The
University
Of
Sheffield.

The LUX-ZEPLIN dark matter experiment

Vitaly A. Kudryavtsev
The University of Sheffield

Outline

- Evidence for dark matter (1 slide).
- Candidates for dark matter (1 slide).
- WIMPs: parameters and detection principles.
- Features of different techniques.
- Xenon detectors.
- LUX results.
- LZ:
  - Detector,
  - Backgrounds and their suppression/rejection strategies,
  - Sensitivity.
- Neutrino floor and beyond.
- Summary.

Evidence for (non-baryonic) dark matter

- Galactic rotation curves.
- Dynamics of galaxy clusters.
- Gravitational lensing effects; bullet cluster.
- Large-scale structure of the Universe.
- Fluctuations in the temperature of cosmic microwave background.
- Primordial (big-bang) nucleosynthesis -> non-baryonic (unless primordial black holes).
- Modified gravity or Modified Newtonian dynamics (MOND).
- … Add your stuff here.
- Generally accepted (from Planck results): about 27% of the matter-density of the Universe is ‘dark matter’, 67% dark energy and 5% normal (baryonic) matter.

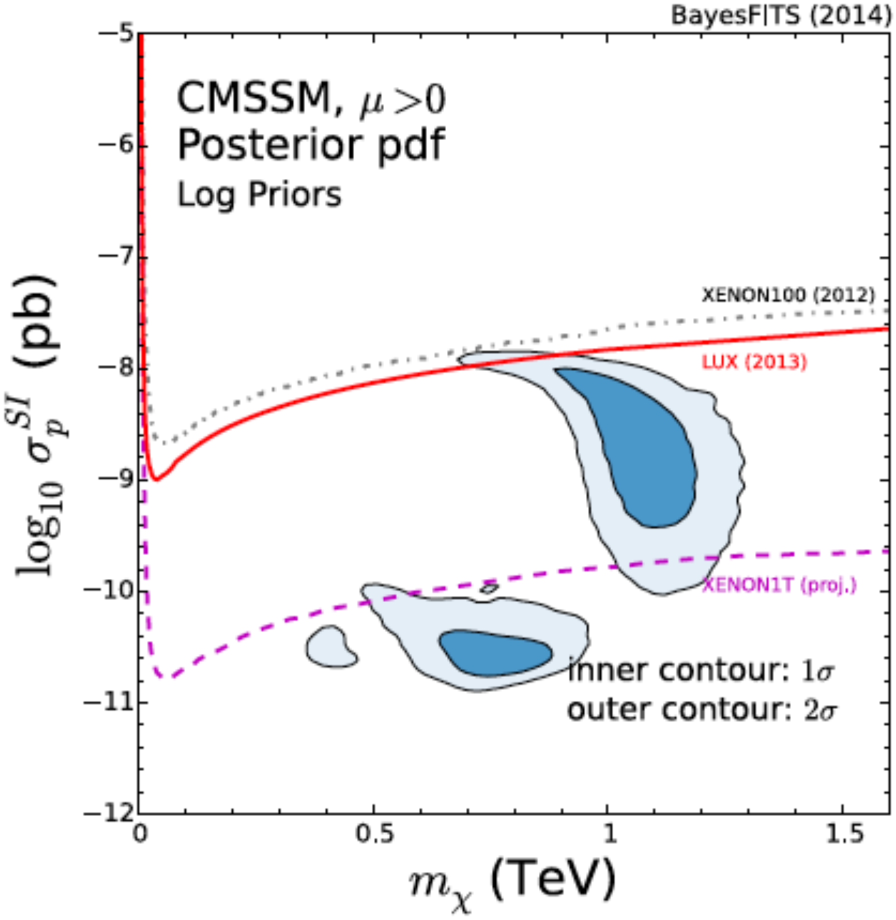
Candidates to (non-baryonic) dark matter

- Weakly interacting massive particles (WIMPs).
    - Satisfy all requirements.
    - Explain most observations.
    - Well motivated by Supersymmetry – neutralino or lightest supersymmetric particle (but no evidence of supersymmetry at LHC yet).
- Axions and axion-like particles (ALPs) – not covered here.
- Sterile neutrinos – not covered here.
- … Add your stuff here.

WIMPs

- Stable.
- Neutral.
- Weakly interacting.
- Should have been produced in large numbers at early stages of the Universe.
- A good candidate is provided by the Supersymmetry (SUSY) – lightest supersymmetric particle, neutralino.
- Mass ~1-1000 GeV/c^2.
- Velocities ~200 km/s; energies – ~keV or tens of keV.
- If WIMPs are responsible for all dark matter in the Galactic halo, then their flux at the Earth should be about 10^5 – 10^7 particles/cm^2/s (compared to the solar neutrino flux of about 10^{11} neutrinos/cm^2/s).

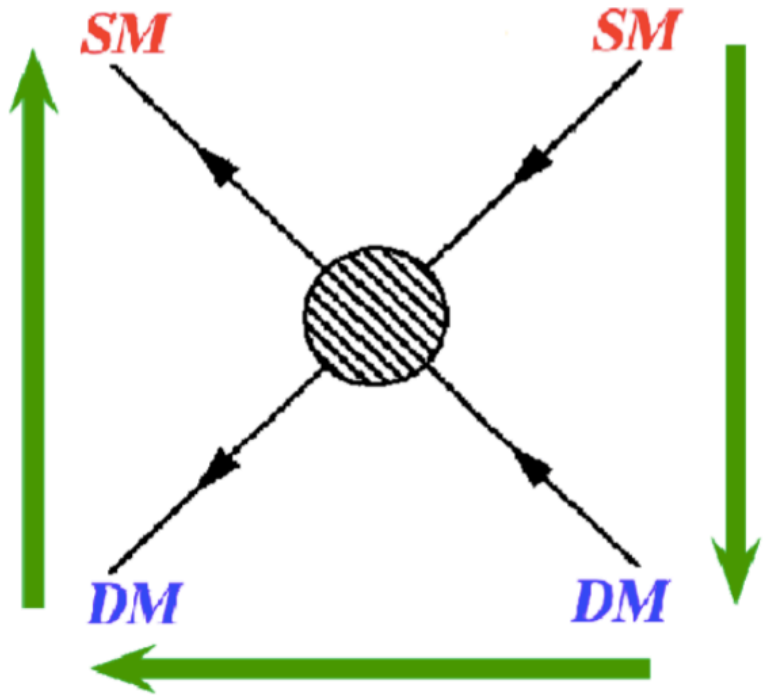
Neutralino as dark matter



Roszkowski et al. JHEP 1408 (2014) 067.

Good arguments for considering WIMPs as neutralinos in SUSY. However, we are looking for WIMPs, which are not necessarily neutralinos.

Principles of dark matter detection



Indirect detection:
WIMP annihilation

Colliders:
WIMP production

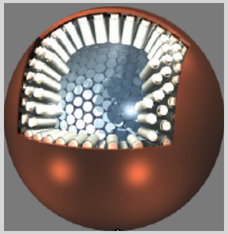
Direct detection:
WIMP scattering

WIMP detection

Phonons

CRESST, $CaWO_4$
(Gran Sasso)

DAMA, NaI
(Gran Sasso)

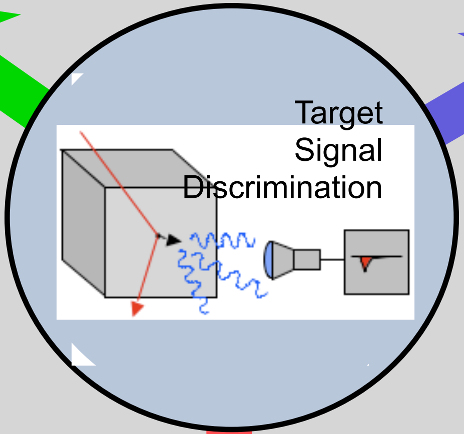


XMASS, LXe
(Kamioka)

Scintillation

DEAP-3600, LAr
(SNOLab)

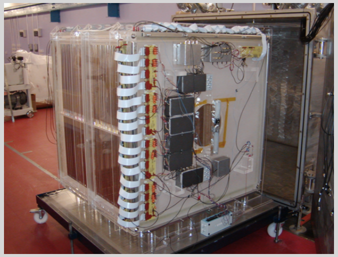
EDELWEISS, Ge
(Modane)



LUX, LXe
(SURF)

Ionisation

SuperCDMS, Ge
(Soudan/SNOLab)



DRIFT, CS_2+F
(Boulby) and
some other
directional
searches

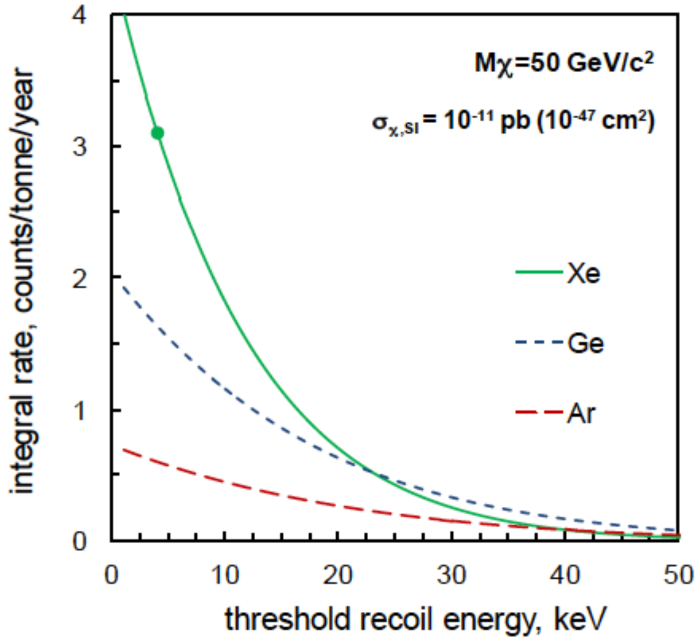
XENON, LXe
(Gran Sasso)

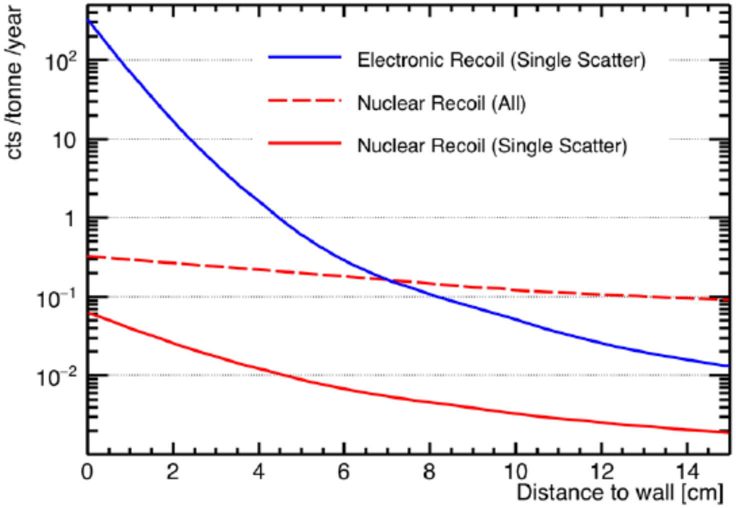
Requirements for WIMP detectors

- High mass.
- Preferably high atomic mass.
- Low energy threshold.
- Radio-pure materials – extensive screening campaign.
- Underground location, > 2.5 km w. e.
- Shielding against radioactivity in rock.
- Target material purification.
- Control of surface events (from radon daughters).
- Reduced activation.
- Rejection of multi-hit events.
- Anticoincidence (active veto) systems.
- Fiducialisation.
- Discrimination between nuclear and electron recoils.
- Good understanding of backgrounds – simulations based on screening.
- Calibrations: electron recoils (ER) and nuclear recoils (NR).

Why liquid xenon

- Good scintillator.
- Two-phase -> TPC with good position resolution.
- Self-shielding.
- Good discrimination between ERs and NRs.
- High atomic mass: spin-independent cross-section $\propto A^2$
- Presence of even-odd isotopes (odd number of neutrons) for spin-dependent studies.
- Other physics:
  - Axion search (not covered here),
  - Neutrinoless double-beta decay.





Two-phase noble detectors

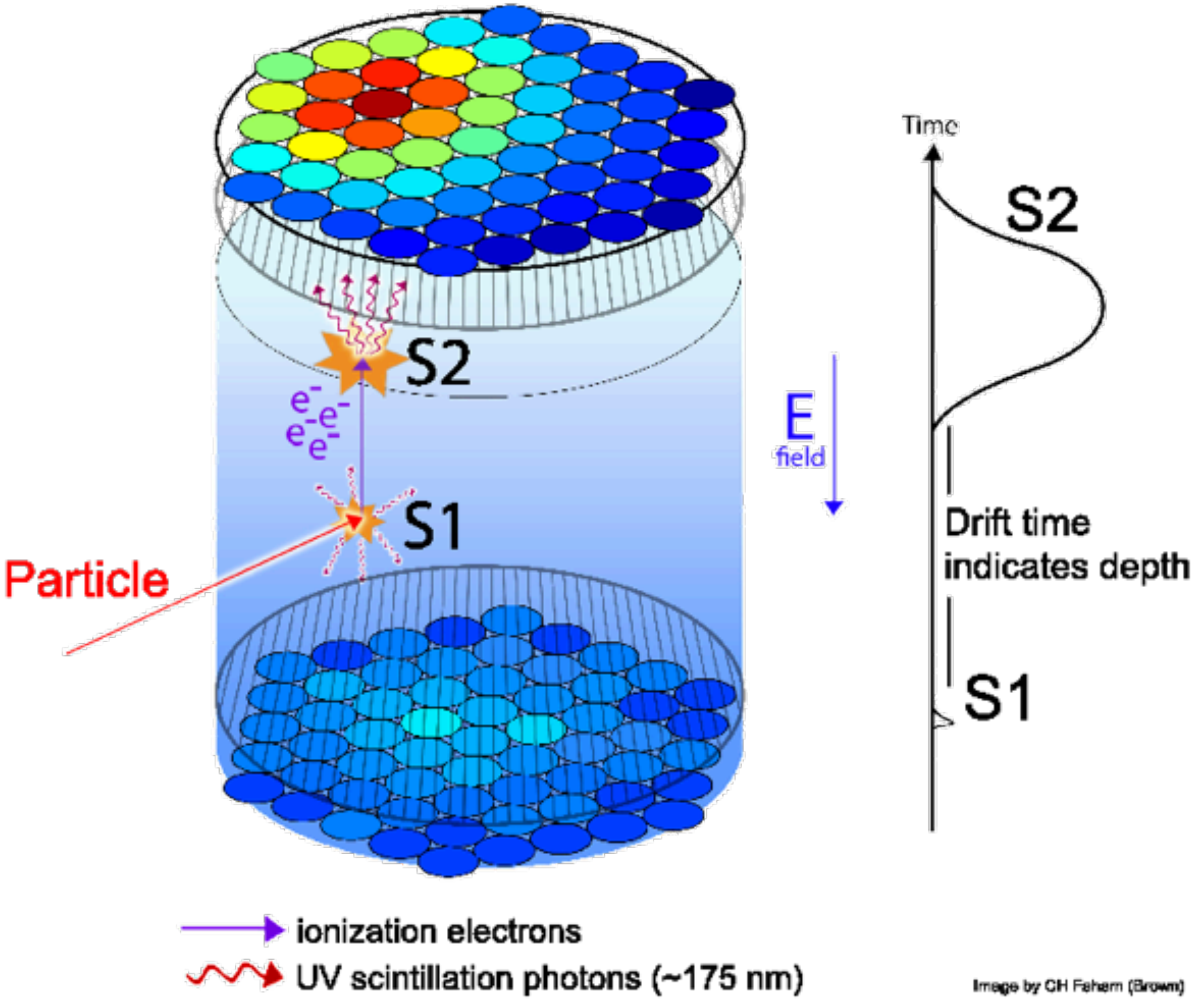


Image by CH Faham (Brown)

- S1 – primary scintillation.
- S2 –secondary scintillation, proportional to ionisation.

LUX: detector

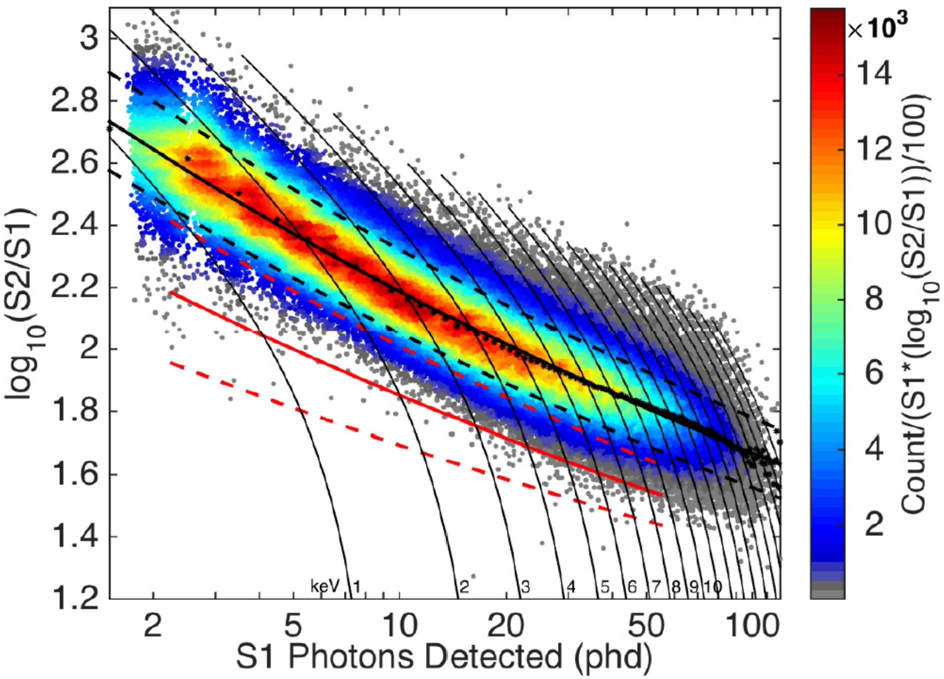
LUX DETECTOR

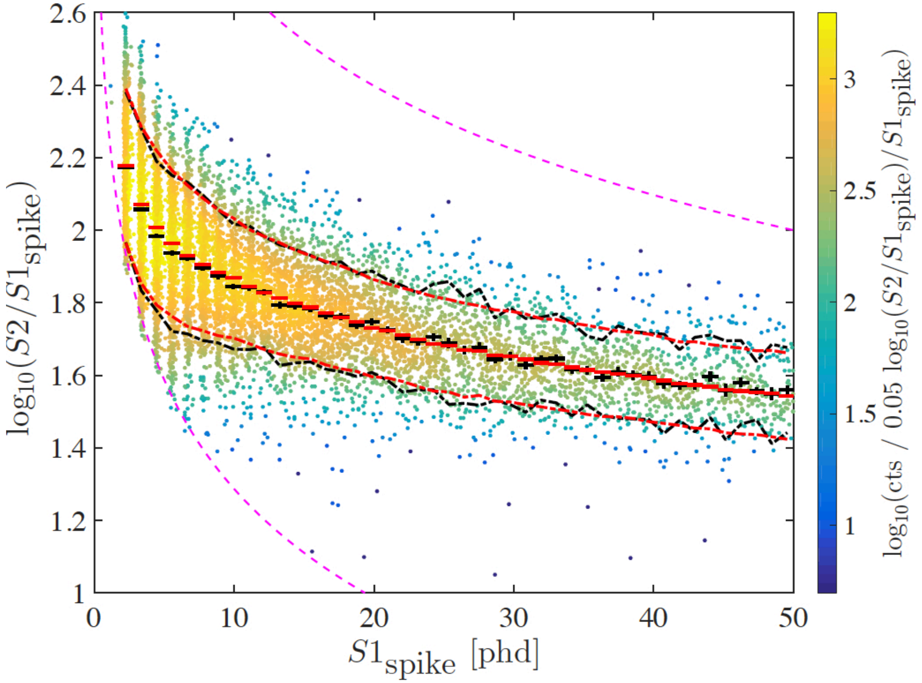
- 48cm diameter by 48 cm height dodecagonal “cylinder”.
- 250.9 kg LXe in active region
- 61 PMTs on top, 61 on bottom, specially produced for low radiogenic BGs and VUV sensitivity.
- Xenon was pre-purified via chromatographic separation, reducing residual krypton.
- Liquid is continuously recirculated (¼ tonne per day) to maintain chemical purity.
- Ultra-low BG titanium cryostat.

A. Manalaysay (LUX). Talk at IDM2016.

Sanford Underground Research Facility (SURF), South Dakota (USA)
~4200 m w. e.

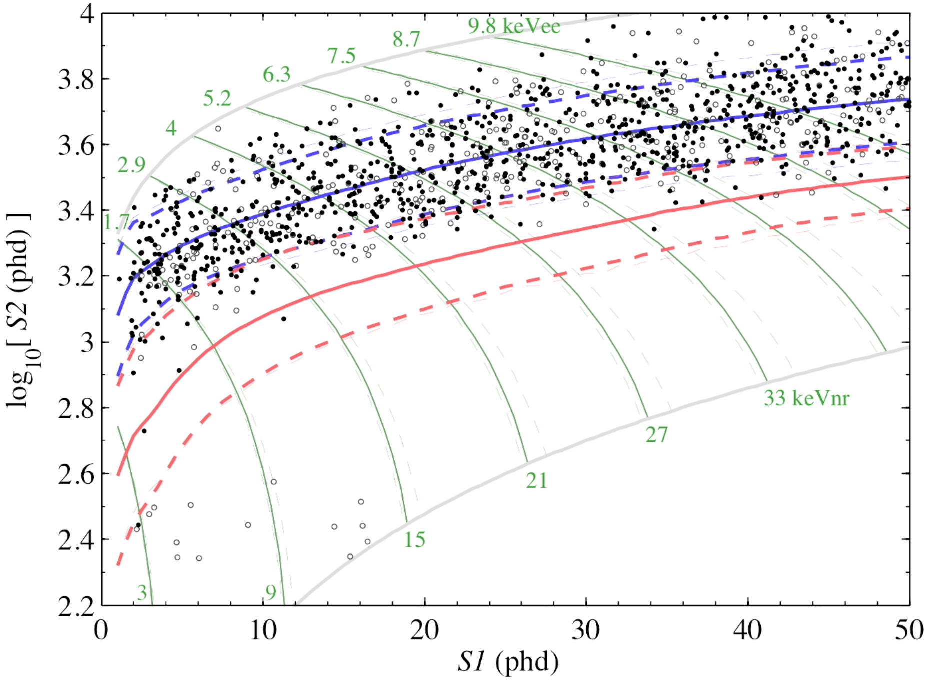
LUX: calibrations

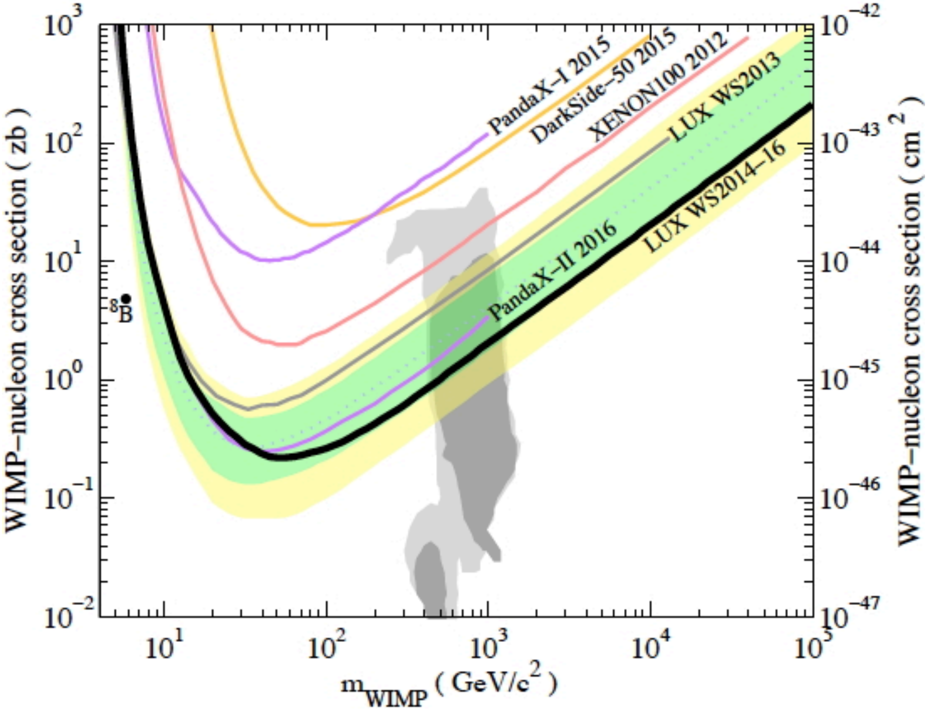




- ^{83m}Kr – uniform distribution, 1.8 hours half-life, weekly.
- CH_3T (tritiated methane) – uniform, removed by purification, 2-3 times a year (left figure), D. Akerib et al. (LUX Collaboration), Phys. Rev. D93 (2016) 072009.
- D-D – generator (right), 2.45 MeV neutrons, collimated, D. Akerib et al. (LUX Collaboration), arXiv:1608.05381 [physics.ins-det].

LUX: results





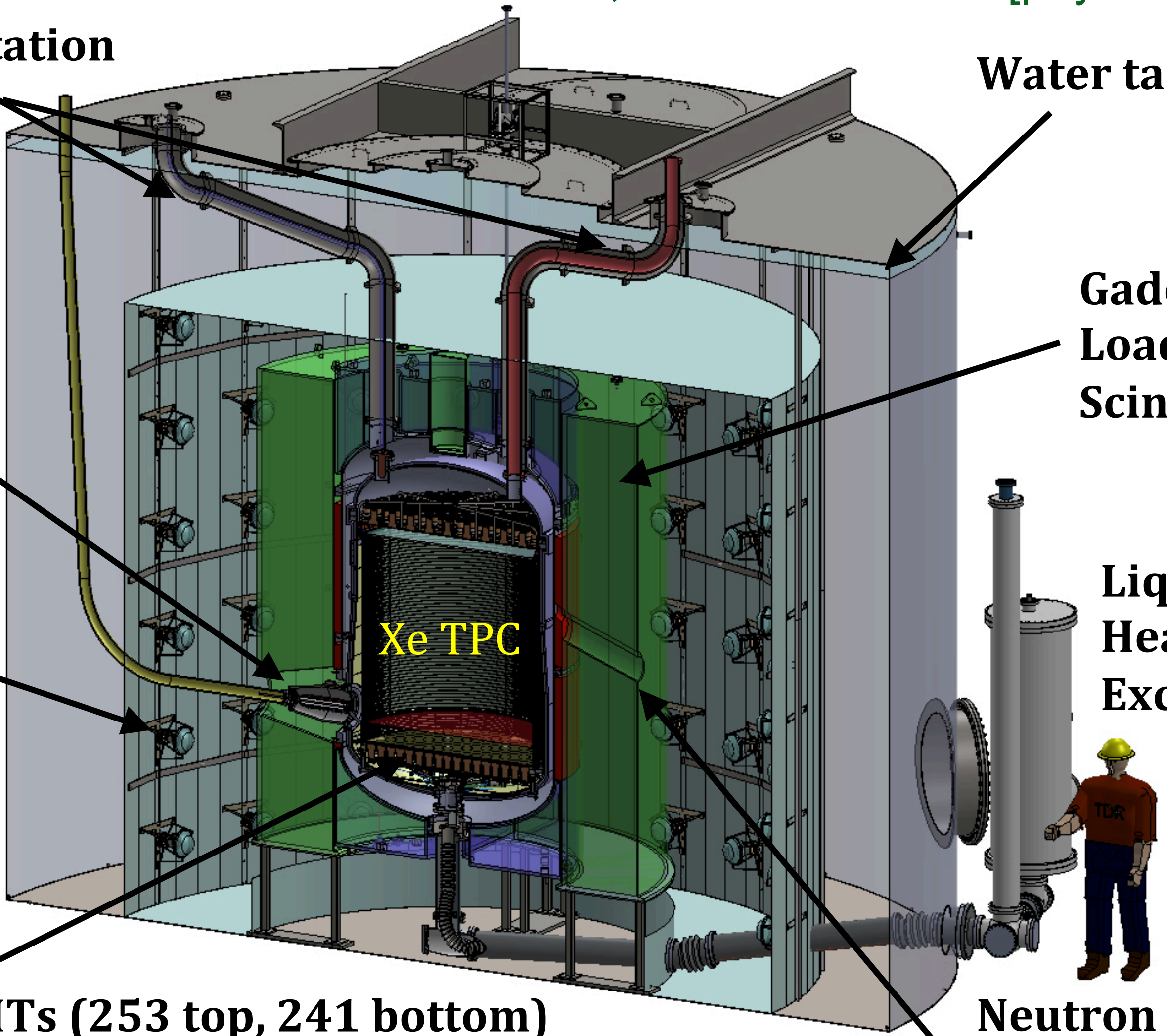
Data after cuts: 332 live days (left).
Limits on spin-independent WIMP-nucleon cross-section (right).
Akerib et al (LUX Collaboration), arXiv:1608.07648 [astro-ph.CO].

LZ Collaboration, Oxford, August 2016

- ✧ Brookhaven National Laboratory
- ✧ Brown University
- ✧ Center for Underground Physics, Korea
- ✧ Fermi National Accelerator Laboratory
- ✧ Imperial College London
- ✧ LIP Coimbra, Portugal
- ✧ Lawrence Berkley National Laboratory
- ✧ Lawrence Livermore National Laboratory
- ✧ MEPhI-Moscow, Russia
- ✧ Northwestern University
- ✧ SLAC National Accelerator Laboratory
- ✧ South Dakota School of Mines and Technology
- ✧ South Dakota Science and Technology Authority
- ✧ STFC Rutherford Appleton Laboratory
- ✧ Texas A&M University
- ✧ University at Albany, SUNY
- ✧ University College London
- ✧ University of Alabama
- ✧ University of California, Berkeley
- ✧ University of California, Davis
- ✧ University of California, Santa Barbara
- ✧ University of Edinburgh
- ✧ University of Liverpool
- ✧ University of Maryland
- ✧ University of Michigan
- ✧ University of Oxford
- ✧ University of Rochester
- ✧ University of Sheffield
- ✧ University of South Dakota
- ✧ University of Wisconsin-Madison
- ✧ Washington University in St. Louis
- ✧ Yale University

LUX-ZEPLIN: LZ

LZ Collaboration, arXiv:1509.02910[physics.ins-det]



Instrumentation conduits

Water tank

HV feed-through

Gadolinium Loaded Liquid Scintillator

120 Outer Detector PMTs

Liquid Xe Heat Exchanger

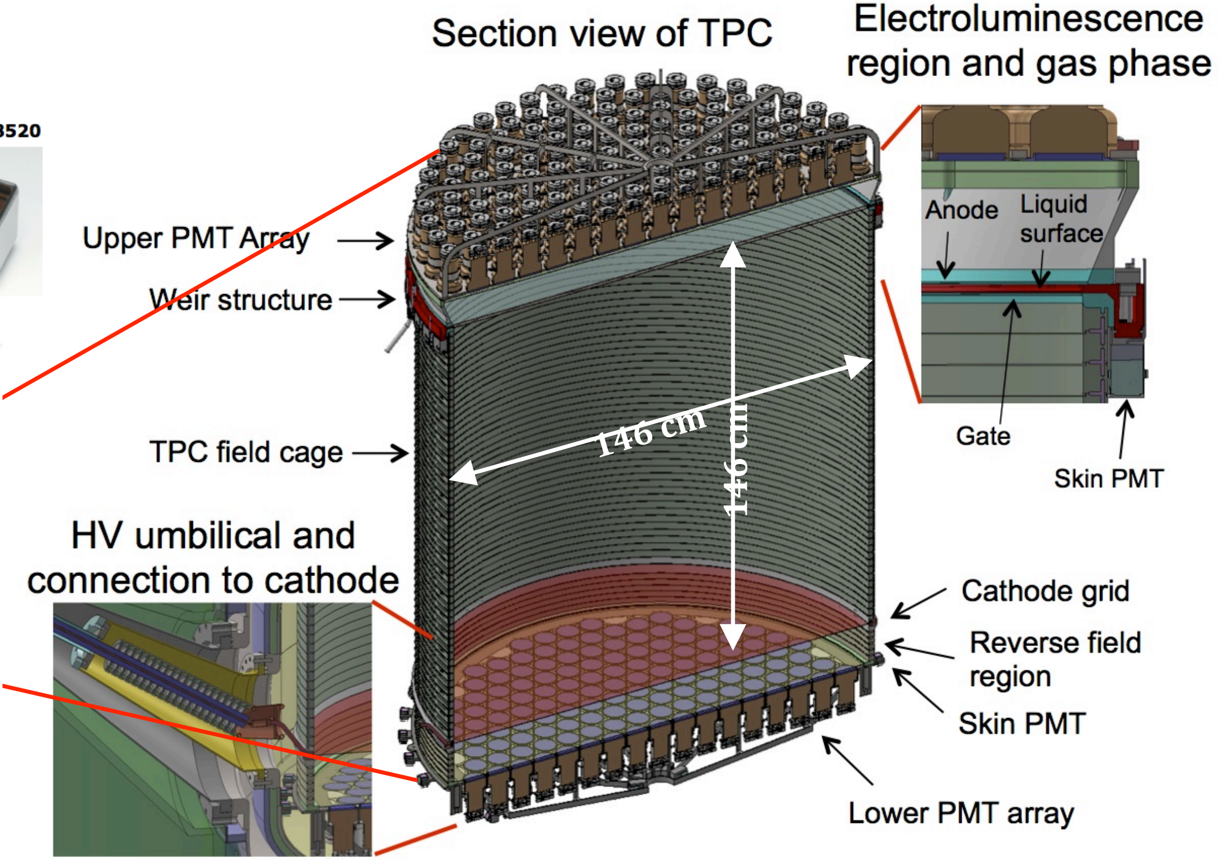
494 TPC-PMTs (253 top, 241 bottom) + 131 skin-PMTs

Neutron calibration tube and external source tubes

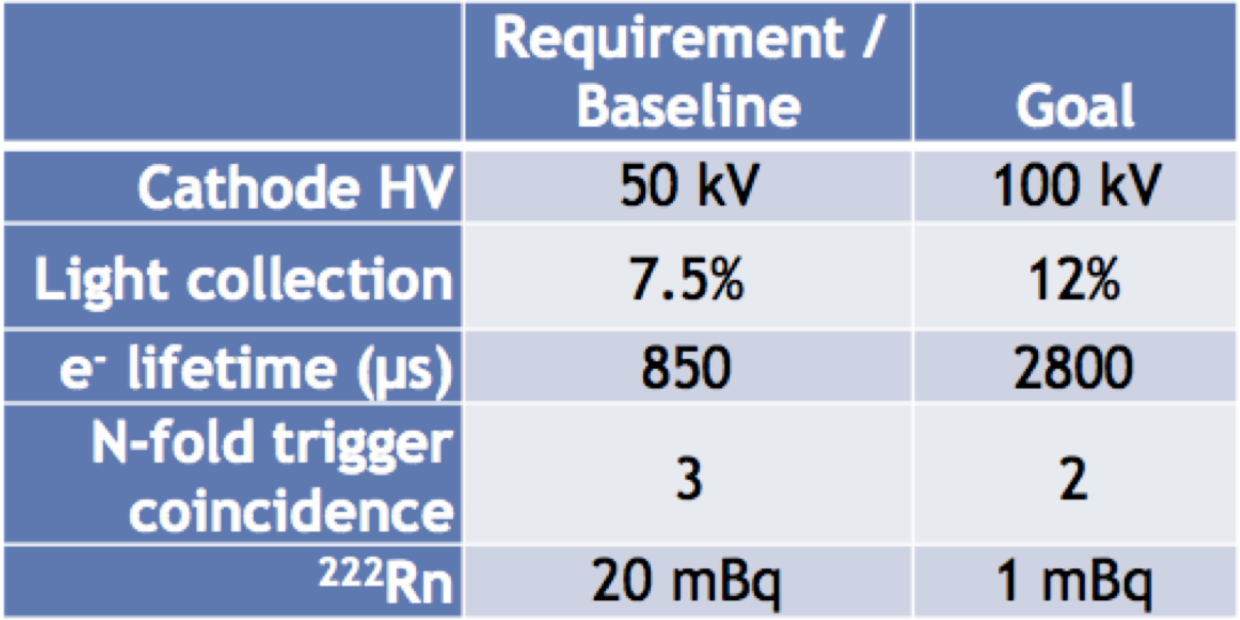
TPC design

- **7-tonne active region (cathode → gate), 5.6 tonne fiducial volume.**
- **253 top + 241 bottom 3” ϕ PMTs (activity ~mBq; high quantum efficiency).**
- **TPC lined with high-reflectivity PTFE ($R_{PTFE} \geq 95\%$).**
- **Instrumented “Skin” region optically separated from TPC.**

Low background Ti vessels



TPC: Main parameters

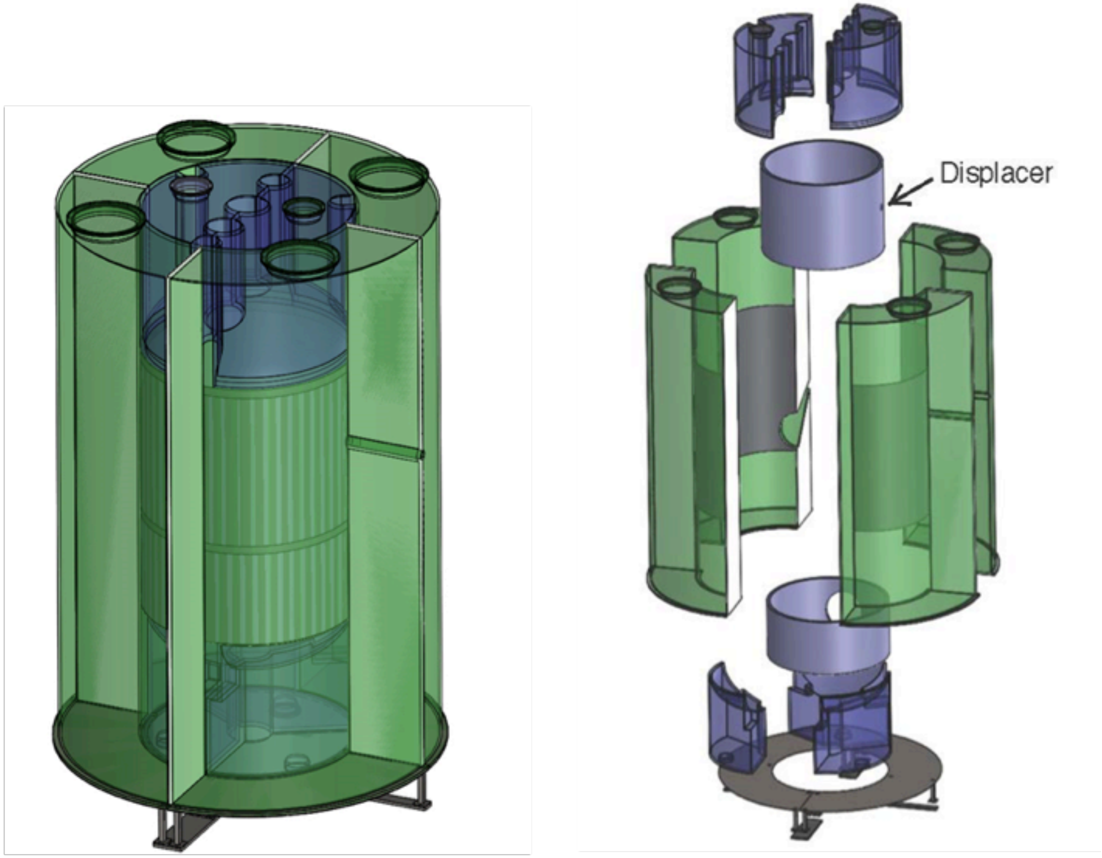


	Requirement / Baseline	Goal
Cathode HV	50 kV	100 kV
Light collection	7.5%	12%
e^- lifetime (μs)	850	2800
N-fold trigger coincidence	3	2
^{222}Rn	20 mBq	1 mBq

- 5.8 keV nuclear recoil energy for the S1 threshold (4.5 keVnr LUX).
- 0.7 kV/cm drift field, 99.5% ER/NR discrimination (already surpassed in LUX at 0.2 kV/cm)

Outer detector

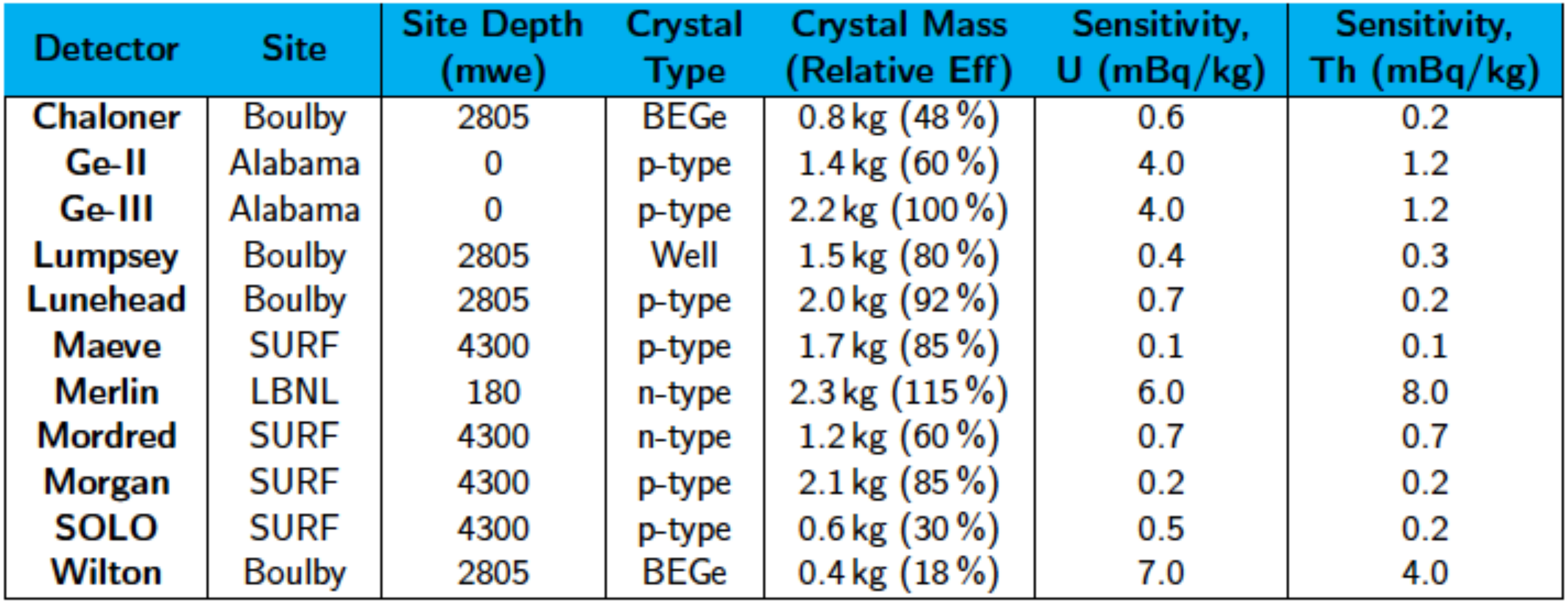
- Essential to maximize fiducial volume.
- 60 cm thick, 17.5 tonnes gadolinium-loaded scintillator, similar to Daya Bay experiment.
- 97% efficient for neutron detection.



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.

Material screening

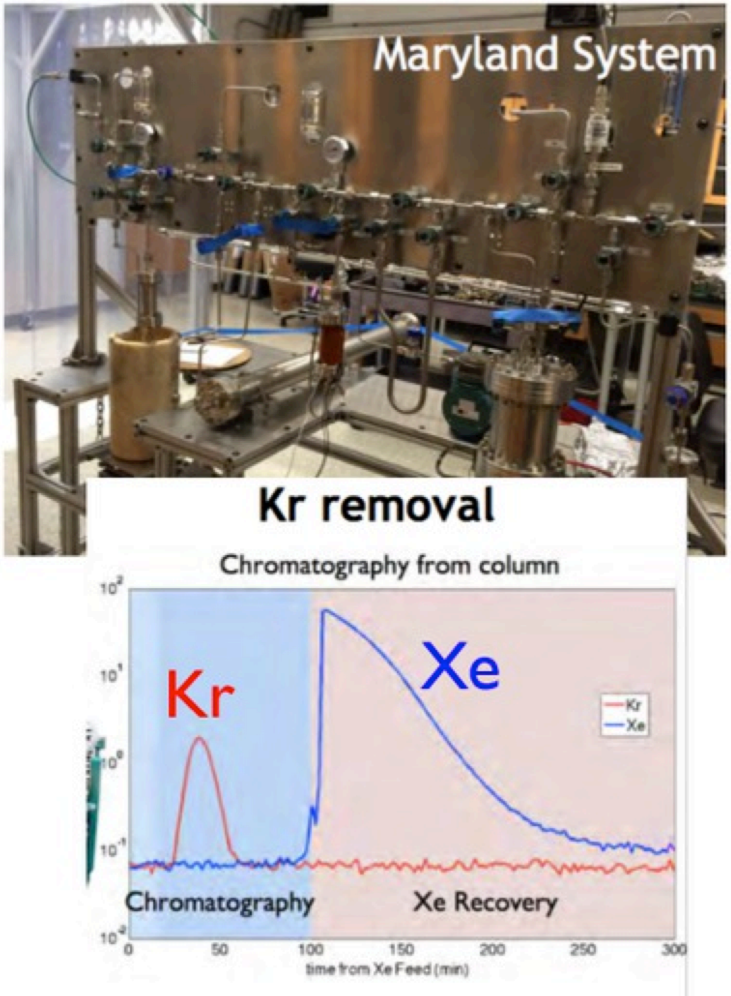
- High-purity Ge detectors: gamma-ray lines; SURF, Boulby.
- ICPMS: parent isotopes in the decay chains: ^{238}U, ^{232}Th, ^{nat}K; UCL, Alabama, Korea.
- Neutron activation analysis: Alabama.
- Radon measurements: South Dakota, UCL, Maryland, Alabama.



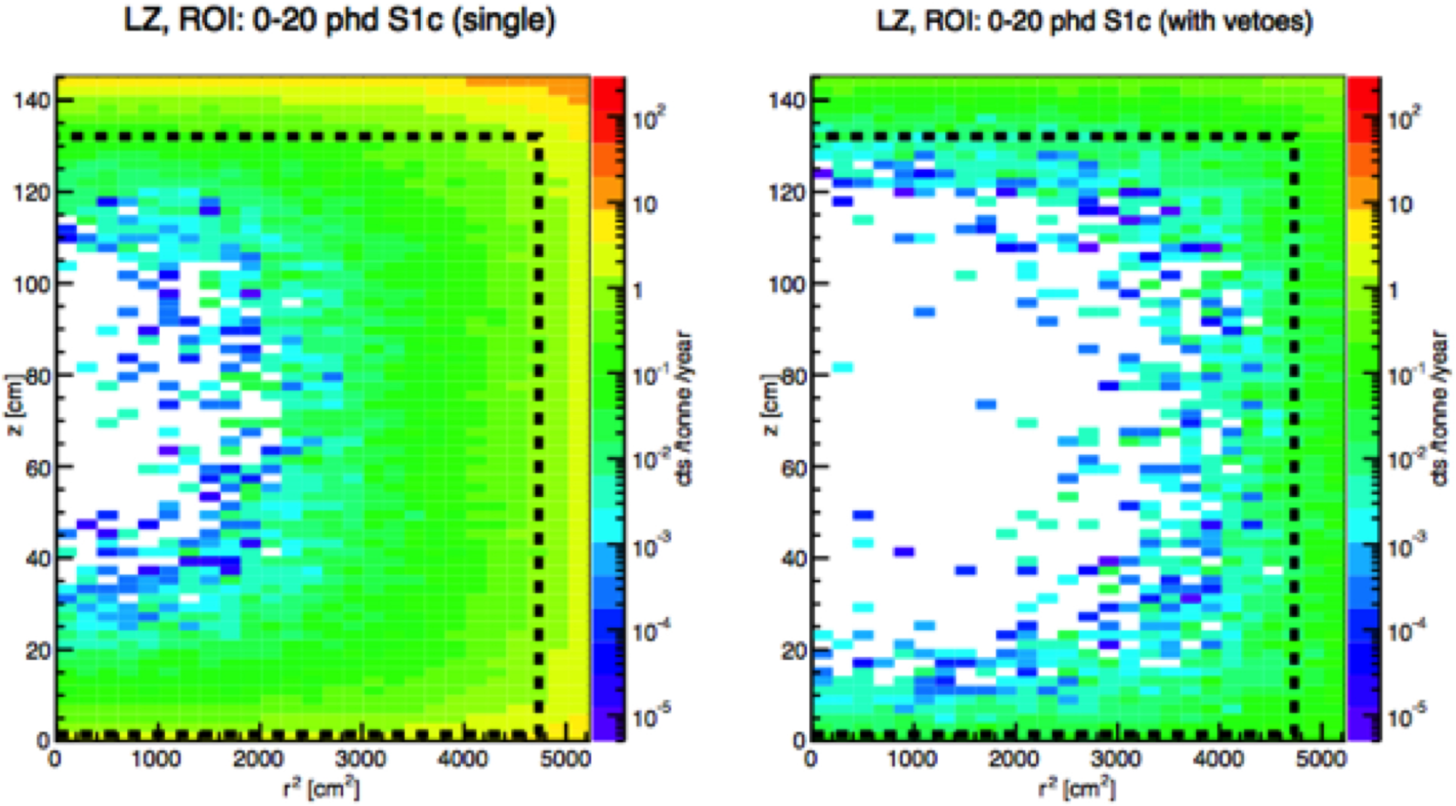
Detector	Site	Site Depth (mwe)	Crystal Type	Crystal Mass (Relative Eff)	Sensitivity, U (mBq/kg)	Sensitivity, Th (mBq/kg)
Chaloner	Boulby	2805	BEGe	0.8 kg (48 %)	0.6	0.2
Ge-II	Alabama	0	p-type	1.4 kg (60 %)	4.0	1.2
Ge-III	Alabama	0	p-type	2.2 kg (100 %)	4.0	1.2
Lumpsey	Boulby	2805	Well	1.5 kg (80 %)	0.4	0.3
Lunehead	Boulby	2805	p-type	2.0 kg (92 %)	0.7	0.2
Maeve	SURF	4300	p-type	1.7 kg (85 %)	0.1	0.1
Merlin	LBNL	180	n-type	2.3 kg (115 %)	6.0	8.0
Mordred	SURF	4300	n-type	1.2 kg (60 %)	0.7	0.7
Morgan	SURF	4300	p-type	2.1 kg (85 %)	0.2	0.2
SOLO	SURF	4300	p-type	0.6 kg (30 %)	0.5	0.2
Wilton	Boulby	2805	BEGe	0.4 kg (18 %)	7.0	4.0

Internal backgrounds

- Rn (and Kr) are the dominant internal background sources.
- Rn:
  - Emanates from most materials.
  - 20 mBq requirement, 1 mBq goal.
  - Four measurement systems with ~0.1 mBq sensitivity.
  - Main assembly laboratory at SURF will have reduced radon air system.
- Kr:
  - 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.



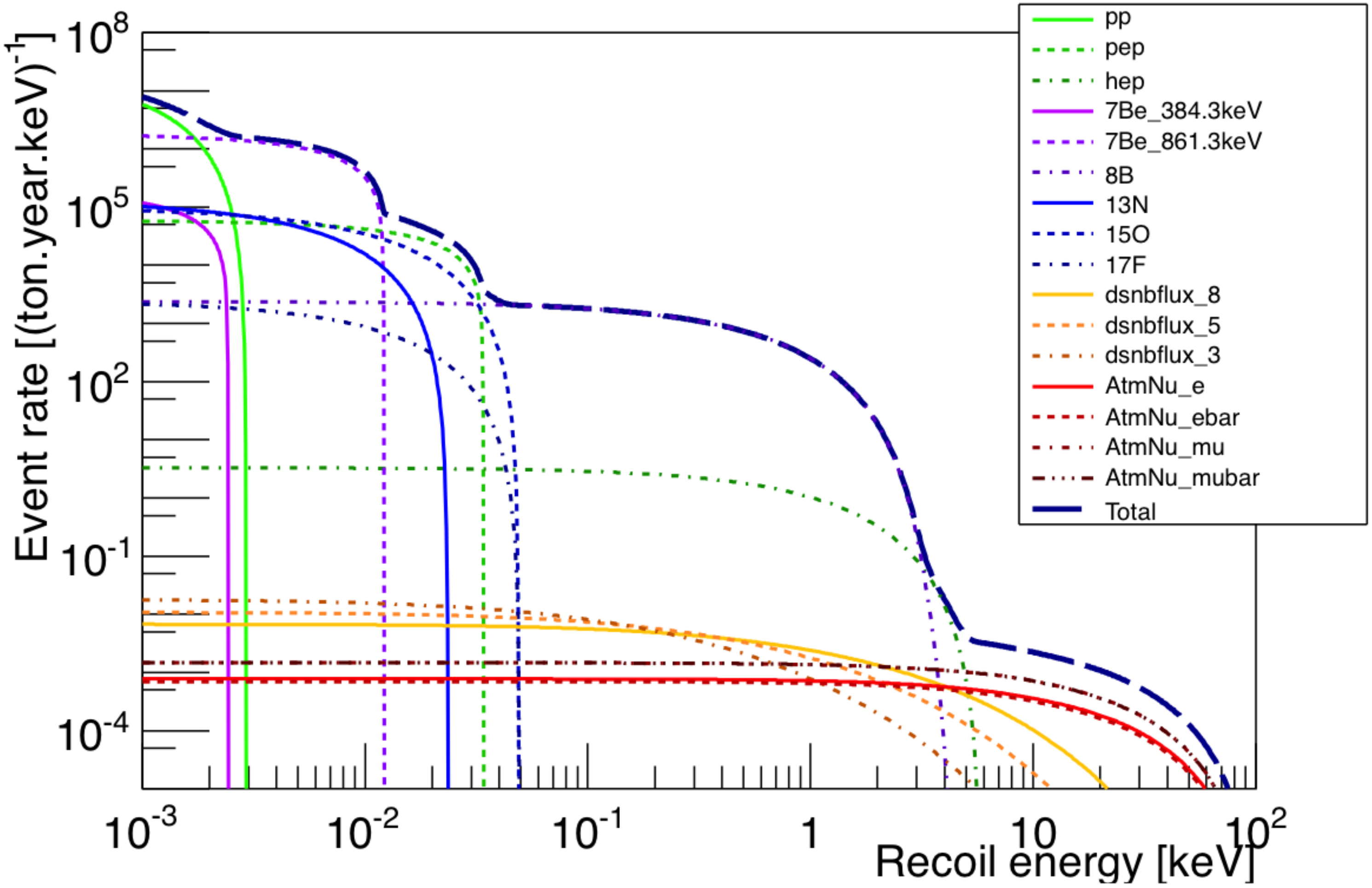
External backgrounds in LZ



- Extensive material screening campaign in the US and UK to select ultra-radio-pure materials for detector components.
- Simulated background from detector components before (left) and after (right) cut on anticoincidence with xenon skin and outer detector (J. Dobson. Talk at IDM2016).

Neutrino background in Xe

Billard et al. PRD 89 (2014) 023524.



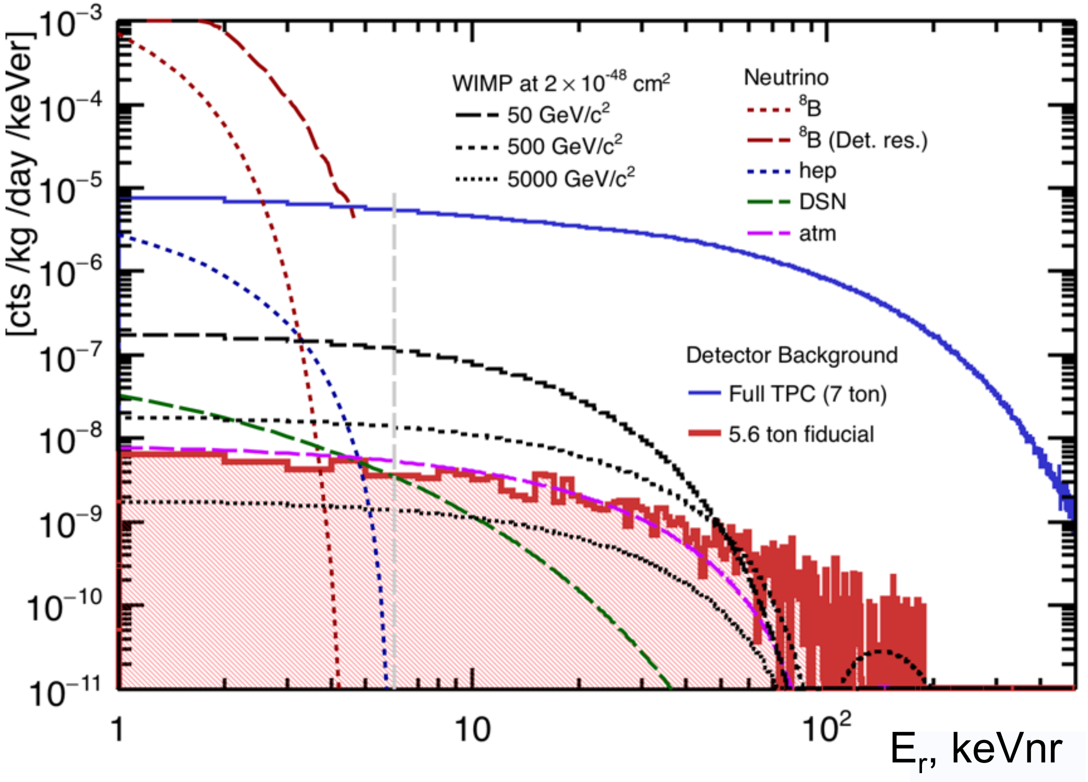
Background rejection: analysis cuts

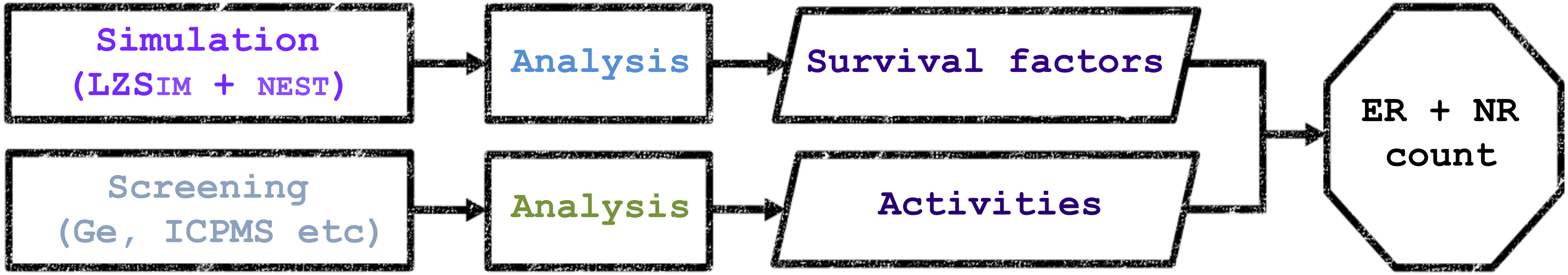
- Region of interest: ~1.5 – 6.5 keV ER, ~6 – 30 keV NR (S1 = 0 – 20 photons, 3-fold coincidences).
- Anticoincidence with xenon ‘skin’: skin pulse >100 keV (3 photoelectrons) within 800 microseconds (max drift time).
- Anticoincidence with the outer detector (liquid scintillator): OD pulse >200 keV within 500 microseconds.
- Position resolution: 0.2 cm in z (drift direction), 3 cm in x–y plane.
- Fiducial volume: 4 cm from TPC (PTFE) cylindrical walls, 1.5 cm from cathode (bottom), 13.5 cm from gate (top). Fiducial mass 5.6 tonnes.

Total background

Source	ER	NR
Detector Components	6.2	0.07
Dispersed radionuclides	911	-
Lab and Cosmogenics	4.6	<0.06
Fixed surface contamination	0.19	0.37
^{136}Xe $2\nu\beta\beta$	67.0	-
Neutrinos	255	0.72
Total events	1244	1.22
WIMP background events (99.5 % discrimination, 50% acceptance)	6.22	0.61
Total ER + NR*	**6.83**	

* Counts per 1000 days, 5.6 ton fiducial volume



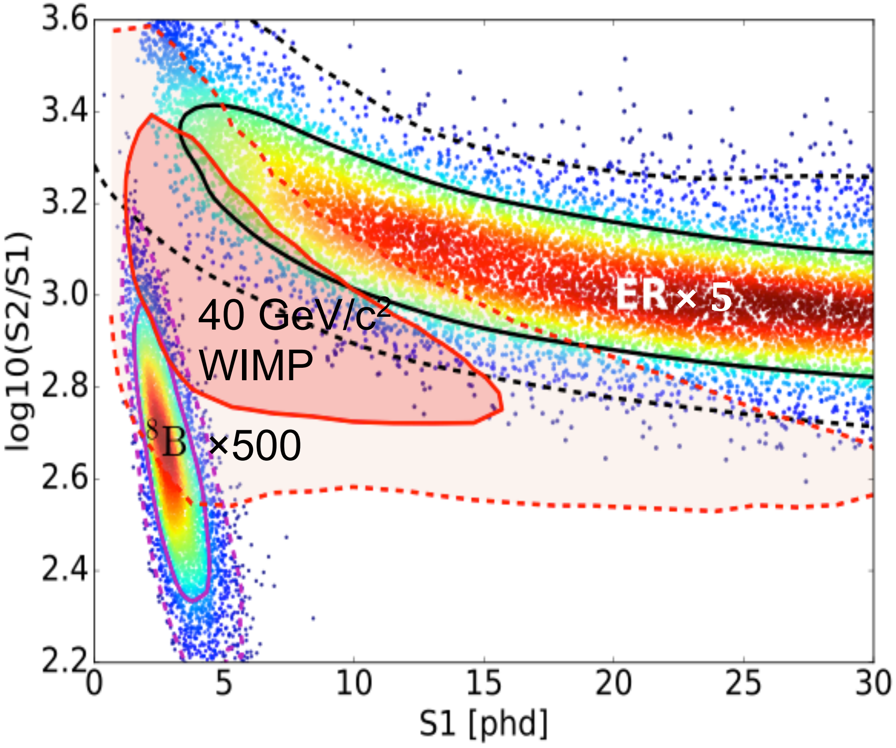


Simulation (LZSIM + NEST) → **Analysis** → **Survival factors**

Screening (Ge, ICPMS etc) → **Analysis** → **Activities**

→ **ER + NR count**

Powerful simulation tools



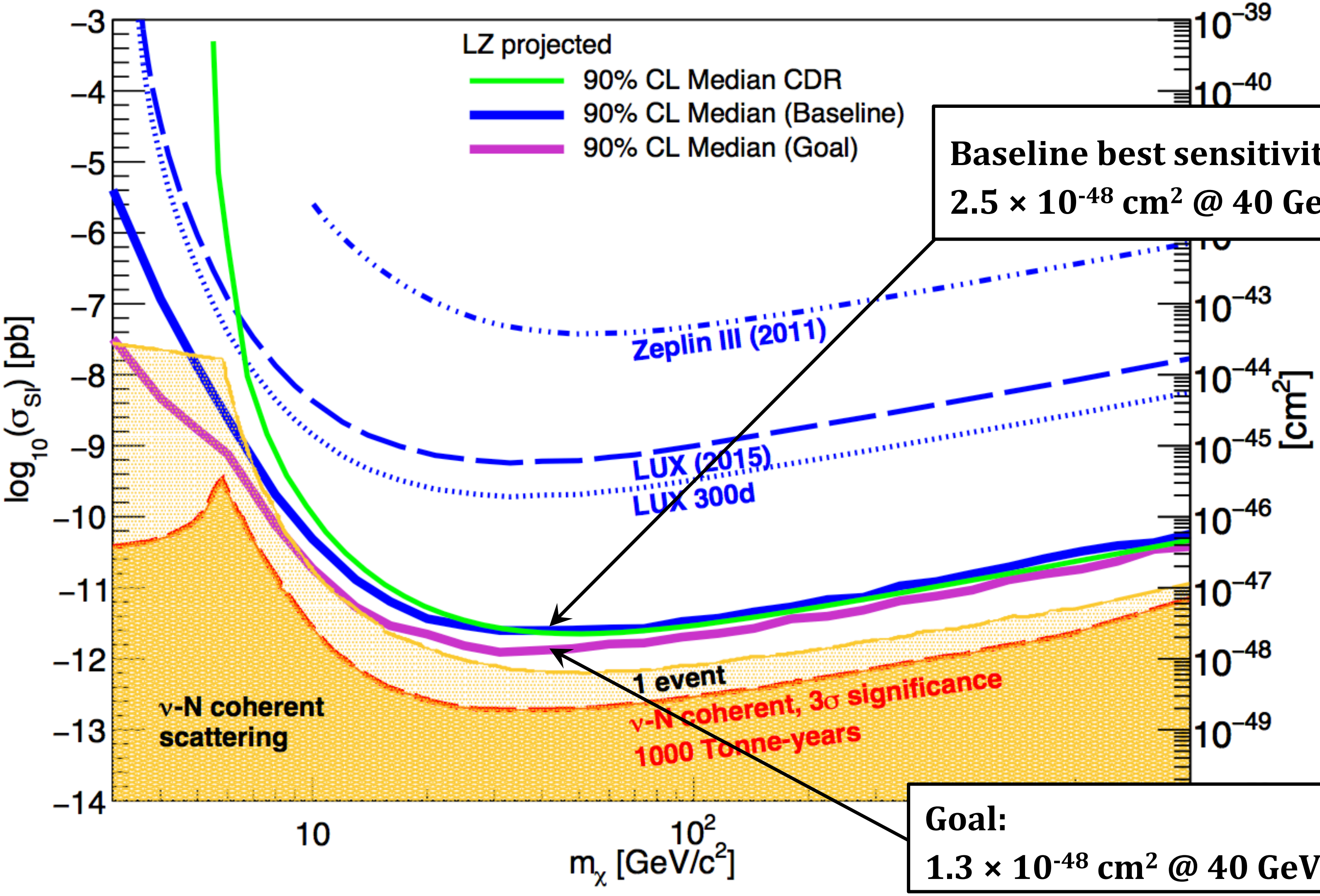
- Based on LUX simulation tools.
- LZ geometry.
- Updated event generators.
- Background normalised to the screening results.
- Noble Element Scintillation Technique (NEST) used to produce S1 (primary scintillation) and S2 (secondary ionisation) signals.
- Profile Likelihood statistical analysis based on probability density functions in multi-dimensional space: S1, S2, r, z.

Calibrations

- Requirements for calibrations:
  - Energy scale for S1 and S2.
  - Position resolution.
  - ER and NR bands for discrimination.
- ^{83m}Kr – uniformly distributed low-energy gammas/electrons, 1.8 hours half-life; position reconstruction.
- CH_3T (tritiated methane) – uniformly distributed betas, removed by purification; electron recoil band.
- D-D – generator, 2.45 MeV collimated neutrons, defines nuclear recoil band and independently light and charge yields for nuclear recoils.
- ^{131m}Xe – uniformly distributed gammas but 11 day half-life; position reconstruction, xenon skin.
- ^{220}Rn – alphas, no long-lived daughters; xenon skin.
- AmLi, YBe – neutrons; low-energy NR response.
- Other standard sources.

Sensitivity predictions

5600 kg fiducial mass, 1000 live days



Baseline best sensitivity:
2.5×10^{-48} cm^2 @ 40 GeV/c^2

Goal:
1.3×10^{-48} cm^2 @ 40 GeV/c^2

What lies beneath (the neutrino floor)?

- Very speculative!
- Improve on systematic uncertainties in calculation of the neutrino background.
- Very big detector (Xe, Ar). Many events, excess over neutrino background, spectrum information. Annual modulation; the phase is different for WIMPs and solar neutrinos. No (or small) modulation for other neutrino sources.
- Very big detector able to reconstruct nuclear recoil tracks (directional detection). Average track orientation is different for WIMP interactions compared to solar neutrinos. The target may be a low-pressure gas (for tracks to be reconstructed) and hence may require a huge detector in volume.
- All methods require very big detectors.

LZ: Timeline

- March 2012 – LZ (LUX-ZEPLIN) Collaboration formed.
- September 2012 – DoE CD-0 for G2 dark matter experiments.
- November 2013 – LZ R&D report submitted.
- July 2014 – LZ project selected in the US and UK.
- April 2015 – DoE CD-1/3a approval, STFC funding for UK, procurement of critical items started (Xe, PMTs, cryostat).
- August 2016 – DoE CD-2/3b approval.
- March 2017 – LUX detector removed, water tank stays.
- August 2017 – Beneficial occupancy surface assembly building.
- June 2018 – Beneficial occupancy for underground installation.
- 2019 – Underground installation.
- April 2020 – Start operations; planning for more than 5 years.

Conclusions

- Two-phase xenon technology has been proven to be the best suited for the first direct observation of WIMPs.
- LUX has currently the world-best limits on spin-independent WIMP-nucleon cross-section.
- LUX will be removed from SURF within a year to free the space for LZ.
- LZ will use 7 t of liquid xenon inside the TPC to search for dark matter WIMPs with a sensitivity extending almost down to the neutrino floor.
- LZ has successfully passed CD2/3a approval by DoE (USA) and funding for construction has also been secured in the UK.
- The construction of various detector parts is ongoing.
- To secure radio-pure environment, an extensive material screening campaign, Monte Carlo modelling of backgrounds and cleaning and purification programme are in place.
- The full-scale operation of LZ is due to start in 2020.