The LUX-ZEPLIN (LZ) Experiment

F. Neves on behalf of the LZ collaboration

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FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

PORTUGAL 2020

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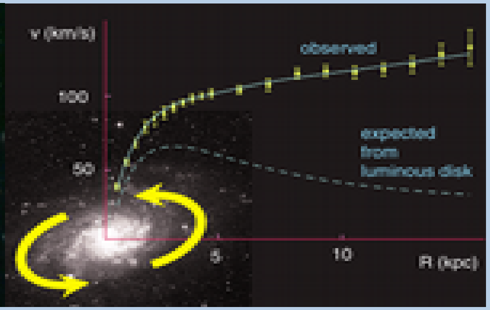
Outline

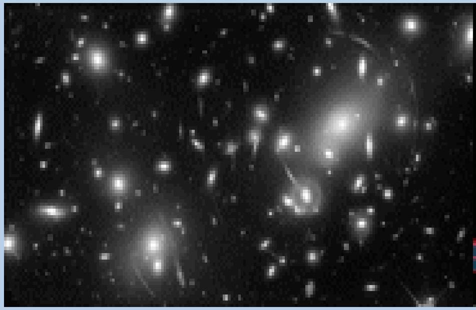
- Dark matter: very brief overview;
- Using liquid xenon for direct detection of dark matter;
- The LZ experiment:
  - Description and timeline;
  - Backgrounds;
  - Sensitivity to WIMPs;
  - Sensitivity to Axion and ALPs;
  - Other physics.

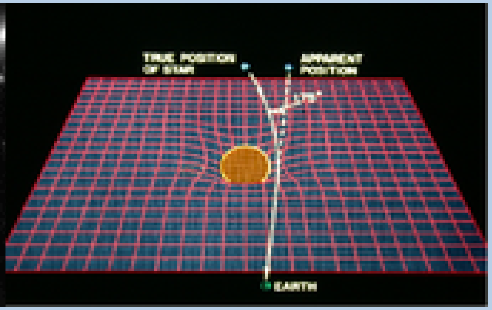
Dark Matter evidence overview

Motion of stars, gas and galaxies
(1st reference in 1933 by Fritz Zwicky)

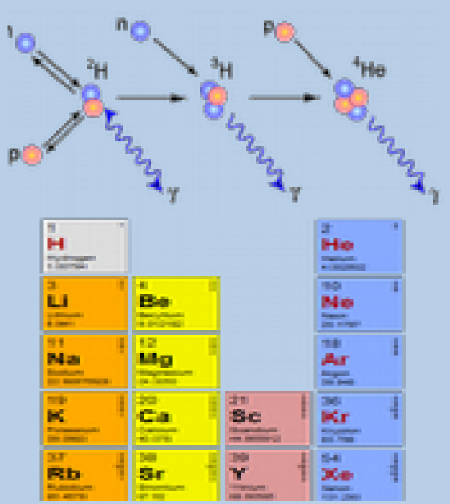


Gravitational Lensing

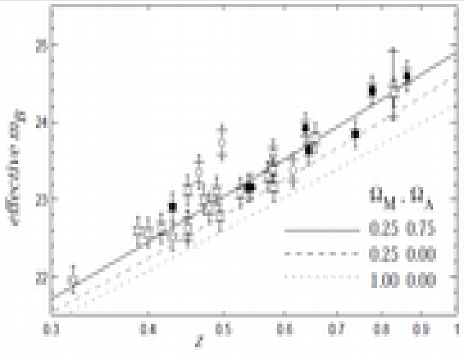




Nucleosynthesis



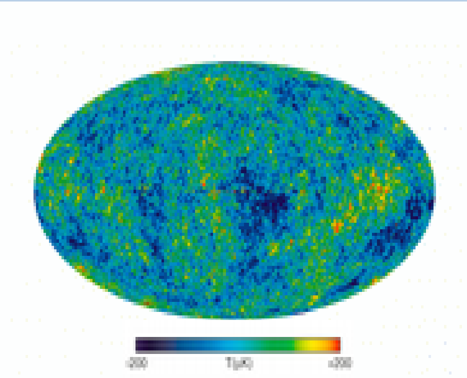
Supernovae



$\Omega_\Lambda = 0.705 \begin{smallmatrix}+0.049\\-0.043\end{smallmatrix}$

$\Omega_m = 0.277 \begin{smallmatrix}-0.021\\+0.022\end{smallmatrix}$

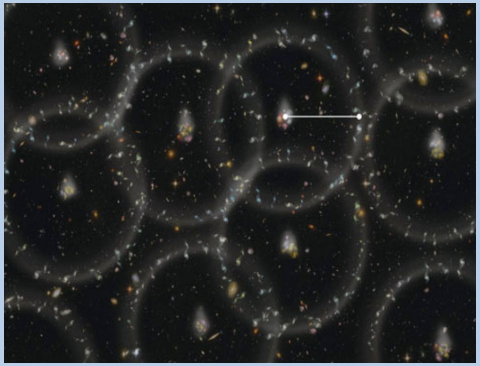
Cosmic microwave background



$\Omega_m = 0.3089 \pm 0.0062$

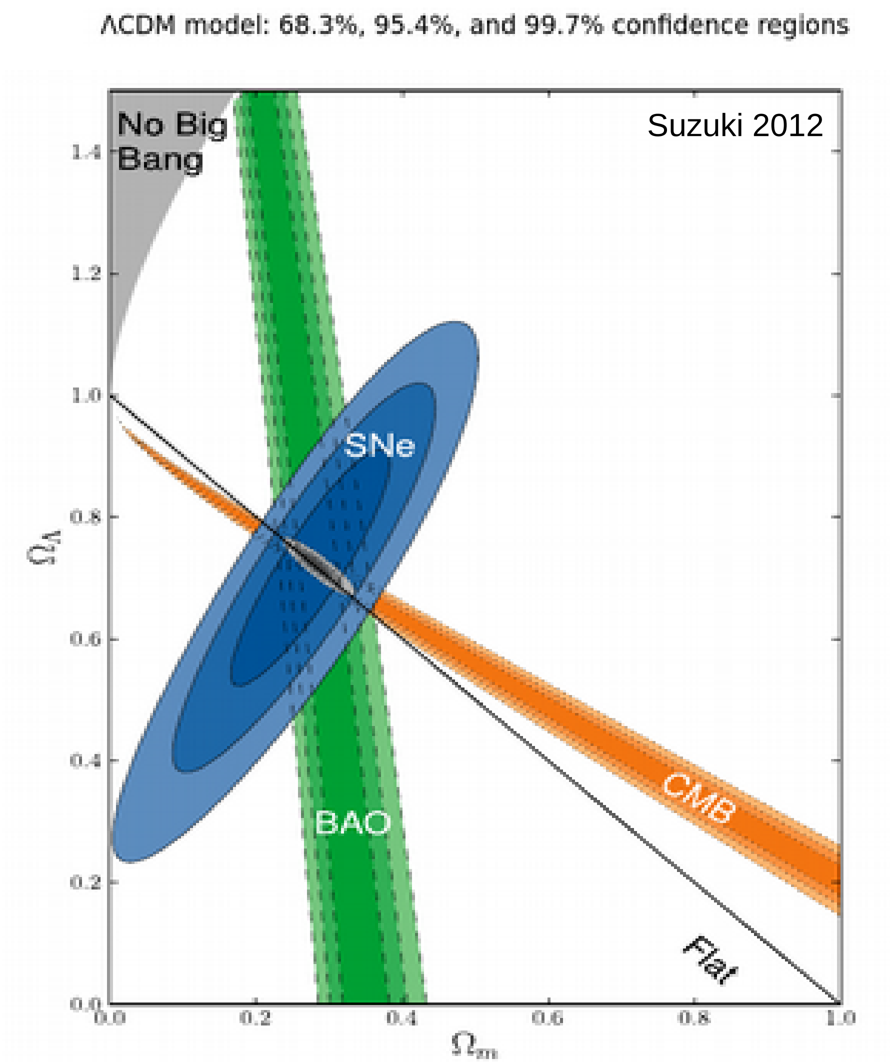
$\Omega_b = 0.0486 \pm 0.0006$

Baryonic acoustic oscillations

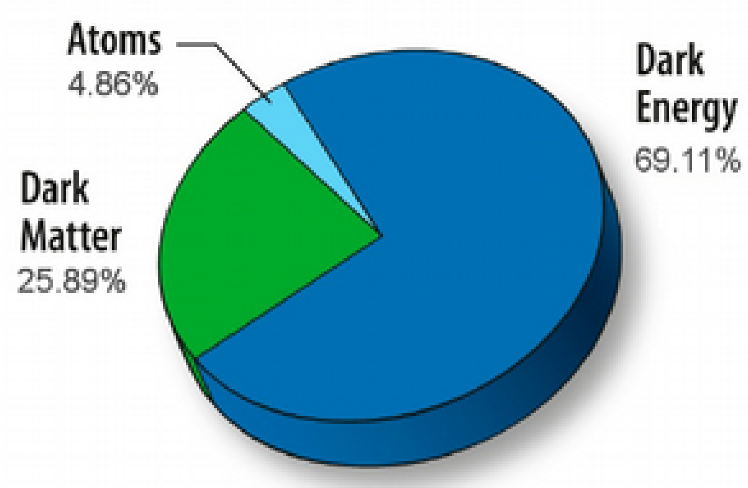


$\Omega_m = 0.277 \pm 0.022$

Combining the evidence



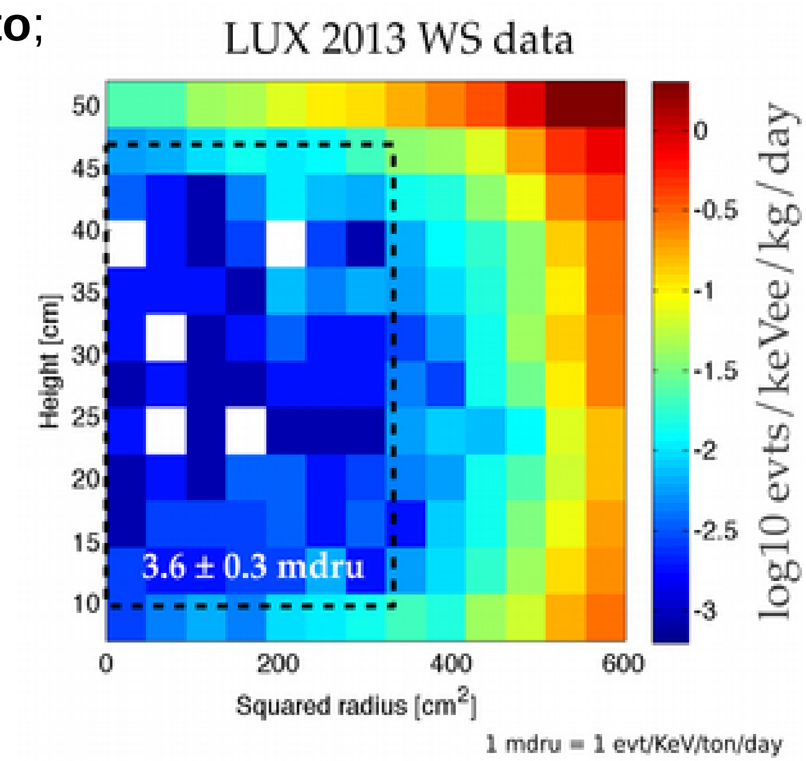
- Extraordinary agreement in precision cosmology;
- Present Universe mostly made out of dark energy, dark matter, and small contribution from baryonic matter;
- **We only understand 5% of the constituents of our universe!**



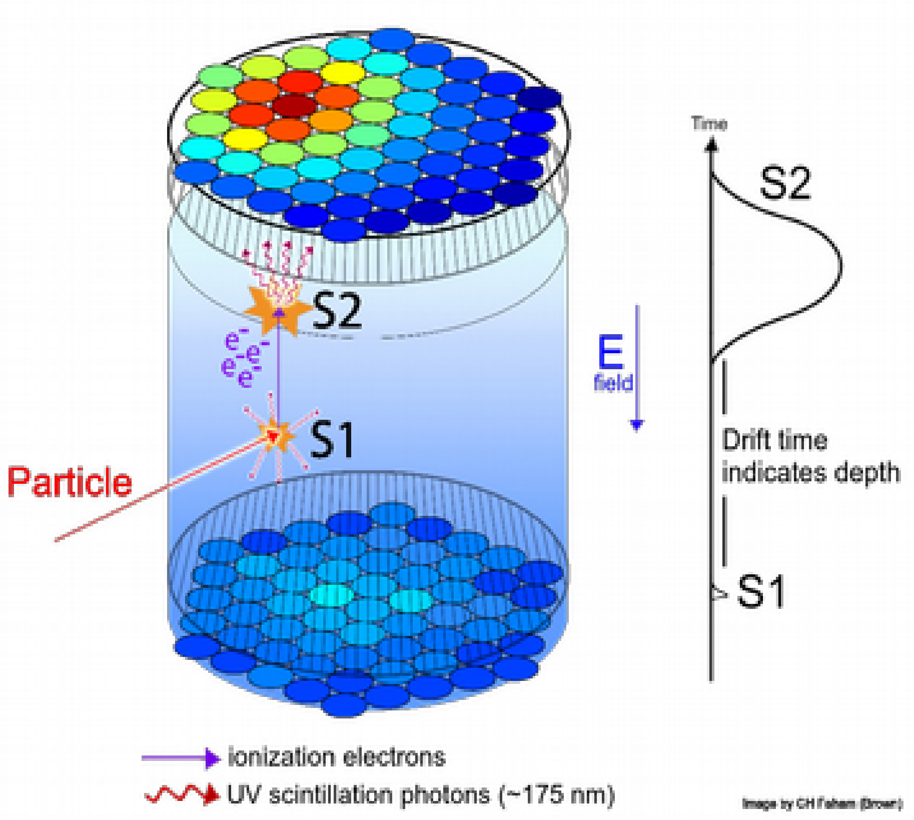
- Many candidate explanations to dark matter: e.g **WIMPs**, Axions, MOND, **...**

Xenon as a WIMP target

- **High density** (2.9 *g/cm³*): manageable detector volumes (R_{WIMP} ~ 10^{-5}-10^{-2} *event/kg/day*);
- **High atomic number** (*A~131*): good for *spin-independent* interactions; plus *spin-dependent* sensitivity (~1/2 odd isotopes in natural xenon);
- Allows **easy/affordable scalability** to ton-level detectors (**LZ**, XENON-1T);
- Allows **self- shielding** by selection of an **inner fiducial volume** while using the (instrumented) **outer *skin* volume as a veto**;
- Natural xenon has **no long-lived radioactive isotopes**; plus Kr contamination can be easily reduced to ppt level;
- **Low energy threshold** (*~1 keVee*);
- **Nuclear recoil vs e^-/γ-ray discrimination** by simultaneous detection of *prompt scintillation* and *charge* drift away of the interaction site by an electric field;

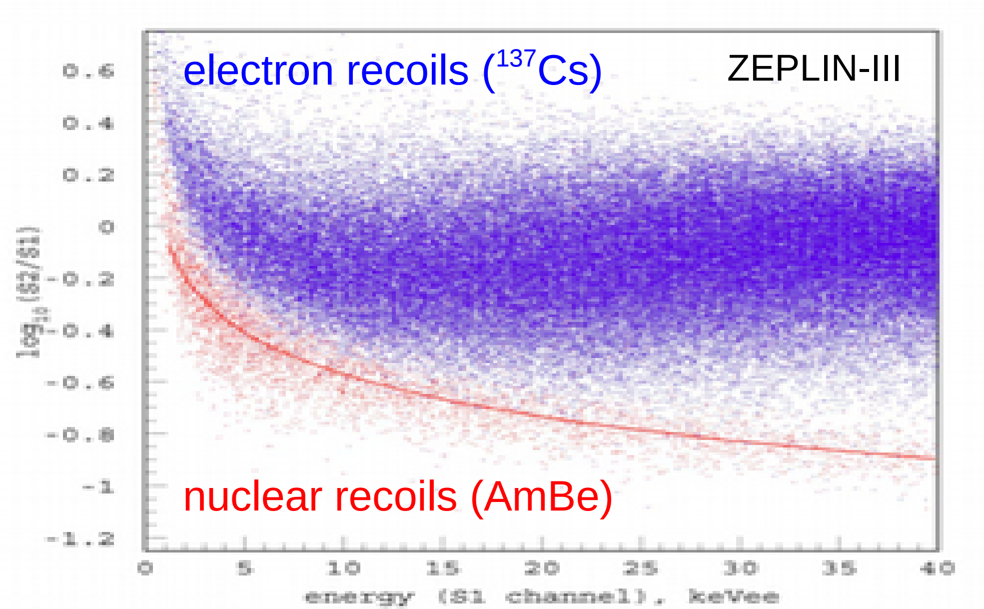


Liquid Xenon TPC

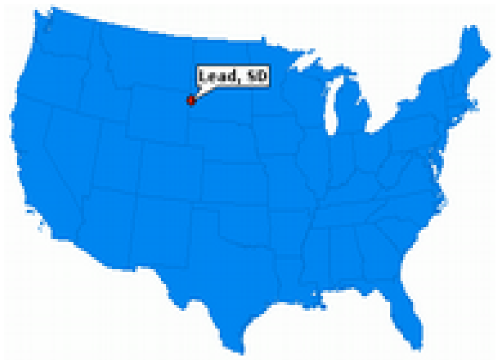


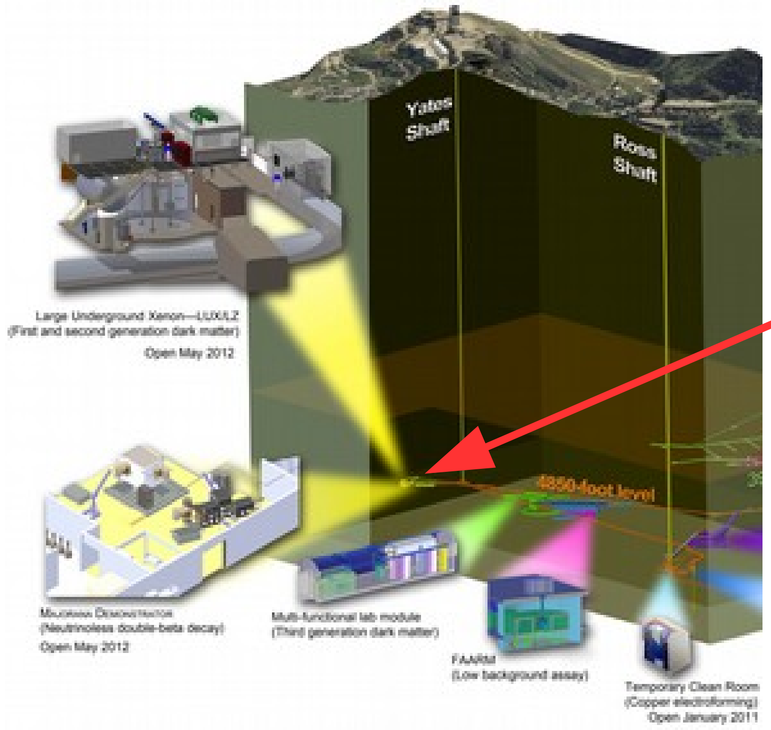
- **(x,y) position reconstruction**: from the S2 light pattern;
- **Depth of interaction (z)**: e⁻ drift time in the liquid (time difference between S2 and S1);

- **Prompt scintillation (S1).**
- **Proportional scintillation (S2)**: measurement of the e⁻ charge extracted from the liquid to the gas.
- **S2/S1** depends on the ionising particle (nuclear/electron recoil): **99.7% ER/NR rejection** @ 50% NR acceptance**.**



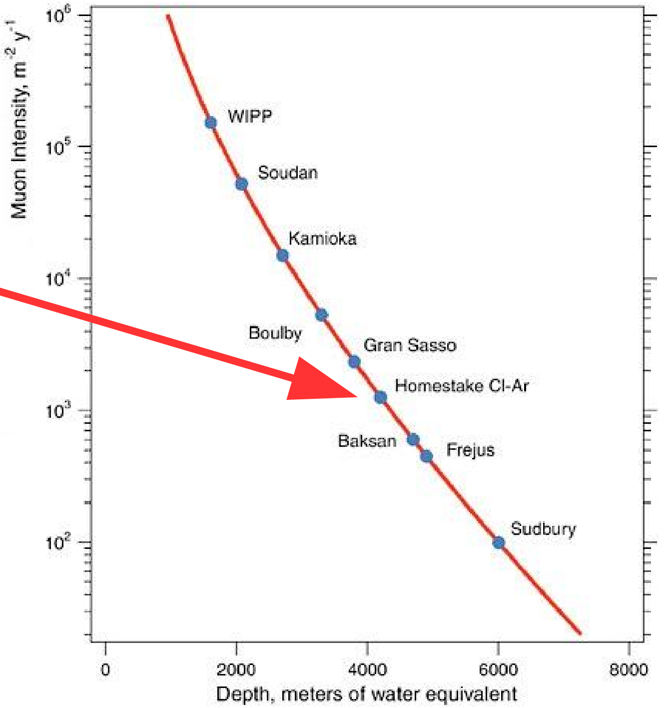
Sanford UG Research Lab





SURF
4850 feet deep
(1478 m)

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



LZ timeline

<u>2012 (March)</u>
LZ (LUX-ZEPLIN) collaboration formed

<u>2014 (July)</u>
LZ Project selected in US and UK

<u>2015 (April)</u>
DOE CD-1/3a approval (similar in UK)
Conceptual Design Report arXiv:1509.02910

<u>2017 (Feb)</u>
DOE CD-3 approval
Technical Design Report: arXiv:1703.09144

<u>2017 (Q2)</u>
Begin preparations for surface assembly @ SURF

<u>2018 (Q4)</u>
Begin underground installation

<u>2020 (Q1)</u>
Commissioning start

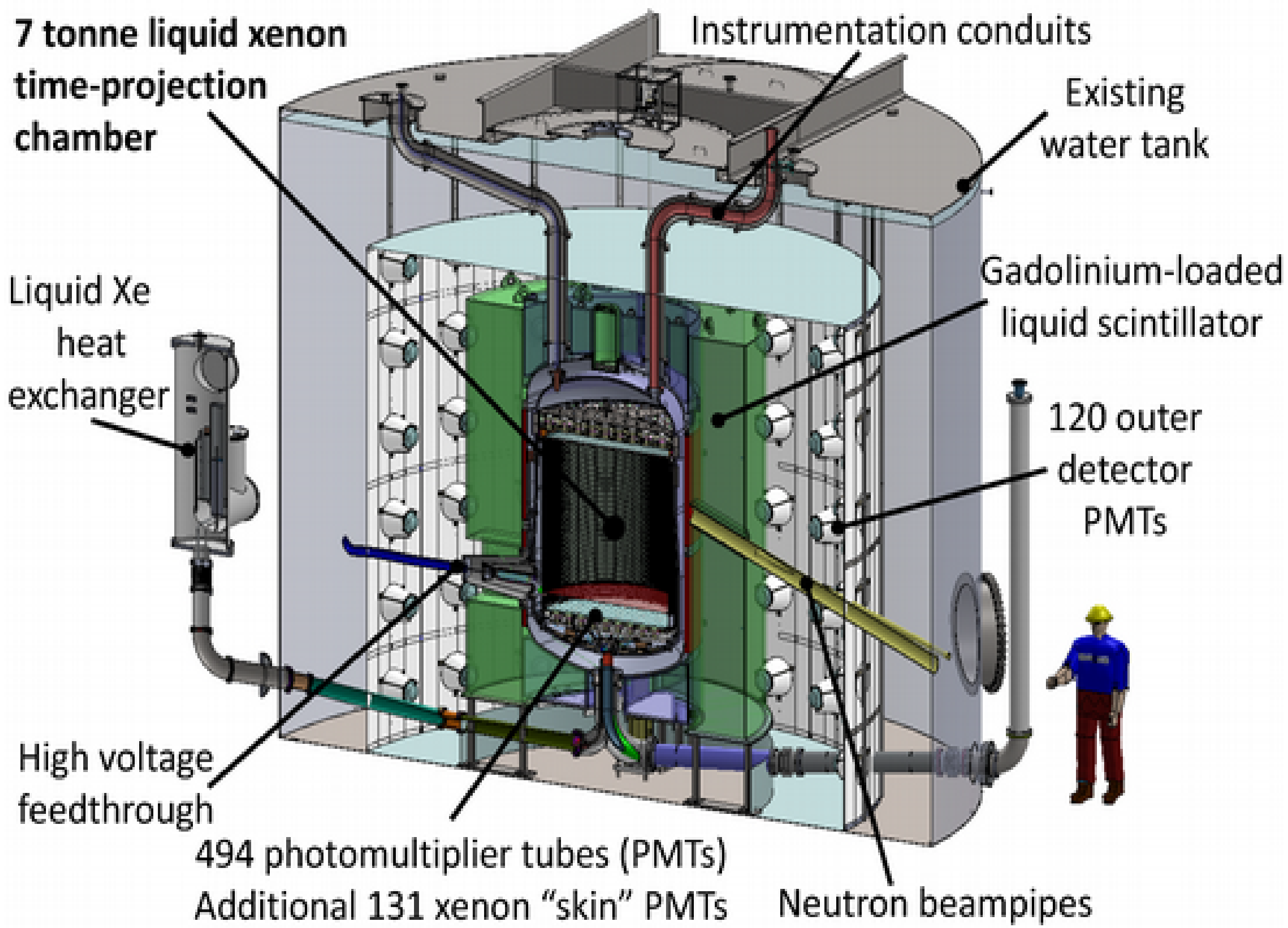
<u>Main milestones (top) and long term production tasks (right)</u>

- final design
- materials screening
- xenon procurement
- PMTs procurement and test
- Gd-LS production

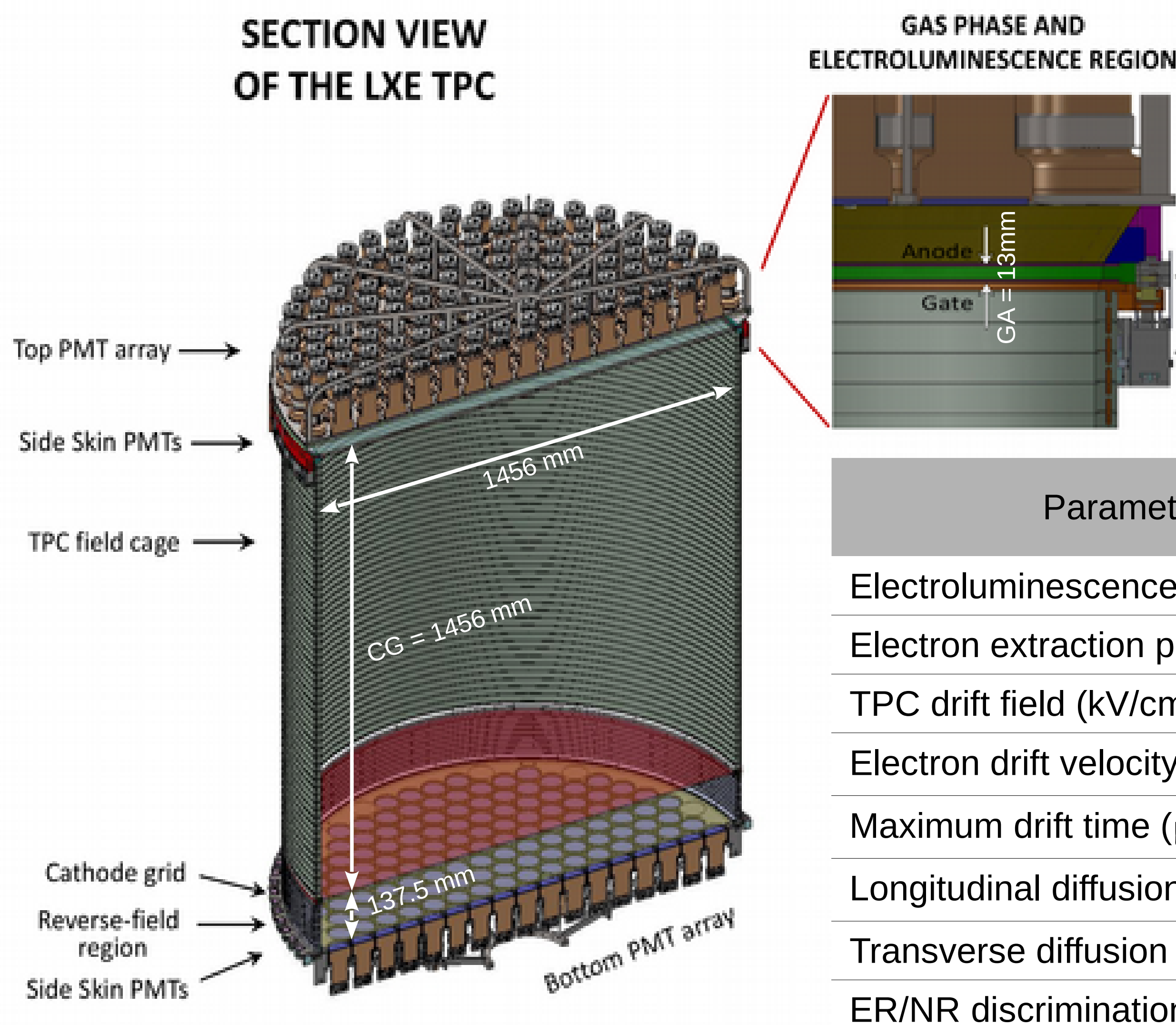
1000 days WIMP search run!

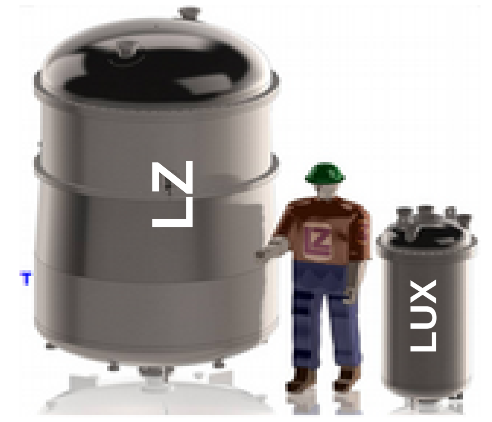
The LZ Detector details

- 10 tonnes of Lxe:
  - 7 ton active;
  - **5.6 fiducial**;
- Will be installed in the same laboratory used for **LUX** and inside the **same water tank**;
- 494 PMTs (in the TPC) acquired in dual-gain;
- Gadolinium-loaded liquid scintillator veto;
- Instrumented skin region (additional veto)



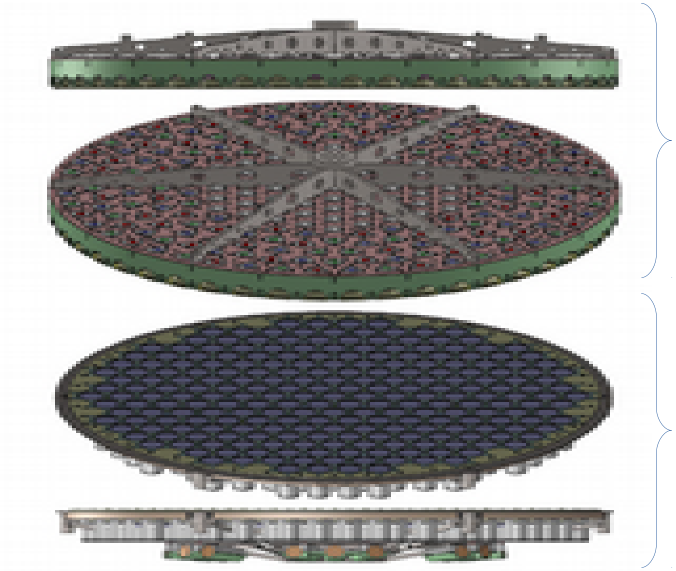
The LZ Detector: LXe TPC





Parameter	Baseline	Goal
Electroluminescence field (kV/cm)	10.2 (8 mm gas)	
Electron extraction probability	95%	99%
TPC drift field (kV/cm)	0.31	0.65
Electron drift velocity (mm/μs)	1.8	2.2
Maximum drift time (μs)	806	665
Longitudinal diffusion (μs)	2.2	2.0
Transverse diffusion (mm)	1.8	1.4
ER/NR discrimination	99.7%	

The LZ Detector: light collection



TOP PMT array
241 3'' PMTs arranged in a hexagonal configuration

Bottom PMT array
253 3'' PMTs arranged in a hexagonal-circular configuration to maximize light collection

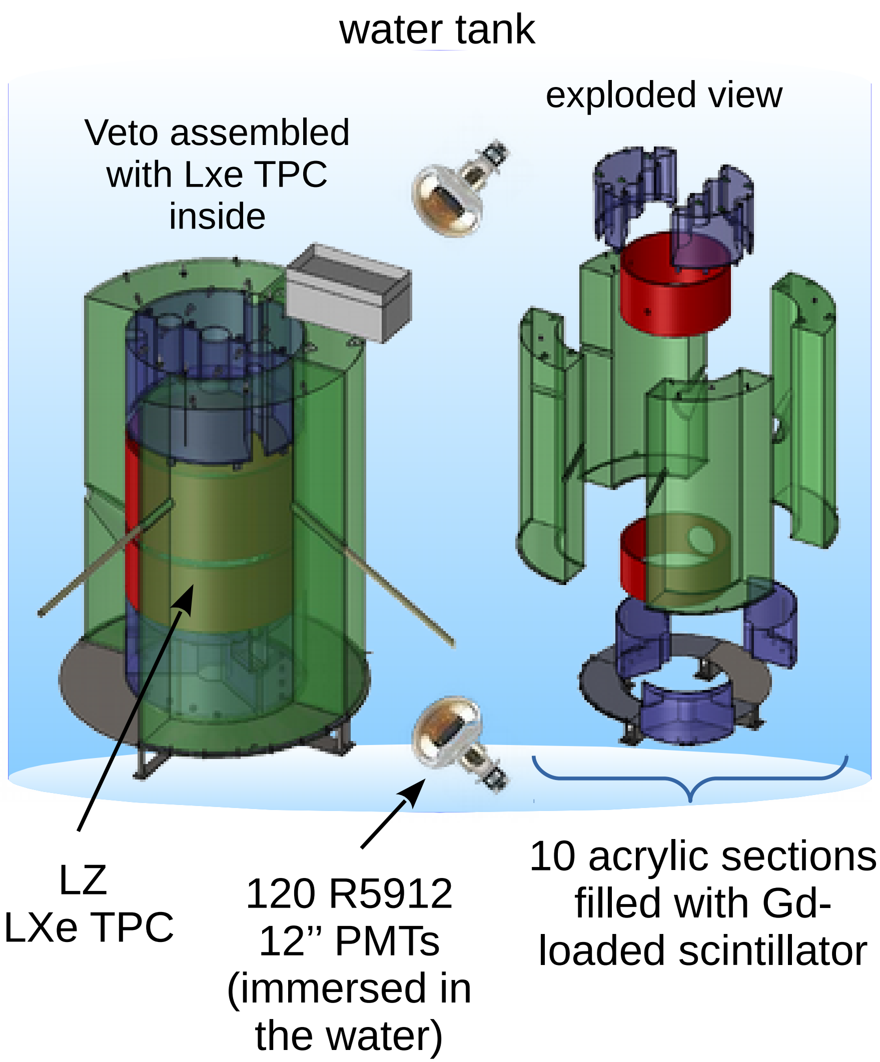
3-inch Hamamatsu R11410 PMT

Property	Baseline	Optimistic
PTFE reflectivity - liquid	95%	97%
PTFE reflectivity - gas	80%	85%
Average PMT QE	25%	28%
Grid reflectivity (liquid and gas)	20%	40%
Absorption length in liquid (m)	30	100
FV-averaged S1 PDE (α_1)	8.5%	13.3%

	Diffuse + Specular model (DS)		
	A	n_{PTFE}	BHR
807NX	0.961 (>0.955)	1.73	0.961 (>0.955)
NXT85	0.975 (>0.973)	1.8	0.975 (>0.973)
LUX	0.978 (>0.975)	1.79	0.978 (>0.975)

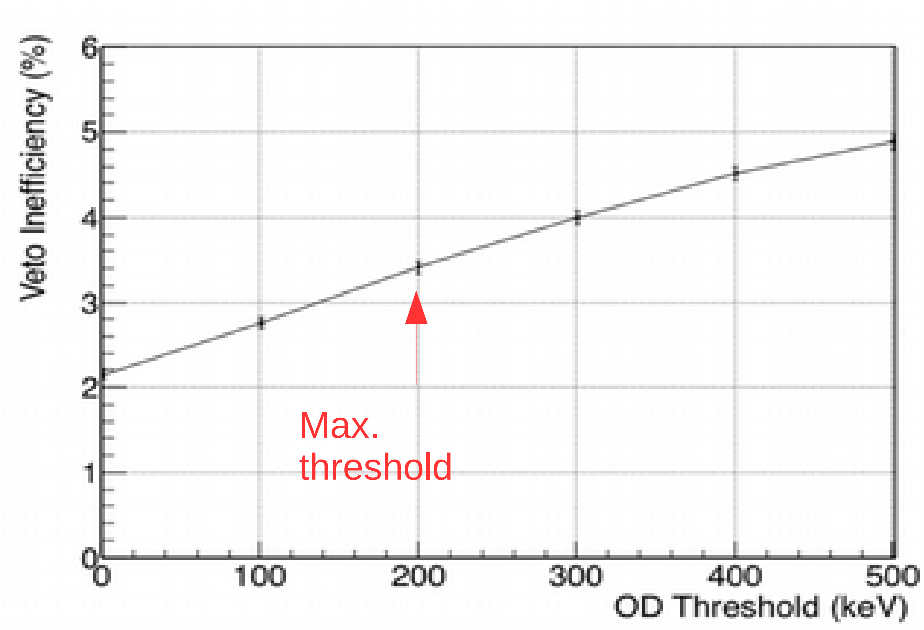
BHR – **B**i-**H**emispherical **R**eflectance.
A – **Al**bedo.

The LZ Outer Detectors



3 independent outer detectors (vetos), for γ with energies in the few MeV range and neutrons from (α,n) reactions or created by cosmic-ray interactions:

- The instrumented "skin" of LXe outside the LXe TPC;
- Gd-loaded liquid scintillator (LAB) acrylic sections;
  - 7% light collection efficiency (130 PE @ 1MeV).
- Surrounding water tank (muon veto);



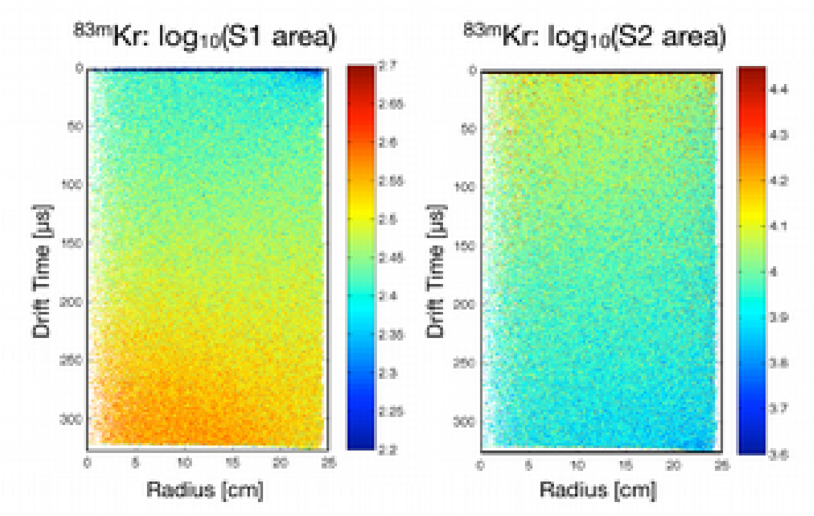
The LZ Detector: calibration

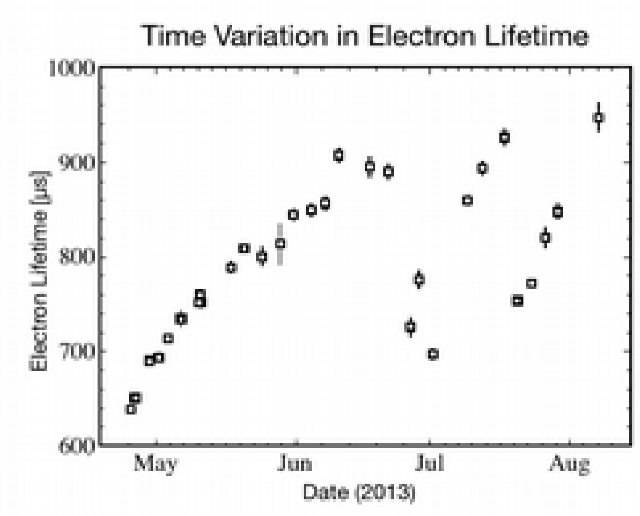
- A rigorous calibration is mandatory for an unambiguous claim of direct detection of any hypothetical dark matter candidate:

Baseline Calibration sources:

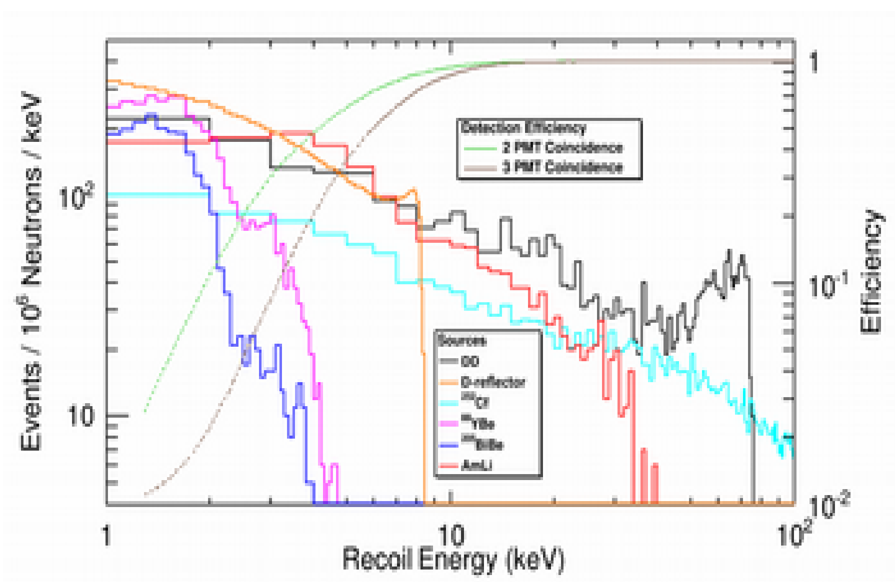
Isotope	What	Purpose	Deployment
Tritium	β, Q = 18.6 KeV	ER band	Internal
^{83m}Kr ^{131m}Xe	β/γ, 32.1KeV and 9.4 KeV γ, 164keV	TPC (x,y,z), Xe skin	Internal
^{220}Rn	α's, various	Xenon skin	internal
AmLi	(α,n)	NR band	CSD
^{252}Cf	Spontaneous fission	NR efficiency	CSD
^{57}Co ^{228}Th ^{22}Na	γ, 122 keV γ, 2.615 MeV, etc 511 keV	Energy scale, TPC, OD sync	CSD
^{88}YBe ^{205}BiBe ^{206}BiBe	n, 152 keV n, 88.5 keV n, 47 keV	Low energy NR response	External
DD	n, 2.450 keV n, 272 keV	NR light and charge yields	External

The LZ Detector: calibration

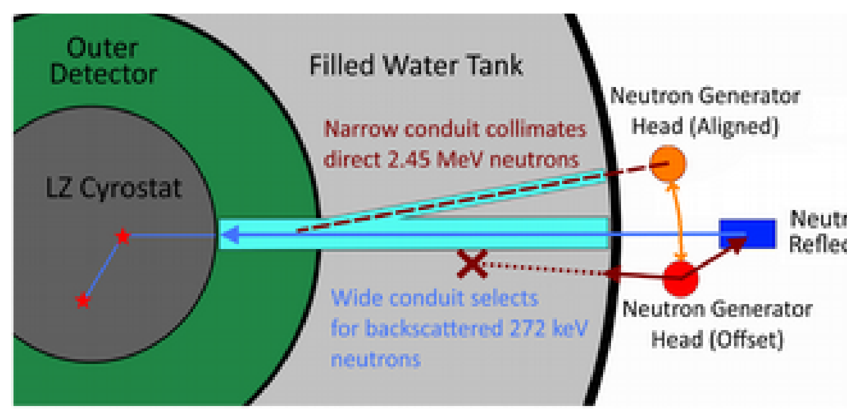




S1 and S2 (x,y,z) dependence (left) and electron lifetime (right), measured from S2(Z), using **LUX ^{83m}Kr calib. data**



Energy spectra (left) covered by the neutron calibrations and schematic representation of the setup for the DD calibration



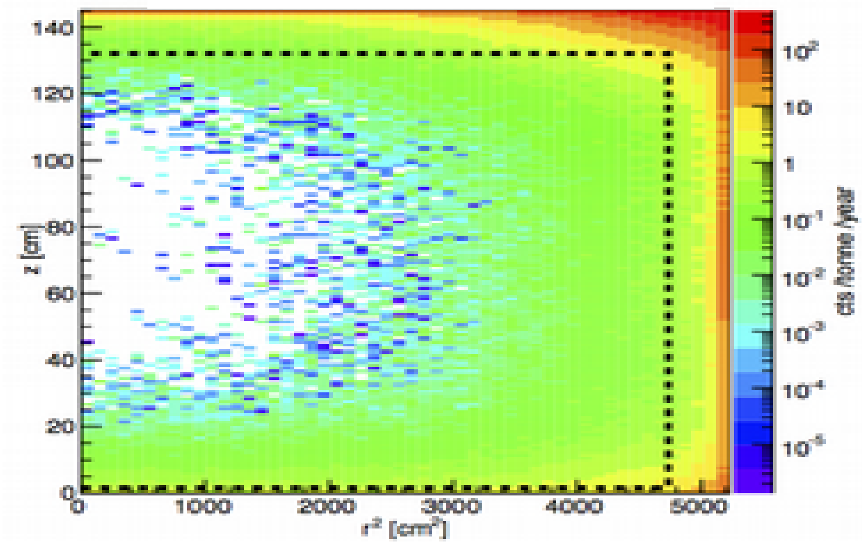
LZ backgrounds

Background source	RE cts	NR cts
Detector components	6.2	0.07
Dispersed radionuclides (Rn, Kr, Ar)	911	–
Laboratory and cosmogenic	4.3	0.06
Fixed surface contamination	0.19	0.37
^{136}Xe $2\upsilon\beta\beta$	67.0	–
Neutrinos (υ-e, υ-A)	255	0.72
Total	**1240**	**1.22**
Total (99.5% ER desc., 50% NR eff.)	**6.22**	**0.61**
Total ER+NR background events	**6.82**	

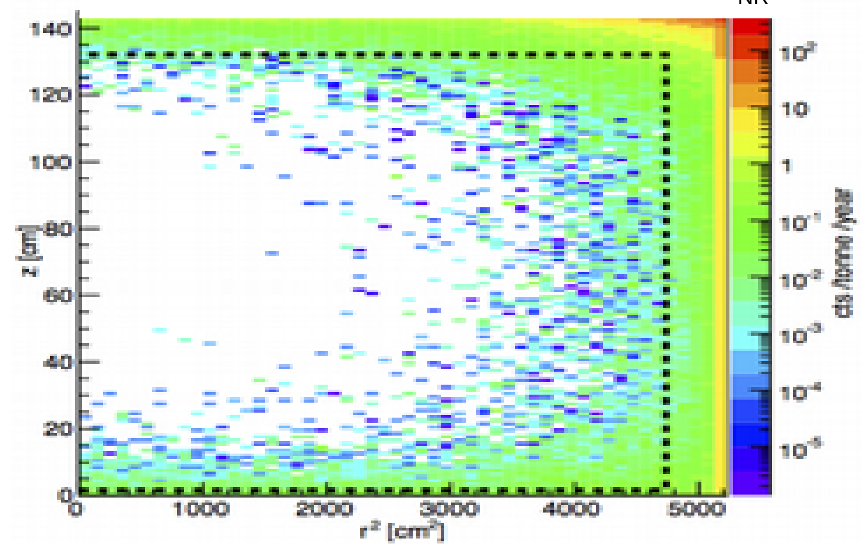
signal-like background events in 1000 live-days

- Largest contribution comes from **Rn**, Followed by **ν-e** solar neutrino scattering and atmospheric **ν-A** scattering;

NR + ER leakage (6 - 30 keV_{NR})

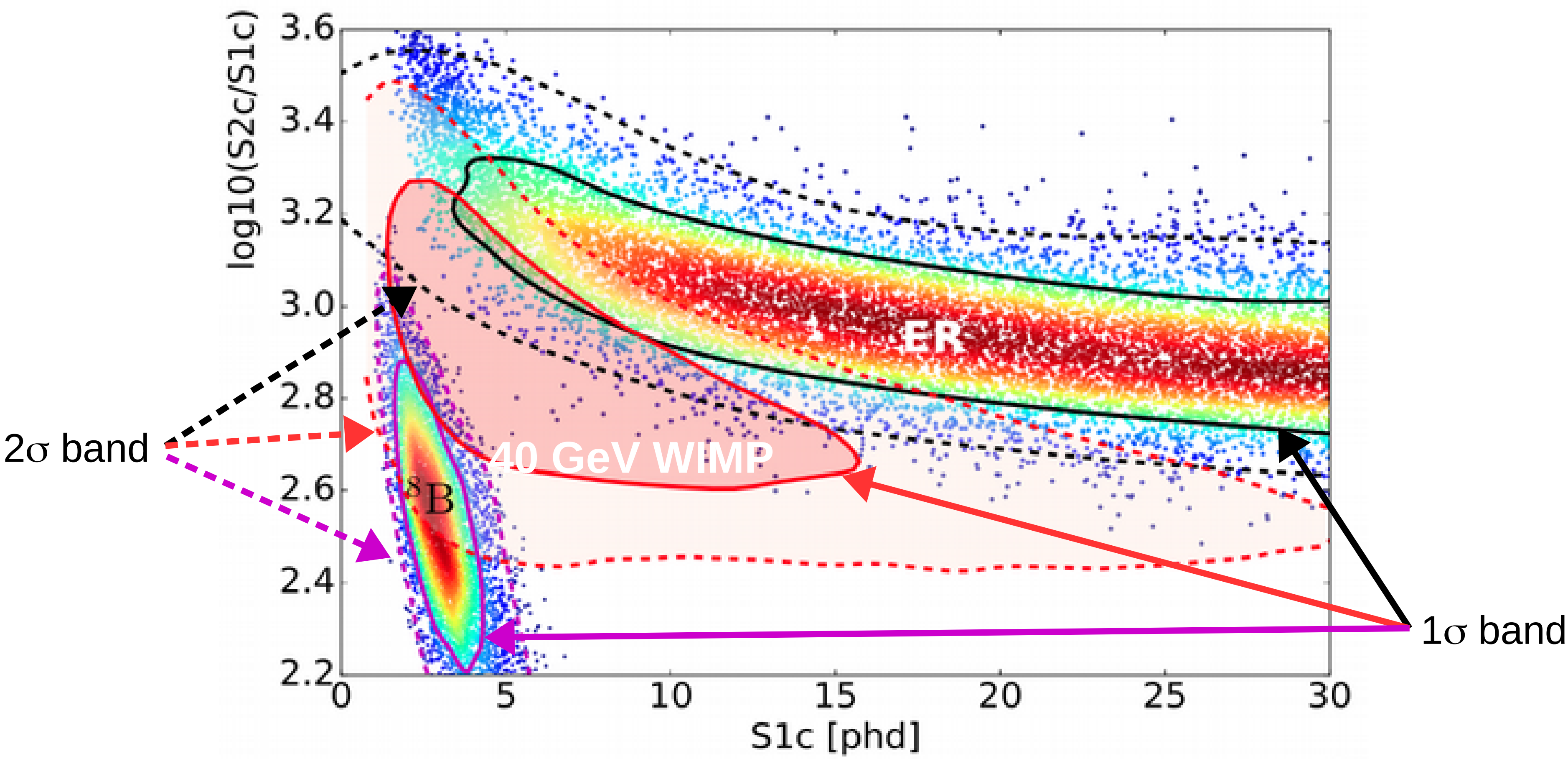


NR + ER leakage + vetoes (6 - 30 keV_{NR})



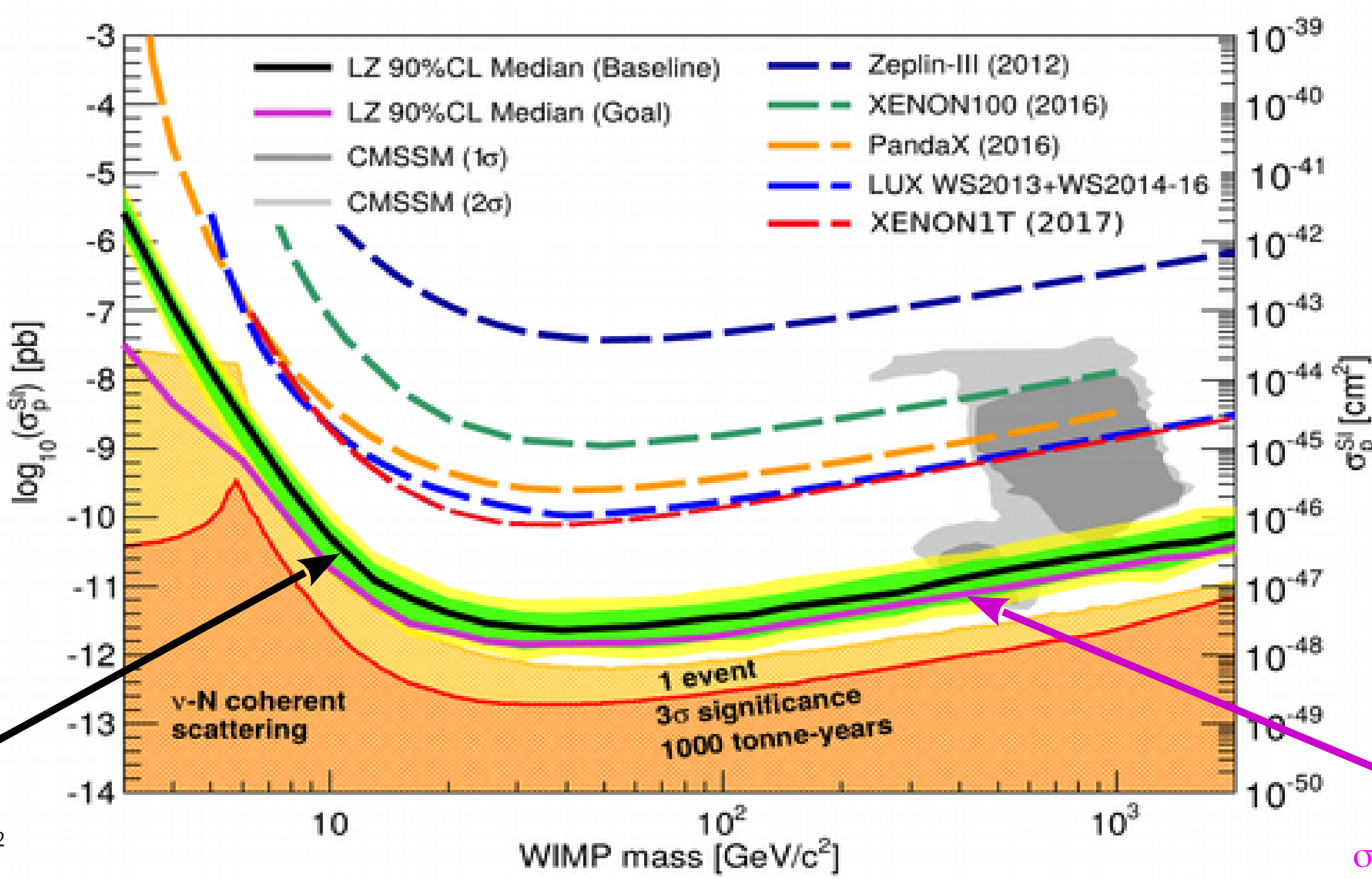
^{8}B Background in LZ

- Using PLR, neutrino background from solar ^{8}B affects low-mass WIMPs only:
  - The statistic shown represent **5x** the expected **ER** background and **500x** the expected **^{8}B** background for the 1000 days run)



LZ sensitivity to WIMPs

- **PLR used to estimate the sensitivity** (further assumptions: **conservative light collection** of **7.5%/12.5%**, electron life time of **859μs/2800μs** and a n-fold trigger of **3/2** for the **baseline** and **goal** estimation respectively)



Baseline:

$\sigma_p^{SI} = 2.3 \times 10^{-48} cm^2$

(40 GeV WIMP)

Goal:

$\sigma_p^{SI} = 1.1 \times 10^{-48} cm^2$

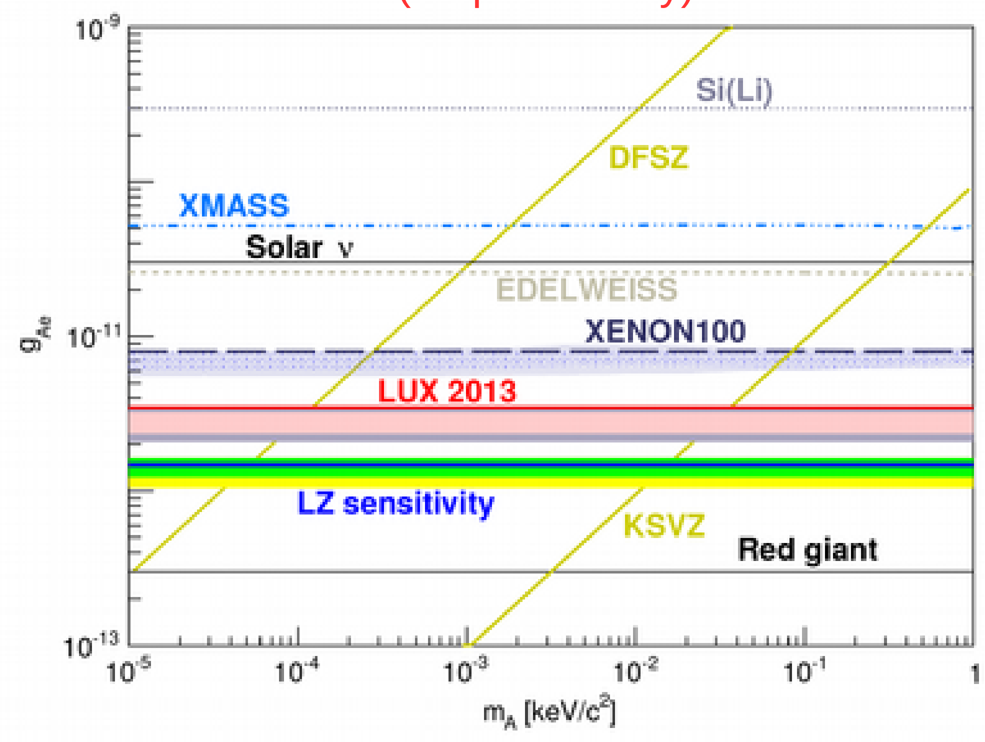
(40 GeV WIMP)

LZ sensitivity to Axions and ALPs

For 1000 live-days, 5.6 ton fiducial mass
(LZ Baseline assumptions)

Axions

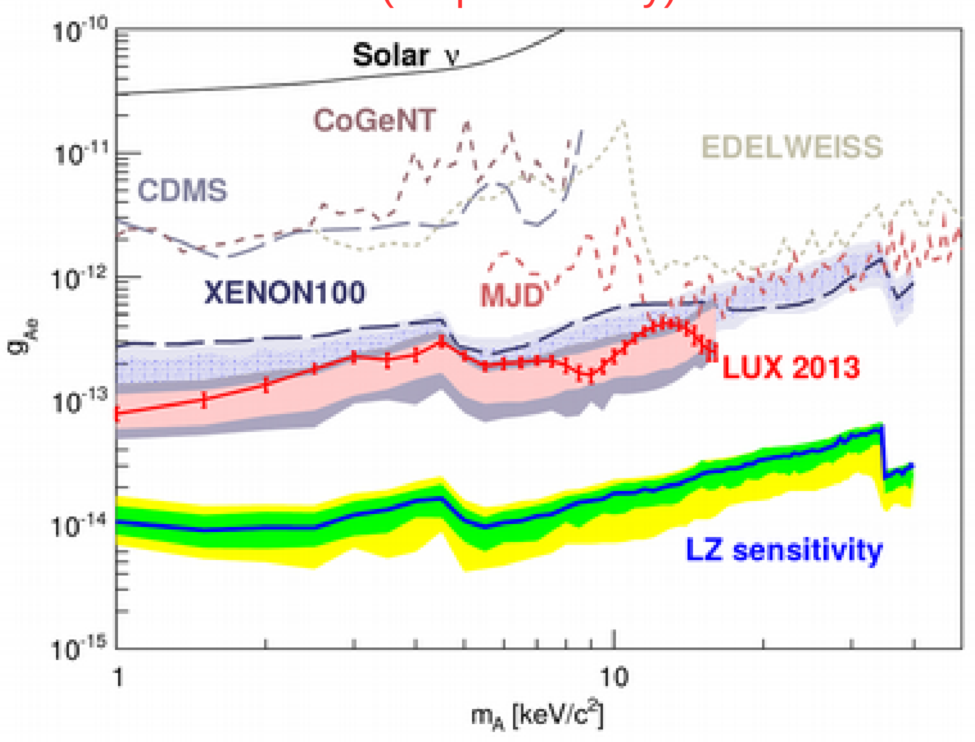
(LZ preliminary)



Excludes $g_{Ae} > 1.5 \times 10^{-12}$ (90% CL)

ALPs

(LZ preliminary)



Excludes $g_{Ae} > 1.5 \times 10^{-12}$ (90% CL) across the mass range 1-40 keV.c^{-2}

LZ Sensitivity to: other physics...

- **Elastic Scattering of Solar Neutrinos**:
  - Expected **838 pp events**, **69 events from ^{7}Be** and **<10 from ^{13}N** (E_ν<220 keV) in the **1.5 to 20 keVee** window (LZ will be sensitive to neutrinos energies significantly lower than SAGE or BOREXINO);
- **Coherent Nuclear Scattering of Solar Neutrinos:**
  - Expected **7 events from ^{8}B** neutrinos (W/ a signal very similar to a 6 GeV WIMP);
- **Neutrino Magnetic Moment:**
  - The LZ ~1 keV energy threshold suggests an increase in sensitivity of ~1 order of magnitude relative to the upper limit of $5.4\text{x}10^{-11}\mu_B$ set by BOREXINO;
- **Neutrinoless Double Beta Decay:**
  - LZ has the potential to a sensitivity limit on the $0\nu\beta\beta$ half-life of ^{136}Xe of 1×10^{26} y, 90% C.L. (the current half-live limit is $1.07\text{x}10^{26}$ y set by KamLAND-Zen);
- **Sterile Neutrinos (*not part of the main scientific goal*):**
  - The excellent spatial resolution of the LZ TPC allows the spatial pattern of electron neutrino oscillation into a sterile neutrino from a 5 MCi ^{51}Cr electron neutrino source to be detected.
- **Electrophilic WIMPs**:
  - Axial-vector WIMP-electron scattering **$\sigma_{We}\geq 6\text{x}10^{-38}$ cm^2** (w/ background subtraction). (The interpretation of the DAMA excess implies a $\sigma_{We}=2\text{x}10^{-32}$ cm^2 @ M_W=50 GeV/c^2).
- …

The LZ collaboration

36 institutions – 250 scientists, engineers, and technicians

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