$0\nu2\beta$ sensitivity of the XLZD rare-event observatory

Based on 2410.19016

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On behalf of the XLZD collaboration

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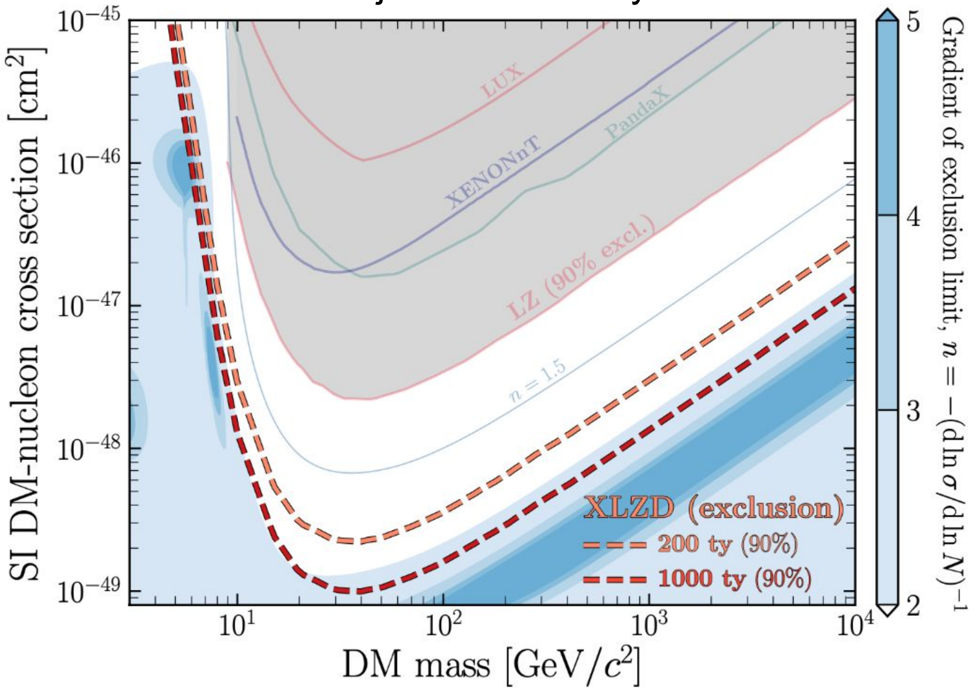
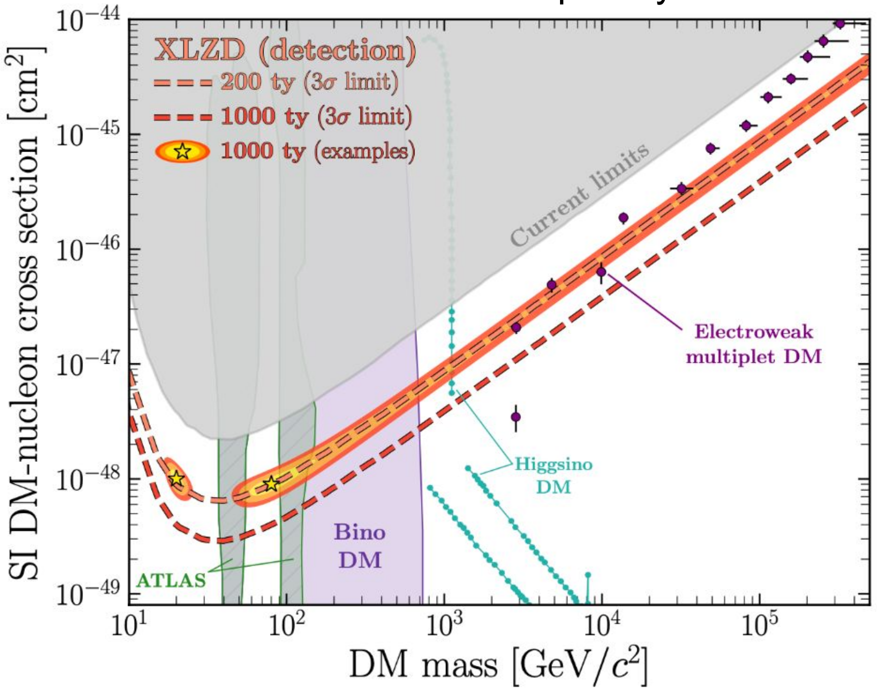
Liquid xenon detectors as definitive tools for WIMP searches

Based on the XLZD design book: [2410.17137]

Projected sensitivity



Detection capability



A multi-tonne liquid xenon time projection chamber will capable of reaching the neutrino fog and constraining DM parameters

Large scale enables a broad rare-event program

Liquid target is scalable

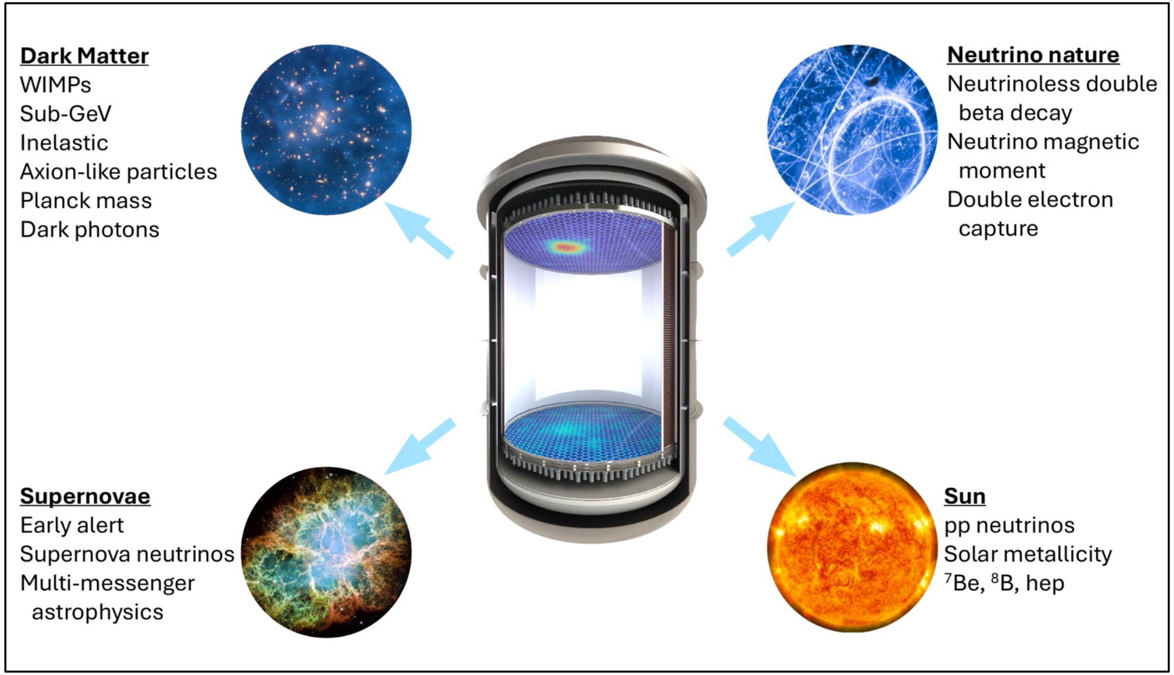
- LZ, XENONnT, PANDAX demonstrating dual-phase TPC at 10t scale

Background controls

- Continuous purification
- Self-shielded fiducial volume
- Material selection

LXe TPC response

- Good energy resolution
- ER/NR discrimination
- Low energy threshold
- Multiple scatter rejection



Physics reach of liquid xenon rare event observatory

The XLZD Collaboration

17 countries

76 institutions

440+ members

Next generation liquid xenon rare event observatory

- select best options from LZ, XENONnT, DARWIN RnD
- combine expertise in radiopurity, HV, cryogenics
- risk management using LZ, XENONnT, and test setups

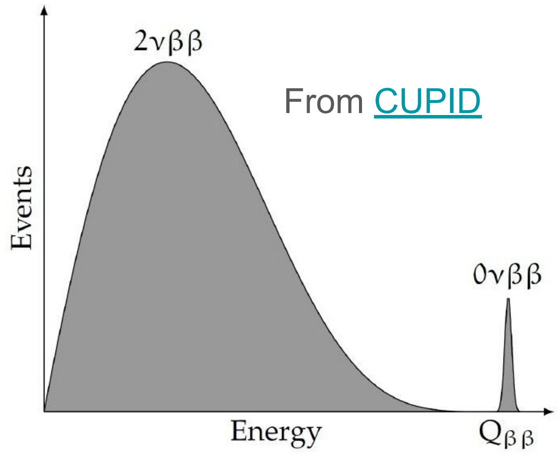
XLZD sensitivity to 0v2β – *2410.19016* studied scenarios:

- Active volume 60t baseline (extendable to 80t pending Xe market)
- Nominal and optimistic cases for
    - Energy resolution, background reduction, site, …

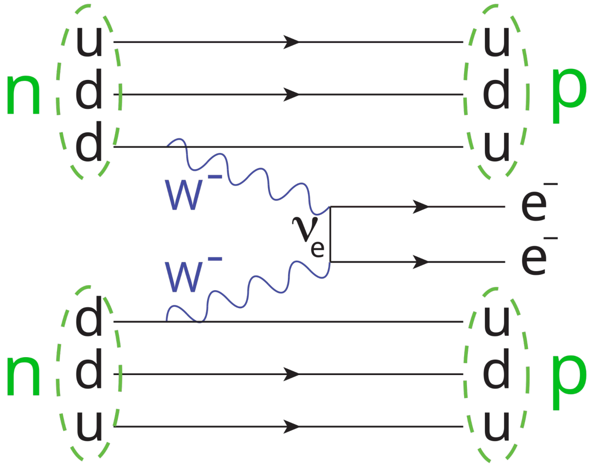
^{136}Xe 0v2b decay and signature

- ^{136}Xe 2v2β decay occurs and is background to WIMP searches
- Hypothesized 0v2β process
  - Violates lepton number and B-L
  - Implies neutrinos are Majorana
- 0v2β at the tail of 2v2β

For ^{136}Xe, **$Q_{\beta\beta}$ = 2457.83 ± 0.37 keV**



From CUPID



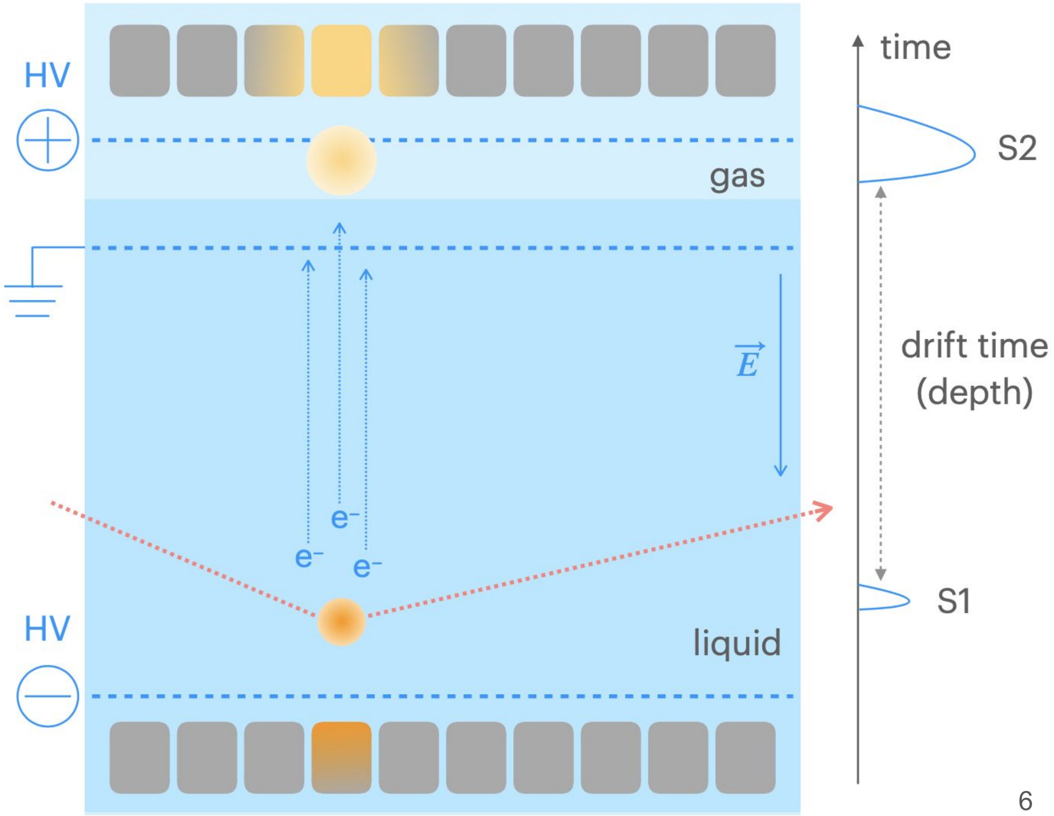
Signal reconstruction in LXe TPCs

Best energy resolution from S1 + S2. Near $Q_{\beta\beta}$

- LZ: **σ/μ = 0.67%** *JINST 18.04 C04007*
- XENON1T: **σ/μ = 0.80%** *EPJ C 80 1-9*
- XLZD targets:
  - Nominal 0.65%
  - Optimistic 0.60%

Good position resolution → multiple scatter rejection

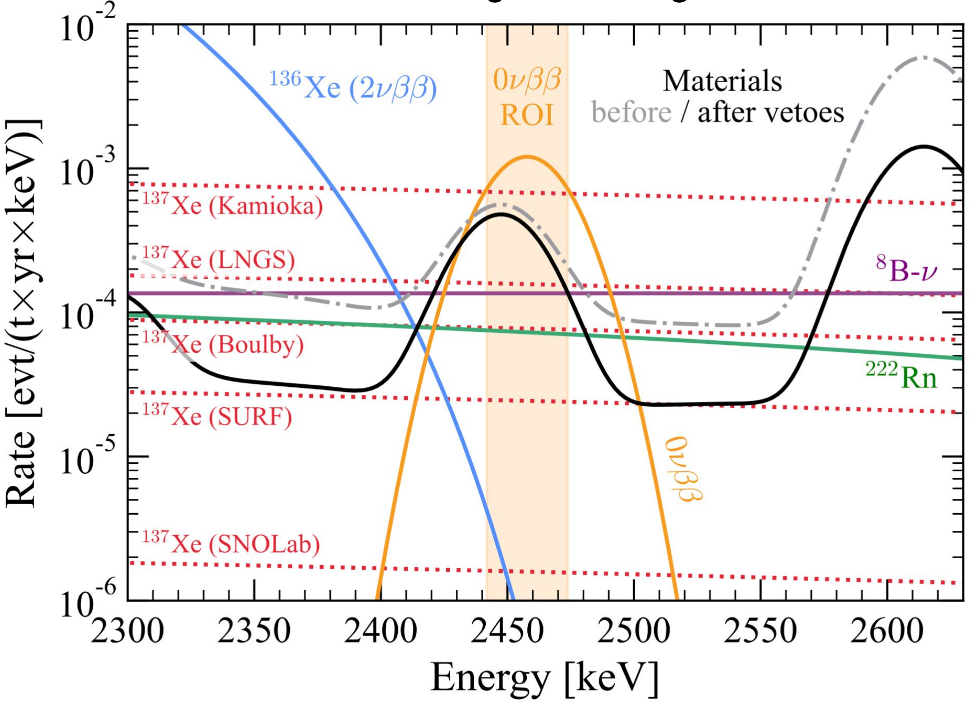
- Z-position from time between S1 and S2
  - 3mm resolution nominal
  - 2mm optimistic – *Saltao thesis*
- (X, Y) from S2 light pattern on top PMT array



Components of search space

Source	Type
^{136}Xe 0v2β	2457 keV $Q_{\beta\beta}$ line
^{214}Bi γ photoabsorption	2448 keV line
^{208}Tl Compton scatters	Continuum
^{222}Rn (^{214}Bi naked-β)	Continuum
^{8}B solar ν-e scatters	Continuum
Activated ^{137}Xe naked β*	Continuum
^{136}Xe 2νββ tail	Continuum (to $Q_{\beta\beta}$)

XLZD nominal performance (σ_E = 0.65%) and background mitigation



Background mitigation summary

Common mitigation for all background sources is good energy resolution!

Source	Type	Further mitigation
^{136}Xe 0ν2β	**2457 keV $Q_{\beta\beta}$ line**	–
^{214}Bi γ photoabsorption	**2448 keV line**	Radiopure materials, self-shielding
^{208}Tl Compton scatters	**Continuum**	Radiopure materials, self-shielding, veto
^{222}Rn (^{214}Bi naked-β)	**Continuum**	Radiopure materials, distillation, Bi–Po tagging
^{8}B solar ν-e scatters	**Continuum**	Irreducible
Activated ^{137}Xe naked β*	**Continuum**	Deep site, shielding
^{136}Xe 2νββ tail	**Continuum (to $Q_{\beta\beta}$)**	Irreducible

Material radiopurity

Minimize γ & β backgrounds (^{214}Bi and ^{208}Tl)

Techniques:

- Strict material choices, e.g.
  a. low-radioactivity PMTs
  b. custom field-shaping resistors
  c. cleanest batches of materials from LZ, XENON, and other assays
- Clean assembly protocols

Performance assumptions:

- Realistic: 25% of LZ's external background rate
  - based on current assays
- Optimistic: 10% of LZ level

^{214}Bi 2448 keV gamma SS counts

	LZ ($967\,\text{kg} \times 1000\,\text{d}$)		XLZD ($8.2\,\text{t} \times 10\,\text{yr}$)
Component	Nominal	Reduced	Projected
TPC PMTs	2.95	0.98	0.61
PMT structures	2.75	0.54	0.33
Field-cage resistors	2.46	0	0
Internal sensors	1.81	0.22	0.14
PMT bases	1.52	0.39	0.24
Cryostat	1.26	0.82	0.51
PMT cables	1.01	0.16	0.10
Field-cage rings	0.97	0.40	0.25
OD tank supports	0.73	0	0
OD foam	0.71	0	0
Skin PMTs	0.69	0.06	0.04
Other skin parts	0.68	0.05	0.03
Other components	3.56	1.42	0.88
Total	21.10	5.05	3.15

LZ projection from *Phys. Rev. C. 102:014602*

Self-shielding and veto systems

Reject external γ-ray backgrounds (^{214}Bi and ^{208}Tl)

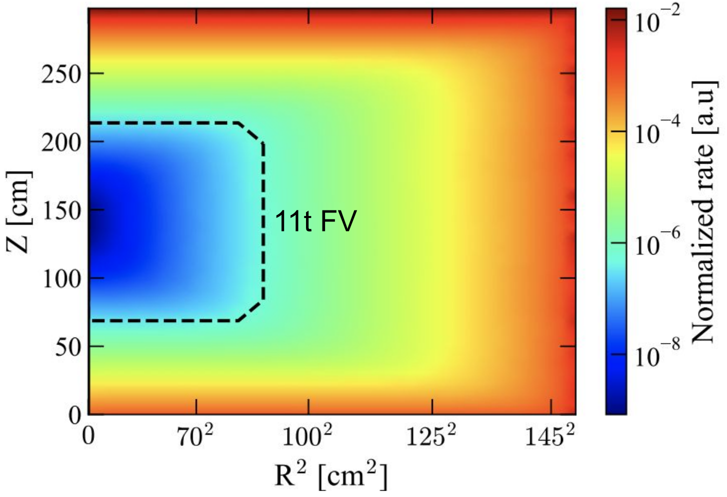
Fiducialize to escape the ^{214}Bi 2448 keV peak

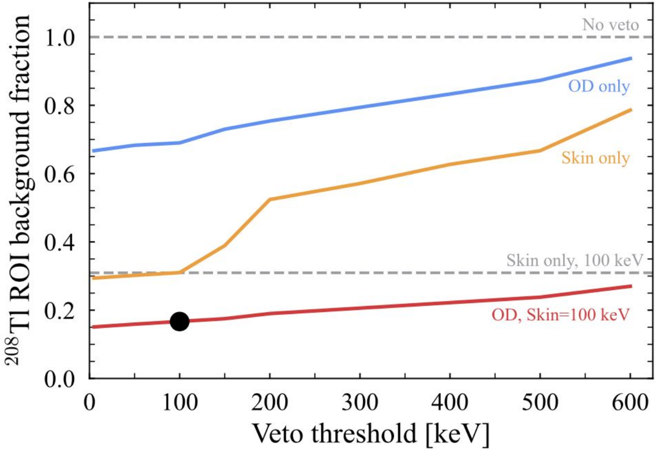
- LXe high density – 10 cm Compton interaction length
- 60t design: 8.2t (nominal) and 11t (optimistic)
- 80t design: 13.6t (nominal) and 17.2t (optimistic)

Veto system to reject ^{208}Tl Compton background

- Xenon skin and outer-detector (100 keV thresholds)
- Tag multiple-scattering Compton or associated gamma
- 83.3% rejection of ^{208}Tl in ROI

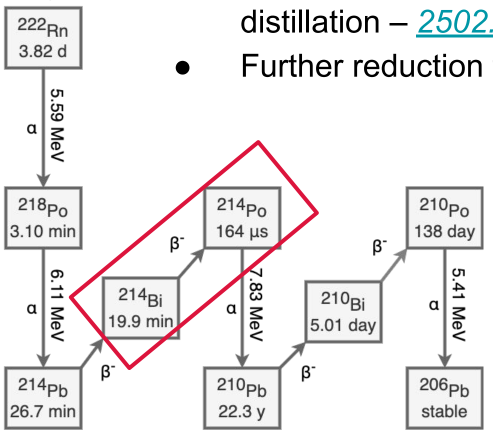
2448 keV single scatters in 60t baseline design





Further reducing β backgrounds

^{214}Bi β-decay



- Parent radon reduced by cryogenic distillation – 2502.04209
- Further reduction from Bi-Po tagging

^{214}Po is α emitter – tag β+α sequence and veto event

Performance assumptions:

- Nominal: 99.95% Bi–Po tagging efficiency
- Optimistic: 99.99%

Cosmogenic ^{137}Xe production

Siting matters: deeper → less muons → less activation

Assume laboratory neutrons can be fully mitigated

Performance assumptions:

- Nominal: LNGS (3600 m.w.e.)
- Optimistic: SURF (4300 m.w.e)

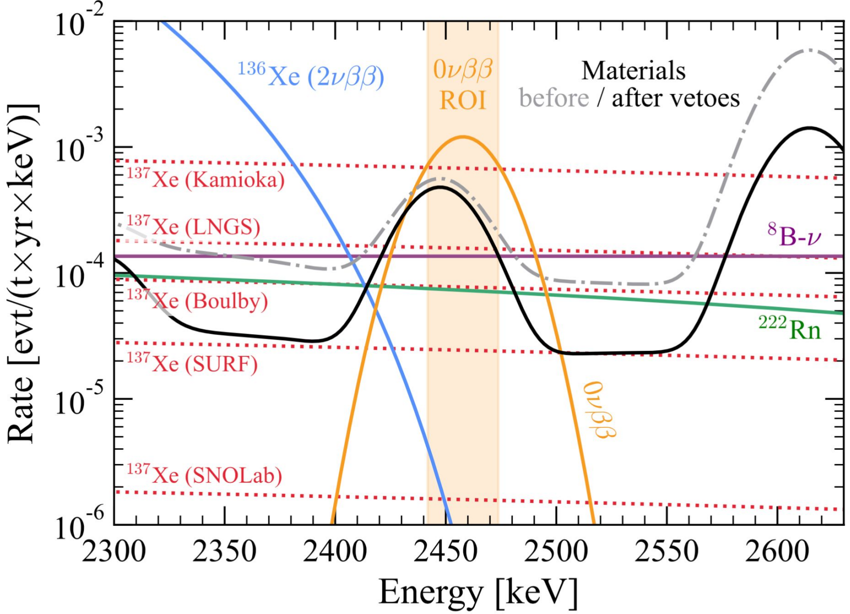
Site	Depth [m]	Depth [m w.e.]	μ flux [/(m^2·d)]	^{137}Xe rate [/(t·yr)]	SS ROI rate [evt/(t·yr·keV)]
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

Summary of projection scenarios

- Nominal
  - existing detector performances,
  - LNGS installation,
  - 25% of LZ gamma background rates
- Optimistic
  - improved detector performance,
  - SURF installation,
  - ambitious gamma reduction (10%)

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

XLZD nominal performance and background mitigation



Sensitivity projections

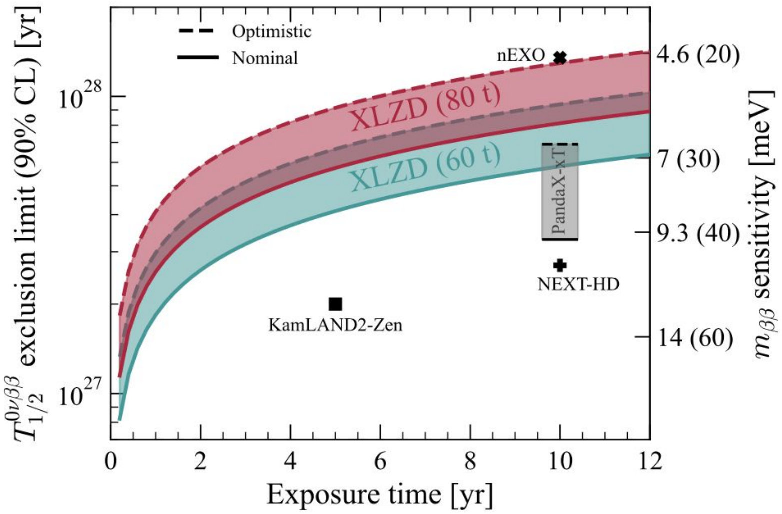
Counting experiment in an optimized fiducial volume

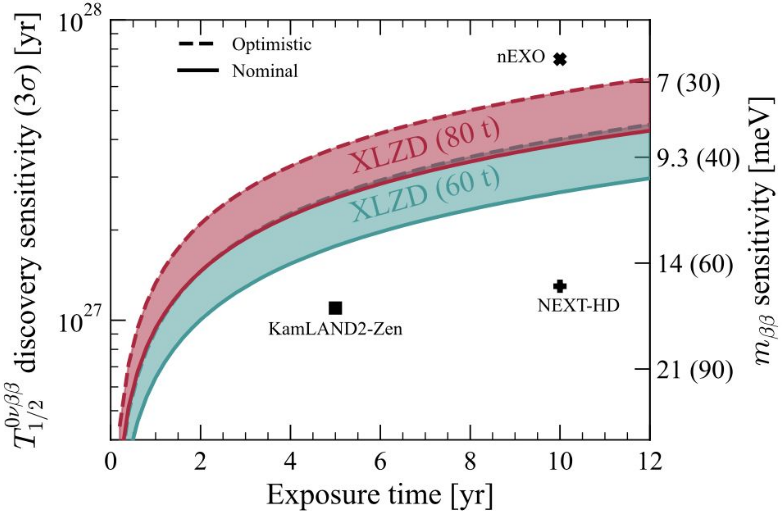
Sensitivity is primarily driven by target mass

Impact of design drivers on 3σ discovery sensitivity

(Loss from reverting each optimistic input to nominal, all else fixed)

- Gamma background: 15.5%
- Experiment depth: 11%
- BiPo tagging efficiency: 6%
- Single-/multiple-scatter discrimination: 4.3%
- Energy resolution: 2.5%



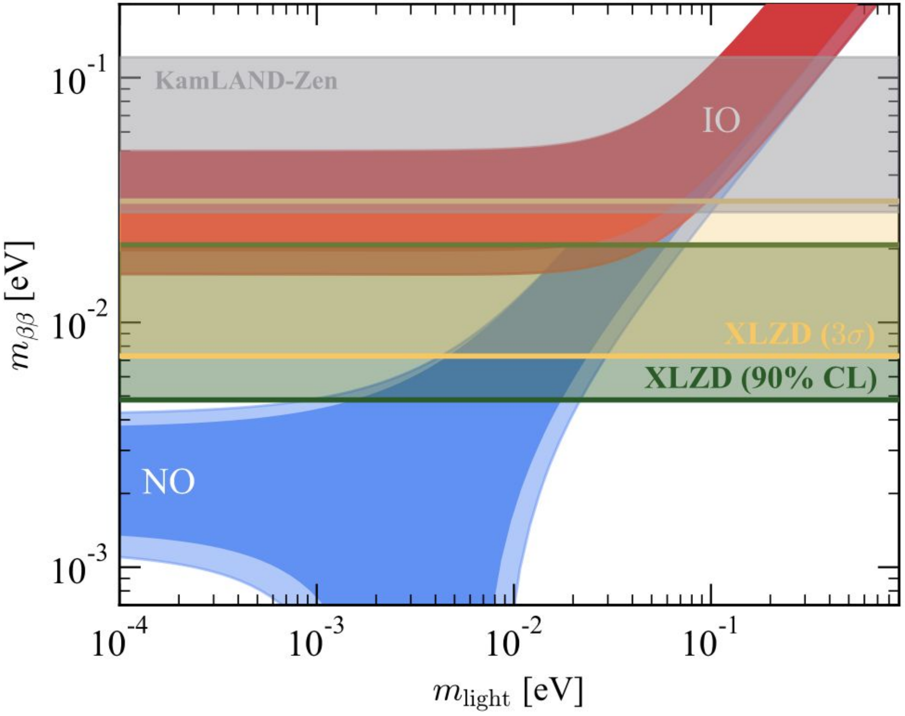


Sensitivity to effective Majorana mass

XLZD probes neutrino mass ordering, assuming only Majorana neutrino exchange

Band widths set by uncertainties of nuclear matrix elements

XLZD 80t optimistic scenario



Conclusions

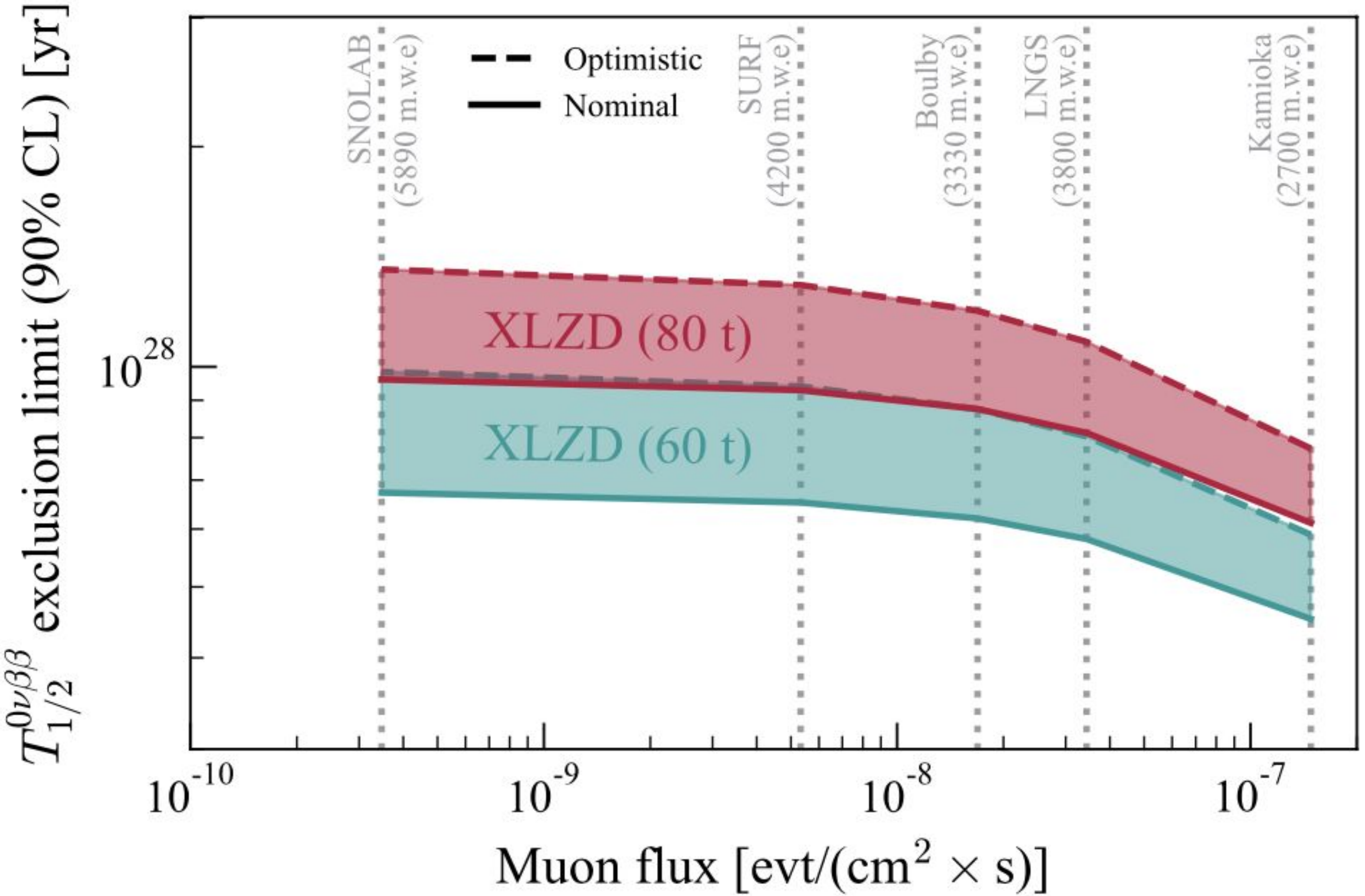
XLZD is a scalable rare-event observatory — with world-leading discovery potential for both dark matter and $0\nu\beta\beta$

XLZD builds on mature dual-phase xenon technology

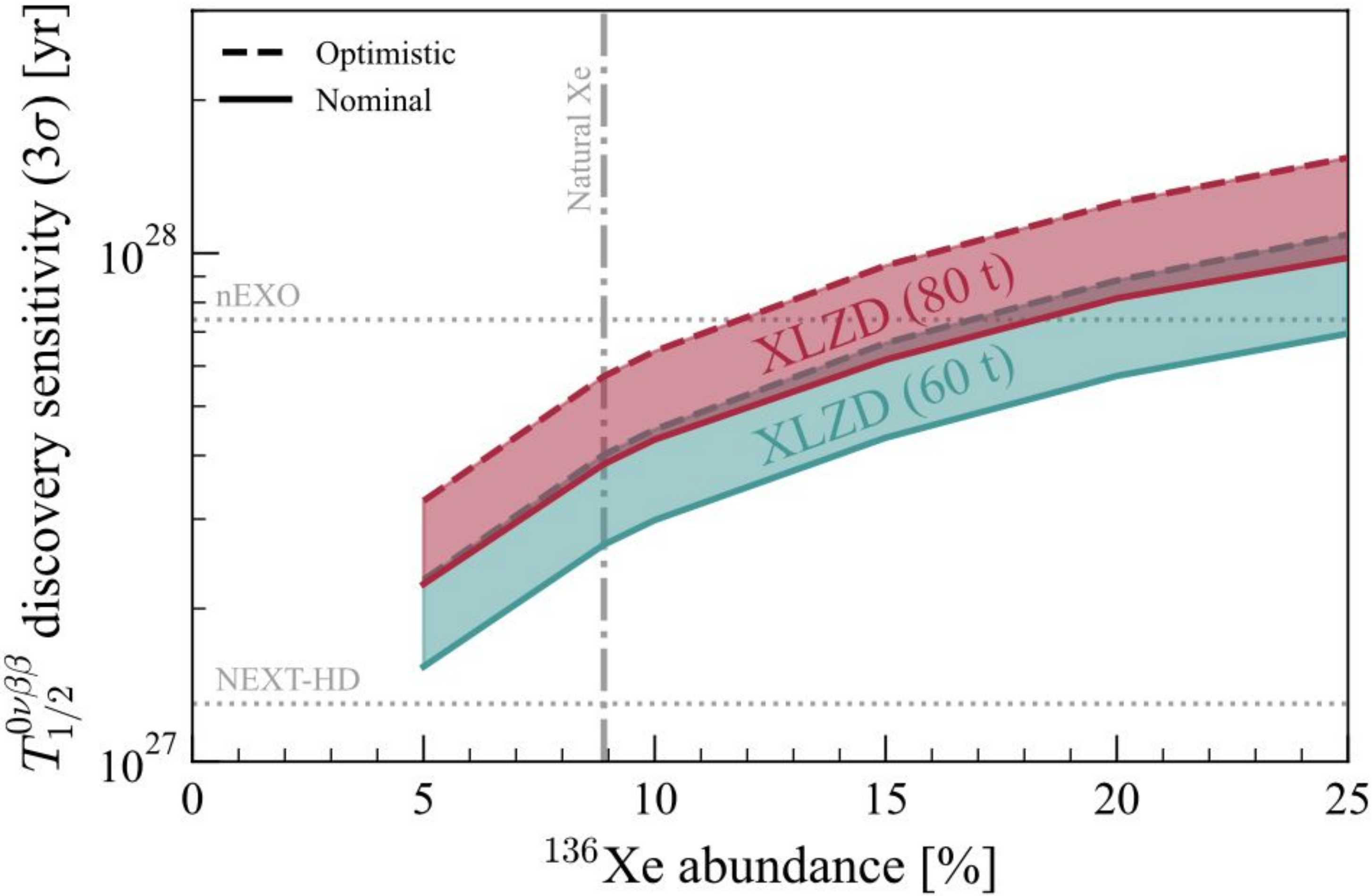
- 60–80t of active mass
- good background control and resolution

With natural xenon 80t optimistic scenario for XLZD can

- Discover $0\nu\beta\beta$ at 3σ for half-lives up to 5.7×10^{27} yr
- Exclude half-lives up to 1.3×10^{28} yr at 90% CL
- Exclude the inverted neutrino mass ordering and explore the normal ordering

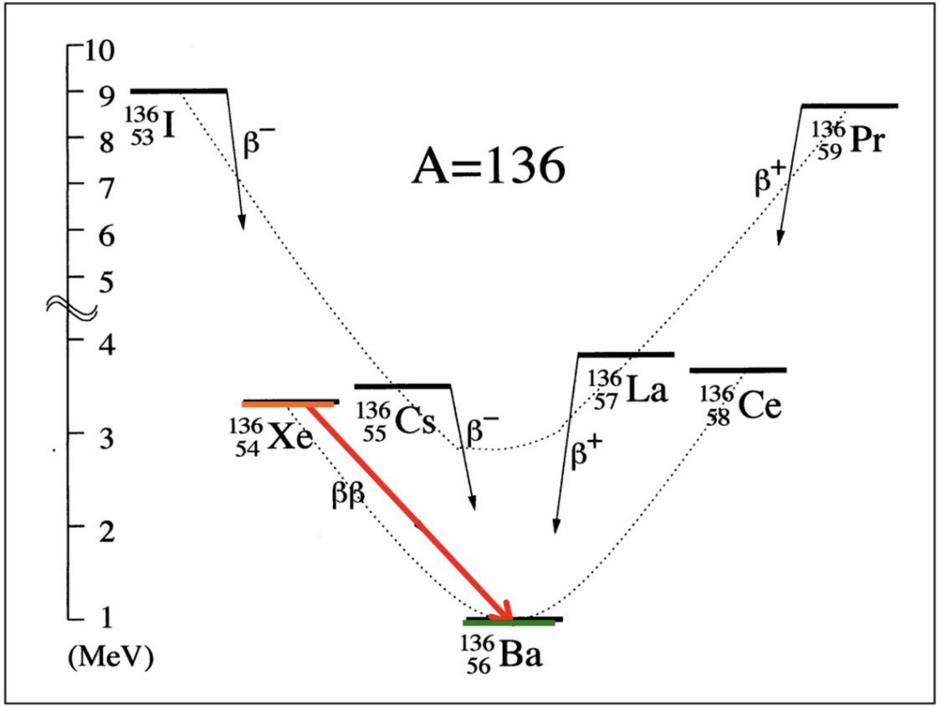


SNOLAB (5890 m.w.e)
SURF (4200 m.w.e)
Boulby (3330 m.w.e)
LNGS (3800 m.w.e)
Kamioka (2700 m.w.e)
Optimistic
Nominal
XLZD (80 t)
XLZD (60 t)
$T_{1/2}^{0\nu\beta\beta}$ exclusion limit (90% CL) [yr]
10^{28}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
Muon flux [evt/(cm^2 × s)]



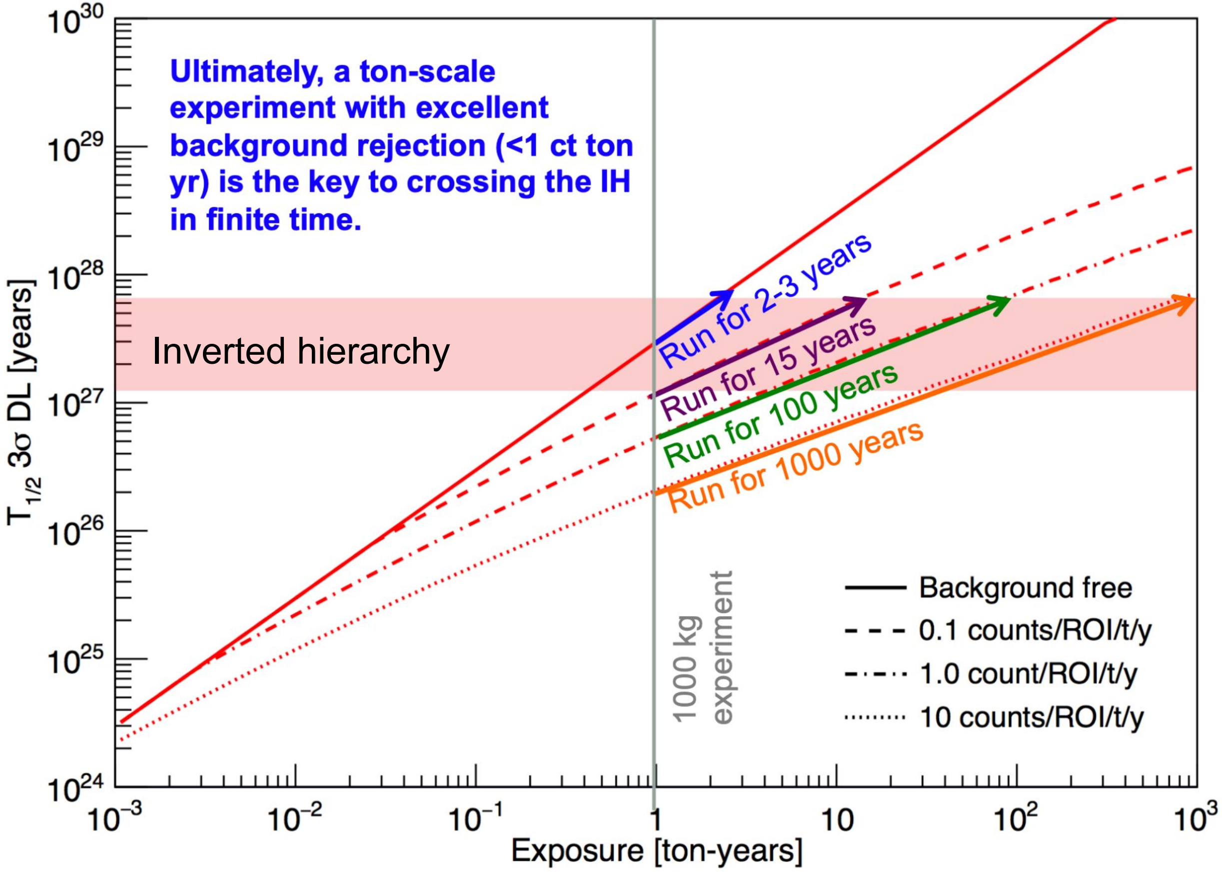
Optimistic
Nominal
Natural Xe
nEXO
NEXT-HD
XLZD (80 t)
XLZD (60 t)
10^{28}
10^{27}
0
5
10
15
20
25
$T_{1/2}^{0\nu\beta\beta}$ discovery sensitivity (3σ) [yr]
^{136}Xe abundance [%]

A = 136 isobar

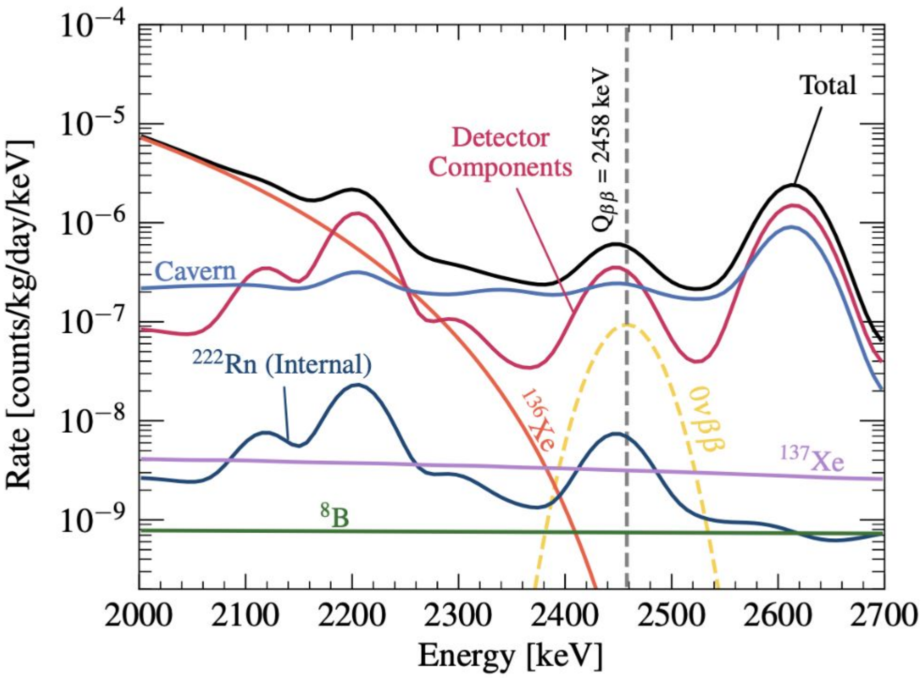


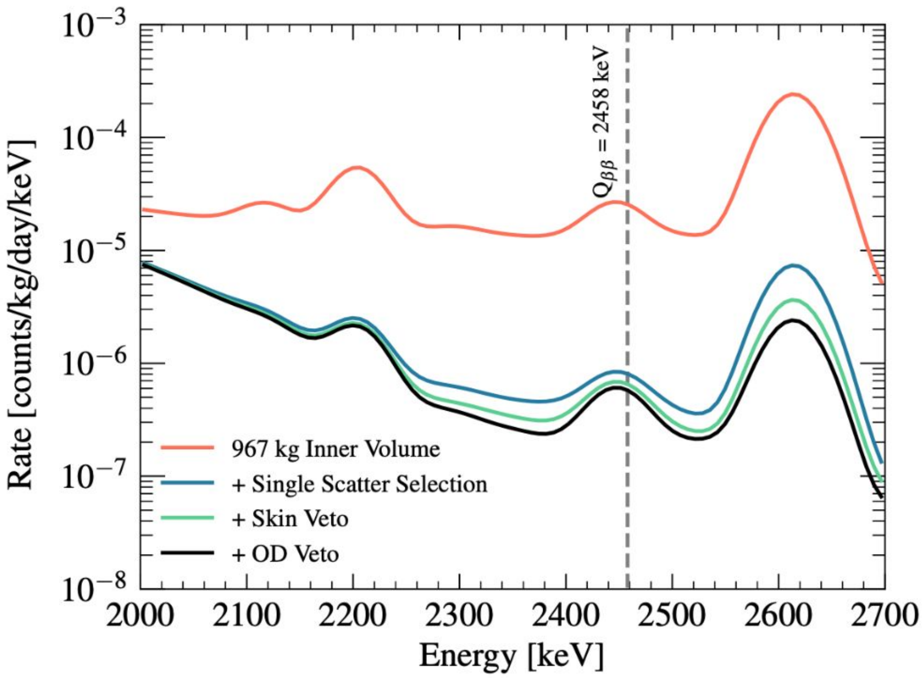
A=136
10
9
8
7
6
5
4
3
2
1
(MeV)
$^{136}_{53}$I
β⁻
$^{136}_{59}$Pr
β⁺
$^{136}_{57}$La
β⁺
$^{136}_{58}$Ce
$^{136}_{55}$Cs
β⁻
$^{136}_{54}$Xe
ββ
$^{136}_{56}$Ba

Physics of 0v2b TASI: https://arxiv.org/pdf/2108.09364



LZ 0V2B simulation





Material screening

- Voltage grading resistors – EXO200 https://arxiv.org/pdf/1202.2192
- PMT base capacitors – XENON1T https://arxiv.org/pdf/1705.01828
- Low radioactivity PMTs – https://indico-tdli.sjtu.edu.cn/event/1861/contributions/11609/attachments/4517/7175/XeSAT2024_PMT12699.pdf
- Cleanest PTFE, stainless steel, copper, Kovar, and Kapton –
    - LZ assay: https://arxiv.org/pdf/2006.02506
    - XENON1T assay: https://arxiv.org/pdf/1202.2192