Direct Dark Matter Searches

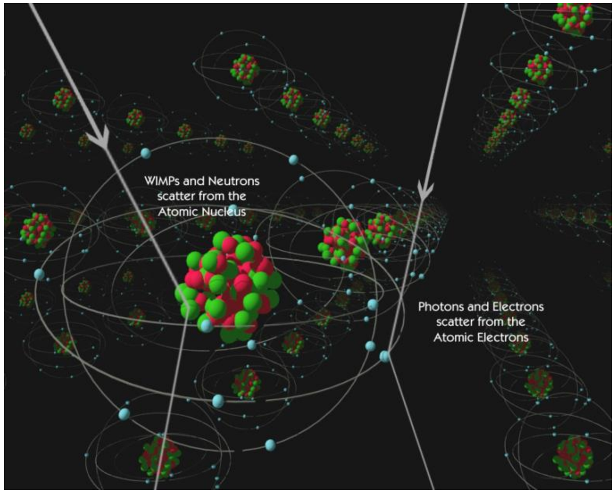
General Overview

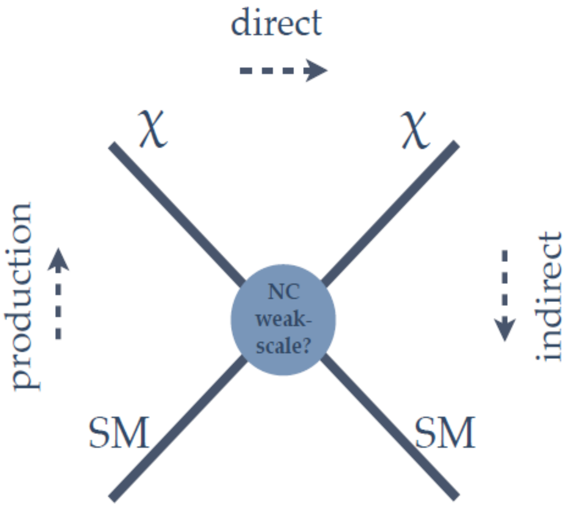
LUX-ZEPLIN

Hans Kraus, Oxford

How to detect dark matter

1. Direct detection (scattering XS)
   - **Nuclear (atomic) recoils from elastic scattering**
   - A- & J-dependence, annual modulation, directionality
   - Galactic DM at the Sun's position – our DM!
   - Mass measurement (if not too heavy)





2. Indirect detection (decay, annihilation XS)
   - High-energy cosmic-rays, γ-rays, neutrinos, etc.
   - Over-dense regions, annihilation signal $\propto n^2$
   - Very challenging backgrounds

3. Accelerator searches (production XS)
   - MET, mono-X, dark photons, etc.
   - Mass measurement may be poor at least initially
   - May not establish that new particle is the DM

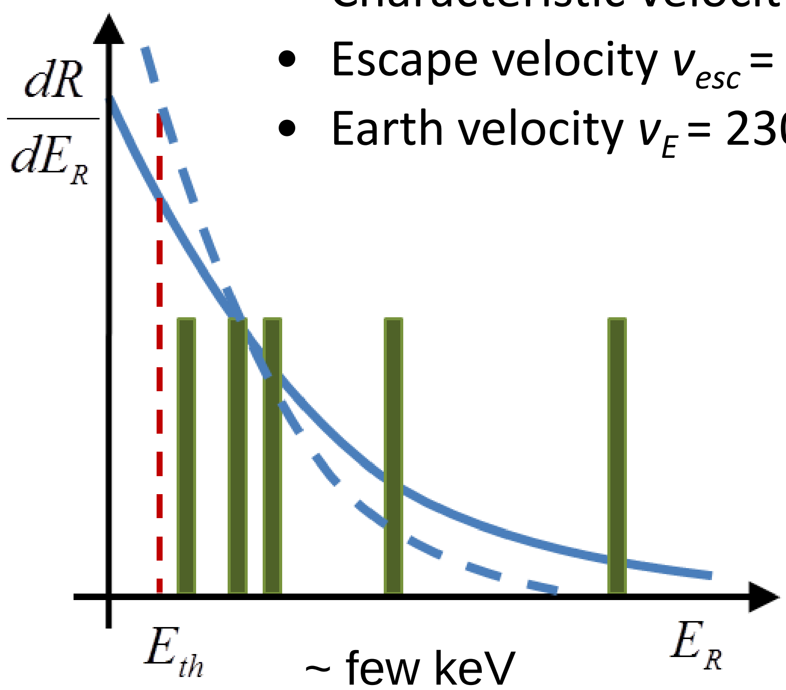
WIMP-nucleus elastic scattering

The simplified spherical galactic model

- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3$ GeV/cm^3

Maxwellian (truncated) velocity distribution, f(v)

- Characteristic velocity $v_0 = 220$ km/s
- Escape velocity $v_{esc} = 544$ km/s
- Earth velocity $v_E = 230$ km/s



Nuclear recoil energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3 v$$

$$\frac{dR}{dE_R} \approx \frac{R_0}{E_0 r} e^{-E_R / E_0 r}, \quad r = \frac{4 m_W m_T}{(m_W + m_T)^2} \leq 1$$

WIMP-nucleon elastic scattering cross sections

- **Coupling to p and n more useful than coupling to nucleus**
  - Compare different targets materials, accelerator & indirect searches
- **Spin-independent (scalar) interaction**

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z) f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

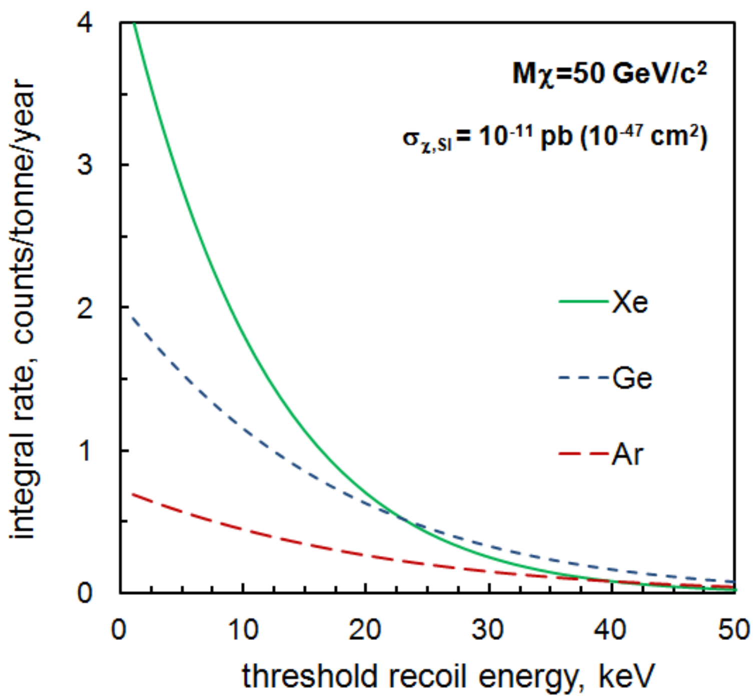
  – Note A^2 enhancement factor (coherence)

- **Spin-dependent (axial-vector) interaction**

$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

  – Note J (nuclear spin) replaces A^2 enhancement – less sensitive than SI
  – Some targets more sensitive to proton, others to neutron scattering

Experimental Challenge



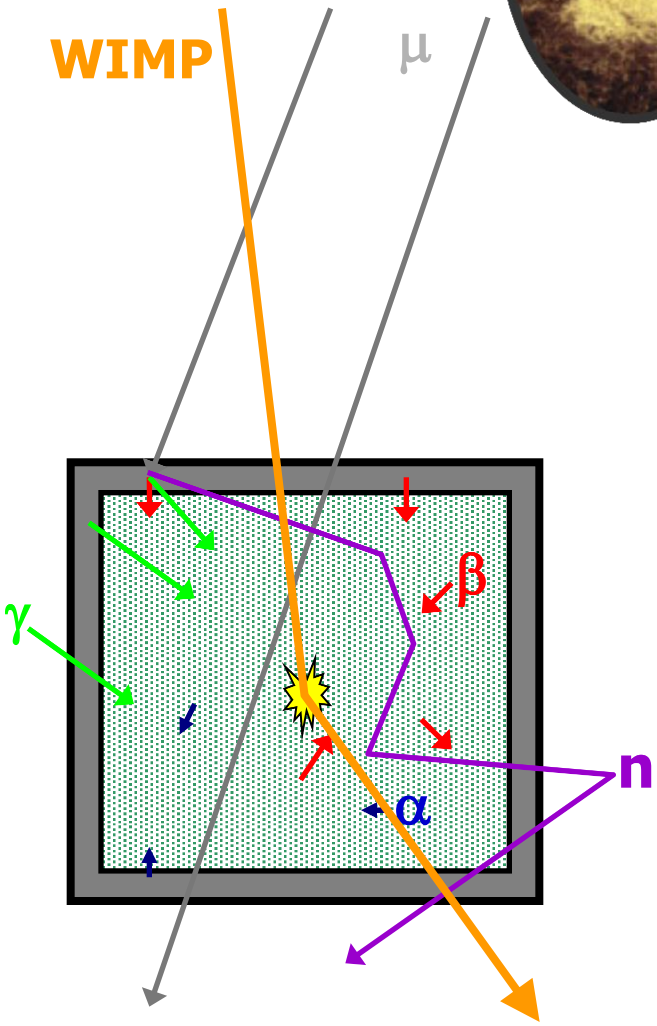
Key requirements

- Large mass x time
  - Low E_R threshold
    - Low background
      - ER/NR discrimination

- Low-energy detection is easy ;)
  - Several technologies allow sub-keV NR detection
- Rare event searches are also easy ;)
  - Not a problem at >100 MeV, think neutrinos
- But doing both is hard!
  - Large is better for shielding against external backgrounds
  - But harder to collect quantum-level signal 'carriers' from deep inside detector volume
- Also: there is no trigger…

Building a WIMP detector

- Consider 1 kg target
  Sensitive to E_{dep}>1 keV
- Expected WIMP rates
  - 0.01−0.000001 evt/day
- However…
- Cosmic rays, α, β, γ-rays
  - >1,000,000 evt/day
- Neutrons are dangerous!
  - Several evt/day
- Neutrinos will be ultimate background



The backgrounds

- **Nuclear recoils – same signature, possibly irreducible**
  - **Neutrons from (α,n) and SFission from U/Th trace contamination**
    - Local environment, shields, vessels, components, target material itself
  - **Nuclear recoils from alpha decay (e.g. radon daughter plate-out)**
    - Contaminating detector surfaces
  - **High energy neutrons from atmospheric muon spallation**
    - Difficult to shield completely even underground
  - ***Eventually, coherent neutrino-nucleus scattering*** *(new!)*
- **Electron recoils – discrimination power is finite**
  - **Gamma-ray background external to target**
    - U/Th, K-40, Cs-137, from environment, shields, vessels, components
  - **Contamination in target bulk and detector surfaces**
    - U/Th betas and gammas (Pb-214, Bi-214, Pb-210,…)
    - Cosmogenic (Ar-39, Ge-68, Ge-71,…), anthropogenic (Kr-85, Cs-137,…)
  - ***Eventually, elastic scattering of solar pp neutrinos off electrons*** *(new!)*

WIMP search detectors

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, DAMIC, DRIFT,
DM-TPC, GENIUS, IGEX, NEWAGE

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, LUX, WARP, DarkSide
Panda-X, XENON, ZEPLIN, LZ

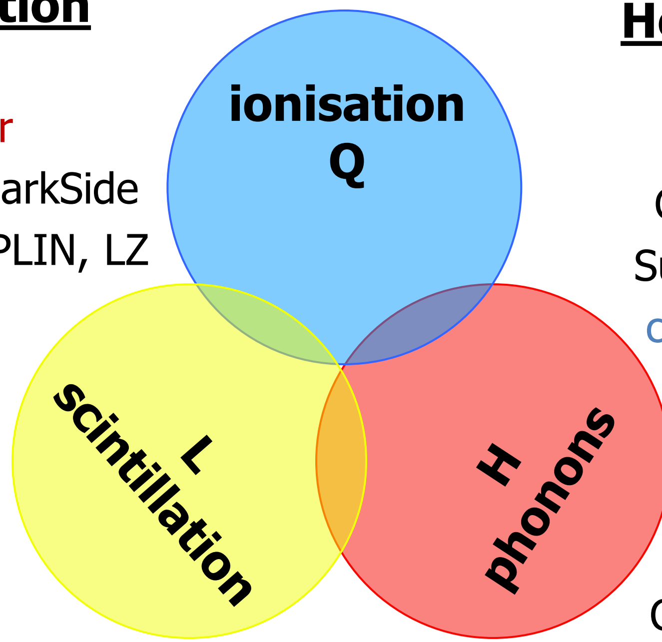
cold (LN_2)

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS
SuperCDMS, EURECA

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, CLEAN, DAMA,
DEAP3600, KIMS, LIBRA,
NAIAD, XMASS, ZEPLIN-I

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, ROSEBUD

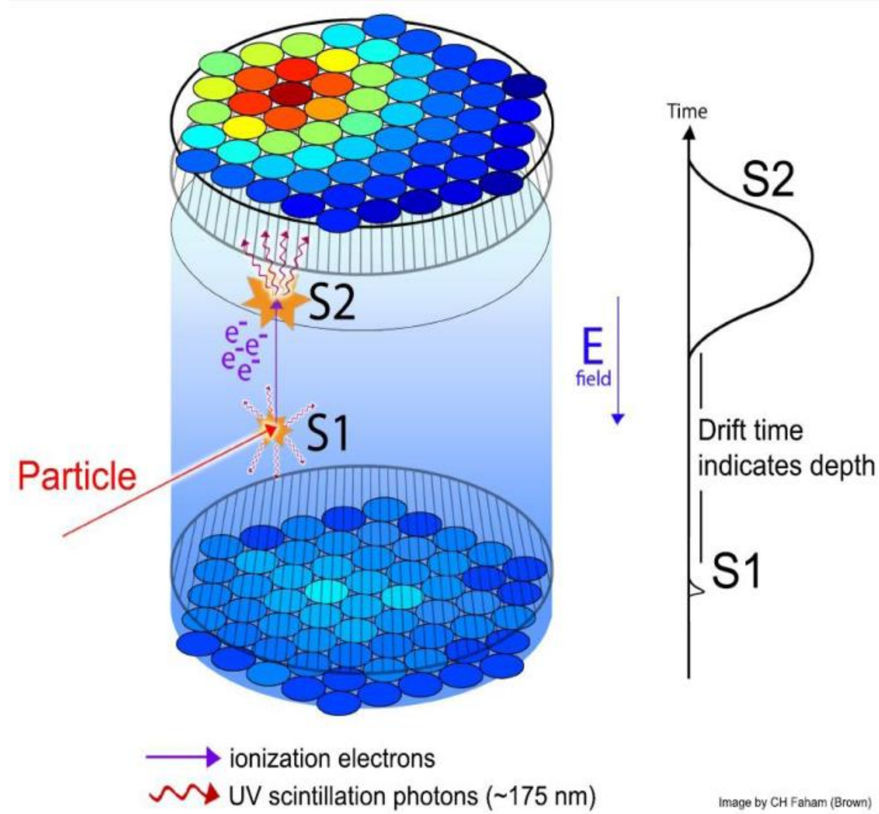
cryogenic (<50 mK)

Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

Two-phase Xenon TPC



S1: prompt scintillation signal

- Light yield: ~60 ph/keV (ER, 0 field)
- Scintillation light: 178 nm (VUV)
- **Nuclear recoil threshold ~5 keV**

S2: delayed ionisation signal

- Electroluminescence in vapour phase
- Sensitive to single ionisation electrons
- **Nuclear recoil threshold <1 keV**

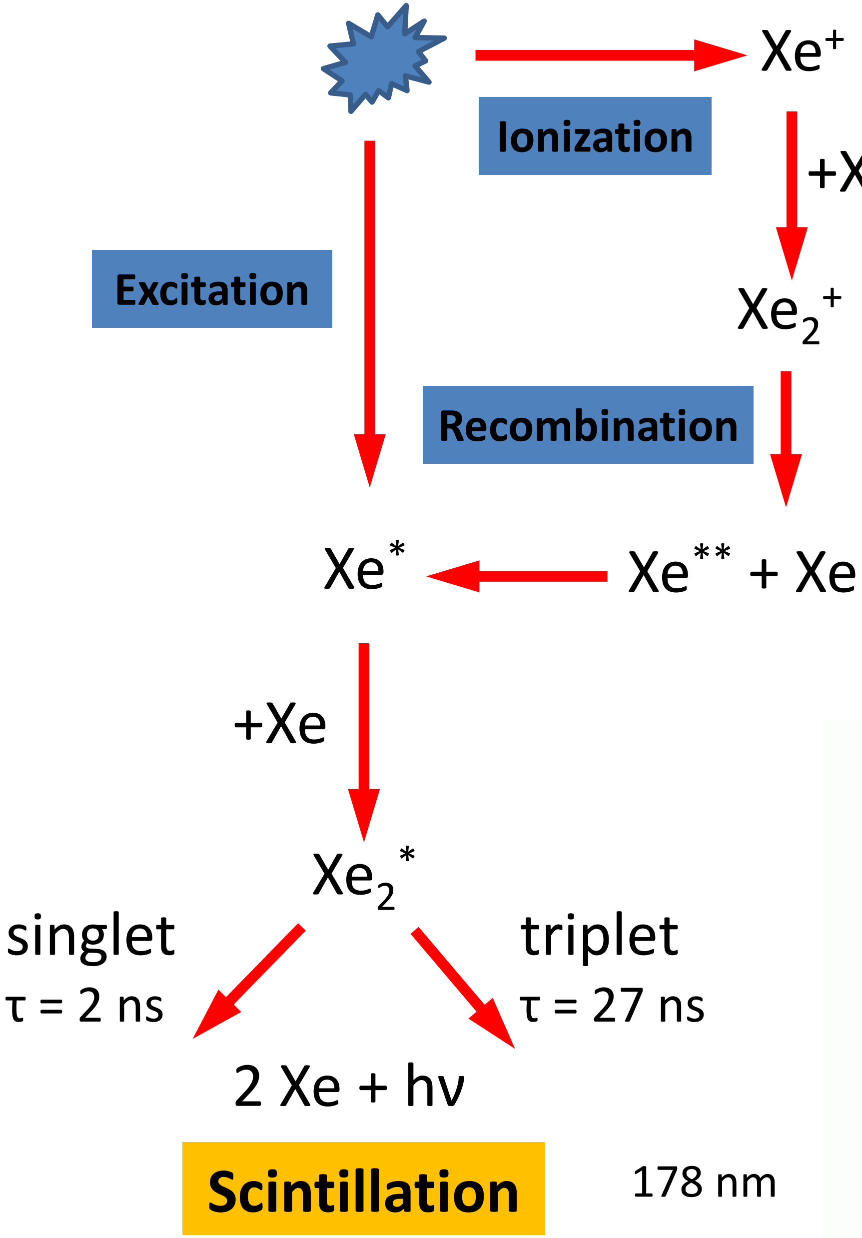
S1+S2 event by event

- ER/NR discrimination (>99.5% rejection)
- mm vertex resolution + high density: *self-shielding* of radioactivity backgrounds

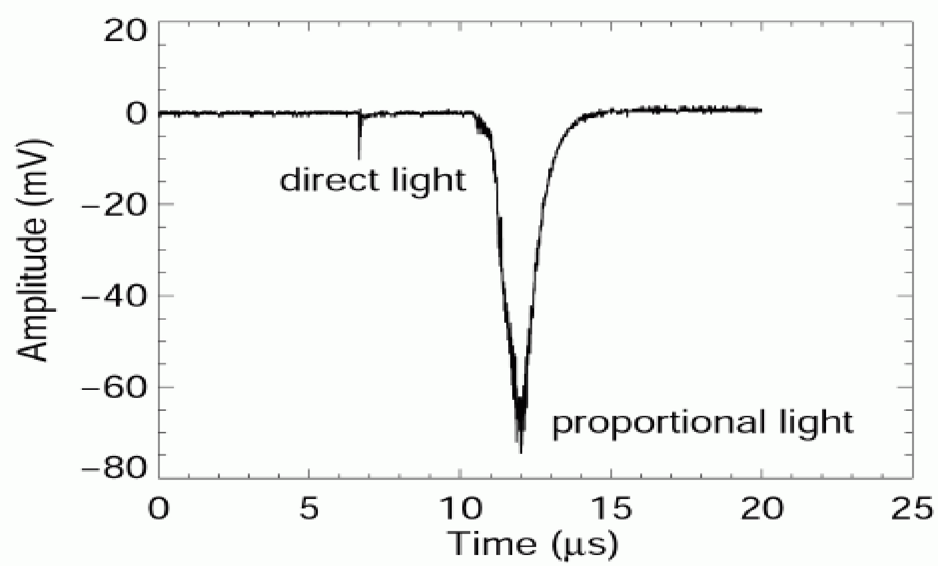
LXe is the leading WIMP target:

- Scalar WIMP-nucleon scattering rate dR/dE~A^2, broad mass coverage >5 GeV
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable SD sensitivity; target exchange
- No damaging intrinsic nasties (^{127}Xe short-lived, ^{85}Kr removable, ^{136}Xe $2\nu\beta\beta$ ok)

Ionization and Scintillation in Xenon



- Excitation / ionization depends on dE/dx.
- Charge signal / Recombination depends on dE/dx and electric field.
- Nuclear recoil: high dE/dx
  Electron recoil: low dE/dx

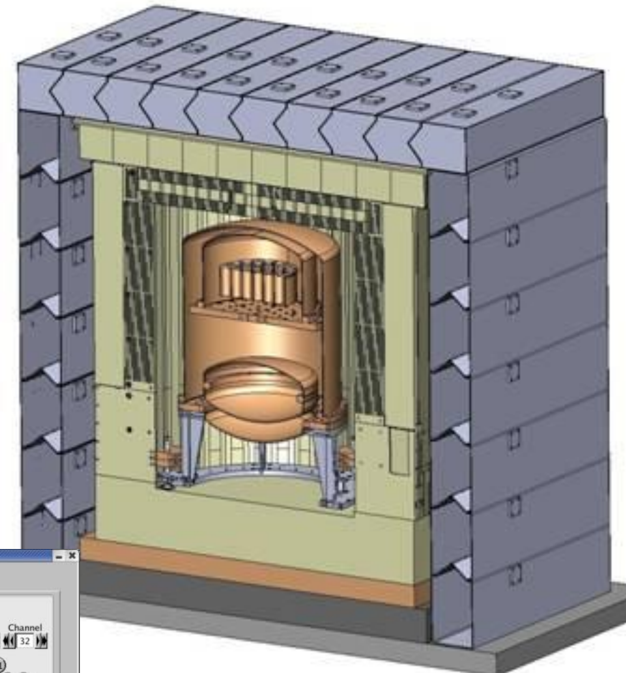


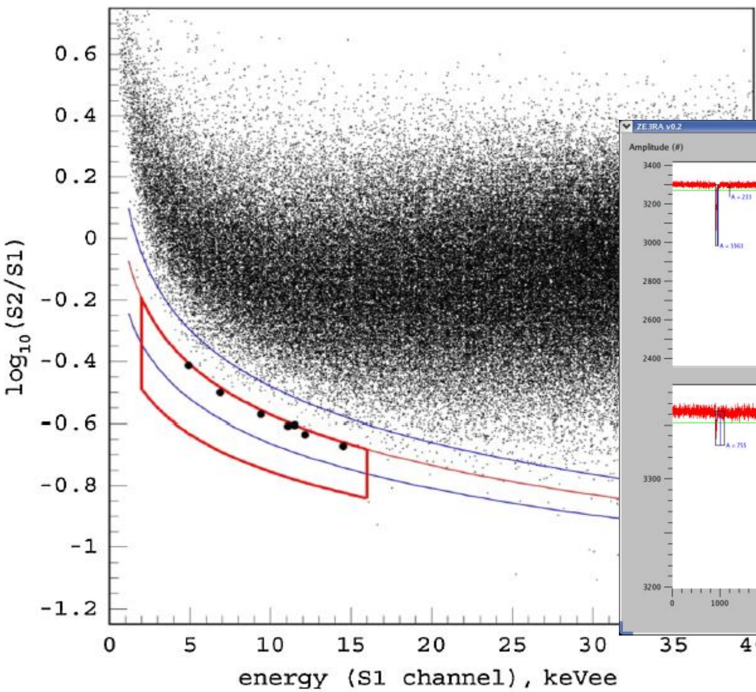
ZEPLIN-III

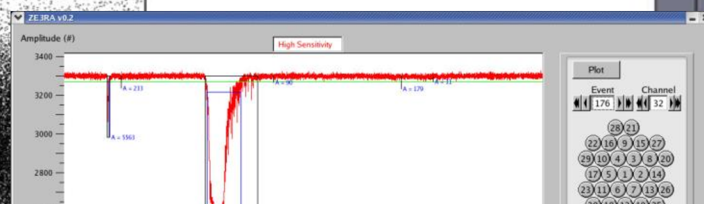
- ZEPLIN developed 2-phase Xe detectors
- Boulby programme completed in 2012
- Z3 achieved best discrimination in LXe

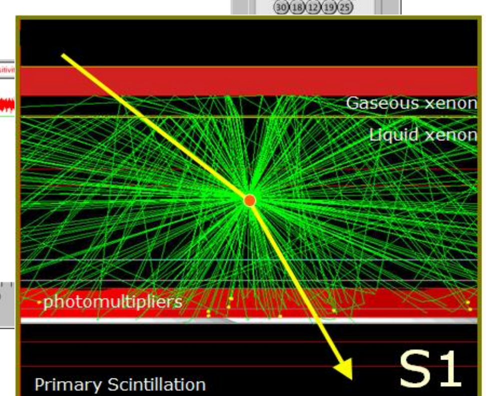
  Lebedenko *et al*, PRD 80 (2009) 052010

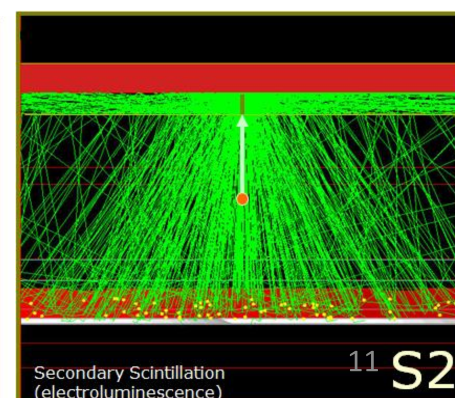
  Akimov et al, PLB 709 (2012) 14





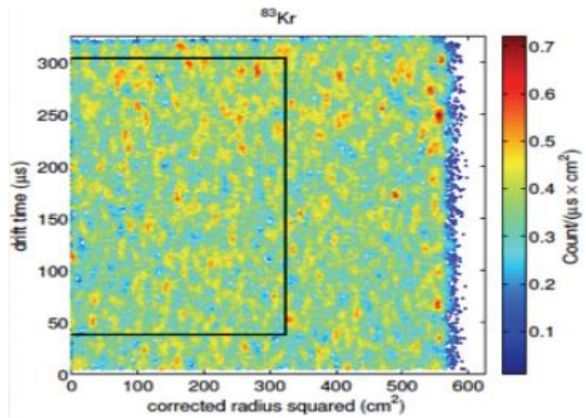


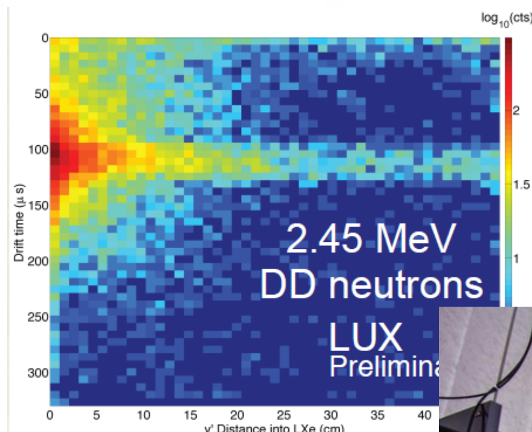


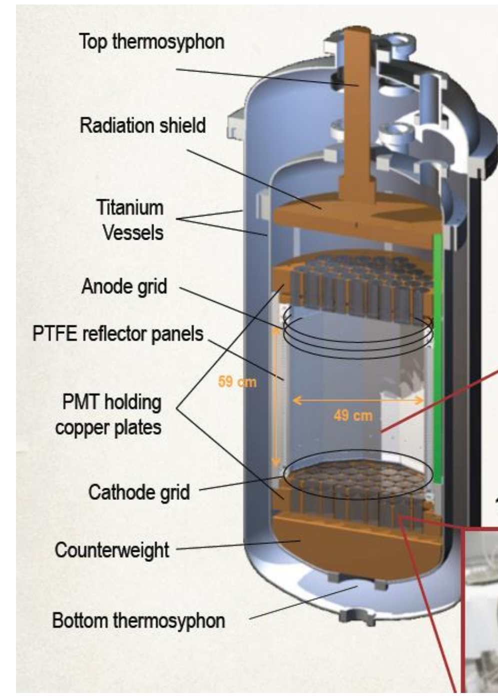


LUX

Liquid xenon TPC
- 250 kg LXe (118 kg fiducial)
- PTFE field cage, 122 PMTs
- 3D imaging (<1 cm)
- Calibration: *in situ* D-D gen, Dispersed ^{83m}Kr and CH_3T
- **Key parameters**
  - Light yield: >8 phe/keVee
  - Drift field: 0.2 kV/cm
  - NR threshold: 4.3 keV
  - ER discrimination: 99.6%
  - Background: 2 ER/day (ROI total!)
- **Sensitivity**
  - 7.6x10^{-46} cm^2 at 33 GeV (Run 3)
- Onwards: LUX-ZEPLIN (7-tonne TPC)

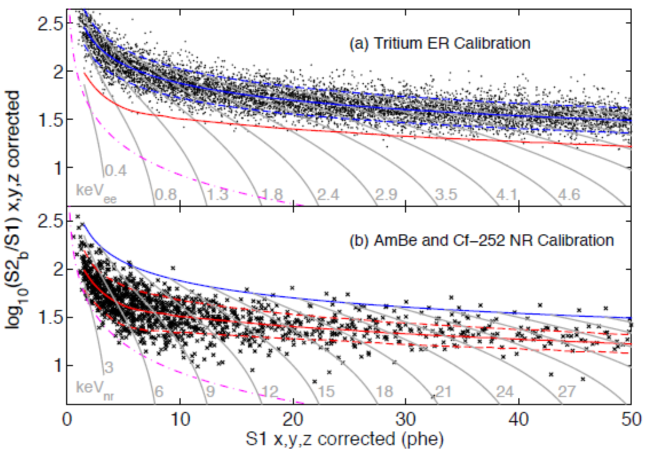


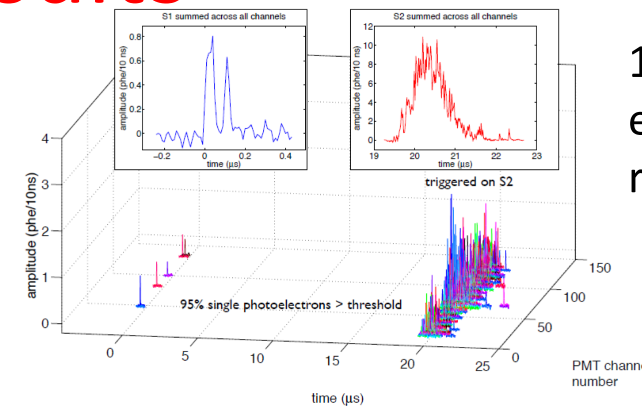




LUX Results

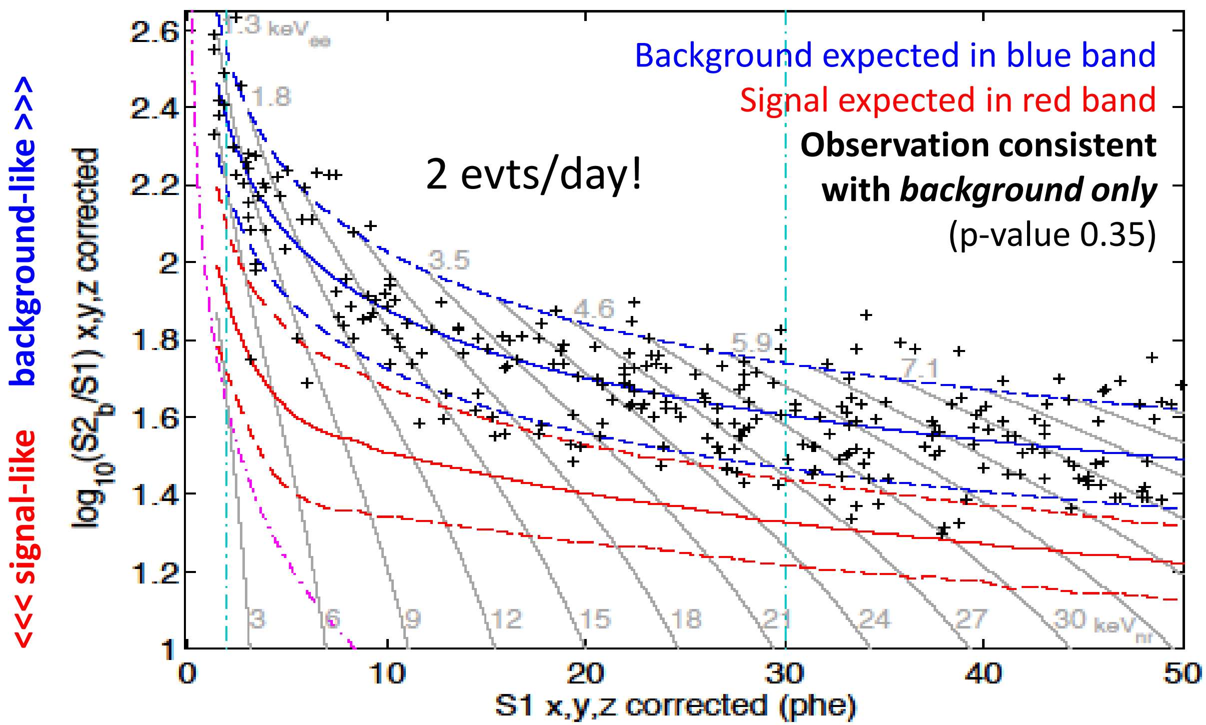
1310.8214





1.5 keV electron recoil

Events recorded in 85.3 live days of exposure



recoil energy (loosely) >>>

The Economist

“Absence of evidence, or evidence of absence?”

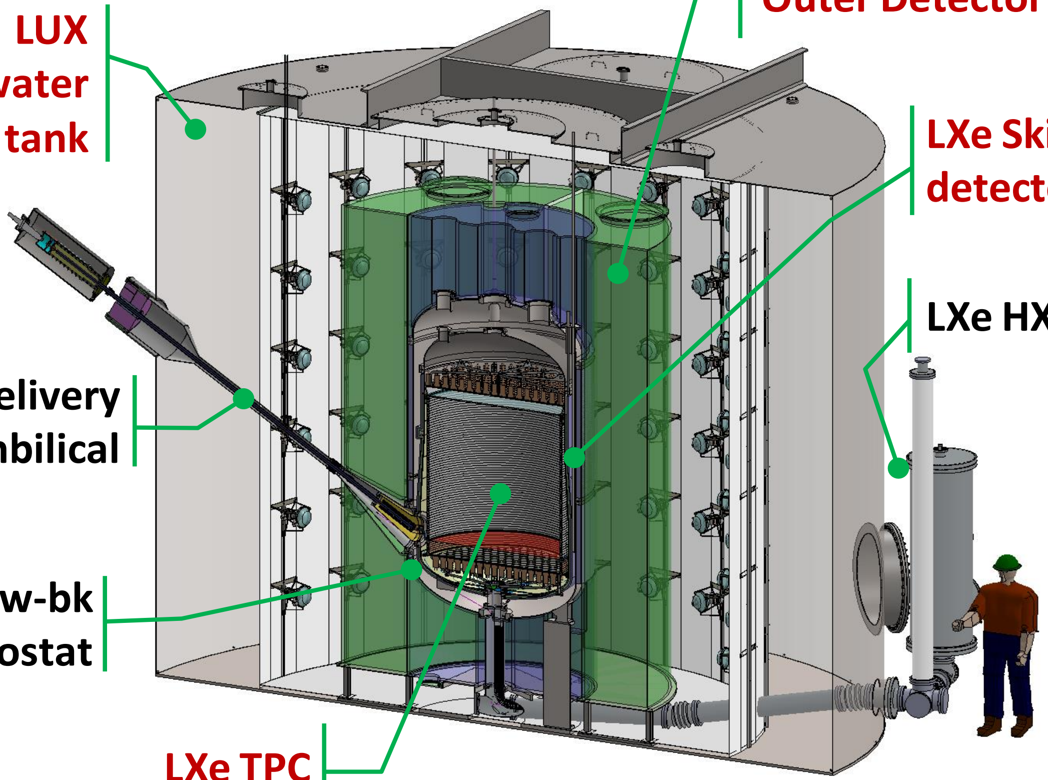
New York Times

“Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly”

LUX-ZEPLIN

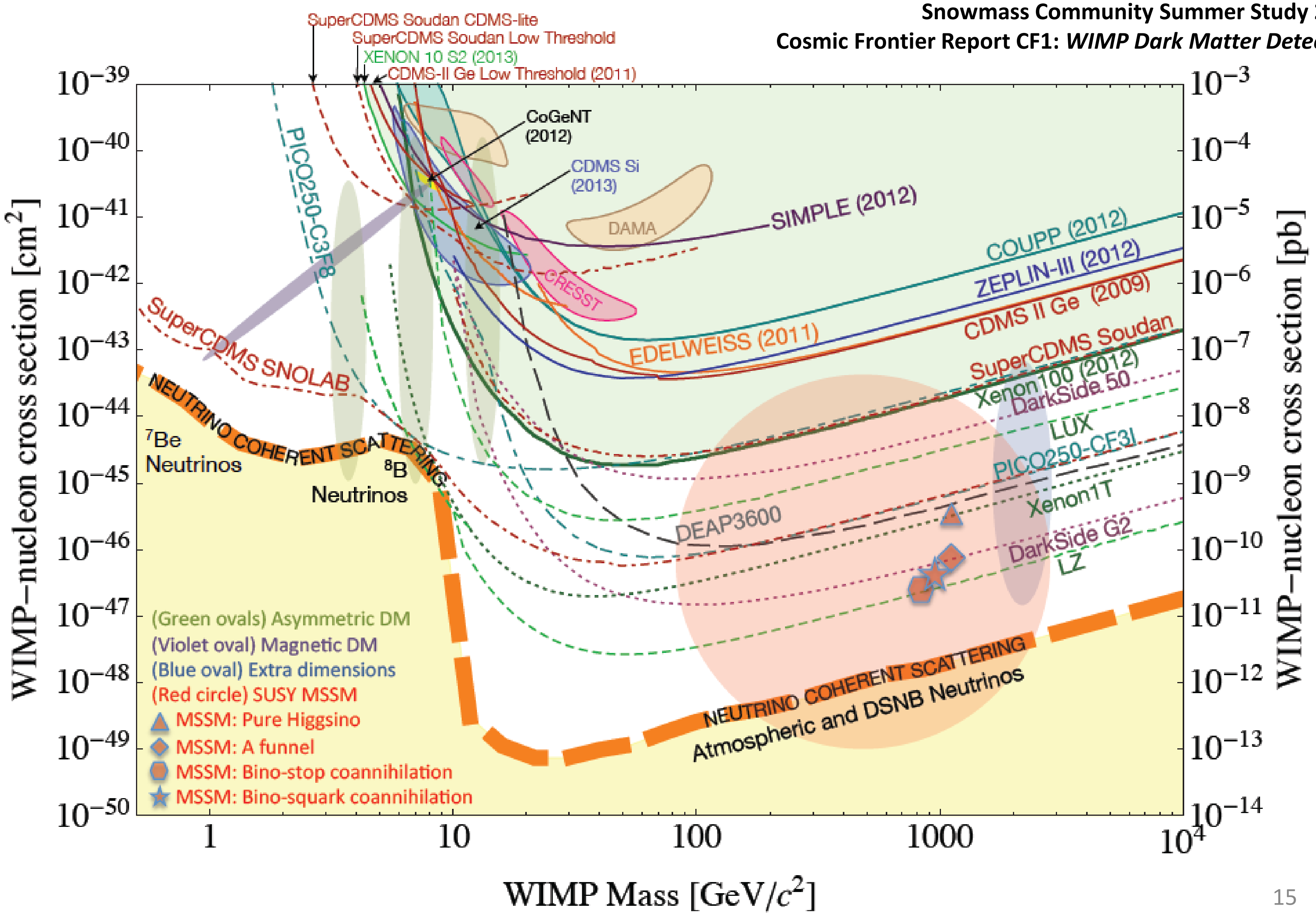
Liquid xenon TPC

- 7.0 t LXe active (5.6 t fiducial)
- LXe Skin detector (~2 t)
- Gd-loaded Scintillator Veto
- 8-m water tank (post-LUX)
- Construction from 2015
- **Key parameters**
  - Light yield: >6 phe/keVee
  - NR threshold: ~10 keV
  - ER discrimination: >99.5%
  - Background: ~1.9 evt (8 t·yr)
- **Sensitivity**
  - 2.5×10^{-48} cm^2 circa 2020
- Onwards: G3 experiment ?

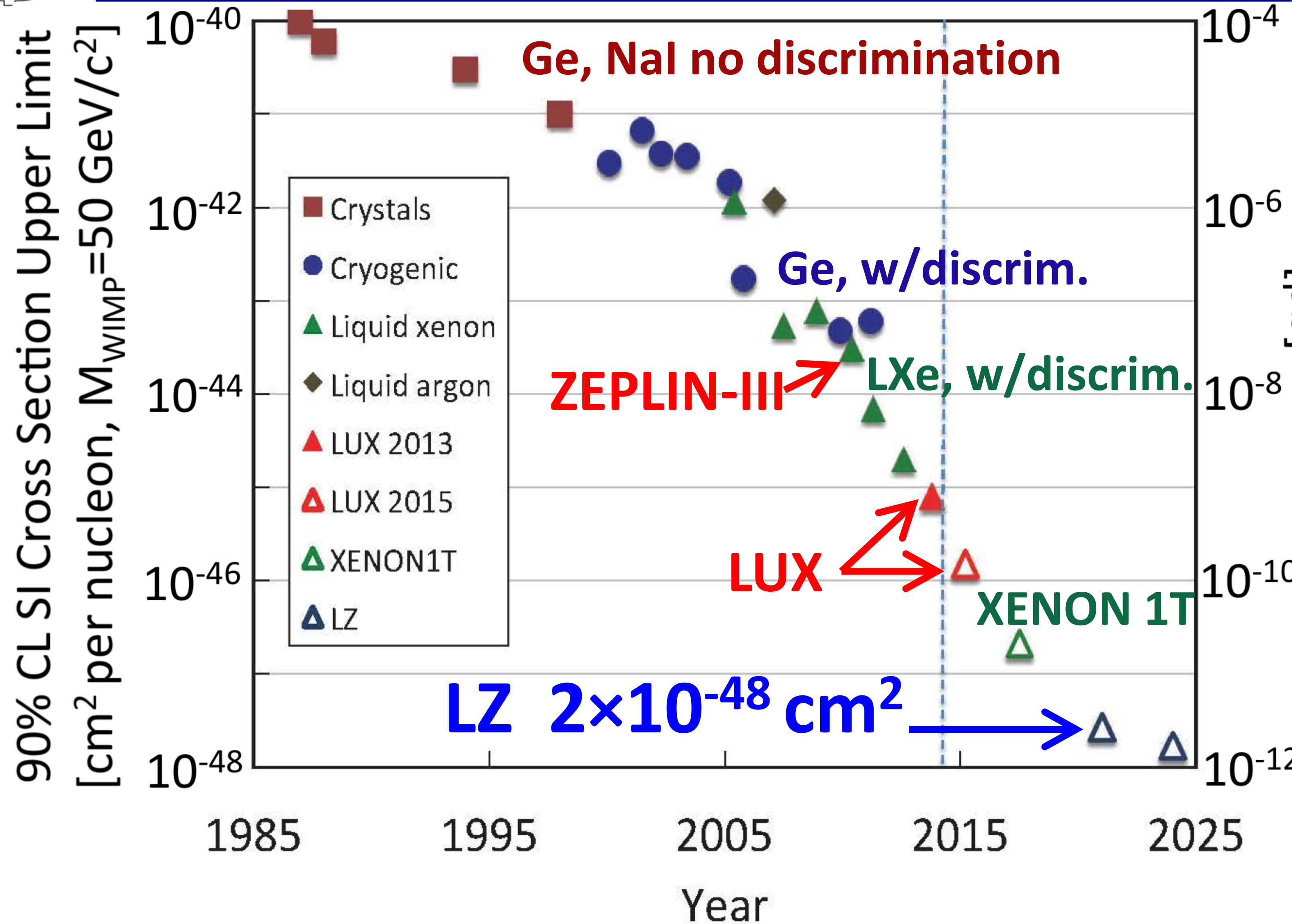


Prospects of finding Dark Matter

Snowmass Community Summer Study 2013
Cosmic Frontier Report CF1: *WIMP Dark Matter Detection*



Time Evolution



LUX-ZEPLIN

LZ = LUX + ZEPLIN

32 institutions currently
About 190 people

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 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

Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LZ in LUX Water Tank
South Dakota USA

LUX removed
by early 2017
Water tank kept

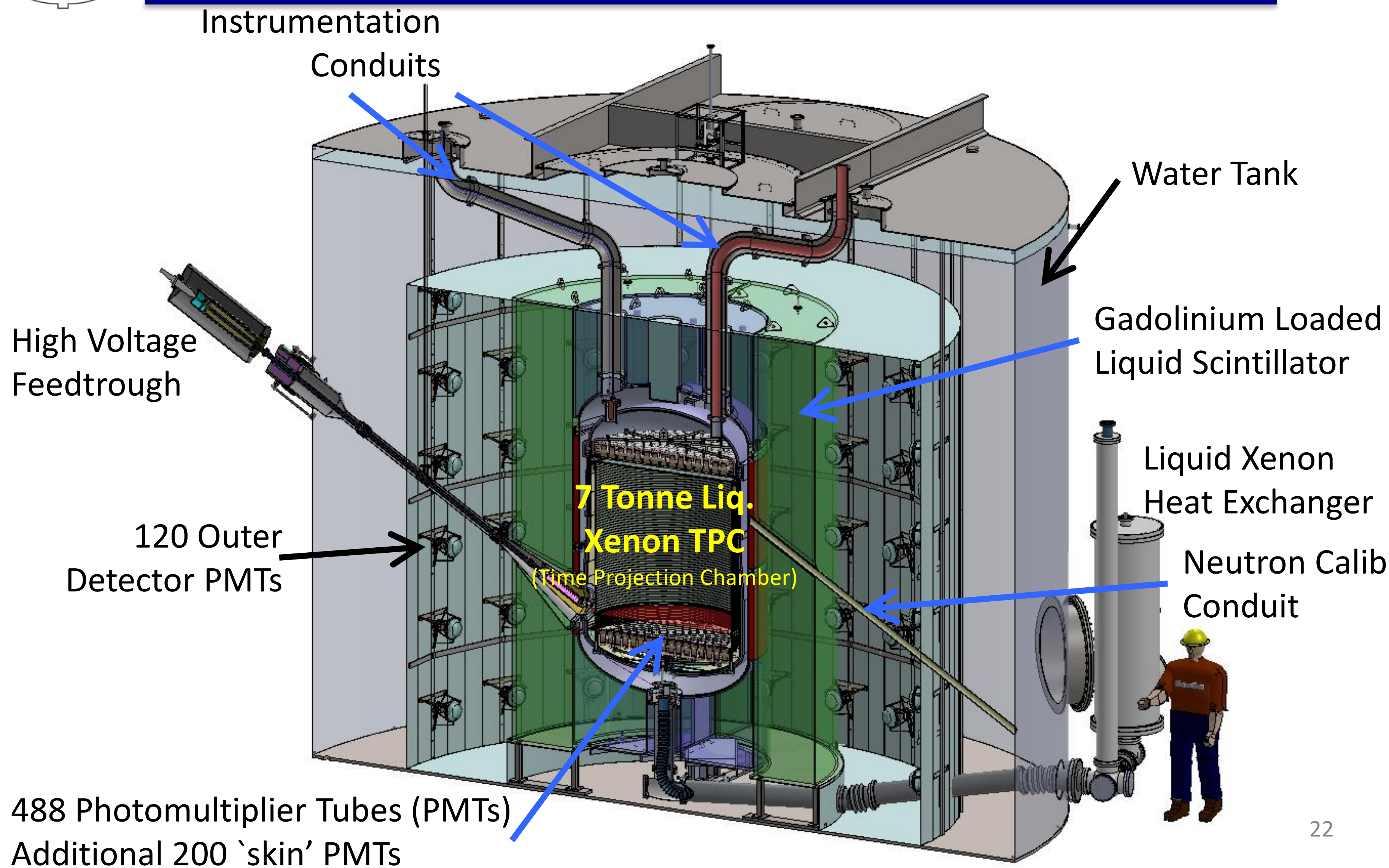
Scale Up ≈50 in Fiducial Mass

LZ

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

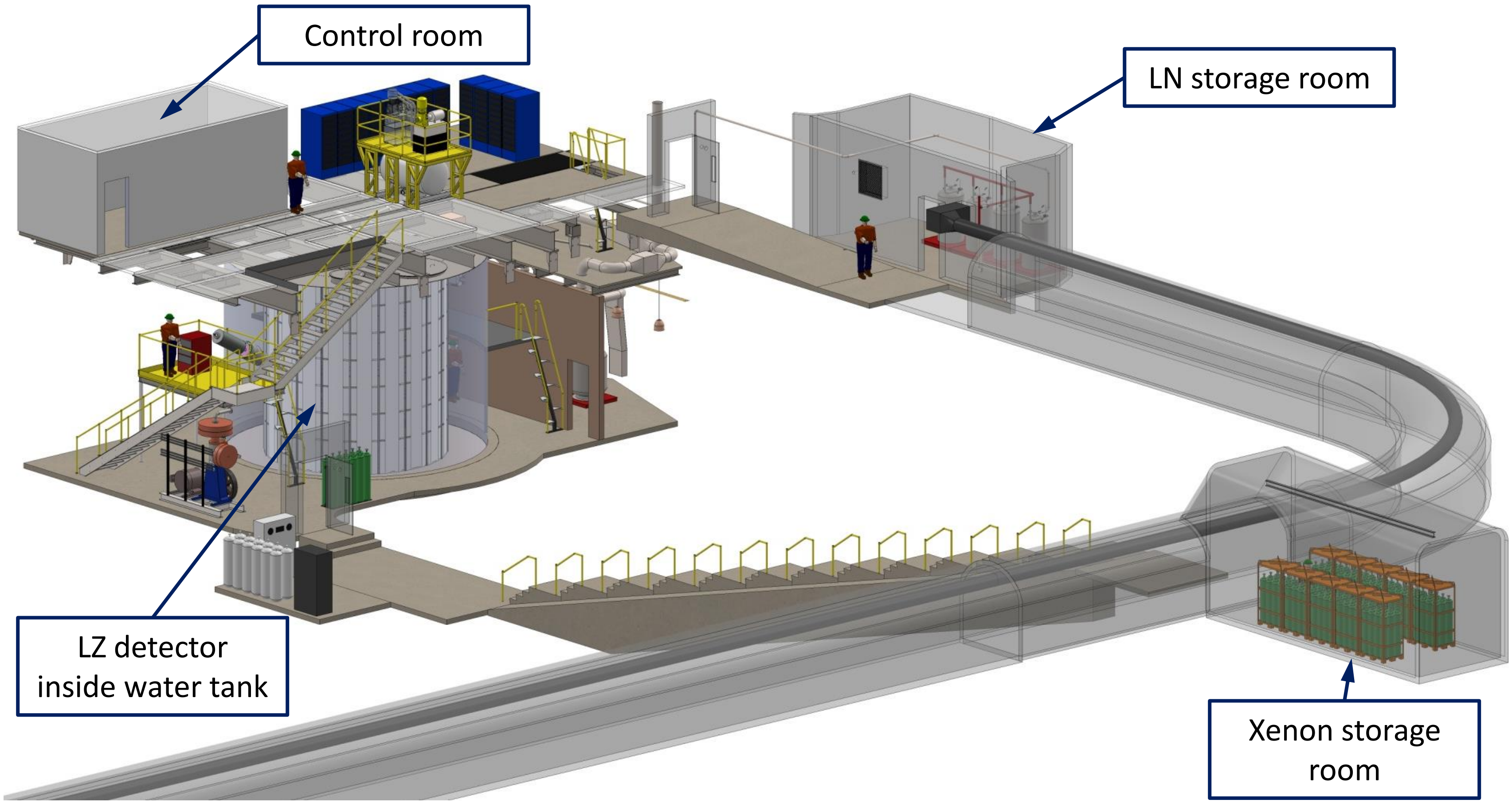
LUX

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

LZ Underground at SURF

Years of experience at SURF from LUX



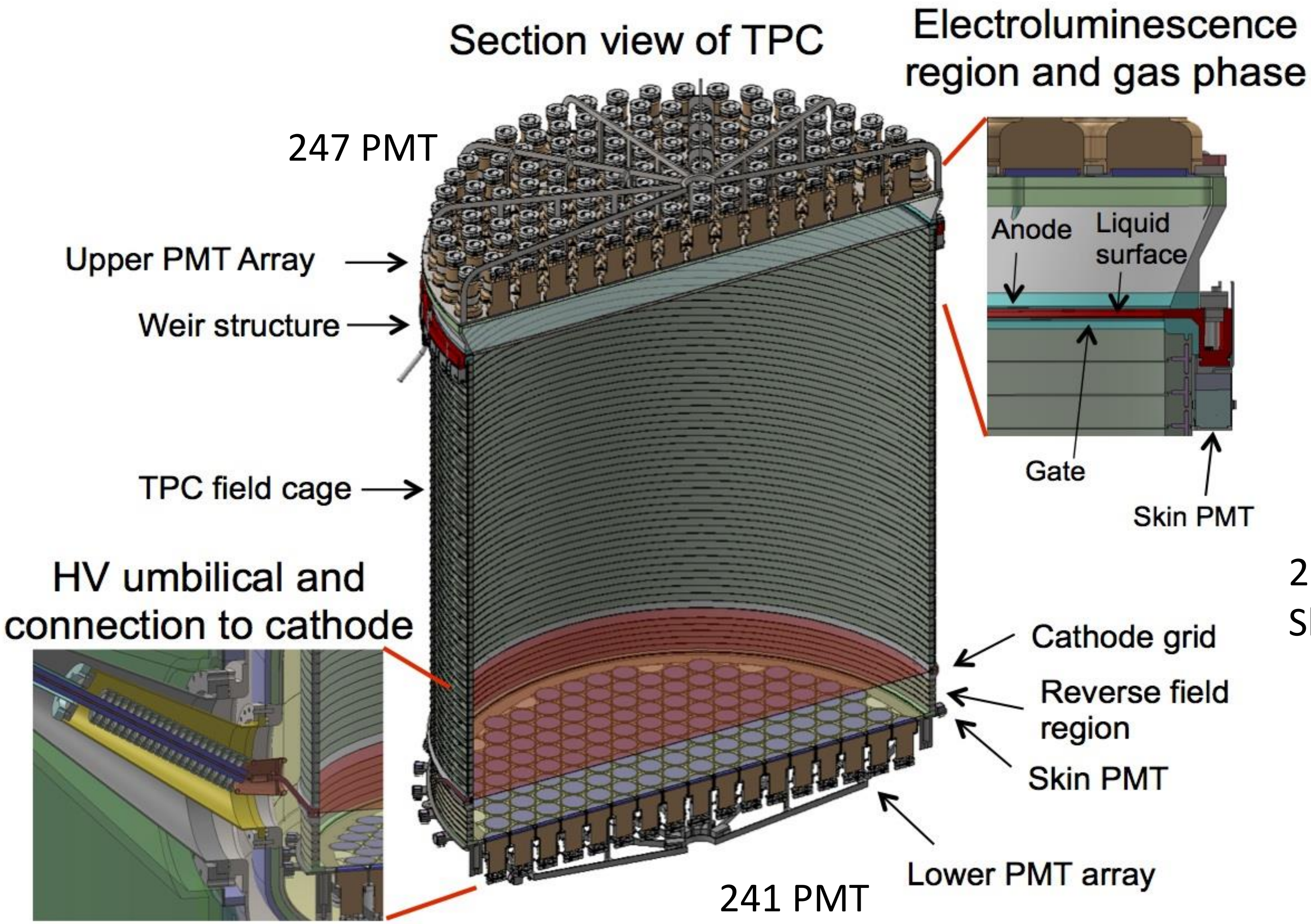
Key Design Points

- 7 active tonnes of LXe can yield 2 x 10^{-48} cm^2 sensitivity in about three years of running
- 5.6 tonne fiducial volume, 1000 days
- Requires all detector systems working together
  - 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 is on arXiv:1509.02910
- 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

Xe TPC Detector



200 total
Skin PMT

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

Xe Detector Prototyping

- Extensive program of prototype development underway
- Three general approaches
  - Testing in liquid argon, primarily of HV elements, at Yale and soon at LBNL
  - 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
  - System test platform at SLAC, Phase I about 100 kg of LXe, TPC prototype testing to begin soon

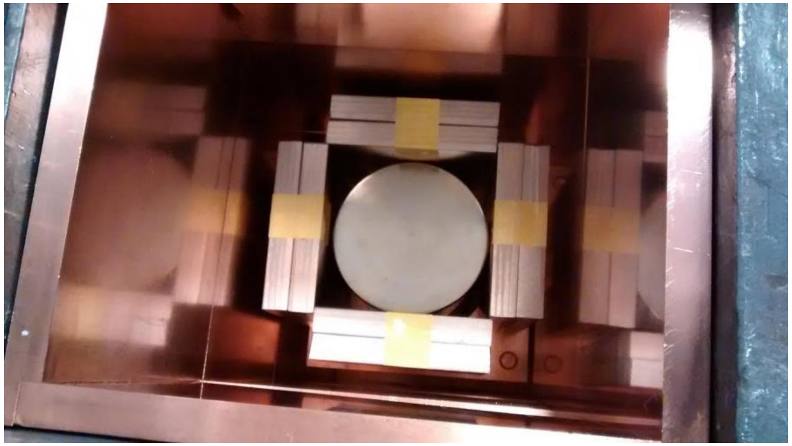
Extensive Calibration

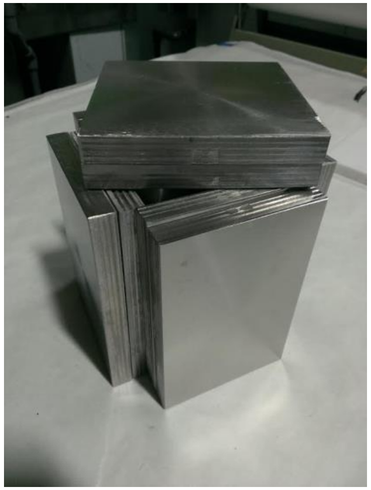
- LUX has led the way to detailed calibrations. LZ will build on this and do more.

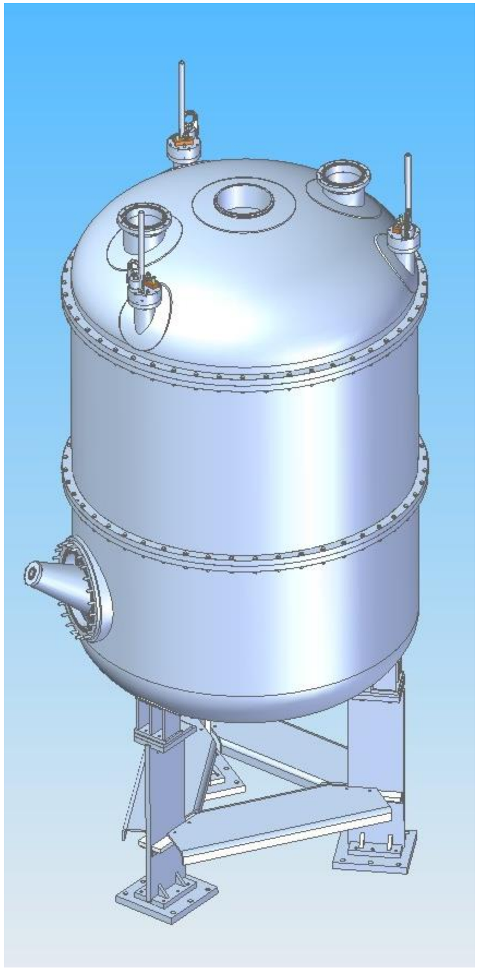
Done in LUX and will be done in LZ	Not done in LUX, but will do in LZ
^{83m}Kr (routine, roughly weekly)	Activated Xe (^{129m}Xe and ^{131m}Xe)
Tritiated methane (every few months)	^{220}Rn
External radioisotope neutron sources	AmLi
External radioisotope gamma sources	YBe
DD neutron generator (upgraded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

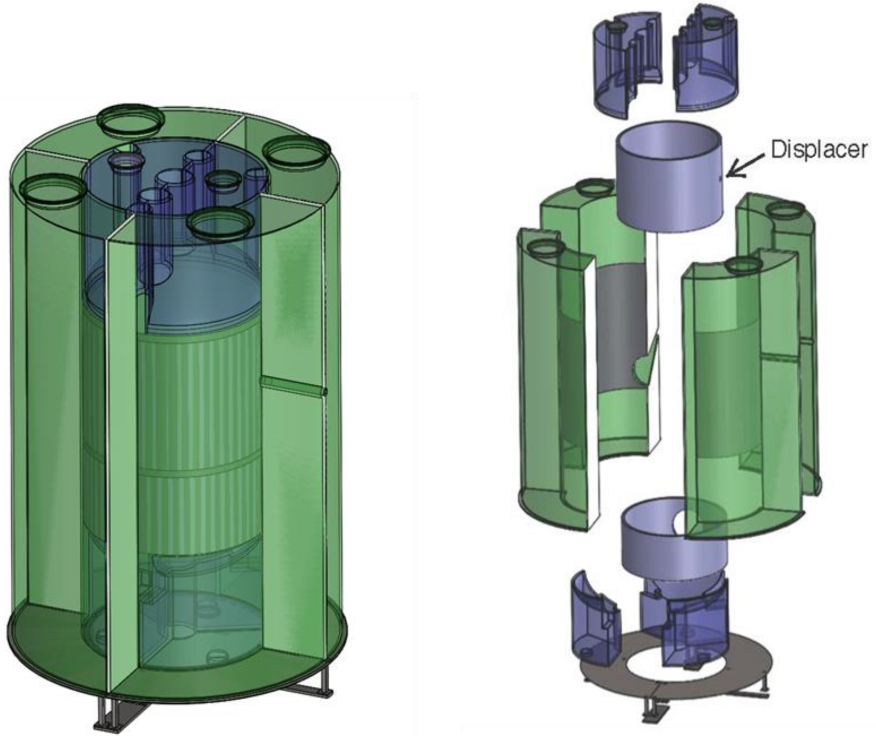






Outer Detector

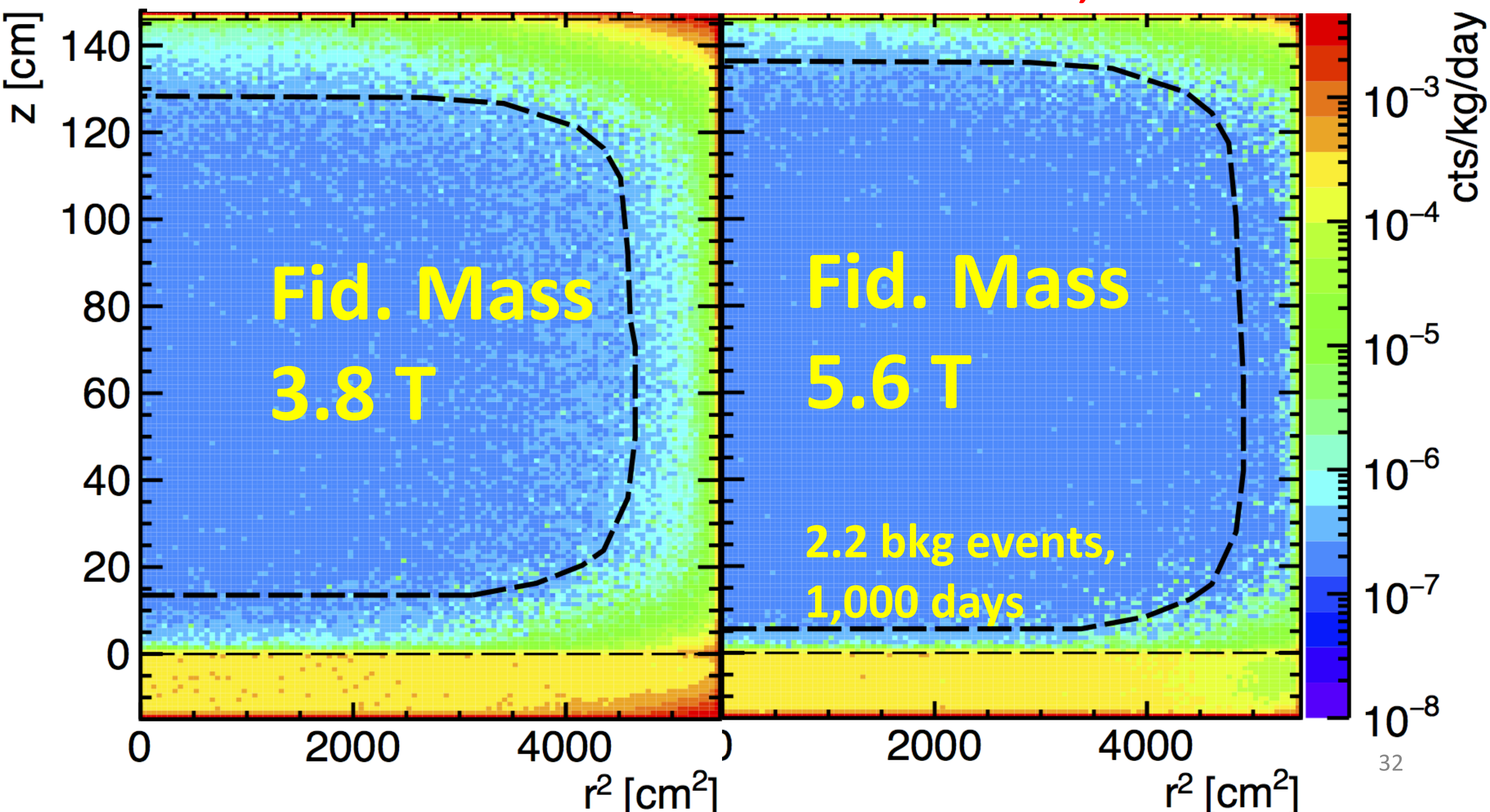
- Essential to utilize most Xe, maximize fiducial volume
- Segmented tanks – installation constraints (shaft, water tank)
- Gadolinium - loaded scintillator, LAB, OK underground
- Daya Bay legacy, scintillator & tanks (and people)
- Advanced conceptual design



Layout of the LZ outer detector system, which consists of nine acrylic tanks. The largest are the four quarter-tanks on the sides. Two tanks cover the top, and three the bottom. The exploded view on the right shows the displacer cylinders placed between the acrylic vessels and the cryostat.

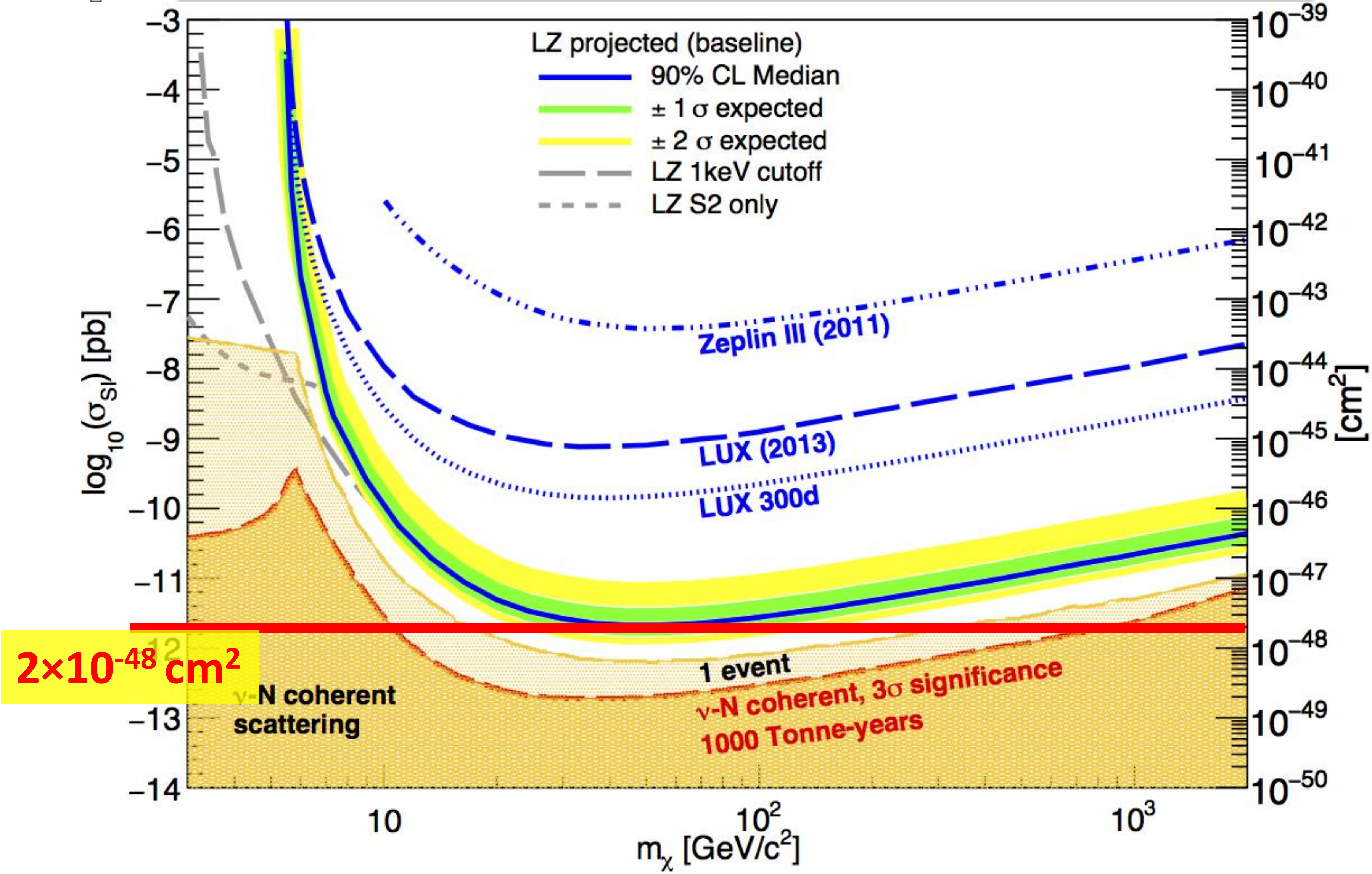
Background Modeled

Just LXe TPC | Use LXe skin, Outer Det.



Projected Sensitivity – Spin Independent

(LZ 5.6 Tonnes, 1000 live days)



Conclusions

- LZ Project well underway, with procurement of Xe, PMTs and cryostat vessels started
- Extensive prototype program underway
- LZ benefits from the excellent LUX calibration techniques and understanding of background
- LZ sensitivity expected to be finally limited by neutrino-induced `background'