Search for 0νββ in xenon – Canadian Strategy

Leveraging Canada's research excellence to host an international breakthrough discovery observatory at SNOLAB, with direct benefit to the Canadian economy and society.

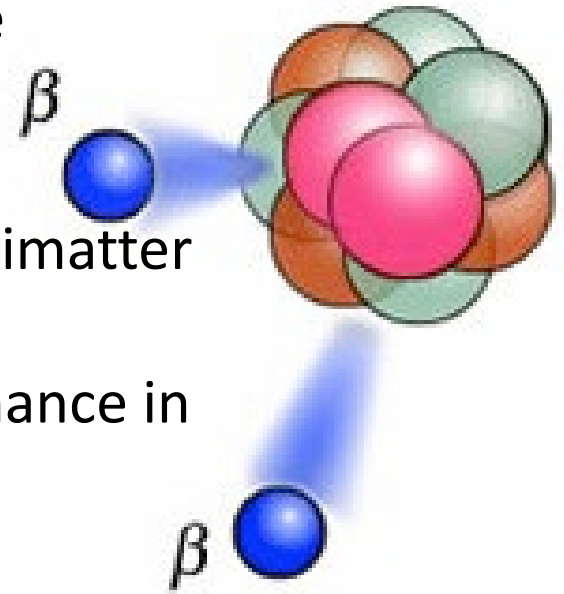
April 30, 2025

Thomas Brunner for the nEXO collaboration

SNOLAB Future Projects Workshop 2025

Motivation: Neutrinoless double beta decay

- Search for neutrinoless double beta decay (0νββ) to learn about the fundamental quantum nature of neutrinos.
- Observation of 0νββ always implies 'new' physics:
  - Prove a process of matter creation without equal number of antimatter particles.
  - Help explain observed cosmic baryon asymmetry (matter dominance in the Universe).
  - May provide insight into the mass of the neutrino.
- This process is not foreseen in the current theoretical framework describing fundamental particle interactions, the Standard Model of particle physics.
- Yet there is good motivation to believe that this process could exist.
- **Due to the significance of a discovery of 0νββ on our understanding of the Universe, this search is a high priority of the international scientific community.**



Reminder: Recent Political Progress

Closing session of the 0νββ summit 2023

SNOLAB

Readout from In Camera Sessions

[Funding agencies (DOE, ISED, …) and lab directors]

- The international stakeholders in neutrinoless double beta decay research who attended this summit (agencies representing Canada, France, Germany, Italy, UK, and USA) agree in principle 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.
- These stakeholders discussed a scenario that could accomplish the goals of the first bullet by deploying CUPID, LEGEND-1000, and nEXO with one tonne-scale experiment in Europe and one tonne-scale experiment in North America.
- These stakeholders agree on the need for a coordinated effort to efficiently and cost-effectively advance the field for the proposed double beta decay experiments, as well as the future of the field. To that purpose, these stakeholders agree that a structure for international collaboration on this research should be explored. (e.g., an international virtual observatory for neutrinoless double beta decay).
- These funding agencies intend to create a working group to explore how such an international effort could be coordinated. The stakeholders welcome additional international partnerships.

- A neutrinoless double beta decay **campaign** is the **highest priority for new experiments** of the US nuclear physics community.
- The **Canadian SAP Long Range Plan identifies the search for 0νββ as a priority**.

Presentation of US NSAC Long Range Plan 2023

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

A NEW ERA OF DISCOVERY THE 2023 LONG

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Observation of $0\nu\beta\beta$ would mean that the neutrino is its own antiparticle.

It would also mean that lepton number is not conserved.

It would mean that matter can be created and help explain why the universe has more matter than antimatter.

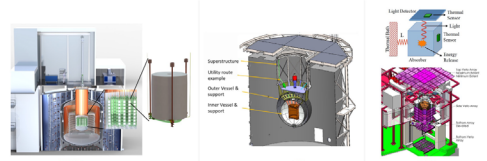
The rate of $0\nu\beta\beta$ has implications for neutrino masses.

Regular beta decay:
$n \rightarrow p + e^- + \bar{\nu}_e$

Double beta decay (DBD):
$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

Neutrinoless DBD:
$2n \rightarrow 2p + 2e^-$

Major discovery potential!



A NEW ERA OF DISCOVERY THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

Source: https://indico.cern.ch/event/1242655/ and https://www.snolab.ca/news/snolab-hosts-2nd-international-summit-on-the-future-of-neutrinoless-double-beta-decay/

Source: https://science.osti.gov/-/media/np/nsac/pdf/202310/Dodge-NSAC-Oct-4-2023-v2.pdf and https://nuclearsciencefuture.org/wp-content/uploads/2024/03/23-G06476-2024-LRP-8.5x11-pcg-v1.5-3.14.24.pdf

Reviews of nEXO

The nEXO project has been **successfully** 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."
  - 8 research topics were rated as "high priority", 5 were rated as "medium priority"

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)

DOE email from December 19/20, 2024

0νββ
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Dear Mike [M. Heffner, nEXO Project Director],

This correspondence provides an update on the Department of Energy Office of Nuclear Physics (DOE NP) plans regarding Ton Scale Neutrinoless Double Beta Decay (TS-NLDBD). Discovery of NLDBD could answer the question of how matter came to dominate over antimatter in the universe – one of the most compelling mysteries of modern physics. While research has been ongoing for many years, the nuclear science community identified TS-NLDBD as the highest priority for new experiment construction in the 2023 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP). The LRP acknowledges the worldwide excitement that has catalyzed the international cooperation essential to carrying out these complex experiments. In addition, the LRP recognizes the ongoing community research on the use of different isotopes and technical approaches, as well as the exceptional incremental progress that has been made on the lifetime limit for NLDBD.

Subsequent assessments by the U.S. community in response to the 2023 NSAC Facilities Charge confirmed that experiments targeting TS-NLDBD, along with the Electron-Ion Collider, a multibillion-dollar accelerator facility, are absolutely central in scientific importance and ready for construction. For TS-NLDBD, DOE NP has further analyzed the concurrent launch of the three technologies within the TS-NLDBD portfolio: the Cryogenic Underground Observatory for Rare Events Upgrade with Particle Identification (CUPID), the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay One Tonne (LEGEND-1000), and the next Enriched Xenon Observatory (nEXO). This analysis recognizes that projections for available resources preclude building multiple experiments simultaneously while acknowledging the scientific importance of multiple experiments to tackle this challenging science.

The decision is to move forward with LEGEND-1000 in the near term. This was a difficult decision given the enthusiasm of each of the research teams for the three concepts. The decision is based on the potential for the experiment to deliver world leading science while addressing the recommendations in the 2023 NSAC LRP, the significant engagement with domestic and international partners, the strong management structure established for both the international and U.S. teams, and possible synergies with other DOE Office of Science programs/offices. LEGEND-1000 is well into planning under the leadership of Oak Ridge National Laboratory. The project team has made excellent progress developing their conceptual design and preparing for Critical Decision-1 (CD-1), Approve Alternative Section and Cost Range, with the funding provided to date. DOE NP anticipates holding a CD-1 independent project review in calendar year 2025. LEGEND-1000's success depends on continued strong support from the broader U.S. nuclear science community as well as substantial international contributions.

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. We will continue to engage with the Double Beta Decay Working Group to establish an organizational framework for coordinating international investments in NLDBD experiments.

Our office acknowledges that this decision is disappointing for the nEXO team. We are committed to working with you to identify areas of research and development that support the project in the longer term.

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: nEXO 2.0

0νββ
@CRYOPIT

- **Opportunity**: Canada is well positioned to take leadership of an international flagship experiment at SNOLAB to search for 0νββ in the isotope ^{136}Xe:
  - Canadian institutions led R&D and project efforts within the nEXO collaboration for more than 10 years.
  - Extensive liquid noble detector expertise in Canada.
  - The SNOLAB deep underground laboratory is the ideal location to host such an experiment.
  - Established close collaboration with international partners on technology development.
  - Recent successful external expert reviews of the nEXO detector concept, including feasibility, scientific reach, requirements, technical feasibility, risk, cost, and project management.
  - CFI IF 2020 and IF 2023 infrastructure funding approved.
- **Time critical**: The experiment concept is ready and must be realized now to be competitive and significant with LEGEND-1000 and, especially, PandaX in China.
- **Leadership**: Release of funds from previous CFI competitions would allow continued momentum, exploiting past expertise development and building a larger collaboration following the recent DOE decision to delay their capital funding.

Goal: a program competitive with LEGEND-1000 in terms of schedule and sensitivity.

Strategy to reach 1x10^{28} years

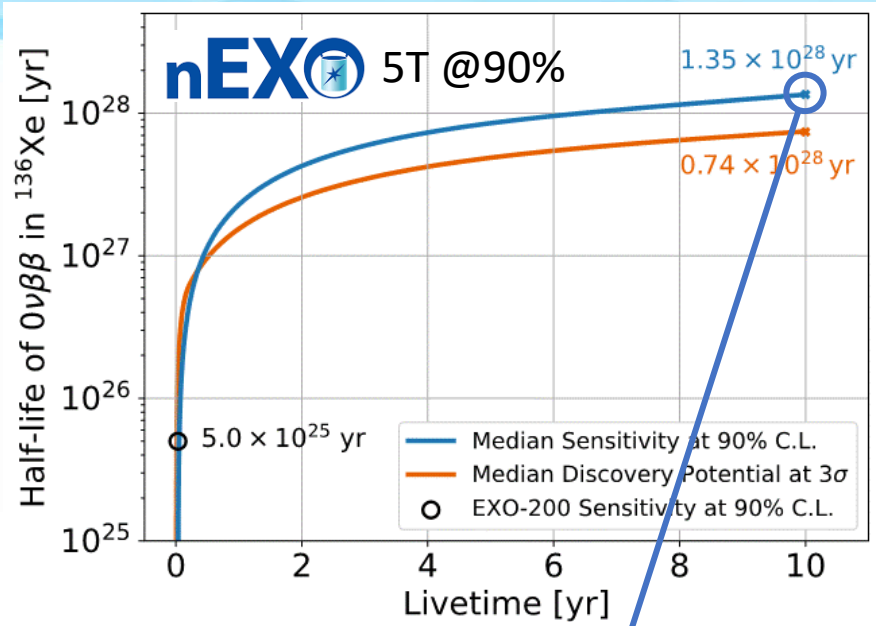
- Bring together the community in a workshop with the goal to develop a roadmap for a competitive experiment.
- **Interest poll for workshop: https://mcgill.ca/x/icV**
- Ultimately, even a background free experiment is limited by the number of atoms → only a global approach will be able to procure sufficient Xe-136 for next-generation and future experiments.

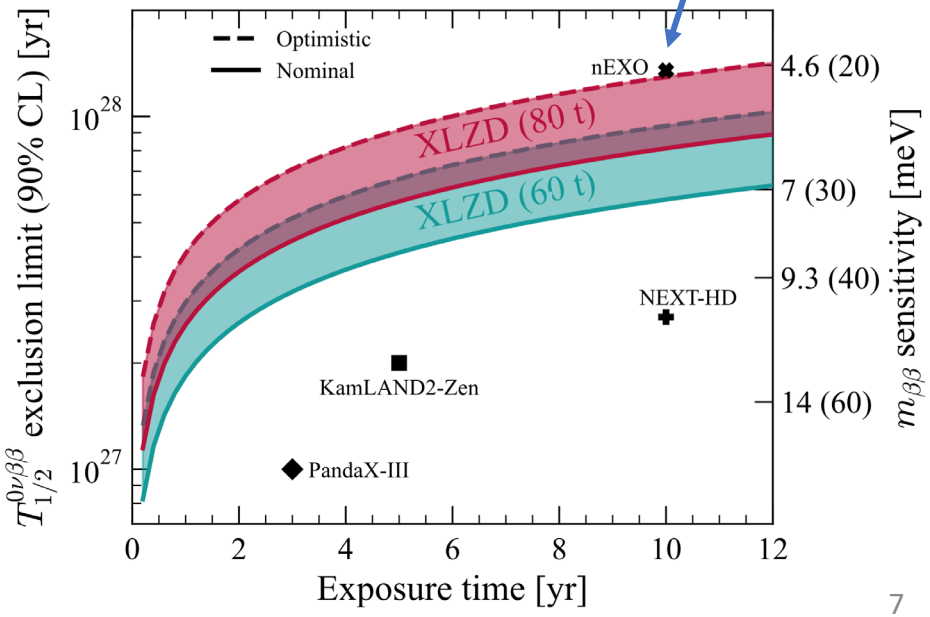
$$\frac{dN}{dt} = \frac{\ln(2)}{T_{1/2}} N$$

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

- **Evaluate readiness of technology, and converge on a common approach for one detector to maximize investments.**

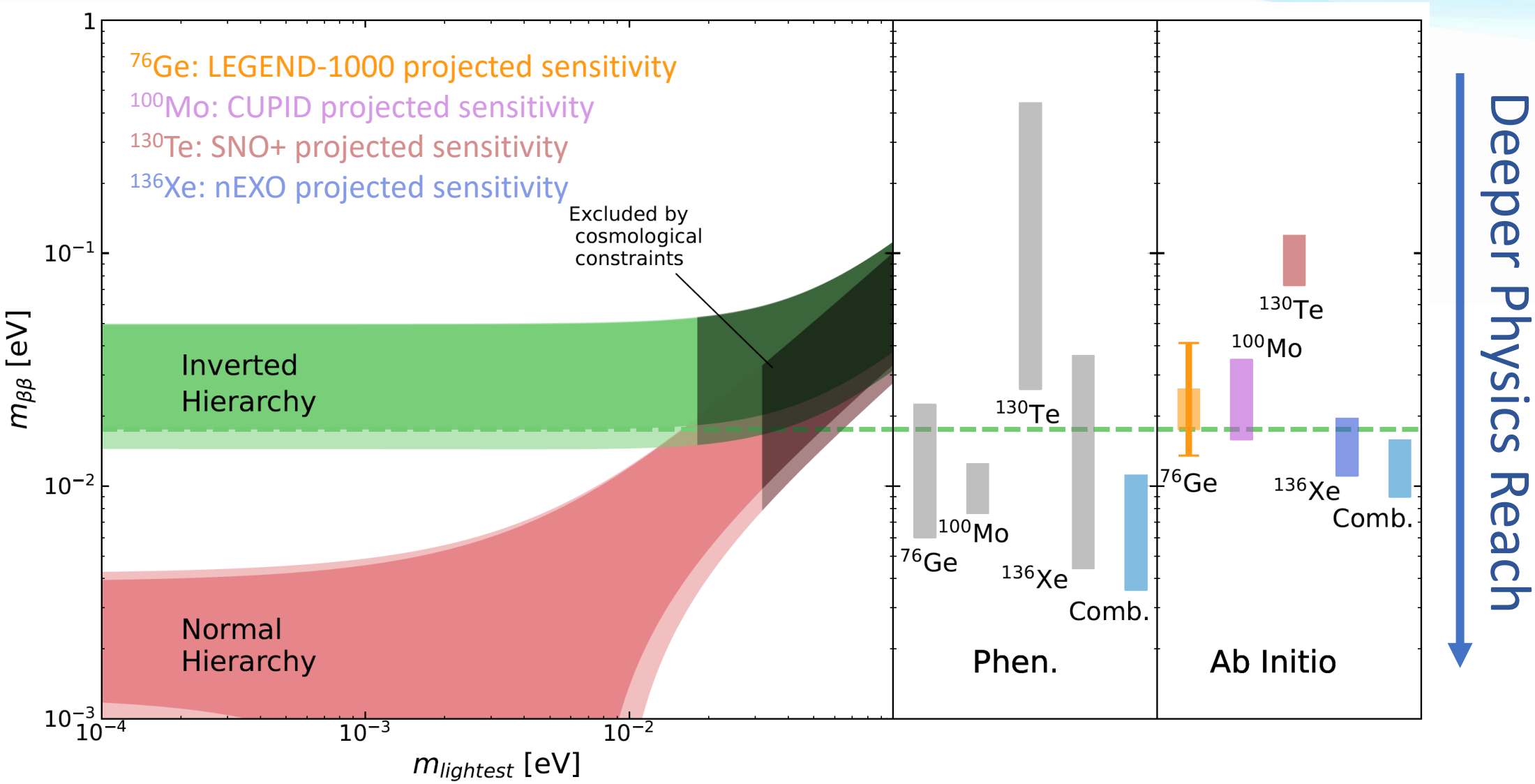
J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)





https://arxiv.org/pdf/2410.19016

Physics Reach of proposed Experiments



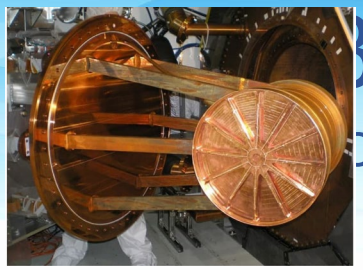
Plot by J. Holt

Strategy to reach 1x10^{28} years

- Proposal:
  - Define a new collaboration with a sensitivity goal of 1x10^{28} years in 10 years.
  - Take the well-reviewed nEXO concept as starting point.
  - Invite collaborators to take on responsibilities for subsystems.
  - Reevaluate technology decisions in terms of risk, performance, and schedule.
  - Aim to start construction in 2026/2027.
- **Liquid noble TPC – a demonstrated technology at the tonne scale.**

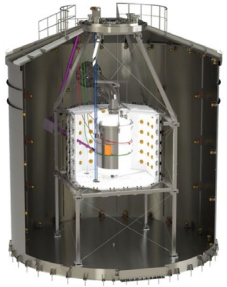
Past

EXO-200 (175 kg)



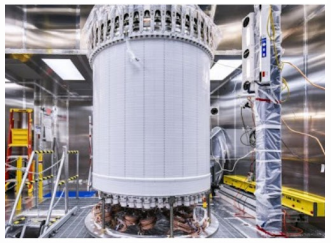
Current Generation

XENONnT
(6 Tonne)



3.7 Tonne

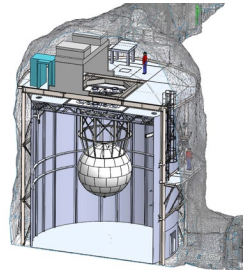
LZ (7 Tonne)



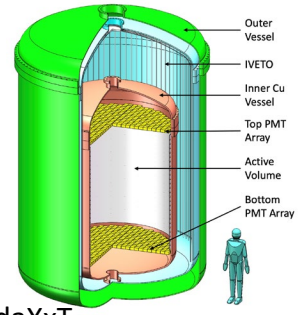
DarkSide-20k
(70 Tonne underground Ar)

MicroBooNE (170 Tonne Ar)

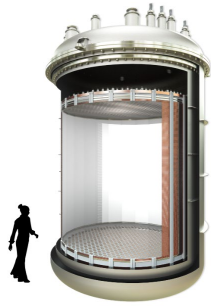
Next Generation



nEXO **2.0**
(5 Tonne)



PandaXxT
(43 Tonne)



XLZD
(60 Tonne)

nEXO at SNOLAB Cryopit well developed

0νββ
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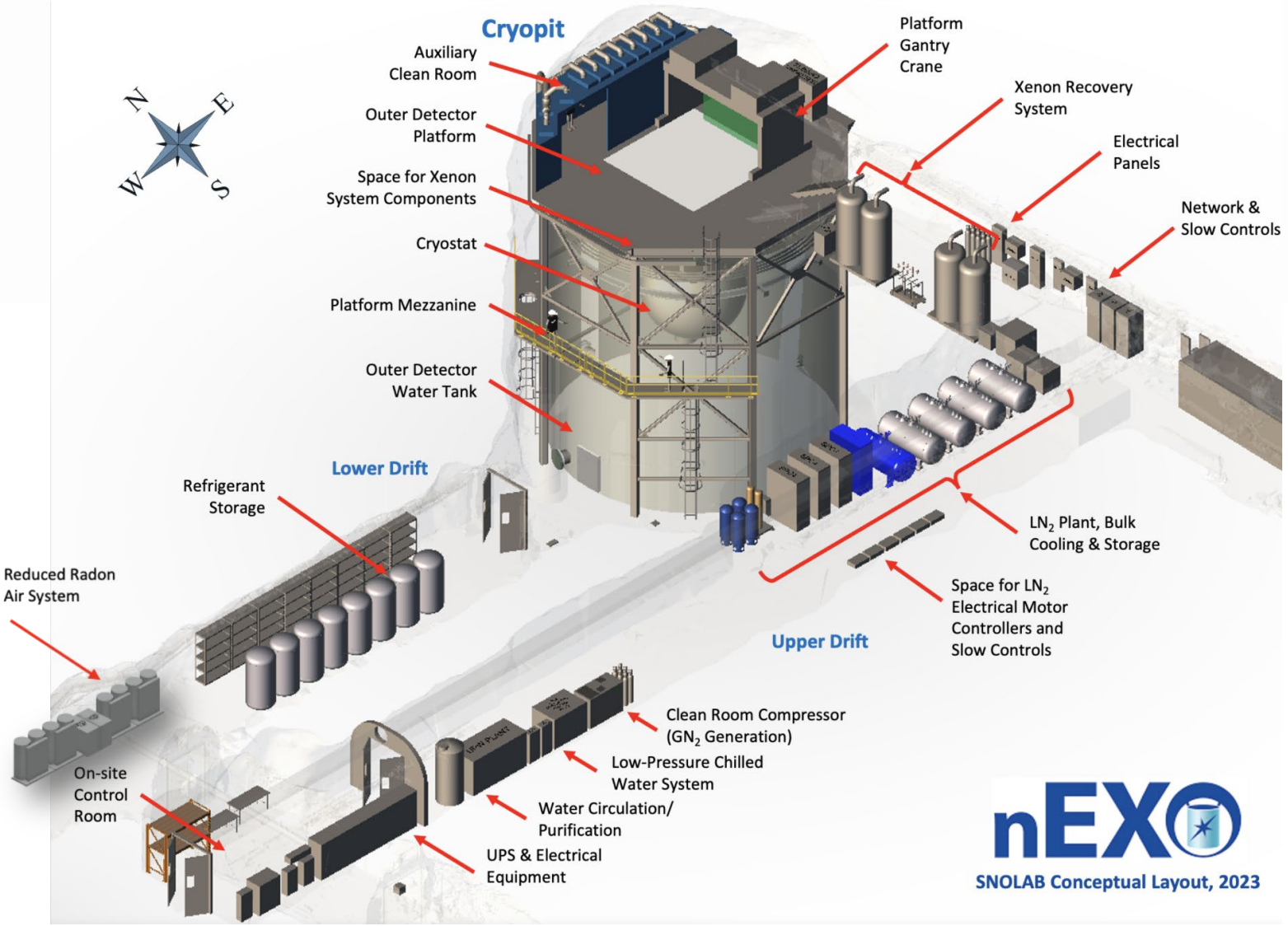

- Models of actual infrastructure placed in 3D scan of Cryopit and surrounding drifts.
- Layout of infrastructure fits within the space of the SNOLAB underground lab.

- Close collaboration between nEXO and SNOLAB.

The nEXO detector in a nutshell

0νββ
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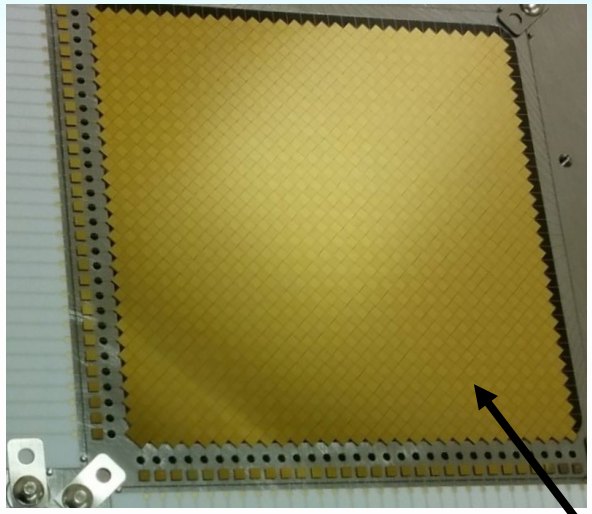
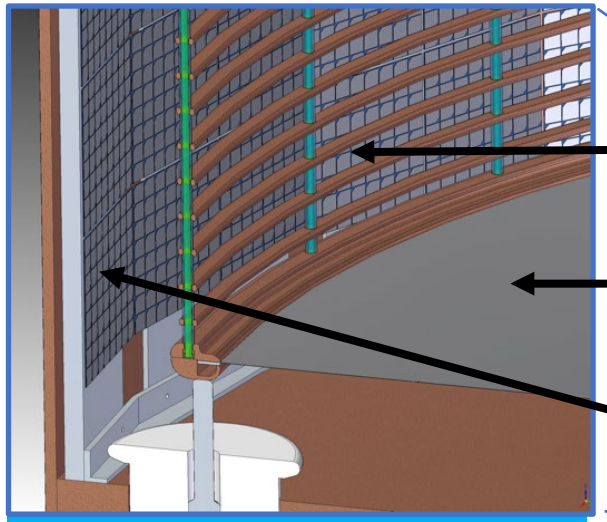
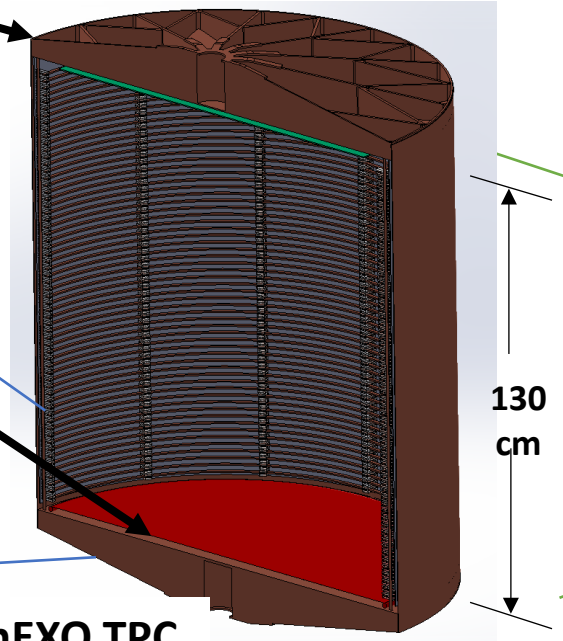
- 5 t liquid xenon TPC similar to EXO-200 (~30x the volume).
- Silicon photomultiplier (SiPM) for 175nm scintillation light detection, ~4.5m^2 SiPM array in LXe.
- Tiles for charge read out in liquid Xe (LXe).
- 3D event reconstruction.
- Combine charge and light readout. Goal → σ/E of <1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.
- Projected sensitivity of 10^{28} years [arXiv:2106.16243]



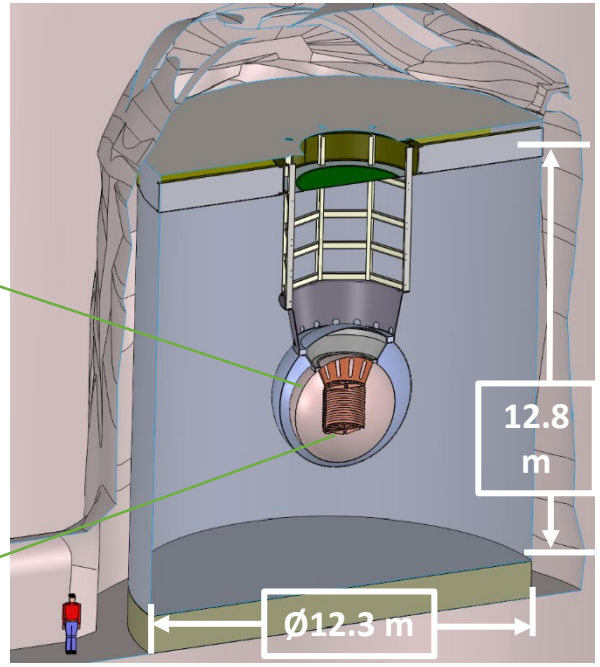
Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.



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



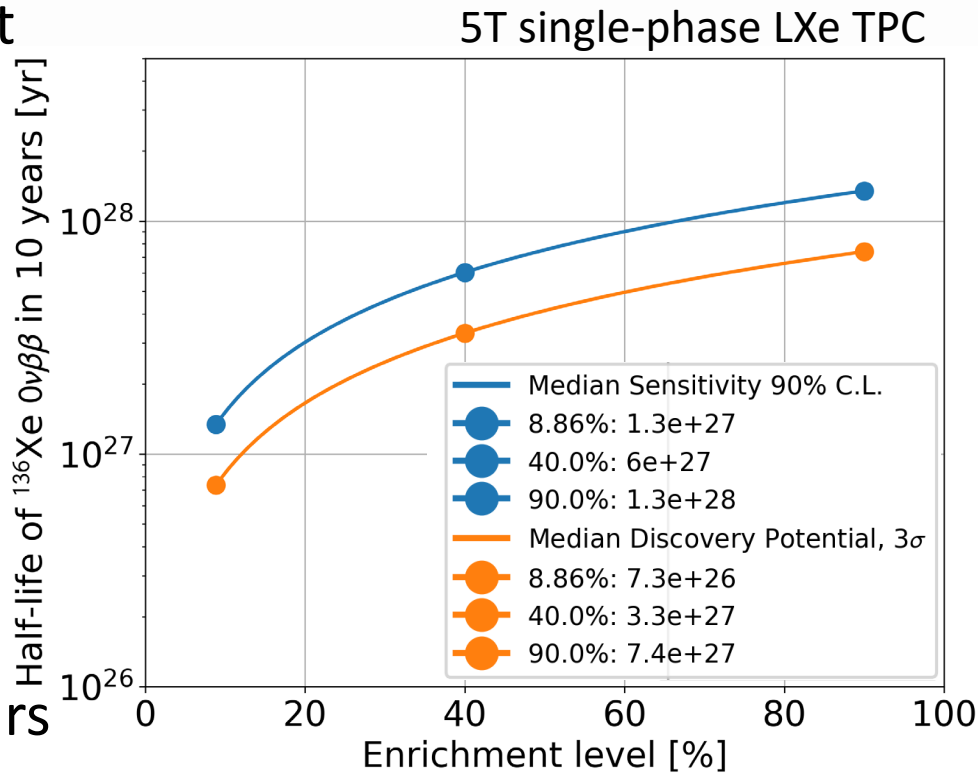
nEXO TPC



nEXO at the SNOLAB Cryopit

Investigation of Phased Approach

- A phased approach derisks the experiment by starting the experiment with less Xe-136 and the option to increase it down the road.
- **Option 1**
  - 1 t single-phase liquid Xe TPC @90% enrichment
- **Option 2**
  - 5 t single-phase liquid Xe TPC with natural Xe
  - *Upgrade Scenario 1:*
    - Upgrade/blend to 40% enrichment in Xe-136
  - *Upgrade Scenario 2:*
    - Upgrade to 90% enrichment in Xe-136 after 5 years
  - *Upgrade Scenario 3:*
    - Early start to enriched Xe procurement, upgrade to 90% enrichment in Xe-136 after 3 years



Xenon Program Schedule

0νββ
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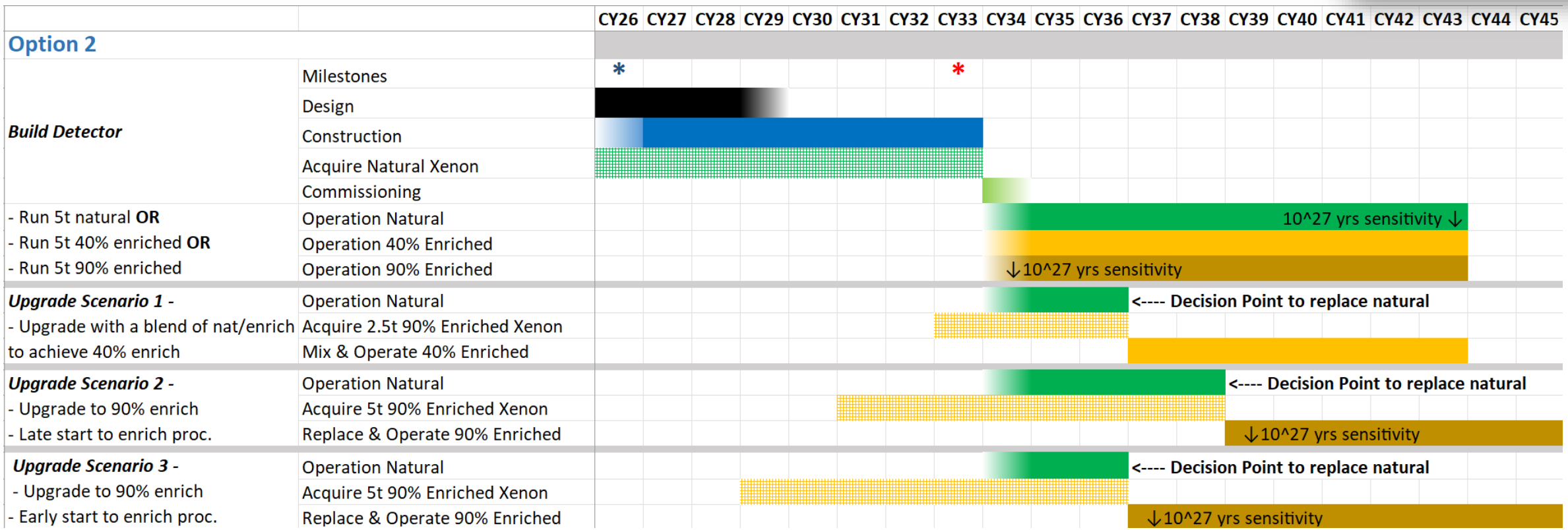
Next steps:

- Imminent release of R&D infrastructure support from 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 ~14 months → attract international partners.
- Start construction of outer detector in 2026 with IF 2023 release.



SNOLAB as a lead institute in endeavor

- **SNOLAB Leading WBSes with Research Scientists and Project Management Resources.**
- **SNOLAB Staff scientists** fully engaged in **developing the technology**.
- SNOLAB **Research Scientists** should **be fully NSERC** eligible and lead research programs.
- **Material logistics**, including surface storage and transport down the mine. Provide the systems to inventory and track items from procurement to deployment.
- Take the **lead on solving bureaucratic issues** and minimizing them. When they cannot be driven to zero, provide the workforce to deal with the issues. Examples: Taxes, regulatory codes, duties and other border issues, environmental requirements, and any other bureaucratic impediments.
- **SNOLAB one of the leading intuitions of nEXO2.0** to make sure the project is completed. Share a common goal and responsibility.
- Provide engineering to solve code, certification, and safety issues.
- Provide the workforce and funding for operations.

Summary

- The physics case remains very strong for a program with more than 1 experiment & isotope.
- A united Xe-136 approach has the potential to be competitive with LEGEND-1000.
- Consider participating in the Xe-136 workshop: https://mcgill.ca/x/icV (poll)
- nEXO is a well-developed concept and **an ideal starting point** for a **united, international effort** to **reach 10^{28} years sensitivity after 10 years**.
- Leveraging past investments and existing expertise, Canada is well positioned to take leadership of a Xe-136 based 0νββ endeavor, located at SNOLAB's cryopit.
- With two CFI IF awards we have funding lined up (contingent) to keep momentum going and demonstrate technical readiness.
- **We consider DOE's announcement an opportunity for a Canada-led search in Xe-136 at the SNOLAB Cryopit.**

Thank you for your attention

0νββ
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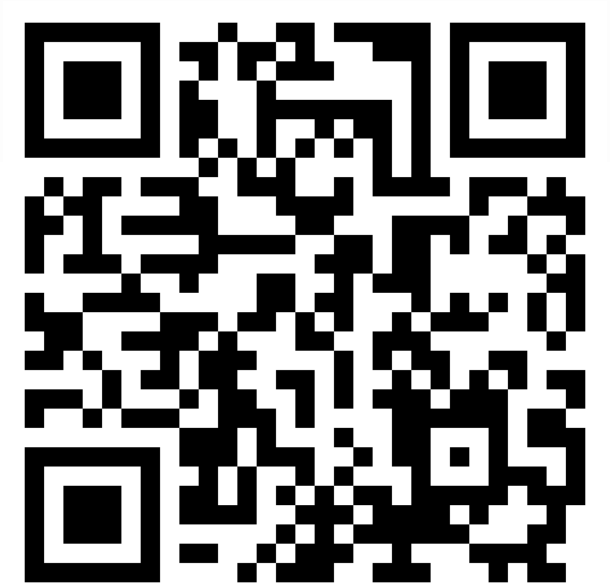
Please fill interest poll for Xe-based double beta decay workshop



https://mcgill.ca/x/icV