Background model and statistical analysis in the LUX-ZEPLIN experiment

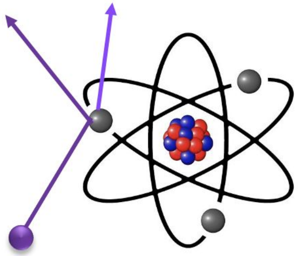
Ibles Olcina (UC Berkeley/LBNL)

IDM, Vienna

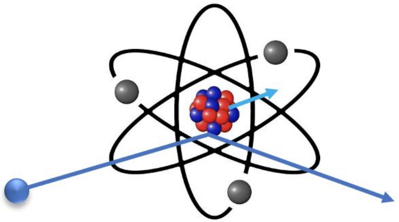
18/07/22

Direct detection of dark matter

- Looking for the scattering of a galactic dark matter particle and a target nucleus
- Two types of signals
  - *Electron recoils*: gamma-rays, beta particles, ν-e scattering, etc.
  - *Nuclear recoils*: neutrons, coherent elastic ν-N scattering (CEνNS), etc.
- WIMP dark matter is well motivated
  - Stable and “cold”
  - Mass and cross section in a range that naturally leads to the correct relic density via thermal production



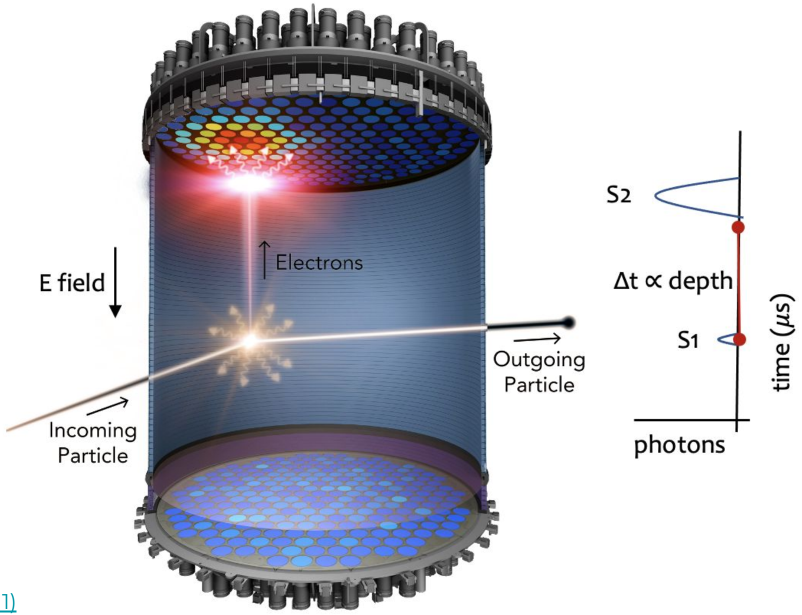
Electron recoil (ER)



Nuclear recoil (NR)

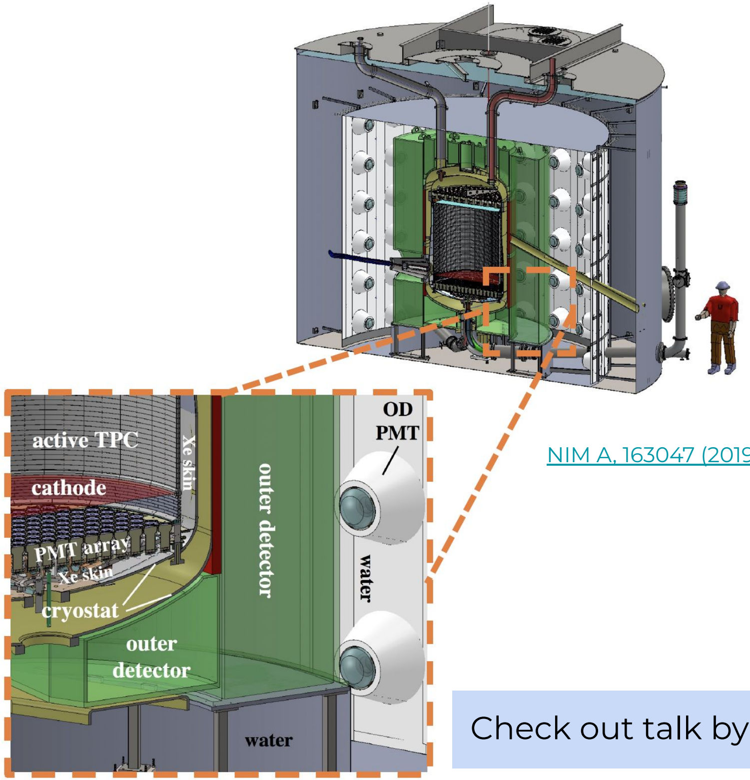
Dual-phase xenon TPC

- Any particle scattering in the liquid produces two types of quanta:
  - Scintillation photons (S1)
  - Ionization electrons, which drift up and produce electroluminescence light in the gas region (S2)
- Excellent reconstruction capabilities
  - Energy resolution of <1% at high energies (> 1 MeV) XeSat, G. Pereira (May 24th, 2022)
  - 3D location information with a resolution of ~mm in XY and sub-mm in Z
- ER and NR events are distinguished by their different charge-to-light ratio
  - The ratio of ionization to excitation is different
    - ~16:1 for ERs (S2/S1 larger) Phys. Rev. A 12, 1771 (1975)
    - ~1:1 for NRs (S2/S1 smaller) Phys. Rev. D 83, 063501 (2011)
  - Dependent on drift electric field and recoil energy



The LZ experiment

- Located at the Sanford Underground Research Facility, in Lead, SD
    - 1 mile deep (4.3 km.w.e)
- Largest Xe TPC in the world
    - 1.5 m tall and wide
    - 7 tonnes of active LXe
- Multi-detector system
    - Xe skin
    - Gd-loaded scintillator OD
- Science Run 1 (SR1)
    - Data collected from end of Dec 2021 to beginning of May 2022
    - Total exposure of 5.5 tonnes and 60.3 livedays

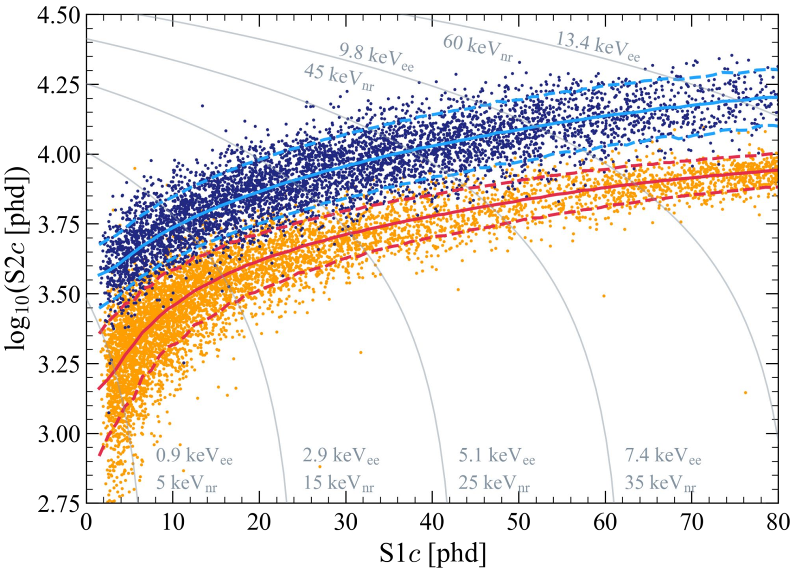


NIM A, 163047 (2019)

Check out talk by A. Fan!

WIMP search strategy

- Tune the detector response model
  - The ER model was fitted to CH_3T data (continuum β spectrum)
    - Detector response simulated using *NEST plus a built-in framework to account for variable drift field maps and position smearing
  - The parameters of the ER model were propagated to the NR model
    - Matches with DD data to <1% in the band means

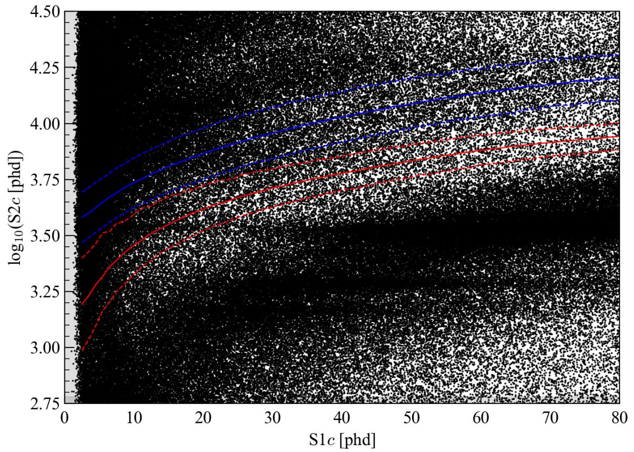


Tritium (blue dots) and DD neutron (orange dots) data, with the ER (blue lines) and NR (red lines) bands as predicted by the detector model overlaid

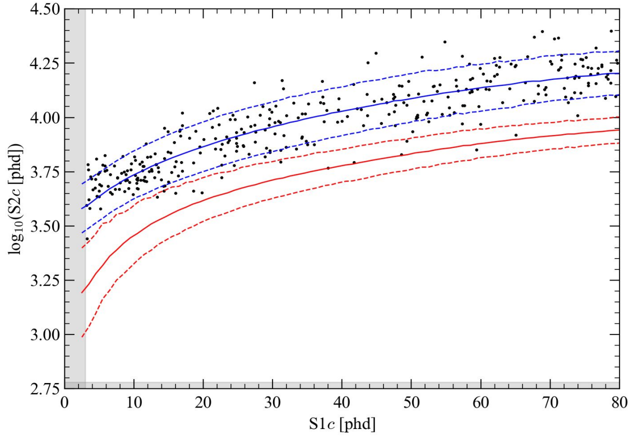
*https://github.com/NESTCollaboration/nest

WIMP search strategy

- Develop analysis cuts to obtain a clean sample of events
  - Types:
    - *Livetime*: cut time periods based on detector activity. They have an impact on livetime.
    - *Pulse-based*: based on features of the S1 or S2 pulses.
  - These cuts have a high rejection power, while maintaining a high signal acceptance (>95%)
  - ROI: S1c in [3, 80] phd, S2 > 600 phd, S2c<1e5 phd
- Develop signal and background models (next)



All single scatters events



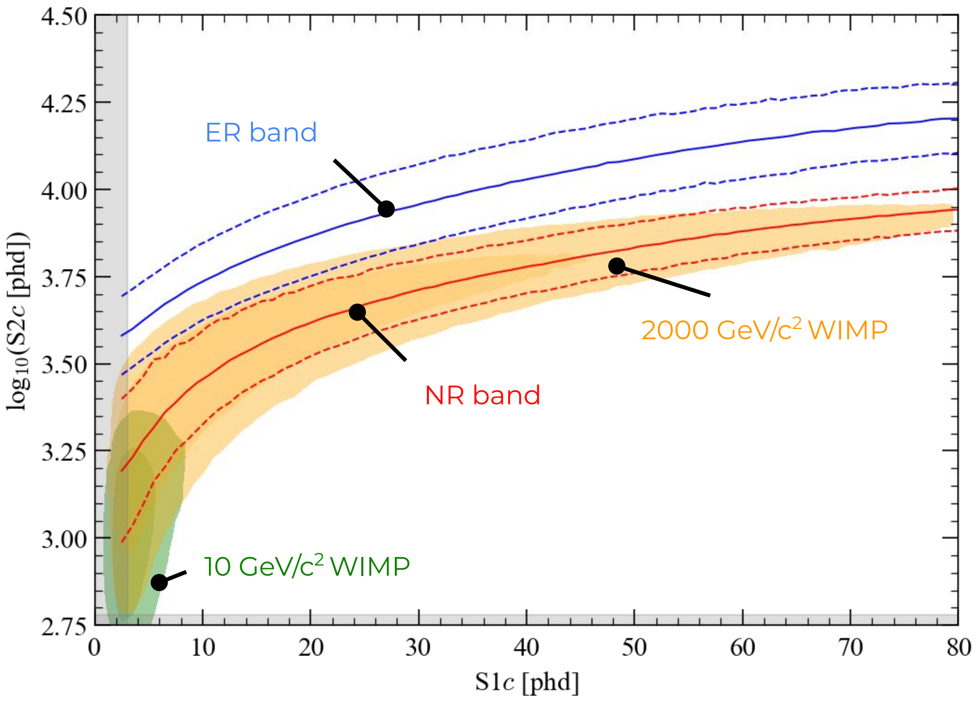
Events after all data quality cuts (335)

Signal model

- Following the canonical WIMP signal model that was agreed to by all major direct detection collaborations*
- LZ's NR model is used to calculate the corresponding (S1, S2) distributions from the predicted recoil energy, and the corresponding signal efficiencies from data analysis are applied

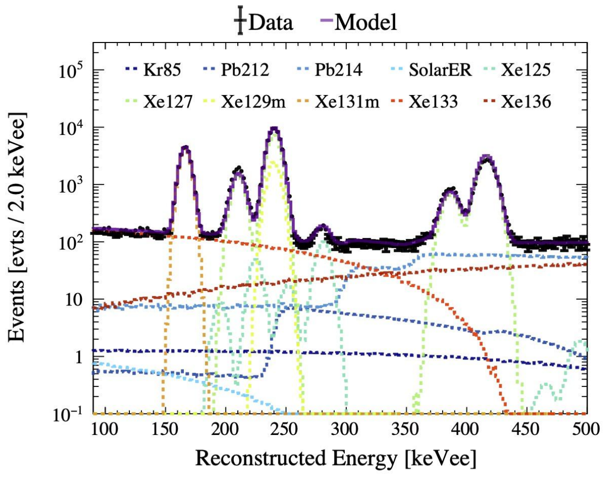
Parameter	Description	Value
ρ_χ	Local dark matter density	$0.3\,\mathrm{GeV/c^2/cm^3}$
v_{esc}	Galactic escape speed	$544\,\mathrm{km/s}$
$\langle\lvert\mathbf{v}_\oplus\rvert\rangle$	Average galactocentric Earth speed	$29.8\,\mathrm{km/s}$
$\mathbf{v}_\circledast$	Solar peculiar velocity	$(11.1, 12.2, 7.3)$ km/s
$\mathbf{v}_0$	Local standard of rest velocity	$(0, 238, 0)$ km/s

*Eur Phys J C, 81:907 (2021)



Background model: ER sources

- **Dissolved beta emitting isotopes**
  - ^{214}Pb and ^{212}Pb are radioactive products of the ^{222}Rn and ^{220}Rn decay chains originating in detector materials and dust (166 and 18 events expected in the ROI)
  - Natural Xe contains traces of ^{85}Kr and ^{39}Ar (33 and 0.6 events)
    - Heavily suppressed via charcoal chromatography at SLAC
  - Standard double beta decay (DBD) decay of ^{136}Xe (15.2 events)
    - Rate based on the half-life measurement by EXO-200 (Phys Rev. C 89, 015502 (2014))
- **Electron capture (EC) (mono-energetic x-ray/Auger cascades)**
  - ^{37}Ar is produced via cosmogenic activation ([0,291] events)
    - Large uncertainty due to nuclear models (Phys Rev. D 105, 082004 (2022))
  - Of all the Xe activation isotopes, ^{127}Xe is the only one that can release energy within the ROI (9.2 events, livetime-averaged)
  - Double electron capture of ^{124}Xe (5 events)
    - Rate based on X1T measurement (arXiv:2205.04158)

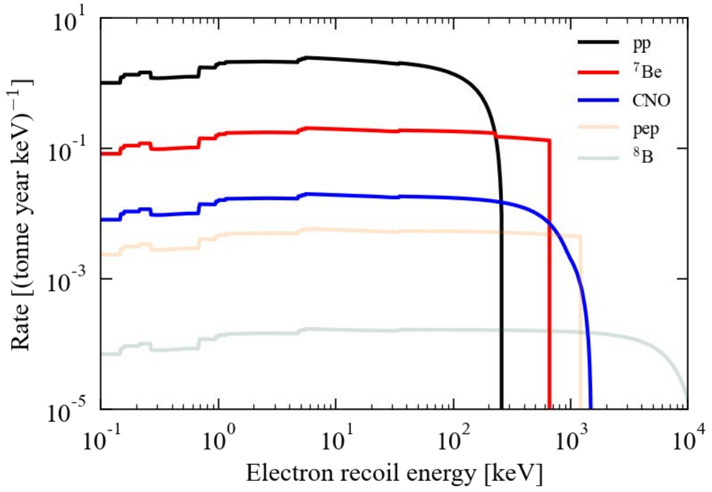


Energy spectra fit to the Xe activation peaks outside of the ROI

Check out posters by A. Mushali!

Background model: ER sources

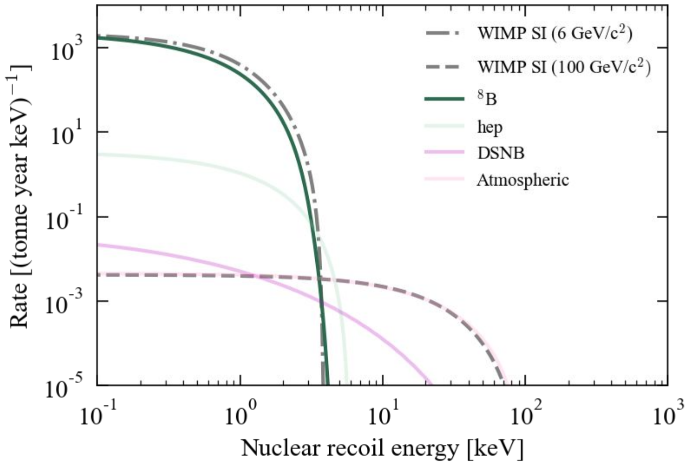
- **Solar neutrinos**
  - The main contributions arise from the pp I-cycle (pp ν) and pp II-cycle (^{7}Be ν) reactions, and the CNO chain (27.3 events)
- **Detector components and cavern walls**
  - They constitute a possible source of gamma emitting isotopes
  - This contribution was made negligible via careful selection of materials, addition of external shielding, and the use of external vetoes (1.2 events)



The contributions from pp, 7Be, and CNO neutrinos are combined into the neutrino ER component

Background model: NR sources

- **Solar neutrinos**
  - The coherent scattering of solar neutrinos with Xe nuclei (CEνNS) is an irreducible background
  - Only the ^{8}B component is included in the background model (0.15 events), as the expected number of events from the other neutrino sources is negligible
- **Detector components**
  - Alpha decays in the ^{238}U and ^{232}Th chains, originating in radioactive materials, cause (alpha,n) reactions that emit radiogenic neutrons
  - Their contribution is predicted to be negligible from a likelihood fit to OD-tagged data (0 events)

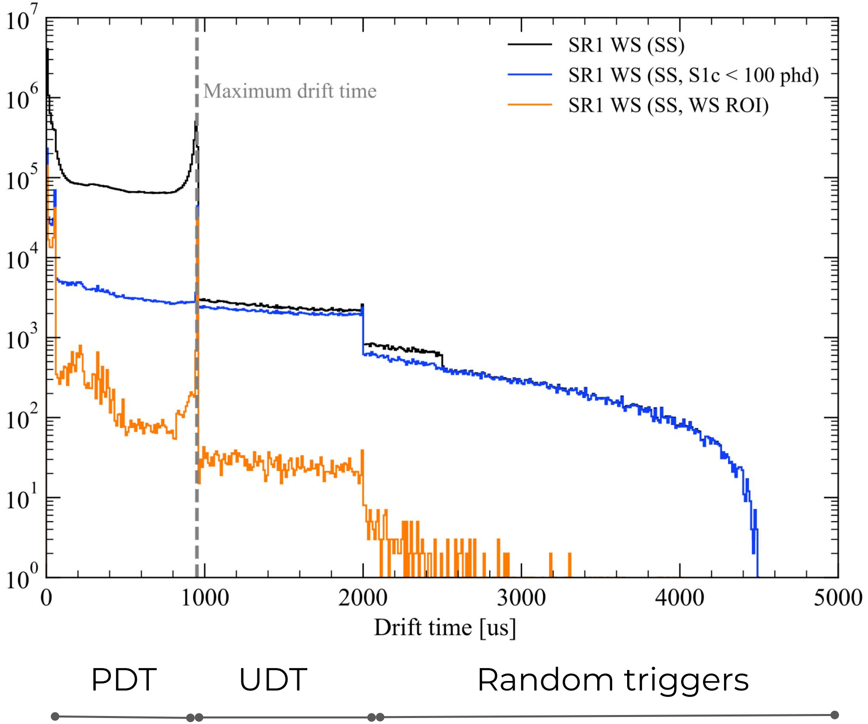


The neutrino NR component in the background model is only composed by ^{8}B neutrinos

Check out talk by A. Monte!

Background model: accidentals

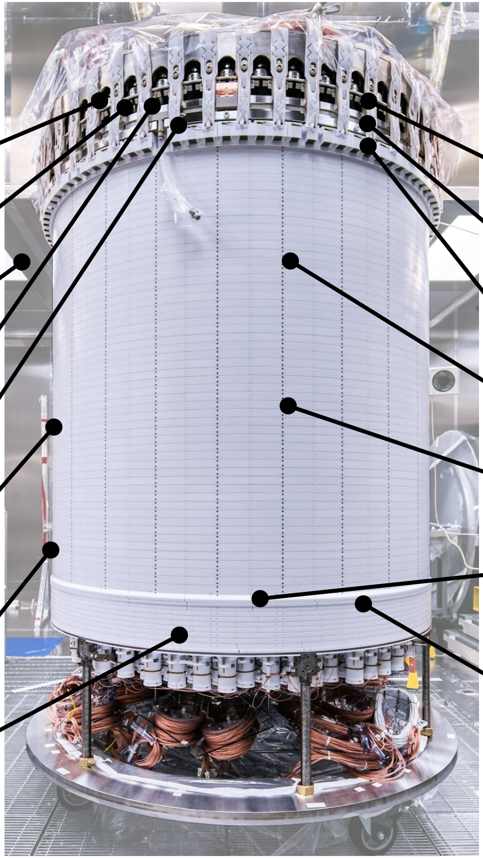
- Uncorrelated S1 and S2 occurring within one maximum drift time
- Unphysical Drift Time (UDT) events constitute a good proxy for accidentals
  - The S1 and S2 must be uncorrelated since they occurred more than one maximum drift time apart
  - Several checks were conducted to confirm the independence of the S1 and S2 variables in UDT data



S1-only sources:

- PMT dark count pile-up
- Above-anode events
- Light leaks from outside TPC
- Radioactivity from grid wires
- Cherenkov from PMT windows
- Fluorescence of PTFE
- Charge loss events near TPC walls
- Reverse Field Region events

Rate of O(1 Hz) after cuts



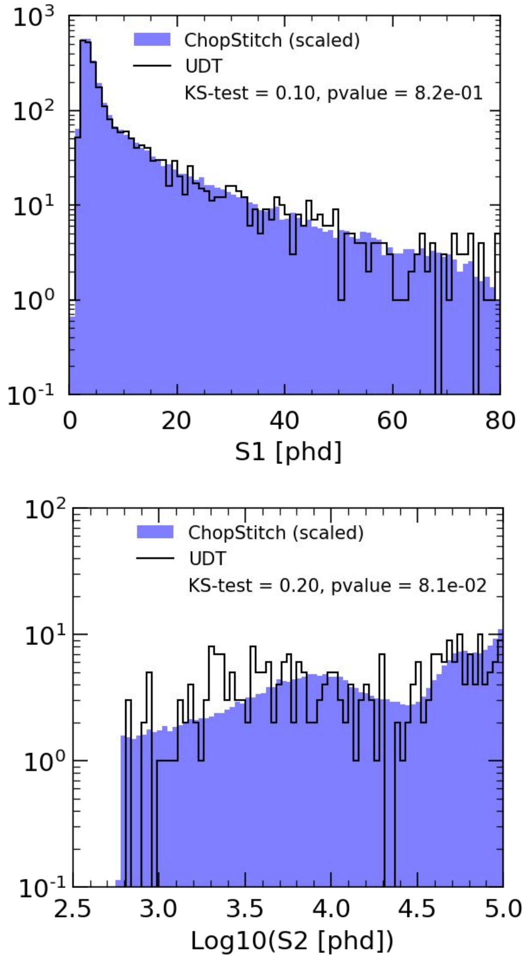
S2-only sources:

- Above-anode events
- Extraction region gas events
- Near liquid surface events
- Sub-S1 threshold ER events
- Electrons in S2 tails
- Radon daughters from cathode
- Electron emission from grids

Rate of O(10^{-3} Hz) after cuts

Background model: accidentals

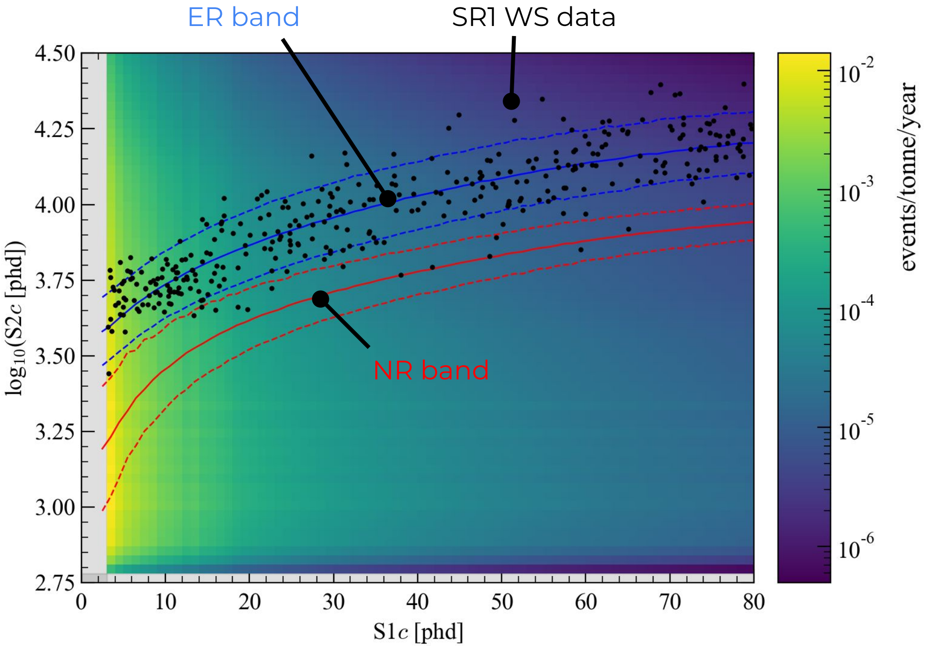
- The accidentals model was built following a data-driven approach
  - Isolated S1 and S2 were combined at the waveform level to form events ("ChopStitch data")
  - A good agreement with UDT data was found in several dimensions (pulse size, drift time, etc.)
- Evaluated on ChopStitch data, the analysis cuts achieved a rejection efficiency of 99.6%



Comparison of ChopStitch and UDT data in pulse size

Background model: accidentals

- 30M Accidental ChopStitch events were generated
  - Only 22k passed all the cuts, which was insufficient
  - A smoothing technique was applied to produce the final PDT
- 1.2 events are expected in the ROI (equivalent to a rate of 0.2×10^{-6} Hz)

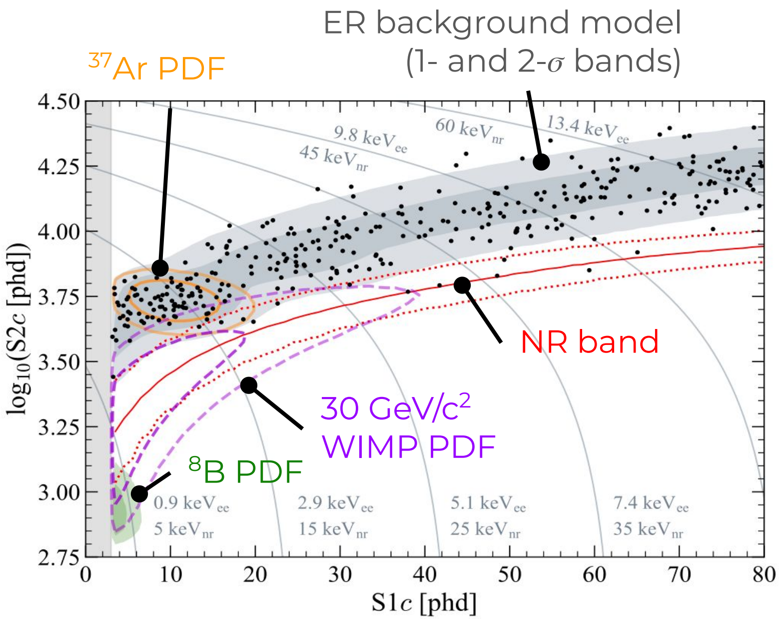


Check out poster by D. Hunt!

Putting it all together

Source	Expected Events
β decays + Det. ER	218 ± 36
ν ER	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.2 ± 2.4
^{8}B CEνNS	0.15 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	276 ± 36
^{37}Ar	[0, 291]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

Expected number of events in the ROI



Main PDF shapes of the event model

The likelihood function

Parameters of interest: signal mean (μ_s)

Observables: (S1, S2)

Nuisance parameters: background means

$$\mathcal{L}(\boldsymbol{\theta}) = \left[\mathrm{Pois}(n_0|\mu(\boldsymbol{\theta})) \prod_{e=1}^{n_0} \frac{1}{\mu(\boldsymbol{\theta})} \left(\mu_s f_s(\boldsymbol{x}_e|\boldsymbol{\theta}) + \sum_{b=1}^{N_c} \mu_b f_b(\boldsymbol{x}_e) \right)\right] \prod_{p=1}^{N_c} f_p(\boldsymbol{g}_p|\mu_p)$$

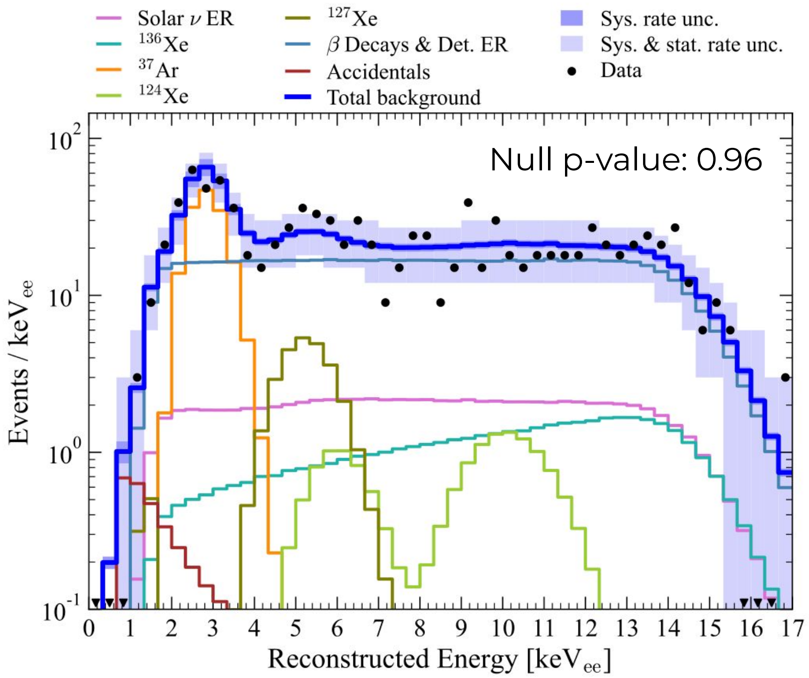
Extended term

Constraint functions

Global observables: expected events

Fit to data

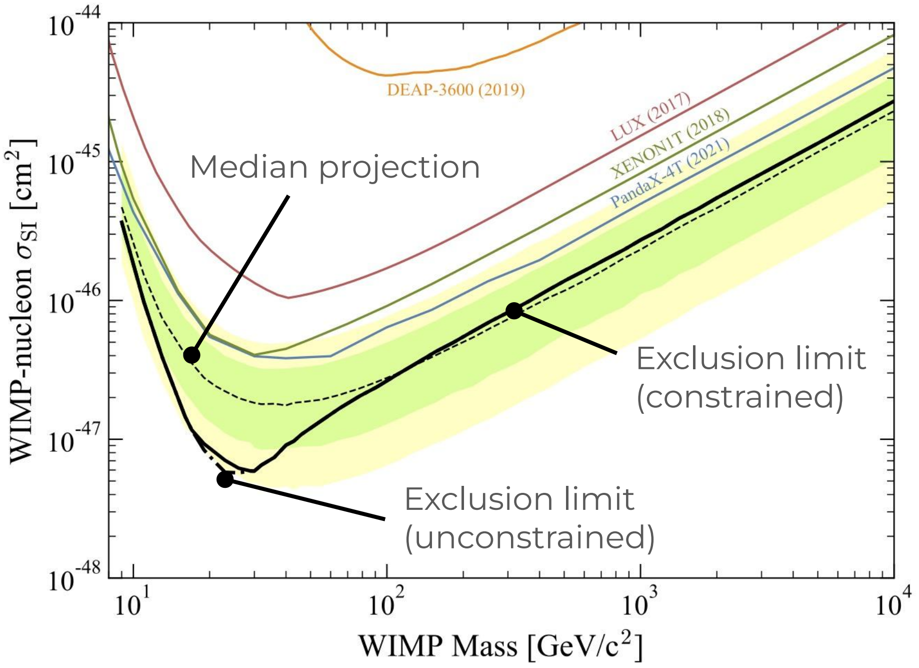
Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



A best-fit value compatible with 0 events was found for all WIMP masses

Limit on SI WIMP-nucleon cross section

- A Frequentist, two-sided profile likelihood ratio (PLR) test statistic was employed
- A power constraint of Π_{crit} = 0.32 was applied, as recommended by Eur Phys J C (2021) 81:907
  - The departure from the -1σ band at low masses is caused by an underfluctuation of data
- This is the lowest limit on the SI WIMP-nucleon cross section to date
  - Minimum cross section of 5.9×10^{-48} cm^2 at 30 GeV/c^2 (90%CL)



Conclusions

- The LZ detectors (TPC, Skin, OD) are performing as designed
- A huge collaborative effort was undertaken to keep the background level as low as possible
  - 335 events were observed in a exposure of 60 livedays*5.5 tonnes (corresponding to a rate of ~25 evts/keVee/tonne/year in the ROI)
- The accidentals background didn't have a big impact on the SI SR1 limit. However, if the rate stayed at 0.2×10^{-6} Hz, it could become a dominant background with a longer livetime (or a larger detector!)
- With 60 livedays of science data, no evidence of WIMPs was found at any mass
  - LZ has set a world-leading limit on the SI WIMP-nucleon cross section of 5.9×10^{-48} cm^2 at 30 GeV/c^2 (90% CL)

Keep your eyes peeled, this is just the beginning!

To learn more, see: arXiv:2207.03764

Thank you!

@lzdarkmatter
https://lz.lbl.gov

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Wisconsin, Madison

US UK Portugal Korea

Thanks to our sponsors and participating institutions!

U.S. Department of Energy
Office of Science

Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Institute for Basic Science

BACK-UP

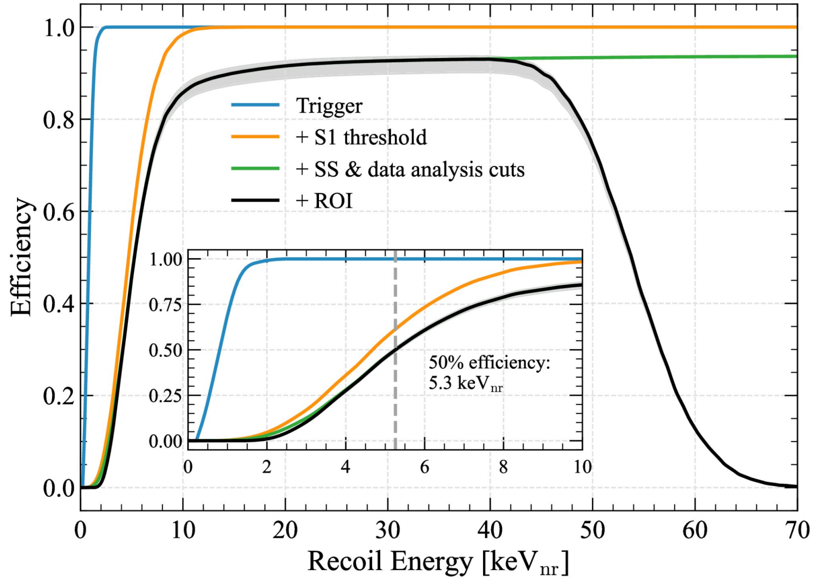
Detector parameters

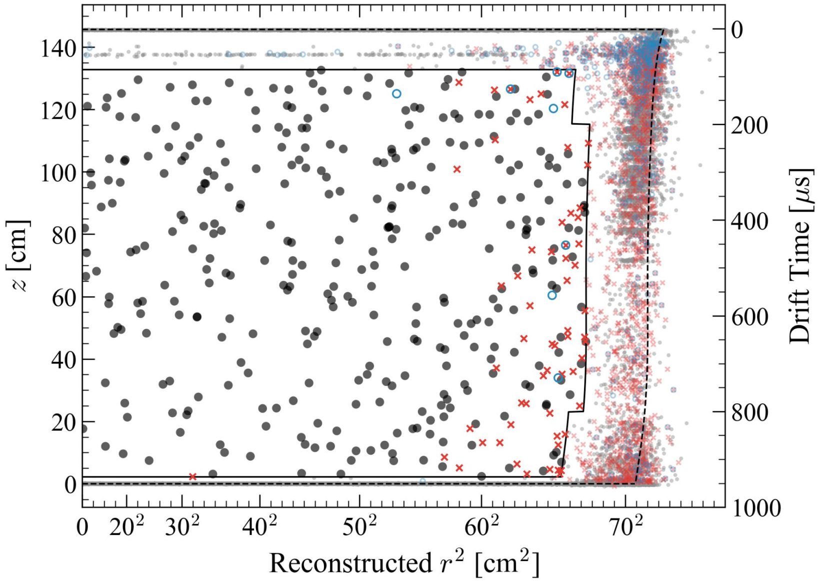
Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron

$$\langle \text{S1c} \rangle = g_1 \langle n_{ph} \rangle \qquad \langle \text{S2c} \rangle = g_2 \langle n_e \rangle$$

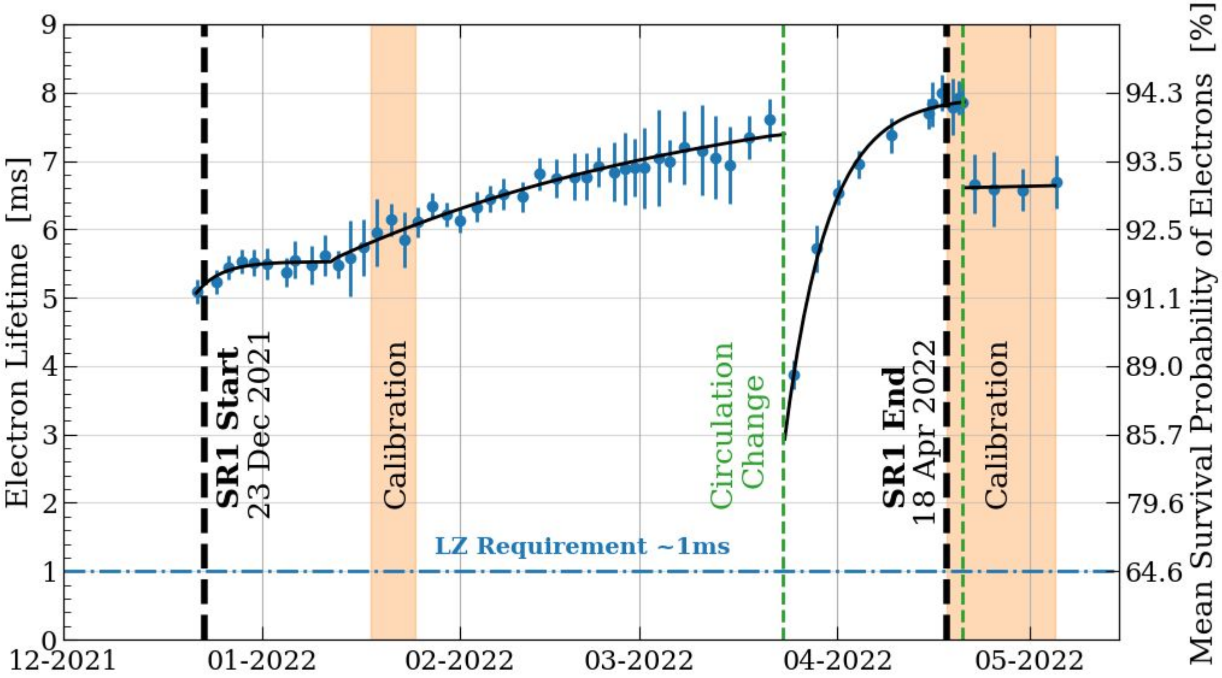
$$g_2 = \langle \text{SE} \rangle \cdot \epsilon_{ext}(\mathcal{E}_{gas}) = g_1^{gas} \cdot Y_e(\mathcal{E}_{gas}, \Delta z_{gas}) \cdot \epsilon_{ext}(\mathcal{E}_{gas})$$

Supplementary plots

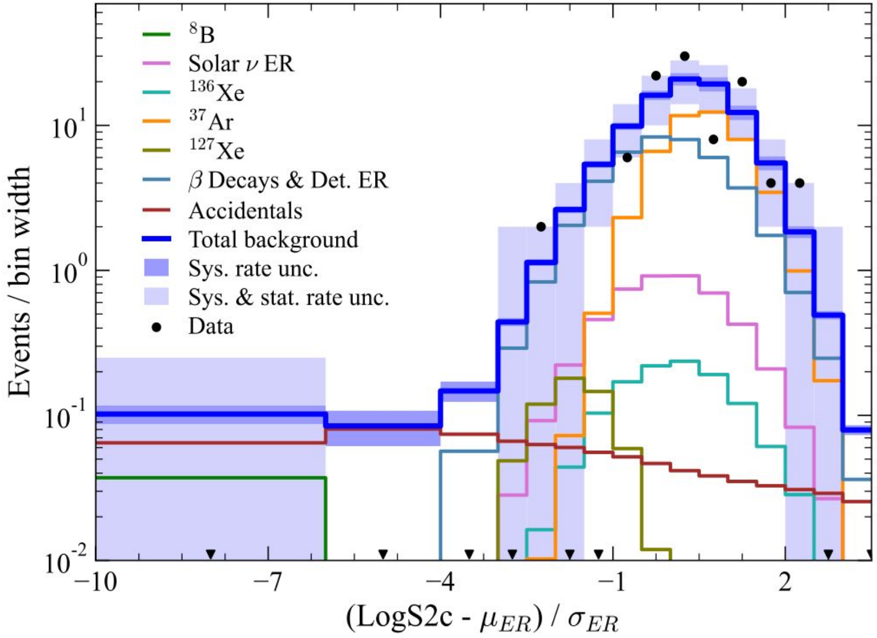




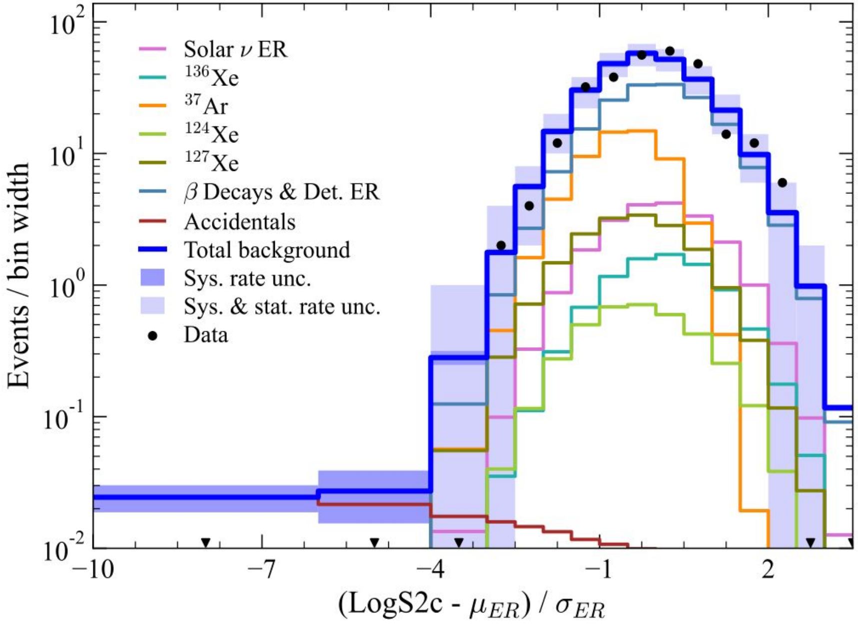
Supplementary plots



Supplementary plots

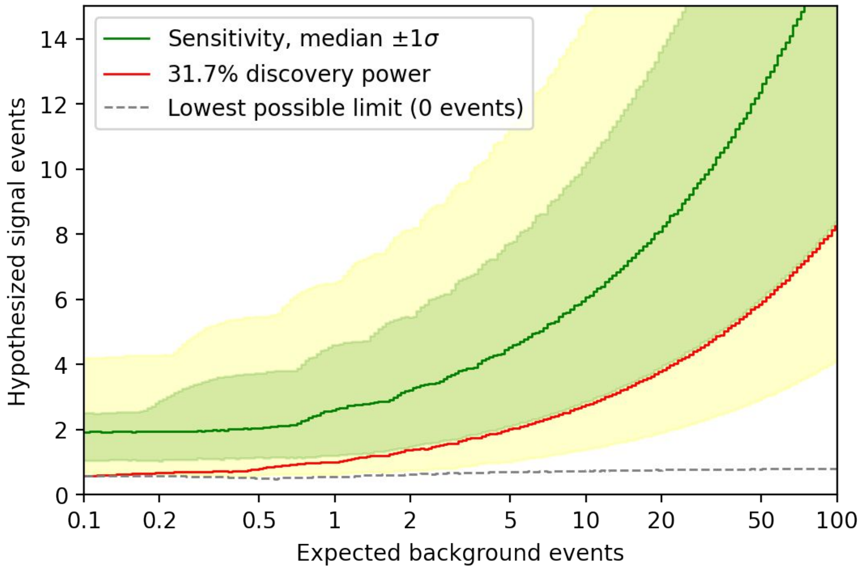


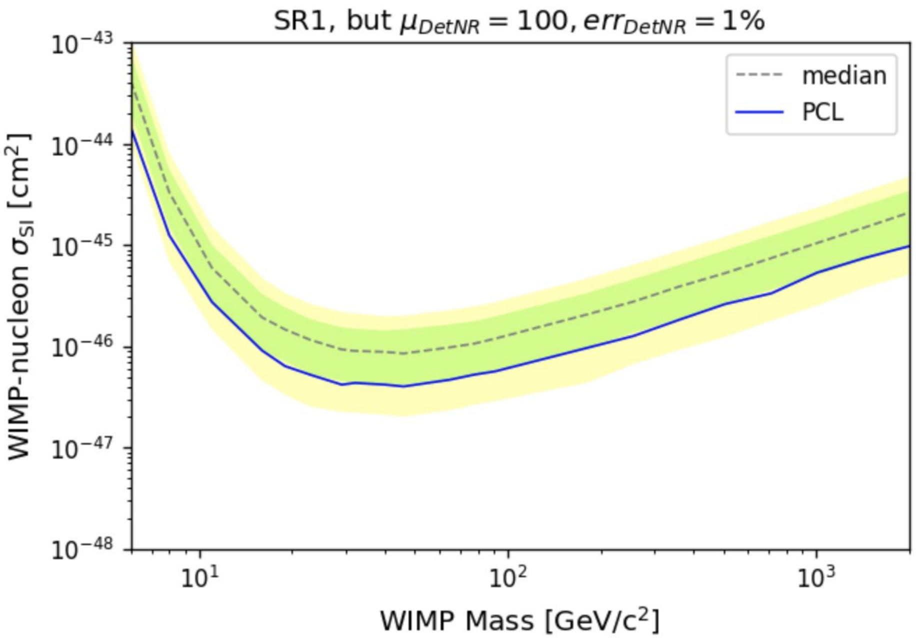
S1c: 0-10 phd



S1c: 10-40 phd

Cross checks on the power constraint





Spin-dependent limits