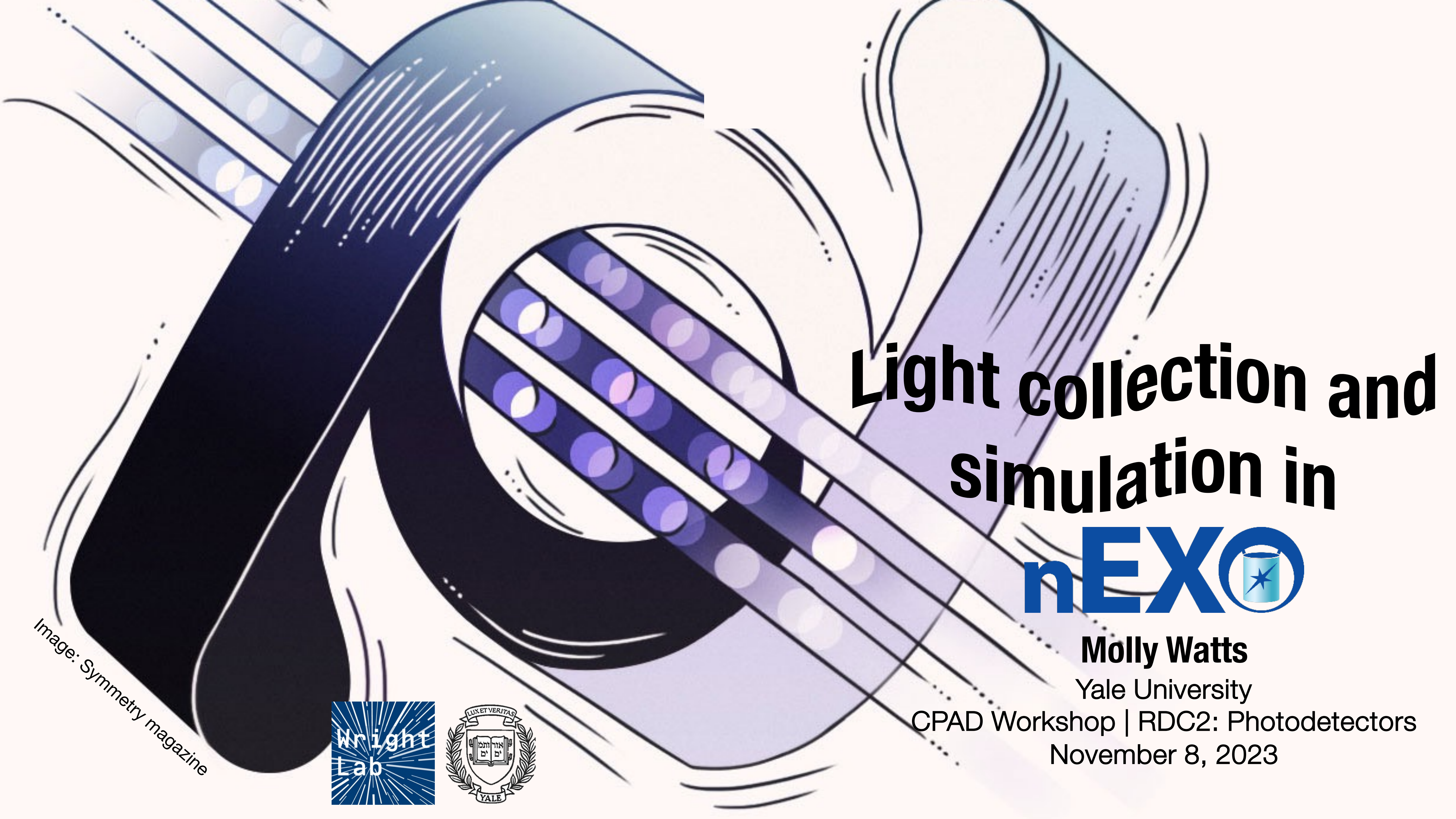


Image: Symmetry magazine

Light collection and simulation in nEXO

Molly Watts

Yale University

CPAD Workshop | RDC2: Photodetectors

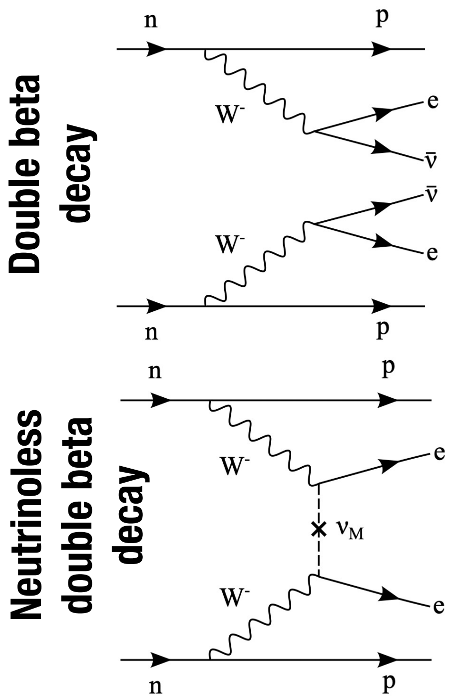
November 8, 2023

Wright Lab

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

Finding $0\nu\beta\beta$ implies physics beyond the Standard Model

1. Lepton number violation



2. New class of elementary particles

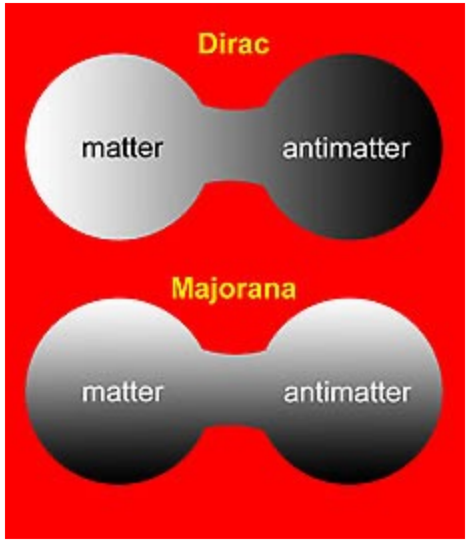


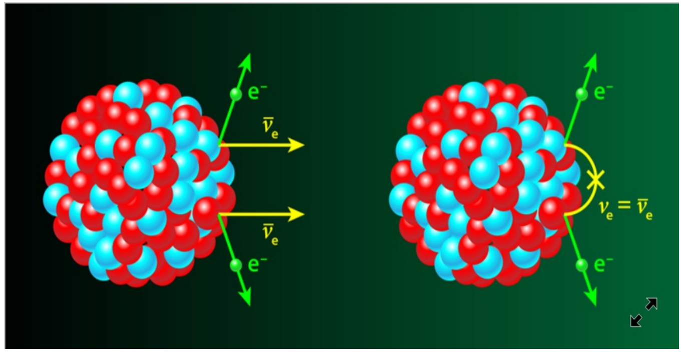
Image: Fermilab Today

Neutrinos are Majorana particles

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

3. Implications for matter-antimatter asymmetry

Image: APS/ Alan Stonebraker



Double beta decay
↓
Leptons & Anti-leptons

Neutrinoless double beta decay
↓
Only leptons

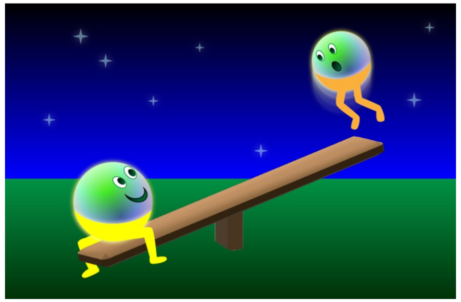
4. Insight into neutrino mass

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

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

&

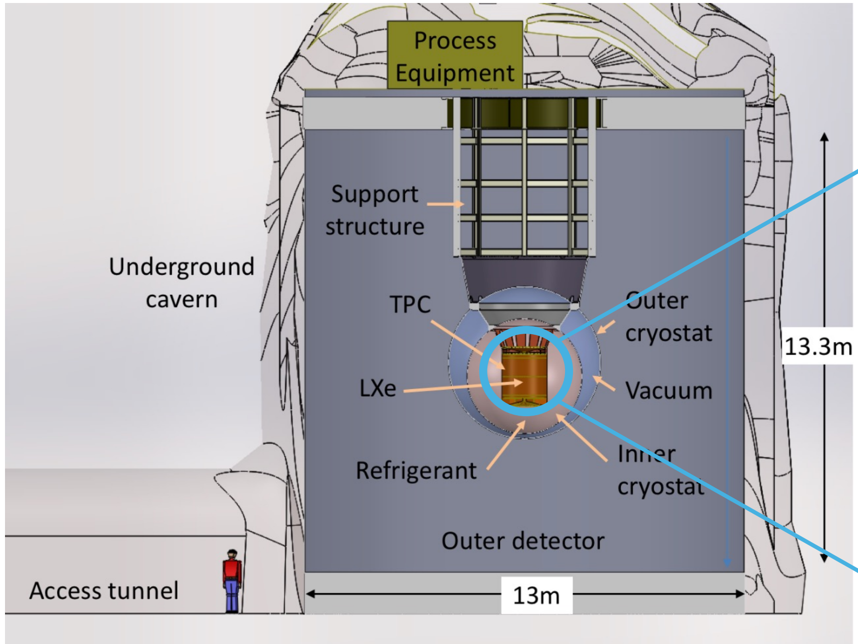
Possible new mass giving mechanism



See-saw mechanism

Image: APS/ A. Stonebraker

nEXO Planned $0\nu\beta\beta$ detector



Builds off success of EXO-200

1st observation of $2\nu\beta\beta$ in ^{136}Xe

Single phase TPC

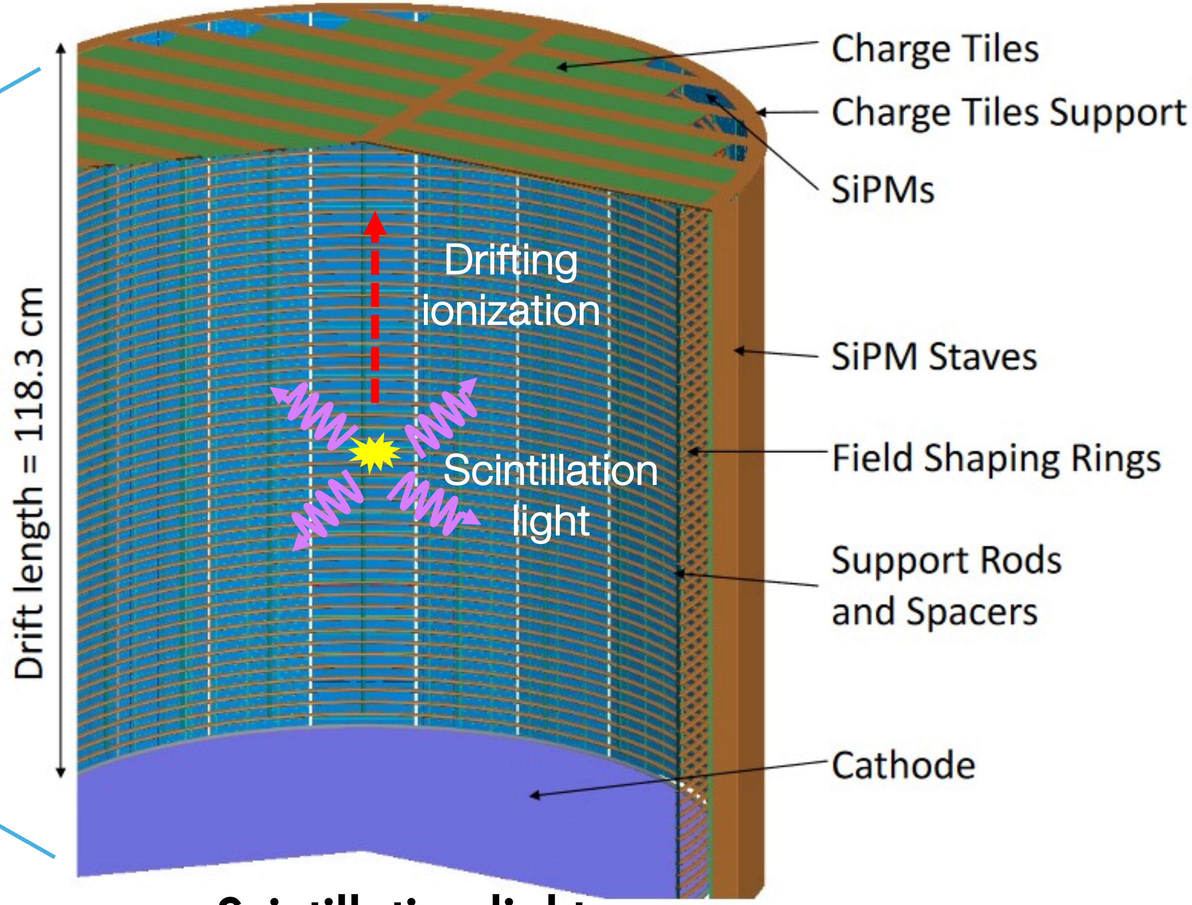
400 V/cm drift field, ~1.2 m drift length

5,000 kg of LXe enriched to 90% ^{136}Xe

High Q-value of 2458 keV

Detector size exceeds gamma ray absorption length

Self shielding, Scalability



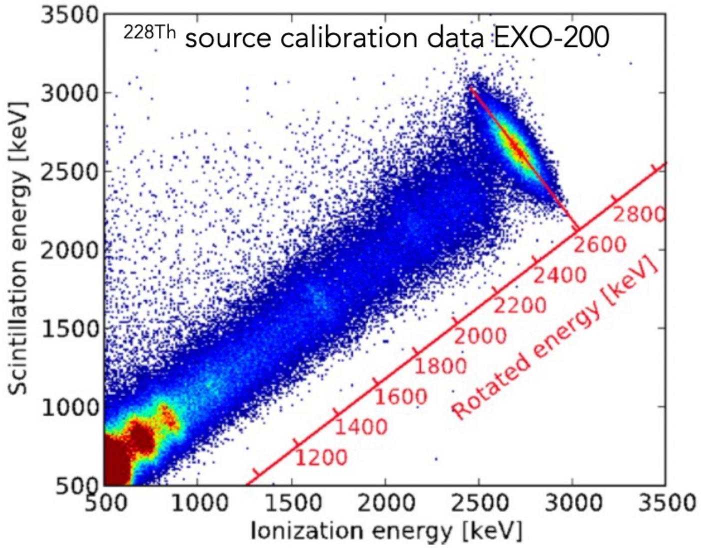
Scintillation light

- Time stamp of interaction time
- Independent measurement of charge and light is instrumental for energy resolution requirement of ≤ 1.1% and our energy resolution goal of ≤0.8%

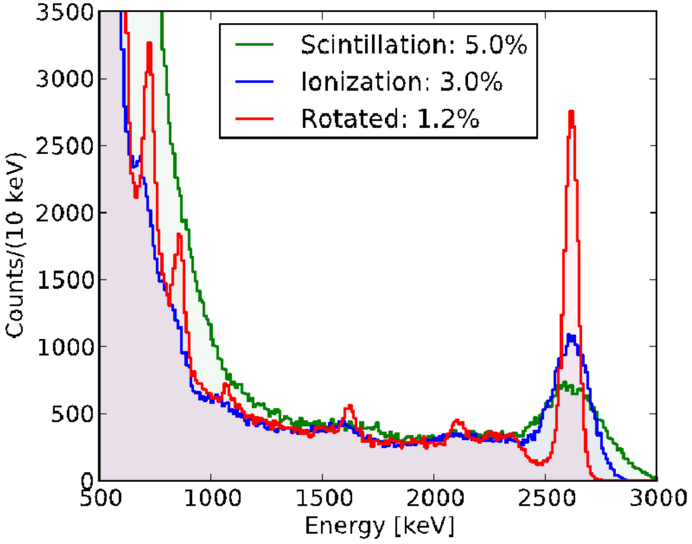
nEXO collaboration, 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

Energy resolution

EXO-200 Th-228 source calibration data



Energy spectra of Th-228 events



Fractional resolution: $\frac{\sigma_E}{E}$

Rotated energy resolution is dominated by light collection efficiency

Light collection efficiency (Ɛ)

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

Photon transport efficiency

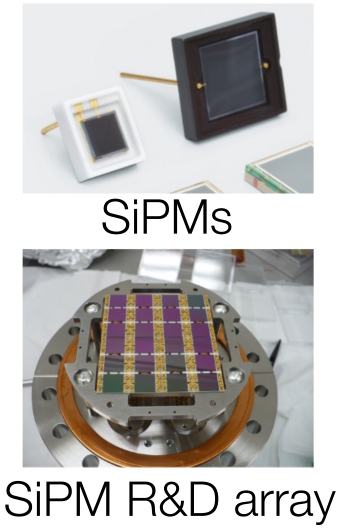
Device avalanche probability

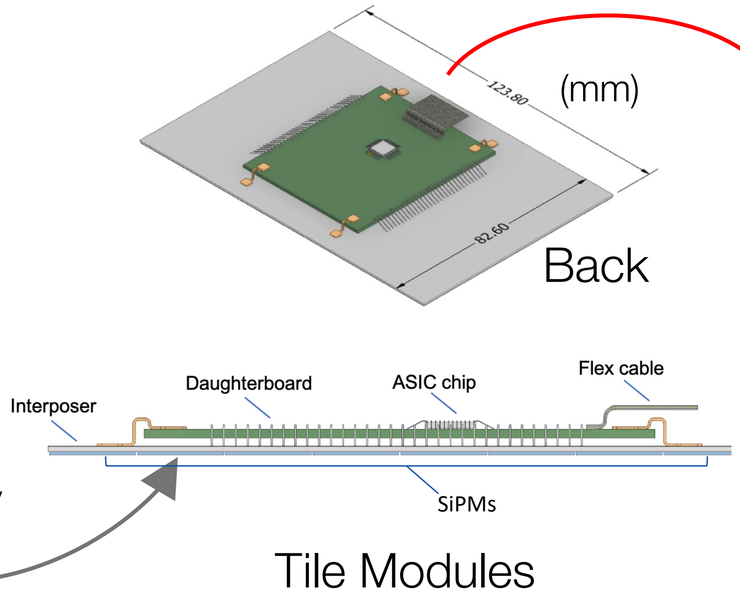
Photon detection efficiency

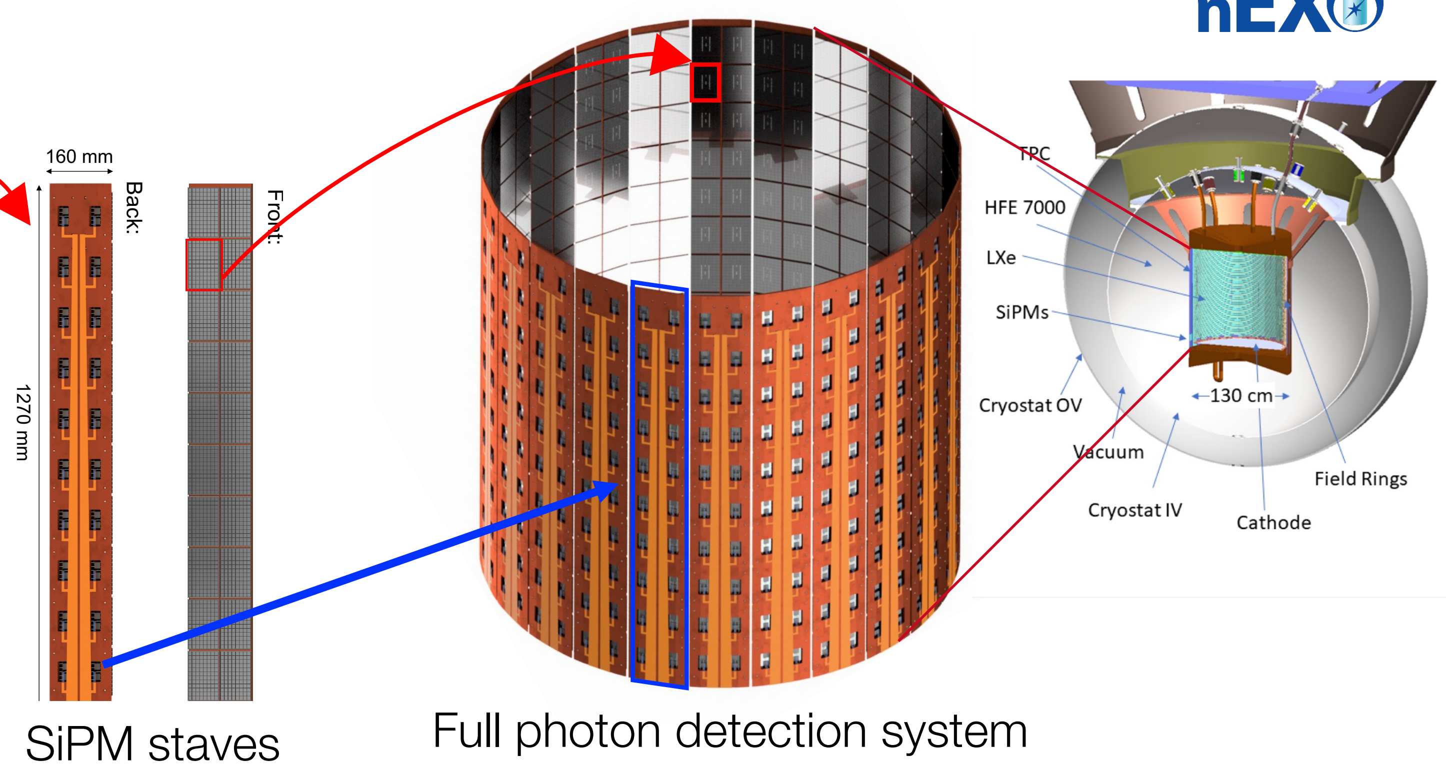
Reflection at normal incidence in vacuum

Light Collection

Photon detection system



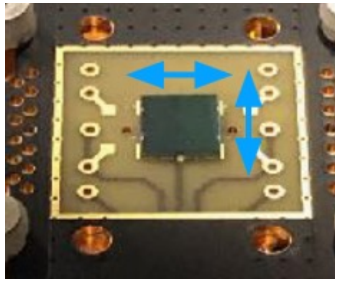




Silicon Photo-Multipliers (SiPMs)	Tile Modules	Staves	Geometry	Photocoverage
Individual SiPMs Grouped in 6 cm^2 sub-arrays → readout channels	16 sub-arrays to tile w/ smaller daughterboard & integrated ASIC 20 tile modules arrayed to form stave	24 staves surround barrel, behind field shaping rings Electroformed copper	Square cylinder Decreases the number of reflections before hitting a photodetector	4.6 m^2 7,680 channels

VUV-sensitive SiPMs in nEXO

FBK



FBK VUVHD3

Replaces previous generation: FBK VUVHD1

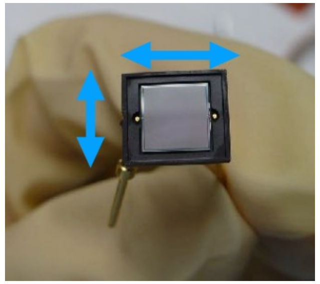
2 candidate manufacturers

Fondazione Bruno Kessler (FBK)

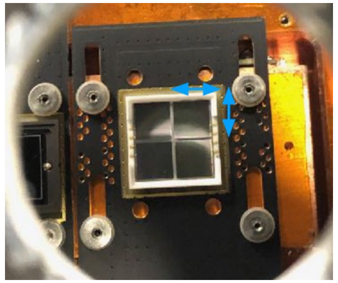
Hamamatsu Photonics (HPK)

Tested 3 devices (6x6mm²)

Hamamatsu



HPK VUV4-50



HPK VUV4-Q-50 Quad

G. Gallina, nEXO collaboration. Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO. Eur. Phys. J. C 82, 1125 (2022)

nEXO requirements to meet ≤1.1% energy resolution	
Photon detection efficiency (PDE)	≥ 15% for 175 nm photons
Dark count rate at -100°C	< 10 Hz/mm²
Fluctuations in correlated avalanches (CAF) per pulse in 100μs at -100°C	< 0.4

Photon detection efficiency (PDE)

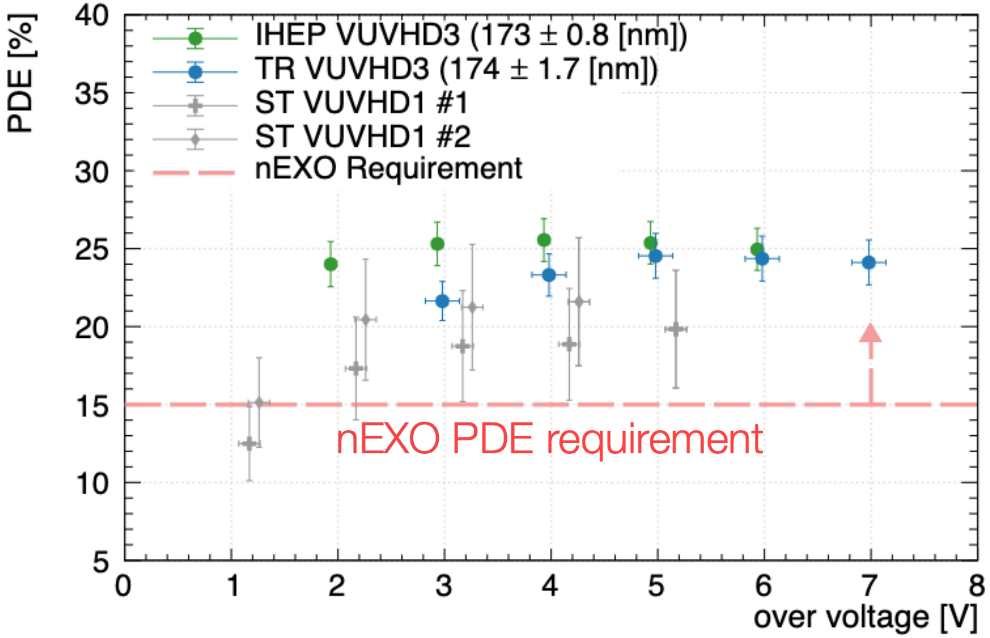
Light collection efficiency (Ɛ):

$$Ɛ = PTE * \frac{PDE}{1-R}$$

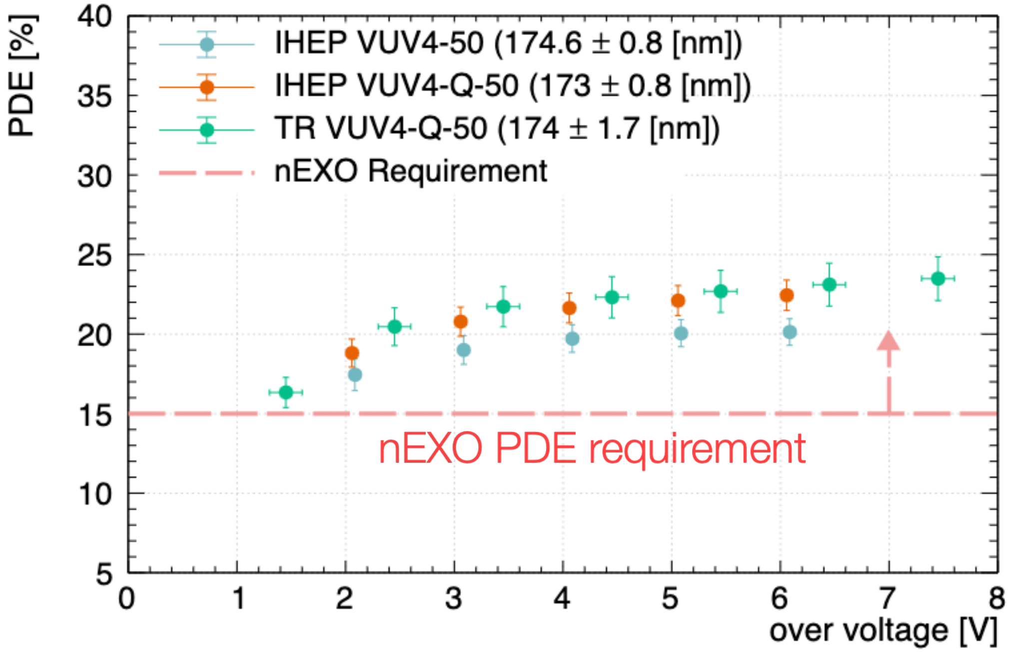
175 nm PDE as function of over voltage

Requirement: ≥ 15% for ~175 nm photons

FBK



Hamamatsu



Devices meet nEXO requirement from 1.5V over voltage!

TRIUMF: 165K
IHEP: 300K

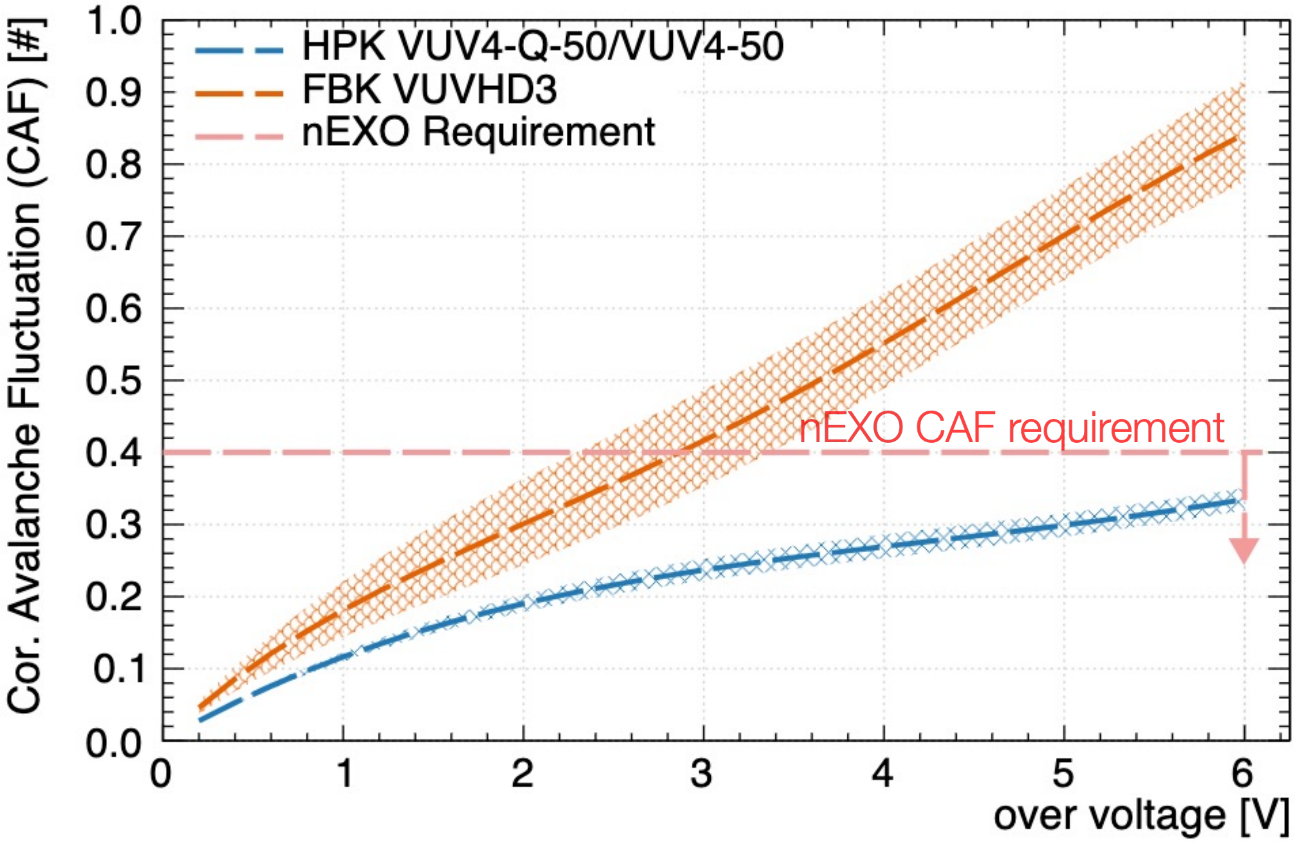
G. Gallina, nEXO collaboration.
Eur. Phys. J. C 82, 1125 (2022)

Correlated avalanche fluctuations (CAF)

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

RMS error of CA charge per photoelectron (PE)

Mean charge in CA per primary PE



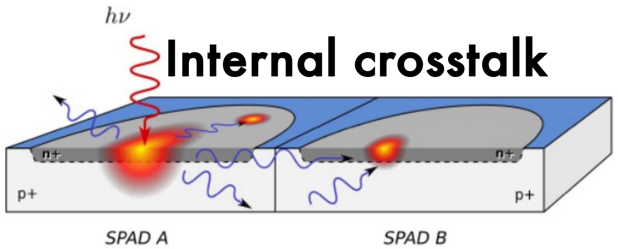


Image: I. Rech (2008)

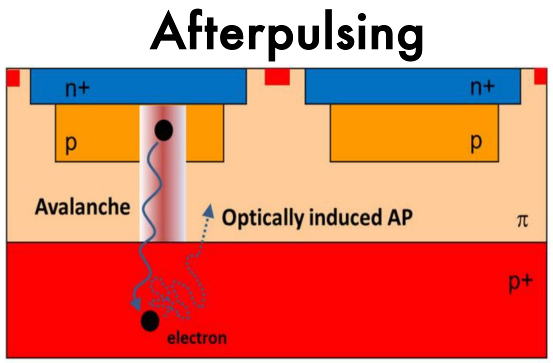


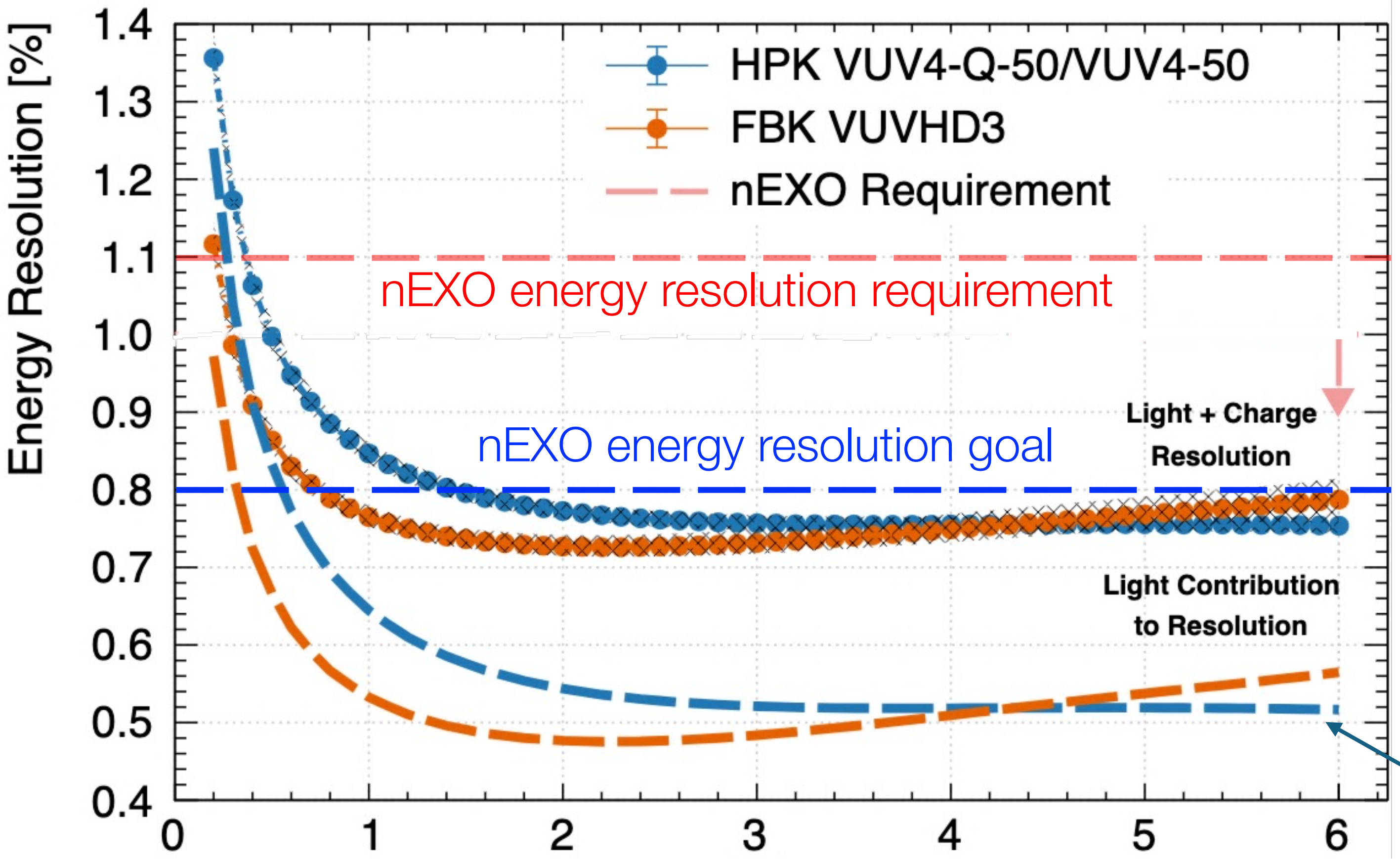
Image: C. Piemonte & A. Gola (2019)

Devices meet nEXO requirement at optimal over voltage

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

nEXO energy resolution with candidate SiPMs

Estimated energy resolution as a function of applied over voltage



Over voltage [V]

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

Energy resolution

nEXO requirement ≤1.1%

nEXO goal ≤ 0.8%

Devices meet our requirements!

Note: Yet to account for external cross talk. Might produce slightly steeper rise but shouldn't impact reaching goal.

Papers from TRIUMF & IHEP out soon!

Contribution to light channel to total energy resolution neglecting recombination fluctuations

Optical Simulations

Chroma

GPU-accelerated ray tracing package

- Up to 300x faster than Geant4
- Can work with detailed geometry

Light collection efficiency (Ɛ):

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

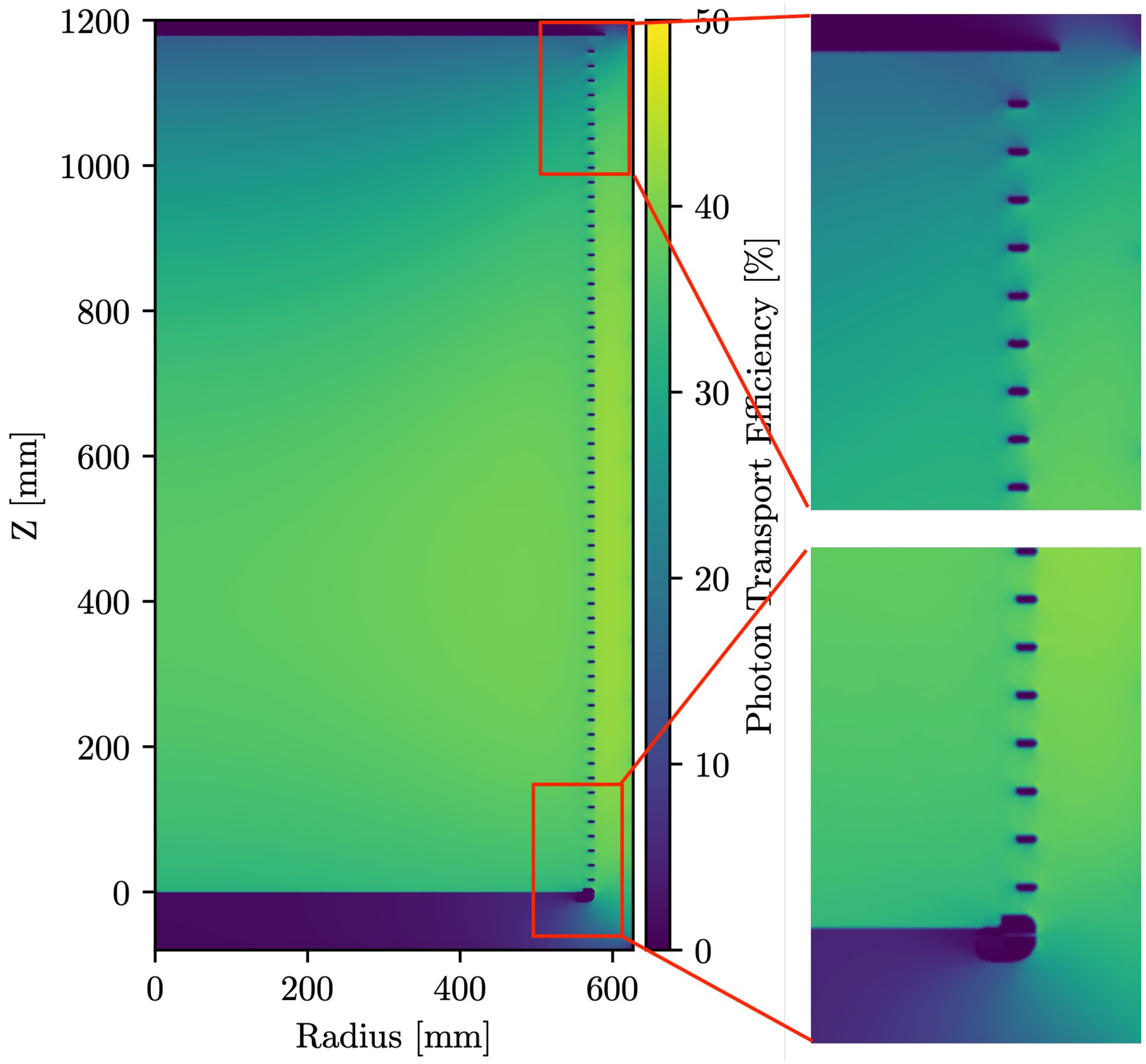
Photon transport efficiency (PTE)

Most detailed light response of nEXO

Contains ~1 trillion photons!

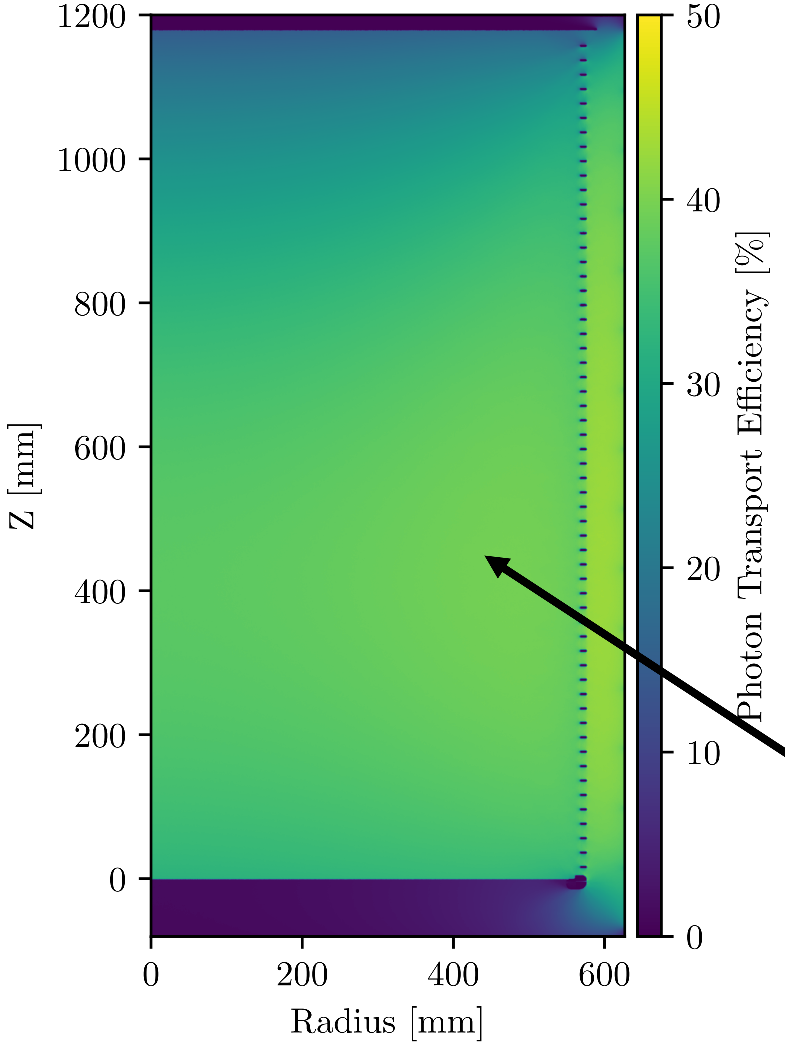
nEXO collaboration, 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

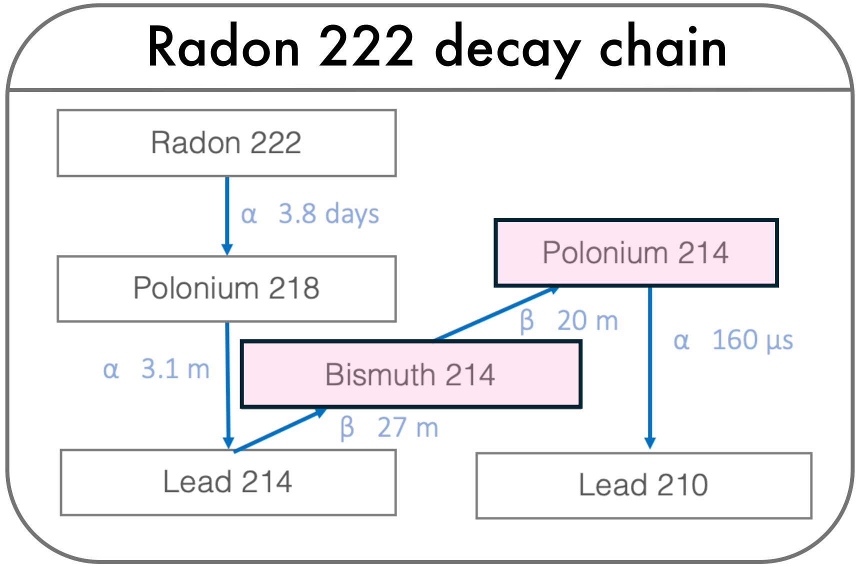
Lightmap from nEXO sensitivity paper



Light Map: Ako Jamil

Improving discrimination for Bi-Po tagging





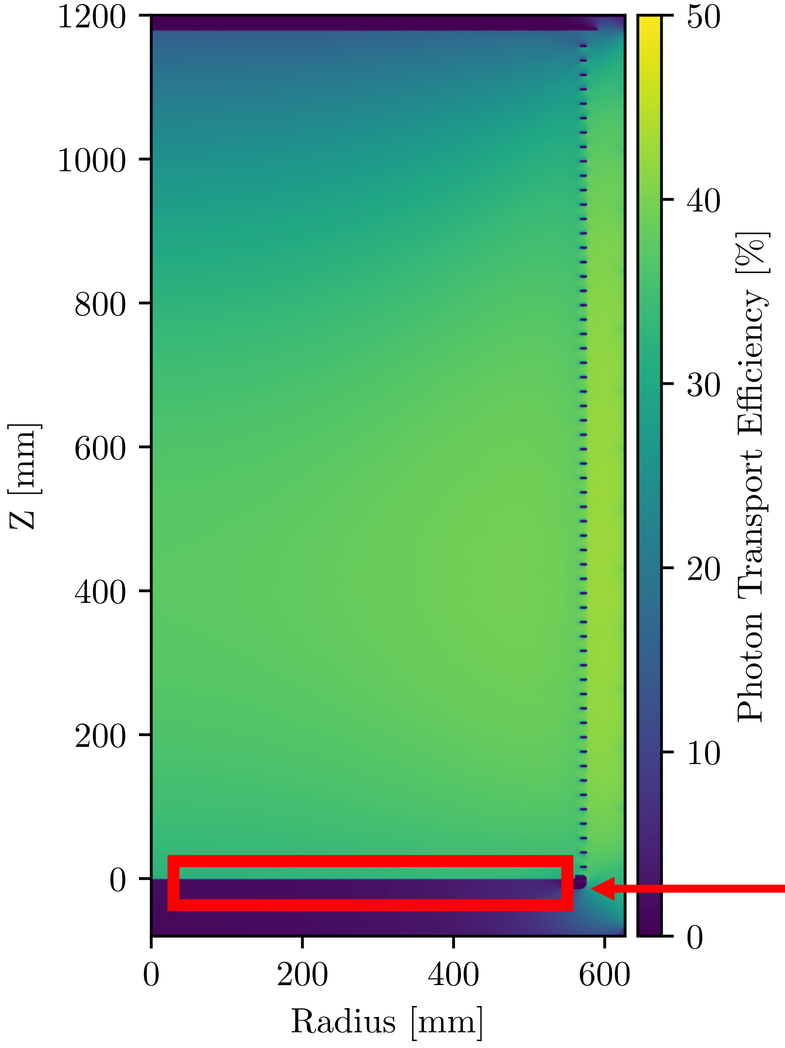
Backgrounds

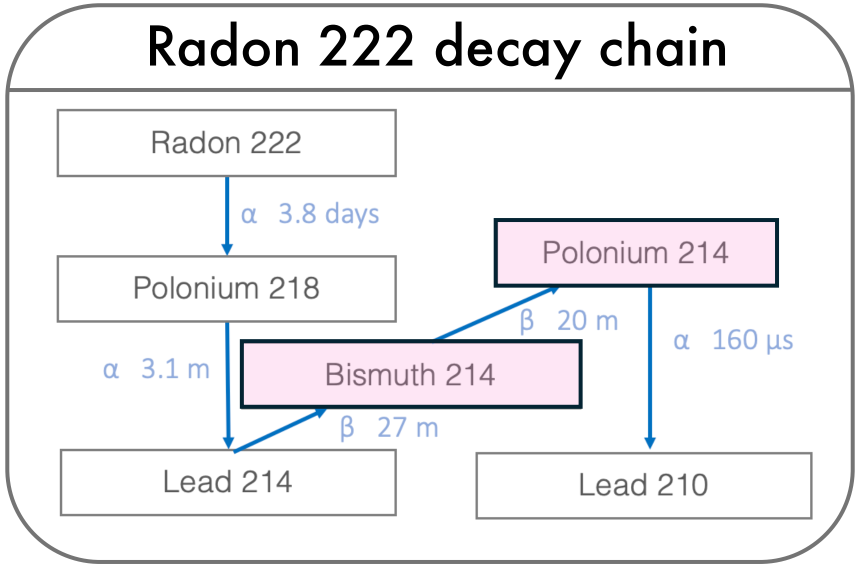
Bi-214 is a dominant background with a gamma close to our 2.5 MeV Q-value

In the volume, we can reject this background with perfect efficiency by tagging Po-214 α

$T^{\alpha}_{1/2} = 160\ \mu s$

Improving discrimination for Bi-Po tagging





Backgrounds

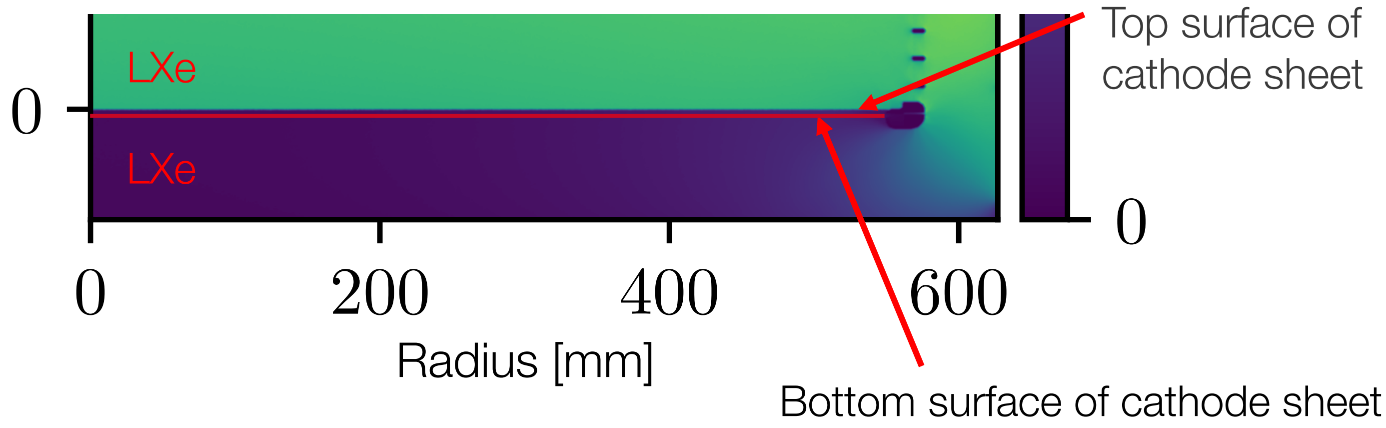
Bi-214 is a dominant background with a gamma close to our 2.5 MeV Q-value

Rn-222 ionized daughters can plate out on cathode

At edges like this, it is more difficult to tag Bi-Po events…

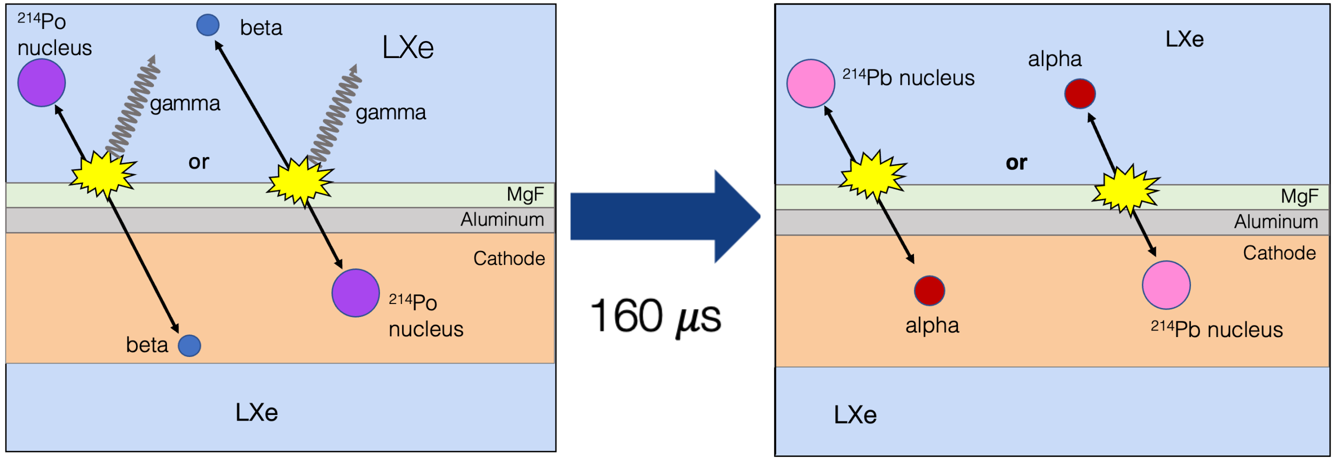
Improving discrimination for Bi-Po tagging

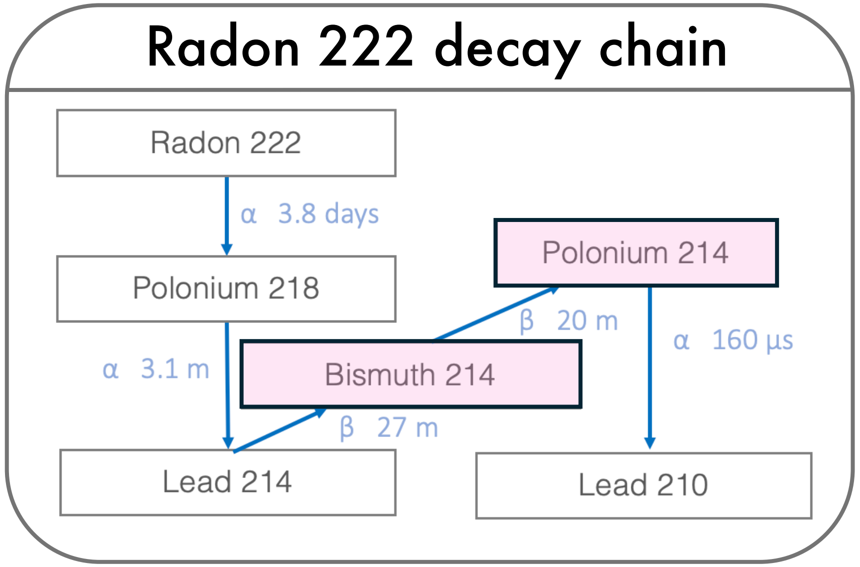
Zoomed in view of cathode



Bi-214 Decay

Po-214 Decay

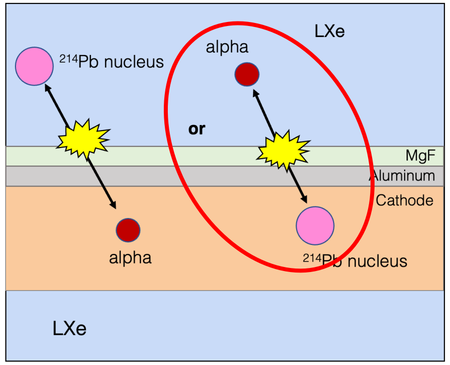




- Current sensitivity projection assumes no tagging based on spatial light discrimination

Alpha particle tagging above cathode

Po-214 beta decay



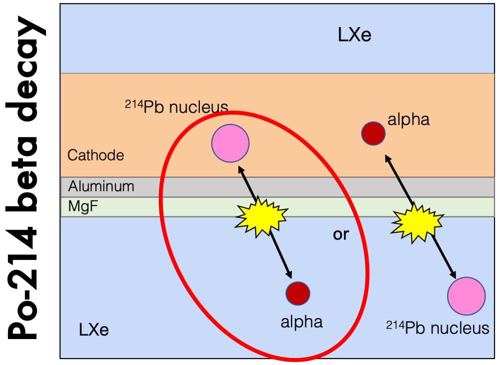
In the volume, we can reject this background with perfect efficiency by tagging Po-214 α

$\mathrm{T}_{1/2}^{\alpha}$ = 160 μs

Under cathode, current sensitivity projection assumes NO tagging

Alpha particle tagging below cathode

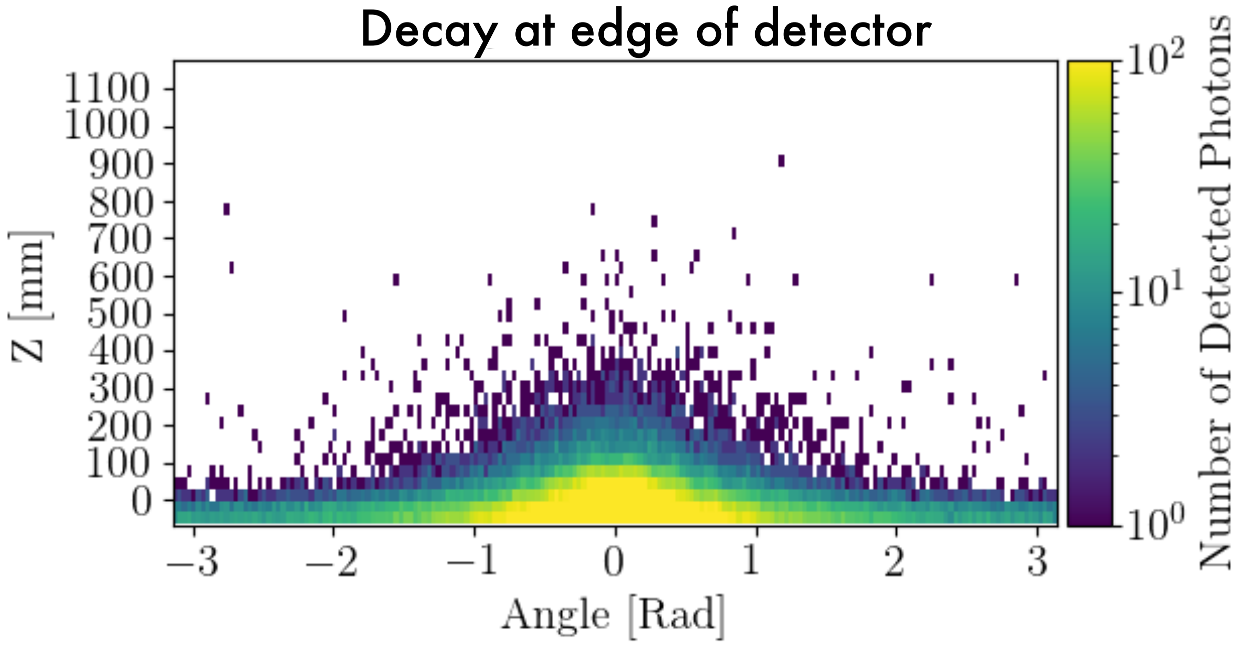
Hit pattern of Po-214 alpha decay below surface of cathode

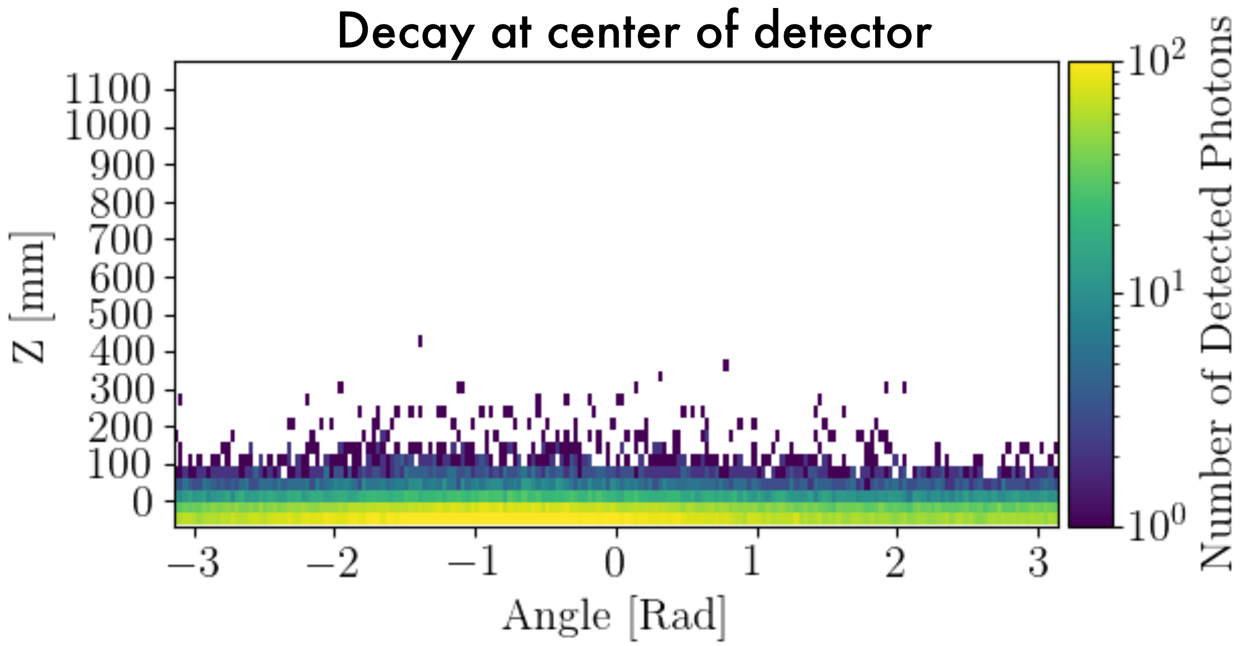


In the volume, we can reject this background with perfect efficiency by tagging Po-214 α

$T^{\alpha}_{1/2} = 160\ \mu s$

Under cathode, current sensitivity projection assumes NO tagging

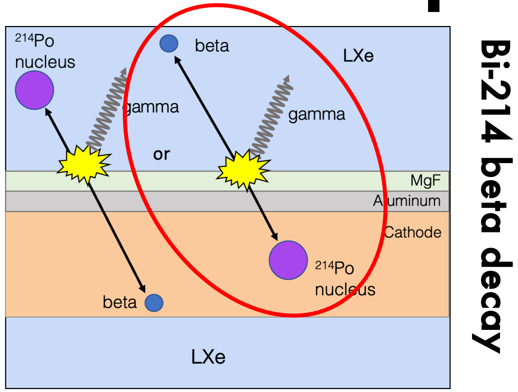


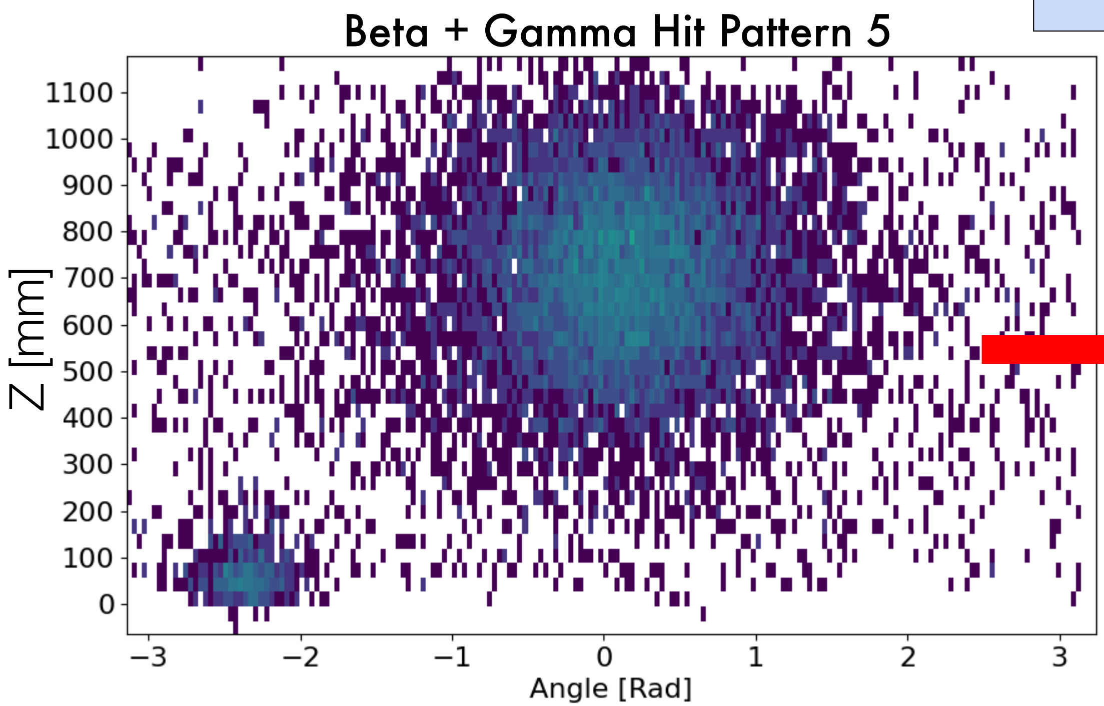


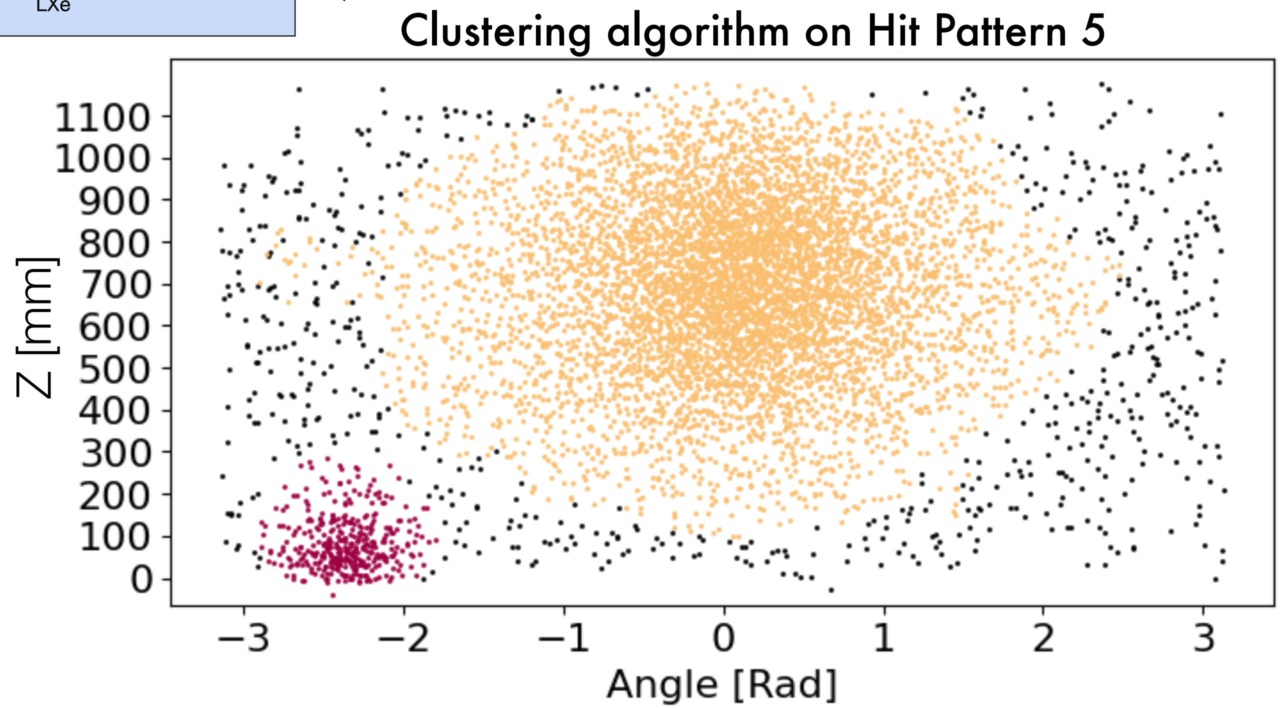
We can tag these alphas based on spatial light discrimination!

Topological discrimination with hit patterns

Hit pattern of Bi-214 beta decay above surface of cathode







Current work: Exploring clustering algorithm to discriminate between background and signal

Future work: Employ Convolutional Neural Network

Summary

Light detection

Have devices from two manufacturers that meet nEXO requirements!!

- Good agreement amongst multiple institutions
- More measurements than shown today

G. Gallina, nEXO collaboration. Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO. Eur. Phys. J. C 82, 1125 (2022)
arXiv:2209.07765

Optical simulations

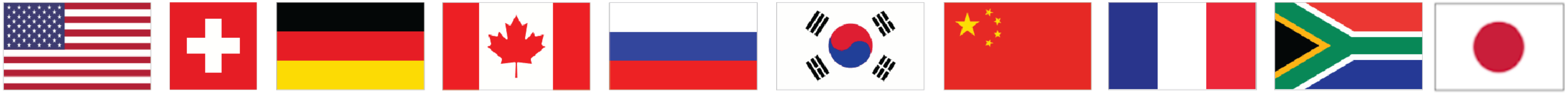
Provide better background rejections and better modeling for energy resolution

- Ongoing discrimination work to better characterize events

Thank you!! Questions?

nEXO

International collaboration involving 10 countries, 36 institutions, ~200 collaborators



Wright Lab

U.S. DEPARTMENT OF ENERGY

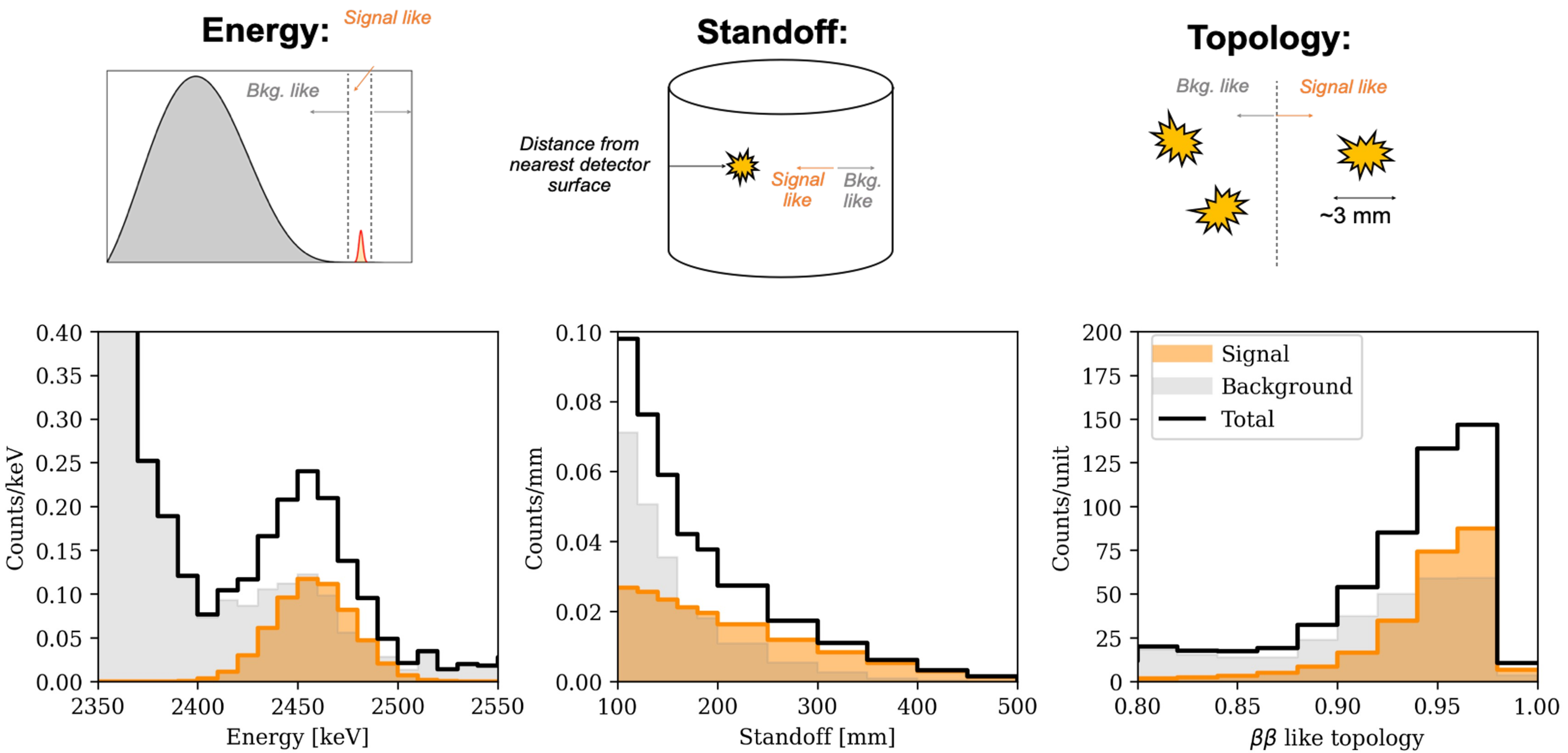
Yale University

NSF

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship.

Back-up slides

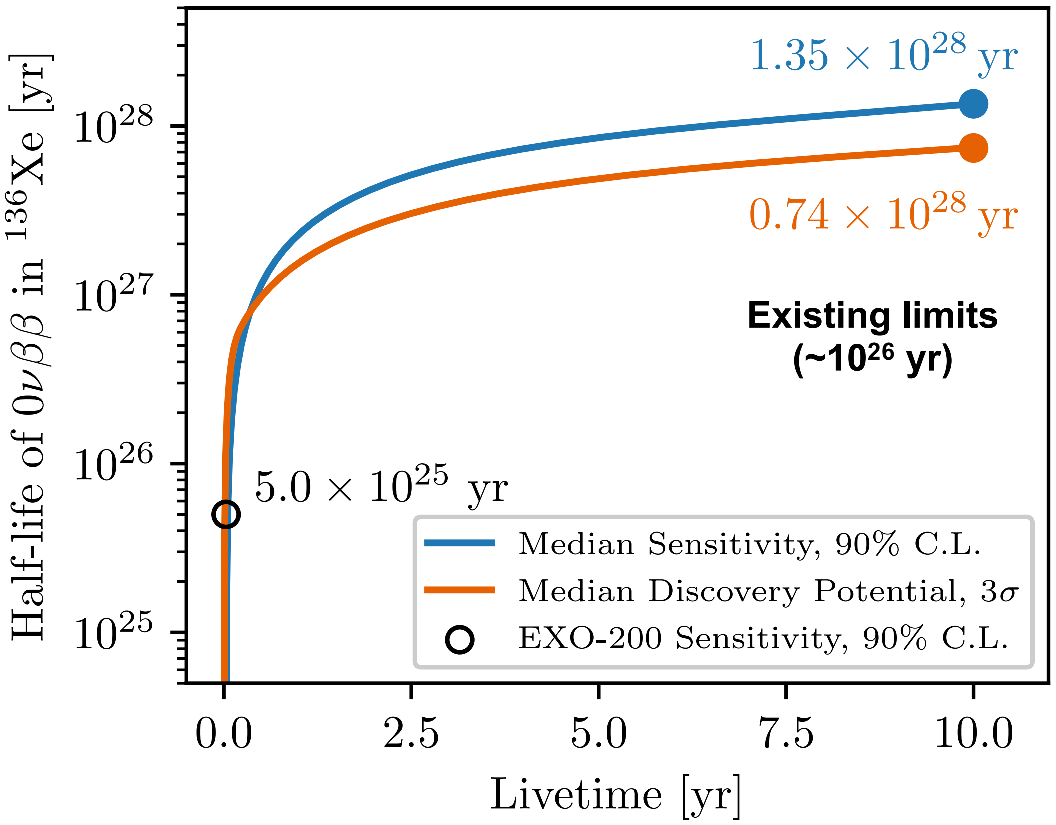
Multiparameter analysis

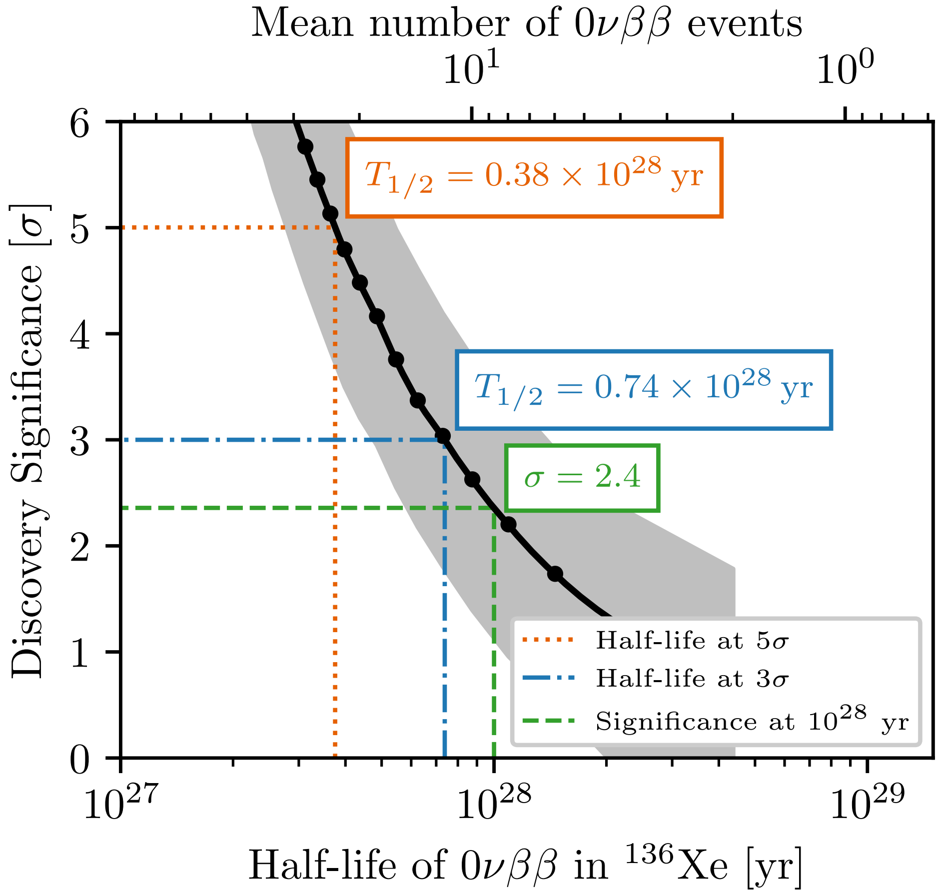


nEXO collaboration, 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

Sensitivity and discovery potential

- Projected half-life: 1.35 x 10^{28} years at 90% confidence level
- Design goal ≤1% energy resolution at Q-value of 2458 keV





nEXO collaboration, 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

Hardware setups

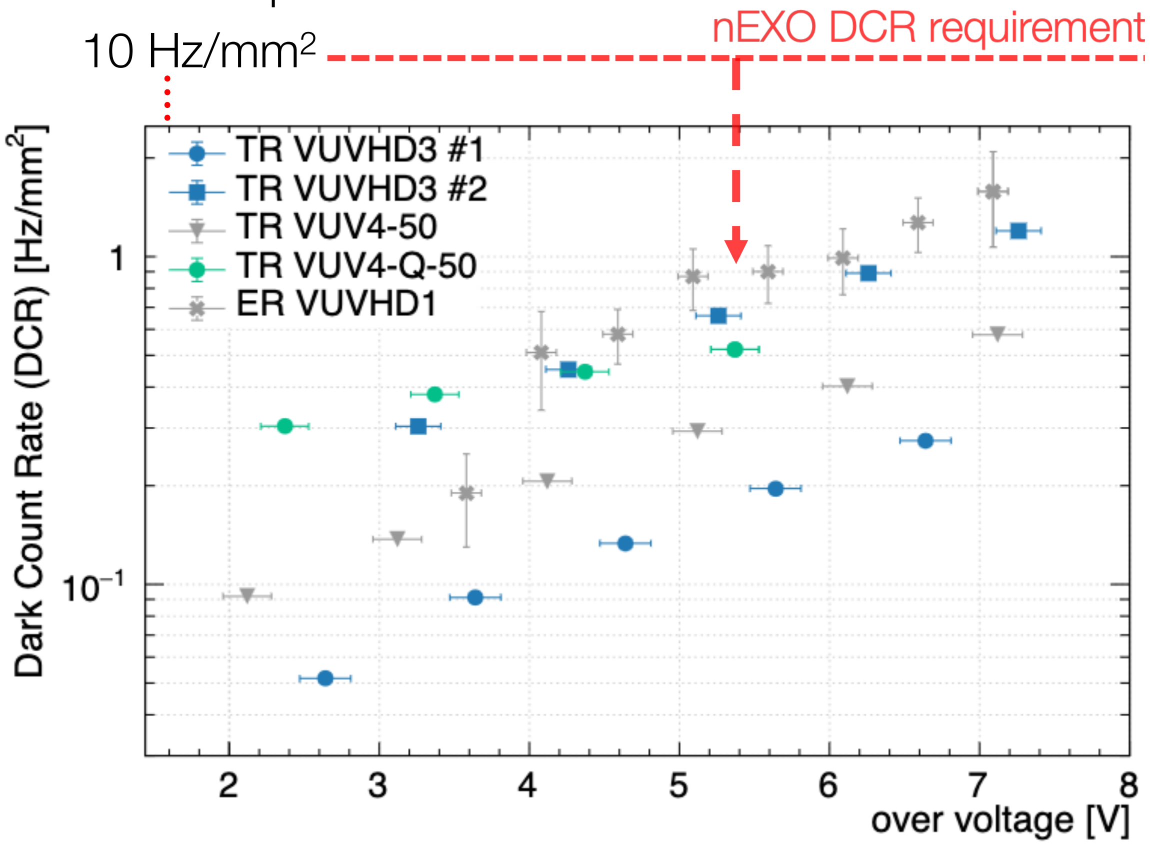
SiPM characterization - combined effort of multiple institutions

	TRIUMF	McGill University	Yale University	University of Massachusetts,Amherst	Brookhaven National Laboratory [28]	Institute of High Energy Physics
Abbreviation	TR	MG	YALE	UMASS	BNL	IHEP
Temperature Stabilisation	Instec MK2000	Lakeshore 350	custom LabVIEW	custom LabVIEW	CryoCon 24C	CTE-SG12012 -02W
Measurement Temperature	163 K	163 K	163 K	190 K/163 K	163 K	300 K/233 K
SiPM Amplification	MAR6-SM+ OPA695 [29]	MAR6-SM+ OPA695 [29]	CR-113-R2 SRS SR-560	CR-113-R2 CR-200-100ns	MAR6-SM+ OPA695 [29]	custom amplifier [20]
DAQ pulse counting	CAEN DT5730B	Rohde & Schwarz RTO2024	Rohde & Schwarz RTB2004	Teradyne ZTEC ZT4421	MSO64 Tektronix	CAEN DT5751
DAQ I-V	Keithley 6487 Keysight B2985A	Keysight B2987	Keithley 6487	Keithley 6482	-	Keithley 6487
LXe/GXe	No	No	Yes	Yes	No	No
SiPM Noise analysis	Yes	Yes	Yes	Yes	Yes	Yes
SiPM PDE	Yes	No	No	No	No	Yes

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

Dark count rate (DCR)

Geiger mode avalanche in absence of a photon



Requirement at 163 K ≤ 10 Hz/mm^2

Requirement met for all devices in the entire range of over voltages!

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

G. Gallina et al. Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO. Eur. Phys. J. C 82, 1125 (2022)

Correlated avalanches (CA)

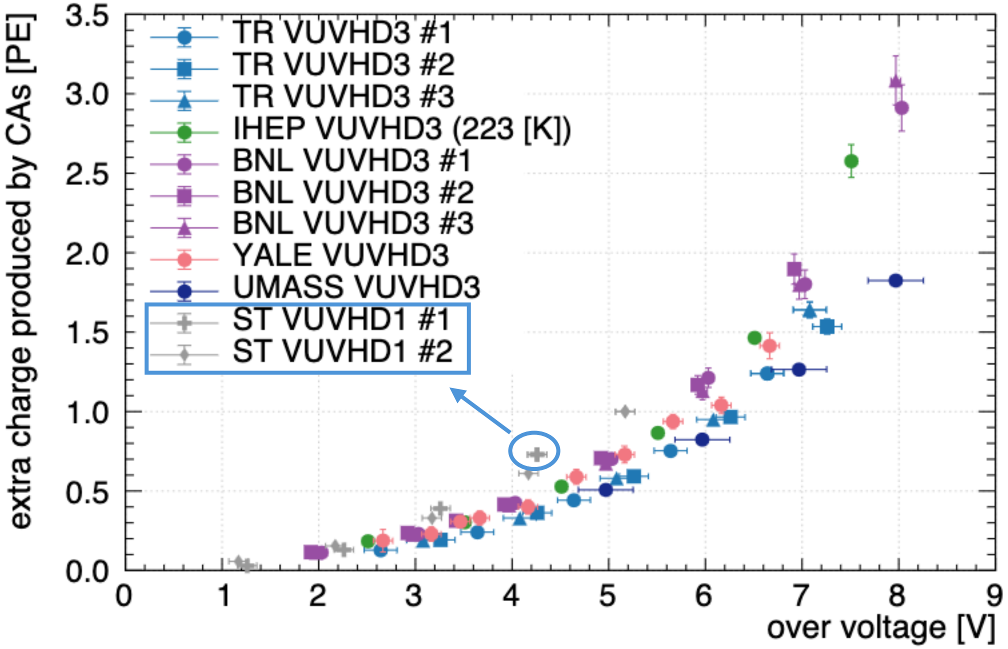
FBK VUVHD3

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

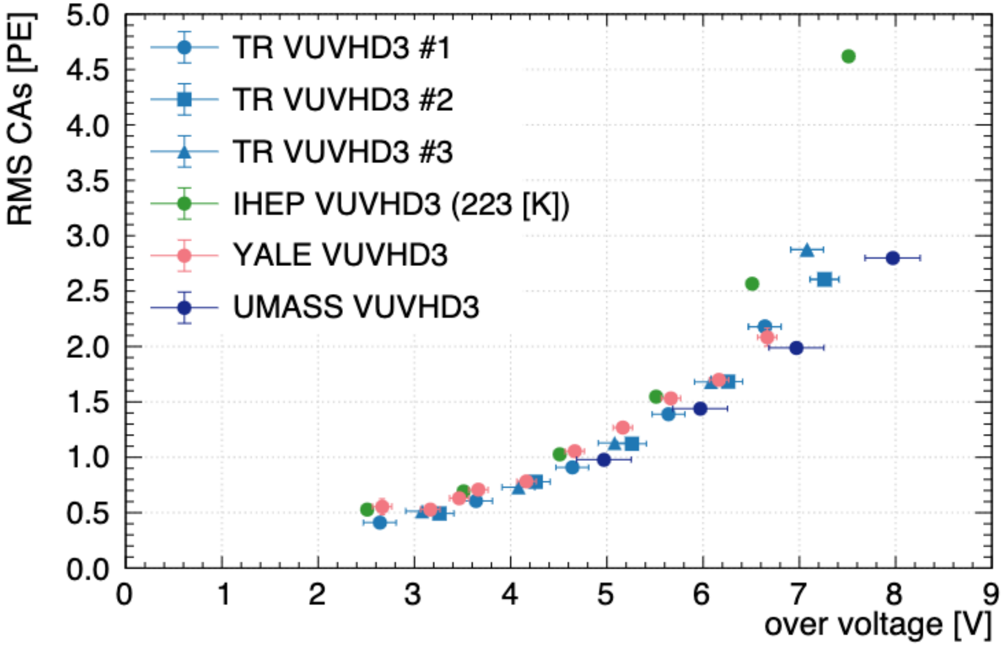
RMS error of CA charge per photoelectron (PE)

Mean charge in CA per primary PE

Avg extra charge produced by CA (Λ) as a function of applied over voltage



RMS error (σ_Λ) as function of over voltage



Grey points are FBK VUVHD1*

New VUVHD3 are an improvement!

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

* A. Jamil et al, IEEE TNS 65 (2018)

Correlated avalanches (CA)

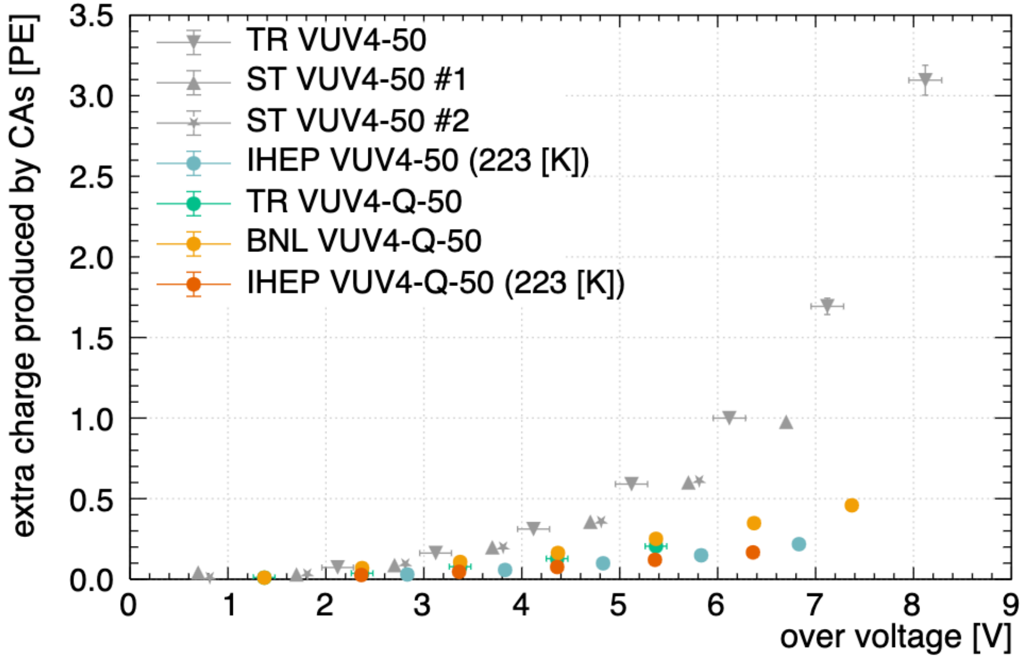
HPK VUV4s

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

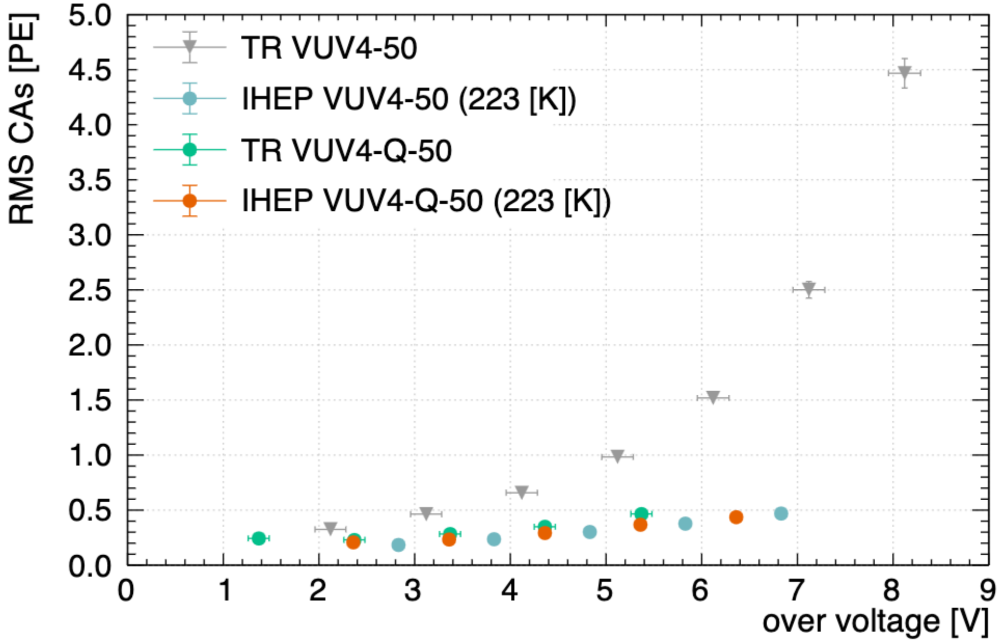
RMS error of CA charge per photoelectron (PE)

Mean charge in CA per primary PE

Avg extra charge produced by CA (Λ) as a function of applied over voltage



RMS error (σ_Λ) as function of over voltage



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

Grey points are older test

HPK VUV4 has almost no correlated avalanches!