R&D on Photosensors for Water and Liquid Scintillator Detectors

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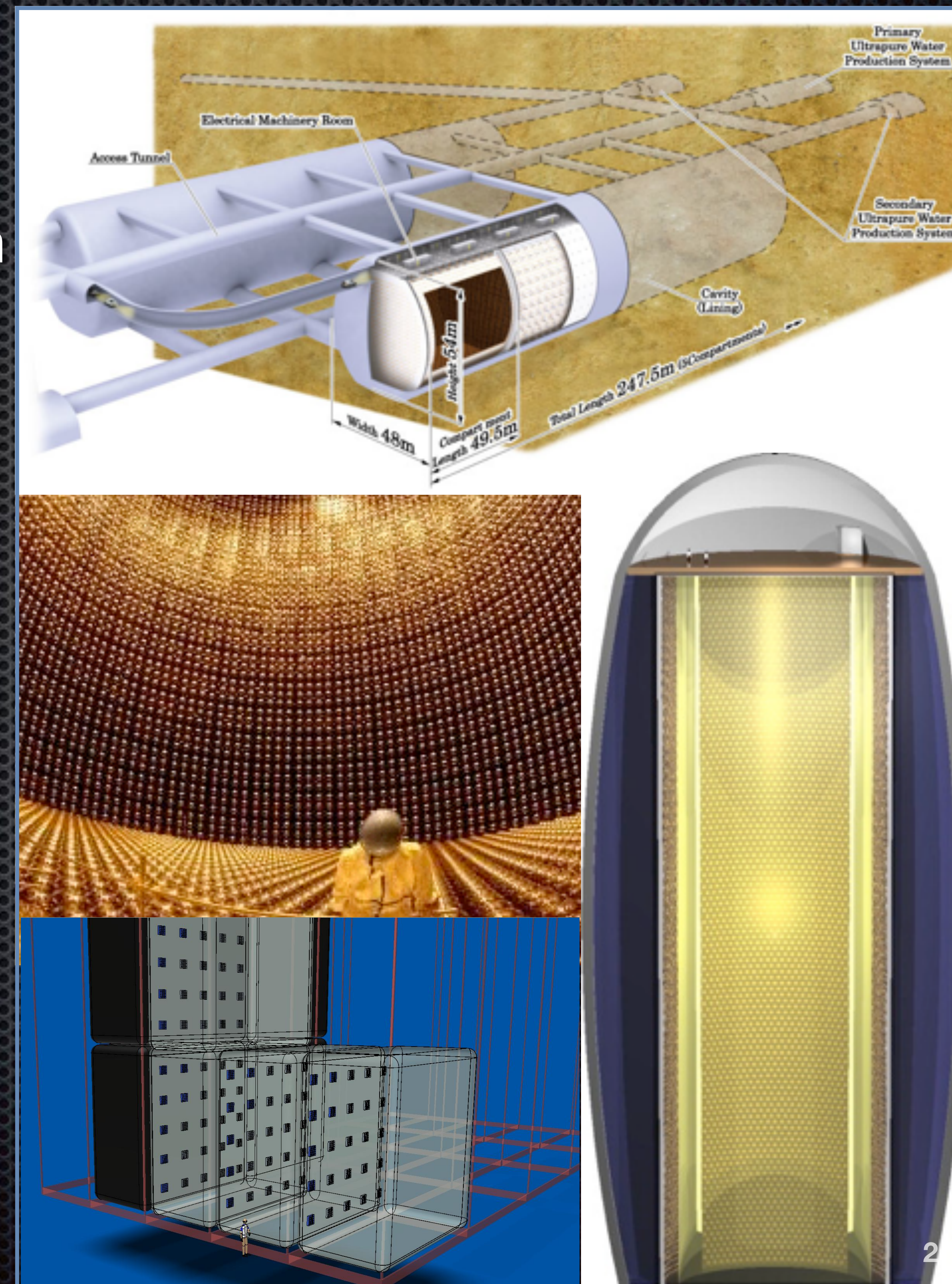
The NNN experiments

- The **Next generation of Neutrino and Nucleon decay experiments** will require massive detectors to reach the sensitivities needed to measure CP violation, the mass hierarchy, the θ_{23} octant, non-standard interactions and nucleon decay.
- One or several **large detectors,** can provide the mass required to the NNN experiments.
- First challenge will be instrumenting the **very large surfaces/volumes**.
- Second challenge will be making **multi-purpose detectors** to enable a broader physics program.



The Next generation of Neutrino and Nucleon decay detectors

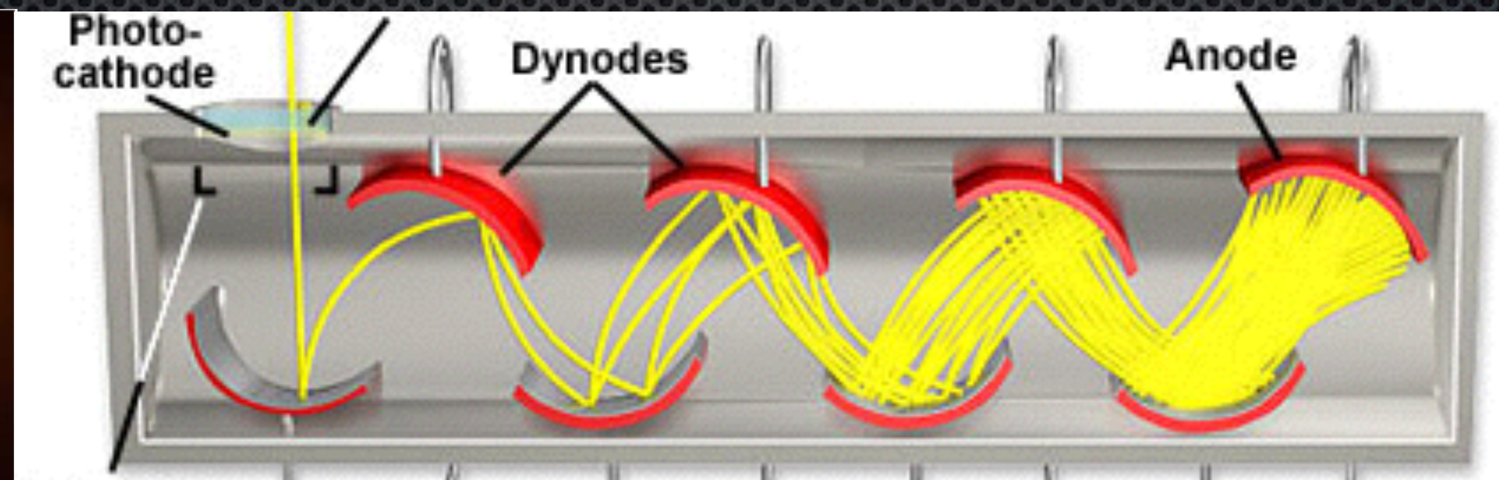
- Several collaborations have investigated or are investigating the feasibility of large liquid-based detectors:

Hyper-K	560 kton water	99K+25K PMTs
Memphys	530 kton water	220K PMTs
LBNE WCh	200 kton water	30-45K PMTs
Chips	100 kton water	17K PMTs
LENA	51 kton liquid scint	30K PMTS
JUNO	20 kton liquid scint	15K PMTs

Ed Kearns

- All attempt a broad range of physics in addition to studying neutrino oscillations including nucleon decay, solar and supernovae neutrinos, etc.
- It is obvious that the next generation of experiments require **continued R&D photosensors.**
- Collaborations working on characterization and design of **larger/cheaper/more efficient photosensors**.

Traditional photomultipliers

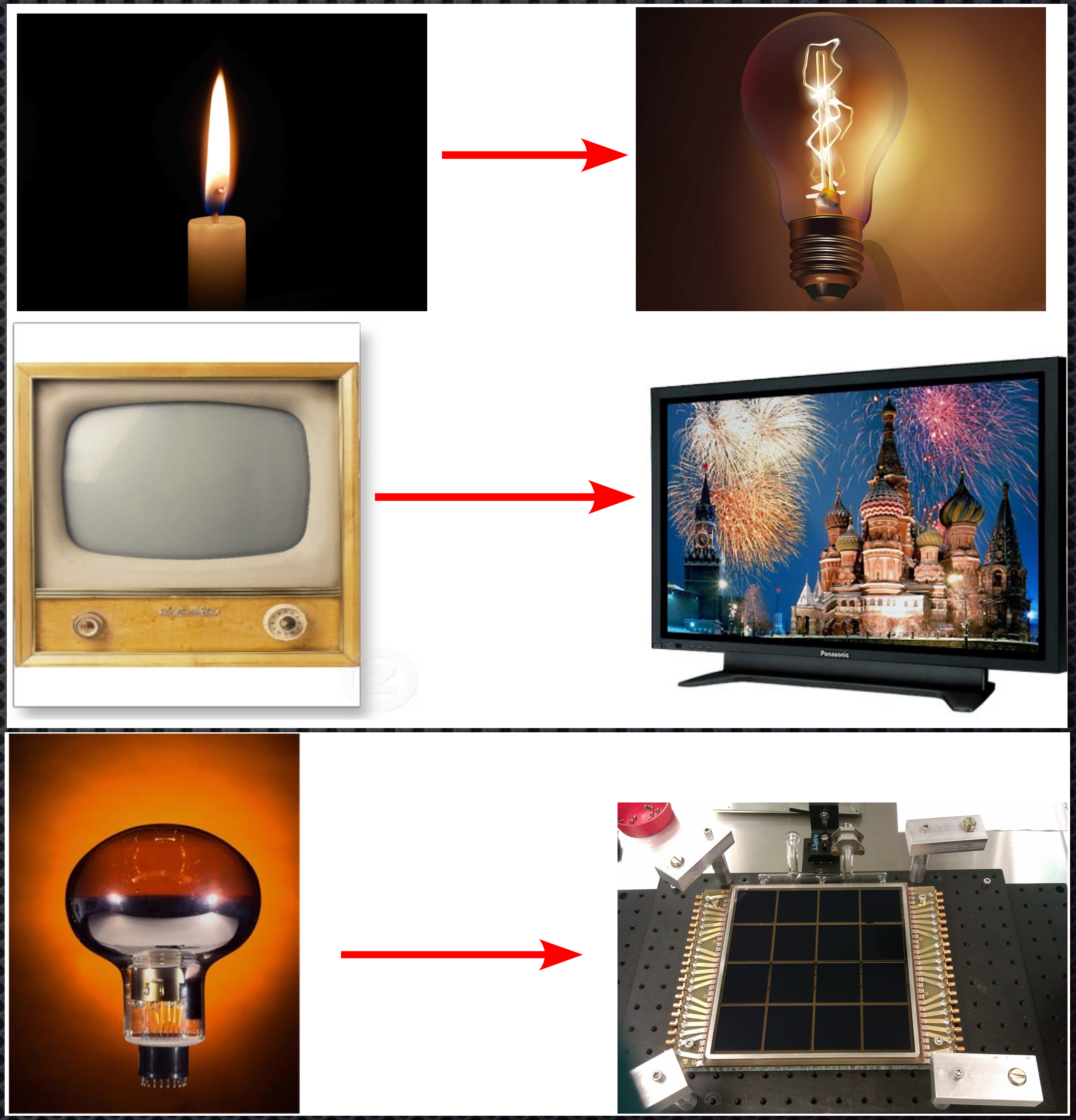


- Classical photomultiplier tubes use photoelectric effect to convert the photon to an electron and then use secondary electron emission to amplify the signal.
- The uncertainty in the electron path causes uncertainty in the signal timing.

Shorter path, better time resolution

Novel photodetector R&D

- **Large-area picosecond photodetectors (LAPPD)** based on microchannel plates are being developed by a close collaboration of US universities, labs and private companies.
- Microchannel technology makes electron path very small.
- For a **NNN application**, the characteristics of these could be tuned to:
  - Timing resolution of **~100 psec** (order of magnitude improvement)
  - Spatial resolution of **~1cm**
- Alternatively, worse timing/less spatial resolution could be a lower price.



Novel photodetector R&D

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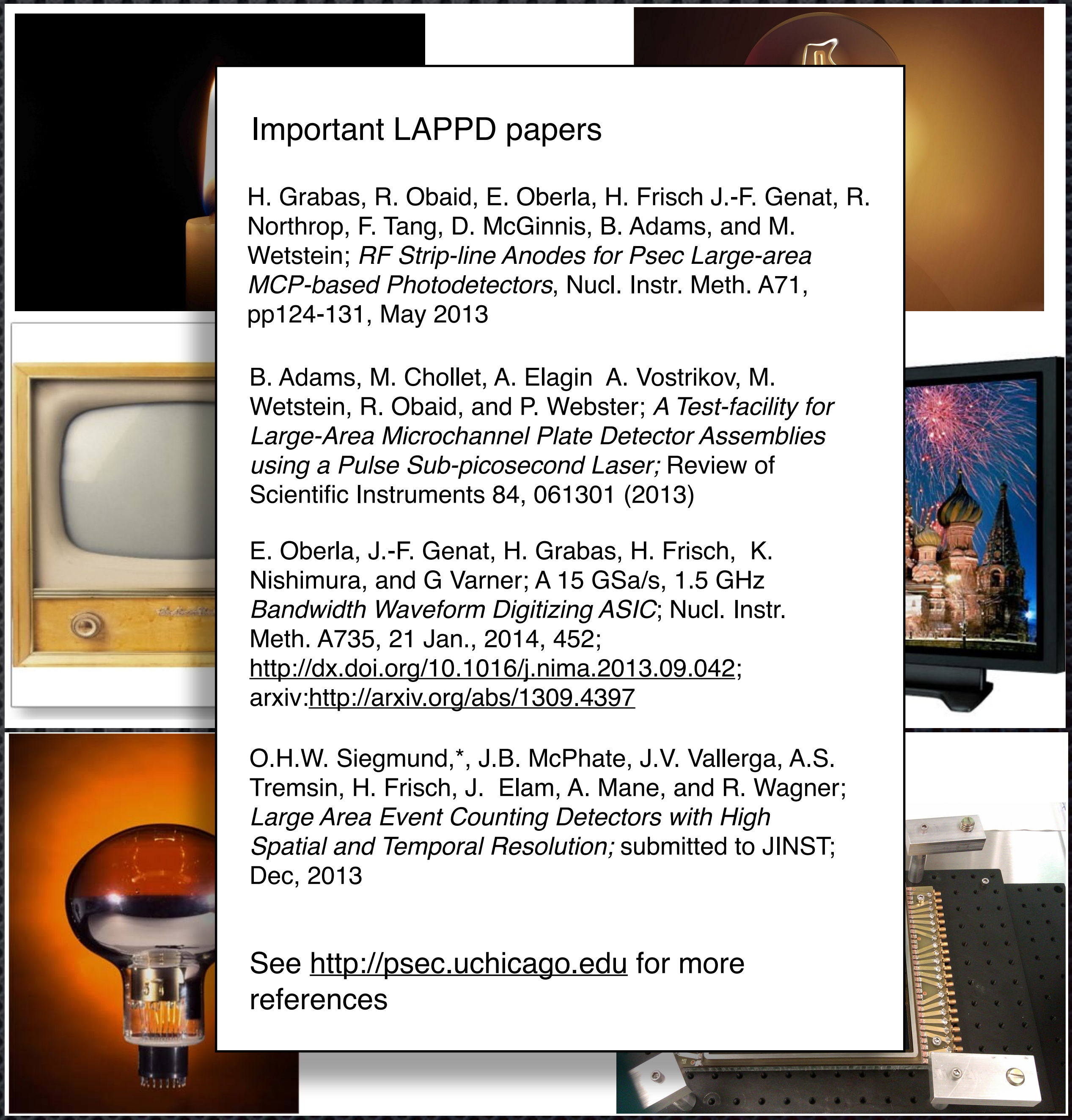


Important LAPPD papers

H. Grabas, R. Obaid, E. Oberla, H. Frisch J.-F. Genat, R. Northrop, F. Tang, D. McGinnis, B. Adams, and M. Wetstein; *RF Strip-line Anodes for Psec Large-area MCP-based Photodetectors*, Nucl. Instr. Meth. A71, pp124-131, May 2013

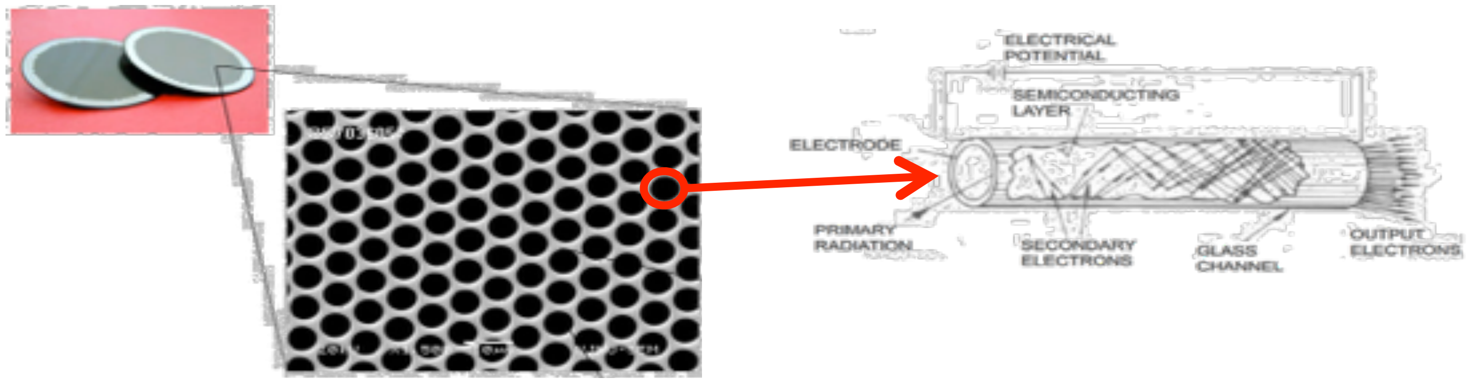
B. Adams, M. Chollet, A. Elagin A. Vostrikov, M. Wetstein, R. Obaid, and P. Webster; *A Test-facility for Large-Area Microchannel Plate Detector Assemblies using a Pulse Sub-picosecond Laser;* Review of Scientific Instruments 84, 061301 (2013)

E. Oberla, J.-F. Genat, H. Grabas, H. Frisch, K. Nishimura, and G Varner; A 15 GSa/s, 1.5 GHz *Bandwidth Waveform Digitizing ASIC*; Nucl. Instr. Meth. A735, 21 Jan., 2014, 452; http://dx.doi.org/10.1016/j.nima.2013.09.042; arxiv:http://arxiv.org/abs/1309.4397

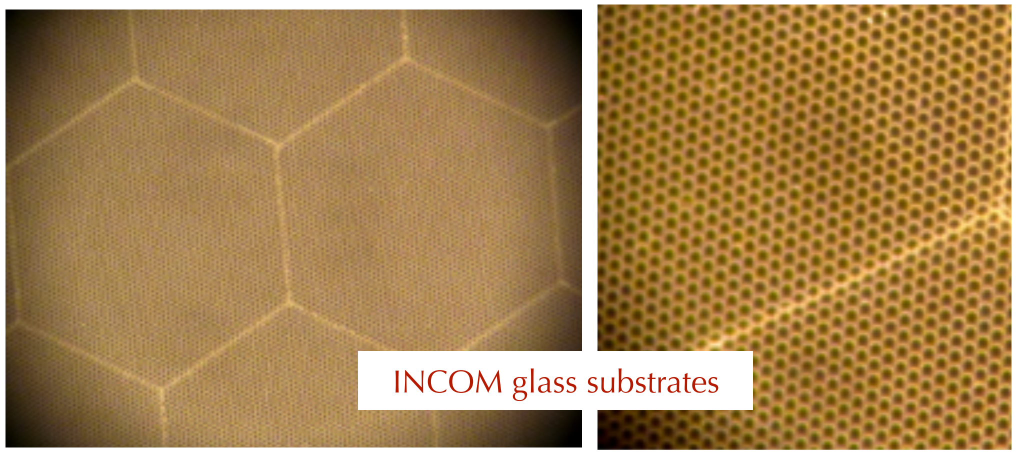
O.H.W. Siegmund,*, J.B. McPhate, J.V. Vallerga, A.S. Tremsin, H. Frisch, J. Elam, A. Mane, and R. Wagner; *Large Area Event Counting Detectors with High Spatial and Temporal Resolution;* submitted to JINST; Dec, 2013

See http://psec.uchicago.edu for more references

Key innovation: large micro-channel plates



LAPPD collaboration



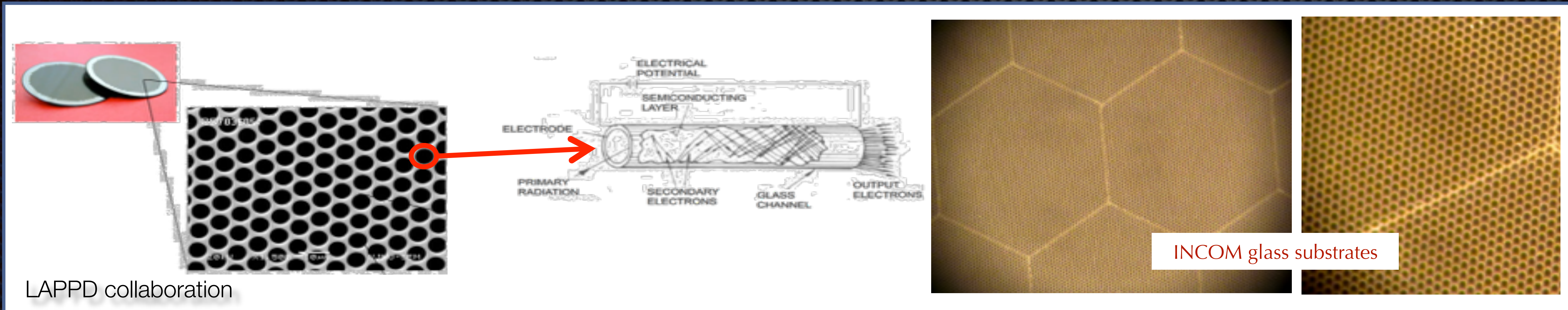
INCOM glass substrates

- 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



- Conventional MCP Fabrication:
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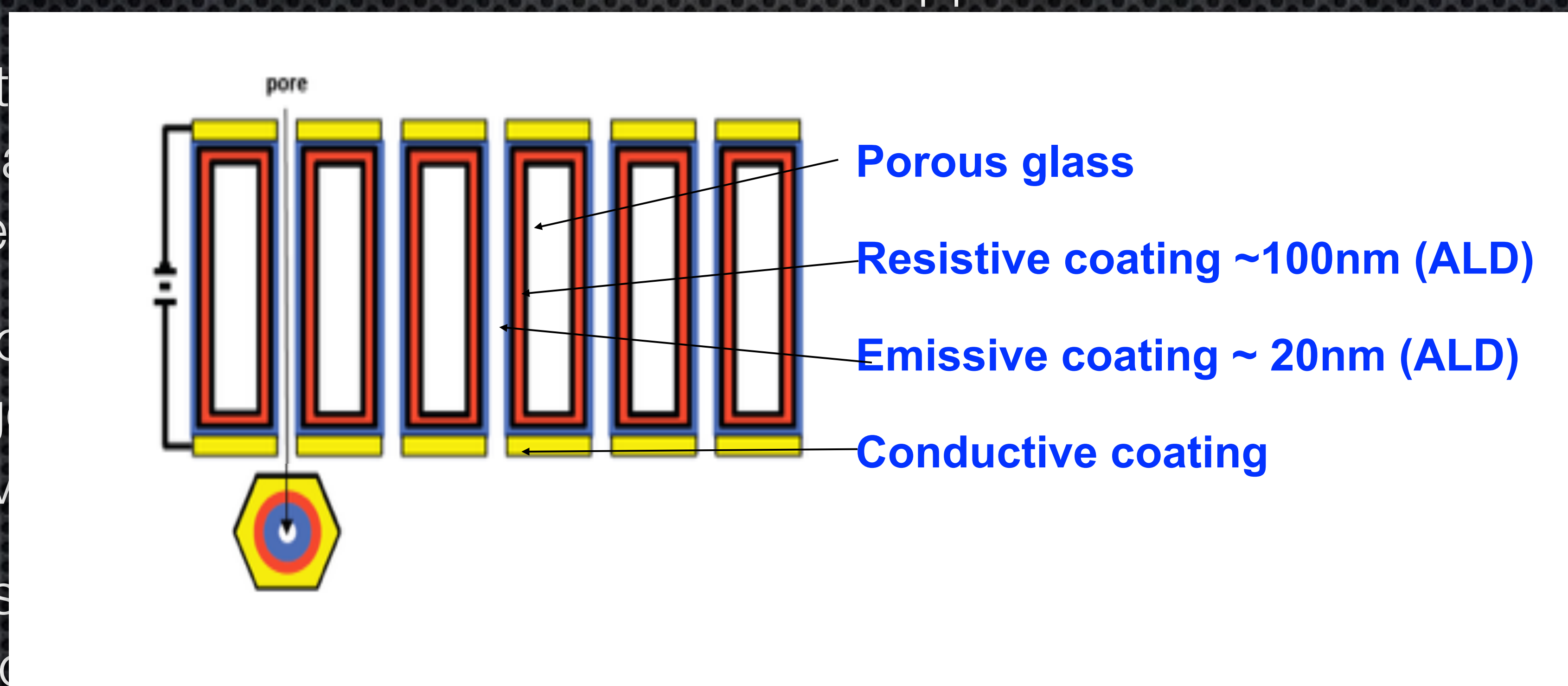

- Approach for LAPPD:
  - nctions:
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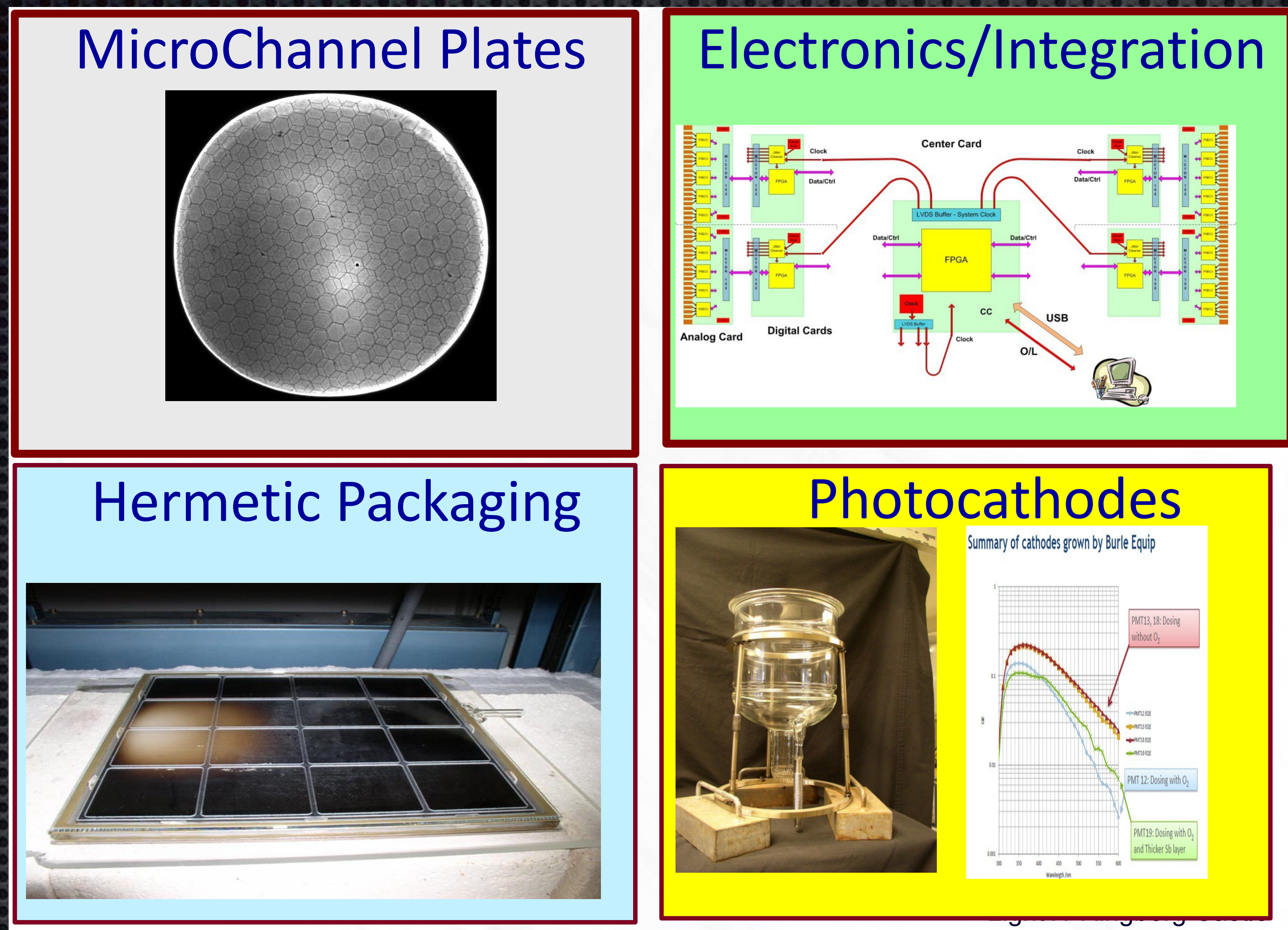
Approach demonstrated for 8-inch tiles

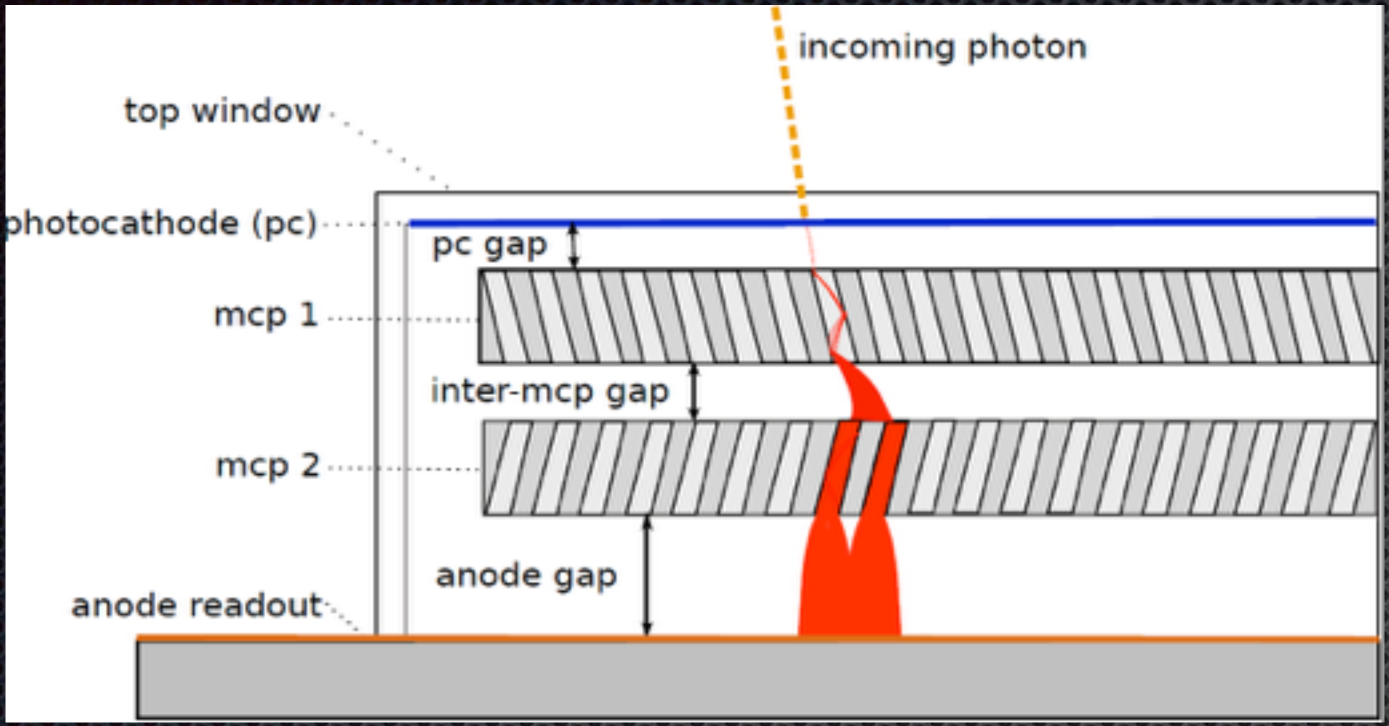
Key components LAPPDs

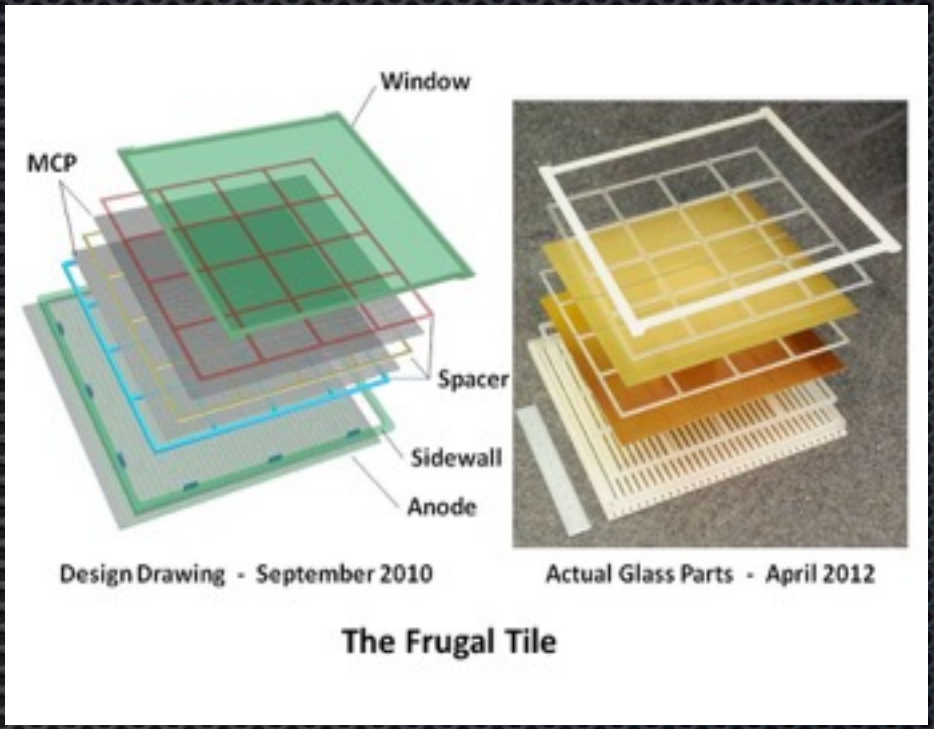


M. Wetstein (UChicago/ANL) and A. Elagin (UChicago)

- Beyond the micro-channel plates several components are needed: electronics, hermetic packaging, photocathodes.

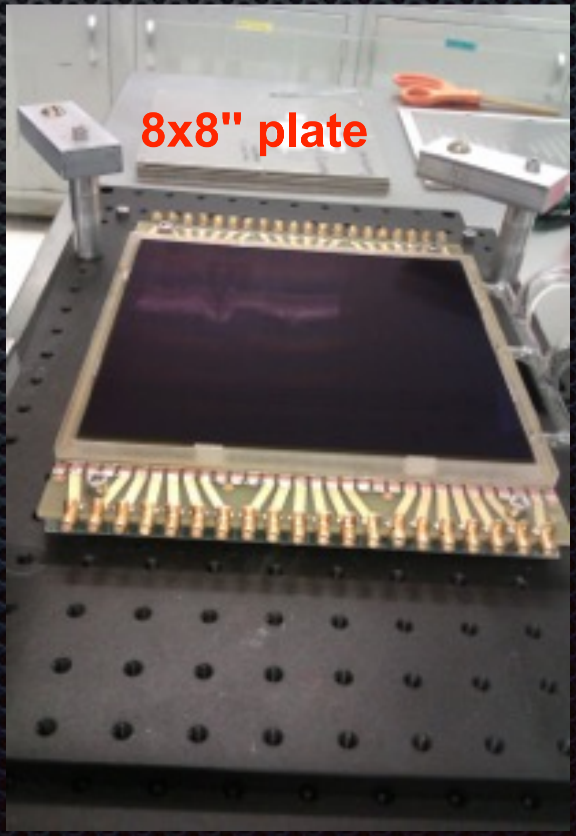
The 8-inch LAPPD glass tile





- 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.

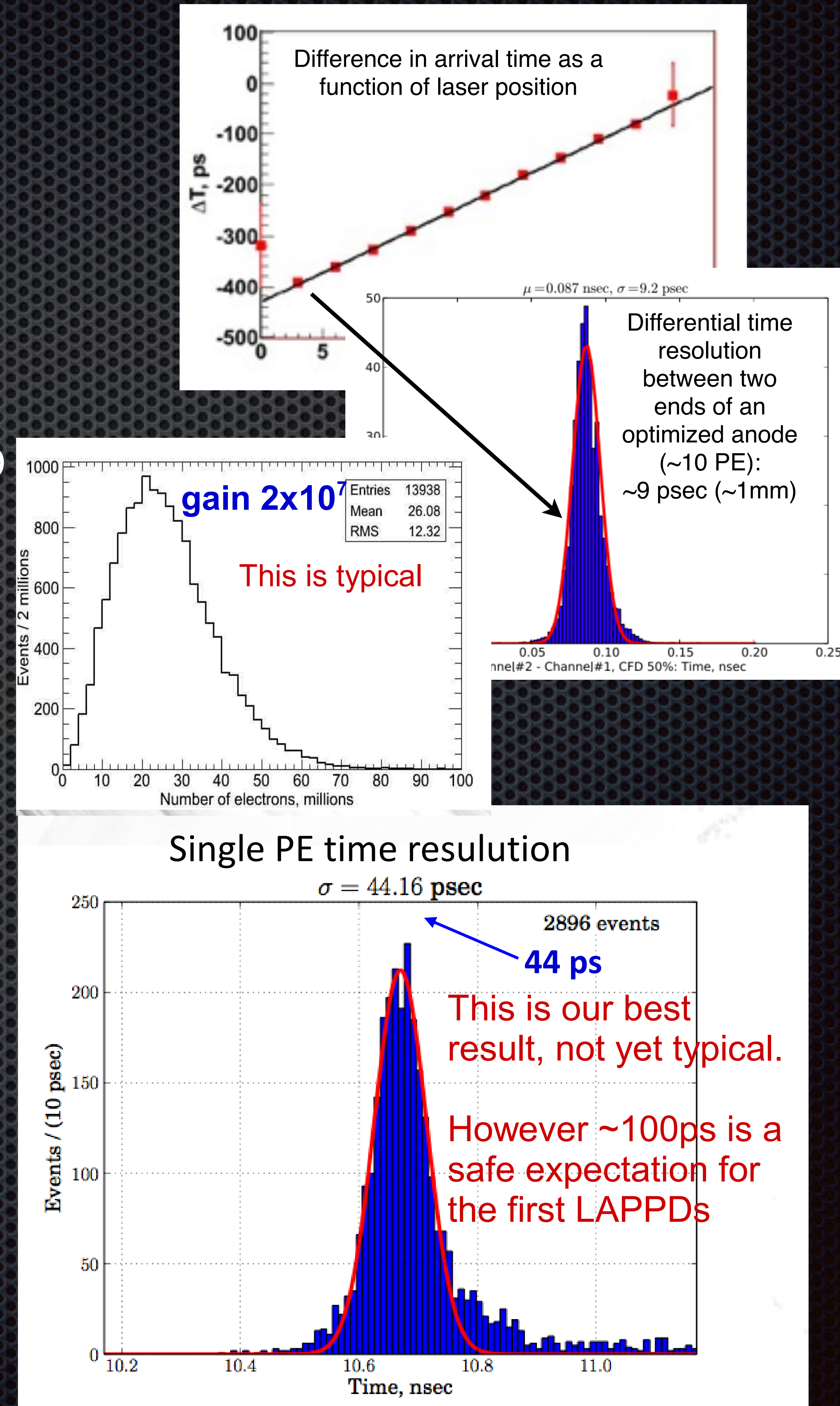


Packaging is to some extent application specific

LAPPD Status

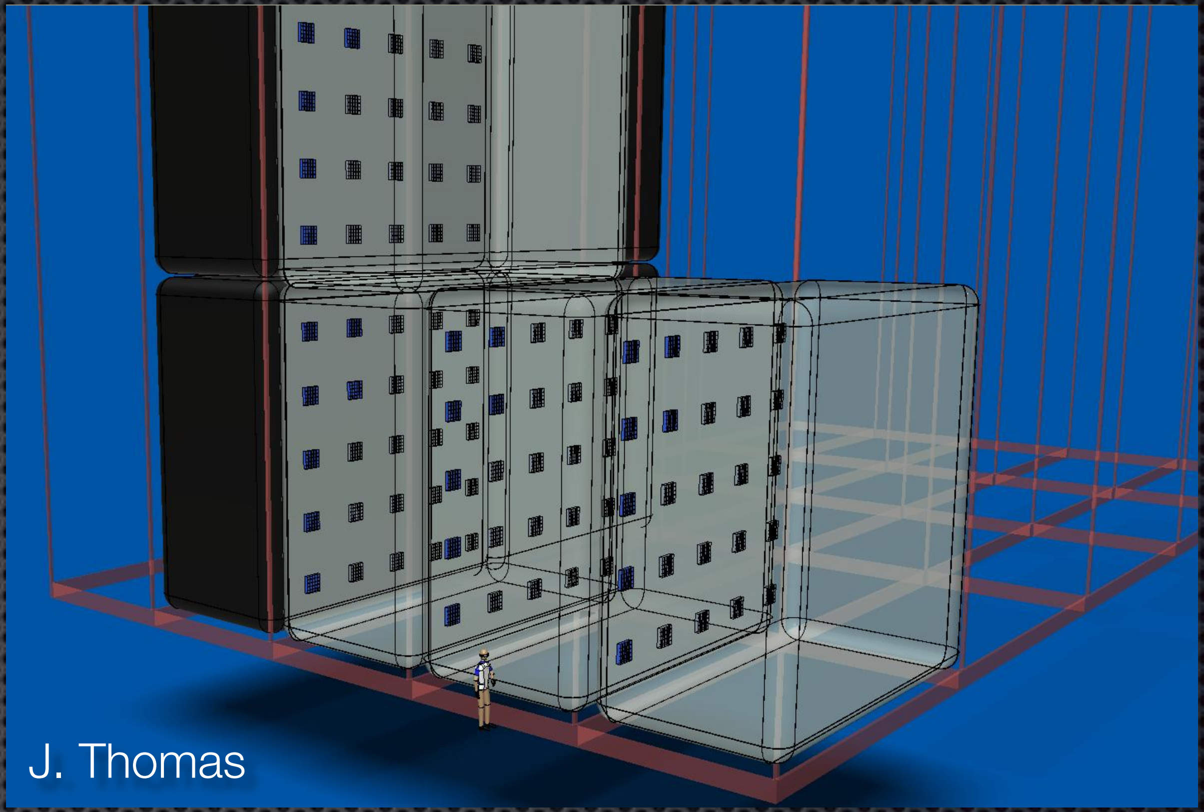
- Testing 8” x 8” (20 x 20 cm) MCPs:
  - Typical pulse height peaked at **2 x 10^7 gain**.
  - Differential time resolution between two ends of delay-line anode <10 psec.
  - **2 mm spatial resolution** parallel to the strip direction, <1 mm in transverse.
  - Best single PE **time resolution ~44 psec**. 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.

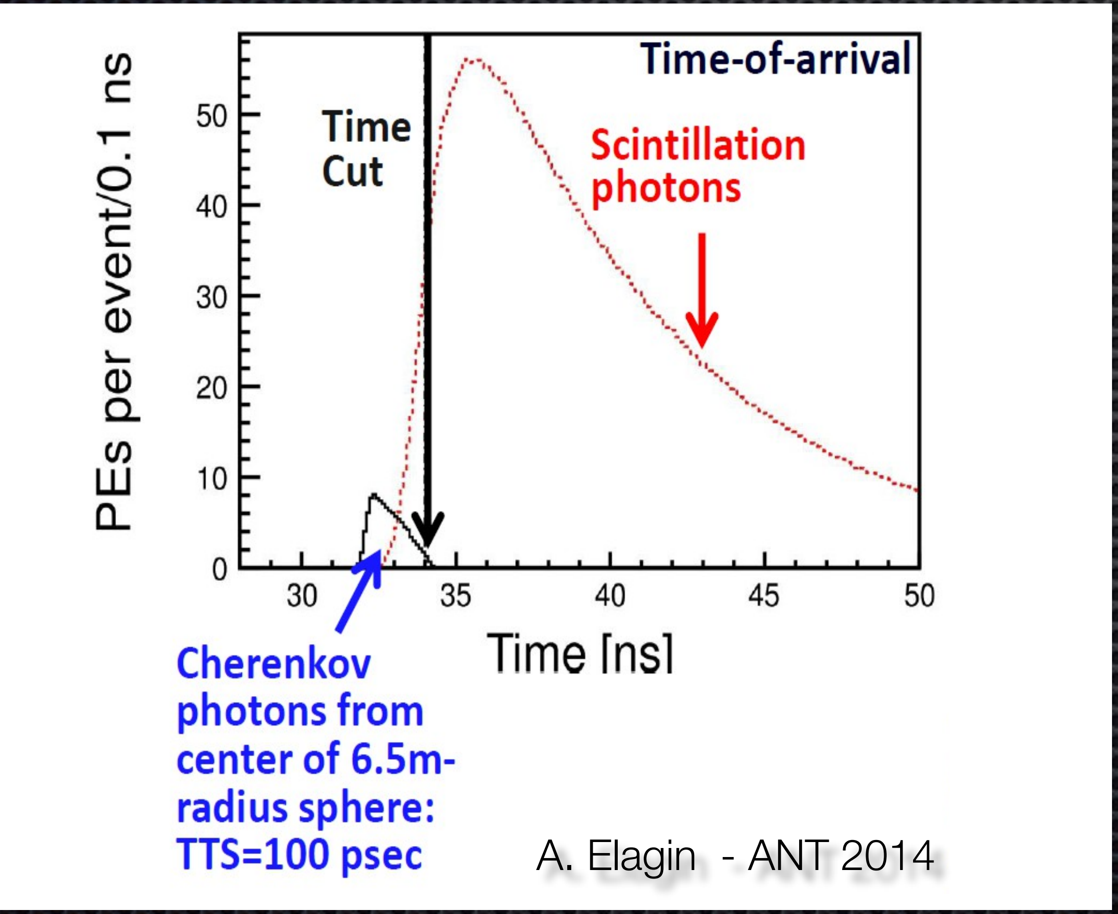
More on status in backup



Using LAPPDs for NNN

- 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**.



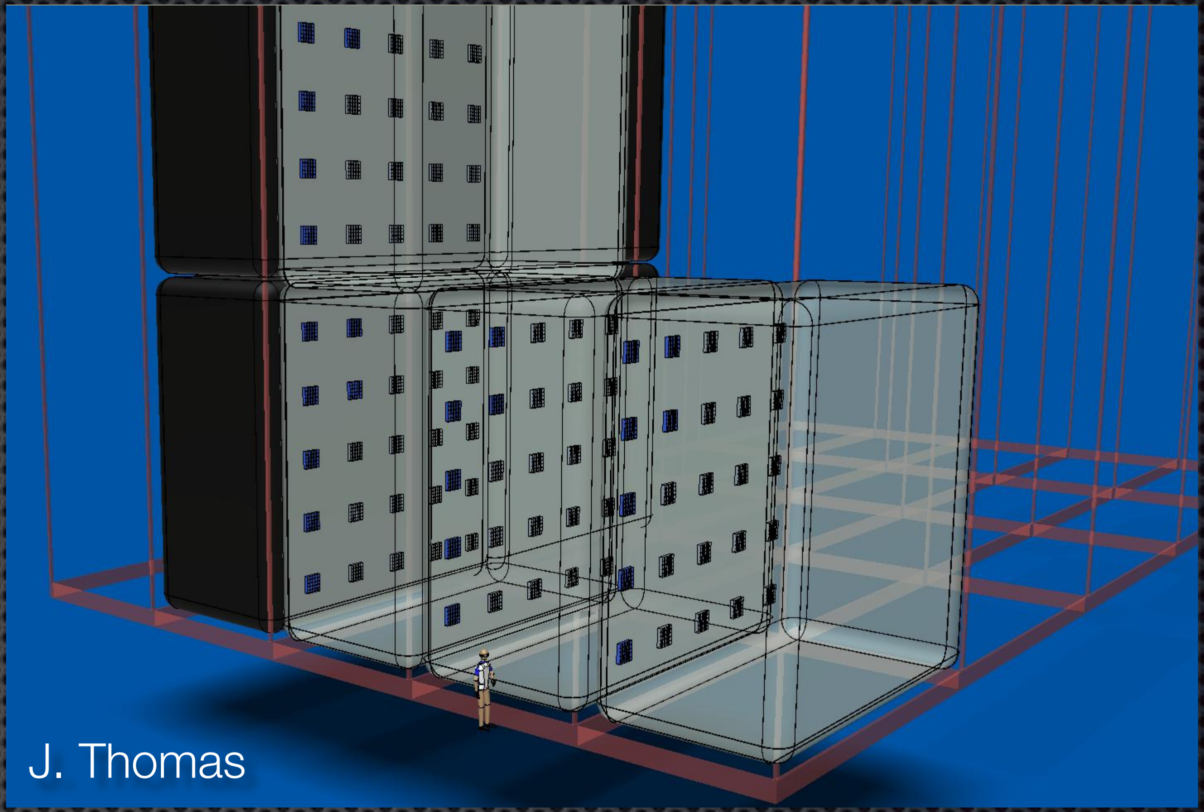


- For water-based liquid scintillator detectors it could help separate Cherenkov from scintillation light (more details in A. Mastbaum talk).

Using LAPPDs for NNN

Water Cherenkov only

- Potential impacts of LAPPDs:
  - Does **better timing information** improve vertex resolution for interactions in Water Cherenkov detectors?
  - What is the impact of **improved granularity or coverage**?
  - Does photon counting (as opposed to integrating charge) provide a significant advantage?

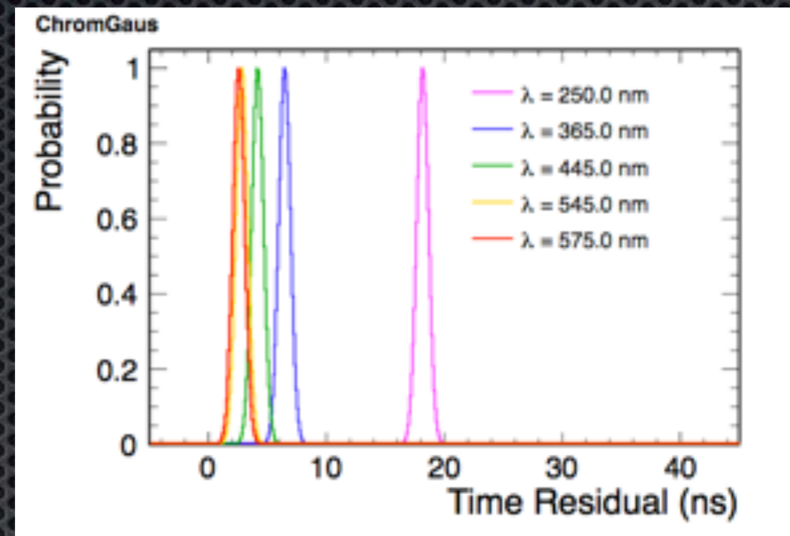


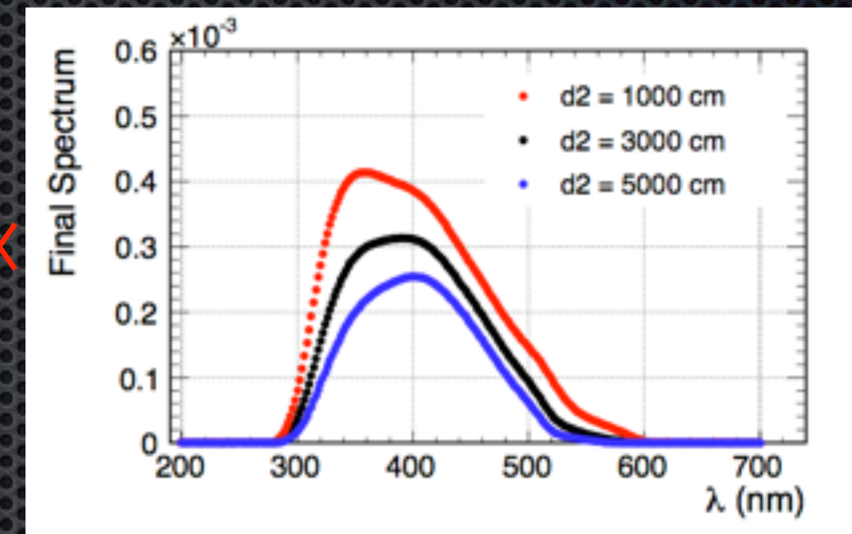
We are using simple **timing-residuals** to study:

- The relationship between vertex resolution and detector parameters.
- Improvements to track reconstruction with chromatic corrections.
- More sophisticated reconstruction is possible albeit slow (See pattern of light/Chroma - A. Mastbaum talk)

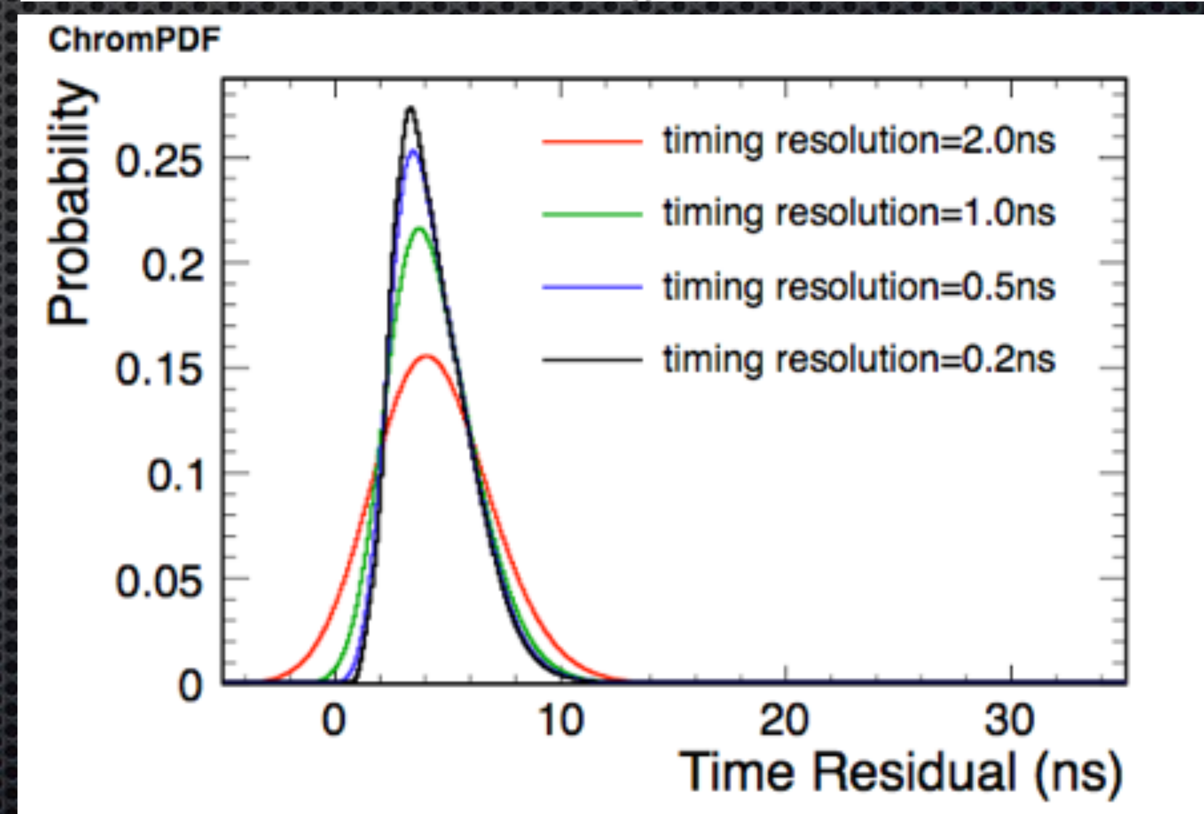
Using Time Residuals

- 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.





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

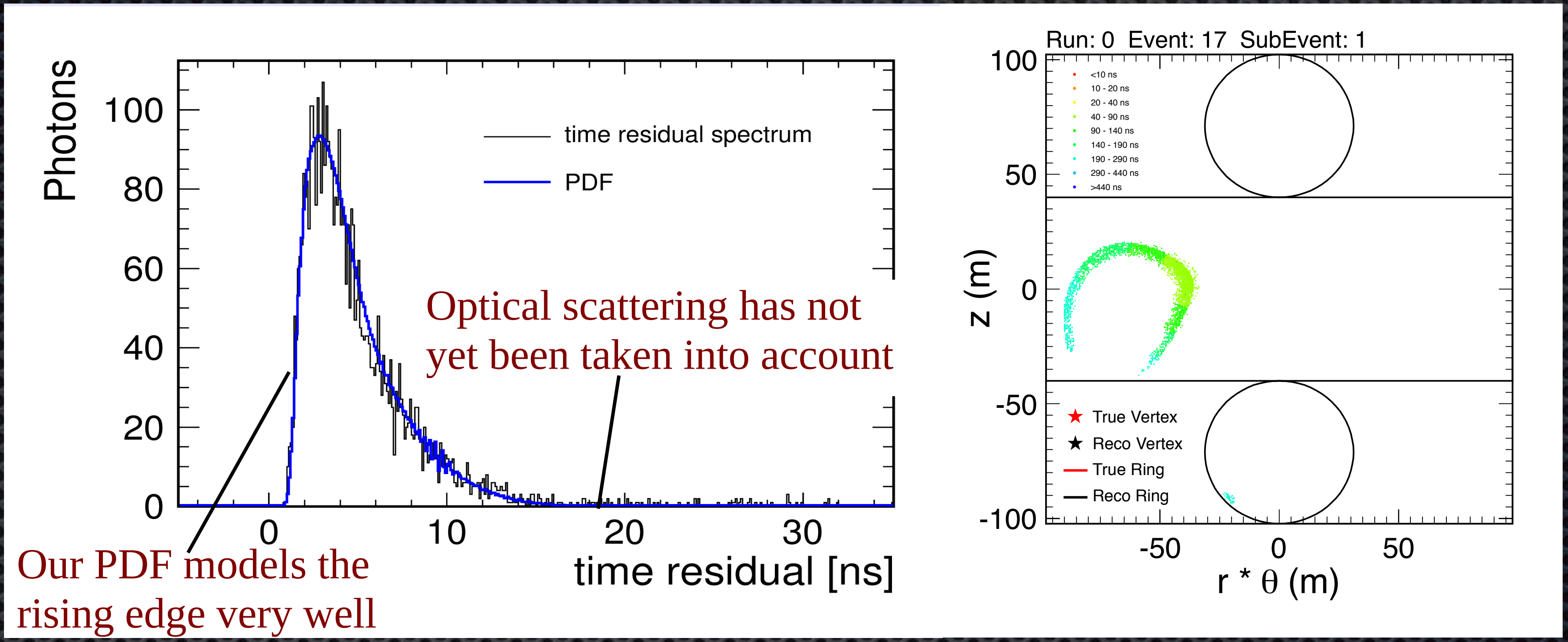


T. Xin, I. Anghel, M. Sanchez, M. Wetstein

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



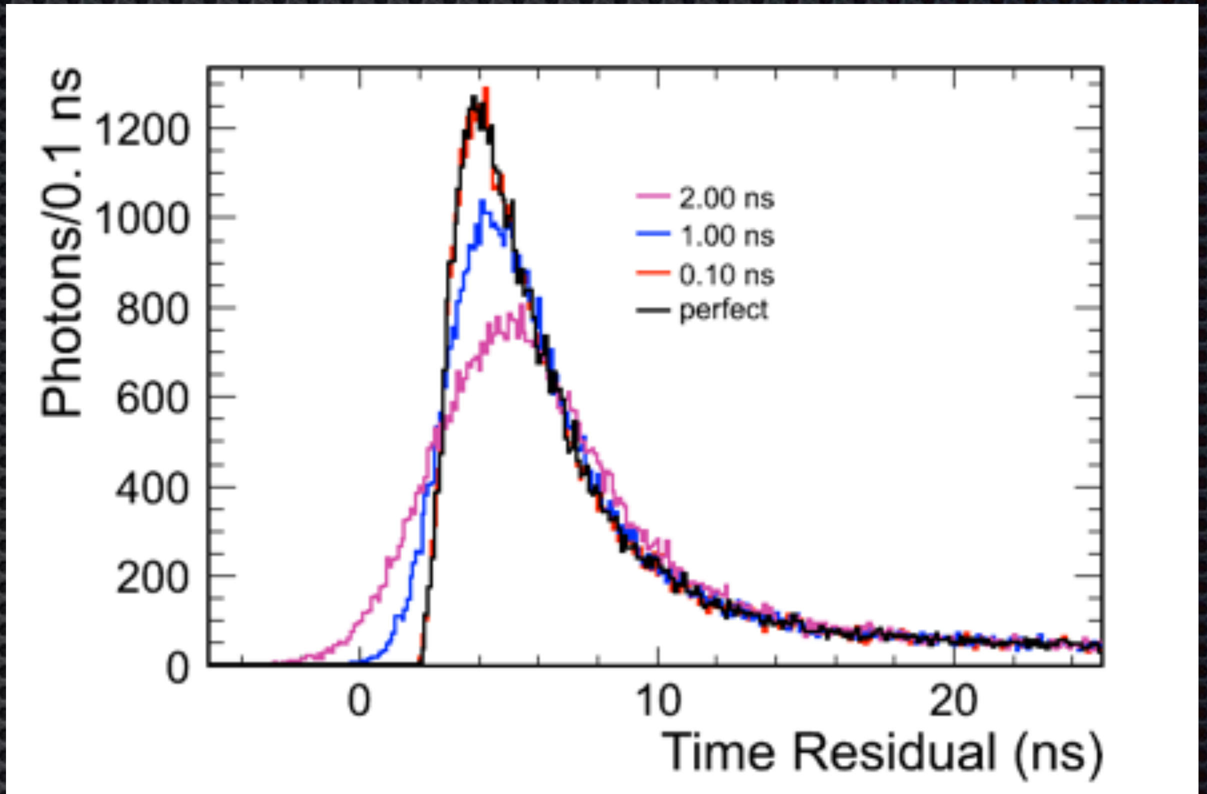
- It is not as sophisticated as full pattern-of-light fitting.
- However in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.

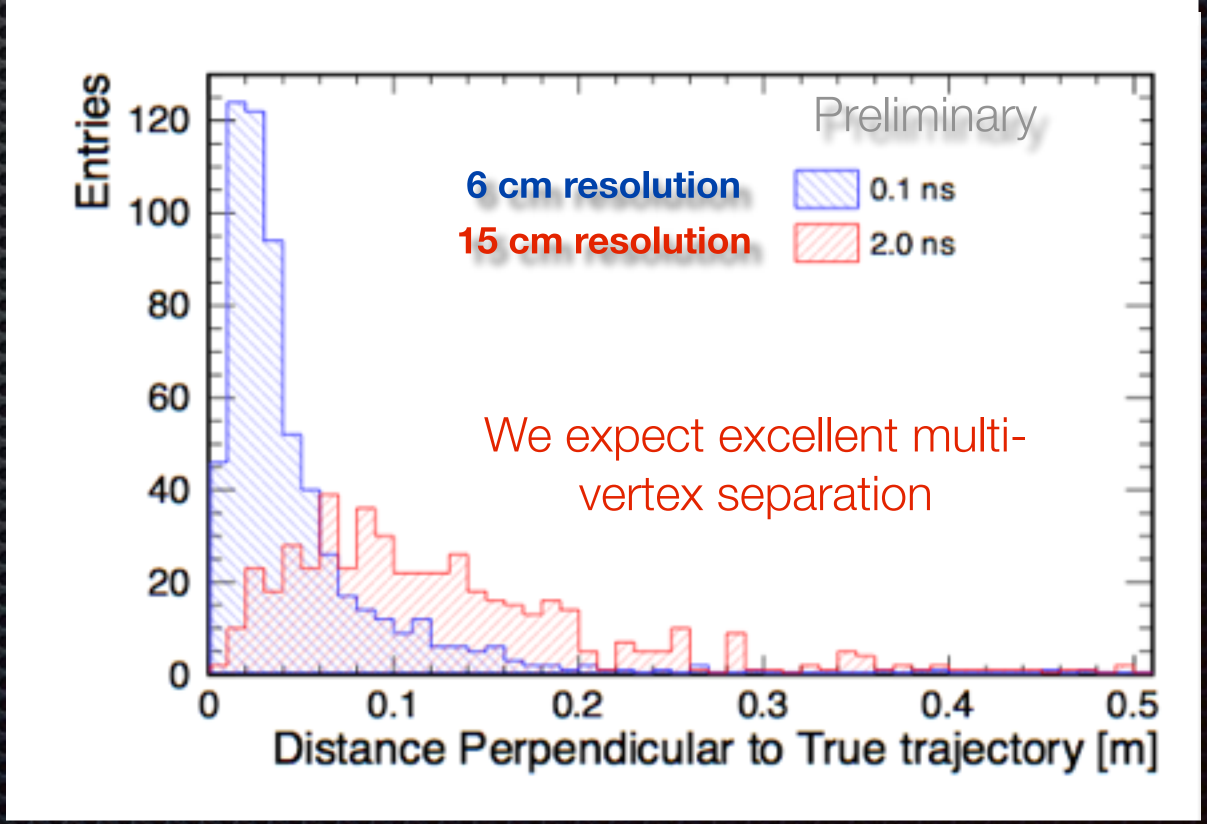
Using WCSim (C. Walter - Duke U.) simulation for these studies. Modifications in digitization appropriate for LAPPDs. Reconstruction developed within WCSimAnalysis framework used in LBNE Water Cherenkov design.

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.

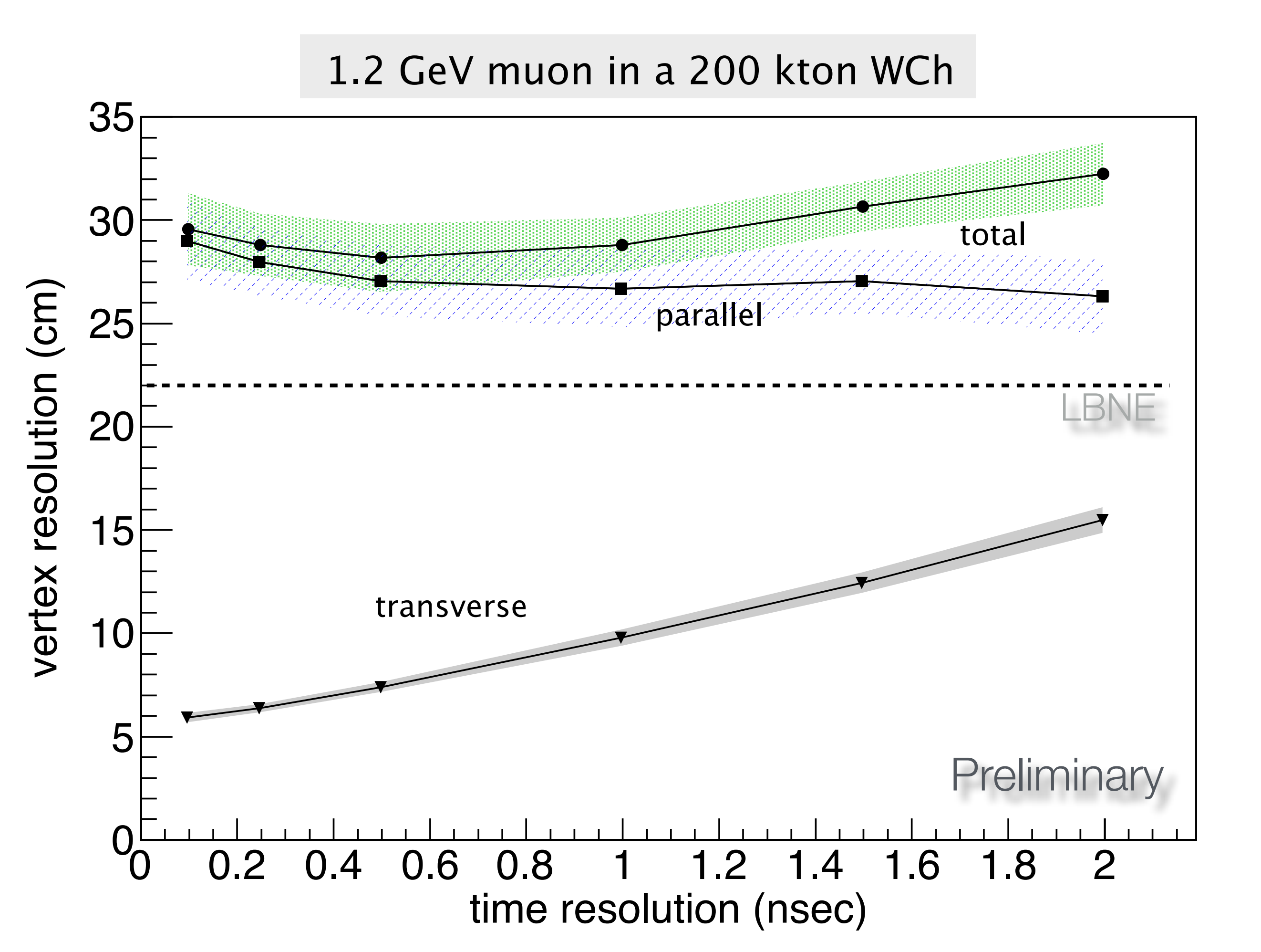
M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL), I. Anghel (ISU), E. Catano-Mur (ISU), T. Xin (ISU)





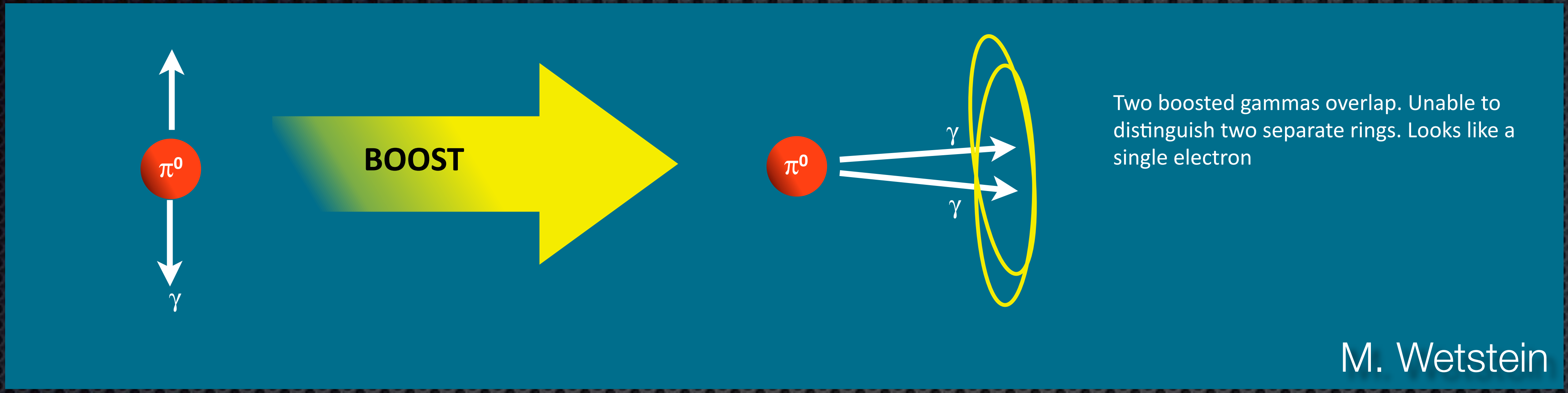
More Time Residuals results

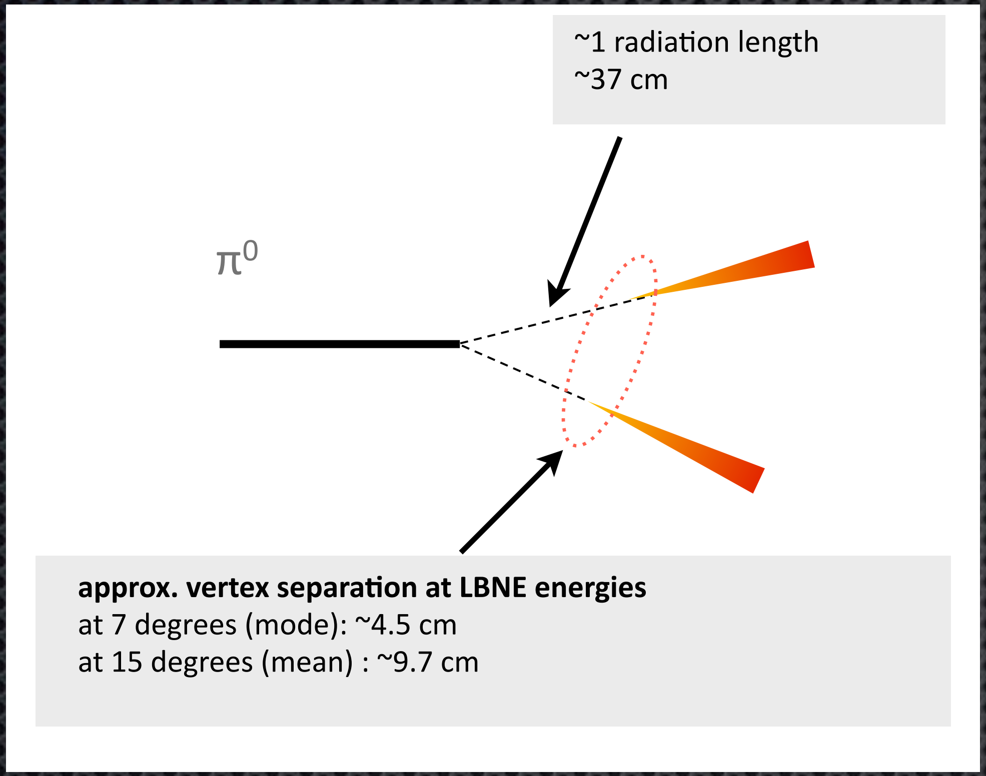
- Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.
  - Compare this vertex resolution to ~22 cm for LBNE WCh design using similar fits with no chromatic corrections and standard digitization.
- Based on pure timing, vertex position along the direction parallel to the 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.

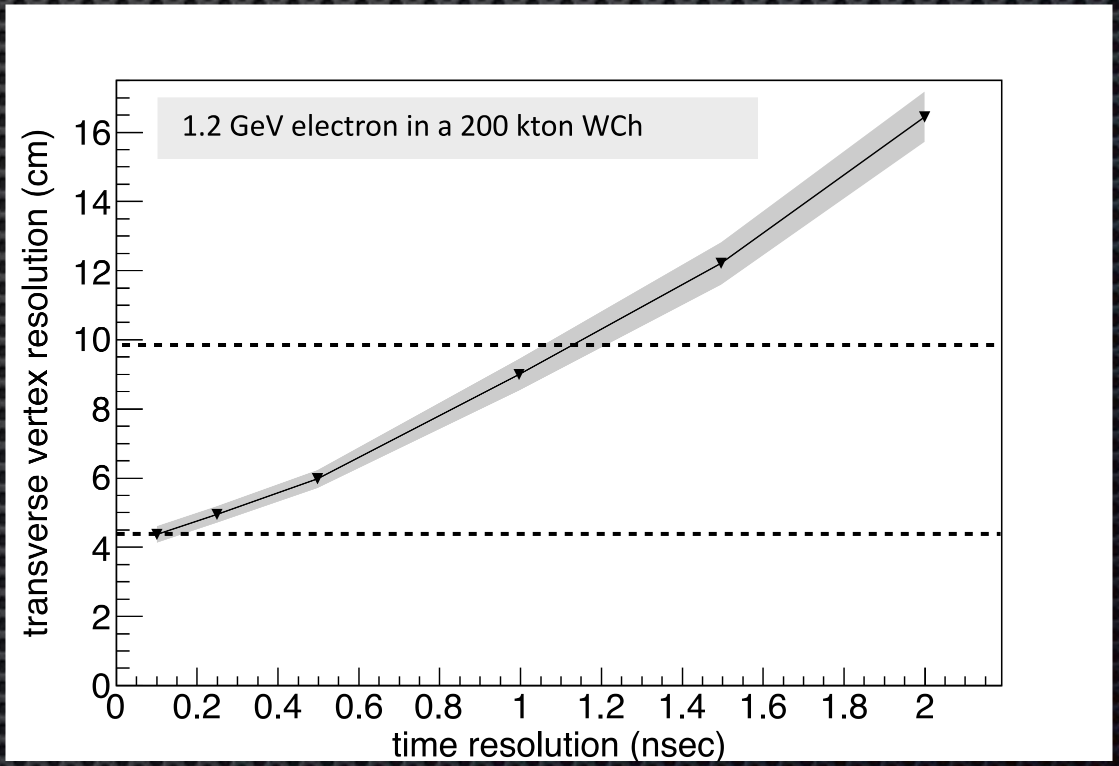


- Note that we also find that, for a given detector, the size of the uncertainties on the transverse vertex resolution scale with coverage consistent with $\sqrt{n}$.

Transverse vertex resolution



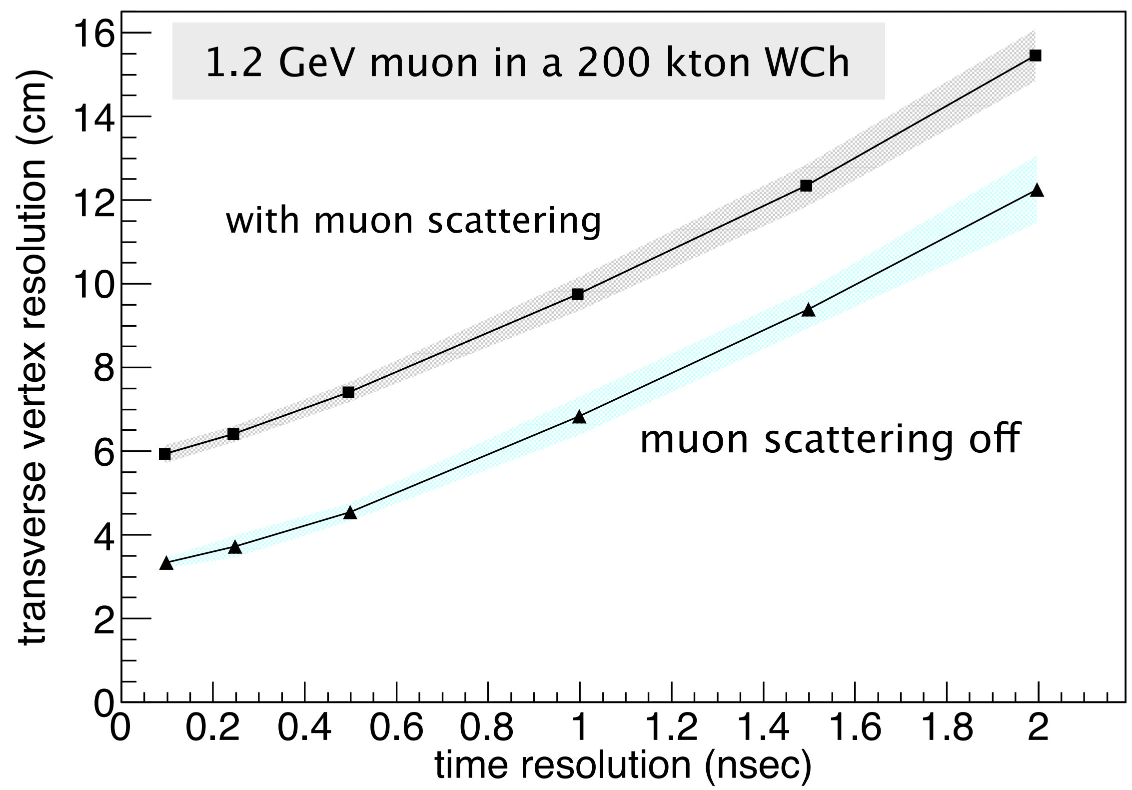


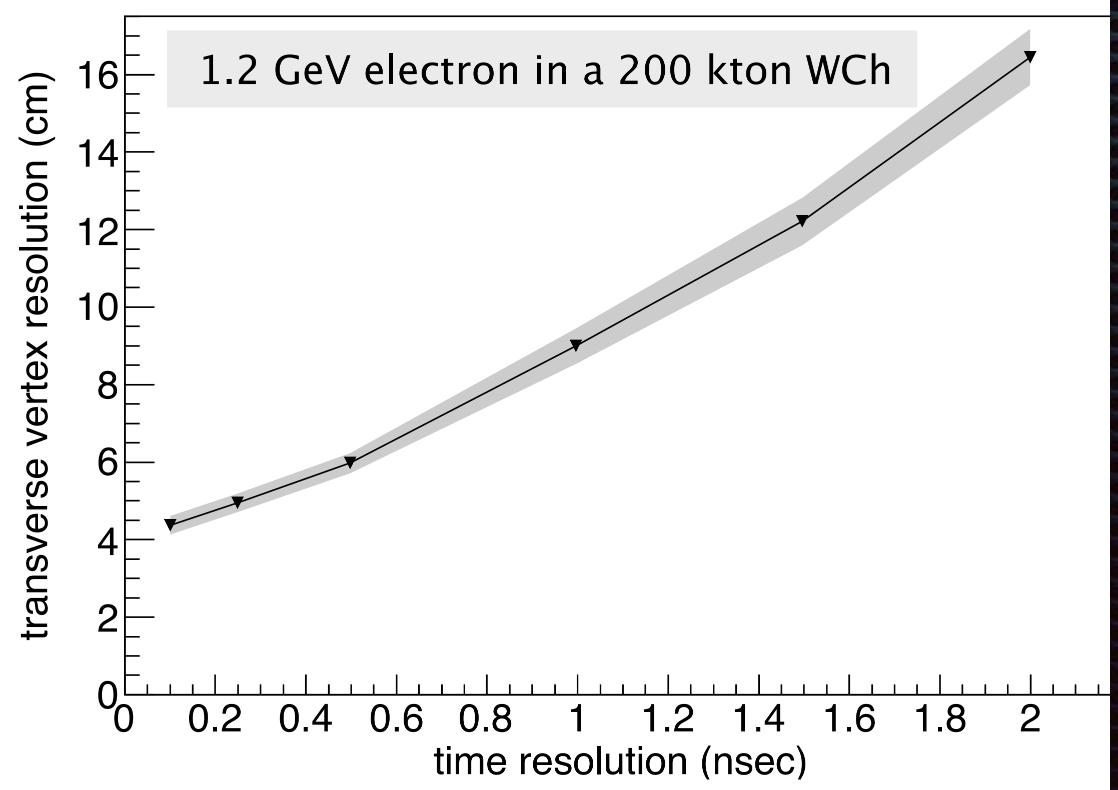


- Transverse vertex resolution is useful in rejection boosted neutral pions.
- Better time resolutions could help to cut deeper into this background.

Transverse vertex resolution

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

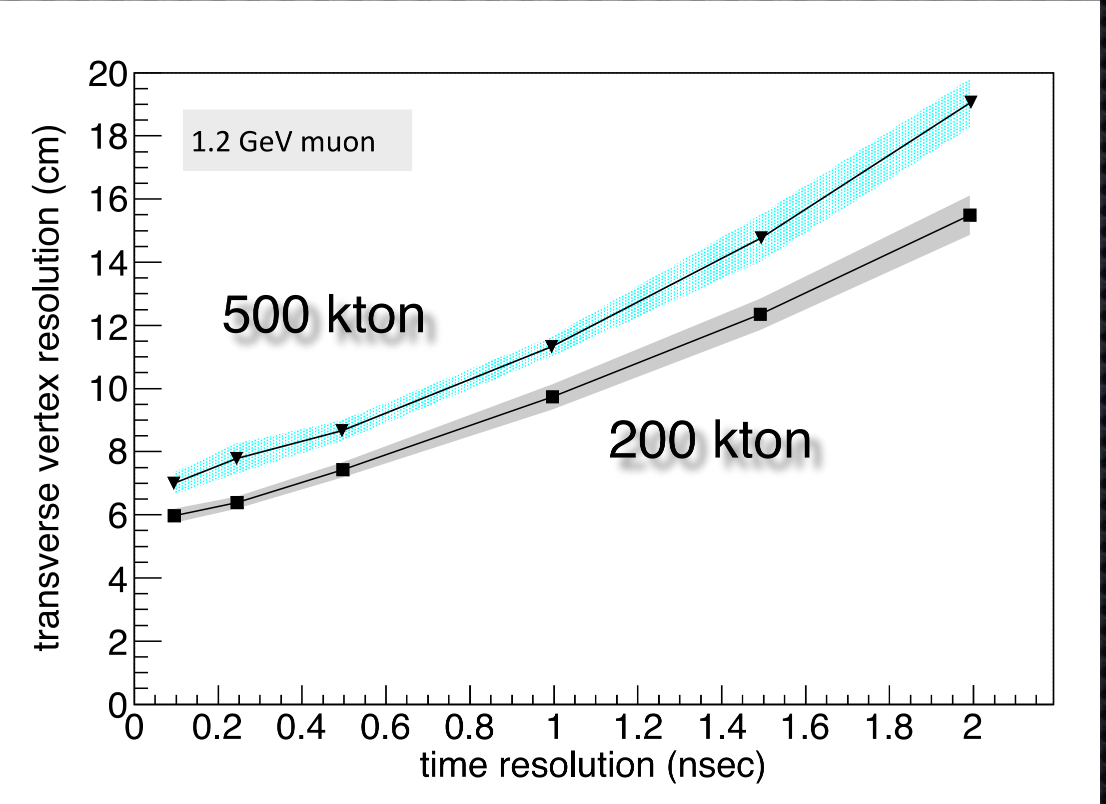


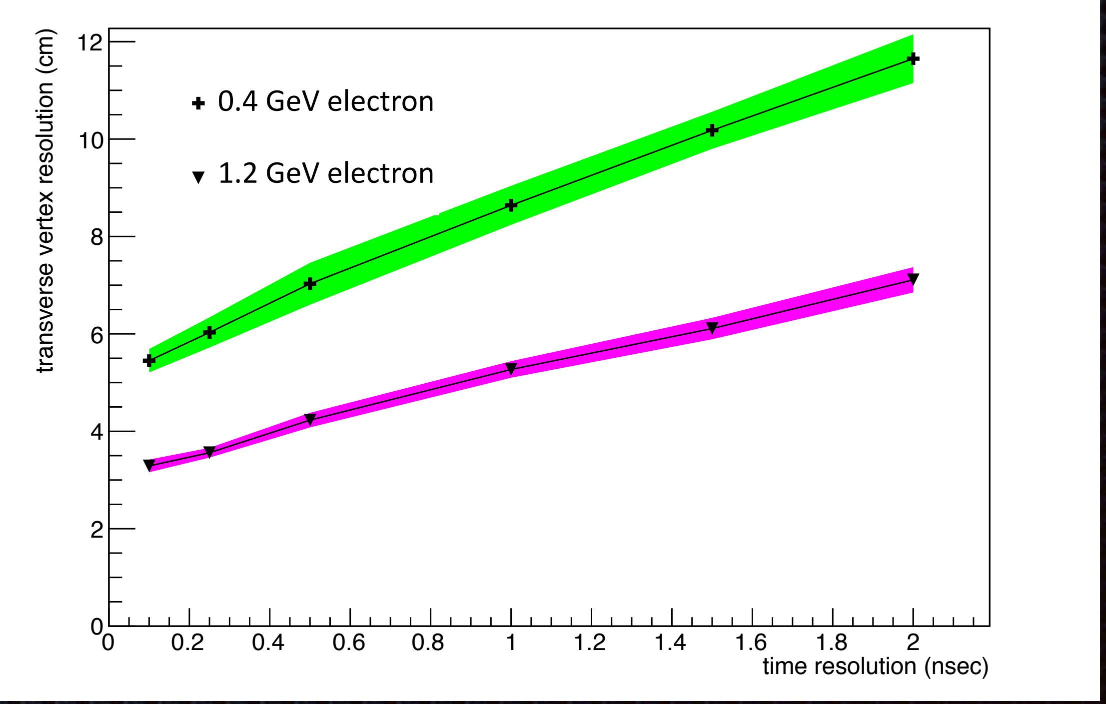


Other detector configurations

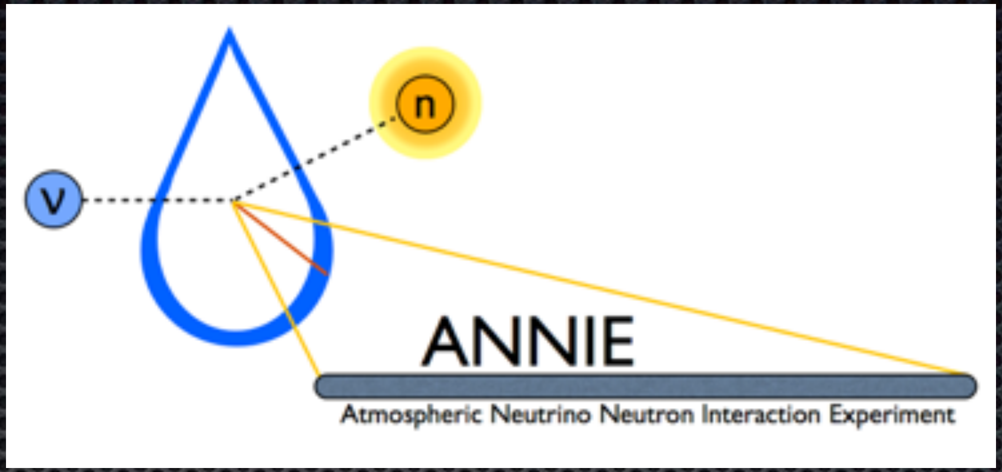
- Currently exploring a variety of detector configurations and particle energies.
- Gains are preserved going from 200 to 500 kiloton detectors. Shown for 1.2 GeV muons.
- Lower energies do have some resolution loss. Shown for 0.4 and 1.2 GeV electrons.

publication coming soon!

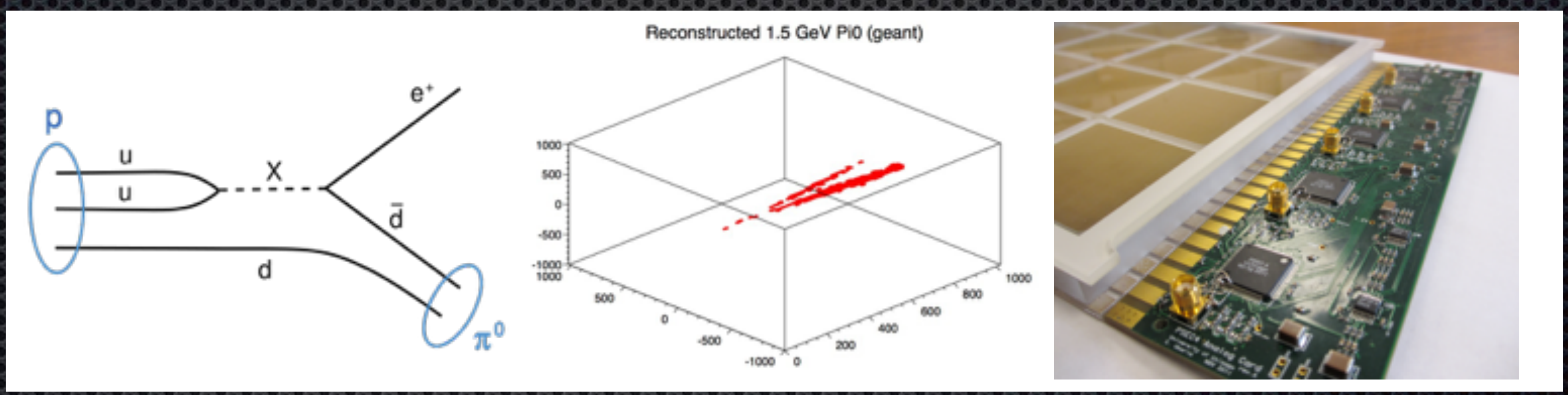




What is next?

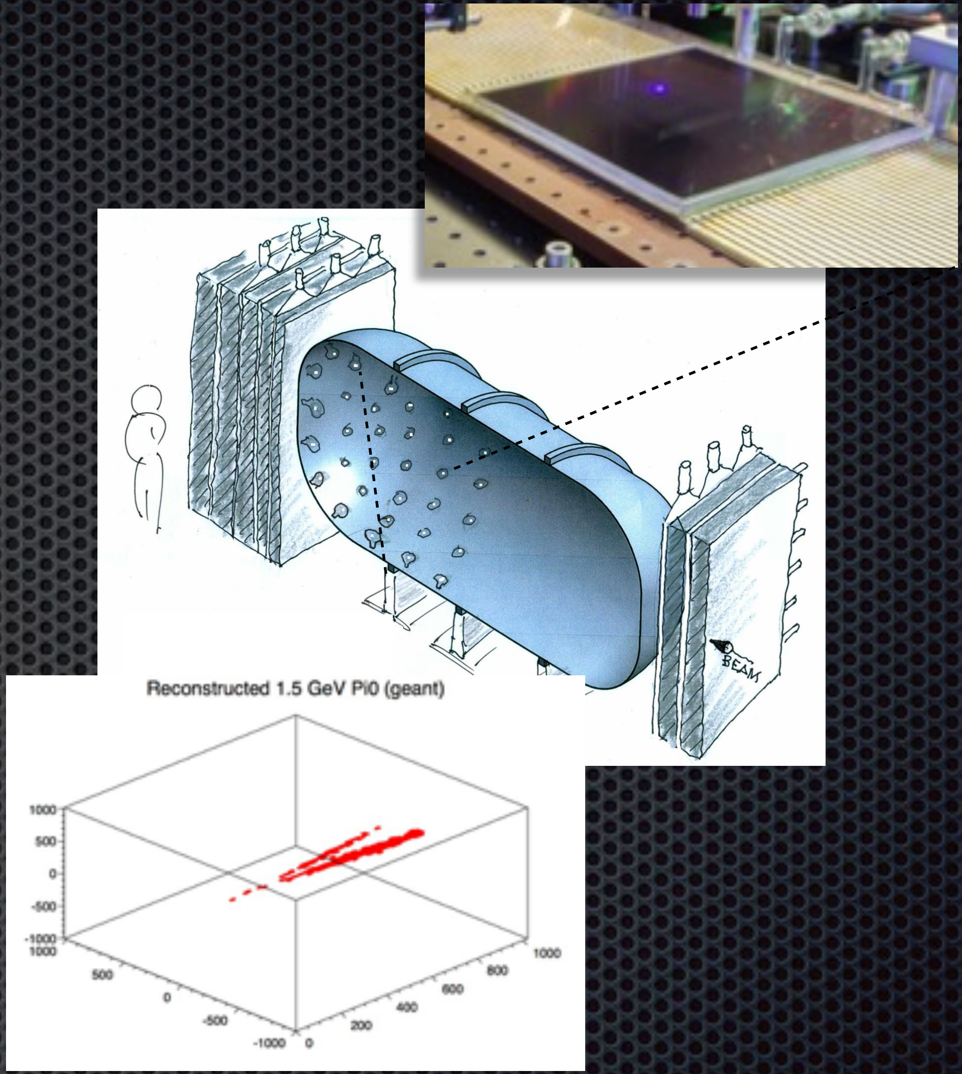


- ANNIE, a proposed experiment at Fermilab could be the first HEP test bed for LAPPDs (see arXiv:1409.5864).
- This experiment seeks to measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy.



- Demonstration of a new approach to neutrino detection: Optical Time Projection Chamber using new photosensor technology.

ANNIE and then...



- ANNIE is ideal as a first test for LAPPDs as it is small enough that is feasible with their initial limited availability.
- A 30-ton detector using Gd-enhanced water for neutron capture. It will combine LAPPDs with standard PMTs.
- The LAPPDs are used to determine vertex of neutrino interaction. Using generalized Hough transforms, detailed track reconstruction is enabled.
- It is a critical first step for efforts to develop an advanced water-based liquid scintillator detector concept (see G. Orebi-Gann talk).
  - Synergy with other concepts such as Watchman.

Part of a larger program:

ANNIE Watchman ASDC

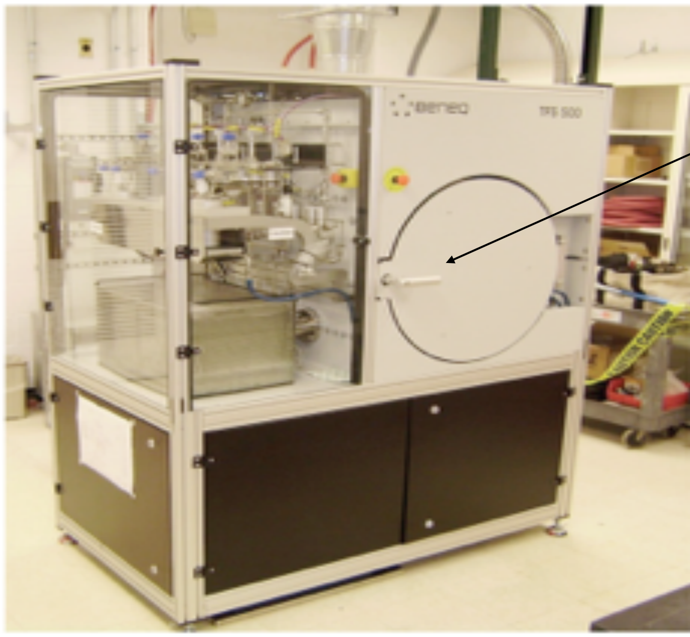
Conclusions

- Hyper-K, JUNO, LENA, Memphys, LBNE and others have worked on evaluating and developing photodetector technology.
- The LAPPD collaboration has made progress in demonstrating key innovations in producing large-area microchannel plates. Commercialization is underway.
- A new generation of larger area photodetectors is in development.
  - Enabling new capabilities in experiments and driving the cost down of key elements such as photocathodes.
  - This technology enables new NNN detectors with better vertex resolution and cherenkov vs scintillation light separation.
- A program for demonstrating these new capabilities is developing.

A portfolio of large-area photodetection technologies is needed to enable a strong neutrino and nucleon decay physics program

Backup

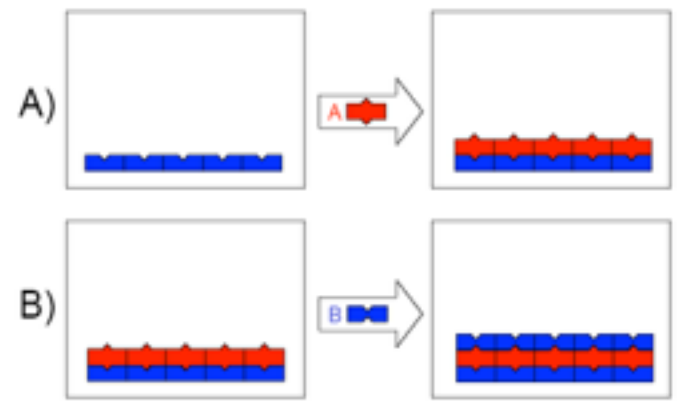
The MCP using Atomic Layer Deposition (ALD)

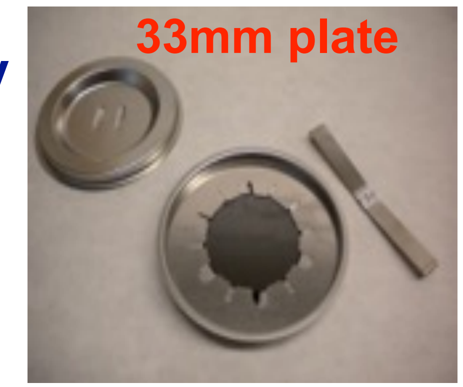


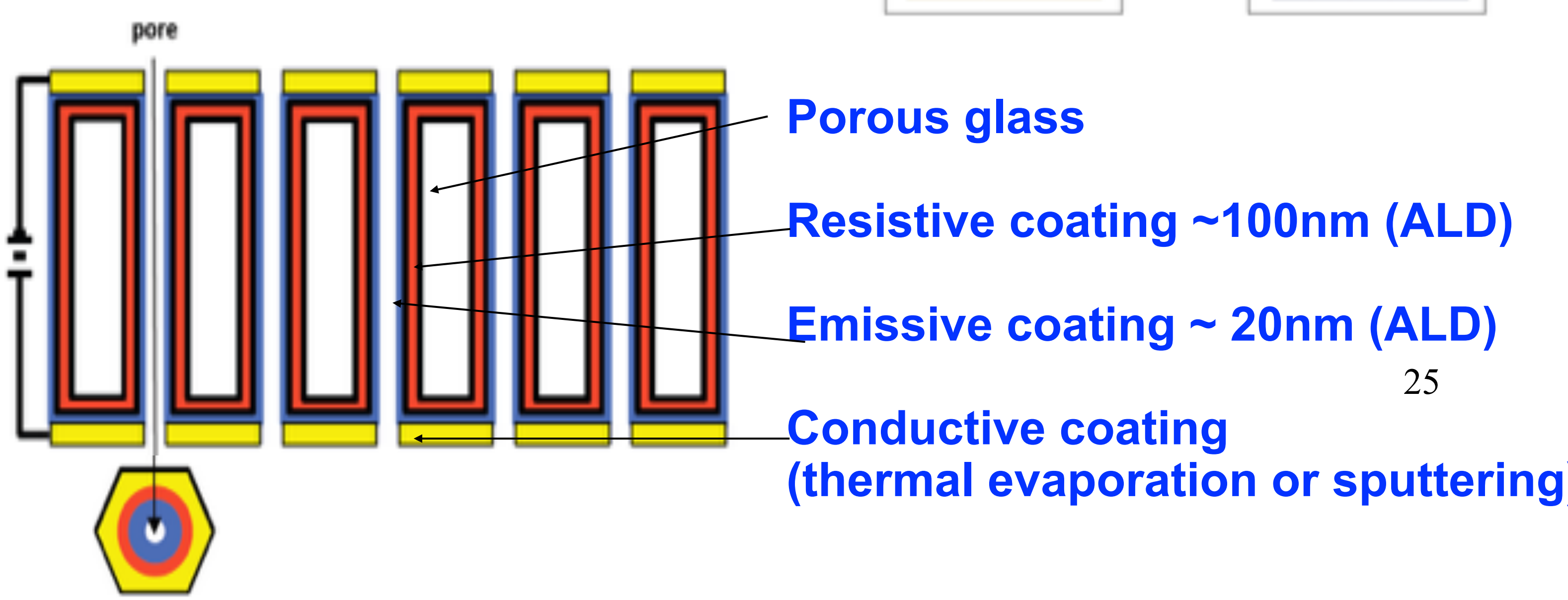
Beneq reactor for ALD

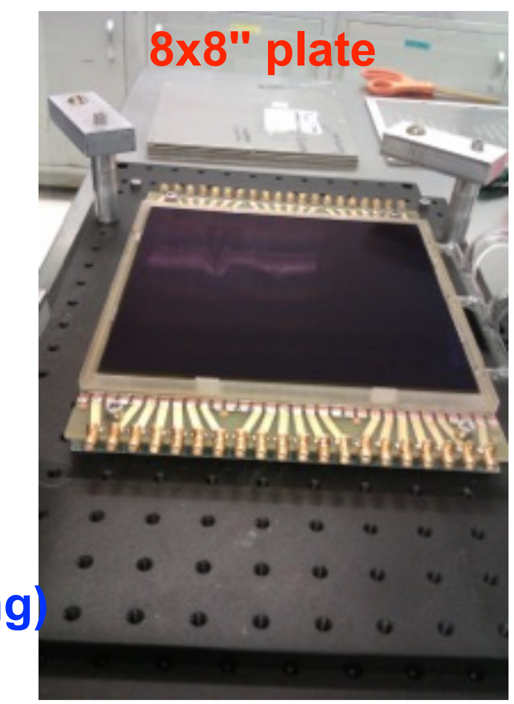
@Argonne National Laboratory

A.Mane, J.Elam



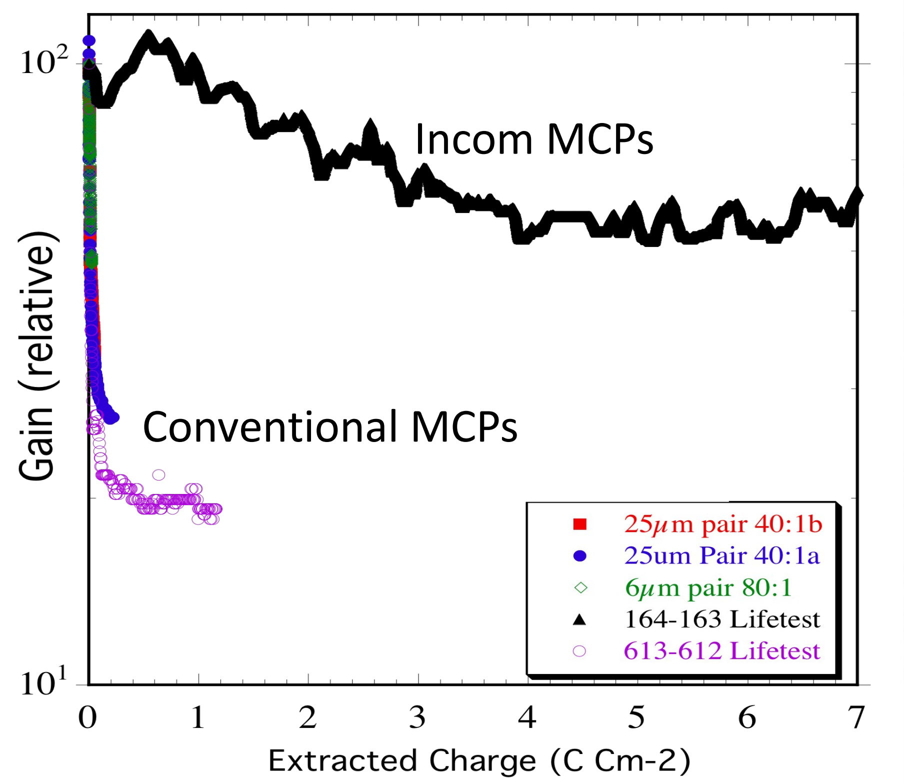


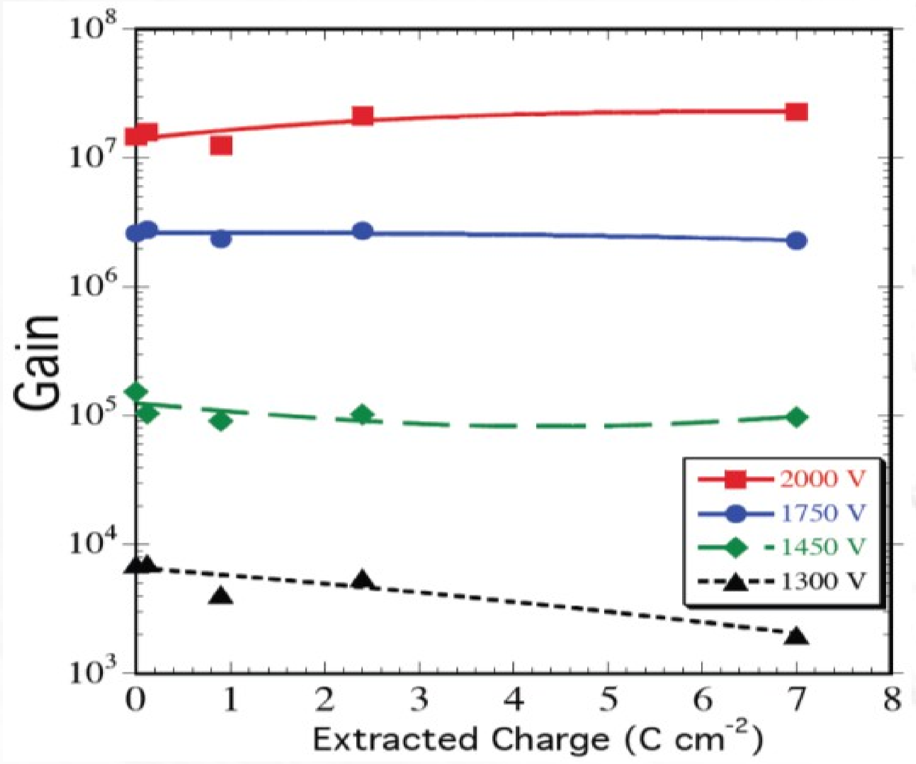




A. Elagin

Gain Stability





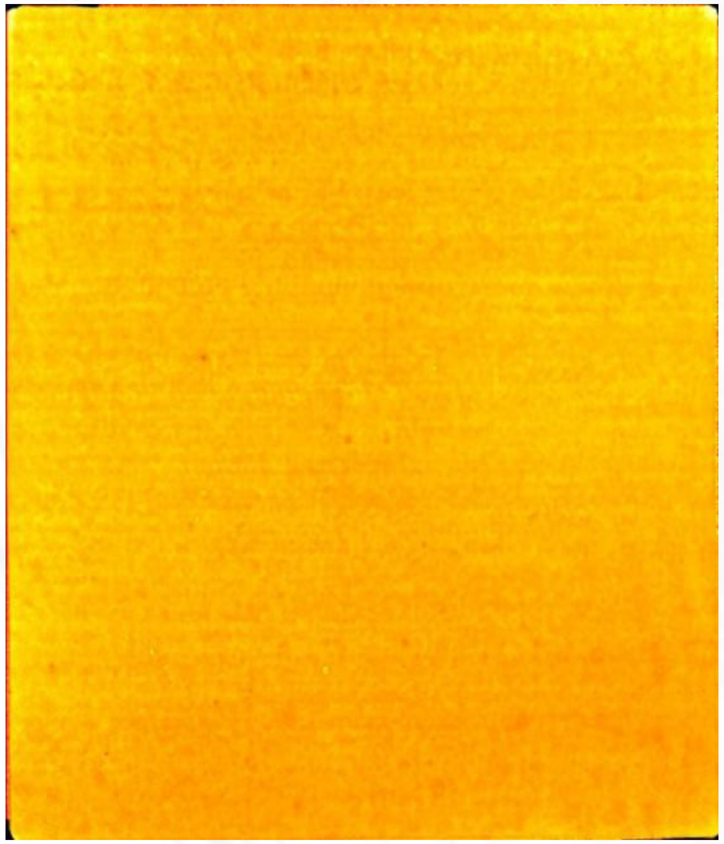
Conventional MCPs require an extensive "burn-in" to achieve a stable gain. Little burn-in is required for Incom MCPs.

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)

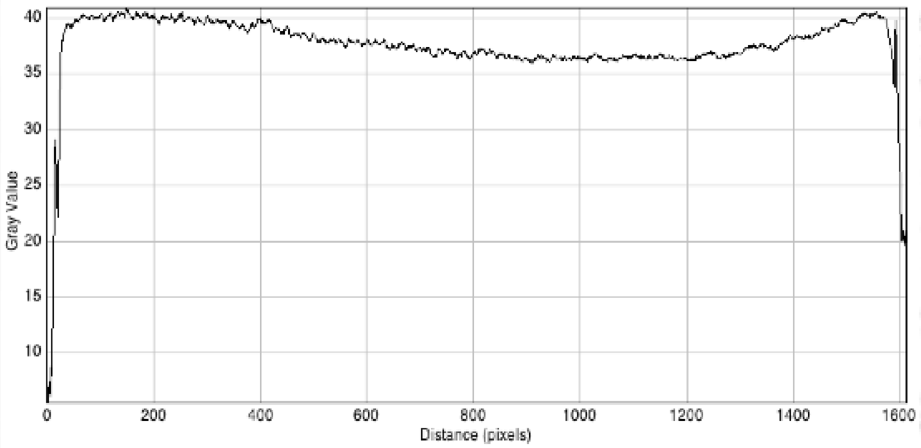
Gain is high and stable vs. extracted charge. Plot is of MCP gain at several fixed voltages during a "burn-in" test extracting 7 C/cm2 at ~3 μA output current for a pair of 33 mm, 60:1 L/D, 20 μm pore ALD MCPs.

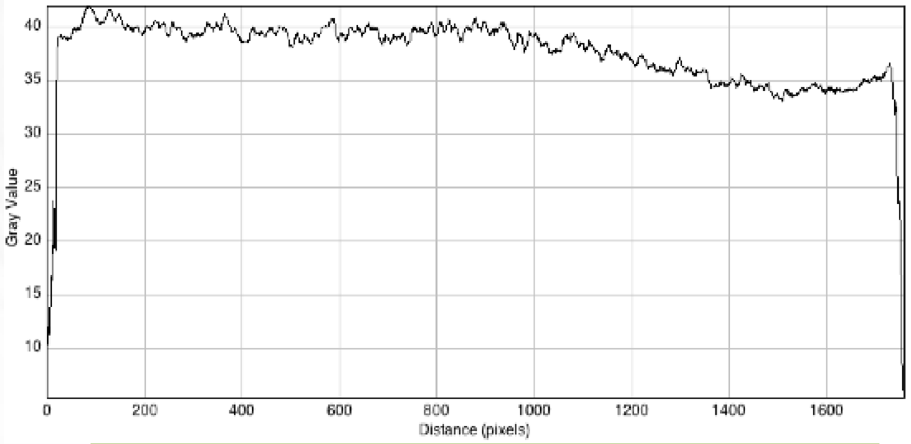
Oswald H. W. Siegmund, John V. Vallerga, Anton S. Tremsin, Jason B. McPhate, Xavier Michalet, Shimon Weiss, Henry Frisch, Robert Wagner, Anil Mane, Jeffrey Elam, Gary Varner, "Large Area and High Efficiency Photon Counting Imaging Detectors with High Time and Spatial Resolution for Night Time Sensing 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





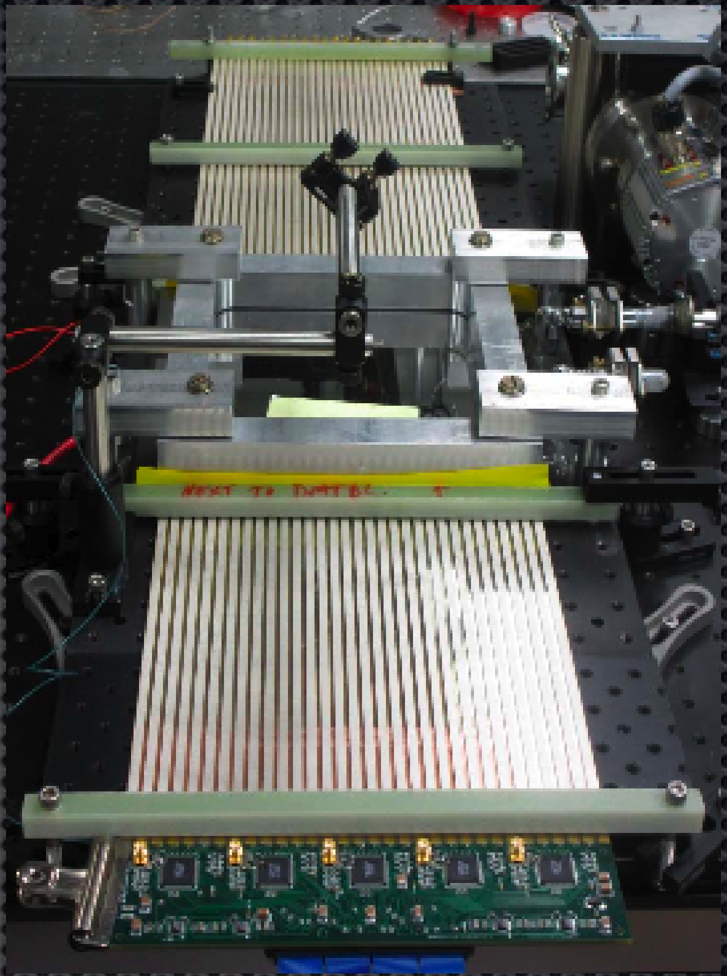
Gain is uniform within ~15% across full 20 x 20 cm^2 area

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).

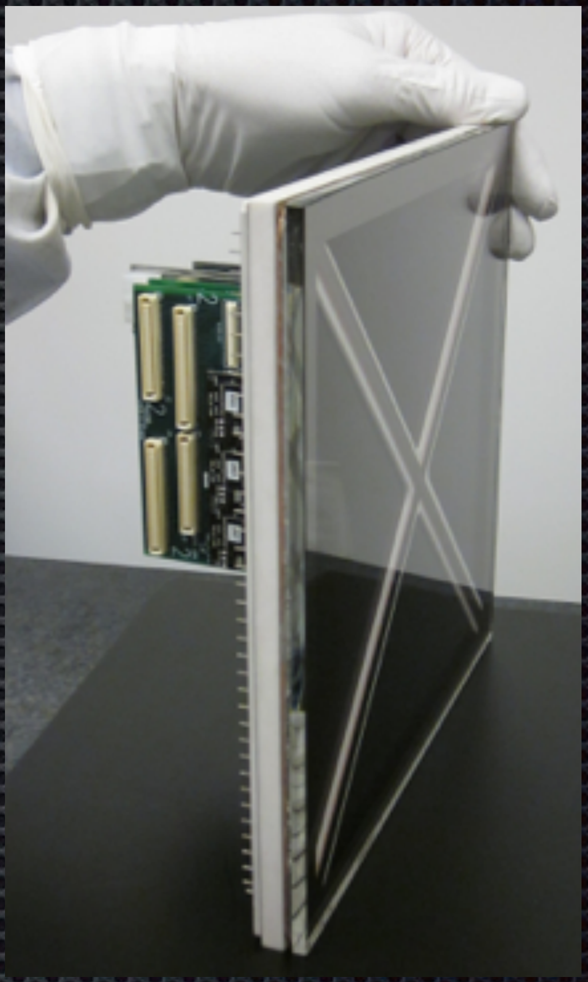
Also, very low noise: <0.1 counts cm^{-2} s^{-1}
a factor of ~4 lower compared to conventional MCPs

LAPPD Status

- 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



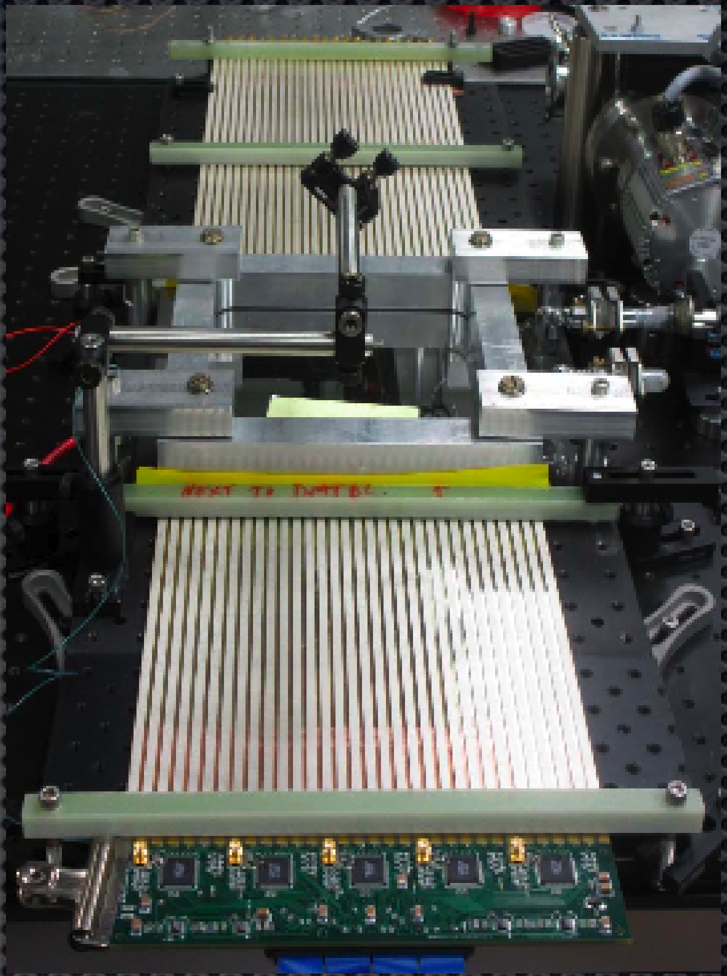
Berkeley SSL detector system- ceramic body LAPPD

UChicago lightweight in-situ assembly

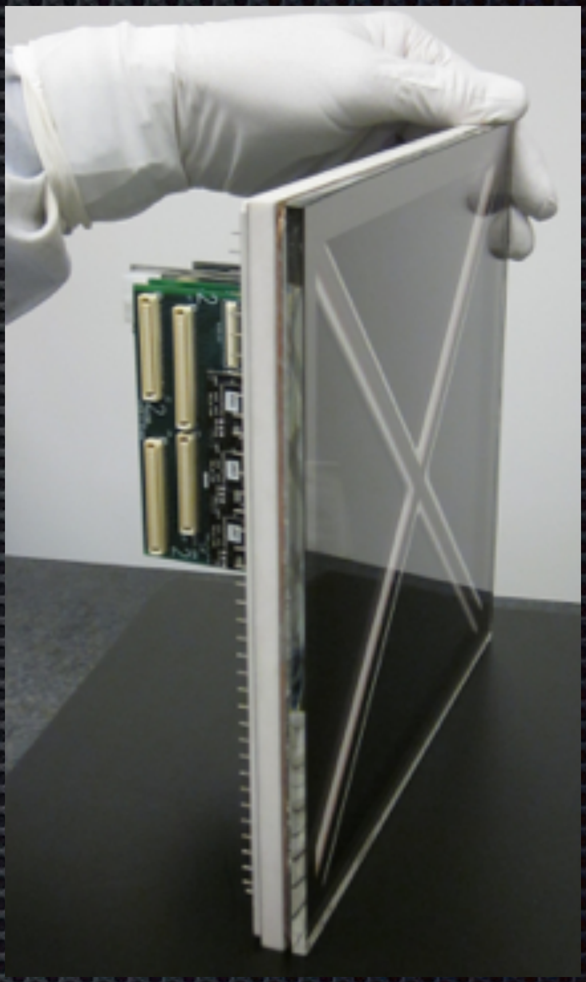
Berkeley SSL Sealed-Tube Processing Tank

LAPPD Status

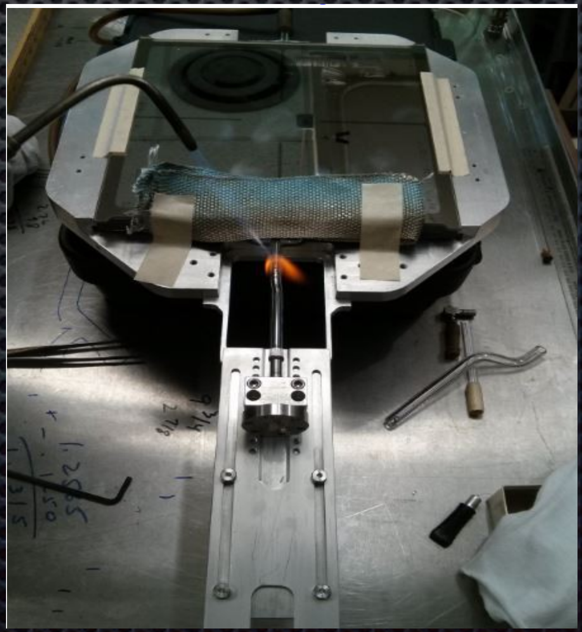
- Psec4 chip benchmarked at:
  - 1.6 GHz analog bandwidth,17 Gsamples/second, ~ 1mV noise
- Psec electronics system is capable of shape-fitting the LAPPD pulses for time, position, and charge at the front-end.
  - NIMA 735, (2014) 452-461. E.Oberla, J.-F. Genat, H. Frisch, K.Nishimura, G.Varner
- A pilot 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.



ANL "demountable" detector system - glass body LAPPD



Berkeley SSL detector system- ceramic body LAPPD



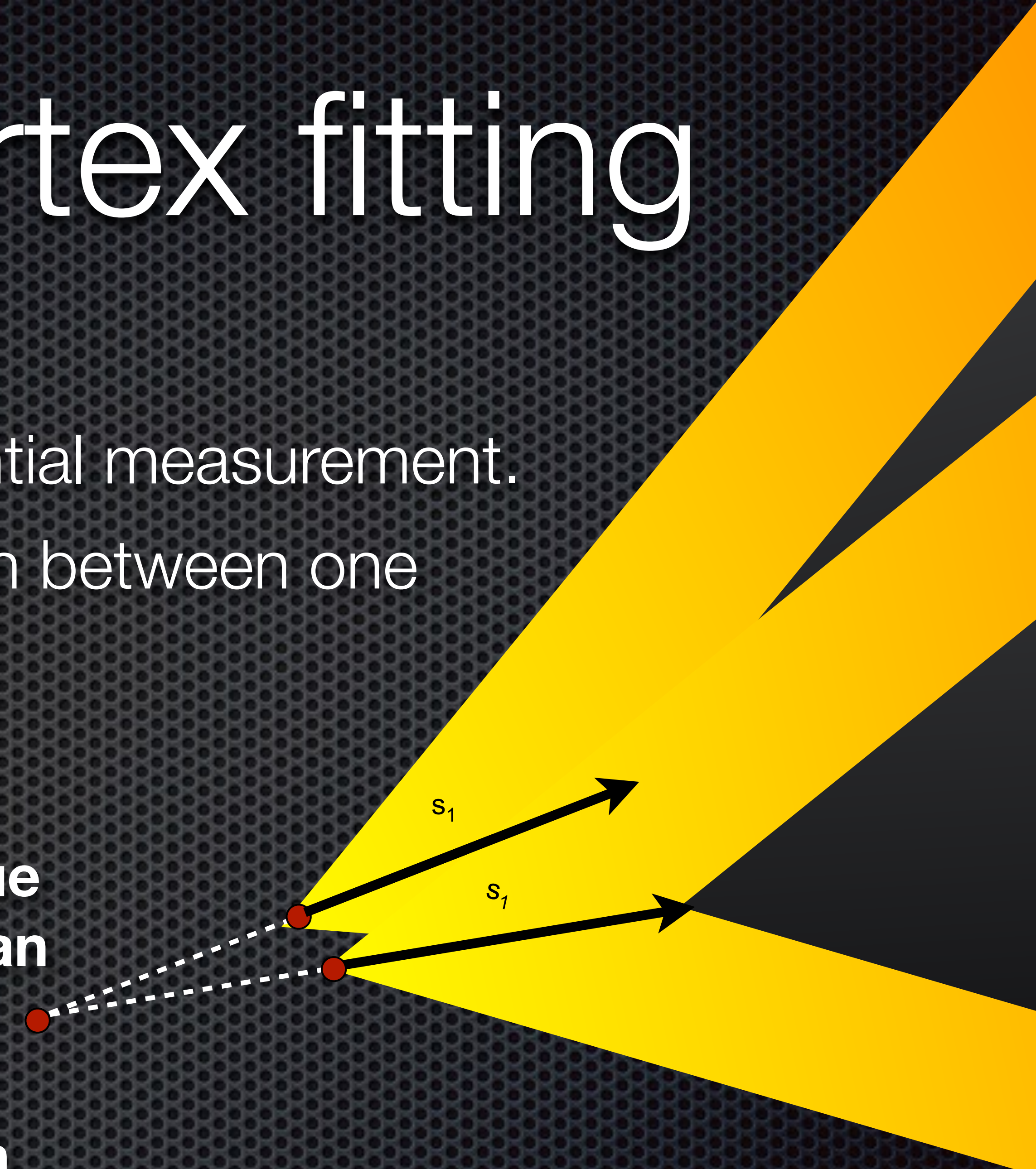
UChicago lightweight in-situ assembly

Berkeley SSL Sealed-Tube Processing Tank

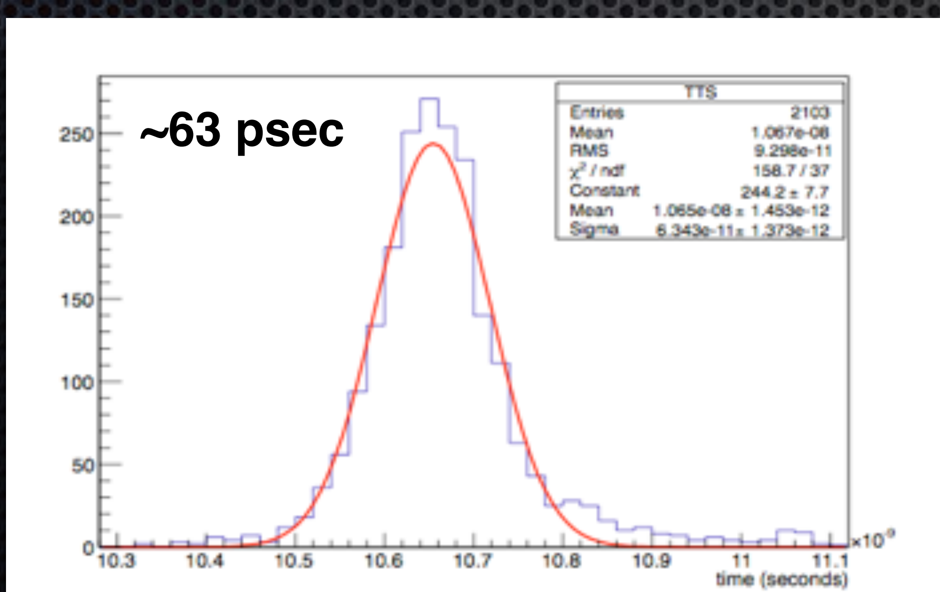
Timing-based vertex fitting

Fortunately, multi-vertex separation is a differential measurement.

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



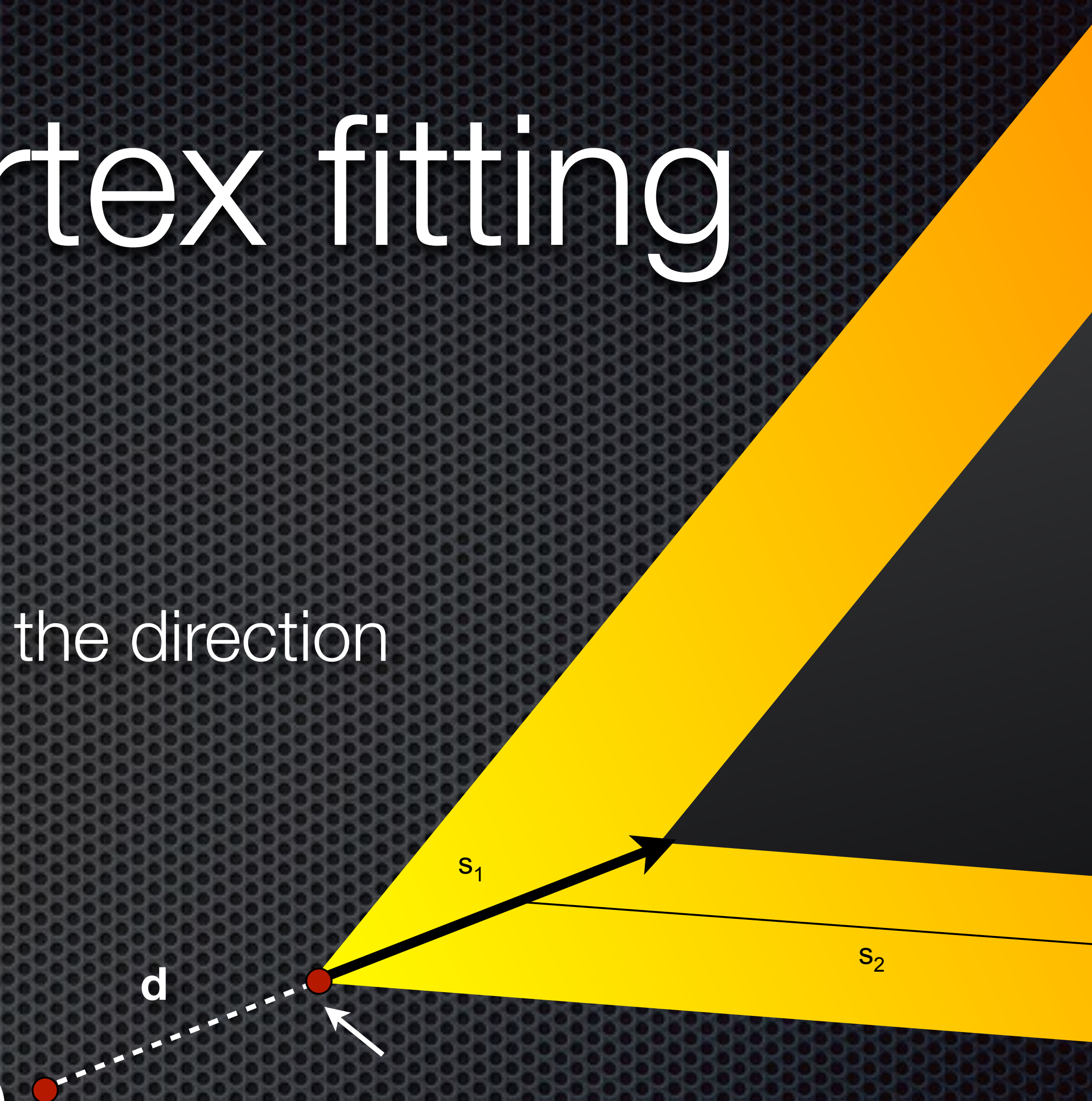
Only one unique solution that can satisfy the subsequent timing of both tracks



100 picoseconds ~ 2.25 centimeters

Timing-based vertex fitting

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



casually consistent vertex hypothesis (albeit non-physical)

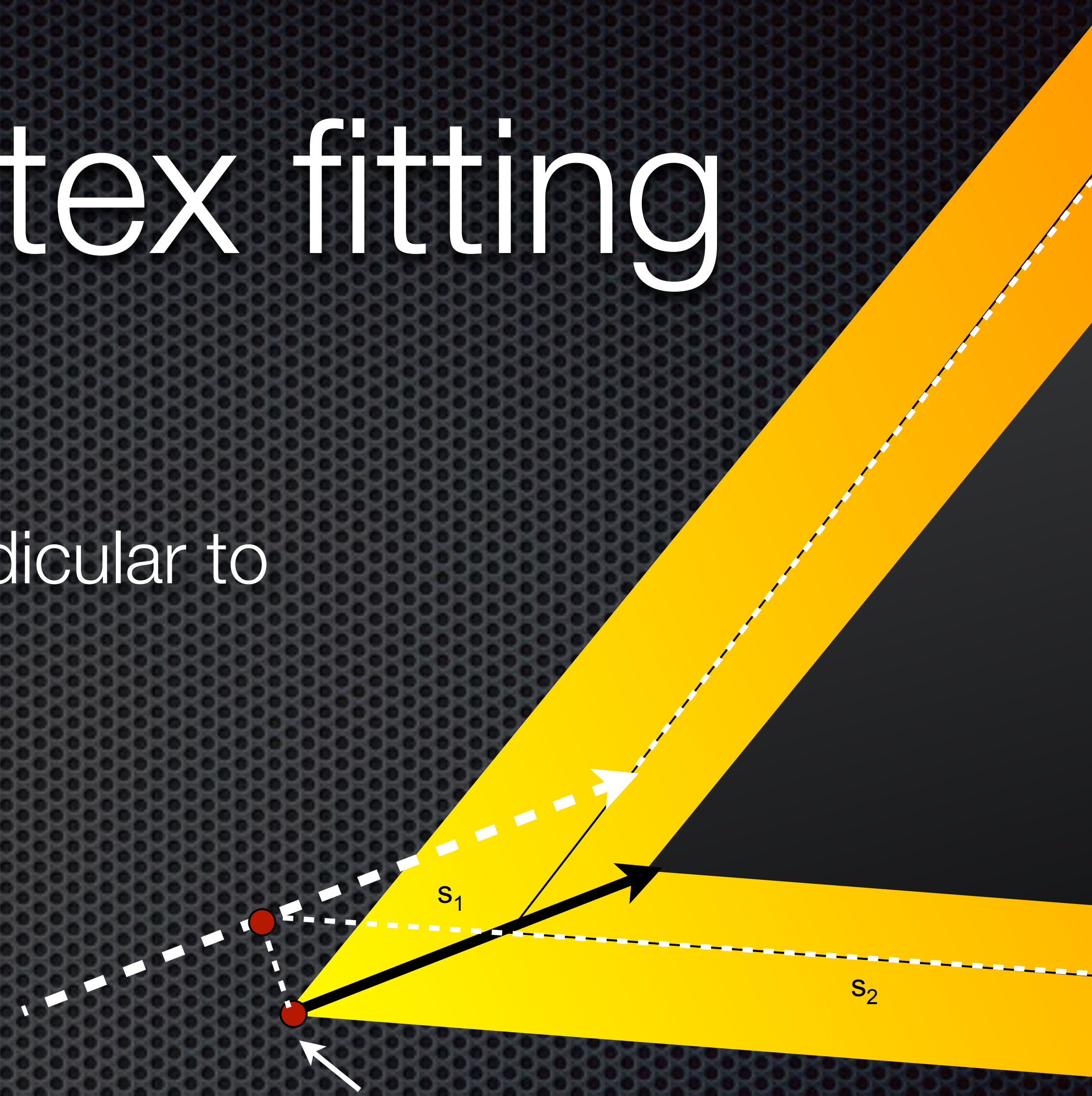
$$T_0' = T_0 - dn/c$$

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 (albeit non-physical)

$T_0' = T_0 - dn/c$

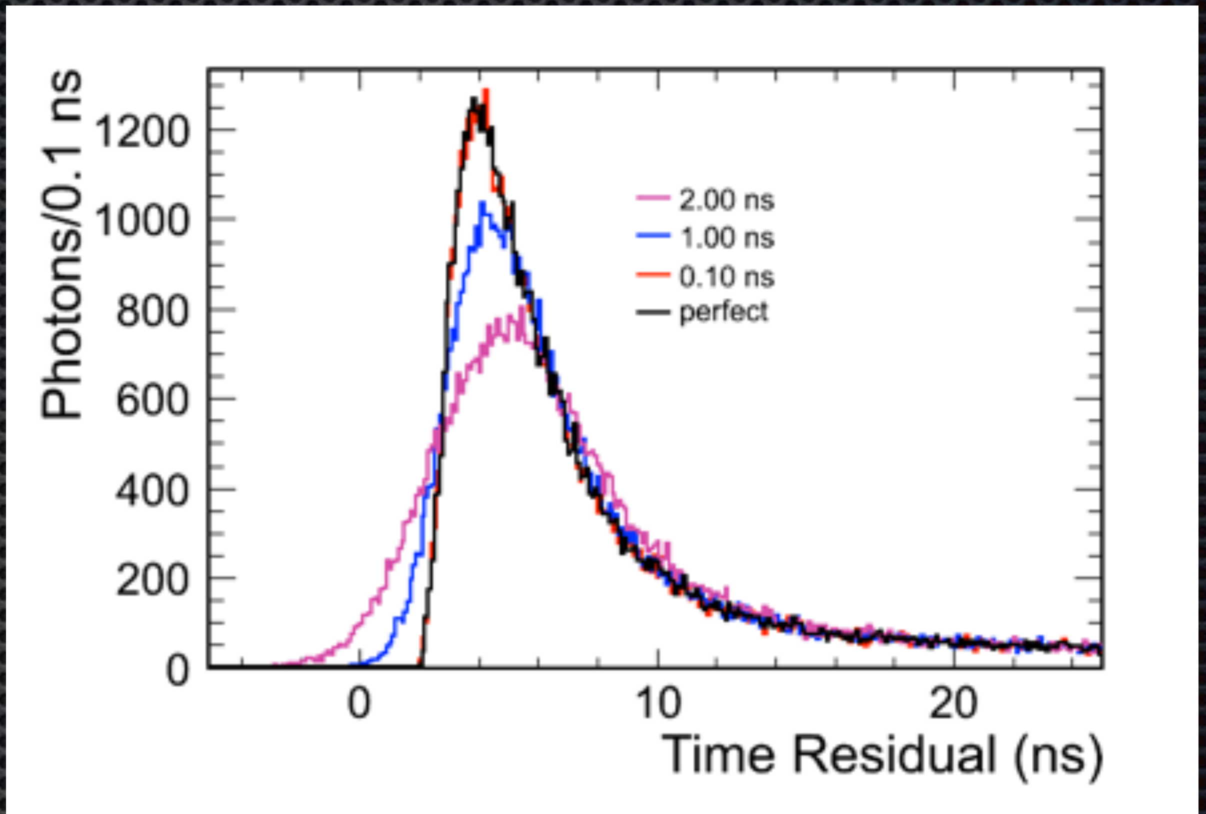
true vertex: point of first light emission

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

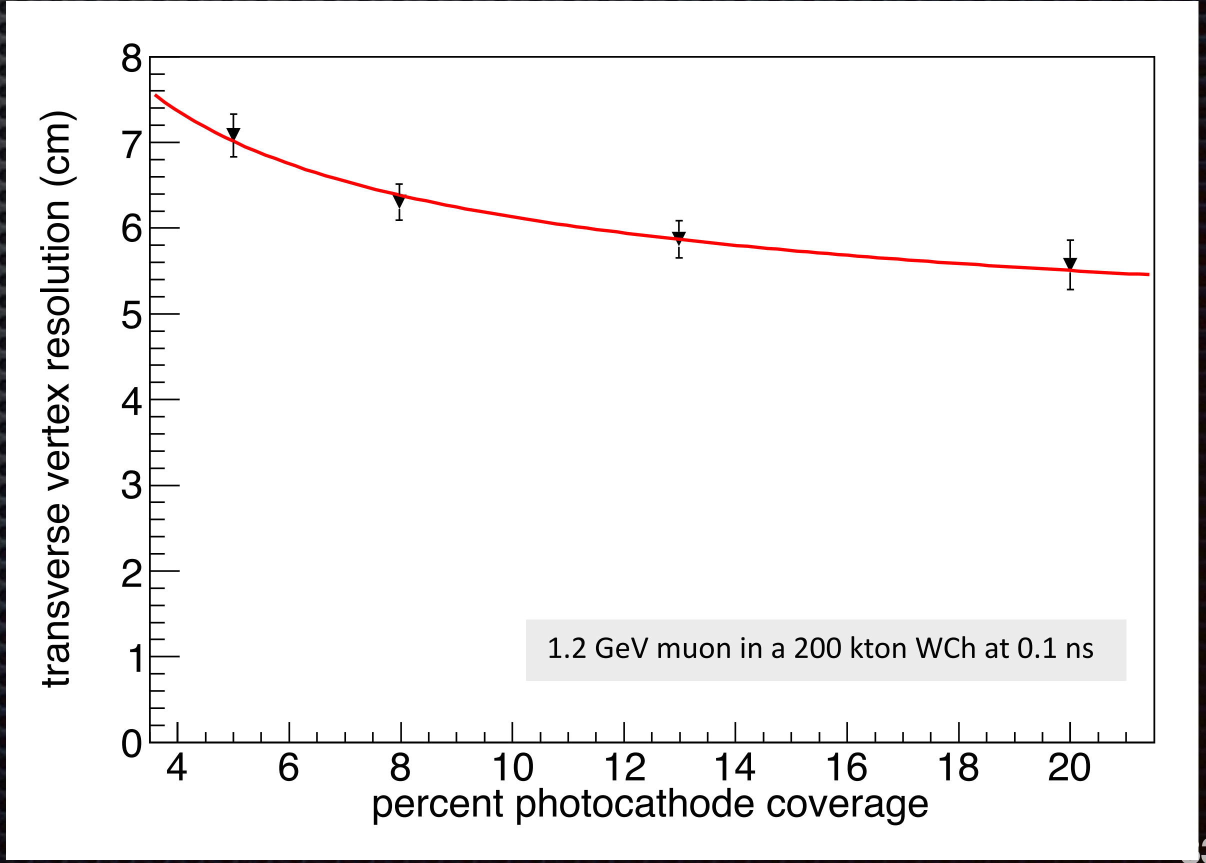
100 picoseconds ~ 2.25 centimeters

Using 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.



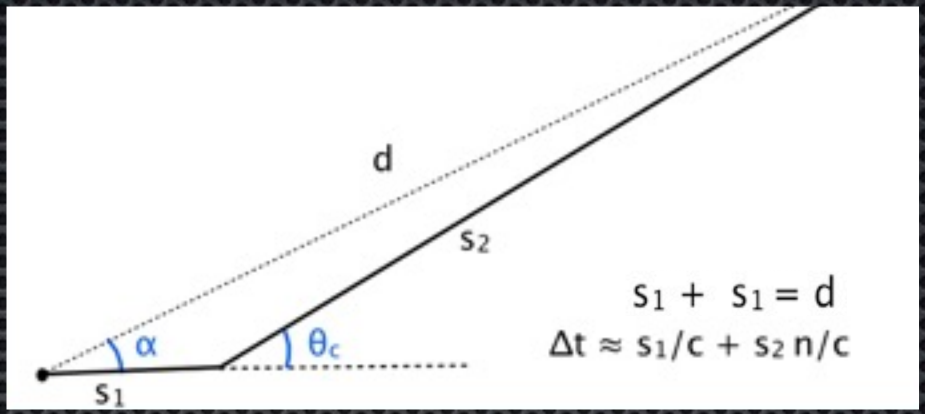
- We also find that, for a given detector, the size of the uncertainties on the transverse vertex resolution scale with coverage consistent with $\sqrt{n}$.

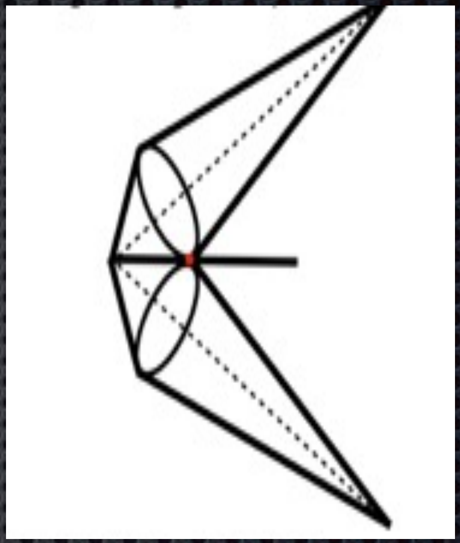


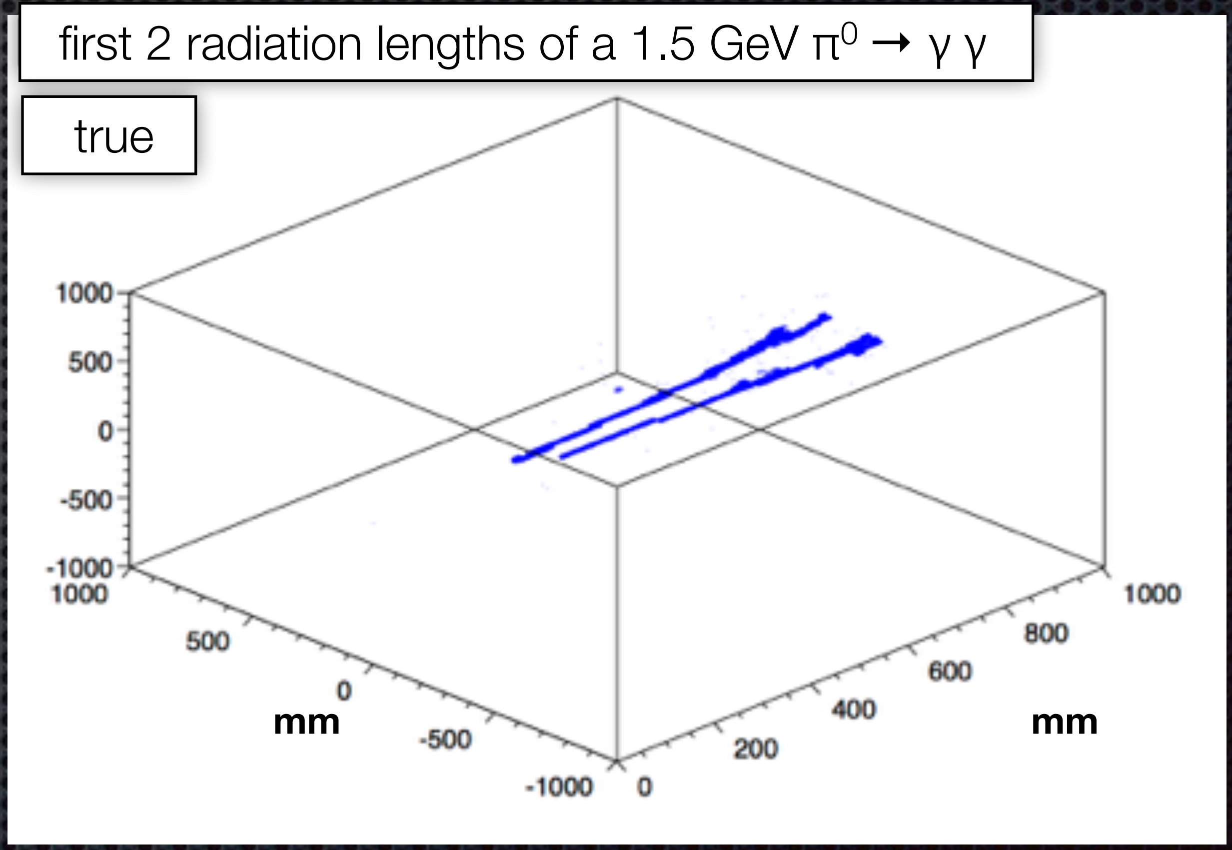
M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL), I. Anghel (ISU), E. Catano-Mur (ISU), T. Xin (ISU)

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.



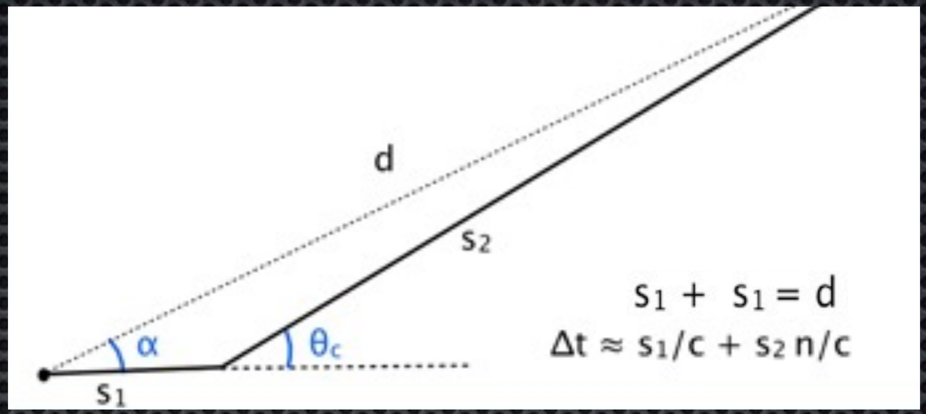


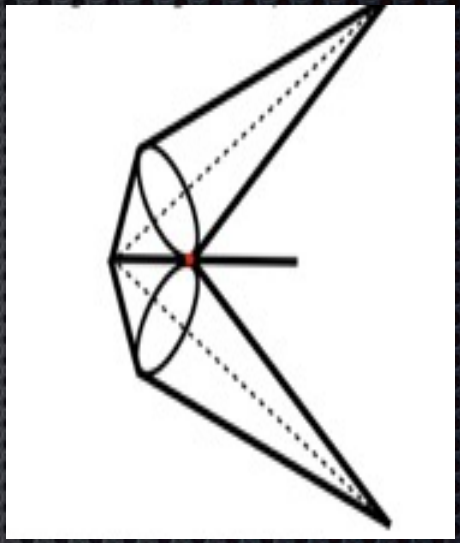


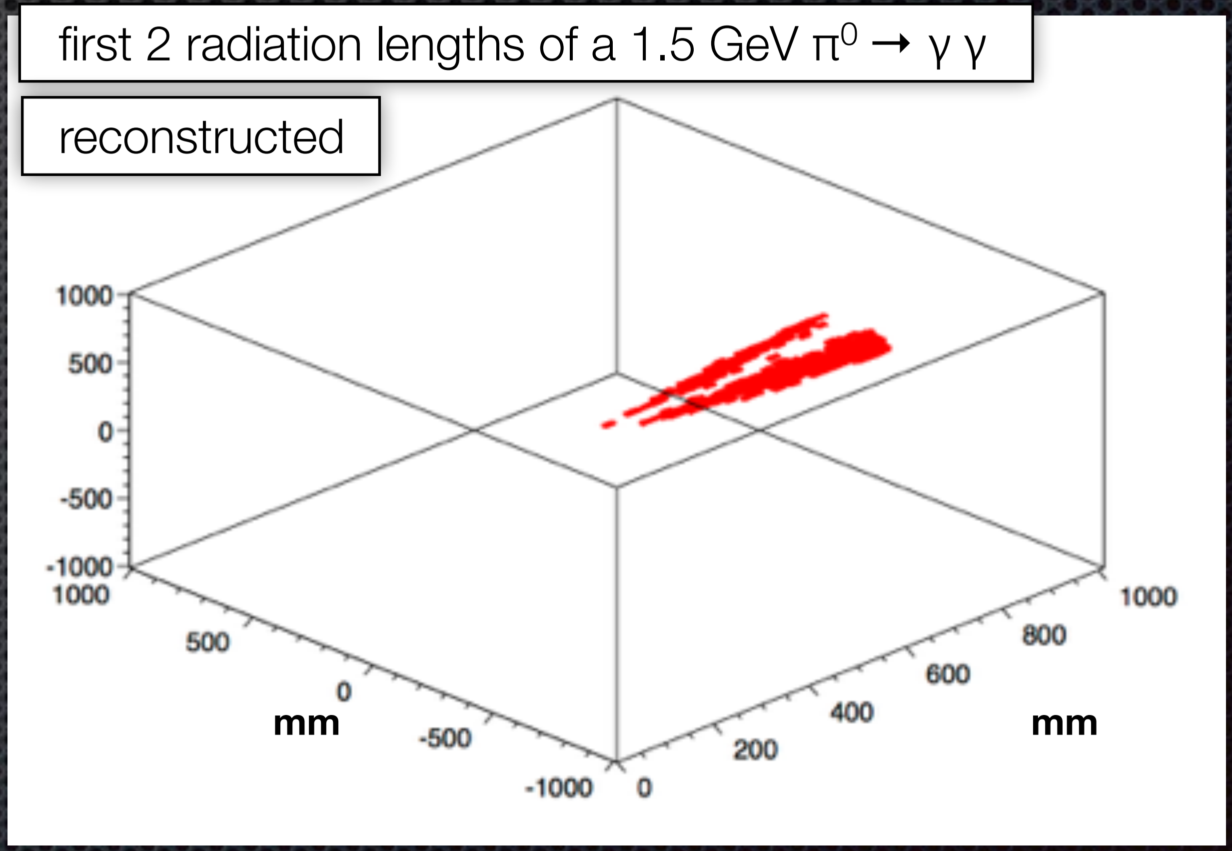
M. Wetstein

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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