0νββ Search in Xenon Challenges and Opportunities

My personal point of view

Thomas Brunner

McGill University

ENTENTE workshop

September 30, 2025

Outline

- ~~Physics motivation~~ (thanks to all the previous speakers for the nice introduction)
- International situation
- Quo Vadis? What is our goal?
- Current state of the art in Xe TPC technology
- Challenges around Xe detectors
- My vision on a path forward
- Conclusion

Close out slides from 3rd 0νββ Summit

Statement from first JOG meeting (1)

The international funding agencies and laboratory directors who attended the 3rd International Summit on Double Beta Decay (the stakeholders) re-affirmed that the science of neutrino-less double-beta decay remains one of the most compelling and important in contemporary physics. The summit meeting summarised the state of the field, including recent developments in different technologies. The stakeholders congratulate the double-beta community for the substantial progress made since the last summit meeting, in a resource restricted environment.

The stakeholders recognise that the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one large tonne-scale experiment implemented in the next decade. Following the 2nd International Summit, a Working Group was struck and charged with exploring possible governance structures to support this objective. The Working Group reported back at this meeting, with a recommendation for a 'hybrid' governance structure to retain flexibility, agility and a forum for maximising impact of available funding.

https://indico.ph.tum.de/event/7802/

Community and funding agencies agree on:

- **0νββ search one of the most compelling and important physics search.**
- International approach is required.
- Searches in different isotopes and technologies required for unambiguous discovery.
- More than one tonne-scale experiment required.

Statement from first JOG meeting (2)

The stakeholders endorse the recommendation of the Working Group, whilst recognising the change in funding environment since the previous summit. It was agreed that the intention is to phase the development of the hybrid governance model. Phase-I is the formation of an initial Joint Oversight Group comprised of interested funding agency representatives and facility directors to ensure a forum for communication and discussion, and, if applicable, coordination by the funding agencies, for deployment of tonne-scale detectors in North America and Europe.

The 3rd Summit meeting closed session on Day 2 was viewed as the initial JOG kick-off meeting where the funding agencies and laboratory directors met under the umbrella of the JOG to discuss the terms of reference and operational mode.

Challenging international funding situation

BUT….

- In Dec. 2024 DOE decided due to financial limitations to advance LEGEND-1000 while continuing R&D for nEXO and CUPID. **This decision was due to budgetary constraints.**
- European countries are supporting LEGEND (^{76}Ge), CUPID (^{100}Mo), SuperNEMO, NEXT (^{136}Xe), and other efforts.
- Japan supports KamLAND2-Zen (^{136}Xe).
- Canada is supporting nEXO (^{136}Xe) and SNO+ (^{130}Te).
- China pursues CDEX (^{76}Ge) and PandaX (^{136}Xe).
- XLZD as "new" player in the 0νββ search in Xe-136 with attractive sensitivity among next-generation experiments (Europe, Japan, UK, USA).

→ While there is good motivation and interest in a "global" 0νββ program, the path is not clear.

Quo Vadis?

Current Limit →

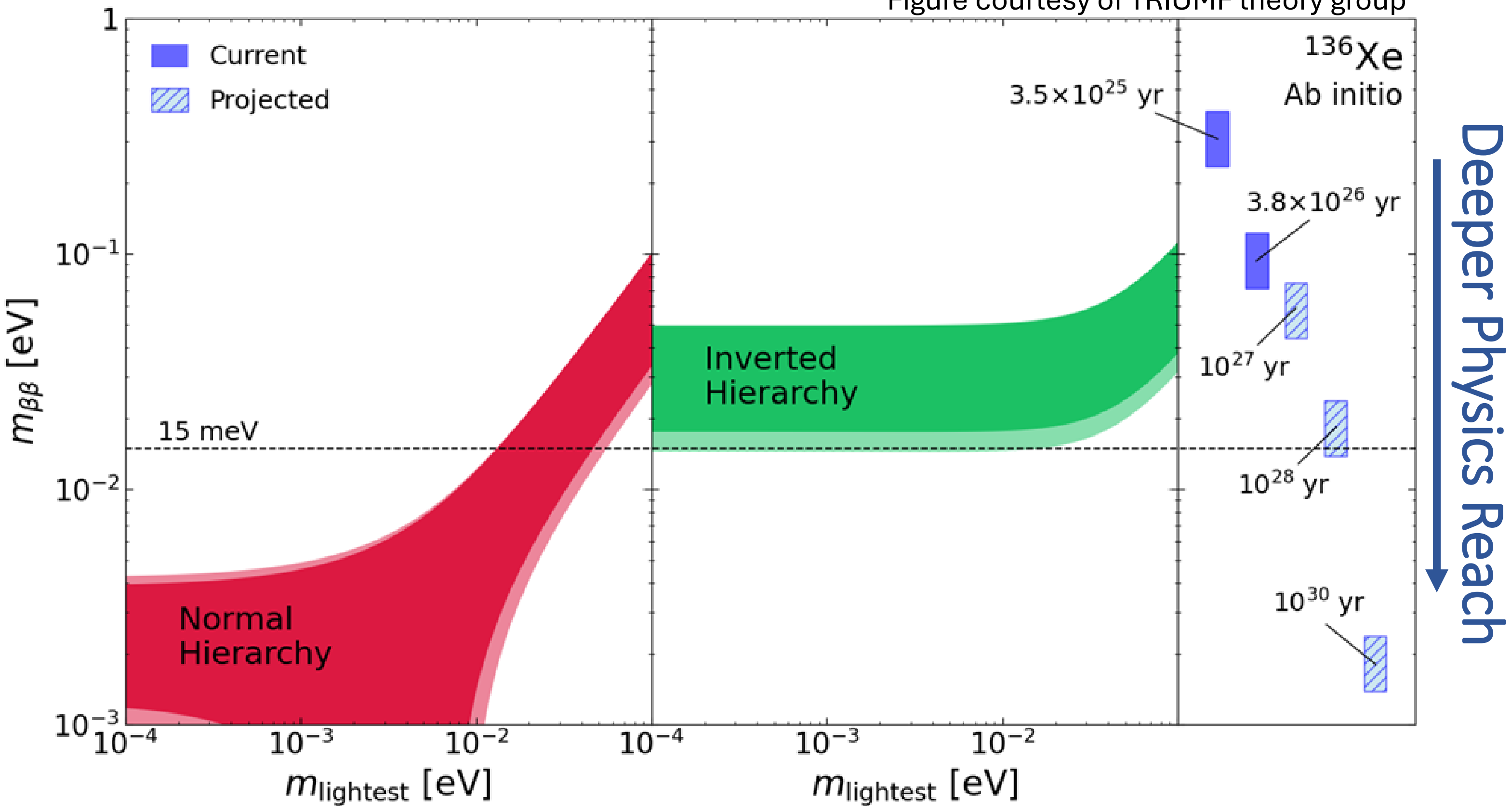
Next-Generation →

We know how to do this but funding unclear

Ultimate Experiment? →

The ultimate goal in 0νββ of ~1 meV

Figure courtesy of TRIUMF theory group



BGND — Energy resolution

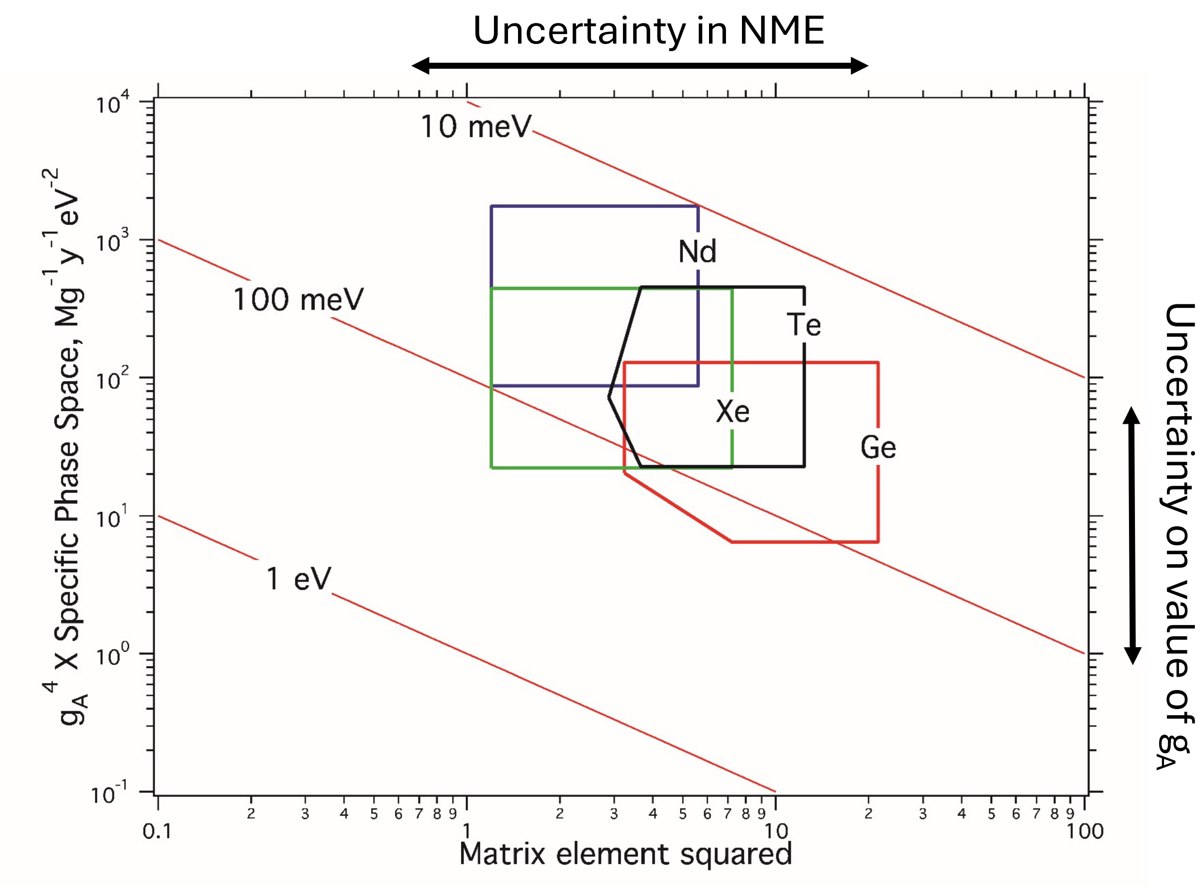
Background scenario: $m_{\beta\beta} \propto \sqrt{1/T_{1/2}} \propto \sqrt{1/\epsilon}\left(\frac{b \cdot \Delta E}{M_{\beta\beta} \cdot t}\right)^{1/4}$

Mass of isotope

Background free scenario: $m_{\beta\beta} \propto \left(\frac{1}{\epsilon \cdot M_{\beta\beta} \cdot t}\right)^{1/2}$

Detector efficiency — Exposure

Is there a preferred isotope for 0νββ searches?



R.G.H. Robertson, MPL A 28 (2013) 1350021
arXiv 1301.1323

There is an “empirical” anticorrelation between phasespace and NME.

Many isotopes have comparable sensitivities (at least in terms of rate per unit neutrino mass).

Based on rate per unit mass, no isotope is clearly preferred.

→ The isotope of choice to go to the NO is dictated by its availability and the scalability of detector technology.

Strategy to reach 10^{28} years: More Isotope

- Ultimately, even a background free experiment is limited by exposure, i.e., by the number of atoms → **a global approach is ideal to procure sufficient Xe-136 for next-generation and future experiments.**

$$\frac{dN}{dt} = \frac{\ln(2)}{T_{1/2}} N = 0.693 \frac{N}{T_{1/2}}$$

<u>^{136}Xe Rate at 10^{28} years:</u>
~0.3 decays/tonne/yr

Mass required for 1 decay/year (average)

Half life [yr]	Atoms	^{76}Ge [t]	^{100}Mo [t]	^{130}Te [t]	^{136}Xe [t]
10^{27} years	$1.4\text{x}10^{27}$	0.18	0.24	0.31	0.32
10^{28} years	$1.4\text{x}10^{28}$	1.82	2.4	3.11	3.26
10^{29} years	$1.4\text{x}10^{29}$	18.2	24	31.1	32.6
10^{30} years	$1.4\text{x}10^{30}$	182	240	311	326

~10 decays/s

0νββ search in ^{136}Xe

- Some of the most competitive 0νββ limits come from Xe experiments:
  - PandaX-4T $T_{1/2} > 2.1 \times 10^{24}$ yr (44.6 kg x yr)
  - EXO-200 $T_{1/2} > 3.5 \times 10^{25}$ yr (234 kg x yr)
  - KamLAND-Zen $T_{1/2} > 3.8 \times 10^{26}$ yr (2.1 t x yr)
- Technical feasibility demonstrated for:
  - Dissolved in scintillator
  - Gas-phase TPC
  - Single-phase **liquid** TPC
  - Dual-phase **liquid** TPC

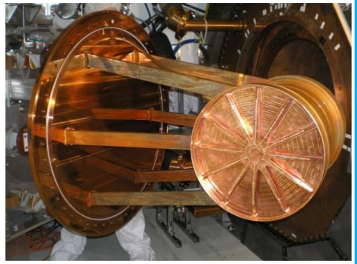
4 technologies!

- **Liquid noble TPC – a demonstrated technology at and beyond the tonne scale.**

0νββ results:
EXO-200: 1906.02723
PandaX-4T: 2412.13979
KamLAND-Zen: 2406.11438

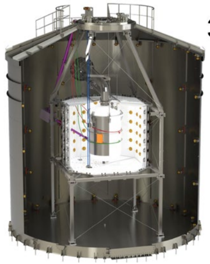
Past

EXO-200 (175 kg)

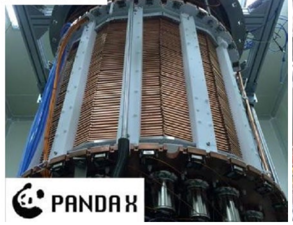


Current Generation

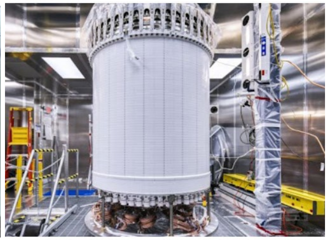
XENONnT
(6 Tonne)



3.7 Tonne

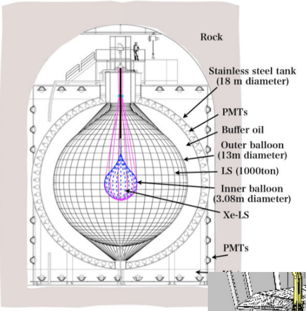


LZ (7 Tonne)

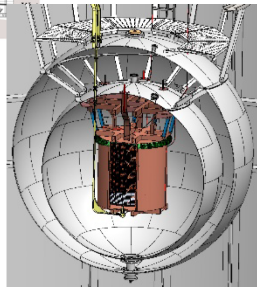


DarkSide-20k
(70 Tonne underground Ar)

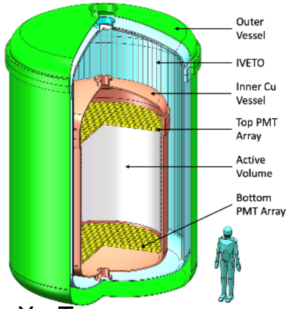
SBND (112 Tonne Ar)



Next Generation Concepts



nEXO
(5 Tonne)



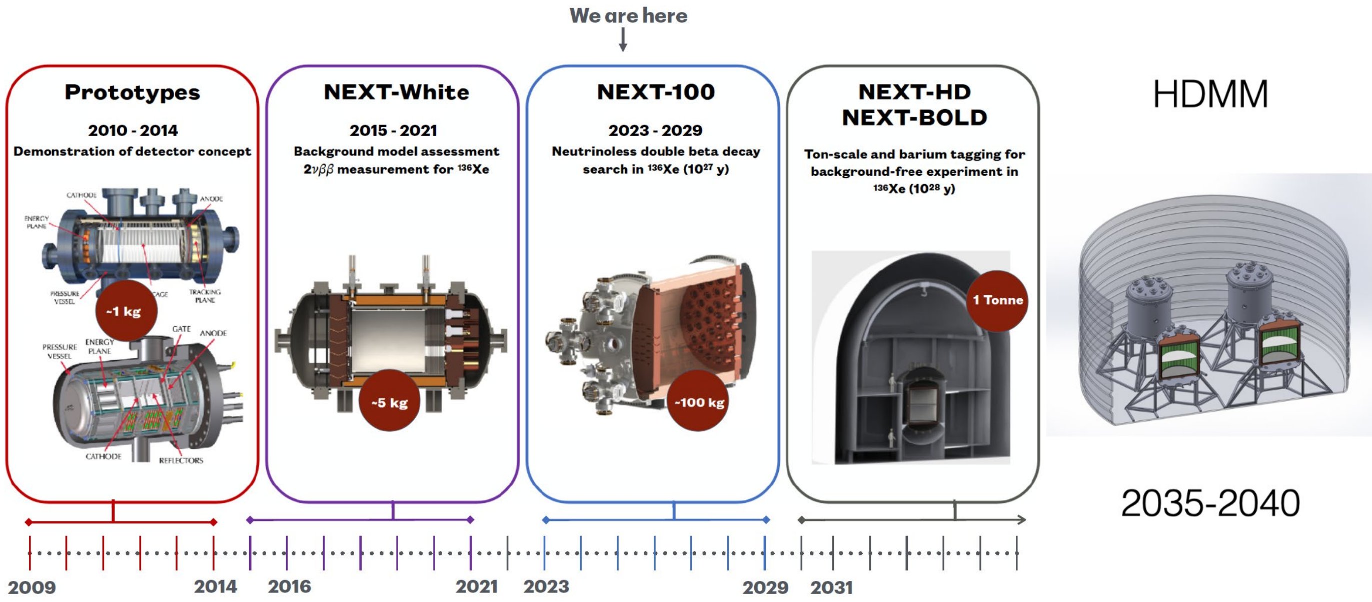
PandaX-xT
(43 Tonne)

XLZD
(60 Tonne)

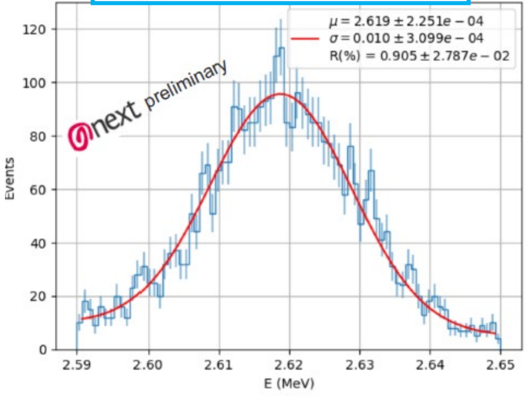
Proposed Next Generation Xenon Experiments

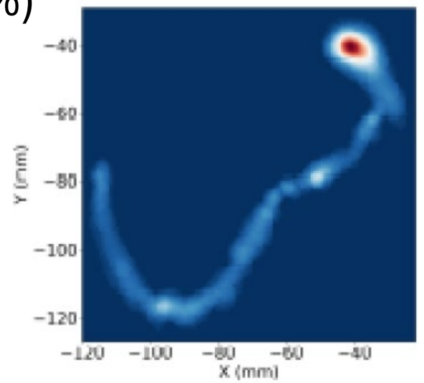
NEXT

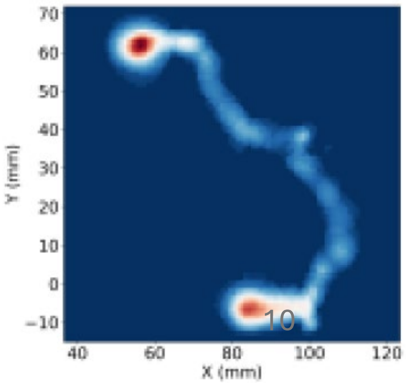
- GXe TPC
- Event topology (single track vs. ββ track).
- BGND characterization at 4 bar ongoing in NEXT-100.
- Run at 10 bar pressure planned.
- Projected 0νββ sensitivity of NEXT-100 after 3 yrs of running ~4x10^{25} yrs (90% CL).
- Tonne-scale detector planned with NEXT-HD (first module at 1 t).
- Upgrade path towards HDMM (total deployed mass 5-10 tons).



$E_{res}(2.61MeV) = 0.90\,\%$ (σ = 0.38%)





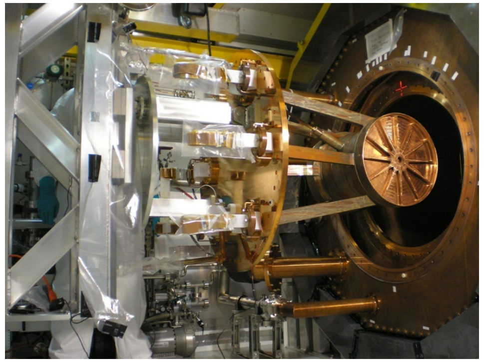


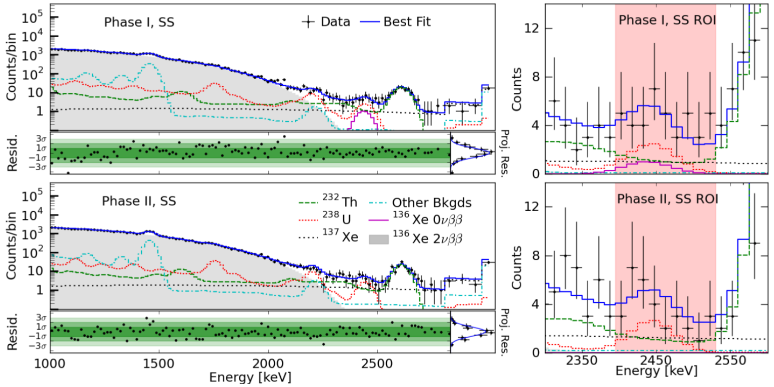
Double-electrons from 1.6MeV double escape peak of ^{208}Tl

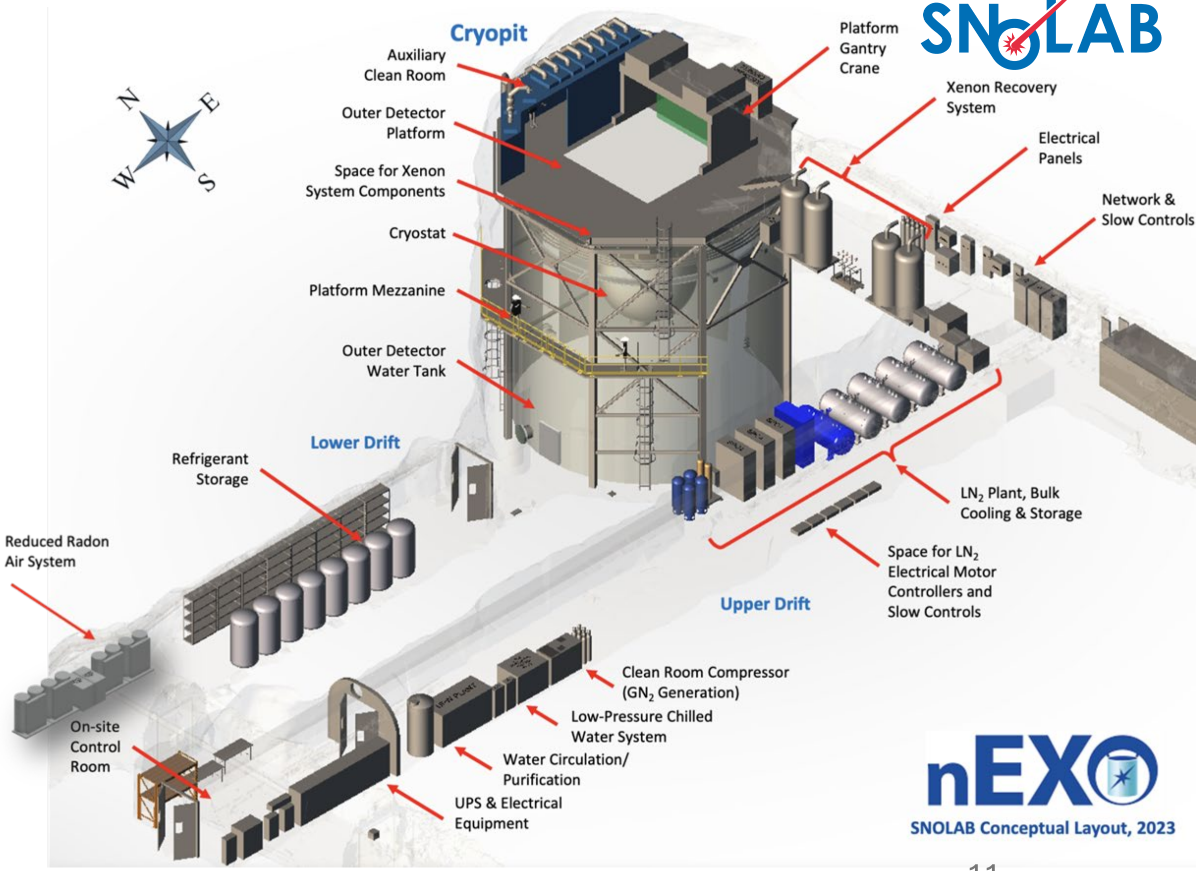
https://indico.ph.tum.de/event/7802/contributions/10295/attachments/6787/9419/NextSummit.pdf
https://indico-cdex.ep.tsinghua.edu.cn/event/175/contributions/2308/attachments/939/1405/TAUP_pres_Def.pdf

nEXO

- LXe single phase TPC.
- Demonstrated technology with EXO-200 (2011-2018).
- EXO-200 energy resolution at $Q_{\beta\beta}$: $\sigma/E = 1.15 \pm 0.02\%$.
- Anticipated resolution for nEXO at $Q_{\beta\beta}$: $\sigma/E < 1\%$ (goal: 0.8%).
- Takes advantage of self-shielding of LXe.
- 5 tonnes of Xe, enriched to 90% in Xe-136
- **Conceptual Design positively assessed at Director's Review.**

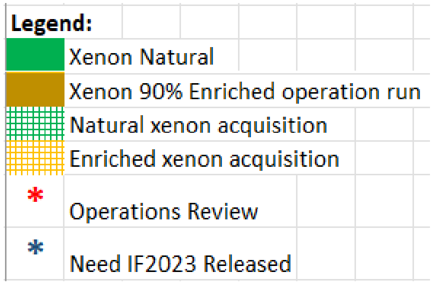


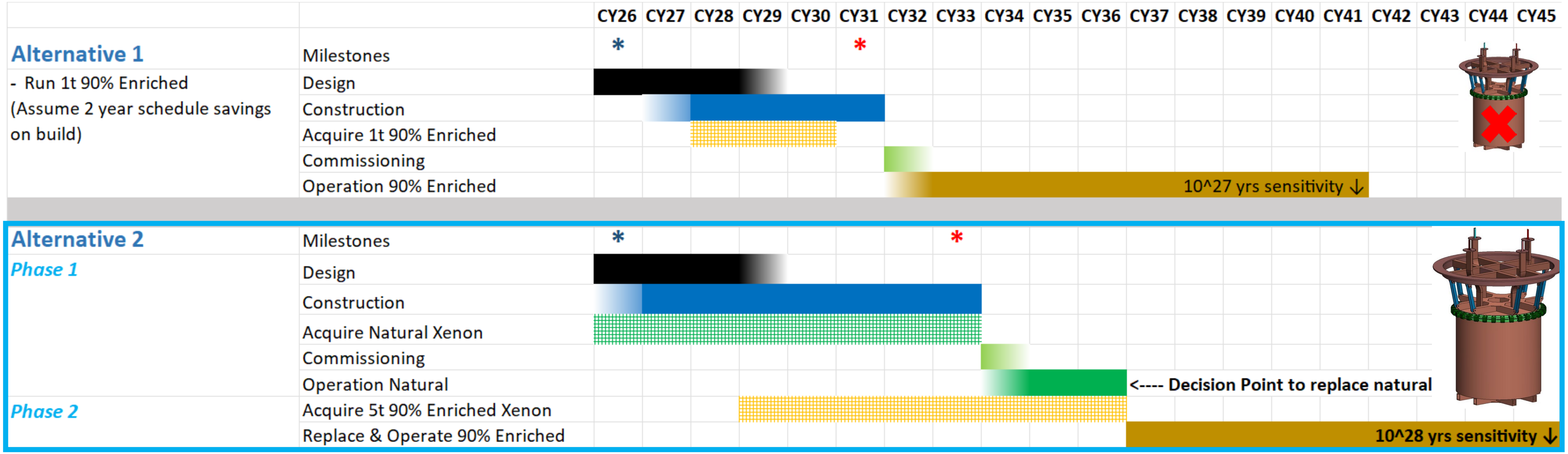




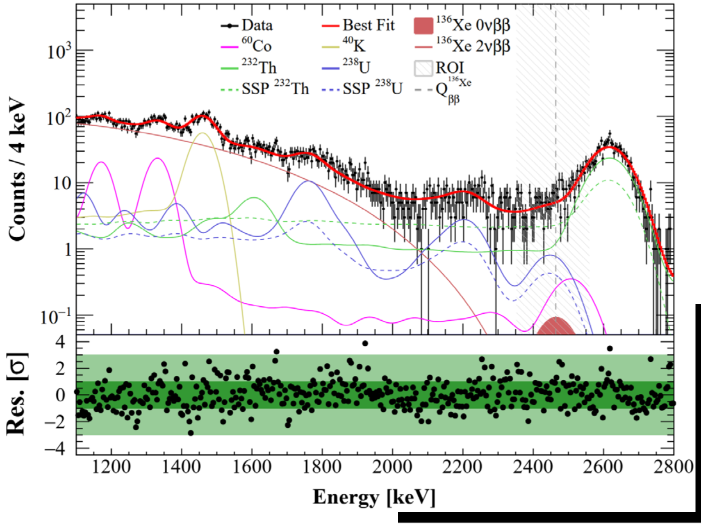
nEXO 2.0: Xenon Program Schedule

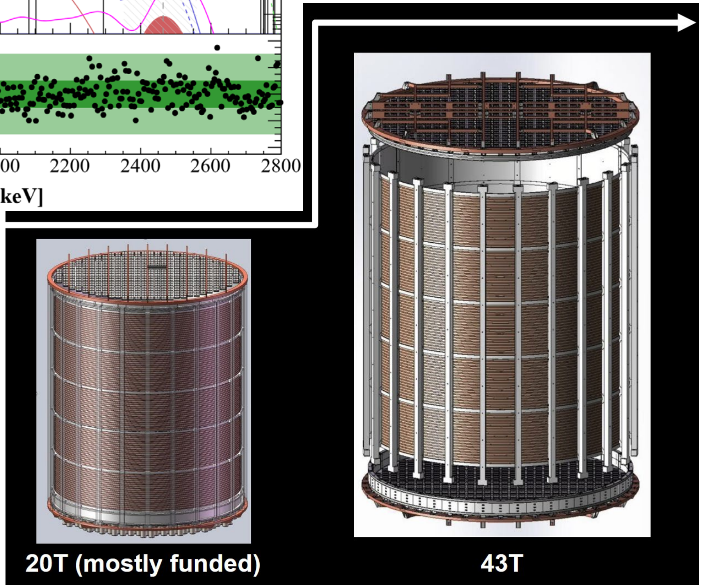
- Preferred solution of 5 tonne TPC with upgrade path natural → 90% enriched.
- Construction of 5 tonne TPC take about 2 years longer than 1 tonne TPC.
- Only 5 tonne TPC can reach 10^{28} years.



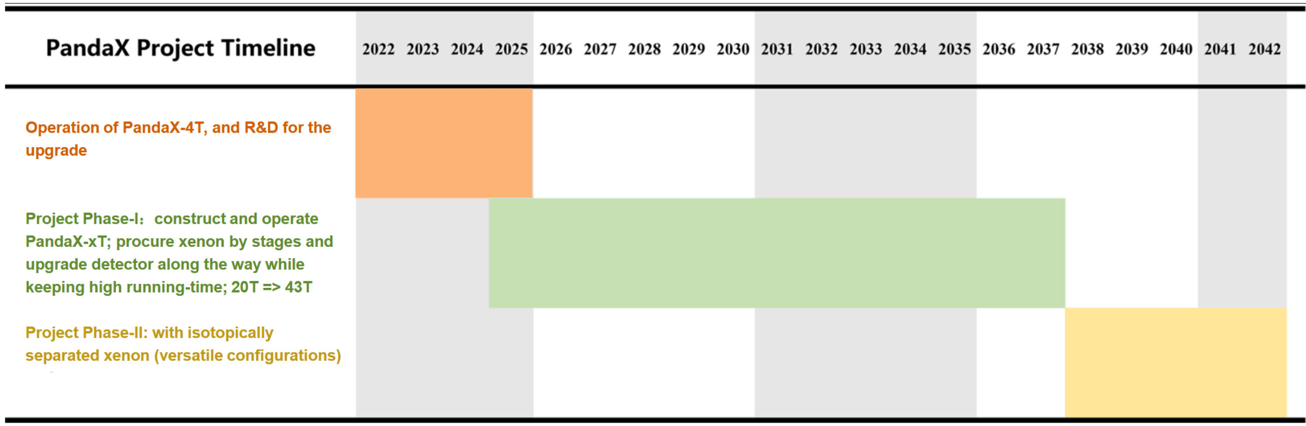


PandaX





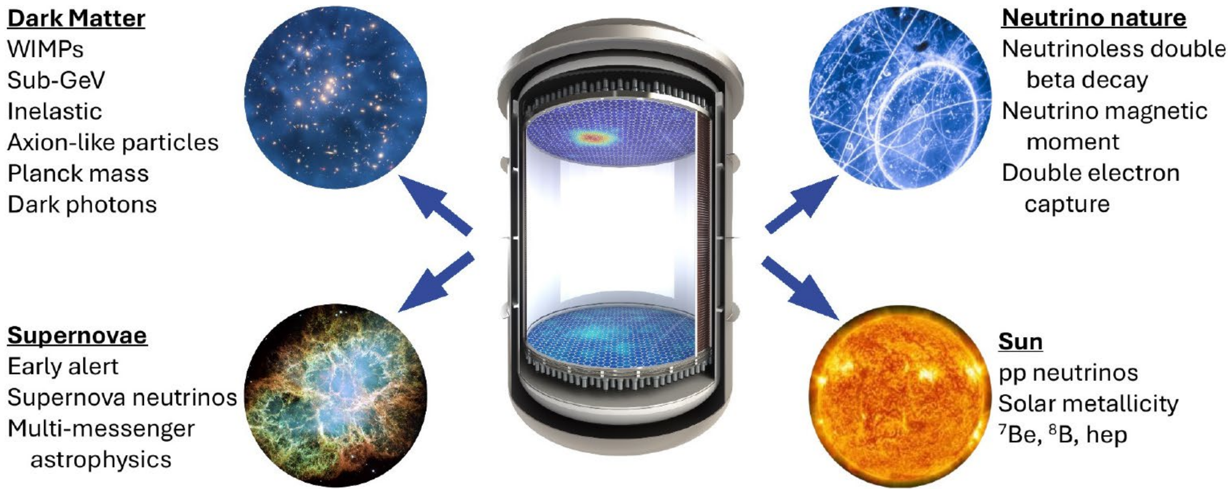
- DM detector at CJPL in China with competitive 0νββ sensitivity
- Phased approach
- PandaX-4T
  - σ = 2% [at 2.6 MeV].
  - Limit for 0νββ of $T_{1/2} > 2.1\text{x}20^{24}$ yrs (90% CL, 44.6 kg x yr).
- Staged approach to get to 43t.
- Building a 20 t detector.
- Phase II: perform experiment with isotopically separated Xe.



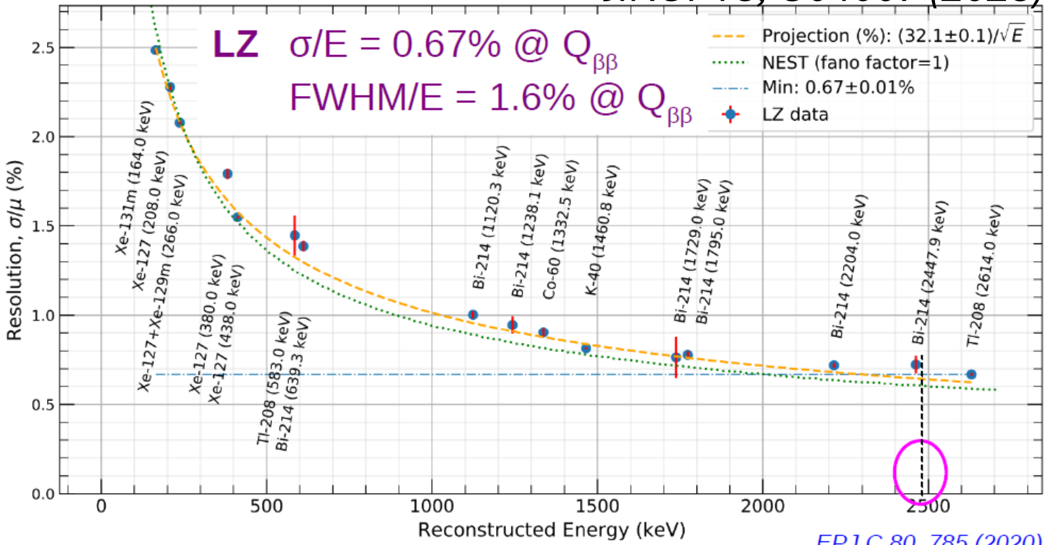
https://indico-tdli.sjtu.edu.cn/event/2934/contributions/14995/attachments/5819/9660/PandaX-Open-Overview.pdf

XLZD

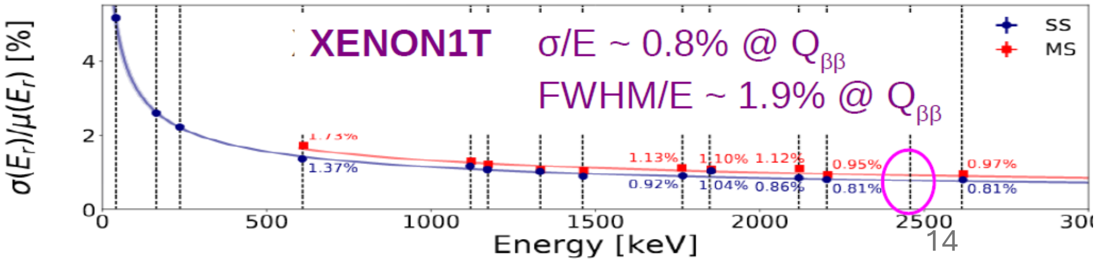
- LXe dual phase TPC
- LXe Dark Matter experiment with competitive sensitivity to 0νββ.
- Merges best demonstrated technologies of LZ and XENONnT.
- 60 t active mass (78 t total) with possibility of 80 t in optimistic funding and Xe market scenario.

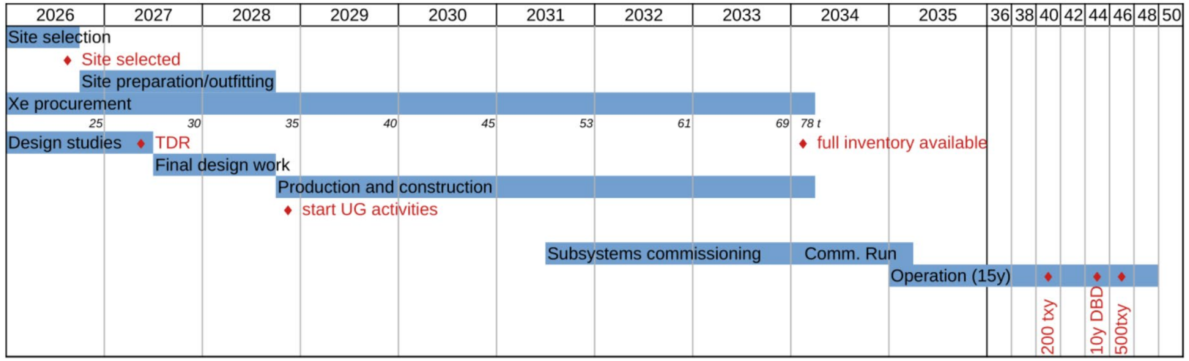


JINST 18, C04007 (2023)



EPJ C 80, 785 (2020)

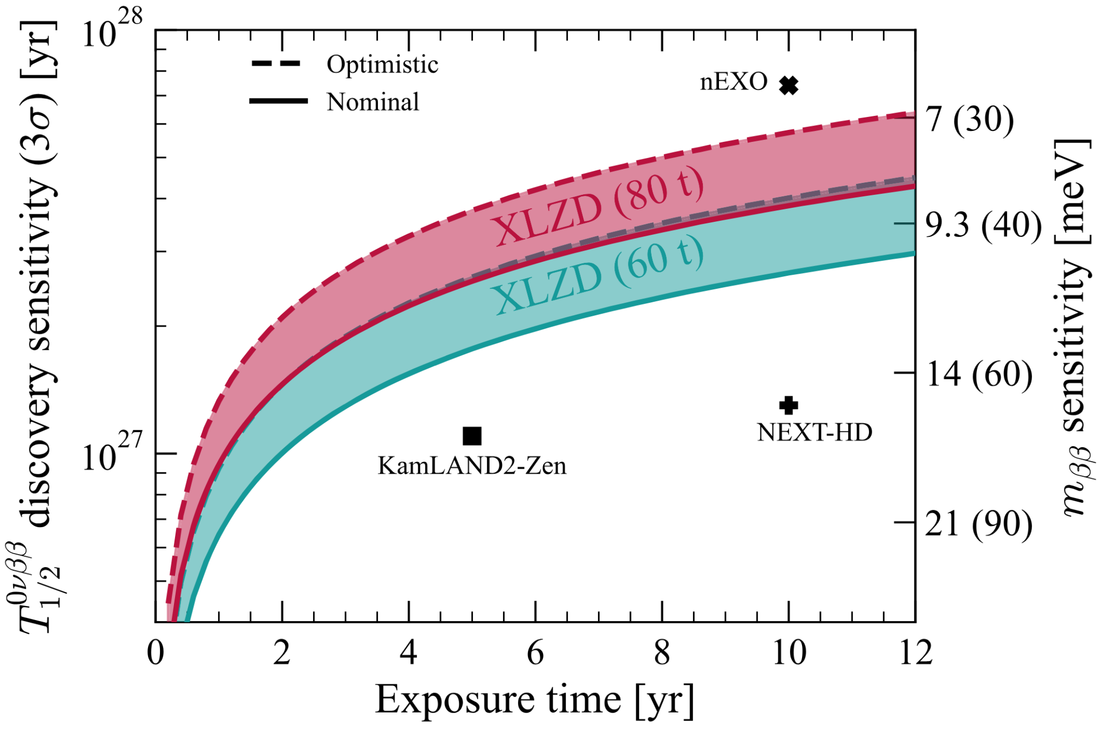


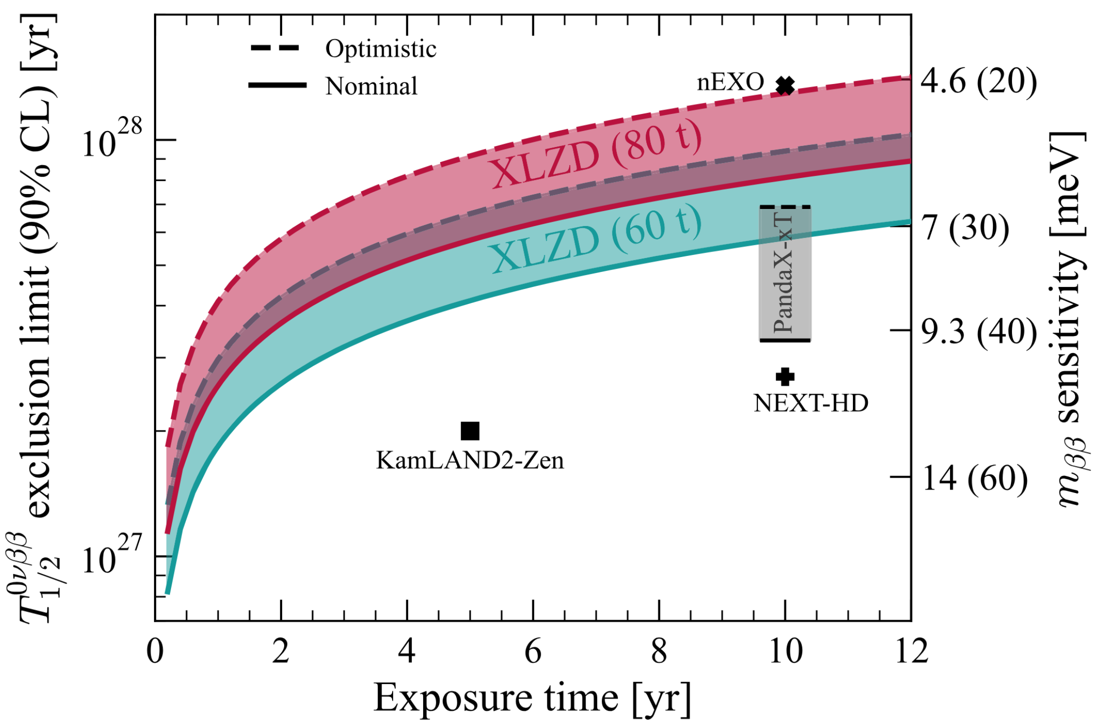


https://indico.ph.tum.de/event/7802/contributions/10293/attachments/6786/9418/XLZD_summit.pdf

Sensitivity Projections

J. Phys. G 52, 045102 (2025)





DM/MP

Experiment	Natural Xe	Xe-136 in detector
XLZD	60 t	5.3 t
XLZD	80 t	7.1 t
PandaX-xT	43 t	3.8 t

0νββ

Experiment	Xe-136 in detector
KL2Z	0.68 t
nEXO	3.4 t (90% enr.)
NEXT-HD	0.9 t*

Challenge Xe Procurement (in tonnes)

* extrapolated

	Experiment	Natural Xe req.		Xe enriched at 90%
$0\nu\beta\beta$	nEXO	**51 t***	←	5 t
$0\nu\beta\beta$	NEXT-HD	**10 t***	←	1 t
$0\nu\beta\beta$	NEXT-HDMM	51 t – 101 t	←	5 t - 10 t
DM/ Multi purpose	XLZD	60 t active **(78 t)**		
DM/ Multi purpose	XLZD	80 t active (100 t*)		
DM/ Multi purpose	PandaX-xT	43 t active **(56 t*)**		
	Total Xe req.	**202 t**		

Experiment	Natural Xe		Enriched Xe
EXO-200	**1.8 t**	←	~200 kg (@80%)
NEXT-100	**1.1 t**	←	~100 kg (@90%
KamLAND-Zen	**7.7 t**	←	~750 kg
XENONnT	**~10 t**		
LZ	**~10 t**		
PandaX-xT	**~20 t**		
Total Xe av.	**50.6 t**		

Crude assumptions (on entire slide!):

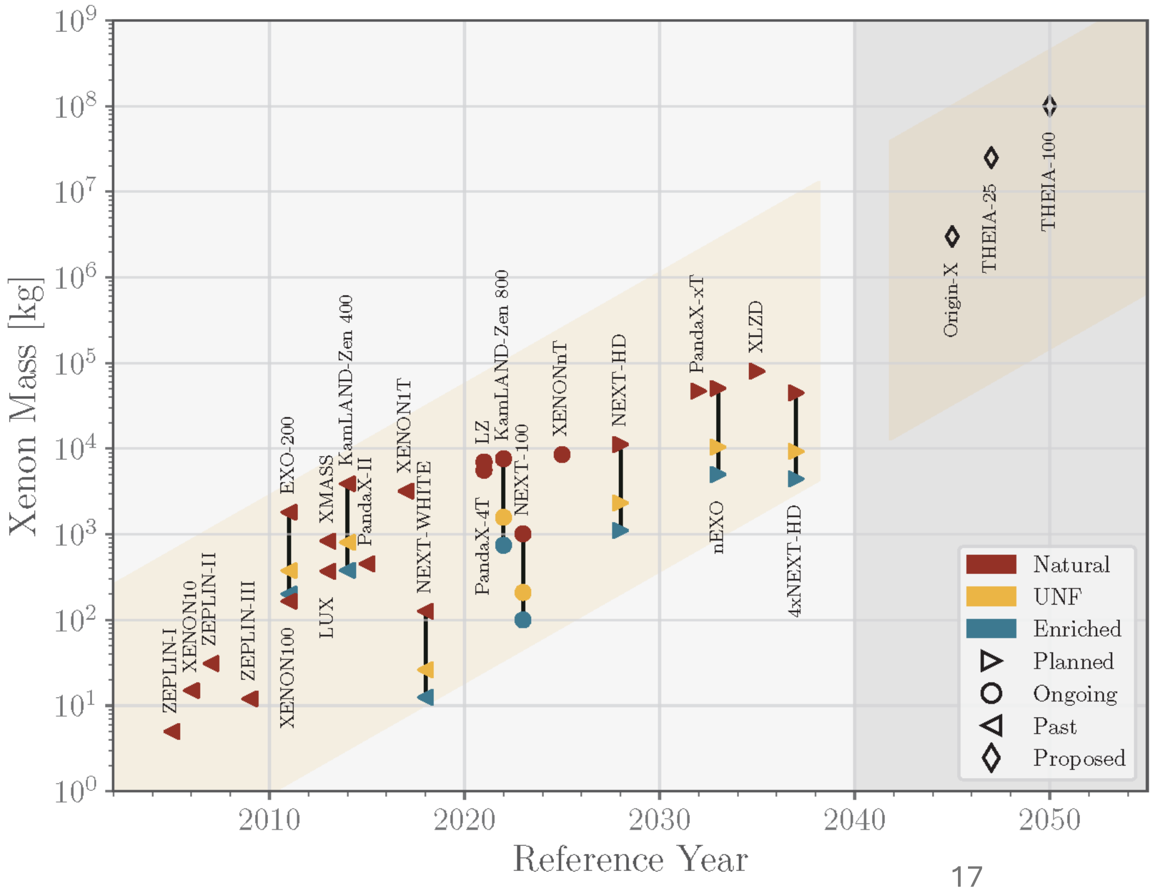
- Proposed next-generation experiments will require ~200 t of ^{nat}Xe by ~2035.
- Experiments hold 51 t equivalent ^{nat}Xe (40 t ^{nat}Xe and 1 t ^{136}Xe @90%).
- Global xenon production is estimated to be between 50 and 60 t per year.
- Assumption: Order of 5 t/yr of Xe plausibly procurable without disrupting market.

Xe - Opportunities

- Extraction of Xe from spent nuclear fuel.
- Canadian spent fuel inventory:
  - 3.3 million used CANDU fuel bundles corresponding to
  - 80 tonnes of Xenon, 36 tonnes of Xe-136
  - Requires gas efficient gas extraction from fuel.
  - Requires Kr removal.

- **Xe sharing between experiments.**

Electron fractograph depicting fission gas bubbles in UO_2



Other Opportunities

- Experiments need experts!
- Experiments require underground lab space.
- **Question: How many experiments can the global Xe community support?**
- **How best to locate the experiments in terms of access, geopolitically location, overburden, …**

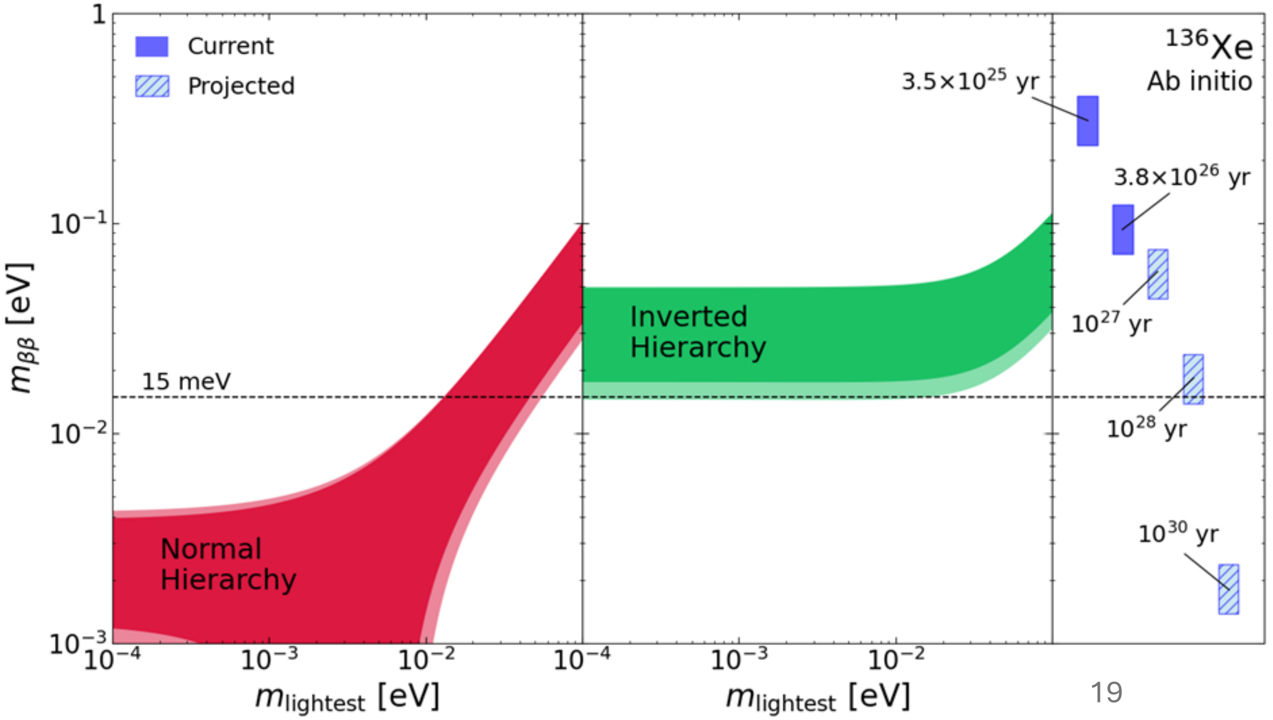
Gemini.google.com: "Please create me a cartoon of scientists that are building a liquid xenon neutrinoless double beta decay detector." and "Call the experiment PHOENIX"

A Path to the Normal Ordering

- Hypothesis:
  - Gas Xe TPC
  - LXe single phase TPC
  - LXe dual phase TPC

Technically capable pf reaching sensitivities of 10^{28}-10^{30}yrs

- Coales the Xe (and more broadly noble) community → the community needs to decide what it wants to build.
- Evaluate technical readiness of 10^{28} yrs detector.
- Pursue R&D to go beyond 10^{28} years.



Technical Readiness

(personal opinion Sept. 2025)

PandaX (CJPL)

LZ (SURF)
7.0t target

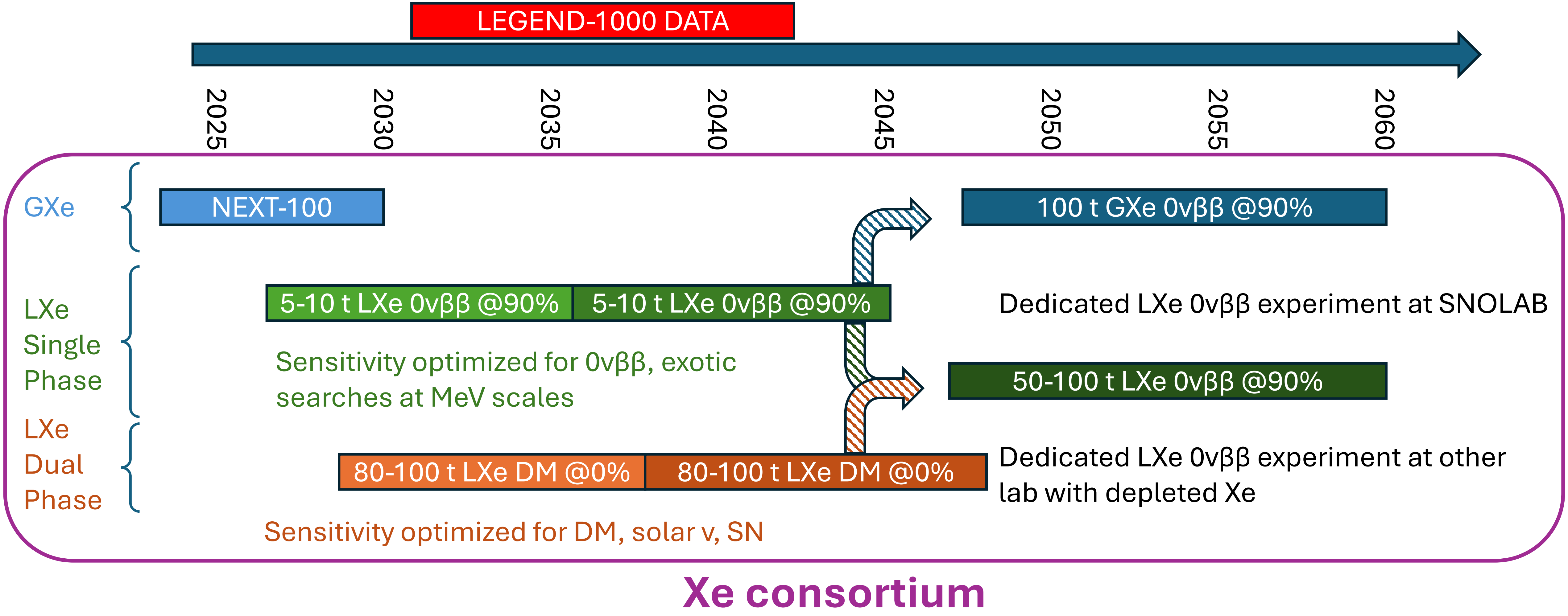
XENONnT (LNGS)
5.9t target

- LXe DM experiments demonstrated:
    - Operation of LXe detectors on tonne scale (LZ, XENONnT, PandaX-4T).
    - Demonstrated excellent electron lifetimes (better than 10 ms).
    - Demonstrated Rn and Kr distillation technologies.
    - Demonstrated energy resolution 0.7% for LZ at 2.5 MeV, 2% [PandaX at 2.6 MeV].
    - PandaX observed a limit for 0νββ of $T_{1/2} > 2.1x20^{24}$ yrs (90% CL, 44.6 kg x yr).
- LXe 0νββ demonstrated:
    - Operation of low-BGND detector at 200kg level.
    - Energy resolution of 1.15% at $Q_{\beta\beta}$.
    - Electron lifetime of 5 – 10 ms.
    - EXO-200 limit for 0νββ of $T_{1/2} > 3.5 \times 20^{25}$ yrs (90% CL, 234.1 kg x yr).
    - Detection efficiency of 96.4 ± 3.0%.
- GXe 0νββ demonstrated:
    - Operation of 100-kg detector at 4 bar.
    - Energy resolution of 0.8% FWHM → 0.34% at $Q_{\beta\beta}$.
    - Two escape electron track from Tl-208 source.

EXO-200 (WIPP)

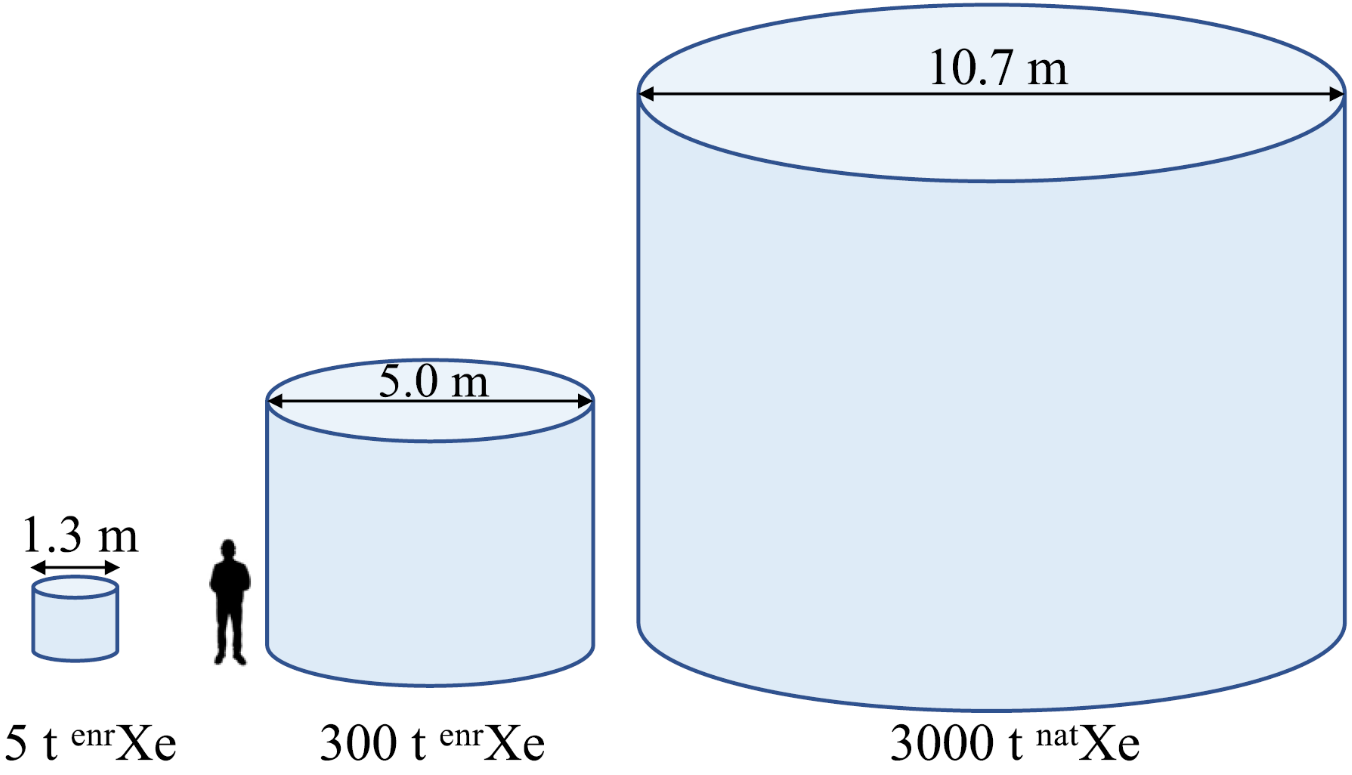
NEXT 100 (LSC)

Maximizing scientific reach (my dream, Sept. 2025)



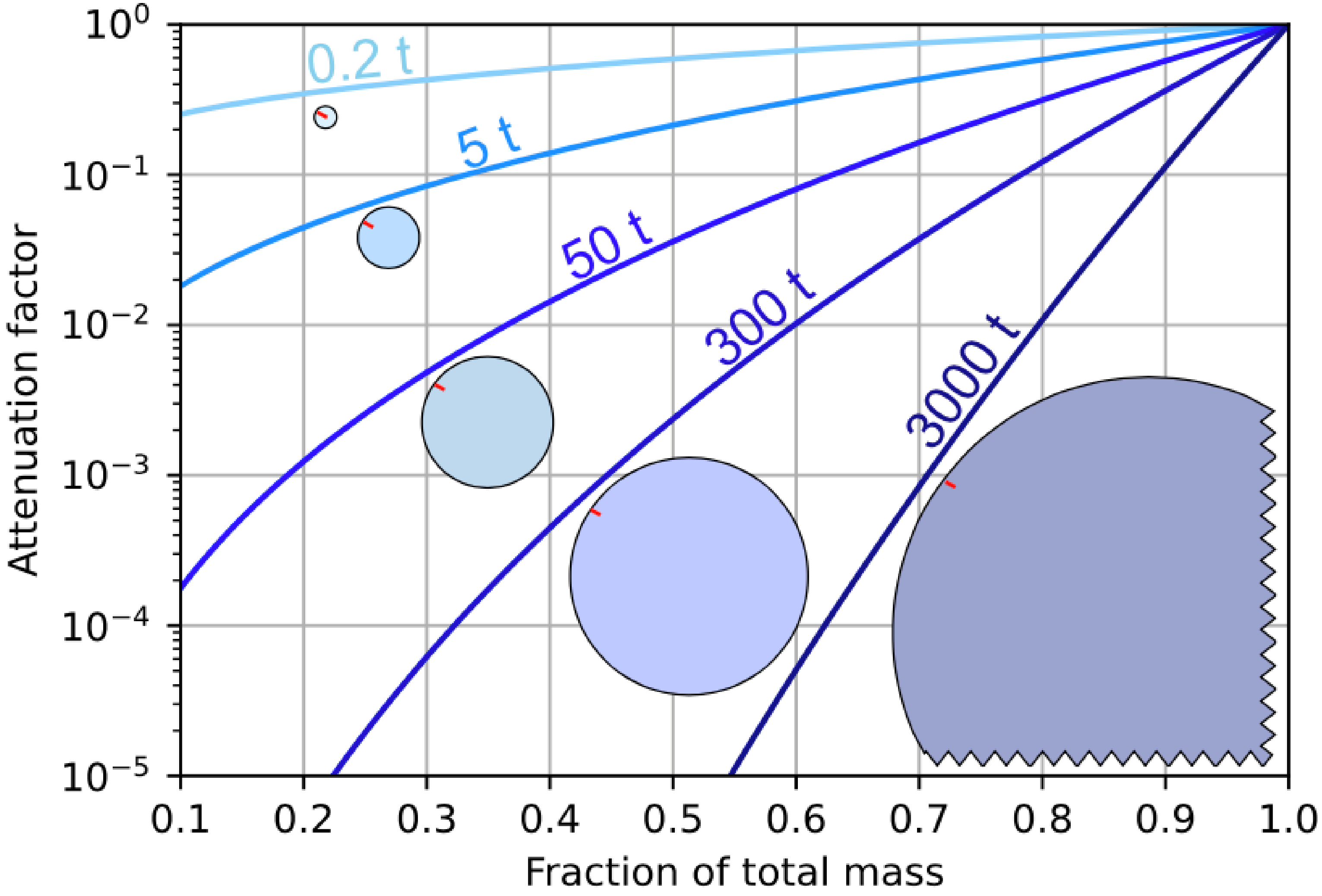
Beyond Tonne-Scale

LXe TPCs are scalable



[Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches](https://doi.org/10.1103/PhysRevD.104.112007)
Phys. Rev. D **104**, 112007 (2021)

The limits: Specific Radioactivity

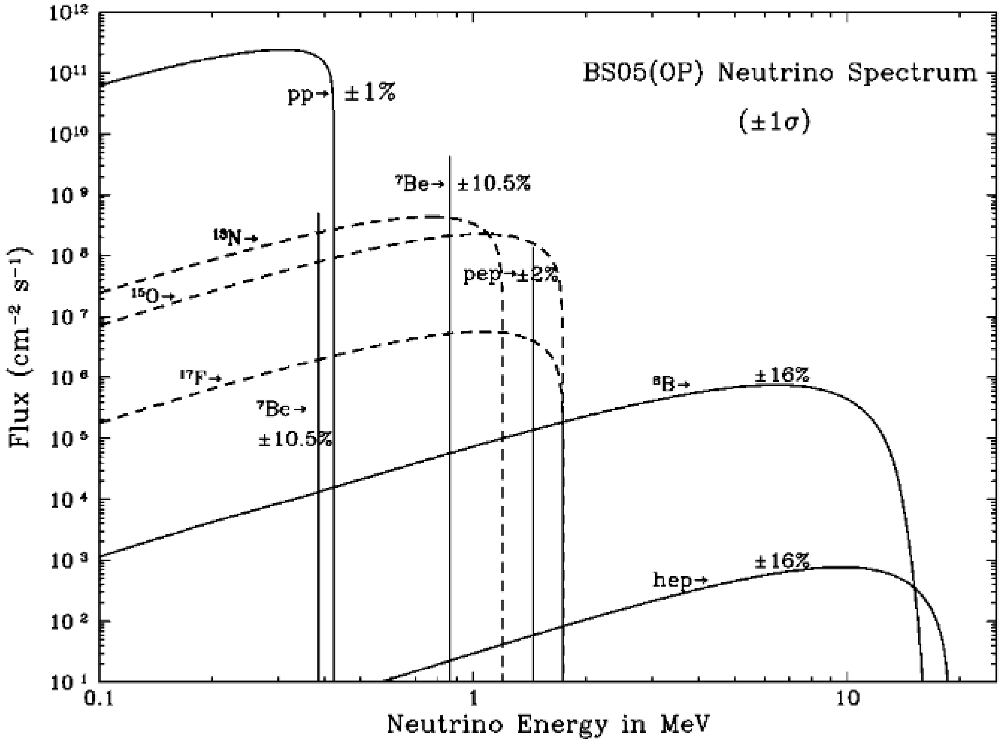


Red line is a factor 10 reduction (2.3 attenuation length)

Phys. Rev. D **104**, 112007 (2021)

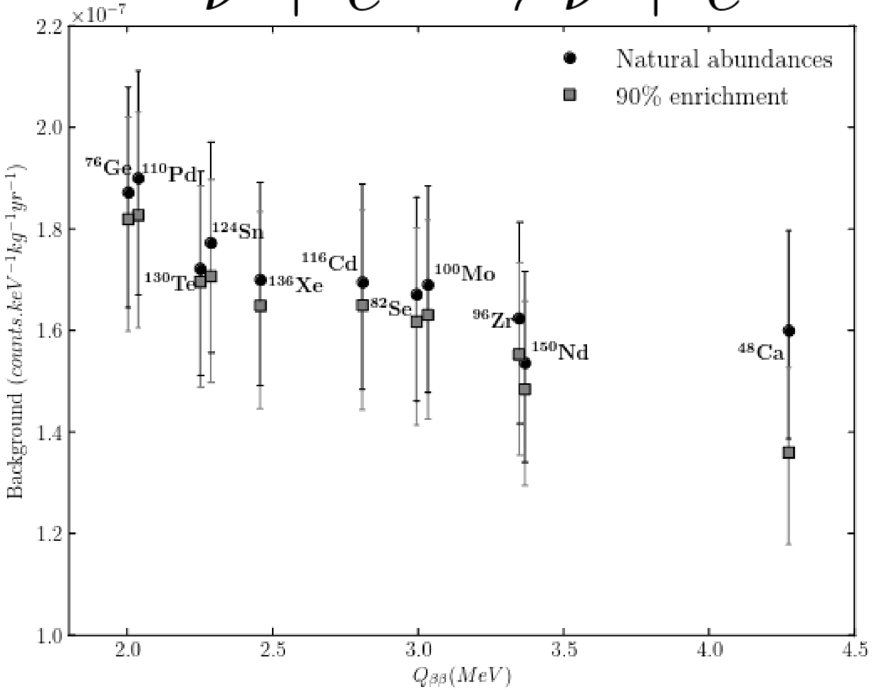
The limits: solar neutrinos

5 (2) evts/(FWHM kTonne yr) @ 0.5% (0.2%)



J. Bahcal, et al, The Astrophysical Journal, 621:L85–L88, 2005

$$\nu + e^- \rightarrow \nu + e^-$$

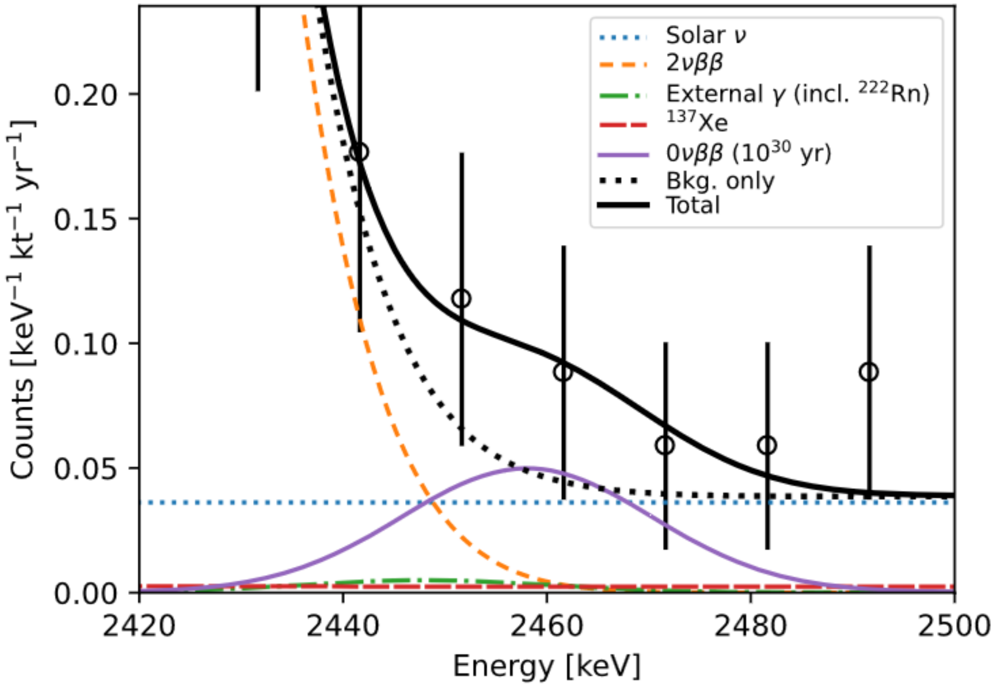


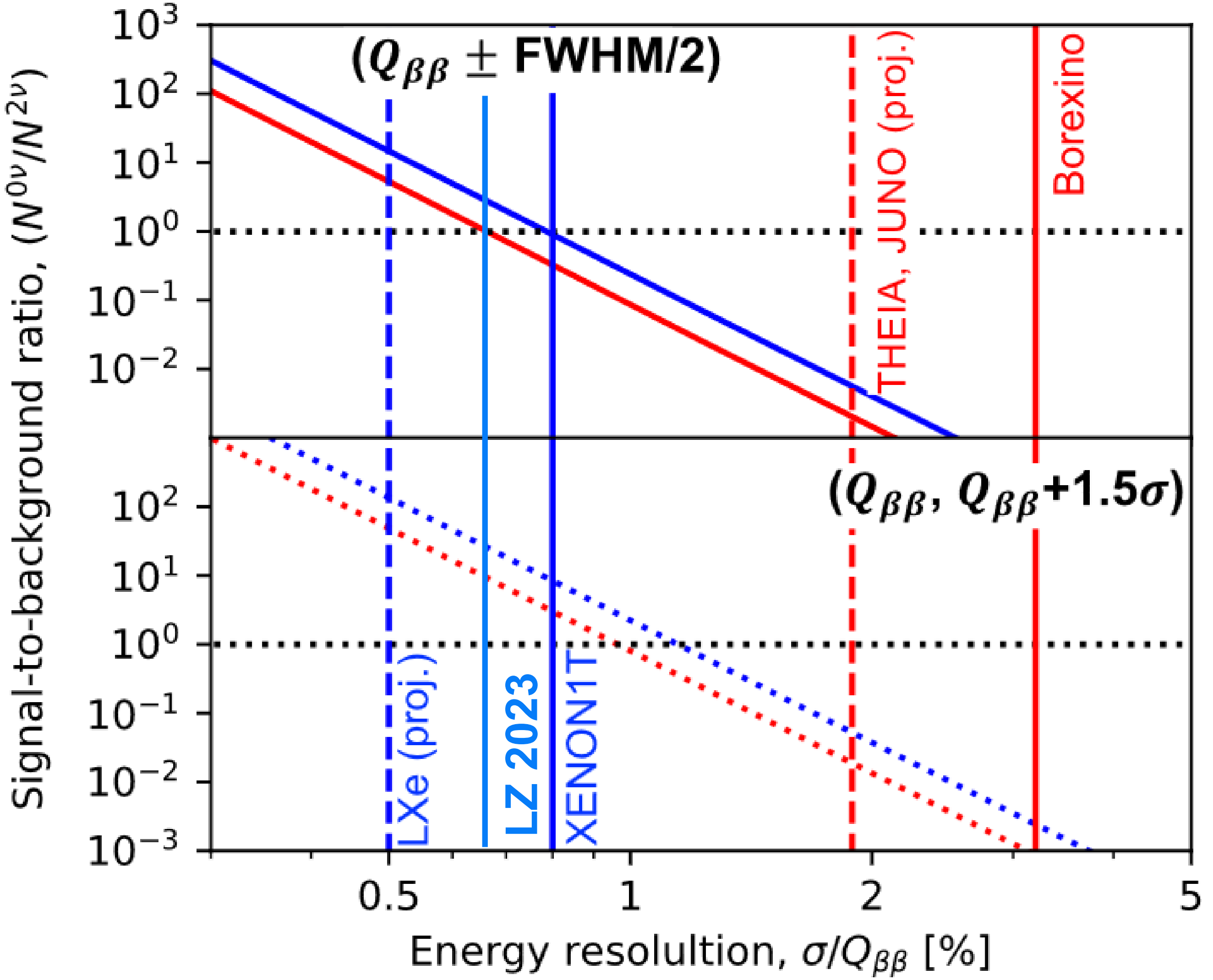
NF deBarros et al, J. Phys. G: Nucl. Part. Phys. 38 (2011) 105201

- Signal/(solar ν BGND) much improved in detectors with enriched target.

- New Technologies:
  - Ba tagging with a high efficiency
  - Cherenkov light analysis
  - Angular resolution
  - ……

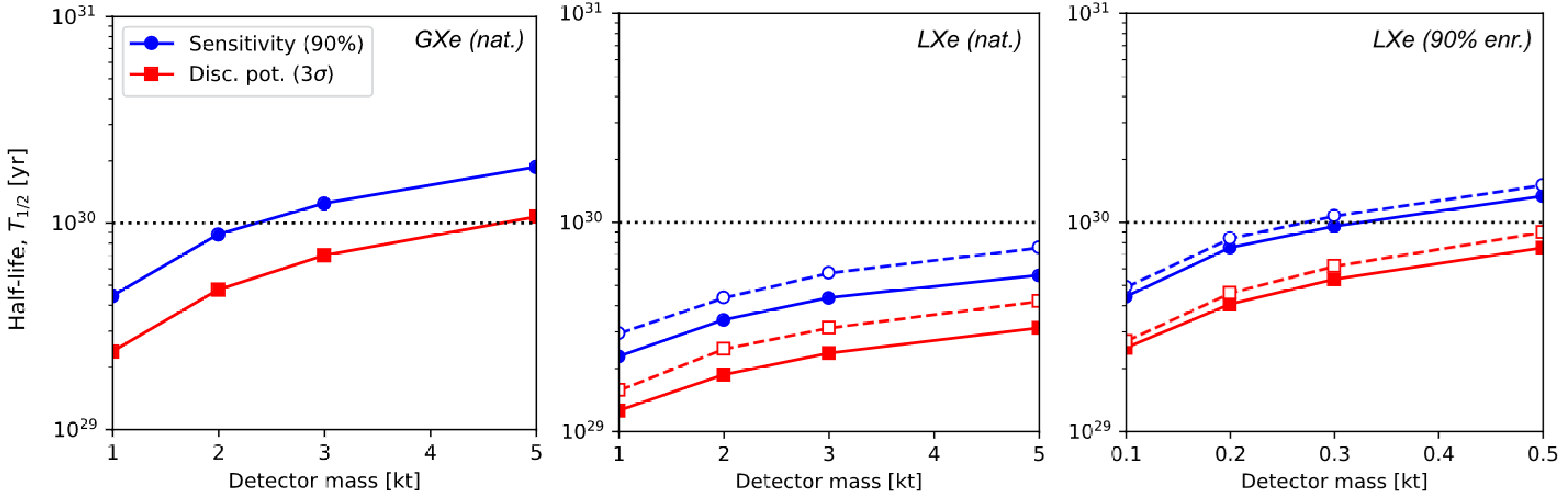
The limits: 2νββ





Phys. Rev. D **104**, 112007 (2021)

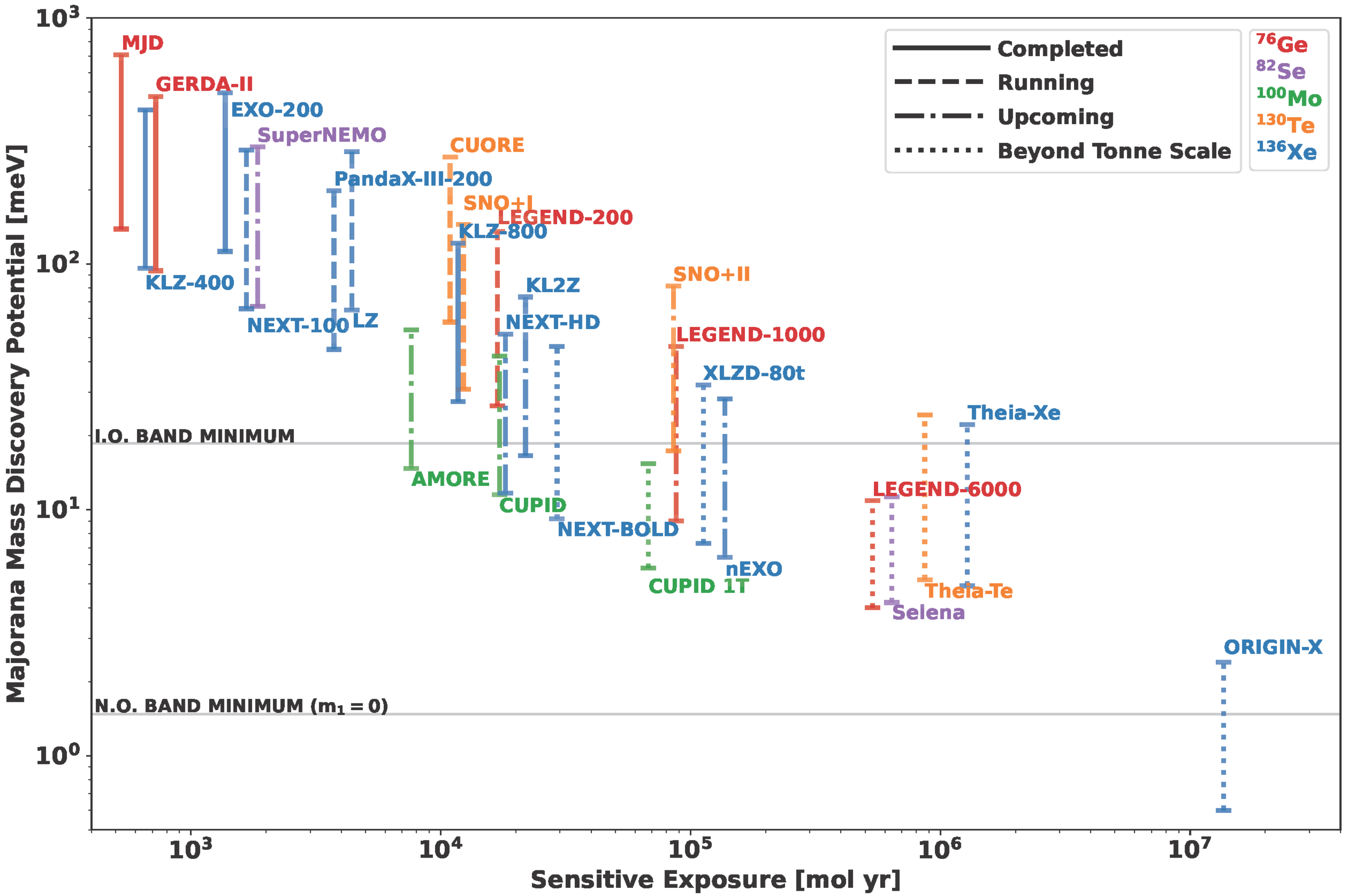
Xe required to reach 10^{30} yrs



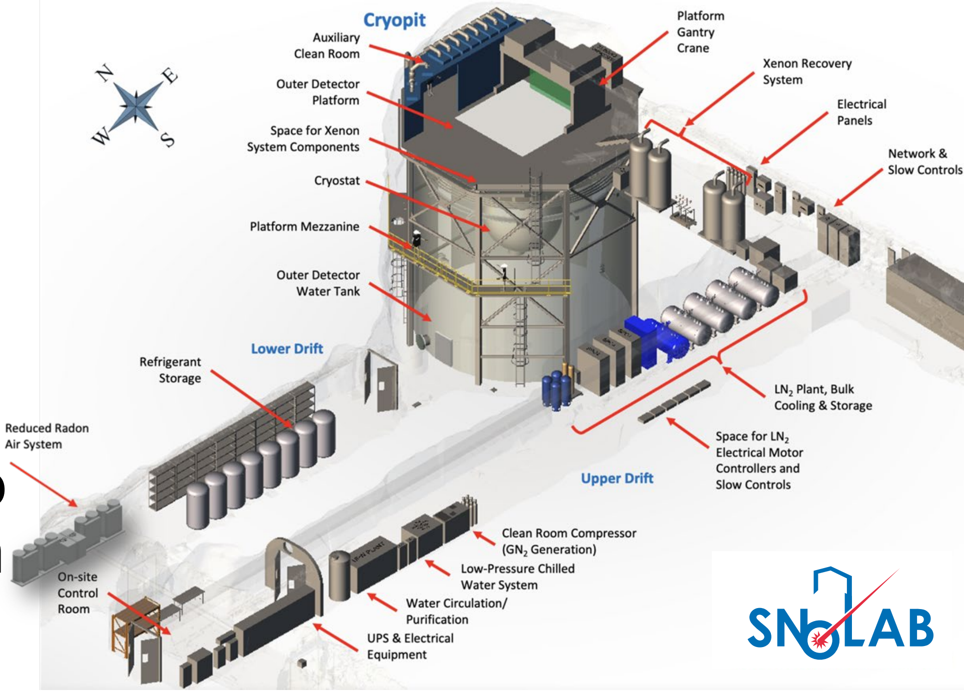
Dashed lines indicate the corresponding sensitivity using the Cherenkov-based rejection efficiency

Phys. Rev. D **104**, 112007 (2021)

Projected reach of 0νββ experiments



Conclusion



- Technologies available to reach 10^{28} yrs.
- LXe single phase TPC sufficiently advanced to compete with LEGEND-1000 and CUPID, both in terms of sensitivity and schedule.
- Funding agencies are supportive of a 0νββ program.
- If the Xe (and noble gas) community can come together and agree on a common strategy, I am convinced that we can advance all our research interests.
- Many of the current challenges are not of technical limitation but due to personal favorites.
- Additional R&D required to reach 10^{30} years.

Advertisement: Neutrinoless double beta decay search in Xe - next-generation experiment workshop

Neutrinoless double beta decay search in Xe - next-generation experiment workshop

12-14 November 2025
Montreal
America/Toronto timezone

https://nyx.physics.mcgill.ca/e/XeDBD

Xe-focused 0νββ workshop in Montreal on November 12-14, 2025!