Photo-detector System with Large Area SiPM in nEXO

Guofu Cao

On behalf of nEXO Collaboration

Institute of High Energy Physics, Beijing, China

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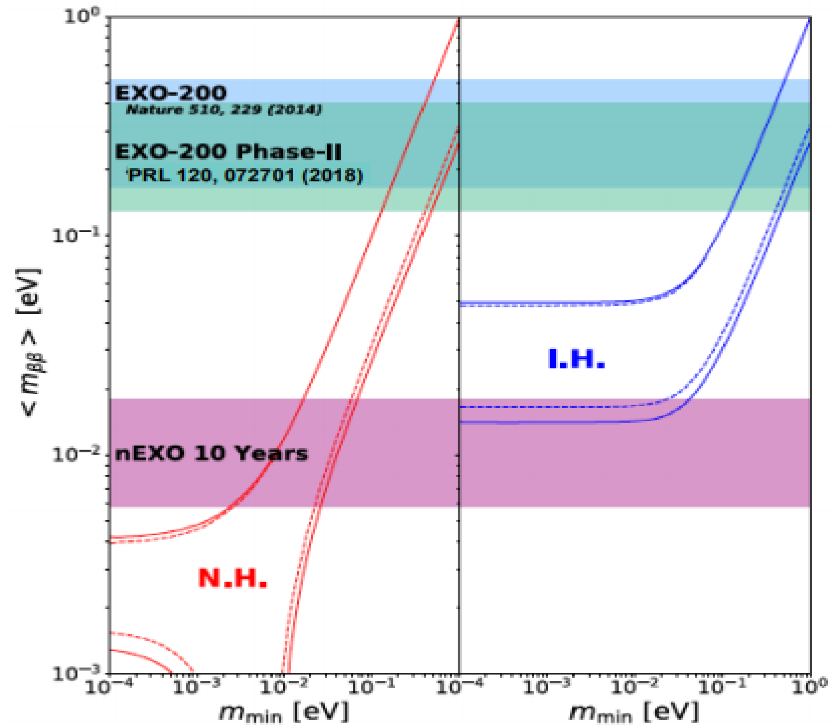
- nEXO is proposed to search for $0\nu\beta\beta$ decays of ^{136}Xe with sensitivity **entirely covering the neutrino mass region of inverted hierarchy**, based on **5 tons liquid xenon TPC**.



- **EXO-200**
  - ~200 kg enriched liquid xenon
  - Phase I: Sep. 2011 – Feb. 2014
  - Phase II: Apr. 2016 -- Dec. 2018

  $T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr, $<m_{\beta\beta}> < 147 – 398$ meV (90% C.L.)

  Phys. Rev. Lett. **120**, 072701 (2018)

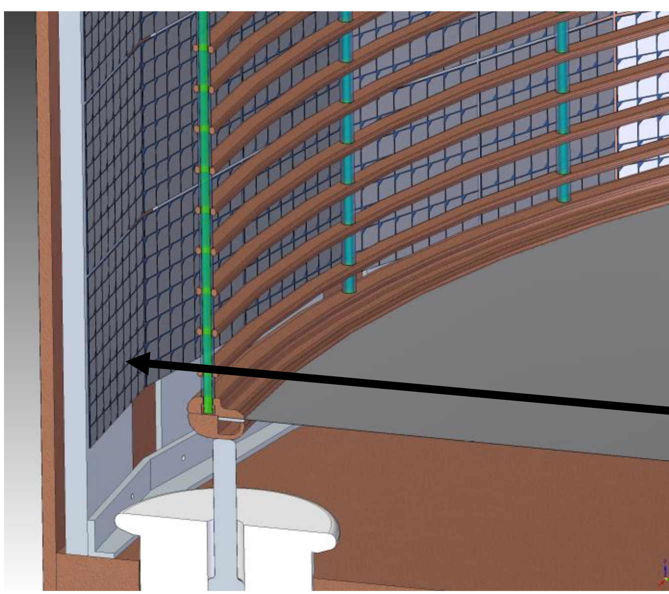
- **nEXO**
  - 5 tones of enriched Xe (>90%)
  - Enhanced self shielding.
  - Similar detection technology with EXO-200, but with lots of optimizations.
  - Excellent energy resolution (1% at Q of $0\nu\beta\beta$) and ultra-low background.
  - Charge collection system and photon-detector system are two key components in TPC.

nEXO sensitivity paper, Phys. Rev. C 97, 065503 (2018)

Conceptual design of nEXO detector

- **5 tones of single phase LXe TPC.**
- **Ionization charge collected by anode.**
- **Instead of LAAPD, 178nm lights detected by ~4 m^2 SiPM array behind field shaping rings.**
- **Combine light and charge to enhance the energy resolution.**

nEXO pre-CDR, arXiv:1805.11142



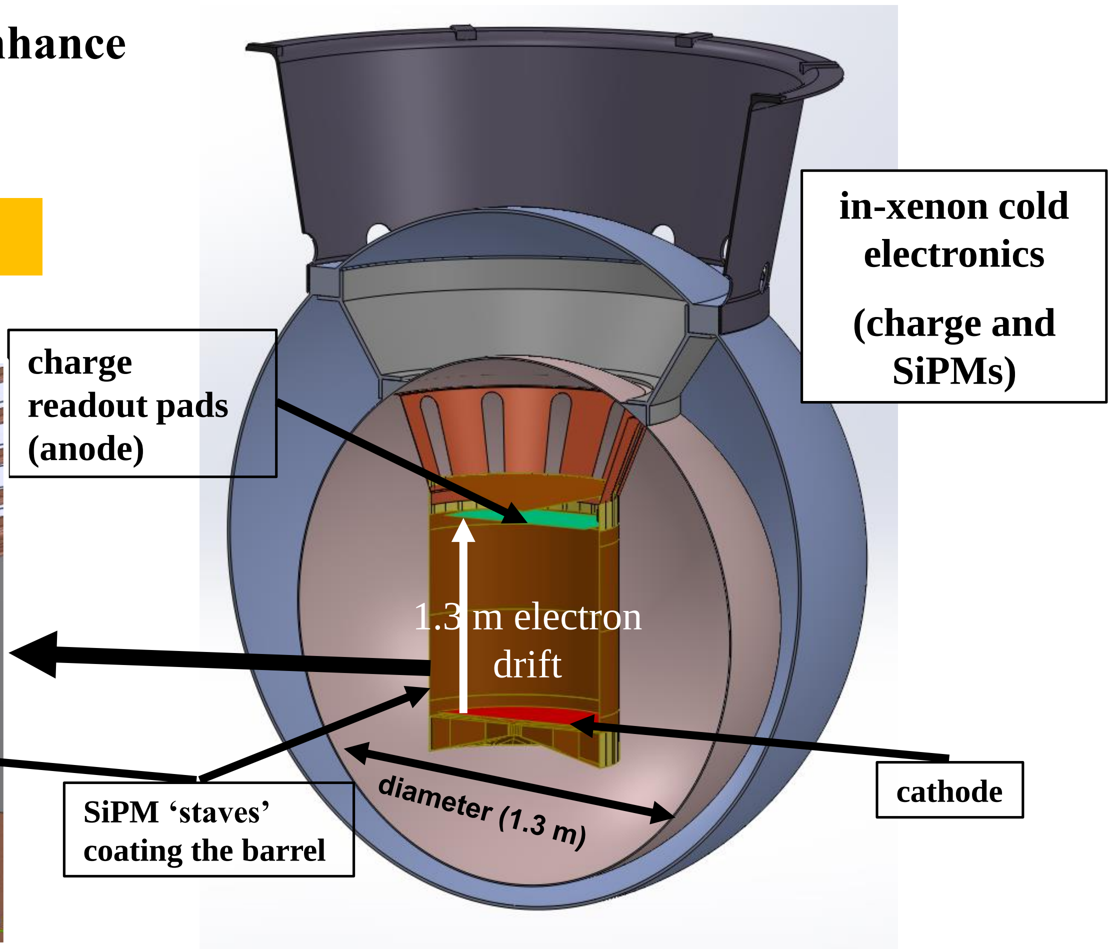
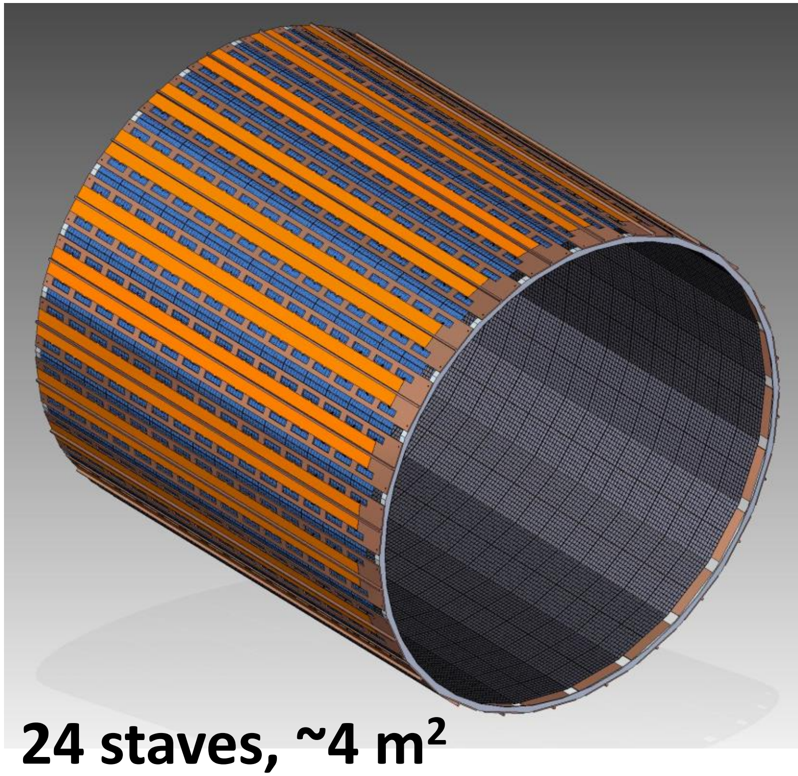
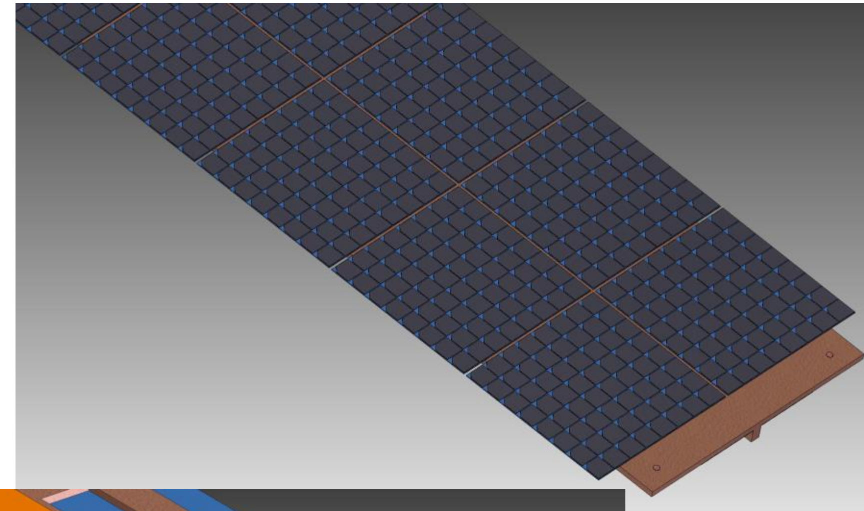
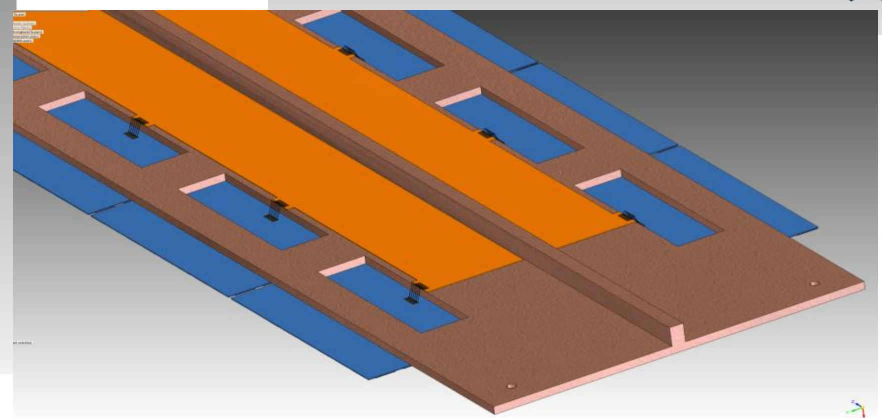


Photo-detector system in nEXO







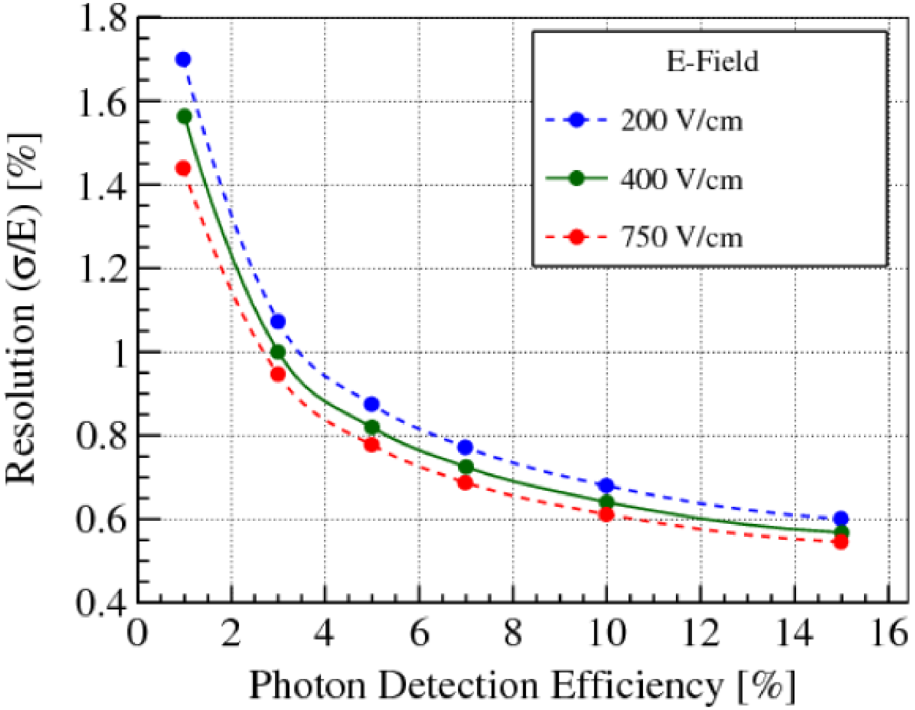
30 tiles per stave, 1.5 mm gaps between tiles, totally 720 tiles

8 x 8 SiPMs per tile, 10mm x 10mm SiPMs with 0.5mm gaps

Totally 46,080 SiPM chips

Photon detection efficiency in nEXO

- **The photon detection efficiency of TPC consists of two parts:**
  - **Photon transport efficiency (PTE)**
    - **Optimized detector geometry**
    - **Reflective electrodes in TPC**
    - **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.**



- **It's crucial to understand the PDE and reflectivity of SiPM in nEXO, usually this is also the case for other SiPM based detectors.**
  - **For VUV, more than 50% of photons will be reflected on SiPM surface, assuming Si-SiO_2 interface.**

Required SiPM specification

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

SiPM characterization

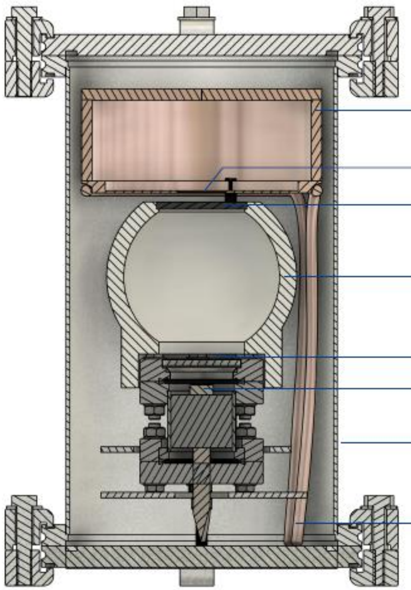
- **SiPM PDE (at VUV region) and nuisance parameters (in cold)**
  - **Stanford U.**
  - **TRIUMF**
  - **Erlangen**
  - **BNL**
  - **IHEP**
  - **U. of Mass.**

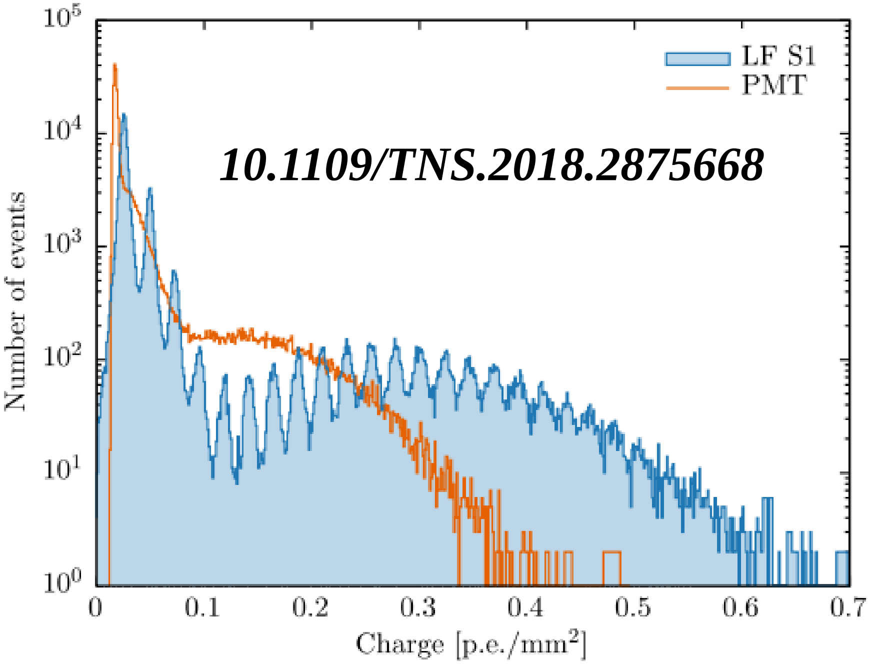
- **Reflectivity of SiPM**
  - **In vacuum or N_2**
    - **IHEP**
    - **TRIUMF**
  - **In liquid xenon**
    - **U. of Alabama**
    - **Erlangen**
    - **UMASS**

- **Tested SiPMs**
  - **FBK**
    - **NUV, VUV-LF-HD, VUV-STD-HD**
  - **Hamamatsu**
    - **VUV3, VUV4**

SiPM PDE at VUV (I)

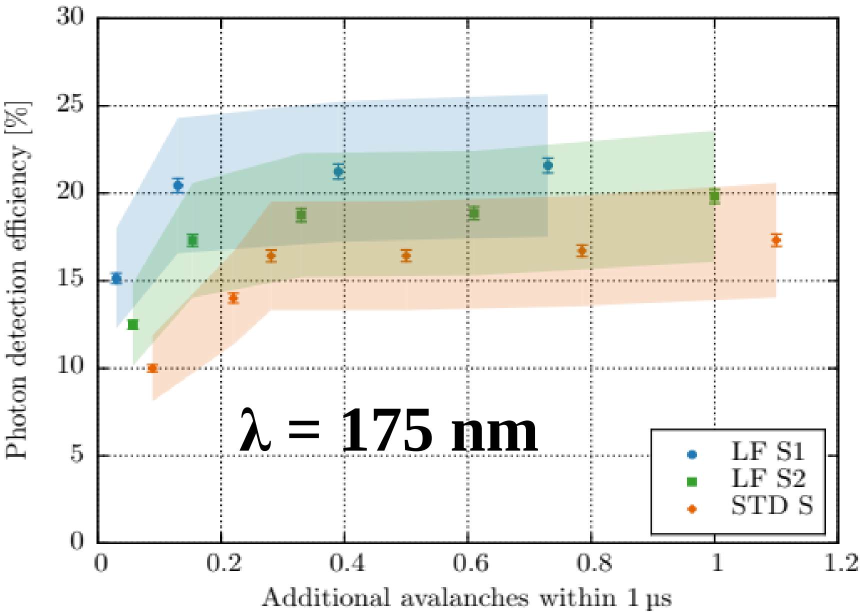
Stanford setup



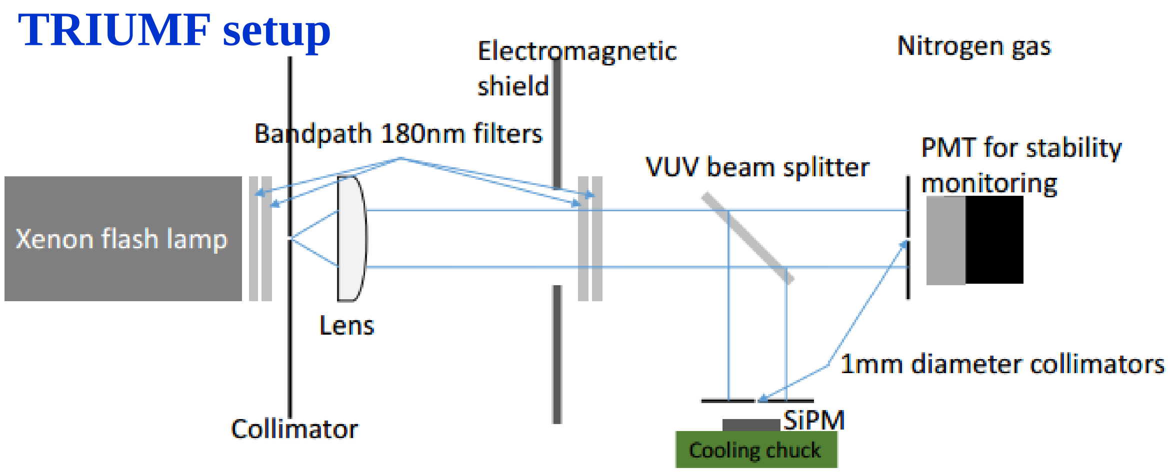


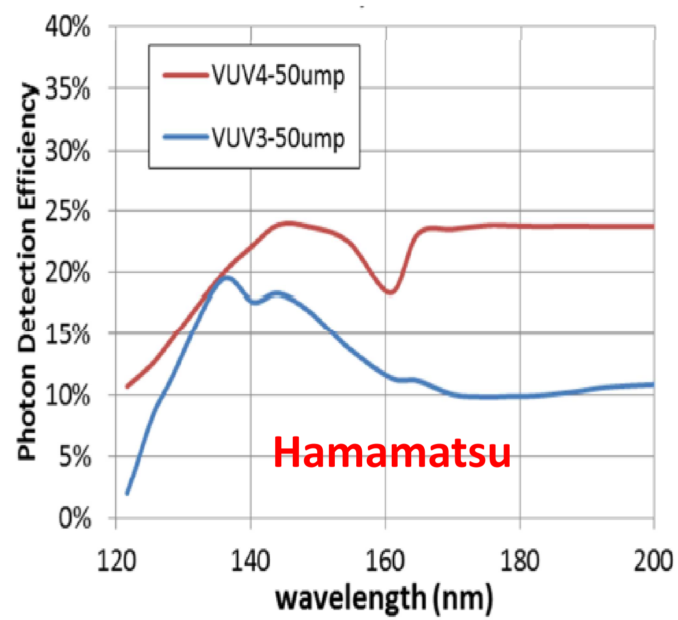
Source of Systematic Error	Value [%]
Solid angle	3
Angular Distribution	1
PMT gain stability	6
PMT gain modeling	10
PMT QE uncertainty	∼ 2
PMT CE uncertainty	∼ 14
Quadratic sum	**∼ 19**

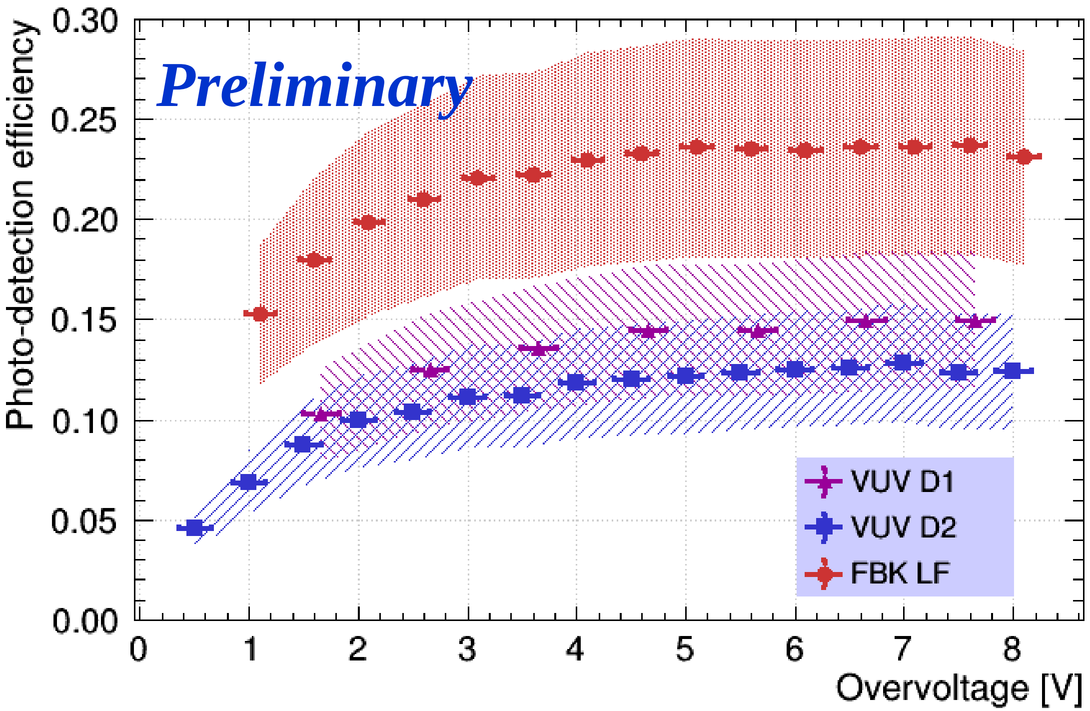
Source of Statistical Error	Value [%]
PMT gain calibration	1
SiPM gain calibration	1
Correlated noise correction	1
Fission peak position	1
Quadratic sum	**2**



SiPM PDE at VUV (II)

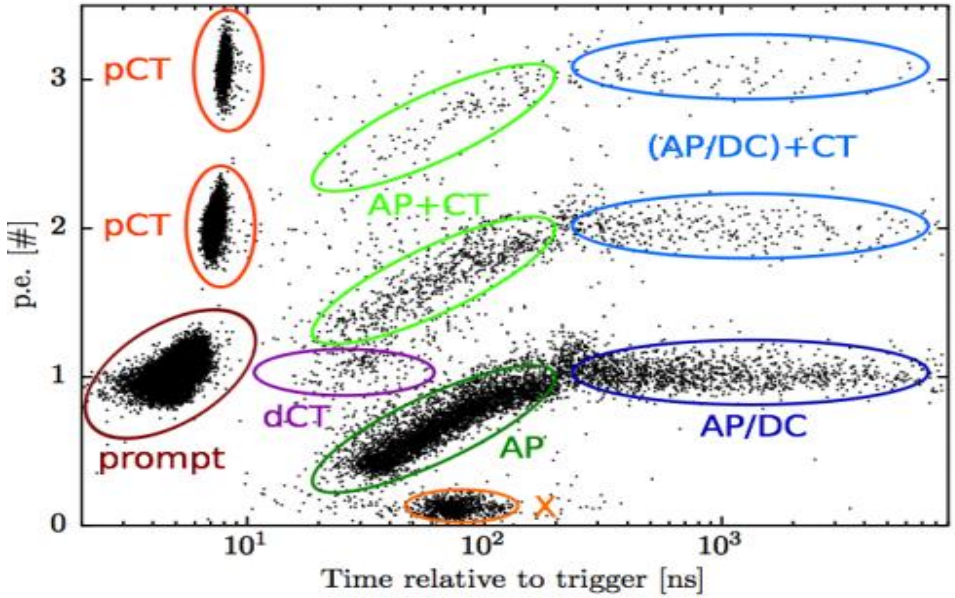






- **Center of wavelength: 180 nm**
- **FBK-VUV-LF shows higher PDE, comparing with VUV4 from Hamamatsu.**
- **The uncertainty is dominated by reference PMT.**

Nuisance parameters

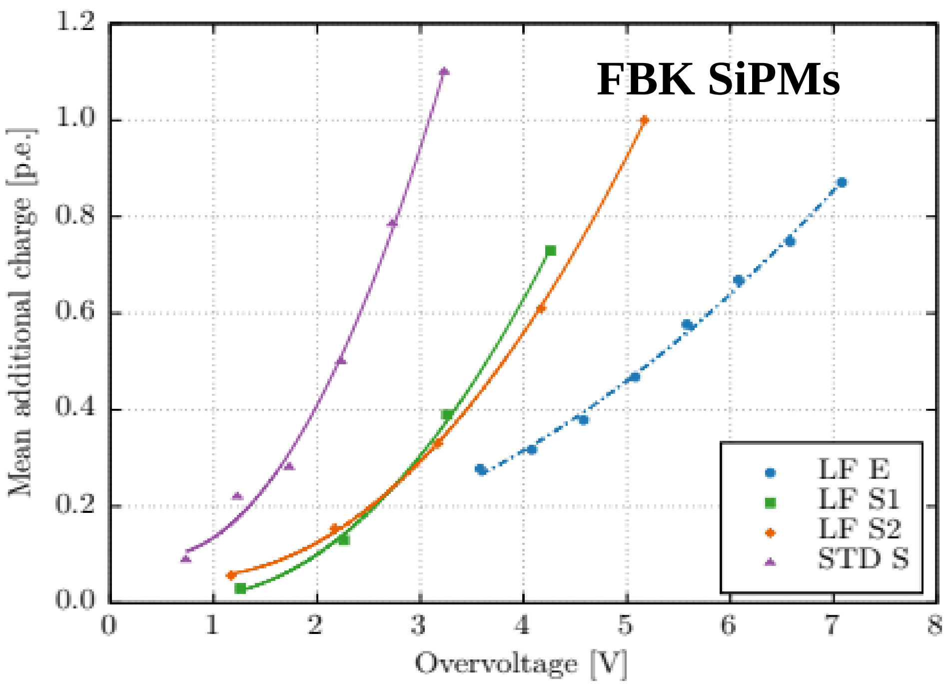


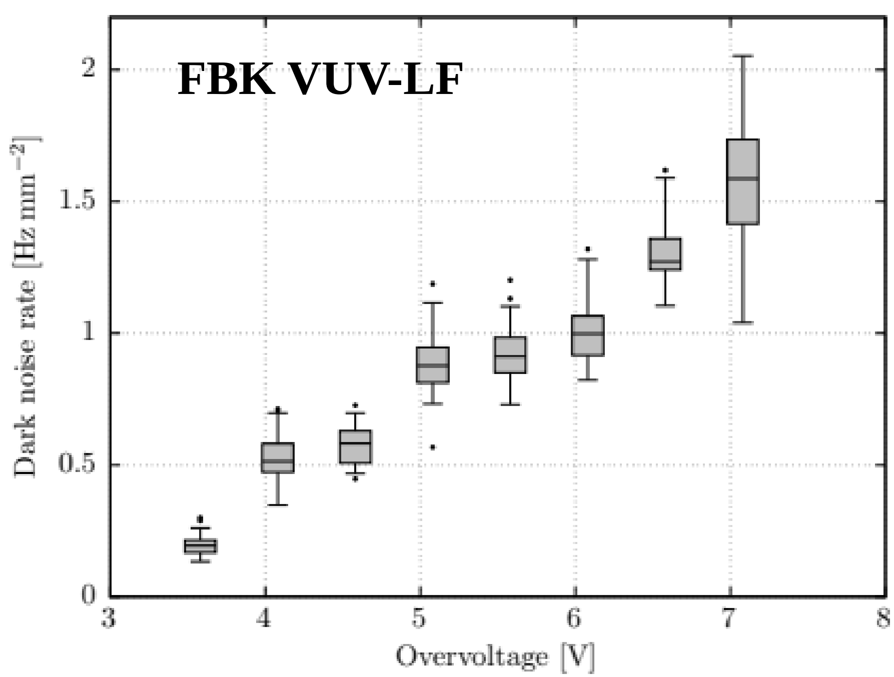
10.1109/TNS.2018.2875668

Temperature: 169 K

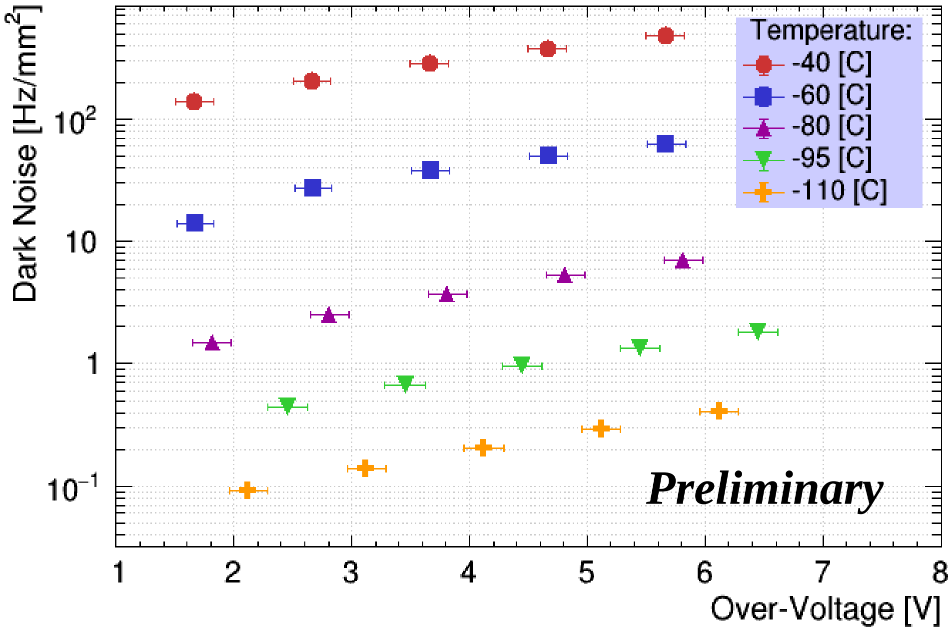
By analyzing output pulses

- ✓ **Charge/amplitude spectrum**
- ✓ **Charge vs time**
- ✓ **Time interval**



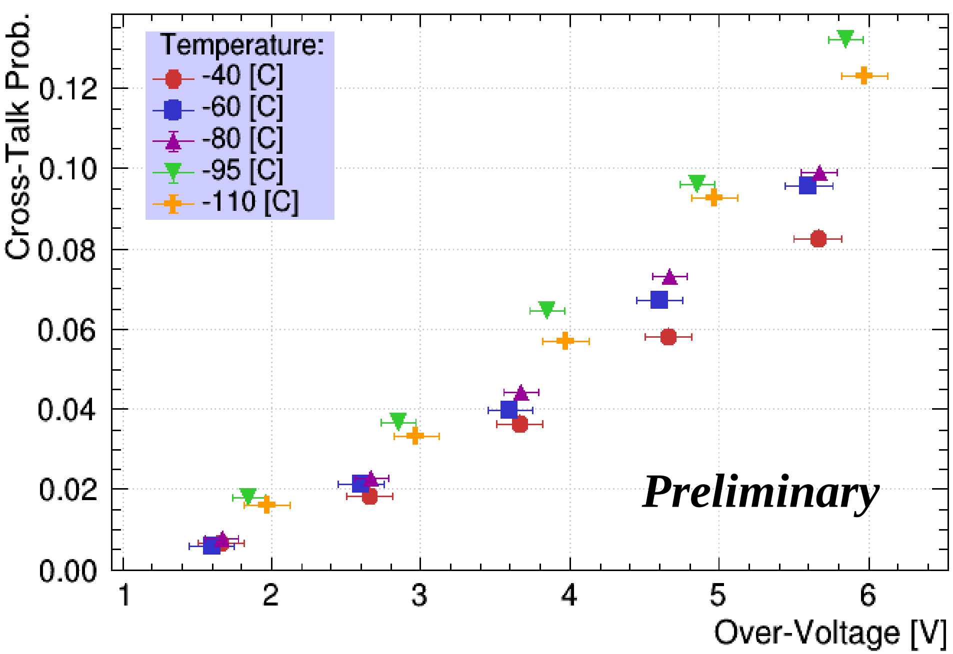


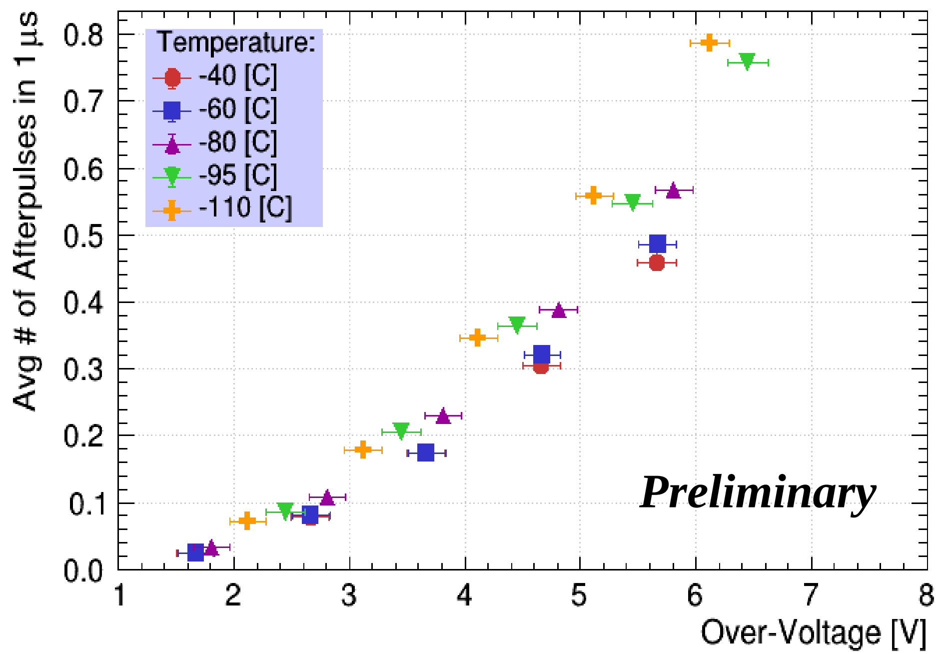
Nuisance parameters cont.



VUV4 SiPM from Hamamatsu (50 um)

Better control of correlated avalanches, comparing with FBK



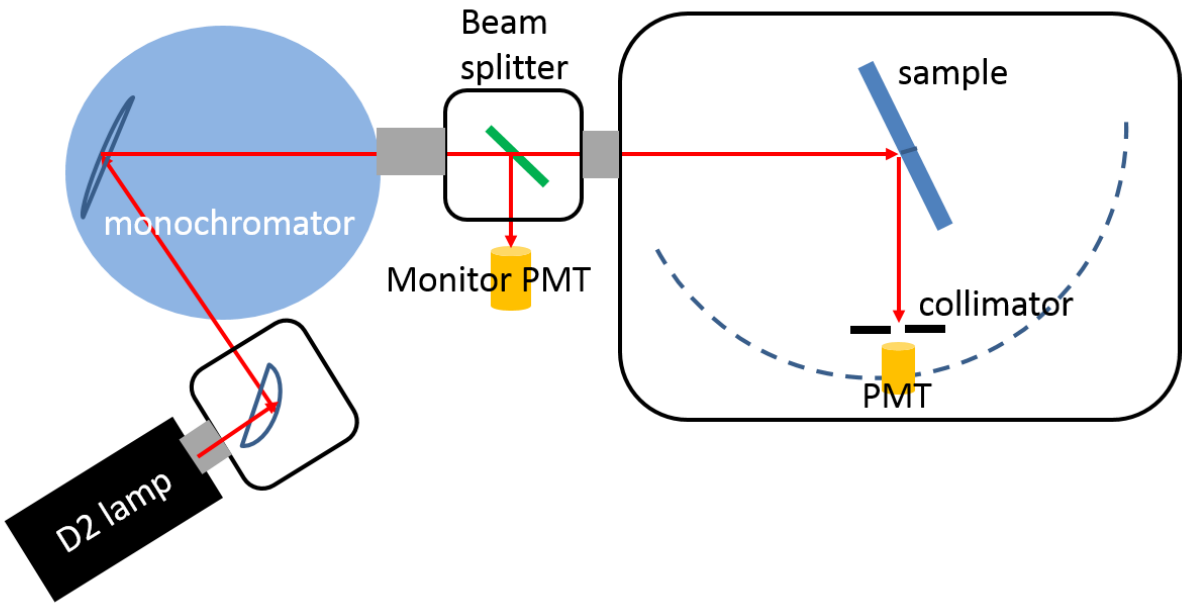


SiPM reflectivity in vacuum

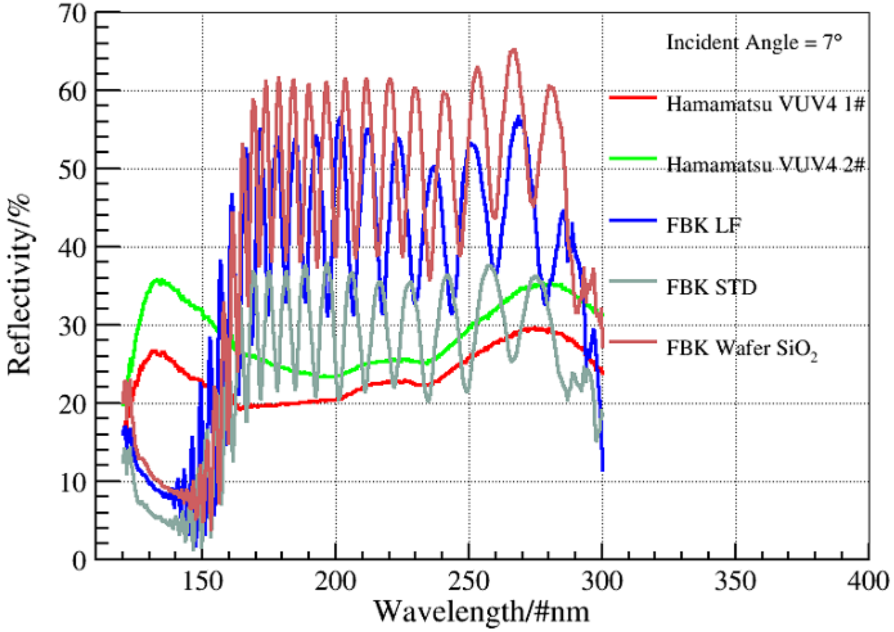
High reflectivity on SiPM surface, it's crucial to make it clear in nEXO.

IHEP & IOE, China

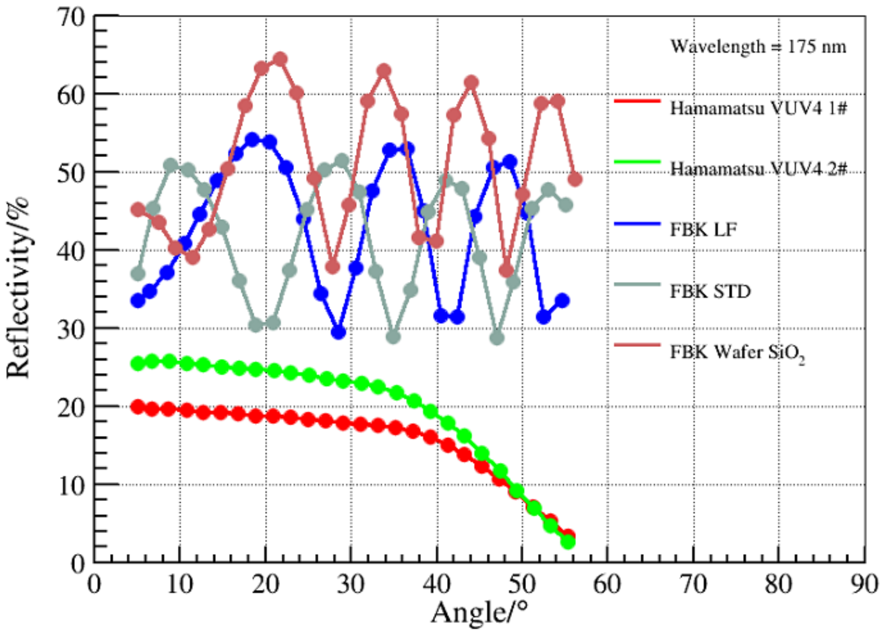
- **Specular reflection**
  - ✓ **Wavelength: 115 nm – 400 nm**
  - ✓ **Angle of incidence: 5 – 55 degree**
- **Diffused reflection**
  - ✓ **Wavelength: 193 nm**
  - ✓ **The component of specular reflection has been excluded.**
- **Measured samples**
  - ✓ **FBK-VUV-STD, FBK-VUV-LF, silicon wafer (with 1.5um SiO_2)**
  - ✓ **VUV4 (50 um, 75 um) from HPK**



Preliminary reflectivity results in vacuum

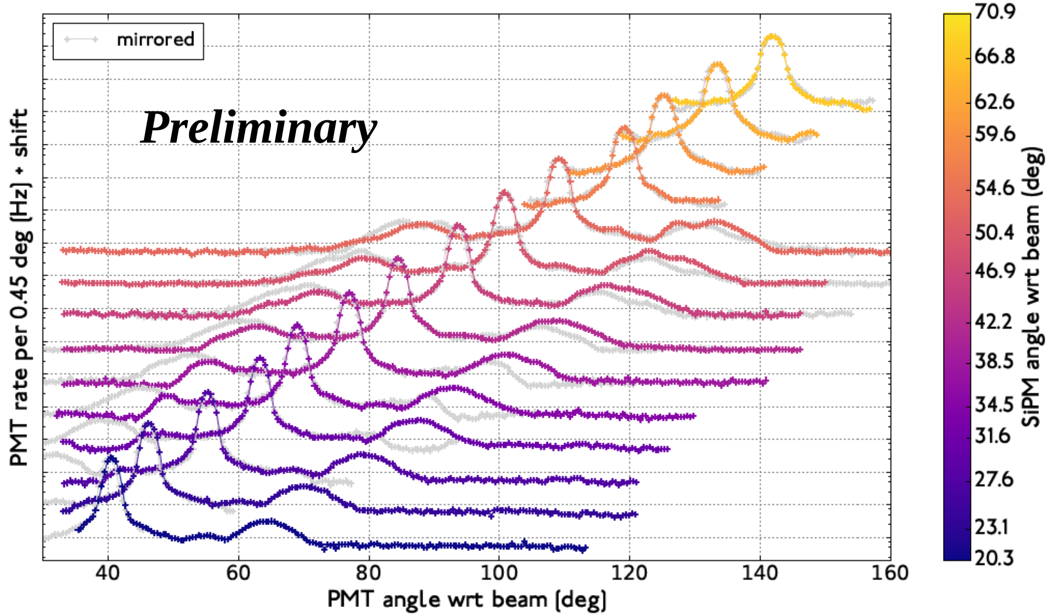


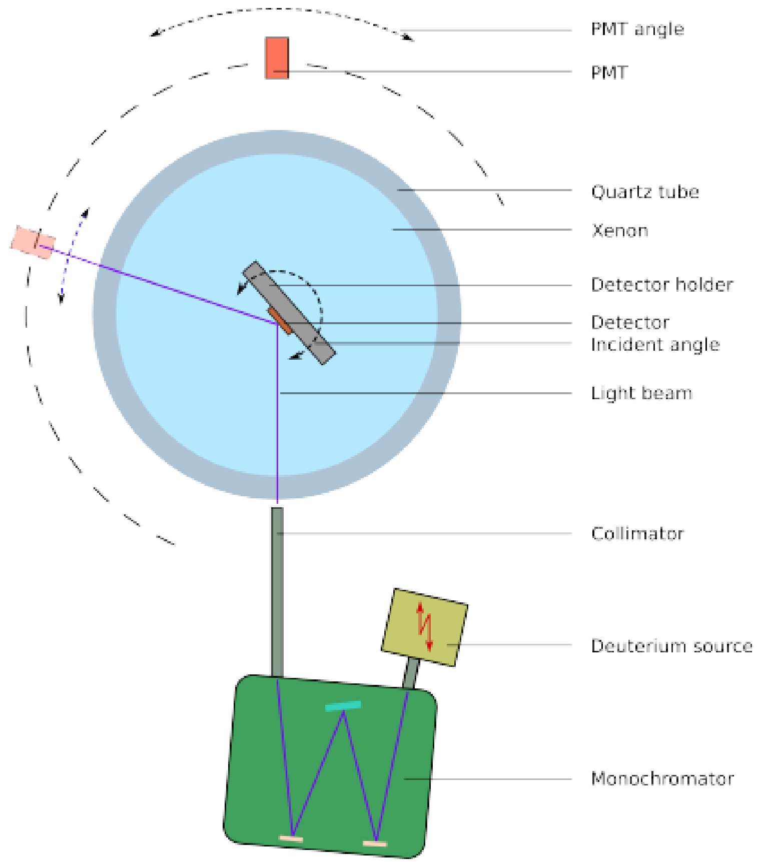
- Lower specular reflectivity for VUV4, comparing to FBK SiPMs.
- Similar diffused reflections between VUV4 and FBK SiPMs.

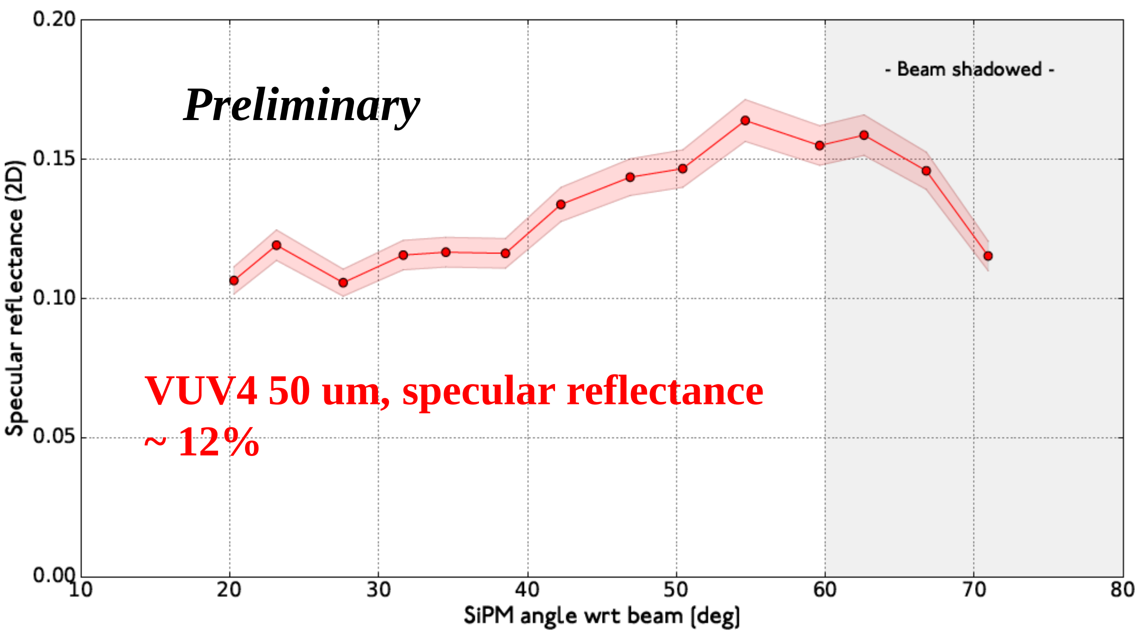


Device	Diffuse(193nm)
FBK-VUV-STD	13%
FBK-VUV-LF	10%
VUV4 1# (50 um)	17%
VUV4 2# (75 um)	10%
Silicon wafer*	0.09%

SiPM reflectivity in liquid xenon



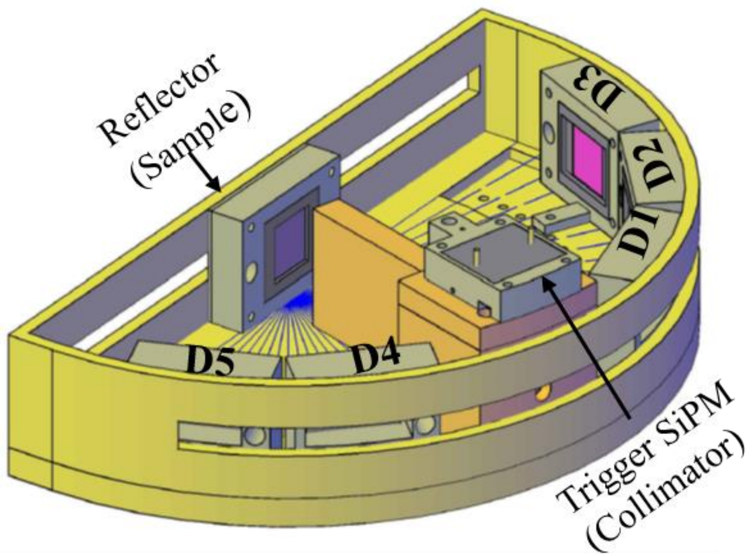




- Done by Erlangan group, based on the setup in U. of Münster
- Secondary peaks may caused by microstructures

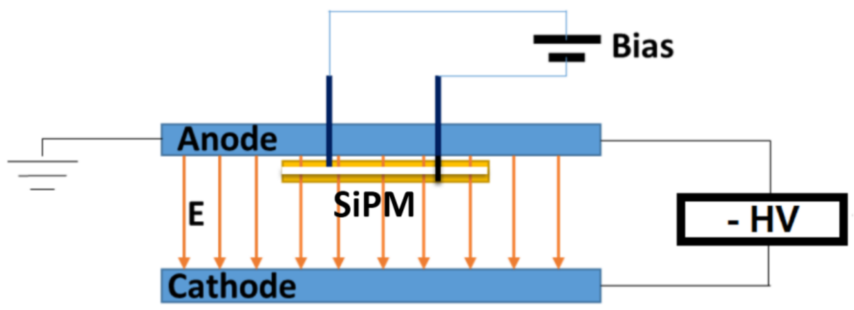
SiPM reflectivity in liquid xenon -- LIXO

U. of Alabama



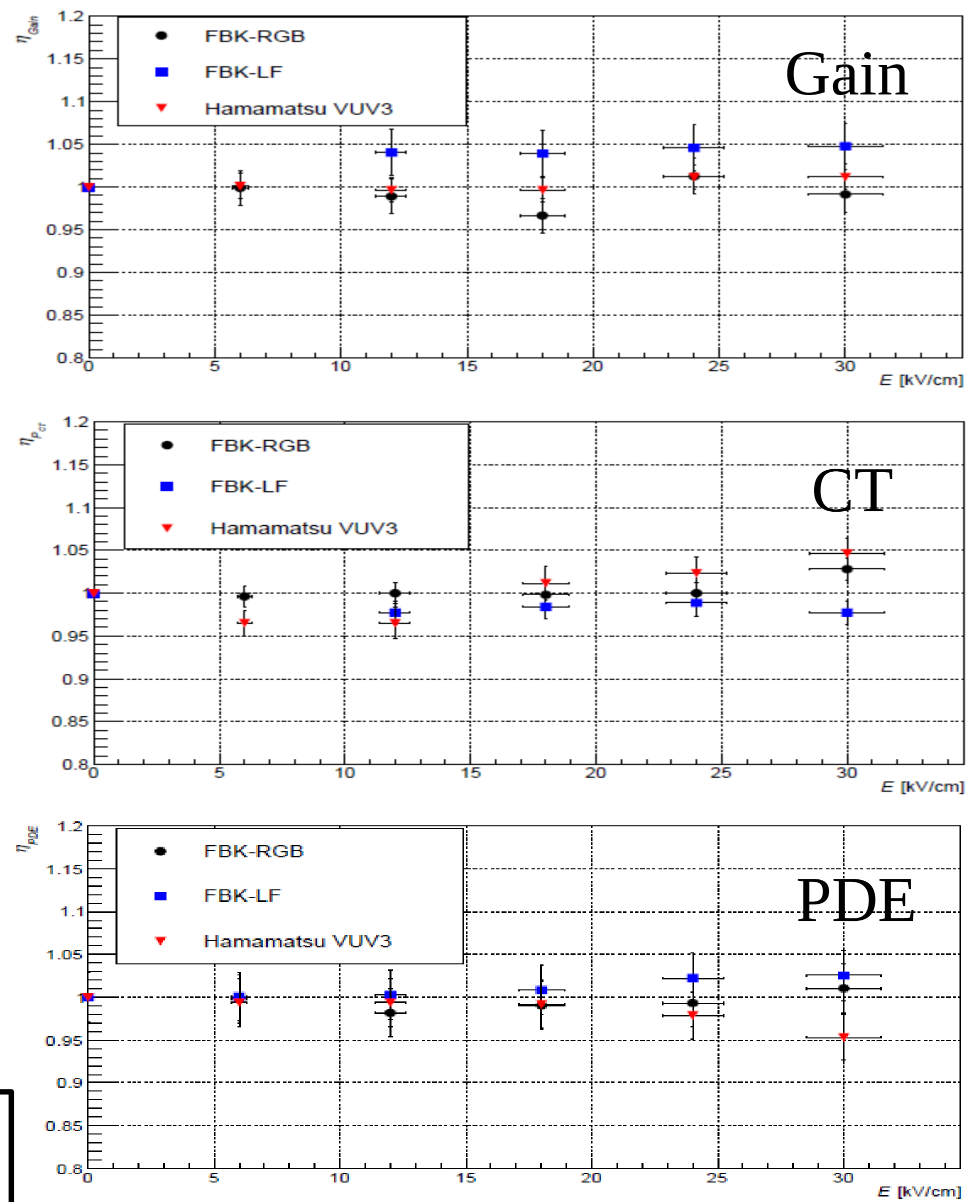
- ✓ Reflectivity measurement of samples in liquid Xenon
  - ➢ active samples: SiPM, etc...
  - ➢ passive samples: Quartz, Peek, Teflon, etc...
  - ➢ as a function of angle
  - ➢ Parasitic reflections minimized by using VUV absorbing materials
- ✓ Relative PDE of SiPM as a function of angle in liquid Xenon
- ✓ ^{252}Cf source excites LXe to generate 175 nm light.
- ✓ Collimator + quartz window helps towards preventing radiation damage and light collimation.
  - ✓ Collimator SiPM for triggering and light stability measurement.
- ✓ Detectors are positioned at D1, D2, D3, .. for specular and diffuse reflectivity measurement.
- ✓ Results coming soon.

SiPM exposed to high electrical field



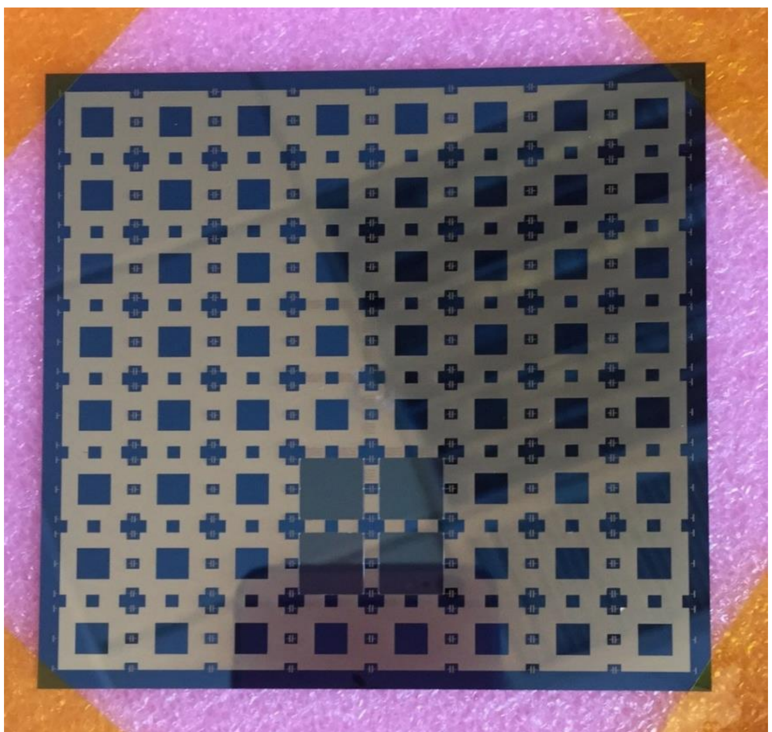
- In nEXO, SiPMs will be exposed to external E-fields up to ~20 kV/cm based on simulation.
- SiPM performance in various E-fields at cryogenic temperatures (~150K) have been tested.
- The tested SiPMs show good stability under the influence of different electric field strengths.

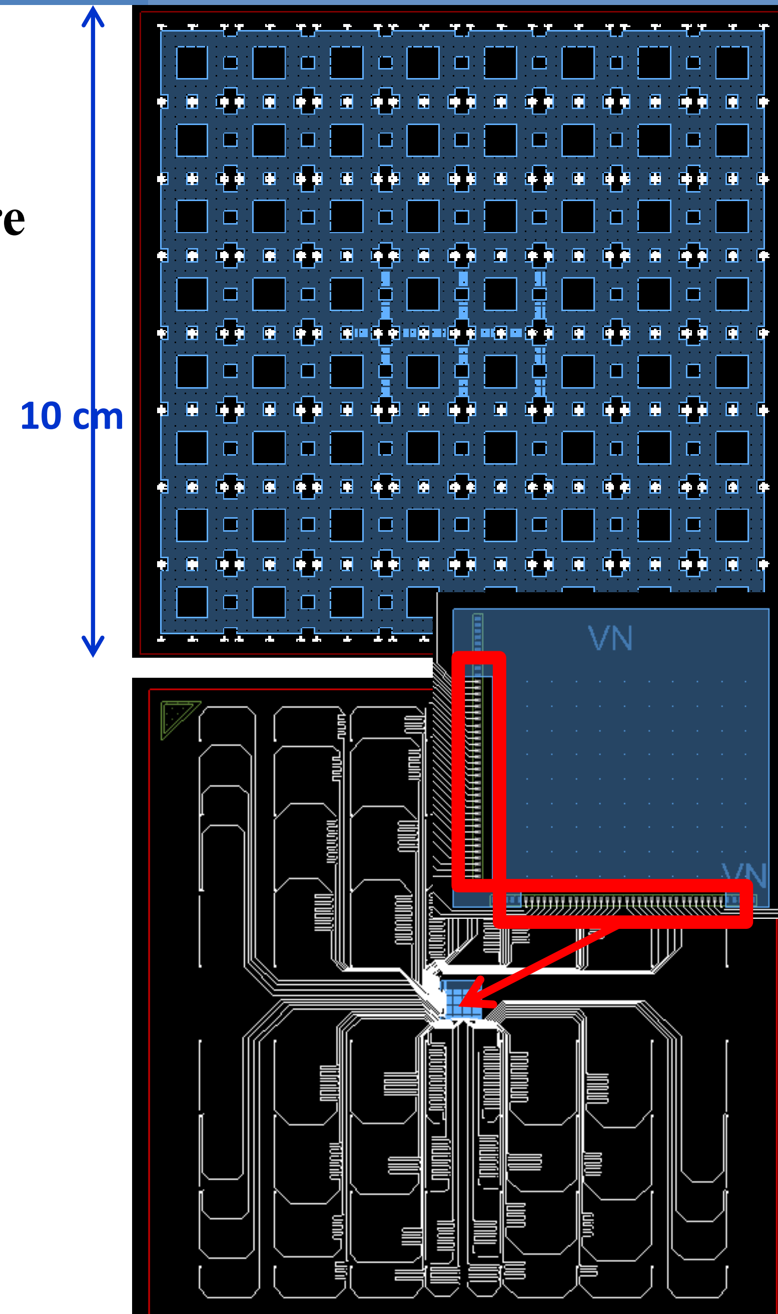
T. Tolba, et.al., and the nEXO collaboration, ***Study of Silicon Photomultiplier Performance in External Electric Fields*****, JINST 13, T09006, 2018.**



Silicon interposer

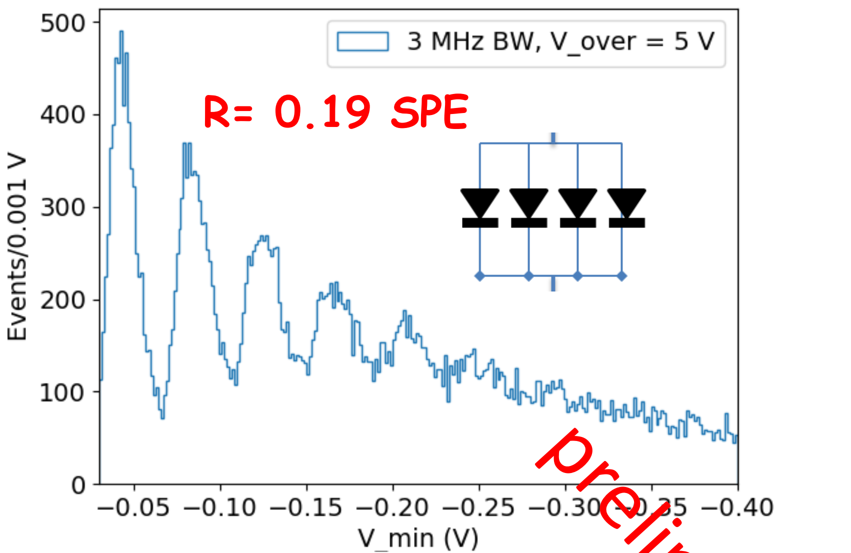
- To support and connect SiPM array and readout electronics
- Good CTE match at cryogenic temperature
- Good radio-purity
- The first prototype (10x10 cm^2) has been made by IME in China.
- The testing work is ongoing.

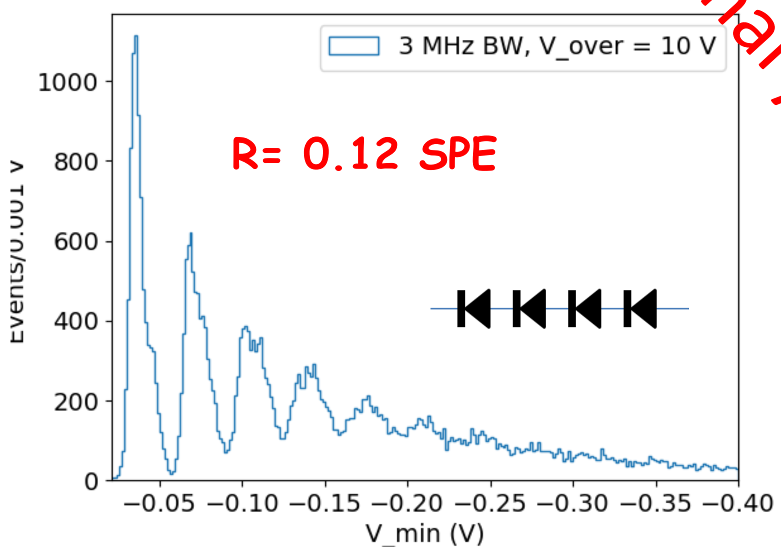


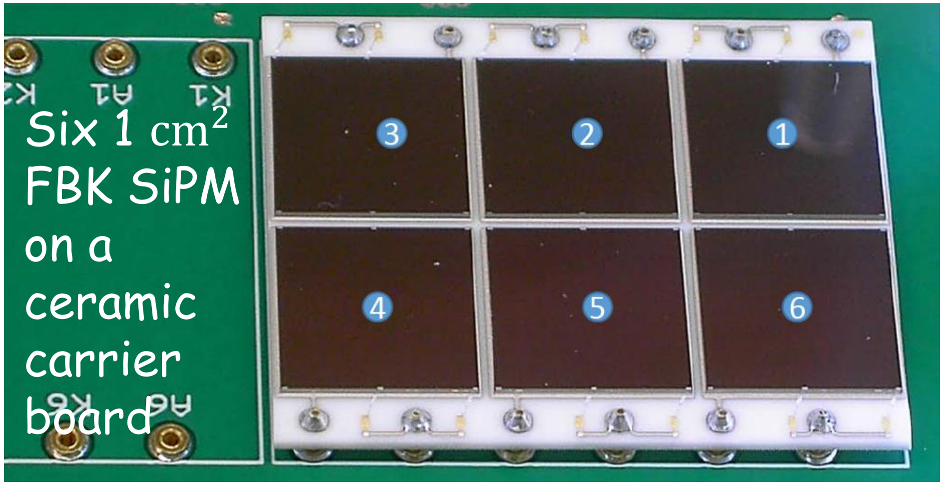


Large area SiPM readout

- **Requirements**
  - **Very large area, ~4 m^2**
  - **SPE detection capability.**
  - **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.**







Summary

- ❄ **~4 m^2 VUV sensitive SiPM will be used to detect scintillation lights in nEXO.**
- ❄ **Lots of efforts have been made to measure SiPM characterization (from different vendors) at VUV wavelength and cryogenic temperature, and the results look promising for nEXO.**
- ❄ **The surface structure of SiPM (ARC) should be optimized, in order to suppress reflections and enhance the PDE of SiPM and overall photon detection efficiency in detector.**
- ❄ **SiPMs become more and more attractive for many large scale cryogenic detectors, due to its good performance and radio-purity.**

Thank you for your attention!