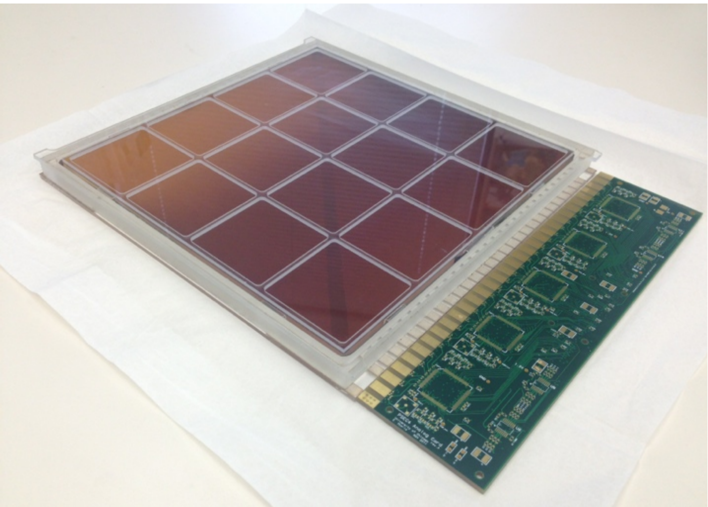
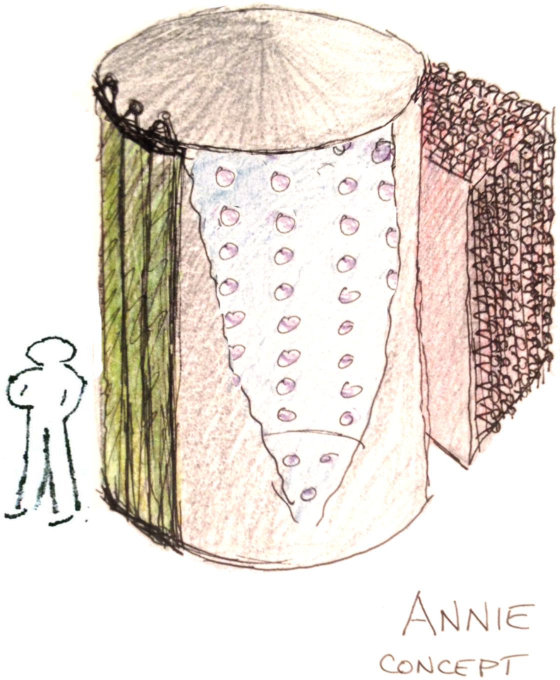
LAPPD Development and Next Steps

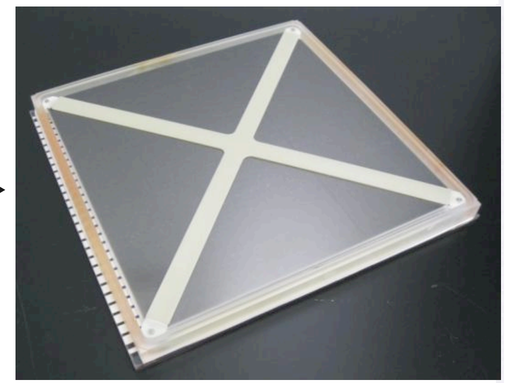
Matt Wetstein (ISU) on behalf of the LAPPD and ANNIE collaborations





NNN15

Reinventing the unit-cell of light-based neutrino detectors



- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

Key Elements of the LAPPD Detector

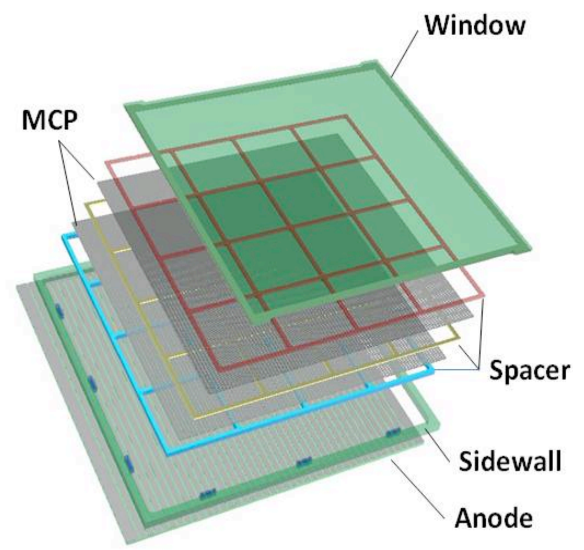
Glass body, minimal feedthroughs

MCPs made using atomic layer deposition (ALD).

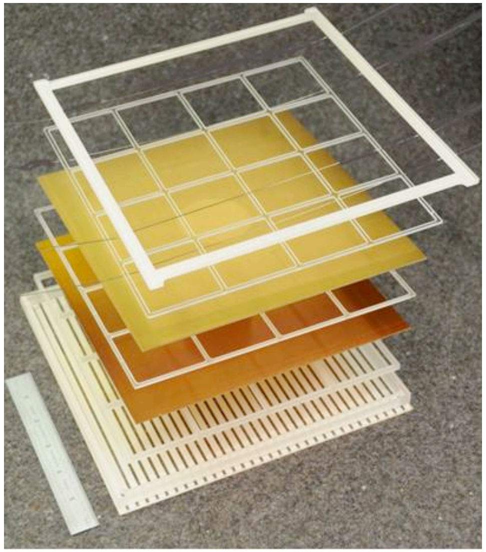
transmission line anode

fast and economical front-end electronics

large area, flat panel photocathodes

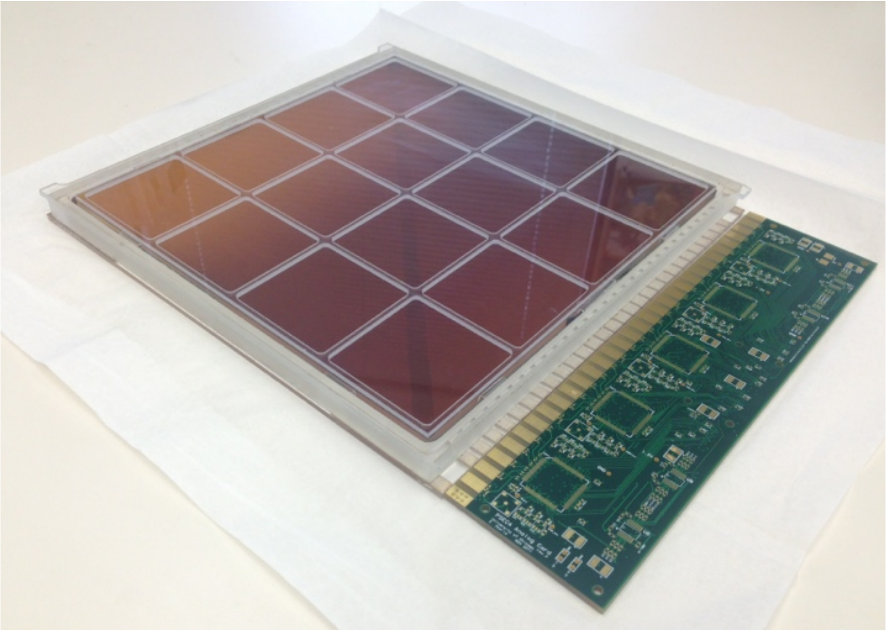


Design Drawing - September 2010



Actual Glass Parts - April 2012

What is the LAPPD Concept



LAPPD detectors:

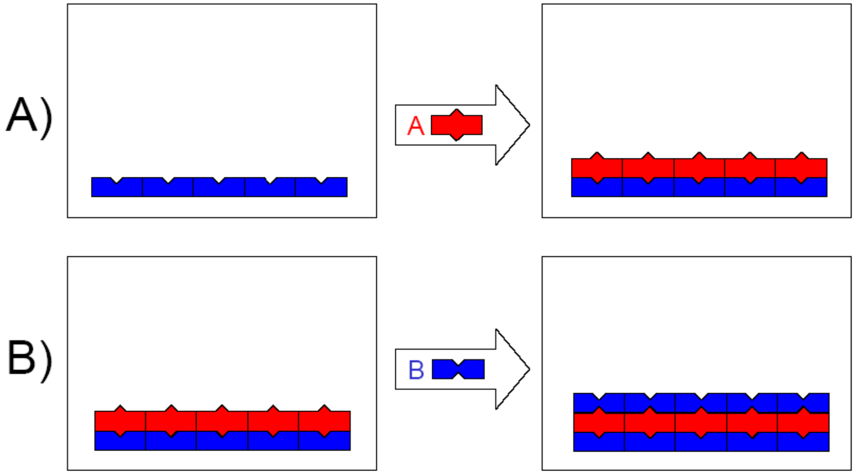
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:

- Conditioning of leaded glass (MCPs)
- Ceramic body
- Not designed for large area applications

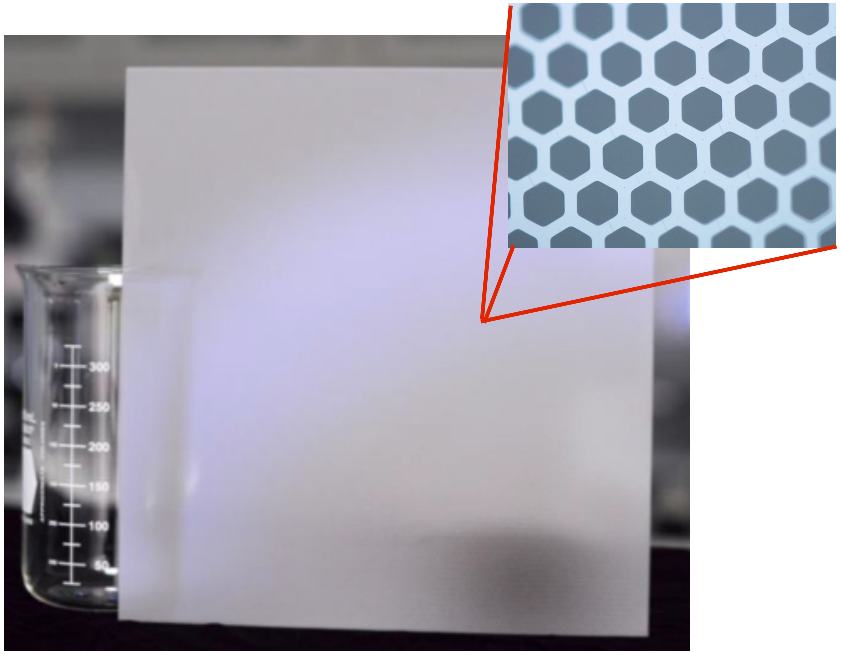
How to Make LAPPDs: Thin Films on Pyrex Glass

Atomic Layer Deposition

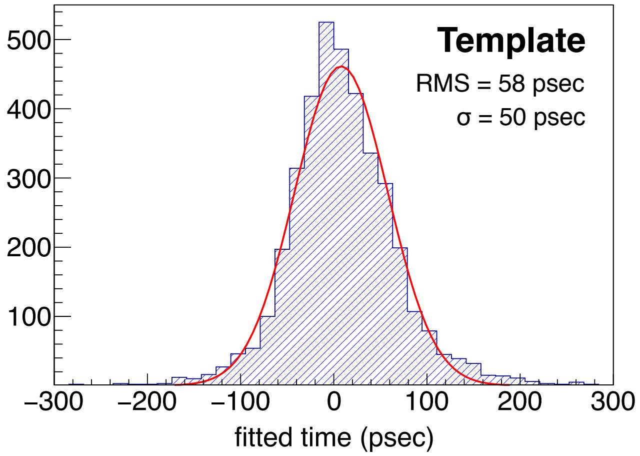


J. Elam, A. Mane

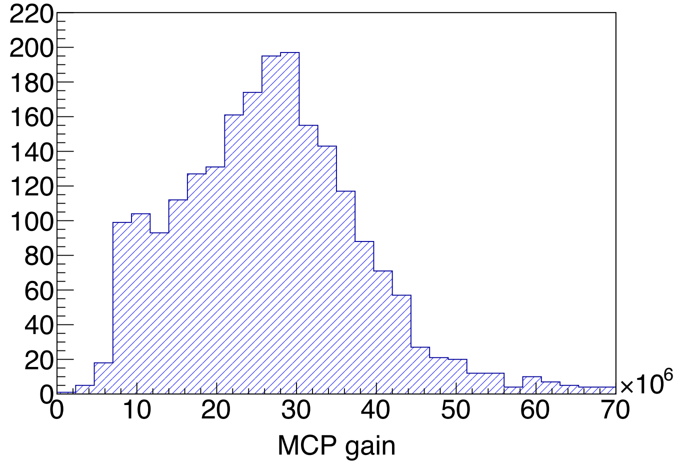
Porous Glass Substrate



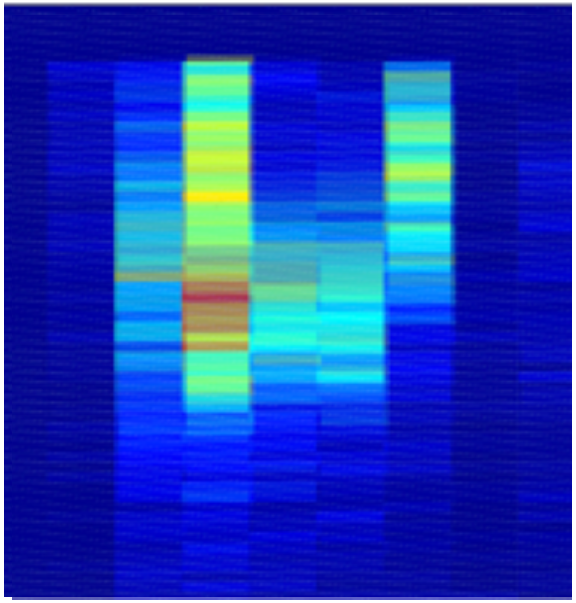
LAPPD Characteristics



<60 psec, single PE resolutions

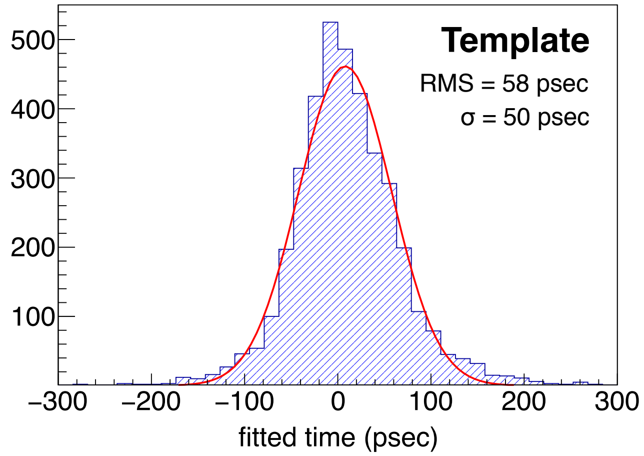


10^7 gains



imaging and single photon resolution

LAPPD Characteristics



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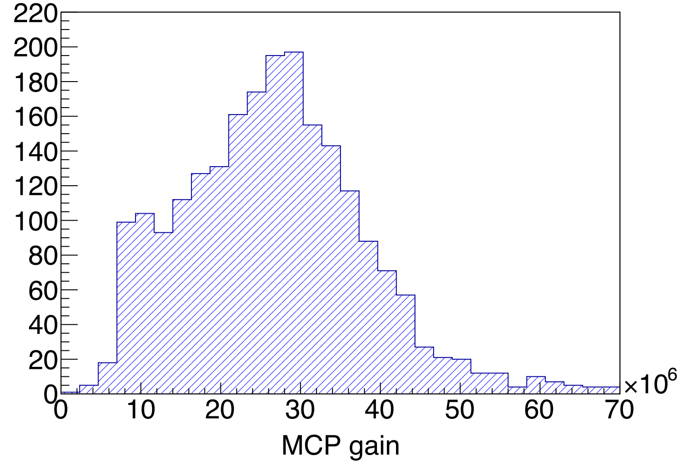
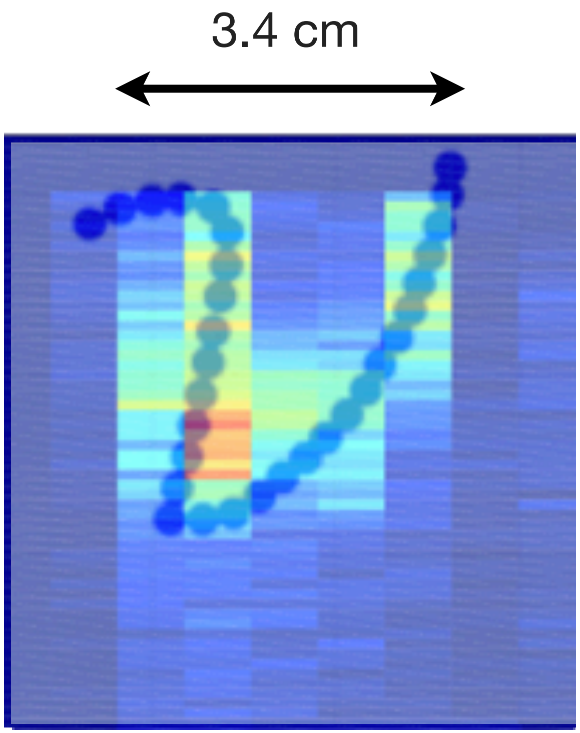
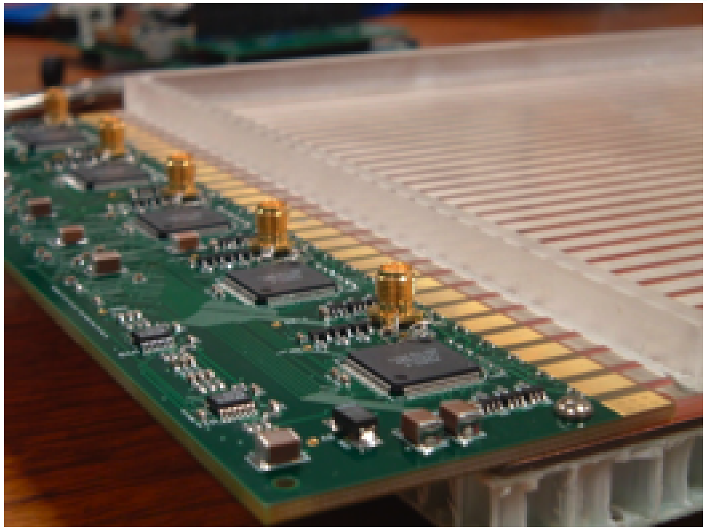


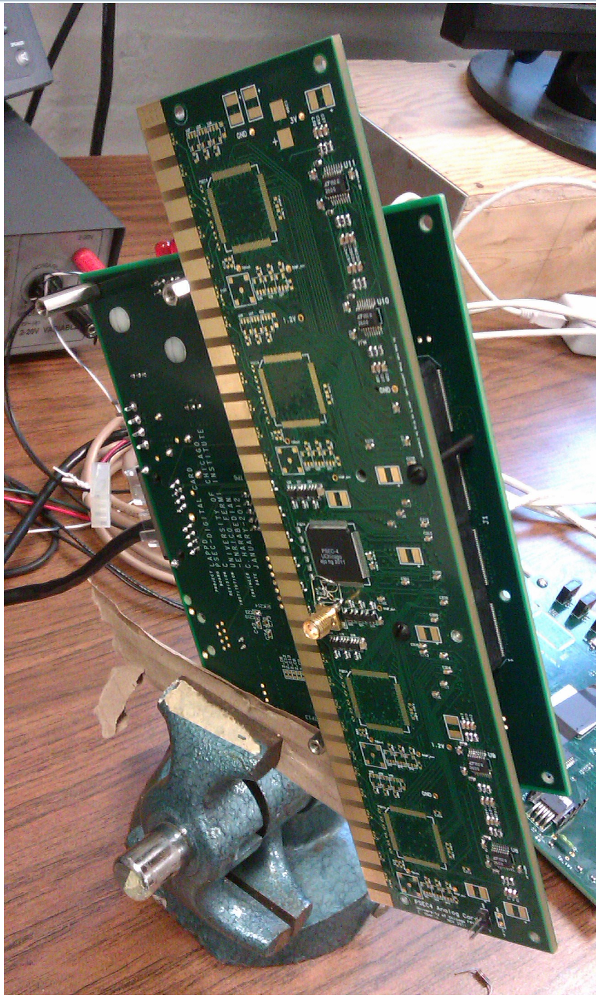
10^7 gains



imaging and single photon resolution

Front-end Electronics





Psec4 chip:

- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

AC-DC card:

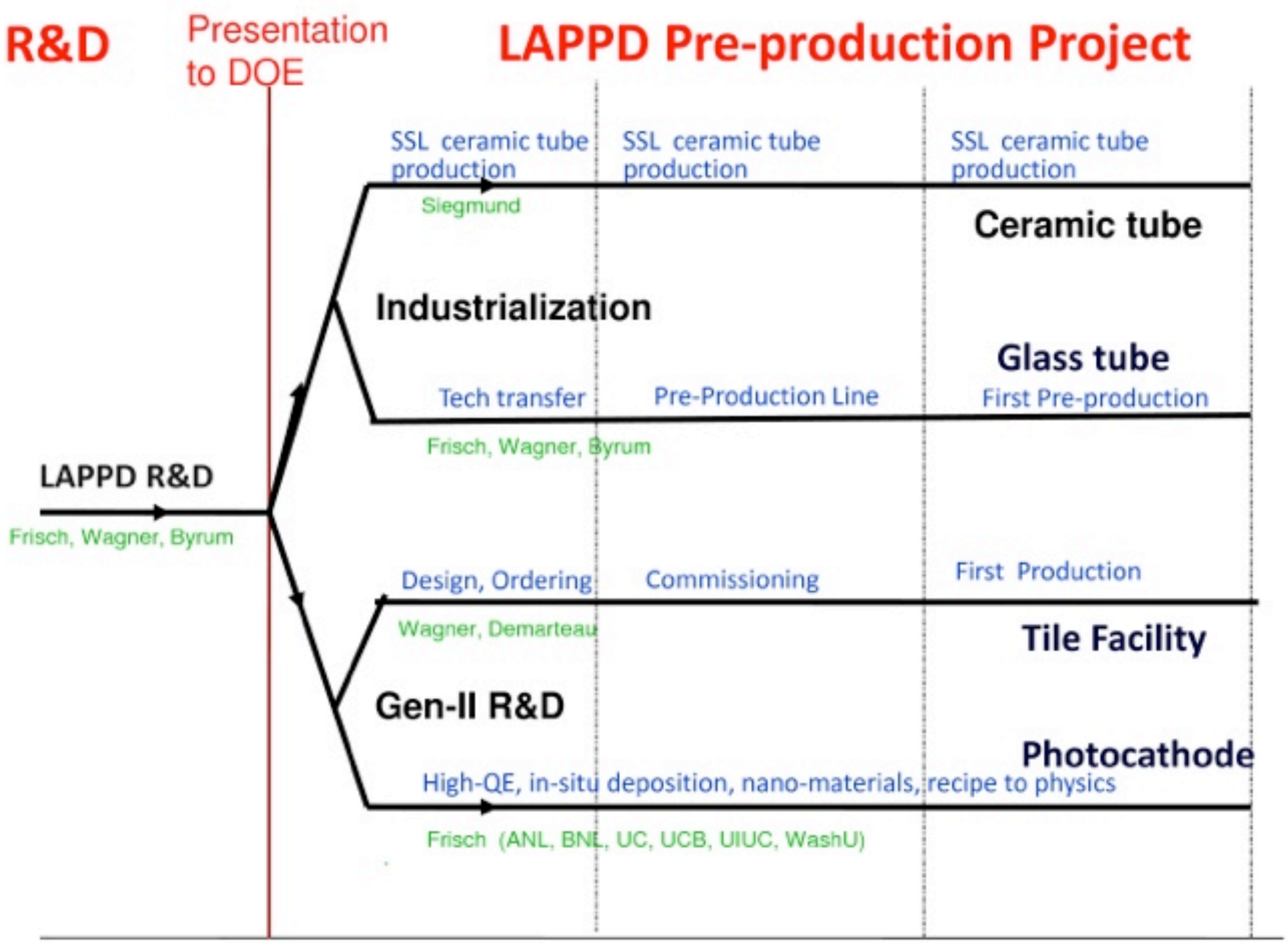
- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)
- Analysis of the individual pulses (charges and times)

Central Card:

- Combines information from both ends of multiple striplines

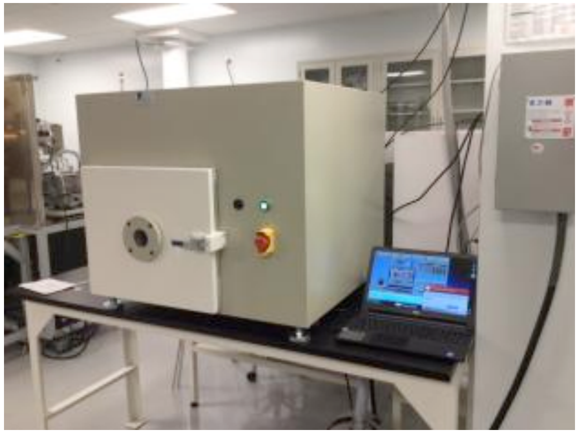
LAPPD project covered the whole system, including readout electronics

LAPPD2 - What's Next



Commercialization Status (Incom)

Plasma cleaner rec'd 9/2015



Vacuum oven due 10/2015

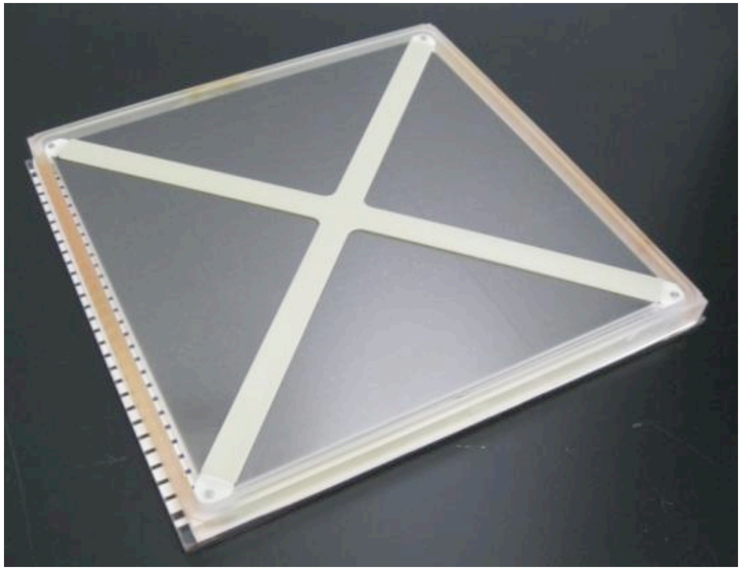
LAPPD integration and sealing tank rec'd 9/2015

Beneq ALD coater with load-lock installed 6/2015

Thermal evaporator commissioned 12/2014

Measurement & test station, commissioned 8/2015

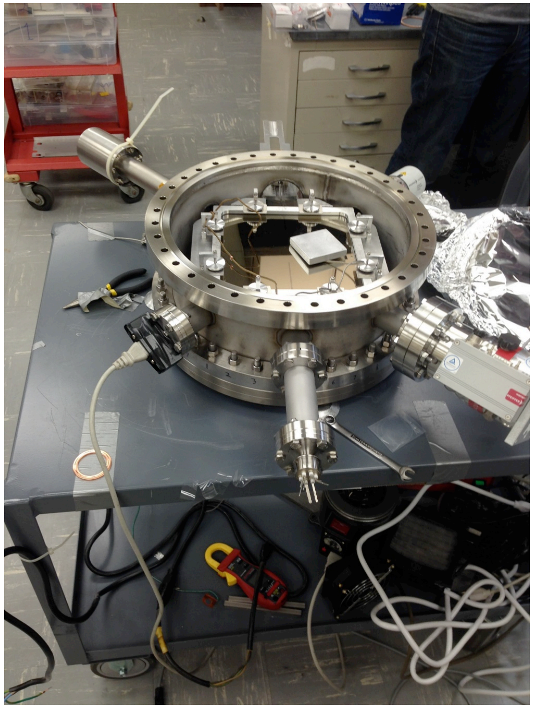
Commercialization Status (Incom)

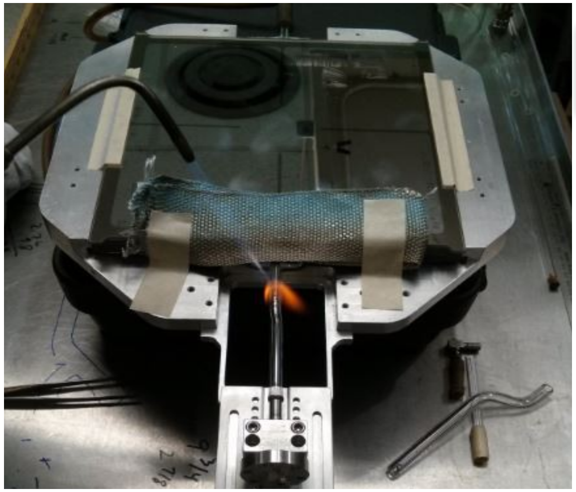


Milestones

- Early-November: seal 1st LAPPD tile at UC Berkeley, Space Sciences Laboratory
- Mid-November: seal a mock tile at Incom that includes anode/ sidewall, glass capillary arrays (not MCPs), X-spacers, top window, no photocathode
- Mid-December: seal 1st LAPPD tile at Incom
- End-December: seal 2nd LAPPD tile at UC Berkeley, Space Sciences Laboratory
- Mid-January: seal 2nd LAPPD tile at Incom

1





GEN II Development: (UC, Incom)

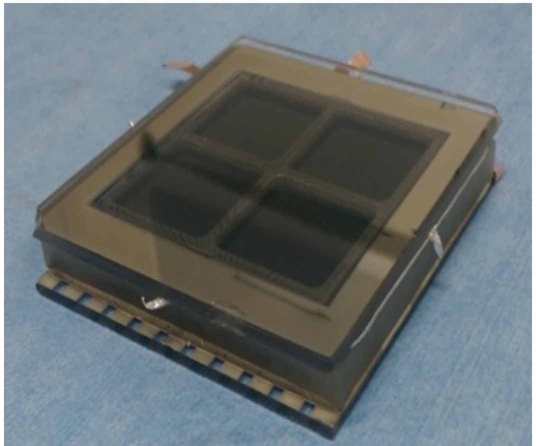
To follow closely behind the ramp up of first Incom tiles.

- reduce fabrication costs and increase volume
- improve performance

- Address the vacuum transfer process.
- New approaches to photocathode production
- cheaper and more robust components

ANL 6cm tiles

- small format, glass MCP detectors based on the LAPPD concept.
- a number of long lived prototypes exist, more are on the way and available for testing.



Completed Tube with Photocathode

Early Adopters

First LAPPDs will not be "cheap" (by HEP standards)
- small volumes
- high operational costs
- small market

Good news is: LAPPD technology is viable outside of particle physics (medical imaging, security, neutron and x-ray imaging, etc)

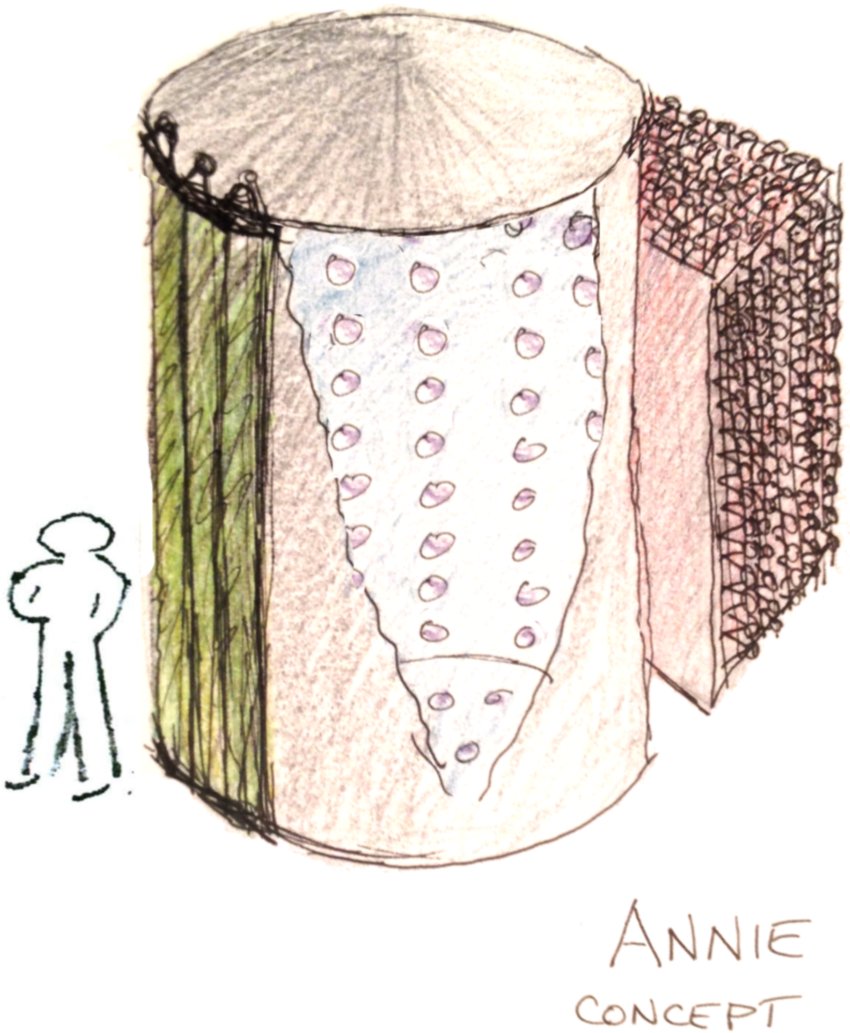
HEP community will benefit from economy of scale.

Gen II could significantly reduce costs.

In the mean time, Incom is very interested in HEP early adopters and is willing to help with costs and availability, *especially* for those who can provide detailed testing/feedback

Successful early demonstrations are critical!

ANNIE: Accelerator Neutrino Neutron Interaction Experiment

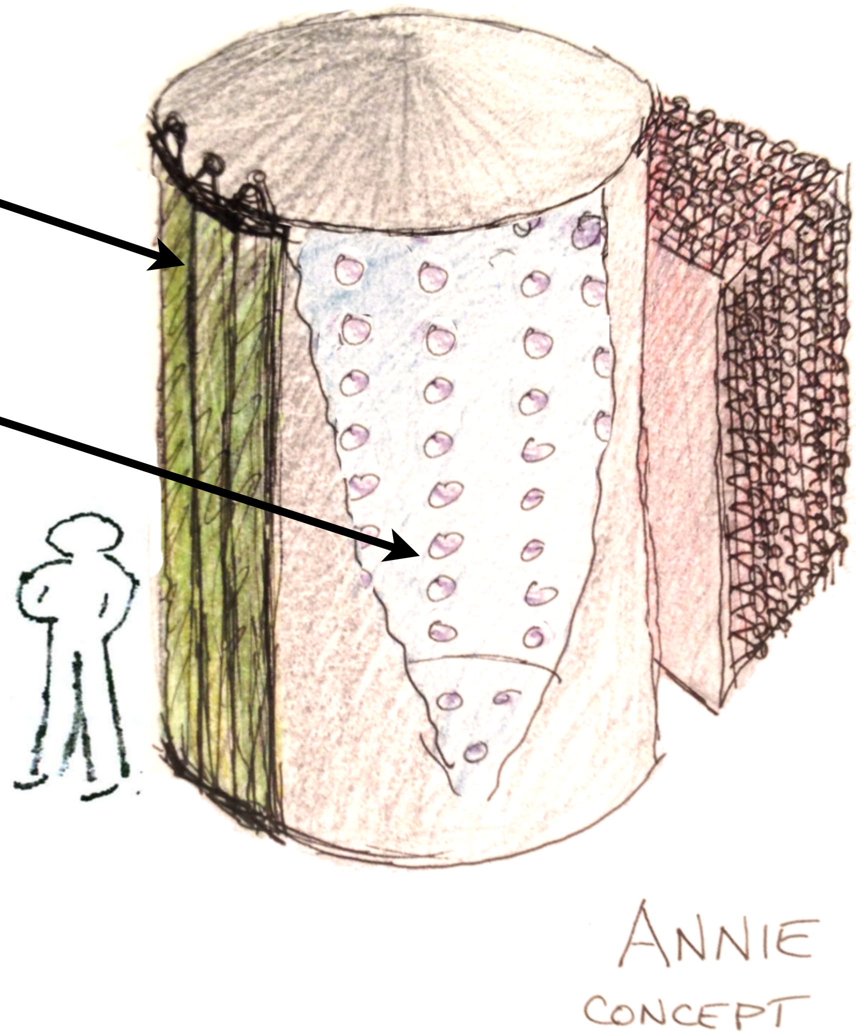


ANNIE: Accelerator Neutrino Neutron Interaction Experiment

Forward Veto

Muon Range Detector

Gd-loaded water volume, mounted w/ LAPPDs and conventional PMTs



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Forward Veto

water volume

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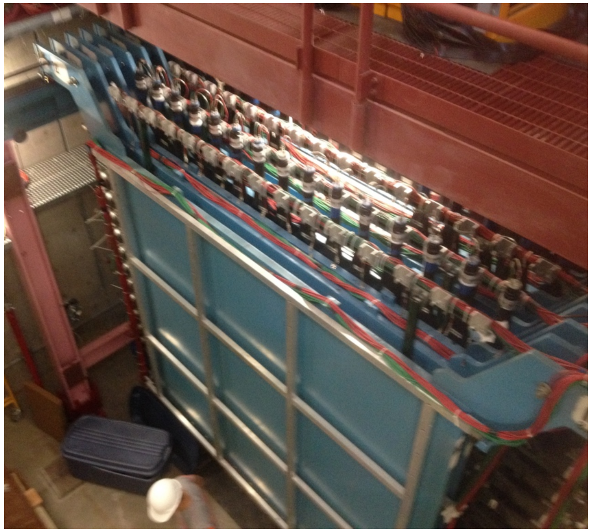
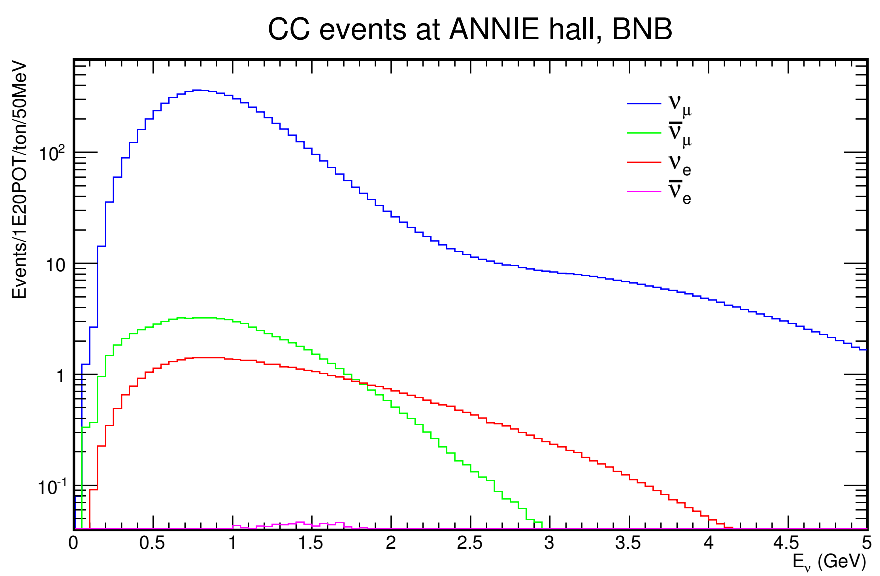
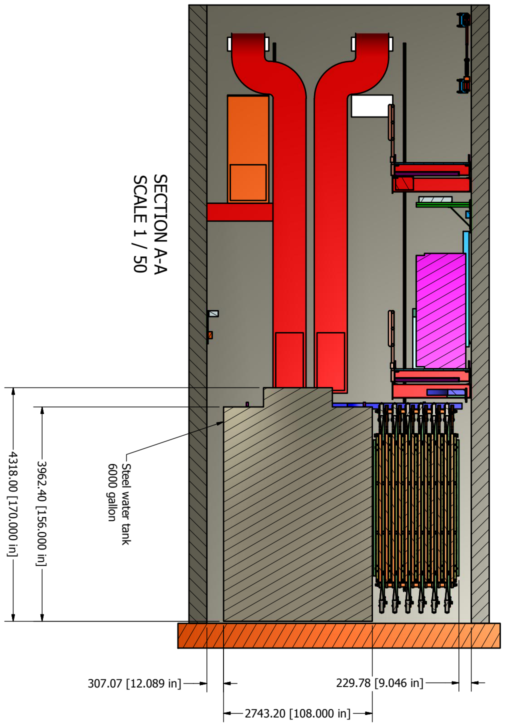


ANNIE: A US Based R&D Water Cherenkov Facility

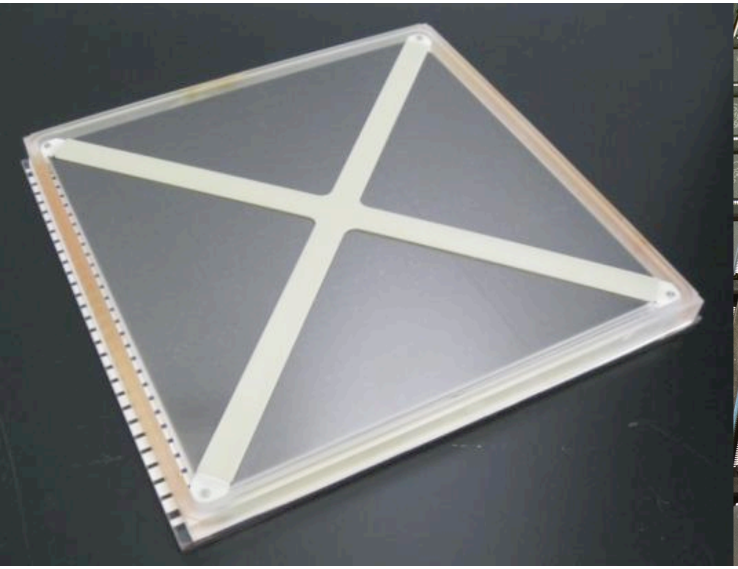
- "ANNIE Hall": A neutrino test beam!
- High intensity: ~10k CC events per cubic meter per year
- Part of the short baseline program (high priority running)
- Relevant energy for proton decay background studies.
- At turn-on for resonance events

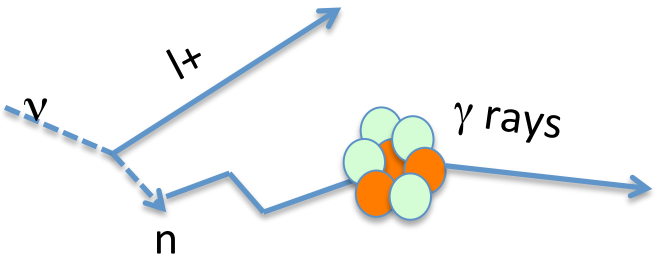




R&D Program

- Demonstration of LAPPDs in a neutrino experiment
- Application of fast, waveform sampling (PSEC) electronics
- First use of Gd on a high energy neutrino beam



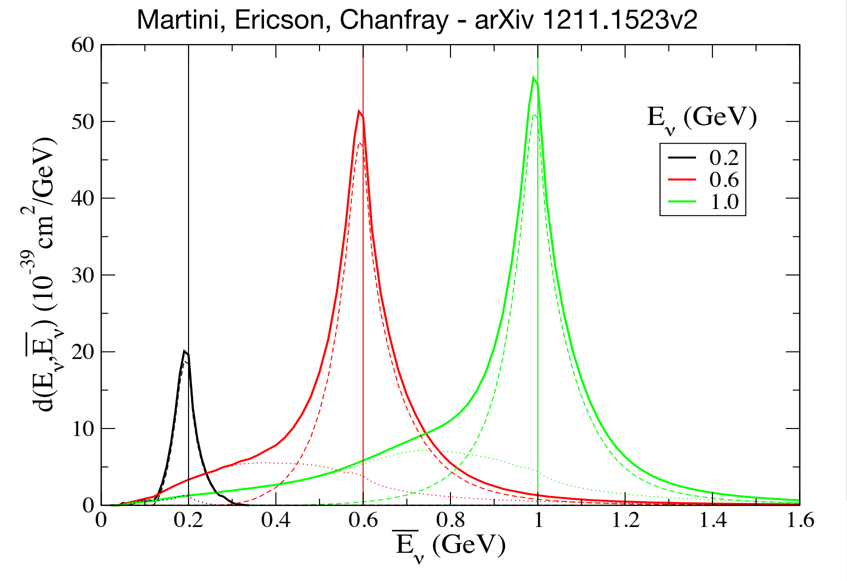


- A test bed for other novel photosensors
- Possible later addition of water-based liquid scintillator

ANNIE: Physics

To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions.

- Dominant source of systematics on future long baseline oscillation physics
- Source of uncertainty and controversy in short baseline anomalies
- We need comprehensive and precise measurement for a variety of targets/E_ν



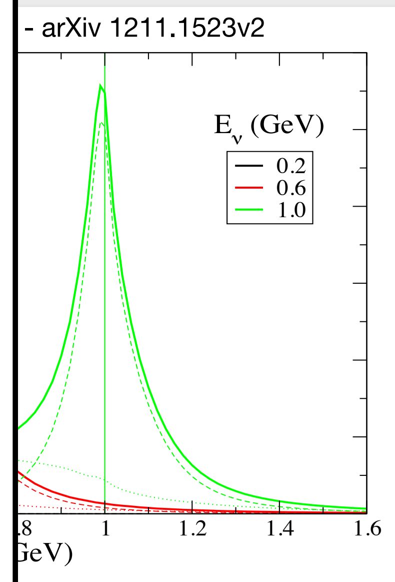
ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

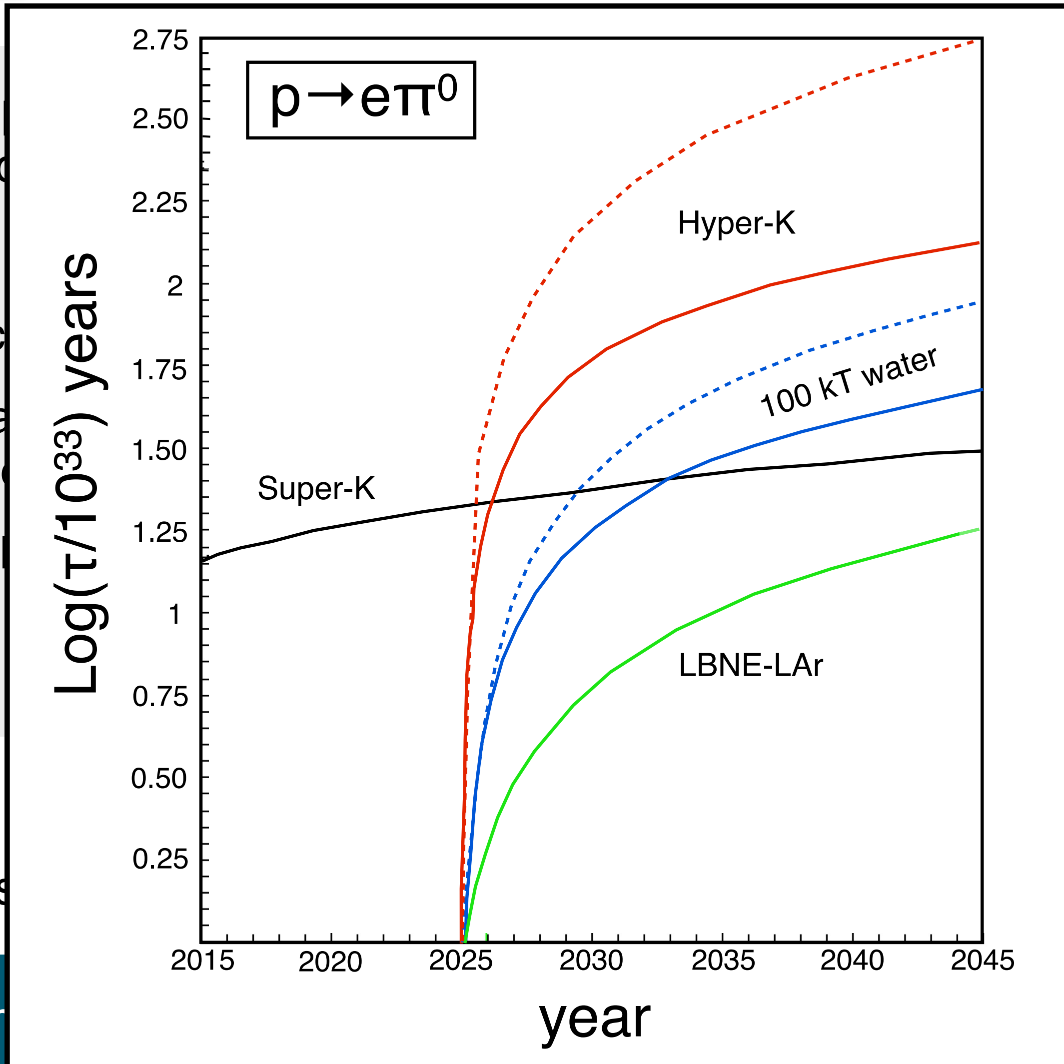
The presence, multiplicity and absence of neutrons is a strong handle for signal-background separation in a number of physics analyses!

ANNIE: Physics

To turn neutrino [...] rstand the complex multi-sc[...]

- Dominant source [...] long baseline osc[...]
- Source of uncerta[...] short baseline an[...]
- We need compre[...] measurement for [...]





ANNIE is a final-s[...] urements in LAr

The presence, r[...] dle for signal-background separation in a number of physics analyses!

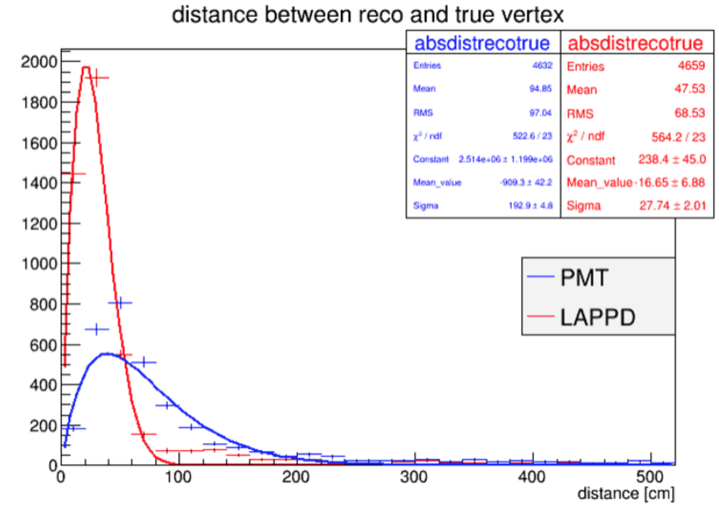
LAPPDs are well suited for ANNIE

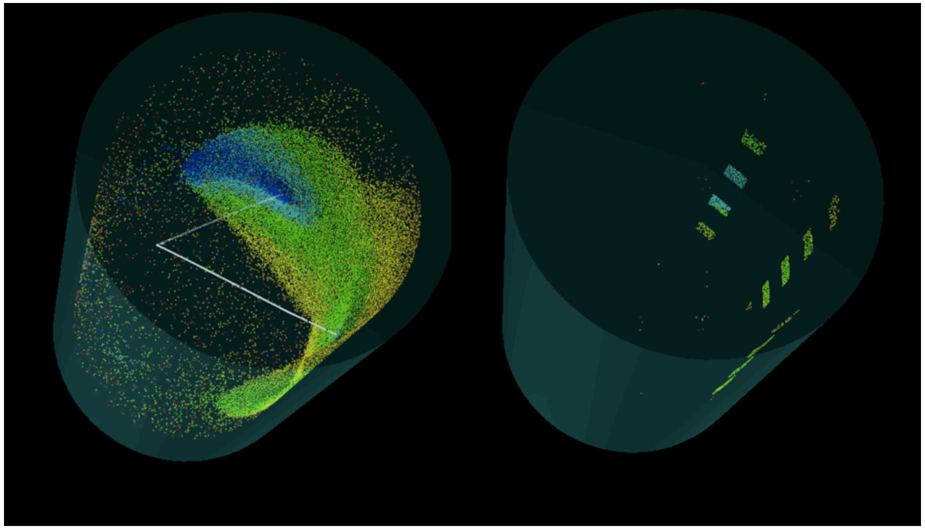
Good vertex reconstruction is important for fiducialization

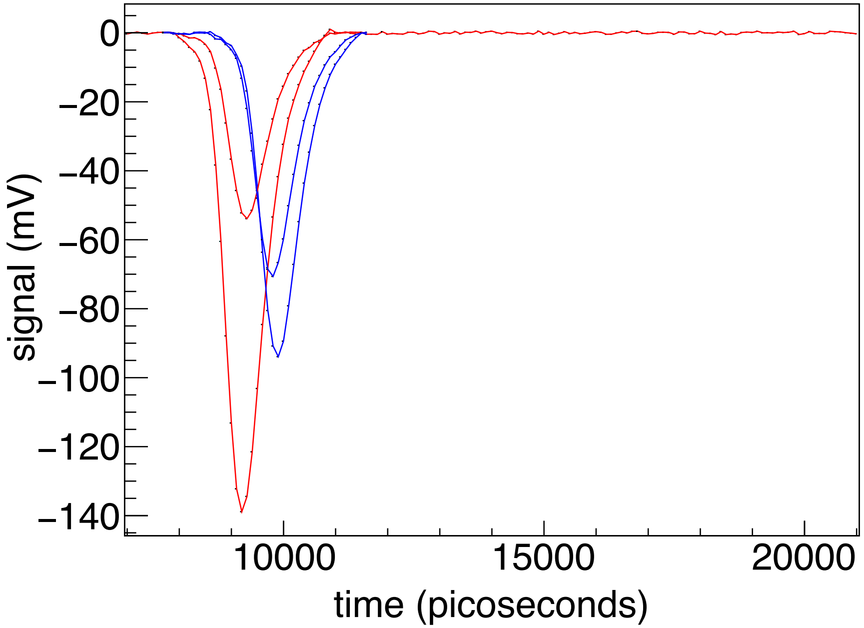
Track counting is important for separating between CCQE-like events and non-CCQE-like events.

Later runs with full LAPPD coverage will attempt to reconstruct NC and CC-RES events.

LAPPDs provide needed time resolution *and* spatial granularity







muon pion

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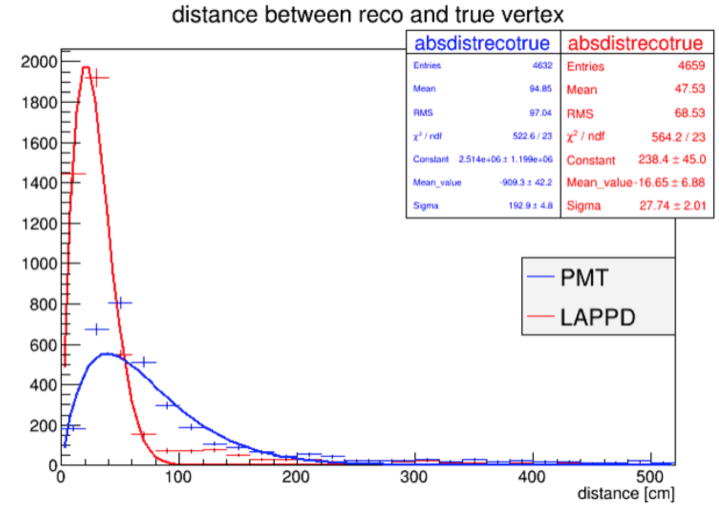

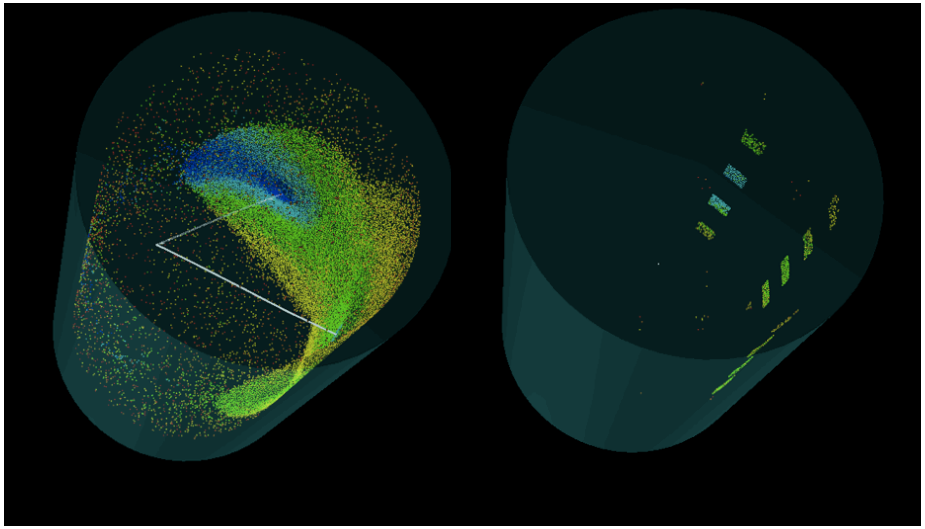

muon

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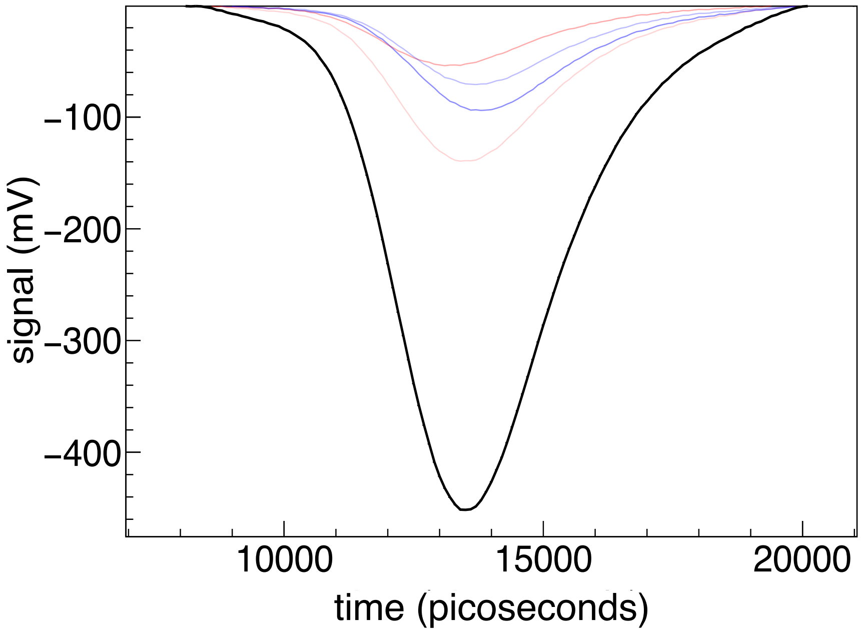
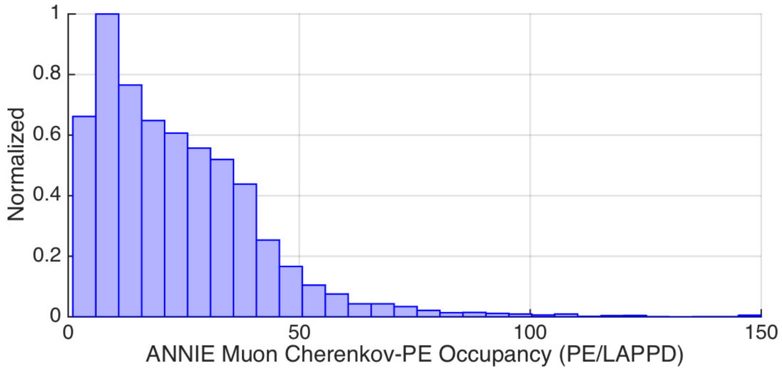
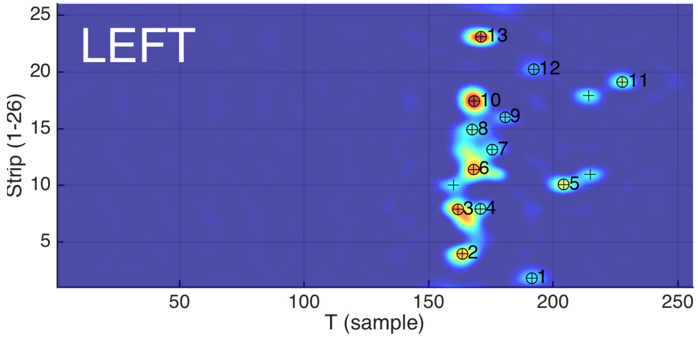


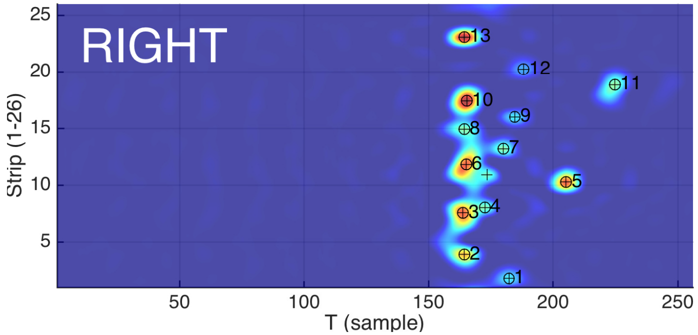
ANNIE is well suited for LAPPDs

credit: Glenn Jocher (Ultralytics, LLC)
Shawn Usman (NGA)



- ANNIE is small enough to do physics with a small number (20) of LAPPDs.
- The event rates, time structure, and photon pileup are compatible with the nominal design of the anode and readout electronics.
- Time table and budget of the experiment match well with costs and availability of early LAPPD prototypes.





Time Table

Fall 2015 – **to Jun 2016**

on-going

- Installation
- **Phase I - Test experiment:**
  measurement of neutron backgrounds
  operate the water volume with 60 8" PMTs
  ready for testing of limited number of LAPPDs
  when available

to Jun 2017

- R&D, procurement, construction, commissioning

to Jun 2018

- **Phase II - First physics run (1 year):**
  limited LAPPD coverage (up to 8), enhanced
  PMT coverage, focus on CCQE-like events

to Mar 2021

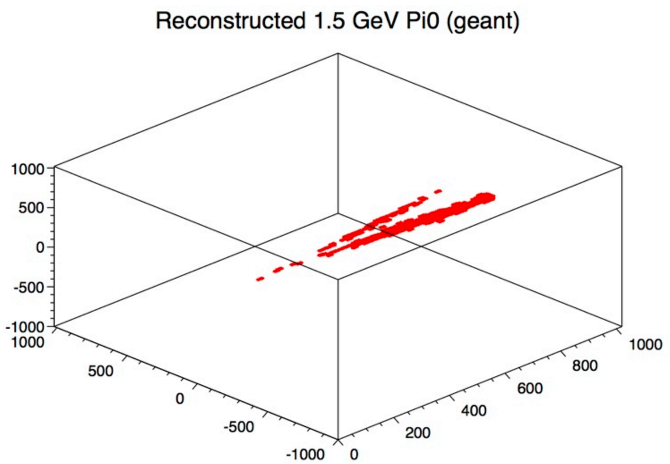
- Second physics run (2 years):
  full LAPPD coverage (up to 20 LAPPDs)
  more detailed event reconstruction
  compare neutron yields for CC, NC, and inelastic

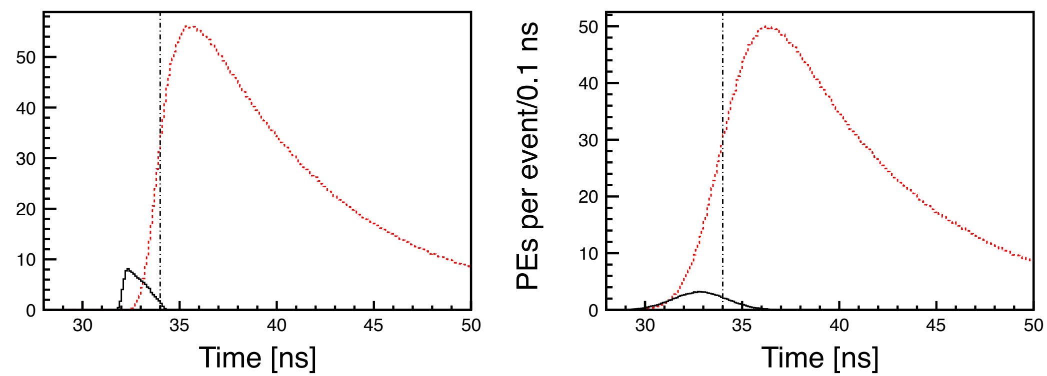
Phase I approved by FNAL PAC.

Phase II proposed to DOE's Intermediate Neutrino Program

Conclusion

- LAPPDs bring exciting new photosensor capabilities into neutrino physics.
- Now moving along in the commercialization phase.
- Limited numbers soon available for early adopters.
- Volume and markets will bring down the price, gen-II research could make an even bigger dent.
- Early successes for LAPPDs and other novel technologies in experiments like ANNIE are important.
- New collaborators and new ideas are welcome!





(a) Default simulation.

(b) Increased TTS (1.28 ns).

Additional Slides

Post Scripts: PSEC4/PSEC4B

Batch of 400 PSEC4 chips has been ordered by ISU for ANNIE:
= 2400 channels
= 40 LAPPDs

Eric Oberla is working on a design for a PSEC4b:

- 4-fold increase the buffer depth to allow multi-event buffering.
- Would enable continuous operation for low rate applications (eg neutrinos)
- design is under way, but looking for feedback from the community

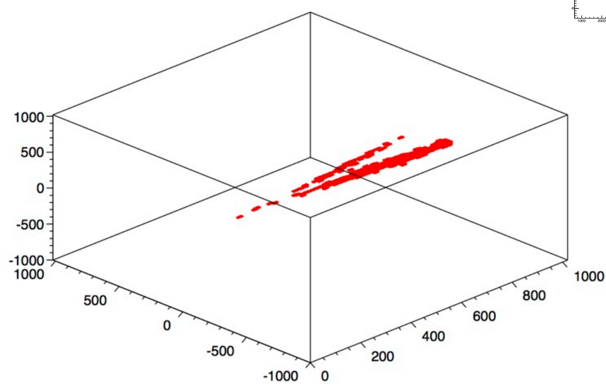
Simulations/Reco

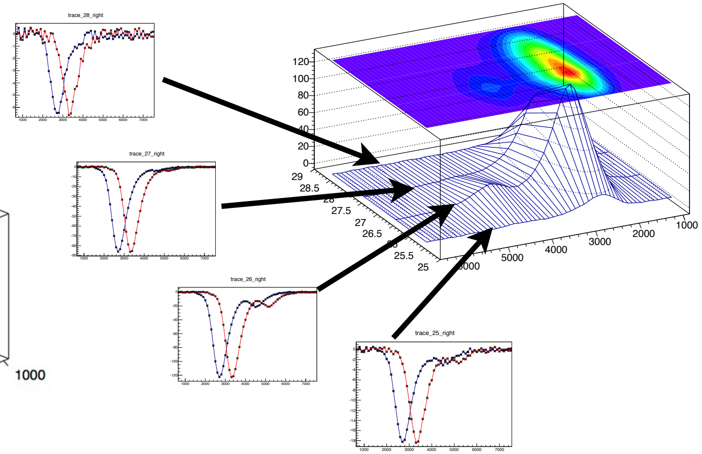
We have a standalone package for simulating LAPPD response.

We also have a light detector simulation: WChSandBox

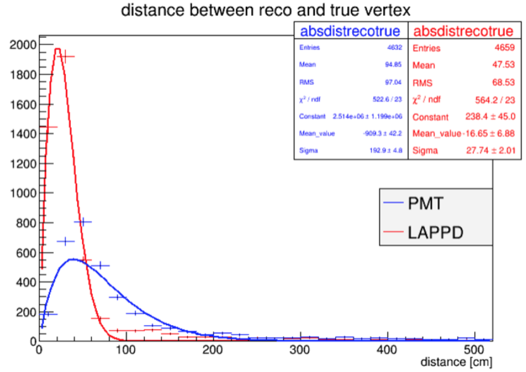
...and an accompanying reconstruction package (developed by Queen Mary, Imperial, and Sheffield)

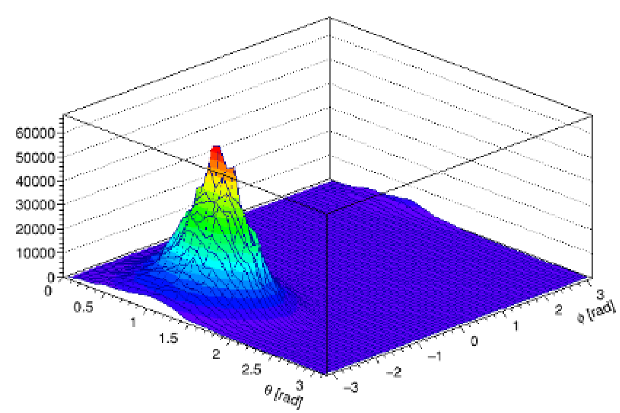
Happy to share these tools and also interested in building a common framework





M. Wetstein (ISU)

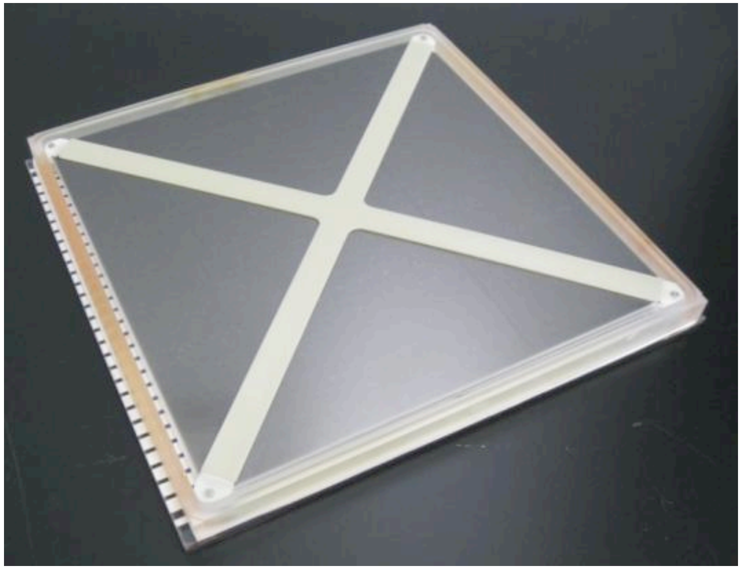




M. Malek (Sheffield)

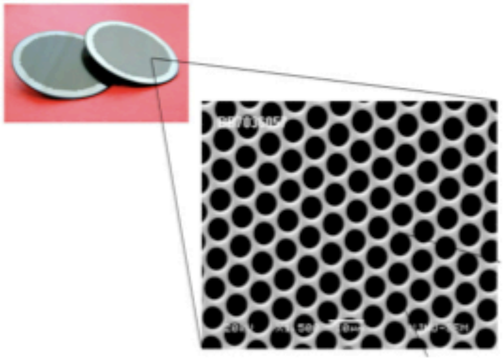
Commercialization Status

- Plasma cleaner
  - To clean GCAs before coating
  - To clean tile components before sealing
- Vacuum oven
  - To bake GCAs prior to coating
  - To post-anneal MCPs after ALD
  - To condition indium for LAPPD sealing
- Thermal evaporator
  - For electroding MCPs and metalizing LAPPD components
  - Commercial coating service, e.g. for ANL and UChicago
- ALD coater
  - For coating resistive and emissive layers
  - Coating of 20 cm (8") MCPs beginning in November
- Measurement & test station
  - Now measuring resistance & gain on 33 mm MCPs
  - Installing cross delay-line readout, 20 cm format testing, timing measurement capability
- Integration and sealing station
  - For assembly of LAPPD tiles
  - Completing system installation



- Major funding provided by DOE under TTO and SBIR grants
- Extensive technical support from Argonne National Laboratory, University of Chicago, and UC Berkeley, Space Sciences Laboratory

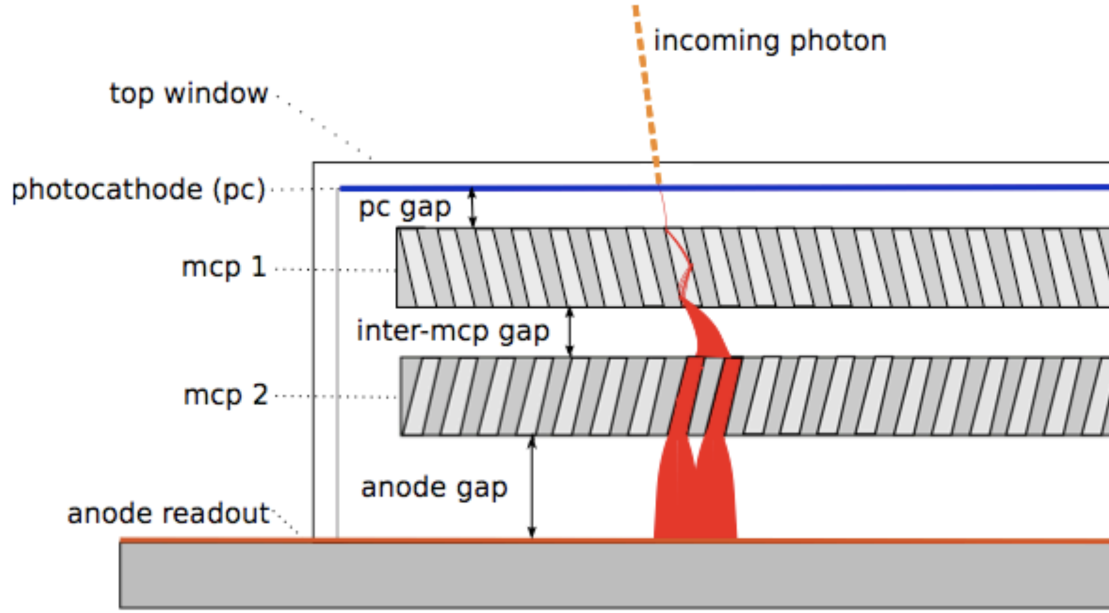
What is an MCP-PMT?



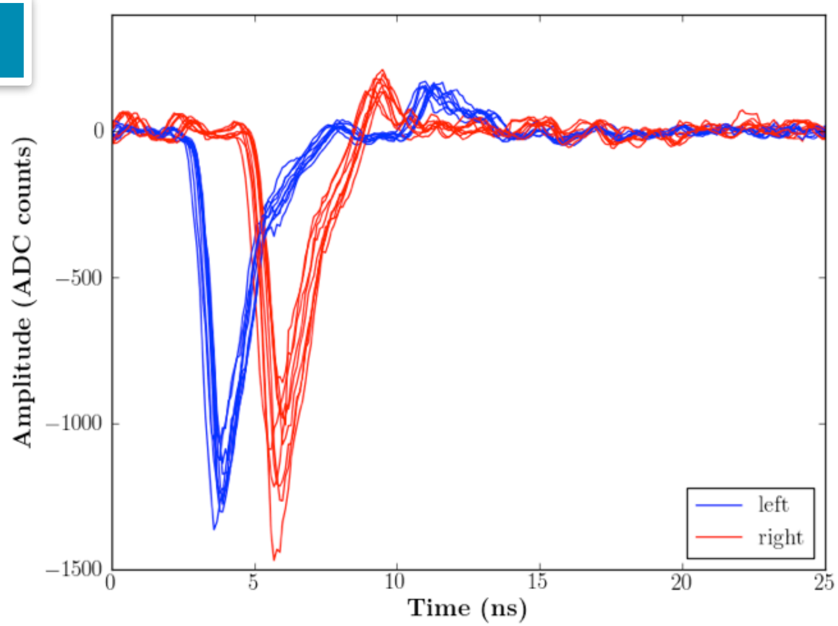
Microchannel Plate (MCP):

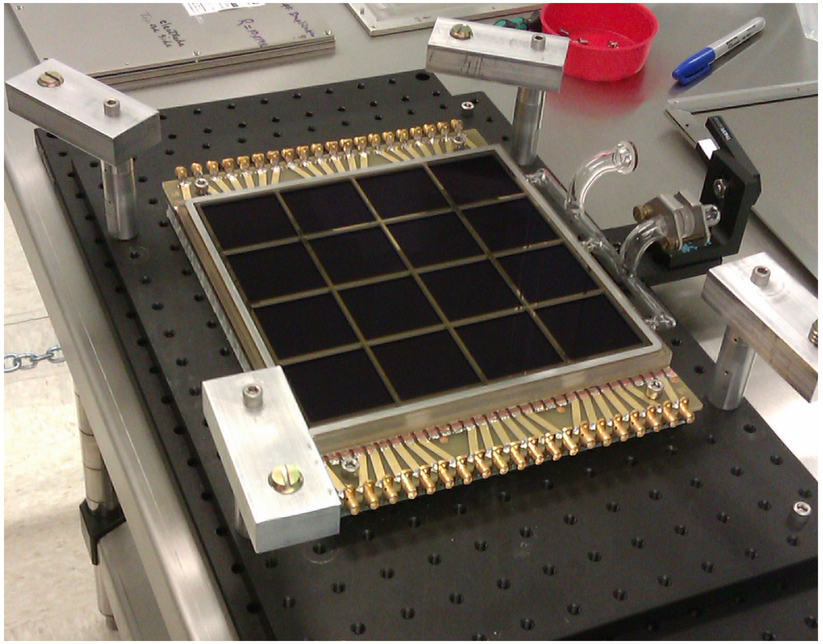
- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode

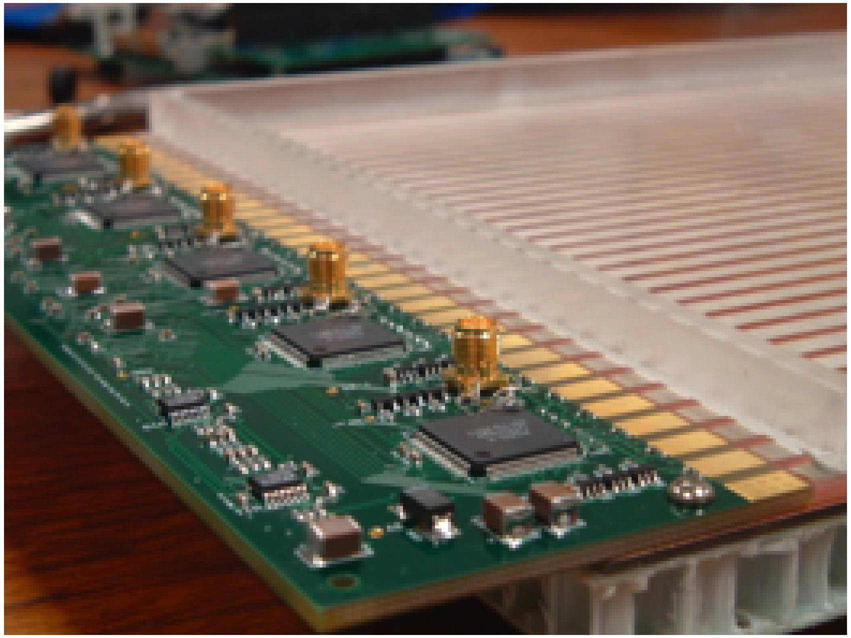


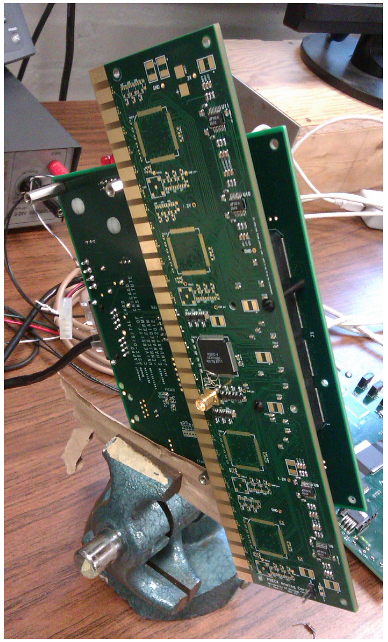
LAPPD





- As an R&D project, the LAPPD collaboration attacked every aspect of the problem of building a complete detector system, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes (“demountable detectors”) with resealable top window, robust



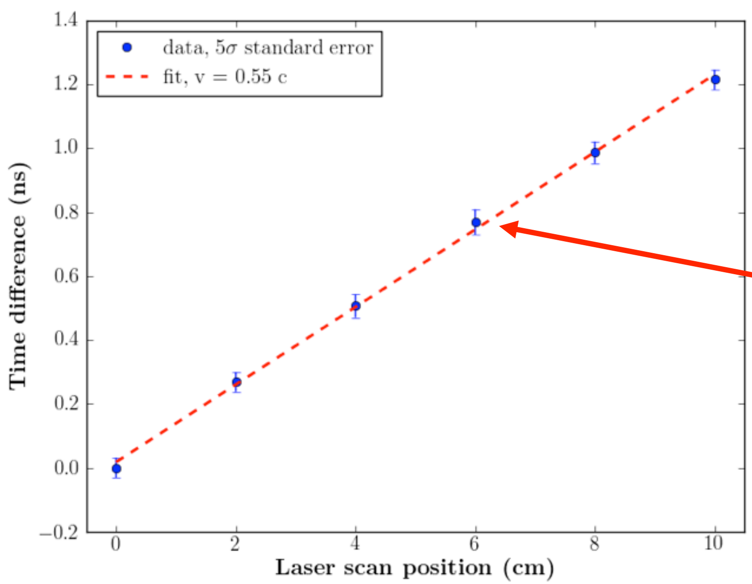


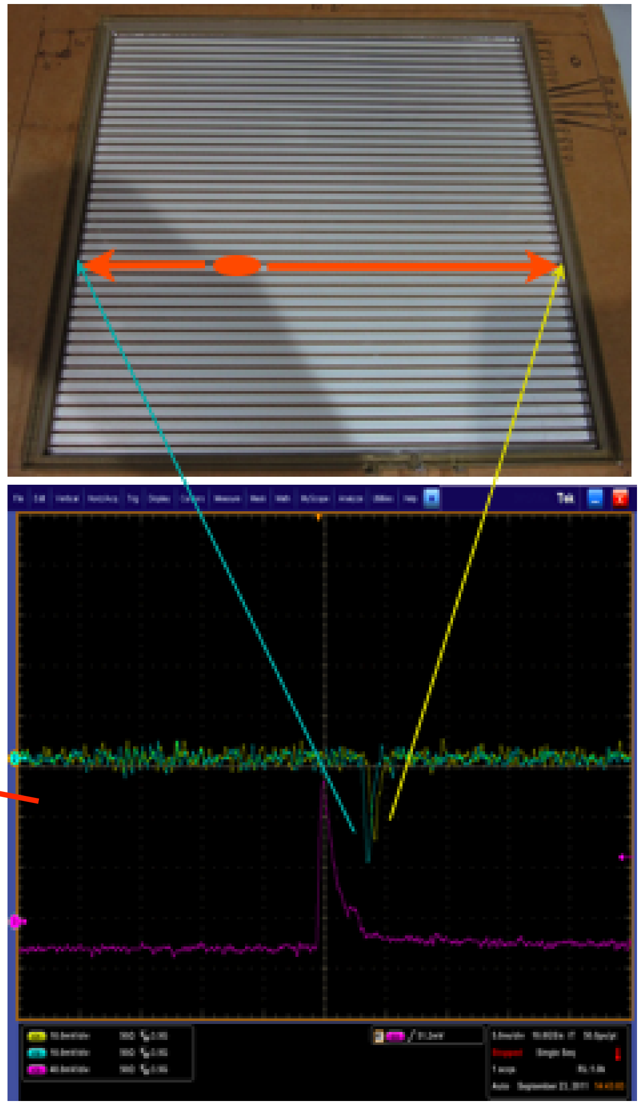
Anode Design: Delay Lines

Channel count (costs) scale with length, not area

Position is determined:

- by charge centroid in the direction perpendicular to the striplines
- by differential transit time in the direction parallel to the strips



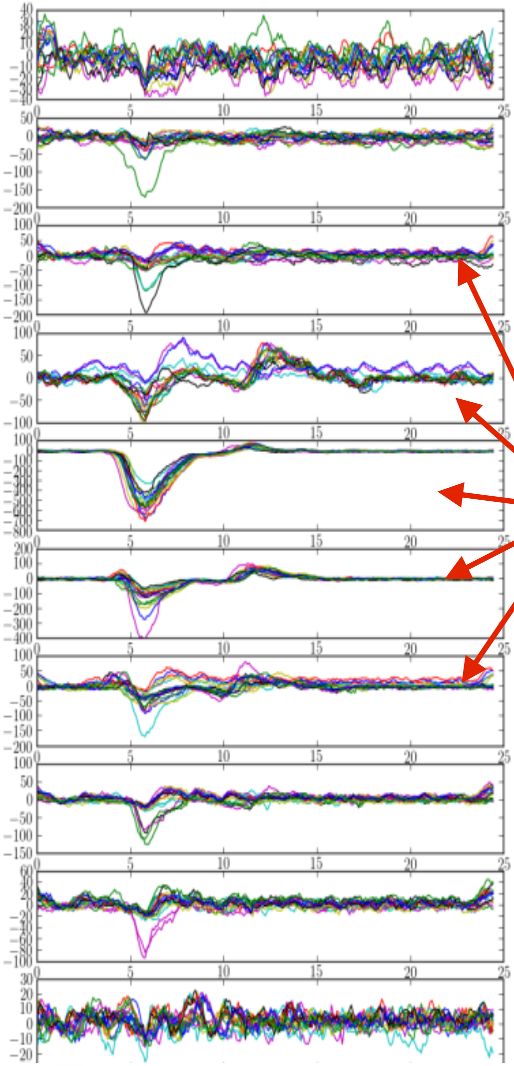


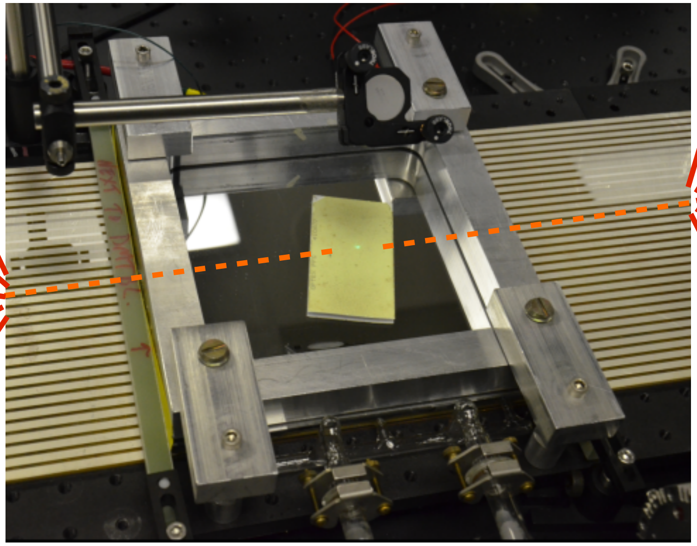
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Anode design

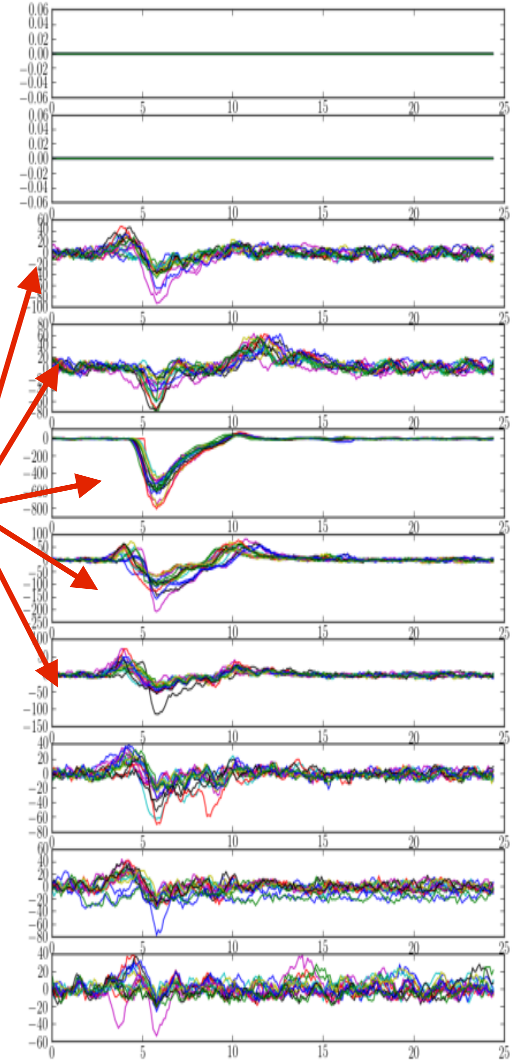
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





Credit: Eric Oberla

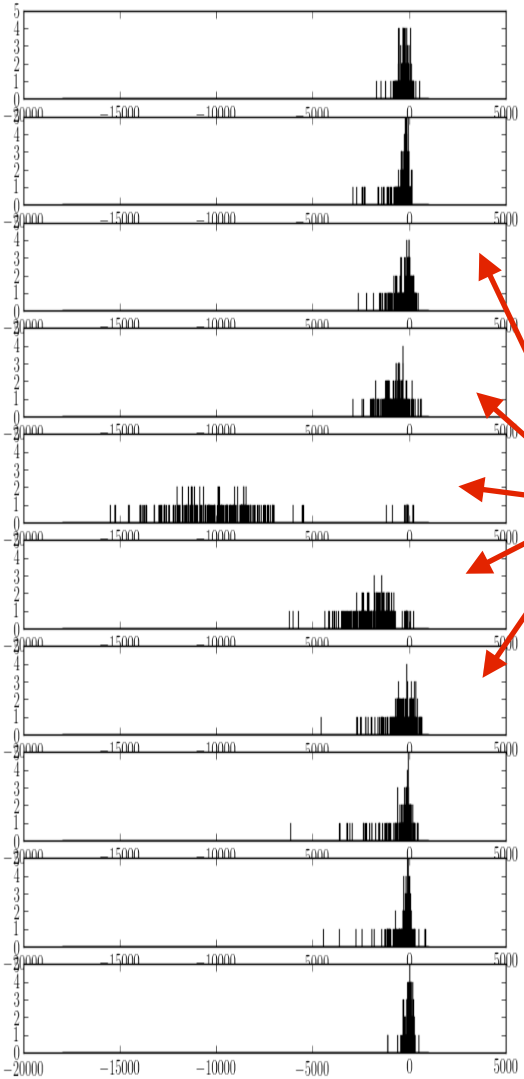


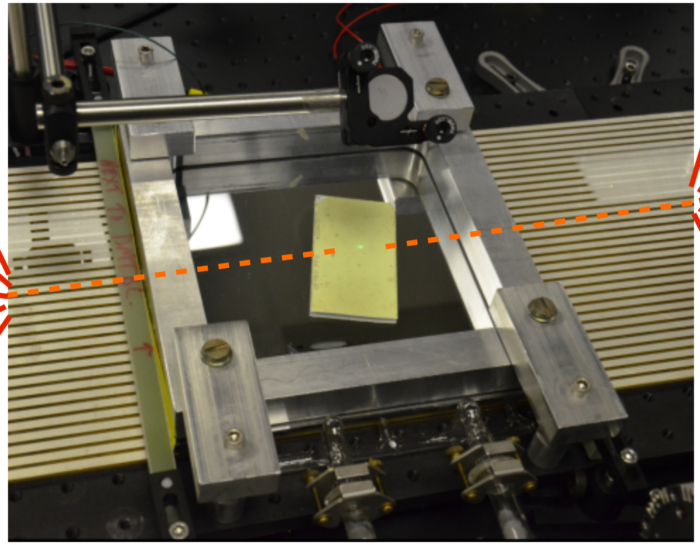
Right Side
Pulses on 10 striplines

Anode design

Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





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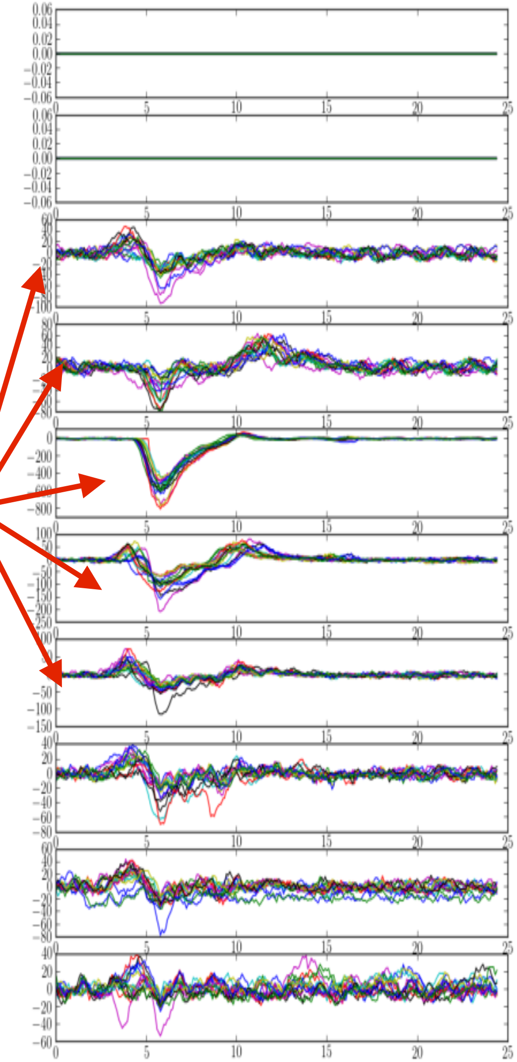
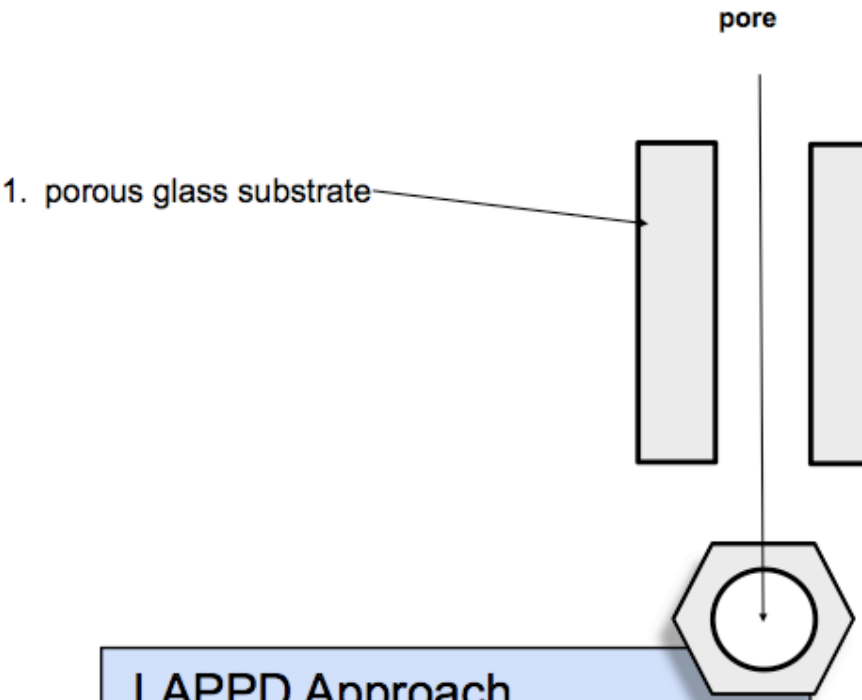


Right Side
Pulses on 10 striplines

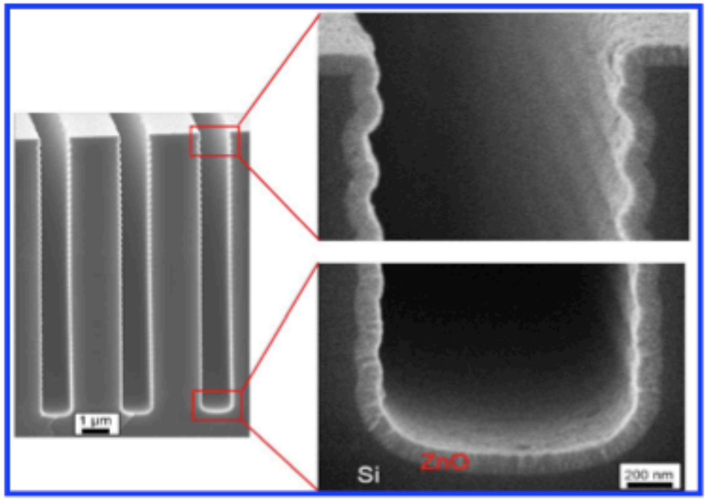
Our Approach

J. Elam, A. Mane, Q. Peng (ANL-ESD),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)



Conventional MCP Fabrication

- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material
- Chemical etching and heating in hydrogen to improve secondary emissive properties.
- Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties. (Problems with thermal run-away).



LAPPD Approach

- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

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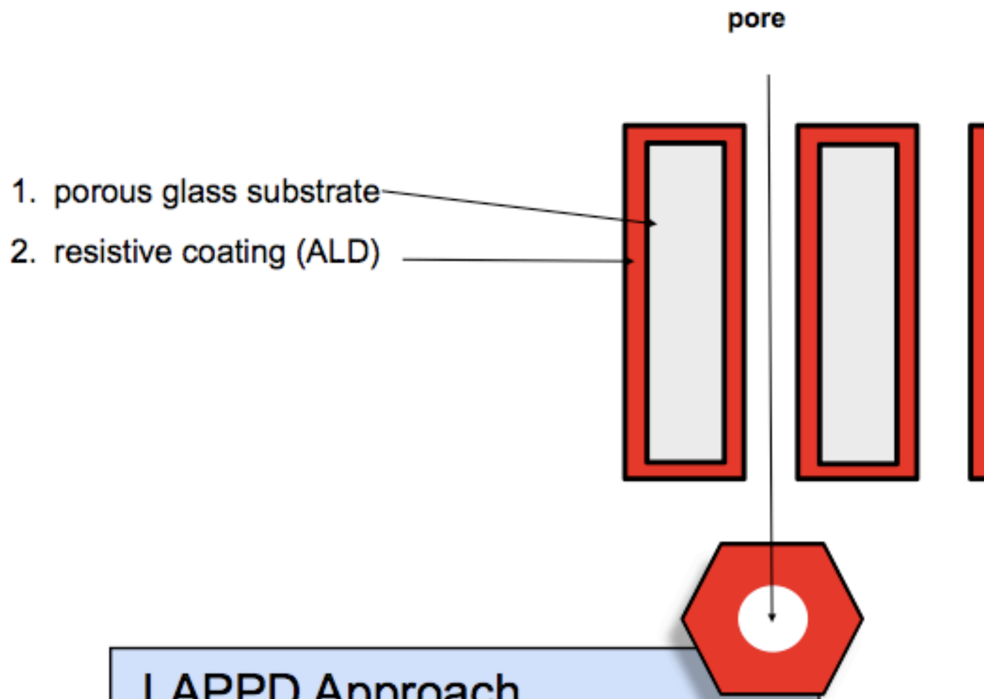

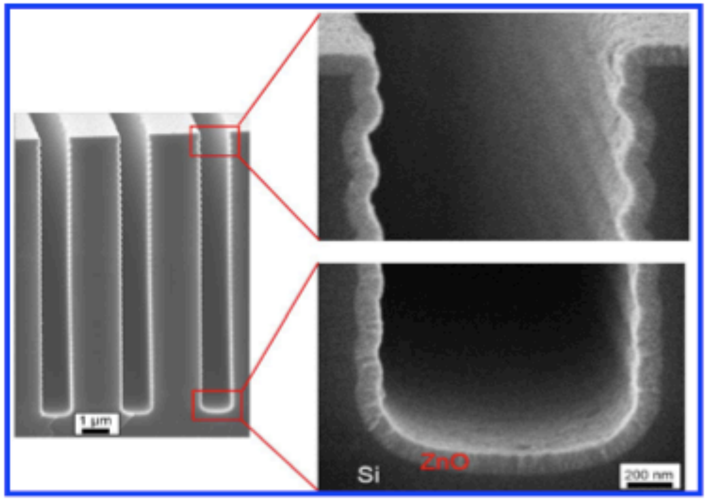

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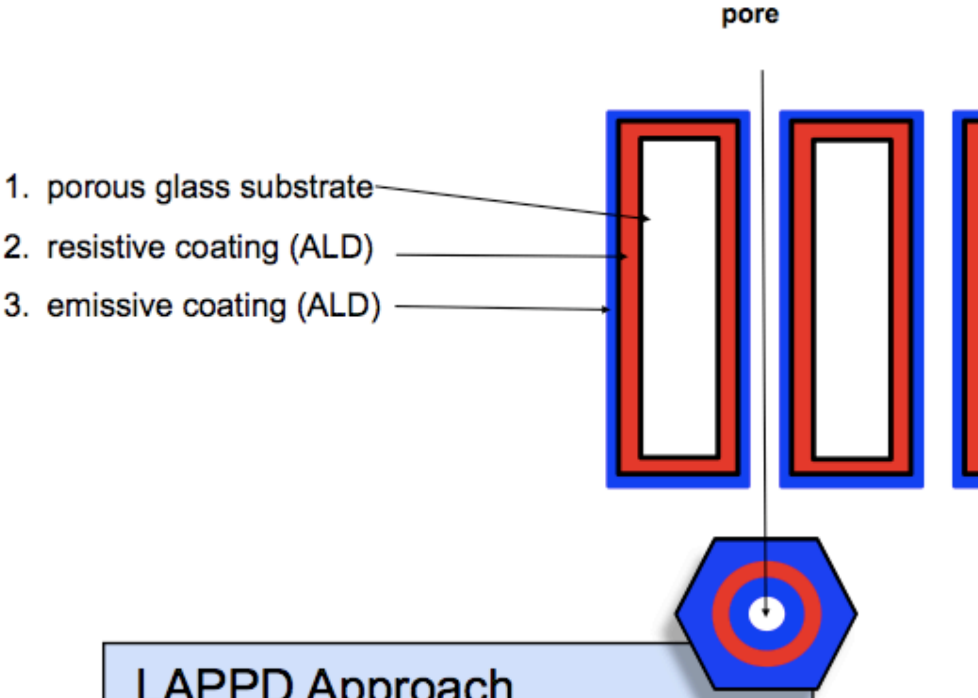

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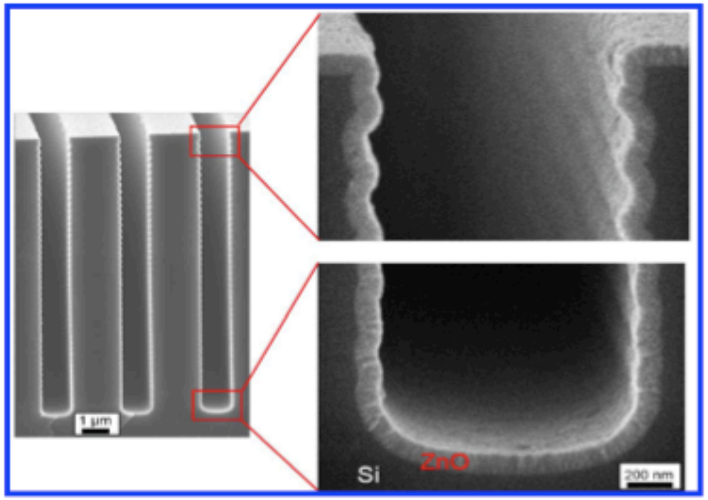

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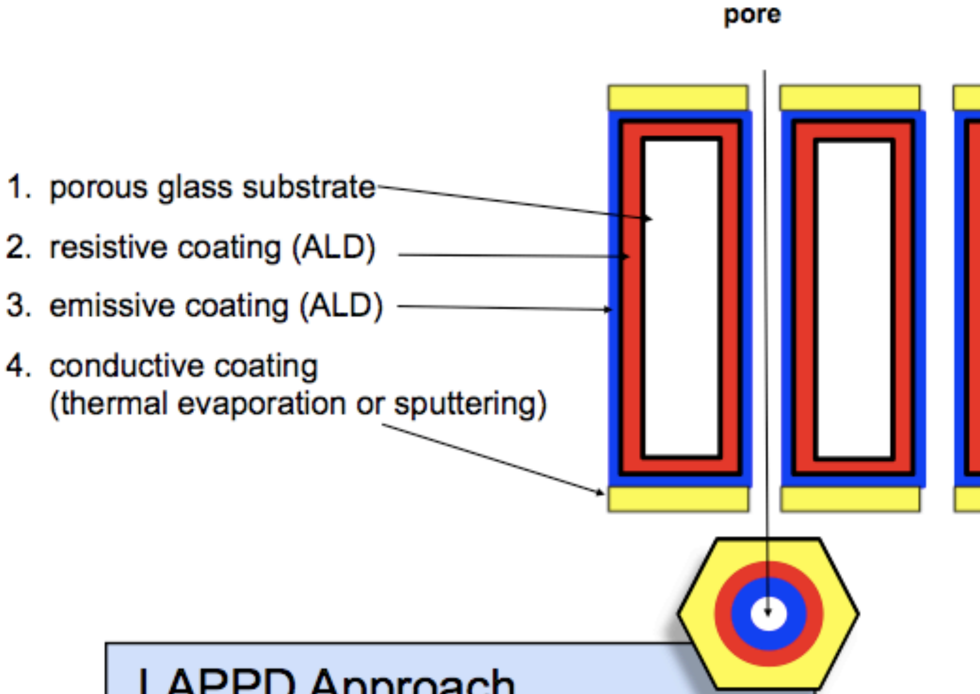

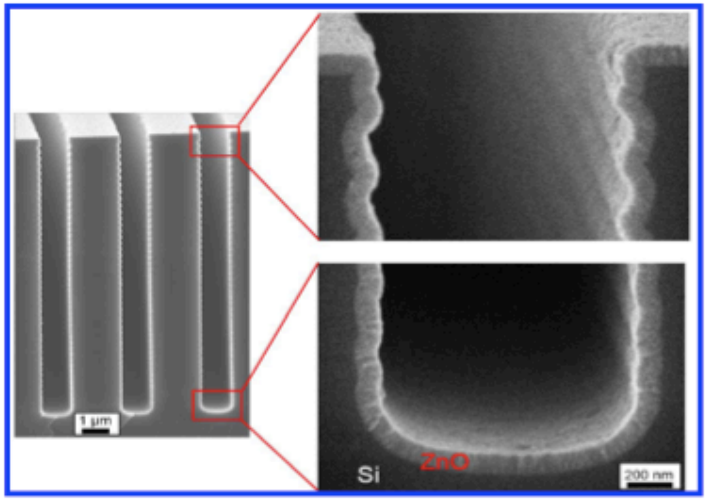

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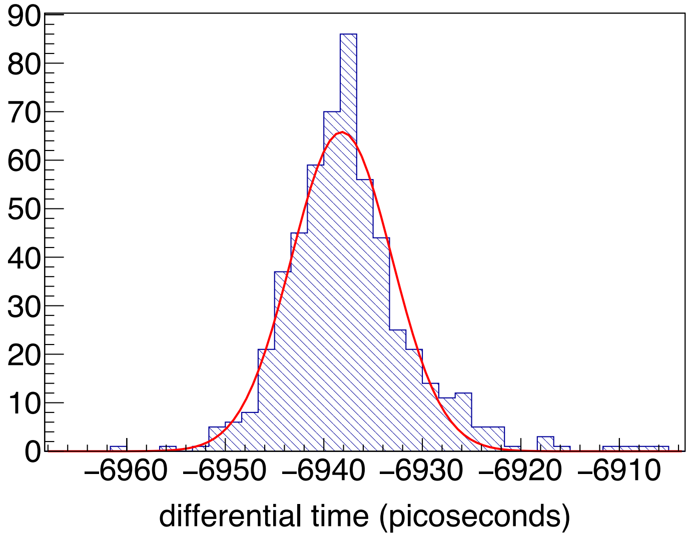
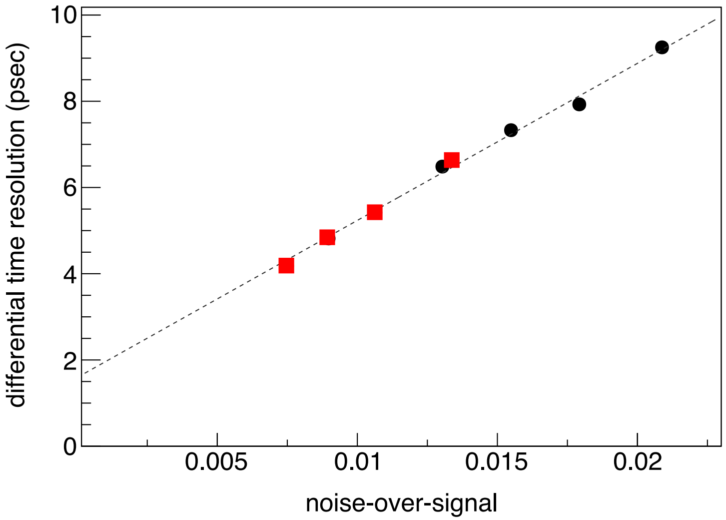
LAPPD Characteristics



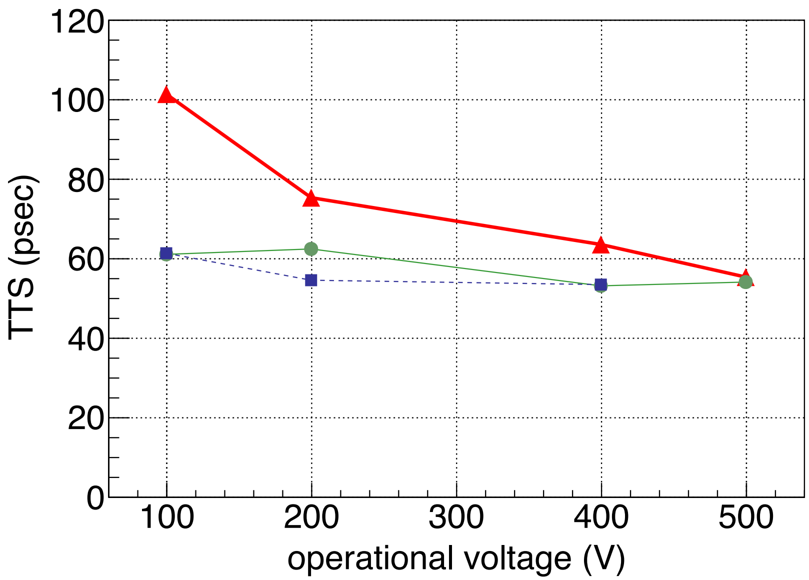
<10 psec, differential time resolution

(2mm spatial resoution)

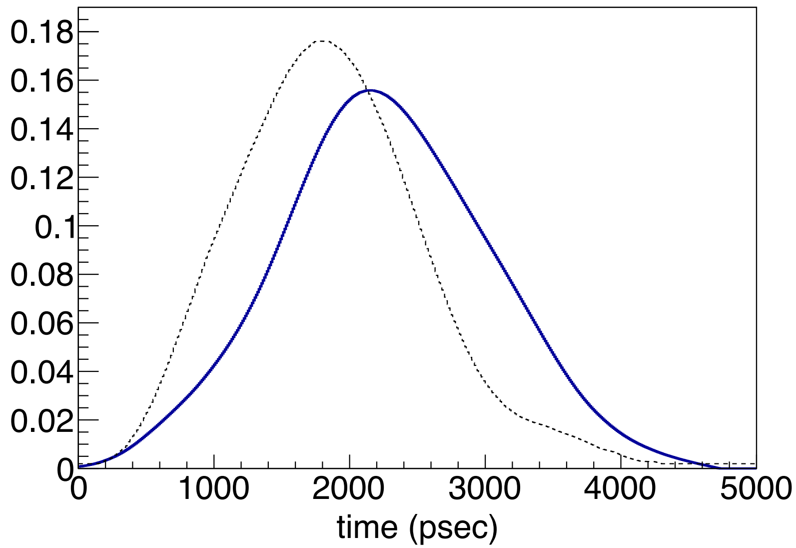


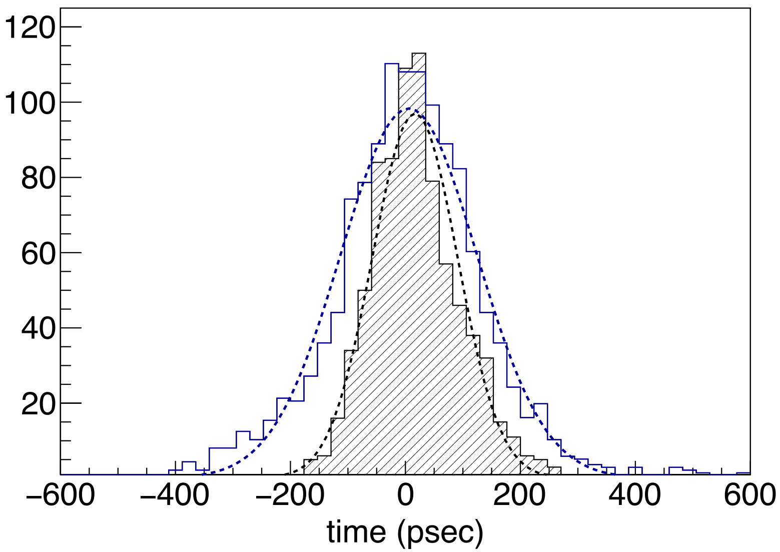
large signal resolutions extrapolating <2 psec

LAPPD Characteristics



Resolutions improve with larger voltages across the gaps





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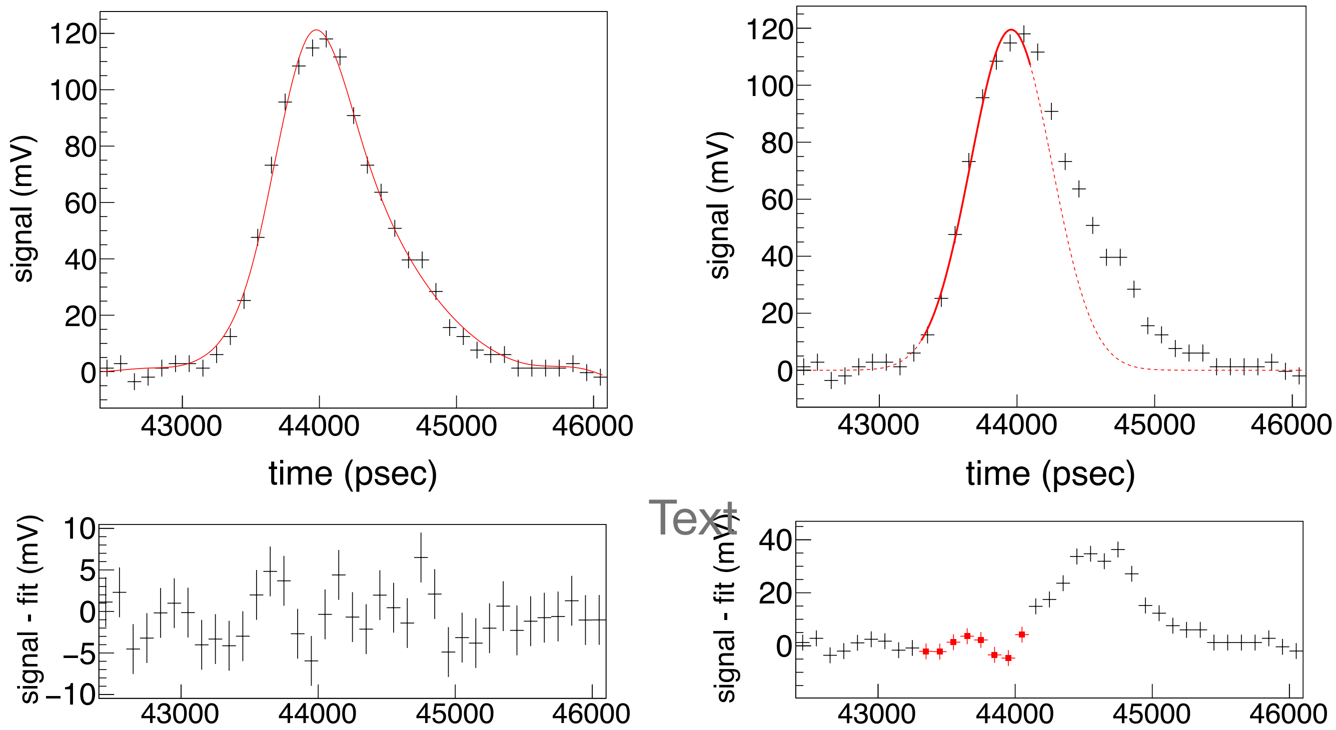
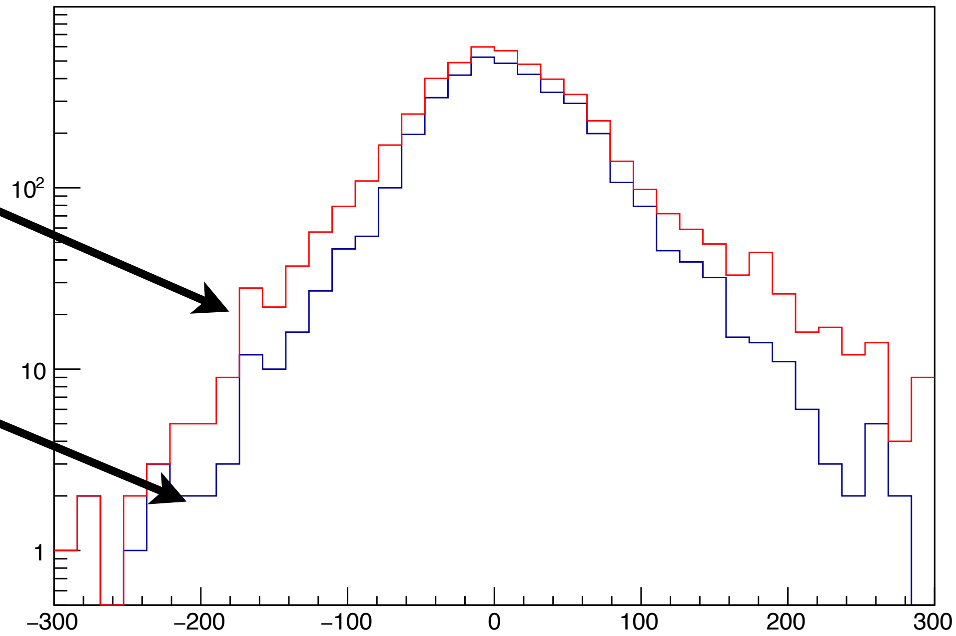


- Pulse shape fitting gives the best time resolution (see J-F Genat et al, NIM A 607 (2) (2009) 387)
- It also provides a strong handle for rejecting after pulses and identifying double pulses.

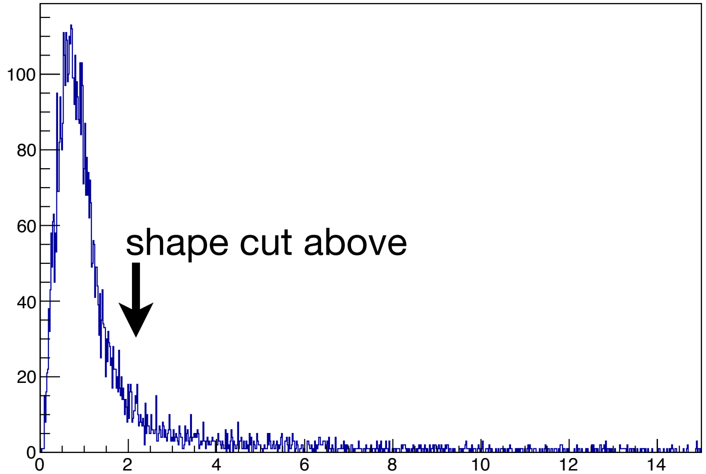
LAPPD Characteristics

No shape cut
RMS = 70 psec

shape cut
RMS = 58 psec
~20% loss

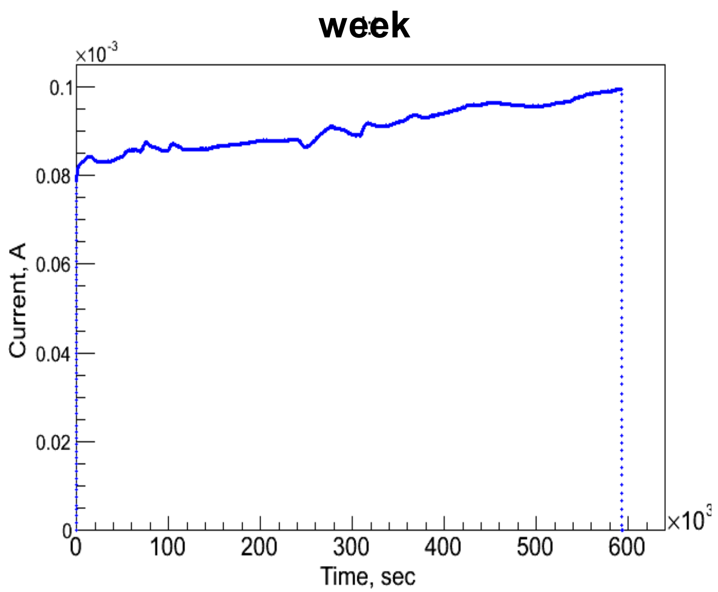


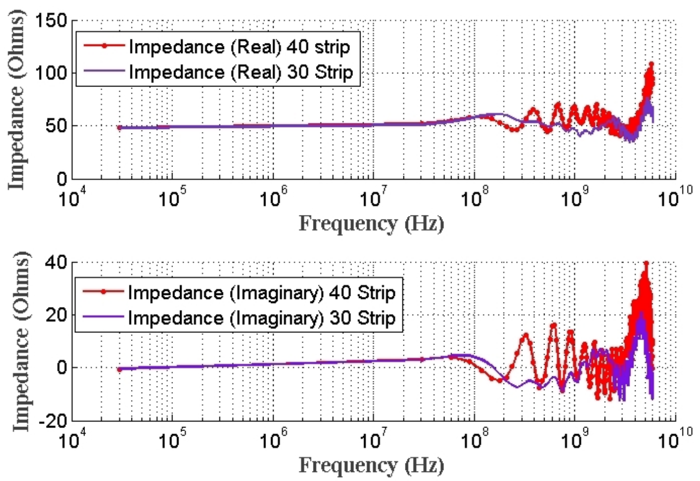
chi2 per deg free

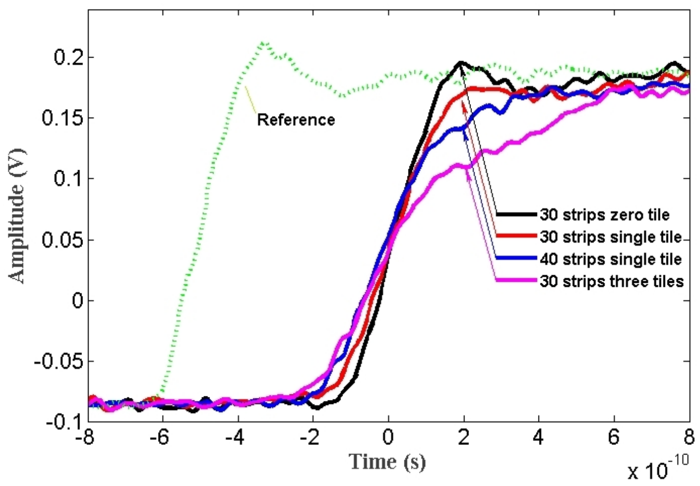


What we measure...Also:

- RF properties
- Losses in anode
- Lifetime and stability issues
- Dark current

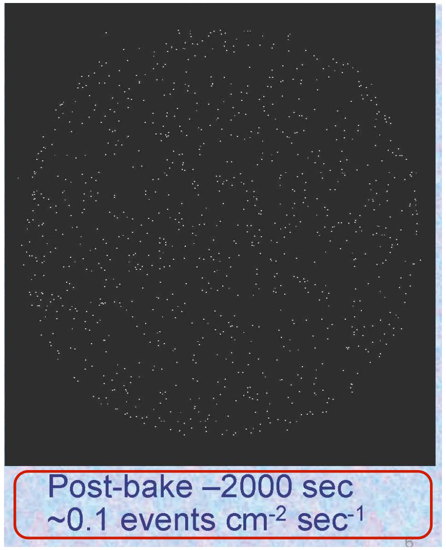




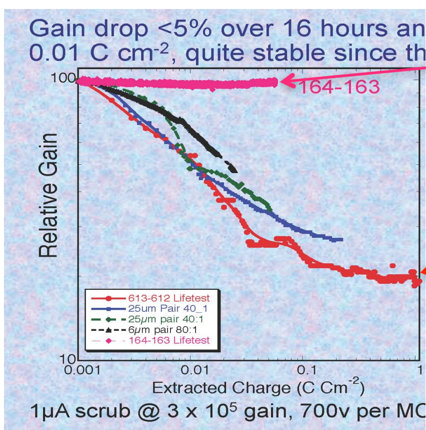


MCP Quality

Low noise



Short break-in



Measured ANL ALD-MCP behavior

Typical MCP behavior- long scrub-times

Measurements by

O.H.W. Siegmund, J. McPhate, A.S. Tremsin, S.R. Jelinsky, R. Hemphill

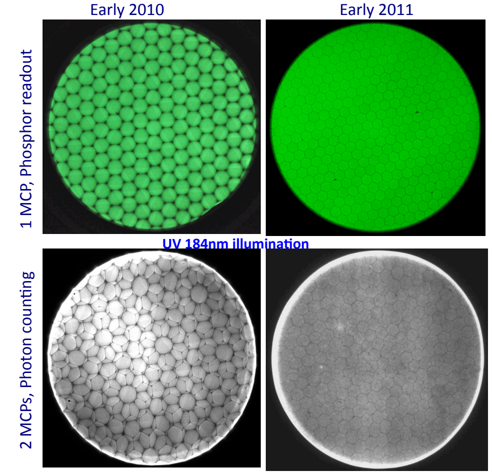
Berekeley SSL

Samples by

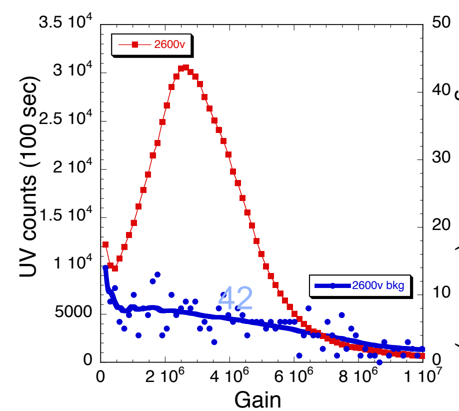
J. Elam, A. Mane, Q. Peng

ANL

Rapidly improving substrates (Arradiance)



bkgd rate of 0.099 evts cm^{-2} sec^{-1} at 1.3 kV per plate



Factors That Determine Time Resolution

credit: Stafan Ritt (Paul Scherrer Institute)

$$\Delta t = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

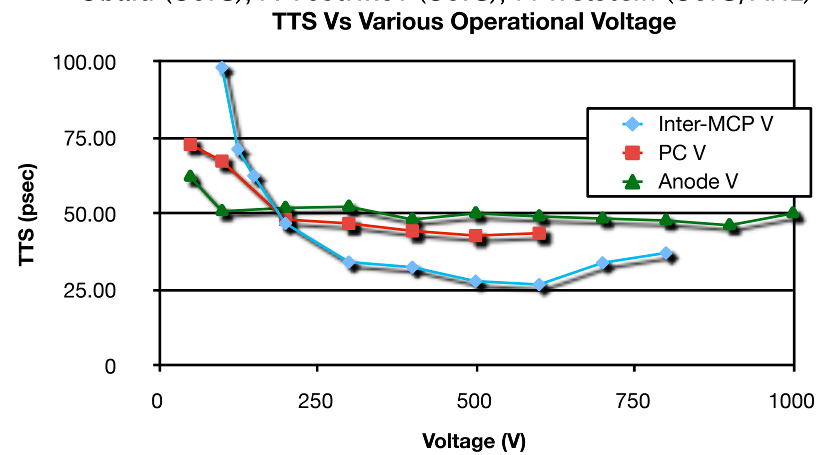
Assumes zero aperture jitter

	U	Δu	f_s	f_{3db}	Δt
today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
next generation:	100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
next generation optimized SNR:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

At the Front End:

- Sampling rate (f_s)
  Nyquist-Shannon Condition
- Analog bandwidth (f_{3DB})
- Noise-to-signal ($\Delta u/U$)

B Adams (APS-ANL), M Chollet (APS-ANL), A Elagin (UoffC/ANL), R Obaid (UofC), A Vostrikov (UofC), M Wetstein (UofC/ANL)

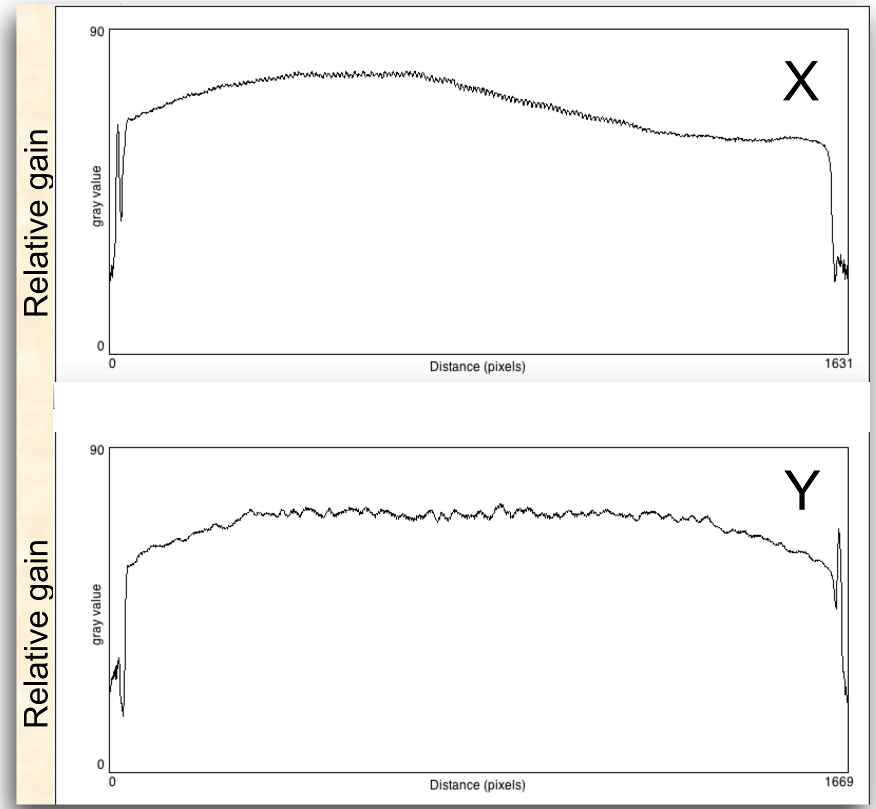


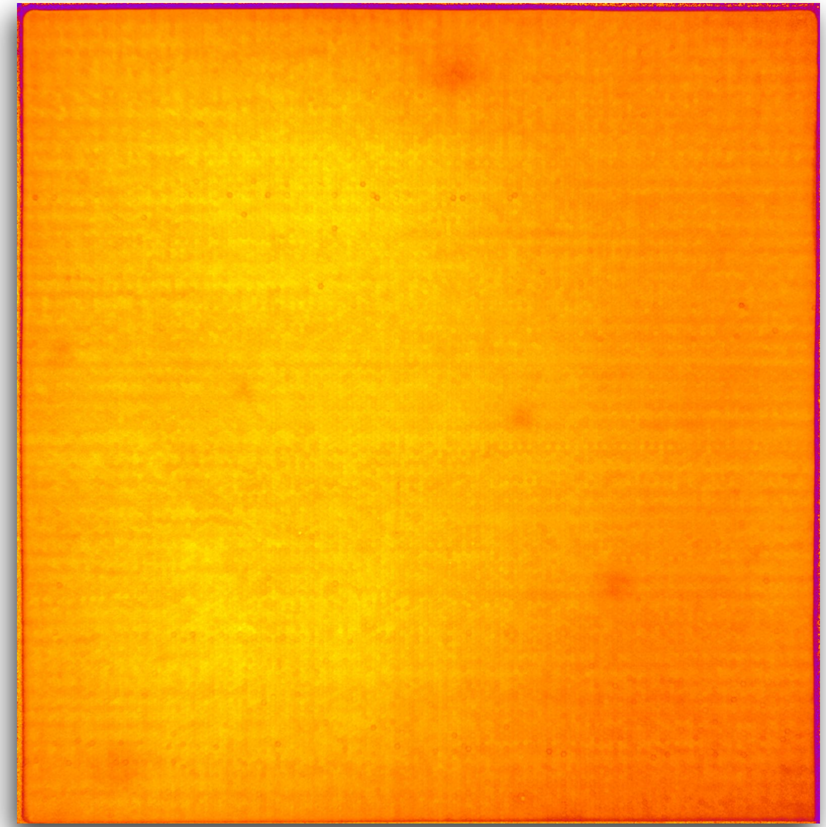
Intrinsic to the MCP:

- Operational voltages
- Gain
- Geometry
  - Pore size
  - Continuous vs discrete dynode

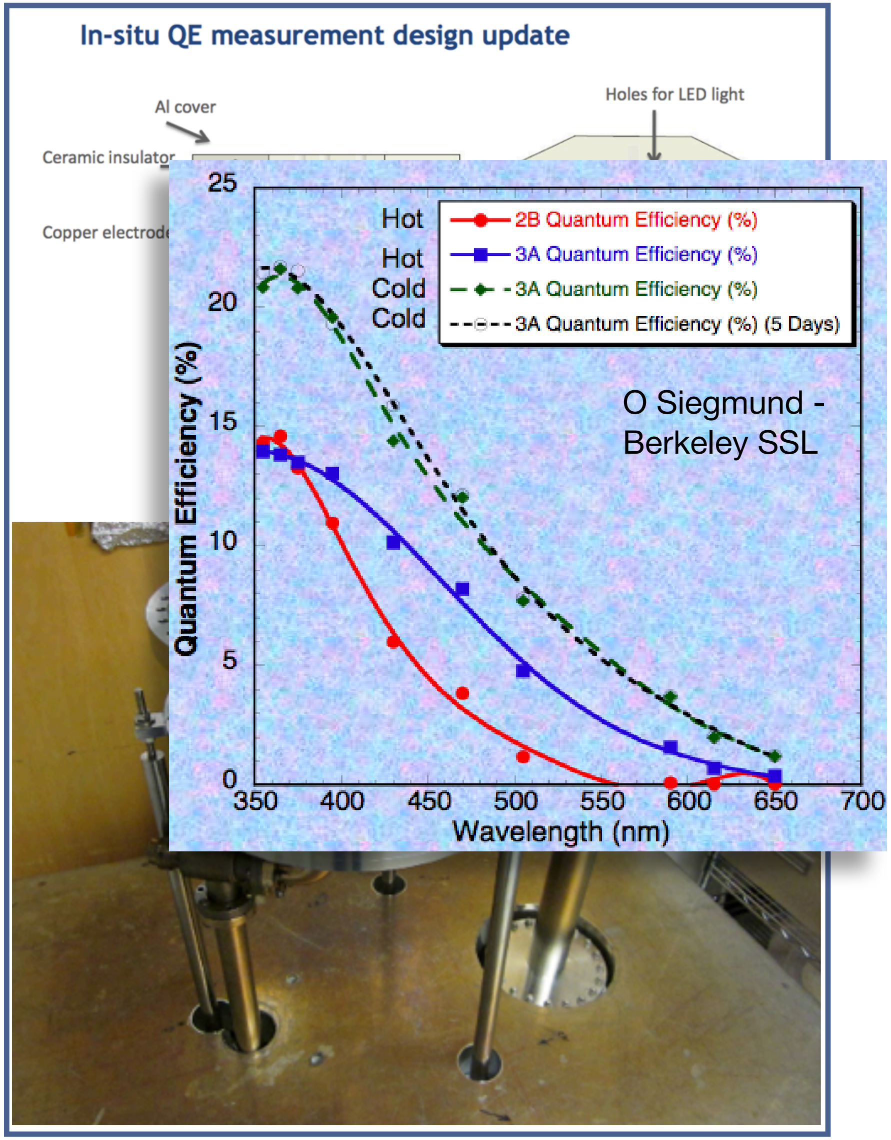
see: workshop on factors that limit time resolution in photodetectors: http://psec.uchicago.edu/workshops/fast_timing_conf_2011/

LAPPD - Gain Uniformity





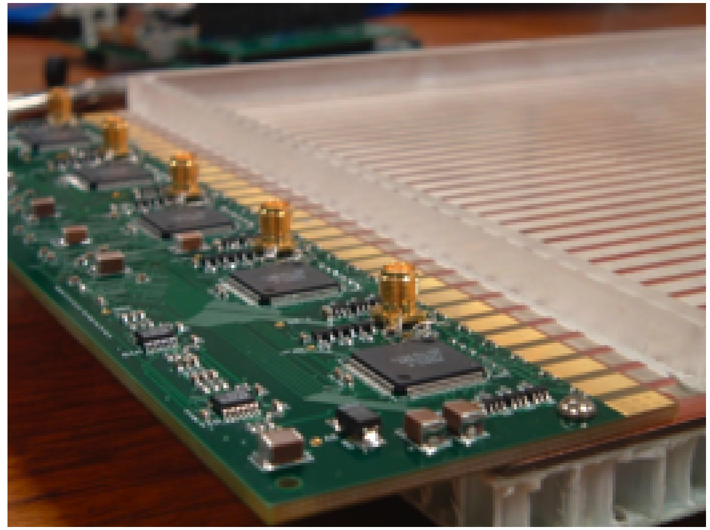
Large Area Photocathodes

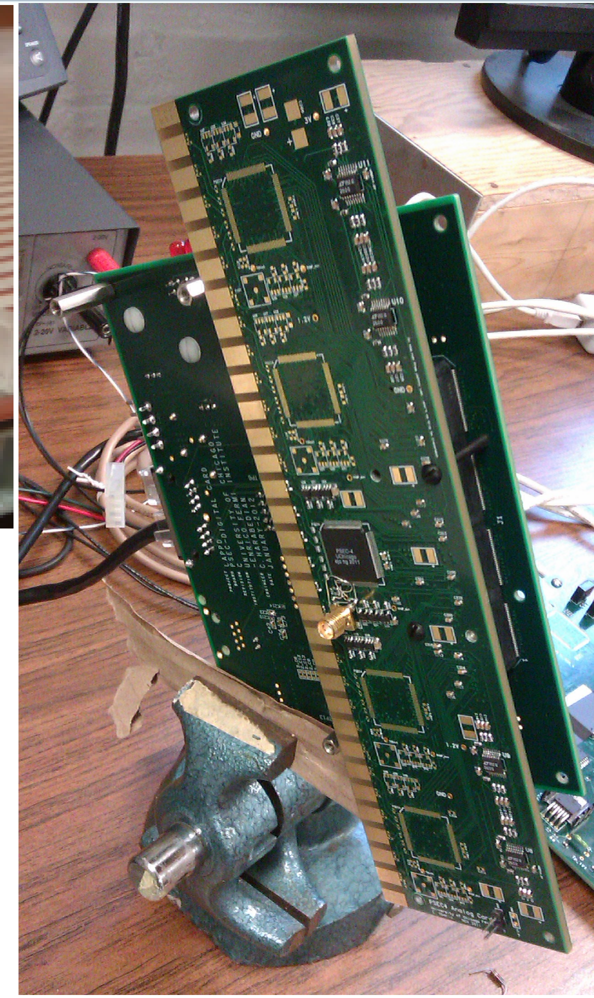


- Two main parallel paths:
  - scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production lines.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries and robustness under conditions relevant to industrial batch processing. Could lead to a longer term photocathode program as part of the new ANL detector center
- Achievements:
  - Commissioning of 8” photocathode facility at UCB-SSL
  - Completion of ANL photocathode lab
  - Acquisition of a Burle-Photonis photocathode deposition system. Progress in adapting it to larger areas.
  - Successful development of a 24% QE photocathode in a small commercial

K. Attenkofer(ANL-APS), Z. Yusof, J. Xie, S. W. Lee (ANL-HEP),
S. Jelinsky, J. McPhate, O. Siegmund (SSL)
M. Pellin (ANL-MSD)

Front-end Electronics





Psec4 chip:

- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

AC-DC card:

- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)
- Analysis of the individual pulses (charges and times)

Central Card:

- Combines information from both ends of multiple striplines

LAPPD project covered the whole system, including readout electronics

Post Scripts: PSEC4/PSEC4B

Batch of 400 PSEC4 chips has been ordered by ISU for ANNIE:

= 2400 channels

= 40 LAPPDs

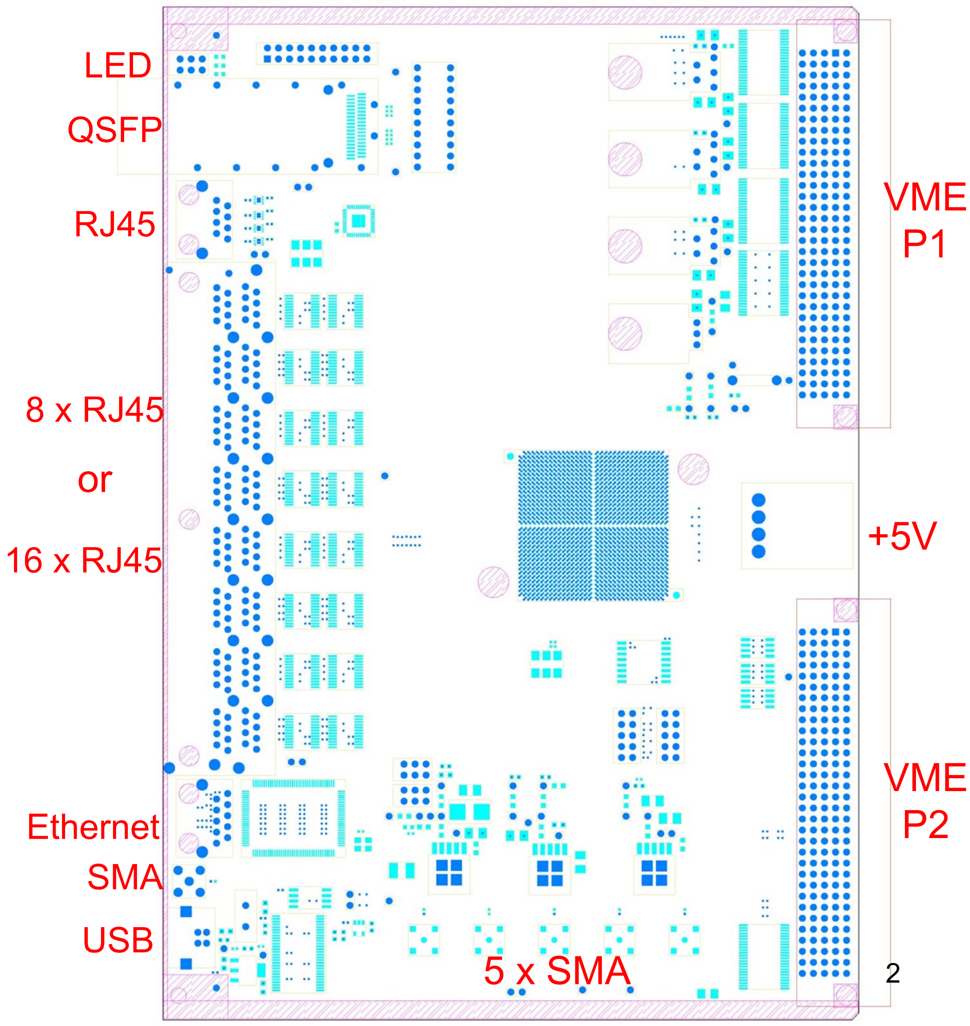
Eric Oberla is working on a design for a PSEC4b:

- 4-fold increase the buffer depth to allow multi-event buffering.
- Would enable continuous operation for low rate applications (eg neutrinos)
- design is under way, but looking for feedback from the community

New Central Card and DAQ Dev

Mircea Bogdan (UC) has a new design for the PSEC central card to allow very large channel-counts.

Prototypes boards are being ordered and will be tested in early 2016.



LAPPDs Application Readiness (water proofing)

LAPPD Water Proofing

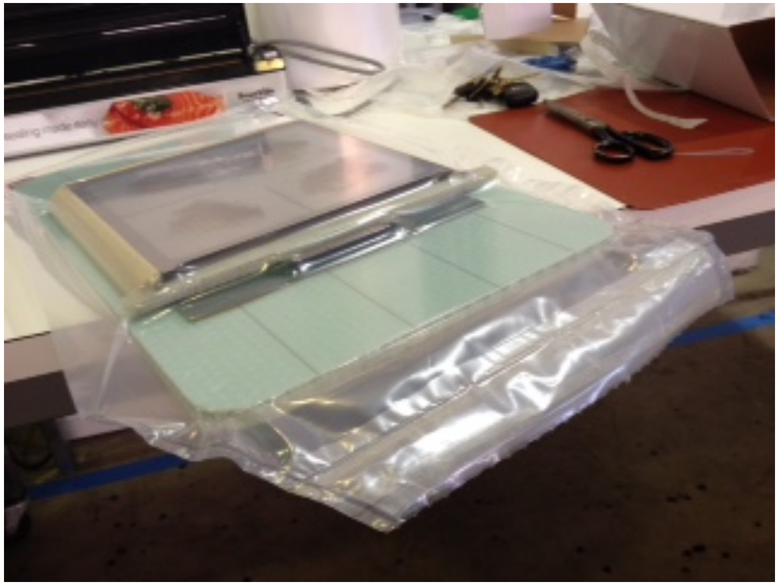
Exploring two paths:

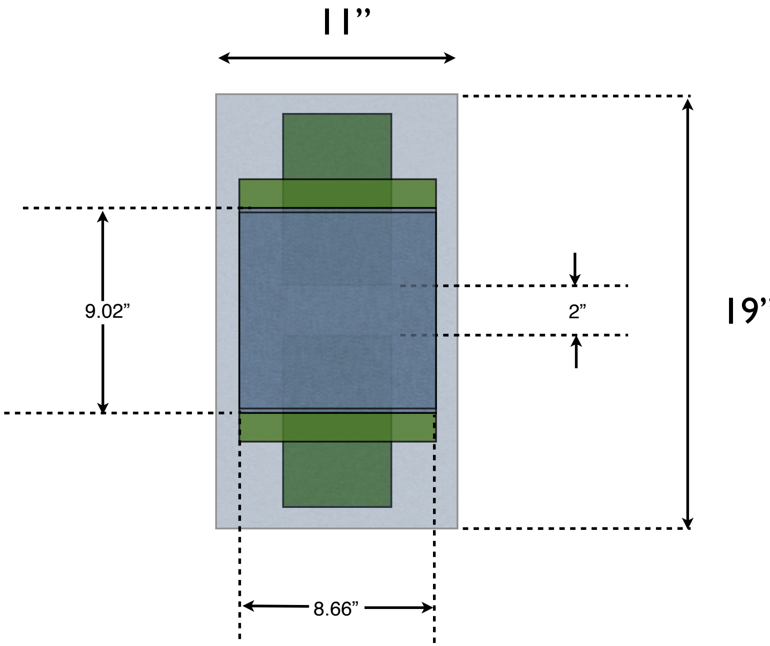
- “Sous Vide”: sealing the LAPPD assembly (w/ front end) in a plastic envelope
- Water-proof box

LAPPD Water Proofing

Sous Vide concept:

- LAPPD is packaged with front-end electronics mounted in the water
- Electronics are in direct thermal contact with the water (cooling comes free)
- Use polyethylene bags (Gd-compatible)
    - thick (abrasion resistance)
    - index of refraction (1.4) is between water and glass - nice optical transition



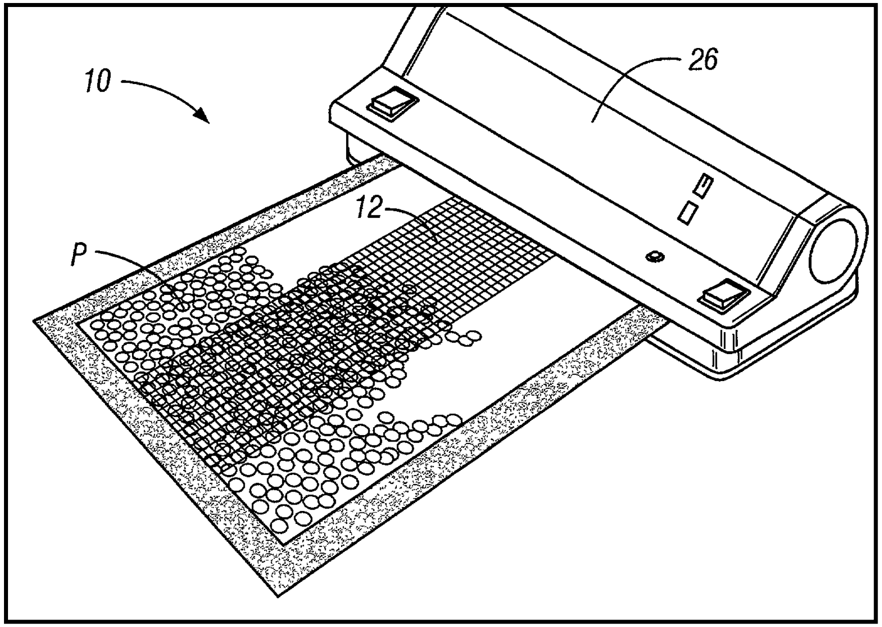


LAPPD Water Proofing

Sous Vide concept:

- Our student was able to make simple custom bags to fit the assembly with polyethylene exterior but nylon inner structure (Sous Vide patent) to allow easy evacuation.

- Eliminating sharp edges was challenging
    - were able to eliminate LAPPD corners with round offs and RTV
    - heats sinks were relplaced with copper ribbon
    - silicone sheets placed over circuit boards



LAPPD Water Proofing

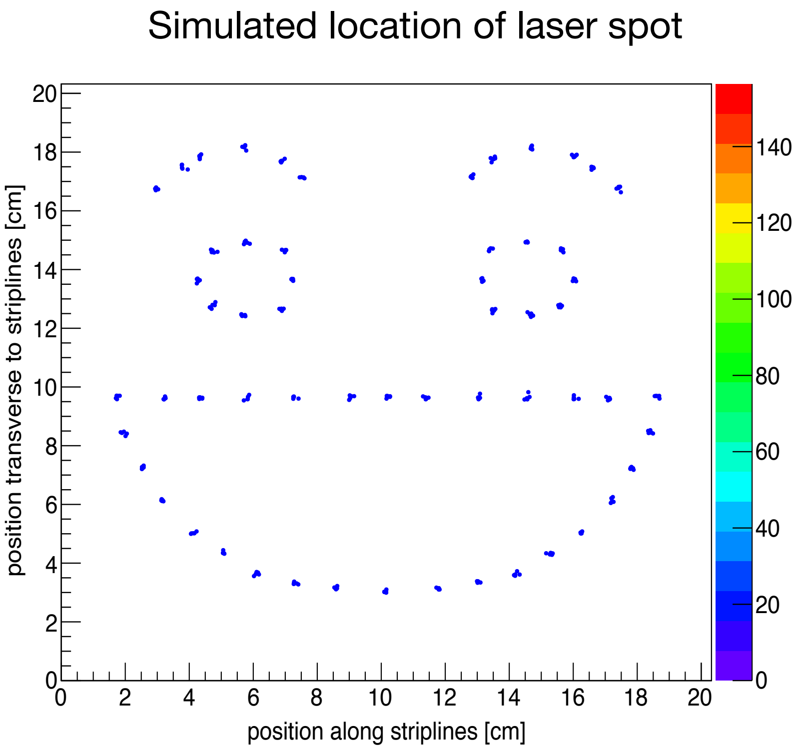
Status:

- We got as far as sealing a test assembly and dunking it in water
- Need to work on feedthroughs (a major challenge)
- Need to study robustness
- Need an operational test

- We lost our undergraduate researcher
- Rich Northrop (UC engineer) has not begun his phase of the work
- This will start soon

LAPPD Reco

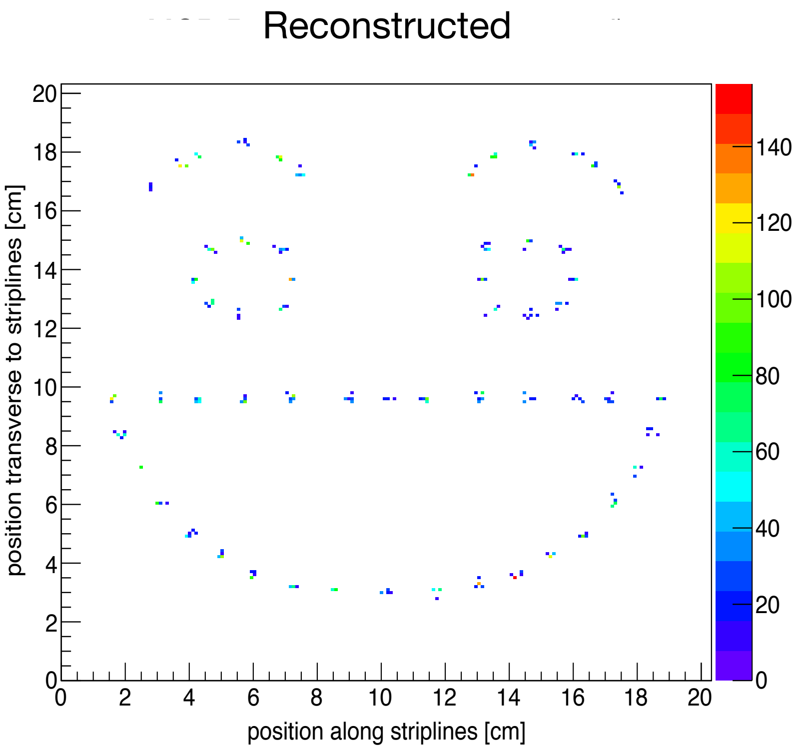
LAPPD Analysis Chain



Full LAPPD/PSEC analysis chain (D. Grzan):

- Able to realistic simulate response of 8” LAPPD (and PSEC digitization) to any pattern of light
- Able to quickly (10 minutes) process toy PSEC4 data

LAPPD Analysis Chain



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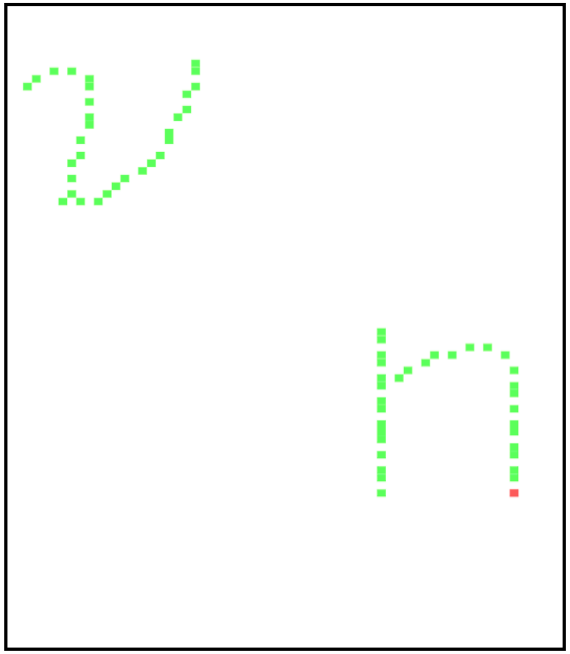
LAPPD Analysis Chain

laser scan positions



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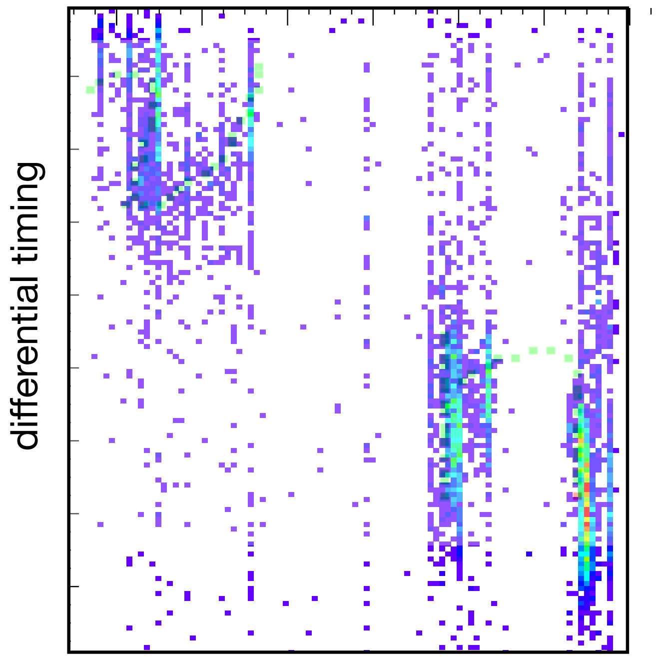

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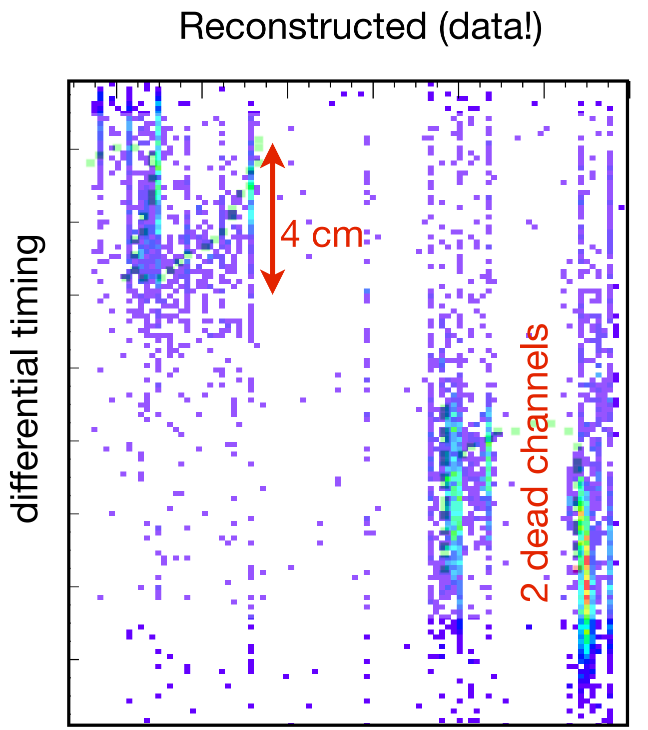

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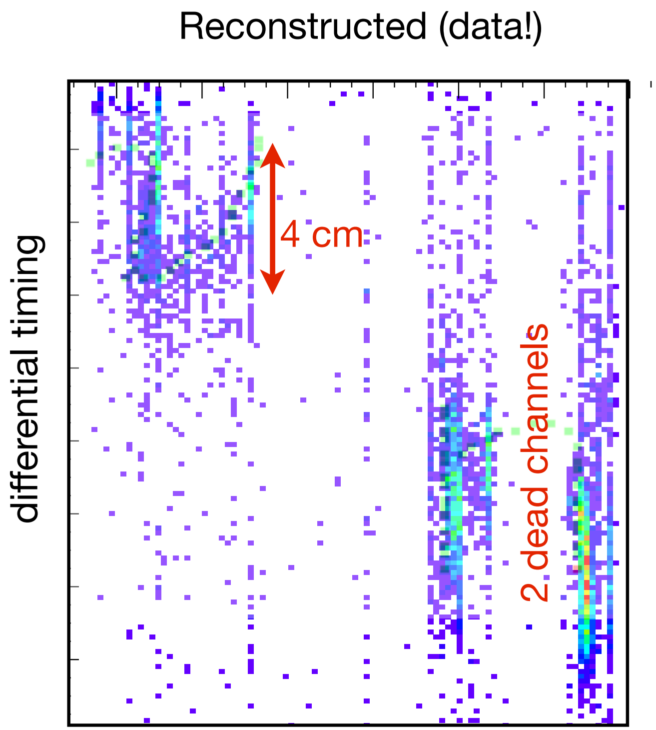
LAPPD Analysis Chain



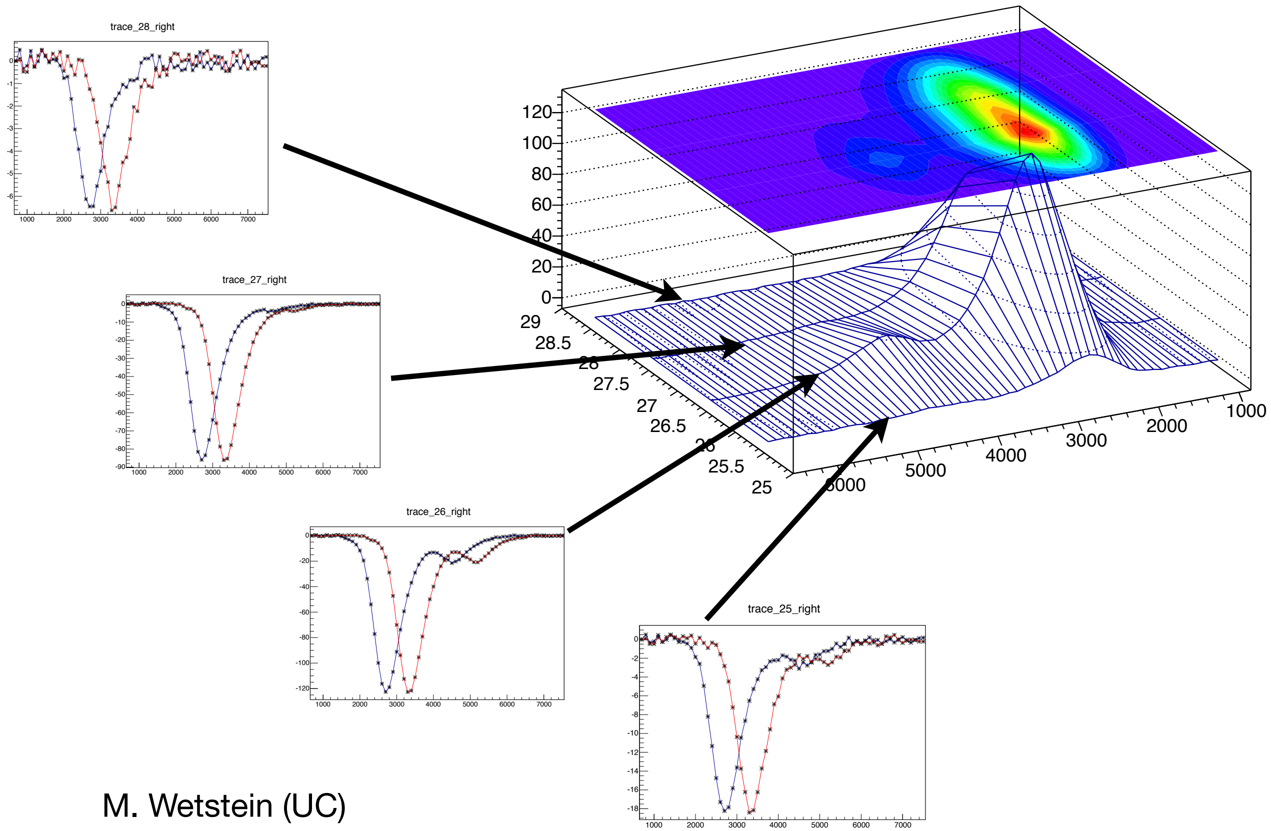
Full LAPPD/PSEC analysis chain (D. Grzan):

- Able to realistic simulate response of 8” LAPPD (and PSEC digitization) to any pattern of light
- Able to quickly (10 minutes) process toy PSEC4 data

New imaging trials starting before November.

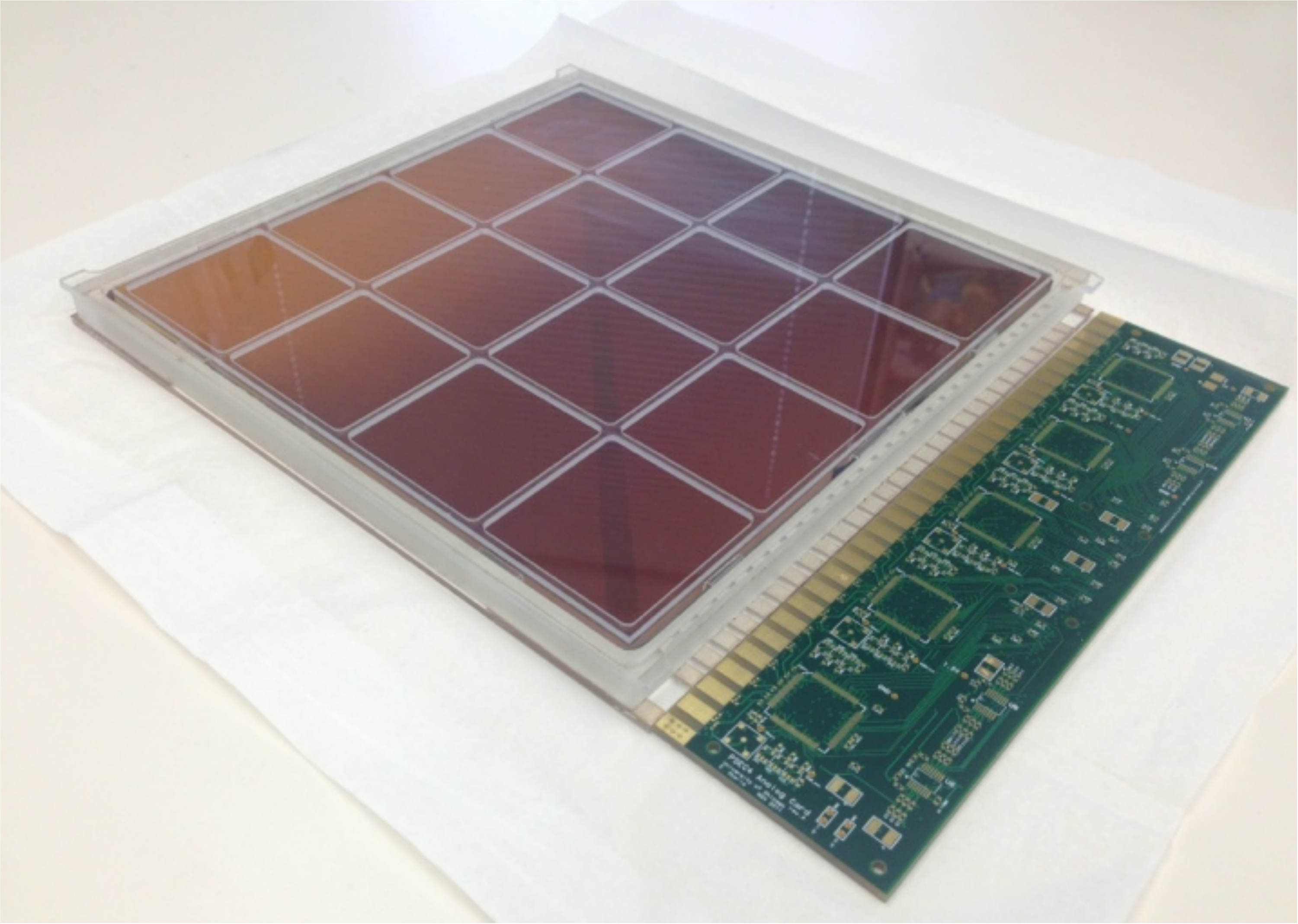
LAPPD Response Simulations

We've been working on using data from the demountable testing to build realistic models of the LAPPD response for use in physics simulations.

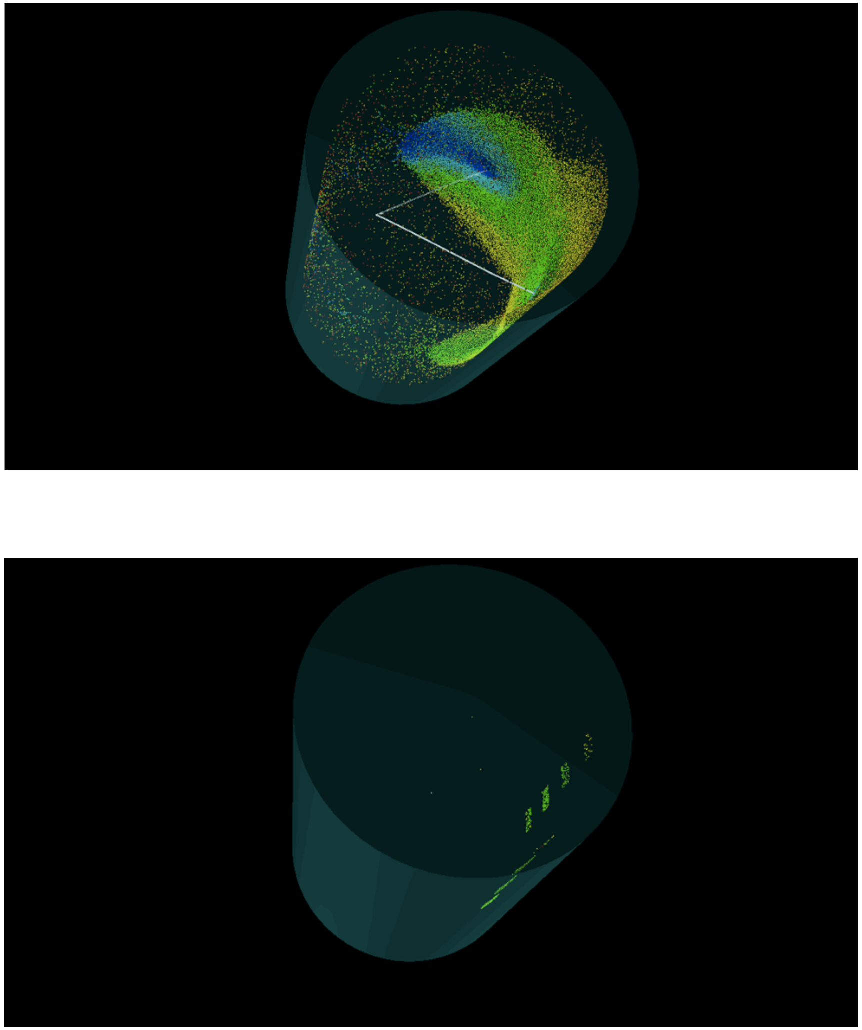


M. Wetstein (UC)

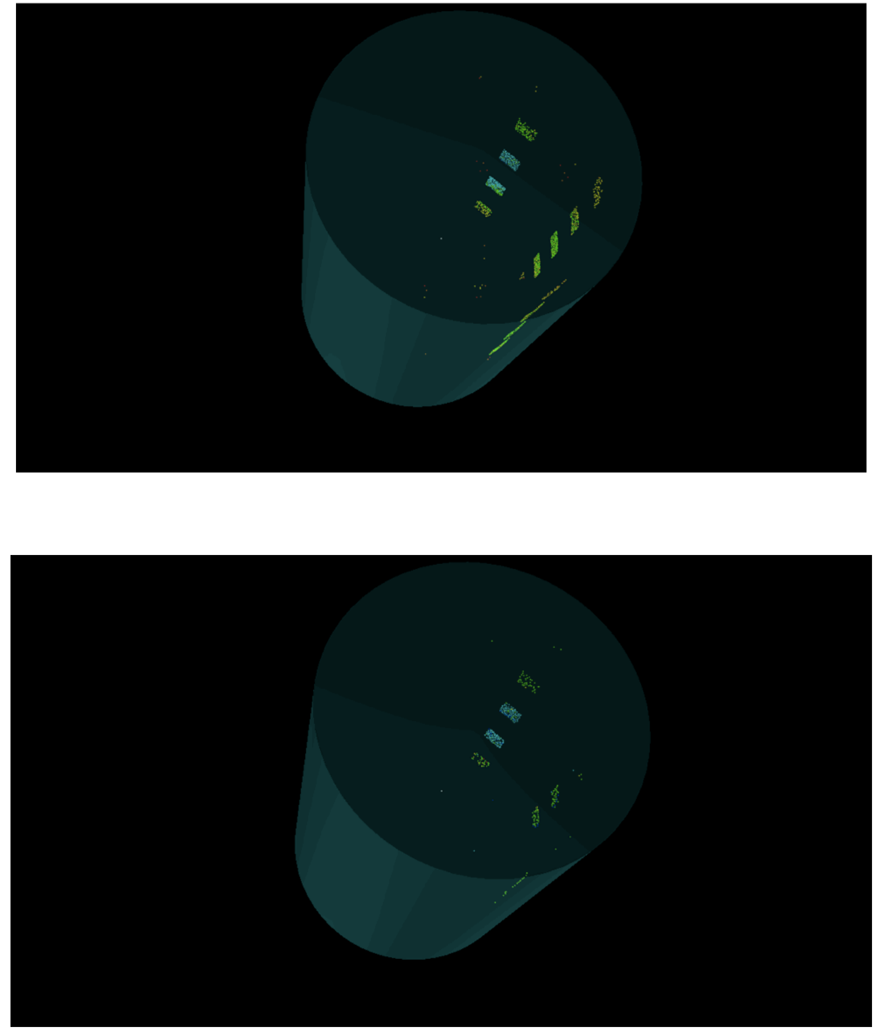
LAPPDs can provide the needed photodetector capabilities



ANNIE Details

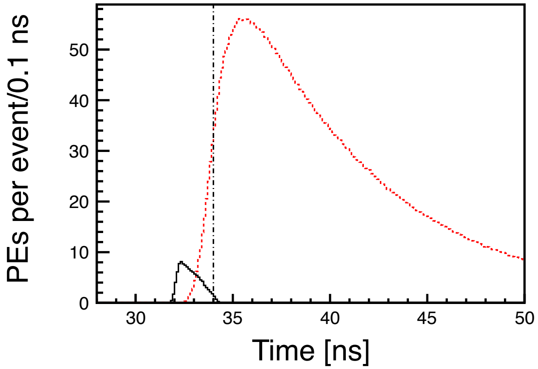


muon

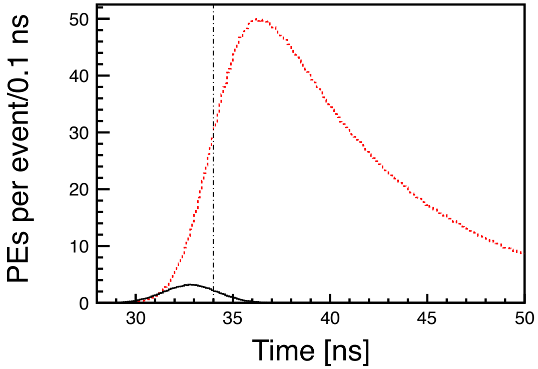


pion

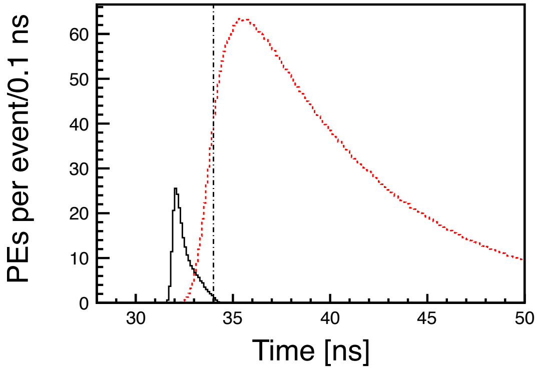
Timing and Scintillation



(a) Default simulation.



(b) Increased TTS (1.28 ns).



(c) Red-sensitive photocathode.

Low Energy/Heavy Particle Sensitivity

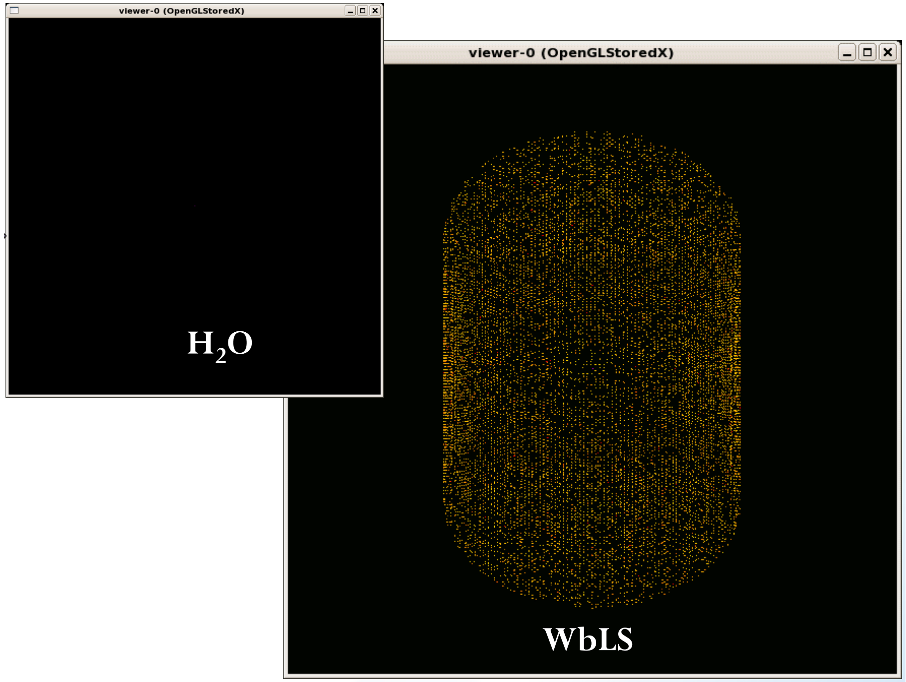
More light/light below Cherenkov threshold

Charged particles only produce Cherenkov light when v > c/n

For massive particles, the threshold for Cherenkov production is >100 MeV

Particle	Threshold
electron	> 0.6 MeV
muon	> 120 MeV
pion	> 160 MeV
kaon	> 563 MeV
proton	> 1070 MeV

K+ in water and liquid scintillator



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	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^+\pi^0$	45%	0.2	45% ?	0.1
$p \rightarrow \nu K^+$	14%	0.6	97%	0.1
$p \rightarrow \mu^+ K^0$	8%	0.8	47%	0.2
n-nbar	10%	21	?	?

SUSY favored proton decay mode:

$$p \rightarrow K^+ \bar{\nu}$$

63.5 % $\rightarrow \mu^+ \nu$ (152 MeV)

20.7 % $\rightarrow \pi^0 \pi^+ \rightarrow 2\gamma\ \mu^+ \nu$ (135 MeV, 4 MeV)

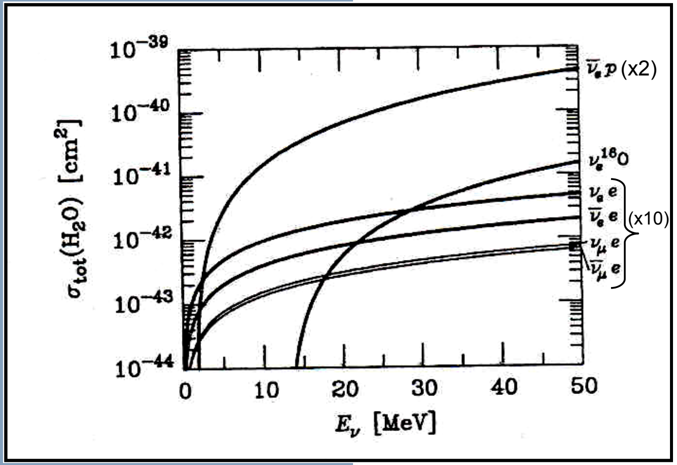
Inefficient channel in water. Cannot see the Kaon

Low Energy/Heavy Particle Sensitivity

Seeing neutrons

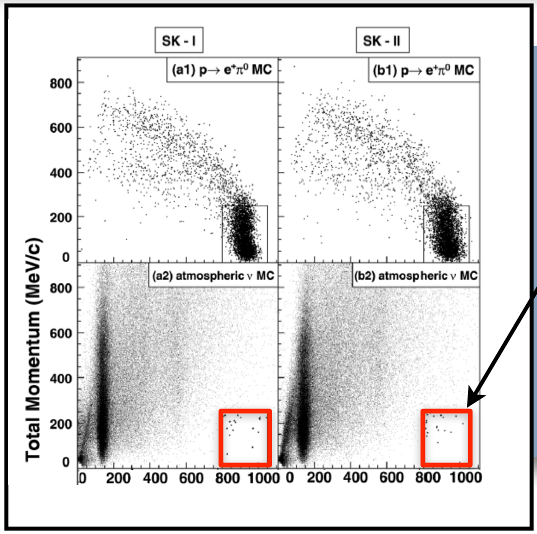
K. Zuber, Neutrino Physics, IOP, 2004

At O(10) MeV energies, inverse beta decay (IBD) has the largest cross-section in water. Neutrons are important for tagging IBD signal events.



Important for:

- Supernova neutrinos
- Solar neutrinos
- Geo neutrinos
- Reactor neutrinos



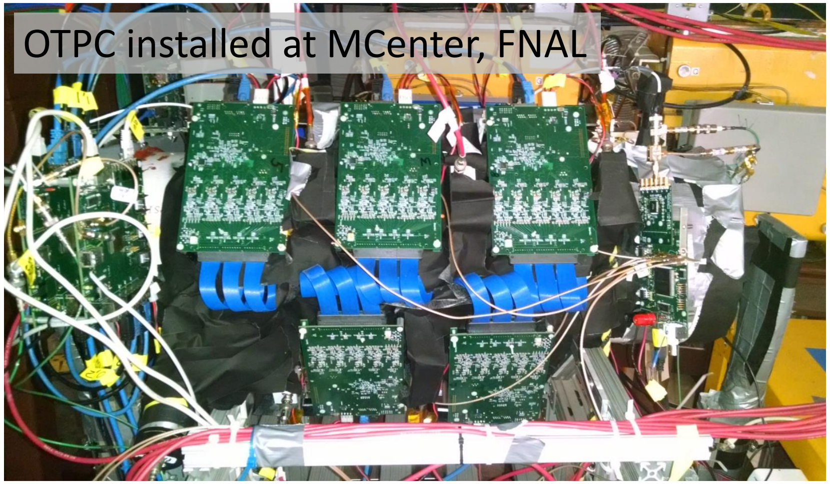
Atmospheric neutrino interactions can fall in the signal region for proton decay in the $p \rightarrow e\pi^0$ channel.

Identifying neutrons is important in tagging this, the largest reducible background.

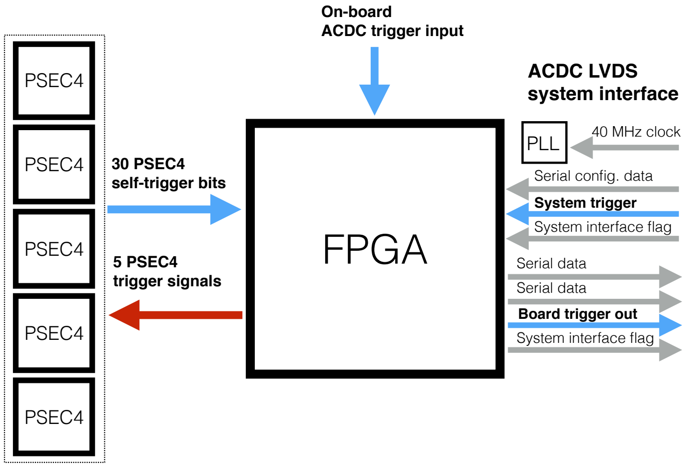
OTPC

1A: LAPPD Self Triggering

Eric Oberla (UC grad student) finished implementing self-triggering in the PSEC electronics firmware. Operated a 180 channel system on a test beam experiment, using the feature.



A picture of the optical TPC installed at MCenter at Fermilab. Along the tube axis, 5 PSEC ACDC cards instrument 5 Planacons in a stereo configuration. One additional Planacon and ACDC card instrument the front of the tube. This 180 channle system is controlled by two Central Cards.



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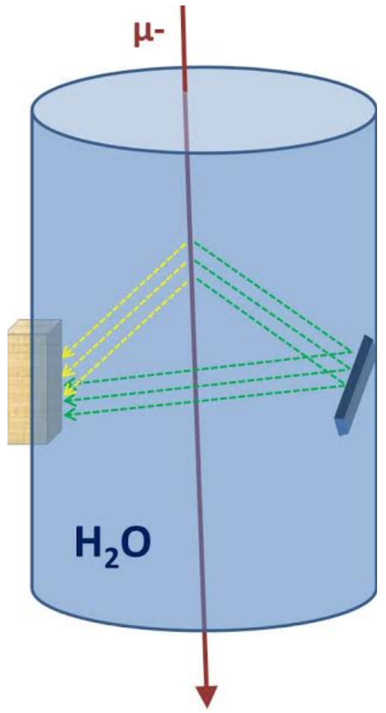

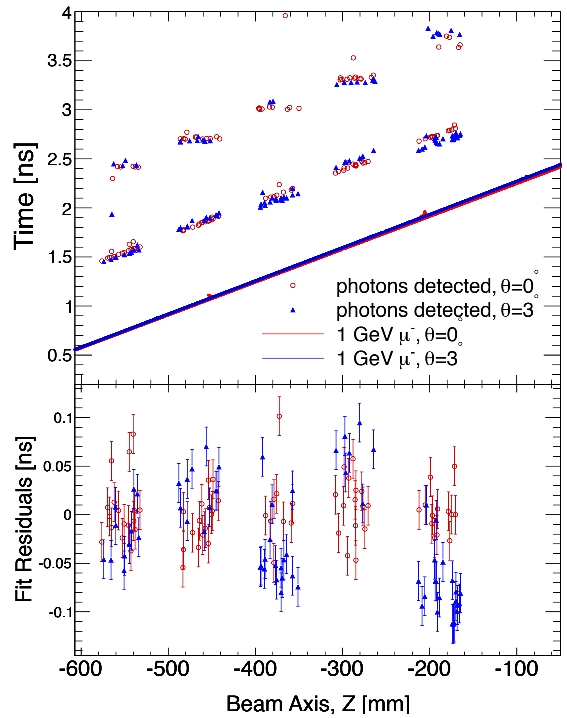

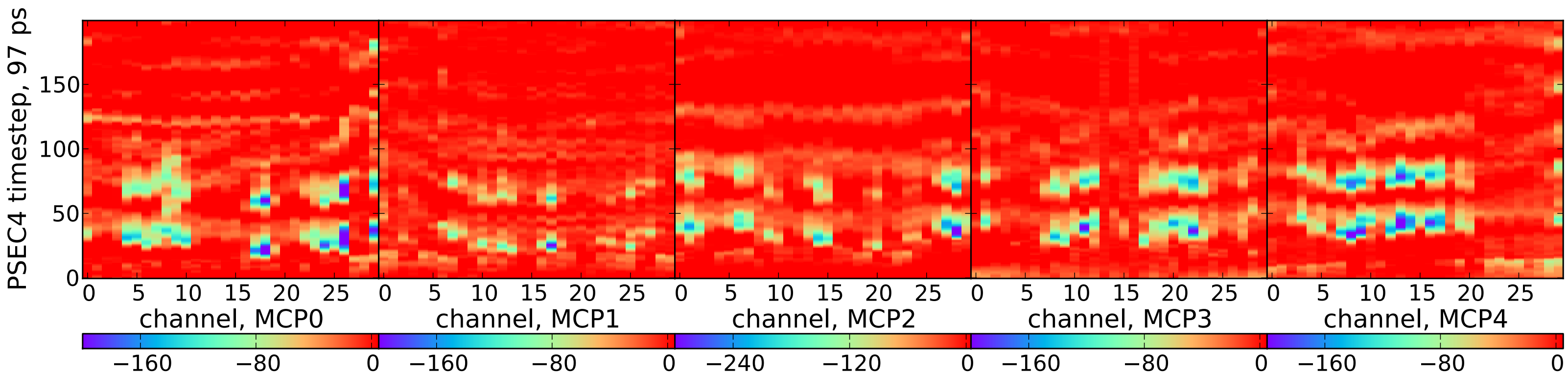

(a)

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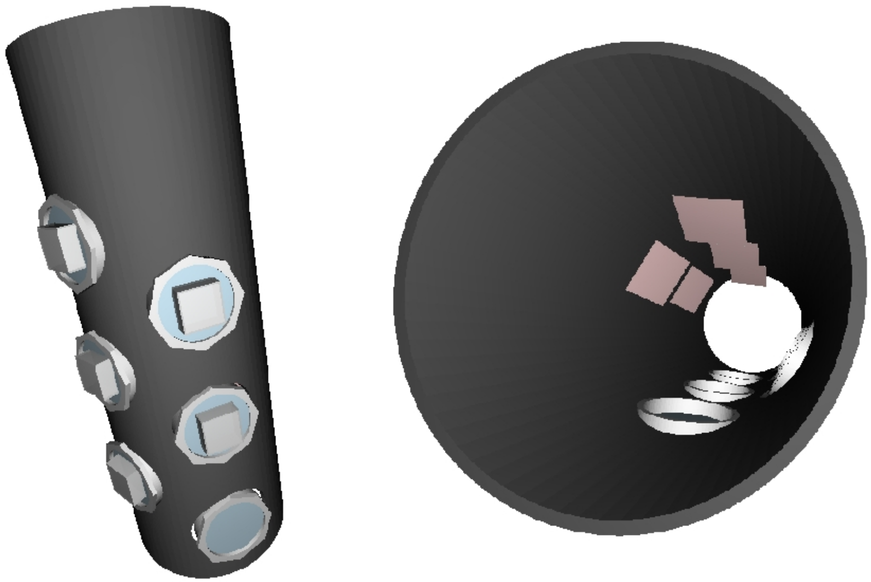

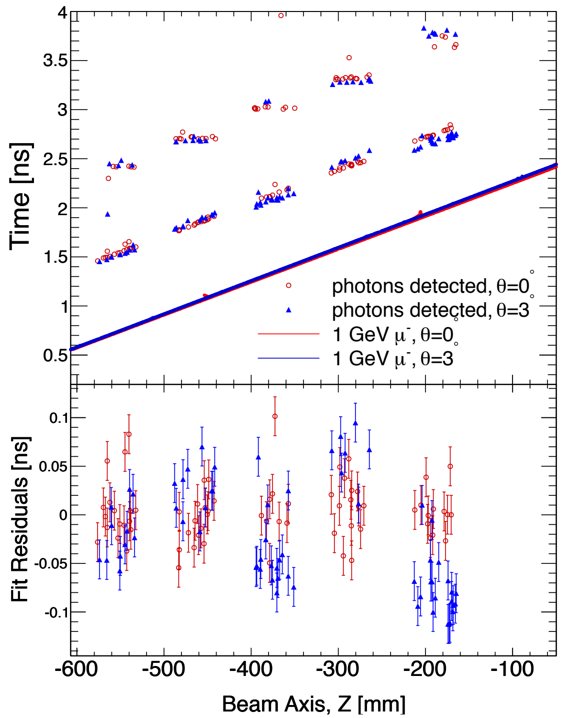

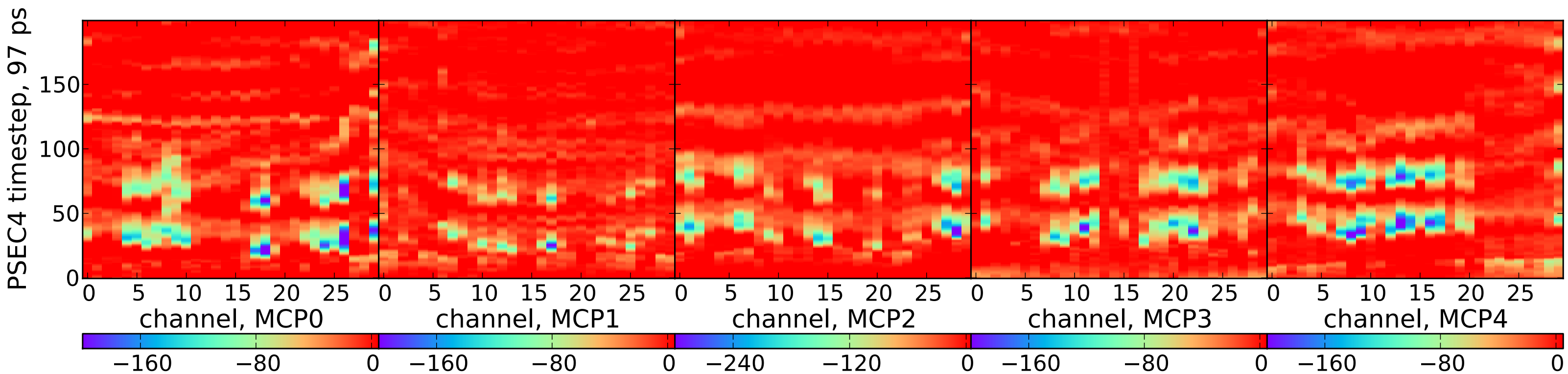

(a)

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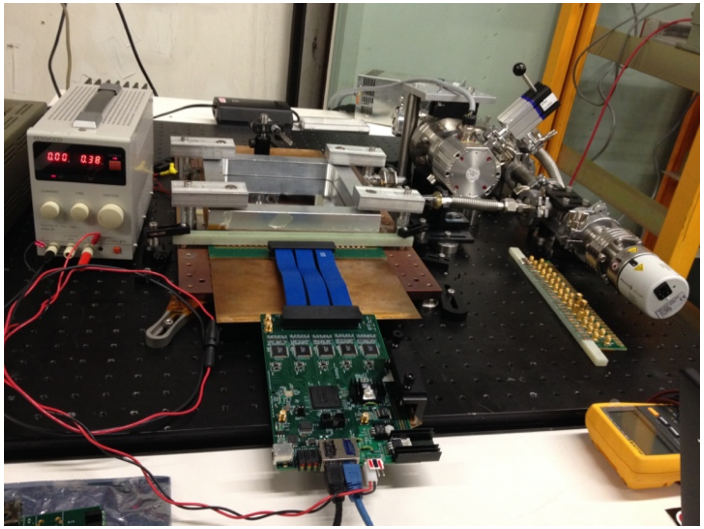

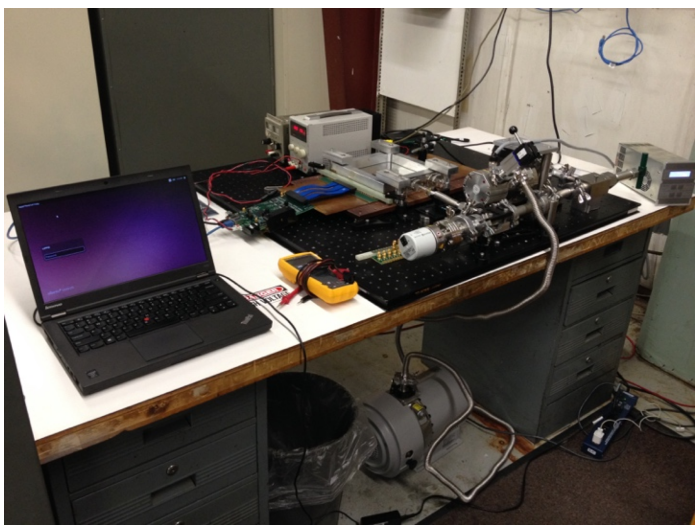

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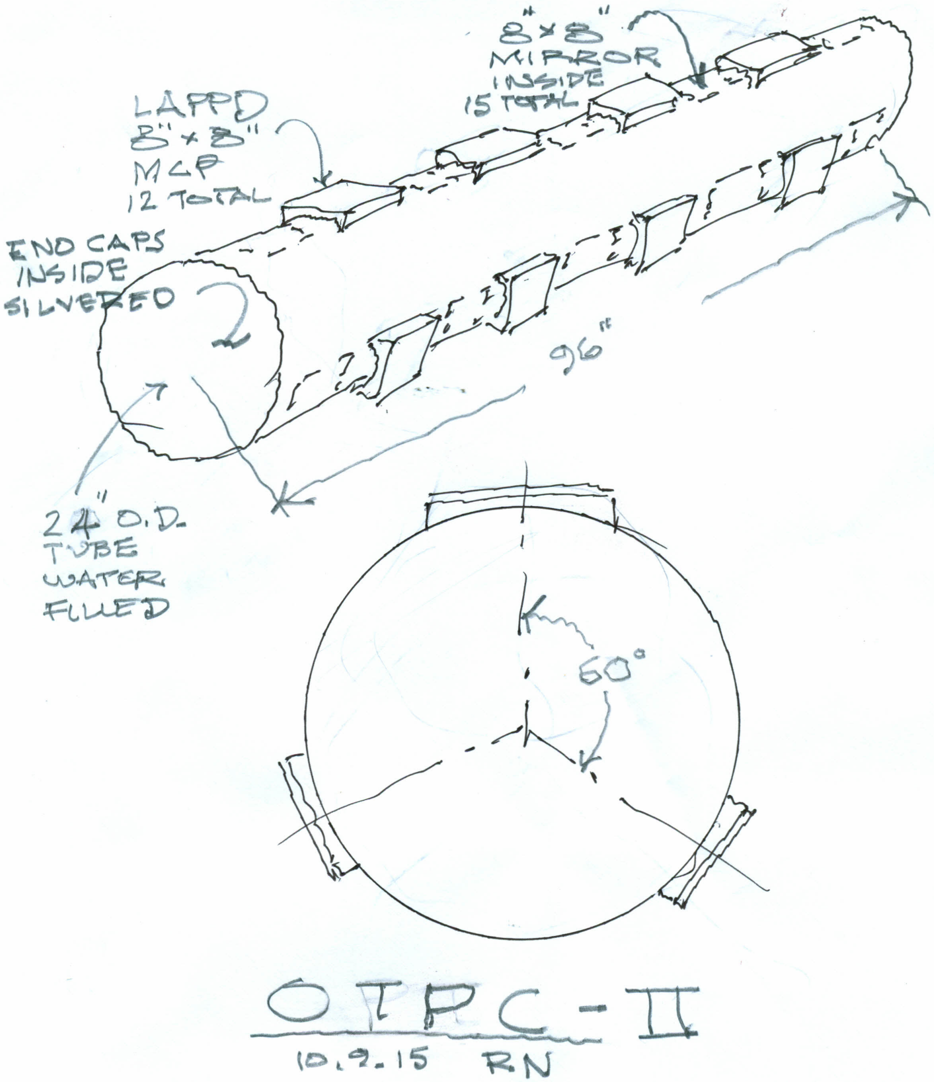
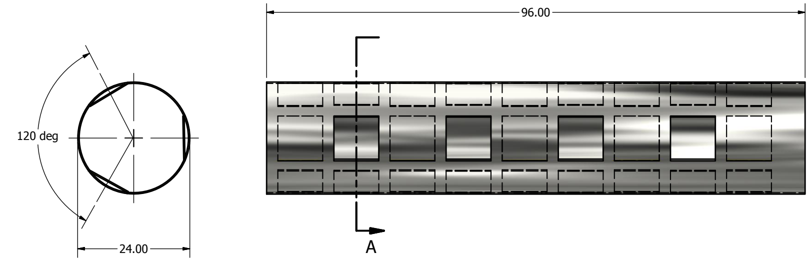
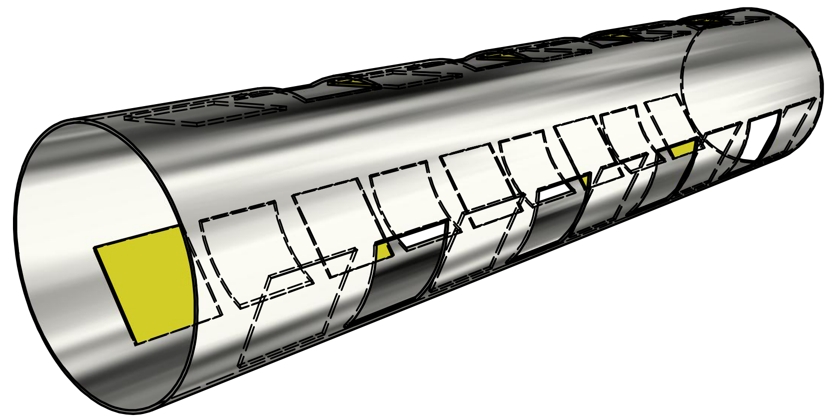
OTPC 2



8" x 8" MIRROR INSIDE 15 TOTAL
LAPPD 8" x 8" MCP 12 TOTAL
END CAPS INSIDE SILVERED
96"
24" O.D. TUBE WATER FILLED
60°
OTPC - II
10.9.15 RN



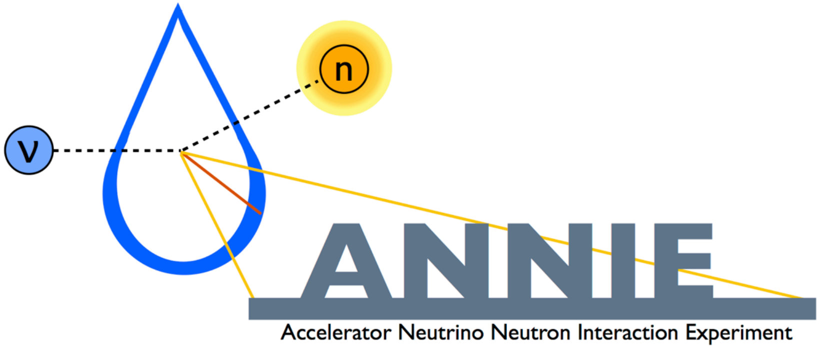
96.00
120 deg
24.00
A



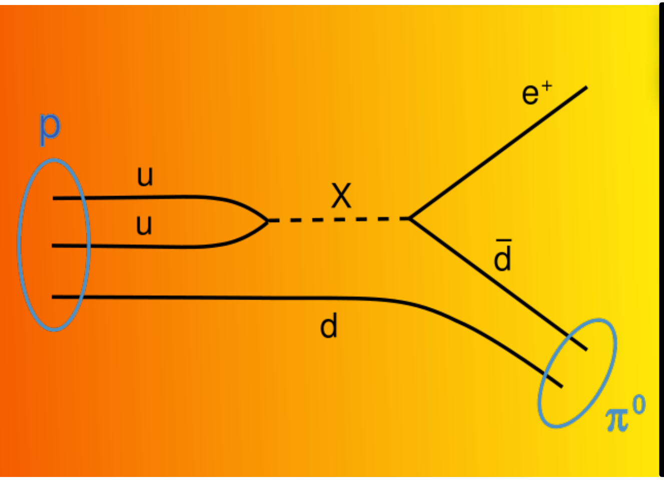
ANNIE Overview

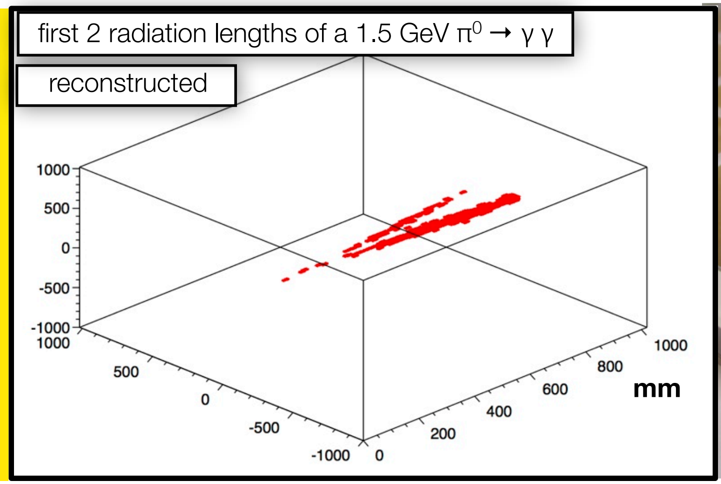
What is ANNIE?

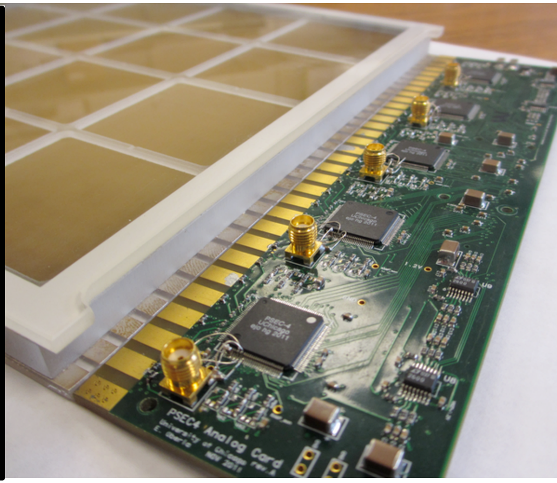
- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.



for understanding neutrino-nucleus interactions and addressing a limiting factor in proton decay and supernova neutrino physics





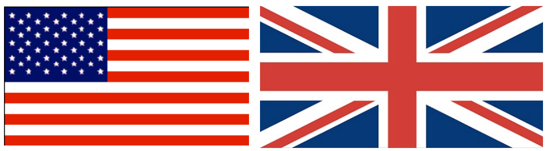


- A new technological path for the long-term Fermilab program
- A community that broadens the Fermilab user base

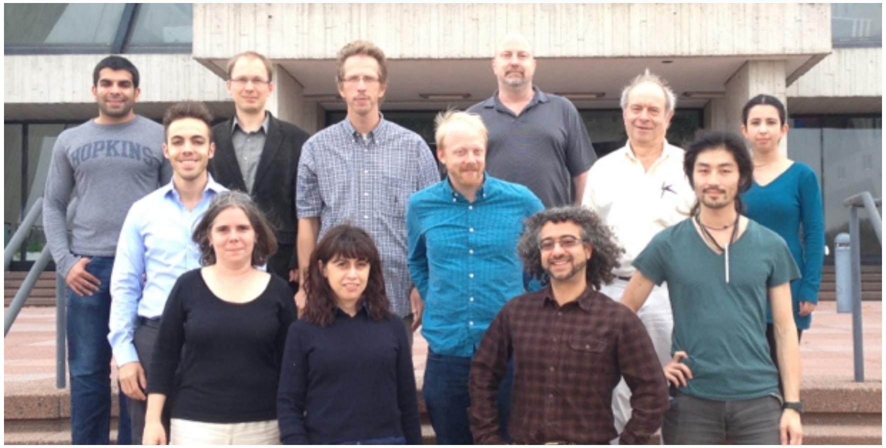
The Collaboration

34 collaborators

15 Institutions



- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- MIT
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine
- University of Chicago, Enrico Fermi Institute
- University of Hawaii
- Queen Mary University of London

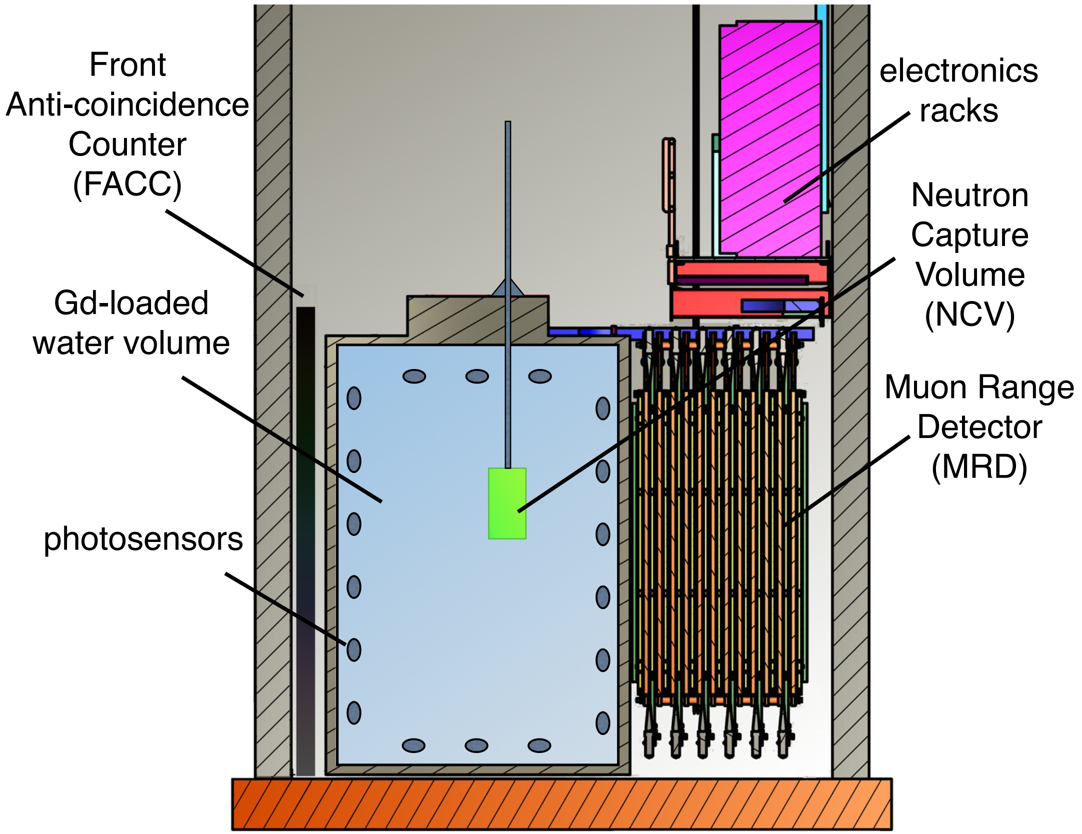


LAPPDs and ANNIE

ANNIE Run I is in the staging phase:

- will use waveform sampling electronics and test large PSEC systems
- we have a commitment from Incom for 20 LAPPDs in Phase II (10% forward coverage)
- first application of Gd neutron tagging in a high-E neutrino beam

ANNIE Details



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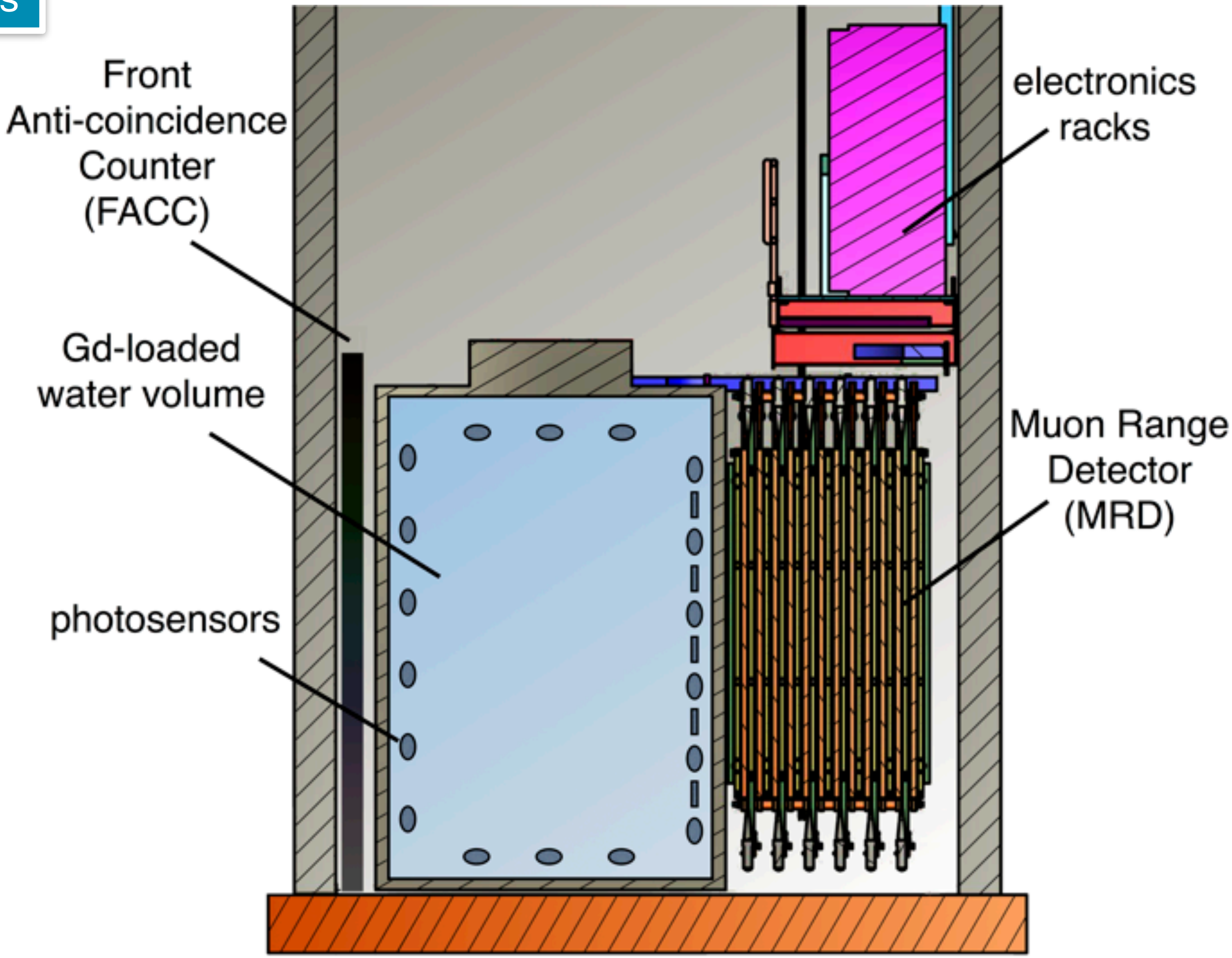

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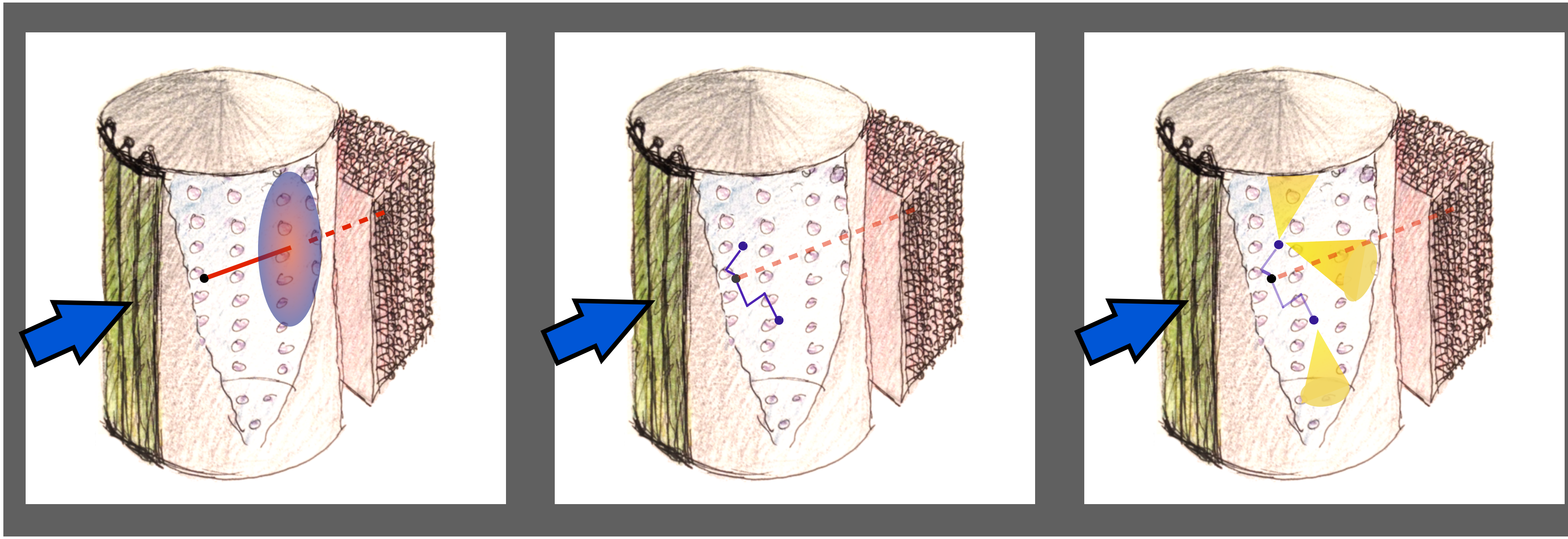
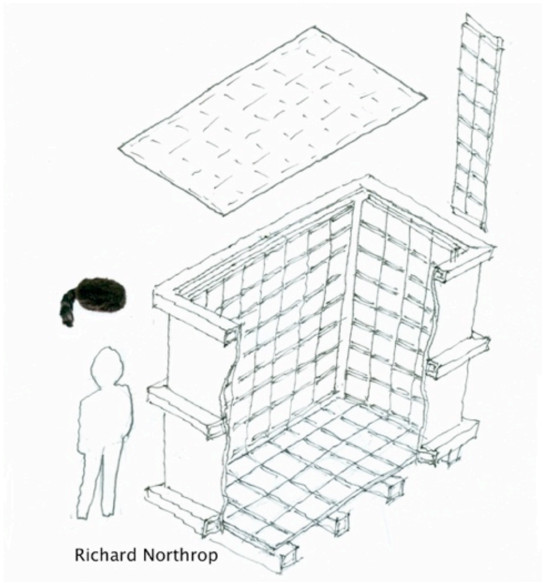
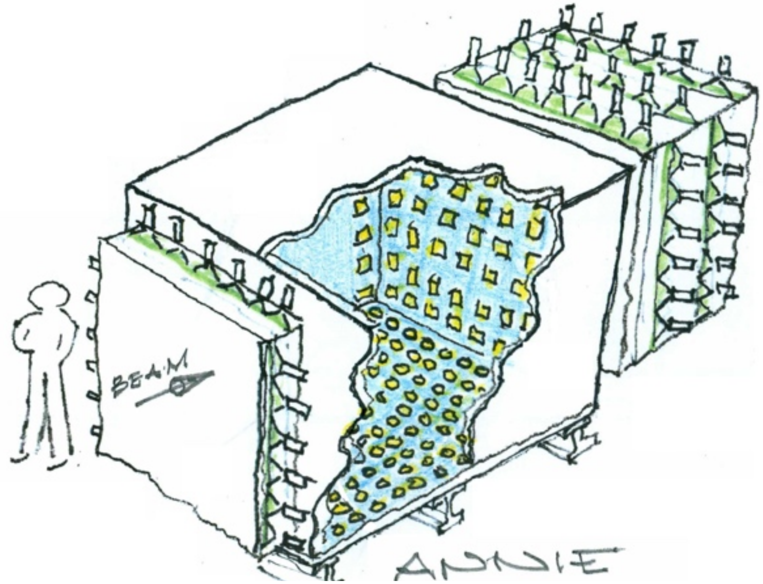
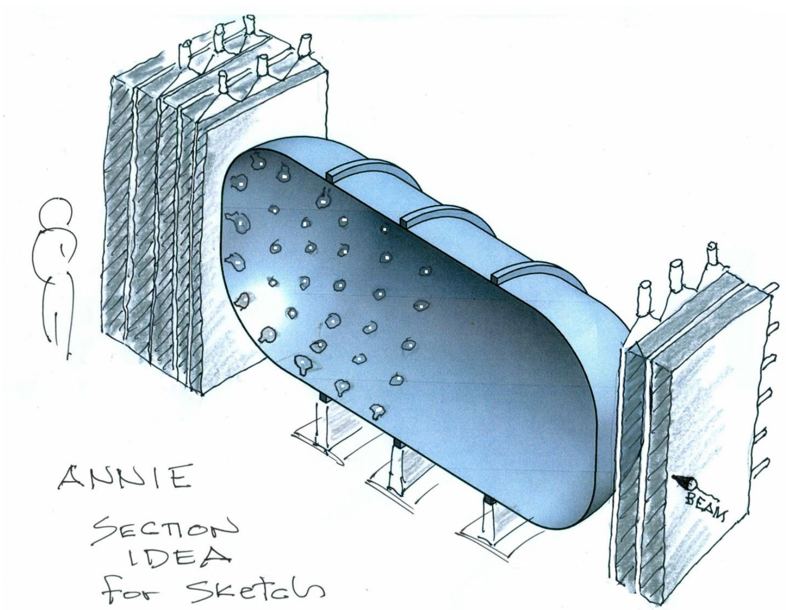
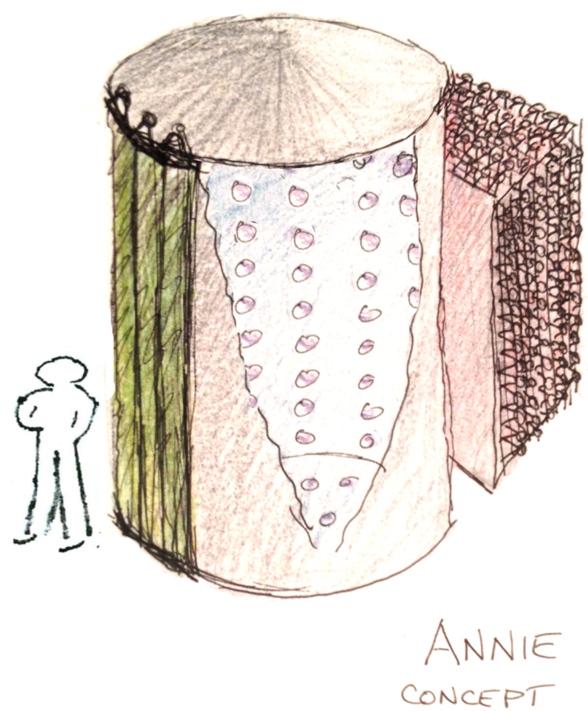



Richard Northrop


BEAM
ANNIE

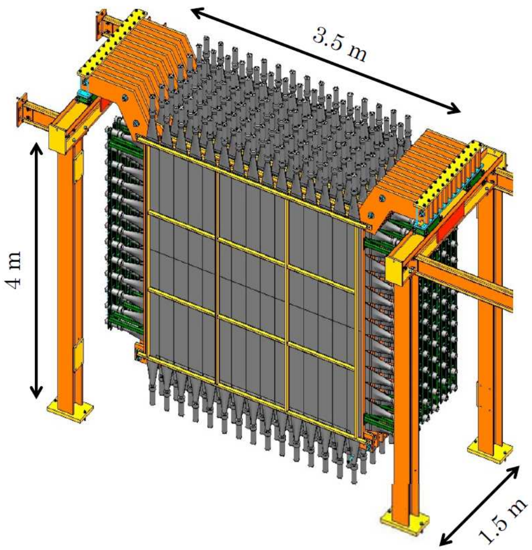

BEAM
ANNIE
SECTION
IDEA
for Sketch

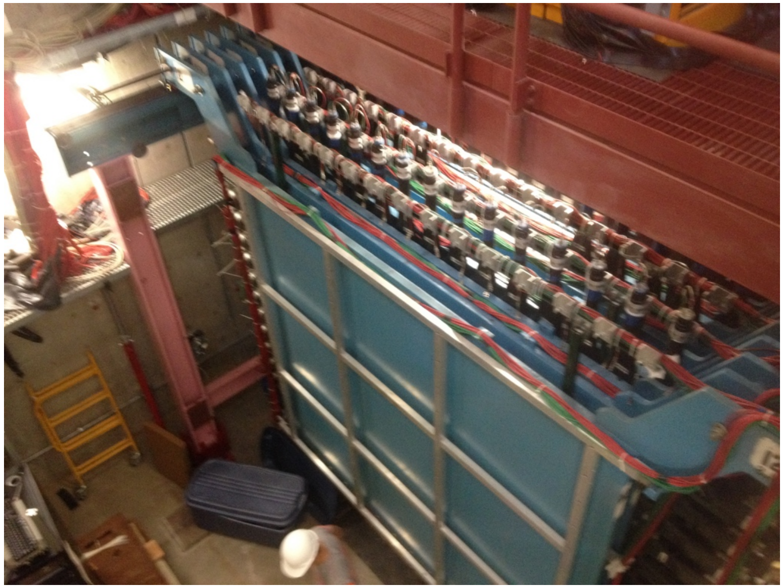

ANNIE
CONCEPT

ANNIE Forward Veto

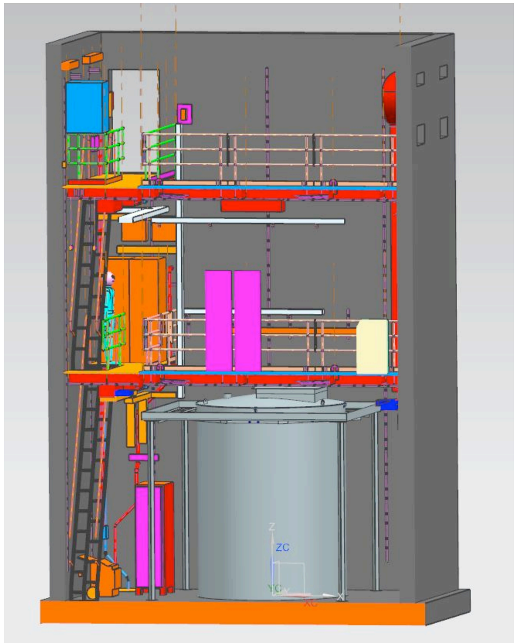
- Forward veto
- used to tag "rock muons"
- consists of reused CDF scintillator paddles
- assembled over the summer with student labor
- PMTs draw ~0.8 mA at full voltage

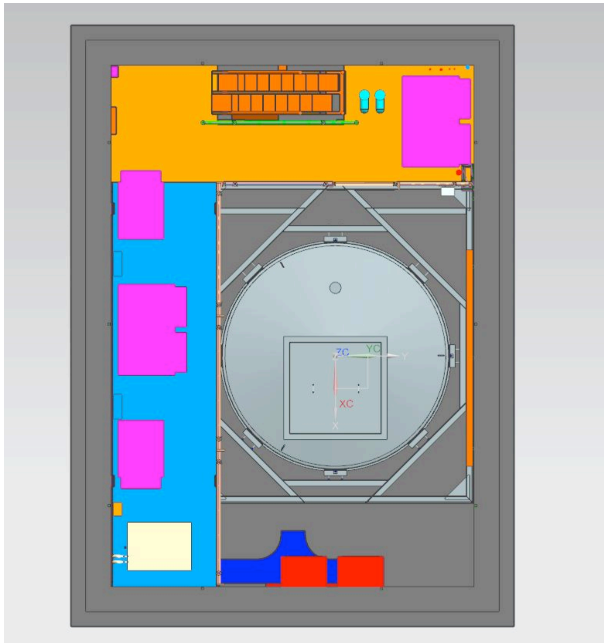
ANNIE MRD

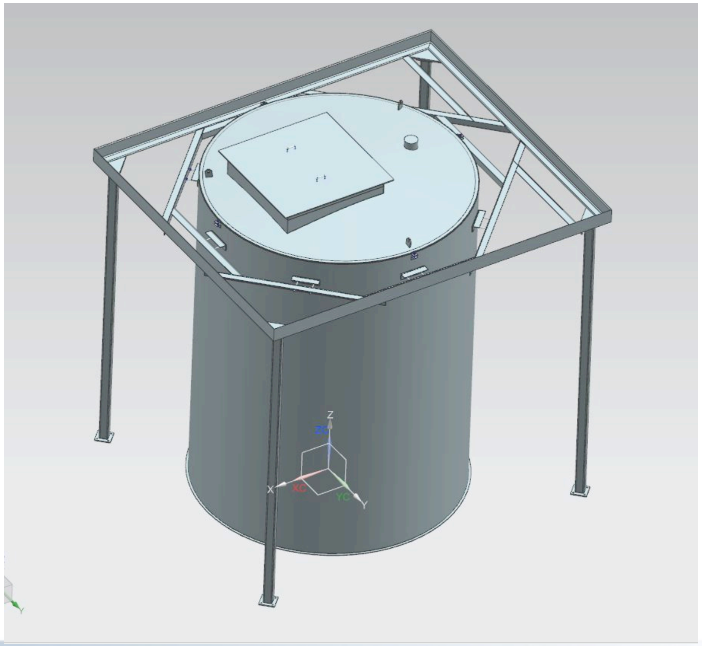




- Existing muon range detector (MRD) inherited from the SciBooNE experiment
- Steel and scintillator sandwich detector
- Some of the paddles have been removed
- FNAL to help ANNIE re-instrument the detector







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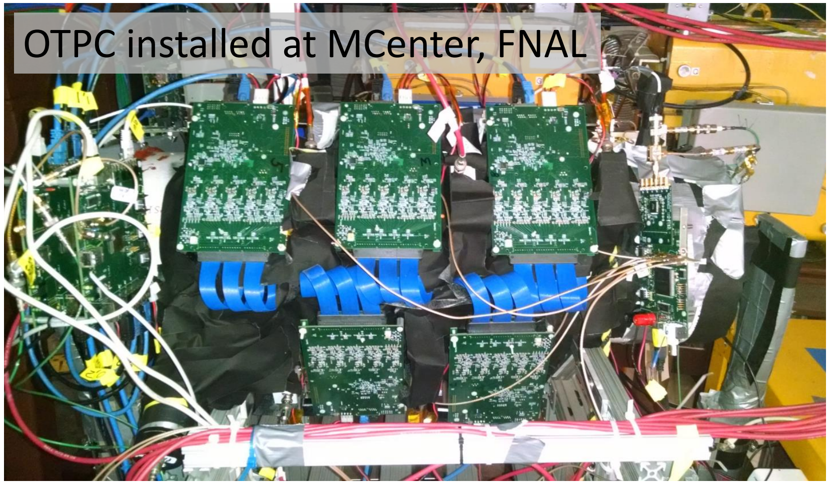

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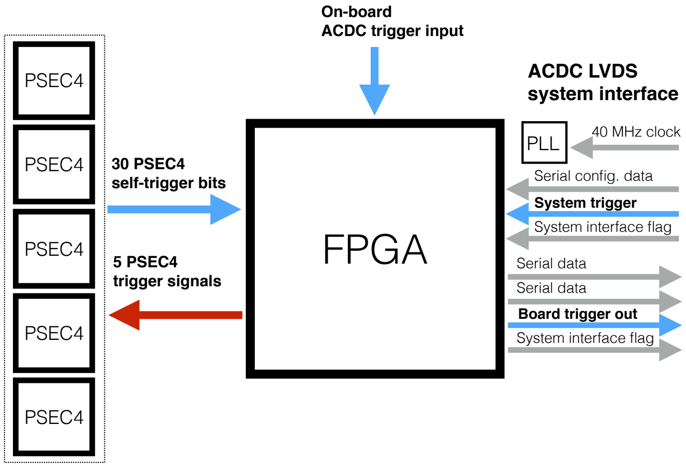

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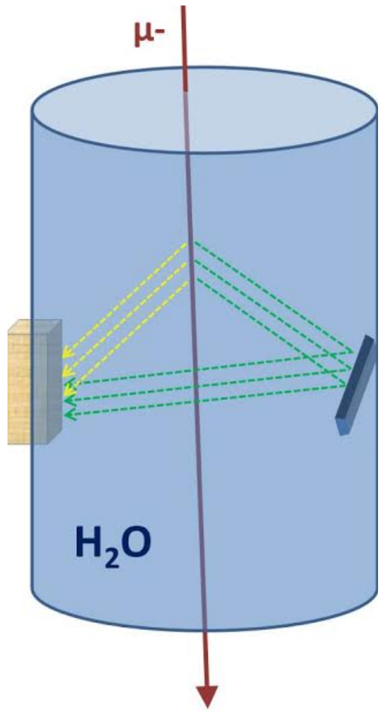

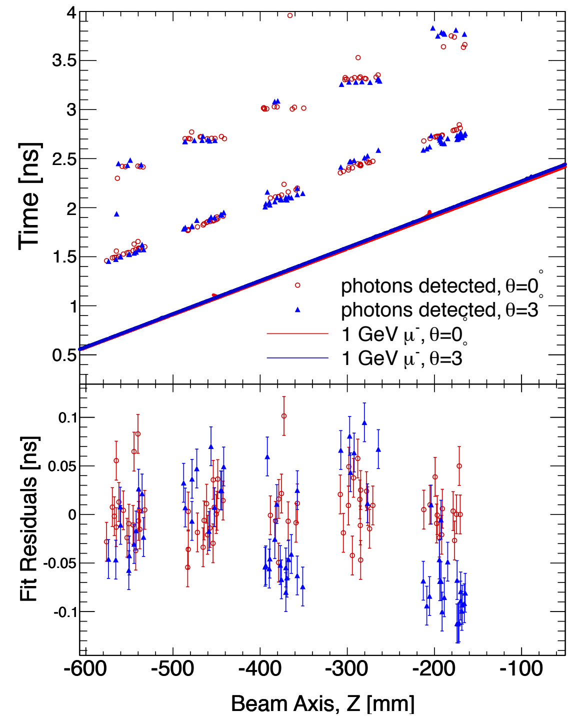

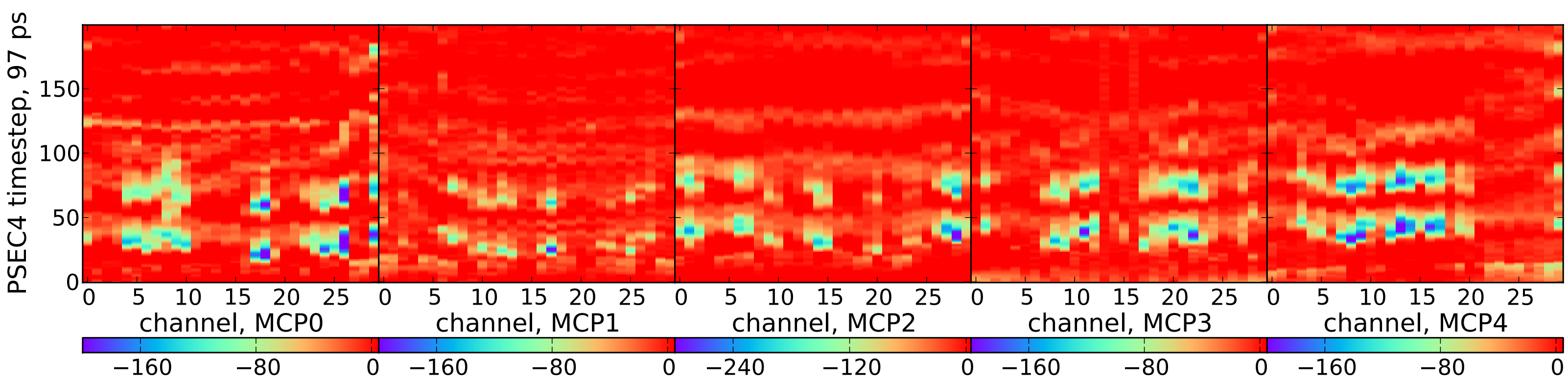

(a)

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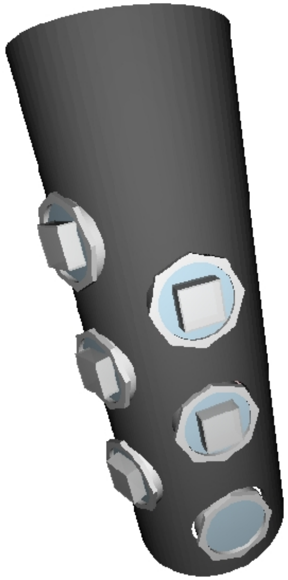

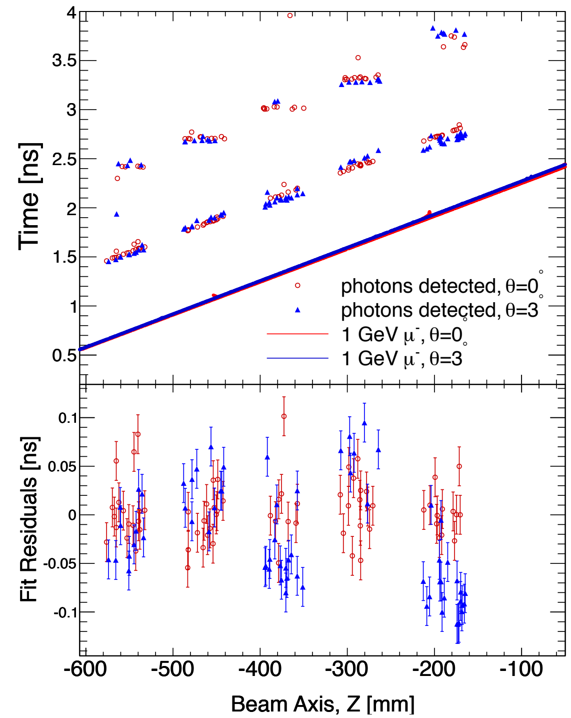

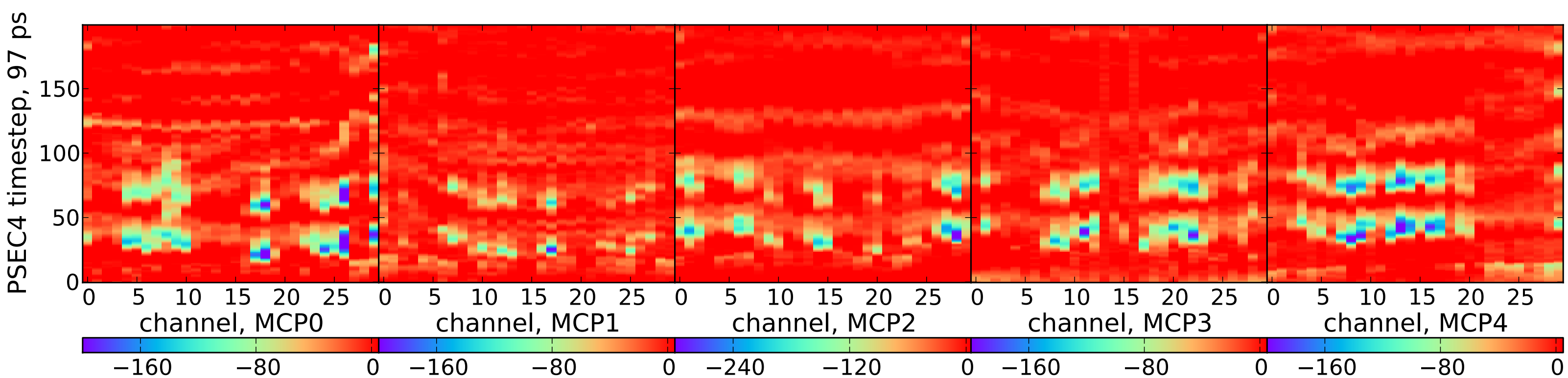

(a)

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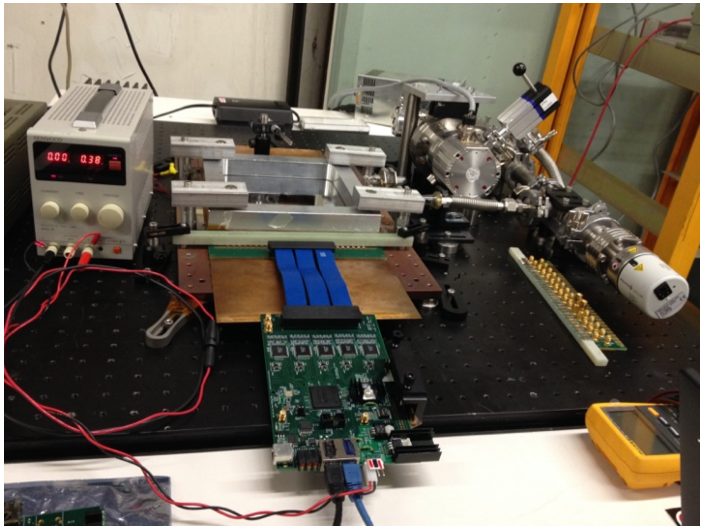

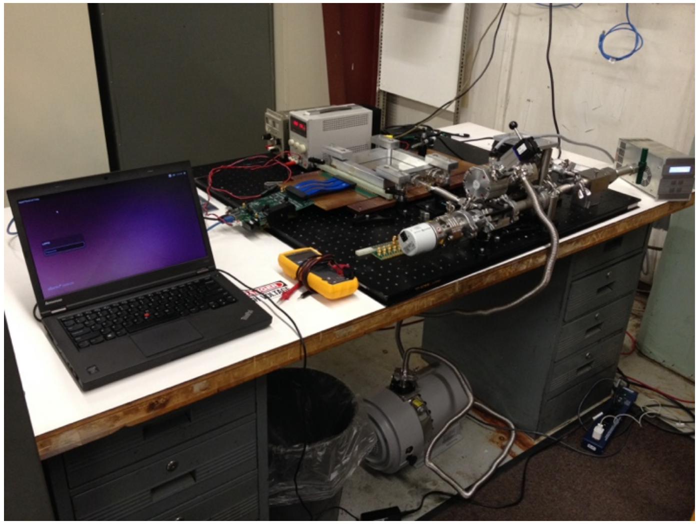

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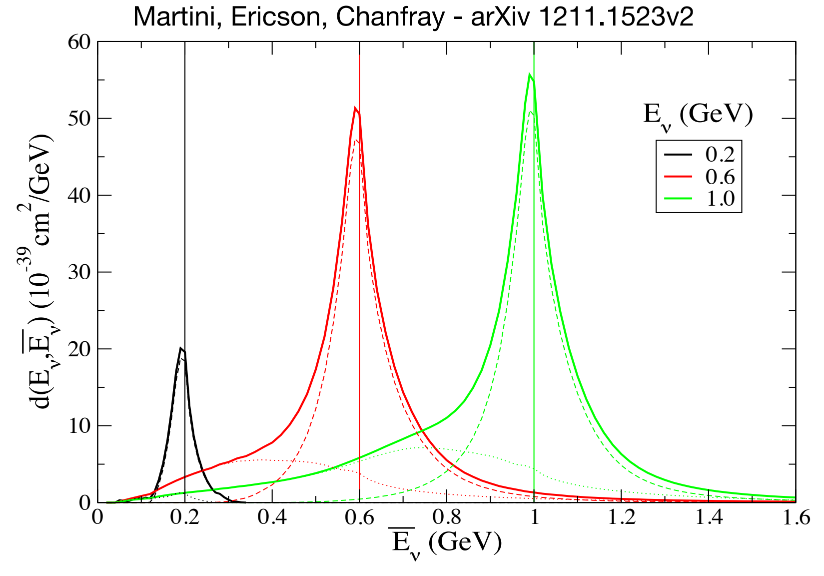
ANNIE Physics

How Do Neutrino's Interact With Nucleii?

To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions.

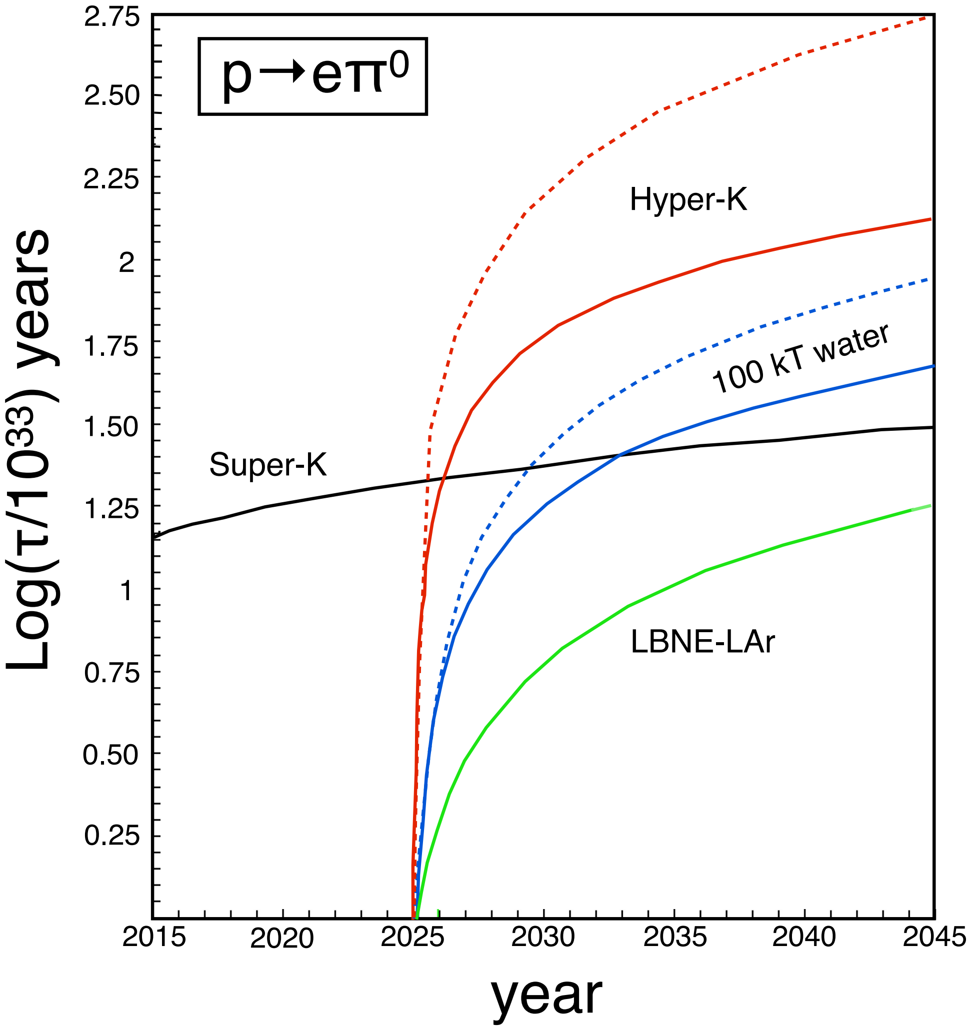
- Dominant source of systematics on future long baseline oscillation physics
- Source of uncertainty and controversy in short baseline anomalies
- We need comprehensive and precise measurement for a variety of targets/E_ν



ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

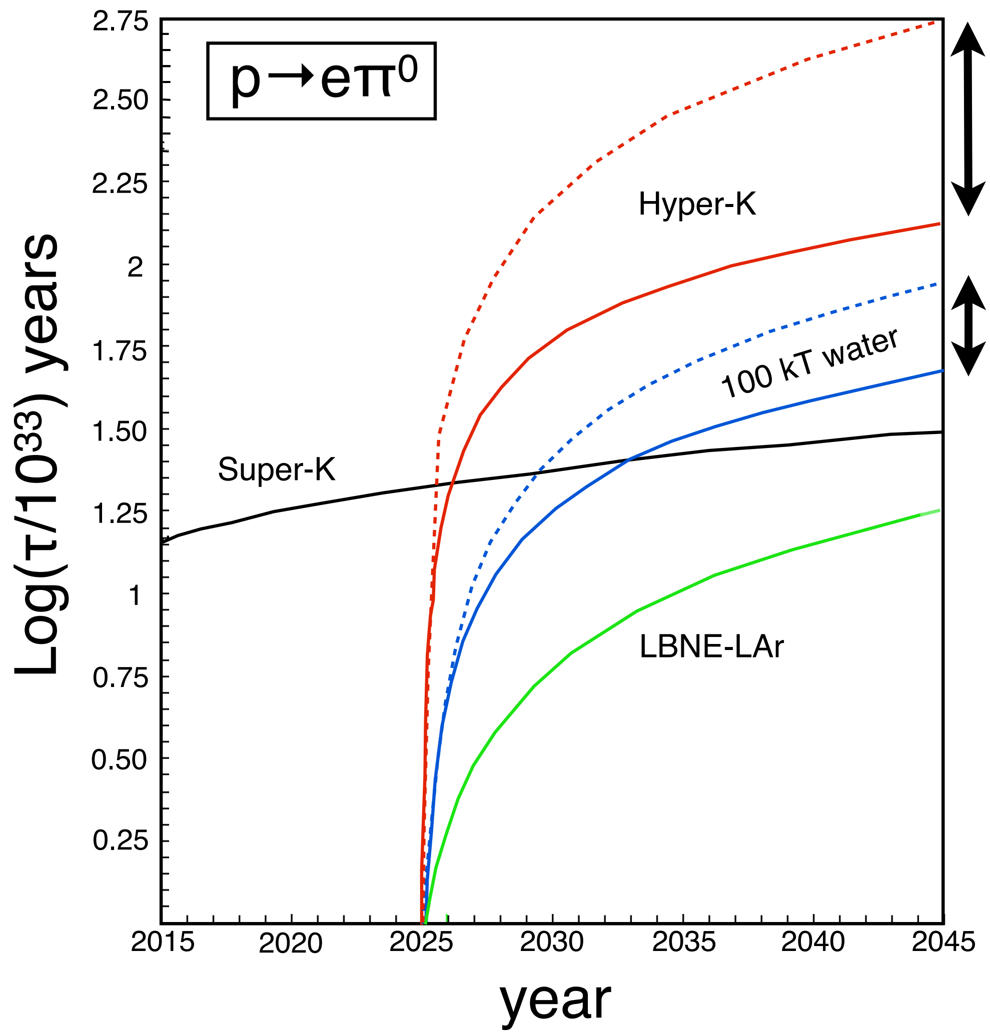
The presence, multiplicity and absence of neutrons is a strong handle for signal-background separation in a number of physics analyses!

Example from Proton Decay



- Next-gen proton decay (PDK) experiments will be background limited (from atmos. neutrinos)
- These backgrounds very often produce final-state neutrons, whereas PDKs rarely do
- The presence of neutrons detected with Gd-loaded water can be used to reject these. (Beacom and Vagins)
- We need data from a controlled beam experiment
- Fermilab can have a large impact on this P5 physics driver ("The Unknown")

Example from Proton Decay



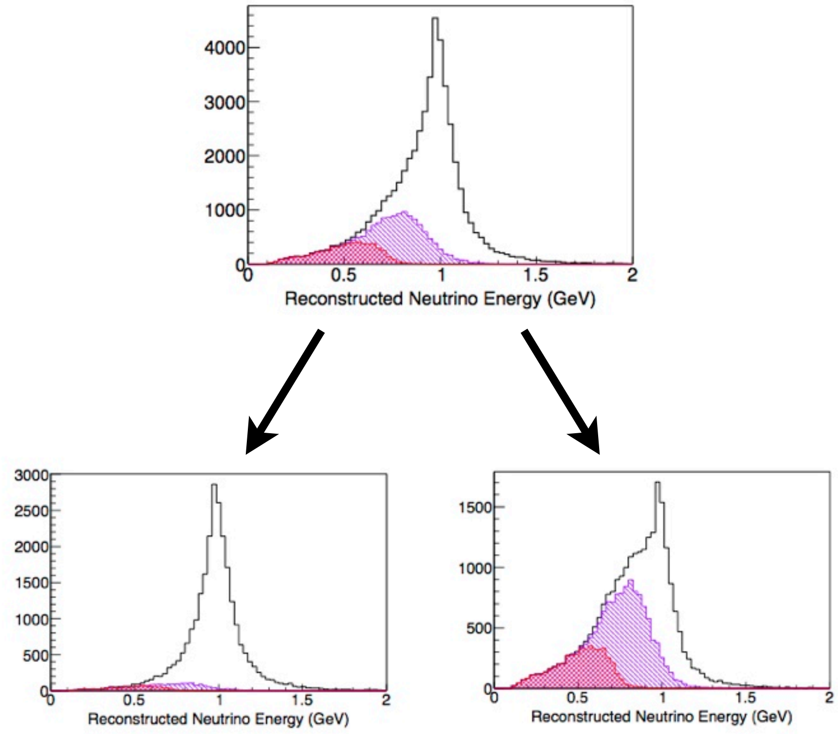
How much background does neutron tagging remove?

How much background does neutron tagging remove?

Background uncertainties are an even bigger problem if you have candidate events and want to attribute confidence.

ANNIE Physics

CCQE-like: final state muon + nucleons



no final-state neutrons   one or more FS neutron