nEXO Photon Detection System and Read-Out Electronics

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Photon Detection Workshop ‘24

November 20, 2024

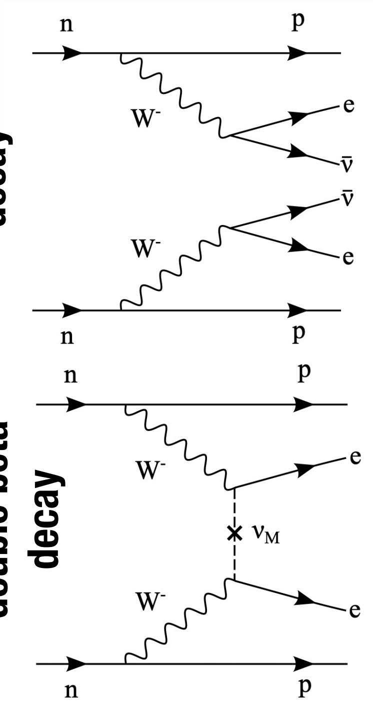
Neutrinoless double beta decay ($0\nu\beta\beta$)

Key to unlocking new physics beyond the Standard Model

1. Lepton number violation

Double beta decay

Neutrinoless double beta decay



2. New class of elementary particles

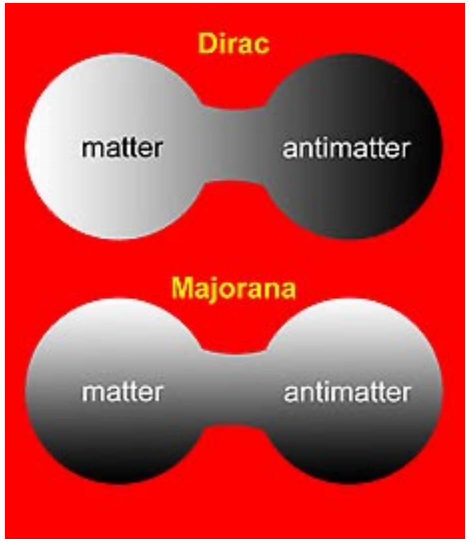


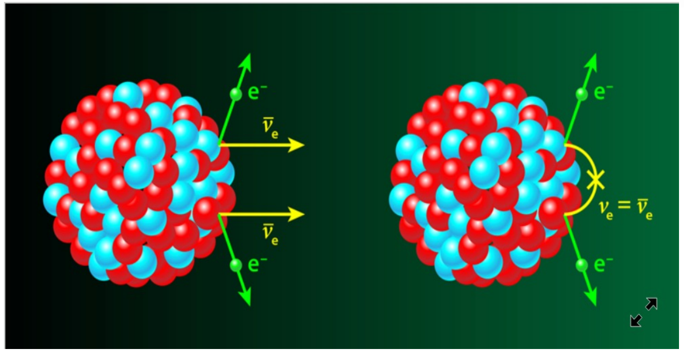
Image: Fermilab Today

Neutrinos are Majorana fermions

$$\nu = \bar{\nu}$$

3. Implications for matter-antimatter asymmetry

Image: APS/ Alan Stonebraker



Double beta decay

Matter & Antimatter

Neutrinoless double beta decay

Only matter!

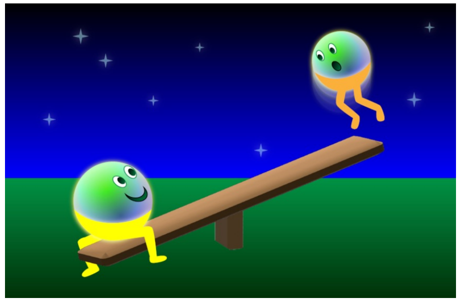
4. Insight into neutrino mass

$\mathbf{T_{1/2}}$ - neutrino mass relationship

$$(T_{1/2})^{-1} \sim |\langle m_{\beta\beta} \rangle|^2$$

&

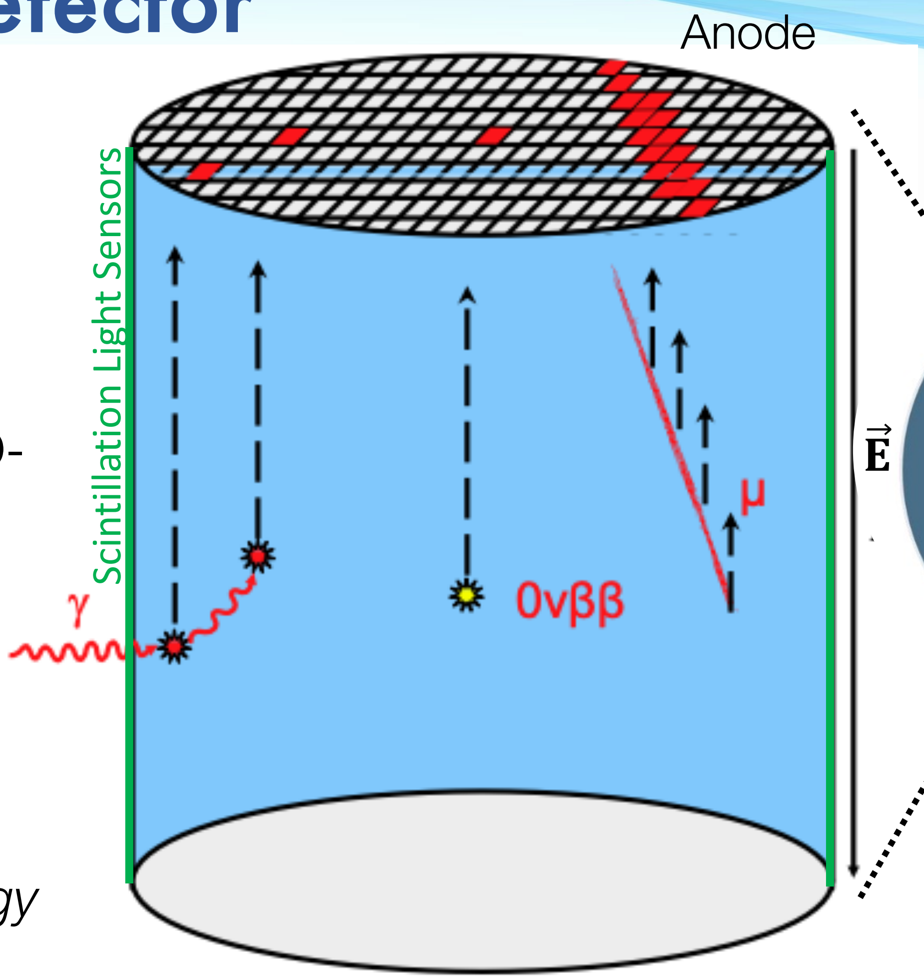
Possible new mass giving mechanism

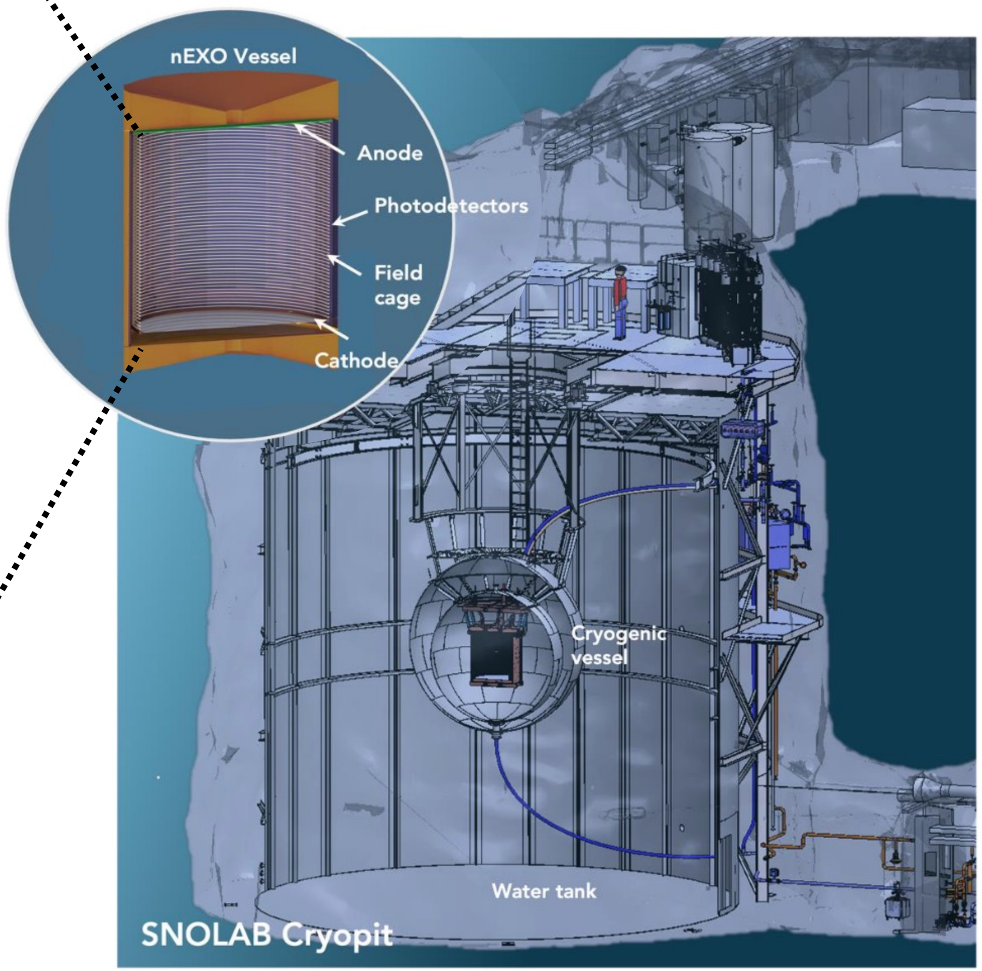


See-saw mechanism

nEXO: $0\nu\beta\beta$ detector

- Single phase TPC with 5000 kg of liquid xenon (LXe), 90% enriched in ^{136}Xe
- Builds off success of EXO-200
- Collect ionization + scintillation signals & perform a multiparameter analysis using:
  Energy, position, topology



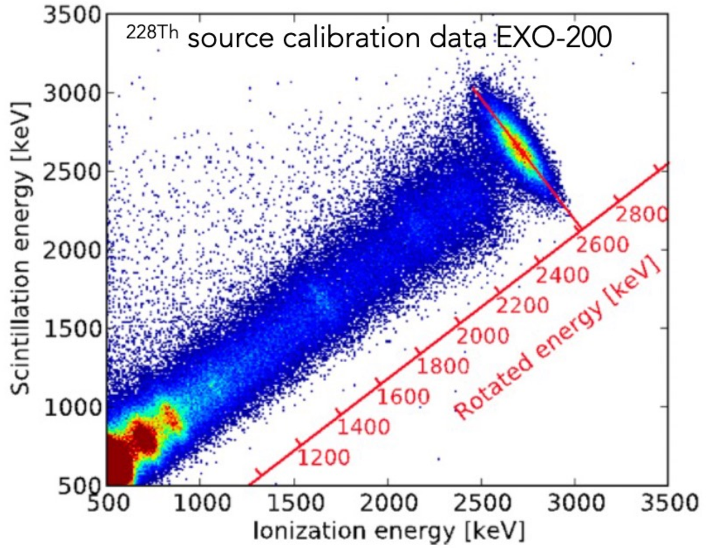


- **Sensitivity:** $T_{1/2} = 1.35 \times 10^{28}$ years

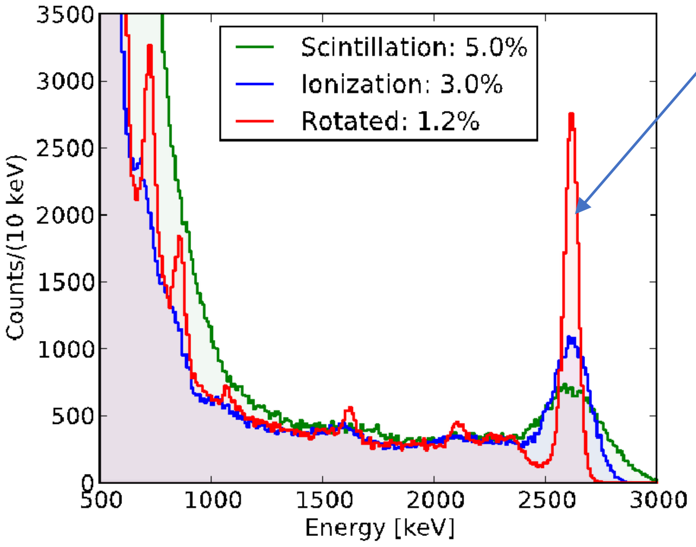
Energy resolution: Requirement: ≤ 1.1%
Design value: ≤ 0.8%

Energy resolution

EXO-200 Th-228 calibration source data



Energy spectra of Th-228 events



Improved fractional resolution ($\frac{\sigma_E}{E}$) using rotated energy basis

Need to optimize both light and charge channels

- ~100% charge collection efficiency
- Only < 10% photon collection efficiency

Rotated energy resolution is dominated by light collection efficiency

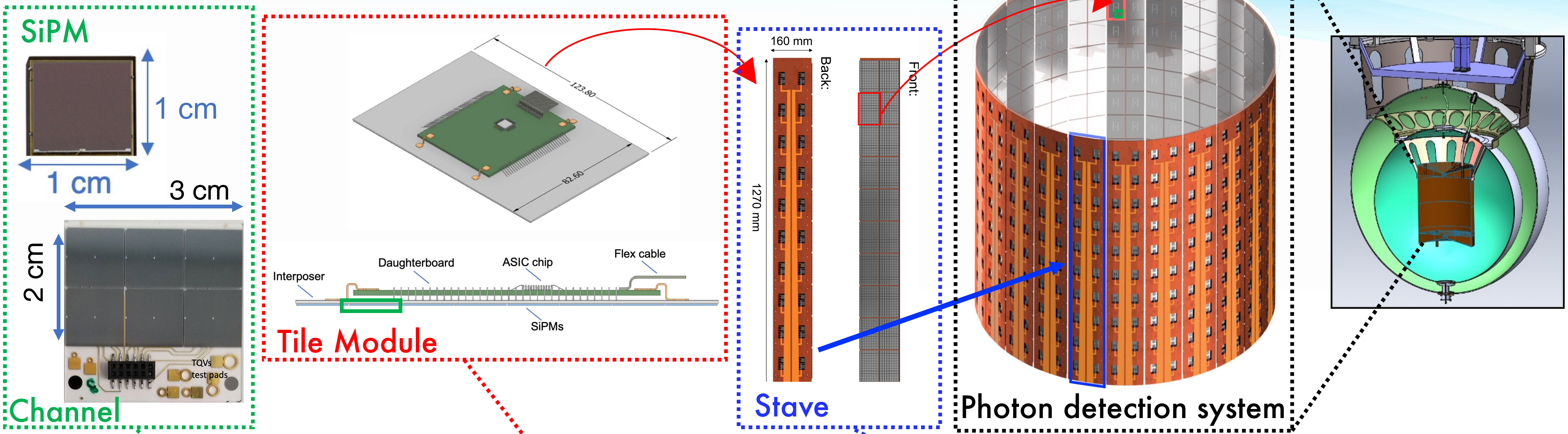
Light collection efficiency (Ɛ)

$$\varepsilon = PTE \times DAP = PTE \times \frac{PDE}{1-R}$$

- PTE: Photon transport efficiency
- DAP: Device avalanche probability
- PDE: Photon detection efficiency
- R: Reflection at normal incidence in vacuum

PD system conceptual design

nEXO



Silicon Photo-Multipliers (SiPMs)

x ~46,000

Individual VUV-sensitive SiPMs

Readout channels: SiPMs grouped in 6 cm^2 sub-arrays

Tile Modules

x 480

16 sub-arrays (96 SiPMs) attached to interposer w/ daughterboard & integrated front end (FE) ASIC

20 tile modules arrayed on stave

Staves

x 24

Digital ASICs (ADCTX) and board at top of stave

24 staves cylindrically surround barrel, behind field shaping rings

Full Photon Detection System

~4.6 m^2 photosensitive area with 7,680 readout channels

Full design guided by radiopurity, thermal, and mechanical considerations

SiPMs: Photon detection efficiency

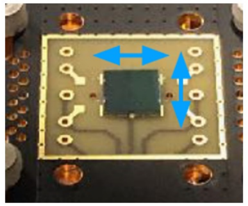
Light collection efficiency (Ɛ):

$$\mathcal{E} = PTE * \frac{PDE}{1-R}$$

175 nm PDE as function of over voltage

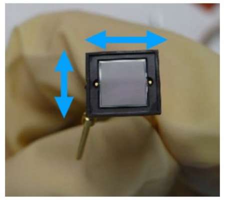
Requirement: ≥ 15% for ~175 nm photons

FBK

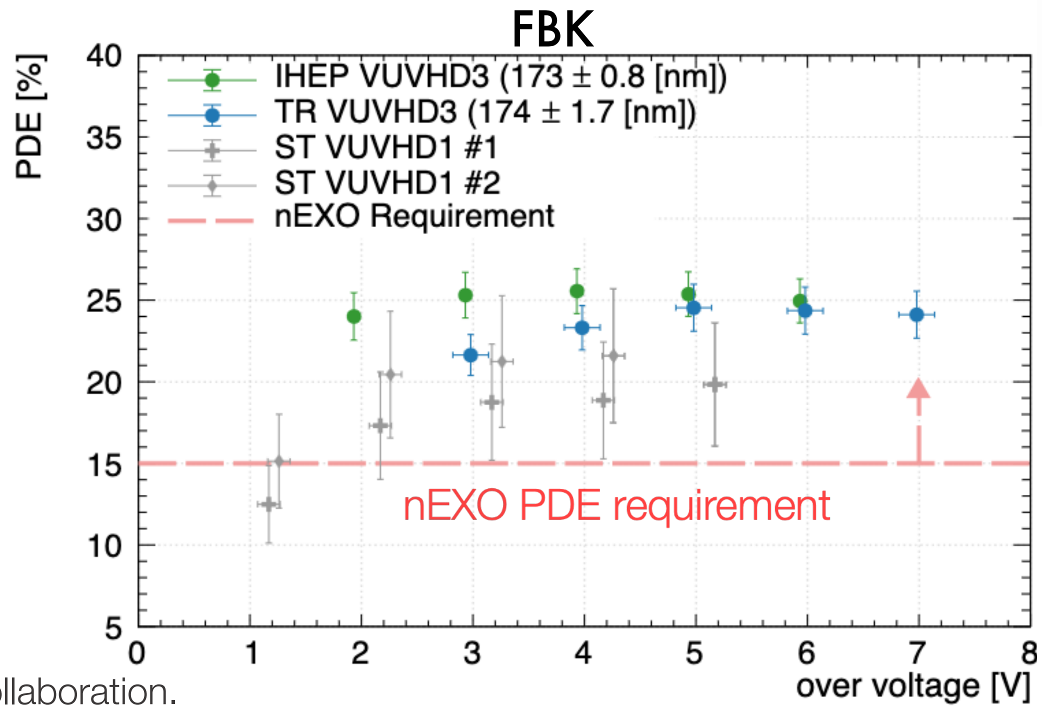


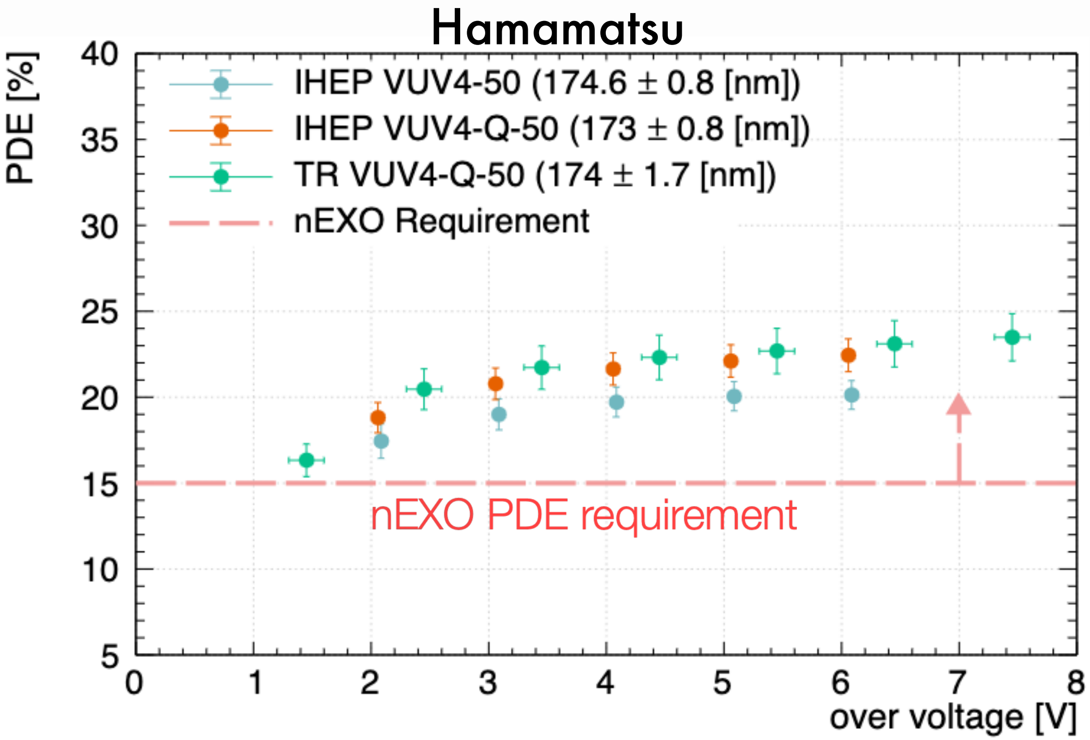
FBK VUVHD3

Hamamatsu



HPK VUV4-50

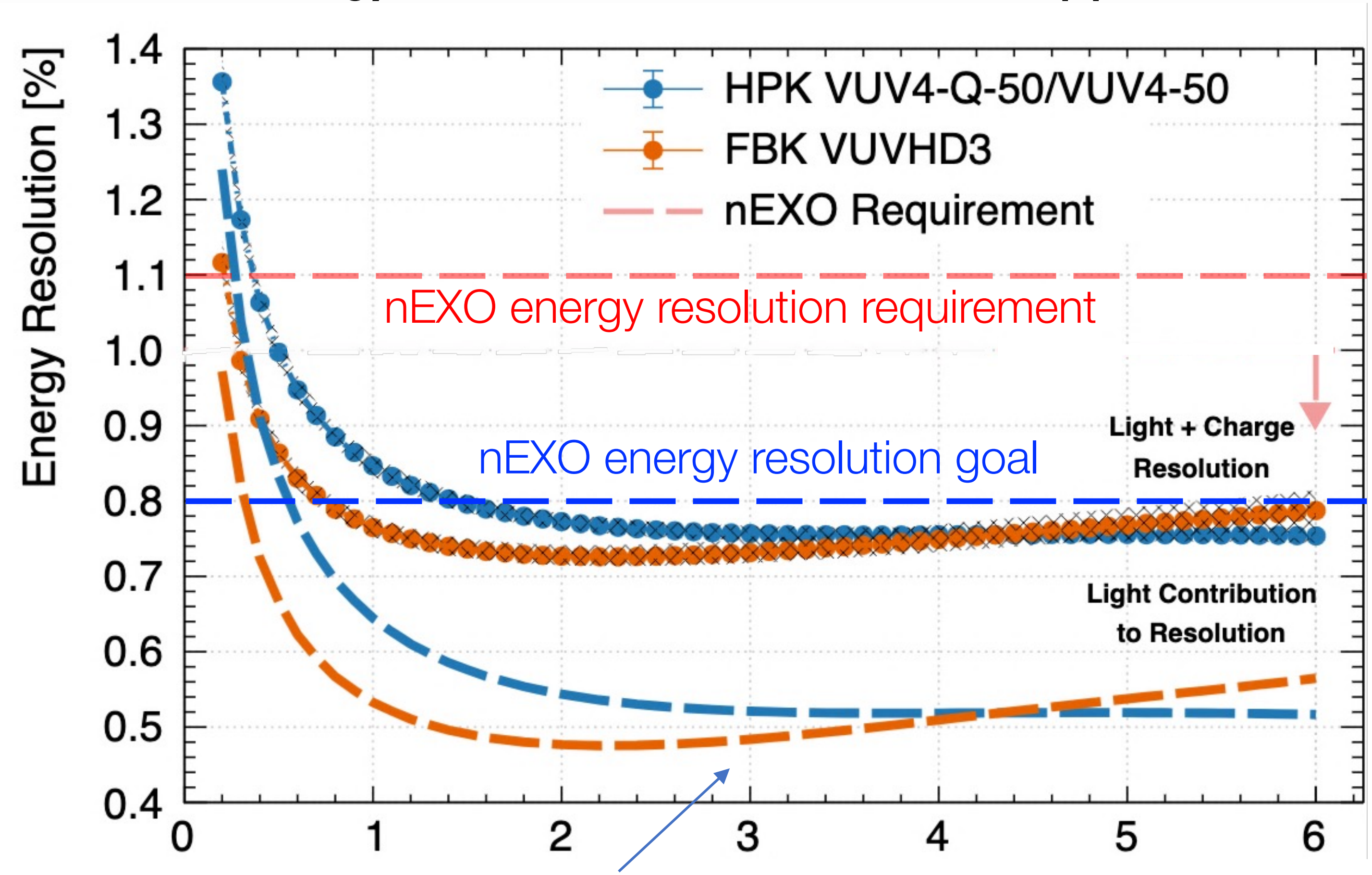




G. Gallina, nEXO collaboration. Eur. Phys. J. C 82, 1125 (2022)

nEXO energy resolution with candidate SiPMs

Estimated energy resolution as a function of applied over voltage



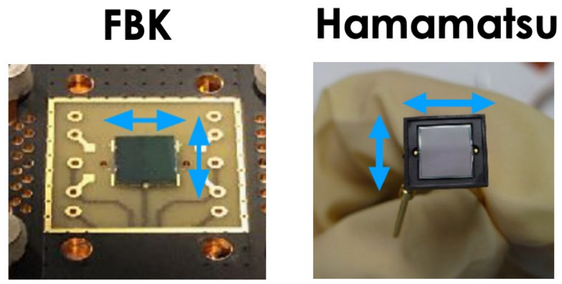
Contribution of light channel to total energy resolution neglecting recombination fluctuations

Energy resolution

nEXO requirement ≤1.1%

nEXO goal ≤ 0.8%

Devices meet our requirements!



FBK VUVHD3 HPK VUV4-50

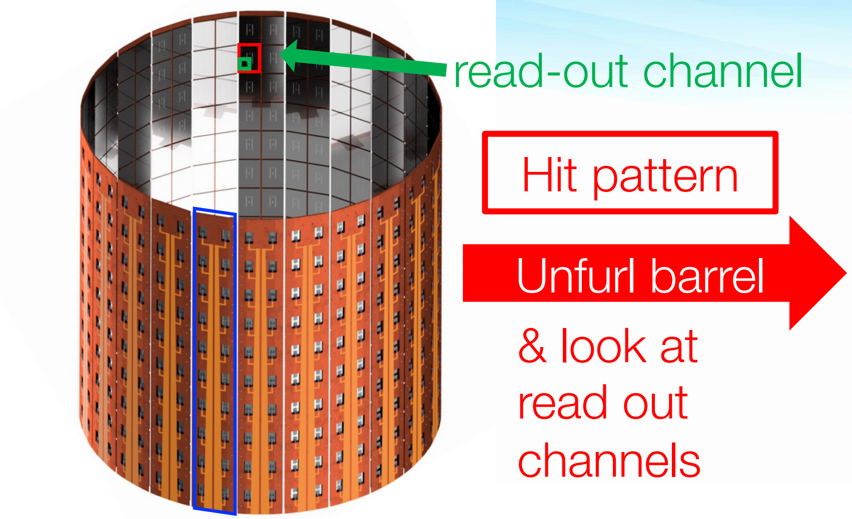
- Energy resolution accounts for PDE, correlated avalanches, and dark count rates

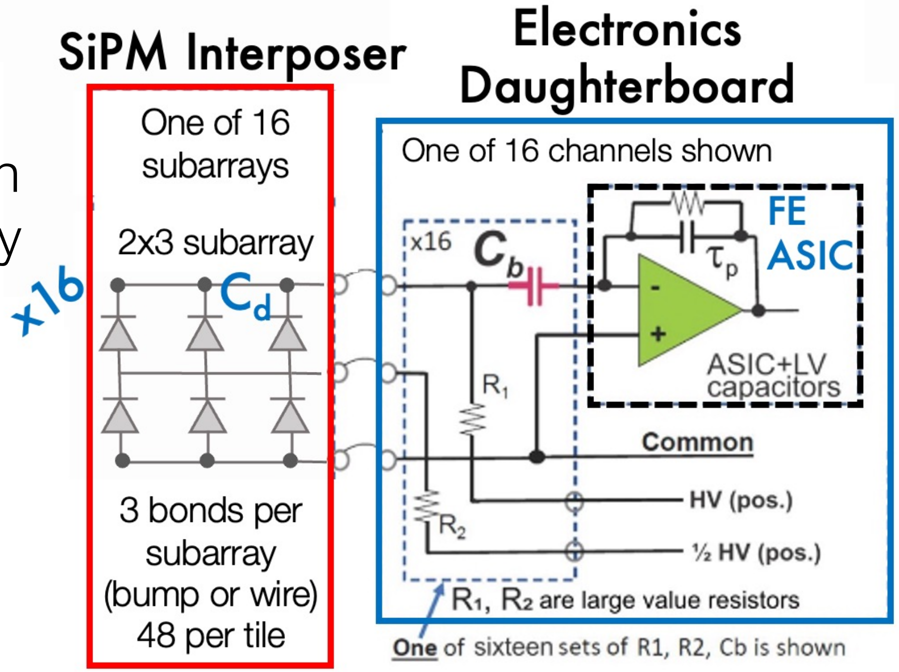
G. Gallina, nEXO collaboration, Eur. Phys. J. C 82, 1125 (2022)

- External crosstalk measurements from TRUMF and IHEP to be incorporated soon

Read-out channel size optimization

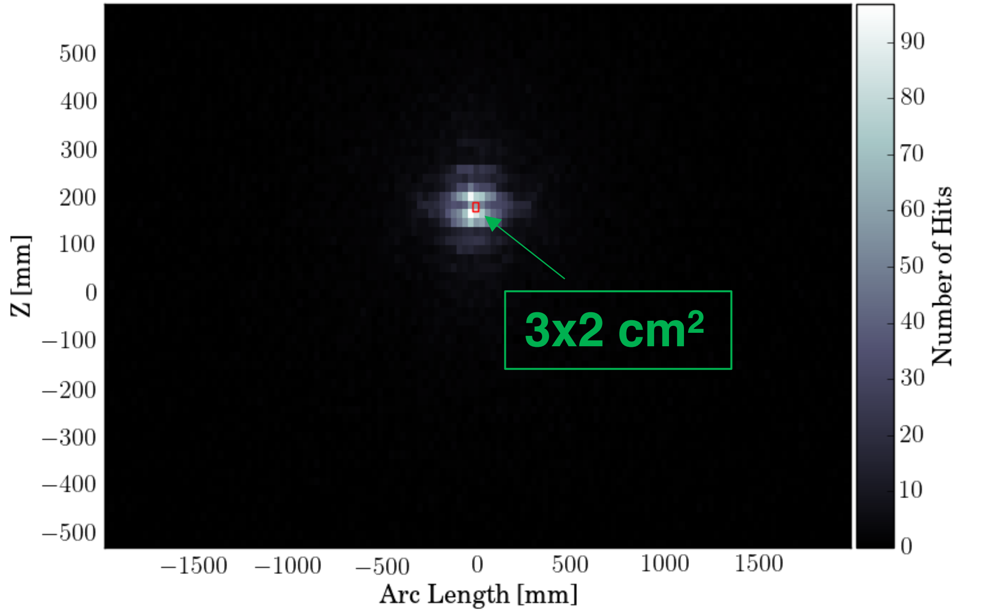
- Channel sizes from readout of a single ~1 cm² device to readout of a full tile ~100 cm² were considered
- Conceptual design uses largest channel size that meets noise spec (3 x 2 cm²) ➞ capacitance grows with channel size
- SiPM subarray capacitance (C_d) can be further reduced by using 3P2S parallel-series configuration ~5 nF





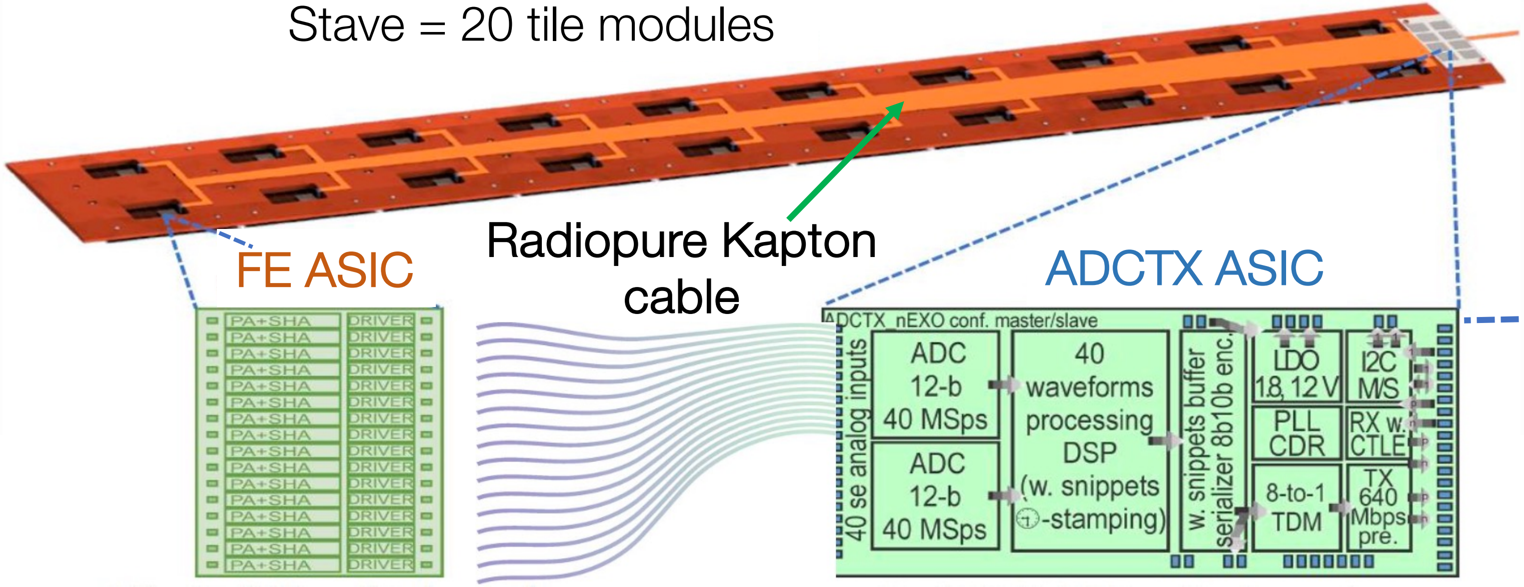
3P2S readout channel

Example collection for fiducial volume edge event

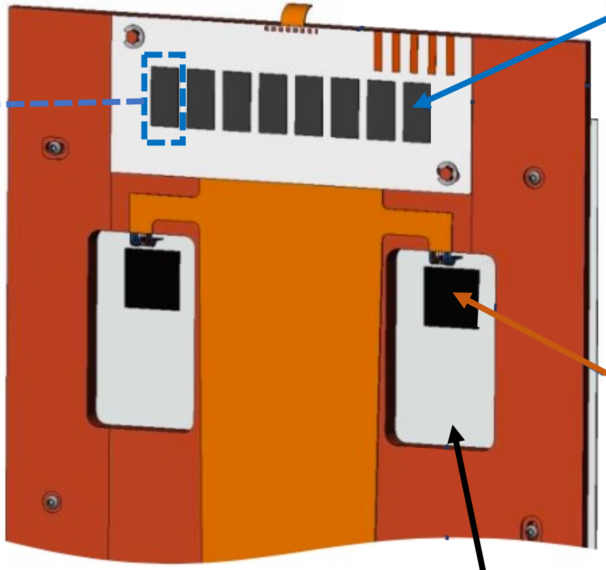


Photon readout ASICs

Stave = 20 tile modules



Close up of ASICs on top of stave



- Photon signals collected by SiPMs amplified and shaped by FE ASIC on daughterboard
- 20 tiles with FE ASIC x 16 channels = 320 channels per stave

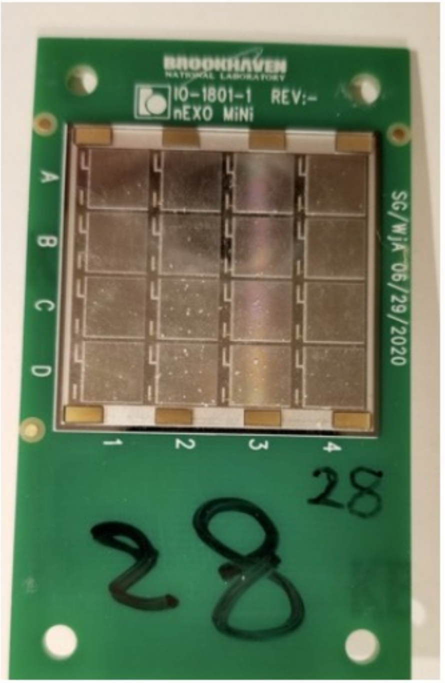
- Analog signals from tiles digitized by ADC ASIC
- Digitized signals multiplexed and transmitted to DAQ
- 8 x ADCTX ASIC x 40 channels 320 channels per stave

Position of ADC at top of stave, moves heat load to top of TPC

24 staves: 7,680 channels

FE ASIC proof-of-concept demonstration

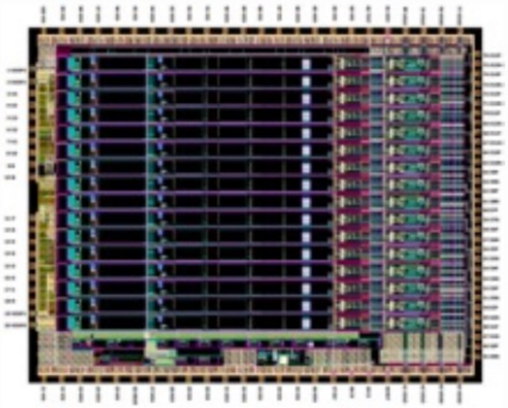
nEXO HPK minitile board



16 x (0.6 x 0.6) cm² SiPMs
Active area: 5.76 cm²

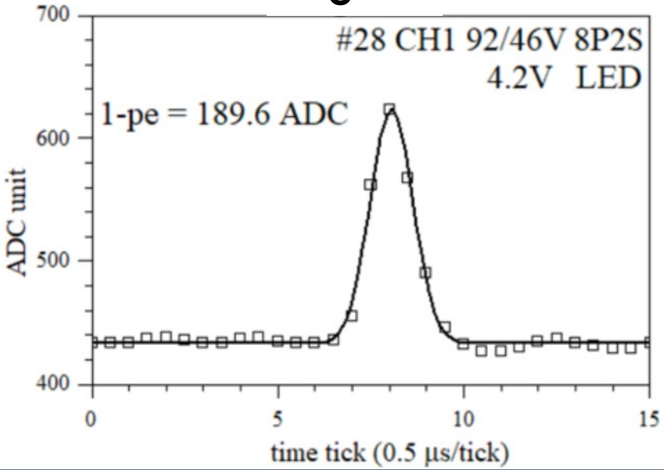
C (16P) SiPM tile ~ 20 nF
C (8P2S) SiPM tile = 4.8 nF

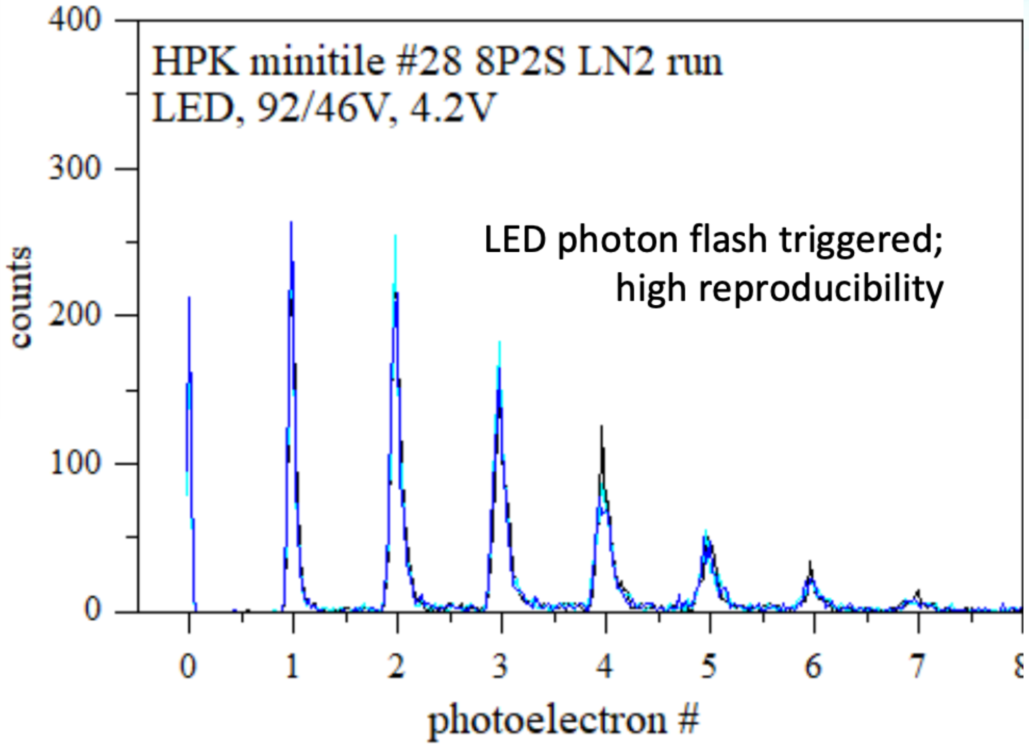
LArASIC



16 channel ASIC based on successful LArASIC board used in ProtoDUNE

Signal

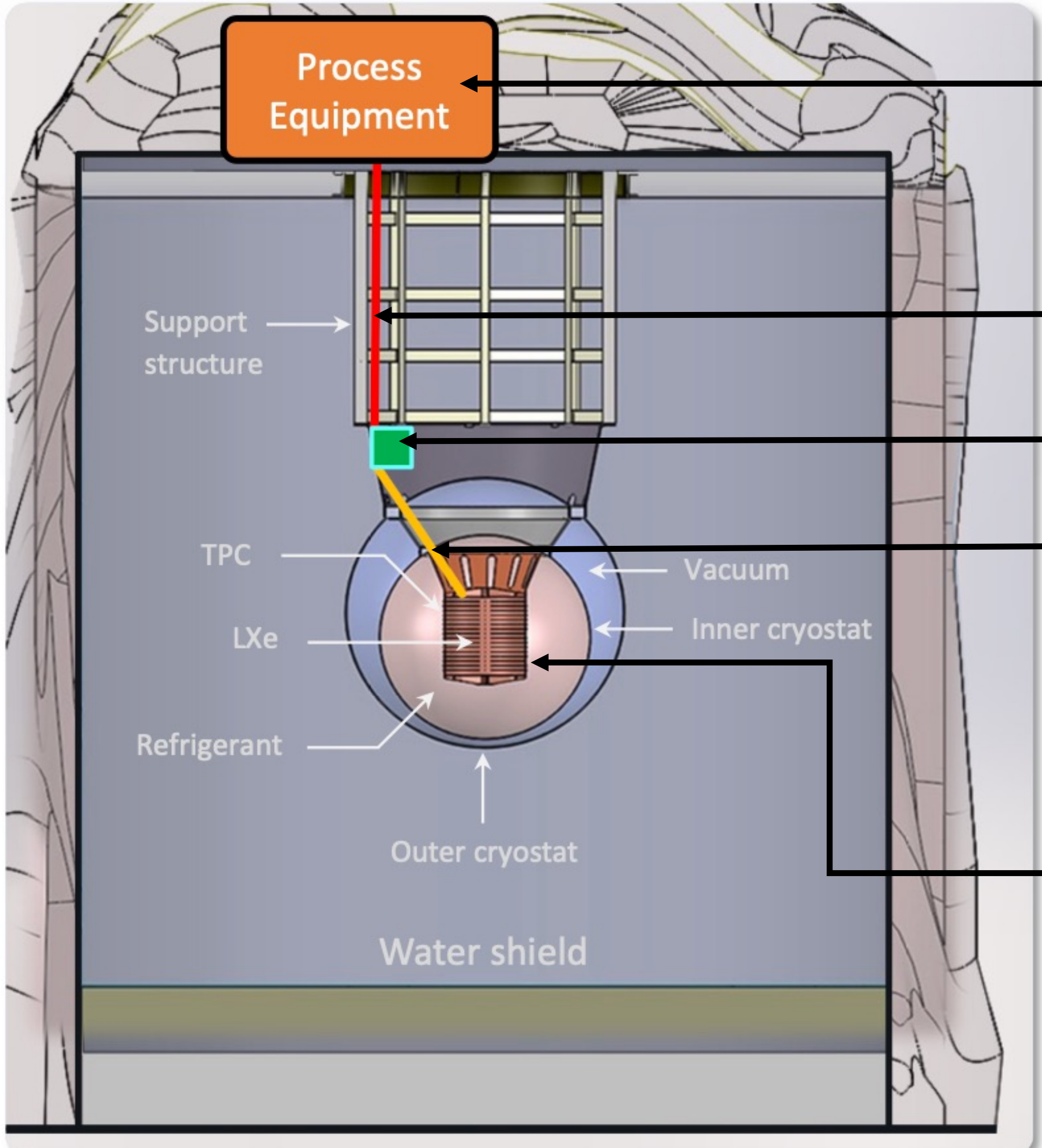




- Signal to Noise Ratio (SNR): **>30**
- Avalanche charge at 4V OV: **0.4 pC**
- Single p.e. resolution (δE): **3-3.5% RMS**
- Coincidence timing (s.p.e. coincidence resolution between two subarrays): **< 20 ns**

Integration in nEXO design

nEXO



Deck

Backend readout:
Controller/Receiver boards
Data reception, slow controls, trigger processing, DAQ

Water Tank

Upper conduit with power and data lines

Warm transition boards and enclosures for PRE

Radiopure high-speed kapton cables

Cryostat/ TPC

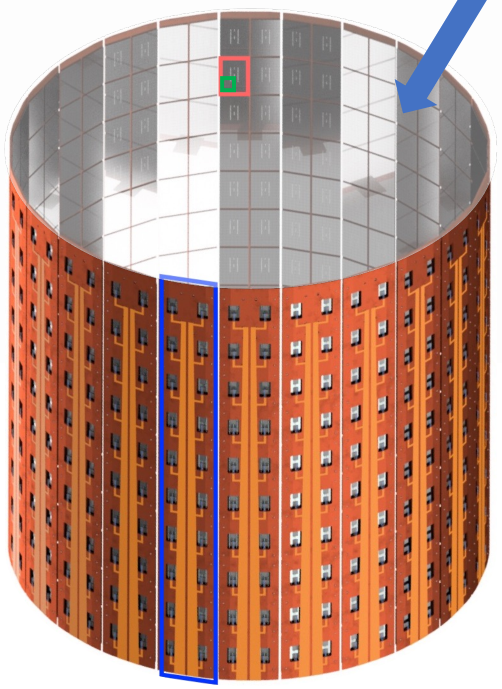
SiPMs → Readout channels

Tile Module:
- FE Daughterboard
- FE ASIC

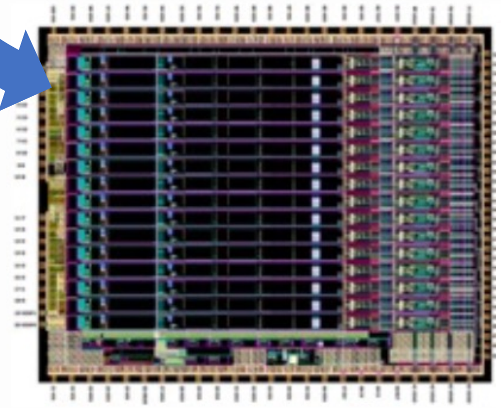
Stave:
- ADCTX Board
- ADCTX ASIC

Summary

- Mature conceptual design of full photon detection system.
- Have identified devices from two vendors that meet our design specifications to reach energy resolution goal.
  - Developed FE ASIC technology with SNR>30.
- ADC ASIC development underway

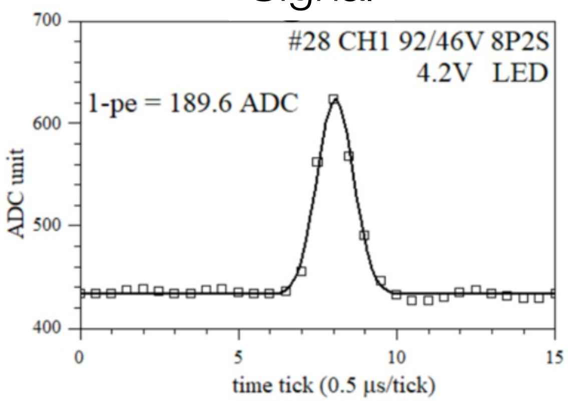


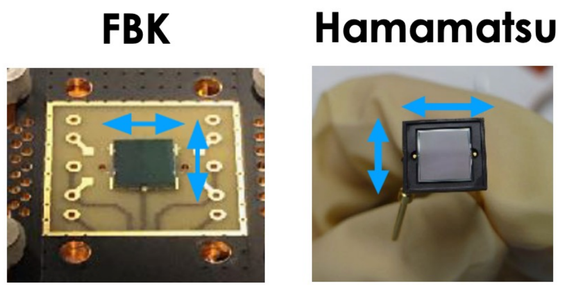
Photon detection system



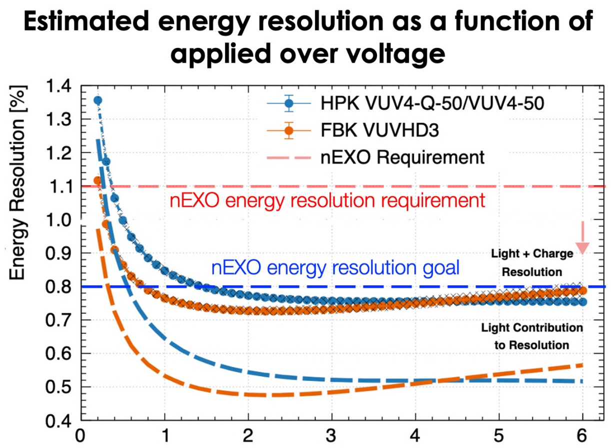
LArASIC

Signal





FBK VUVHD3 HPK VUV4-50



Thank you!! Questions?

2023 Winter collaboration meeting at Livermore, CA

Wright Lab

U.S. DEPARTMENT OF ENERGY

Yale University

NSF

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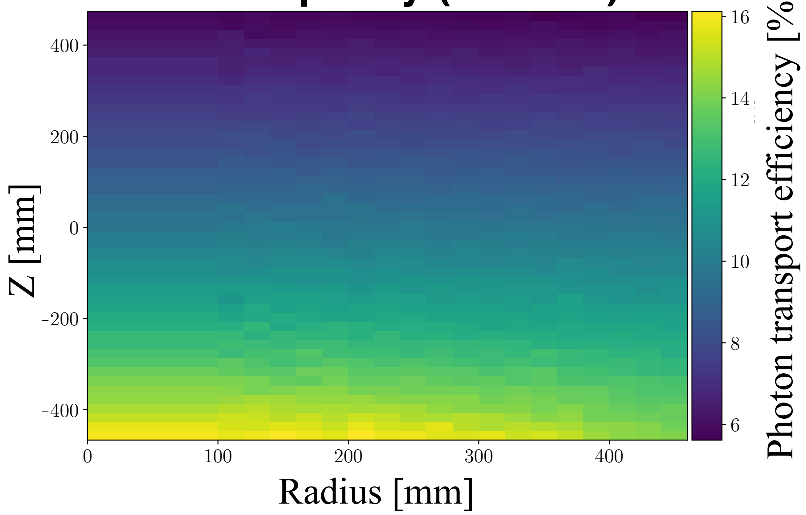
Back-up slides

Photodetector location

Considered several locations for photodetector location:

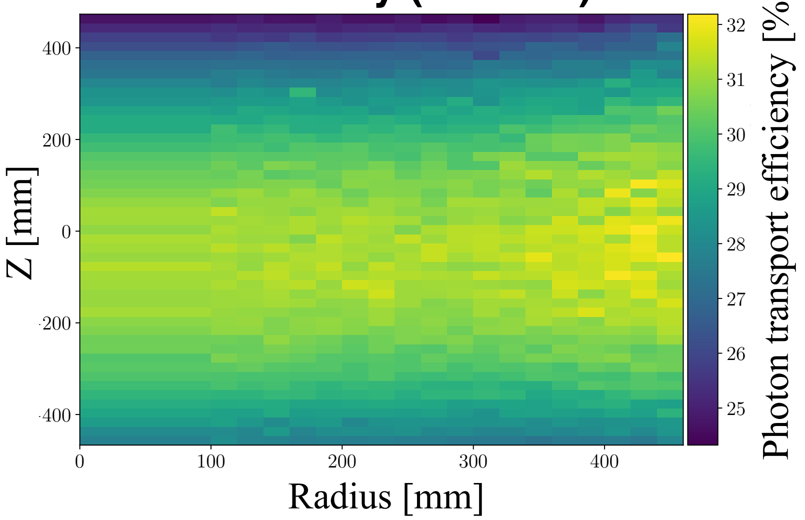
Photon transport efficiency, ε, versus position:

Endcap only (ε = 10%):



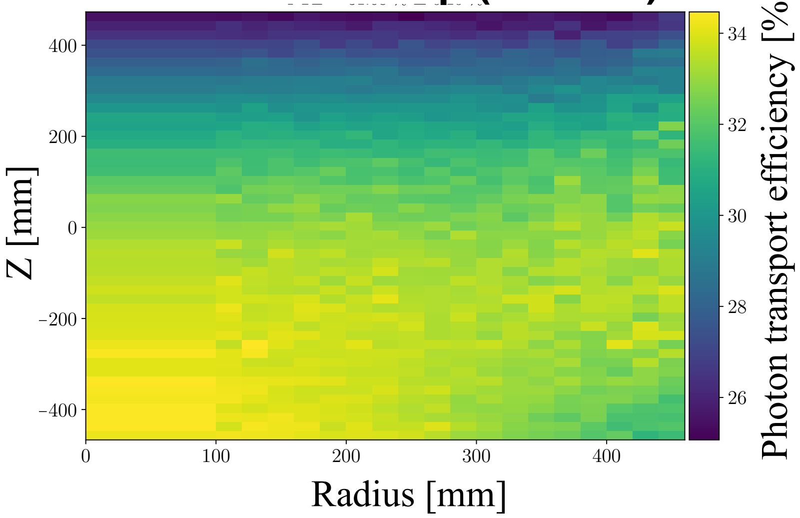
Detectors behind cathode only w/ a PTFE reflector

Barrel only (ε = 29%):



Detectors behind cathode only w/ a PTFE reflector

Barrel + endcap (ε = 31%):



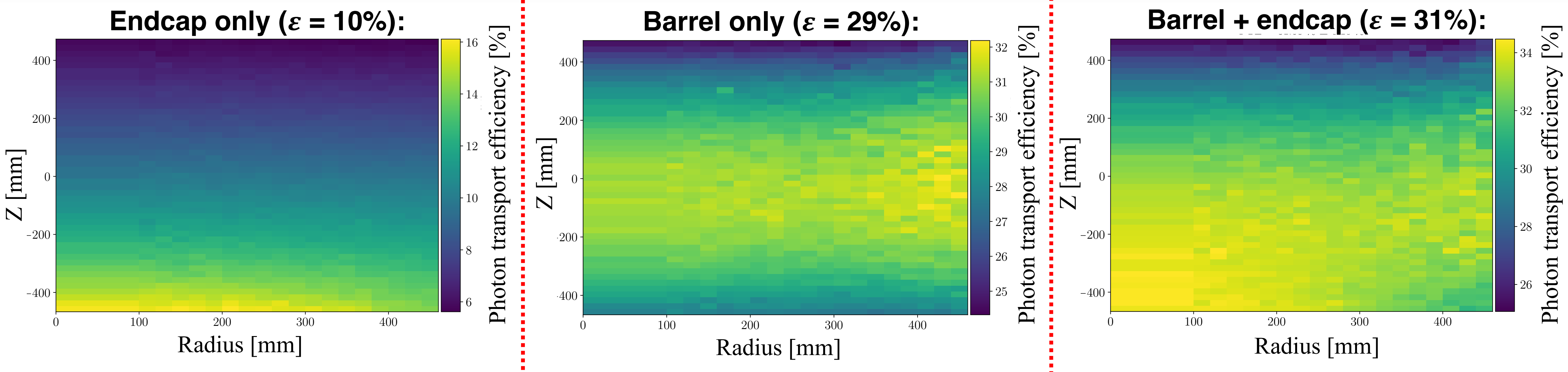
Detectors behind cathode only w/ a PTFE reflector

* Opaque charge collection tiles employed at anode

Photodetector location

Considered several locations for photodetector location:

Light transport efficiency, ε, versus position:



Conceptual design selection

- Background reduction from endcap light detectors not significant (~percent level)
- Detectors below cathode carry risk of boiling

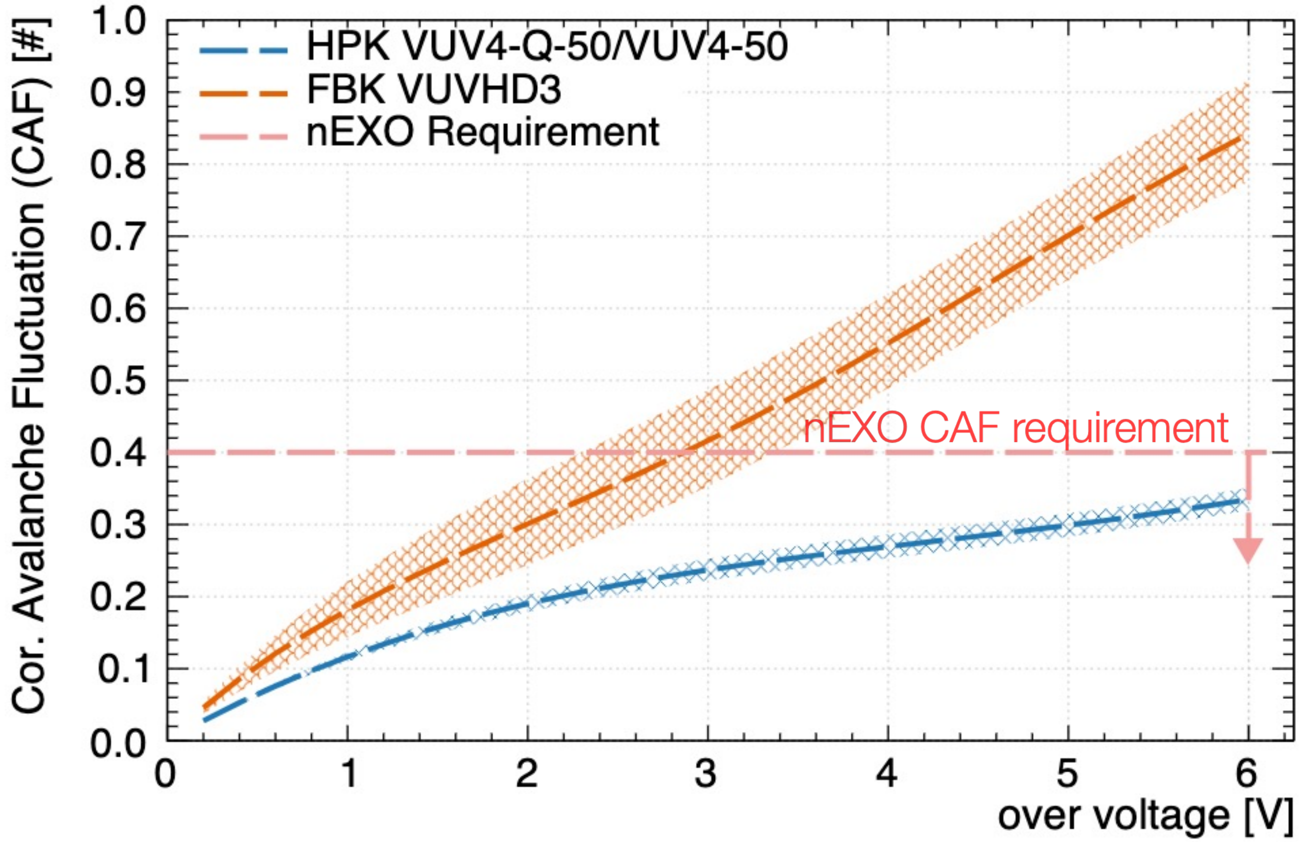
Correlated avalanche fluctuations (CAF)

nEXO

$$CAF = \frac{\sigma_\Lambda}{1 + \langle \Lambda \rangle}$$

σ_Λ: RMS error of CA charge per photoelectron (PE)

$\langle \Lambda \rangle$: Mean charge in CA per primary PE



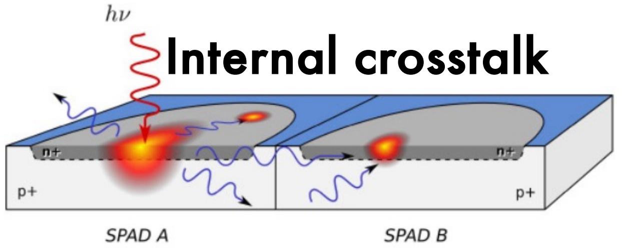


Image: I. Rech (2008)

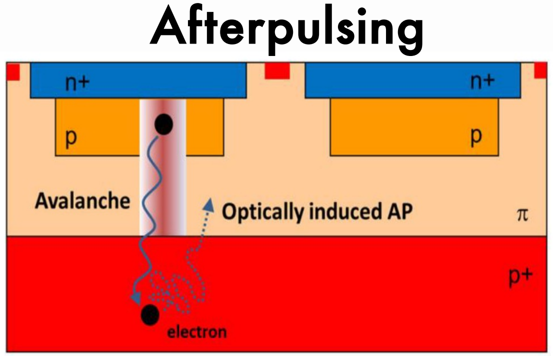
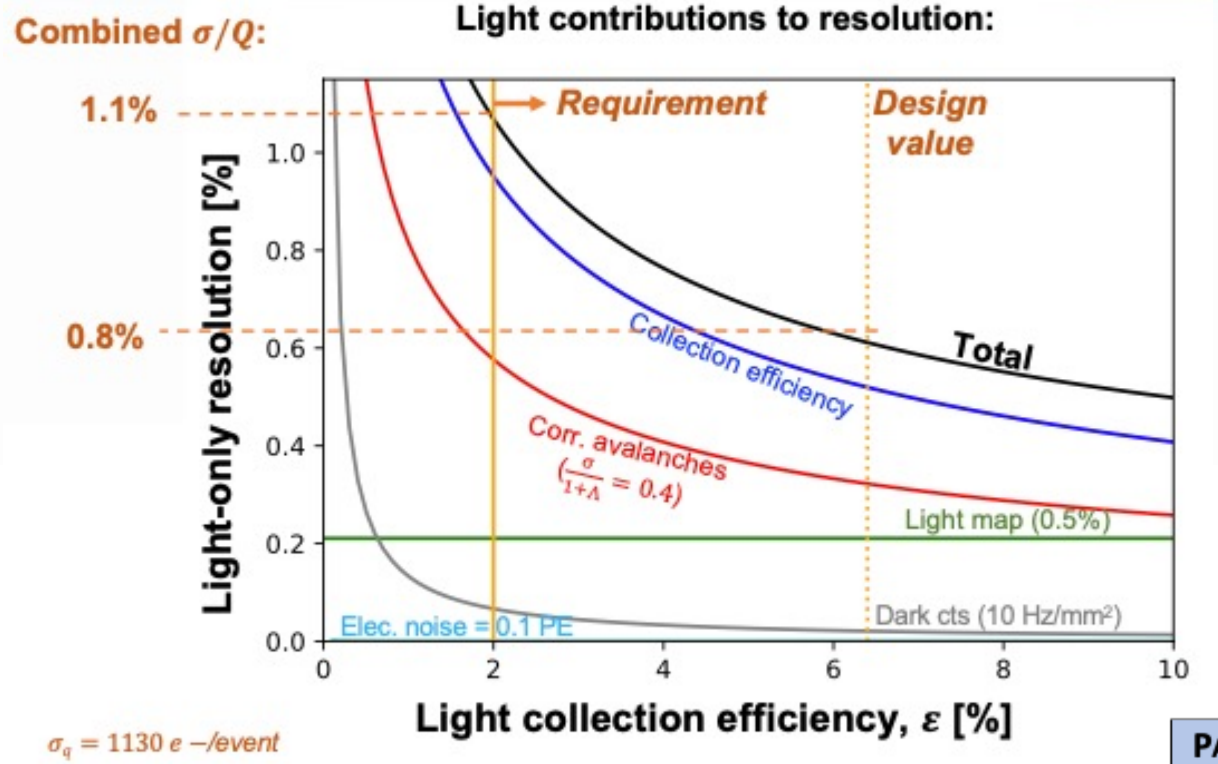


Image: C. Piemonte & A. Gola (2019)

Devices meet nEXO requirement at optimal over voltage

G. Gallina, nEXO collaboration. Eur. Phys. J. C 82, 1125 (2022)

SiPMs



- Set requirements on photodetectors and system
- Electronics noise must be < 0.1 PE

Key technical performance parameters to meet energy requirements

Parameter:	Requirement:	Design value:
Total instrumented area	4.6 m^2	4.6 m^2
Overall light collection efficiency, ε	$\geq 2\%$	6%
SiPM PDE, ε_{PD} (175 nm, normal incidence)	$\geq 15\%$	20%
Dark Count Rate, DCR	< 10 Hz/mm^2	5 Hz/mm^2
Fluctuation in correlated avalanches, $\sigma_\Lambda/(1+\bar{\Lambda})$	< 0.4	0.2