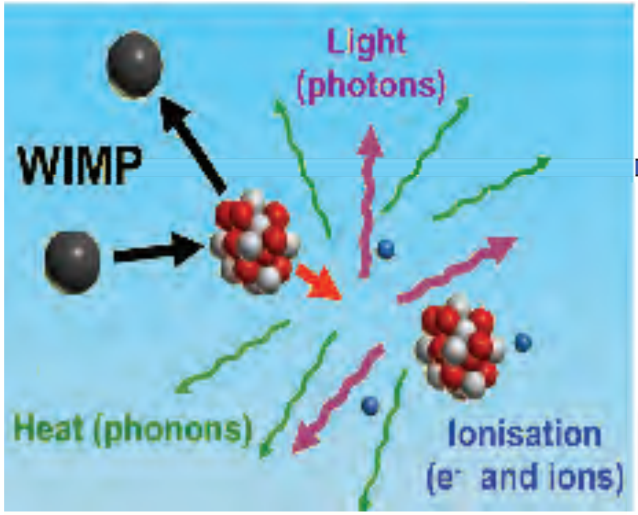
Higher Sensitivity in the range 5 keV < E < 25 keV.

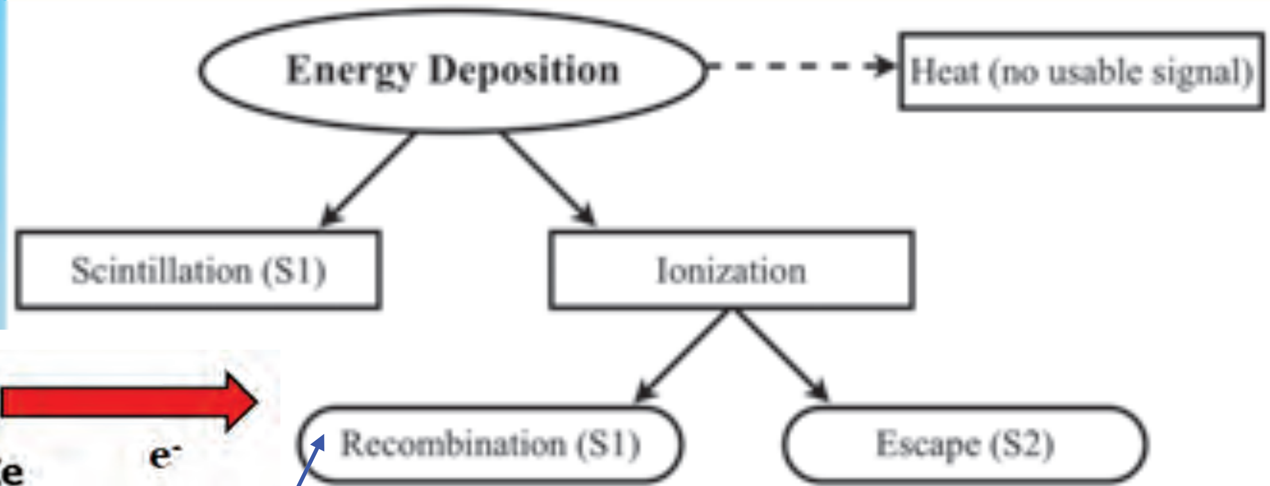
Long electron drift lengths (few m) => scalable

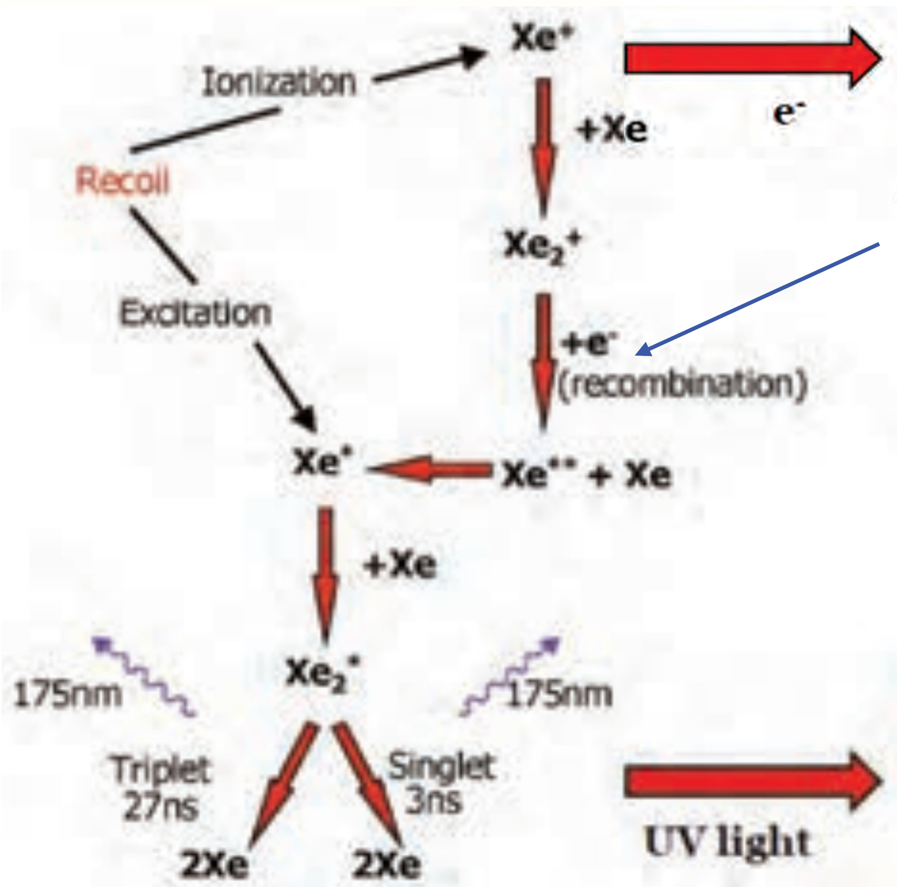
Efficient scintillator



Scintillation process in LXe







Difference in in recombination efficiency is exploited to discriminate between electron and nuclear recoils.

Xenon is transparent to its own scintillation light !

Figure of merit derived from plots of:

Log (charge escaping recombination/ total primary light produced)

Xe Response Handled by NEST

- **N**oble **E**lement **S**imulation **T**echnique is a a data-driven model explaining the scintillation and ionization yields of noble elements as a function of particle type, electric field, and *dE/dx* or energy
- Provides a full-fledged Monte Carlo (in Geant4) with
  - Mean yields: light and charge, and photons/electron
  - Energy resolution: key in discriminating background
  - Pulse shapes: S1 and S2, including single electrons

$$\text{Energy} = [\ N_{ph} + N_{e-}\ ] * W$$
$$= [\ (\ S1\ /\ g_1\ ) + (\ S2\ /\ g_2\ )\ ] * 13.7\text{e-3 keV(ee)}$$

M. Szydagis et al., JINST 8 (2013) C10003. arxiv:1307.6601
M. Szydagis et al., JINST 6 (2011) P10002. arxiv:1106.1613
J. Mock et al., Submitted to JINST (2013). arxiv:1310.1117

LZ = LUX + ZEPLIN

32 institutions currently
About 190 people
Still Growing

LIP Coimbra (Portugal)
MEPhI (Russia)
Edinburgh University (UK)
University of Liverpool (UK)
Imperial College London (UK)
University College London (UK)
University of Oxford (UK)
STFC Rutherford Appleton Laboratories (UK)
Shanghai Jiao Tong University (China)
University of Sheffield (UK)

University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
University of California, Berkeley
Brookhaven National Laboratory
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Kavli Institute for Particle Astrophysics & Cosmology
Lawrence Livermore National Laboratory
University of Maryland
University of Michigan
Northwestern University
University of Rochester
University of California, Santa Barbara
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University
University of Wisconsin
Yale University

LZ Meeting at U. of Alabama

LZ: Evolution of LUX and ZEPLIN

Building on experiences gained in both programs, the proposed new experiment will utilize the LUX infrastructure at the Sanford Underground Research Facility to mount a state-of-the-art detector. Highlighted features include:

- LUX water shield and an added liquid scintillator active veto.
- Instrumented "skin" region of peripheral xenon as another veto system.
- Unprecedented levels of Kr removal from Xe.
- Radon suppression during construction, assembly and operations.
- Photomultipliers with ultra-low natural radioactivity.
- Cryogenics and Xe purification systems made external to the main detector in a unique design.
- Fully digital deadtime-less data acquisition and trigger system.

LZ Timeline

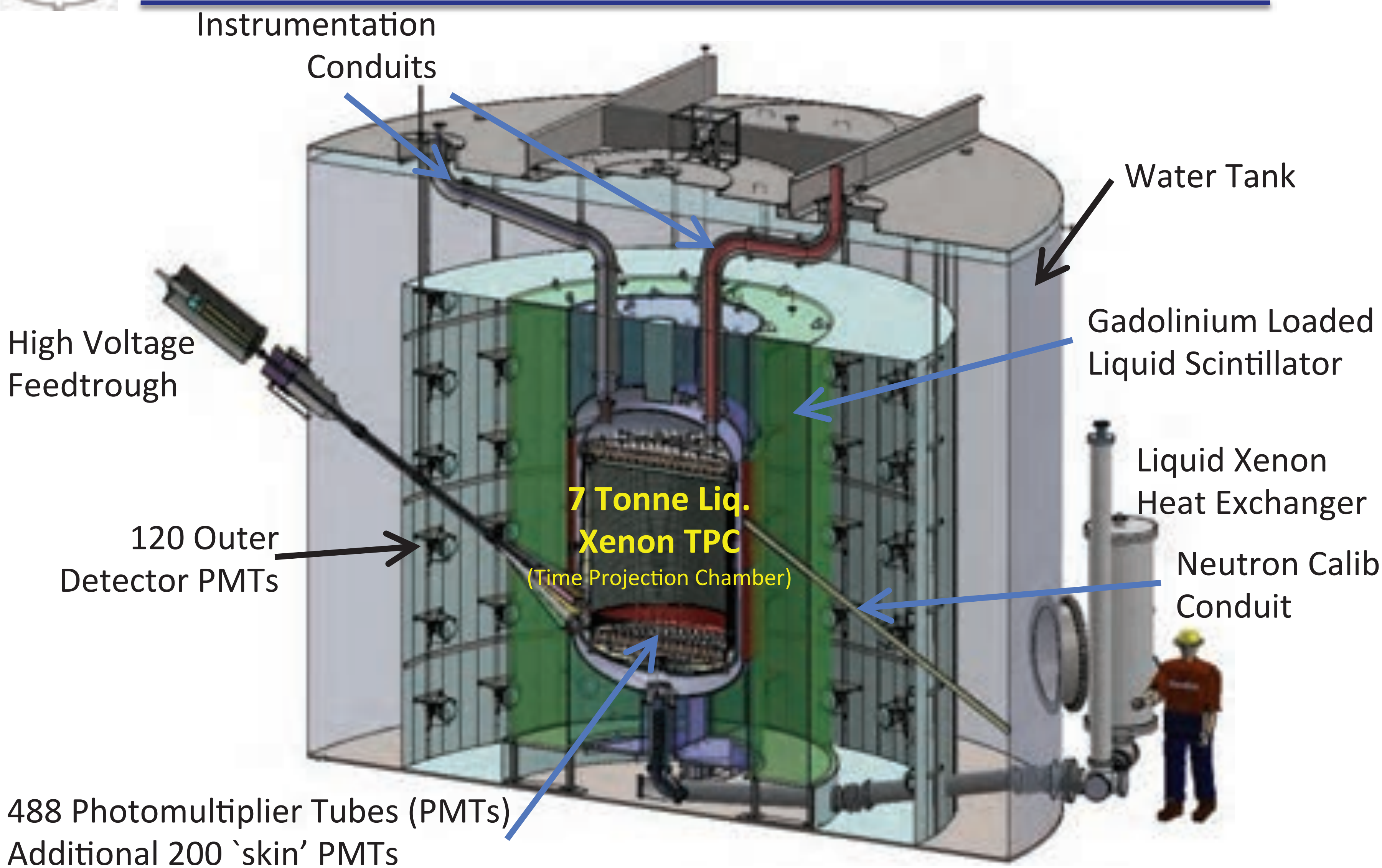
Year	Month	Activity
2012	March	LZ (LUX-ZEPLIN) collaboration formed
	May	First Collaboration Meeting
	September	DOE CD-0 for G2 dark matter experiments
2013	November	LZ R&D report submitted
2014	July	LZ Project selected in US and UK
2015	April	DOE CD-1/3a approval, similar in UK Begin long-lead procurements(Xe, PMT, cryostat)
2016	April	DOE CD-2/3b approval, baseline, all fab starts
2017	June	Begin preparations for surface assembly @ SURF
2018	July	Begin underground installation
2019	Feb	Begin commissioning

Scale Up ~50x in Fiducial Mass

LZ

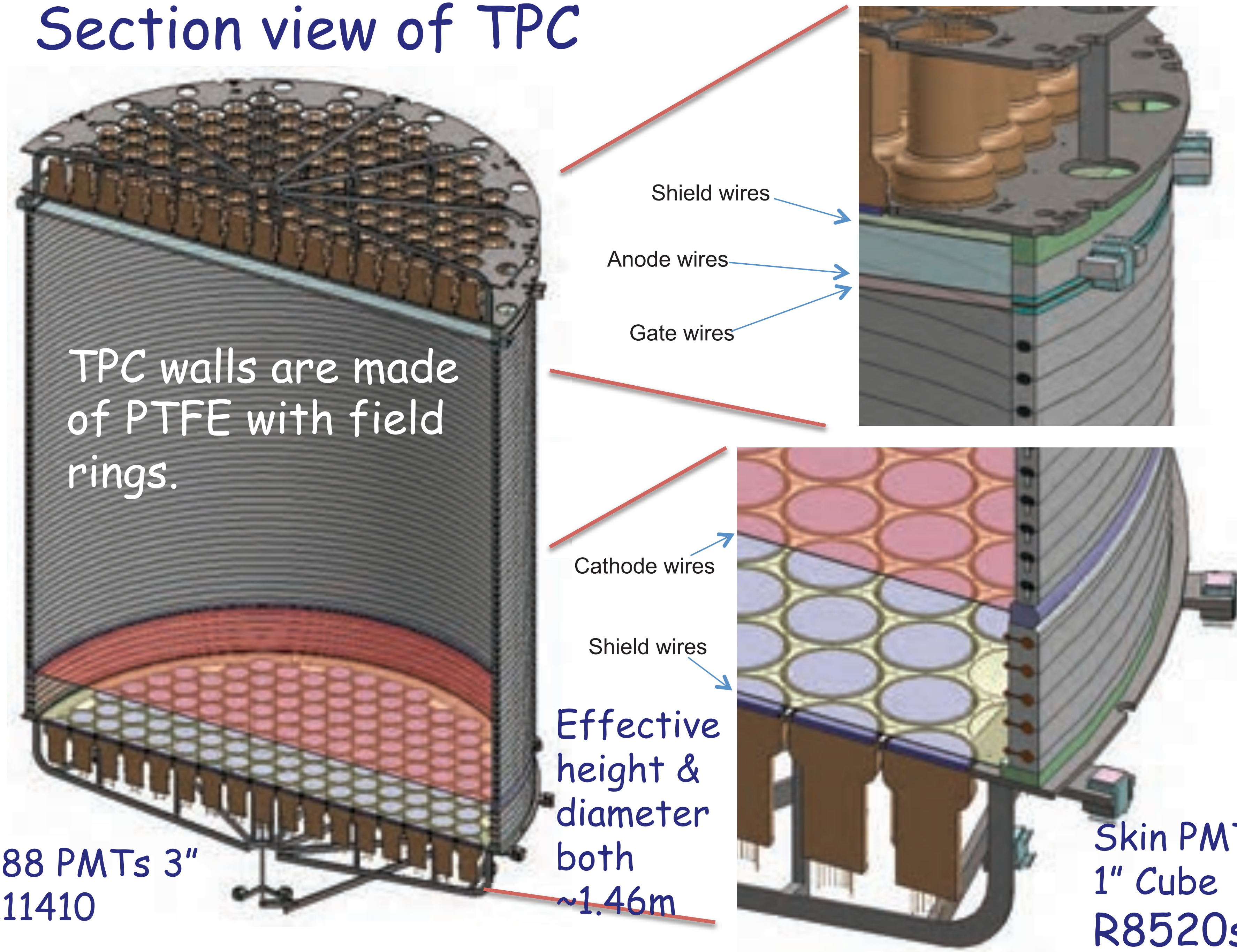
Total mass – 10 T
Active Mass – 7 T
Fiducial Mass – 5.6 T

LZ Overview



Instrumentation
Conduits
Water Tank
High Voltage
Feedtrough
Gadolinium Loaded
Liquid Scintillator
Liquid Xenon
Heat Exchanger
7 Tonne Liq.
Xenon TPC
(Time Projection Chamber)
120 Outer
Detector PMTs
Neutron Calib.
Conduit
488 Photomultiplier Tubes (PMTs)
Additional 200 `skin' PMTs

Section view of TPC



TPC walls are made of PTFE with field rings.

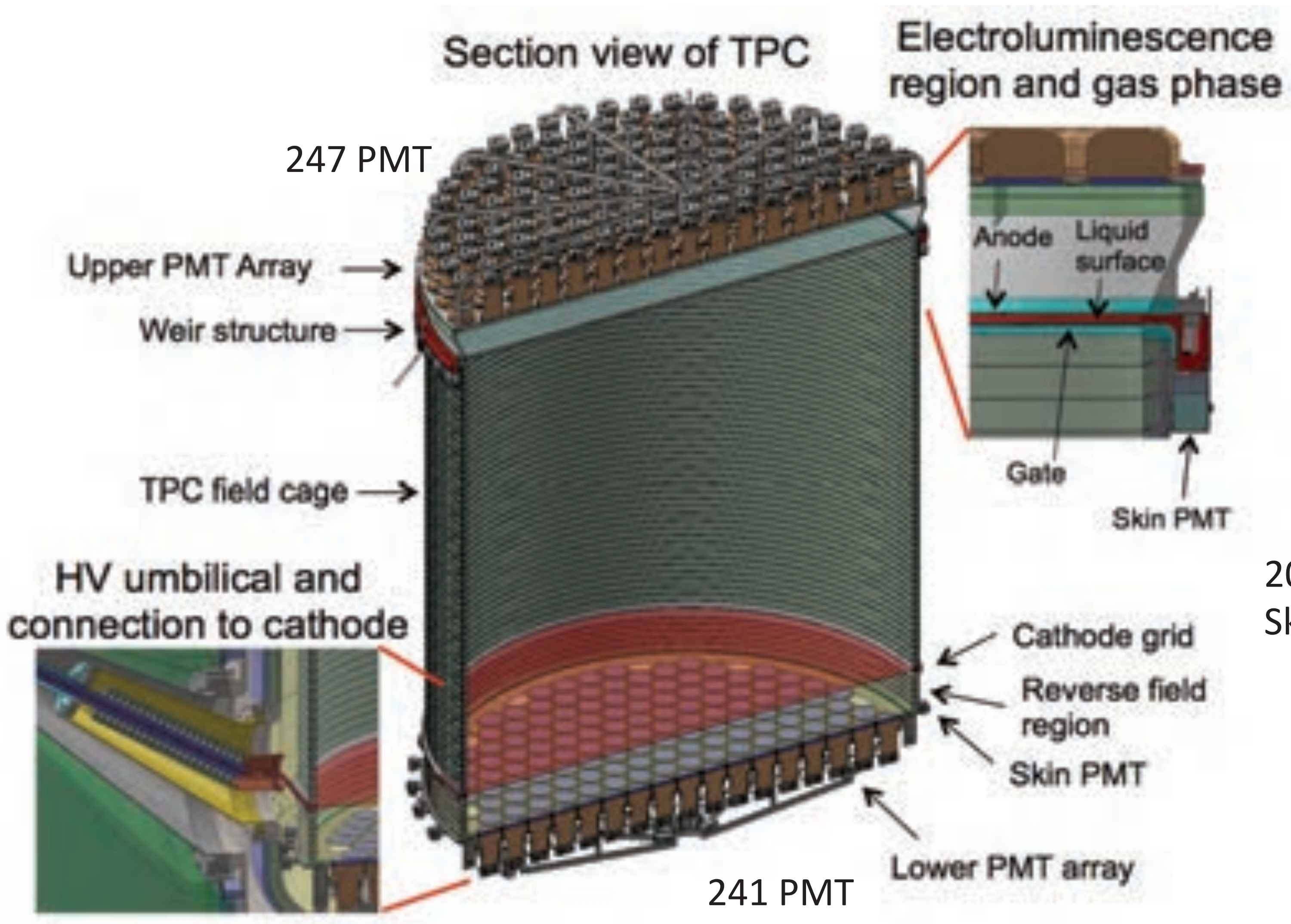
488 PMTs 3″
R11410

Effective height & diameter both ~1.46m

Skin PMTs
1″ Cube
R8520s

Further Details

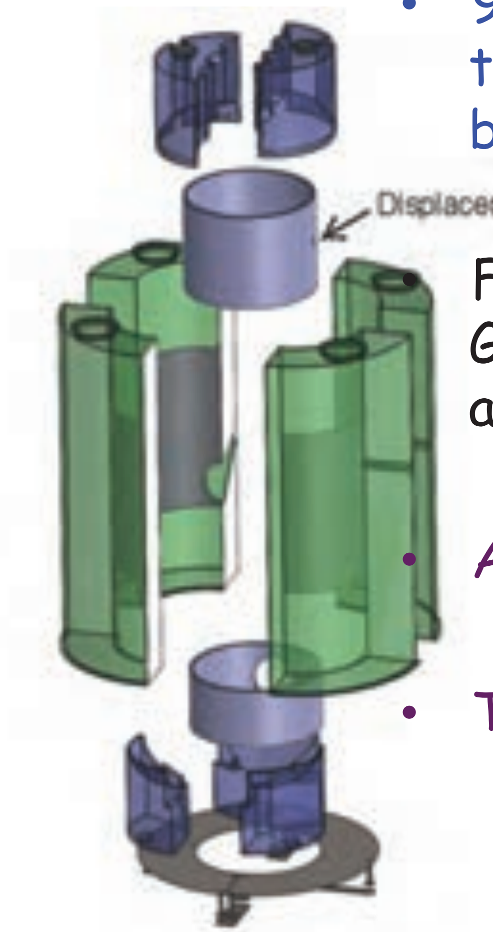
247 PMT



200 total
Skin PMT

241 PMT

Outer Detector: Gamma/neutron veto system



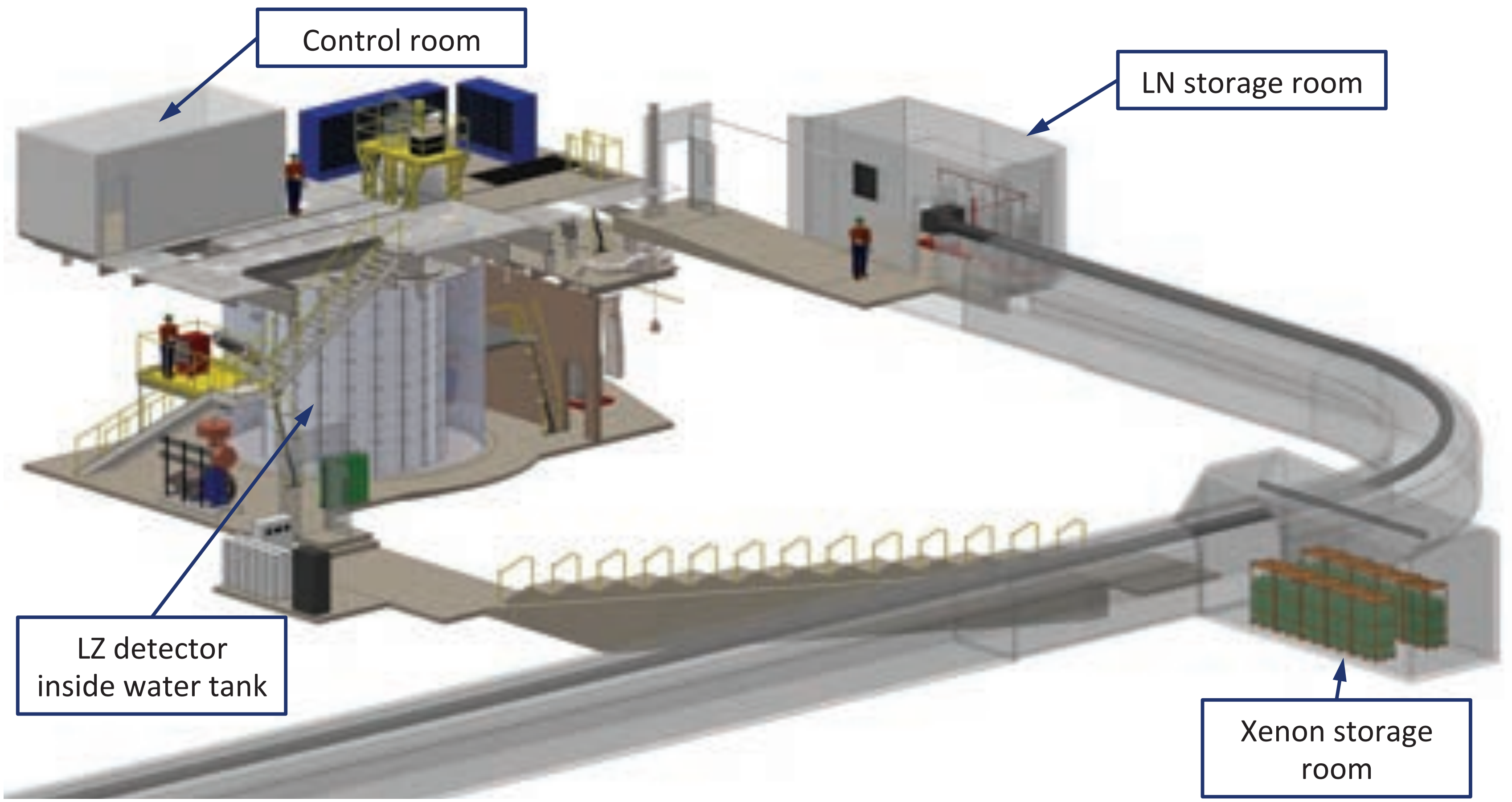
- 9 acrylic tanks surrounding the detector (4 side, 2 top, 3 bottom). 120 8" PMTs.
- Filled with liquid scintillator: Gd loaded (0.2%) LAB (linear alkyl benzene).
- Average thickness ~ 0.75m
- Total LAB Mass: 25 tonnes.

Enables suppression of neutron-induced nuclear recoil rate to below neutrino expectation for active xenon volume.

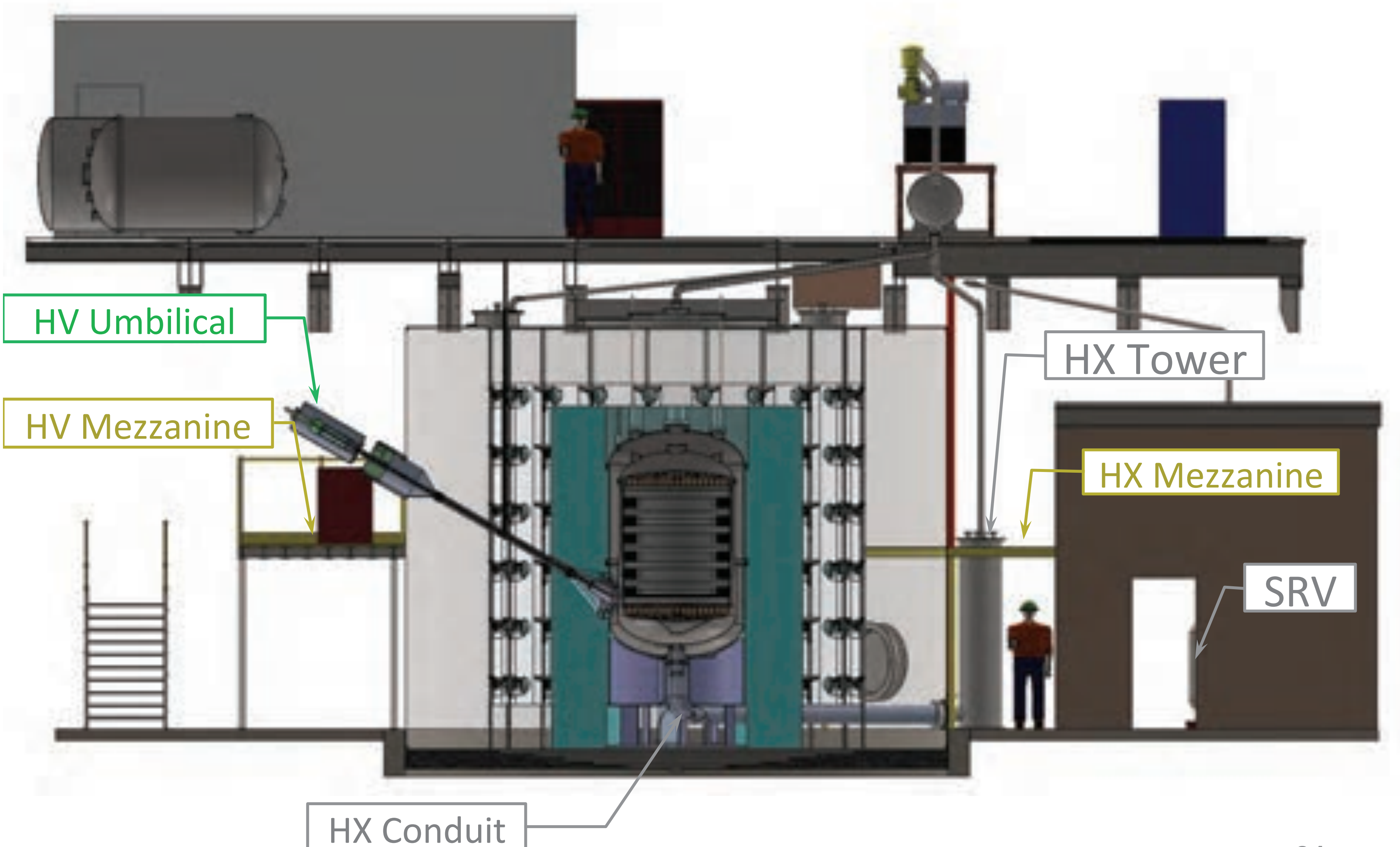
Daya Bay legacy, scintillator & tanks (and people)

LZ Underground at SURF

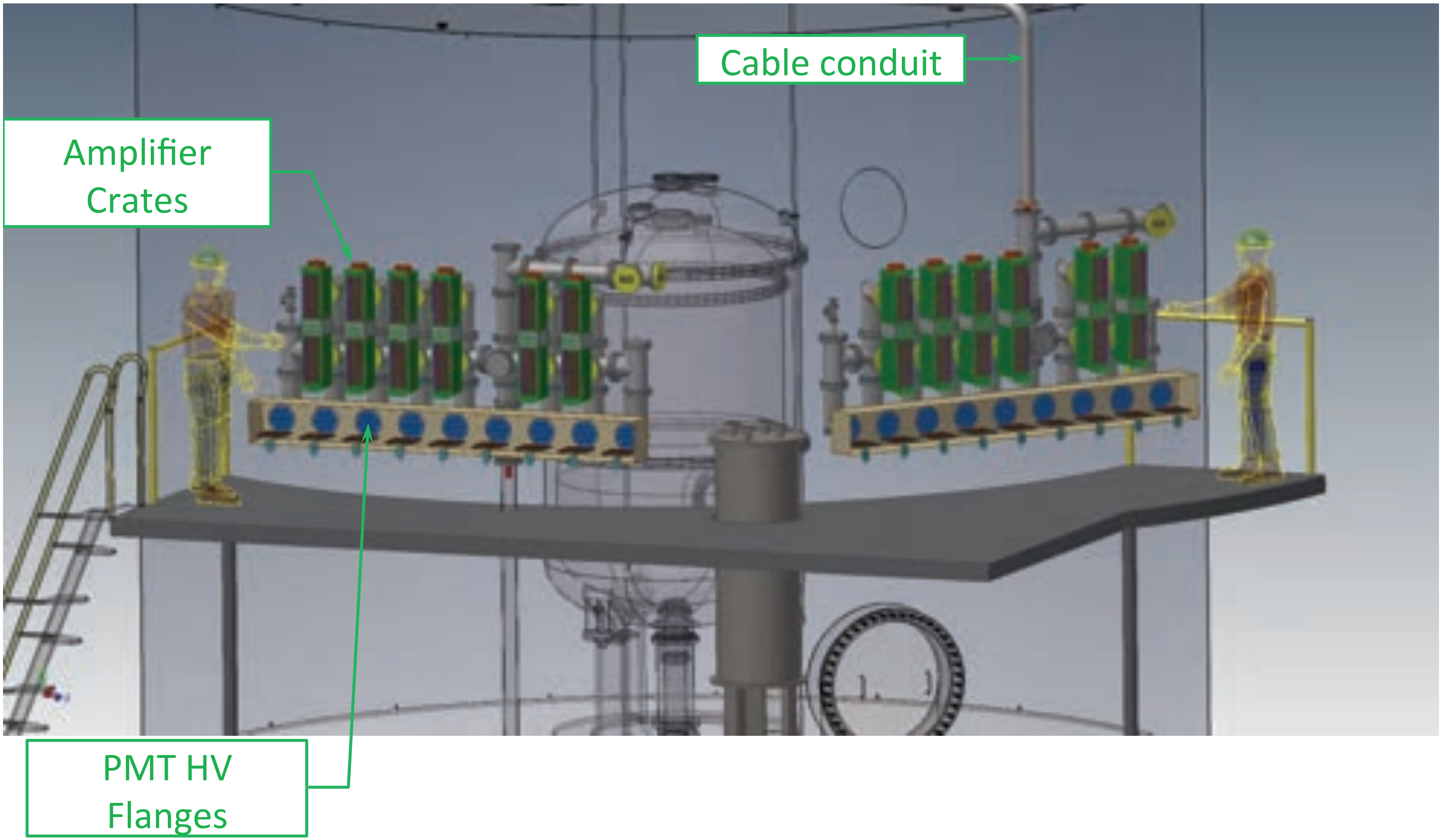
Years of experience at SURF from LUX



Section view



Mezzanine Level



Key Design Points

- ✓ 7 active tonnes of LXe can yield 2×10^{-48} cm^2 sensitivity in about three years of running
- ✓ 5.6 tonne fiducial volume, 1000 days

  - ◆ Xe detector with good light collection, reasonable background rejection (ER discrimination) and good signal detection efficiency
  - ◆ Sophisticated veto system: skin (outside active Xe region) + scintillator/water allows maximum fiducial volume to be obtained, maximizes use of Xe and substantially increases reliability of background measurements
  - ◆ Control backgrounds, both internal (within the Xe) and external from detector components/ environment

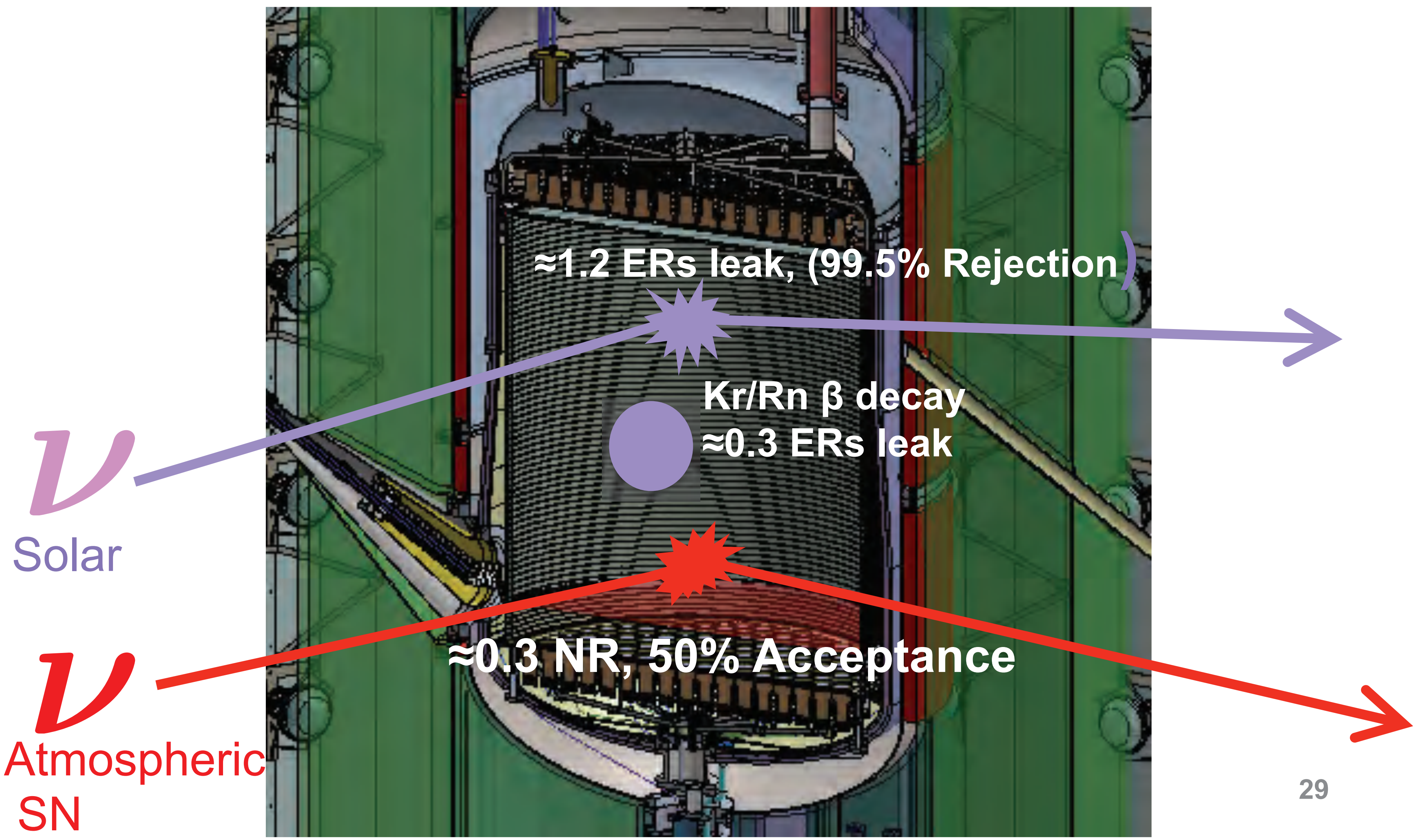
Design Status Summary

- Conceptual, and in some cases more advanced design, completed for all aspects of detector
- Conceptual Design Report about to appear on arXiv
- Acquisition of Xenon started
- Procurement of PMTs and cryostat started
- Collaboration – wide prototype program underway to guide and validate design
- Backgrounds modeling and validation well underway

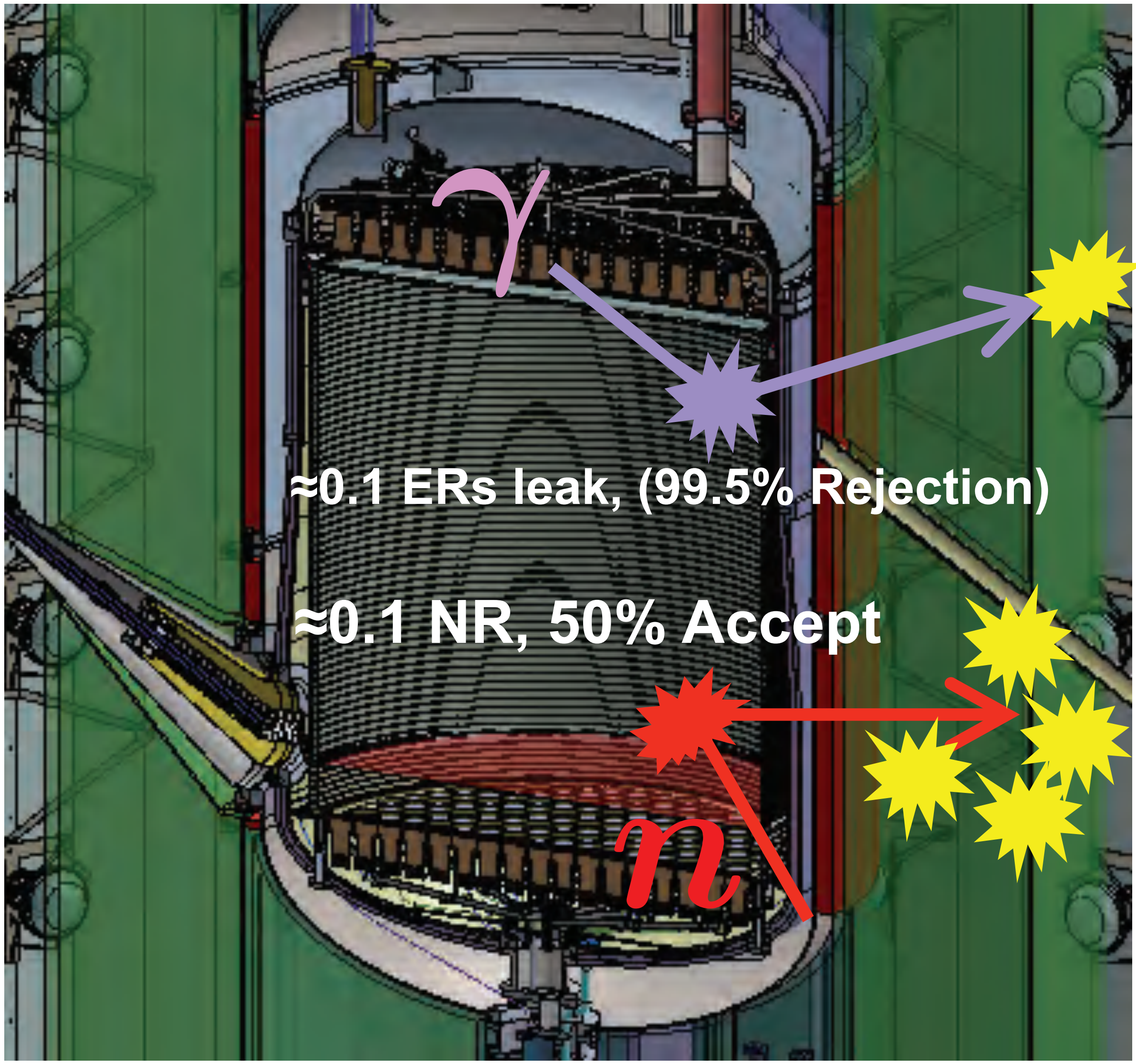
Backgrounds & Discrimination

- Nuclear recoils due to neutrons from detector structures such as PMTs, Ti cryostat, etc., are sub-dominant to leakage from electron recoils.
- Goal for Krypton: <0.02 ppt. This will represent ~10% of solar pp rate. Best production level obtained by LUX is ~0.2 ppt, which would be equal to pp rate. However, we are confident about achieving purity close to the goal level.
- Goal for Radon in LXe: <0.6 mBq.
- Discrimination: >99.5% for 4-30 keVnr, for NR Acceptance of 50%
- PRELIMINARY Estimates: For a total exposure of 1000 days and 5600 kg fiducial mass:
  pp neutrino leakage events ~1.2
  coherent neutrino scatter NR events ~0.3 (for 50% acceptance)

Backgrounds: Uniform Through Volume

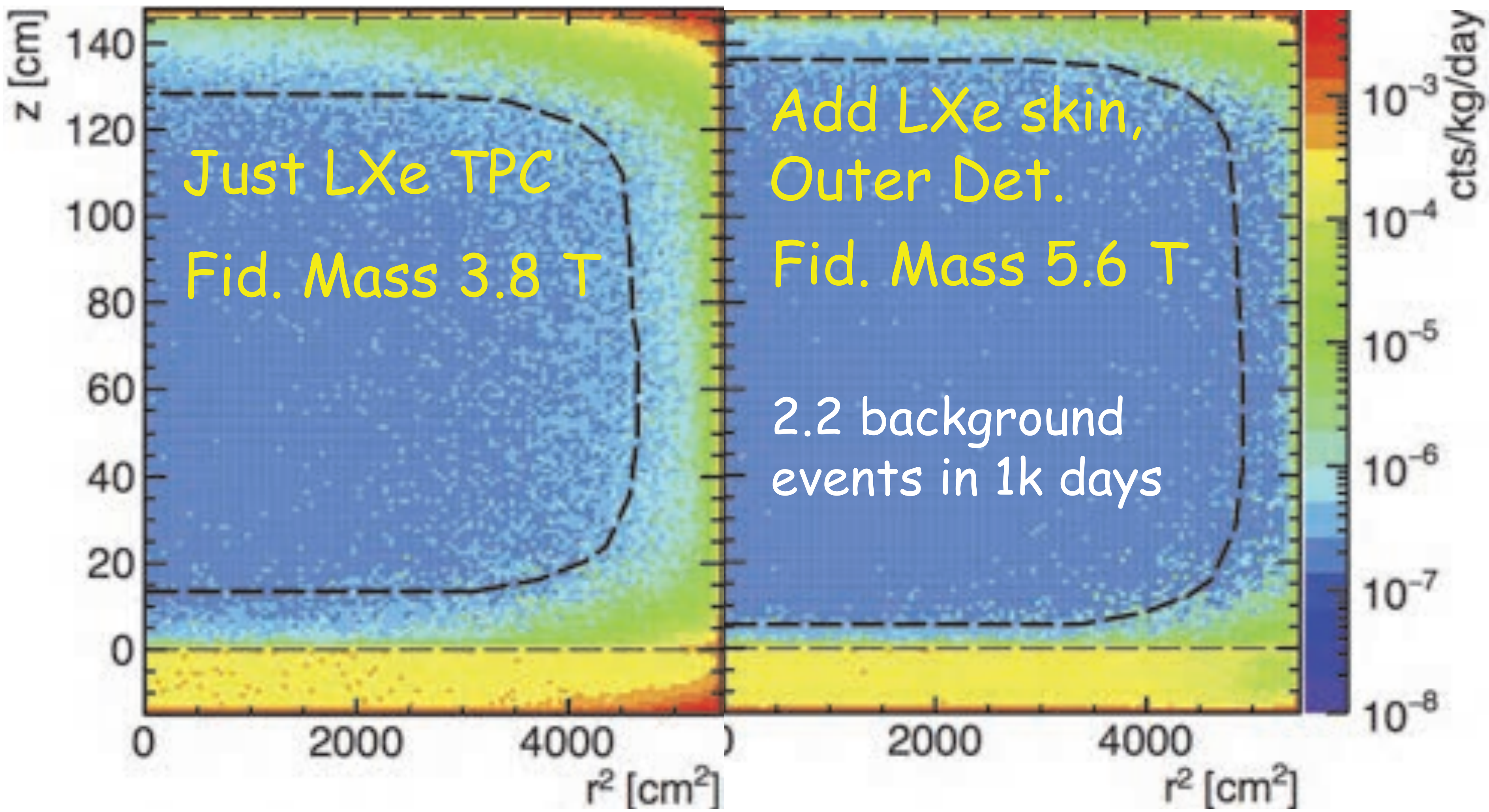


Backgrounds: External Material



Background Modeled

Geant4 based simulations, pioneered in LUX, have been carried forward to LZ.



Xe Detector Prototyping

- Extensive program of prototype development underway. Three general approaches:

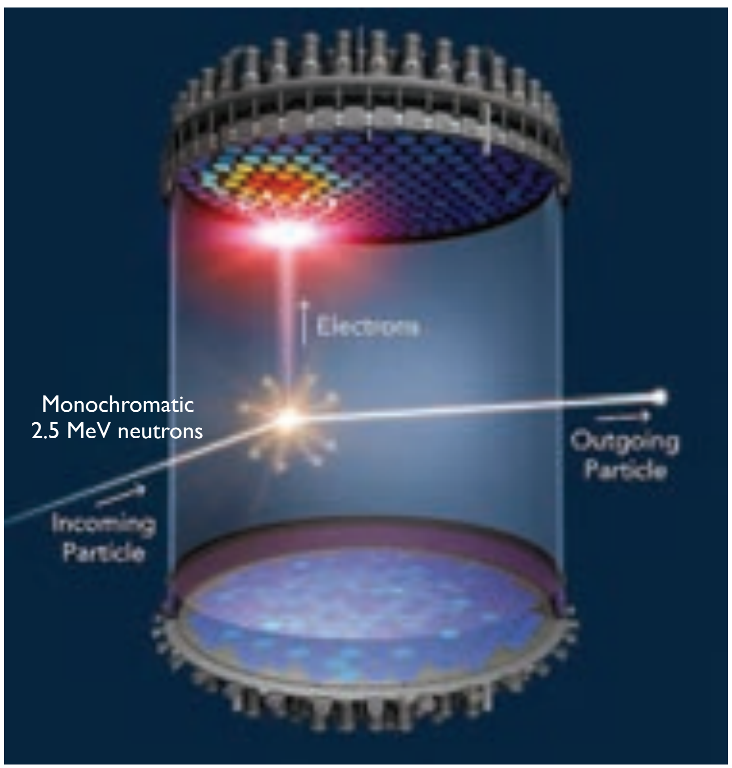
1. Testing in liquid argon, primarily of HV elements, at Yale and soon at LBNL

2. Design choice and validation in small (few kg) LXe test chambers in many locations: LLNL, Yale-> UC Berkeley, LBNL, U Michigan, UC Davis, Imperial College, MEPhI

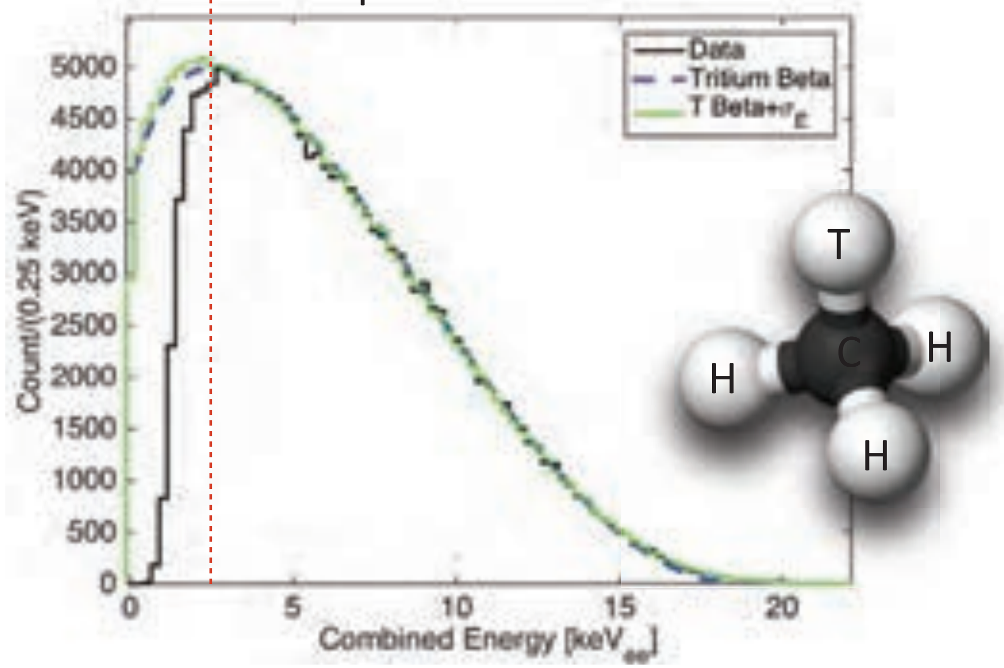
3. System test platform at SLAC, Phase I about 100 kg of LXe, TPC prototype testing to begin in few months

LZ Calibrations

- Demonstrated in LUX. Calibrate The Signal and Background Model *in situ.*
- DD Neutron Generator (Nuclear Recoils)
- Tritiated Methane (Electron Recoils)
- Additional Sources e.g. YBe Source for low energy (Nuclear Recoils)



Tritium Beta Spectrum Measured in LUX



Extensive Calibration

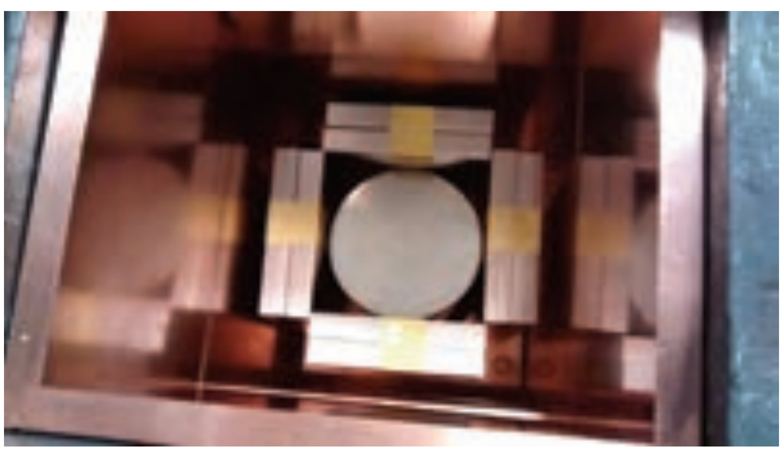
✦ LUX has led the way to detailed calibrations. LZ will build on this and do more.

Done in LUX and will be done in LZ	Not done in LUX, but will do in LZ
^{83m}Kr (routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
Tritiated methane (every few months)	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator(upgraded early next year to shorten pulse)	

Cryostat Vessels

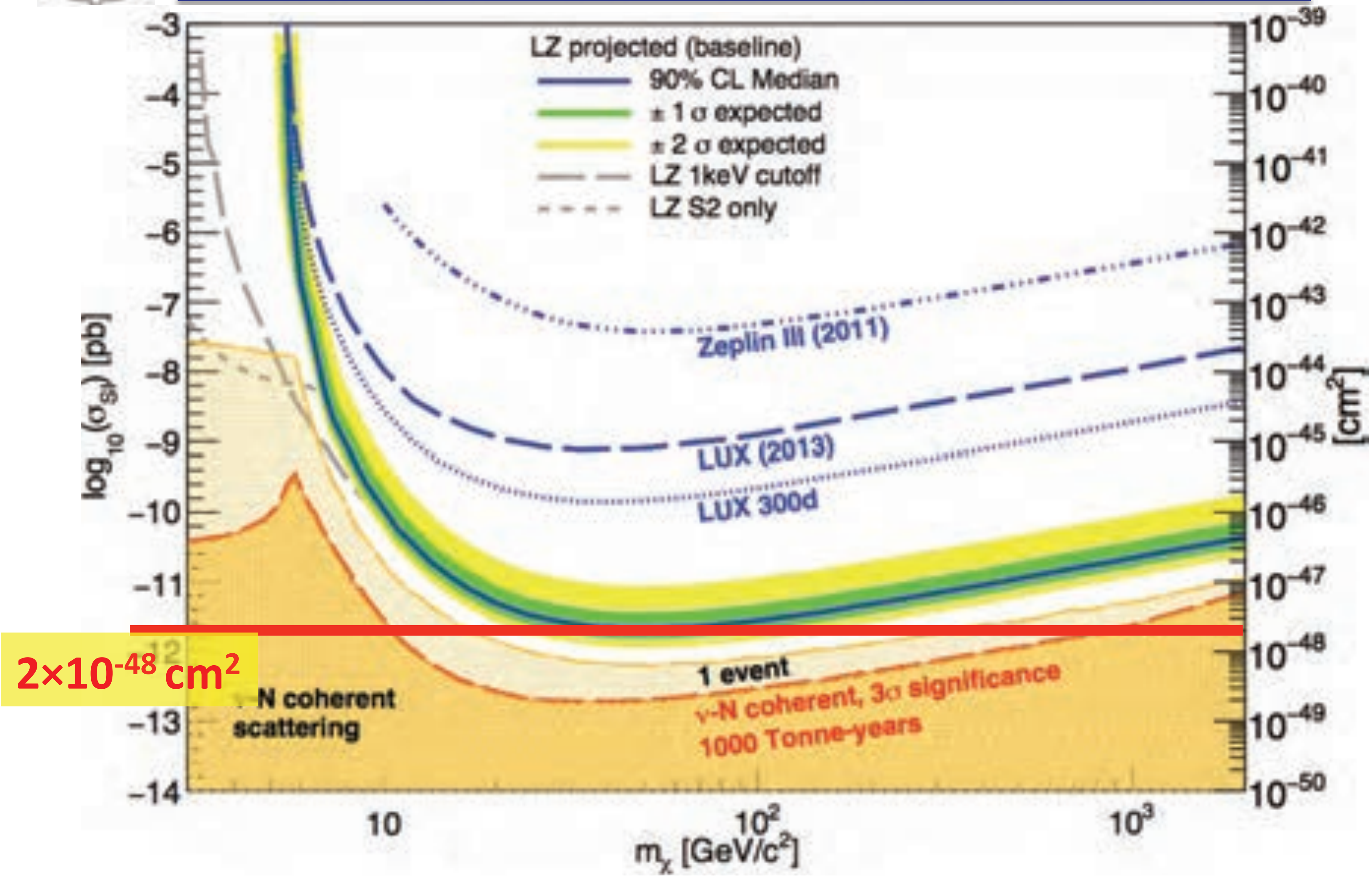
- UK responsibility
- Low background titanium chosen direction

  SS alternative advanced as backup
- Ti slab for all vessels(and other parts) received and assayed
- Contributes < 0.05 NR+ER counts in fiducial volume in 1,000 days after cuts

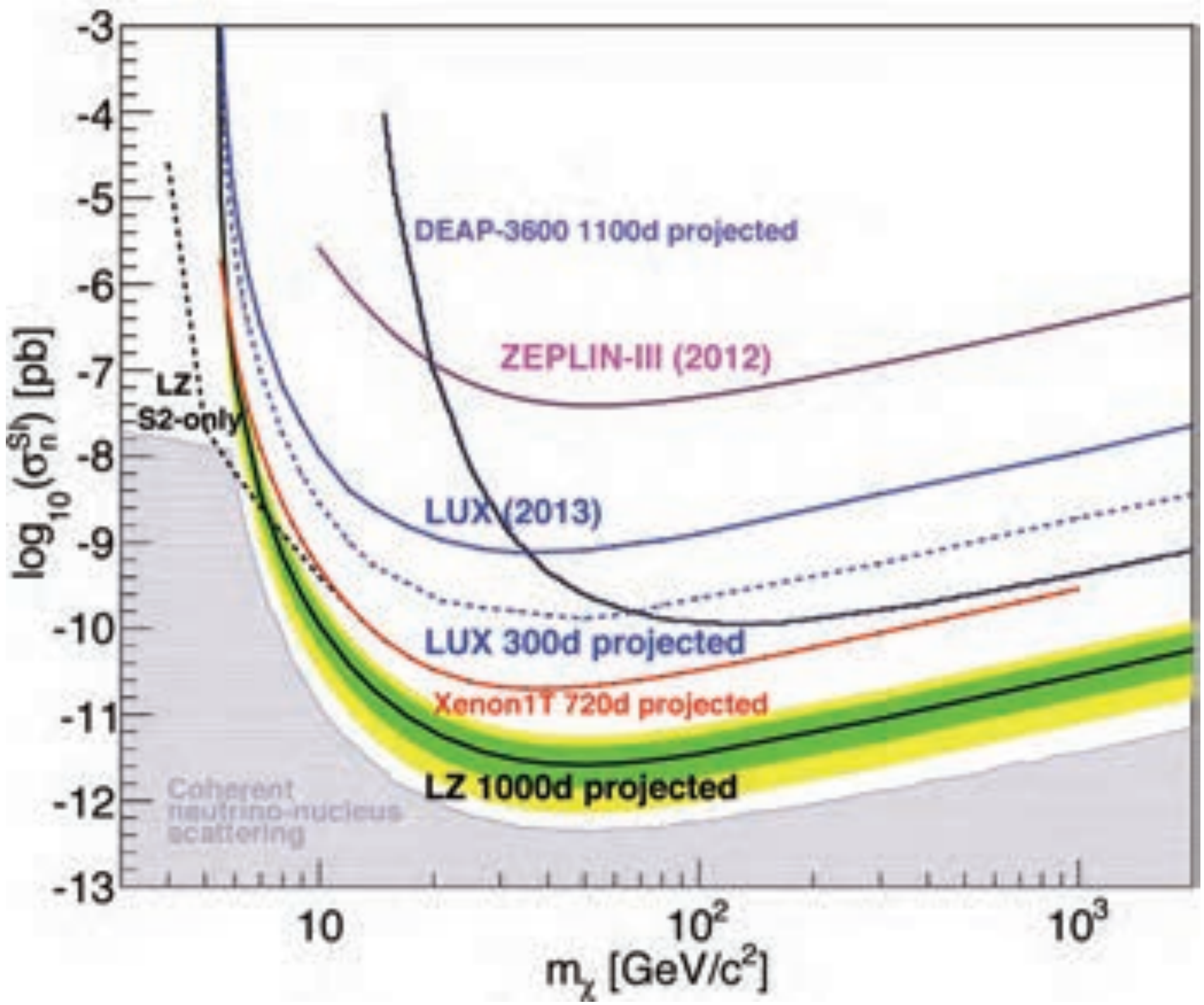


Projected Sensitivity - Spin Independent

(LZ 5.6 Tonnes, 1000 live days)



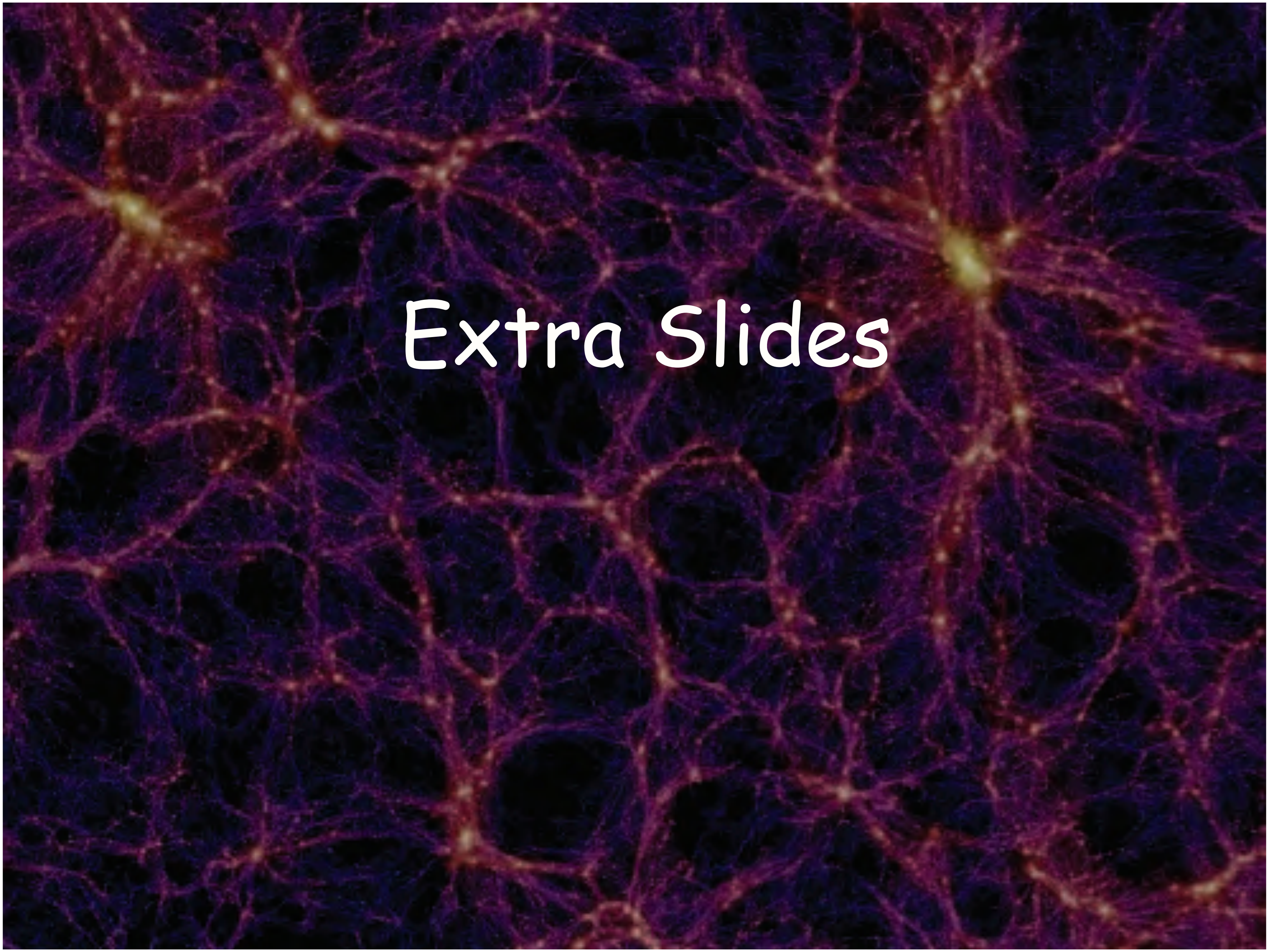
Sensitivity Comparison



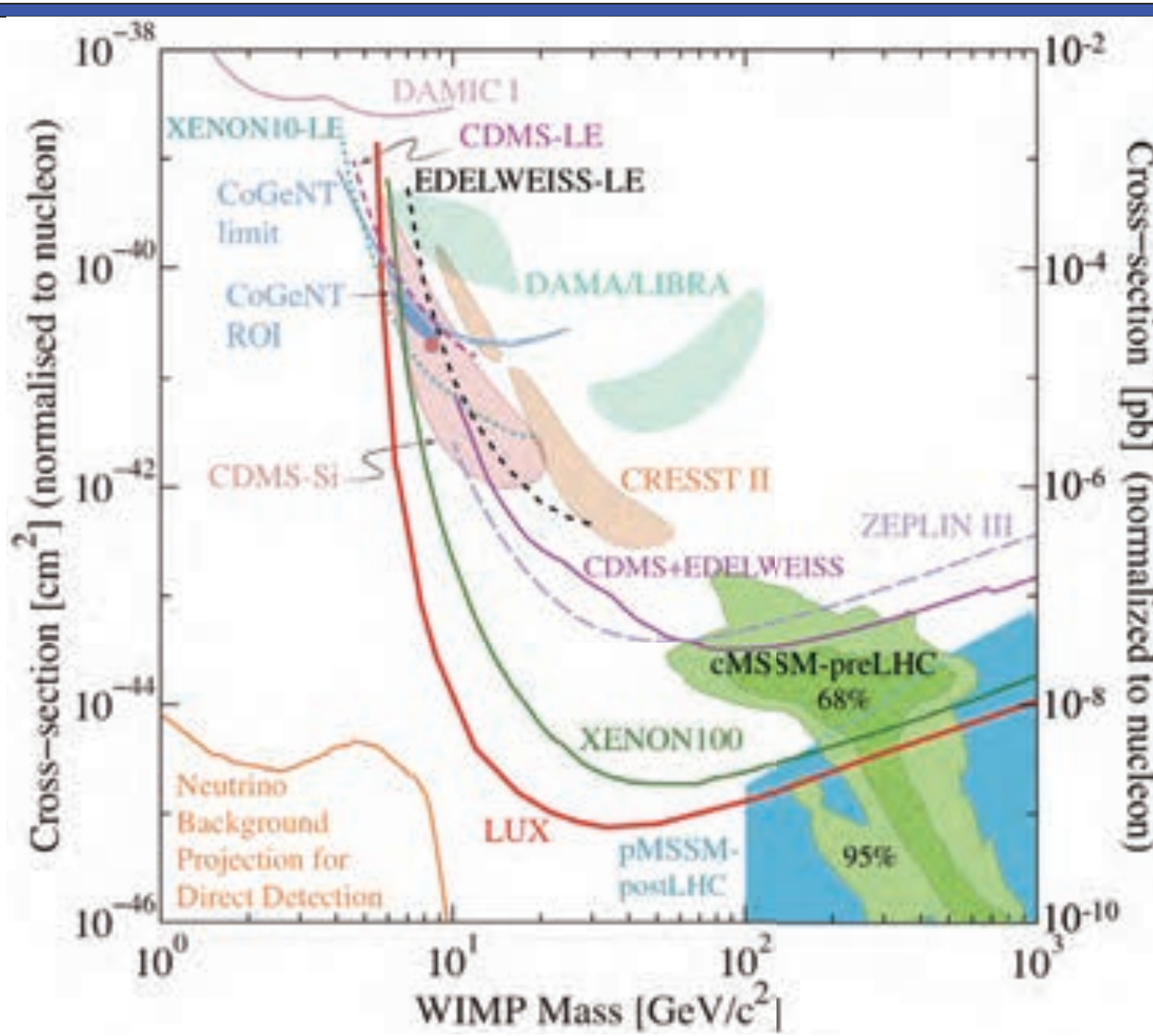
Summary

- LUX has provided the most stringent limit on the WIMP-nucleon spin-independent interaction cross-section, and pioneered techniques with internal calibration sources.
- LZ holds the promise to be the ultimate WIMP search experiment. Limited by neutrino-induced `background'.
- LZ Project well underway. Procurement of Xe, PMTs and cryostat vessels started. Extensive prototyping program.
- Projected commissioning in 2019.

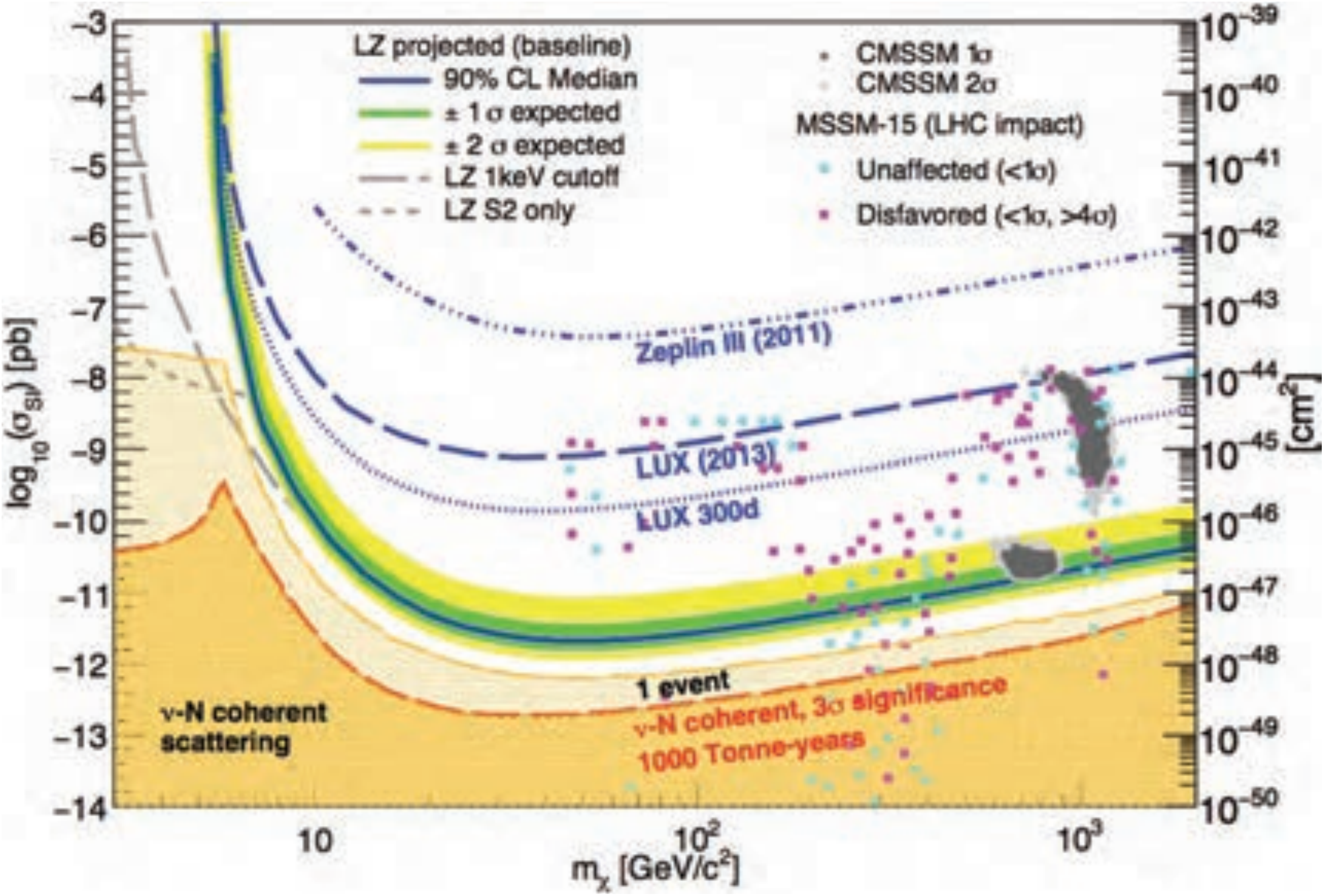
Waiting for the Jackpot


Extra Slides

LUX Limit


DAMIC I
XENON10-LE
CDMS-LE
EDELWEISS-LE
CoGeNT limit
CoGeNT ROI
DAMA/LIBRA
CDMS-Si
CRESST II
ZEPLIN III
CDMS+EDELWEISS
cMSSM-preLHC
68%
95%
XENON100
LUX
pMSSM-postLHC
Neutrino Background Projection for Direct Detection
Cross−section [cm^2] (normalised to nucleon)
Cross−section [pb] (normalized to nucleon)
WIMP Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3

Sensitivity with SUSY Theories



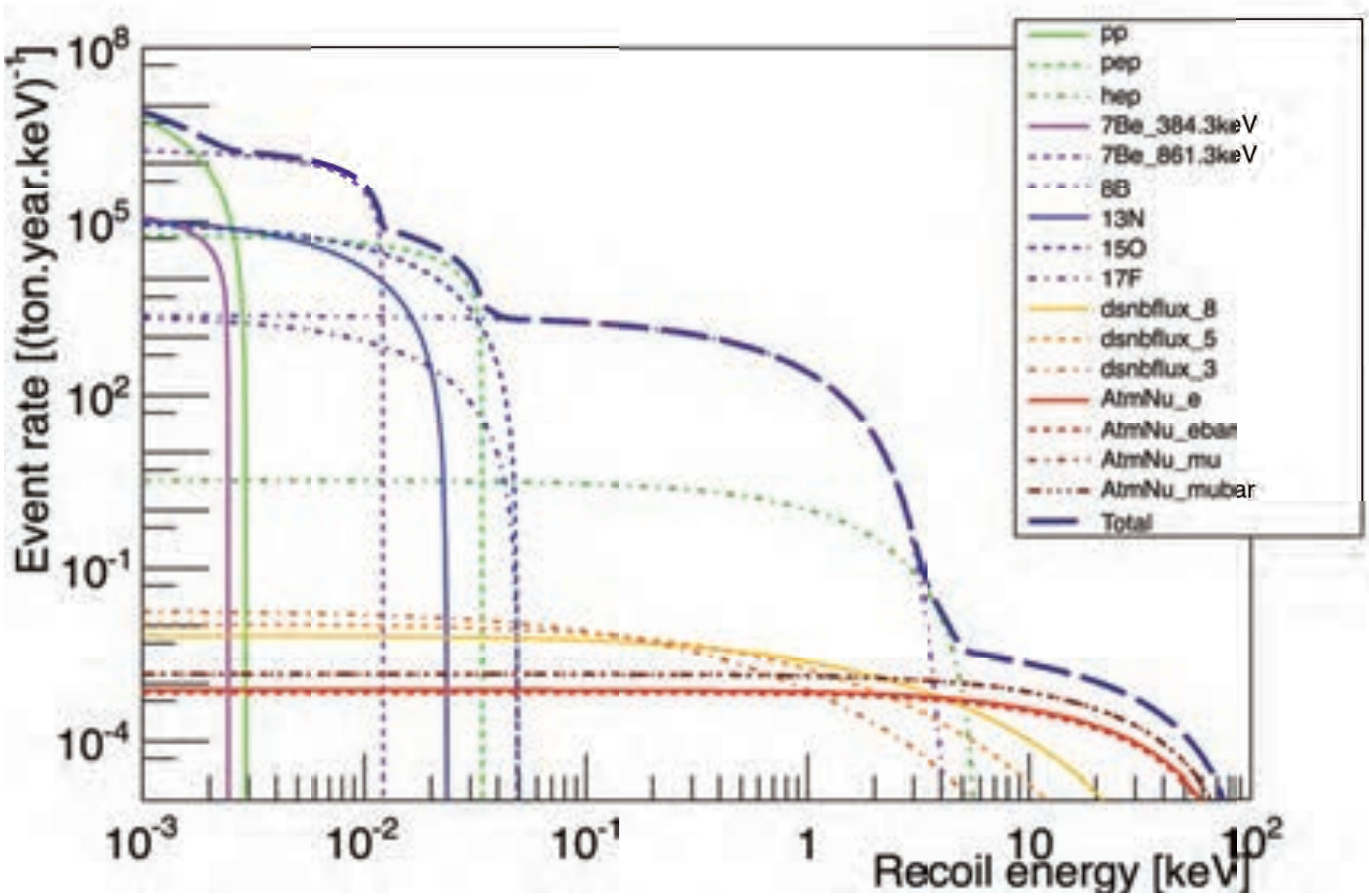
Other Physics…

- ✦ Effective Field Theory Interaction Decomposition

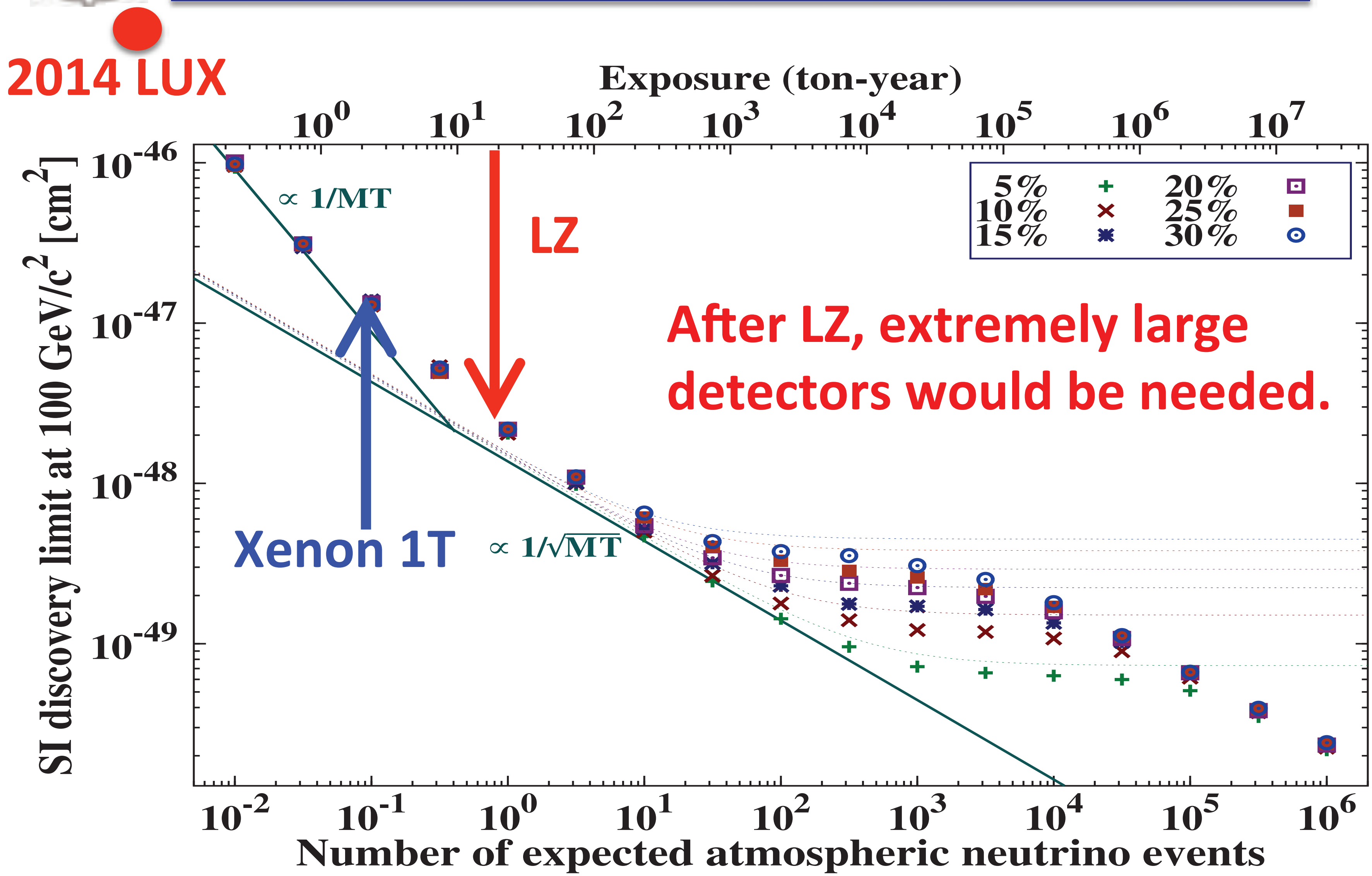
- ✦ Double Beta Decay

- ✦ External Neutrino Physics
  - ☐ Solar
  - ☐ Supernova
  - ☐ Sterile Neutrino

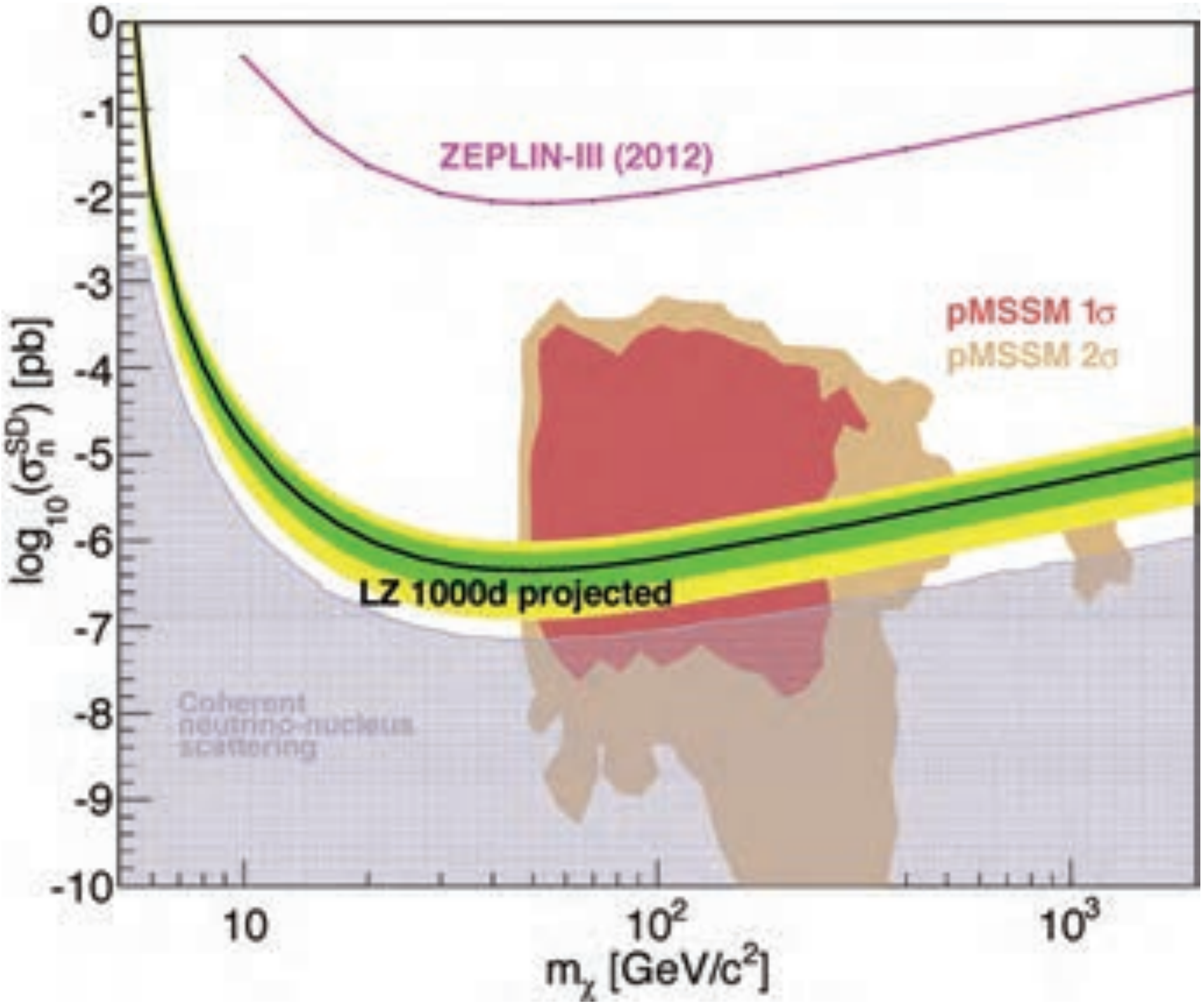
Response of Xe to Neutrinos arXiv:1307:5458



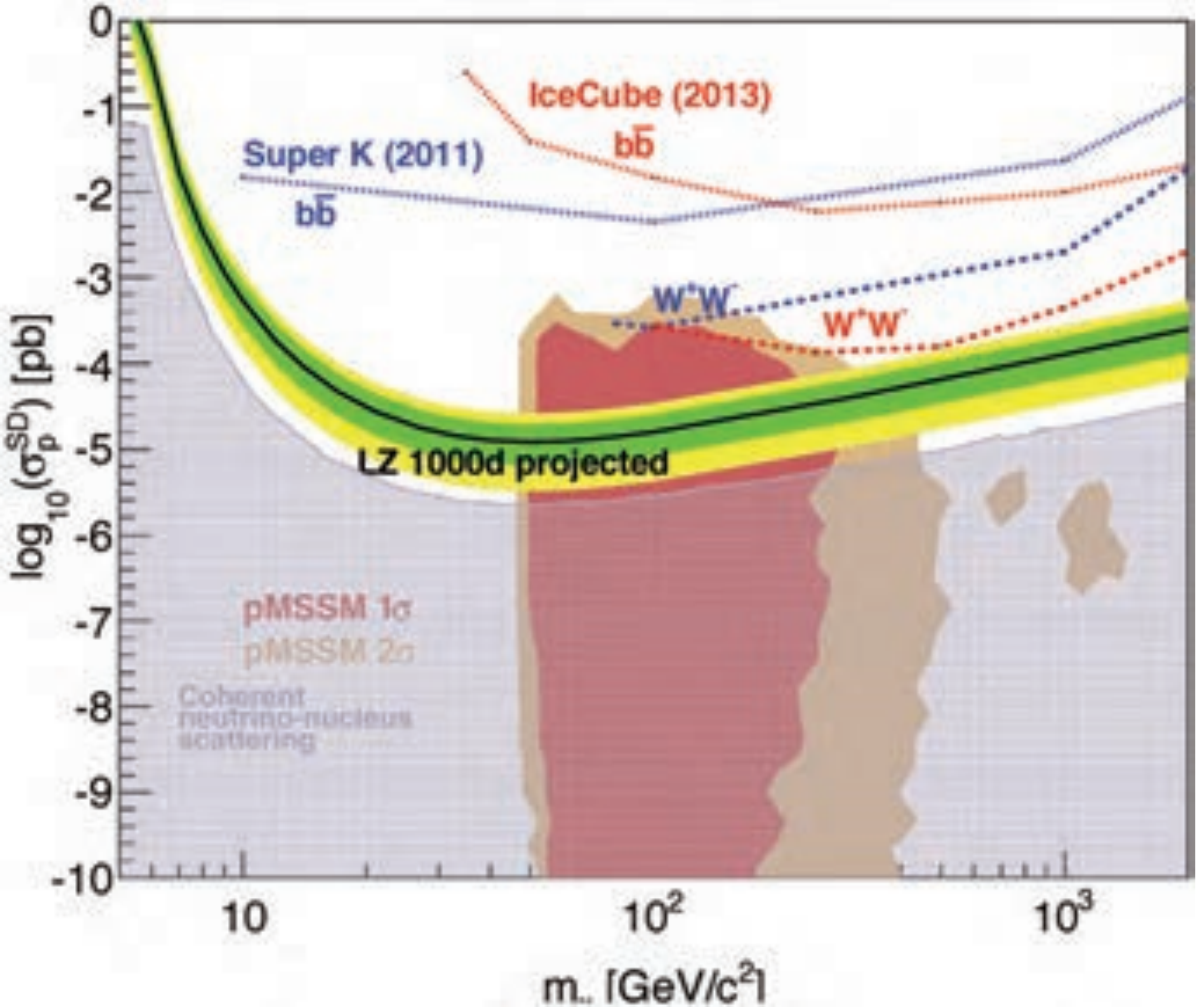
LZ – At the neutrino `knee' arXiv:1408.3581



Spin Dependent Neutron

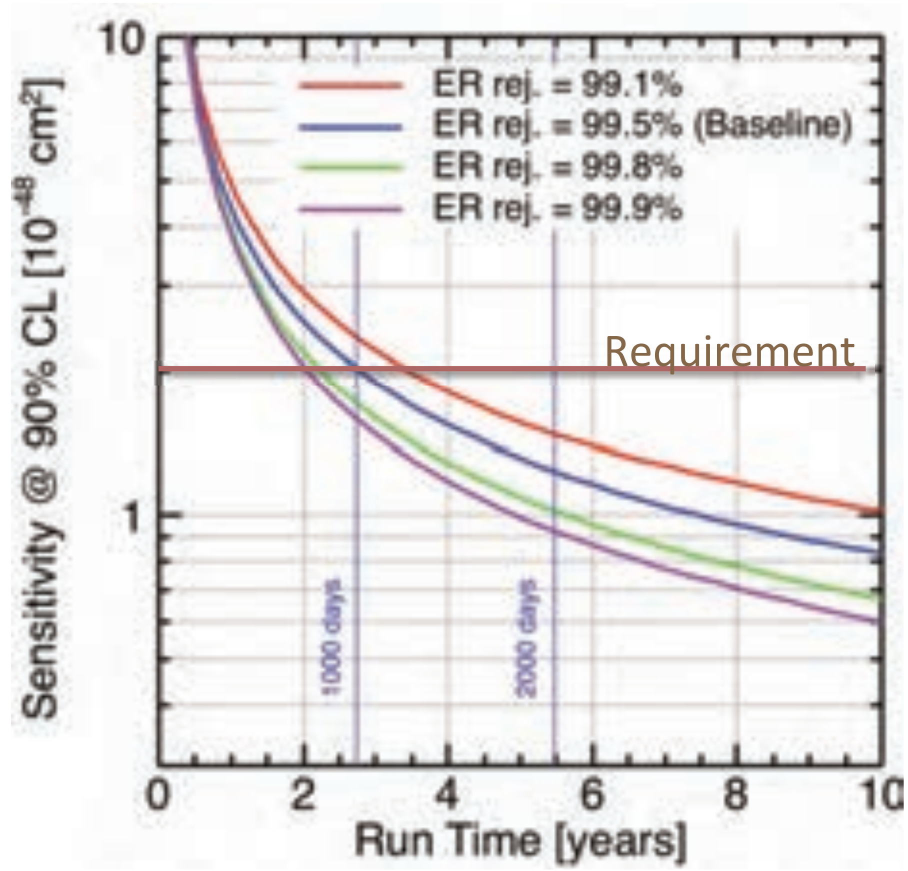


Spin Dependent Proton



Running Time

- ✦Sensitivity vs. running time.
- ✦1,000 days is the nominal.
- ✦Baseline backgrounds
- ✦Rapid improvement in sensitivity
- ✦Potential to eventually get to ~ 1×10^{-48} cm^2



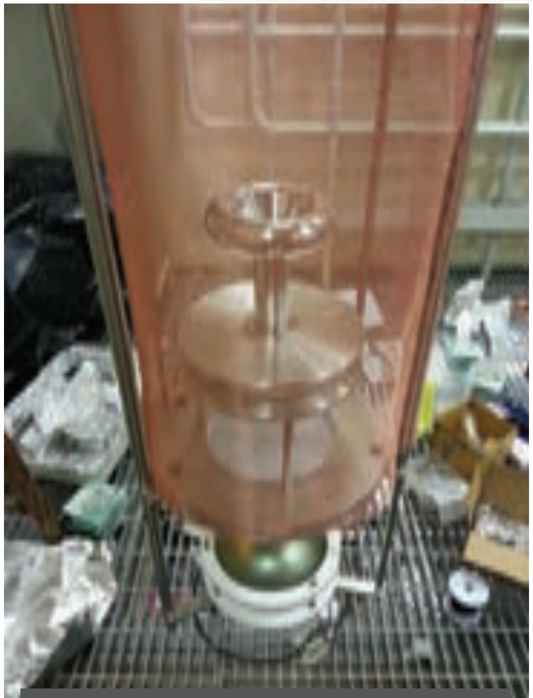
^{85}Kr Removal and Screening

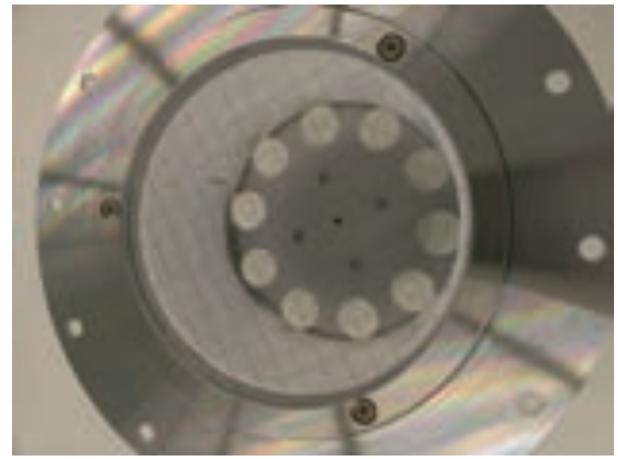
- Remove Kr to <15 ppq (10^{-15} g/g) using gas chromatography.
- Best LUX batch 200 ppq
- Setting up to process 200 kg/day at SLAC
- Have a sampling program to instantly assay the removal at SLAC and continuously assay in situ

Xe Detector PMTs

- R11410-22 3” PMTs for TPC region
  - Extensive development program, 50 tubes in hand, benefit from similar development for XENON, PANDA-X and RED
  - Materials ordered and radioassays started prior to fabrication.
  - First production tubes early 2016.
  - Joint US and UK effort
- R8520-406 1” for skin region
  - Considering using 2” or 3” for bottom dome region, recycle tubes from older detectors

High Voltage Studies





Prototype of highest E-field region tested in LAr

Wire grid tests ongoing

- ✦ Cathode voltage design goal: 200 kV (provides margin)
- ✦ LZ nominal operating goal: 100 kV (~700 V/cm)
- ✦ Feedthrough prototype tested to 200 kV
- ✦ Prototype TPC for 100 kg LXe system fabrication starting
- ✦ HV prototyping expanding at Berkeley