Projected sensitivity of the LUX-ZEPLIN experiment to WIMP dark matter

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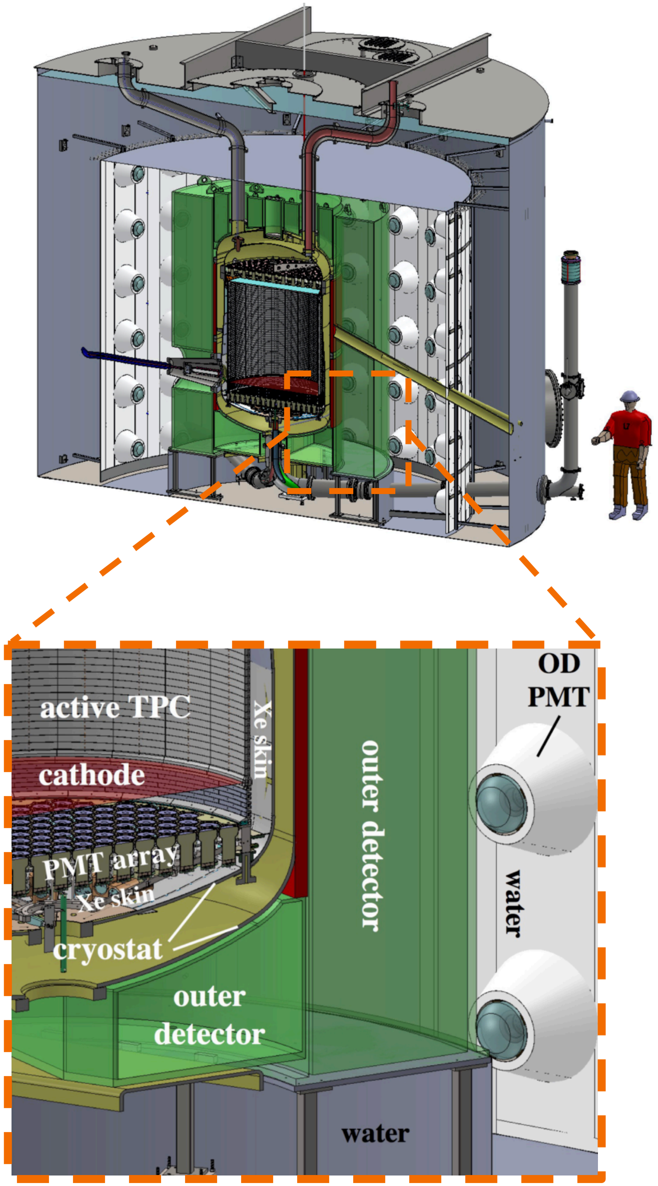
Imperial College London

LZ: overview

- WIMP search experiment
- Location: 1.5 km underground @SURF (US)
- LZ (LUX-ZEPLIN), ~250 collaborators

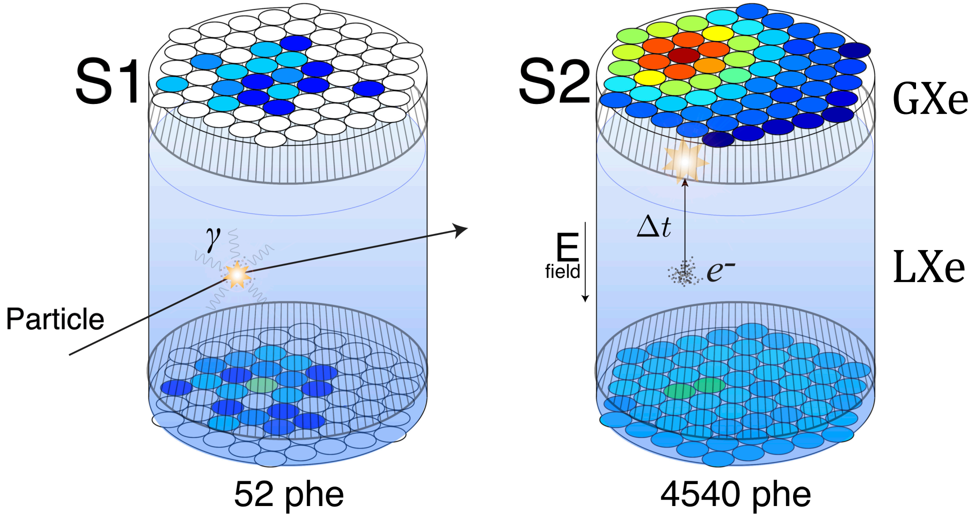
- Two phase (liquid and gas Xe) time projection chamber (TPC)
  - Total mass: 10 t
  - Active mass: 7 t
- Low-energy threshold: ~5 keV
- Two veto systems:
  - Xenon skin
  - Liquid scintillator (Gd-LS) outer detector

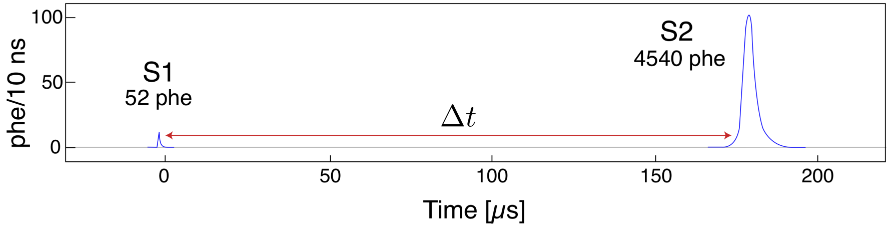
- Underground installation starting in 2019
- Physics data taking from 2020



arXiv:1703.09144

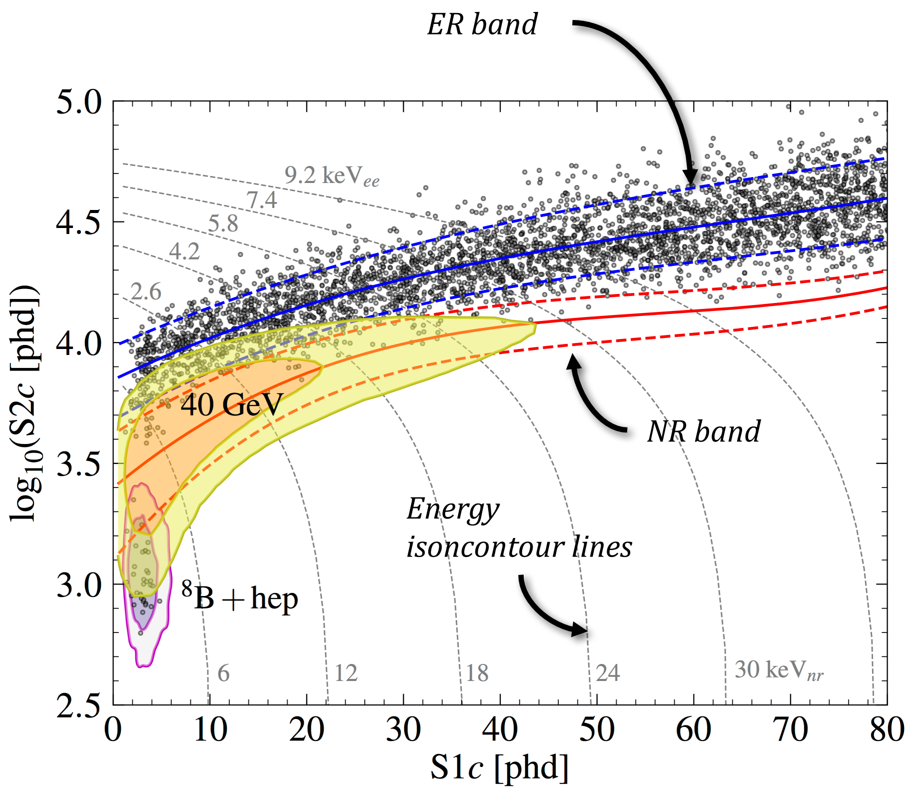
LZ: detection principle





- Particle interactions in the active region create:
  - Prompt scintillation (**S1**)
  - Electrons from ionisation
    - drifted upward to GXe
    - delayed proportional scintillation (**S2**)
- Both energy and position can be reconstructed from S1 and S2
- Two distinctive types of particle interactions:
  - **Electron recoil** (ER): β's, γ's , ν-e scattering
  - **Nuclear recoil** (NR): WIMPs, n's, ν-N (CEνNS)

LZ: analysis strategy



Simulated dataset inside the fiducial volume for the full LZ exposure (1000 days × 5600 kg)

ER: electron recoil
NR: neutron recoil

- ER and NR events discriminated from their different S2/S1 proportion
- ER and NR bands obtained through calibration
- Many γ and n events occur close to the TPC wall
  - Veto them: Xe skin and OD
  - Define a fiducial region: 5.6 t for the WIMP search

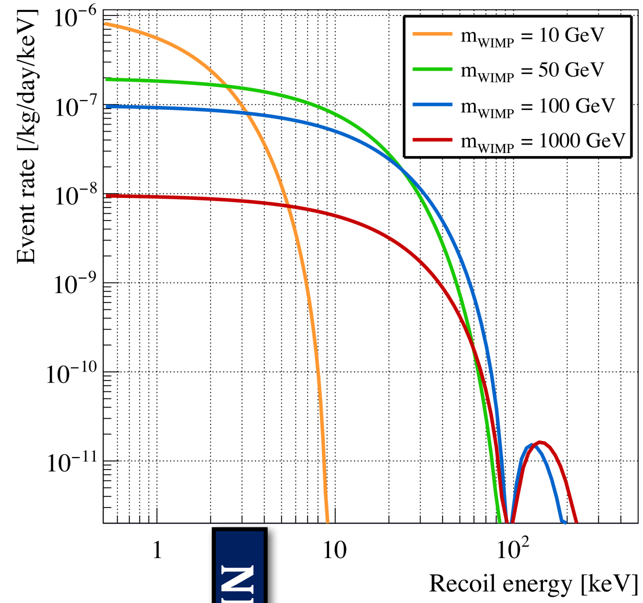
WIMP signal model

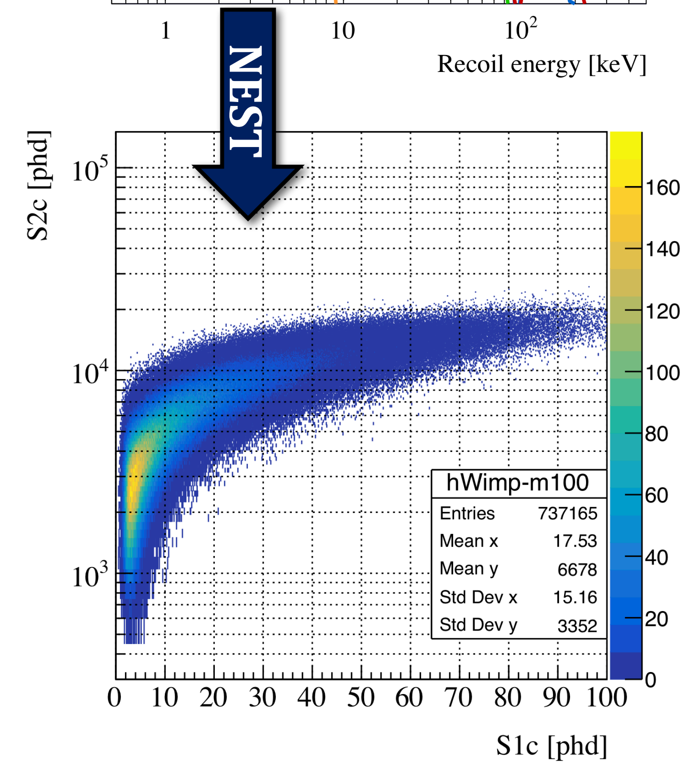
- **WIMP differential scattering rate**

$$\frac{dR}{dE_r} = \frac{\rho_0 \, \sigma_A}{2 \, m_{\mathrm{WIMP}} \, \mu_A^2} F^2(E_r) \int_{v_{\min}(E_r)}^{\sim v_{\mathrm{esc}}} \frac{f_{\oplus}(v)}{v} d^3 v$$

  - **Astrophysics**: local DM density (ρ_0), WIMP galaxy escape velocity (v_{esc}), WIMP velocity distribution ($f_{\oplus}$)
  - **Nuclear physics**: nuclear form factor (F)
  - **Particle physics**: WIMP mass (m_{WIMP}), WIMP-nucleus scattering cross section (σ_A)

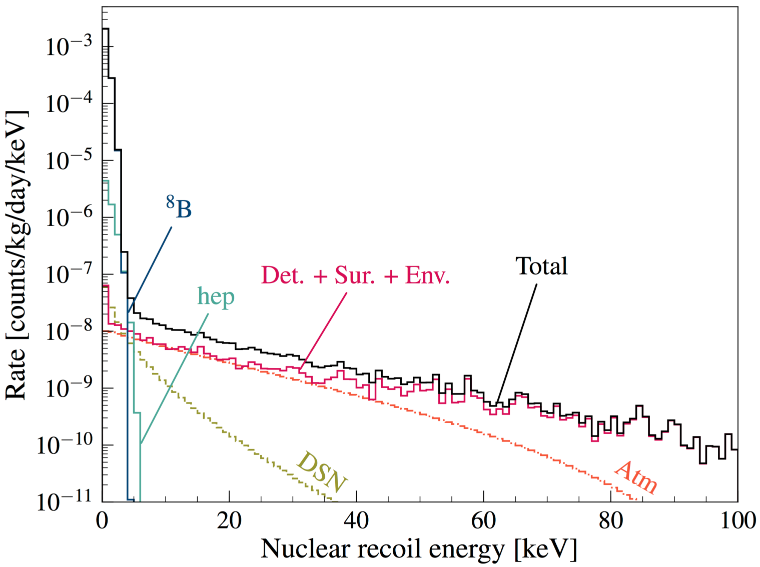
- **NEST software package** (arXiv:1307.6601)
  - Estimates charge and light production in LXe
  - Accounts for anti-correlations between ionisation and scintillation
  - Incorporates calibration results from LUX that go down to ~1 keV (arXiv:1512.03506)



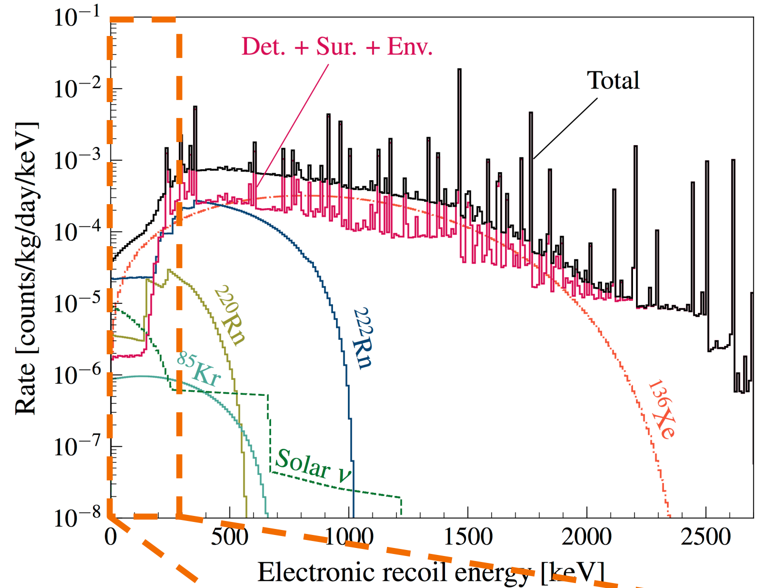


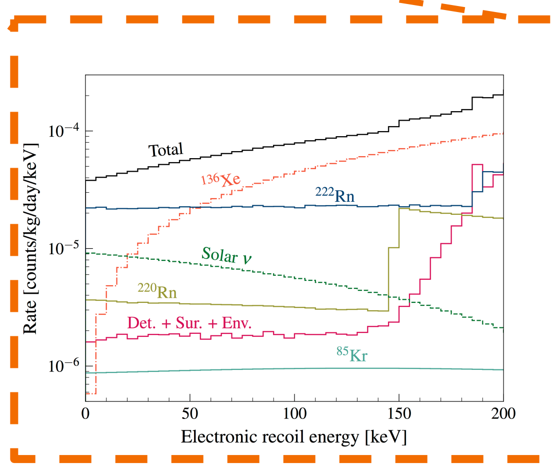
Backgrounds to the WIMP search

Nuclear recoils



Electron recoils





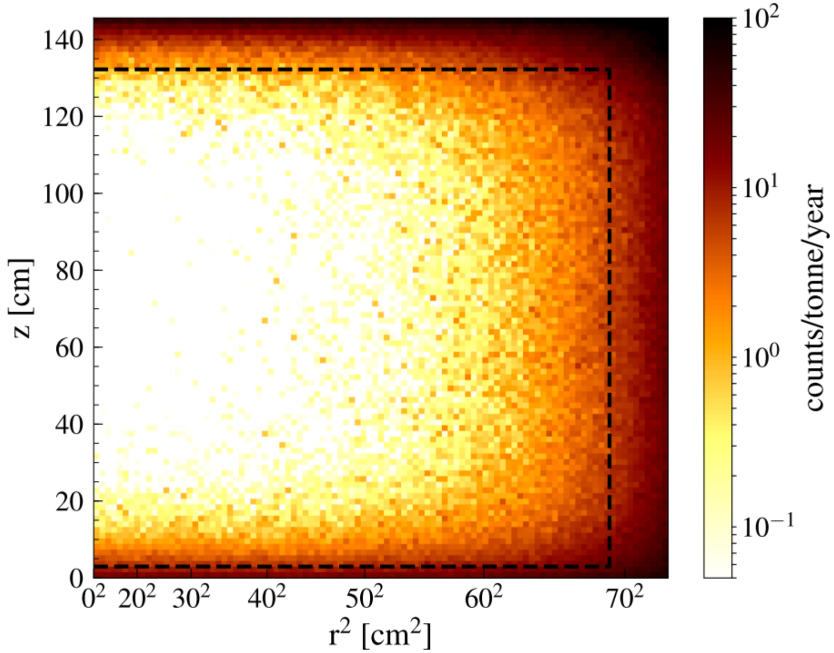
Background mitigation strategy

- Underground installation of the detector
- Extensive radio-assay campaign for detector materials
- Strict surface cleanliness programme
- Xenon purification to remove ^{85}Kr and ^{39}Ar
- Active vetoes: Xe skin and outer detector

Backgrounds to the WIMP search

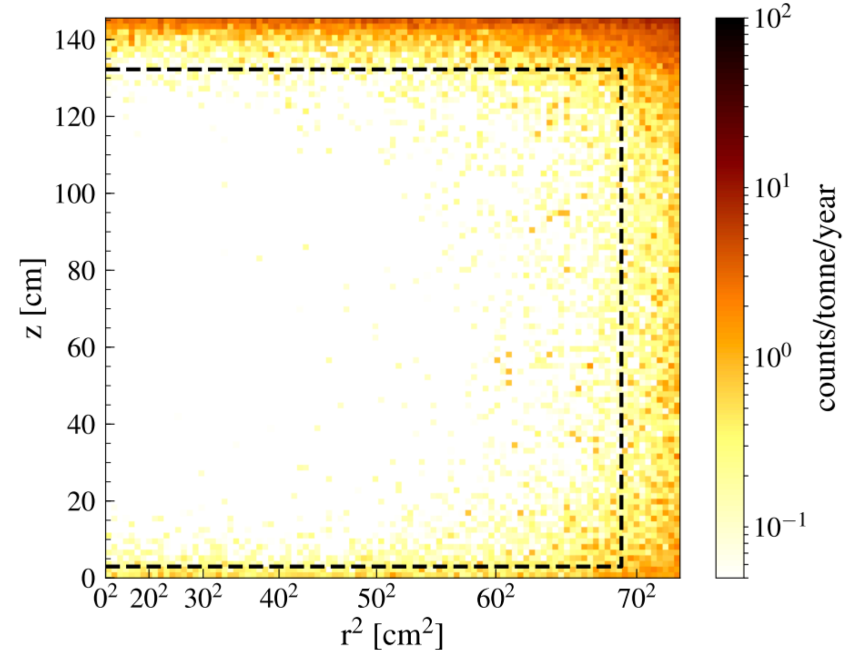
NR background events in the WIMP region of interest $(6 - 30\ \mathrm{keV}nr)$ are highly suppressed by the veto system:

Before veto



Integrated counts for
5.6 tonne FV×1000 days: 10.4

After veto



Integrated counts for
5.6 tonne FV×1000 days: 1.0

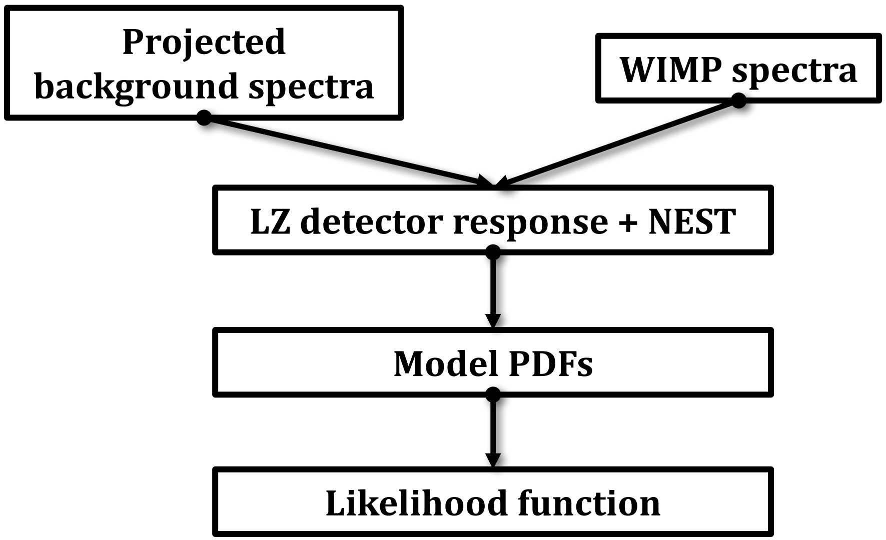
LZ likelihood function

$$L(\sigma, \boldsymbol{\nu}|\mathfrak{D}) = \left[\text{Pois}(n_0|\mu) * \prod_{e=1}^{n_0} \frac{1}{\mu} \left(\mu_s(\sigma) f_s(\boldsymbol{x_e}|m_{\text{WIMP}}) + \sum_{b=1}^{N_b} \mu_b f_b(\boldsymbol{x_e}|\boldsymbol{\nu}) \right) \right] * \prod_{p=1}^{N_p} f_p(\boldsymbol{g_p}|\nu_p)$$

Extended term

Event probability model

Constraint term



Legend

- Observables: $\boldsymbol{x} = \{S1, S2\}$
- Parameter of interest: $\sigma_{\text{WIMP}-N}$
- Nuisance parameters:
  $$\boldsymbol{\nu} = \{\mu_b\}_{b=1}^{b=N_b}$$
- Global observables:
  $$\mathbf{g} = \{\langle\mu_b\rangle, \sigma_b\}_{b=1}^{b=N_b}$$

LZ sensitivity: methodology

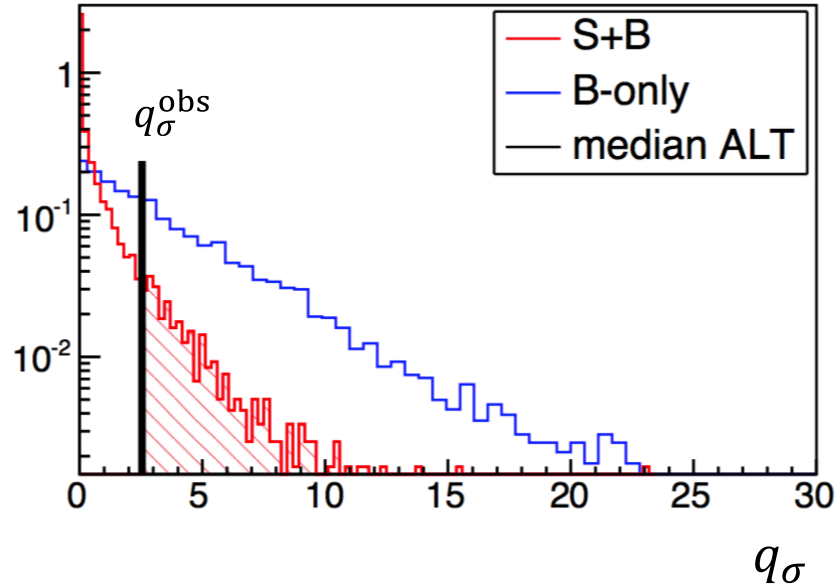
- To calculate the projected exclusion upper limit to a particular WIMP cross section, a one-sided profile likelihood ratio test statistic is used:

$$q_\sigma = \begin{cases} -2\ln\left(\frac{L(\sigma,\hat{\hat{\boldsymbol{\nu}}})}{L(\hat{\sigma},\hat{\boldsymbol{\nu}})}\right) & \hat{\sigma} \leq \sigma \\ 0 & \hat{\sigma} > \sigma \end{cases}$$

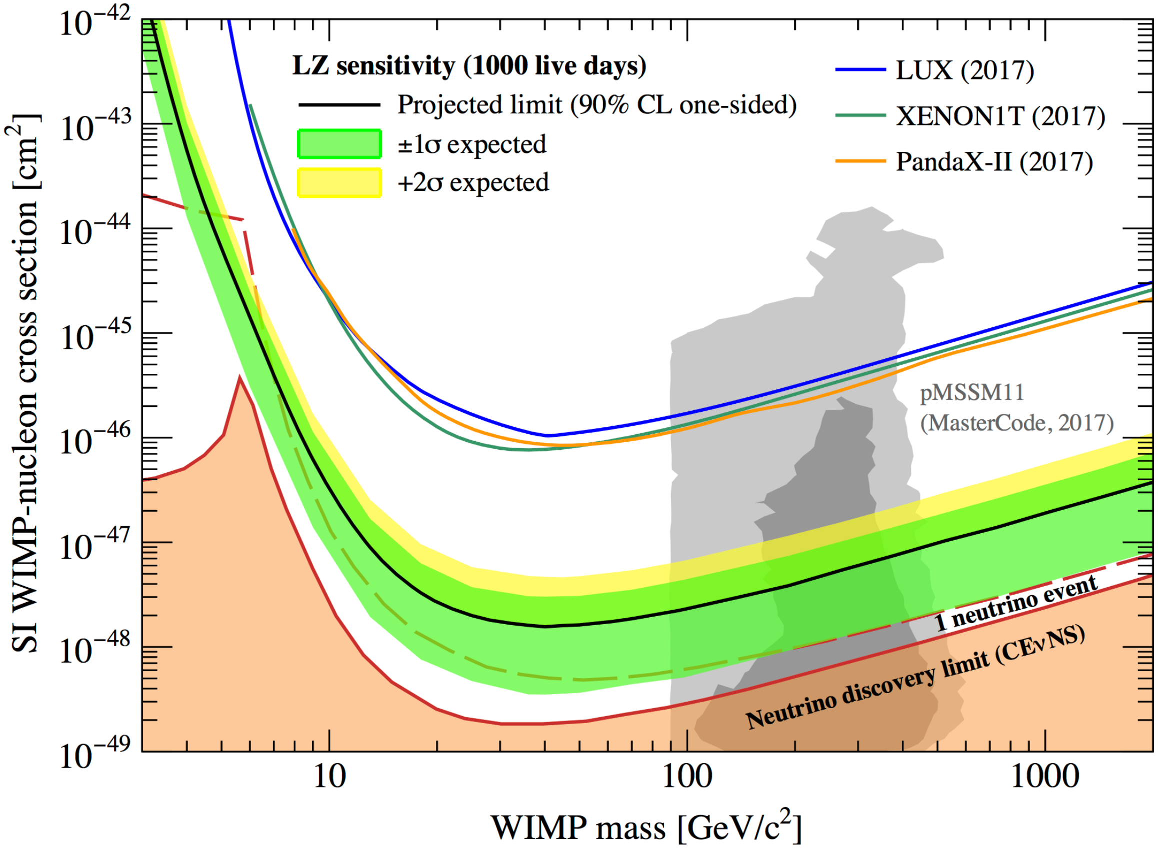
$0 \leq q_\sigma \leq \infty$

greater incompatibility between data and tested cross section

- Many Monte Carlo trials are simulated to construct distributions under the NULL (S+B) and ALTERNATIVE (B-only) hypotheses
  - For sensitivity studies: $q_\sigma^{\rm obs} = \text{median}\big(f(q_\sigma|\text{B– only})\big)$



LZ sensitivity to SI interactions



Minimum point

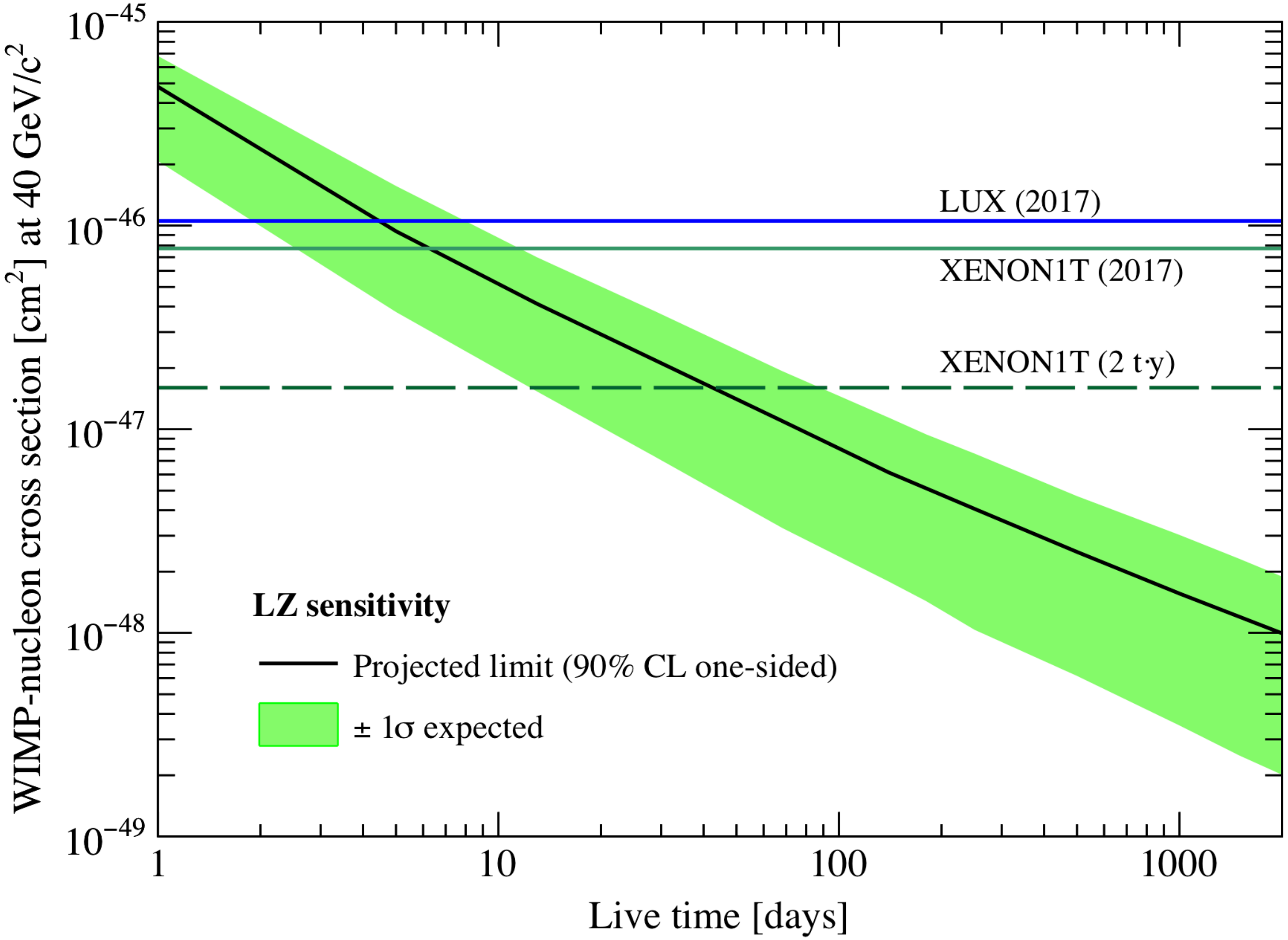
- 1.6×10^{-48} cm^2 at 40 GeV/c^2

The lower part of the 2σ band is not included

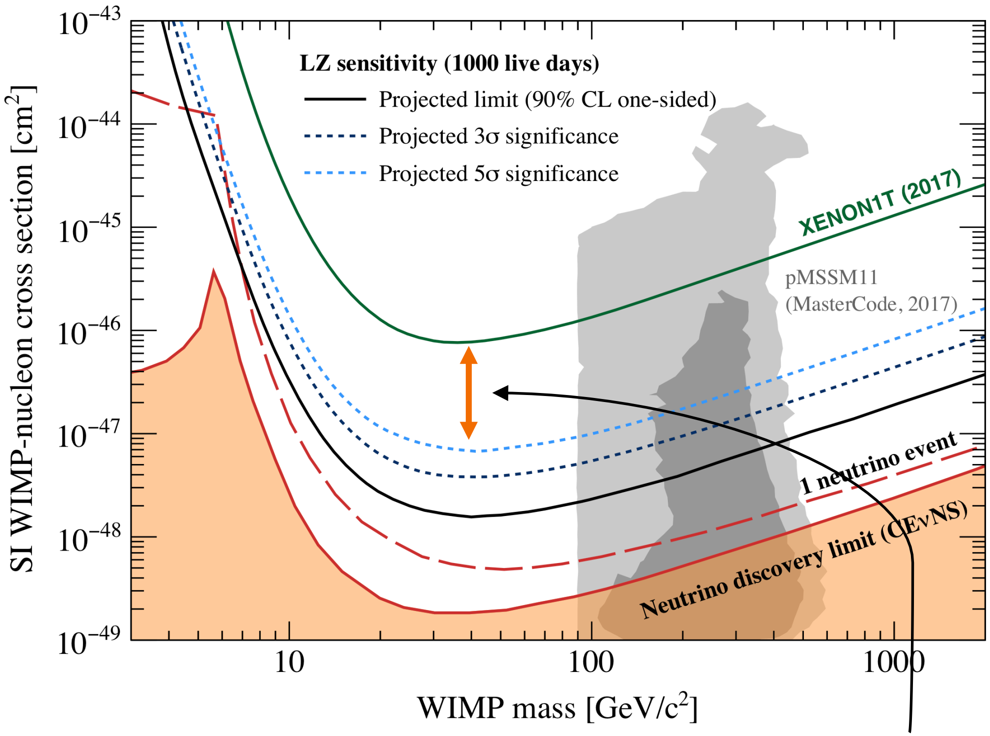
- The actual limit will be power-constrained at -1σ

- LZ projected sensitivity paper: arXiv:1802.06039

LZ sensitivity to SI interactions



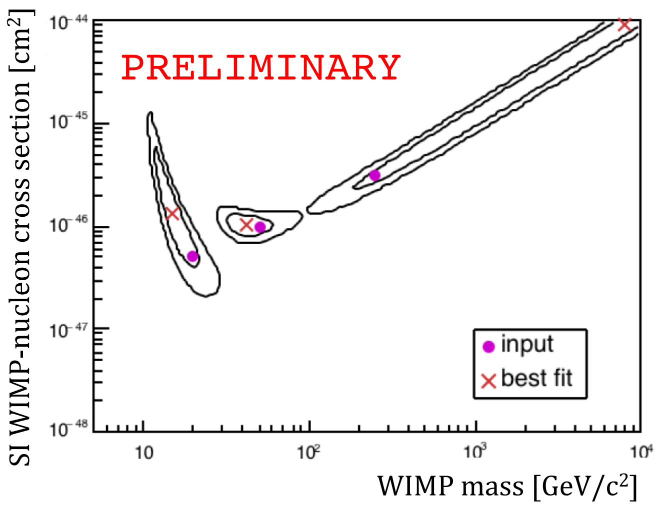
Projected discovery significance



5σ discovery within reach!

- Minimum points
  - 3.8×10^{-48} cm^2 @40 GeV/c^2 (3σ)
  - 6.7×10^{-48} cm^2 @40 GeV/c^2 (5σ)

Getting ready to characterise WIMP signals from the very start:

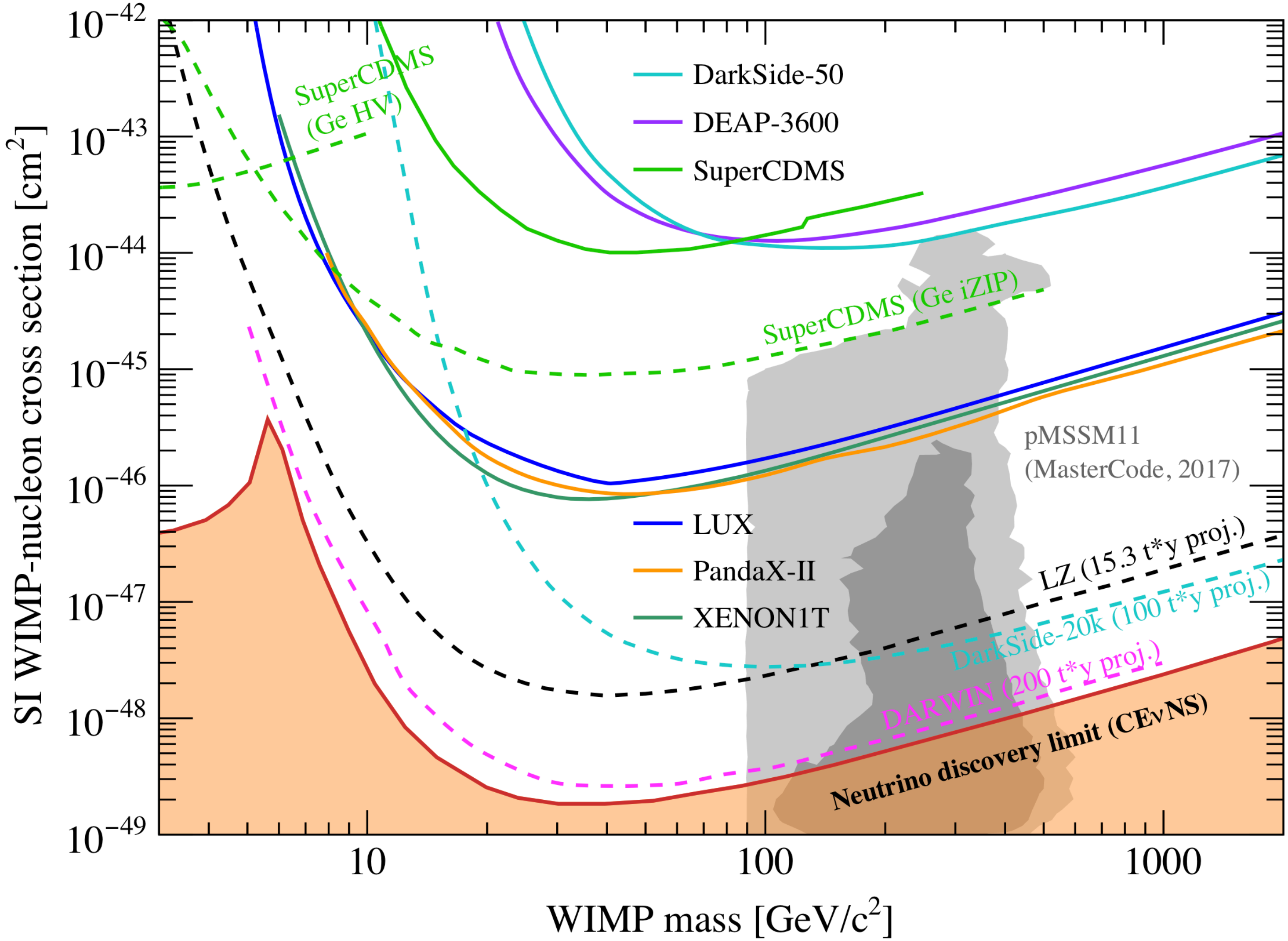


Summary

- The LZ experiment is fully optimised for a WIMP search
  - 7 tonnes of Xe active mass
  - Robust background control, after lessons learned from LUX and ZEPLIN
  - Veto system to suppress extra NR backgrounds
- Likely to probe most of the remaining WIMP parameter space before new astrophysical backgrounds come in
  - 100 times more sensitive than current best limits
  - 5σ discovery potential
- Other searches are possible too
  - SD interactions, axion-like particles (ALPs), astrophysical neutrinos, $0\nu\beta\beta$'s, ...
- Physics data taking from 2020!!

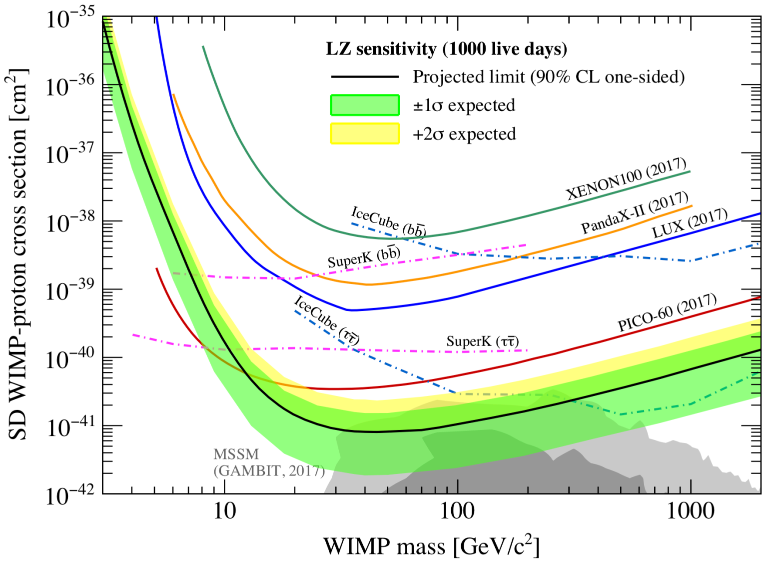
BACKUP

WIMP search: present and future



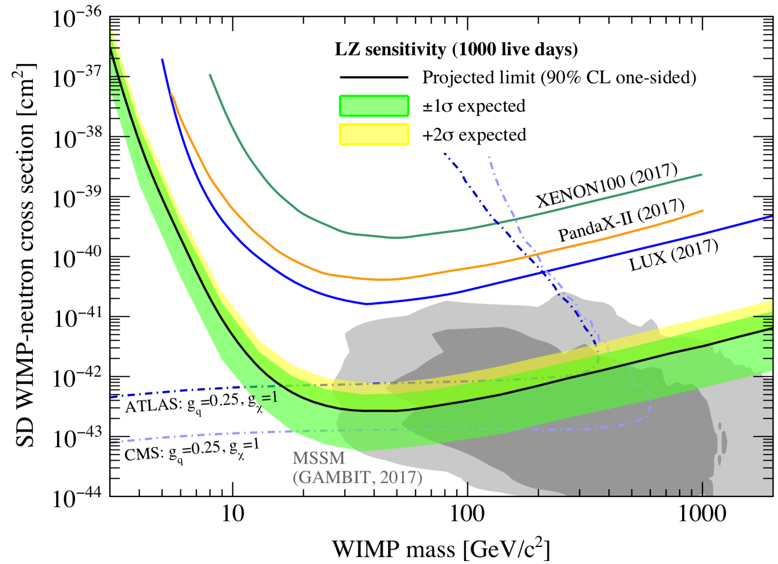
LZ sensitivity: SD interactions

WIMP-proton



- Minimum point
  - 8.1×10^{-42} cm^2 @40 GeV/c^2

WIMP-neutron



- Minimum point
  - 2.7×10^{-43} cm^2 @40 GeV/c^2

- Natural Xe contains odd-neutron isotopes: ^{129}Xe (26.4%) and ^{131}Xe (21.2%)
- Structure factors taken from arXiv:1304.7684

Backgound count estimates

	Background Source	Mass (kg)	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr	ER (cts)	NR (cts)
External Backgrounds	**Detector Components**									**9**	**0.07**
	PMT Structures	122	3.89	0.95	0.72	0.65	0.23	3.28	13.6	0.31	0.002
	R11410 3" PMTs	92	71.6	3.20	3.12	2.99	2.91	15.4	81.8	1.27	0.011
	R8778 2" PMTs	6	138	59.4	16.9	16.9	16.2	413	53.0	0.05	0.006
	R8520 Skin 1" PMTs	2	62.2	5.29	4.91	4.85	24.4	337	53.7	0.02	0.005
	PMT Bases	3	359	78.0	39.1	33.4	1.06	55.4	28.9	0.28	0.002
	PMT Cabling	83	6.19	7.06	1.34	1.67	0.01	6.45	17.5	0.89	0.001
	TPC PTFE	184	0.02	0.02	0.03	0.03	0.00	0.12	22.5	0.04	0.006
	Grid Wires and Rings	96	7.39	2.76	2.49	2.28	10.0	28.0	16.3	3.64	0.005
	Field Shaping Rings	92	5.49	1.14	0.72	0.65	0.00	2.00	41.0	0.65	0.011
	TPC Sensors and Thermometers	5	21.8	5.82	2.29	1.88	1.32	61.0	6.75	0.06	0.001
	PMT Conduits, HX and Tubing	215	3.18	0.46	0.46	0.56	1.23	1.39	5.87	0.03	0.001
	HV Conduits and Cables	138	3.61	2.30	0.61	0.76	1.4	2.5	26.5	0.02	0.001
	Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
	Outer Detector	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
	Surface Contamination									**40**	**0.39**
	Dust (intrinsic activity, 500 ng/cm2)									0.2	0.05
	Plate-out (PTFE panels, 50 nBq/cm2)									-	0.05
	210Bi mobility (0.1 µBq/kg)									40.0	-
	Ion-misreconstruction (50 nBq/cm2)									-	0.16
	210Pb (in bulk PTFE, 10 mBq/kg)									-	0.12
	Laboratory and Cosmogenics									**5**	**0.06**
	Laboratory Rock Walls									4.6	0.00
	Muon Induced Neutrons									-	0.06
	Cosmogenic Activation									0.2	-
Internal Backgrounds	**Xenon Contaminants**									**816**	**0**
	222Rn (1.81 µBq/kg)									678	-
	220Rn (0.09 µBq/kg)									111	-
	natKr (0.015 ppt g/g)									24.5	-
	natAr (0.45 ppb g/g)									2.5	-
	Physics									**322**	**0.51**
	136Xe 2νββ									67	0
	Solar neutrinos (pp+7Be+13N)									255	0
	Diffuse supernova neutrinos									0	0.05
	Atmospheric neutrinos									0	0.46
	Total									1192	1.03
	Total (with 99.5% ER discrimination, 50% NR efficiency)									5.96	0.51
										6.48	

Detector parameters

Detector Parameter	Value
Photon Detection Efficiency (PDE)	
PDE in liquid (g_1) [phd/ph]	0.119
PDE in gas ($g_{1,gas}$) [phd/ph]	0.102
Single electron size [phd]	83
Effective charge gain (g_2) [phd/e]	79
PTFE-LXe reflectivity	0.977
LXe photon absorption length [m]	100
PMT efficiency at 175 nm	0.269
Other Key Parameters	
Single phe trigger efficiency	0.95
Single phe relative width (Gaussian)	0.38
S1 coincidence level	3-fold
S2 electron extraction efficiency	0.95
Drift field [$\mathrm{V\,cm^{-1}}$]	310
Electron lifetime [µs]	850