Requirements from $0\boldsymbol{\nu}\beta\beta$

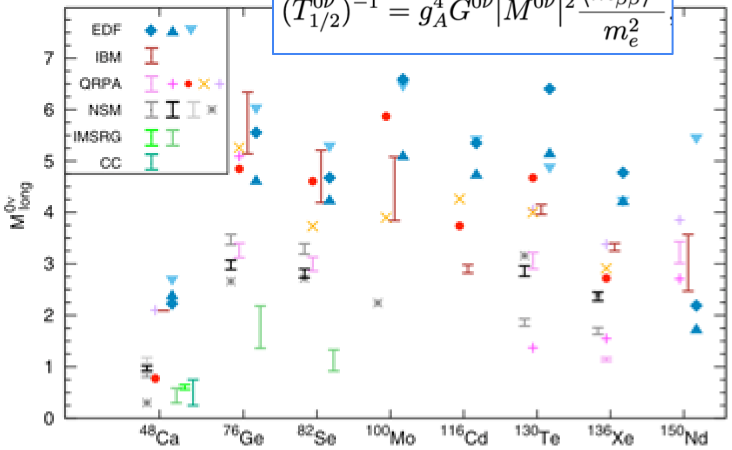
XLZD Collaboration Meeting

Alex Lindote, July 1 2025

Main $0\nu\beta\beta$ science requirement

- What is a reasonable main scientific requirement?
  - Should be science driven and lead to an interesting result for the community
  - Should imply reasonably achievable secondary requirements (backgrounds, performance, size, etc.)
- Set in half-life or effective Majorana mass?
  - Our sensitivity is set on the half-life, direct comparison with other ^{136}Xe experiments
  - But it should have a connection to $m_{\beta\beta}$ for comparison with other isotopes and to frame it in the overall $0\nu\beta\beta$ landscape
    - This implies a dependency on nuclear models (and iterations of these models)
    - “Standard” NMEs range 1.11 – 4.77 (note that higher is *better*)
    - Updated models include an additional short range term and a quenched g_A
      - Overall, a wider interval (0.98 – 5.49)

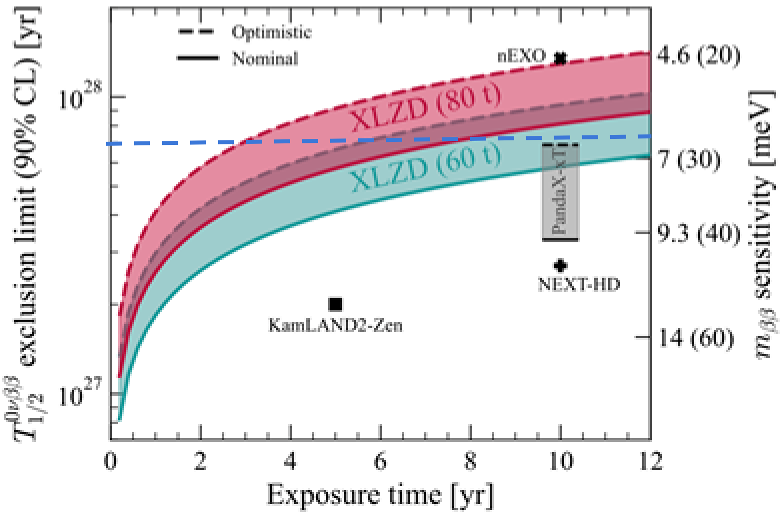
$$(T_{1/2}^{0\nu})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$



Main $0\nu\beta\beta$ science requirement

Suggestion: use a 90% CL exclusion $\mathbf{T_{1/2} > 7x10^{27}}$ **yr** as our requirement

1. >10x higher than current best limits for ^{136}Xe ($3.8x10^{26}$ yr, from KL-Zen)
2. Higher than the PandaX-xT best sensitivity (for a very optimistic scenario), meaning we would be world leaders in ^{136}Xe
   - Pending future of nEXO 2.0
3. Within the reach of a 60 t detector for the range of scenarios tested



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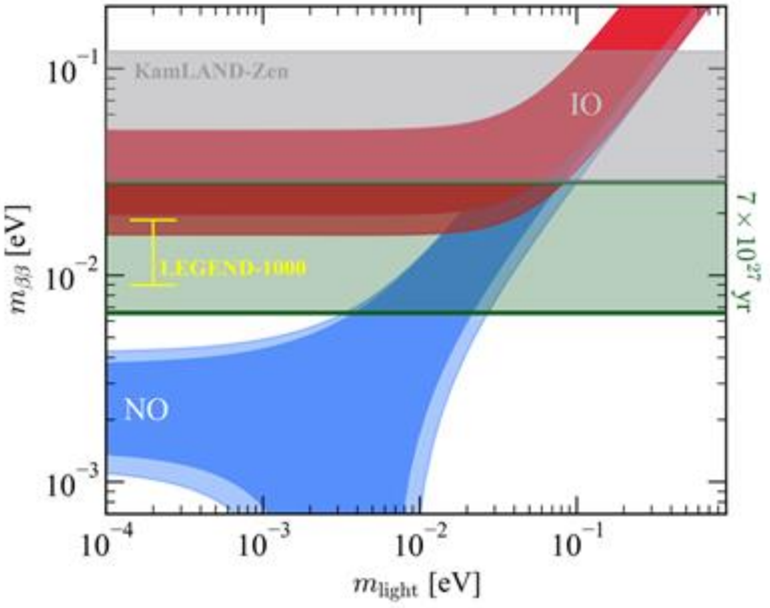
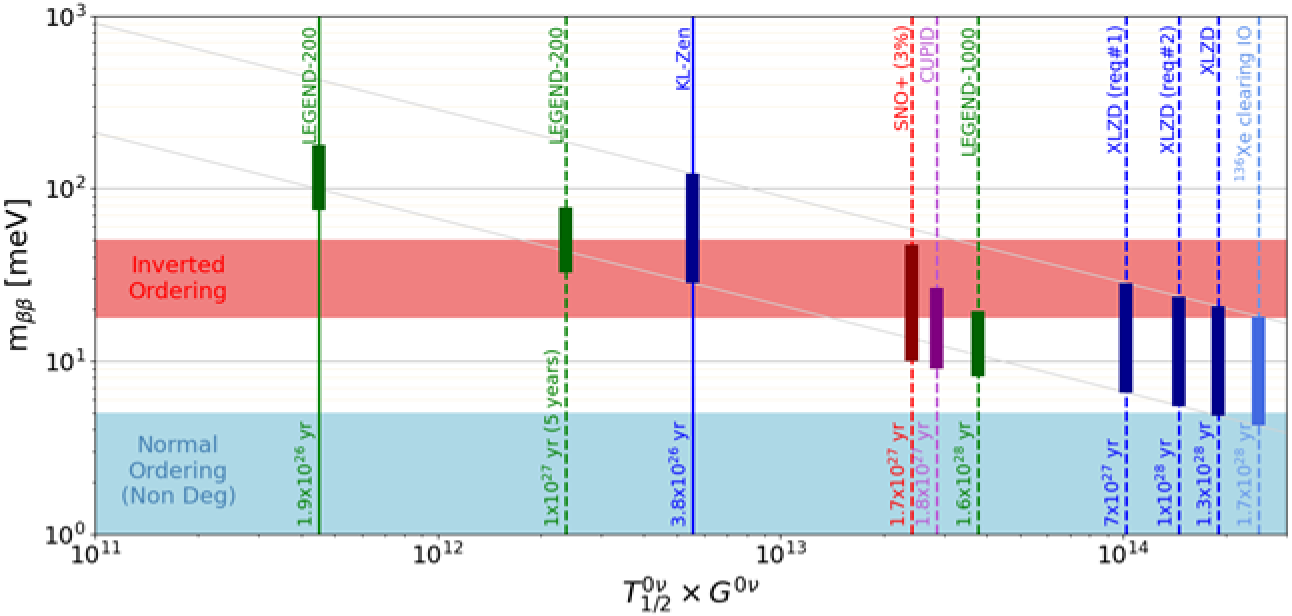
3. Within the reach of a 60 t detector for the range of scenarios tested
4. **Allows us to beat LEGEND-1000 90% CL exclusion**



Comparison with other experiments

- 7×10^{27} yr is enough to put us in the lead in the 90% CL exclusion metric
  - ^{136}Xe has a wider range of NMEs compared with ^{76}Ge and ^{130}Te)
  - $G^{0\nu}$ helps us here (6x higher than for ^{76}Ge)

Isotope	$G^{0\nu}$ ($\times 10^{-15}$ /yr)	NME range
^{76}Ge	2.36	2.66 - 6.34
^{100}Mo	15.9	2.24 - 6.59
^{130}Te	14.2	1.37 - 6.41
^{136}Xe	14.6	1.11 - 4.77



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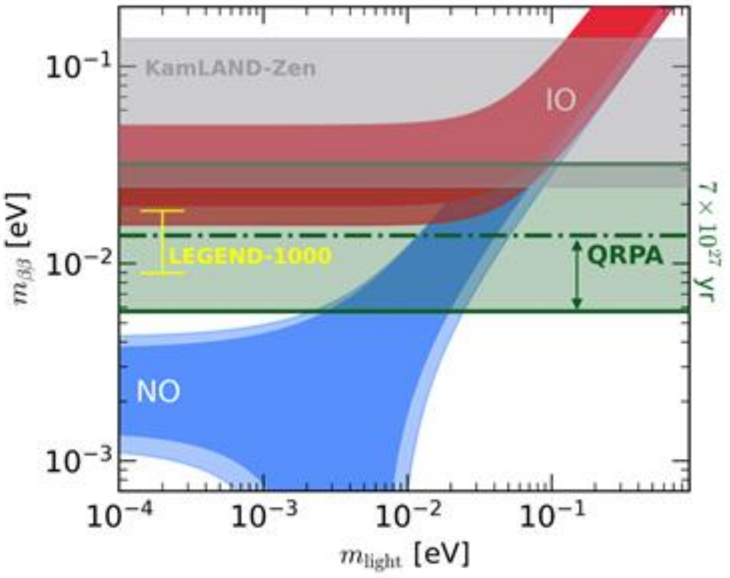
2. Higher than the PandaX-xT best sensitivity (for a very optimistic scenario), meaning we would be world leaders in ^{136}Xe (nEXO 2.0?)
3. Within the reach of a 60 t detector for the range of scenarios tested
4. Allows us to beat LEGEND-1000 90% CL exclusion
5. It completely excludes the IO region for a range of updated QRPA models



Bonus: It's equivalent to the 3x10^{27} yr 3σ discovery potential requirement used in the site selection report

Secondary requirements

Use the main science requirements to study the range of compatible background levels and detector performance parameters, set secondary requirements

- HE γ-ray background
- ^{222}Rn level (and/or BiPo tagging efficiency)
- Energy resolution
- SS/MS discrimination
- ^{137}Xe (laboratory depth)

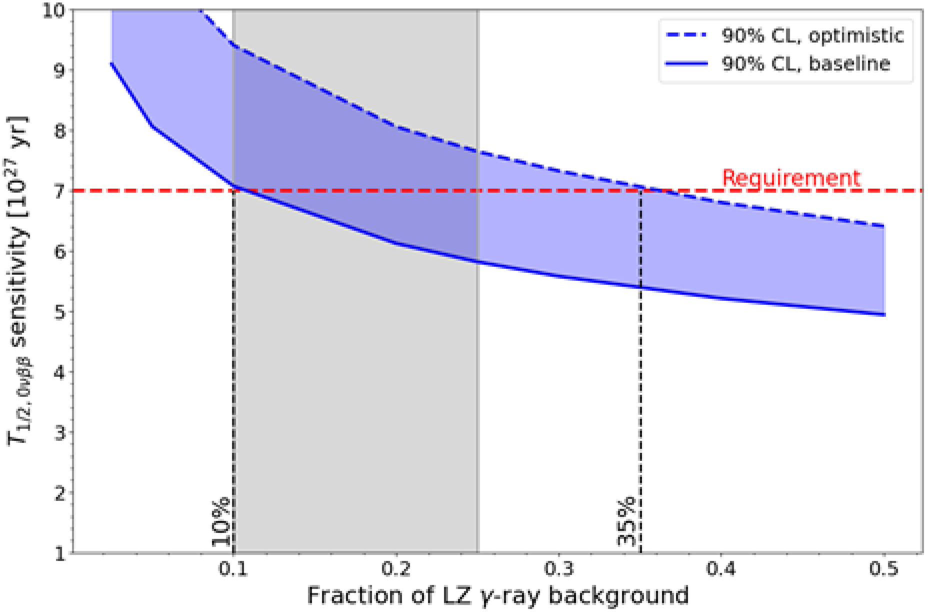
Note: these requirements can be softened once we use a PLR for the sensitivity estimate – or conversely, we can maintain them and improve the science requirement

γ-ray background requirement

Parameter	Scenario Nominal	Scenario Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	N/A	
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2

Focusing on 90% CL, 10 yr exposure

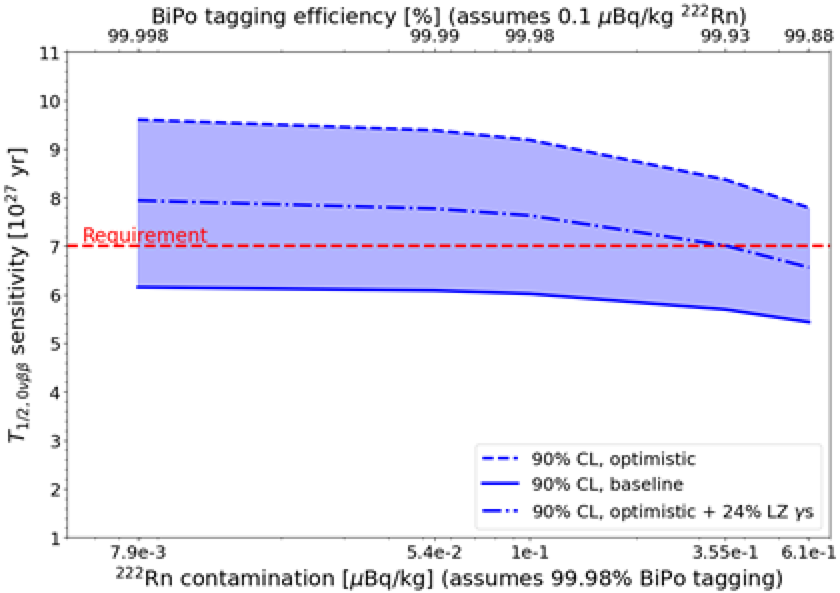
- Band width shows the impact of the remaining parameters between scenarios
- Some wiggle room for the γ-ray requirement (with optimistic assumptions for other parameters)
- Installation lab depth crucial to set the γ-ray requirement limits
  - 10 – 19 % at LNGS
  - 15 – 27 % at Boulby
  - 18 – 35 % at SURF
  - 21 – 41 % at SNOLab



Parameter	Scenario Nominal	Optimistic
^{222}Rn concentration [μBq/kg]	N/A	
BiPo tagging efficiency [%]		
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2

^{222}Rn level requirement

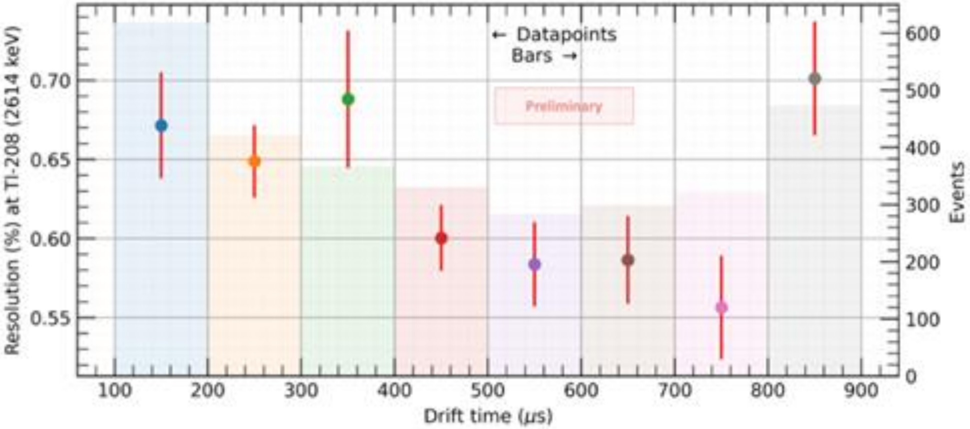
- Testing [0.0079, 0.05395, 0.1, 0.355, 0.61] µBq/kg
  - Using expected BiPo tagging efficiency of 99.98%
  - Can be interpreted as varying BiPo efficiency for the nominal 0.1 µBq/kg
- Little dependency below 0.1 µBq/kg (above 99.98%)
- Could accommodate 0.355 µBq/kg with 24% LZ γs (17% for 0.6 µBq/kg) and installation at SURF



Energy resolution requirement

- From studies in LZ we know we can achieve a similar energy resolution for a range of drift fields (~0.67% in the WS2022/WS2024 range, 97–193 V/cm)
- Light collection will affect the resolution (needs detailed study), so a requirement needs to be set there

LZ WS2022 E_{res} vs drift time



Energy resolution requirement

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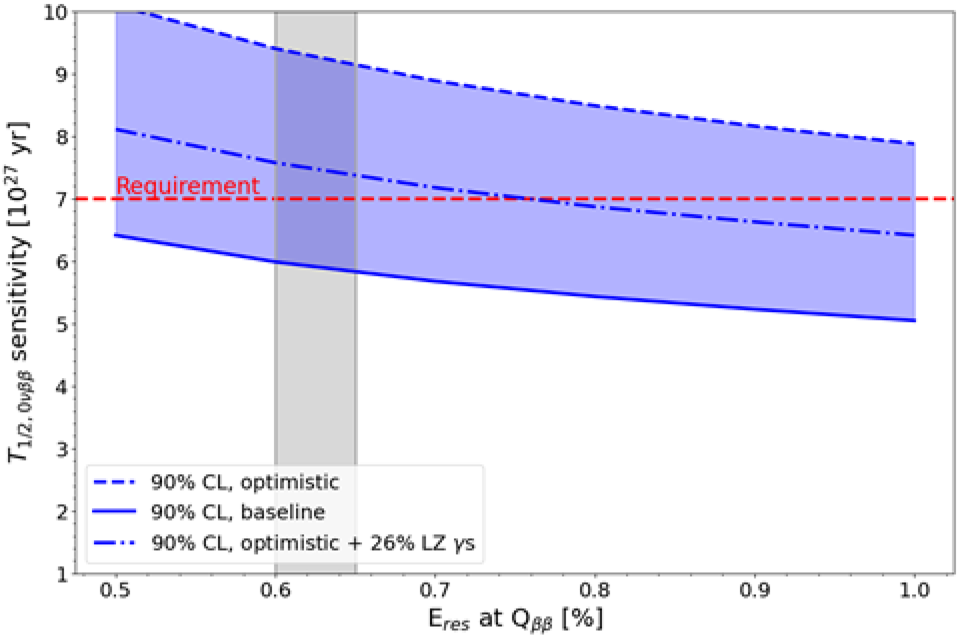
Installation site	LNGS	SURF
Energy resolution [%]	N/A	
SS/MS vert. separation [mm]	3	2

- Varied E_{res} between very optimistic 0.5% and conservative 1%
- Weak dependency (especially for worst resolutions)
- Could accommodate 0.75% with 26% LZ γs (22% for 0.85%) and installation at SURF



Requirements scenarios

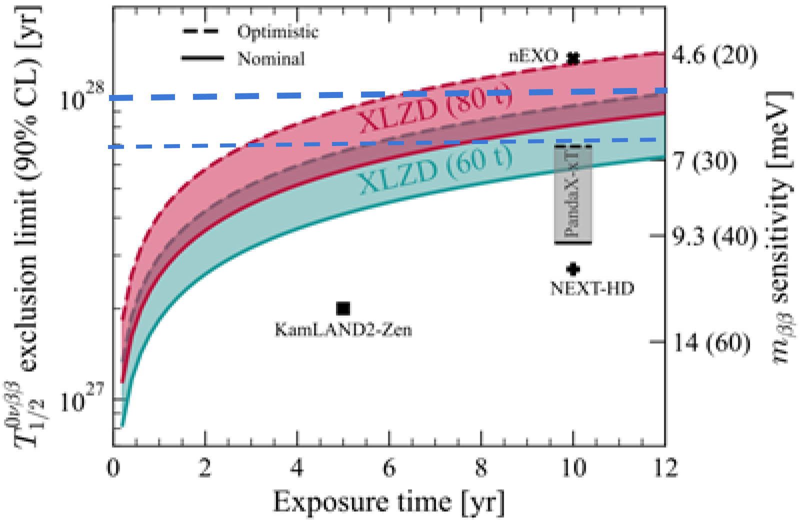
Many possible combinations, requirements depend on installation lab.
A lower external γ-ray level can compensate for poorer performance in other parameters
Table shows a few examples

222Rn [µBq/kg]	Eres [%]	SS/MS [mm]	Lab	γ-ray [% LZ]
0.1	0.65	3	LNGS	12
			Boulby	18
			SURF	23
			SNOLab	27
0.1	0.6	2	Boulby	26
0.355	0.75	3	SNOLab	15

A more ambitious $0\nu\beta\beta$ science requirement

A 90% CL exclusion **$T_{1/2}$ > 1×10^{28} yr**

- Requires an 80 t detector
- World leadership in 3σ discovery potential
- Achievable with similar BG and performance requirements
- Allows us to reach more ambitious science goals
  - Probe lower $m_{\beta\beta}$ regions if an hint of a signal is observed (longer run and/or some enrichment)
  - Fully exclude IO (some enrichment required)



Some thoughts

- A 90% CL half-life exclusion of 7×10^{27} yr requirement is
  - Competitive (may be world leading) for ^{136}Xe based experiments
  - Competitive (may be world leading) in excluding effective Majorana mass region across planned experiments
  - Achievable with a 60 t TPC and reasonable (?) requirements
- We need full simulations to properly set requirements
- Requirements obtained with the FoM estimator are too stringent and can be relaxed once we have a PLR (or the main requirement improved)
- Main dependency is with the external gammas, with the requirement strongly depending on the installation laboratory
  - This model focuses mainly on ^{214}Bi, but skin and OD thresholds will be crucial to keep ^{208}Tl at a manageable level
- Weaker dependency with other parameters which can be compensated by the γ level requirement
- We can (should) explore other parameters that may help relax requirements (e.g. SS/MS discrimination in xy)
- An 80 t detector with similar requirements gives us world leadership in discovery sensitivity and allows us to reach more ambitious science goals

References

- XLZD 0vbb sensitivity paper studies on github
- XLZD 0vbb requirements code on github
- Modified LZ γ background model (Excel file)

Extra

Recap of the sensitivity paper

Main backgrounds

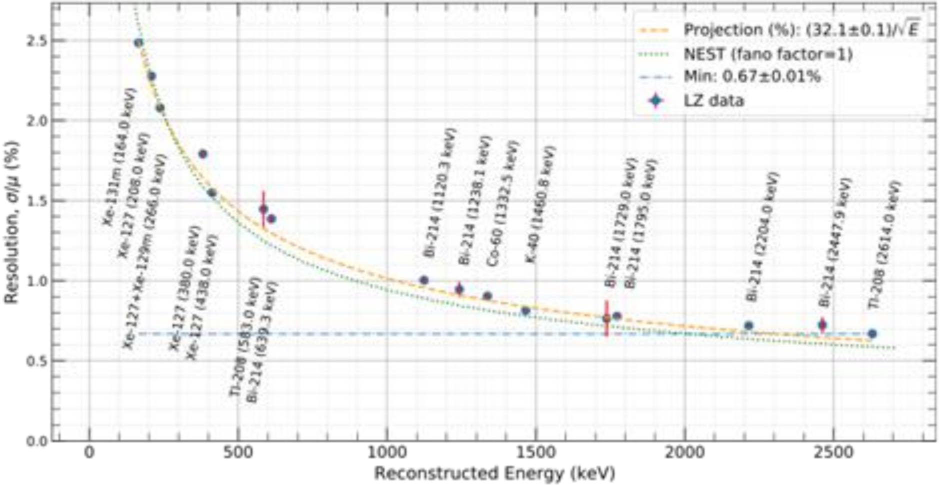
- HE gammas from ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl)
- ^{8}B neutrinos (irreducible)
- ^{136}Xe $2\nu\beta\beta$ decay continuum
- ^{222}Rn (^{214}Bi “naked” beta)
- ^{137}Xe (neutron activation, cosmogenic component depends on installation lab)

Important performance parameters

- Energy resolution
- SS/MS discrimination

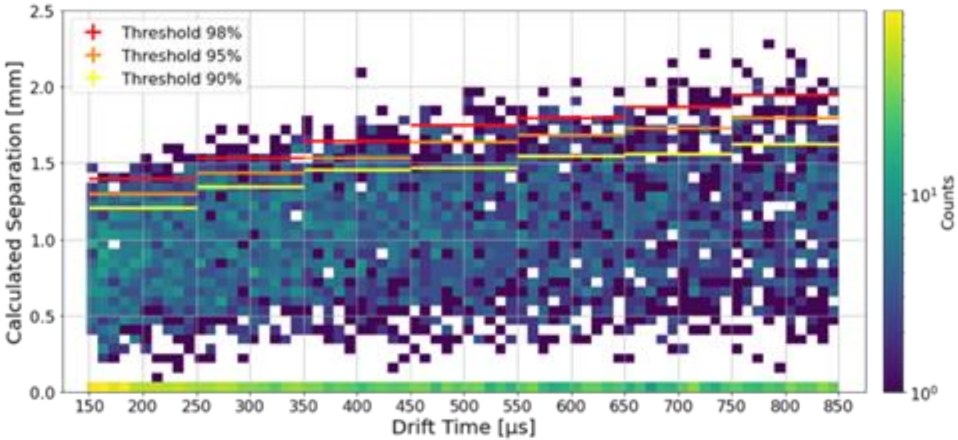
Recap of the sensitivity paper – Performance parameters

- Based on proven performance in LZ/XENON
- Energy resolution
  - 0.67% demonstrated in LZ with α-based corrections is SR1
  - Similar resolution in WS2024 with lower drift field (preliminary)
  - **Assumed 0.65% (0.6%) for XLZD**



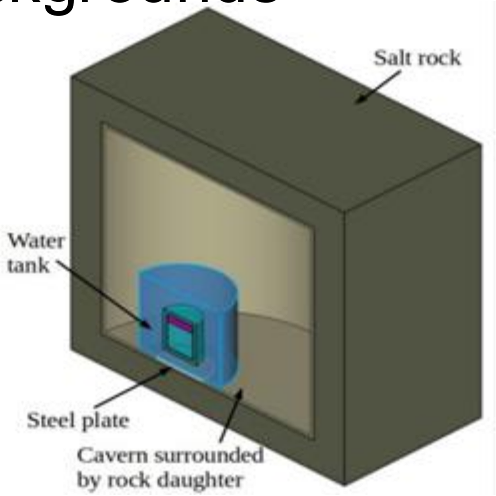
Recap of the sensitivity paper – Performance parameters

- Based on proven performance in LZ/XENON
- Energy resolution (**0.65/0.6 %**)
- SS/MS discrimination
  - Only explored vertical separation
  - S2 double gaussian fits point to <2 mm in LZ WS2022
  - Other algorithms being explored
  - **Assumed 3 mm (2 mm) for XLZD**
    - 85% signal efficiency
    - Excludes 90% HE γ in ROI
    - Rejects 23% of single e^- BG



Recap of the sensitivity paper – Main backgrounds

- HE gammas from ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl)
  - Cavern rock gammas reduced to negligible level
    - Simulation work from Jemima and Vitaly
    - **Requires a minimum shielding of 4 m w.e.** (water + organic scintillator + steel on the bottom)



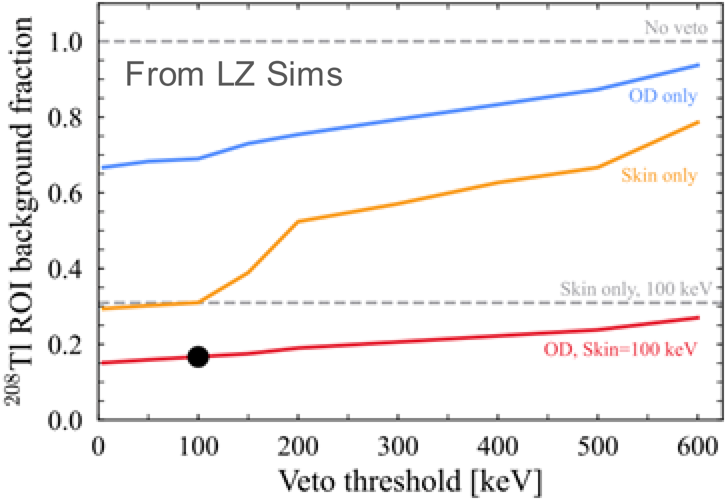
Normalised to Boulby measurements

	0 - 20 keV	0 - 100 keV	2408 - 2508 keV
Isotope	Rate [year^{-1}]	Rate [year^{-1}]	Rate [year^{-1}]
^{232}Th	$(7.2^{+8.2}_{-4.6}) \times 10^{-5}$	$(2.9^{+1.1}_{-0.9}) \times 10^{-4}$	0.057 ± 0.014
^{238}U	$0^{+0.00027}_{-0}$	$(2.3^{+2.5}_{-0.8}) \times 10^{-4}$	0.071 ± 0.003
^{40}K	$0^{+0.1}_{-0}$	$0^{+0.1}_{-0}$	n/a

63 t FV (71 t TPC)
$Q_{\beta\beta} \pm 50$ keV
$\sigma_Z < 0.5$ cm, $\sigma_R < 5$ cm

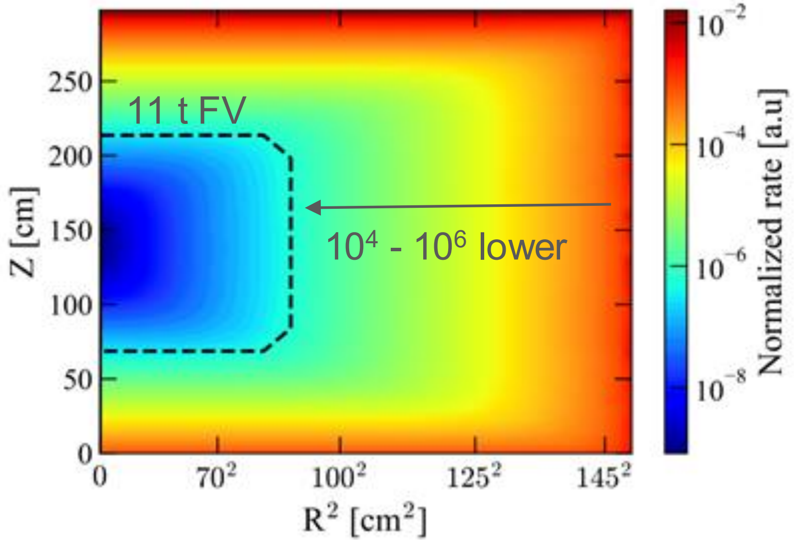
Recap of the sensitivity paper – Main backgrounds

- HE gammas from ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl)
  - Detector materials
    - Skin + OD are very efficient at vetoing ^{208}Tl gammas
      - Coincident gammas, Compton scatters
      - Assumed a **100 keV threshold** in both skin and OD



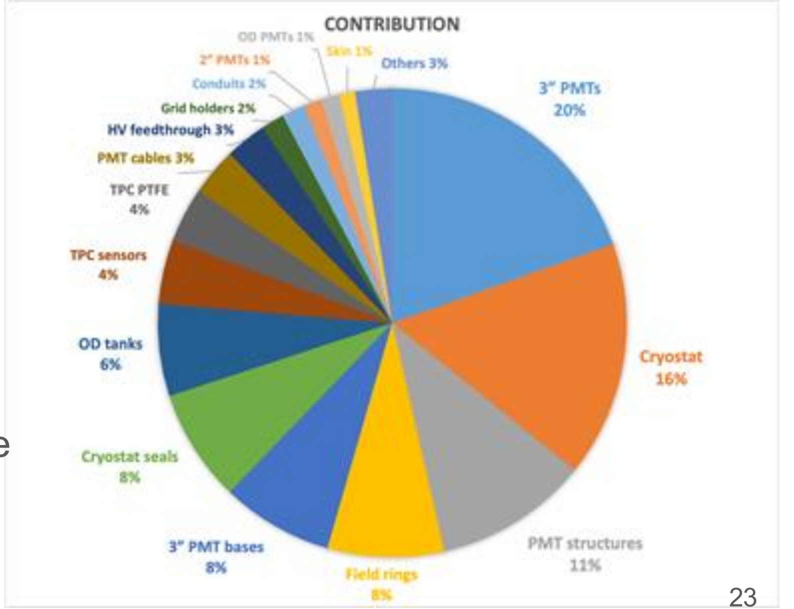
Recap of the sensitivity paper – Main backgrounds

- HE gammas from ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl)
  - Detector materials
    - Gammas are highly attenuated (~8 cm Compton s.l., 3 m detector)
      - SS rate decreases several orders of magnitude in the central region



Recap of the sensitivity paper – Main backgrounds

- HE gammas from ^{238}U (^{214}Bi) and ^{232}Th (^{208}Tl)
  - Detector materials
    - Assumed various material radioactivity optimisations in LZ model (^{238}U only)
      - New 3” PMTs with ⅓ of U_{late}
      - Custom made field shaping rings
      - Cleaner capacitors in PMT bases
      - Clean copper in PMT cables
      - Low radioactivity PMTs in the skin
      - Avoid water displacer foams
      - Use clean (identified) batches of SST, PTFE, copper, Kovar and Kapton
    - Overall, this results in a **75% reduction** of the LZ ^{214}Bi gamma background in the ROI



Clean materials and subsystem radioactivity

Cleanest material batches in LZ and XENON radioassay campaigns

Material	U_{late} (mBq/kg)	Source
Titanium	<0.04	LZ (66)
SST	0.27	LZ (54)
PTFE	<0.02	LZ (138)
Copper	<0.04	XENON (#1)
PEEK	4.0	LZ (447)
Kovar	<0.63	LZ (131)
Kapton	<4.6	LZ (1035)
Aluminium (SI)	1.13	GERDA (#11)
PTFE (SI)	0.34	GERDA (#11)

Values shown are average for each subsystem after mitigation assumptions (25% initial LZ)

Subsystem	$\langle U_{late} \rangle$ (mBq/kg)	U_{late} (mBq)	Reduction (%)
3" PMTs	1.07	98.8	67
Cryostat	0.05	139	35
PMT structures	0.65 / 0.16	35.2 / 18.6	81
Field rings	0.1	9.1	58
3" bases	19.4	54.2	74
Cryostat seals	3.17	176	0
OD tanks	0.06	198	38
TPC sensors	0.94	4.40	88
PMT cables	4.16	369	84

Recap of the sensitivity paper – Main backgrounds

- ^{8}B neutrinos (irreducible)
  - Not much we can do about this one, but the 3 mm vertical SS/MS discrimination helps
- ^{136}Xe $2\nu\beta\beta$ decay continuum
  - Negligible for the assumed energy resolution
- ^{222}Rn (^{214}Bi “naked” beta)
  - Assumed 0.1 µBq/kg
  - ~20% of decays are naked beta (3270 keV end point)
  - Daughter ^{214}Po has a 162.3 µs half-life, α decay
  - A 290 V/cm drift field requires a minimum of 2 ms long waveforms (for 60 t, 3 m height)
    - 99.98% of BiPo decays contained
    - A lower field and/or 80 t (4 m) TPC has even higher efficiency
  - In the paper we assumed 99.95% (99.99%)

Recap of the sensitivity paper – Main backgrounds

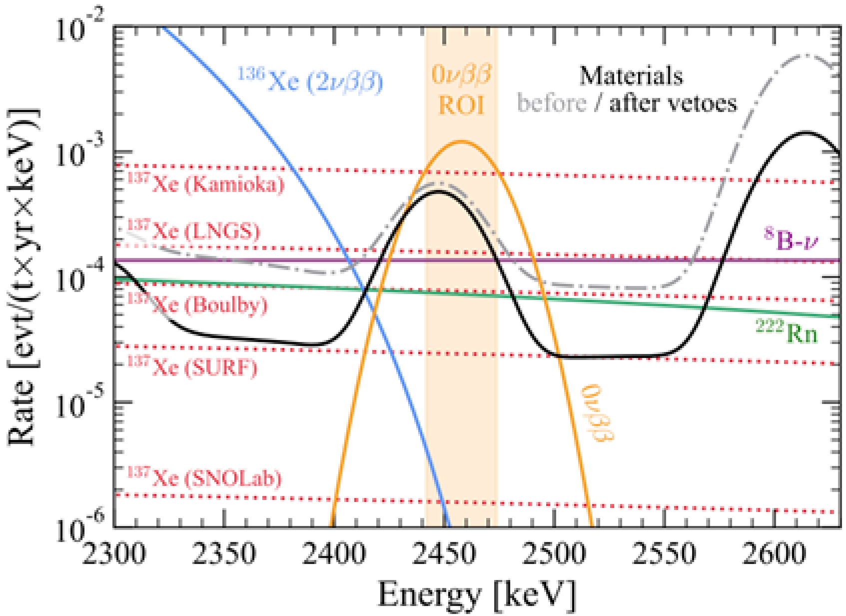
- ^{137}Xe (neutron activation of ^{136}Xe)
  - Short half-life (3.82 min), 67% of decays by naked beta (4173 keV end point)
  - Activation by environment neutrons for xenon outside the water tank
    - Requires local shielding around Xe circulation and Rn removal system (needs a detailed study)
    - Can also be minimised with ‘decay tanks’ inside the water tank
    - **Assumed negligible in the paper**
  - Cosmogenic activation
    - Depends on muon flux, thus on the installation lab
    - Some vetoing may be possible:
      - Using the muon (large dead time)
      - Looking for the ^{136}Xe capture (difficult as it immediately follows the muon signal)
    - **In the paper we assumed no vetoing**
      - But use the 23% SS/MS discrimination

Site	Depth [m]	Depth [m w.e.]	μ flux [/(m^2·d)]	^{137}Xe rate [/(t·yr)]	SS ROI rate [evt/(t·yr·keV)]
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

Recap of the sensitivity paper – BG model

- Background model using the nominal scenario in a 60 t detector
- Selected fiducial volume with similar internal and external backgrounds

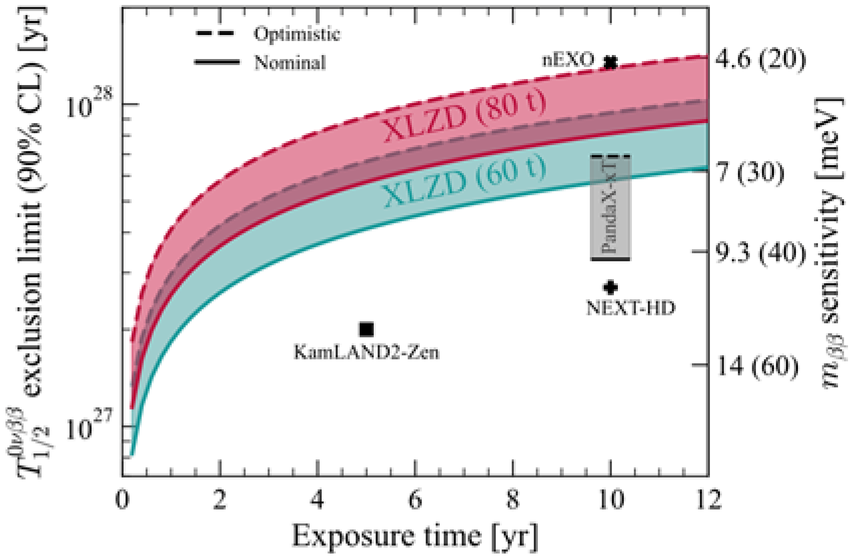
Parameter	Scenario Nominal	Scenario Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2



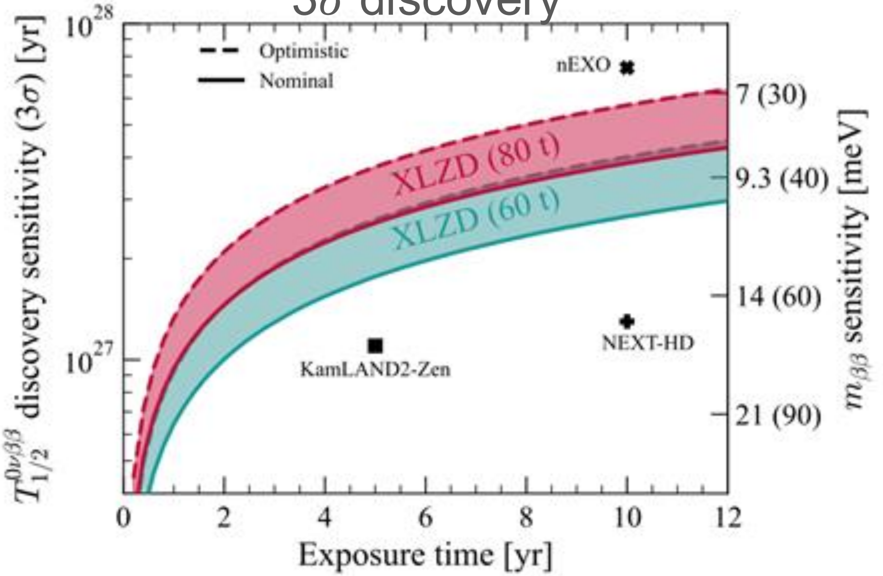
Recap of the sensitivity paper – Sensitivity

- Sensitivity estimates using figure-of-merit $T^{0\nu}_{1/2} = \ln 2 \frac{N_A \mathcal{E}}{M_{\mathrm{Xe}} S(B)}$

90% CL exclusion

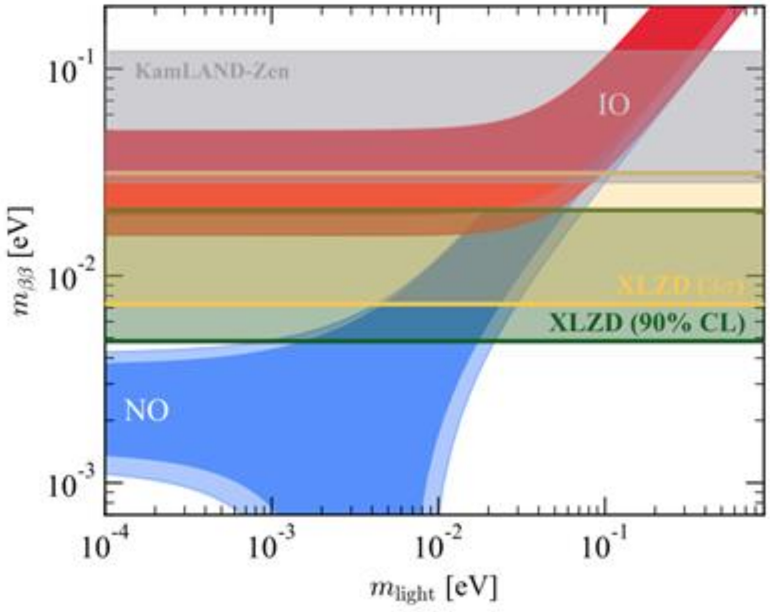


3σ discovery

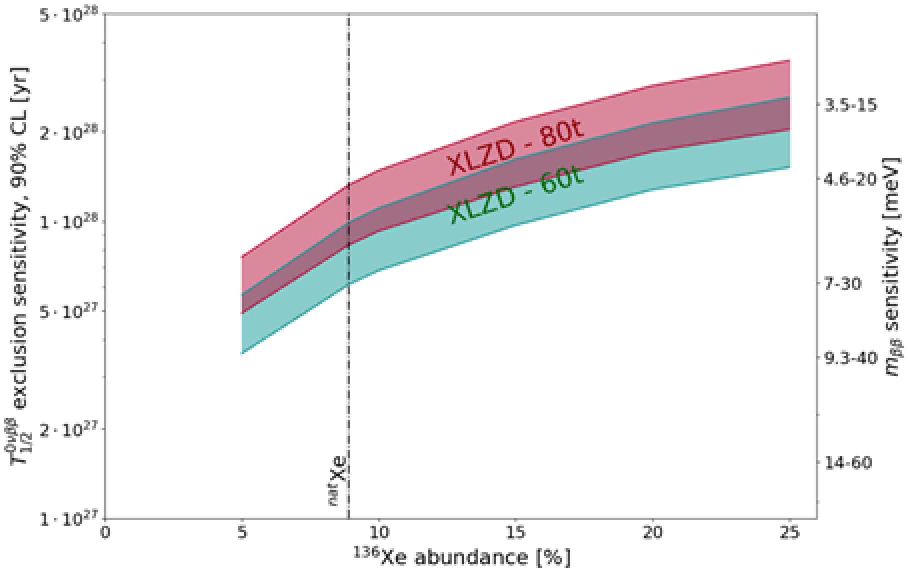


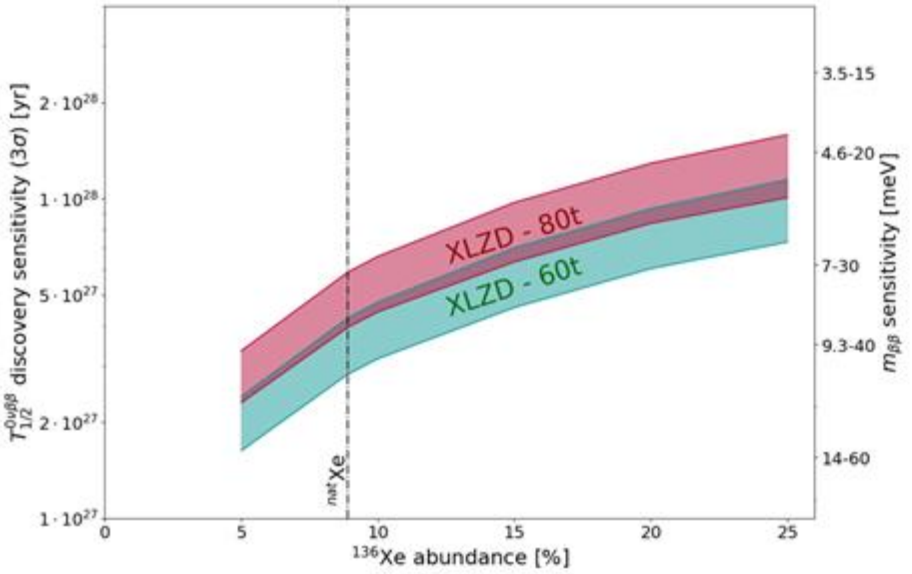
Effective Majorana mass sensitivity

- Translating decay half-life sensitivity to effective Majorana mass requires knowledge of the Nuclear Matrix Element (NME)
- Multiple nuclear models, and multiple variants/updates of these models
- Here we used ‘classical’ models, which don’t include recent developments (g_A quenching and short range term)
- The NME range [1.11, 4.77] leads to the observed bands in $m_{\beta\beta}$
- Bands shown here are for an 80 t TPC



Enrichment scenarios





“Classical” Nuclear Matrix Elements

From Agostini M. et al., Rev. Mod. Phys. 95, 025002 (2023), arXiv:2202.01787

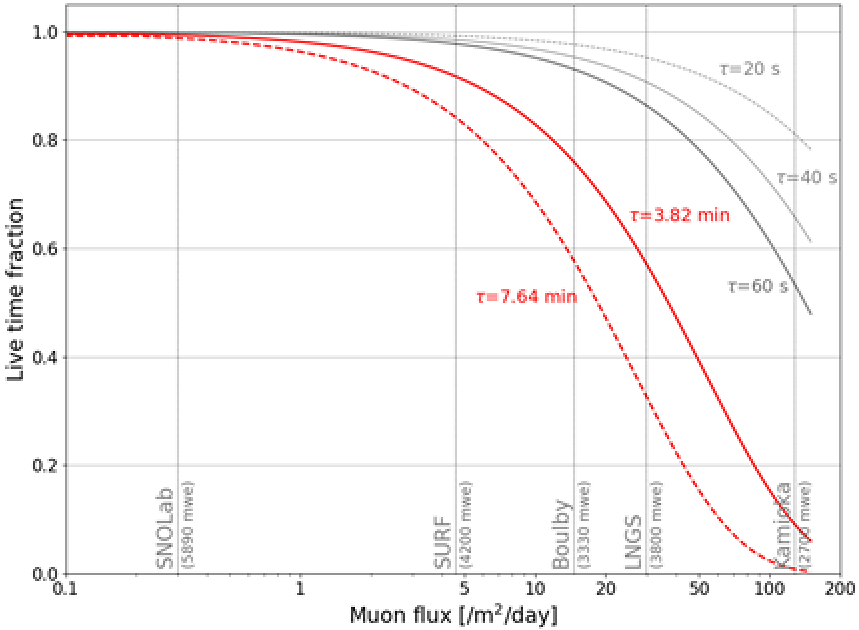
TABLE I. NMEs $M^{0\nu}$ for light-neutrino exchange calculated with the shell model, QRPA, EDF theory, and IBM methods for the $0\nu\beta\beta$ decay of nuclei considered for next-generation experiments. The combined NME range for each many-body method is also shown. All NMEs were obtained with the bare value of g_A and do not include the short-range term proportional to g_ν^{NN}.

	Reference	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
Shell model	Menéndez (2018)	2.89, 3.07	2.73, 2.90	...	2.76, 2.96	2.28, 2.45
	Horoi and Neacsu (2016b)	3.37, 3.57	3.19, 3.39	...	1.79, 1.93	1.63, 1.76
	Coraggio *et al.* (2020, 2022)	2.66	2.72	2.24	3.16	2.39
	min–max	2.66–3.57	2.72–3.39	2.24	1.79–3.16	1.63–2.45
QRPA	Mustonen and Engel (2013)	5.09	...	...	1.37	1.55
	Hyvarinen and Suhonen (2015)	5.26	3.73	3.90	4.00	2.91
	Šimkovic, Smetana, and Vogel (2018)	4.85	4.61	5.87	4.67	2.72
	Fang, Faessler, and Šimkovic (2018)	3.12, 3.40	2.86, 3.13	...	2.90, 3.22	1.11, 1.18
	Terasaki (2020)	...	...	...	4.05	3.38
	min–max	3.12–5.26	2.86–4.61	3.90–5.87	1.37–4.67	1.11–3.38
EDF theory	Rodriguez and Martinez-Pinedo (2010)	4.60	4.22	5.08	5.13	4.20
	López Vaquero, Rodríguez, and Egido (2013)	5.55	4.67	6.59	6.41	4.77
	Song *et al.* (2017)	6.04	5.30	6.48	4.89	4.24
	min–max	4.60–6.04	4.22–5.30	5.08–6.59	4.89–6.41	4.20–4.77
IBM	Barea, Kotila, and Iachello (2015a)[a]	5.14	4.19	3.84	3.96	3.25
	Deppisch *et al.* (2020)	6.34	5.21	5.08	4.15	3.40
	min–max	5.14–6.34	4.19–5.21	3.84–5.08	3.96–4.15	3.25–3.40

[a]With the sign change in the tensor part indicated by Deppisch *et al.* (2020).

Deadtime model

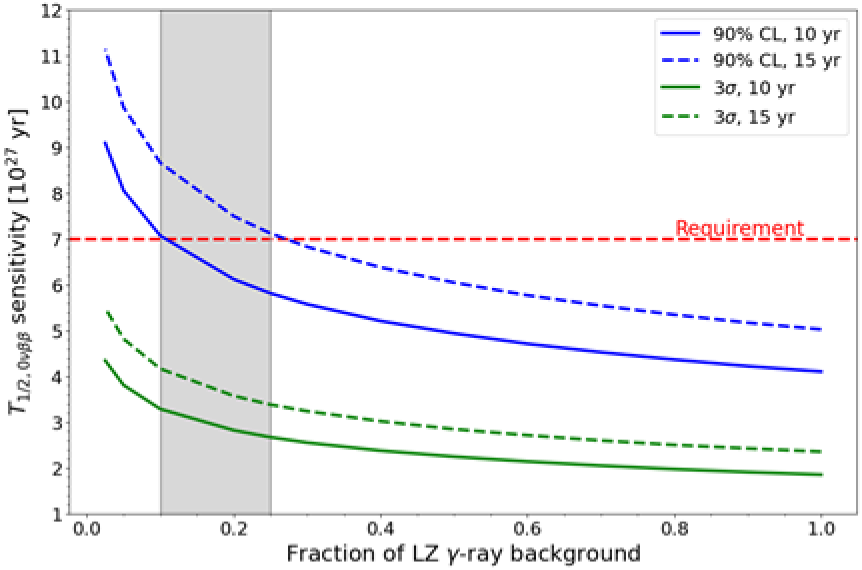
- Shows effect of PMT ‘blindness’ following muon events and a possible muon veto for ^{137}Xe decays – assumes a 3 m diameter TPC at Boulby 1300 m



γ-ray background requirement

Parameter	Scenario Nominal	Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2

- Until we have a full simulation this requirement is expressed as a fraction of the LZ background
  - Can be converted to ^{238}U activities assuming LZ geometry and paper baseline scenario
  - Example curves use **nominal** scenario and **60 t** detector
  - Gray band shows the paper nominal and optimistic γ-ray scenarios
  - Included a 15 yr scenario just to have an idea of how exposure can be used to soften other requirements
  - Curves for 3σ discovery potential show it's harder to have a competitive science requirement in this metric with a 60 t detector

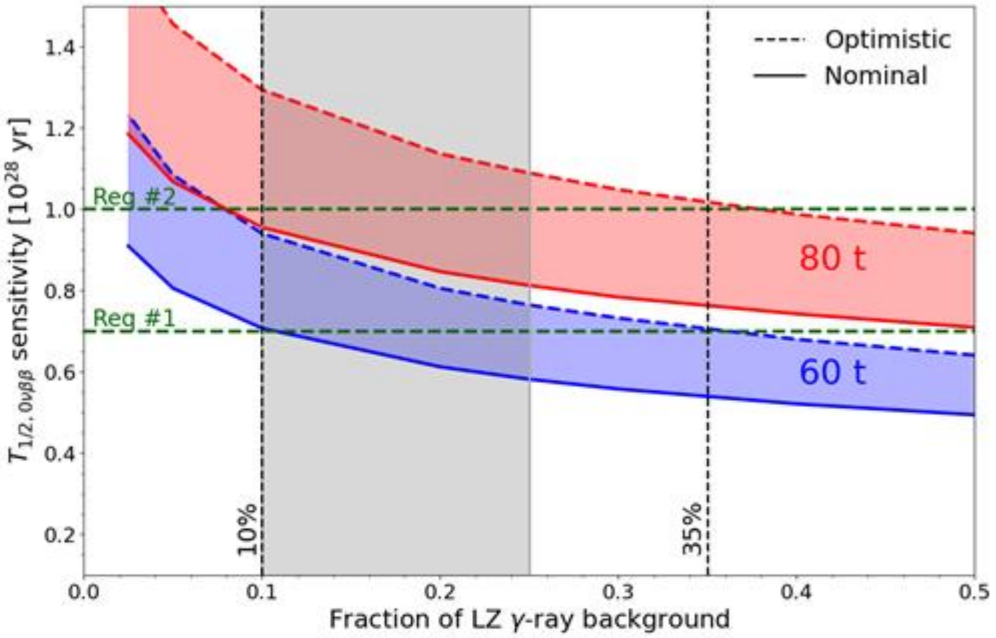


γ-ray background requirement

Parameter	Scenario Nominal	Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	N/A	
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2

Focusing on 90% CL, 10 yr exposure

- Band widths show the impact of the remaining parameters between scenarios
- 80 t detector can comfortably reach R1; R2 impossible with 60 t
- Some wiggle room for the γ-ray requirement (with optimistic assumptions for other parameters)
- Installation lab depth crucial to set the γ-ray requirement limits, e.g. for 60t R1
    - 10 – 19 % at LNGS
    - 15 – 27 % at Boulby
    - 18 – 35 % at SURF
    - 21 – 41 % at SNOLab



^{222}Rn level requirement

Parameter	Scenario Nominal	Scenario Optimistic
^{222}Rn concentration [μBq/kg]	N/A	
BiPo tagging efficiency [%]		
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2

- Testing [0.0079, 0.05395, 0.1, 0.355, 0.61] μBq/kg
  - Using expected BiPo tagging efficiency of 99.98%
  - Can be interpreted as varying BiPo efficiency for the nominal 0.1 μBq/kg
- Little dependency below 0.1 μBq/kg (above 99.98%)
- Could accommodate higher ^{222}Rn levels with stricter γ BG:
  - e.g. 0.355 μBq/kg with 24% LZ γs in 60 t for R1