XLZD WIMP search performance studies

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A quick note on scope

- We have been tasked with defining top-level requirements relevant for WIMP-like searches with XLZD

- This is a **first pass** at this: here we have taken more of a physics-driven approach (vs. an engineering-driven approach)

- Importantly, we have built **easy to use** frameworks such that these studies can be (relatively) easily extended, working towards a more realistic implementation of the XLZD detector

- If people disagree with what we've done, or would like to see something done differently, please raise it! We can very probably run the study you would like to see following this meeting

Approach and methodology

Background model and ROI

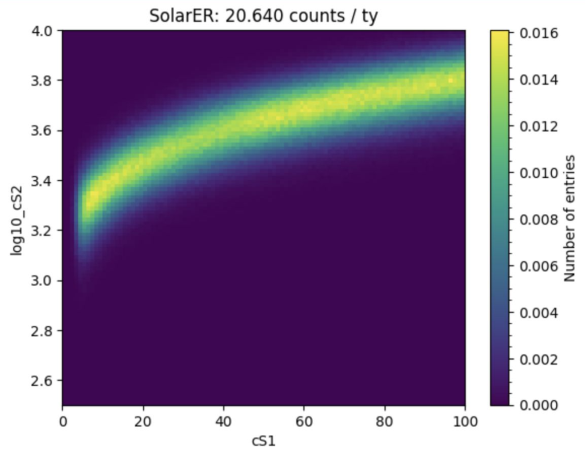
Component	Spectrum
Pb214	**Normalisation:** 2007.13686 **Shape:** taken from LZ simulations
Kr85	**Normalisation:** $T_{1/2}$ = 10.76 yr; 2×10^{-11} isotopic abundance; 99.6% ground-state branching ratio **Shape:** taken from LZ simulations
Xe136 2vBB	**Normalisation:** 1306.6106 **Shape:** taken from LZ simulation
Xe124 2vDEC	**Normalisation:** 2205.04158 **Shape:** taken from LZ simulation
Solar neutrino ERs (PP + 7Be + CNO)	From DMCalc (LZ)
CEvNS (B8 + hep)	From DMCalc (LZ)
CEvNS (atmospheric + DSNB)	From DMCalc (LZ)
Neutrons	From GEANT4 simulations (Sally Shaw et al.)

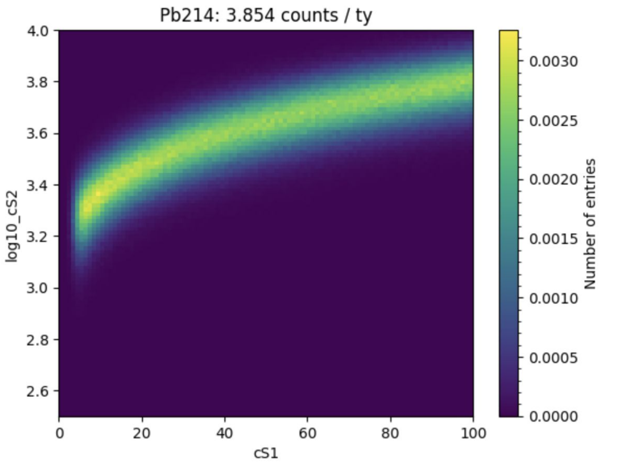
$0 < cS1 < 100$ phe

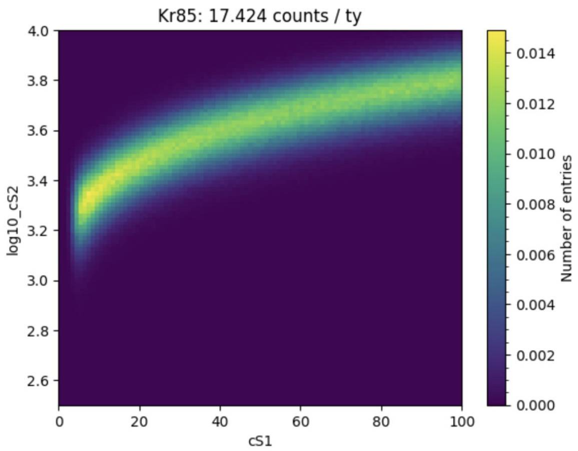
$2.5 < \log_{10}(cS2\ [\mathrm{phe}]) < 4$

4-fold coincidence

Templates and constraints: ER





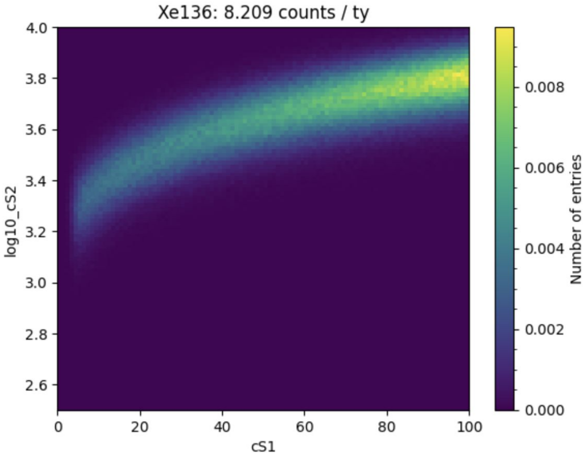


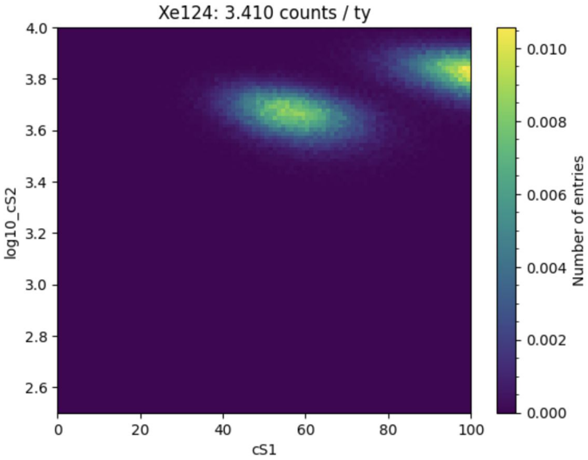
Constrained @ 4.64% (flux etc.)

Constrained @ 16.7% (based on LZ)

Constrained @ 16.7% (based on LZ)

Templates and constraints: ER

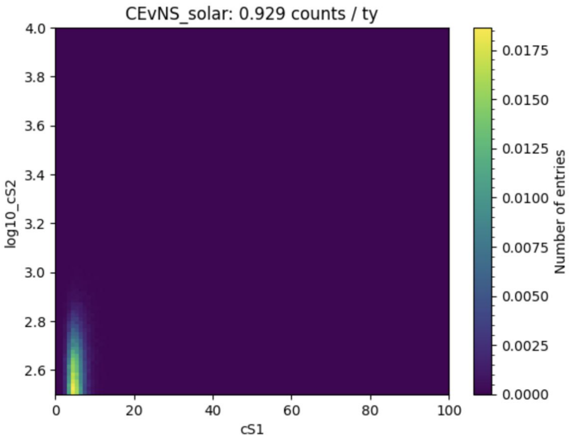


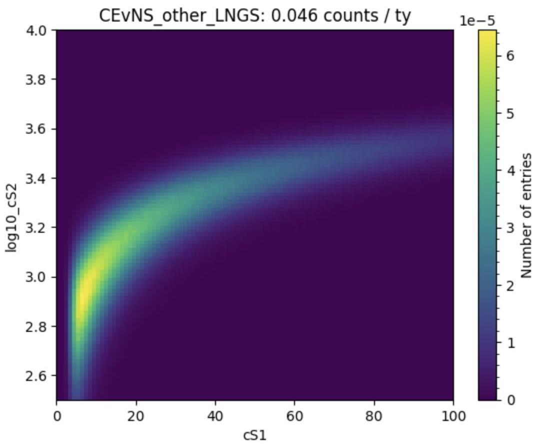


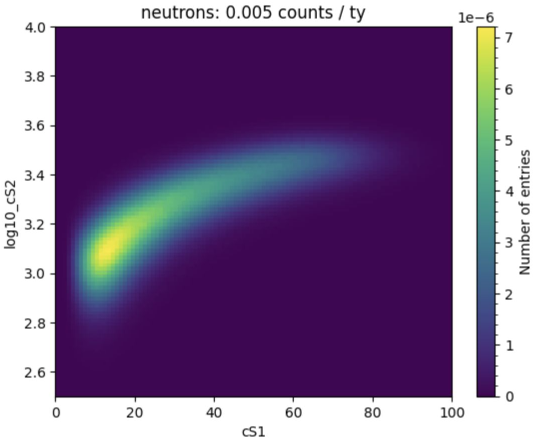
Constrained @ 15% (based on LZ)

Constrained @ 20% (loosely based on LZ)

Templates and constraints: NR







Constrained @ 3.97% (flux etc.)

Constrained @ 19.5% (flux etc.)

Constrained @ 20% (loosely based on LZ)

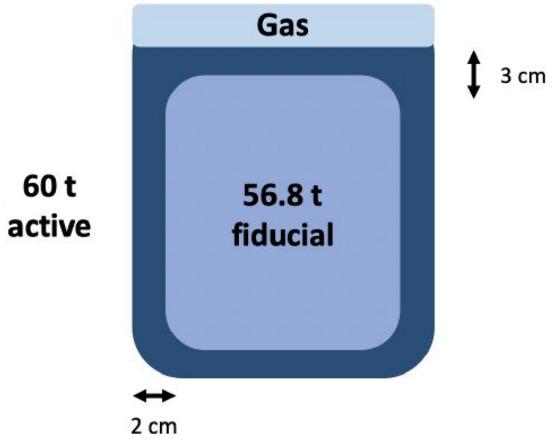
A quick note on neutrons

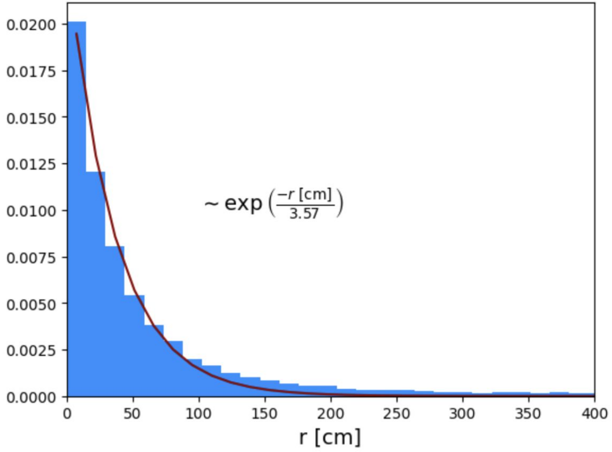
- Setting requirements on the neutron rate without accounting for attenuation within the fiducial volume would be misleading

- We did not want these studies to be dependent on a particular FV definition; nor did we want there to be issues coming from a mismatch between the geometry assumed here and that used for the neutron GEANT4 simulations handed off to us

- As such, we will make recommendations on the neutron rate **relative to atmospheric + DSNB CEvNS**, tracking sensitivity scaling with **exposure**

- We use 2D x 1D PDFs (S1c, log10(S2c)) x (r^2), i.e. assuming perfect position reconstruction. We assume all other components to be uniform in r^2. Whilst a little overly optimistic, this is more realistic than assuming no attempts to include r^2 in the likelihood





– What we’re *not* doing here

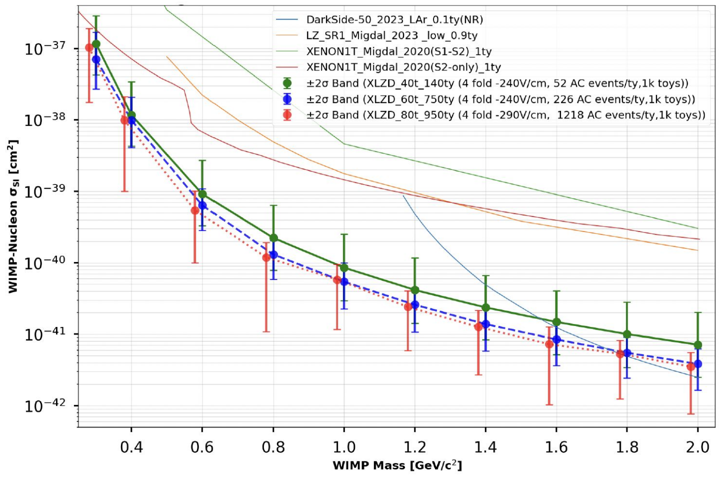
- These studies are primarily focussed on higher mass (> 20 GeV) WIMP-like signals

- We are **not** including an accidentals model
- We are **not** studying efficiency near threshold
- We are **not** considering low energy Xe microphysics uncertainties
- We assume a **4-fold coincidence** requirement in these studies

- Good progress has been made on incorporating an empirical accidentals model (Tina Pollmann, Pranati Kharbanda) into the workflow used here, for low mass WIMP (Migdal) studies

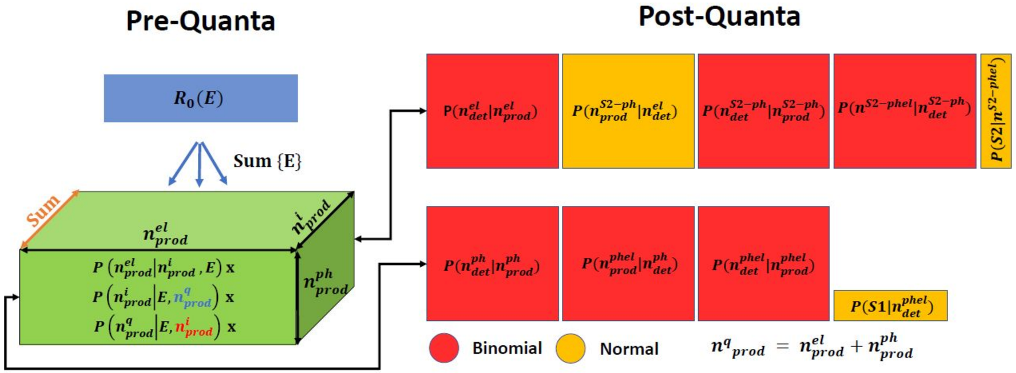
- Should aim to repeat/extend some of the studies here with this incorporated, following this meeting

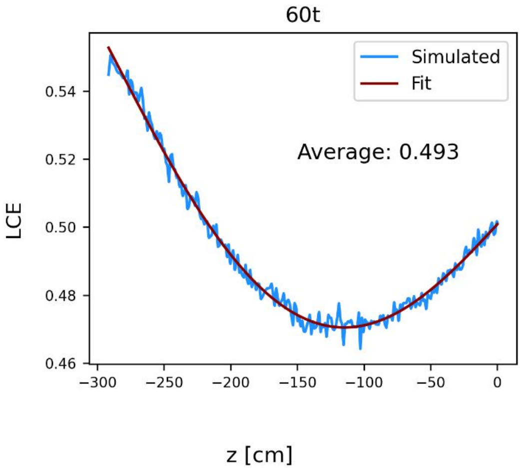
See poster by Federica Pompa et al.



Simulation: BACCARAT + FlameNEST

- Here, we use **FlameNEST** (spoken about at length at previous XLZD meetings) as a **simulator** for MC template generation (for the scope of these studies, this was all we needed)
- All detector-related parameters are input in a NEST-like way (v2.2.2, LZ-like), the exception being light collection efficiency (LCE), which was derived from BACCARAT simulation (Theresa Fruth)
- As such, certain aspects of these studies/requirements are very high-level

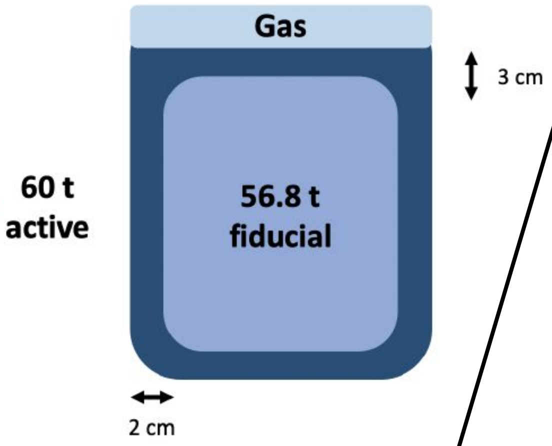




– Fixed parameters

Detector geometry

"Nominal" 60t XLZD design (BACCART config, FlameNEST config)



***Note:** in some of our later studies, we will vary this as an effective control on light collection efficiency*

Detector parameters

Parameter	Value used
PMT QE	0.31
Temperature [K]	174.1
Pressure [bar]	1.79
Number of PMTs	902
PMT DPE probability	0.2
Coincidence level	3
$g1_{gas}$ [phd]	0.1
S2 Fano	2
S2 threshold [phe]	198
SPE resolution [phe]	0.38
SPE threshold [phe]	0.375
SPE efficiency	1

– Versioning etc.

- Keeping careful track of fixed and varied detector parameters throughout these studies was key: requirements taskforce made an effort to do this via .yaml config files in a sharedsd repository (fogtask)

- Template generation via FLAMEDISX/FlameNEST

- Outputs files that can be used for inference via both alea (public code from XENON) and FlameFitSimple (public version of code from LZ)

- If you see a plot from us and wish to check what the parameters were, you can check here!

- Inference config files in both repositories allow for reliable reproduction of results

robertsjames Parameter values for final LNGS meeting plots.

167 lines (164 loc) · 3.92 KB

Code Blame

```
# Detector parameters
parameters:
  # Parameters varied for initial studies
  drift_field:
    value: 80.
    range:
      - 25.
      - 50.
      - 80.
      - 100.
      - 300.
    unit: V/cm
    definition: average drift field in liquid
  gas_field:
    value: 6.
    range:
      - 6.
      - 6.75
      - 7.5
    unit: kV/cm
    definition: extraction field in gas
  PMT_quantum_efficiency:
    value: 0.37
    range:
      - 0.25
      - 0.31
      - 0.37
    unit: PMT hit / photon
    definition: probability of an incident photon to cause a PMT hit
  electron_livetime:
```

Inference approach

- Nothing unfamiliar: profile likelihood ratio (PLR) approach, using $\tilde{t}_\mu$ (sensitivity/exclusion)and q_0 (discovery) test statistics

- We assume 1st order asymptotic distributions of the test statistics, and O(1000) toy MC datasets for evaluating median sensitivity and discovery significances

- Commonality with tools current in use within both XENONnt and LZ: should enable easy adoption for extensions of these XLZD studies

Performance direction: site

Approach to siting in these studies

- The **only** difference we consider here between sites is a scaling of the atmospheric neutrino flux
- We do **not** consider logistical/operational/funding issues, or differences in e.g. cavern gammas (c.f. Monday's discussions)

LNGS:

Using flux calculation from FLUKA, as recommended in DMDD white paper

SURF (≈ SURF/Boulby/SNOLAB):

Approximately scaling the LNGS flux using the table below, without change in shape (to be improved)

Site	Solar max flux ((m^2 sec sr GeV)^-1)						Solar min flux ((m^2 sec sr GeV)^-1)					
	NuMu	NuMubar	NuE	NuEbar	Total	Ratio to JUNO	NuMu	NuMubar	NuE	NuEbar	Total	Ratio to JUNO
Kamioka	7.43E+03	7.56E+03	3.54E+03	3.55E+03	2.21E+04	1.28	8.00E+03	8.14E+03	3.84E+03	3.80E+03	2.38E+04	1.29
LNGS	1.04E+04	1.06E+04	4.98E+03	4.93E+03	3.09E+04	1.79	1.15E+04	1.17E+04	5.54E+03	5.40E+03	3.41E+04	1.86
SNOLAB	1.42E+04	1.44E+04	6.90E+03	6.58E+03	4.21E+04	2.44	1.68E+04	1.70E+04	8.30E+03	7.65E+03	4.98E+04	2.71
SURF	1.41E+04	1.43E+04	6.86E+03	6.57E+03	4.19E+04	2.43	1.67E+04	1.69E+04	8.22E+03	7.61E+03	4.94E+04	2.69
JUNO	5.79E+03	5.90E+03	2.77E+03	2.77E+03	1.72E+04	1.00	6.18E+03	6.29E+03	2.98E+03	2.94E+03	1.84E+04	1.00

Performance direction: background rates

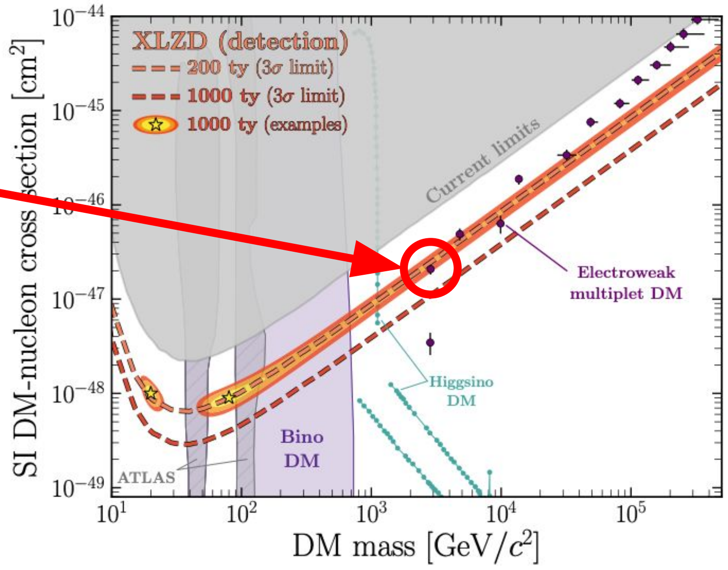
Overview

- In these (first pass) studies, we treat requirements on background levels and detector parameters in a somewhat independent way

- Following a number of earlier studies, and much hard work already done for DARWIN R&D, our approach has been
    - Propose a set of requirements following earlier studies
    - For fixed set of “nominal” detector parameters: propose requirements on background levels, study the effects of their variation
    - For those requirements on background levels, study different combinations of detector parameters that could achieve ~the same level of ER/NR discrimination. Quantify the impact of not meeting this level of discrimination, at this level of background

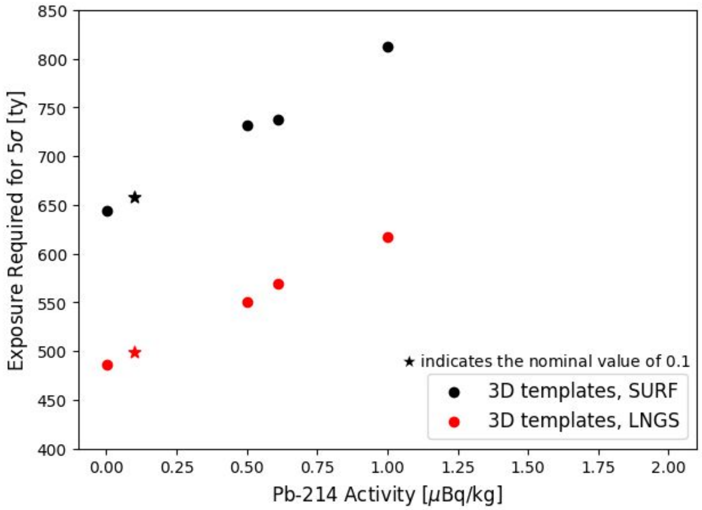
A benchmark metric

- **Question:** in difference performance scenarios, what exposure is needed to reach 5σ discovery potential of benchmark WIMP model?
  - $m_\chi = 2827$ GeV, $\sigma = 2.05\times10^{-47}$ cm^2
- **Methodology**
  - 5000 toys run at each exposure,
  - Discovery significance bands calculated at each exposure from toys
  - Determine crossing point of median significance at 5σ

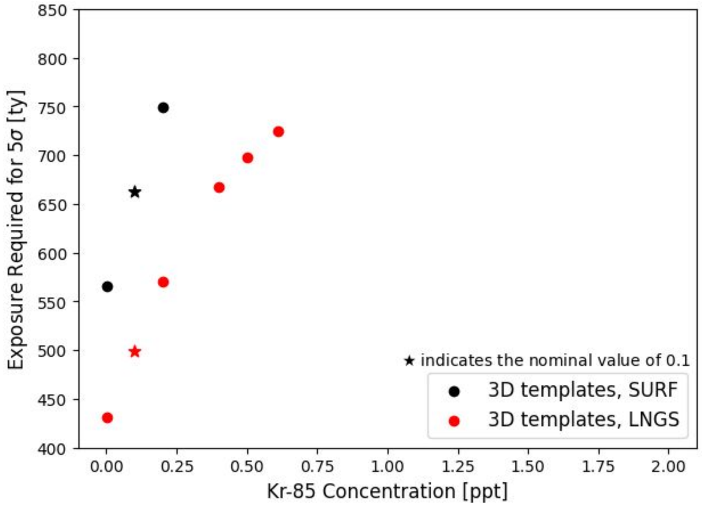


Pb214/Kr85 concentration

Pb214

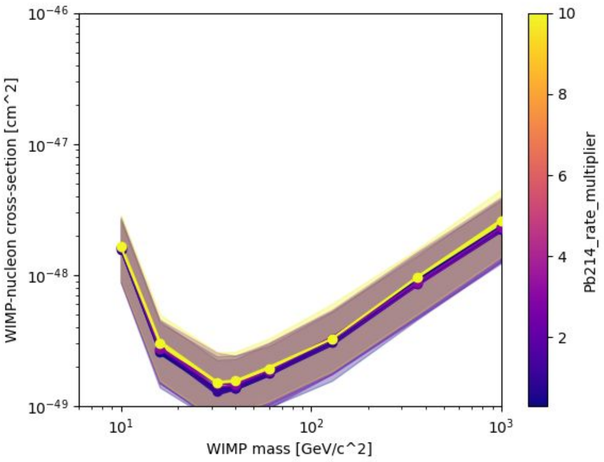


Kr85



- We propose a requirements of
  - **Pb214 concentration @ 0.1 μBq / kg** (same as DARWIN nominal)
  - **Kr85 concentration @ 0.1 ppt** (same as DARWIN nominal)
- Leads to a (median) 5σ discovery significance of benchmark model in reasonable levels of exposure, for both SURF and LNGS

– Pb214 concentration



With the working point chosen, Pb214 is subleading to neutrino-ER interactions

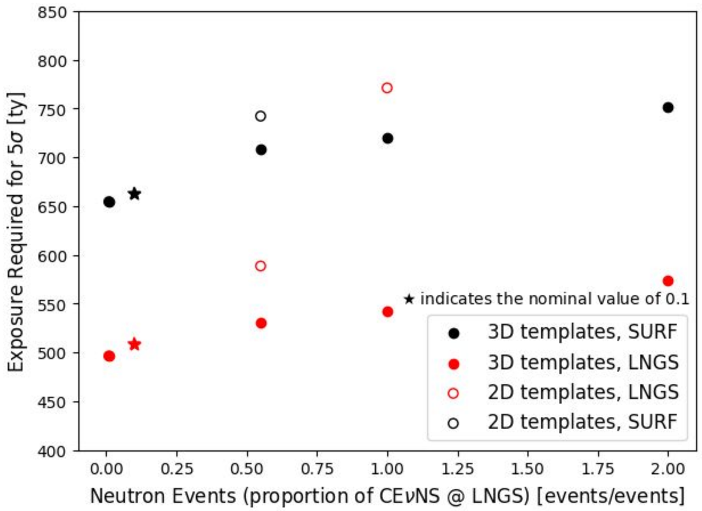
$M_{\mathrm{WIMP}} = 10\mathrm{GeV}/c^2$ ^{214}Pb activity [μ Bq/kg]	Exposure = 600 ty Median Upper limit
0.03	$1.57^{+0.08}_{-0.05} \times 10^{-48}$ cm^2
0.10	$1.63^{+0.07}_{-0.06} \times 10^{-48}$ cm^2
0.30	$1.64^{+0.07}_{-0.10} \times 10^{-48}$ cm^2
1.00	$1.65^{+0.07}_{-0.05} \times 10^{-48}$ cm^2
$M_{\mathrm{WIMP}} = 1000\mathrm{GeV}/c^2$ ^{214}Pb activity [μ Bq/kg]	Exposure = 600 ty Median Upper limit
0.03	$2.36^{+0.06}_{-0.10} \times 10^{-48}$ cm^2
0.10	$2.24^{+0.11}_{-0.07} \times 10^{-48}$ cm^2
0.30	$2.30^{+0.05}_{-0.09} \times 10^{-48}$ cm^2
1.00	$2.59^{+0.11}_{-0.10} \times 10^{-48}$ cm^2

– Neutron rate

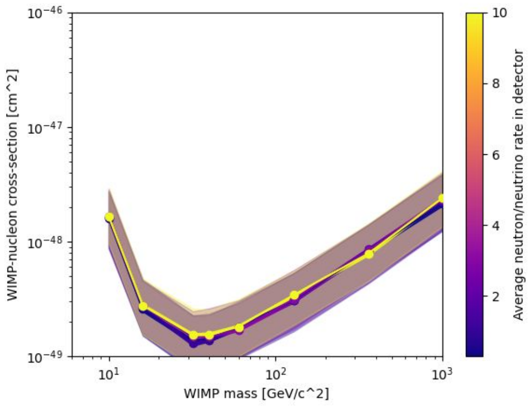
- We propose a requirement on neutron rate in the fiducial volume: **10% of atmospheric + DSNB CEvNS**
  - Leads to a (median) 5σ discovery significance of benchmark model in reasonable levels of exposure, for both SURF and LNGS

- At this level, we find very little difference in inference results between 3D [(S1c, log10(S2c)) x (r^2)] and 2D [(S1c, log10(S2c))]

- It is clear that at higher neutron rates, our ability to resolve radial position becomes more critical



– Neutron rate



Including r^2 as an analysis dimension reduces the neutron impact immensely

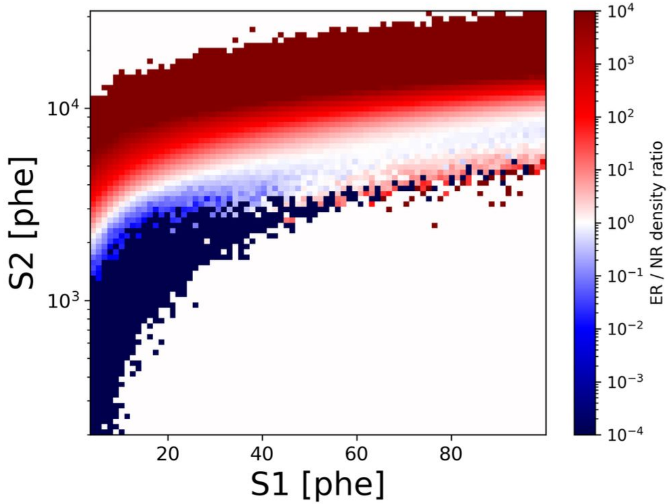
Neutron expectation relative to CR ν	Median Upper limit
0.30	$1.60^{+0.04}_{-0.07} \times 10^{-48}$ cm^2
1.00	$1.63^{+0.07}_{-0.06} \times 10^{-48}$ cm^2
3.00	$1.66^{+0.08}_{-0.08} \times 10^{-48}$ cm^2
10.00	$1.66^{+0.05}_{-0.06} \times 10^{-48}$ cm^2

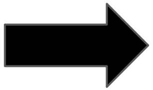
$M_{\mathrm{WIMP}} = 1000\mathrm{GeV}/c^2$ Neutron expectation relative to CR ν	Exposure = 600 ty Median Upper limit
0.30	$2.16^{+0.10}_{-0.10} \times 10^{-48}$ cm^2
1.00	$2.24^{+0.11}_{-0.08} \times 10^{-48}$ cm^2
3.00	$2.31^{+0.13}_{-0.07} \times 10^{-48}$ cm^2
10.00	$2.38^{+0.06}_{-0.09} \times 10^{-48}$ cm^2

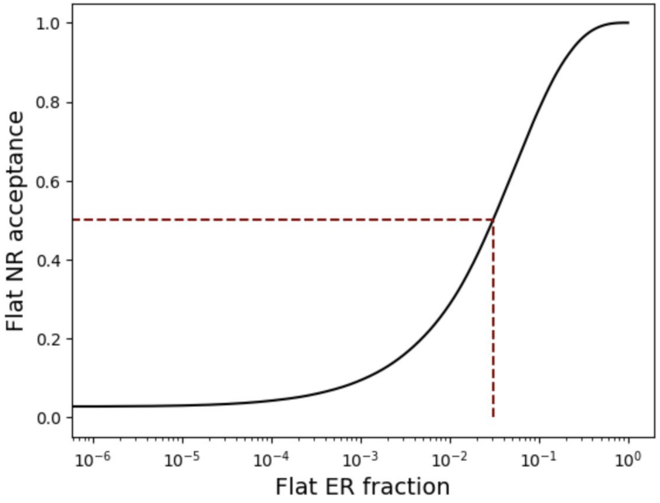
Performance direction: ER/NR discrimination

Methodology

- We focus primarily here on ER/NR discrimination
- For different detector parameters, we calculate this using flat ER and NR bands, computing the ER fraction @ 50% NR acceptance using 2D ROC curves in (S1, S2) (via likelihood ratio ordering)

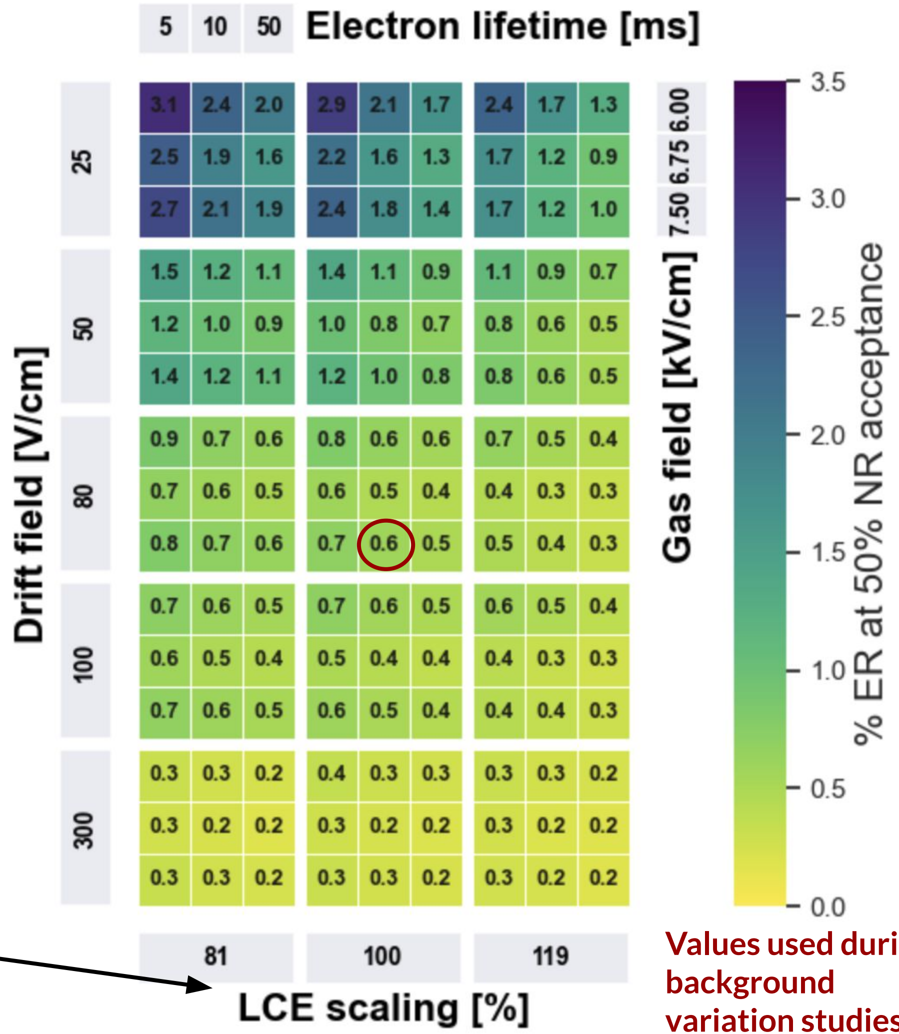






– Detector parameter scan

- Clear that we have a 'cliff' in drift field
- Lot of freedom in how we choose the other parameters, but many implications for their values beyond these studies
- Let's explore how this grid maps onto our time-to-discovery metric: 1st order approach, vary only drift field as a dial on leakage

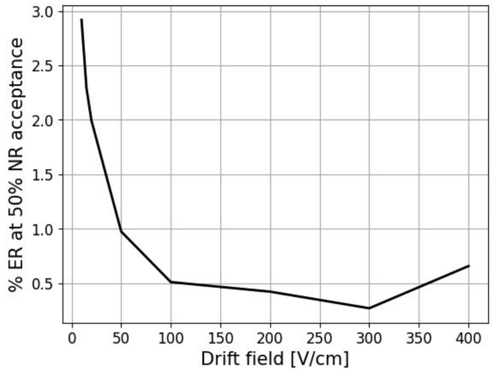


Relative to that calculated via BACCARAT simulation (c.f. slide 10)

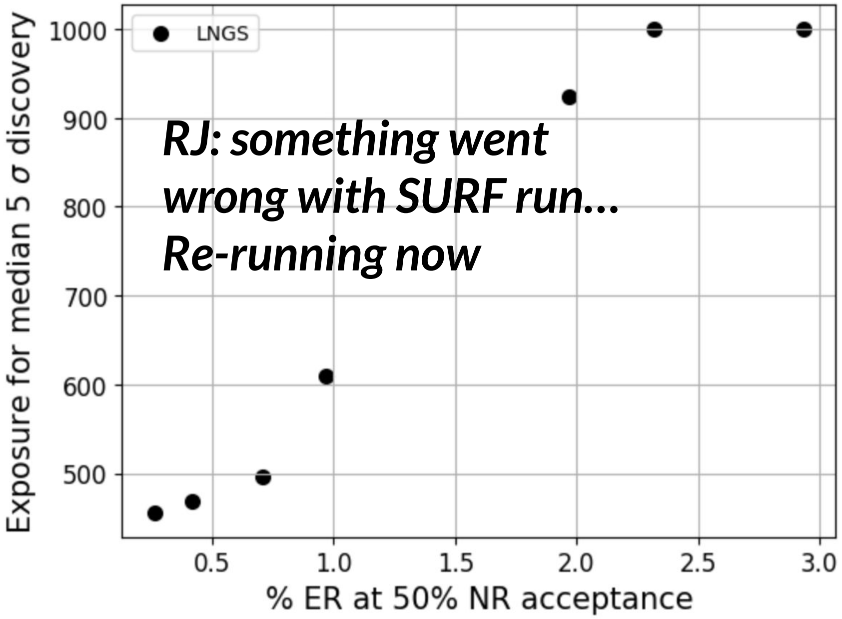
Values used during background variation studies

Detector parameter scan

Fixed: 100% LCE, 7.5 kV/cm gas field, 10 ms electron lifetime



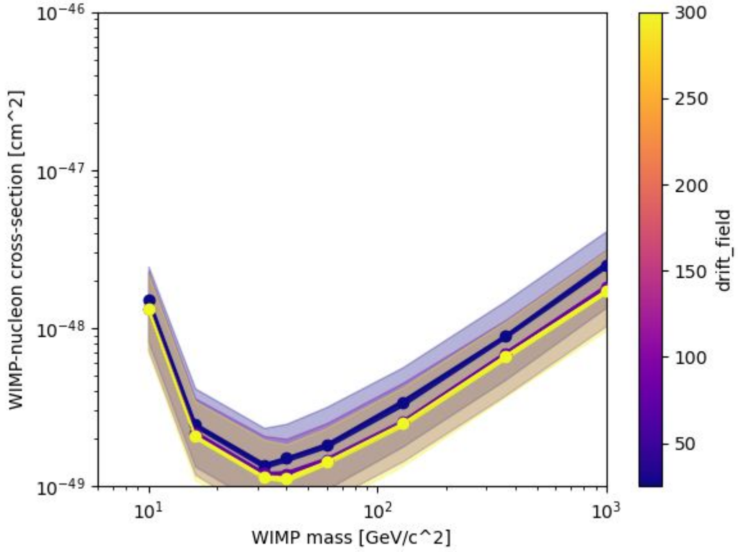
- We propose a requirement on **leakage** to be **0.5% ER at 50% NR acceptance**
- Going back to the grid, clear that this should correspond to a requirement on **drift field ≥ 80 V/cm**



Sensitivity vs. drift field

Similar story in terms of sensitivity: 3 scans over drift field indicates a significant reduction in performance for 25 V/cm, but little improvement above 80 V/cm

As is the case for most parameter variations considered here, more obvious impact in terms of discovery than sensitivity



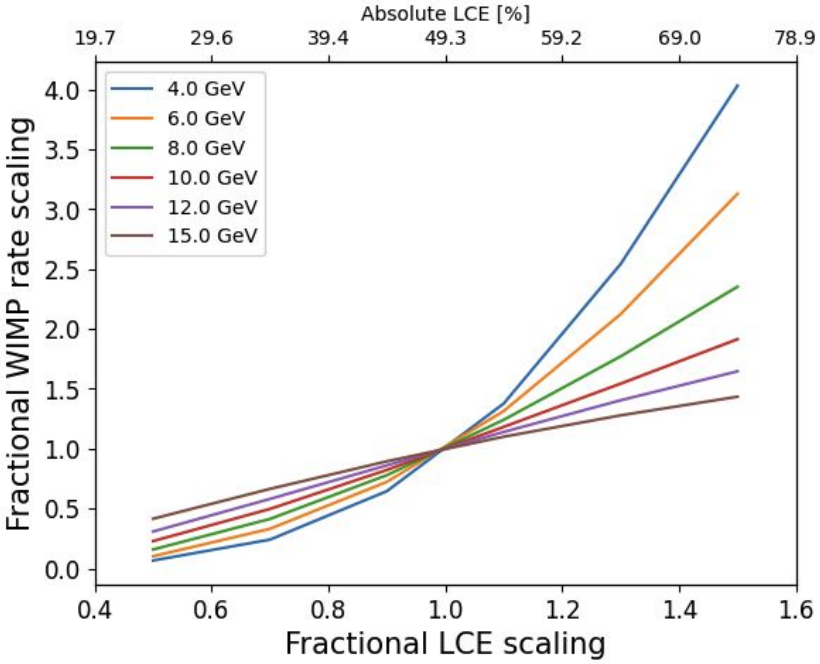
$M_{\mathrm{WIMP}} = 10\mathrm{GeV}/c^2$ Drift Field [V/cm]	Exposure = 600 ty Median Upper limit
25.00	$1.52^{+0.06}_{-0.06} \times 10^{-48}$ cm^2
80.00	$1.32^{+0.06}_{-0.03} \times 10^{-48}$ cm^2
300.00	$1.32^{+0.03}_{-0.05} \times 10^{-48}$ cm^2
$M_{\mathrm{WIMP}} = 1000\mathrm{GeV}/c^2$ Drift Field [V/cm]	Exposure = 600 ty Median Upper limit
25.00	$2.50^{+0.12}_{-0.08} \times 10^{-48}$ cm^2
80.00	$1.80^{+0.09}_{-0.06} \times 10^{-48}$ cm^2
300.00	$1.72^{+0.03}_{-0.05} \times 10^{-48}$ cm^2

What about threshold?

- Remember, we have **not** yet done complete/mature studies on low mass WIMP sensitivity (accidentals model + threshold effects)

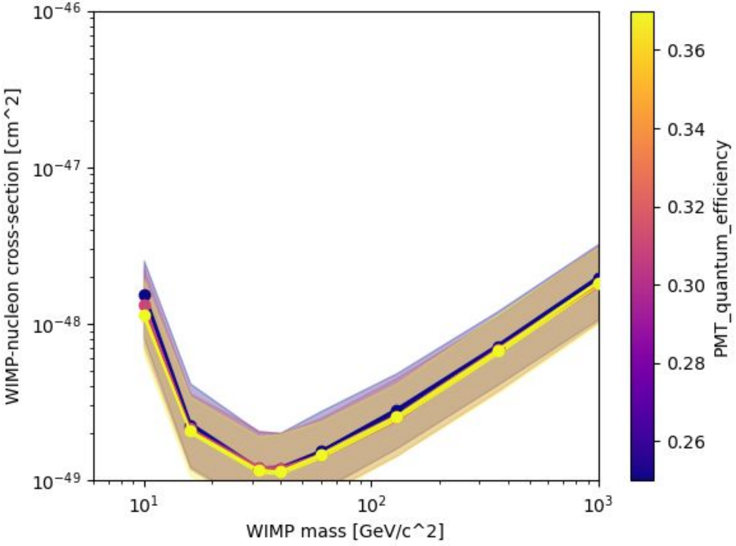
- LCE has a strong effect on threshold. For now, quickly check this impact in terms of **WIMP rates at different masses and LCEs**

- Clearly we should aim for **as high an LCE as possible**. We propose a **requirement of 50%** (semi-optimistic prediction from simulation), and a **goal of 60%**



What about threshold?

At 10 GeV, we get a 40% difference between an 80% and 120% LCE (vs. simulation prediction) - here, mapped via a scaling of the effective PMT QE from the nominal value of 0.31



$M_{\mathrm{WIMP}} = 10\mathrm{GeV}/c^2$ PMT QE	Exposure = 600 ty Median Upper limit
0.25	$1.55^{+0.06}_{-0.04} \times 10^{-48}\ \mathrm{cm}^2$
0.31	$1.32^{+0.06}_{-0.03} \times 10^{-48}\ \mathrm{cm}^2$
0.37	$1.13^{+0.06}_{-0.04} \times 10^{-48}\ \mathrm{cm}^2$
$M_{\mathrm{WIMP}} = 1000\mathrm{GeV}/c^2$ PMT QE	Exposure = 600 ty Median Upper limit
0.25	$1.96^{+0.09}_{-0.09} \times 10^{-48}\ \mathrm{cm}^2$
0.31	$1.80^{+0.10}_{-0.05} \times 10^{-48}\ \mathrm{cm}^2$
0.37	$1.83^{+0.07}_{-0.06} \times 10^{-48}\ \mathrm{cm}^2$

Summary and recommendations

- We propose a requirement on **leakage**: **0.5% ER at 50% NR acceptance**

- In order to achieve this, we propose a further requirement on **drift field**: **≥ 80 V/cm**

- We note the freedom in multiple combinations of LCE, electron lifetime and gas field that could achieve the leakage requirement at this field. We propose a detector design with **as high a LCE as is achievable**, with a requirement of **at least 50%**

- For these field and LCE values, it is clear that a number of combinations of **electron lifetime** (**≥10 ms**) and **gas field** (**≥ 6.75 kV/cm**) could meet the leakage requirement. Further studies here are needed before setting precise requirements (e.g. grid voltages → accidentals rate)

For now

- For the purposes of the following projected sensitivity/discovery plots, we use the following values
  - Drift field: 80 V/cm
  - LCE: 120% of that coming from optical simulation with current detector geometry i.e. ~60%
  - Electron lifetime: 10 ms
  - Gas field: 6 V/cm

- These correspond to 0.5% ER leakage at 50% NR acceptance (c.f. slide 20)

- This does not map perfectly onto our requirements, which were subject to some last minute revisions, but other than the caveats already given for low mass WIMPs, this **will not affect** the results we show here for higher mass WIMPs

Background counts and corresponding sensitivity at our requirements

Requirements taskforce recommendations

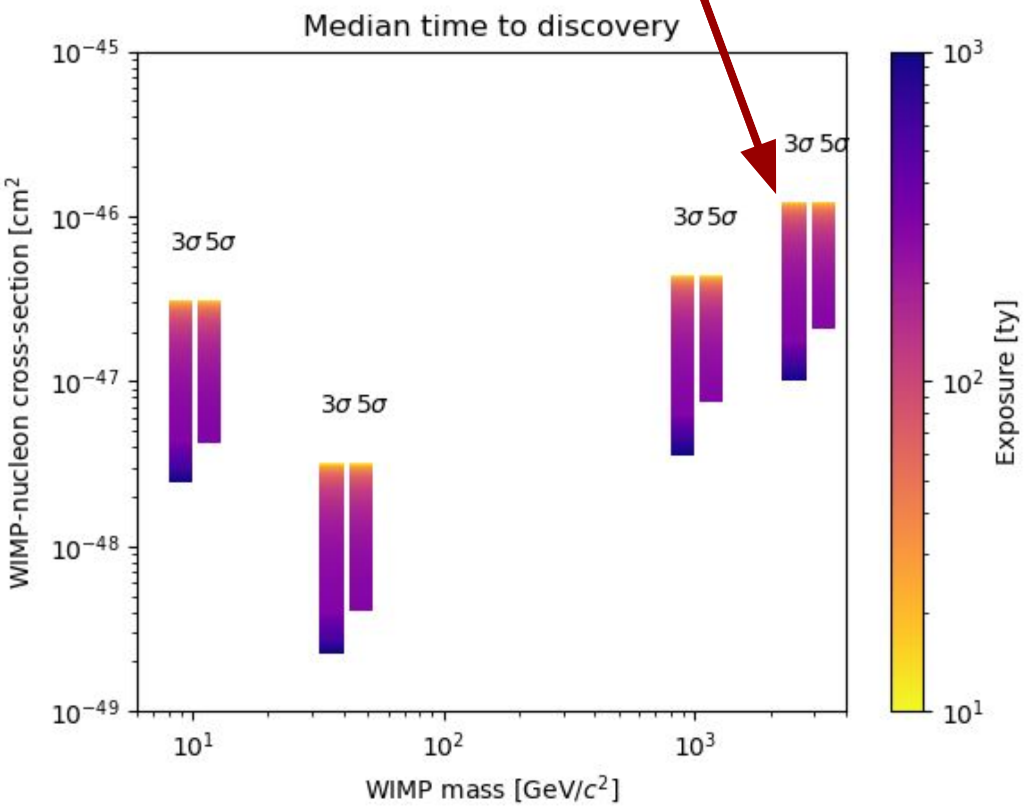
0 < cS1 < 100 phe
2.5 < $\log_{10}$(cS2 [phe]) < 4
4-fold coincidence

Background	**Counts [events / ty]**	**Counts [fraction of solar ν ER]**	**Counts [fraction of atmospheric + DSNB CEvNS @ LNGS, post discrimination @ 50% NR acceptance]**
Pb214	3.9	0.19	0.83
Kr85	17.4	0.84	3.76
Xe136 2vBB	8.2	0.40	1.77
Xe124 2vDEC	3.4	0.17	0.73
Solar neutrino ERs (PP + 7Be + CNO)	20.6	1.00	4.45
CEvNS (B8 + hep)	0.93		20.2
CEvNS (atmospheric + DSNB)	0.046 @ LNGS 0.064 @ SURF		1.00 @ LNGS 1.39 @ SURF
Neutrons	0.0046		0.10

— WIMP discovery potential

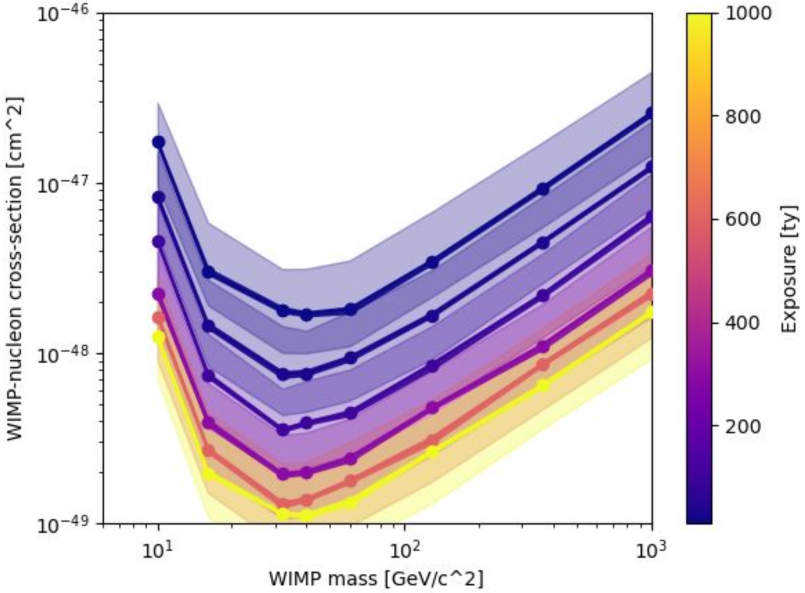
- Median exposure vs. discovery for 3 WIMP masses, indicated with colour scale
- Consider 3σ and 5σ median significance

Our benchmark EW multiplet from before

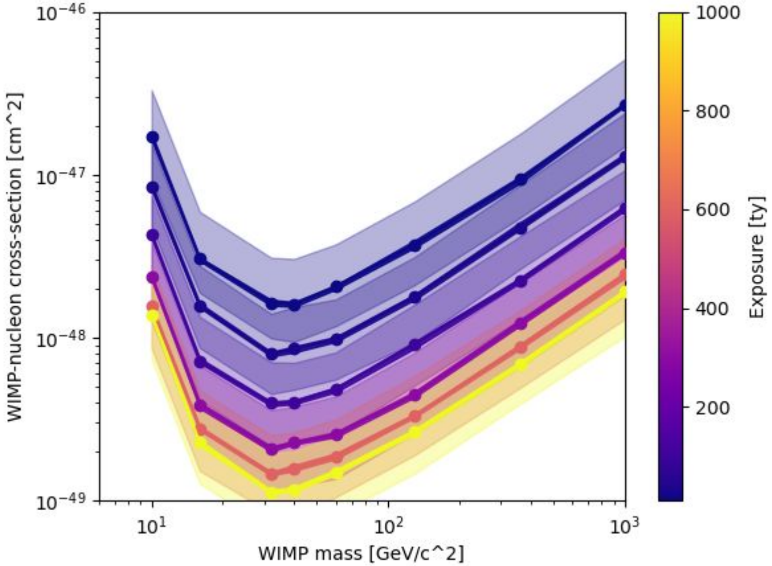


–   WIMP sensitivity

LNGS



SURF

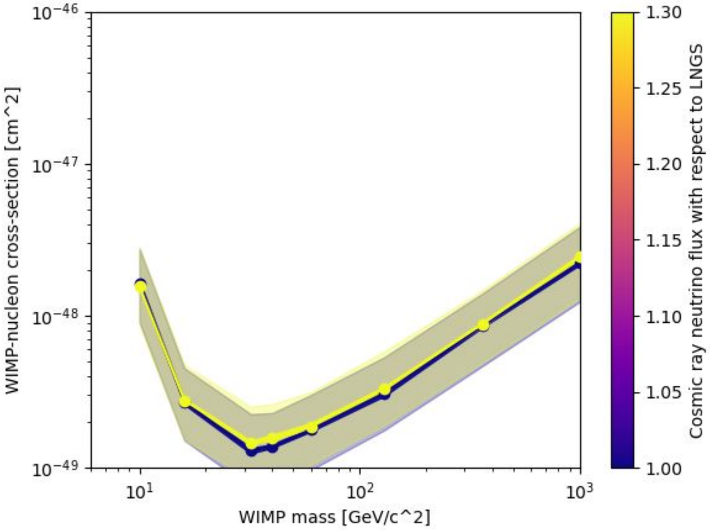


– Atmospheric neutrino flux

- The current scaling approach is quite rough: Dan Tovey has contacted U. Oxford experimentalists to recompute atmospheric neutrino expectations. If there are any spectral differences between sites, it would matter

- Currently greatest impact at medium WIMP masses

- Once again: more obvious impact for discovery than for sensitivity!



$M_{\mathrm{WIMP}} = 10\mathrm{GeV}/c^2$ CR ν flux relative to LNGS	Exposure = 600 ty Median Upper limit
1.00	$1.63^{+0.07}_{-0.06} \times 10^{-48}$ cm^2
1.30	$1.56^{+0.05}_{-0.04} \times 10^{-48}$ cm^2
$M_{\mathrm{WIMP}} = 1000\mathrm{GeV}/c^2$ CR ν flux relative to LNGS	Exposure = 600 ty Median Upper limit
1.00	$2.24^{+0.11}_{-0.08} \times 10^{-48}$ cm^2
1.30	$2.44^{+0.10}_{-0.10} \times 10^{-48}$ cm^2

Corresponding sensitivity to other physics channels

Overview

- Came out of a request to Tina Pollmann + Mark Schumann, to show XLZD sensitivity to a number of other channels, for EPPSU dark matter session
  - O6 EFT operator → **done here**
  - DM-electron scattering with a heavy mediator → not done here; would need dedicated low threshold study
  - DM-electron scattering, where the dark matter is an ALP (not solar axions, ALP as galactic DM component) → **done here**
  - Limits on dark/hidden photons → **done here**

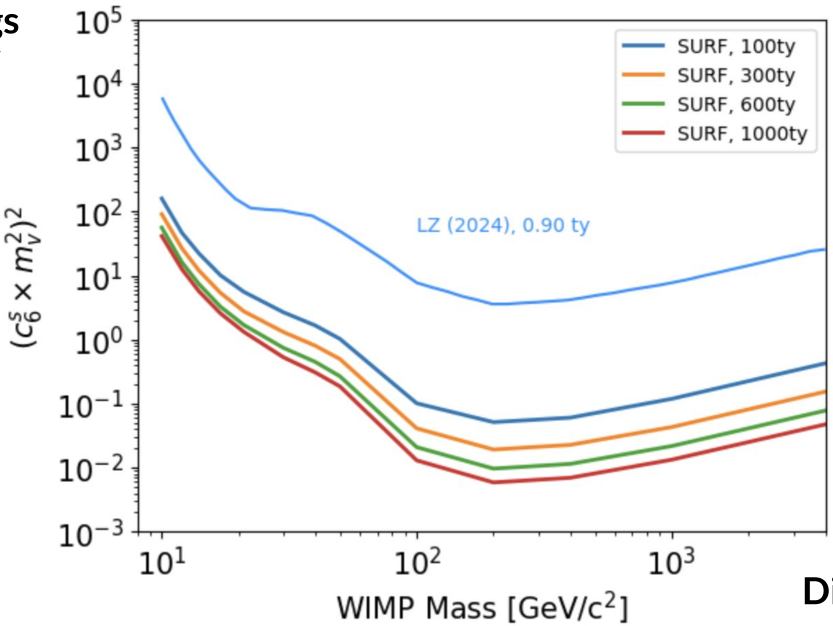
- EFT spectra taken from LZ (isospin representation, Ananad et al.). Same analysis as SI WIMPs: (S1c, log10(S2c)) x (r^2)

- ALP and HPs are mono-energetic signals; rates calculated using wimprates. Analysis in 1D reconstructed energy (CES) space: 0 - 15 keV

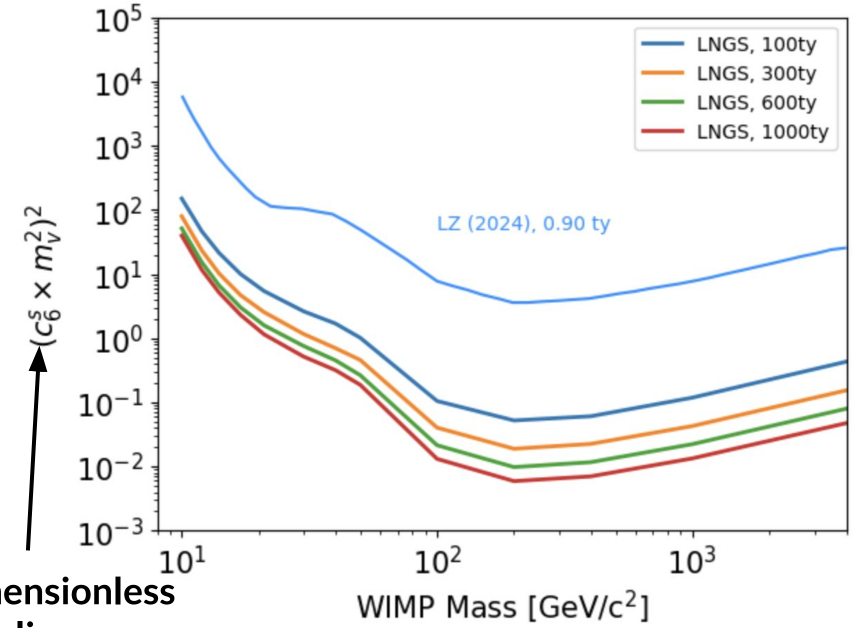
– NREFT sensitivity (O6 scalar operator)

LNGS

Higgs VEV



SURF



Dimensionless coupling

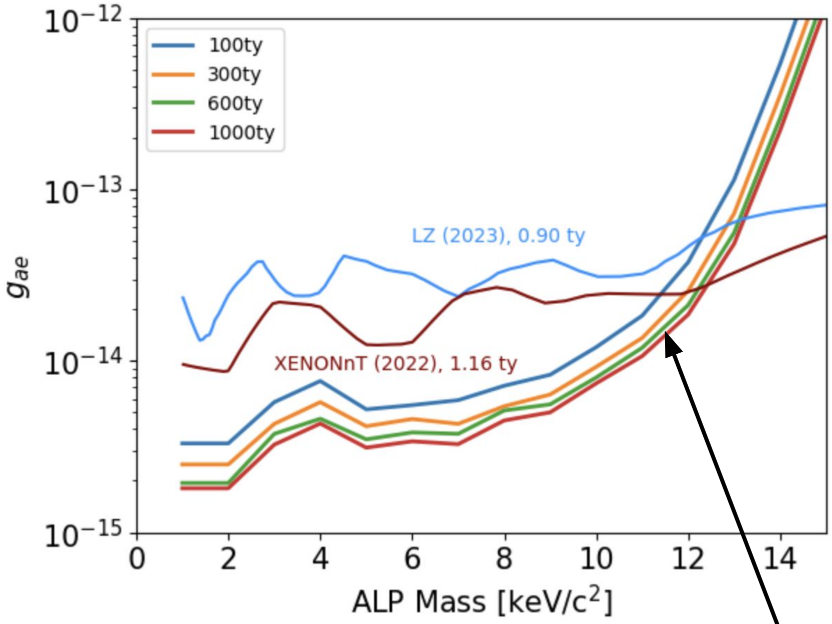
0 < cS1 < 720 phe

2.5 < $\log_{10}$(cS2 [phe]) < 4.4

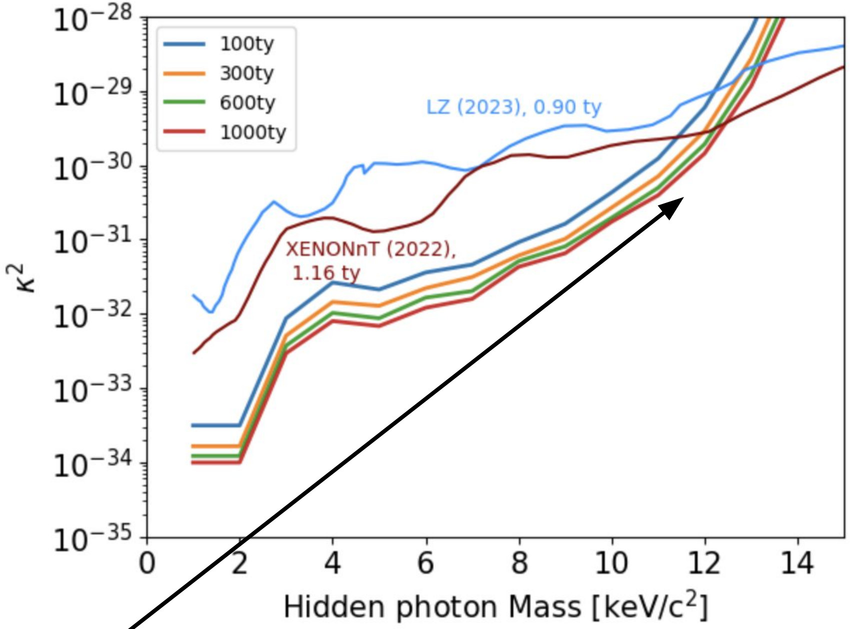
4-fold coincidence

– Mono-energetic ER signal sensitivity

ALPs (as galactic DM)



Dark/hidden photons



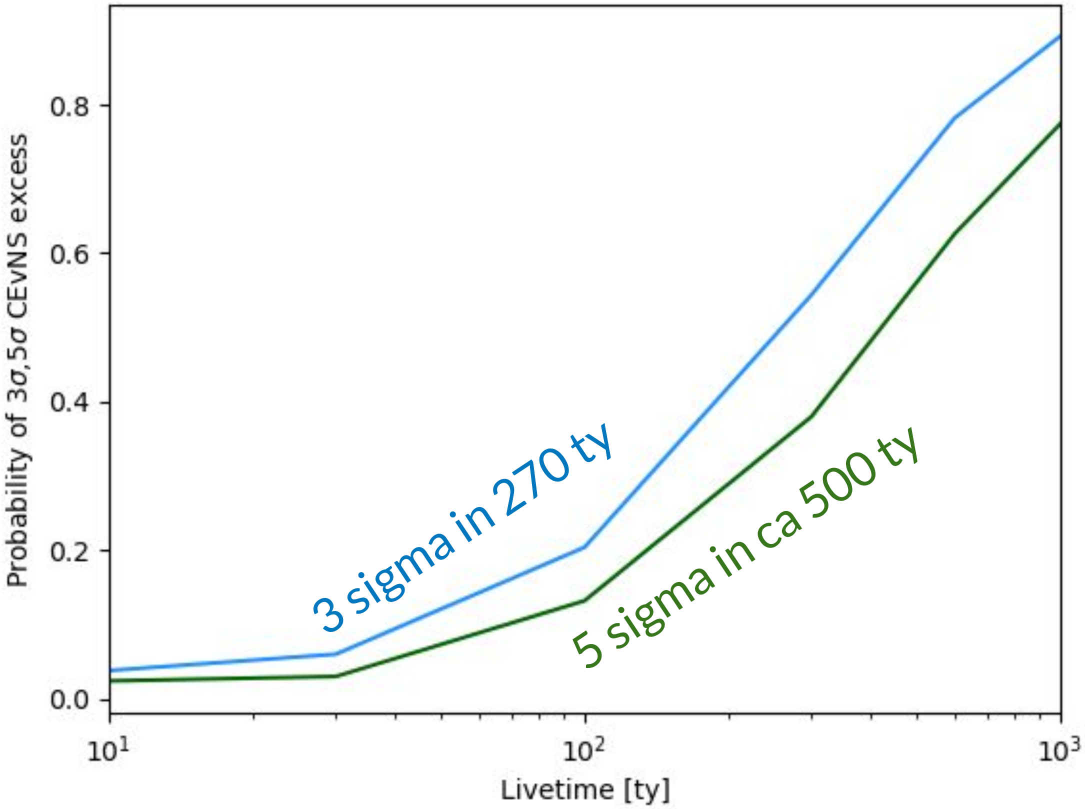
$0 < cS1 < 100$ phe
$3.4 < \log_{10}(cS2\ [phe]) < 4.5$
4-fold coincidence

Need to extend ROI definition

CEvNS as a target

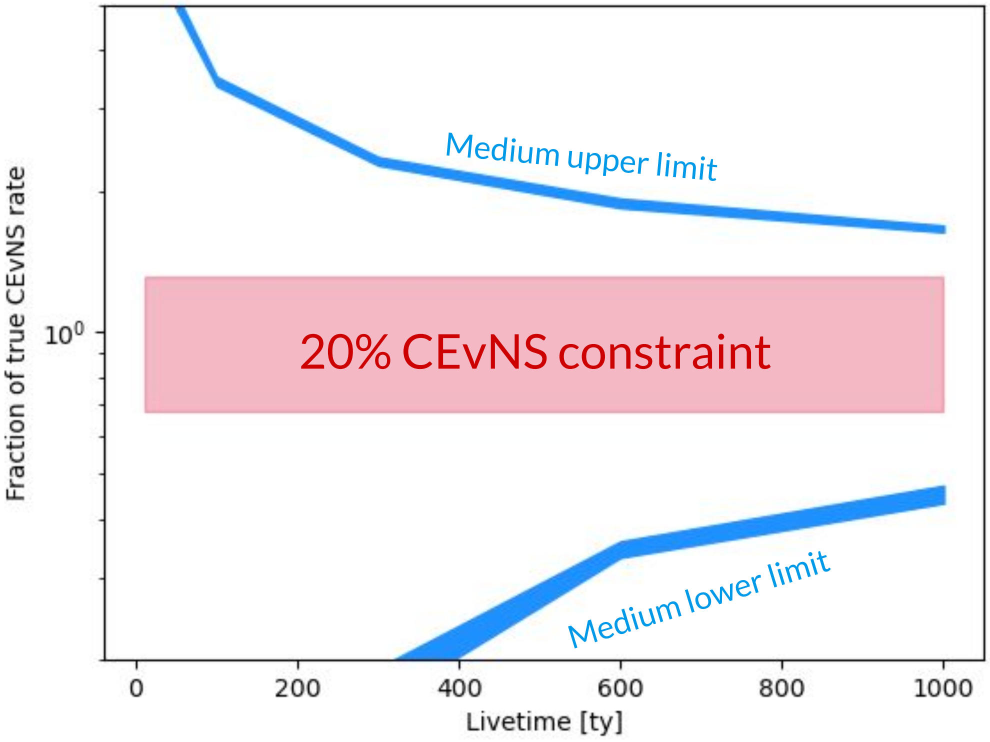
CEvNS discovery

We expect a 3sigma atmospheric excess at ca. 300ty



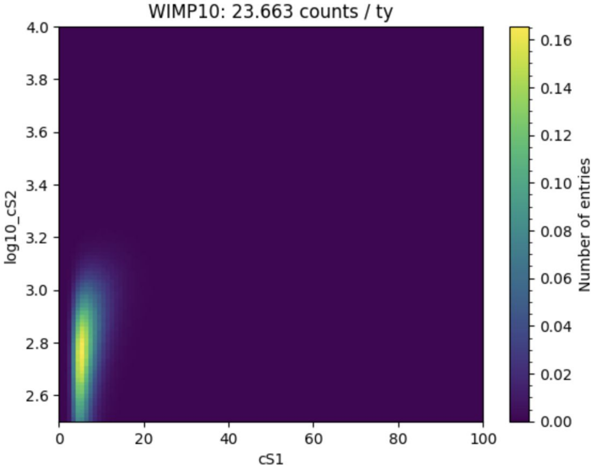
CEvNS measurement

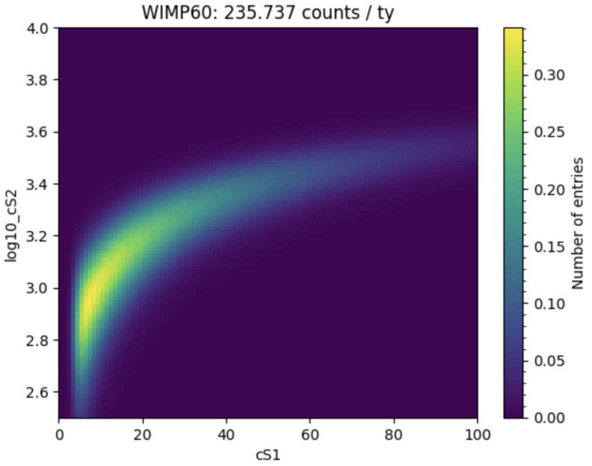
And for our measurement to grow more precise– but not stronger than our ancillary constraint

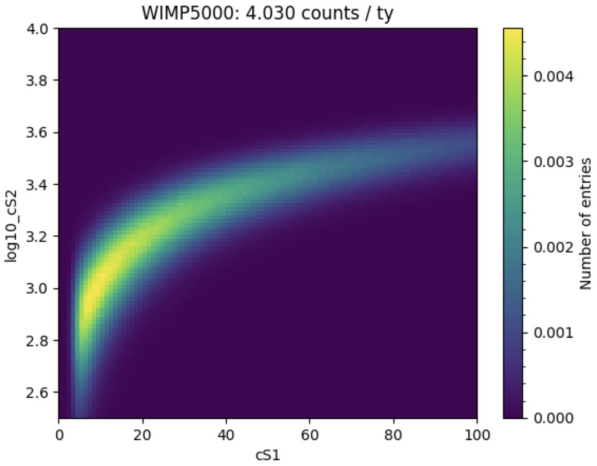


Backup

— SI WIMP template examples







– Kr85 sanity check

b is selected arbitrarily

n = 1.1 x b

σ = √b