Charge and light readout characterization for the nEXO experiment

Gaosong Li (Stanford University)

For the Stanford nEXO group

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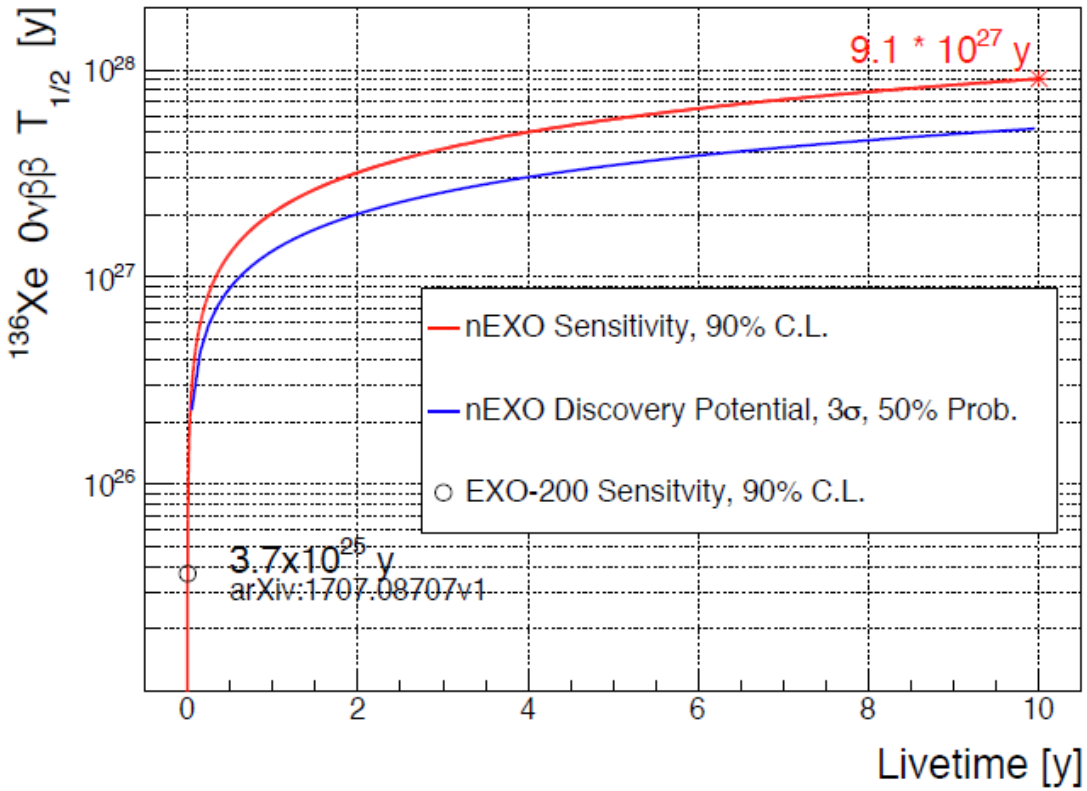
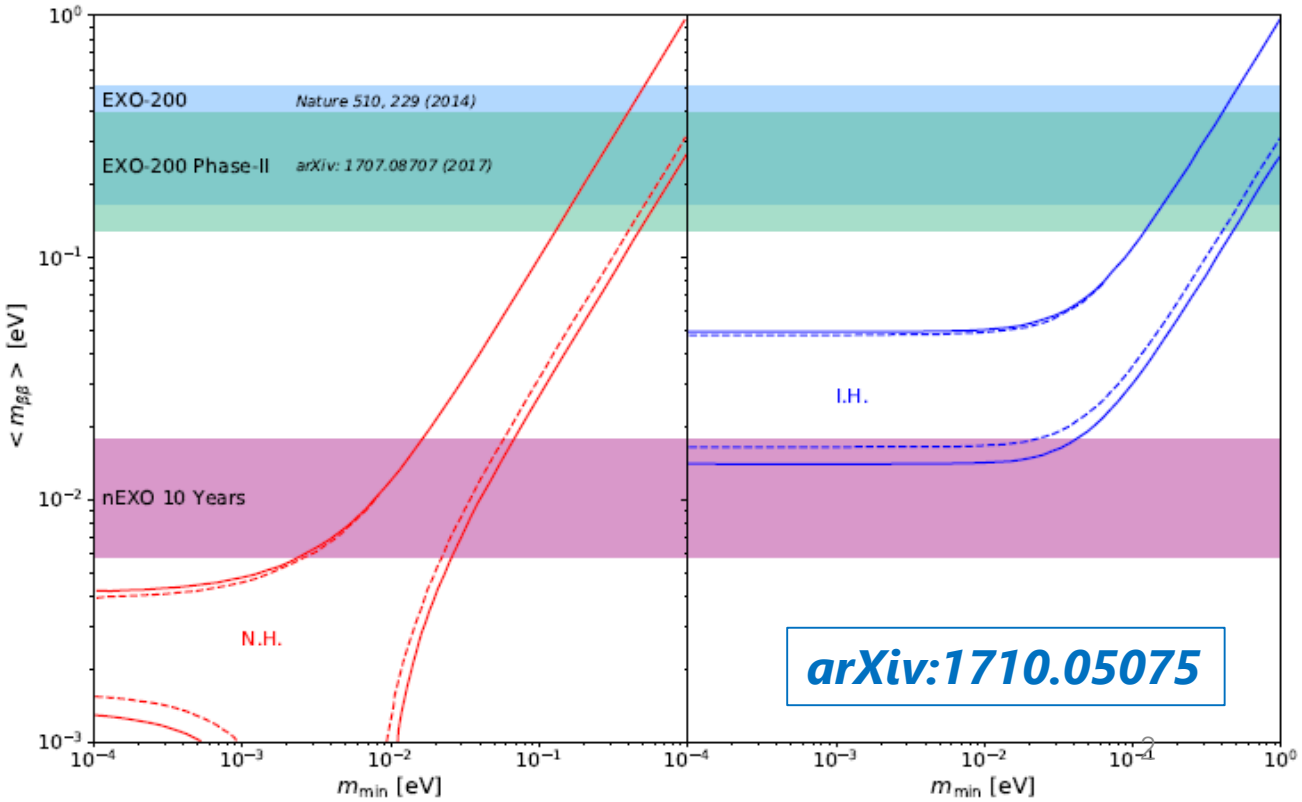
nEXO, search for $0\nu\beta\beta$

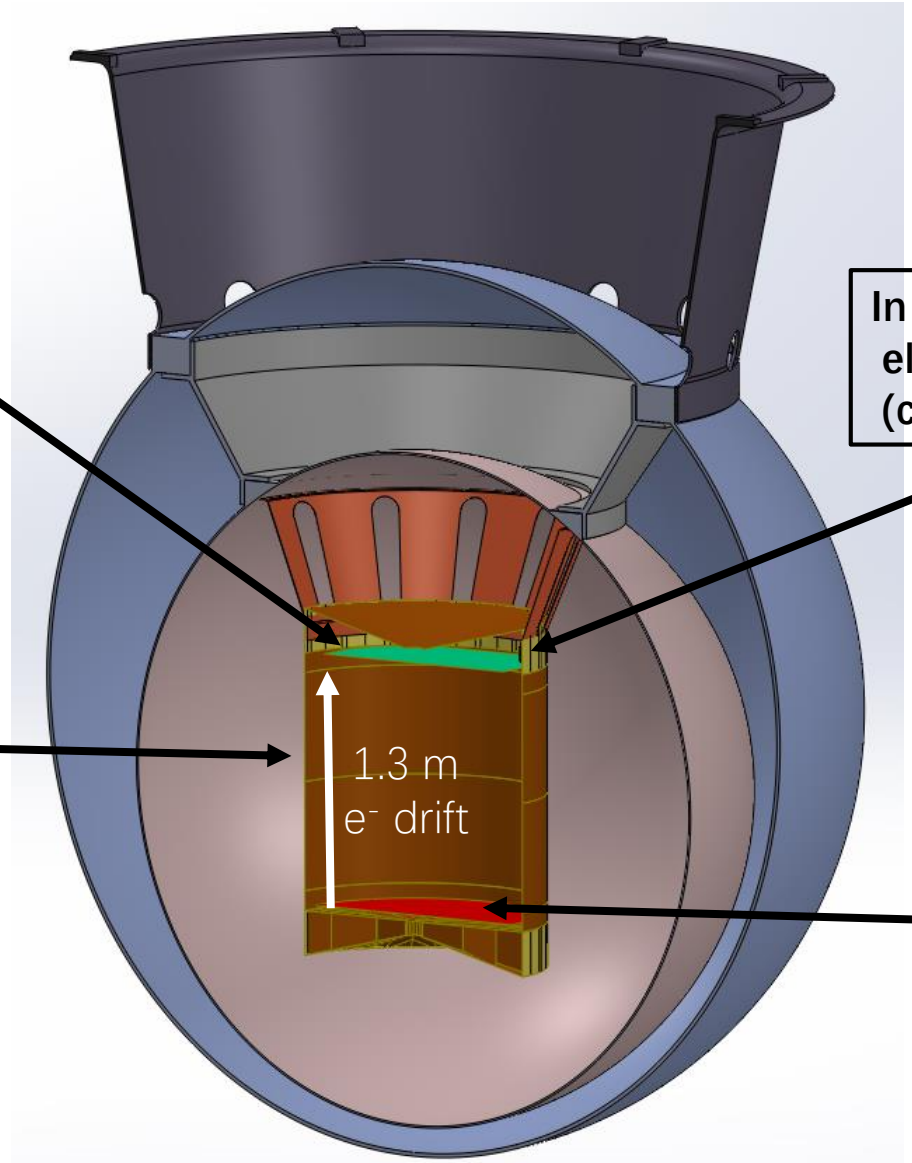
- $0\nu\beta\beta$ search has rich implications on nuclear and particle physics: lepton number violation, majorana fermion, neutrino absolute mass scale
- nEXO, planned tonne-scale experiment
  - build on the successful running of EXO-200 detector
  - Baseline design sensitivity to Xe136 $0\nu\beta\beta$ $T_{1/2}$ ~10^{28} yr in 10 yrs
  - Possible barium tagging would further increase sensitivity

$$t_{1/2} \sim \sqrt{\frac{MT}{\Delta EB}}$$



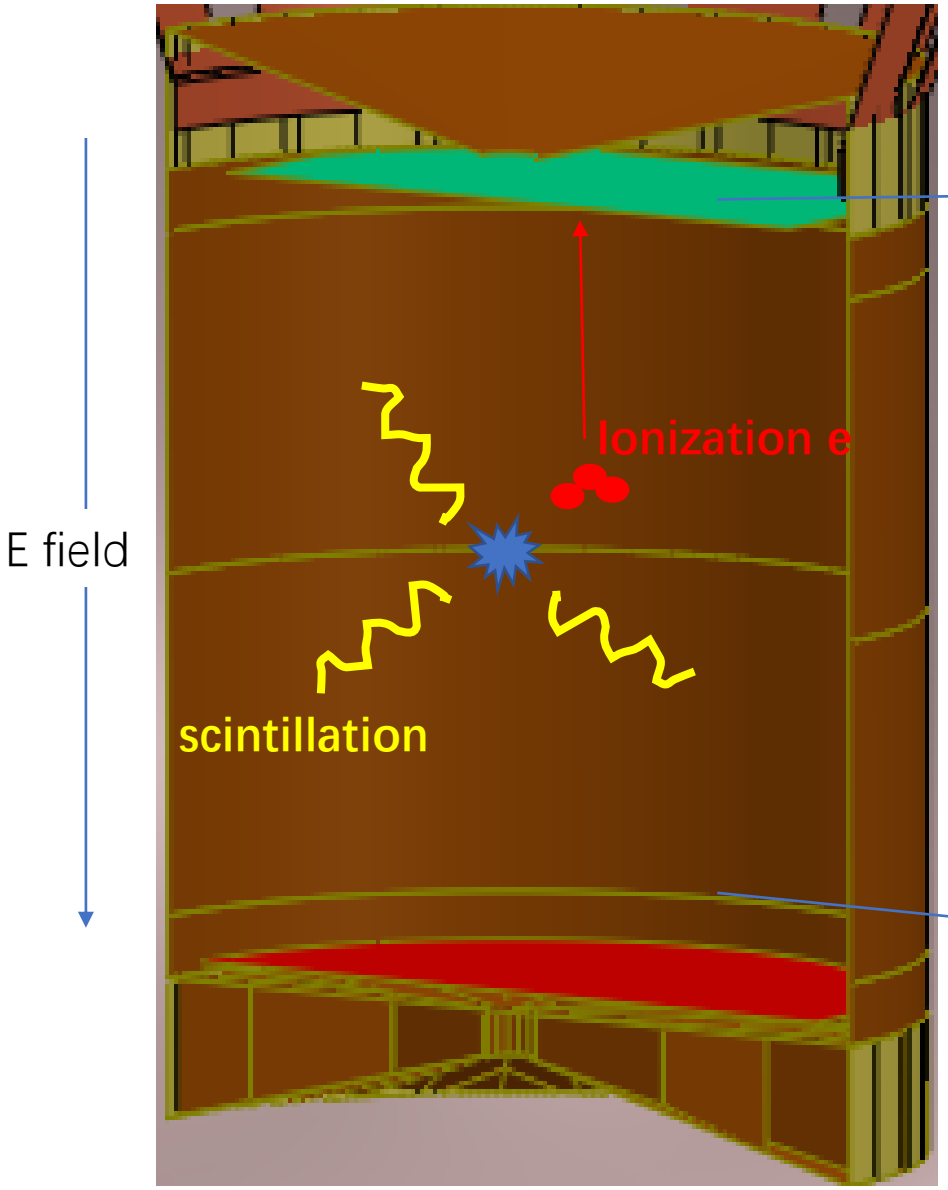


nEXO TPC baseline design

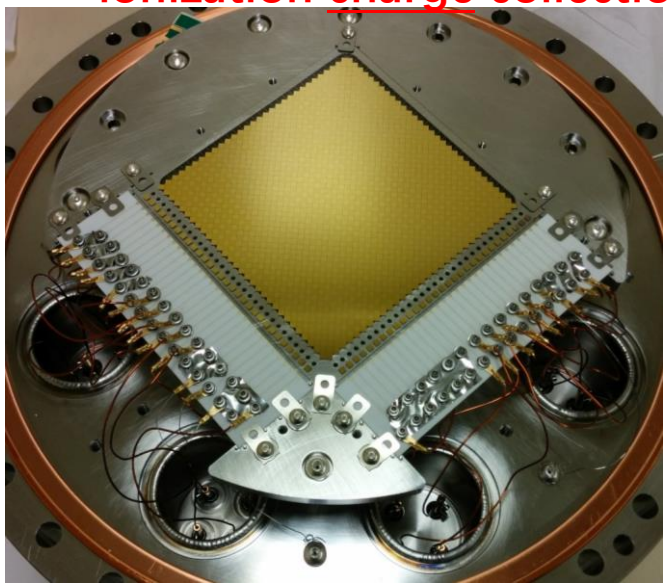


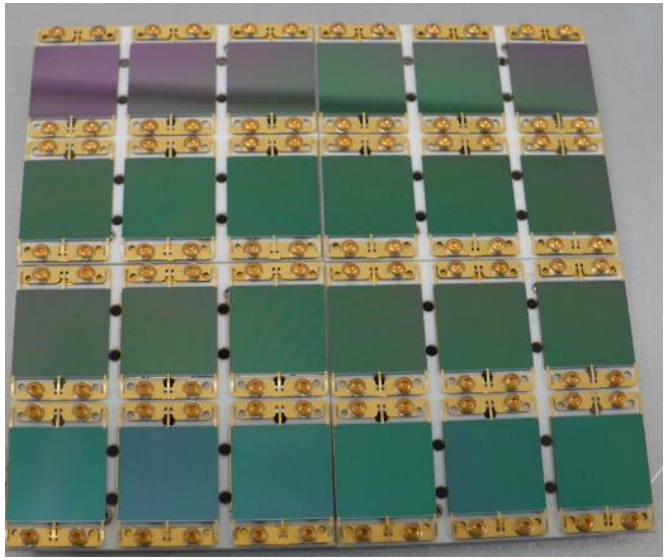
~5 tonne single phase TPC with enriched Xe136

Detection principle



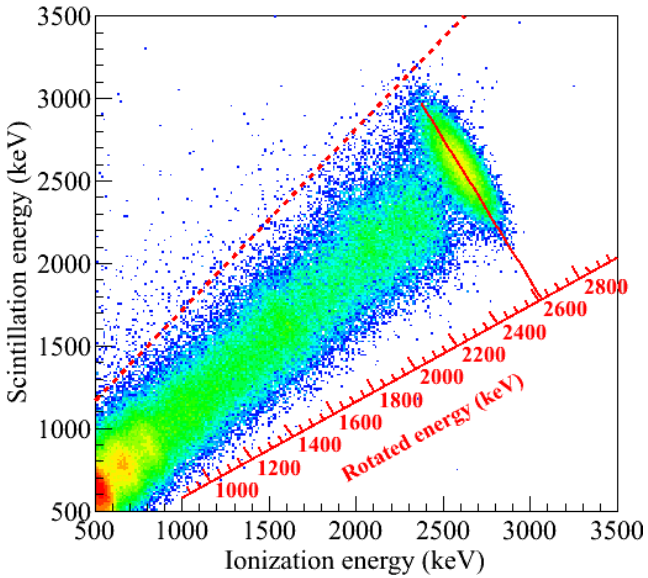
Charge tile anode for ionization charge collection





SiPM covered barrel (4 m^2) for scintillation light detection

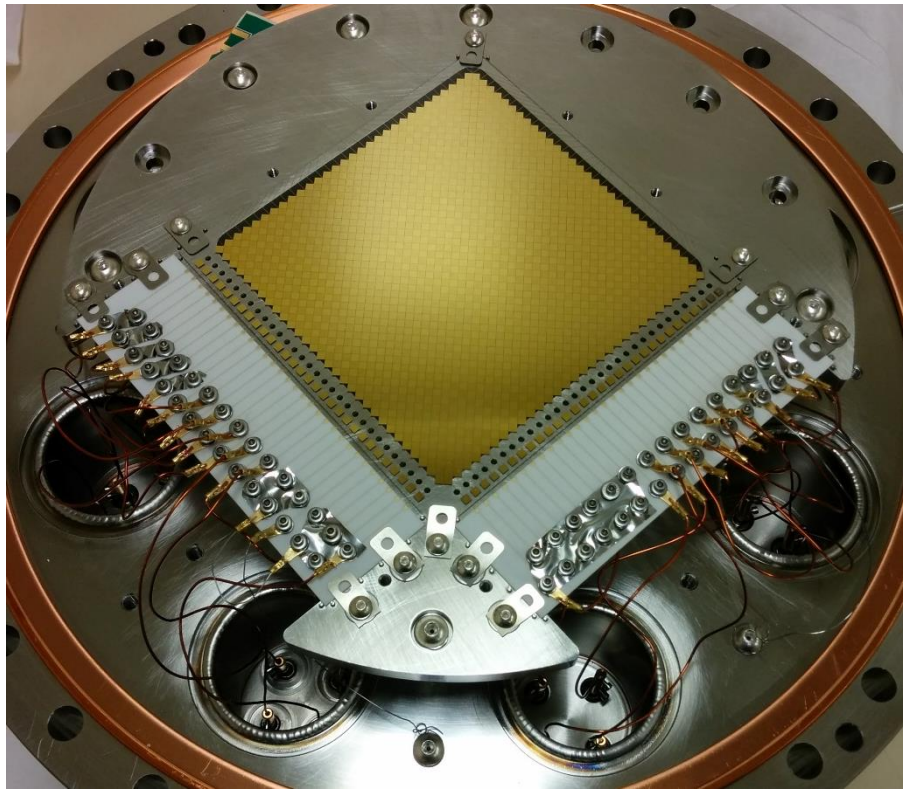
Energy anti-correlation

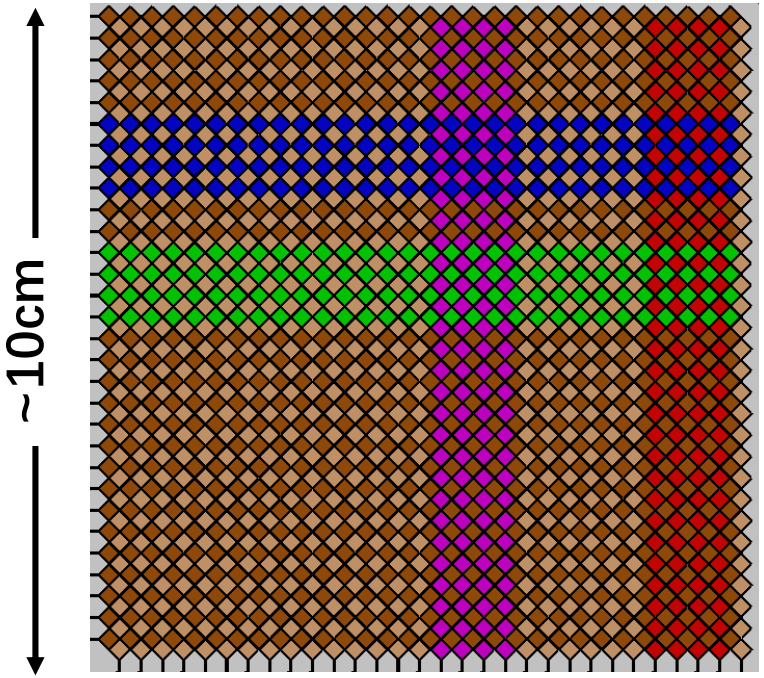


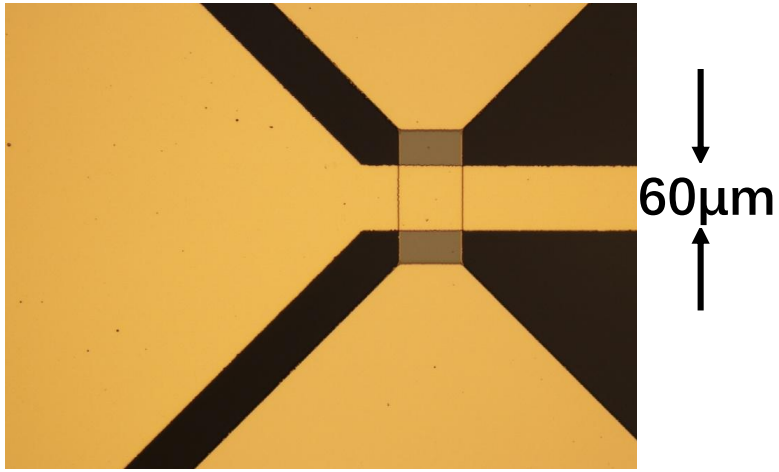
Charge tile

Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity



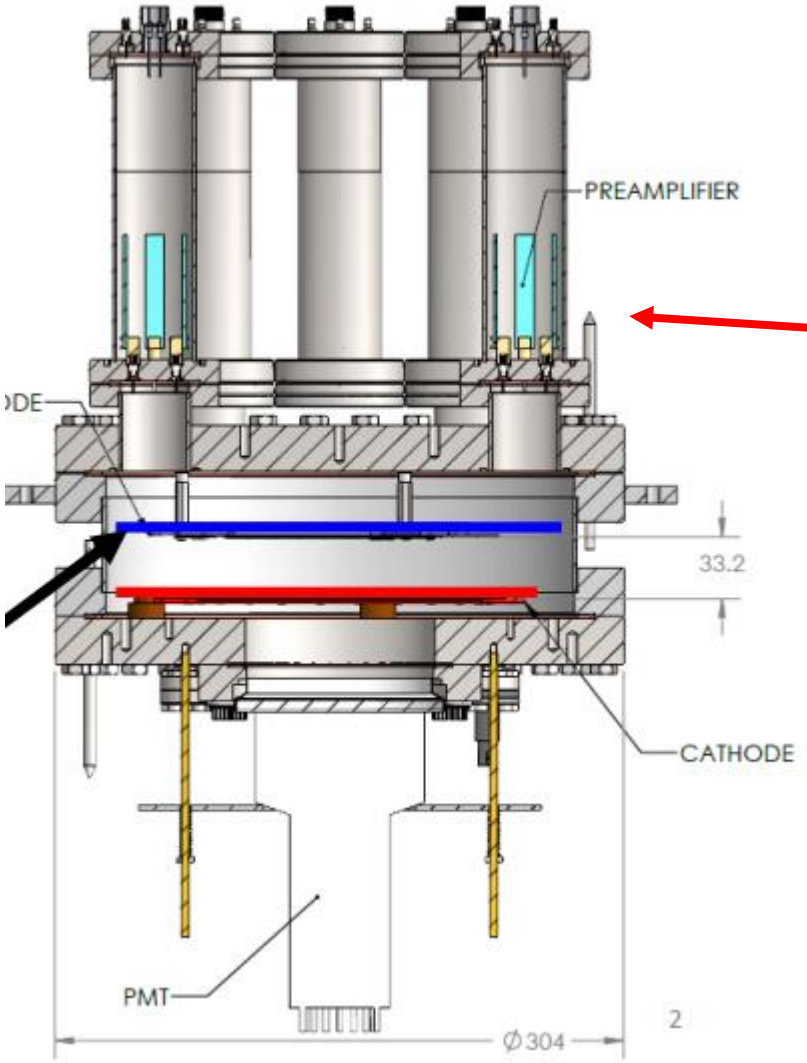


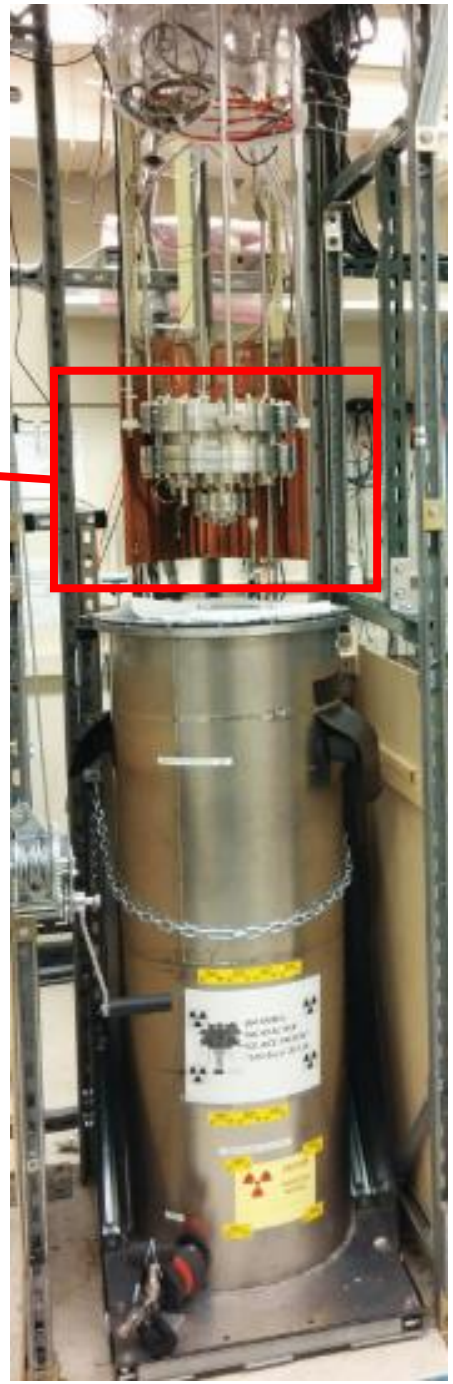


Max metallization cover with min capacitance

Test stand TPC

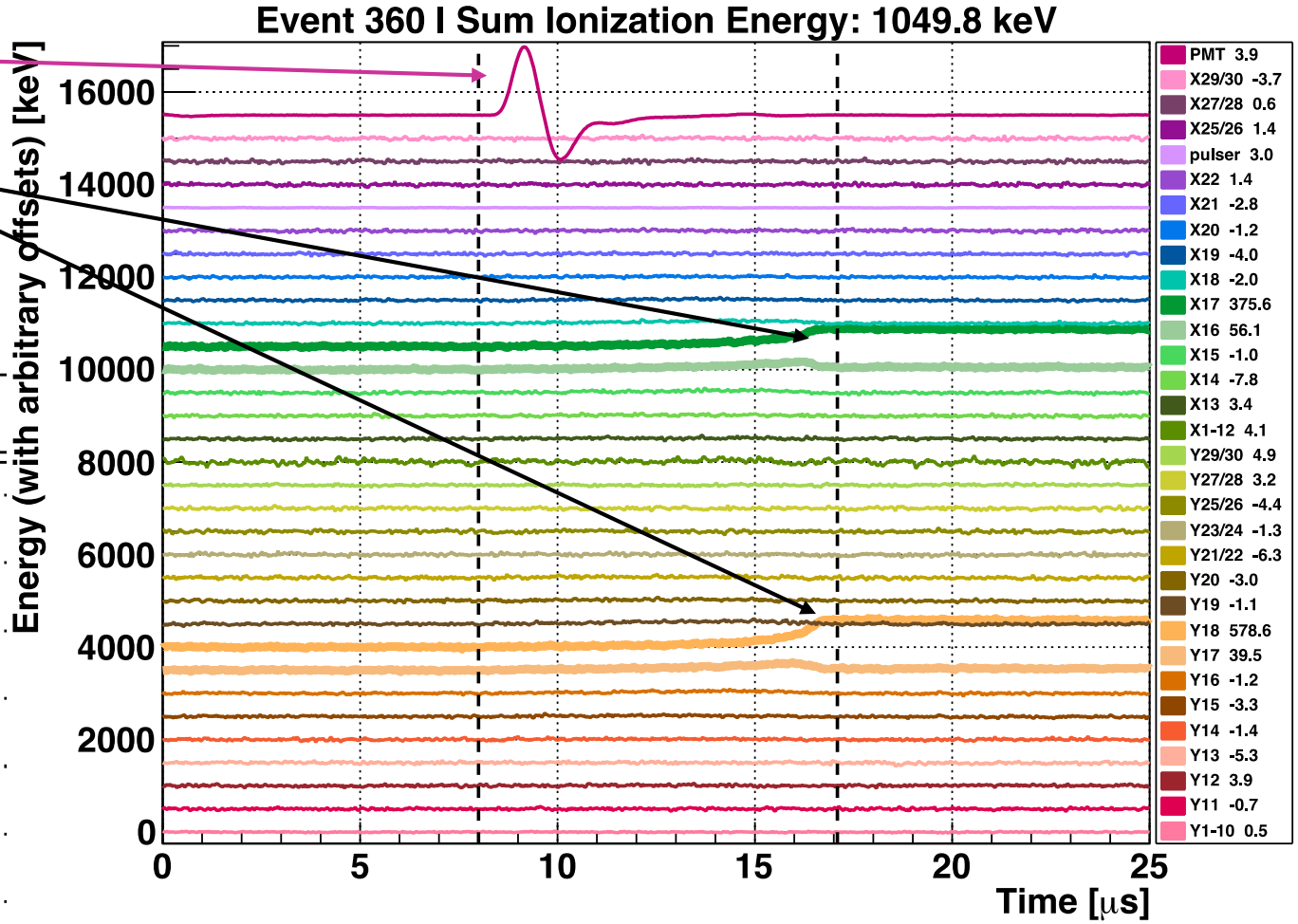
- 3.3 cm of drift length
  - Operating up to 1 kV/cm field
- Charge tile anode with
  - 30 X strips + 30 Y strips
- PMT for light detection
  - Low efficiency though

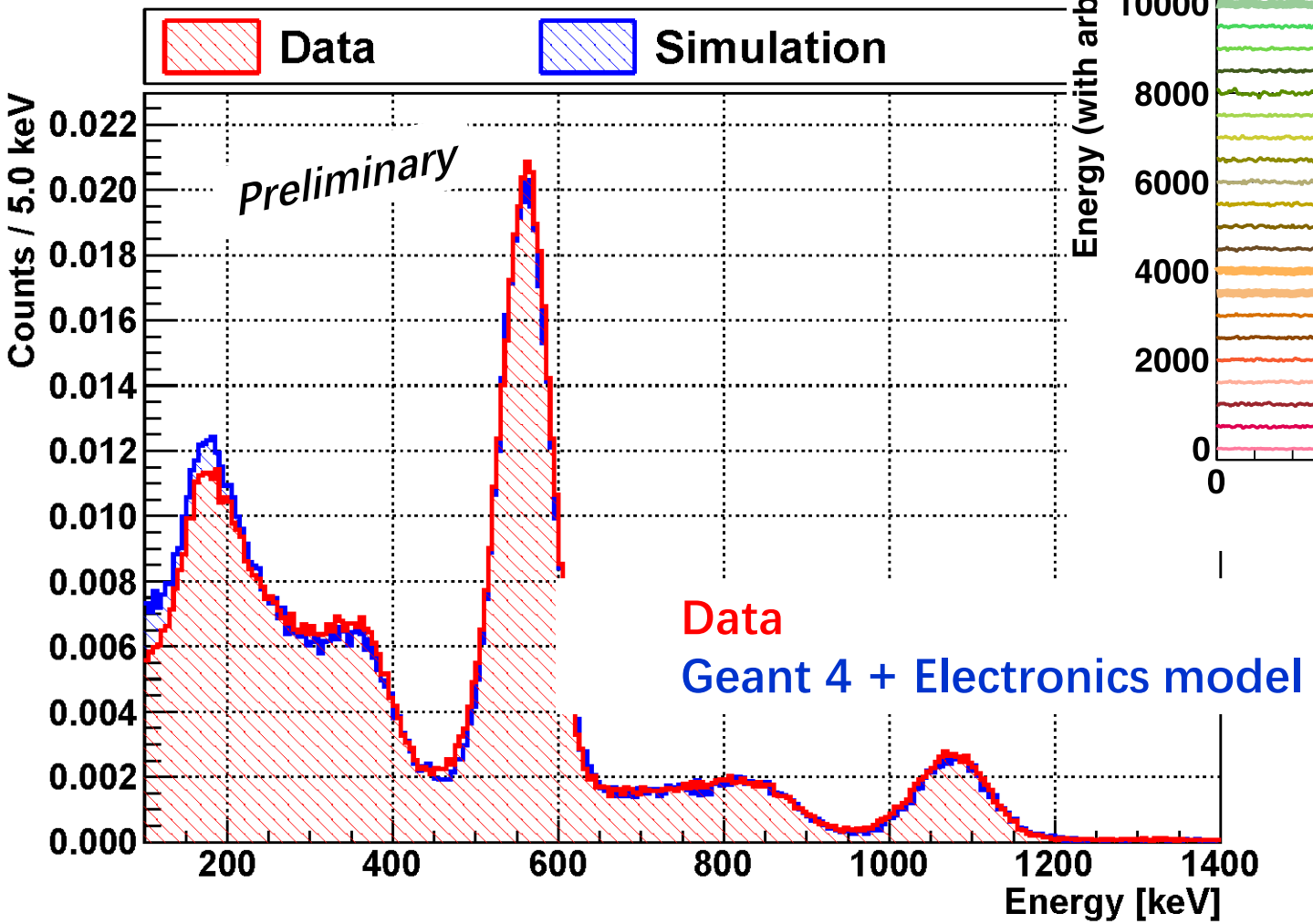




PMT (trigger)

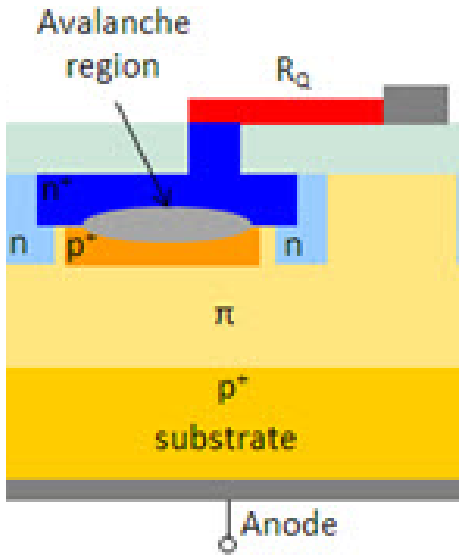
Charge collection

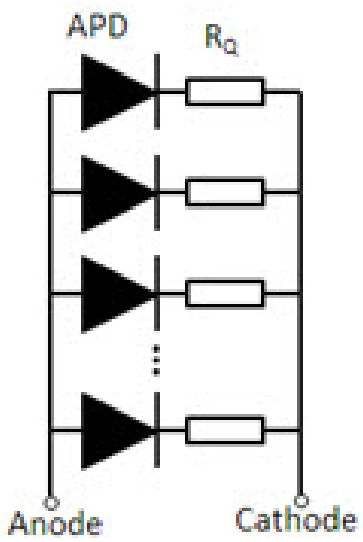


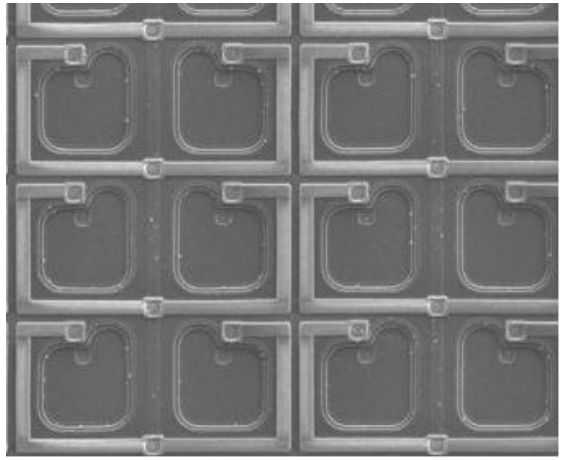


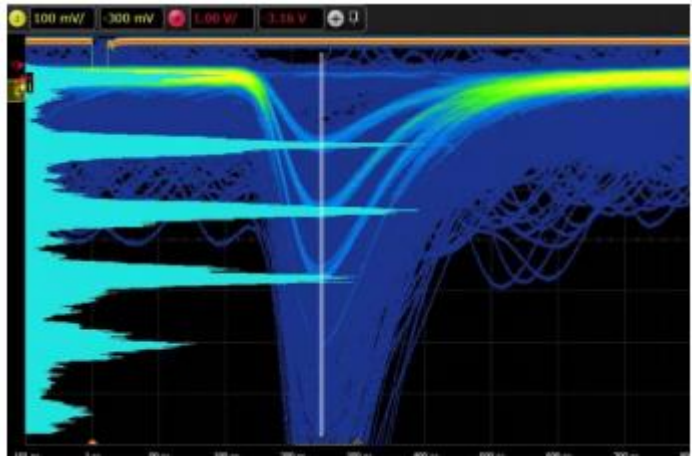
arXiv:1710.05109

Silicon photomultiplier (SiPM) for light readout







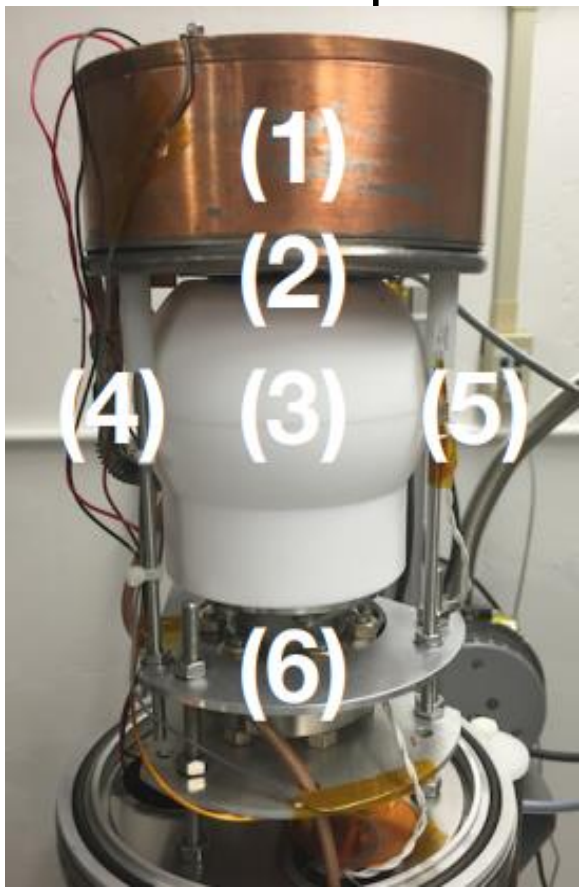


- Parallel connected arrays of SPADs operated in Geiger mode
- Passive quenching resistor stops avalanche
- "Binary" output from each pixel
- Final output is the summation of all fired pixels

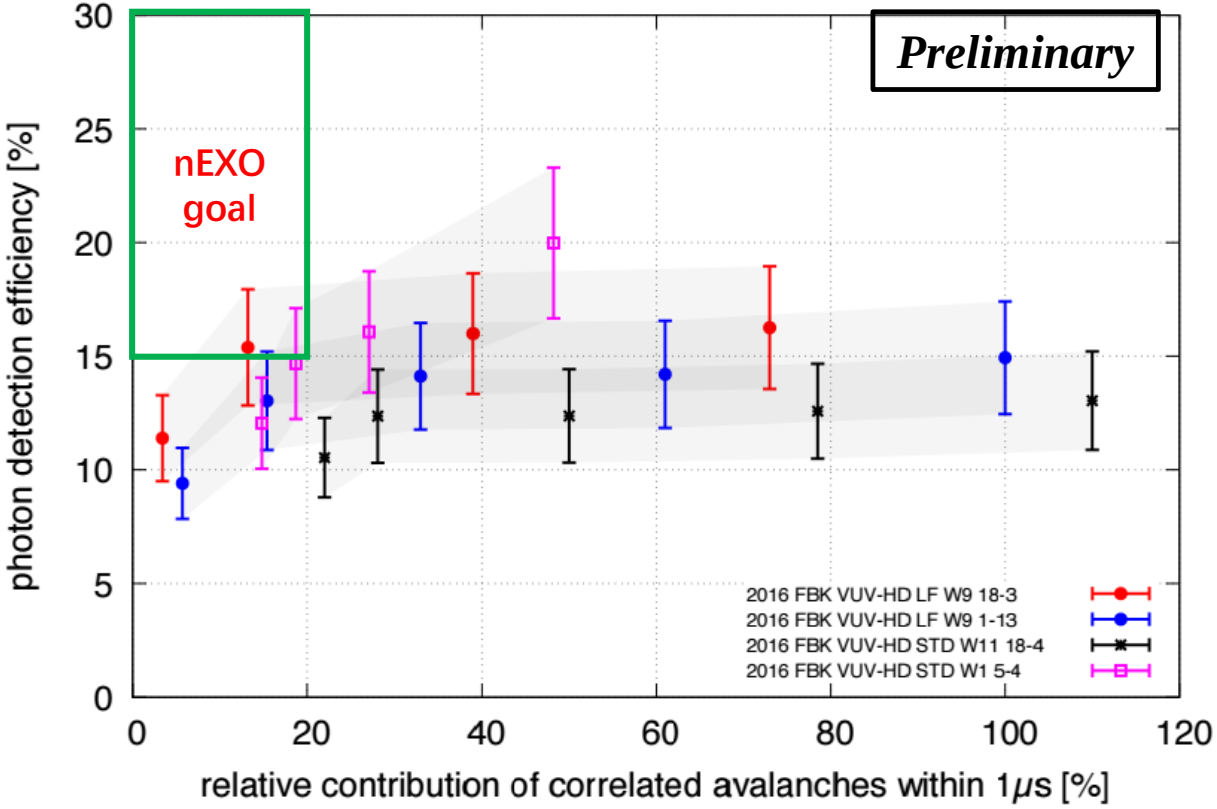
Pros
- High gain (~1e6)
- Low radioactivity
- Immune to magnetic field
- compact

Cons
- High dark rate (drastically reduced at cryogenic temperature though)
- After pulse and cross talk
- Large capacitance per unit area

SiPM performance characterization



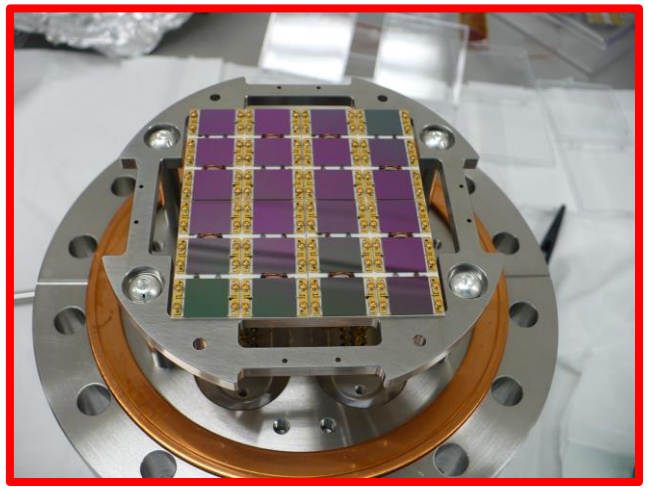
1. Detector chamber
2. Bandwidth filter
3. Reflector
4. cooling gas tube
5. LED
6. Xe scintillation light souce

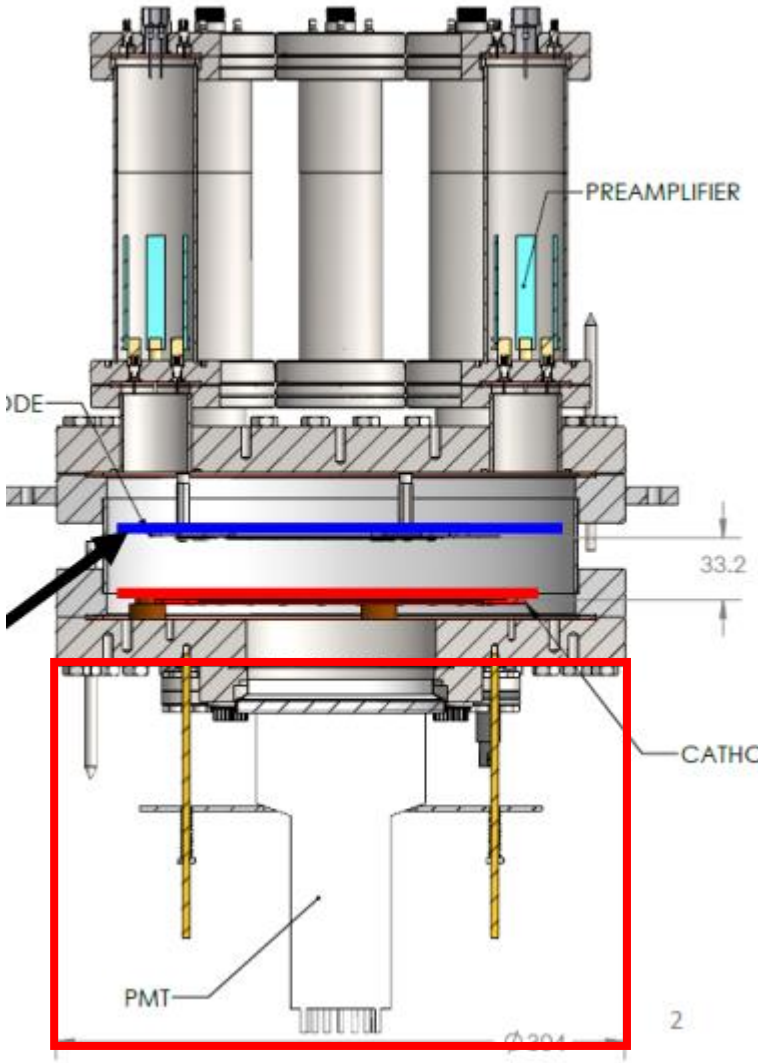


- Work closely with FBK to develop SiPM satisfying nEXO specifications
- Latest generation showed promising result
- 2016 FBK VUV-HD STD (**black, magenta**)
  - Limited overvoltage (OV) range
- 2016 FBK VUV-HD LF (**red, blue**)
  - One candidate found

Integrate large area SiPM array to the test stand

- Implemented an array of 24 SiPMs (24 cm^2) to replace the PMT in the test stand for light detection
  - The first close-to-nEXO-style detector
  - Improved light collection efficiency (5-10x)
  - Hope to see scint/ion energy anti-correlation

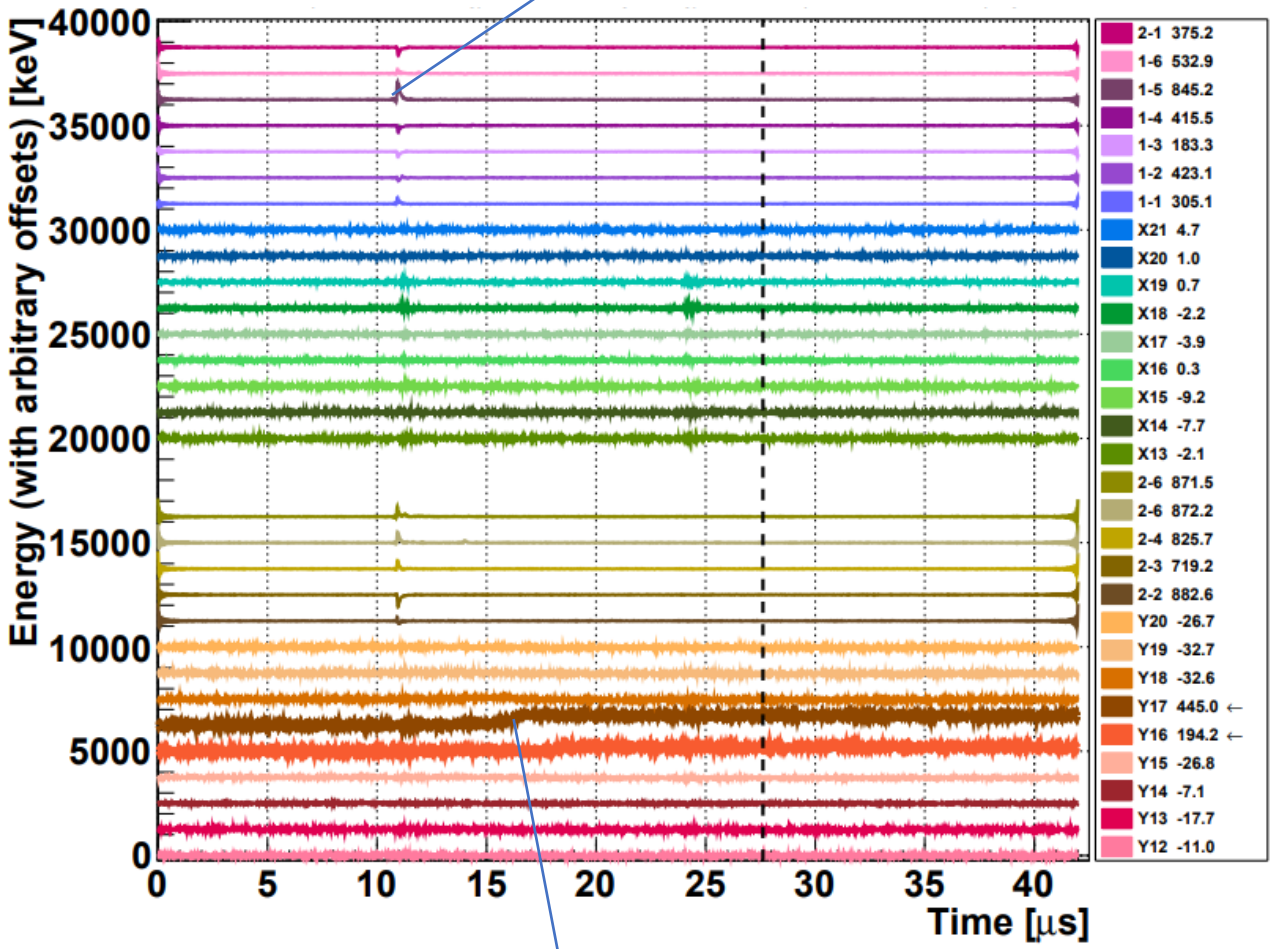




(Very) recent run

- Just finished taking the first data with the integrated system this past week!
  - Saw Xe scintillation light with SiPMs
- However …
  - Electronics noise and cross talk among SiPM channels limit our ability to make good light energy measurement this time
- Analysis with this data set to characterize SiPM performance
- Fix electronics problems before we see can see anti-correlation for the next run

Scintillation light seen by SiPM



Charge collection on charge tile

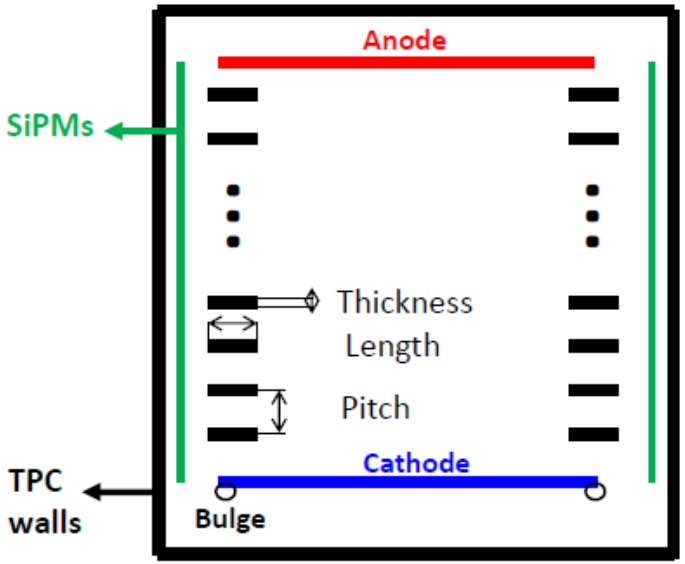
Summary

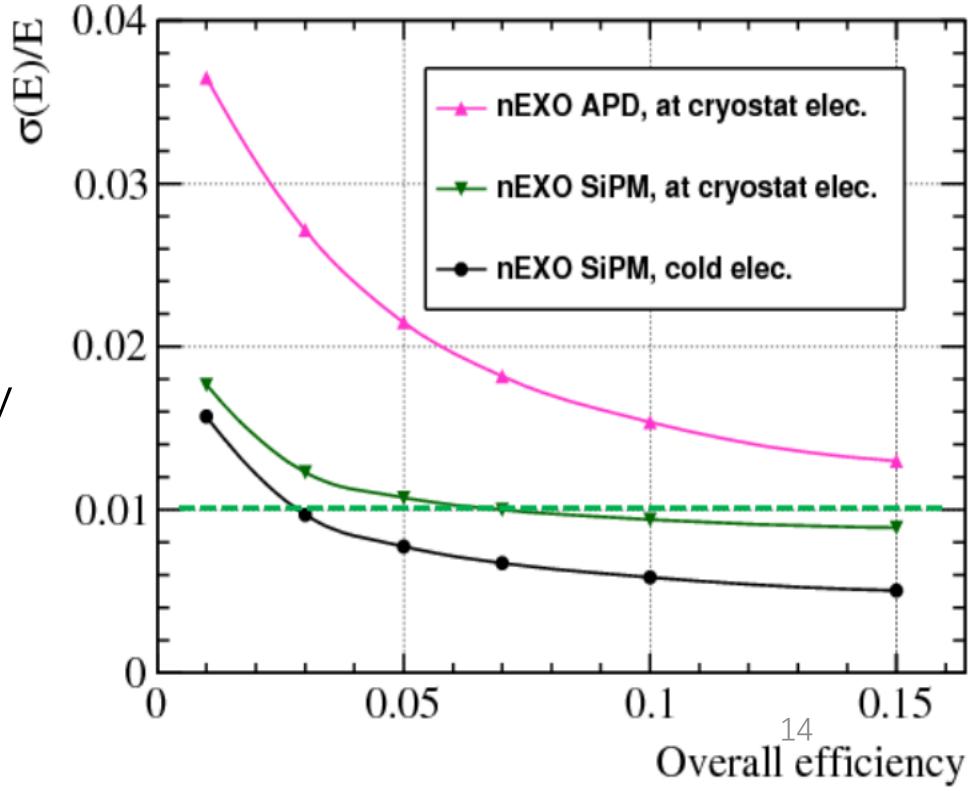
- Substantial R&D in progress to fine-tune the nEXO ~5 tonne LXe TPC, which will search for $0\nu\beta\beta$, covering the entire neutrino mass inverted hierarchy and with substantial sensitivity to normal hierarchy
- A new charge tile anode design for charge readout for nEXO is tested, and performance is satisfying
- Lots of work on characterization of SiPMs to meet the light readout requirements of nEXO, and results are promising
- Upgraded the LXe TPC test stand with SiPM for light collection, towards to seeing energy anti-correlation in the first close-to-nEXO-like style detector

Backup slides

Light detection

- Target: <1% resolution at $Q_{\beta\beta}$ of Xe136
- Requires high overall light efficiency, which includes
  - Light transport efficiency
    - Detector geometry
    - Reflectivity of TPC components: field shaping rings, cathode, anode
    - **Reflectivity** of SiPM
  - Photon detection efficiency (PDE) of SiPM
    - Quantum efficiency, filling factor, avalanche probability
- Important to measure PDE and reflectivity of SiPM

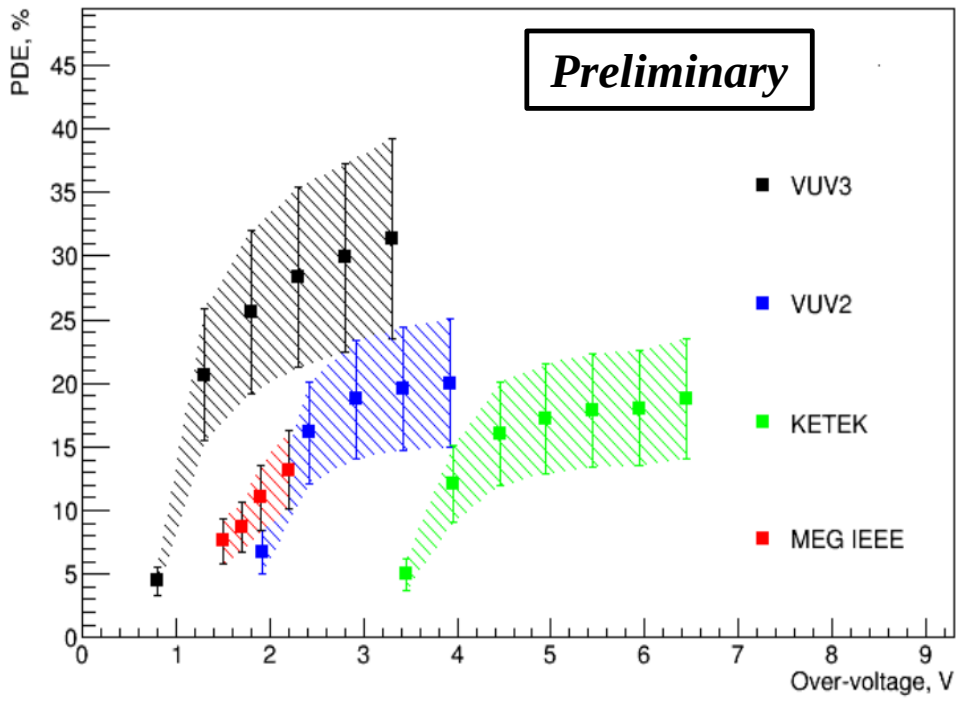


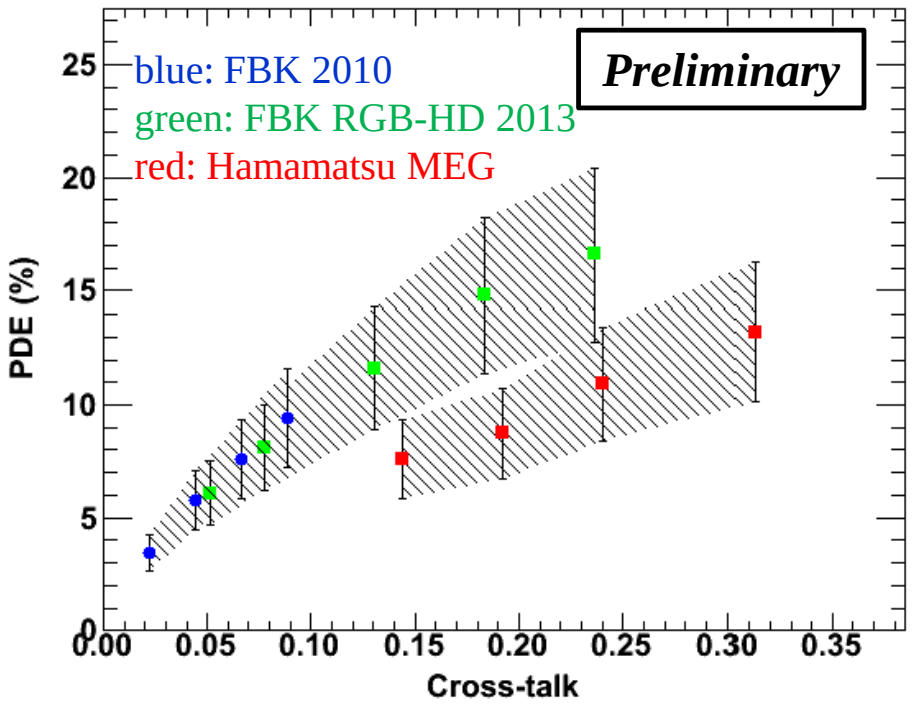


Requirement

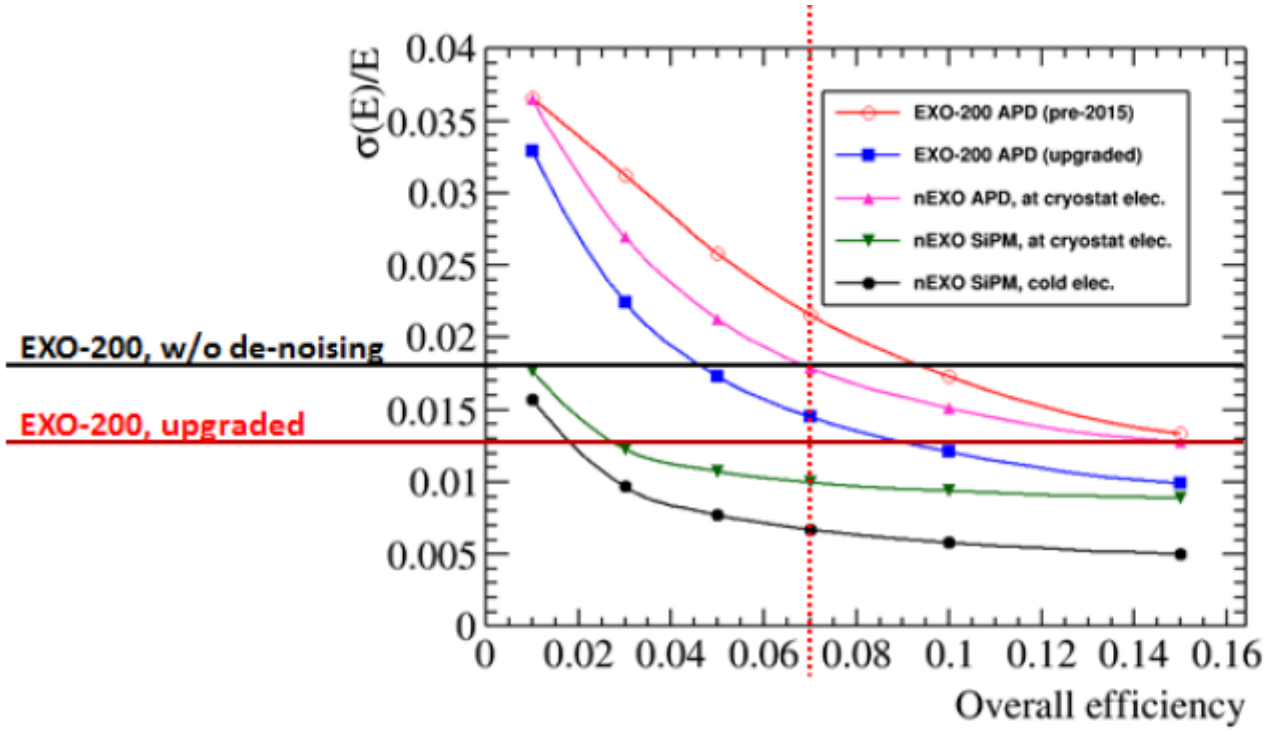
Parameter	Specification	Comment
Photo-detection efficiency	> 15%	At **170-180** nm, in gas/vacuum
Dark noise rate	< 50 Hz/mm^2	At -104 ℃
Correlated avalanche rate	< 20%	At -104 ℃, combining cross-talk and after pulsing integrated within 1μs
Single photodetector active area	> 1 cm^2	
Capacitance	< 50 pF/mm^2	For readout electronics
Radio purity	0.1, 1, 10 nBq/mm^2	For ^{238}U, ^{232}Th and ^{40}K respectively
Gain fluctuations and electronic noise	< 0.1 p.e.	

PDE Measurement



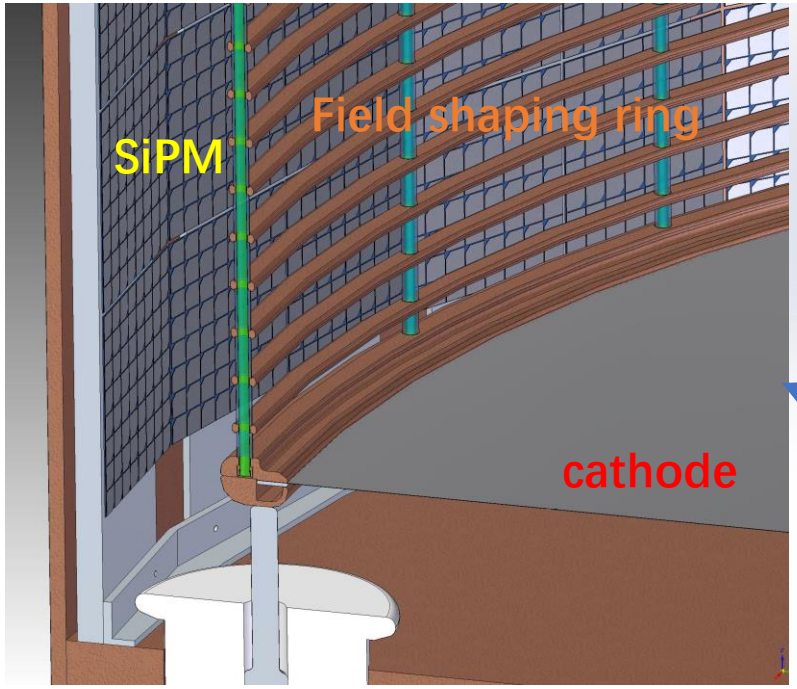


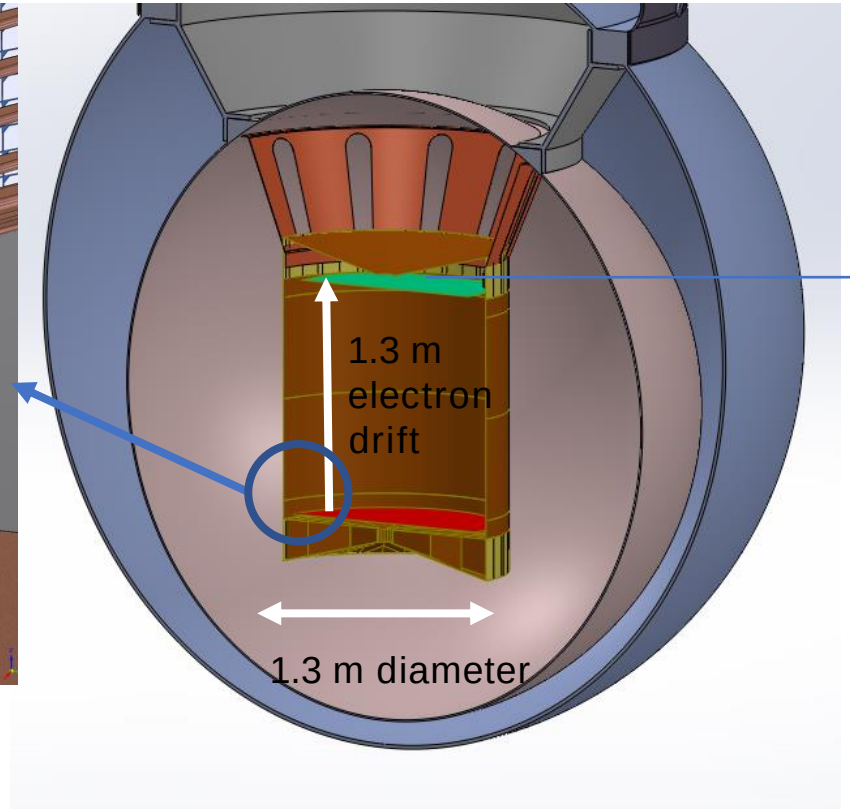
- Investigated SiPMs from different vendors
- PED measurement at VUV, in vacuum at -104 C
- SiPM developed fast and promising improvement over years



EXO-200 APD (pre-2015): ENCq=720e-, ENCs=300pe, lambda=0.01, excess noise=4.3
EXO-200 APD (upgraded): ENCq=720e-, ENCs=110pe, lambda=0.01, excess noise=4.3
nEXO APD, at cryostat elec.: ENCq=600*sqrt(6.25)e-, ENCs=160pe, lambda=0.01, excess noise=4.3
nEXO SiPM, at cryostat elec.: ENCq=600*sqrt(6.25)e-, ENCs=5pe, lambda=0.2, no excess noise
nEXO SiPM, cold elec.: ENCq=200*sqrt(6.25)e-, ENCs=5pe, lambda=0.2, no excess noise

nEXO TPC baseline design

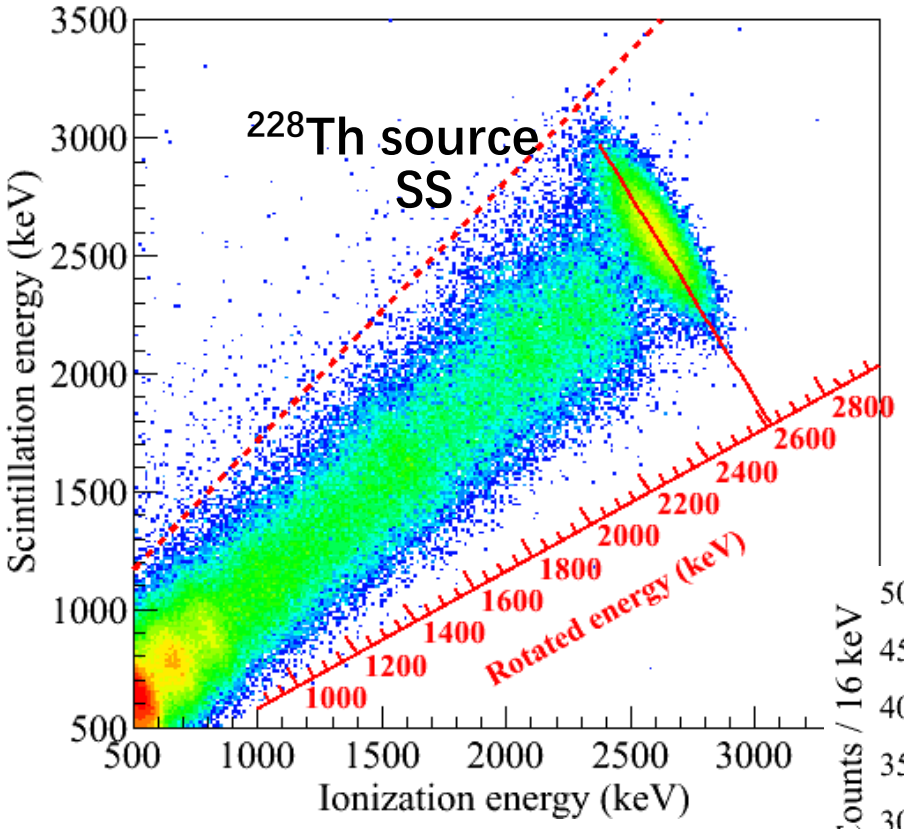




Charge tile anode

- ~5 tonne single phase TPC with enriched Xe136
- Single drift volume (1.3 m)
- Ionization charge signal collected by anode plane **(charge tiles)**
- Scintillation light signal (175 nm) collected by **SiPMs (~4 m^2 area)** behind field shaping rings

Combining Ionization and Scintillation

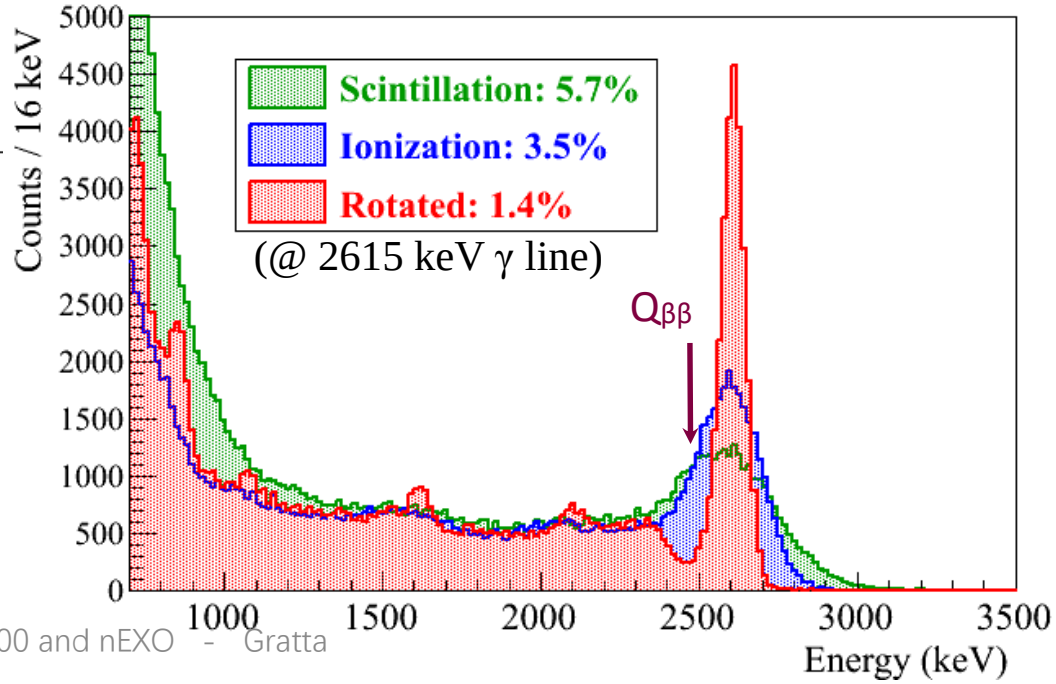


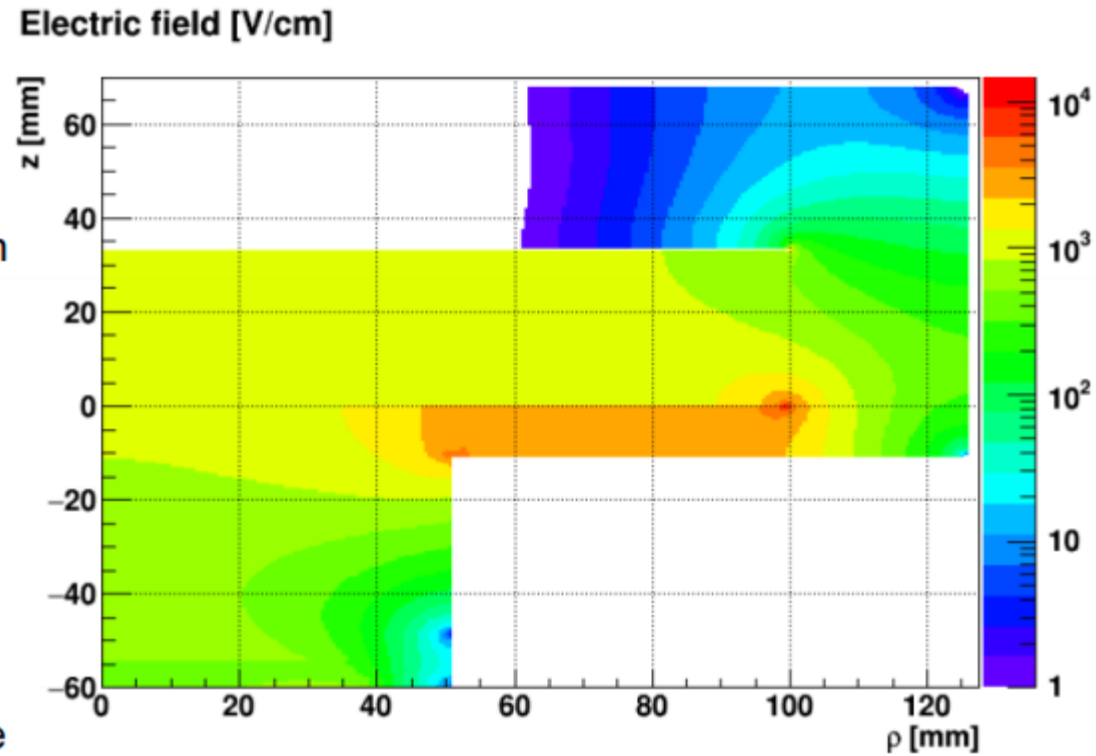
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

E.Conti et al.
Phys Rev B 68 (2003) 054201

By now this is
a common technique in LXe

Rotation angle chosen to optimize energy resolution at 2615 keV



Charge Tile Monte Carlo

- GEANT4 Simulation for Energy Deposits
  - Use nEXO MC with our geometry in place of nEXO Geometery
  - Incorporates NEST for correct Light/Charge response
  - Use COMSOL Electric Field Model in Simulation for Charge/Light yield variations
- nEXO Analysis Charge Simulation
  - Use nEXO Analysis Branch to simulate Tile Response
  - Analytic model for Induced Charge on Tile Channels
  - Includes Diffusion of Charge
  - Add Real Noise from Data to MC Waveforms
  - MC Waveforms than Analyzed Exactly the same as Data