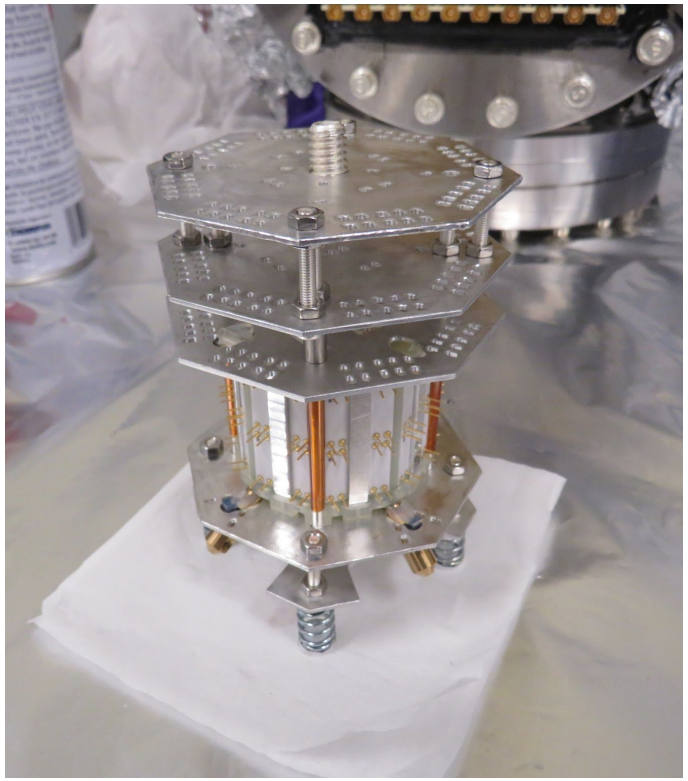
Light only Liquid Xenon experiment (LoLX)

Physics goals and Nitrogen Gas Commissioning



Austin de St. Croix

Queen's PhD Student at TRIUMF

TIPP 2021

Discovery, accelerated

LoLX Collaboration:

TRIUMF

Fabrice Retière, Austin de St. Croix, Peter Margetak, Aleksey Sher, Liang Xie, Mayur Patel

McGill

Thomas Brunner, Soud Al Kharusi, Thomas McElroy, Christopher Chambers, Xiao Shang, Eamon Egan

Carleton UNIVERSITY

Simon Viel, Bindiya Chana, Damian Goeldi

SNOLAB

Pietro Giampa

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

Luca Galli
Marco Francesconi
Simone Stracka

UNIVERSITÉ DE SHERBROOKE

Marc-André Tétrault
Julien Roy-Sabourin

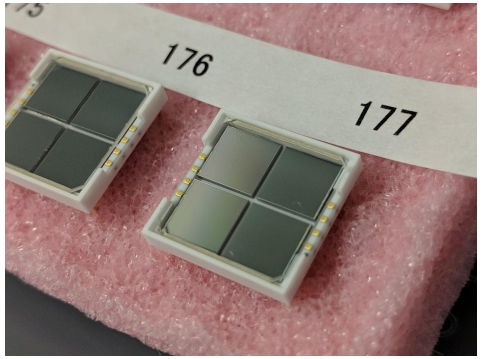
LoLX Overview and Phases

Detector

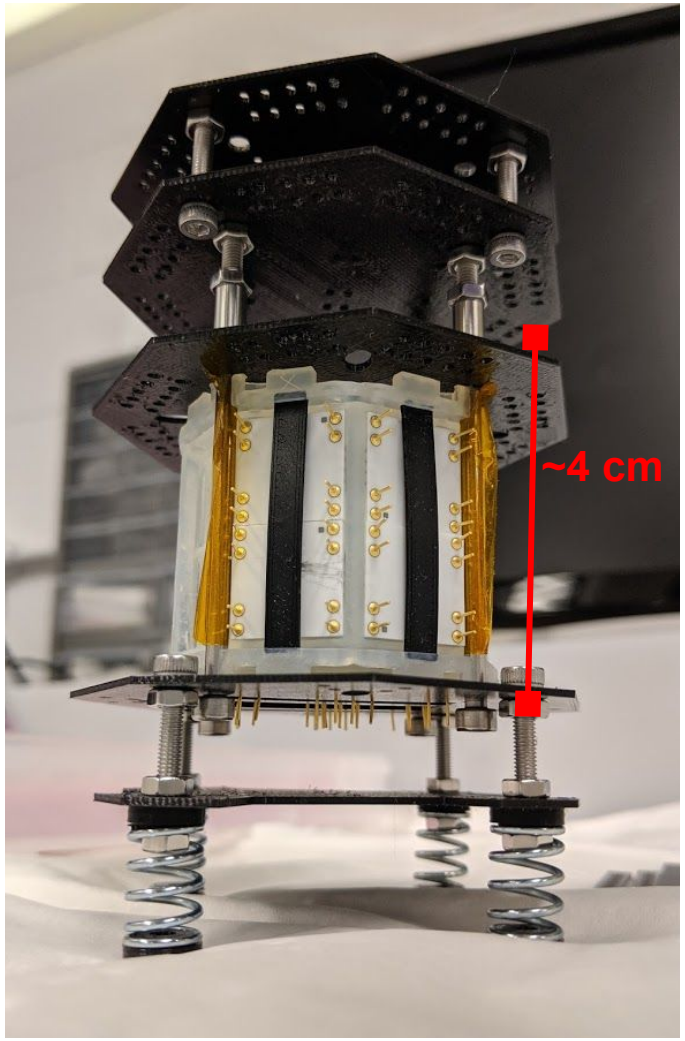
- Single phase LXe, zero applied field
- silicon photomultipliers (**SiPM**s) for light collection
- design focus is *high speed timing*

Main Physics Goals

- measure **Cherenkov** and scintillation yields
- study prompt light characteristics
- external cross-talk in SiPMs



VUV4 SiPMs (w/ quartz window)



LoLX prototype detector body, black pieces for cable routing (McGill)

LoLX Overview and Phases

Detector

- Single phase LXe, zero applied field
- silicon photomultipliers (**SiPM**s) for light collection
- design focus is *high speed timing*

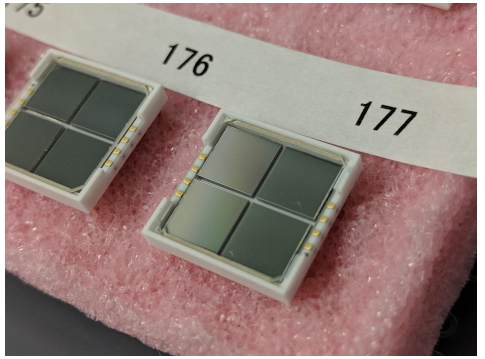
Main Physics Goals

- measure **Cherenkov** and scintillation yields
- study prompt light characteristics
- external cross-talk in SiPMs

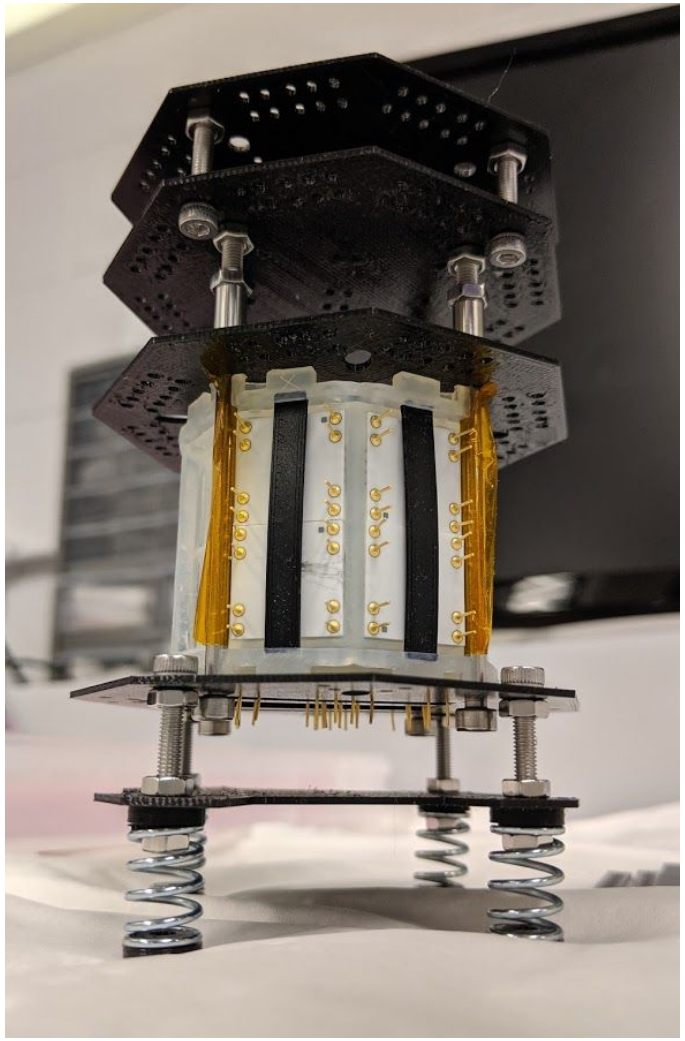
Experimental Phases

Phase 1: Separation using optical filters, slow digitizer, Hamamatsu SiPMs

~ few ns resolution



VUV4 SiPMs (w/ quartz window)



LoLX prototype detector body, black pieces for cable routing (McGill)

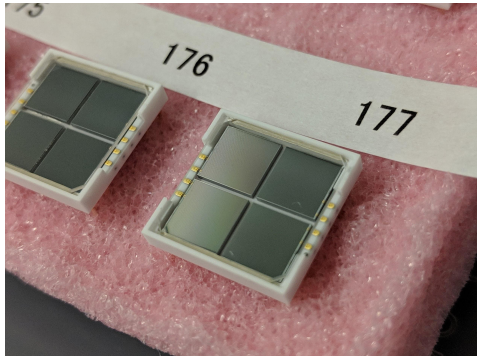
LoLX Overview and Phases

Detector

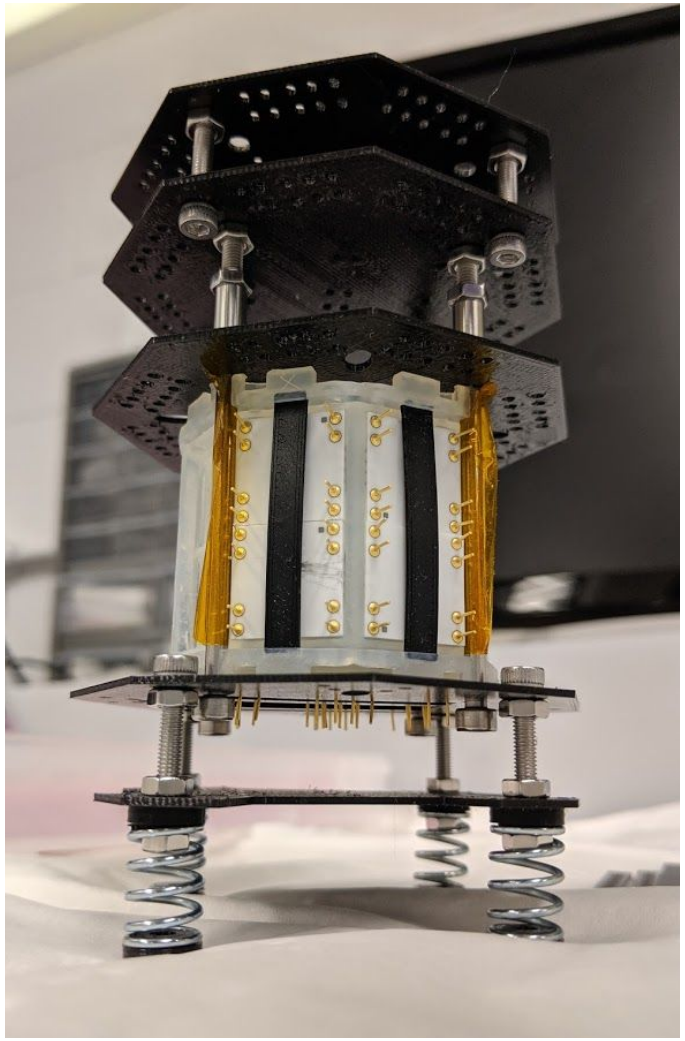
- Single phase LXe, zero applied field
- silicon photomultipliers (**SiPM**s) for light collection
- design focus is *high speed timing*

Main Physics Goals

- measure **Cherenkov** and scintillation yields
- study prompt light characteristics
- external cross-talk in SiPMs



VUV4 SiPMs (w/ quartz window)



LoLX prototype detector body, black pieces for cable routing (McGill)

Experimental Phases

Phase 1: Separation using optical filters, slow digitizer, Hamamatsu SiPMs
~ few ns resolution

Phase 2: upgrade to GHz digitizer (from MEG2 experiment)
~ 100ps resolution?

Phase 3: Digital SiPMs, temporal separation of **Cherenkov** and scintillation light
~ 10ps resolution?

The Detector (Phase 1)

Optical filters

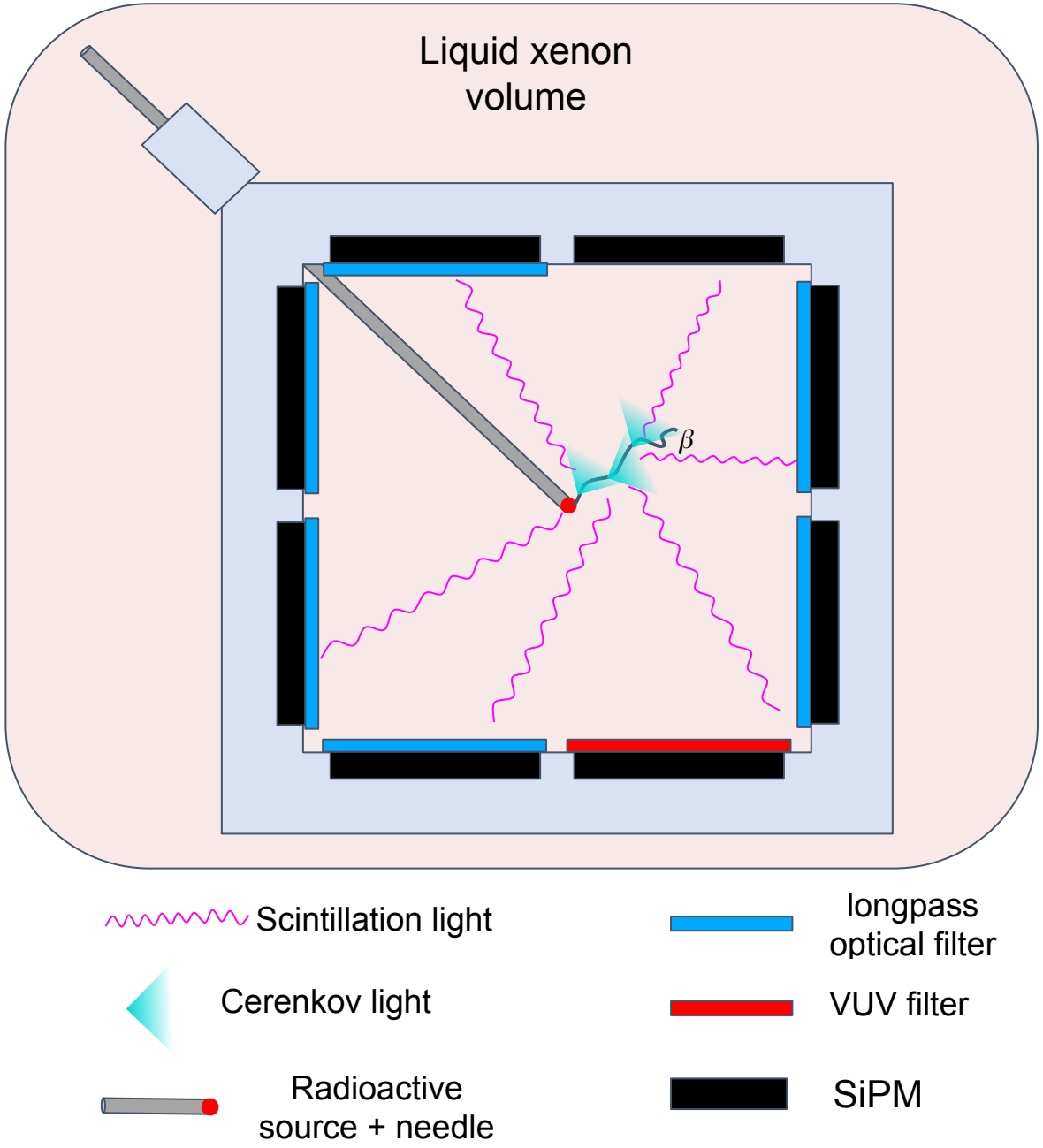
- separate **Cherenkov** and scintillation light

24 Hamamatsu VUV4 SiPMs

- efficiency ~15% at 175 nm (see ref [5])
  (LXe scintillation wavelength)
- 1.5cm x 1.5cm

Radioactive sources placed on needle tip, 370 Bq

- Sr-90 beta (0.55 MeV) → Y-90 beta (2.28 MeV)
- Po-210 alpha (5.4 MeV)
  - not installed



The Detector (Phase 1)

Optical filters

- separate **Cherenkov** and scintillation light

24 Hamamatsu VUV4 SiPMs

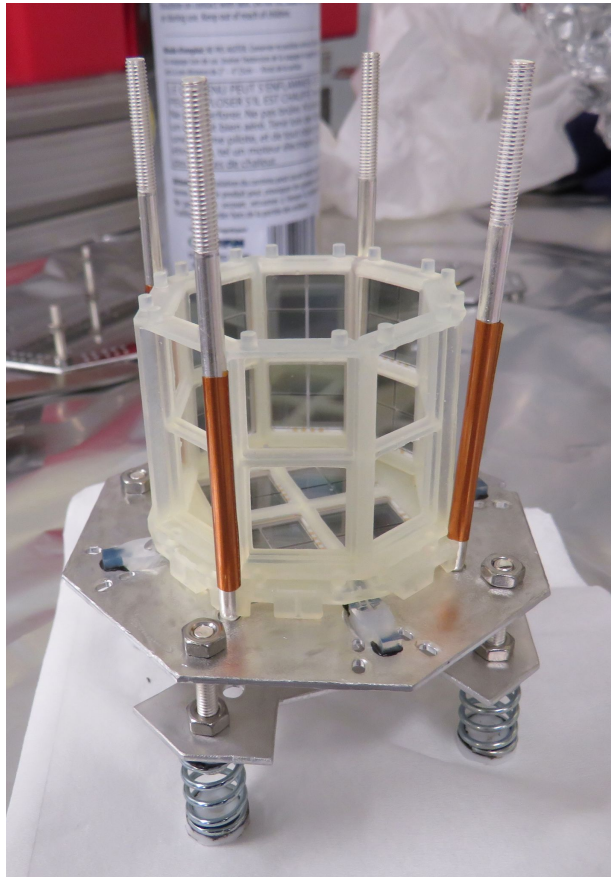
- efficiency ~15% at 175 nm (see ref [5])
  (LXe scintillation wavelength)
- 1.5cm x 1.5cm

Radioactive sources placed on needle tip, 370 Bq

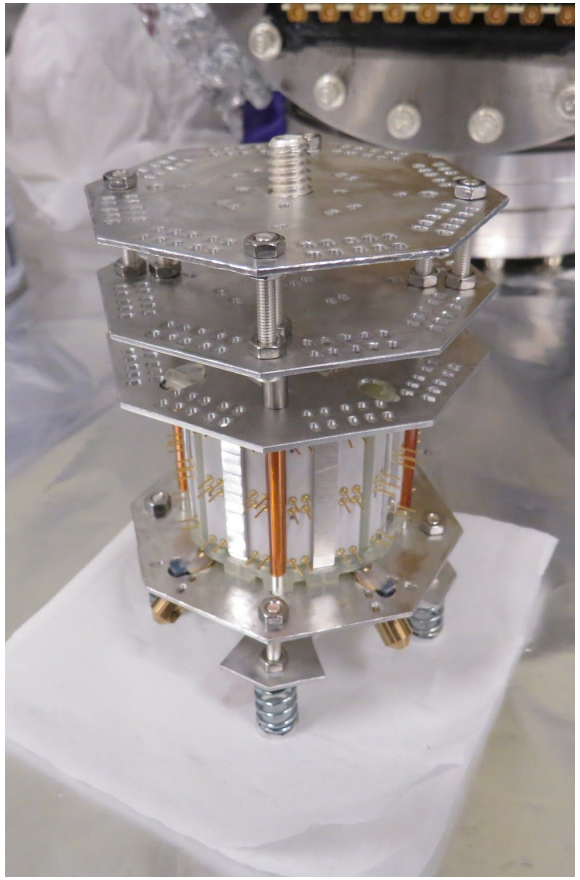
- Sr-90 beta (0.55 MeV) → Y-90 beta (2.28 MeV)
- Po-210 alpha (5.4 MeV)
  - not installed

Body is hexagonal prism

- 3D printed body, 'Formlabs SLA 3D Durable Resin'
- ~ 60% photo coverage



Partially assembled body (McGill)



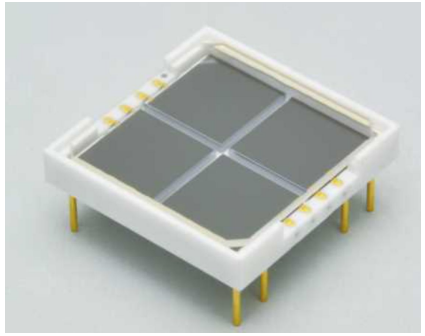
Assembled, unwired body (McGill)
plates for cable routing

SiPM Layout

24 Silicon Photomultipliers

- Each SiPM has 4 readouts

  ↳ 96 outputs



results in lots of cables!

SiPM Layout

24 Silicon Photomultipliers

- Each SiPM has 4 readouts

  ↳ 96 outputs

22 Cherenkov SiPMs: Longpass optical filter

↳ blocks scintillation light

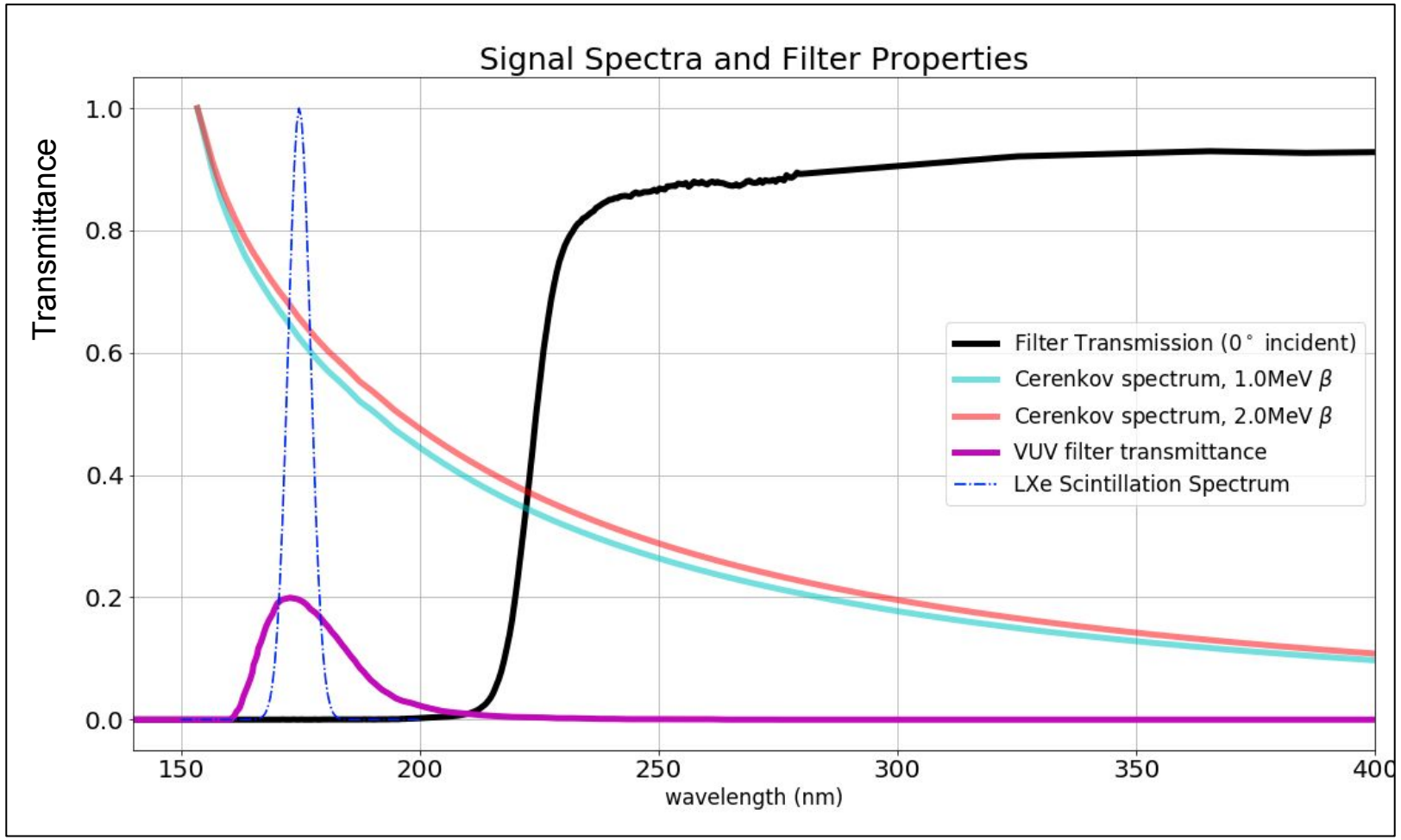
1 Scintillation SiPM: UV bandpass filter

↳ allows only scintillation light

1 bare SiPM

↳ view scintillation and **Cherenkov** light

↳ emit cross-talk photons



SiPM Layout

24 Silicon Photomultipliers

- Each SiPM has 4 readouts

  ↳ 96 outputs

22 Cherenkov SiPMs: Longpass optical filter

↳ blocks scintillation light

4ch summing → **+22** digitized channels

1 Scintillation SiPM: UV bandpass filter

↳ allows only scintillation light

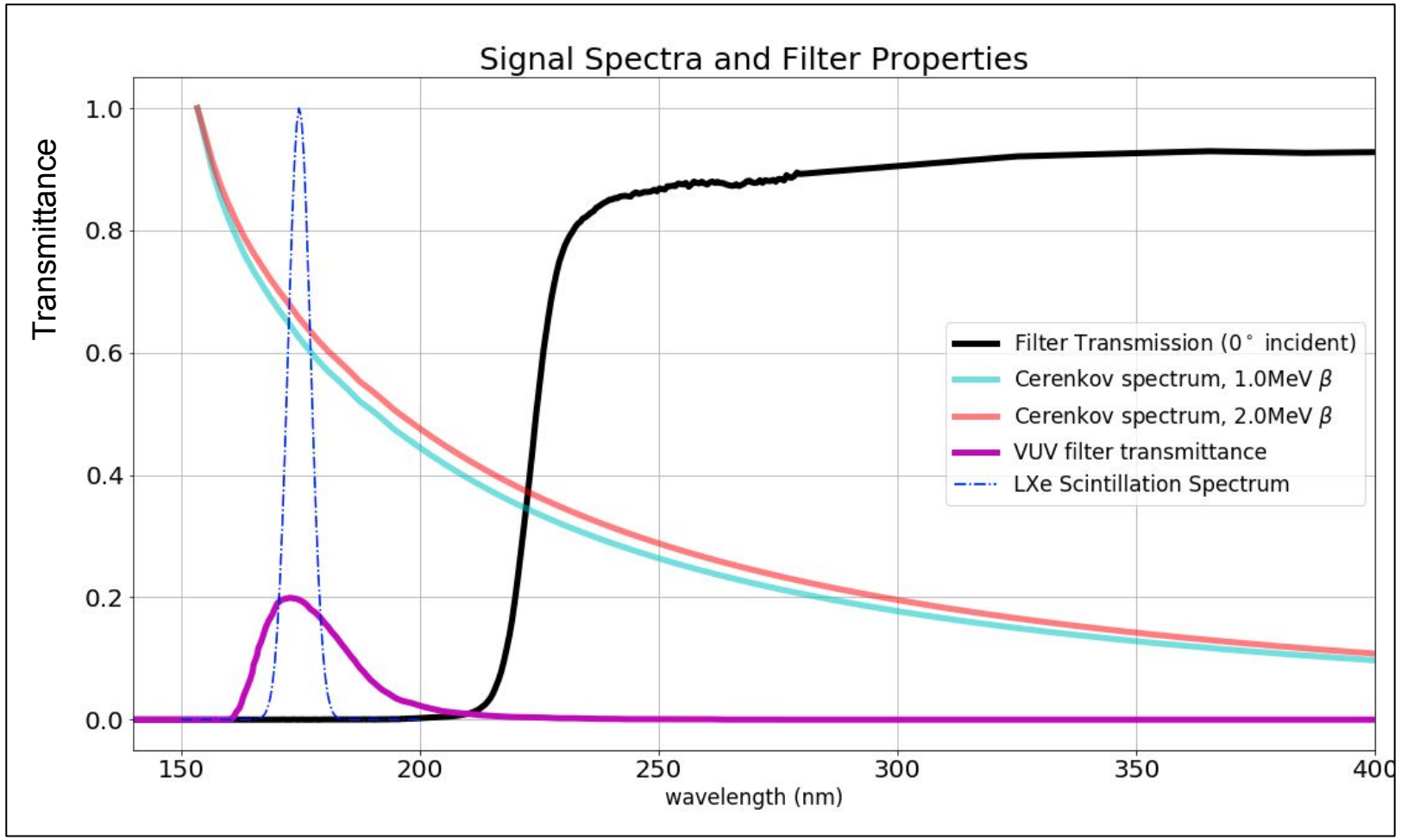
no summing → **+4** channels

1 bare SiPM

↳ view scintillation and **Cherenkov** light

↳ emit cross-talk photons

no summing → **+4** channels



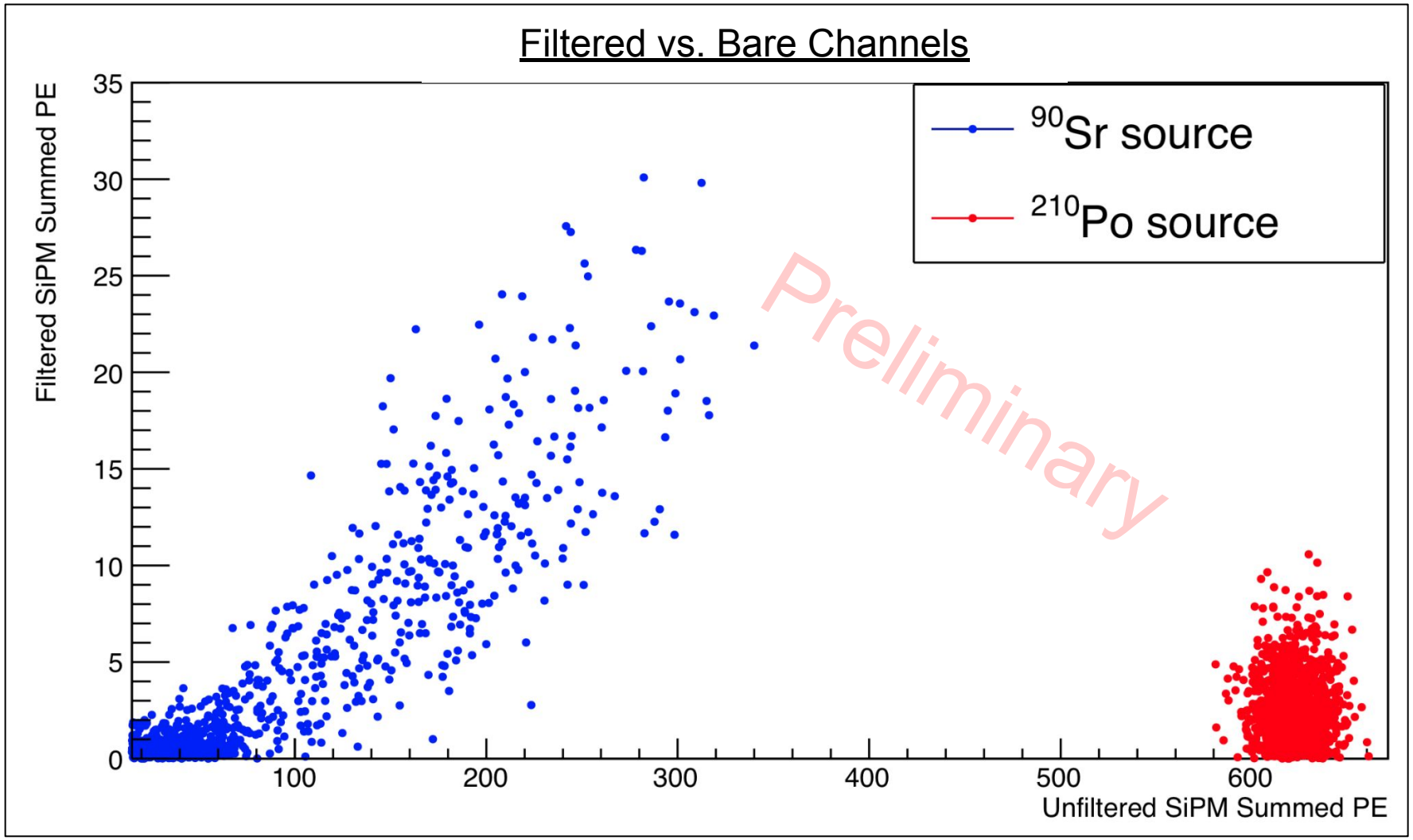
8 + **22** = 30 digitized channels

Simulation

- detector simulated in GEANT4

- preliminary optical data used for detector

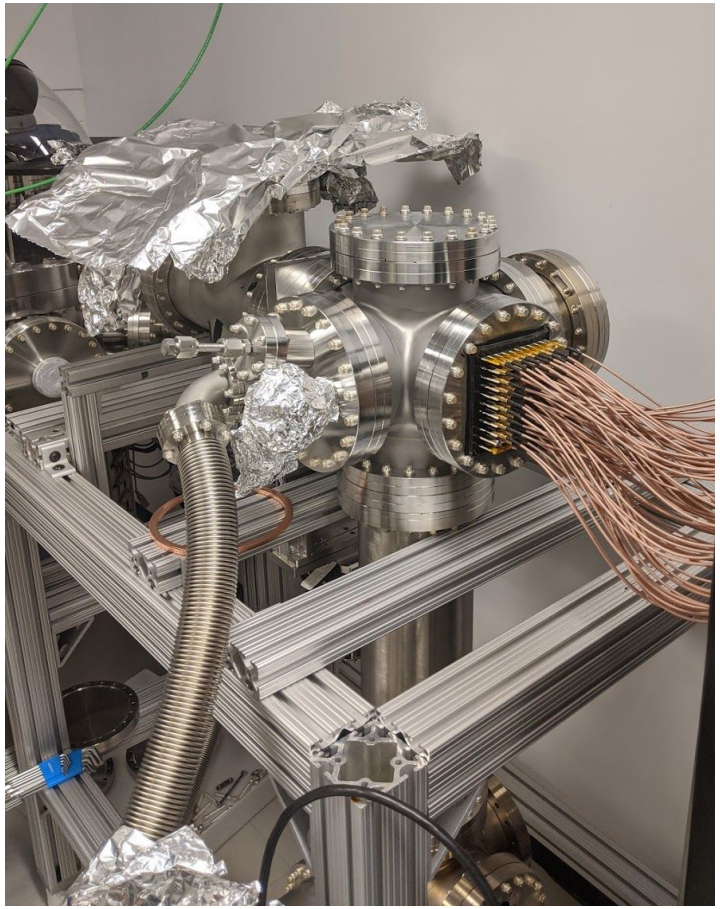
- separation between alpha and beta events



^{90}Sr - Q = 2.28 MeV

^{210}Po - Q = 5.4 MeV

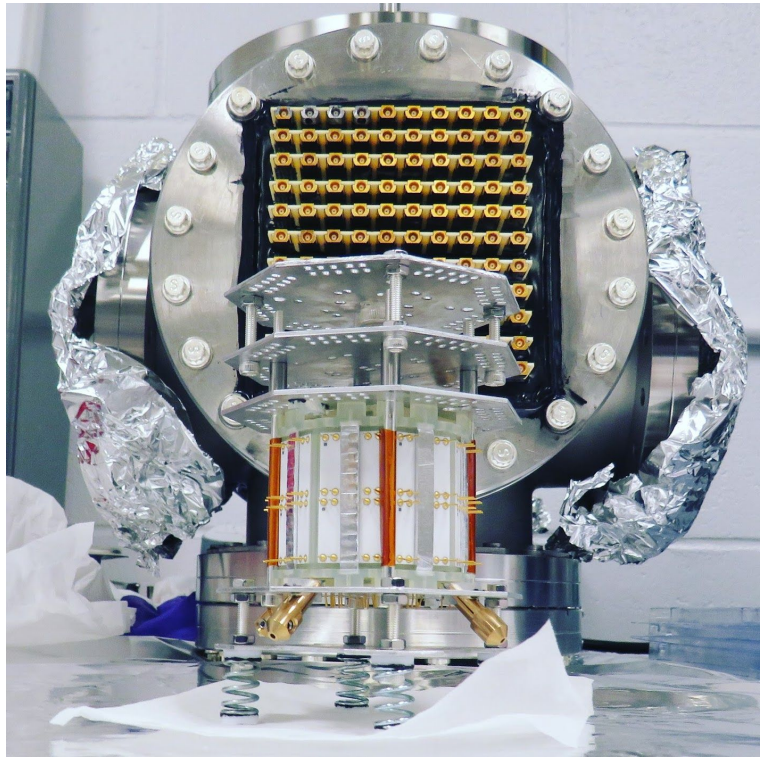
Cryostat

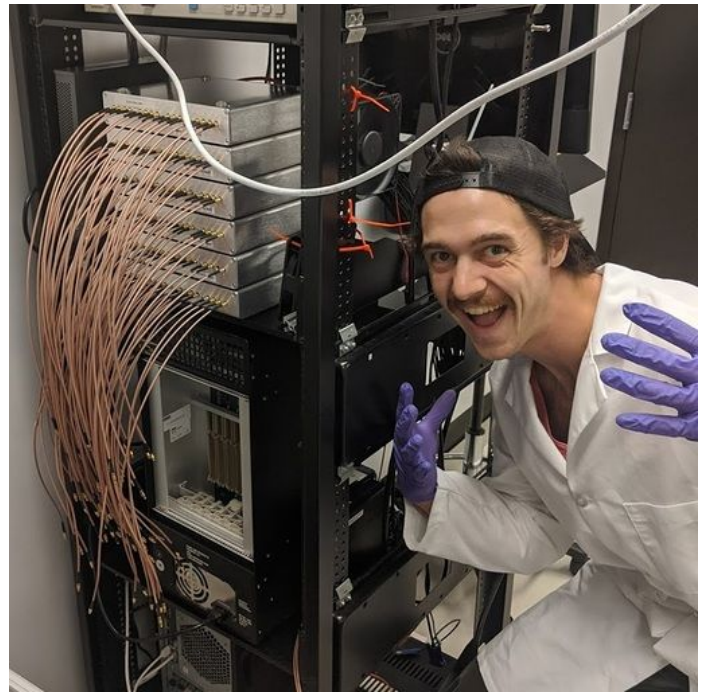


Cryostat at McGill

Detector held upside-down in vacuum Flange

System Installed!





DAQ System Installed!

Motivation A: nEXO

nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in **~ 4.5 m²** of SiPMs
- requires ~1% ΔE for background rejection

  ↳ gammas from ^{238}U, ^{232}Th near $Q_{0\nu\beta\beta}$

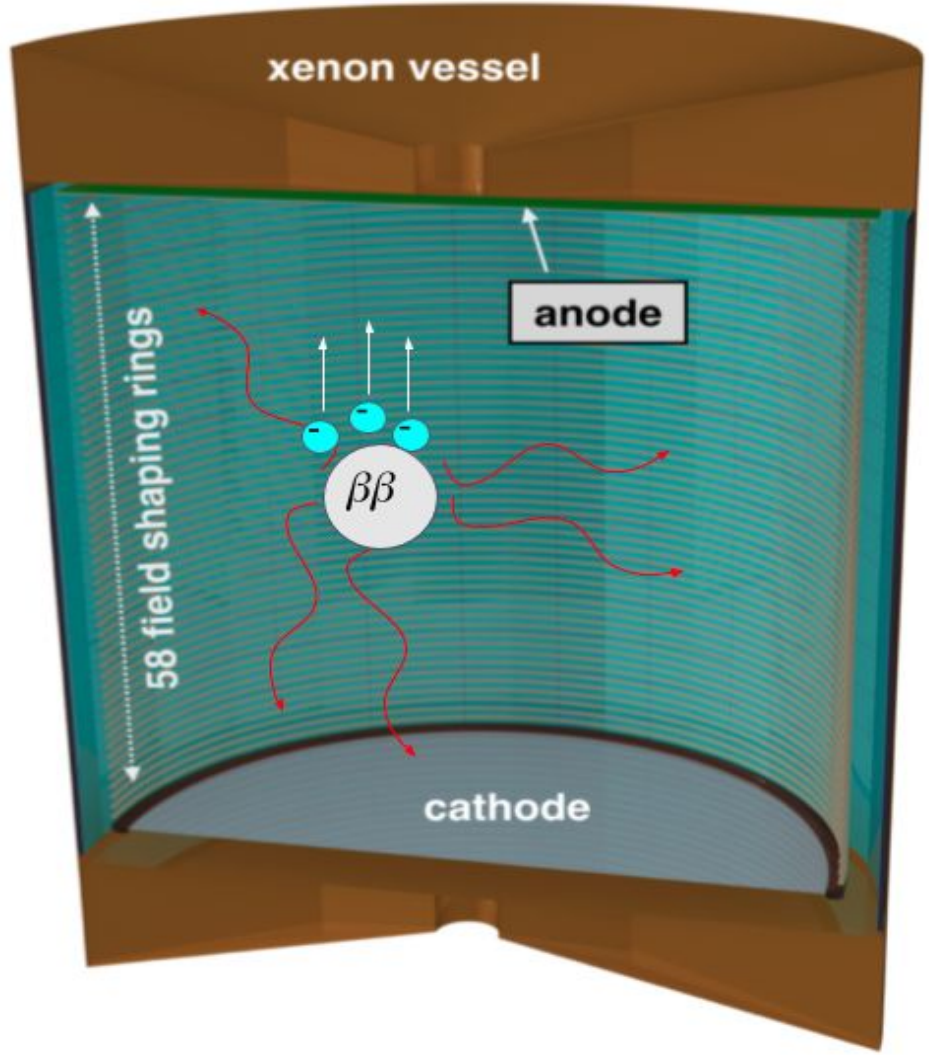


Diagram of a $\beta\beta$ event in nEXO detector (adapted from [4])
Cylinder walls lined with SiPMs

Motivation A: nEXO

nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in **~ 4.5 m²** of SiPMs
- requires ~1% ΔE for background rejection

  ↳ energy resolution driven by light collection efficiency (see ref [4])

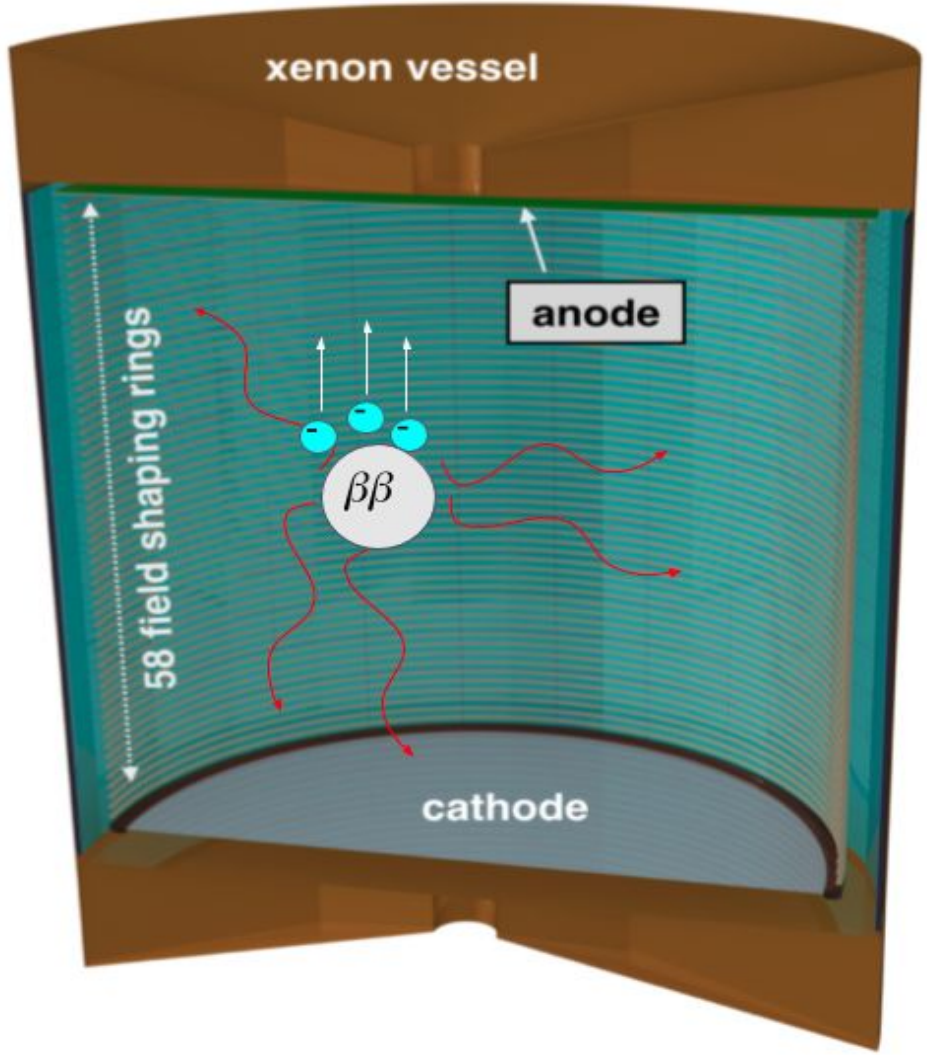


Diagram of a $\beta\beta$ event in nEXO detector (adapted from [4])
Cylinder walls lined with SiPMs

Motivation A: nEXO

nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in **~ 4.5 m²** of SiPMs
- requires ~1% ΔE for background rejection

  ↳ energy resolution driven by light collection efficiency (see ref [4])

LoLX is complementary to nEXO**:**

- validate photon transport simulations

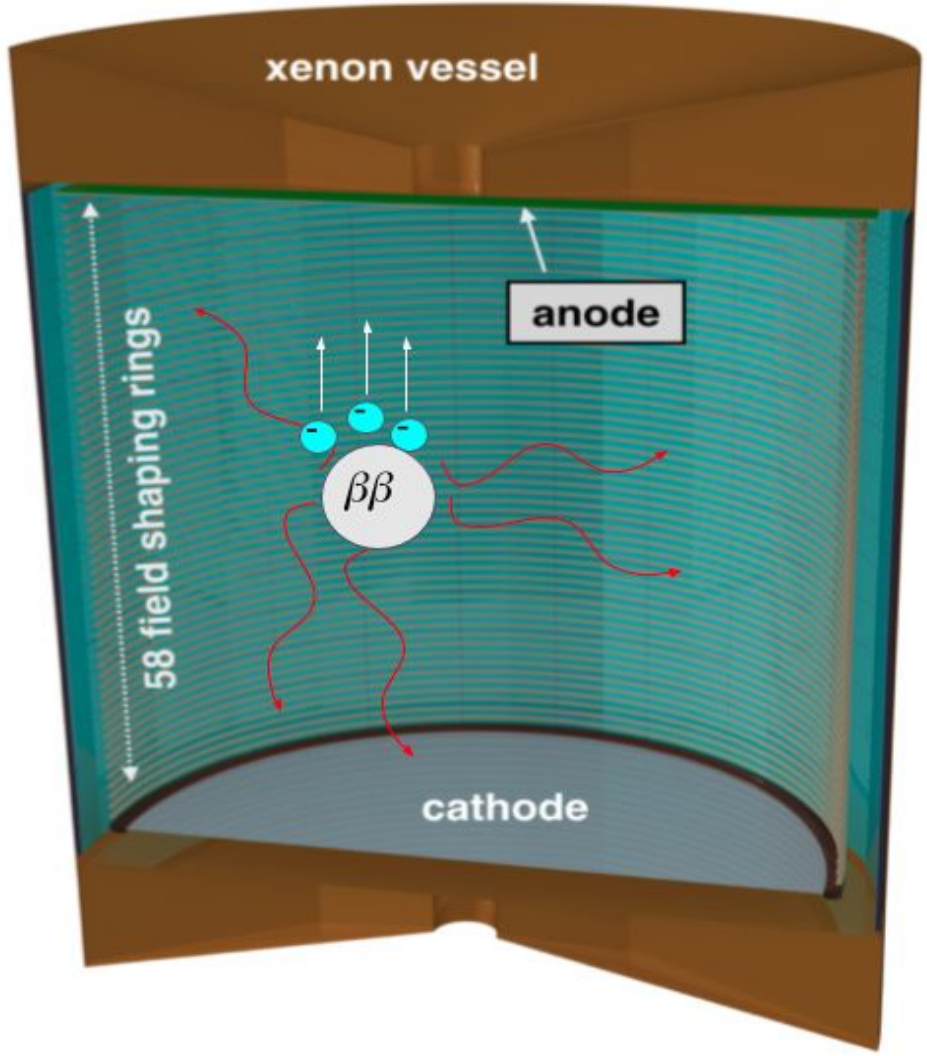


Diagram of a $\beta\beta$ event in nEXO detector (adapted from [4])
Cylinder walls lined with SiPMs

Motivation A: nEXO

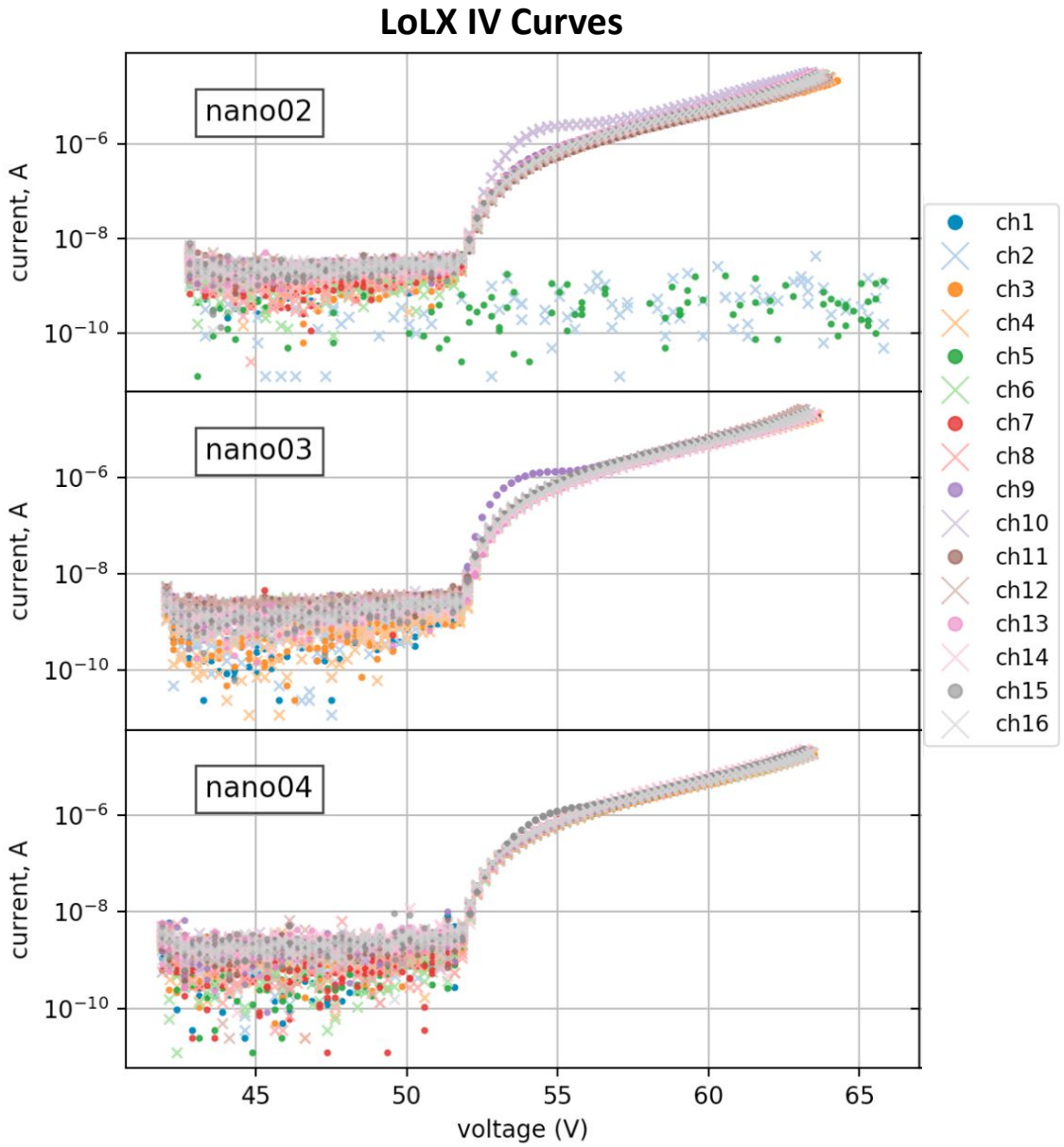
nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in **~ 4.5 m²** of SiPMs
- requires ~1% ΔE for background rejection

  ↳ energy resolution driven by light collection efficiency (see ref [4])

LoLX is complementary to nEXO**:**

- validate photon transport simulations
- gain experience operating many SiPMs in LXe
  - stability of photo-detection efficiency
  - **monitor SiPMs using IV curves**



In situ IV curves of 48/96 SiPMs in LoLX (at room temperature)

Motivation A: nEXO

nEXO is a planned large scale LXe $0\nu\beta\beta$ experiment

- TPC cylinder walls covered in ~ **4.5 m²** of SiPMs
- requires ~1% ΔE for background rejection

  ↳ energy resolution driven by light collection efficiency (see ref [4])

LoLX is complementary to nEXO**:**

- validate photon transport simulations
- gain experience operating many SiPMs in LXe
  - stability of photo-detection efficiency
  - monitor SiPMs using IV curves
- study ***external cross-talk*** **(eXT)** between SiPMs
  - charge avalanches produce IR photons, trigger other SiPMs

    ↳ see talk by Joe McLaughlin, Thursday, Photodetectors Session

    "External Cross-talk characterization from dark avalanches in SiPMs"
  - relevant for other experiments such as **Darkside-20k**, **DUNE** (large area SiPMs facing one another)

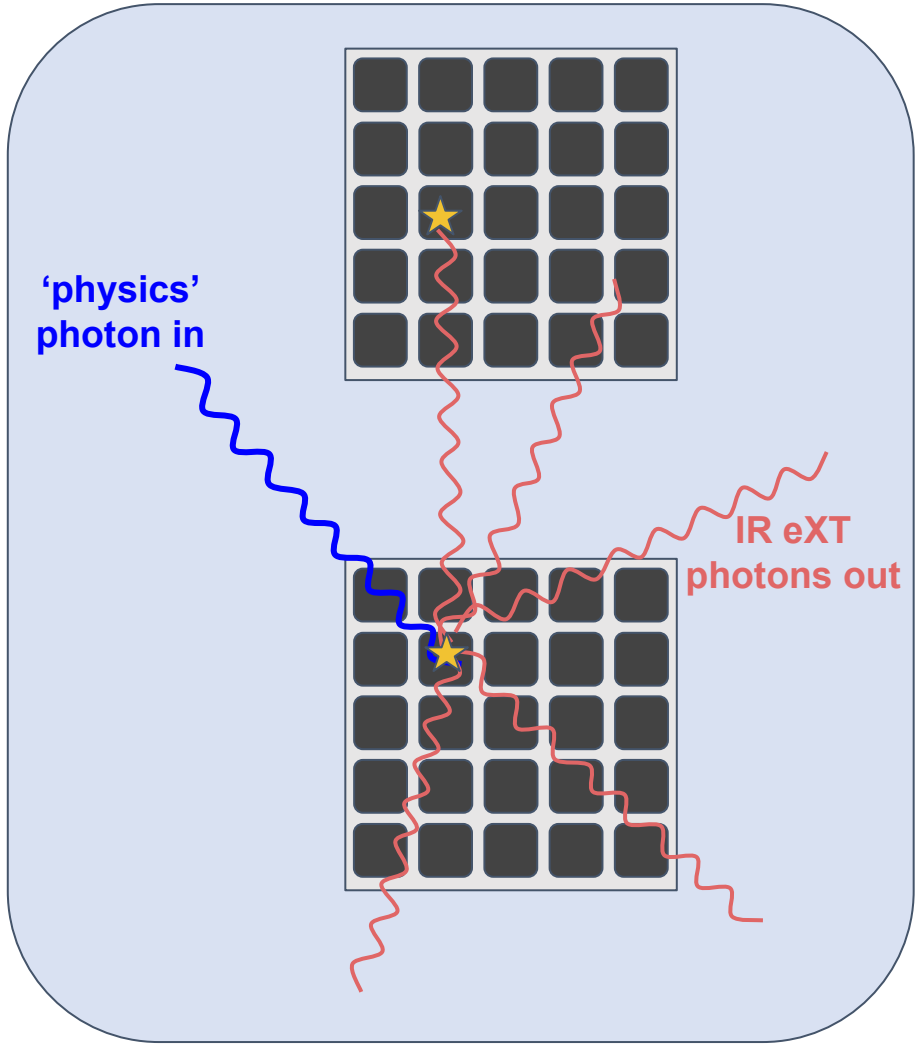
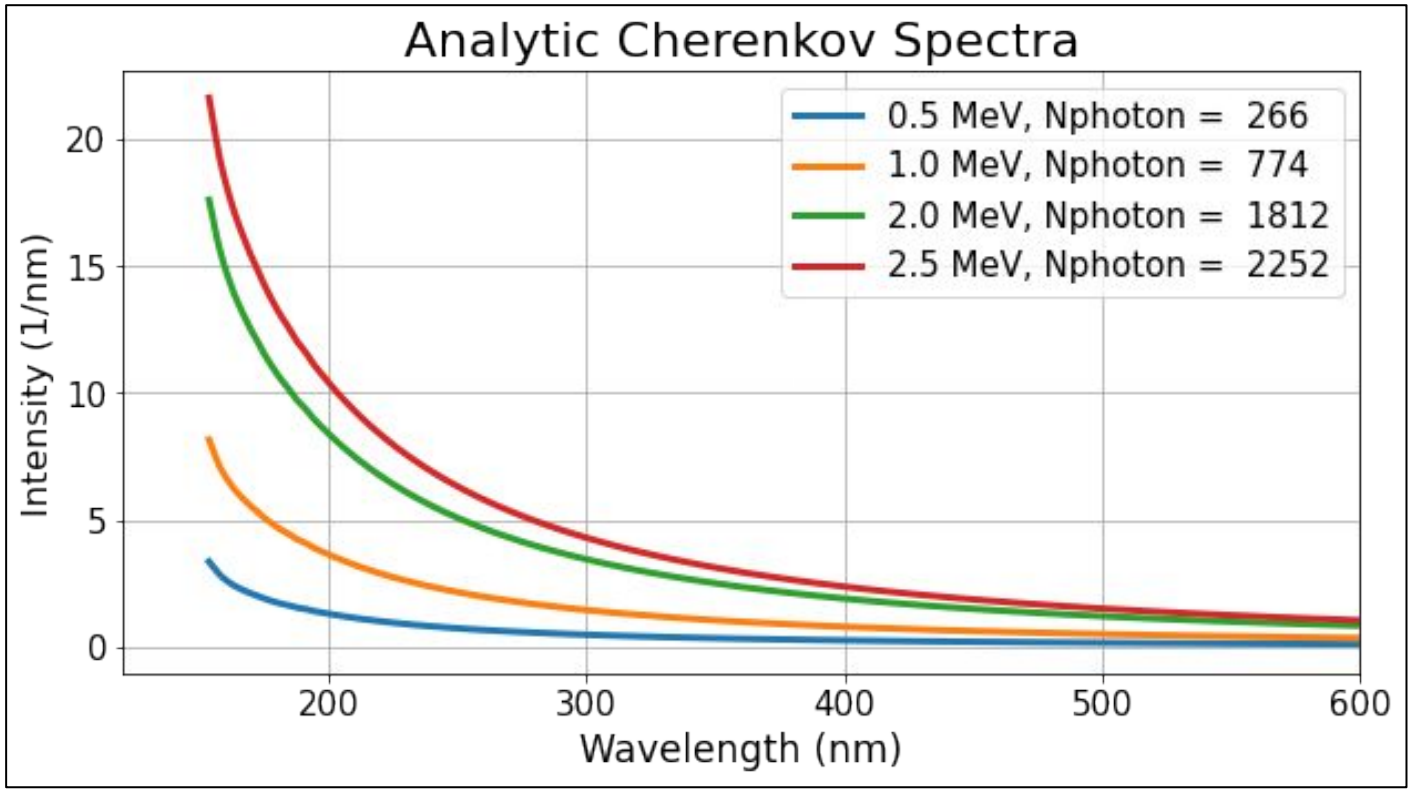


Diagram of eXT occurring between two SiPMs. ★ designates charge avalanche

Motivation B: Study Cherenkov Light

Cherenkov light in LXe:

- broadband (~150 nm to IR)
- extremely prompt (~ few ps)
- slight directionality in LXe (scattering)
- low yield



Analytic Cherenkov yields for electrons in LXe
(calculated using NIST-eStar data, LXe refractive index from ref [8])

Motivation B: Study Cherenkov Light

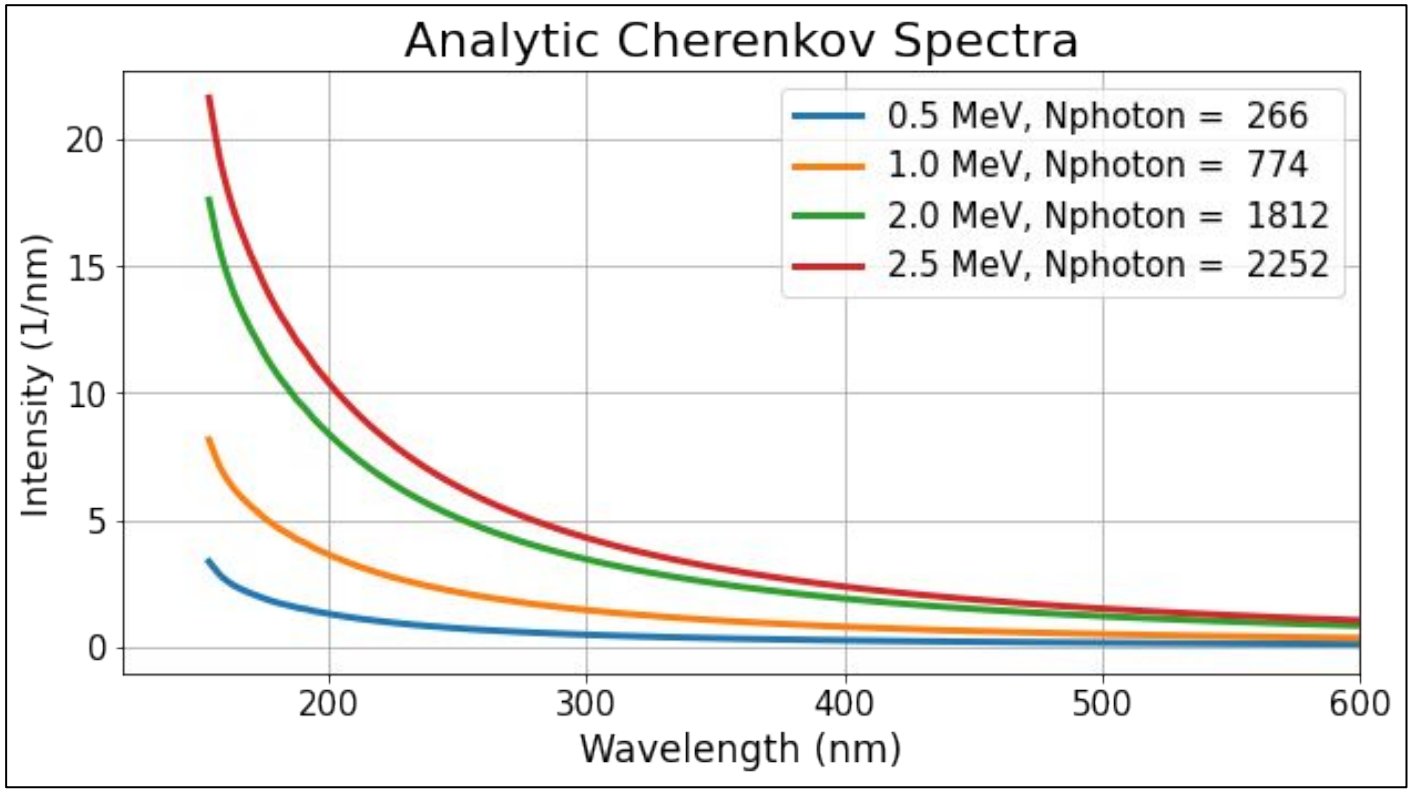
Cherenkov light in LXe:

- broadband (~150 nm to IR)
- extremely prompt (~ few ps)
- slight directionality in LXe (scattering)
- low yield

Applications of Cherenkov light:

Future LXe $0\nu\beta\beta$ experiments (not nEXO !)

- discrimination against single-scatter gammas: (see ref [1], [7])



Analytic Cherenkov yields for electrons in LXe
(calculated using NIST-eStar data, LXe refractive index from ref [8])

Motivation B: Study Cherenkov Light

Cherenkov light in LXe:

- broadband (~150 nm to IR)
- extremely prompt (~ few ps)
- slight directionality in LXe (scattering)
- low yield

Applications of Cherenkov light:

Future LXe $0\nu\beta\beta$ experiments (not nEXO !)

- discrimination against single-scatter gammas: (see ref [1], [7])

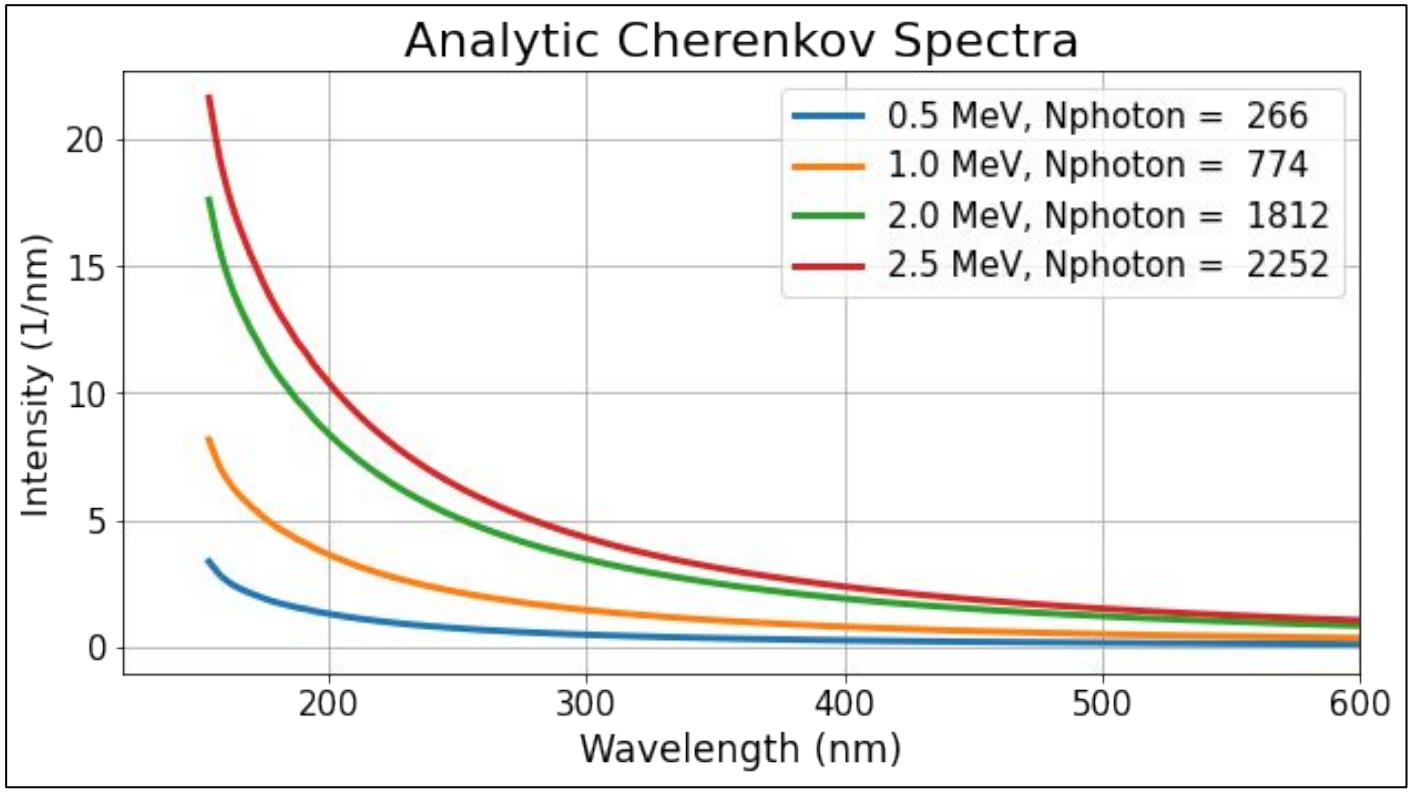
Timing Resolution

- **Time-Of-Flight** in nuclear medical imaging:

  ↳ **10ps** resolution (see ref [2], [3])

- higher energy gammas (1-100MeV)

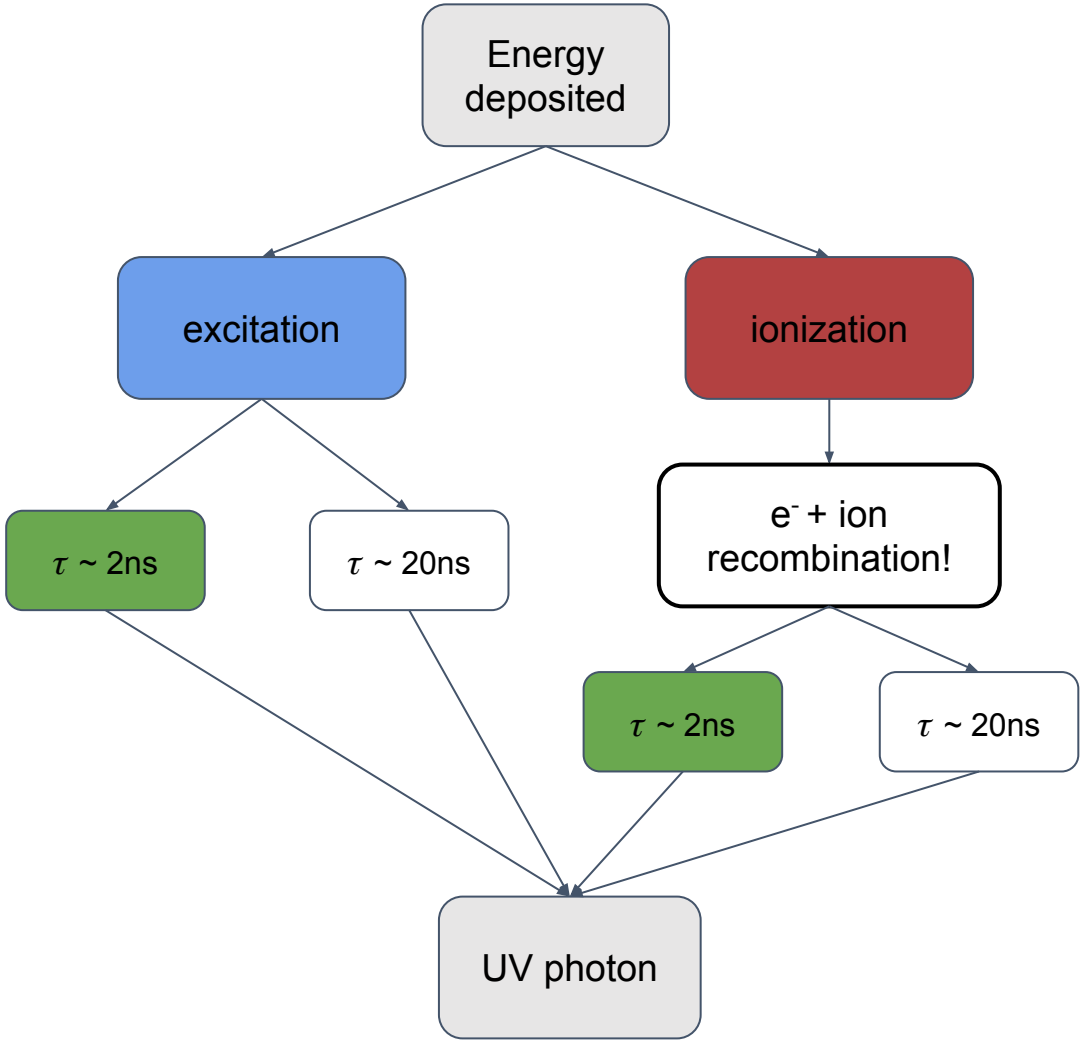
  ↳ TOF calorimetry?



Analytic Cherenkov yields for electrons in LXe
(calculated using NIST-eStar data, LXe refractive index from ref [8])

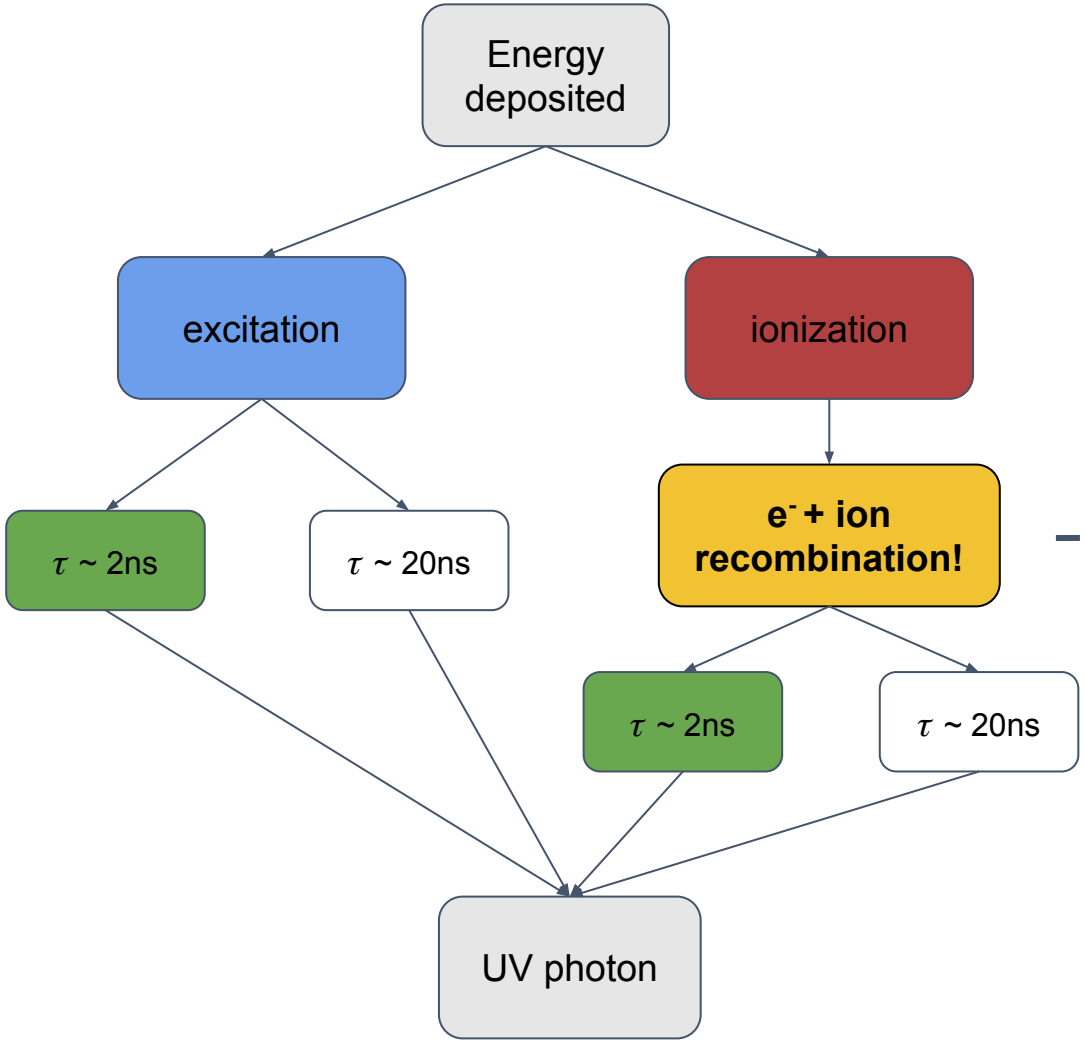
Motivation C: Scintillation Signal

scintillation signal has 4 contributions:
excitation / **ionization** **singlet (~2ns)** / triplet (~20ns)



Motivation C: Scintillation Signal

scintillation signal has 4 contributions:
excitation / **ionization** **singlet (~2ns)** / triplet (~20ns)



Prompt light!

- **alphas or nuclear recoils:** *fast* recombination
- **Electron Recoils:** *slow* recombination

Motivation C: Scintillation Signal

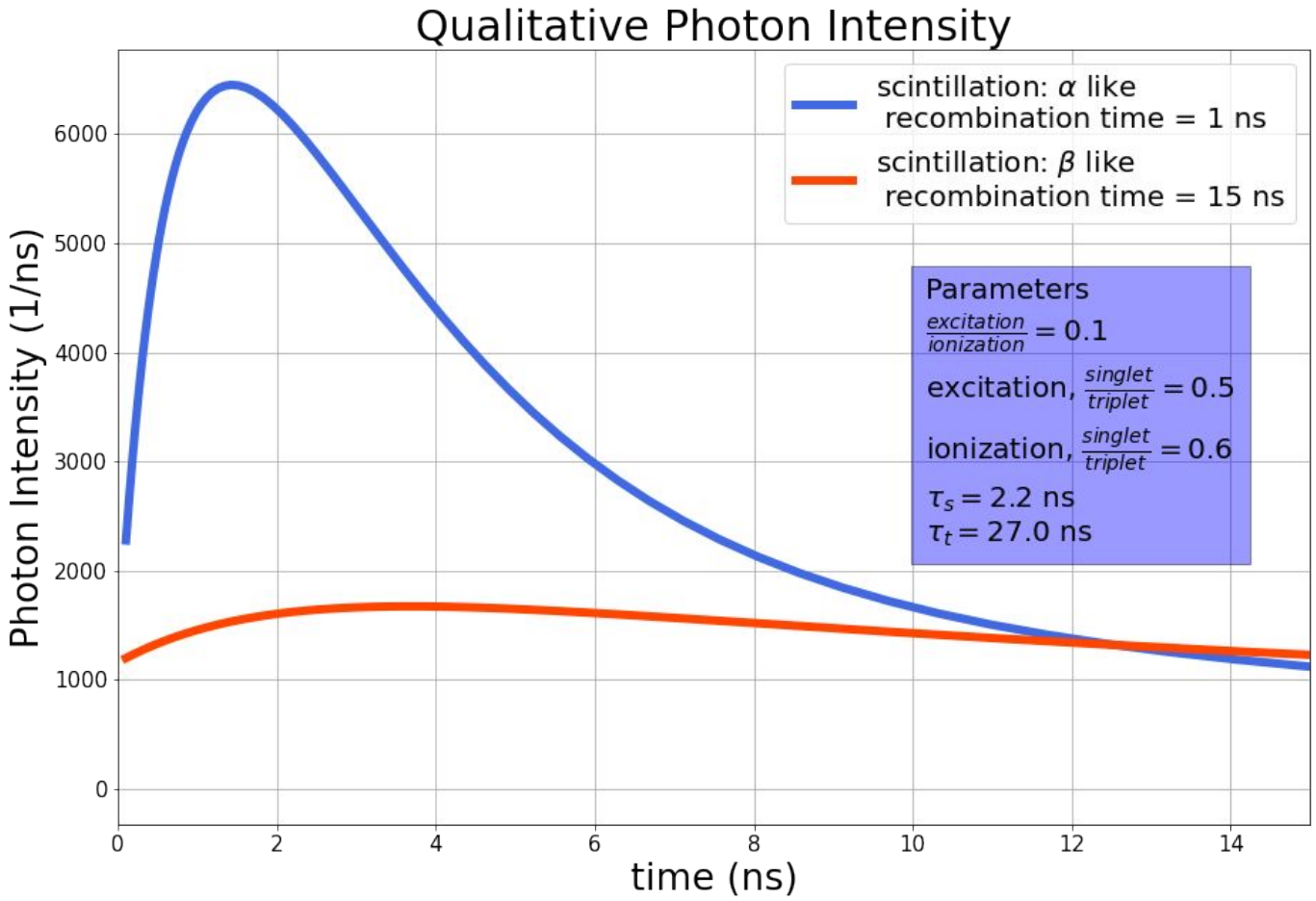
scintillation signal has 4 contributions:
excitation / ionization singlet (~2ns) / triplet (~20ns)

Prompt scintillation signal:

- **alphas or nuclear recoils:** *fast* recombination
- **Electron Recoils:** *slow* recombination

prompt signal → timing resolution

discrimination → high mass DM search, other applications



Toy model showing recombination contribution to prompt light

Motivation C: Scintillation Signal

scintillation signal has 4 contributions:
excitation / ionization singlet (~2ns) / triplet (~20ns)

Prompt scintillation signal:

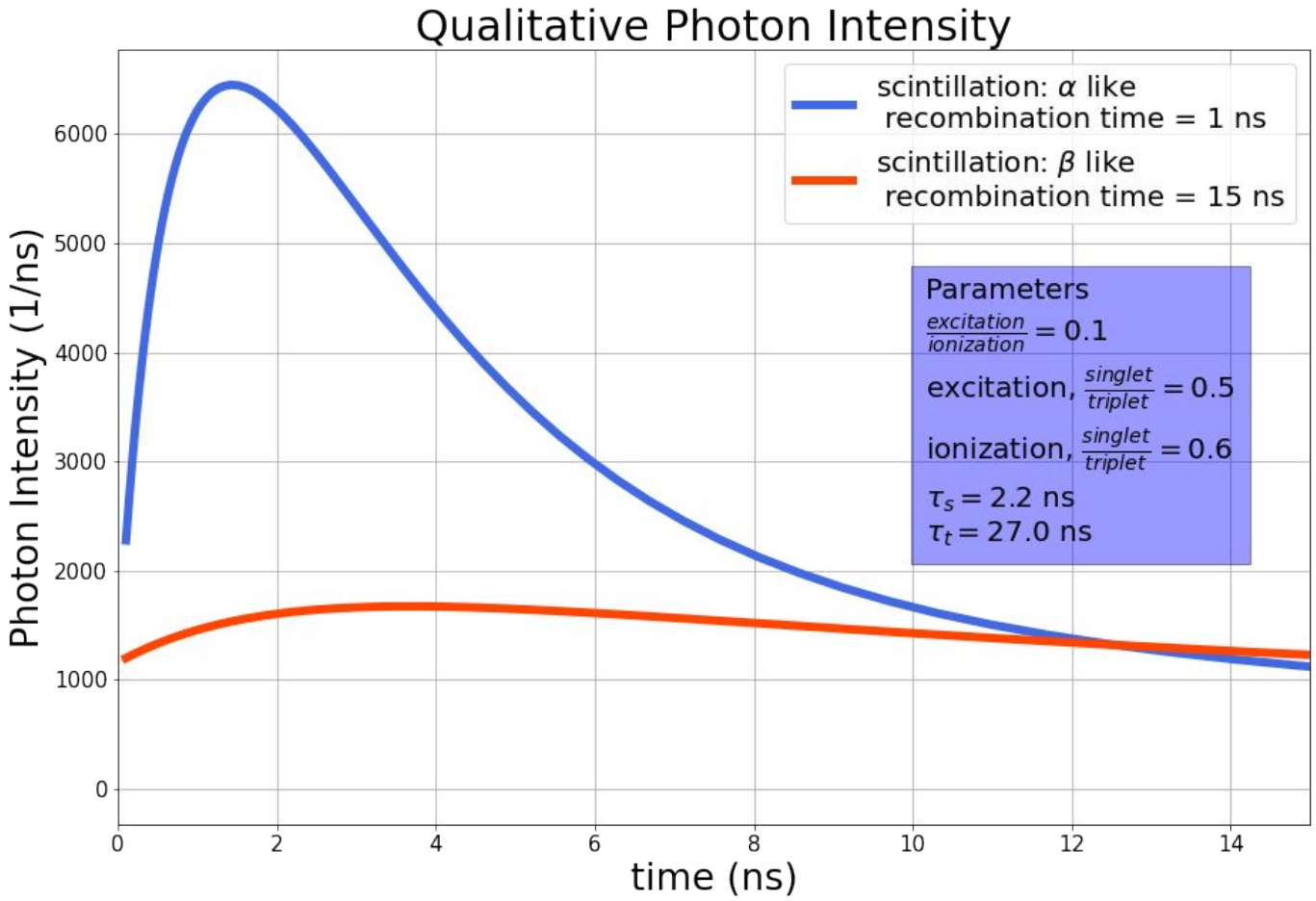
- **alphas or nuclear recoils:** *fast* recombination
- **Electron Recoils:** *slow* recombination

prompt signal → timing resolution

discrimination → high mass DM search, other applications

Other studies:

- IR light production
- recombination vs Cherenkov yield
  - ionization fluctuations



Toy model showing recombination contribution to prompt light

Commissioning: Gaseous Nitrogen

Data taken during summer 2020

- filled with **Nitrogen gas** to cool entire detector
  - operating between -90C to -110C

Goals for GN_2 run:

- commission electronics
- study **external cross-talk** between SiPMs
  - LoLX sensitive to **variety of geometries**
  - (primarily generated by dark noise)

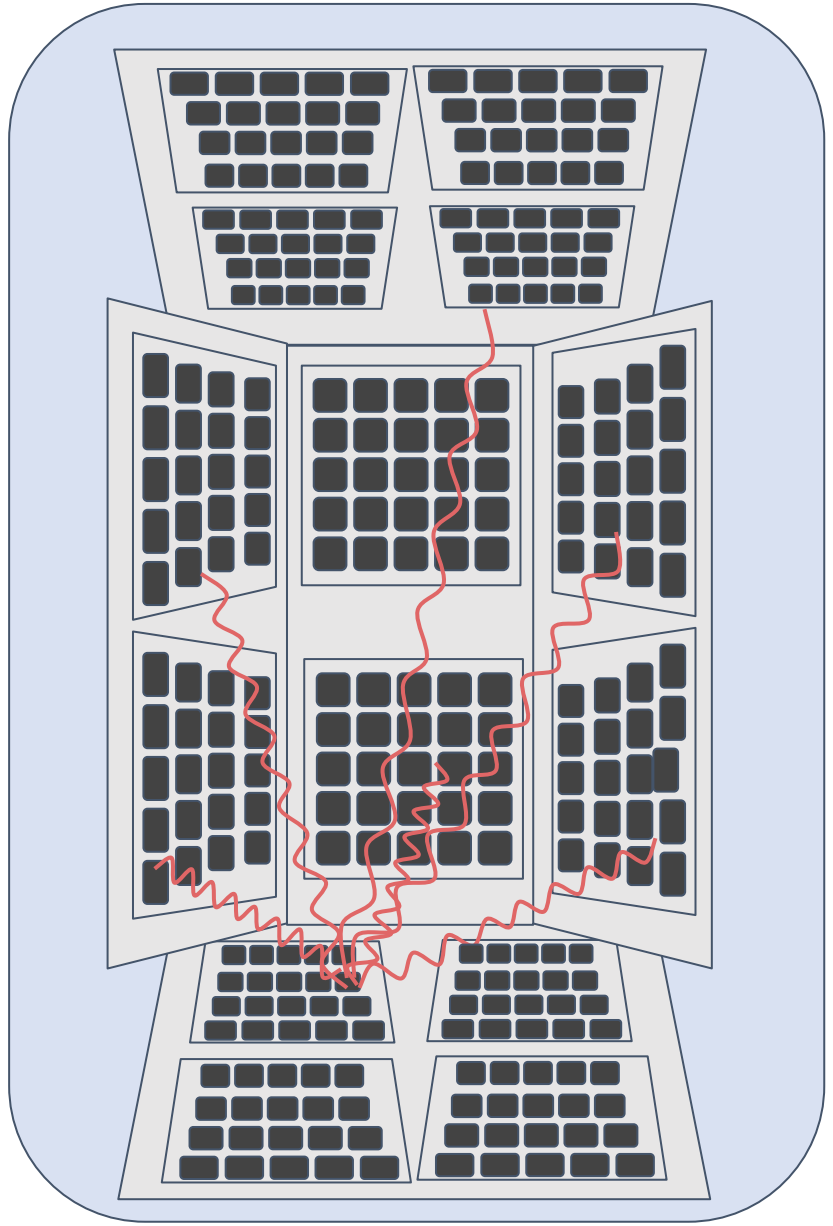
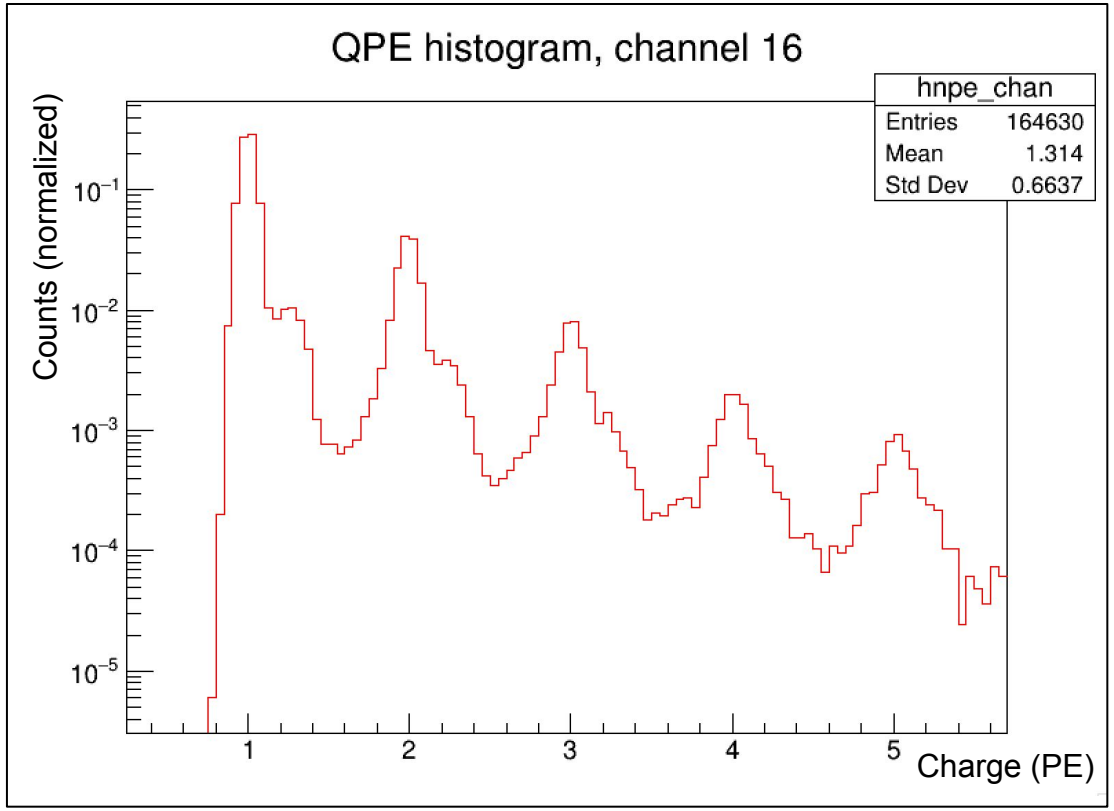


Diagram of eXT between SiPMs in LoLX

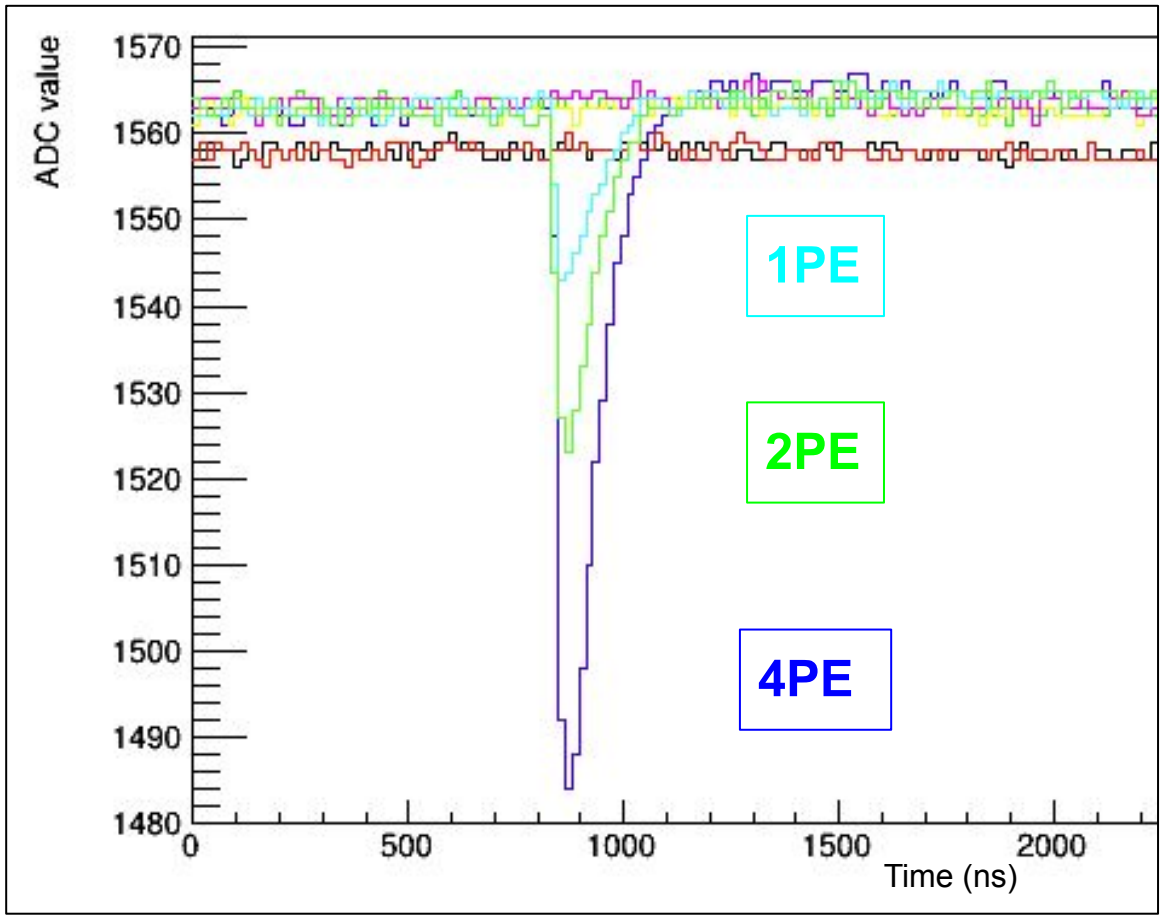
Commissioning: Gaseous Nitrogen

Signal Quality/Commissioning

- great SPE resolution
- consistent breakdown voltages



Charge histogram for summed channel (4 inputs)



Example Waveforms from cold GN2 data

Commissioning: Gaseous Nitrogen

BUT ^{90}Sr source still installed!

- Nitrogen gas scintillates
- literature reports low LY (24 ph/MeV) ref [9]
  - room temperature, field of ~250 V/cm

Variables

NPE - total photons

Nhit - occupancy (channels with > 0.5PE)

Commissioning: Gaseous Nitrogen

BUT ^{90}Sr source still installed!

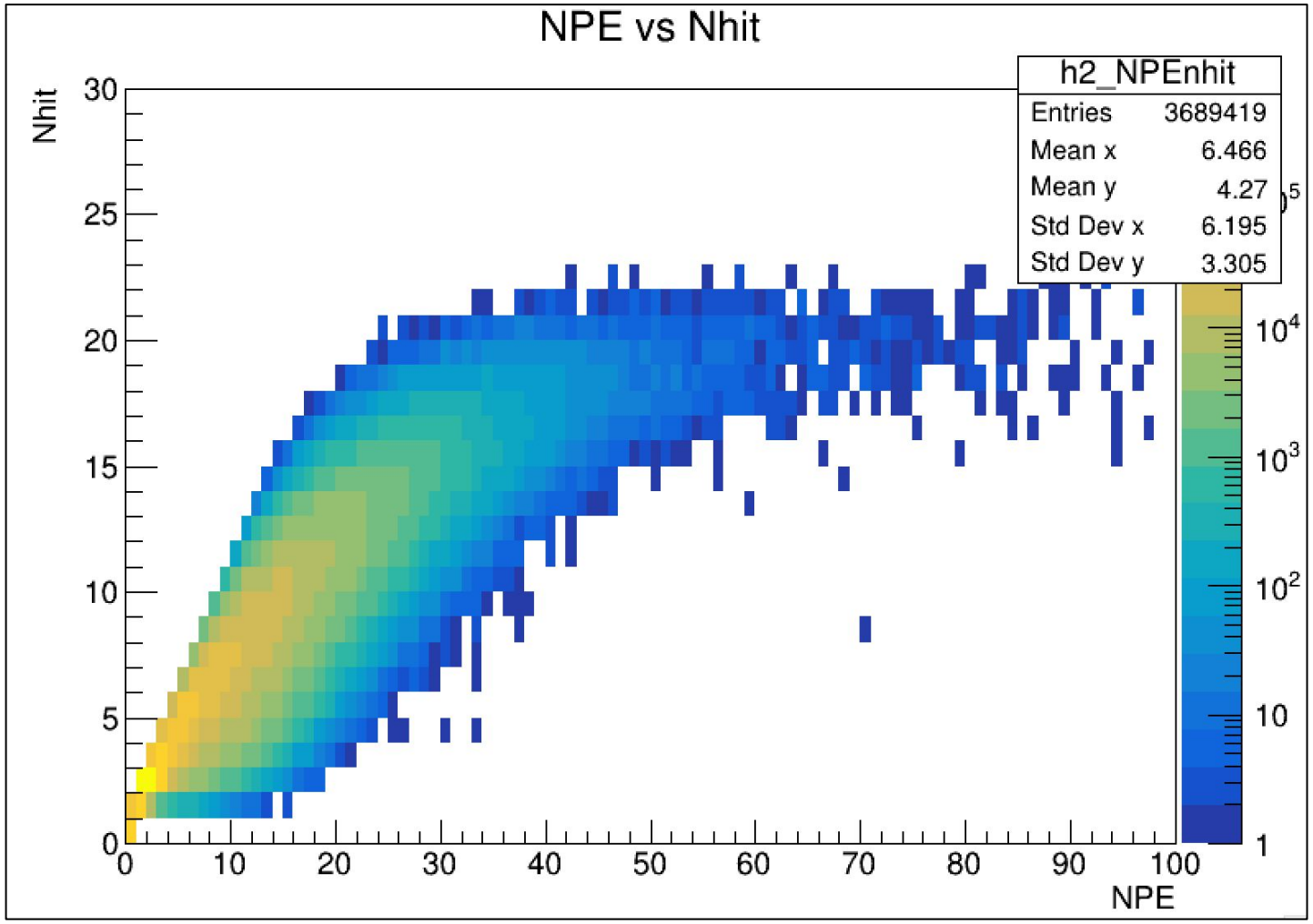
- Nitrogen gas scintillates
- literature reports low LY (24 ph/MeV) ref [9]
  - room temperature, field of ~250 V/cm
- see LOTS of light!
  - distributed across detector

Variables

NPE - total photons

Nhit - occupancy (channels with > 0.5PE)

investigate Nhit = 2

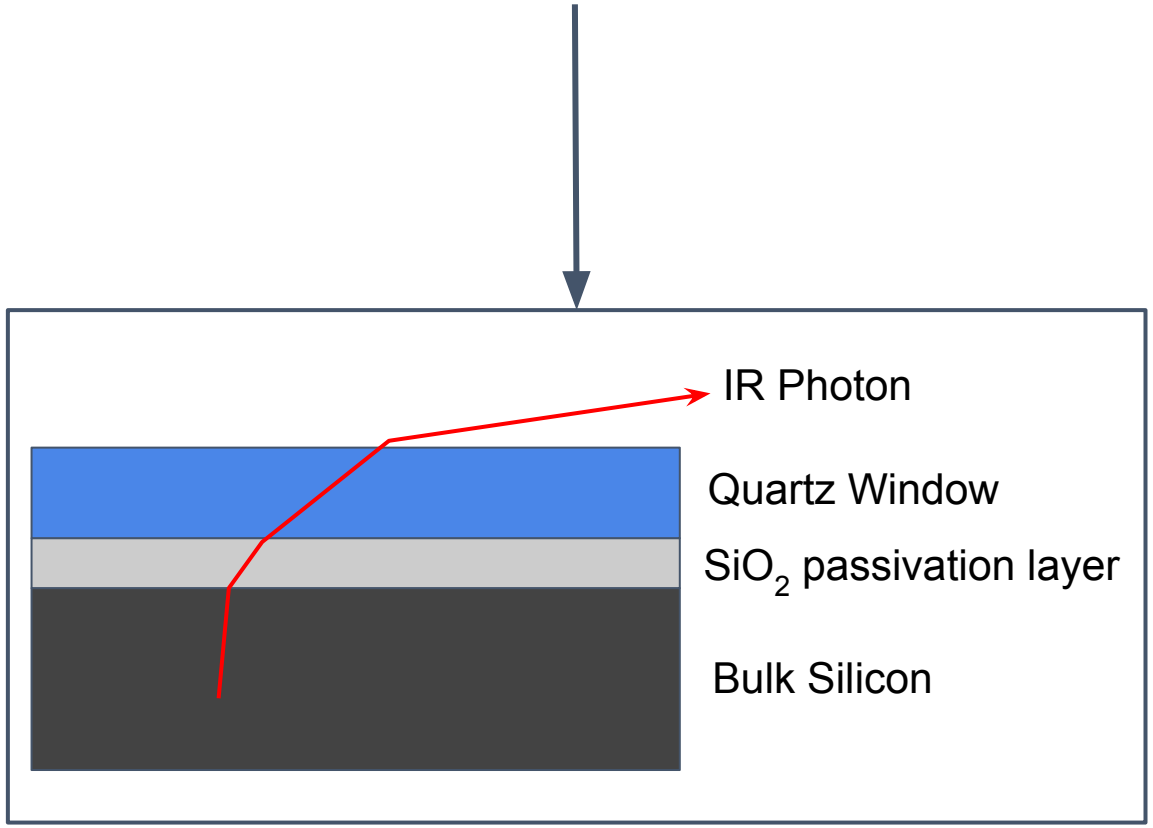


Gaseous Nitrogen Data

External Cross-Talk (eXT)

What does it look like?

- prompt pulse pairs across channels
- **geometric effect** (emitted light refracted ‘down’)

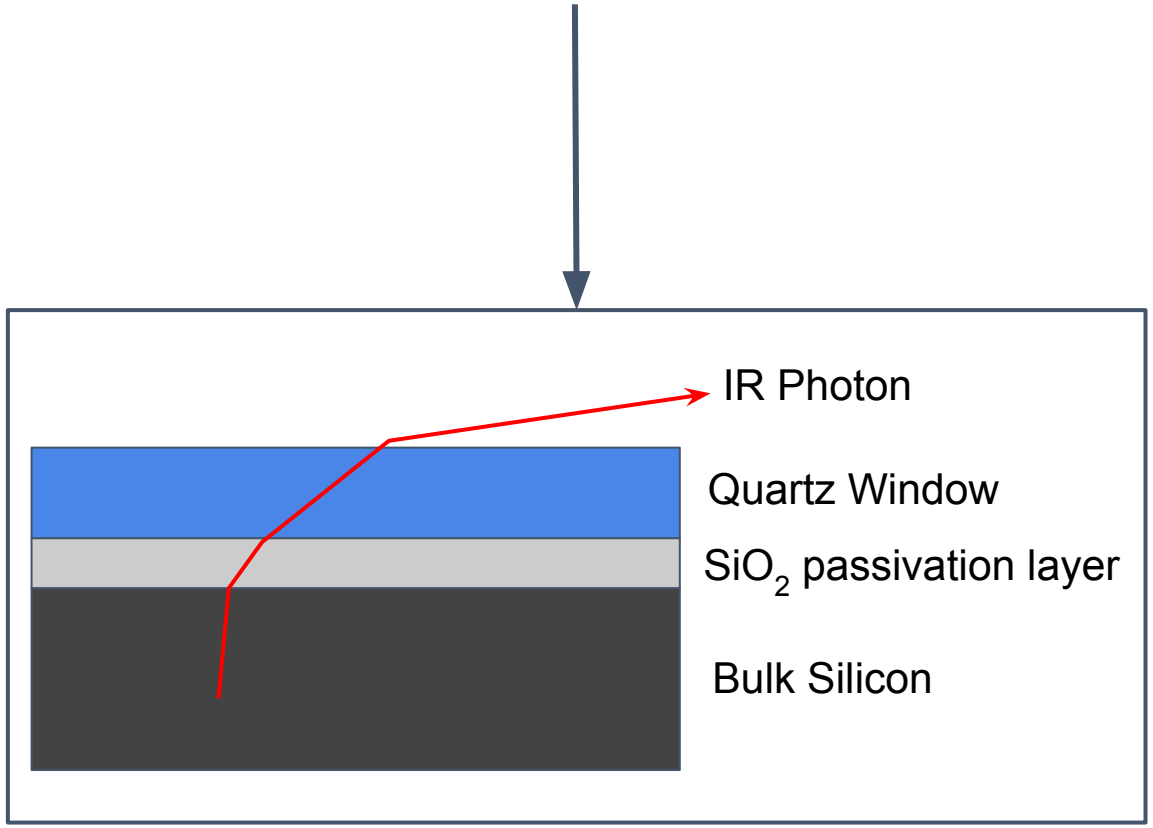


Gaseous Nitrogen Data

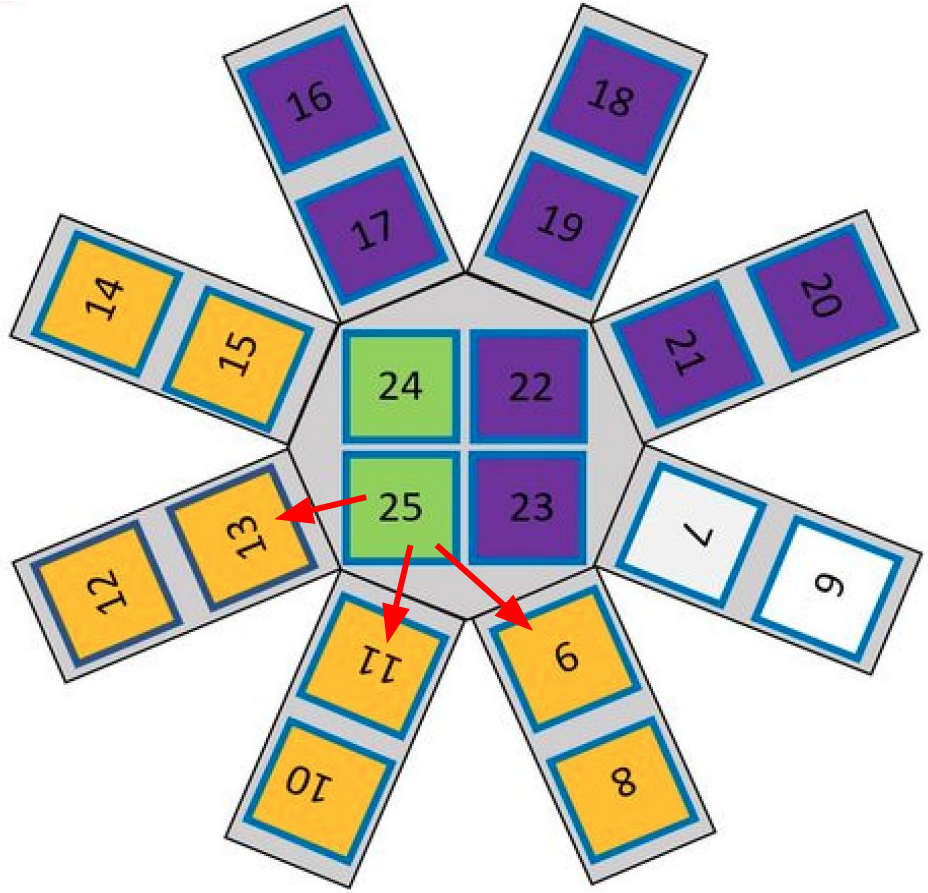
External Cross-Talk (eXT)

What does it look like?

- prompt pulse pairs across channels
- **geometric effect** (emitted light refracted ‘down’)



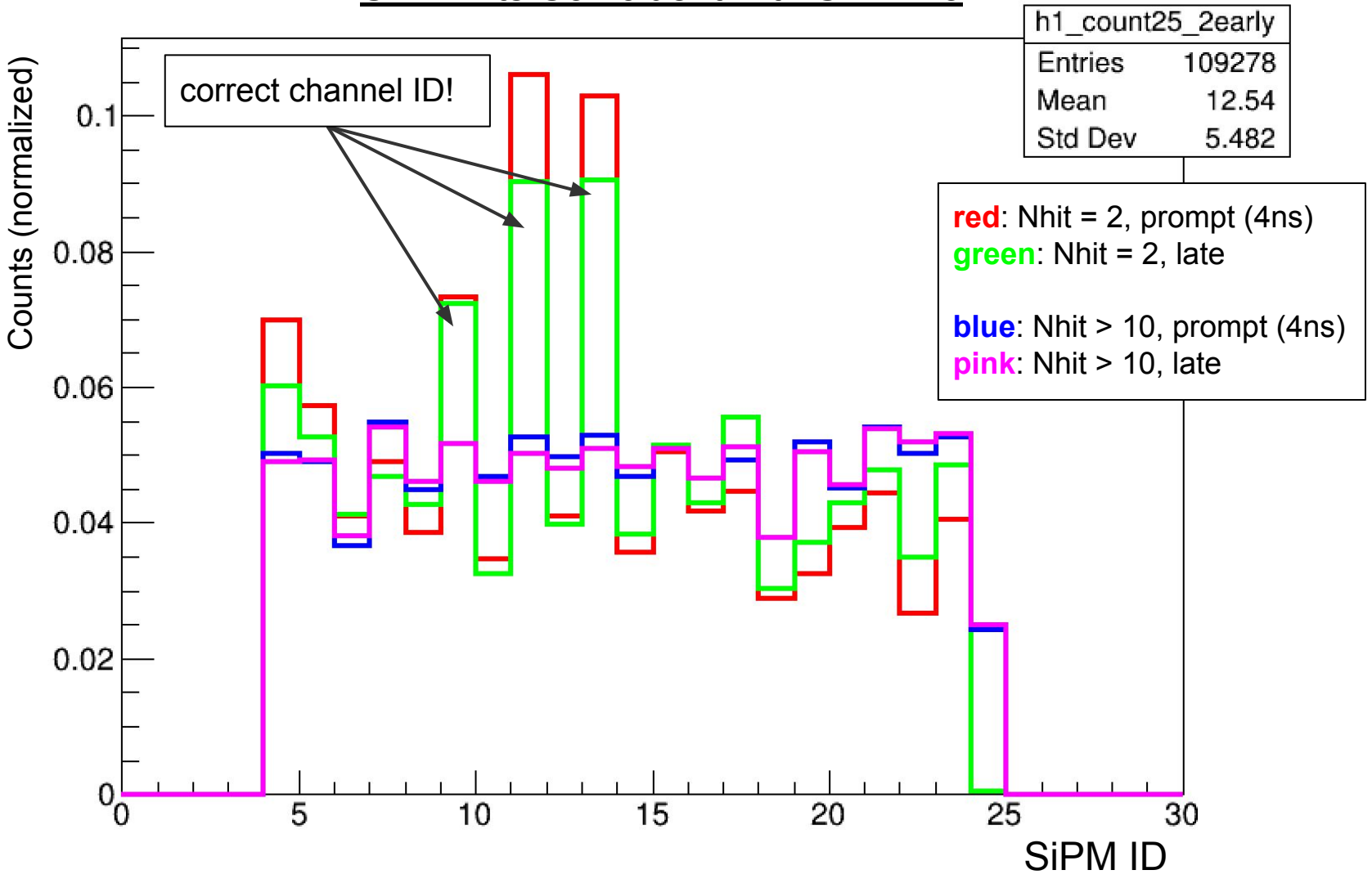
LoLX Detector Unfolded



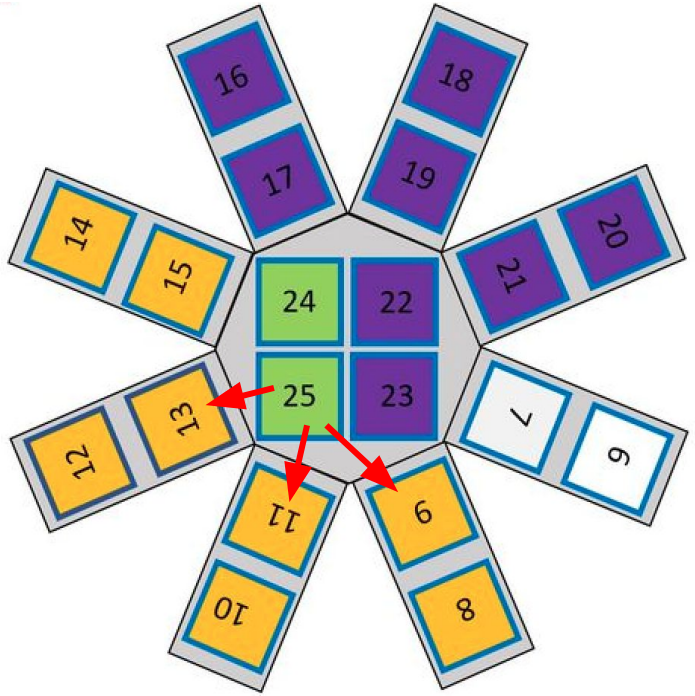
eXT expectation: channel 25 will be coincident with ‘close’ SiPMs

Gaseous Nitrogen Data

SiPM hits Coincident with SiPM 25



LoLX Detector Unfolded



eXT expectation: channel 25 will be coincident with ‘close’ SiPMs

Gaseous Nitrogen Data

Not so conclusive...

- SiPM 25 shows qualitative evidence for eXT
  - other channels **do not** show similar ‘step structure’ 😔

Gaseous Nitrogen Data

Not so conclusive...

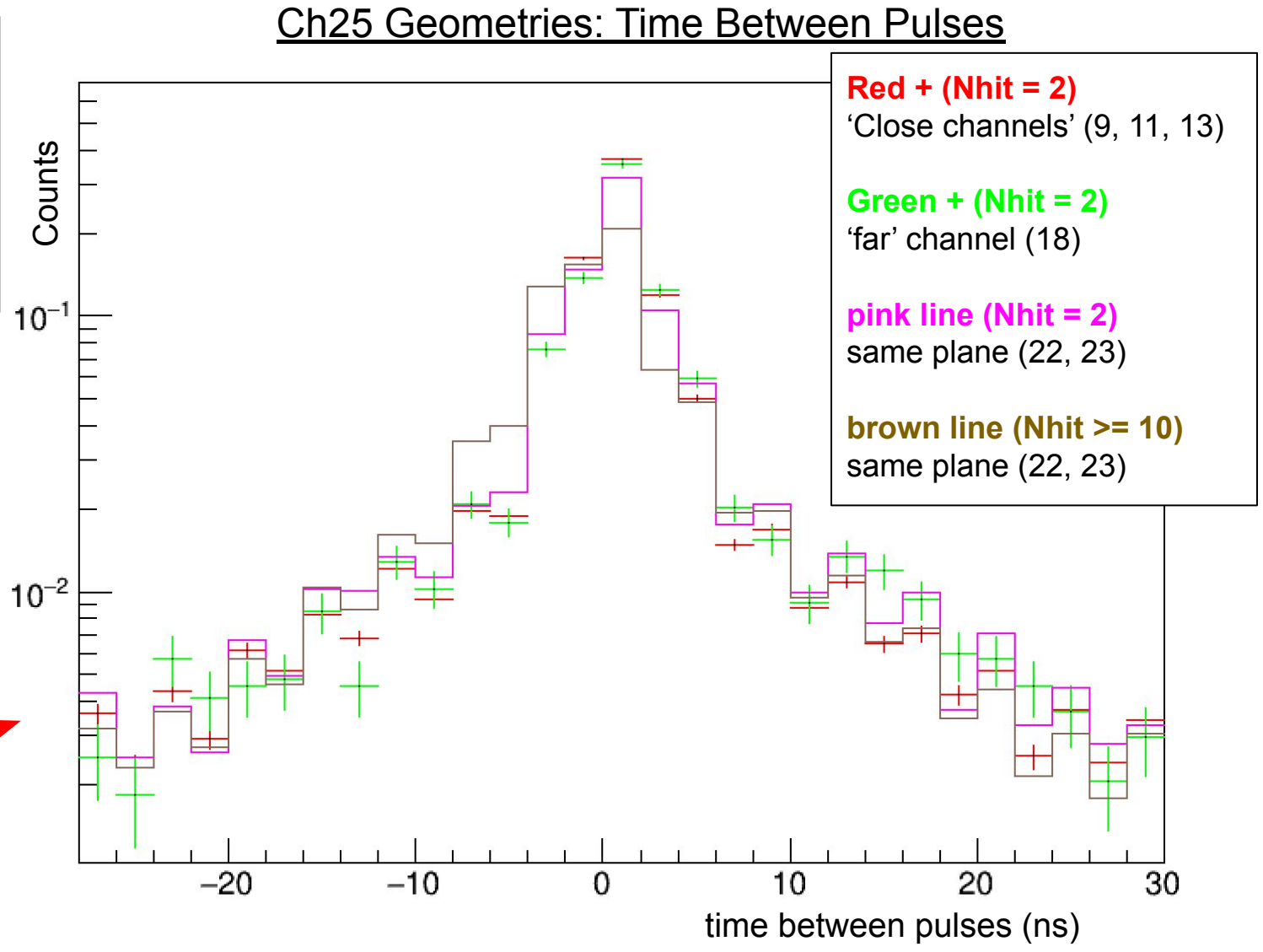
- SiPM 25 shows qualitative evidence for eXT
  - other channels **do not** show similar ‘step structure’ 😔

investigate in **time domain**

↳ time between pulses on different channels

- eXT contribute a large peak around zero
- preserves exponential decay from scintillation
  - everything looks the same!

conclusion: other **fast** processes dominate



Gaseous Nitrogen Data

What fast processes?

- N_2 scintillation with **2.5 ns** lifetime (see ref [9])
  - data taken at room temperature, E field

- Cherenkov/Fluorescence in glass!
  - β hit wall due to detector size
  - light in filter/quartz **backscatters** into detector

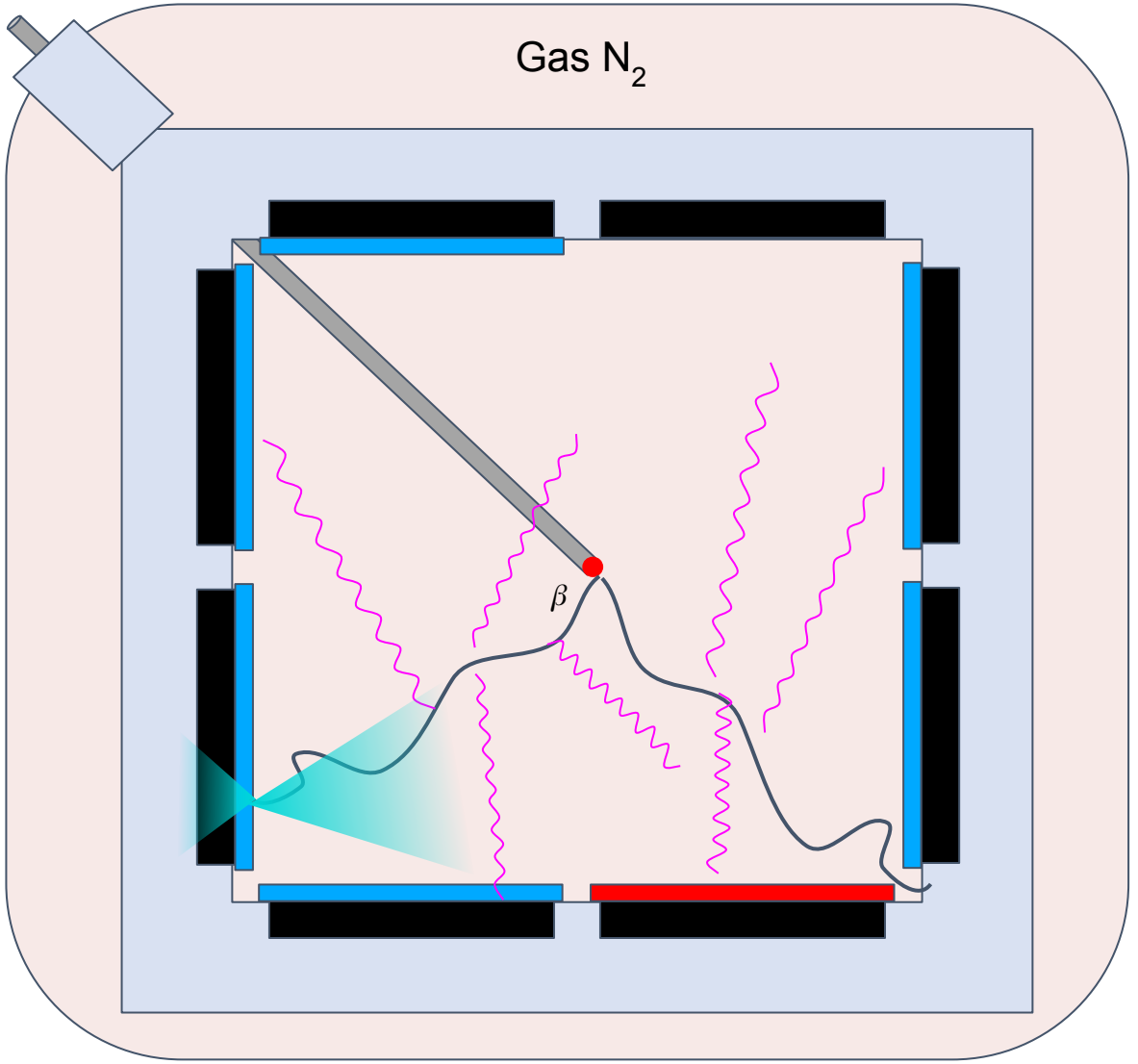


diagram beta hitting window

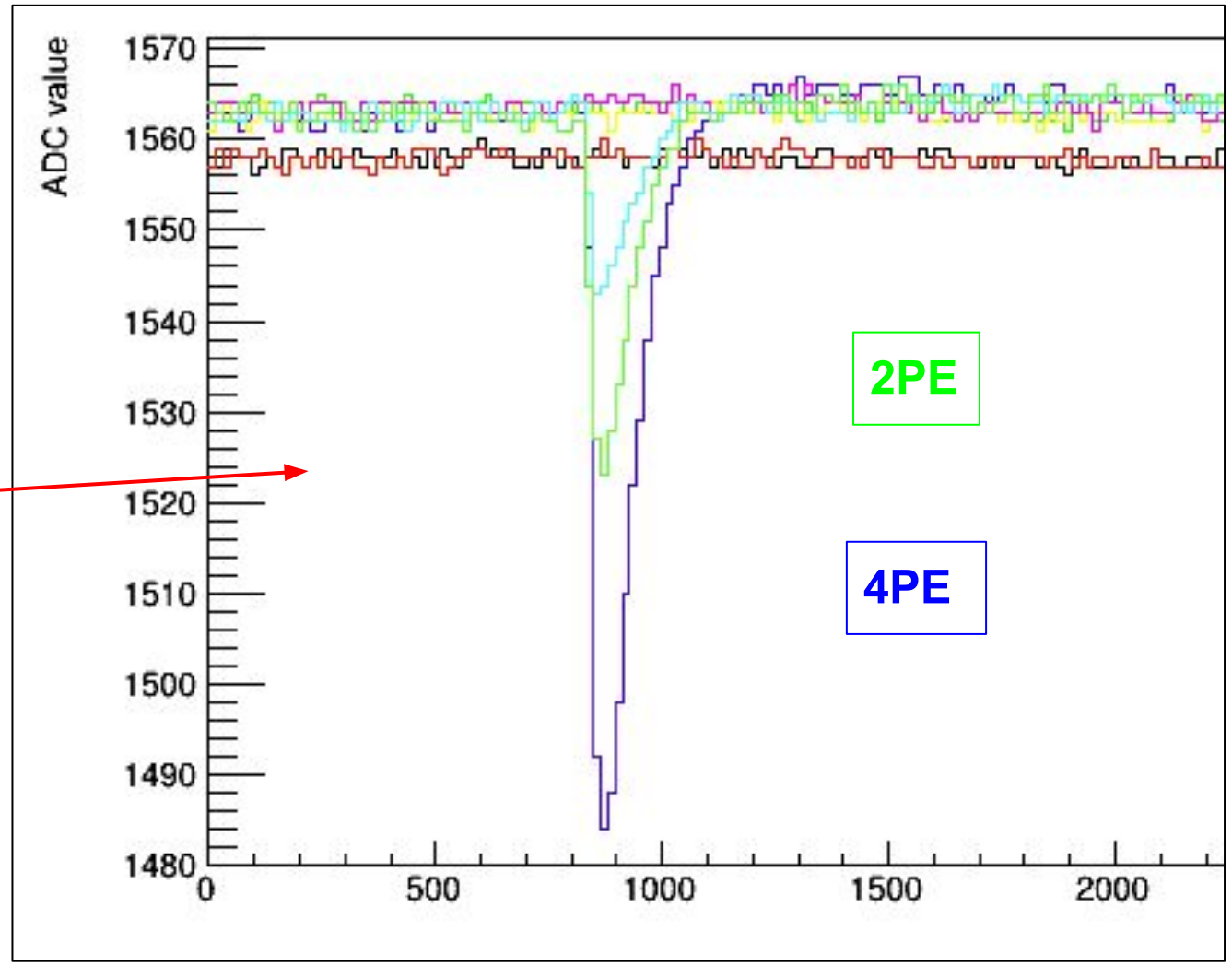
Gaseous Nitrogen Data

new variable

- **Fgap** - charge ratio of two brightest channels

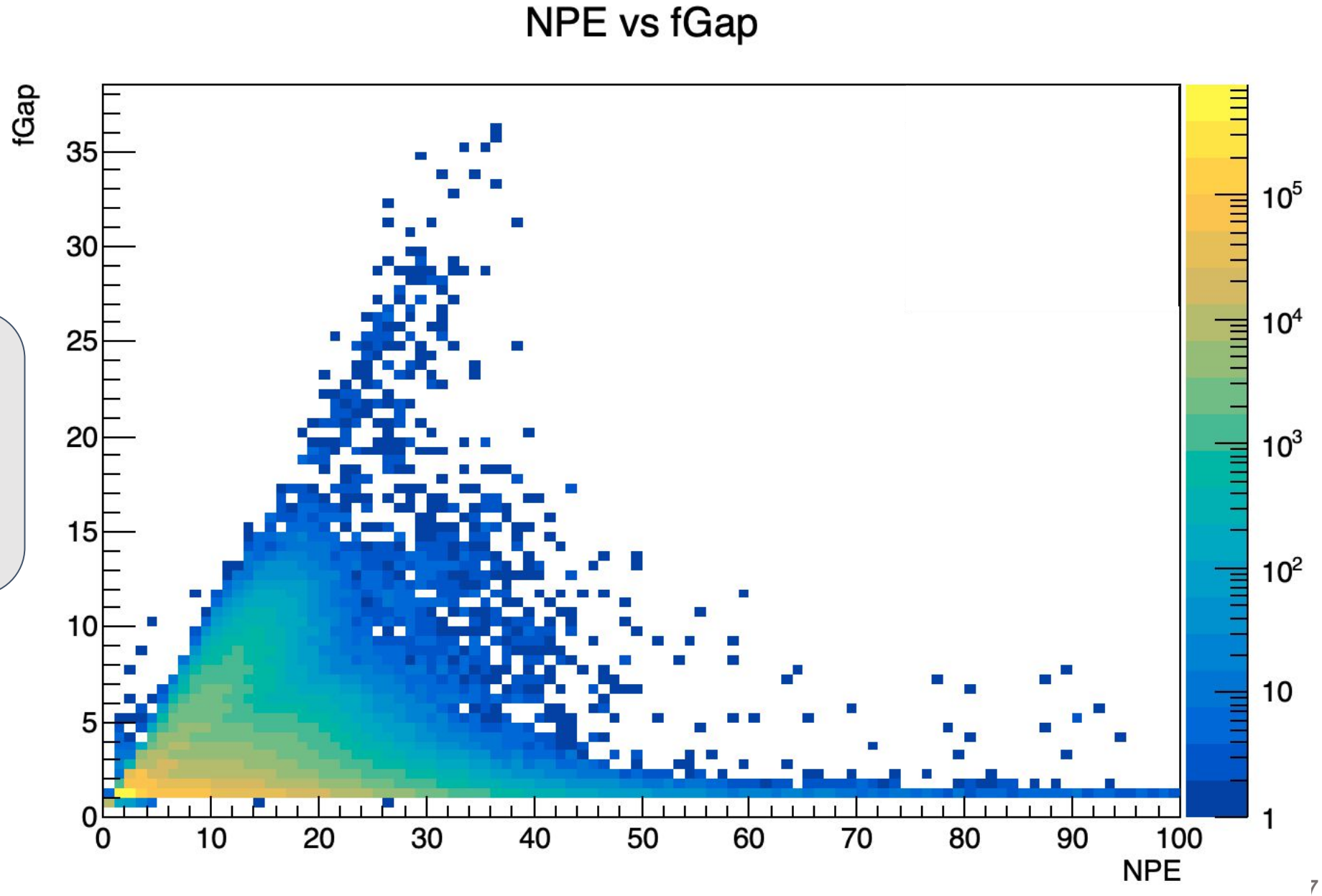
  example: **Fgap = 2**

- Pure scintillation → low Fgap
- Window event → high Fgap



Gaseous Nitrogen Data

Data for *all* channels



new variable

Fgap = charge ratio of two brightest channels

NPE - total photons

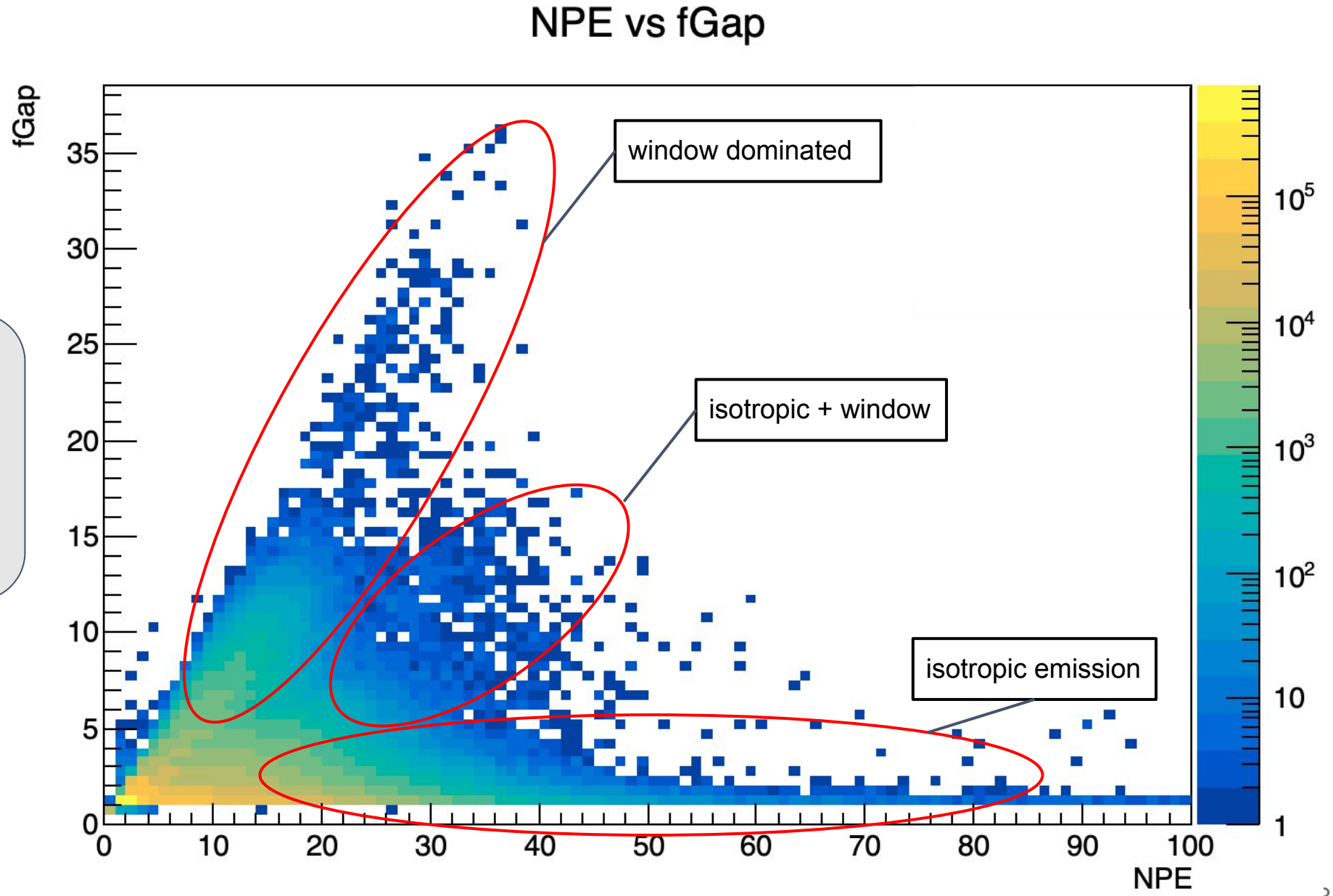
Gaseous Nitrogen Data

Data for *all* channels

new variable

Fgap = charge ratio of two brightest channels

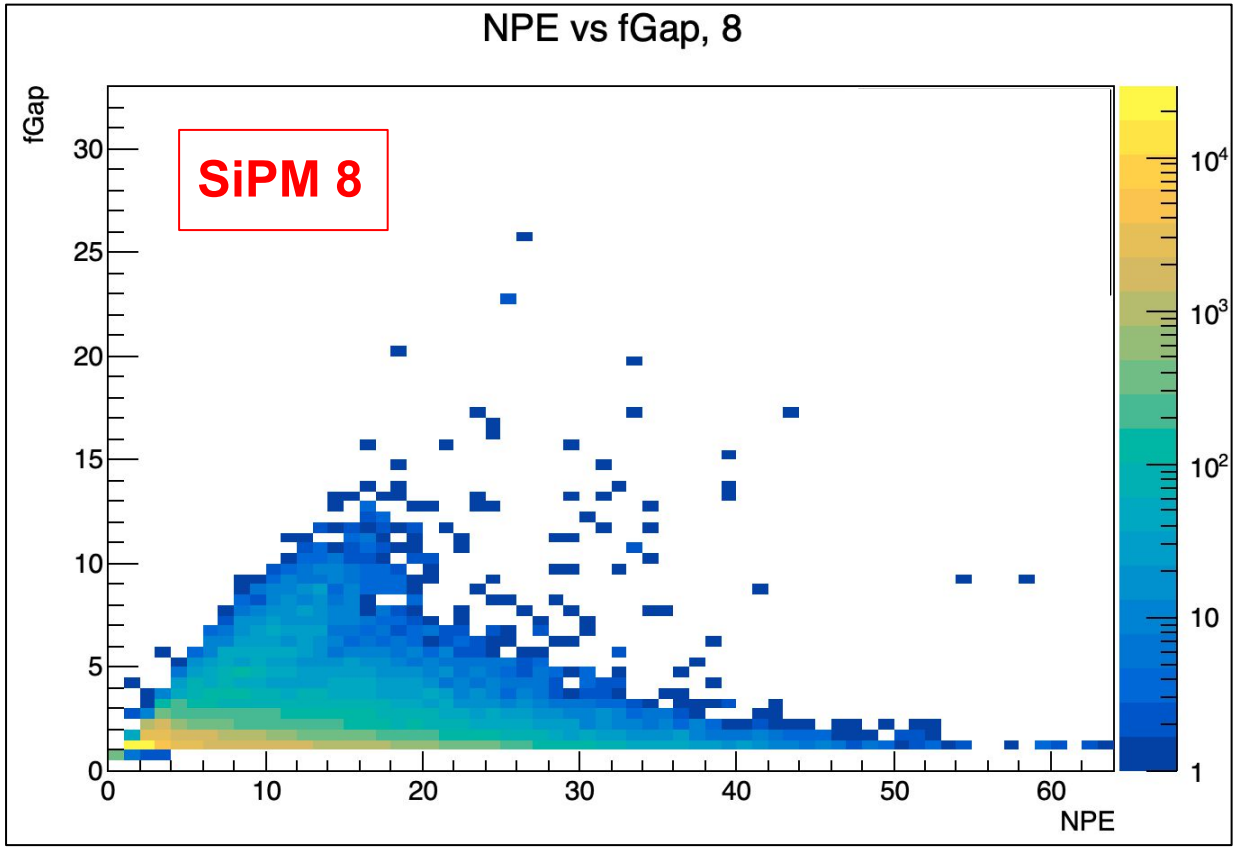
NPE - total photons

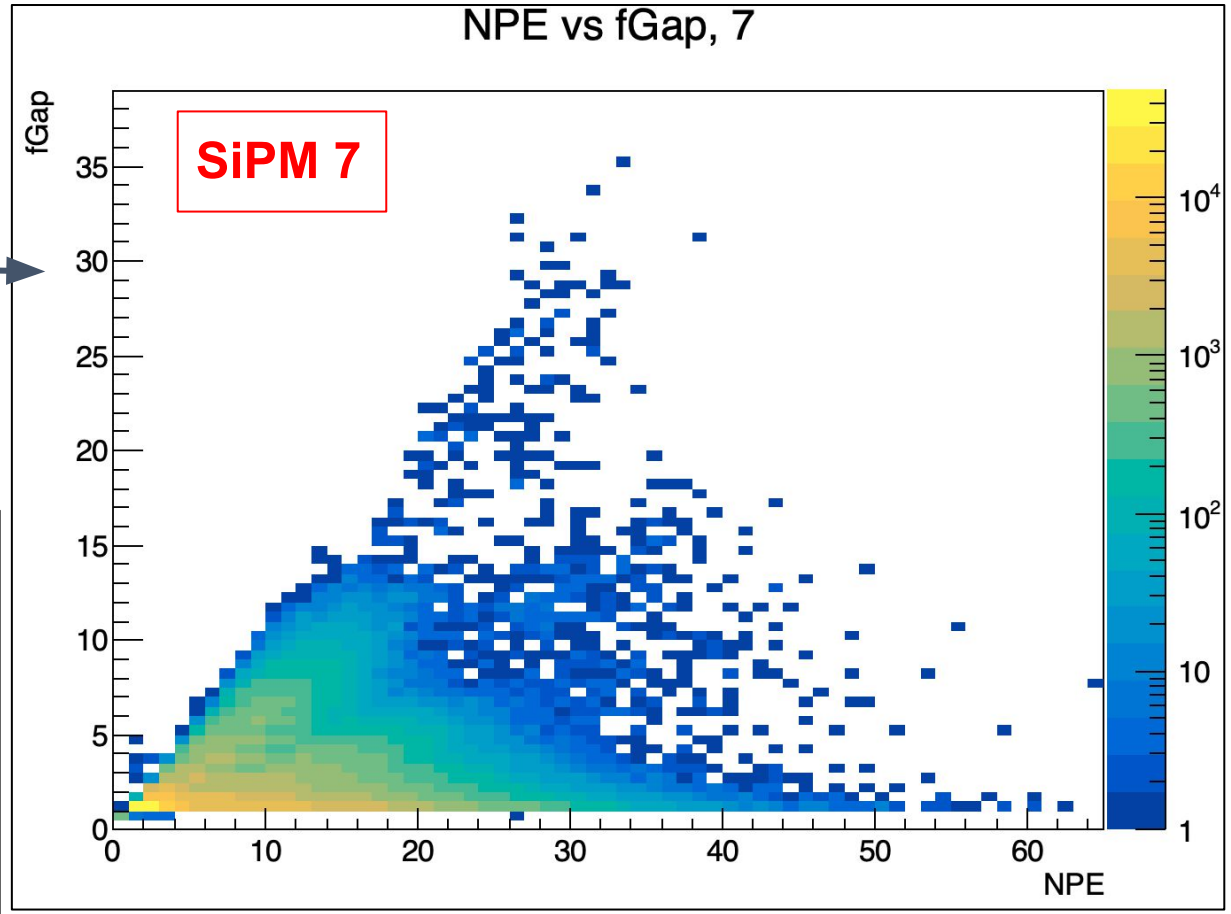


Gaseous Nitrogen Data

Window dominated events are **not isotropic!**

- dominant in SiPMs centered on 7
- source **anisotropy**
  - useful for **Cherenkov** study in LXe!





Outlook for LoLX

Commissioning in cold N_2 gas

- some evidence for eXT ...
- other prompt processes make it difficult to extract eXT signal
  - N_2 scintillation, window cherenkov/fluorescence
- source directionality!
- bigger fish to fry → LXe runs

Future outlook

- LXe cooldowns commencing in June!
- use bare SiPM at varying voltage as ‘source’ of eXT photons
- **Cherenkov** measurement incoming
- other scintillation physics!

- WaveDAQ digitizer prepared for shipping

  phase 2 coming soon!

External Funding

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Fonds de recherche
Nature et
technologies
Québec

References

[1] - JP Brodsky *et al.* “Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light”
https://arxiv.org/abs/1812.05694v1

[2] - Budinger TF. “Time-of-Flight Positron Emission Tomography: Status Relative to Conventional PET.” J Nucl Med **24**(1) 73-78 (1983)
https://jnm.snmjournals.org/content/24/1/73

[3] - M. Conti, “Focus on time-of-flight PET: The benefits of improved time resolution,” Eur. J. Nucl. Med. Mol. Imaging, **38**(6) 1147–1157 (2011)
http://dx.doi.org/10.1007/s00259-011-1763-7

[4] - nEXO collaboration, “nEXO Pre-Conceptual Design Report”
https://arxiv.org/abs/1805.11142

[5] - Characterization of the Hamamatsu VUV4 MPPCs for nEXO
https://arxiv.org/abs/1903.03663

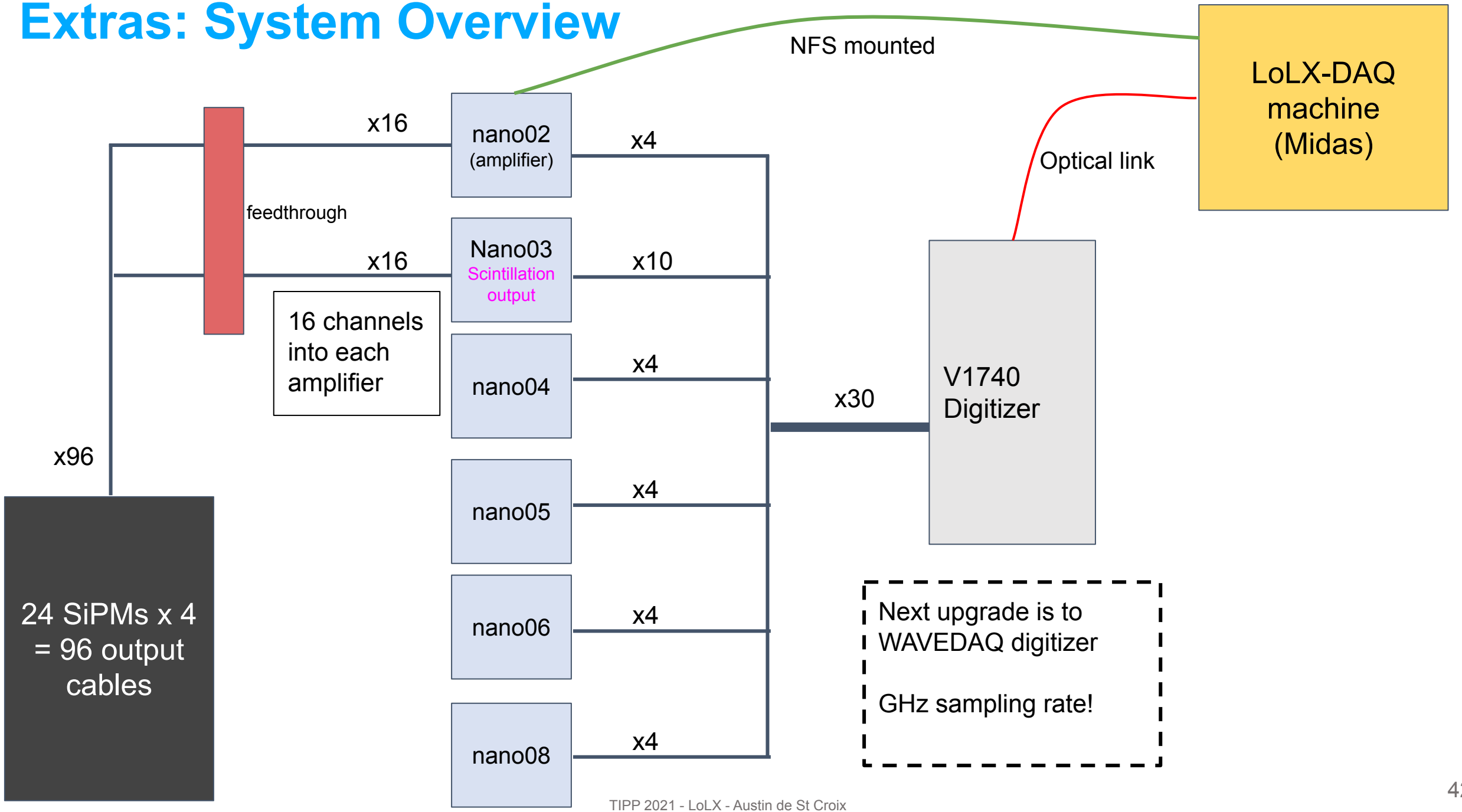
[6] - K Fujii *et al.* “High-accuracy measurement of the emission spectrum of liquid xenon in the vacuum ultraviolet region”
https://doi.org/10.1016/j.nima.2015.05.065

[7] - G. Signorelli, S. Dussoni. “Possible usage of Cherenkov photons to reduce the background in a 136Xe neutrino-less double-beta decay experiment”
https://doi.org/10.1016/j.nima.2015.11.099

[8] - P. Laporte and I. T. Steinberger. “Evolution of excitonic bands in fluid xenon”
https://doi.org/10.1103/PhysRevA.15.2538

[9] - G. Lehaut *et al.* “Scintillation properties of N2 and CF4 and performances of a scintillating ionization chamber”
https://doi.org/10.1016/j.nima.2015.05.050

Extras: System Overview



Extras: Electronics Layout

Cryostat at McGill

x96

16ch input amplifier

- in situ IV curves!

RF amp

DC to 2GHz BW

op-amp

optional 4ch

summing

CAEN DT1740

Digitizer

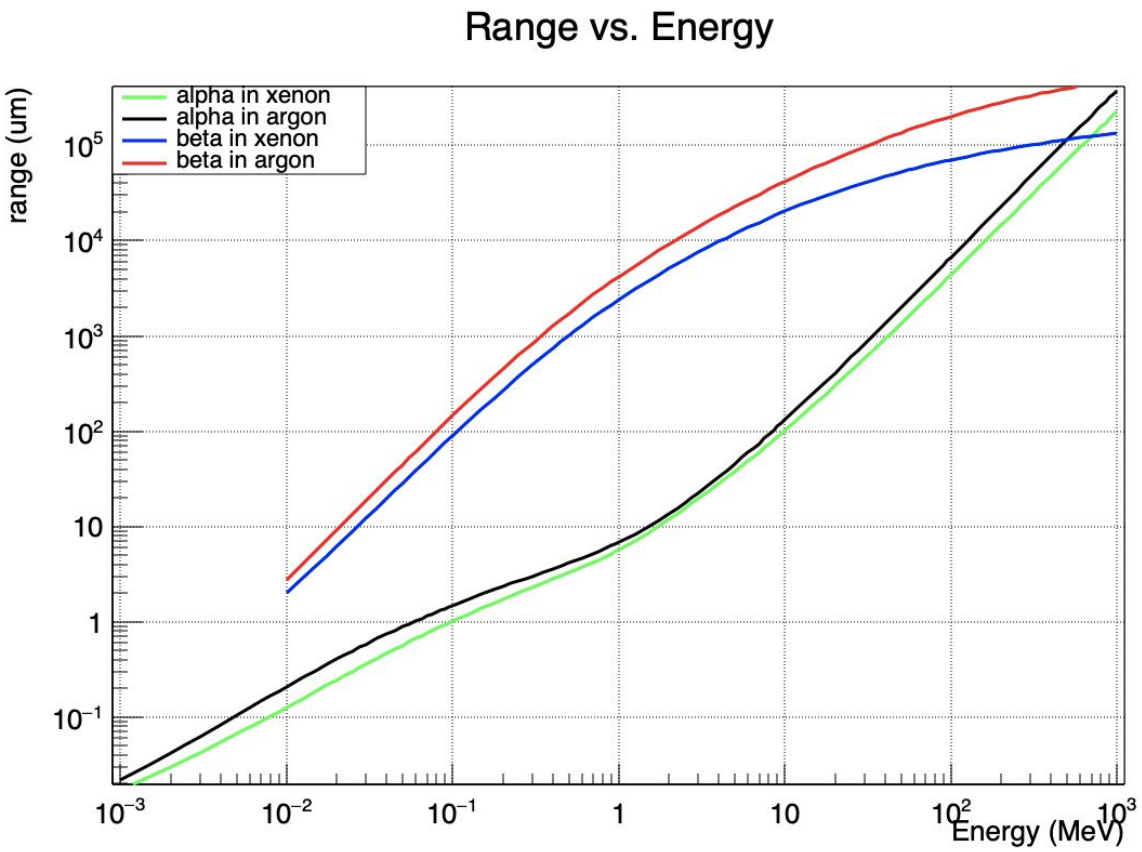
62.5MHz sampling

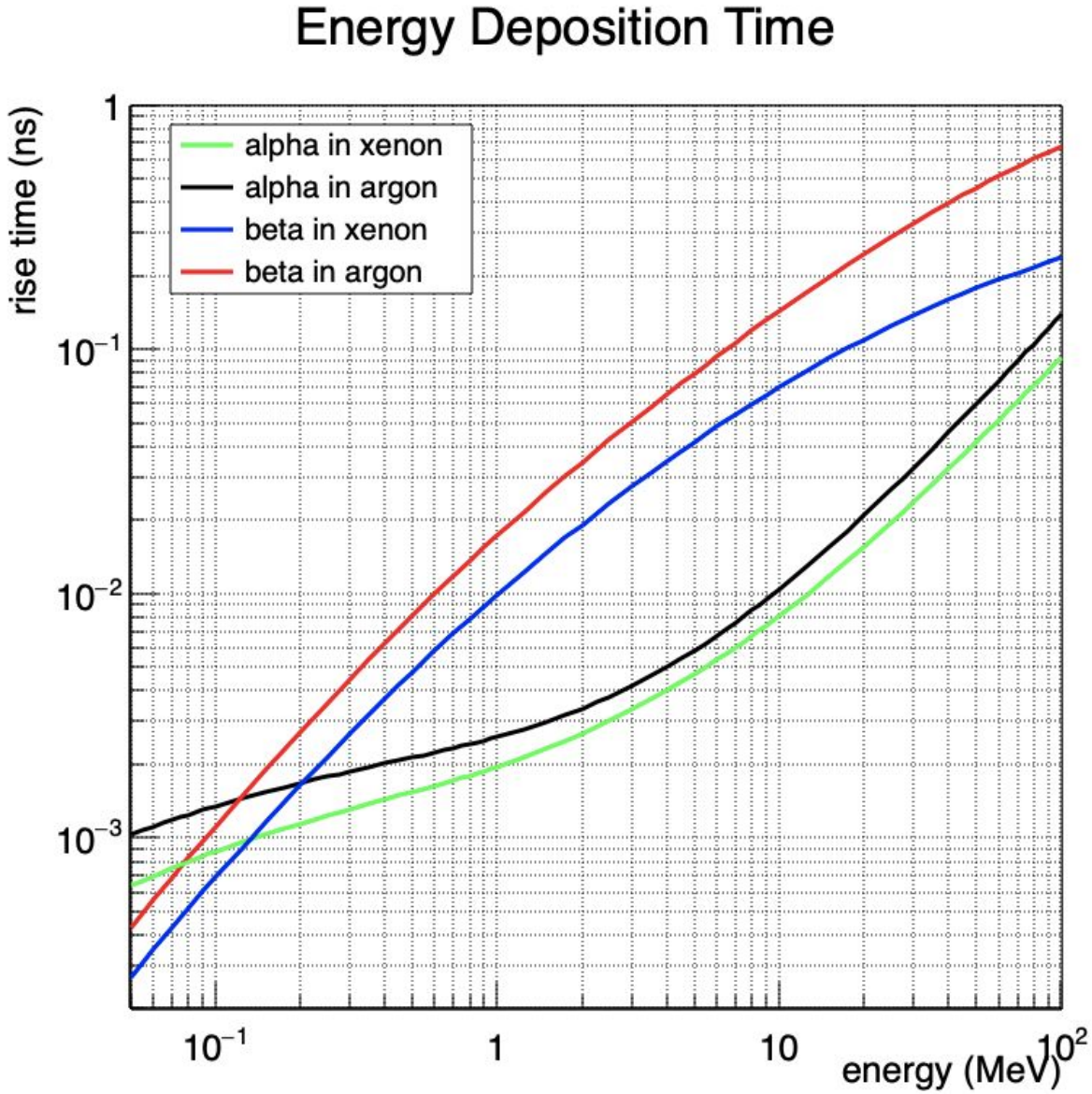
(16ns, slow)

Cherenkov SiPMs are summed → 22 channels
Bare and bandpass SiPMs unsummed → 8 channnels

Extras: Deposition time

Inverting and integrating range as a function of energy, we can find the time for the particle to slow down. This sets the lower limit on the scintillation rise time





Toy MC: Overview

Variables:
NPE = number of photons per event
tau_1, tau_2 = lifetimes
rho = N_{fast}/ N_{slow}
P = probability of eXT occurring
res = timing resolution (spread of eXT photons)

1. generate scintillation photon times (NPE)
   beta = rho / (1 + rho)
   store in vector<float> timesPure

$$f(x) = \frac{\beta}{\tau_1} e^{-t/\tau_1} + \frac{1-\beta}{\tau_2} e^{-t/\tau_2}$$

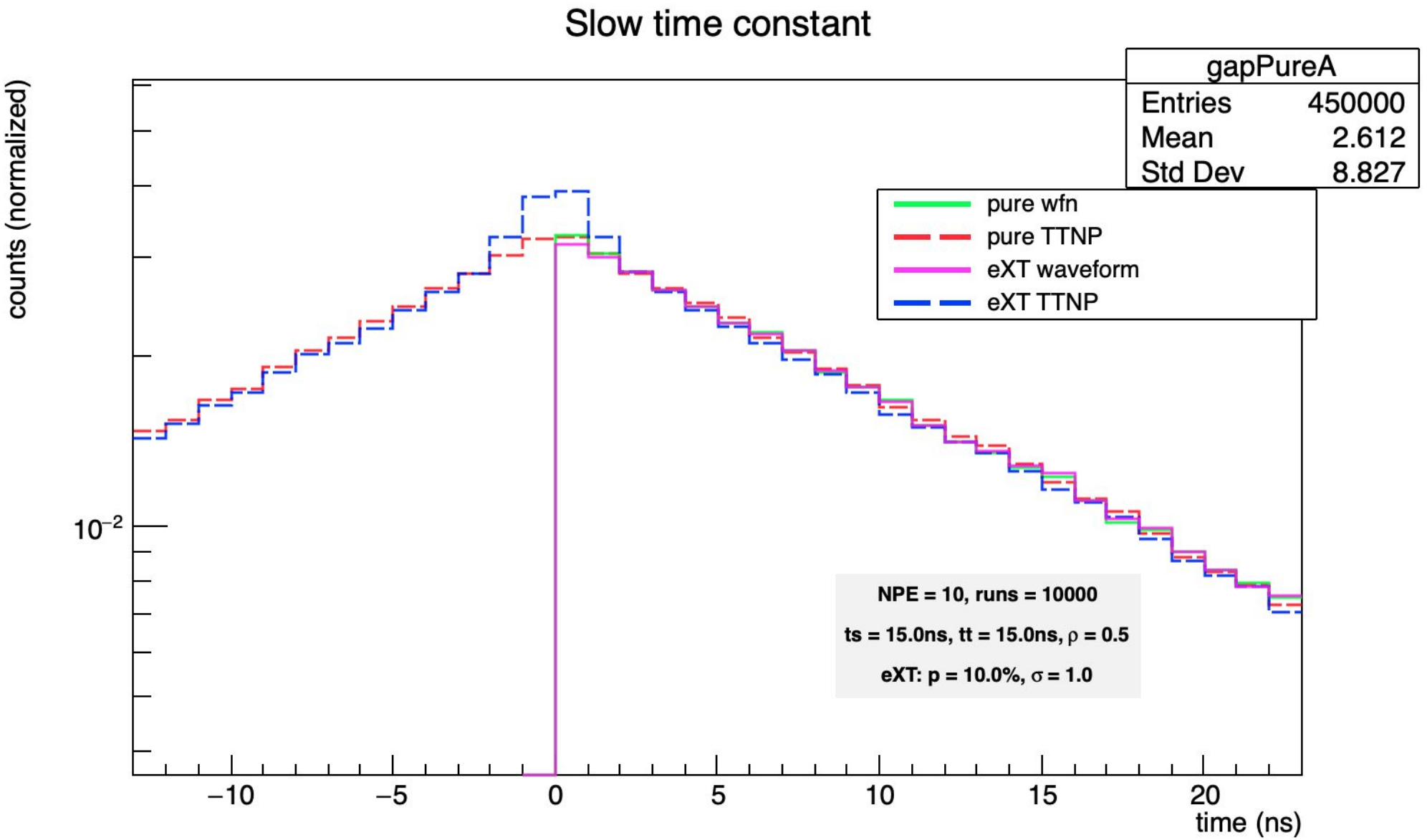
2. generate all TTNP combinations using nested forloops, store in vector<float> gapsPure
3. add eXT induced times for each photon

```
loop on photons
  t0 //photon time
  if rand() < p_ext
      timesPure.push_back(t0 + rand::gaus(0, res))
```

4. calculate TTNP times again
5. repeat for certain 'number of runs' → NPE = 10, run x 1000 is not the same as NPE = 1000, run x10

45

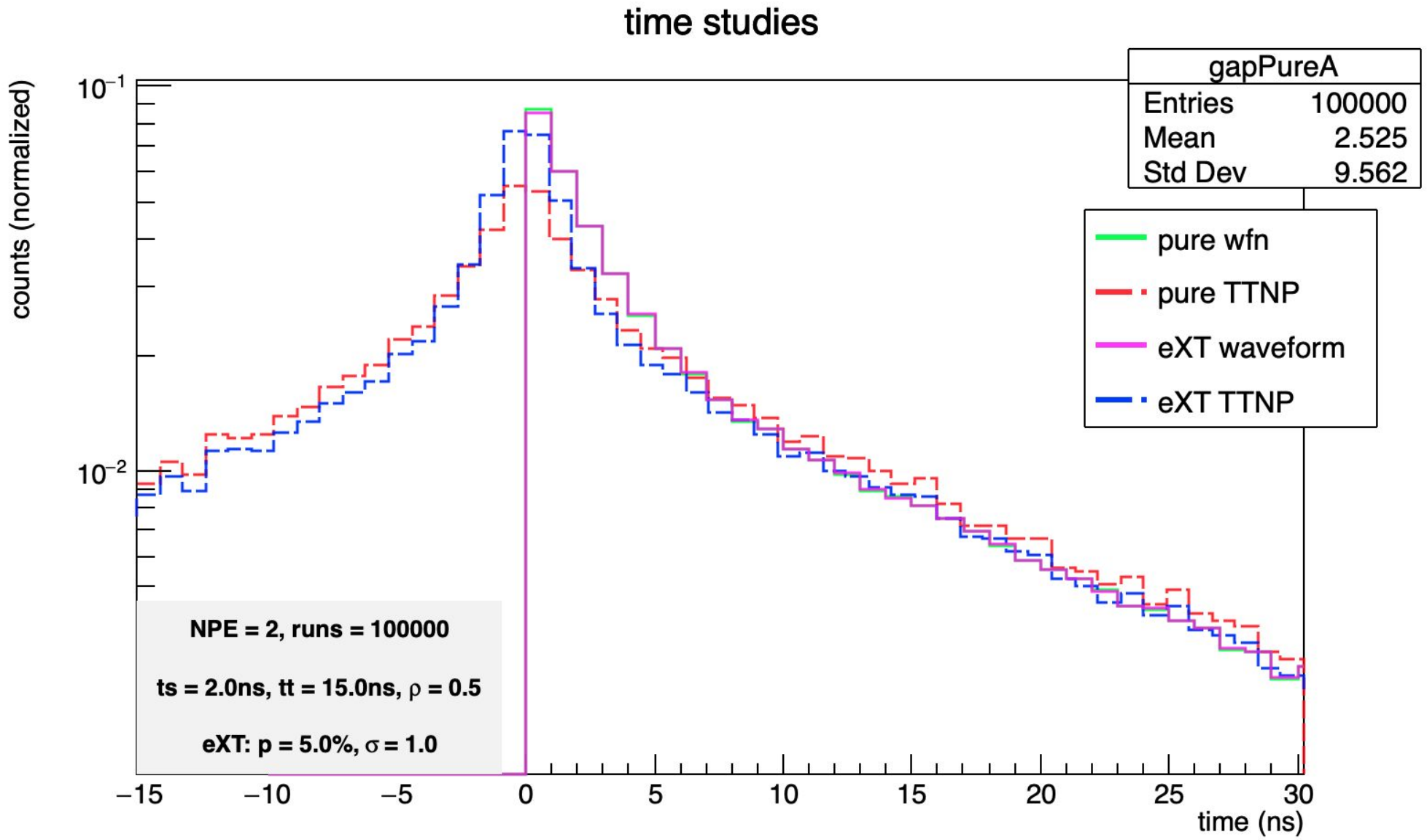
Toy MC: only slow scint, eXT = 10%, NPE = 10



46

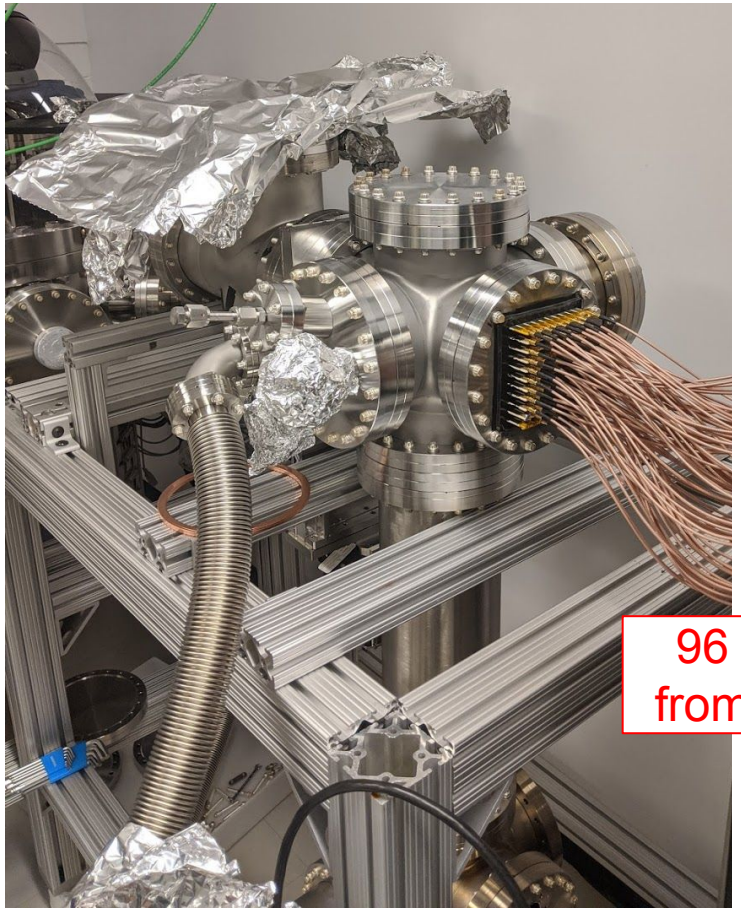
Toy MC: adding fast scint, eXT = 5%, NPE = 2

Again: do better with lower NPE

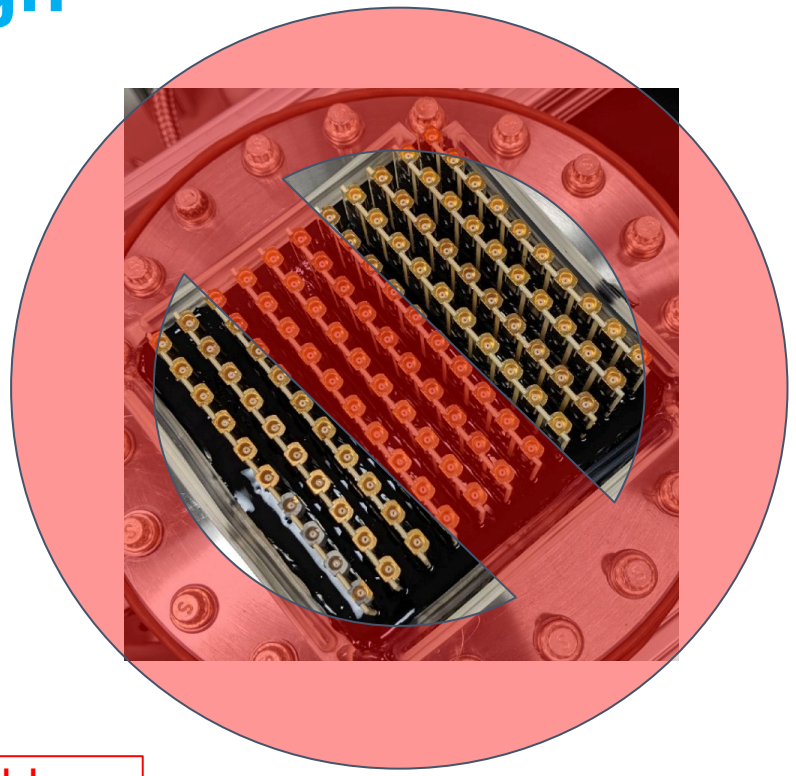


47

Cryostat: Feedthrough

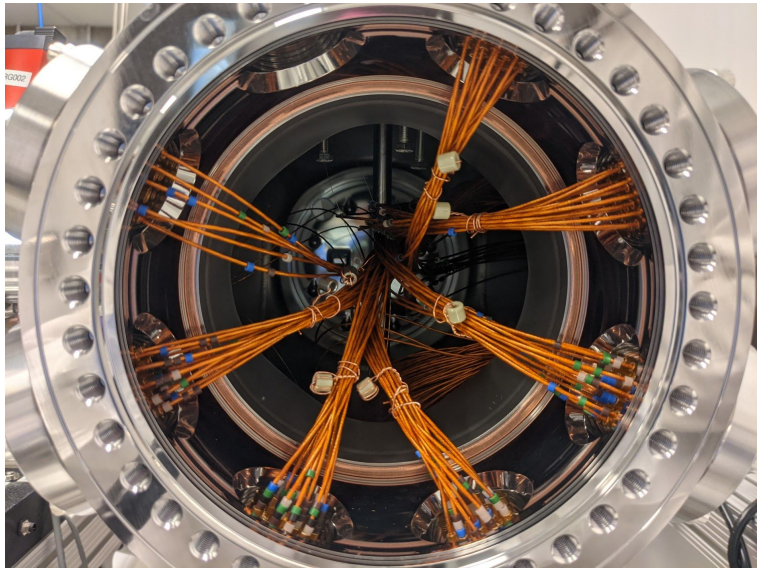


96 cables from SiPMs



Feedthrough Challenges

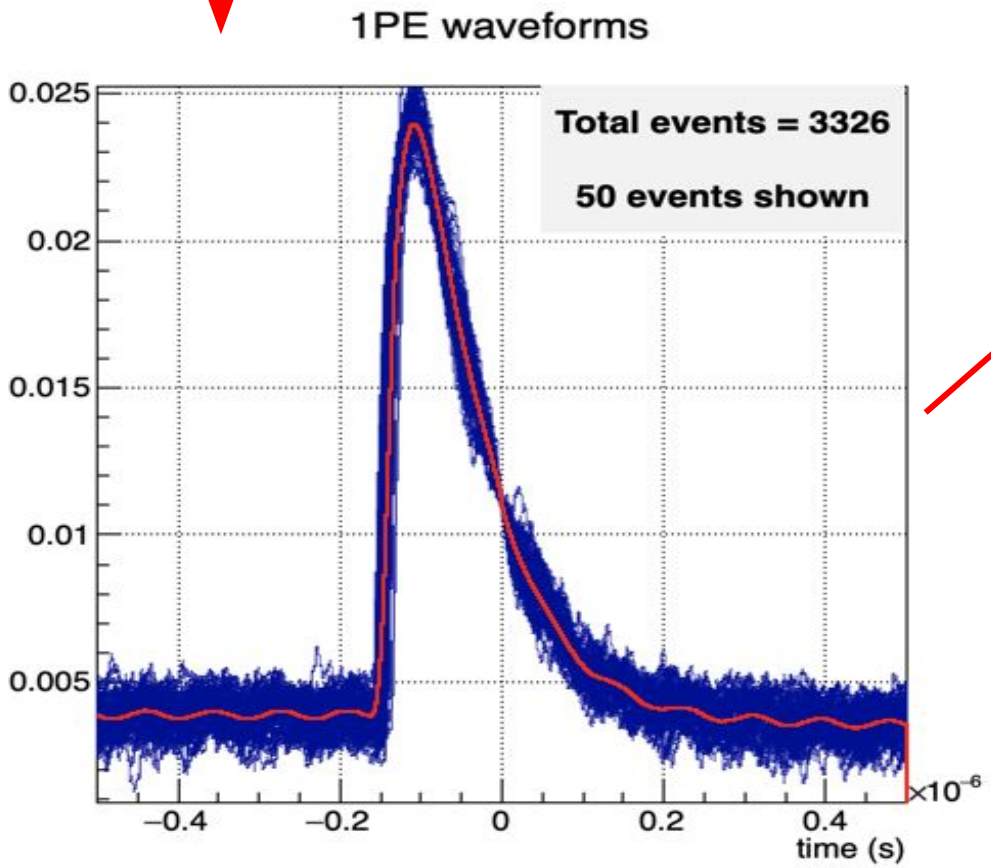
- PCB potted feedthrough using STYCAST 2850FT epoxy Black
  - developed a leak
- switched to new strategy using multiple smaller feedthroughs

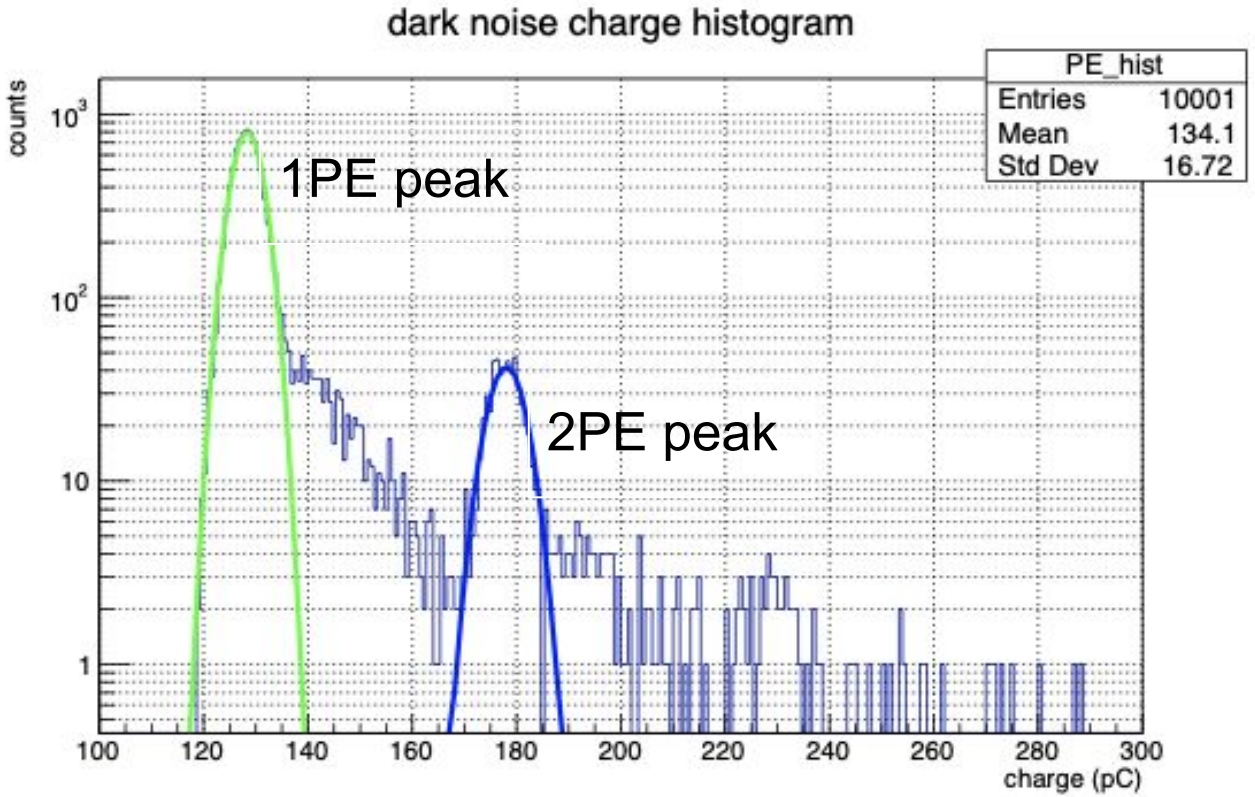


Cryostat at McGill

Extras: Single PE resolution (Oscilloscope)

Histogram charge from many waveforms





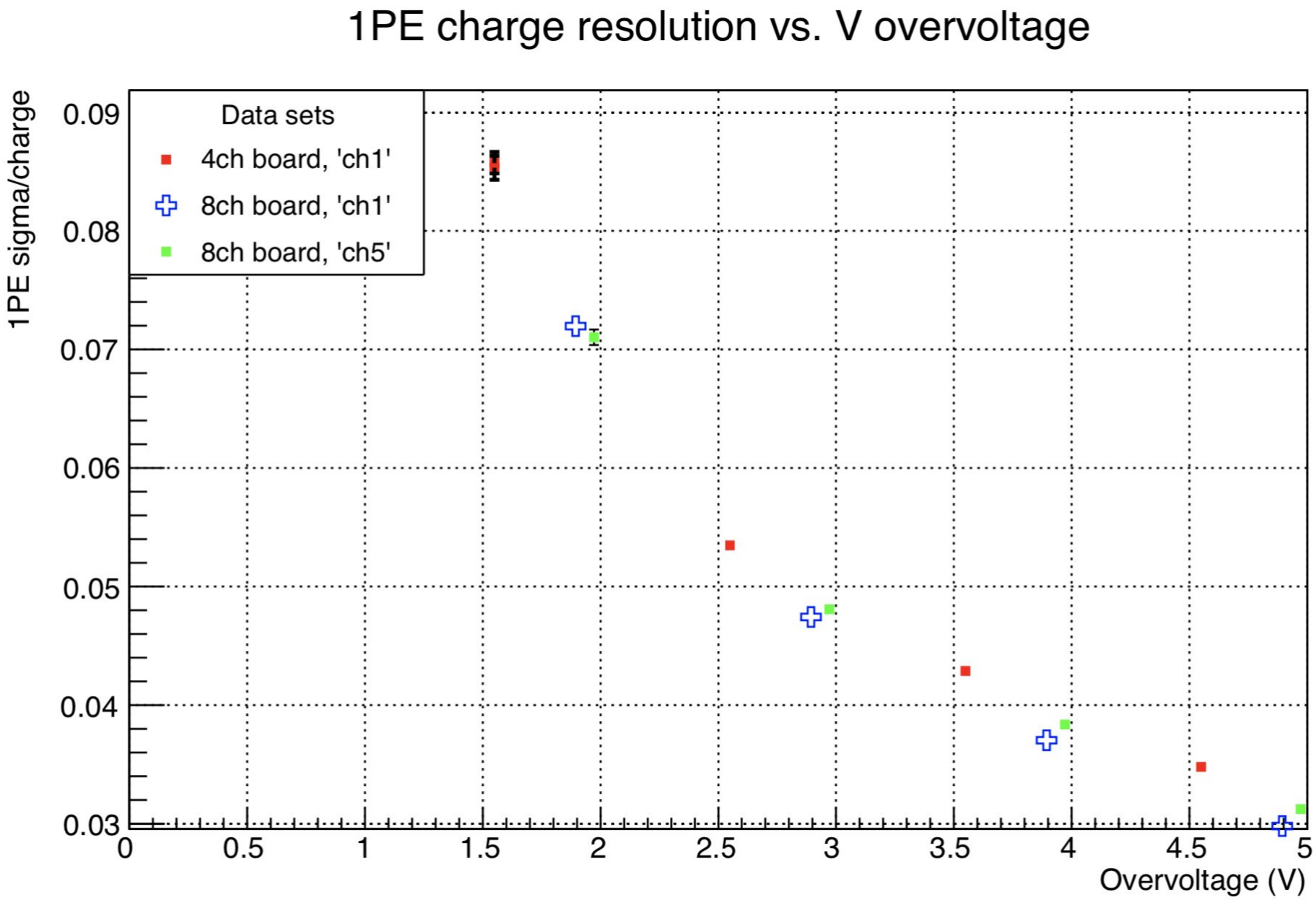
Single PE resolution is given by

1PE charge vs gaussian width

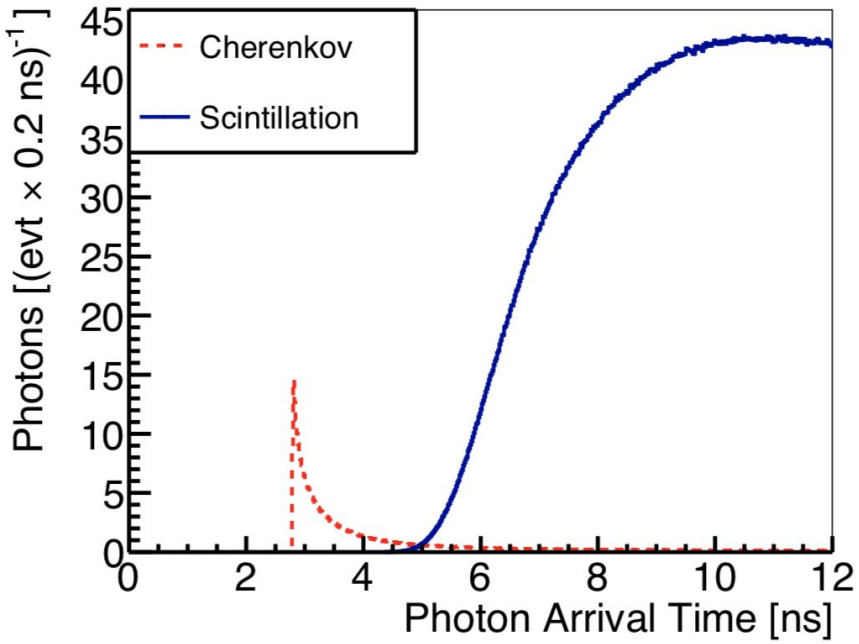
Extras: Single PE resolution (Oscilloscope)

Charge resolution is good (with scope)

*no horizontal error bars, which represent uncertainty in breakdown voltage due to temperature uncertainty

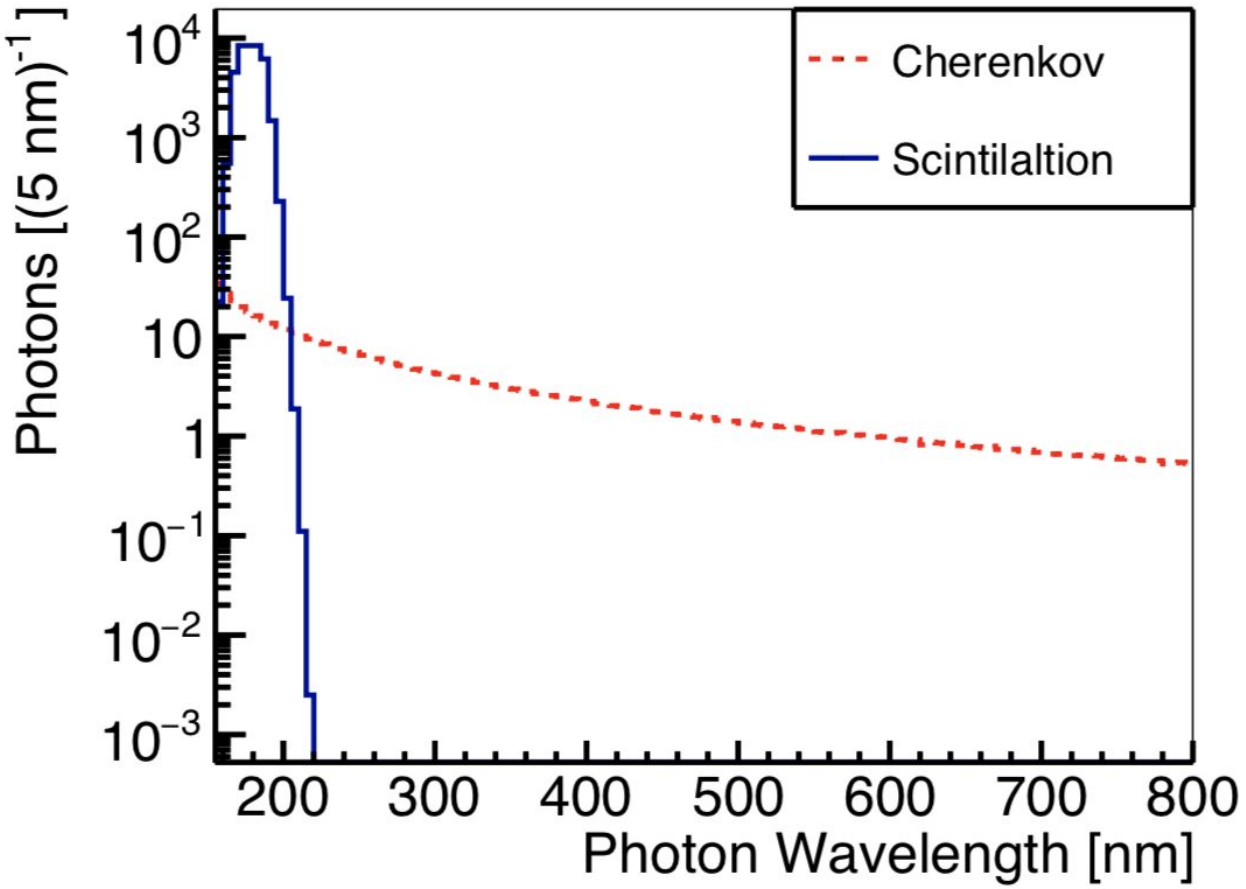


Extras: Cerenkov helping 0vBB Experiments



Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light

Jason Philip Brodsky[a], Samuele Sangiorgio[a], Michael Heffner[a], Tyana Stiegler[a]

[a]*Lawrence Livermore National Laboratory*

Case	Description	Sensitivity improvement
1	Baseline	1.43
2	Compton Scatters included	1.11
3	Perfect background rejection	7.61
4	Back-to-back evenly-split $0\nu\beta\beta$	1.96
5	Back-to-back, even split $0\nu\beta\beta$ and straighter tracks	5.53
6	Truth-value Cherenkov ID	1.40
7	100% detection efficiency	1.59
8	10% detection efficiency	1.20
9	No directional information	1.34