The ANNIE experiment

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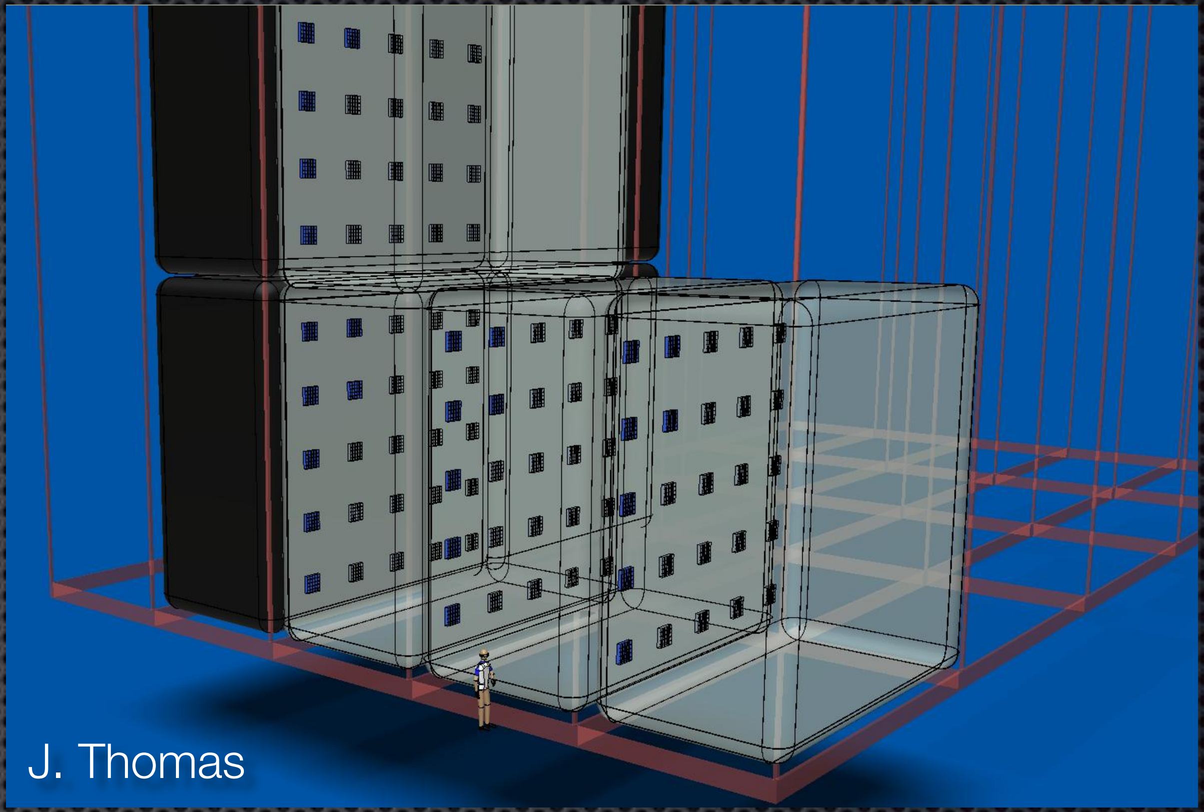
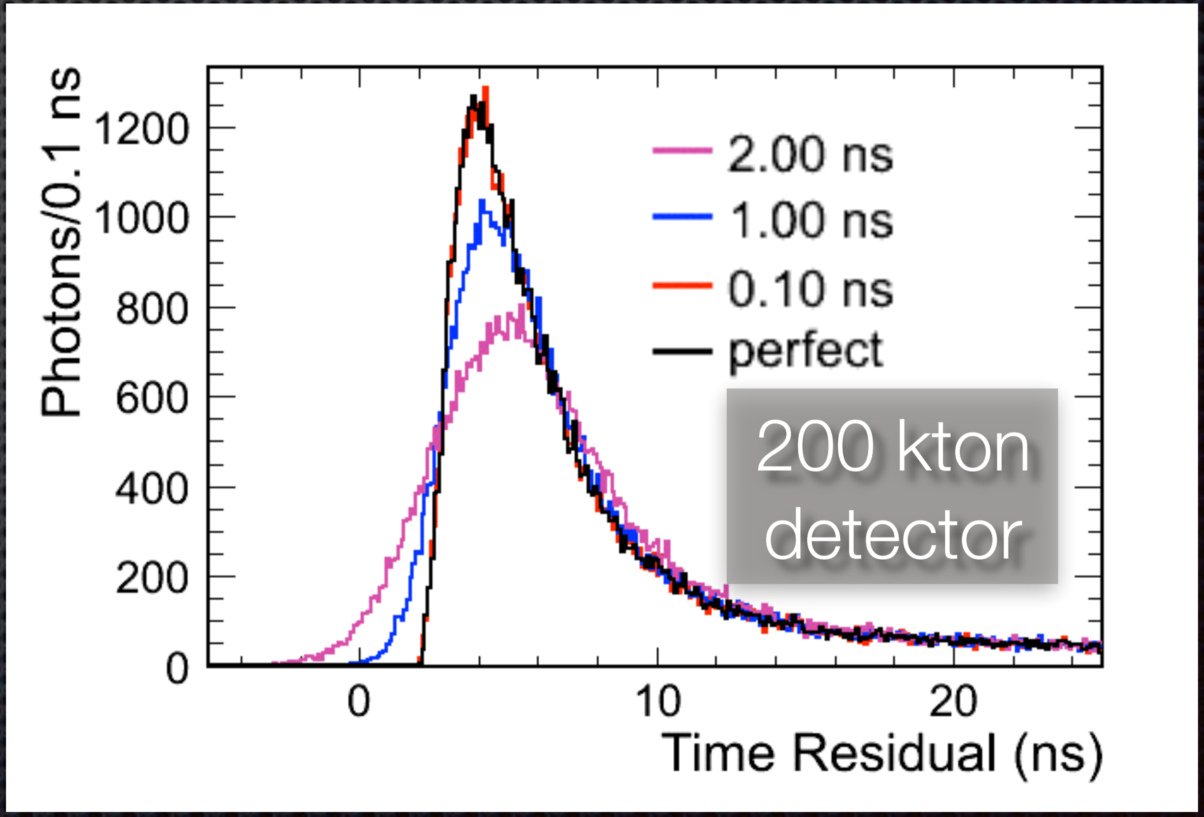
NNN2015 Satellite Meeting - Stony Brook University - October 27, 2015

Using LAPPDs for neutrinos

- This new technology applied to **Water Cherenkov detectors** could open the door to better background rejection and vertex resolution as well as high intensity (near det.) situations.

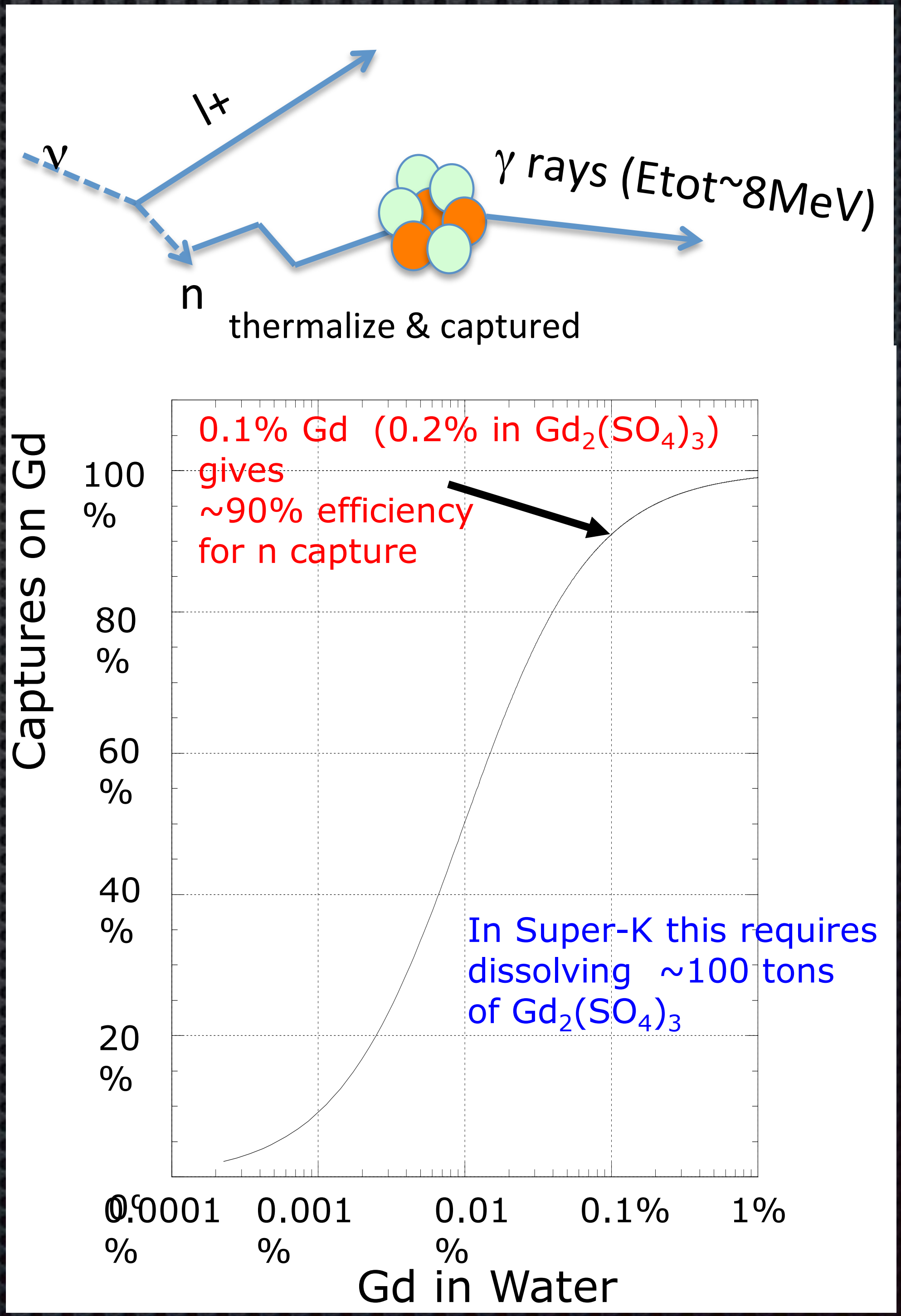
- Potential impact of LAPPDs:
  - Does **better timing information** improve vertex resolution for interactions in Water Cherenkov detectors?
  - Does **improved granularity and/or coverage** improve particle ID?





Using Gd for neutrinos

- Dissolving gadolinium (Gd) in water as neutron absorber has been proposed: Beacom and Vagins PRL93, 171101.
- Increasing the cross section of the neutron capture and shortening the time delay of the capture reduces the background for several physics measurements:
  - Supernova relic neutrino
  - Proton decay
  - Long baseline neutrino oscillations (wrong-sign contamination)



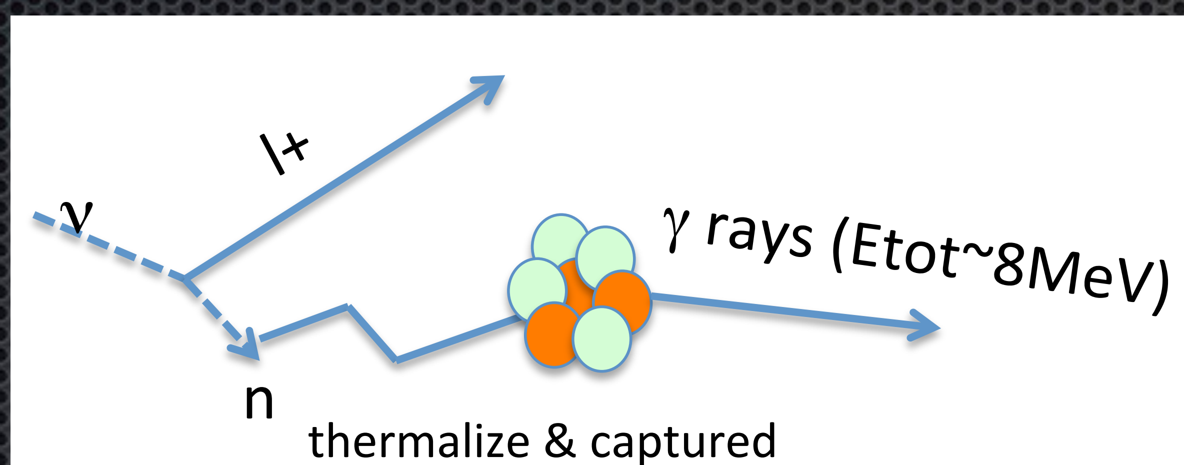
Super-K has decided on June 27, 2015 it will add Gd

see Sekiya-san's talk - TAUP 2015

The ANNIE experiment

- Seeks to measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy (arXiv: 1409.5864, arXiv:1504.01480).

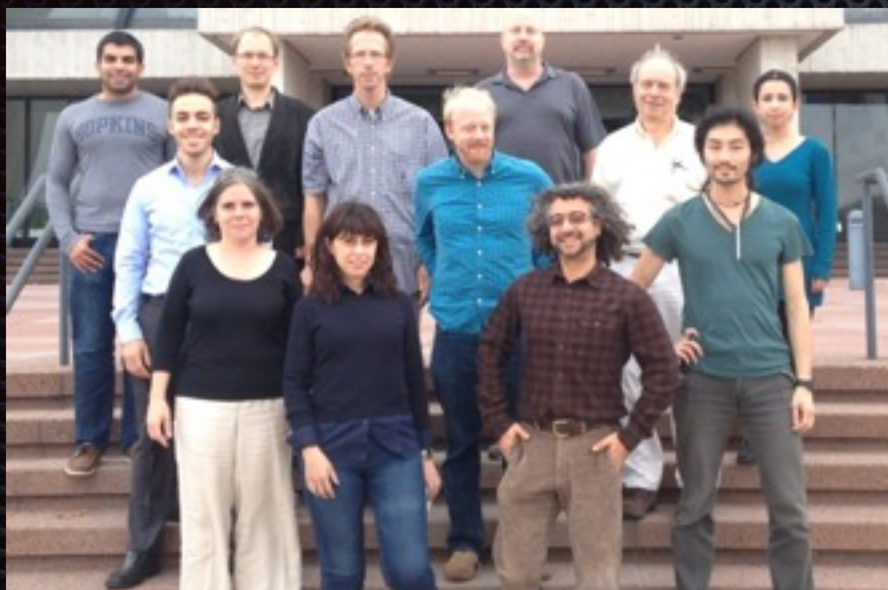
- **Tests LAPPDs in a neutrino experiment for the first time!**



- A key physics measurement in understanding the nature neutrino-nucleus interactions.
- Application of a promising technology for detecting neutrinos.

Phase I - neutron background measurement - approved
Phase II - physics measurement - proposed to DOE

The ANNIE collaboration



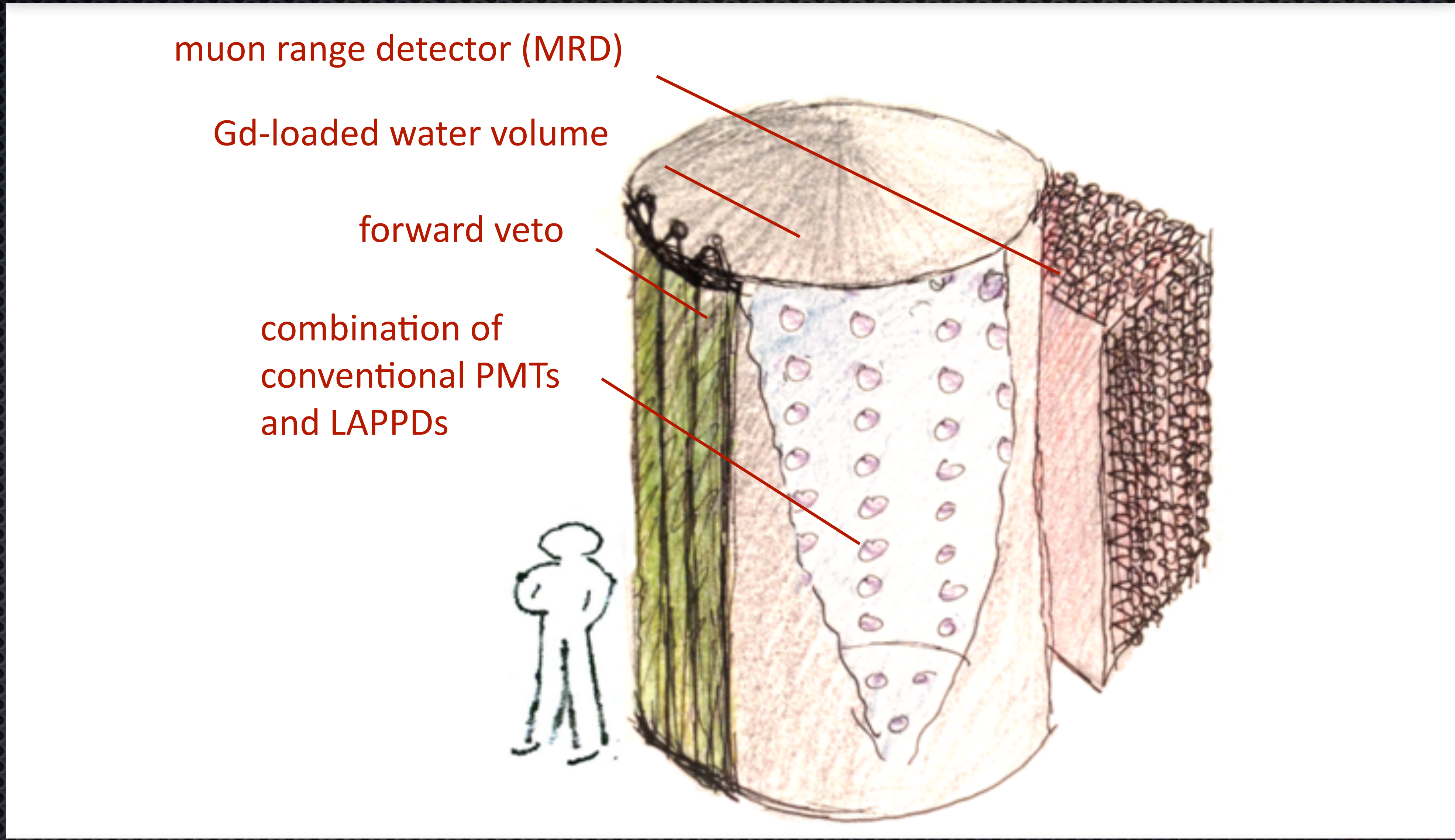
Argonne National Laboratory
Brookhaven National Laboratory
Fermi National Laboratory
University of California at Berkeley
University of California at Davis
University of California at Irvine
University of Chicago
Iowa State University
Ohio State University
University of Sheffield
Queen Mary University of London

2 countries **11 Institutions** **30+ collaborators**

New collaborators are welcome!

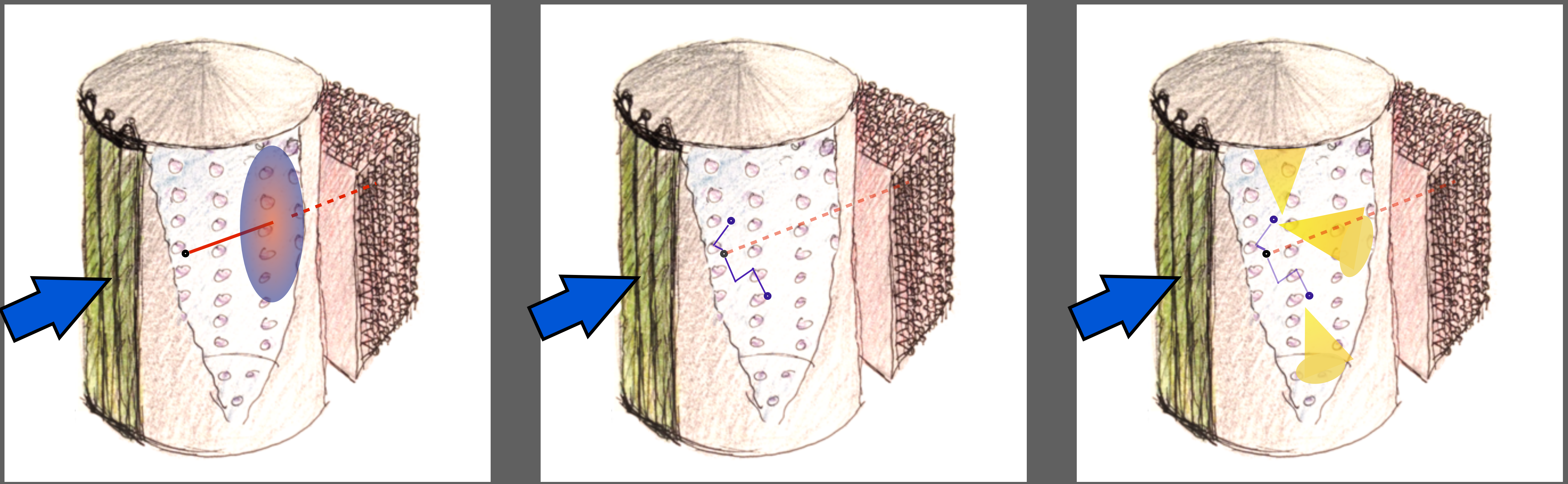
The ANNIE concept

A 23-ton tank filled with Gd-loaded water



The tank diameter is 3 m and height is 4 m.

The ANNIE concept



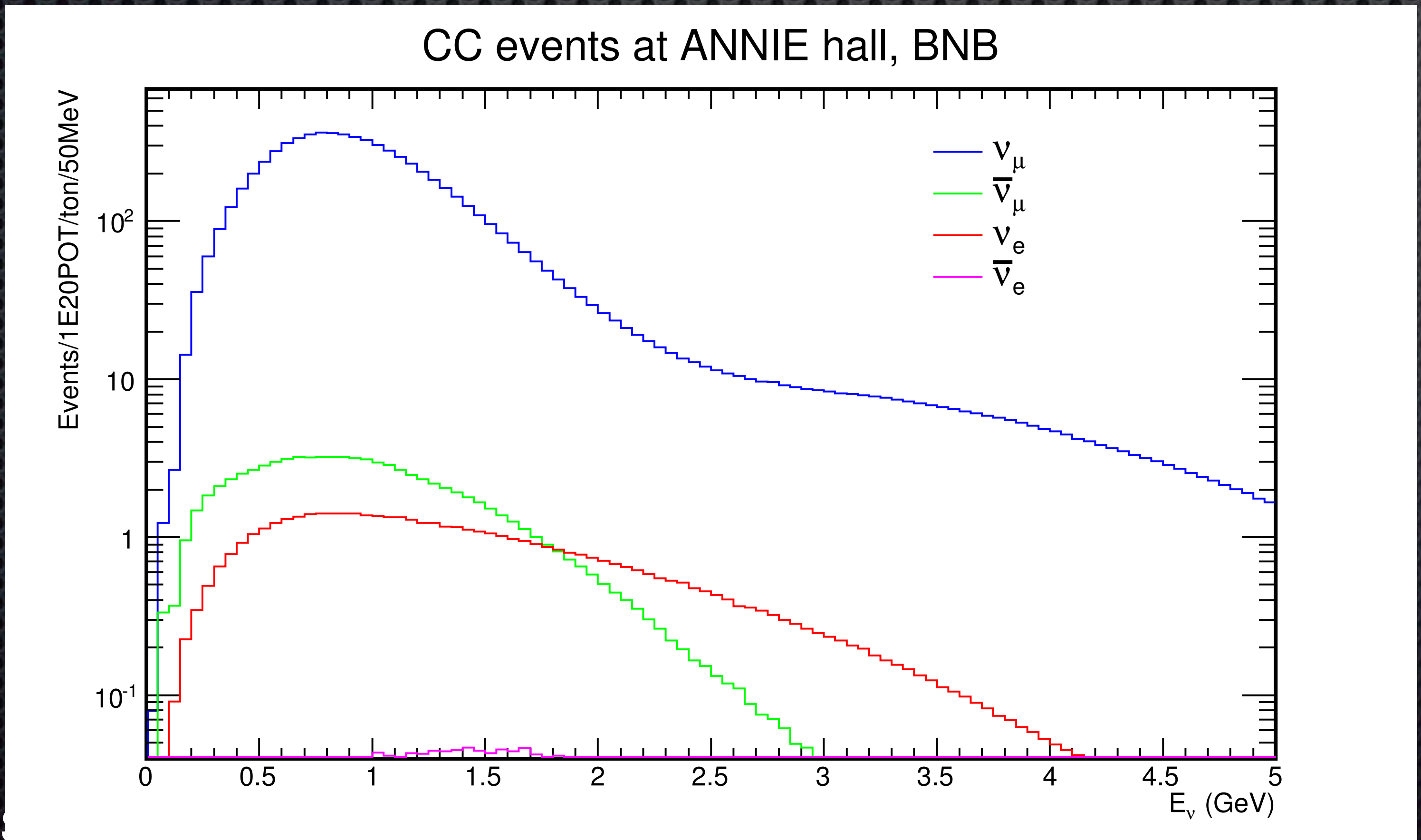
Prompt muon tracks through water volume, ranges in MRD

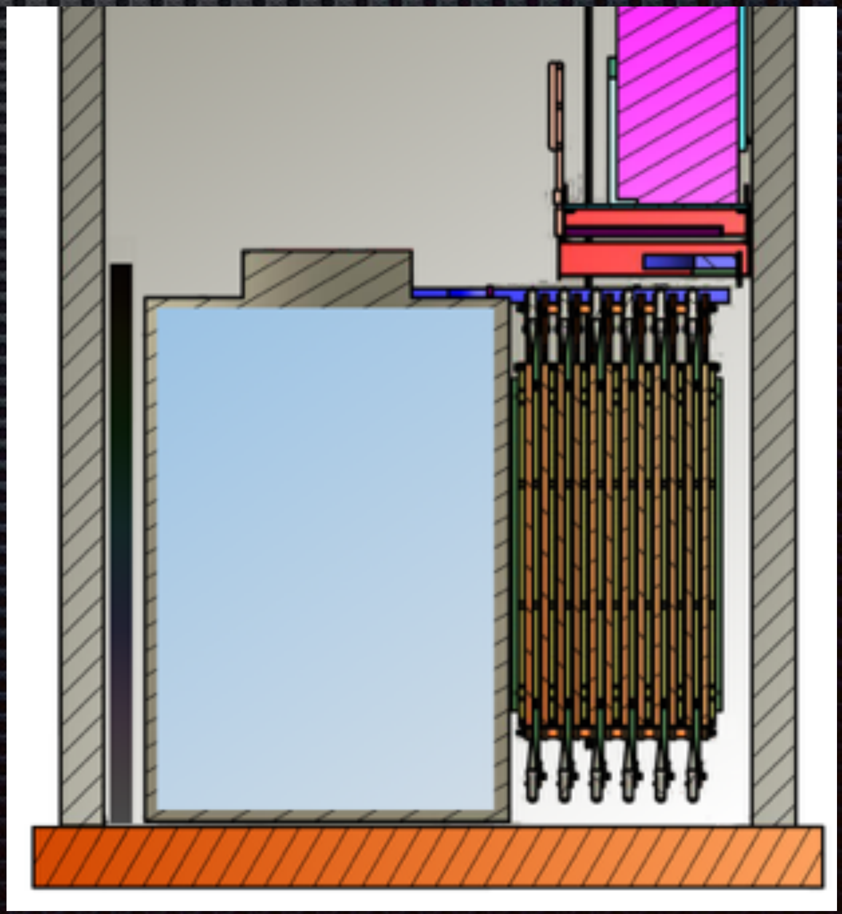
neutrons are produced from the interaction, vertex is determined by LAPPDs

neutrons thermalize and capture on Gd, flashes of light are detected by PMTs

ANNIE: A US-based R&D water Cherenkov facility

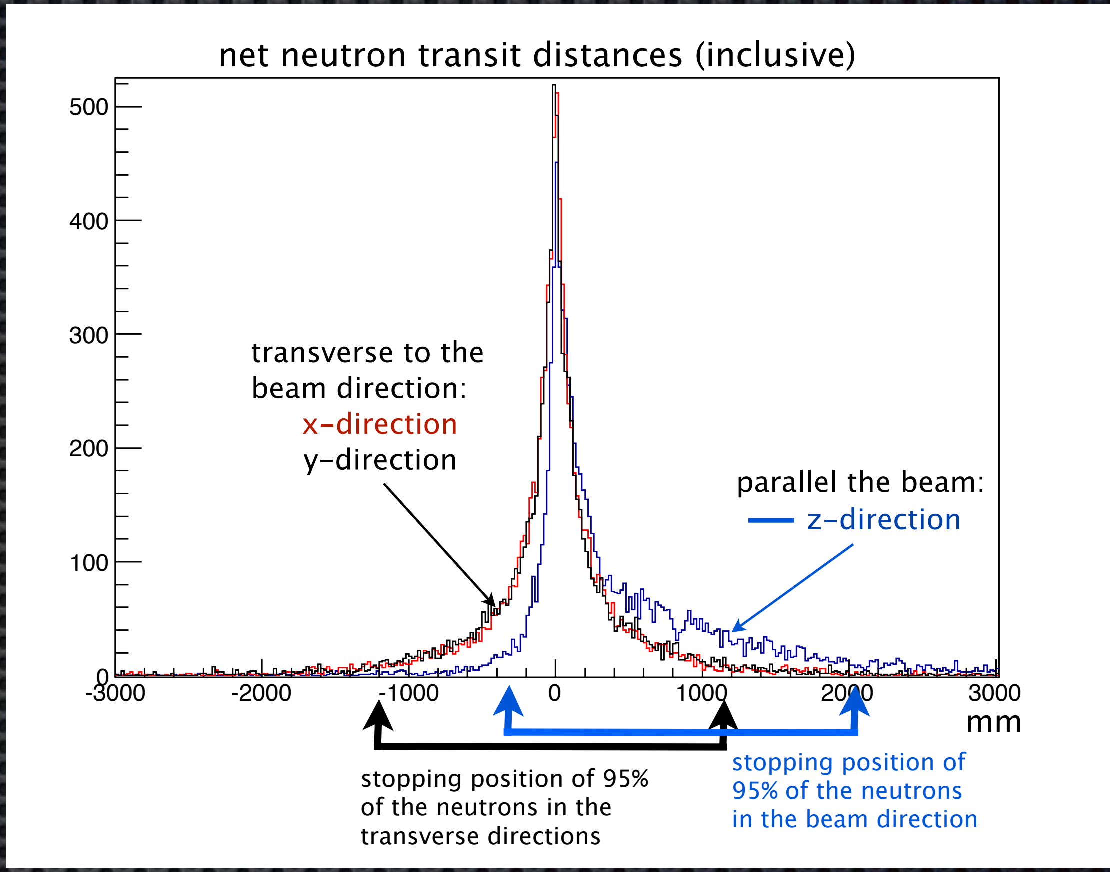
- “ANNIE Hall”: A neutrino test beam!
- High intensity: ~10k CC events per cubic volume per year
- Part of the short baseline program (high priority running)
- Relevant energy for proton decay background studies. At turn-on for resonance events.
- **First stage of ANNIE will measure neutron backgrounds in the hall.**

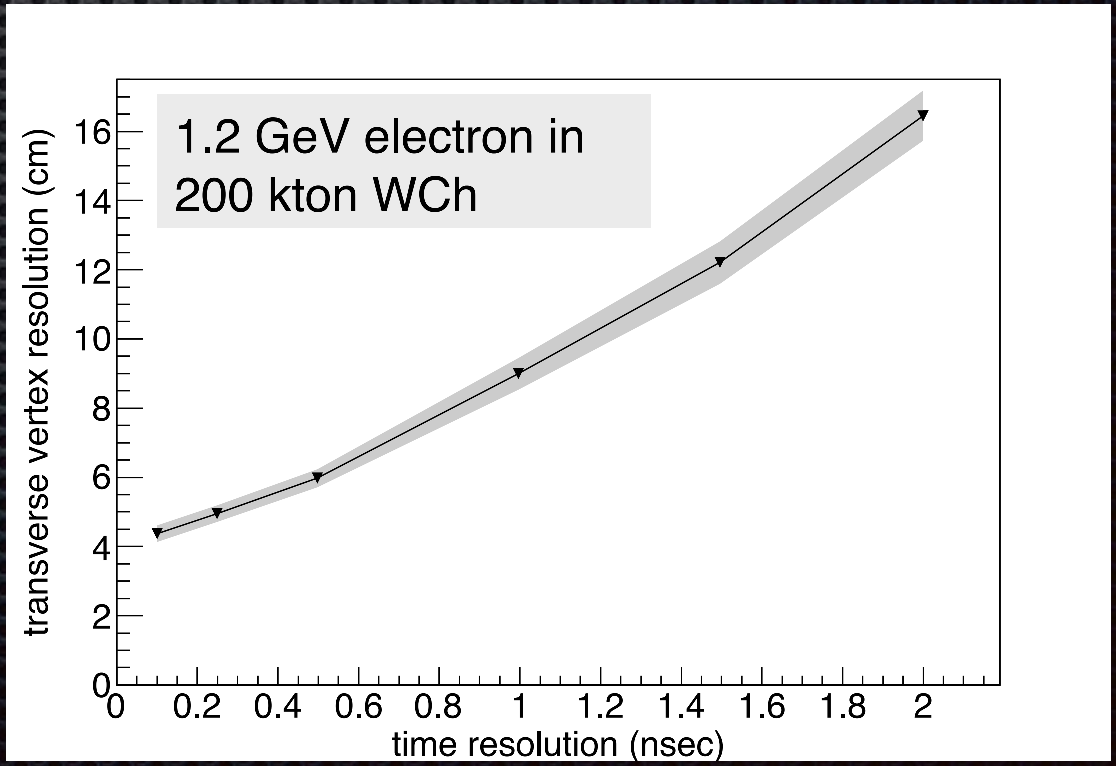




Using LAPPDs for ANNIE

- Interactions must be sufficiently far from the walls of the detector, so that neutrons do not escape.
- The majority of neutrons stop within ± 1 m of their starting point in the directions transverse to the beam.
- They fall in a ~ 2m forward region from their starting position in the beam direction.
- LAPPDs provide excellent position and time resolution even for large detectors. They will allow locating the neutrino interaction point in a small ~1 ton fiducial volume.





Phased approach

on-going

Fall 2015

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

to Jun 2016

- R&D, procurement, construction, commissioning

to Jun 2017

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

to Jun 2018

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

to Mar 2021

Phase I approved by FNAL PAC.

Phase II proposed to DOE’s Intermediate Neutrino Program

Status of ANNIE

- The tank has arrived to Fermilab and the forward veto has been completed!
- Work is underway to finish the mechanical design for inner structure, design the electronics, procure PMT coverage, etc.
- Purchase order for PSEC chips has been placed.
- Work on tank and the inner volume is planned to occur shortly.

Neutron background data taken by Summer 2016

Key technology in ANNIE

- We will use water Gd loading in a neutrino beam experiment.
- We will use waveform sampling electronics.
- We will test a sizable PSEC system.
- We have a commitment from Incom for 20 LAPPDs in Phase II (10% forward coverage).

ANNIE Technological Program

- As currently proposed:
  - First physics measurement using Gd-loaded water on high-E beam.
  - First demonstration of LAPPDs in a Water Cherenkov detector.
  - Testing out new waveform sampling and PSEC4 electronics.
- **Potential enhancements:**
  - Other photosensor technologies.
  - Water-based liquid scintillator (wbLS).
  - Magnetizing muon range detector.

ANNIE software status

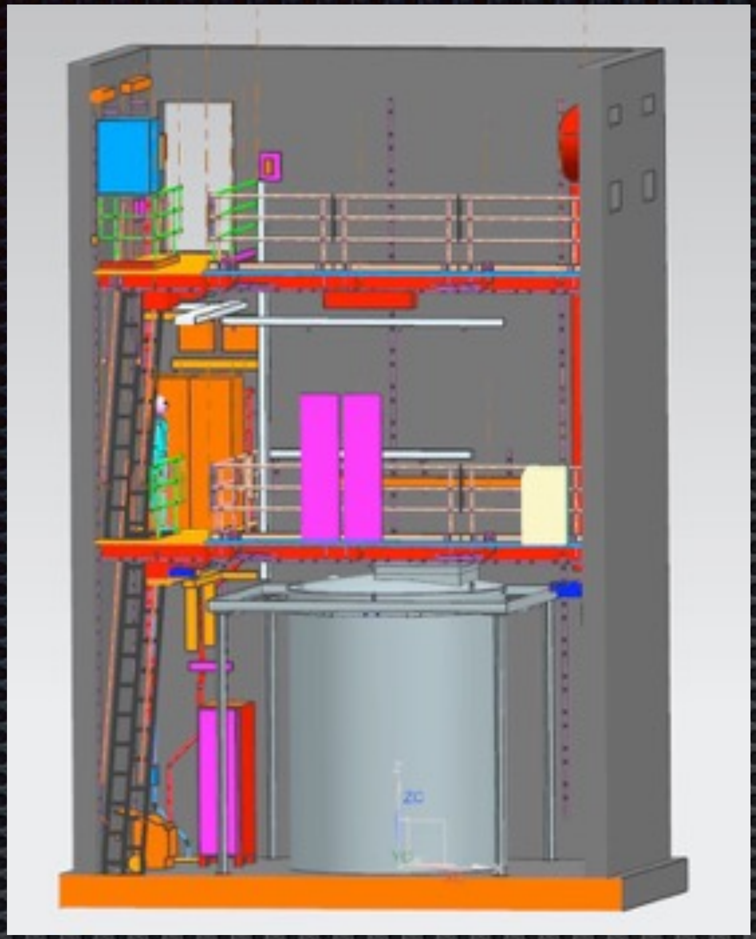
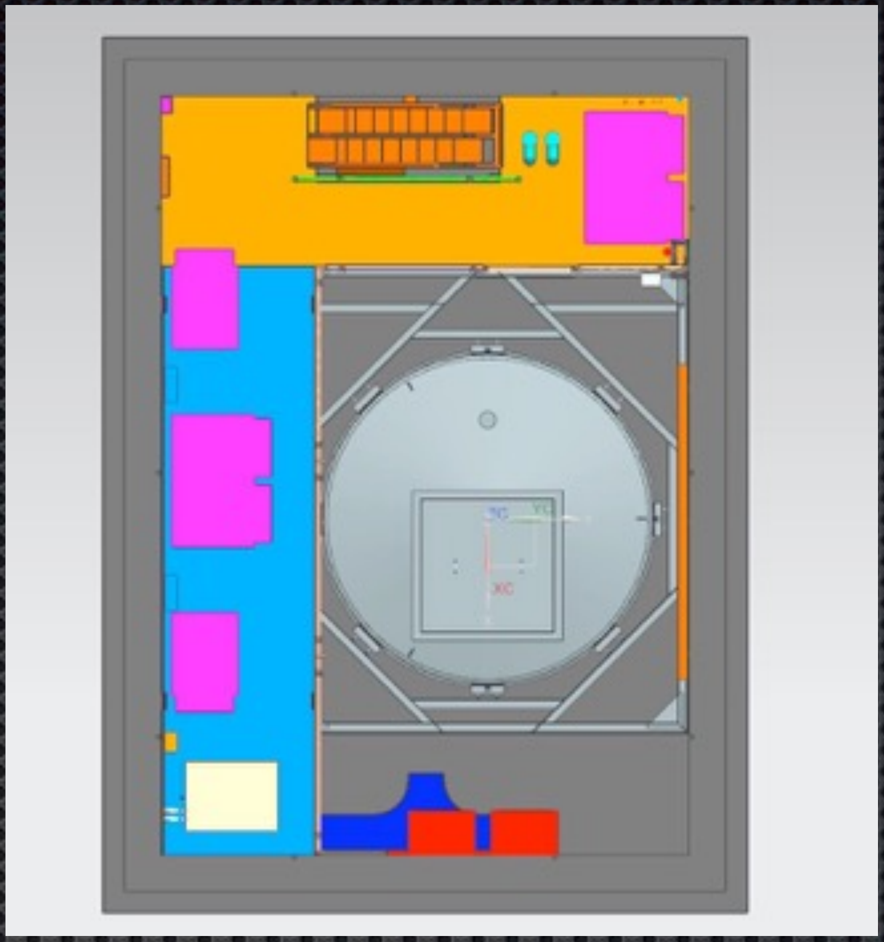
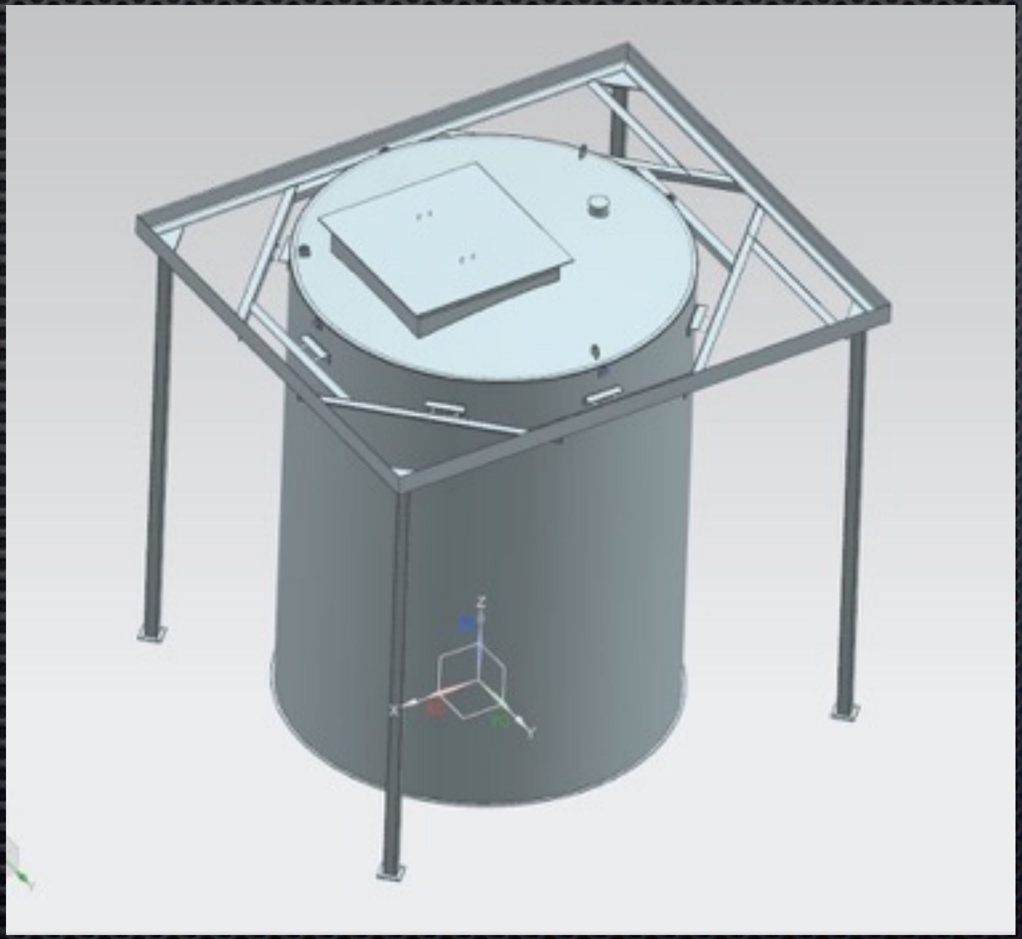
- Current:
  - Simulation of flux in the hall exists in collaboration with FNAL.
  - Detector simulation based on WChSandbox.
  - Standalone package for simulating LAPPD response.
  - Reconstruction being developed by UK groups in the context of TITUS: High energy and low energy.
  - Software not fully integrated yet.
- **Potential directions:**
  - Modified WCSim for detector simulation is possible.
  - Some interest in RATPAC.
  - Detector simulation must allow simultaneous systems.
  - Considering integration of reconstruction/analysis end with ART.

Decisions need to be made soon

ANNIE and then…

- ANNIE is ideal as a first test for the application of LAPPDs as it is small enough that is feasible with the expected initial limited availability.
  - It enables a promising technology for neutrino detection.
- A 20-ton detector using Gd-enhanced water for neutron capture. It is an interesting application of this technique.
  - Of high interest to Super-K adding Gd.
  - Also for ND concepts to Hyper-K.
- It is a critical first step for efforts to develop an advanced water-based liquid scintillator detector concept: Theia.

Backup

Status of the ANNIE experiment

> "The PAC therefore recommends that the ANNIE collaboration be granted stage 1 approval and be supported to proceed with Phase I of their proposed work."

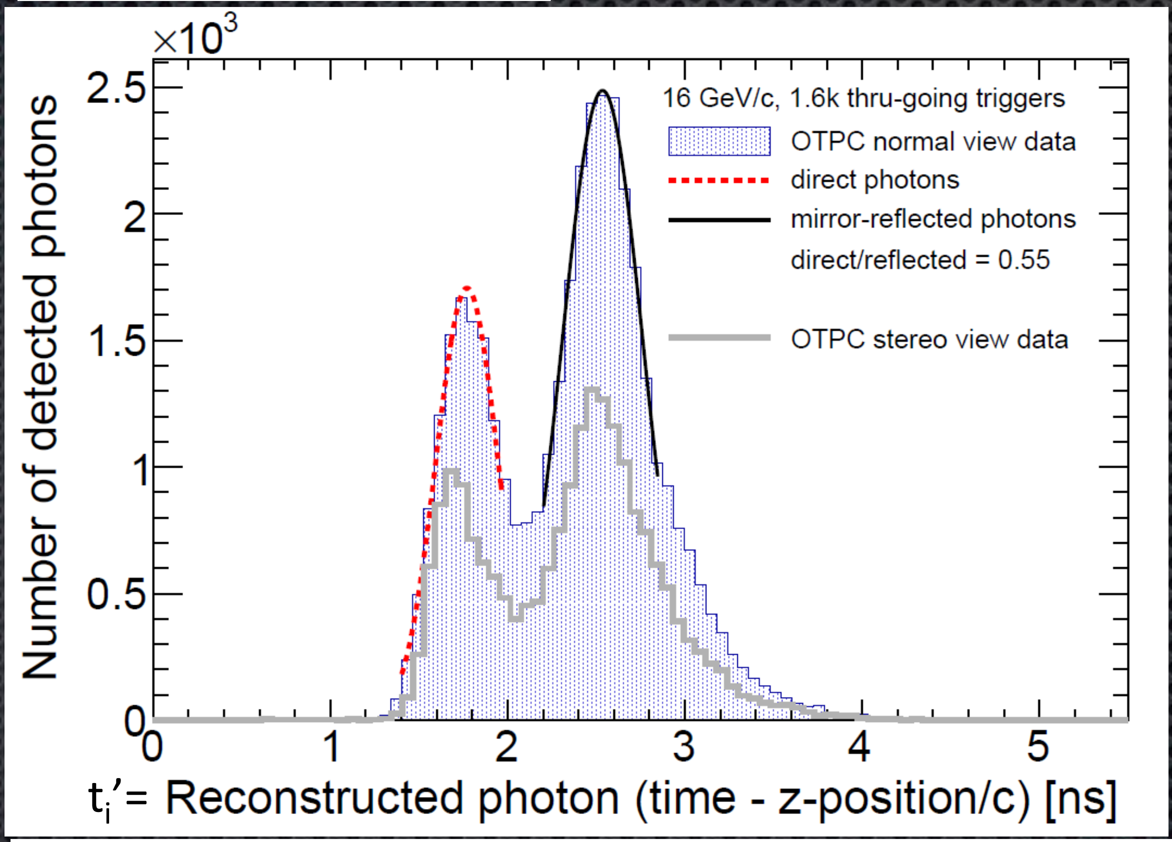
- ANNIE has been approved for Phase I construction by the Fermilab directorate and is on schedule.
- Fermilab and the community have provided significant support.
- A proposal for the Intermediate Neutrino Program FOA is under preparation for Phase II.

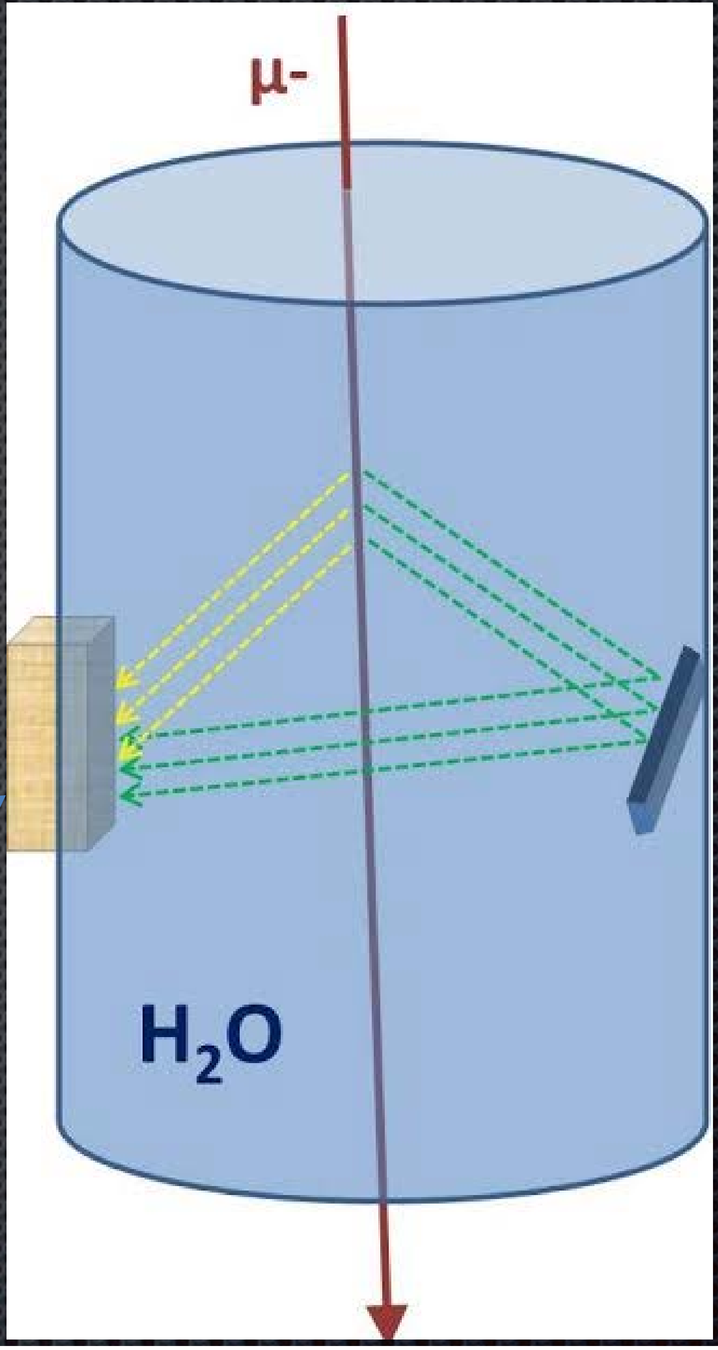
New collaborators are welcome!

Optical TPC proof of concept

The detector is constructed from a 24 cm inner-diameter PVC cylndrical pipe cut to a length of 77 cm

- Photodetector modules (PM) are mounted on 2 columns along the longitudinal axis with an azimuthal separation of 65 degrees ('normal' and 'stereo' view)
- For each PM, an optical mirror is mounted on the opposing wall, facing the PM port
- Remaining exposed PVC surfaces painted black
- Detector volume is 40 L of water





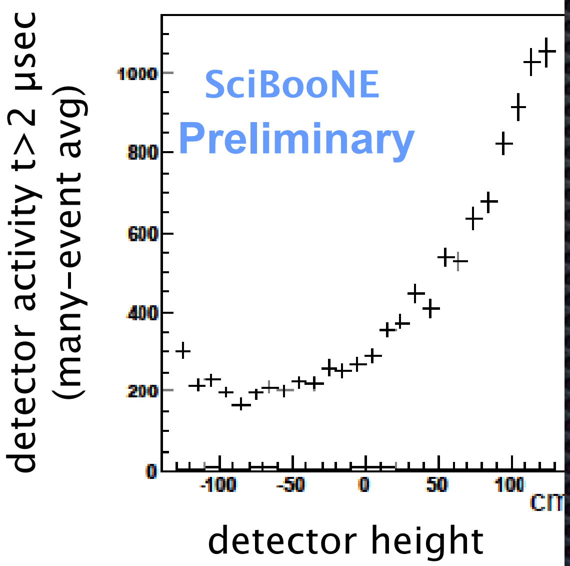
By time and space resolving, we measure an angular resolution of a few degrees (50 mrad) and a spatial resolution on particle tracks of 15 mm

E. Oberla - UChicago Ph.D. Thesis - 2015

ANNIE phase I

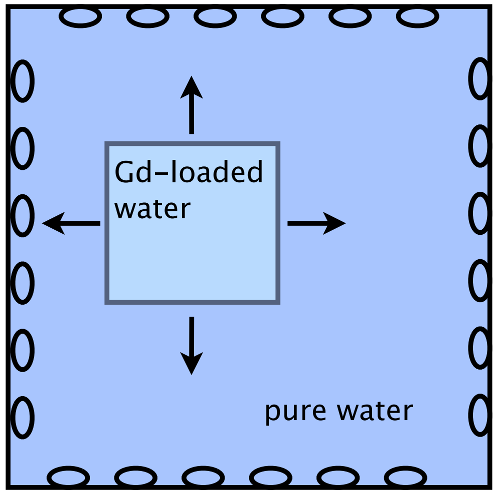
ANNIE will see neutron backgrounds from 2 sources:

- **skyshine:** neutrons from the beam dump migrating into the Hall from above
- **dirt neutrons:** neutrons produced by neutrino interactions in the rock, upstream of the detector



We need to understand these backgrounds before we determine the final configuration of ANNIE.

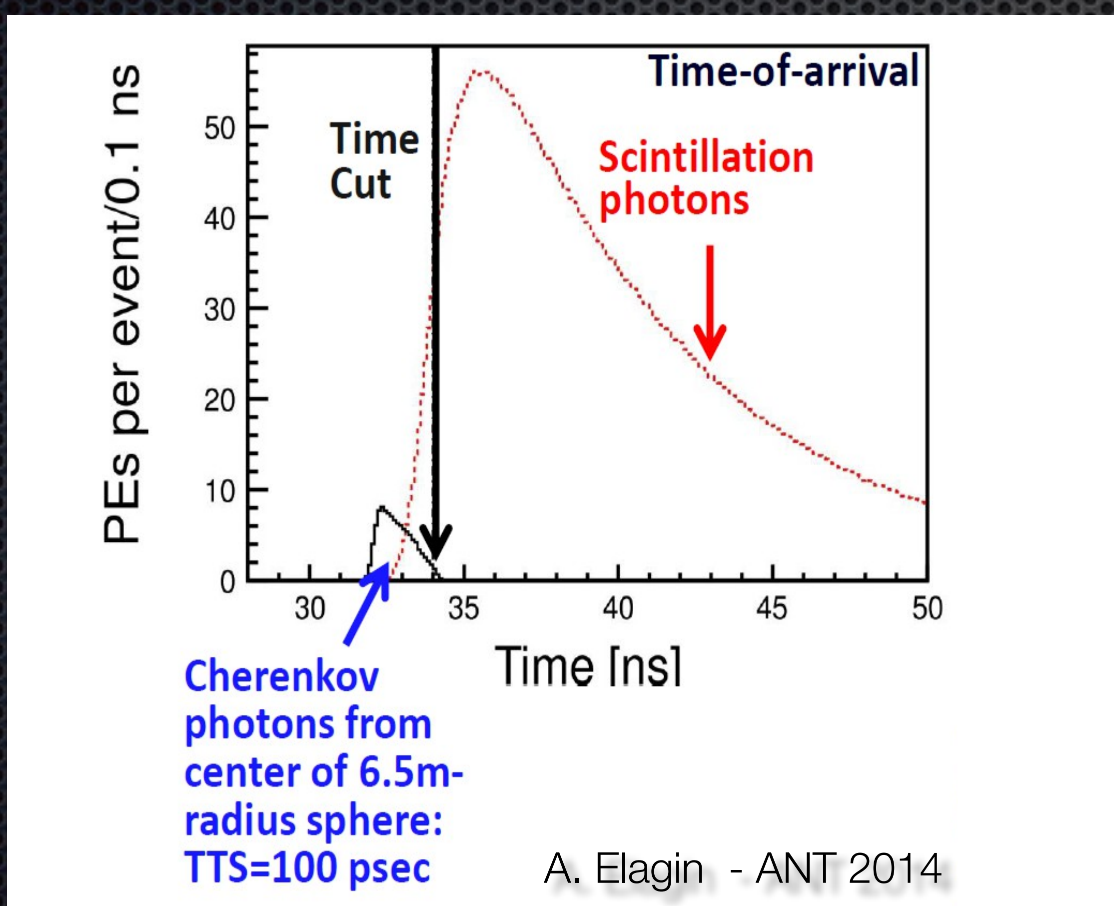
With a Phase I detector, we can test the first LAPPDs submerged in water, as they become available.

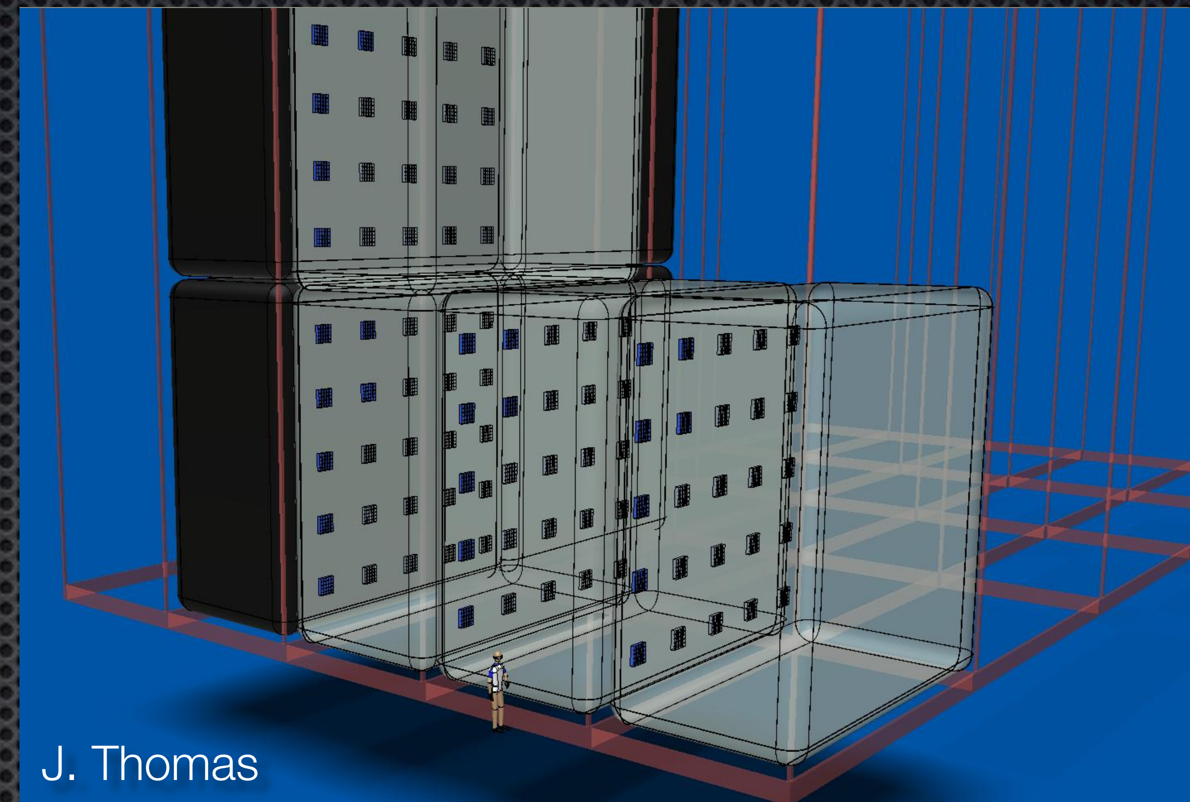


Requires input and coordination with Fermilab.

Using LAPPDs for neutrinos

- This new technology applied to **large Water Cherenkov detectors** could open the door to better background rejection and vertex resolution by **improving spatial and timing information**.



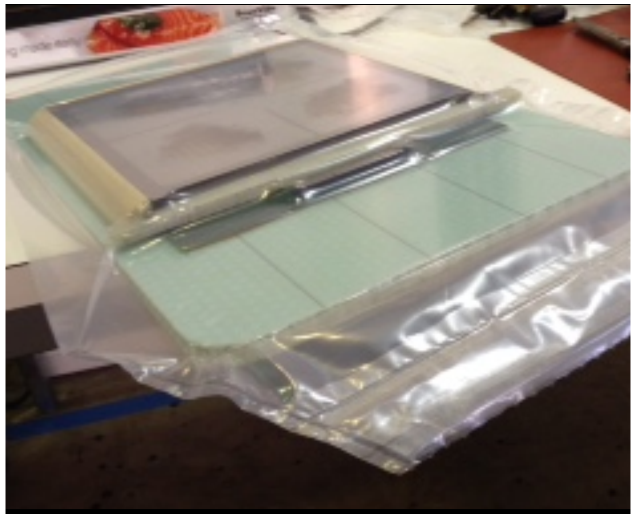


- For water-based liquid scintillator detectors it could help separate Cherenkov from scintillation light.

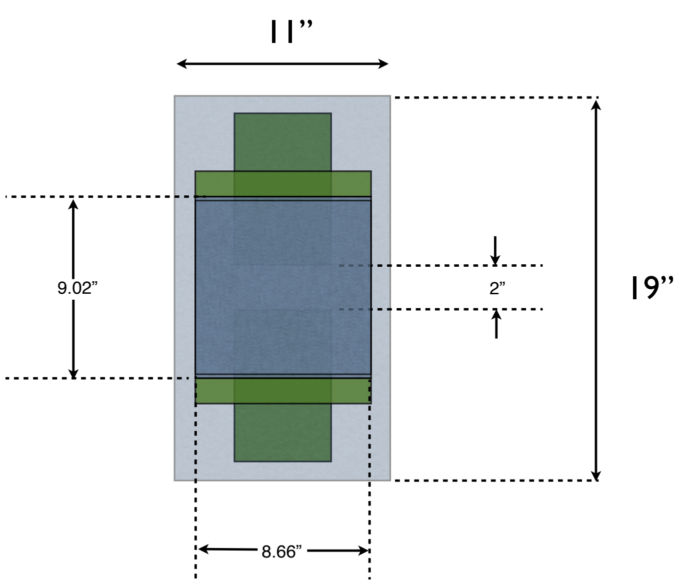
(not described this talk)

LAPPD R&D for ANNIE and beyond

- ANNIE not only benefits from the capabilities of LAPPDs, but it will carry out R&D to enable these to be used in future detectors.
- Operation in water (or other liquid environments) is a key step for ANNIE and potential future liquid-based experiments.
- UChicago is pursuing several paths for the WATCHMAN effort:
    - Vacuum sealing LAPPD assemblies in a plastic envelope (“Sous Vide”).
    - Commercially available water-tight casing.

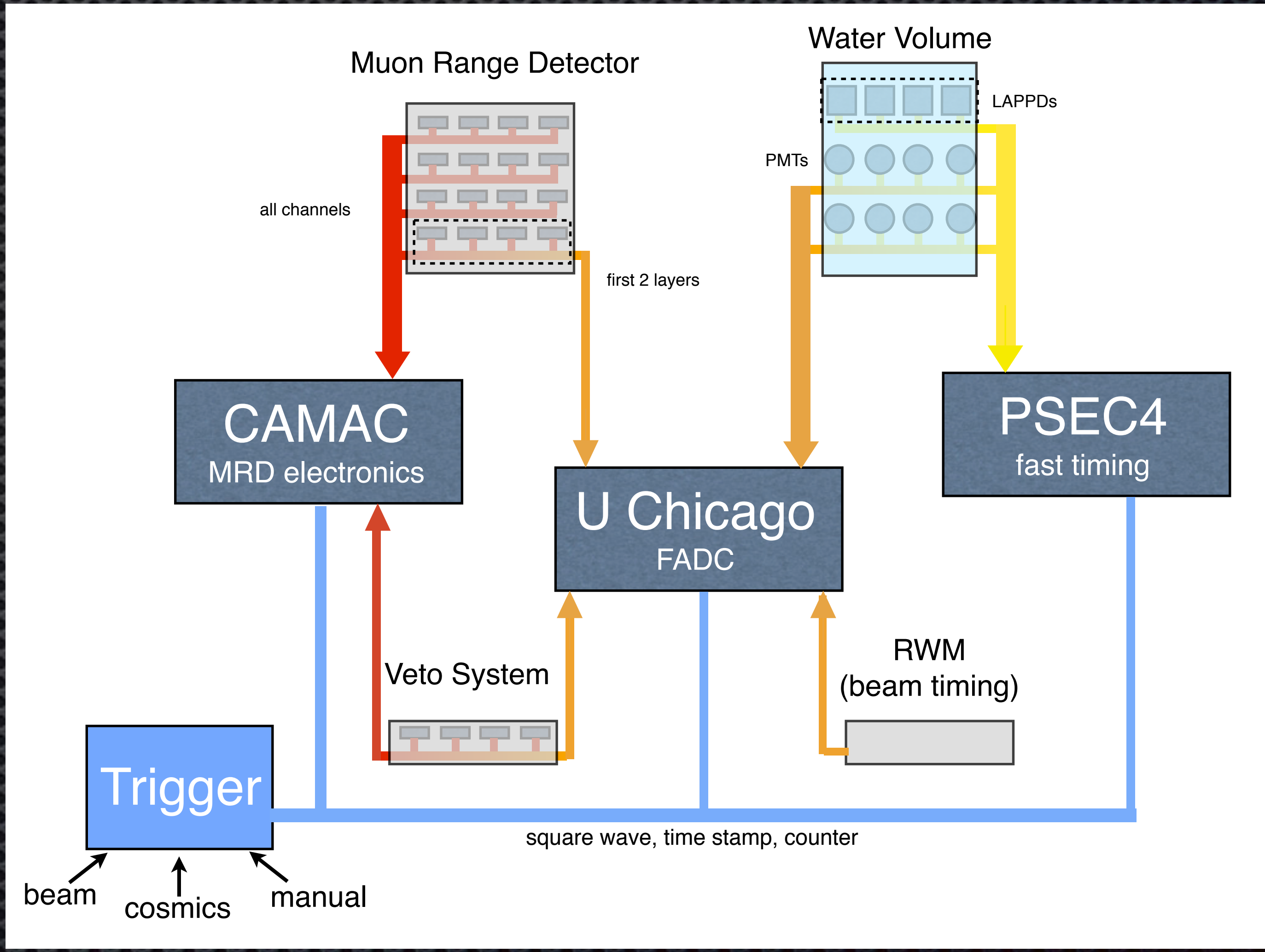


credit: Brooke Adams



LAPPD R&D for ANNIE and beyond

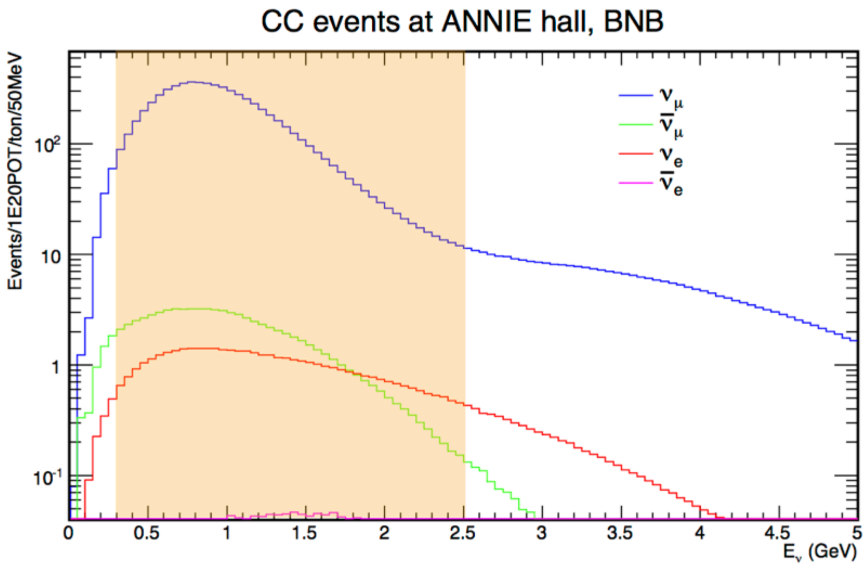
- A working 240 channel DAQ system with self-triggering already exists, thanks to the U Chicago optical TPC (E. Oberla, H. Frisch, M. Bogdan).
- The next step is to generalize to higher channel counts and integrate LAPPDs with more complicated detector systems.
- The ANNIE electronics group (ISU, UChicago, Queen Mary) is developing a dual readout system for digitizing both the conventional PMTs and LAPPDs.



Beam rates and requirements

We need 3 things in a beam:

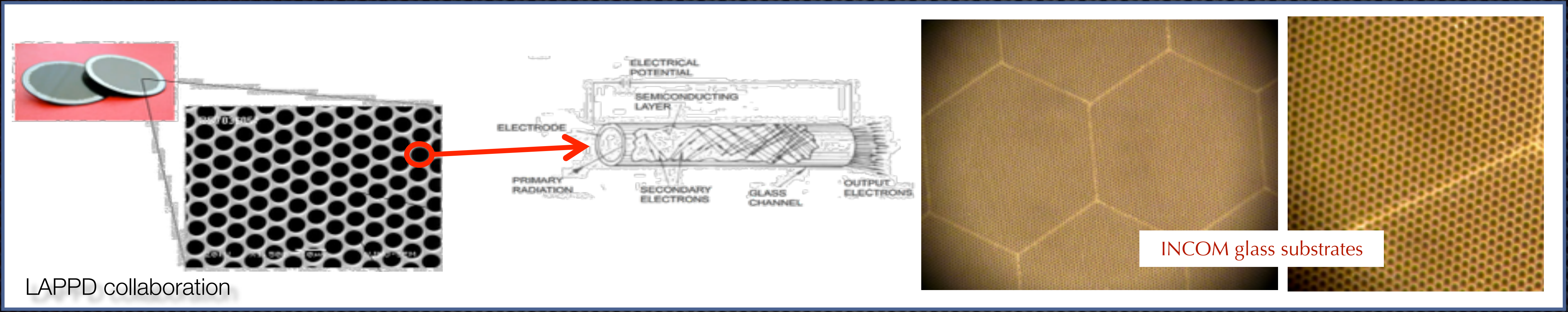
- Energy peaked in the range of the proton mass/atmospheric neutrino flux (1-2.5 GeV)
- Statistics
- Low pileup rate



Location	ν_μ CC [0.25-2.5 GeV]	ν_μ CC [0-10 GeV]	Percentage
SciBooNE Hall	6626	6991	95%
SciBooNE surface	708	847	84%
MINOS ND	3362	168078	2%
NOvA ND	8115	12074	67%
NDOS	76	91	84%

events/ton/10^{20} POT

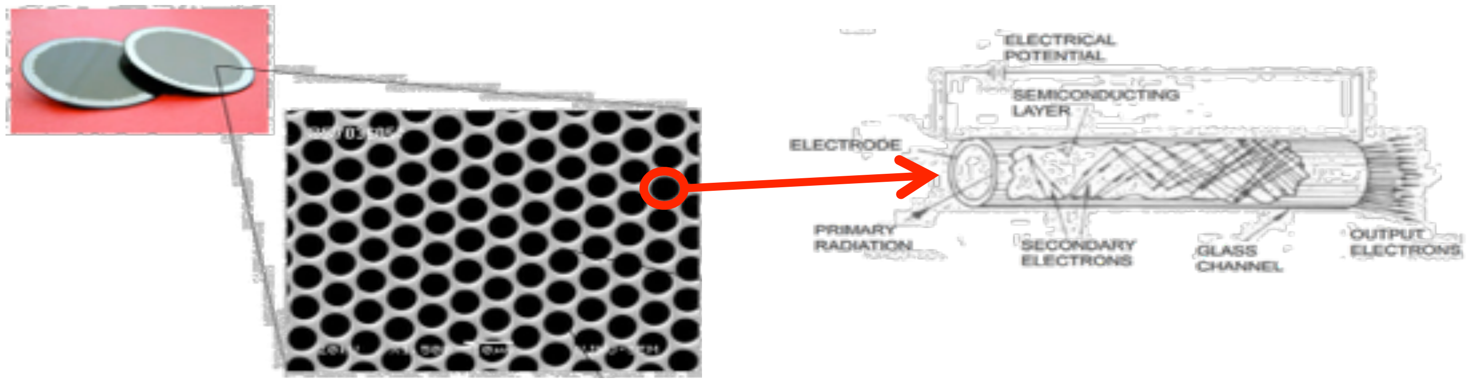
Key innovation: large micro-channel plates



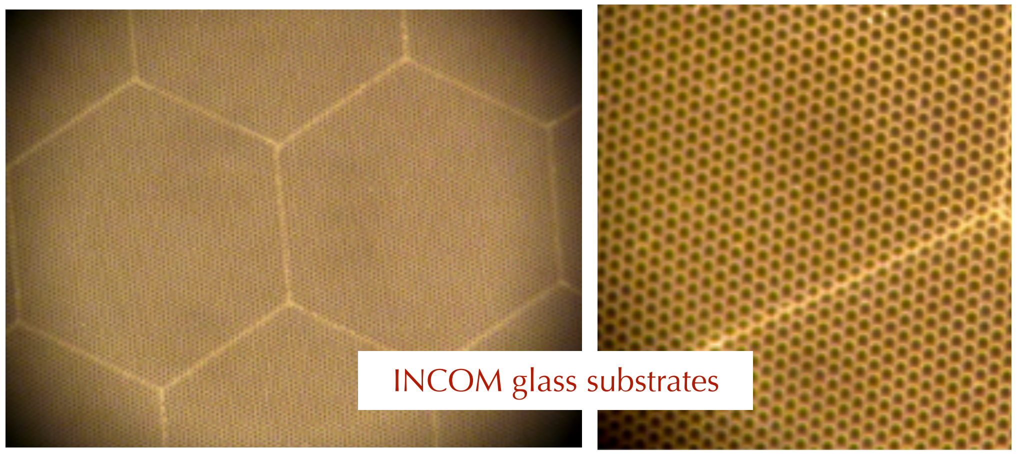
- Conventional MCP Fabrication:
  - Pore structure formed by slicing lead-glass fiber bundles. The glass also serves as the resistive material.
  - Chemical etching and heating in hydrogen to improve secondary emissive properties.
  - Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties.
- Approach for LAPPD:
  - Separate out the three functions: resistive, emissive and conductive coatings.
  - Handpick materials to optimize performance.
  - Use Atomic Layer Deposition (ALD), a cheap industrial batch method.

Approach demonstrated for 8-inch tiles

Key innovation: large micro-channel plates



LAPPD collaboration



- Conventional MCP Fabrication:
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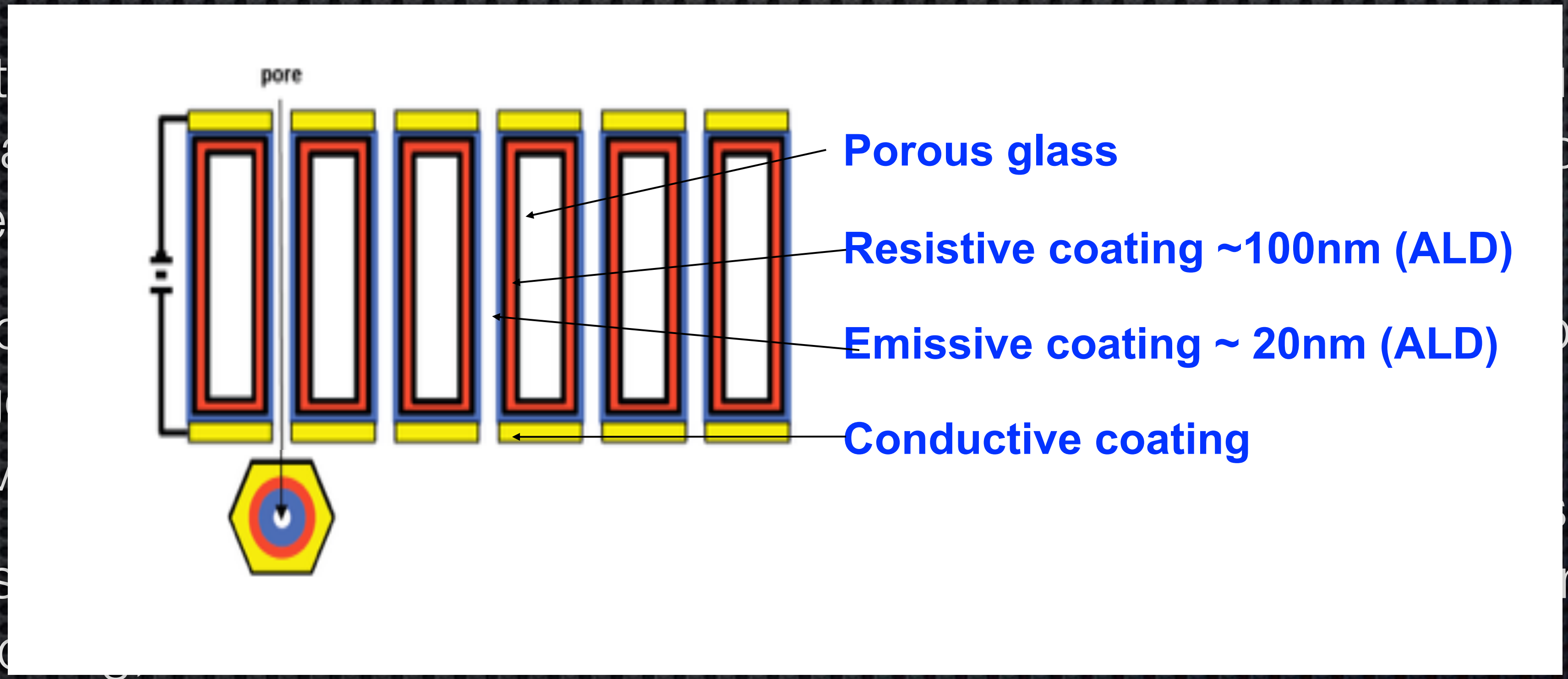
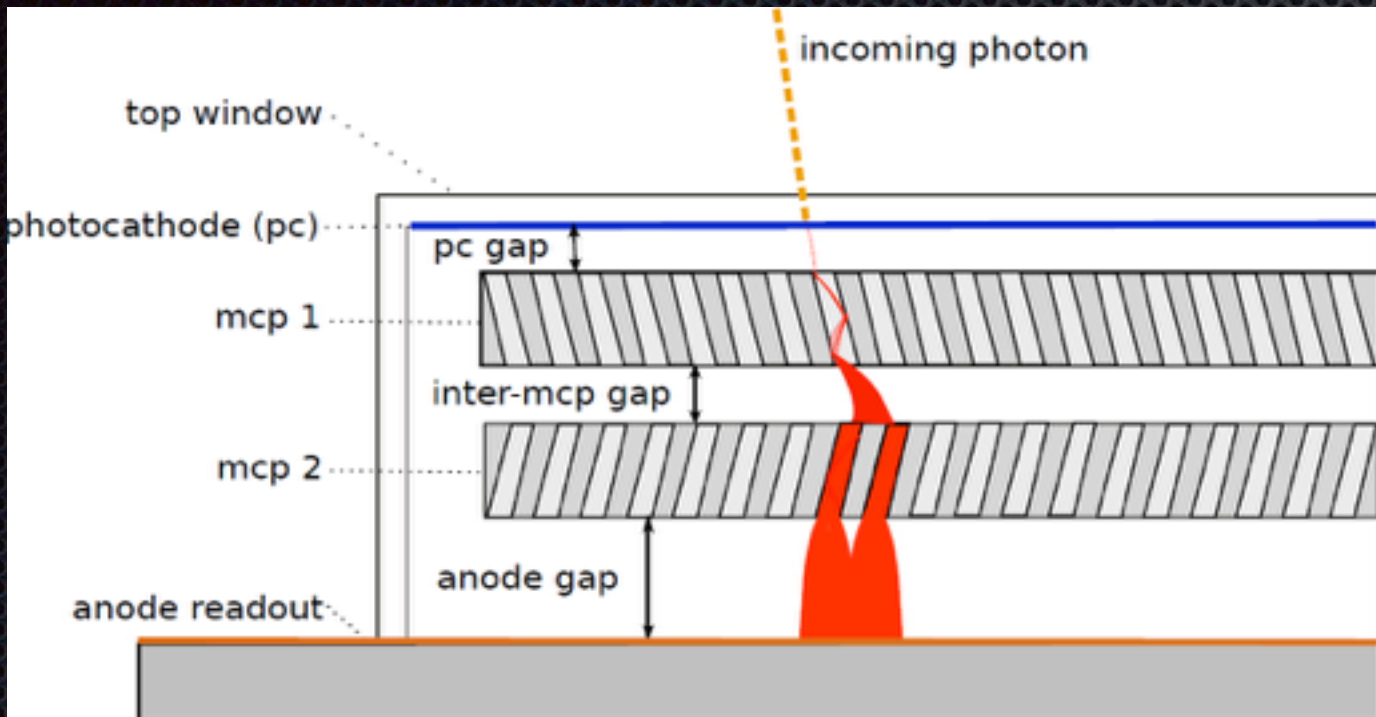
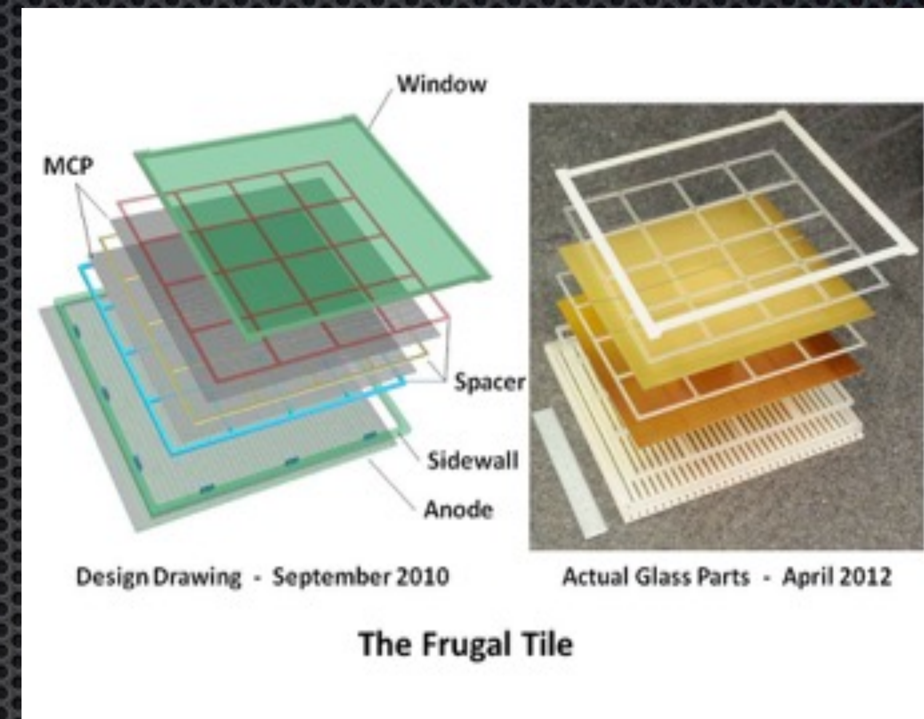


- Approach for LAPPD:
  nctions:
  onductive
  timize
  ition (ALD),
  method.

Approach demonstrated for 8-inch tiles

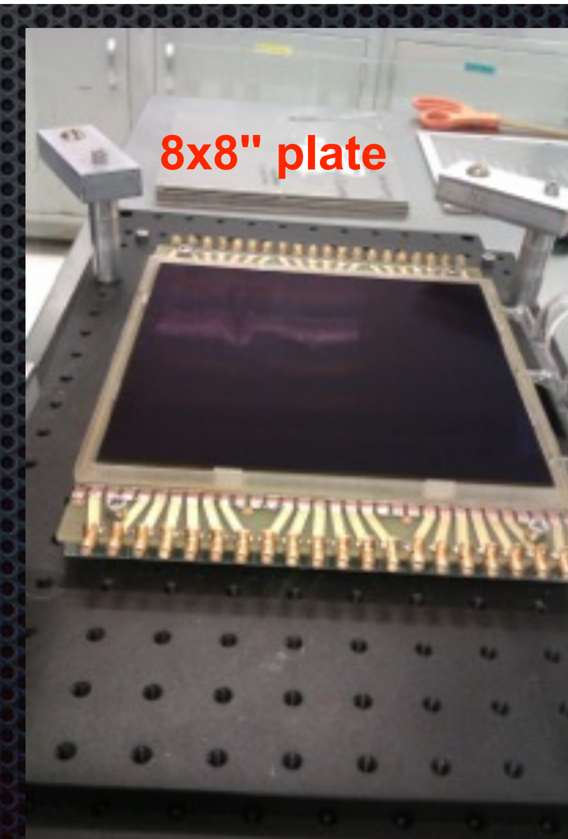
The 8-inch LAPPD glass tile





- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable

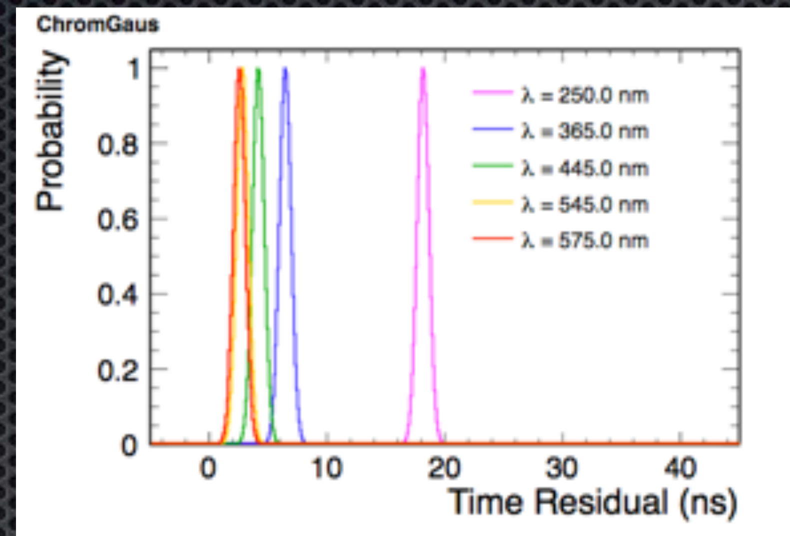
- Modular design
- Designed for fast timing
- Alternative more traditional ceramic packaging developed at Berkeley/SSL.

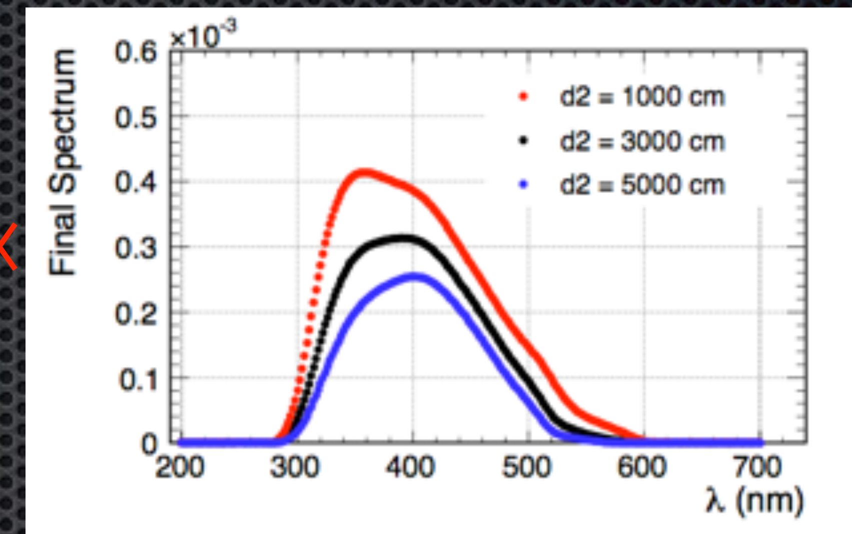


Packaging is to some extent application specific

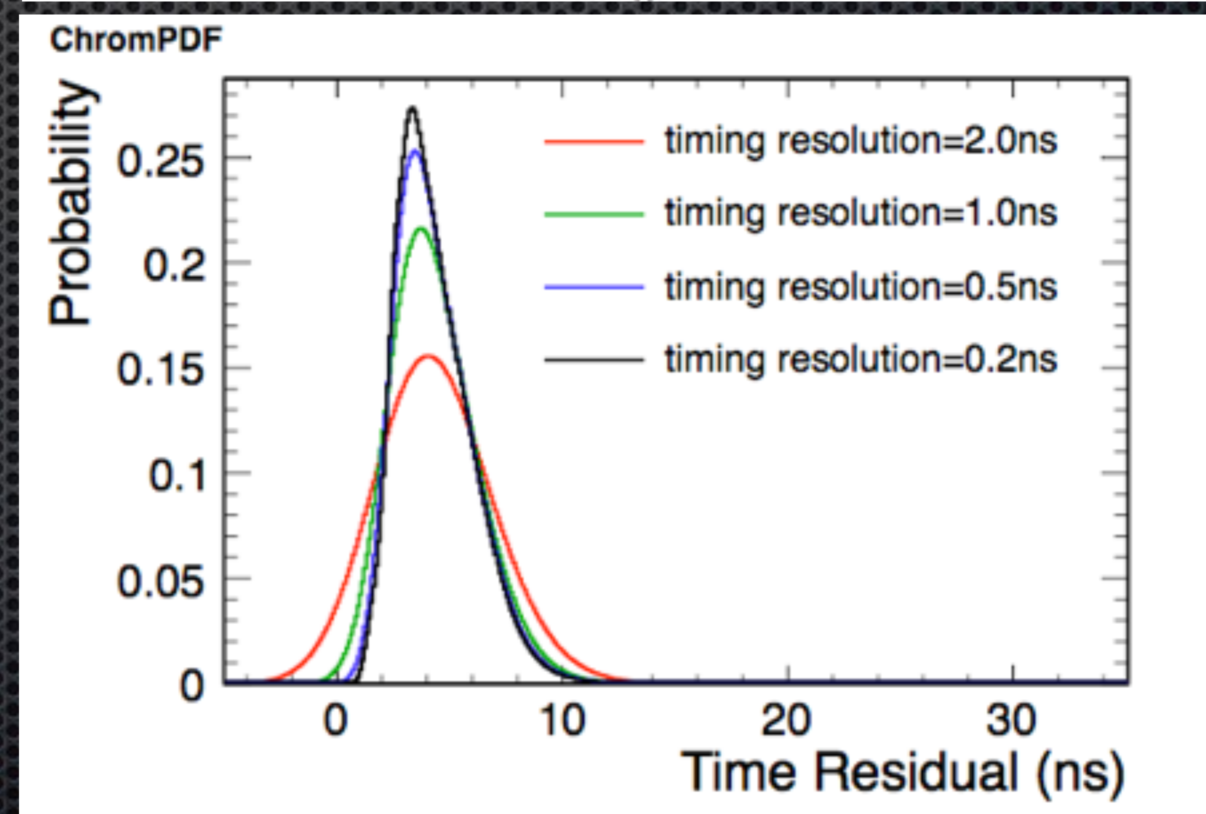
Using Time Residuals

- We build a timing residual-based fit assuming an extended track.
- The 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 LAPPDs, we fit each photon rather than fitting integrated charge for each PMT.





$$\mathrm{ChromPDF}(\lambda, \mathrm{d}) = \frac{\sum_\lambda \mathrm{ChromGaus}(\delta t(\lambda), \mathrm{d}) \times \mathrm{FinalSpectrum}(\lambda, \mathrm{d})}{\sum_\lambda \mathrm{FinalSpectrum}(\lambda, \mathrm{d})}$$

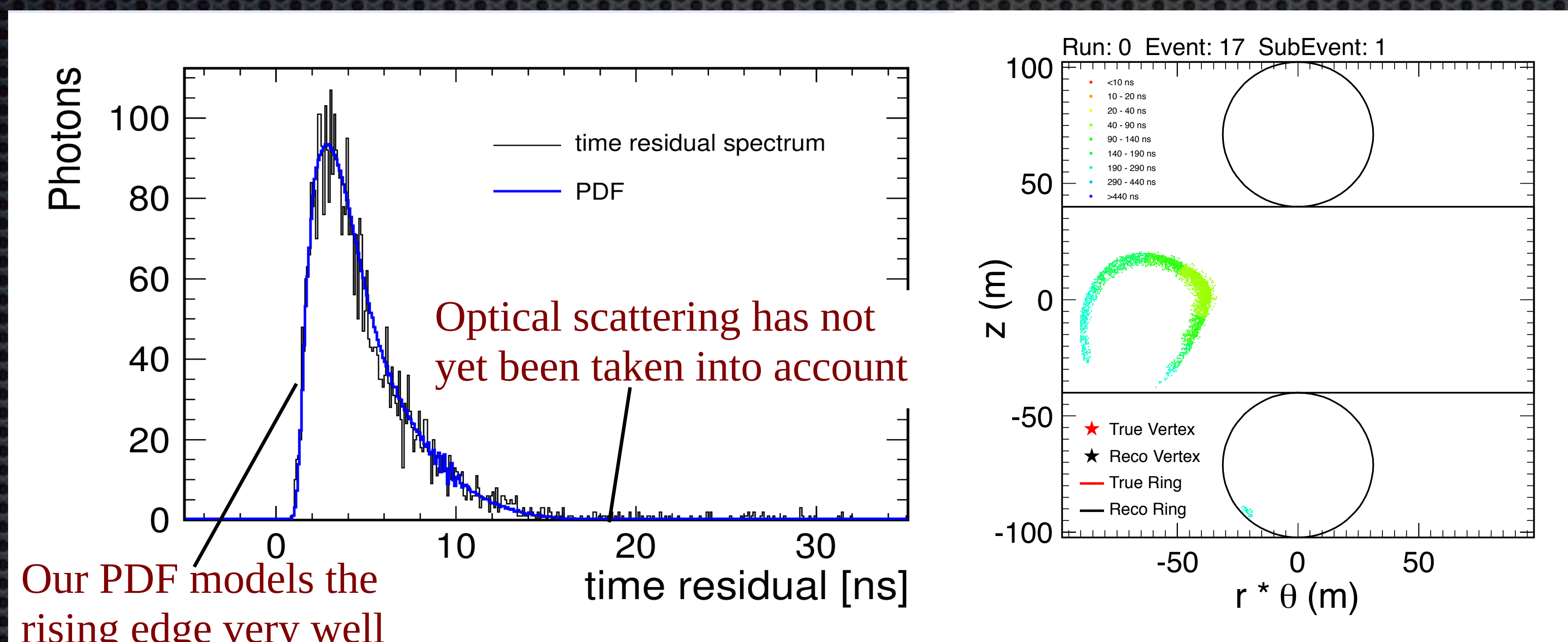


T. Xin, I. Anghel, M. Sanchez, M. Wetstein

Using Time Residuals

- Likelihood captures the full correlations between space and time of hits (not factorized in the likelihood).
- A simple window excludes any light that projects back to points far away from the vertex hypothesis.

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

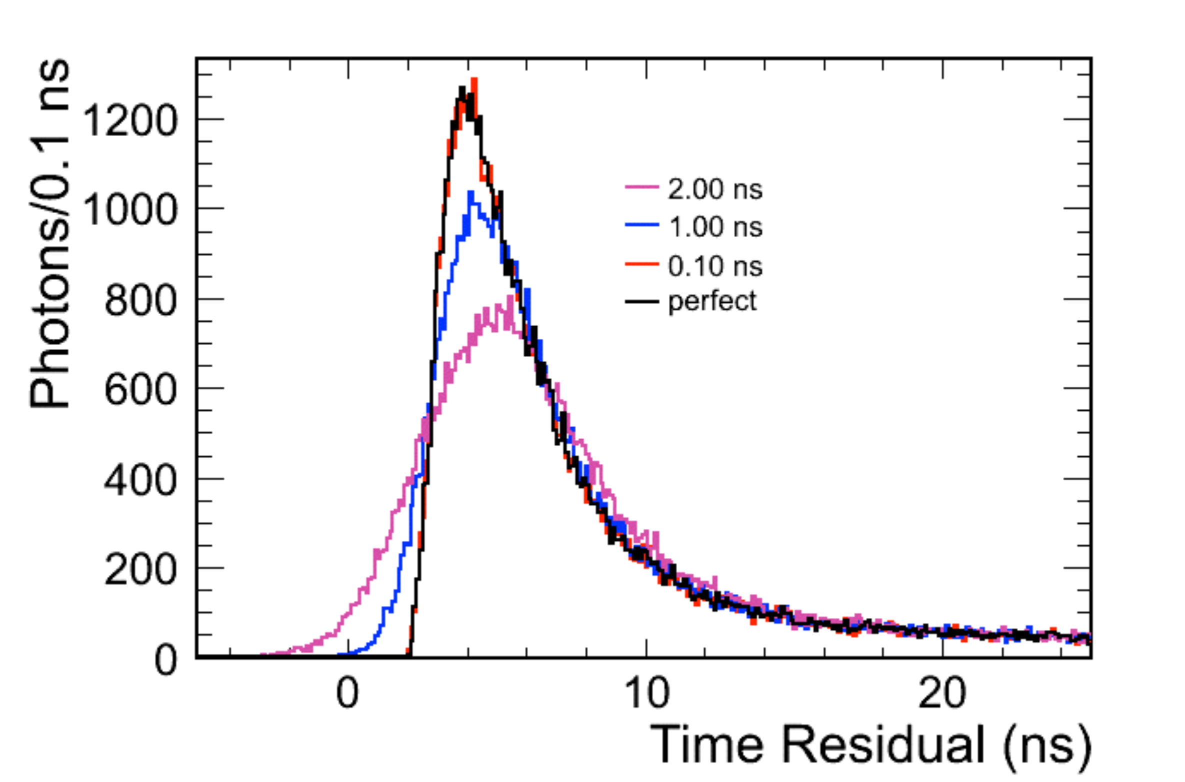


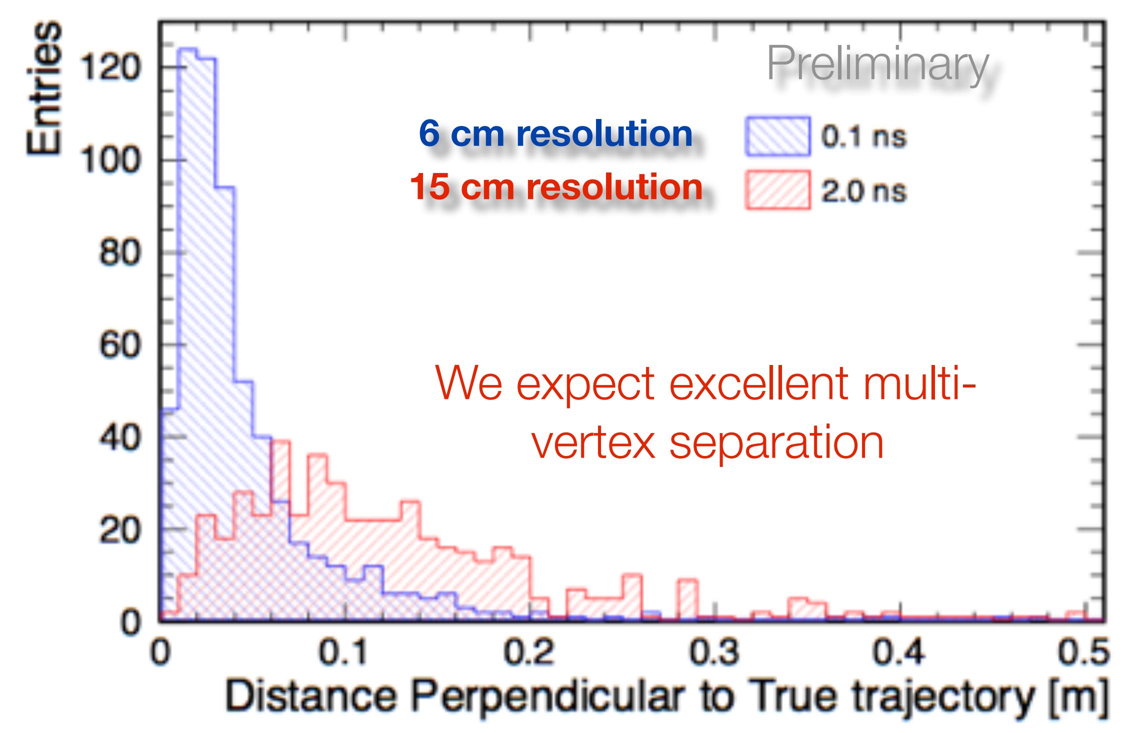
- It is not as sophisticated as full pattern-of-light fitting.
- However in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.

Using WCSim (C. Walter - Duke U.) simulation for these studies. Modifications in digitization appropriate for LAPPDs. Reconstruction developed within WCSimAnalysis framework used in LBNE Water Cherenkov design.

Using Time Residuals

- Our studies show that beyond 100 psec there are no gains to be had when using time residual distributions in a 200kton detector.
- If we use a 200 kton simulated detector with 13% photodetector coverage.
  - 1.2 GeV muons uniformly distributed.
  - Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.

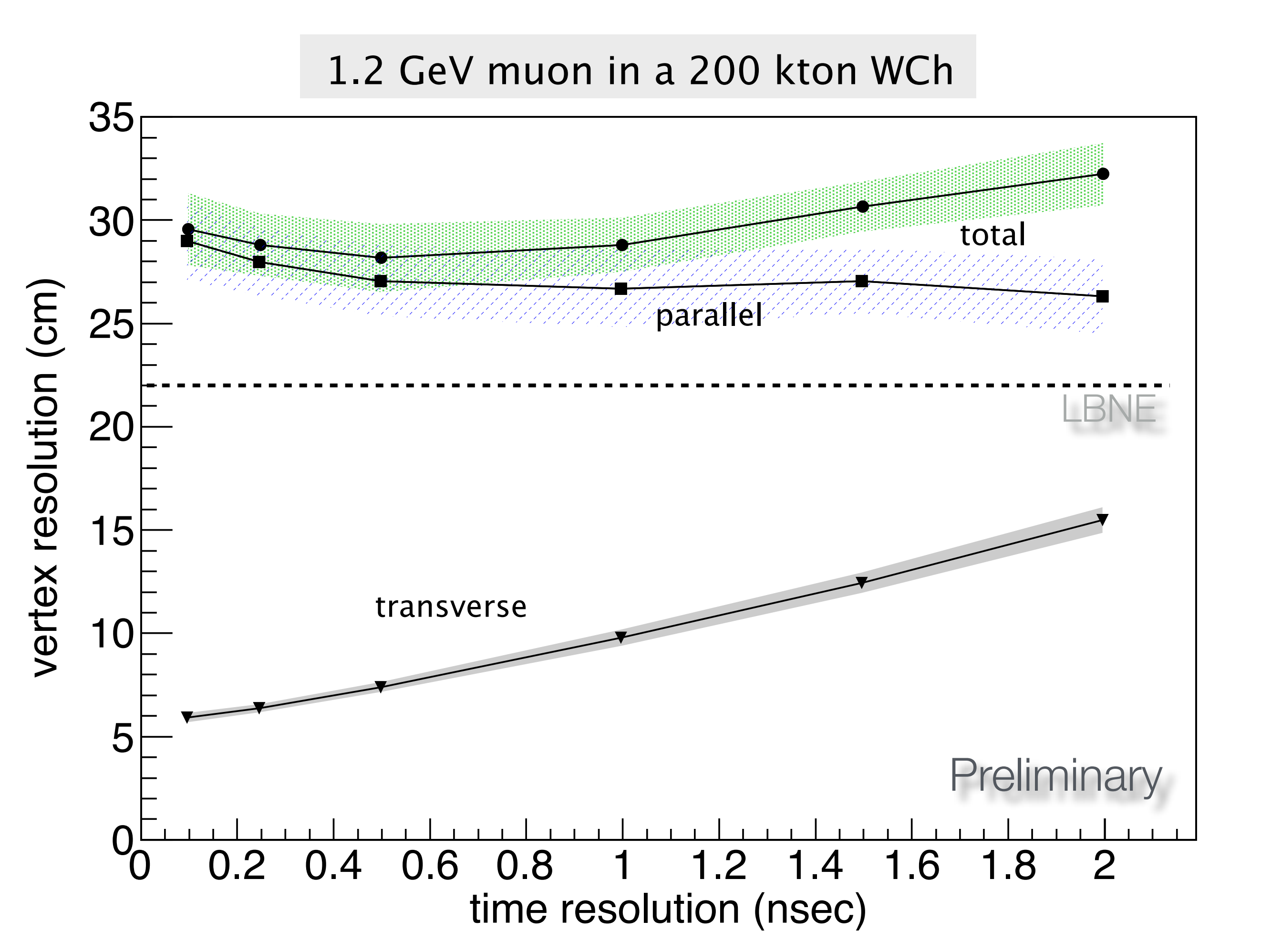




M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL), I. Anghel (ISU), E. Catano-Mur (ISU), T. Xin (ISU)

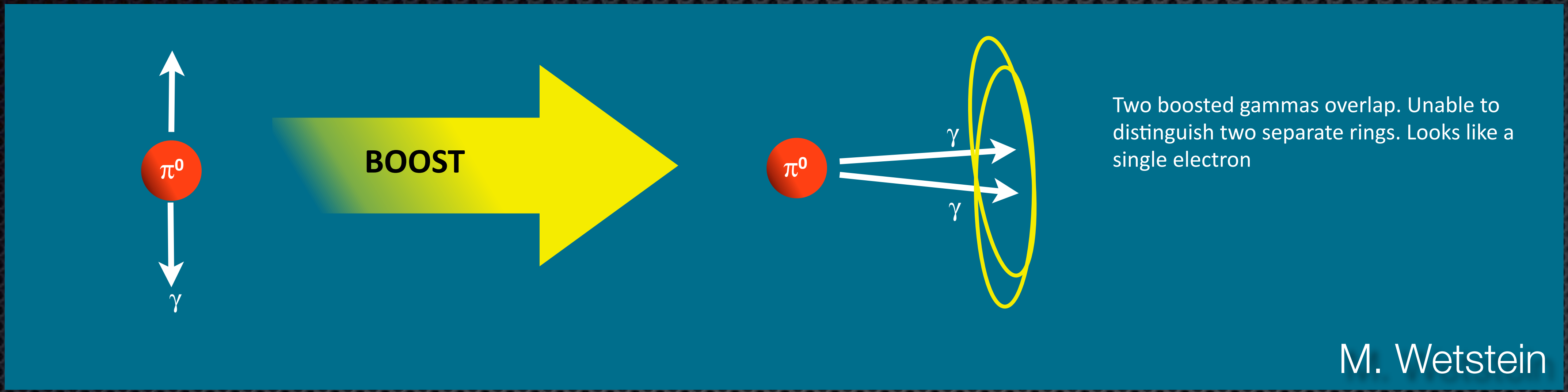
More Time Residuals results

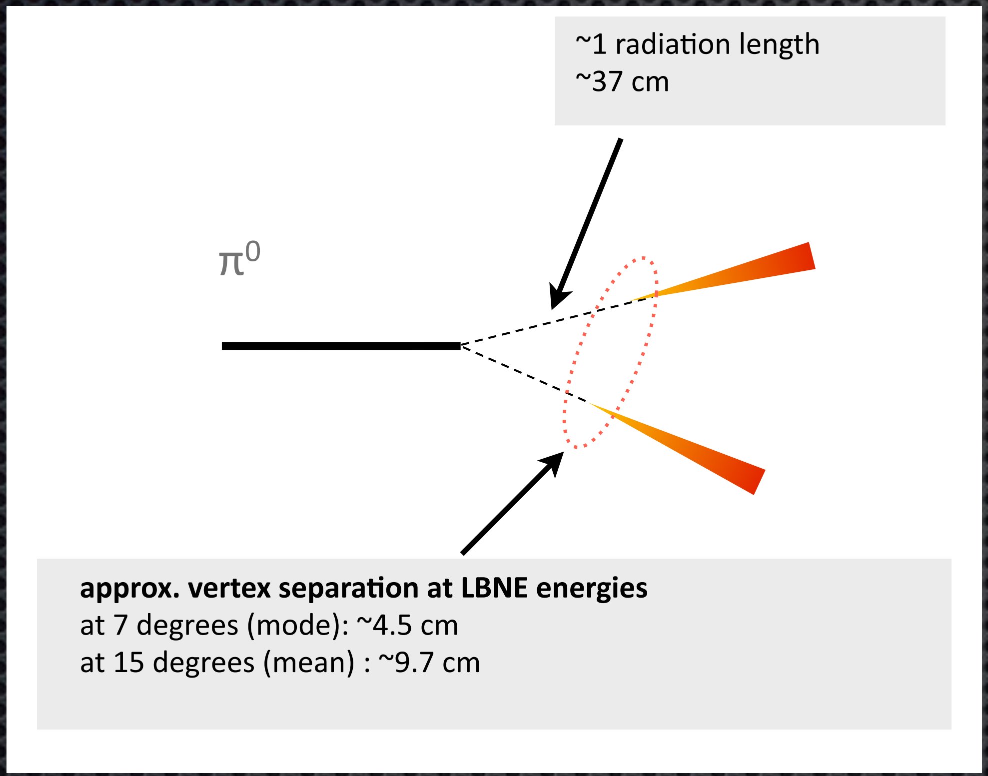
- Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.
  - Compare this vertex resolution to ~22 cm for LBNE WCh design using similar fits with no chromatic corrections and standard digitization.
- Based on pure timing, vertex position along the direction parallel to the track is unconstrained.
  - Must use additional constraint: fit the "edge of the cone" (first light).
  - Better algorithms using full pattern of light with better spatial resolution could help here.

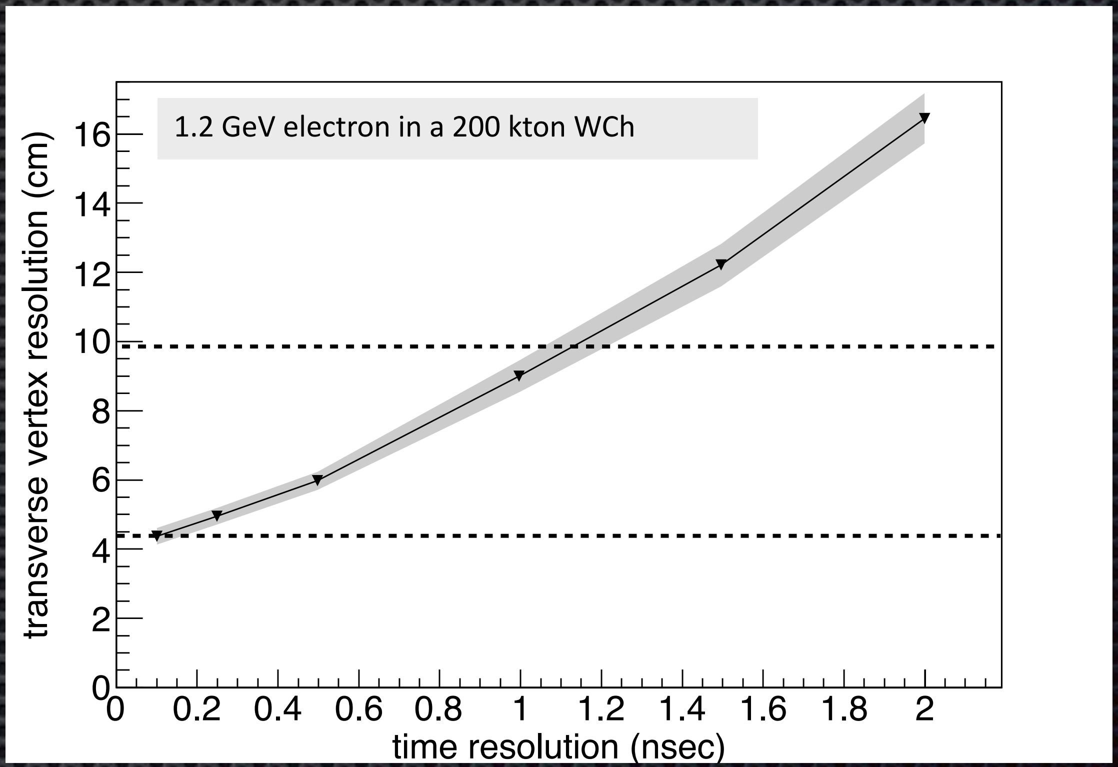


- Note that we also find that, for a given detector, the size of the uncertainties on the transverse vertex resolution scale with coverage consistent with $\sqrt{n}$.

Transverse vertex resolution



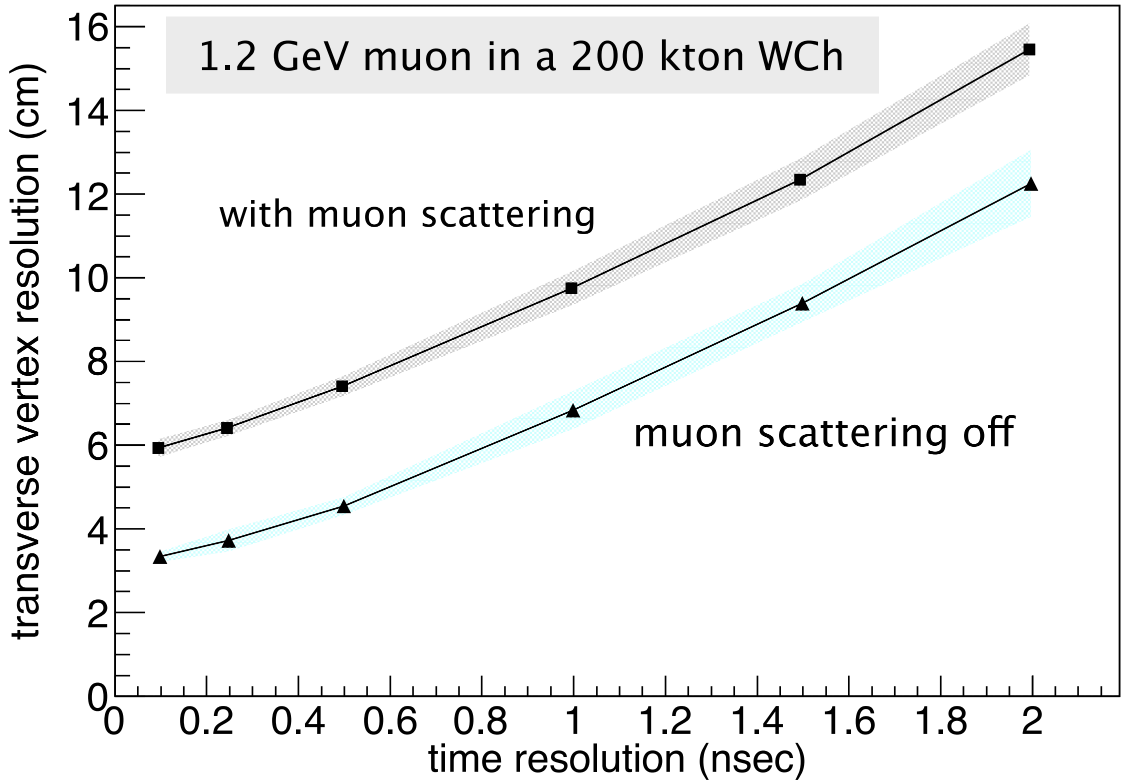


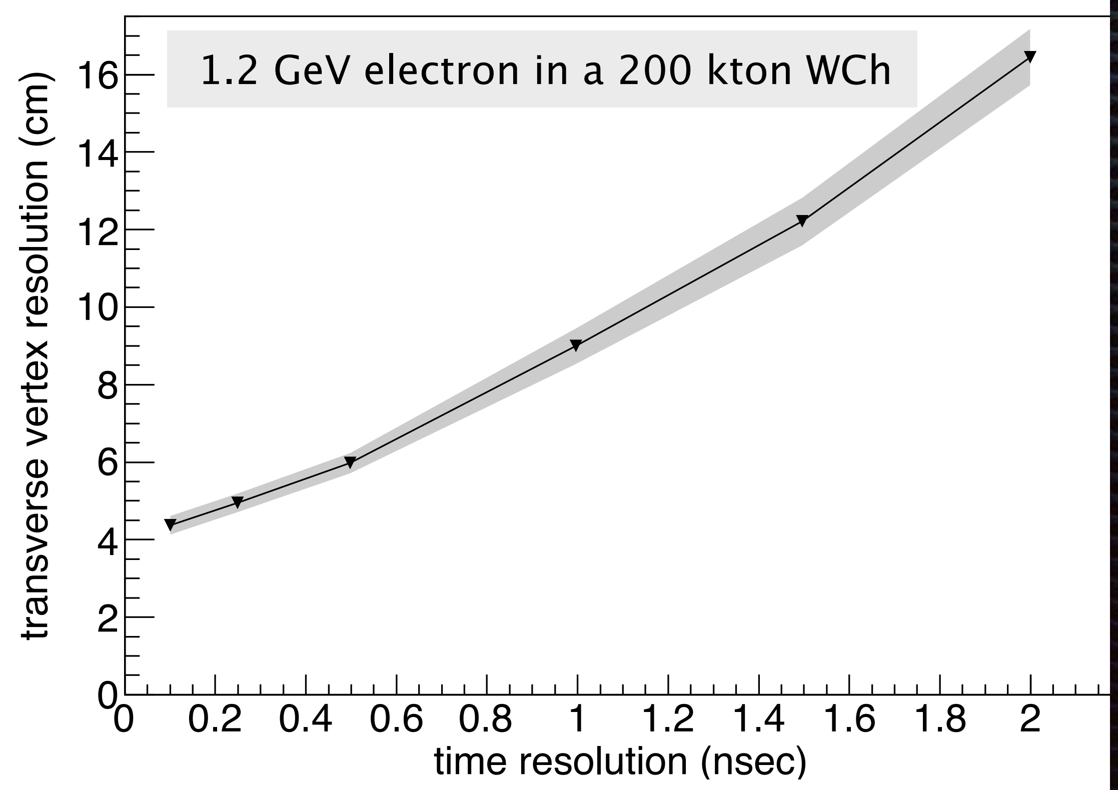


- Transverse vertex resolution is useful in rejection boosted neutral pions.
- Better time resolutions could help to cut deeper into this background.

Transverse vertex resolution

- Muon scattering is not a limiting factor for the gains observed.
- Electrons show slightly better vertex resolutions.

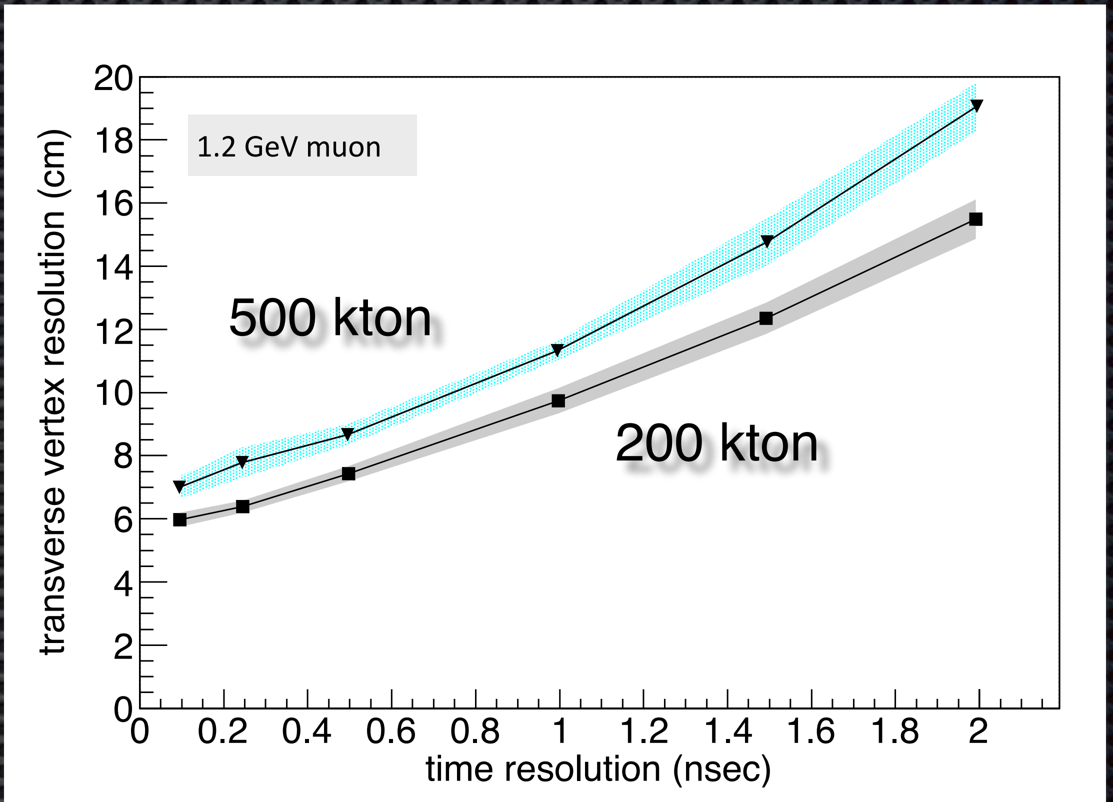


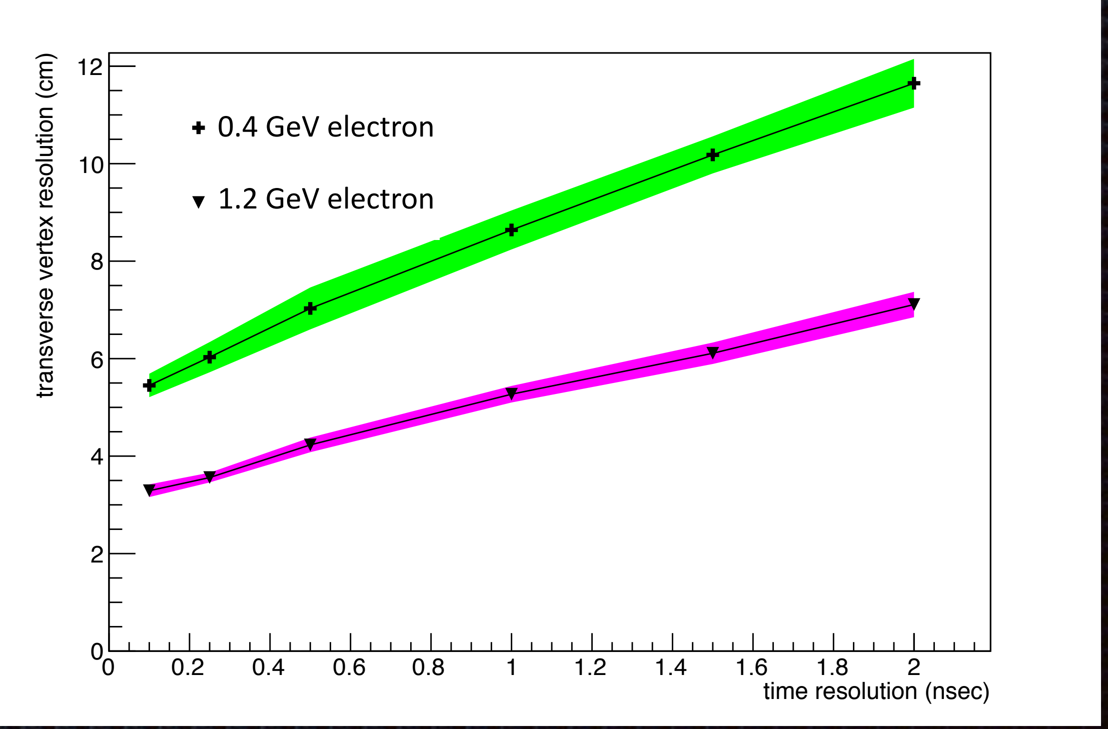


Other detector configurations

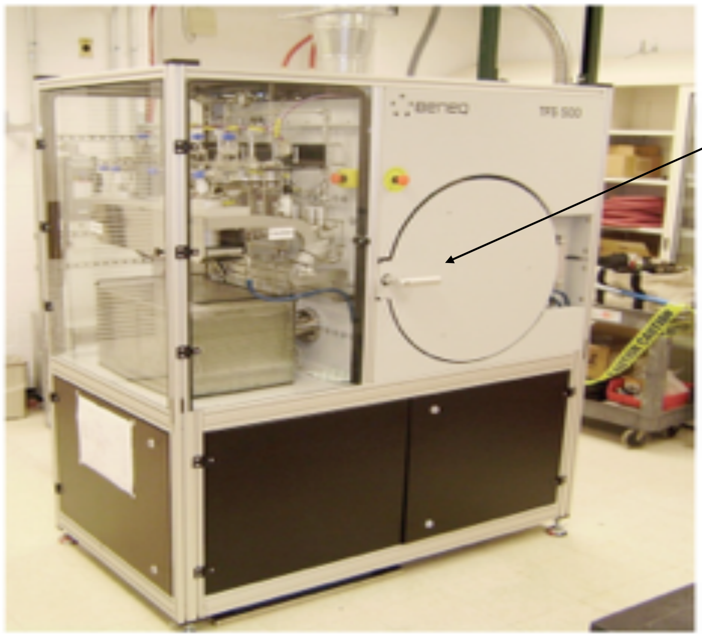
- Currently exploring a variety of detector configurations and particle energies.
- Gains are preserved going from 200 to 500 kiloton detectors. Shown for 1.2 GeV muons.
- Lower energies do have some resolution loss. Shown for 0.4 and 1.2 GeV electrons.

publication coming soon!

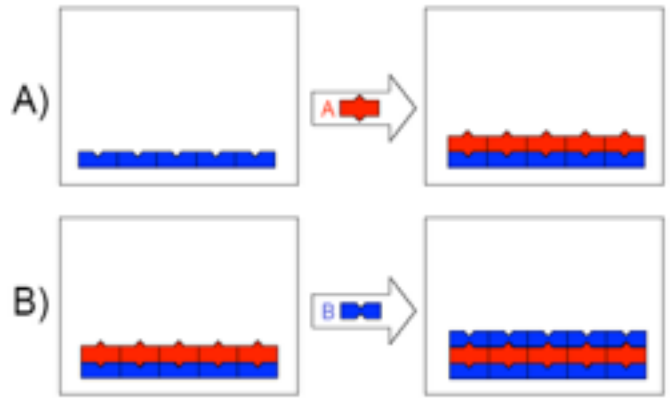


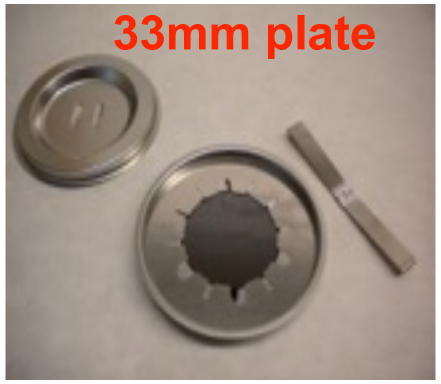


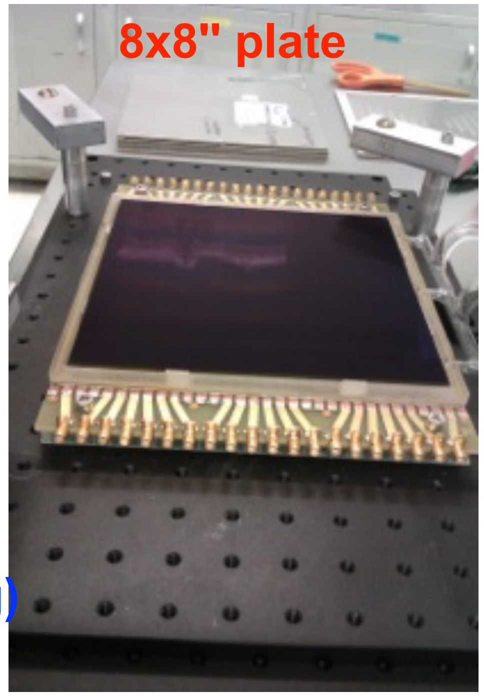
The MCP using Atomic Layer Deposition (ALD)

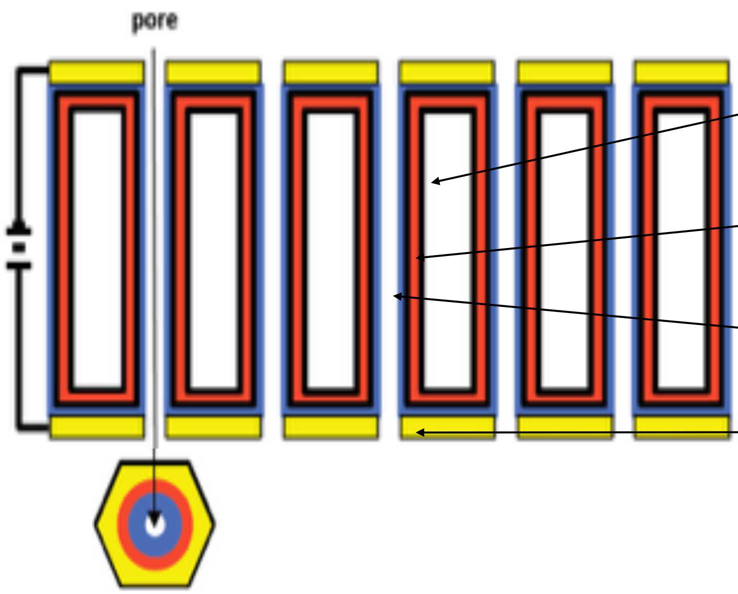


Beneq reactor for ALD
@Argonne National Laboratory
A.Mane, J.Elam









Porous glass

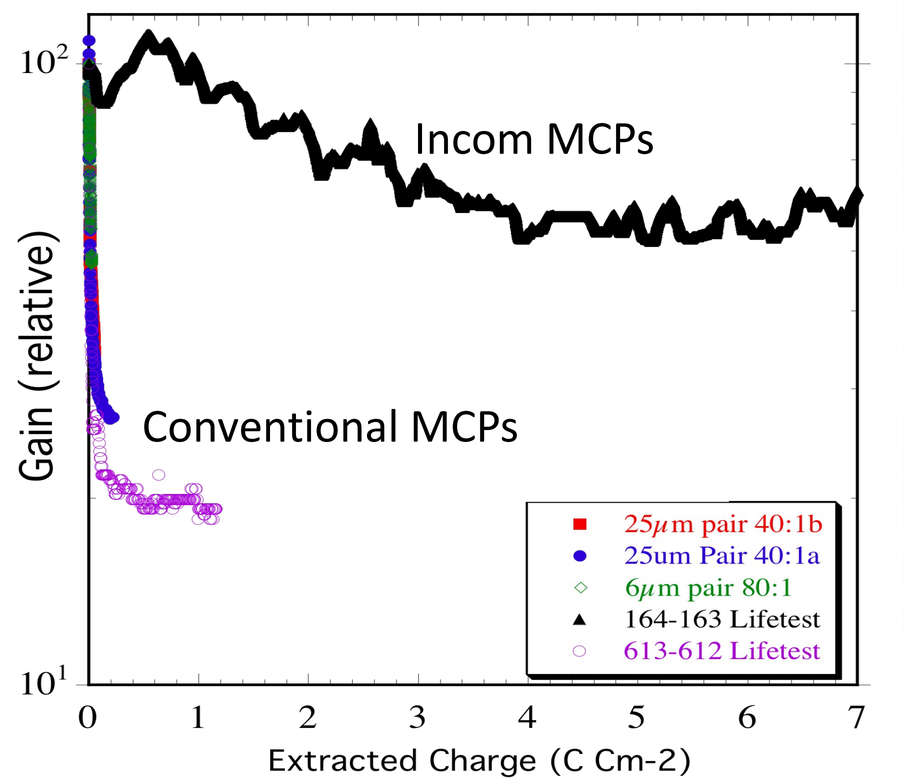
Resistive coating ~100nm (ALD)

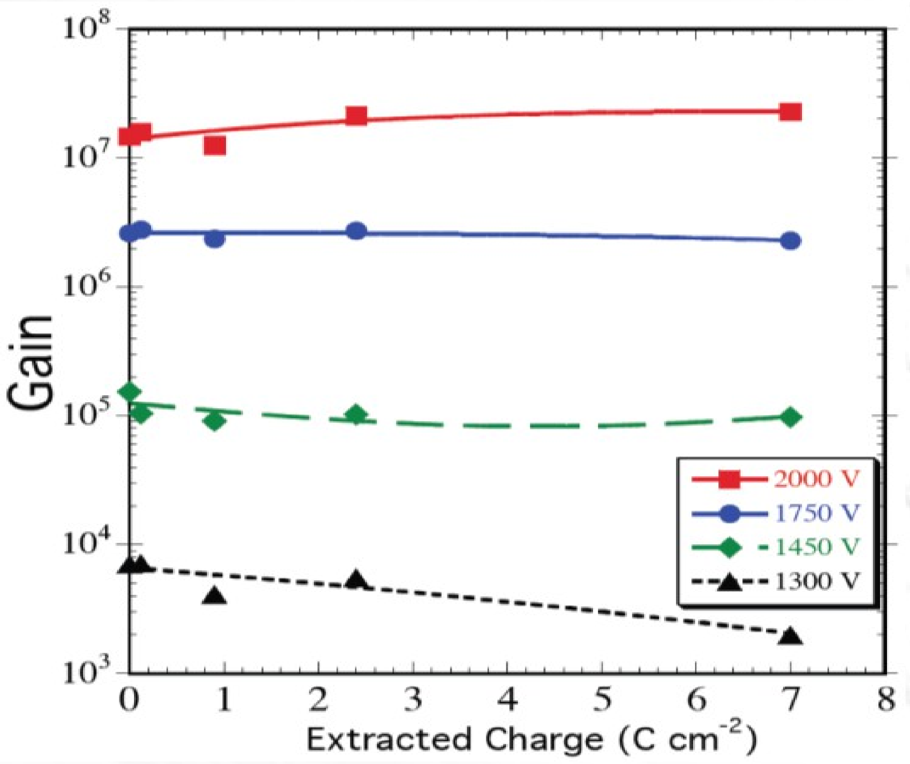
Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)

A. Elagin

Gain Stability





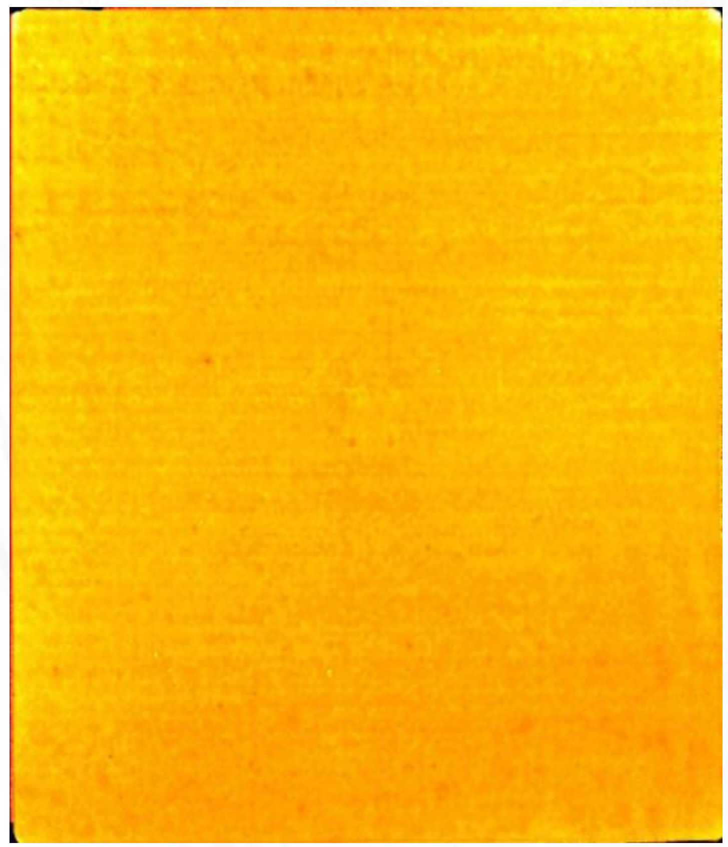
Conventional MCPs require an extensive "burn-in" to achieve a stable gain. Little burn-in is required for Incom MCPs.

O.H.W. Siegmund, J.B. McPhate, S.R. Jelinsky, J.V. Vallerga, A.S. Tremsin, R.Hemphill, H.J. Frisch, R.G. Wagner, J. Elam, A. Mane and the LAPPD Collaboration, "Development of Large Area Photon Counting Detectors Optimized for Cherenkov Light Imaging with High Temporal and sub-mm Spatial Resolution," NSS/MIC, IEEE.N45-1, pp.2063-2070 (2011)

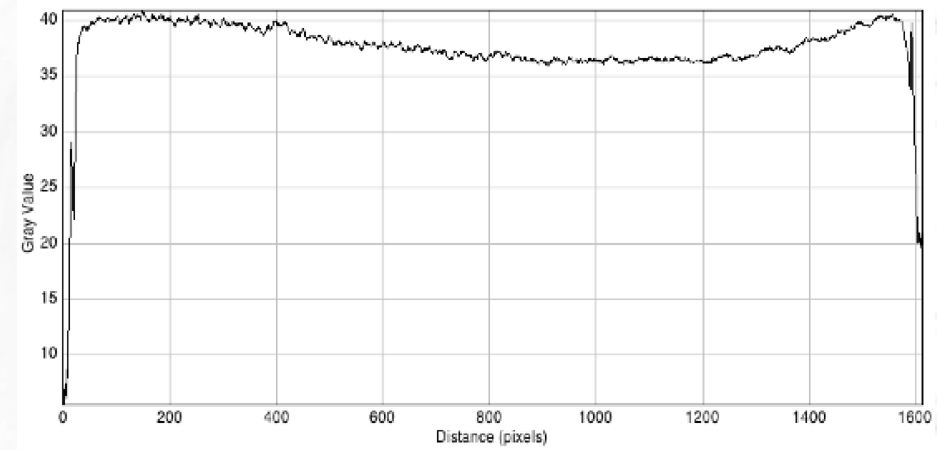
Gain is high and stable vs. extracted charge. Plot is of MCP gain at several fixed voltages during a "burn-in" test extracting 7 C/cm2 at ~3 μA output current for a pair of 33 mm, 60:1 L/D, 20 μm pore ALD MCPs.

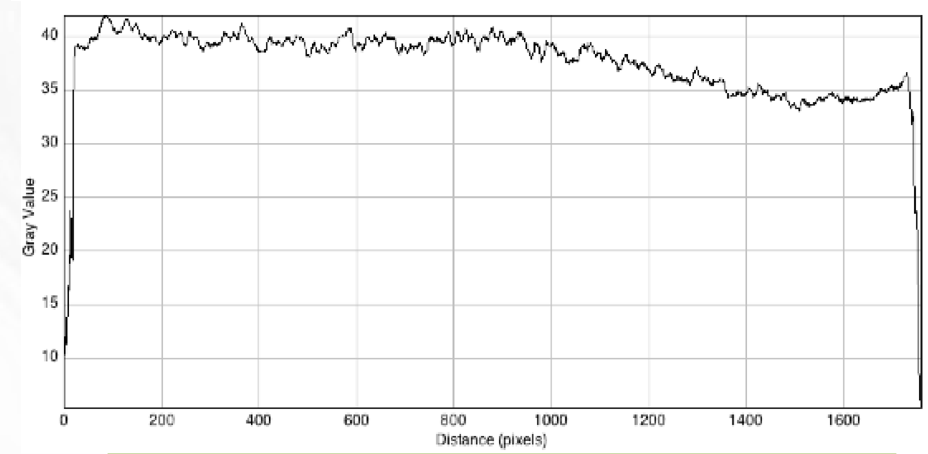
Oswald H. W. Siegmund, John V. Vallerga, Anton S. Tremsin, Jason B. McPhate, Xavier Michalet, Shimon Weiss, Henry Frisch, Robert Wagner, Anil Mane, Jeffrey Elam, Gary Varner, "Large Area and High Efficiency Photon Counting Imaging Detectors with High Time and Spatial Resolution for Night Time Sensing and Astronomy," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, in press, (2012).

Gain Uniformity



Gain map image for a pair of 20 µm pore, 60:1 L/D, ALD borosilicate MCPs, 950 V per MCP, 184 nm UV





Gain is uniform within ~15% across full 20 x 20 cm^2 area

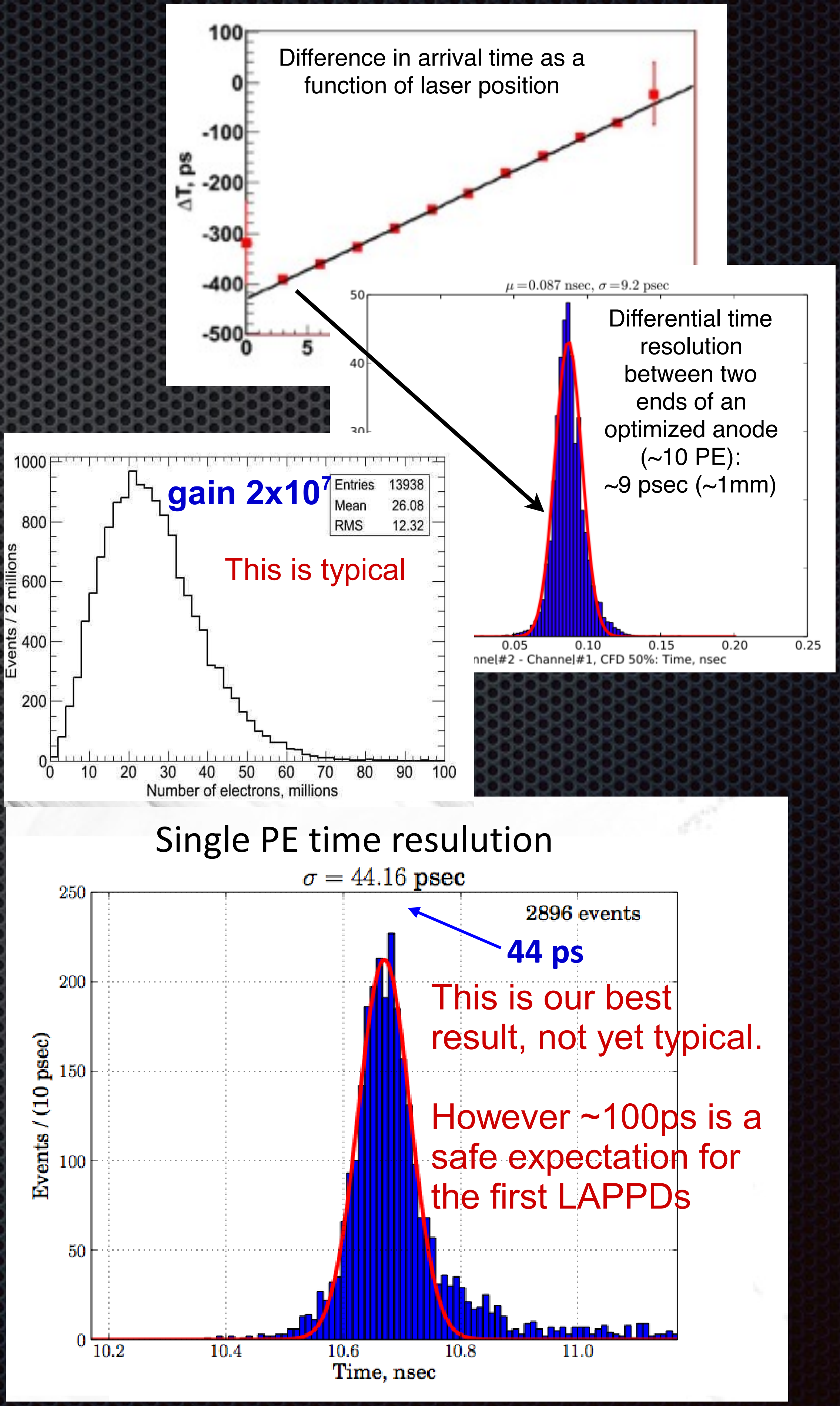
O.H.W. Siegmund, N. Richner, G. Gunjala, J.B. McPhate, A.S. Tremsin, H.J. Frisch, J. Elam, A. Mane, R. Wagner, C.A. Craven, M.J. Minot, “Performance Characteristics of Atomic Layer Functionalized Microchannel Plates” Proc. SPIE 8859-34, in press (2013).

Also, very low noise: <0.1 counts cm^{-2} s^{-1}

a factor of ~4 lower compared to conventional MCPs

LAPPD Status

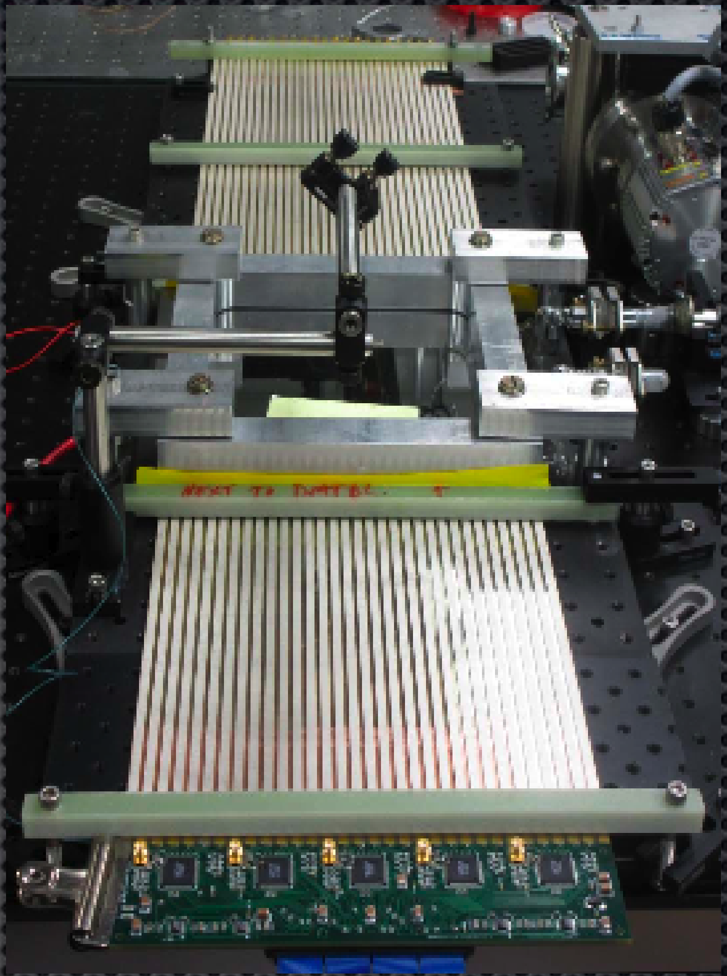
- Testing 8" x 8" (20 x 20 cm) MCPs:
  - Typical pulse height peaked at **2 x 10^7 gain**.
  - Differential time resolution between two ends of delay-line anode <10 psec.
  - **2 mm spatial resolution** parallel to the strip direction, <1 mm in transverse.
  - Best single PE **time resolution ~44 psec**. Order of 100 psec is safe expectation for first generation.
  - Tests of gain stability and uniformity also done. Demonstrating little burn is required to achieve stable gains.



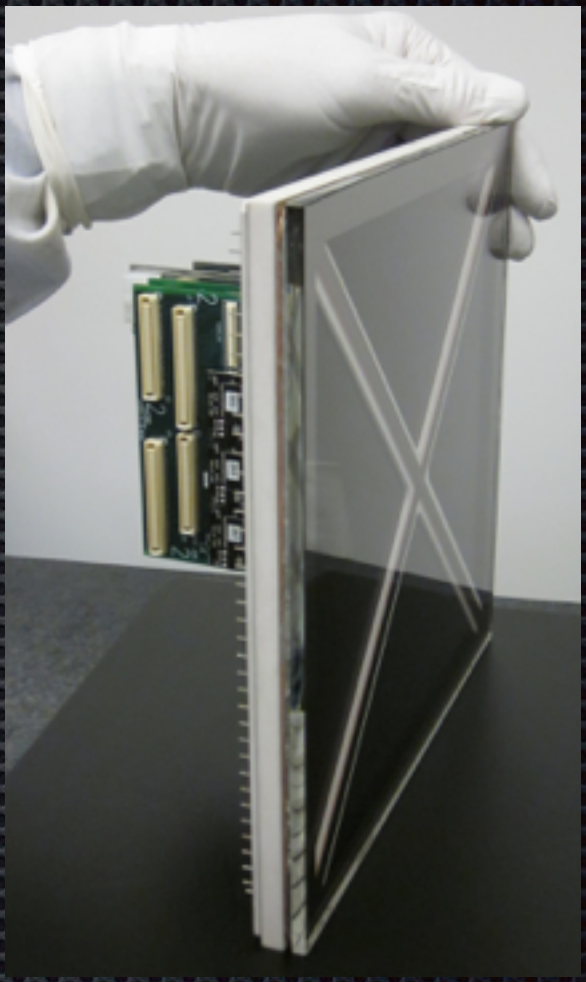
M. Wetstein (UChicago/ANL) and A. Elagin (UChicago)

LAPPD Status

- Tested end-to-end detector system:
  - "demountable" glass-body 8" MCP-detector with full readout and front-end electronics.
- An 8" Sealed-Tube processing tank at Berkeley SSL is being used to produce sealed tiles.
- An effort at UChicago for a lightweight in-situ assembly is also in progress.
- ANL has a setup to produce smaller 6x6 cm prototype tiles.



ANL "demountable" detector system - glass body LAPPD



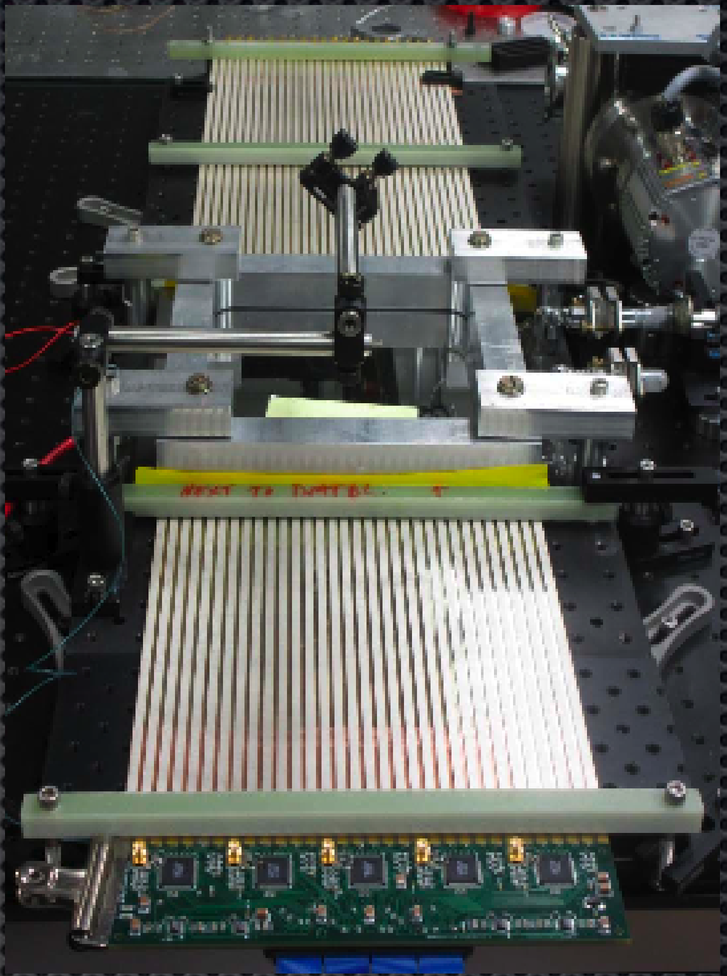
Berkeley SSL detector system- ceramic body LAPPD

UChicago lightweight in-situ assembly

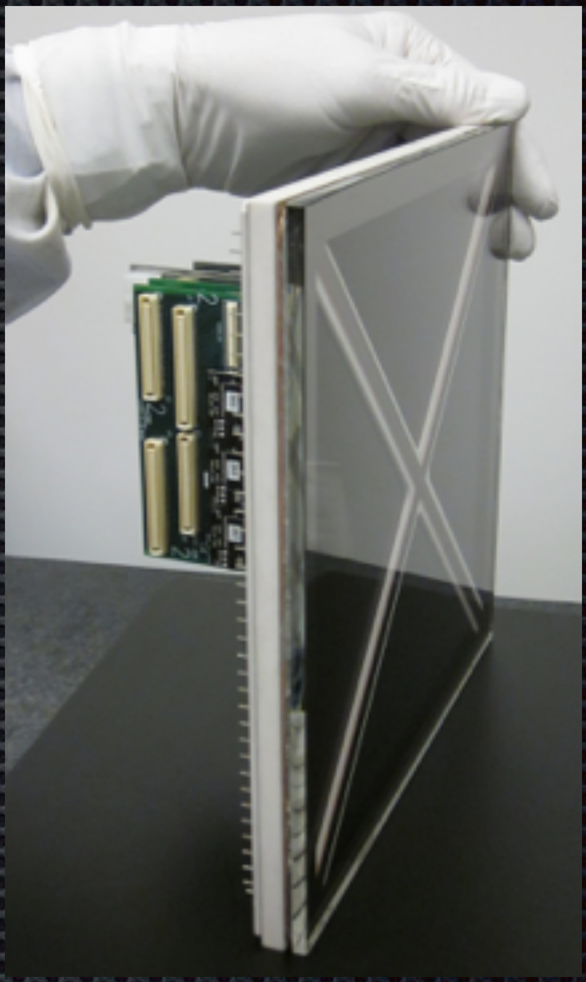
Berkeley SSL Sealed-Tube Processing Tank

LAPPD Status

- 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.
  - NIMA 735, (2014) 452-461. E.Oberla, J.-F. Genat, H. Frisch, K.Nishimura, G.Varner



ANL “demountable” detector system - glass body LAPPD



Berkeley SSL detector system- ceramic body LAPPD

- A pilot production line is being built at Incom Inc as part of a 3 year technology transfer program.
- SBIRs with different companies to improve performance of: photocathodes, electronics and micro-channel plates.

UChicago lightweight in-situ assembly

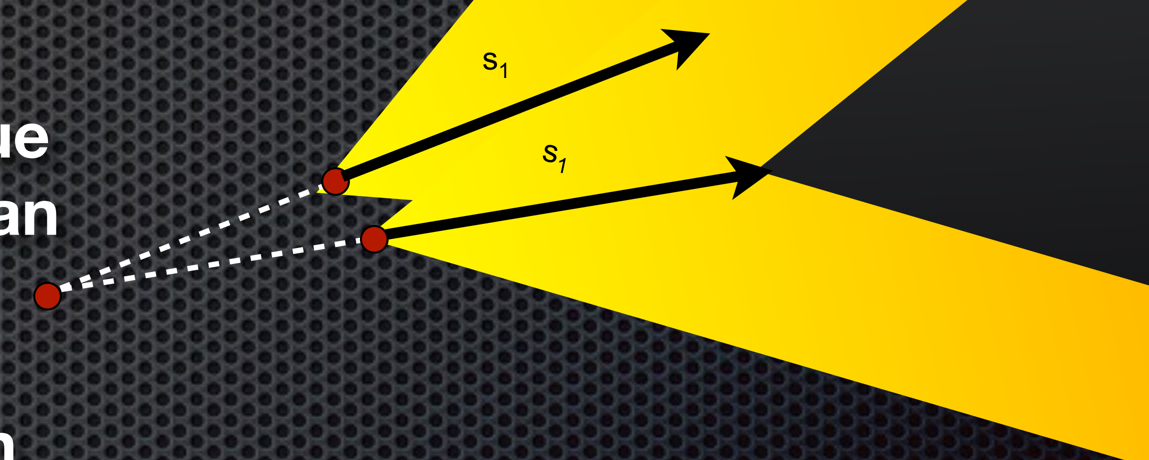
Berkeley SSL Sealed-Tube Processing Tank

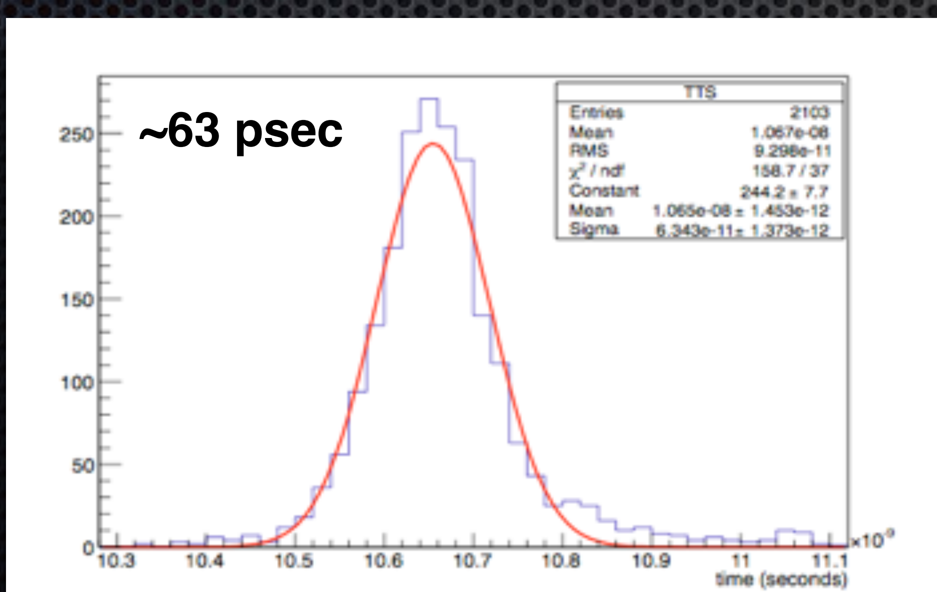
Timing-based vertex fitting

Fortunately, multi-vertex separation is a differential measurement.

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

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

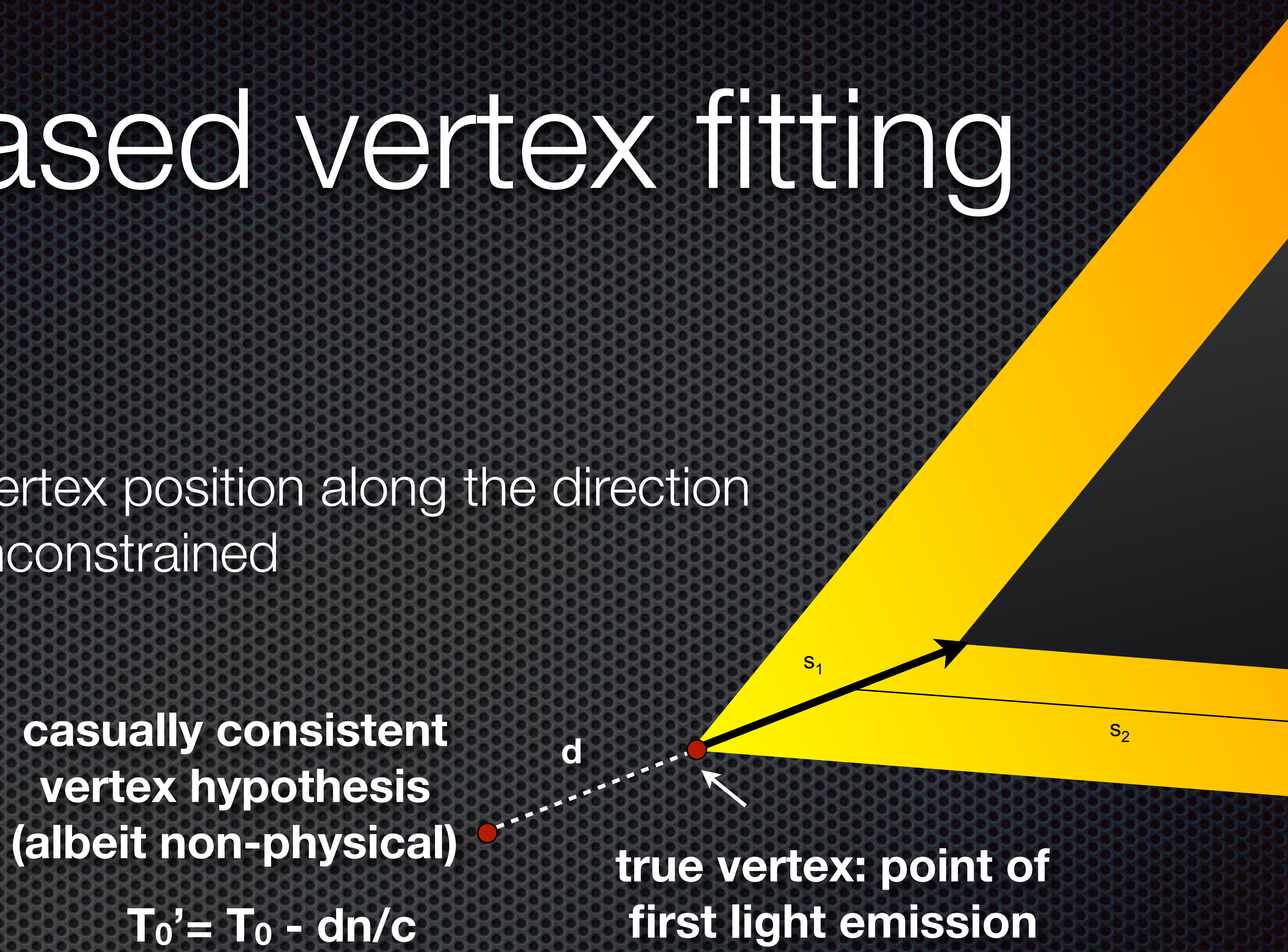




100 picoseconds ~ 2.25 centimeters

Timing-based vertex fitting

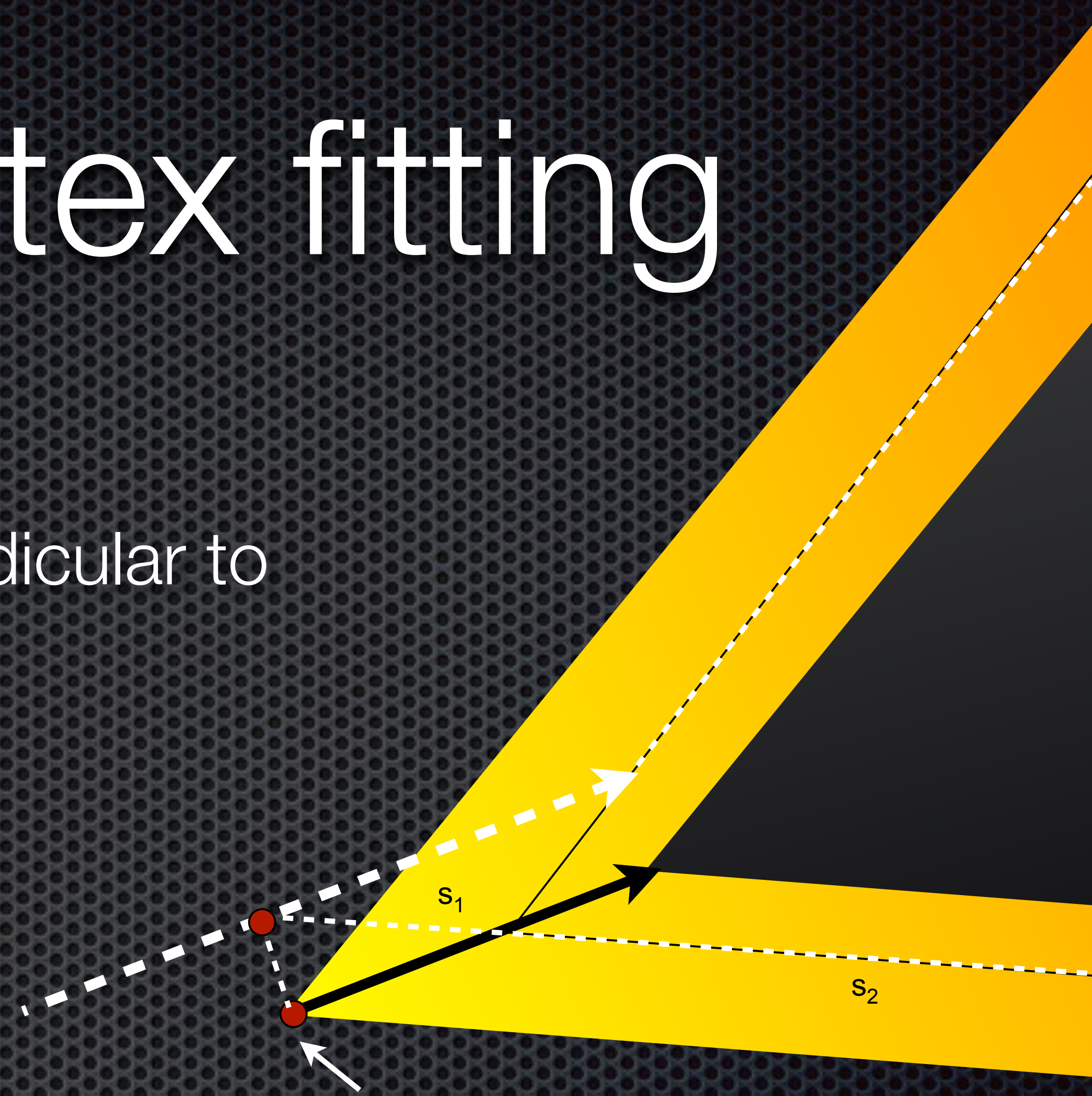
Based on pure timing, vertex position along the direction parallel to the track is unconstrained



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 (albeit non-physical)

$T_0' = T_0 - dn/c$

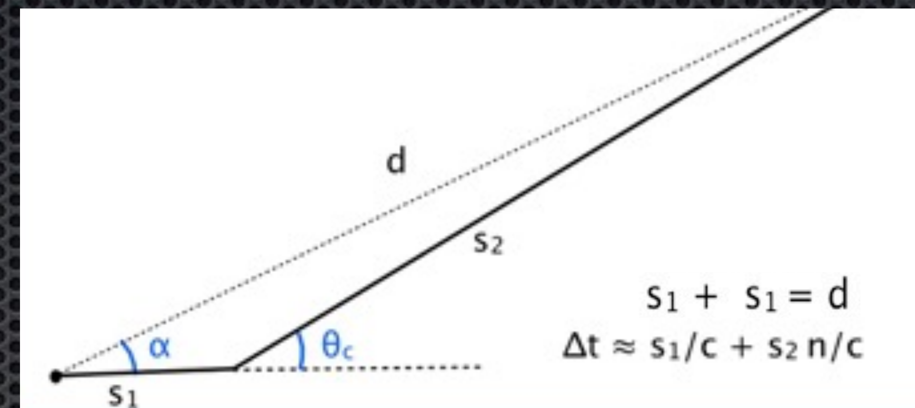
true vertex: point of first light emission

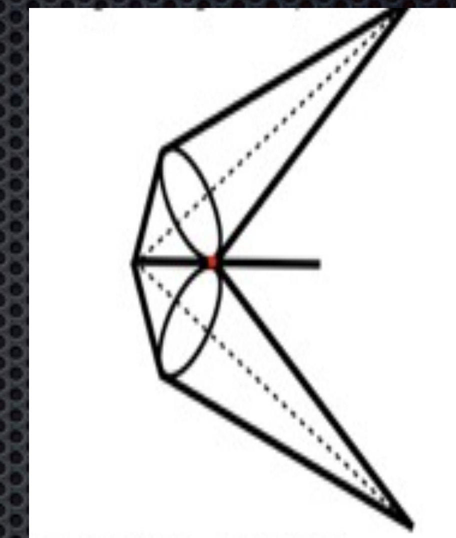
For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

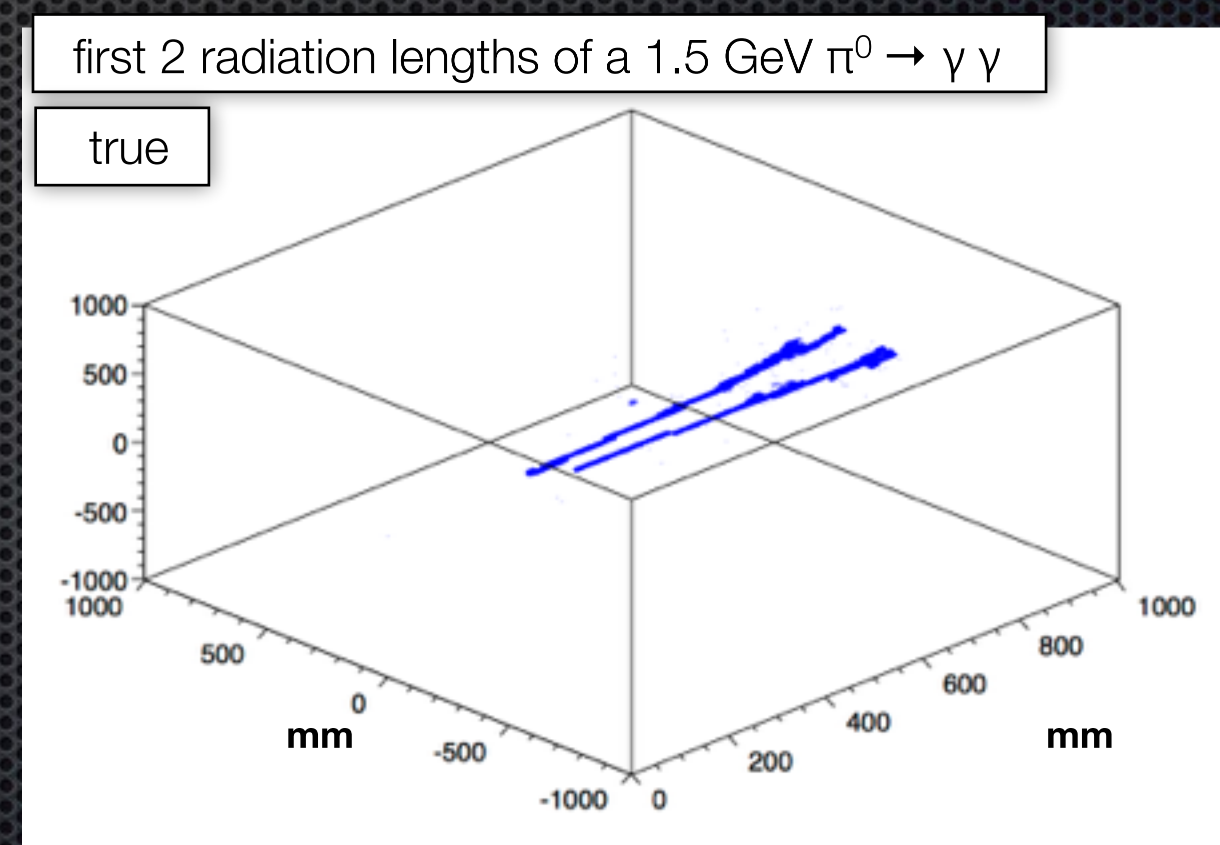
100 picoseconds ~ 2.25 centimeters

Using the Isochron method

- The isochron transform is a **causal Hough transform**, that build tracks from a pattern of hits in time and space.
- This approach **requires a seed vertex**, but no prior assumption about number of tracks or event topology.
- It connects each hit to the vertex through a two segment path, one that of the charged particle, the other representing emitted light.
- The rotational ambiguity is easily resolved, since the same track will intersect maximally around their common emission point.



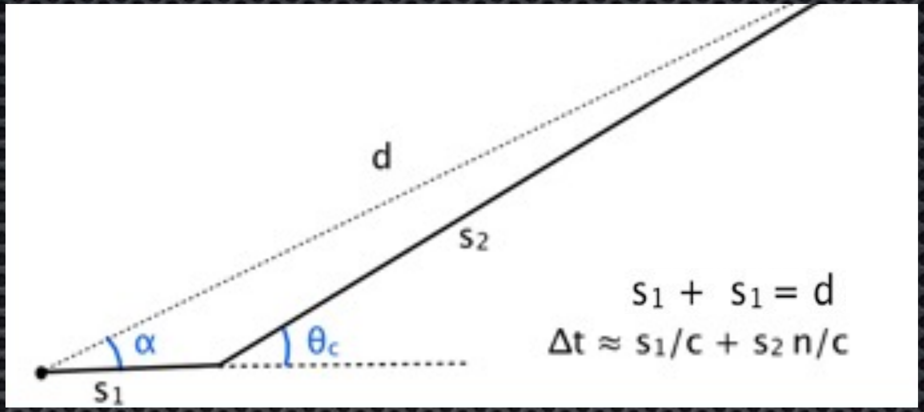


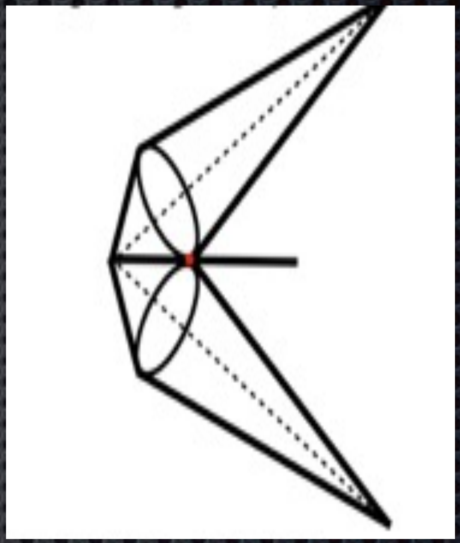


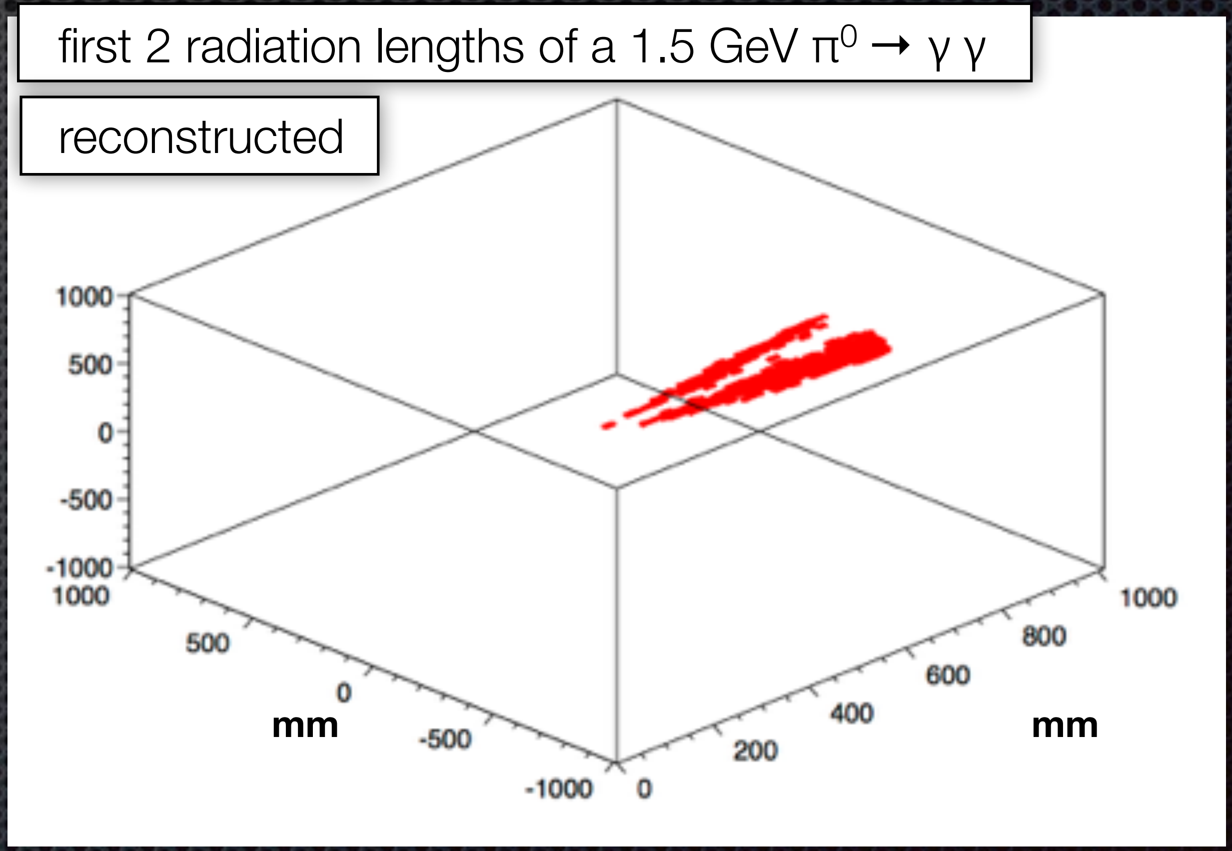
M. Wetstein

Using the Isochron method

- Track-like clusters emerge from density of intersections:
  - This density is sensitive to the position of the vertex hypothesis.
  - Image sharpness can be used as a figure of merit for fitting the vertex.
- Initial implementation tested on a 6m spherical detector with 100% coverage and perfect resolution.
- Full optical effects are applied
  - Not yet correcting for chromatic dispersion.
  - Not using any timing-based quality cuts.
- Challenges for realistic implementation: optimization for larger detectors, sparser coverage, less resolution.







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