Light Detection with SiPMs in the nEXO Experiment

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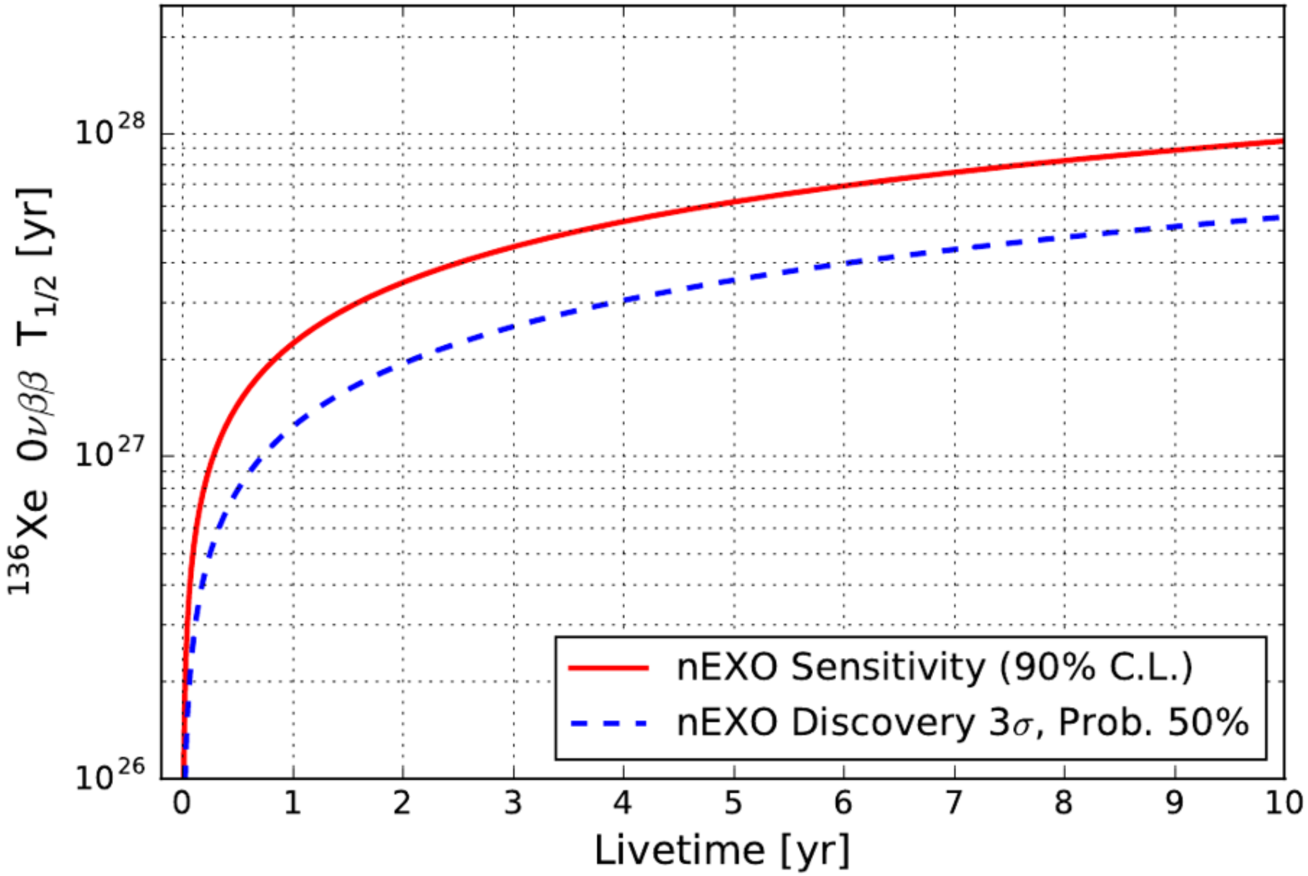
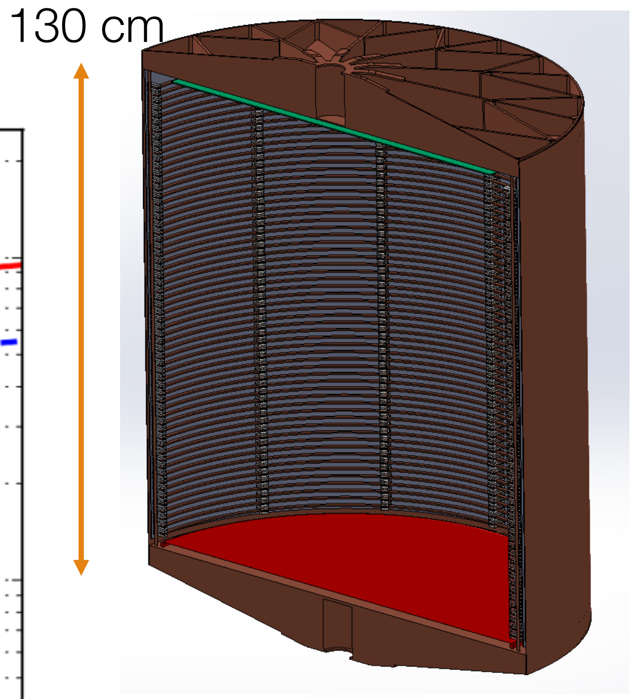
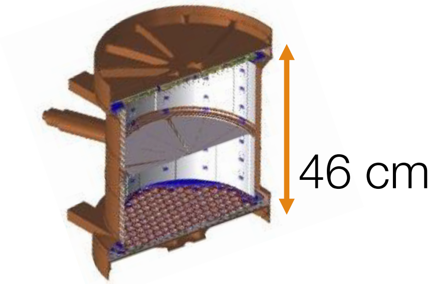
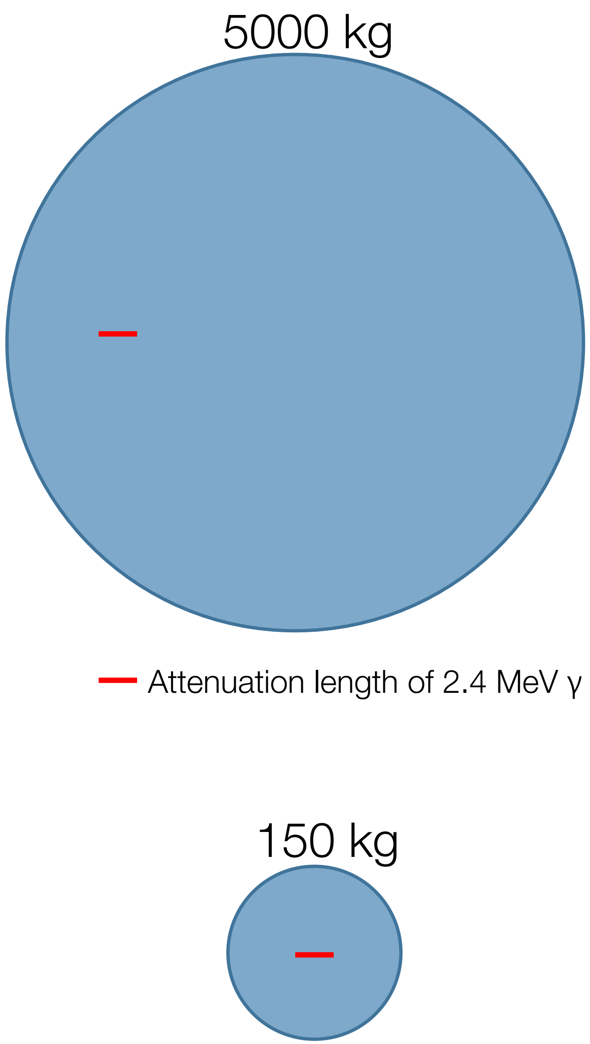
$0\nu\beta\beta$ - from EXO-200 to nEXO

- nEXO will reach half-life sensitivity of ~$6 \cdot 10^{27}$ yrs for $0\nu\beta\beta$ of ^{136}Xe after 5 years of data taking

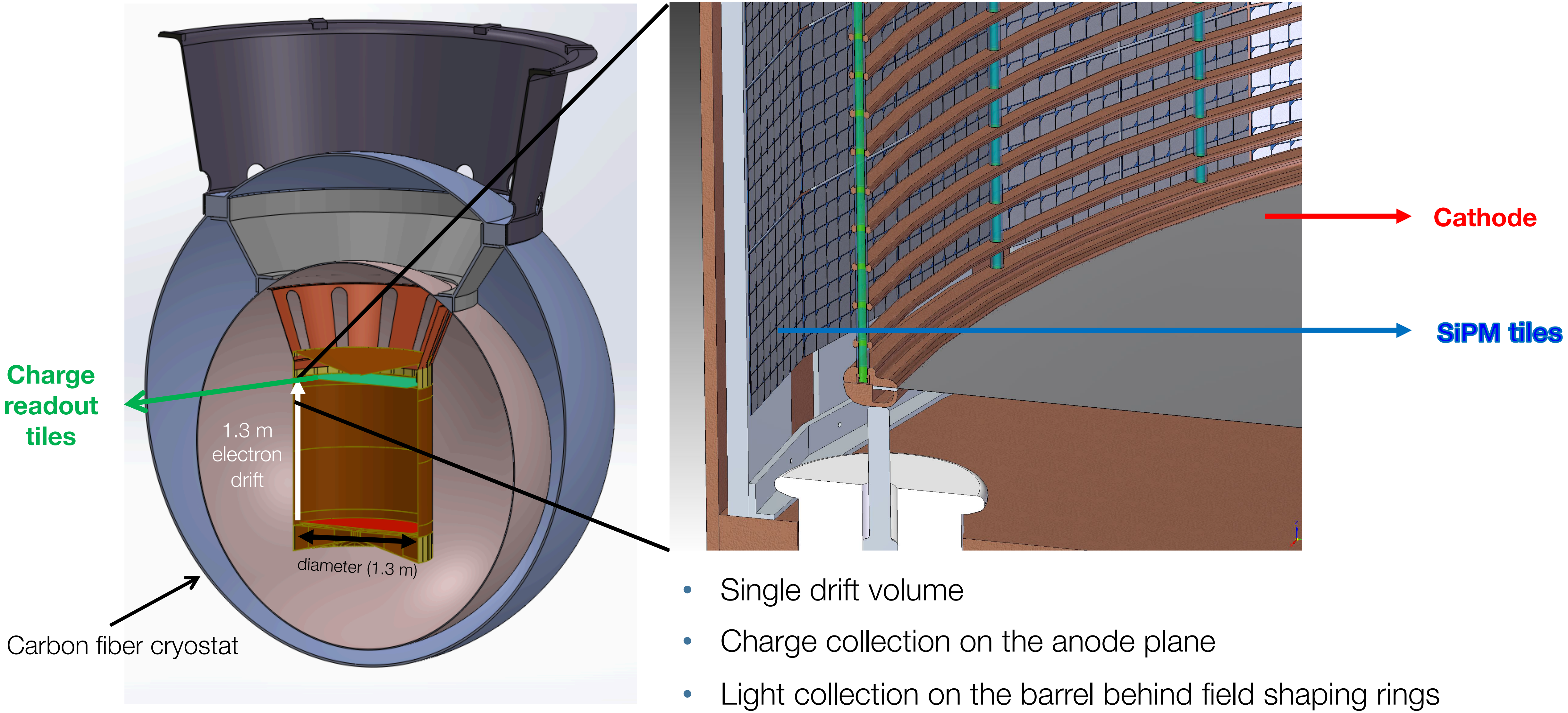








Conceptual Design for nEXO



- Single drift volume
- Charge collection on the anode plane
- Light collection on the barrel behind field shaping rings

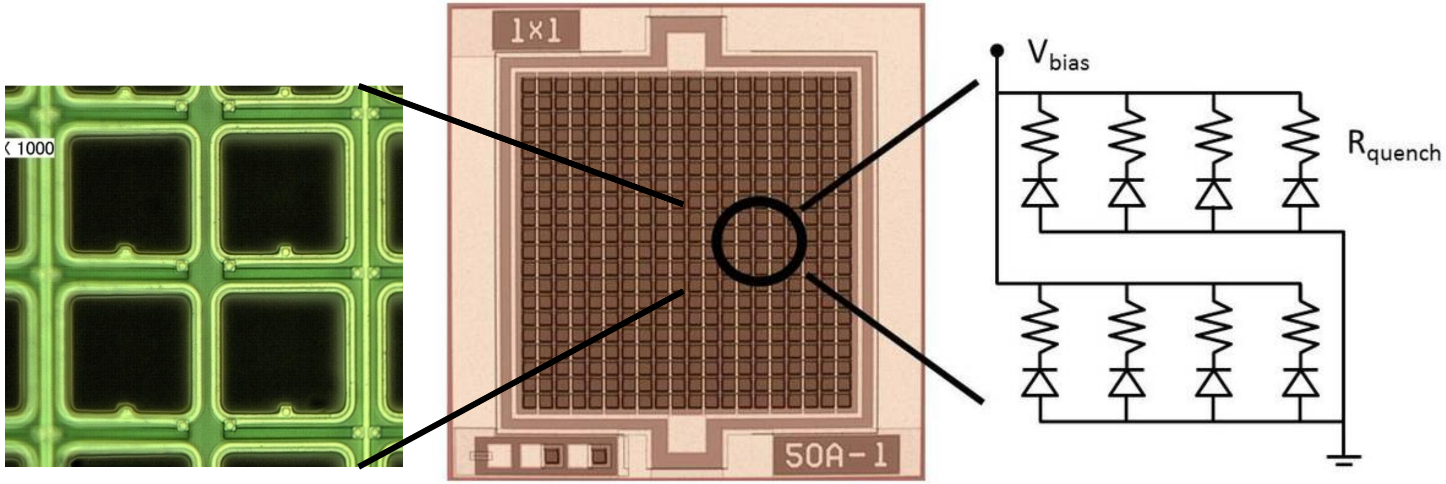
SiPMs for Light Detection in nEXO

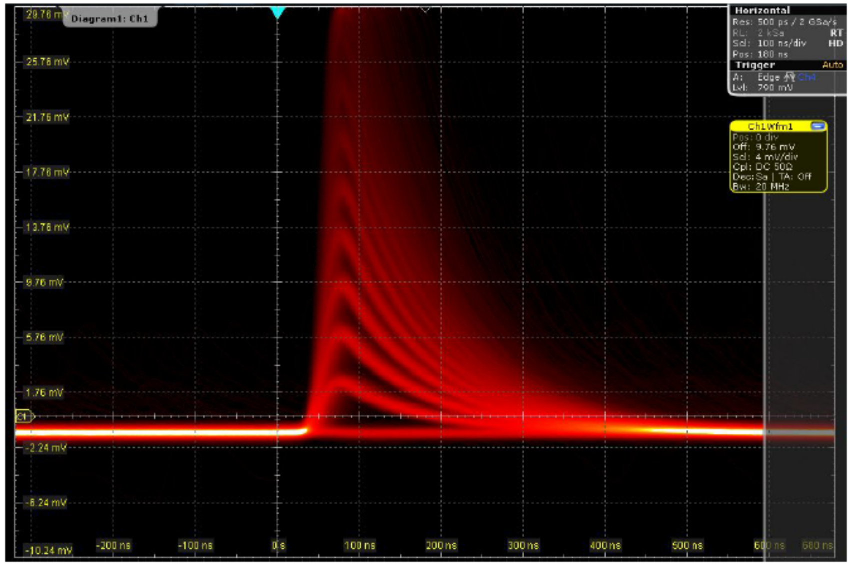
- Many pixels in parallel operated in Geiger mode
- Incident photon creates an electron that triggers an avalanche
- Current is passively quenched by a resistor
- Channel signals are added together

  → allows for single photon resolution

Advantages:

- High gain → low noise
- Possible high radio-purity
- Large manufacturing capabilities
- Efficiency getting close to what we need

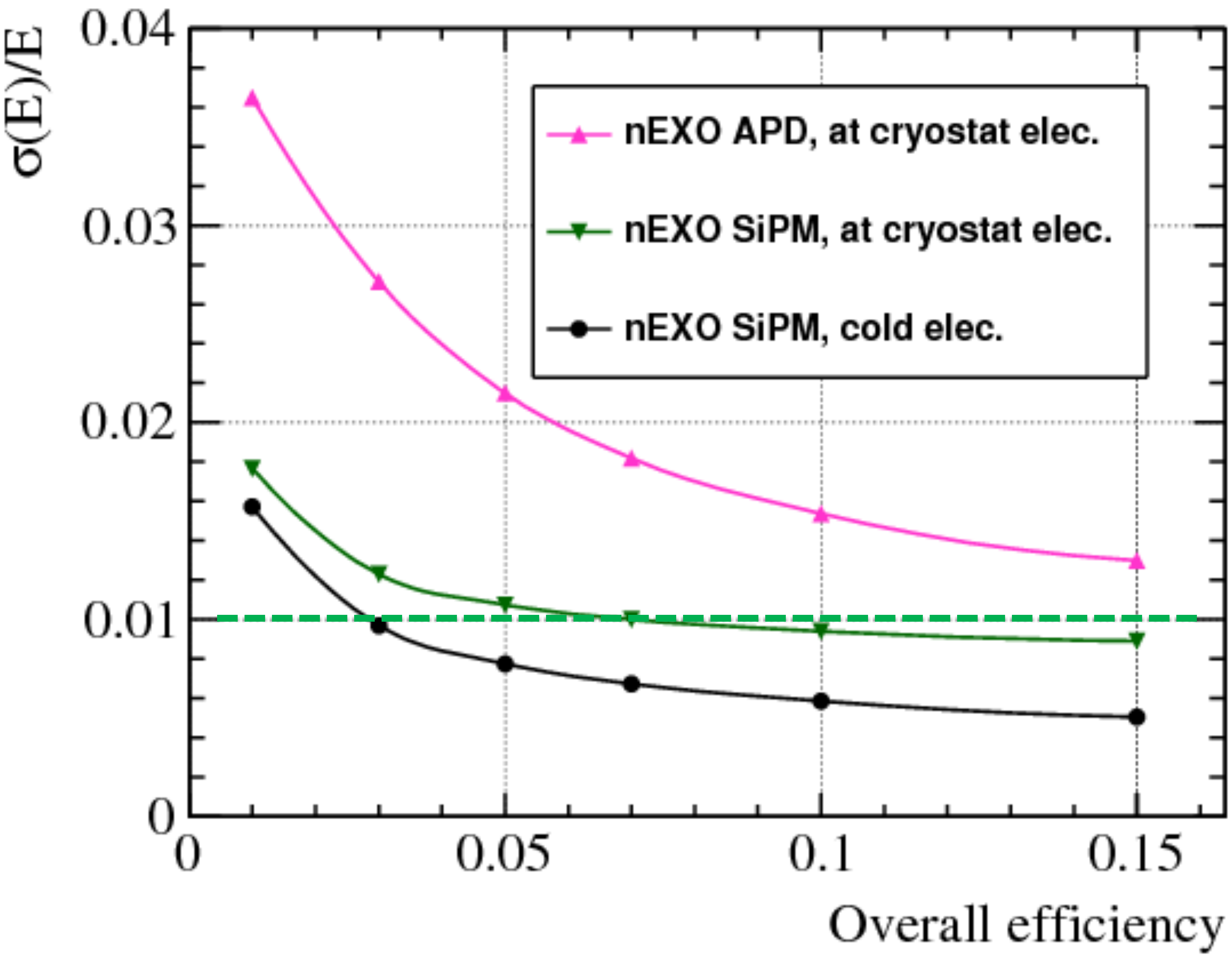




Light collection in nEXO

- Overall efficiency = PDE · CE
- ~4m^2 of SiPMs
- Large improvement with SiPMs instead of APDs
- nEXO specification:

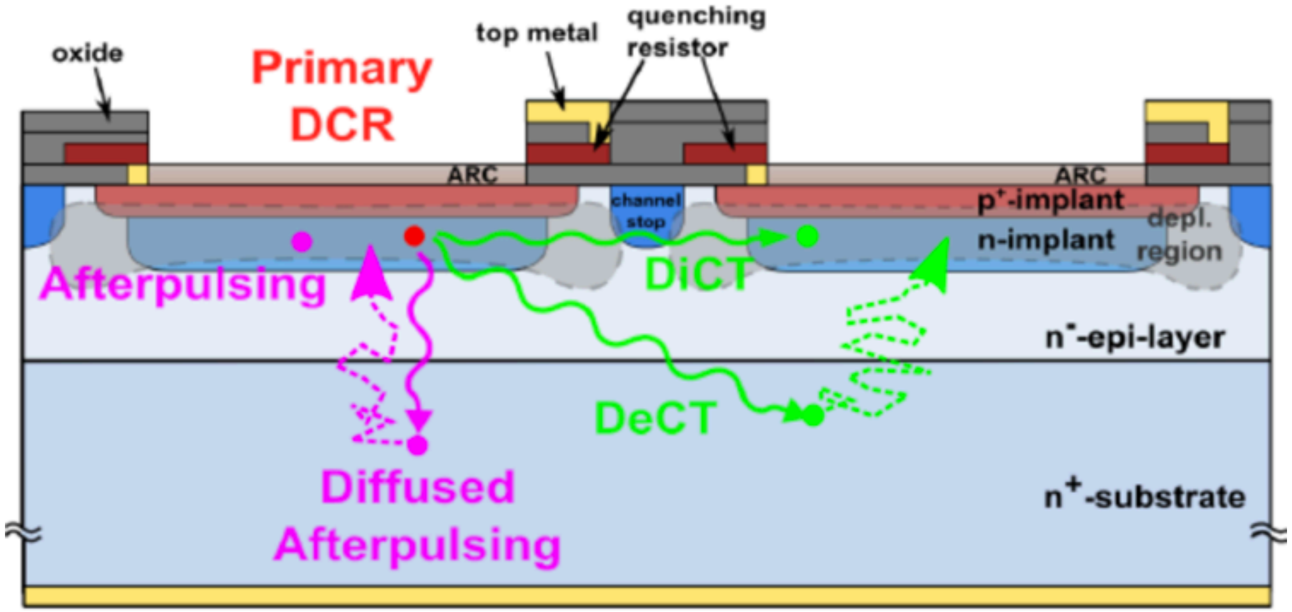
$\frac{\sigma(E)}{E}$ of 1% at Q-value

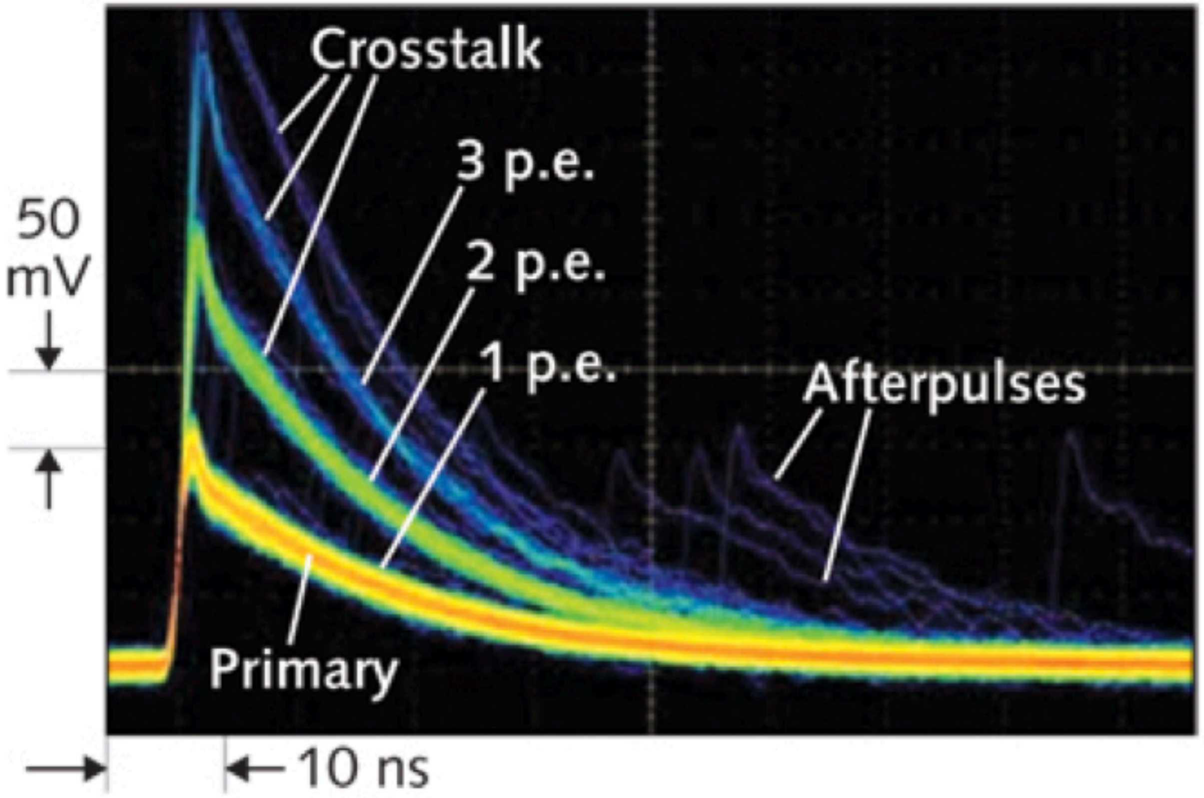


SiPM Requirements for nEXO

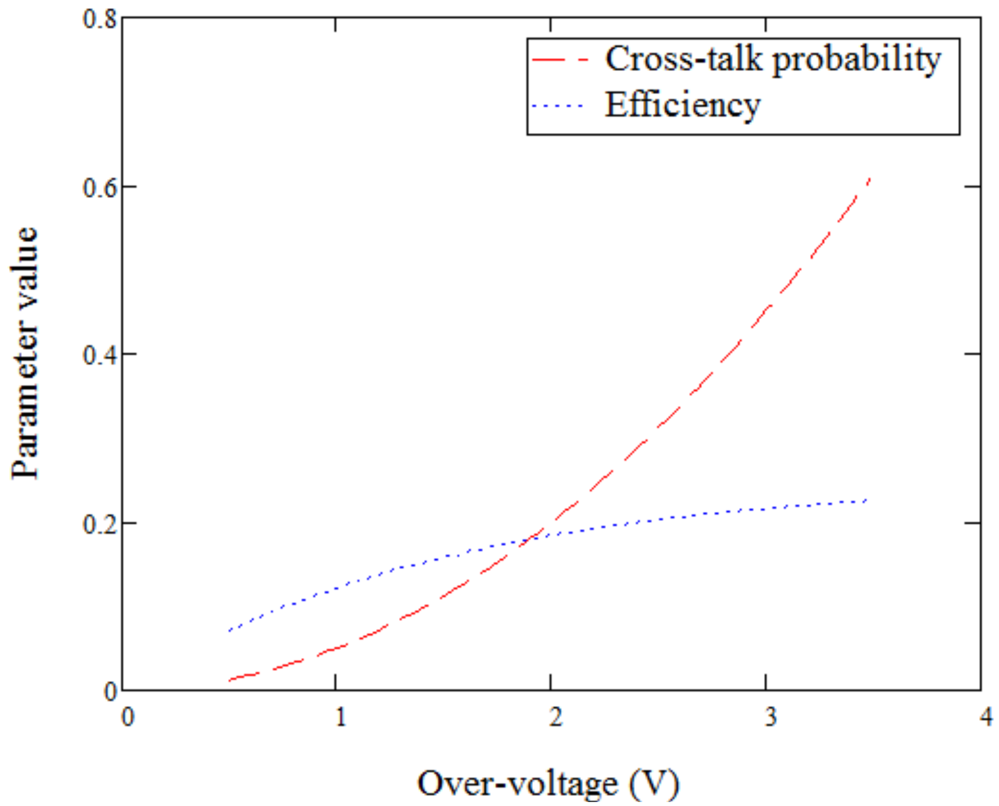
Parameters	Value
Photo-detection efficiency at 175-178nm in liquid Xenon	≥ 15%
Radio purity: contribution of photo-detectors to the overall background	< 1%
Dark noise rate at -100°C	≤ 50 Hz/mm^2
Average number of correlated avalanches per parent avalanche at -100°C within 10 μs	≤ 0.2
Single photo-detector active area	≥ 1cm^2
Capacitance per area	< 50 pF/mm^2
Gain fluctuations + electronics noise	< 0.1 PE

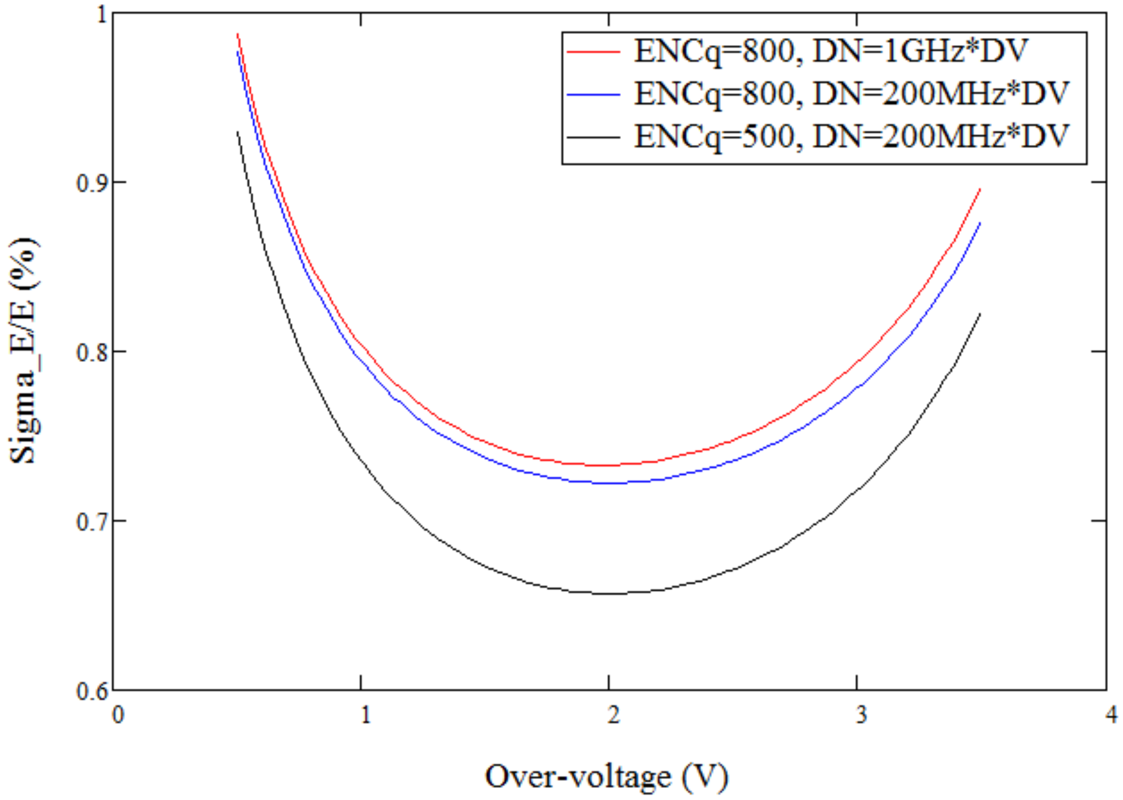
Correlated Noise in SiPMs





Significance of Correlated Avalanches

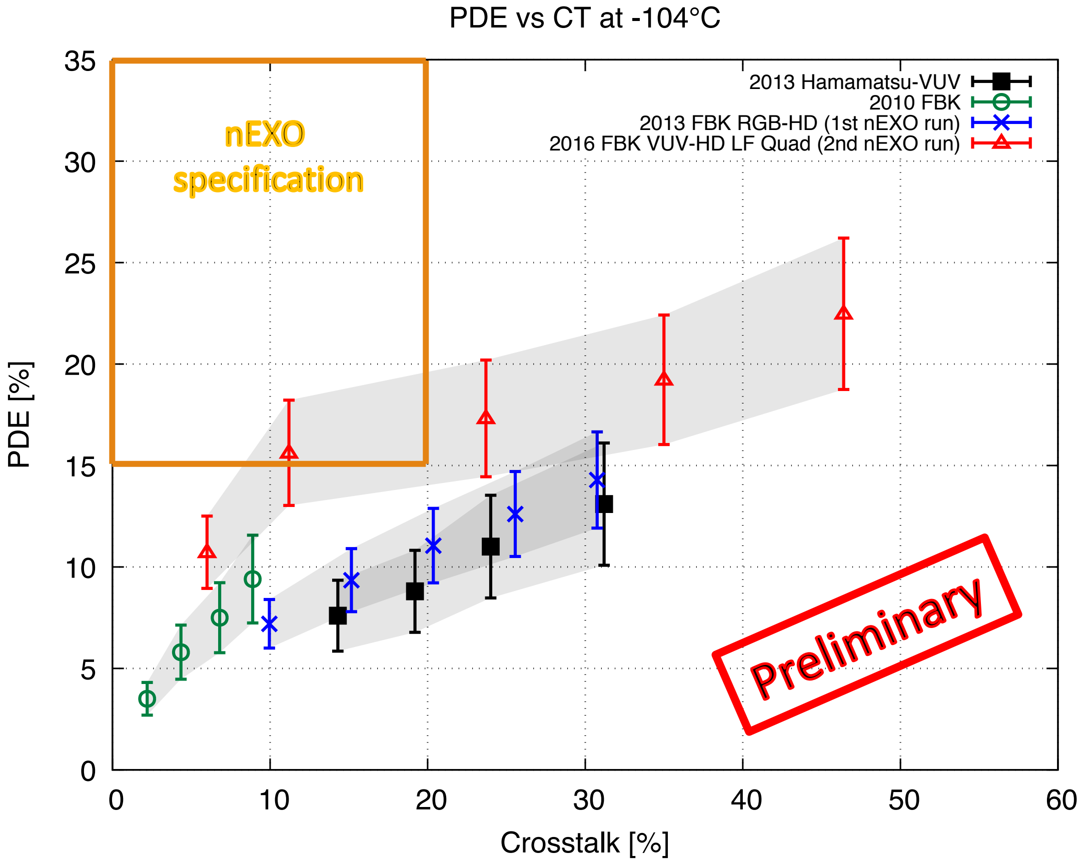


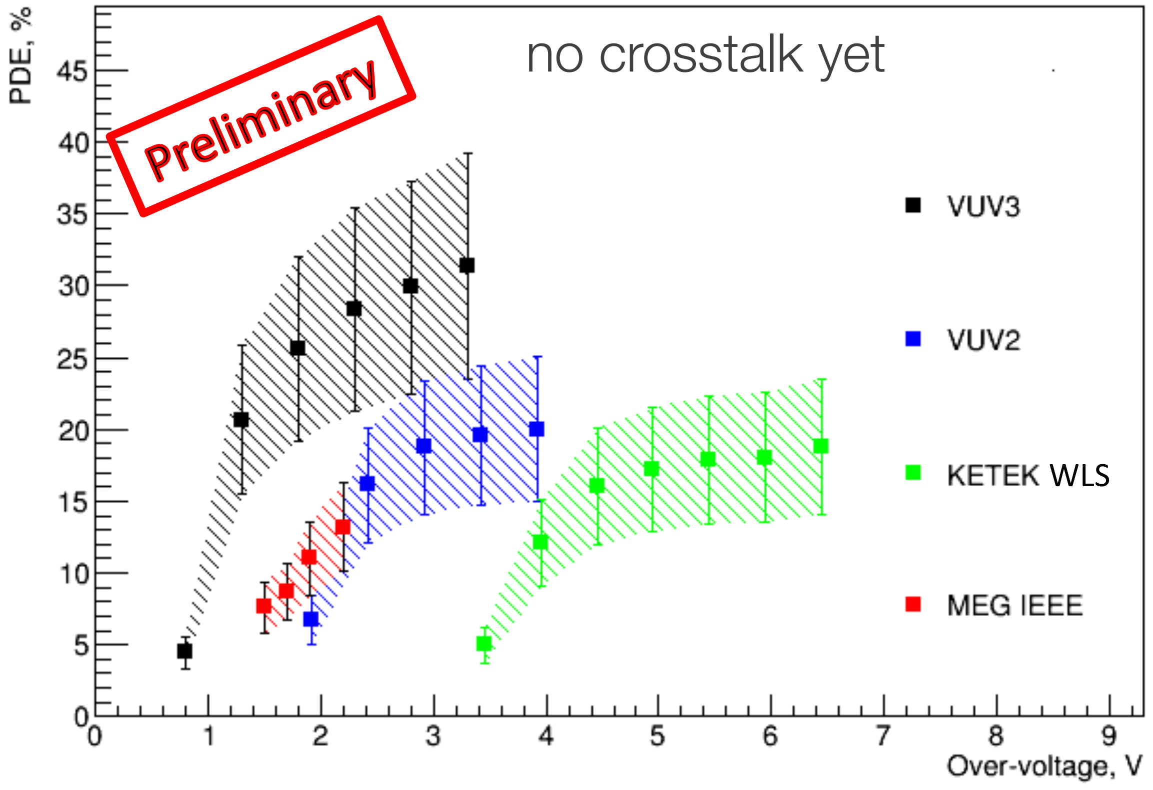


- Overvoltage changes everything
- Highest efficiency does NOT mean highest energy resolution
- Need to look at set of **Correlated Avalanche Rate and PDE**

Latest Efficiency Measurements

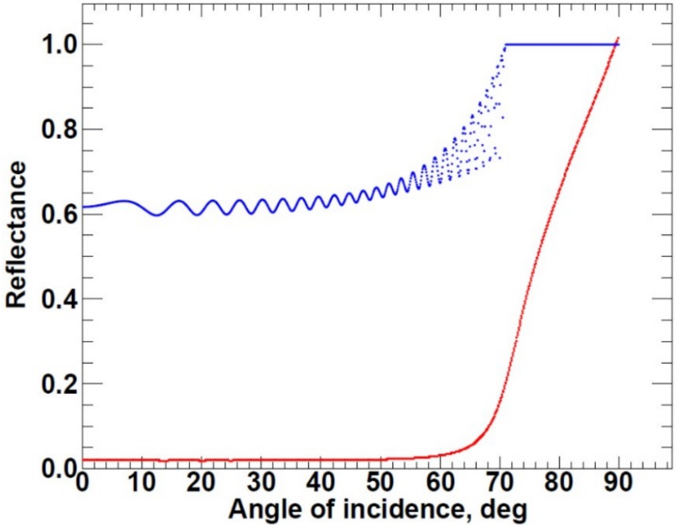
- Promising improvement over the past years

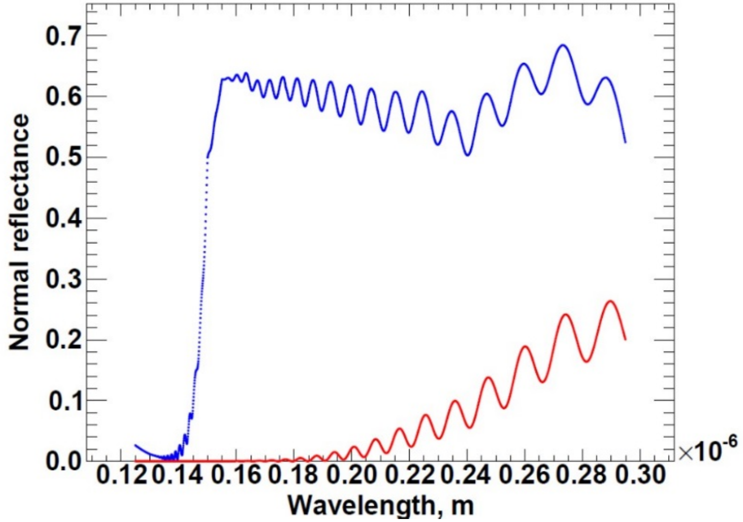




Open Issue – Reflectivity

- What happens to the photons?
  - ~15% detected by SiPM (PDE)
  - ~60% expected to be reflected due to refractive index mismatch
    - Photon might be detected by another SiPM
    - Anti-reflective coating is an option
  - ~25% will be absorbed without detection
- Recent measurements showed only ~30% reflectivity
- Highly depending on surface layers and thickness
- May vary widely due to production
- **Need efficiency as function of correlated avalanche rate AND reflectivity!**

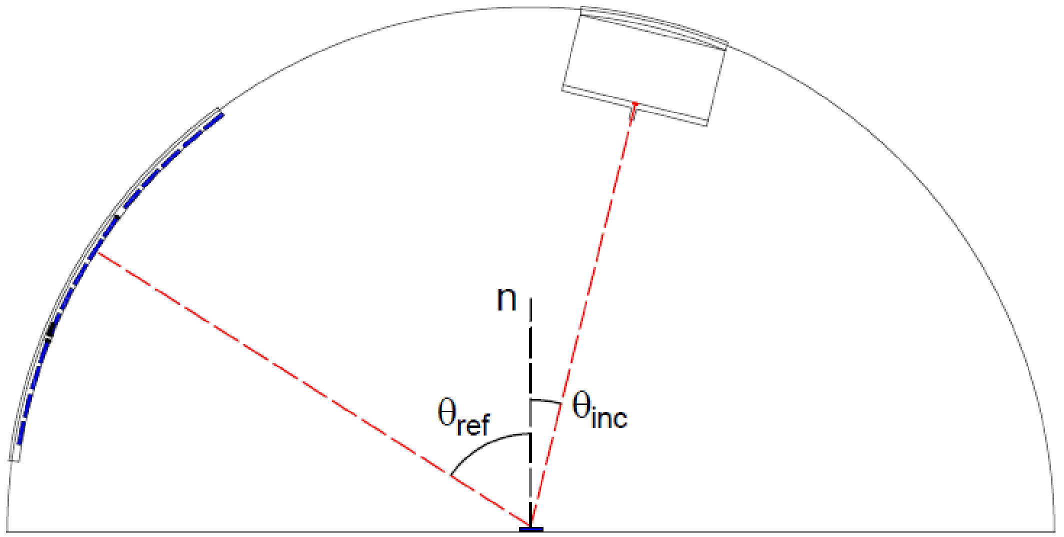




Calculated reflectance of an FBK SiPM as a function angle (left) and wavelength (right) for two measured values of SiO_2 extinction coefficient. In the low extinction (blue) case, ~60% of light is reflected by SiPM, which can be collected by opposing sensors. The high extinction (red) case is detrimental for nEXO.

LIXO: LIquid Xenon Optical characterization Setup

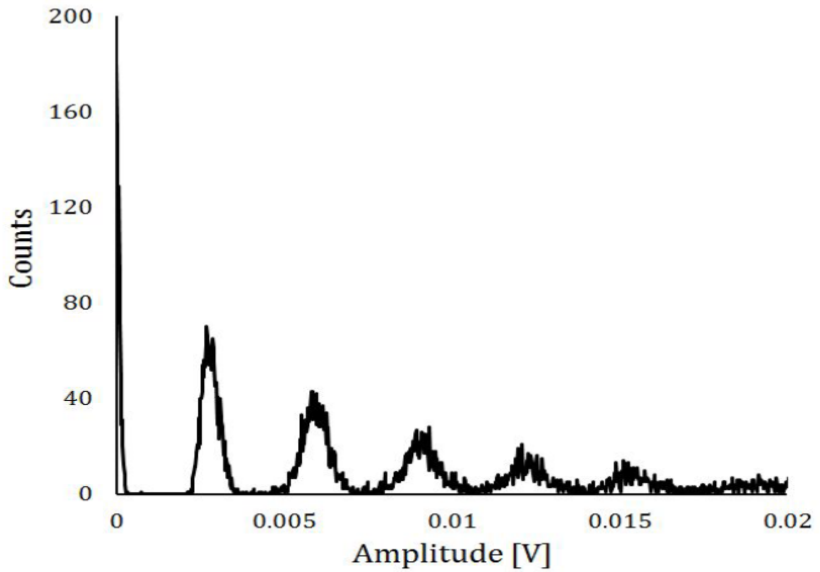
- Understanding VUV reflectivity of materials and SiPMs in LXe is critical for nEXO
- nEXO plans to study VUV reflectivity and PDE as a function of angle in LXe (UAlabama) – LIXO
- LIXO will be complementary to a more versatile vacuum setup (TRIUMF) that will probe wide range of wavelength, from VUV to IR



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

Large Area SiPM Readout

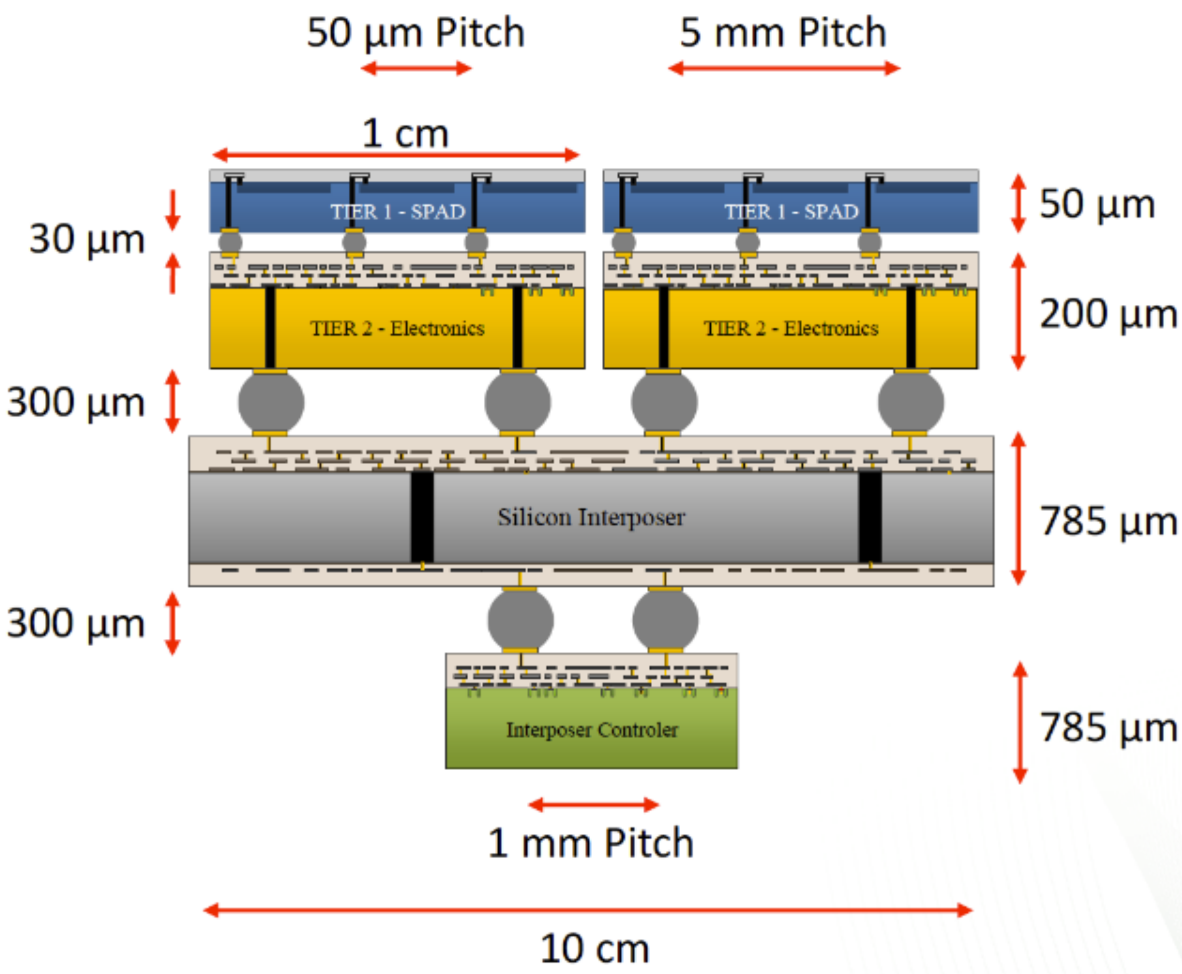
- nEXO needs to maximize area/channel under a power/channel constraint
- Single p.e. resolution still needs to be maintained (0.1 SPE rms)
- We have investigated relation between sensor area capacitance, readout noise, power and shaping time
- **We have seen that gain/capacitance is what really matters**
- We can comfortably readout ~6cm^2/channel with 85pF/mm^2



- -100°C
- 0.5 mW/cm^2
- SensL 4x4 array as one channel (parallel)
- $3 \cdot 10^6$ gain
- 20 MHz bandwidth

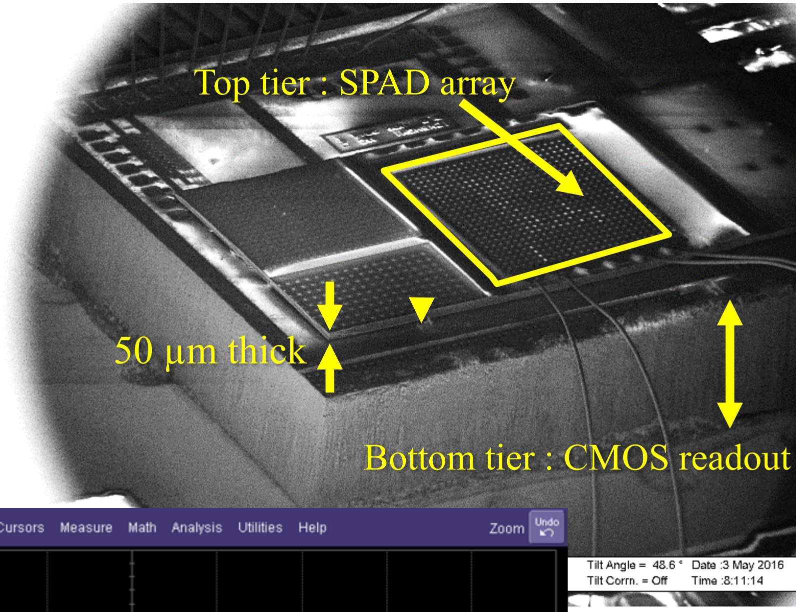
3-Dimensionally integrated digital SiPM

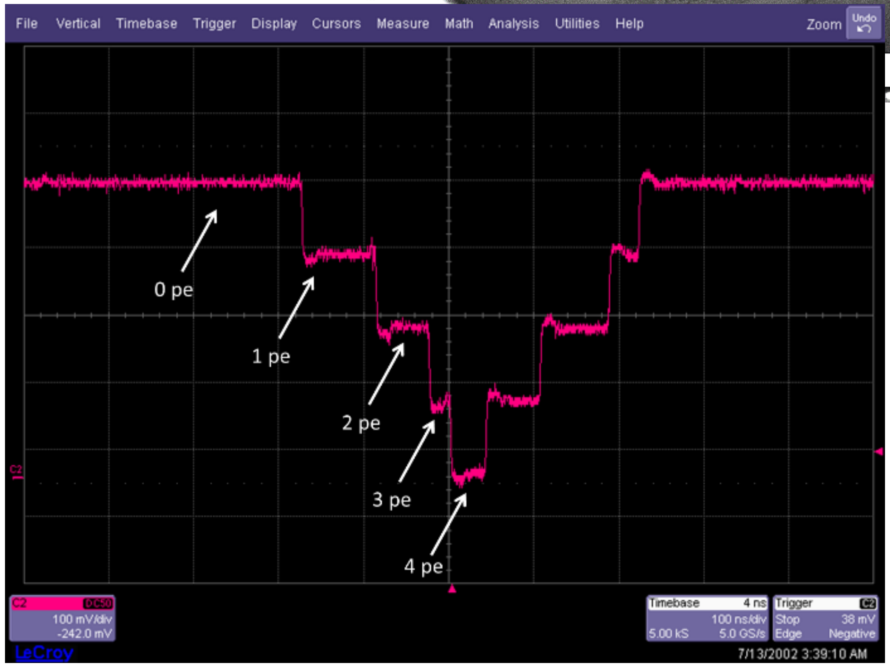
- 3 layers (tier) system
  - Tier 1: Single Avalanche Photo-Diode Array (SPAD) with one Through-Silicon-Via (TSV) per SPAD
  - Tier 2: One quenching and avalanche counting circuit per SPAD
  - Tier 3: Data aggregator and trigger circuit. One routing "chip" and one controller chip
    - Routing chip may be a silicon interposer
- High performances with low power



3DdSiPM for nEXO

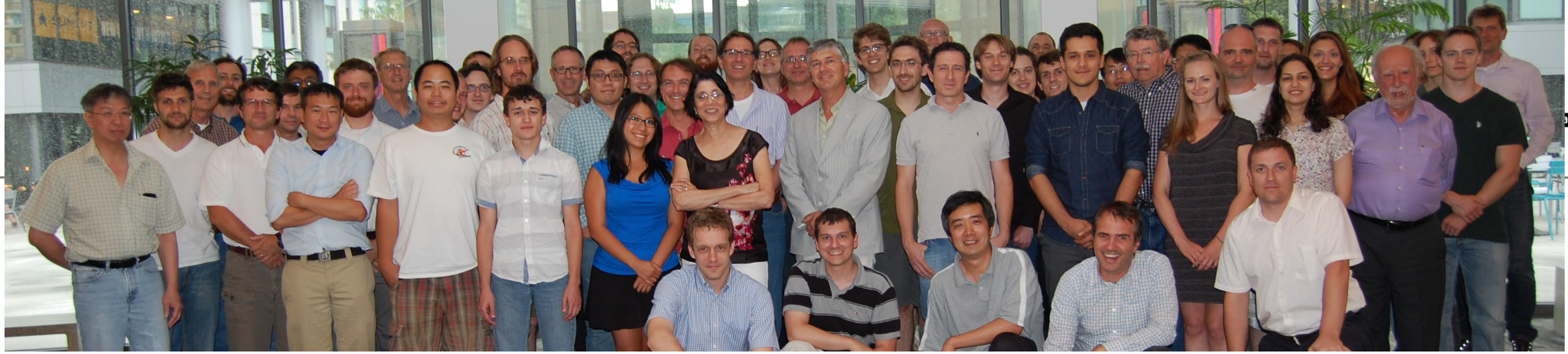
- Advantages over analog SiPM + analog electronics
  - All in one chip assembly: **photon come in, bits come out**
  - Power scales with avalanche count not with capacitance
    - Allow lower power or better timing resolution and granularity
  - After-pulsing can be completely eliminated for a given time scale
    - Digital holdoff vs resistive (RC) quenching
- Challenges
  - Need custom SPAD array
  - Scaling to large area





Summary of R&D for Light Detection in nEXO

- Combine Efficiency **and** Reflectivity measurements in the VUV → have analog SiPM candidate(s) that meet(s) all our requirements
- Proof of principle $10\times10\text{cm}^2$ analog SiPM tile and readout electronics
- Test of SiPMs in the presence of electric field
- Investigate 3D-integrated digital SiPMs



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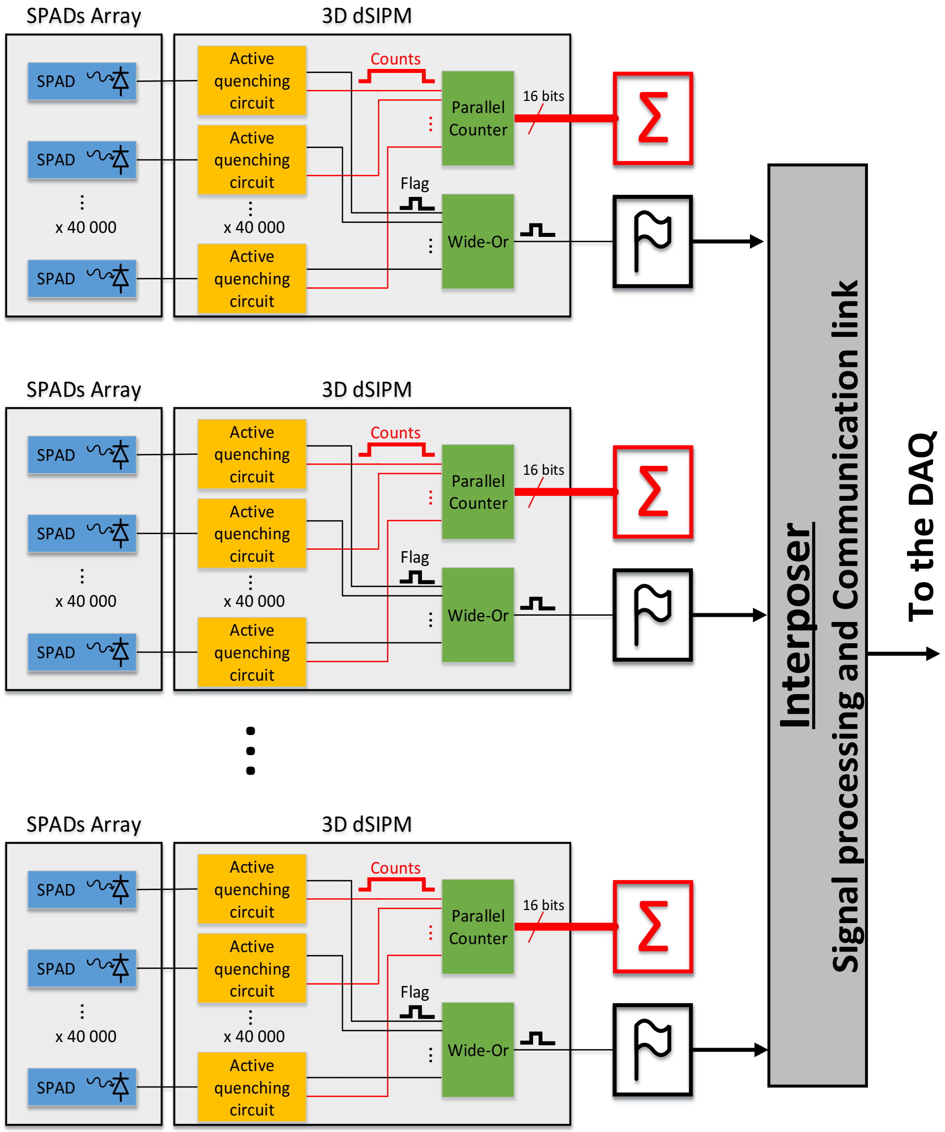
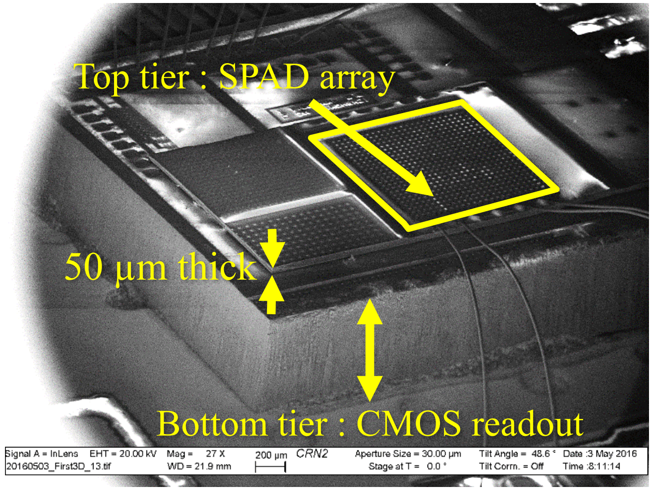
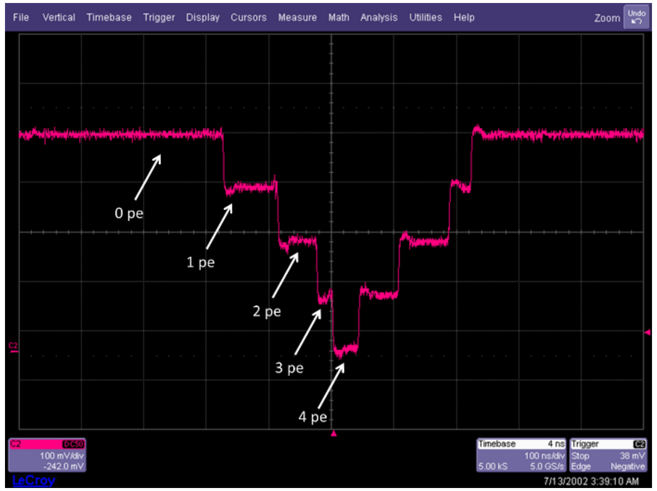
Backup Slides

3DdSiPM Architecture for nEXO





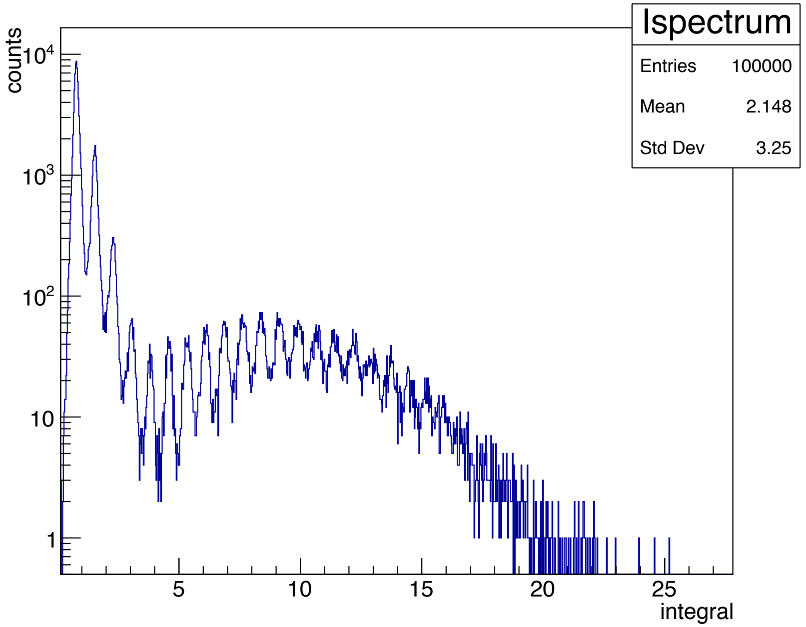


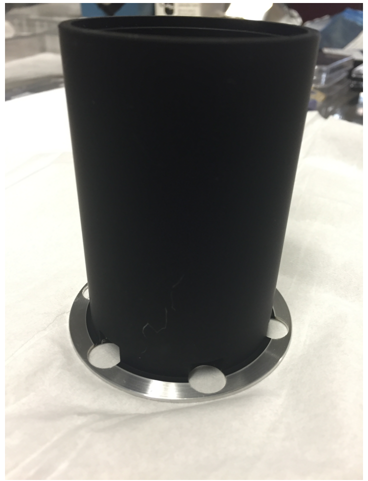
Interposer

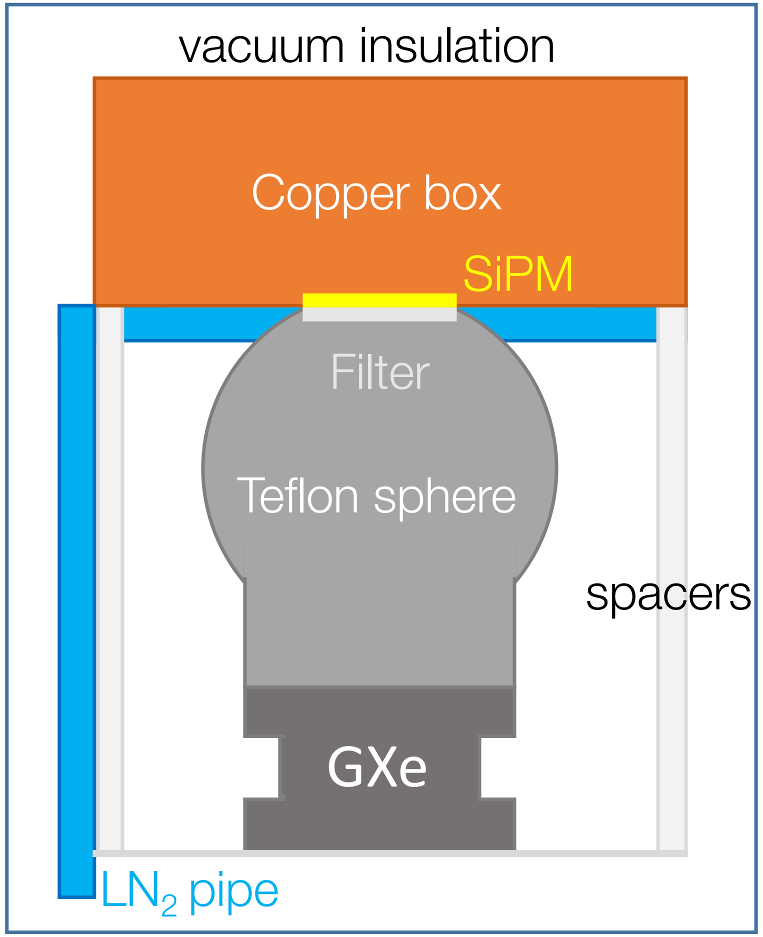
- Same coefficient of thermal expansion
- Adjustable coincidence window
- Adjustable threshold
- A trigger is generated when:
  - Flag count > threshold
  - Inside the coincidence window
- The parallel adder of each 3DdSiPM is activated for the duration of the scintillation
- Data transmission logic

Stanford Setup for Absolute PDE

- Scintillation light from spontaneous fission of ^{252}Cf in GXe
- Wavelength band-pass filter
- Reference PMT from Hamamatsu with calibrated efficiency at 175nm
- Teflon sphere to avoid parasitic reflections
- Black coated cylinder for reflection-free measurments

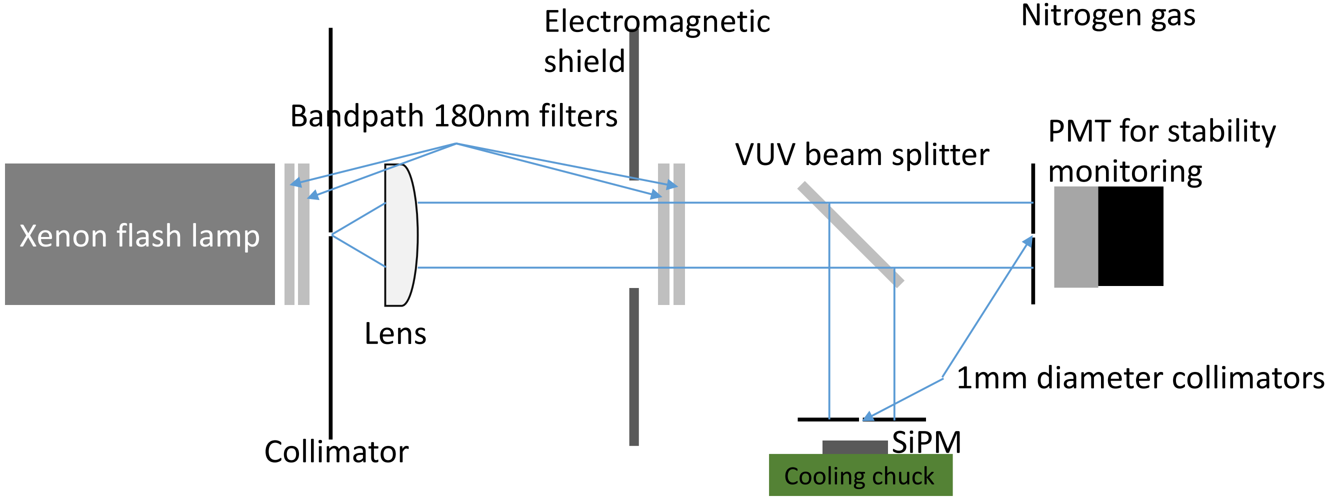


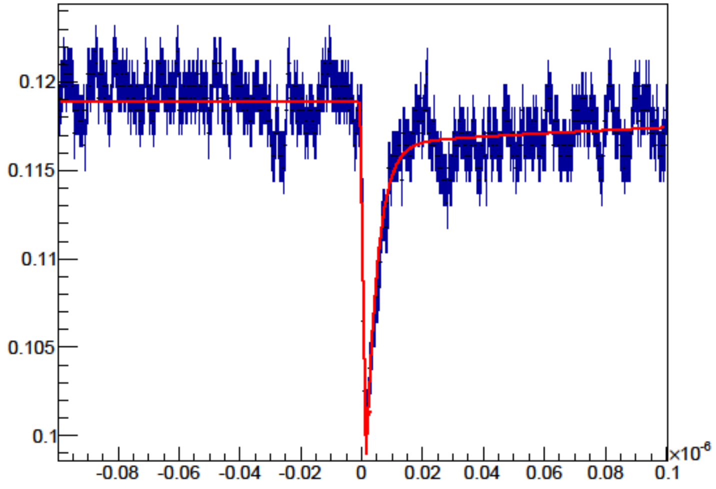


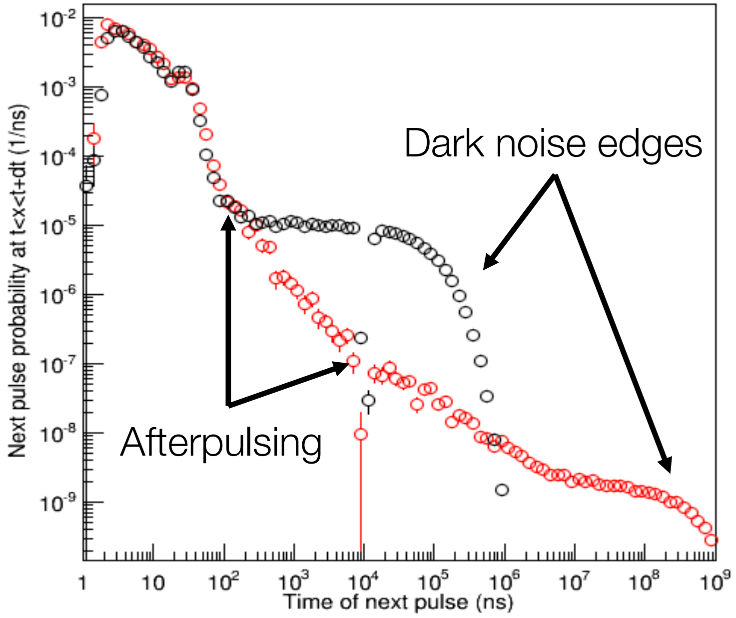


Aktar coating absorbs >99.9% at 175nm

TRIUMF Setup for Correlated Avalanche Measurement



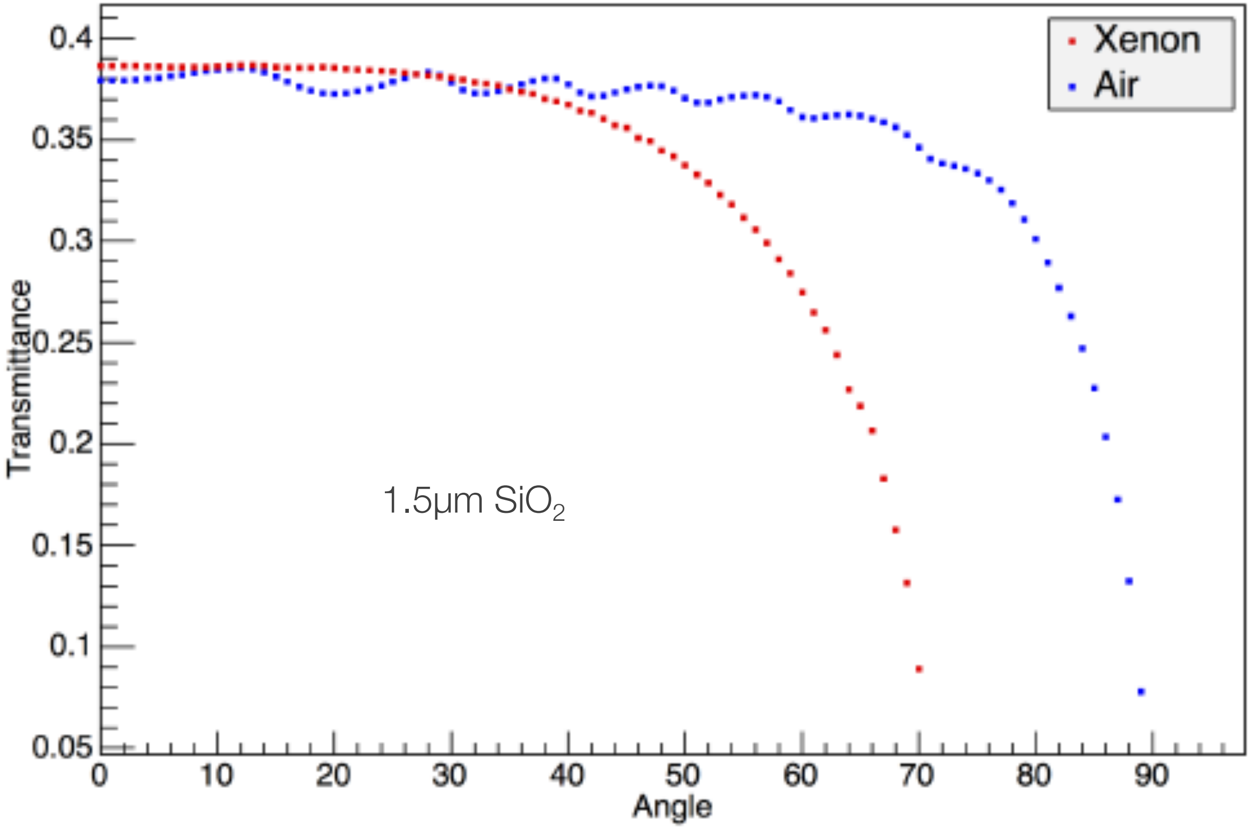




- Low light intensity: 0.1-0.15 p.e. per pulse
- Able to do correlated avalanche free measurement
  - $\langle PE \rangle = -\ln\left(\frac{N_{0L}}{N_{0D}}\right)$
  - N_{0L}: number of events with no pulses in the flash lamp window
  - N_{0D}: number of events with no pulses in a dark region

Measurements in Air vs. LXe

- Are measurements done in vacuum/gas representative for LXe?
- SiPMs are covered with a thin SiO_2 layer (FBK)
- For angles smaller than 45° the systematic error is small compared to other systematics



APD vs. SiPM

Source of fluctuations	APD	SiPM (2m^2)	SiPM (4m^2)
Efficiency: 12%*55% (APD) and 15% (SiPM)	1.3%	2.25%	1.57%
Dark noise fluctuation 50 Hz/mm^2	0	0.17%	0.12%
Correlated avalanche fluctuation	0	1.14%	0.80%
Gain fluctuation	1.4%	0.08%	0.06%
Electronics noise: ENCph = 198 (APD), 5 (SiPM)	3.7%	0.25%	0.18%
Total detector induced fluctuations (light only)	**4.2%**	**2.5%**	**1.8%**
LXe intrinsic fluctuations (light only)	5.4%	5.4%	5.4%
Light only resolution	**6.84%**	**5.98%**	**5.70%**
Combined with charge (800 e^- noise for charge)	**1.64%**	**1.04%**	**0.78%**
Contribution from LXe intrinsic to combined resolution		0.04%	0.04%
Contribution from charge noise to combined resolution		0.38%	0.38%
Contribution from light noise to combined resolution		0.97%	0.68%