Photomultiplicateurs au silicium pour nEXO

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pour la collaboration nEXO

Congrès de l'Association canadienne des physiciens et physiciennes

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Silicon Photomultipliers for nEXO

Simon Viel
(Carleton University)

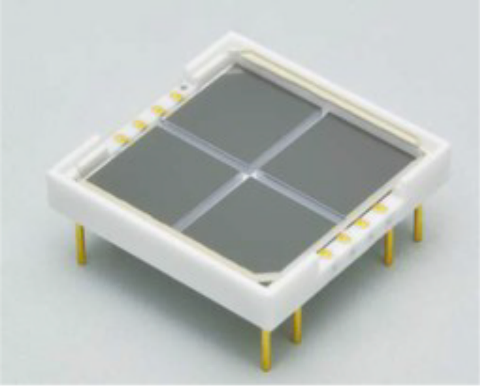
on behalf of the nEXO Collaboration

Canadian Association of Physicists Congress

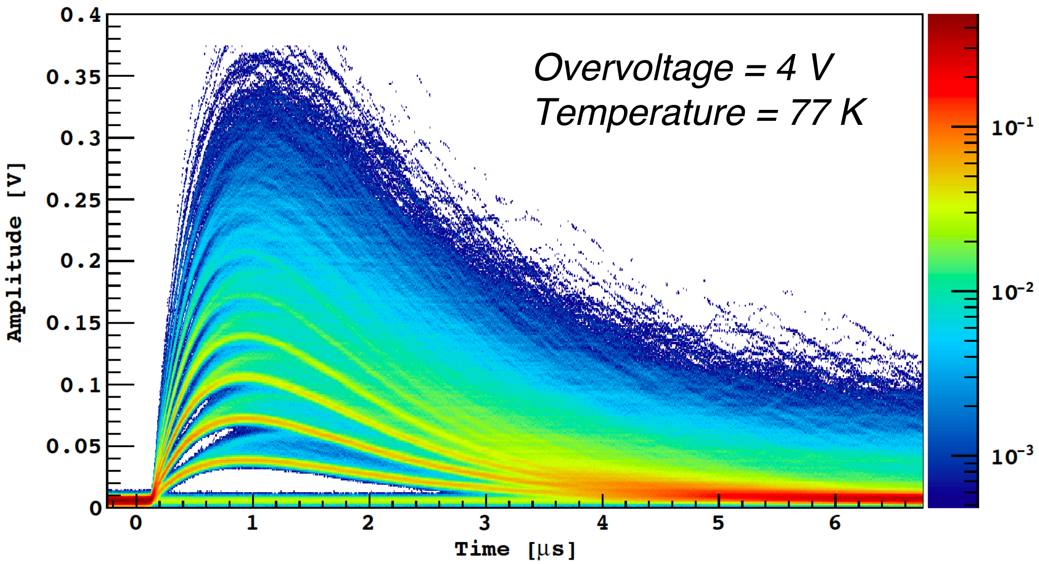
June 9th, 2020

Silicon photomultipliers (SiPM)

- 2D array of single-photon avalanche diodes (SPADs)
  - Operated in Geiger mode
    i.e. reverse bias > breakdown voltage
- Diodes typically connected in parallel: each array is read out as one channel
  - Signal proportional to number of photons detected
- Many advantages:
  - Low mass → Low radioactivity
  - Operating voltage around 50 V
  - Resistant to electromagnetic fields
  - Operation at noble liquid temperatures!

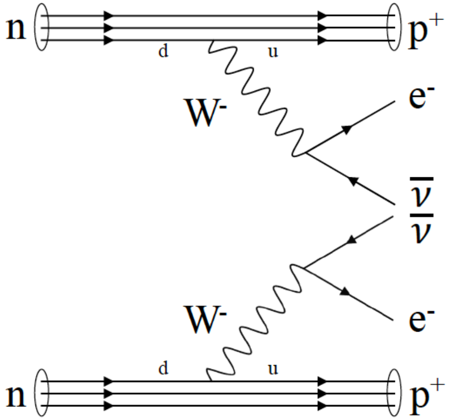


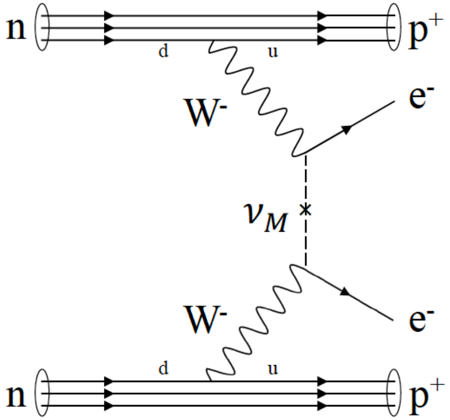
Hamamatsu VUV4 2x2 MPPC array

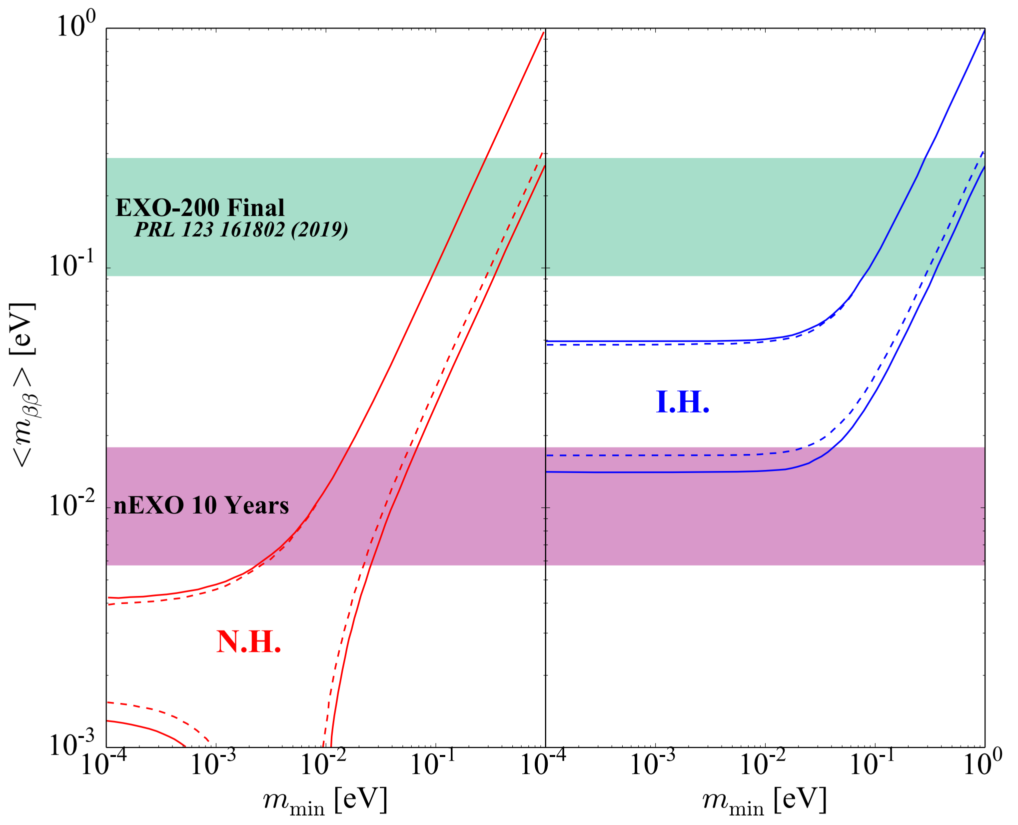


Example persistence plot from FBK NUV-HD-LF-HRq SiPM

Search for 0νββ in ^{136}Xe

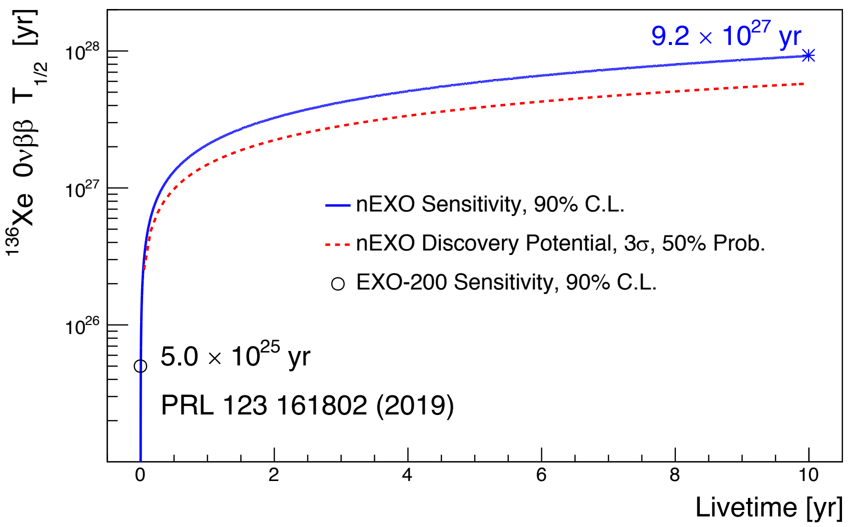






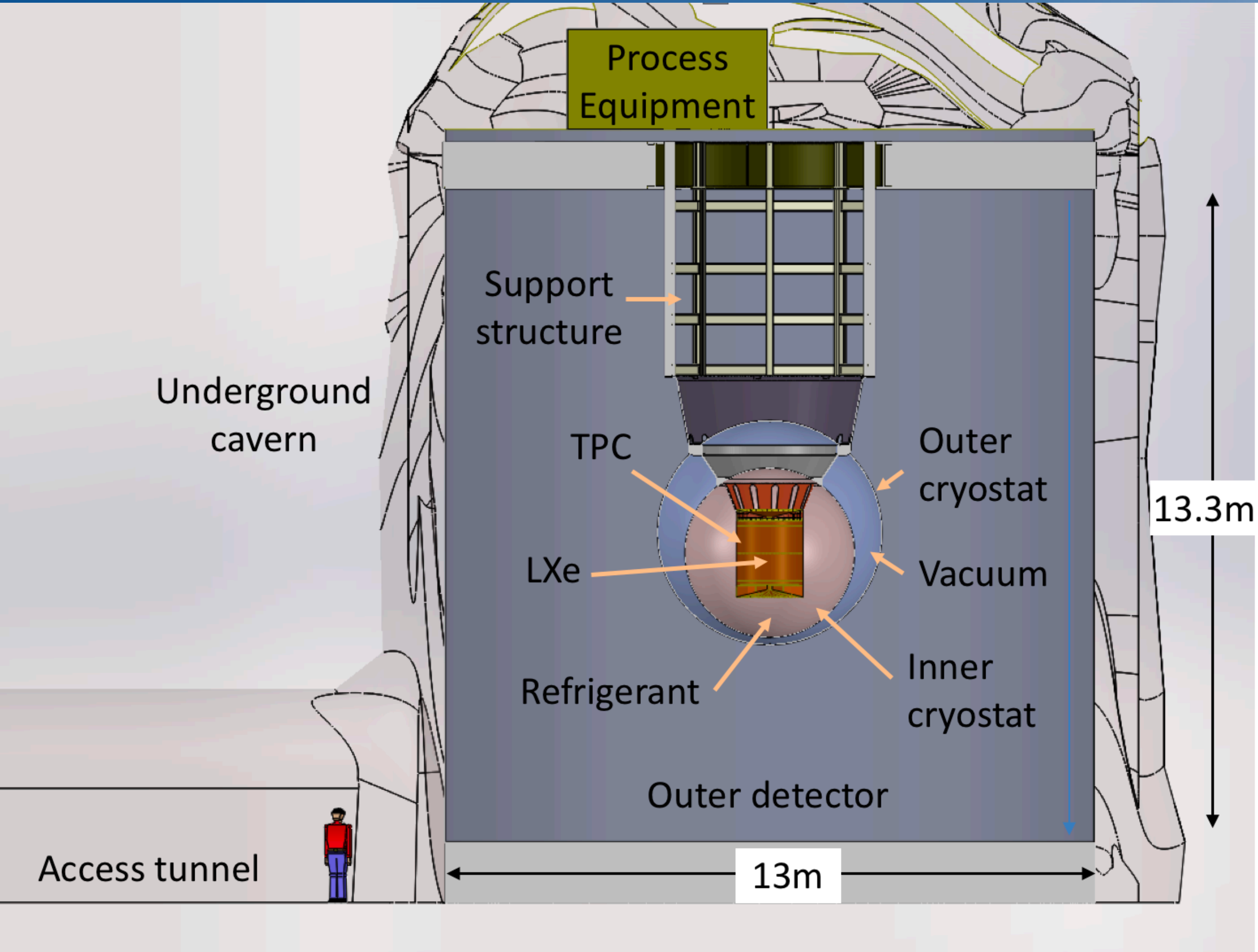
Main goal of nEXO: Sensitivity to **neutrinoless** double beta decay

Are neutrinos their own antiparticles?



nEXO Pre-Conceptual Design Report, arXiv:1805.11142

nEXO proposal at SNOLAB



- **5 tonnes 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, and is the nEXO collaboration's preferred site

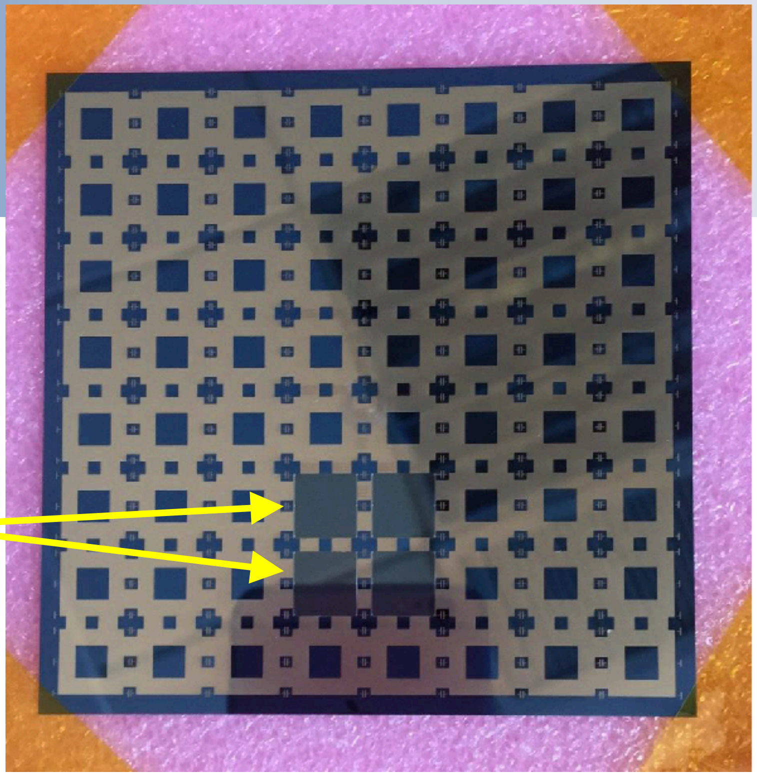
nEXO Pre-Conceptual Design Report, arXiv:1805.11142

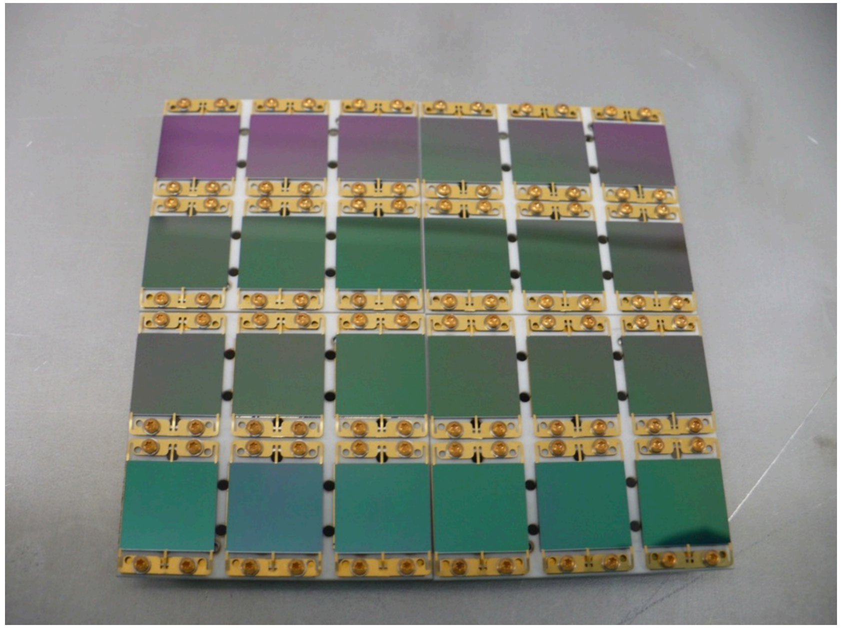
Photon detection in nEXO

- SiPMs in barrel configuration
  - Need at least 4 m^2 of detection area: plan to build 5 m^2
- Modular design:
  - SiPMs are mounted on **Tiles**
  - Tiles are mounted on Staves
  - Staves form the full Barrel

Silicon Tile Interposer with 8 x 8 SiPMs (IME)

10 mm x 10 mm SiPMs





Prototype VUV SiPM array (FBK)

LXe-compatible ASIC electronics

Photon detection in nEXO

- SiPMs in barrel configuration
  - Need at least 4 m^2 of detection area: plan to build 5 m^2
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  - SiPMs are mounted on Tiles
  - Tiles are mounted on **Staves**
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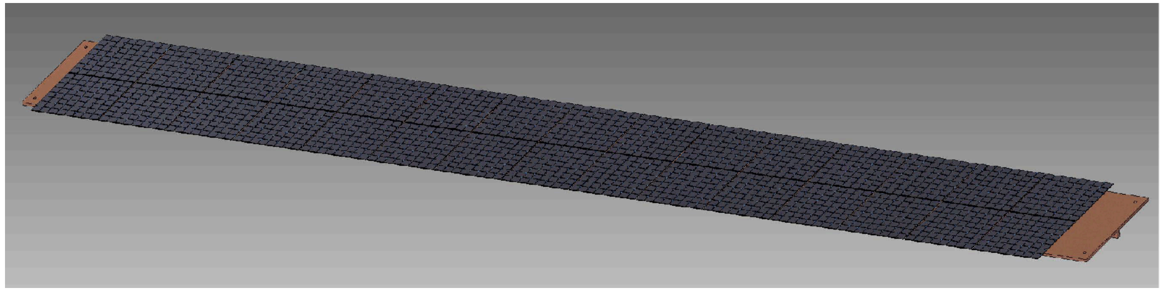
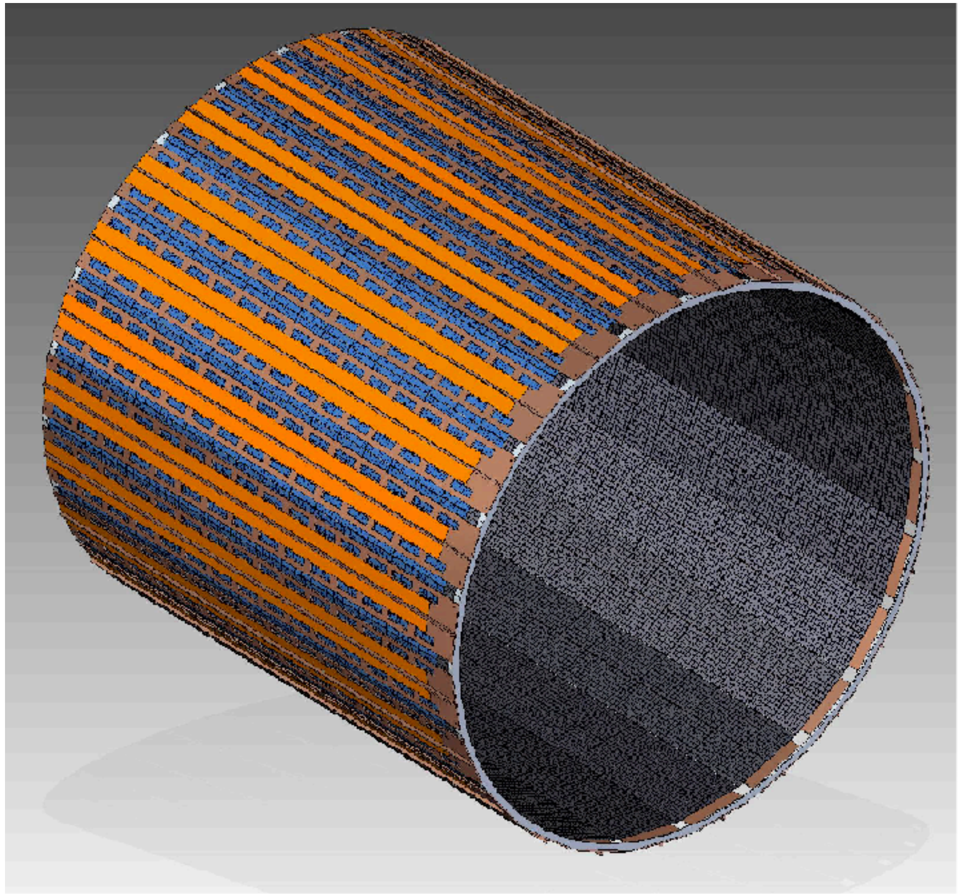


Very preliminary: Stave design with 15 x 2 Tiles

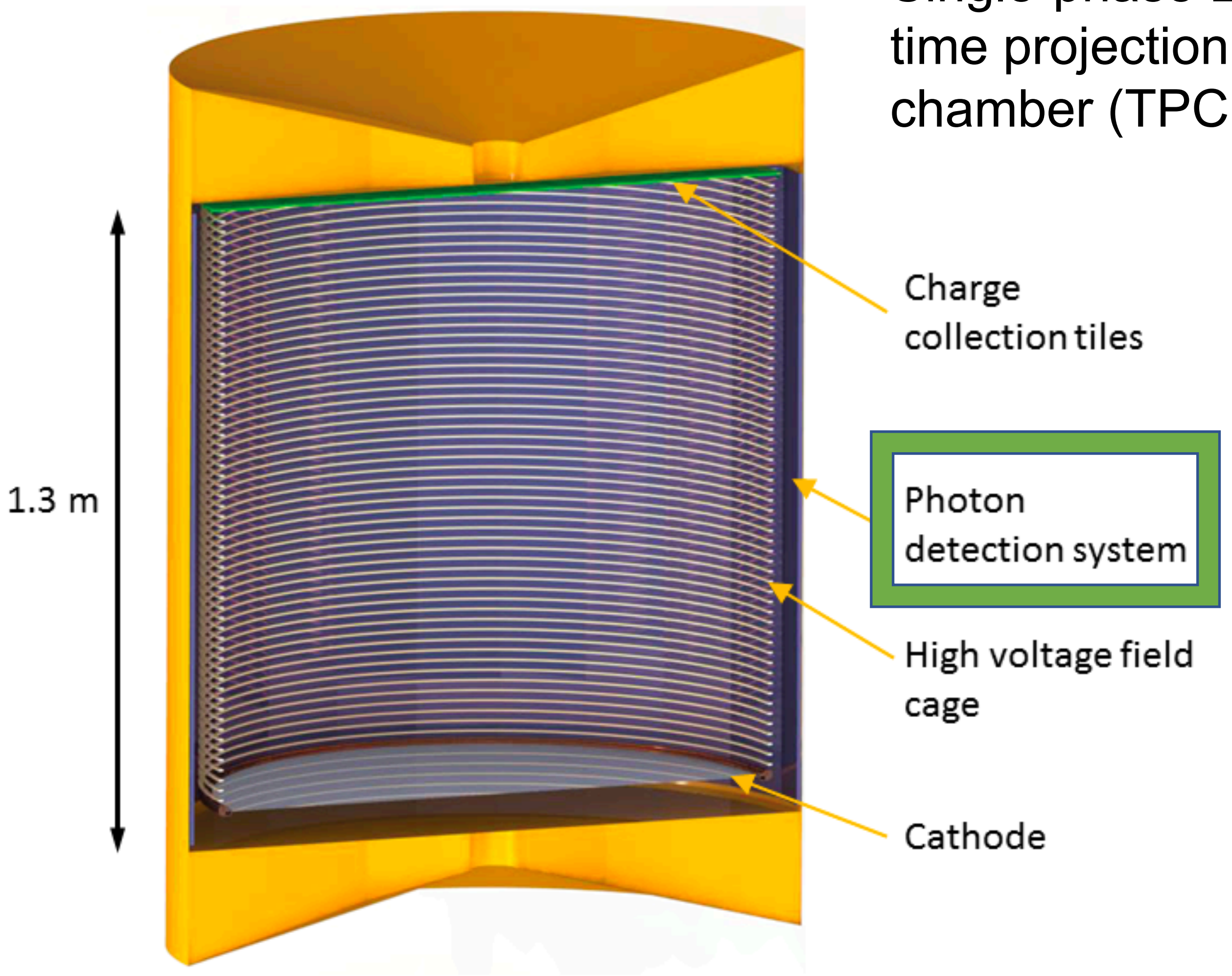


Preliminary: Barrel design with 24 Staves

Photon detection in nEXO

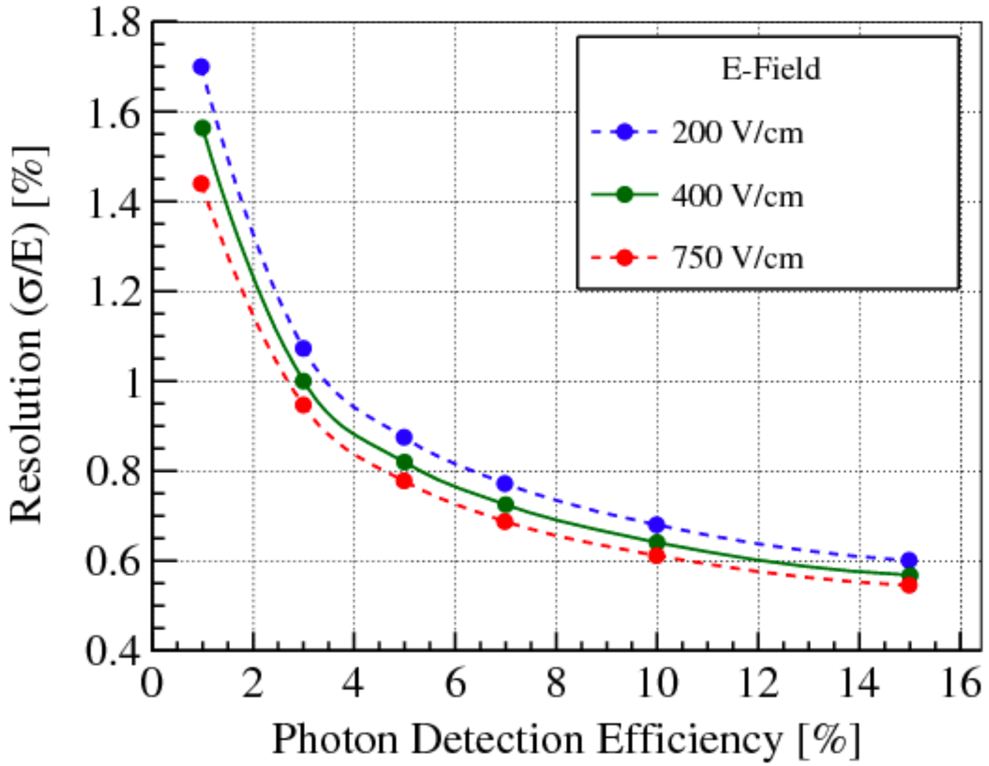
- SiPMs in barrel configuration
  - Need at least 4 m^2 of detection area: plan to build 5 m^2
- Modular design:
  - SiPMs are mounted on Tiles
  - Tiles are mounted on Staves
  - Staves form the full **Barrel**
- Energy resolution in nEXO relies on the **combination** of **charge and light collection**

Single-phase LXe time projection chamber (TPC)



Photon detection in nEXO

- Energy resolution in nEXO expected to be dominated by light detection
  - To achieve 1% energy resolution overall, need **3% total efficiency** for detecting scintillation photons
    - Assuming 20% geometrical acceptance, implies **15% photodetector efficiency at the LXe scintillation wavelength (175 nm)**
    - Without wavelength-shifter
    - With negligible noise
- Evaluating vacuum ultraviolet (VUV) sensitive SiPM candidate technologies



Expected energy resolution of nEXO vs. overall photon detection efficiency, for different drift electric fields

Photon detection requirements

Parameter	Value
Total instrumented area	$\simeq 4.5\ \mathrm{m}^2$
Overall light detection efficiency	$\epsilon_o > 3\ \%$
SiPM PDE (175 nm, normal incidence)	$\epsilon_{PD} > 15\ \%$
Overvoltage	> 3 V
Dark noise rate	$< 50\ \mathrm{Hz/mm}^2$
Correlated avalanche rate	< 0.2

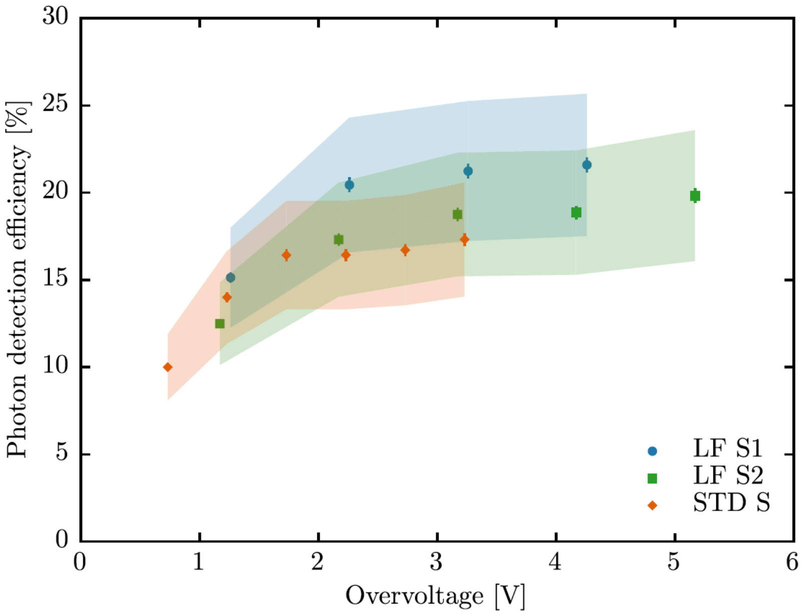
- Photon transport simulations show that the **SiPM photodetection efficiency needs to be > 15%**
    - Caveats: Simulations need tuning, assume SiPM reflect >50% of the photons, and assume that electrodes are reflective
    - ➢ **Measurements are needed to constrain simulations**
- Electronics noise negligible as long as there is enough gain (overvoltage > 3 V)
- Correlated avalanche rate < 0.2 to have negligible effect on resolution
- Dark noise rate requirement comes from trigger threshold, and easily satisfied

SiPM measurements towards nEXO

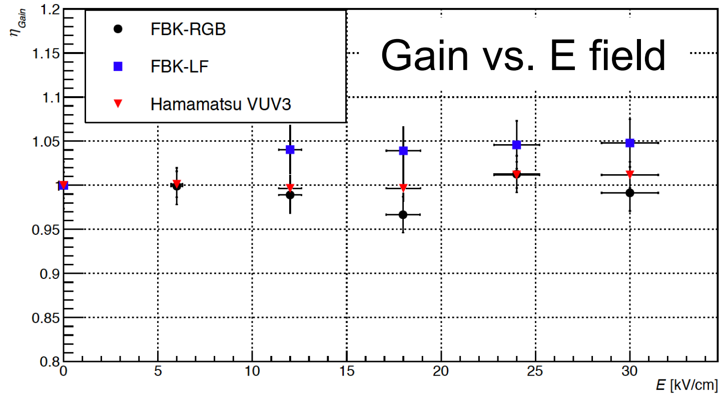
with emphasis on Canadian contributions

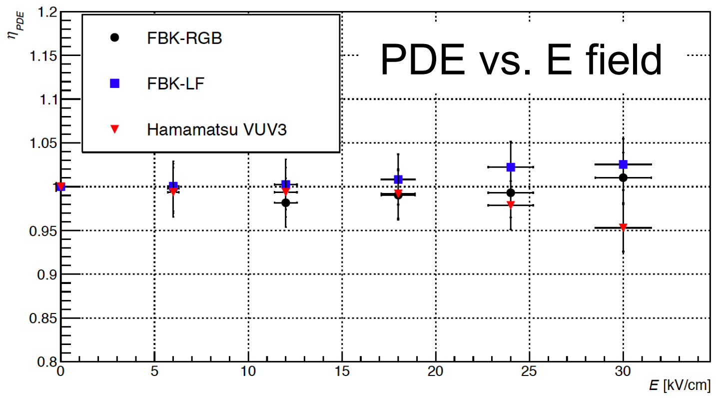
SiPM characterization

- Measurements of photon detection efficiency, reflectivity, stability in external electric fields

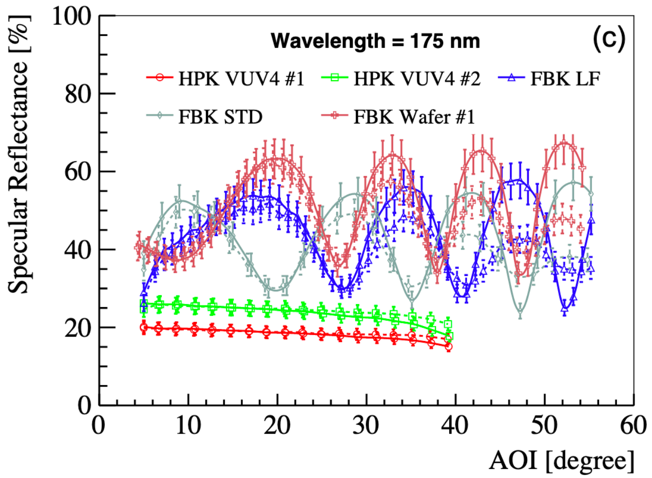


“VUV-sensitive silicon photomultipliers for xenon scintillation light detection in nEXO”, *IEEE Transactions on Nuclear Science* (2018) 65, 11, 2823

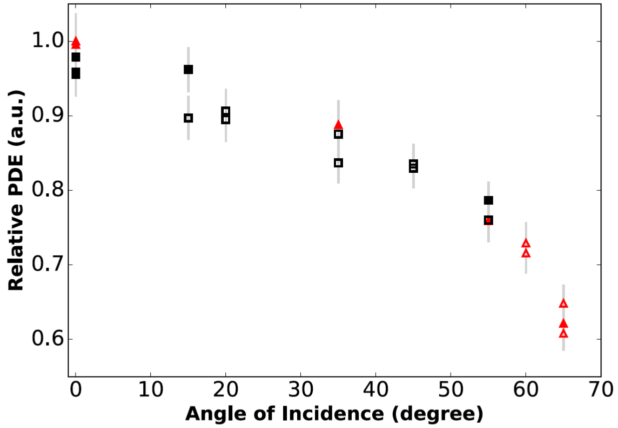




“Study of silicon photomultiplier performance in external electric fields”, *JINST* (2018) 13, 09, T09006



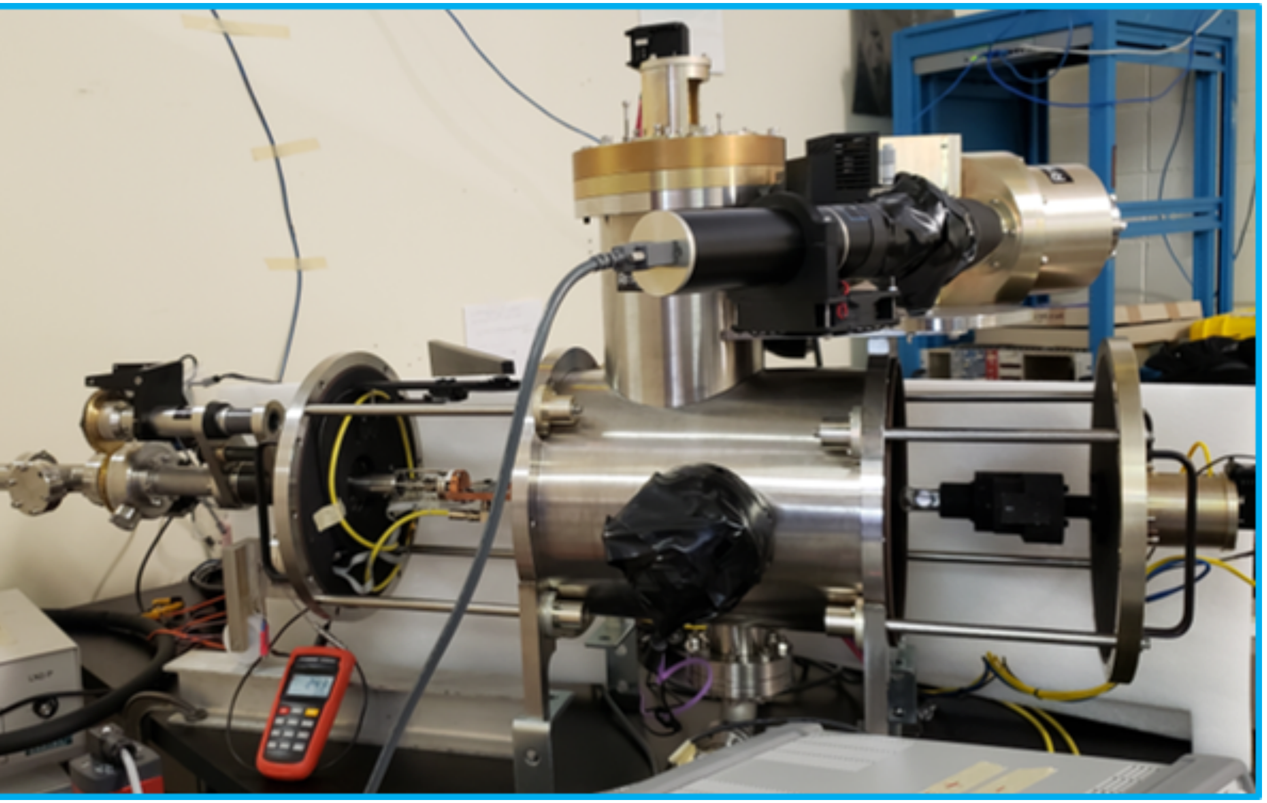
“Reflectance of silicon photomultipliers at vacuum ultraviolet wavelengths”, arXiv:1912.01841

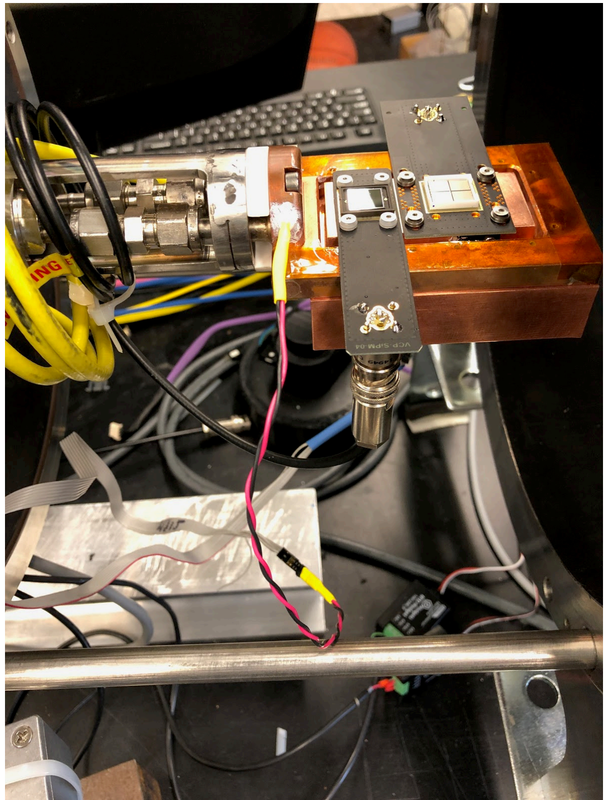


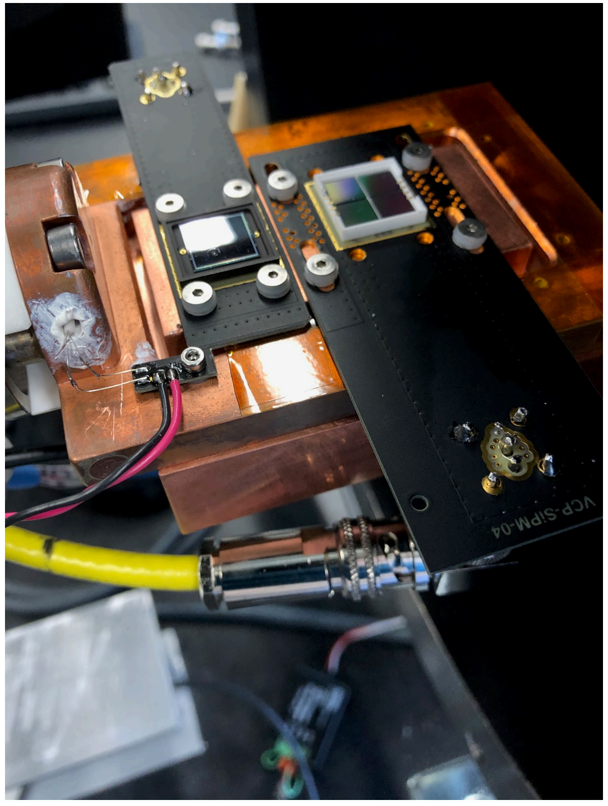
“Reflectivity and PDE of VUV4 Hamamatsu SiPMs in liquid xenon”, *JINST* (2020) 15, 01, P01019

SiPM characterization

- Vacuum ultra-violet efficiency, reflectivity and absorption (VERA) test setup at TRIUMF
  - Measuring reflectivity and efficiency at the same time
  - New improvements to temperature control → stability better than 0.1 K

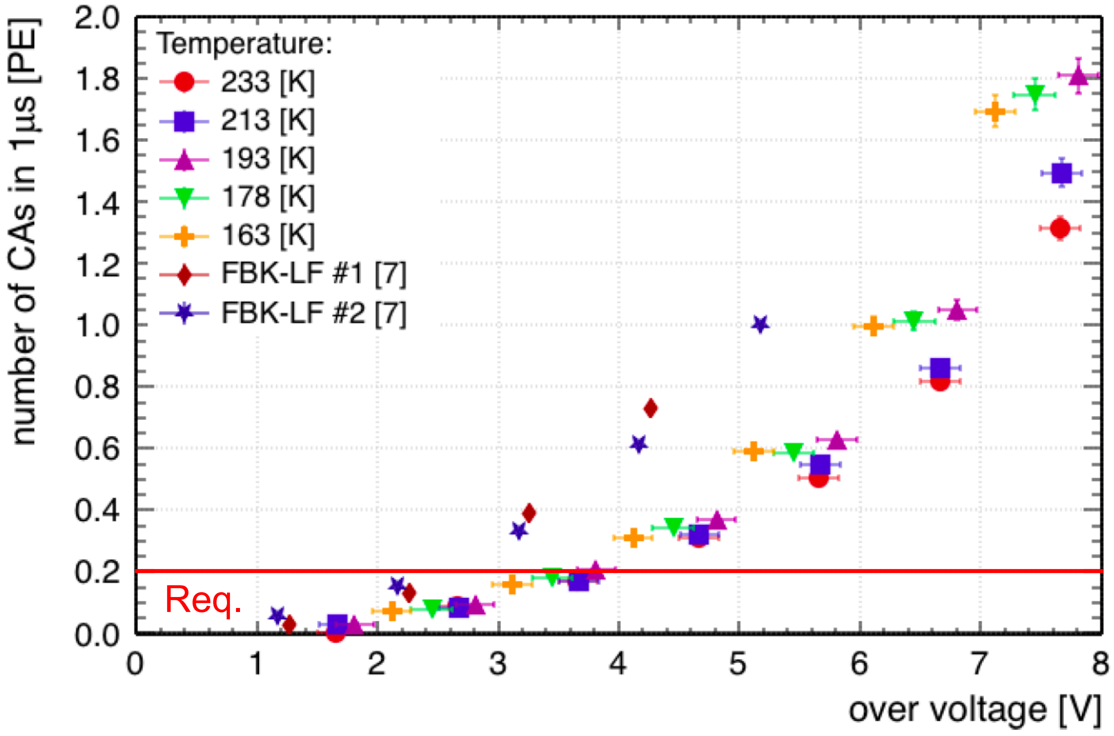


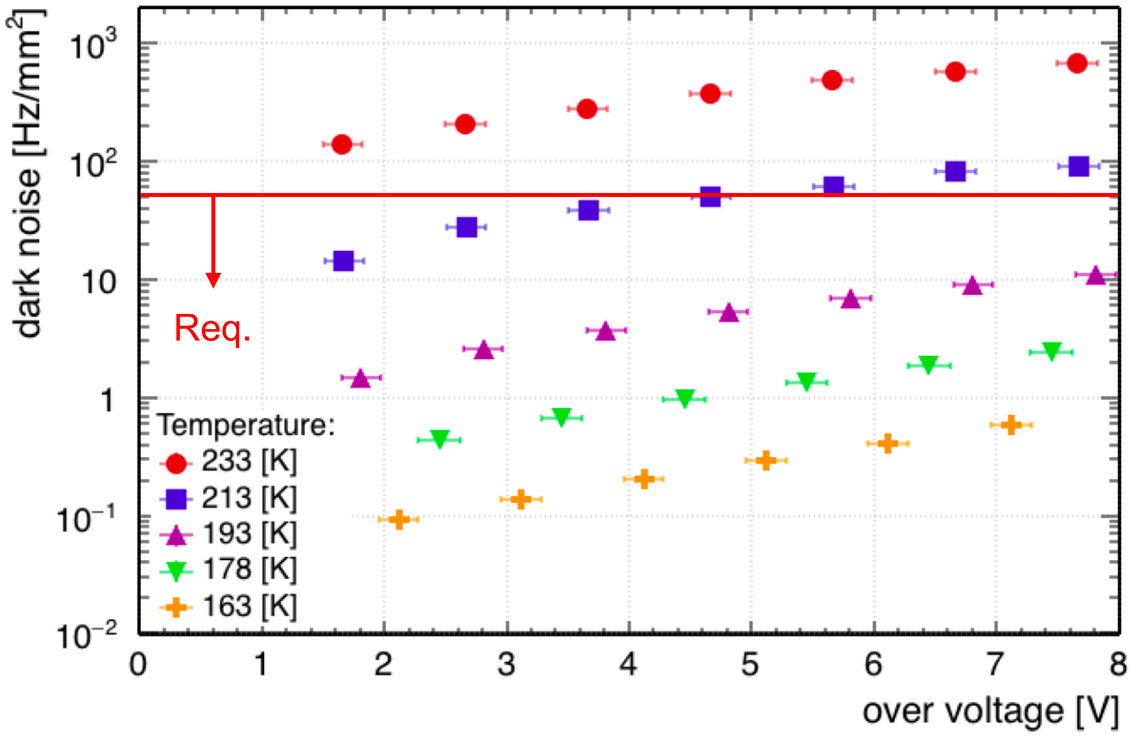




SiPM characterization

- Measurements at TRIUMF generally show satisfactory performance from FBK and Hamamatsu devices at LXe temperature (165 K)
  - Correlated avalanches: Hamamatsu device can be operated at higher overvoltage compared to FBK
  - Dark noise rate requirement easily satisfied

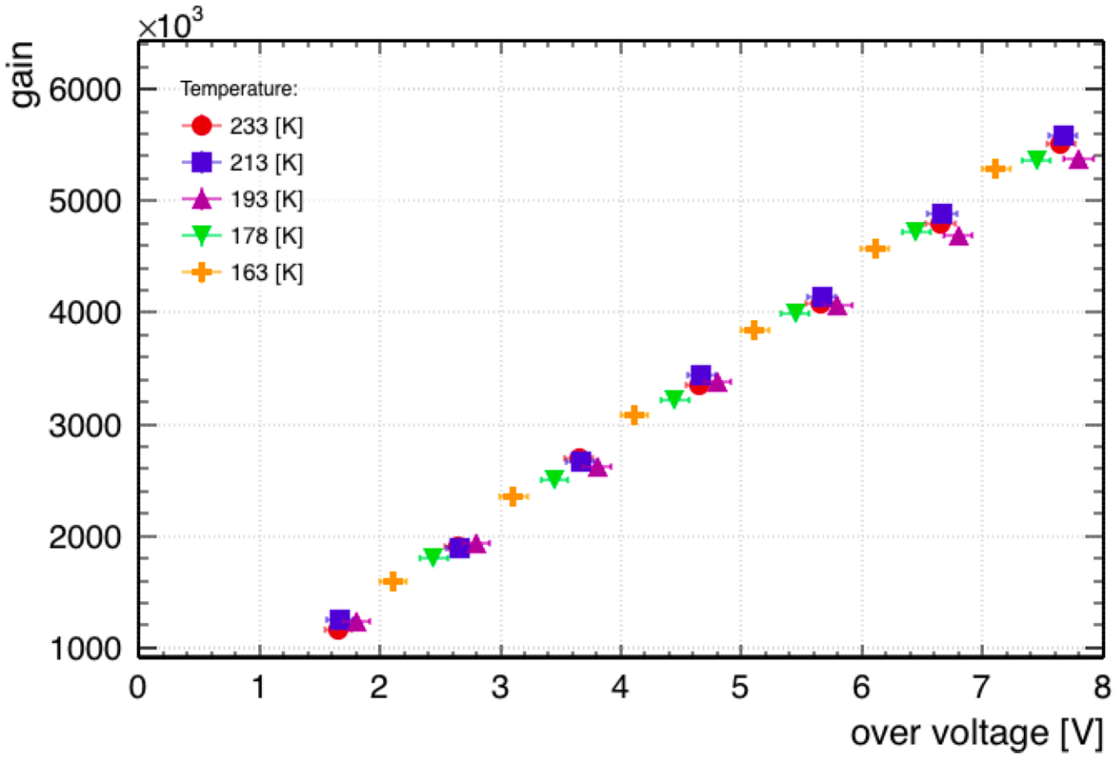


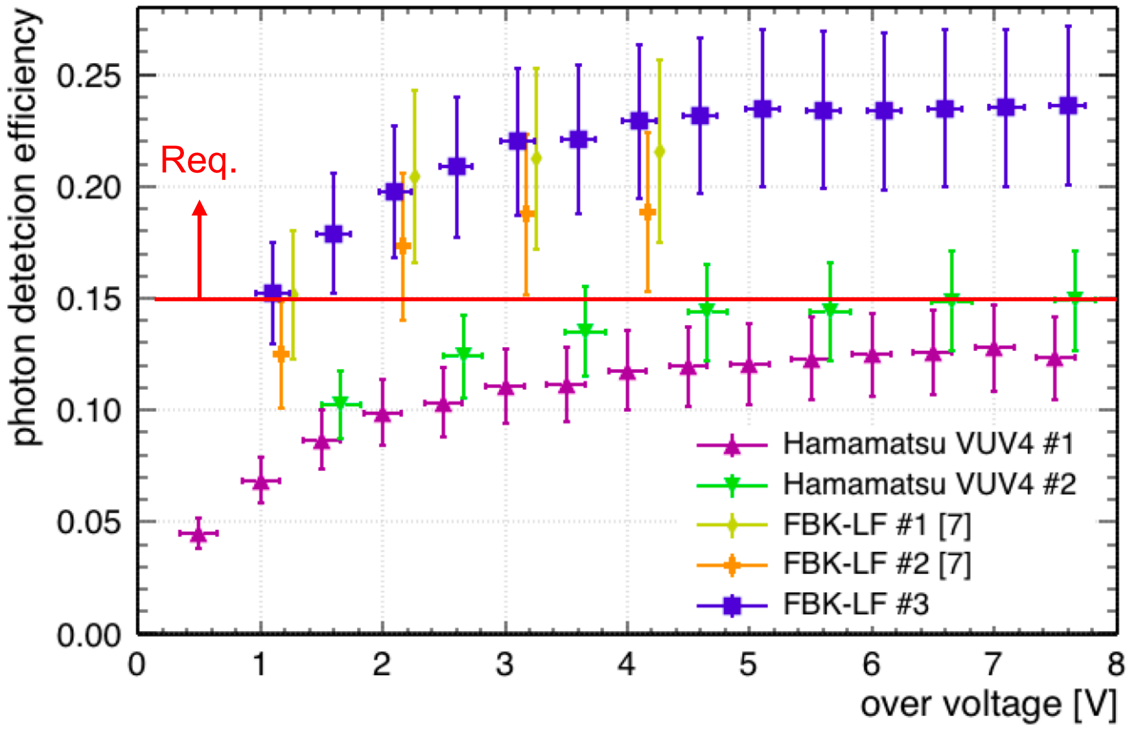


"Characterization of the Hamamatsu VUV4 MPPCs for nEXO", *NIM A* (2019) C940, 6

SiPM characterization

- Measurements at TRIUMF generally show satisfactory performance from FBK and Hamamatsu devices at LXe temperature (165 K)
  - Photon detection efficiency: FBK meets specification, Hamamatsu comes close

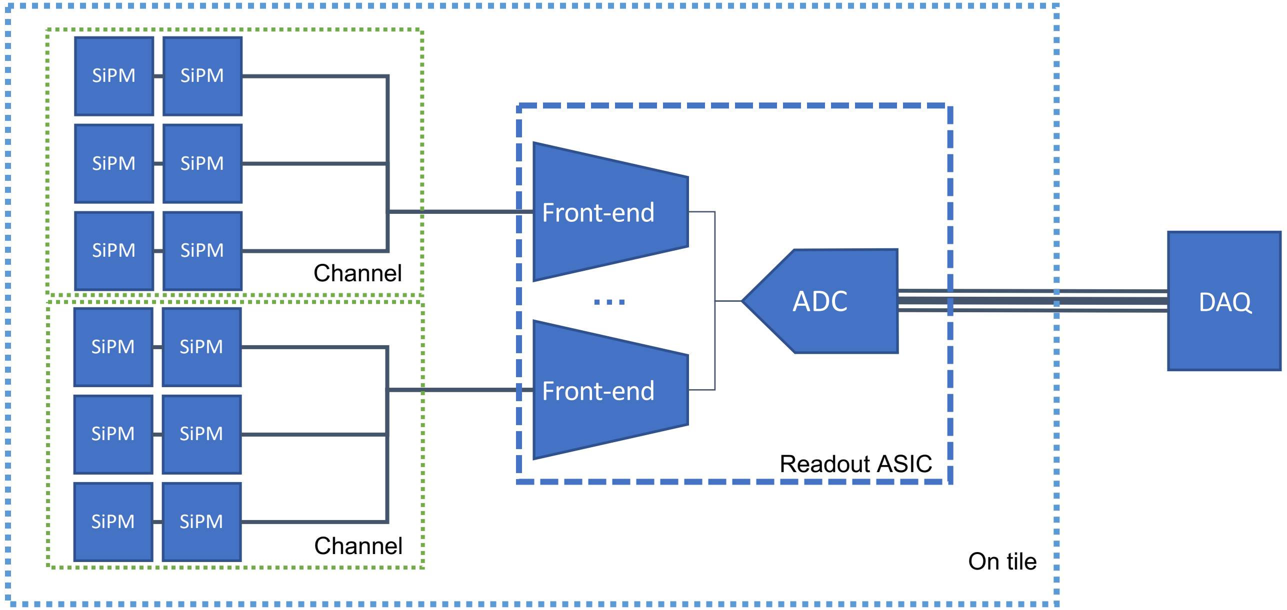




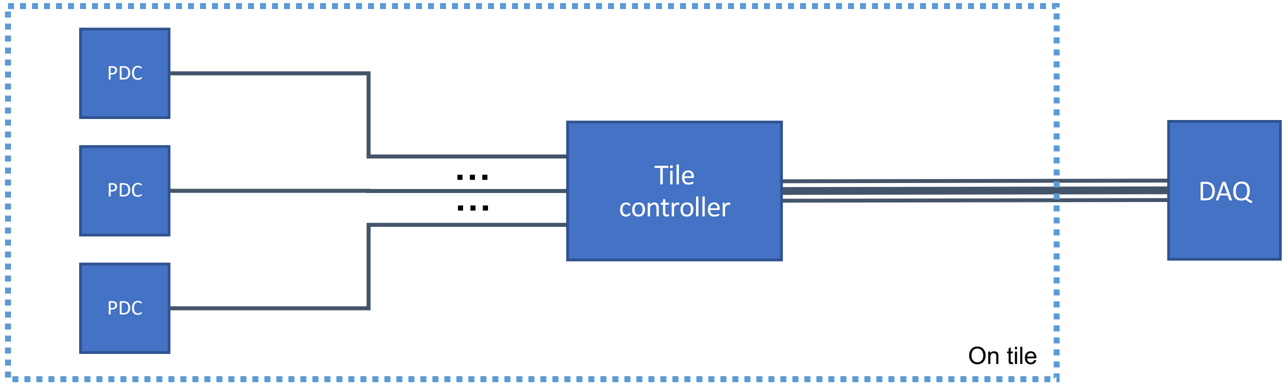
"Characterization of the Hamamatsu VUV4 MPPCs for nEXO", *NIM A* (2019) C940, 6

Photodetector system options

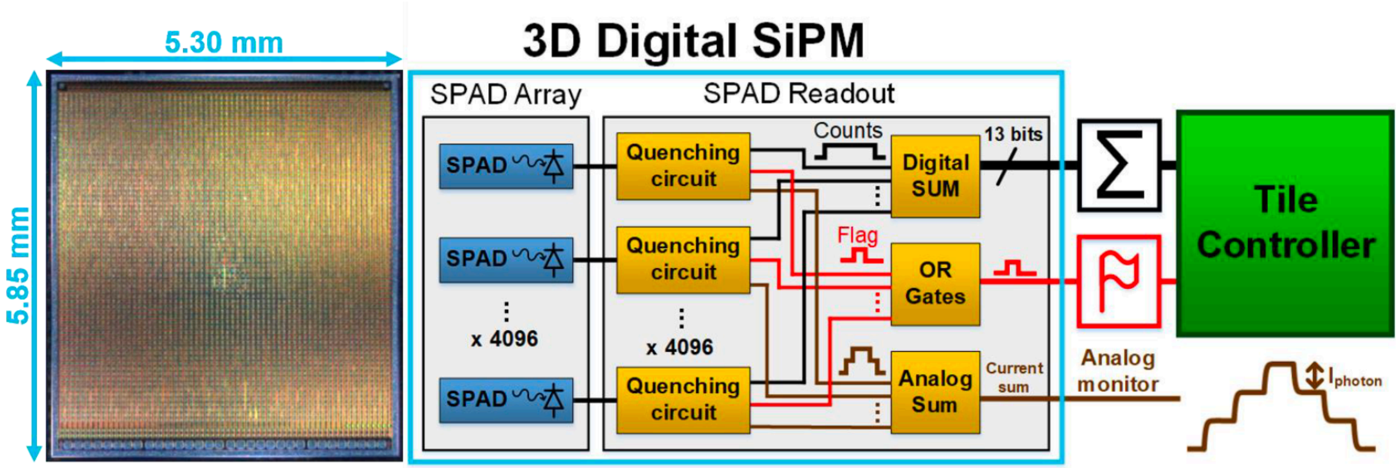
Analog SiPM tiles,
with front-end circuits and ADC
on readout ASIC



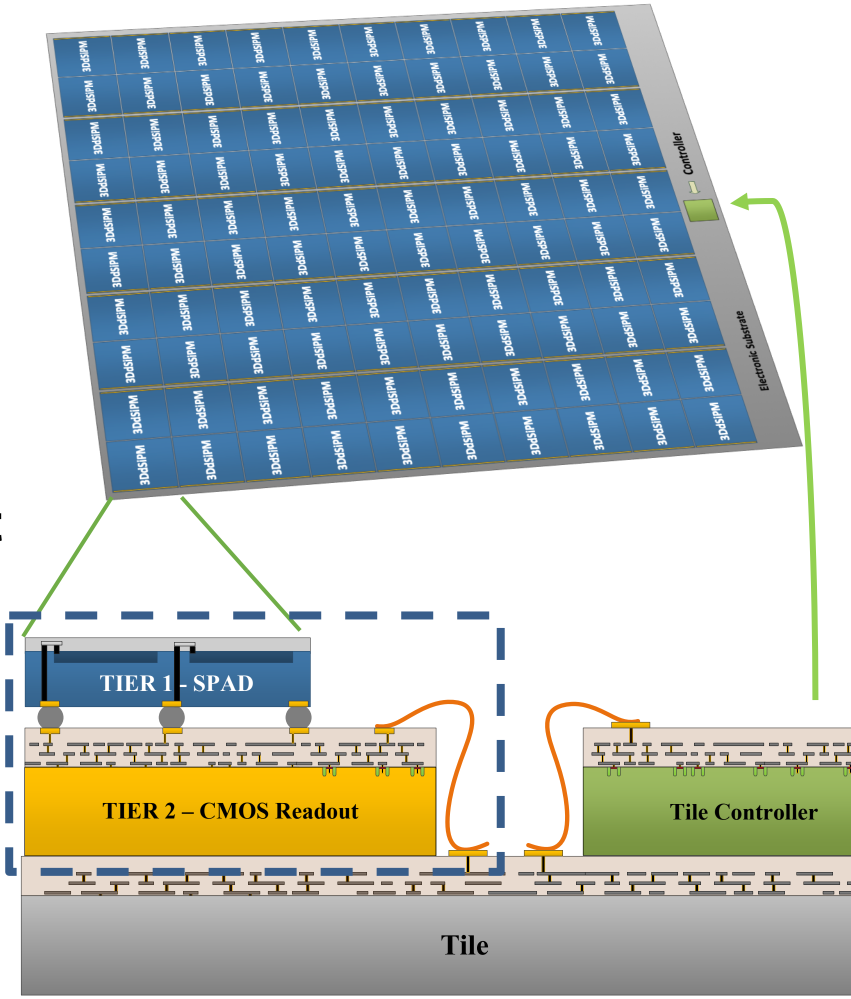
Photon to **Digital** Converter (PDC)
arrays with tile controller ASIC



Photon to Digital Converters



Photon to digital converter tile concept

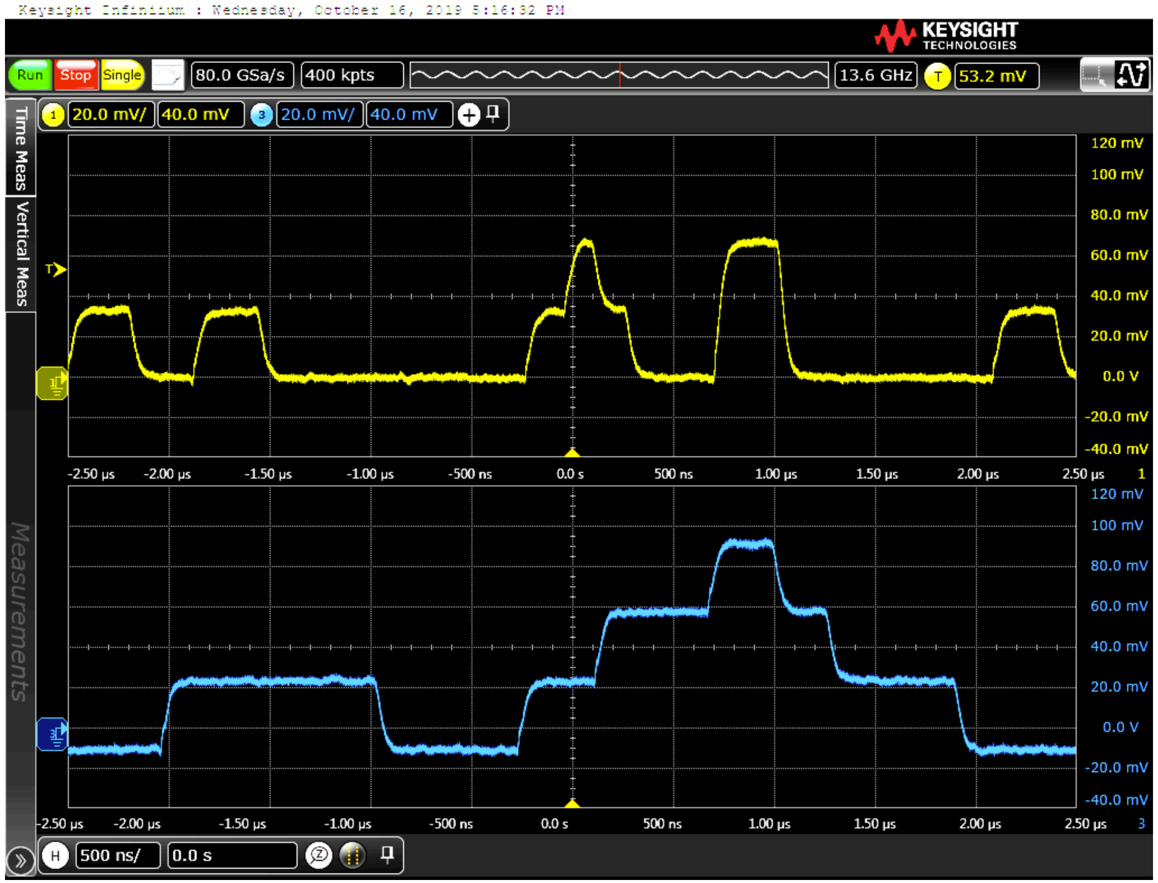


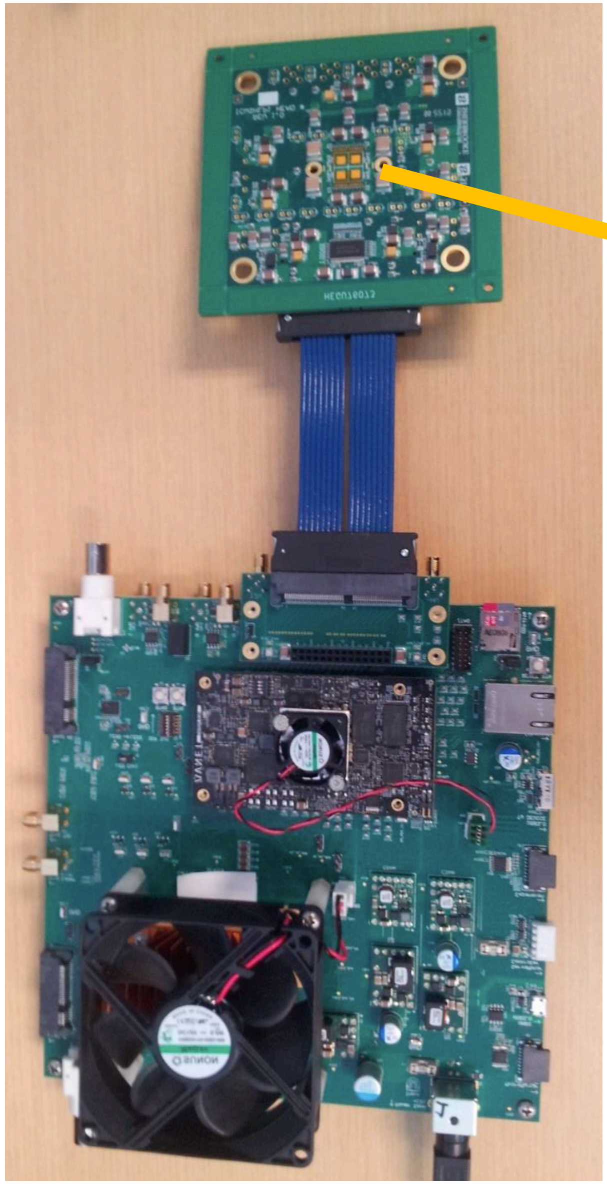
- Prototype PDC achieved at U. de Sherbrooke:
  - Analog front-end circuit replaced by **digital quenching readout**
    - Digitize signals from each photodiode in situ
    - Reduced power dissipation
    - Noise reduction owing to enhanced capabilities and flexibility of *configurable digital readout electronics*
- **3D integration**, maximizing sensitive area

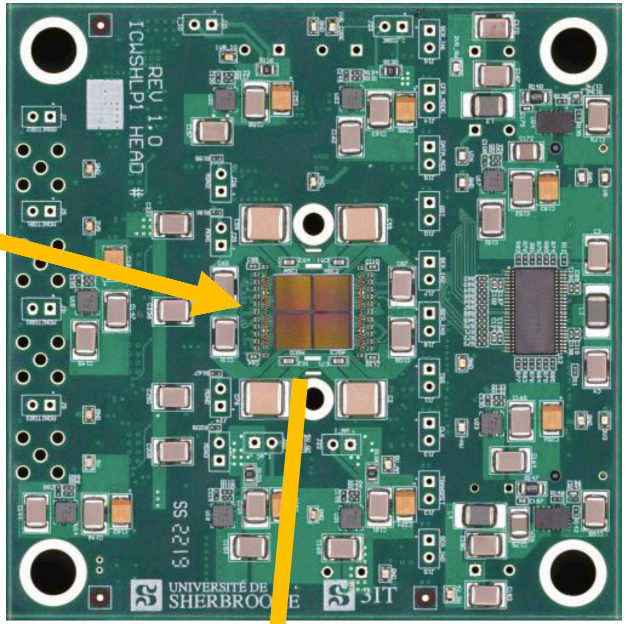
Photon to Digital Converters

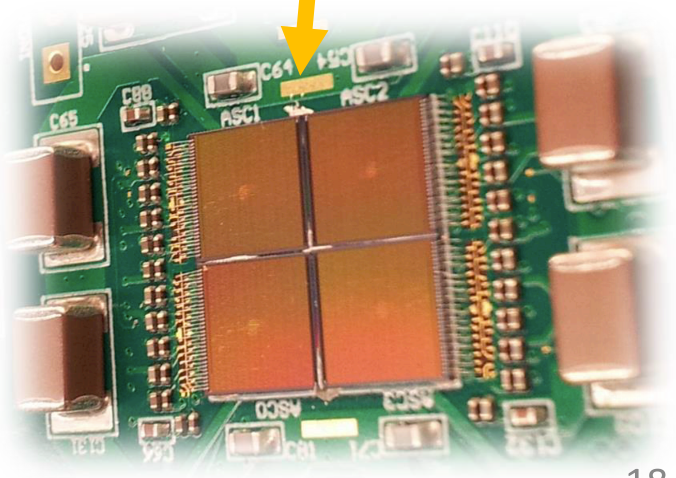
nEXO

- PDC CMOS readout chip is now fully operational (U. de Sherbrooke)





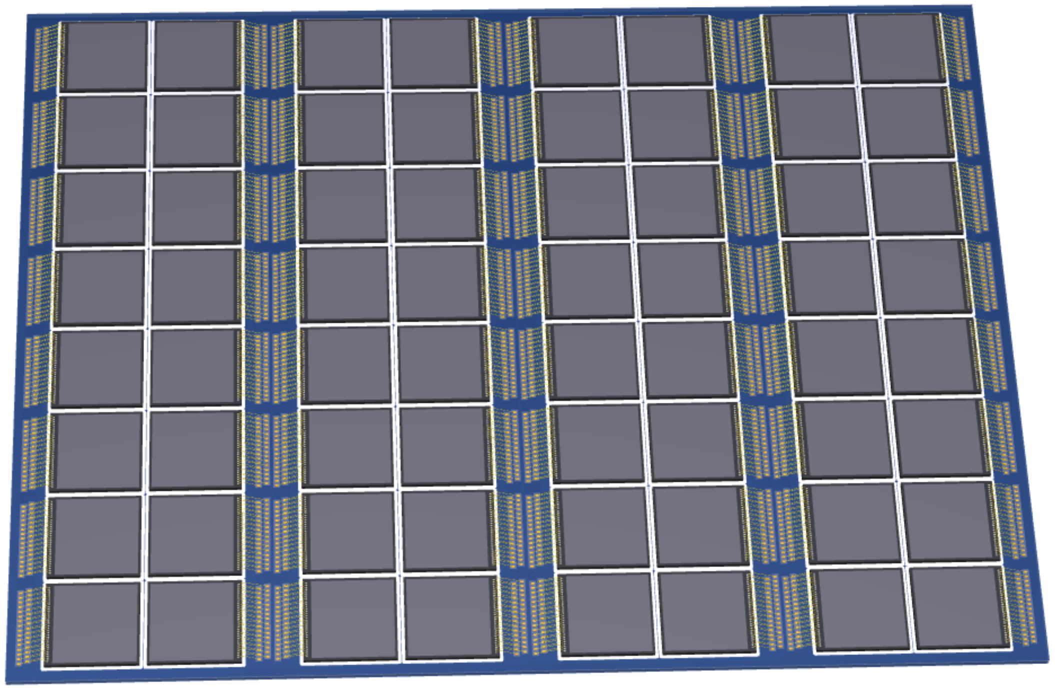




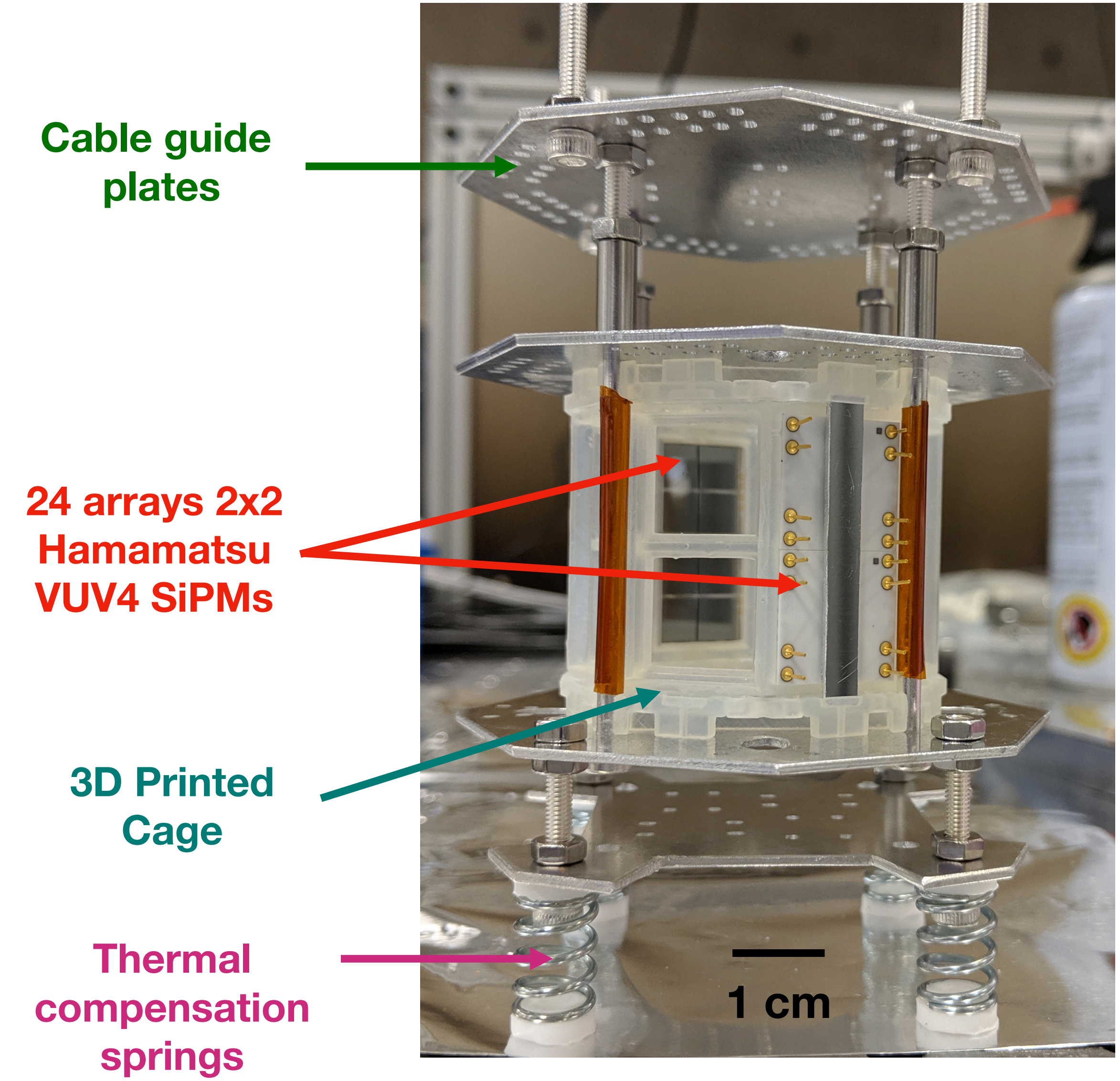
2x2 array of PDC readout ASIC

Photon to Digital Converters

- Next R&D objectives for PDC:
  - VUV-sensitivity
    - Strategy 1: Delta doping in collaboration with LBNL
    - Strategy 2: Teledyne e2v backside-illuminated tech.
  - Silicon interposer
    - Match coefficient of thermal expansion of PDC with its electrical/mechanical substrate
    - Low radioactivity
    - Low contaminant for LXe
    - Collaboration with IZM Fraunhofer (Berlin)
    - Establish yield vs. size
    - “Long” transmission lines with low resistivity and low capacitance (analog and digital signals)



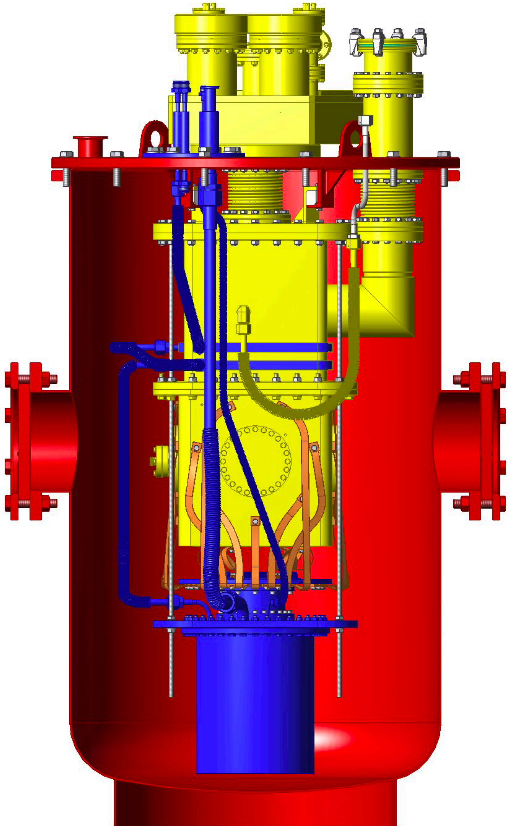
Light-only Liquid Xenon (LoLX)



- Canadian collaboration (mostly)
- Phase 1 objectives
  - Gain experience operating many SiPM channels: first in vacuum, then in LXe
  - Measure scintillation and Cherenkov light yields
    - Using ^{90}Sr and ^{210}Po sources
  - Ex-situ optical measurements to verify GEANT4 optical simulations
  - Assess external cross-talk (light emission by SiPMs)
- Status: Currently running at McGill

Further SiPM tests in LXe

- Existing LXe cryostat: EXO-100
  - Current inner detector used for nEXO HV tests
- Planning future SiPM tests with LoLX-HV:
  - Ensure functionality of tiles in nEXO's harshest possible environment
    - **High electric field** with possible charge-up
    - **High rate** when calibrating with sources
  - Operation of tiles in LXe
  - Detection of surface alphas
    - Very bright localized light flashes

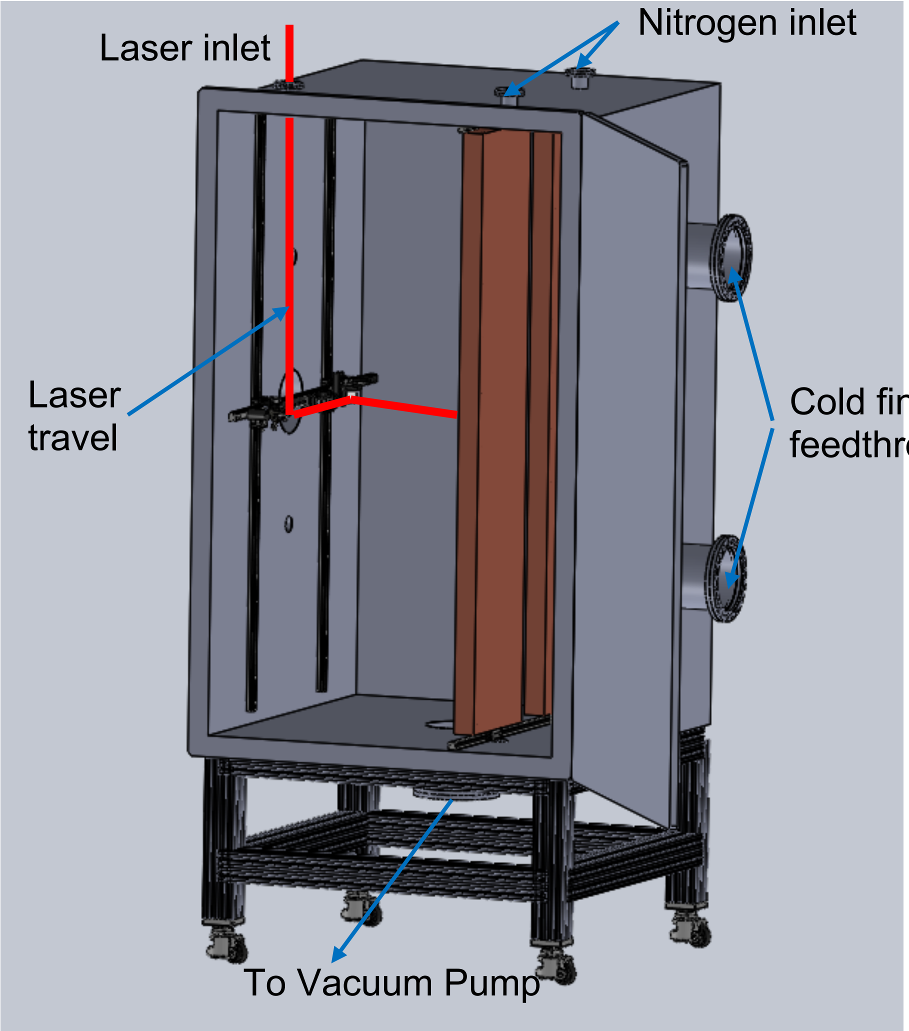


EXO-100 cryostat
currently being recommissioned at Carleton U.

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

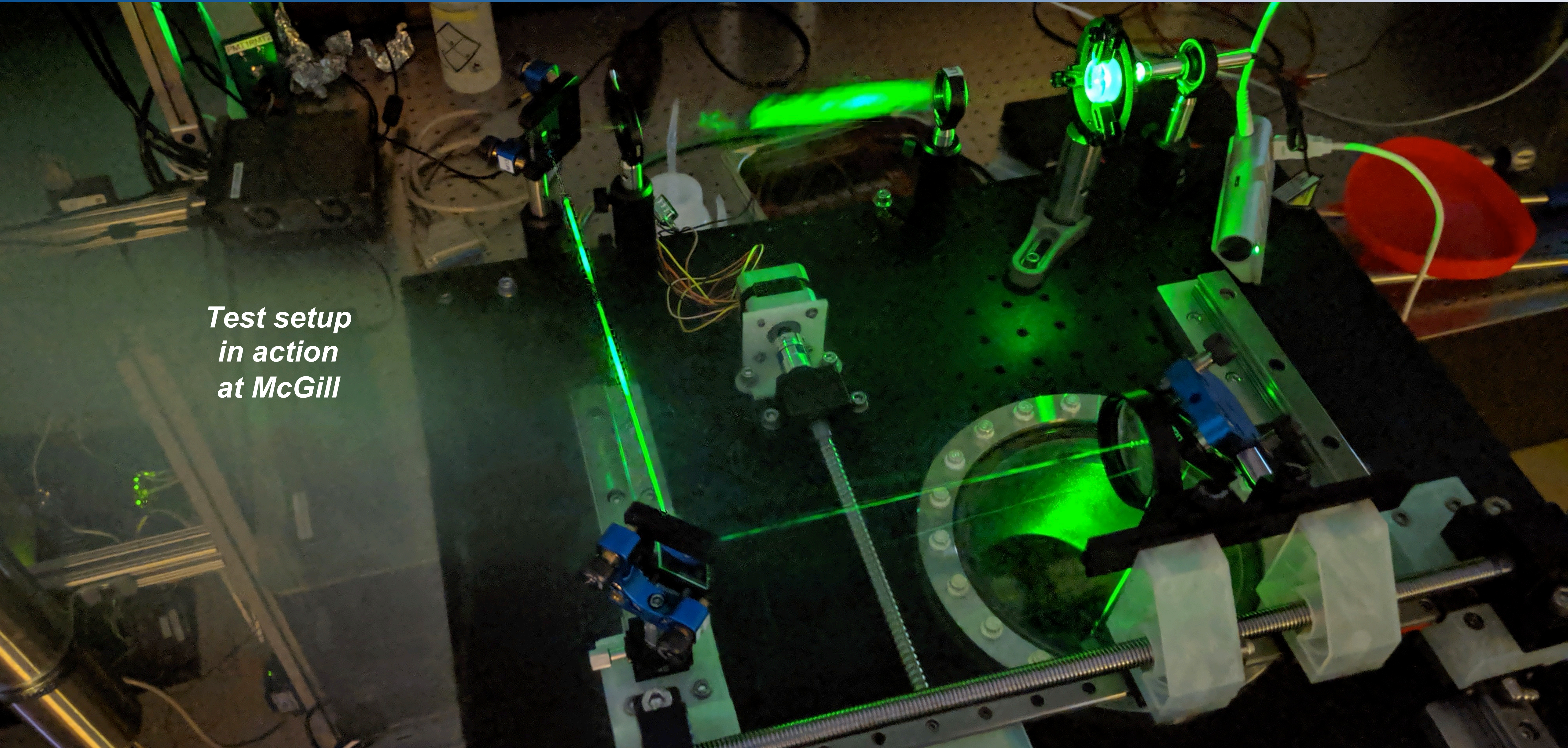
Large-scale integration and testing

- **Getting ready for nEXO construction**
  - TRIUMF proposed as main SiPM wafer testing and dicing site, and backup tile production facility (BNL primary)
  - McGill developing and prototyping procedure for SiPM stave testing and assembly in nEXO underground
    - Very fragile staves must be handled with great care!
- **Quality control**: Ensure that staves will survive 10 years of operation in nEXO
  - Long term stability, Temperature cycle, Vibrations
- **Functionality tests** with environmental chamber:
  - Movable mirrors guide photons to SiPM stave under test
  - Electroluminescent source of VUV photons under development at McGill



Design of full-length stave test chamber

Large-scale integration and testing



Summary and Outlook

- **Light detection using VUV-sensitive SiPM** is critical for nEXO
  - Excellent energy resolution → Sensitivity to $0\nu\beta\beta$
- Canadian contributions to **photodetector R&D**
  - Characterize SiPM performance to make sure that nEXO photo-detector requirements are satisfied
  - Test SiPM single devices and tiles optically, and in LXe
  - Complete development of VUV-sensitive Photon to Digital Converters and silicon interposer technology
- **Getting ready for nEXO construction**

Thank you! Merci !

nEXO Collaboration, June 2019

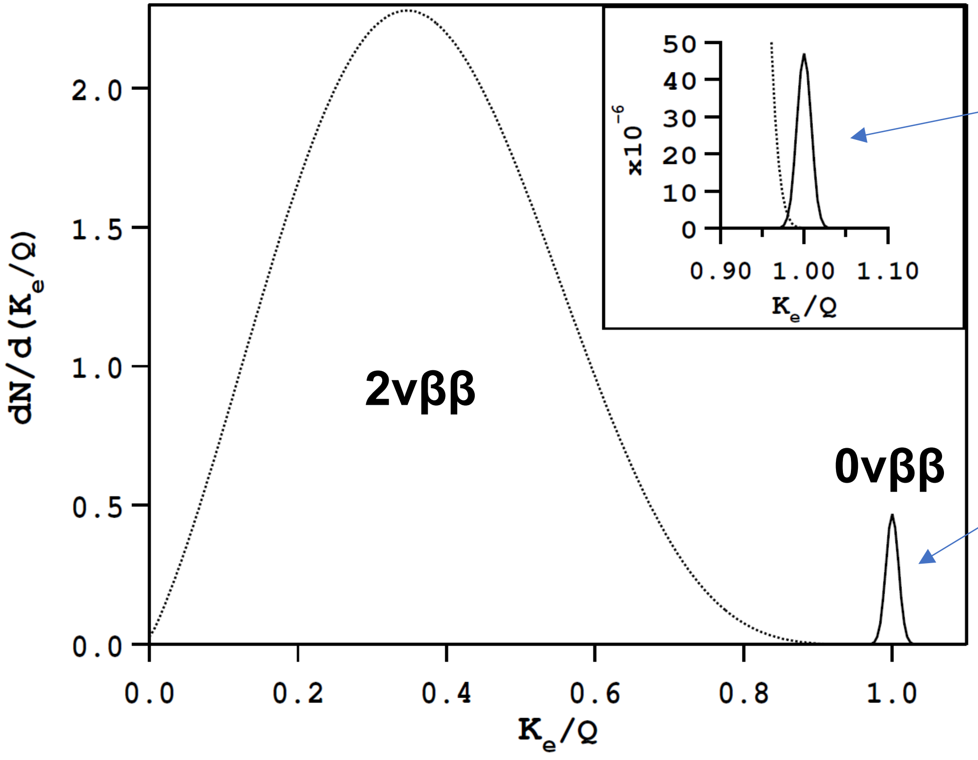
nEXO

TRIUMF · THE UNIVERSITY OF BRITISH COLUMBIA · LaurentianUniversity UniversitéLaurentienne · Carleton UNIVERSITY · McGill · UNIVERSITÉ DE SHERBROOKE

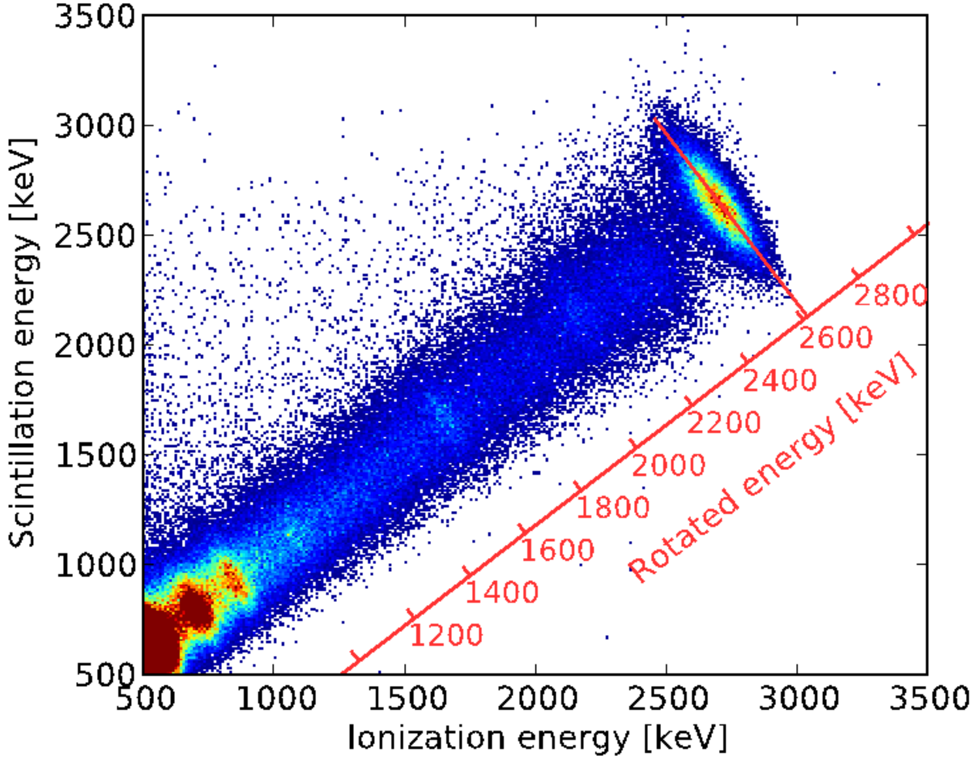
Bonus slides

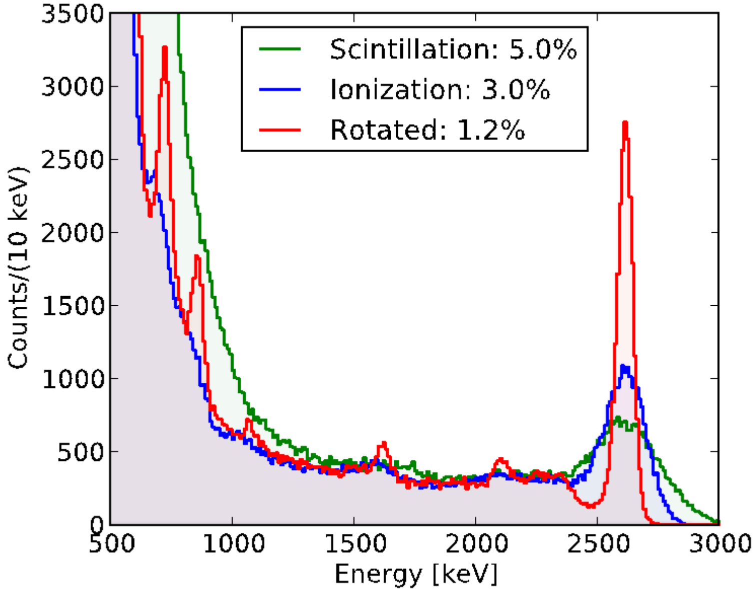
Energy resolution in nEXO

- Neutrinoless double beta decay discovery requires the best possible energy resolution
  - Relies on the combination of **charge and light collection** in the single-phase LXe TPC
  - Cancels fluctuations in ionization vs. scintillation yield



P. Vogel, "Neutrinoless double beta decay", arXiv:hep-ph/0611243

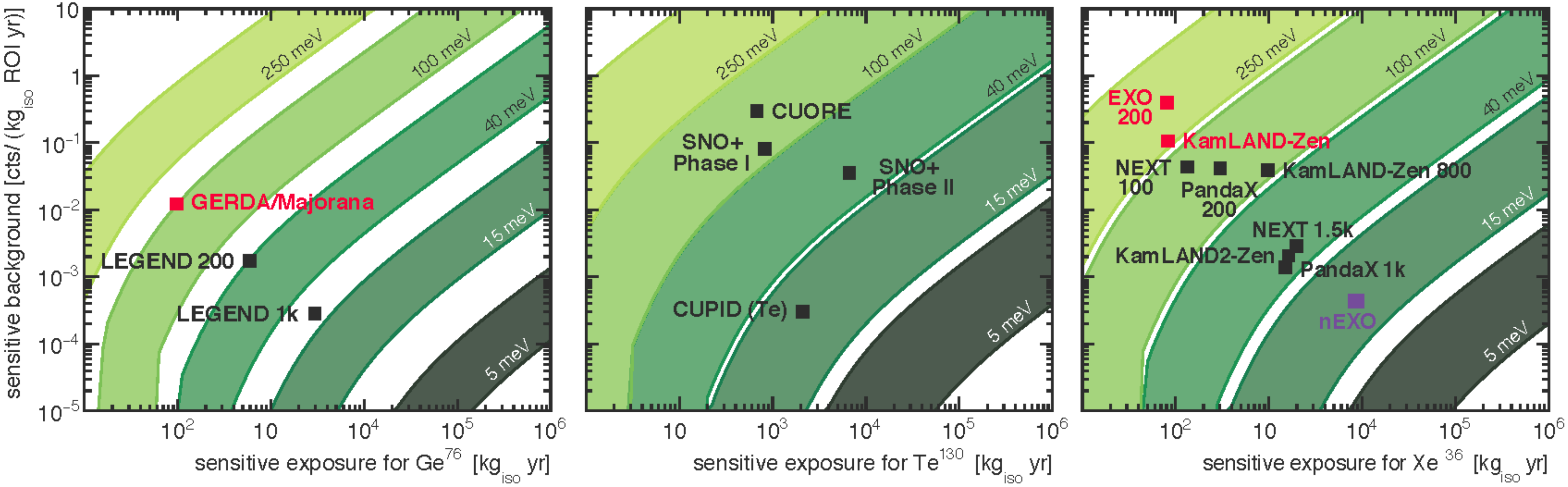




EXO-200 energy resolution

0νββ experiments sensitivity

- At $\langle m_{\beta\beta} \rangle \sim 0.01$ eV, nEXO projected sensitivity compares favourably with current and proposed 0νββ experiments



Agostini, Benato, Detwiler, PRD 96 (2017) 053001; and A. Caldwell et al., PRD 96 (2017) 073001