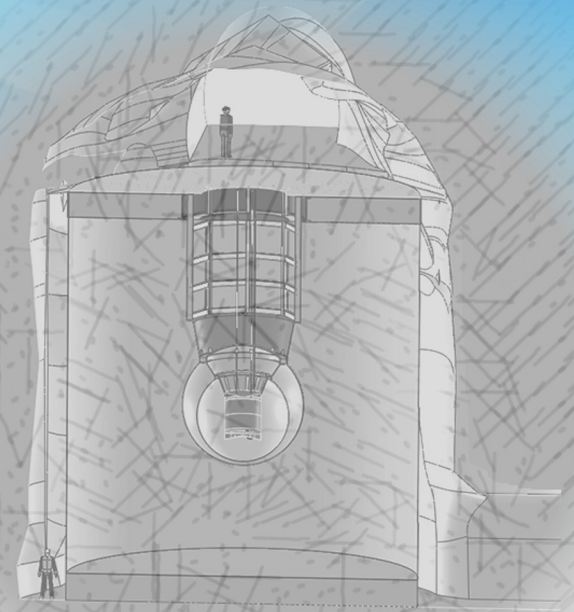


Status of nEXO

Simon Viel (Carleton University)

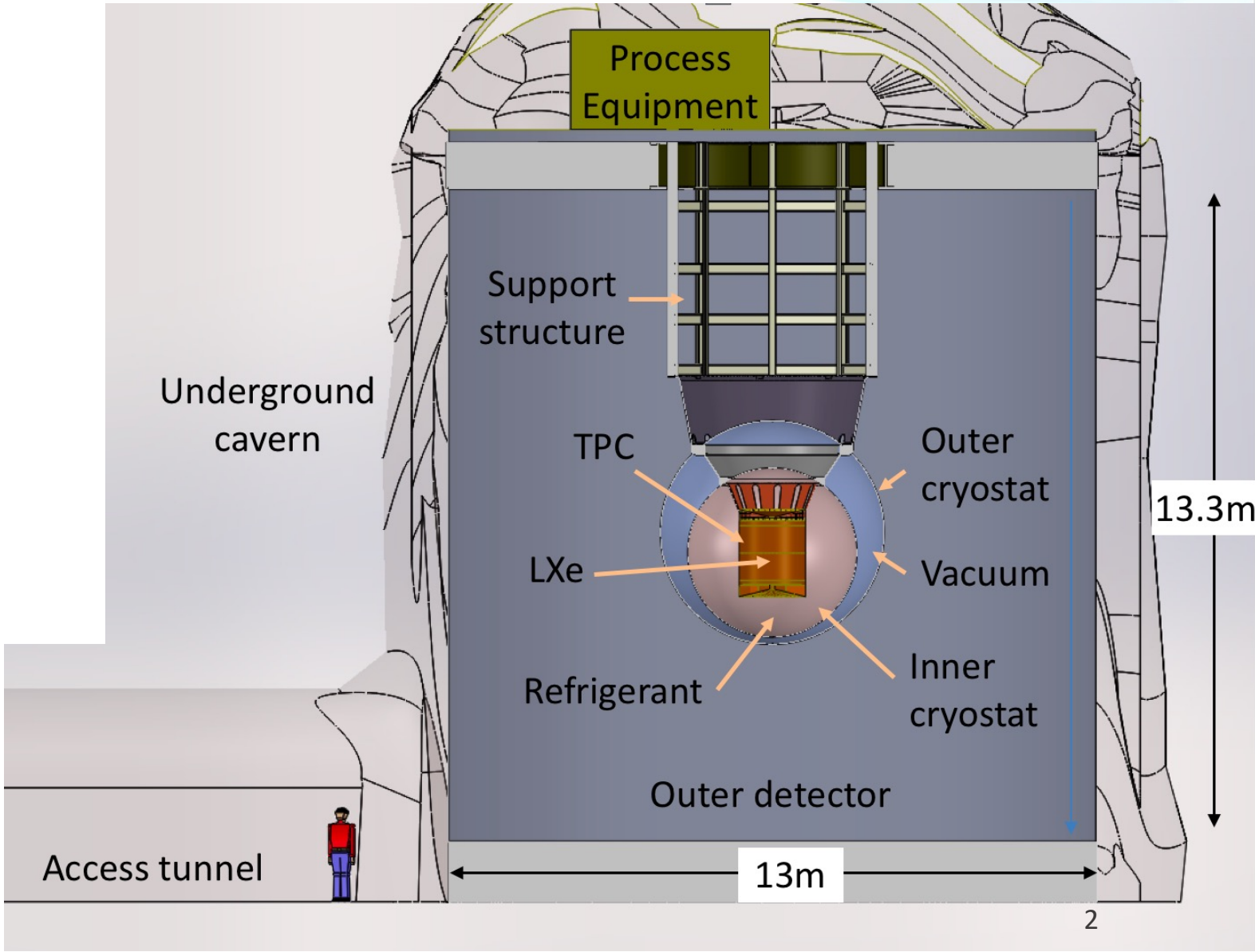
Canadian Astroparticle Physics Community Meeting

August 8th, 2024

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

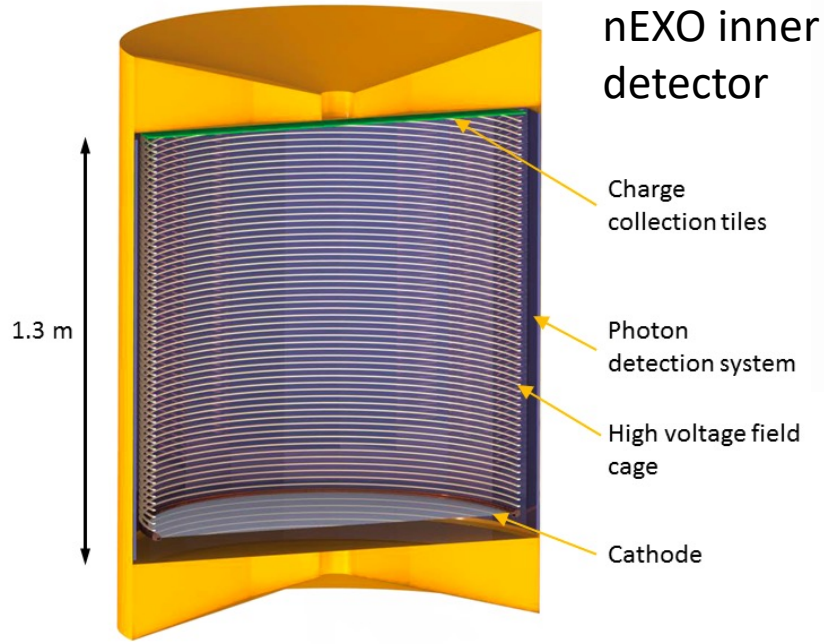
nEXO is a proposed experiment at SNOLAB

- Main goal of nEXO: world-leading sensitivity to **Neutrinoless double beta decay** (0νββ)
  - Observation of 0νββ would be physics beyond the Standard Model
  - Could lead to understanding the neutrino mass mechanism and matter-antimatter asymmetry
- **Time-projection chamber (TPC)** with **5 tonnes liquid xenon (LXe)**, enriched in ^{136}Xe to 90% isotopic purity
- Pending selection by US DOE of 0νββ detector technology and host site
- **SNOLAB Cryopit** cavern is committed to a large-scale 0νββ detector that could be nEXO
  - SNOLAB is the nEXO collaboration's preferred site



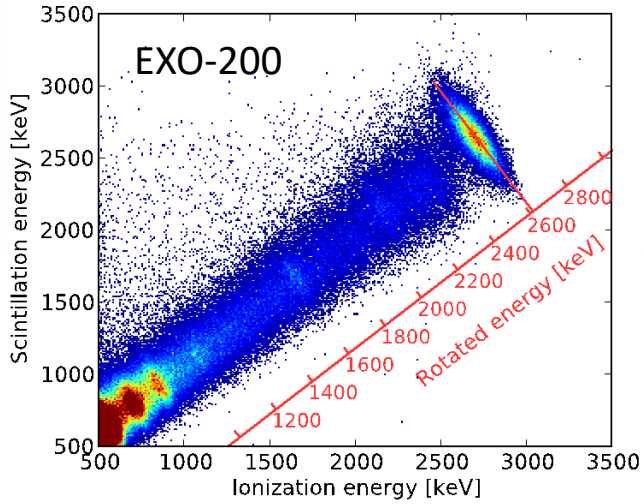
nEXO search for 0νββ in ^{136}Xe

- **Energy resolution** in nEXO relies on the combination of **charge** and **light** detection in the LXe TPC
  - Canadian focus on light collection with silicon photomultipliers (SiPM)
- Self-shielding LXe: fiducial volume
- "ββ like topology" of events determined using neural network



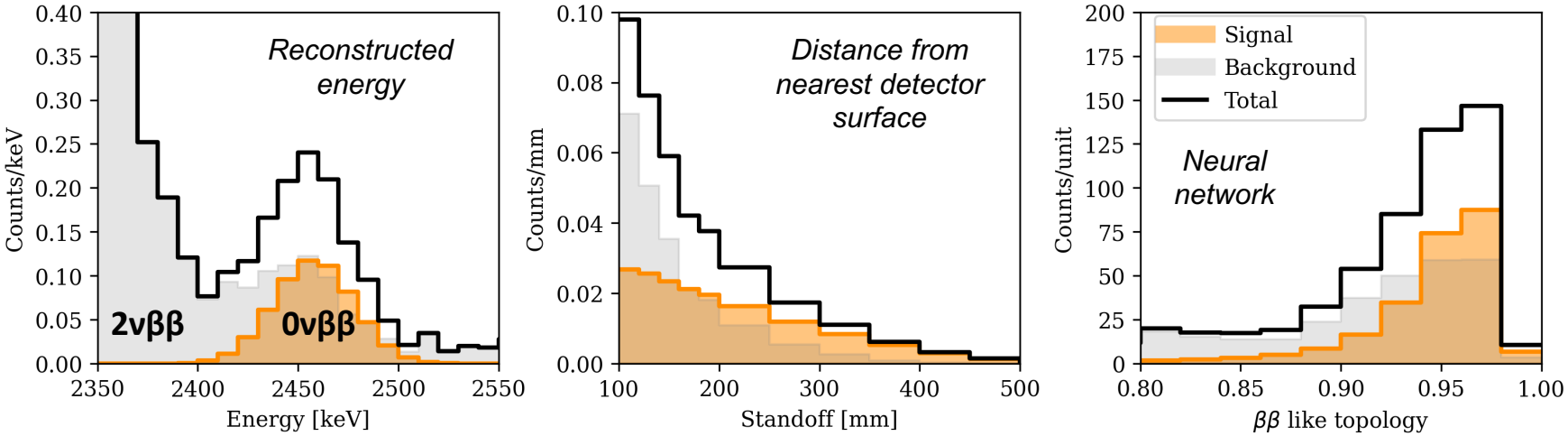
nEXO inner detector

Ionization and scintillation yield are anti-correlated



Likelihood fit of 3 variables

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



nEXO sensitivity to ^{136}Xe 0νββ: half-life of 10^{28} years

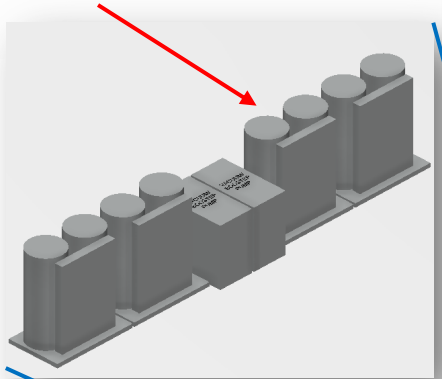
Canadian infrastructure for nEXO

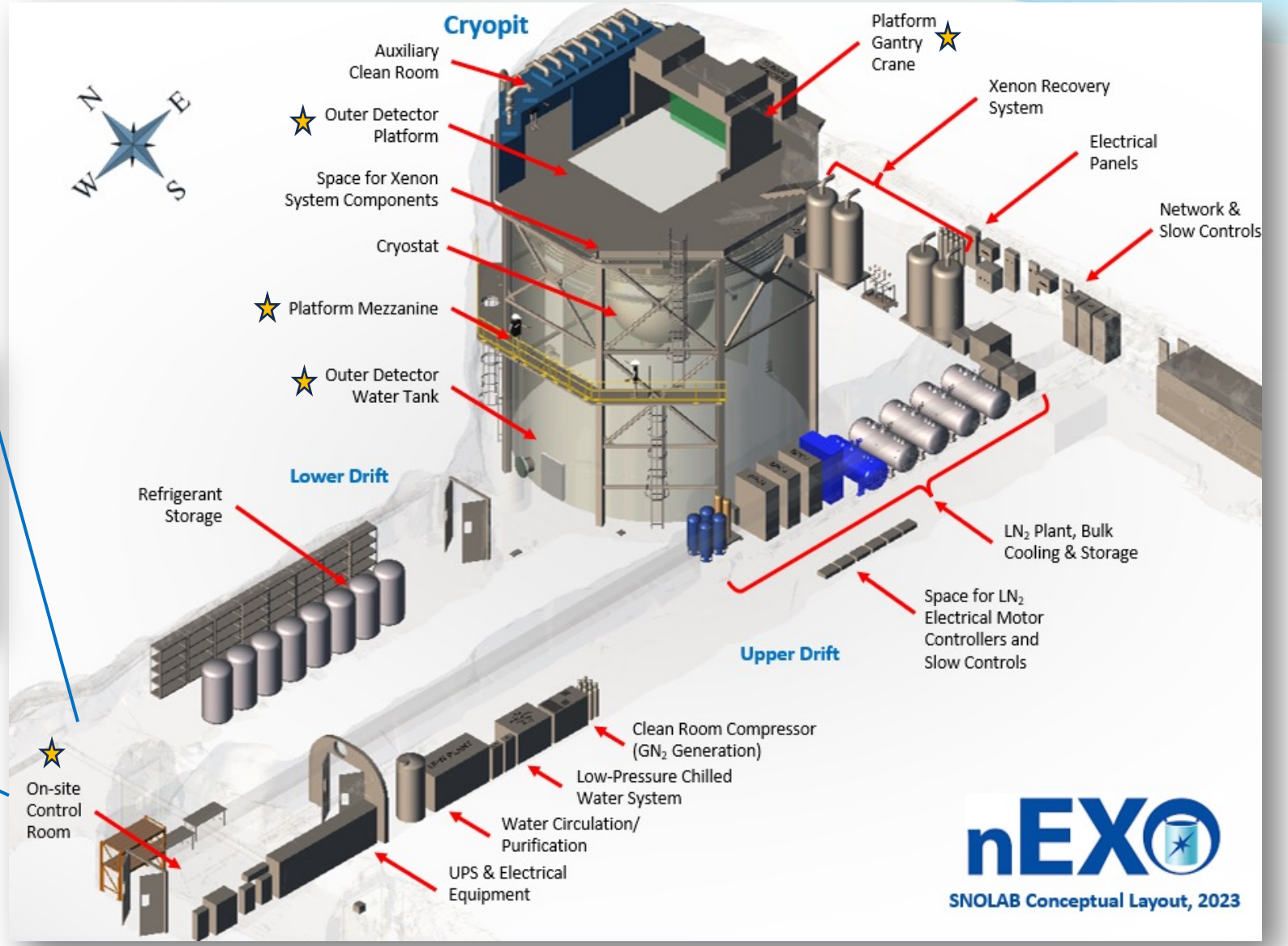
- nEXO is an international collaboration
  - It is a US DOE project, with Canadian contributions on critical items
- CFI IF 2020 award for nEXO: equipment at participating institutions
  - Ultraviolet-sensitive silicon photomultiplier (SiPM) research and development, toward vendor selection for nEXO inner detector
  - Cryogenic SiPM wafer-level testing, SiPM dicing and handling at UBC/TRIUMF
  - Cryogenic SiPM tile test setup at Carleton
  - Cryogenic SiPM stave test setup at McGill
  - Muon veto photomultiplier tube (PMT) test facility at Laurentian
  - Radon screening facility at Windsor
- Fully-funded, started spending
- CFI IF 2023 (conditionally funded) and CFI IF 2025 (proposed) to support nEXO construction at SNOLAB [next two slides]

Canadian infrastructure for nEXO

★ CFI IF 2023 deliverables at SNOLAB

Reduced Radon Air System





Would like to start water tank construction

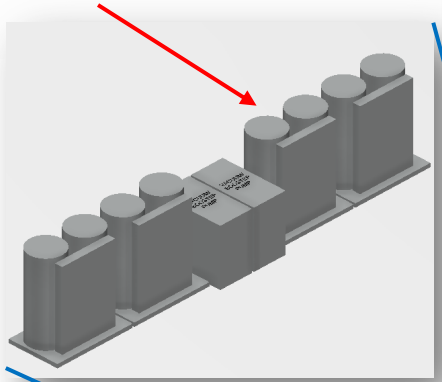
+ SiPM characterization and test systems in liquid xenon at TRIUMF and McGill

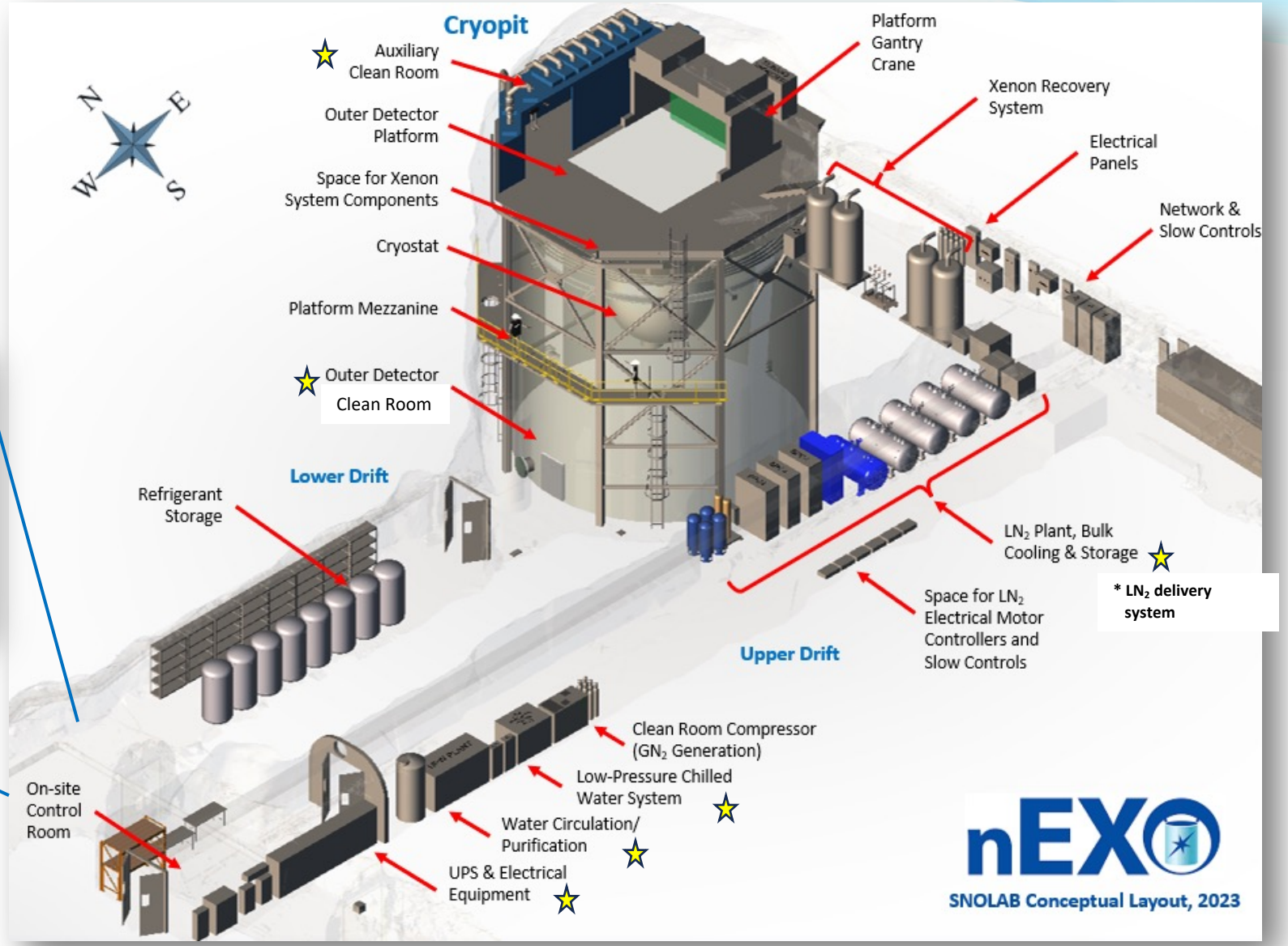
+ Silicon interposer development at Sherbrooke

Canadian infrastructure for nEXO (proposed)

☆ CFI IF 2025 deliverables at SNOLAB

Reduced Radon Air System ☆





Also planning to apply to CFI IF 2027

+ New storage buildings at SNOLAB surface

+ SiPM purchase for nEXO inner detector

+ Data acquisition development at TRIUMF

+ Electroforming copper facility at Queen's

Equity, Diversity and Inclusion

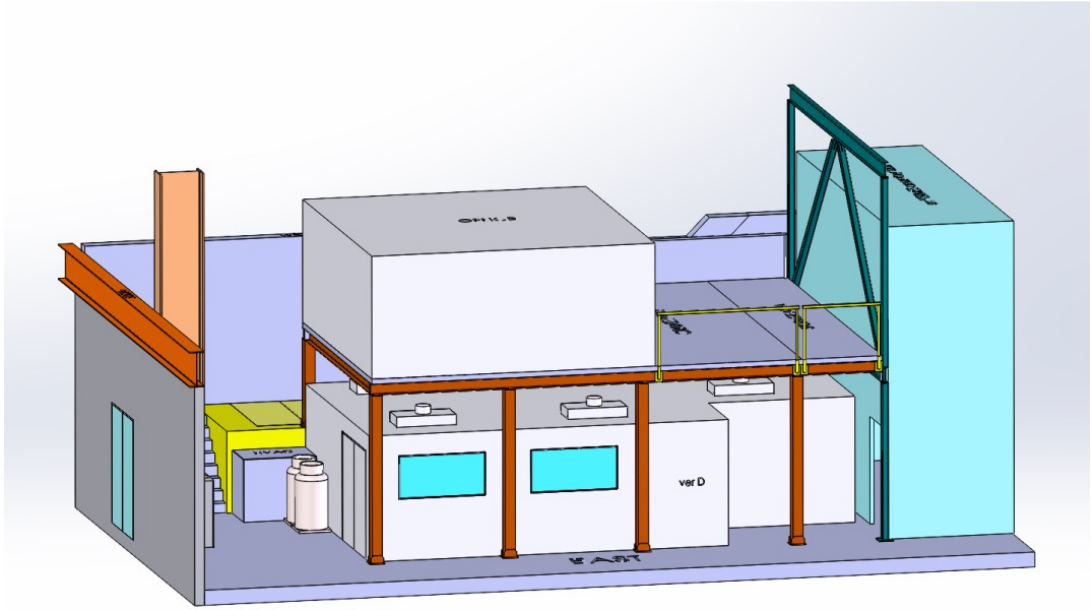
- EDI is embedded in nEXO collaboration structure
  - One of the first collaborations to adopt a code of conduct (2019)
  - Diversity, Equity and Inclusion Committee meets monthly and interacts with Board; with events at collaboration meetings
  - RENEW grant from US DOE in 2023, to support EDI initiatives
  - Climate surveys give us a look at self-reported demographics, with suggestions from members on the best use of EDI dedicated funds
- Concrete actions taken to improve EDI in nEXO
  - Facilitate an improved, more equitable distribution of conference talks and posters
  - Give younger members roles and voices in governing bodies
  - Increase mechanisms for distributing credit and highlighting accomplishments
  - Run a monthly newsletter with information on workshops and job opportunities
  - Organize a seminar series dedicated to EDI
  - Set up a mentorship program

Current nEXO R&D in Canada

SiPM mass testing at TRIUMF

- Equipment for testing 5 m^2 of SiPMs (CFI IF 2020)
  - and prototype tile assembly
- Aim to complete the clean room and to finalize testing methodology by the end of this year
- First tile prototype a few months from now
- Equipment foreseen in clean room:
  - High-throughput probe station (cryogenic?)
  - Assembly equipment
  - Characterization equipment:
    MI-funded vacuum UV – IR supercontinuum laser

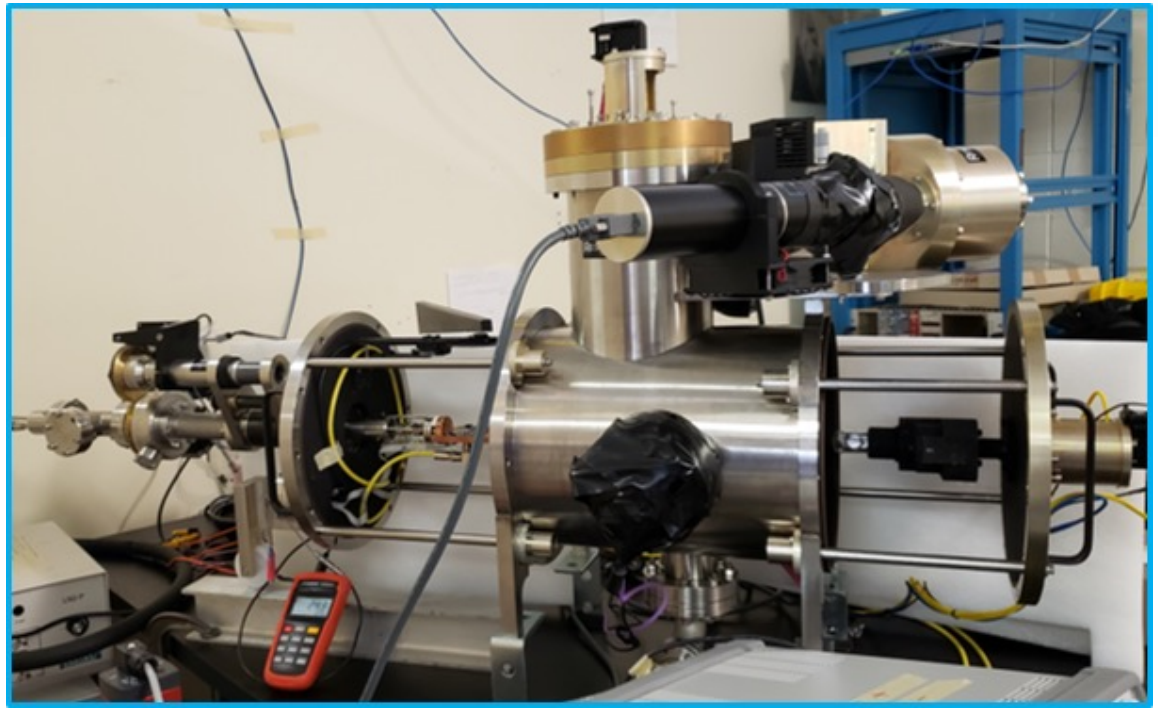
Proposed site of the nEXO clean room and above office facility in the Meson Hall Extension

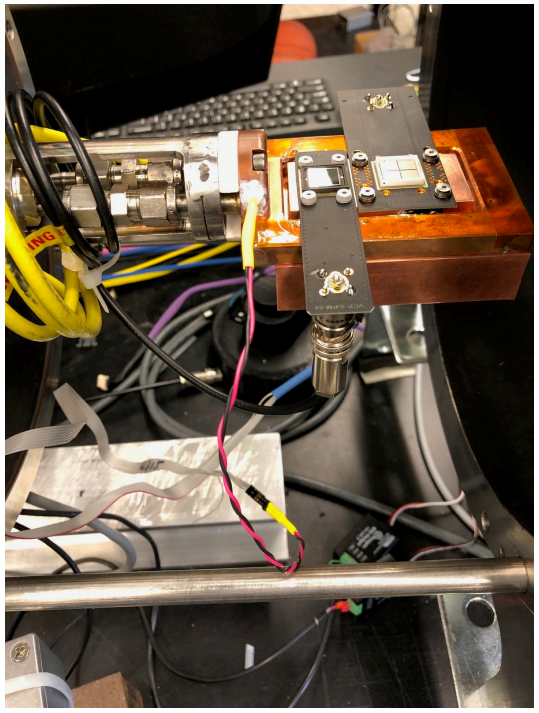


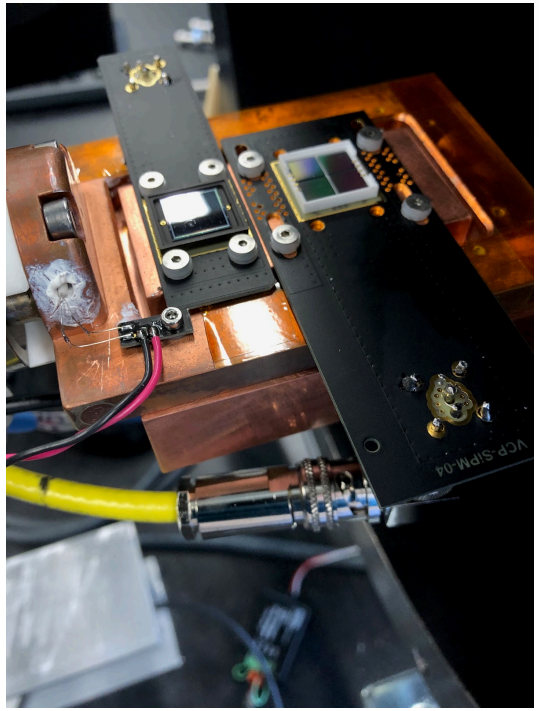
Conceptual illustration of the proposed nEXO facility and above office on the mezzanine

SiPM characterization at TRIUMF

- Vacuum ultra-violet efficiency, reflectivity and absorption (VERA)
  - Measuring reflectivity and efficiency at the same time
  - Recent improvements to temperature control → stability better than 0.1 K
  - Newly automated for faster throughput



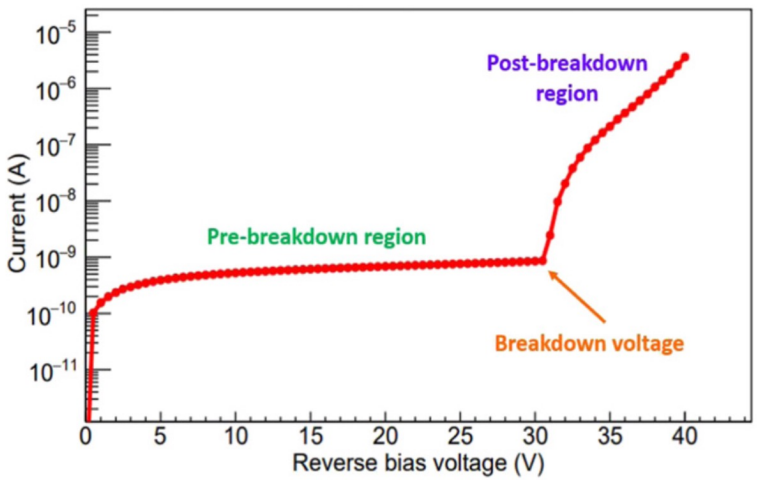


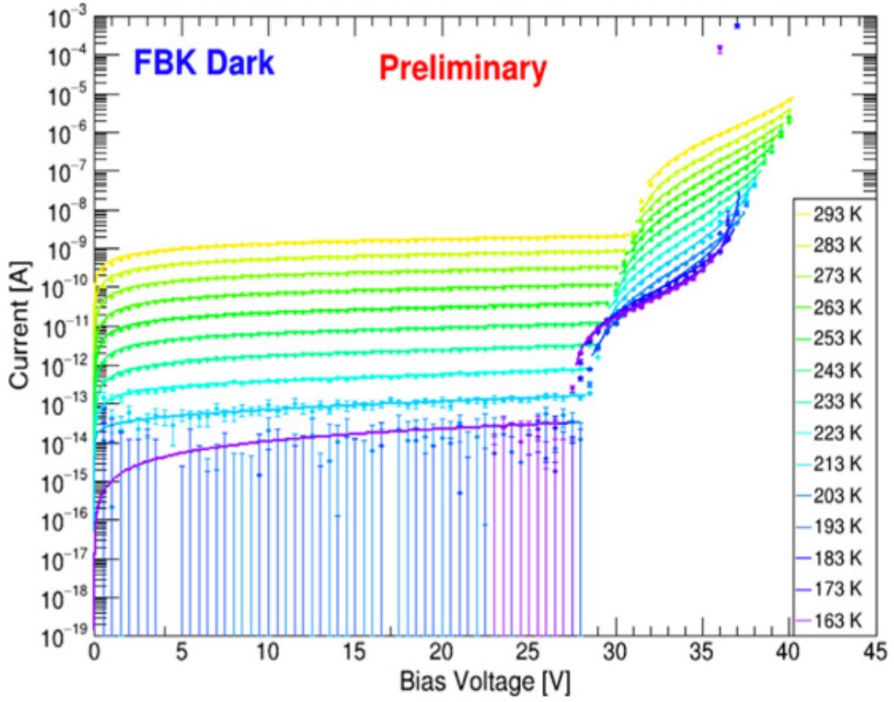


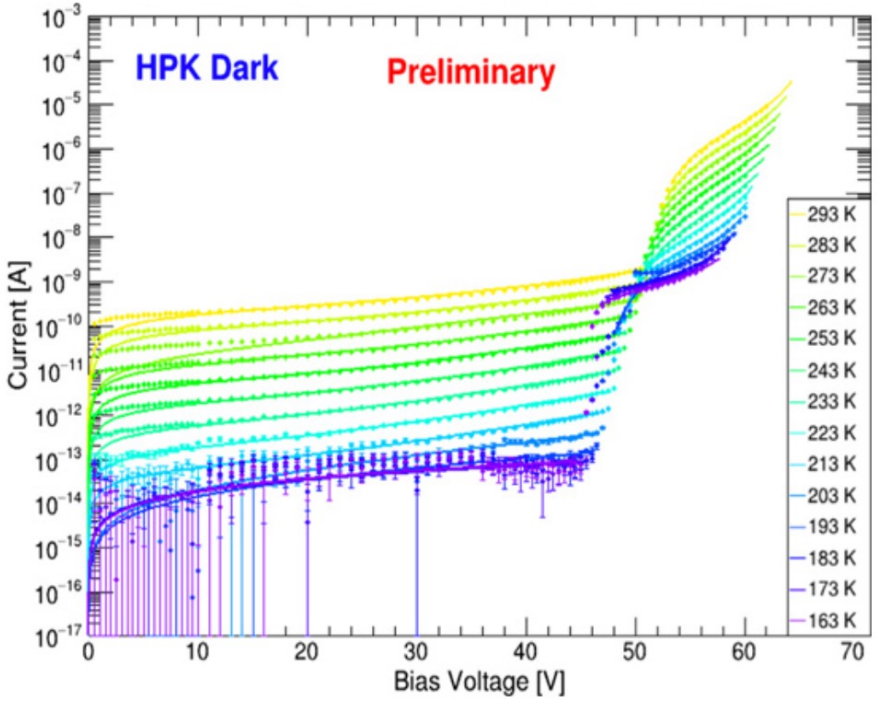
- Microscope for the Injection and Emission of Light (MIEL)
  - SiPM imaging and spectroscopic measurements

SiPM characterization at TRIUMF

- Developed a model for current-voltage (IV) characterization using VERA data
  - Extract dark count rate and correlated noise probability in post-breakdown region
  - Validation against pulse data
  - Useful for quality control during detector construction





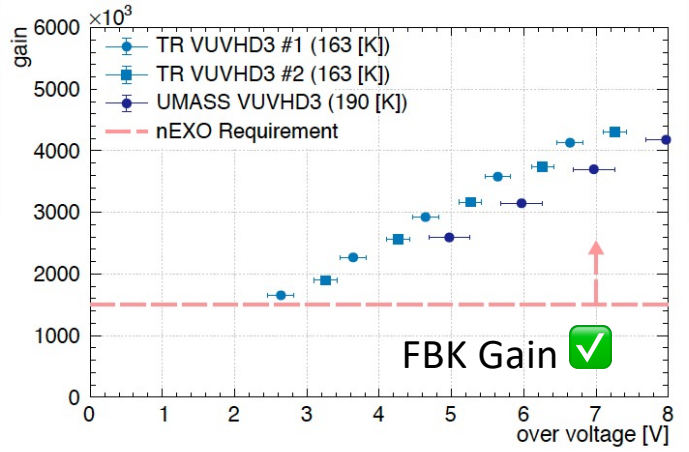


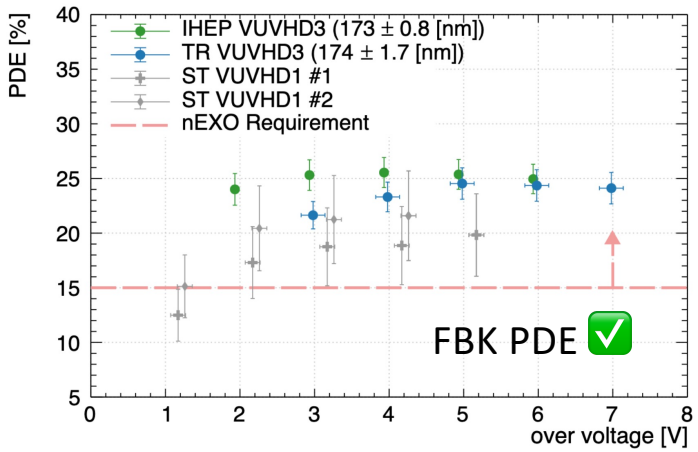
B. Chana, M. Mahtab, F. Retière, S. Viel (2023) Rapid characterization of silicon photomultipliers for noble liquid experiments. *JINST 18, C03004*

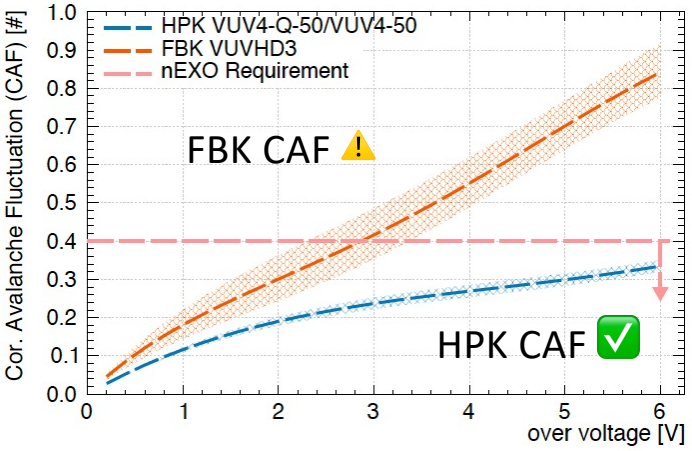
SiPM characterization at TRIUMF

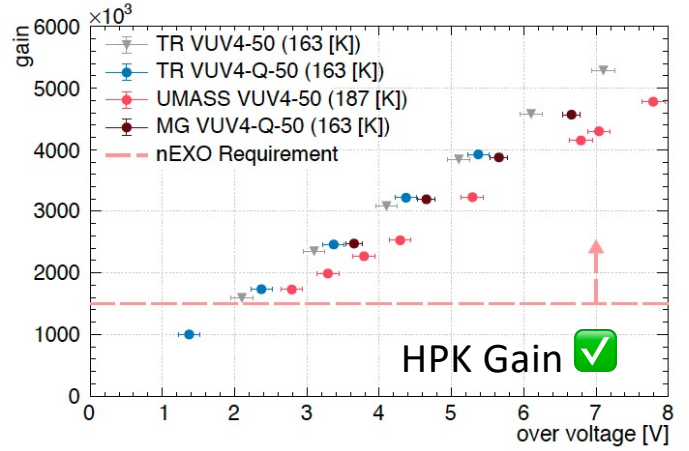
- Two SiPM vendor candidates, Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics (HPK), offering **vacuum ultraviolet (VUV) sensitivity** at 175 nm, are evaluated against nEXO photodetection requirements

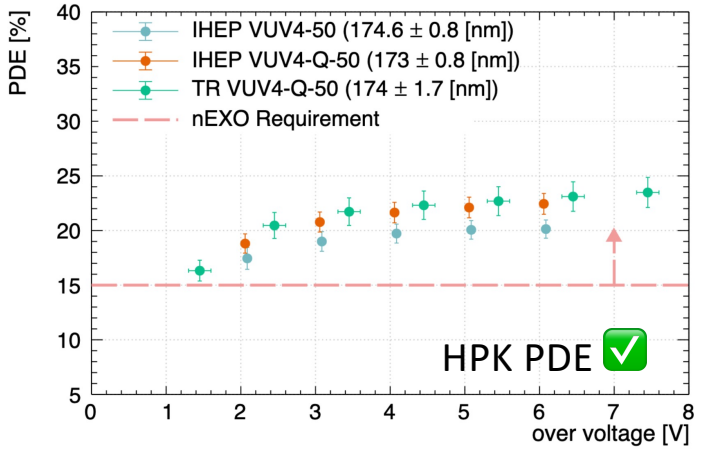
G. Gallina et al. [nEXO Collaboration] (2022) EPJC 82, 1125

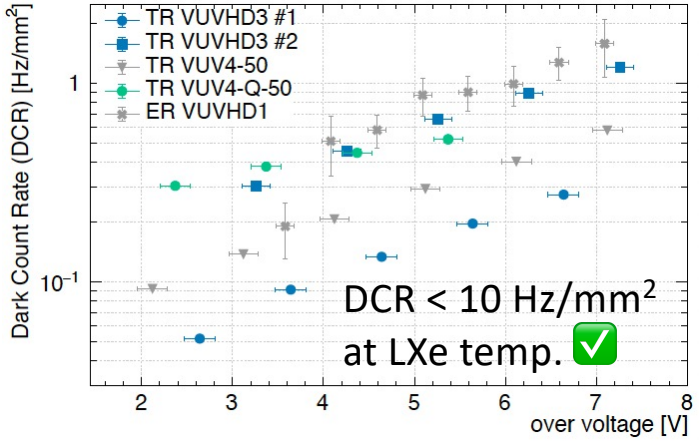










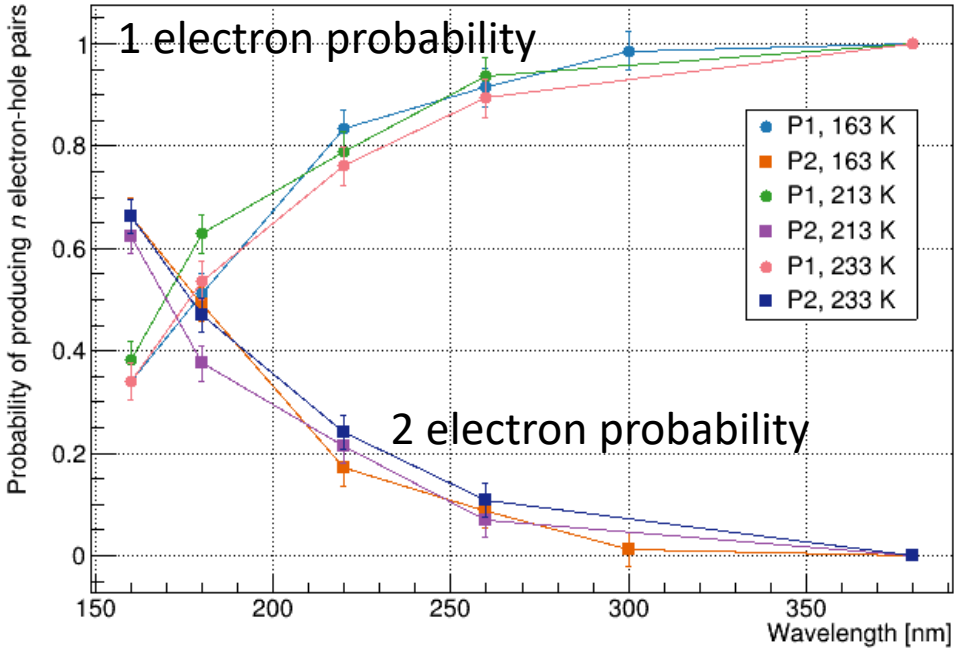


Excellent radiopurity, and through-silicon vias (TSV) are also required

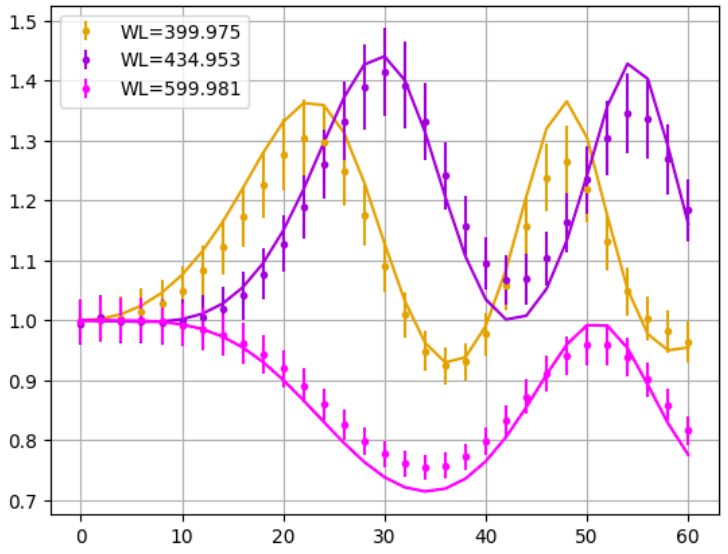
SiPM characterization at TRIUMF

Papers to be submitted very soon:

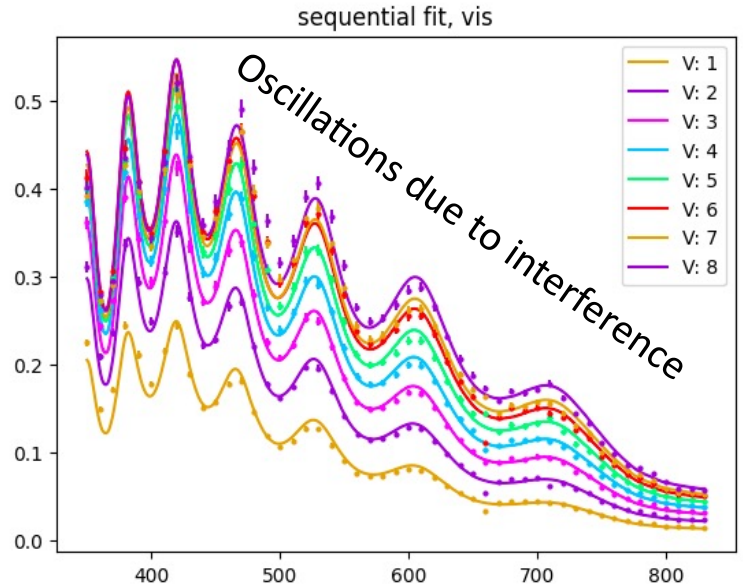
- Measurements of absolute photodetection efficiency (PDE) vs. wavelength and angle of incidence
  - Also important for near-unity efficiency sensors (for quantum technologies)
- Quantum yield of “number of electrons created per photon”
  - Understand efficiency at LXe scintillation wavelength
  - Directly relevant for dark photon search in silicon



PDE ratio wrt normal incidence

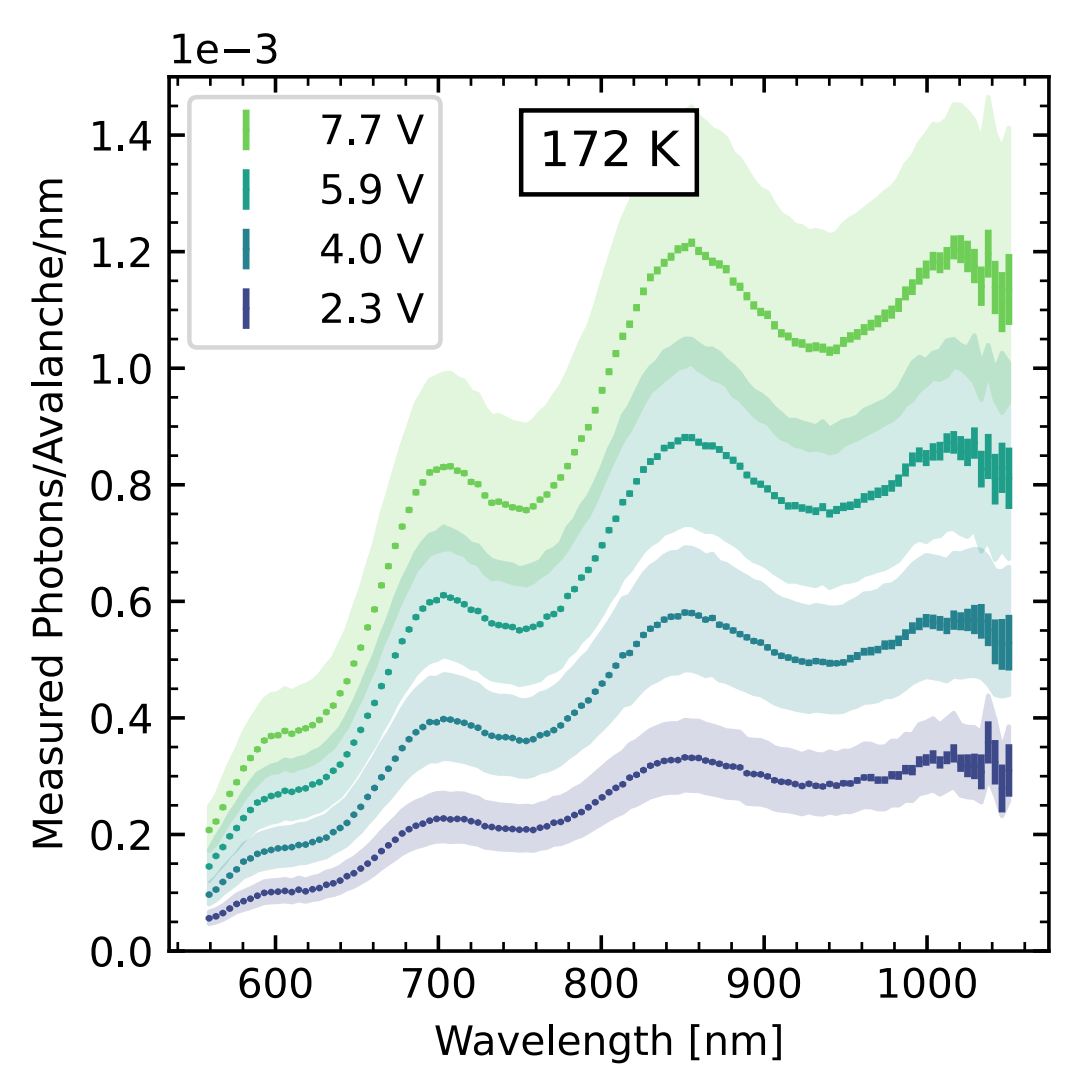


PDE for FBK VUV-HD3 device



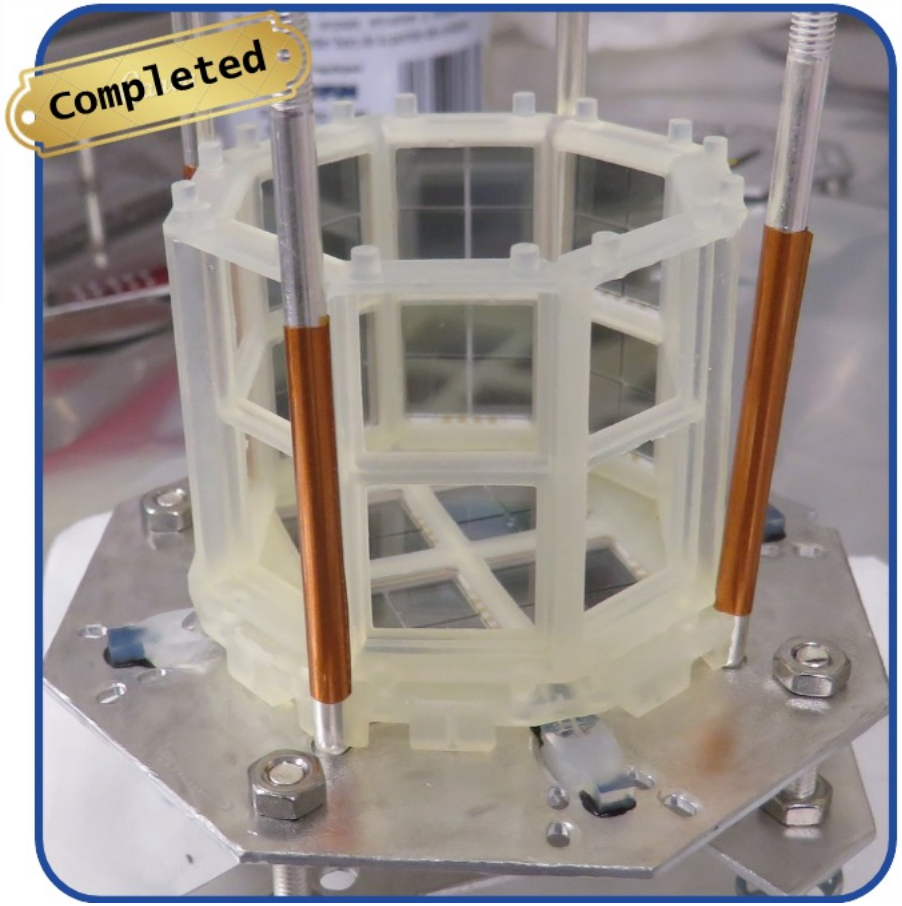
Light emission in SiPMs and external cross-talk

- External cross-talk is a concern in the design of large noble liquid detectors with SiPMs
- Measurement with a microscope, within a cone with angle < 26 degrees
  - Extrapolation to all angles is a significant source of uncertainty
- Photons produced per avalanche in LXe:
  - 1.8 ± 0.4 for FBK
  - 1.2 ± 0.4 for Hamamatsu
- To be published in IEEE Trans. El. Dev.

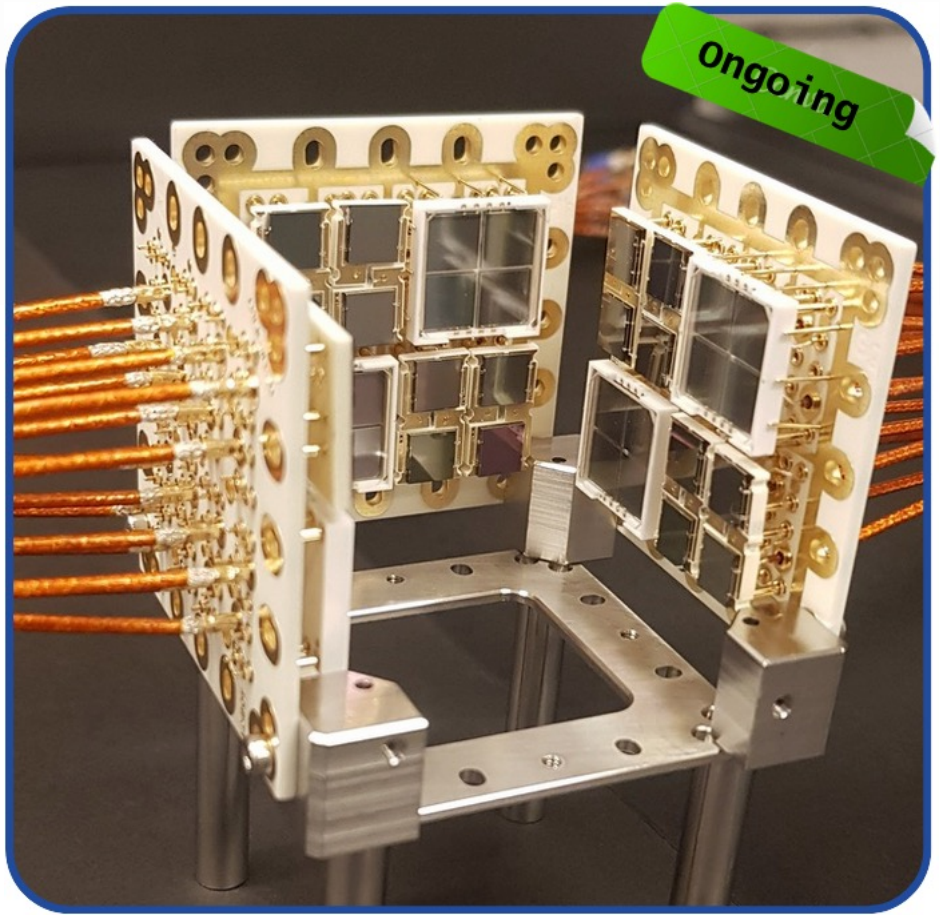


Light-only Liquid Xenon (LoLX) experiment at McGill

LoLX Phase 1



LoLX Phase 2



Objectives:

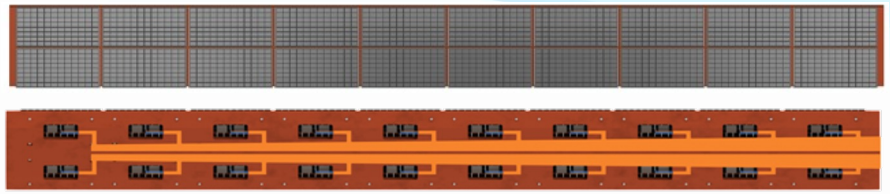
- Understand SiPM performance in LXe
- Study light emission from LXe (and other detector materials)
- Improve modelling of light transport (CHROMA GPU software)

Upcoming paper on external cross-talk

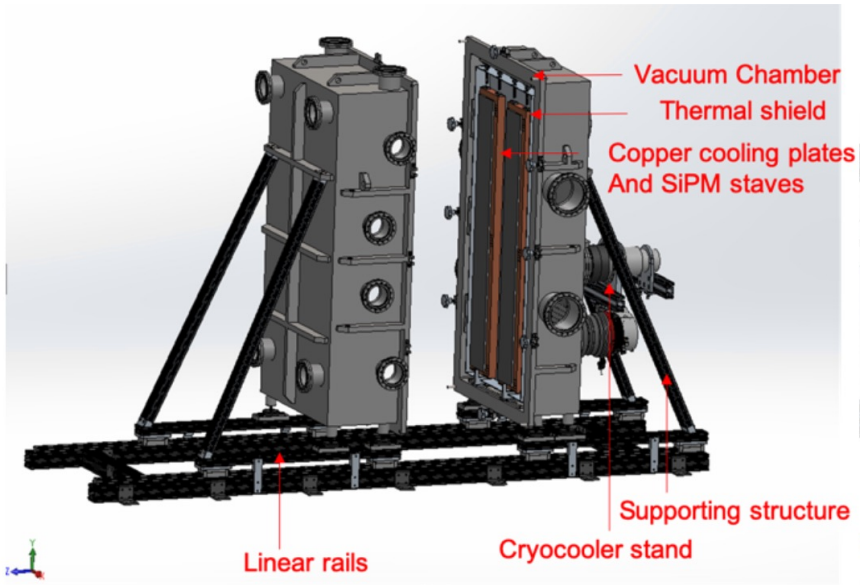
Collaboration between McGill, TRIUMF, Carleton, Sherbrooke, INFN Pisa

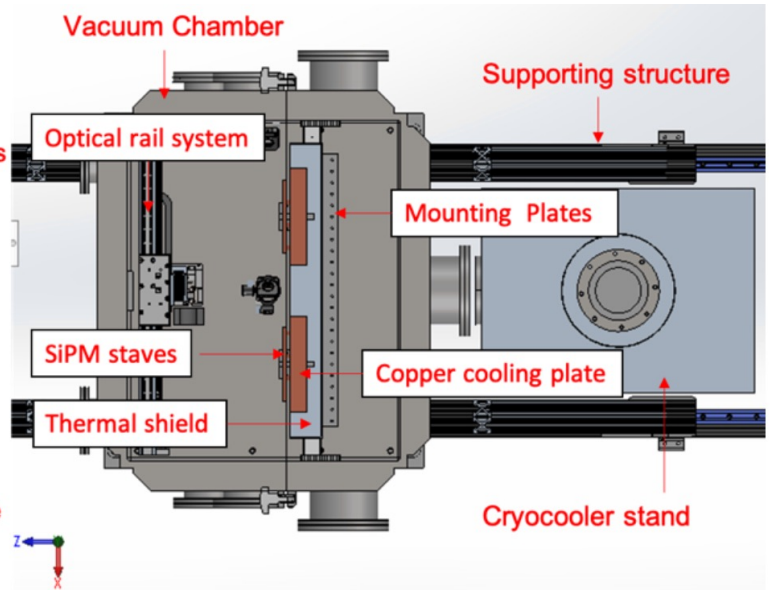
SiPM stave test stand at McGill

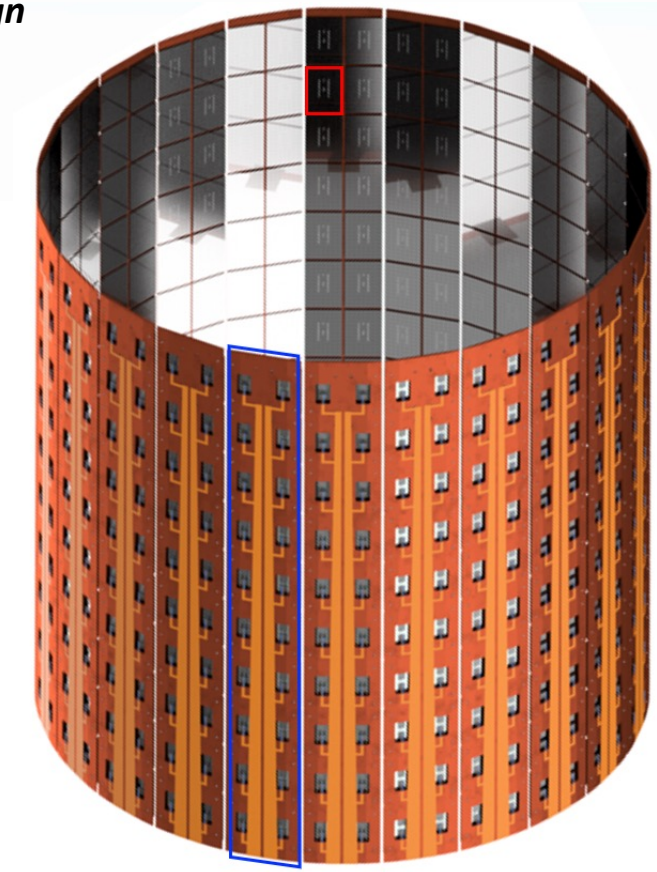
- System to characterize staves in nEXO operating conditions (CFI IF 2020)
  - Temperature of 168 K, vertical orientation
  - Test two full-size staves per vacuum cycle
- Custom x-y scanner to scan light across stave
- Possibility for multiple light sources



Preliminary stave design

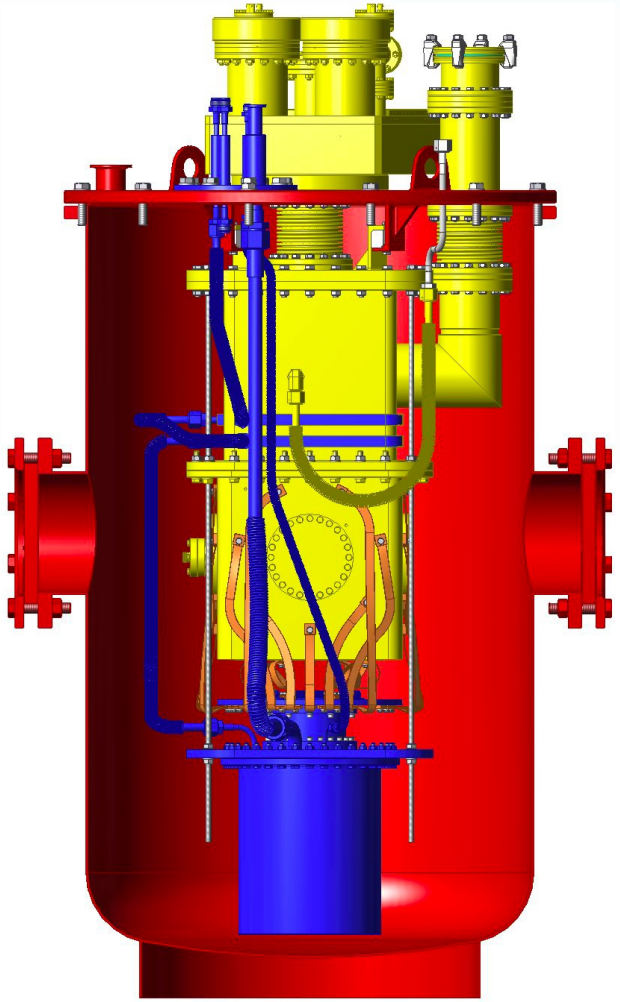






Preliminary barrel design

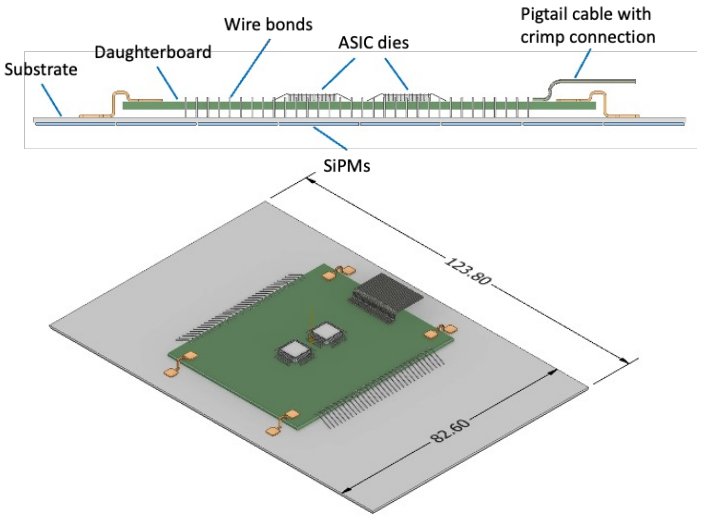
Test SiPM tiles in LXe at Carleton



EXO-100 cryostat recommissioned at Carleton

Yellow: Inner chamber for detector in LXe
Blue: Liquid nitrogen tank with exhaust lines
Red: Outer insulation vacuum vessel

- EXO-100 cryostat at Carleton
  - Current inner detector has been used for high-voltage tests and barium-tagging studies
- Planning SiPM tile testing with XeCube (CFI IF 2020, collaboration with TRIUMF):
  - Operation of SiPM tiles in LXe
  - Detection of surface alphas
  - Ensure functionality of tiles in nEXO's harshest possible environment with high voltage
    - High electric field with possible charge-up
    - High rate when calibrating with sources
- Test digital SiPMs when available

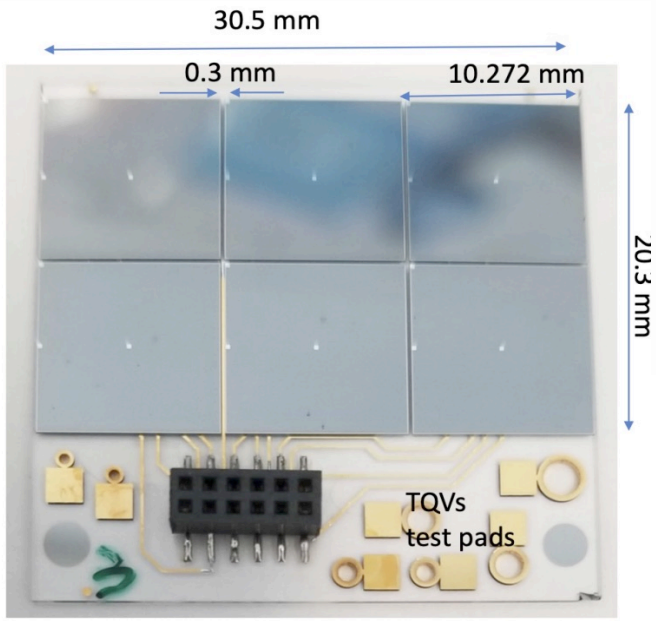


Preliminary tile design

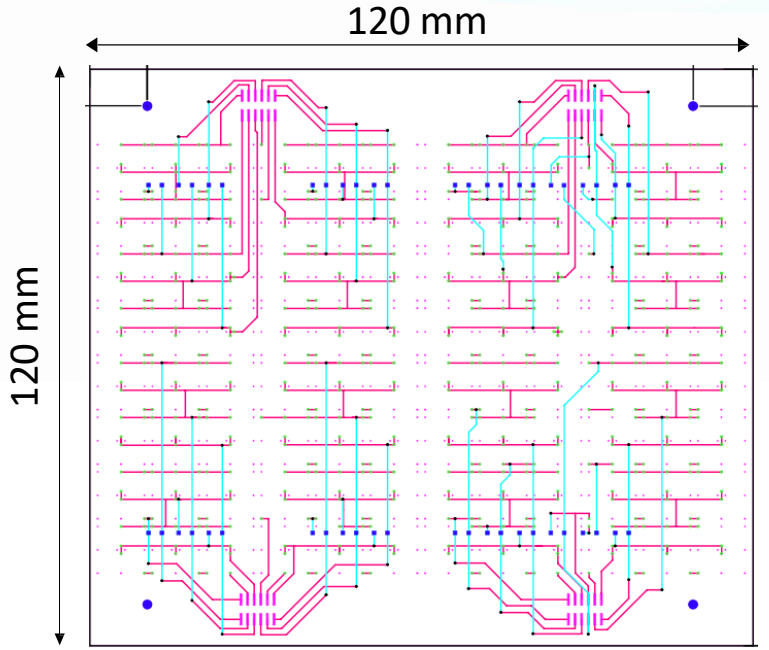
Silicon interposer development at Sherbrooke

- New interposer run funded by CFI IF 2020
- Single-wafer, 3-layer architecture:
  - NiAu pads on top
  - 2 top layers with Al enclosed in SiO_2 (M1 and M2)
  - 1 bottom layer in Cu (M0)
  - Cu TSVs

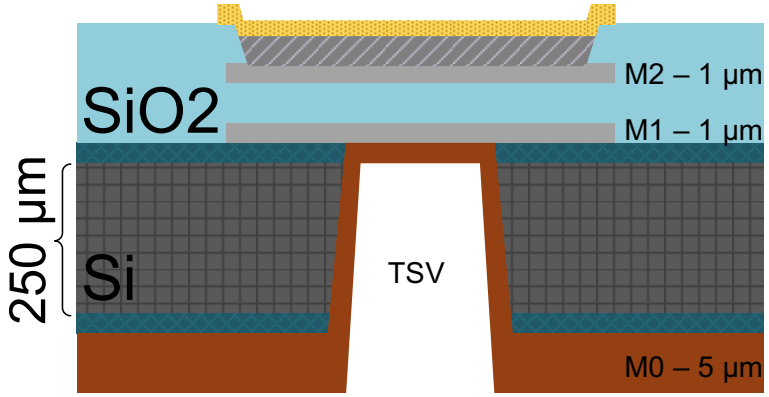
SiPM tiles on fused silica wafer



Layout for 96 SiPM tile (2023 version)



Design from Al Dellapena, Eric Raguzin



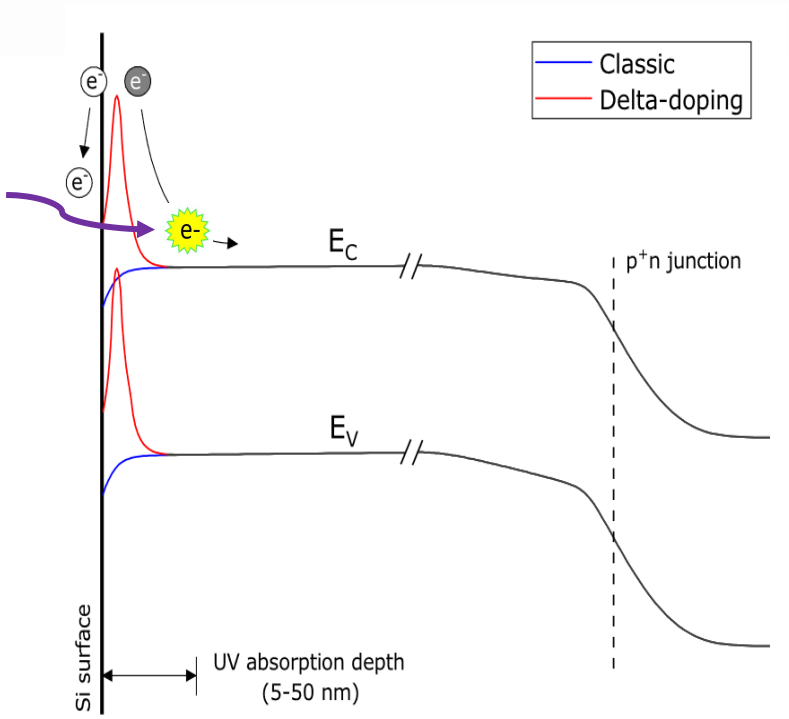
Translating BNL's fused silica into Si interposer

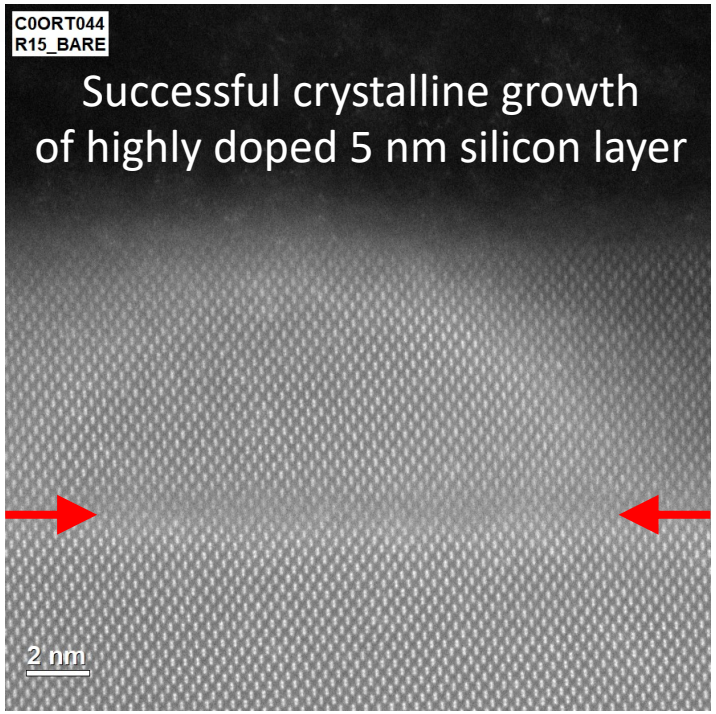
- Including minimal test structures
- Design kit is ready for fabrication by Fraunhofer IZM (like previous run)

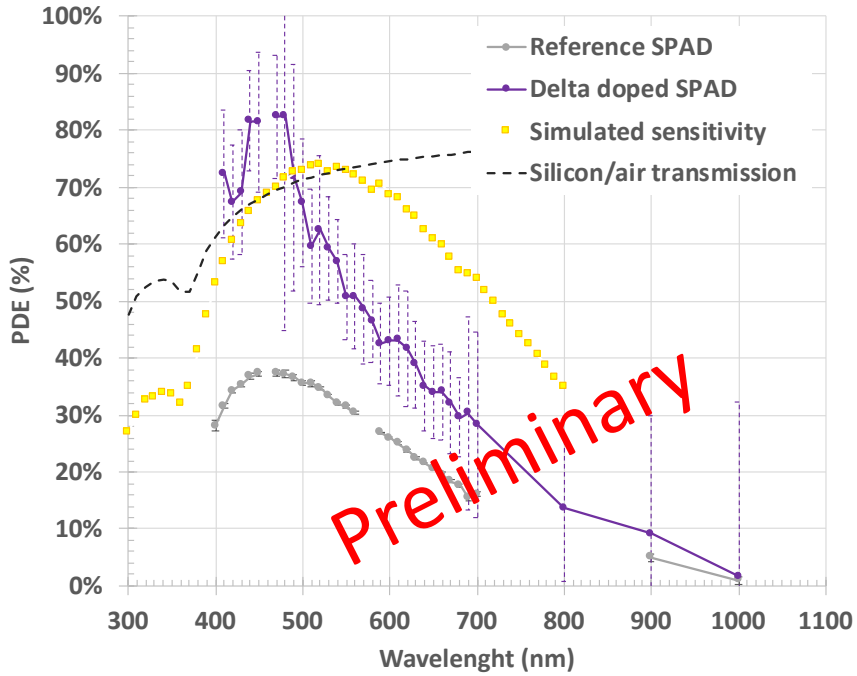
Ultraviolet sensitivity enhancement: delta doping

Vacuum ultraviolet (VUV) photons have very short absorption length in silicon

- Sharp peak of p type dopant (boron) “pushes” minority carriers toward depletion zone
- Low-temperature molecular beam epitaxy of doped silicon on SPAD devices at LBNL (with Sherbrooke)
- Preliminary results show increased sensitivity in the visible
- Tests at short wavelengths expected this fall







PMT test facility at Laurentian/SNOLAB

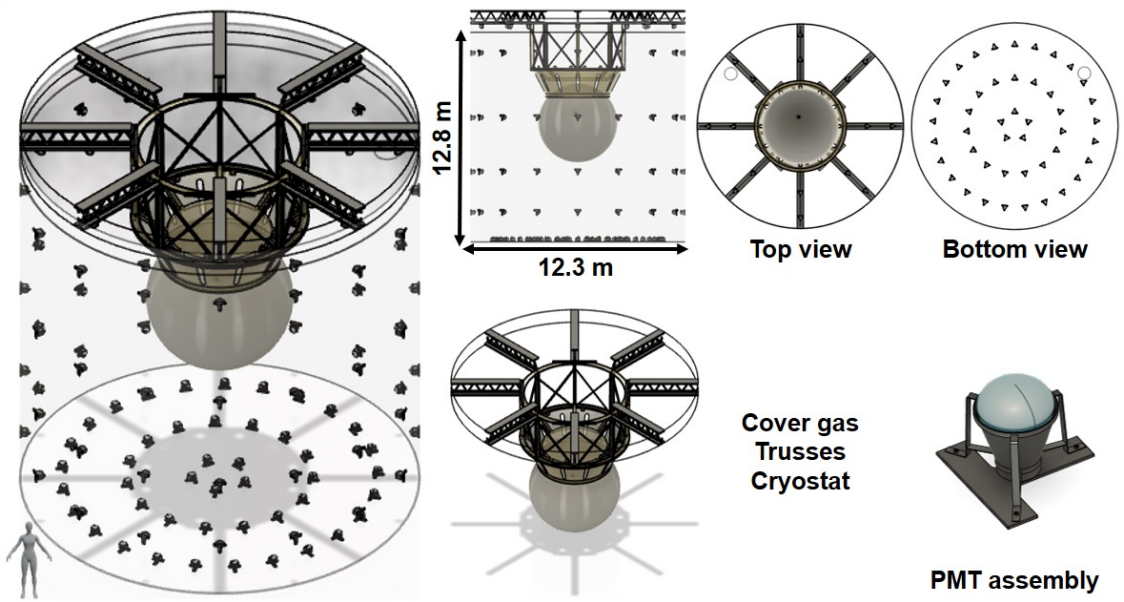
Objective: Test the 125 outer detector PMTs, originally from Daya Bay in the more stringent pressure conditions required for operation in nEXO (CFI IF 2020)

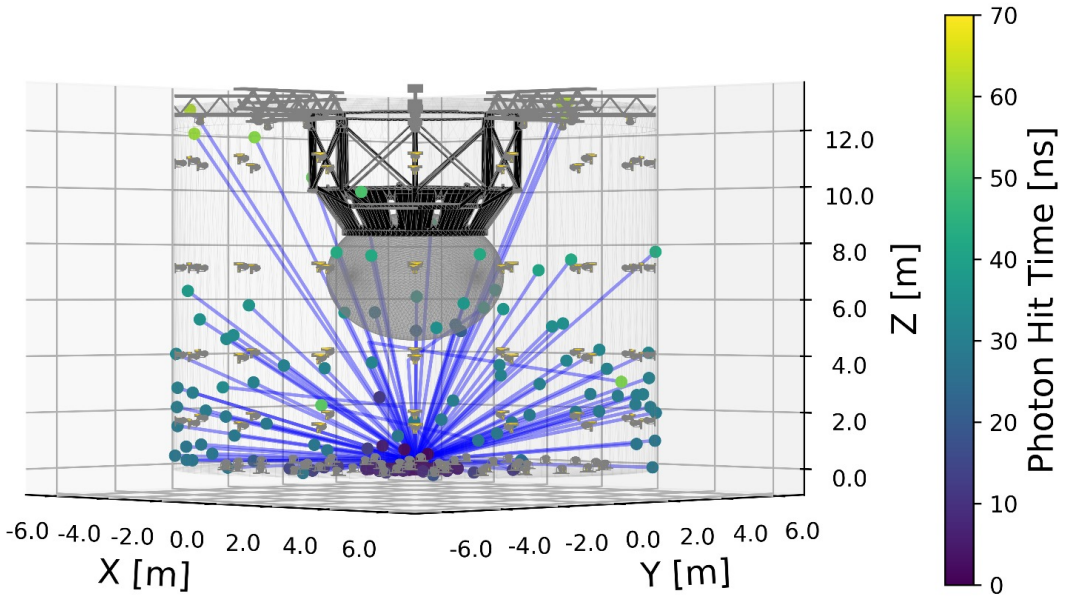
Chiller system for the PMT test facility prototype

Designing the light source for the PMT test facility prototype

Development of an automated radon assay system for nEXO outer detector (CFI IF 2025 proposal)

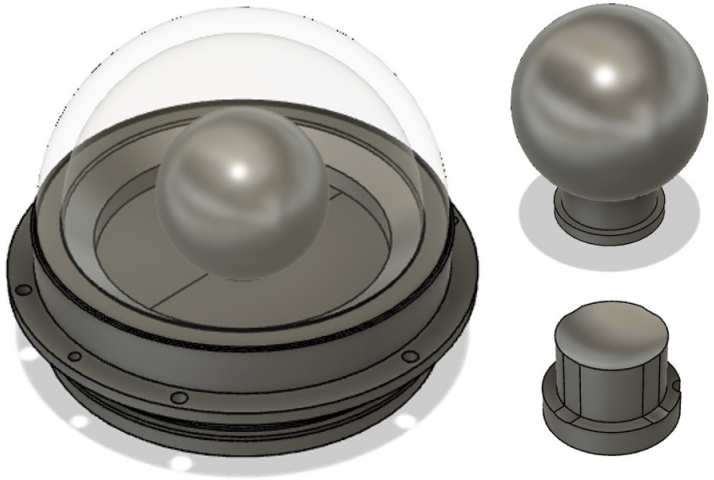
Outer detector calibration system design at McGill





Optimizing placement of the outer detector veto PMTs and calibration system, using simulations

Light from laser sources is transferred via optical fibers to diffuser balls located inside the water tank



Diffuser balls are composed of an optical Teflon plug and an optical Teflon sphere

New laboratory at Windsor

- Exploring deep-learning applications for EXO-200 data and nEXO simulated data
- Validation of charge induction in simulations
- Construction of the Radon Screening Facility (CFI IF 2020)

Conclusions

- nEXO is working toward securing approval
  - US DOE “Critical Decision 1” (CD-1) is the *critical* next step
    - Director’s Review at LLNL went very well in July 2024
    - Independent Project Review by the DOE is forthcoming
  - SNOLAB Gateway process in parallel (GW-1)
  - SNOLAB site allocation to nEXO requires GW-1, CD-1, and recommendation from the Experimental Advisory Committee
- Keep working to improve EDI
- nEXO-Canada research
  - SiPM characterization and testing, detector prototypes including LoLX
  - Silicon interposer, VUV sensitivity development
  - PMT test facility, radon screening facility, automated radon assay system
  - Simulation software, optical model, data analysis
- Getting ready to build nEXO at SNOLAB

Thank you!


Carleton University
SNOLAB
Queen's University
Université de Sherbrooke
McGill
University of Massachusetts Amherst
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Brookhaven National Laboratory
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Laurentian University / Université Laurentienne
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SLAC National Accelerator Laboratory
IMECAS
Stanford University
Universität Bern
Caltech
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama 1831
Oak Ridge National Laboratory
University of Kentucky
University of the Western Cape
UNCW University of North Carolina Wilmington
Drexel University
Subatech