University of Chicago

Argonne NATIONAL LABORATORY

Thinking Fast, Building Big:

Large Area Picosecond Photodetectors and Neutrino Physics

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on behalf of LAPPD and Fast Timing Neutrino Reconstruction Group

Caltech Seminar

April 28, 2013

U.S. DEPARTMENT OF ENERGY

Detecting Neutrinos – a numbers game

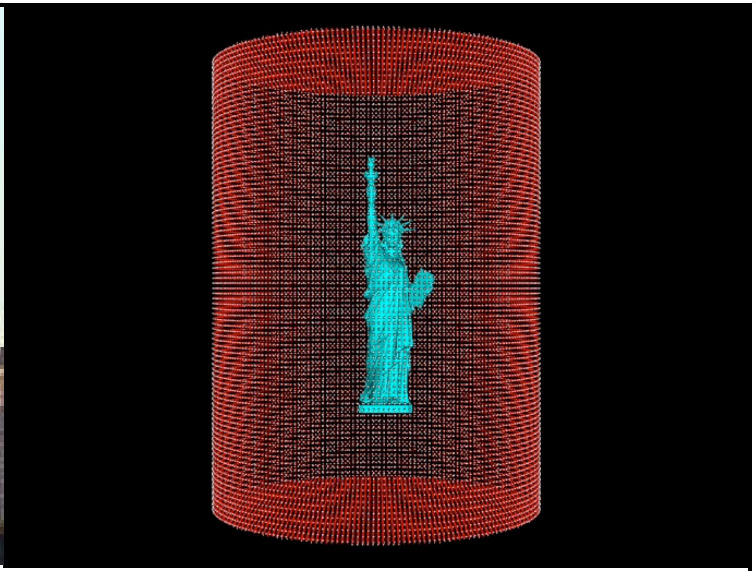
Incredibly small cross sections demand:

- **large fiducial mass**
- time
- high intensity
- low noise

LENA, the proposed European liquid scintillator detector: A nice addition to the Philly skyline?

credit Jürgen Winter

Proposed LBNE Water Cherenkov detector would have comfortably contained the Statue of Liberty



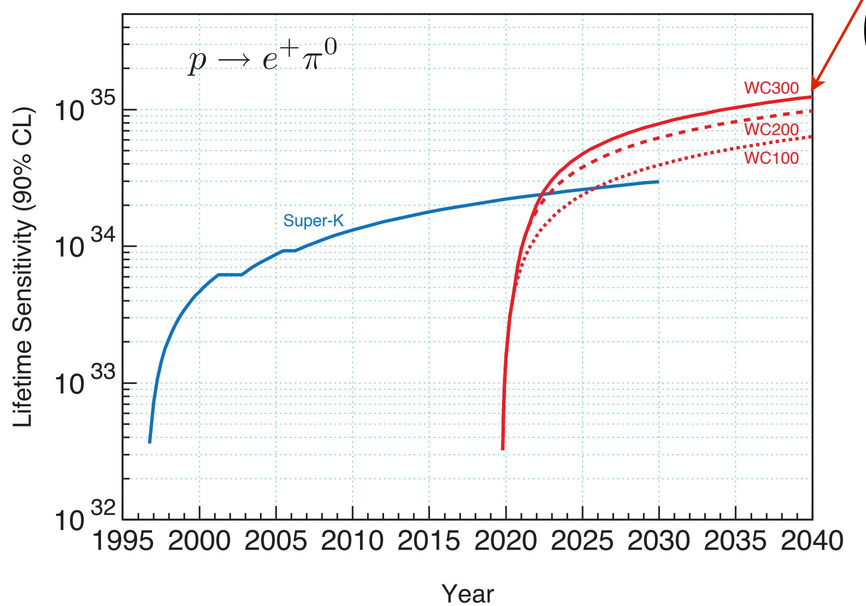
credit Anthony La Torre

Detecting Neutrinos (proton decay) – a numbers game

Incredibly small cross sections demand:

- **large fiducial mass**
- time
- high intensity
- low noise

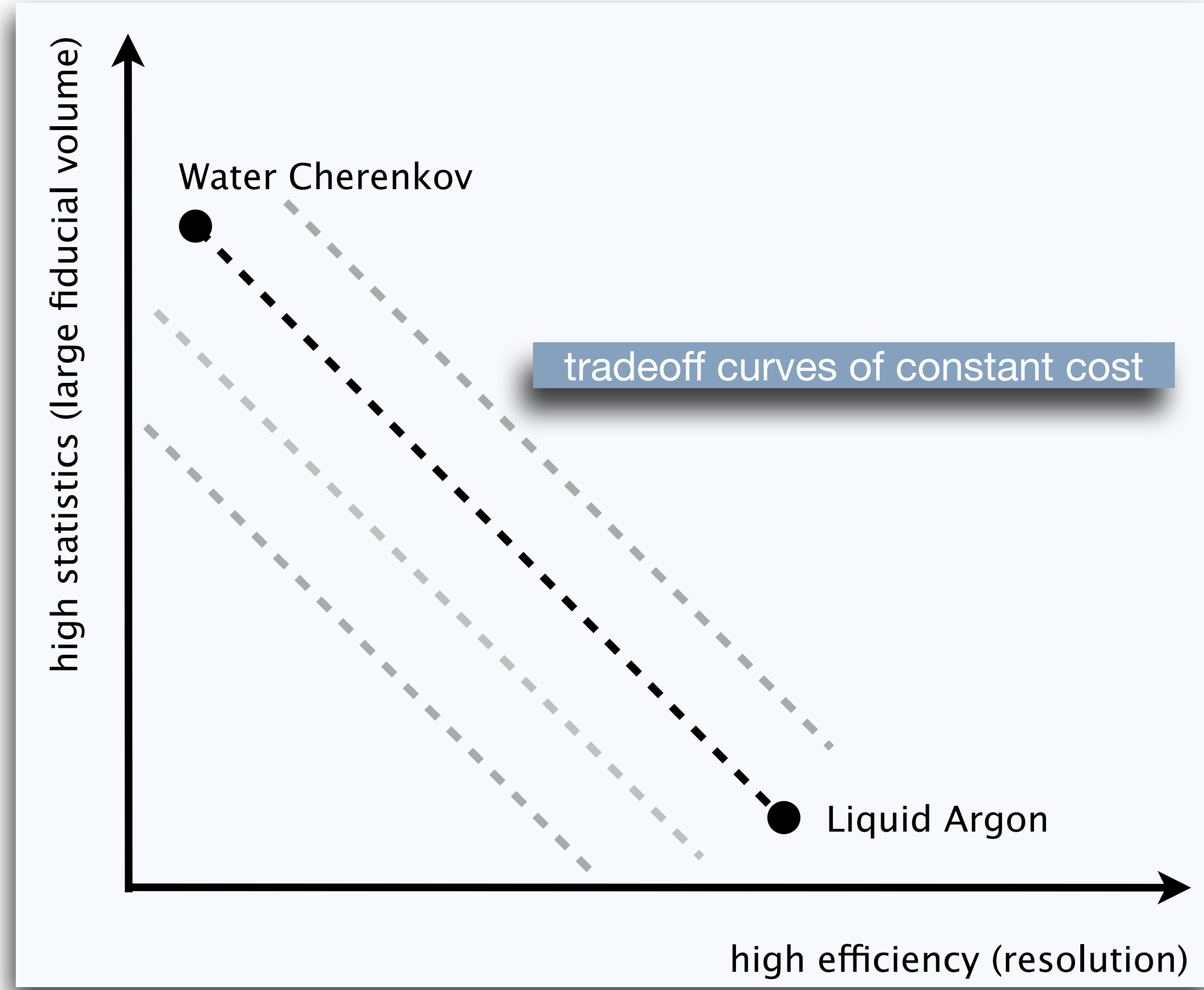
I turn 61 here.



plot by Ed Kearns, BU

The Limits of Thinking Bigger

Neutrino experiments often face tough choices.



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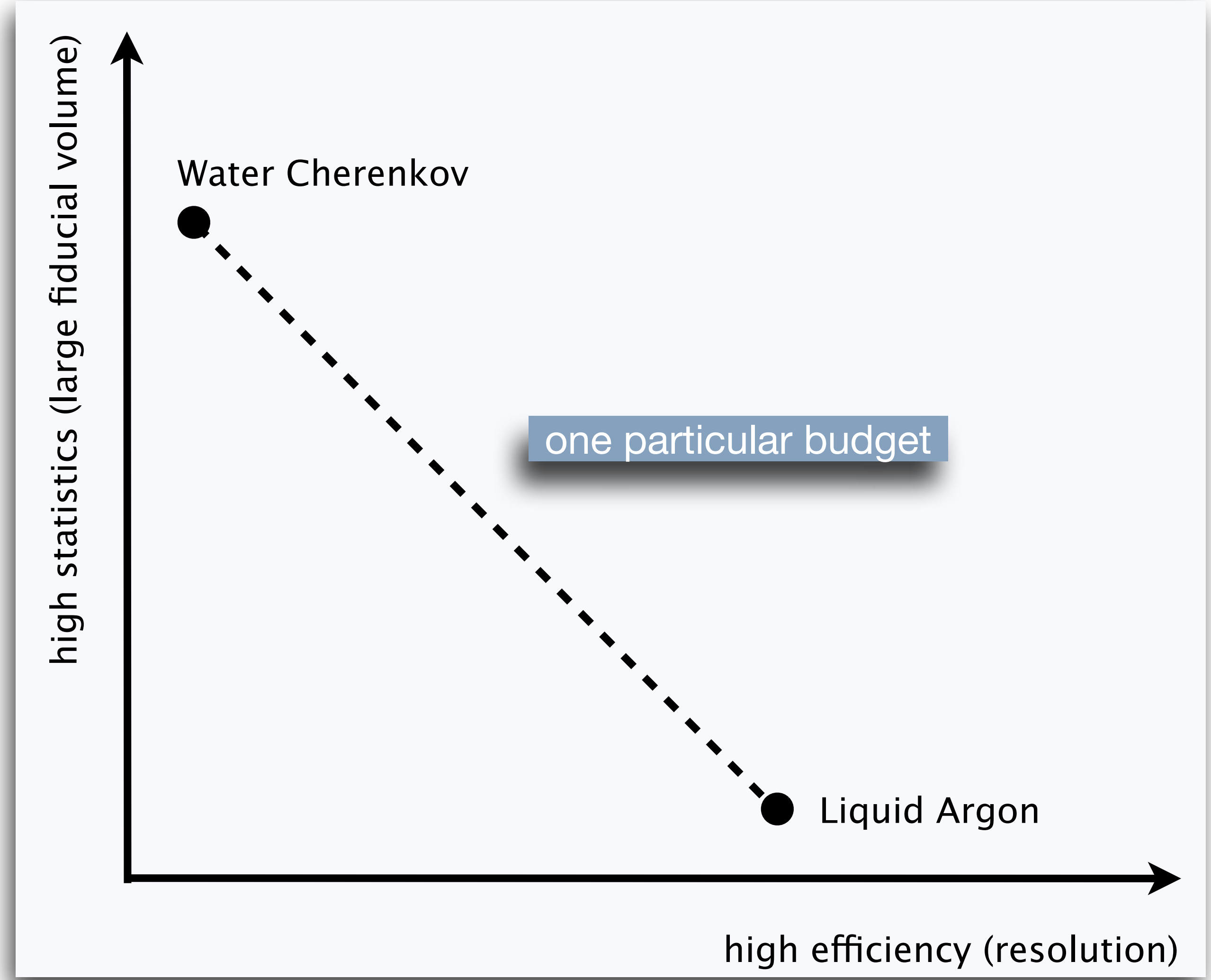
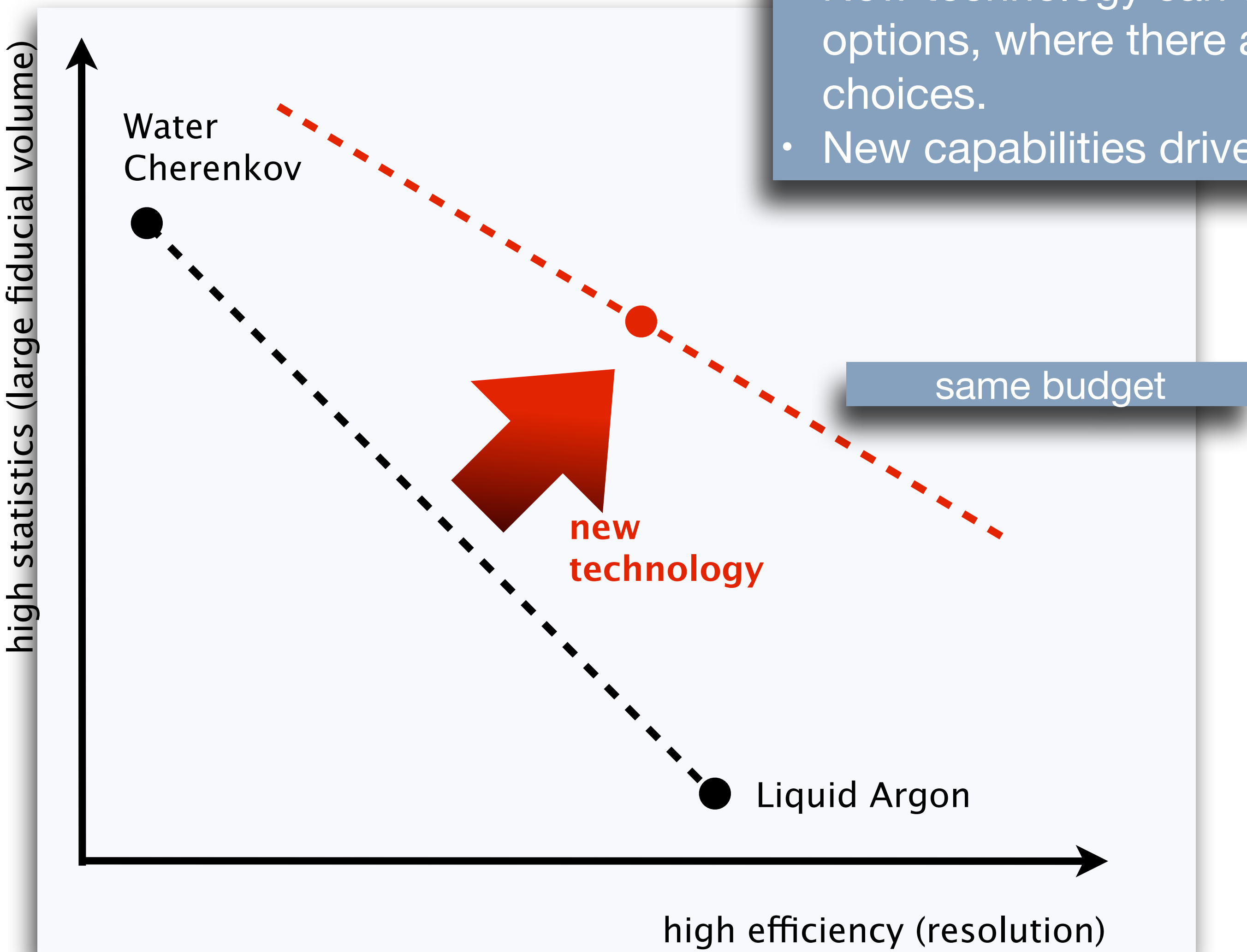
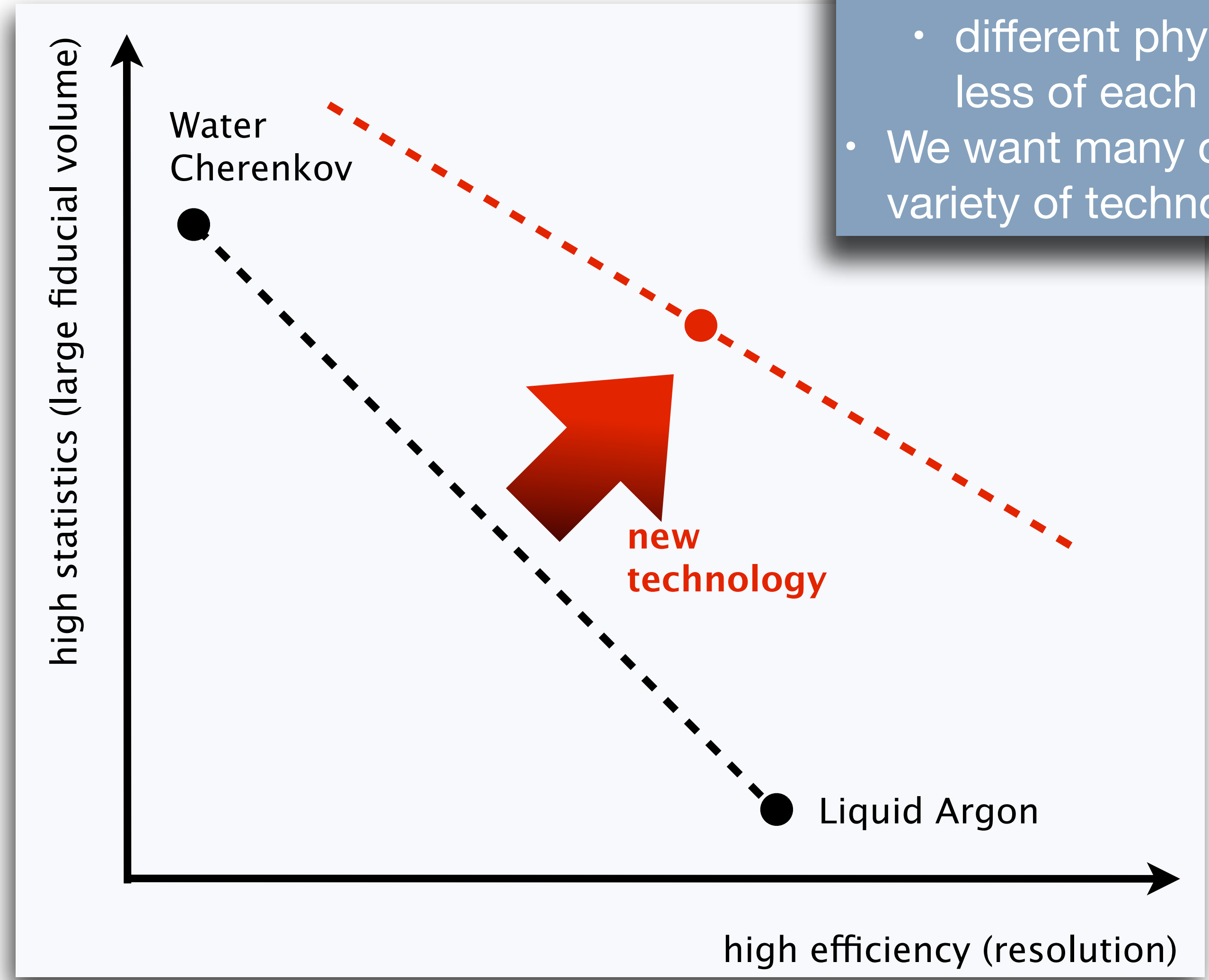


The Limits of Thinking Bigger

- The development of new technology could push this frontier forward.
- New technology can create intermediate options, where there are only a few choices.
- New capabilities drive new physics.



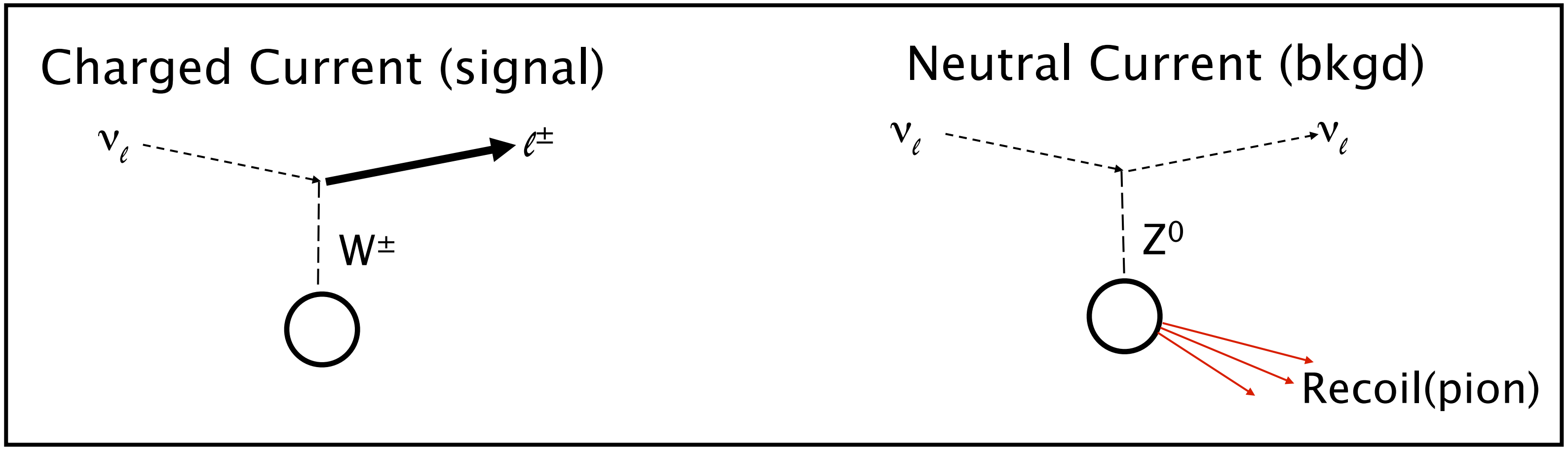
The Limits of Thinking Bigger

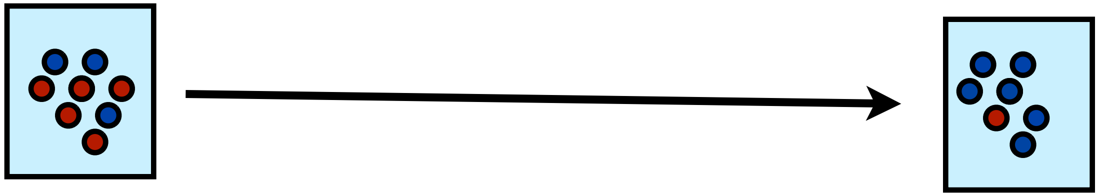


- Other dimensions to this graph:
  - particular target masses have different cross-sections/sensitivity
  - different physics goals need more or less of each capability
- We want many choices and we want a variety of technology options in play

Neutrino Detection Basics

- We detect neutrinos through the products of their interactions with matter.
- Neutrino flavor can be determined by charged-current interactions, which produce charged leptons of like flavor.





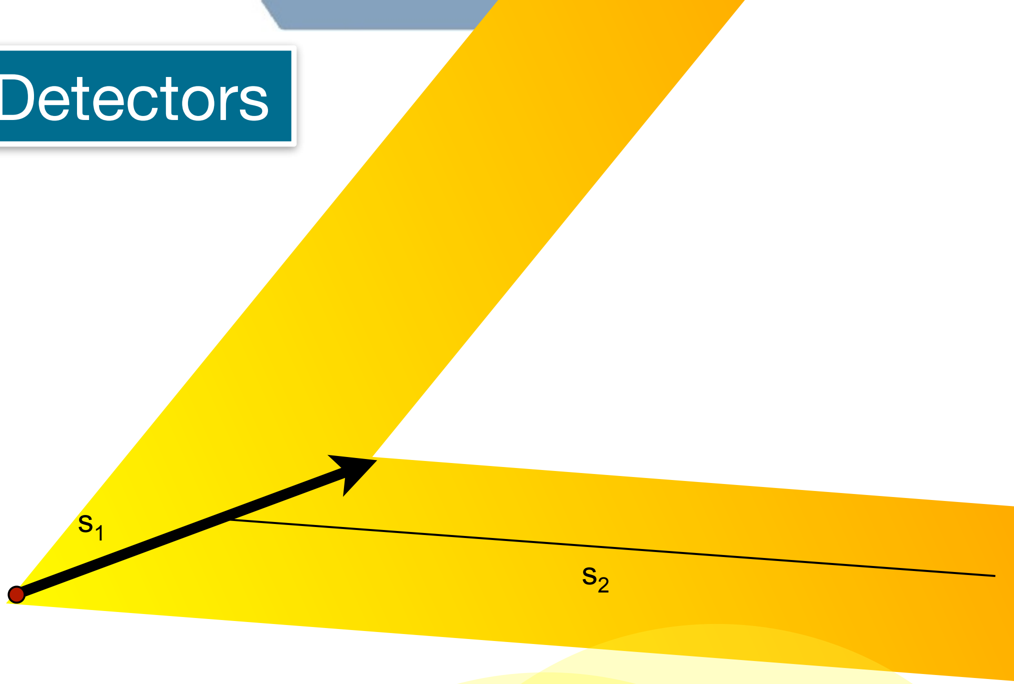
this experiment measures blue appearance and red disappearance.

Typical neutrino oscillation experiments count the relative fractions of leptons of each flavor produced at a near detector, compared with those fractions at a far detector

Light Production In Neutrino Detectors

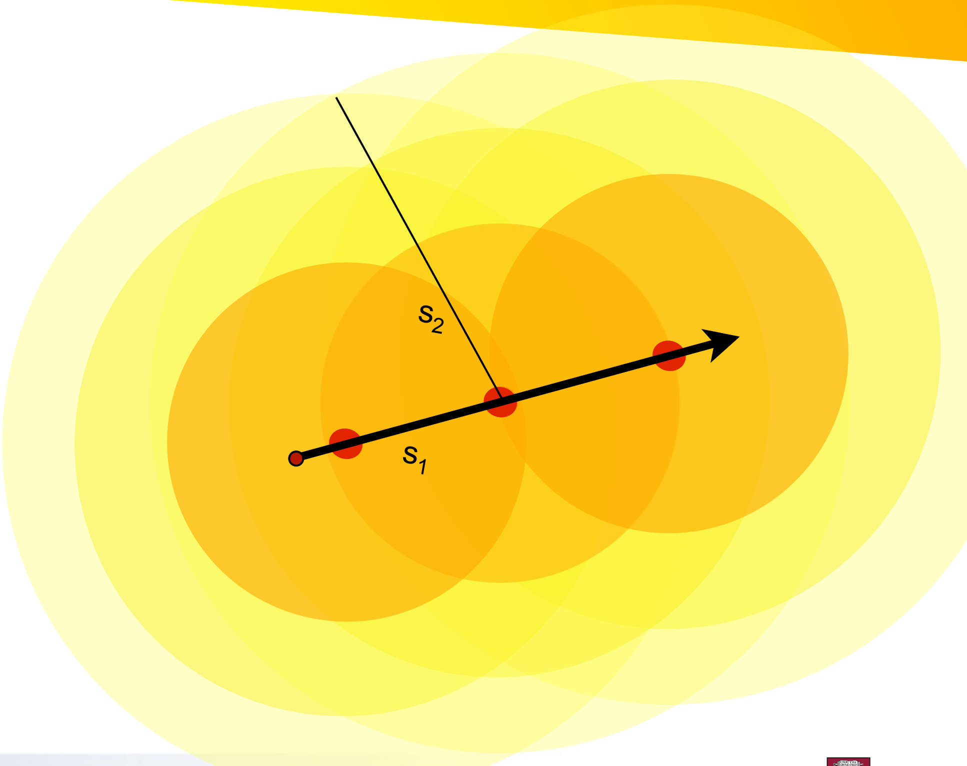
Cherenkov Effect

- An shockwave of optical light is produced when a charged particle travels through a dielectric medium faster than the speed of light in that medium: c/n
- This light propagates at an angle θ_C = acos(1/nβ) w.r.t. the direction of the charged particle…
- Geometry is well-constrained



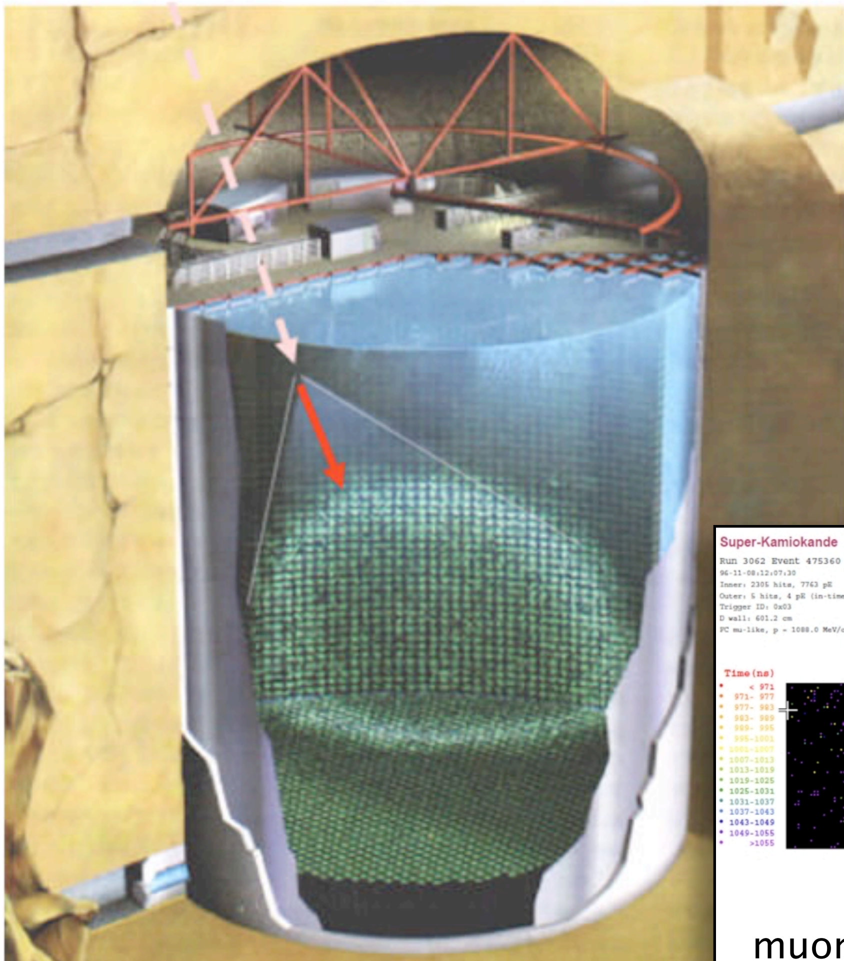
Scintillation

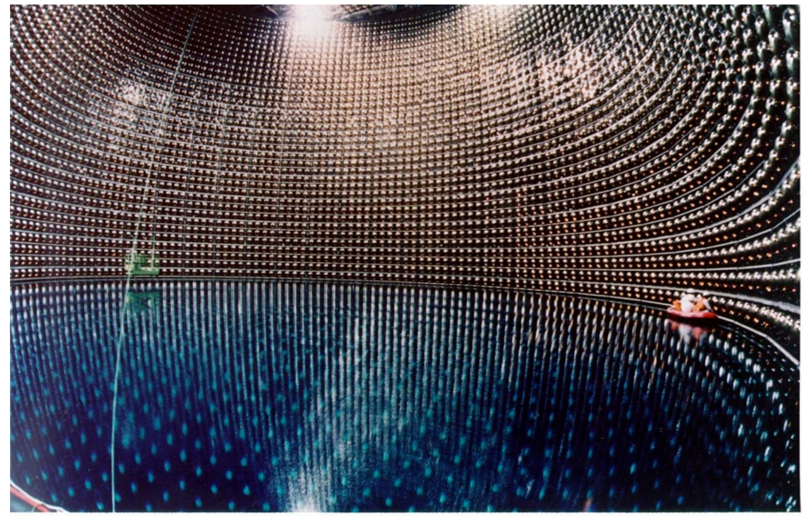
- Light produced by flourescence of ionized atoms
- Narrower spectral range
- Light yield is much higher
- Energy threshold lower
- But, light is emitted isotropically about emission points along the track
- Emission times are delayed and dispersed

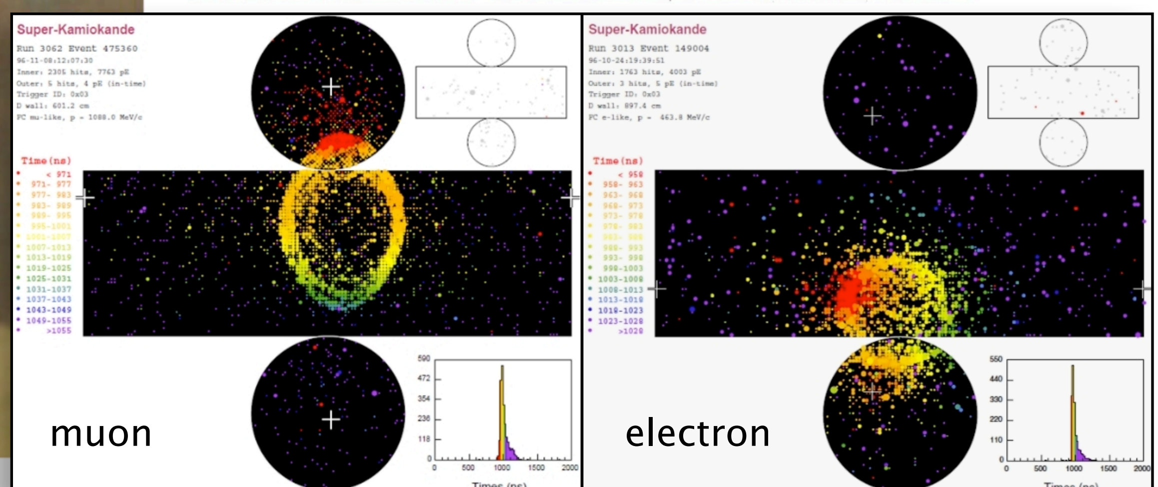


Light Detection In Neutrino Detectors

- Water Cherenkov detector – volume of water instrumented with photosensors on the bounding surface (or in a 3D array
- Detects ring patterns produced by Cherenkov light from charge particles







Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

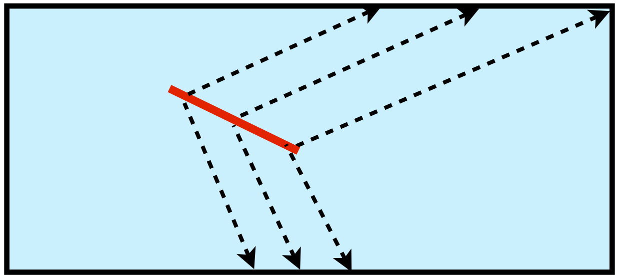
~20 photons/mm (Cherenkov)

2. “Drift time” (photon transit time)

~225,000mm/microsecond

3. Topology

drift distances depend
on track parameters



4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation? Chemical enhancement

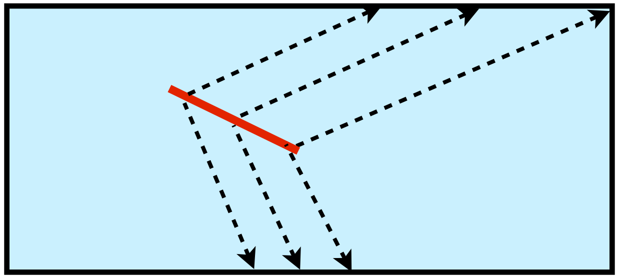
2. "Drift time" (photon transit time)

~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution.**

3. Topology

drift distances depend on track parameters



This presents some reconstruction challenges, but not unconquerable.

4. Optical Transport of light in water

Appropriate reconstruction techniques are needed.

Three Needed Improvements in Physics Capabilities

1. Granularity
2. Low E/heavy particle sensitivity
3. Energy Resolution

Three Needed Improvements in Physics Capabilities

1. Granularity

2. Low E/heavy particle sensitivity

3. Energy Resolution

1. Can water Cherenkov/liquid scintillator detectors achieve fine-grained tracking?
   - resolve multiple track event topologies with small opening angles?
   - resolve substructure/systematic differences in EM showers?

2. Can we resolve more kinematic details in "low energy" (O(10) MeV) events, particularly details of nuclear recoil? Can we see heavy charge particles below Cherenkov threshold?

3. Can we Improve energy resolutions for low energy (O(10) MeV) neutral, charged, and showering particles?

Three Needed Improvements in Physics Capabilities

1. Granularity

2. Low E/heavy particle sensitivity

3. Energy Resolution

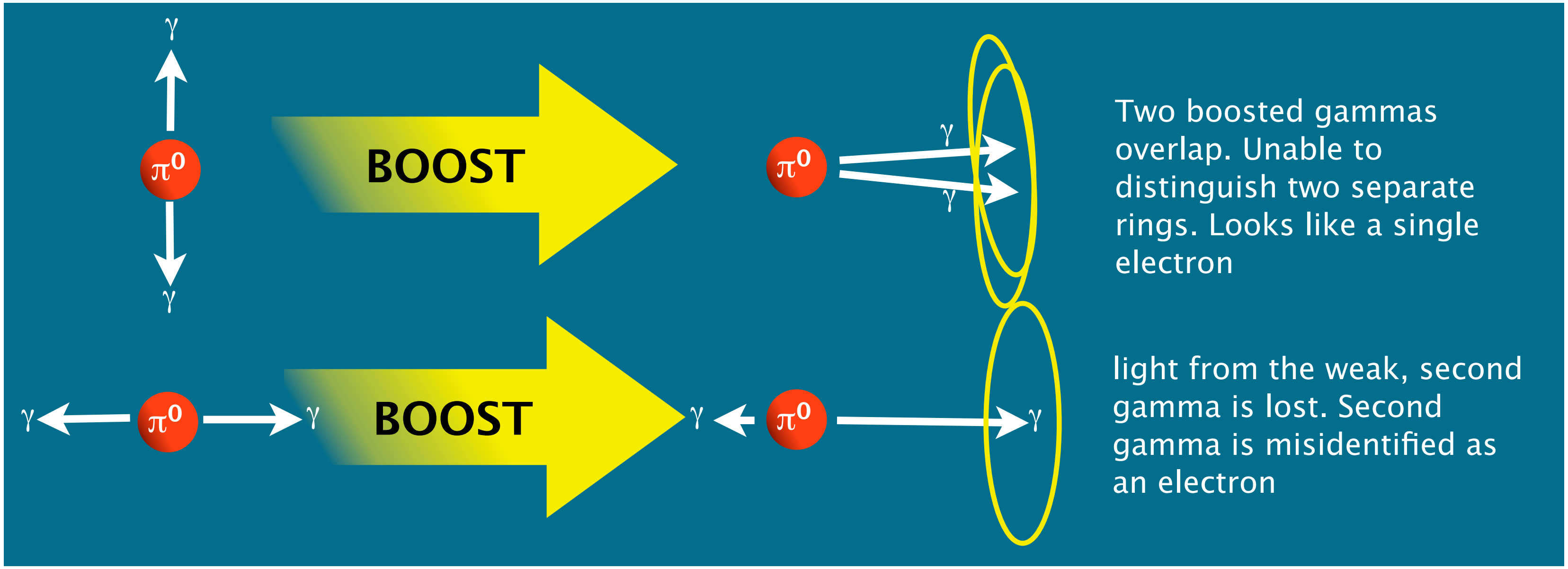
In this talk we will look at

- a few examples of physics questions limited by these 3 capabilities
- ways in which new technology could address these problems
- specifically, we will focus on the Large Area Picosecond Photodetector (LAPPD) collaboration

Section I:

A Sampling of Neutrino and PDK Problems Limited by WC Technology

Granularity



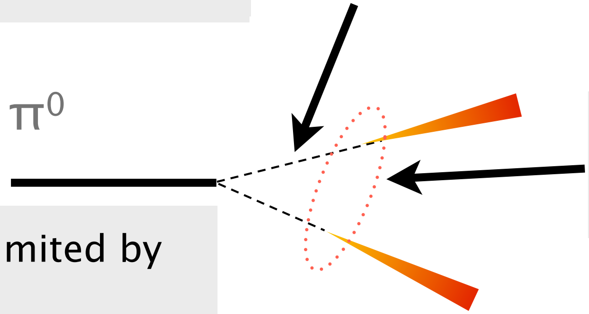
Largest reducible background at ~GeV energies. In WC, in order to achieve a pure electron sample (~1% π^0), one needs harsh quality cuts at the cost of signal efficiency.

There is still a room for significant improvement in the physics capabilities for a given mass of water.

Granularity

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~37 cm

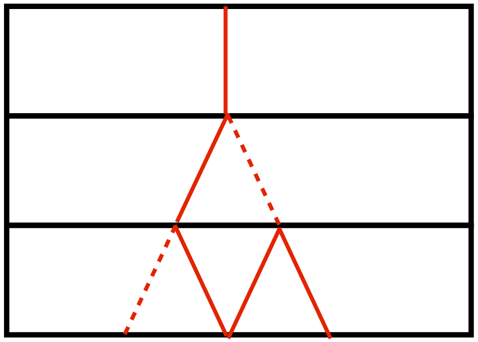


vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

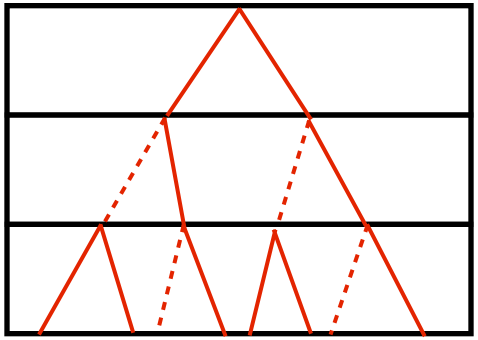
- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

Can we reconstruct the first several stages of an EM shower?

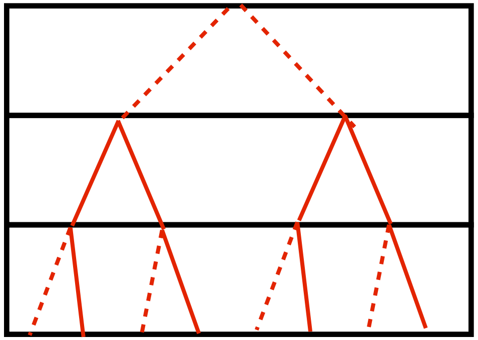
electron shower



single gamma



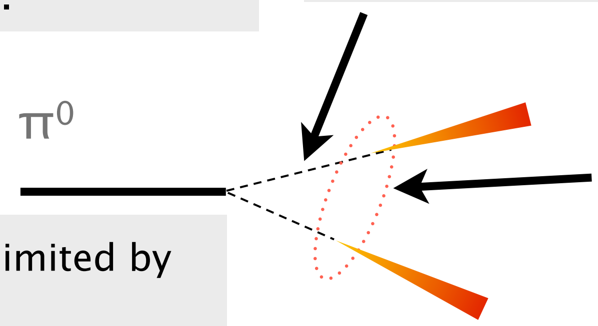
pi0



Granularity

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~1.64 nsec



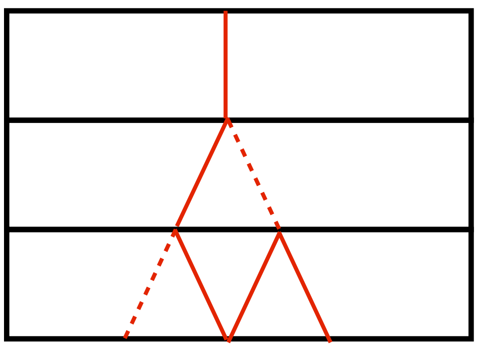
in term of time:
at 7 degrees: ~200 psec
at 15 degrees: ~425 psec

speed of light in water: ~44 psec/cm

- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

Can we reconstruct the first several stages of an EM shower?

electron shower



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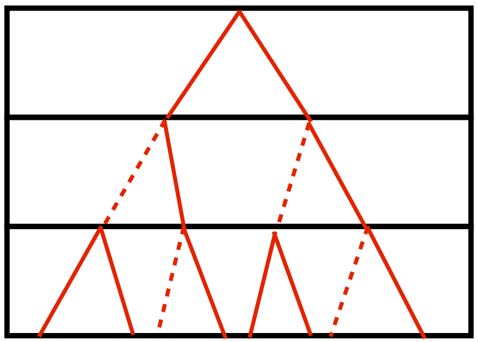
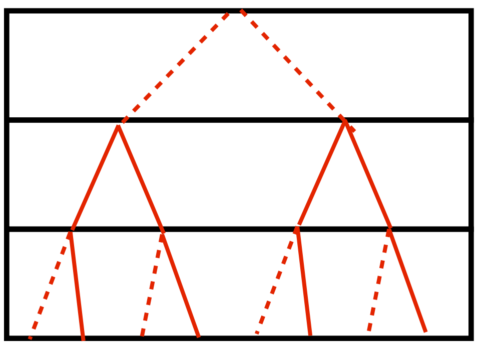


pi0



Low Energy/Heavy Particle Sensitivity

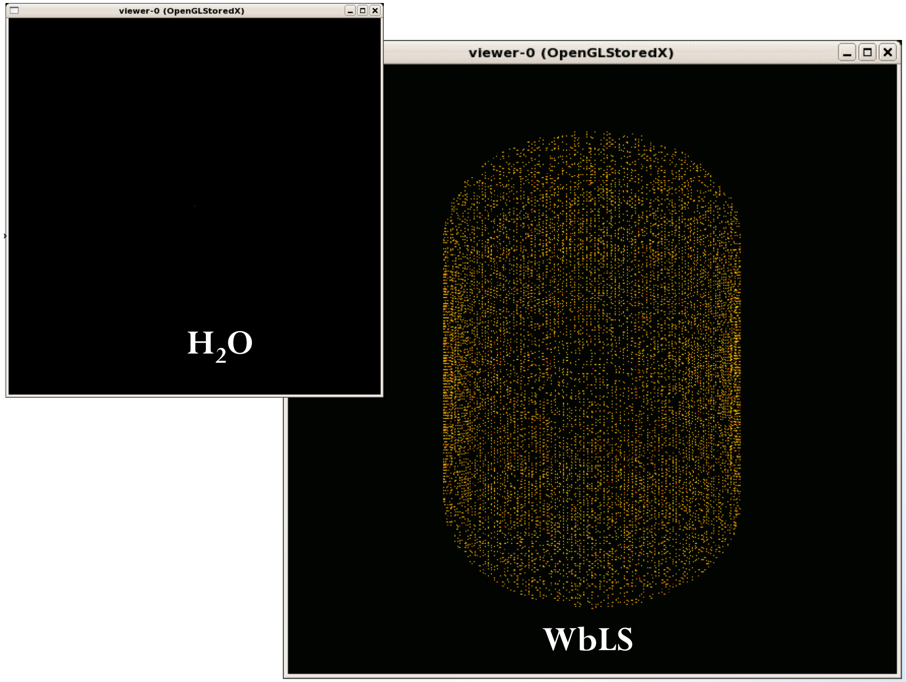
More light/light below Cherenkov threshold

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

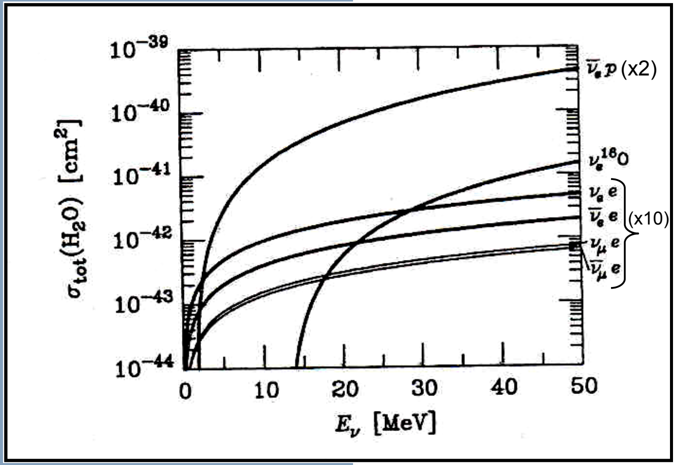
Inefficient channel in water. Cannot see the Kaon

Low Energy/Heavy Particle Sensitivity

Seeing neutrons

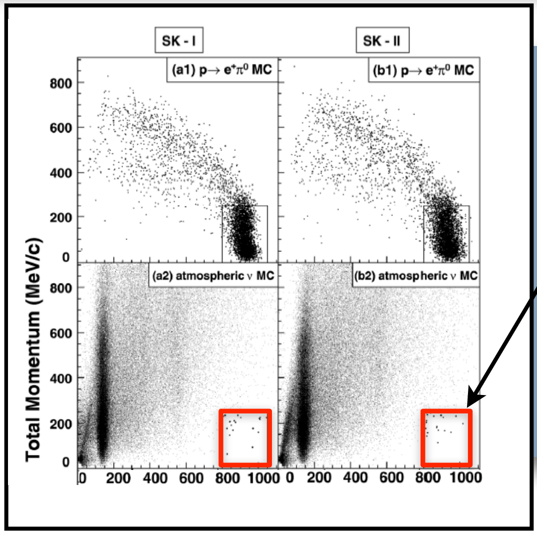
K. Zuber, Neutrino Physics, IOP, 2004

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.

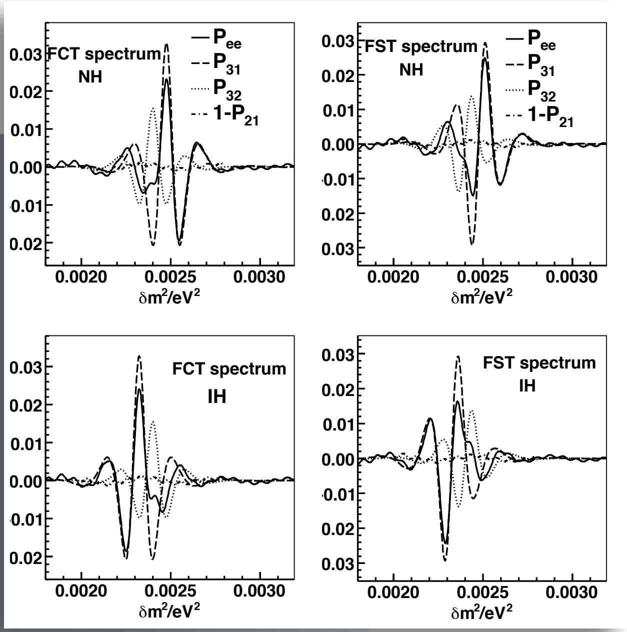
Identifying neutrons is important in tagging this, the largest reducible background.

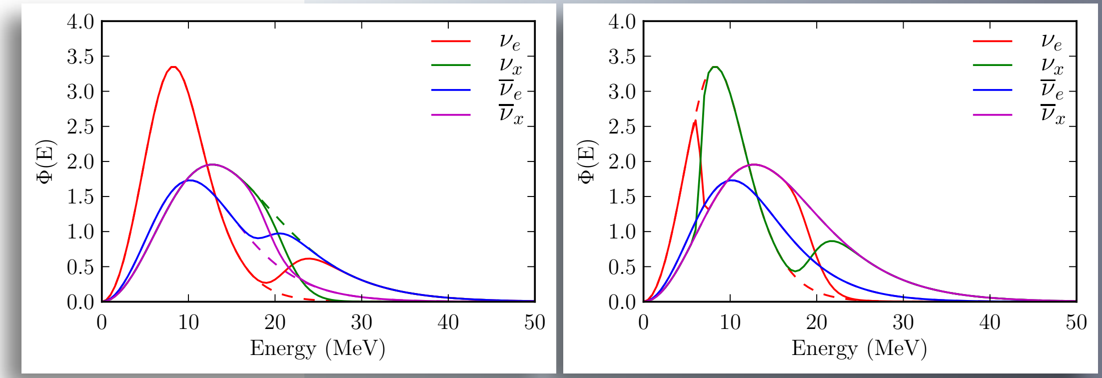
Energy Resolution

Daya Bay II

- Proposed reactor neutrino experiment to determine the neutrino mass hierarchy based on a novel approach.
- 10 kton liquid scintillator detector on a 60 km baseline

Need excellent energy resolutions: 3%/sqrt(E)!





- Core Collapse Supernova
  - the ultimate intensity frontier
    - ~99% of energy is carried away by neutrinos
    - neutrino densities are so high that neutrino-neutrino interactions dominate
  - an experiment we could never afford to build
  - predicted to occur a few times a century in our galaxy

Section II:

Leveraging Technology to Address the Challenges

3 Key Questions ➡ 3 Areas of Technological Improvement

1. Granularity
2. Low E/heavy particle sensitivity
3. Energy Resolution

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➡

1. Photodetector Technology
2. Chemical Enhancements to the Target Volume
3. Geometry and Coverage

LAPPD Collaboration
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

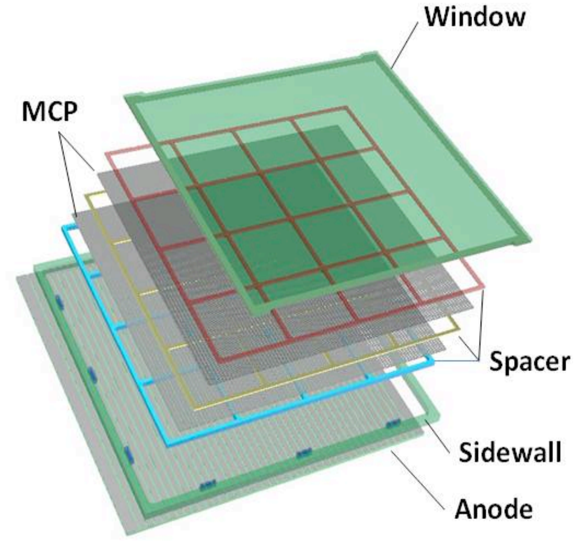
Glass body, minimal feedthroughs

MCPs made using atomic layer deposition (ALD).

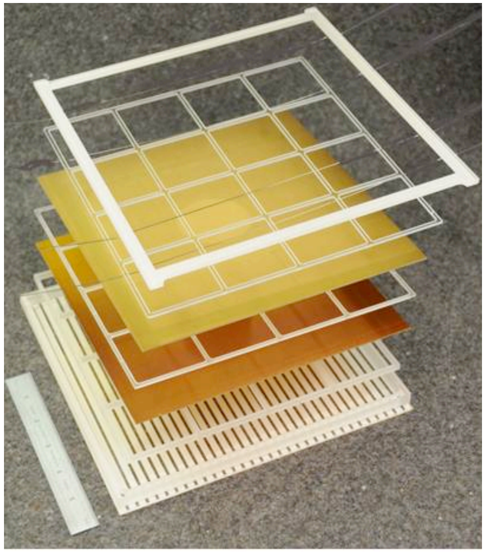
transmission line anode

fast and economical front-end electronics

large area, flat panel photocathodes

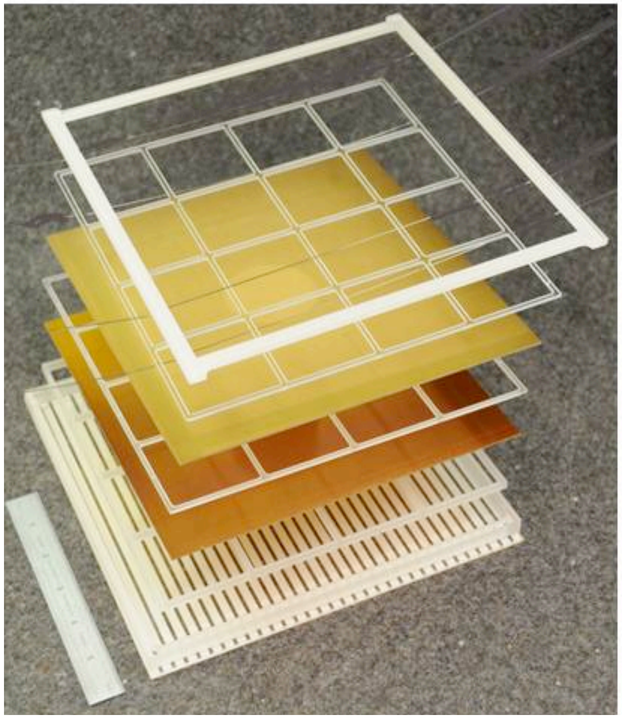


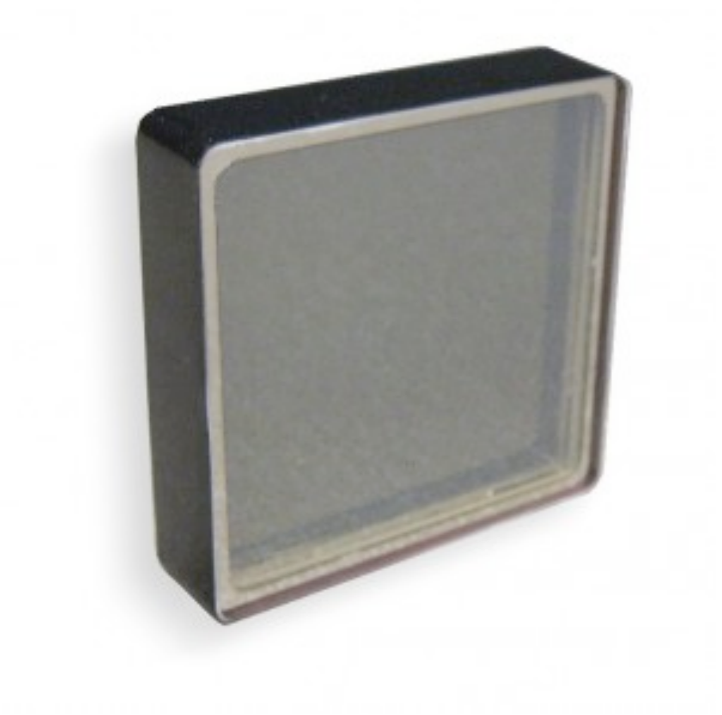
Design Drawing - September 2010



Actual Glass Parts - April 2012

What is the LAPPD Concept

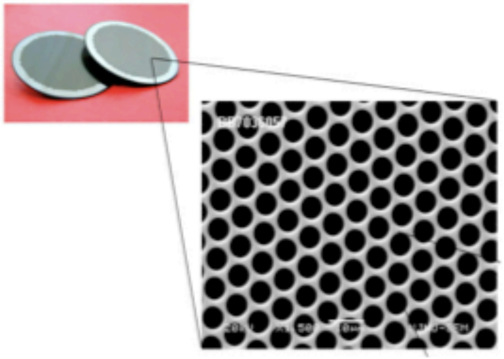




LAPPD detectors:
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

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

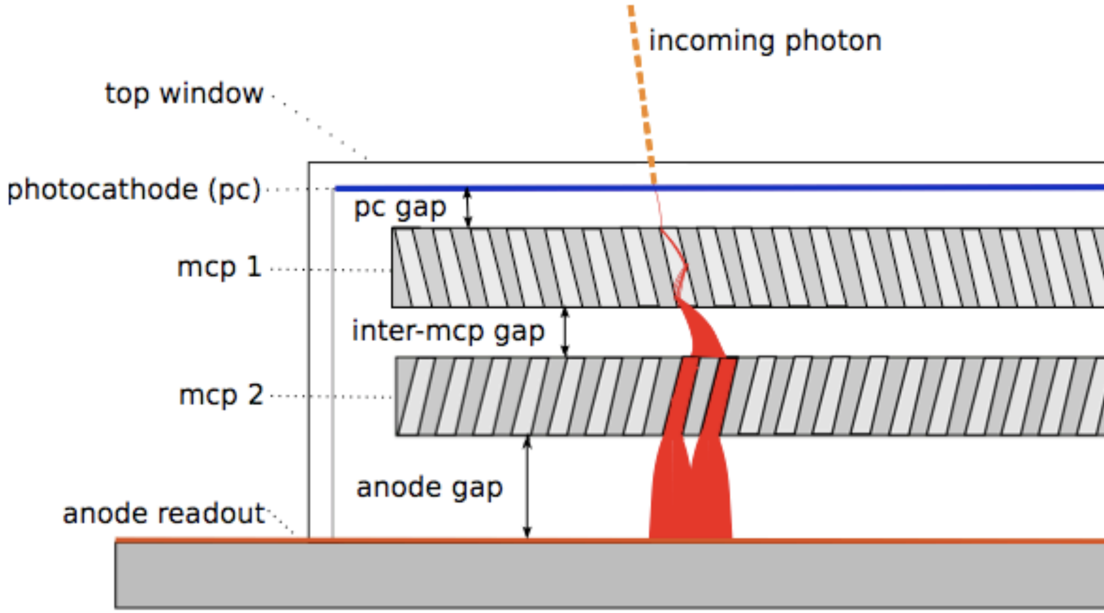
What is an MCP-PMT?



Microchannel Plate (MCP):

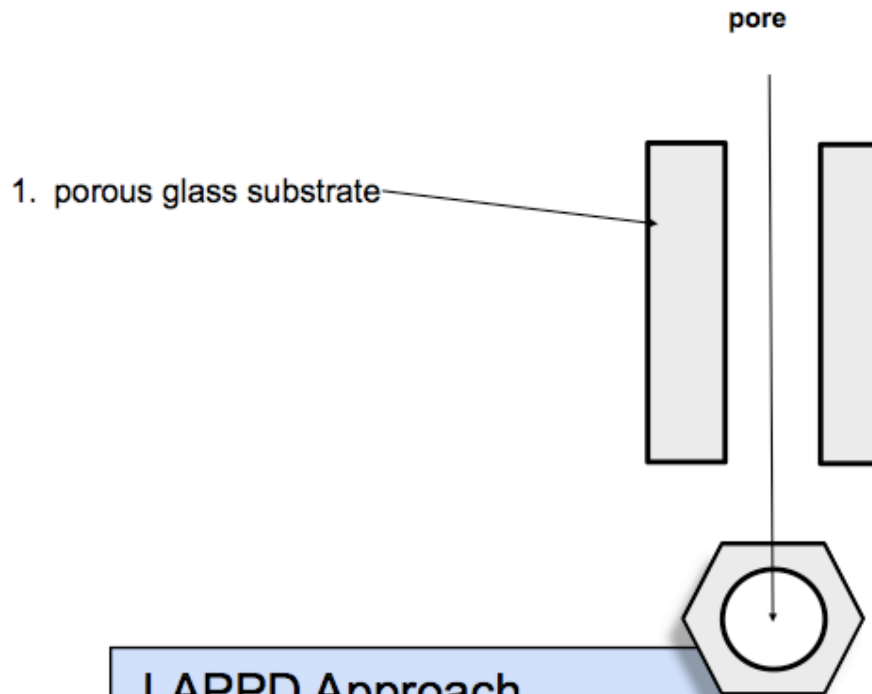
- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- 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



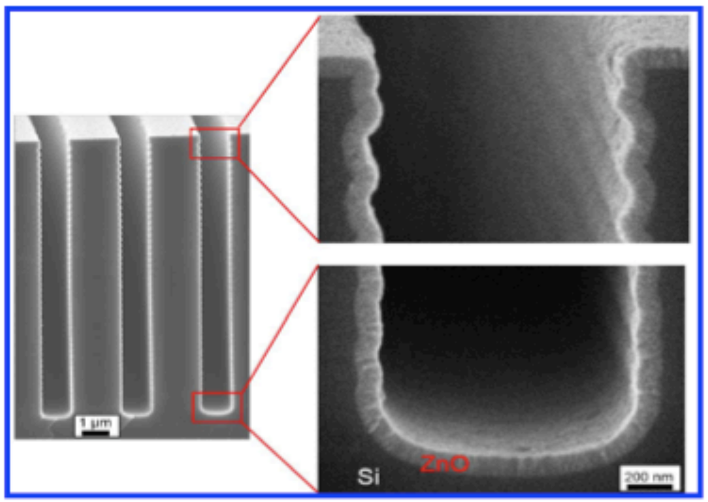
Our Approach

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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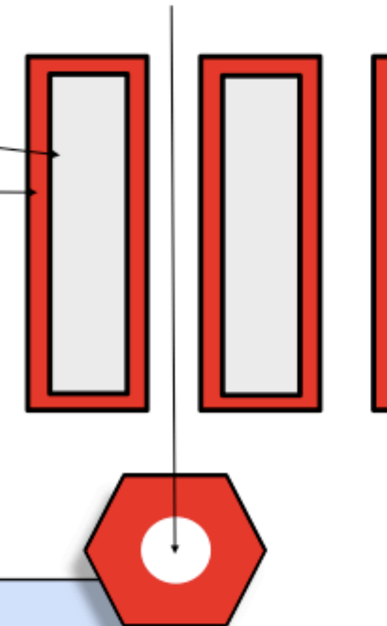
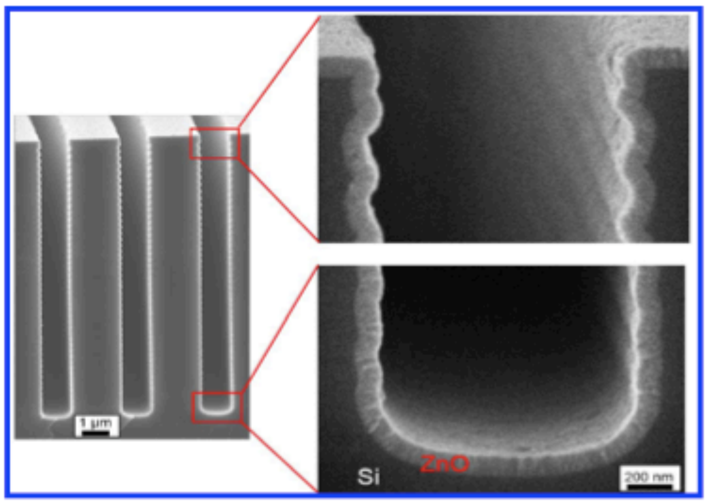
pore

1. porous glass substrate
2. resistive coating (ALD)





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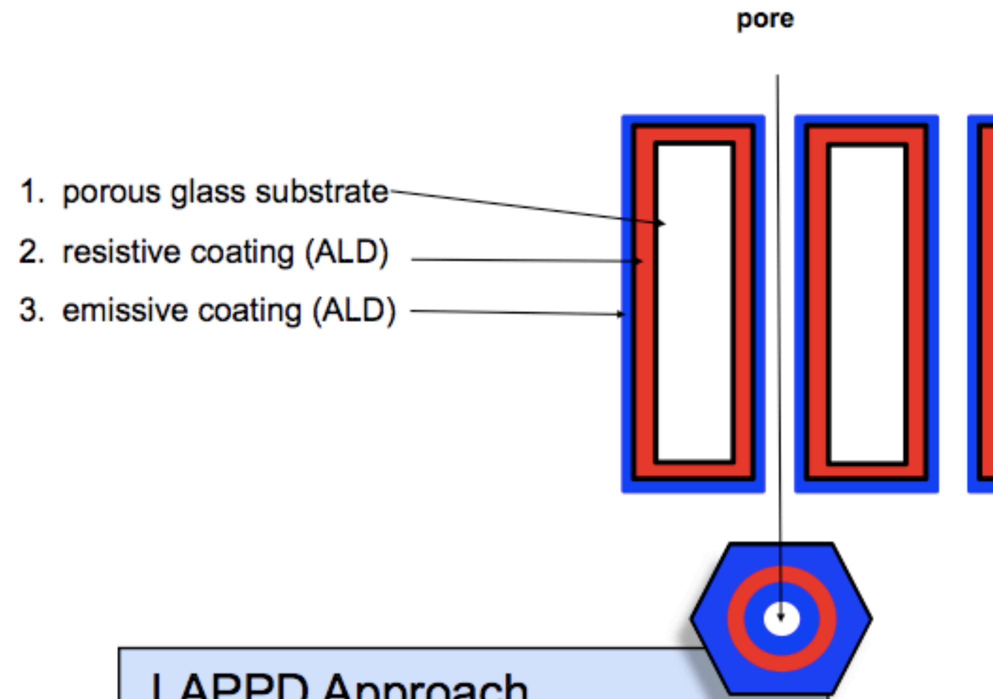

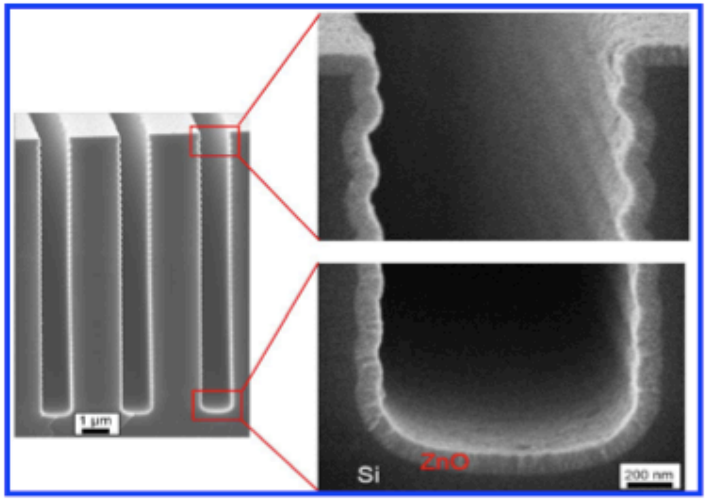

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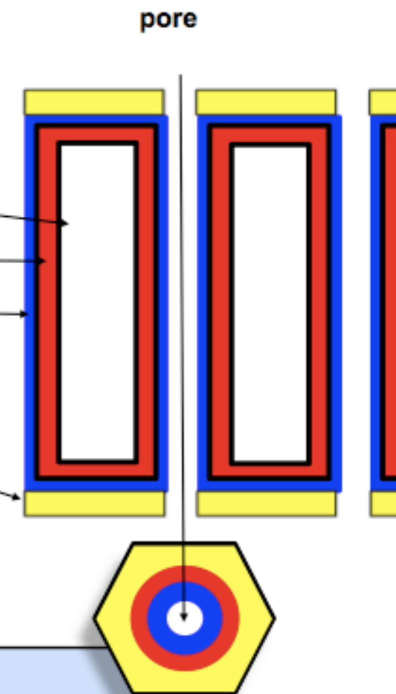
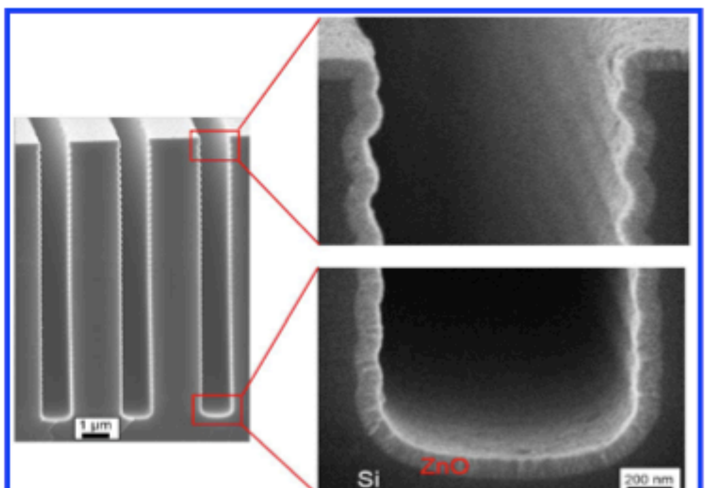
1. porous glass substrate
2. resistive coating (ALD)
3. emissive coating (ALD)
4. conductive coating (thermal evaporation or sputtering)





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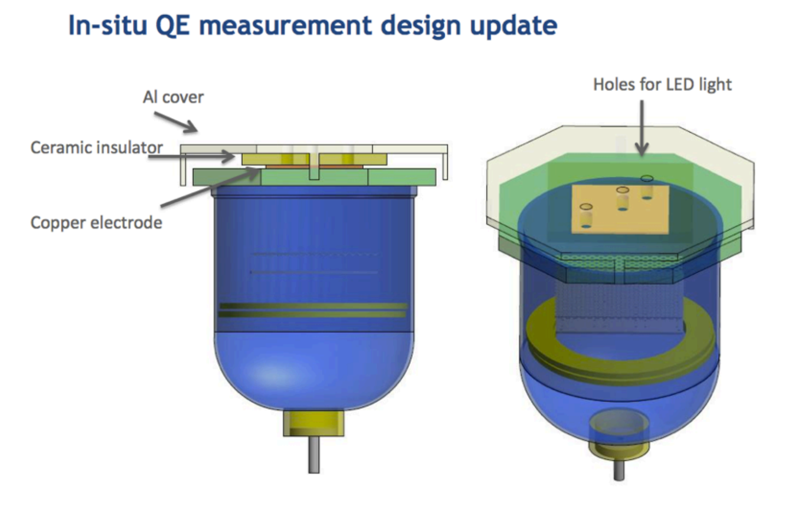
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

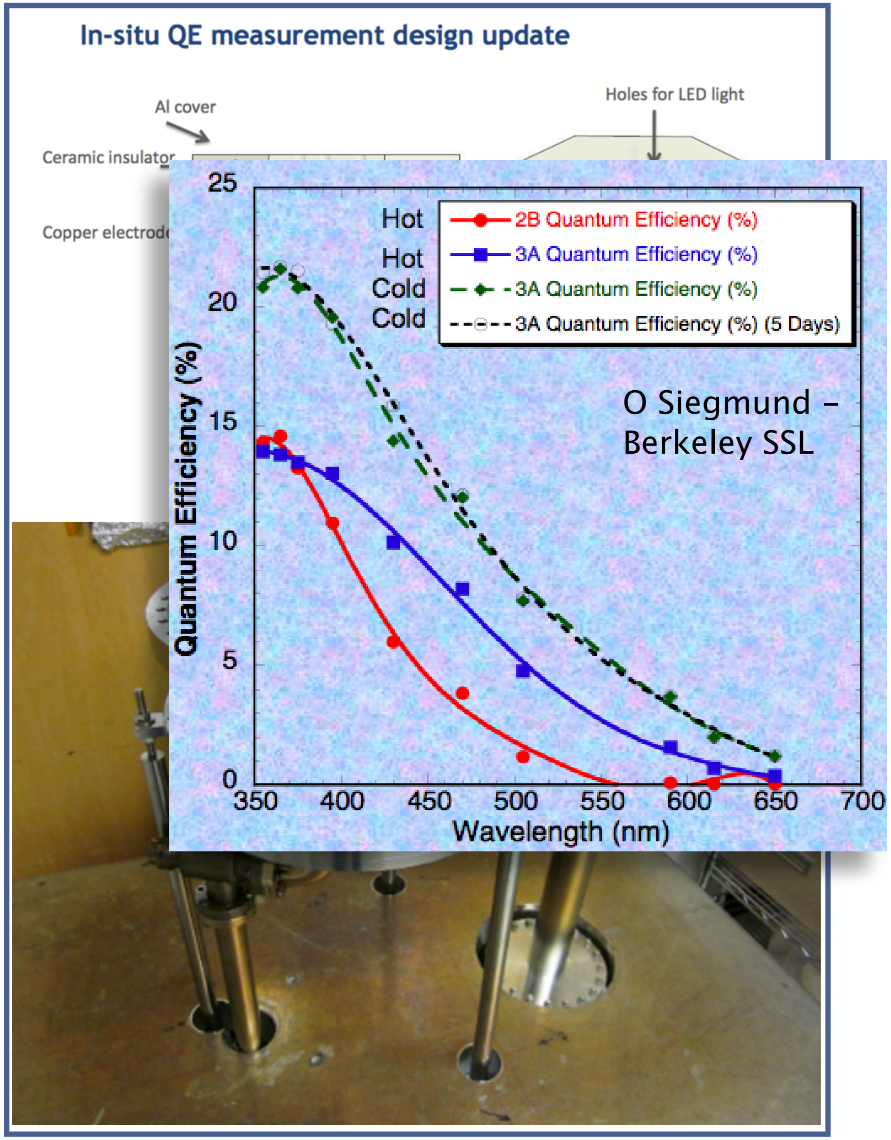
Large Area Photocathodes



- 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)

Large Area Photocathodes



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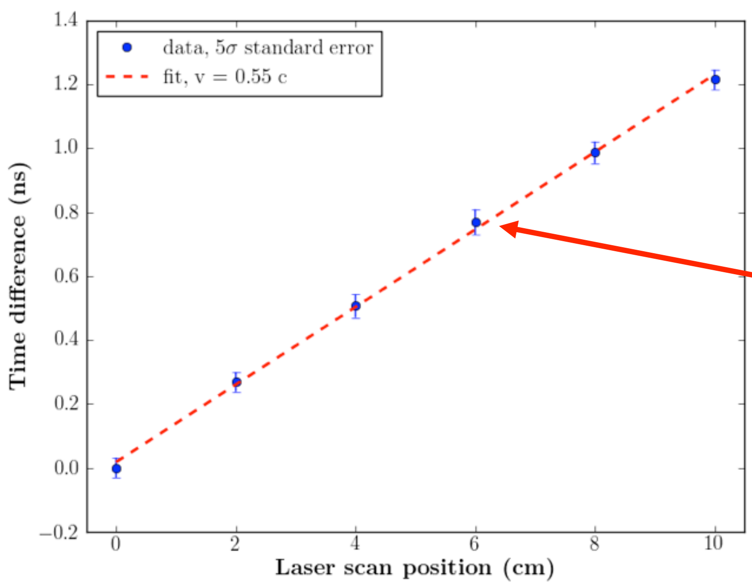
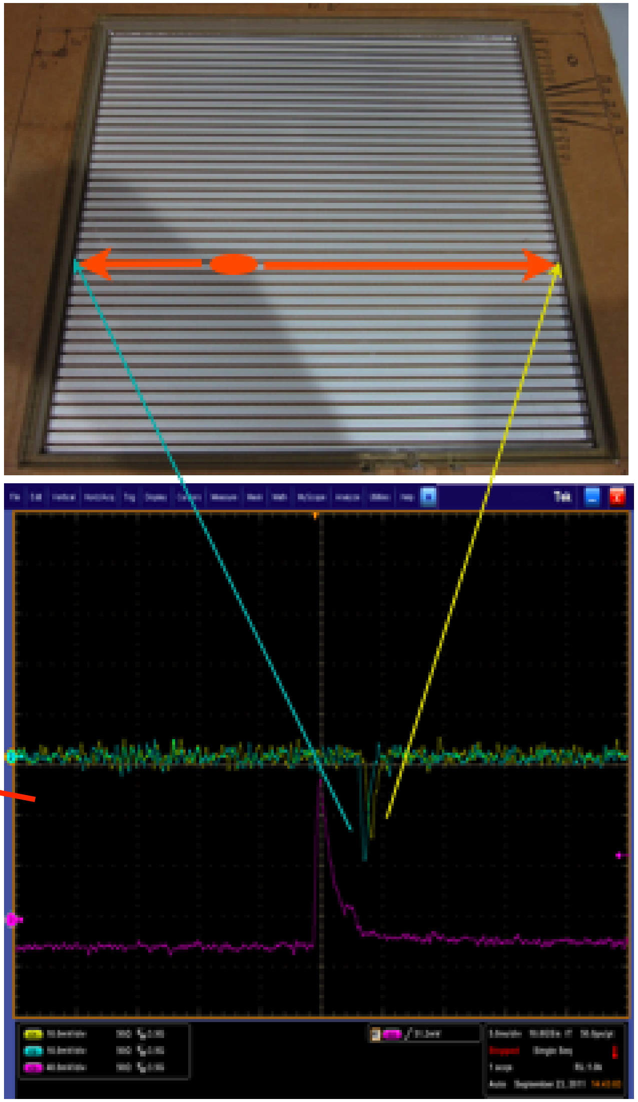
Anode Design: Delay Lines

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





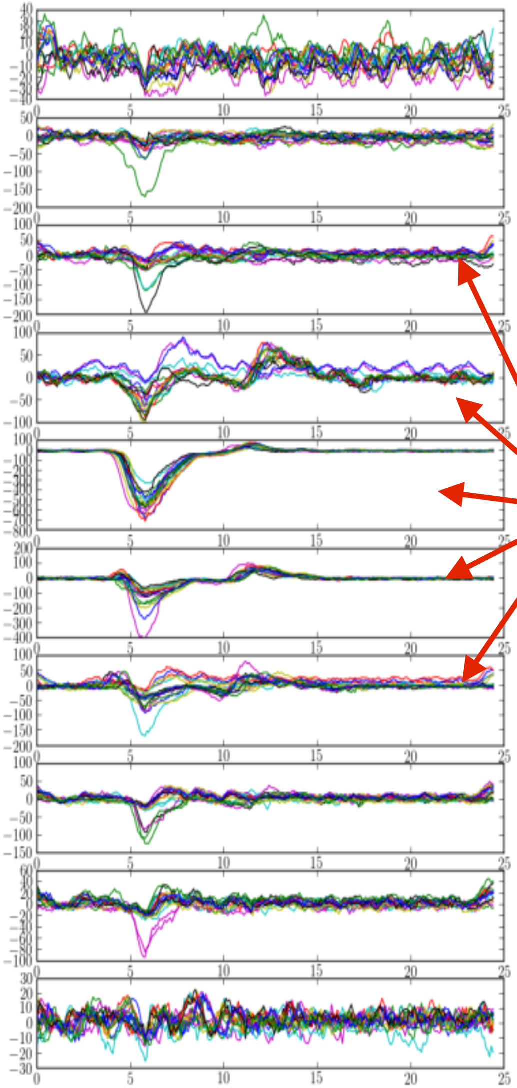
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

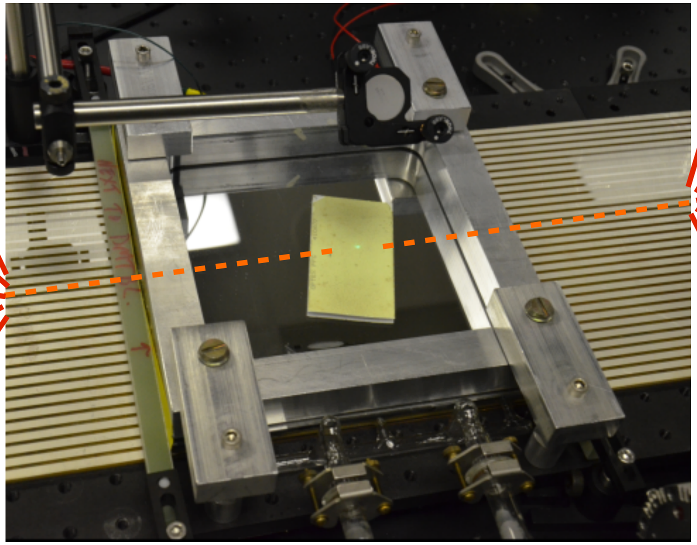
Anode design

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

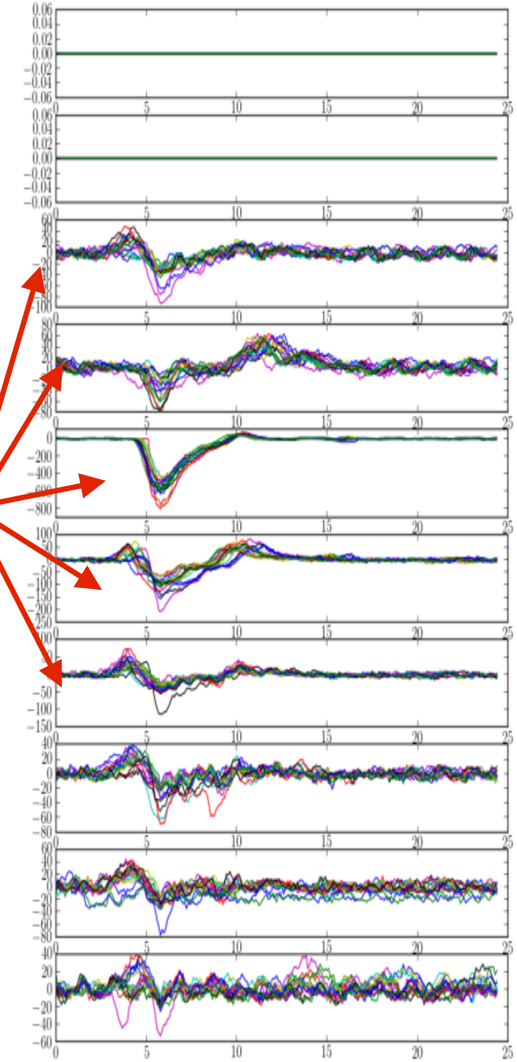
Pulses on 10 striplines

Left Side





Credit: Eric Oberla



Right Side

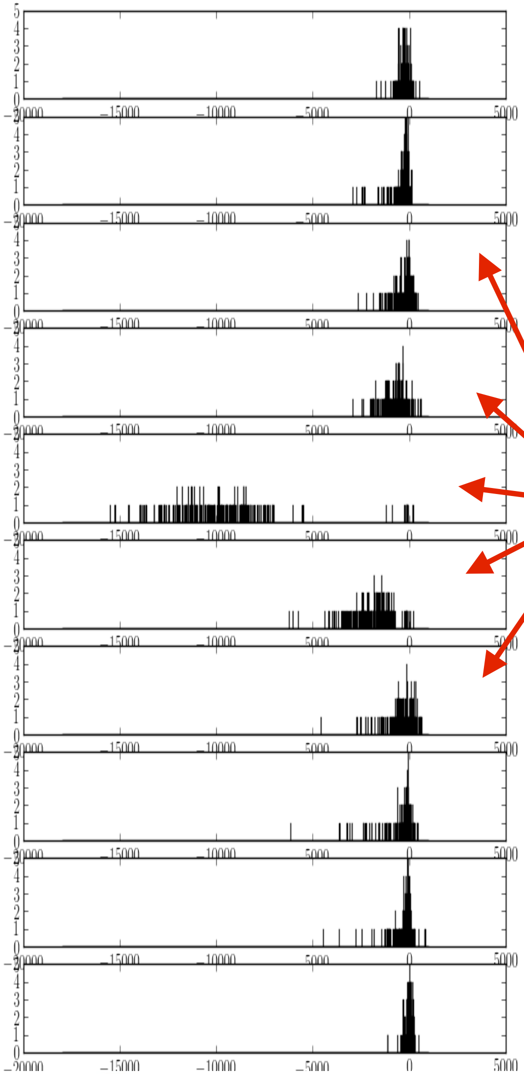
Pulses on 10 striplines

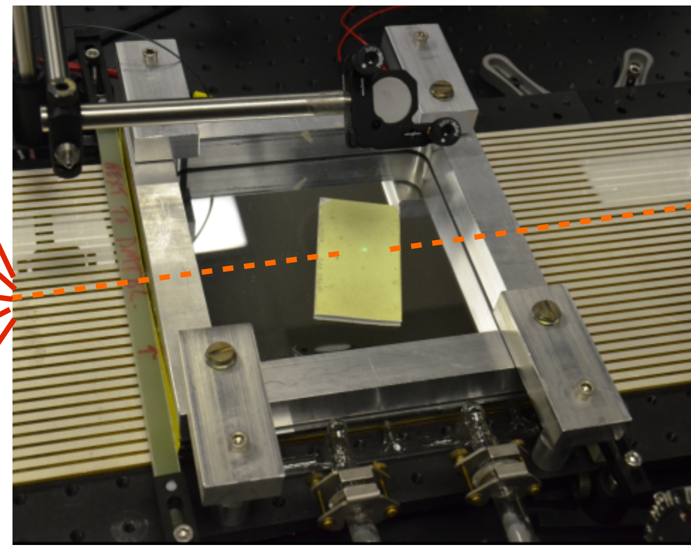
Anode design

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

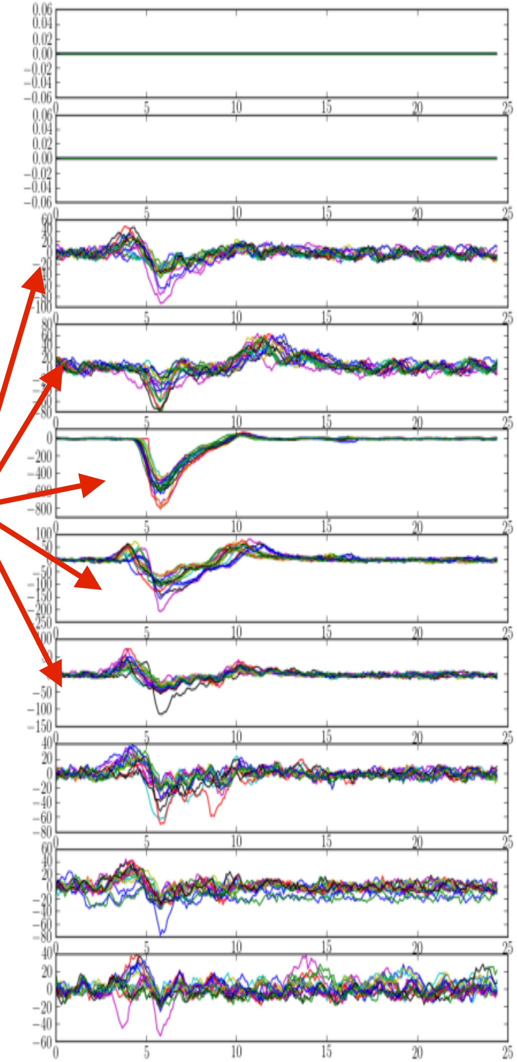
Pulse Heights (ADC counts)

Left Side



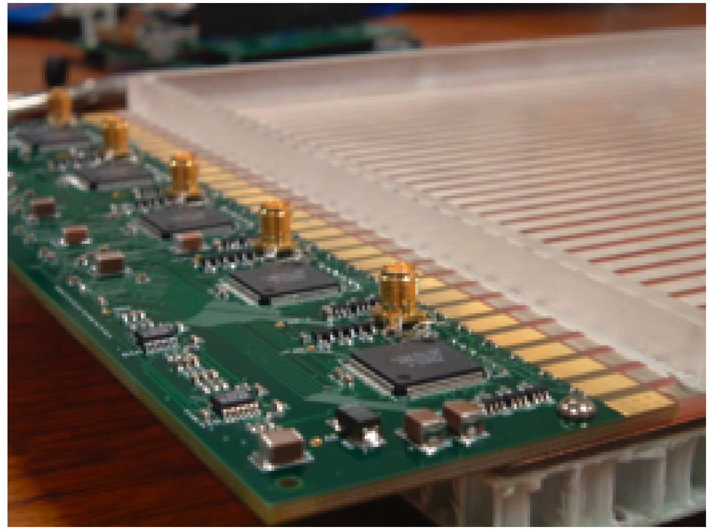


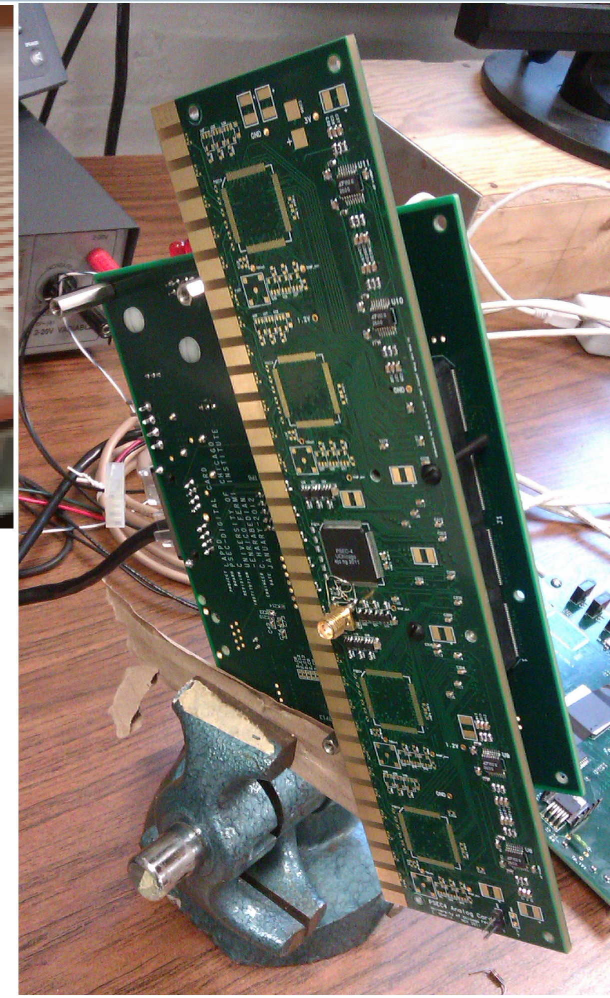
Credit: Eric Oberla



Right Side
Pulses on 10 striplines

Front-end Electronics





Psec4 chip:

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

Analog Card:

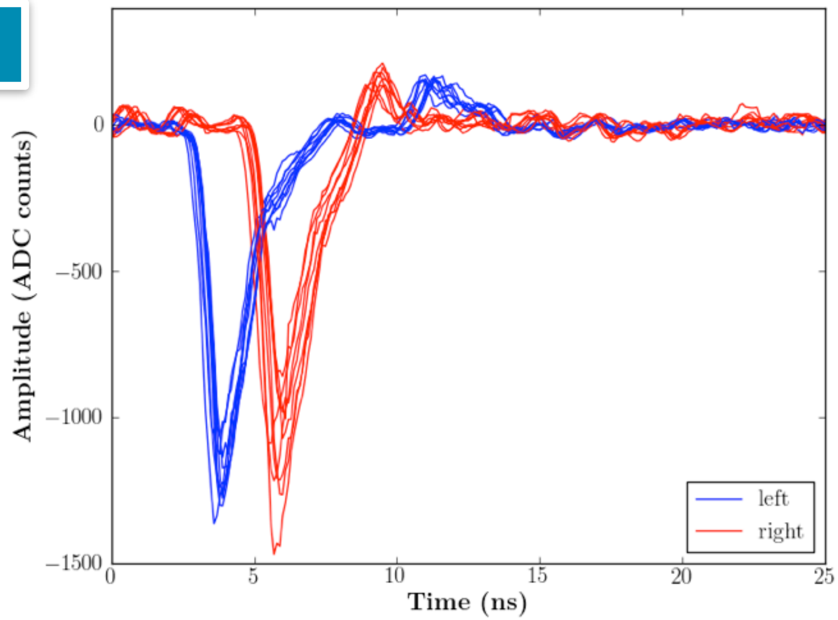
- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

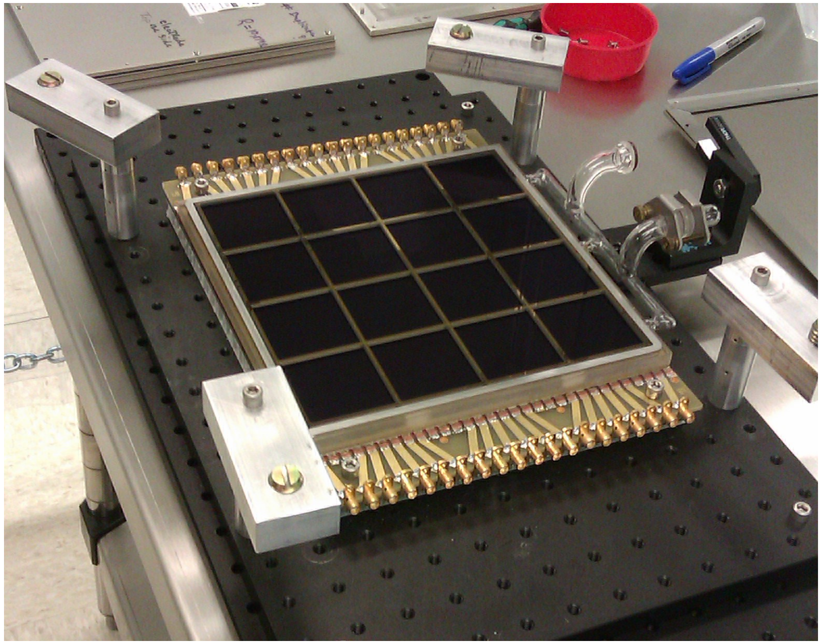
Digital Card:

- Analysis of the individual pulses (charges and times)

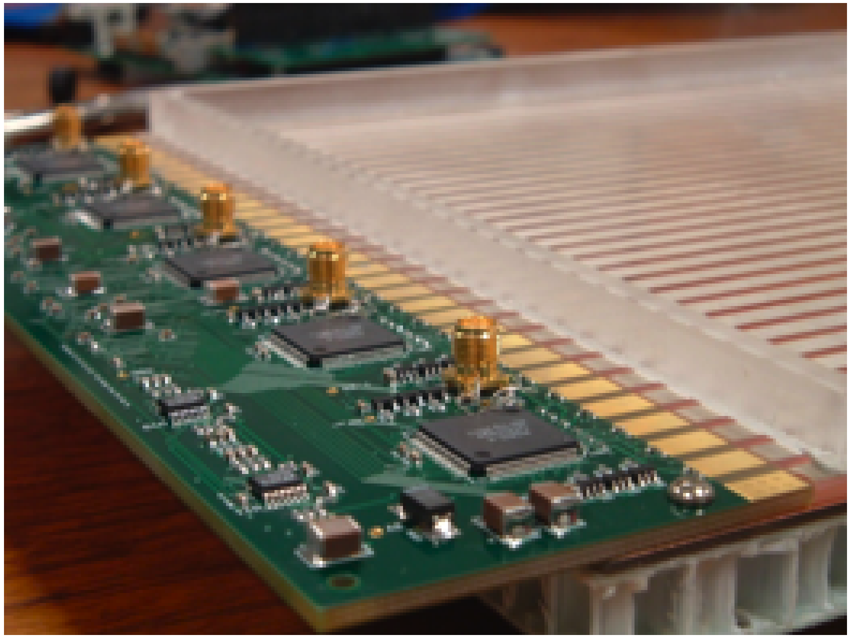
Central Card:

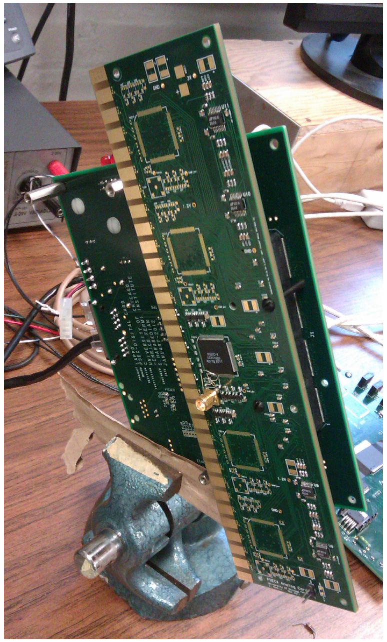
- Combines information from both ends of multiple striplines





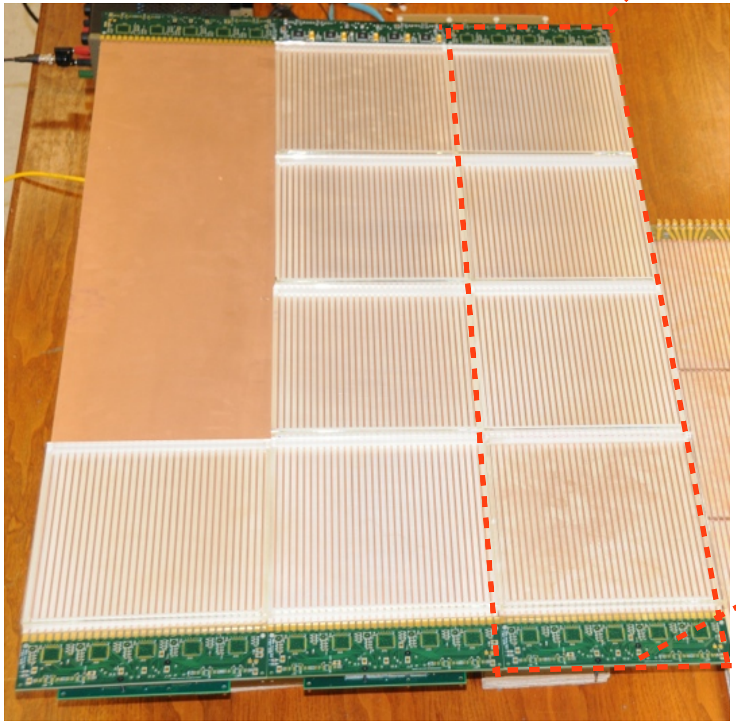
- As an R&D project, the LAPPD collaboration attacked every aspect of the problem of building a complete detector system, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes (“demountable detectors”) with resealable top window, robust

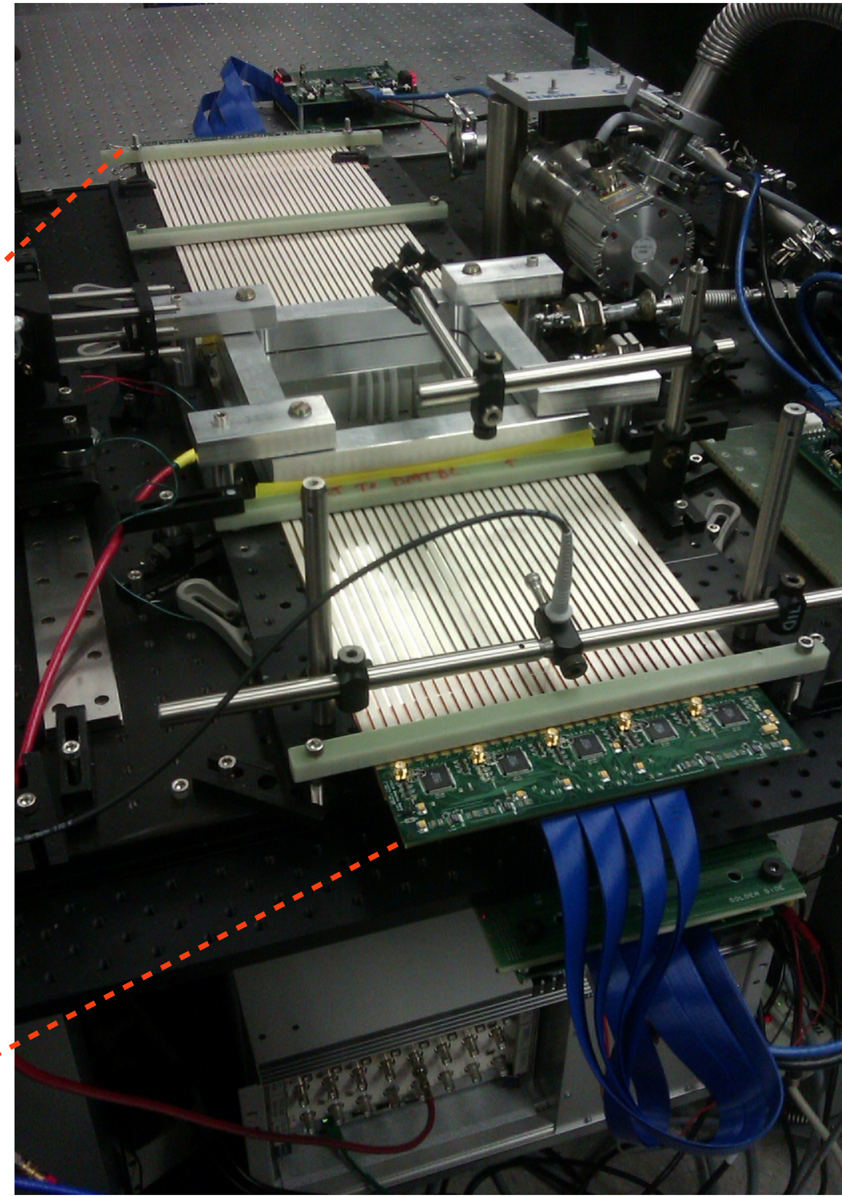




"SuMo Slice"

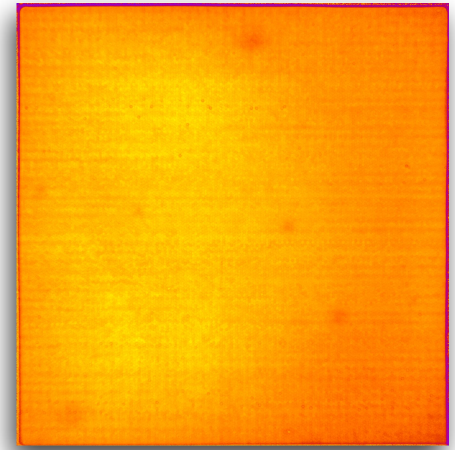
We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system ("SuMo slice").

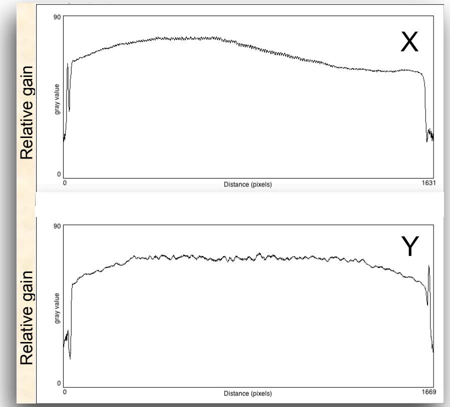


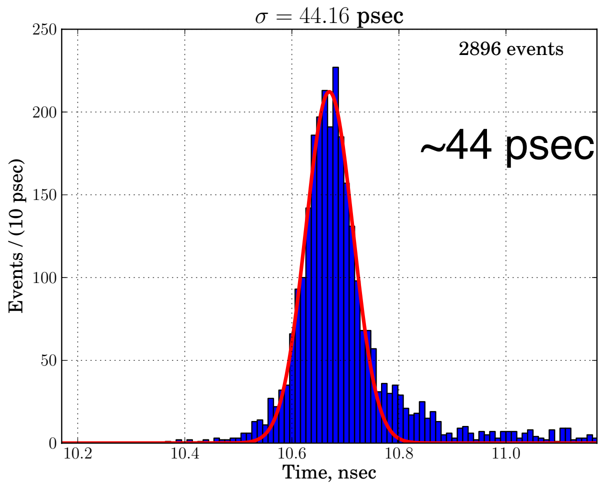


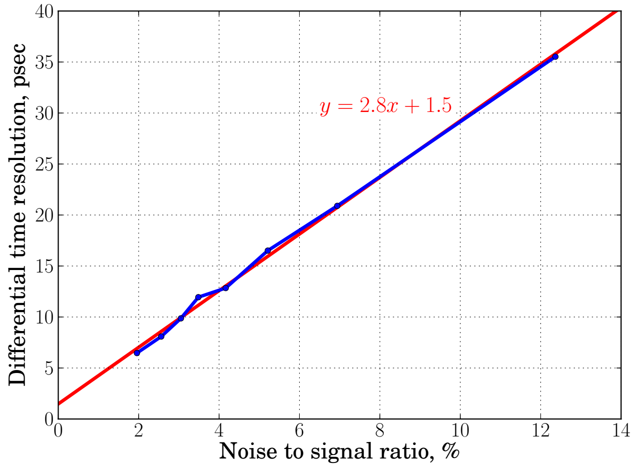
We observe:

- Typical gains of O(10^7)
- Single photoelectron time resolutions of ~40 picoseconds.
- Timing in the many-photoelectron limit approaching single picoseconds





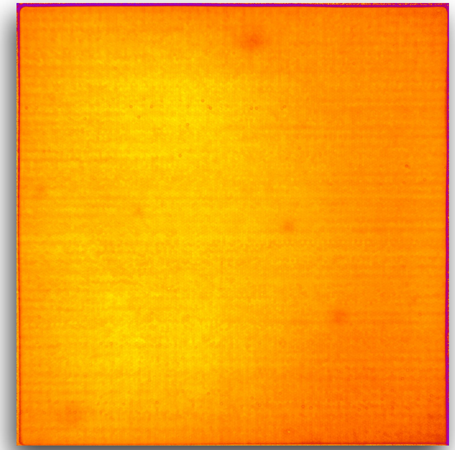


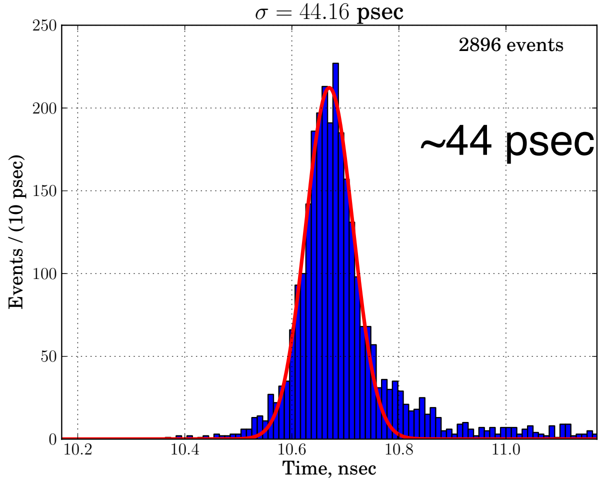


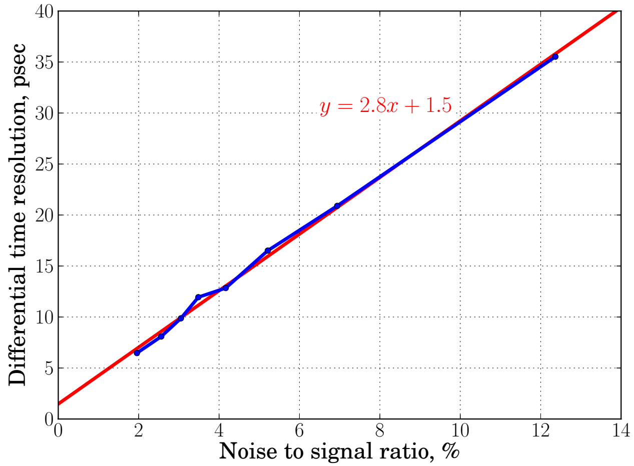
LAPPD

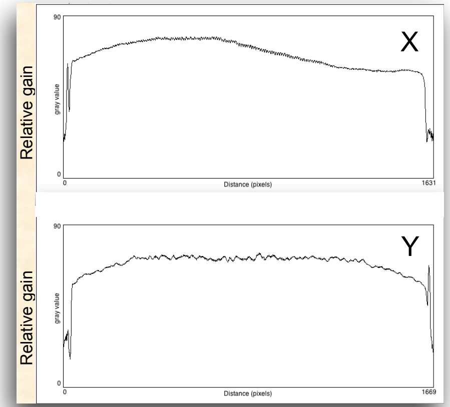
DOE has awarded Phase I of a $3M STTR (Small Tech TRansfer) grant to Incom Inc to start work on making complete sealed tubes

Typical commercialization times ~3 years, but we hope to get test detector systems out into the community much sooner.

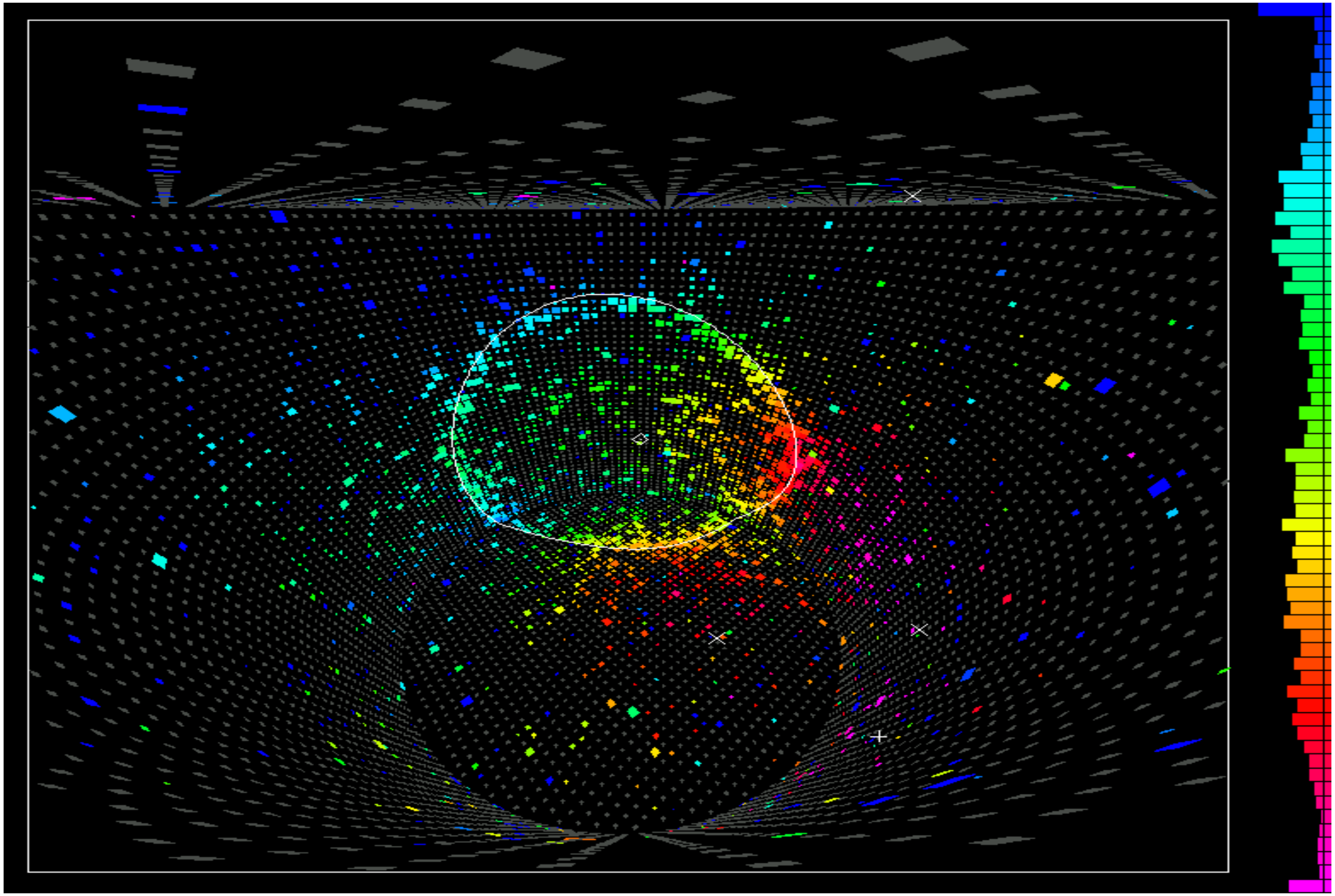






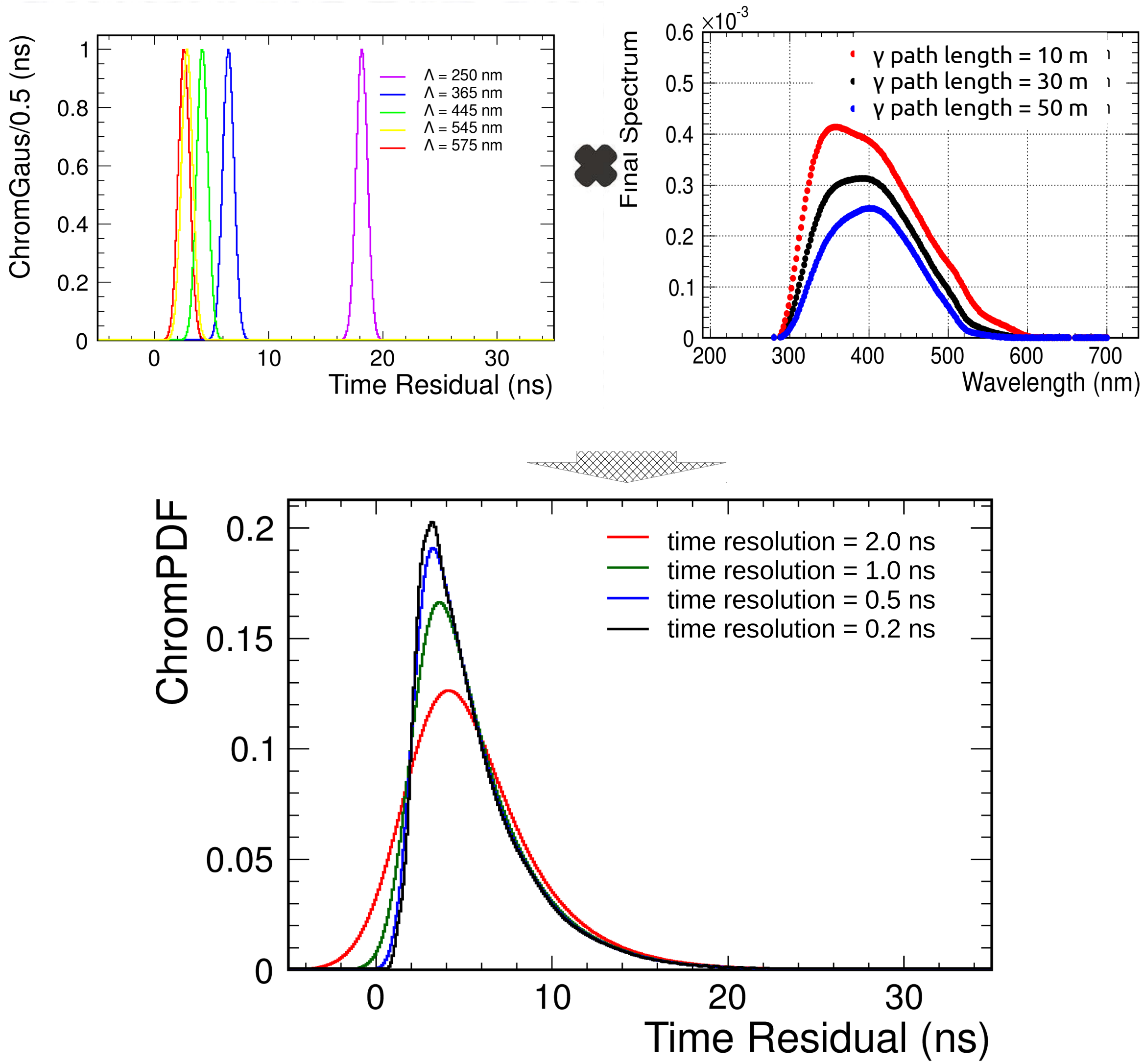


Using Imaging Photosensors in Large WC Detectors



"Simple Vertex" Reconstruction

- A timing residual-based fit, assuming an extended track.
- Model accounts for effects of chromatic dispersion and scattering.
  - separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits (not factorized in the likelihood).
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.



Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

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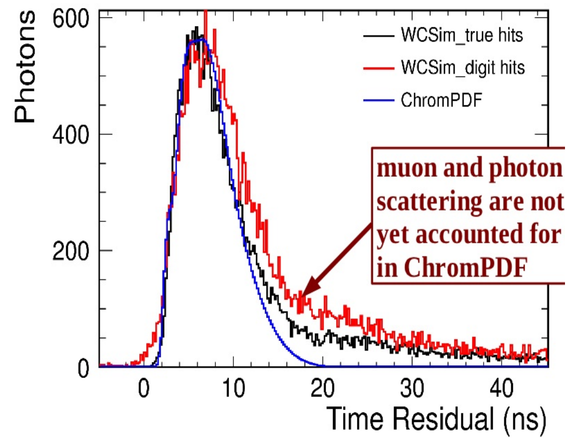
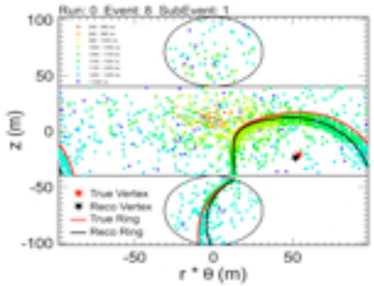
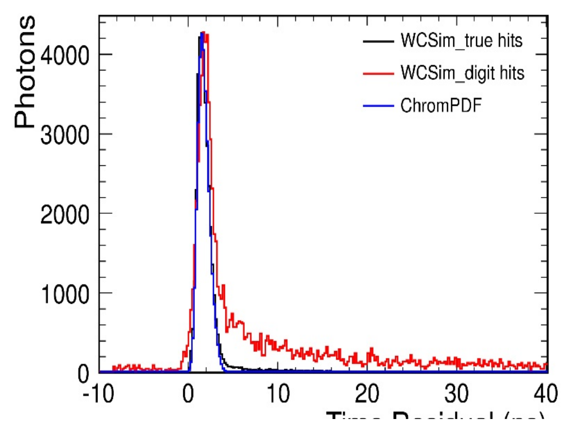
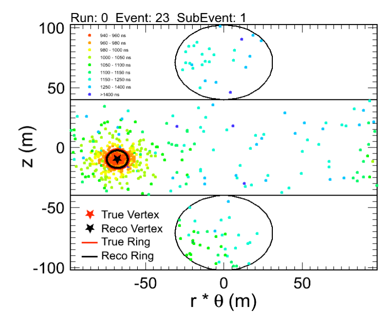




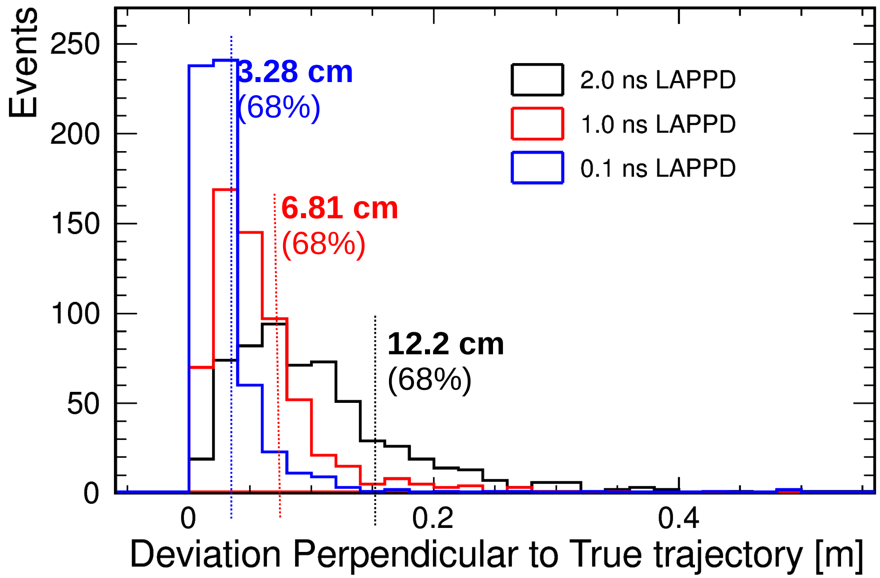


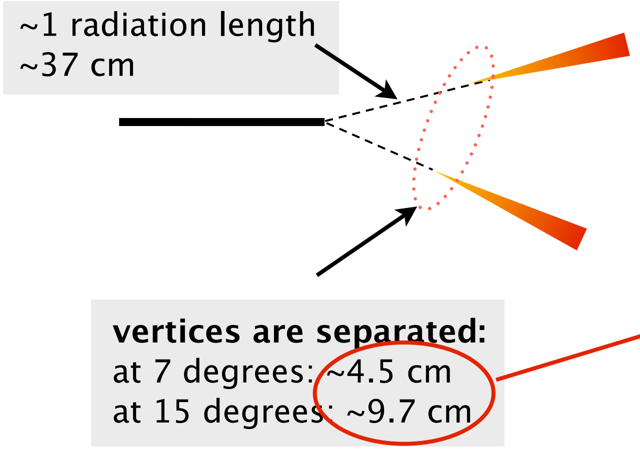


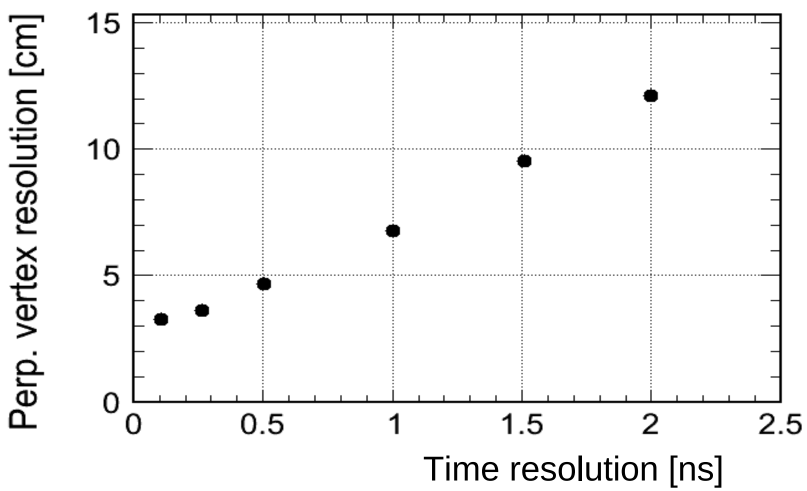
Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Simple Vertex Reconstruction

- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.
- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.



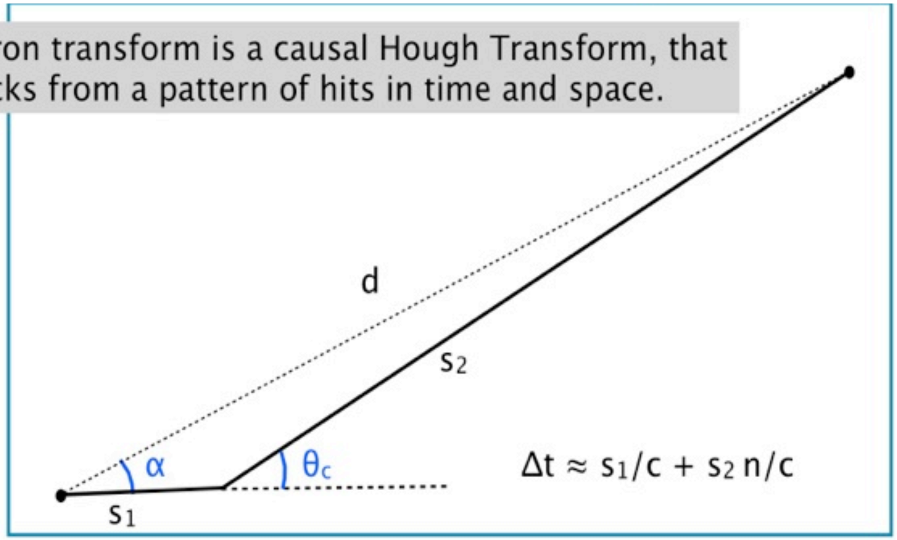




Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Isochron

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



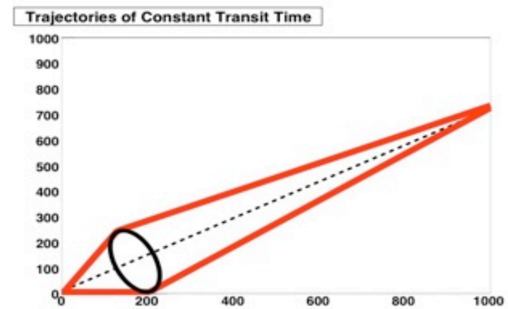
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

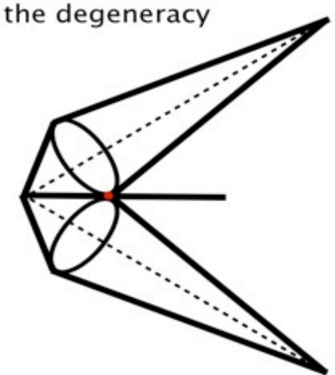
but there are two constraints:

$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

For a single PMT, there is a rotational degeneracy (many solutions).



But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy



M. Wetstein

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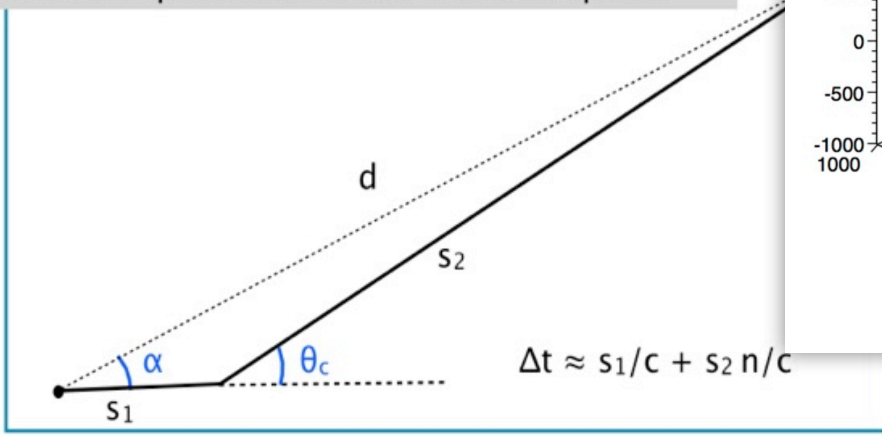

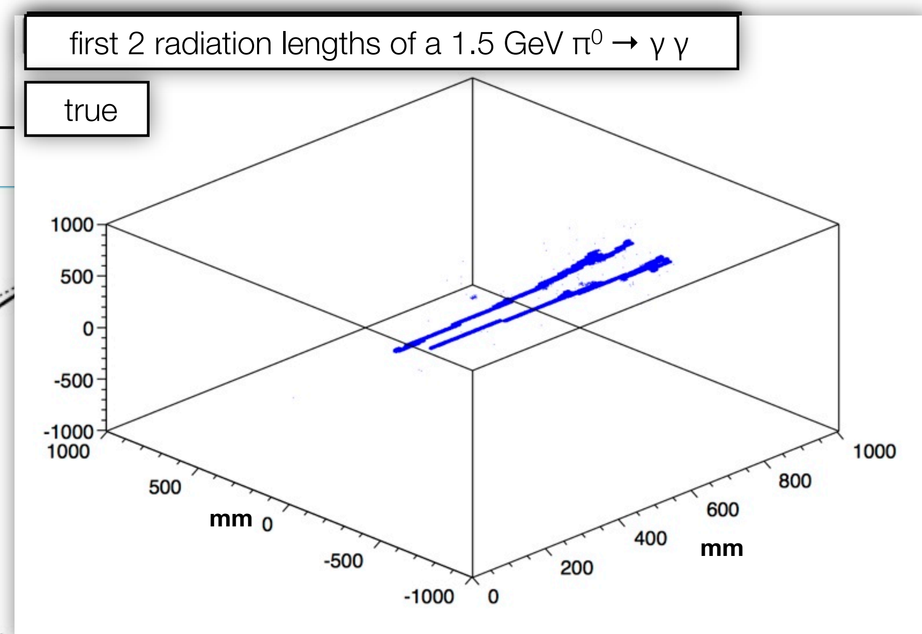

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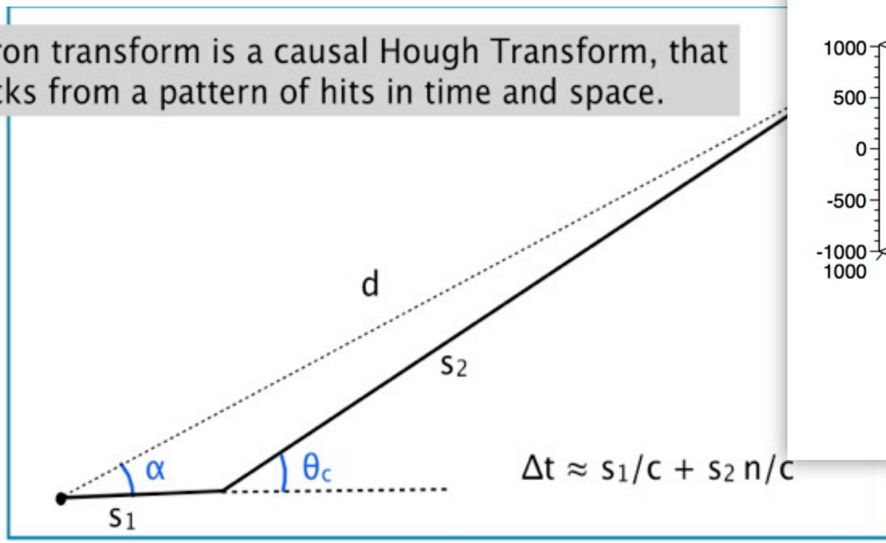

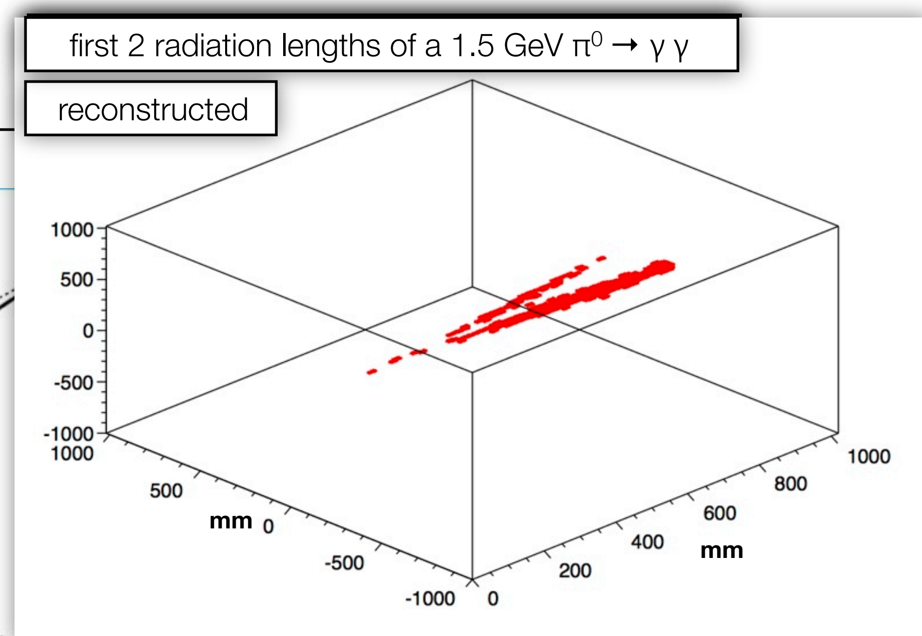

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M. Wetstein

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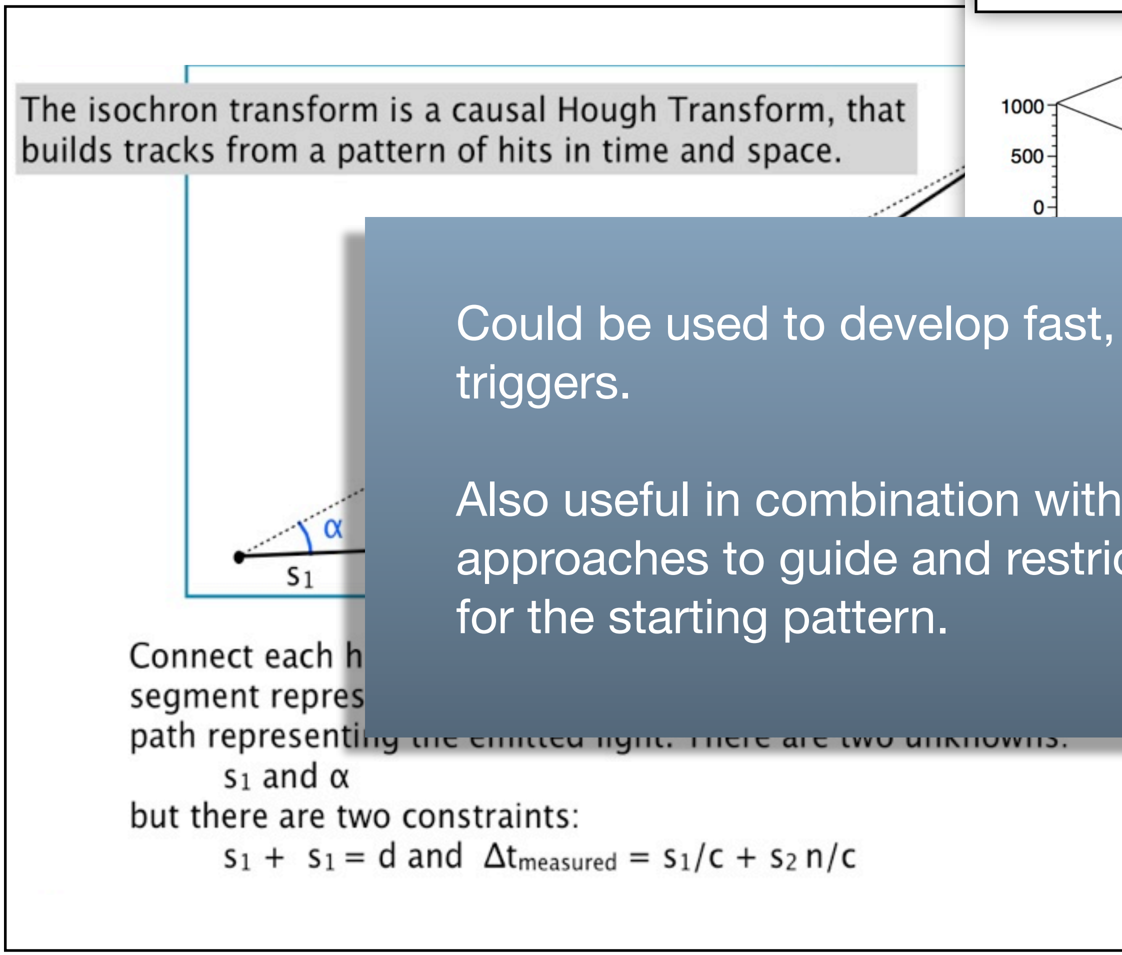
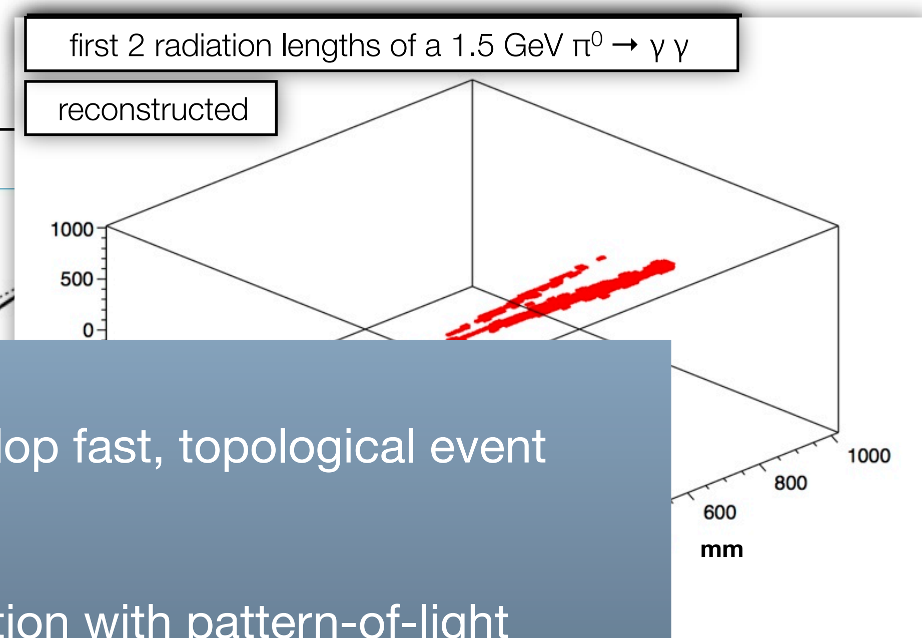




Could be used to develop fast, topological event triggers.

Also useful in combination with pattern-of-light approaches to guide and restrict the combinatorics for the starting pattern.

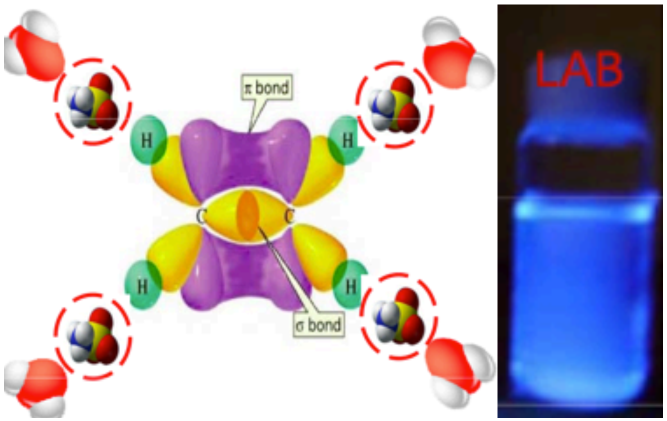
M. Wetstein

New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

Linear Alkylbenzene (LAB) – Industrial detergent
Key innovations:

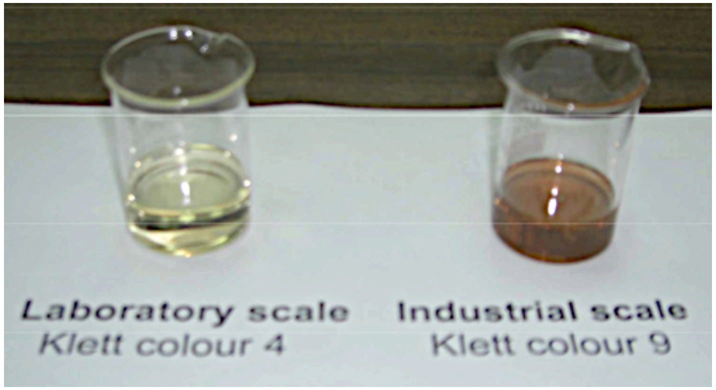
- ability to create stable solutions
- purification to achieve longer attenuation lengths

Minfang Yeh et al, Brookhaven National Lab



Ideal for large scale experiments

- Non-toxic
- Non-flammable
- Stable
- Cheap



The scintillation light might be difficult to resolve with timing, but...

- It may be possible to have both Cherenkov and scintillation light, separated in time
- The spatial/statistical gains would be considerable.

This slide is courtesy of M. Yeh.

New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

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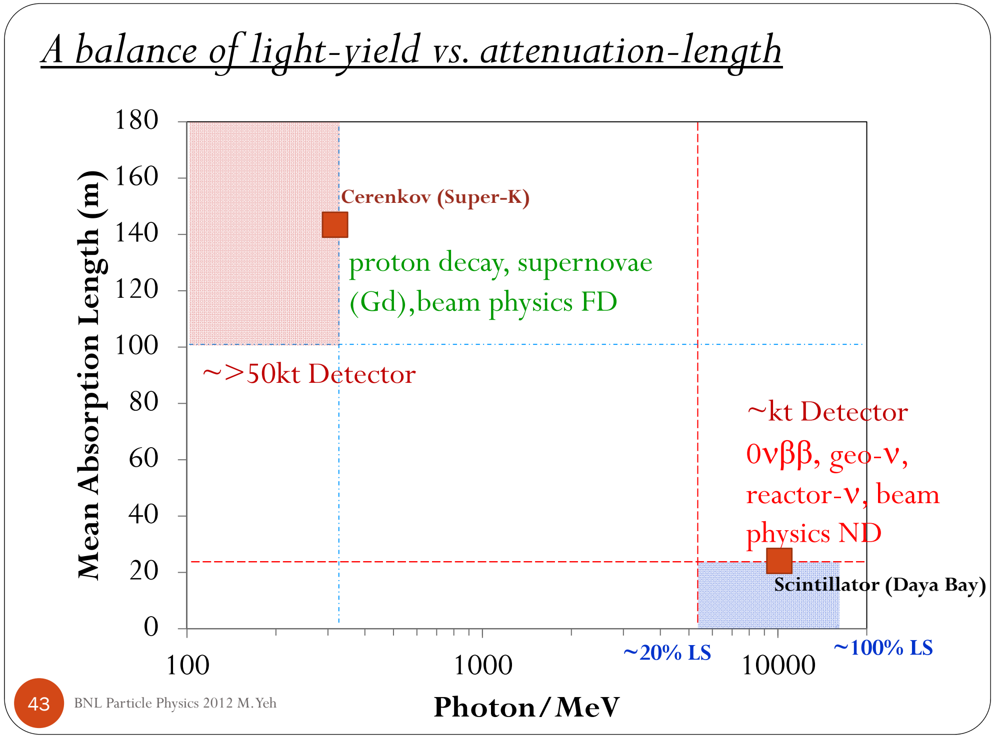

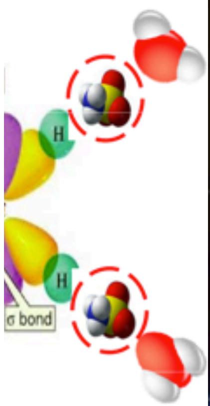

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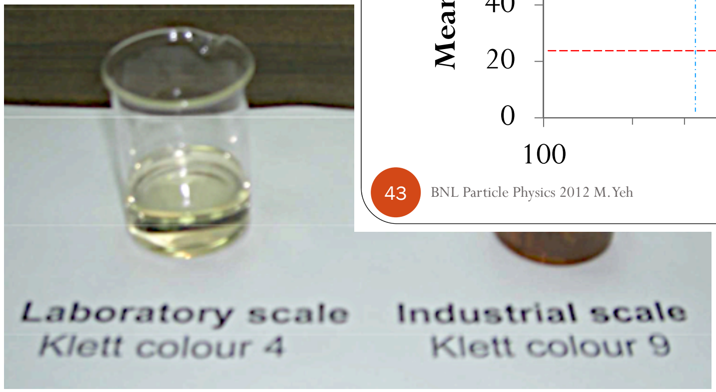

might be difficult
, but...

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scintillation light, separated in time

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This slide is courtesy of M. Yeh.

Chemical Enhancements to the Target Volume

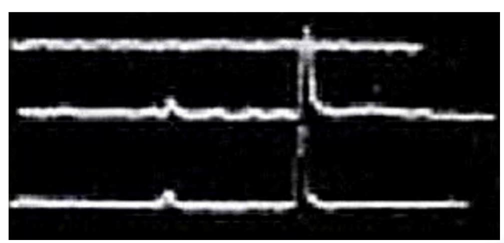
- high energy neutrino events are accompanied by n
- assume proton decay is not accompanied by n
  - * surely not for free proton
  - * also not for γ-tag states
- consider Gd addition to WC to increase n-capture tag efficiency
- Gadolinium R&D underway at SK

Inverse Beta Decay Detection with Gd

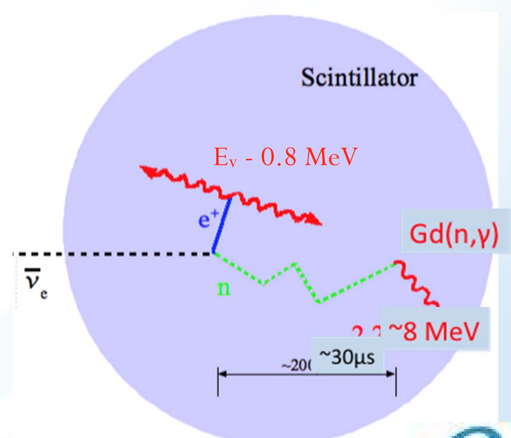
- $E_{threshold} = 1.8\ MeV$
- *'Large' cross section* $\sigma \sim 10^{-42}\ cm^2$
- *Distinctive coincidence signature in a large liquid scintillator detector*

$$\bar{\nu}_e + p \rightarrow \boxed{e^+} + n$$

$$\mathrm{n} + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \boxed{\gamma' s}$$



Cowan & Reines, Savannah River 1956



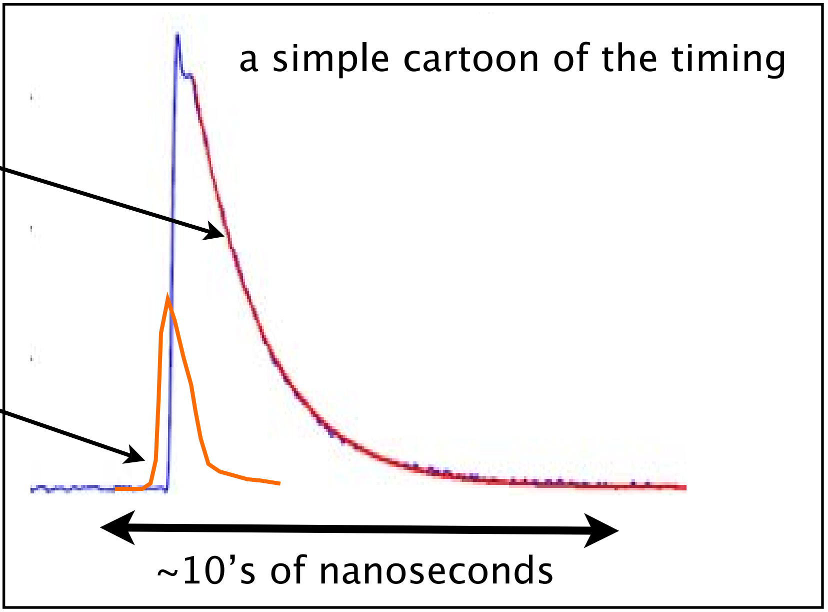
This slide is courtesy of M. Yeh.

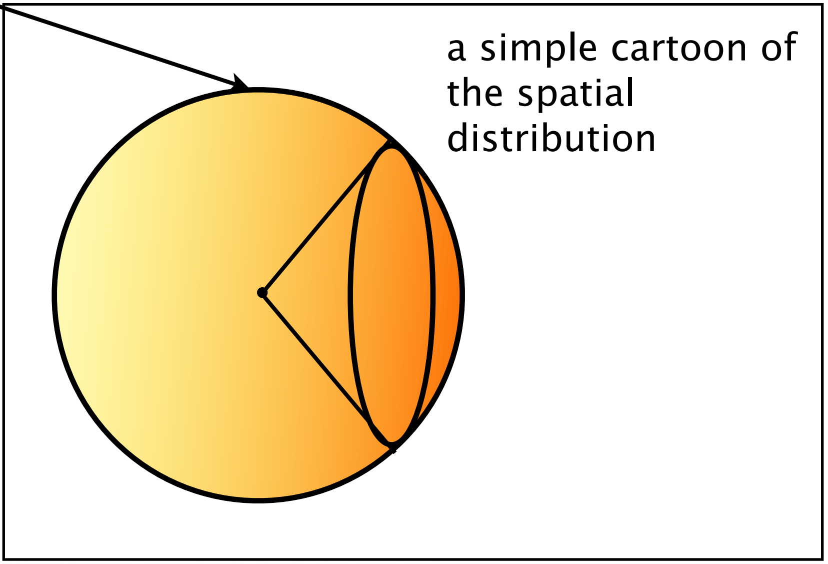
Discriminating Between Scintillation and Cherenkov Light

Scintillation light more spread out in time

Red component of the Cherenkov light arrives O(100) picoseconds earlier than the (blue-ish) scintillation light

Scintillation light is spread isotropically, while Cherenkov is constrained to a ~42 degree angle



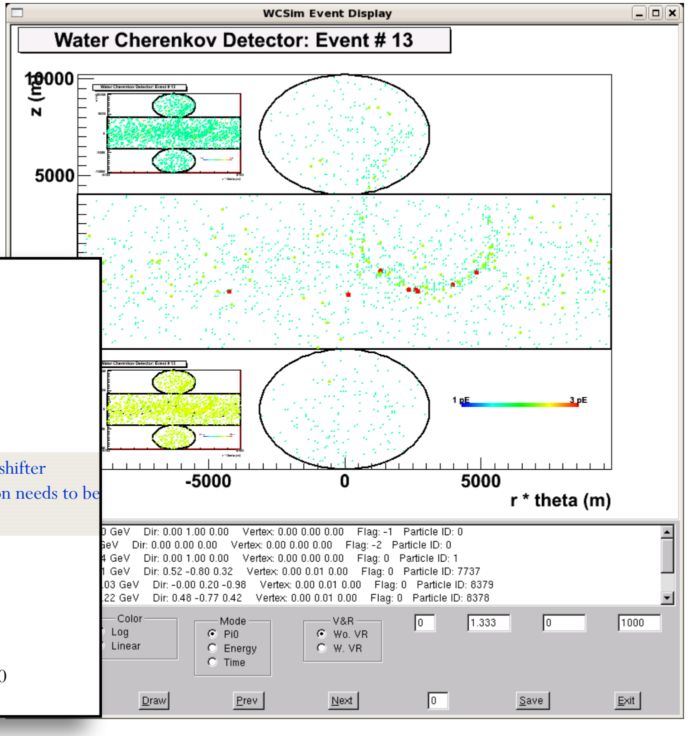


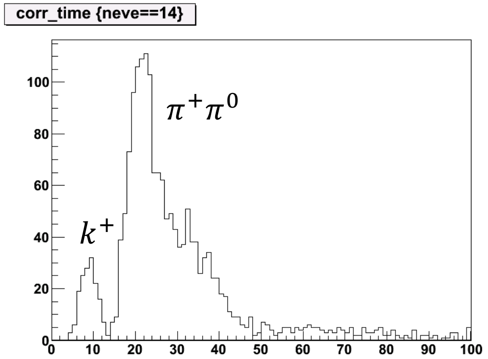
Discriminating Between Scintillation and Cherenkov Light

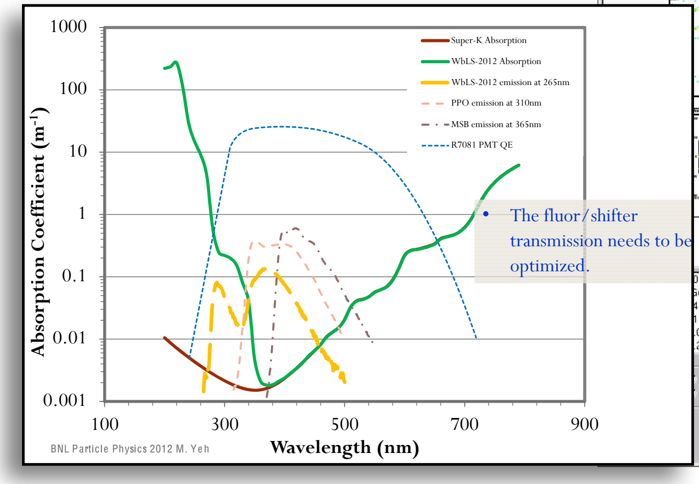
Can potentially tune:

- relative light yield
- wavelength
- timing

A quick look of $k^+ \rightarrow \pi^+\pi^0$







- Very clear Cerenkov ring even without cut

This slide is courtesy of M. Yeh.

Energy Resolution

Sen Qian

	KamLAND	Daya Bay II
Detector	~1 kt Liquid Scintillator	➢10 kt Liquid Scintillator
Energy Resolution	$6\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV

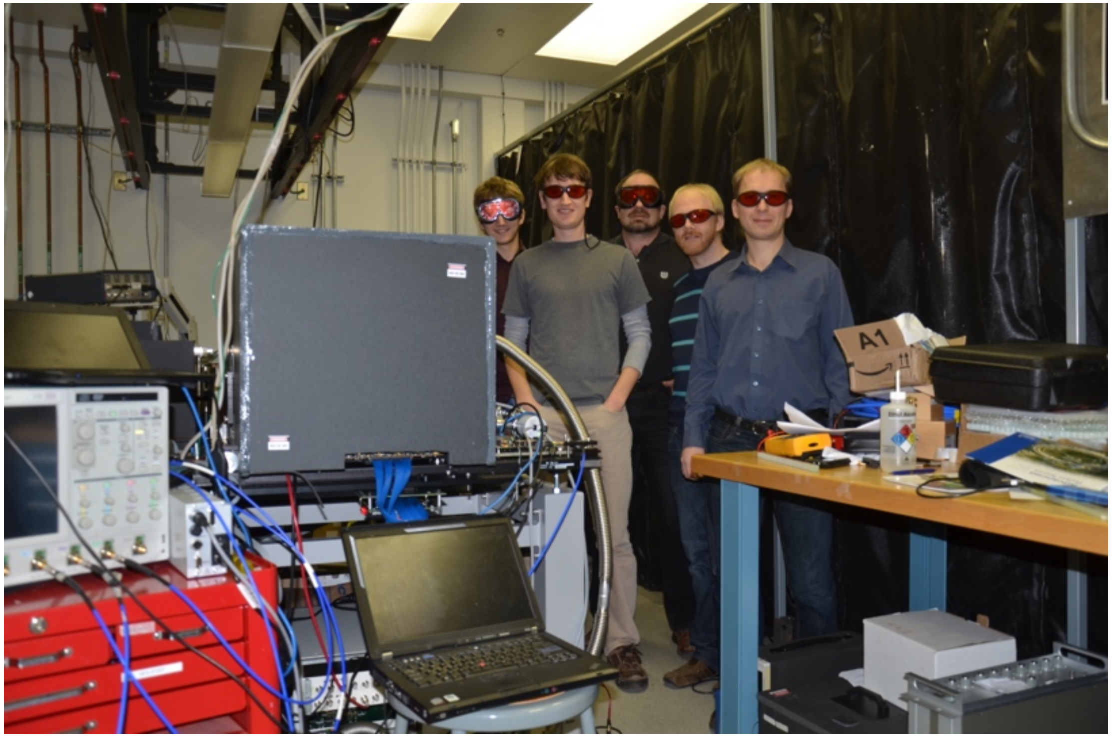
More photons, how and how many ?

How?

4.3 – 5.0 ➔ (3.0 – 2.5)% /√E

- Increased QE
- Light collection
- Higher Light yield
- Digital photon counting?

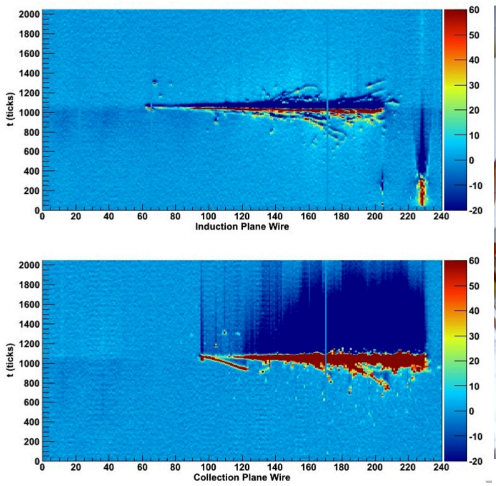
Conclusions

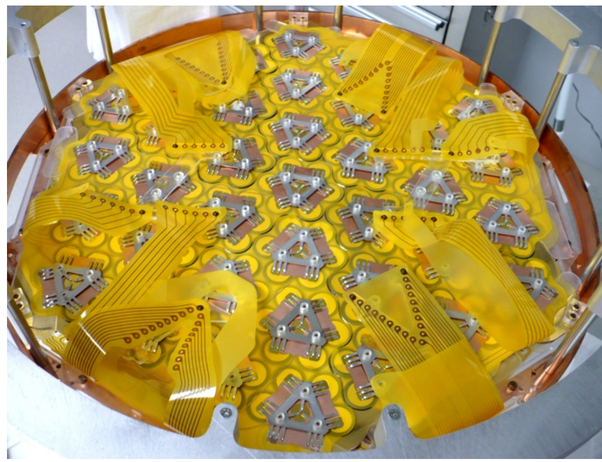


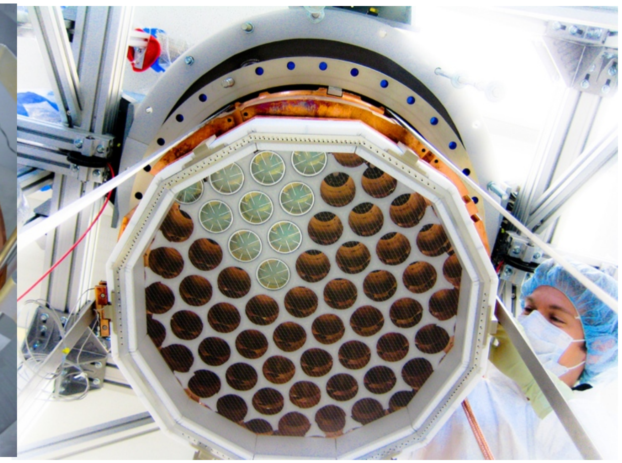
Other Possible Opportunities

LAPPD-based detectors can be non-cryogenic, but they don’t have to be. This technology Could be useful for photodetection in cryogenic experiments:

- LBNE near and far detectors (LAr)
- double beta decay (dark matter) experiments?

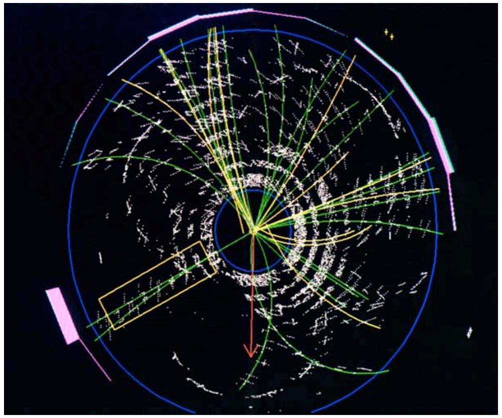


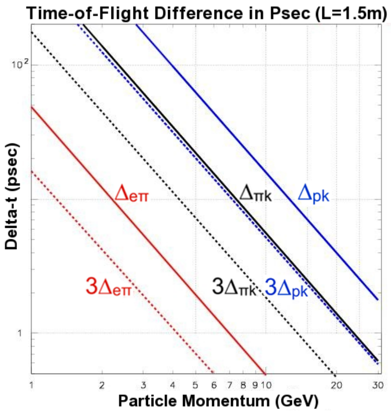




LAPPD was inspired by collider applications: time-of-flight based particle ID.

Also many potential practical applications: PET, security...



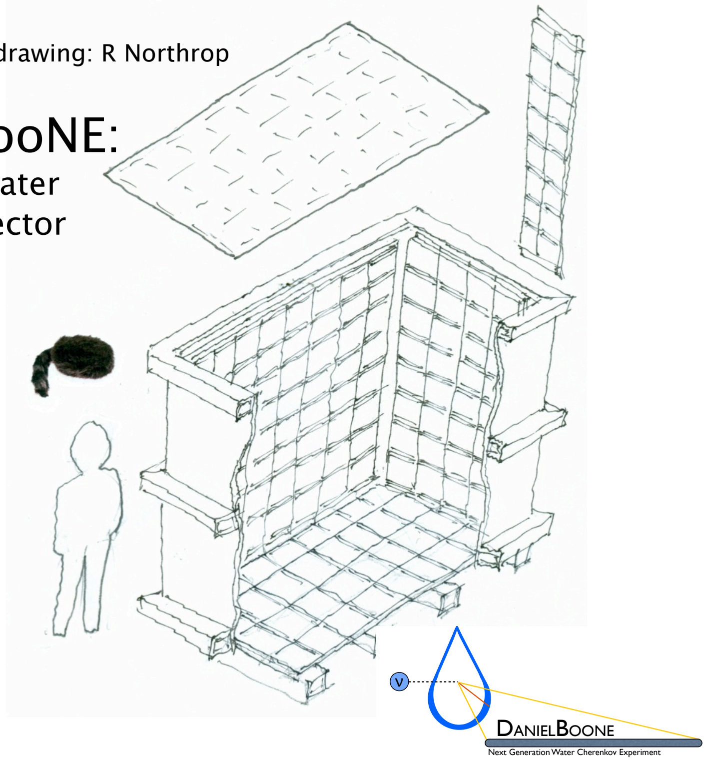


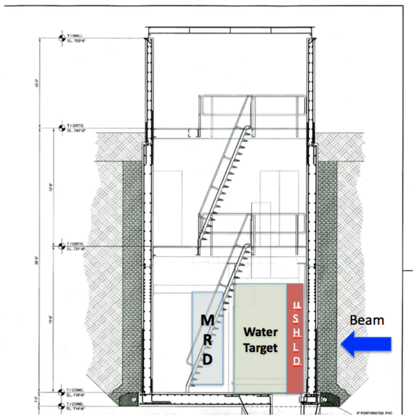
Closing Thoughts

- Radically new technology can come from old ideas
- Often - the enabling technology is not one single innovation but the combination of several new ideas
- There is a strong future for advanced WC/ scintillation detectors
- The combination of fine timing and space resolution makes for much improved tracking and analysis capabilities
- The introduction of liquid enhancements (Gd, WbLS, etc) can radically change sensitivities to low energy and high-mass particles
- Need for demonstration experiments over the next few years
- Need for a strong and imaginative community!

drawing: R Northrop

"Daniel" BooNE:
Experimental Water Cherenkov Detector





ANNIE:
Atmospheric Neutrino Neutron Interaction Experiment

Thank you

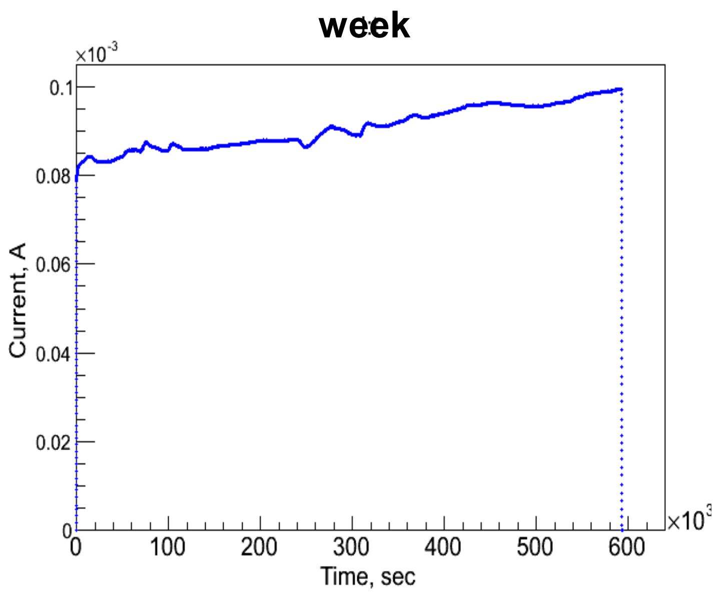
Thanks also to all of my LAPPD and "fast timing" neutrino colleagues
for all of the work presented in this talk

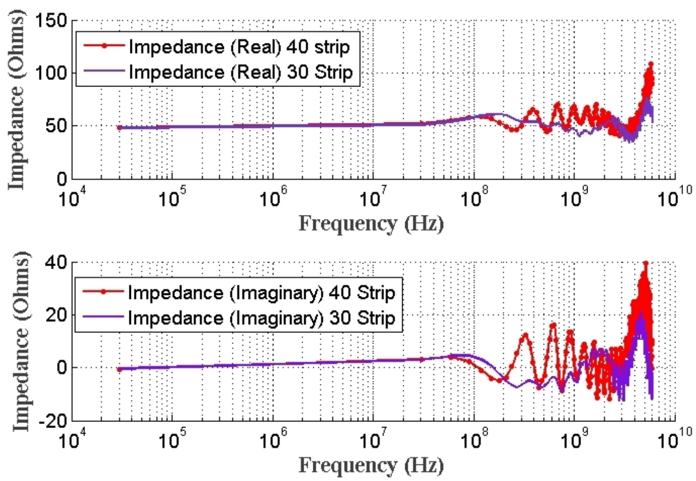
Any Questions?

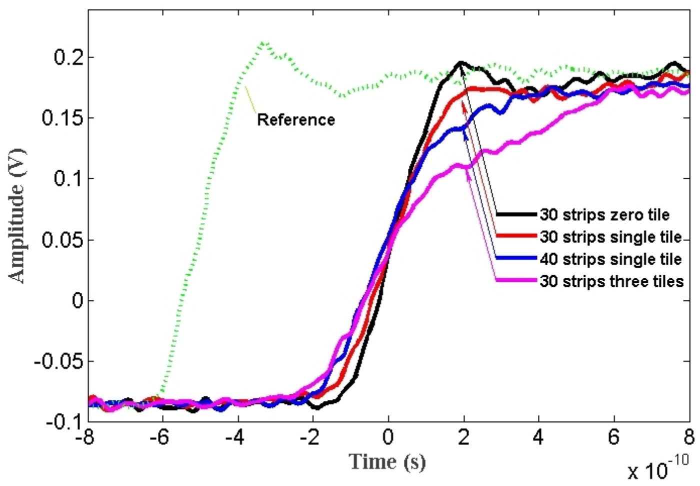
Backup Slides

What we measure...Also:

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

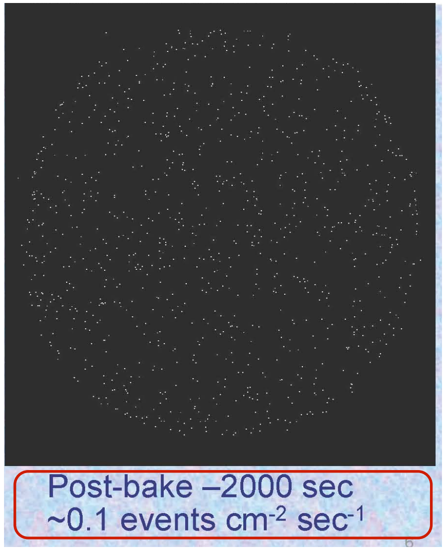




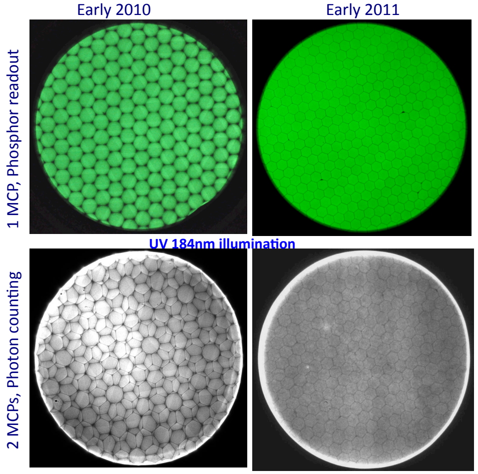


MCP Quality

Low noise



Rapidly improving substrates (Arradiance)



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

Measurements by

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

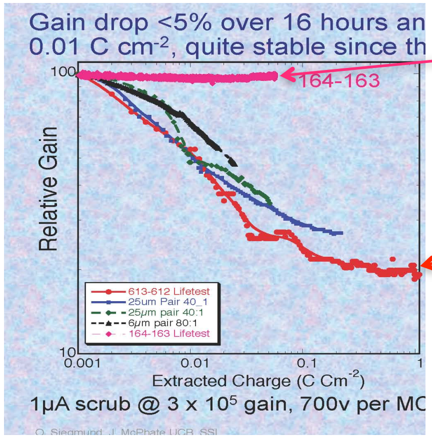
Berekeley SSL

Samples by

J. Elam, A. Mane, Q. Peng

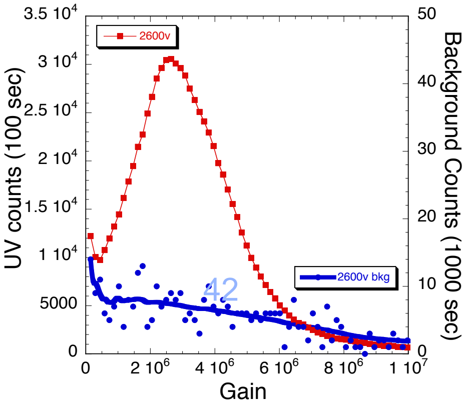
ANL

Short break-in



Measured ANL ALD-MCP behavior

Typical MCP behavior- long scrub-times



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

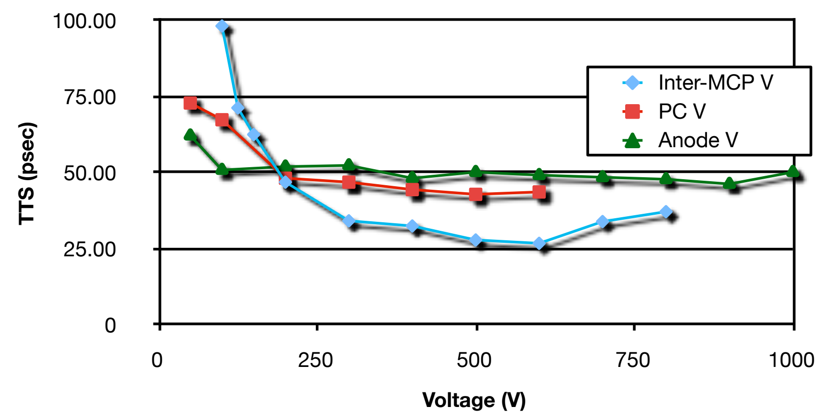
	U	Δu	f_s	f_{3db}	Δt
today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
next generation:	100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
next generation optimized SNR:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

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)

TTS Vs Various Operational Voltage



Intrinsic to the MCP:

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

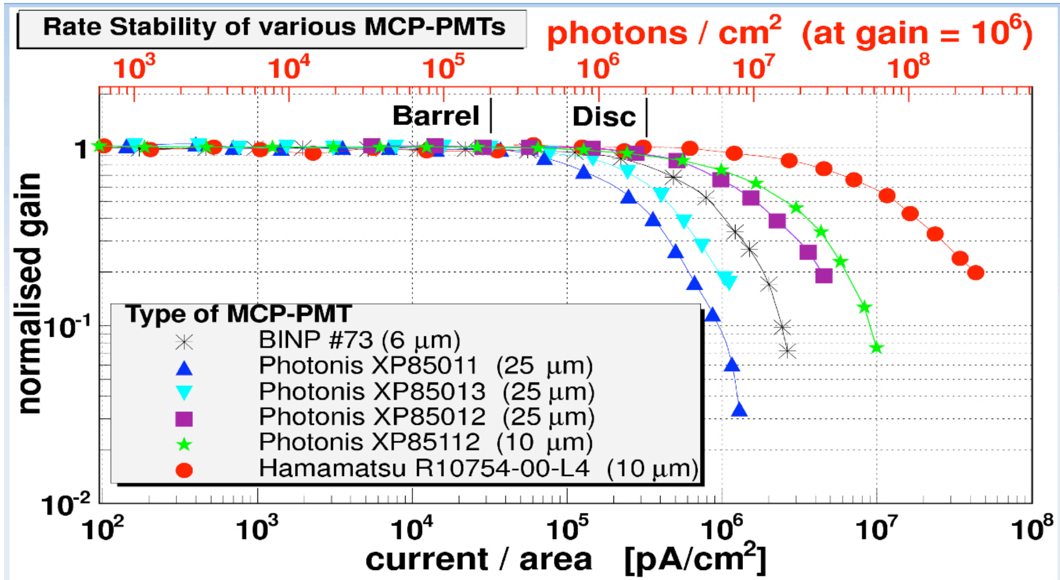
see: workshop on factors that limit time resolution in photodetectors: http://psec.uchicago.edu/workshops/fast_timing_conf_2011/

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.

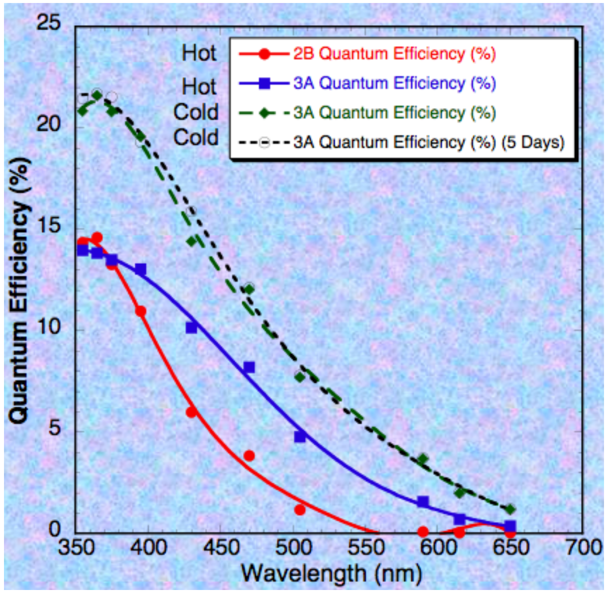
Rate Limitations of ALD-MCPs

- 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**

Photocathode

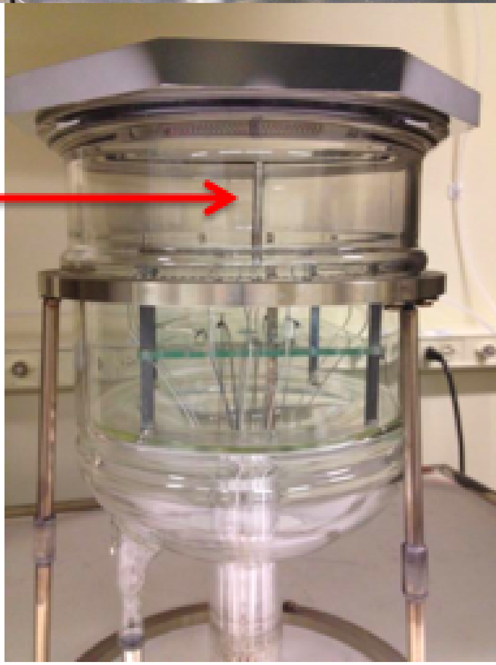
- Two main parallel paths:
  - scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production lines.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries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

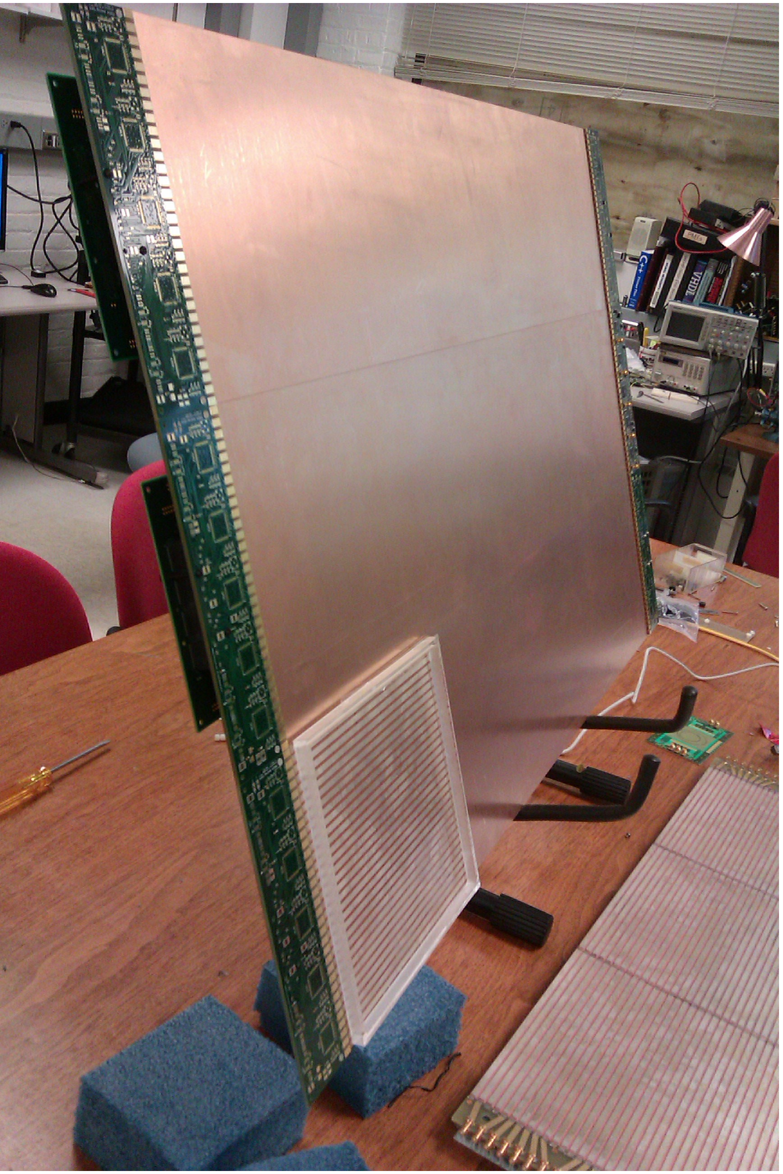


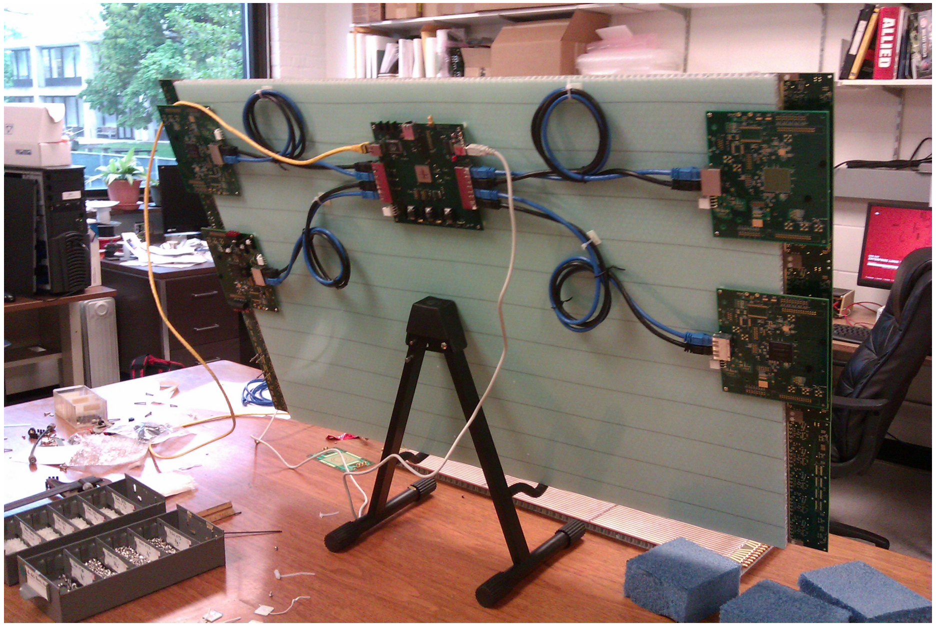
8" Tile-Assembly Chamber (UCB)

The "Chalice" (ANL)

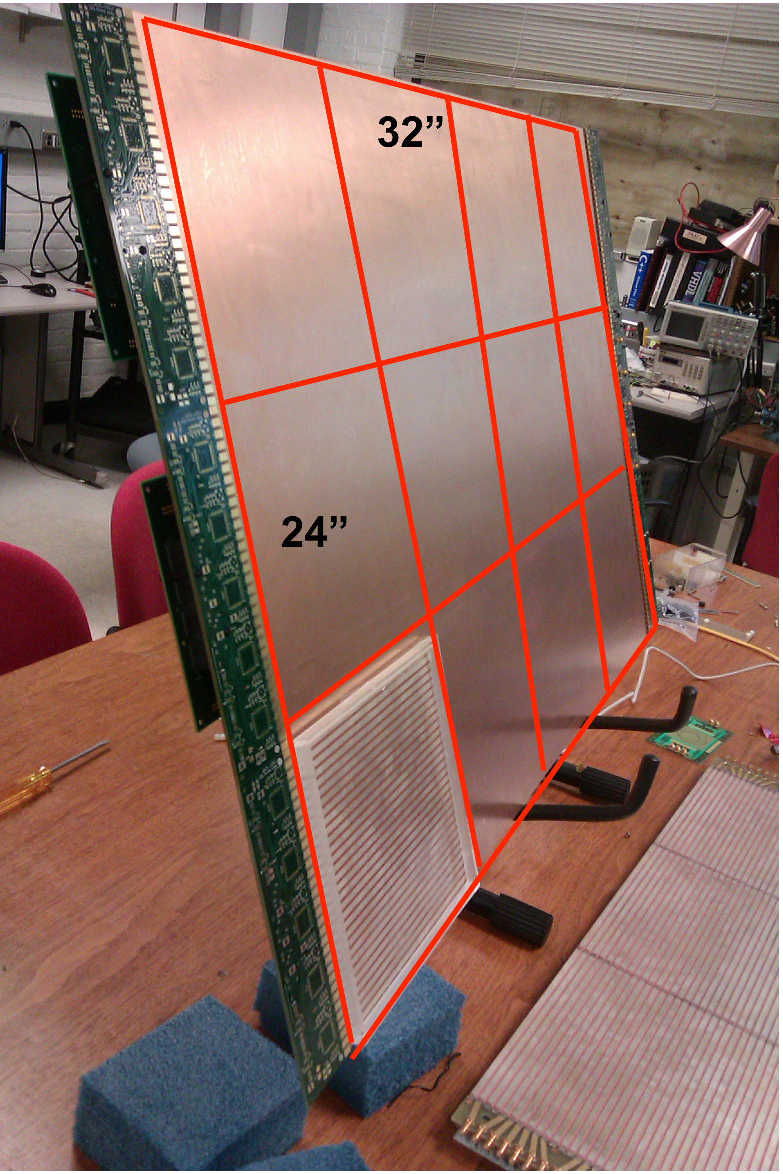


The Big Picture



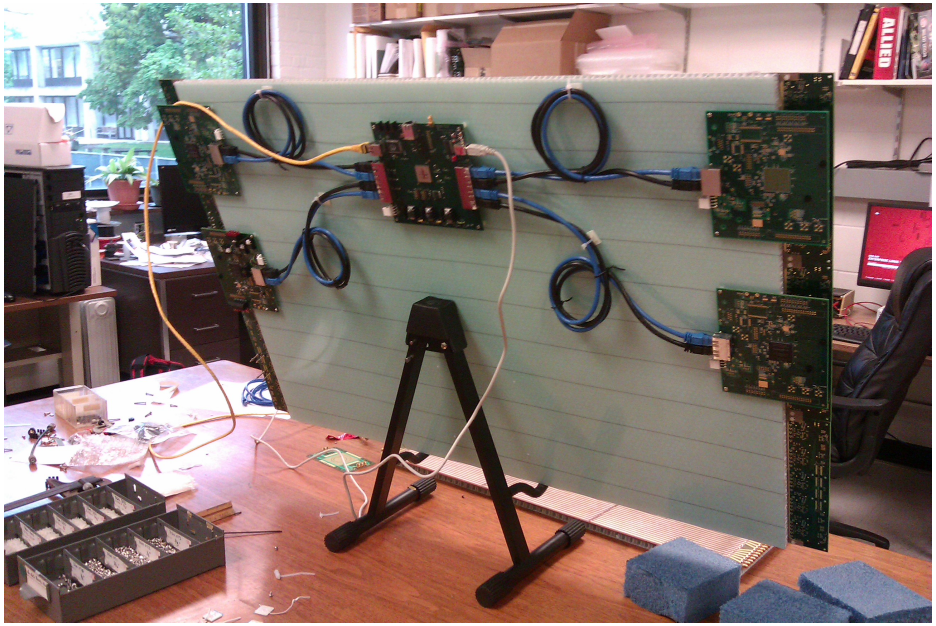


The Big Picture

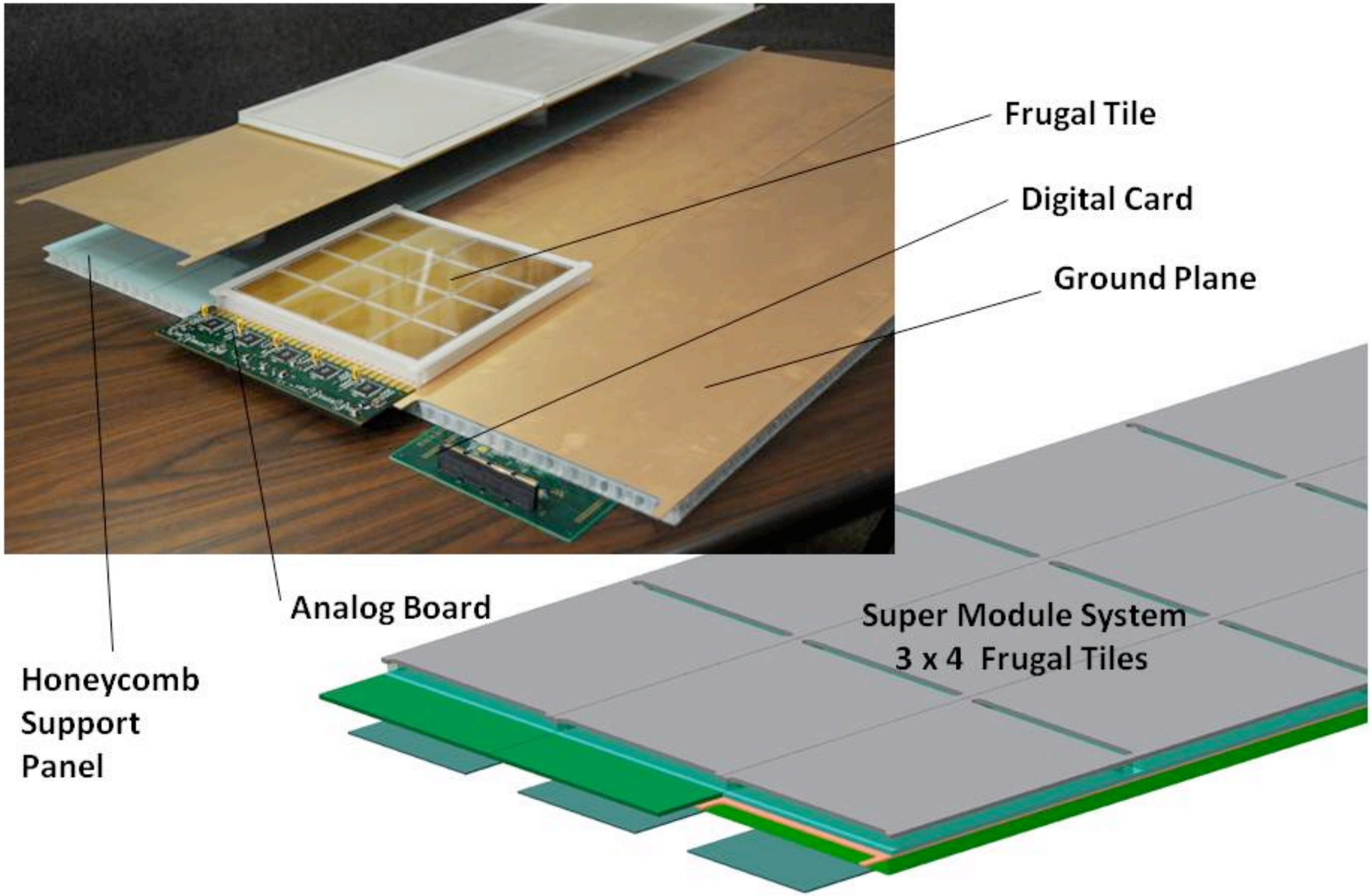


Supermodule:

- 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

Advantageous Characteristics for Neutrino Detection

Compactness

Excellent Photon Counting

Don't need to rely on charge only:

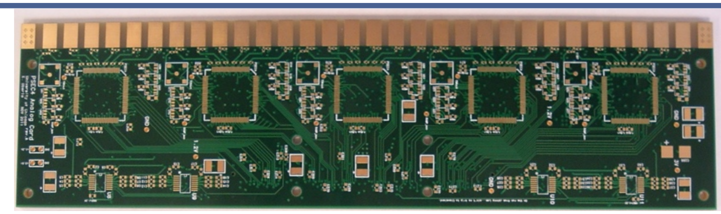
- **Can see individual photons based on where and when they hit.**
- **Could mean improved energy resolution.**

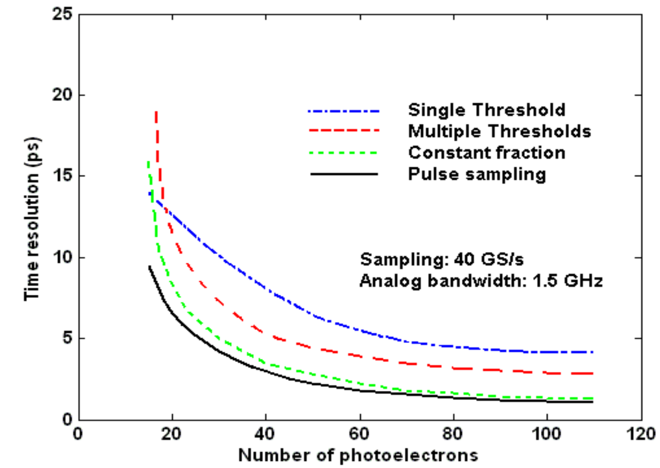
Front-End Electronics

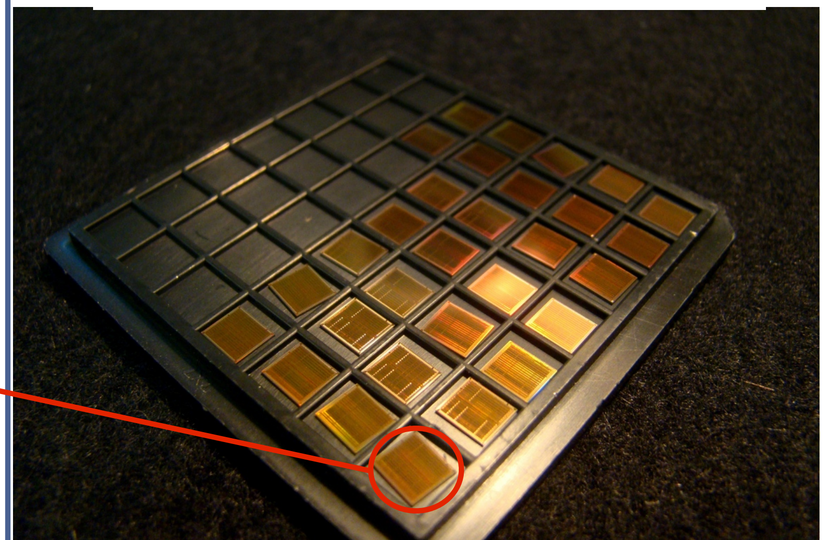
- Collaboration between UChicago and Hawaii.
- Resolution depends on number of photoelectrons, analog bandwidth, and signal to noise ratio.
- Wave-form sampling is best and can be implemented in low-power widely available CMOS processes. Low cost per channel.
- For neutrinos a time resolution of ~100 psec should be sufficient.

Achievement: Successful development and testing of PSEC-4 sampling chips.
- 17 GS/sec
- ~1 mV noise
- 4-channels
- “scope on a chip”

J-F. Genat, G. Varner, M. Bogdan, M. Baumer, M. Cooney, Z. Dai, H. Grabas, M. Heintz, J. Kennedy, S. Meehan, K. Nishimura, E. Oberla, L. Ruckman, F. Tang







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

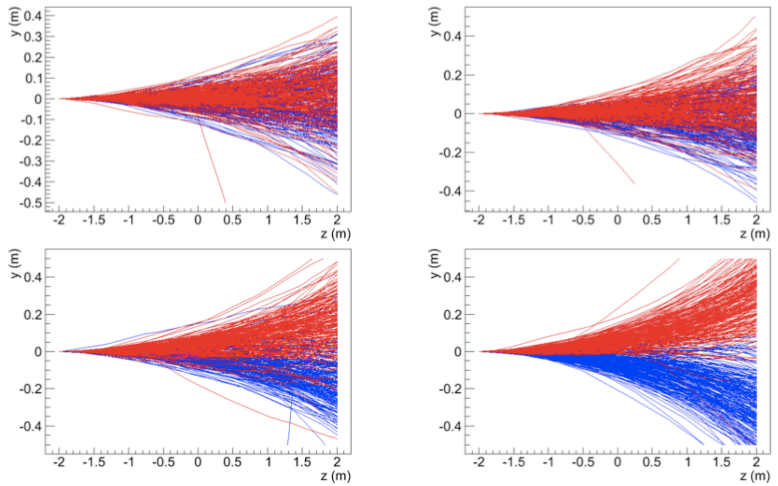


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

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

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

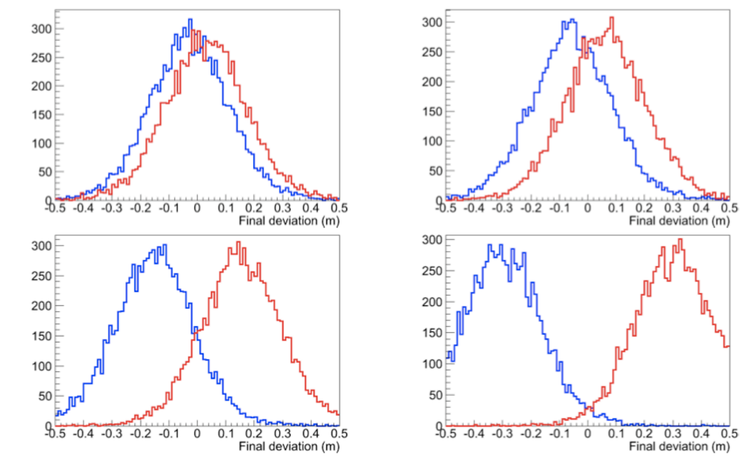


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

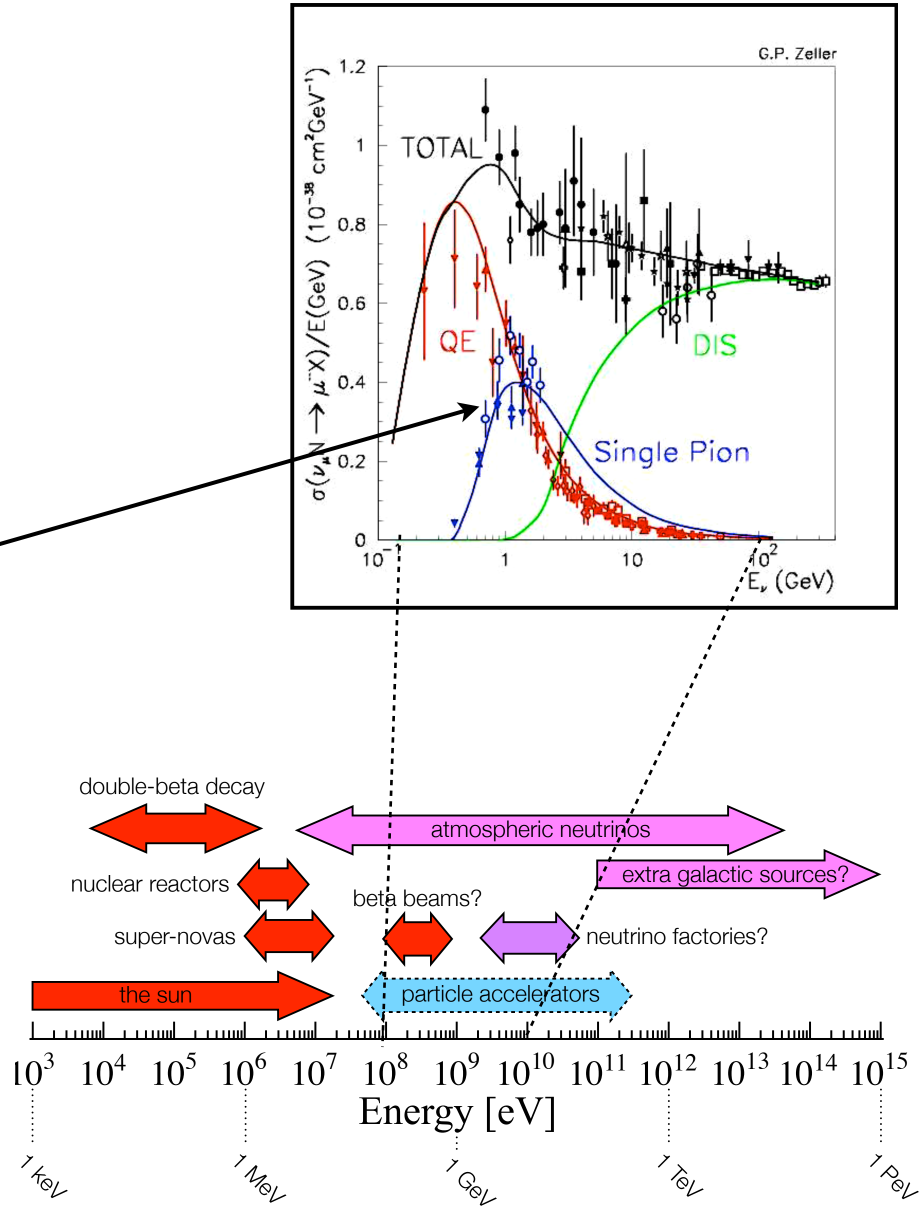
Figure: $B = 200$ gauss (top), $B = 1$ kgauss (bottom).

Work by Alexander Vostrikov (U. Chicago)

Granularity

Medium energy ranges typical of accelerator and atmospheric neutrino physics fall into the “transition region” between Quasi-elastic scattering and deep inelastic scattering.

Pion production (from excited nuclear states) peaks at these energies.



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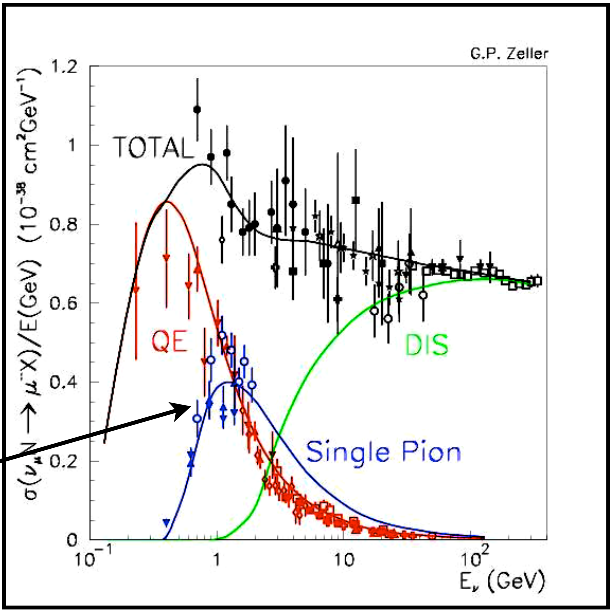


Pion production (from excited nuclear states) peaks at these energies.

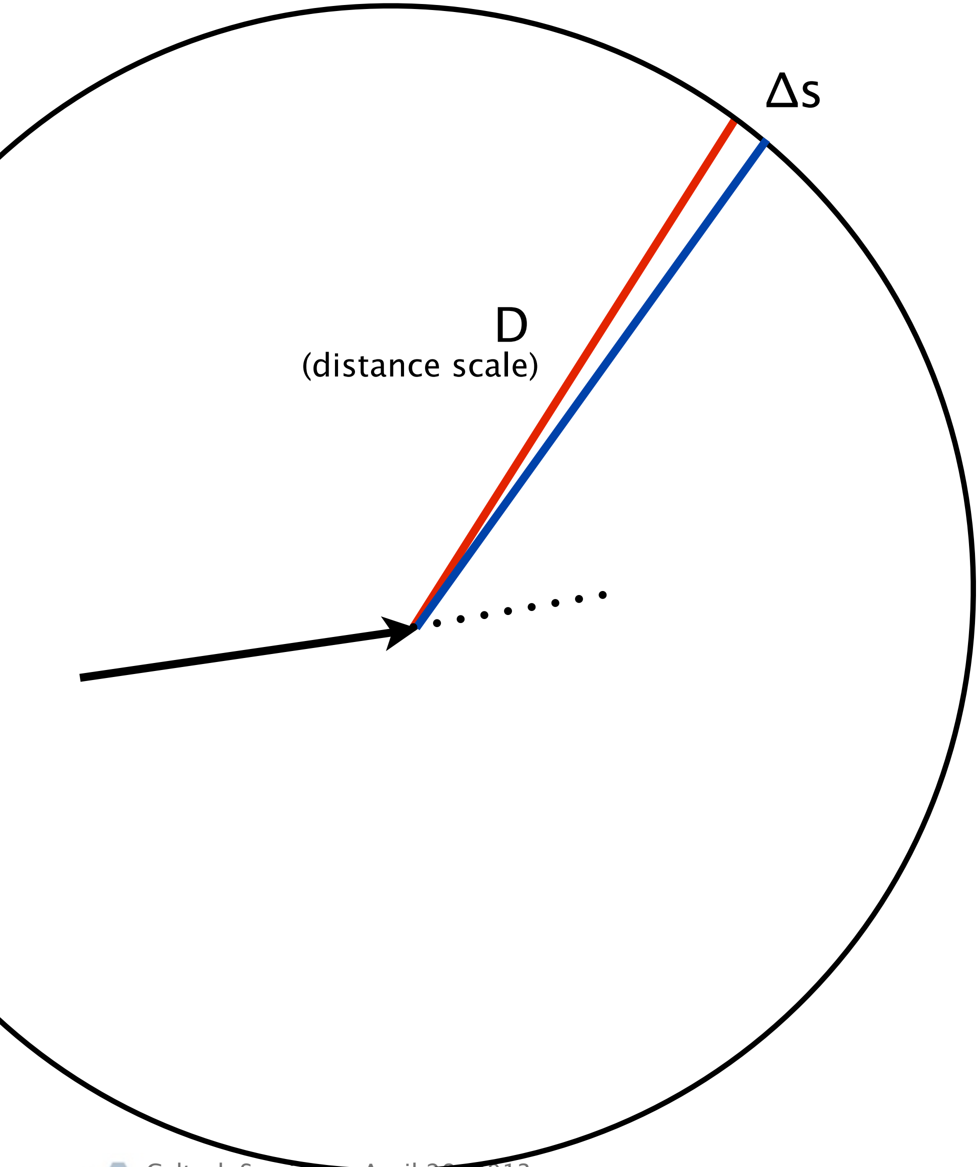
CC

$$\nu_\mu p \to \mu^- p \pi^+, \qquad \bar{\nu}_\mu p \to \mu^+ p \pi^-,$$
$$\nu_\mu n \to \mu^- p \pi^0, \qquad \bar{\nu}_\mu p \to \mu^+ n \pi^0,$$
$$\nu_\mu n \to \mu^- n \pi^+, \qquad \bar{\nu}_\mu n \to \mu^+ n \pi^-$$

NC

$$\nu_\mu p \to \nu_\mu p \pi^0, \qquad \bar{\nu}_\mu p \to \bar{\nu}_\mu p \pi^0,$$
$$\nu_\mu p \to \nu_\mu n \pi^+, \qquad \bar{\nu}_\mu p \to \bar{\nu}_\mu p \pi^+$$
$$\nu_\mu n \to \nu_\mu n \pi^0, \qquad \bar{\nu}_\mu n \to \bar{\nu}_\mu n \pi^0,$$
$$\nu_\mu n \to \nu_\mu p \pi^-, \qquad \bar{\nu}_\mu n \to \bar{\nu}_\mu p \pi^-.$$

Understanding Chromatic Dispersion



Light of different colors arrives at different times, but also at different Cherenkov angles.

At 10 meters distance, 250nm light arrives ~6.5 nsec later than 550 nm.

Given the difference in θ_c for the two colors (0.885 versus 0.747 radians), the spatial separation between the red and blue light at 10 meters is ~1.4 meters

with resolution on Δt approaching 100 picoseconds, one can distinguish between colors much closer on the spectrum, but only if one can also resolve the corresponding Δs which is 2.4 cm

in LBNE, granularity of PMTs is 10" (25.4 cm) with more the 1 meter separation between phototubes.

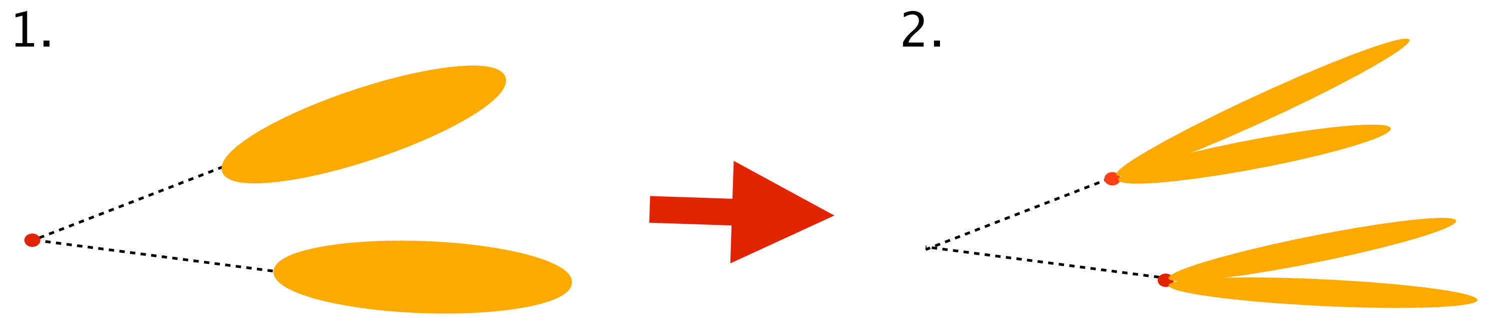
Optimizing the Transform

Once candidate showers have been identified, each stage of the shower needs to be independently transformed.

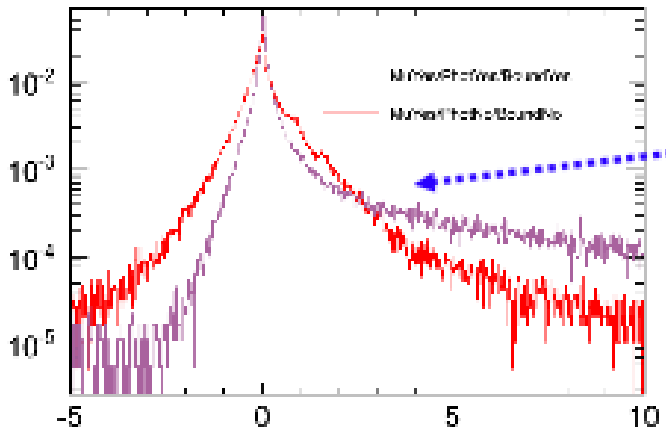
Isochron algorithm works best over one single stage of a shower. Each new branch point can be transformed iteratively, using the branch point as the new starting vertex.

Crude, first application of the isochron transform is useful to identify the original vertex, location of first light, number of shower candidates in the next stage. But, these are important particle ID handles. Can be used to make initial cuts.

In this first stage, before later applying chromatic corrections, we can very the index of refraction to look for shower candidates.

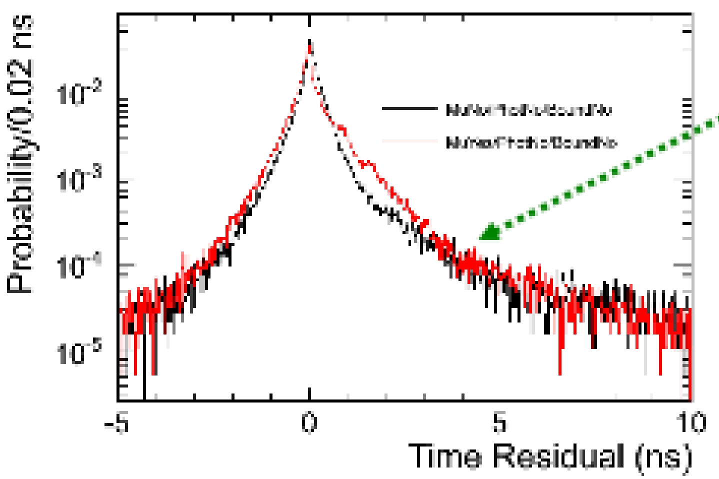


Timing and Spatial Resolution – Imaging Capabilities

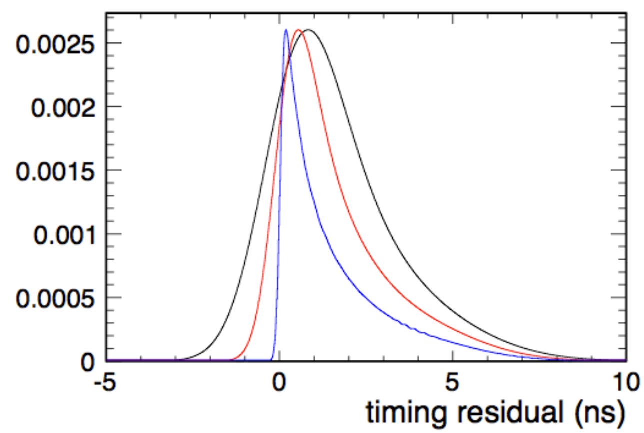


Optical scattering broadens the tail of the timing residual but sharpens the rising edge

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

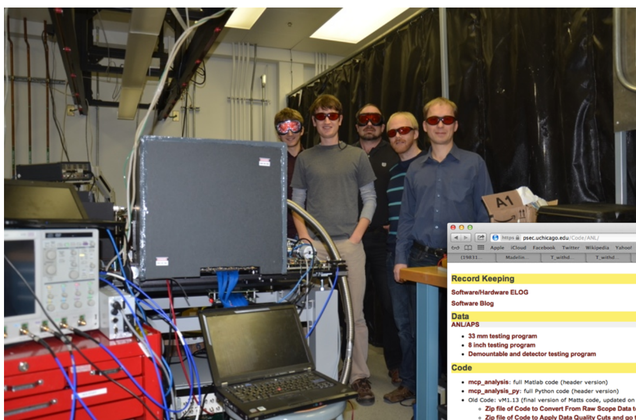


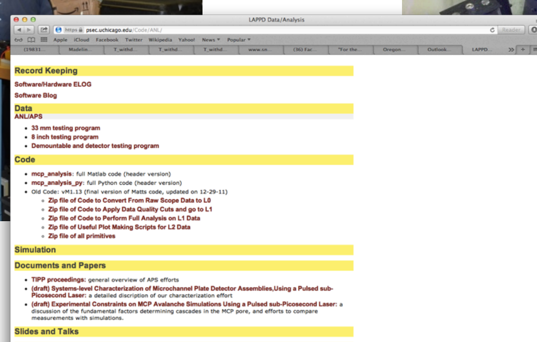
Shape of rising edge depends on distance and color composition, as well as detector resolution



Work by Tian Xin (Iowa)

- We've also developed a vast pool of resources:
  - unique hardware
  - But also:
    - software
    - documentation
    - papers
    - human resource
    - techniques and procedures





LAPPD Data/Analysis

https psec.uchicago.edu/Code/ANL/

Record Keeping

Software/Hardware ELOG

Software Blog

Data

ANL/APS

- 33 mm testing program
- 8 inch testing program
- Demountable and detector testing program

Code

- mcp_analysis: full Matlab code (header version)
- mcp_analysis_py: full Python code (header version)
- Old Code: vM1.13 (final version of Matts code, updated on 12-29-11)
  - Zip file of Code to Convert From Raw Scope Data to L0
  - Zip file of Code to Apply Data Quality Cuts and go to L1
  - Zip file of Code to Perform Full Analysis on L1 Data
  - Zip file of Useful Plot Making Scripts for L2 Data
  - Zip file of all primitives

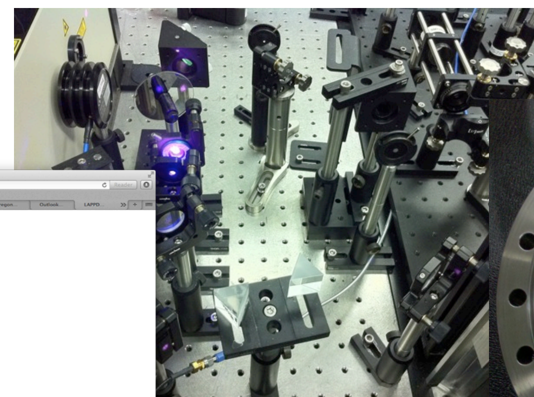
Simulation

Documents and Papers

- TIPP proceedings: general overview of APS efforts
- (draft) Systems-level Characterization of Microchannel Plate Detector Assemblies,Using a Pulsed sub-Picosecond Laser: a detailed discription of our characterization effort
- (draft) Experimental Constraints on MCP Avalanche Simulations Using a Pulsed sub-Picosecond Laser: a discussion of the fundamental factors determining cascades in the MCP pore, and efforts to compare measurements with simulations.

Slides and Talks

Pictures



https://psec.uchicago.edu/Code/ANL/

Understanding Chromatic Dispersion

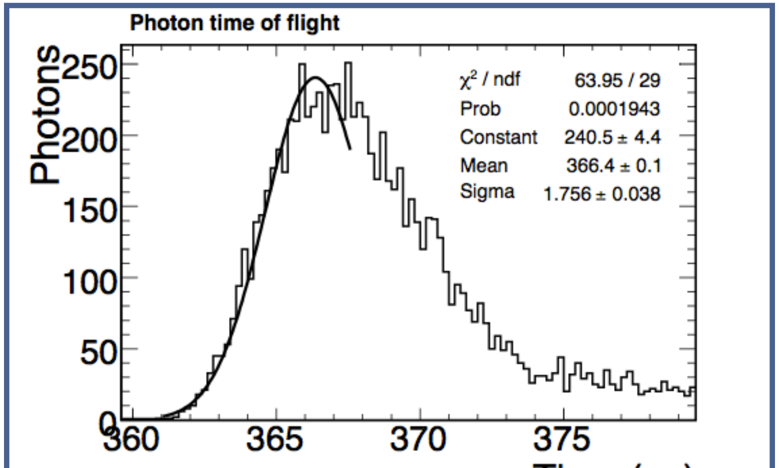
- A concern in using fast timing are the effects of frequency dependent dispersion, scattering and absorption.

- Using a fast toy MC originally developed by J. Felde we study the time of arrival for photons in an spherical detector.

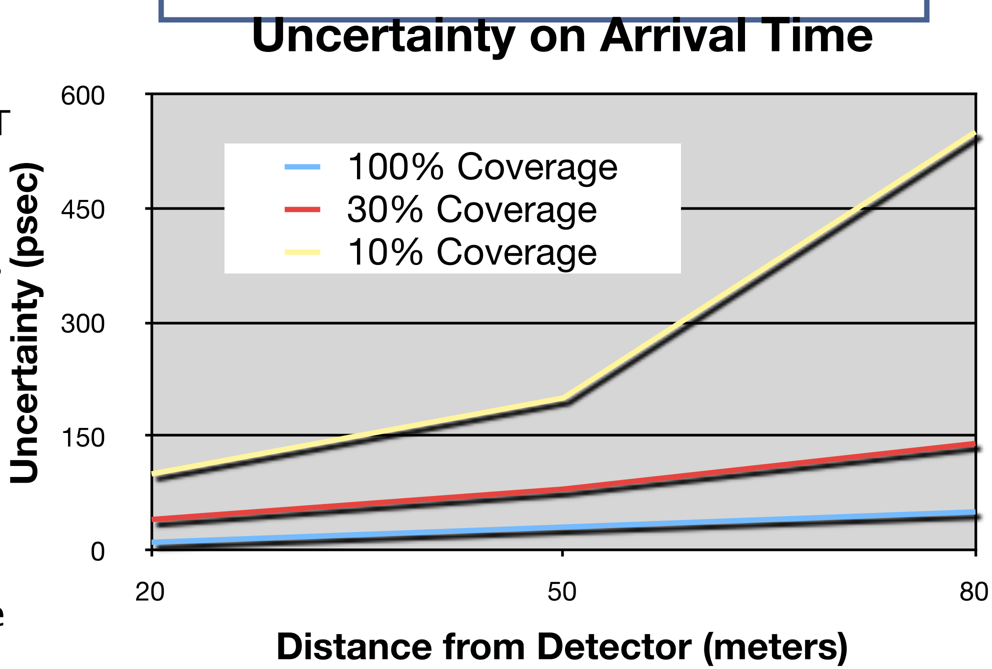
- For a 50m detector with 100% coverage, the rise time (t_{90}–t_{10}) is of the order of 2 ns which cannot be sampled with standard PMT technology.

- For a given detector size, the rise time stays constant and the uncertainty in the position of the leading edge becomes smaller if larger photodetector coverage is considered.

- A combined improvement in photodetector coverage (for reduced uncertainty in risetime) and faster timing (to better sample the risetime) allows for better use of timing information in Water Cherenkov detectors.



J. Felde, B. Svoboda UC Davis



3 Generic Approaches to Event Reconstruction

Fast/parametric

(simple track fits)

Useful for seed fits and helpful for pedagogical understanding of detector tradeoffs

Limited in Possible Complexity

Work with timing-residual based muon fits to study

- the relationship between vertex resolution and detector parameters
- improvements to track reconstruction with chromatic corrections

Working Backward

(Generalized Hough Transforms)

Requires no initial assumptions about event topology

Only makes use of direct light

- Isochron Transform: Causality-based Hough transform for building trakc segments from photon hit parameters
- exploring more detailed reconstruction of EM shower structure

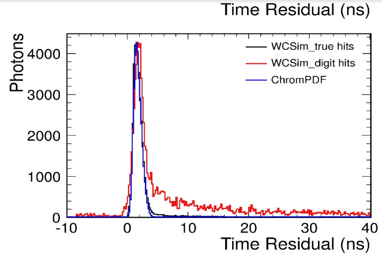
Working forward

(pattern of light)

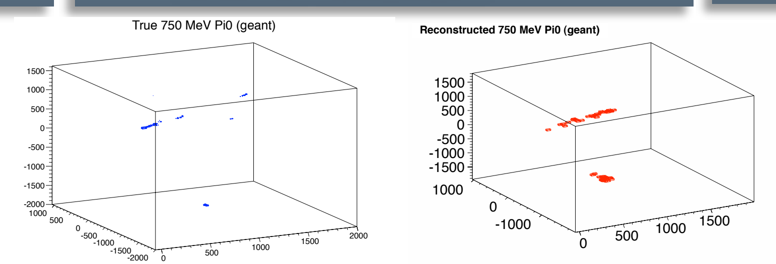
Makes fullest use of all photon information, both direct and indirect light

Becomes computationally prohibitive as one tries to resolve finer structure in the event topology

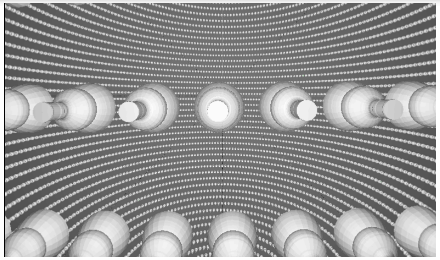
- Chroma: Geant-based, fast photon-tracking MC.
- Capable of rapidly generating large sample MC for a wide variety of detector designs
- Also capable of pattern-of-light fits, where the light pattern for each track hypothesis is generated in real-time.



T. Xin, I. Anghel (Iowa State)

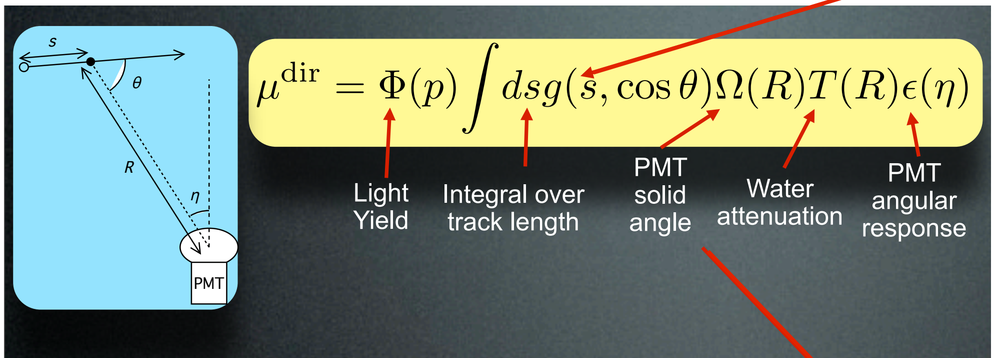


M. Wetstein (U Chicago)



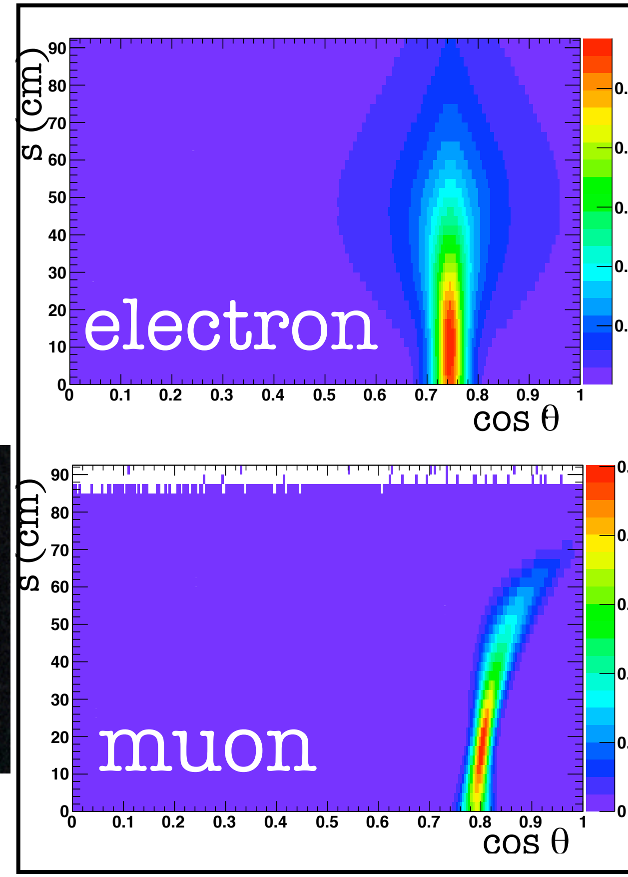
S. Seibert, A. La Torre (U. Penn)

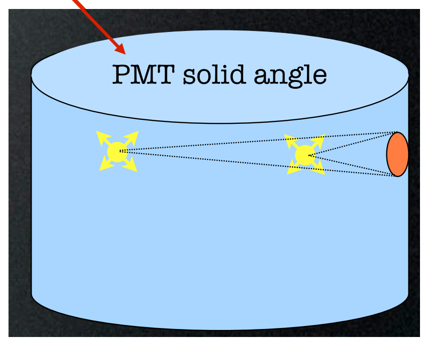
Pattern of Light Fitting



slide credit – M. Wilking, Triumf

Cherenkov emission profile





For each event hypothesis, one essentially runs a complete simulation –

- high energy cross sections
- EM showering, ionization, scattering, energy loss, Cherenkov emission
- light propagation through water

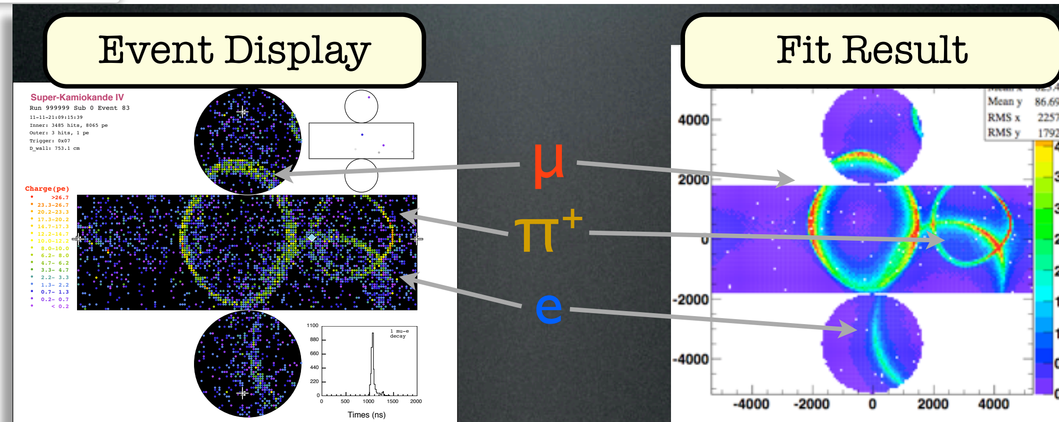
The emergent light pattern is compared with the observed light pattern and a likelihood is constructed.

Pattern of Light Fitting With LAPPDs

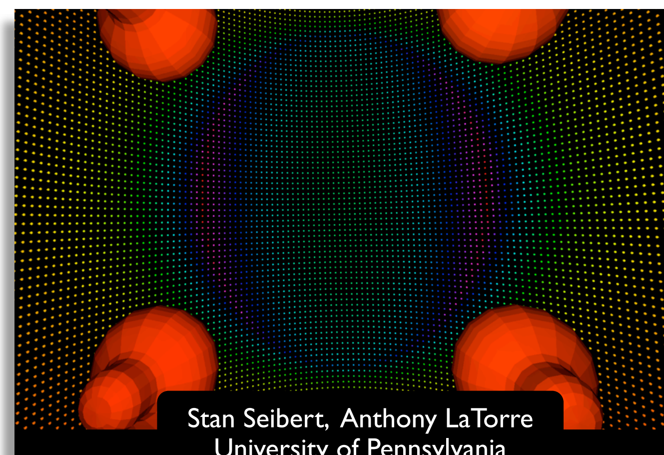
Several things to consider:

LAPPDs are digital photon counters - one can separate photons in space and time (not just estimating based on charge). Likelihood must be viewed in terms of optical photons rather than "charge"

Because we have time and space information on a photon-by-photon basis, correlations between time and space contain good information. One might not want to factorize the time and space likelihoods.

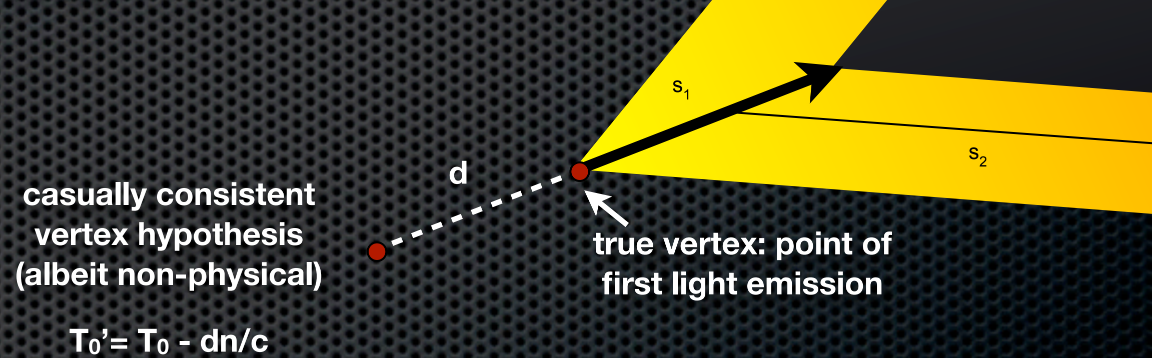


M. Wilking



Timing-based vertex fitting

Based on pure timing, vertex position along the direction parallel to the track is unconstrained



Must used additional constraint: fit the “edge of the cone” (first light)

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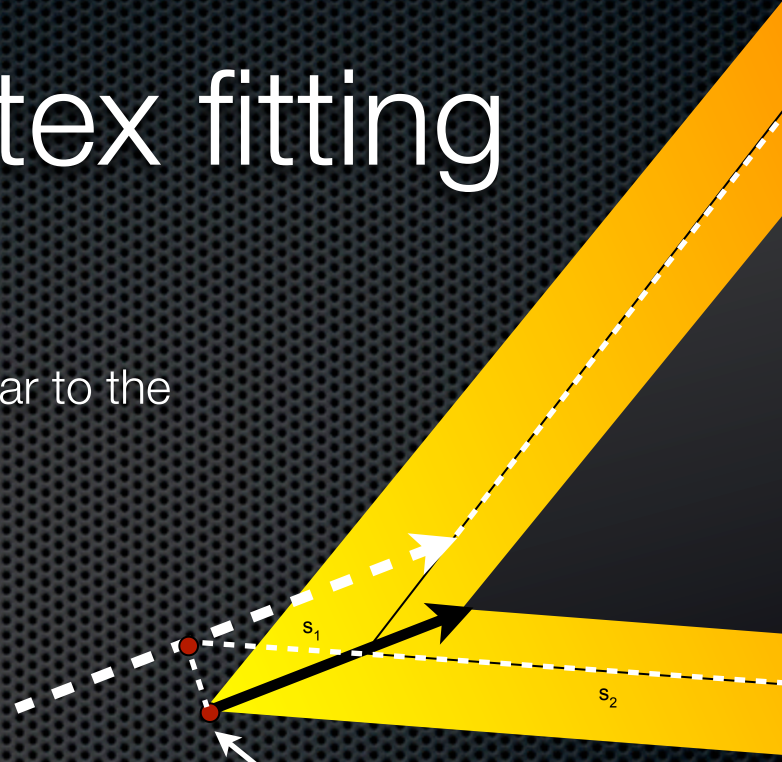
Timing-based vertex fitting

Position of the vertex in the direction perpendicular to the track *is* fully constrained by causality



For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

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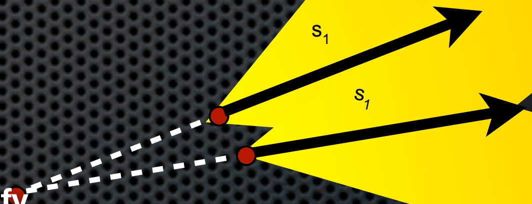
Timing-based vertex fitting

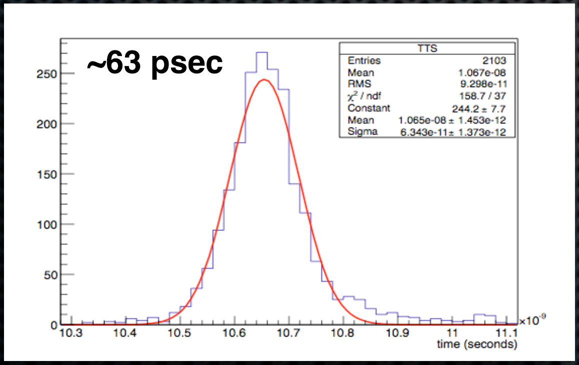
Fortunately, multi-vertex separation is a differential measurement.

Causality arguments are fully sufficient to distinguish between one and two vertices.



Only one unique solution that can satisfy the subsequent timing of both tracks

actual single PE time resolution for 8” detector (M. Wetstein, A. Elagin, S. Vostrikov)



100 picoseconds ~ 2.25 centimeters

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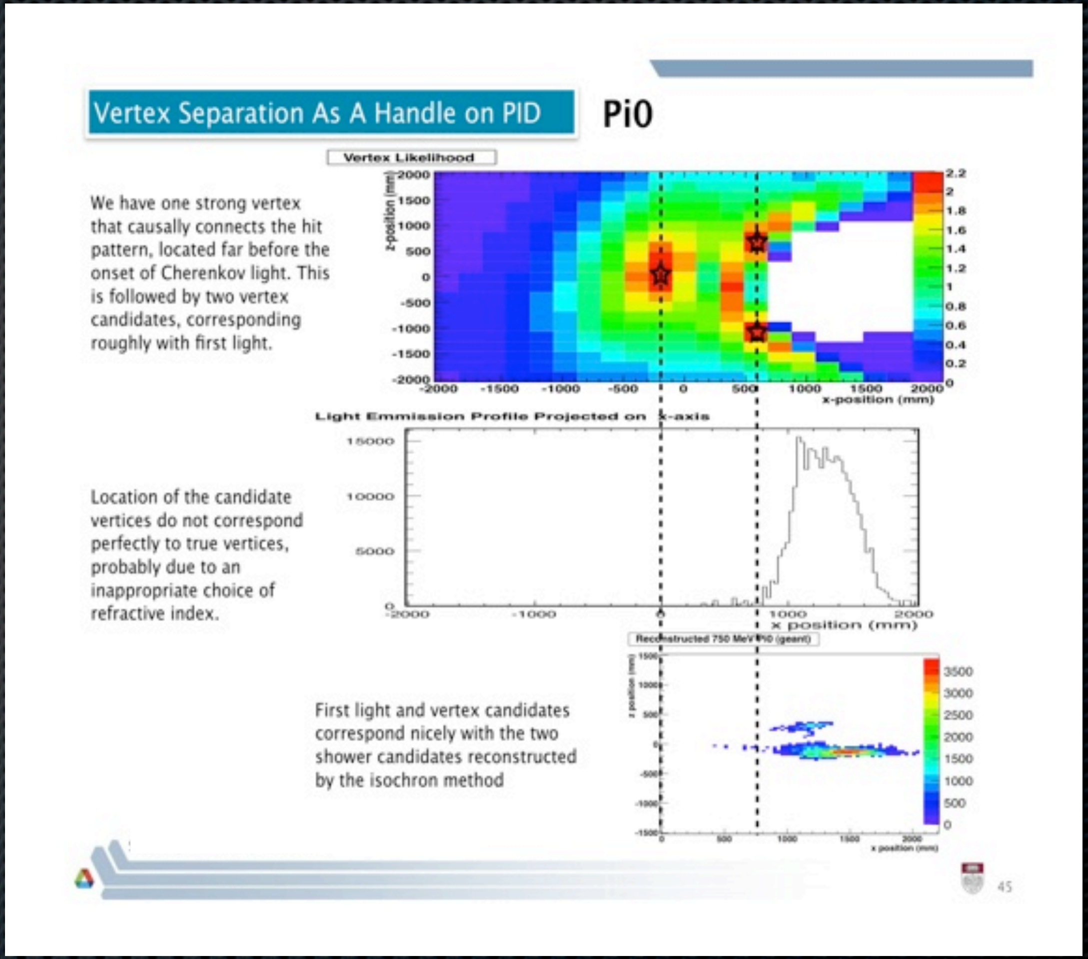
Isochron method

M. Wetstein

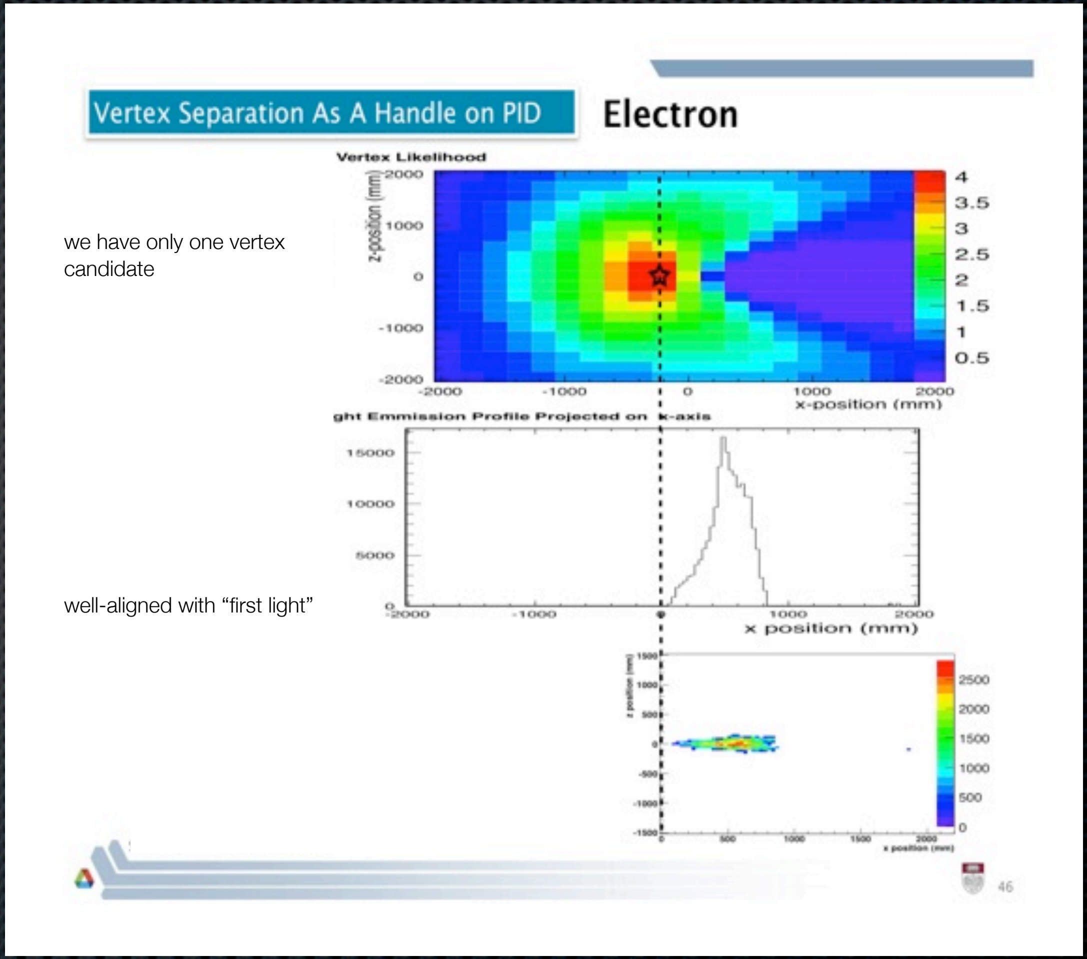
- But, one can use the density of intersections as a figure of merit to optimize the four-vertex
- One can plot density of intersections as a function of position in this vertex-likelihood space and try to discriminate between multiple vertices and single vertices



Isochron method

M. Wetstein

- But, one can use the density of intersections as a figure of merit to optimize the four-vertex
- One can plot density of intersections as a function of position in this vertex-likelihood space and try to discriminate between multiple vertices and single vertices.
- New results coming very soon. Stay tuned.



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