Overview of searches for $0\nu\beta\beta$ in Xe

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Recommended Values for Neutrinoless Double Beta Decay Matrix Elements
Institute for Nuclear Theory
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Why ^{136}Xe?

Why ^{136}Xe?

"Xe (and Te).... from the shell model perspective, they are my favorite ones"

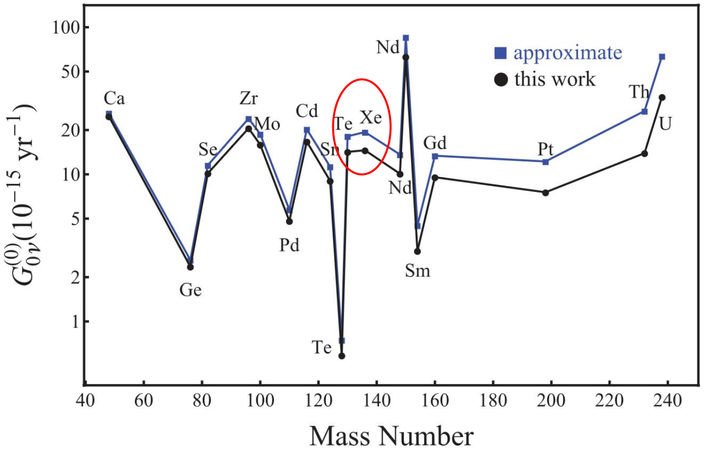
- Luigi, yesterday

Why Xe?

Isotope	Natural abundance (%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Dolinski et al., ANRPS **69** 219-251 (2019)

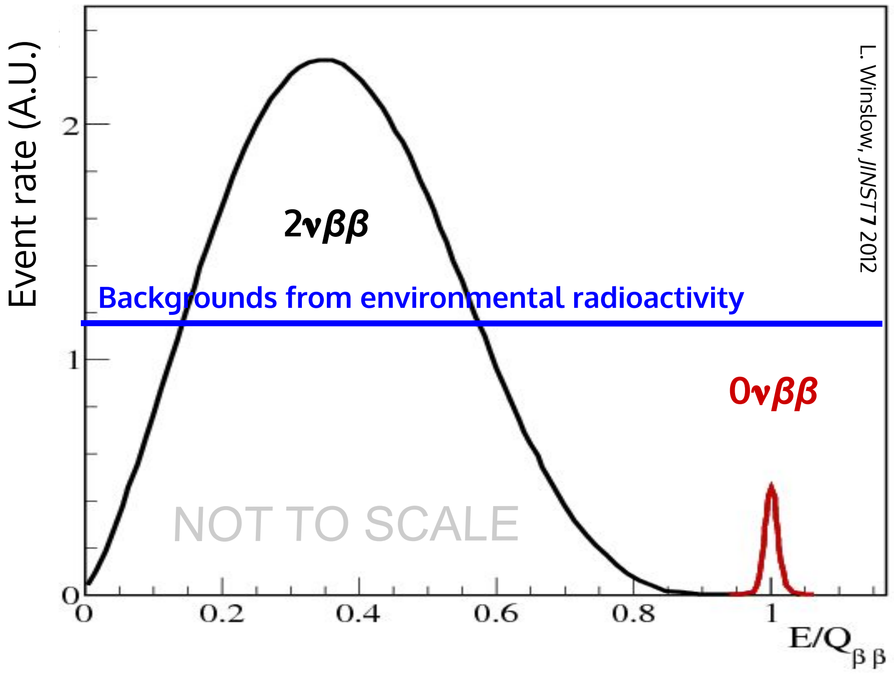
Phase space factors



Kotila & Iachello, PRC **85** 034316 (2012)

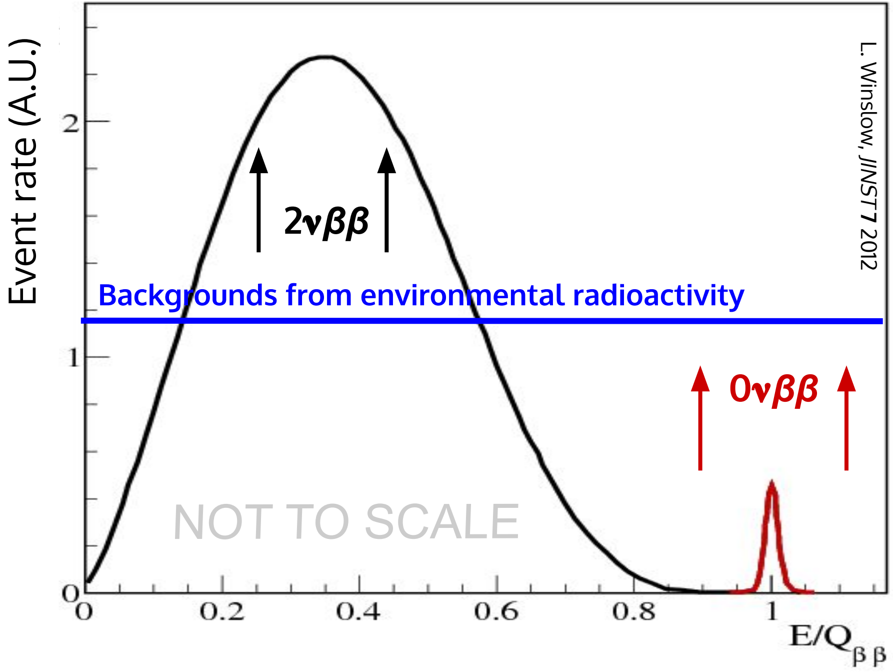
- Relatively high natural abundance of ^{136}Xe (8.9%)
- Relatively high Q-value (Q_{bb} = 2.457 MeV)
- Gaseous and inert in its natural form, straightforward purification and enrichment
- No long-lived radioactive isotopes
- **Highly scalable, ultra-low-background detector technologies available**

Optimizing a 0νββ search



What drives the sensitivity of a 0νββ search experiment?

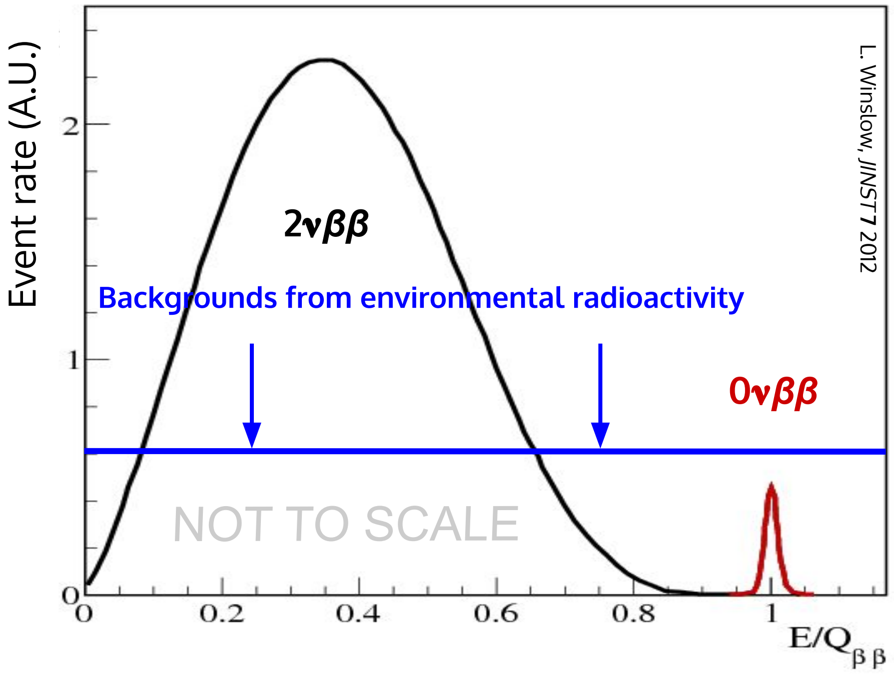
Optimizing a 0νββ search



What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope

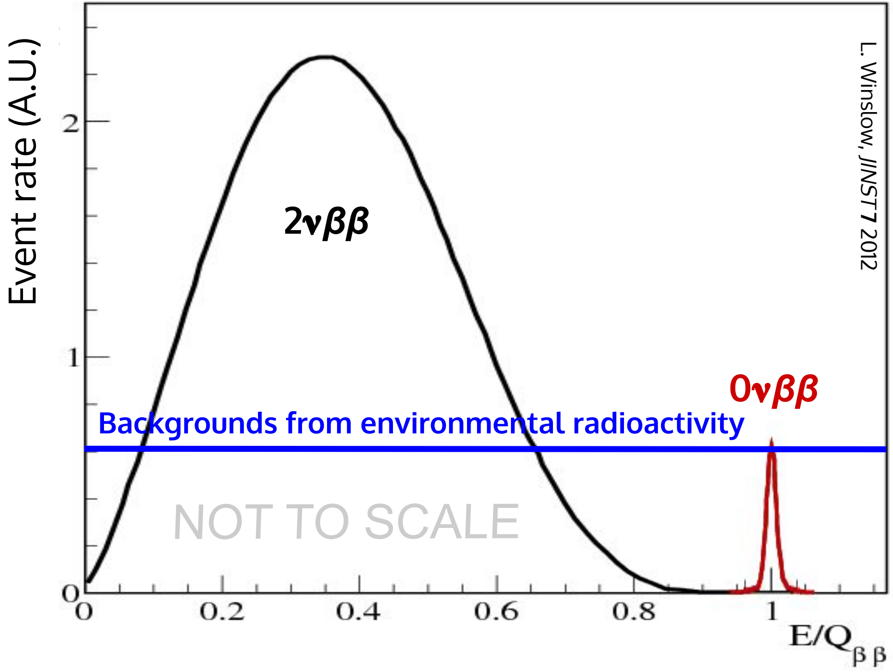
Optimizing a 0νββ search



What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope
2. Ultra-low backgrounds

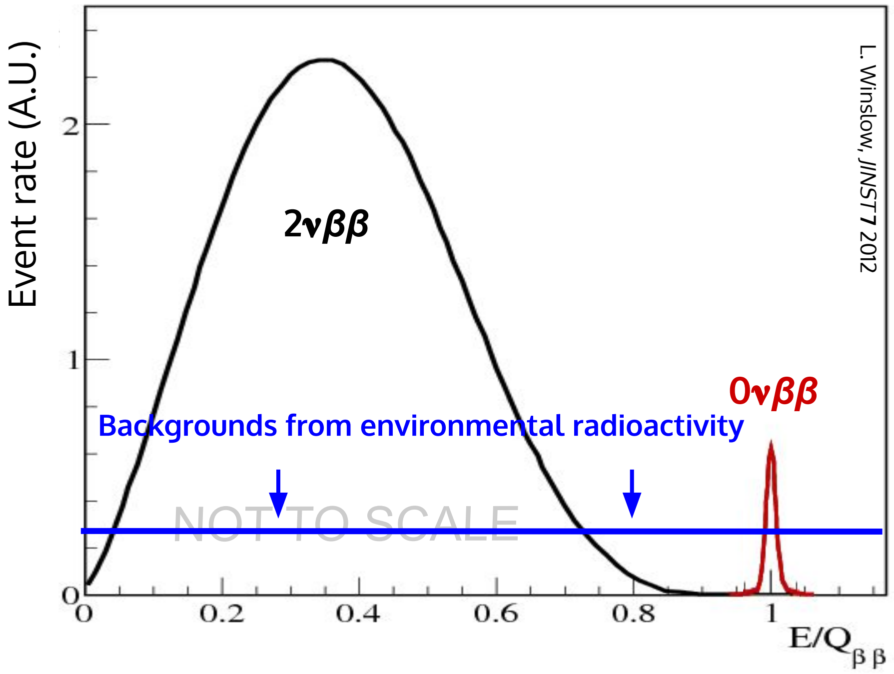
Optimizing a 0vββ search



What drives the sensitivity of a 0vββ search experiment?

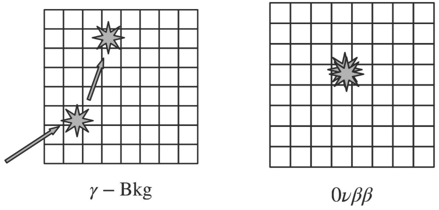
1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
3. Good energy resolution

Optimizing a 0νββ search



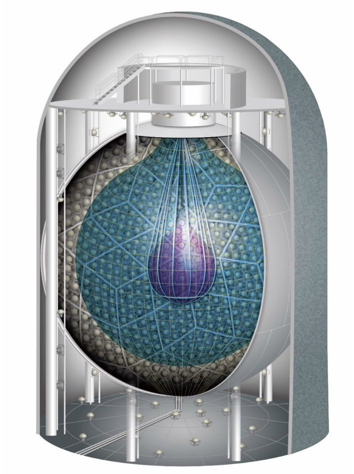
What drives the sensitivity of a 0vββ search experiment?

1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
3. Good energy resolution
4. Signal/background discrimination capabilities: **particle ID**



Experimental approaches with Xe

Loaded liquid scintillator

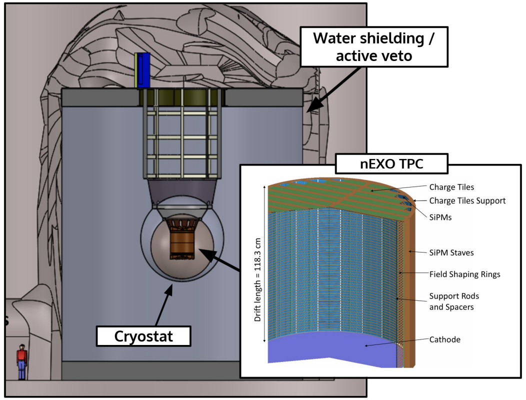


Cost effective and "simple", already scaled to ~1 tonne

Very little material near sensitive Xe volume, lots of shielding/veto

Background ID via timing & position reconstruction

Liquid xenon time projection chamber (LXe TPC)



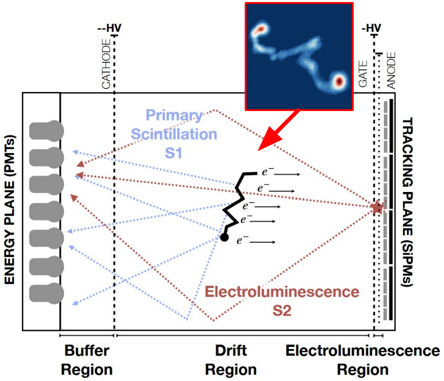
Mature technology for 0νββ (EXO-200)

Scalable: multi-tonne-scale detectors demonstrated (LZ/XENON/PandaX)

Monolithic, dense LXe provides self-shielding and in-situ bkg measurement

Excellent additional background rejection w/ 3D vertex reconstruction

Gaseous xenon time projection chamber (TPC)



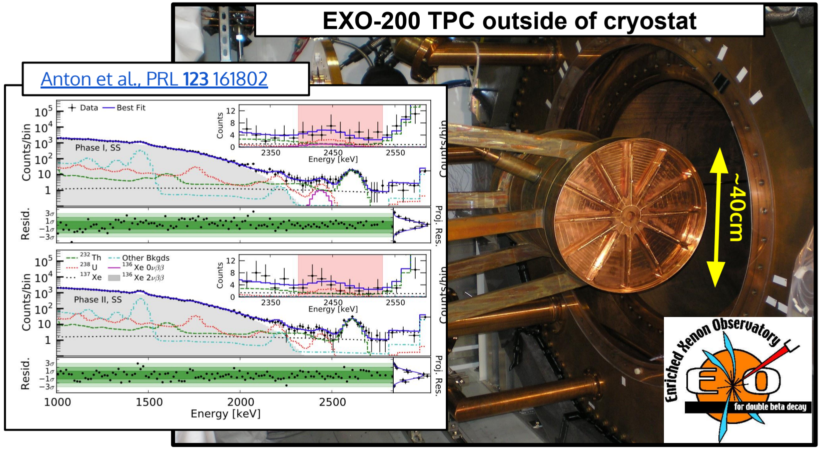
Scalable, in principle (100kg running now)

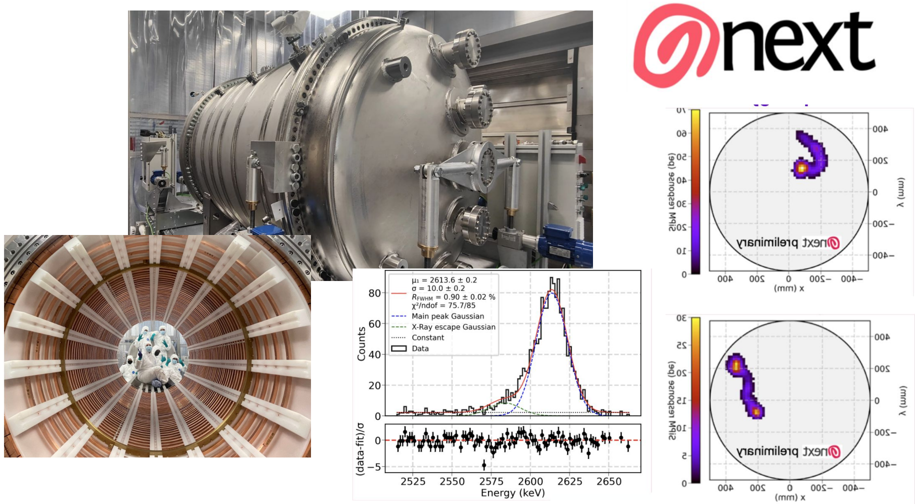
Full tracking provides powerful bkg rejection (also new physics sensitivity??)

Excellent energy resolution (<1% FWHM)

Not yet as mature as others, but very attractive for the future (Ba-tagging?)

Dedicated LXe and GXe TPCs for 0νββ





EXO-200: 2011 - 2018

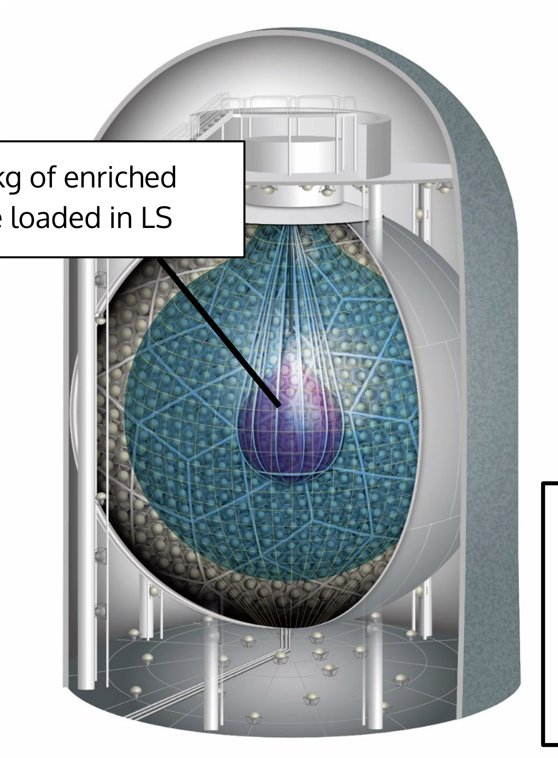
- First 100kg-class 0νββ search
- Discovered 2νββ in ^{136}Xe
- $T_{1/2} > 3.5 \times 10^{25}$ yr for 0νββ in ^{136}Xe (*PRL* **123**, 2019)
- Multiple leading limits on other decay modes of ^{136}Xe and ^{134}Xe
- Pioneered ultra-low-background LXe TPC technology, laid groundwork for tonne-scale

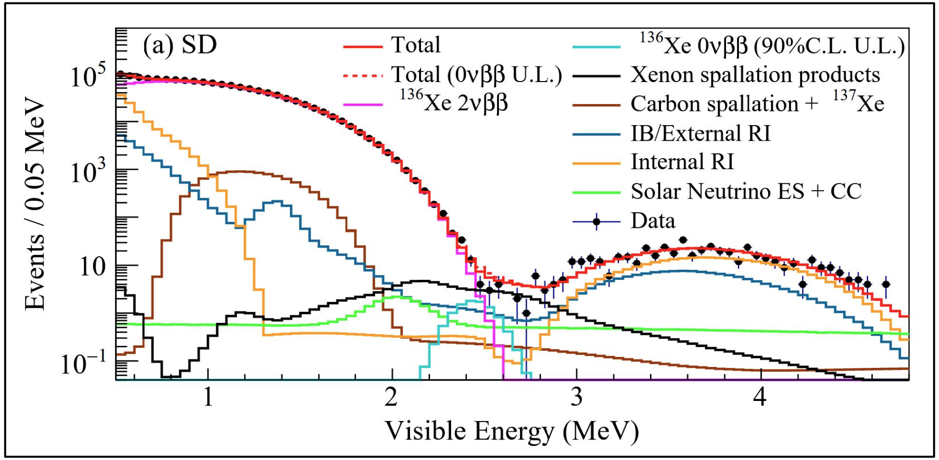
NEXT: ongoing

- High-pressure gas xenon TPC program
- Demonstrated measurement of 2νββ, excellent energy res., powerful tracking and topological reconstruction
- Currently running NEXT-100 (100kg target)
  - Low-pressure data in hand, working to move to high-pressure, exp. sensitivity $T_{1/2} \sim 10^{25}$ yrs

KamLAND-Zen 800

745kg of enriched ^{136}Xe loaded in LS





Currently world-leader: $\mathbf{T_{1/2} > 3.8 \times 10^{26}}$ **yrs**

Key backgrounds:

- **Long-lived Xe spallation products** → Muon flux
- **Tail of $2\nu\beta\beta$ distribution** → Energy resolution
- **Radioactivity, mainly inner balloon** → Material selection / PID

Material borrowed from [Haruhiko Miyake's slides from XeSAT 2026]

The near future: KamLAND2-Zen

Targeted upgrades to reach $T_{1/2} > 10^{27}$ yrs

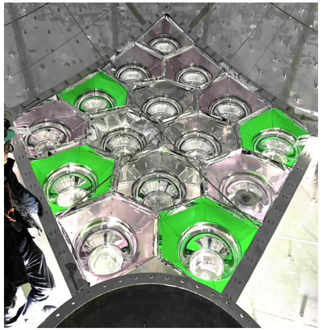
Increasing ^{136}Xe mass to ~1000kg

Reducing radioactive background from balloon

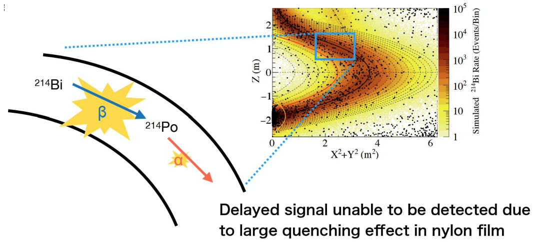
- Investigating *scintillating* balloon for α tagging

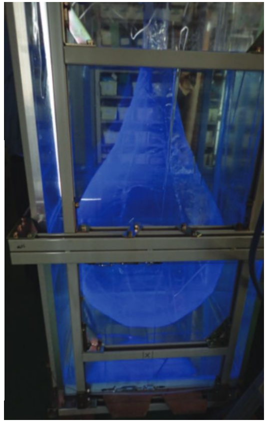
Improving energy resolution: 4% → ~2% FWHM @ 2.6 MeV

- Improved light yield of scintillator
- Improved DAQ
- Improved light collection w/ mirrors and high-QE PMTs

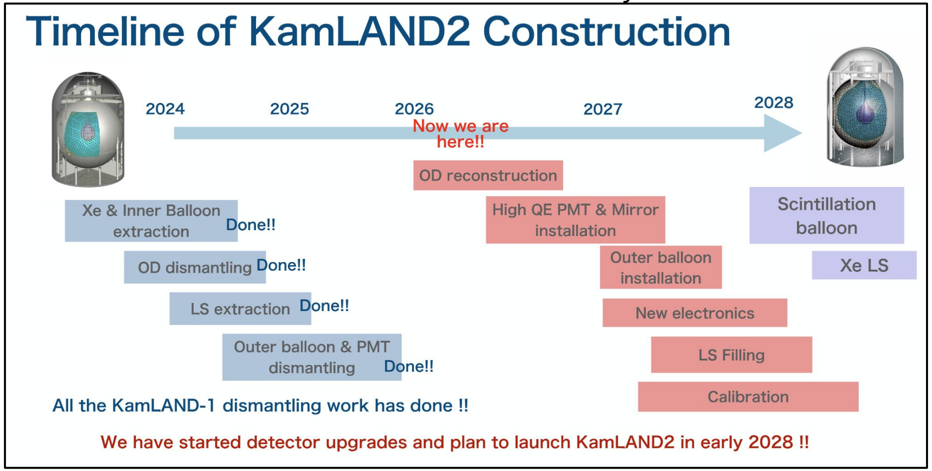


Make balloon from scintillating PEN to tag surface alphas



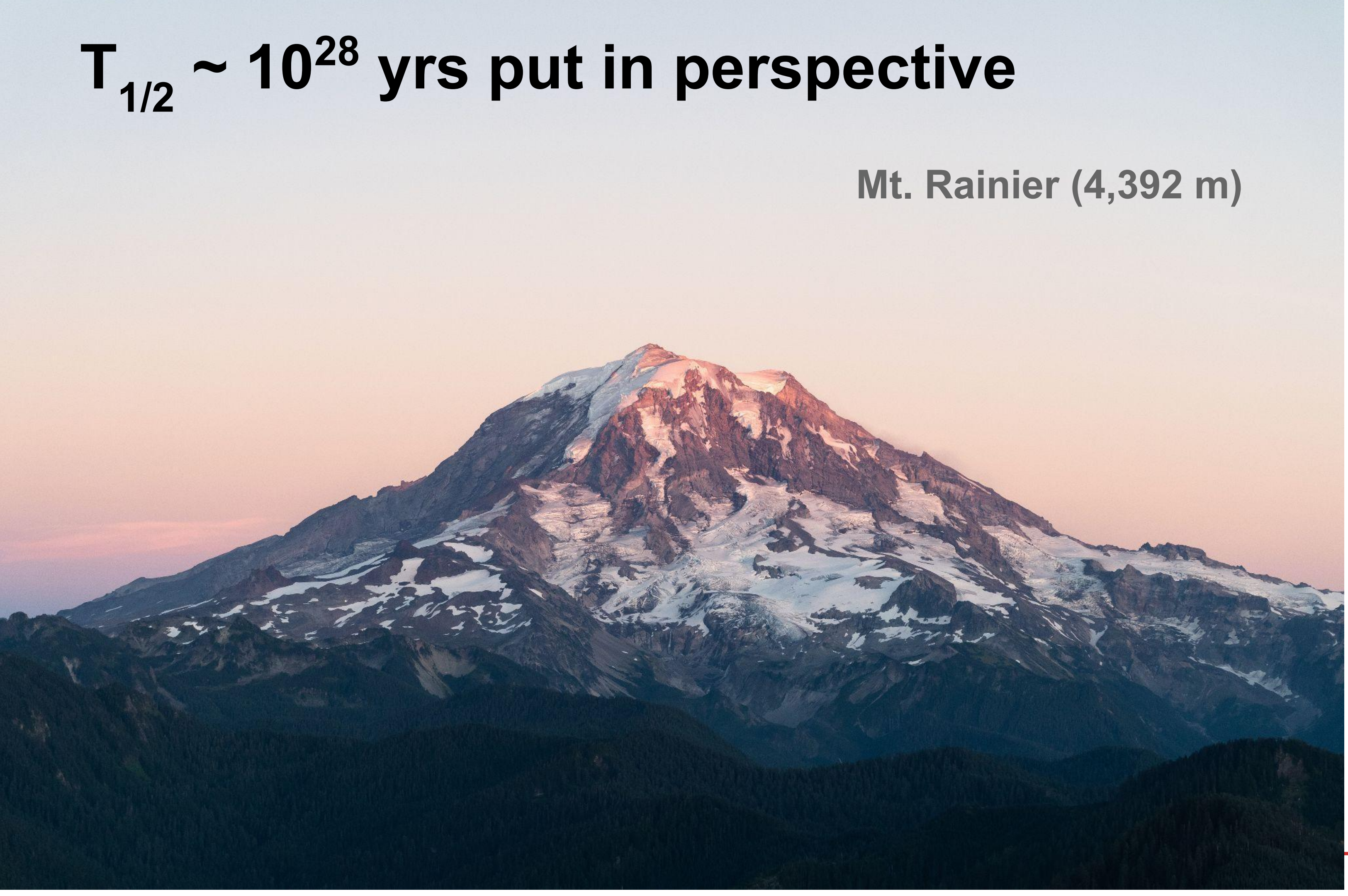


Slide taken from H. Miyake



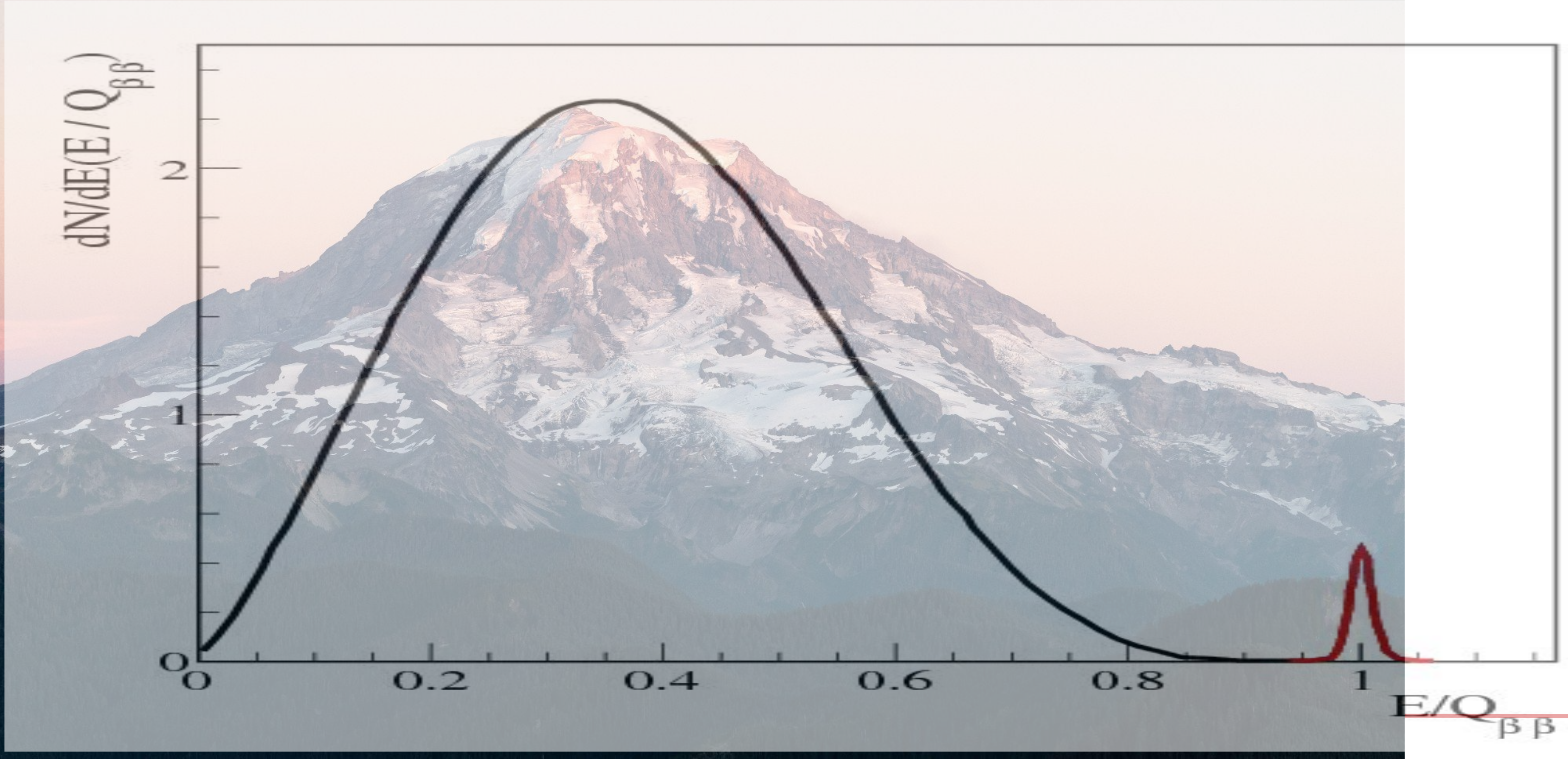
Looking towards the tonne-scale

$T_{1/2} \sim 10^{28}$ yrs put in perspective

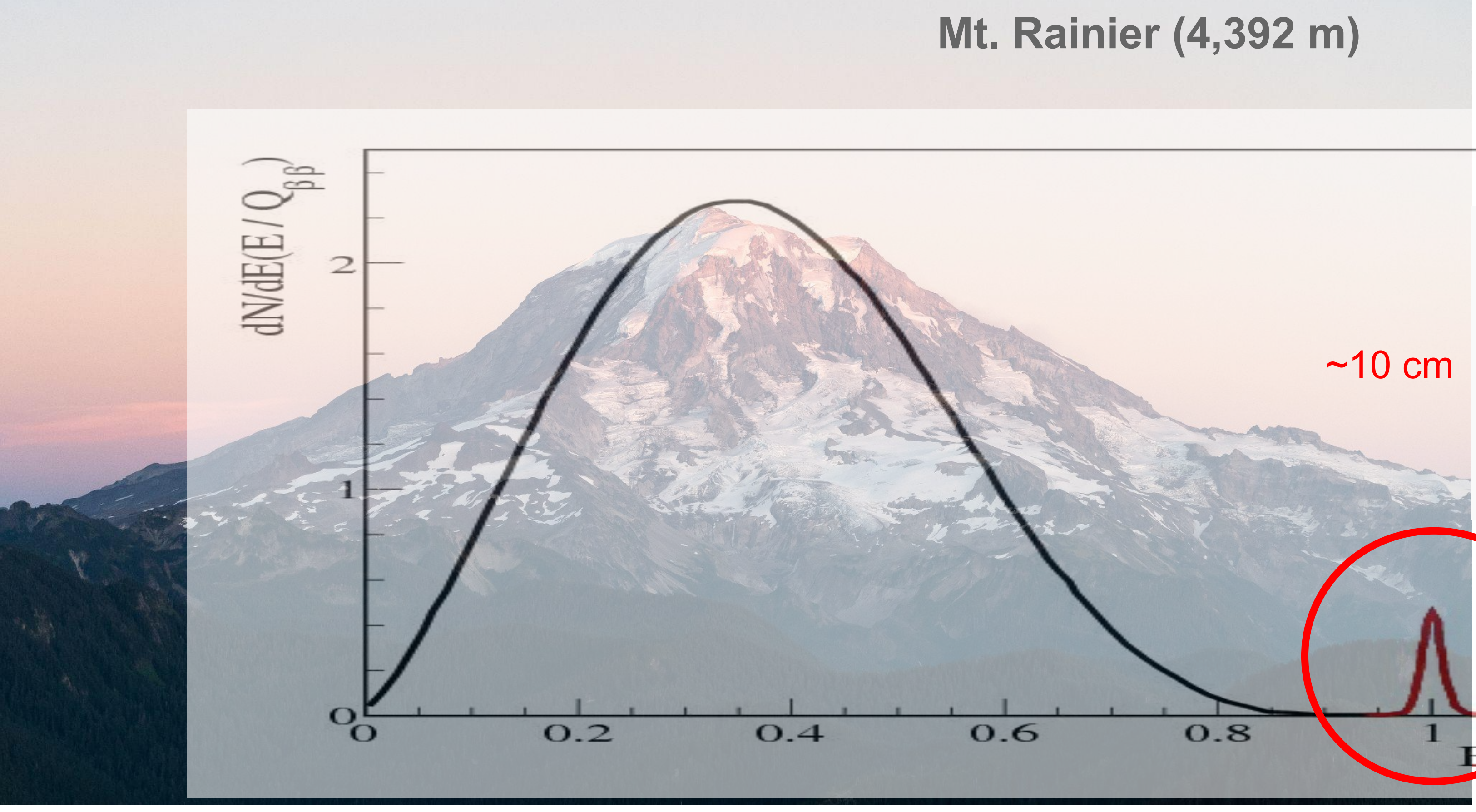


$T_{1/2} \sim 10^{28}$ yrs put in perspective

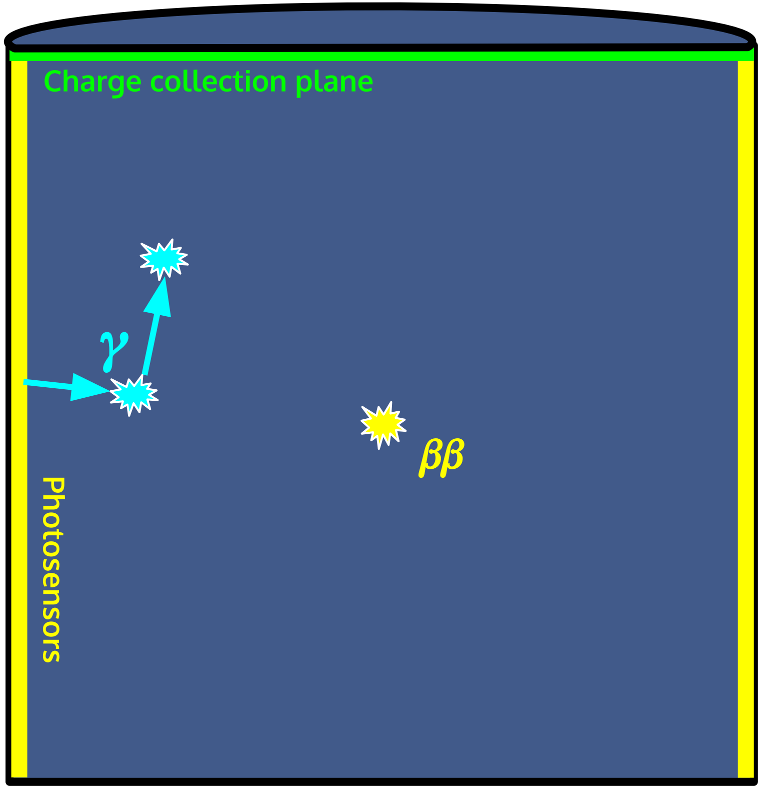
Mt. Rainier (4,392 m)



$T_{1/2} \sim 10^{28}$ yrs put in perspective



LXe TPCs can address this challenge



A LOT of the ββ isotope (^{136}Xe)

- Ton-scale LXe TPCs are already operating
- Enrichment is straightforward

Low, well-characterized backgrounds in MeV range (low radioactivity)

- Very low intrinsic backgrounds
- Excellent self-shielding reduces external radioactivity

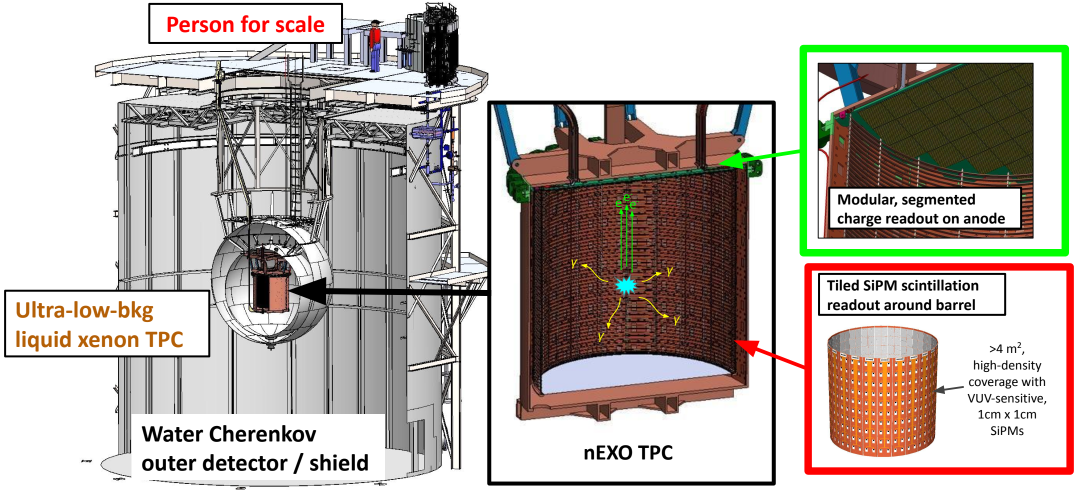
Good energy resolution

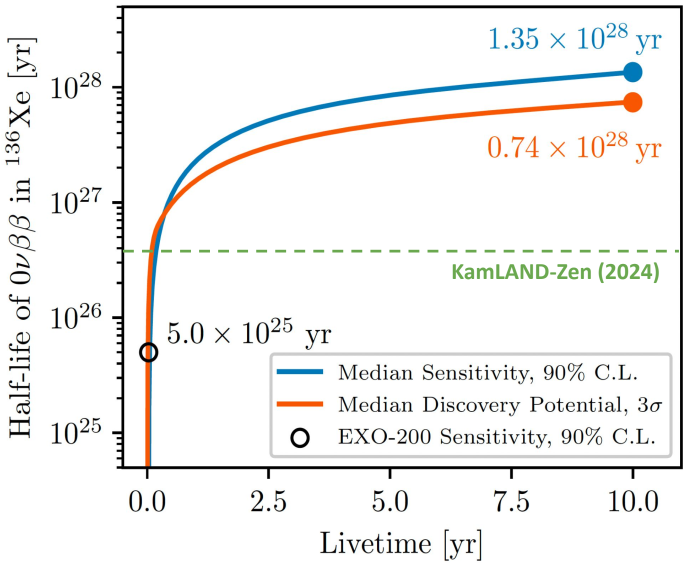
- Combining charge and light can reach <1%

Signal/background discrimination

- Powerful position reconstruction and multi-site rejection to characterize and reject BG

Enriched LXe TPC: nEXO

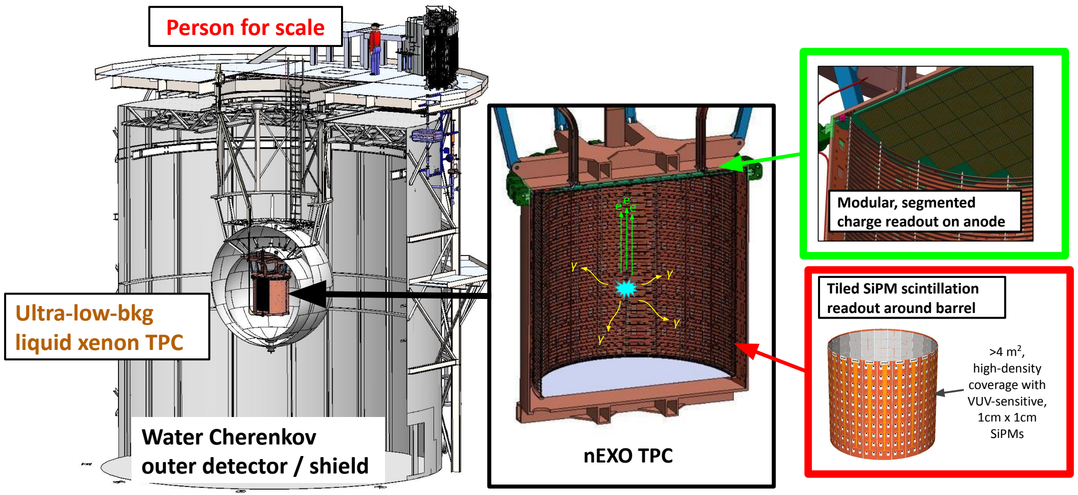


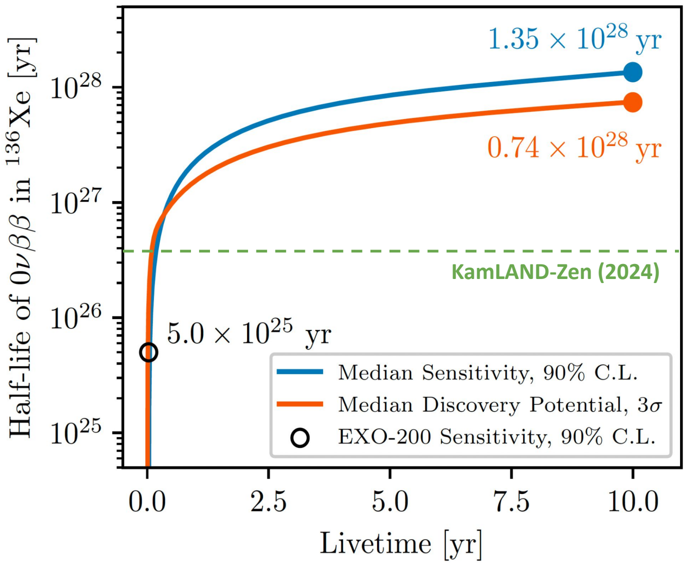


Mature, "shovel-ready" conceptual design for a 5-tonne, 90%-enriched LXe TPC

Extensive R&D program developed readout and detector hardware to achieve $T_{1/2}$ ~ 10^{28} yr sensitivity

Enriched LXe TPC: nEXO





Mature, “shovel-ready” conceptual design for a 5-tonne, 90%-enriched LXe TPC

Extensive R&D program developed readout and detector hardware to achieve $T_{1/2} \sim 10^{28}$ yr sensitivity

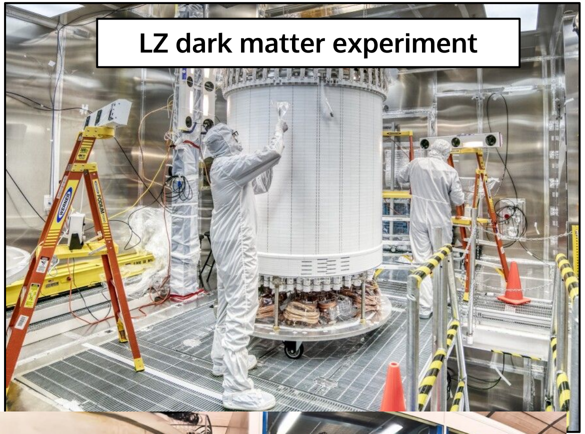
CD-1 Director’s Review successful in July 2024, but project was **paused indefinitely by DOE in Dec. 2024 due to funding constraints in DOE-NP**

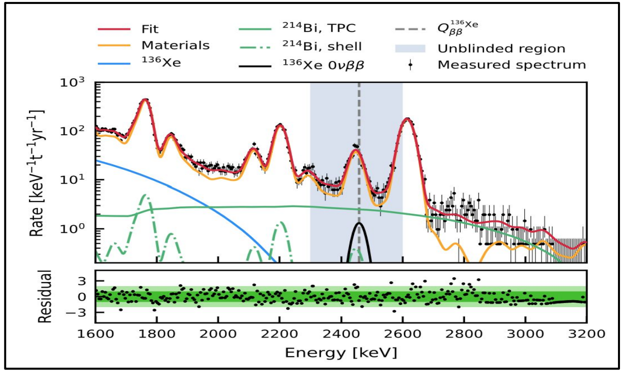
Unfortunately, there may not be a path forward for nEXO in the current funding environment.

A possible path forward: dual-phase ^{nat}Xe TPCs

Low-background ^{nat}Xe TPCs are widely deployed to search for WIMP dark matter

- LZ, XENONnT, and PandaX-4T **already operating tonne-scale, low-background ^{nat}Xe detectors**
- Demonstrated **long-term stable operation, event reconstruction, and excellent energy resolution (σ<0.7%)**
- Currently **background limited for ββ** due to material choices and shielding geometries





XENON, PhysRevC.106.024328

PandaX-xT

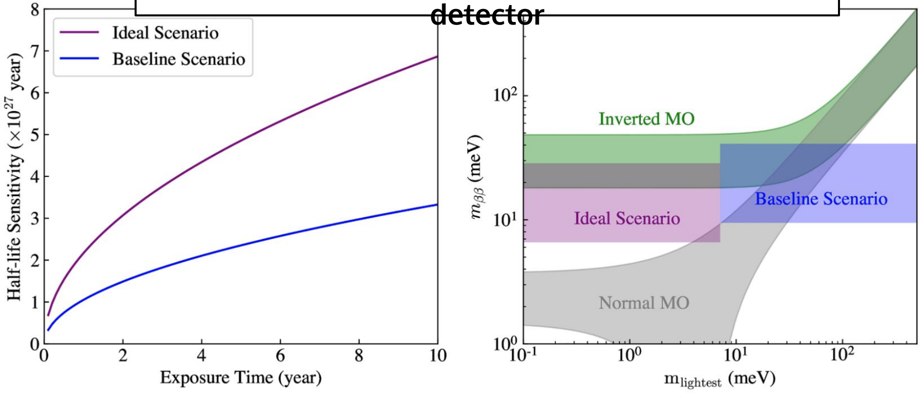
20tons of Xe! Photos borrowed from Ning Zhou's XeSAT talk

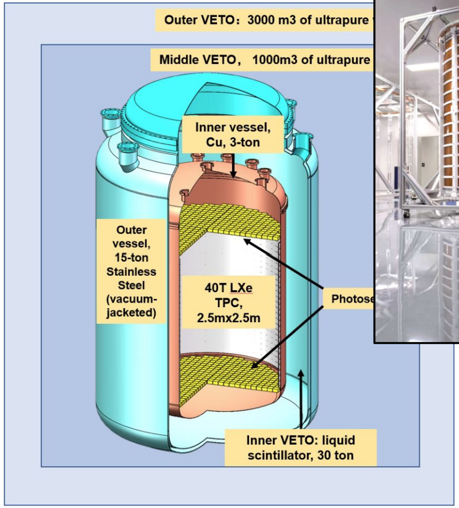
Next-generation dual-phase TPC at Jinping Underground Laboratory in Liangshan, China

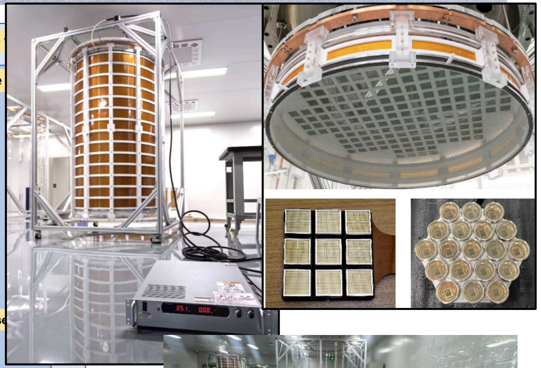
Ambitions for a 40t fiducial volume of ^{nat}Xe, but staged approach **starting with 20 ton DM search**

- PandaX-20T commissioning 2027, physics operation planned to start 2028

^{136}Xe $0\nu\beta\beta$ sensitivity projections for 40t detector

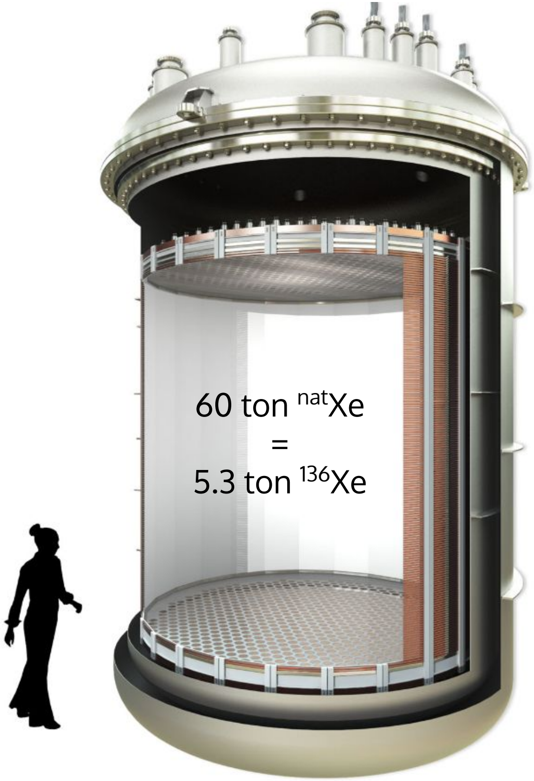






Abdukerim et al., Sci Chi Phys **68** 221011 (2025)

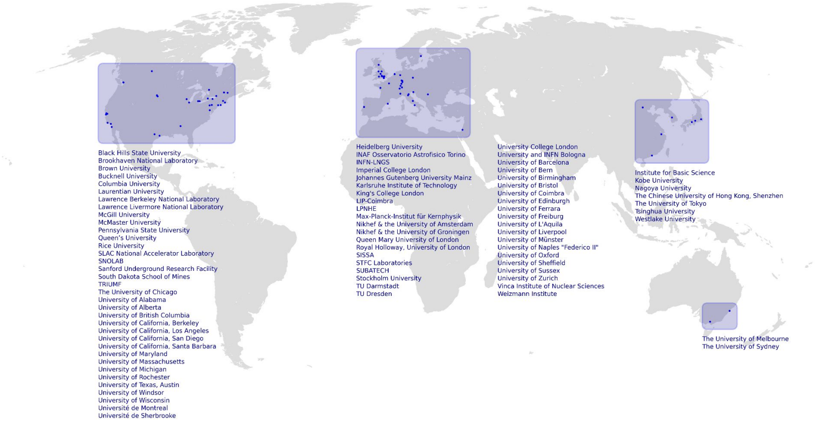
The XLZD rare event observatory



Global collaboration aiming to develop the next-generation dual-phase LXe detector → **conceptual design report in prep**

- 60 ton initial design, 80t option if Xe market favorable
- Primary science targets: WIMP dark matter & ^{136}Xe 0νββ search
- Four sites identified as feasible: Boulby, SNOLAB, SURF, LNGS

→ **Opportunity for both G3 dark matter (P5) and tonne-scale 0νββ search (NP LRP) in same detector**

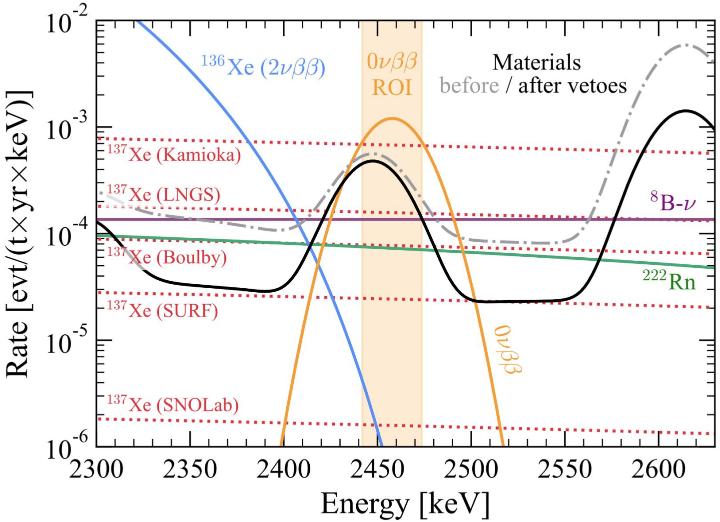


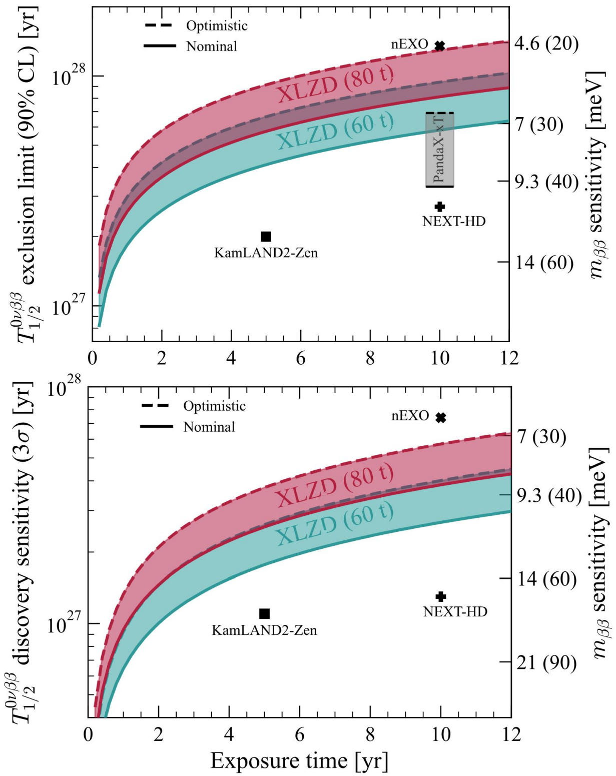
XLZD Design Book: Eur. Phys. J. C (2025) 85: 1192

0νββ sensitivity of XLZD

Initial assessment of 0νββ sensitivity published: XLZD, *J Phys G* **25** (2025) 045102

- Simplified sensitivity estimate with scaled up detector design and background model from LZ
- Identified/evaluated key backgrounds and design options for improving sensitivity
- **After nEXO, XLZD could be the most sensitive next-gen ^{136}Xe search**





Currently ongoing: new, bottom-up sensitivity projection to establish conceptual design and requirements

Other interesting rare decays in ^{nat}Xe

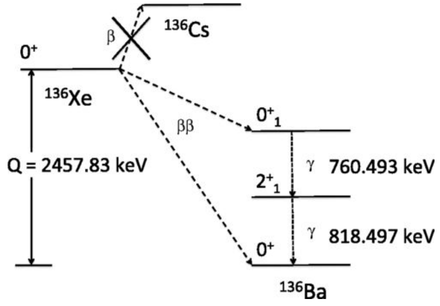
Isotope	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
Abundance, ε (%)	0.09	0.09	1.92	26.44	4.08	21.18	26.89	10.44	8.87

^{124}Xe
Q = 2.857 MeV
EC/EC, EC/β^+, $\beta^+\beta^+$

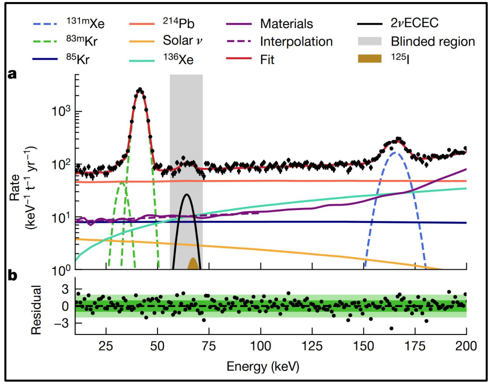
^{136}Xe
Q = 2.457 MeV
$\beta^-\beta^-$

^{134}Xe
Q = 0.824 MeV
$\beta^-\beta^-$

^{136}Xe to excited states ongoing

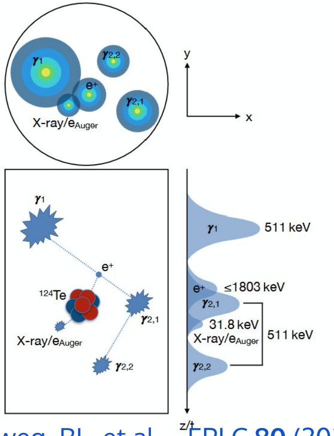


^{124}Xe EC/EC observed!



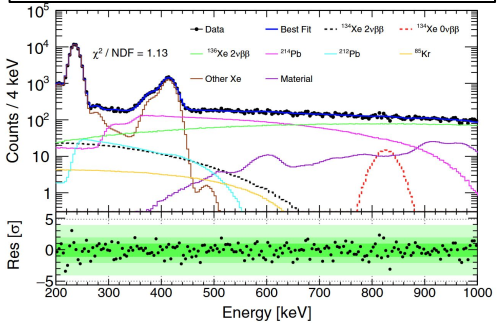
[XENON, Nature **568** 532-535 (2019)]

^{124}Xe EC/β^+ coming soon



[C. Wittweg, BL, et al., , EPJ C **80** (2020)]

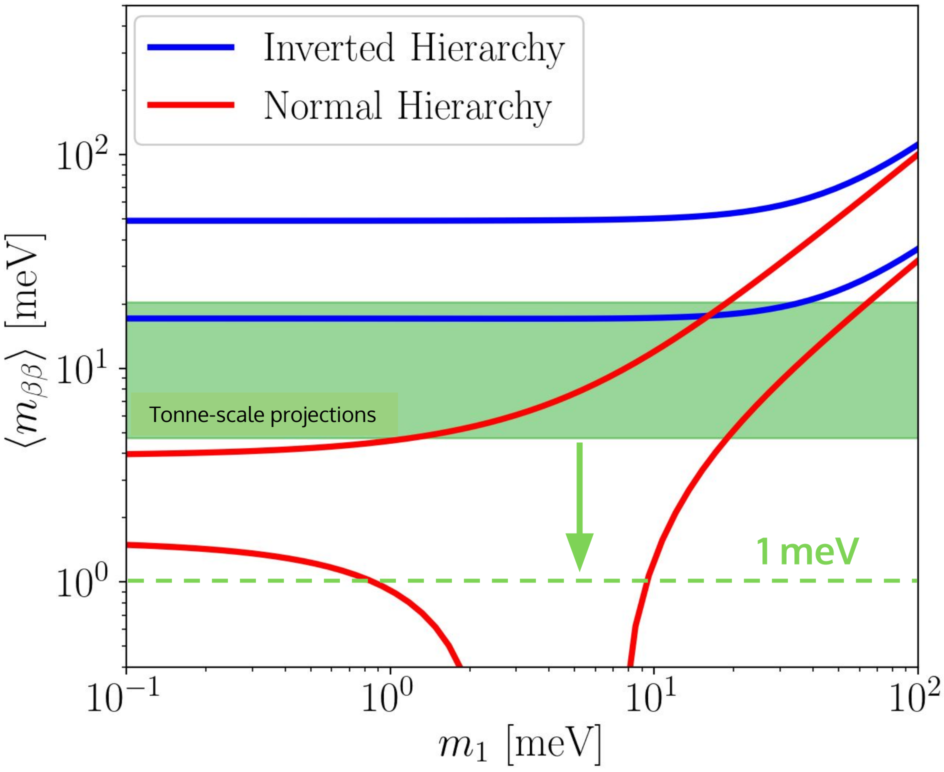
^{134}Xe $\beta^-\beta^-$ searches ongoing



Monolithic ^{nat}Xe TPCs have rich datasets and can precisely reconstruct final state *energies and topologies*, providing powerful event tagging and low-bkgs

Going beyond the ton-scale?

0νββ beyond the normal hierarchy



If we want to access $\langle m_{\beta\beta} \rangle = 1$ meV, how much isotope do we need?

Isotope	g_A^4 x $G^{0\nu}$ (x10^{-14} yrs^{-1})	$M^{0\nu}$ (avg)	$T_{1/2}$
^{136}Xe	3.56	2.9	0.87 x 10^{30} yrs
^{100}Mo	3.89	4.6	0.31 x 10^{30} yrs
^{76}Ge	0.57	4.8	2.0 x 10^{30} yrs

$$1 \text{ evt/yr} \; @ \; (T_{1/2} = 10^{30} \text{ yrs}) \;\rightarrow\; \sim 300 \text{ tons}$$

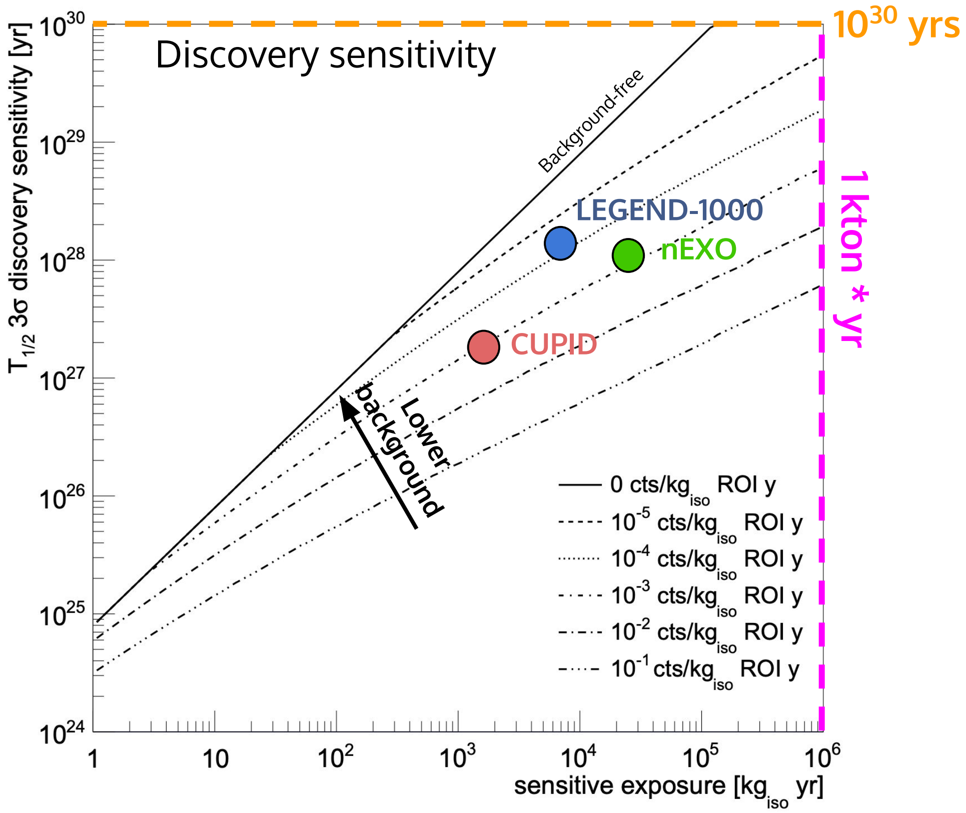
Detector requirements at the kton scale

Technical requirements:

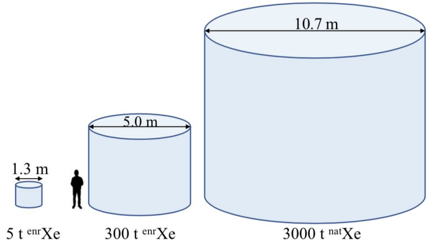
- Can we achieve sufficiently low background rates?

Practical requirements:

- Can we amass enough of the isotope?
- Can detector technologies scale up?

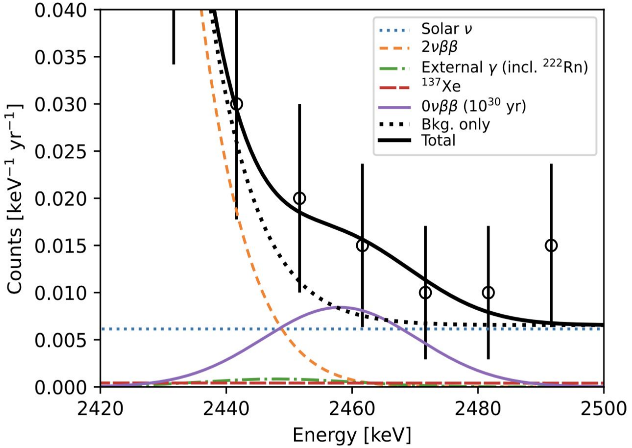


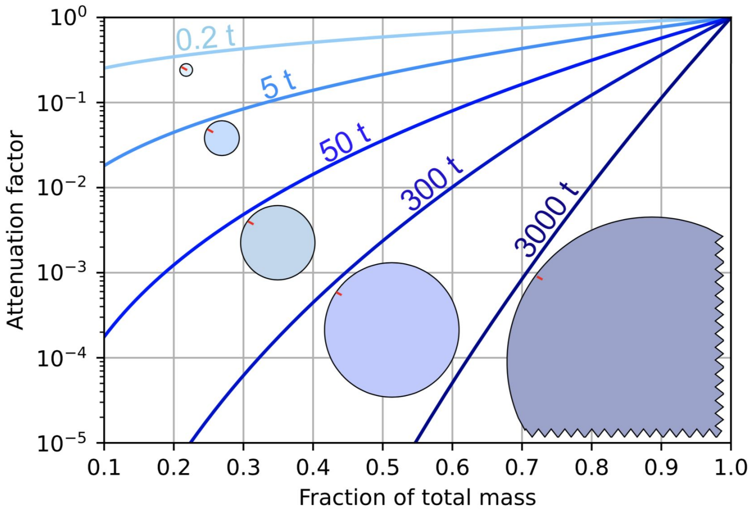
Liquid xenon TPCs at the kton scale



Crazy idea! But, is it *too* crazy?

- Scaling detector to kton sizes appears feasible
- Powerful self-shielding *eliminates* gamma ray bkgs
- Isotope acquisition appears to be the biggest challenge





"Kilotonne-scale xenon detectors for neutrinoless double beta decay and other new physics searches, " A. Avasthi et al., *Phys Rev D* **104** (2021)

Thank you