Status of nEXO

13 June 2025

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SNOLAB

McGill UNIVERSITY

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The nEXO Experiment

0νββ
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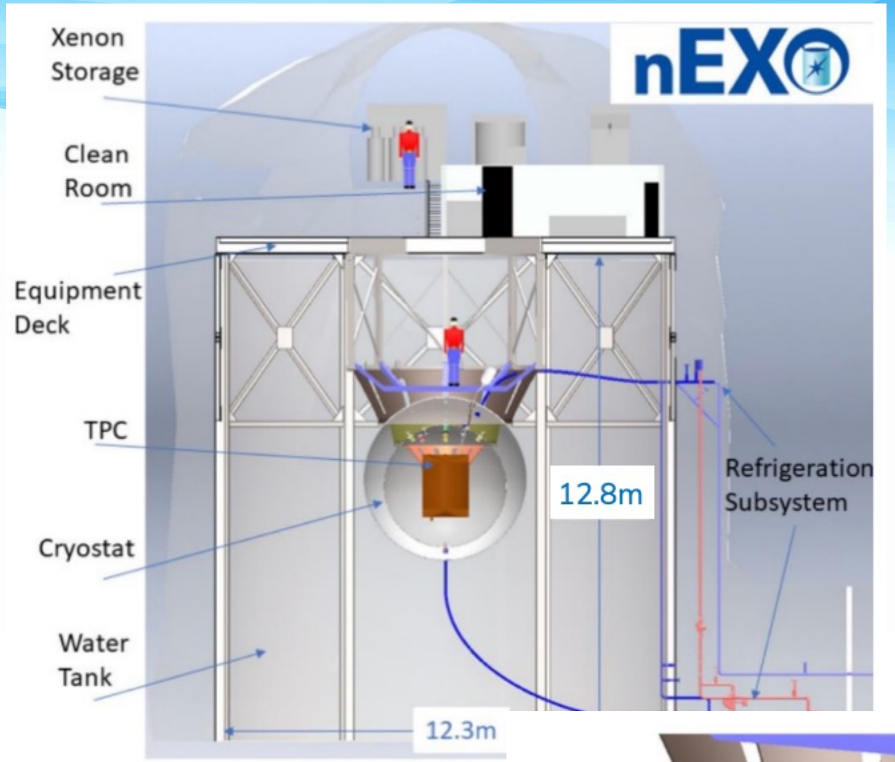
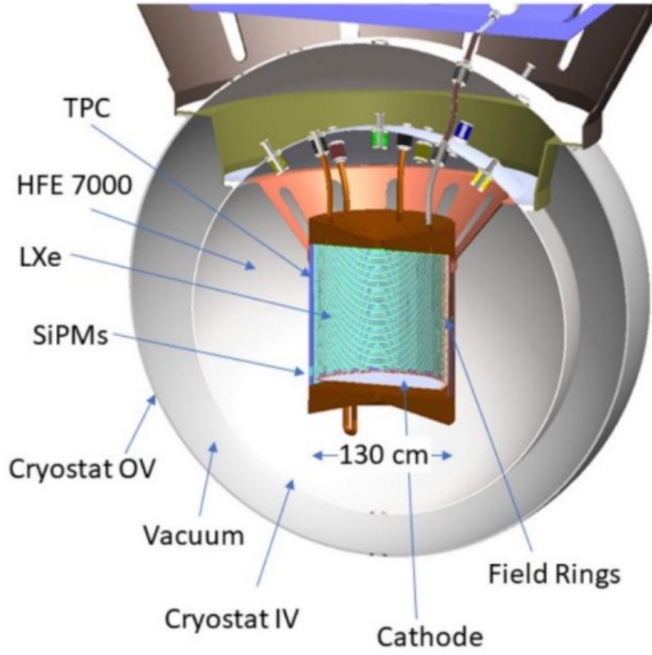
- TPC with 5000 kg of 90% enriched ^{136}Xe
- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified, No long-lived cosmogenically activated Xe isotopes
  - $Q_{\beta\beta}$=2457 keV



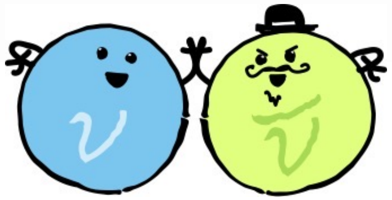
- 1.5 kT UPW in instrumented Outer Detector to veto muons
- Monolithic design means self-shielding from external backgrounds
- Multi-parameter measurement from detection of scintillation light and ionization signal



0νββ Searches Aim to Provide Insight to Deep Questions on Neutrino Nature

Quantum Nature of Neutrino

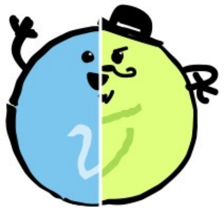
Theory 1: Neutrinos behave just like other matter particles and there are distinct matter and antimatter versions.



Neutrino **Antineutrino**

Paul Dirac

Theory 2: The neutrino and antineutrino are the same thing.

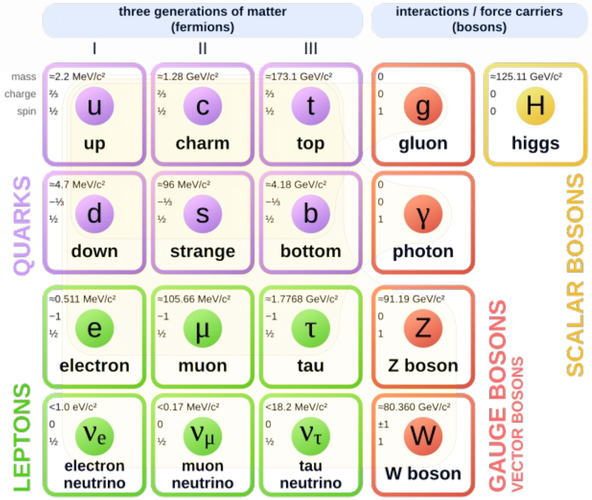


Ettore Majorana

Mass Generation

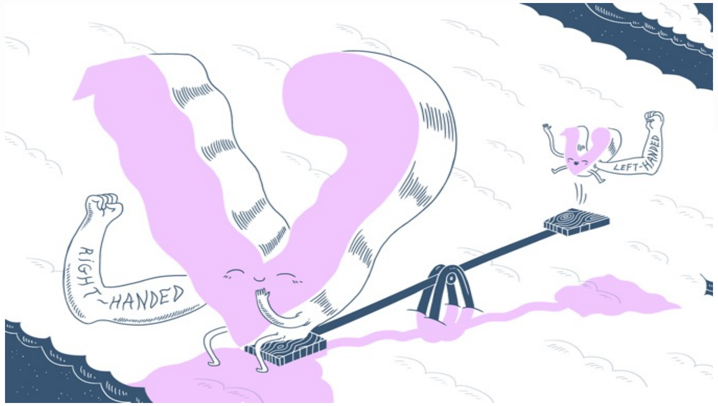
Nature of the Neutrino (and origin of its mass) is not accounted for in the Standard Model.

Standard Model of Elementary Particles



New Physics

0νββ observation supports the See-Saw mechanism theory.



Why neutrino masses are not zero, but many orders of magnitude less than other fundamental particles?

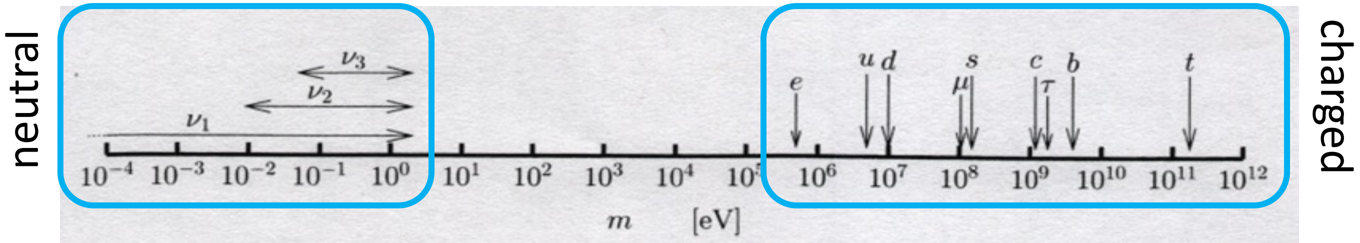


FIG. 14.1. Order of magnitude of the masses of leptons and quarks.

Scientific Goal: Sensitivity Beyond 10^{28} yrs

0νββ
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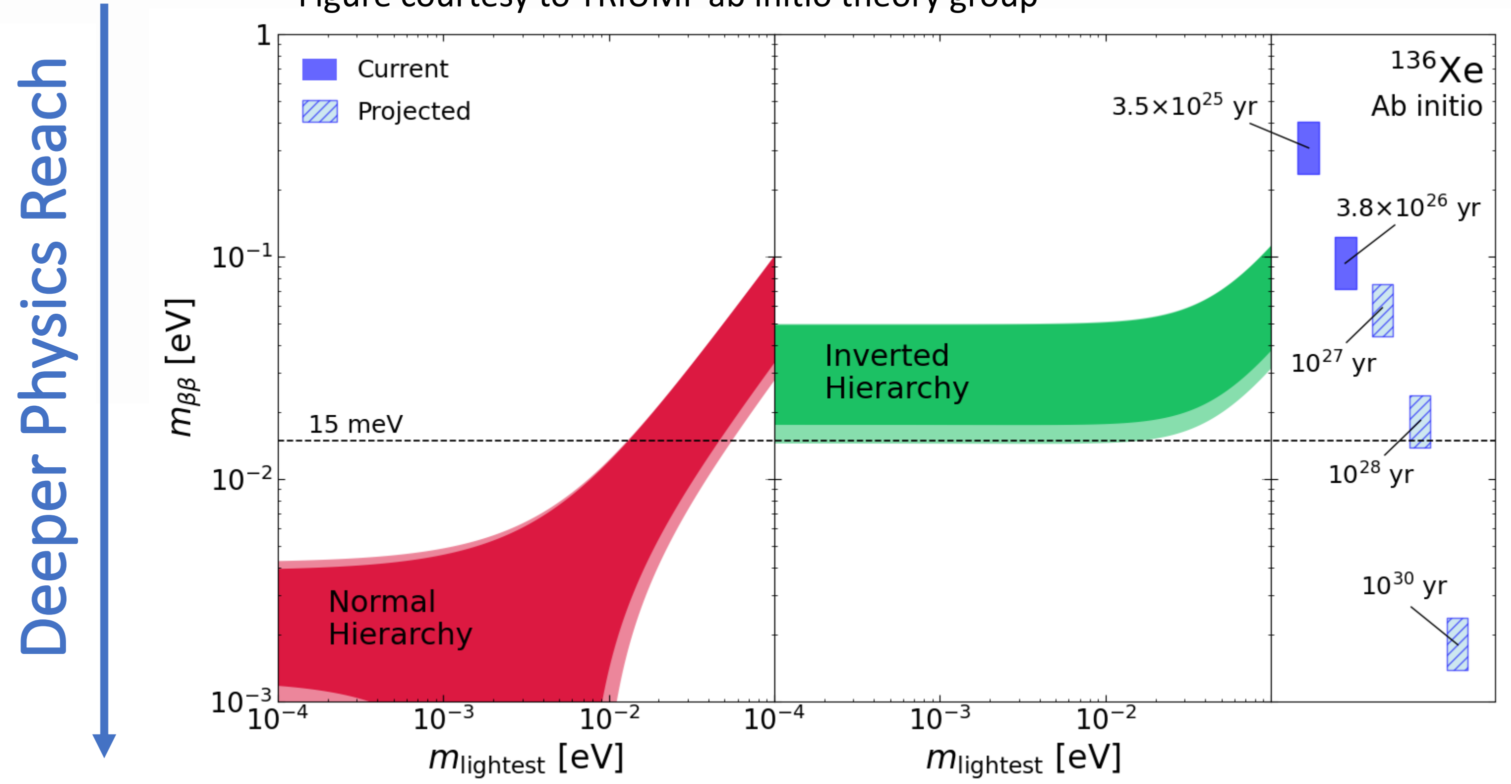
Figure courtesy to TRIUMF ab initio theory group



Final EXO-200 limit

Current best limit in Xe from KamLAND ZEN

Expected reach of current experiments

Reach of 5T experiment with 90% Xe-136

The ultimate goal in 0νββ of ~1 meV

Effective Majorana mass $\langle m_{\beta\beta}\rangle$ is an effective, albeit imperfect, metric to compare physics reach between isotopes and experiments.

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

Phase space factor — Axial coupling, $g_A = 1.27$ — NME

Status

- nEXO was one of the three contenders in an international 0νββ program.
- nEXO is based on the successful EXO-200 predecessor:
  - Conducted a competitive search for 0νββ, with a Majorana neutrino mass sensitivity comparable to Ge experiments.
- The nEXO design is vetted at the conceptual level as a whole. Some of its subsystems are ready for construction (water tank and other facilities, SiPM pre-production, some parts of TPCS).
- DOE's decision from December 2024:

> Dear Mike [M. Heffner, nEXO Project Director],
>
> … The decision is to move forward with LEGEND-1000 in the near term. …
>
> While CUPID and nEXO are viewed as demonstrating high potential for scientific impact, under constrained budgets it is unlikely that U.S. funding will allow these projects to advance significantly in the near term. R&D activities will continue, supported through the DOE NP fundamental symmetries research program, with the level dependent upon appropriations. **DOE NP remains committed to working with the international community to realize an international campaign with multiple isotopes and more than one large ton-scale experiment, with the potential for future investment in these experiments. …**
>
> Paul Mantica (he/him/his)
>
> Director, Facilities and Project Management Division, Office of Nuclear Physics (NP), US Department of Energy (DOE), Office of Science (SC)

An Opportunity for Canada

0νββ
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- **Opportunity**: Canada has taken leadership of the international nEXO 2.0 experiment at SNOLAB, following DOE's December 2024 announcement:
  - **The search for 0νββ is among the most exciting science of our time.**
  - **The international physics community has determined that searches in multiple isotopes are required for a definitive discovery.**
  - Thomas Brunner and Giorgio Gratta are co-spokespersons
  - Extensive liquid noble detector expertise in Canada.
  - SNOLAB's deep underground laboratory is the ideal location to host the experiment.
  - Established close collaboration with international partners on technology development.
  - CFI IF 2020 and IF 2023 infrastructure funding approved (on hold following DOE decision).
- **Time critical**: The experiment is ready to start construction and must be realized now to be competitive and significant with LEGEND-1000 in Italy and PandaX in China.

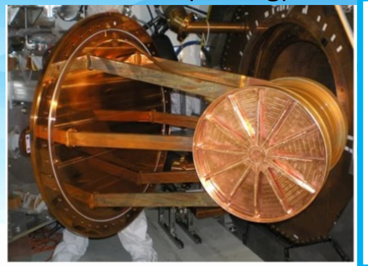
Goal: Build a competitive experiment designed for 10^{28} years.

nEXO 2.0 proposal

- Leveraging advanced design, nEXO 2.0 can be ready to start construction in the next ~year:
  - Coalesce a new collaboration with a sensitivity goal of greater than 10^{28} years in 10 years.
  - Take the well-reviewed nEXO design as basis.
  - Invite collaborators to take on responsibilities for subsystems and contribute their expertise.
  - Refine technology decisions in terms of cost, risk, performance, and schedule.
- **Liquid noble TPC – a demonstrated technology at the tonne scale.**

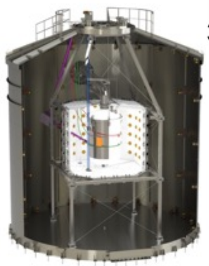
Past

EXO-200 (175 kg)



Current Generation

XENONnT
(6 Tonne)



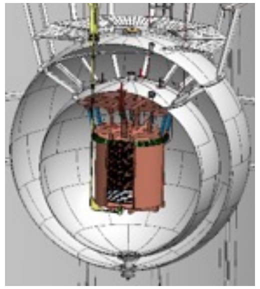
3.7 Tonne

LZ (7 Tonne)

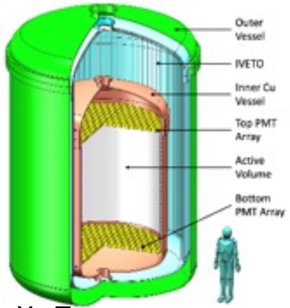
DarkSide-20k
(70 Tonne underground Ar)

SBND (112 Tonne Ar)

Next Generation Concepts



nEXO
(5 Tonne)



PandaX-xT
(43 Tonne)

XLZD
(60 Tonne)

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

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

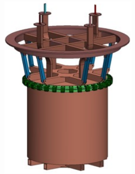
12-14 November 2025
Montreal
America/Toronto timezone

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

Xe-focused $0\nu\beta\beta$ workshop planned in Montreal on November 12-14, 2025!

nEXO 2.0 in a Phased Approach

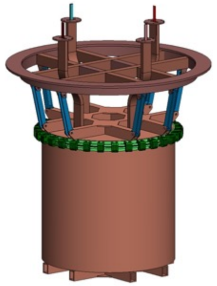
- Investigated cost and scientific reach of a phased approach with two alternatives:
- **Alternative 1**
  - 1 t single-phase liquid Xe TPC @90% enrichment
  - 8% cost savings compared to 5T TPC with natural xenon
  - No upgrade path, sensitivity limited to 10^{27} years



H=D=~75 cm

H=D=~130 cm

- **Alternative 2**
  - 5 t single-phase liquid Xe TPC
  - Phase 1: Start with natural Xe
  - Phase 2: subsequent loading with 90% enriched Xe

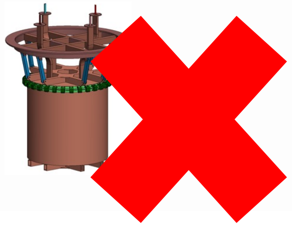


Alternative 2 is the preferred option:

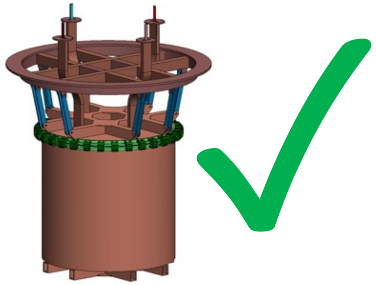
- Enables phased approach
- Decouples procurement risk of enriched xenon

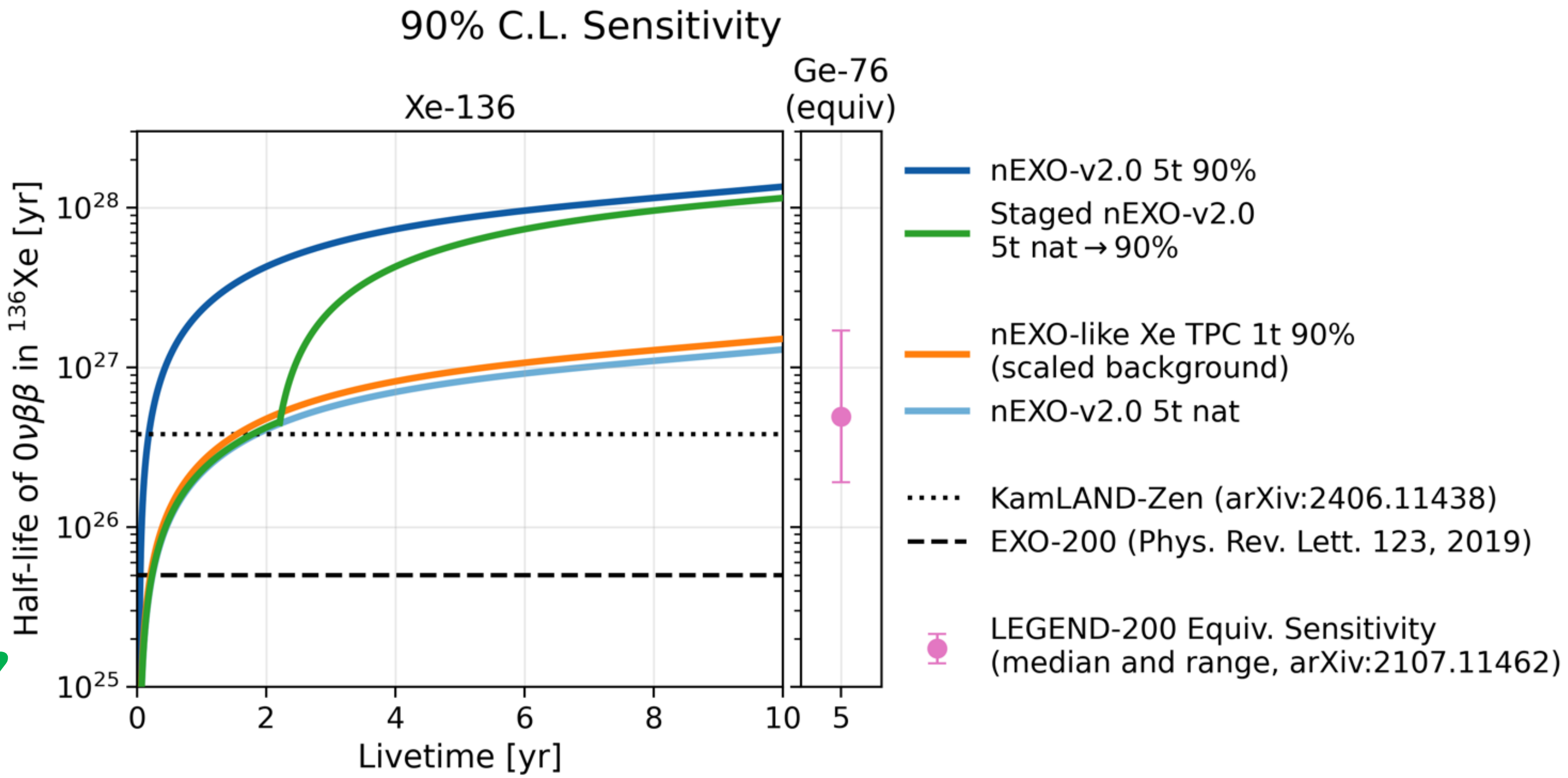
Sensitivity Comparison of Alternatives

- **Alternative 1**
  - 1 t single-phase liquid Xe TPC @90% enrichment



- **Alternative 2**
  - 5 t single-phase liquid Xe TPC

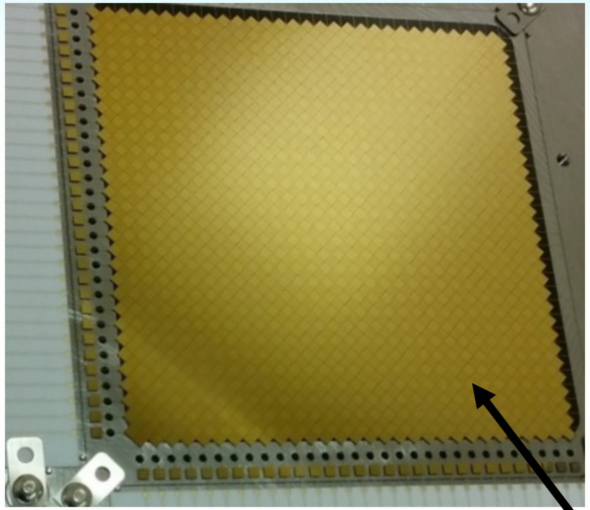




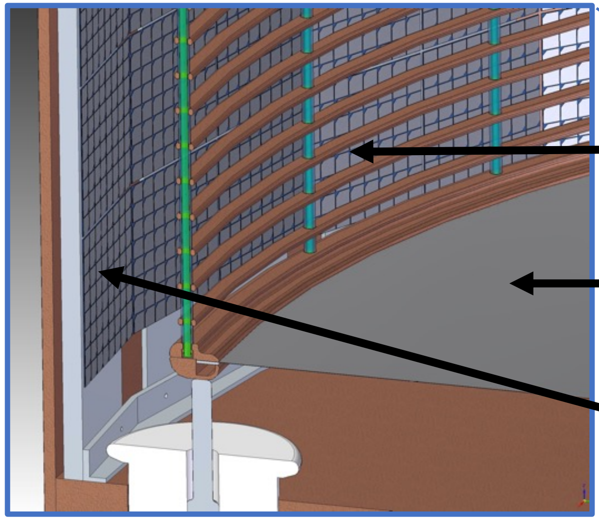
- **Mass matters → Alternative 2 is the preferred option.**
- Starting with a 5T detector with natural Xe
  → load with 90% enriched Xe after ~2 years of running.

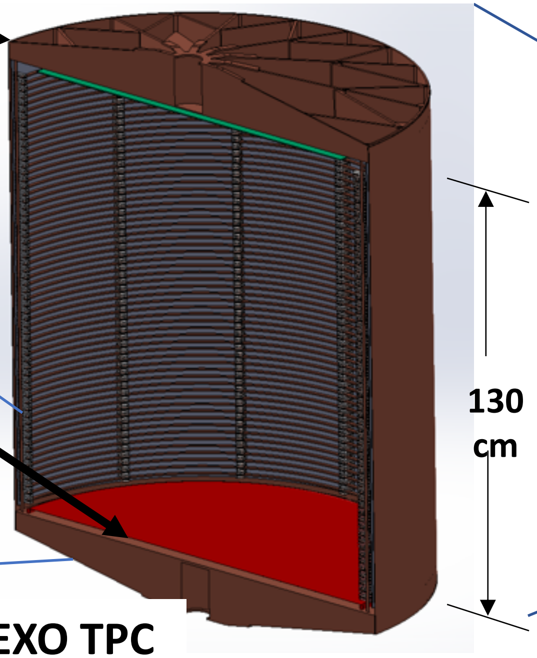
The nEXO detector design

- 5 t single-phase liquid xenon TPC.
- Silicon photomultiplier (SiPM/PDC) for 175nm scintillation light detection, ~4.5m^2 SiPM array inside liquid Xe.
- Instrumented, segmented anode for charge read out in liquid Xe.
  → 3D event reconstruction.
- Combine charge and light readout. Goal → σ/E <1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.
- Projected sensitivity of 10^{28} years [J. Phys. G **49** 015104 (2021)]



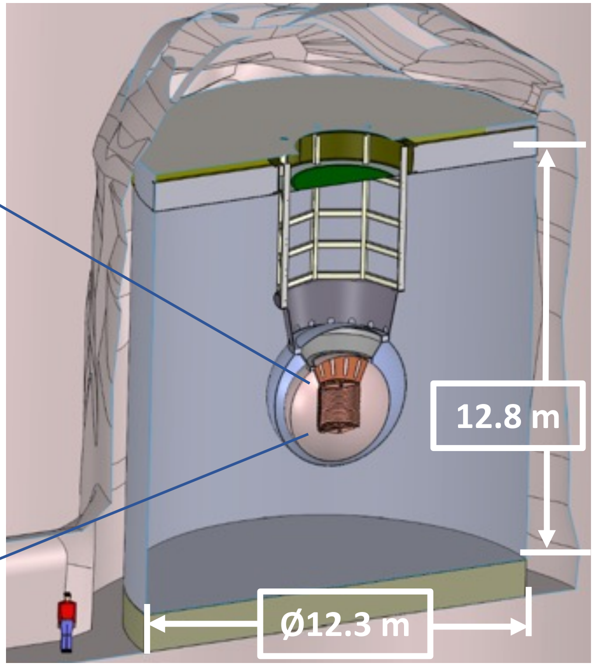
Picture: 10 x 10 cm^2 tile prototype [JINST 13, P01006 (2018)]
Tile simulation: [JINST 14, P090200 (2019)]





nEXO pre-CDR, [arXiv:1805.11142]
CDR available upon request

nEXO TPC



nEXO at the SNOLAB Cryopit

nEXO at SNOLAB Cryopit well developed

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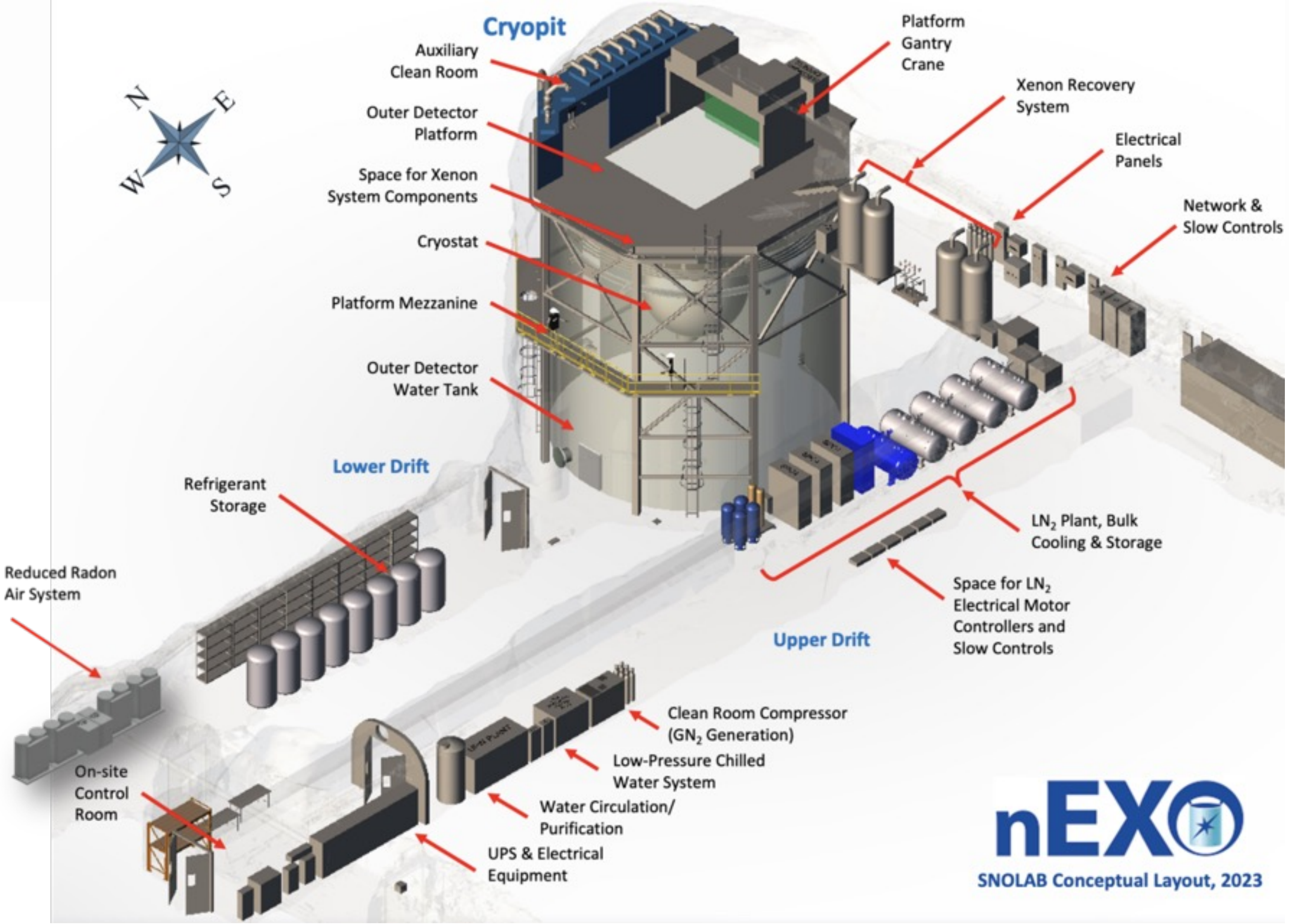


- Models of actual infrastructure placed in 3D scan of Cryopit and surrounding drifts.
- Layout of infrastructure fits within the space of the SNOLAB underground lab.
- Close collaboration between nEXO and SNOLAB.

Reviews of nEXO

The nEXO project has been **<u>successfully</u>** reviewed multiple times:

- DOE Portfolio Review in 2021
- Conceptual Design Review (CoDR, internally organized external review) of all subsystems in late 2023 and early 2024
- Director's Review at LLNL in July 2024, combined with SNOLAB Gateway 1 review

Recommendation by Review Committee:
Proceed to the CD-1 Independent Project Review.

- SNOLAB/TRIUMF Gateway 1A reviews in 2022 and 2024 for CFI IF infrastructure
- December 4, 2024 NSERC Expert review:
  - "**The physics questions addressed are important and timely**, and **nEXO is the experiment of choice in Canada** to approach these topics."
  - "The nEXO Canada collaboration has a successful record of HQP training at all levels."
  - "The proposal outlines an excellent plan for HQP training, offering opportunities to engage in cutting-edge research and detector development."

High-profile Canadian presence at Director's Review at LLNL in July 2024:

- Eva Luc, Senior Policy Analyst with Innovation, Science and Economic Development Canada (ISED)
- Minodora Iordan, Associate Director, Research Development, McGill University
- Nigel Smith, Executive Director, TRIUMF
- Jodi Cooley, Executive Director, SNOLAB (remote attendance)

More than 50 individual external experts have reviewed nEXO over the past 24 months

The international nEXO collaboration

nEXO

Canadian contingent within nEXO
- 15 PIs members of nEXO
- ~45 undergraduate and graduate students and postdocs
- Canadian groups constitute ¼ of the collaboration
- Significant engineering and project management support from SNOLAB

List of collaborators available at https://nexo.llnl.gov/

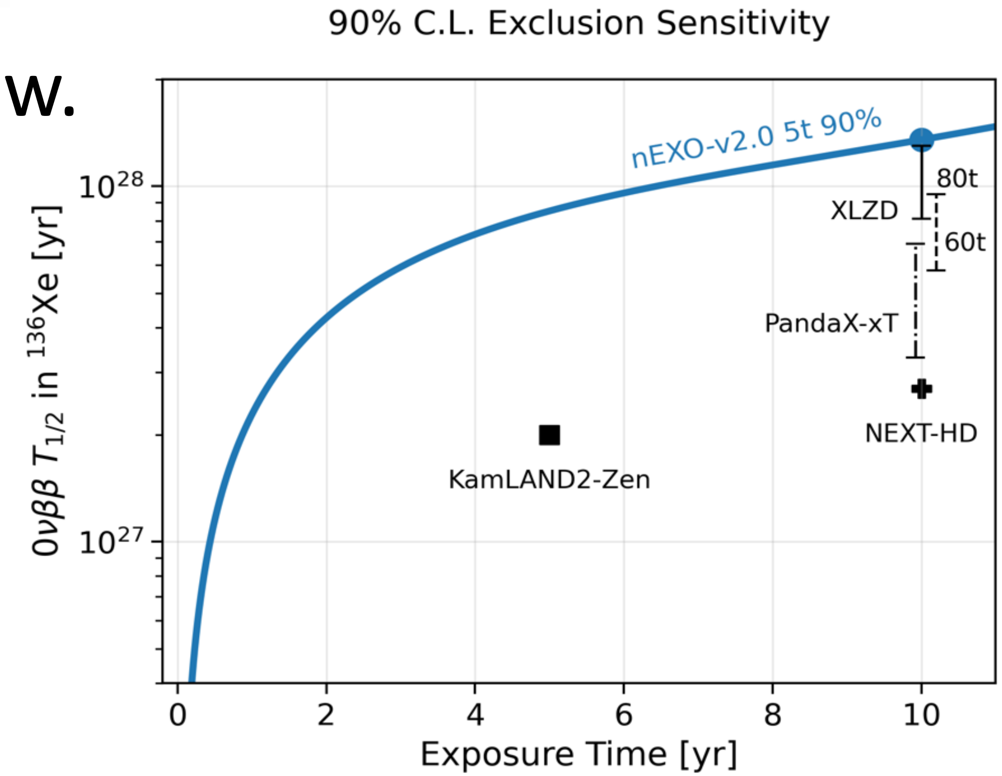
>200 scientists, 42 institutions in 10 countries on 4 continents

Funding

- Like many large projects, our NSERC award was significantly reduced this round
- We are working with CFI to release the IF-2020 award following the summit.
- Despite the decision from the US DOE, we received NSERC funding to support the development of a strategy to move forward
- In discussions with NSDERC on best path forward to increasing support for nEXO 2.0

XLZD?

- Dark Matter Experiment, 60 t natural Xe target
  - contains 5.34 t of ^{136}Xe
- Pitched as a general “xenon observatory”
- Detector ***not*** optimized for 0νββ
- XLZD has not yet undergone serious review.
  - Showed aggressive timeline
  - Not really “shovel ready”
- Planning to make siting decision in 2026
- Considering Boulby, LNGS, SNOLAB, SURF



Close out slides from 3rd 0νββ Summit

0νββ
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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.

3rd International Summit on the Future of Neutrinoless Double-beta Decay

May 26 – 27, 2025
Max Planck Institute for Nuclear Physics
Europe/Berlin timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Travel Information

Support
anja.berneiser@mpi-hd....

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

- **Canadian Agencies participating at summit in person:**
  - ISED
  - CFI
  - NSERC
- Jodi Cooley & Nigel Smith represented SNOLAB & TRIUMF.
- nEXO was one of five experiments invited to the summit.
- Nigel Smith interim chair of "Joint Oversight Group (JOG)"

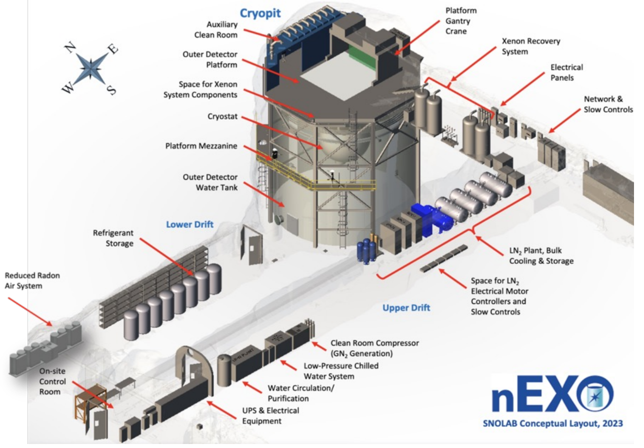
Statement from first JOG meeting (2)

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.

Summary

- The nEXO design is optimized for a sensitivity of 10^{28} yrs, has been extensively vetted by peer-reviews and the technology is well proven.
- Funding agencies agreed to pursue a 0νββ program in different isotopes with experiments in Europe and North America.
- Canada is now leading the nEXO 2.0:
  - The space is ready at SNOLAB.
  - The design is well advanced, construction in ~1yr.
  - Additional partners/collaborators are welcome.
- **The experiment is ready to move forward.**
- **We are looking for new collaborators to join our endeavor!**



Backup slide

Xenon is an ideal medium to search for 0νββ

0νββ @CRYOPIT

- Unanimous agreement that more than one isotope is needed for a believable discovery of neutrinoless double beta decay.
- Recent decisions by some funding agencies have triggered increased discussion within the community on how to optimize the sensitivity of next-generation experiments to pursue neutrinoless double beta decay.
- Xenon detectors are ideal candidates for competitive large-scale detectors:
  - Current best limits provided by Xe detector: KamLand-Zen.
  - Long, successful history of technology demonstration (EXO-200/nEXO, NEXT, ZEPLIN-I/II/III/LUX/LZ, XENON10/100/1T/nT, XMASS, PandaX/4T, AXEL, and others).
  - Unique opportunity for discovery cross-check and background control with different Xe isotopic concentration.
  - Potential evolutionary path towards normal ordering with larger quantity of 136Xe and addition of Ba tagging.
- Proposed Xe ton-scale experiments all have the potential to reach 10^{28} yrs sensitivity.
- The xenon community is exploring how to maximize the scientific reach:
  - Xe communities started to collaborate under DRD2.
  - nEXO, NEXT, AXEL and XLZD are exploring common strategies to leverage existing collaborative efforts.
  - Conversations with other players in the field, beyond those present at this summit, have restarted.
  - International Workshop for Xe 0νββ to sustain productive interactions across the Xe community.

Xenon Program Schedule

0νββ
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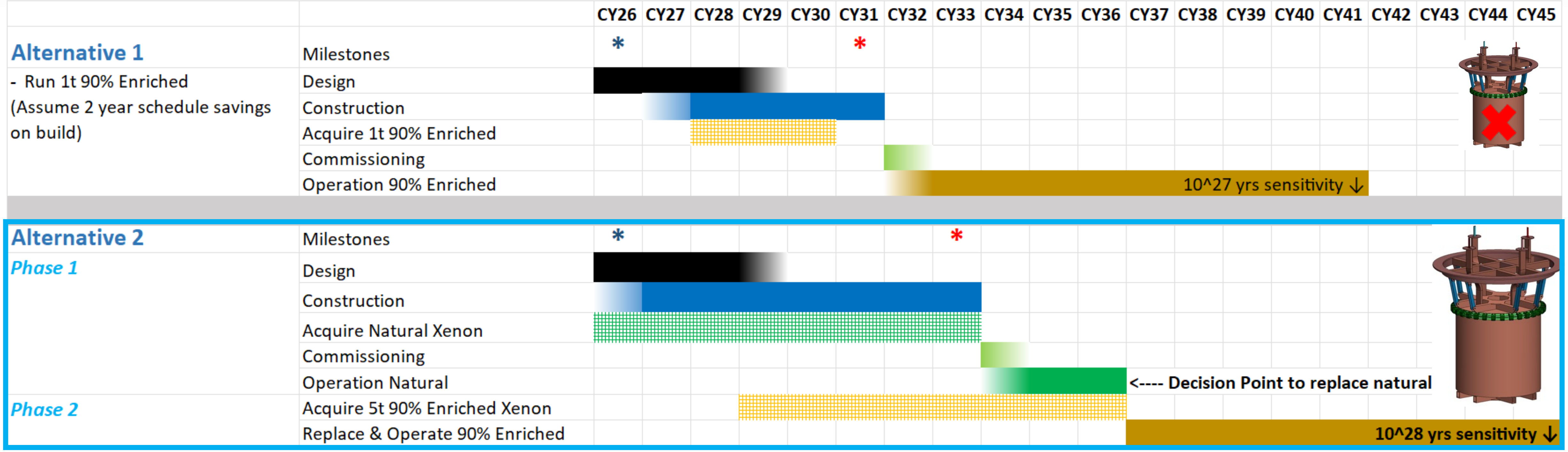
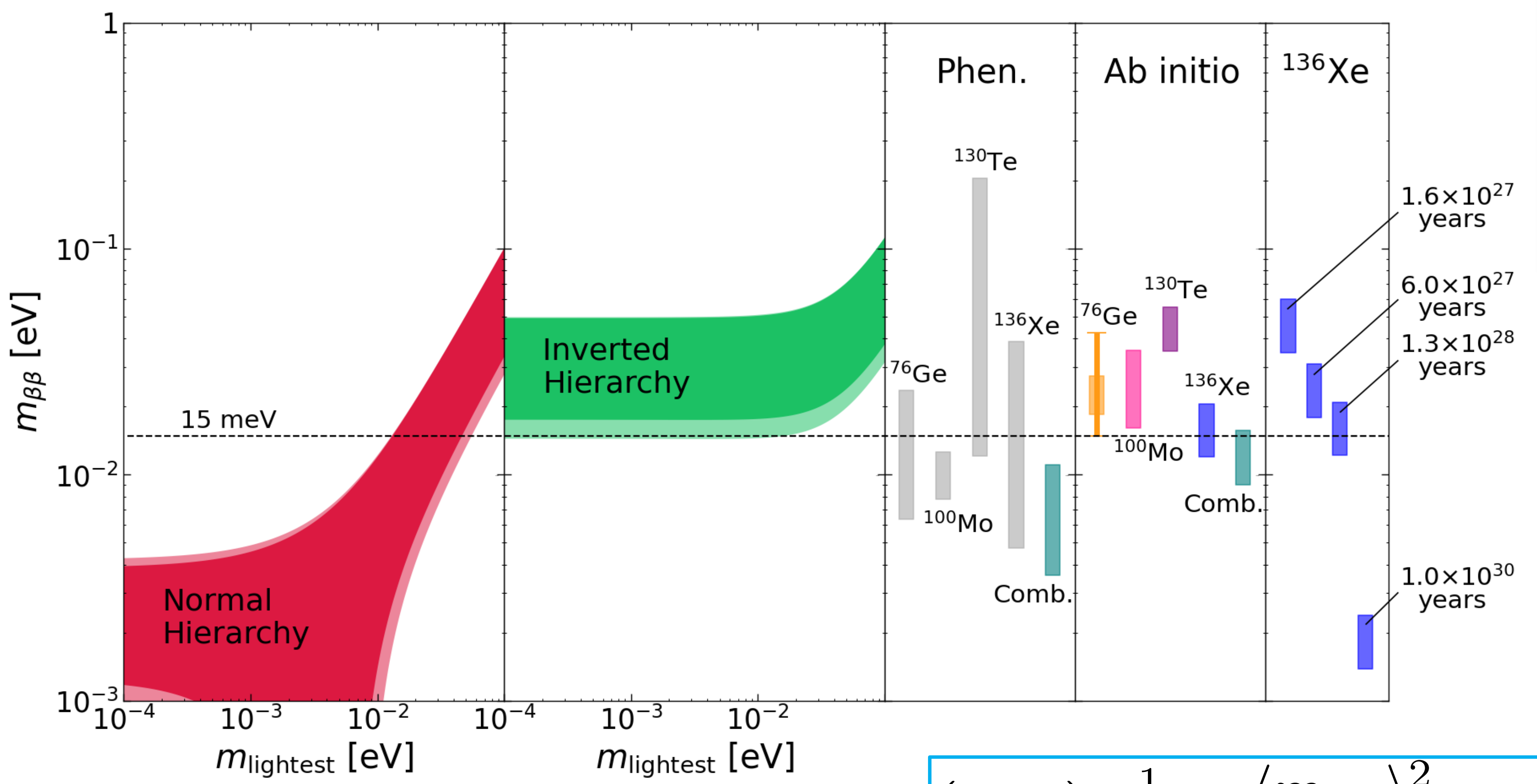
Next steps:

- Need imminent release of R&D infrastructure support from CFI IF 2020 and IF2023 to keep momentum, advance technical readiness, and demonstrate Canadian interest to lead Xe-136 program at SNOLAB.
- Collaboration building for the next ~1 year→ attract international partners.
- Start construction of outer detector in late 2026 with IF 2023 release.

Legend:
- Xenon Natural
- Xenon 90% Enriched operation run
- Natural xenon acquisition
- Enriched xenon acquisition
- * Operations Review
- * Need IF2023 Released



Scientific Reach of Phased Approach



1T, 90% or 5T, natural

5T, 40%

5T, 90%

Goal of a future search

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

Figure courtesy to TRIUMF ab initio theory group

Powerful Technology in Either Outcome

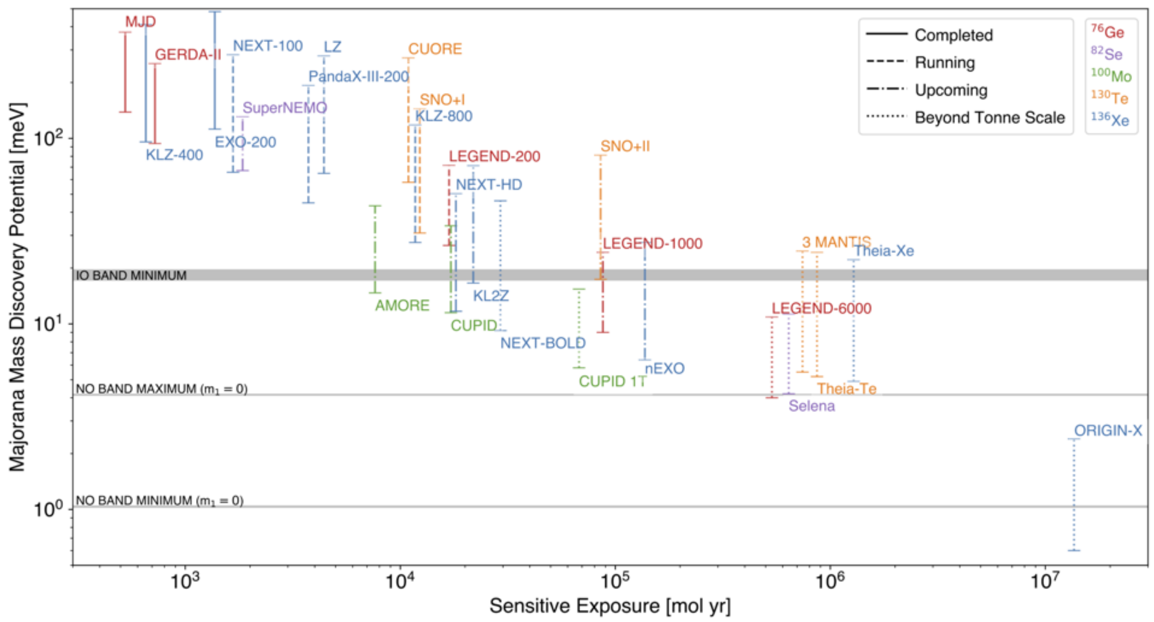
Advancing <u>nEXO 2.0</u> is an investment into technology and personnel development with a clear path for the future:

If nEXO 2.0 discovers 0νββ decay:

- Confirmation will be done in the same detector with depleted or natural xenon, no other experiment needed for the confirmation.
- The investment in xenon can be completely recaptured with follow-up experiments to investigate the underlying physics.

If nEXO 2.0 does not discover 0νββ decay:

- Should 0νββ decay not be discovered by next-generation experiments, larger detectors using the same or closely related technology are plausible.



nEXO 2.0: a Once-in-a-Generation Opportunity

0vββ
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- Understanding the origin of matter in the Universe via 0vββ will be the biggest subatomic physics discovery of a generation; we know how to do it!
- The physics community has determined that searches in multiple isotopes are required for a definitive discovery.
- nEXO 2.0 is the DOE nEXO project under Canadian leadership, realizing opportunities for improvement:
  - A next-generation 0vββ experiments that reaches 10^{28} yrs on a competitive timescale.
  - Well reviewed and vetted plan. Ready to start construction within a year of receiving funding.
  - We are looking for international partners to realize the experiment under shared governance (one goal of this meeting).
- <u>Time is of the essence to make a discovery.</u> This search is highly competitive.

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.**

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

Rate at 10^{28} years:
~0.3 decays/tonne/yr

^{136}Xe Mass for 1 decay/year (average)	Half life
3.3 Tonnes	10^{28} years
326 Tonnes	10^{30} years

Opportunities through partnerships

0νββ
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- The burden to the Canadian funding could be substantially reduced by partnerships.
- Collaboration well established with international partners in 9 countries.
- Anticipated support from current collaborators:
  - US-based expertise maintains engagement.
  - Contributions from France.
  - Chinese collaborators interested in providing 1T of 90% Xe and possibly charge readout plane.
- Partnering with other Xe experiments to coordinate strategy.
  - **Welcome new partners under a shared governance.**
- Emerging technologies on the horizon to improve detector performance.
- Experiment as a steppingstone towards a detector with larger mass to explore longer half-lives in case of no observation.

	Xe-136
Xe-124	0. 001
Xe-126	0. 001
Xe-128	0. 058
Xe-129	0. 027
Xe-130	0. 008
Xe-131	0. 037
Xe-132	0. 150
Xe-134	3. 155
Xe-136	96. 564

Future Potential for Either Outcome

0νββ
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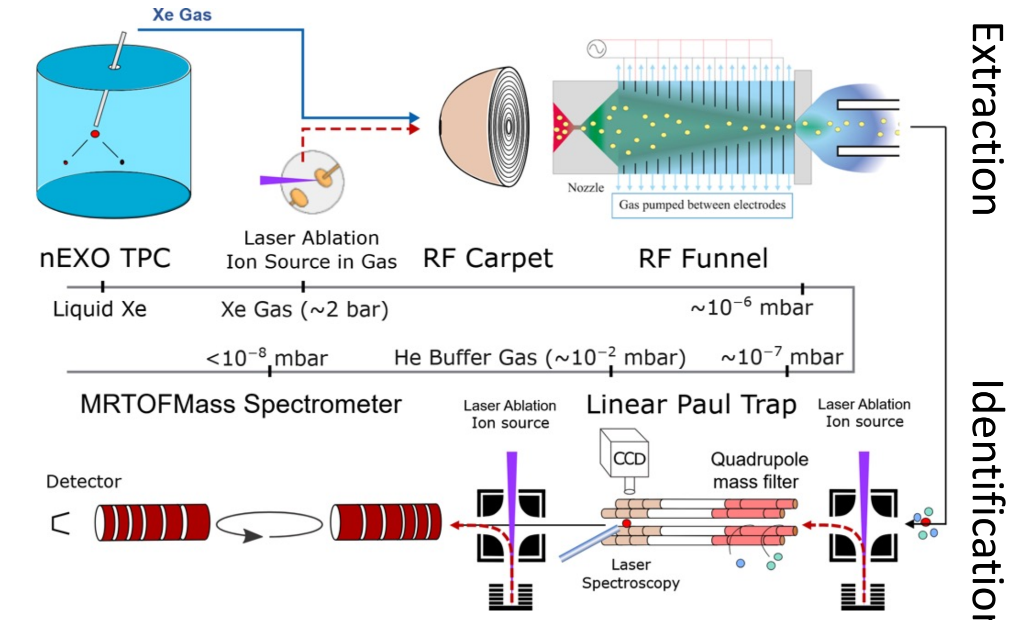
If nEXO 2.0 discovers 0νββ decay:

- The enriched xenon is NOT "frozen" in a particular detector.
- Should 0νββ decay be discovered then:
  1. **Natural Xe data provides a benchmark on scaling of 0νββ signal with enrichment level.**
  2. Reused enriched Xe in a different experimental configuration to investigate the underlying physics.

If nEXO 2.0 does not discover 0νββ decay:

- The advantages of the homogeneous detector keep improving with size.
- Should 0νββ decay not be discovered by next-generation experiments, larger detectors using the same technology are plausible.
- Emerging technologies expected to improve detector sensitivity.
- Technologies (Ba-tagging) are being developed to further reduce backgrounds in future detector upgrades.

Ba-ion tagging – possibility for future upgrades



Atoms **2024**, *12*(12), 71