Characterization of VUV-sensitive SiPMs for LXe scintillation light detection in nEXO

Michael Wagenpfeil (on behalf the nEXO collaboration)
ICASiPM, Schwetzingen, 12.06.2018

nEXO

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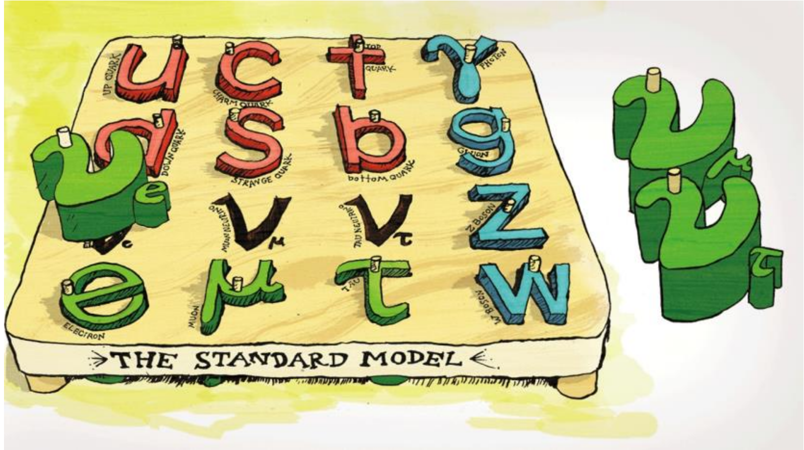
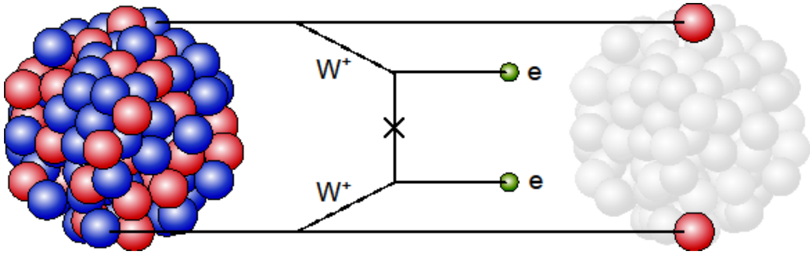
Particle Physics Motivation

Physics beyond Standard Model



- Massive neutrino doesn’t fit in the Standard Model
- Search for 0νββ-decay to decide Majorana/Dirac nature

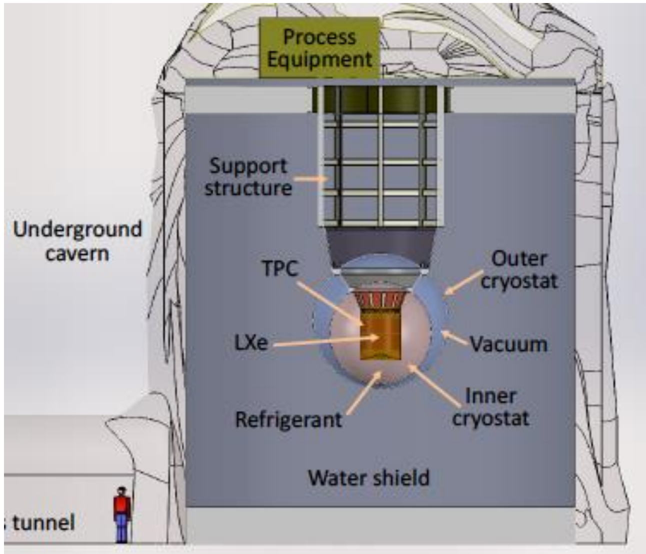
Neutrinoless double beta decay

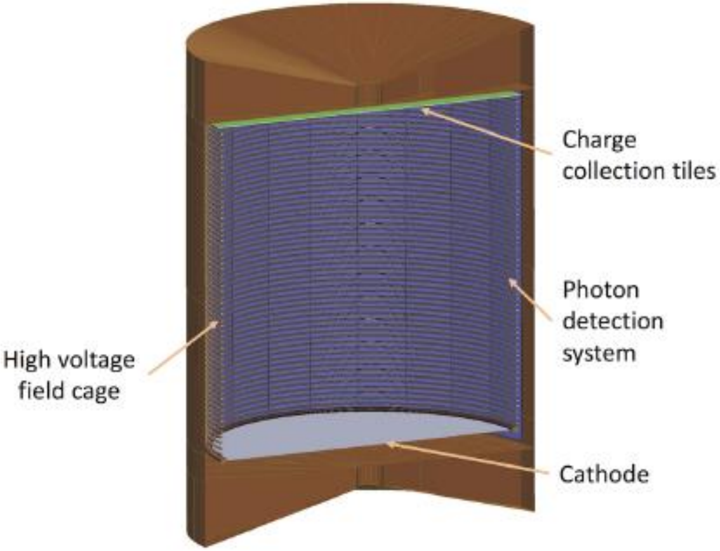


- Hypothetical weak interaction
- Possible only if neutrinos are their own anti-particles
- Current half-life limit (depending on nuclide): ~ O(10^{24-26} yr) [4]
- Further sensitivity improvement by tonne-scale detectors

The nEXO experiment [1]

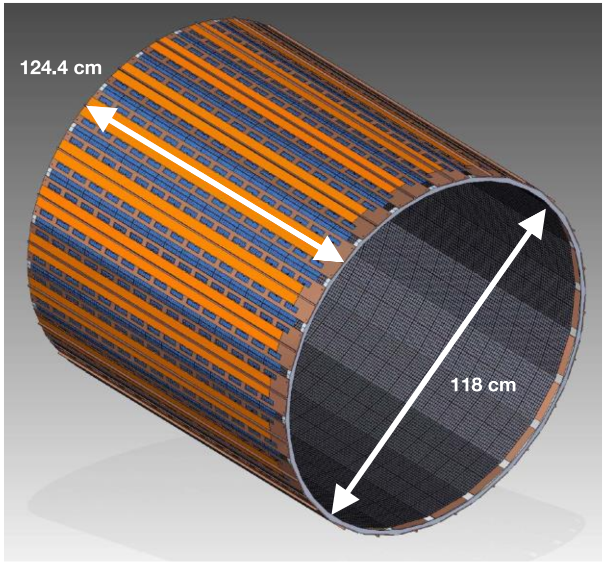
- ➢ Planned 0νββ-decay search detector
- 5 t LXe time projection chamber
- 90 % enrichment in ^{136}Xe
- Drift height ~ diameter ~ 120 cm
- Modular anode tiles on top
- Electric drift field ~400 V/cm
- 4 m^2 covered with VUV-sensitive SiPMs
- Low-radioactivity material screening [3]
- TPC immersed in cooling agent HFE
- 600 m^3 water tank as veto and shield
- Planned location: SNOLAB (6010 m.w.e.)
- ➢ 0νββ - 2νββ separation only via event energy → good energy resolution required [2]

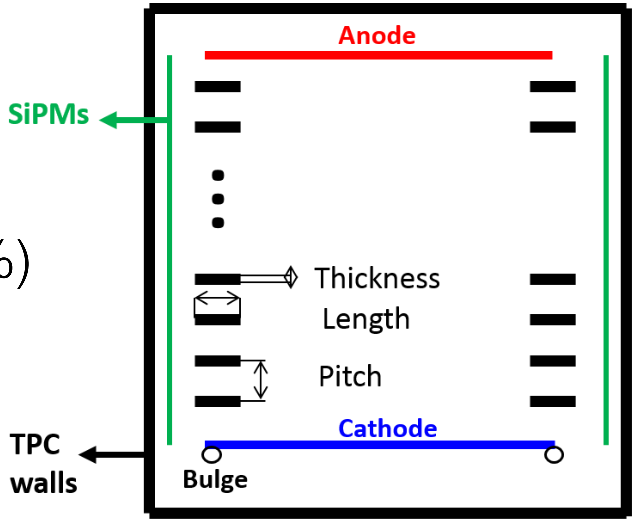




VUV-sensitive SiPMs

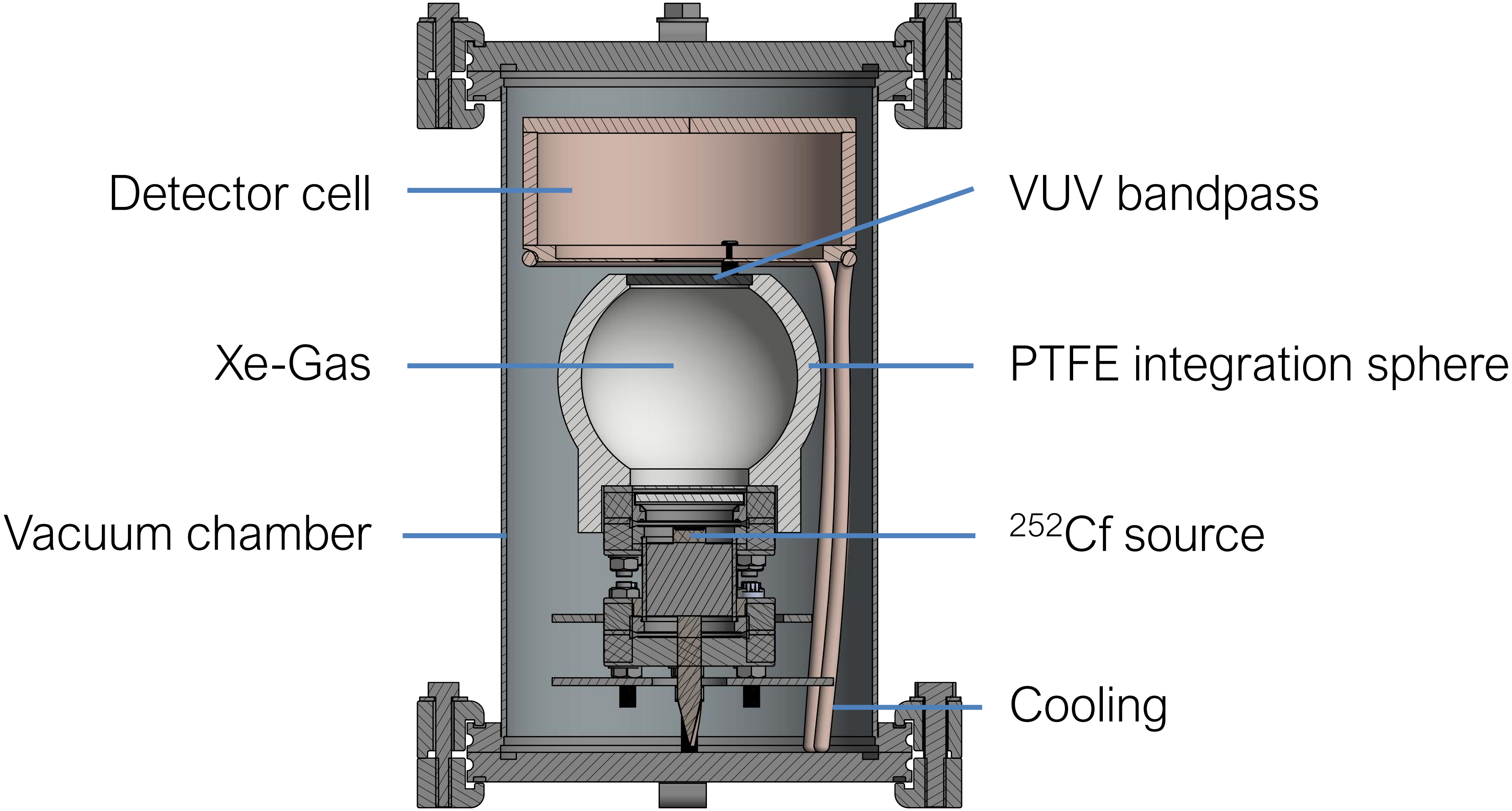
- LXe scintillation at 178 nm → VUV detectors
- SiPMs interesting:
  - Excellent single photon resolution
  - Possibility for low radioactivity level materials
  - Compact in size, low bias, high gain ~O(10^6)
- ➢ Energy resolution goal σ/E: 1 % at 2.458 MeV
- Limited by photon collection efficiency
- Collection efficiency baseline: $\gtrsim 3\%$
- Photon transport efficiency (PTE) = N_{abs} / N_0
  - Studied by GEANT4 toolkit
  - SiPM surface reflections taken into account
- SiPM photon detection efficiency (PDE > 15 %)
  - Can be measured by stand-alone setups
  - PDE = filling factor * QE (θ) * trigger-probability
- ➢ Important to understand SiPM reflectance





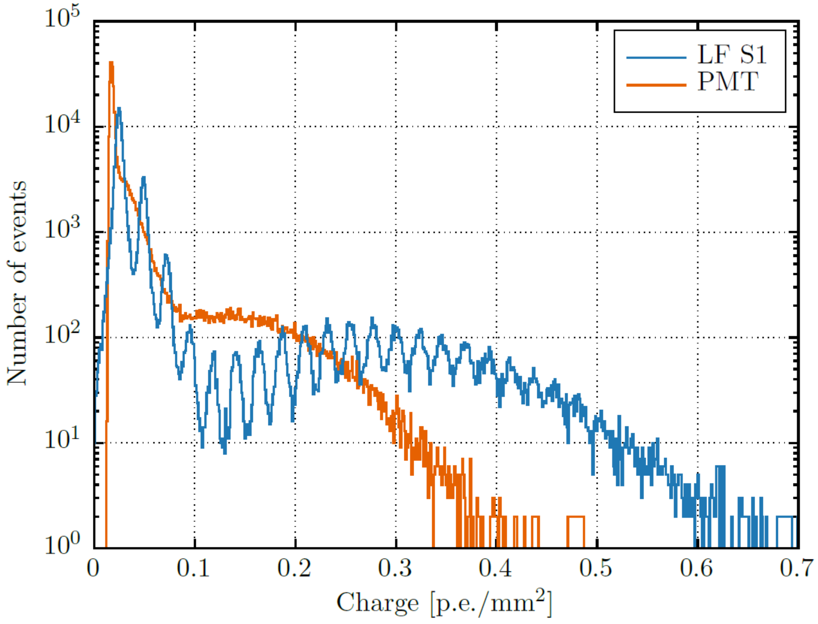
PDE

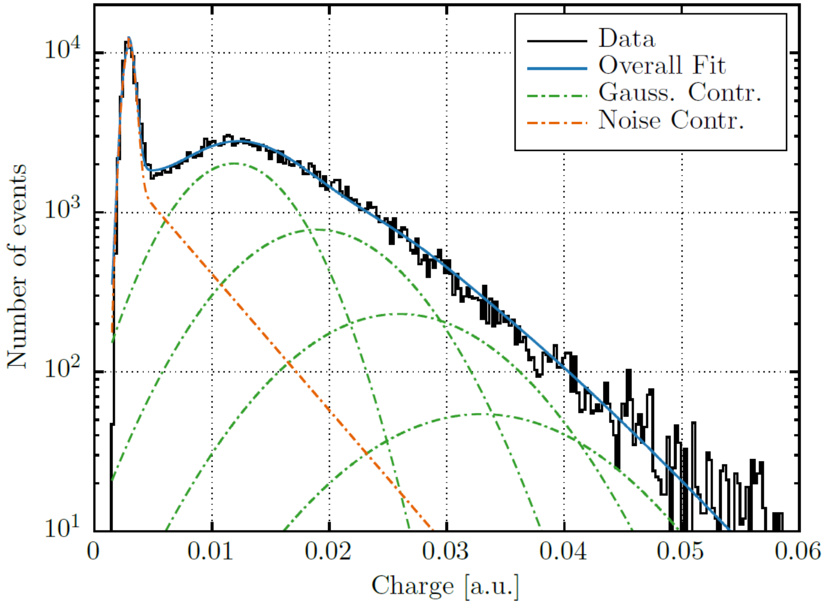
- PDE measurements at Stanford (in vacuum) [5, 6]



PDE

- Measure ^{252}Cf spectra for PMT and SiPM via integrated waveforms
- Proper description of PMT gain crucial
- Transfer PMT detection efficiency to SiPM PDE via spontaneous fission peak of ^{252}Cf
- SiPM in this study: FBK 2016 LF, STD

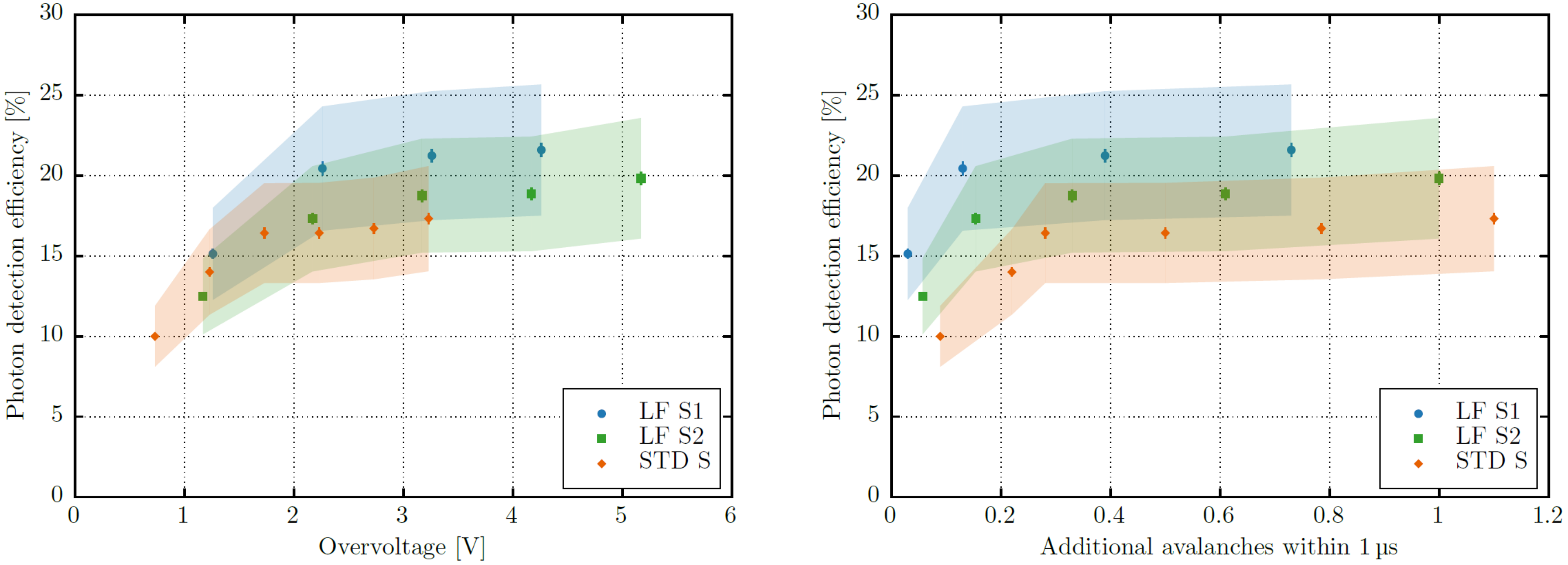




PDE

- PDE vs. overvoltage for two FBK LF and one FBK STD device
- PDE increases with bias voltage
- So does mean number of correlated avalanches

➢ nEXO requirements fulfilled



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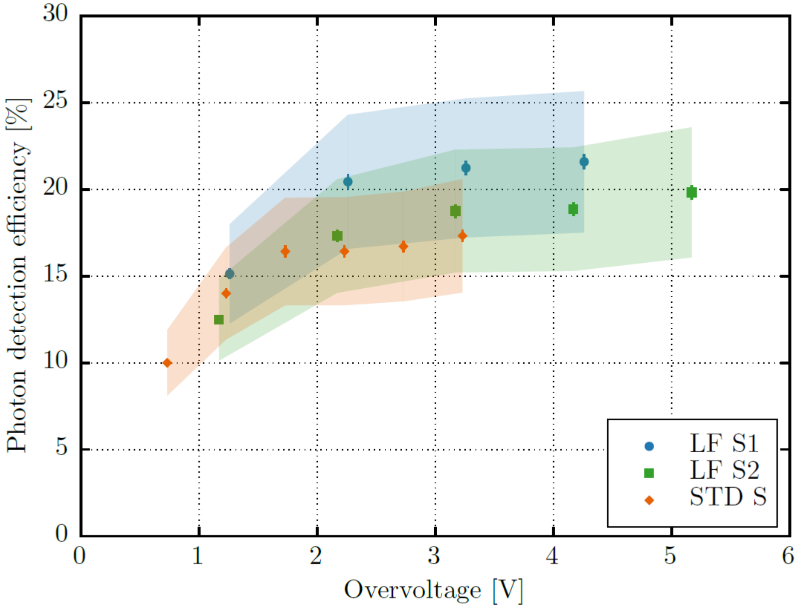
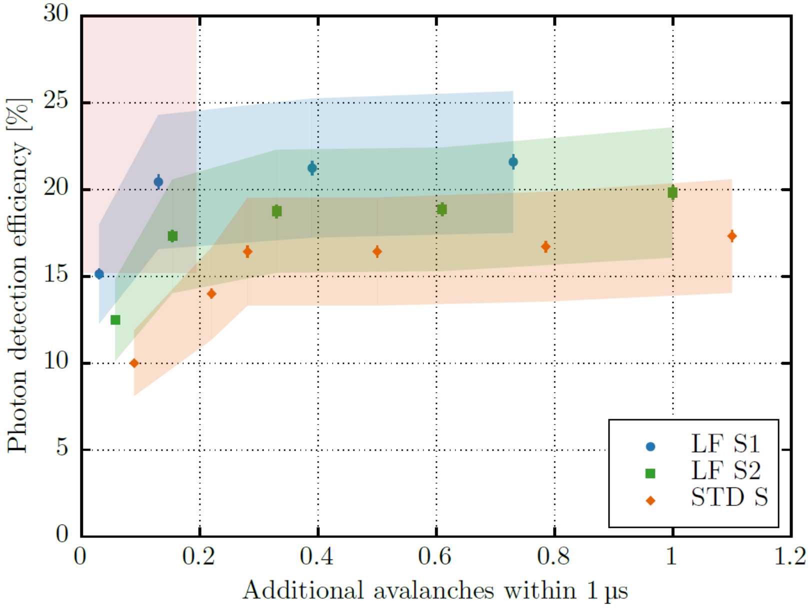
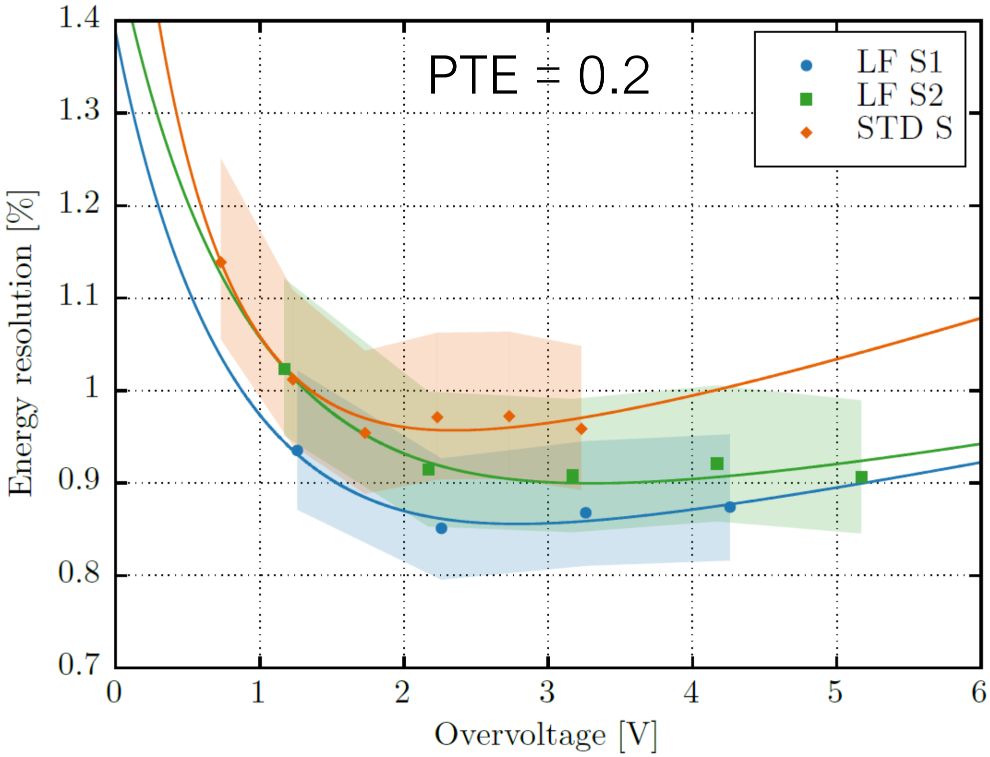




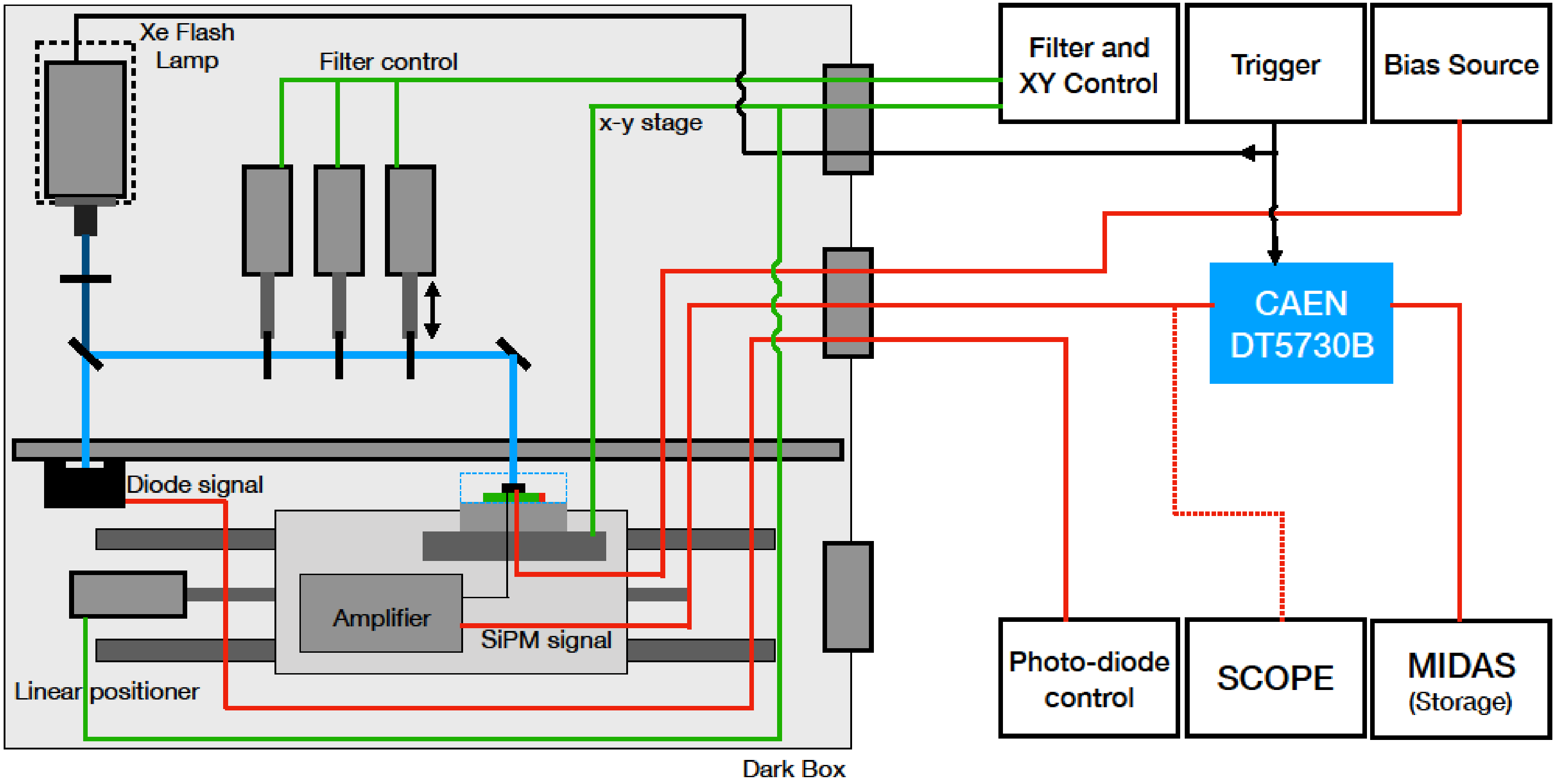
PDE

- Noise in light channel dominant for nEXO energy resolution
- ➢ Determine fluctuation of energy estimator based on scintillation and ionization yield
- Electronics noise neglected
- Consider high reflectance coating for cathode and field shaping rings
- Publication: [6]

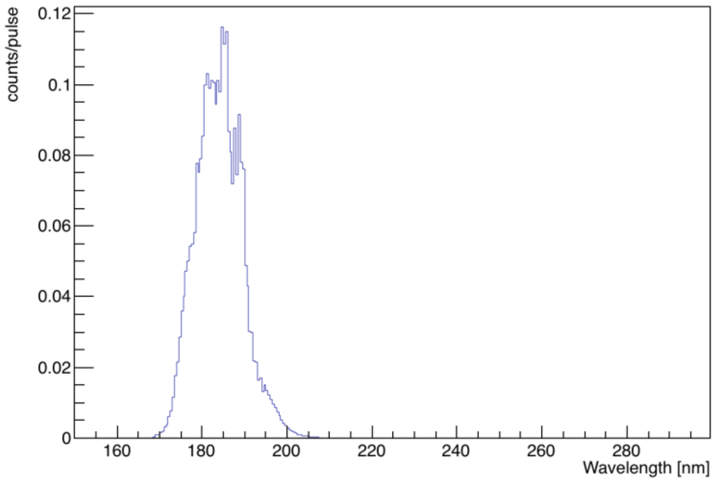


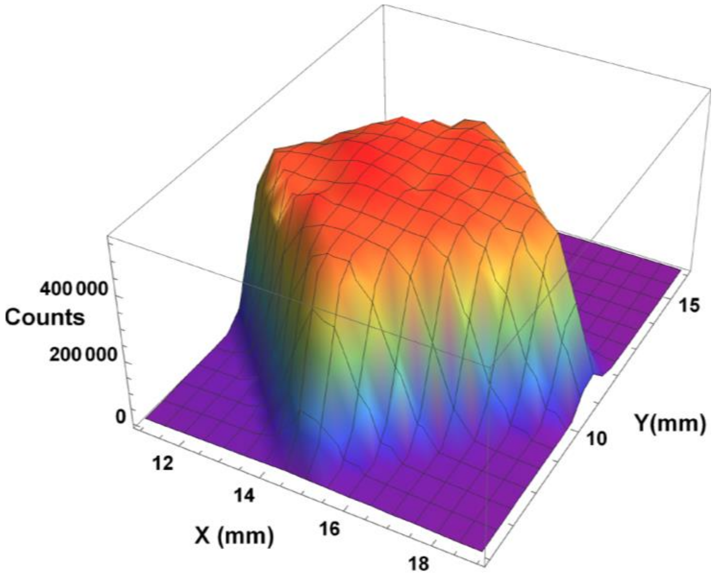
PDE

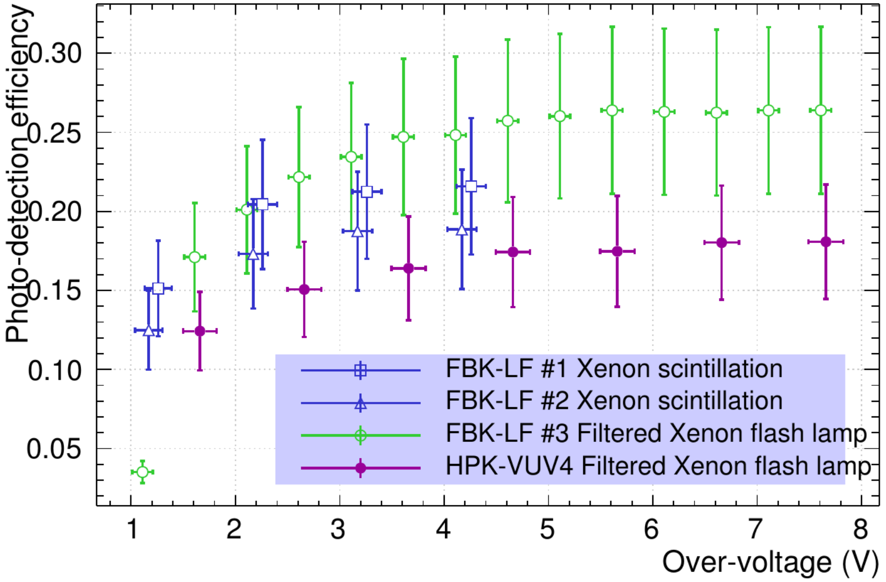
- PDE measurements at TRIUMF, Vancouver



PDE





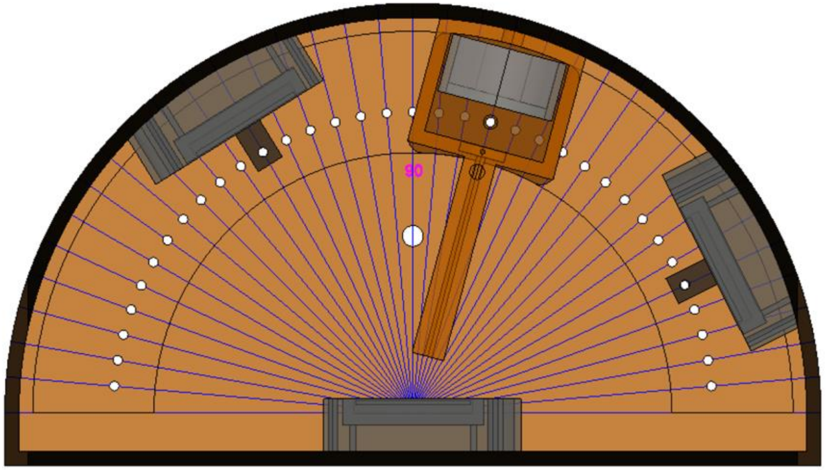


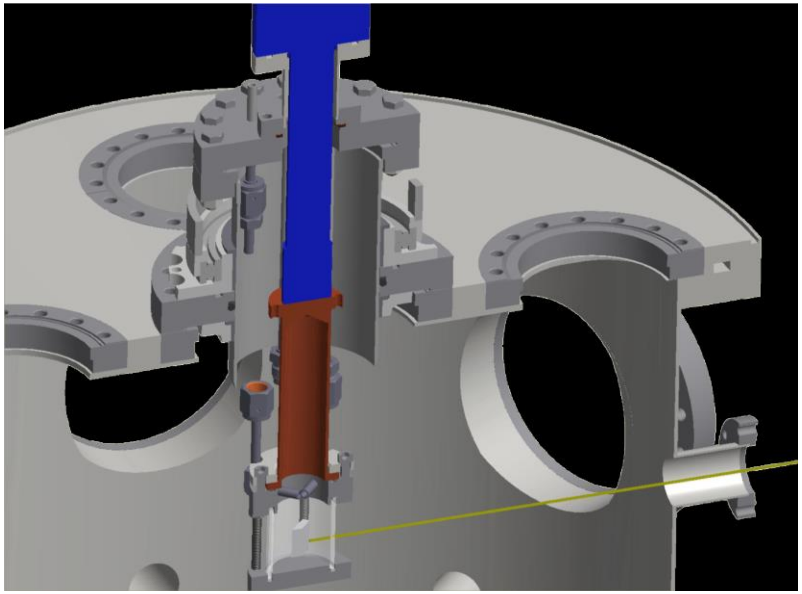
- PDE determined via mean number of detected photo-electrons
- Corrected for dark noise
- Devices: FBK 2016 LF & Hamamatsu VUV4
- Stanford: Xenon scintillation light TRIUMF: Xenon flash lamp

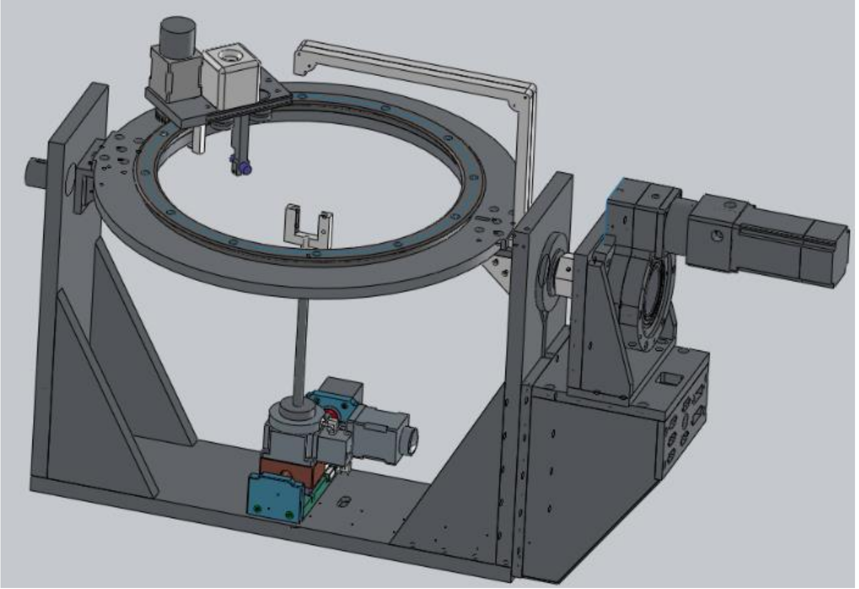
Reflectance

Several LXe test setups

- ECAP in collaboration with U. Münster (LXe, monochrome)
- IHEP, Beijing (Vac., monochrome)
- LIXO, UA (LXe, scintillation)



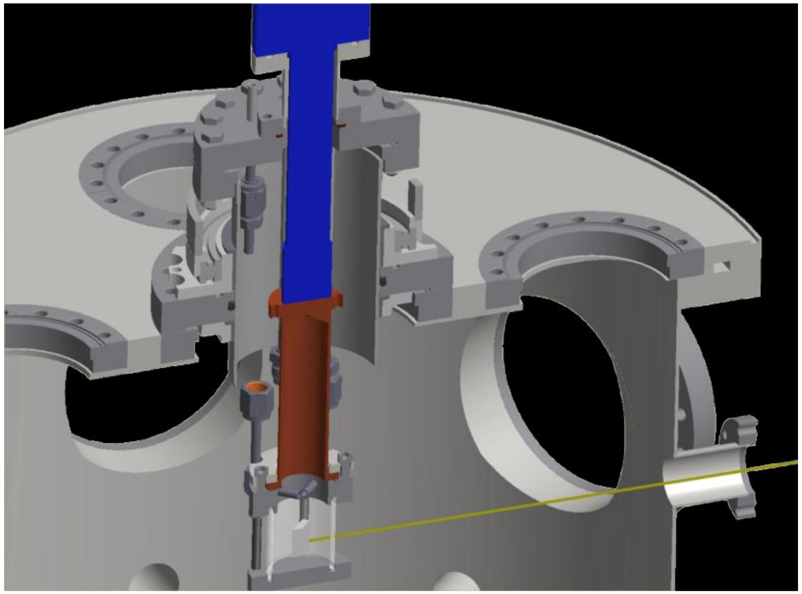


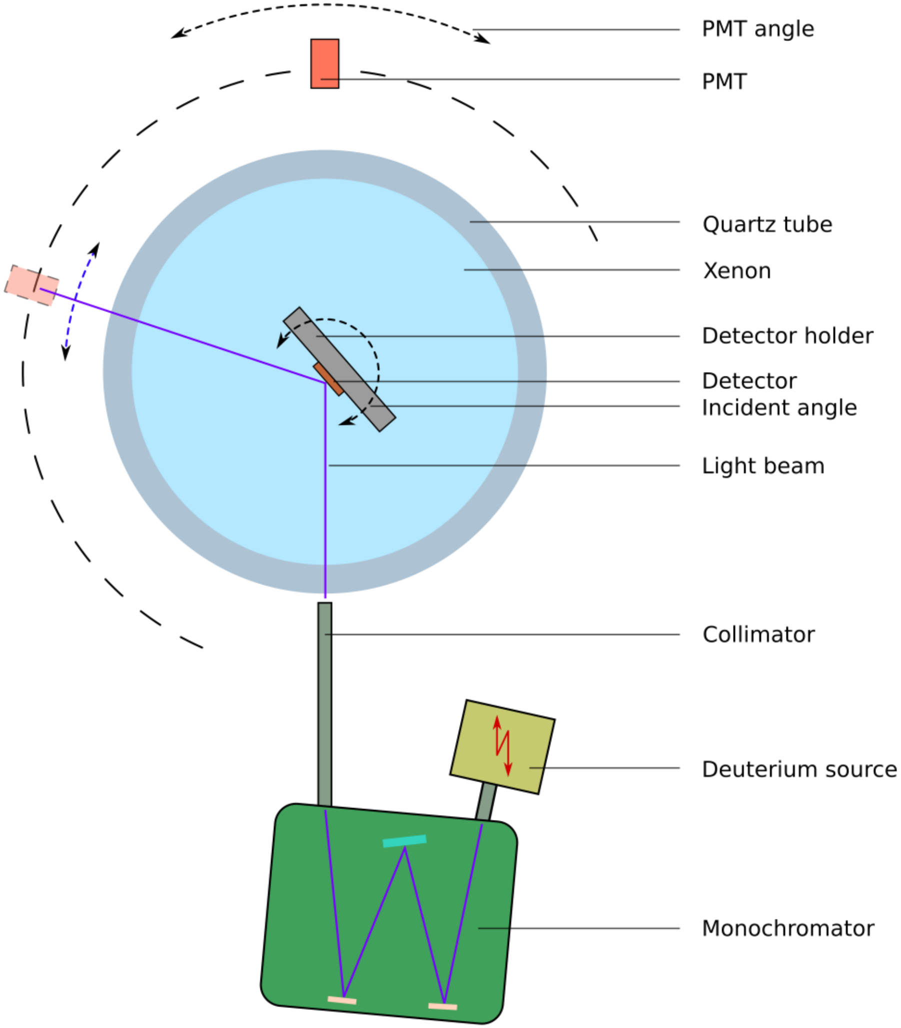


Reflectance – ECAP/Münster

U. Münster

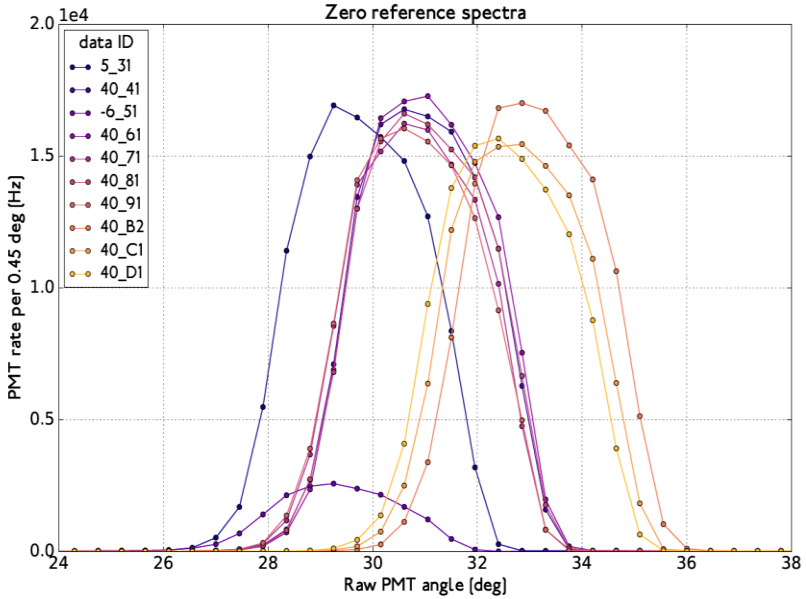
- Test setup for XENON coll.
- SiPM in LXe in quartz tube
- 178 nm photons
- First measurement of VUV-reflectance of SiPMs in LXe





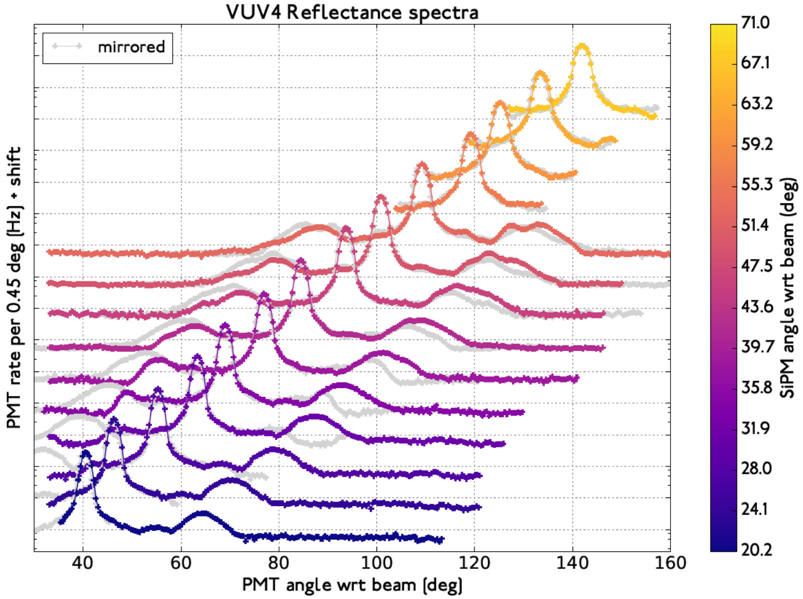
Reflectance – ECAP/Münster

Zero reference peaks



- Reference peak integral stable within measurement run ~O(d)
- PMT dark rate stable

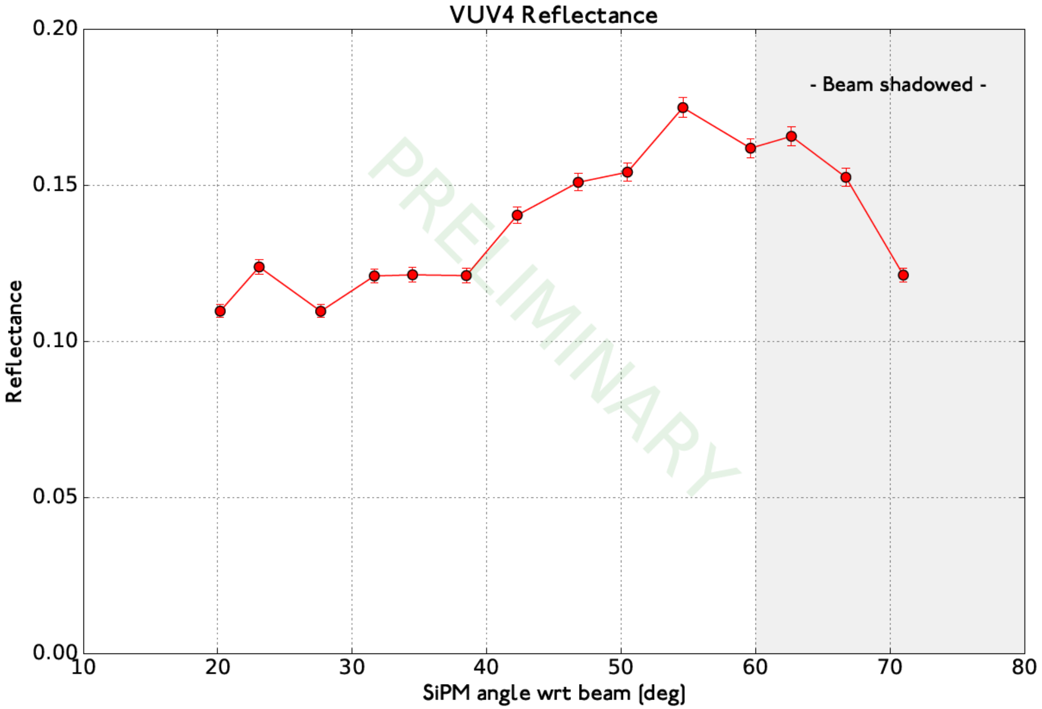
Reflectance angular distributions



- Strong specular reflections
- Side-peaks around specular peaks due to microstructure

Reflectance – ECAP/Münster

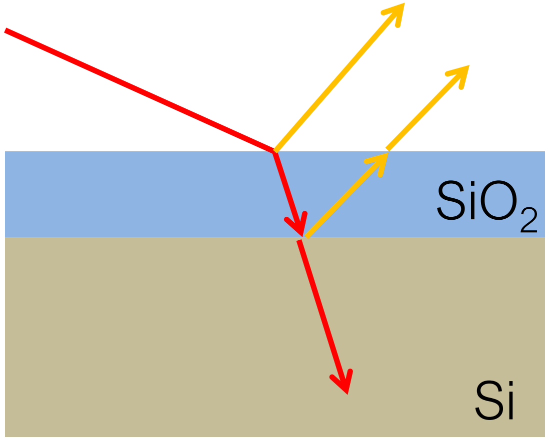
- Calculate reflectance via ratio of peak integrals
- Subtract PMT dark noise
- Measurements for 14 angles of incident
- Beam shadowing at large incident angles
- Statistical uncertainties only



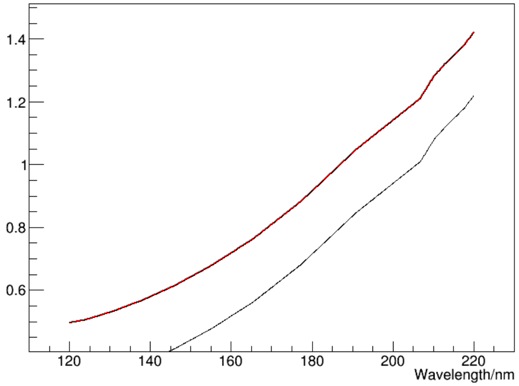
Reflectance – IHEP

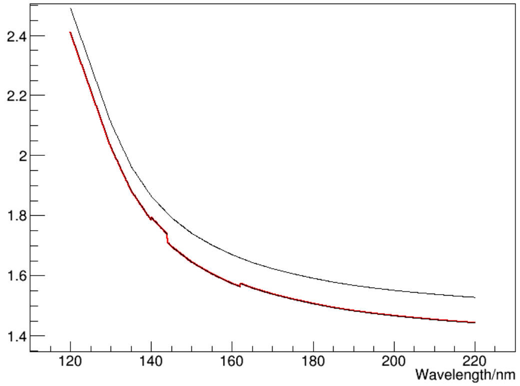
IHEP setup, Beijing

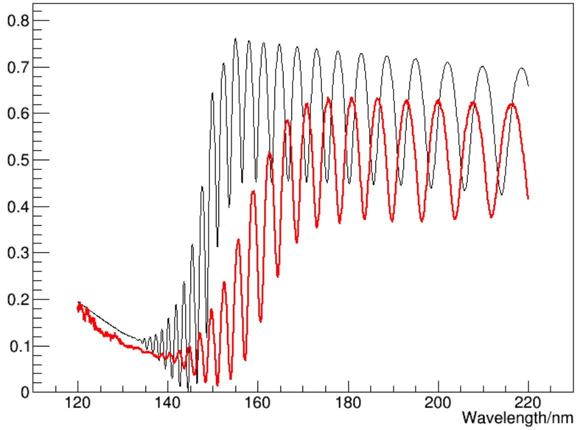
- Two setups at IOE for specular and diffuse reflectance measurements in vacuum
- Silicon waver, FBK, 1.5 µm SiO_2 on top
  - R vs AoI for wavelengths within 128-200 nm
  - R vs. wavelength for different AoI
- Reflectance calculation from optical theory for simple Si – SiO_2 – vacuum stack
- Comparison with measurement yields refractive index n and extinction coefficient k of Si and SiO_2

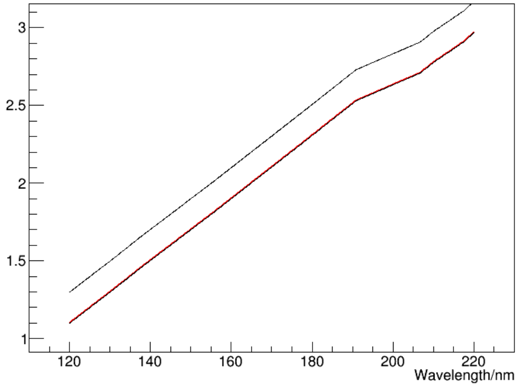


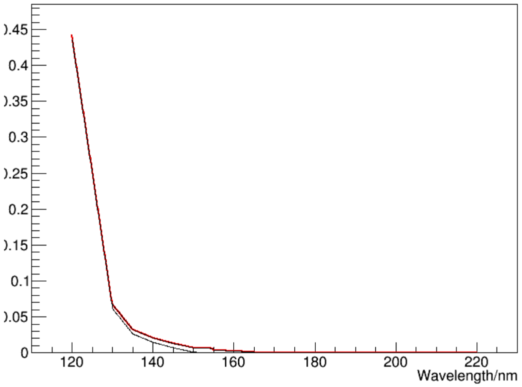
Reflectance – IHEP


Si_n

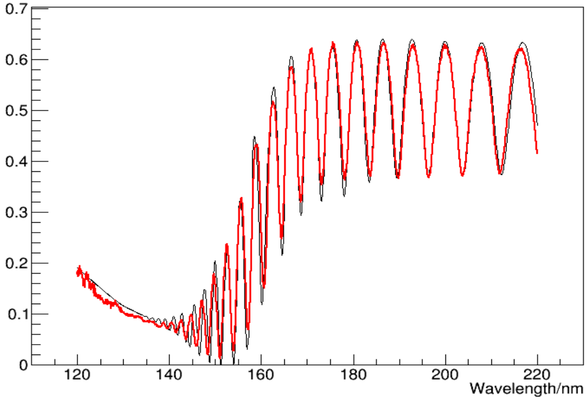

SiO2_n




Si_k


SiO2_k

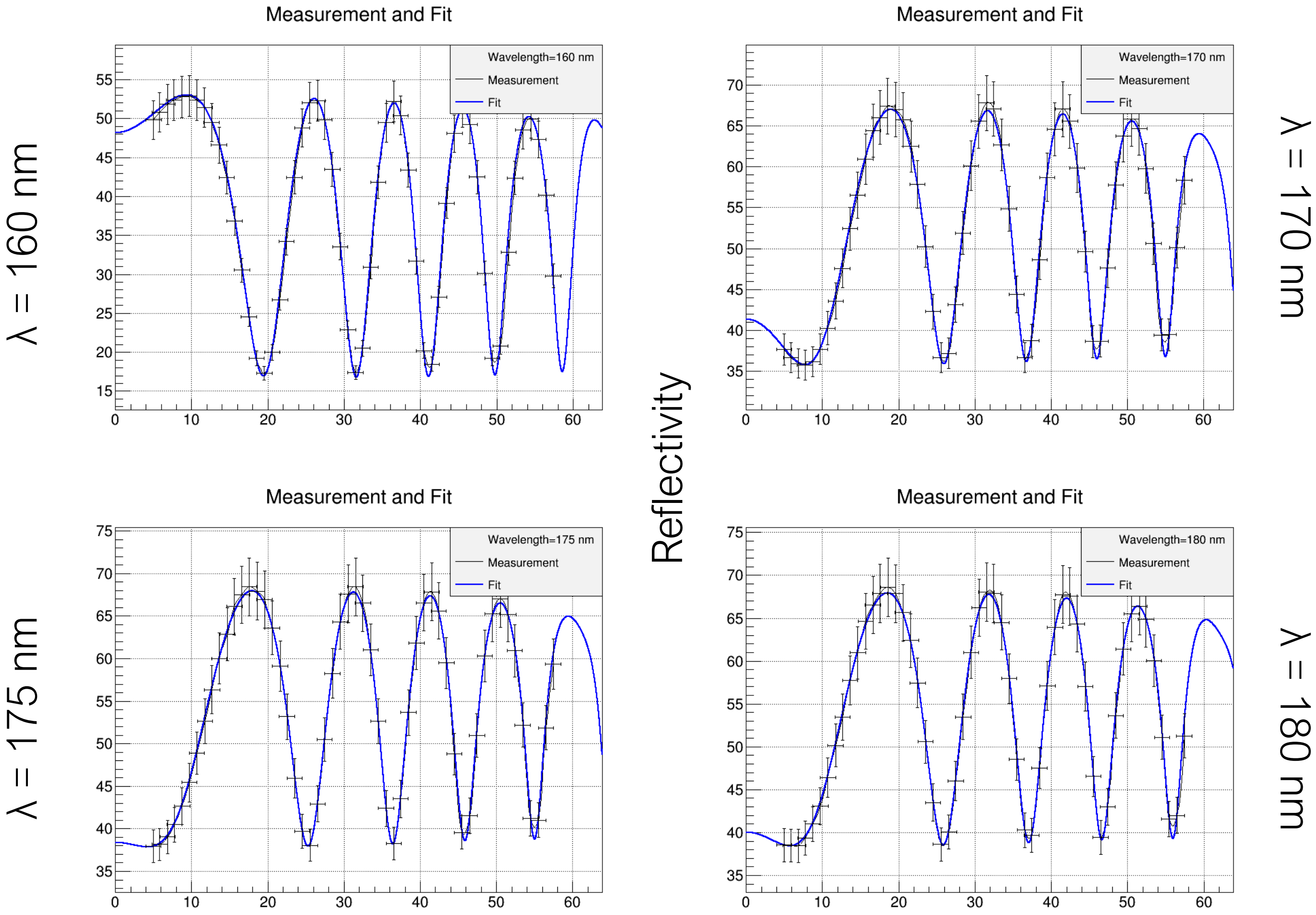
Reflectance



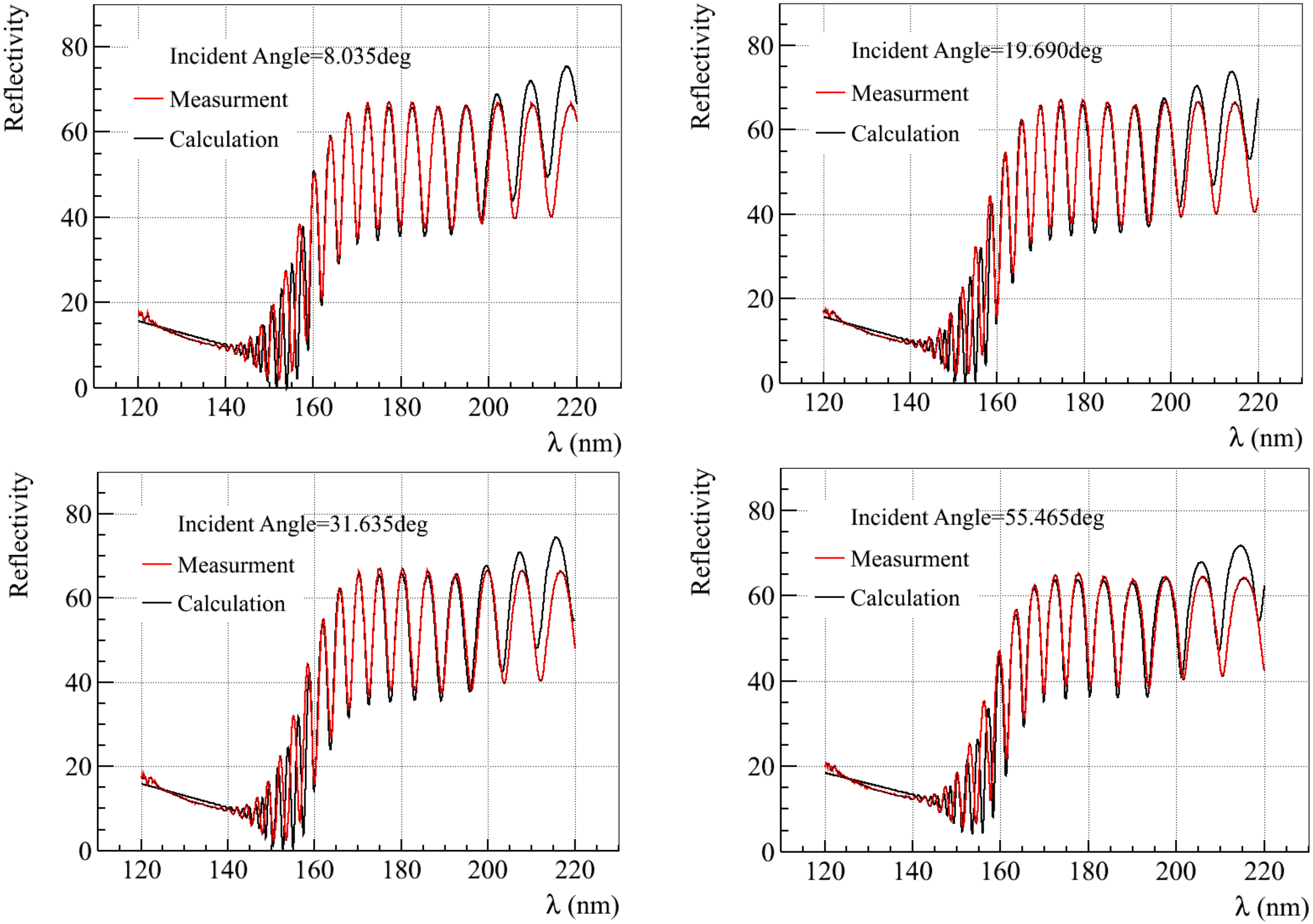
Red: Tuned based on measurements
Black: from literature

Black: Fresnel simulation
Red: Measurement
AOI: 10°

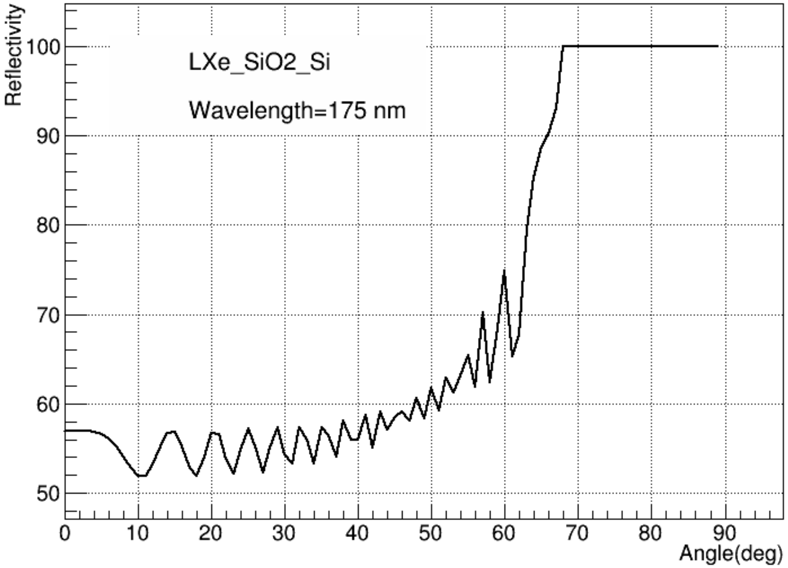
Reflectance – IHEP

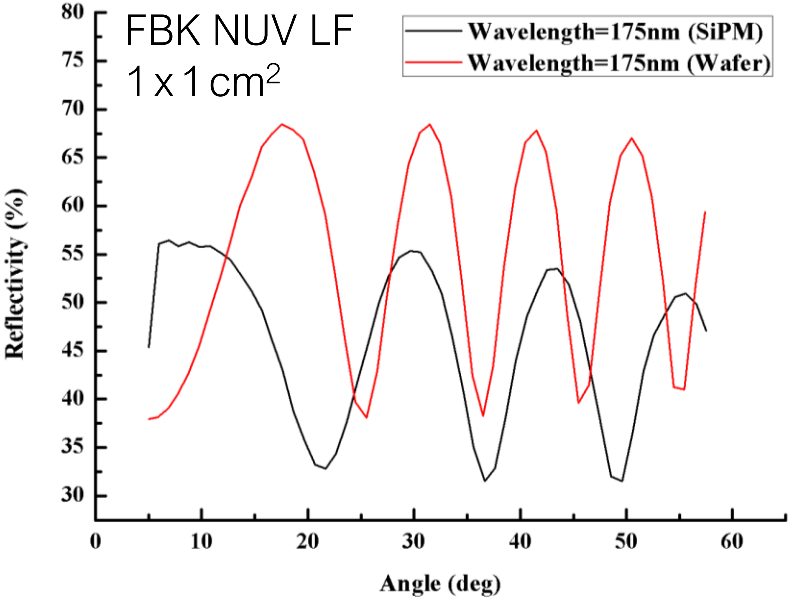


Reflectance – IHEP



Reflectance – IHEP

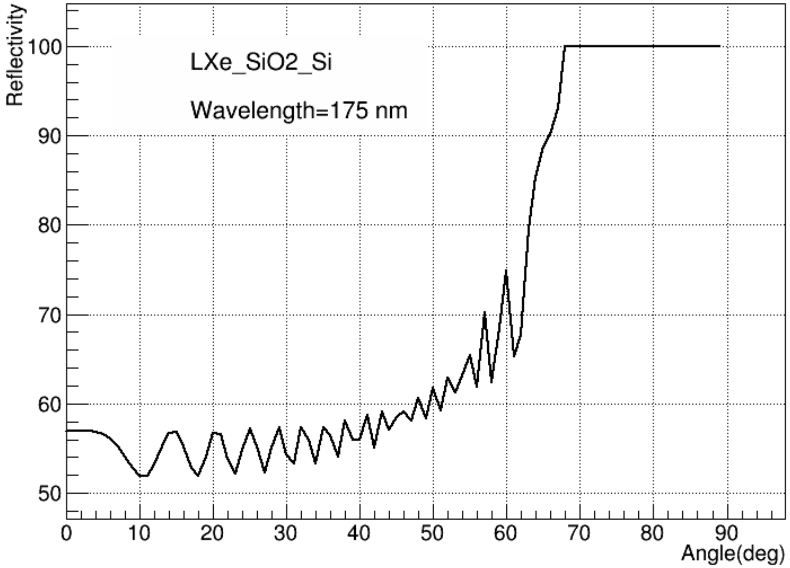


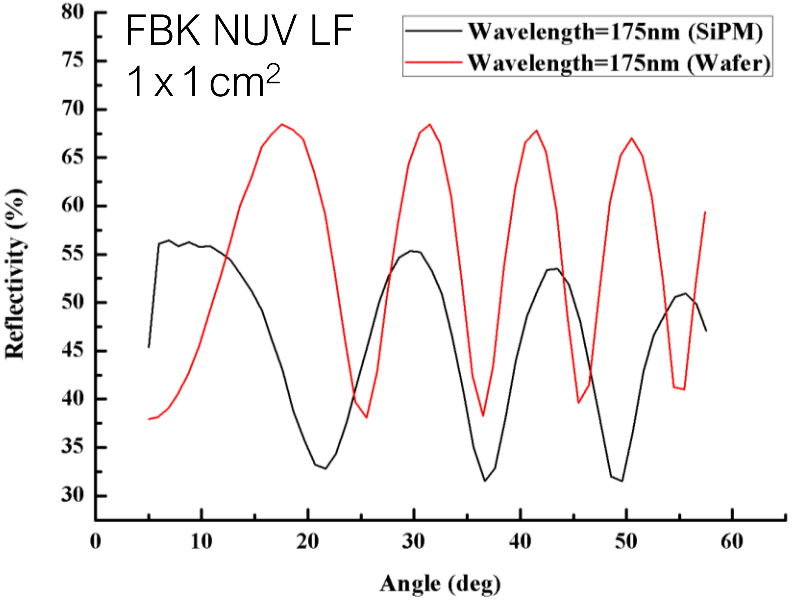


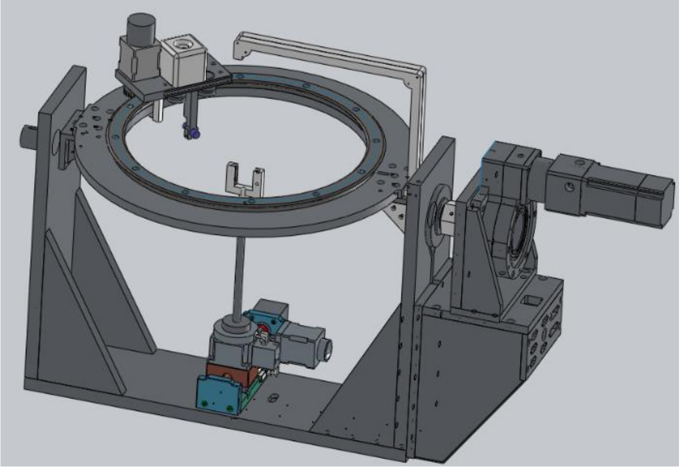
Device	Specular (177 nm, 10°)	Diffuse (193 nm)
FBK-VUV-STD	35%	11.5%
FBK-VUV-LF	40%	12.3%
FBK-RGB	38%	17%
FBK wafer	50%	0.16%

- Complicated microstructure on SiPM surface
- SiPMs have more diffuse reflections compared to waver

Reflectance – IHEP





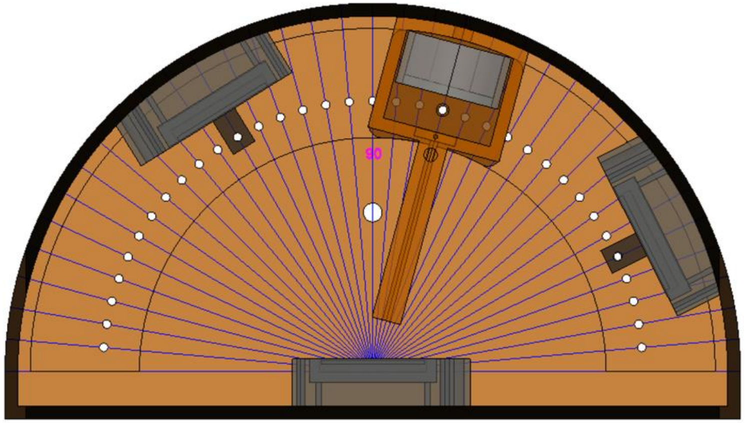


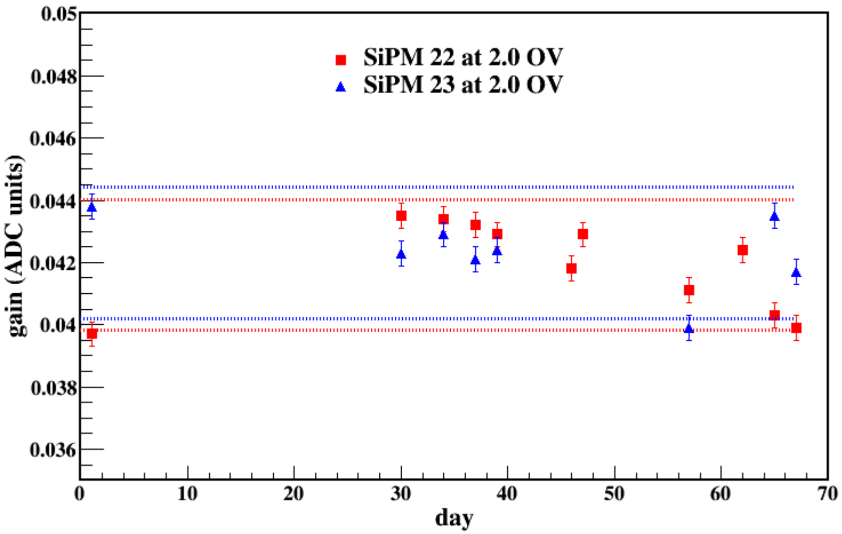
- Complicated microstructure on SiPM surface
- SiPMs have more diffuse reflections compared to waver

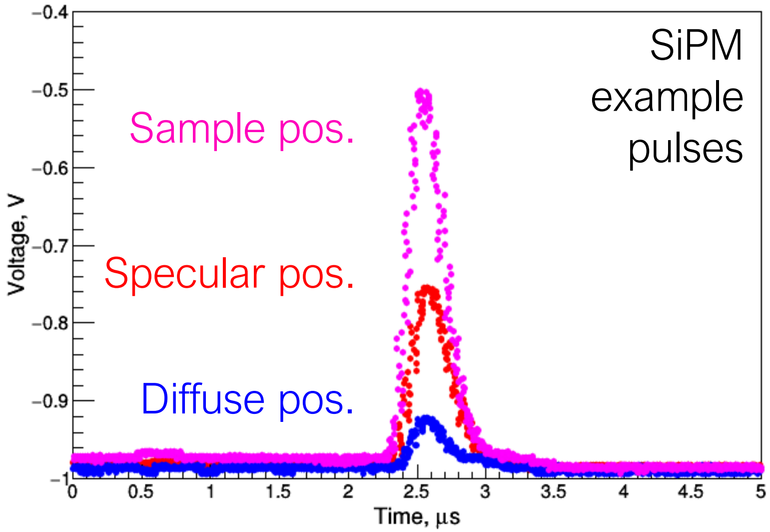
Reflectance – LIXO

LIXO (UA)

- Cu semi-cylinder filled with LXe
- ^{252}Cf source for LXe scintillation light
- SiPMs as reflection sample, specular and diffuse reflectance monitor
- Reflectance measurements will start later in 2018



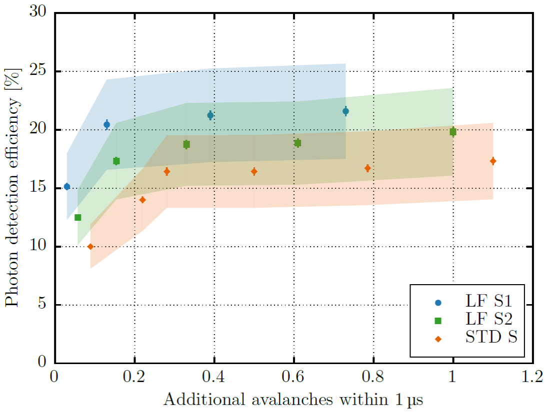


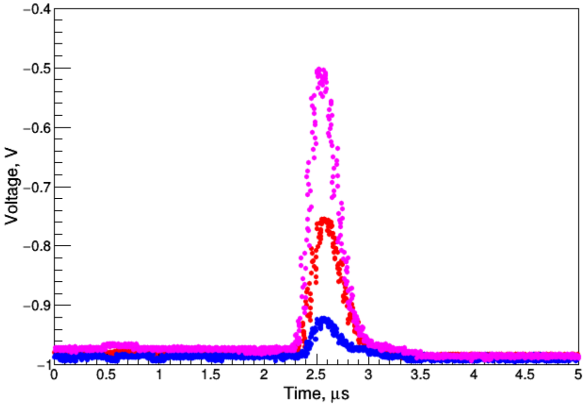


Summary

- Characterization of VUV-sensitive SiPM candidates in full progress
- Dedicated PDE studies at low temperature
- nEXO PDE specifications are achievable
- VUV-sensitive SiPM array for first test TPC

- First VUV-reflectance measurements of SiPMs in LXe accomplished
- Many more setups in preparation to understand SiPM reflectance behavior





Literature

nEXO:

[1] Al Kharusi et al. [nEXO coll.], arXiv:1805.11142 (2018)

Simulation and sensitivity:

[2] J.B. Albert et al. [nEXO coll.], arXiv:1710.05075v1 (2017)

[3] D. S. Leonard et al. [EXO-200 coll.], *Nucl. Instrum. Meth.* **A871**, 169 (2017)

[4] J.B. Albert et al. [EXO-200 coll.], *Phys. Rev. Lett.* **120**, 072701 (2018)

VUV-sensitive SiPM:

[5] A. Jamil et al. [nEXO coll.], arXiv: 1806.02220 (2018)

[6] I. Ostrovsky et al., *IEEE Trans. Nucl. Sci.* **62** (4) (2015) 825-1836

The nEXO collaboration

nEXO

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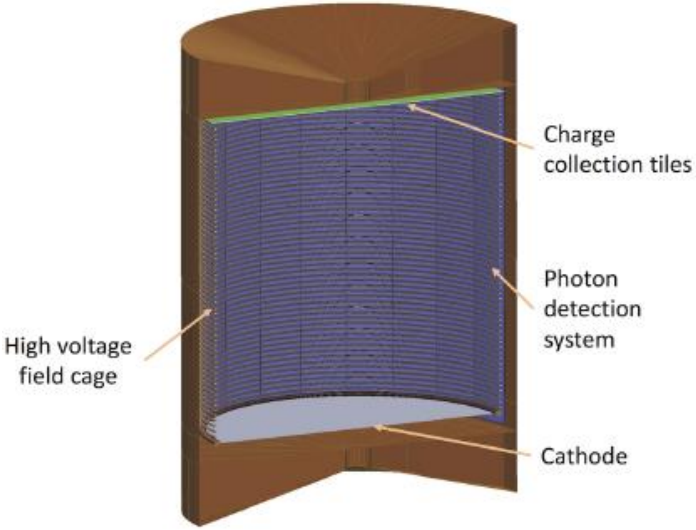
Backup

The nEXO experiment

➢ Need for tonne-scale detectors!

Parameters for performance of nEXO:

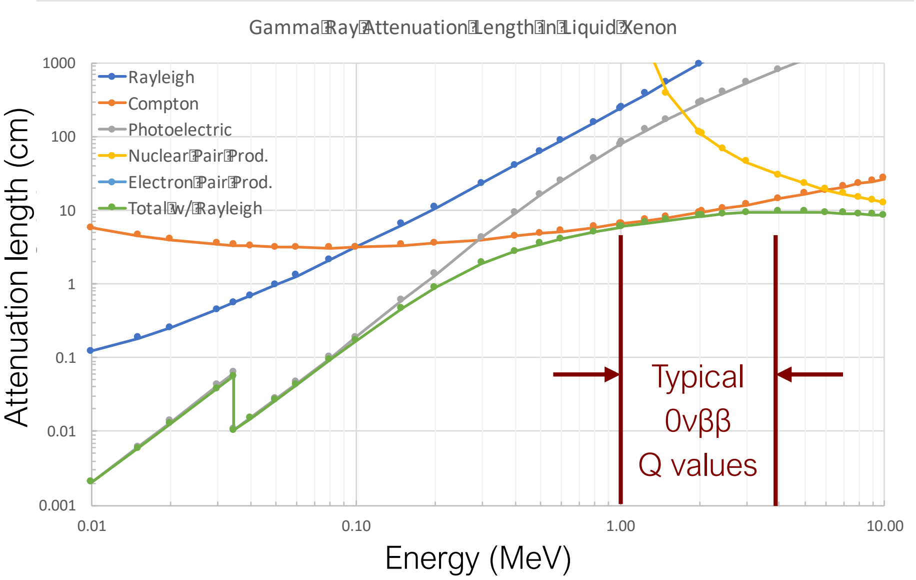
- Experience from EXO-200
- Inherent low-background design
  - ^{232}Th and ^{238}U traces of great concern
  - ^{136}Xe 2νββ
  - ^{137}Xe from neutron-capture in ^{136}Xe
- Multi-parameter measurement capability
  - Energy (ionization and scintillation)
  - Standoff distance
  - Multiplicity: Single Site and Multi Site
  - Particle type



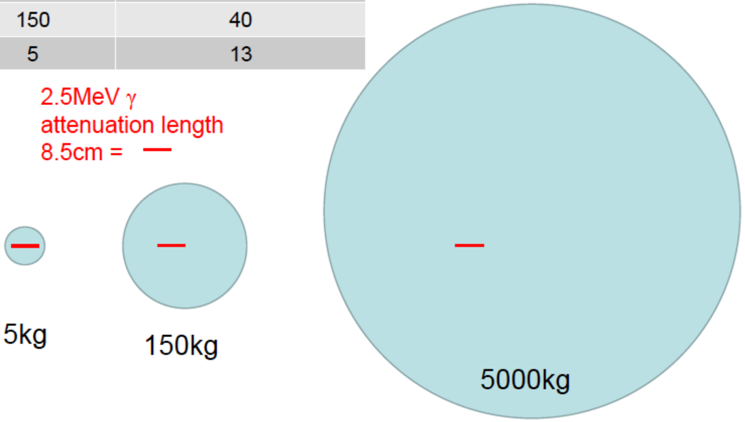
Component	Nuclides Simulated	Material	Mass or Surface Area
Outer Cryostat	^{238}U, ^{232}Th, ^{40}K	Carbon Fiber	1774 kg
Inner Cryostat	^{238}U, ^{232}Th, ^{40}K	Carbon Fiber	338 kg
Inner Cryostat Liner	^{238}U, ^{232}Th	Titanium	161.4 kg
HFE	^{238}U, ^{232}Th	HFE-7000	32700 kg
TPC Vessel	^{238}U, ^{232}Th	Copper	553.4 kg
Cathode	^{238}U, ^{232}Th	Copper	26.0 kg
Field Rings (FR)	^{238}U, ^{232}Th	Copper	73.2 kg
FR Support Leg	^{238}U, ^{232}Th, ^{40}K	Sapphire	0.94 kg
FR Support Spacer	^{238}U, ^{232}Th, ^{40}K	Sapphire	2.21 kg
SiPM	^{238}U, ^{232}Th, ^{40}K	SiPM	4.69 kg
SiPM Support	^{238}U, ^{232}Th	Copper	136.4 kg
SiPM Module Backing	^{238}U, ^{232}Th	Quartz	3.2 kg
SiPM Electronics	^{238}U, ^{232}Th	ASICs	2.04 kg
SiPM Glue	^{238}U, ^{232}Th, ^{40}K	Epoxy	0.12 kg
SiPM Cables	^{238}U, ^{232}Th	Kapton	1×10^4 cm^2
Charge Module Cables	^{238}U, ^{232}Th	Kapton	1×10^4 cm^2
Charge Module Electronics	^{238}U, ^{232}Th	ASICs	1.0 kg
Charge Module Glue	^{238}U, ^{232}Th, ^{40}K	Epoxy	0.35 kg
Charge Module Support	^{238}U, ^{232}Th	Copper	11.7 kg
Charge Module Backing	^{238}U, ^{232}Th	Quartz	0.94 kg
TPC LXe Volume	^{137}Xe, ^{222}Rn, $2\nu\beta\beta$, $0\nu\beta\beta$	Xenon	4038 kg
Outer LXe Volume	^{137}Xe, ^{222}Rn, $2\nu\beta\beta$, $0\nu\beta\beta$	Xenon	1071 kg

The nEXO experiment

- ➢ Need for tonne-scale detectors!
- ● γ interaction cross section
- ● Shielding ββ decay detectors is difficult
- ● Detector size of tonne-scale detectors exceeds γ interaction length
- ➢ It pays to be homogeneous while having event topology capability



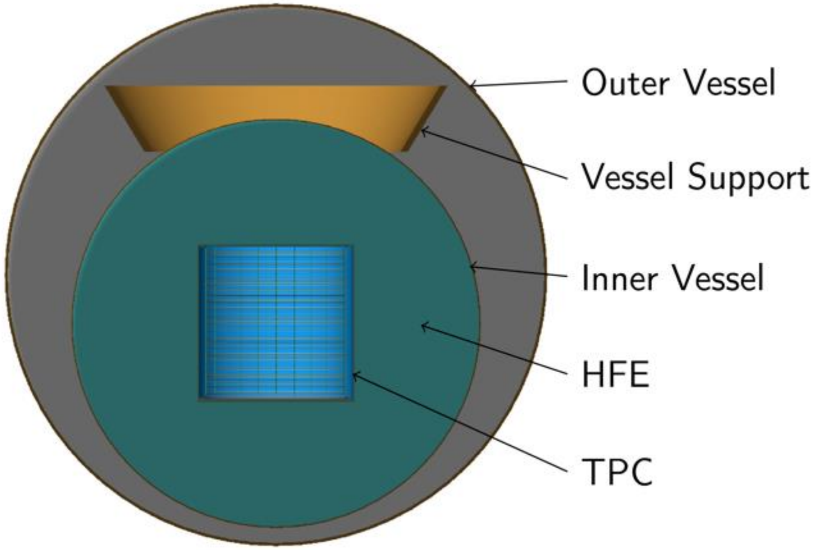
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

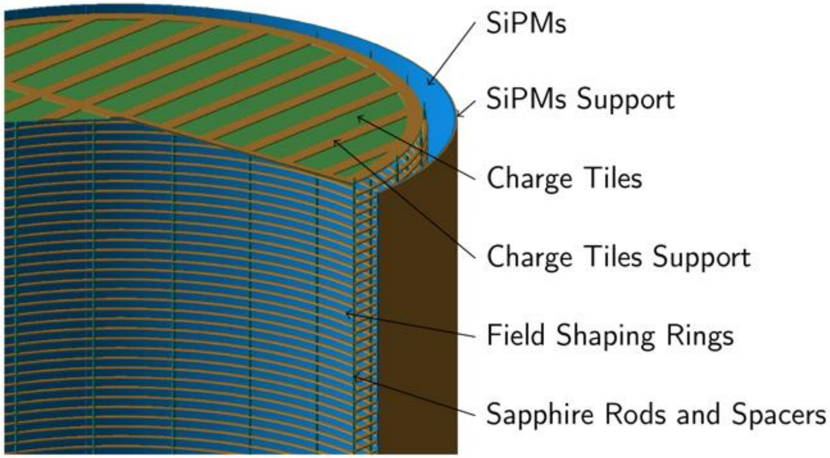

2.5MeV γ attenuation length 8.5cm = —

Sensitivity

Simulation

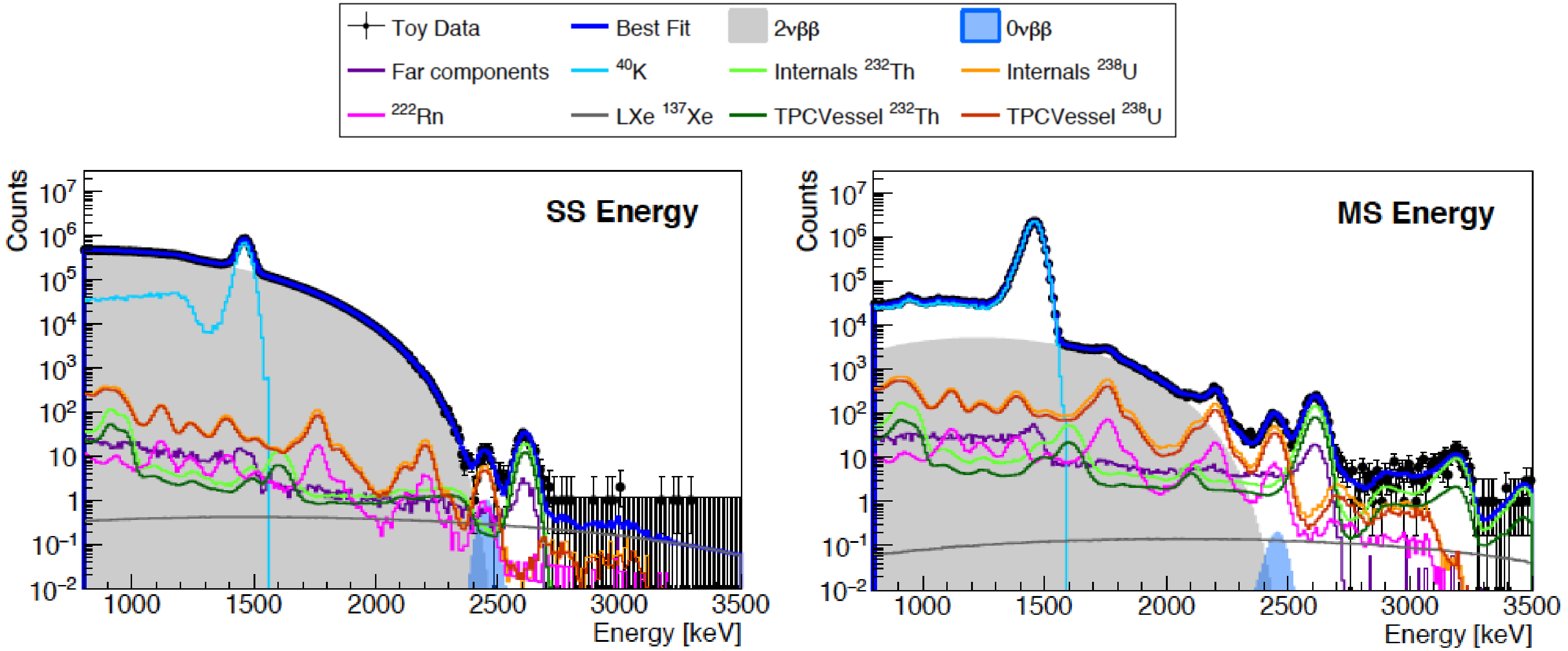
- GEANT4 geometry model
- 2νββ and background MC event generation
- Energy deposition algorithm: 3 mm cluster
- Fiducial cut (outer 1.5 cm)
- Energy resolution estimation: $\sigma/Q_{\beta\beta} = 1\,\%$
- Light collection efficiency ~ 3 %
- Electron lifetime of 10 ms sufficient
- Post-simulation reconstruction with help of NEST





Sensitivity

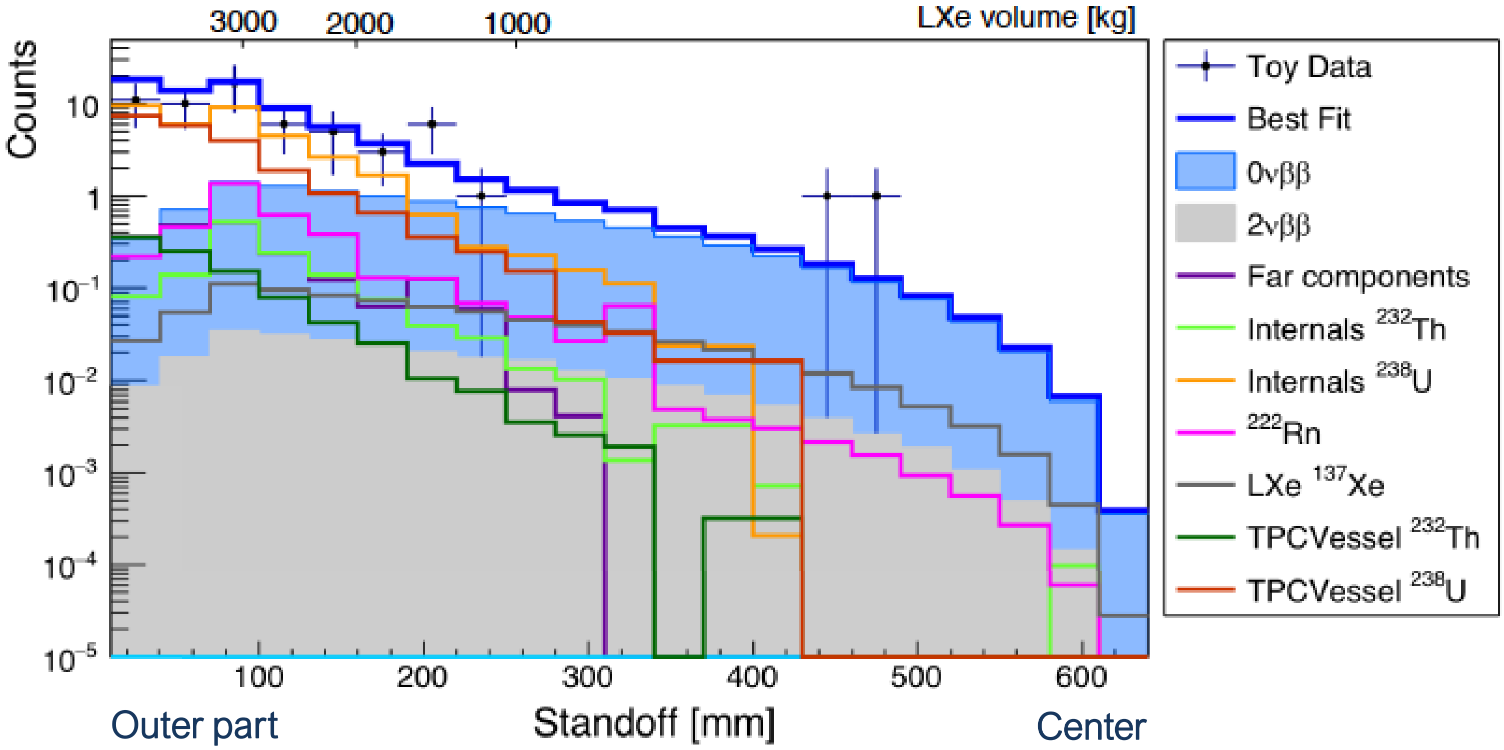
- Frequentist approach to sensitivity calculation
- Ensemble of toy experiments using radioassay values
- Simultaneous Log-Likelihood fit of energy, standoff distance and multiplicity



(0νββ half-life of 5.7×10^{27} y and 10 years live time)

Sensitivity

- Cut to SS and FWHM around $Q_{\beta\beta}$ highlights BG of greatest concern
- Power of homogeneous detector and multi-parameter fits
- Inner LXe part provides sensitivity while outer part constrains BG



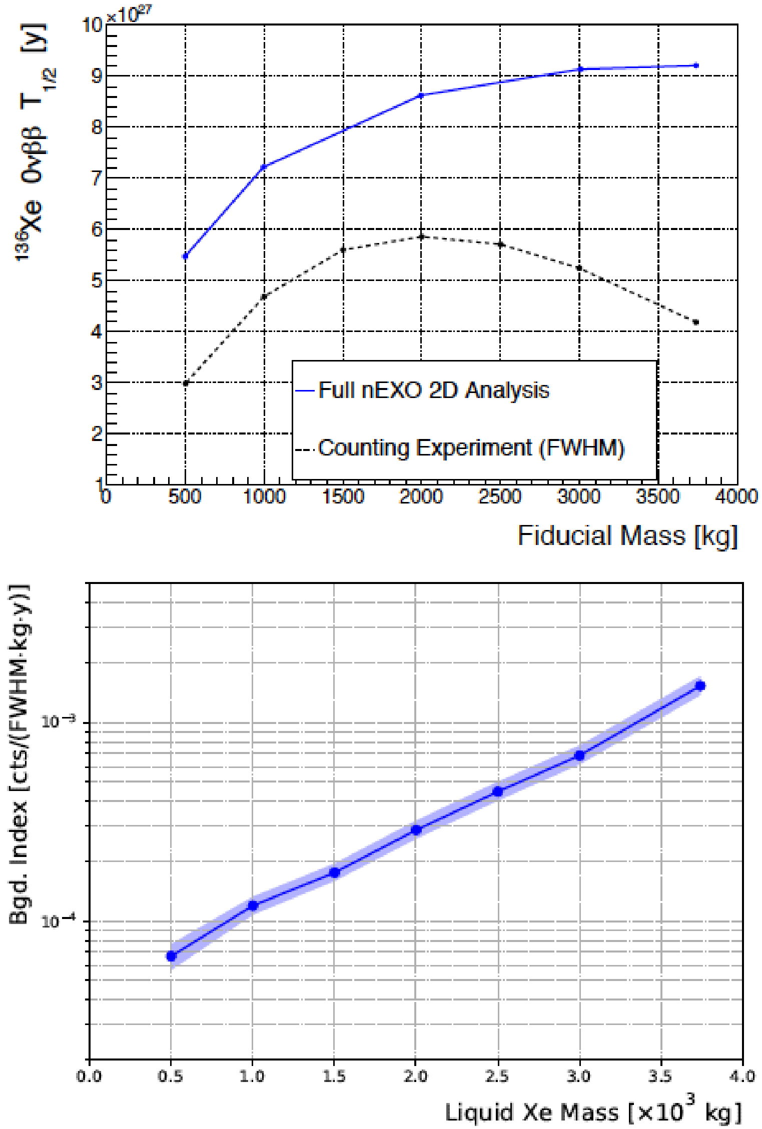
(0νββ half-life of 5.7×10^{27} y and 10 years live time)

Sensitivity

- Power of homogeneous detector and multi-parameter fits
- Inner LXe part provides sensitivity while outer part constrains BG
- No single background index in nEXO but position-dependent function
- BG rate prediction (inner 2000 kg):

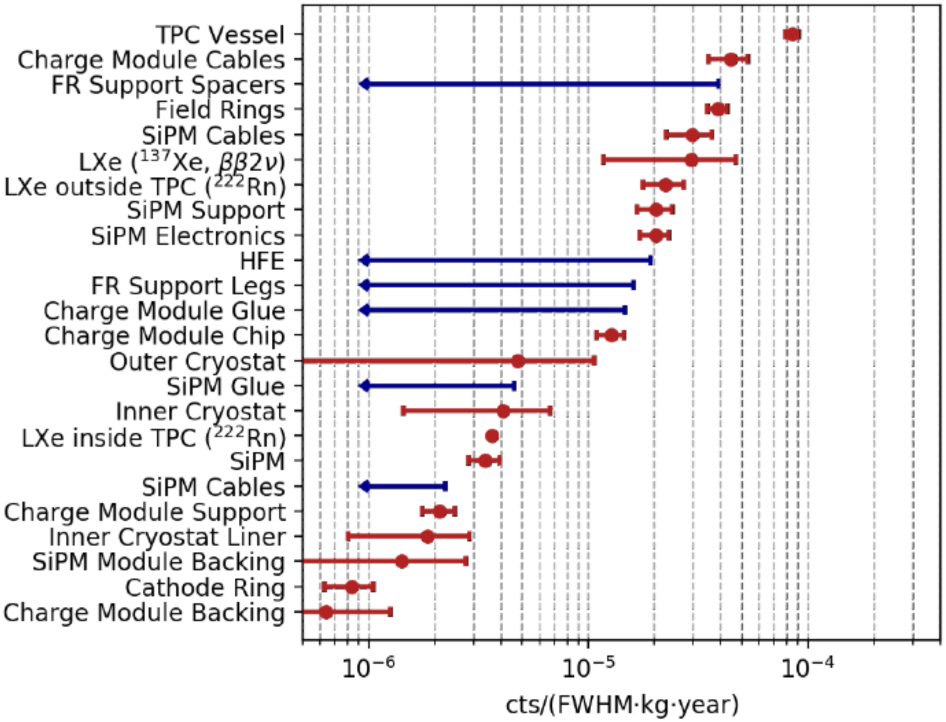
  2.9×10^{-4} cts/(FWHM·kg•y)

  [> 70 % from ^{238}U]



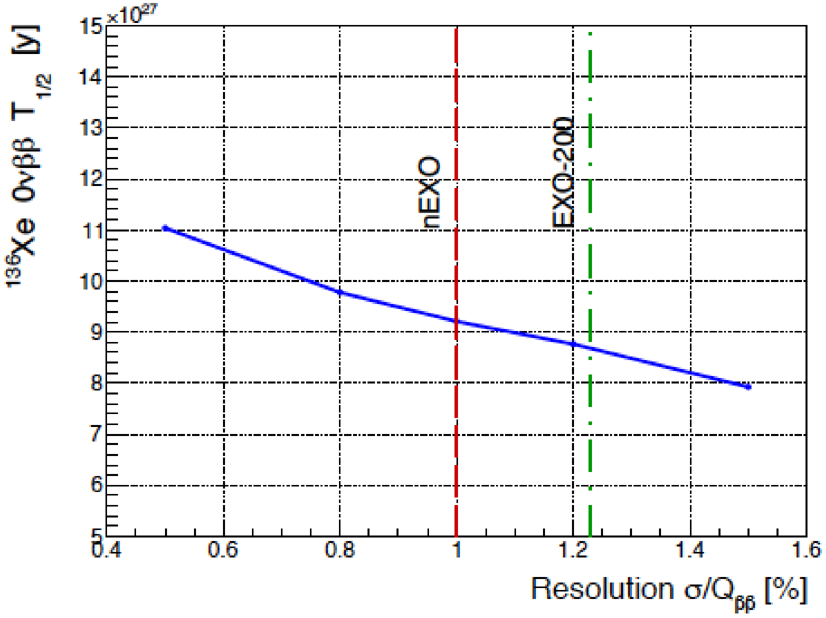
Sensitivity

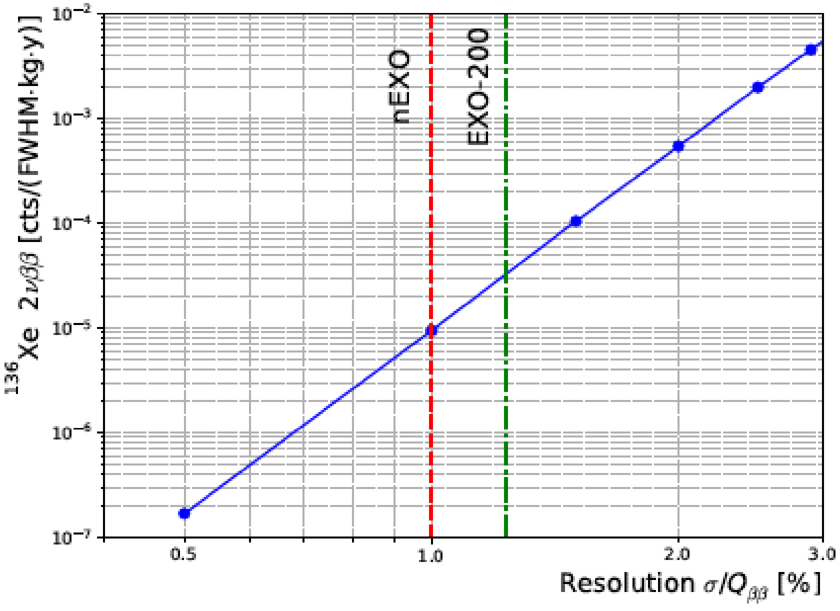
- Same procedure for estimating BG budget as validated for EXO-200
- Components in the TPC dominate
- BG counts rather evenly distributed across various components



Sensitivity

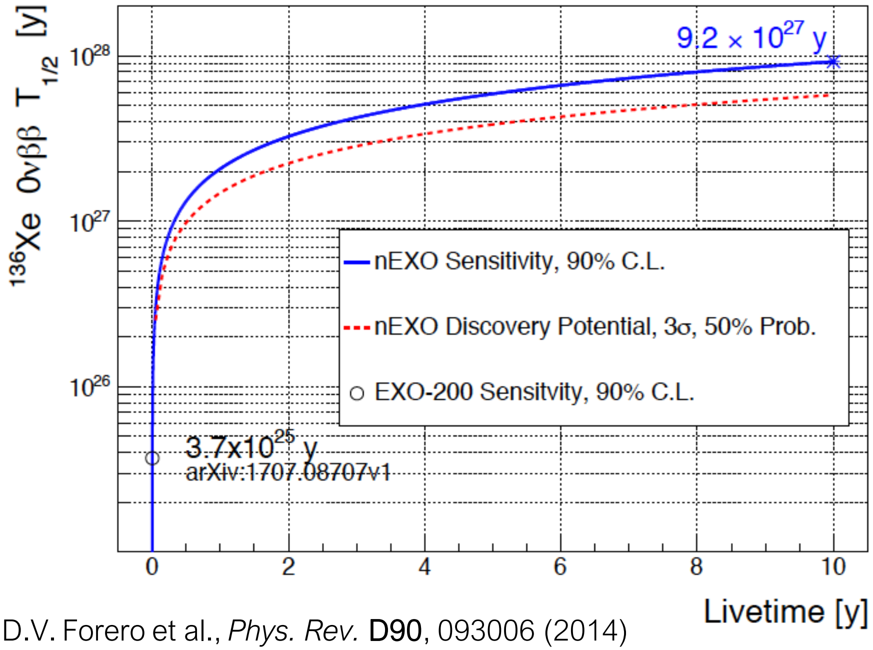
- Only relatively small improvements with energy resolution
- 2νββ almost negligible: 0.34 counts in 10 years in the entire LXe (however strongly worsens with energy resolution)

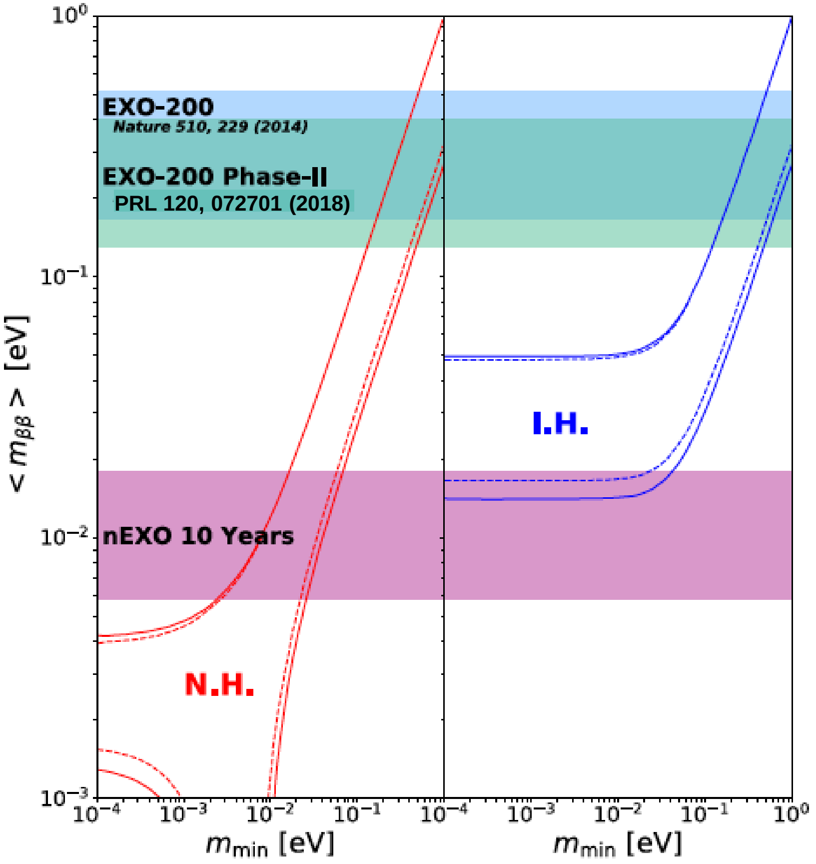




Sensitivity

- Exclusion limit at 90 % CL computed as the median upper limit of an ensemble of 10^4 toy experiments
- Majorana neutrino mass sensitivity after in 10 years: 5.7 – 17.7 meV at 90 % CL





D.V. Forero et al., *Phys. Rev.* **D90**, 093006 (2014)

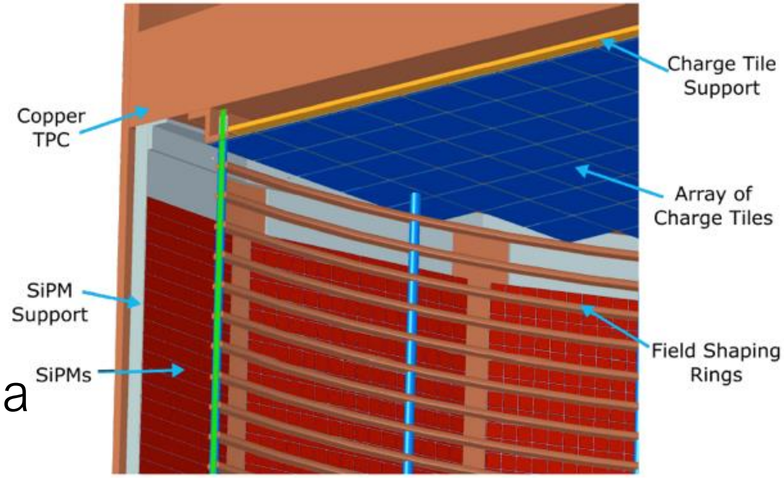
N. Lãşpez Vaquero et al., *Phys. Rev. Lett.* **111**, 142501 (2013)

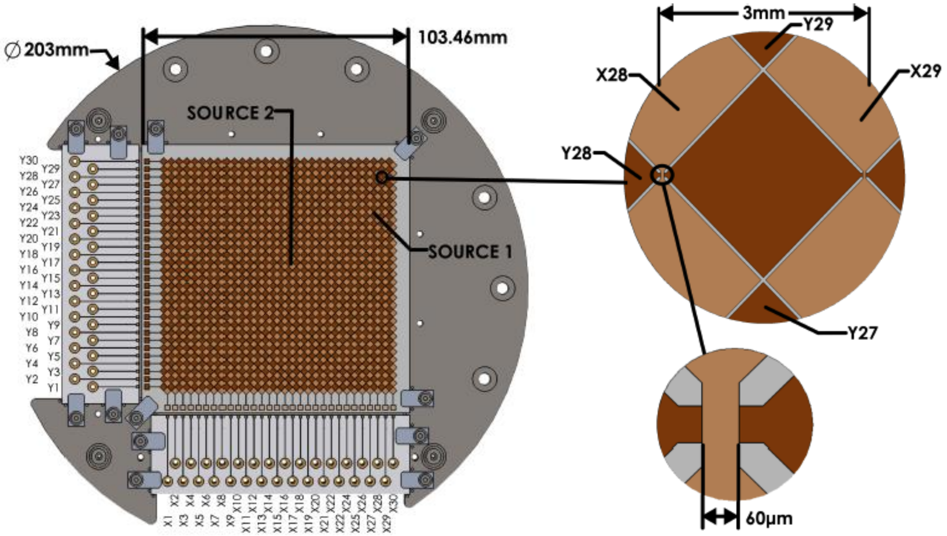
M.T. Mustonen and J. Engel, *Phys. Rev.* **C87**, 064302 (2013)

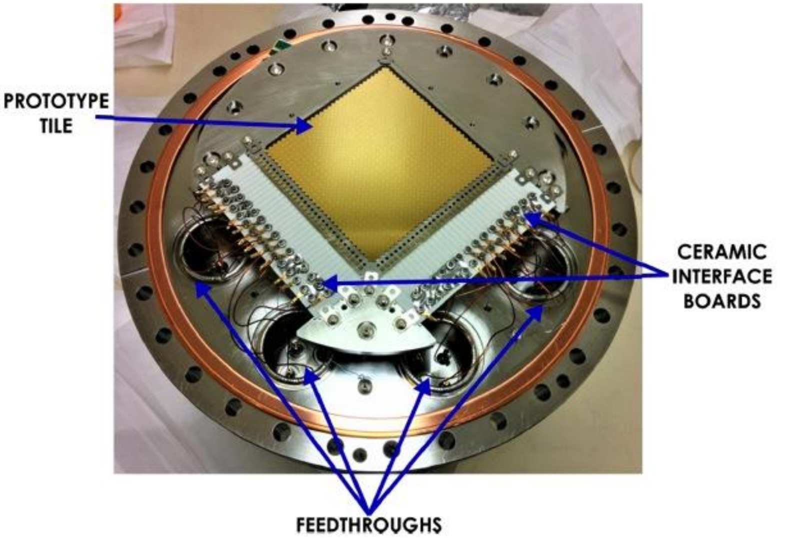
C. Patrignani et al. (PDG), *Chin. Phys.* **C40** 100001 (2016)

Ionization tile readout

- Wire planes demand tensioning frame
- ➢ Modular segmented anode tiles
- Fabrication with low contamination
- Prototype of 10 cm x 10 cm x 300 µm
- 2 x 30 isolated Au/Ti strips on fused silica substrate
- 30 pads per strip (3 mm diagonal)



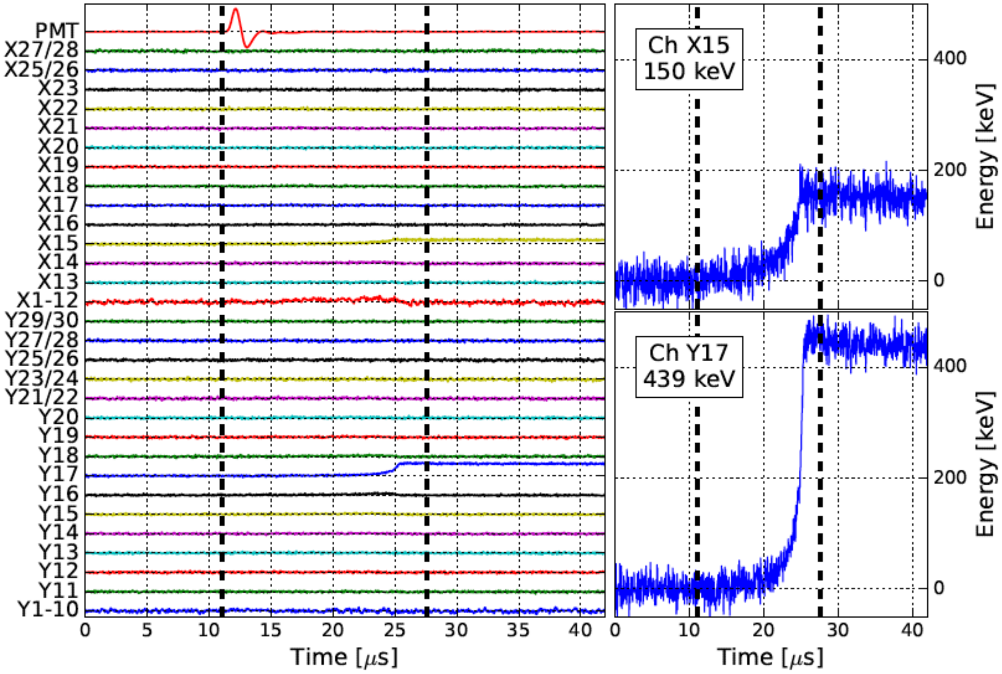


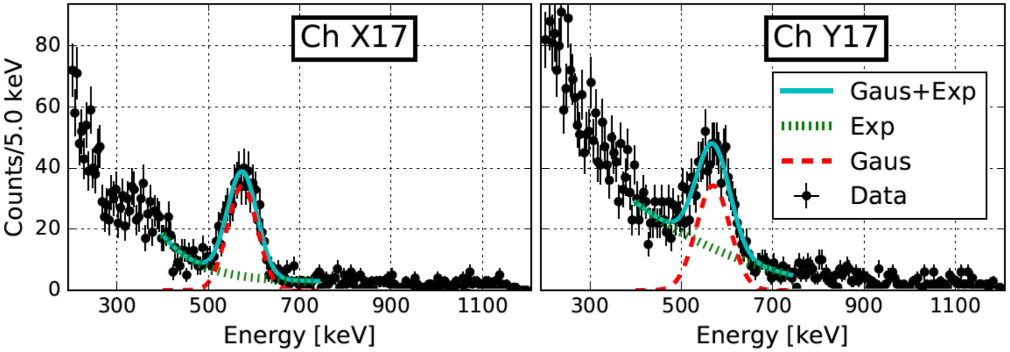


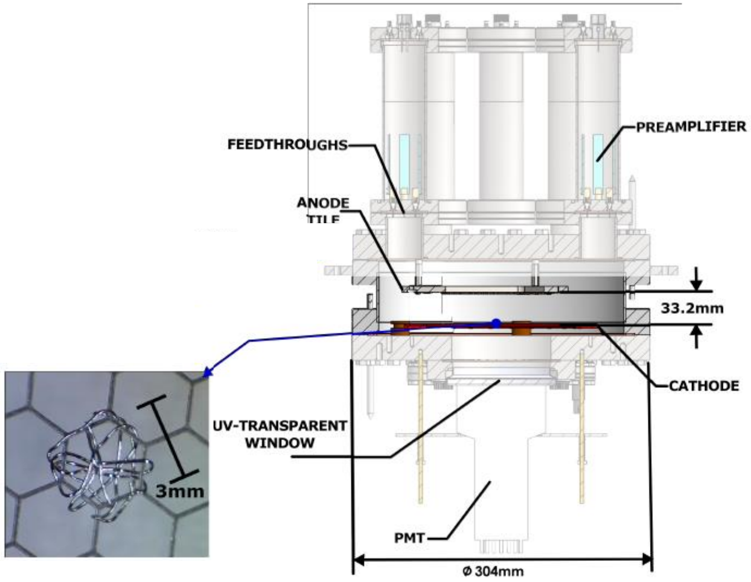
Ionization tile readout

Test cell filled with LXe

- ^{207}Bi source (570 keV)
- Electric field: 936 V/cm
- Electron lifetime: ~ 150 µs
- Cold preamps close to feedthroughs

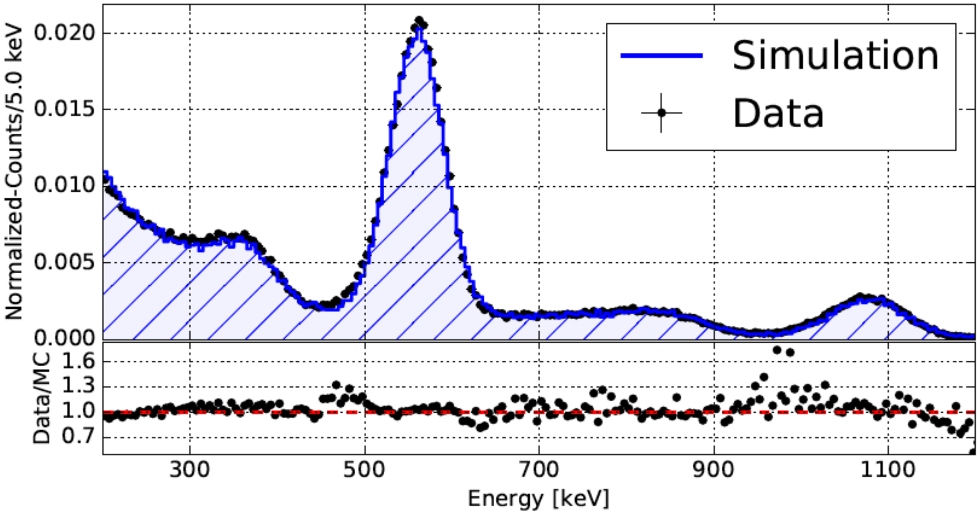


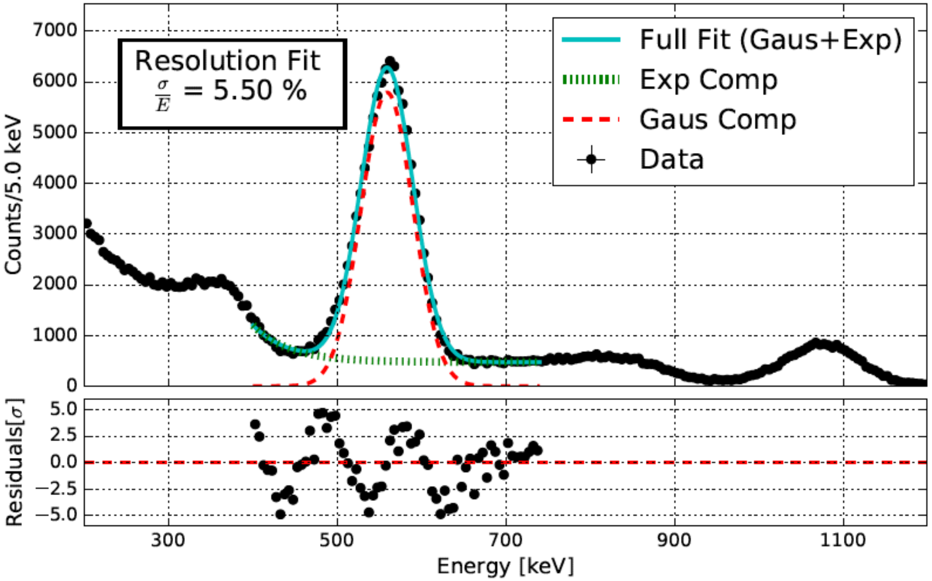




Ionization tile readout

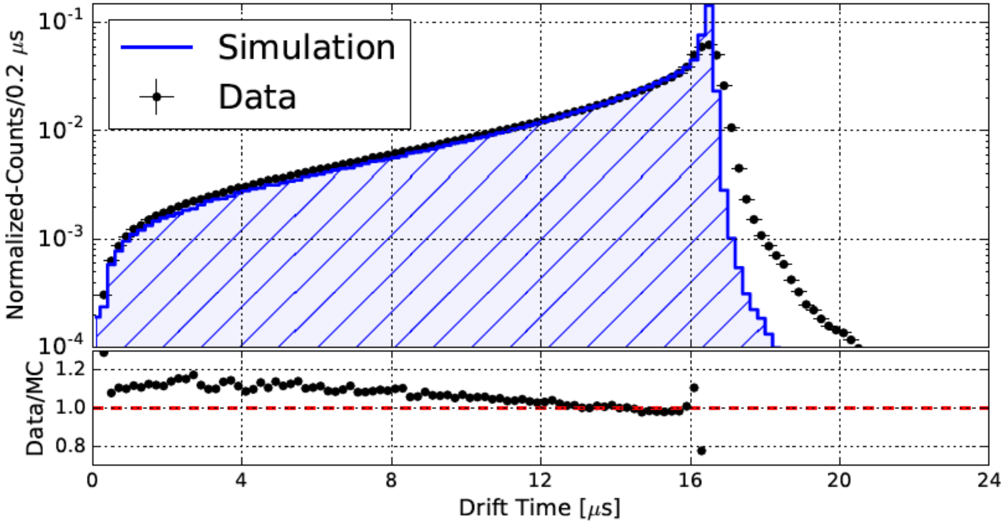
- Two stage simulation:
  - GEANT4 & NEST
  - Drift signal simulation
- Cuts on multiplicity, single-strip channels and drift time
- **Ionization-only** energy resolution consistent with literature

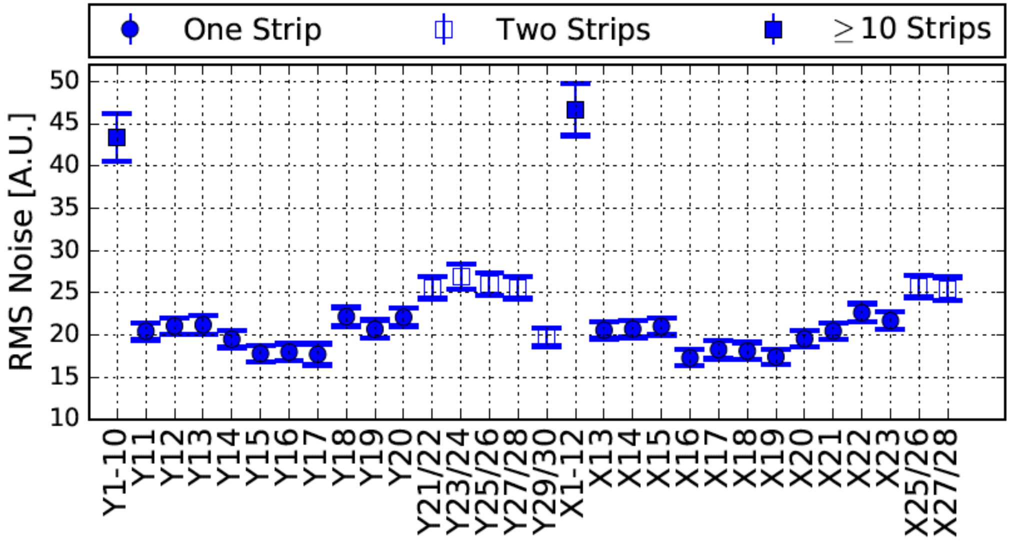




Ionization tile readout

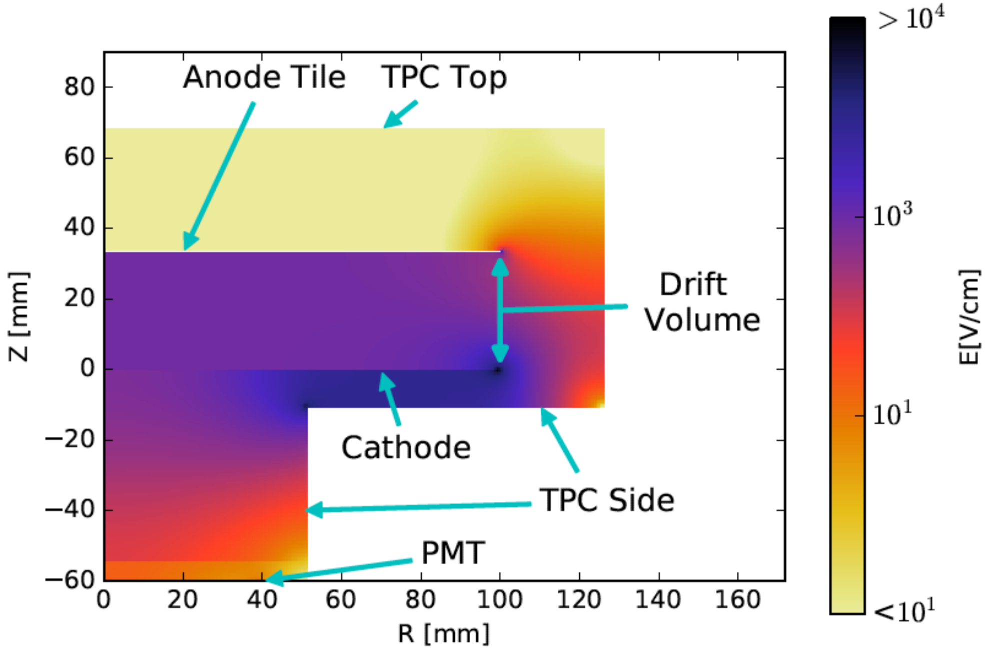
- Drift velocity: ~ 2 mm/μs
- Discrepancy in peak due to mesh electrostatics

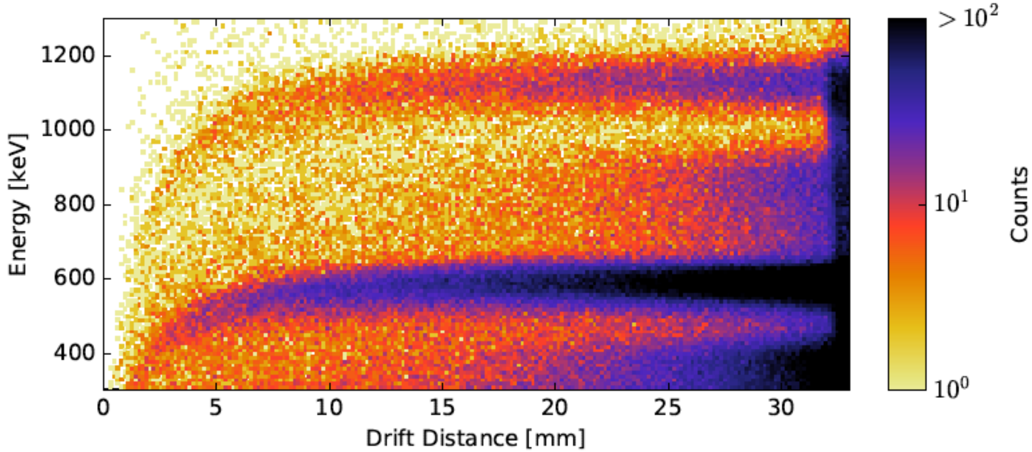




Ionization tile readout

- Electric field map via COMSOL
- Drift time cut to exclude variations du to electrostatic effects





VUV-sensitive SiPMs

- Noise in light channel dominant for nEXO energy resolution
- Photon transport efficiency crucial parameter
- Determine fluctuation of energy estimator based on scintillation and ionization yield