nEXO无中微子双beta衰变实验

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第三届地下和空间粒子物理与宇宙物理前沿问题研讨会
2024年5月8日，四川，西昌

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

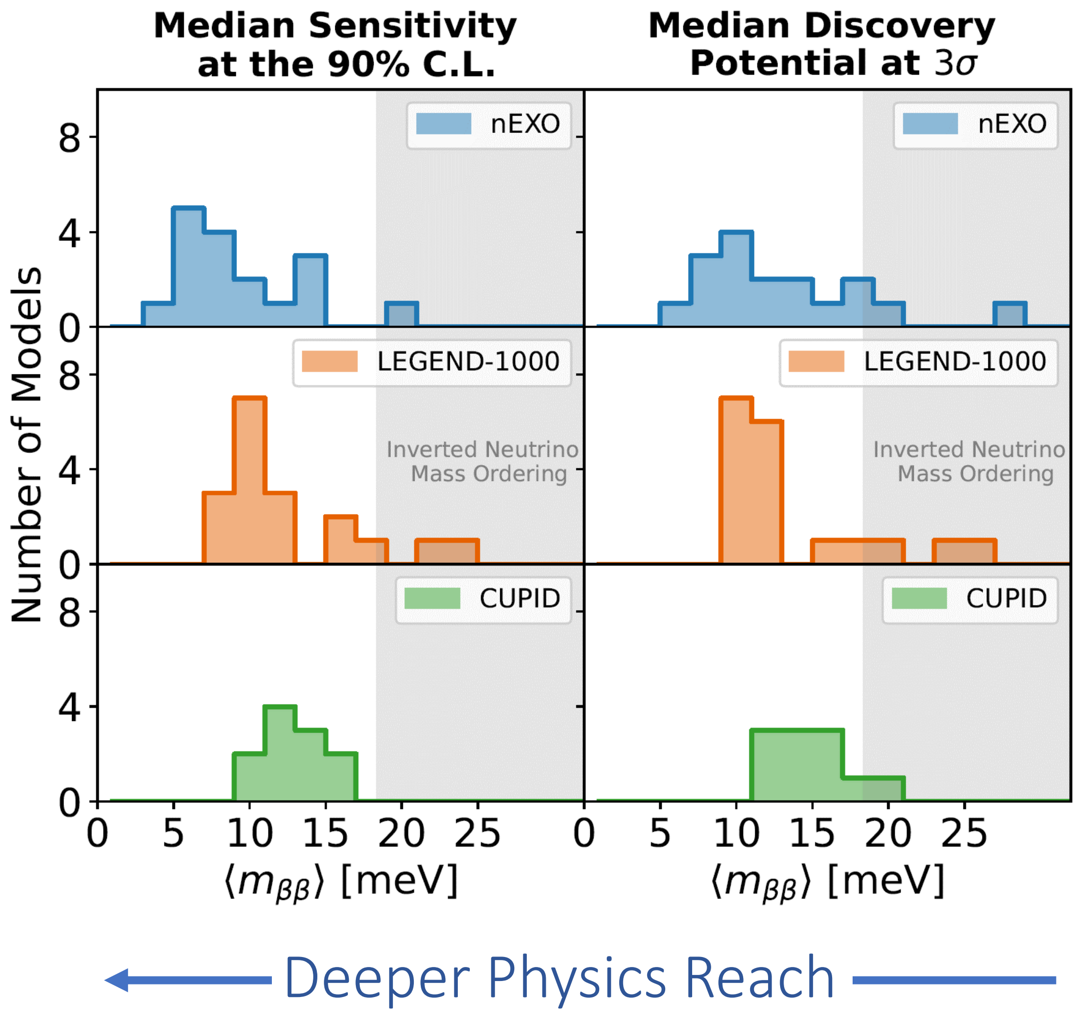
概要

- 0νββ 及nEXO介绍
- 探测器设计，软件与物理
  - nEXO灵敏度分析
  - nEXO探测器设计
- 探测器 R&D
  - 电荷读出系统
  - 光探测系统
  - 主要工作
- 高能所小型液氙时间投影室MiniTPC
- 总结

nEXO简介

- nEXO （next Enriched Xenon Observatory） 是EXO-200的升级实验，其将在5吨的^{136}Xe同位素中寻找无中微子双贝塔衰变。为了尽可能排除放射性干扰，实验预期置于加拿大安大略省萨德伯里的SNOLAB地下两千多米的深度下进行。
- **低本底事例率**、**高能量分辨率**是其两个核心的设计指标。

不同实验预期$m_{\beta\beta}$ 对比



有效马约拉纳质量 $\langle m_{\beta\beta}\rangle$ 是一个有效的，用来比较同位素和实验物理范围的指标。

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

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

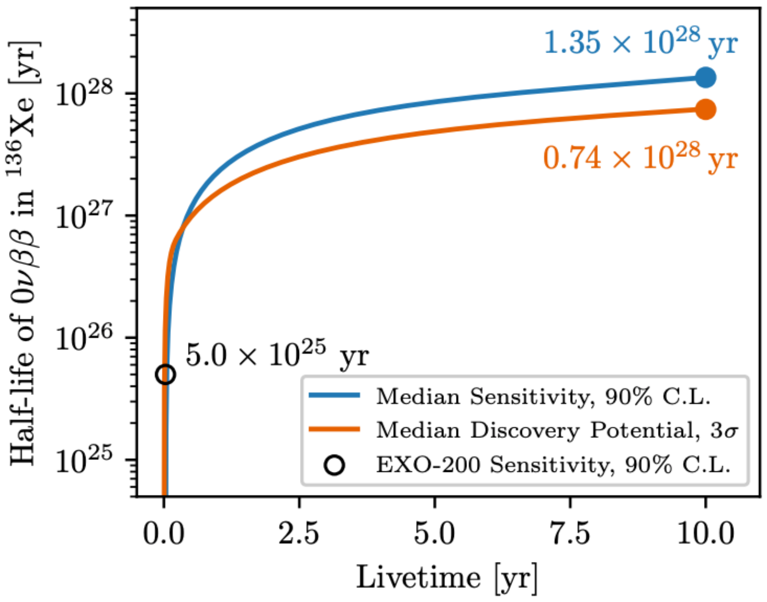
	$m_{\beta\beta}$ [meV], (*median* NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

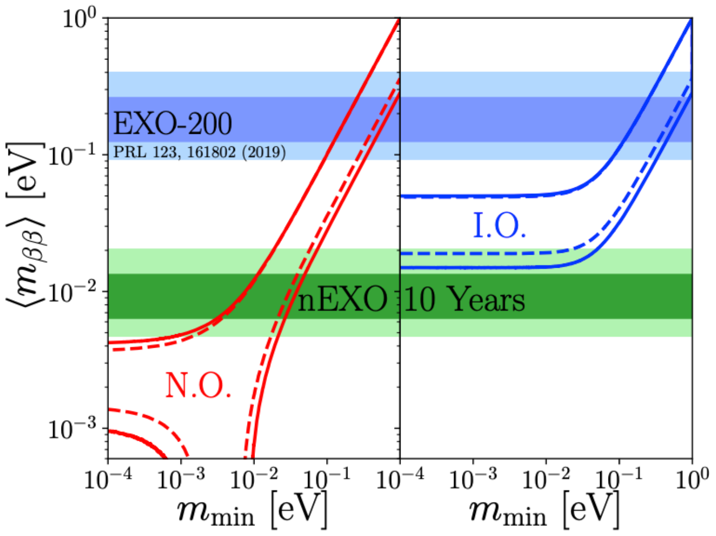
*T1/2 values used [x1028 yr]:
nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.) [2]
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

[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

0νββ灵敏度

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





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

预期有效马约拉纳质量$m_{\beta\beta}$的灵敏范围将会覆盖整个中微子质量反序的空间， 对正序的情况也有一定的深入。

Projection of the median sensitivity and 3σ discovery potential to 0νββ decay with nEXO as functions of the detector livetime.
10年取数时间给出半衰期灵敏度将超过10^{28} 年。

	Limit /Discovery sensitivity	Reference
EXO-200	0.35×10^{26}yr(90% CL)	PRL 123(2019) 161802
KamLAND-Zen	2.3×10^{26}yr(90% CL)	PRL. 130, 051001
nEXO	0.38×10^{28}(5σ) 0.74×10^{28}(3σ)	J.Phys.G: Nucl.Part.Phys. 49 (2022) 015104

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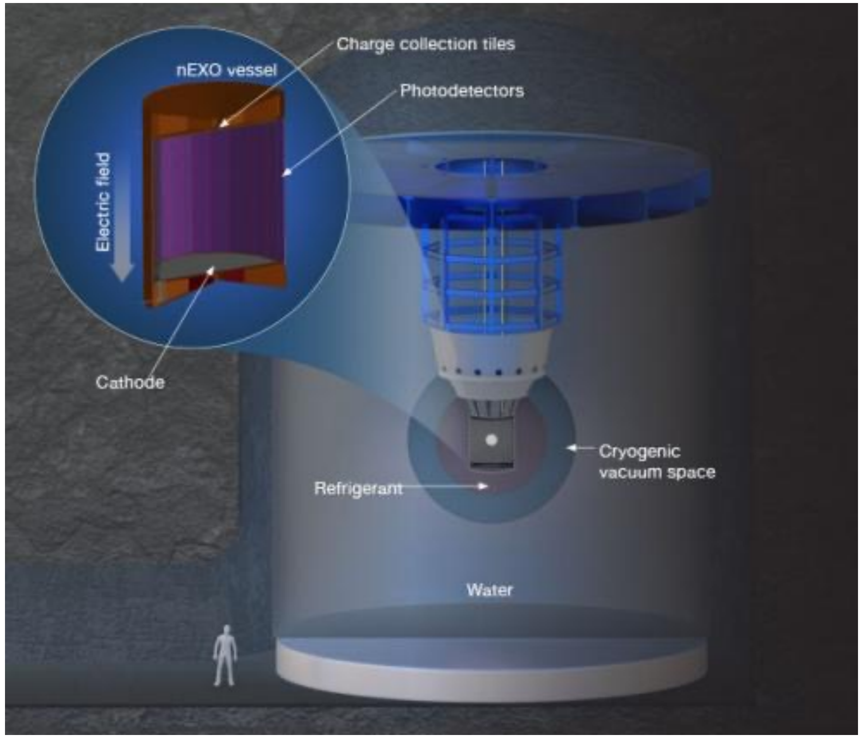
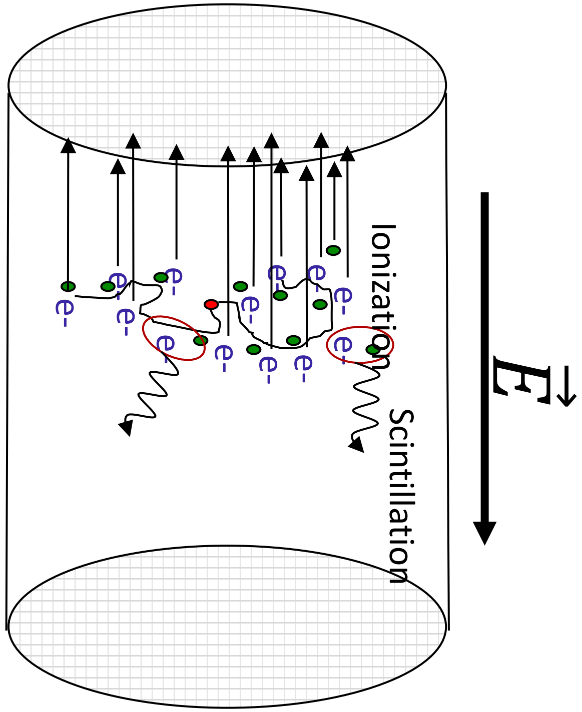
nEXO

nEXO TPC 探测器概念设计



nEXO 探测器主要参数

- 5吨液态氙
- 富集氙 (Xe-136) ~90%
- 探测器工作温度 165 K
- 漂移电场 400 V/cm
- 直径 116 cm
- 液氙发光特征波长 175 nm
- 光探测器SiPM覆盖面积 4.5平方米
- 能量分辨率好于1%
- 1.5千吨水切伦科夫探测器用于宇宙线缪子标记和屏蔽。



nEXO pre-CDR, arXiv:1805.11142

高能所nEXO团队广泛参与了探测器模拟（GEANT4）、概念设计以及优化以及nEXO 0νββ 灵敏度分析

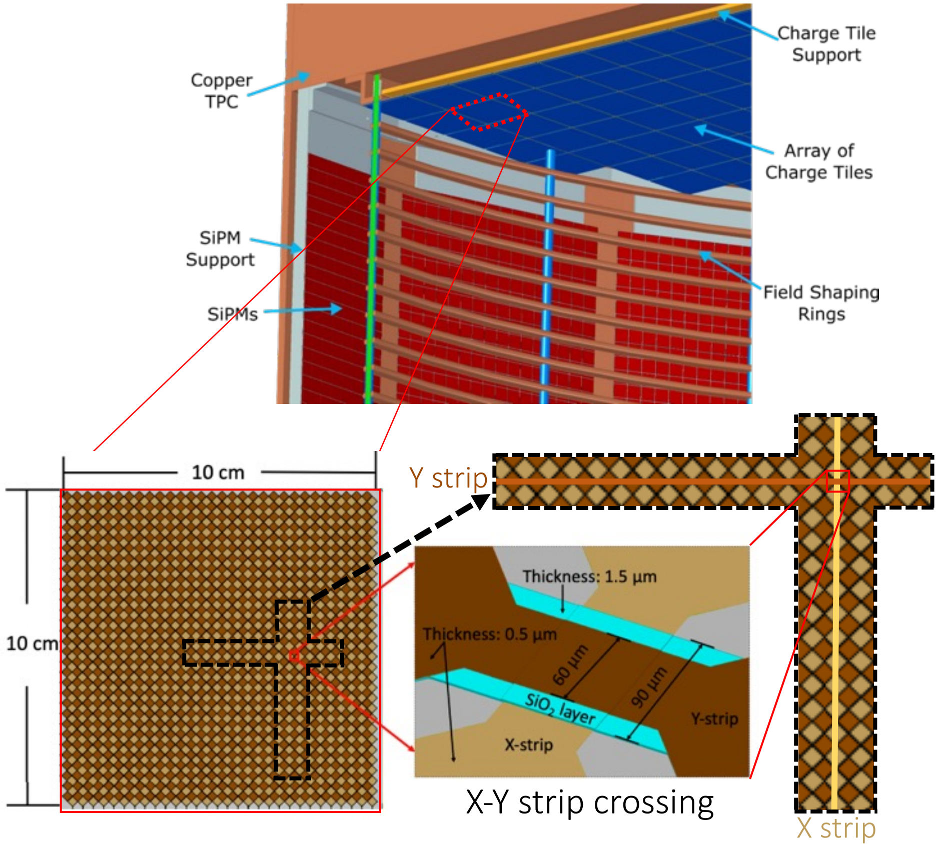
阳极电荷读出

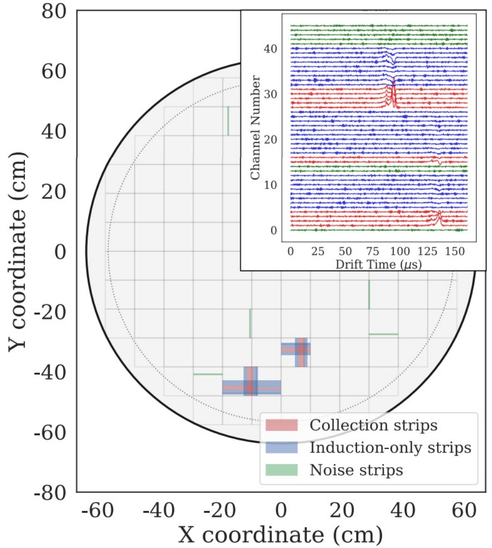
- 阳极板接收漂移电荷
- 完整的模拟工作，优化设计
    - Crossed strips with no shielding grid
    - Channel pitch: 6mm
    - Tile size: 10 cm x 10 cm

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

- 电荷读出板的液氙环境测试

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)

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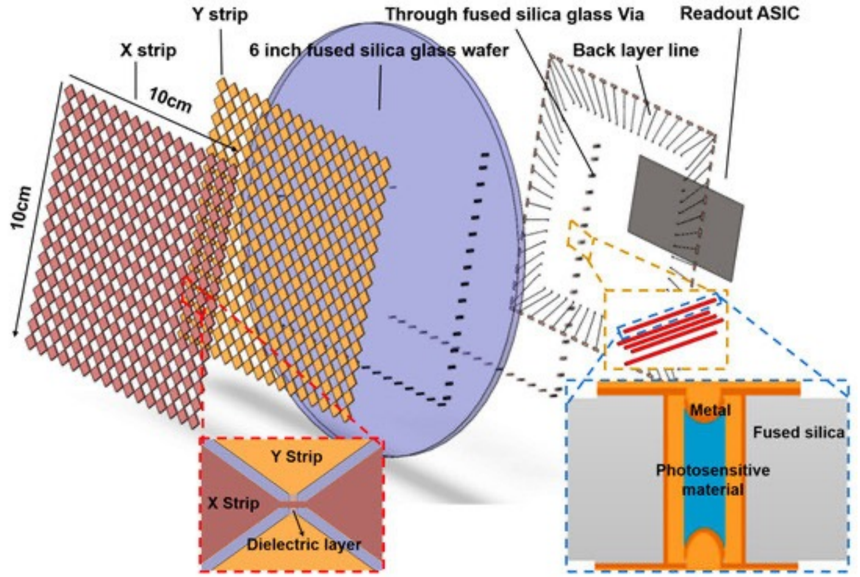
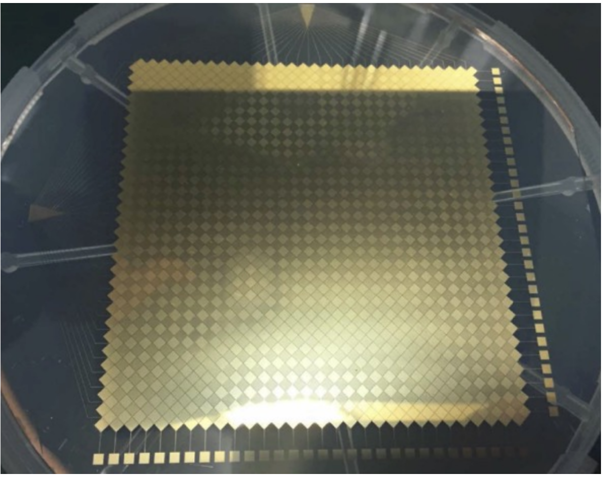
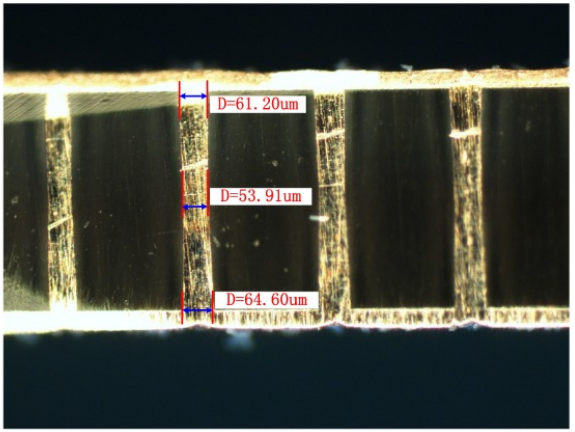
阳极电荷读出

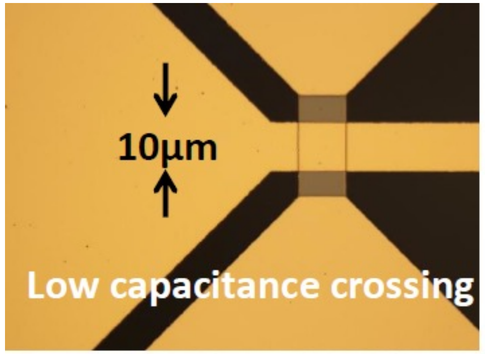
10厘米×10厘米 石英晶圆charge tile设计，样品以及测试 by IHEP/IME group



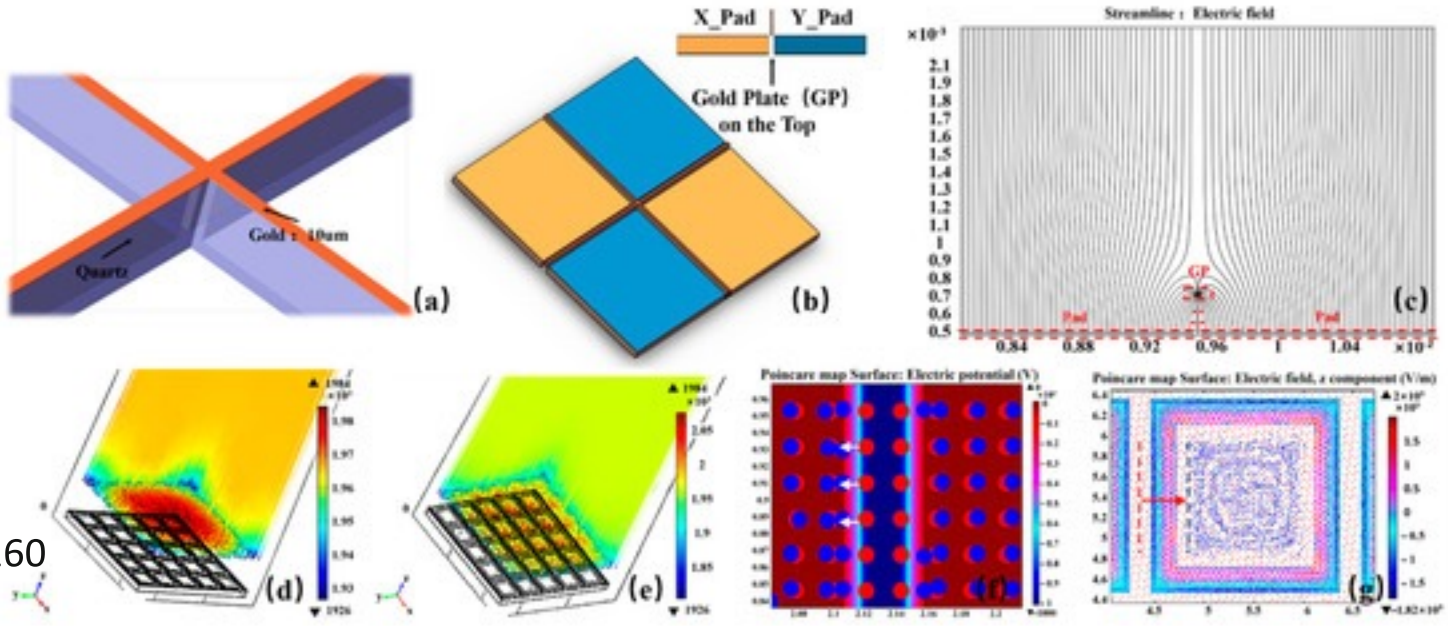




80 fF at crossings
0.86 pF between adjacent strips



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

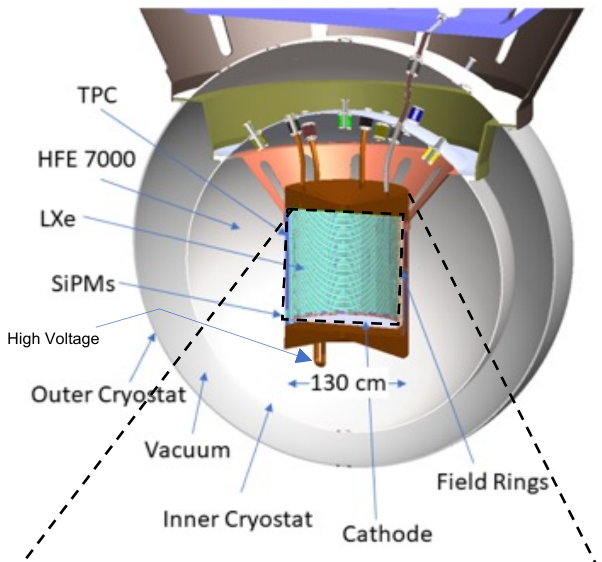


Electronics **2023**, *12*(4), 1045;

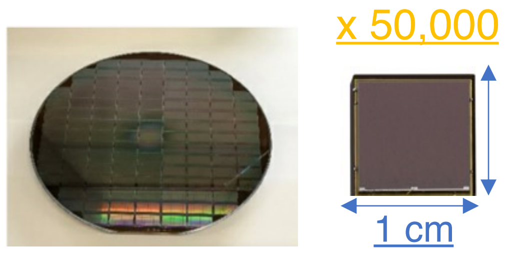
光探测器

采用硅光电倍增管（SiPM）的优势
1. 更低的放射性本底
2. 更高的探测效率 > 能量分辨率
3. 工作在较低偏压

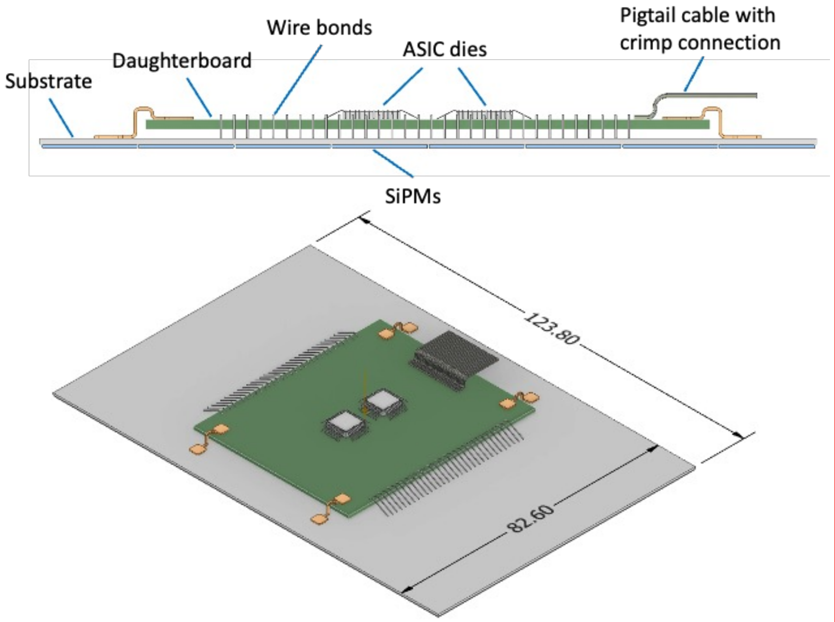
影响能量分辨率的主要因素:
- 175nm 光子探测效率（PDE）
- 光子传输效率（PTE）
- SiPM表面反射率
- SiPM的相关性噪声（串扰等）



SiPM Devices

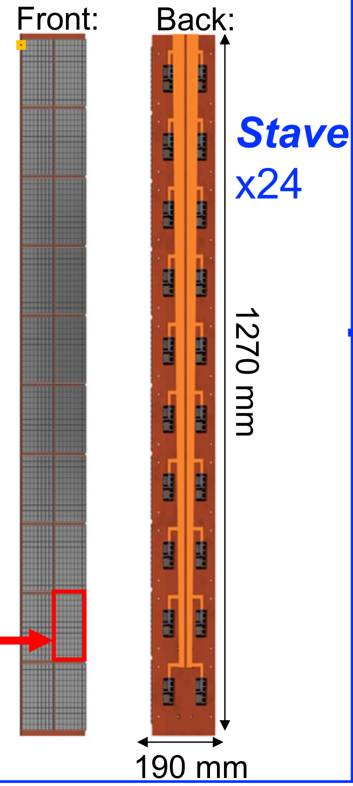


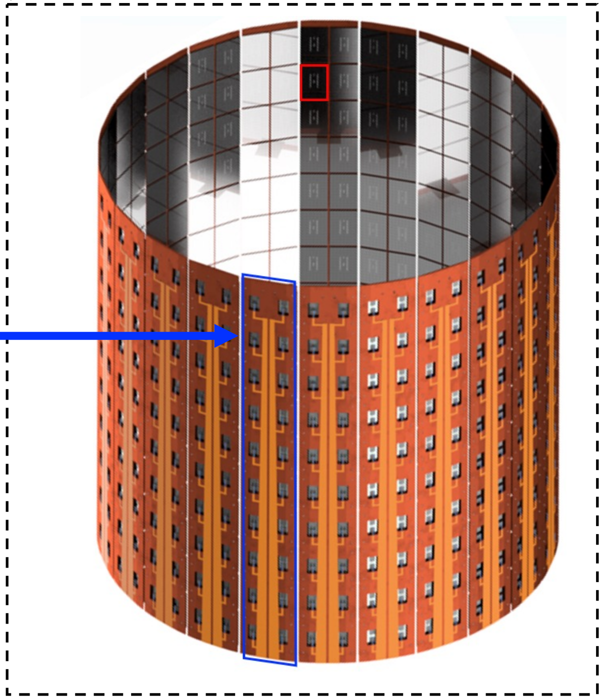
Tested SiPMs
- **FBK: VUV-LF-HD, VUV-STD-HD**
- **Hamamatsu: VUV4**



Tile module

x 480





Photon detector (PD)

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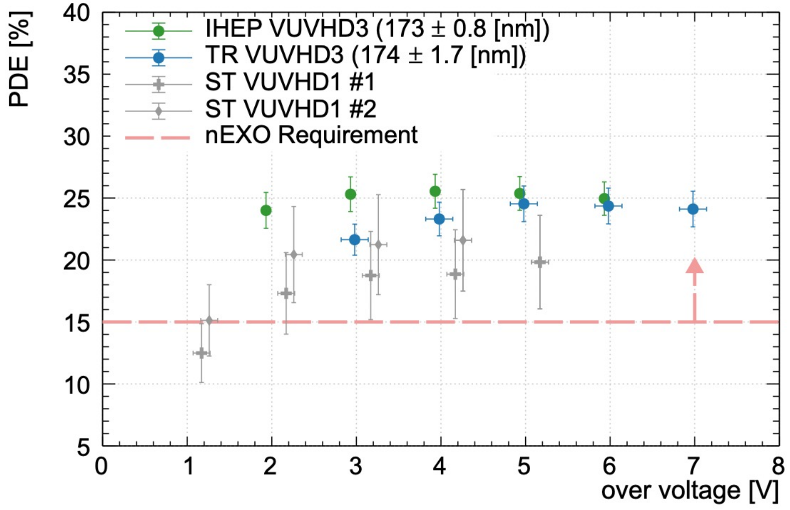
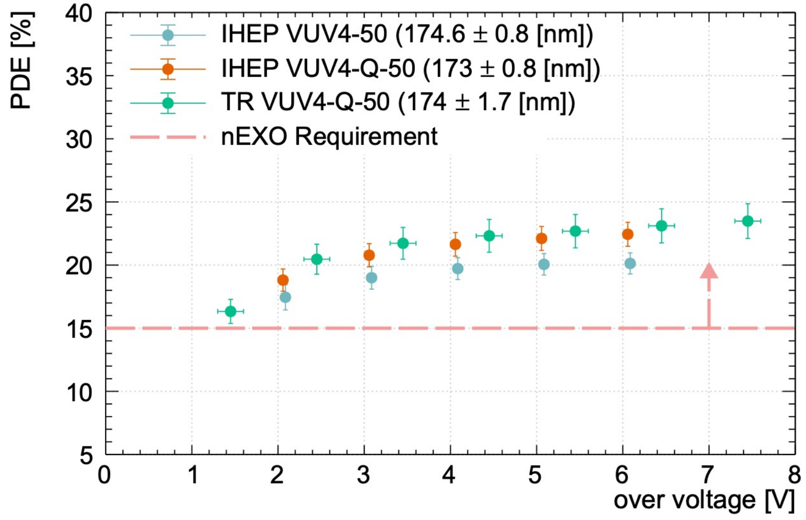
nEXO

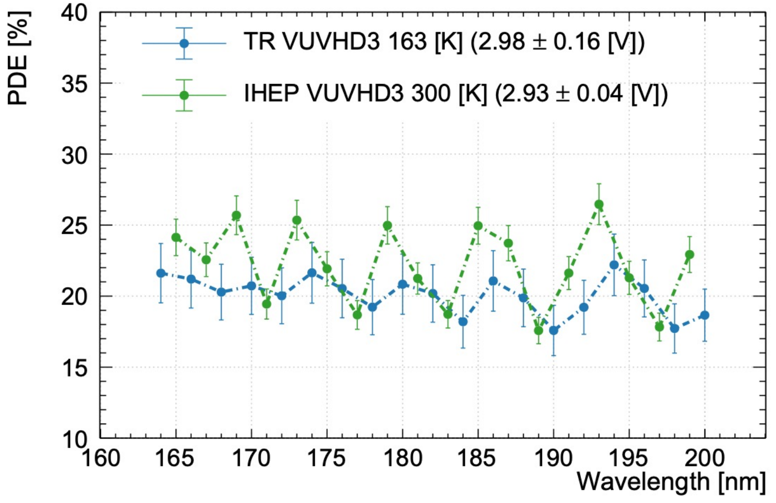
SiPM 性能参数要求

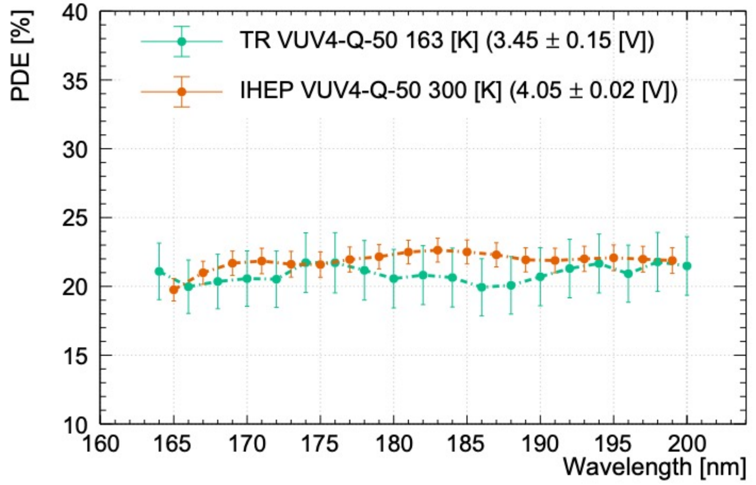
Parameter	Specification	Comment
Photo-detection efficiency	> 15%	At 170-180nm, including reflectivity
Dark noise rate	< 50 Hz/mm^2	At -104 ℃
Correlated avalanche rate	< 20%	At -104 ℃, combing cross-talk and after pulsing integrated within 1μs
Area per channel	1 – 5 cm^2	
Capacitance	< 50 pF/mm^2	For 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

真空紫外SiPM光探测性能测量









1. SiPM在真空紫外(VUV)波段的绝对光探测效率(PDE)一直是nEXO的重要研究课题。
2. nEXO之前发布的系统误差一直在20-30%的水平。
3. 首次提出了一种使用连续波(CW)模式测量VUV波段SiPM绝对PDE的方法。
4. 在165nm至200nm范围内进行了PDE测量，测量误差已降至约5%。并对BNL和TRIUMF实验组的测量结果进行比较。结果发表在

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

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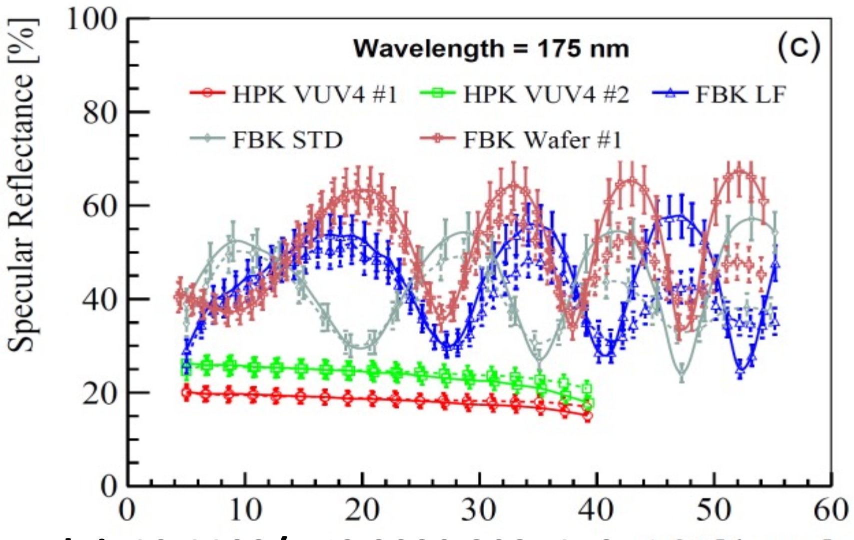
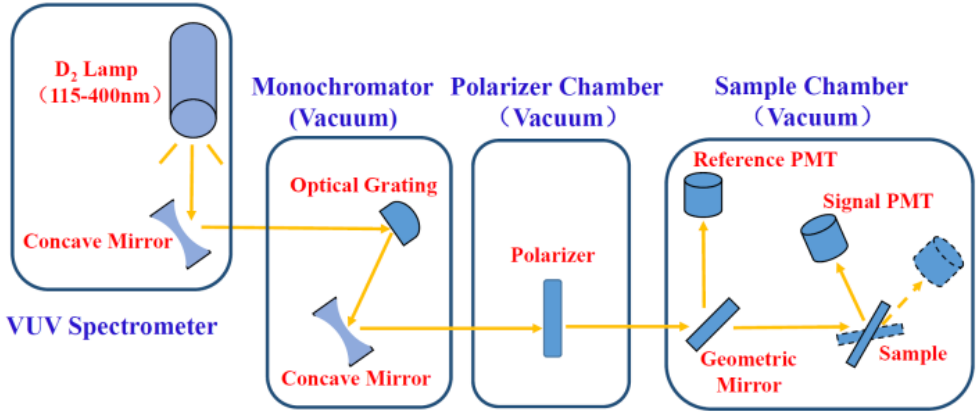
nEXO

SiPM反射率测量

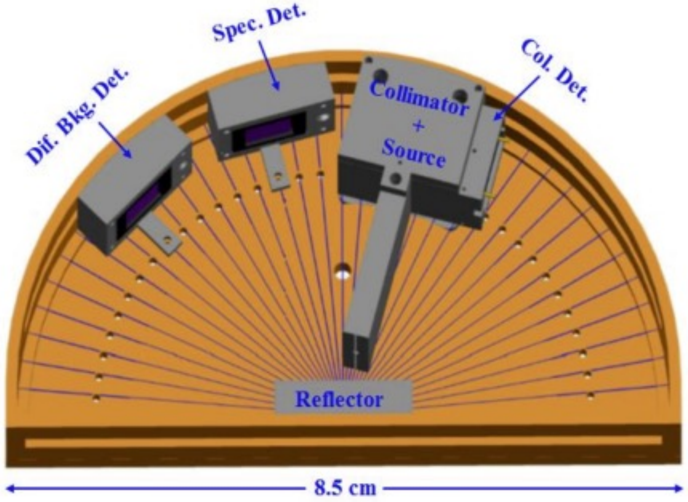
- 研发了一套测量真空中SiPM反射率的装置，联合成都光电所，测量波长范围115纳米至400纳米，角度5至55度
- 另外两套测量SiPM在液氙中反射率的装置
  - LIXO (by UA 亚利桑那大学)
    - 设备浸入液态氙中，使用252Cf源激发液态氙闪烁光（约175纳米光）
    - 准直器 + 石英窗组件，用以防止辐射损伤并帮助光线准直。
  - Erlangen & U. of Münster



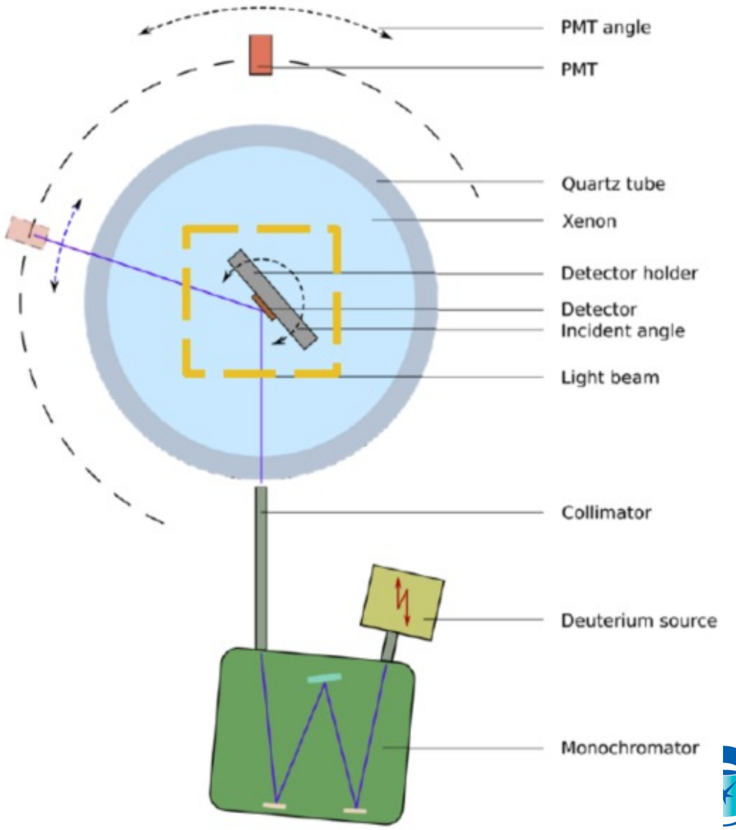
doi: 10.1109/TNS.2020.3035172



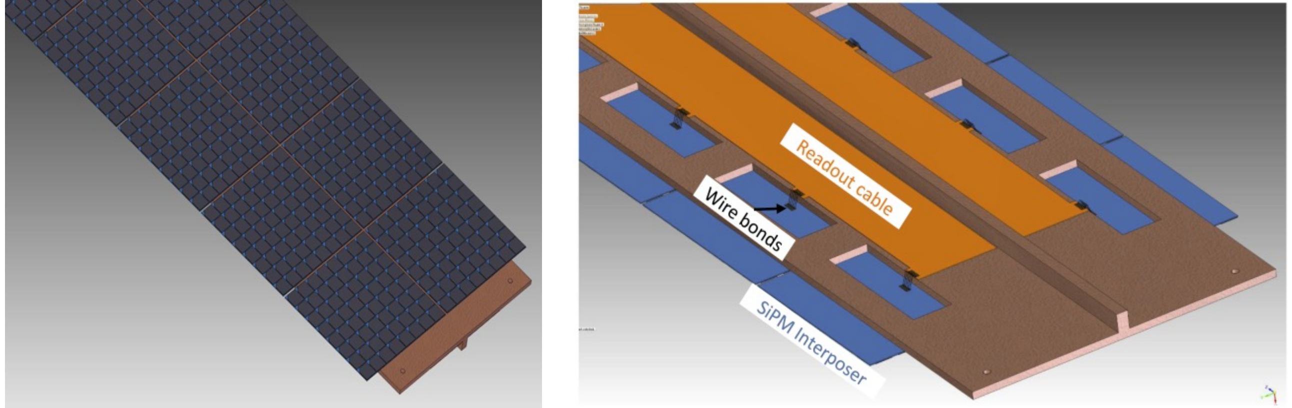
IEEE TRANS. NUC. SCIENCE, doi: 10.1109/TNS.2020.3035172



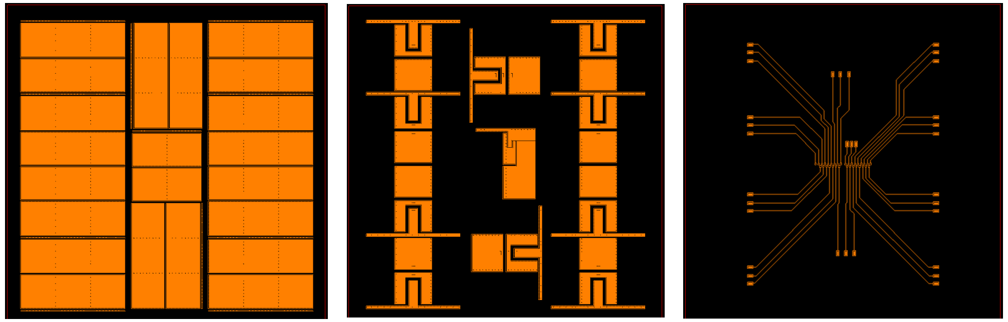
JINST 15 (2020) P01019

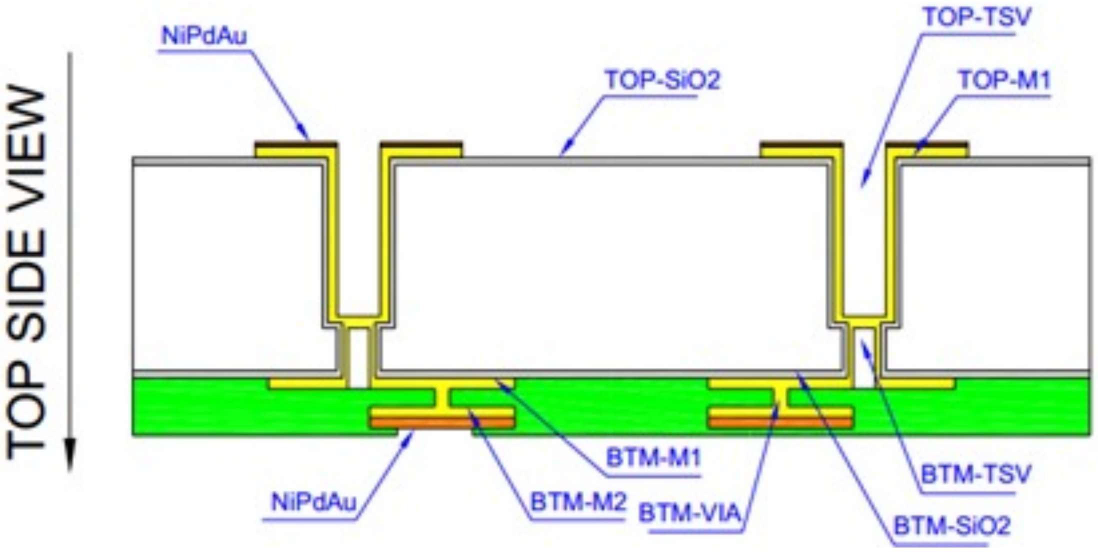


低反射性硅基转接板
Silicon interposer



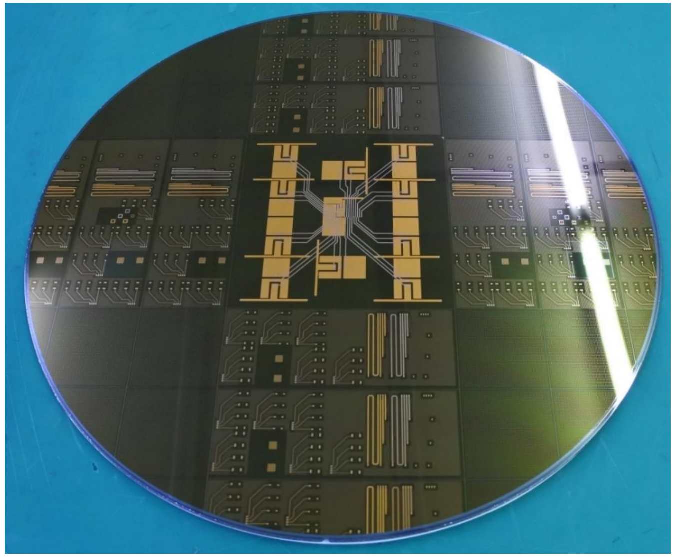
- 为了满足nEXO苛刻的低放射性要求
- 第一代Silicon interposer原型于2017年由高能所和微电子所研制
- 第二代Silicon interposer的研制与测试 (DOI: 10.1109/TNS.2022.3232125)
- 目前正在进行第三代 Silicon interposer的性能测试工作，（工艺改进，有更好的绝缘性）

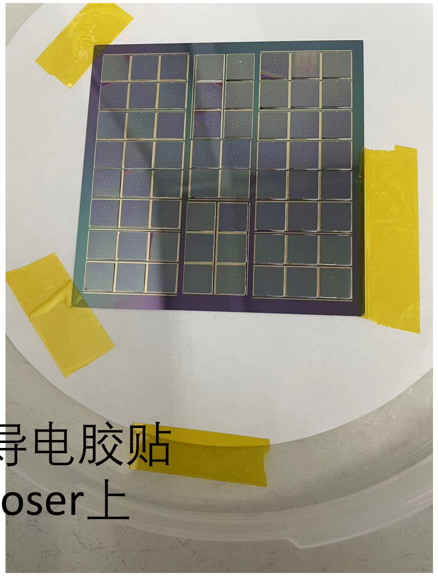




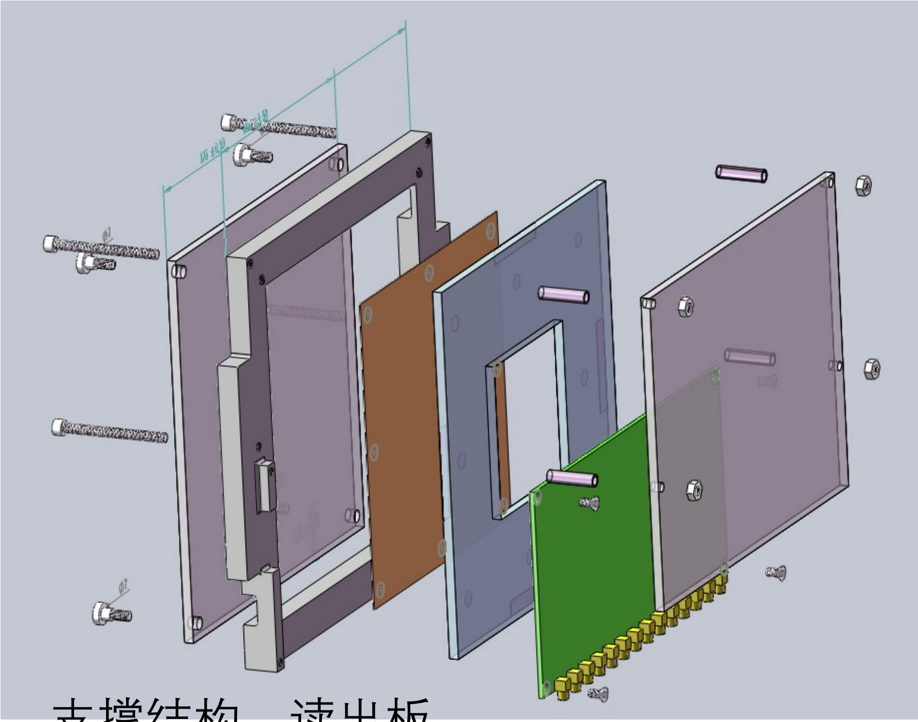
TSV网络结构示意图

低反射性硅基转接板
Silicon interposer

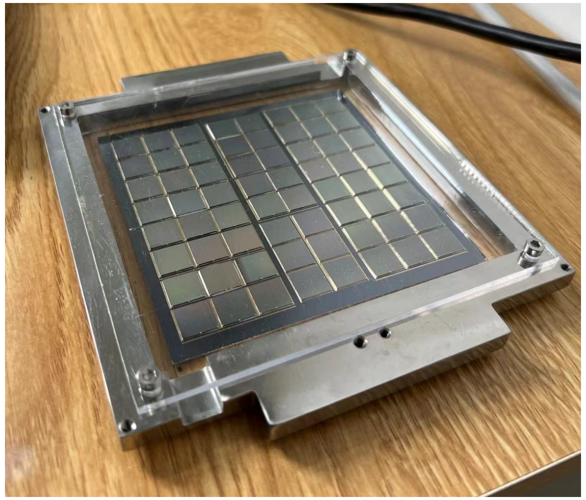


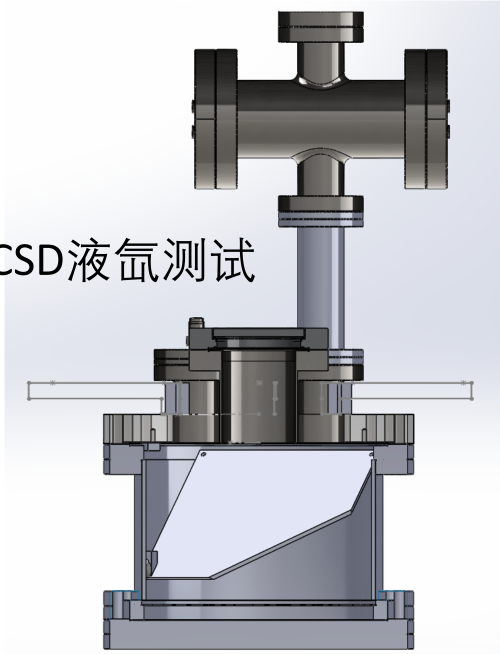


SiPM用导电胶贴到interposer上

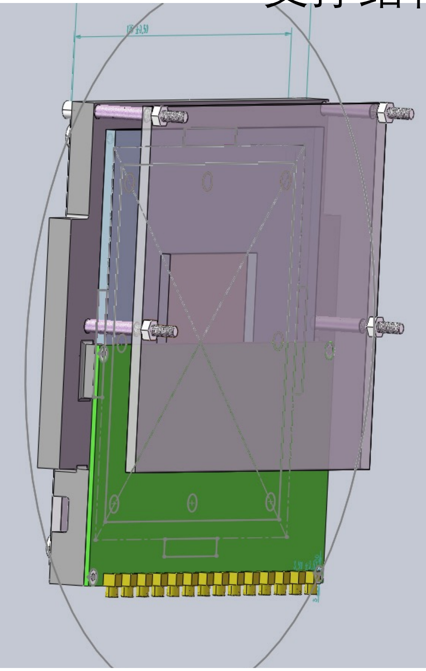


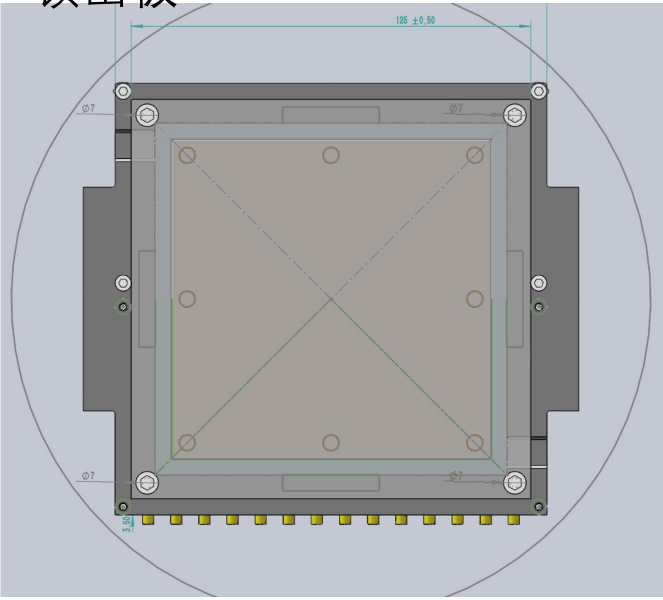
支撑结构，读出板





UCSD液氙测试

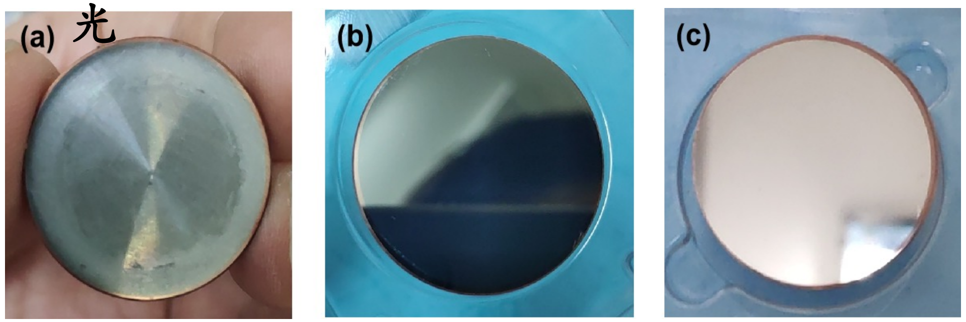


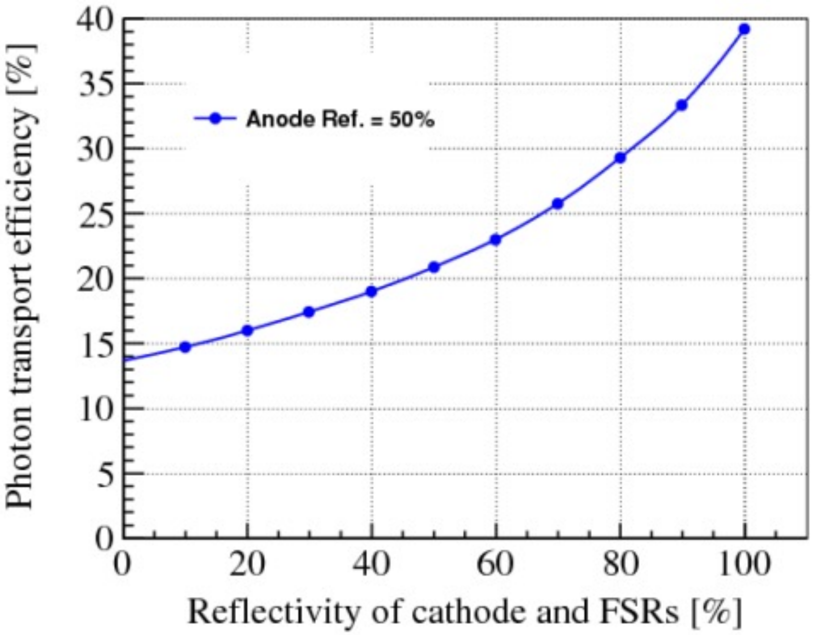


阴极板以及成形环的抛光和镀膜

- 探测器内阴极板以及成形环对VUV的反射率将直接影响闪烁光的传输效率
- 与成都光电所合作，从2019年底开始开发基于铜的VUV高反射率技术。
- 铜铝合金的问题得到解决，实现了约80%的总反射率，满足了nEXO的要求（>70%）。方法和结果已总结并发表（Vacuum 197 (2022) 110806）。
- 目前正在进行新一轮的样品抛光和镀膜工作，并且将在高能所的液氙TPC环境下进行光收集效率的测试。

未抛光　　金刚石抛光　　光学抛光





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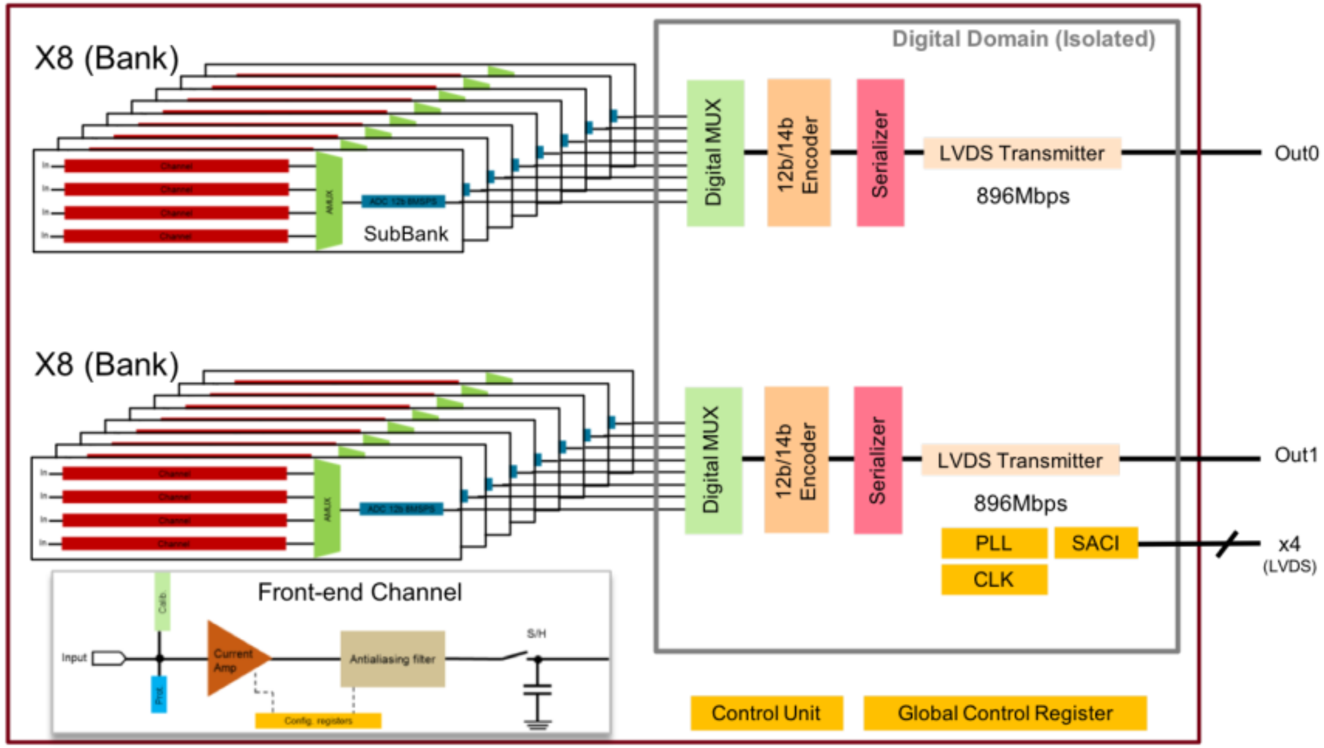
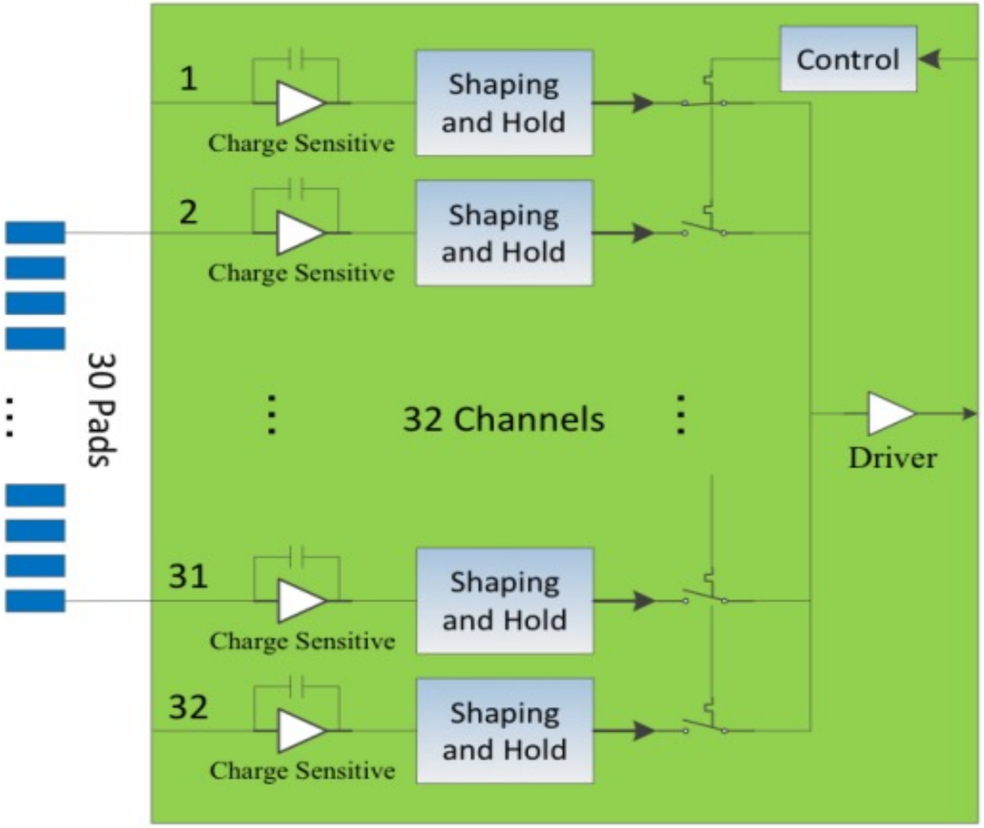
nEXO

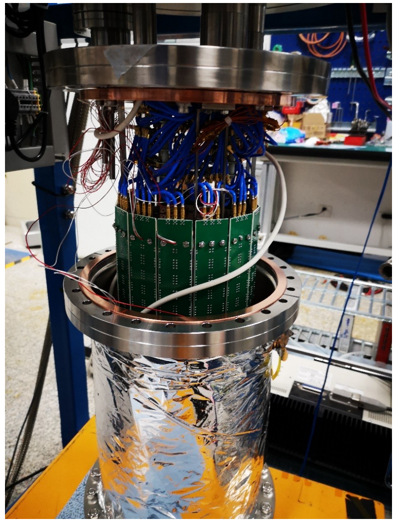
低温电子学

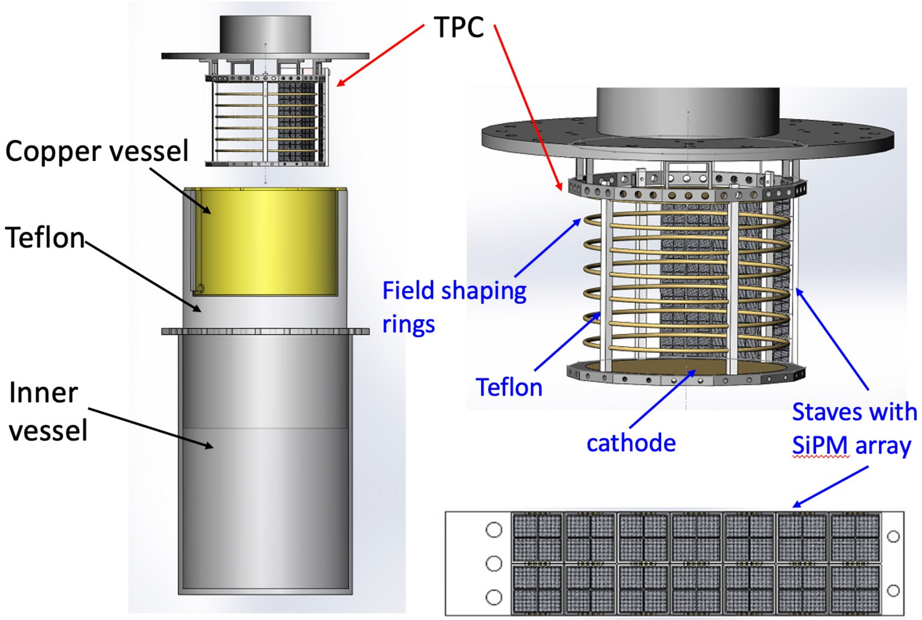
- CRYO ASIC (SLAC)
  - Digital electronics on chip
  - 64 channels, 4 channels share one ADC (12-bit, 8 MS/s)
- Analog chip (IHEP)
  - Analog waveforms are multiplexed inside an ASIC and transmitted outside of the TPC
  - Digital conversion and processing at room temperature





小型液氙时间投影室MiniTPC





总结

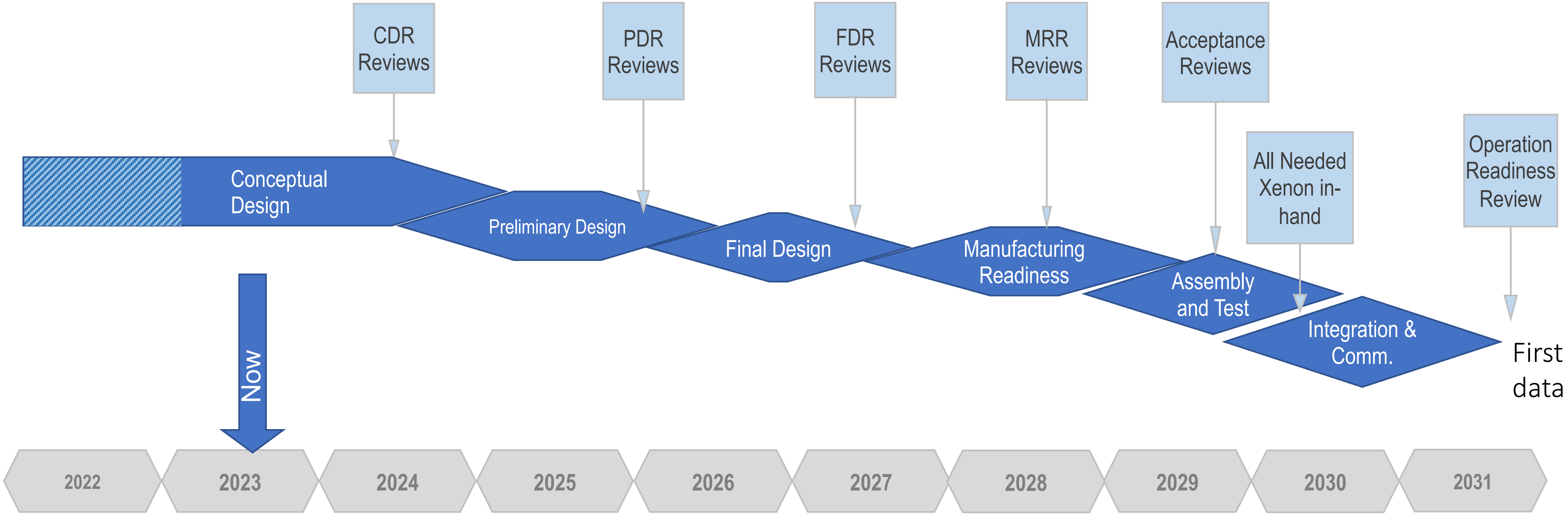
- nEXO实验预期将氙同位素0νββ的半衰期灵敏度再度提升接近两个量级，10^{26} -> 10^{28}，这得益于其出色的能量分辨率（小于1%），以及苛刻的放射性本底控制。
- 这些物理目标对我们的R&D工作提出了很高的要求，但目前主要的技术难点都已克服，同时高能所、微电子所nEXO团队广泛地参与于其中，承担了许多关键性的课题，也解决了许多核心问题。
- 目前小型液氙TPC实验正在做最后的筹备工作，预期很快将会进行SiPM dry run，还有带放射源的取数，欢迎感兴趣的同行提议、交流。

Back-up

The international nEXO collaboration

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

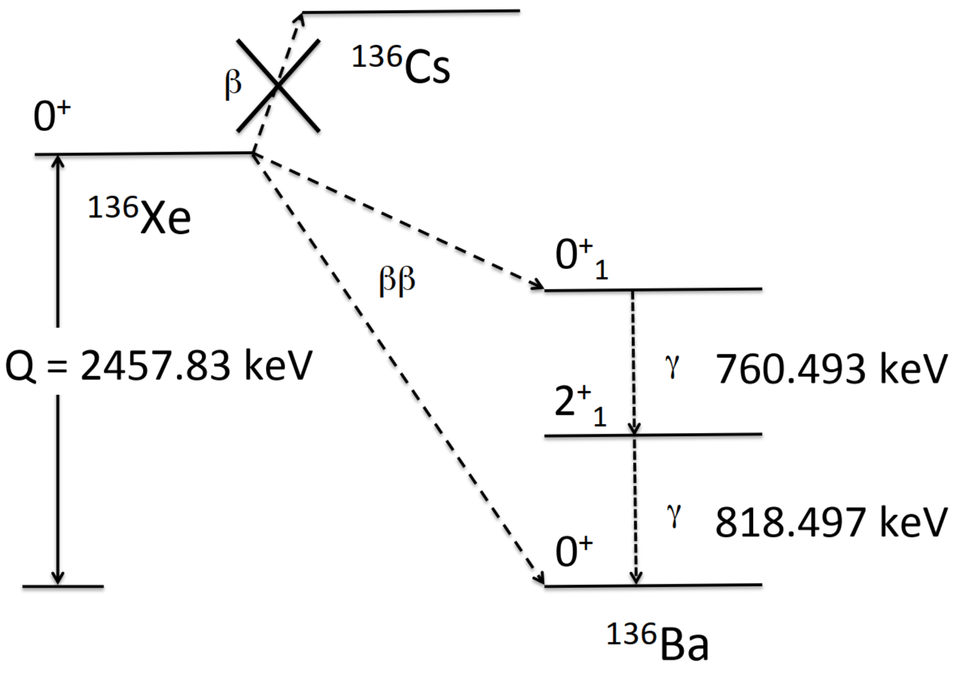
nEXO schedule



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)

Enriched ^{136}Xe in the nEXO TPC



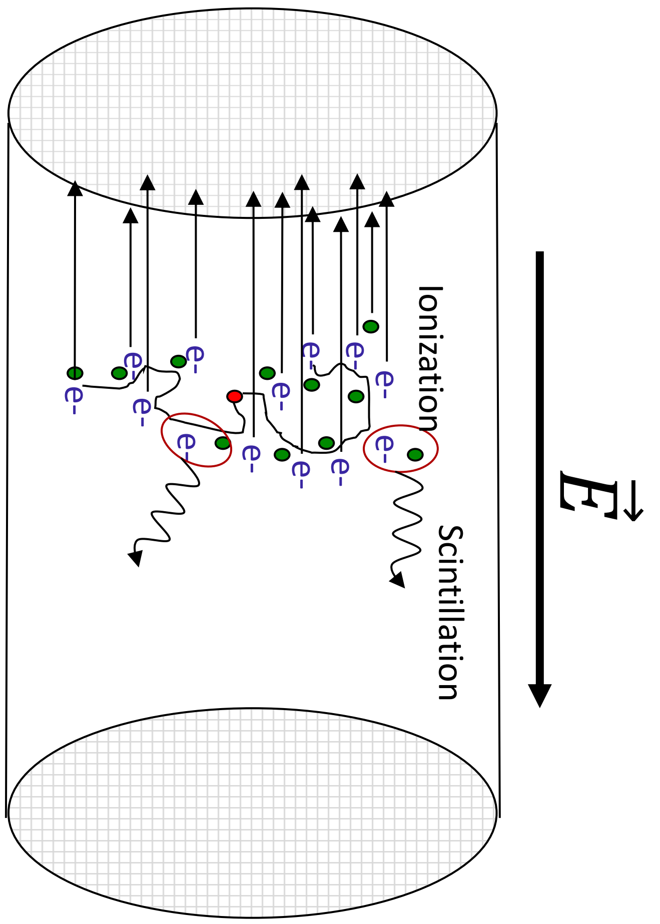
Level scheme of the ββ decay of ^{136}Xe

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))

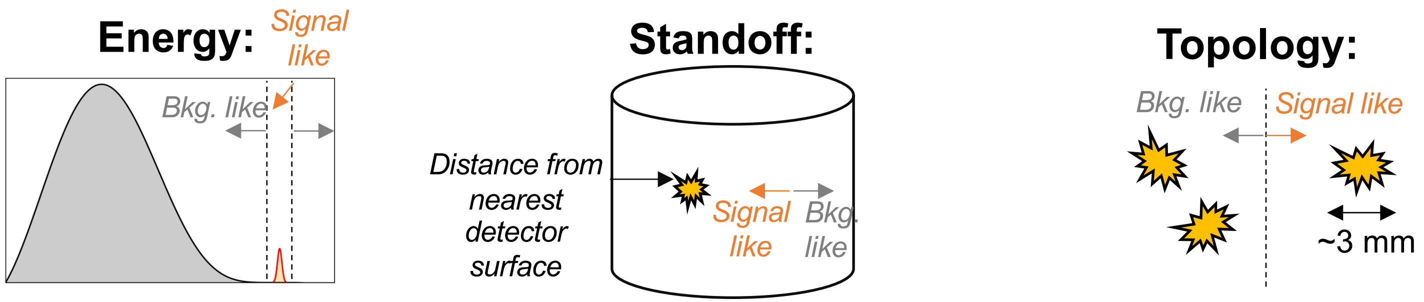
nEXO Signal and Background

Segmented Anode

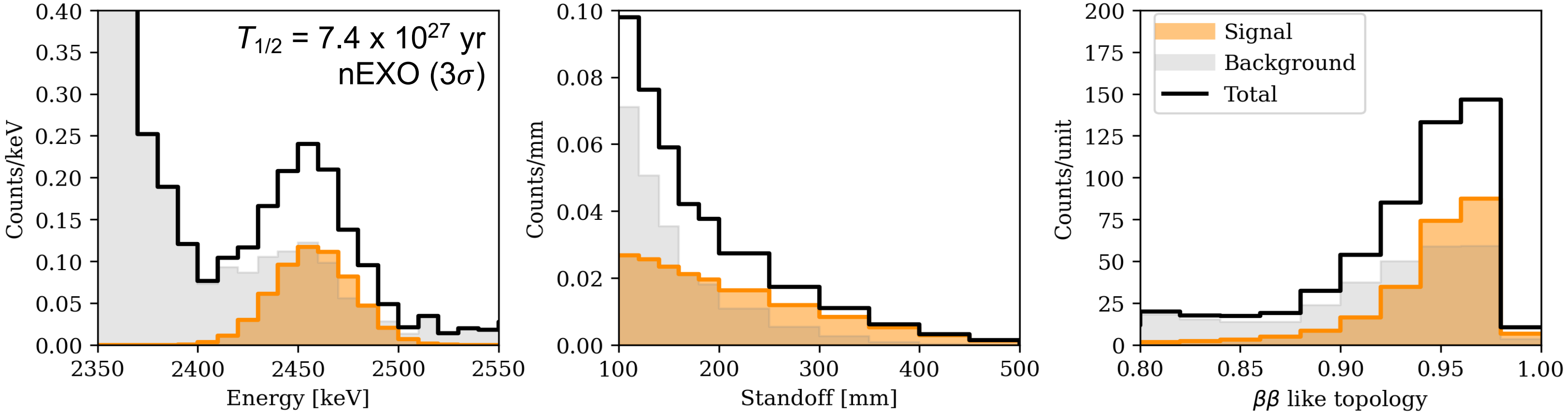


Cathode

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

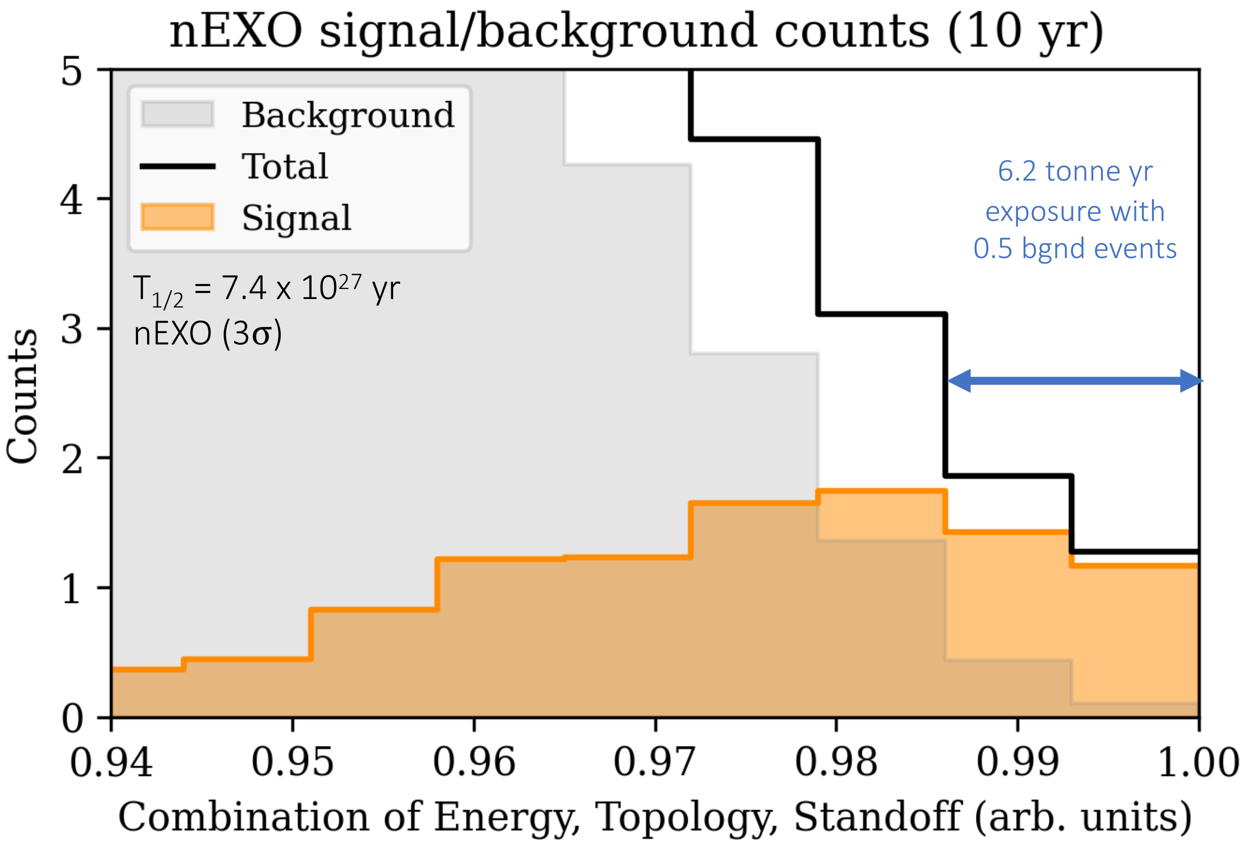
Position distribution from 3D event reconstruction

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