LoLX : studying light in liquid xenon using SiPMs

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(On behalf of the LoLX Collaboration)

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Stony Brook University

Collaboration

LoLX

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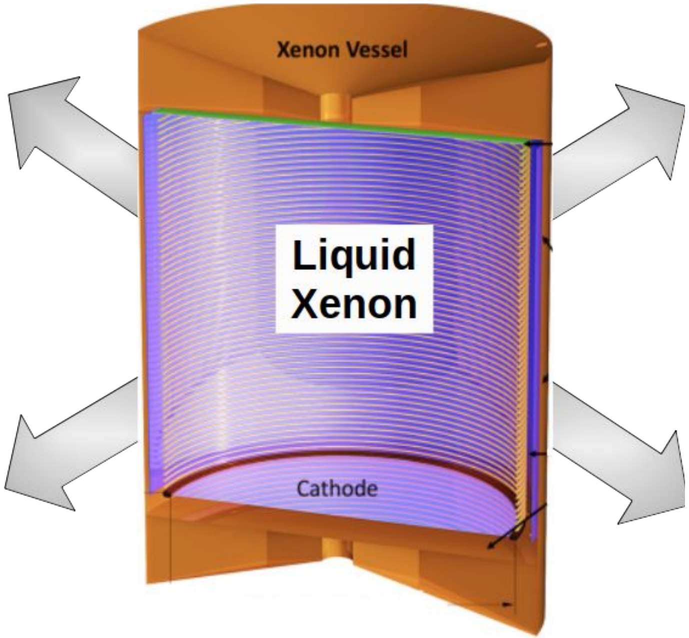
Liquid Xenon as a Detector

LoLX

Liquid xenon as medium for radiation detection
- First recognized in **1968**[1]

Since used in various applications



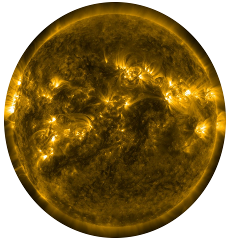
- High γ stopping power
  - ✔ Self shielding
- High density
  - ✔ Compact detector
- High ionization & scintillation yield
- Scintillates at 175 nm
  - ✘ Wavelength shifter
- Fast time response

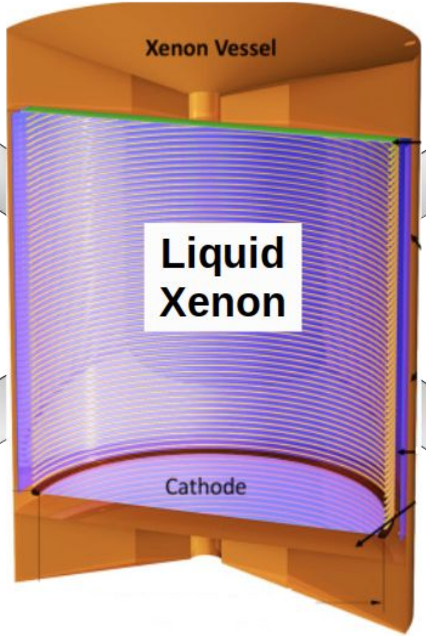
[1] Alvarez, L. W., 1968, Lawrence Radiation Laboratory, Physics Notes 672.

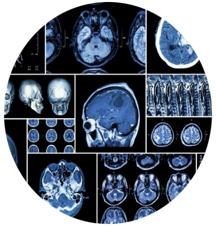
Liquid Xenon Detectors in Physics [2]

Direct Dark Matter Search

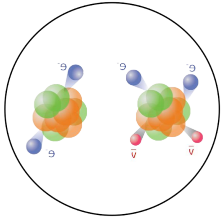
Gamma-Ray Astrophysics







Medical Imaging



Neutrinoless Double Beta Decay in ^{136}Xe

[2] A. Aprile, T. Doke, Rev.Mod.Phys.82:2053-2097 (2010)

Interaction in LXe

LoLX

Energy depositing event in liquid xenon (LXe)

- Ionization
- Excitation => scintillation (175 nm) [3]
- Cherenkov radiation => Broadband (> 150 nm)

nEXO

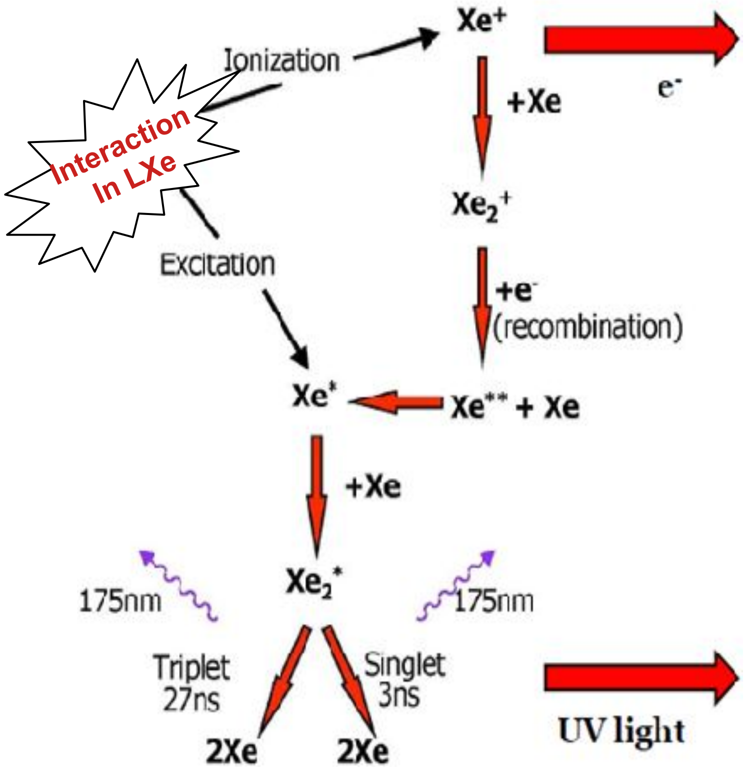


Fig. from N. Larsen (2012) Thesis Prospectus, Yale University

[3] M. Martin, J. Chem. Phys. 54, 3289 (1971)

Interaction in LXe : How to detect?

Energy depositing event in liquid xenon (LXe)

- Ionization
- Excitation => scintillation (175 nm) [3]
- Cherenkov radiation => Broadband (> 150 nm)

nEXO

Silicon Photomultipliers (SiPMs)

- fast, single photon counters
- Can be made radio-pure
- sensitive from UV to Visible

Ideal with LXe detectors for rare event searches

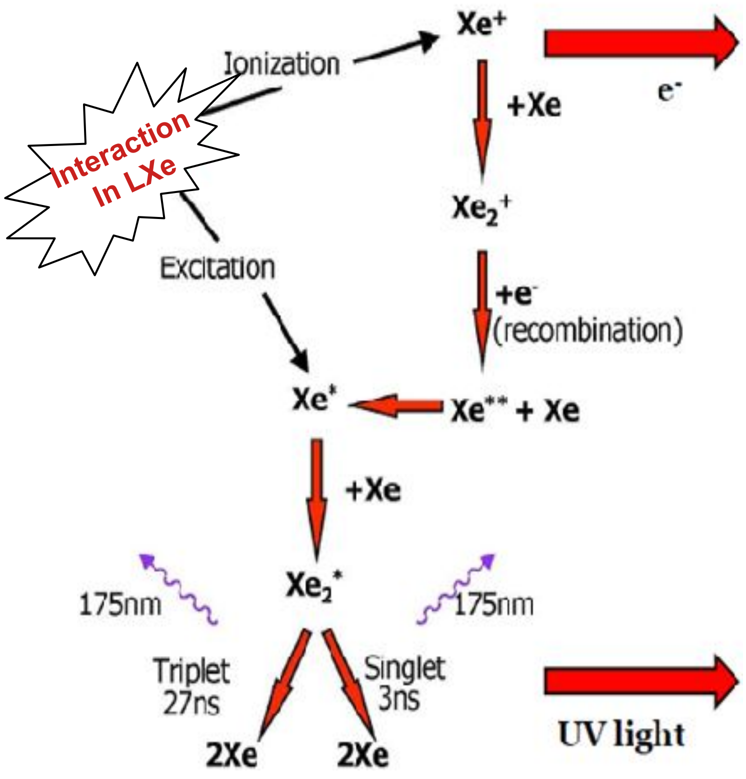


Fig. from N. Larsen (2012) Thesis Prospectus, Yale University

[3] M. Martin, J. Chem. Phys. 54, 3289 (1971)

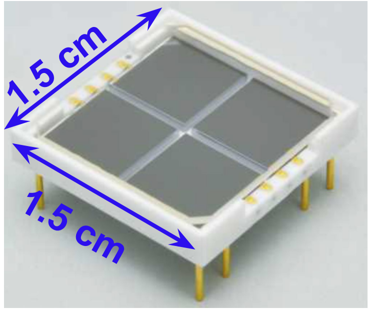
We developed a detector to

- Study behavior of multiple SiPMs in LXe and understand external cross-talk.
- Study the prompt light characteristics of LXe with fast electronics.
- Measure the Cherenkov and scintillation light yield in liquid xenon at zero electric field.

Light-only Liquid Xenon Experiment aka LoLX

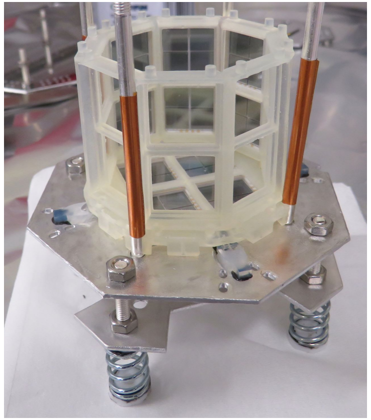
Experiment to characterize and validate performance of multiple **Silicon Photomultipliers** (SiPMs) in Liquid Xenon

- Modular, light signal only detector
- SiPMs mounted on 3D printed cage
- Immersed in liquid xenon

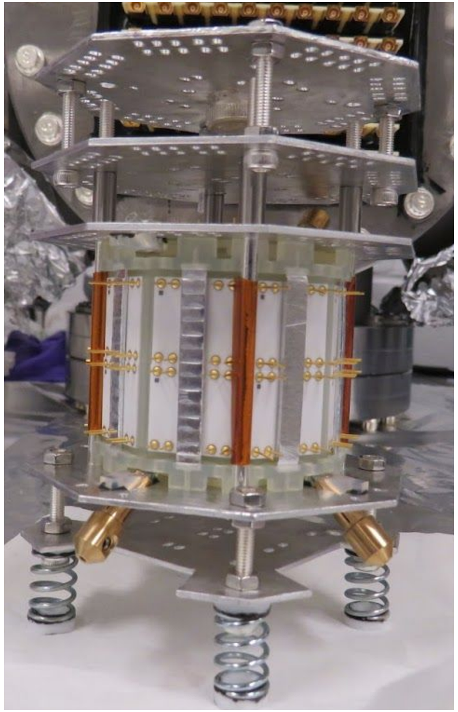


Hamamatsu VUV4 SiPM Quad

Pictures : LoLX photo archive



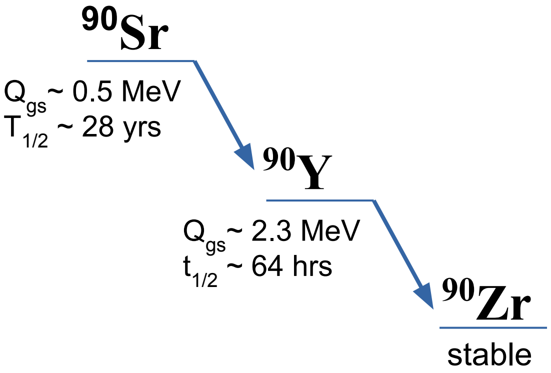
3D printed cage for holding the SiPM modules

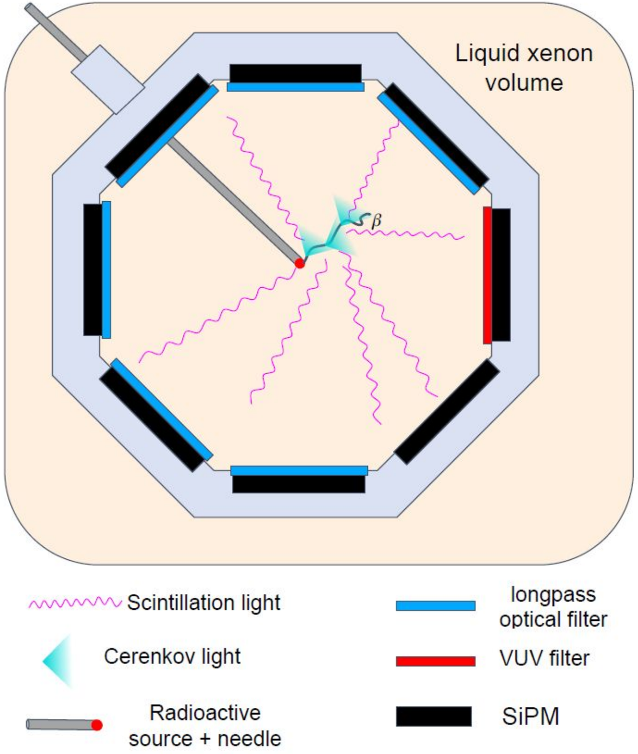


LoLX detector body, aluminum plates for cable routing

Detector Principle

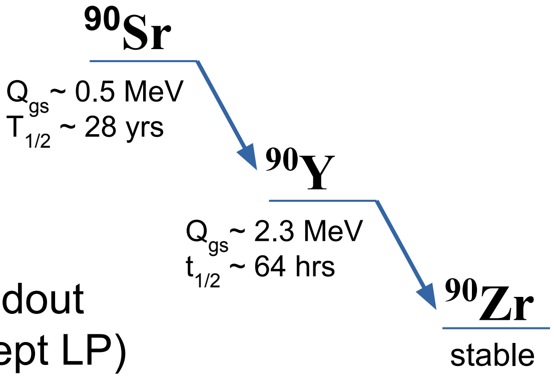
- Beta source

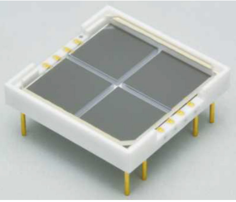




Detector Principle

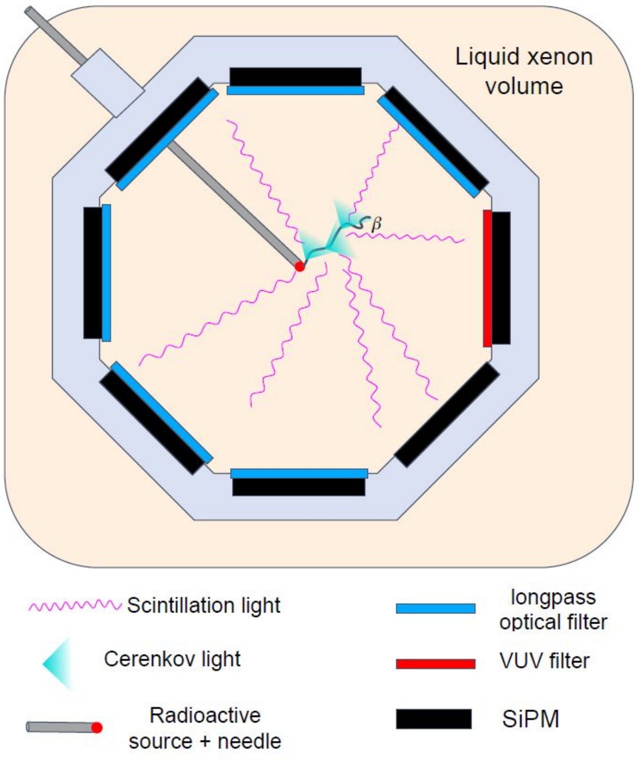
- Beta source





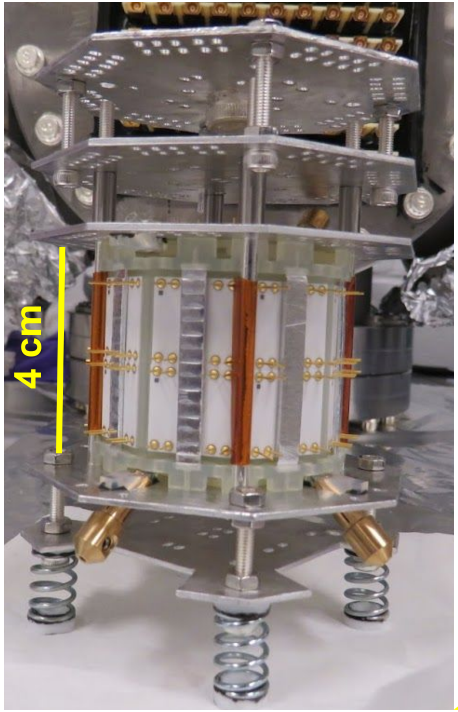
= 4 separate readout channels (except LP)

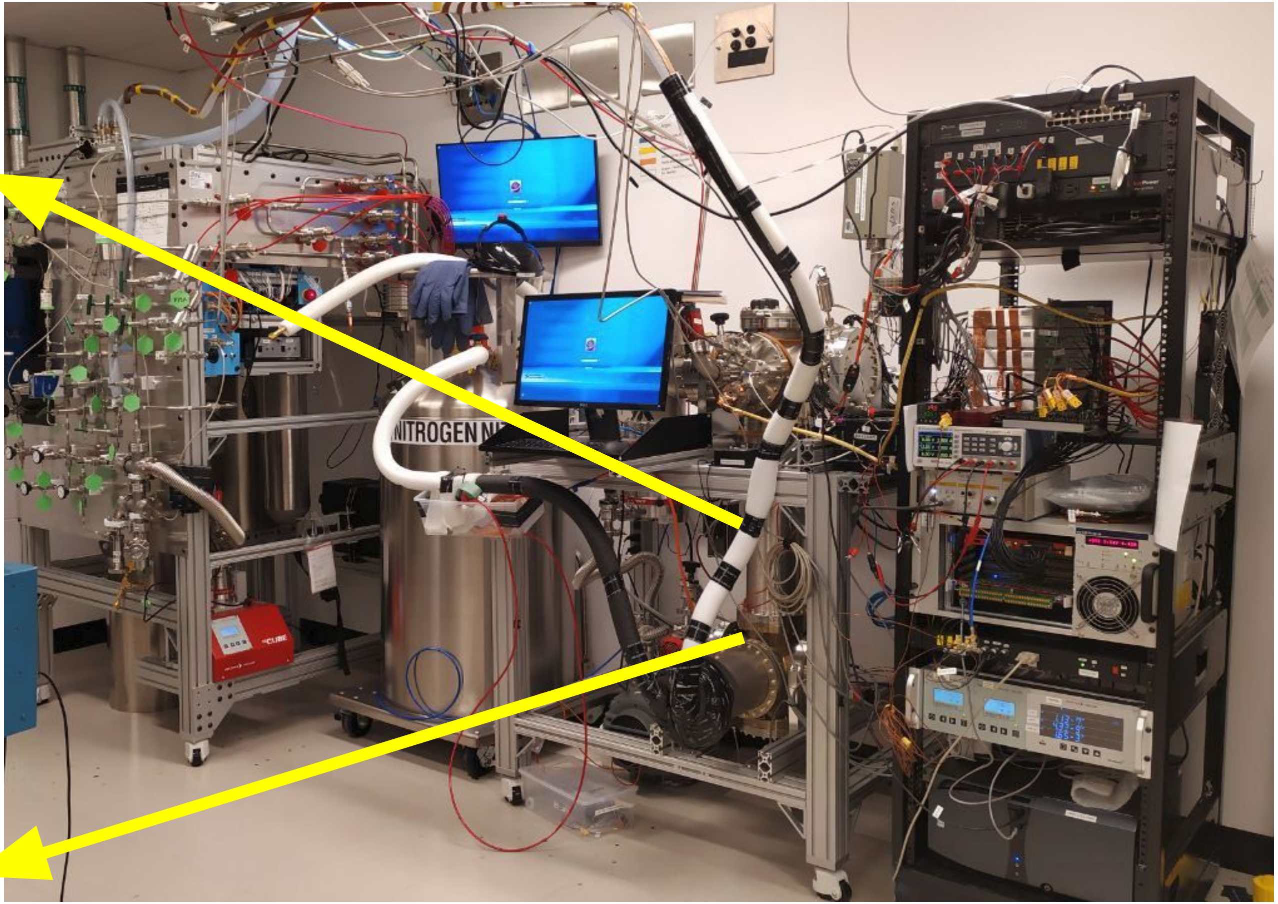
- 24 Hamamatsu[3] VUV4 SiPM modules (96 individual SiPM wafers)
  - 22 modules with long-pass filter : Cherenkov (λ> 225 nm)
  - 1 module with band-pass filter centered at 175 nm : Scintillation
  - 1 module with no filter : everything



[3] Gallina *et al.*, NIM **940** (2019) 371-379

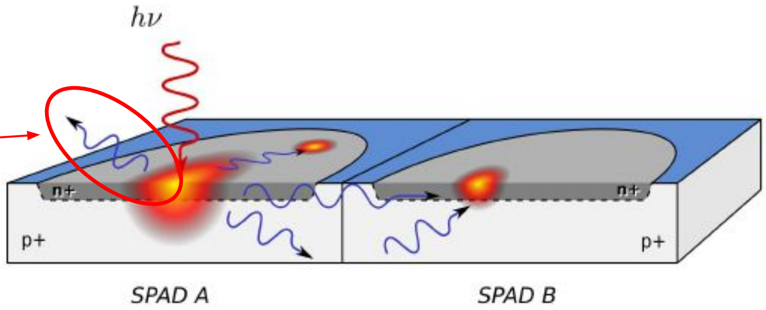
LoLX in BNL at McGill in June 2022





External Cross Talk

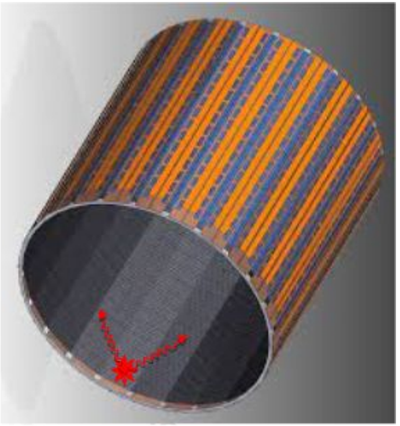
Could trigger an avalanche in neighboring SiPM aka **eXT**



Schematic representation of optical crosstalk between two SiPM SPADs. Figure from Rech *et al.* [4]

- Photon avalanche can create **visible to infrared** photons that could potentially trigger other SiPMs → **external cross talk (eXT)**
- Depending on detector geometry, eXT could affect photon counting statistics and thus **energy resolution**

LoLX : study the probability of eXT and angular distribution



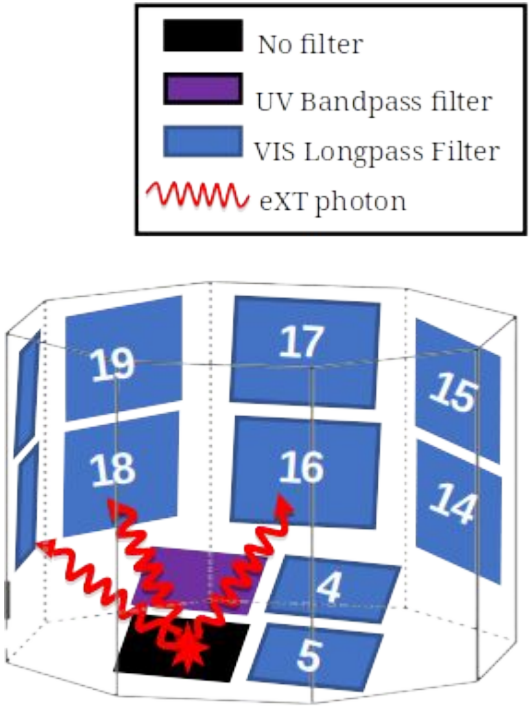
nEXO stave, conceptual design
arXiv:1806.02220 [physics.ins-det]

[4] I. Rech et al, (2008) https://doi.org/10.1364/OE.16.008381.

External Cross Talk

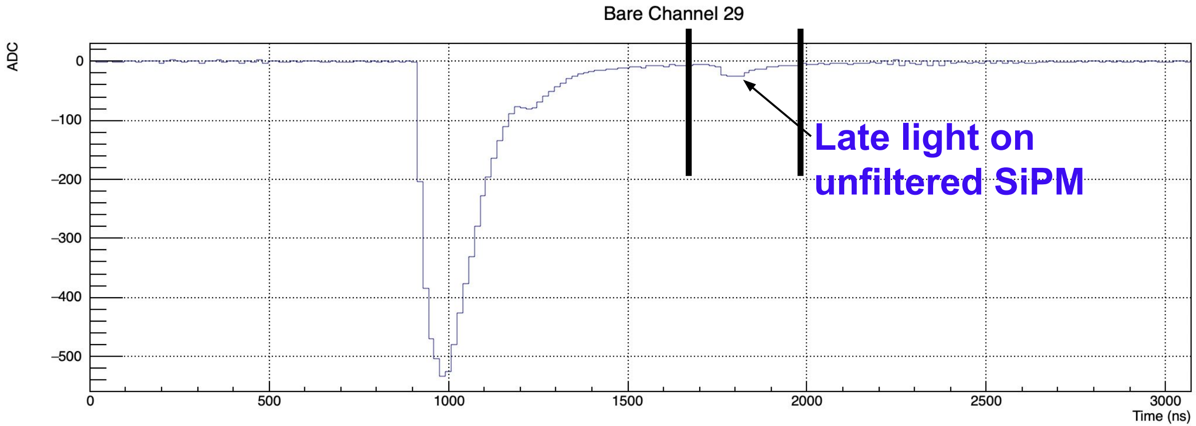
LoLX

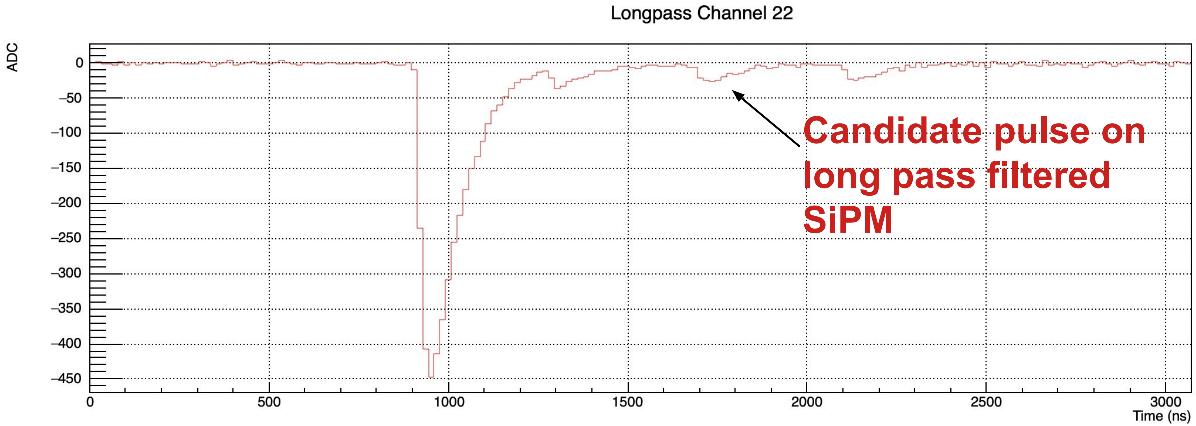
1. **Late pulses on unfiltered SiPMs (900-1500 ns after primary event)**
   - Correlated pulses on long pass filtered SiPMs in ΔT window [-100, 300] ns.
   - Scan over multiple voltage settings (same over voltage on all SiPMs)
2. **GEANT4 simulations to further understand experimental results and get angular dependance**



Schematic of the LoLX cage.

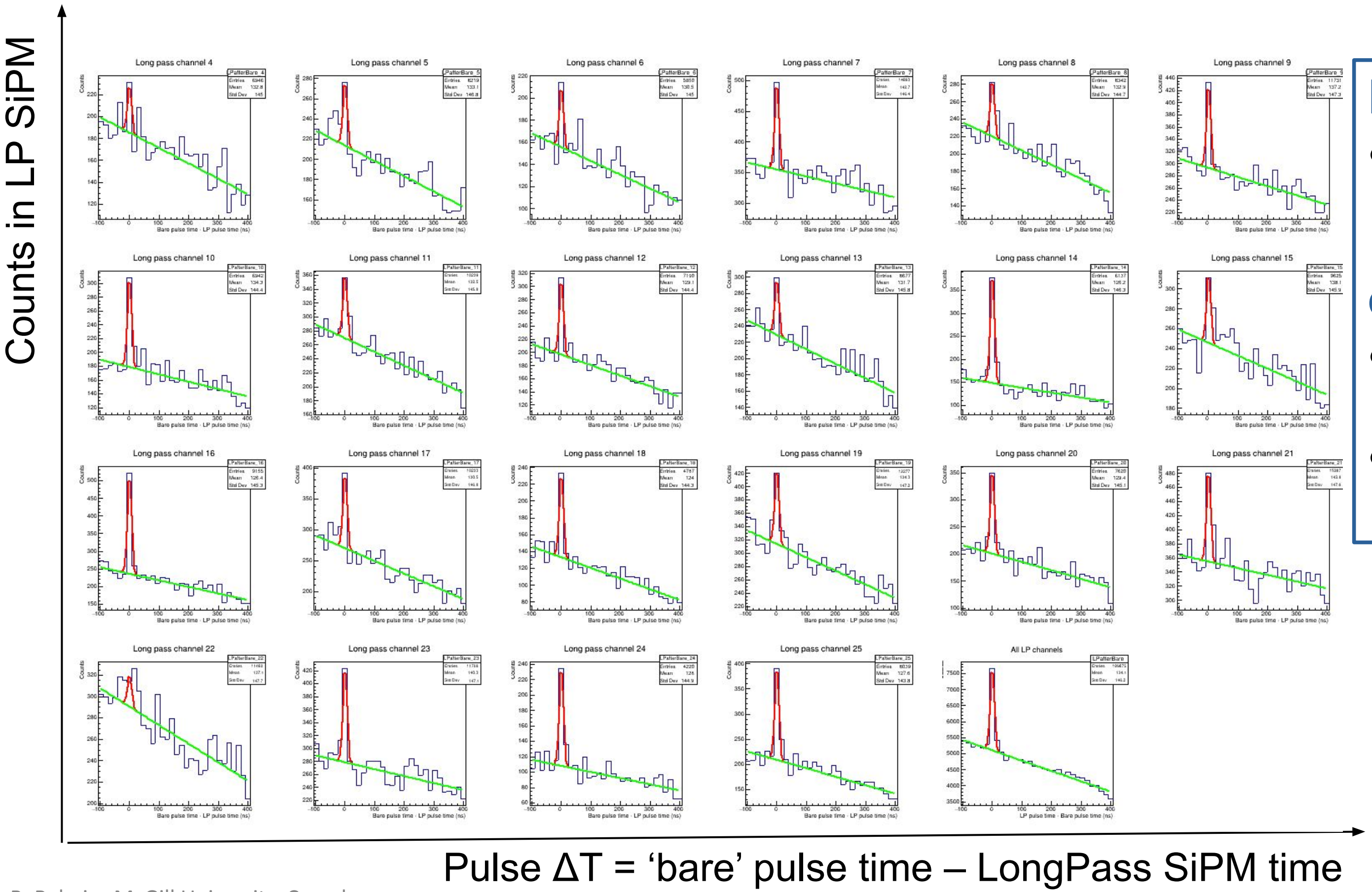
External Cross Talk : Data





1. Event trigger threshold 2 photon avalanche (2PE) on bare SiPM.
2. Late pulses on **unfiltered** SiPM
   a. 900-1500 ns after primary pulse
   b. eXT threshold < 2PE
3. Subsequent pulses on Long pass filtered SiPMs
   a. [-100, 300] ns around bare SiPM pulse
4. ΔT = pulse time(bare SiPM - LP SiPM)

External Cross Talk : Data



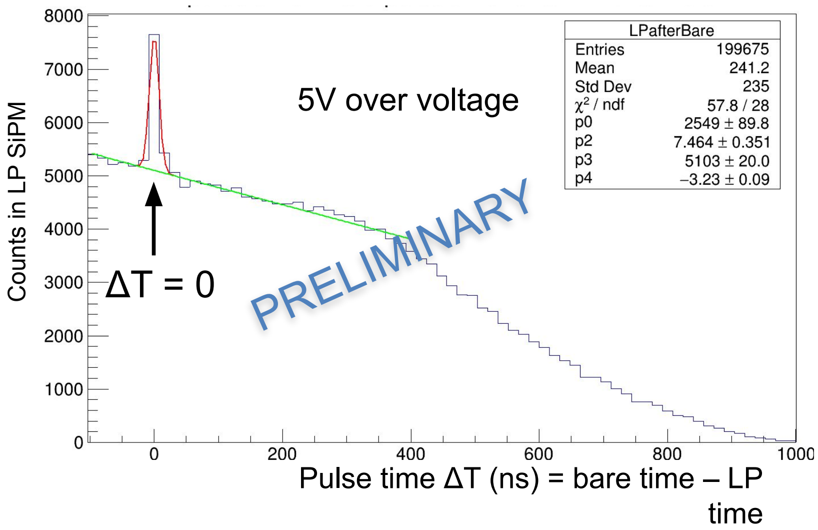
Fit function

- Gaussian + linear background

eXT signal : prompt

- Mean of Gaussian fixed at zero
- CAEN V1740 timing resolution 16ns

External Cross Talk : Data



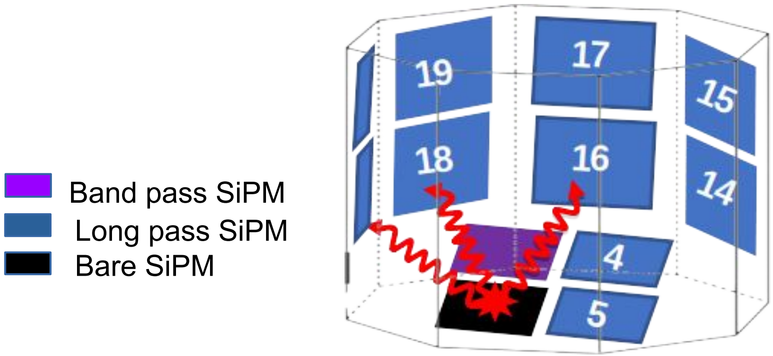
Probability of correlated hits on **summed** long pass channels

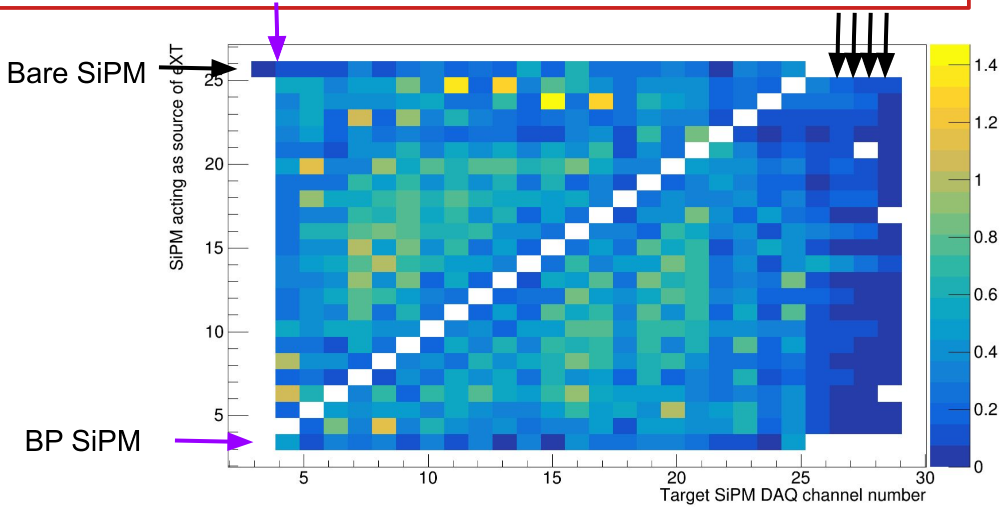
$$Prob = \frac{Total\ counts - background}{Counts\ \ bare\ \ SiPM}$$

- At **4V** OV : 3.4 ± 0.2* %
- At **5V** OV : 6.6 ± 0.3* %

PRELIMINARY

*Statistical uncertainties only





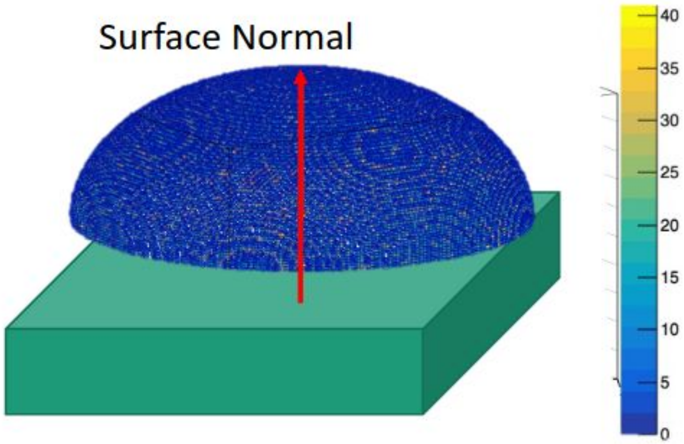
Correlated hit probability (%) from source to target SiPM

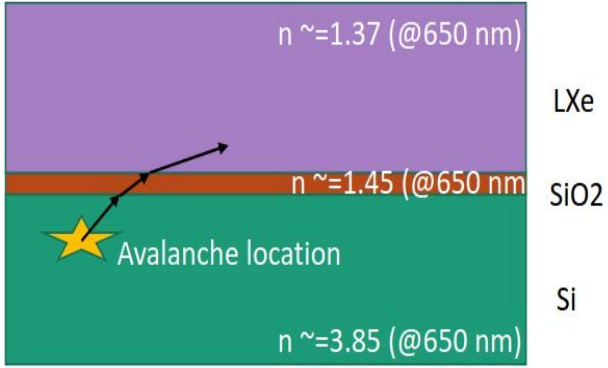
External Cross Talk : Monte-Carlo

Cannot say for sure if bare SiPM was source or target :
CAN choose source SiPM in simulations

MC Simulations using GEANT4 with modified **G4OpBoundaryProcess** class

- Photon bomb isotropically distributed in hemisphere
- Hit on **Unfiltered SiPM** creates eXT photons
  - photons flagged as eXT
  - eXT photon emission follows SiPM+LXe optics, thus accounting for refraction at interfaces (~96% reduction of flux at 650 nm)
  - Emission intensity as function of wavelength based on measured data [McLaughlin *et al.* Sensors **2021**, *21*(17), 5947; https://doi.org/10.3390/s21175947].



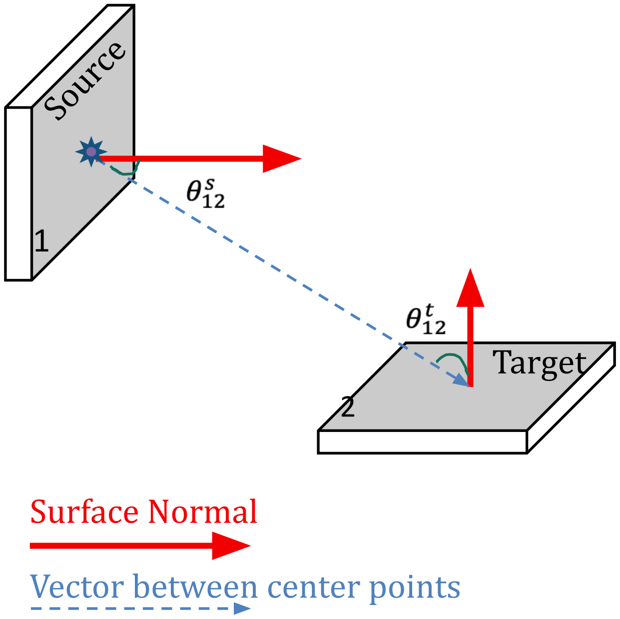


External Cross Talk : Monte-Carlo

Cannot say for sure if bare SiPM was source or target :
CAN choose source SiPM in simulations

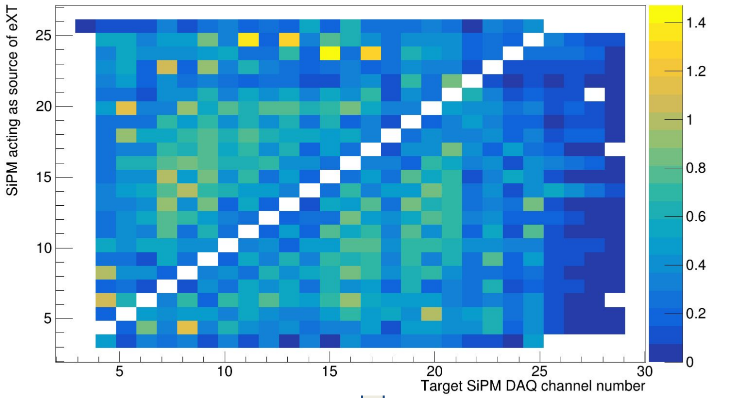
MC Simulations using GEANT4 with modified **G4OpBoundaryProcess** class

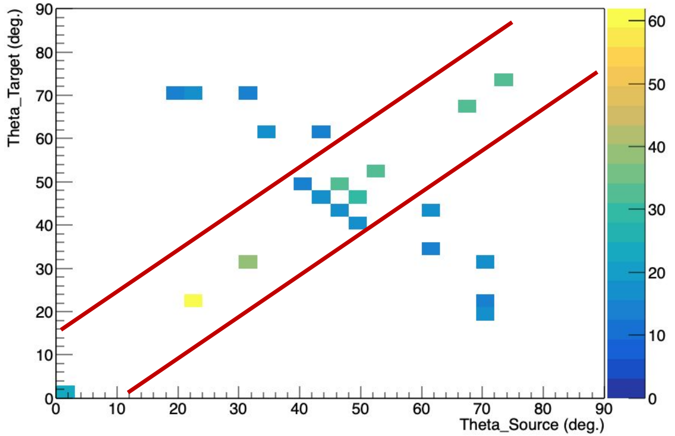
- Control eXT parameters :
  - Source SiPM orientation (θ^{s}_{12}) => affects angle of emission of eXT photon
  - Target SiPM orientation (θ^{t}_{12}) => depends on detection efficiency
  - Optical transport efficiency in near infrared



External Cross Talk : Results

- Correct experimental probability for solid angle
- Select SiPM pairs with similar angular acceptance
  - Easier interpretation of results when SiPMs facing each other





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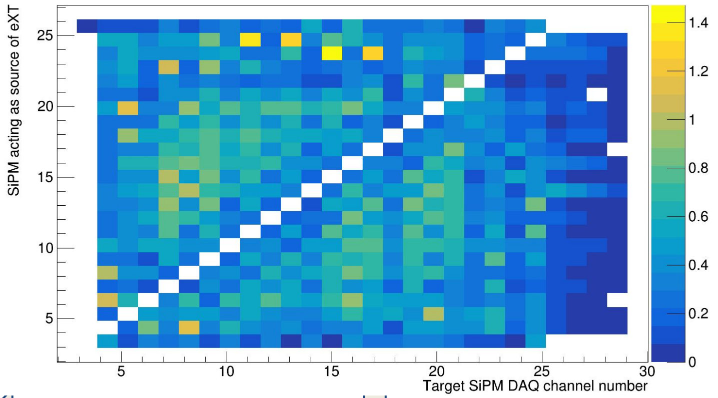
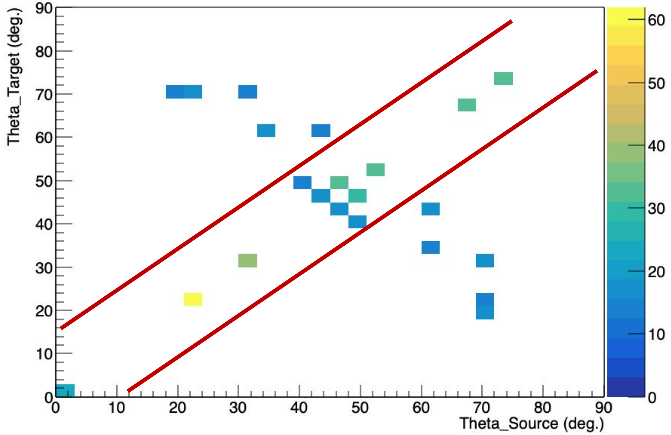
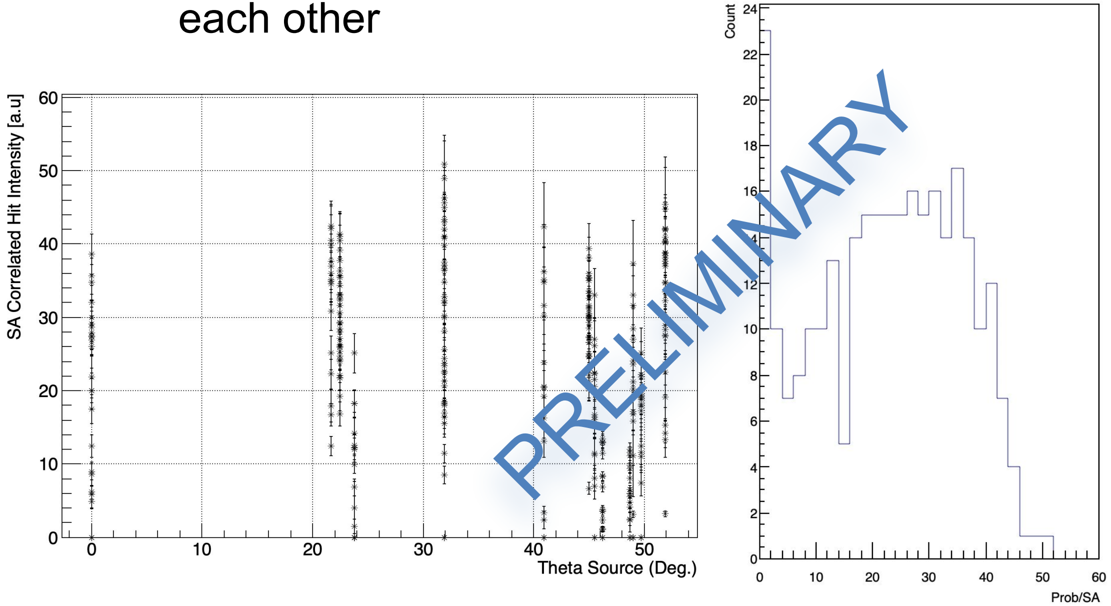






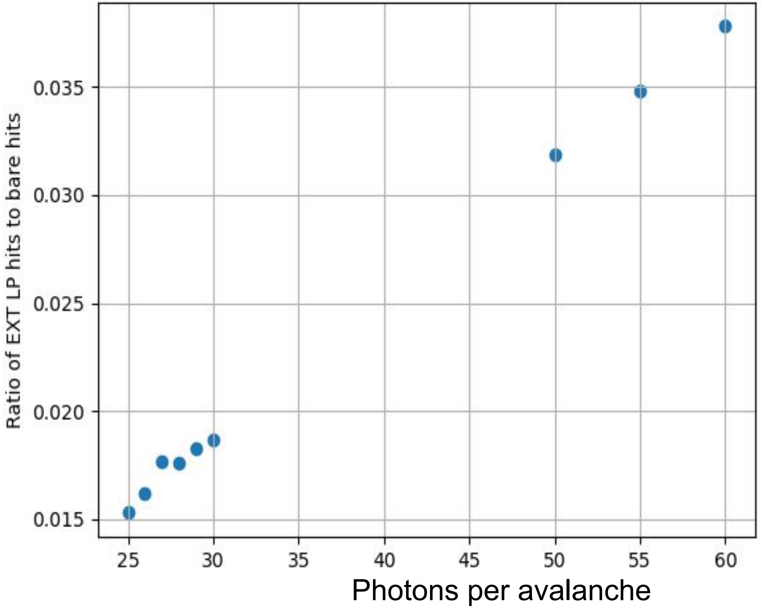
Left - Comparison of SA Scaled Correlated Hit Probability for a selection of LoLX SiPM pairs, 5V OV bias. **Right** – 1D projection of left plot along y-axis

External Cross Talk : Results

L💡LX

- Correct experimental probability for solid angle
- Select SiPM pairs with similar angular acceptance
  - Easier interpretation of results when SiPMs facing each other

- At 4V oV, simulations predicts ~55 photons/avalanche to match experimental data
  - Assuming conservatively 50% contribution from backward correlation (LP= source, Bare=target)
  - Correcting for hemisphere of emission
  - **On average about 15-20 photons/avalanche**



PRELIMINARY!!

External Cross Talk : To do …

Correct experimental results for systematics

- Choice of bare pulse time window
- Effect of temperature (value of 1PE threshold)

Need experimental inputs to improve simulations

- Wavelength of eXT photon wrt angle (TRIUMF)
- SiPM efficiency in NIR (TRIUMF).
- Optical response of filters to NIR photons.
- SiPM efficiency vs NIR incidence angle.
- Angular distribution of emitted photons in liquid xenon

Manuscript coming up soon …

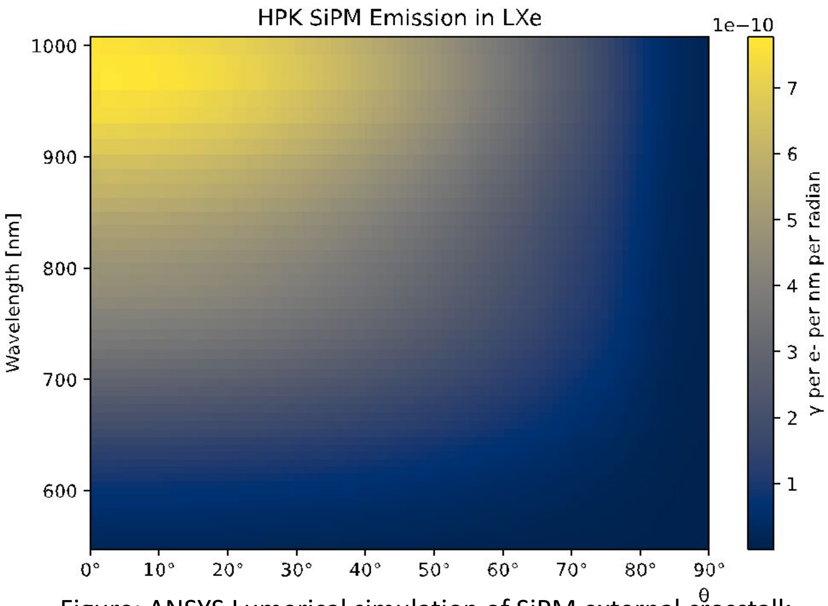
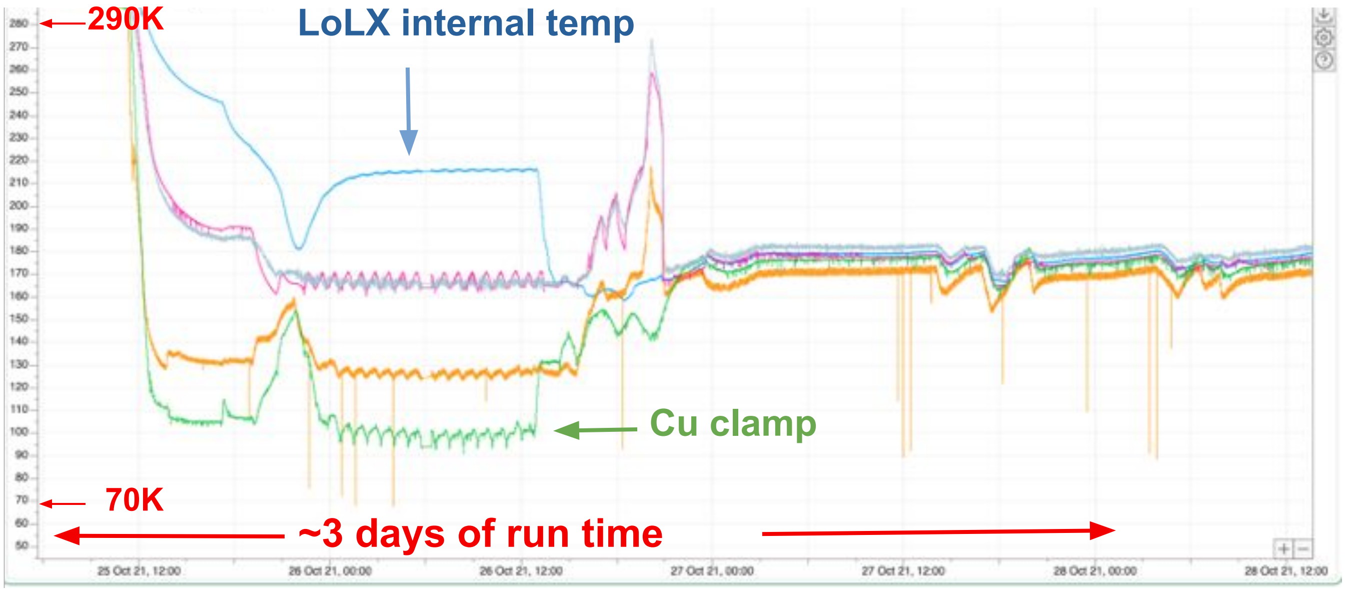


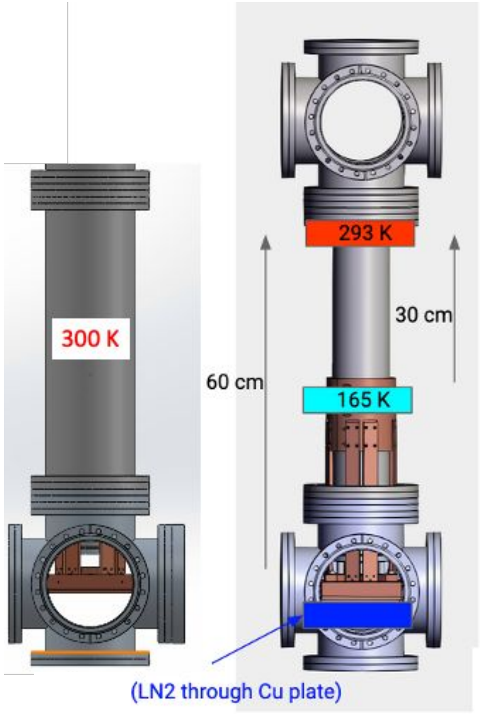
Figure: ANSYS Lumerical simulation of SiPM external crosstalk from Hamamatsu VUV4-Q in LXe, z-axis is scaled to **preliminary** results from TRIUMF on EXT emission measurements vs SiPM current

LoLX : looking forward…

Long-term SiPM stability studies require stable LXe environment.

- Current system using liquid nitrogen to cool : difficult to maintain steady temperatures over long time periods

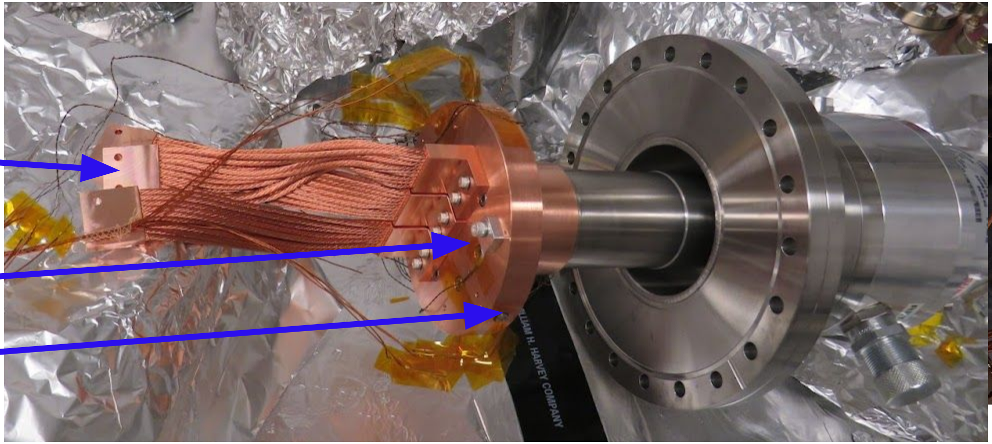




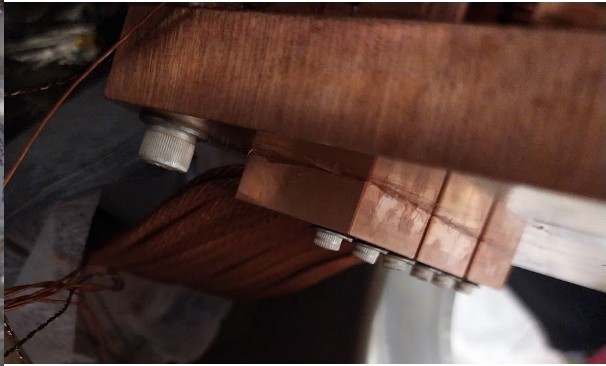
LoLX : looking forward…

Long-term SiPM stability studies require stable LXe environment.

- Upgrade to cryo-cooler completed in **November 2022**
  - 4x highly precise RTDs + 6x cartridge heaters installed.
- **Dec 2022**, will test the upgraded cryogenics and run with xenon in Jan 2023



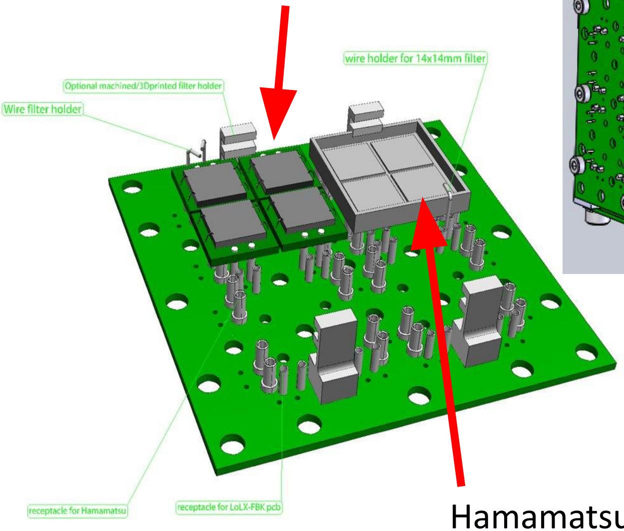
Cold head with RTDs and heaters

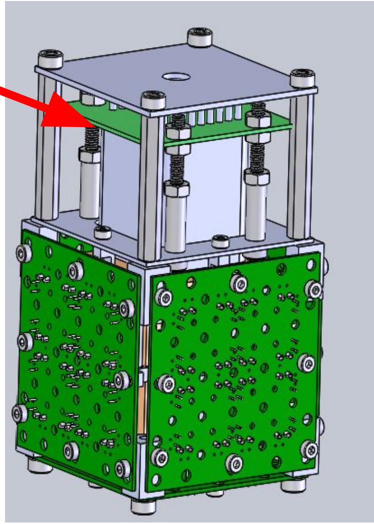


Cu straps coupled to mount plate

LoLX^2 : next generation LoLX

- Test 40 Hamamatsu and 40 FBK SiPMs under same experimental conditions
  - Photo detector efficiency
  - long term stability
- VUV sensitive PMT (Hamamatsu R8520-406)
  - Comparison for SiPM PDE measurement
- Upgraded DAQ : WAVEDAQ from MEGII
  - Tuneable sampling speed : 1 GHz - 3GHz
  - Commissioned in Nov 2021 with GXe
- Opportunity for further studies
  - LXe scintillation at higher time resolution
  - Ratio of cherenkov/scintillation yield





Summary

LoLX

LoLX : light-signal only liquid xenon detector

- Can study multiple VUV SiPMs at LXe temperatures
- External cross talk of SiPMs in a closed geometry
- Perform long-term SiPM stability studies
- Faster DAQ with 1- 3 GHz sampling speed
  - Probe LXe microphysics at sub-nanosecond level
- We welcome new collaborations to join on this exciting journey

thank you