Aiming for discovery with nEXO 2.0

May 26, 2025

Thomas Brunner (nEXO co-spokesperson)

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

0νββ
@CRYOPIT

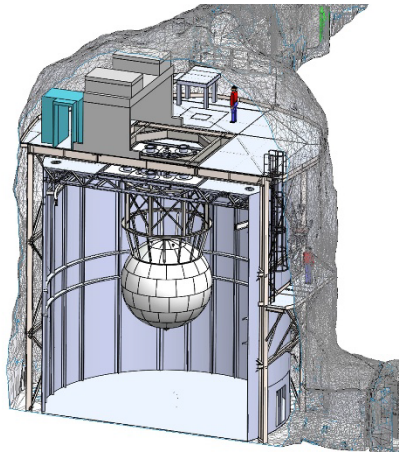
- Understanding the origin of matter in the Universe via 0νββ will be the biggest subatomic physics discovery of a generation; we know how to do it!
- The physics community has determined that searches in multiple isotopes are required for a definitive discovery.
- nEXO 2.0 is the DOE nEXO project under Canadian leadership, realizing opportunities for improvement:
  - A next-generation 0νββ 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.

Building nEXO 2.0

0νββ
@CRYOPIT

Some high-level numbers

- Total cost to get to 10^{28} yr sensitivity: $450M CAD (~$324M USD).
- Phase 1 ($305.1M CAD) realizes the full experiment (detector and auxiliary infrastructure) with natural xenon and 10^{27} years sensitivity:
  - Phase 1:
    - $149.1M CAD has already been identified through conventional funding streams.
    - $156.1M CAD required to complete the detector. Exploring funding possibilities and an attractive opportunity for other countries to play a significant role in this project.
- Could start construction in ~1 year in the SNOLAB Cryopit.
- Operating detector after 7-8 years.
- Phase 2 achieves ultimate physics goal of 10^{28} years:
  - Phase 2:
    - $145M CAD in Xe-136 cost required to reach the sensitivity of 10^{28} years.



Status

- 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).
- nEXO was one of the three contenders in an international 0νββ program.
- 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

- **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.**
  - **Exploring a funding approach with key Canadian partners.**
  - 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.

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 ^{136}Xe 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.

(Joint statement by nEXO, NEXT, XLZD)

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

0νββ @CRYOPIT

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

12-14 November 2025
Montreal
America/Toronto timezone

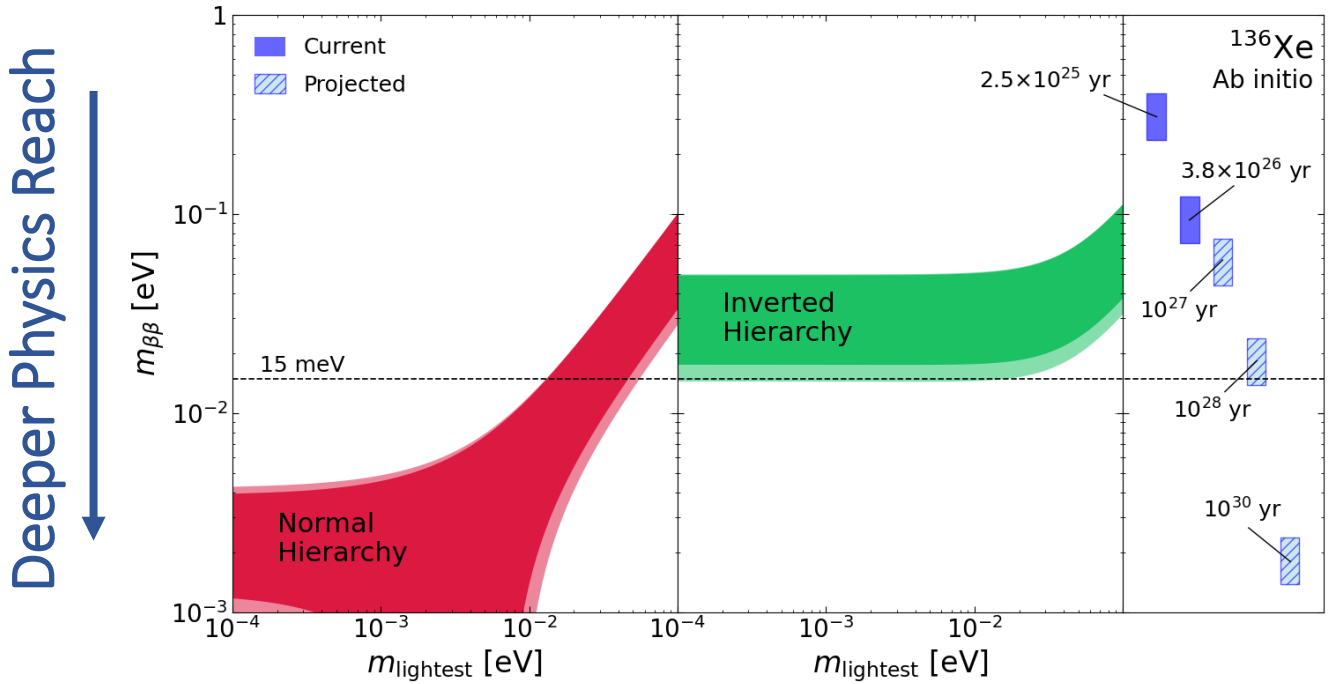
https://nyx.physics.mcgill.ca/e/XeDBD

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

Scientific Goal: Sensitivity Beyond 10^{28} yrs

- Expected reach of current experiments is in the 10^{27} yrs range.
- Next generation experiments aim for a sensitivity goal of 15 meV, which in the case of Xe-136 requires a sensitivity beyond 10^{28} yrs.

→ Goal: probe the inverted hierarchy parameter space and part of the normal hierarchy parameter space.



Final EXO-200 limit

Current best limit in Xe from KamLAND ZEN
Reach of 5T experiment with natural Xe

Reach of 5T experiment with 90% Xe-136

The ultimate goal in 0νββ of ~1 meV

Figure courtesy to TRIUMF ab initio theory group

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

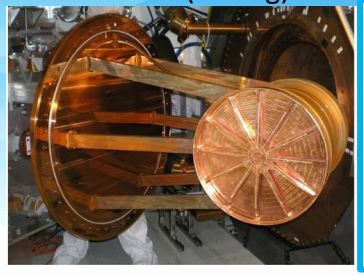
^{136}Xe Mass for 1 decay/year (average)	Half life
3.3 Tonnes	10^{28} years
326 Tonnes	10^{30} years

nEXO 2.0 proposal

- Leveraging advanced design, <u>nEXO 2.0</u> can be ready to start construction in the next ~year:
  - Coalesce a new collaboration with a <u>sensitivity goal of greater than 10^{28} years in 10 years</u>.
  - 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.**

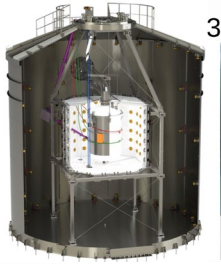
Past

EXO-200 (175 kg)



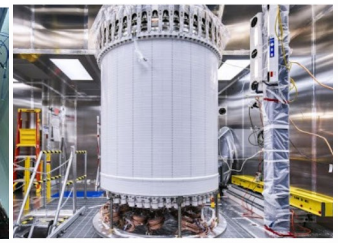
Current Generation

XENONnT
(6 Tonne)



3.7 Tonne

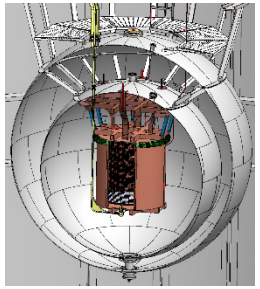
LZ (7 Tonne)



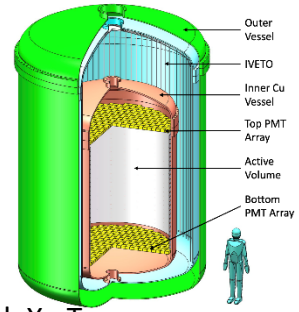
DarkSide-20k
(70 Tonne underground Ar)

SBND (112 Tonne Ar)

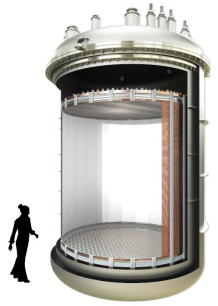
Next Generation Concepts



nEXO
(5 Tonne)



PandaX-xT
(43 Tonne)



XLZD
(60 Tonne)

nEXO ready for construction

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

The nEXO project has been **positively** 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 (DR) at LLNL in July 2024, combined with SNOLAB Gateway 1 review

Recommendation by DR/SNOLAB Review Committee:

- **The science-driven technical design has advanced to or beyond the conceptual design stage [..], documentation and planning is also very advanced for this stage.**
- **nEXO meets all requirements to pass SNOLAB Gateway 1.**

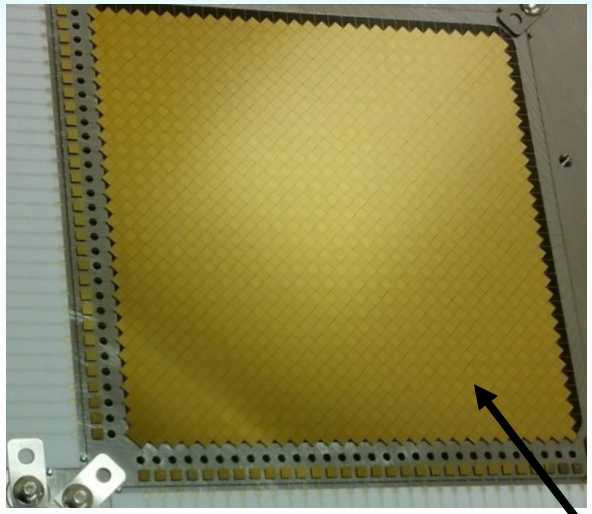
High-profile Canadian presence at Director's Review at LLNL in July 2024:

- 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)

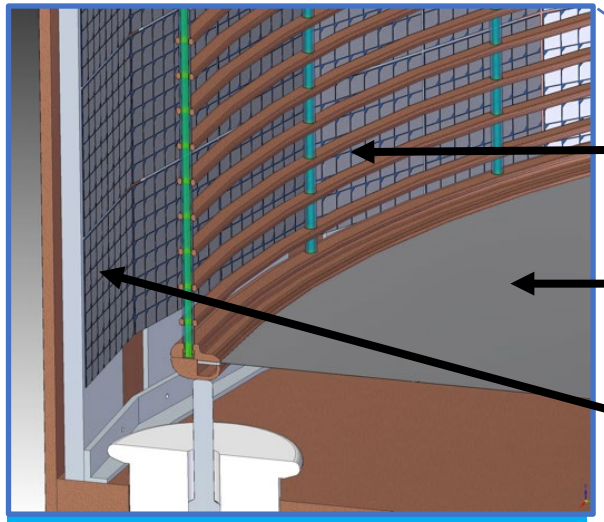
The nEXO detector design

0νββ
@CRYOPIT

- 5 tonne 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 [arXiv:2106.16243].

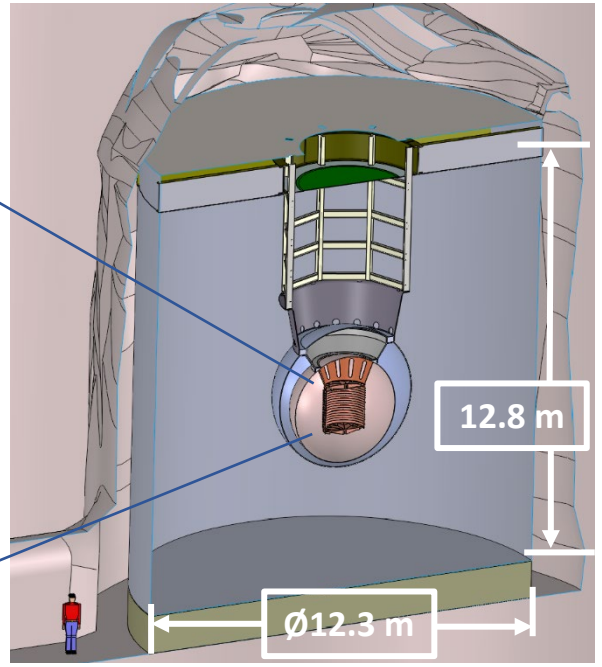


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.



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

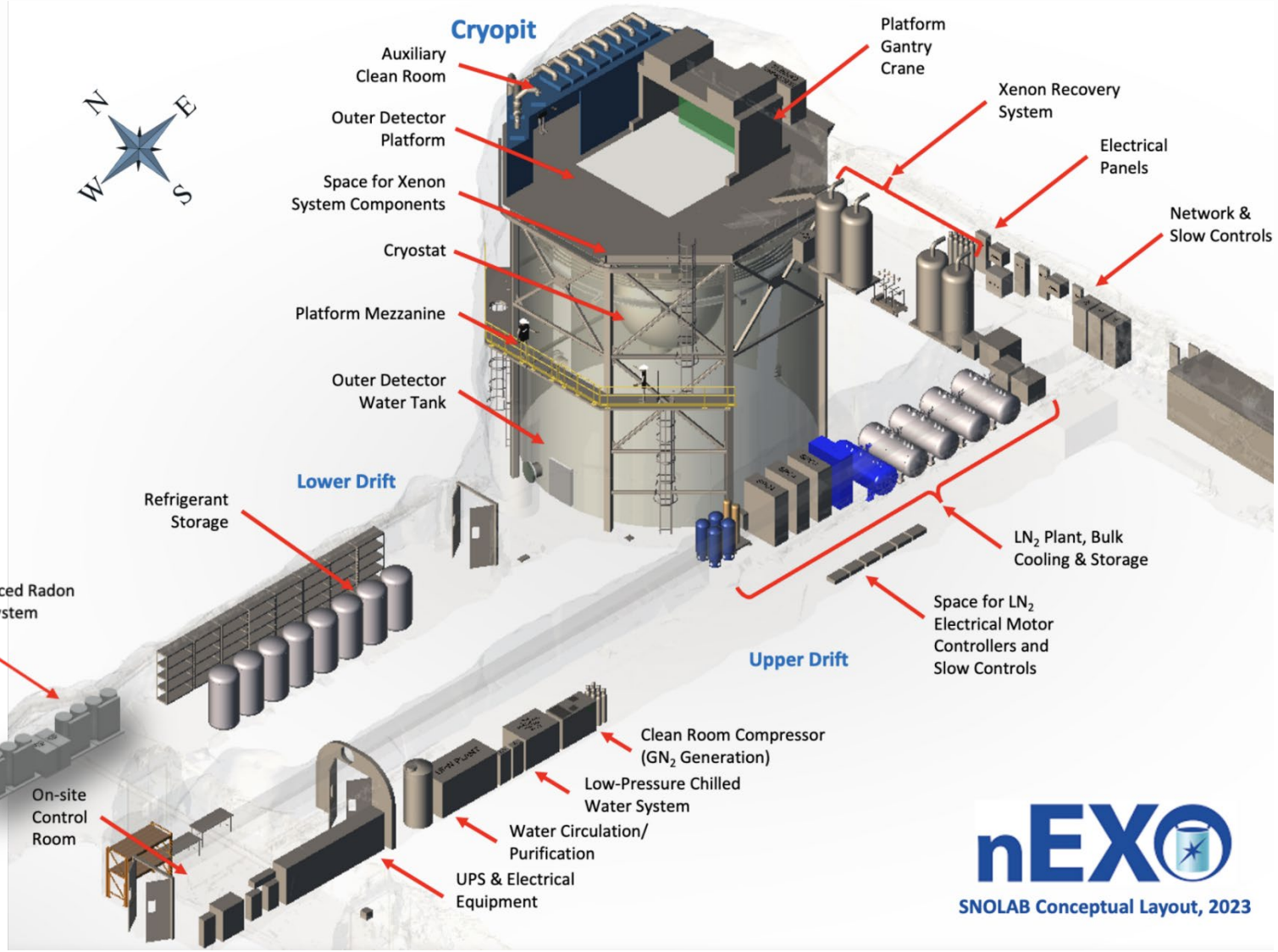
nEXO TPC



nEXO at the SNOLAB Cryopit

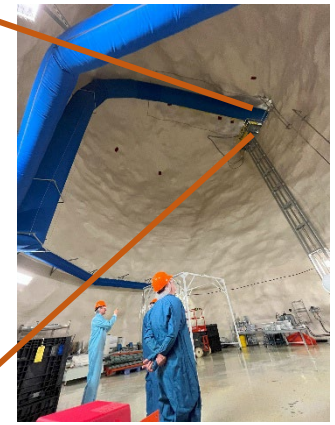
nEXO at SNOLAB Cryopit well developed

0νββ
@CRYOPIT



- 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.



Costing approach

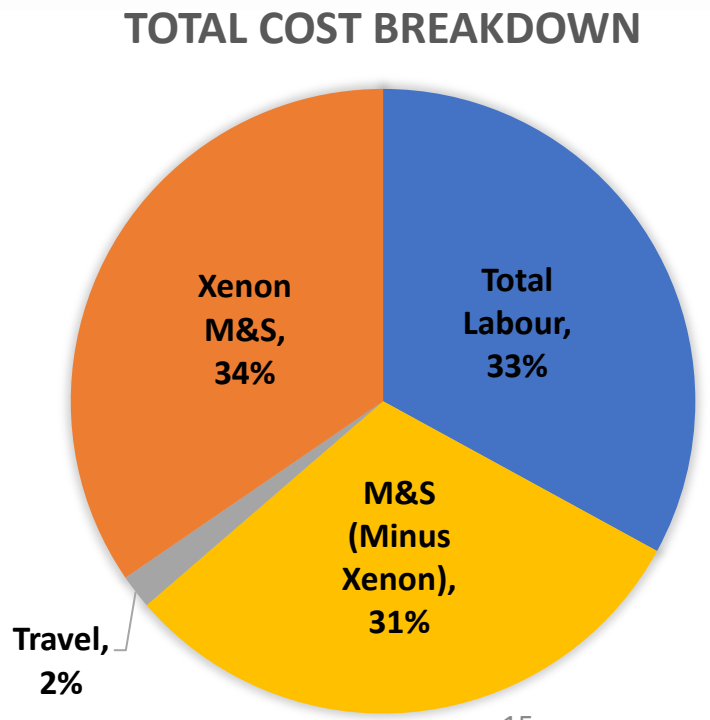
- Based off the DOE costing exercise in preparation for CD-1, we costed nEXO 2.0 using Canadian accounting for the base plan (5T LXe @ 90% enrichment).
- **More than 15,000 individual cost entries.**
- Task-based uncertainties included in the cost estimate.
- The cost includes **all** personnel cost, including faculty and staff scientist cost.
- Salaries and existing funding are captured as “Opportunities”.

- Starting from this base plan cost, we considered different options for a “phased” approach and costed these using Canadian accounting.

EXO 2.0 Base Plan Cost estimate

- To benchmark, we costed the nEXO 2.0 (base plan: 5T @90% Xe-136) using Canadian accounting.
- Labour includes the cost for faculty and research scientists (typically not charged to project).
- Xenon materials & supply (M&S) represents 34% of total cost.
- **Significant investment in highly-qualified personnel.**

WBS & Description	Labour (CAD$M)	M&S (CAD$M)	Travel (CAD$M)	Total (CAD$M)
1.01: Management, Project Controls, QA and ES&H	$ 15.9	$ 1.0	$ 1.1	$ 18.0
1.02: System Engineering and Integration / Commissioning	$ 31.8	$ 2.0	$ 1.6	$ 35.4
1.03: Time Projection Chamber (TPC)	$ 19.4	$ 17.8	$ 0.4	$ 37.6
1.04: Photon Detector (PD)	$ 9.1	$ 22.6	$ 0.5	$ 32.2
1.05: Time Projection Chamber Support Systems (TPCS)	$ 6.2	$ 29.6	$ 0.4	$ 36.2
1.06: Electronics (Photon Readout - PRE and Charge Readout - CRE)	$ 12.3	$ 8.1	$ 0.4	$ 20.8
1.07: Radioactive Background Control (RBC)	$ 10.9	$ 7.6	$ 1.8	$ 20.3
1.08: Computing, Controls and Software (CCS)	$ 7.5	$ 1.5	$ 0.3	$ 9.3
1.09: Xenon (XE)	$ 6.4	$ 150.0	$ 0.5	$ 156.9
1.10: Outer Detector (OD)	$ 11.9	$ 23.1	$ 0.3	$ 35.3
1.11: Facilities (FAC)	$ 11.7	$ 20.0	$ 0.4	$ 32.1
Total	**$ 143.1**	**$ 283.3**	**$ 7.7**	**$ 434.1**



Possible Sources of Funding in Canada

0νββ
@CRYOPIT

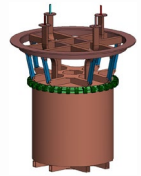
Funding Sources in Canada [CAD$M]		
Funding Source 1: L2 faculty/scientists	$	13.0
Funding Source 2: McDonald Institute*	$	2.5
Funding Source 3: NSERC (300k/year)	$	4.5
Funding Source 4: IF2020*	$	6.5
Funding Source 5: IF2023*	$	16.0
Funding Source 6: SNOLAB MSI	$	20.5
Funding Source 7: SNOLAB MRF	$	7.3
Funding Source 8: Future CFI IF Awards	$	78.8
Anticipated Funding	**$**	**149.1**

* Awarded, construction support

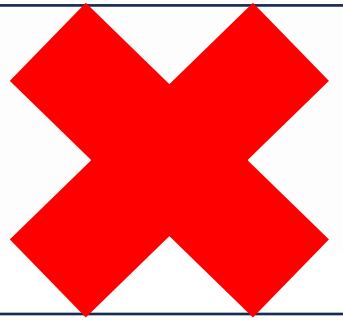
- "Standard" funding Sources in Canada have been identified to support our Xe-based neutrinoless double beta decay program.
- We are in conversations with Canadian funding agencies about possibilities of additional funding.

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

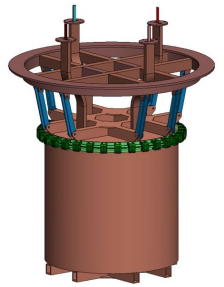


H=D=~75 cm



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

H=D=~130 cm



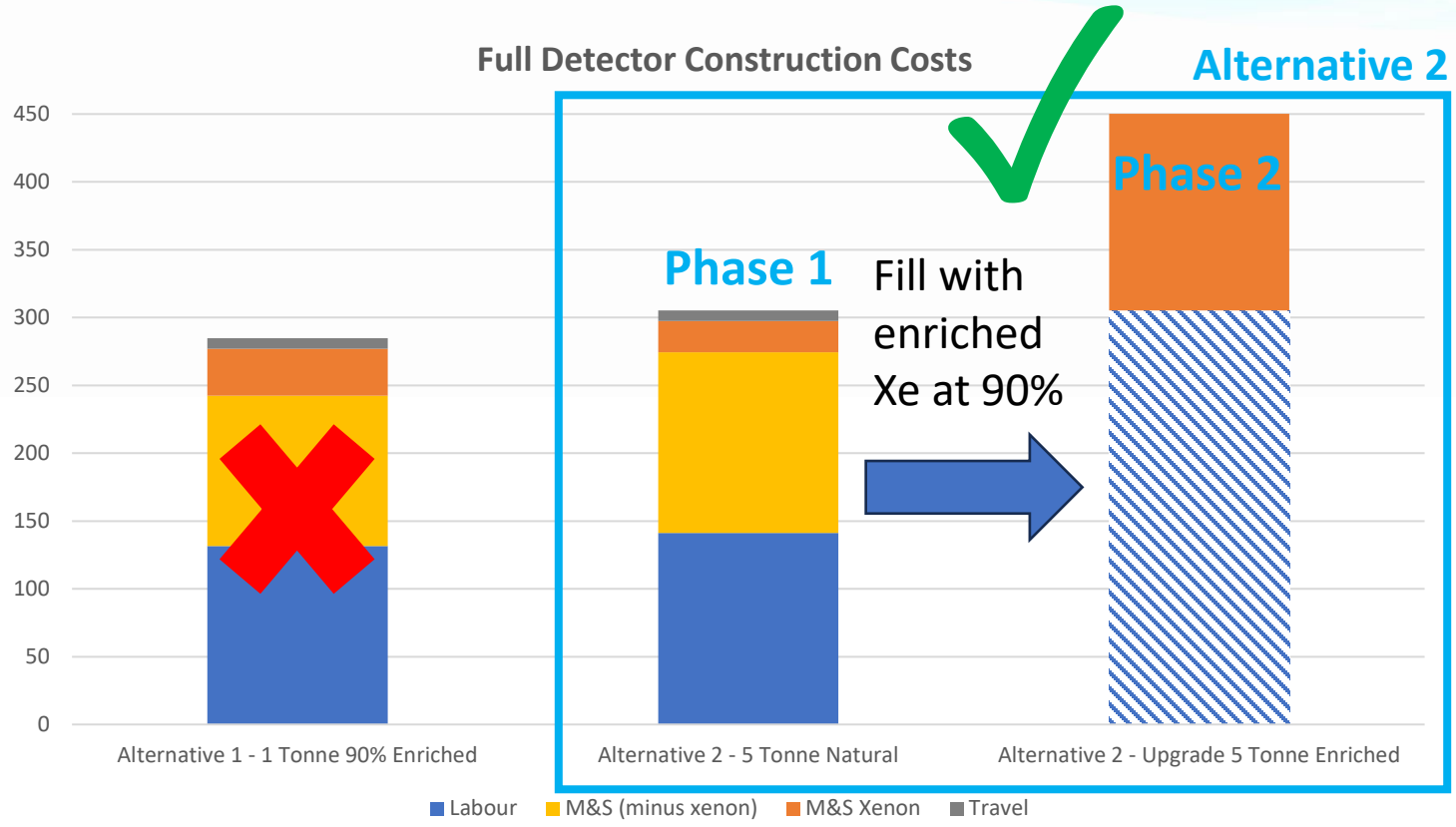
Alternative 2 is the preferred option:

- Enables phased approach
- Decouples procurement risk of enriched xenon

Detailed Cost of Options

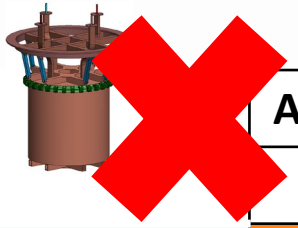
0νββ
@CRYOPIT

	Alternative 1	Alternative 2	
		Phase 1	Phase 2
WBS & Description	Total (CAD$M)	5T natural (CAD$M)	5T 90% (CAD$M)
1.01: Management, Project Controls, QA and ES&H	$18.0	$18.0	
1.02: System Engineering and Integration / Commissioning	$30.6	$35.4	
1.03: Time Projection Chamber	$32.5	$37.6	
1.04: Photon Detector (PD)	$25.6	$32.2	
1.05: Time Projection Chamber Support Systems (TPCS)	$29.7	$36.2	
1.06: Electronics (PRE&CRE)	$15.5	$20.8	
1.07: Radioactive Background Control (RBC)	$20.3	$20.3	
1.08: Computing, Controls and Software (CCS)	$9.30	$9.3	
1.09: Xenon (XE)	$40.2	$28.0	Δ$145
1.10: Outer Detector (OD)	$33.6	$35.3	
1.11: Facilities (FAC)	$29.3	$32.1	
Total	**$284.6**	**$305.2**	**Δ$145**

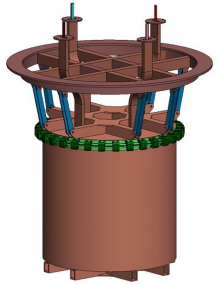


- **Alternative 1 bad investment due to limited physics reach at significant cost.**
- **Alternative 2 is the preferred option.** Building a 5T detector natural Xe experiment with subsequent loading with enriched Xe paves path toward reaching the normal ordering.

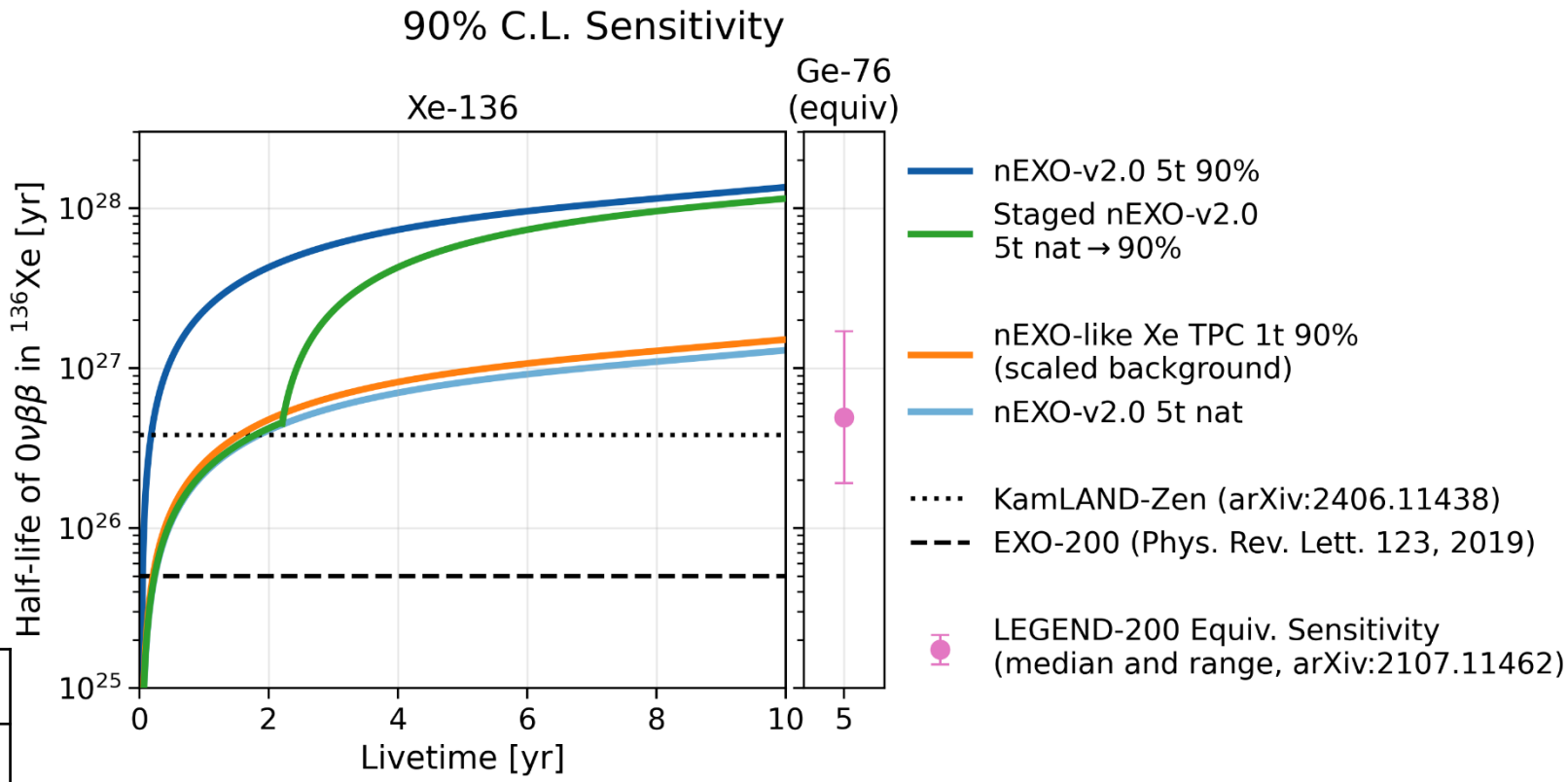
Sensitivity Comparison of Alternatives



	Alternative 1
	1 tonne
Enrichment	90%
Sensitivity	~1.4 x 10^{27}
Total Cost	**CAN$284.7M**



	Alternative 2	
	Phase 1	**Phase 2**
	5 tonne	
Enrichment	Natural	Nat → 90%
Sensitivity	1.3 x 10^{27}	~1.1 x 10^{28}
Total Cost	**CAN$305M**	**Δ CAN$145M**



- **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.

Xenon Program Schedule

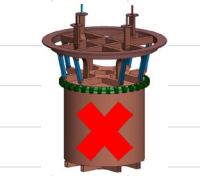
0νββ
@CRYOPIT

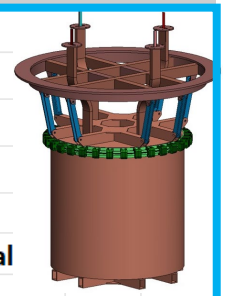
Next steps:

- 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

		CY26	CY27	CY28	CY29	CY30	CY31	CY32	CY33	CY34	CY35	CY36	CY37	CY38	CY39	CY40	CY41	CY42	CY43	CY44	CY45
Alternative 1	Milestones	*					*														
- Run 1t 90% Enriched (Assume 2 year schedule savings on build)	Design																				
	Construction																				
	Acquire 1t 90% Enriched																				
	Commissioning																				
	Operation 90% Enriched																10^27 yrs sensitivity ↓				
Alternative 2	Milestones	*							*												
Phase 1	Design																				
	Construction																				
	Acquire Natural Xenon																				
	Commissioning																				
	Operation Natural												<---- Decision Point to replace natural								
Phase 2	Acquire 5t 90% Enriched Xenon																				
	Replace & Operate 90% Enriched																				10^28 yrs sensitivity ↓





Opportunities through partnerships

- 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% ^{136}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

Powerful Technology in Either Outcome

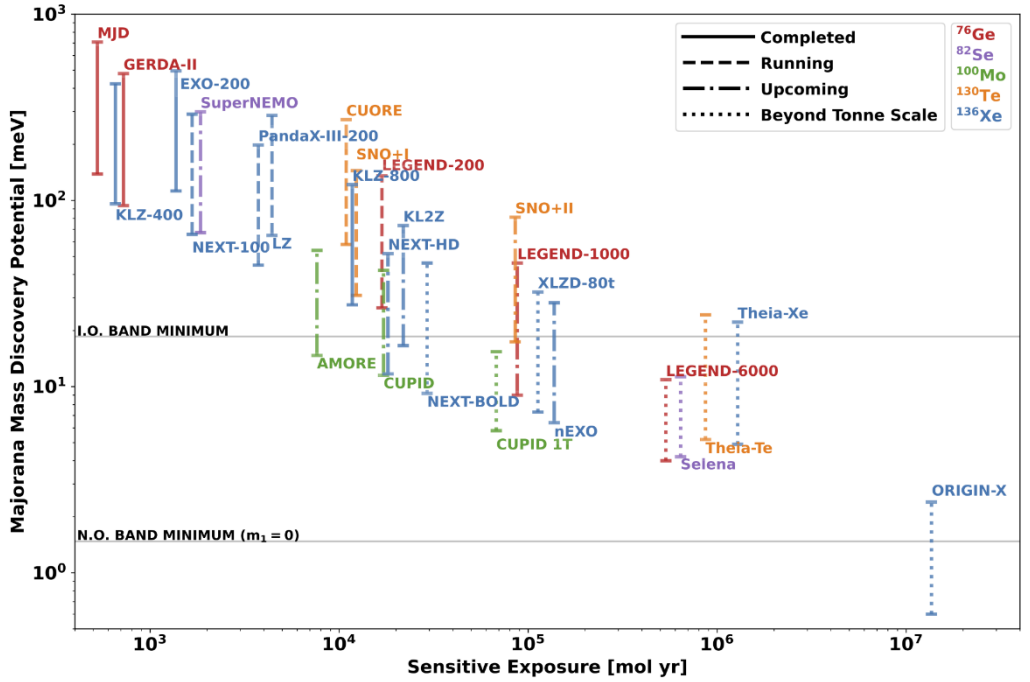
Advancing nEXO 2.0 is an investment into technology and personnel development with a clear path for the future:

If nEXO 2.0 discovers 0νββ decay:

- Confirmation could be done in the same detector with depleted or natural xenon, i.e., with a different isotopic ratio of the xenon.
- 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 with significantly increased Xe-136 mass using the same or closely related technology are plausible.



Summary

- Understanding the origin of matter in the Universe via 0νββ will be the biggest subatomic physics discovery of a generation!
- 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.
- Canada is now leading the nEXO 2.0:
  - The space is ready at SNOLAB.
  - The design is well advanced, construction in ~1yr.
  - $149.1M CAD have been identified.
  - $156.1M CAD exploring a funding approach with key Canadian partners (opportunity for additional partners).
  - $145M CAD xenon-136 (opportunity for additional partners).
  - Additional partners/collaborators are welcome.
- **The experiment is ready to move forward.**