Canadian Involvement in nEXO's Search for 0νββ

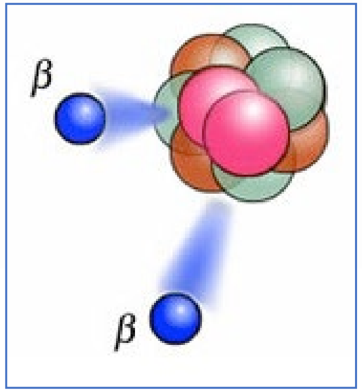
Thomas Brunner (thomas.brunner@mcgill.ca)

For the nEXO Collaboration

IPP AGM, May 31, 2024

The nEXO Search for 0vββ decay

Goal: observation of neutrinoless double beta decay (0vββ)



0vββ only possible if neutrinos are special particles, so-called Majorana particles.

→**Observation would violate lepton number in weak decays**

→ Observation would prove existence of a process in which matter is produced without equal amounts of anti-matter!

A water-Cherenkov muon veto for the nEXO $0\nu\beta\beta$ experiment

Soud Al Kharusi
CAP Congress 2024
May 29th 2024

soudk@stanford.edu
https://www.soudkharusi.com/
Google Slides link
Supervisors: Thomas Brunner & Daryl Haggard

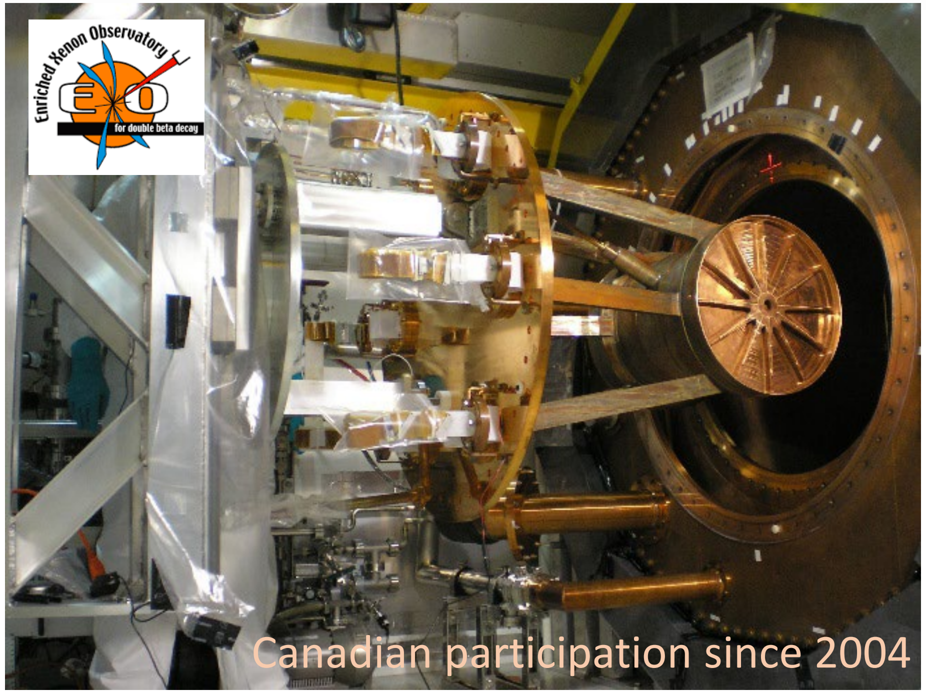
For more details on physics motivation for 0vββ see talk by S. Al Kharusi (CAP-PPD thesis prize winner) in W2 – 2.

Searching for 0νββ in ^{136}Xe – a phased approach

EXO-200 at WIPP (Decommissioned in Dec. 2018):

- EXO-200 first 100-kg class ββ experiment
- 175 kg liquid-Xe TPC with ~80% Xe-136
- Discovered 2νββ in Xe-136
- **Demonstrated excellent background identification through multiplicity and location of event in TPC**

  → this is essential for nEXO design

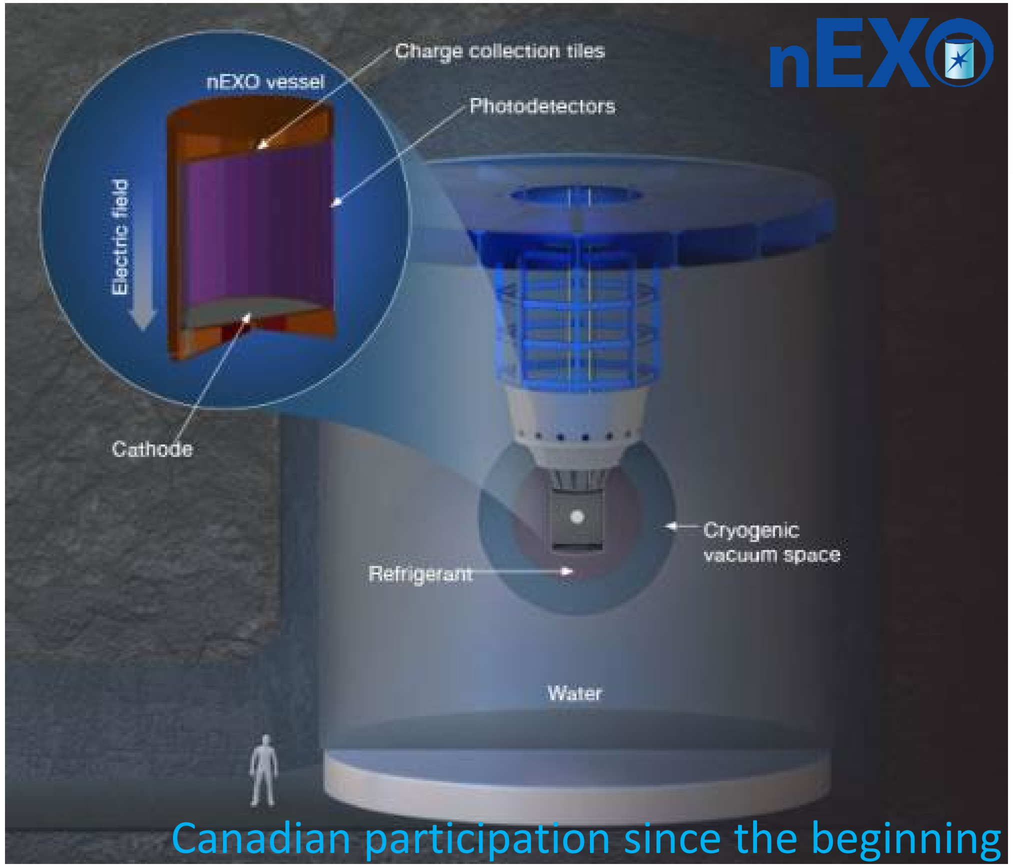


Canadian participation since 2004

https://www-project.slac.stanford.edu/exo/

nEXO:

- 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration

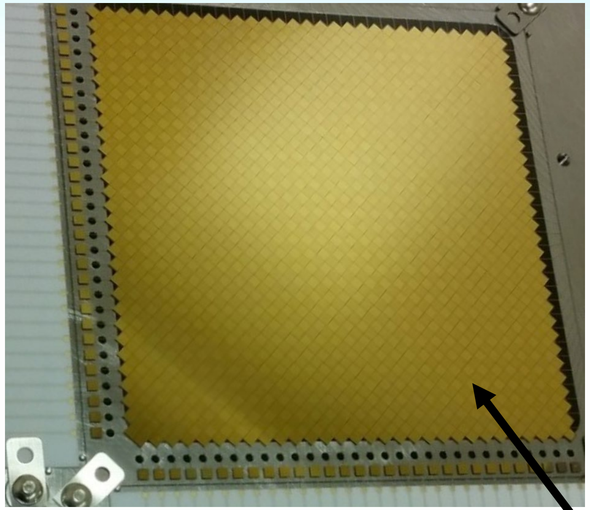


Canadian participation since the beginning

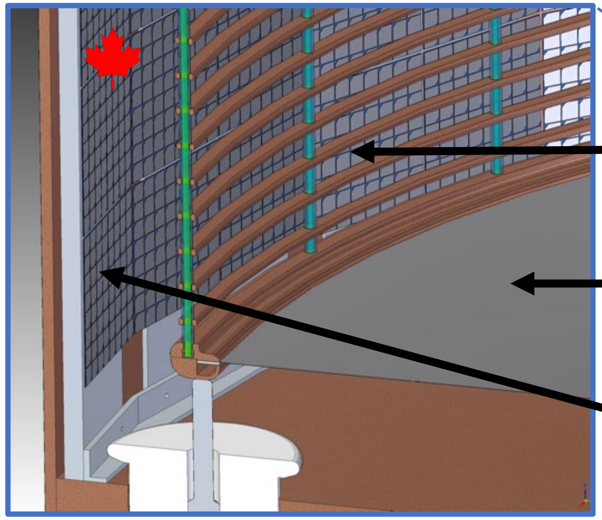
https://nexo.llnl.gov/

nEXO in a nutshell

- **nEXO anticipated to be located at SNOLAB**
- 5 t liquid xenon TPC similar to EXO-200 (~30x the volume, 90% Xe-136).
- SiPM for 175nm scintillation light detection, ~4.5m^2 SiPM array in LXe.
- Tiles for charge read out in LXe.
- Cold electronics inside TPC in liquid Xe.
- 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.



Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: JINST 14 P09020 (2019)

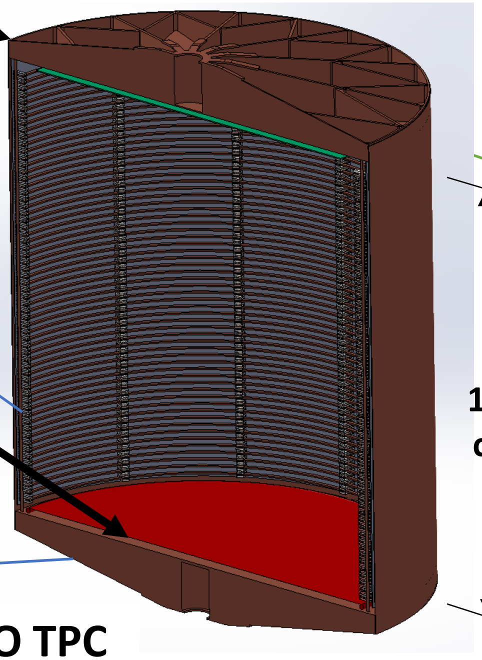


charge readout pads (anode)

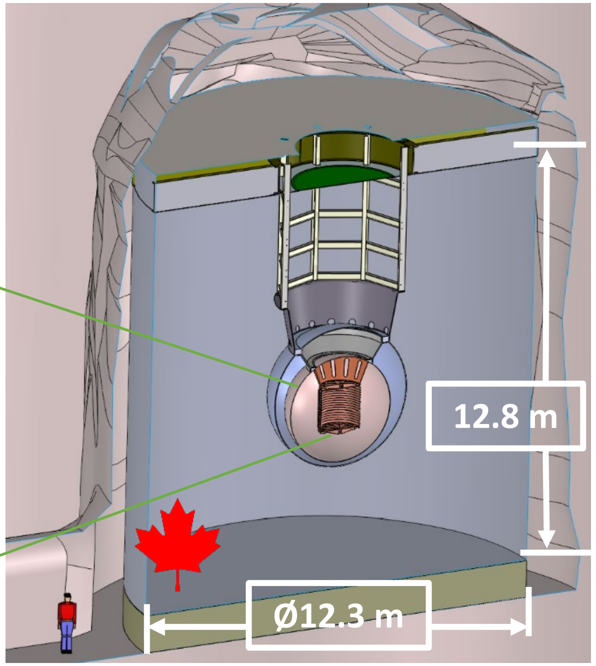
Field shaping rings

Cathode

SiPM 'staves' covering the barrel



nEXO TPC



nEXO pre-CDR, arXiv:1805.11142

Anode Charge Readout

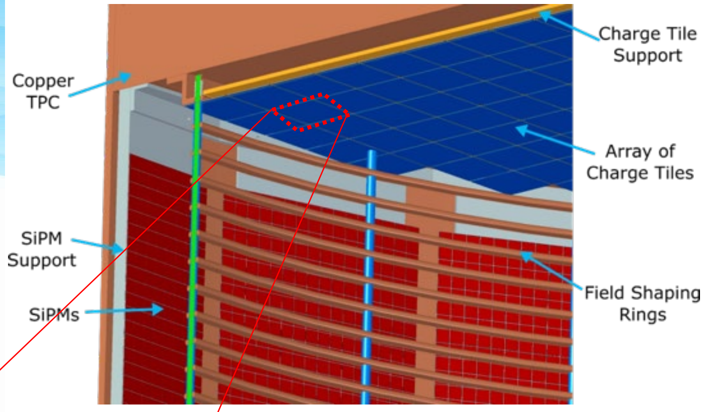
- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

Z. Li et al. (nEXO Collab) "Simulation of charge readout with segmented tiles in nEXO," JINST 14 P09020 (2019)

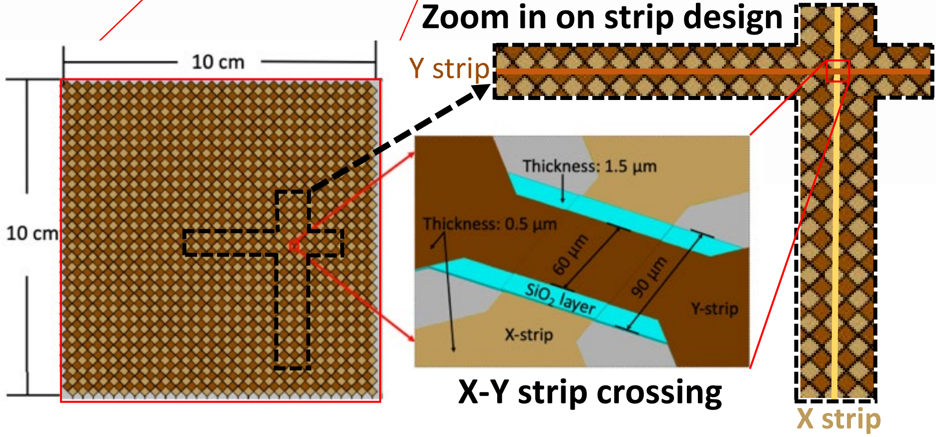
- Prototype tiles have been measured in LXe to validate simulation

M. Jewell et al. (nEXO Collab) "Characterization of an ionization readout tile for nEXO," JINST 13 P01006 (2018)

Zoom in on upper corner of TPC:

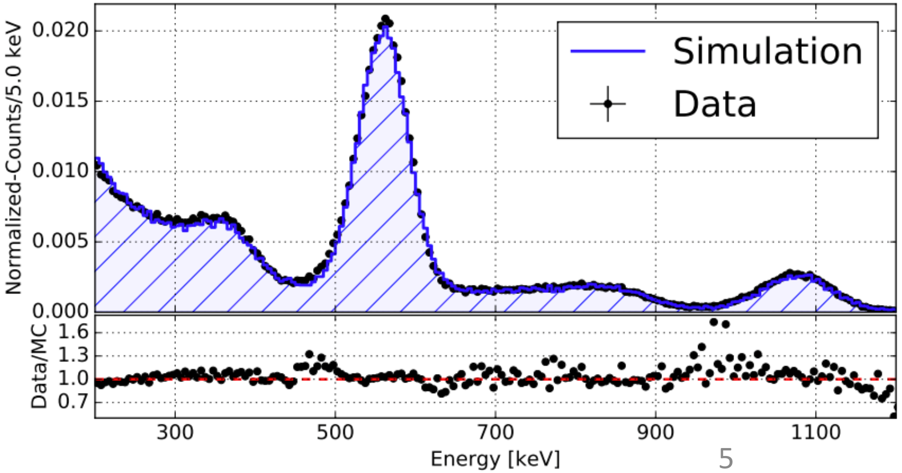


Zoom in on strip design



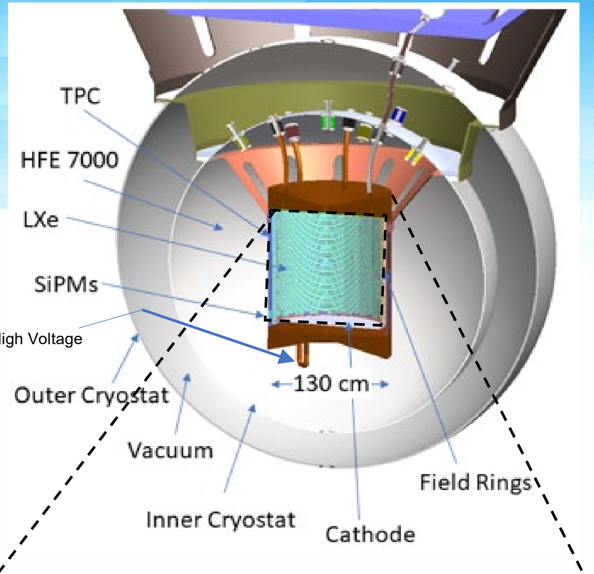
X-Y strip crossing

Source calibration (^{207}Bi) with prototype tile:

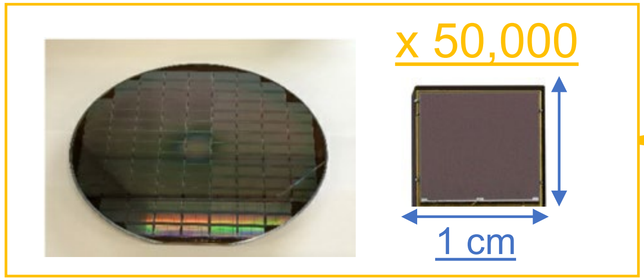


SiPMs for photon detection

- Advantages of SiPMs for photon detection
  - Low intrinsic radioactive backgrounds.
  - Improved energy resolution (SiPMs high gain).
  - Lower bias required for SiPMs (~50 V versus ~1.5 kV).
  - Devices from 2 vendors meeting requirements, demonstrated through R&D.



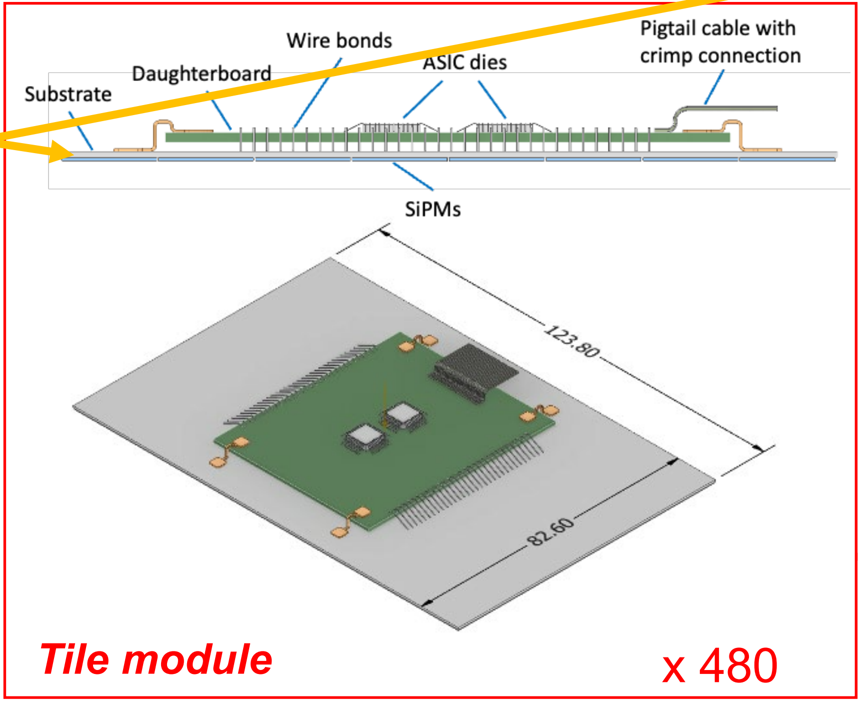
SiPM Devices



A. Jamil et al. (nEXO collab.) “VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO,” IEEE Trans. Nucl. Sci. 65, 11 (2018)

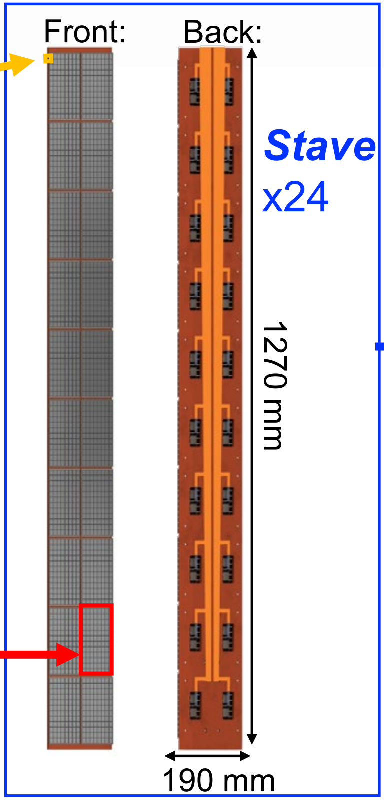
G. Gallina et al. (nEXO collab.) “Characterization of the Hamamatsu VUV4 MPPCs for nEXO,” NIM A 940, 371 (2019)

G. Gallina et al. (nEXO), “Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO,” Eur. Phys. J. C 82, 1125 (2022)



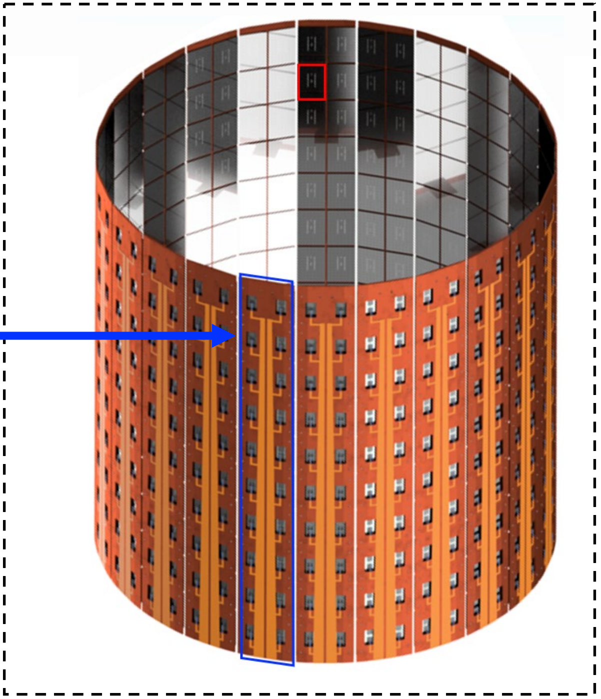
Tile module

x 480



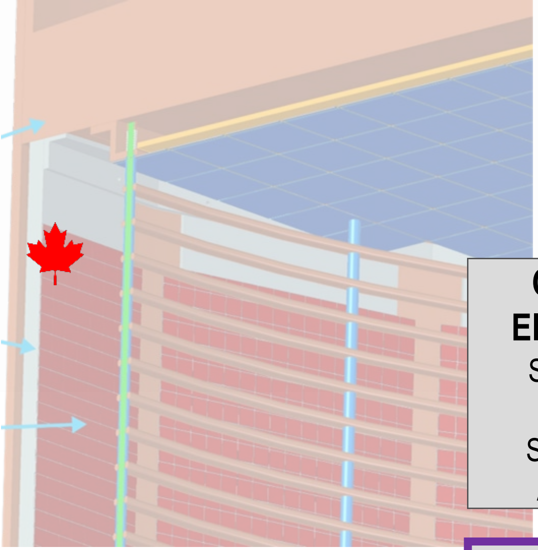
Stave

x24



Photon detector (PD)

Canadian contributions to nEXO Project



WBS with Canadian contributions

SNOLAB is the leading institution for two detector systems

Charge Readout Electronics (SLAC)
Subsystem Scientist:
L. Yang (UCSD)
Subsystem Manager:
A. Dragone (SLAC)

Photon Readout Electronics (BNL)
Subsystem Scientist:
M. Chiu (BNL)
Subsystem Manager:
L. DeMino (BNL)

TPC (PNNL)
Subsystem Scientist:
J. Orrell (PNNL)
Subsystem Manager:
A. Gorham (PNNL)

Photon Detector (BNL)
Subsystem Scientist:
D. Moore (Yale)
Subsystem Manager:
M. Worcester (BNL)

Computing, Control and Software (LLNL)
Subsystem Scientist:
S. Sangiorgio (LLNL)
Subsystem Manager:
TBD

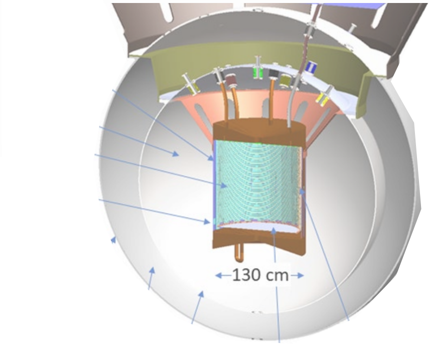
Radioactive Background Control (SLAC)
Subsystem Scientist:
A. Piepke (UA)
Subsystem Manager:
TBD

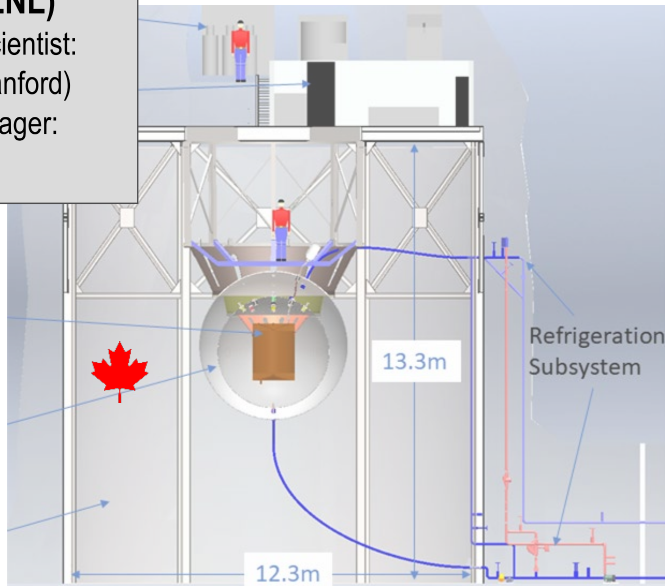
TPC Support Systems (LLNL)
Subsystem Scientist:
A. Pocar (Umass)
Subsystem Manager:
A. House (LLNL)

Xenon (LLNL)
Subsystem Scientist:
G. Gratta (Stanford)
System Manager:
TBD

Facility (SNOLAB)
Subsystem Scientist:
E. Caden
Subsystem Manager:
D. Hawkins

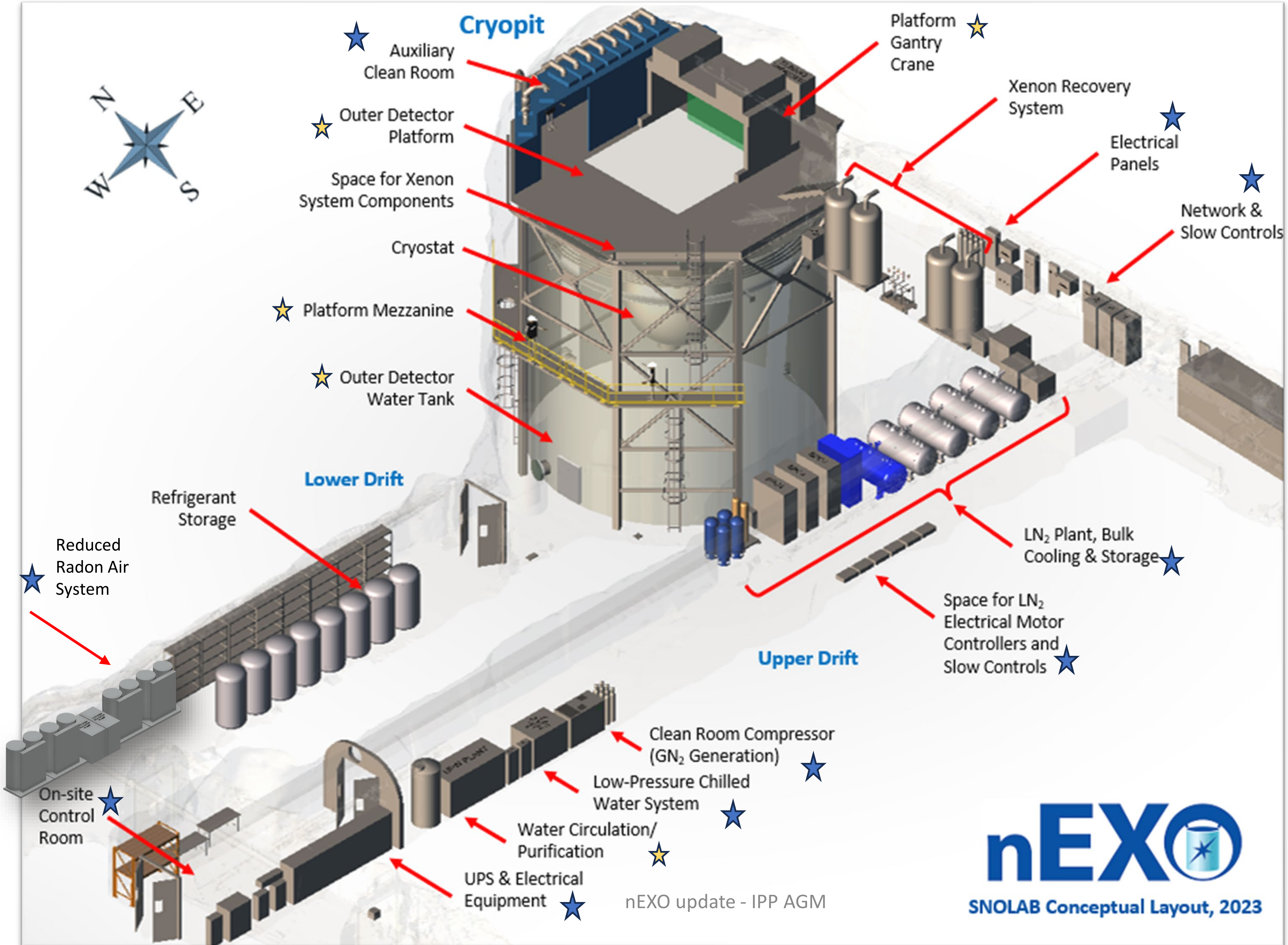
Outer Detector (SNOLAB)
Subsystem Scientist:
T. Brunner
Subsystem Manager:
D. Hawkins





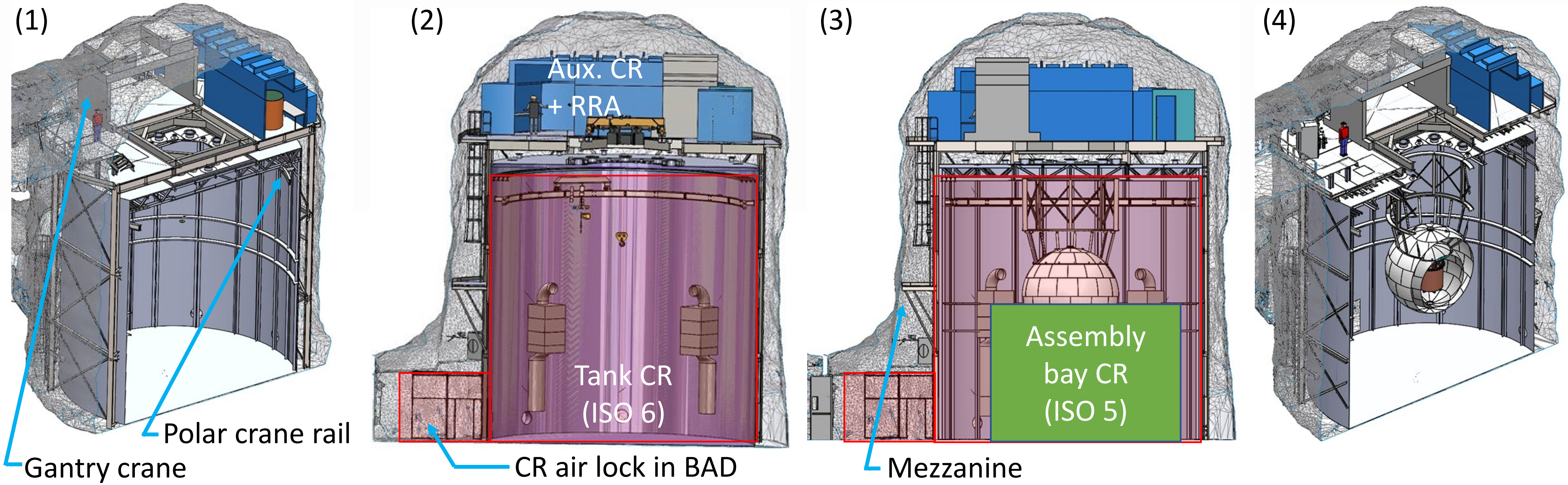
☆ WBS 1.10 Deliverable

★ WBS 1.11 Deliverable



nEXO Construction Stages in Cryopit

(3): cryostat in final configuration shown for reference



1) Water Tank and Platform (**IF2023** deliverables) are complete; leak and light tightness test completed.
2) Tank as clean room (CR) to fabricate the cryostat shells. Auxiliary CR with radon-removed air (RRA) for TPC assembly (**IF2025** anticipated).
3) Assembly bay (ISO 5) CR with radon-removed air for final assembly of TPC and inner detector.
4) nEXO in its final configuration ready to be filled.

Anticipated Canadian Funding Schedule

CFI secured

CFI proposal anticipated

			CD-1									CD-4		
Anticipated Eligibility for Spend	CY23	CY24		CY25	CY26	CY27	CY28	CY29	CY30	CY31	CY32		CY33	CY34
MSI (SNOLAB)	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩
IF2020		🟩		🟩	🟩	🟩	🟩							
IF2020 MF	🟩	🟩		🟩	🟩									
IF2020 IOF				🟩	🟩									
IF2023*				🟩	🟩	🟩	🟩	🟩						
IF2023* MF				🟩	🟩	🟩	🟩	🟩						
IF2023* IOF							🟩	🟩	🟩	🟩	🟩			
IF2025					🟩	🟩	🟩	🟩	🟩					
IF2025 MF					🟩	🟩	🟩	🟩	🟩					
IF2025 IOF									🟩	🟩	🟩		🟩	🟩
IF2027								🟩	🟩	🟩	🟩			
IF2027 MF								🟩	🟩	🟩	🟩			
IF2027 IOF											🟩		🟩	🟩
NSERC	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩
McDonald Institute	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩					

MF: CFI management fund
IOF: CFI Infrastructure Operating Fund
*: conditional
CD dates anticipated

- Anticipated Canadian funding sources supporting the nEXO project, as of May 2024.
- The funding schedule is based on the current interests and commitments of the Canadian contingent in nEXO and the need for this infrastructure in the construction schedule.
- **We are actively engaging other scientists in Canada to grow our team and the Canadian efforts towards nEXO.**
- Critical Decision 4 review (CD-4, Independent Project Review). The experiment will be operational after CD-4.

IF 2023 Funding for nEXO

CFI IF 2023 (co-led by Thomas Brunner, McGill, and Chloe Malbrunot, UBC, \$19.9M + \$4.6M in-kind)

Searching for neutrinoless double beta decay with nEXO at SNOLAB

- nEXO construction
  - Outer detector water tank, platform, and lifting appliances
- nEXO R&D and infrastructure to mitigate risk to photon detector (PD) subsystem
  - CLEAR setup at TRIUMF to measure optical properties on interfaces in liquid xenon
  - LXe setup at McGill for long-term stability tests of PD tiles in LXe
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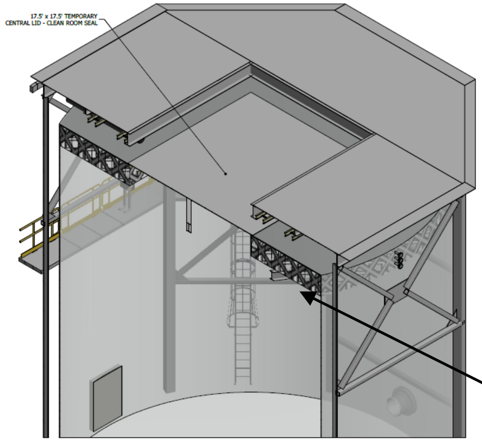
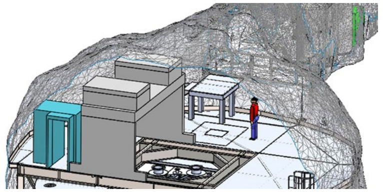
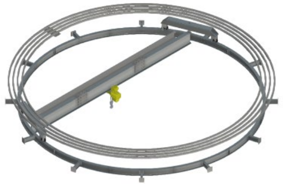
→ Hardware and engineering development and start of nEXO construction at SNOLAB Cryopit

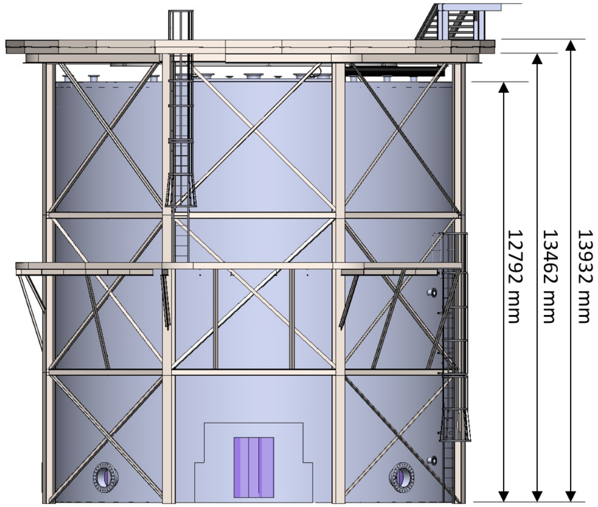




Gantry crane

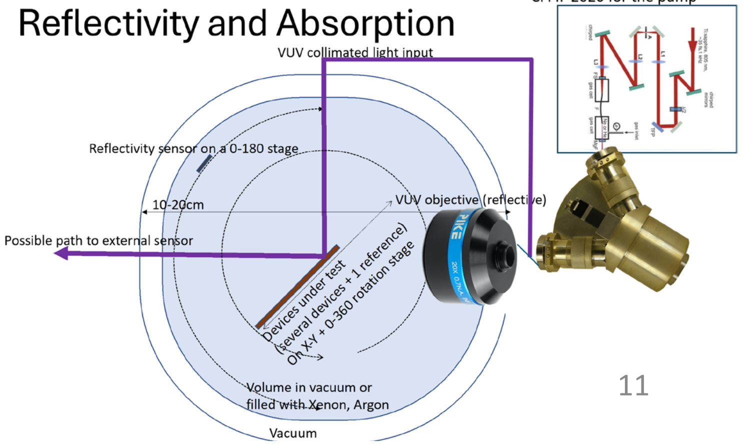


Polar crane



Cryogenic Liquid Efficiency Reflectivity and Absorption

VUV – IR Supercontinuum laser
Enabled by McDonald Institute and CFI IF 2020 for the pump



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Director's review scheduled for July 2024 → next milestone towards Critical Decision 1

Funding for capital infrastructure

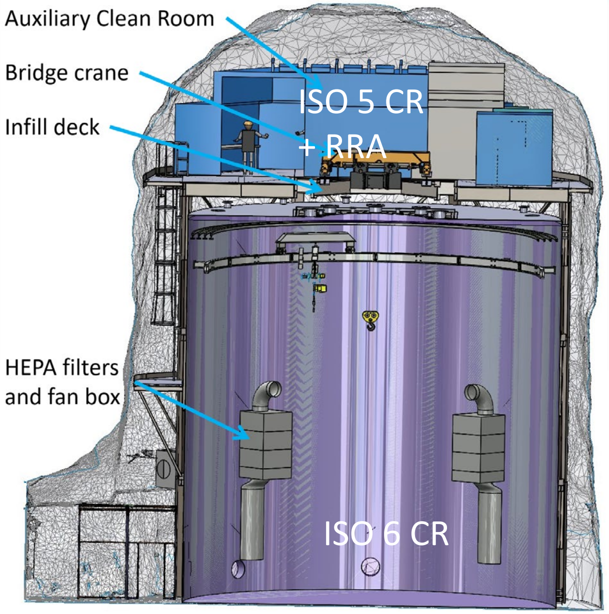
CFI IF 2025

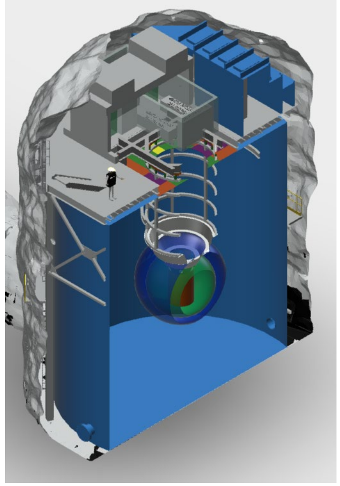
- Construction CFI (processes started at member institutions)
  - Clean room infrastructure (Outer Detector CR and platform CR)
  - Radon removal system to supply low-radioactivity air
  - Electrical and chilled water infrastructure connecting to lab-interface points
  - Water circulation and assaying system for outer detector
  - Copper electroforming facility
  - Infill deck structure
  - Purchase of SiPM photodetectors
  - Liquid nitrogen lines

CFI IF 2027

- Construction CFI
  - Muon veto installation and DAQ hardware
  - Convert tank structure from construction space to water tank (muon veto and radiation shield)
- Canadian contribution to enriched Xe (~500 kg)

New Members Welcome





The international nEXO collaboration

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, 38 institutions in 10 countries on 4 continents

nEXO EDI Efforts

- Ad-hoc committee developed a Code of Conduct. Approved by collaboration board in 2018.
  - https://nexo.llnl.gov/diversity-equity-inclusion
  - Used by TUCAN and other collaborations to form their codes
  - Mentioned in SNOWMASS whitepaper as a resource
- Now a standing Code of Conduct committee (since 2019).
- Introduced two ombudspersons for the collaboration. Elected for a 2-year term.
- Enthusiasts formed the DEI/EDI committee in 2020 with strong Canadian contributions & leadership
  - Inaugural co-chair: Erica Caden (SNOLAB)
  - Current co-chair: David Gallacher (McGill student)
  - Various subgroups developed programs to support EDI initiatives
    - Mentorship program
    - Ask Me Anything
    - DEI meeting every collaboration meeting
    - DEI talks at collaboration meetings
    - Junior scientist presentation events
    - EDI talks every 1-2 months

Promotional Video:
https://youtu.be/O8UGn_E5F4g

nEXO EDI Events: Group Run & AMA

- July Collaboration Meeting at Montreal, QC
- January Collaboration meeting at Livermore, CA

nEXO EDI Efforts

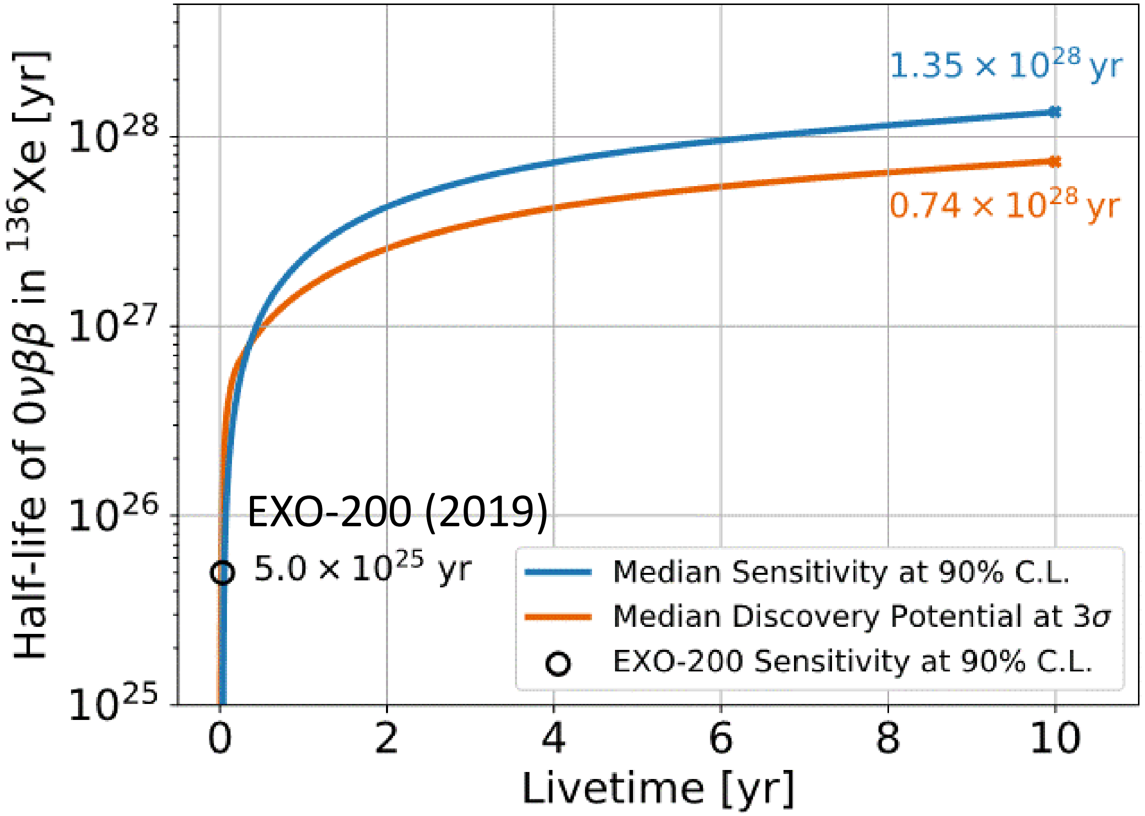
- Received DOE RENEW grant in 2023 to support nEXO's DEI efforts
  - $83k over 3 years for:
    - Future iteration of the Climate Survey
    - Dependent Care Travel Grants
    - Ombudsperson Training
    - Targeted Job Boards for Underrepresented Groups
    - DEI Workshop for Collaborations
      - Summer 2025
    - DEI Seminar Series Speaker Support
      - January 2024: Melissa Dancy spoke on "Dismantling inequity in physics: The essential role of over-represented groups"

nEXO

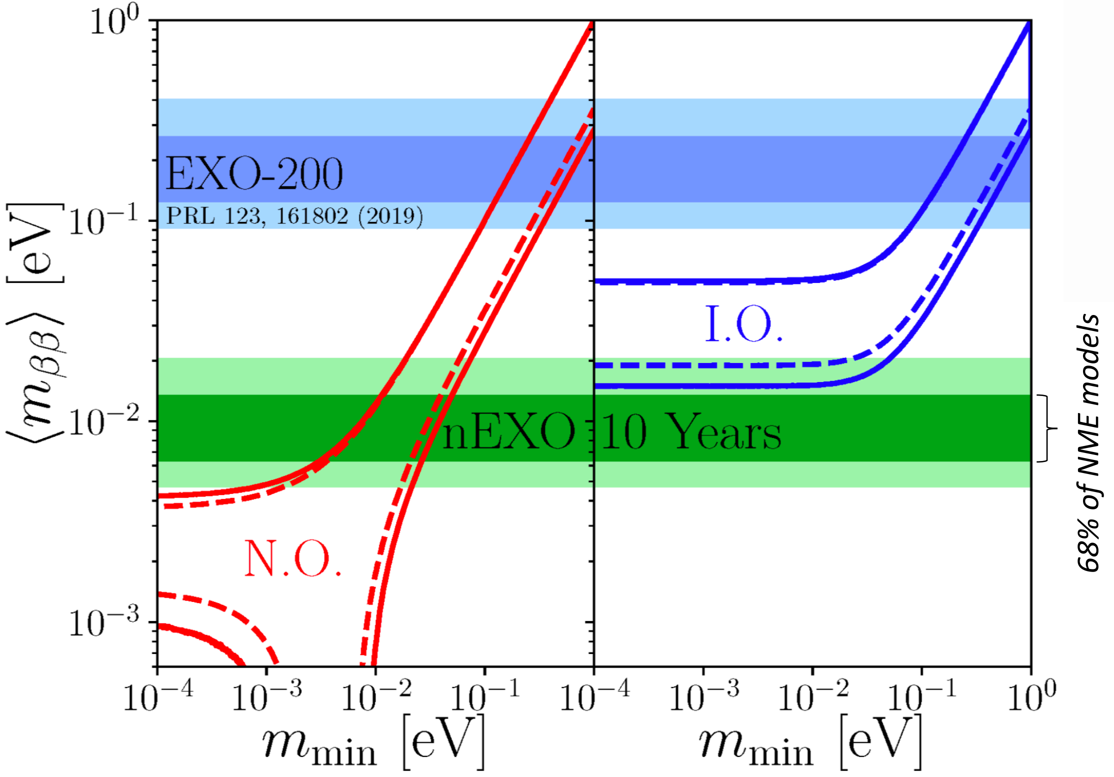
Collaboration Meeting in Montreal 2023

nEXO Projected Sensitivity

J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022), arXiv:2106.16243



Allowed parameter space and nEXO exclusion sensitivity (90% CL):



nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Projected sensitivity based on background levels measured in samples of all detector materials!

nEXO Projected Sensitivity

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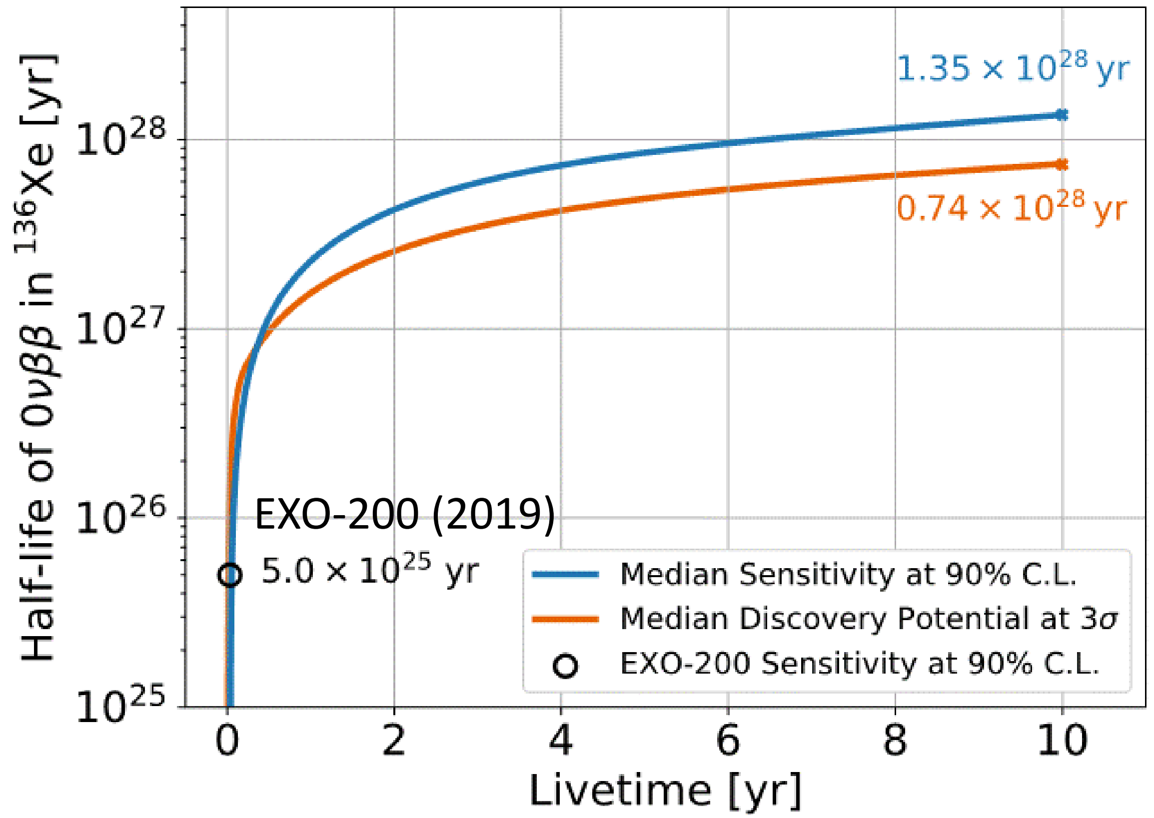
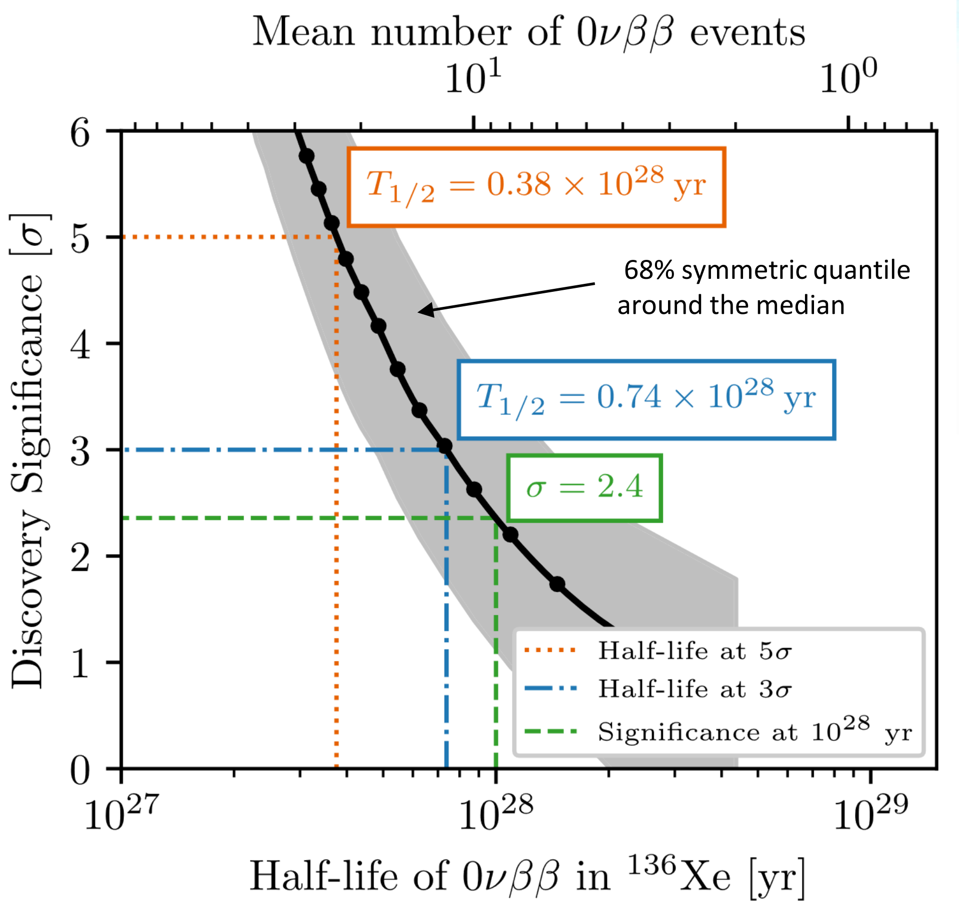




nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Projected sensitivity based on background levels measured in samples of all detector materials!

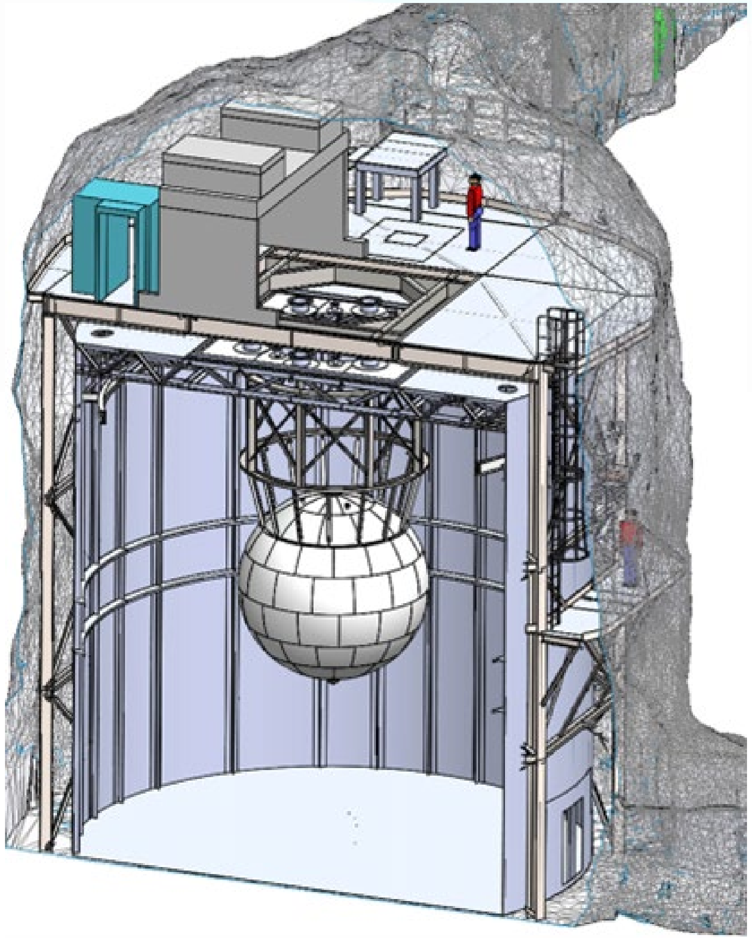
nEXO publications

- The nEXO collaboration is pursuing a targeted, successful research program.
- **Most of the studies were led by graduate students and postdocs.**

- **Supernova Electron-Neutrino Interactions with Xenon in the nEXO Detector,** S. Hedges, et al., to be submitted to the arXiv shortly (2024)
- **An integrated online radioassay data storage and analytics tool for nEXO,** R.H.M. Tsang, et al., NIMA 1055, 168477 (2023)
- 🍁 **Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO,** G. Gallina, et al., Eur. Phys. J. C 82, 1125 (2022)
- **Development of a ^{127}Xe calibration source for nEXO,** B. G. Lenardo, et al., JINST, 17, 07, P07028 (2022)
- **nEXO: neutrinoless double beta decay search beyond 10^{28} year half-life sensitivity,** G. Adhikari et al., J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)
- **Reflectivity of VUV-sensitive silicon photomultipliers in liquid Xenon,** M. Wagenpfeil, et al., JINST 16 P08002 (2021),
- **SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy,** SNEWS 2 collaboration, New J. Phys. 23 031201 (2021)
- **Event Reconstruction in a Liquid Xenon Time Projection Chamber with an Optically-Open Field Cage,** T. Stiegler, et al, NIMA 1000, 165239 (2021)
- **Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths,** P. Lv, et al, IEEE Trans. Nucl. Sci. 67, 2501 (2020)
- **Reflectivity and PDE of VUV4 Hamamatsu SiPMs in liquid xenon,** P. Nakarim, et al., JINST 15, P01019 (2020)
- **Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode,** O. Njoya, et al., NIM A 972, 163965 (2020)
- 🍁 **Characterization of the Hamamatsu VUV4 MPPCs for nEXO**, G. Gallina, et al., NIMA 940, 371 (2019)
- **Simulation of charge readout with segmented tiles in nEXO,** Z. Li, et al., JINST 14, P09020 (2019)
- **Imaging individual Ba atoms in solid xenon for barium tagging in nEXO,** C. Chambers, et al., Nature 569, 203 (2019)
- **Study of Silicon Photomultiplier Performance in External Electric Fields,** X.L. Sun, et al., JINST 13, T09006 (2018)
- **VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO,** IEEE Transactions on Nuclear Science 1 (2018)
- **nEXO Pre-Conceptual Design Report,** arXiv:1805.11142v2
- **Characterization of an Ionization Readout Tile for nEXO,** M. Jewell, et al., JINST 13, P01006 (2018)
- **Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay,** J.B. Albert, et al., Physical Review C 97, 065503 (2018)

Summary

- **nEXO is a discovery focussed 0νββ experiment.**
- nEXO is being designed to reach a sensitivity beyond ~10^{28} years and will probe the entire inverted ordering parameter space.
- We have been growing the Canadian team within nEXO.
- We are pursuing a successful funding strategy to deliver key infrastructure to nEXO.
- nEXO will be **THE** international flagship experiment on Canadian soil for the next decade+.
- **We invite the IPP community to join the exciting search for 0νββ with nEXO!**



Thank you for your attention!

Closing session of the 0νββ summit

Readout from In Camera Sessions

- 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.

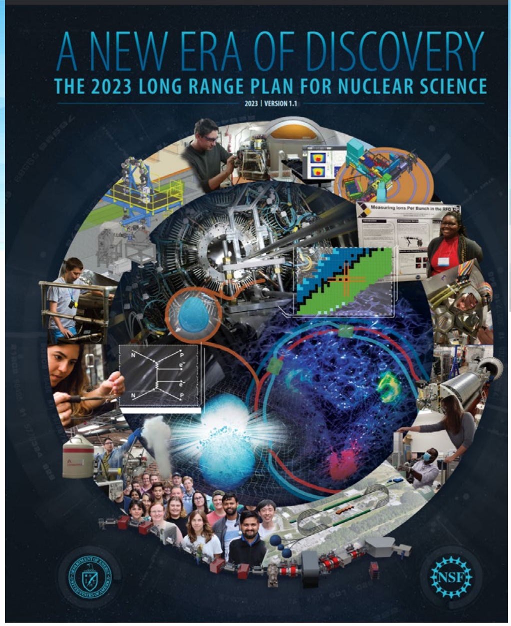
Source: https://indico.cern.ch/event/1242655/ and https://www.snolab.ca/news/snolab-hosts-2nd-international-summit-on-the-future-of-neutrinoless-double-beta-decay/

NSAC Recommendation

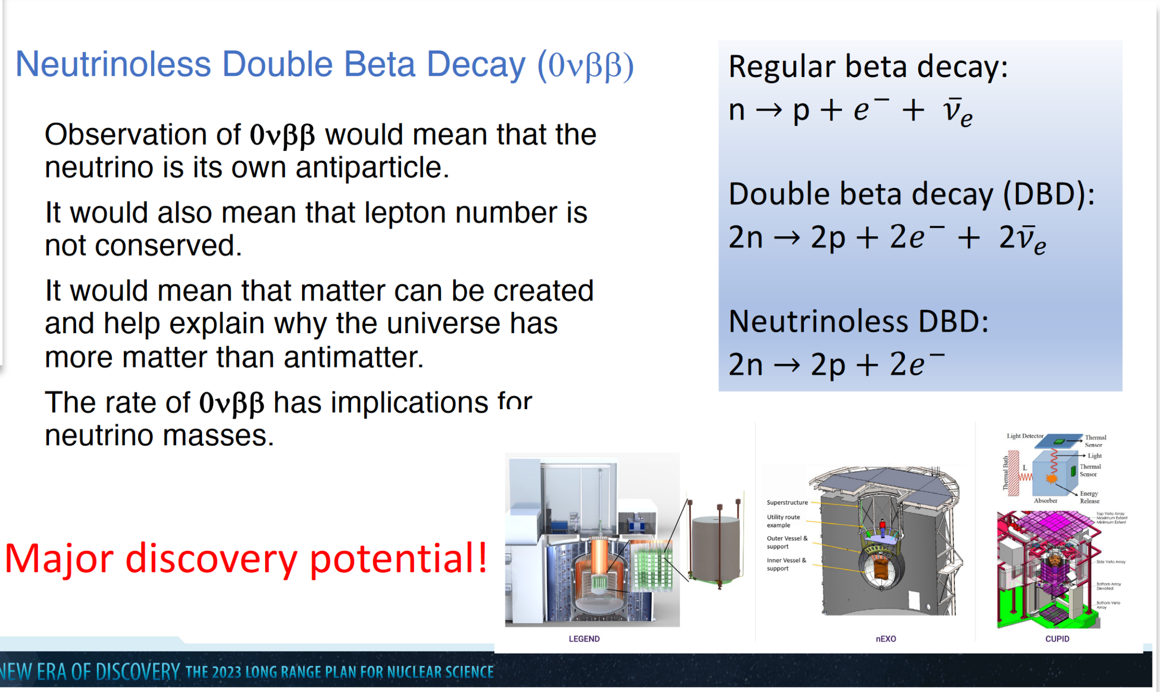
RECOMMENDATION 2

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 RANGE PLAN FOR NUCLEAR SCIENCE



A NEW ERA OF DISCOVERY
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE
2023 | VERSION 1.1



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):
$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

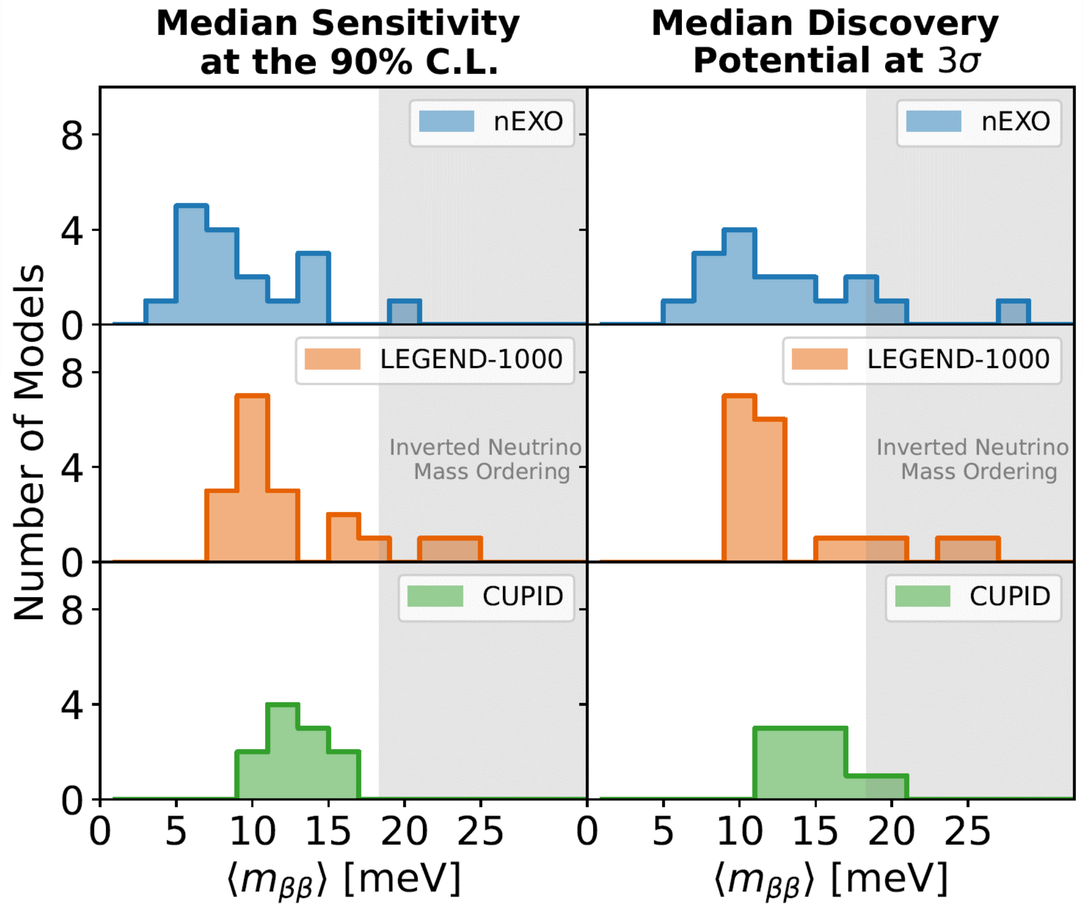
Neutrinoless DBD:
$2n \rightarrow 2p + 2e^-$

Major discovery potential!

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

Source: https://science.osti.gov/-/media/np/nsac/pdf/202310/Dodge-NSAC-Oct-4-2023-v2.pdf and https://science.osti.gov/-/media/np/nsac/pdf/202310/October-4-LRP-Report.pdf

Comparison with other experiments


Median Sensitivity at the 90% C.L.

Median Discovery Potential at 3σ

← Deeper Physics Reach —

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

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

Phase space factor

Axial coupling, $g_A = 1.27$

NME

	$m_{\beta\beta}$ [meV], (*median* NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

*$T_{1/2}$ values used [x10^{28} yr]:

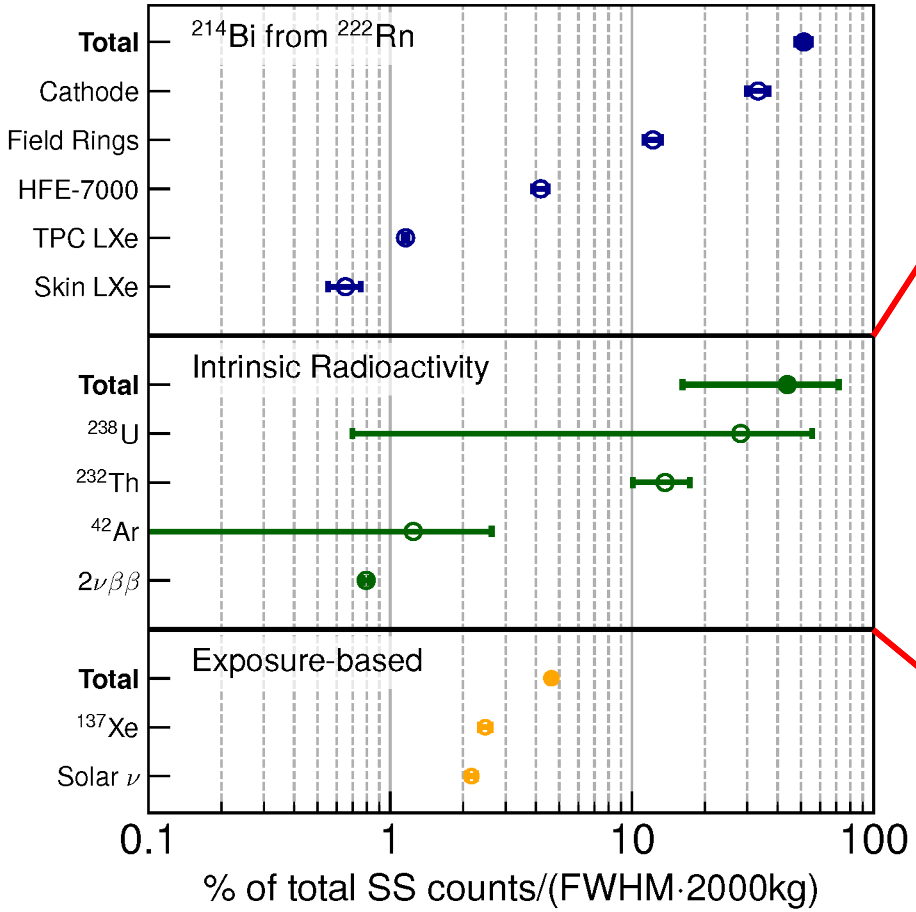
- nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]
- LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.) [2]
- CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

[1] nEXO collaboration, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243

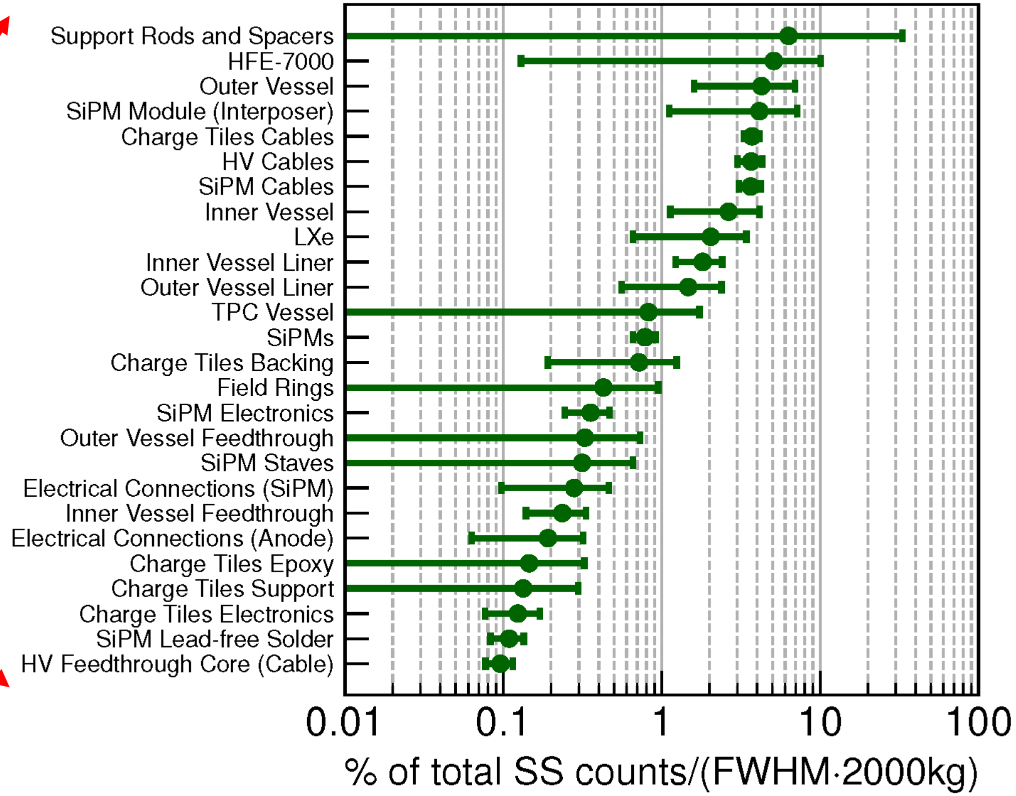
[2] LEGEND pCDR, arXiv: 2107.11462

[3] CUPID pCDR, arXiv:1907.09376

nEXO is well optimized

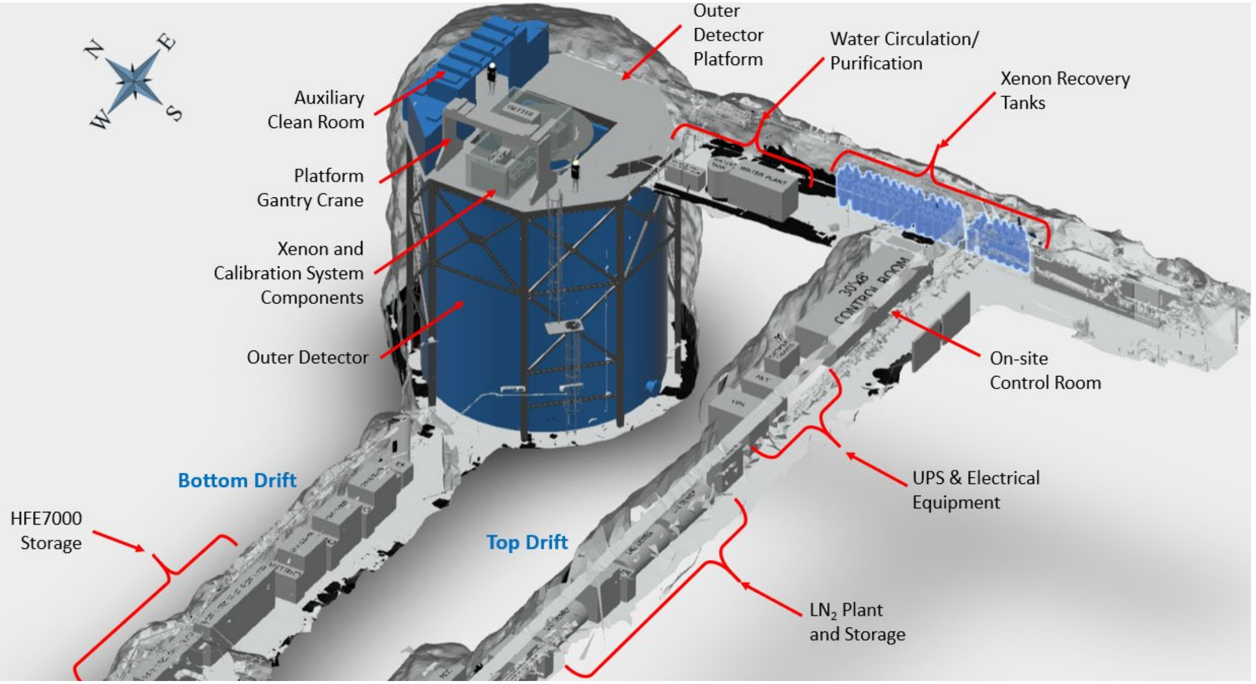


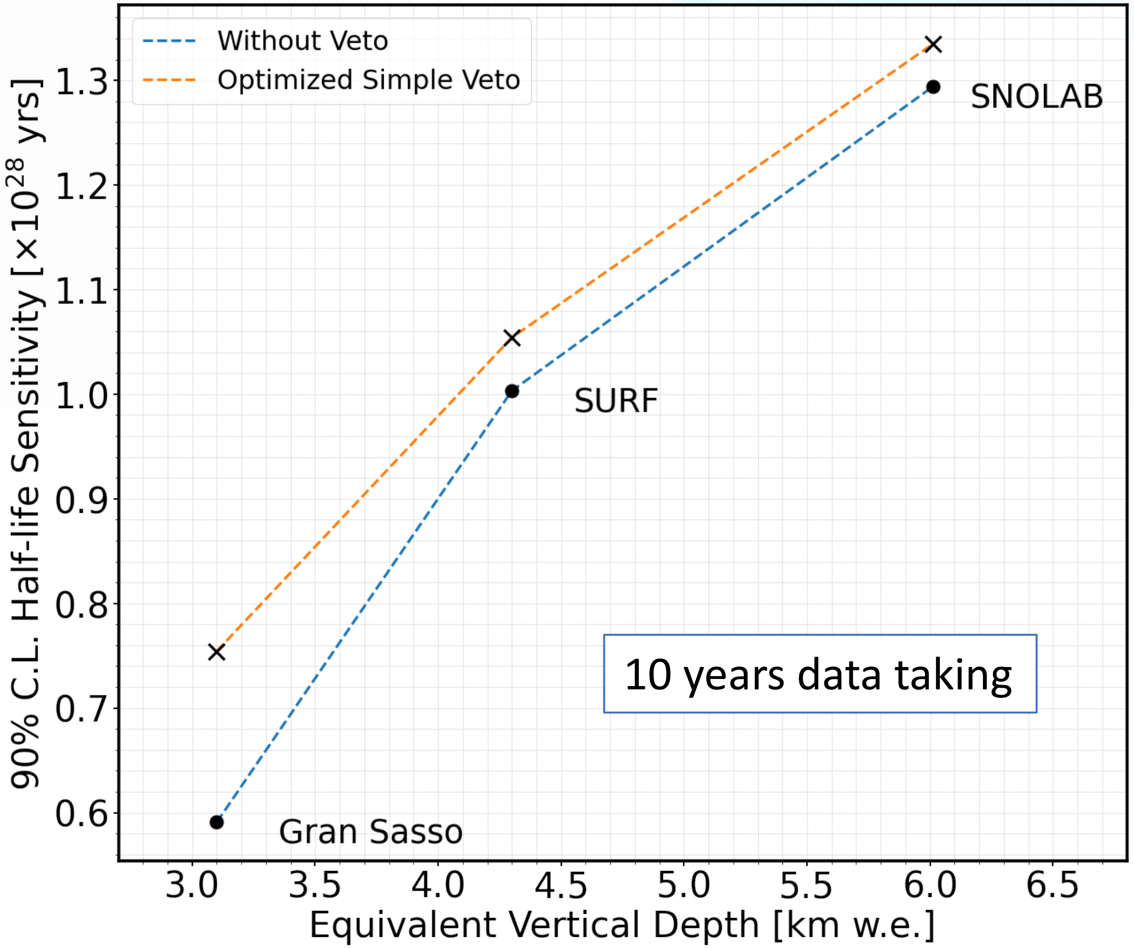
No detector component dominates the background.



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

nEXO at SNOLAB





SNOLAB is the best location for nEXO
→ Biggest scientific reach due to exceptional depth.

- Cosmic muons create spallation neutrons → Neutron capture on ^{136}Xe to ^{137}Xe ($T_{1/2}$=3.8min, Q_{β}=4.2MeV)