Using Fast Photosensors in Water Cherenkov Neutrino Detectors

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on behalf of the FastTiming group

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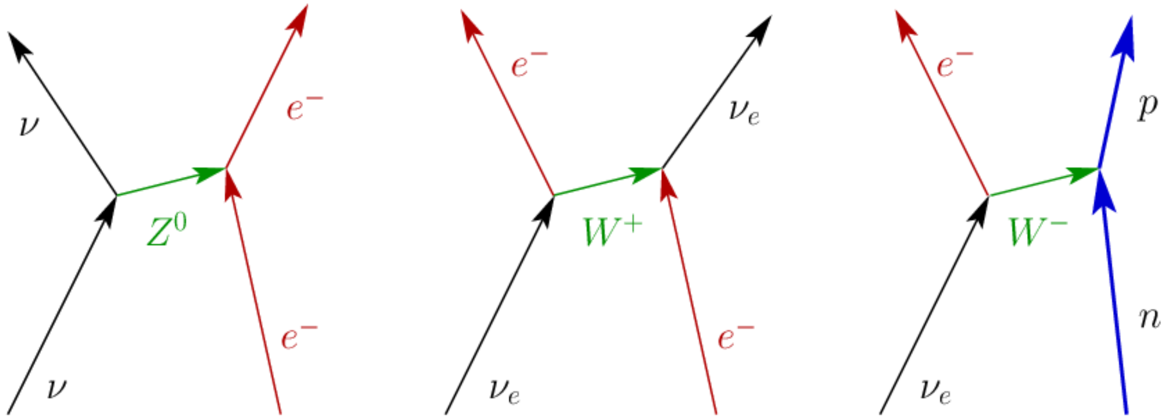
Neutrino Detection Basics

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

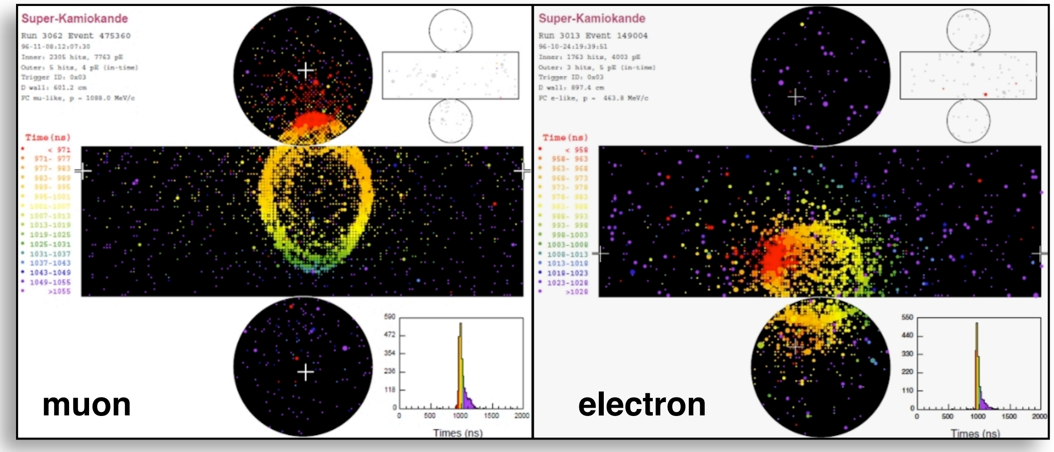


Neutral current

background

Charged current

signal



Neutrino Detection Basics

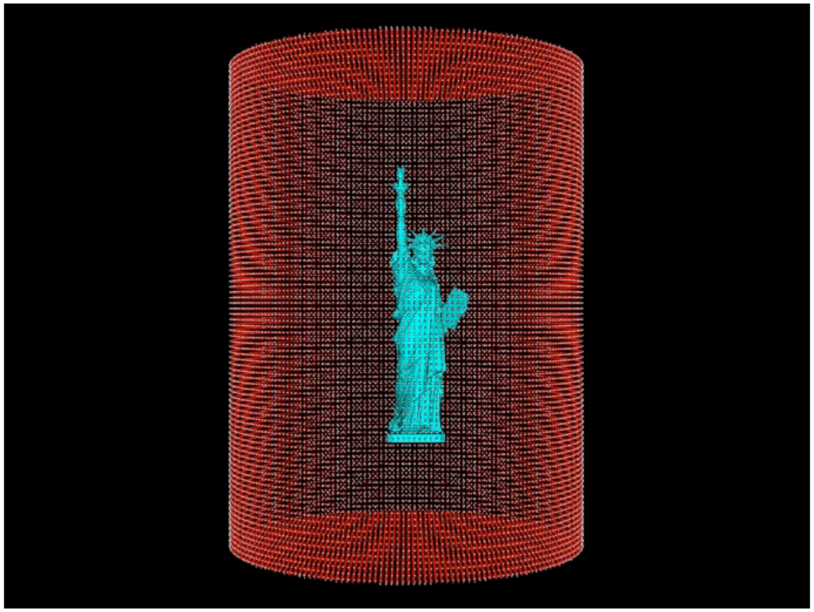
Neutrinos have a very small interaction cross section. Thus, in order to increase the interaction probability we must:

- **design detectors with large fiducial mass**
- create a high intensity neutrino beam

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



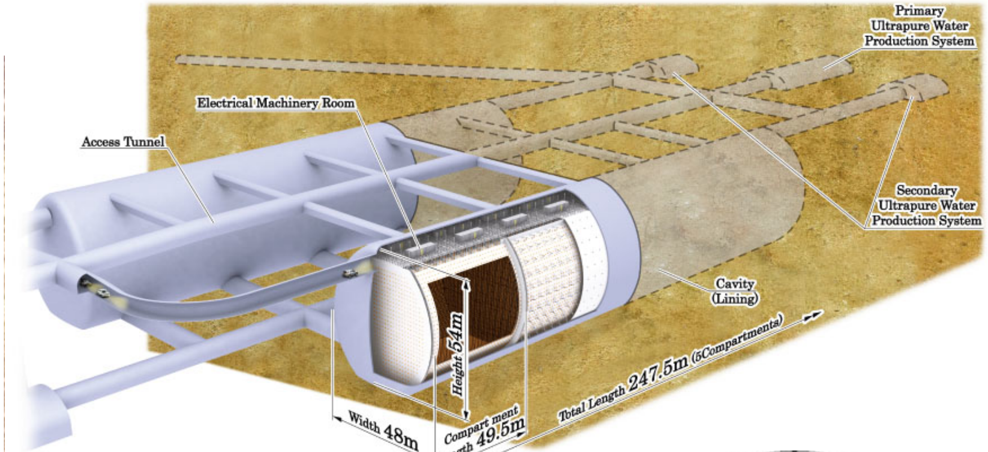
credit Anthony La Torre

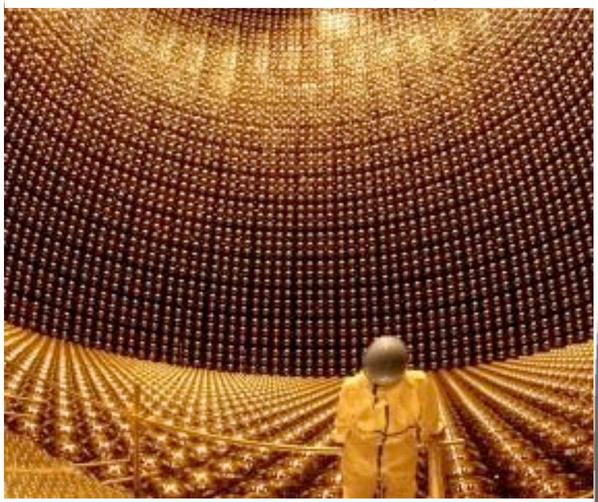
Next Generation of Neutrino Experiments

- The next generation of neutrino and nucleon decay experiments will require **massive detectors** to reach the sensitivities needed to measure CP violation, mass hierarchy, θ_{23} octant and non-standard interactions.

- Very large detectors can provide the mass required to the next generation of long-baseline, reactor and underground experiments.

- The challenge of such detectors is to instrument the very large volumes/ surfaces while efficiently detecting neutrinos.

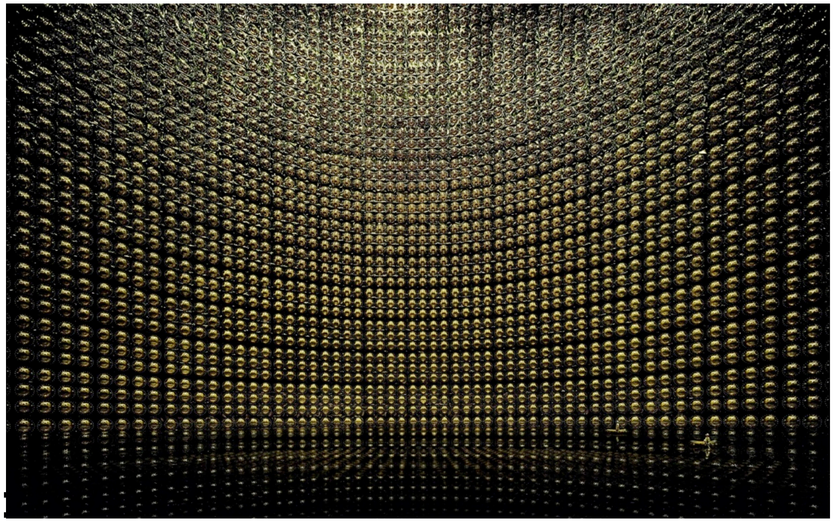




Future Multi-Purpose Large Detectors

- Super-Kamiokande detector: a 22.5 kton water detector (fiducial volume) with 13K PMTs was built over a decades ago using state-of-the-art technology.

- It is still the baseline detector for water Cherenkov design to this day.



- There are new experiments in their planning stages:

Experiment	Fiducial mass	Number of PMTs
Hyper-K	560 kton water	99K PMTs
~~LBNE WCh~~	200 kton water	30-45K PMTs
Chips?	100 kton water	17K PMTs
LENA	51 kton liquid scint	30K PMTS
Daya Bay II	20 kton liquid scint	15K PMTs

20 x Super K

10 x Super K

5 x Super K

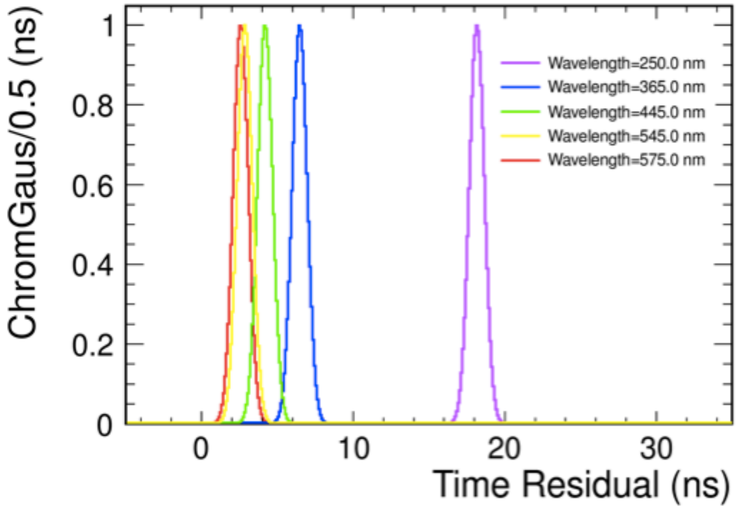
Bigger detectors, lower coverages

- All will attempt a broad range of physics in addition to neutrino oscillations.

Future Multi-Purpose Large Detectors

- Designing multi-purpose detectors to enable a broader physics program is a challenge, in particular when it requires **very large volume detectors**

- Not only instrumenting the very large volumes/surfaces can be challenging, but new issues arise that have not been dealt with before.
  - For example in going to very large water volumes we must confront issues of chromatic dispersion.



- Also new features in *photodetector technology*:
  - **faster timing resolution**
  - **better spatial granularity**
  - **large-area coverage (at lower costs)**

might enable new/more efficient detector designs.

New Photodetector Technologies

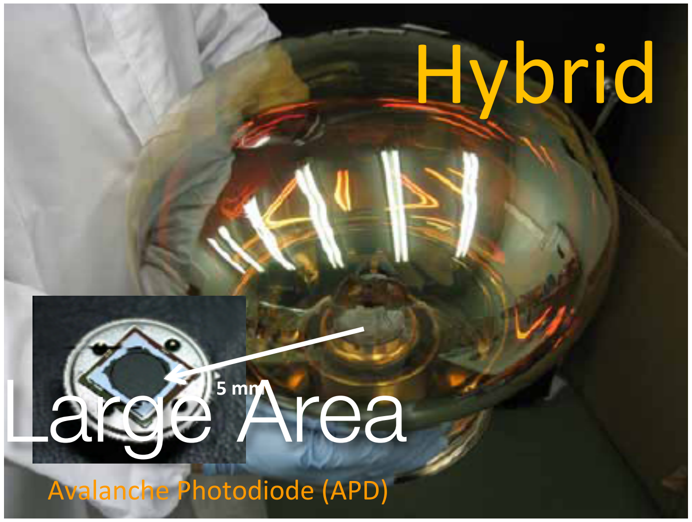
- Examples of two promising new large-area photosensors in development are:

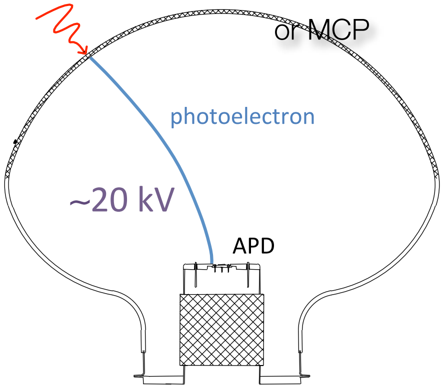
Hybrid Photo-Detector : ~ 600 to 2200 psec timing resolution depending on HPD size

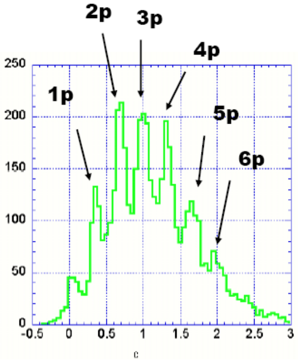
Large Area Pico-Second Photodetector : ~100 psec timing + ~1cm spatial res

E. Kearns

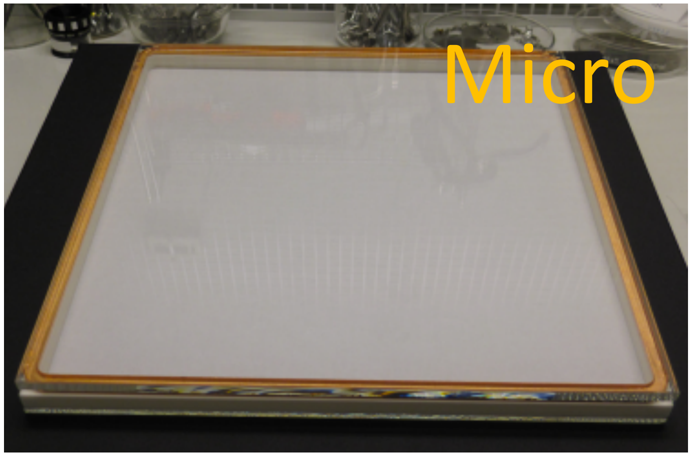
Hybrid Photo-Detector

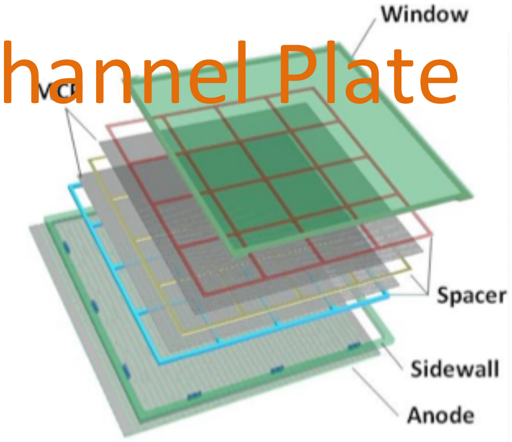






Micro Channel Plate





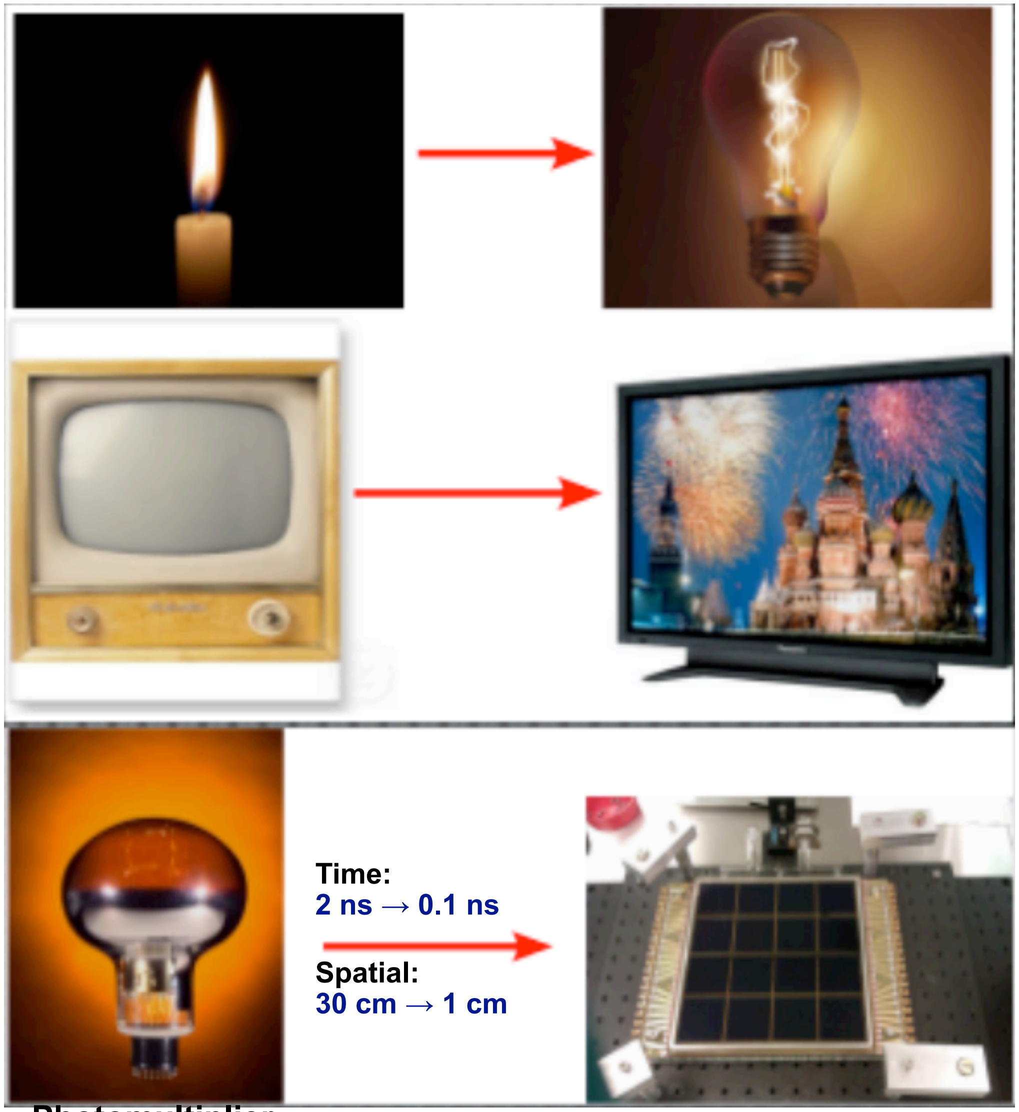
<100 ps timing

Large Area Picosecond Photo-Detectors

- **Large-Area Picosecond Photo-Detector (LAPPD)**, a new type of photosensor, is being developed at Argonne National Lab.

- LAPPD design is based on micro-channel plate, but atomic layer deposition is used as a technique to deposit materials with different functions

- Potential properties of LAPPD would include:
    - Time resolution of **~ 100 psec**.
    - Spatial resolution of **~ 1 cm**.

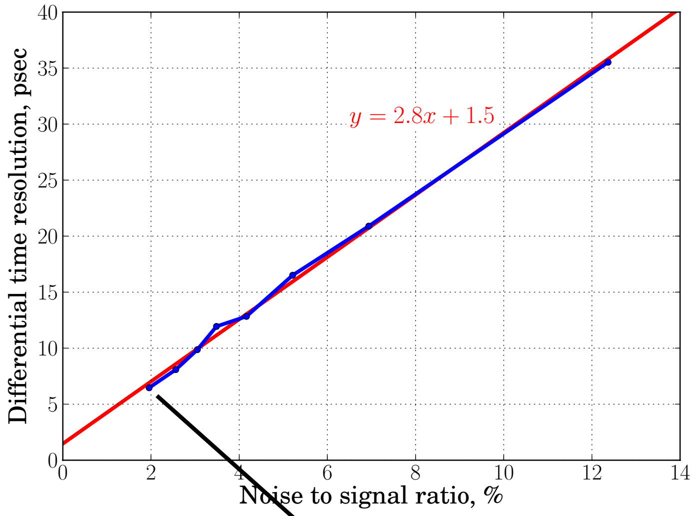


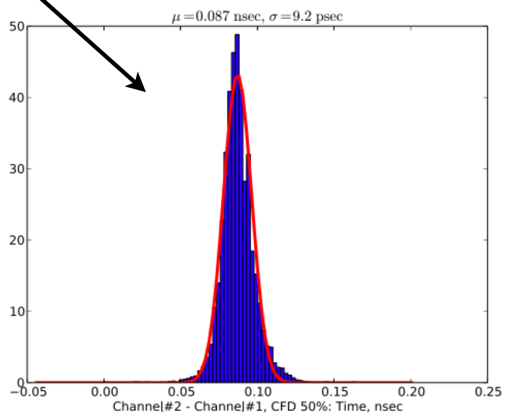
Time:
2 ns → 0.1 ns

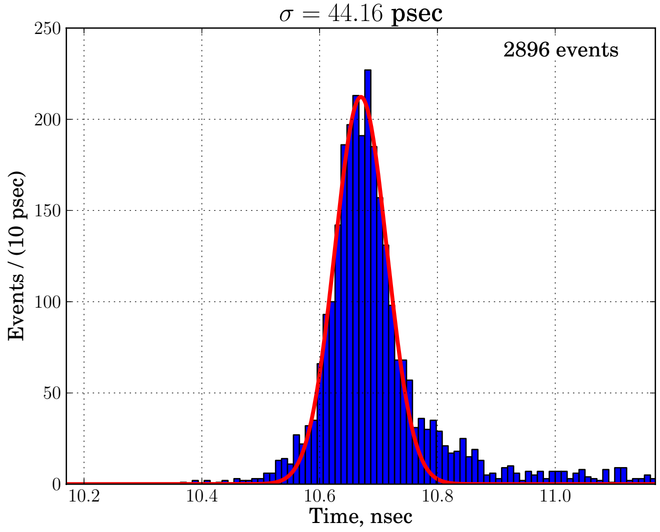
Spatial:
30 cm → 1 cm

LAPPD Status

- **Testing 8”x 8” Argonne made MCPs**
  - Pulse height peaked at **10^7 gain**
  - Differential time resolution between two ends of delay-line anode < 10 psec
  - **2 mm spatial resolution** parallel to the strip direction < 1 mm in transverse
  - **Time resolution of ~ 40 psec** using economical anode design







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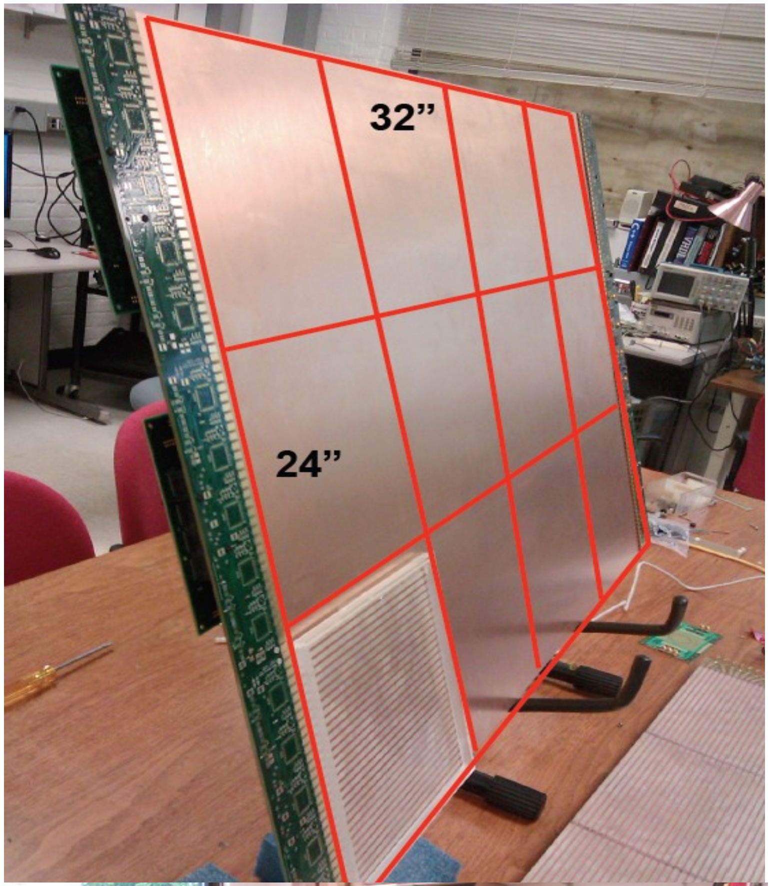
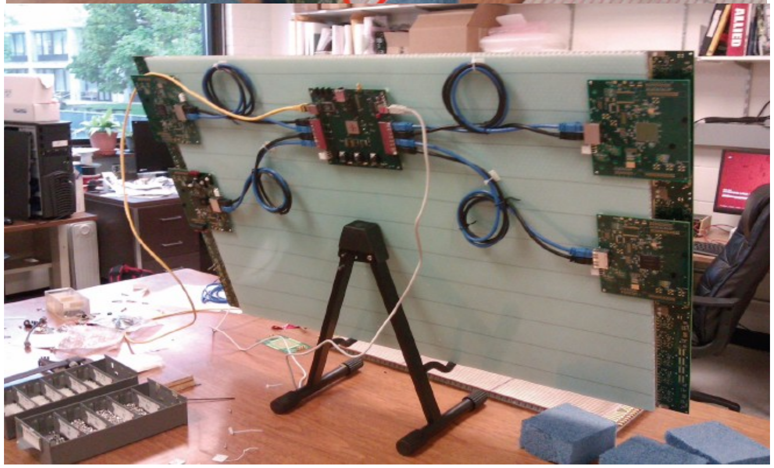
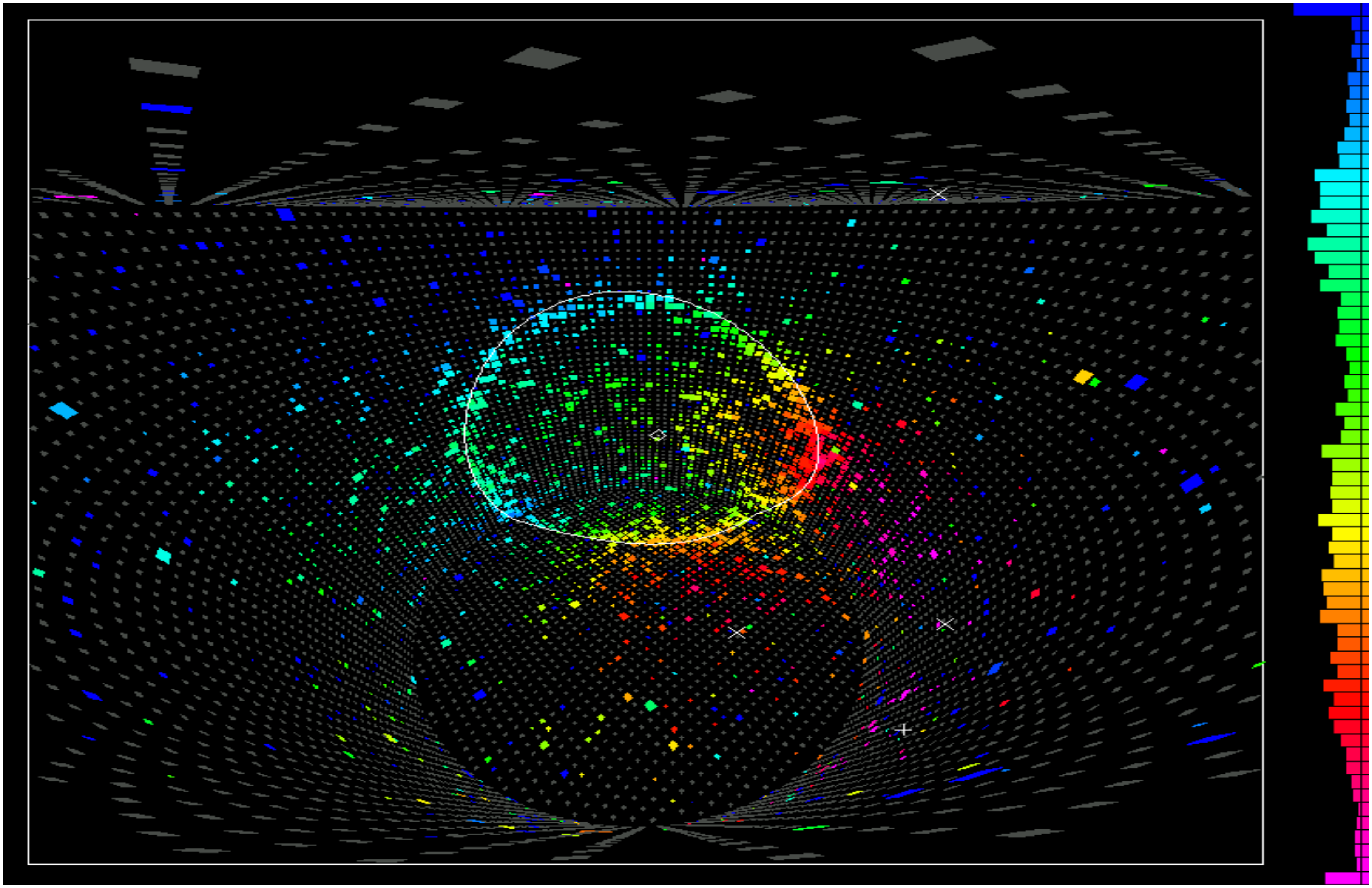
Next: LAPPD for Neutrinos

- Micro-channel plate photosensor in 8” x 8” tiles arranged in 24” x 32” super-module
- 100 psec time resolution / 1 cm spacial resolution
- Channel count optimized to large area/ desired granularity
- Integrated double-sided readout
- Scaled high QE photocathode
- Large area flat panel provides robust construction. Low internal volume and use of known glass.
- No magnetic susceptibility





Using Fast Photosensors in Large Water Cherenkov Detectors

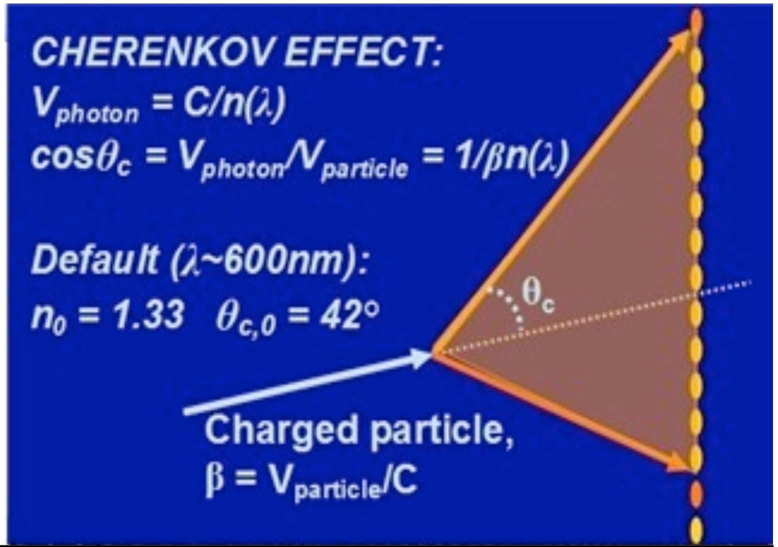


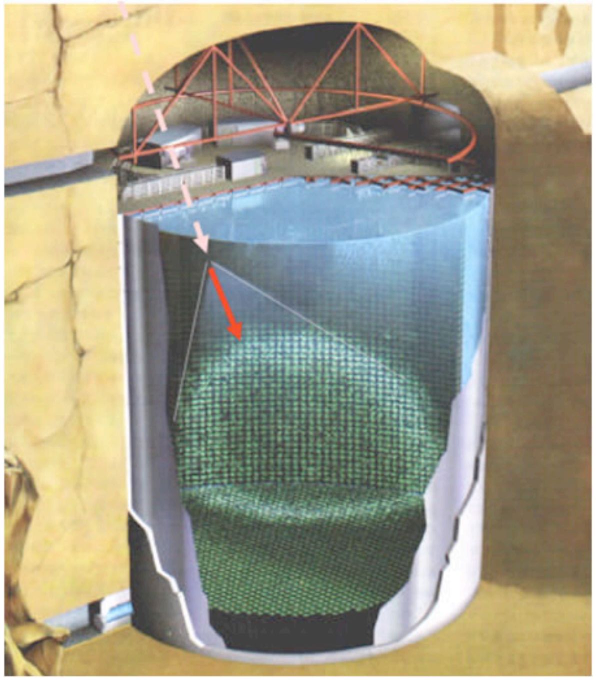
Water Cherenkov Neutrino Detectors

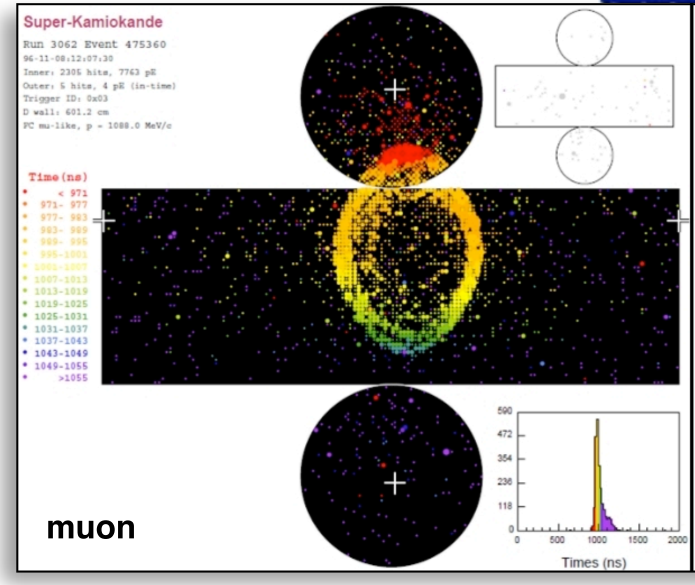
- A Water Cherenkov (WCh) detector implies using a volume of water instrumented with photosensors on the surrounding surface.

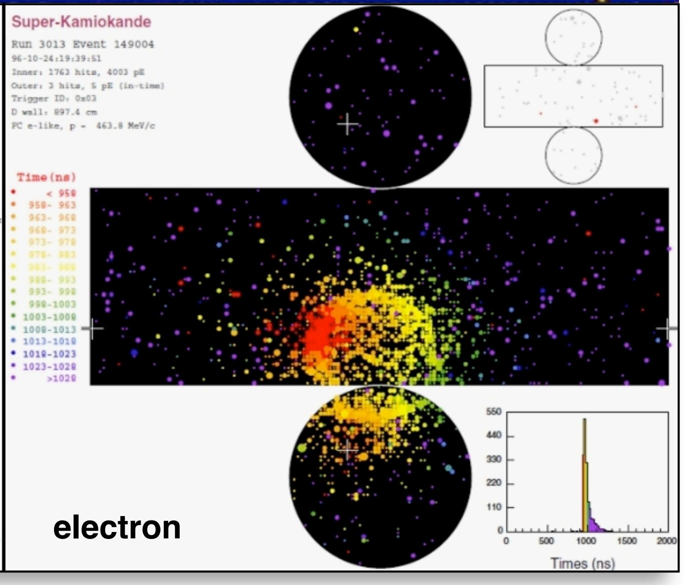
Cherenkov Effect

- 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 $\theta_C = \text{acos}(1/n\beta)$ w.r.t. the direction of the charged particle.







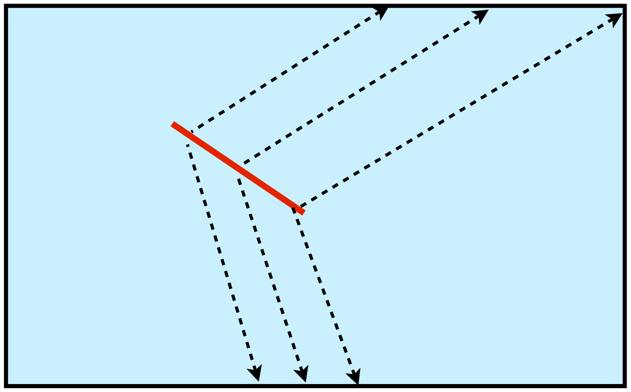


Reconstruction Using Cherenkov Light

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

Light collection, acceptance and coverage are important to detect more photons.



Reconstruction Using Cherenkov Light

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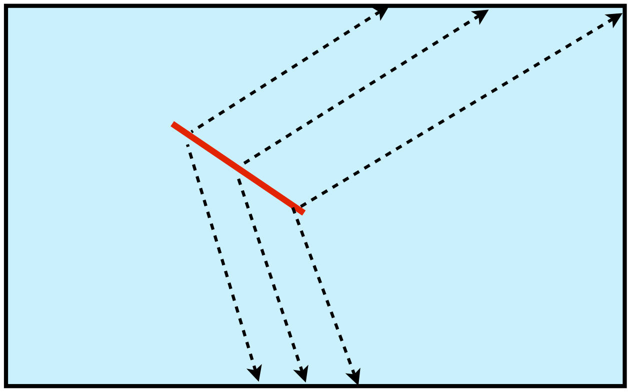
Light collection, acceptance and coverage are important to detect more photons.

2. Pattern of light on the wall

Spatial resolution, granularity and coverage are important to distinguish patterns of light.



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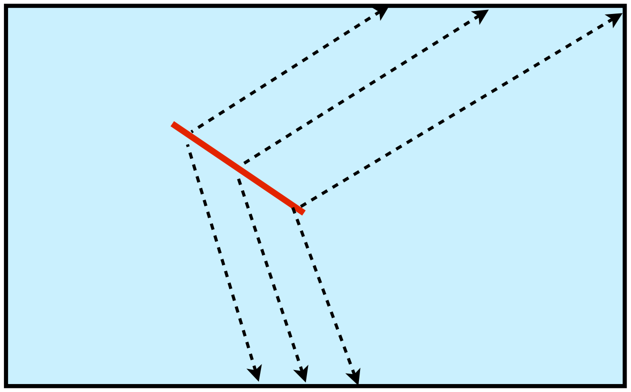
3. “Drift time” (photon transit time)

   ~225,000mm/microsecond

Timing resolution can be important for better vertex reconstruction.



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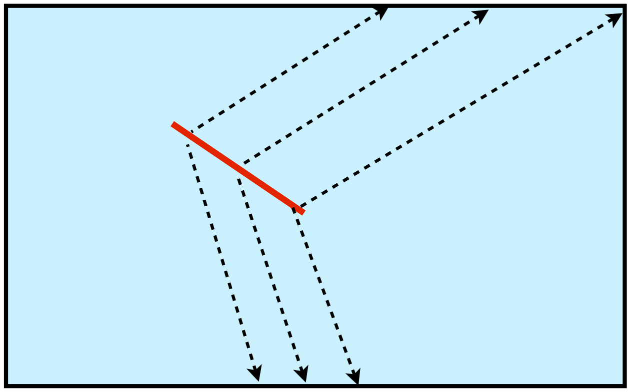
4. Optical Transport of light in water

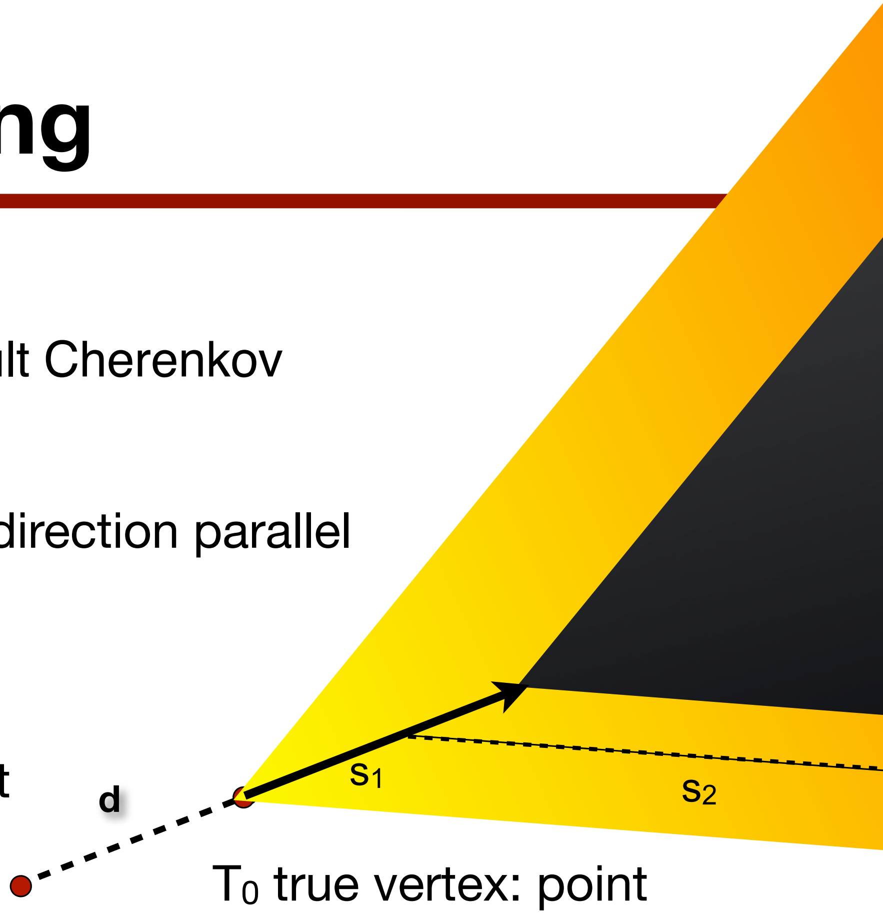
Effects like chromatic dispersion will smear some of the gains and need to be taken into account.



Timing-based Vertex Fitting

- Project photon hits back onto the track with default Cherenkov angle to get predicted propagation path.

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



casually consistent vertex hypothesis (non-physical)

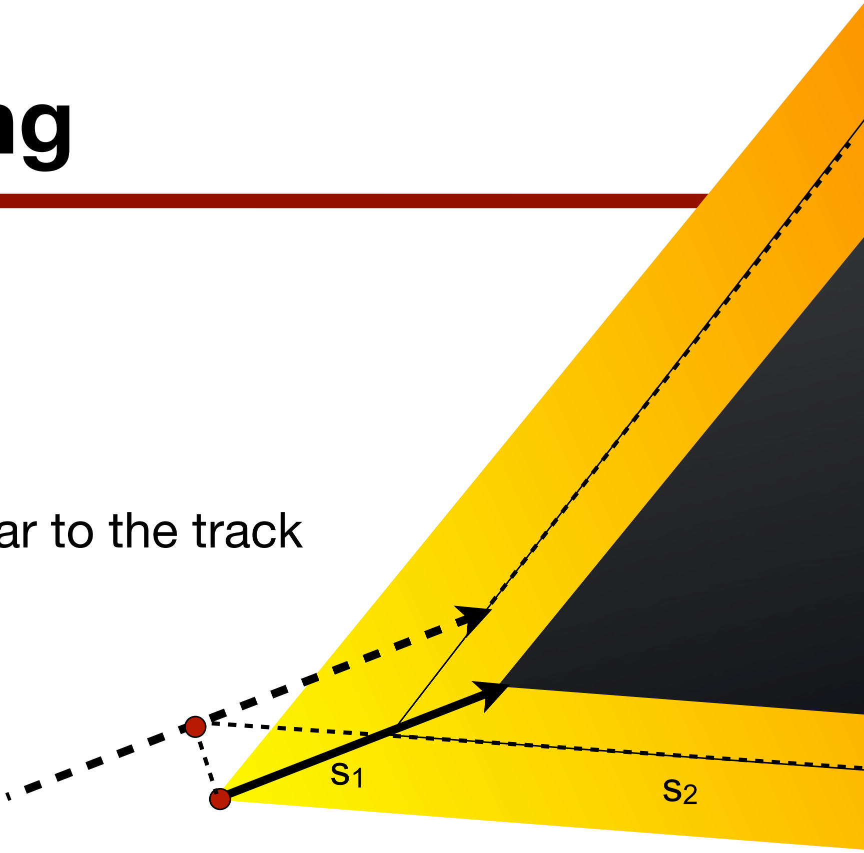
$T_0' = T_0 - dn/c$

T_0 true vertex: point of first light emission

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

Timing-based Vertex Fitting

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



casually consistent
vertex hypothesis
(non-physical)

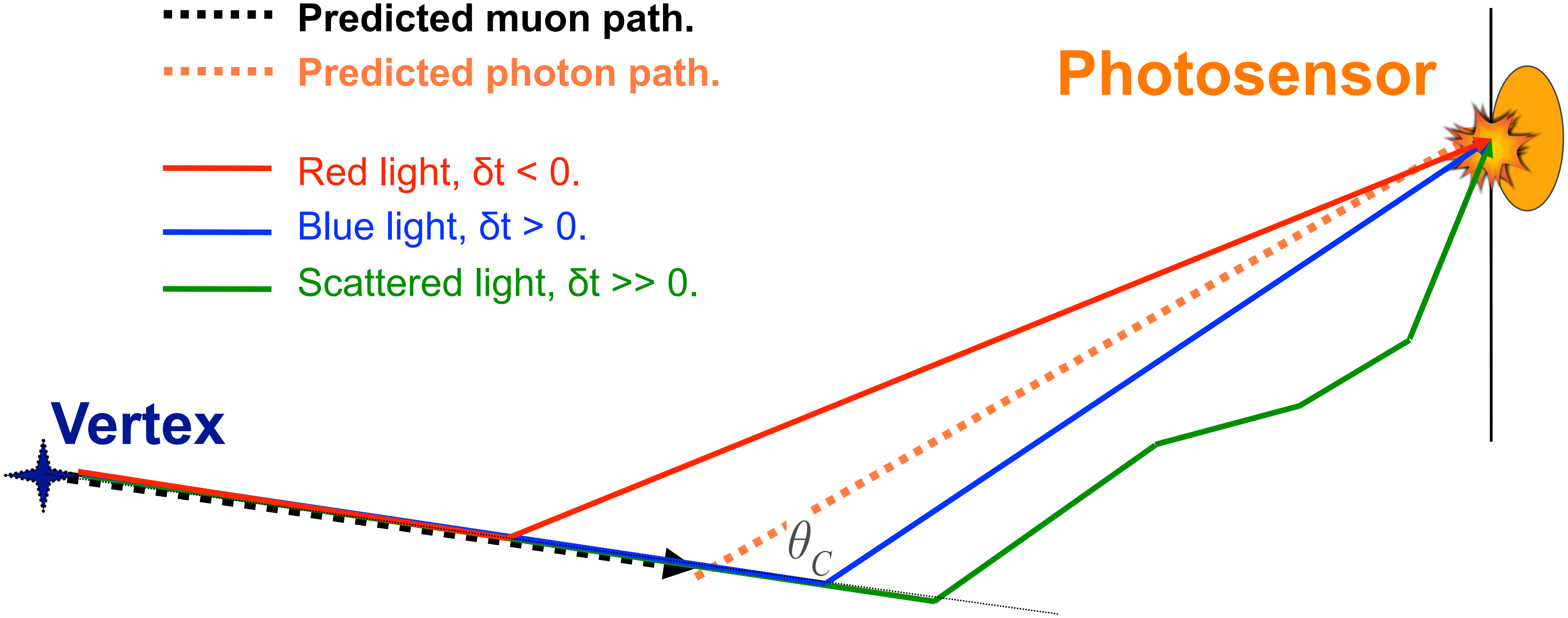
$$T_0' = T_0 - (T_1 - T_2)$$

T_0 true vertex: point
of first light emission

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

Time Residual

- **Time residual** (δt) is defined as the difference between the actual propagation time and the predicted propagation time.



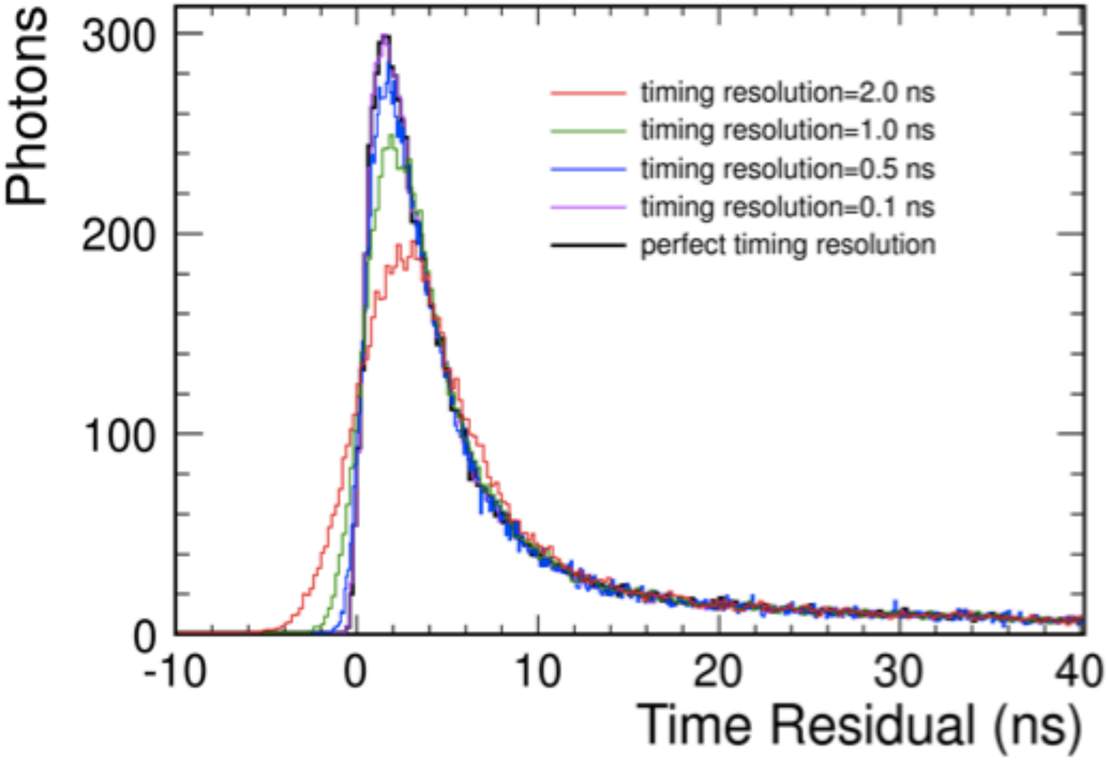
- **The larger the distances travelled by light, the larger the chromatic effect is (important in large detectors!!)**

Time Residual Spectrum

- A 200 kton WCh detector with 13% PMT coverage is used for our current studies as an example of 10x SuperK.

- We show that the study of time residual for a 200 kton WCh detector does not require time resolution better than 0.1 ns.

- The rising edge is smeared by **chromatic dispersion** and is comprised mostly by direct light.



When using photosensors with better timing and spatial resolution (e.g. LAPPD), we must account for chromatic dispersion in our reconstruction algorithms.

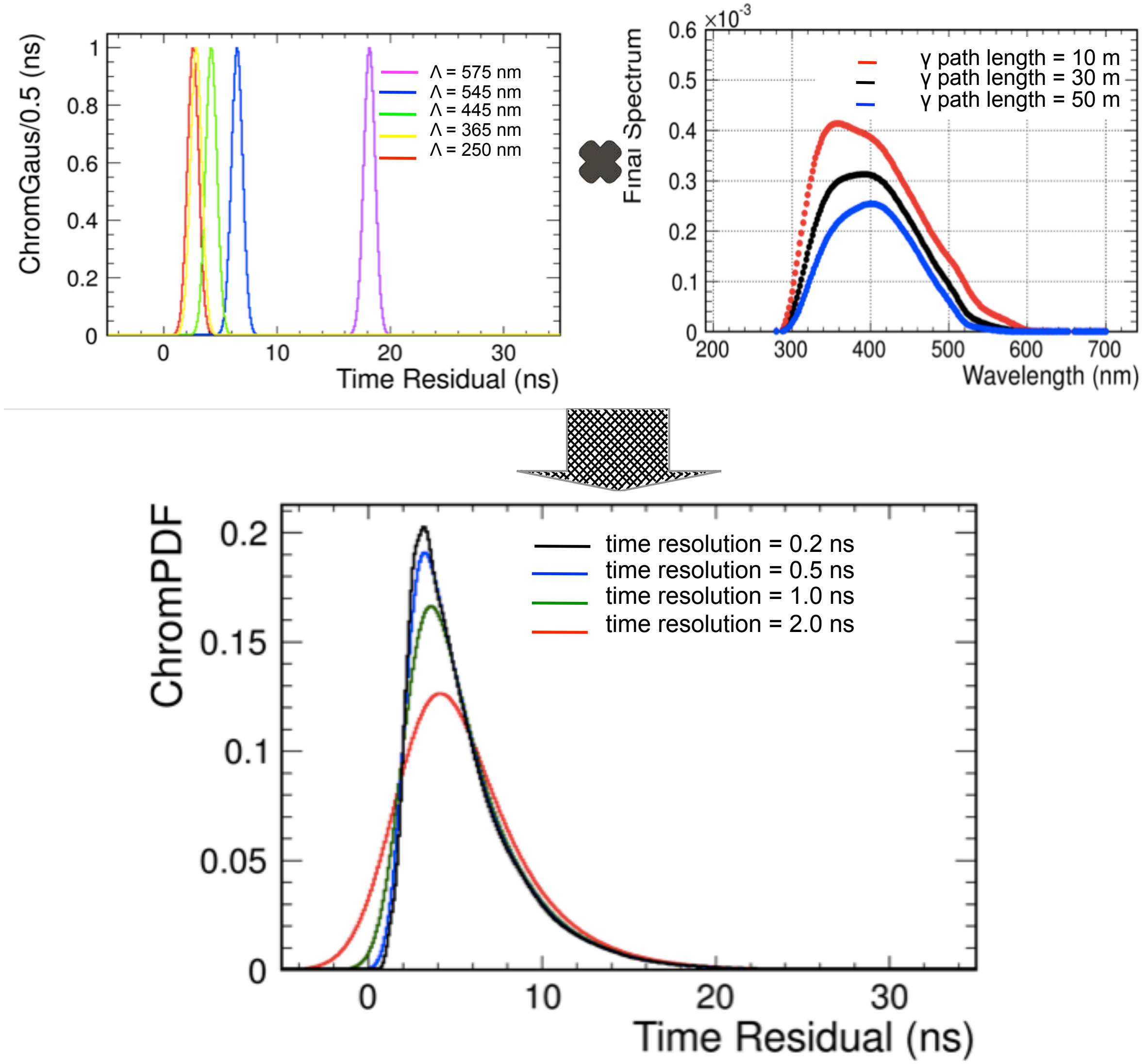
By using better timing resolution and correcting for the chromatic dispersion we can improve the reconstructed vertex resolution.

Building a Probability Density Function

- The built PDF needs to model the shape of time residual spectrum. This PDF is taking into account chromatic dispersion, optical attenuation and quantum efficiency.

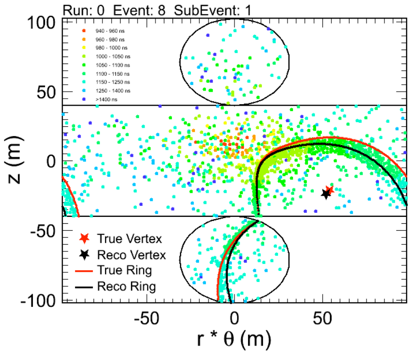
- The final PDF (**ChromPDF**) is computed by summing over all the possible colors.

- The PDF is then used in a maximum likelihood method based vertex reconstruction algorithm.

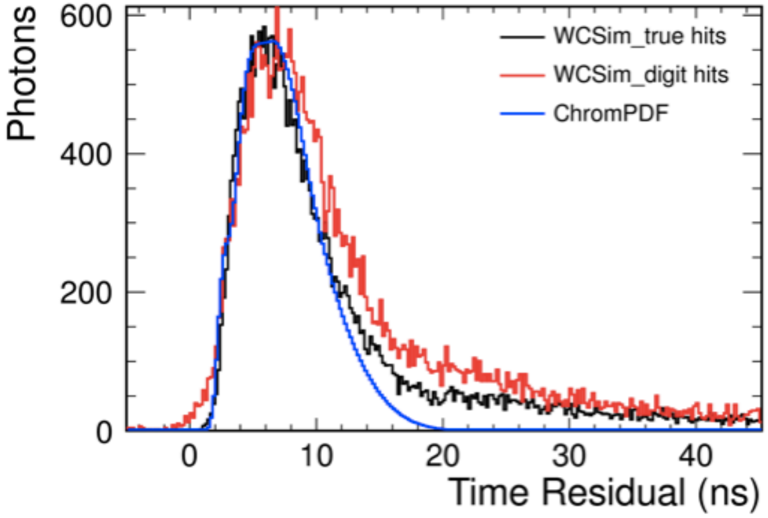


Building a Probability Density Function

- ChromPDF models well the rising edge of time residual spectrum.

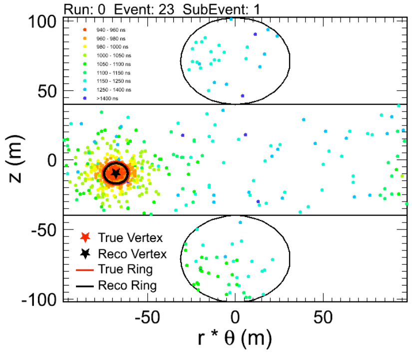


200kton WCh, 1.2 GeV, Event008
Distance to wall = 1245cm

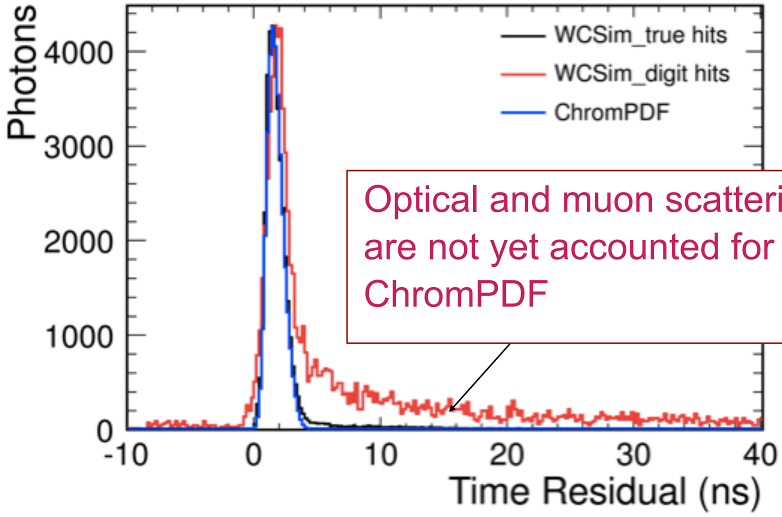


- True hits:
  - Perfect timing resolution.
  - True hit position.

- Digit hits:
  - Time resolution as a function of QEPs.
  - The center of PMT



200kton WCh, 1.2 GeV, Event023
Distance to wall = 434cm



Optical and muon scattering are not yet accounted for in ChromPDF

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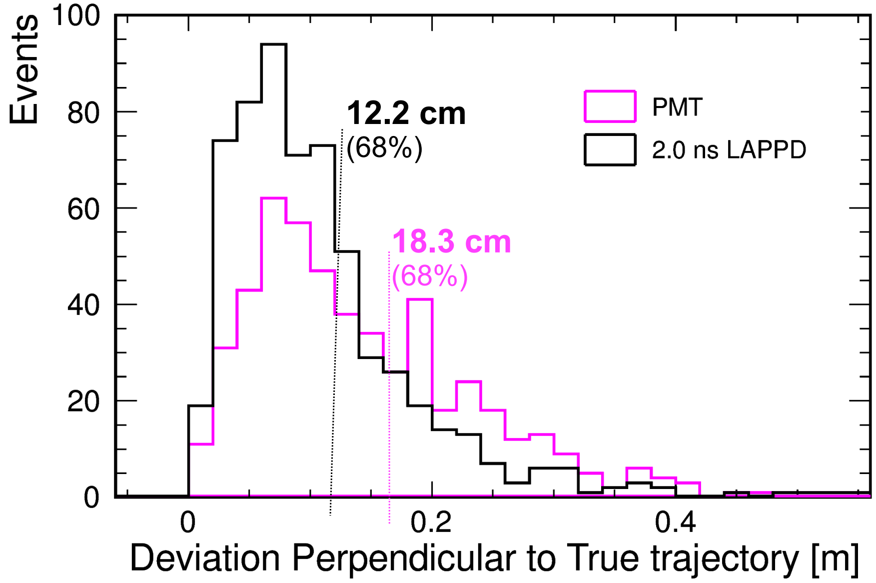
Vertex Reconstruction Results: LAPPD vs PMT

- Muon events are generated using WCh simulation (WCSim) which is a Geant4 based simulation validated by the LBNE collaboration.
  - 200 kton detector with 13% photosensor coverage.
  - 1.2 GeV muons.
  - No muon scattering.

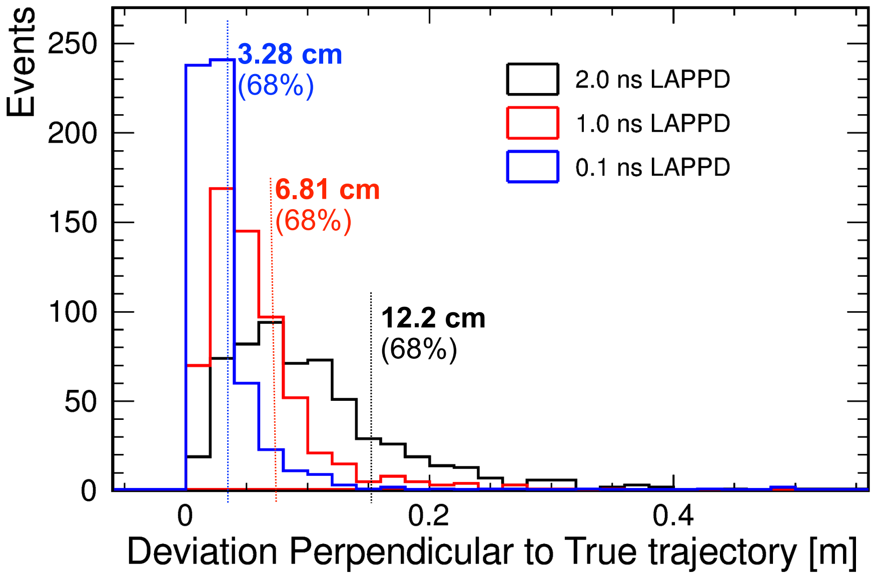


- For a detector equipped with **PMTs with 2.0 ns time resolution**, we can achieve a ~ **18 cm** perpendicular vertex resolution.
- For a detector equipped with **LAPPD with 2.0 ns time resolution** we obtain a roughly equivalent performance in perpendicular vertex resolution as with PMTs.

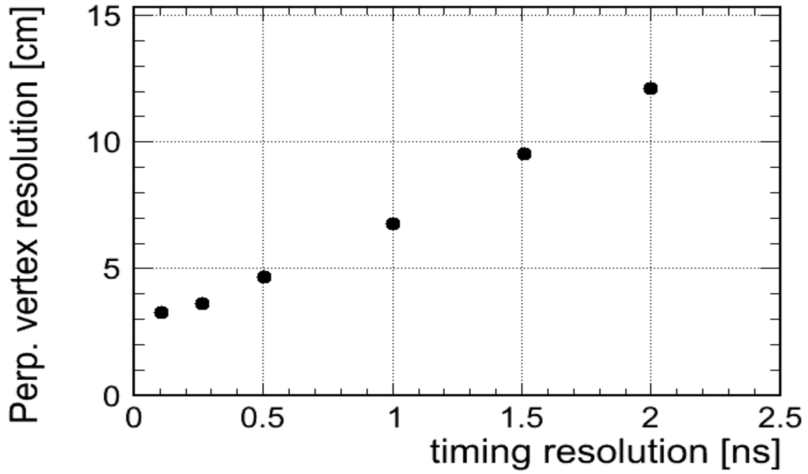
WCSim: https://wiki.bnl.gov/dusel/index.php/WCSim, Chris Walter, Duke University

Vertex Reconstruction Results: LAPPD with different time resolutions

- We observe **3×** gains in the perpendicula vertex resolution as the time resolution of LAPPD improves from 2.0 ns to 0.1 ns.



- By using LAPPDs with 0.1 ns time resolution, we get a ~ **3 cm** perpendicular vertex resolution – very **promising** improvement.

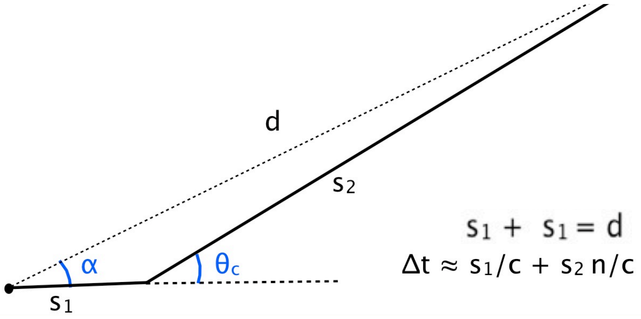


Building Tracks in Water Cherenkov

- **The isochron method** is a casual Hough transform, that builds tracks from a pattern of hits in time and space.

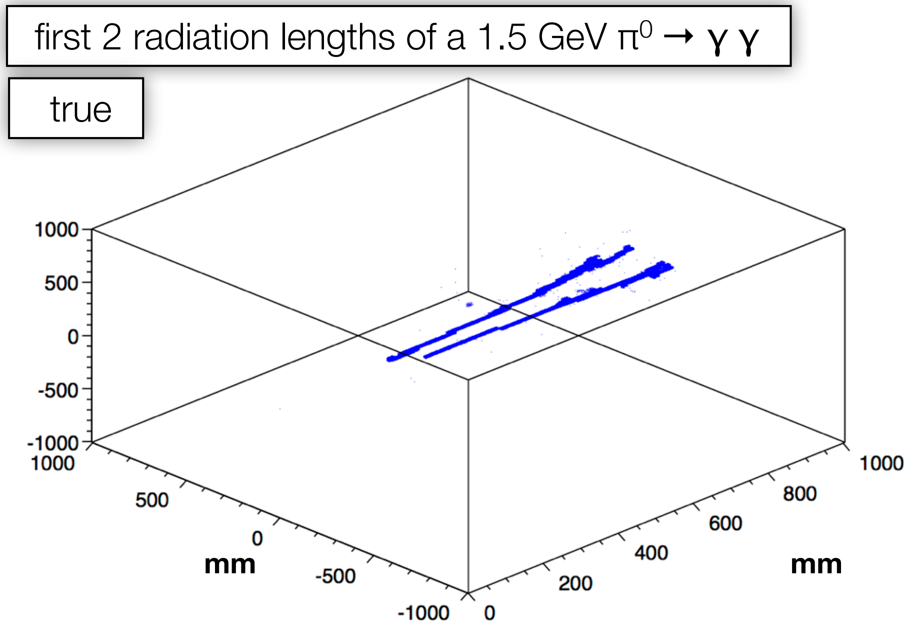
- This approach requires a seed vertex but no prior assumption about the number of tracks or event topology.

- It connects each hit to the vertex though a 2 segment path, one of the charge particle, the other representing emitted light.



$s_1 + s_1 = d$

$\Delta t \approx s_1/c + s_2\, n/c$



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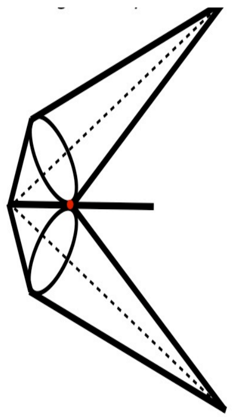
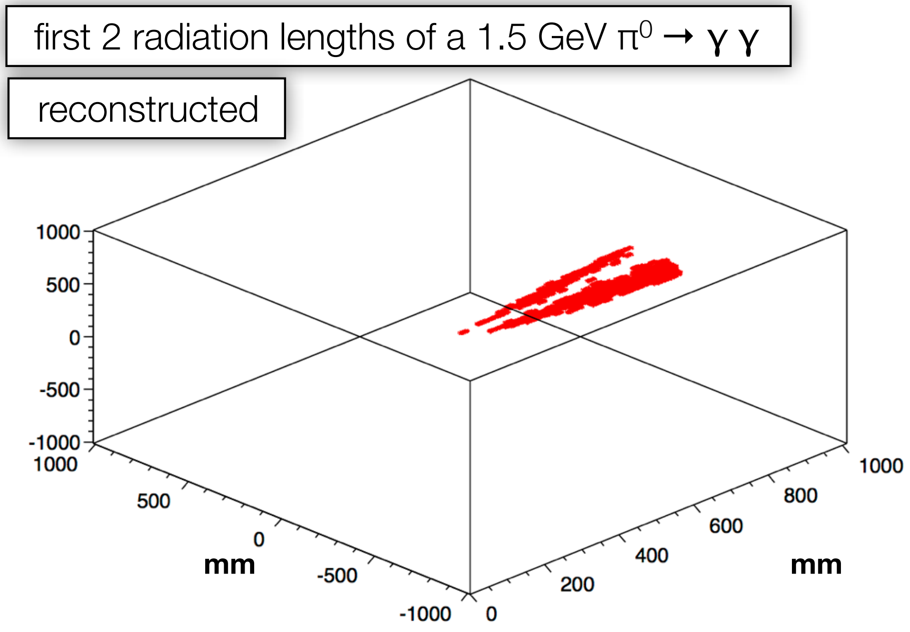
Building Tracks in Water Cherenkov

- The rotation ambiguity is easily resolved since the same track will intersect maximally around their common emission point.



- Track-like clusters emerge from density of intersections:
  - this density is sensitive to the position of the vertex.
  - image sharpness can be used as a figure of merit for fitting the vertex.
- Current implementation tested on a 6m spherical detector with 100% coverage and perfect resolution.
- Full optical effects are applied. Not yet correcting for chromatic dispersion, no time-based quality cuts.
- Ideal for small/high intensity applications.
- Challenges for implementation in larger detectors: sparser coverage, less resolution.



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Summary

- The next generation of neutrino experiments will use very large volume liquid filled detectors. New photosensors such as HPDs and LAPPDs could have an impact on the design of these detectors.

- When using photosensors with better timing and spacial resolution (e.g. LAPPD), we must account for chromatic dispersion, which becomes an important effect in very large detectors.

- We have shown that by doing these we can exploit the features of new photosensors to obtain improved resolution in vertex reconstruction.
  - using LAPPD with 100 psec time resolution, we achieved 3 cm in perpendicular vertex resolution when reconstructing 1.2 GeV muons in a 200 kton detector with very low coverage

- The combination of fine timing and spatial resolution provides improved tracking and analysis capabilities that could be used for enhanced background rejection, energy resolution and fiducial volume definition.

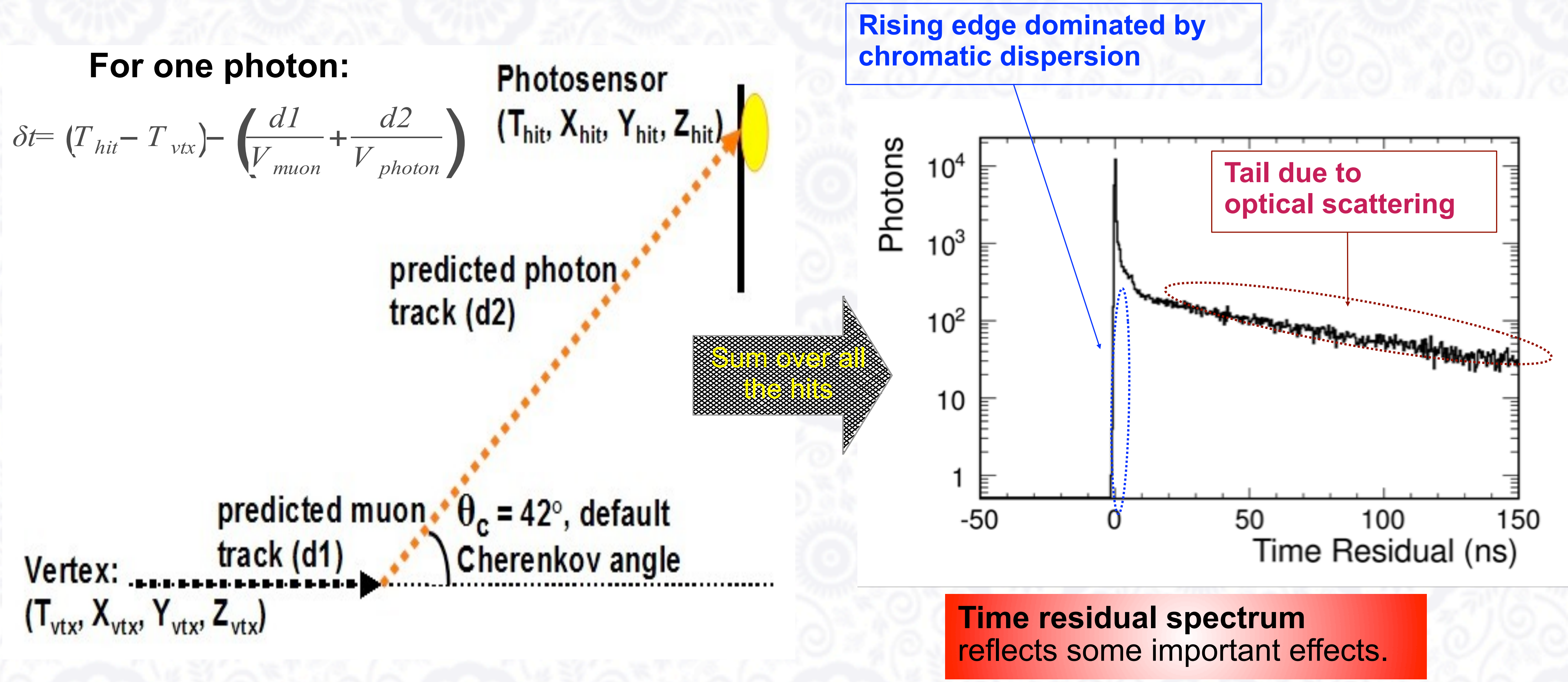
BACK-UP

Timing-based vertex fitting_time residual

- **Time residual** (δt) is defined as the difference between the actual propagation time and the predicted propagation time.

For one photon:

$$\delta t = (T_{hit} - T_{vtx}) - \left(\frac{d1}{V_{muon}} + \frac{d2}{V_{photon}}\right)$$



Rising edge dominated by chromatic dispersion

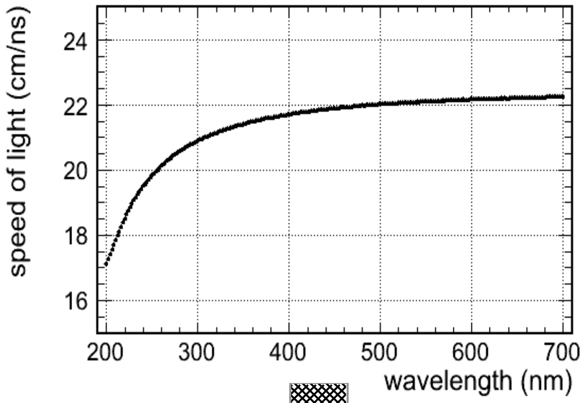
Tail due to optical scattering

Time residual spectrum reflects some important effects.

Chromatic dispersion

- Different color light propagates at different speeds, which leads to different time residuals.

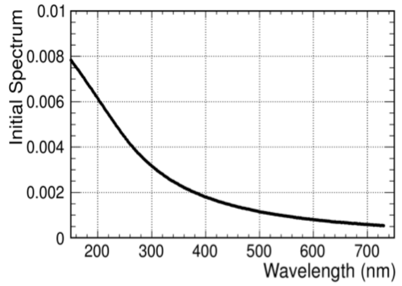
$$\mathrm{Vg} = \frac{\mathrm{d}\omega}{\mathrm{dk}} = \mathrm{c} \times \left(\frac{1}{\mathrm{n}(\lambda)} + \frac{\lambda}{\mathrm{n}^2(\lambda)} \times \frac{\mathrm{dn}(\lambda)}{\mathrm{d}\lambda}\right)$$



$$\delta t_\lambda = \delta t_{default} + \left(\frac{d2}{Vg_{default}} - \frac{d2}{Vg_\lambda}\right)$$

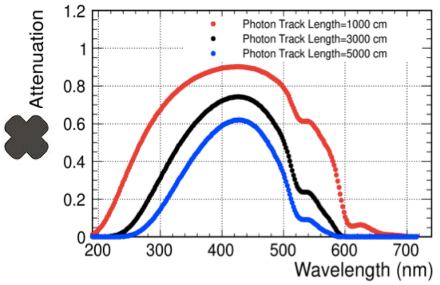
- Different color light has different final surviving probabilities, which is defined as the product of initial radiation proability, attenuation probability and quantum efficiency (QE).

Initial radiation spectrum



×

Attenuation probability, including absorption and scattering



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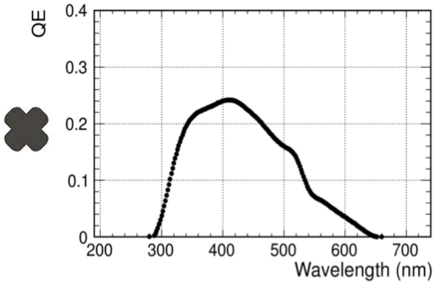
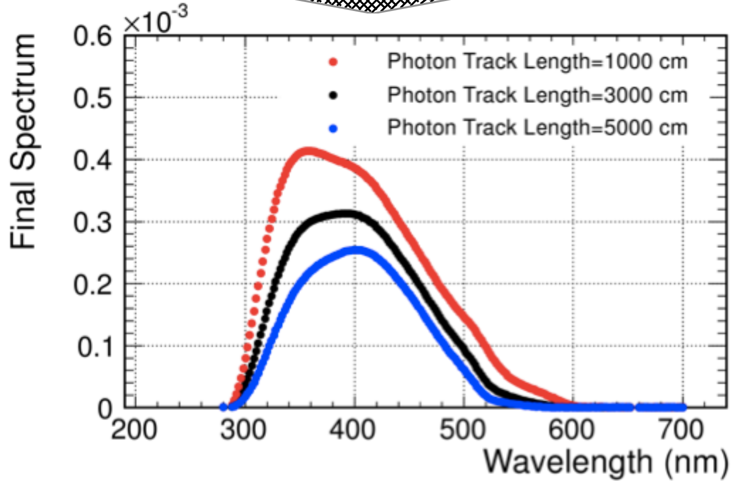
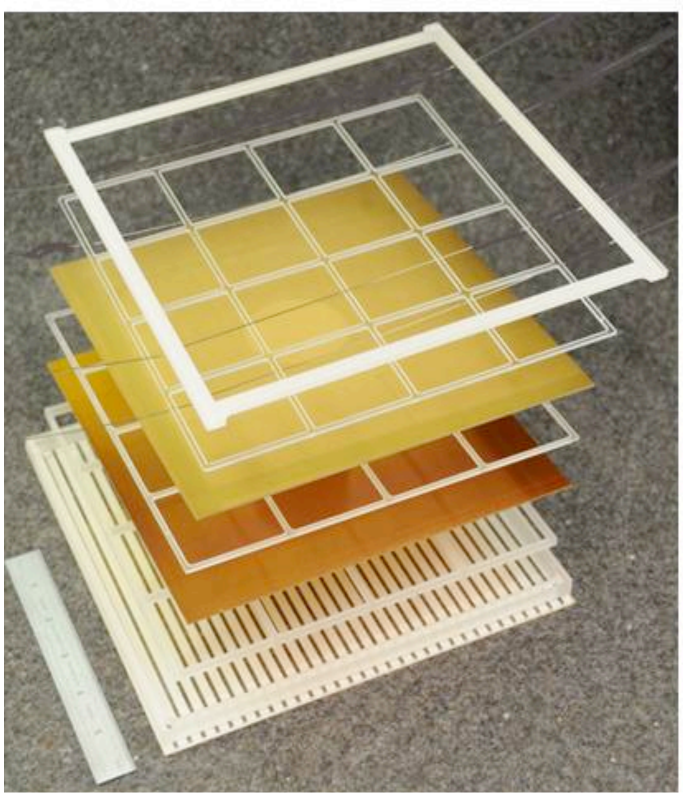
Quantum efficiency

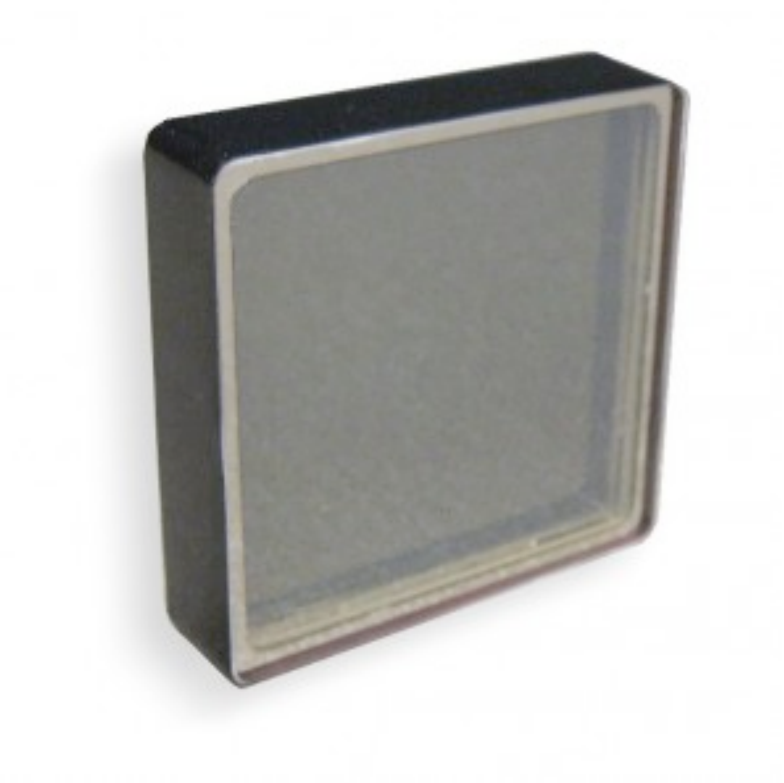


$$\mathrm{Final}(\lambda, \mathrm{d}) = \mathrm{Initial}(\lambda) \times \mathrm{Attenuation}(\lambda, \mathrm{d}) \times \mathrm{QE}(\lambda)$$



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:

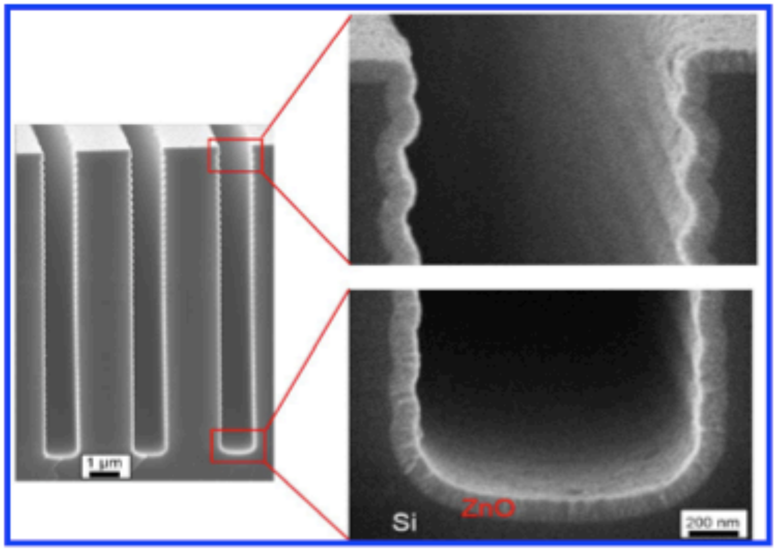
- Conditioning of leaded glass (MCPs)
- Ceramic body
- Not designed for large area applications

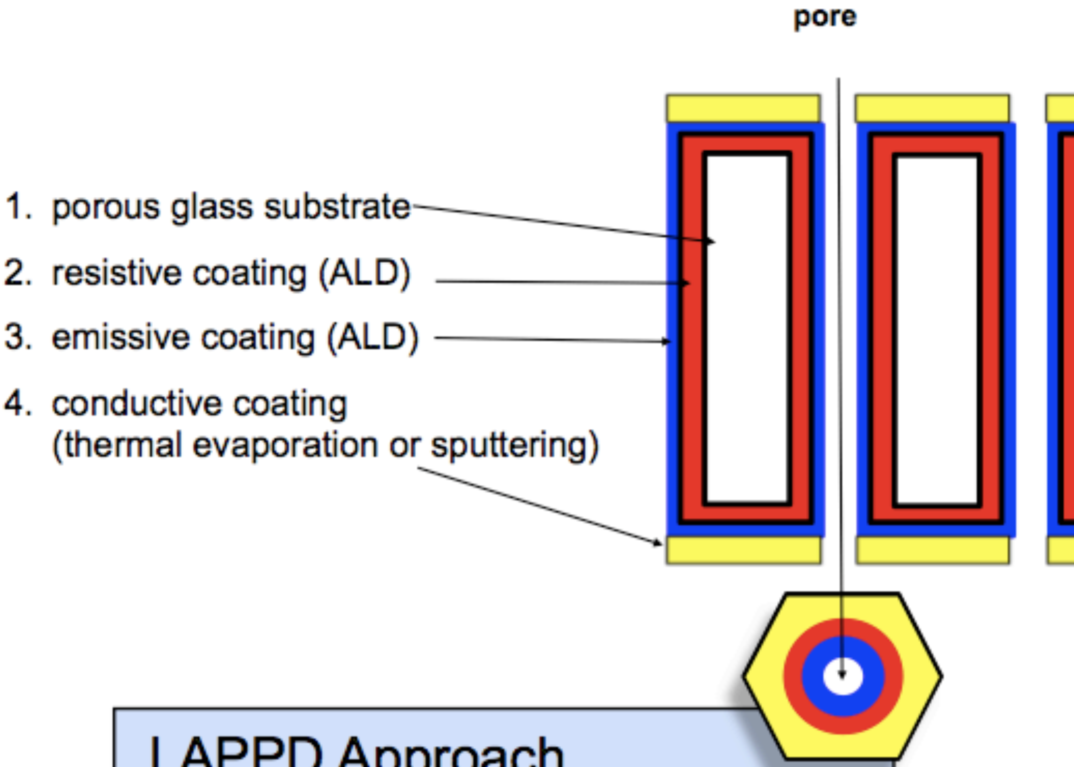
Our Approach

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).



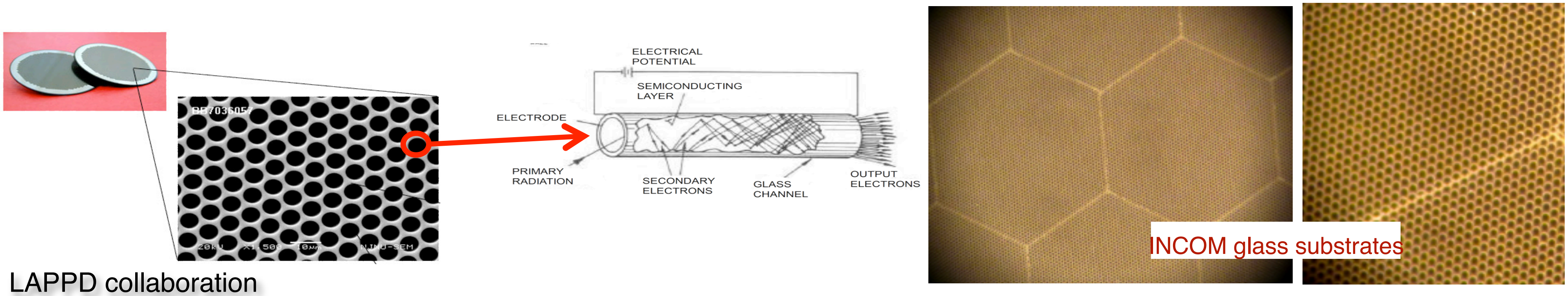


1. porous glass substrate
2. resistive coating (ALD)
3. emissive coating (ALD)
4. conductive coating
   (thermal evaporation or sputtering)

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

LAPPD Design Approach



INCOM glass substrates

LAPPD collaboration

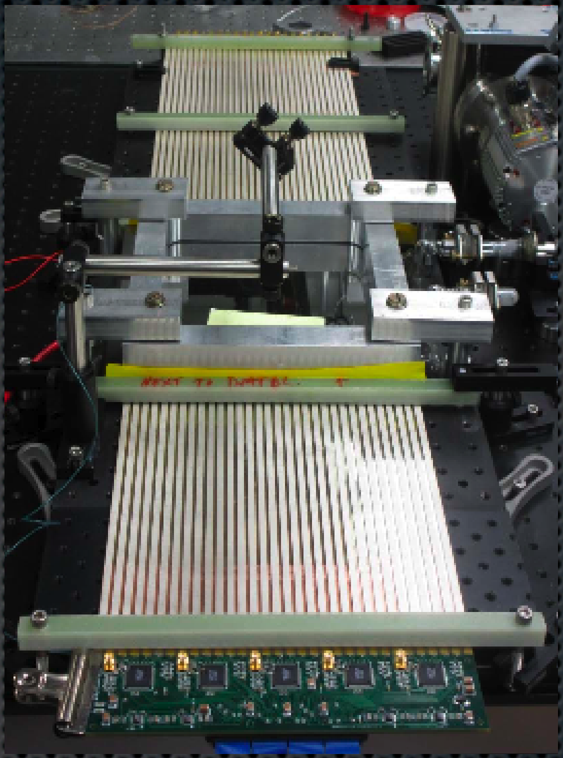
- **Conventional MCP fabrication**
  - Pore structure formed by slicing lead-glass fiber bundles. The glass also serves as resistive material.
  - Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties.

- **LAPPD approach**
  - Separate out the three functions: resistive, emissive and conductive coatings.
  - Use atomic layer deposition (ALD), a cheap industrial batch method. ALD is diffusive, conformal and allows application of material in single atomic monolayers

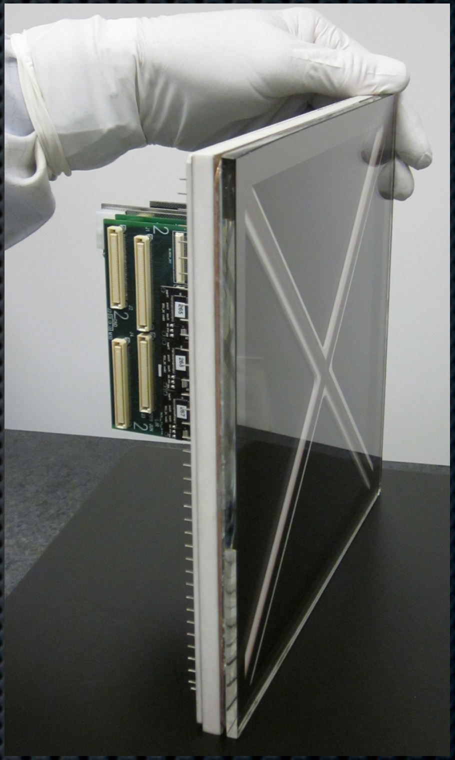
Approach demonstrated for 8-inch tiles

LAPPD Status

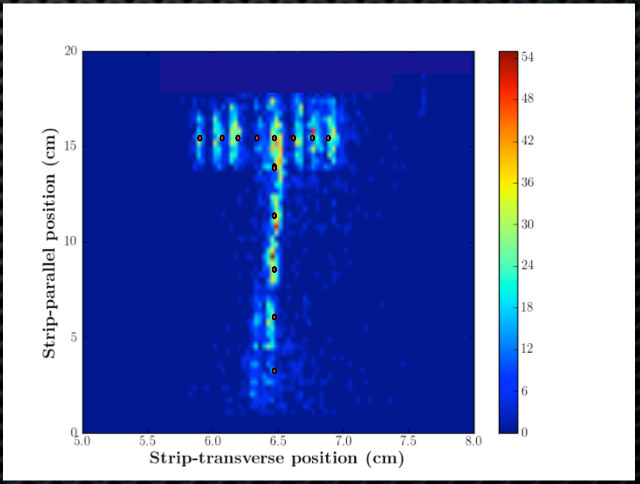
- Testing end-to-end detector system:
  - near-complete “demountable” glass-body 8” MCP-detector.
  - full readout and front-end electronics.
- Producing and testing separate 8” x 8” tile, bialkalai photocathodes with QE > 20%
- There is also 8” Sealed-Tube processing tank at Berkeley SSL built and being tested.
- Psec4 chip benchmarked at:
  - 1.6 GHz analog bandwidth,17 Gsamples/second, ~ 1mV noise
- Psec electronics system is capable of shape-fitting the LAPPD pulses for time, position, and charge at the front-end.



ANL “demountable” detector system - glass body LAPPD
Reconstruct of a “T” below



Berkeley SSL detector system- ceramic body LAPPD

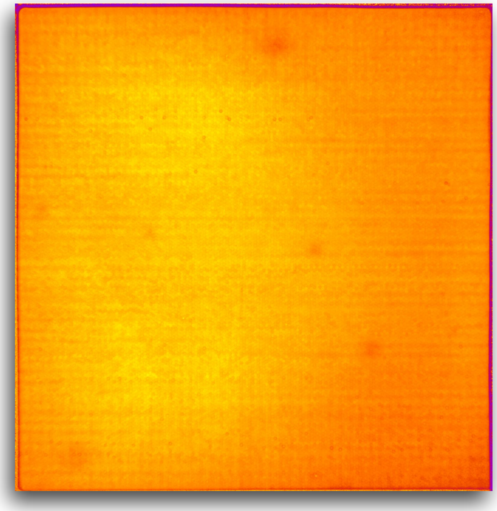


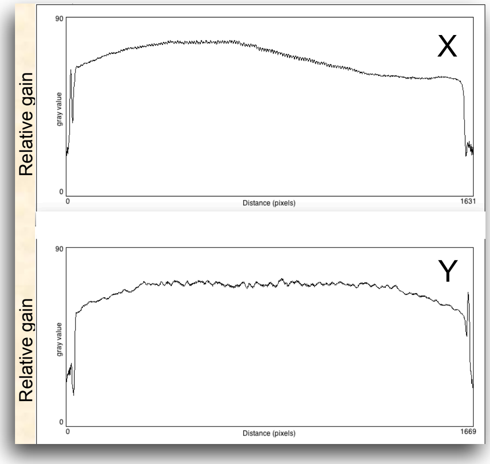
Berkeley SSL Sealed-Tube Processing Tank

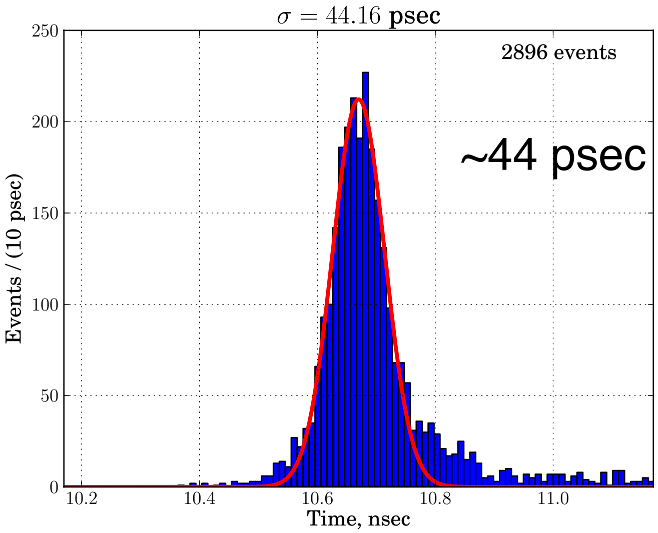
LAPPD

We observe:

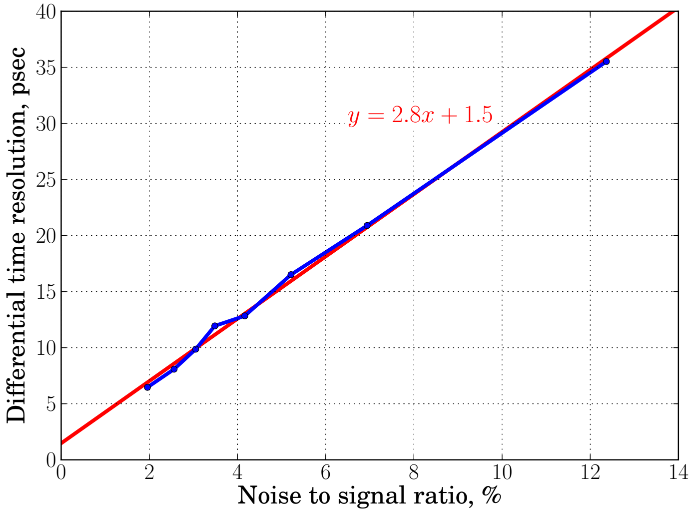
- Typical gains of O(10^7)
- Single photoelectron time resolutions of ~40 picoseconds.
- Timing in the many-photoelectron limit approaching single picoseconds





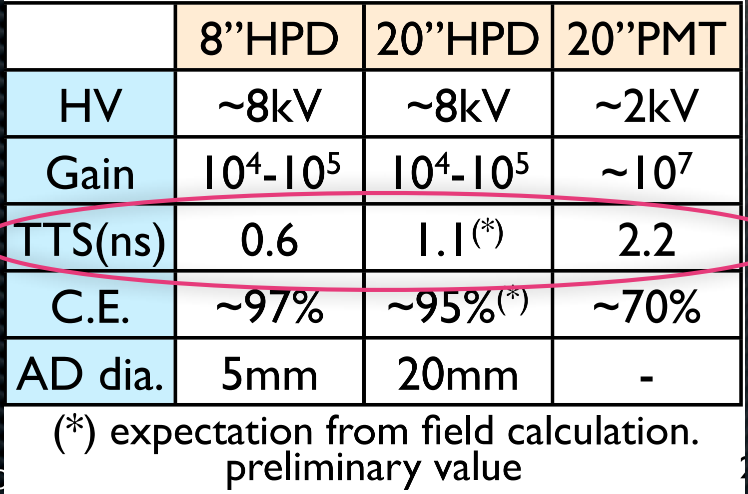


~44 psec



Photodetector R&D for Hyper-K

- Hyper-K photosensor candidates:
    - 20-inch hybrid photodetector (HPD)
    - 20-inch improved or HQE PMT
- 99K required for 20% coverage
- 58K HQE for 13% coverage
- **Expected time resolution gains for HPDs:**



	8"HPD	20"HPD	20"PMT
HV	~8kV	~8kV	~2kV
Gain	10^4-10^5	10^4-10^5	~10^7
TTS(ns)	0.6	1.1(*)	2.2
C.E.	~97%	~95%(*)	~70%
AD dia.	5mm	20mm	-

(*) expectation from field calculation.
preliminary value

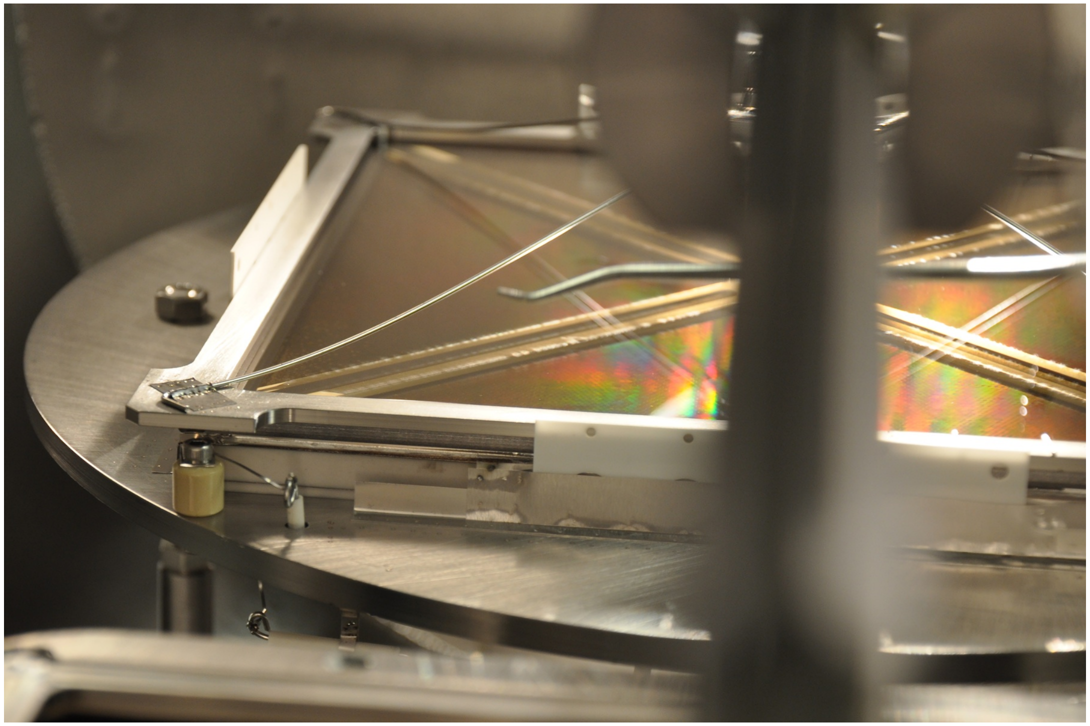
H. Tanaka - ISOUPS

M. Shiozawa/ T. Nakaya

LAPPD Status

First complete LAPPD (with photocathode) has been sealed at Berkeley SSL.

Will be brought to air shortly. This is a significant milestone.



Tube with window hot indium seal completed

Commercialization progress:

$3 M awarded in SBIR funding to a company to commercially develop LAPPDs.