An overview of the nEXO Experiment for the search of 0νββ

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for the nEXO collaboration

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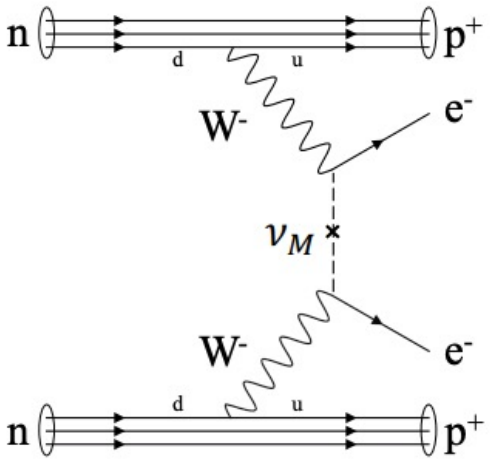
Search for New Physics with 0νββ

- 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
  - the matter-antimatter asymmetry
  - a new mass generation mechanism
  - how the universe expands and evolves
- A tonne-scale double-beta decay experiment is highly recommended and has great discovery potential for 0νββ

taken from https://www.space.com/25303-how-many-galaxies-are-in-the-universe.html



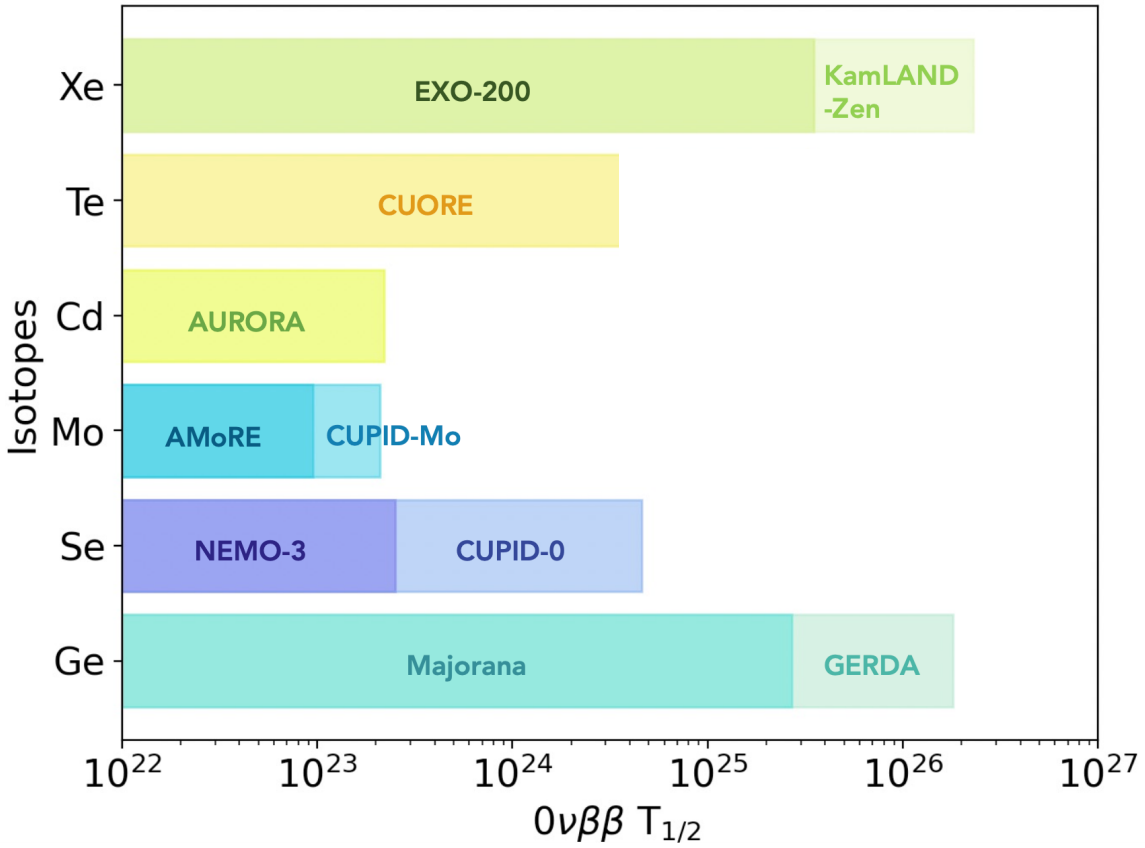
0νββ landscape

State-of-art results of different isotopes

- CUORE ^{130}Te: $T_{1/2} > 3.6 \times 10^{24}$ y
- Gerda ^{76}Ge: $T_{1/2} > 0.9 \times 10^{26}$ y
- EXO-200 ^{136}Xe: $T_{1/2} > 3.5 \times 10^{25}$ y
- KamLAND-Zen ^{136}Xe: $T_{1/2} > 2.3 \times 10^{26}$ y

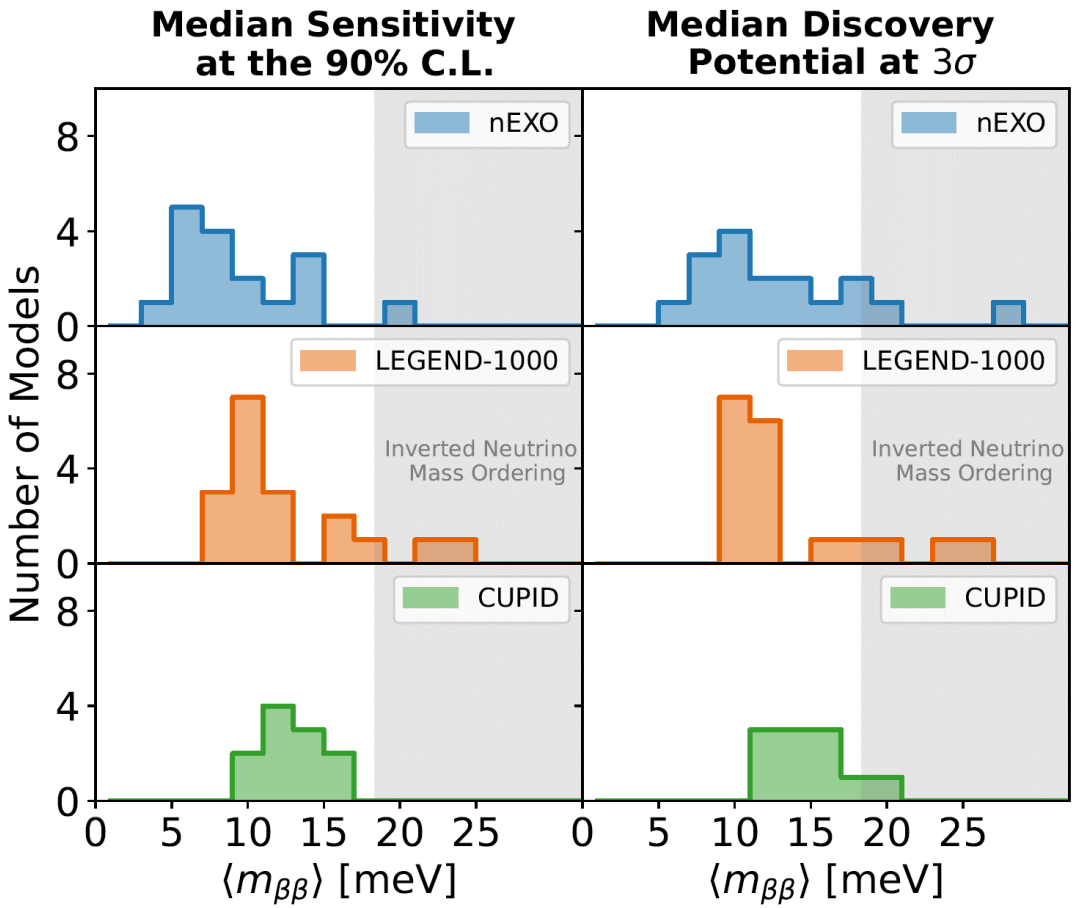
3 leading experiments launched using different isotopes and technologies

- nEXO: TPC using ^{136}Xe
- LEGEND-1000: PC using ^{76}Ge crystals
- CUPID: calorimeters using ^{100}Mo doped crystals



(Particle Data Group), Prog. Theor. Exp. Phys. 2020, 2021 update
D. Q. Adams et al. (CUORE Collaboration), Phys. Rev. Lett. 129, 2022
Gerda Collaboration, Phys. Rev. Lett. 125, 2020
G. Anton et al., Phys. Rev. Lett. 123, 2019
KamLAND-Zen Collaboration, Phys. Rev. Lett. 130, 2023 arXiv:2207.09577 [nucl-ex]

Majorana Neutrino Physics Reach of nEXO



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

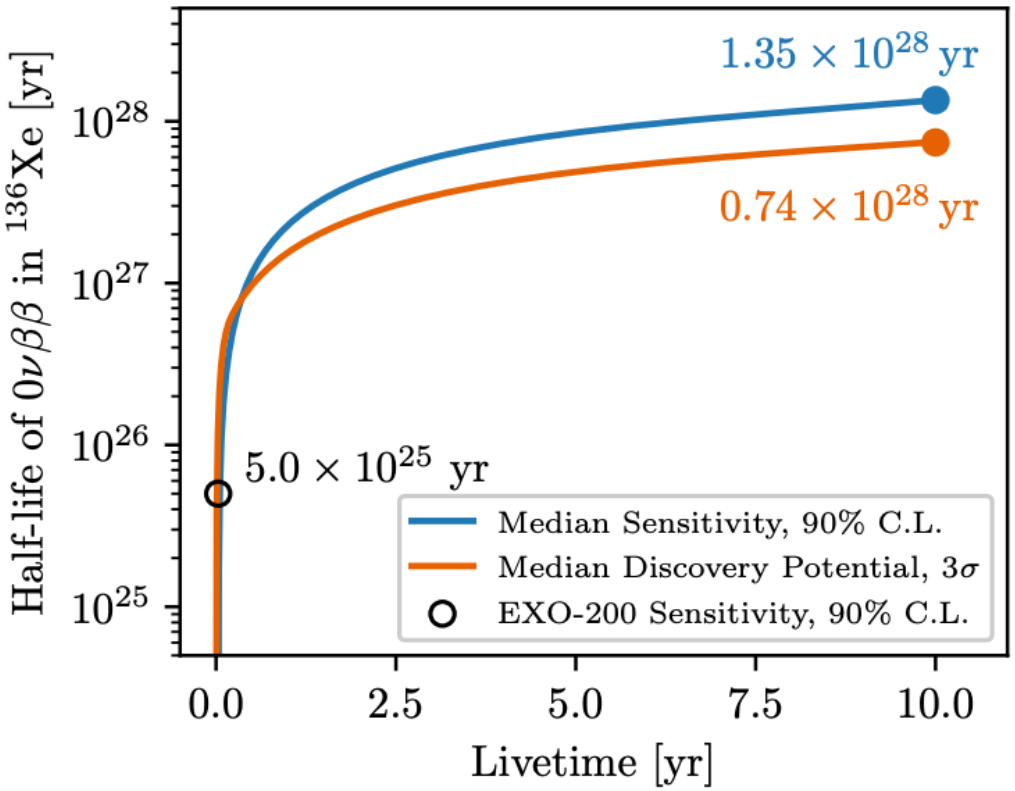
	$m_{\beta\beta}$ [meV], (*median* NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

*T1/2 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]

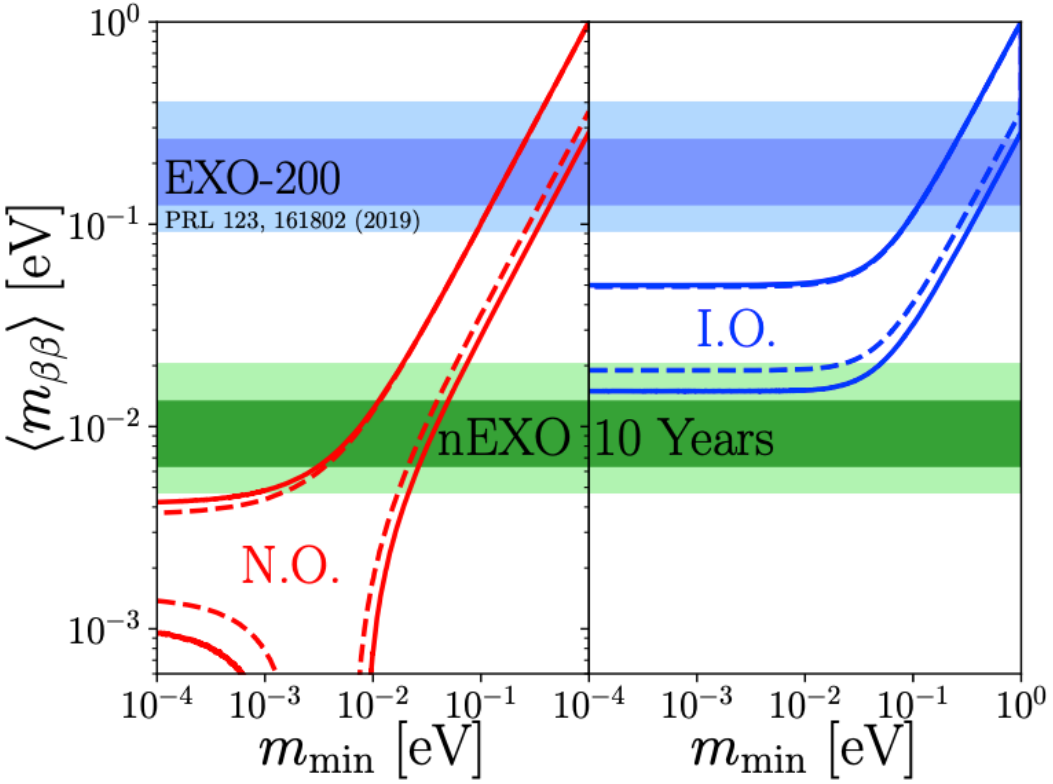
[1] nEXO collaboration, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243
[2] LEGEND pCDR, arXiv: 2107.11462
[3] CUPID pCDR, arXiv:1907.09376

nEXO sensitivity and discovery potential

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

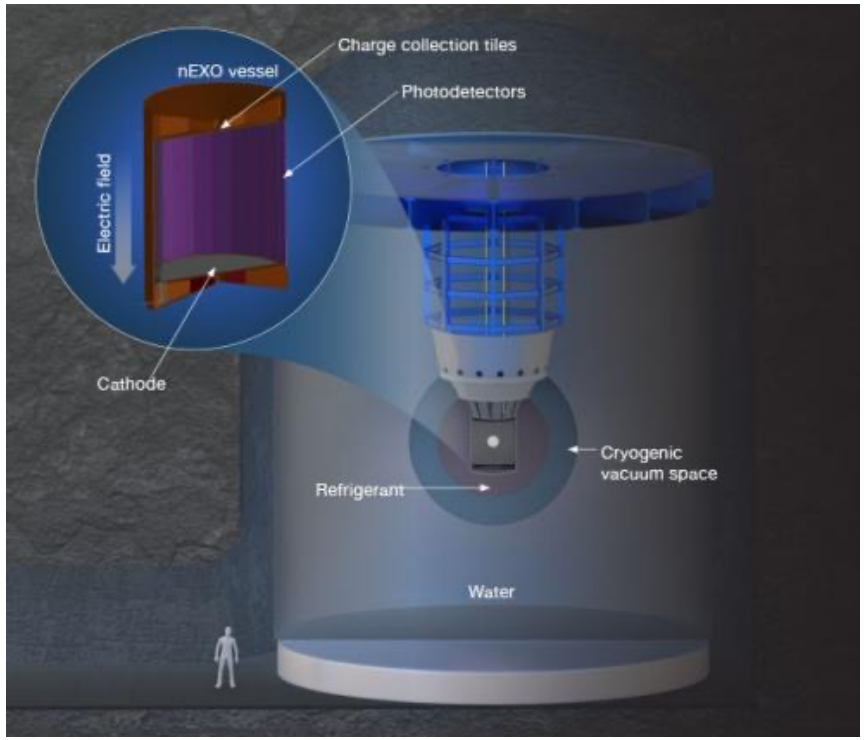


Projection of the median sensitivity and 3σ discovery potential to 0νββ decay with nEXO as functions of the detector livetime.



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

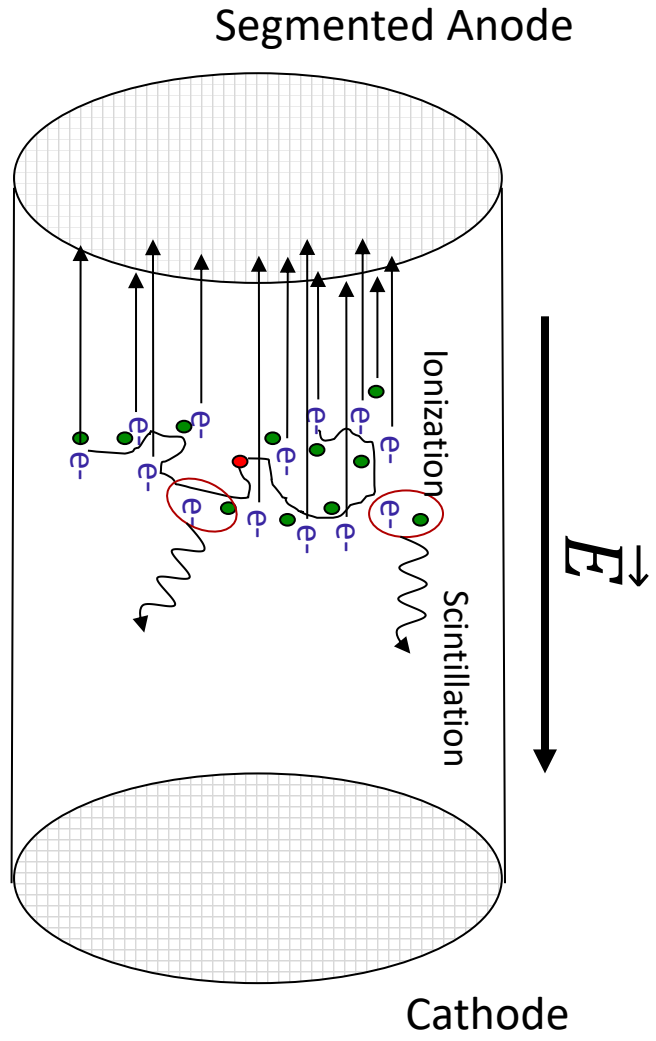
nEXO detector design



nEXO TPC detector:

- 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

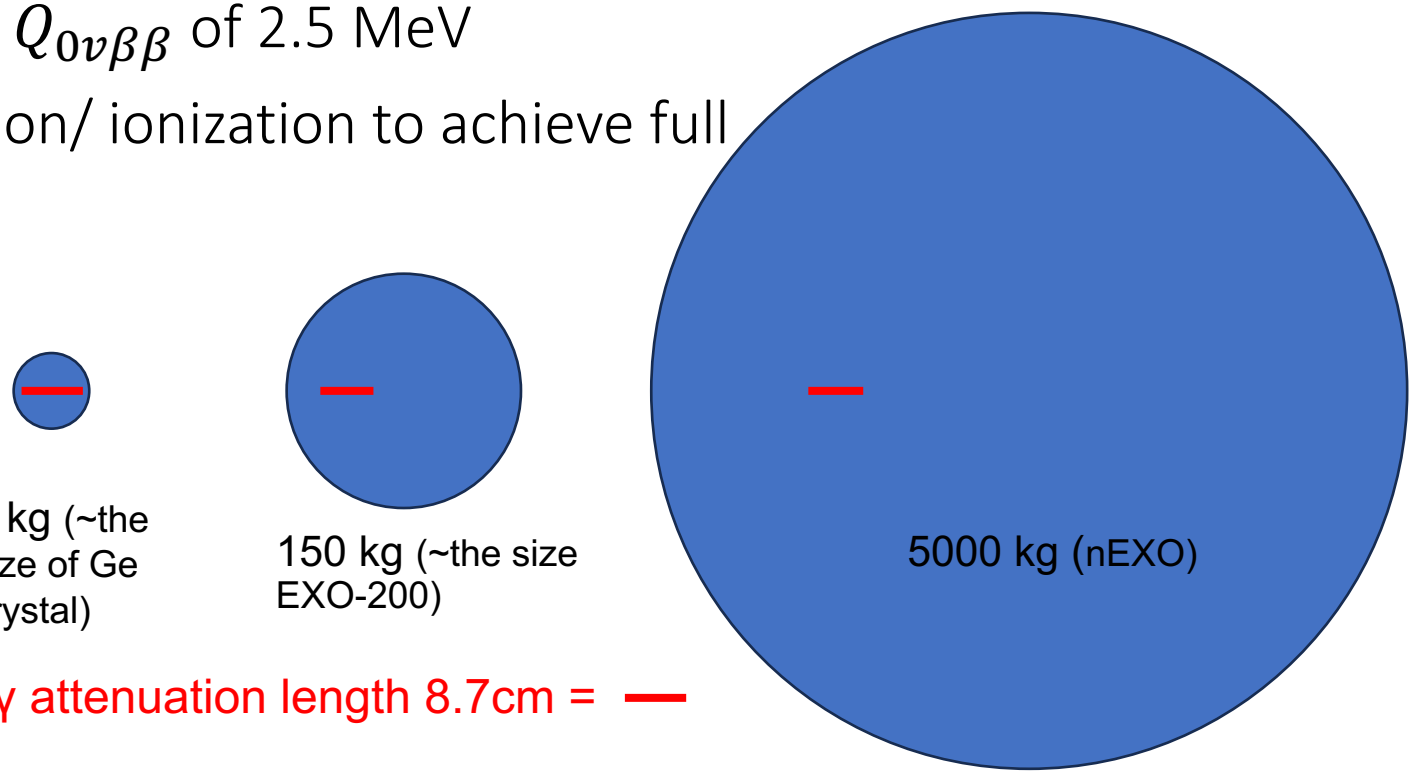
nEXO pre-CDR, arXiv:1805.11142



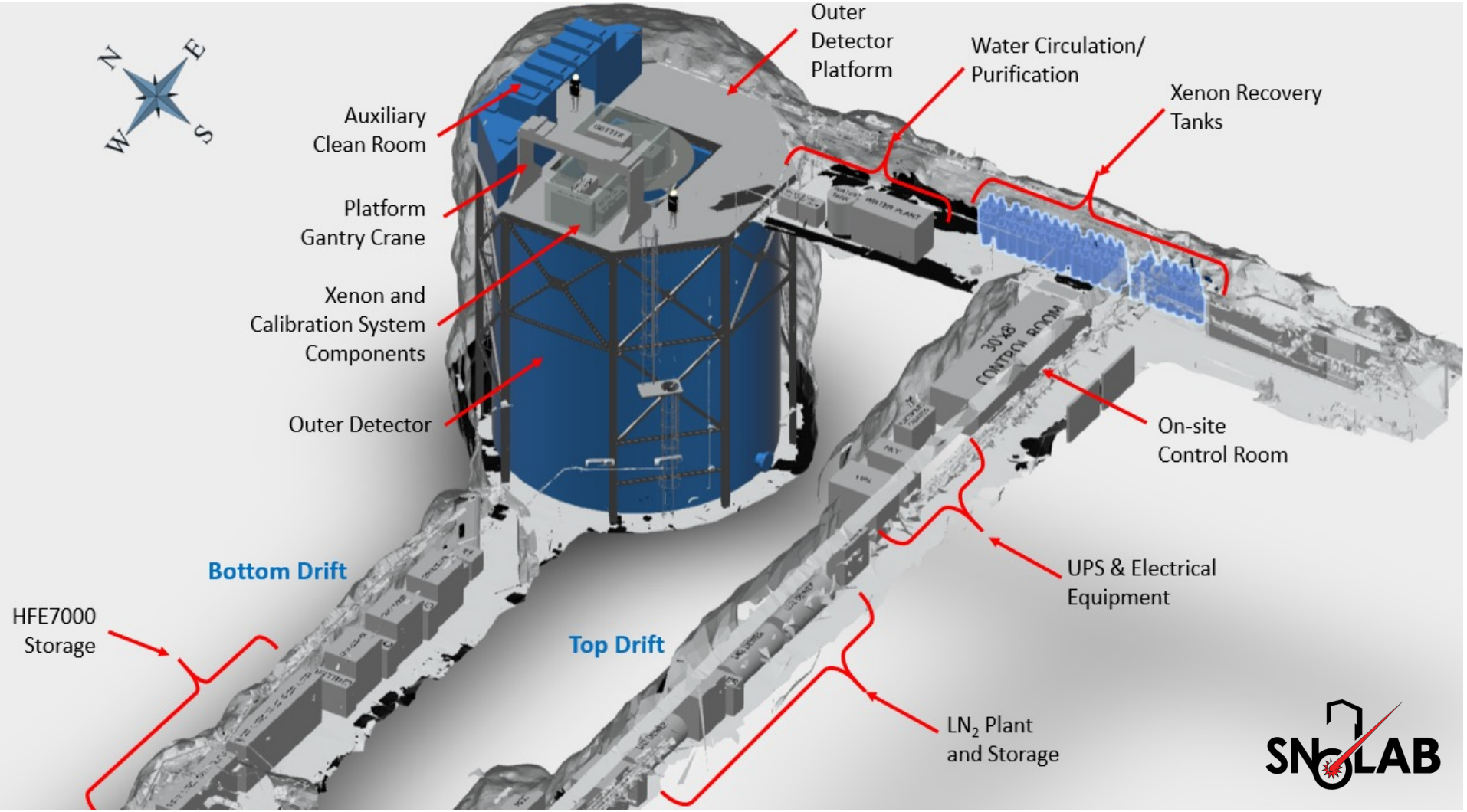
Ton-scale Monolithic/Homogeneous TPC

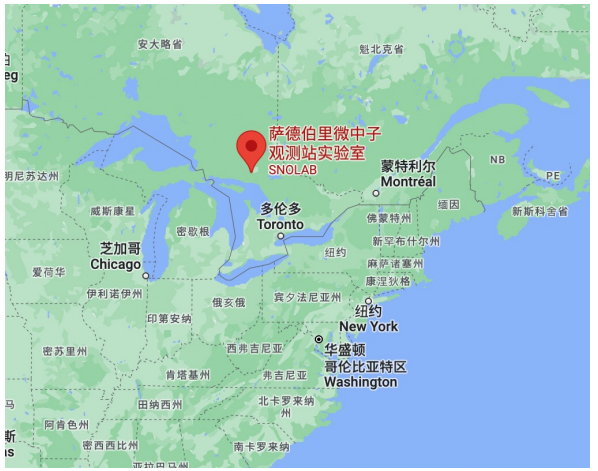
- Proved technology in EXO-200
- Scalable, re-purifiable, transferable enriched liquid xenon (LXe)
- Low radioactivity in LXe and strong self-shielding
- Better energy resolution (<1%) at $Q_{0\nu\beta\beta}$ of 2.5 MeV
- Independent readout of scintillation/ ionization to achieve full 3D event reconstruction
- Powerful background rejection

LXe Mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

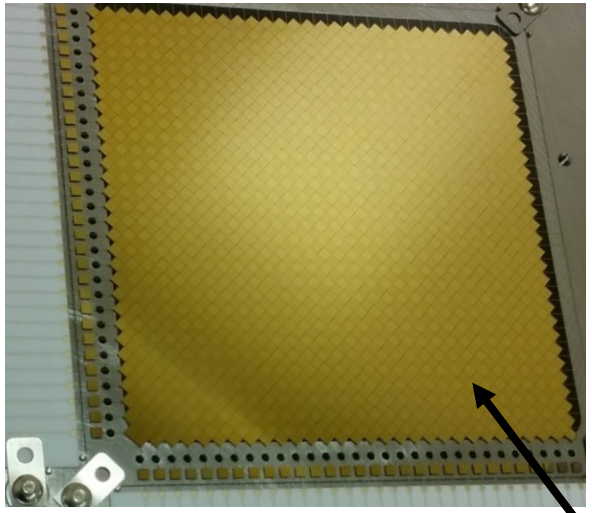


location: the Cryopit at SNOLAB



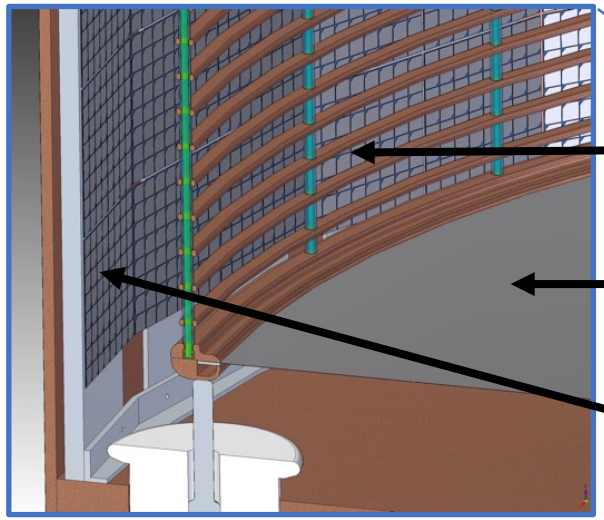


The nEXO detector

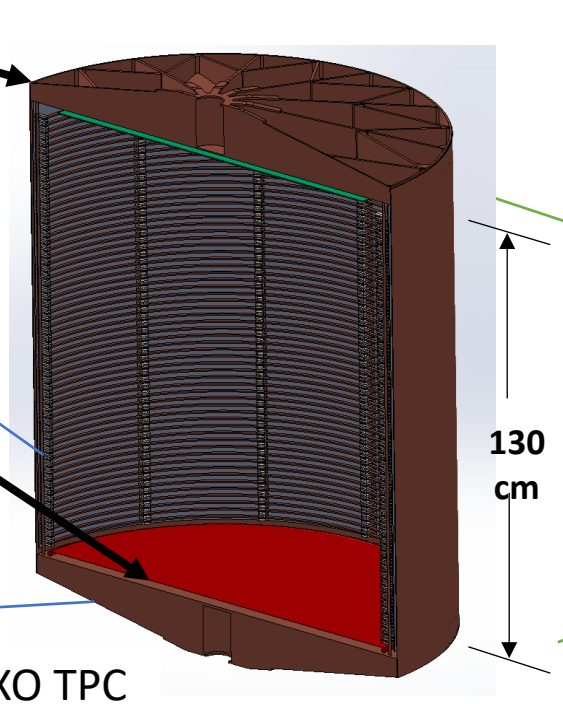


- SiPM for 175nm scintillation light detection, ~4.5m^2 SiPM in LXe.
- Tiles for charge read out in LXe.
- Cold electronics inside TPC in liquid Xe.
- Combine charge and light readout. Goal → σ/E of <1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.

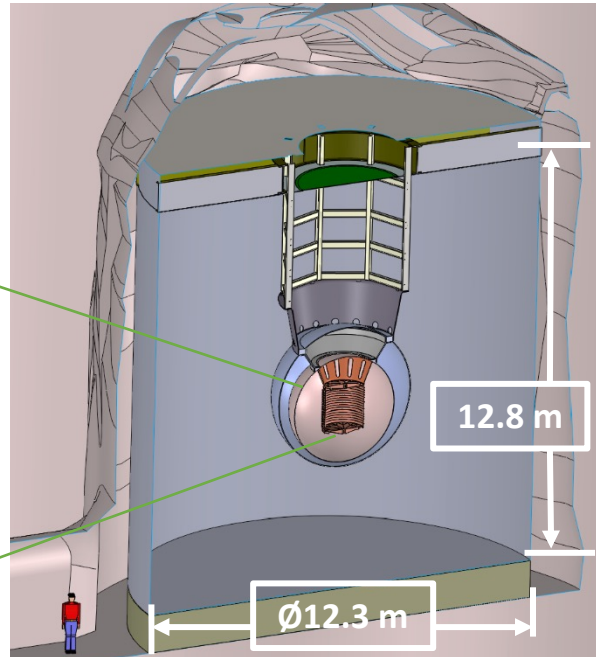
Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: JINST 14 P09020 (2019)



nEXO pre-CDR, arXiv:1805.11142



0νββ nEXO TPC



nEXO at the SNOLAB Cryopit

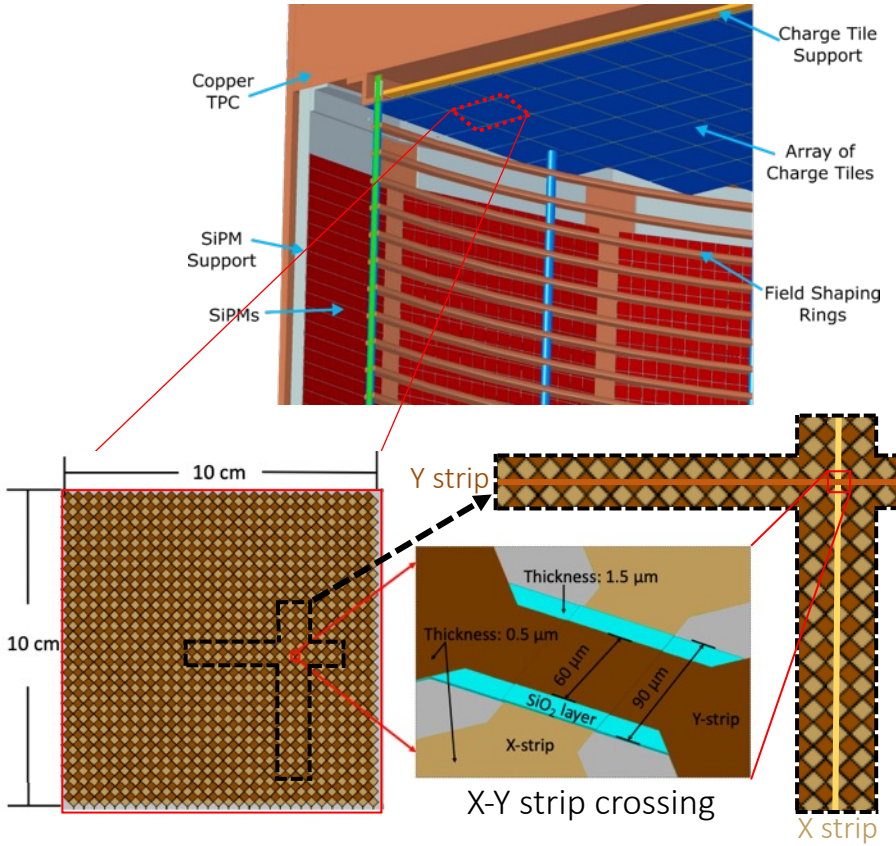
Anode Charge Readout

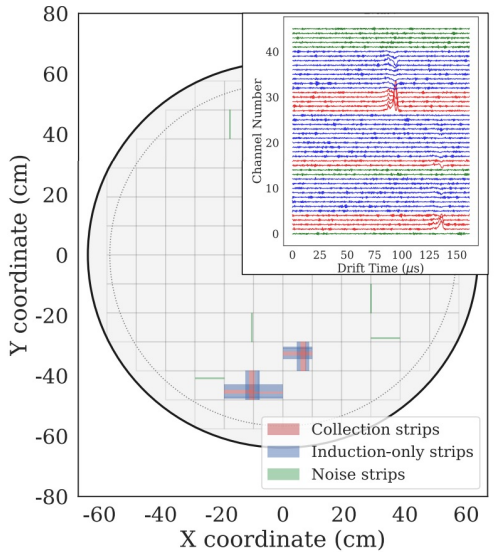
- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

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 Collaboration) "Characterization of an ionization readout tile for nEXO," JINST 13 P01006 (2018)



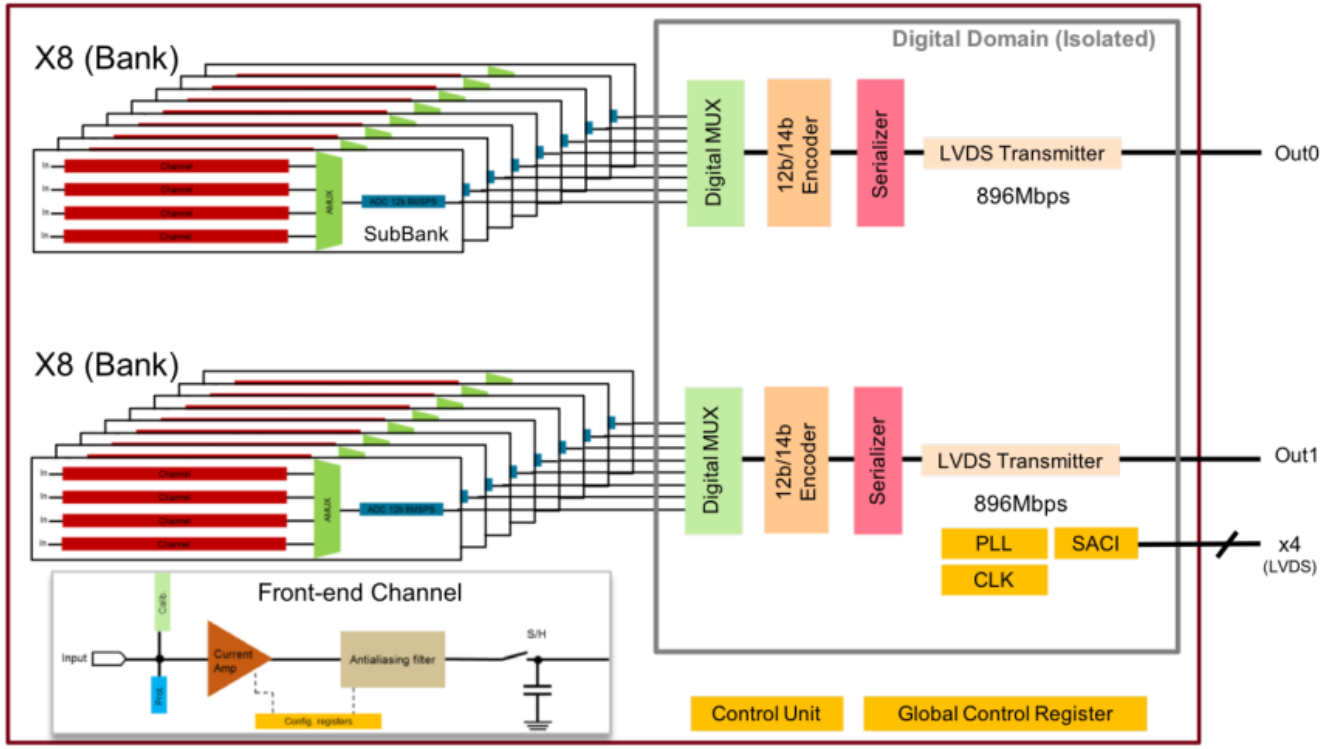


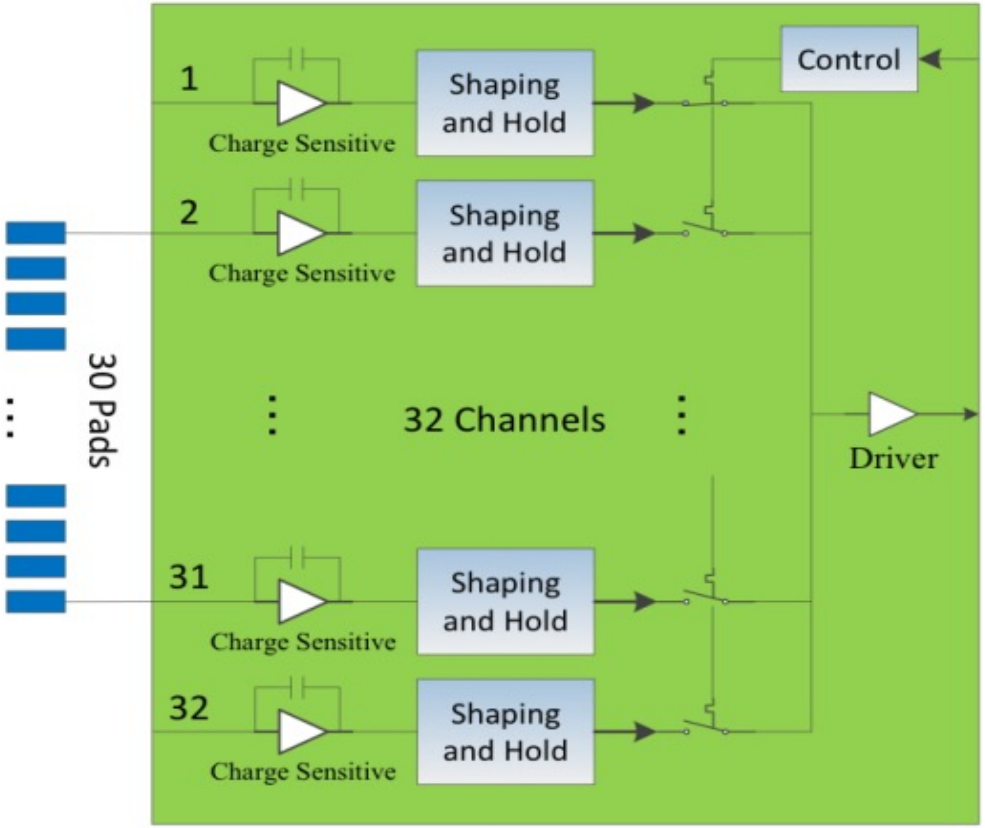
waveforms from simulations

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

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





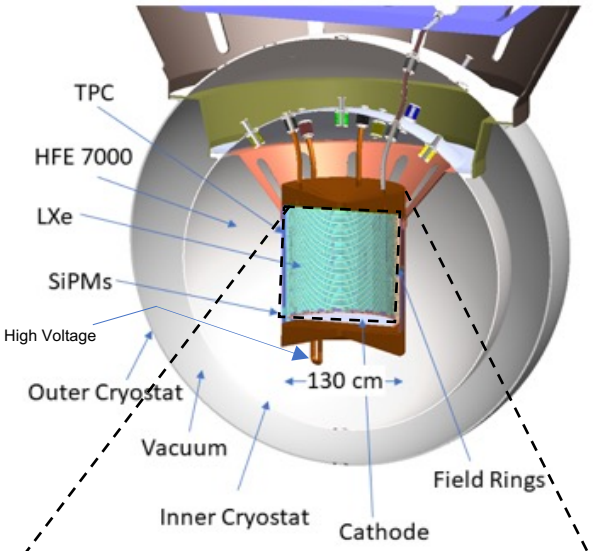
SiPM Photo-detector

Advantages of SiPMs for photon detection

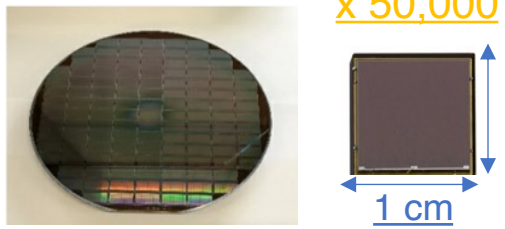
- Low intrinsic radioactive backgrounds.
- Improved energy resolution (SiPMs high gain).
- Lower bias required for SiPMs (~50 V versus ~1.5 kV).
- Devices from 2 vendors meeting requirements, demonstrated through R&D.

Energy resolution:

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

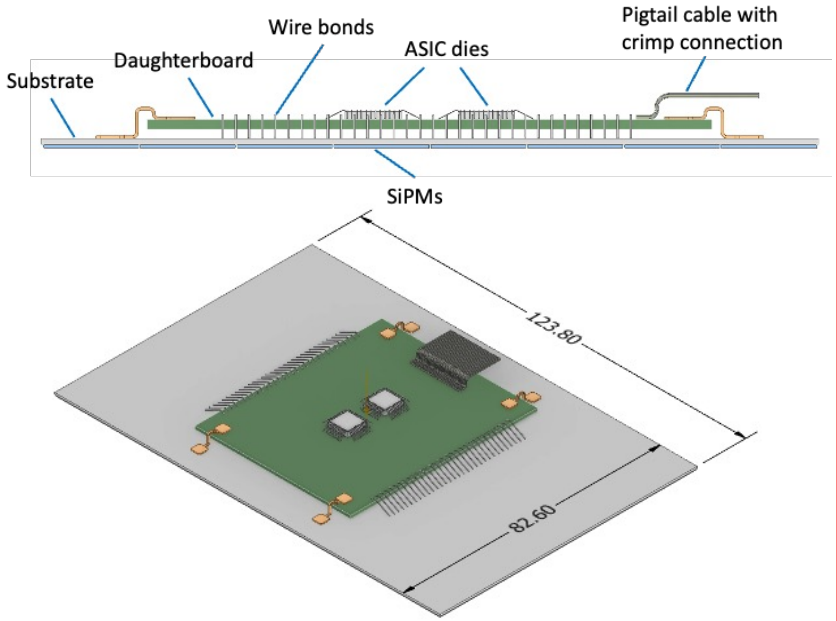


SiPM Devices



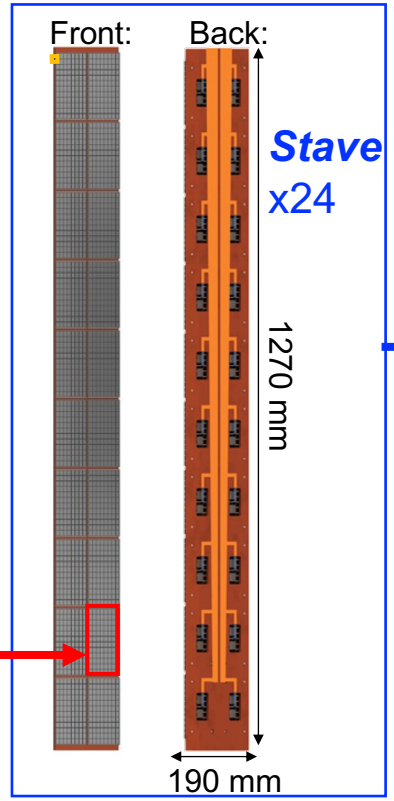
Tested SiPMs

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

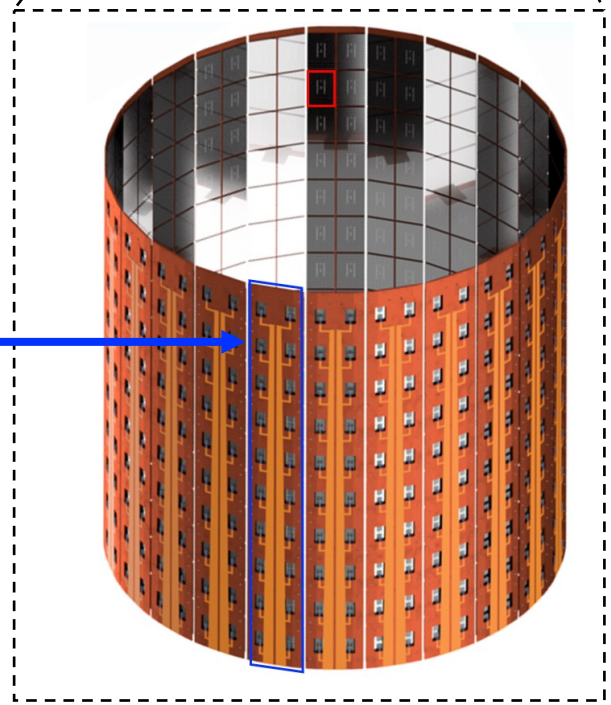


Tile module

x 480



Stave
x24

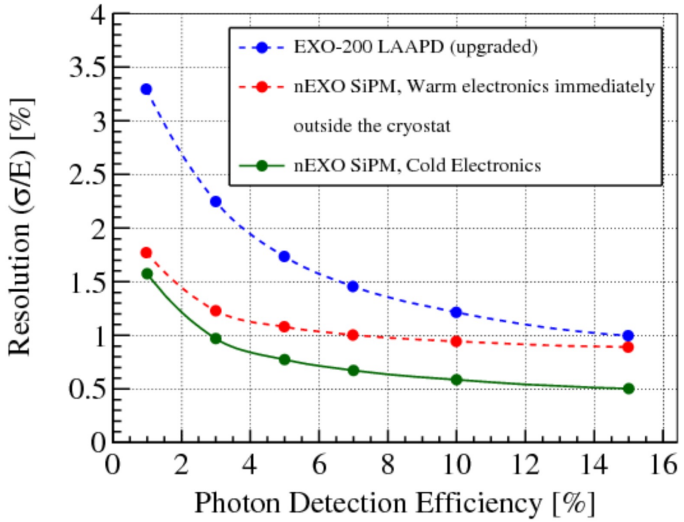


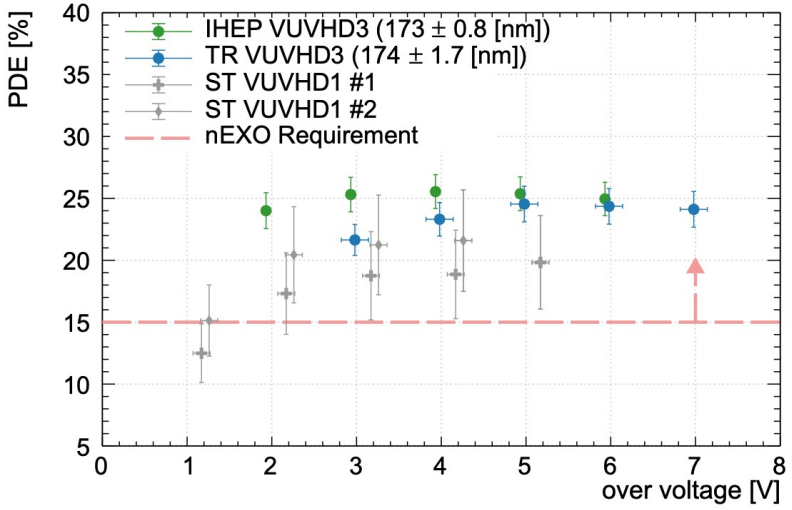
Photon detector (PD)

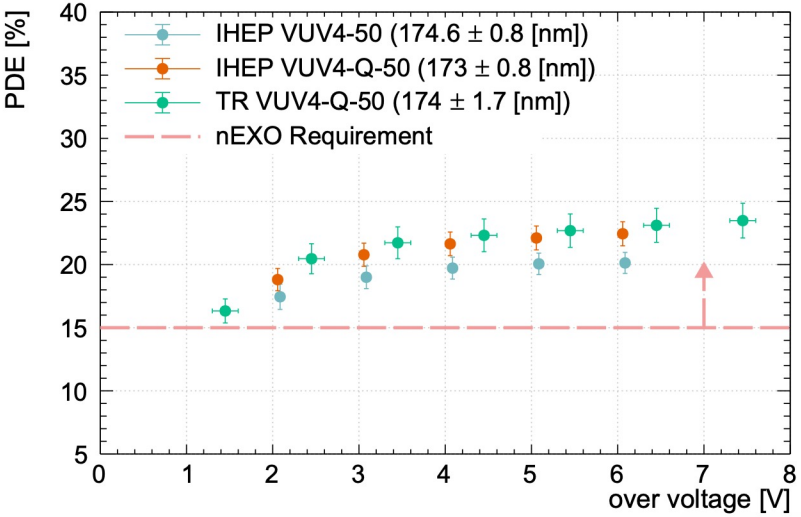
SiPM technical requirements

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

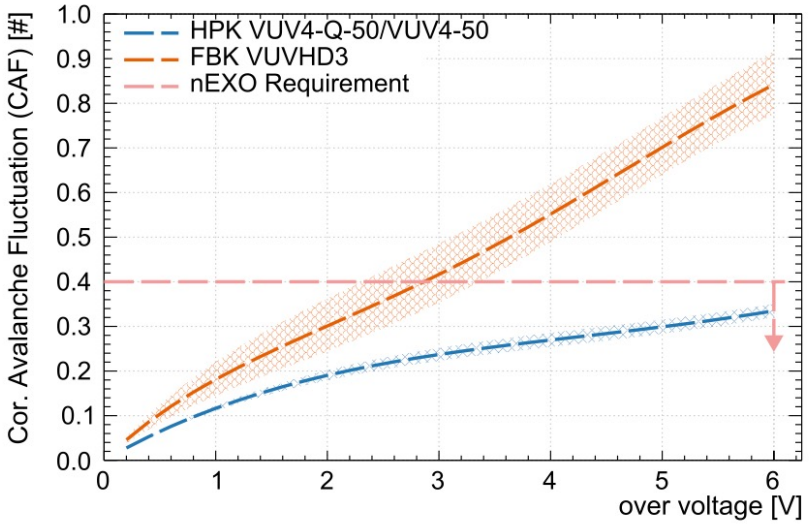
VUV-sensitive SiPMs performance test

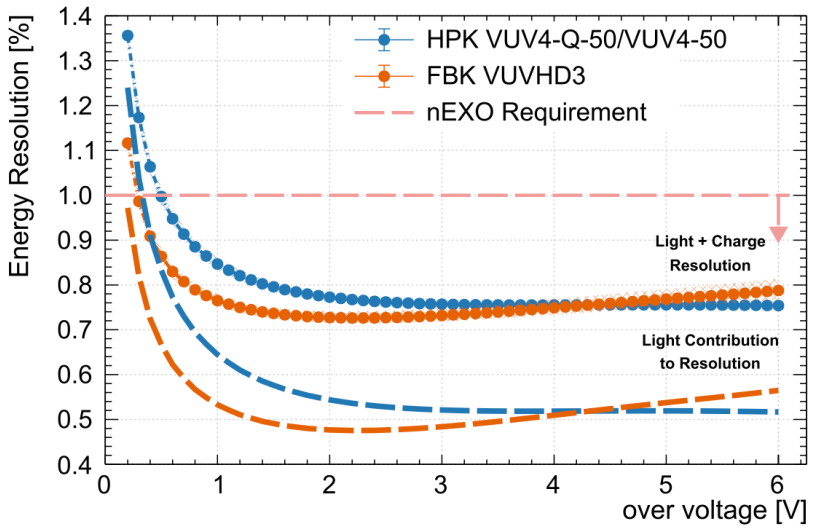






- SiPM photon detection efficiency is crucial to the nEXO energy resolution
- Independent tests have been performed by Triumph, BNL and IHEP

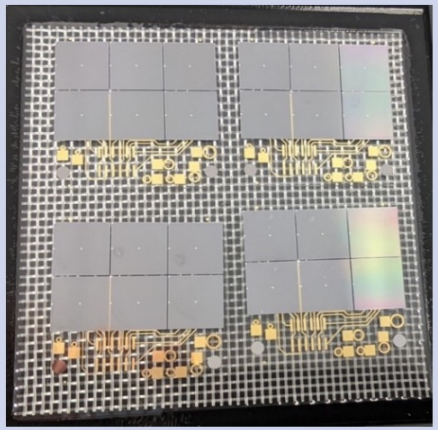


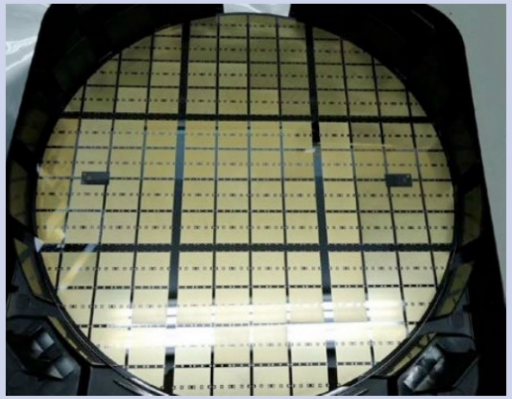


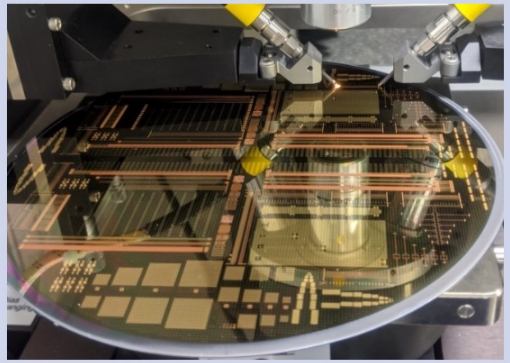
Eur. Phys. J. C **82**, 1125 (2022)
nEXO

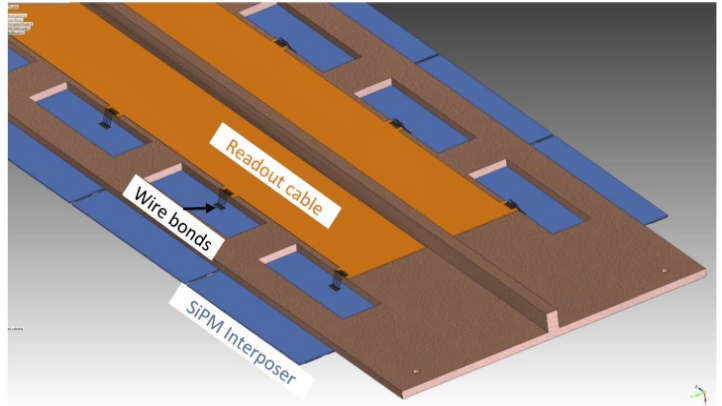
Interposer technologies

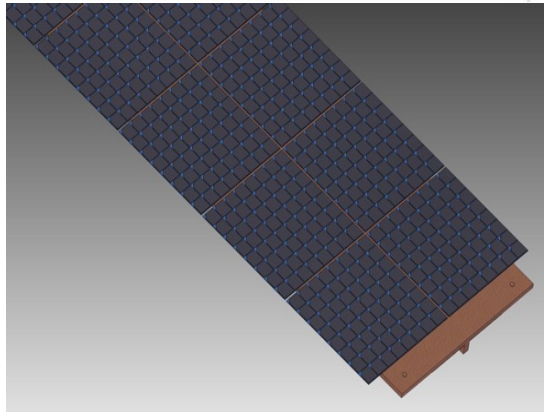
USA Brookhaven National Laboratory	CHINA IHEP-IME	CANADA Sherbrooke-TRIUMF-IZM
Fabricated by Tecdia (USA) Silica substrate, passive 2 layers (1|1), TQV	Fabricated by IHEP (China) Silicon substrate, passive 3 layers (1|2), TSV	Fabricated by IZM (Germany) Silicon substrates, passive Up to 10 layers (4|2|4), TSV

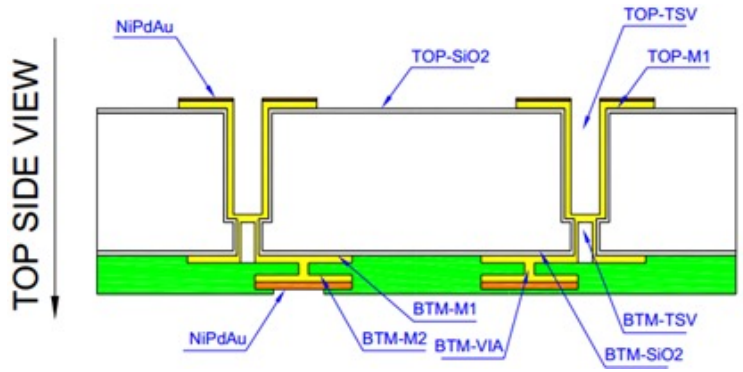






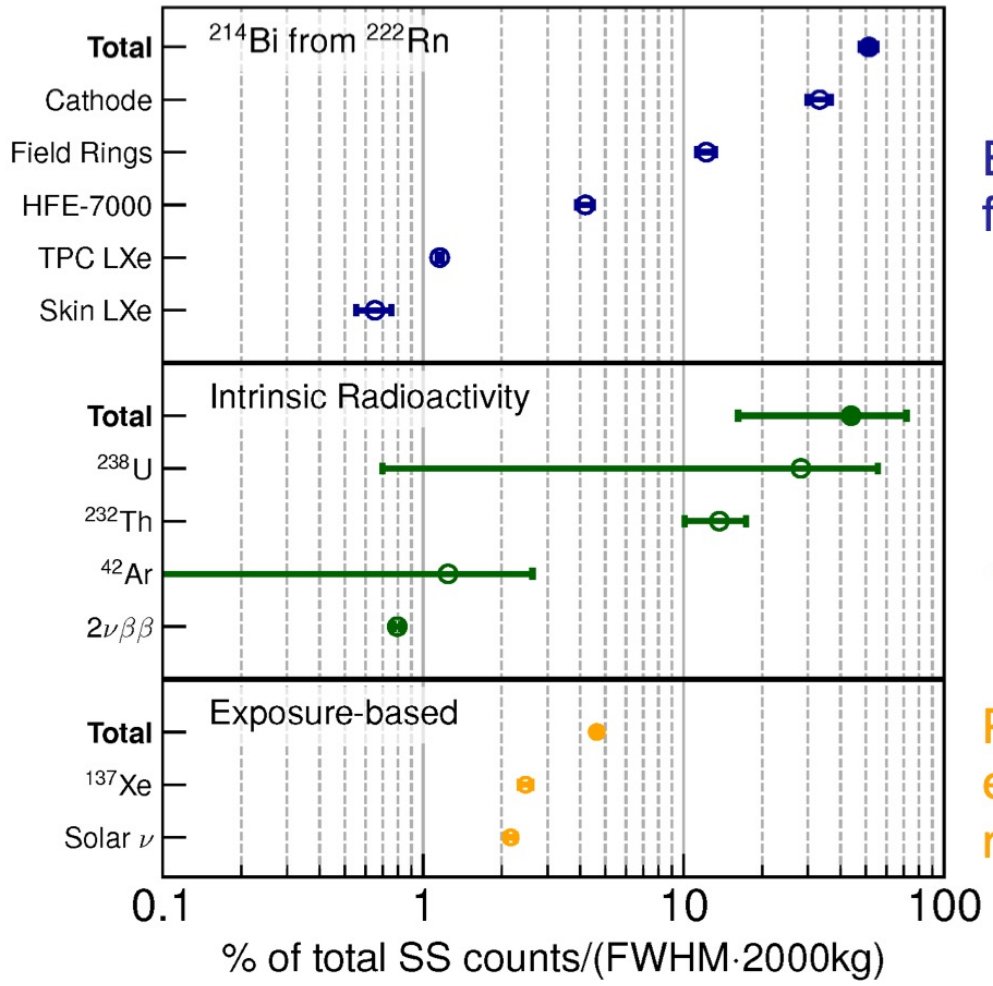






- To meet the requirement of ultralow radioactivity background
- Both silicon and quartz interposer are under development

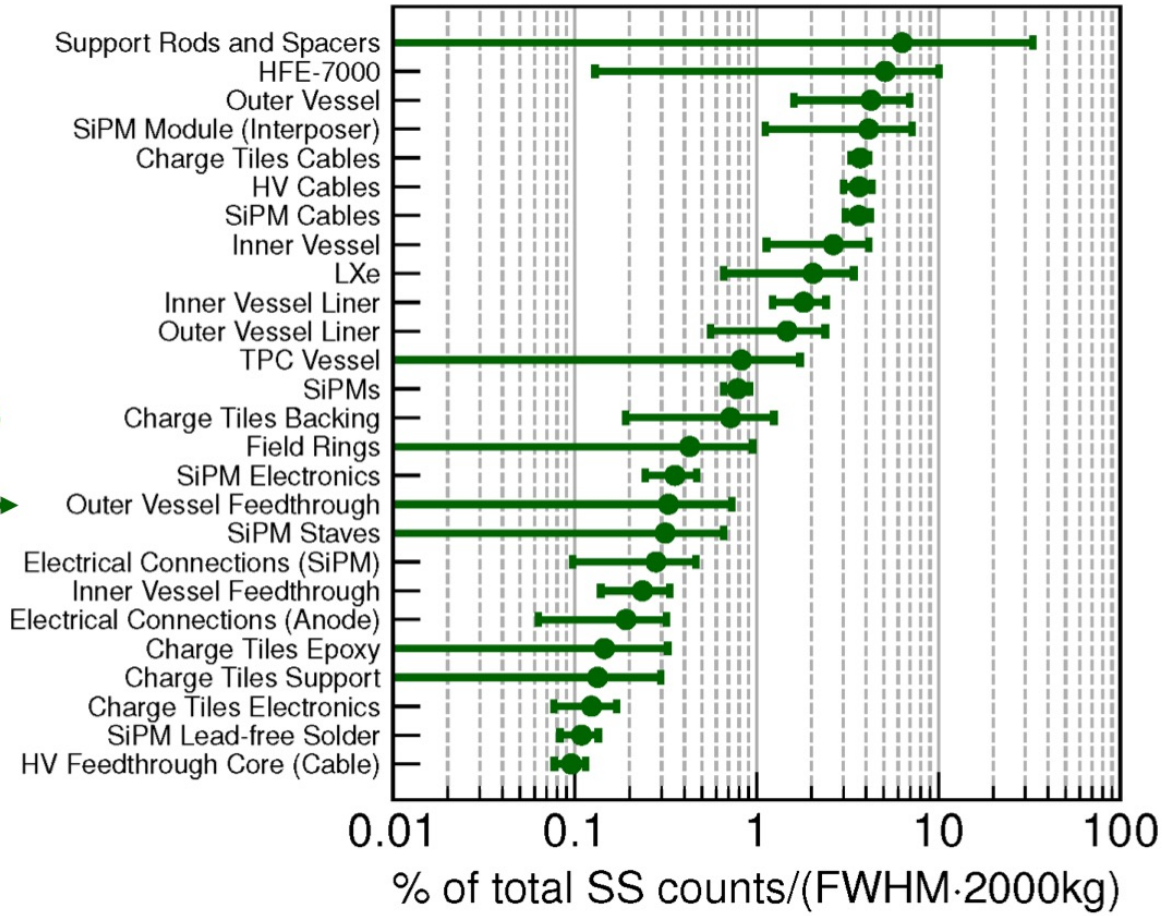
Background budget



Extrapolated from EXO-200

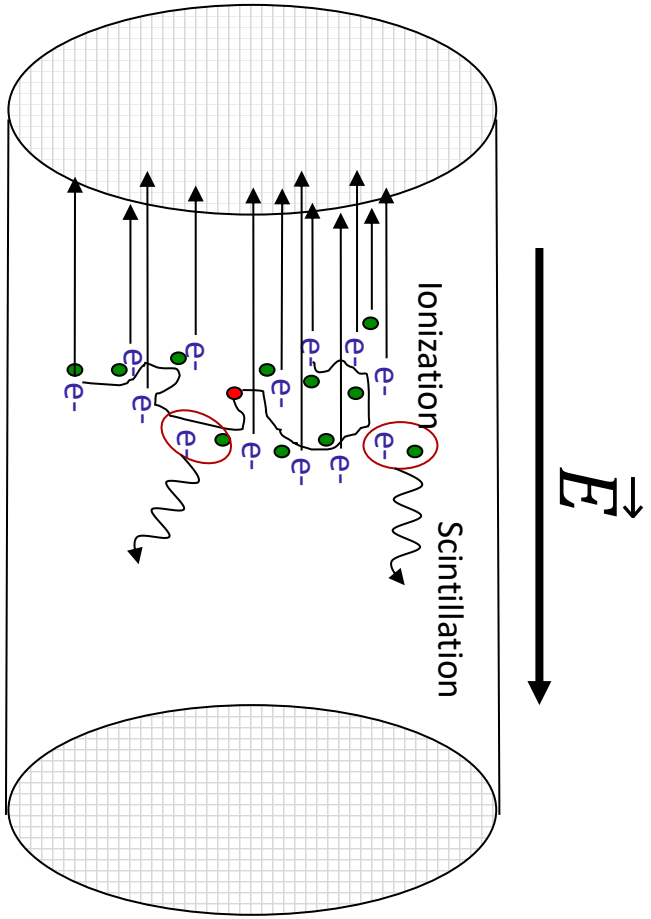
Radioassay measurements of materials

Predicted via external measurements



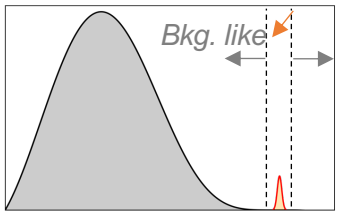
nEXO Signal and Background

Segmented Anode

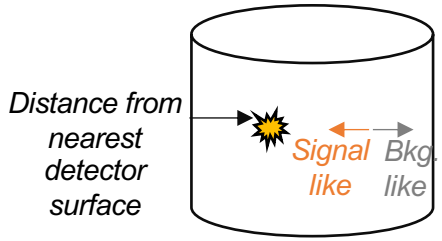


nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal

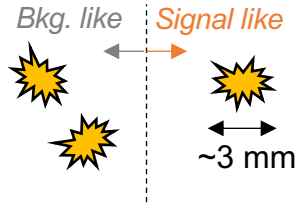
Energy: *Signal like*



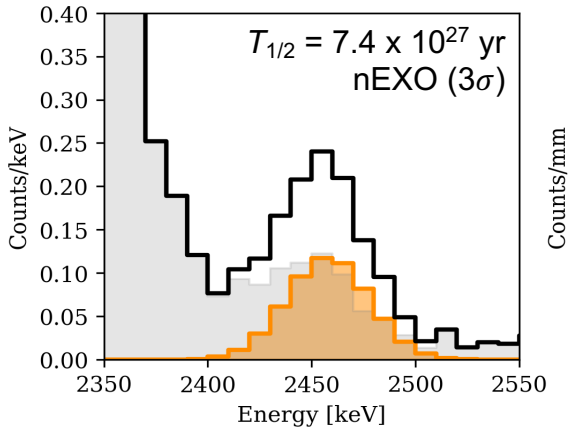
Standoff:

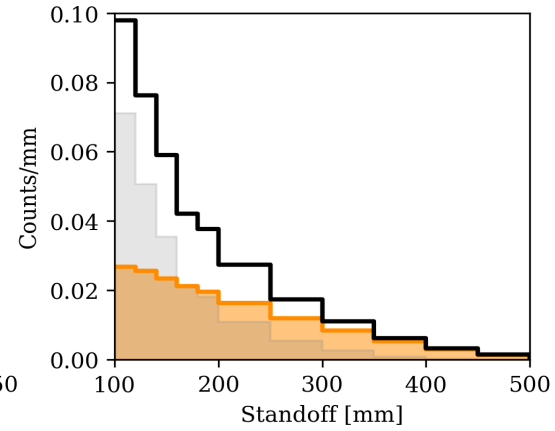


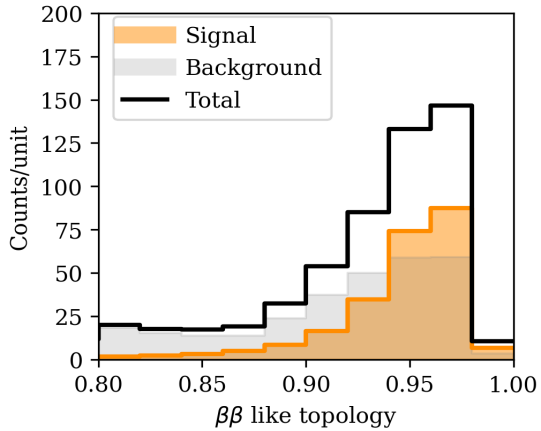
Topology:



1D projections of simulated nEXO signal and backgrounds:







Energy from combined scintillation/ionization

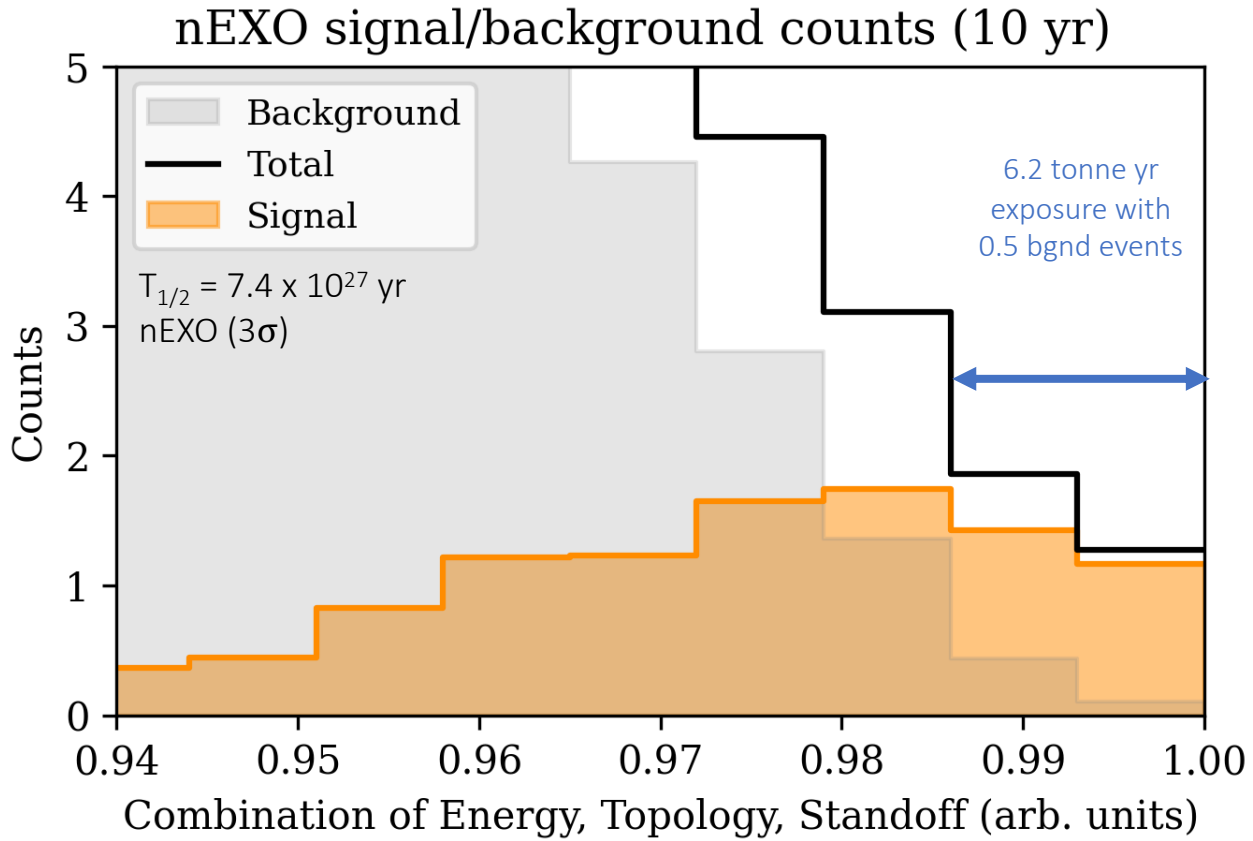
Position distribution from 3D event reconstruction

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

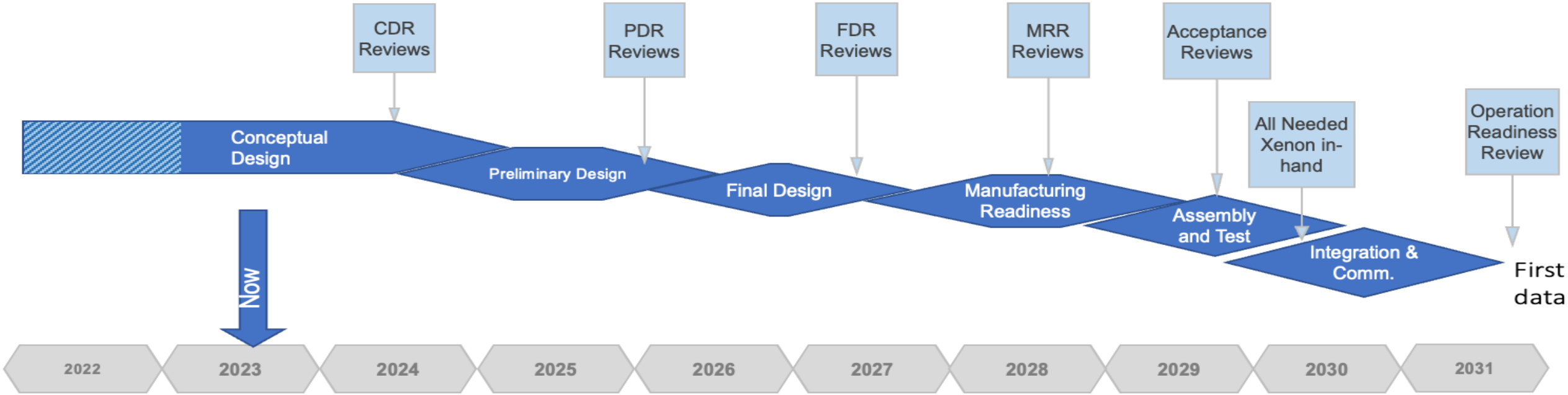
➔ nEXO is a "background-free" experiment

The international nEXO collaboration

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

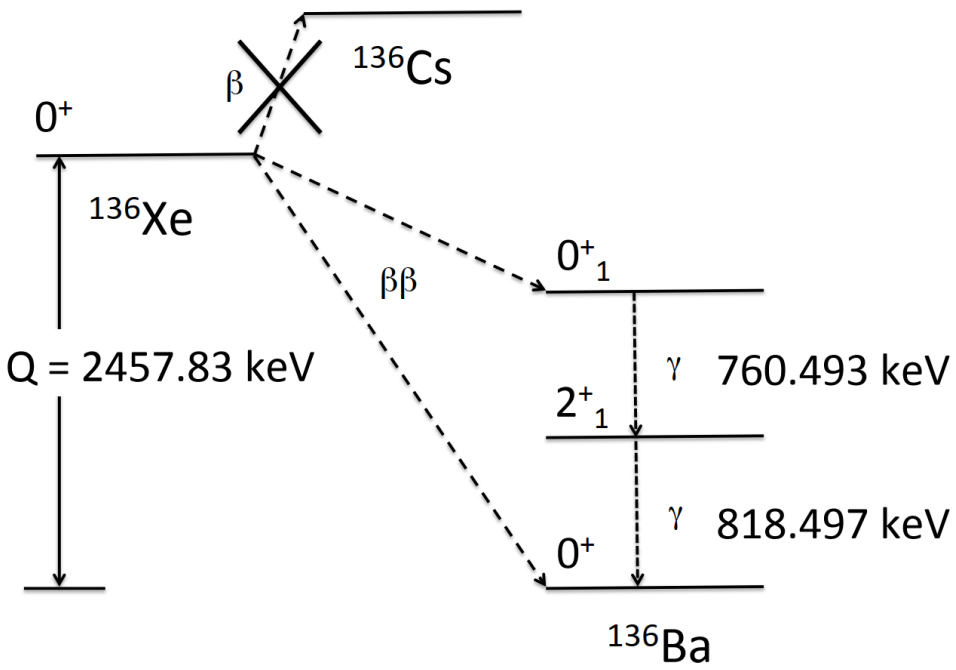
Summary

- nEXO is a discovery focussed 0νββ experiment.
- nEXO has conducted extensive R&D work and now we have a mature detector design. We are still working on further improvements.
- 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 a large parameter space of $m_{\beta\beta}$.



Back-up

Enriched ^{136}Xe in the nEXO TPC



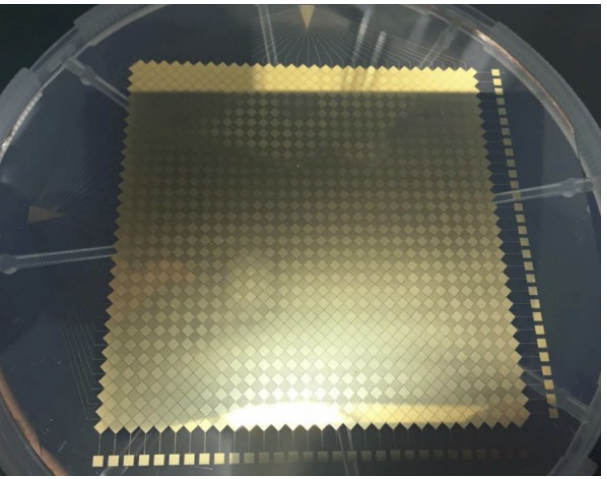
Level scheme of the ββ decay of ^{136}Xe

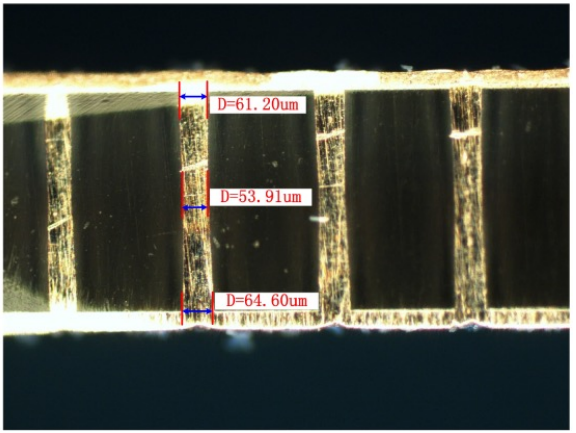
Phys. Rev. C 93 (2016), 035501
Phys. Rev. Lett. 98, (2017) 053003

- 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))

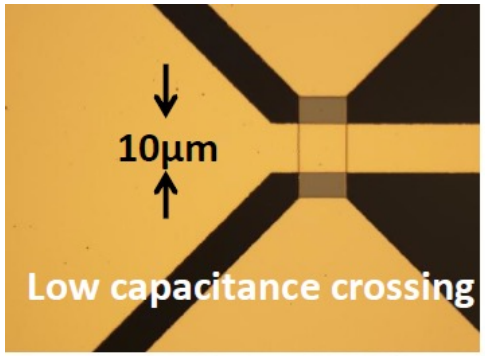
Charge detector design

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

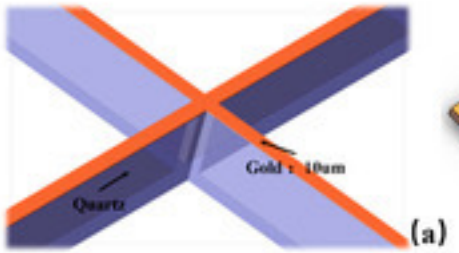


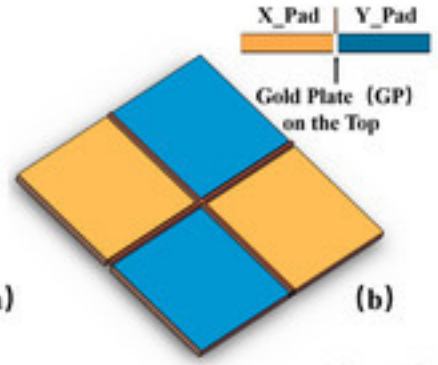


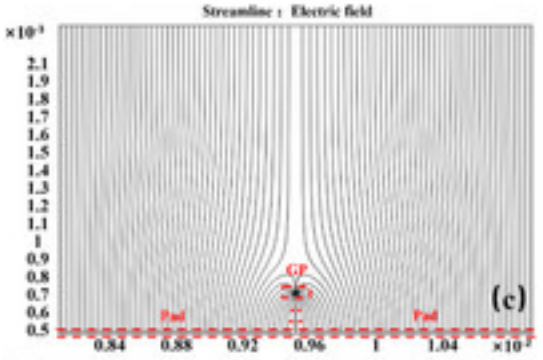
80 fF at crossings
0.86 pF between adjacent strips

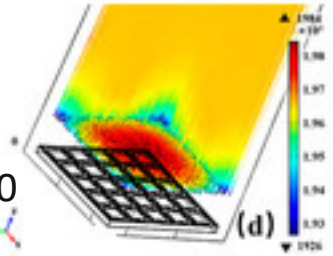


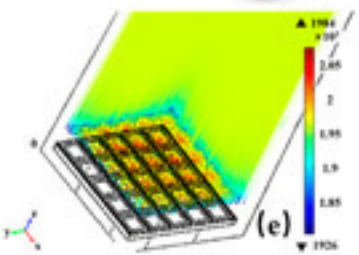
Radiation Detection Technology and Methods (2019) 3:12 https://doi.org/10.1007/s41605-018-0090-y

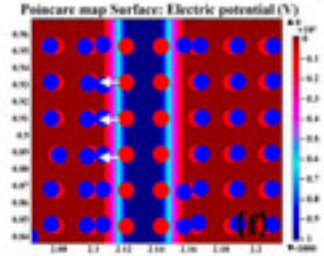


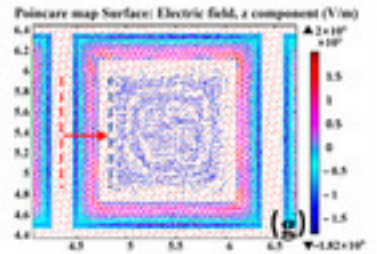


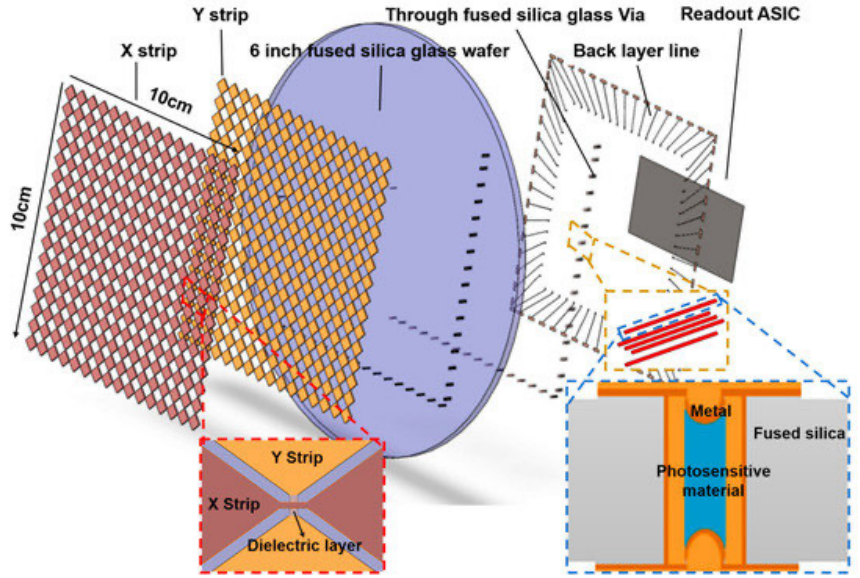










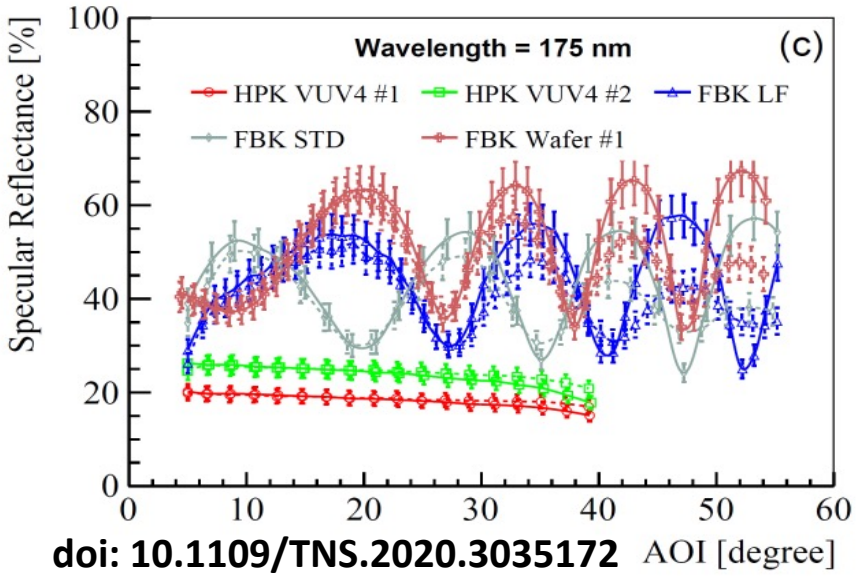


Electronics **2023**, *12*(4), 1045;

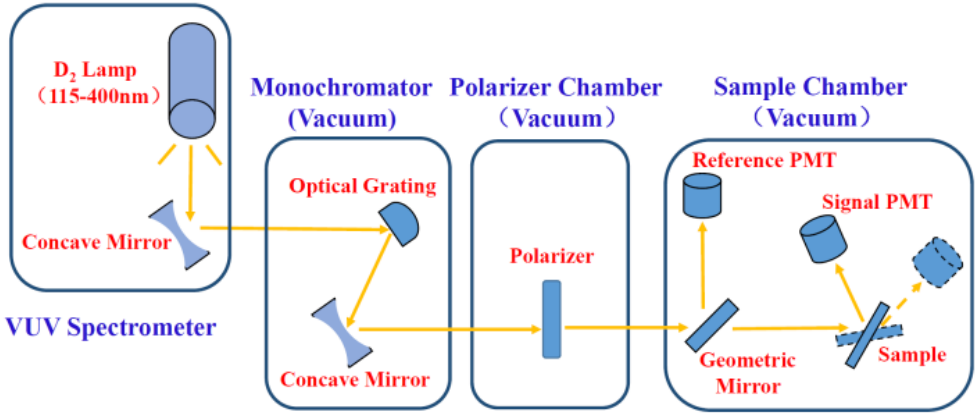
nEXO

SiPM reflectivity study

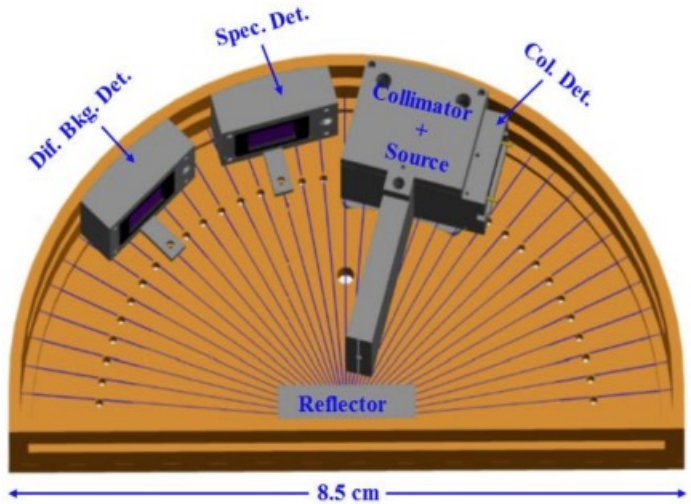
- One setup to measure SiPM reflectance in vacuum
  - IHEP & IOE, 115 nm to 400 nm, 5 – 55 degree
- Two dedicated setups for measuring reflectance in LXe
  - LIXO (UA)
    - Apparatus immersed in Lxe, use ^{252}Cf source to excite LXe (~175nm light)
    - Collimator + quartz window assembly, to prevent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



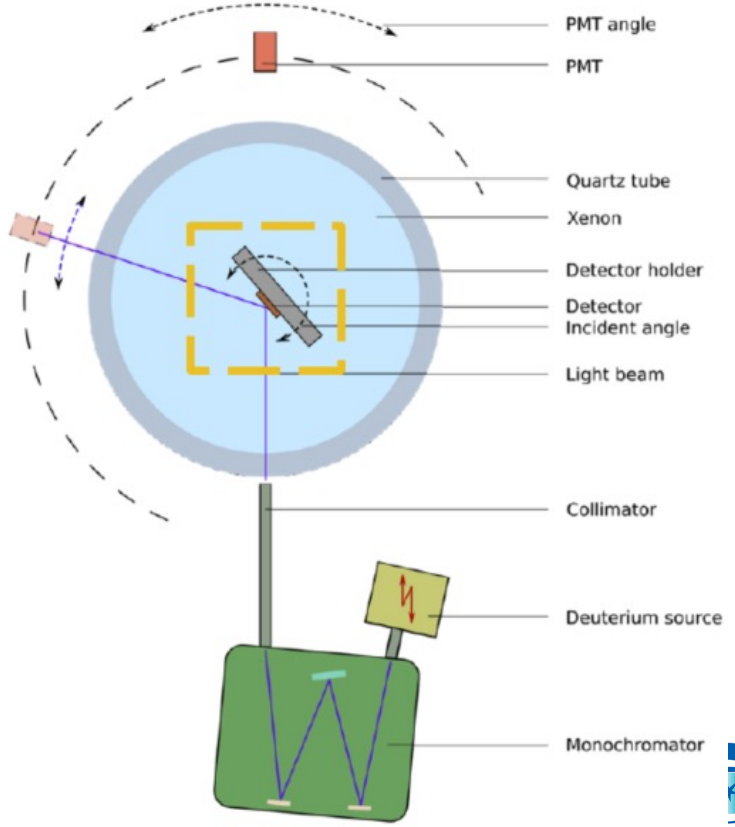
doi: 10.1109/TNS.2020.3035172



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

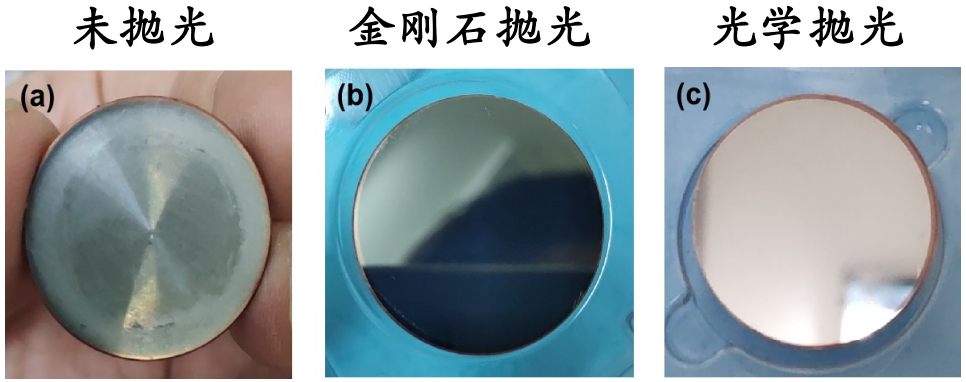


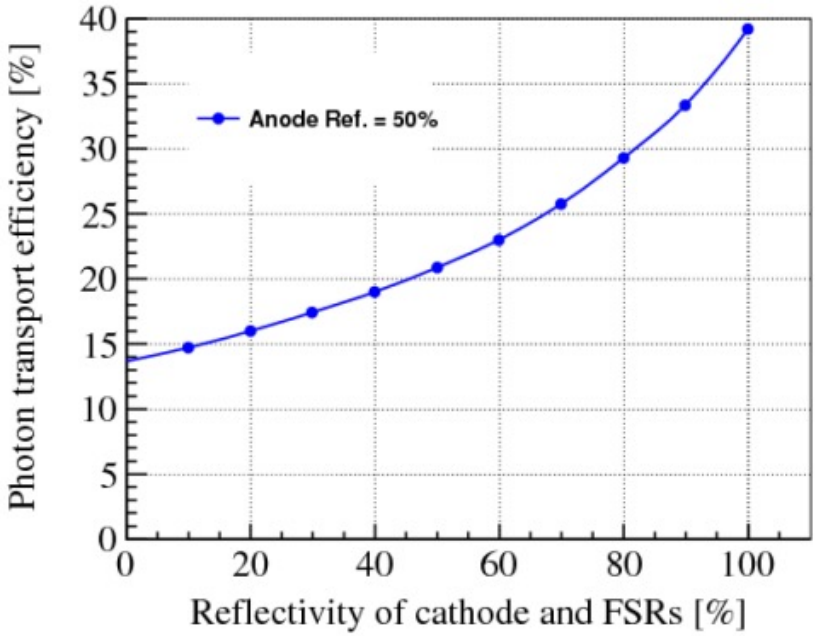
JINST 15 (2020) P01019



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.





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