The nEXO Experiment for the search of $0\nu\beta\beta$

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on behalf of IHEP nEXO team

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Institute of High Energy Physics
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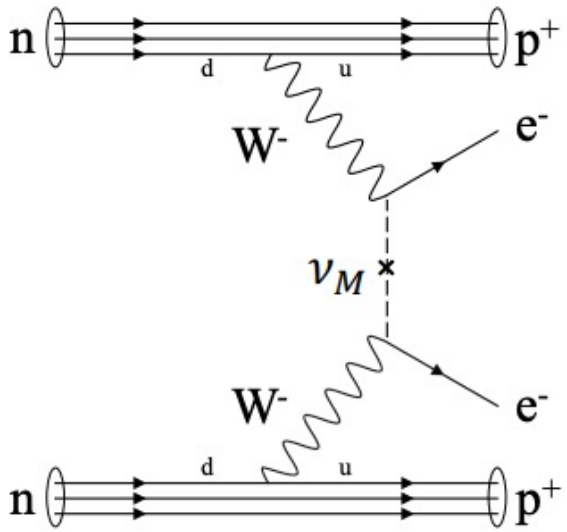
Outline

- 0νββ 及nEXO介绍
- 探测器设计，软件与物理
  - nEXO探测器模拟
  - nEXO灵敏度分析
- Detector R&D
  - Charge readout system电荷读出系统
  - Photo-detector system 光探测系统
    - SiPM performance
    - Silicon Interposer
    - Reflective electrodes
  - Cold electronics
- Summary

Search for New Physics with 0νββ decay

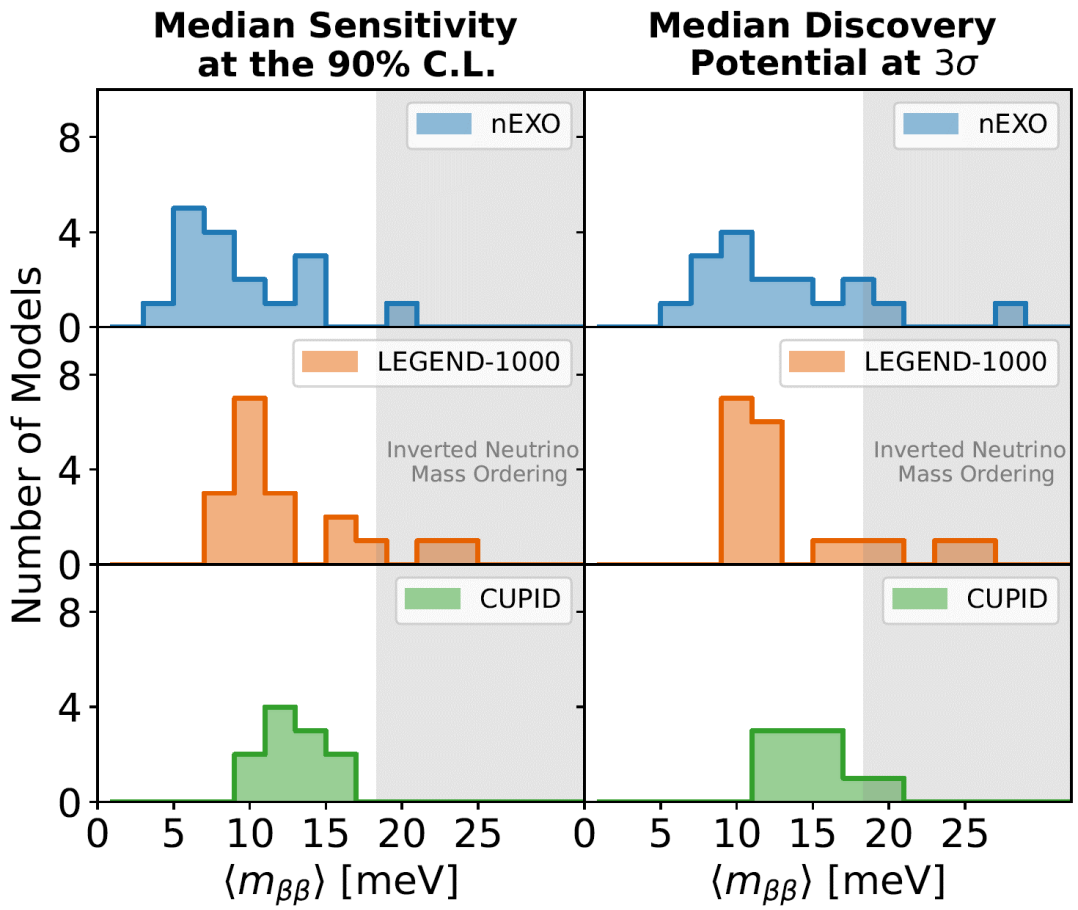
- A tonne-scale double-beta decay experiment is highly recommended and has great discovery potential for 0νββ
- Once discovered, 0νββ will irrefutably provide the evidence for
  - violation of lepton number conservation
  - a new type of fundamental fermion, Majorana neutrinos

  and possible explanations for
  - a new mass generation mechanism
  - the matter-antimatter asymmetry
  - how the universe expands and evolves



Feynman diagram representing neutrinoless double beta (0νββ) decay

Comparison with other experiments



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.

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

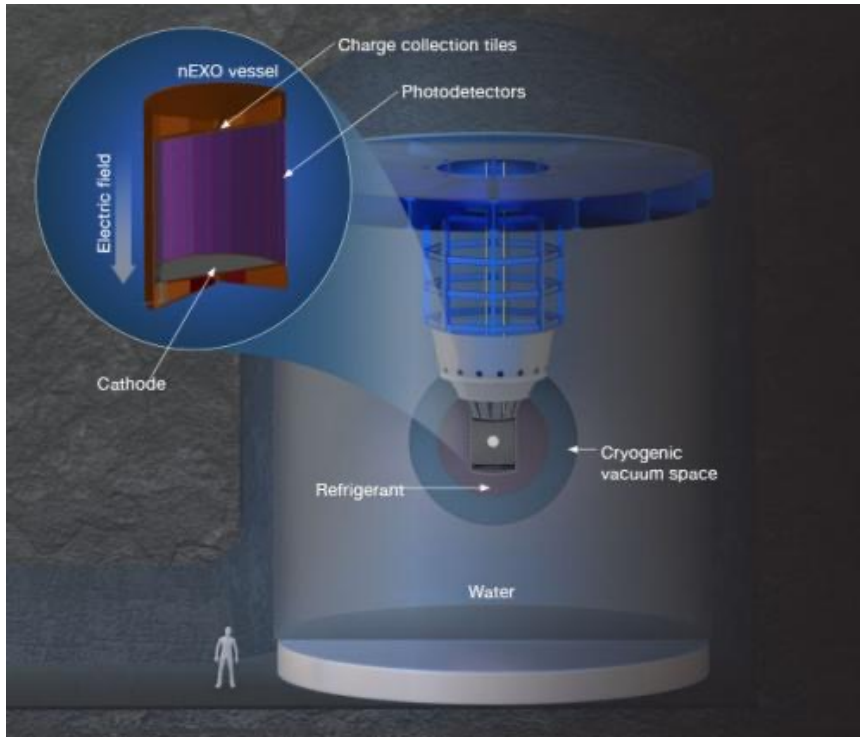
Phase space factor — Axial coupling, $g_A = 1.27$ — NME

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

*T1/2 values used [x1028 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]

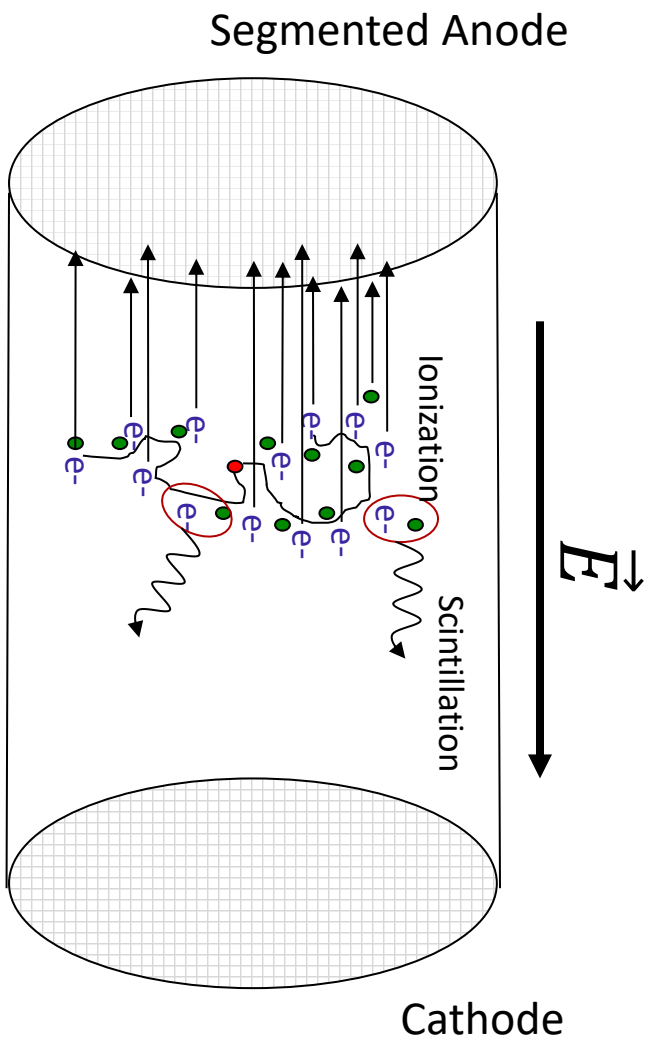
[1] nEXO collaboration, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243
[2] LEGEND pCDR, arXiv: 2107.11462
[3] CUPID pCDR, arXiv:1907.09376

nEXO TPC Conceptual Design



nEXO (next Enriched Xenon Observatory) :

- 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- Xe-136 operating temperature 165 K
- Electric drift field 400 V/cm
- Diameter of drift volume 116 cm
- LXe scintillation light wavelength 175 nm
- Photodetector area 4.5 m^2



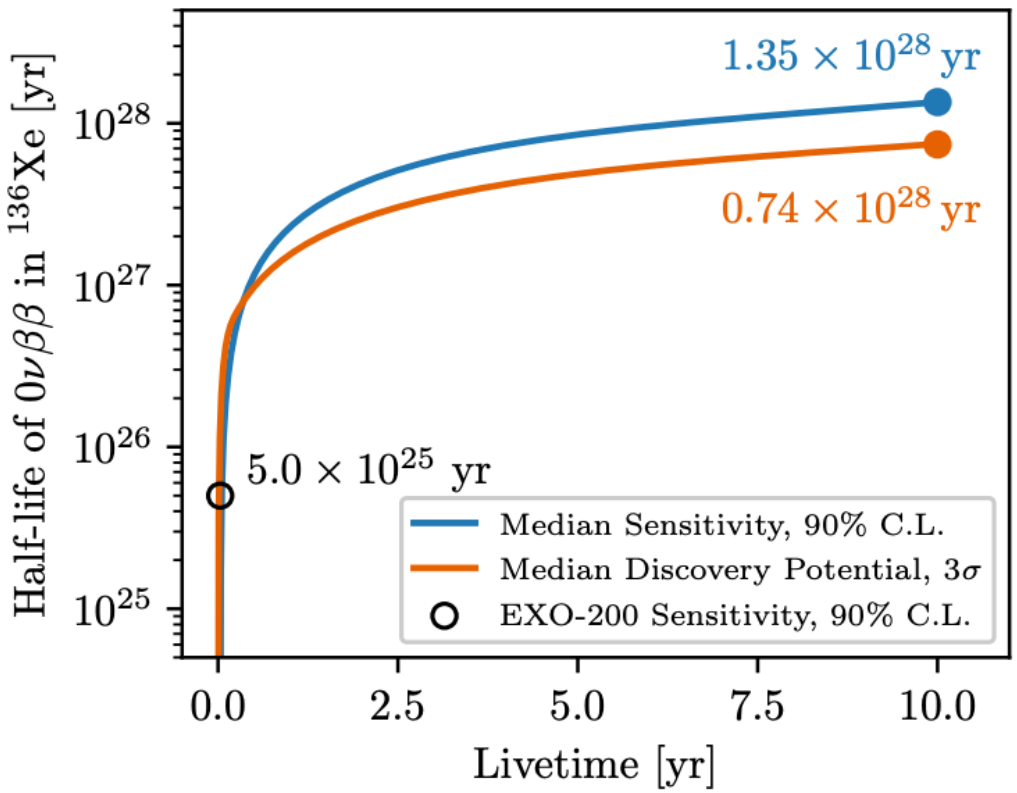
nEXO pre-CDR, arXiv:1805.11142

Contributions (software, conceptual design and sensitivity study) from IHEP:

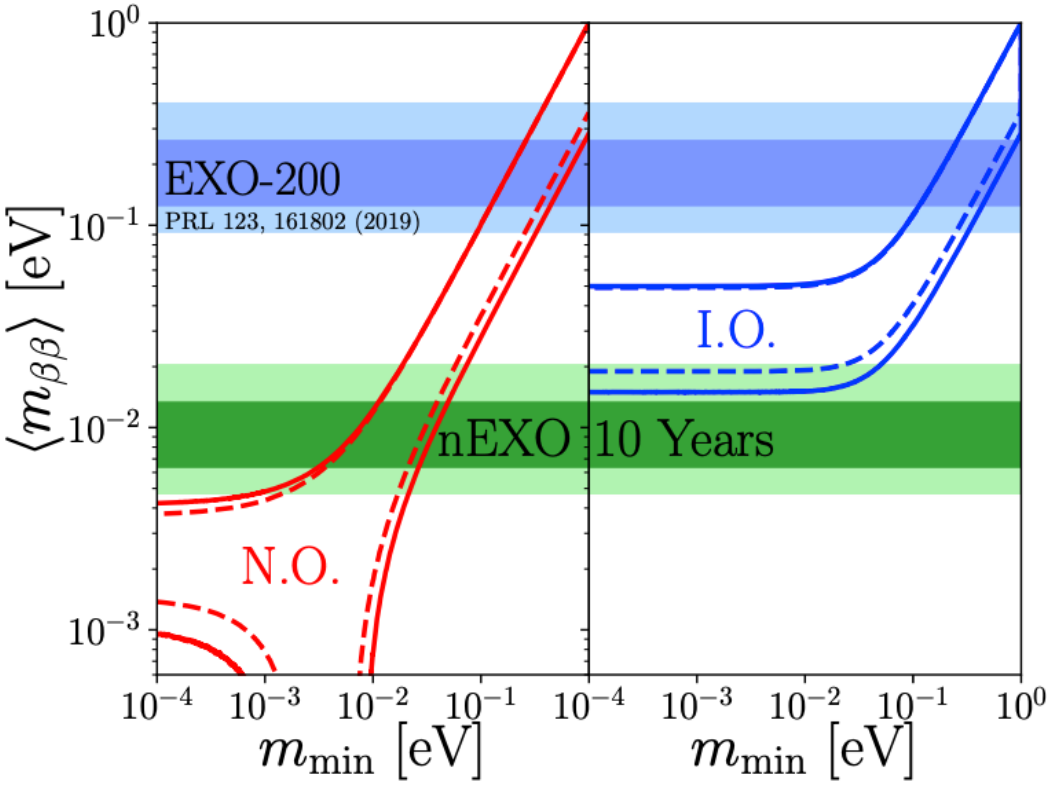
- **Simulation software development and detector design optimization based on GEANT4**
- **0νββ decay sensitivity and discovery potential study**

nEXO sensitivity and discovery potential

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

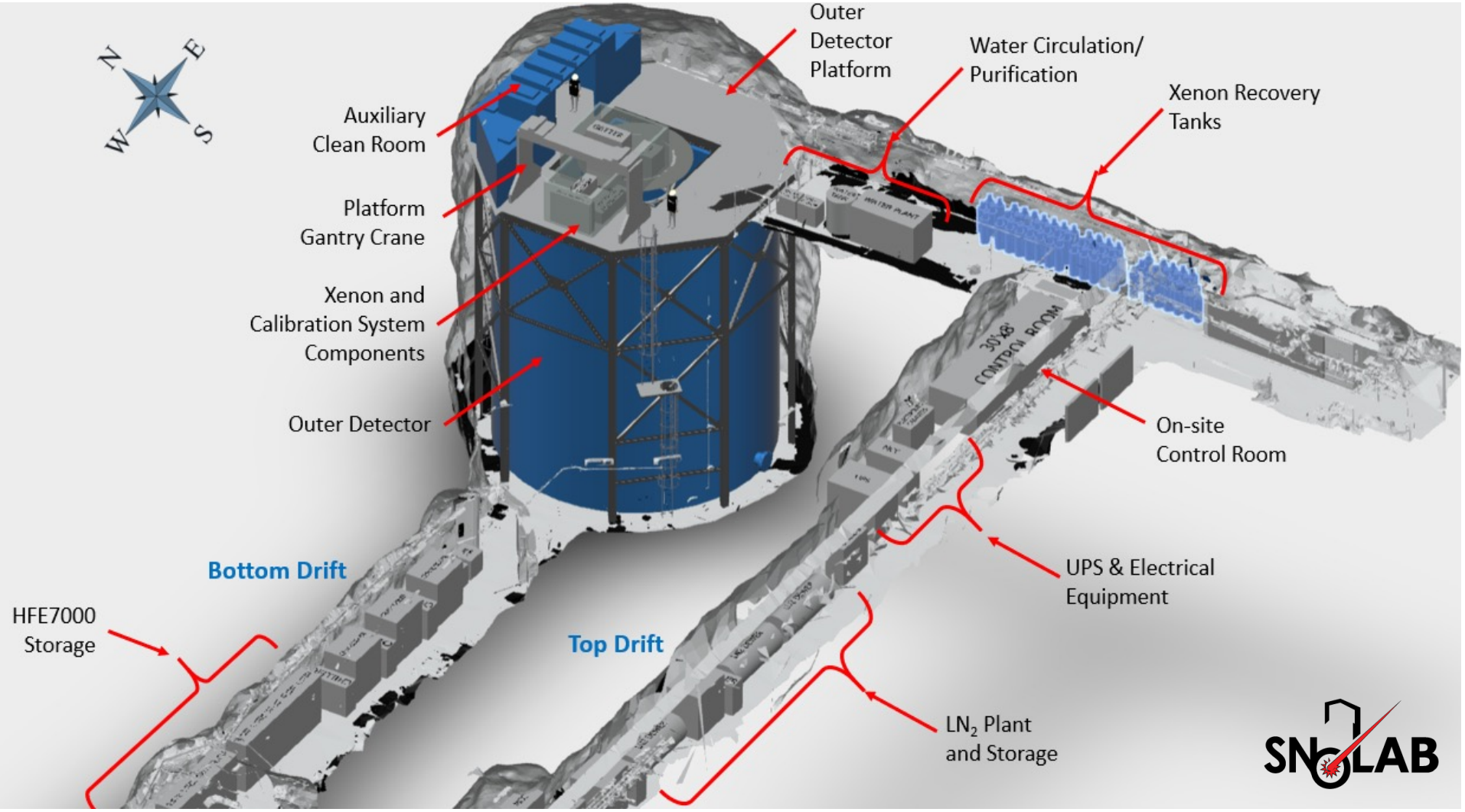


Projection of the median sensitivity and 3σ discovery potential to 0νββ decay with nEXO as functions of the detector livetime.

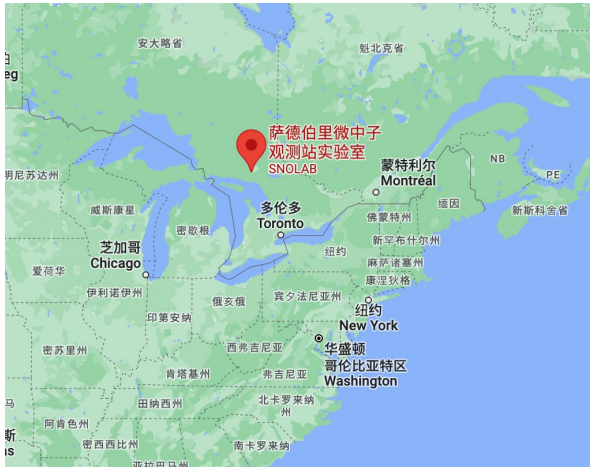


Allowed parameter space and nEXO exclusion sensitivity (90% CL)

location: the Cryopit at SNOLAB

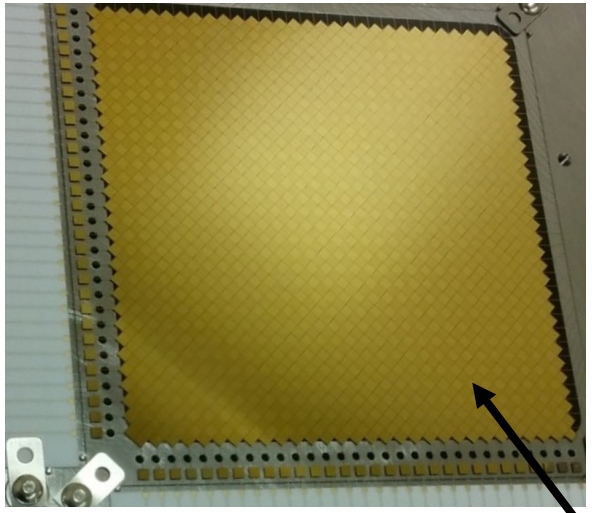


SNOLAB is Canada's deep underground research laboratory, focusing on the neutrino and dark matter studies

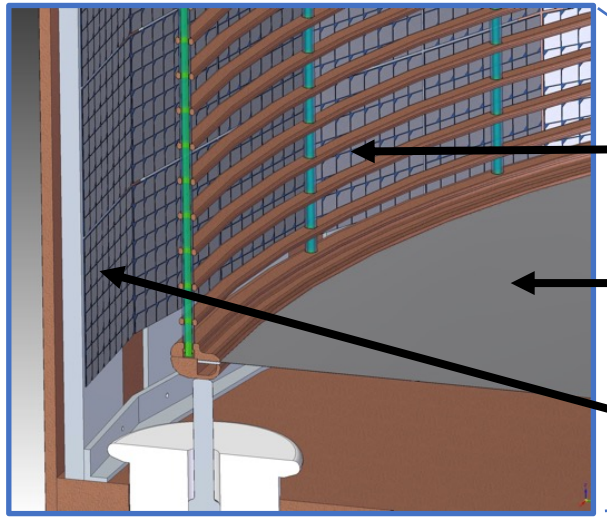


The nEXO detector

- 5 ton liquid xenon
- SiPM for 175nm scintillation light detection, ~4.5m2 SiPM array in LXe.
- Tiles for charge read out in LXe.
- Cryogenic 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)



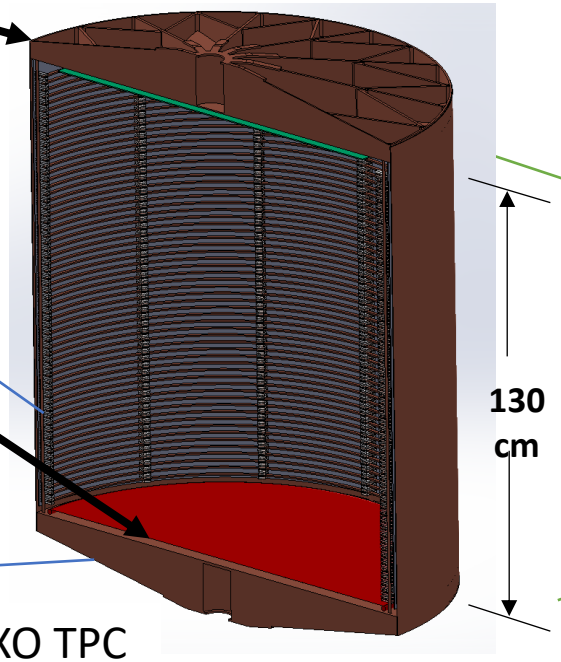
nEXO pre-CDR, arXiv:1805.11142

charge readout pads (anode)

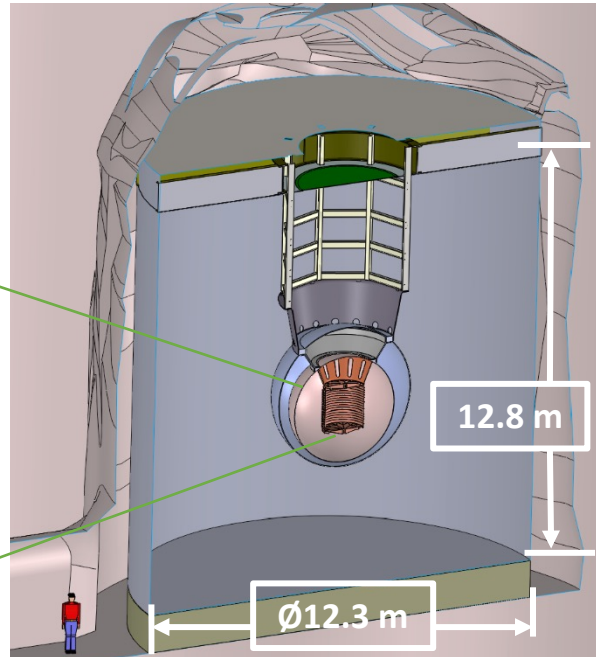
Field shaping rings

Cathode

SiPM 'staves' covering the barrel



0νββ nEXO TPC



nEXO at the SNOLAB Cryopit

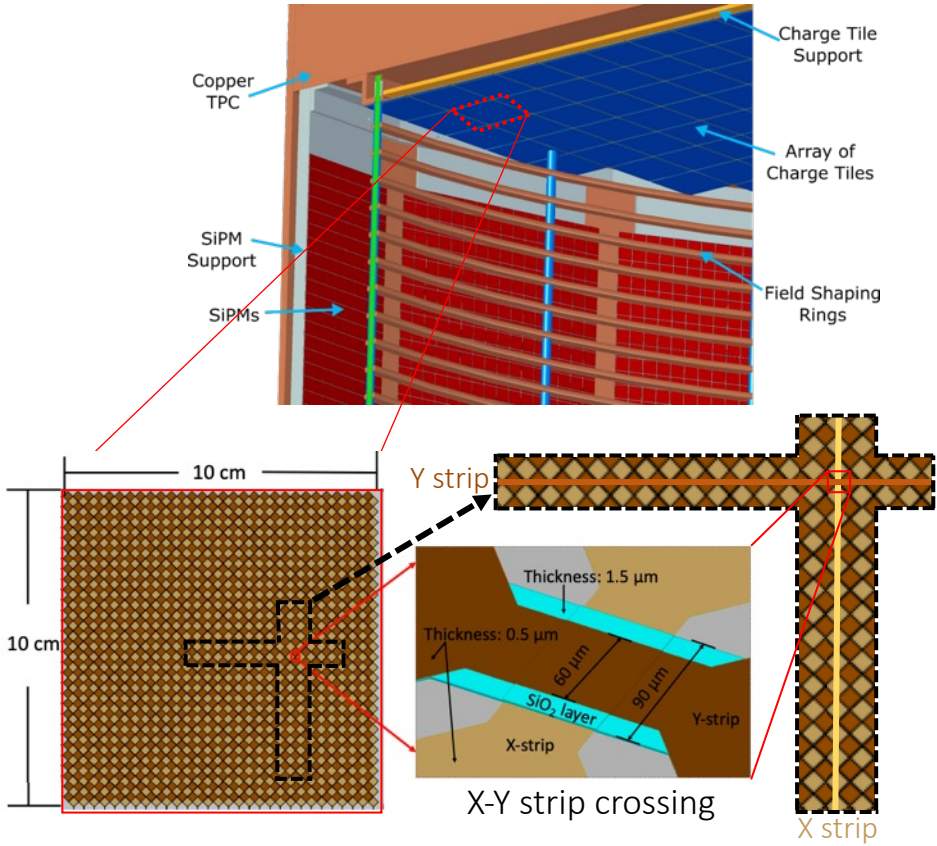
Anode Charge Readout

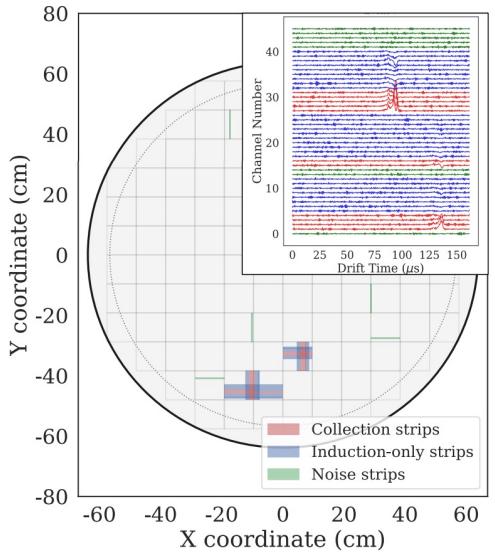
- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

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)



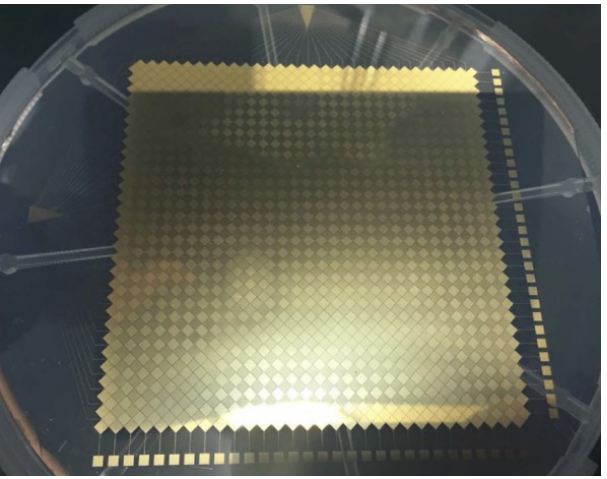


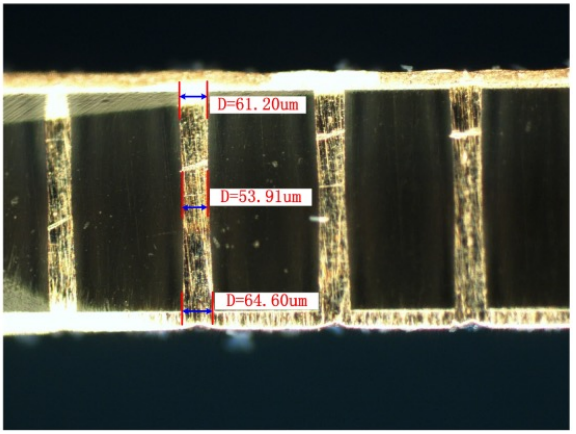
current waveform display

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

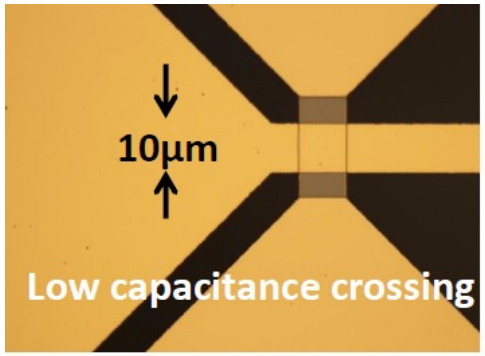
Charge detector design

Prototype 3 mm pitch, crossed strips deposited on a 10 cm x 10 cm quartz tile produced by IHEP/IME

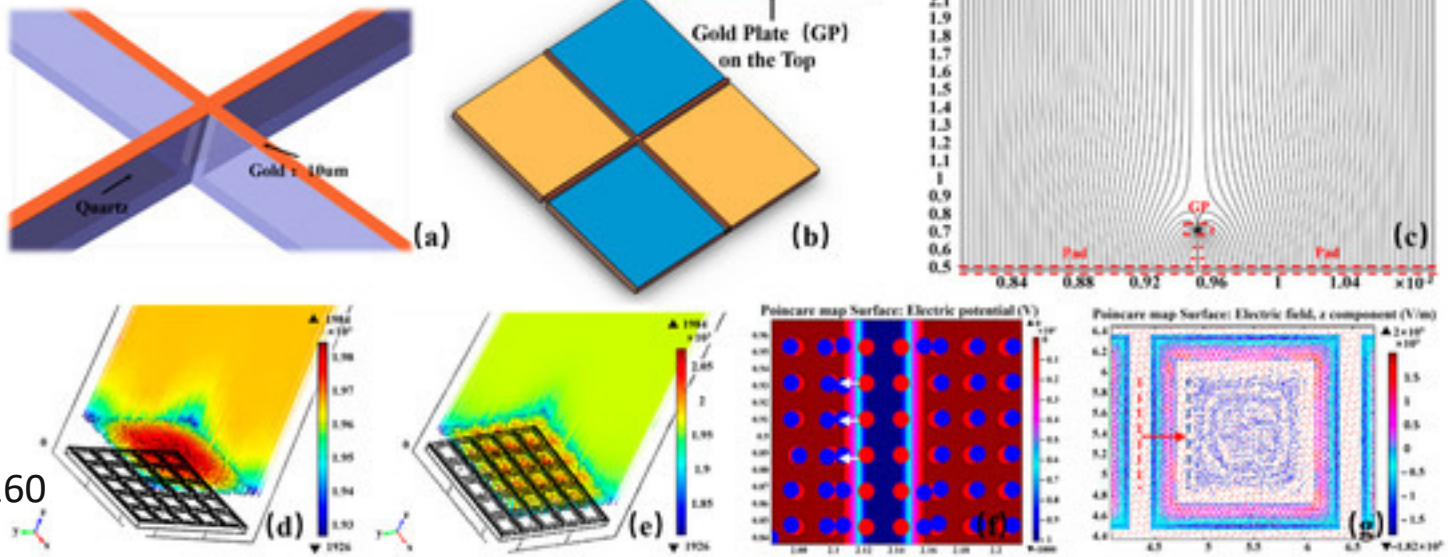


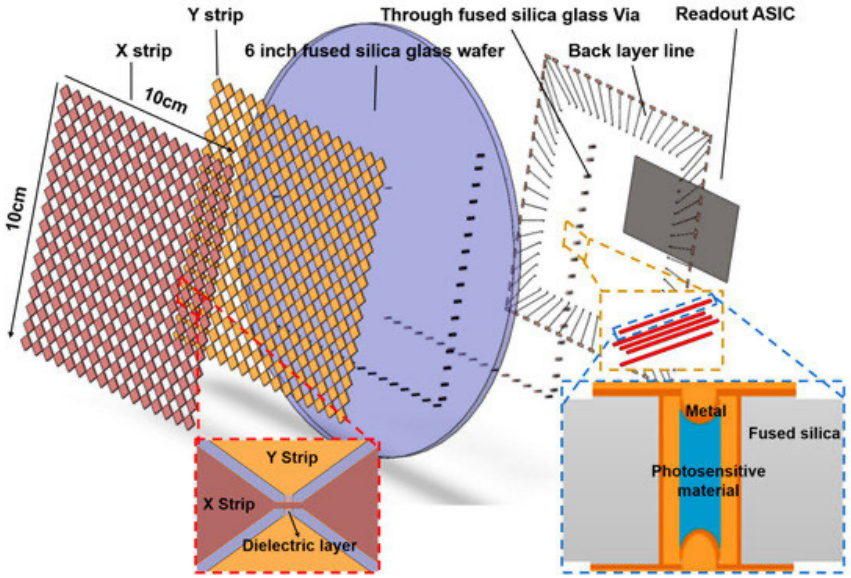


80 fF at crossings
0.86 pF between adjacent strips



Radiation Detection Technology and Methods (2019) 3:12 https://doi.org/10.1007/s41605-018-0090-y





Electronics **2023**, *12*(4), 1045;

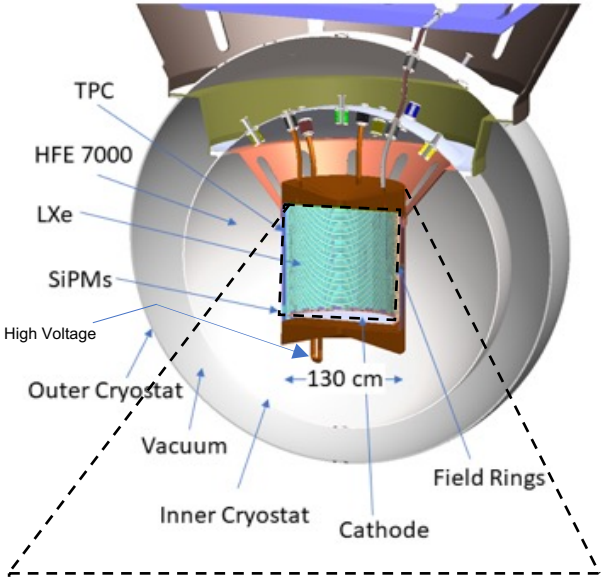
SiPM Photo-detector

Advantages of SiPMs for photon detection

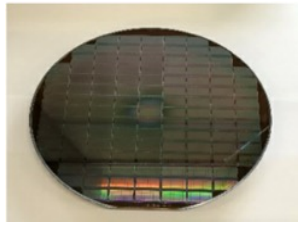
- Low intrinsic radioactive backgrounds.
- Improved energy resolution (SiPMs high gain).
- Lower bias required for SiPMs (~50 V versus ~1.5 kV).
- Devices from 2 vendors meeting requirements, demonstrated through R&D.

Energy resolution:

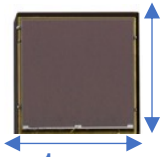
- SiPM PDE at 175 nm
- Photon transport efficiency (PTE)
- Reflectivity of SiPM
- Correlated noise of SiPM



SiPM Devices



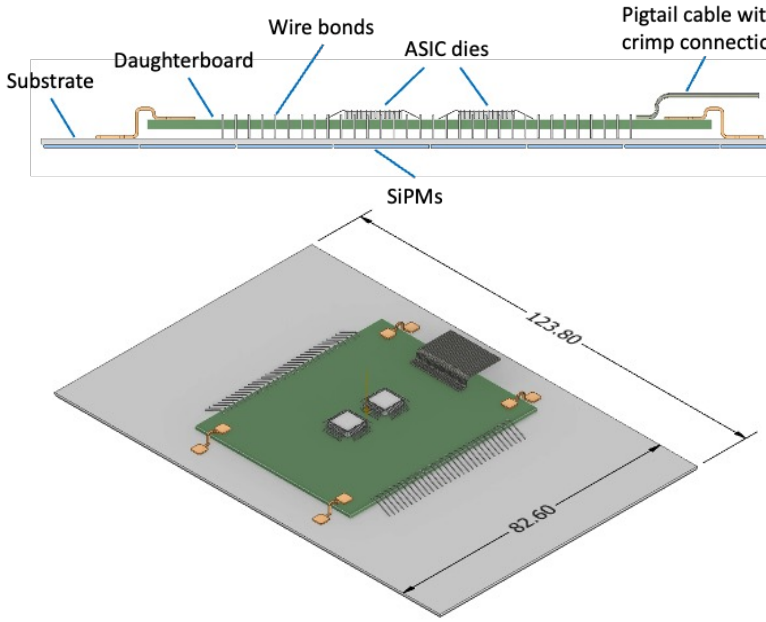
x 50,000



1 cm

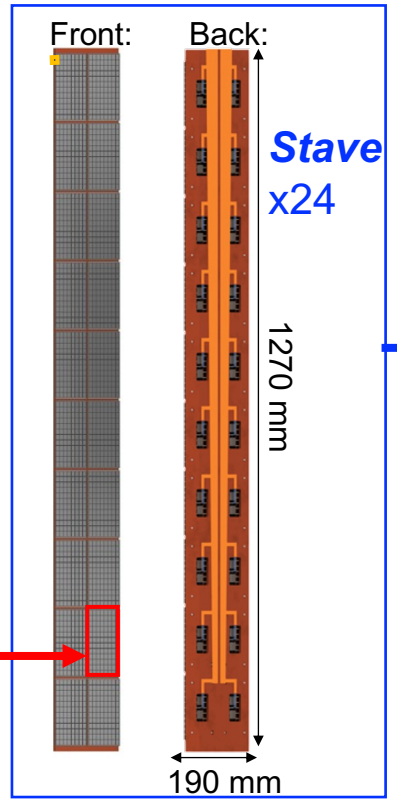
Tested SiPMs

- **FBK: VUV-LF-HD, VUV-STD-HD**
- **Hamamatsu: VUV4**

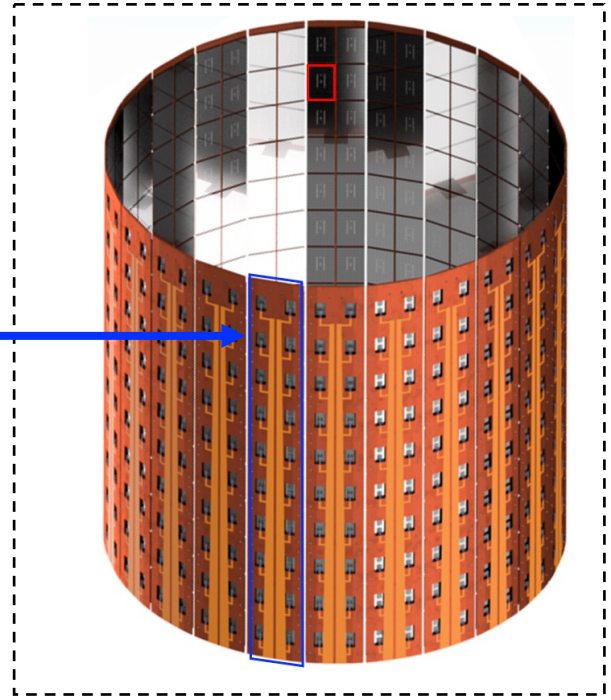


Tile module

x 480



Stave
x24



Photon detector (PD)

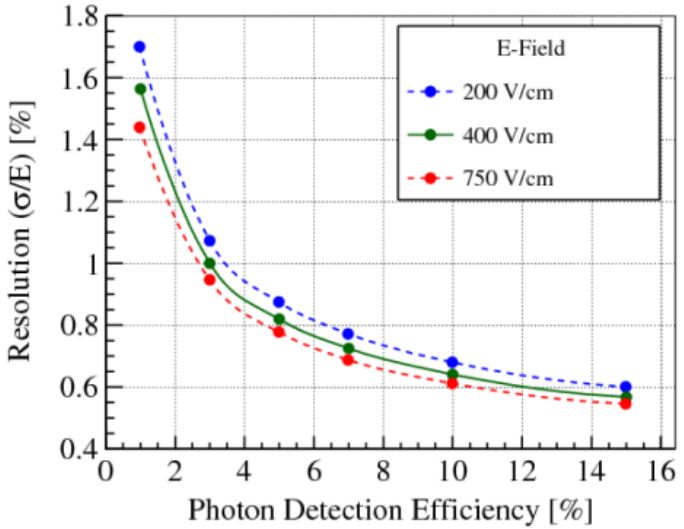
SiPM technical requirements

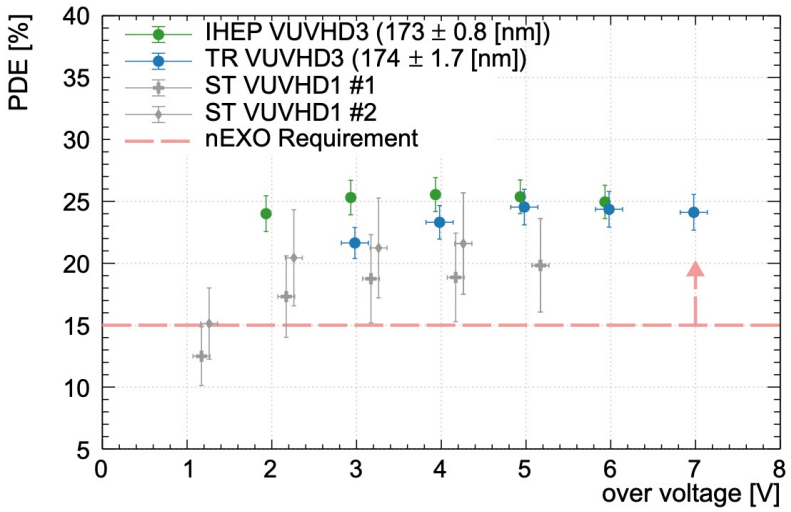
Parameter	Specification	Comment
Photo-detection efficiency	> 15%	At 170-180nm, including reflectivity
Dark noise rate	< 50 Hz/mm^2	At -104 ℃
Correlated avalanche rate	< 20%	At -104 ℃, combing cross-talk and after pulsing integrated within 1μs
Area per channel	1 – 5 cm^2	
Capacitance	< 50 pF/mm^2	For readout electronics
Electronics noise	< 0.1 SPE	
Pulse width	< 0.5 μs	
Radio purity	0.1, 1, 10 nBq/cm^2	For ^{238}U, ^{232}Th and ^{40}K respectively

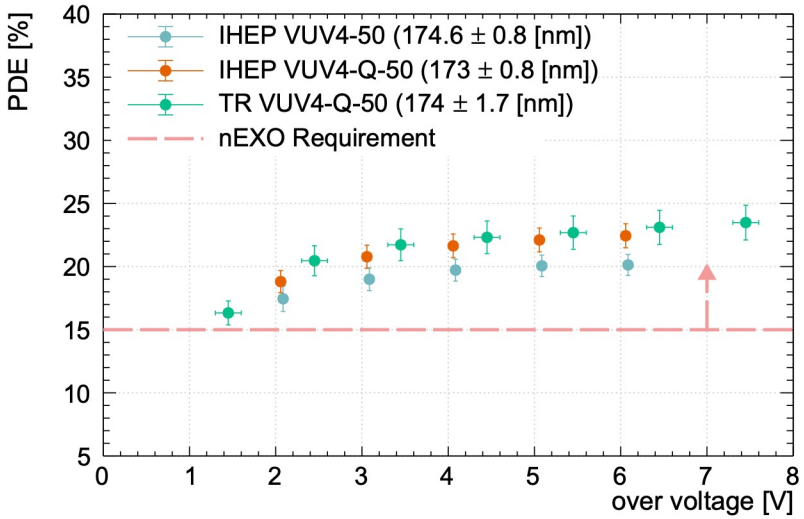
VUV-sensitive SiPM performance test at IHEP

- The absolute photon detection efficiency (PDE) of SiPM in the vacuum ultraviolet (VUV) band has always been an important research topic for nEXO. The previously nEXO published systematic error has been at the level of 20-30%.
- We proposed for the first time a method for measuring the absolute SiPM PDE in the VUV band using the CW mode.
- We performed the PDE measurement in the range of 165nm-200nm, and the measurement error has been reduced to ~5%.
- A final decision has been made on the different measurement results of the BNL and TRIUMF experimental groups.
- The results are published last year (Eur. Phys. J. C 82, 1125 (2022))

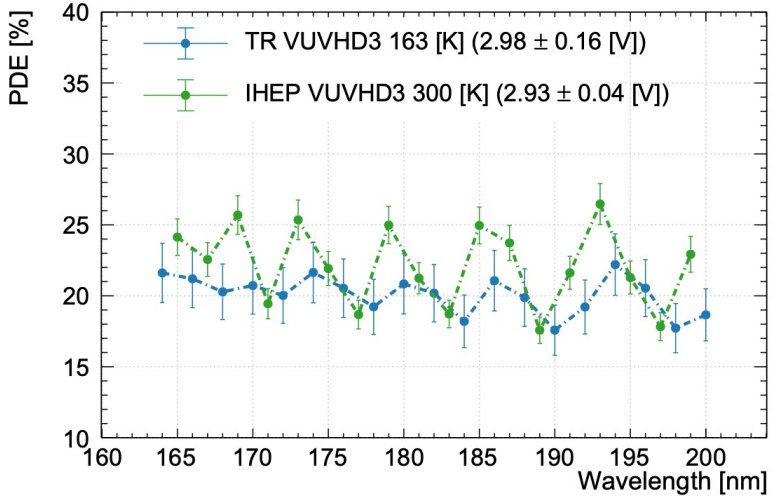
VUV-sensitive SiPMs performance test

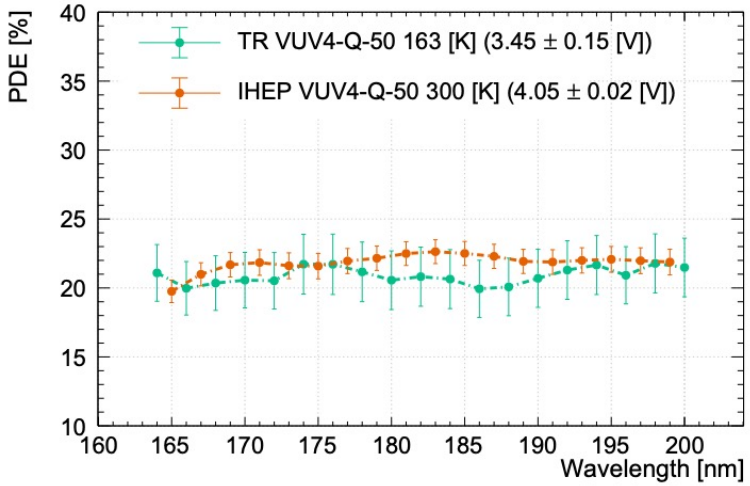






- SiPM photon detection efficiency is crucial to the nEXO energy resolutior
- Independent tests have been performed by IHEP and Triumph
- A dedicated experimental setup is developed for the environment-sensitive vacuum ultra-violet SiPM test

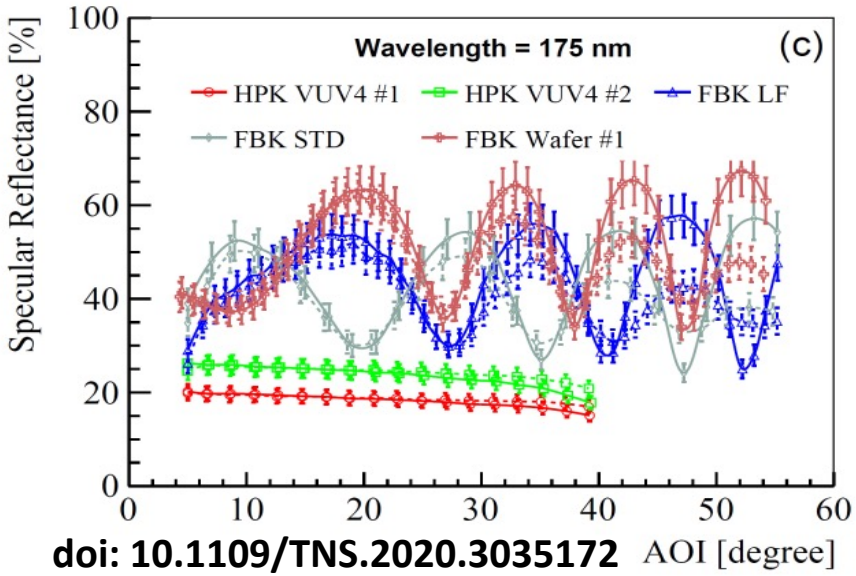




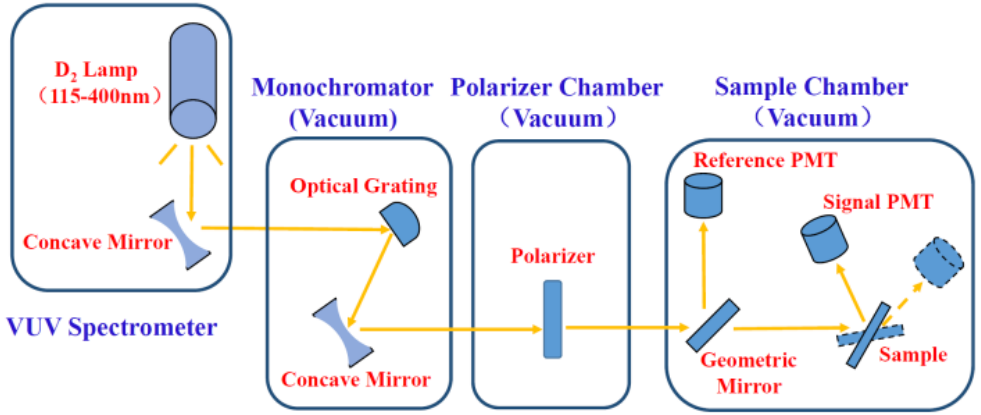
Eur. Phys. J. C **82**, 1125 (2022)

SiPM reflectivity study

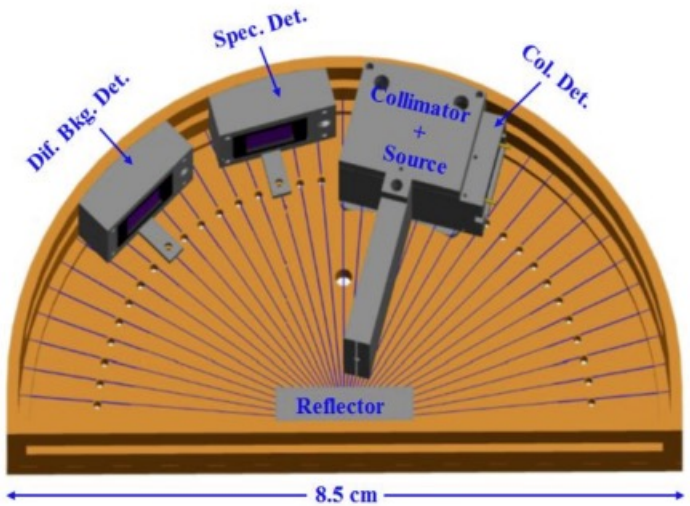
- One setup to measure SiPM reflectance in vacuum
  - IHEP & IOE, 115 nm to 400 nm, 5 – 55 degree
- Two dedicated setups for measuring reflectance in LXe
  - LIXO (UA)
    - Apparatus immersed in Lxe, use ^{252}Cf source to excite LXe (~175nm light)
    - Collimator + quartz window assembly, to prevent radiation damage and help in light collimation.
  - Erlangen & U. of Münster



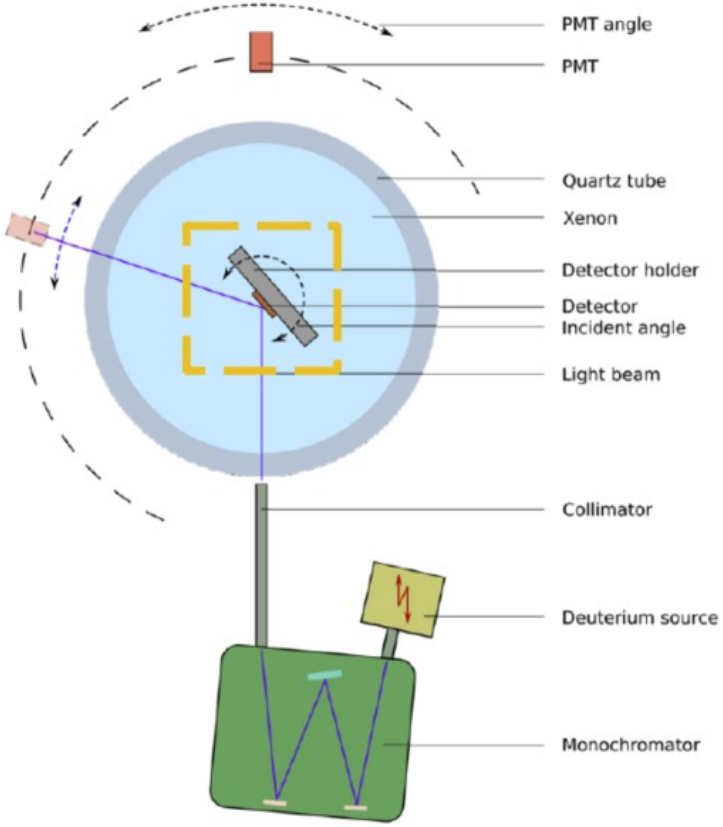
doi: 10.1109/TNS.2020.3035172



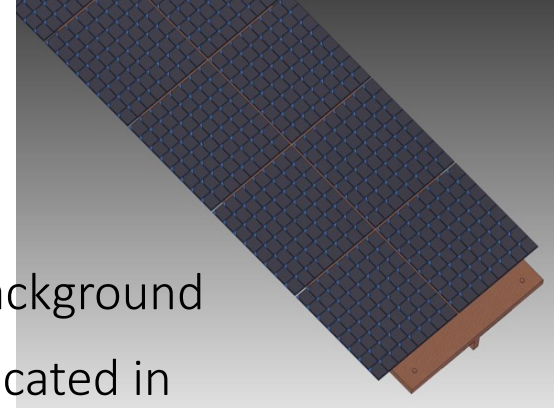
IEEE TRANS. NUC. SCIENCE, doi: 10.1109/TNS.2020.3035172

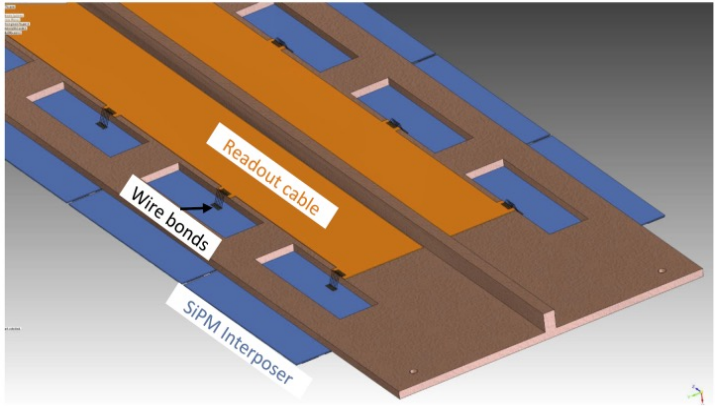


JINST 15 (2020) P01019

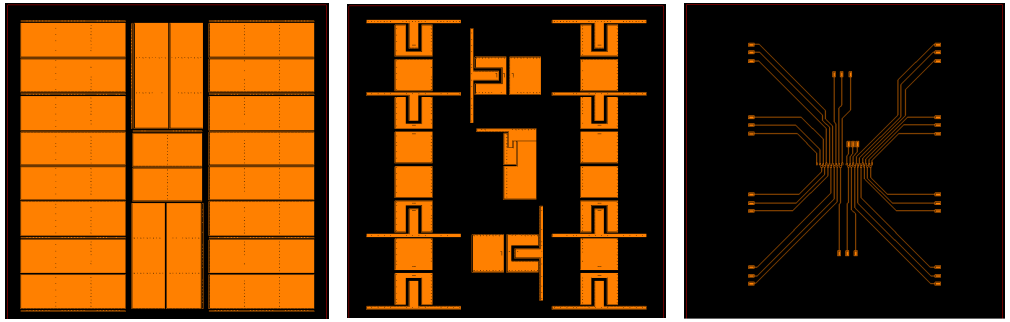


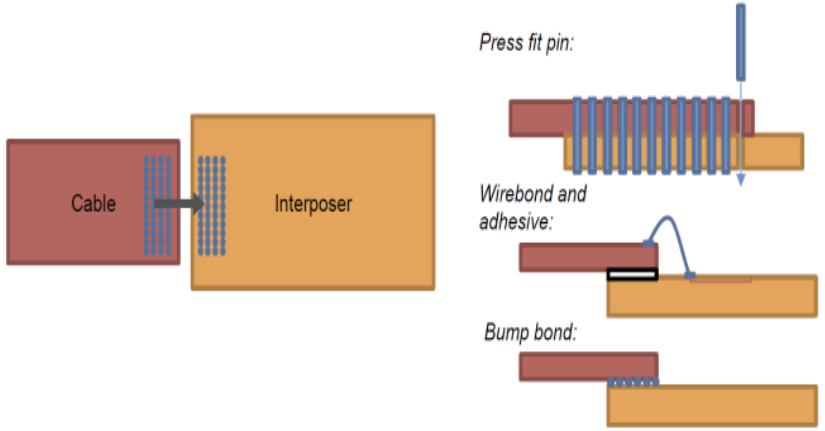
SiPM interposer

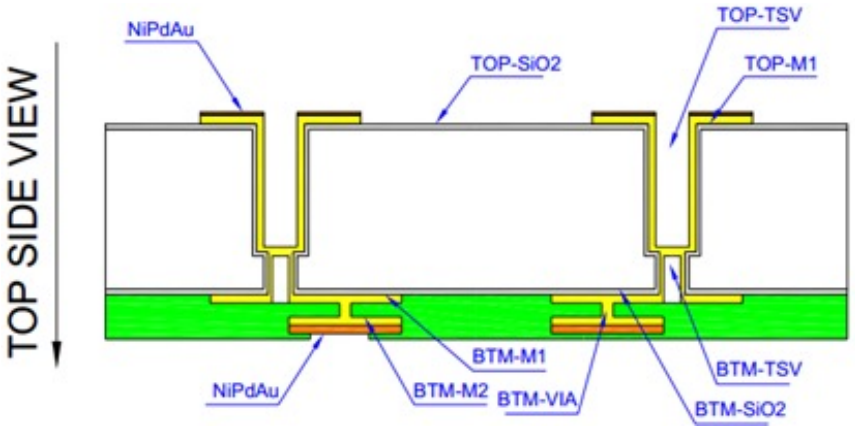




- To meet the requirement of ultralow radioactivity background
- The 1st version prototype silicon interposer was fabricated in 2017 by IHEP & IME (中科院微电子所)
- The 2nd version silicon interposer (DOI: 10.1109/TNS.2022.3232125)
- Both silicon and quartz interposer are under development
  - Quartz interposer at BNL
- The 3rd version silicon interposers have been produced and are waiting for further performance test and system-integrated test

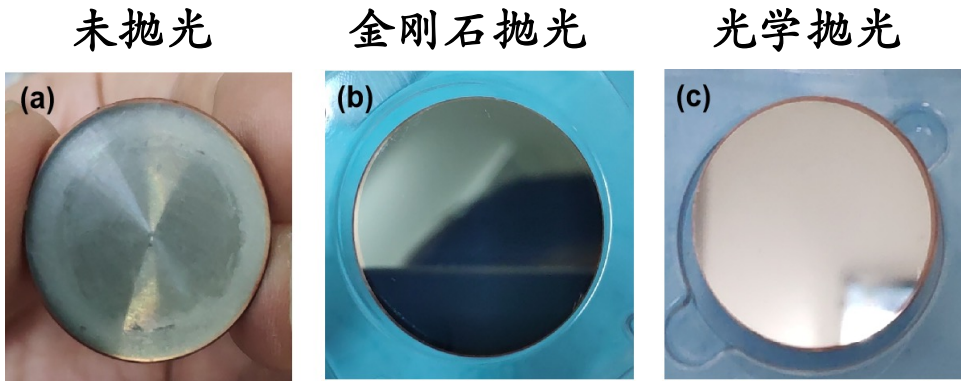


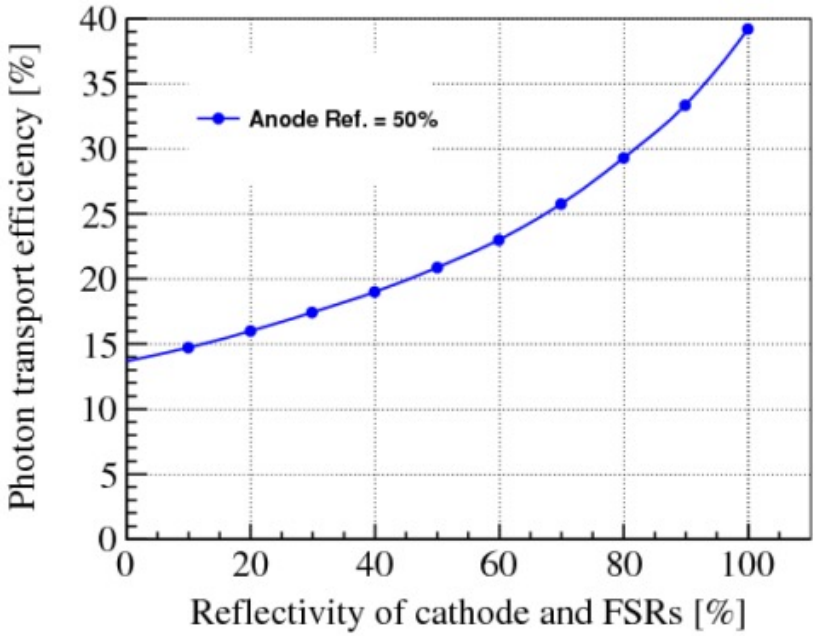




Reflective electrodes

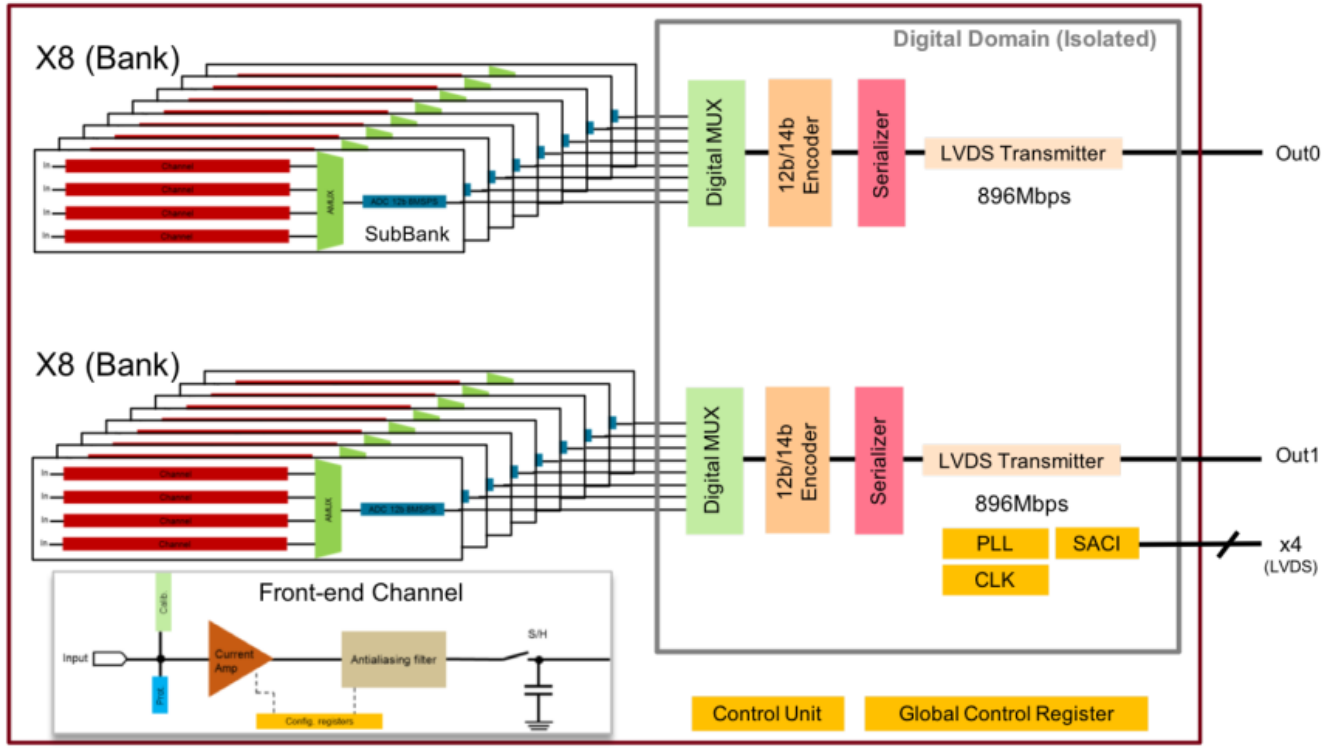
- The VUV reflectivity of electrodes are one of the key factors in achieving the expected energy resolution of nEXO.
- In collaboration with Chengdu Institute of Optics and Electronics（中科院光电技术研究所，成都），IHEP started developing copper-based VUV reflectors at the end of 2019.
- The issue of copper-aluminum alloy was resolved, achieving a total reflectivity of ~80%, meeting the requirements of nEXO (>70%).
- Method and results are summarized and published (Vacuum 197 (2022) 110806).
- According to nEXO's requirements, a new round of sample coating work has been carried out.

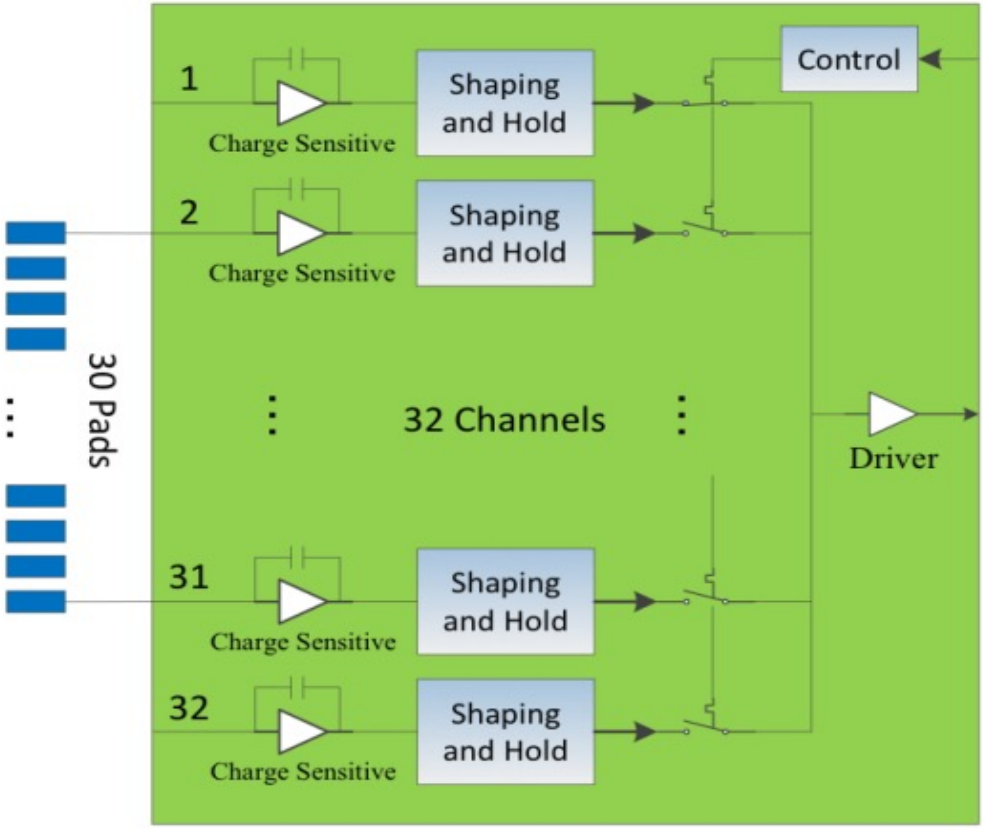




Cold electronics

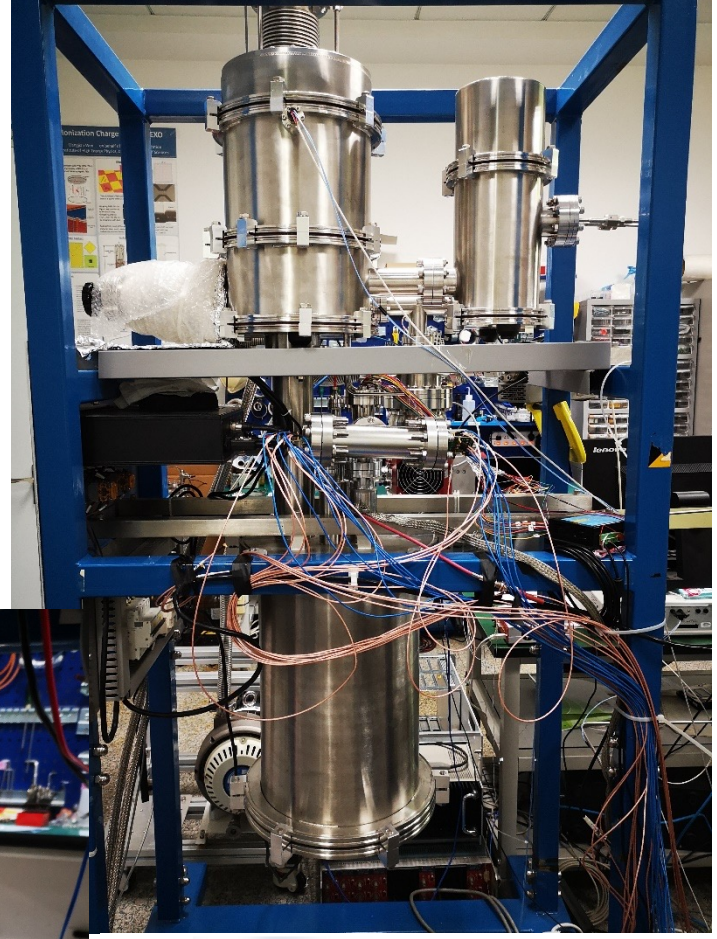
- CRYO ASIC (SLAC)
  - Digital electronics on chip
  - 64 channels, 4 channels share one ADC (12-bit, 8 MS/s)
- Analog chip (IHEP)
  - Analog waveforms are multiplexed inside an ASIC and transmitted outside of the TPC
  - Digital conversion and processing at room temperature

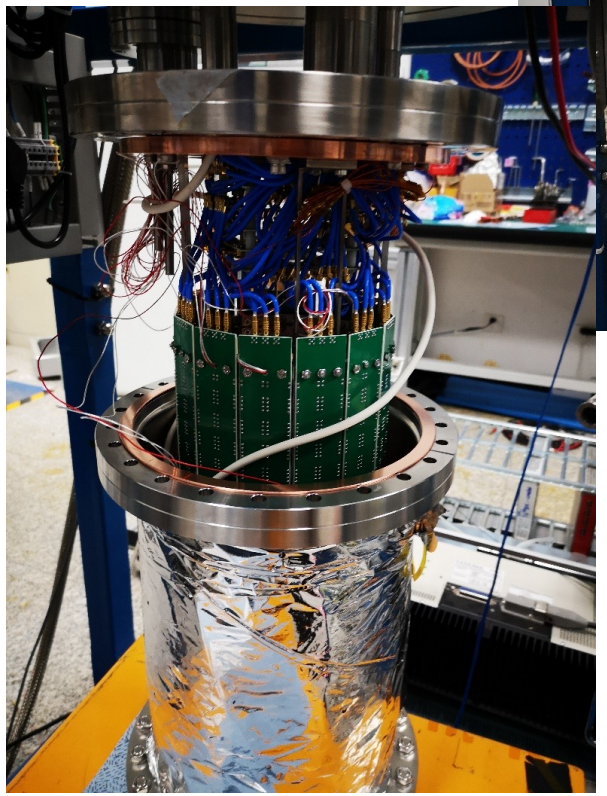


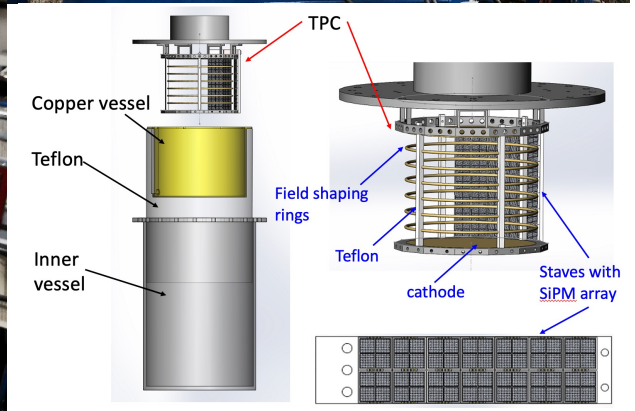


MiniTPC at IHEP

- We've developed a LXe MiniTPC system and testing platform at IHEP: a mini version of the nEXO TPC detector with a similar design
- An efficient and affordable way for the validation of core technologies, detector design and expected goals (e.g. charge readout, light detection and energy resolution)
- The mini-TPC has been installed and operated using CF4







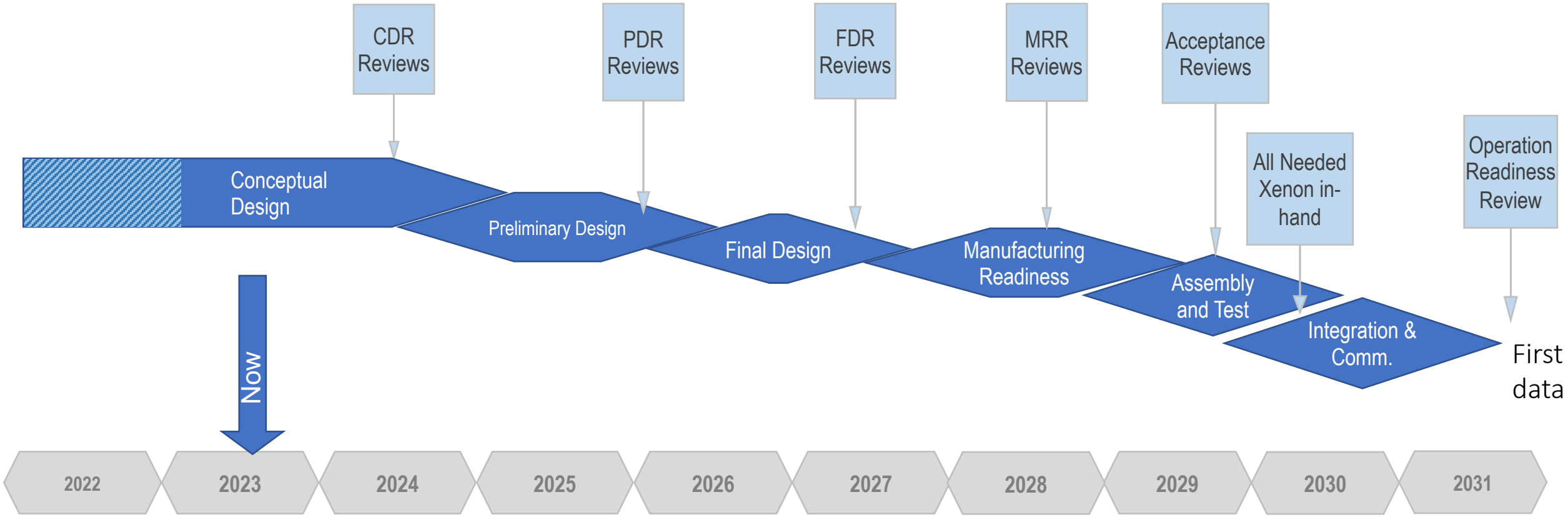
nEXO publications

- An integrated online radioassay data storage and analytics tool for nEXO, R.H.M. Tsang, et al., submitted to NIM A, arXiv:2304.06180 (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)

The international nEXO collaboration

~200 scientists,
34 institutions in
9 countries on
4 continents

nEXO schedule

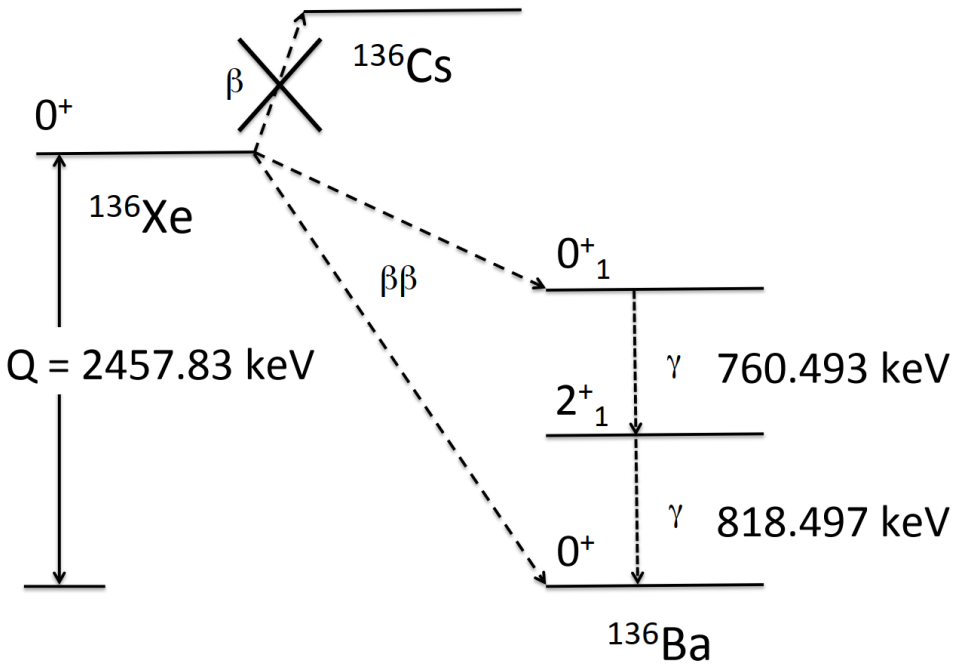


Summary

- nEXO is a discovery focussed 0νββ experiment.
- nEXO's multi parameter signal extraction enables a "background-free" 0νββ search that is particularly robust against unknown backgrounds.
- nEXO is being designed to reach a sensitivity beyond ~10^{28} years and will probe the entire inverted ordering parameter space.
- IHEP's involvement in the experiment has been extensive, including simulation software development, charge and light detector design, cold electronics, etc.
- IHEP has directly participated in the research and breakthroughs of the most core technology of the nEXO detector. It is committed to furthering its contributions to the ongoing experiment.

Back-up

Enriched ^{136}Xe in the nEXO TPC



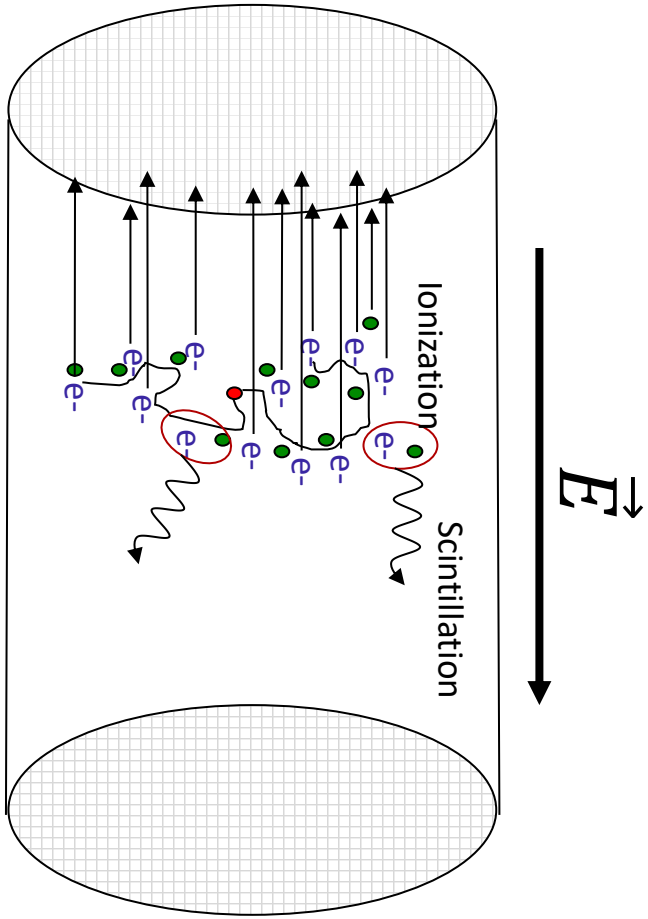
Level scheme of the ββ decay of ^{136}Xe

Phys. Rev. C 93 (2016), 035501
Phys. Rev. Lett. 98, (2017) 053003

- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified.
- Q value $M[^{136}Xe]-M[^{136}Ba])c^2 = 2457.83(37)$ keV
- The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics.
- The advantages of the homogeneous detector keep improving with size. Should 0νββ decay not be discovered by nEXO, larger detectors using the same technology are possible (A. Avasthi et al, Phys. Rev. D 104, 112007 (2021))

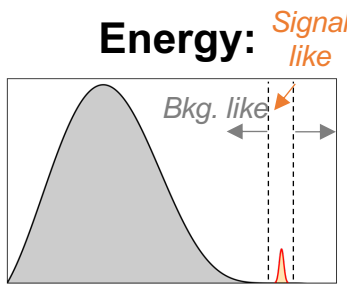
nEXO Signal and Background

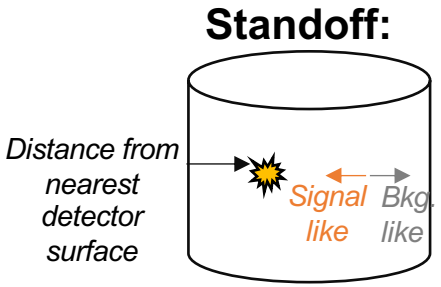
Segmented Anode

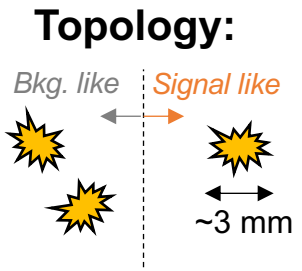


Cathode

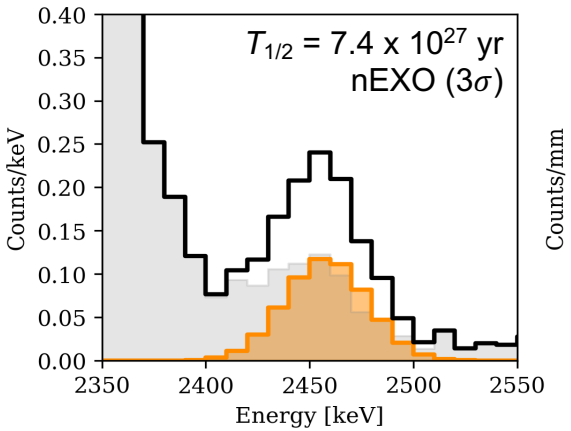
nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal

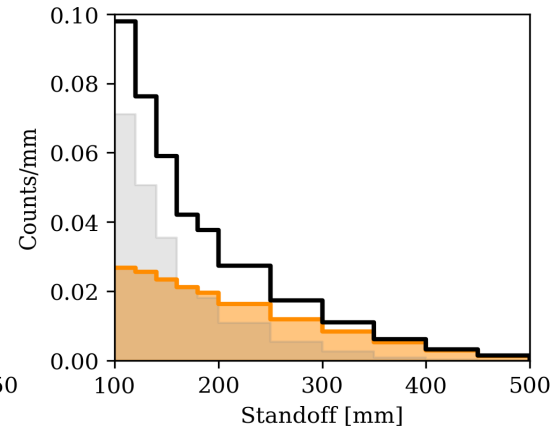


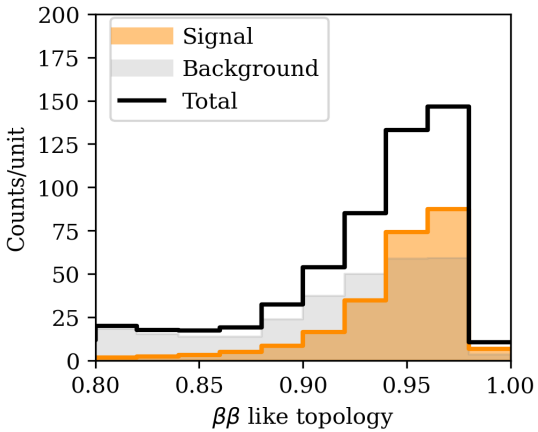




1D projections of simulated nEXO signal and backgrounds:







Energy from combined scintillation/ionization

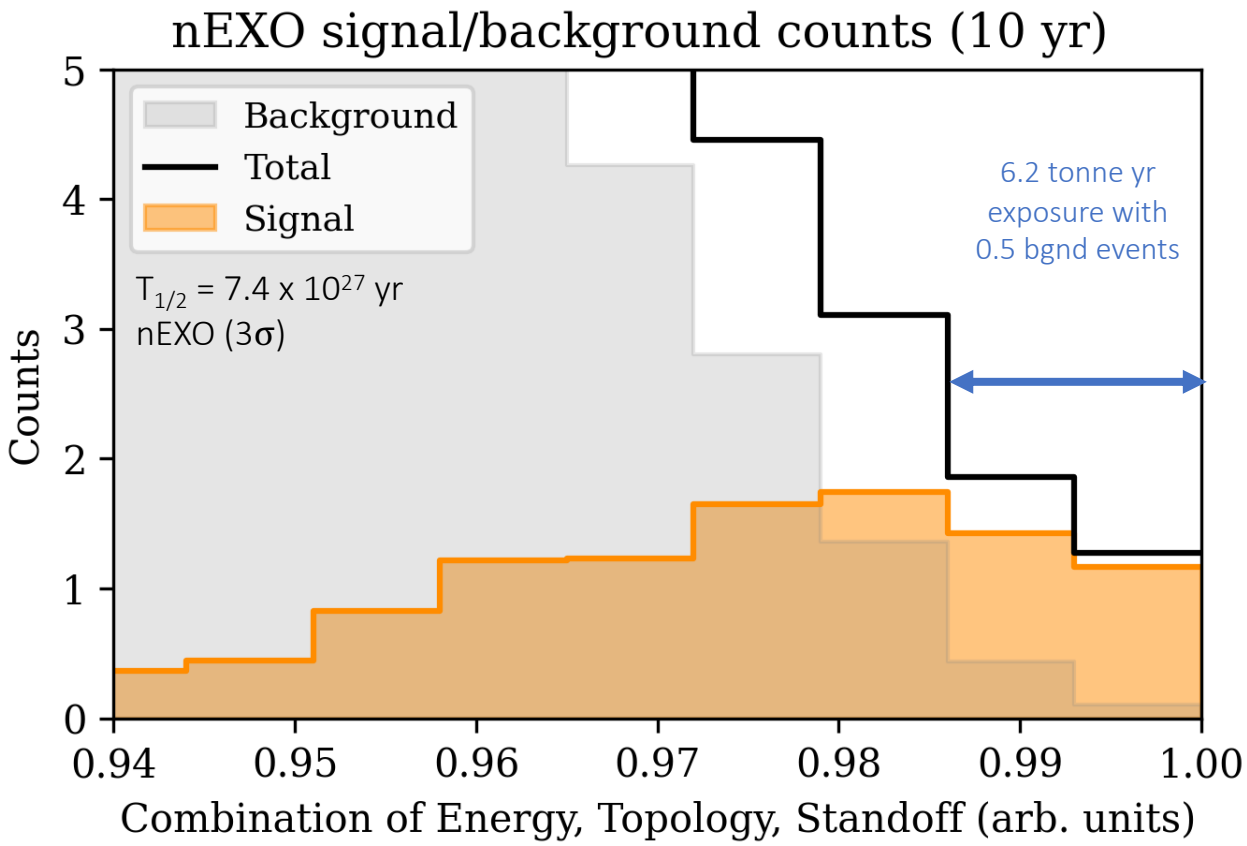
Position distribution from 3D event reconstruction

Topology, e.g., single-site or multi-site

nEXO Signal and Background

For clarity, we arrange the 3D bins into 1D, ordered by signal-to-background ratio.

Combine energy, topology, and standoff (preserving correlations)



0 ← Background-like

Signal-like → 1

➔ nEXO is a "background-free" experiment