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

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Preparing for Dark Matter Particle Discovery
Chalmers University, Göteborg
11-15th June 2018

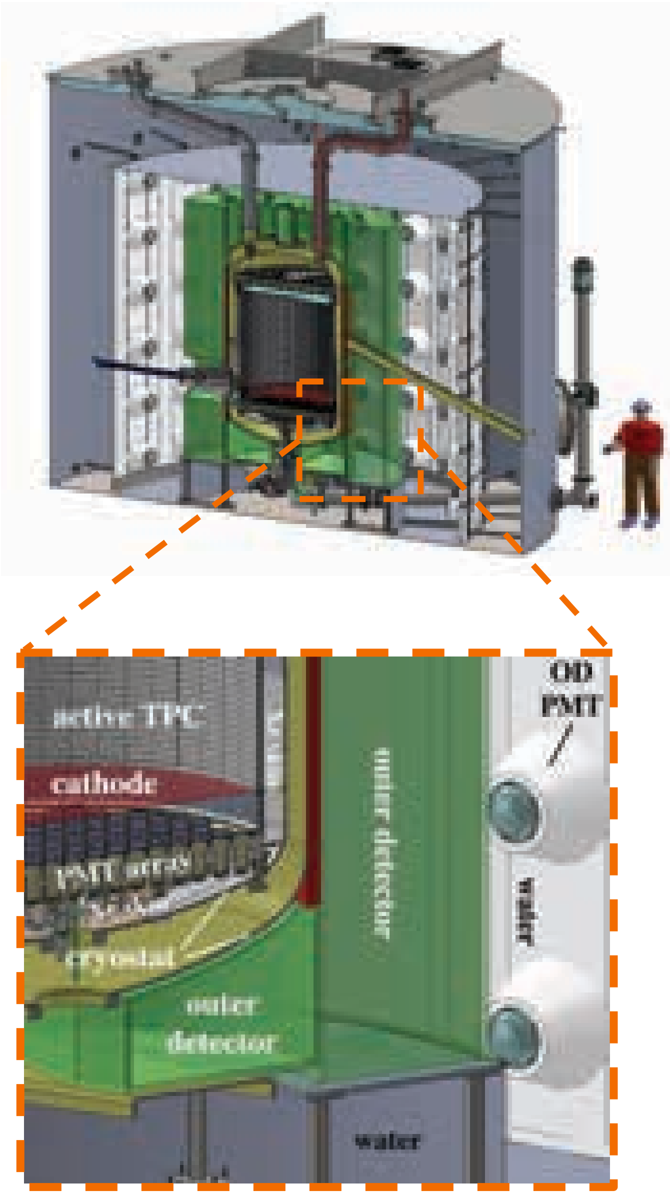
Imperial College London

LZ: overview

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

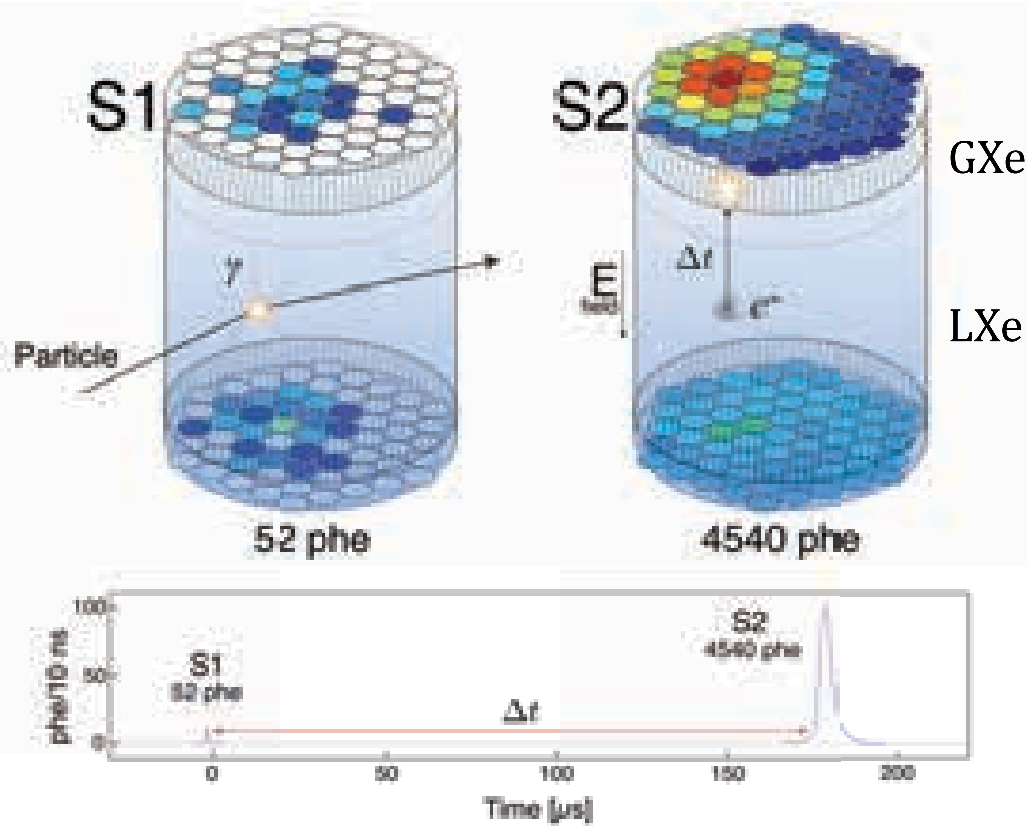
- Two phase Xe (liquid and gas) time projection chamber (TPC)
  - Total mass: 10 t
  - Active mass: 7 t
- Low energy threshold: ~5 keV
- Two veto systems:
  - Xenon skin
  - Liquid scintillator (Gd) outer detector

- Underground installation in 2019
- Physics data taking from 2020



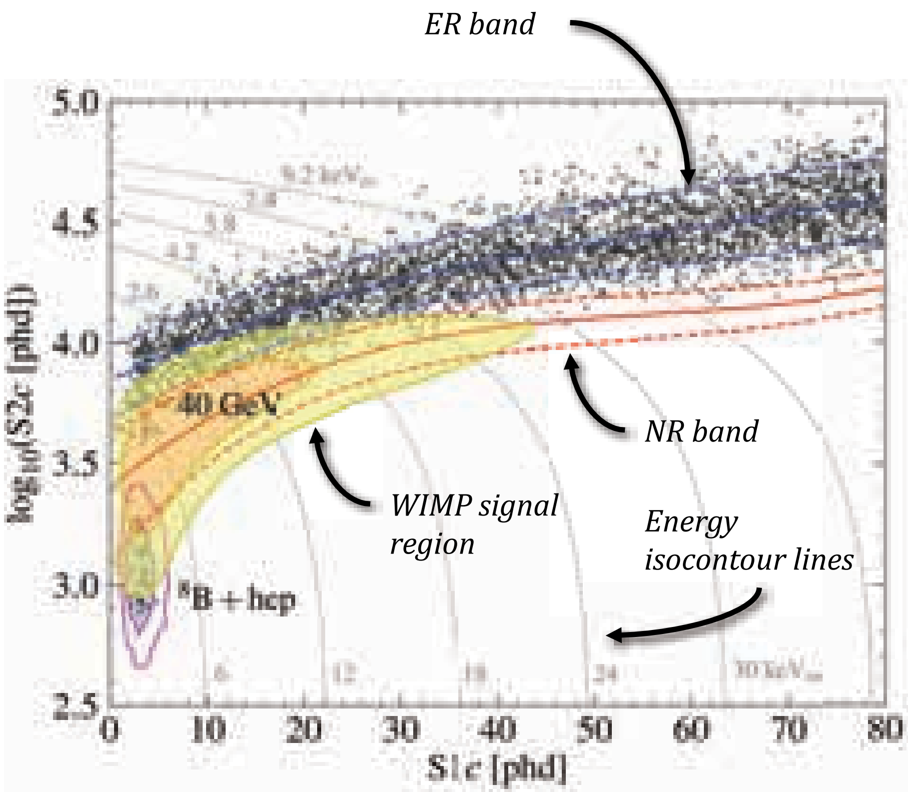
arXiv:1703.09144

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 are discriminated from their different S2/S1 proportion
- ER and NR bands will be 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

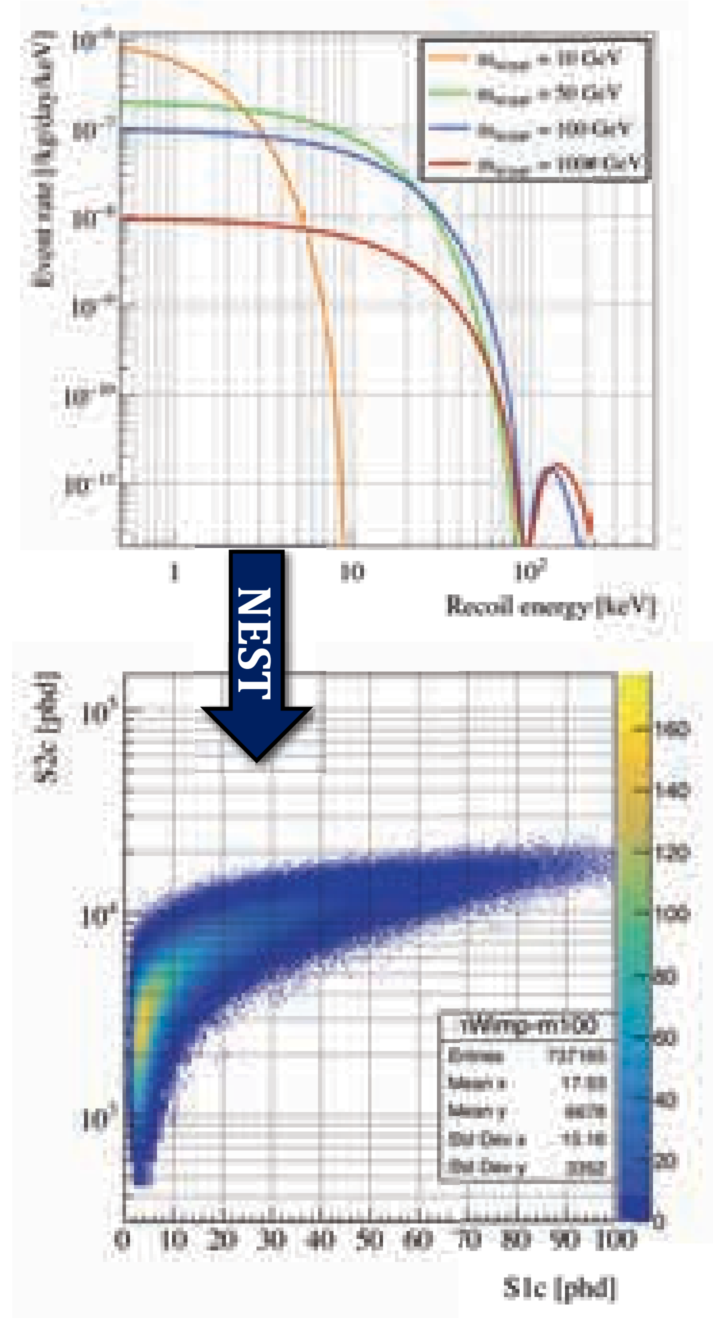
WIMP signal model

- **Standard WIMP event rate**

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

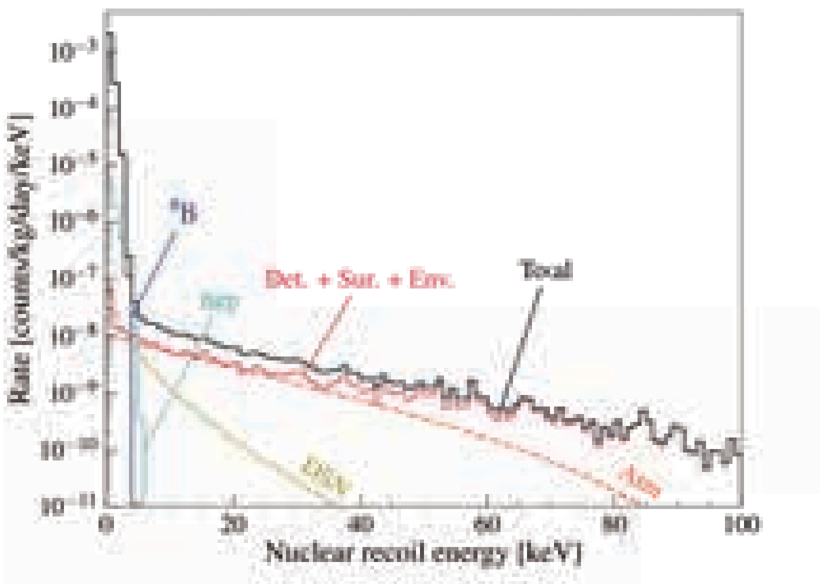
  - **Astrophysics**: local DM density (ρ_0), WIMP galaxy escape velocity (v_{esc}), WIMP velocity distribution ($f_{\oplus}$)
  - **Nuclear physics**: nuclear form factor (F)
  - **Particle physics**: WIMP mass (m_{WIMP}), WIMP-nucleus scattering cross section ($\sigma_{\mathrm{WIMP-A}}$)

- **NEST software package** (2013 JINST **8** C10003)
  - 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 (Phys. Rev. Lett. 116, 161301)

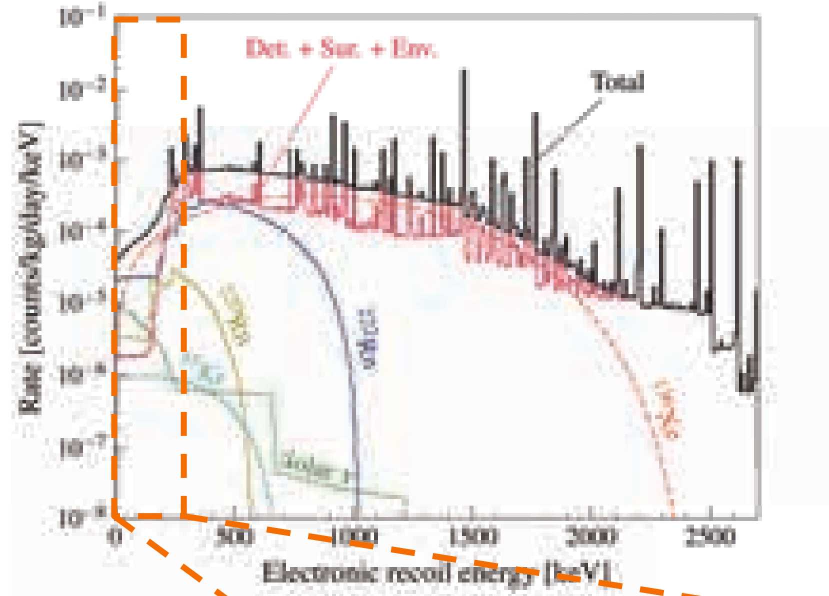


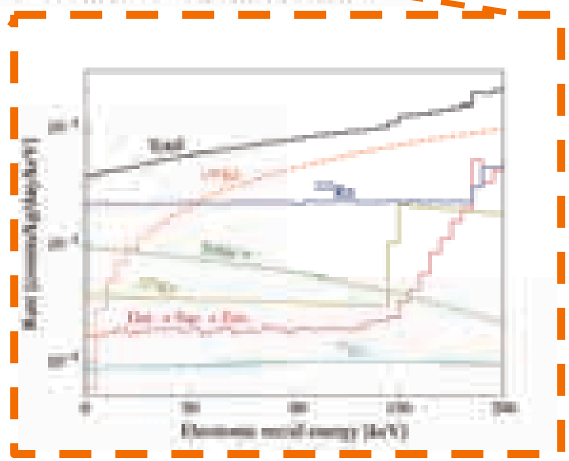
Backgrounds to the WIMP search

Nuclear recoils



Electron recoils





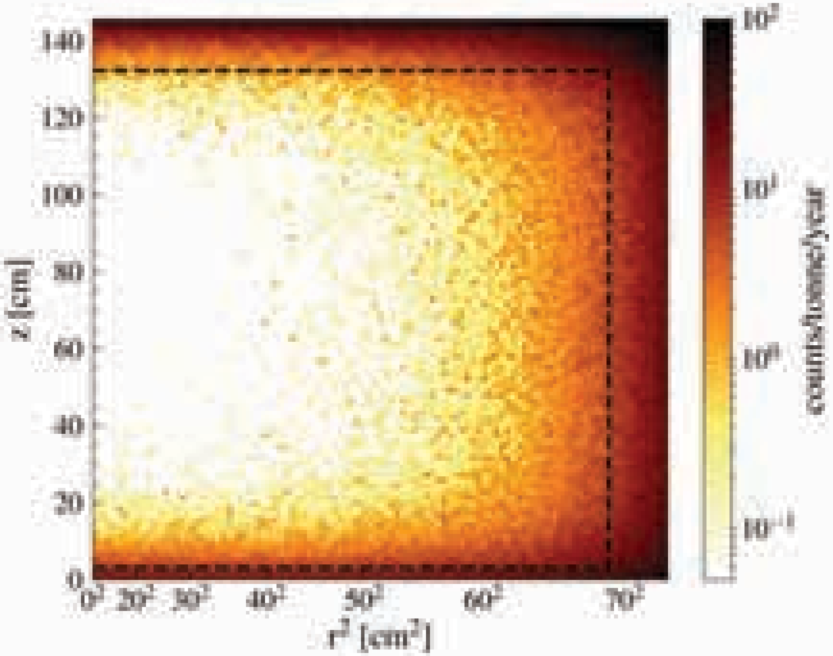
Background mitigation strategy

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

Backgrounds to the WIMP search

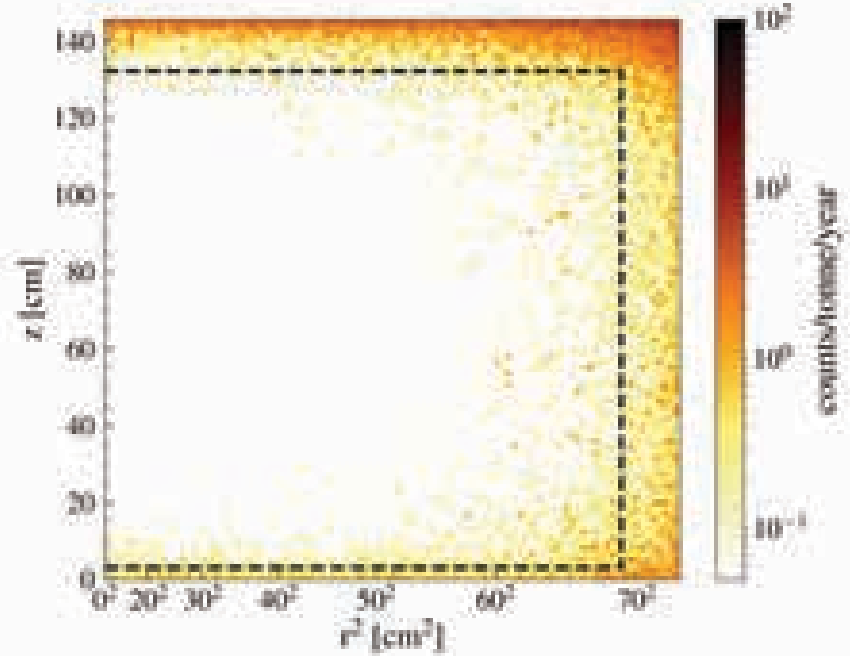
NR background events in the WIMP region of interest (6 – 30 keVnr) are highly suppressed by the veto system:

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

$$L(\sigma, \boldsymbol{\nu}|\mathfrak{D}) =$$

Extended term

Event probability model

$$\left[\mathrm{Pois}(n_0|\mu) * \prod_{e=1}^{n_0} \frac{1}{\mu} \left(\mu_s(\sigma) f_s(\boldsymbol{x_e}|m_{\mathrm{WIMP}}) + \sum_{b=1}^{N_b} \mu_b f_b(\boldsymbol{x_e}|\boldsymbol{\nu}) \right) \right]$$

$$* \prod_{p=1}^{N_p} f_p(\boldsymbol{g_p}|\nu_p)$$

Constraint functions

- Observables:
  $\boldsymbol{x} = (S1, S2)$ (for now)
- Parameter of interest:
  $\sigma_{\mathrm{WIMP}-N}$
- Nuisance parameters:
  $\nu = \{\mu_b\}_{b=1}^{b=N_b}$ (for now)

Background
^{222}Rn (ER)
pp+^{7}Be+^{14}N ν (ER)
^{220}Rn (ER)
^{136}Xe $2\nu\beta\beta$ (ER)
Det. + Env. (ER)
^{85}Kr (ER)
^{8}B solar ν (NR)
Det. + Env. (NR)
Atmospheric ν (NR)
hep ν (NR)
DSN ν (NR)

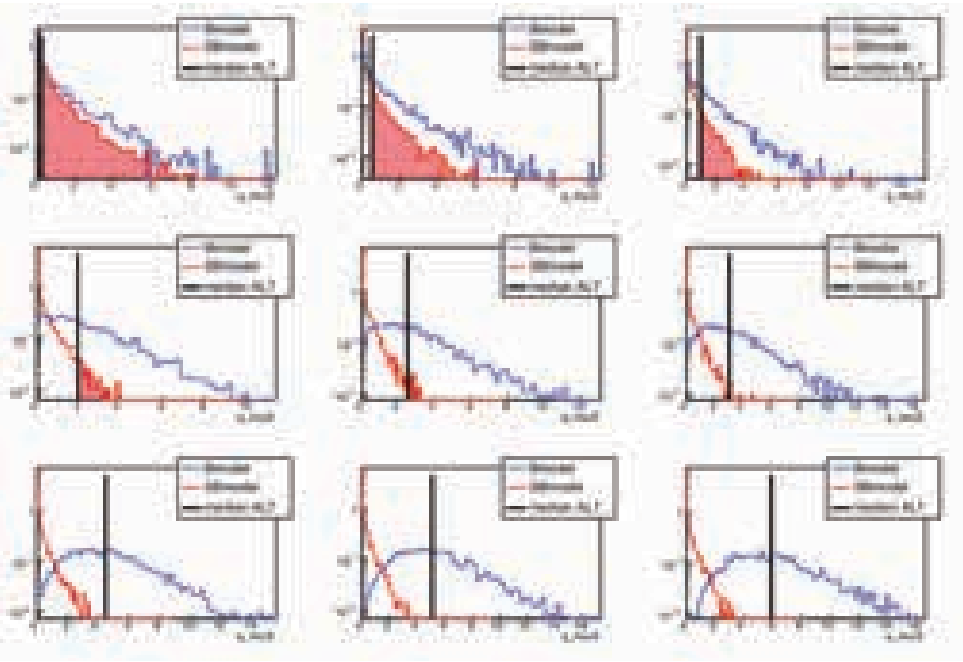
Methodology

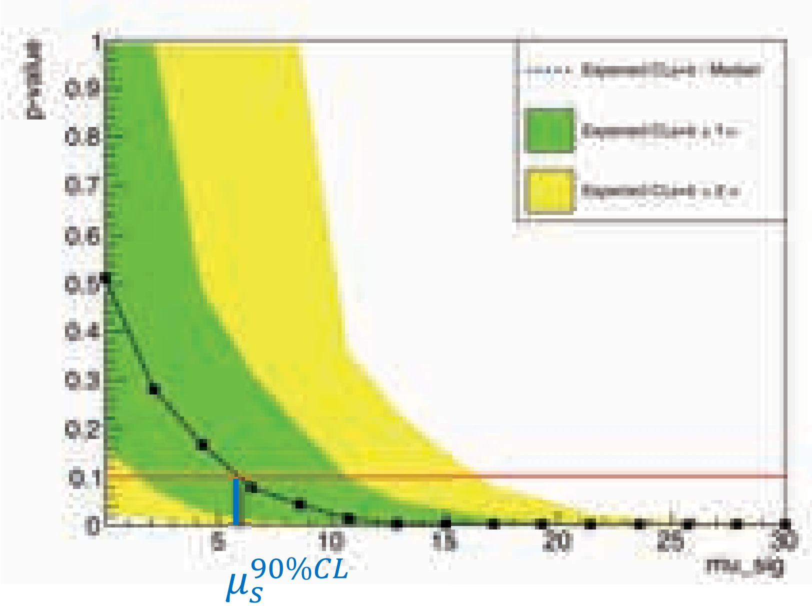
- A one-sided profile likelihood ratio test statistic is used to calculate the projected exclusion upper limit:

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

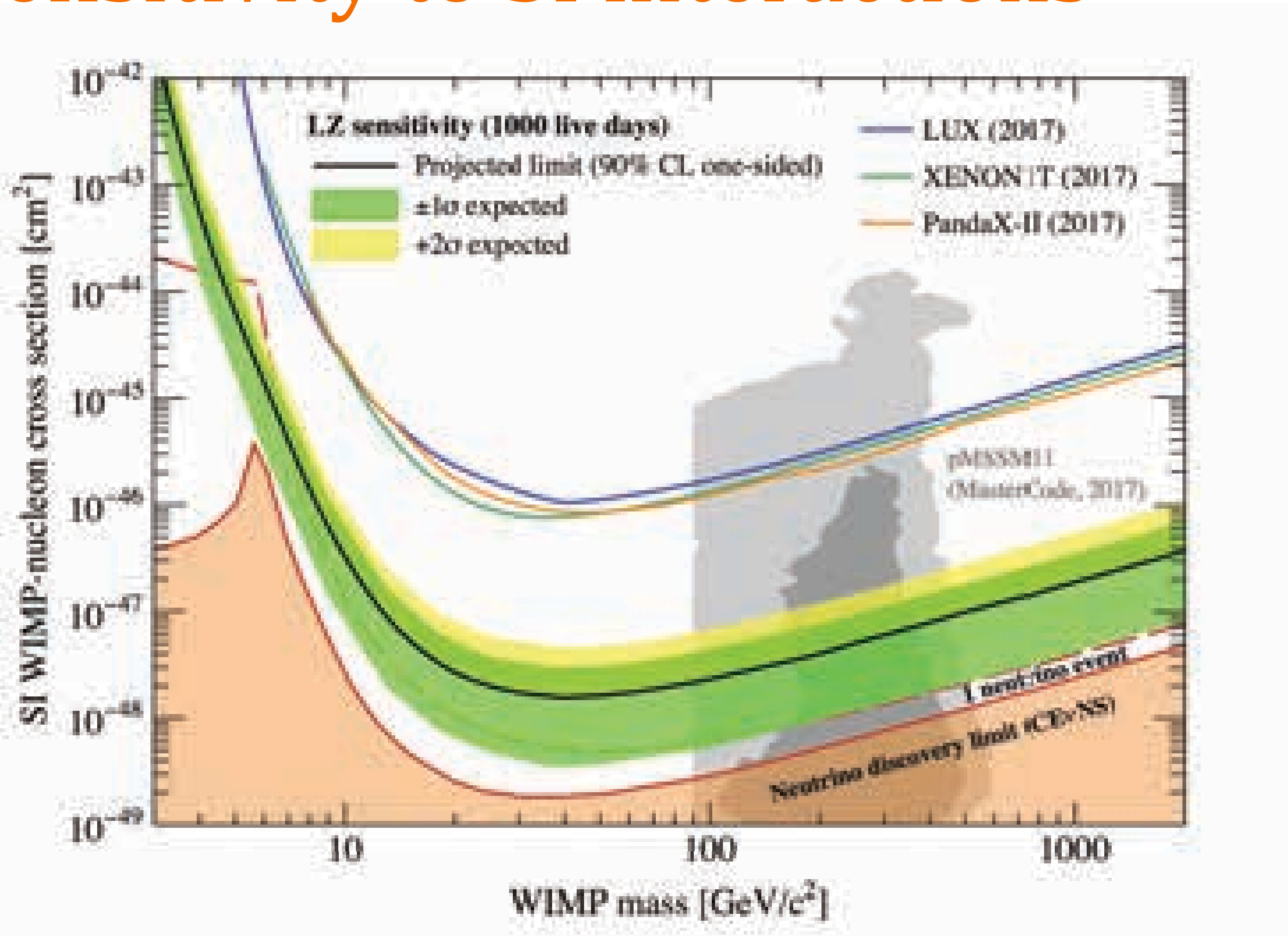
$$0 \le q_\sigma \le \infty$$

- Many Monte Carlo trials are simulated to construct distributions under H_0 (S+B) and H_a (B-only) hypotheses
  - For a sensitivity study: $q_\sigma^{obs} = \text{median}\big(f(q_\sigma|H_a)\big)$ (vertical black line in top plot)





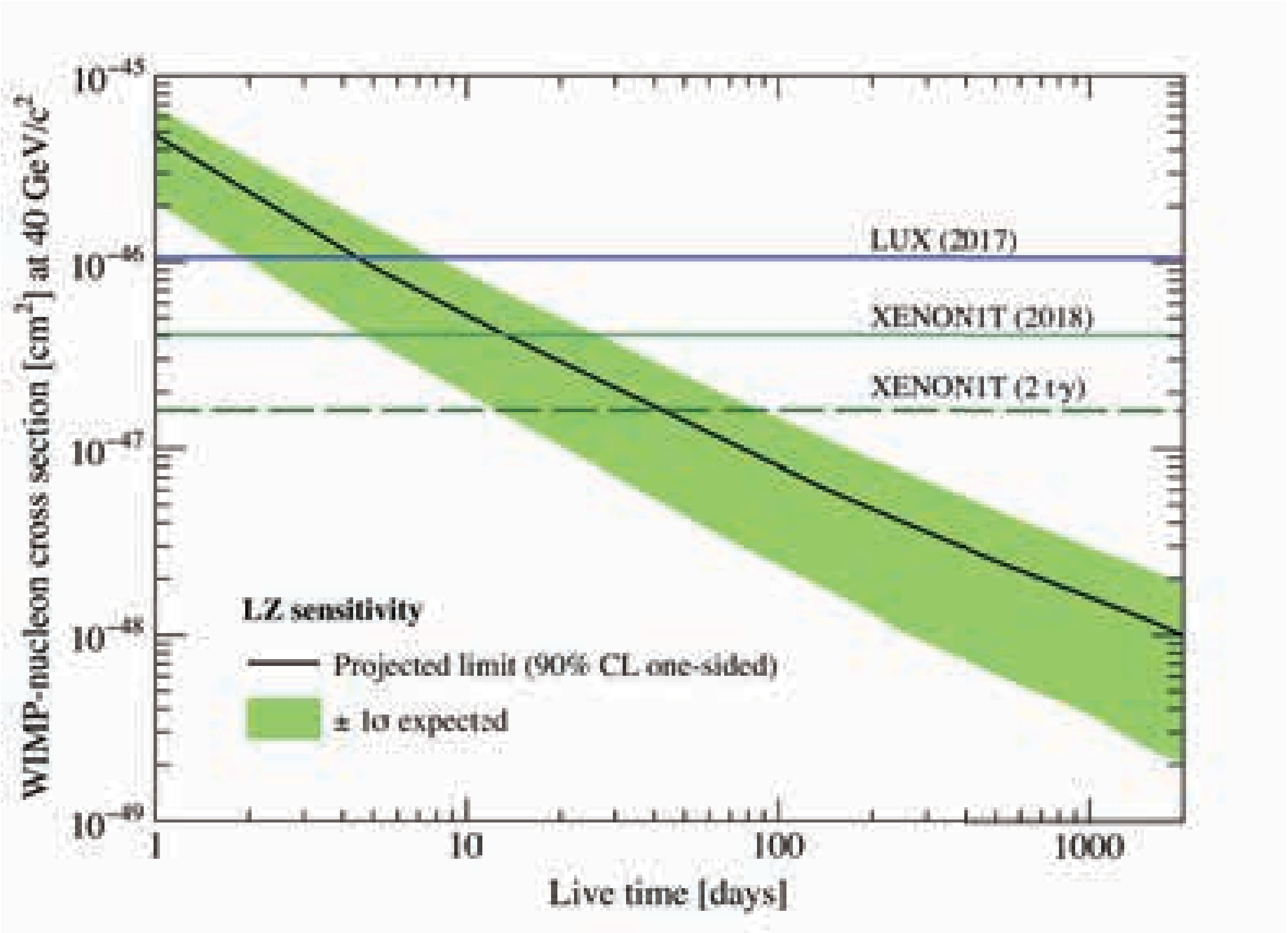
LZ sensitivity to SI interactions



- Minimum point:
  - 1.6×10^{-48} cm² @40 GeV/c²

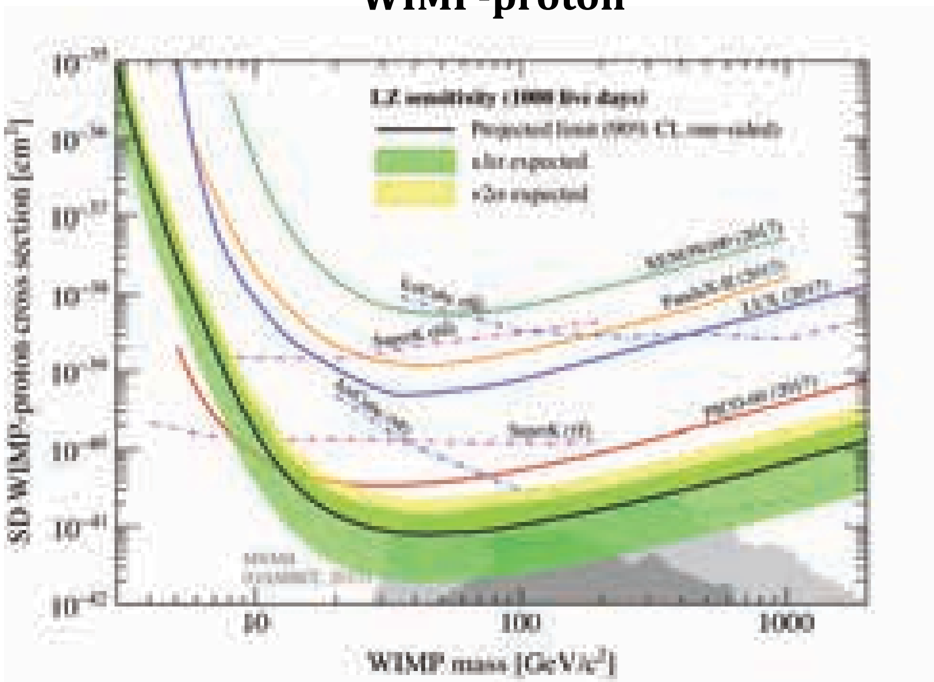
arXiv:1703.09144

LZ sensitivity to SI interactions



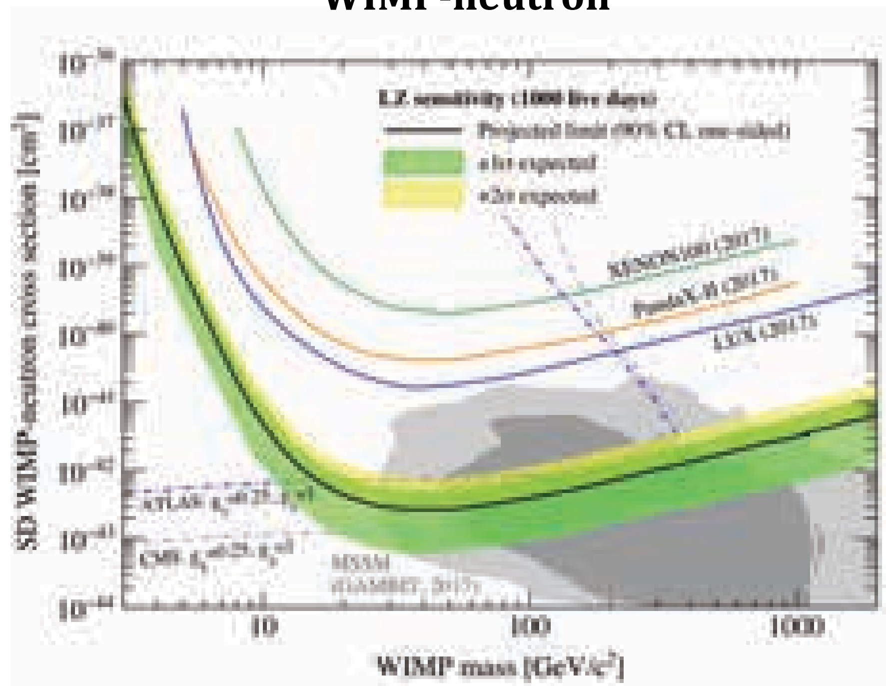
LZ sensitivity to SD interactions

WIMP-proton



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

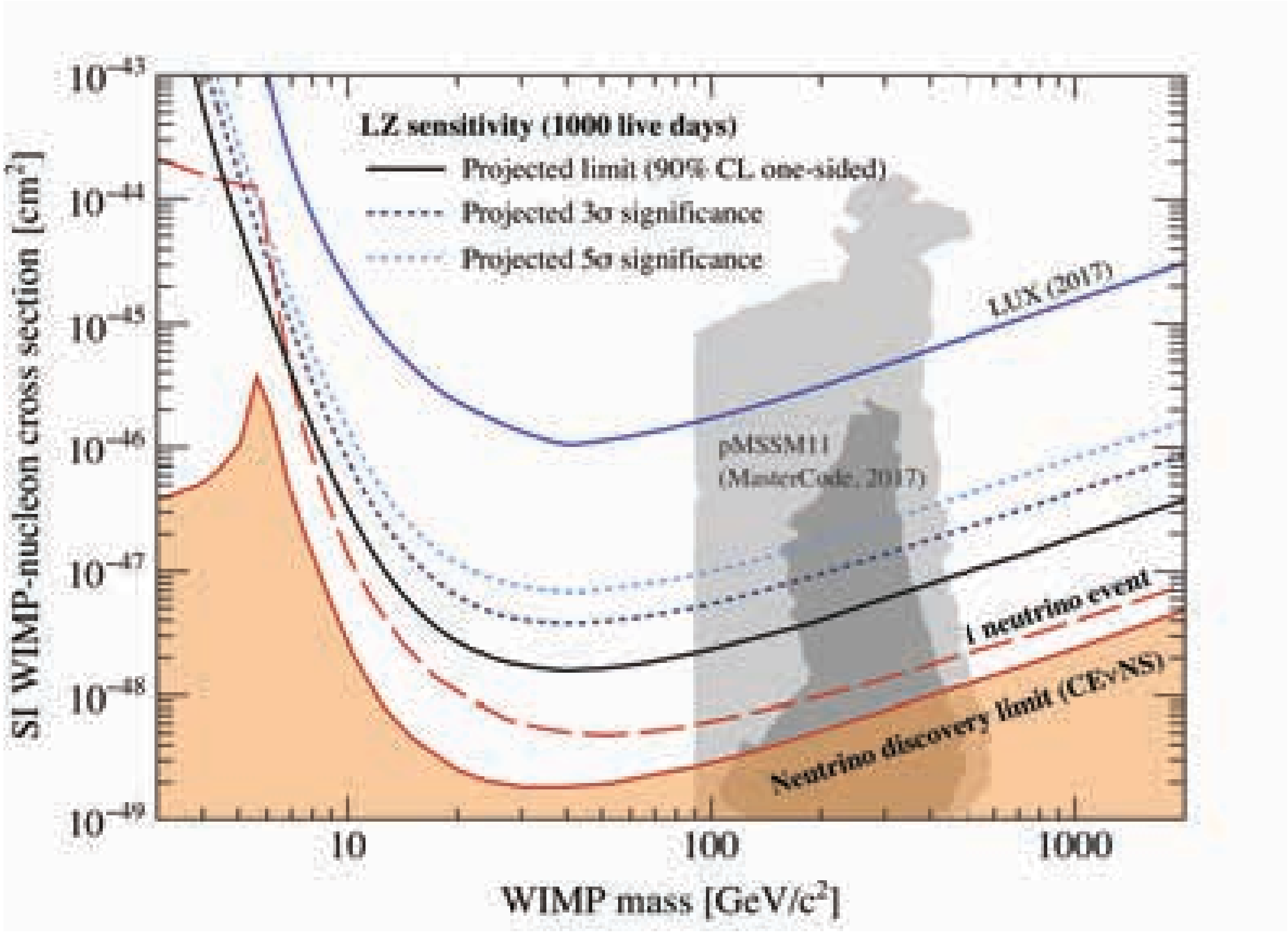
WIMP-neutron



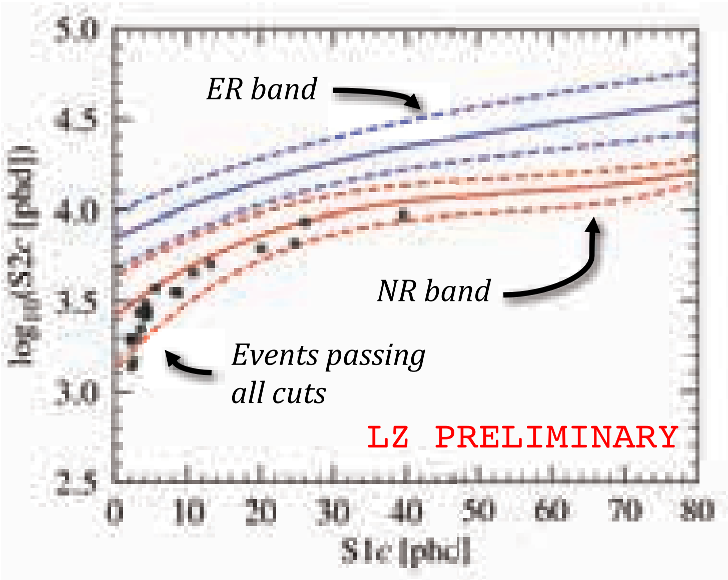
- Minimum point
  - $2.7{\times}10^{-43}$ cm^2 @40 GeV/c^2

- Odd-neutron isotopes in natural xenon: ^{129}Xe (26.4%) and ^{131}Xe (21.2%)
- Structure factors taken from Phys. Rev. D 88, 083516

Projected LZ discovery significance

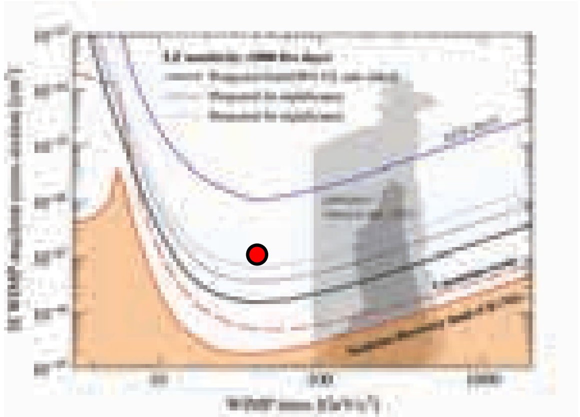


Reconstruction of WIMP signals

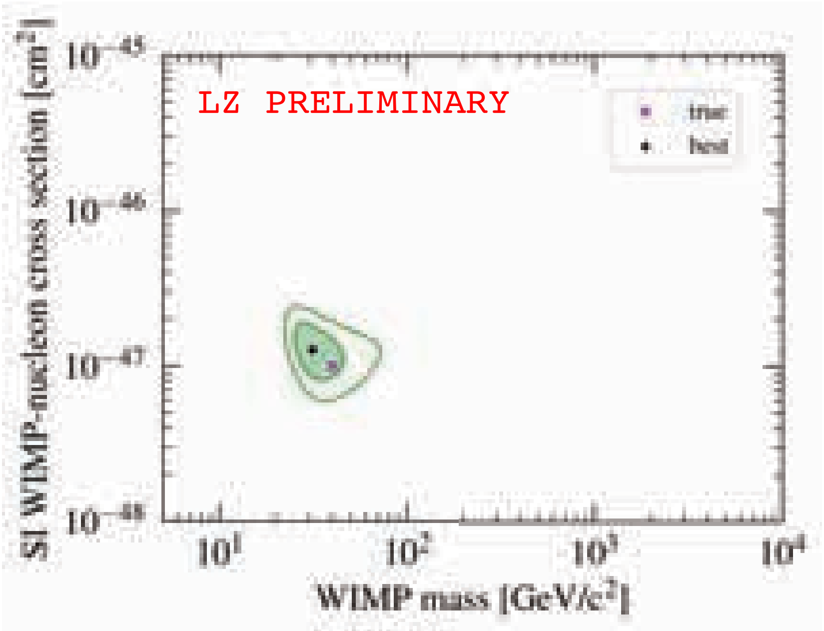


Observation

- $\mu_s = 18.5$
- $n_{obs} = 21$ (Poisson)



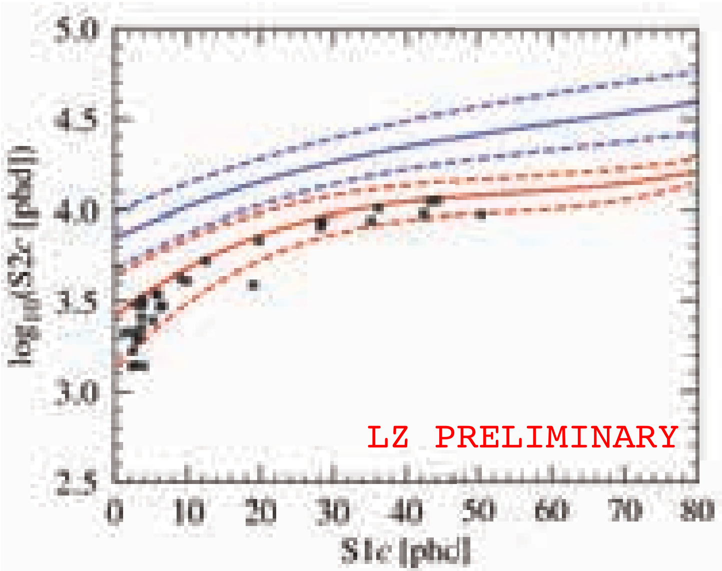
- Input WIMP mass = 40 GeV



Parameter inference

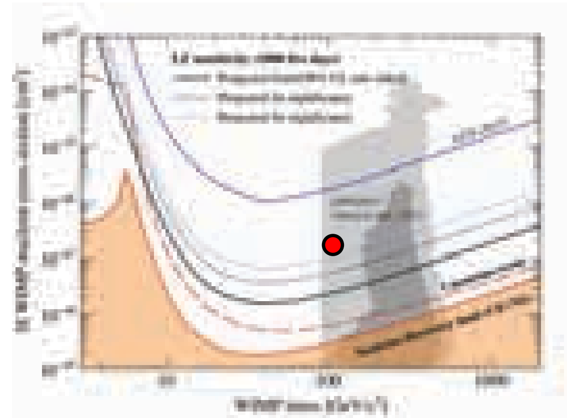
- Bayesian parameter inference, using flat and log-flat priors for mass and x-section
- Any event above the NR median line is not considered

Reconstruction of WIMP signals



Observation

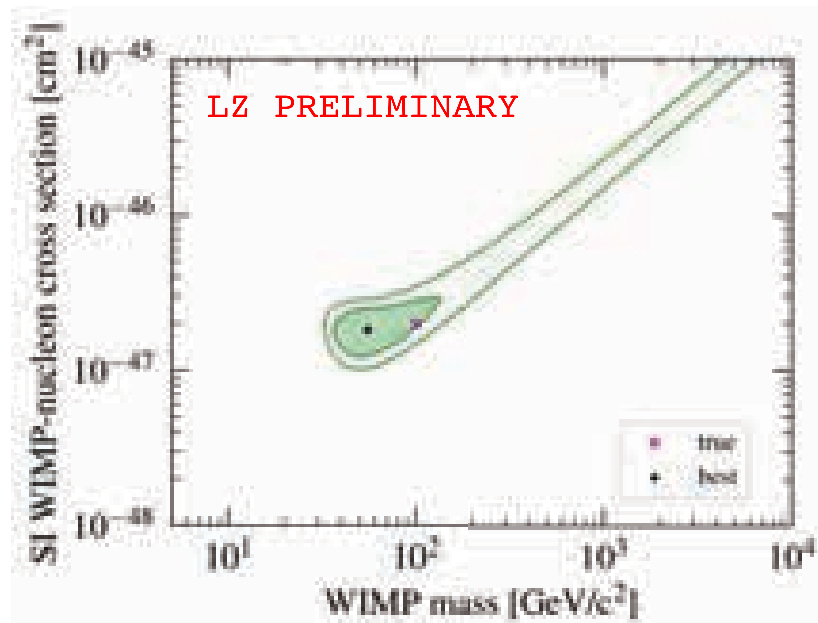
- $\mu_s = 28.3$
- $n_{obs} = 33$ (Poisson)



➤ Input WIMP mass = 100 GeV

Parameter inference

- For heavy WIMP masses, reconstruction becomes worse due to the degeneracy between mass and x-section in the WIMP rate



Summary

- The LZ experiment is fully optimised for the 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 unavoidable astrophysical backgrounds become dominant
  - $\sim$2 order of magnitude more sensitive than current best limits
  - 3σ discovery potential at reach
- Other searches are possible too
  - SD interactions, axion-like particles (ALPs), astrophysical neutrinos, $0\nu\beta\beta$'s, ...
- Physics data taking from 2020!!

BACKUP

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 [V cm^{-1}]	310
Electron lifetime [μs]	850

Estimated background rates

Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								subtotal	**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 μBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
								subtotal	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.81 μBq/kg)									681	-
^{220}Rn (0.09 μBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N									255	-
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**322**	**0.51**
Total									1195	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.97	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									6.49	

Counts are for a region of interest relevant to a 40 GeV/c^2 WIMP:
* 1.5–6.5 keV for ERs
* 6–30 keV for NRs

Application of the single scatter, skin and OD veto, and 5.6 tonne fiducial volume cuts are considered.