Requirements Task Force Report

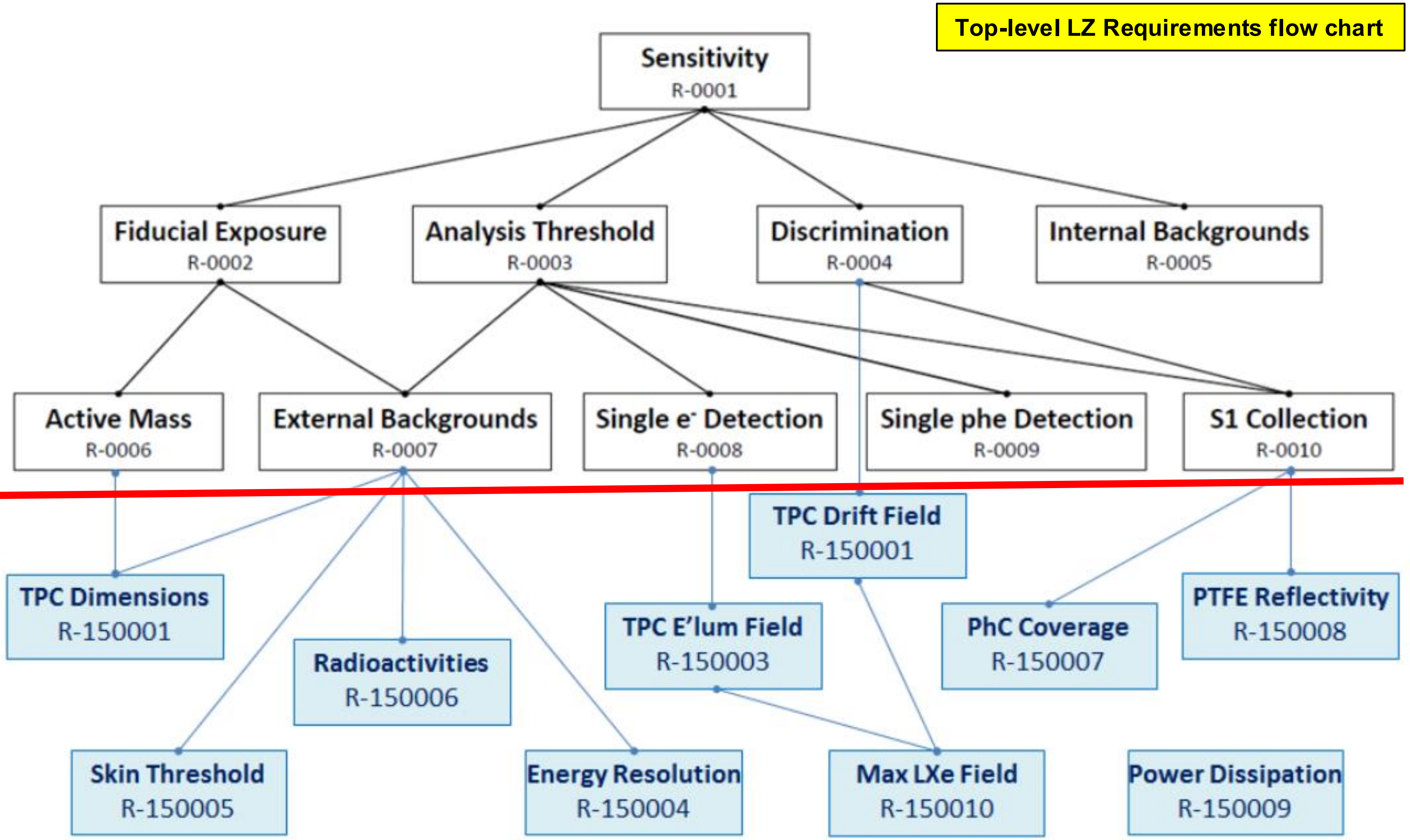
Dan Tovey,

on behalf of the Requirements TF:

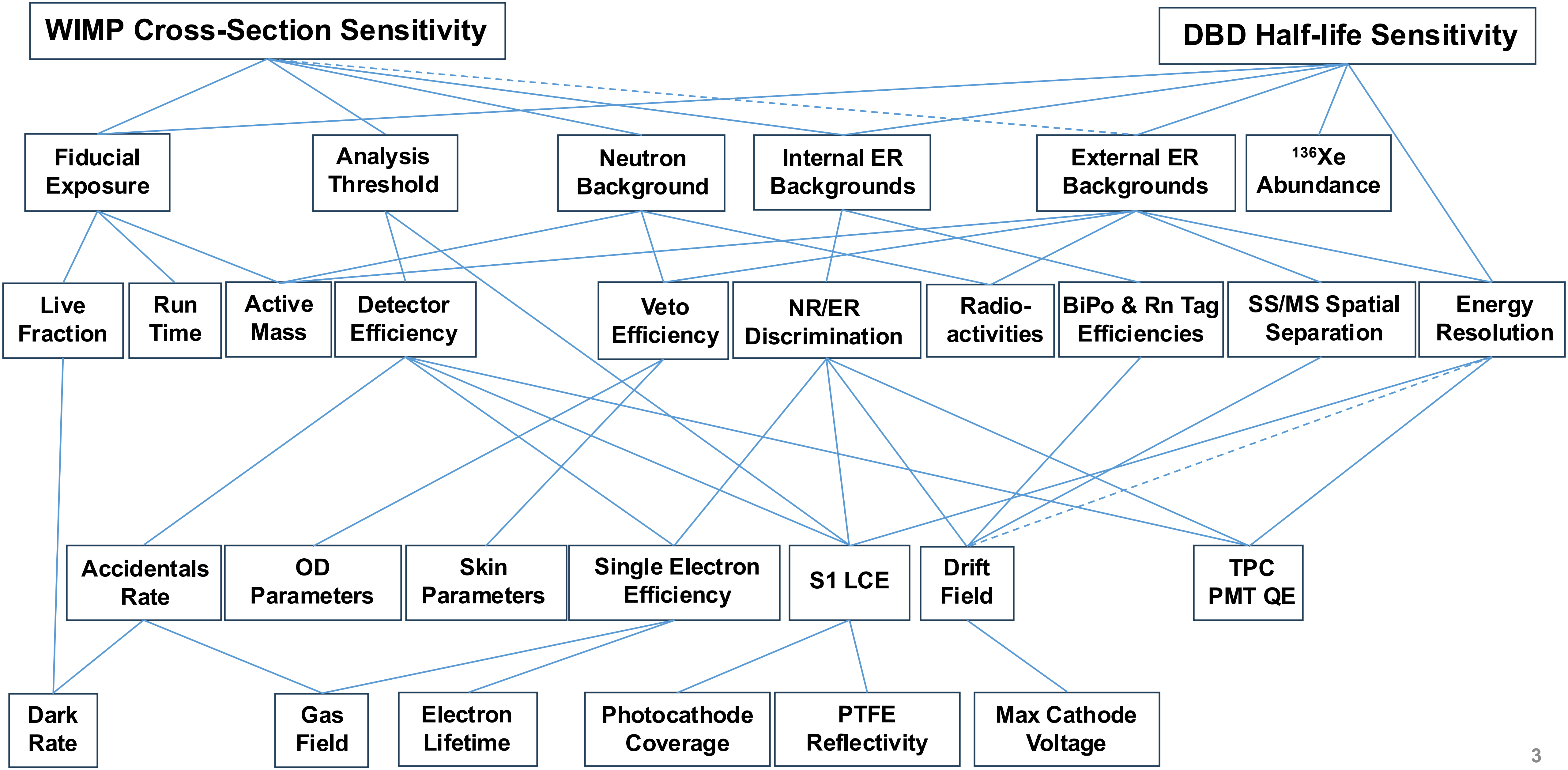
Amy Cottle, Maike Doerenkamp, Rob James, Asher Kaboth, Alvine Kamaha, Alex Lindote, Hugh Lippincott, Teresa Marodan, Rory Matheson, Knut Mora, Jo Orpwood, Tina Pollmann, Marc Schumann

Charge

- The brief is to develop the upper-level requirements for XLZD to capture the science case(s) accurately and flow these down to main experimental parameters (mass, thresholds, background, …) – but excluding the technical requirements that apply to the detector subsystems.
- Define *requirements* but not necessarily *goals*
- Should be ambitious, yet achievable



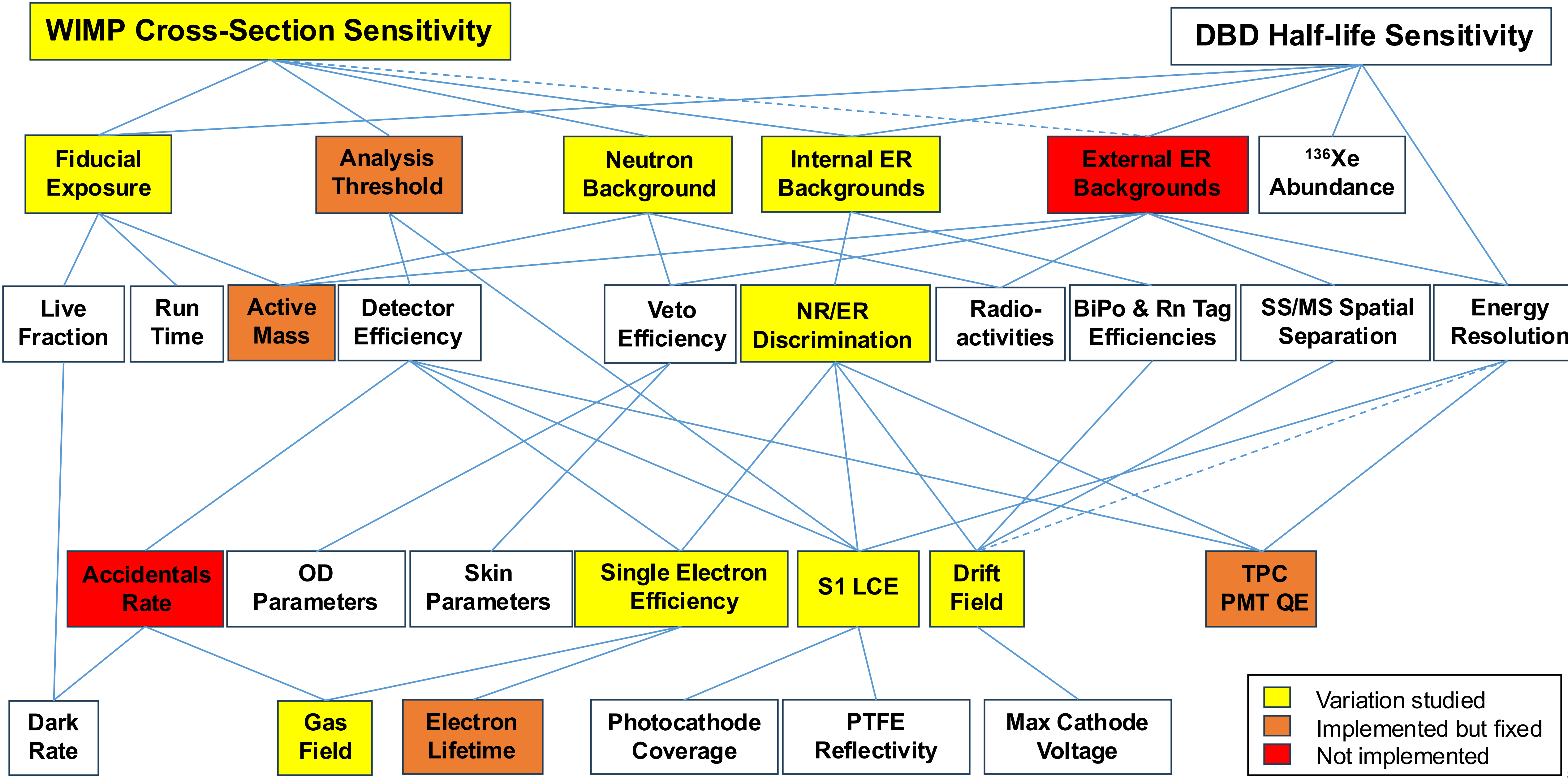
Draft Requirements Flowdown



WIMP Search

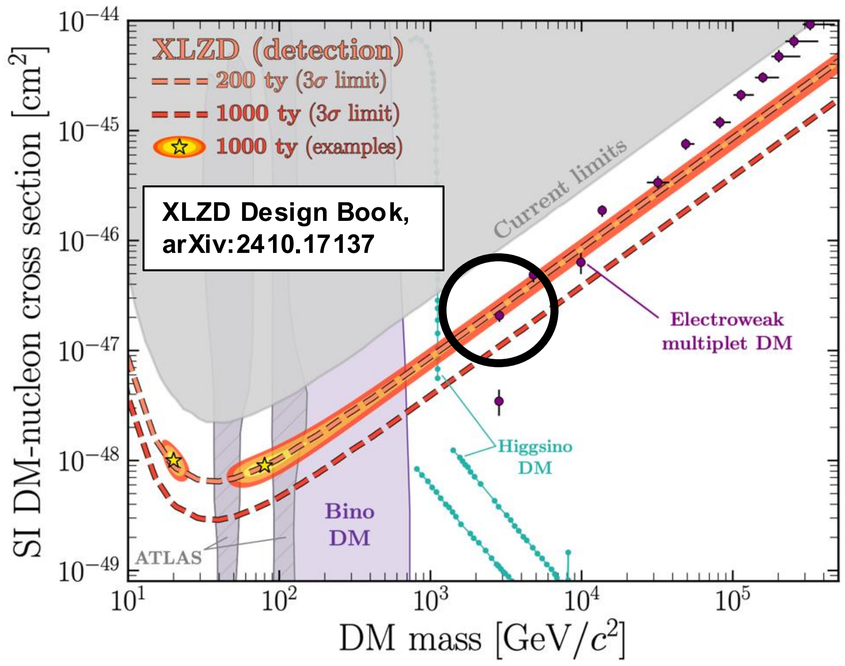
- Focus on observation/discovery at 5 sigma significance of key benchmark WIMP models
- Aim for experiment to be dominated by irreducible 'physics' backgrounds:
  - Neutrino CEvNS (mostly atmospheric, +DSNB) for NR background
  - Solar neutrino (mostly ^{8}B) for ER background
- Implies constraints on dominant reducible backgrounds
  - Neutron induced NR backgrounds → quote as fraction of Neutrino CEvNS rate above threshold
  - ^{214}Pb and ^{85}Kr ER backgrounds (compare also with CEvNS NR rate after ER/NR discrimination)
- Aim to set requirements on performance parameters that avoid 'cliff-edge' degradation
- Requirements coherent (where relevant) with $0\nu\beta\beta$ requirements
- In practice input parameters defined by what can easily be varied in FlameNEST

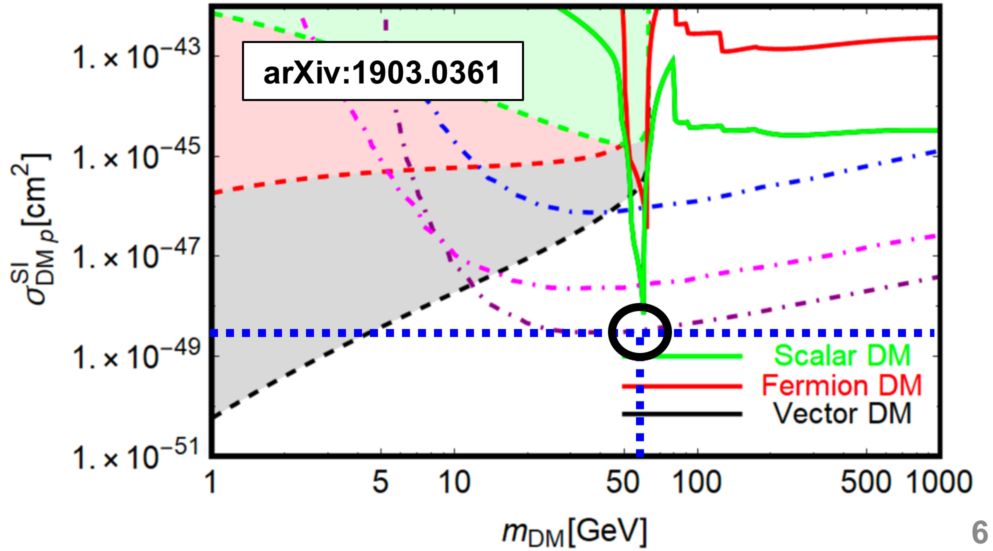
WIMP Search Requirements Flowdown



WIMP Search Science Requirements

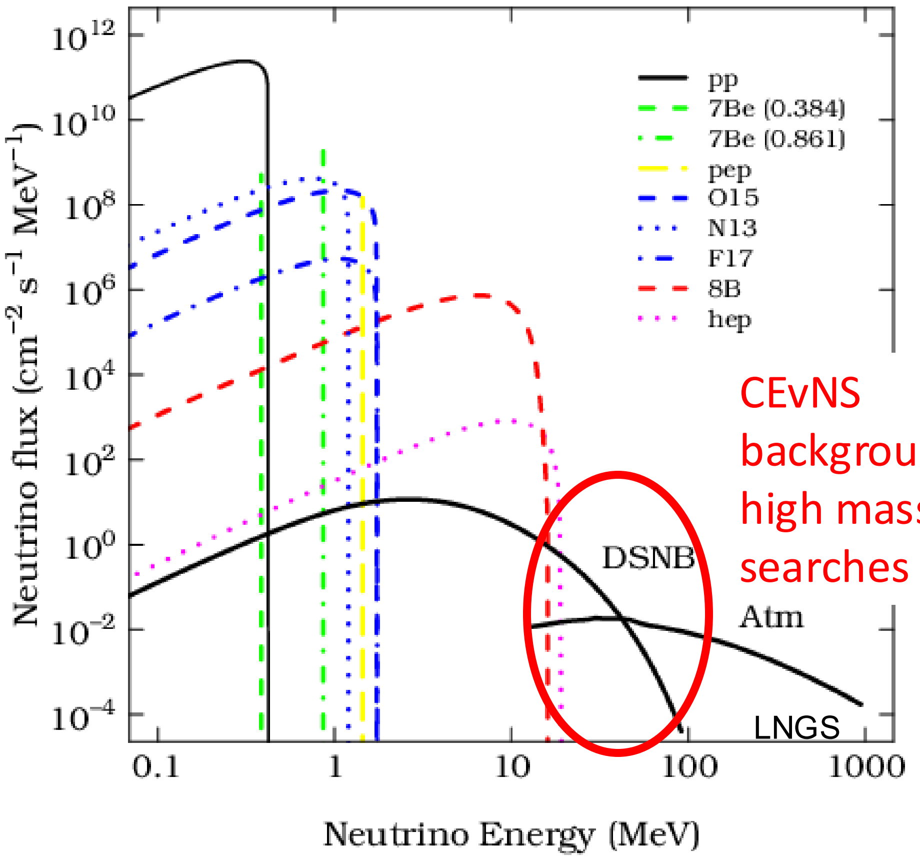
- Possible Requirement: 5σ observation of majorana triplet model with m_χ=2800 GeV, $\sigma \sim 2\times10^{-47}$ cm^2.
  - Rationale: Would allow 5 sigma discovery of many other EW multiplet benchmark points.
  - NB: not all EW multiplet models accessible to XLZD, due to neutrino floor
- Possible Requirement: Exclude at 90% CL model with $\sigma=2\times10^{-49}$ cm^2 and m_χ=60 GeV
  - Rationale: Would exclude majority of Higgs portal DM models. Higgs portal models most challenging at $m_\chi \sim m_H/2 \sim 60$ GeV. Complementary to LHC invisible Higgs searches – these lose sensitivity at ~60 GeV.
  - NB: detailed studies by Arcadi et al. suggest Higgs portal minimum is lower ~6.7×10^{-50} cm^2 . Unlikely to be excludable …
- Aim to study low mass m_χ=10 GeV point, however this requires an accidentals model



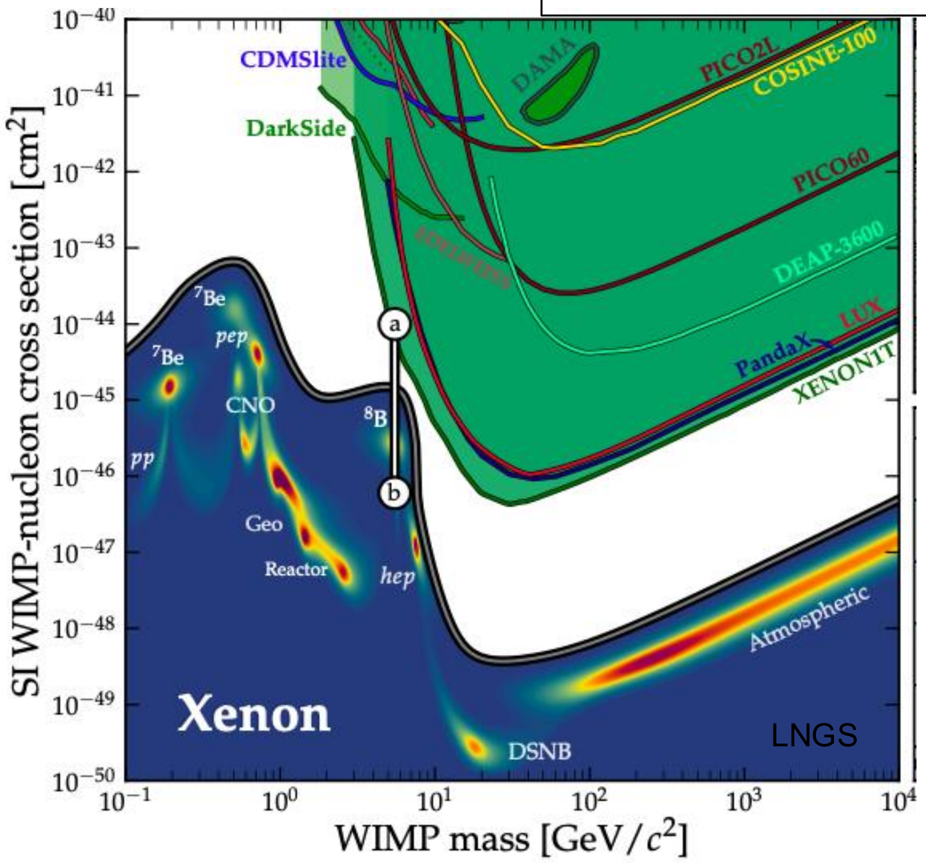


Neutrino CEvNS Background

- Atmospheric neutrino + DSNB CEvNS is likely to be the dominant background to the high mass (m > 40 GeV) WIMP search
- Shape of nuclear recoil energy spectrum is very similar to a high mass WIMP NR signal → ~irreducible background

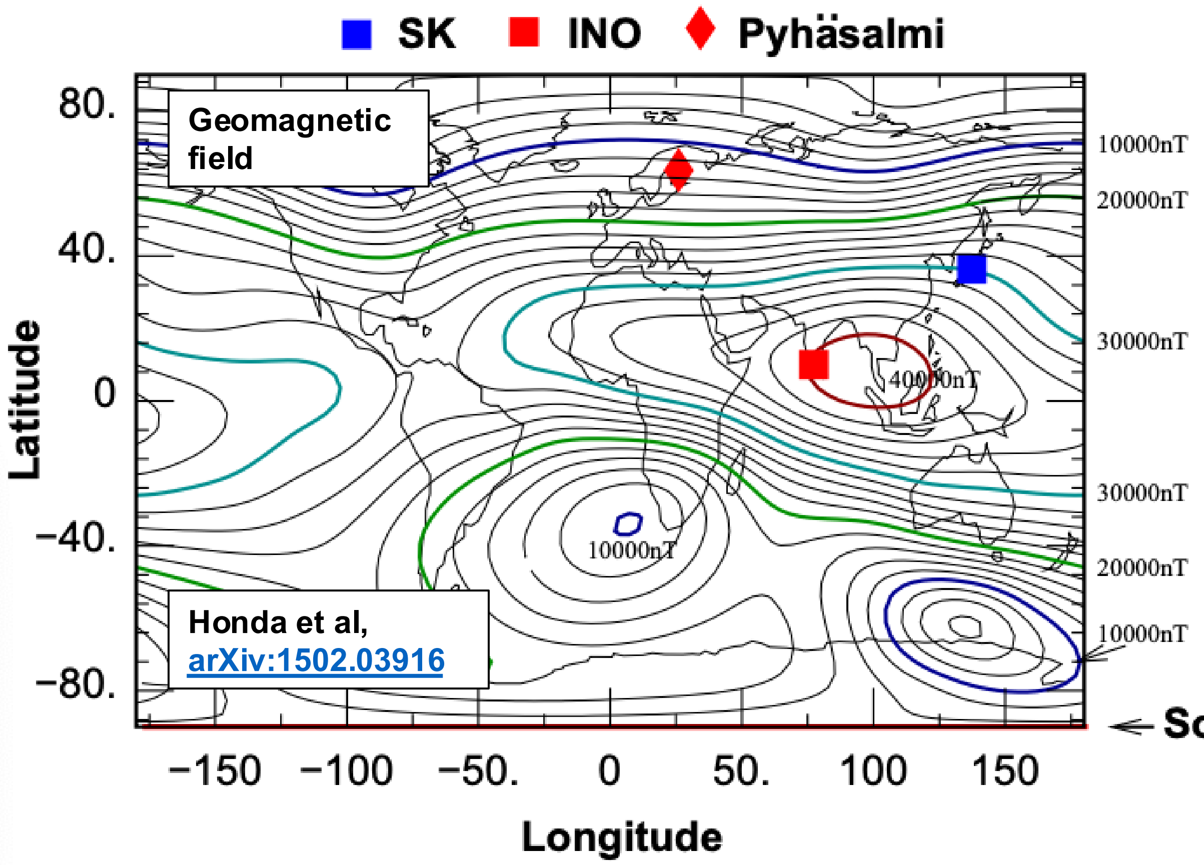


O'Hare arXiv:2109.03116



What is the Atmospheric Neutrino Flux?

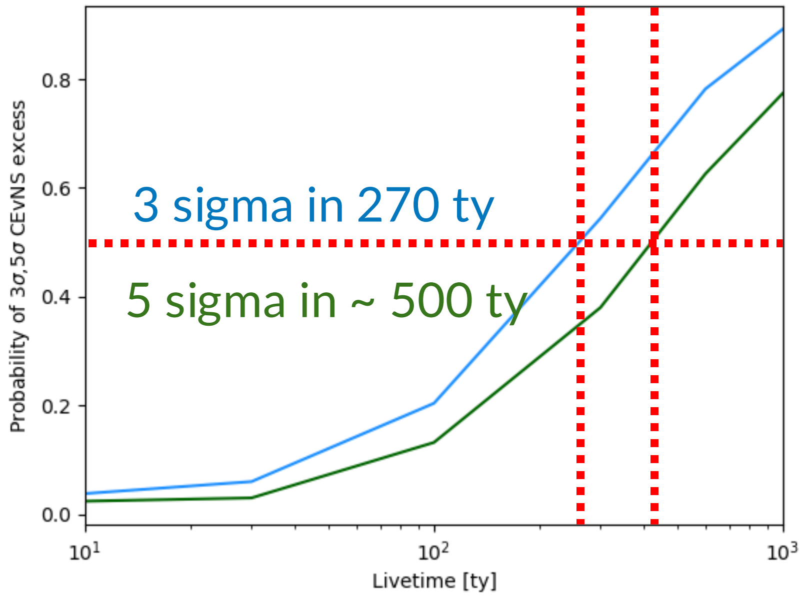
- Flux (and spectrum?) is site dependent
  - Systematic uncertainty canonically ~20%
- Calculations of angle-integrated all-flavour fluxes performed by Honda et al.
  - Only single bin for E < 100 MeV.
- Variation in flux ~ 1.4 (2.6) between LNGS (JUNO~CJPL) and SNOLAB/SURF/Boulby
- Updated calculation of flux and spectrum using Bartol model by Barr and Yang (Oxford) underway

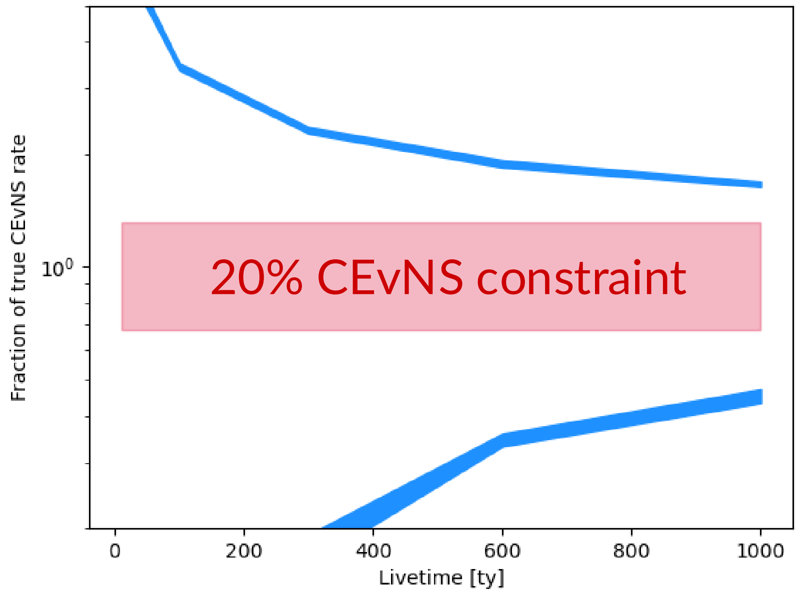


Site	Solar max flux ((m^2 sec sr GeV)^-1)						Solar min flux ((m^2 sec sr GeV)^-1)					
	NuMu	NuMubar	NuE	NuEbar	Total	Ratio to JUNO	NuMu	NuMubar	NuE	NuEbar	Total	Ratio to JUNO
Kamioka	7.43E+03	7.56E+03	3.54E+03	3.55E+03	2.21E+04	1.28	8.00E+03	8.14E+03	3.84E+03	3.80E+03	2.38E+04	1.29
LNGS	1.04E+04	1.06E+04	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

Neutrino Fog

- Two definitions:
  - Exposure at which become sensitive (3σ) to atmospheric nu CEvNS signal (*neutrino fog*)
  - Exposure at which stat uncertainty on total background equals syst uncertainty, from 20% uncertainty on atmos nu CEvNS background (*systematics dominated*).
- XLZD will probably enter the *neutrino fog* after a ~300 tonne-years of exposure
- XLZD will not be *systematics dominated* for any likely exposure at any site.





Proposed WIMP Search Requirements

- Compare NR with CEvNS: 0.046 (0.061) cnts / t-y at LNGS (Boulby/SNL/SURF)
- Compare ER with solar ER: 24.4 cnts / t-y ($2.5 < \log_{10}$(cS2[phe]) < 5)
  - For comparison, 0.1 μBq/kg Pb-214 corresponds to 3.4 cnts / t-y in same range.
  - Corresponds to 0.017 NR-band cnts / t-y for 0.5% ER/NR leakage.
  - Compare with 0.023 (0.031) CEvNS cnts / t-y at LNGS (Boulby/SNL/SURF) for 50% NR acceptance
- Backgrounds taken into account but fixed in fit:
  - Solar ER, atmos+DSNB CEvNS, Xe-124 DEC, Xe-136 $2\nu\beta\beta$
- Detector performance parameters fixed in fit:
  - PMT QE, analysis threshold, electron lifetime, fiducial mass
- Not taken into account:
  - Accidental backgrounds
  - External ER / Compton backgrounds
- More details in talks by Rob James and Knut Mora that follow

Preliminary Draft WIMP Search Requirements

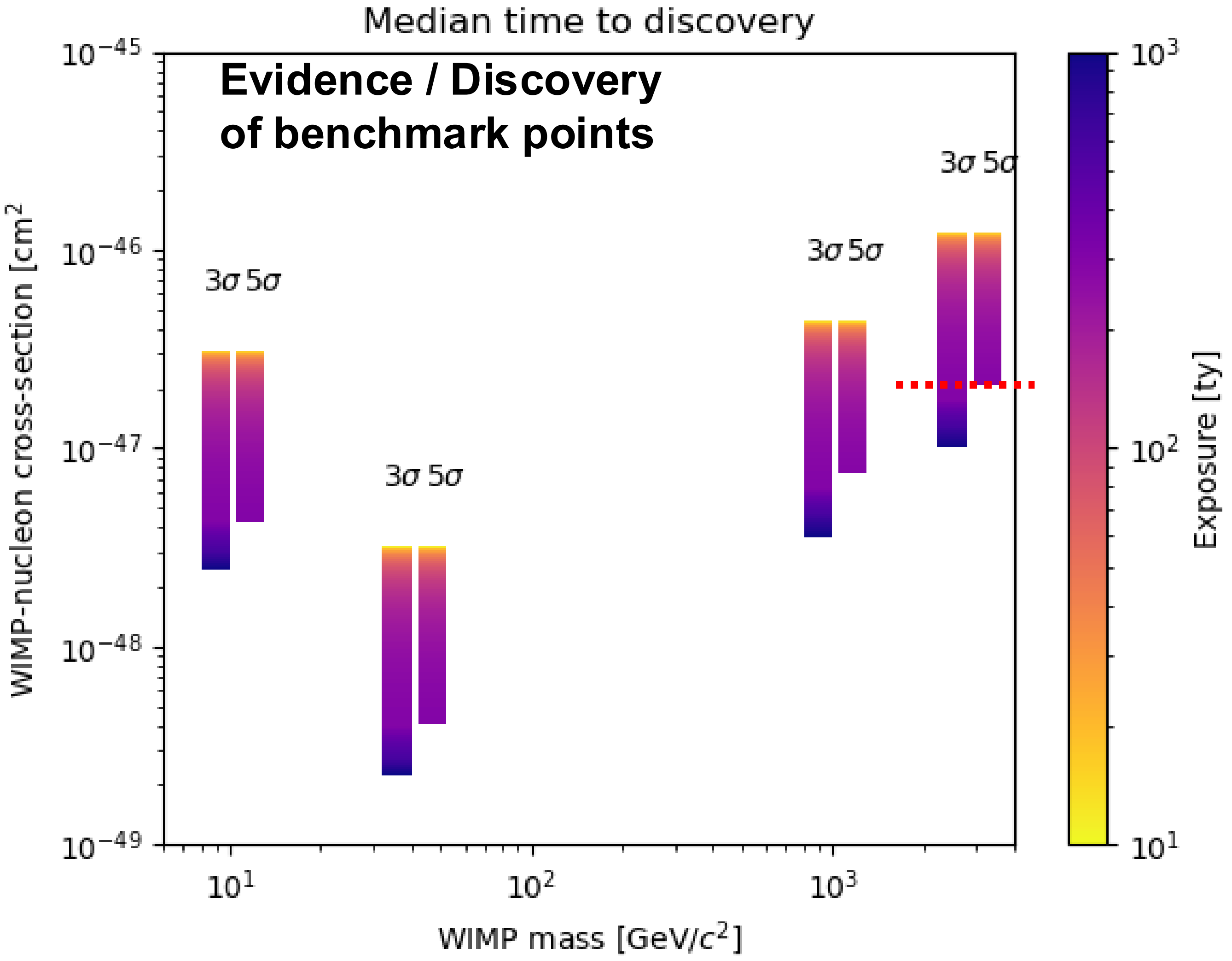
Parameter	Units	Proposed Requirement	Comment
WIMP cross-section 5σ sensitivity at 2800 GeV/c^2	cm^2	< 2x10^{-47}	Observation of Majorana triplet model and higher mass EW multiplet models
WIMP cross-section 90% exclusion at 60 GeV/c^2	cm^2	< 2x10^{-49}	Exclusion of majority of Higgs portal models
Fiducial exposure	t-y	> 500 – 650	Range corresponds to LNGS – Boulby/SNL/SURF
Analysis threshold	pe	<= 4	i.e. no worse than a 4-fold coincidence requirement. FIXED
Neutron NR background	cnts/t-y	< 0.0046-0.0064	Aim for rate <10% of CEvNS NR. Range corresponds to LNGS – Boulby/SNL/SURF
Pb-214 activity	μBq/kg	< 0.1	Aim for rate < solar ER (and < CEvNS NR after discrimination)
Kr-85 concentration	ppt	< 0.1	Aim for rate < solar ER (and < CEvNS NR after discrimination)
Active mass	tonne	> 60	FIXED
ER leakage @50% NR acc	%	< 0.5	
Single electron efficiency	%	XXX	TBD. Derived in FlameNEST.
LCE	%	> 50	Averaged absolute LCE
Drift field	V/cm	> 80	
TPC PMT QE	%	> 31	FIXED
Gas field	kV/cm	> 6.75	
Electron lifetime	ms	> 10	FIXED

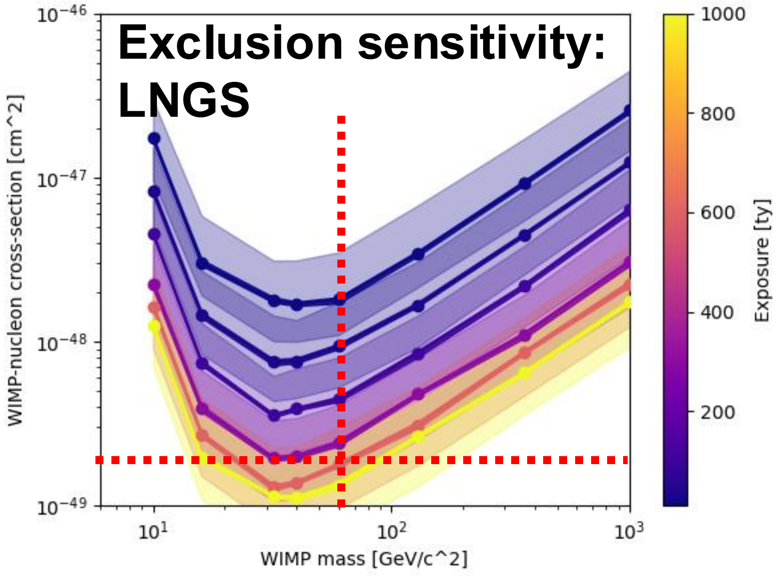
Preliminary Draft -- for Discussion

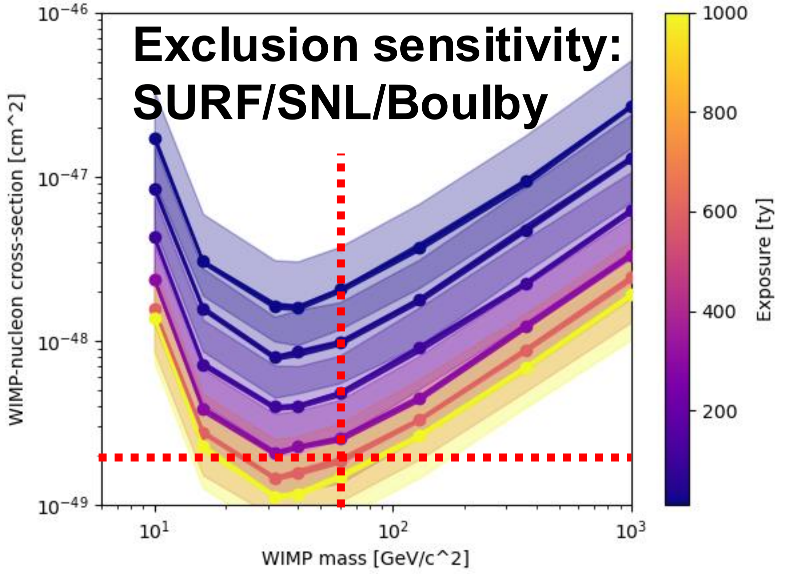
WIMP Search Backgrounds

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

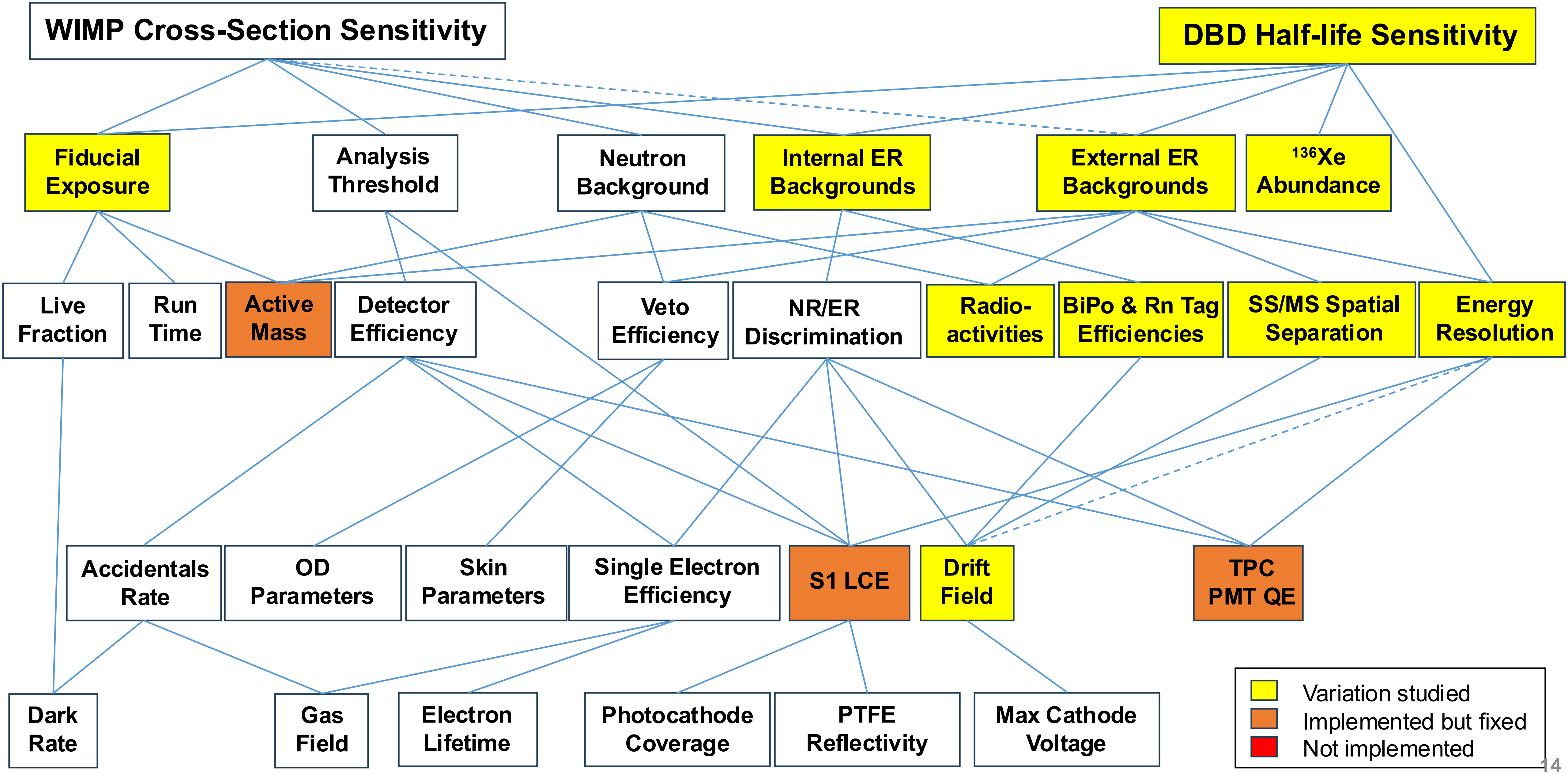
WIMP Search Performance







$0\nu\beta\beta$ Requirements Flowdown



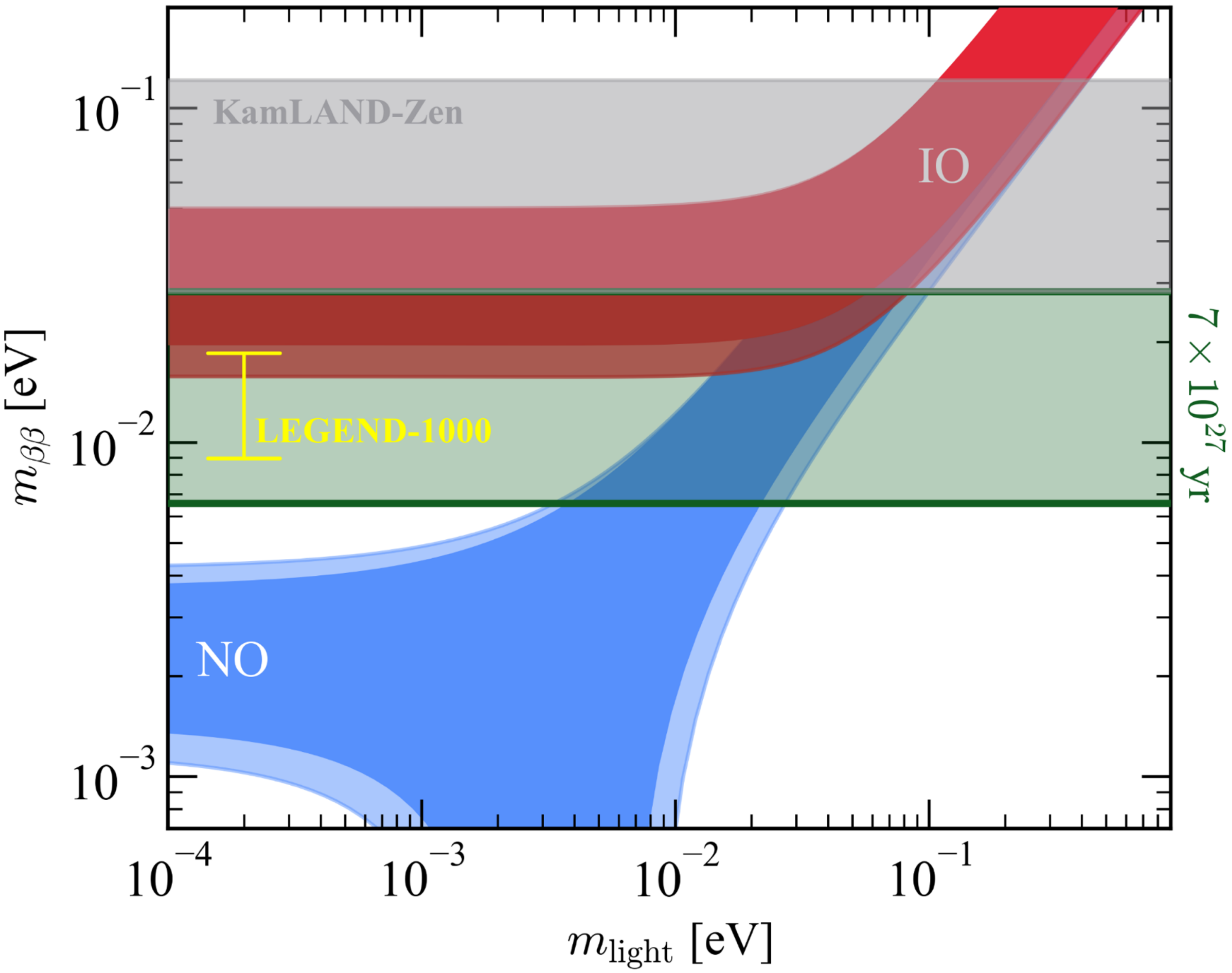
Preliminary Draft $0\nu\beta\beta$ Search Requirements

- Starting from studies from XLZD $0\nu\beta\beta$ paper (arXiv:2410.19016)
- Aim to set top-level requirement on $T_{1/2}$ sensitivity, rather than $m_{\beta\beta}$, to avoid dependence on nuclear models
- Note that a more aggressive goal might be achievable with 80 t + enrichment
- More details in talk from Alex Lindote yesterday

Parameter	Units	Proposed requirement	Comment
^{136}Xe $0\nu\beta\beta$ half-life 90% exclusion	years	> 7×10^{27}	Ensures world leadership in ^{136}Xe half-life and $m_{\beta\beta}$ exclusion (pending on the future of nEXO)
Fiducial livetime	years	> 10	Assumes tighter FV cuts wrt WIMP search
Pb-214 activity	μBq/kg	< 0.1	Consistent with WIMP search but probably not the driver. Assumes secular equil for ^{214}Bi.
External gammas	%	< 25	Currently relative to LZ. Mainly Bi-214 (peaking) and Tl-208 (tail). Site dependent.
^{136}Xe abundance	%	> 8.9	Assume natural abundance. FIXED
Active mass	tonne	> 60	FIXED
Bi-Po tagging efficiency	%	> 99.95	99.95% assumed in XLZD $0\nu\beta\beta$ paper.
SS/MS vertical separation	mm	< 3	Seems robust against drift-field variation
Energy resolution	%	< 0.65	
LCE	%	> 100	Currently relative to LZ. Current assumption. FIXED
Drift field	V/cm	> 80	Consistent with WIMP search requirement
TPC PMT QE	%	> 31	Current assumption. FIXED

Preliminary Draft -- <u>for Discussion</u>

0nbb Performance

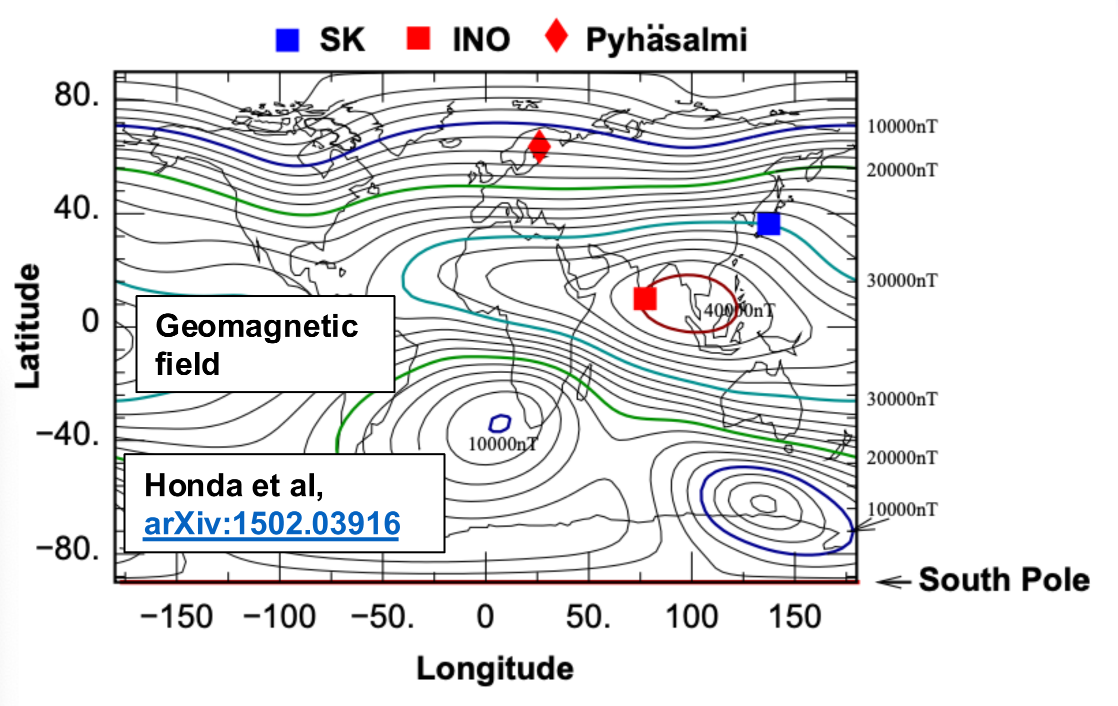


- More details in Alex Lindote's talk

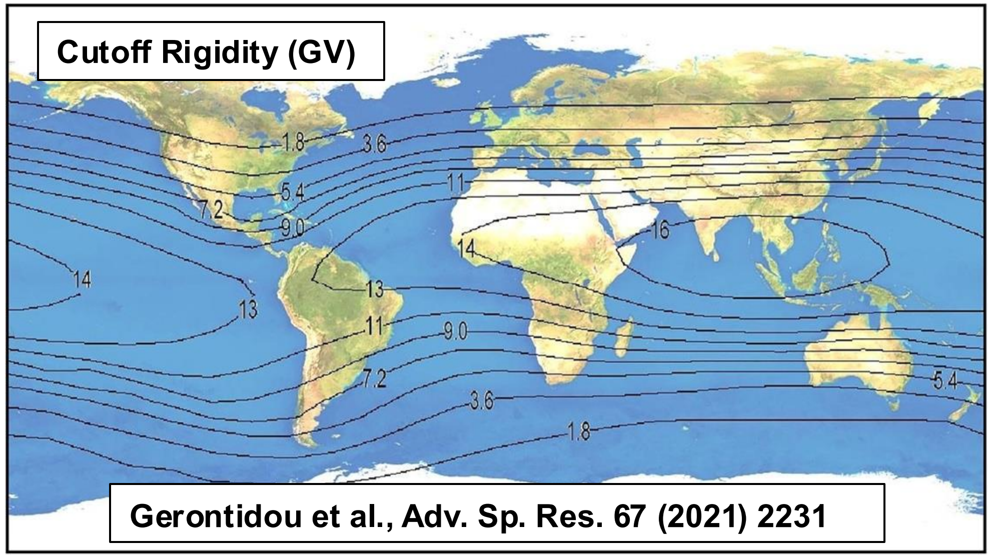
Backup

What is the Atmospheric Neutrino Flux?

- Atmospheric neutrinos are formed in the atmosphere from primary cosmic ray spallation on nuclei
- Flux is strongly dependent on flux of primary cosmic rays reaching atmosphere.
- Depends on:
  - Time: solar maximum vs. solar minimum
  - Latitude of site: geomagnetic field shields detectors close to the equator
  - Longitude of site: geomagnetic field varies across earth's surface due to details of the geodynamo
- Can quantify degree of shielding with 'cutoff rigidity' → rigidity below which primary cosmic rays are shielded by geomagnetic field



Honda et al, arXiv:1502.03916



Gerontidou et al., Adv. Sp. Res. 67 (2021) 2231