

Analog Photon Processor (APP) ASIC

- Photon waveforms and feature extraction
- Analog Photon Processor (APP)
 - Requirements
 - Development
 - Status

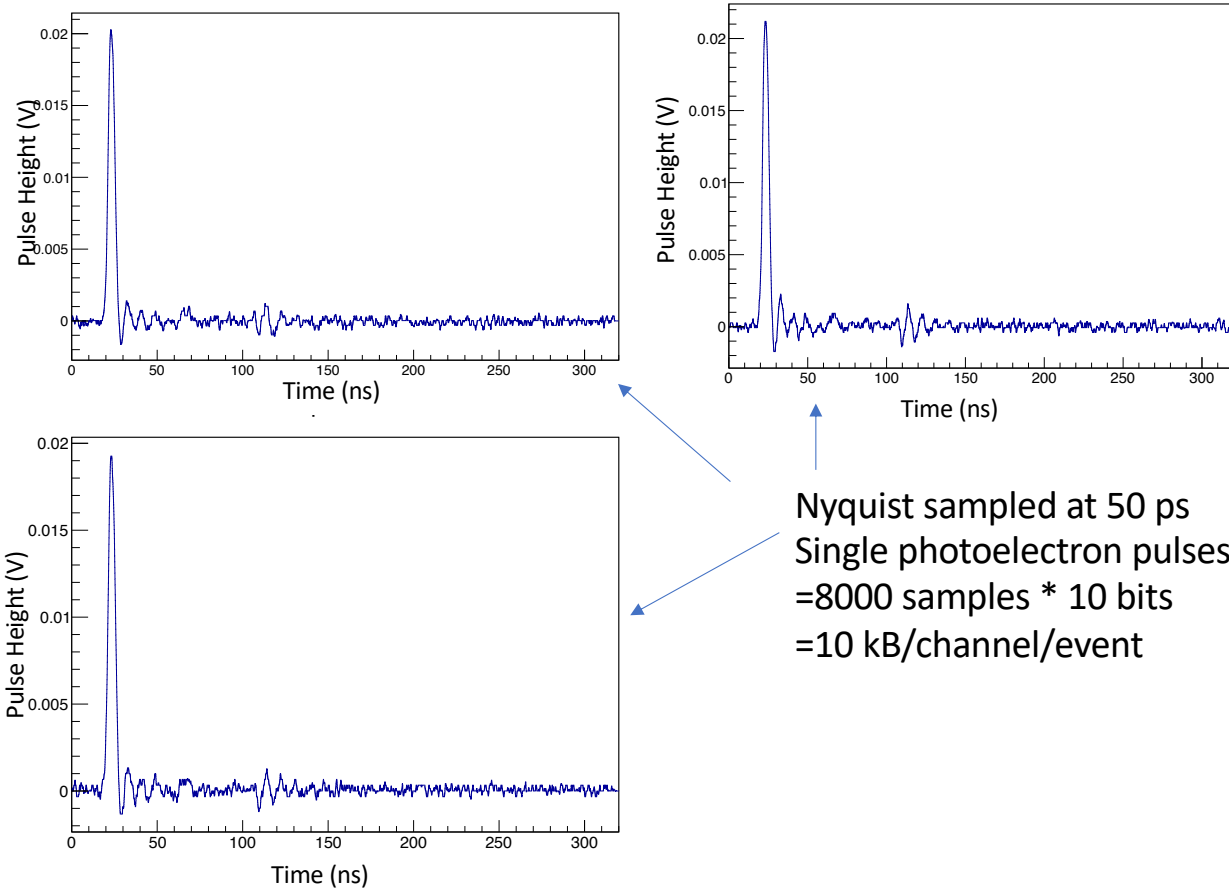
The Goal

- “Waveforms” in photon-based detectors are typically the sum of a small number of similar-looking pulses in each sensor (PMT, SiPM, etc.)

This approach recovers all the information contained within the bandwidth limit.

But we only care about N_{photons} and arrival times t_i —pulse shape does not matter here.

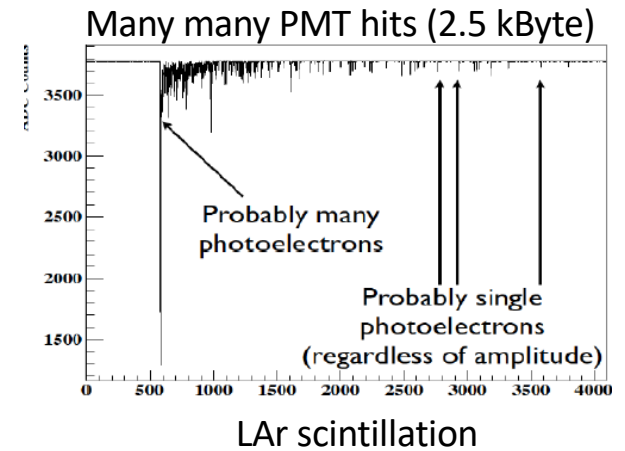
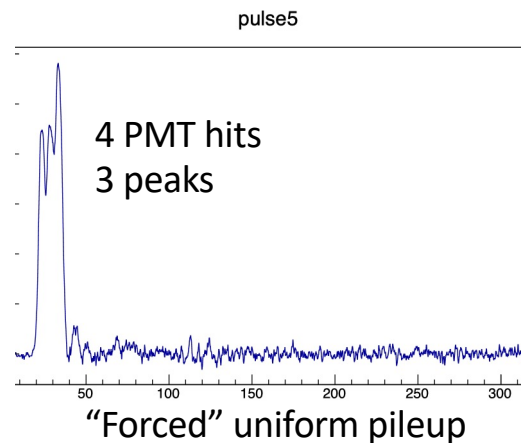
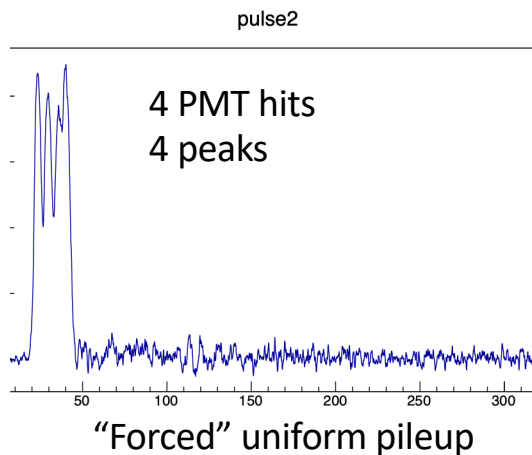
In single pe regime ($N_{\text{photons}}=1$), this is just one number.



The Goal

- For multi-pe waveforms: $w(t) = \sum_{i=0}^{N_{photons}} p(t - t_i)$

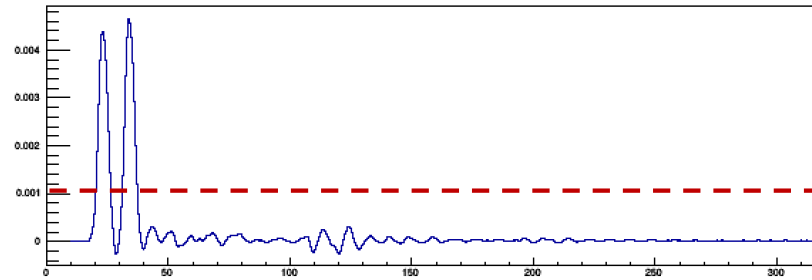
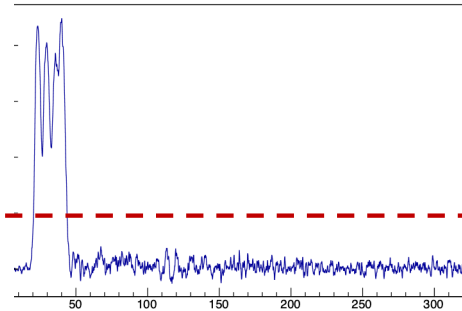
Shape of waveform depends on distribution dN/dt of light



Are there features we can extract that give us $N_{photons}$ and t_i well enough that we do not need full waveform digitization, even in the multi-pe regime?

Definition of “Resolved Pulse Packet”

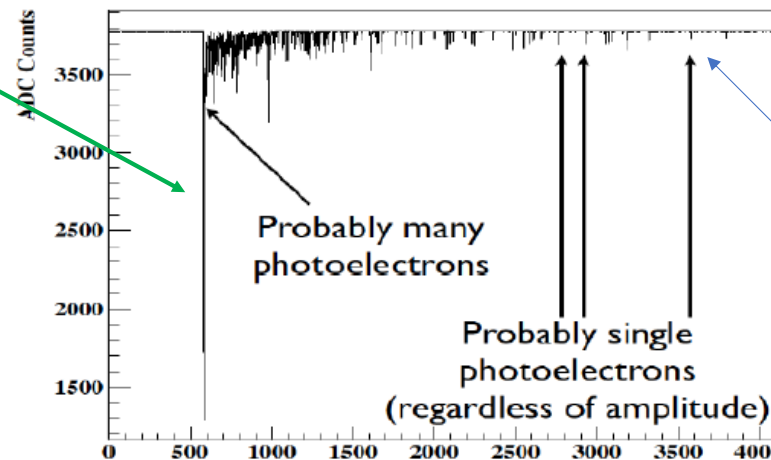
Critical to feature extraction



“Fully resolved” means pulses that fall below threshold and then have a second rising edge above threshold

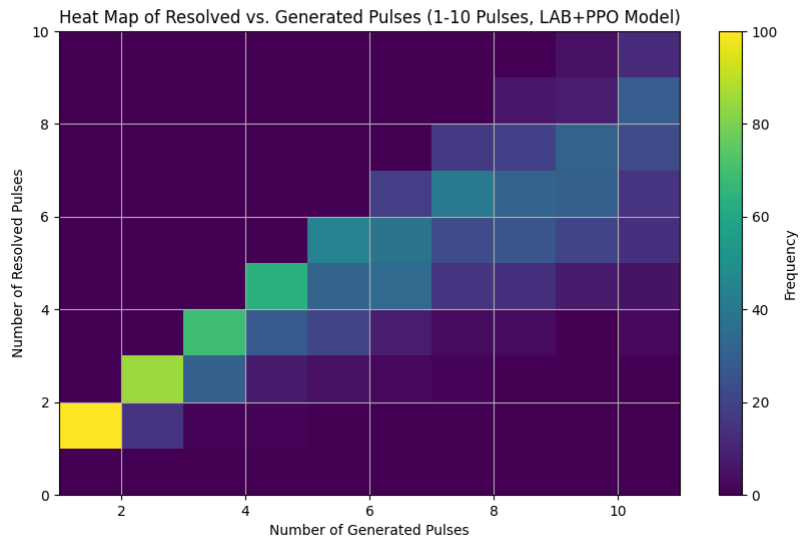
Not resolved

Analysis of fully resolved pulses just recapitulates analysis of unresolved pulses ---resolved pulses each can have their own analysis

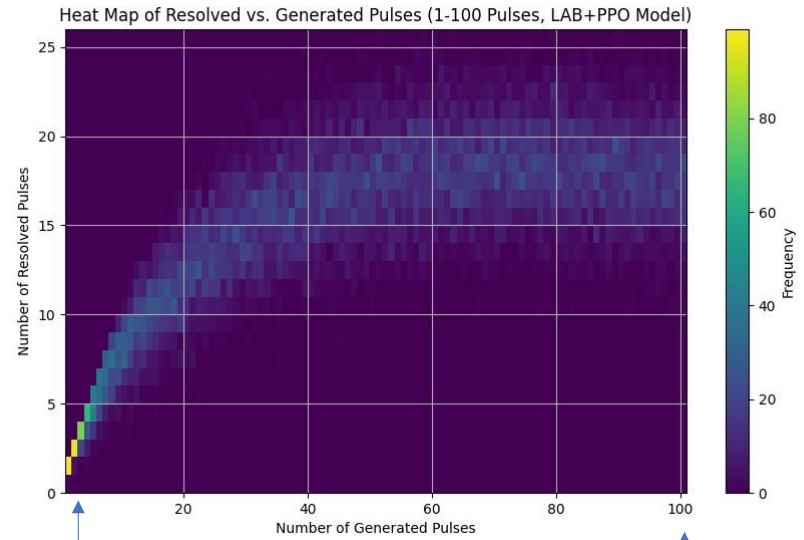


How Many Resolved Packets vs. Total Photons?

PMT-like pulses with $2.5 \text{ ns } \sigma$



Light Yield (per channel) for Solar ν in LAB-PPO Theia

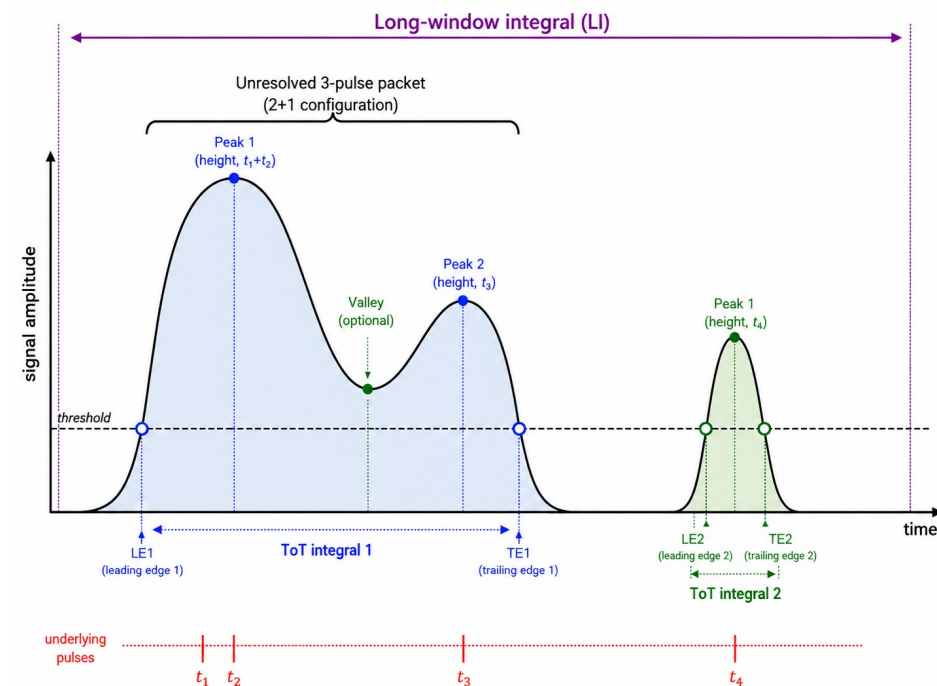


Light Yield/chan for 1 GeV Muon
going through LAB-PPO in Theia

Analog Photon Processor Requirements

- Retriggerability – to create resolved pulse packets
 - In practice this will depend on realistic bandwidths
- Integrator dynamic range 500 pe
 - INL <1% after calibration
- SNR > 10-20
- Peak detection for at least two peaks/resolved packet
 - Amplitude and time
- Time resolution and precision 25 ps leading edge
- 8-deep analog memory FIFO

We have worked within TSMC's 65 nm process to ensure we are fast enough



Analog Feature Extraction

Clearly, features could be found with FPGA operating on digitized data but:

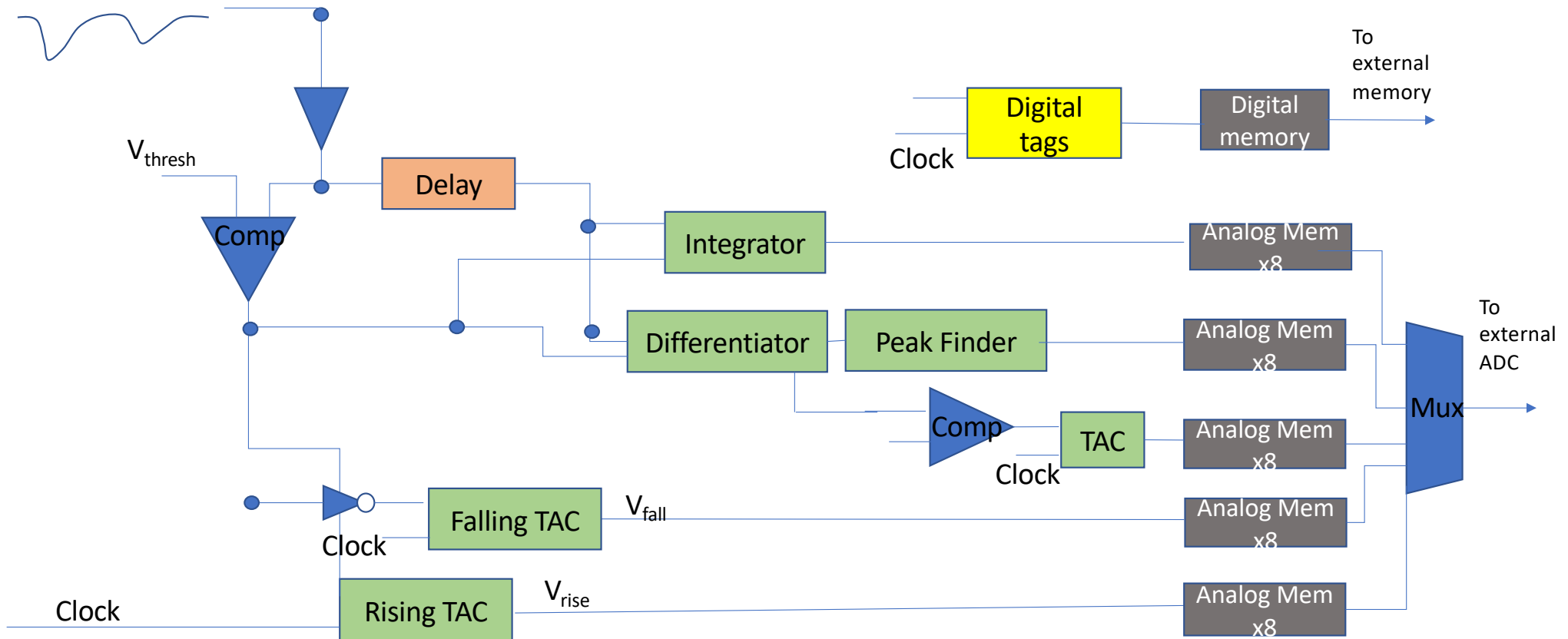
- High-end FPGAs (e.g. RFSocS) are not cheap
- Firmware is frustrating (or expensive)
- Fast sampling ADCs are power-hungry and expensive
- Bandwidth must be limited to sample at Nyquist---limits timing precision

Analog approaches can measure all the features and:

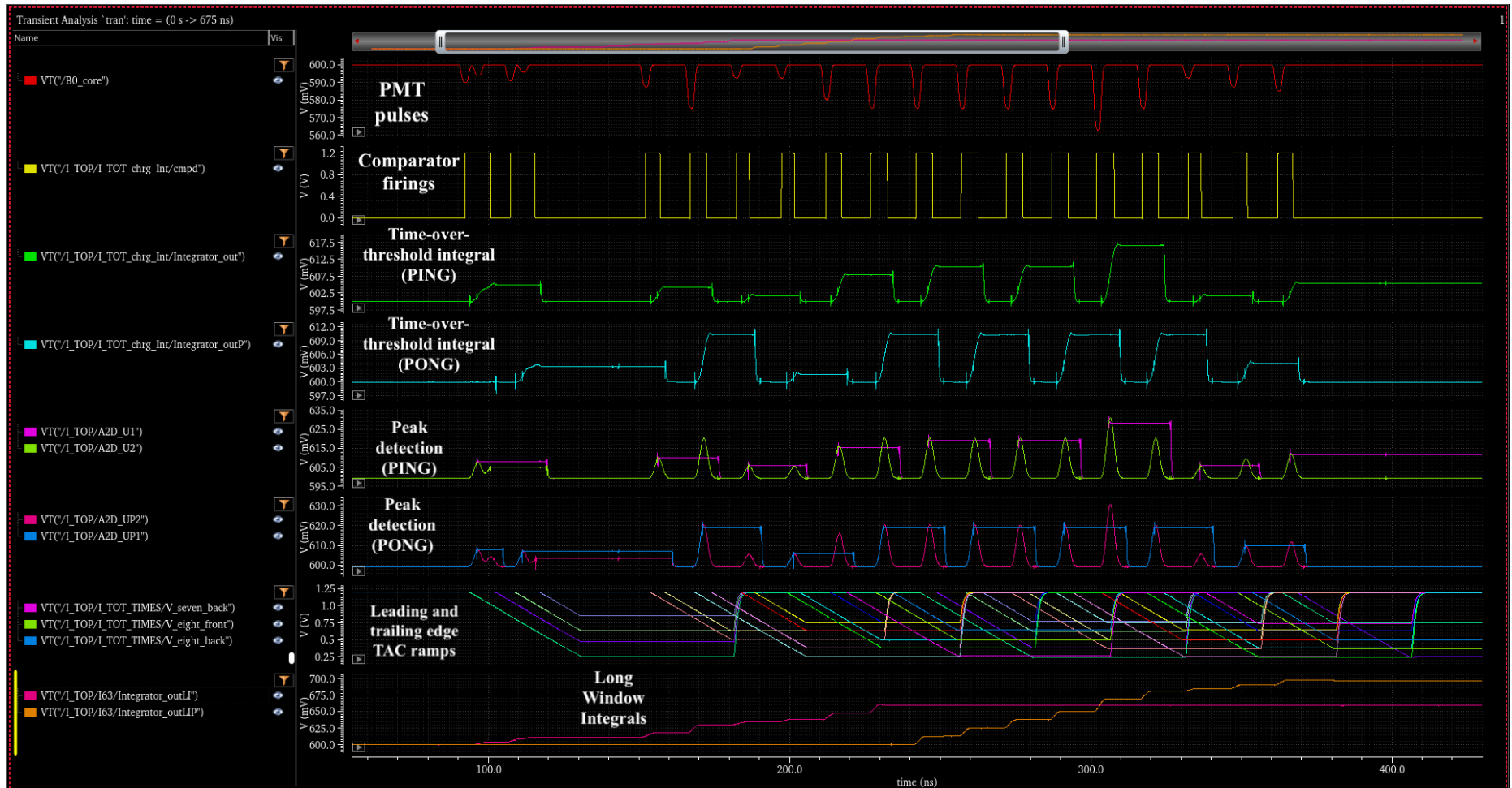
- Much cheaper (\$40/channel for a large system?)
 - ADCs can be very slow (1-10 μ s conversions)
- All “useful” information but with much smaller data size---faster data analysis, less storage
 - Up to 8 measurements/packet (for two peaks) @ 12 bits ~ **13 Bytes/packet**
- Can have better timing precision because marginal Nyquist restrictions
- Little to no deadtime
 - Only during switch from one resolved packet to another---could be zero

Analog Photon Processor ASIC

Feature Block Diagram

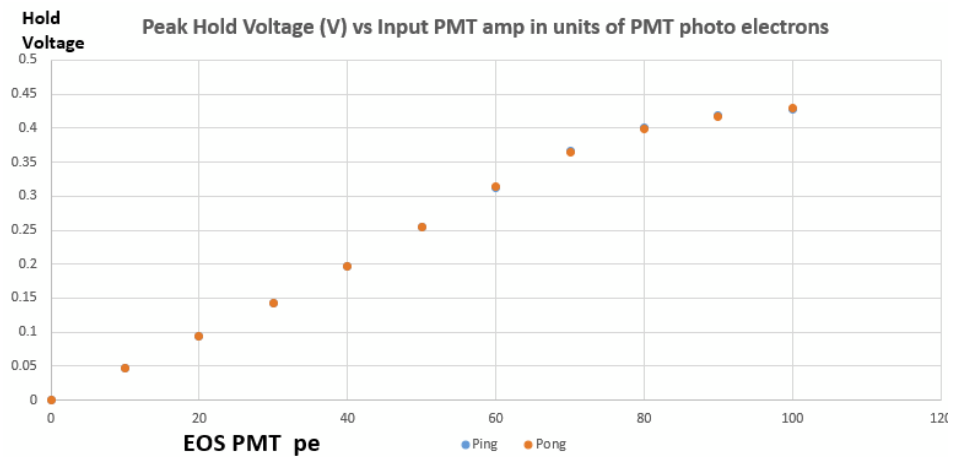
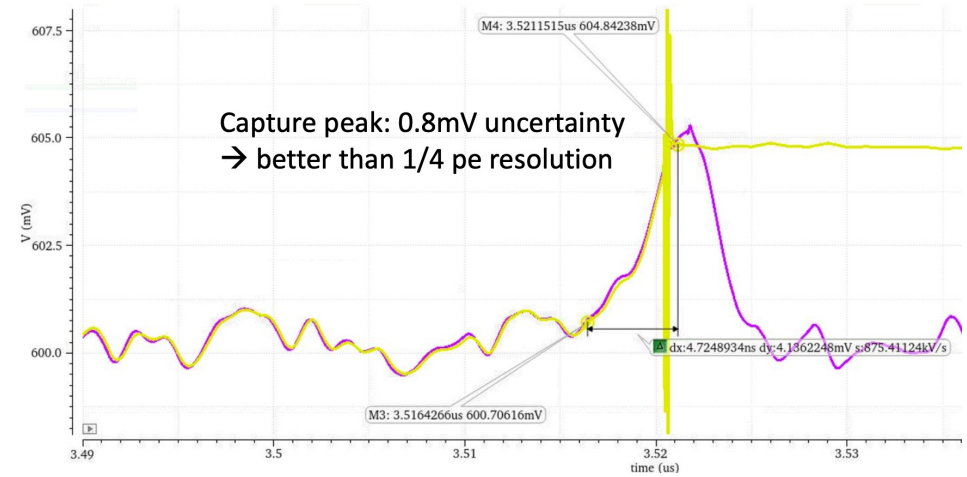
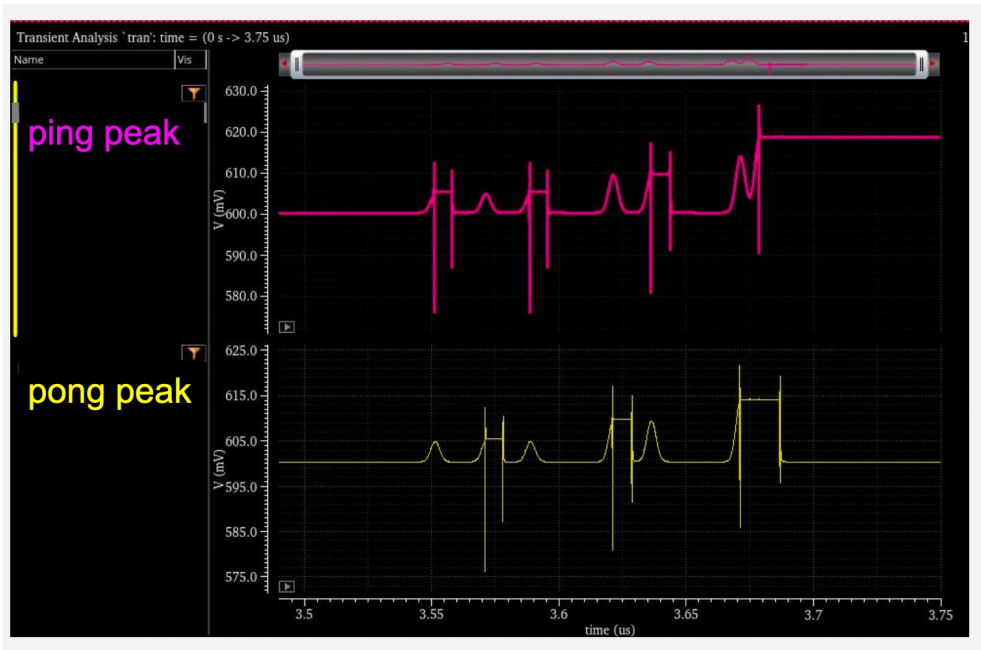


TSMC 65 nm simulation



TSMC 65 nm simulation

Peak Detection



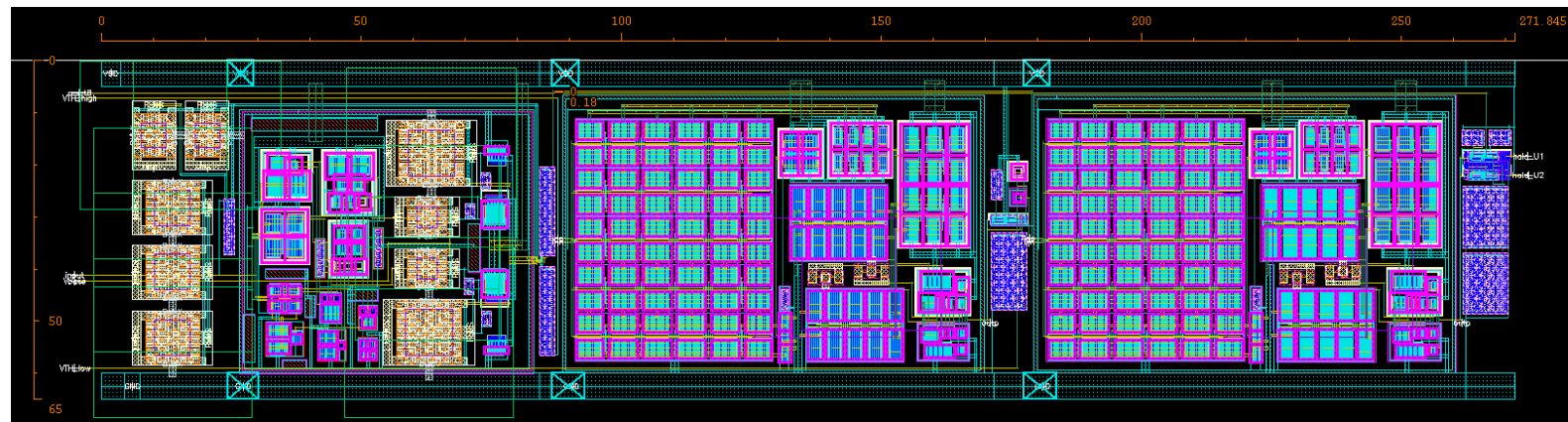
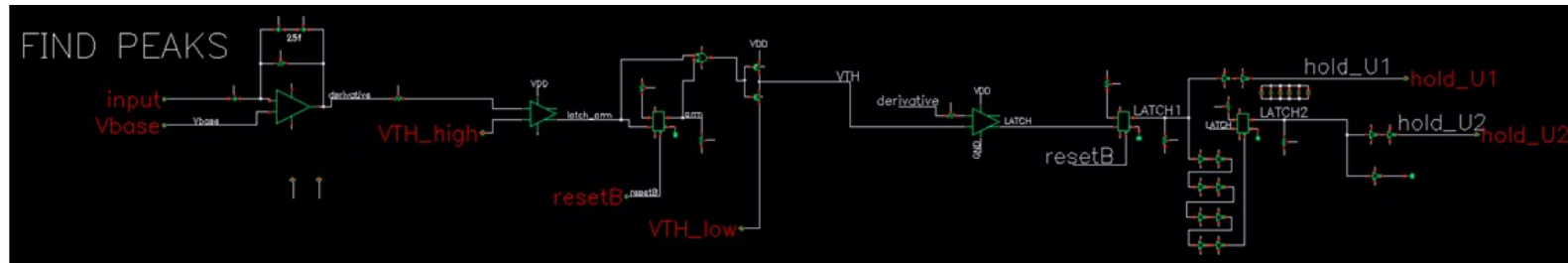
Deadtime Mitigation

1. PING/PONG on time-over-threshold integrals
2. PING/PONG on peak heights and times
3. Comparator counts --- every firing in an event is counted
4. 1 TAC for every memory location (ie, up to 8 for each measurement)
5. Long window integral

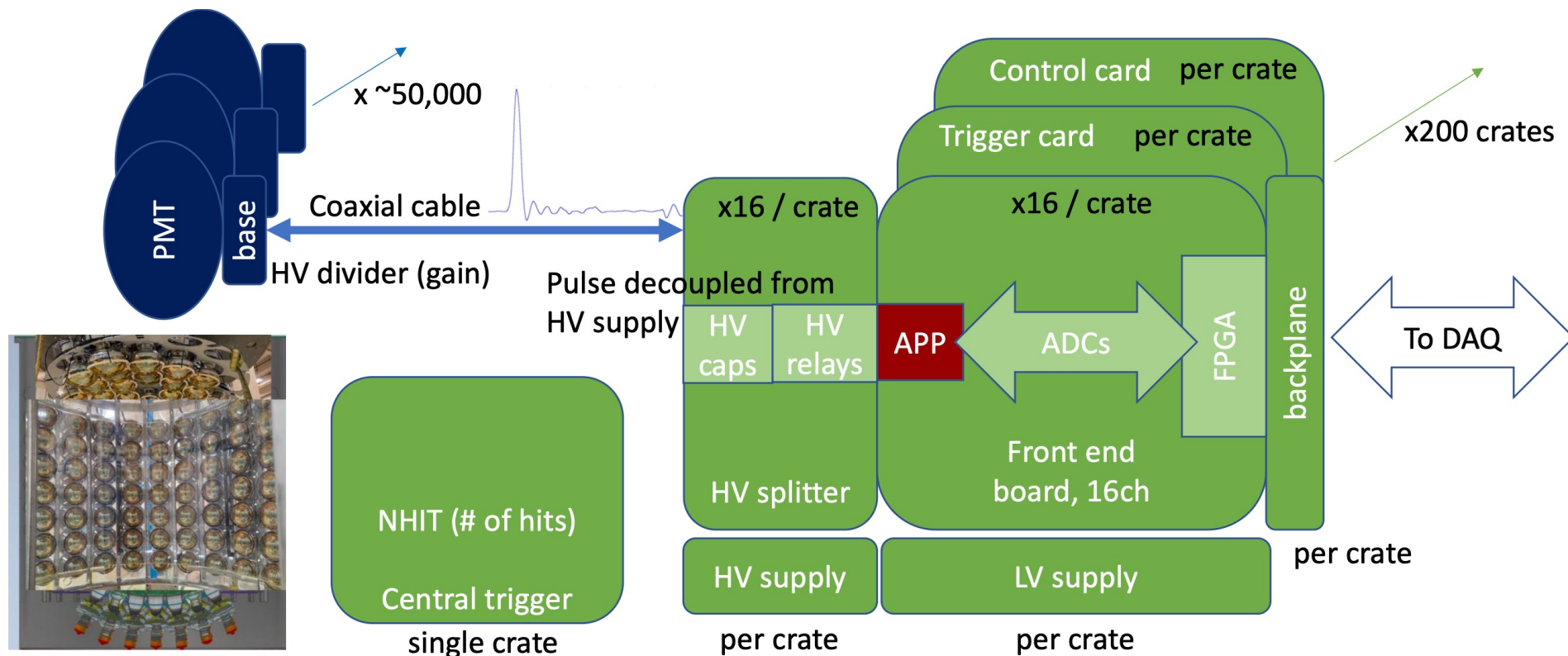
Example: If a third resolved pulse packet comes (PING/PONG/PING) and the first PING is not yet written, we integrate just part
But: the third comparator firing is recorded, the time-over-threshold is recorded, and the long-window integral sees it

Hard deadtime limit is if 8-deep FIFO is filled up---rarely happens in
a real detector, even for muon+micel

Find peak (Layout & schematic)



Pre-conceptual Design for APP-based DAQ for Eos



APP+ADC costs = \$88/channel
(much smaller for a larger system)

Status

- Analog design complete and undergoing extensive process-corner testing
- Conceptual digital design (triggering, memory reads, metadata) complete
- Implementing RTL and testing for synthesizability now
- Pad ring design 90% finished
- Layout underway
- Expect tapeout this year

Summary

- Analog processing provides a low-cost, low-data volume option for large PMT detectors
- (Nearly) deadtimeless feature extraction retains most important information
- Chips should be in hand soon for testing
- Possibly a complete system for testing at Eos
- For a very large detector, cost and power savings should be very helpful

- Current APP team:, David Drobner³, Carl Grace⁸, Paul Keener², Josh Klein¹, Godwin Mayers², Mitch Newcomer², Adrian Nikolica², Ravi Pitelka³, Rick Van Berg², Jihao Yang²
- Past contributors: Nandor Dressnandt², Yiming He⁴, Bill Heintzelman⁷, Ben Land⁶, Chengjun Li⁴, Ke Liu⁴, Xiaokai Ma⁴, Max Malakhovets⁵, Meijun Tian⁴, Hao Yan⁴

¹Principal investigator

²Instrumentation group

Physics ⁶postdocs, ³PhD students, ⁷visiting scholars

Electrical Engineering ⁴Master's students, ⁵undergraduate students

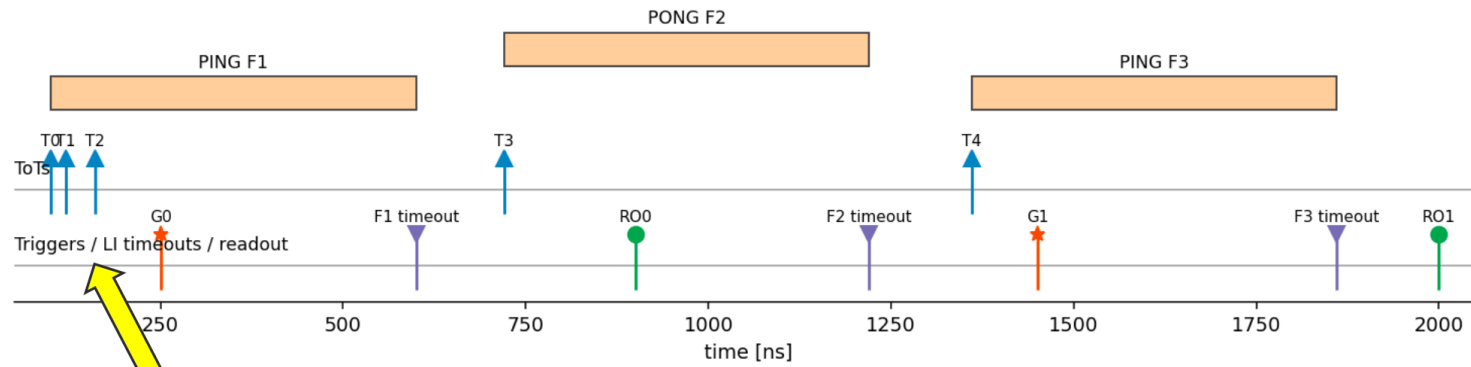
⁸Collaborators



Funded by Department of Energy, Office of High Energy and Nuclear Physics, grant number DE-SC0007901

Backups

Specified ToT / trigger / readout times



ToT written at 120.0 ns



ToT written at 160.0 ns



Trigger at 250.0 ns



F1: LI timeout, descriptor written

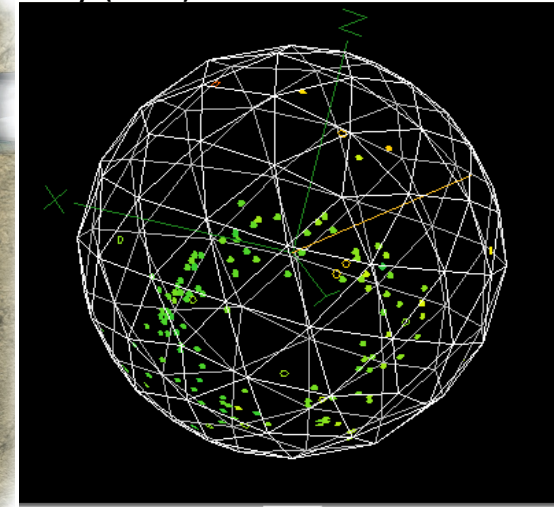
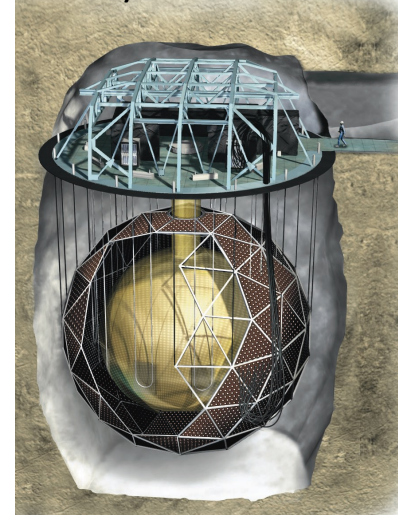
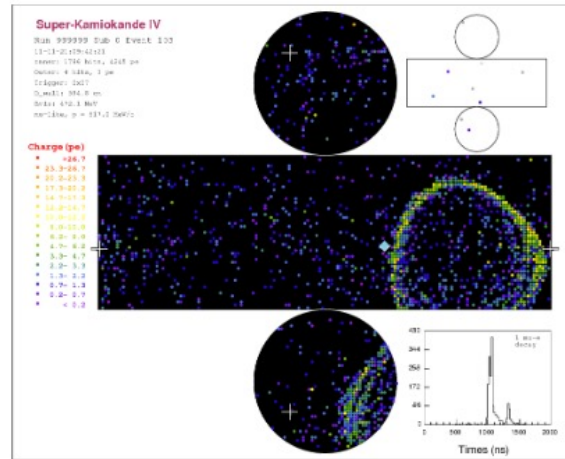
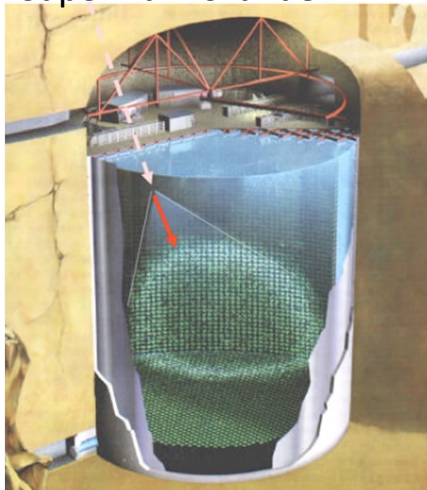


The Goal

Water Cherenkov neutrino detectors have signals that are primarily single pe with up to 10-20 pe/channel

Sudbury Neutrino Observatory (SNO)

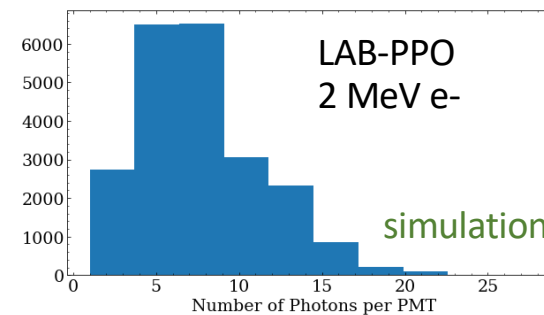
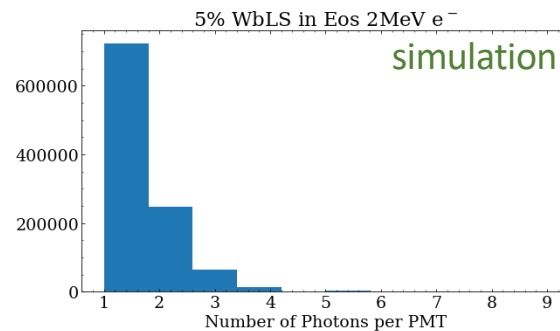
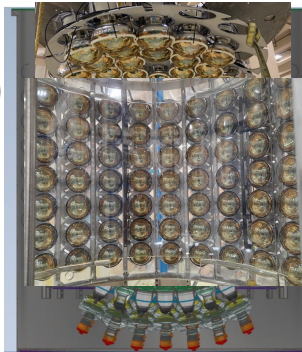
Super-Kamiokande



Scintillation or Water-based scintillation have higher occupancies, depending on energy and position

Eos

(240 PMTs)

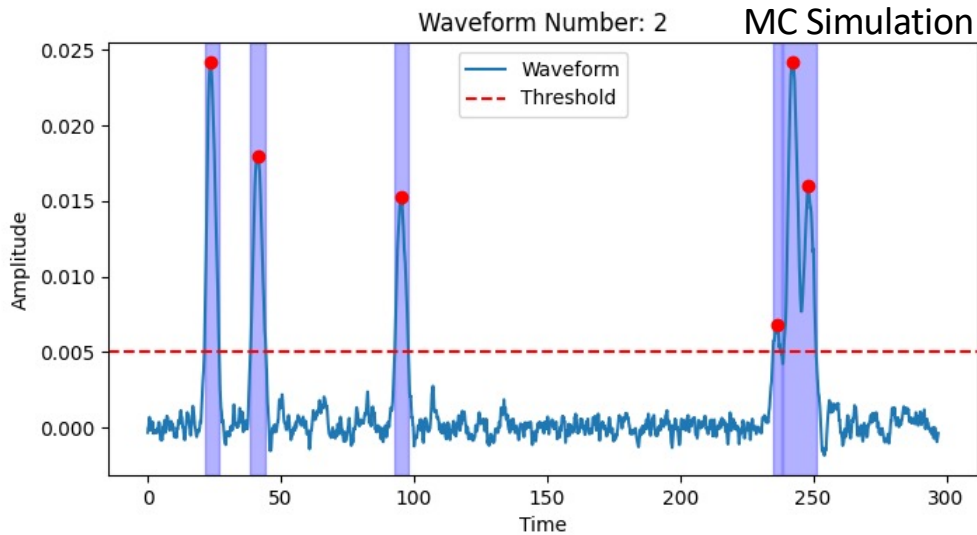


Feature List

MC Simulation

Within each resolved pulse packet measure:

- Start of rising edge t_r
- End of falling edge t_f ($t_f - t_i$ = time over threshold)
- Peak times and values
- Total integral



“retriggerability” necessary to start analysis of each pulse packet

```
Waveform Data:
  Number of Resolved Packets: 5
Packet Info:
  Packet:
    Start Time: 21.257383966244728
    Integral: 0.09355681358849272
    Time Over Threshold: 5.6160337552742625
    Number of Peaks: 1
  Peak:
    Time: 23.624472573839665
    Height: 0.024190603362512775
Packet Info:
  Packet:
    Start Time: 38.616033755274266
    Integral: 0.07561360795008586
    Time Over Threshold: 5.755274261603375
    Number of Peaks: 1
  Peak:
    Time: 41.58649789029536
    Height: 0.01792827392637264
Packet Info:
  Packet:
    Start Time: 92.82700421940929
    Integral: 0.05996750654964445
    Time Over Threshold: 5.105485232067508
    Number of Peaks: 1
  Peak:
    Time: 95.14767932489453
    Height: 0.015224094975565095
Packet Info:
  Packet:
    Start Time: 234.8523206751055
    Integral: 0.020924396618506546
    Time Over Threshold: 3.10970464135022
    Number of Peaks: 1
  Peak:
    Time: 236.75527426160338
    Height: 0.006779438317607855
Packet Info:
  Packet:
    Start Time: 238.8438818565401
    Integral: 0.1741331640922245
    Time Over Threshold: 12.206751054852333
    Number of Peaks: 2
  Peak:
    Time: 242.46413502109706
    Height: 0.02419060538522899
  Peak:
    Time: 248.12658227848104
    Height: 0.0160305989702465
```