Large Area Photodectors

M. Wetstein
U Chicago

Photodetector Systems

- Large Water/Scintillation Detectors
- TOF Systems
- RICH and DIRC
- Atmospheric Cherenkov Arrays

Photodetector Contexts

- Low Rate
- High Rate Detectors

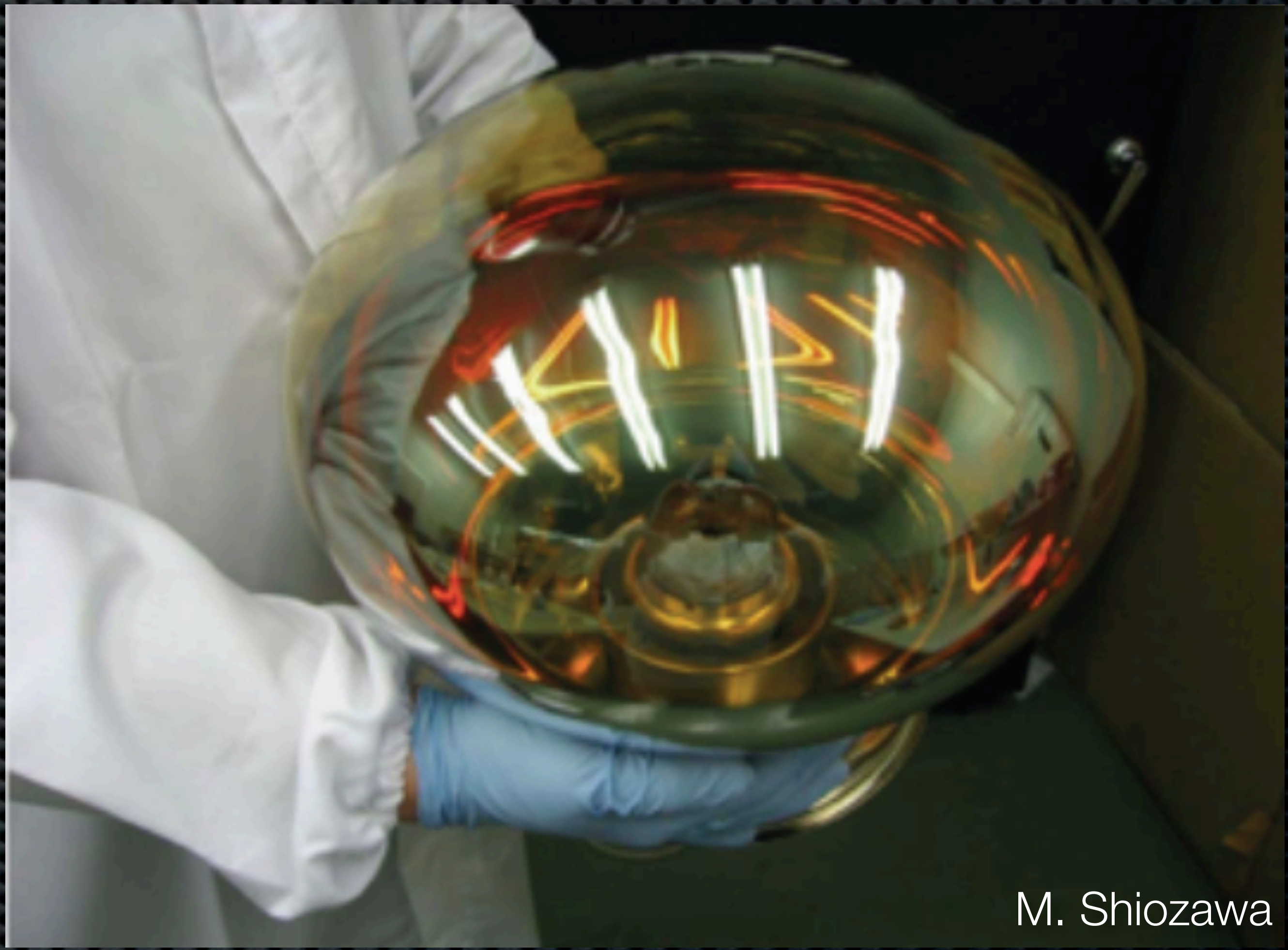
Needed Capabilities

- Cost Per Unit Area
- Imaging Capabilities
- Precision Timing
- Single Photon Counting
- Noise and Radiopurity
- Rate Handling
- Robustness
  - mechanical
  - low T
  - rad hardness

Photodetector R&D

Building your detector within the next few years

- All groups working on neutrino detectors have considered photodetector technology in the market at this time.
- Collaborations working on characterization and design of **larger/cheaper/more efficient photosensors**.
- Also working with Hamamatsu (sole manufacturer on many cases) on development of new options.



M. Shiozawa

Significant R&D work done/being done by LBNE, HyperK, Daya Bay II, LENA

Cost Per Unit Area

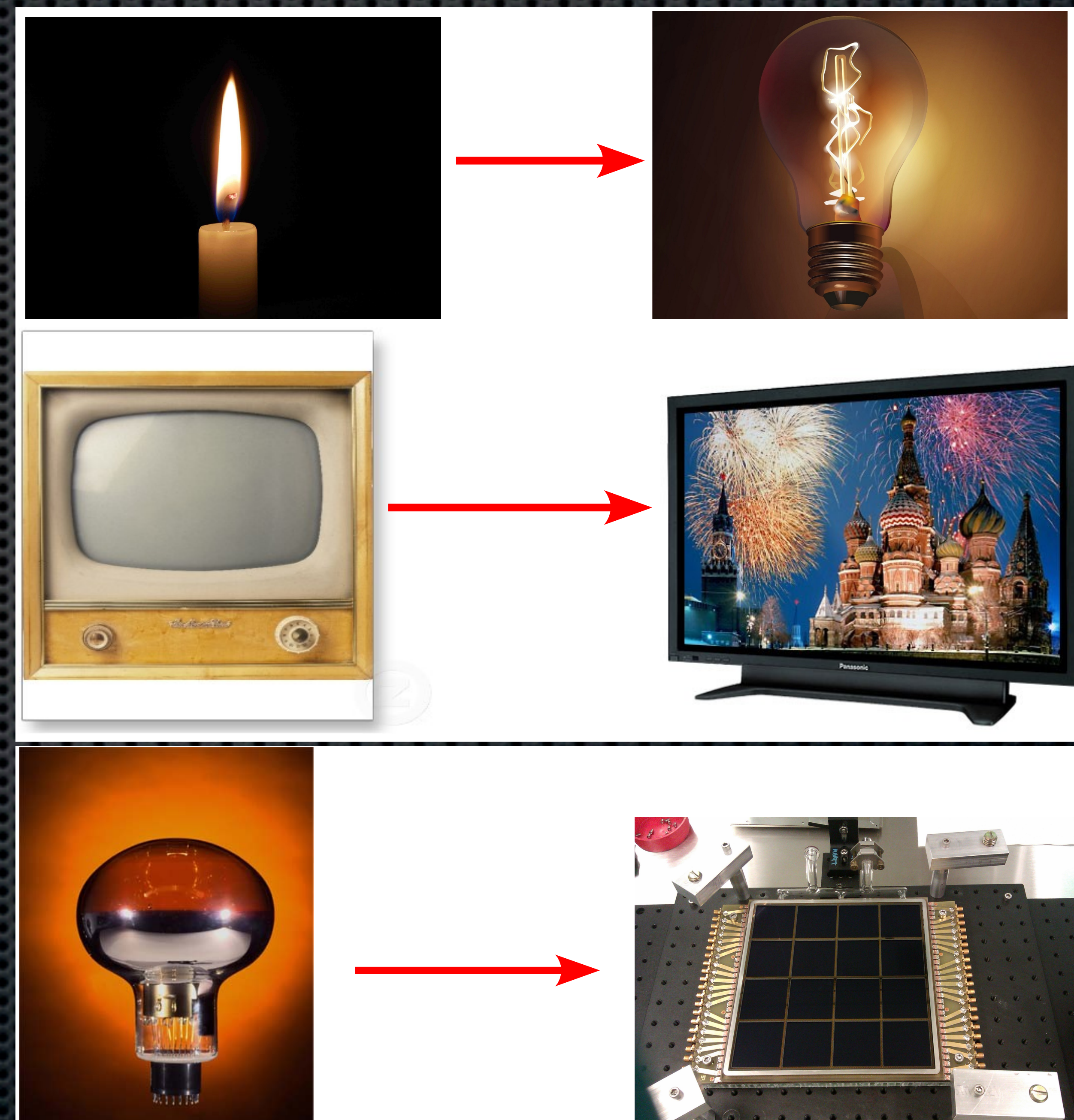
Photodetector

2012 R&D 100 50th ANNIVERSARY

generic

Building your detector in the next decade

- **Large-area picosecond photodetectors (LAPPD)** based on microchannel plates are being developed at Argonne National Laboratory in close collaboration with universities, other labs and private companies.
- For a **neutrino application**, these could be tuned to:
  - Timing resolution of **~100 psec** (order of magnitude improvement)
  - Spatial resolution of **~1cm**
- Alternatively, worse timing/less spatial resolution could be a lower price.



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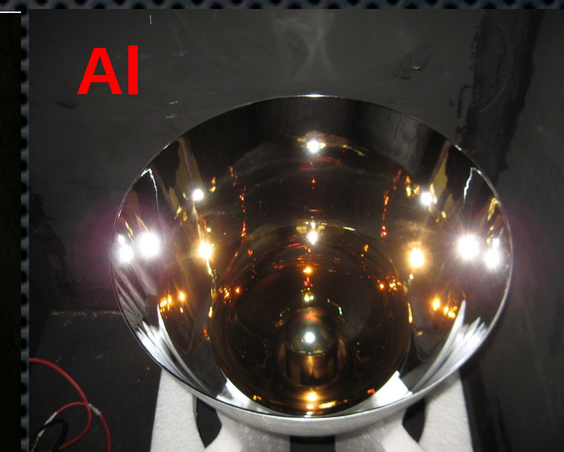
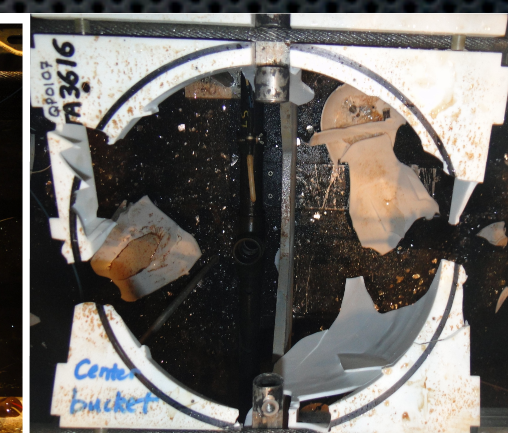
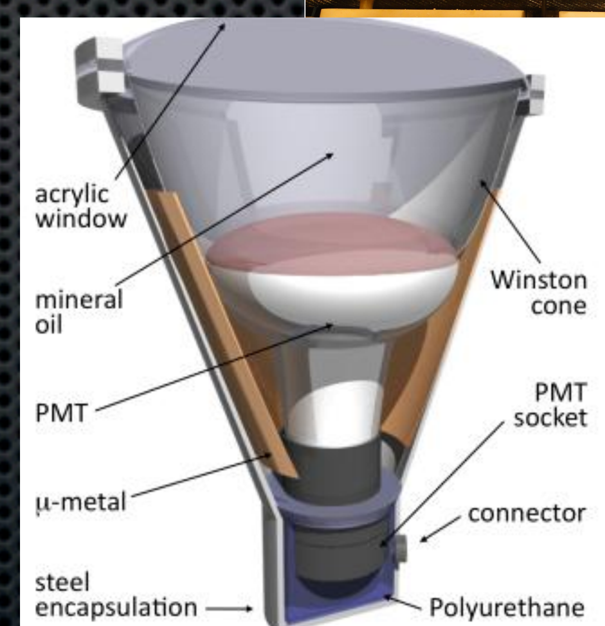
Cost Per Unit Area

Photodetector R&D for LBNE/LENA

- Reduced number of phototubes requires additional light collection technologies:
  - Winston cones and Wavelength shifting plates R&D done by Drexel and Colorado State groups for LBNE.
- Phototubes in large detectors are subject to high pressure environment.
  - Testing program has been completed at NUWC by Brookhaven for LBNE.
  - Up to 300 psi.
  - Designed housing.
- Other studies include glass R&D.
- **LENA has similar process of characterization and design.**

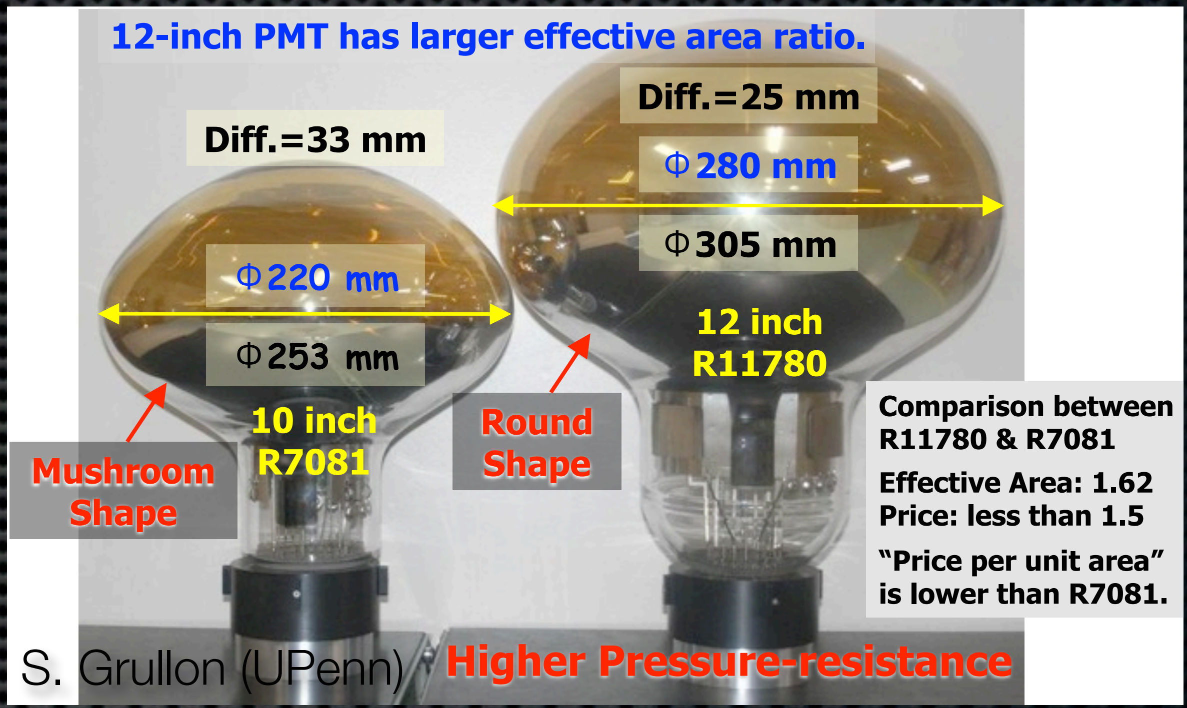






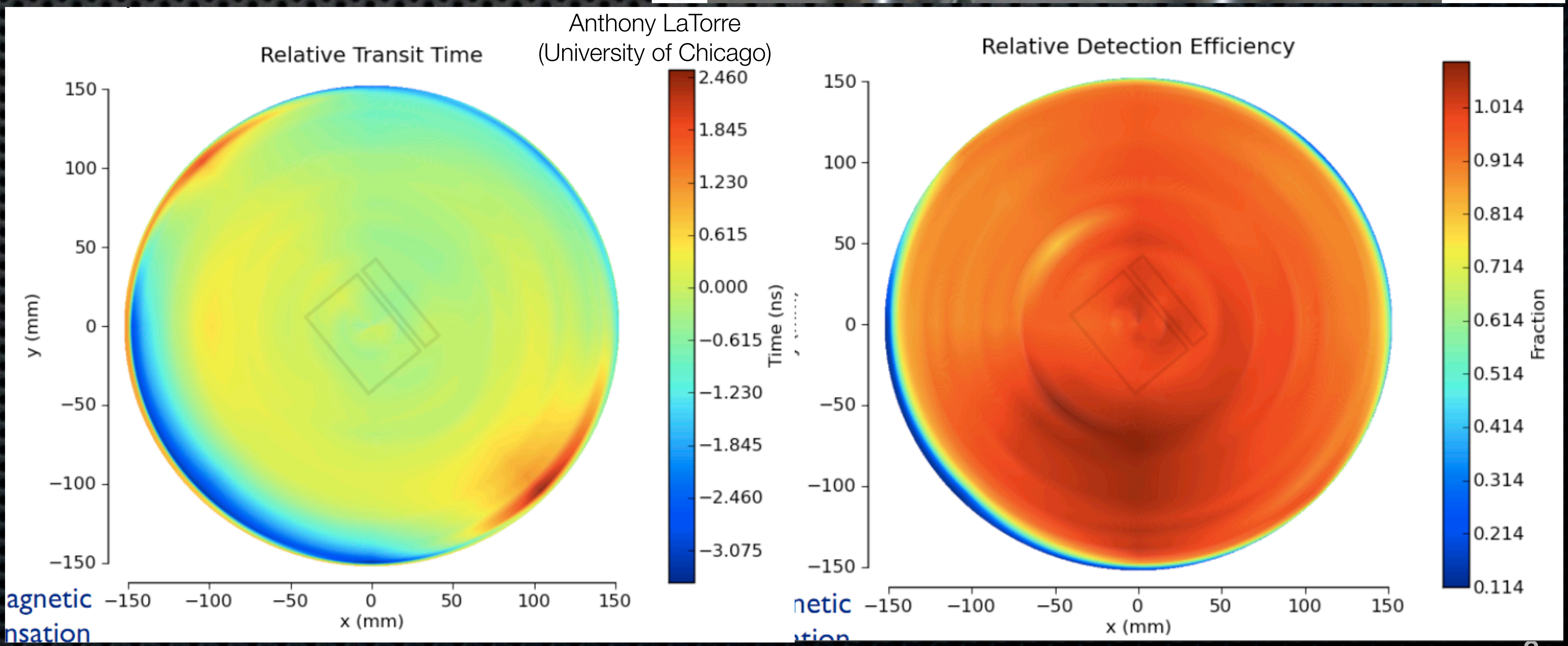
Photodetector R&D for LBNE

- 12-inch photomultiplier tubes (Hamamatsu R11780) were chosen for LBNE Water Cherenkov design.
- Detailed characterization work done by the UPenn group for LBNE shows transit times varying by as much as 3ns face of detector.
  - Need changes to dynode structure.



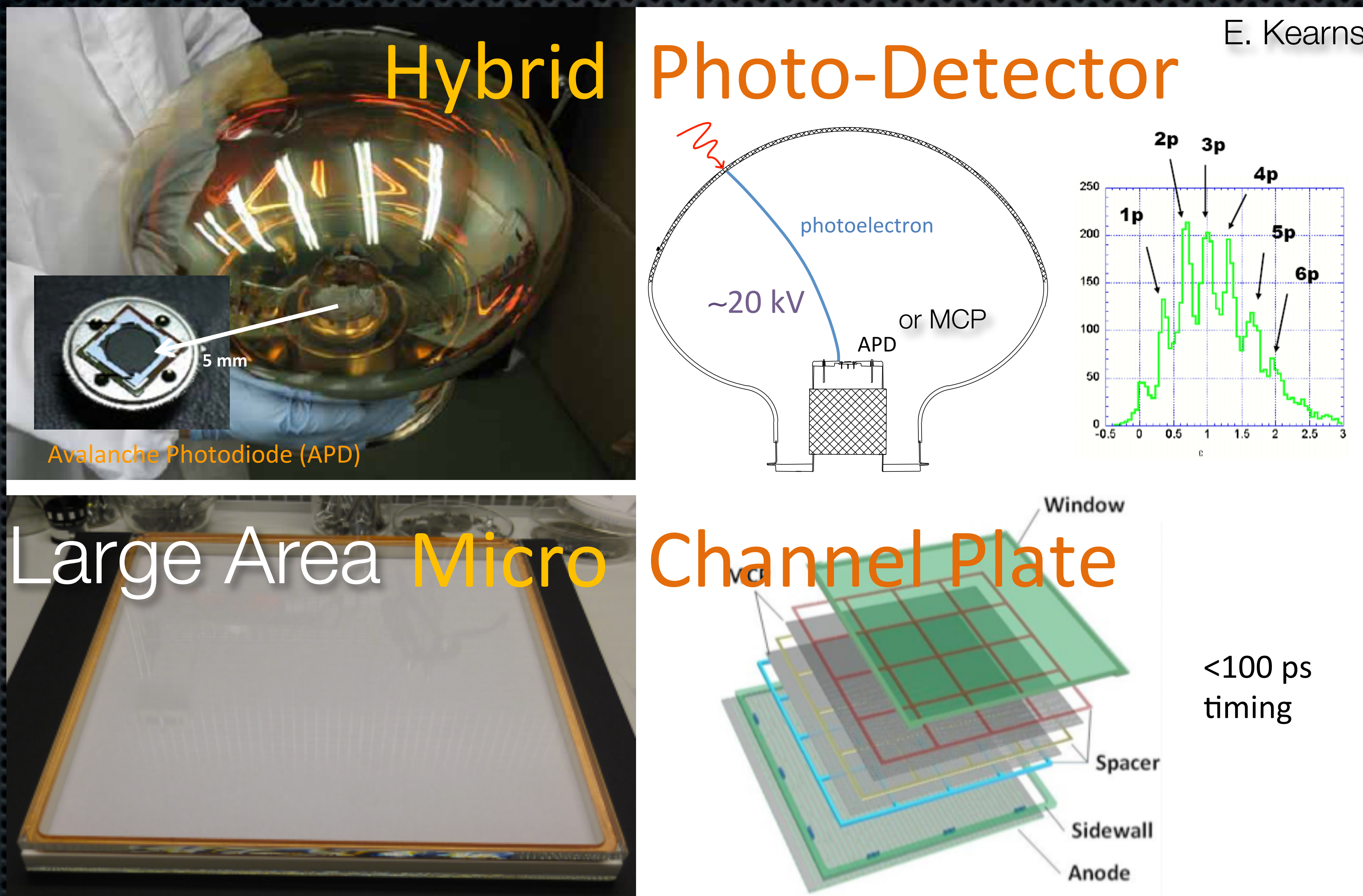
- **Timing resolutions ~ 1-2 ns.**
- **QE 21 & 32% available.**
- NIM paper describing characterization:

  arxiv:1219.2765



Photodetector R&D

Building your detector within this decade



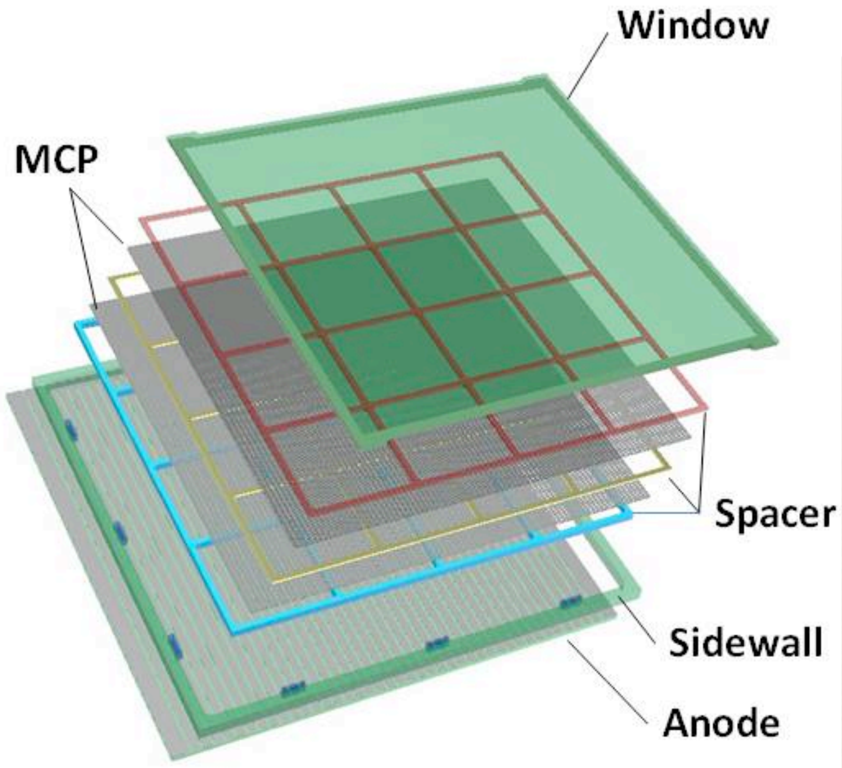
Large-Area Photodetector options

Photodetector R&D for Hyper-K

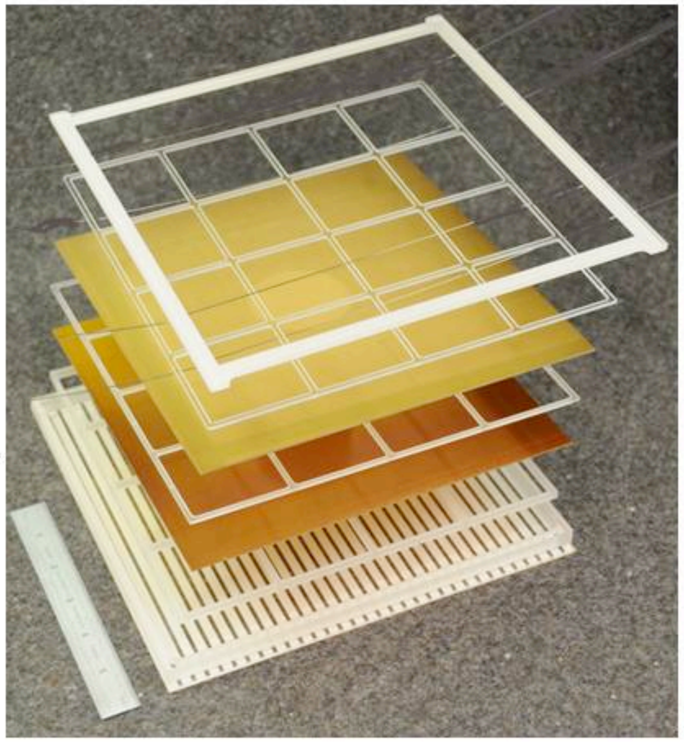
- Hyper-K planning to use either:
  - 20-inch hybrid photodetector (HPD) or a 20-inch improved PMT provided by Hamamatsu.
- **Expected production time for 99K photosensors is 4 years.**
  - The R&D projected time is about the same!

M. Shiozawa/ T. Nakaya

What is the LAPPD Concept



Design Drawing - September 2010



Actual Glass Parts - April 2012

The Frugal Tile

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

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

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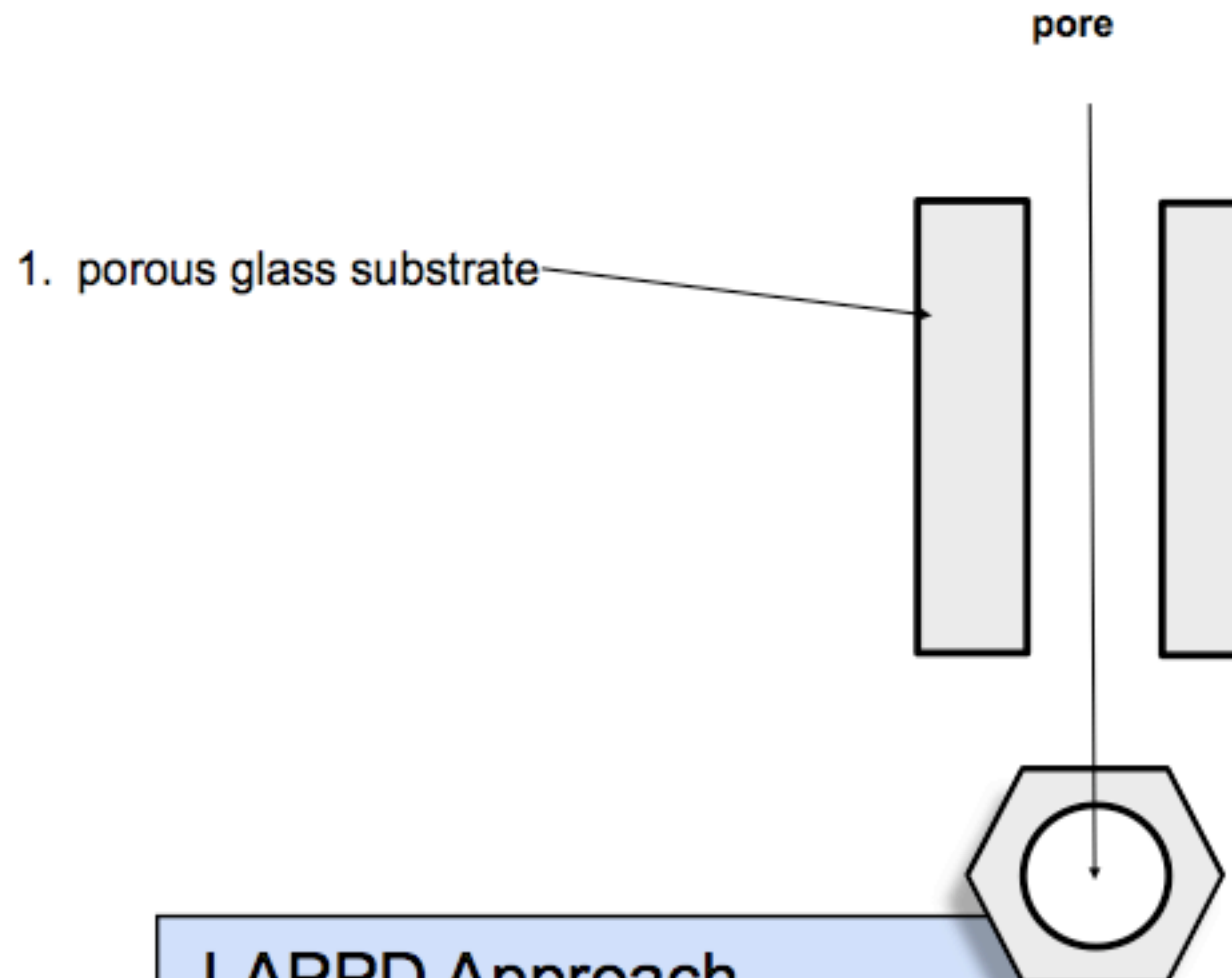

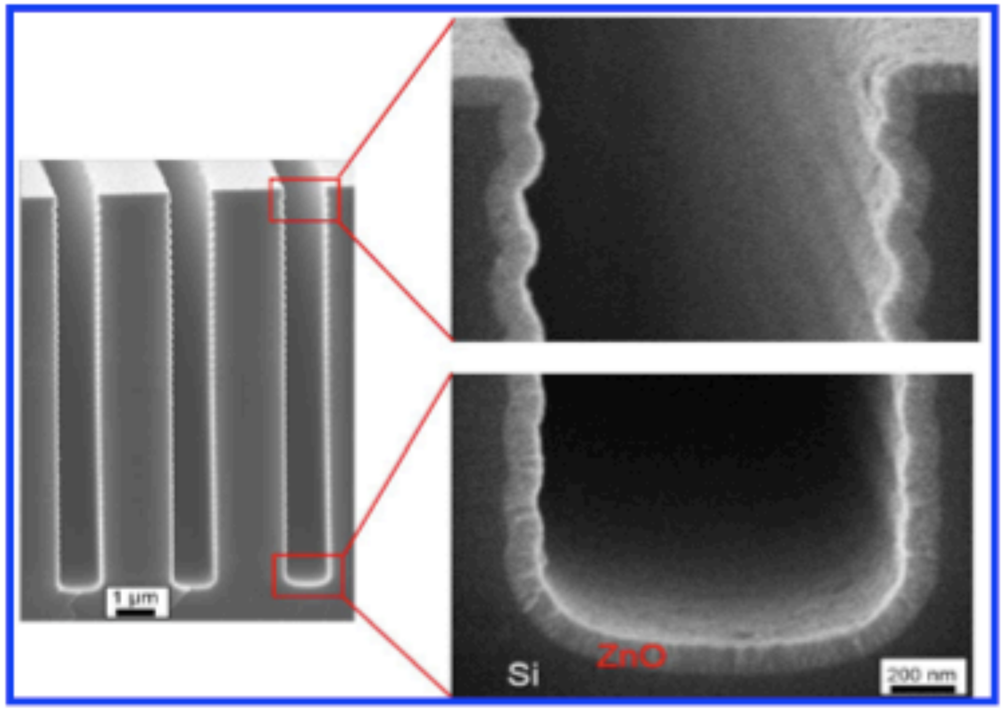

LAPPD Approach

- 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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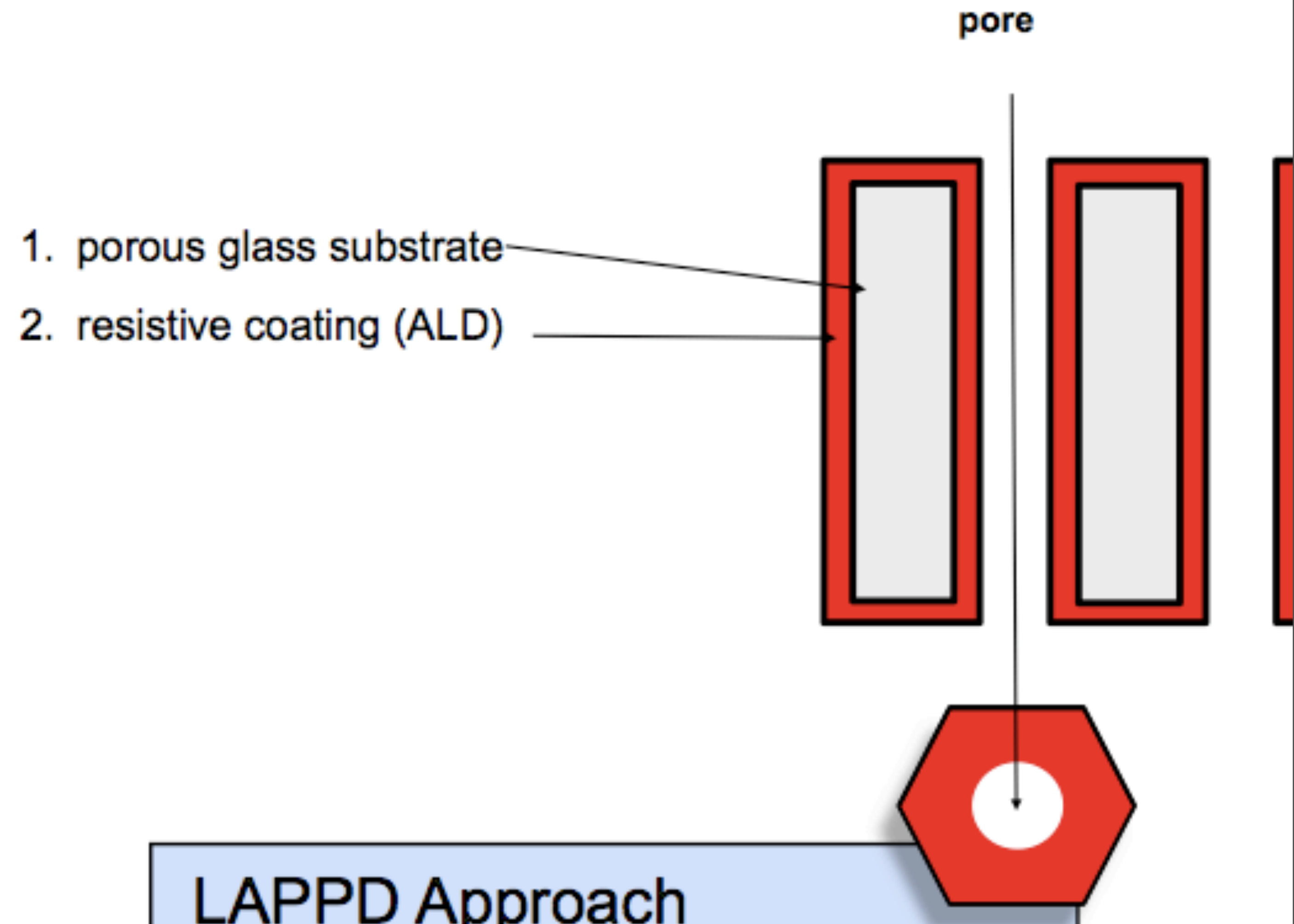

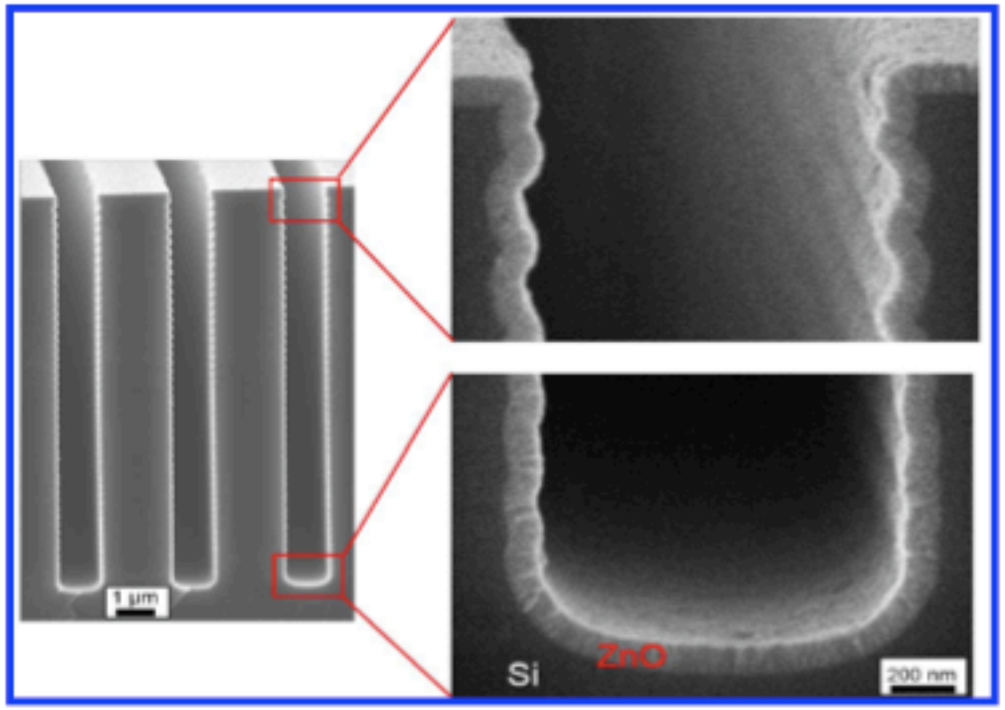

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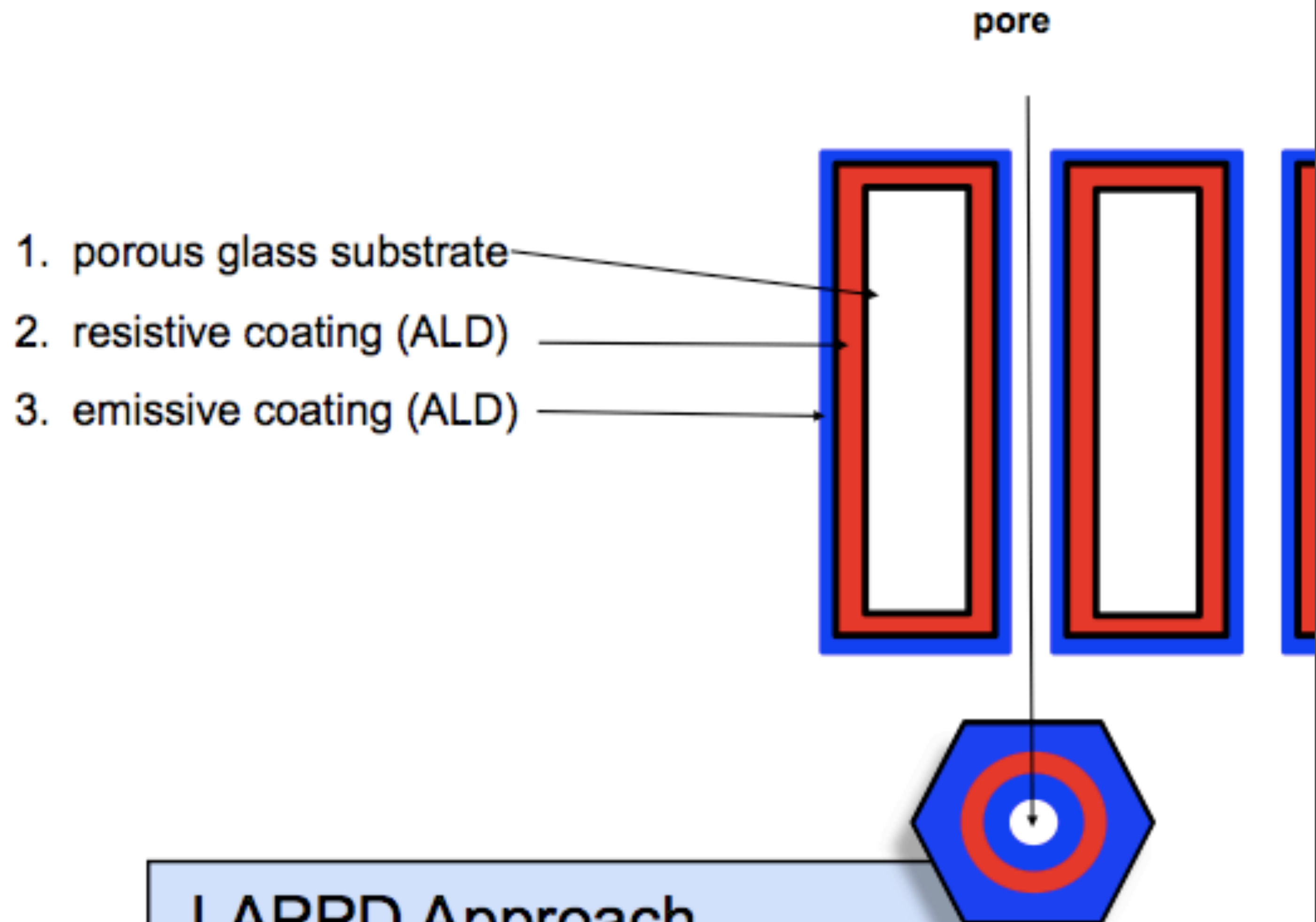

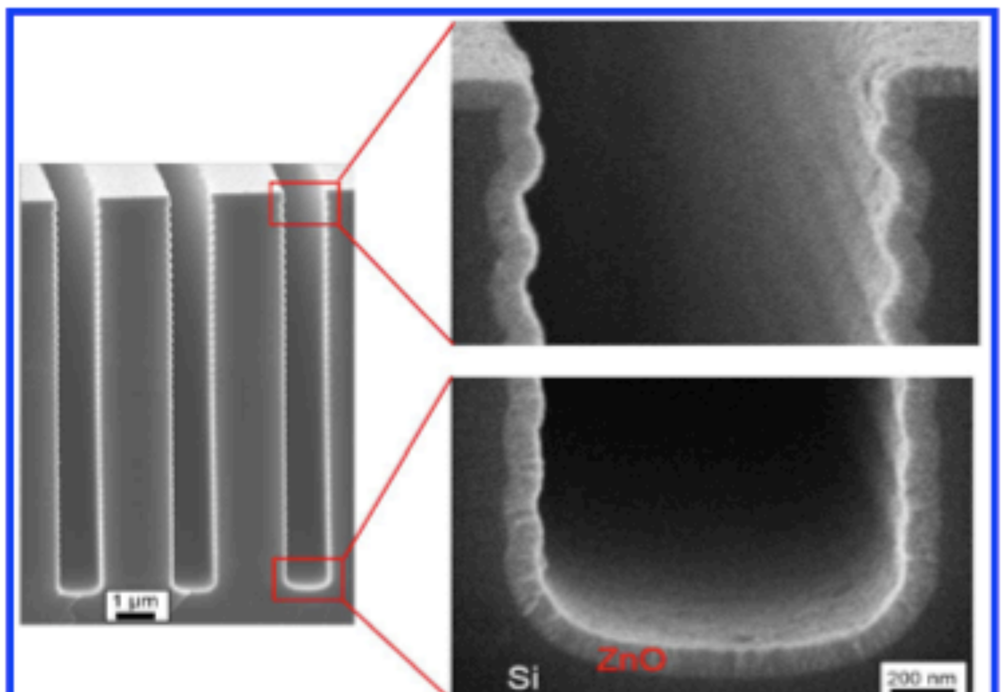

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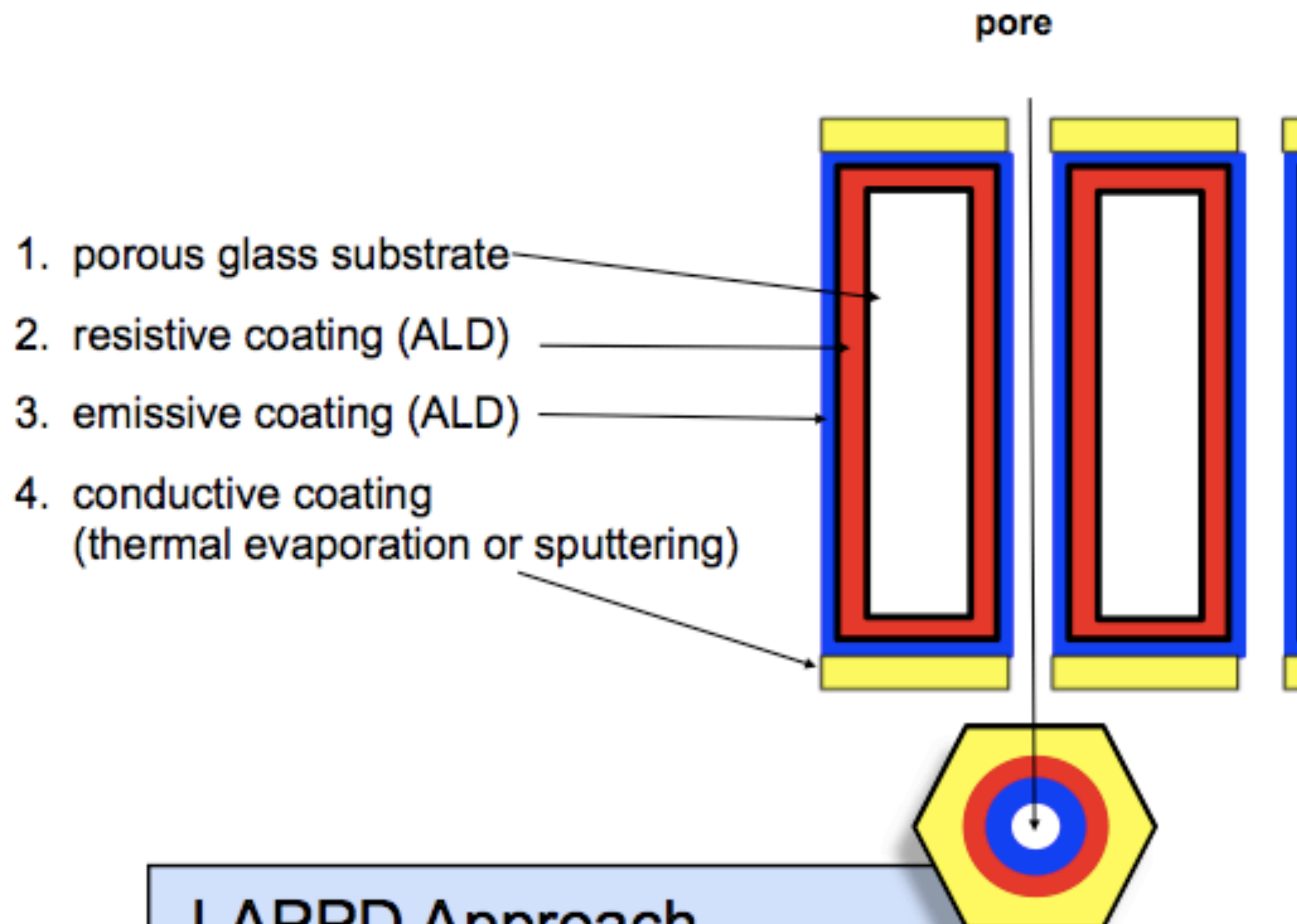

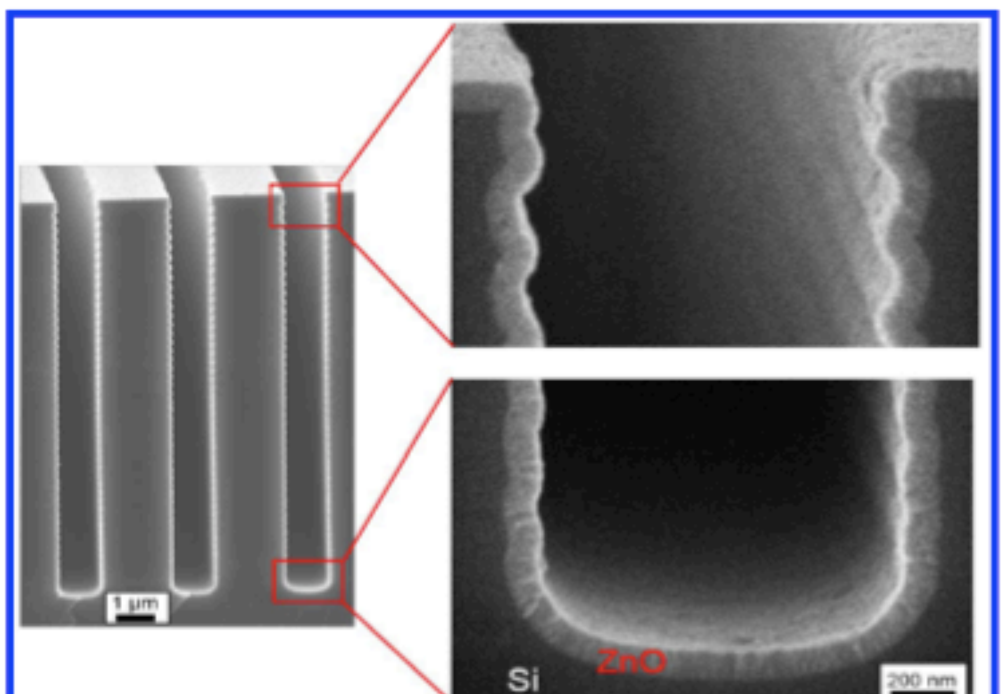

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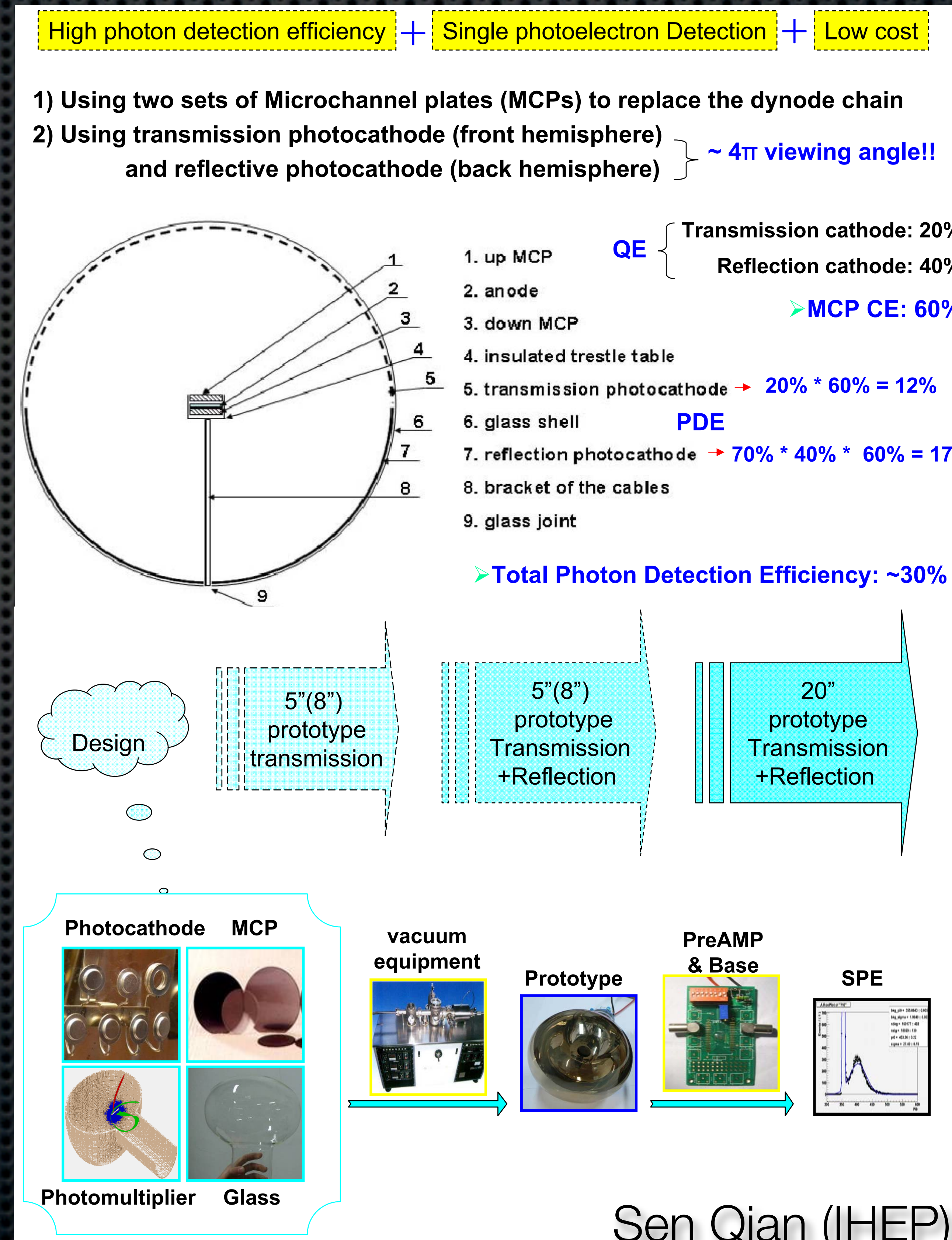
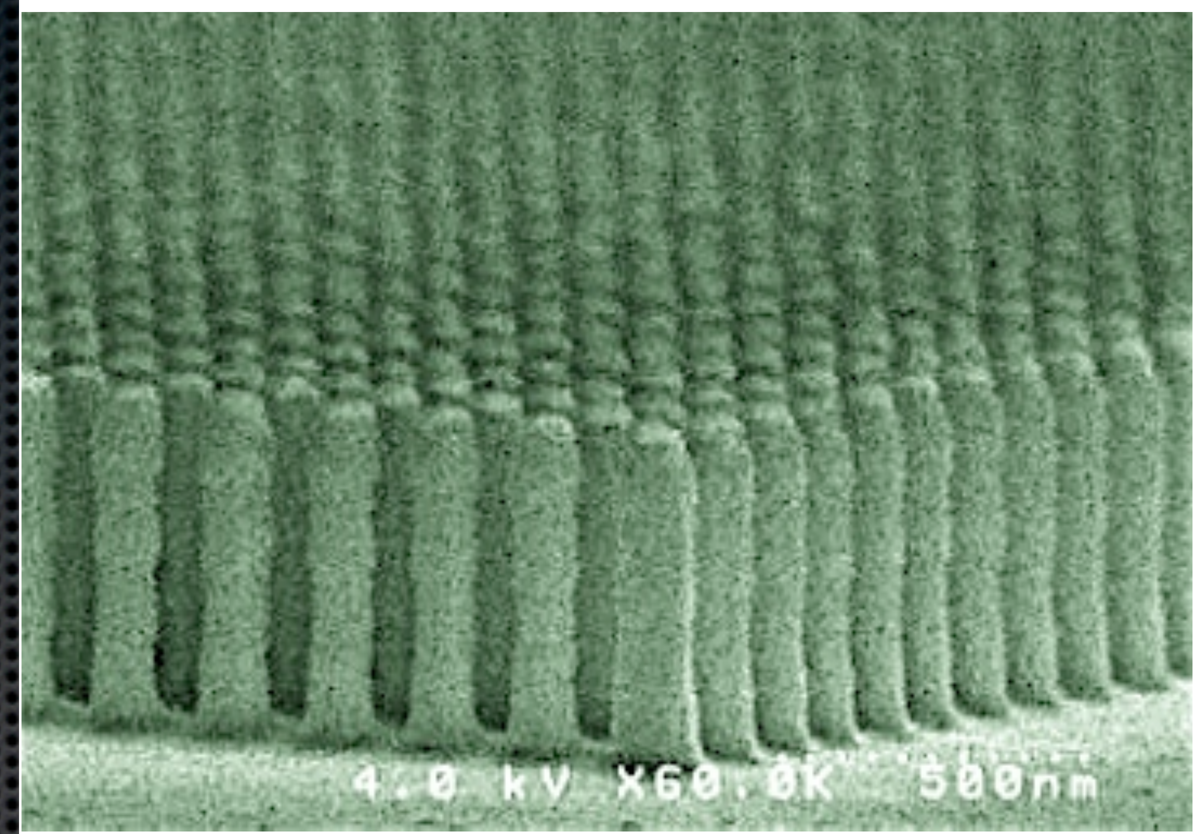
Photodetector R&D for Daya Bay II

- Daya Bay II is looking at 15K 20” PMTs for an optical **coverage of 70-80%**. Possibly combining with 8” PMTs with better timing.
- Options:
  - 20” UBA/SBA photocathode PMT from Hamamatsu QE 35-43% (does not exist?).
  - **Design new hybrid PMT.**
- Use MCPs and trasmission/reflective photocathodes to improve photon detection efficiency by x2.
- Obtain cheap (rejects) MCPs from night vision goggle industry.



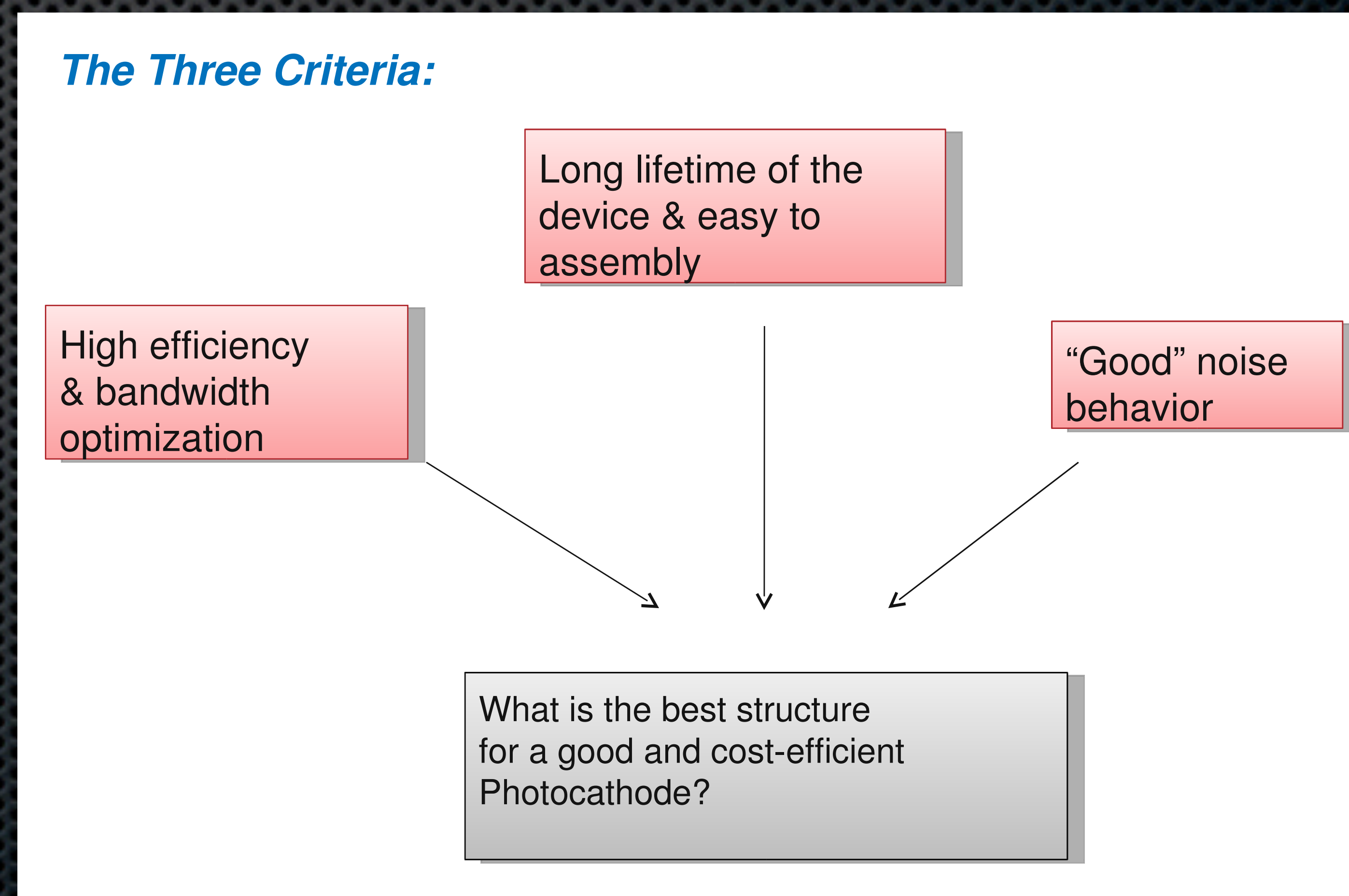
Photocathodes



Major area for innovation

Basic physics poorly understood

see:
https://psec.uchicago.edu/workshops/2nd_photocathode_conference/



K. Attenkoffer

Precision Timing

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 ↓

At the Front End:

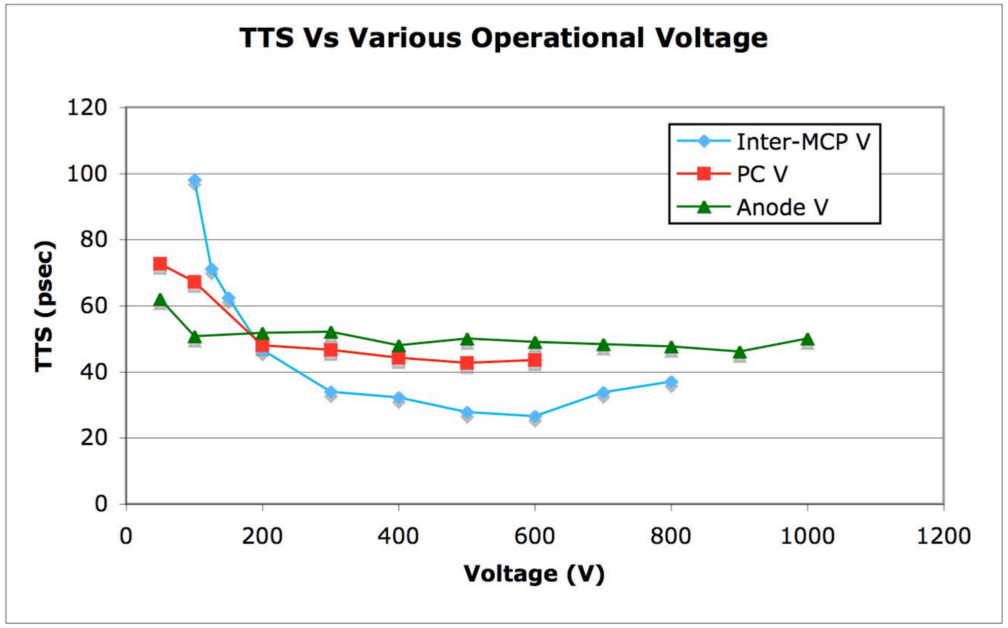
- Sampling rate (f_s)
  Nyquist-Shannon Condition
- Analog bandwidth (f_{3DB})
- Noise-to-signal ($\Delta u/U$)

	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

Intrinsic to the MCP:

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

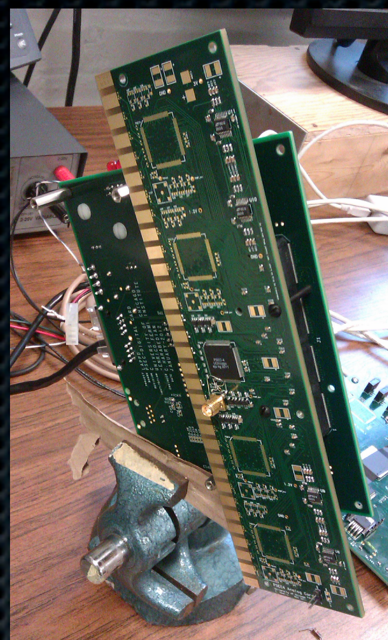
B Adams (APS-ANL), M Chollet (APS-ANL), A Elagin (UoffC/ANL), R Obaid (UofC), A Vostrikov (UofC), M Wetstein (UofC/ANL)

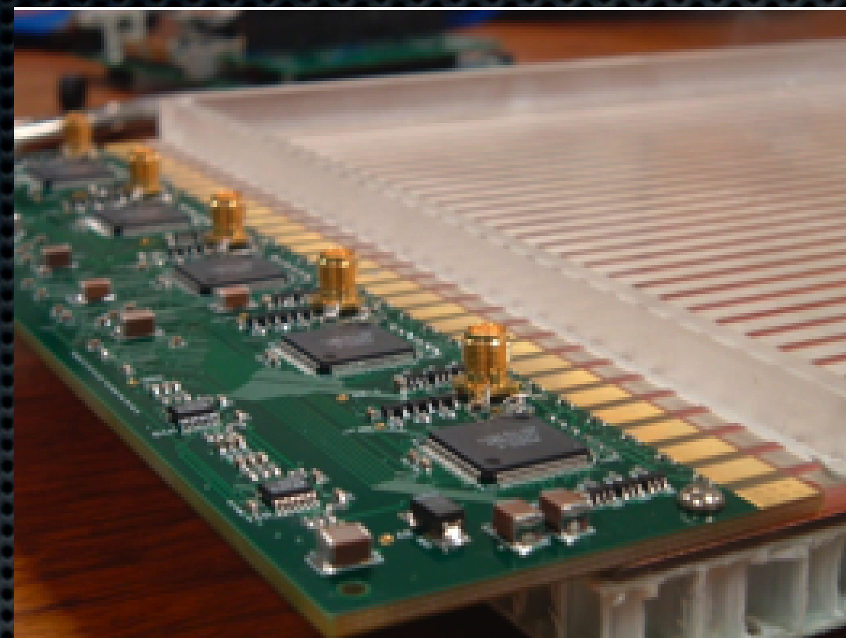


see: workshop on factors that limit time resolution in photodetectors: http://psec.uchicago.edu/workshops/fast_timing_conf_2011/

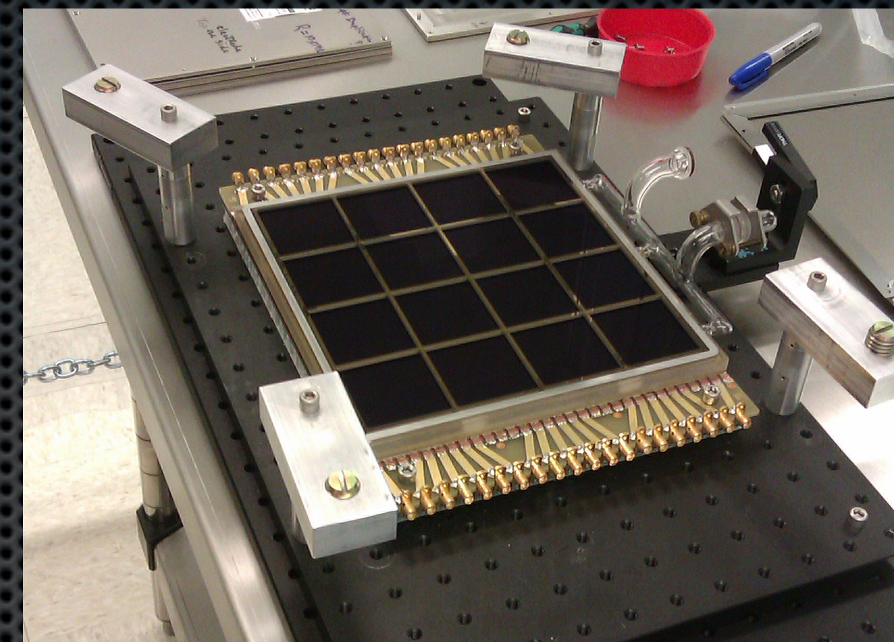
Precision Timing

PSEC 4 readout system

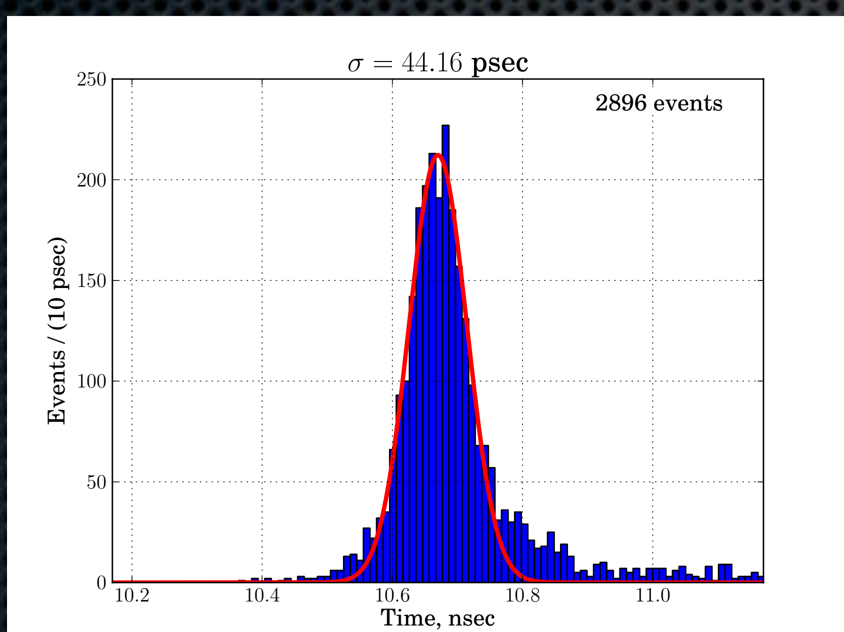




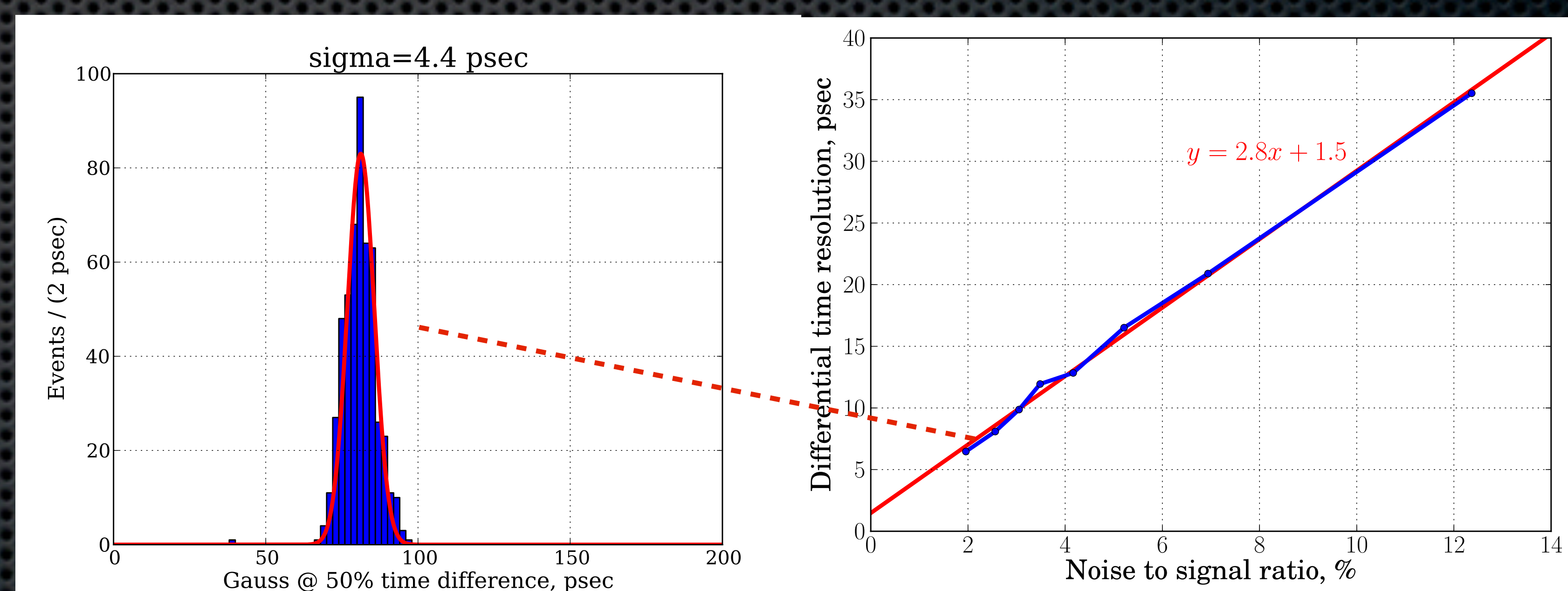
8” Demountable Detector



single PE timing

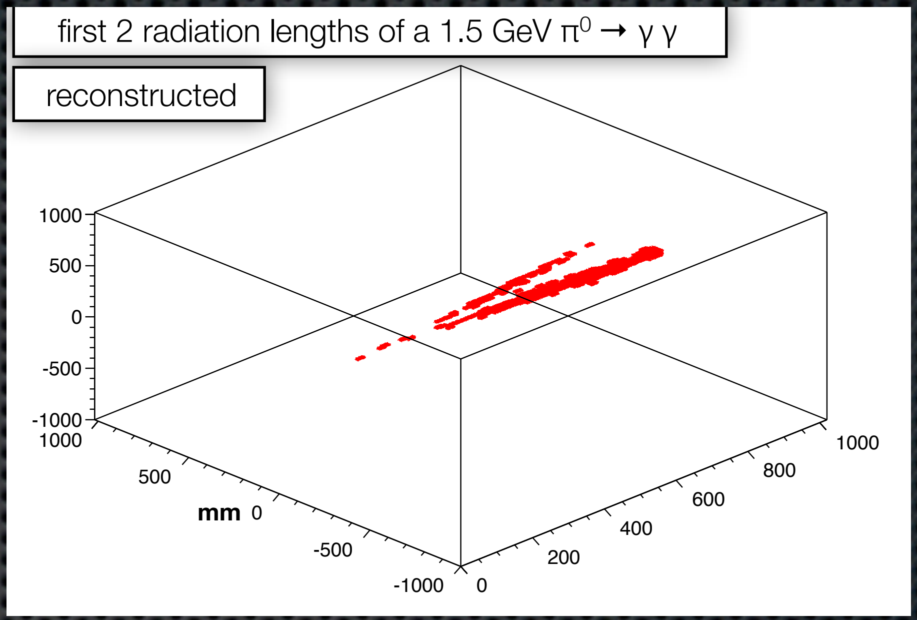


Large signal timing



Imaging

simultaneous space and time is important (4-vectors) for complete event reconstruction



Single PE counting

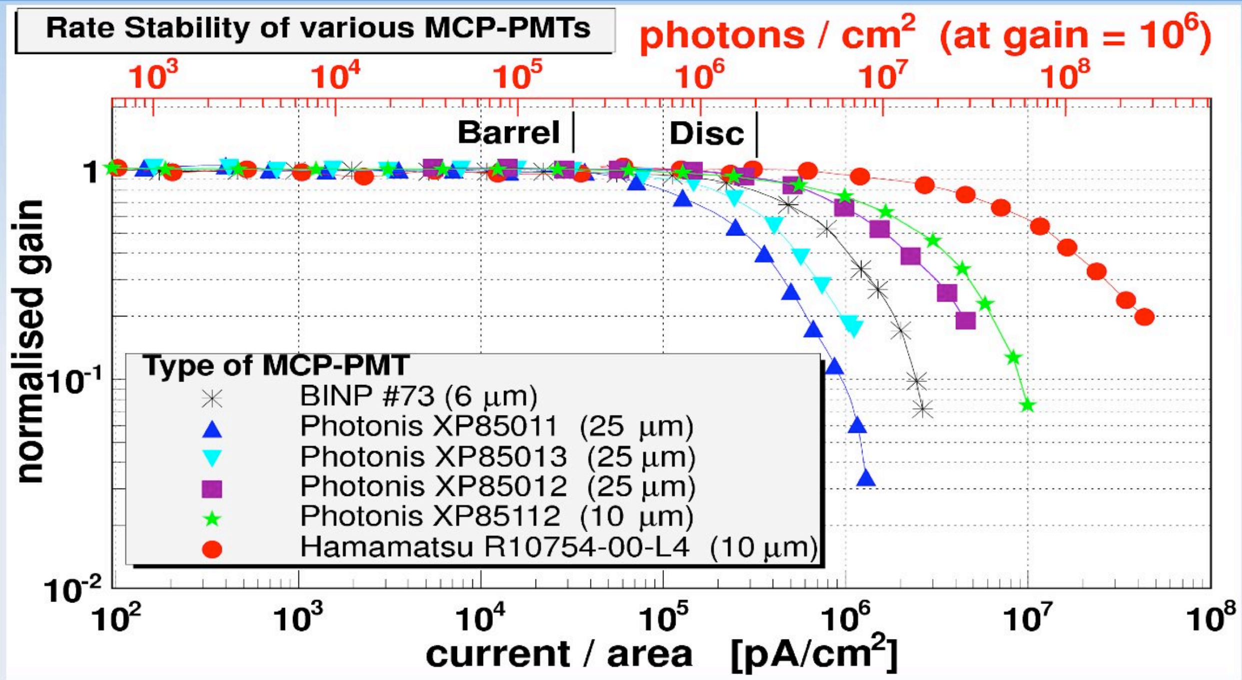
Important for low E, low rates
Energy resolution in WC detectors

Factors That Determine Rate Limitations

- The rate capacity of MCPs is primarily driven by pore capacitance and resistance (RC circuit)
- Sctive pores will deplete some charge from their neighbors, decreasing the overall relaxation time
- Rate capacity depends not only on the event frequency, but the spatial distribution

- Rate capacity can be improved
  - by reducing MCP resistance
  - reducing pore size
  - operating at lower gain
- Some commercial plates are already capable of stable operation at MHz rates and are being tested for use in accelerator applications.
- See work by
  - J Va'vra, Anton Tremsin, Ossy Siegmund
  - PANDA Collaboration
  - (among others...)

From Fred Uhlig's talk at NDIP Lyon 2011



- XP85112 (10µm) and XP85012 (25µm) stable up to ~ 2 MHz/cm^2 s.ph.
- Hamamatsu R10754 stable up to ~ 7 MHz/cm^2 s.ph.

Lifetime Issues

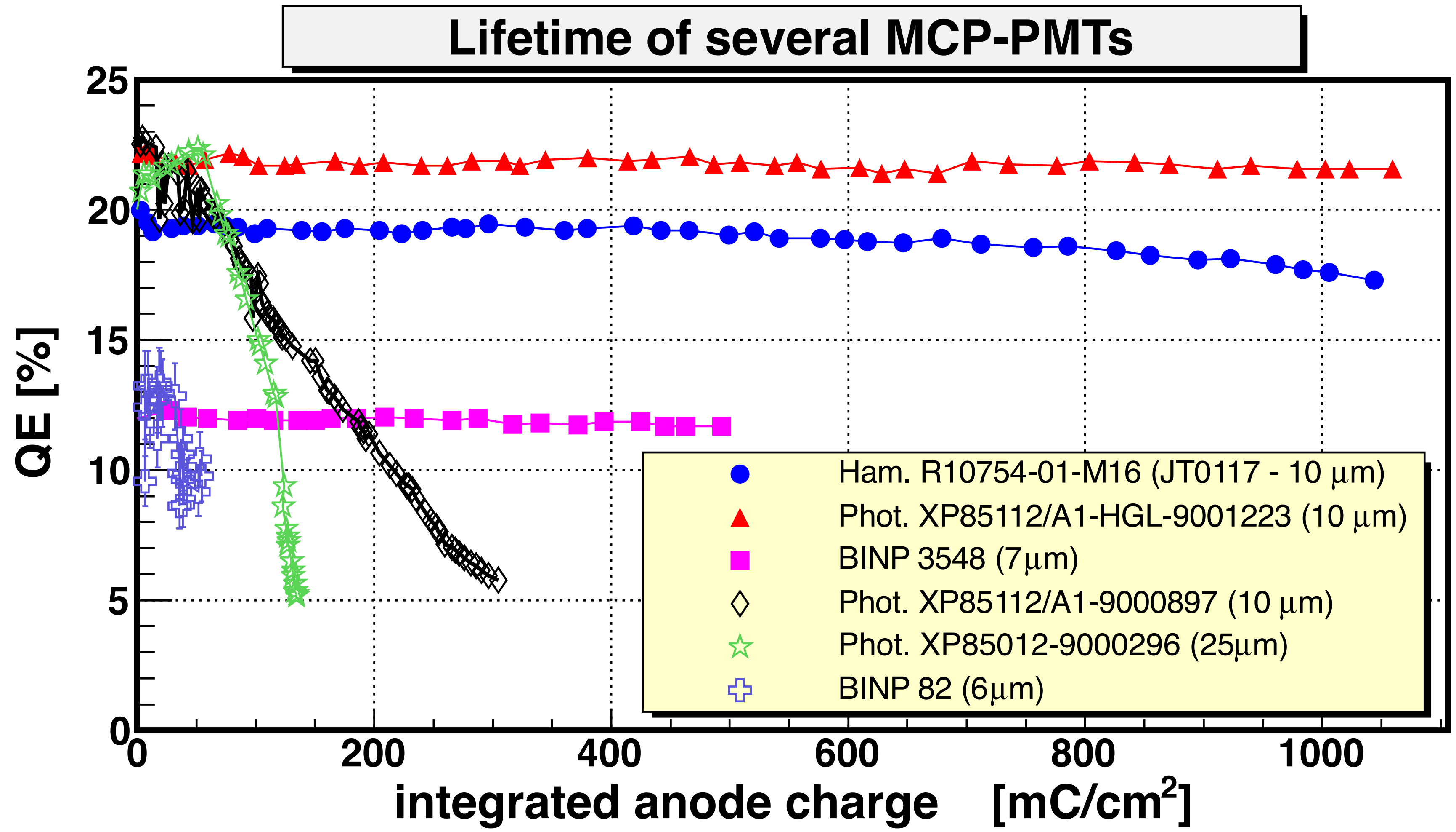


Figure 1: QE at 400 nm for old (open) and new generation (solid dots) MCP-PMTs as function of the anode charge.

Lifetime of latest generation Microchannel Plate PMT's

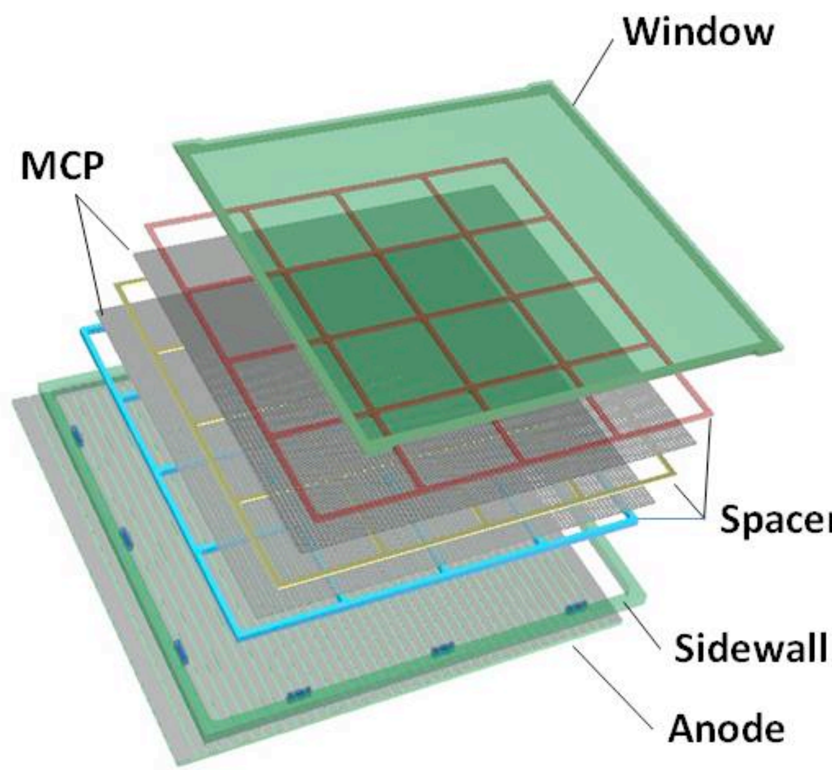
A. Britting[1], W. Eyrich[1], A. Lehmann[† 1], F. Uhlig[1], and PANDA Cherenkov group

Efforts

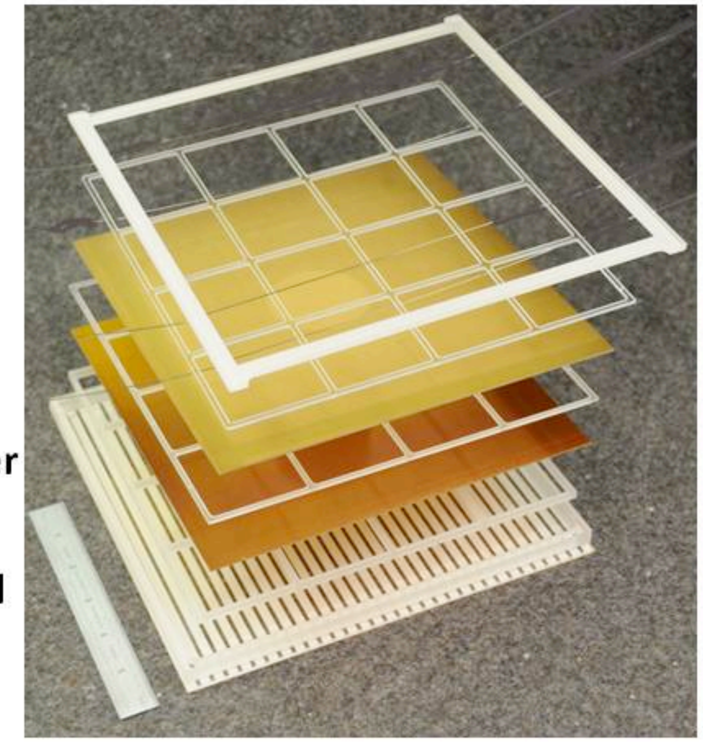
- LAPPD
- MLAP
- Light collectors
- QE development
- Hybrid APDs
- Rad Hardness Developments for Colliders?
- Ring Imaging and DIRC systems?
- Cosmic Frontier?

LAPPD Project

What is the LAPPD Concept



Design Drawing - September 2010



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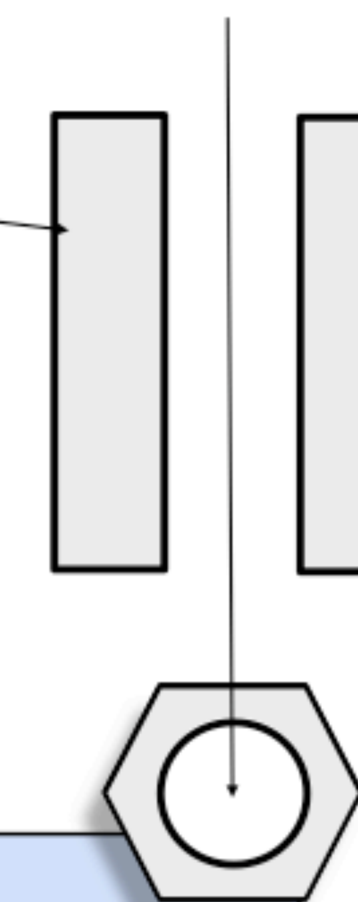

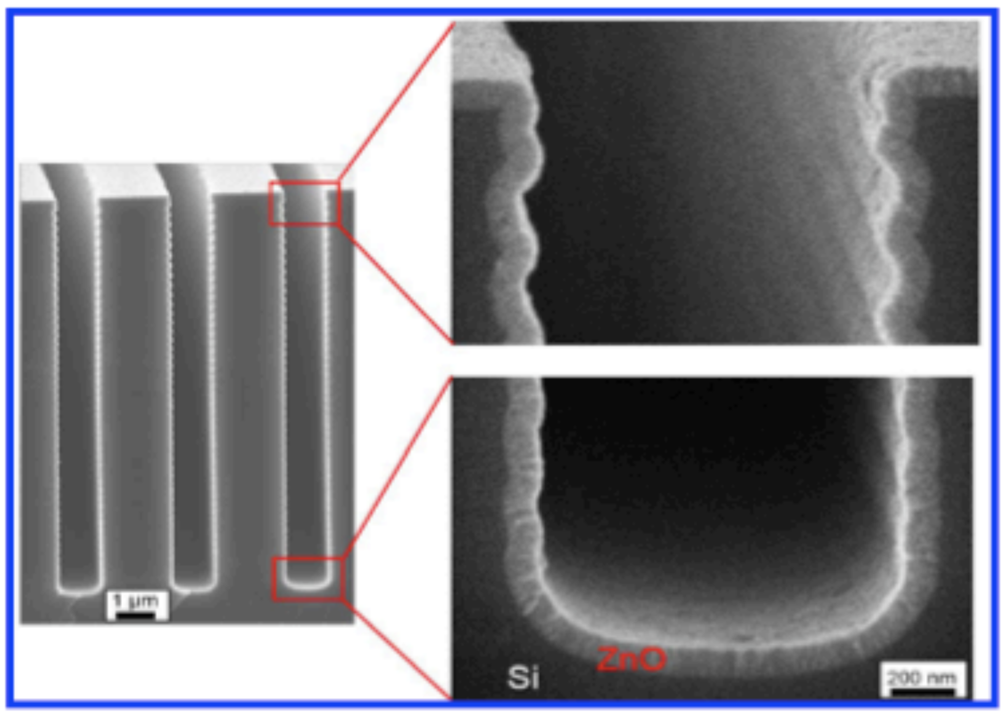

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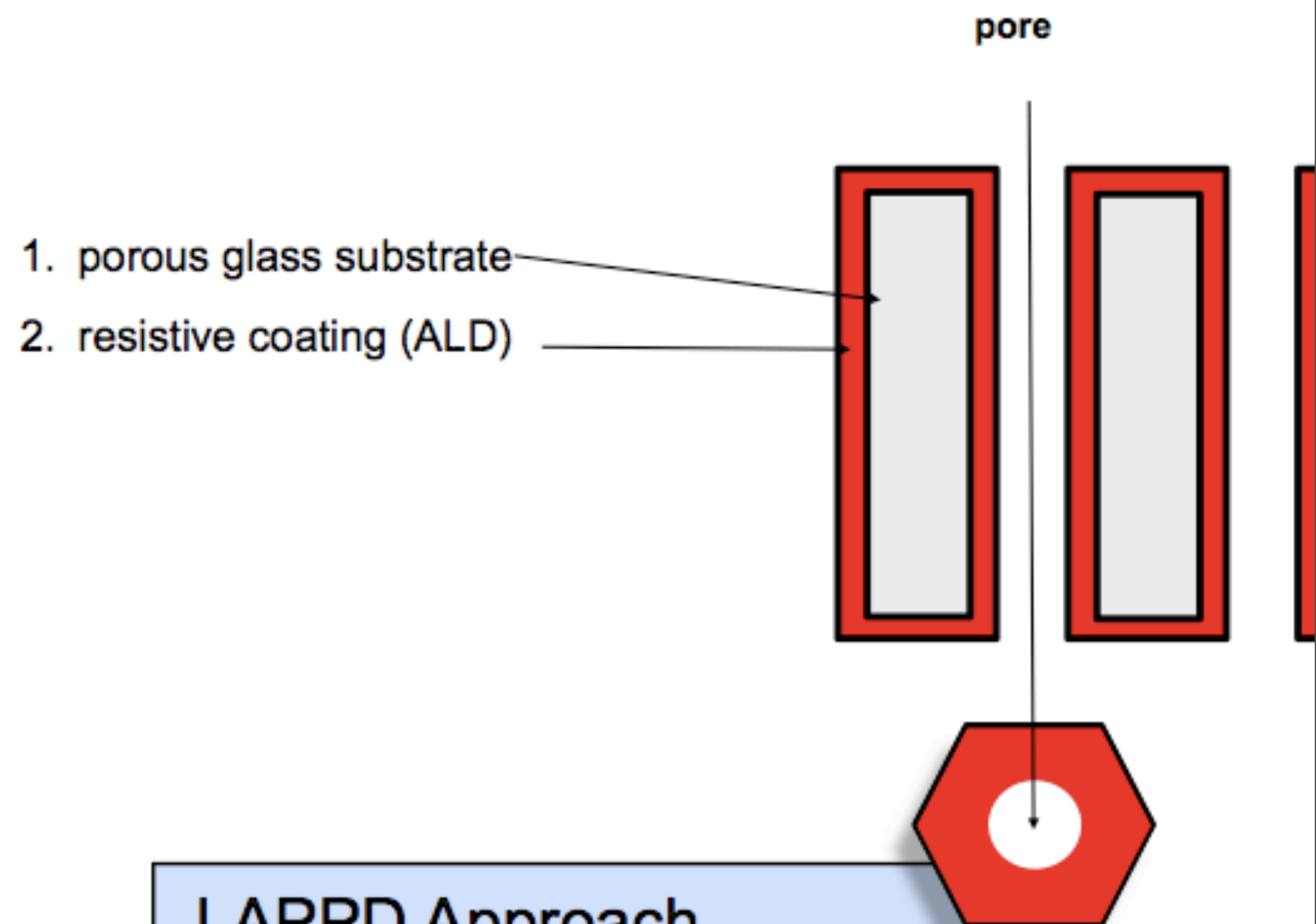

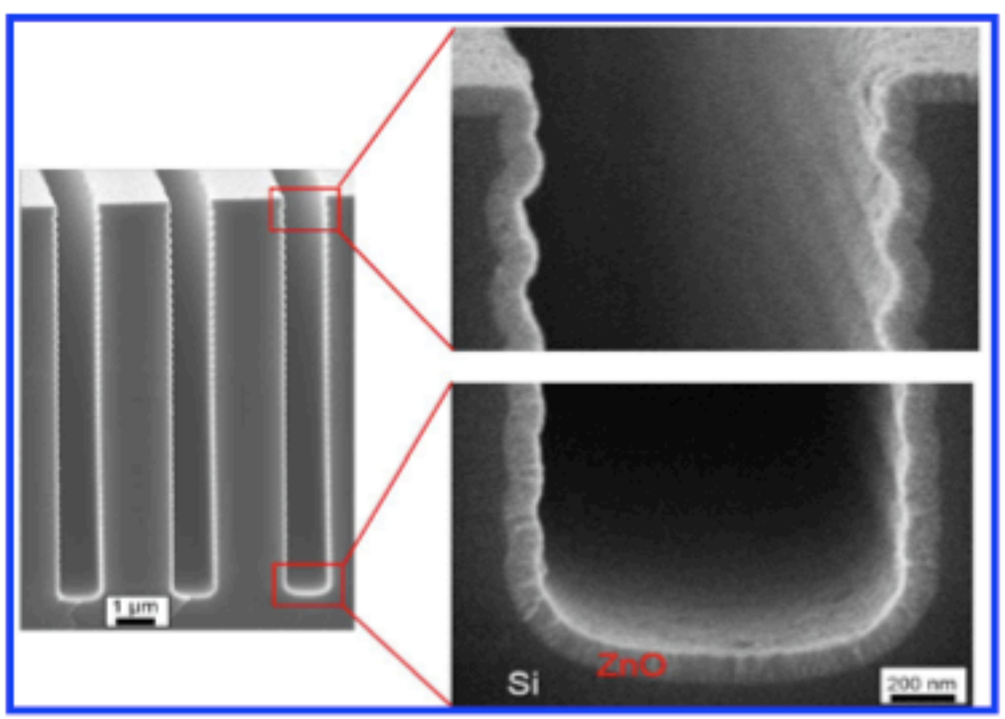

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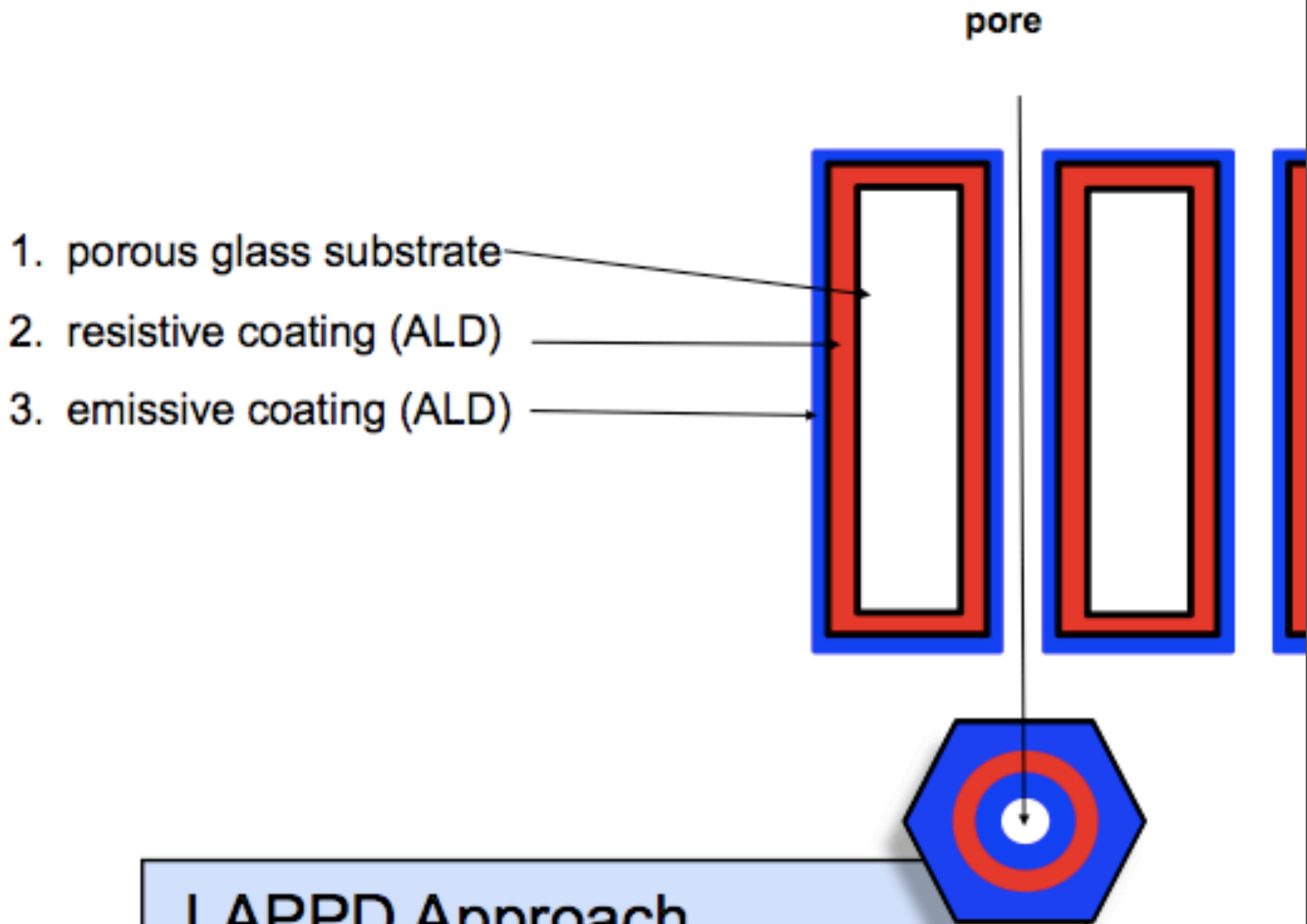

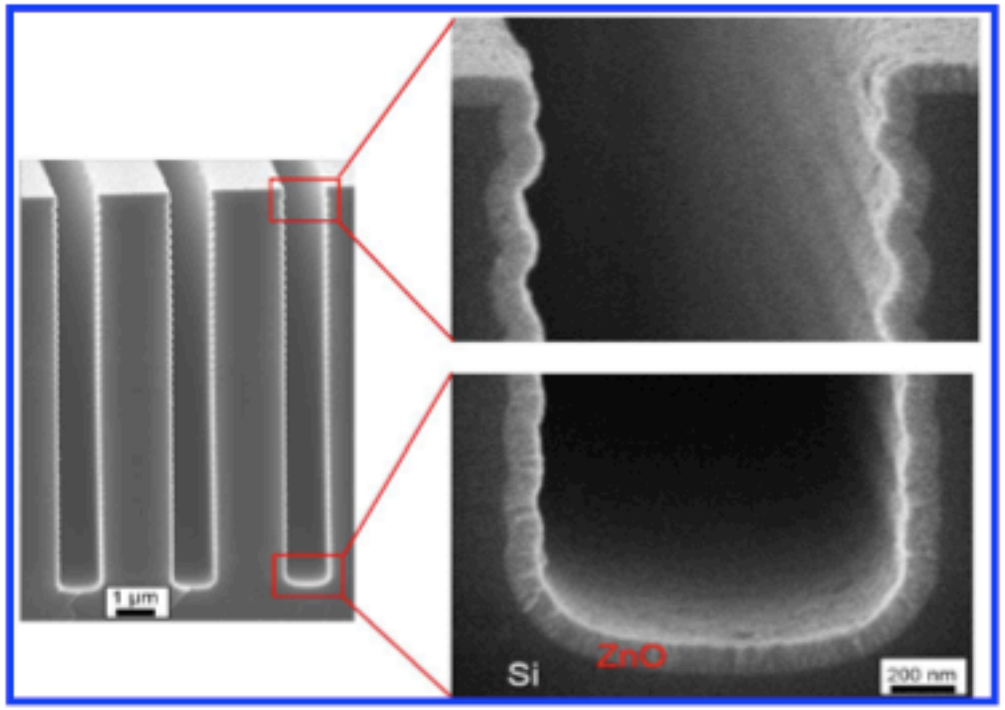

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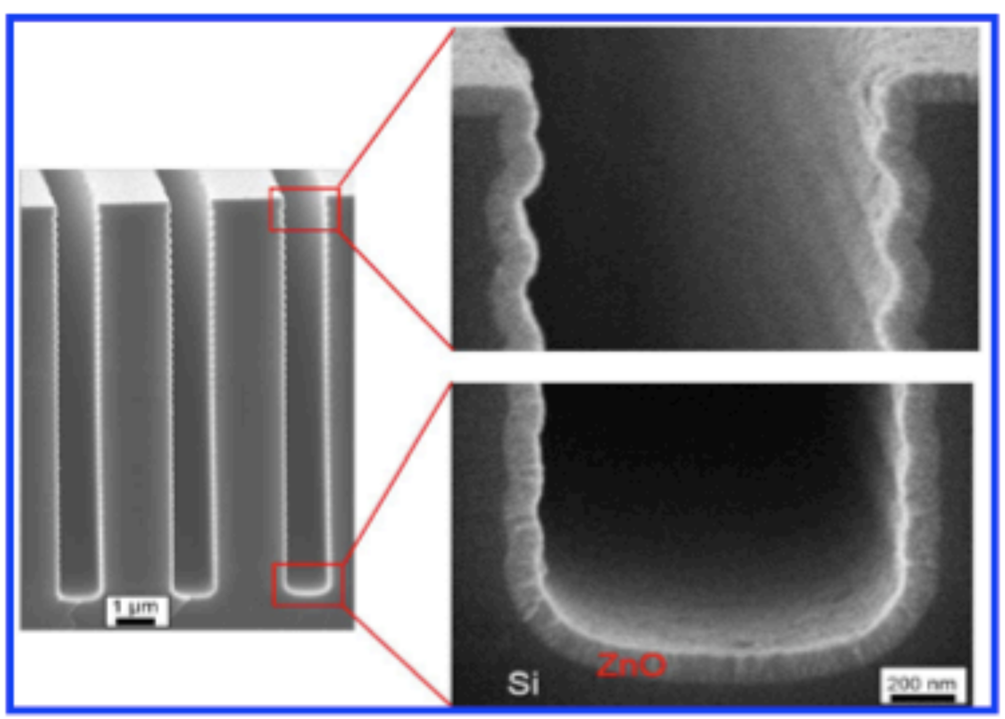
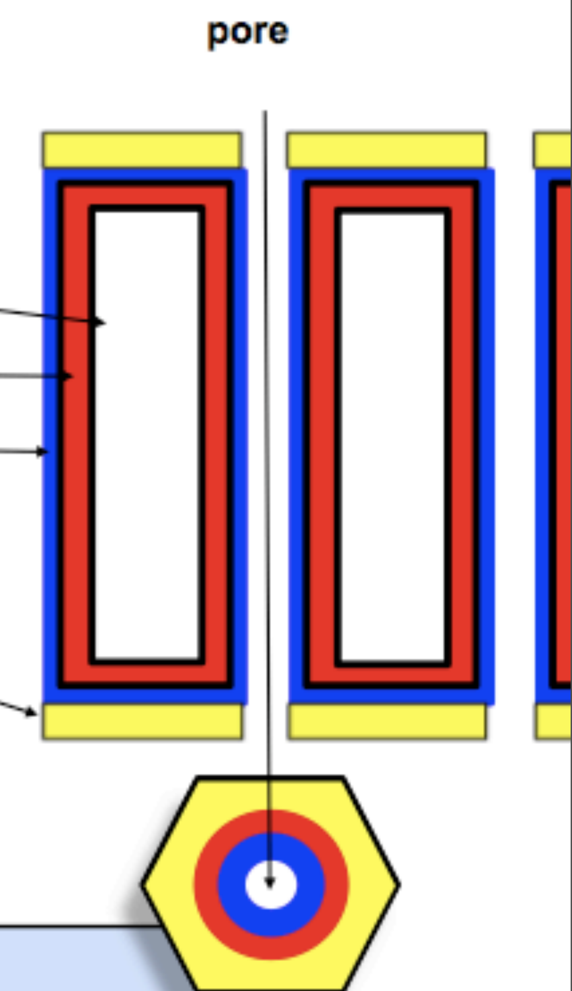


1. porous glass substrate
2. resistive coating (ALD)
3. emissive coating (ALD)
4. conductive coating (thermal evaporation or sputtering)



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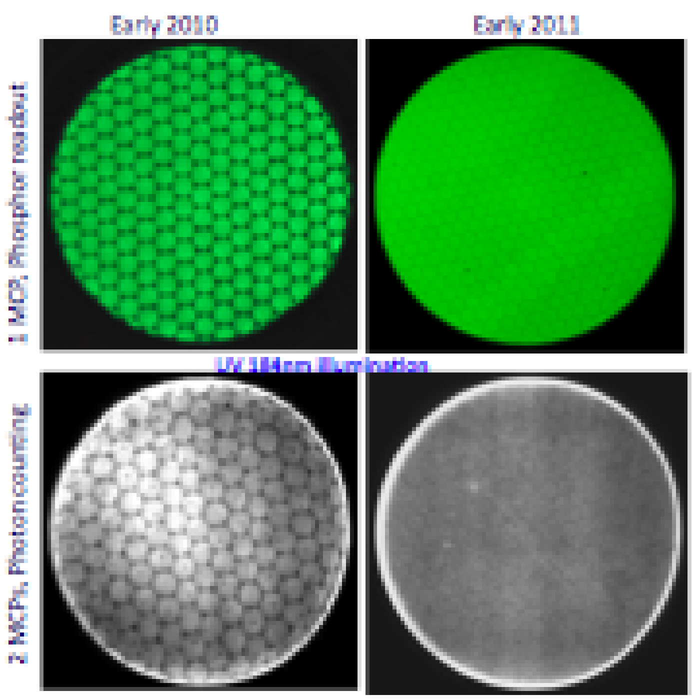
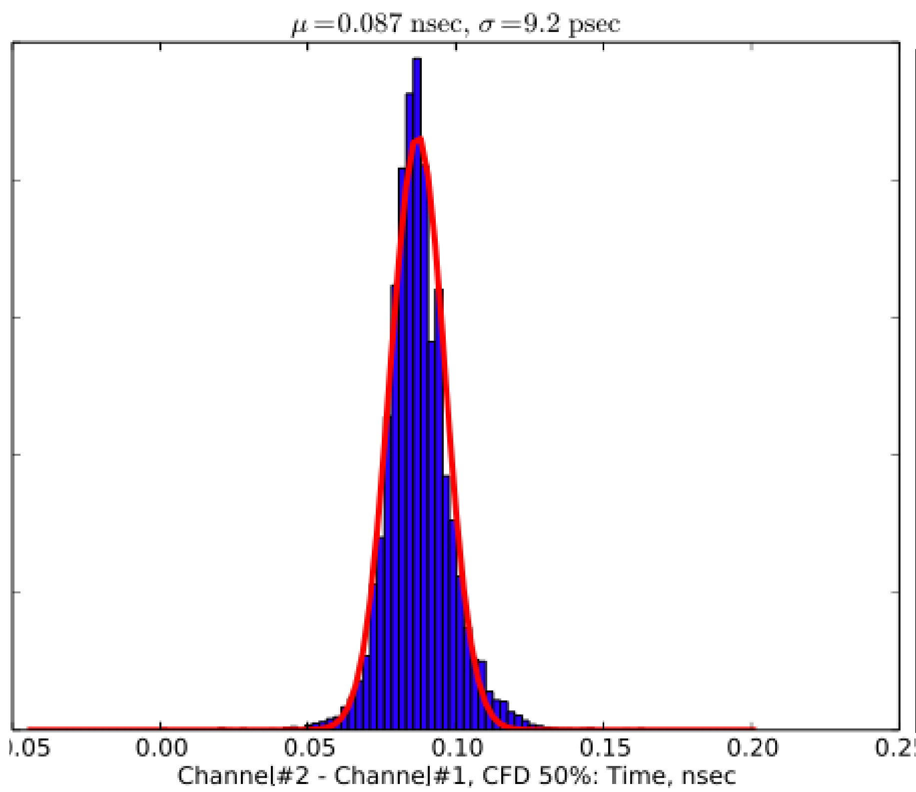
Microchannel Plates

Rapidly improving substrates (Arradiance)

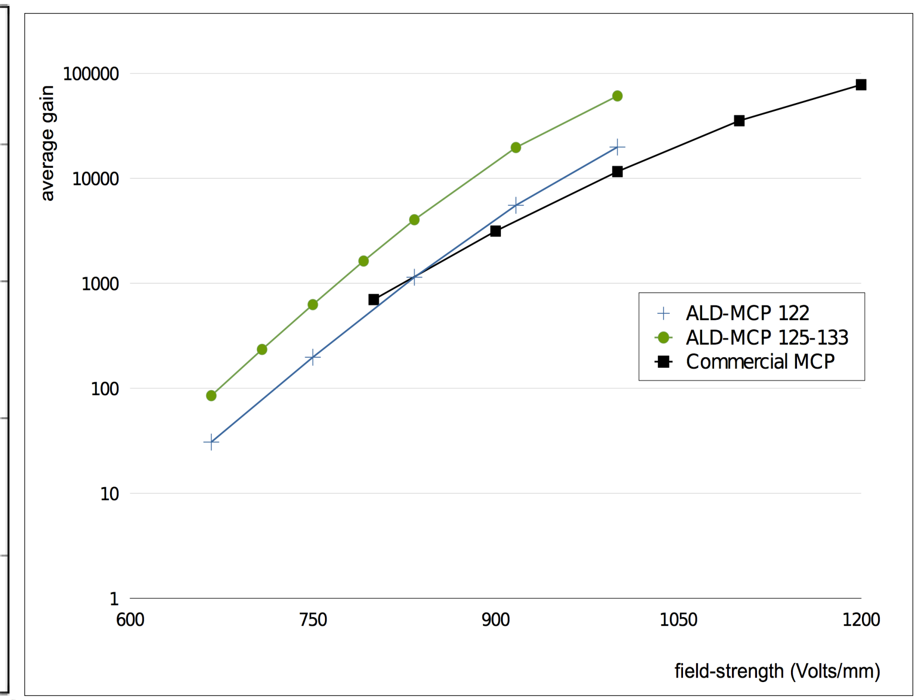


bkgd rate of 0.099 evts cm^{-2} sec^{-1} at 1.3 kV per plate

Differential Time Resolution ~9 psec



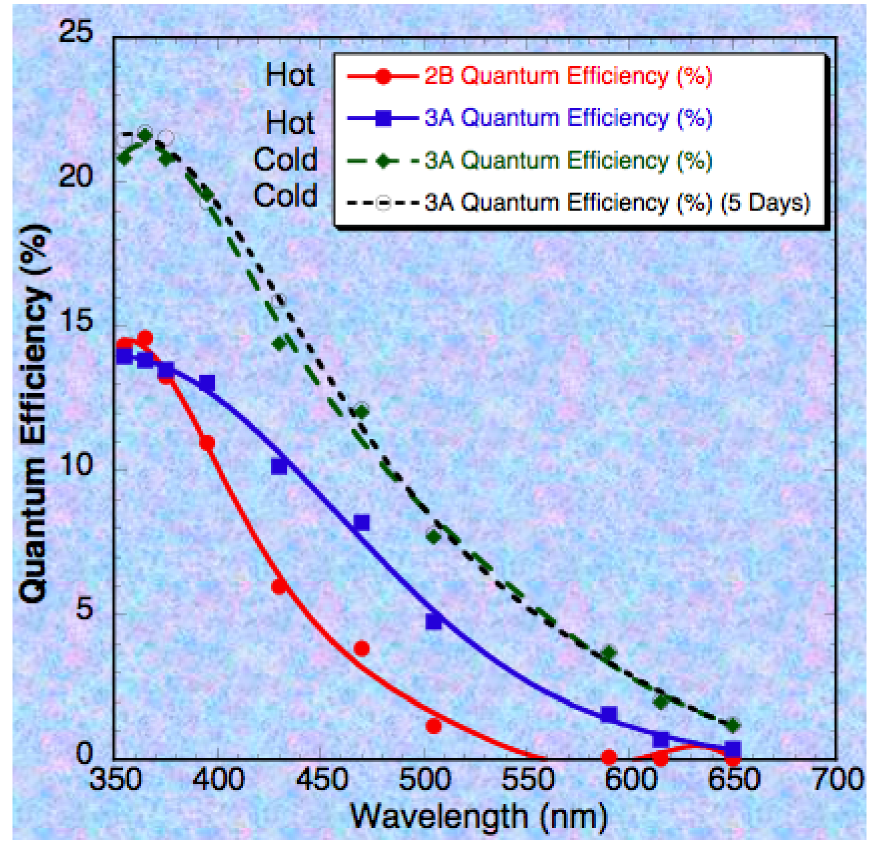
Gains better than high performance commercial plates (>10e5)



Photocathode

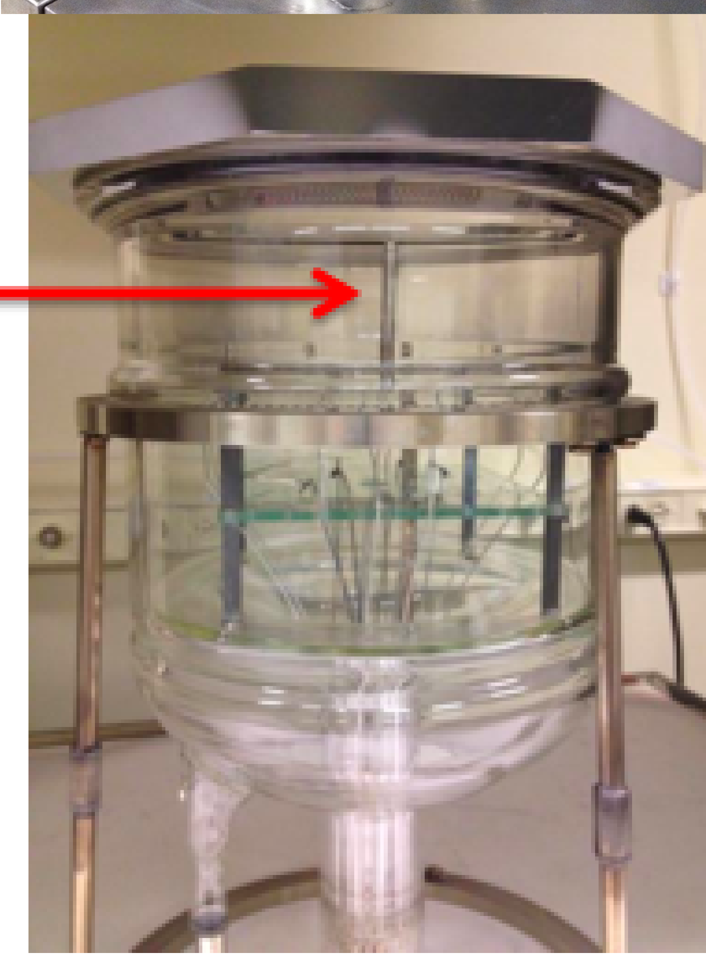
- Two main parallel paths:
  - scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production lines.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries 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)



8” Tile-Assembly Chamber (UCB)

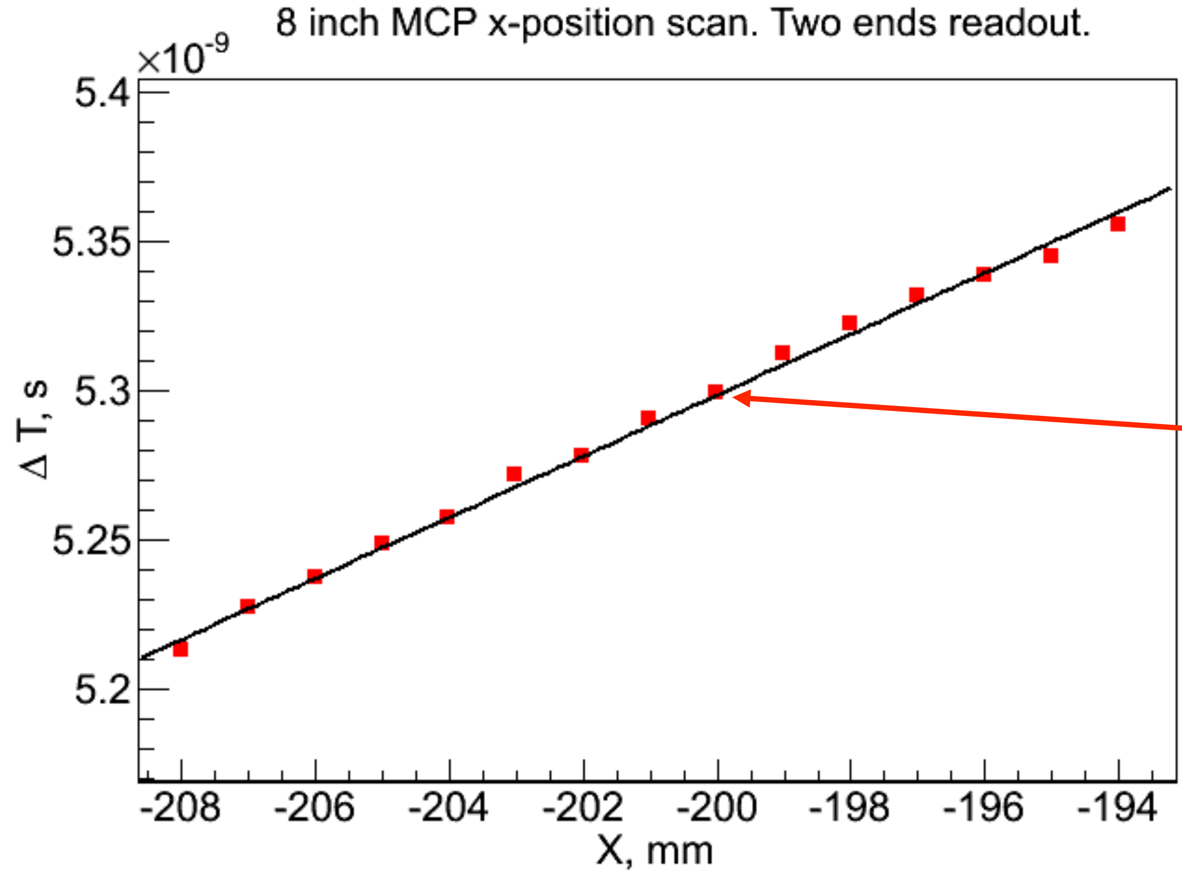
The “Chalice” (ANL)

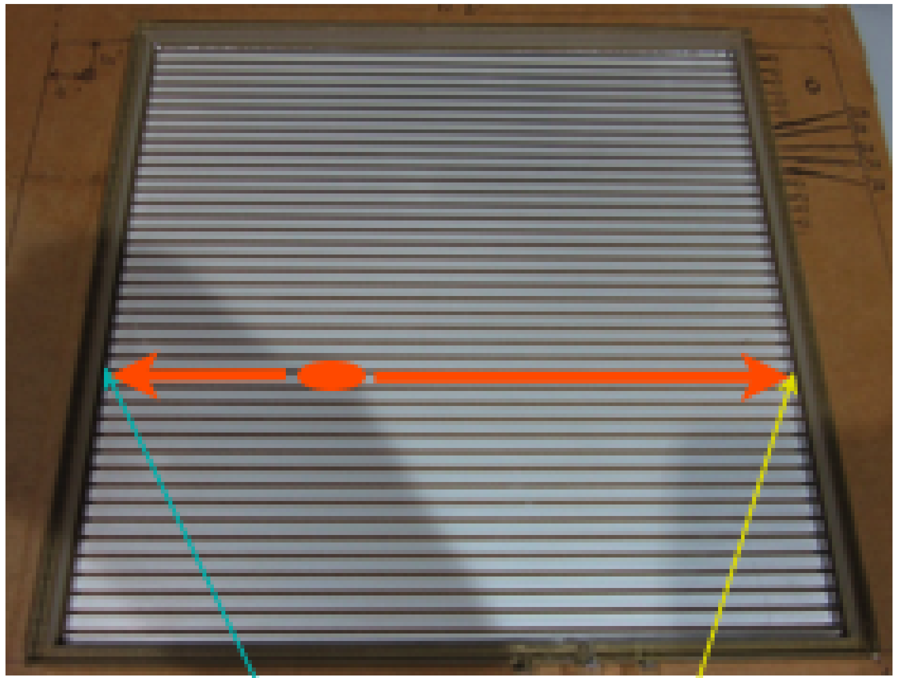


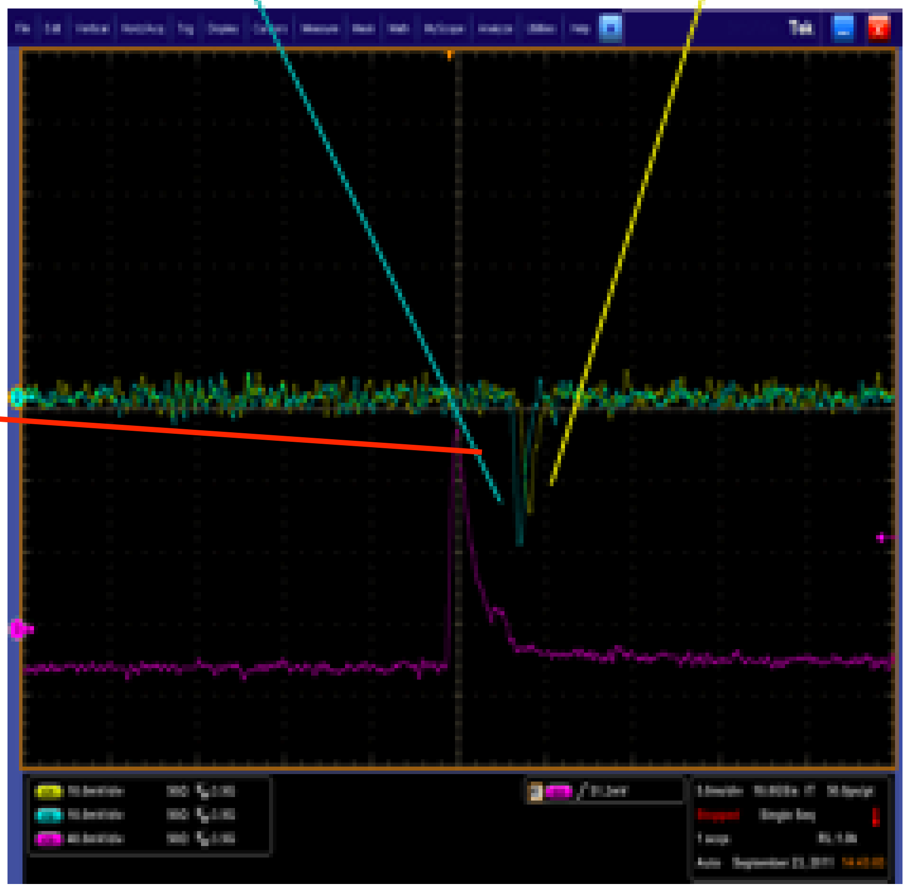
Anode Design: Delay Lines

Channel count (costs) scale with length, not area
Position is determined:

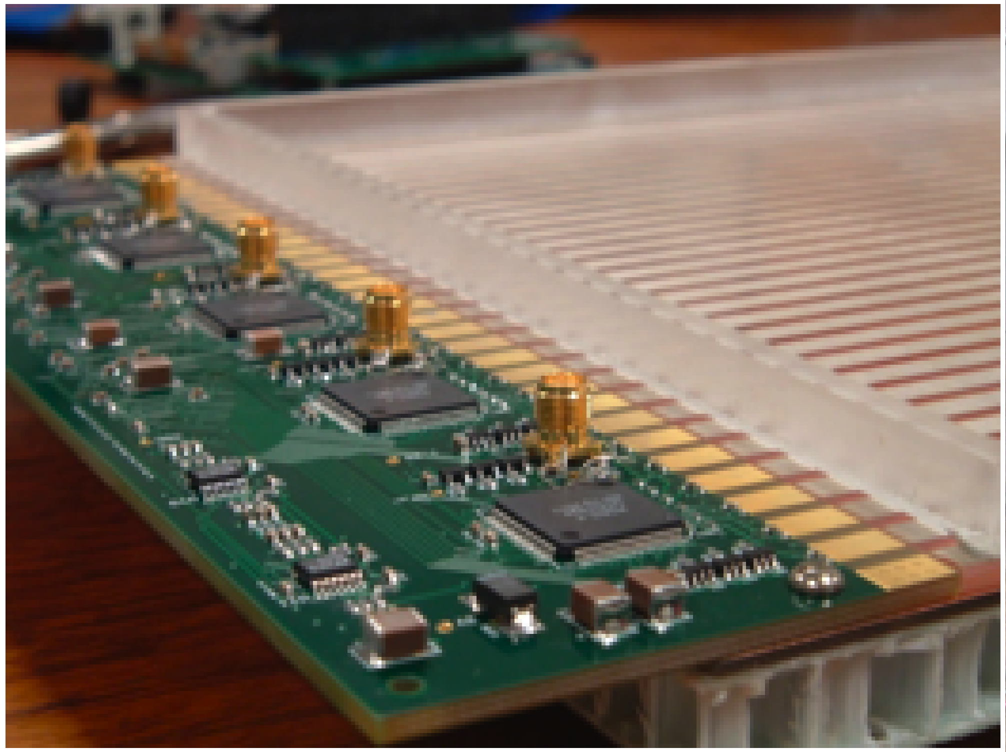
- **by charge centroid in the direction perpendicular to the striplines**
- **by differential transit time in the direction parallel to the strips**

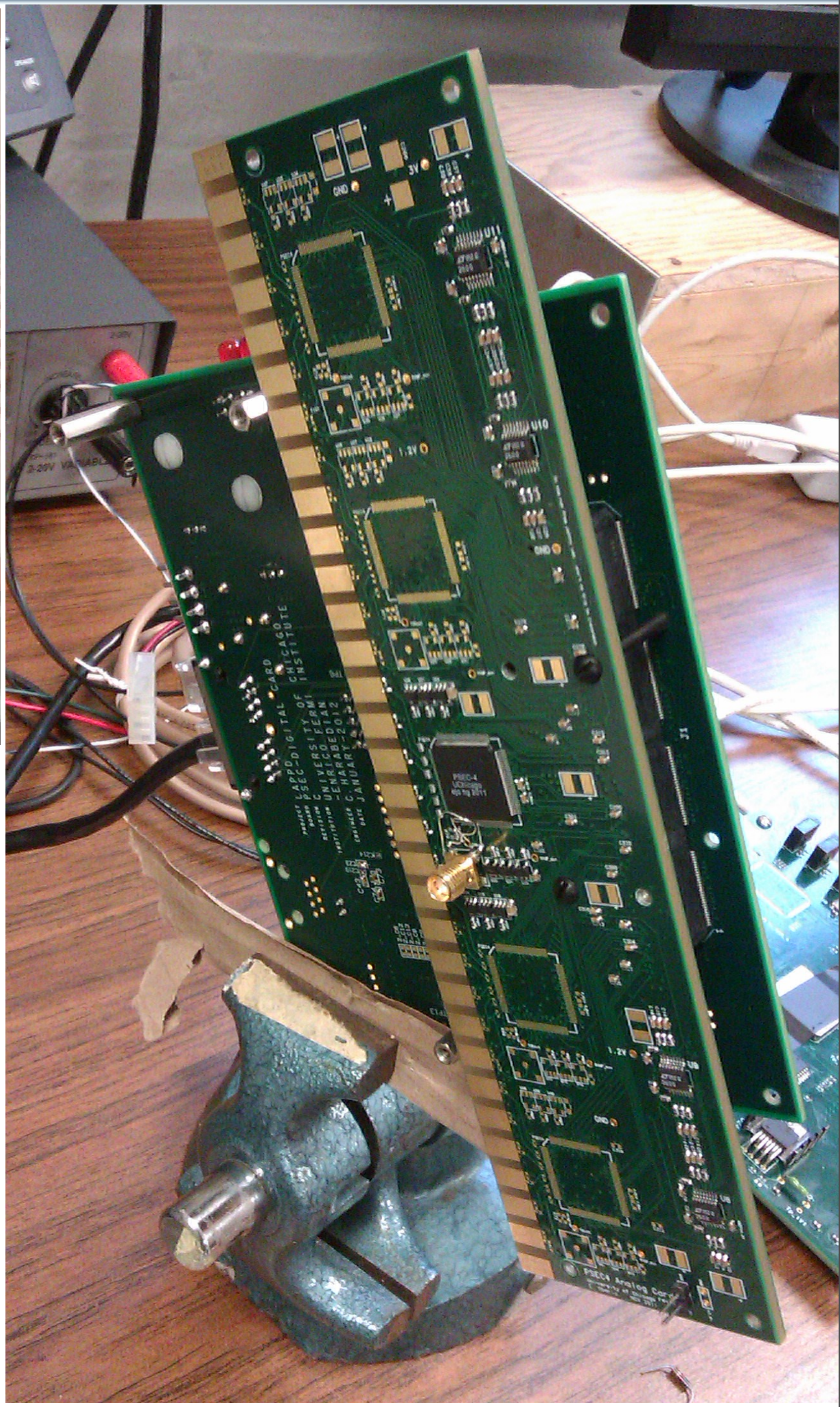






Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm





Psec4 chip:

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

Analog Card:

- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

Digital Card:

- Analysis of the individual pulses (charges and times)

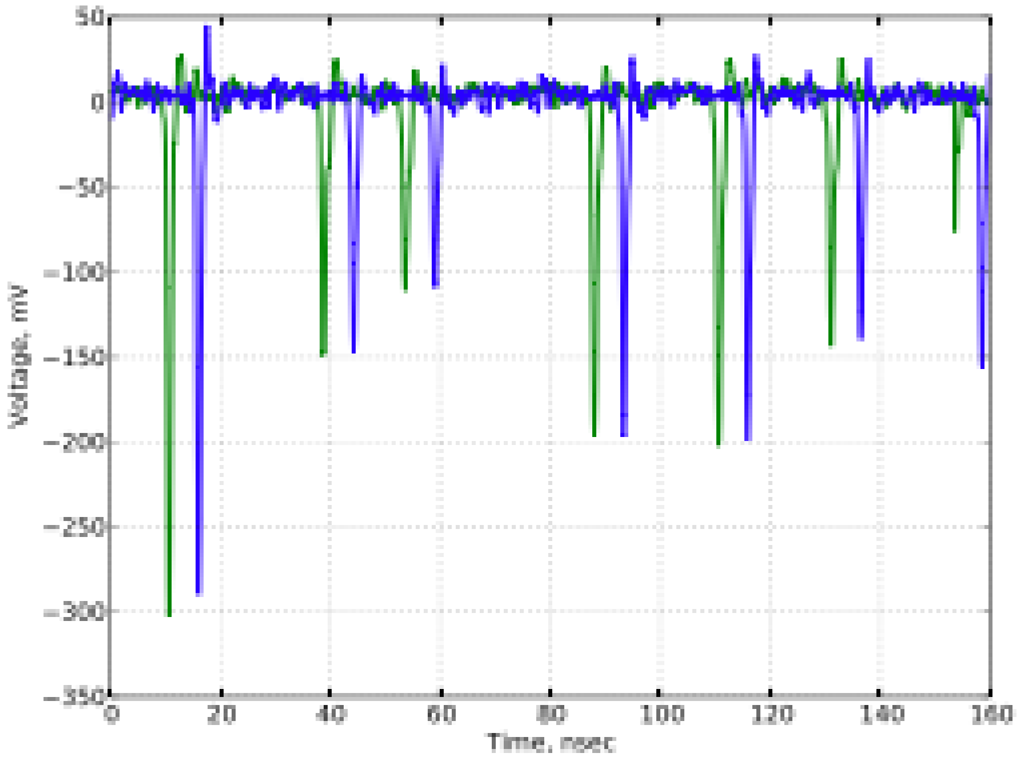
Central Card:

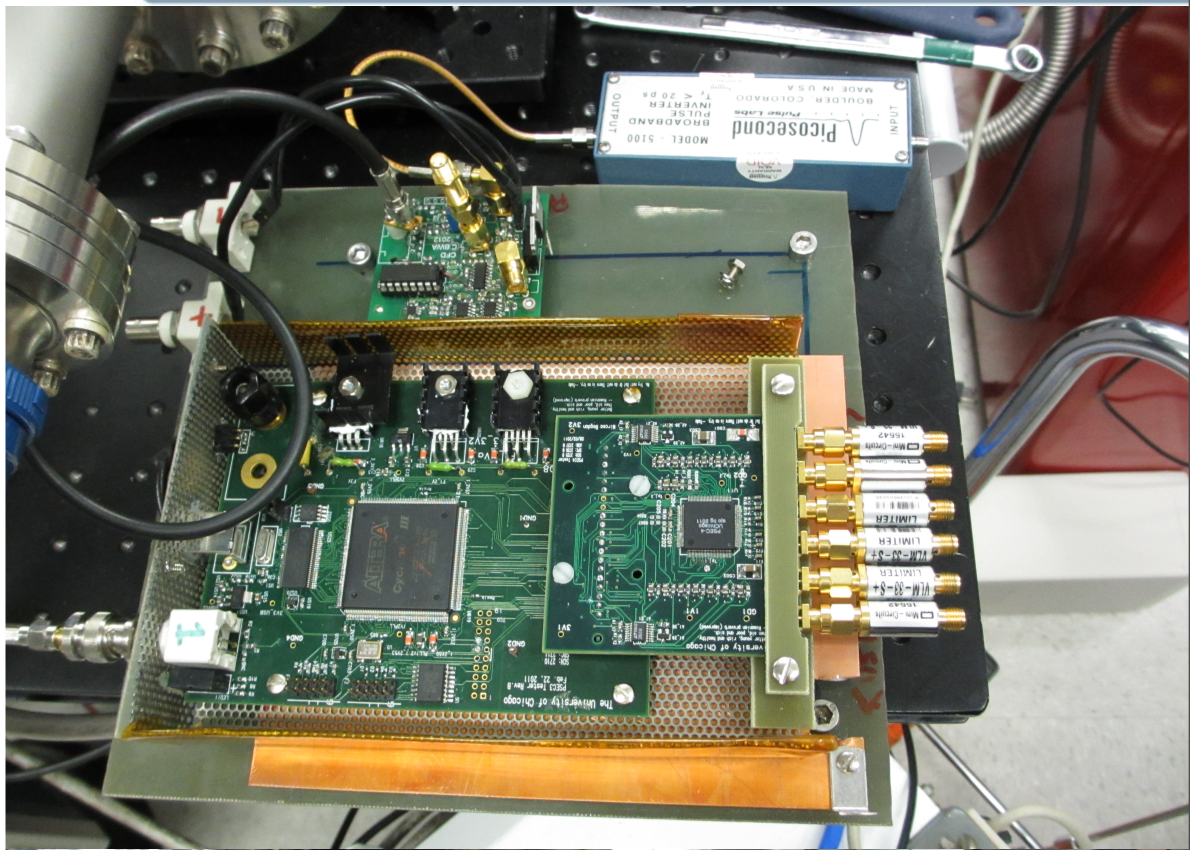
- Combines information from both ends of multiple striplines

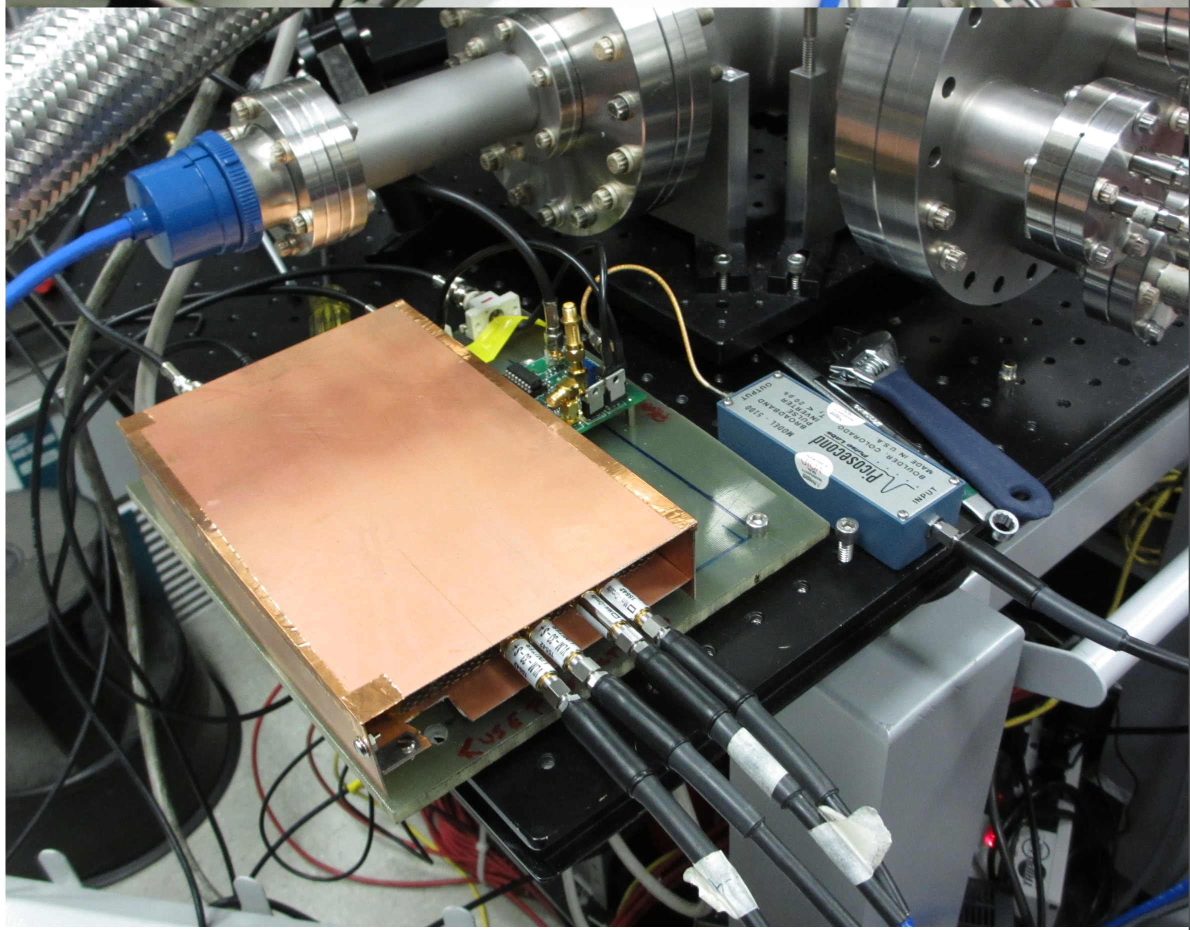
scope-in-a-box

We are now able to test the psec4 chip integrated with our detector system.

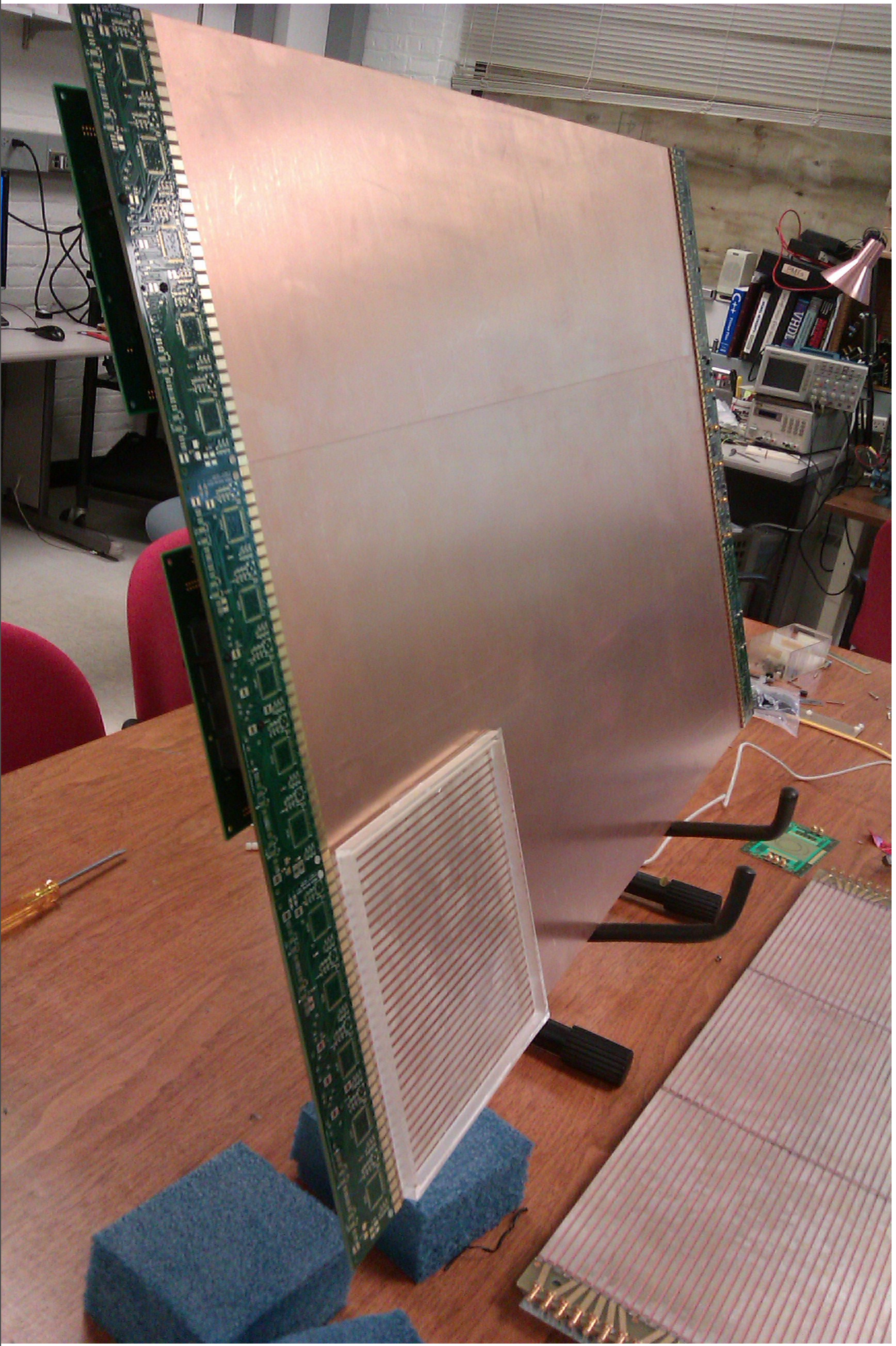
Scope-in-a-box is a six channel oscilloscope, built around our psec4 chip and digital electronics.

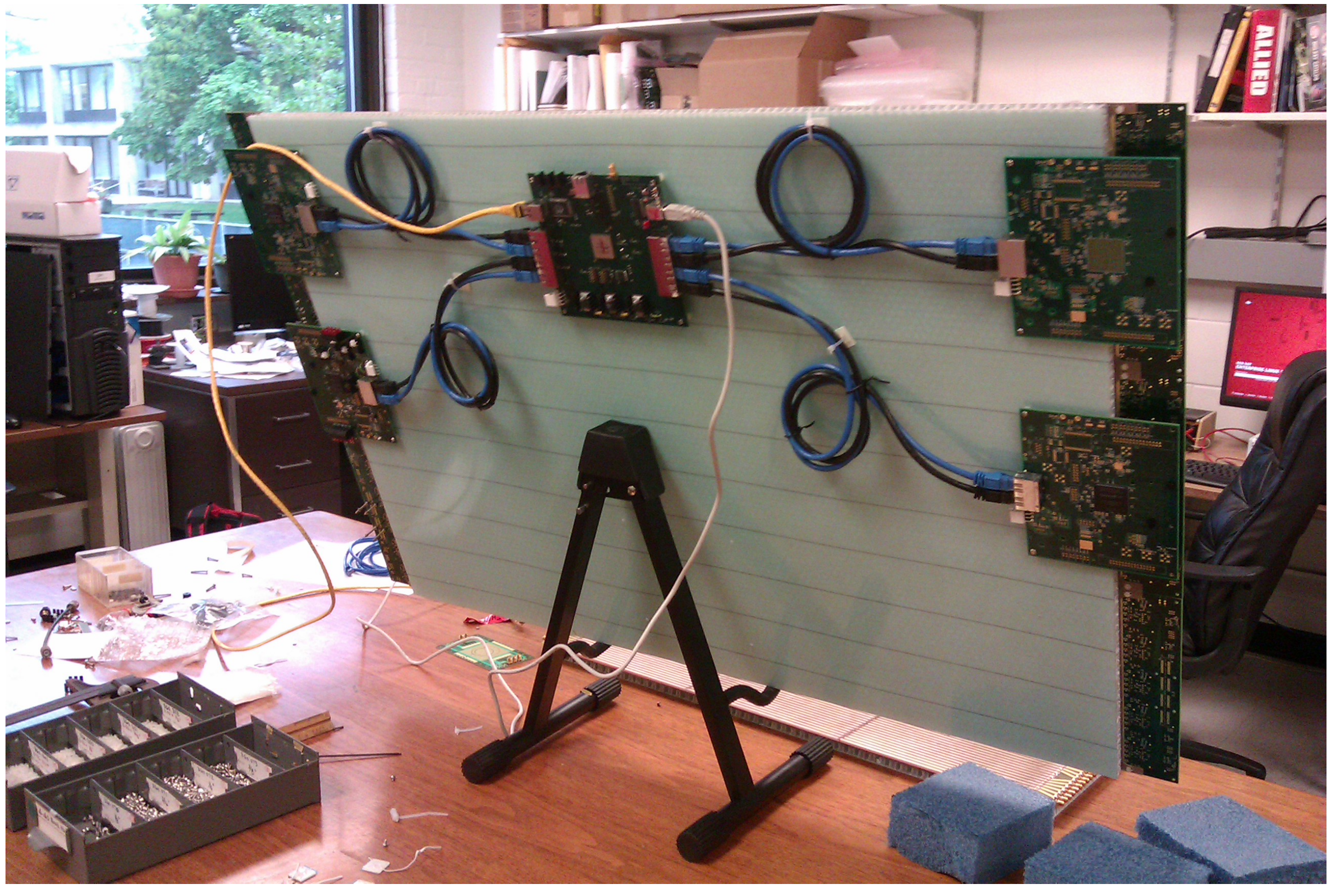




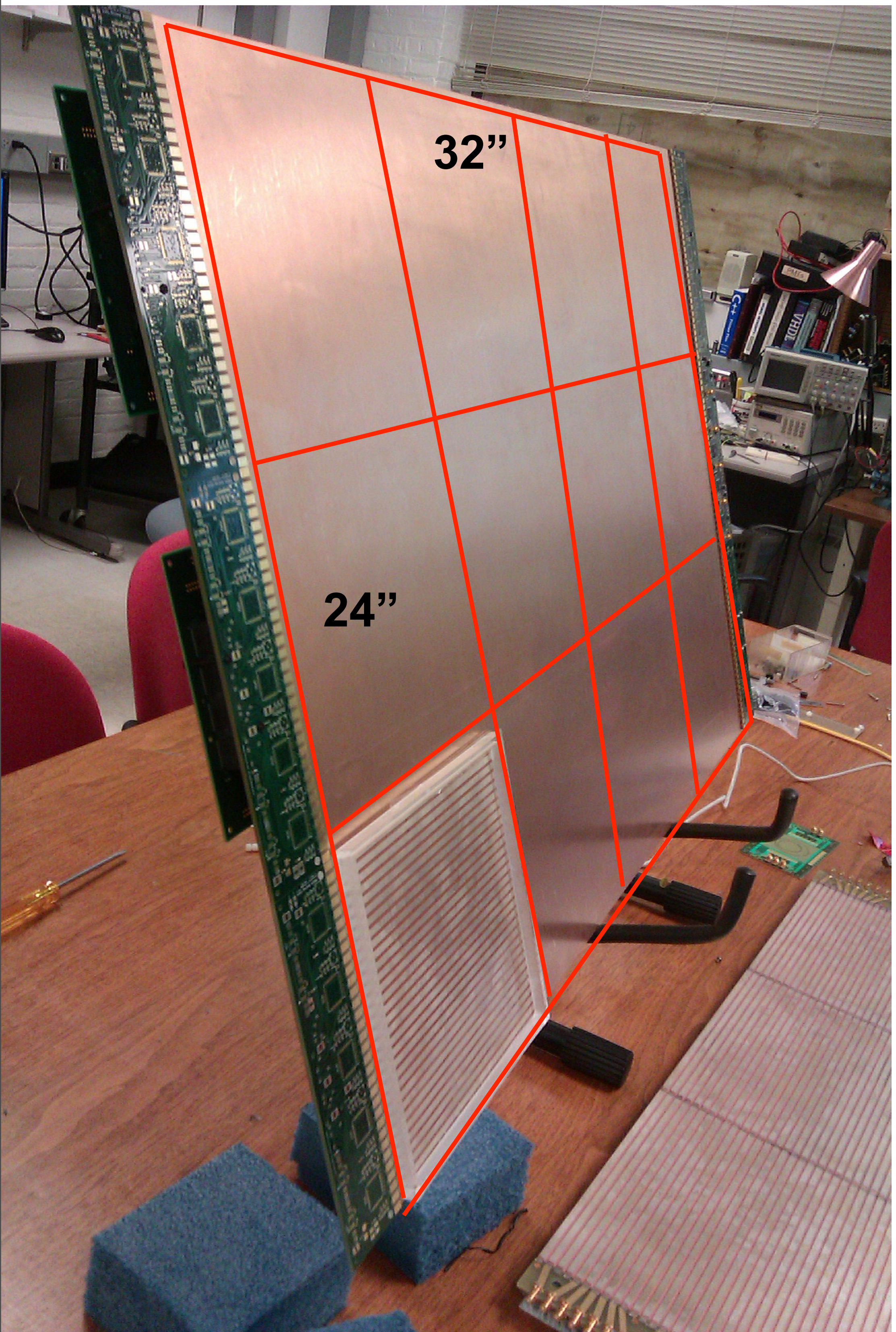


The Big Picture



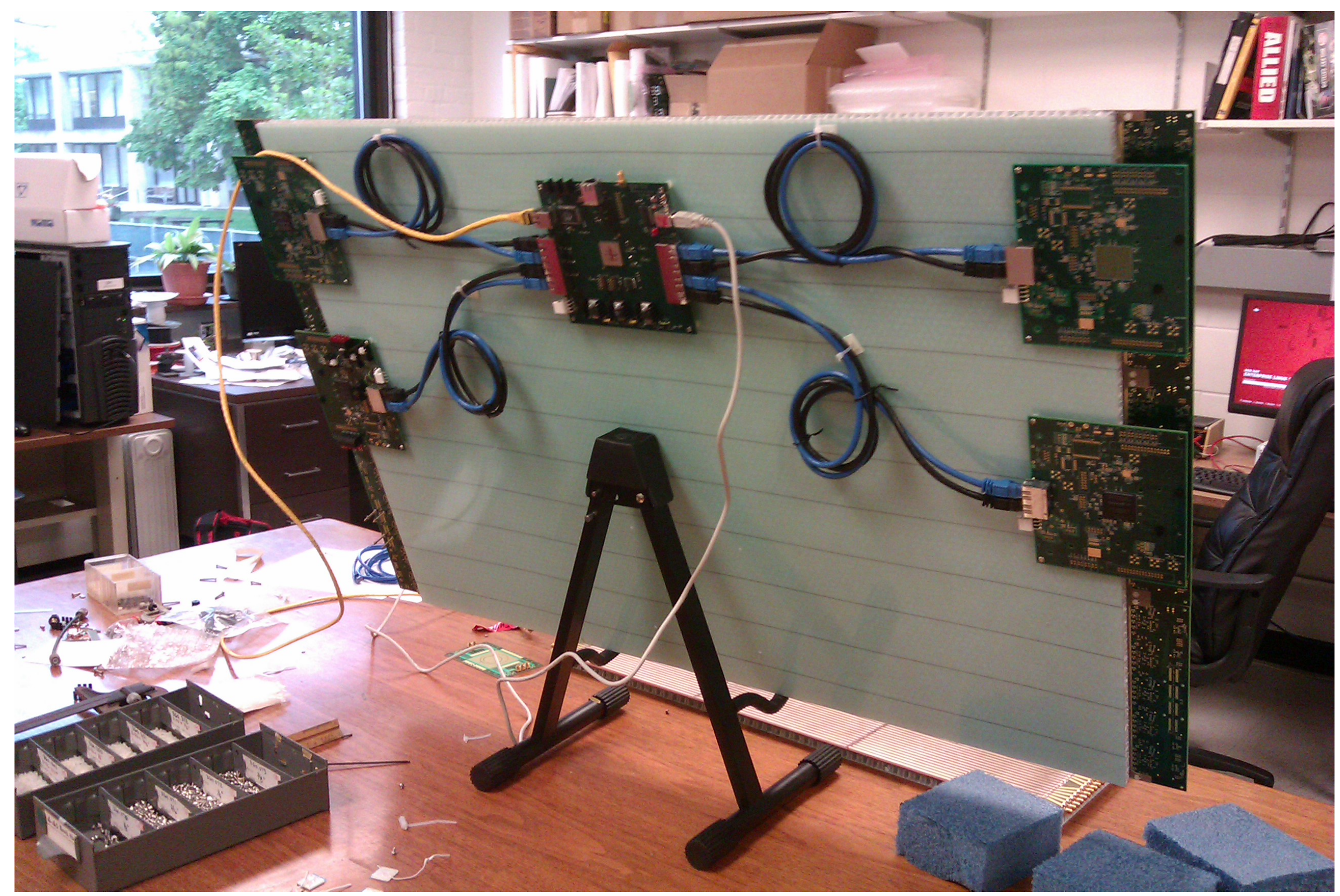


The Big Picture

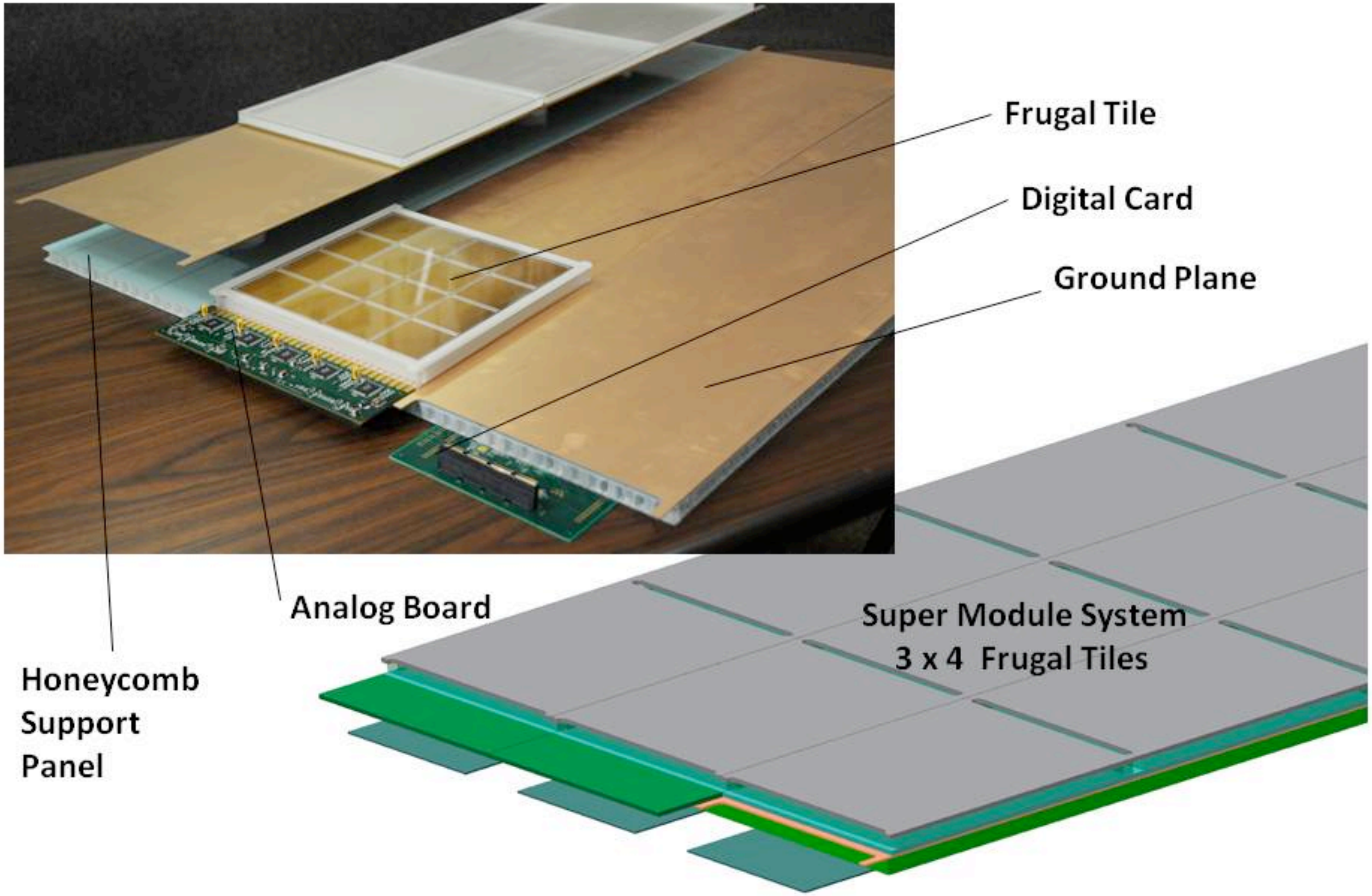


Supermodule:

- Multiple MCP detectors share a single delay line anode.
- Reduced channel count (slight loss of bandwidth)
- Fully integrated electronics
- Minimal cabling
- Thin!



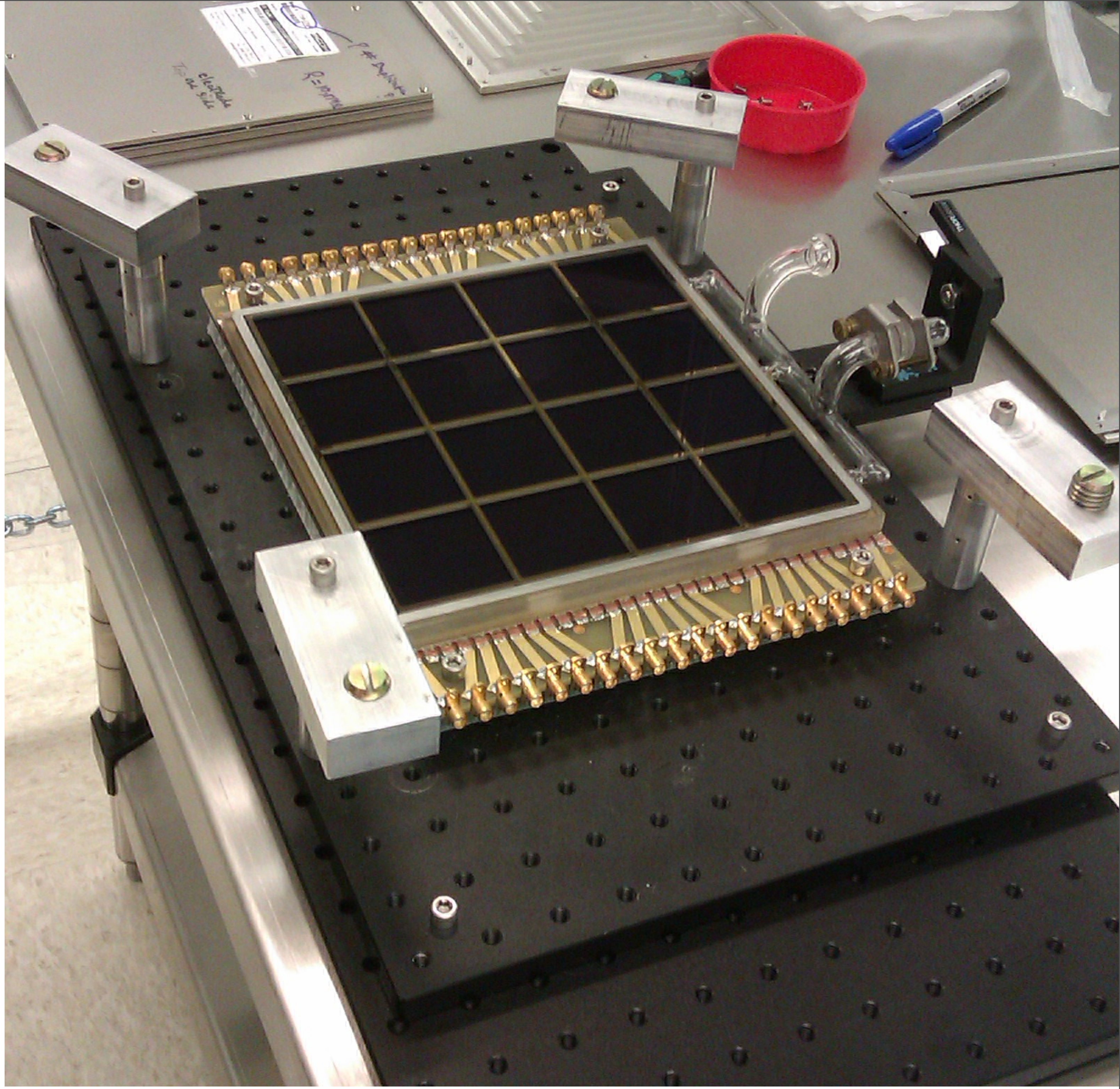
The Big Picture



Tray and Tiles - The Super Module System

Status and Next Steps

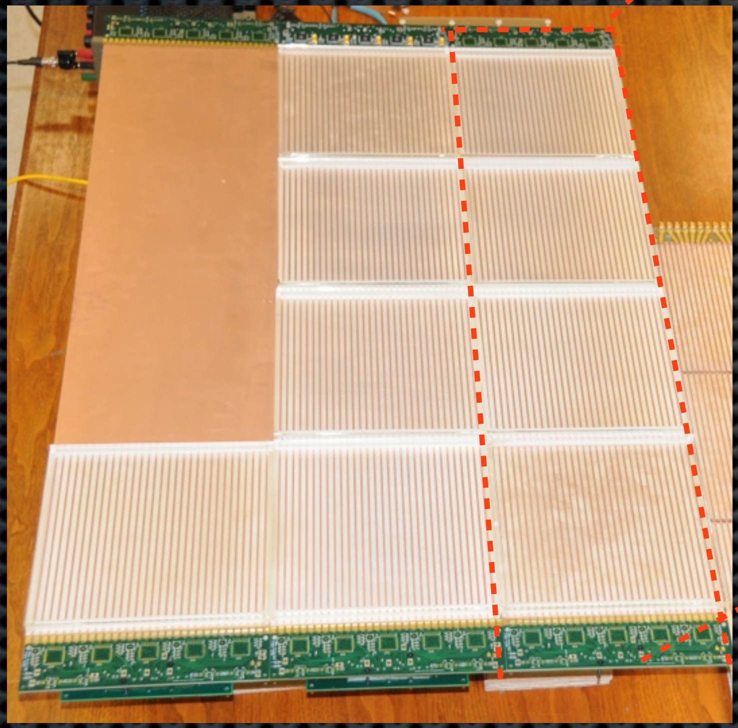
- Many of the individual components are now working
- Next Challenges:
    - Integration
    - Commercialization



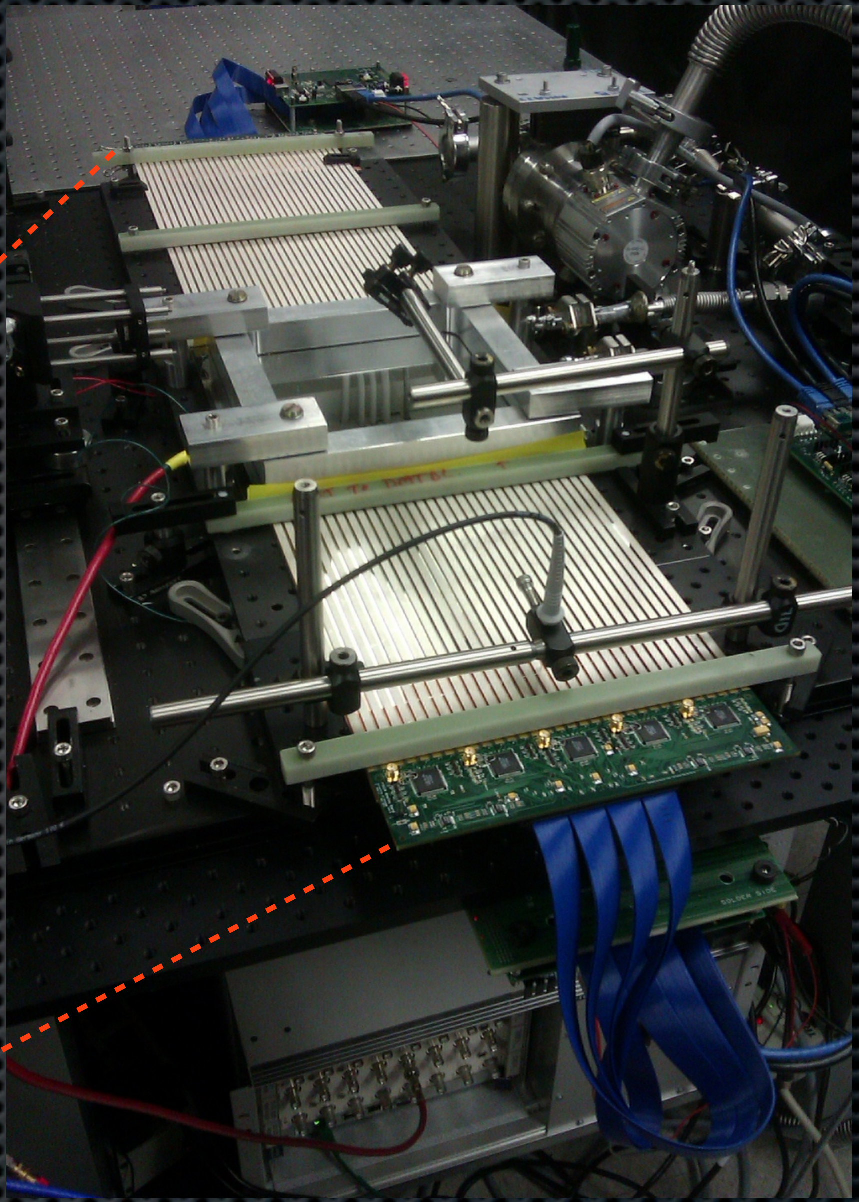
Now testing the "demountable tile":

- Test tile consisting entirely of LAPPD made parts
- Close to a final product except:
    - Aluminum PC
    - Top window sealed with an O-ring
    - Active Pumping
- Active components under vacuum as of this week.

LAPPD Project in pictures...



mock-up of a "Super Module (SuMo)



Testing a working SuMo slice with 90cm anode

Rate Limitations of ALD-MCPs

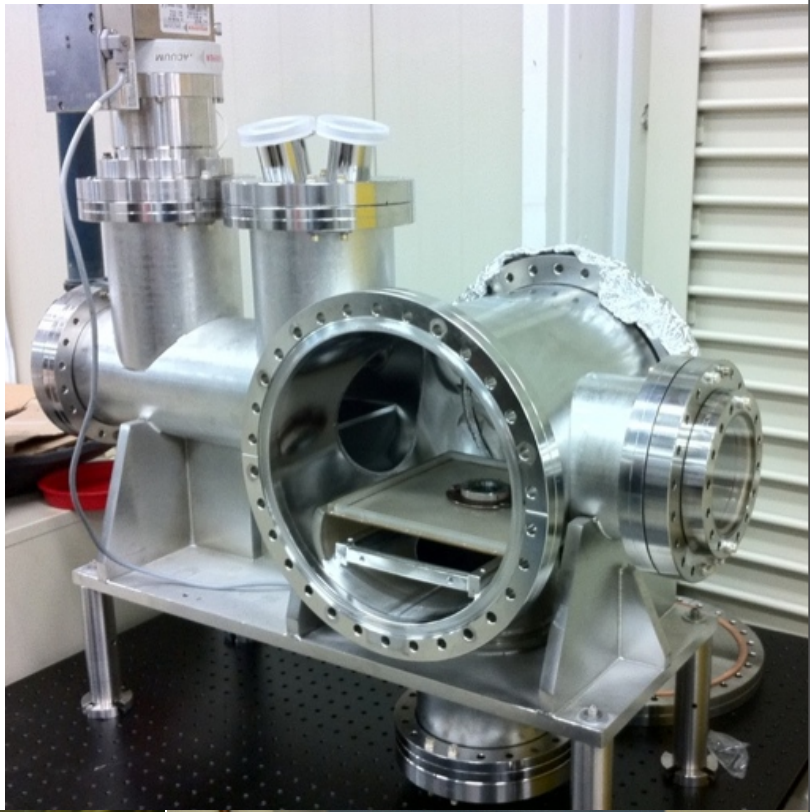
- ALD-based MCPs are expected to perform similarly to commercial plates with comparable parameters.
- Several properties of ALD-MCPs may even be advantageous in high rate contexts
  - Resistance is in the surface not bulk (potentially faster relaxation time):
  - MCPs are made of pure materials (potentially less ion feedback, longer photocathode lifetimes)
  - MCP gain behavior seems more stable with time (so far)
  - **This needs to be tested**

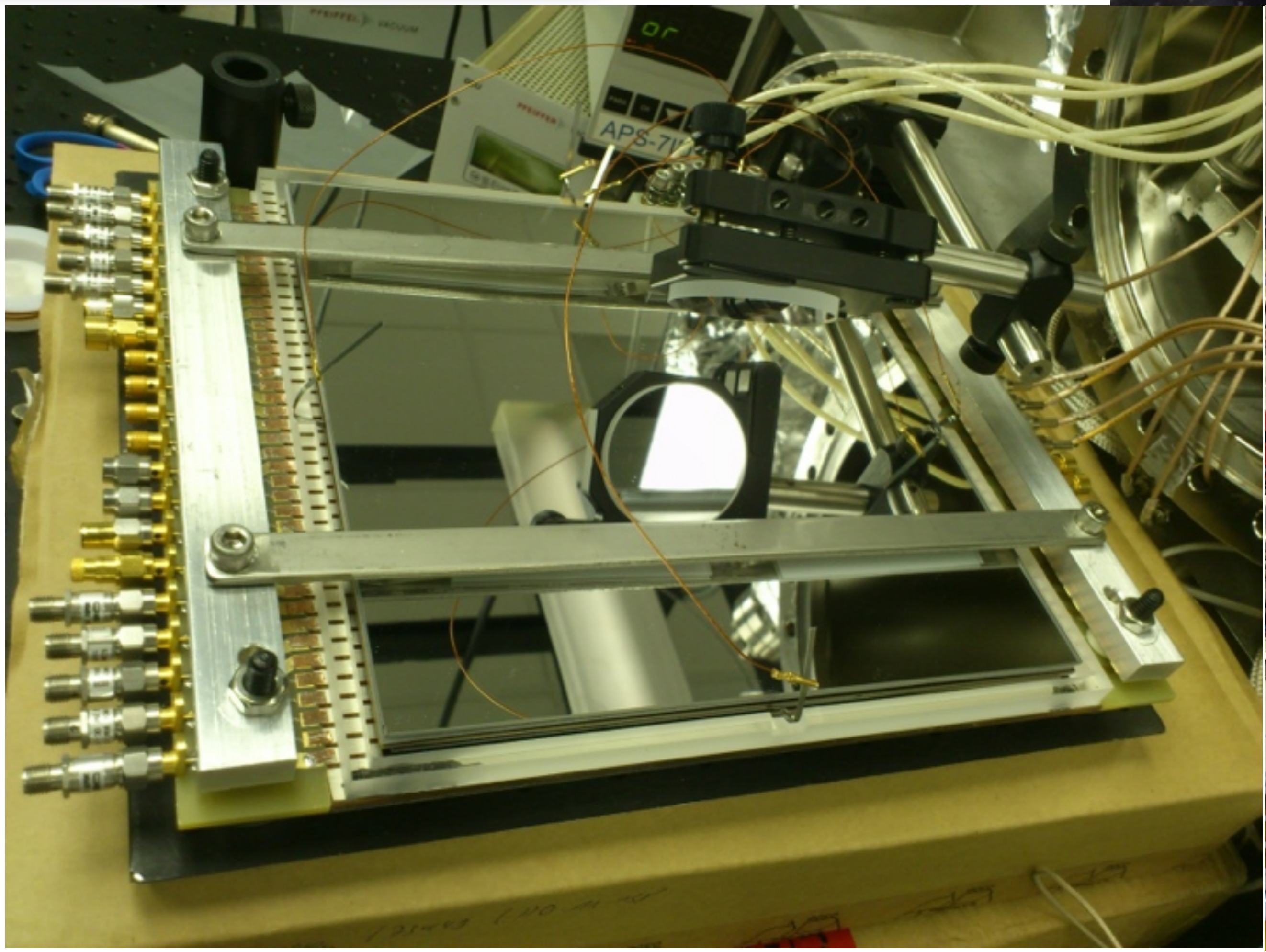
A random smattering of backup slides

mm

8” Program

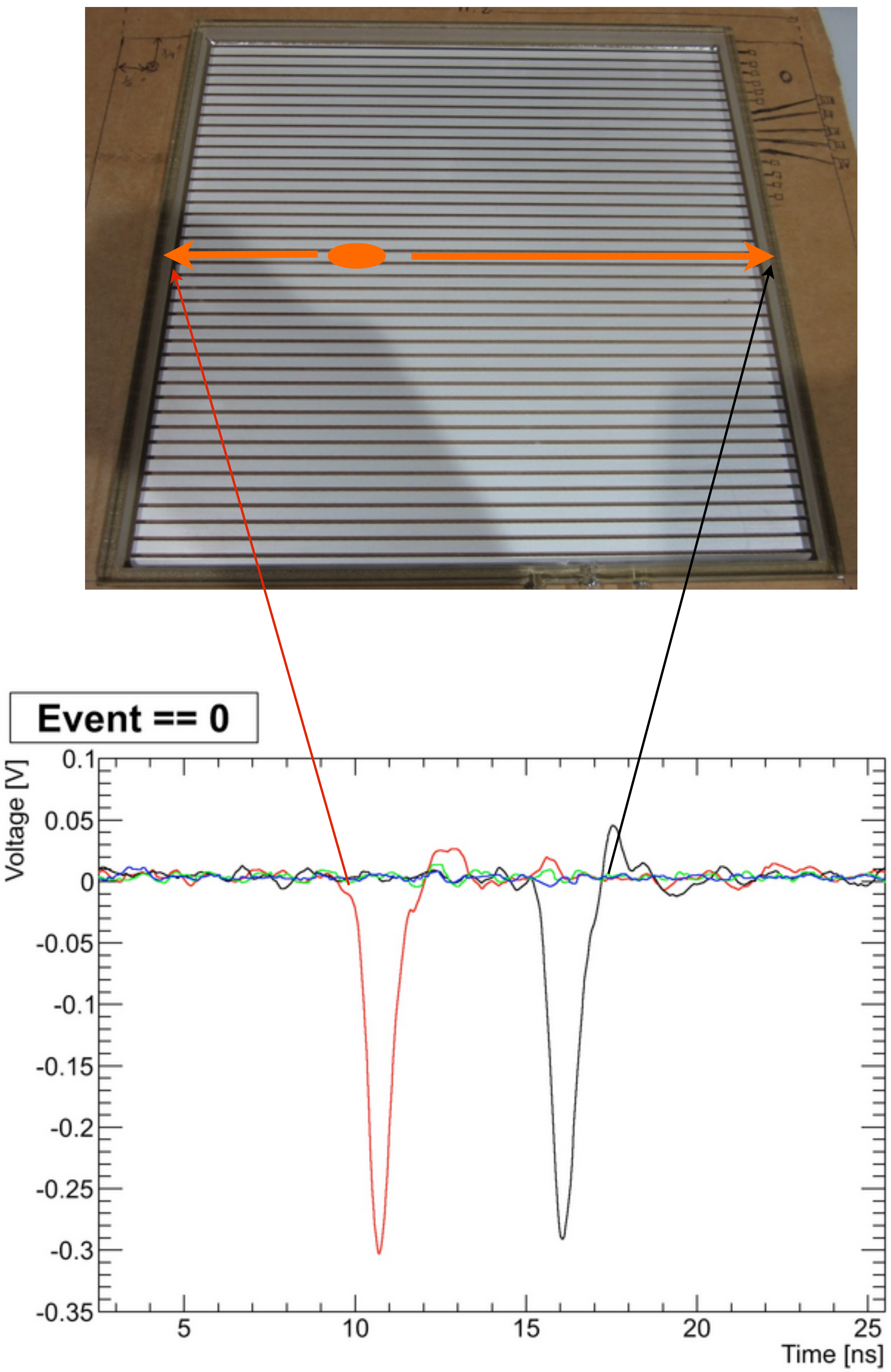
- To demonstrate full-sized detector systems.
- To study operation with the “frugal anode” design (silk-screened silver microstrip delay lines)
- To benchmark some of the key resolutions to be expected in sealed-glass LAPPDs



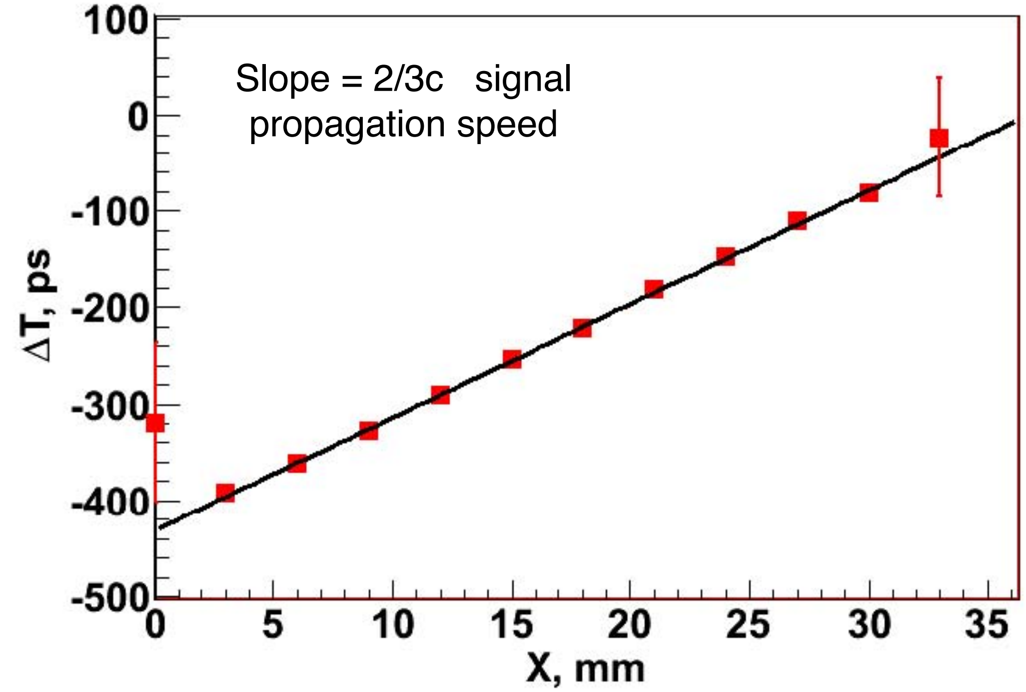


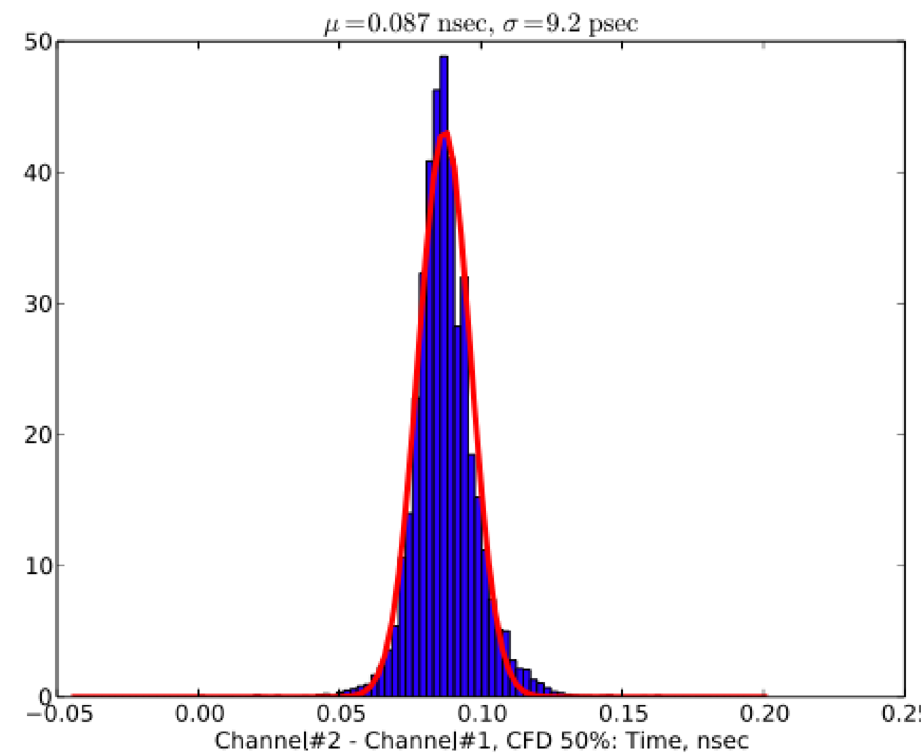
8” Program

Photon position is determined by signal centroid in the transverse direction and difference in signal arrival time in the parallel direction.



Difference in arrival time as a function of laser position

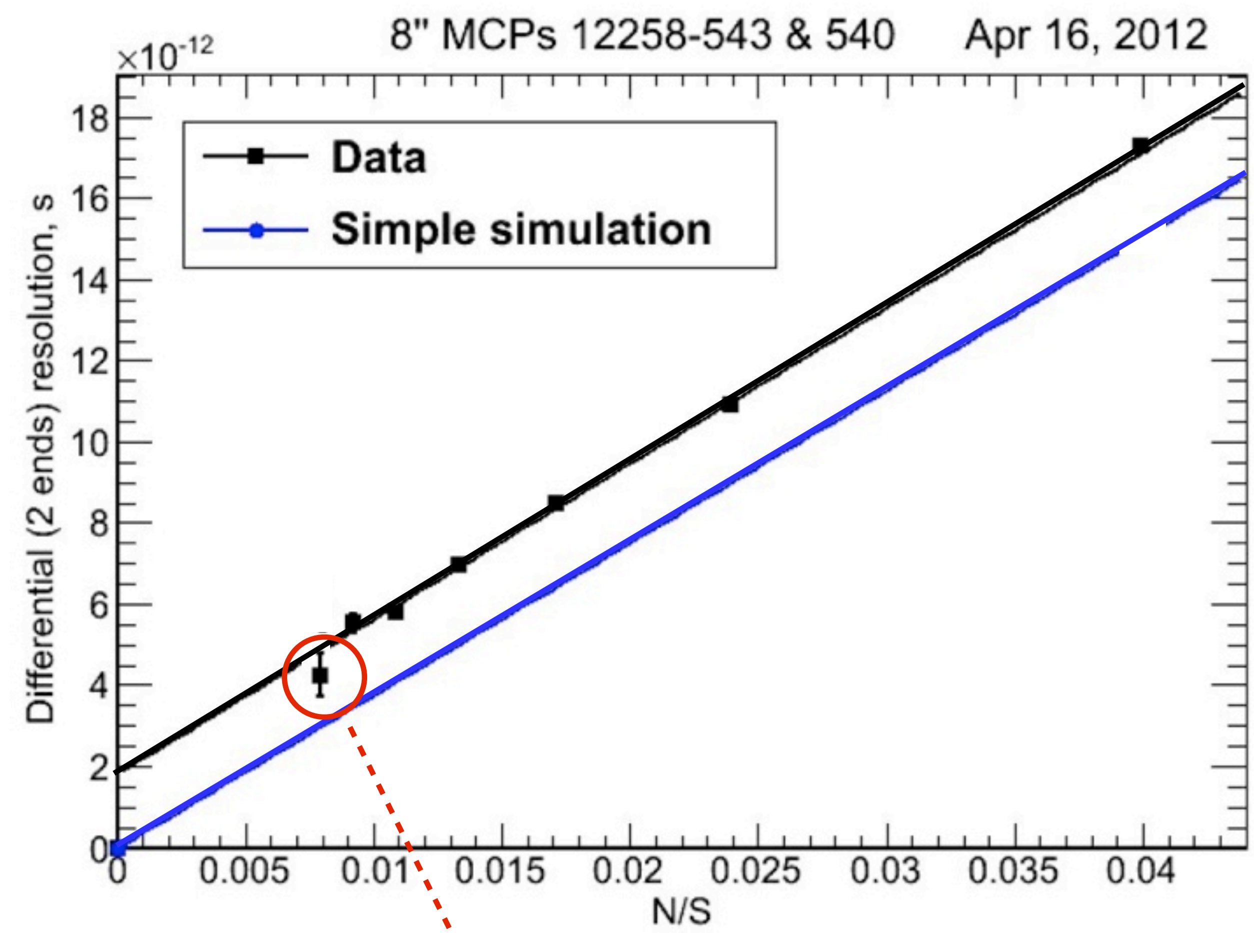


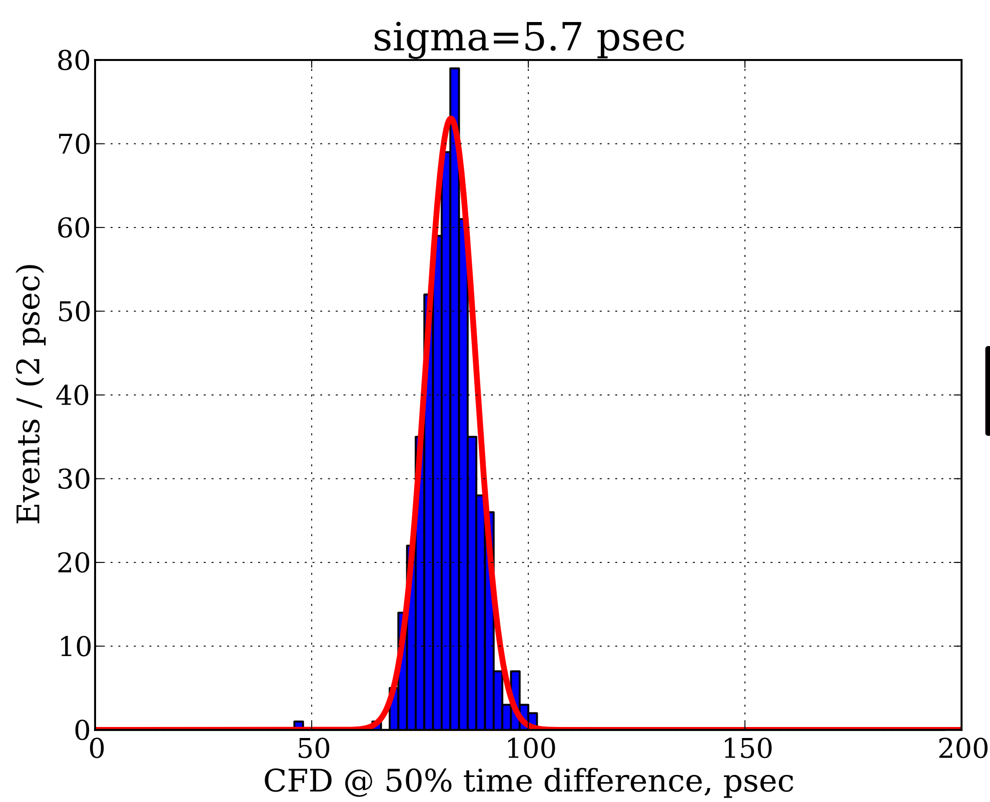


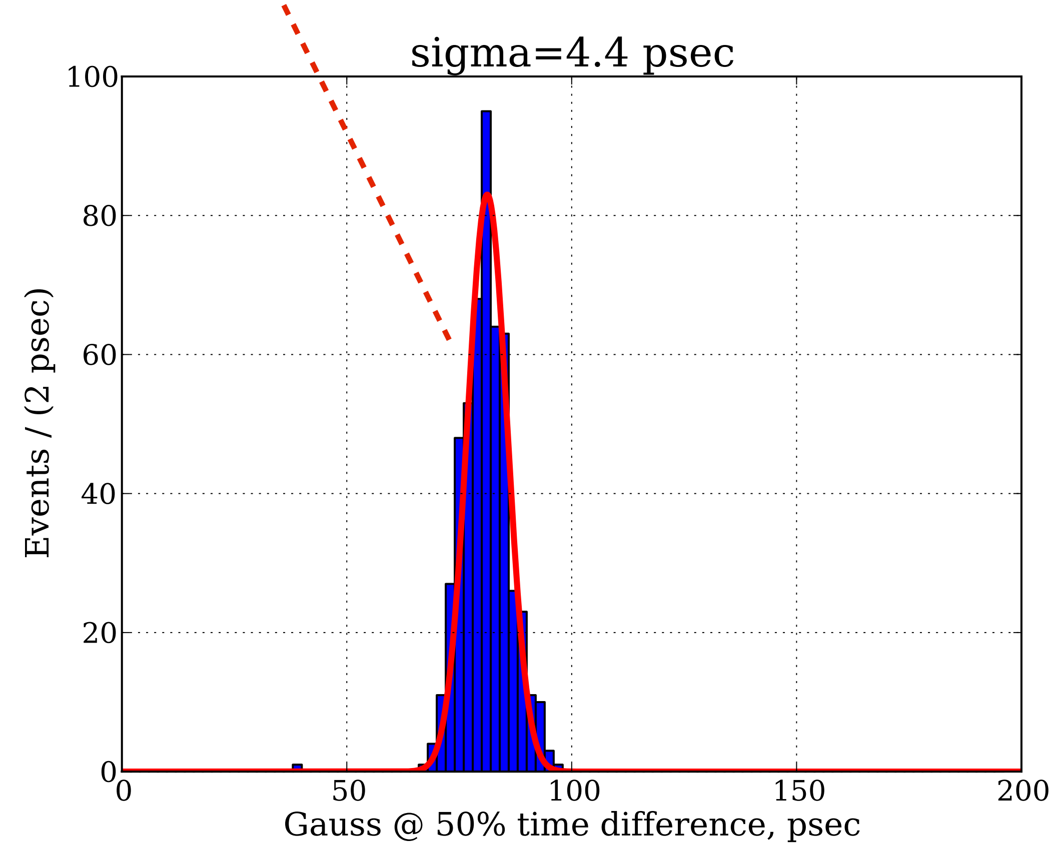
Differential time resolution between two ends of an optimized anode (~10 PE): ~9 psec (~1mm)

8” Program

With improved fitting to the rising edge of the MCP pulses, we reconstruct an even narrower TTS!

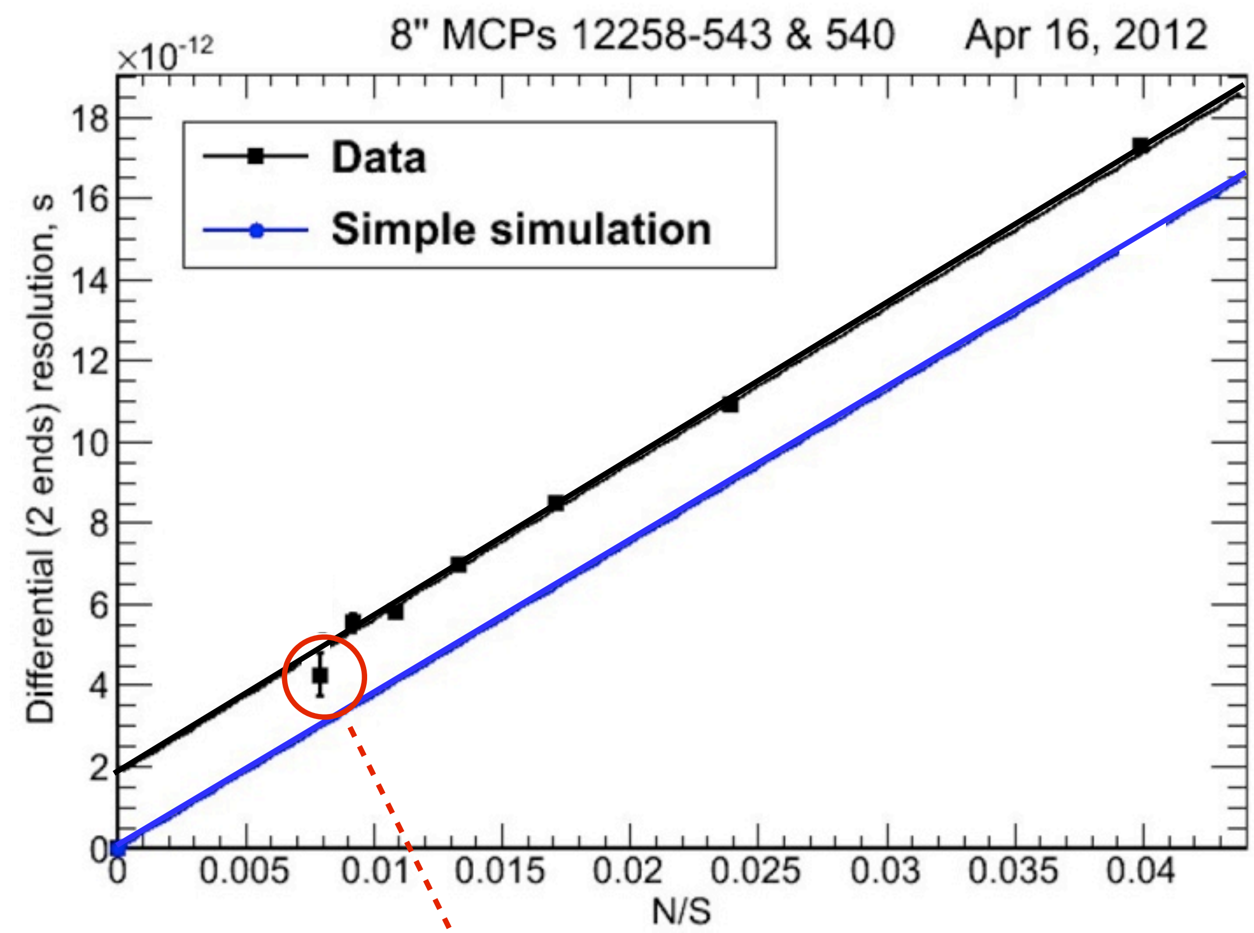




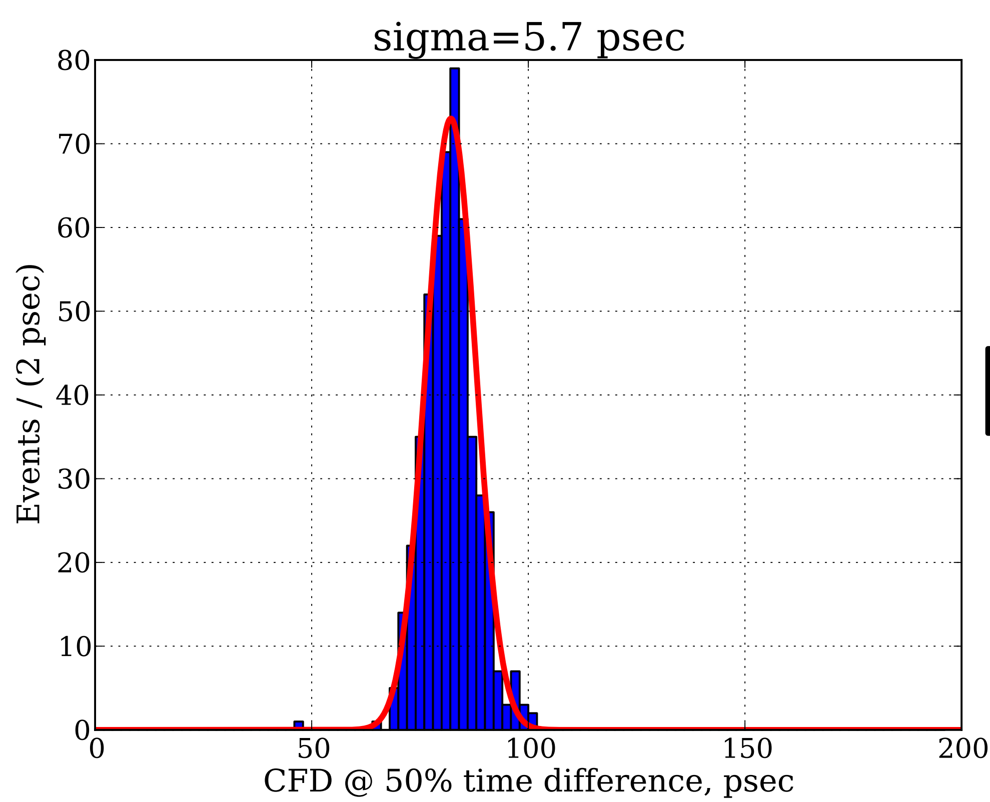


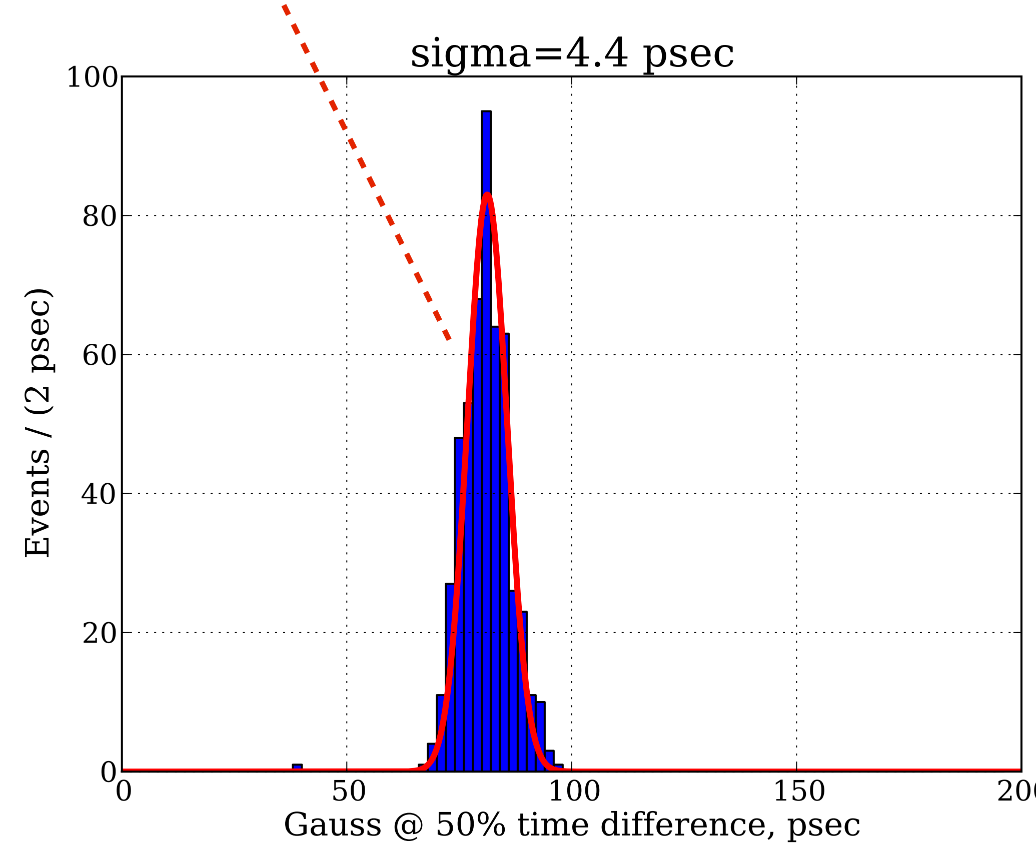
8” Program

With improved fitting to the rising edge of the MCP pulses, we reconstruct an even narrower TTS!



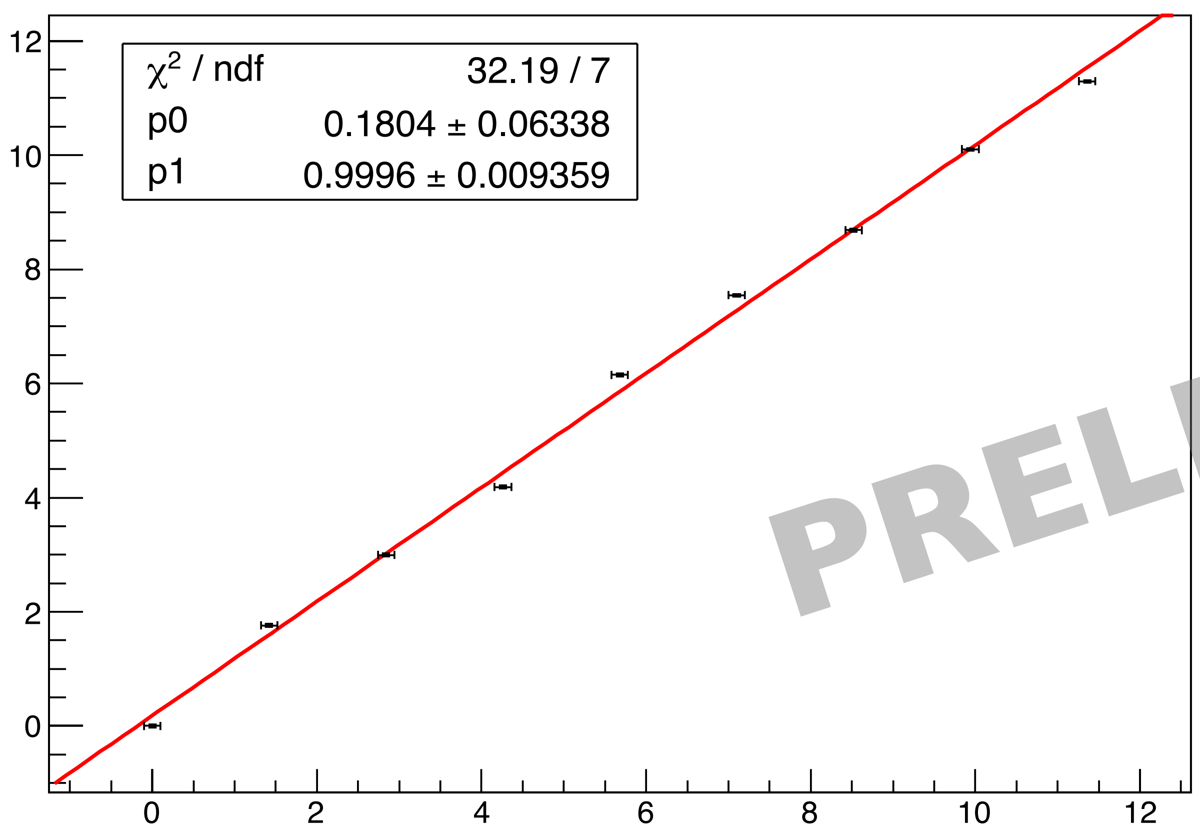
Currently editing the rough draft of a NIM paper on first 8”x8” results

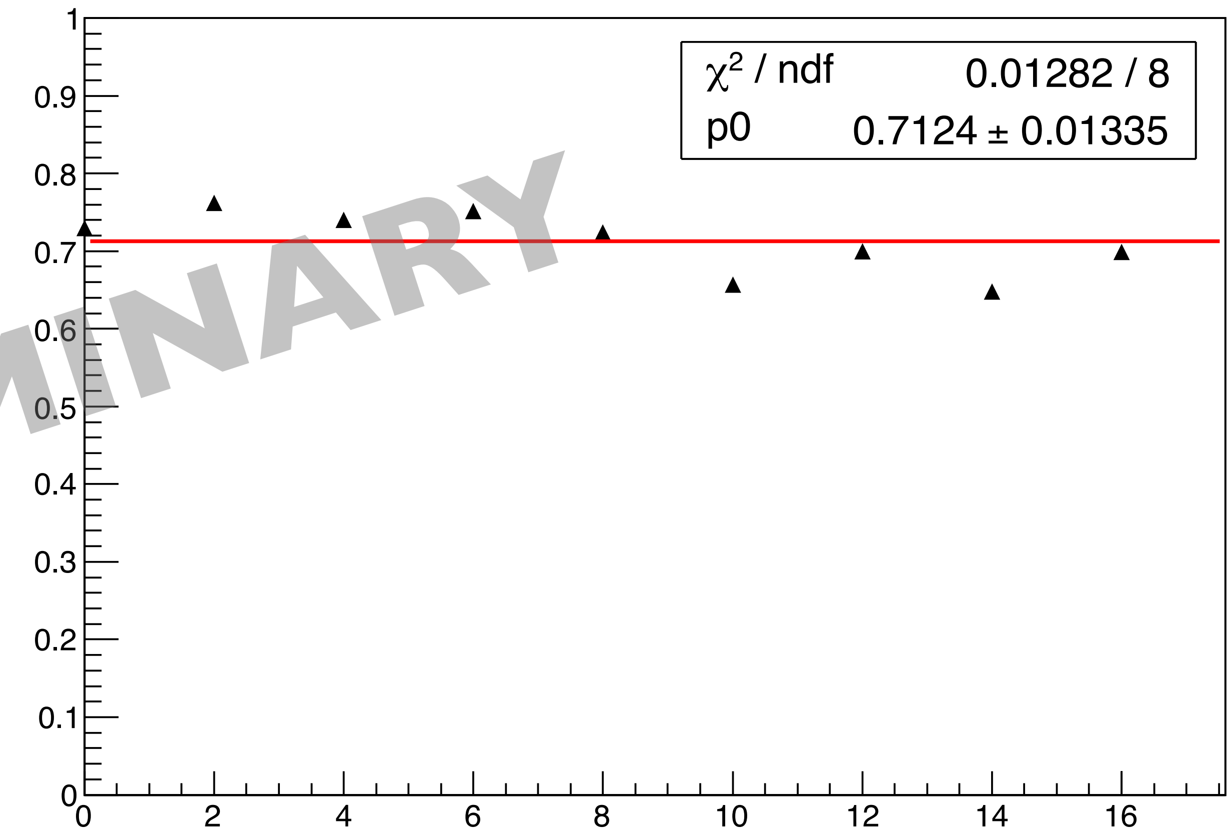




SuMo Slice – Full PSEC Readout

Position in the transverse direction, reconstructed even using a naive, out-of-the-box 5-strip centroid algorithm gives us resolutions consistently below 1 mm.

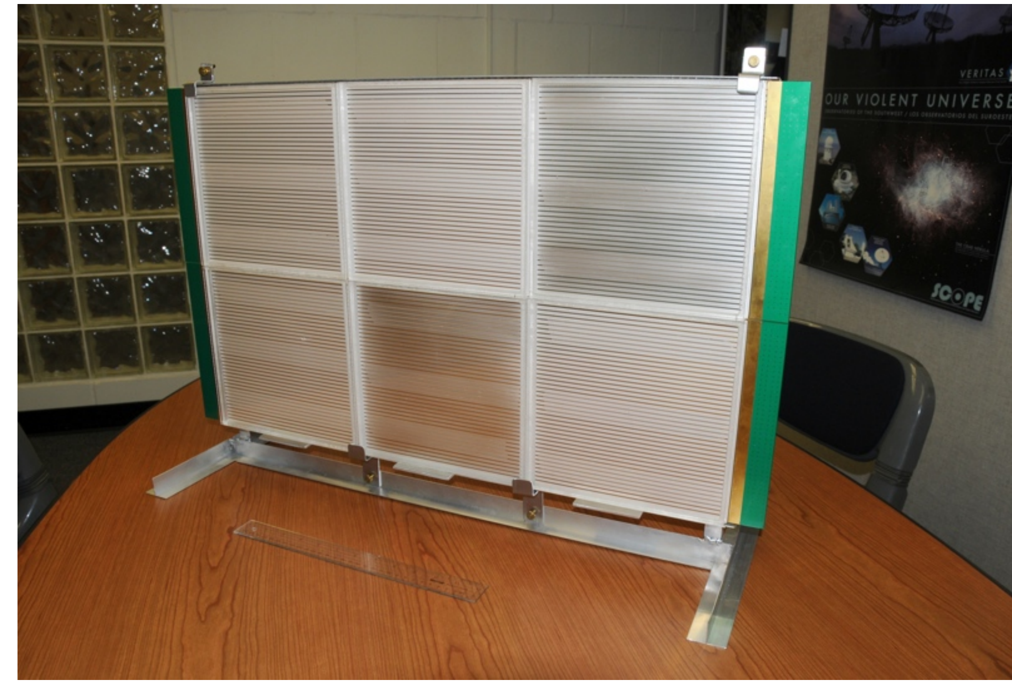




New Developments in Water-Based Detectors: Large Area, High Resolution MCP-PMTs

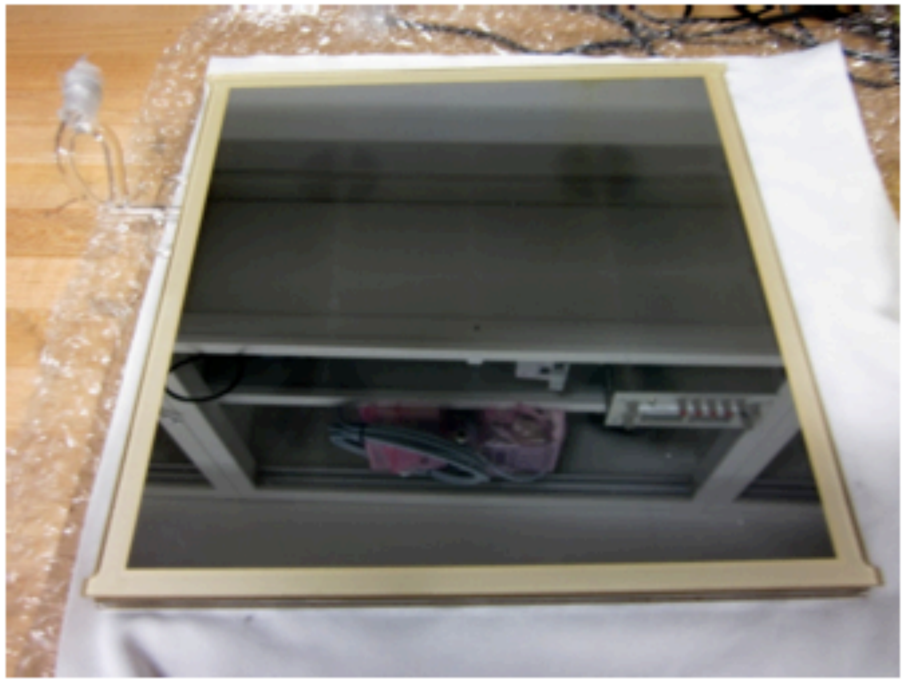
LAPPD (Large-Area Picosecond Photodetector) Project:

Make large-area MCPs with low-cost, bulk materials and batch industrial techniques



- We're attacking all aspects of this problem from the photocathode to the MCPs to vacuum sealing technology
- Goal is not just proof of principle...It's the development of a commercializable product.

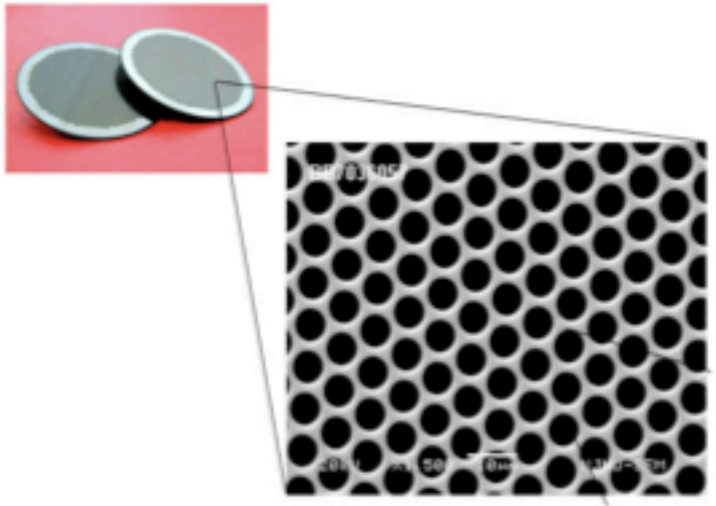
Reinventing the unit-cell of light-based neutrino detectors



- 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

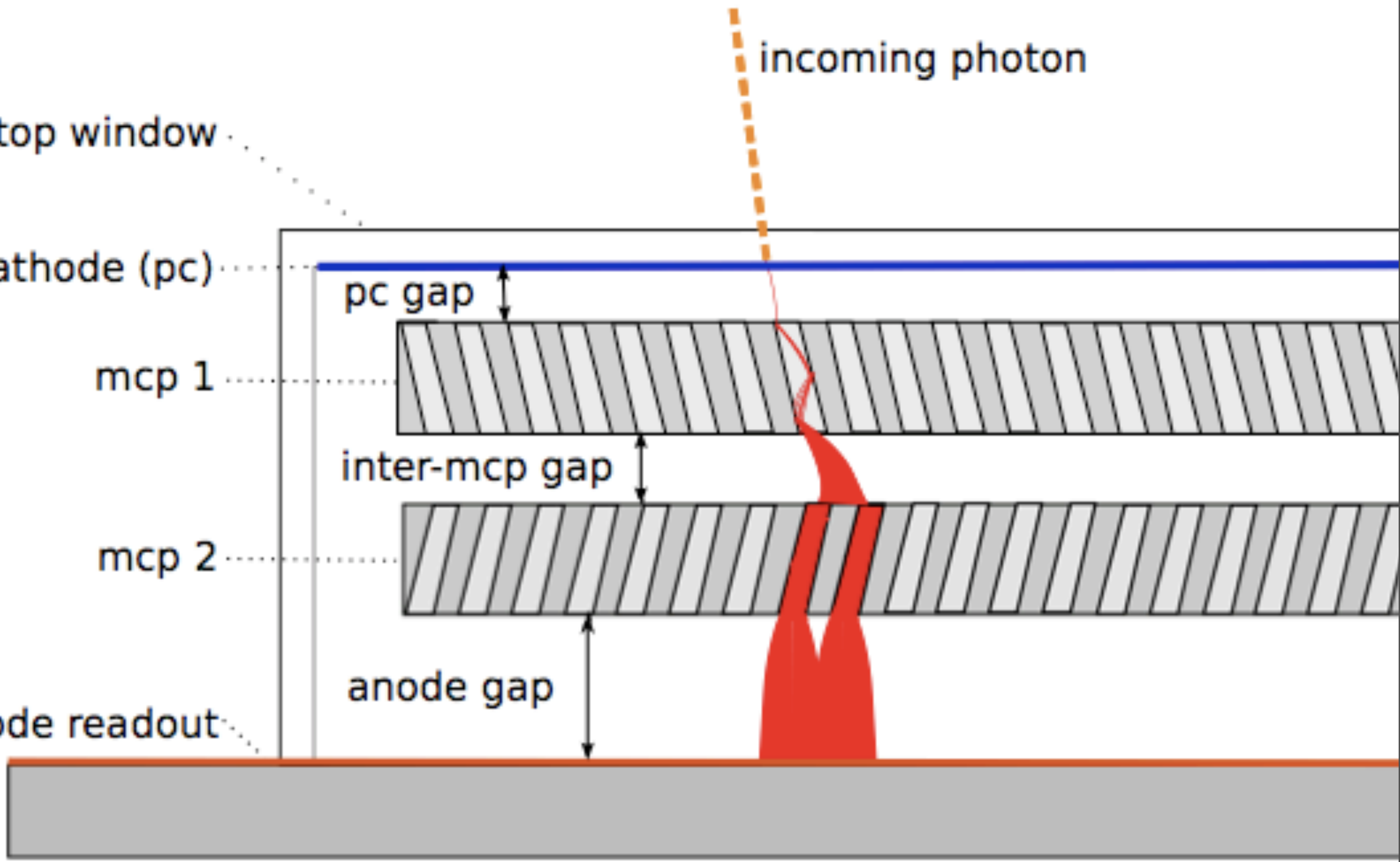
What is an MCP-PMT?



Microchannel Plate (MCP):

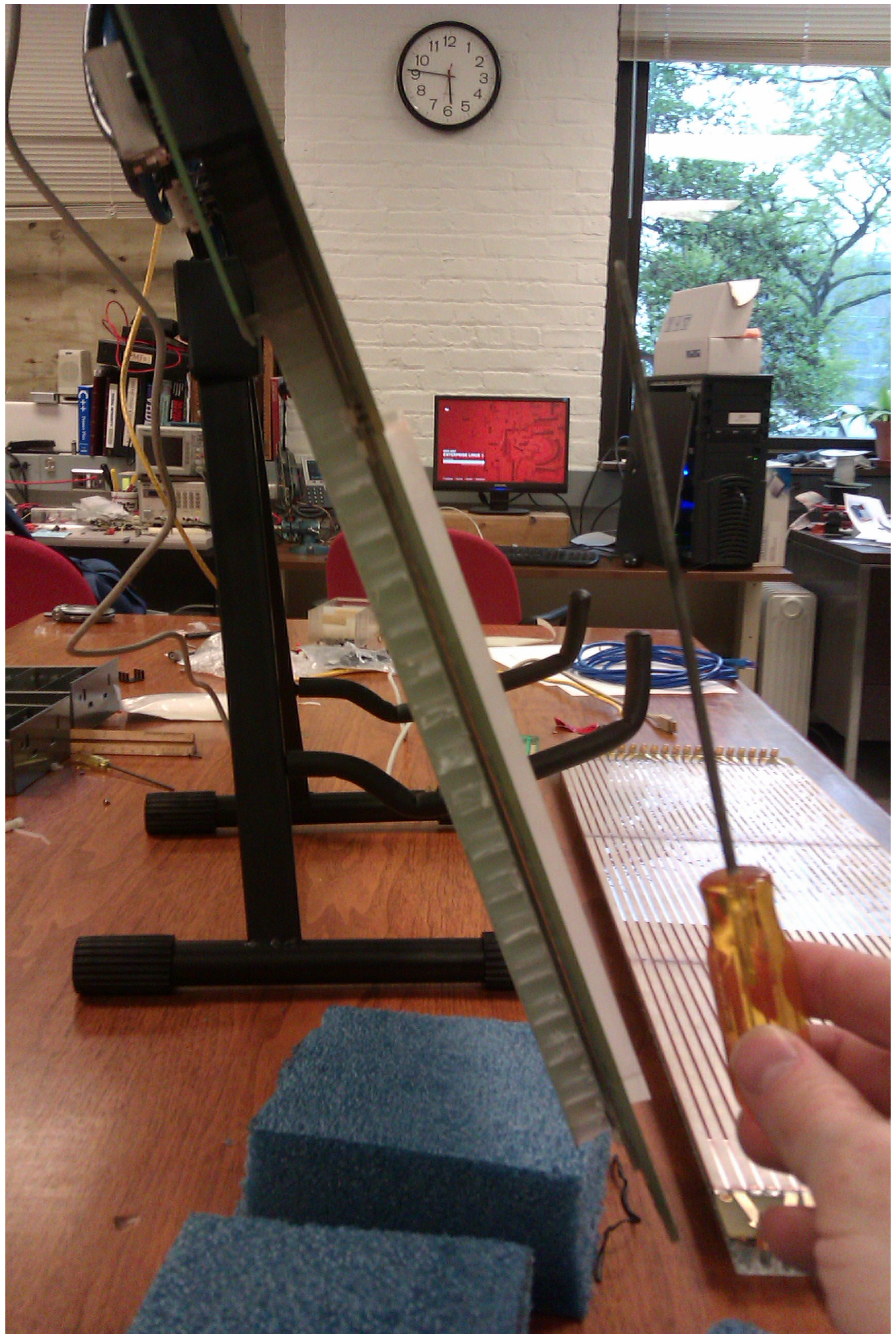
- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- 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



Advantageous Characteristics for Neutrino Detection

Compactness



Excellent Photon Counting

Don't need to rely on charge only:

- **Can see individual photons based on where and when they hit.**
- **Could mean improved energy resolution.**

Operation in a Magnetic Field

MCPs can operate in a magnetic field. Bend magnets could be used to determine sign.

Geant4 simulations: Tracks at $1 \times 1 \times 4$ m

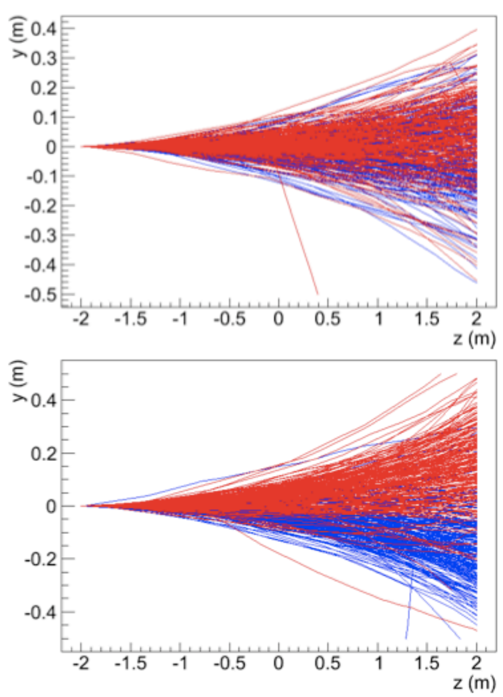


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

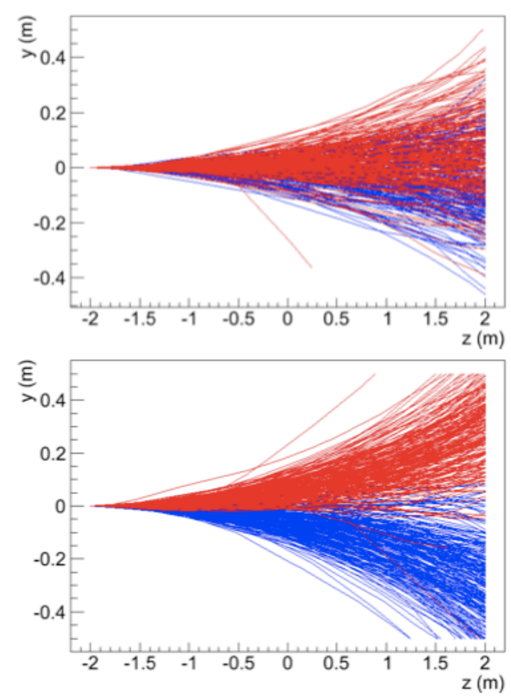


Figure: $B = 200$ gauss (top), $B = 1$ kgauss (bottom).

Geant4 simulations: Naive resolution at $1 \times 1 \times 4$ m

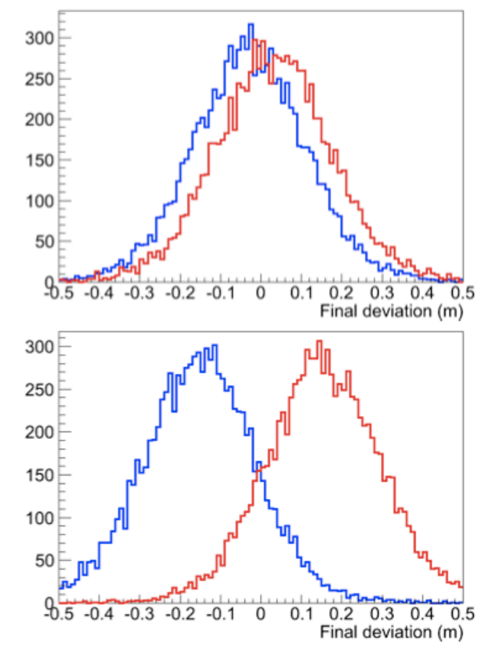


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

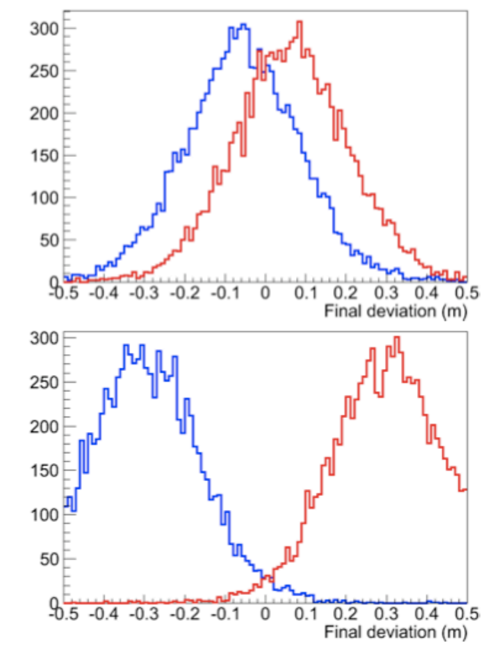
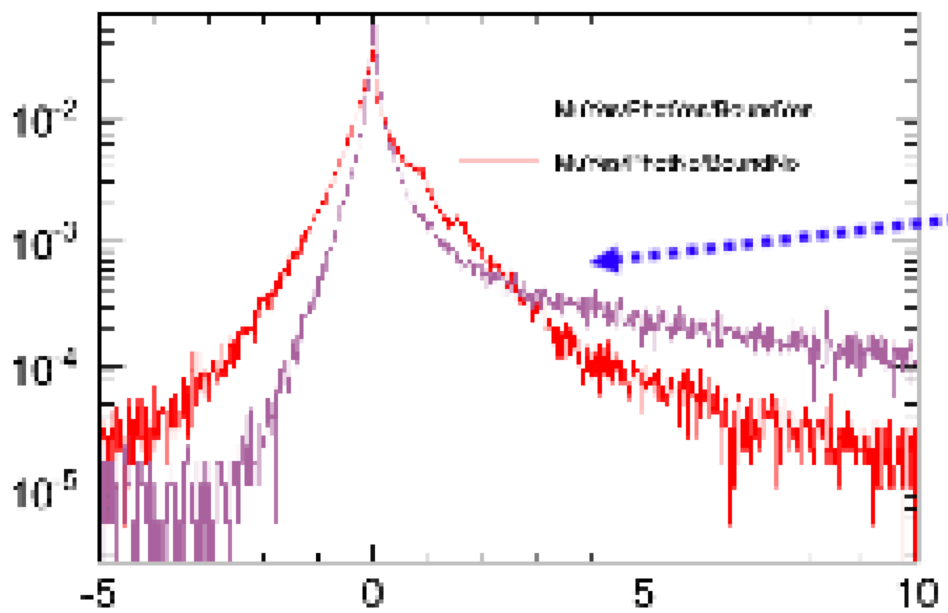


Figure: $B = 200$ gauss (top), $B = 1$ kgauss (bottom).

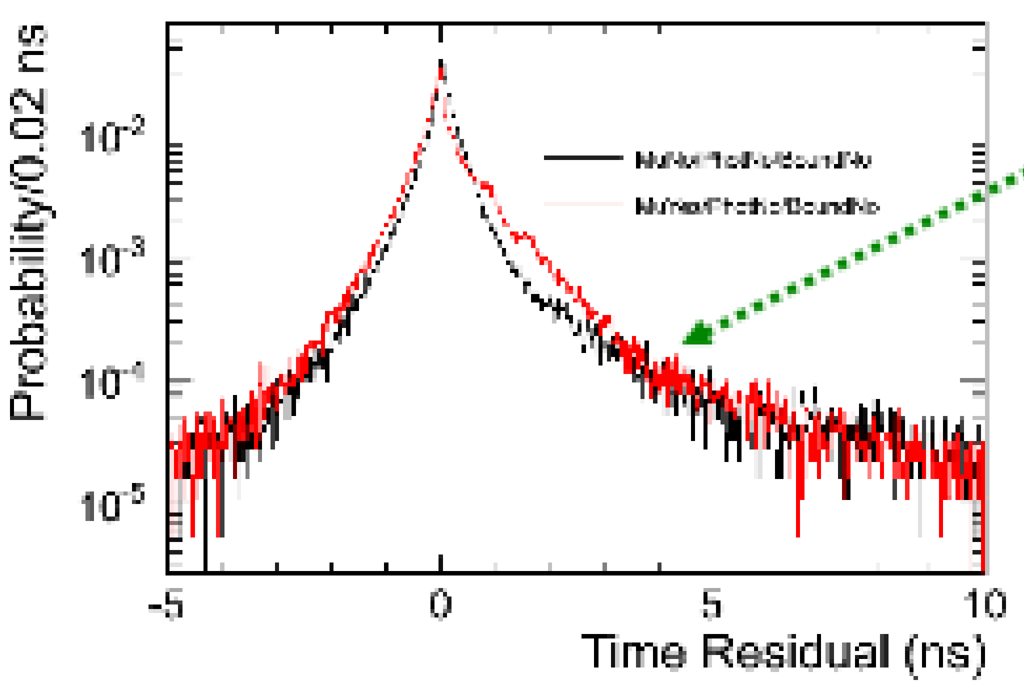
Work by Alexander Vostrikov (U. Chicago)

Timing and Spatial Resolution – Imaging Capabilities

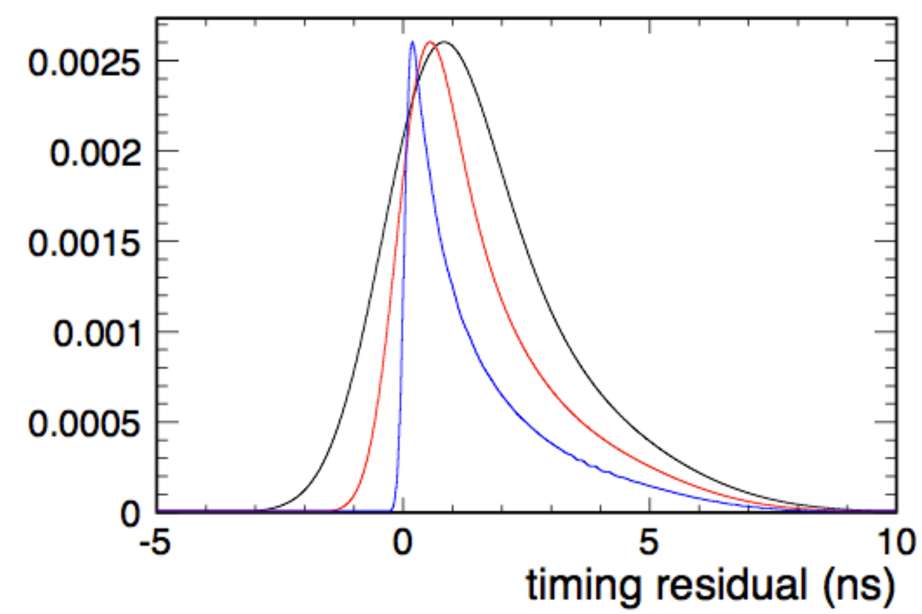


Optical scattering broadens the tail of the timing residual but sharpens the rising edge

Forward scattering of muons can have shape effects on the timing resolution.

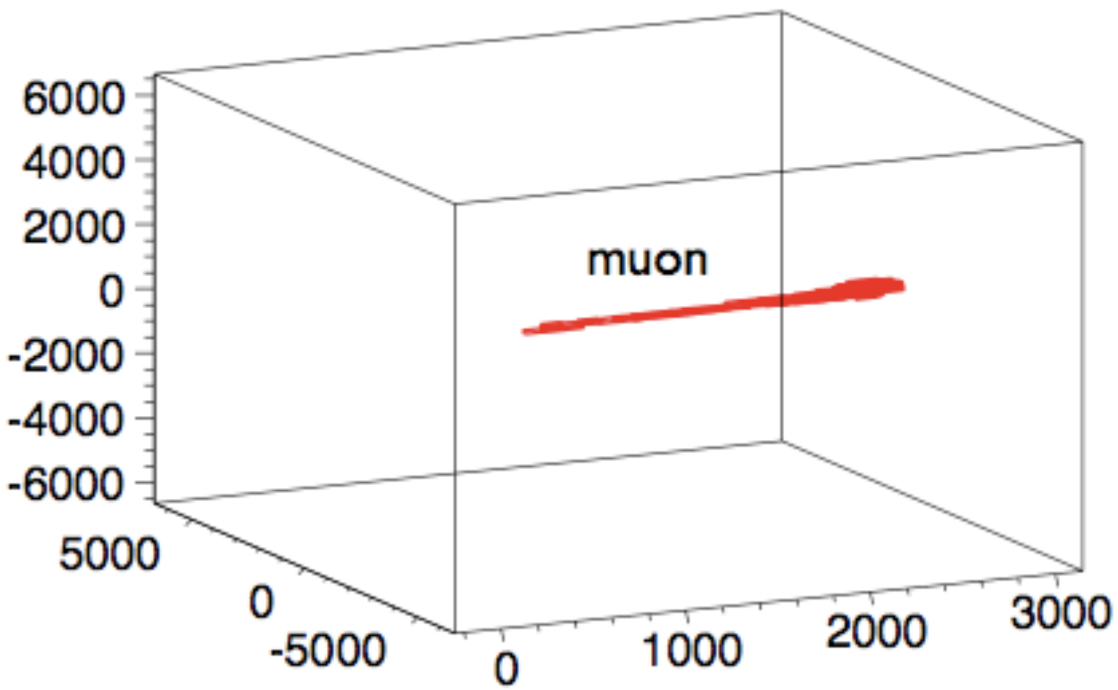


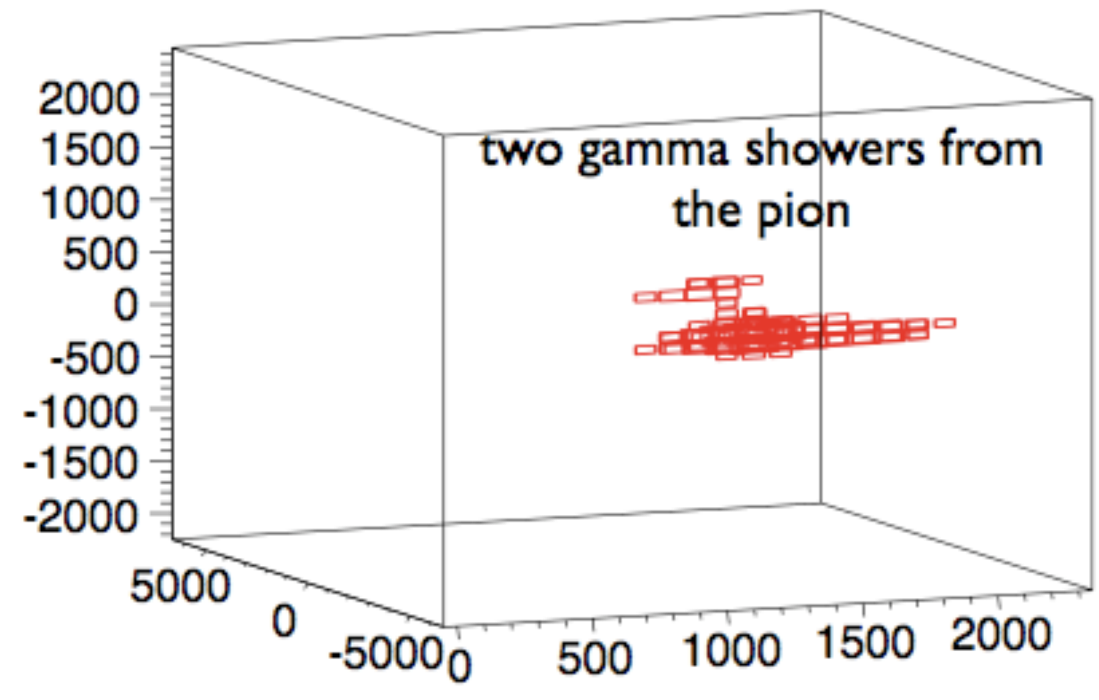
Shape of rising edge depends on distance and color composition, as well as detector resolution

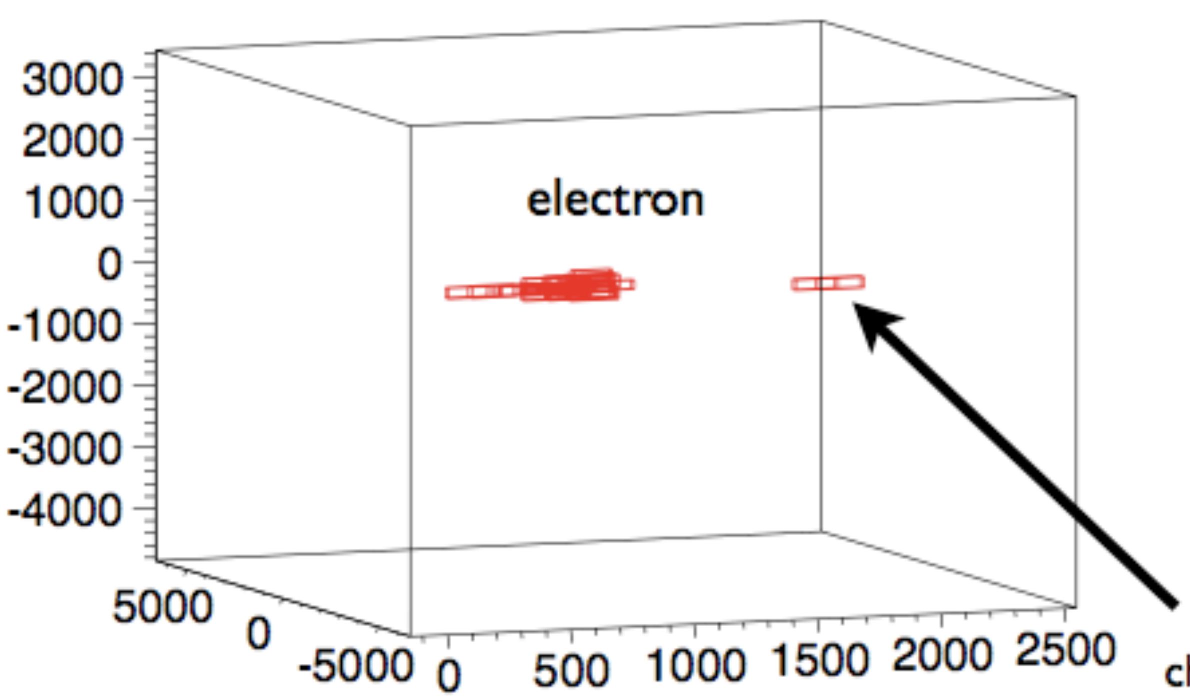


Work by Tian Xin (Iowa)

Reconstructing Geant Events



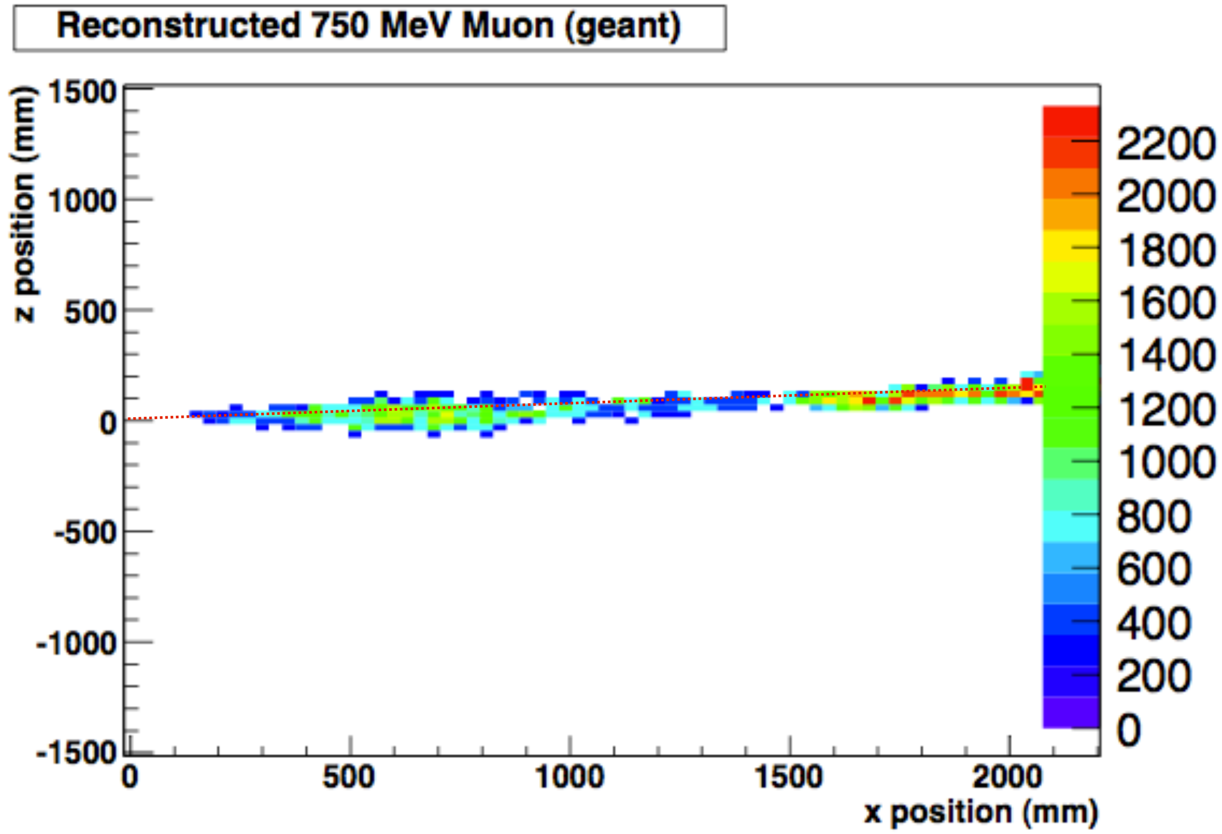


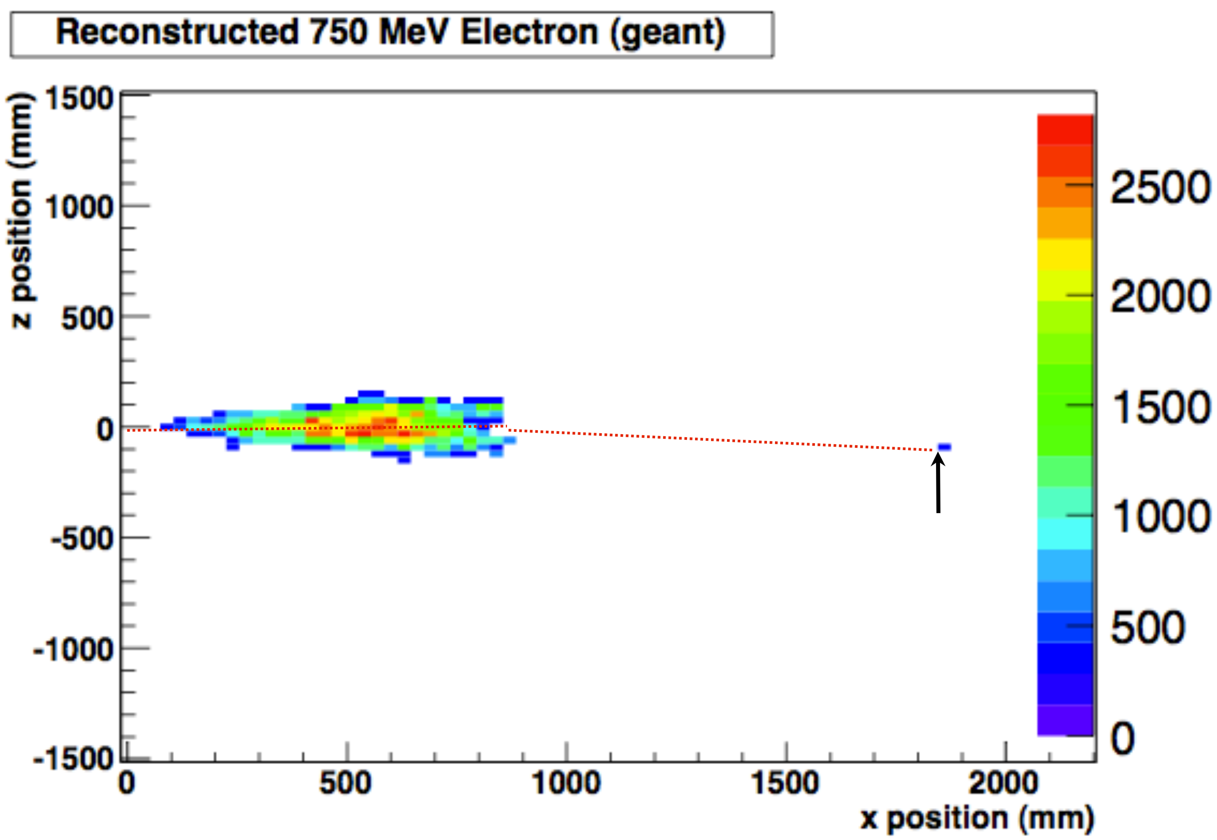


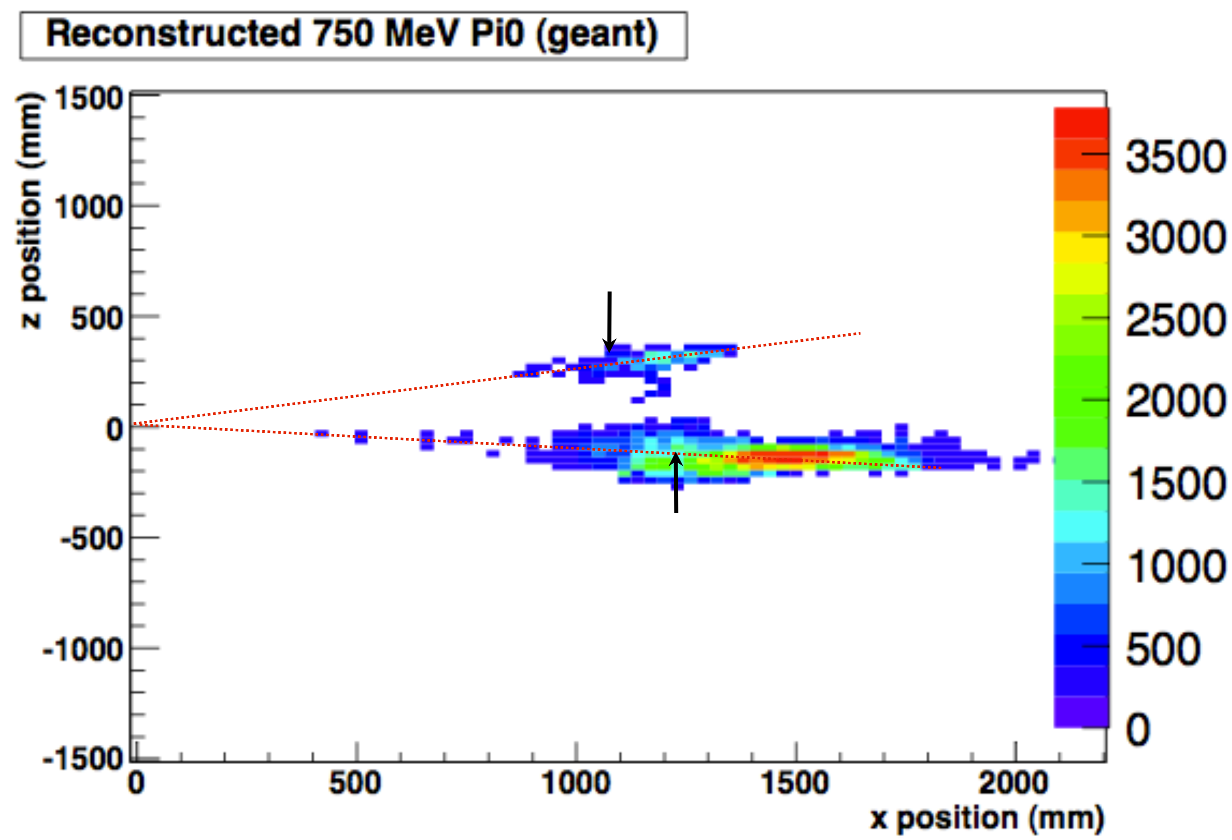
check out the detached shower from the bremstrahlung!!!

Comparing Isochron Reconstruction....

If I hand draw track hypotheses through these transforms...

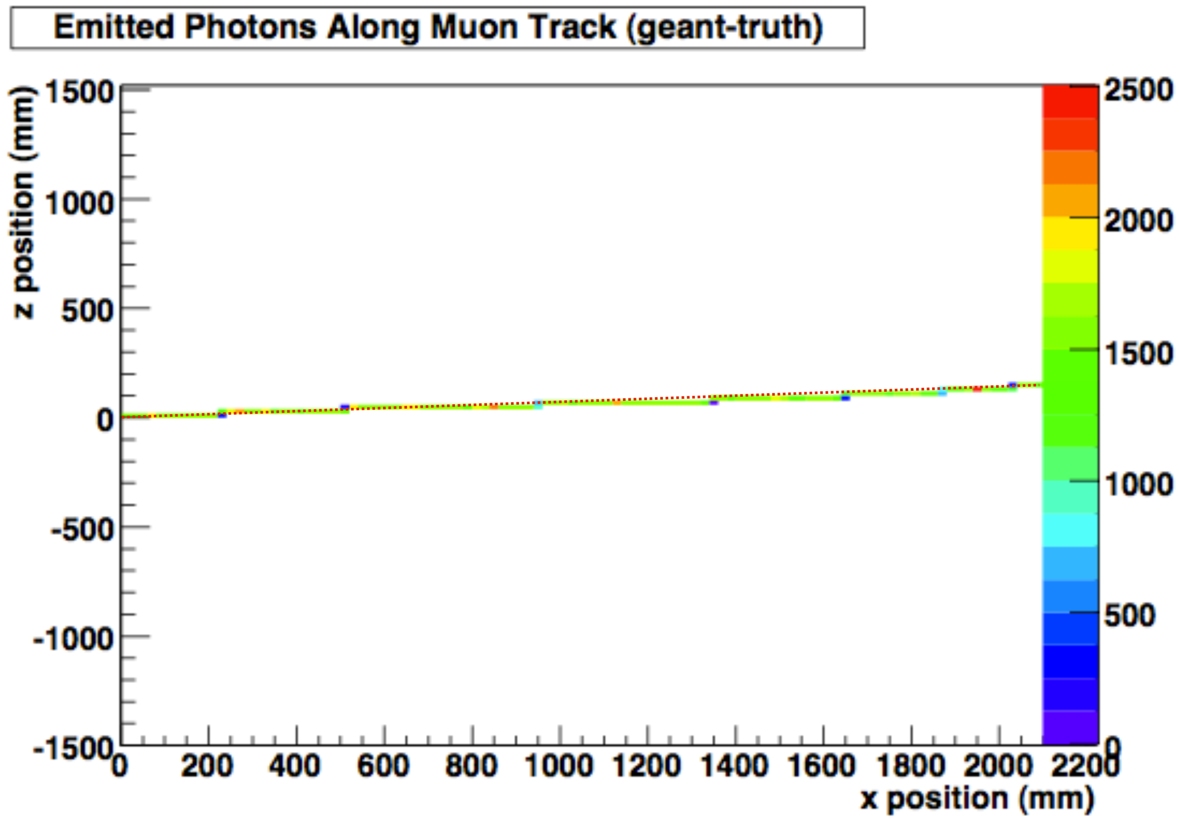


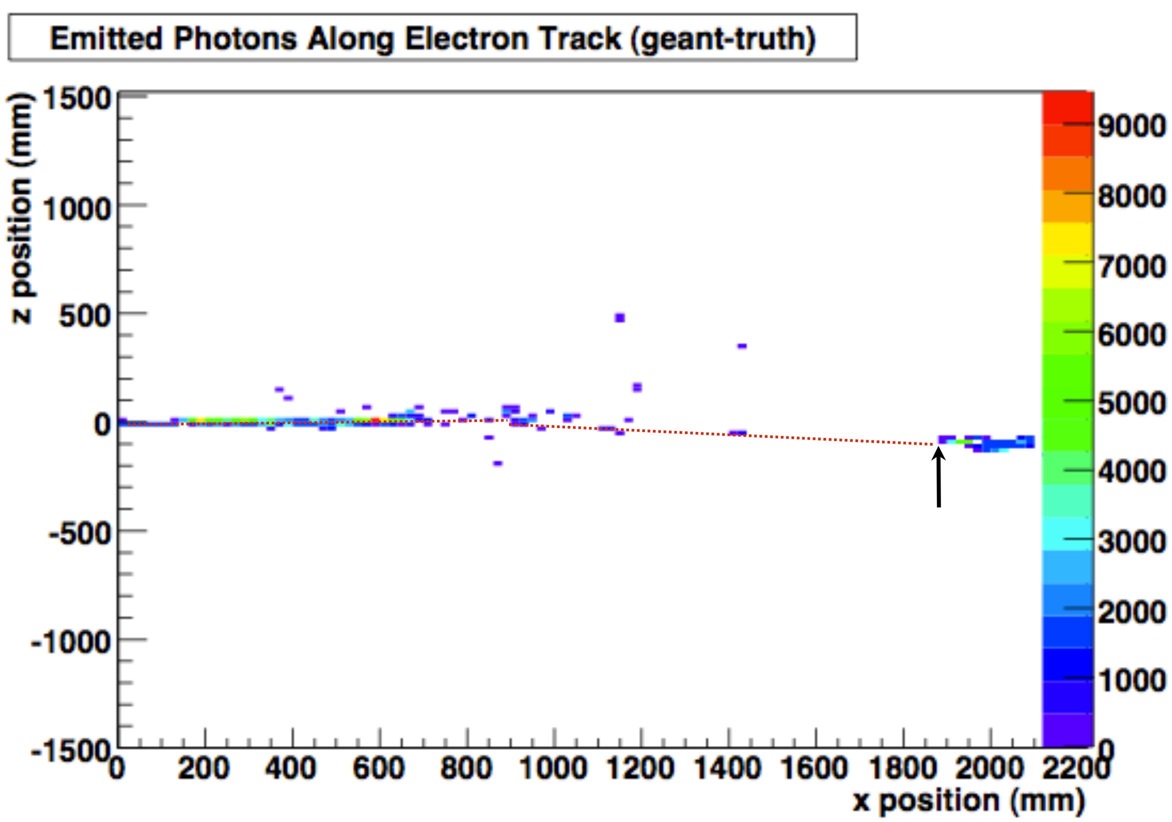


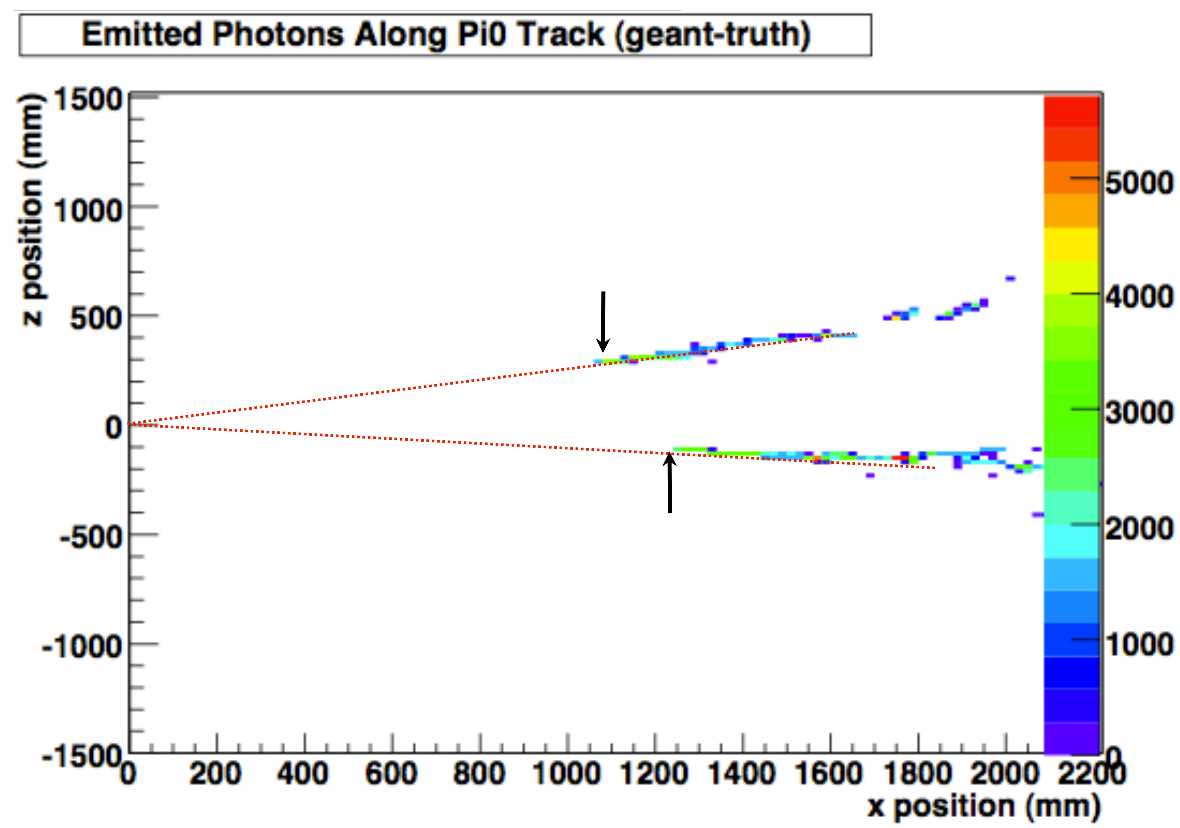


With True Tracks

They match very nicely with the truth-level tracks/shower constituents



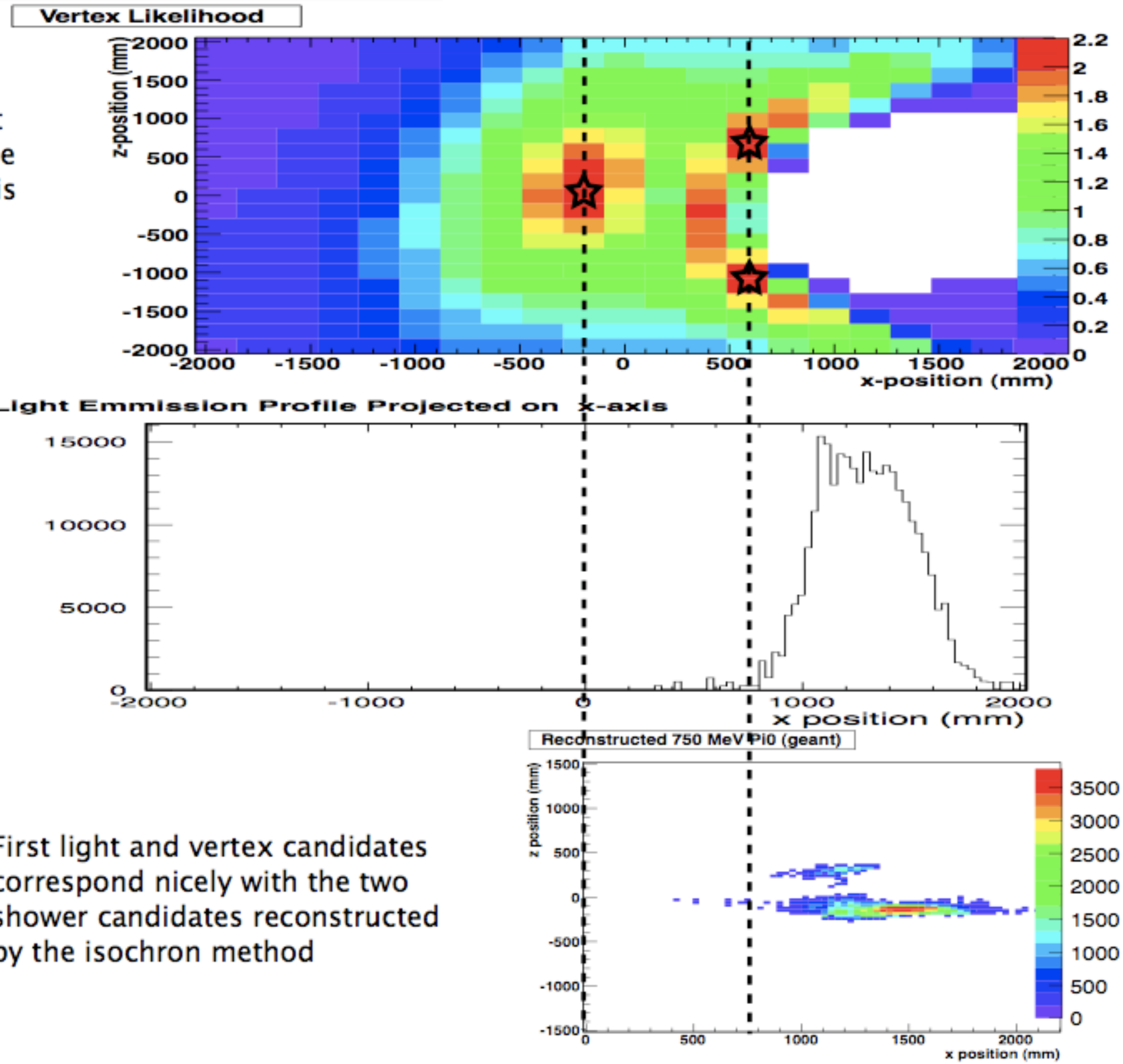




Vertex Separation As A Handle on PID

Pi0

We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.



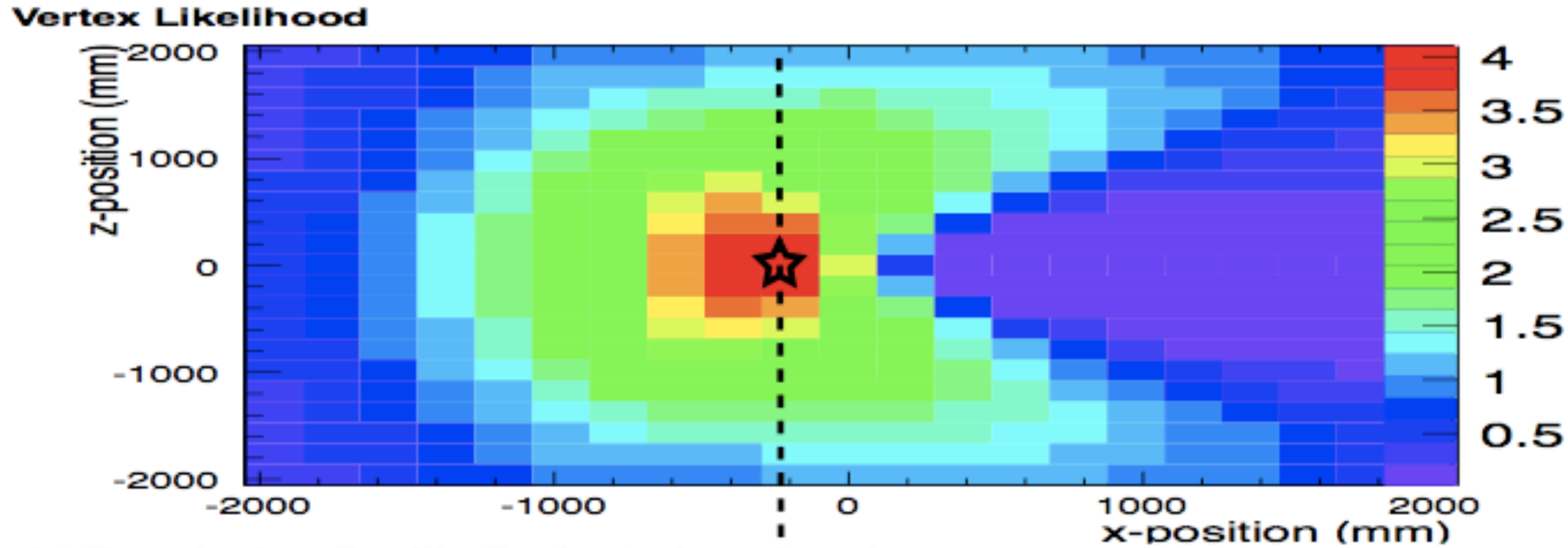
Location of the candidate vertices do not correspond perfectly to true vertices, probably due to an inappropriate choice of refractive index.

First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method

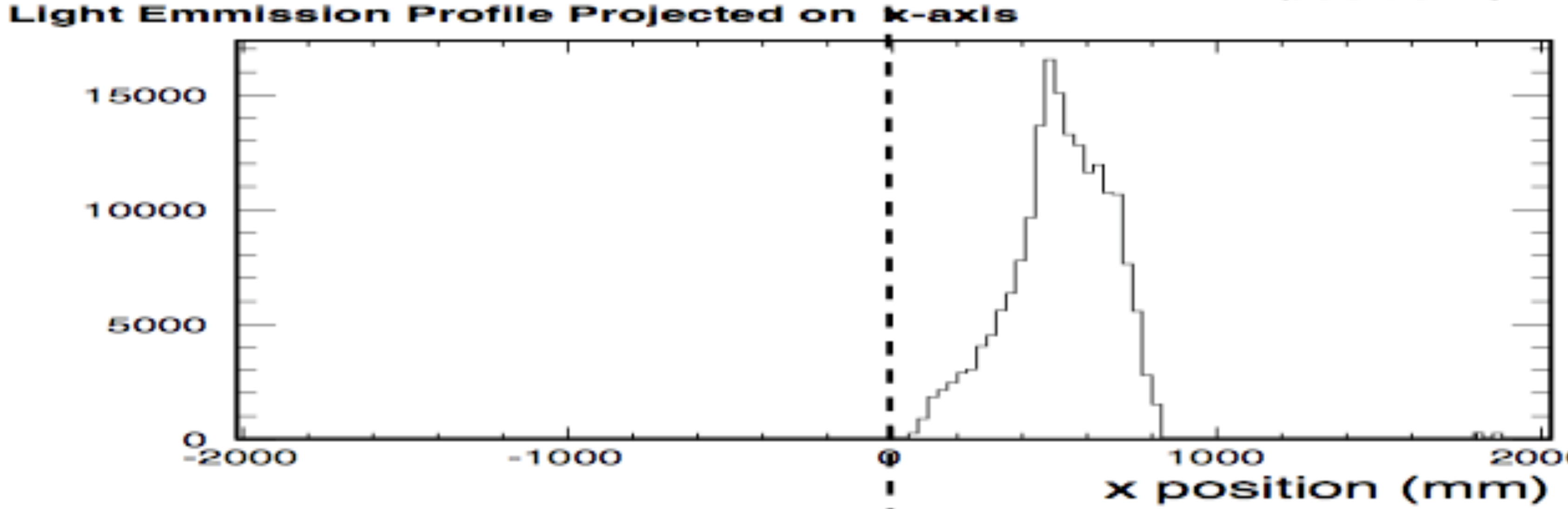
Vertex Separation As A Handle on PID

Electron

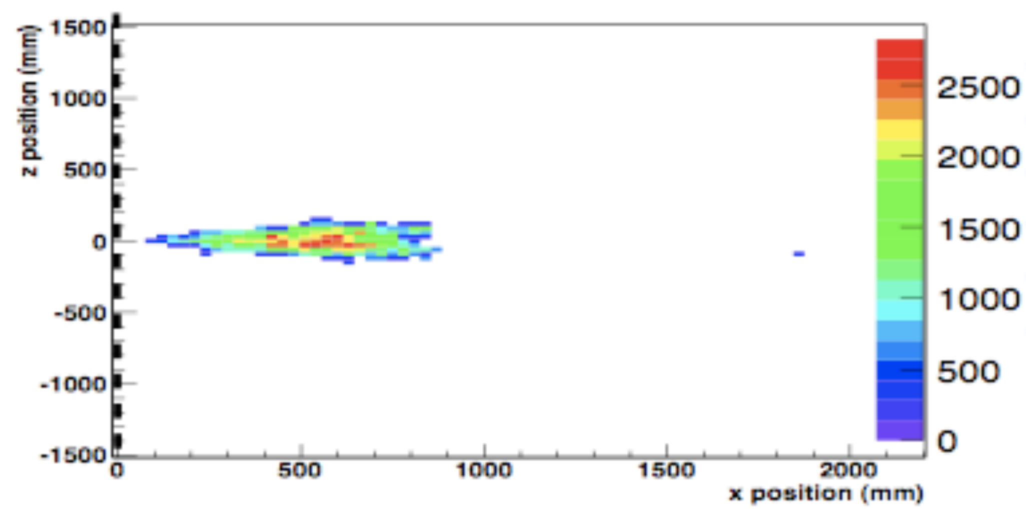
We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.



Location of the candidate vertices do not correspond perfectly to true vertex, probably due to an inappropriate choice of refractive index (I used the wrong value).

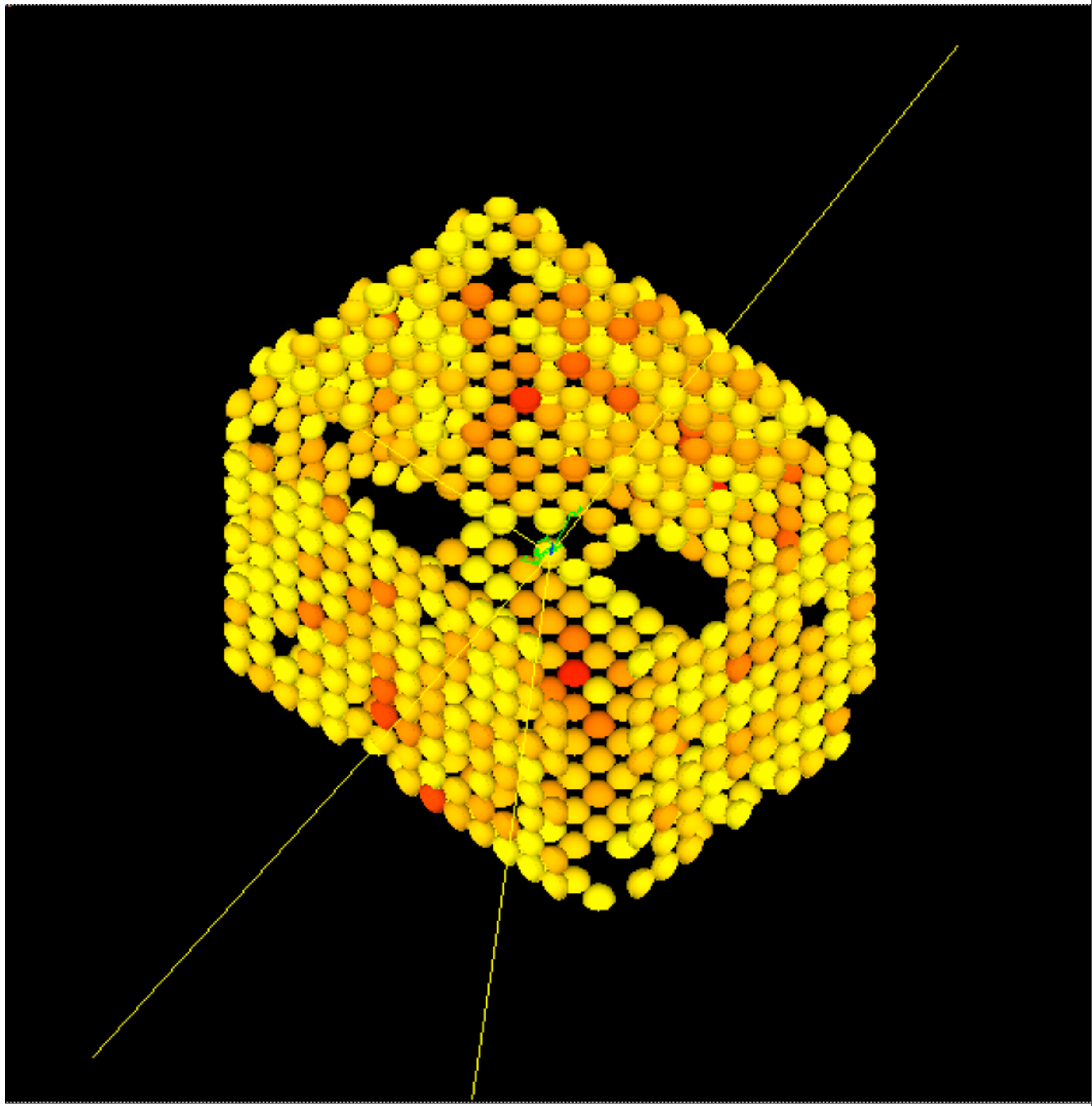


First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method



Next Steps and Conclusions

- LAPPD detectors open up the possibility for advanced water and scintillator based neutrino detectors.
- Commercialization is the crucial first step.
- An important parallel step is to develop a strong simulations/reconstruction program. This work has already started
- It is also an interesting time to start thinking about application specific uses.
- Could they be useful in SNS-based experiments?



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