Light Detection with Large Area DUV Sensitive SiPMs in nEXO

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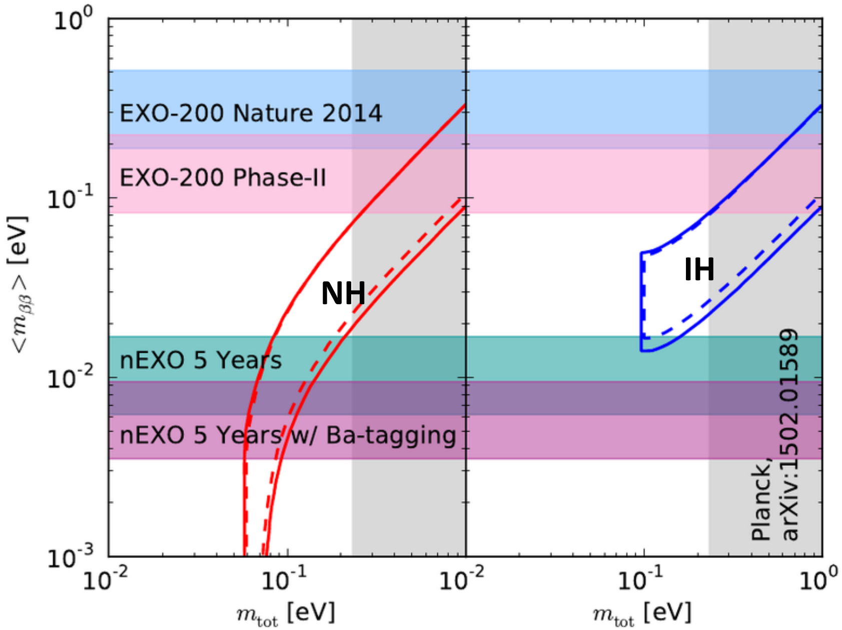
- **Enriched Xenon Observatory (EXO) uses liquid Xenon TPC to search for $0\nu\beta\beta$ decays of ^{136}Xe.**

- **EXO-200**
  - **~200kg enriched liquid xenon**
  - **Phase I: Sep. 2011 – Feb. 2014**

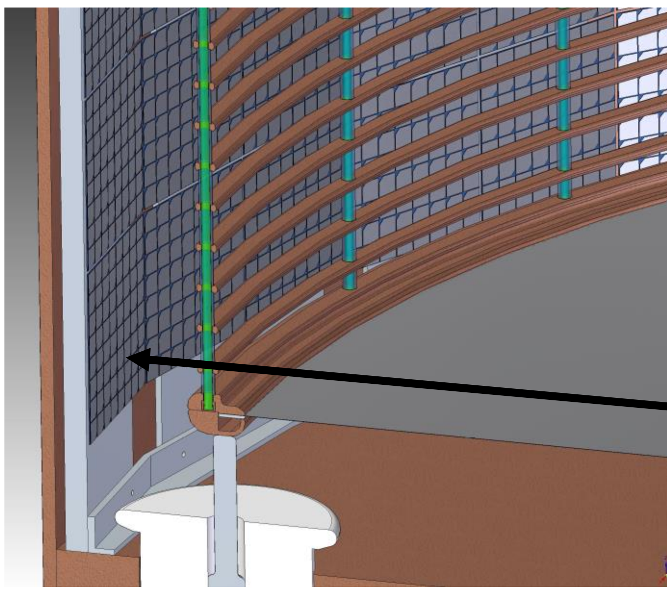
    $T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr, Nature (2014) doi:10.1038/nature13432
  - **Phase II: Apr. 2016 -- ~2018**

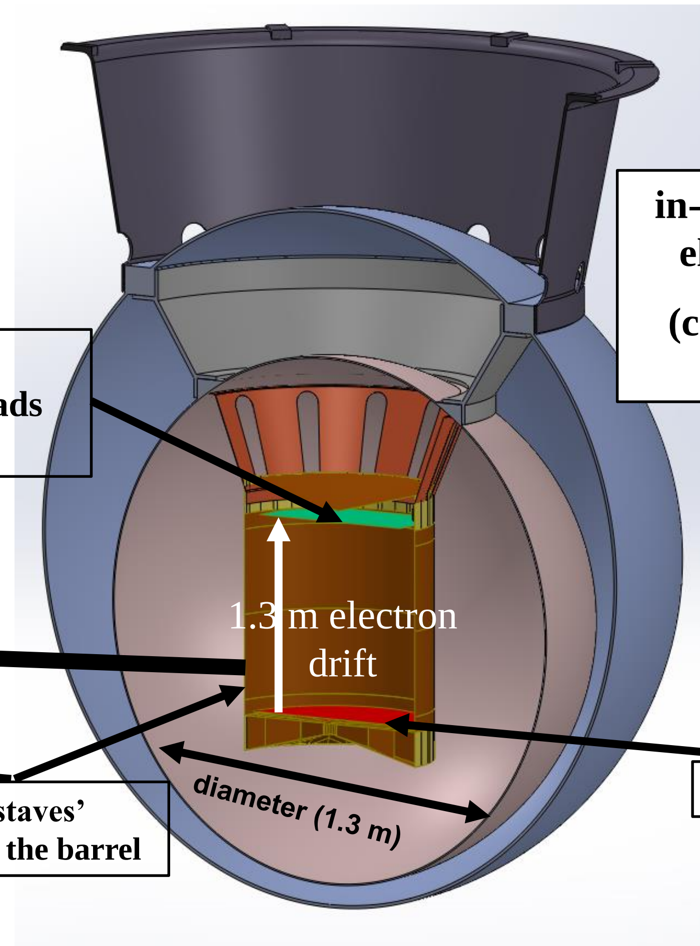


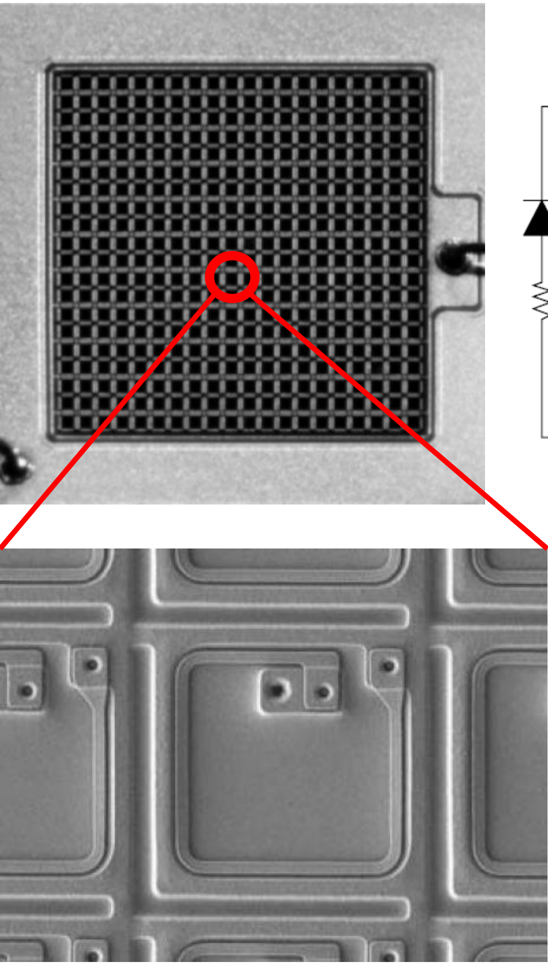
- **nEXO**
  - **5 tones of enriched Xe (>90%)**
  - **Enhanced self shielding.**
  - **Similar detection technique with EXO-200, but with lots of optimizations.**
  - **< 1% (σ/E) at Q of $0\nu\beta\beta$, extremely low background are two key points in nEXO.**
  - **nEXO goal: $T_{1/2}$ ($0\nu\beta\beta$ ^{136}Xe) > 10^{28} y at 90% C.L. at 5 years' exposure.**

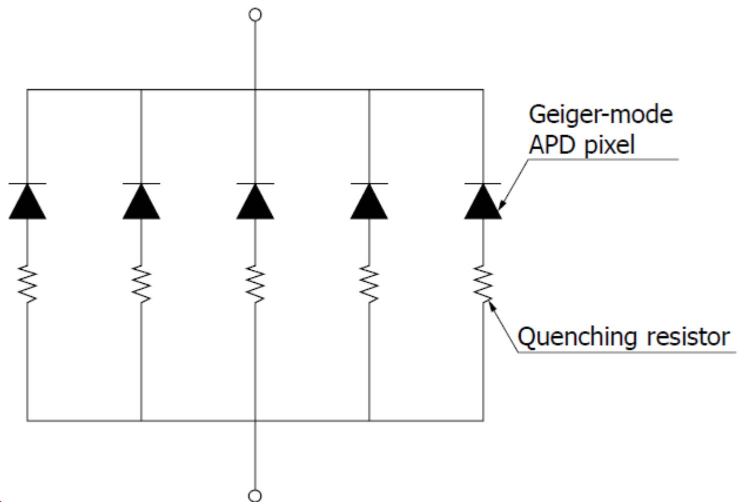
Conceptual design of nEXO detector

- 5 tones of single phase LXe TPC.
- Ionization charge collected by anode.
- Instead of LAAPD, 178nm lights detected by 4m² SiPM array behind field shaping rings.
- Combine light and charge to enhance the energy resolution.









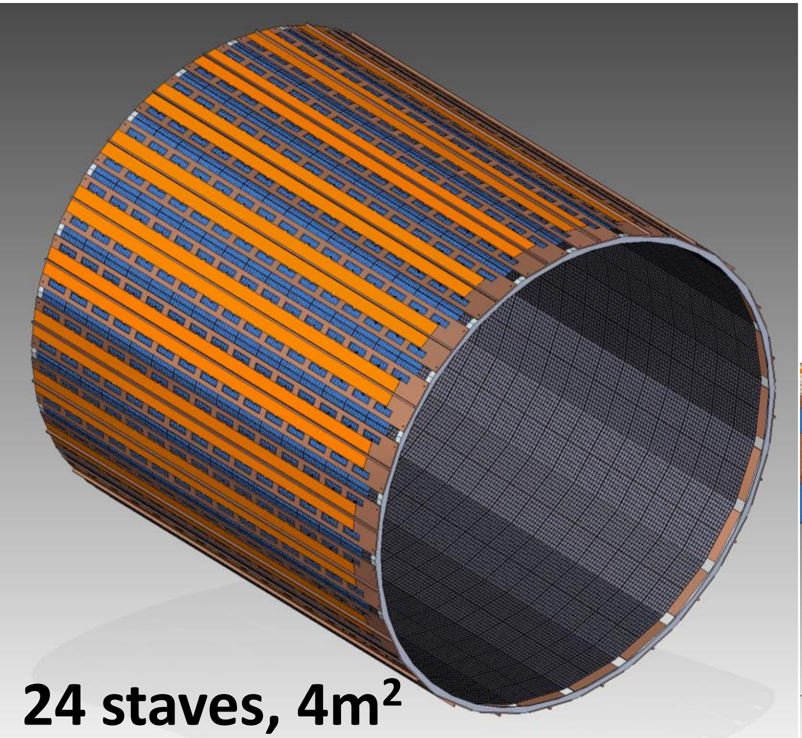
- ❄ **Many APD pixels in parallel operated in Geiger mode.**
- ❄ **Quenching resistor needed for each pixel.**
- ❄ **Each pixel is a binary photon counter.**

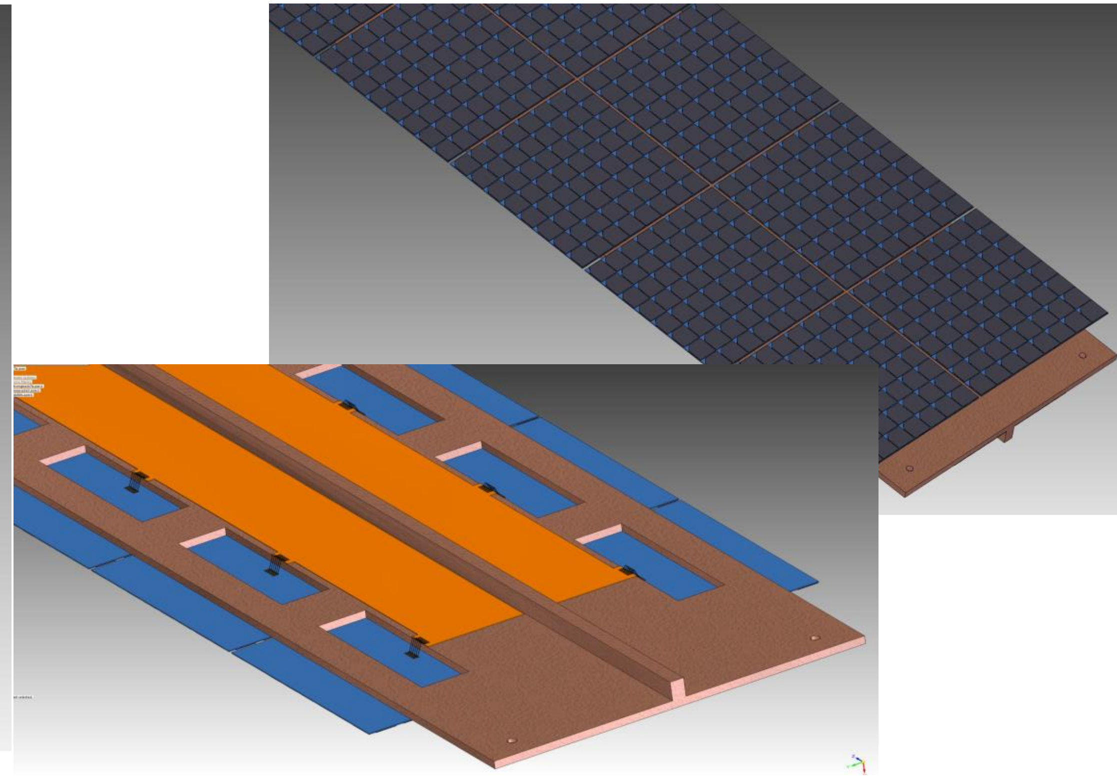
❄ **Advantages**

- ➢ **High gain**
- ➢ **Low radioactive background**
- ➢ **Low operating voltage.**
- ➢ **Acceptable photon detection efficiency at DUV region.**
- ➢ **Compact and easily scale to large area.**

❄ **Drawbacks**

- ➢ **Dark noise rate (much better at cryogenic temperature)**
- ➢ **Optical cross talk**
- ➢ **After pulse**

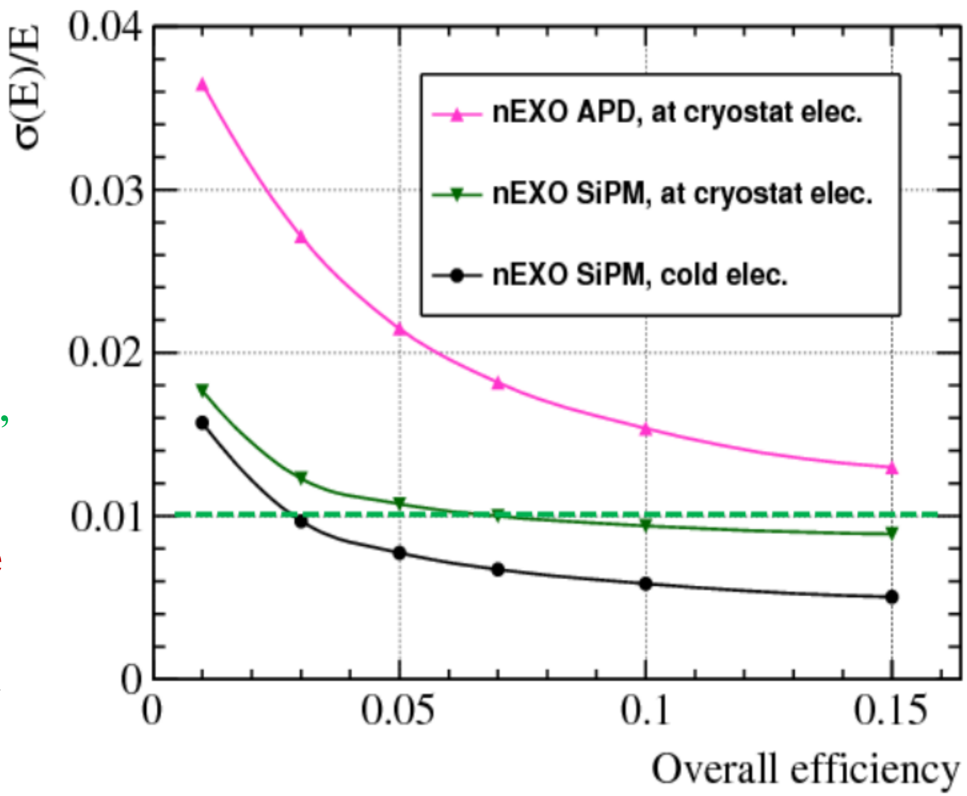




10mm x 10mm SiPMs with 0.5mm gaps, 1.5 mm gaps between tiles, 8 x 8 SiPMs per tile

30 tiles per stave, totally 46,080 chips on 720 tiles

- **The overall light detection efficiency in nEXO consists of two parts:**
  - **Light transport efficiency, determined by**
    - **Detector geometry.**
    - **Reflectivity of cathode, anode and field shaping rings in detector.**
    - **Reflectivity of SiPM.**
  - **Photon detection efficiency (PDE) of SiPM**
    - **Determined by filling factor, transmittance, quantum efficiency and trigger efficiency.**
    - **It can be measured by a standalone setup.**
- **The above two parts are coupled due to reflections on SiPM.**
  - **For DUV, more than 50% of lights will be reflected on SiPM surface.**

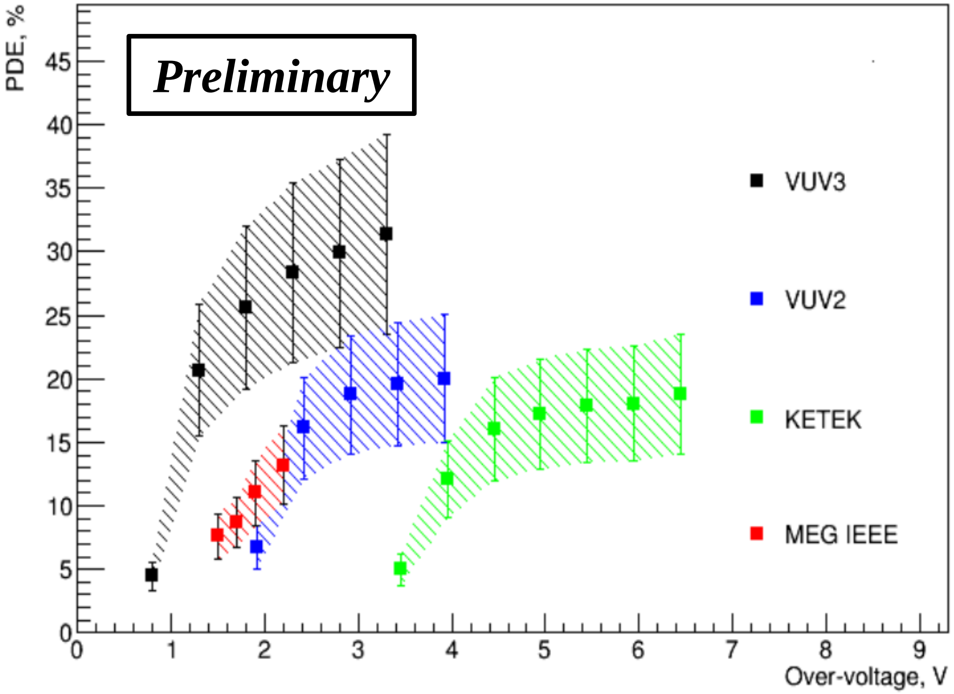


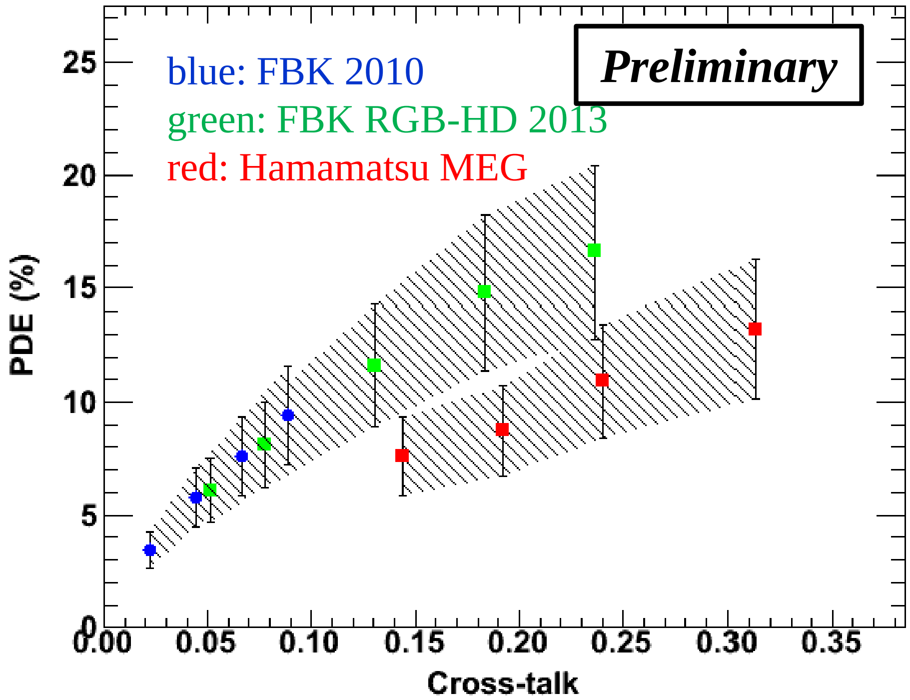
It's crucial for nEXO to measure PDE and reflectivity of SiPM.

Required SiPM specification in nEXO

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
Pulse width	< 0.5 μs	
Radio purity	0.1, 1, 10 nBq/mm^2	For ^{238}U, ^{232}Th and ^{40}K respectively

PDE measurements



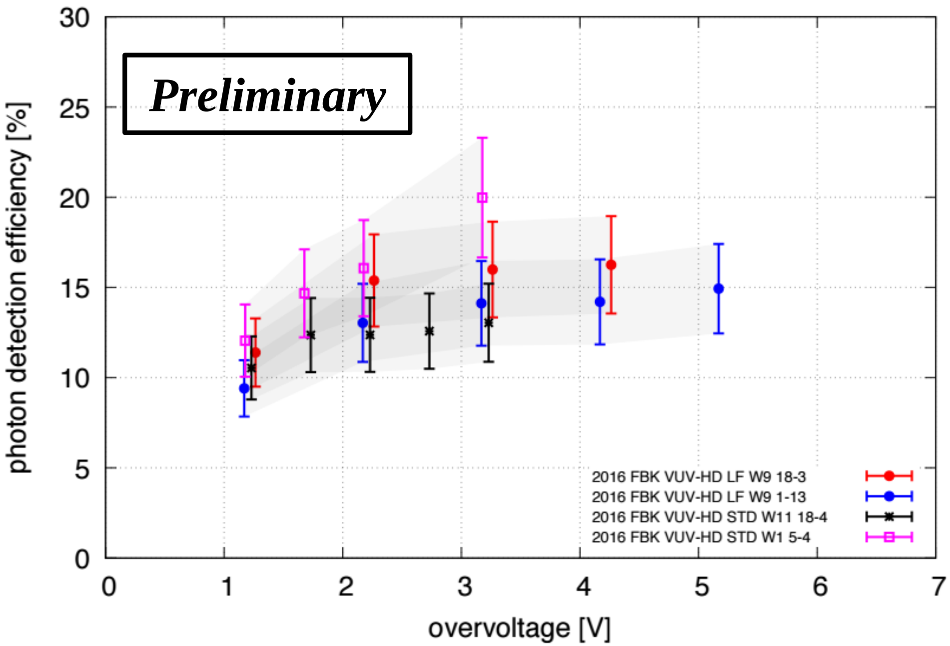


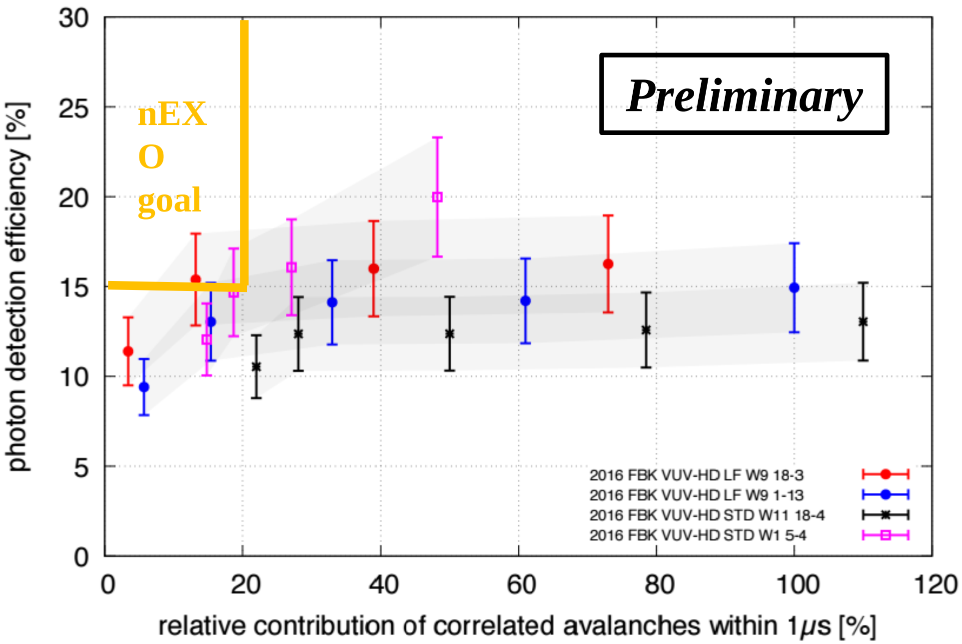
KETEK device is covered with wavelength shifter.

MEG device is expected to be identical to Hamamatsu VUV2.

Reported in 2016 IEEE NSS/MIC.

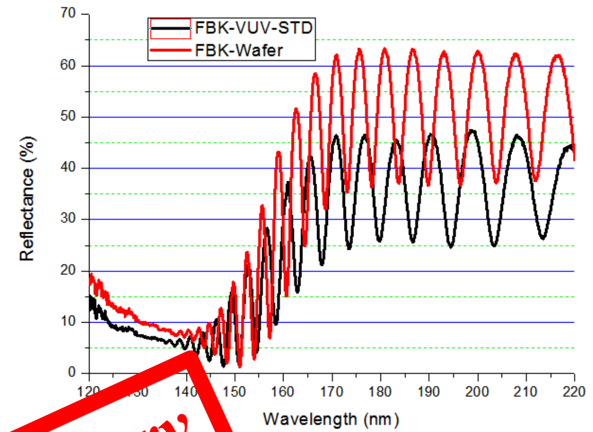
Latest PDE measurements



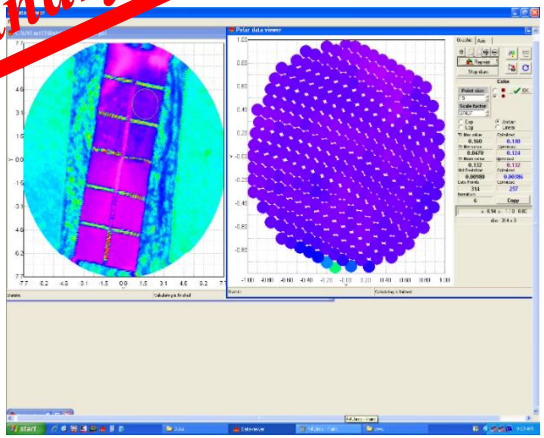


- Red and blue: two different FBK VUV-HD LF devices made in 2016.
- Black and pink: two different FBK VUV-HD STD devices made in 2016.

- **PDE of SiPMs contributed by**
  - **Transmittance, filling factor, QE and trigger efficiency.**
  - **~60% of 177nm lights will be reflected due to refractive index mismatch.**
  - **Reflected lights may be detected by other SiPM, but not the case when we measure the PDE.**
- **Strongly depending on surface and thickness.**



Device	Specular (177nm, 10 degree)	Diffuse(193 nm)
FBK-VUV-STD	35%	11.5%
FBK-VUV-LF	40%	12.3%
FBK-RGB	38%	17%
FBK wafer*	50%	0.16%

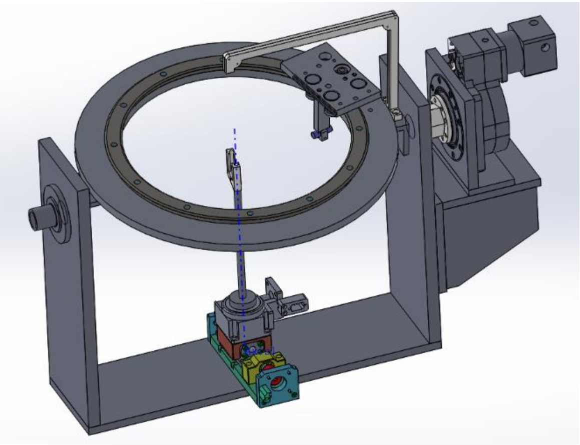


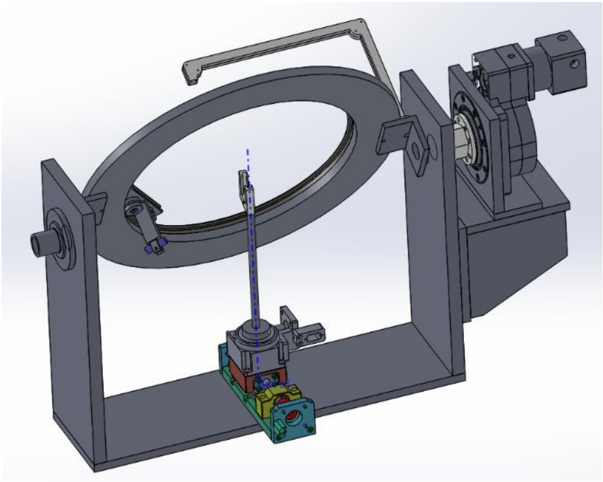
*: pure silicon, but with 1.5μm thickness of SiO_2 on top.

Measurement made in Institute of Optics and Electronics, CAS

❄ **The setup is designed to measure reflectivity (specular + diffused) in N_2/Ar or vacuum.**

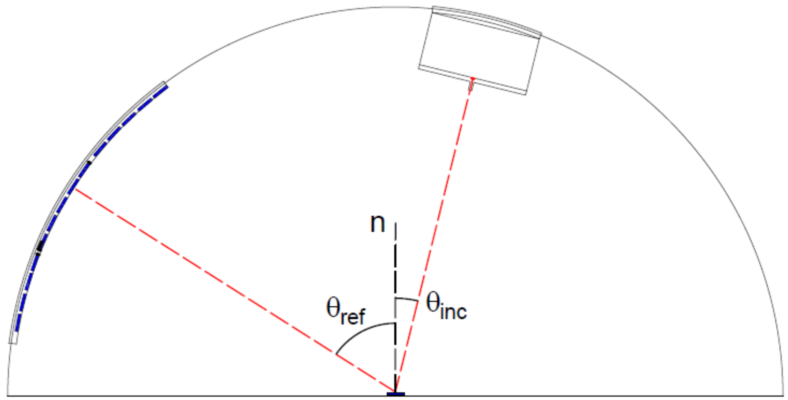
- **Can deploy different light source.**
- **3D measurements, automatically controlled.**
- **The company is making the setup for us.**





LIXO: LIquid Xenon Optical characterization

- **Understanding reflectivity of materials and SiPMs in liquid xenon (LXe) is critical for nEXO.**
- **nEXO plans to study reflectivity and photo-detection efficiency at 175 nm as a function of angle in LXe – LIXO @ The University of Alabama.**
- **The LIXO setup is being commissioned.**



Sketch diagram of LIXO setup. Radioactive point source illuminates sample. Reflected light detected by array of SiPMs. Both source and SiPMs can slide along the rail.

LIXO setup at the University of Alabama.

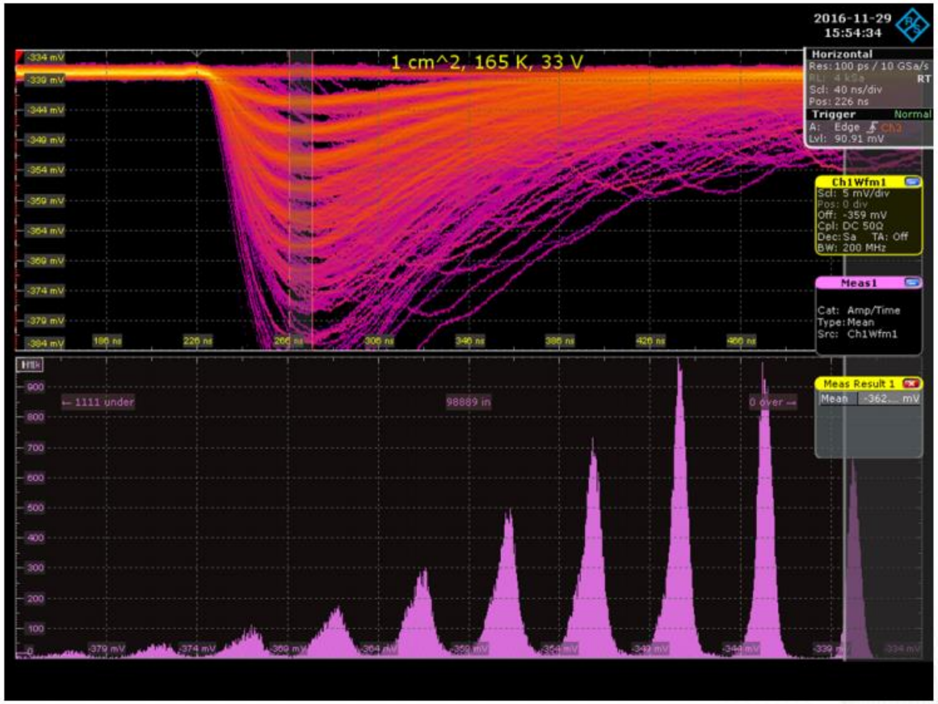
❄ Requirements

- Very large area, $4m^2$
- Need low noise (< 0.1 p.e.) and fast readout.
- Can readout one channel of ~6 cm^2 with 3-9nF/cm^2.

❄ We have investigated relation between sensor area capacitance, readout noise, power and shaping time.

❄ Analog readout

- Both series and parallel connections are under testing.



At 165 K, resolution ~0.08 SPE r.m.s., BW 200 MHz

Summary

- ❄ **A photo-detector system with large area SiPM is proposed in nEXO.**
- ❄ **It's a key system in nEXO to achieve designed energy resolution.**
- ❄ **Lots of efforts were made to study SiPM characterization and its reflectivity from different vendors.**
- ❄ **The results look promising for nEXO.**
- ❄ **The following two R&D items will be discussed by my collaborators.**
  - ➢ **SiPM performance in high electric field**
    - **Talk will be given by Tamer on Wed. afternoon R4-Photon detector session.**
  - ➢ **3D integrated digital SiPM**
    - **Talk will be given by Fabrice on Wed. afternoon R4-photon detector session.**

The nEXO Collaboration

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Backup slides

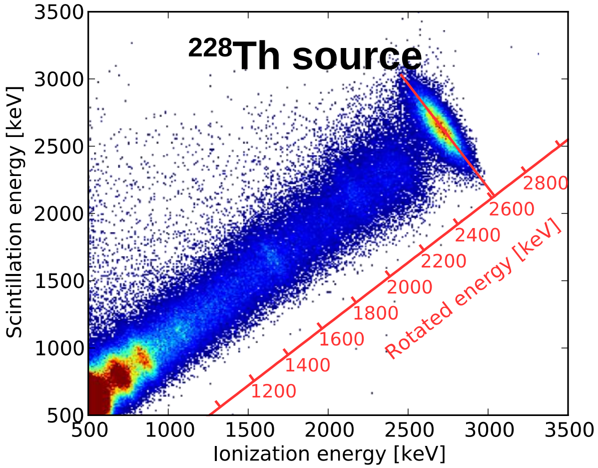
- ❄ **Combine light and ionization to enhance energy resolution**

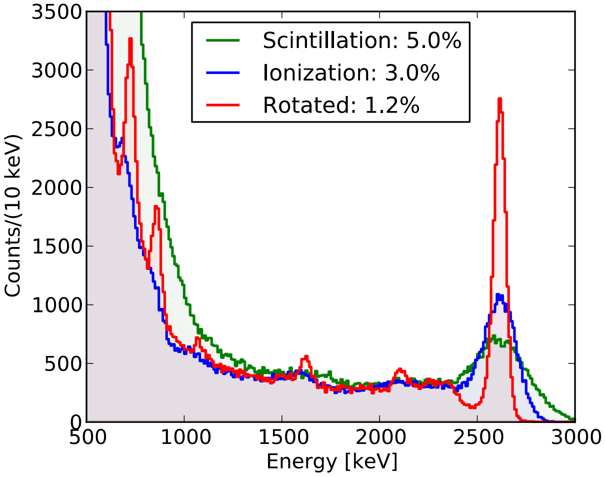
(E.Conti et al. Phys Rev B 68 (2003) 054201)

- ❄ **EXO-200 has achieved ~1.28% energy resolution at the Q value.**
- ❄ **nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.**

However, LXe TPC IS NOT A PURE CALORIMETER, it can use optimally more than just the energy.

- ◆ **Event multiplicity (SS/MS in EXO-200)**
- ◆ **Distance from the TPC surface**
- ◆ **Particle ID (α-electron)**





Optimizations from EXO-200 to nEXO

Optimization	Reason
Up to 40 × volume/mass	Inverted hierarchy sensitivity
Move cathode to end	Remove all internal sources of background
6x high voltage	Longer drift length
> 3 × electron lifetime	Longer drift length
Increased photo-coverage	Energy resolution (to 1% σ/E), scintillation threshold
SiPMs over LAAPDs	Higher gain, lower bias, less material, energy resolution, lower scintillation threshold
In LXe front end electronics	Lower noise/lower threshold to ID Compton
Low outgassing materials	Longer electron lifetime
New calibration methods	To calibrate 'deep' detector (by design)
Deeper site	Reduced cosmic activation
Charge tiles over wires	3mm position resolution, simpler/smaller mechanical supports, lower radioactivity

- In order to increase the light transport efficiency, we need to make electrodes (anode/cathode/field shaping rings) to be highly reflective.
- It's challenge to make DUV reflective film (>80% reflectivity) on ~1.2m diameter copper plates or rings.
- Some R&D works are ongoing.