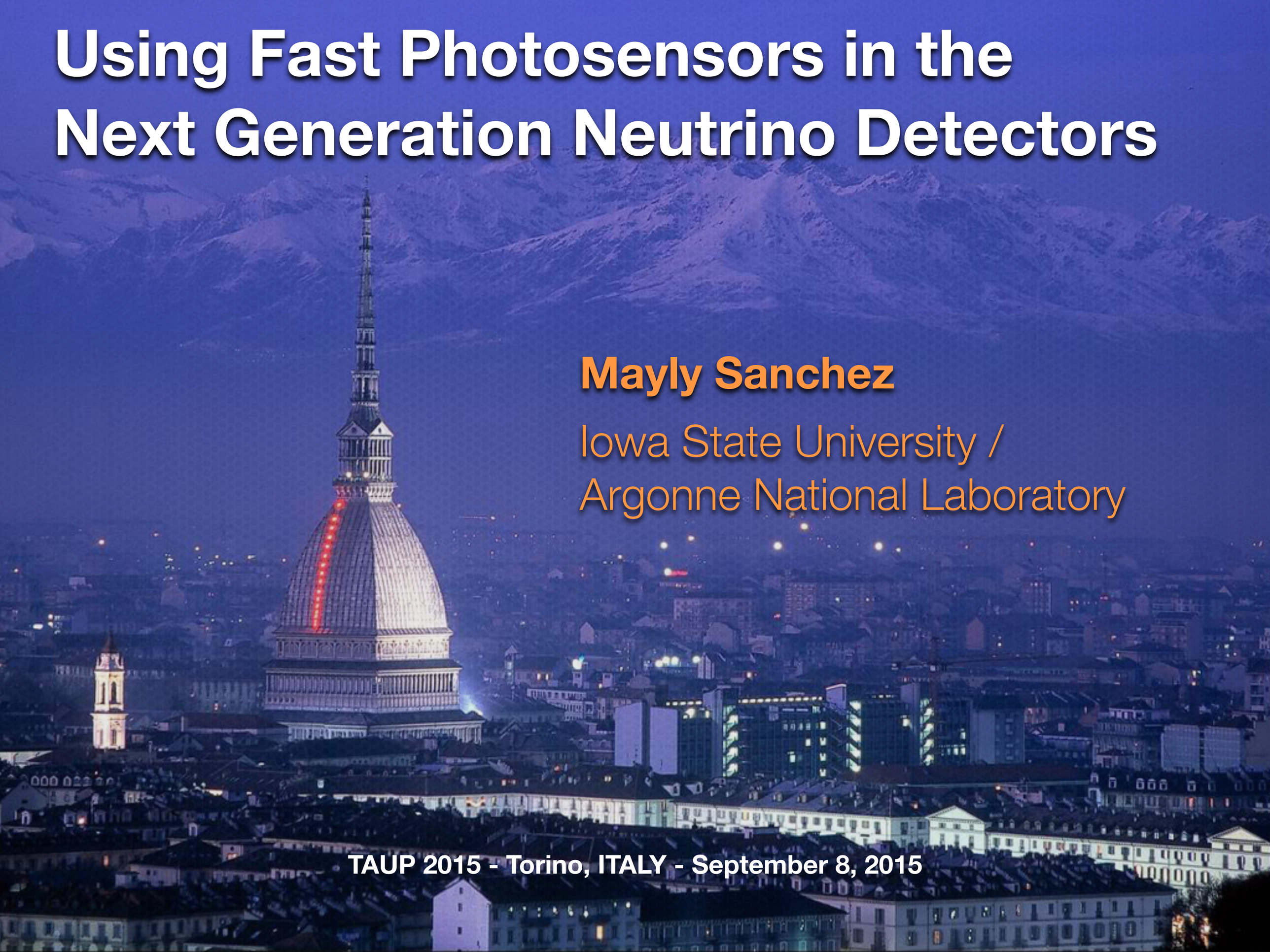
Using Fast Photosensors in the Next Generation Neutrino Detectors

Mayly Sanchez

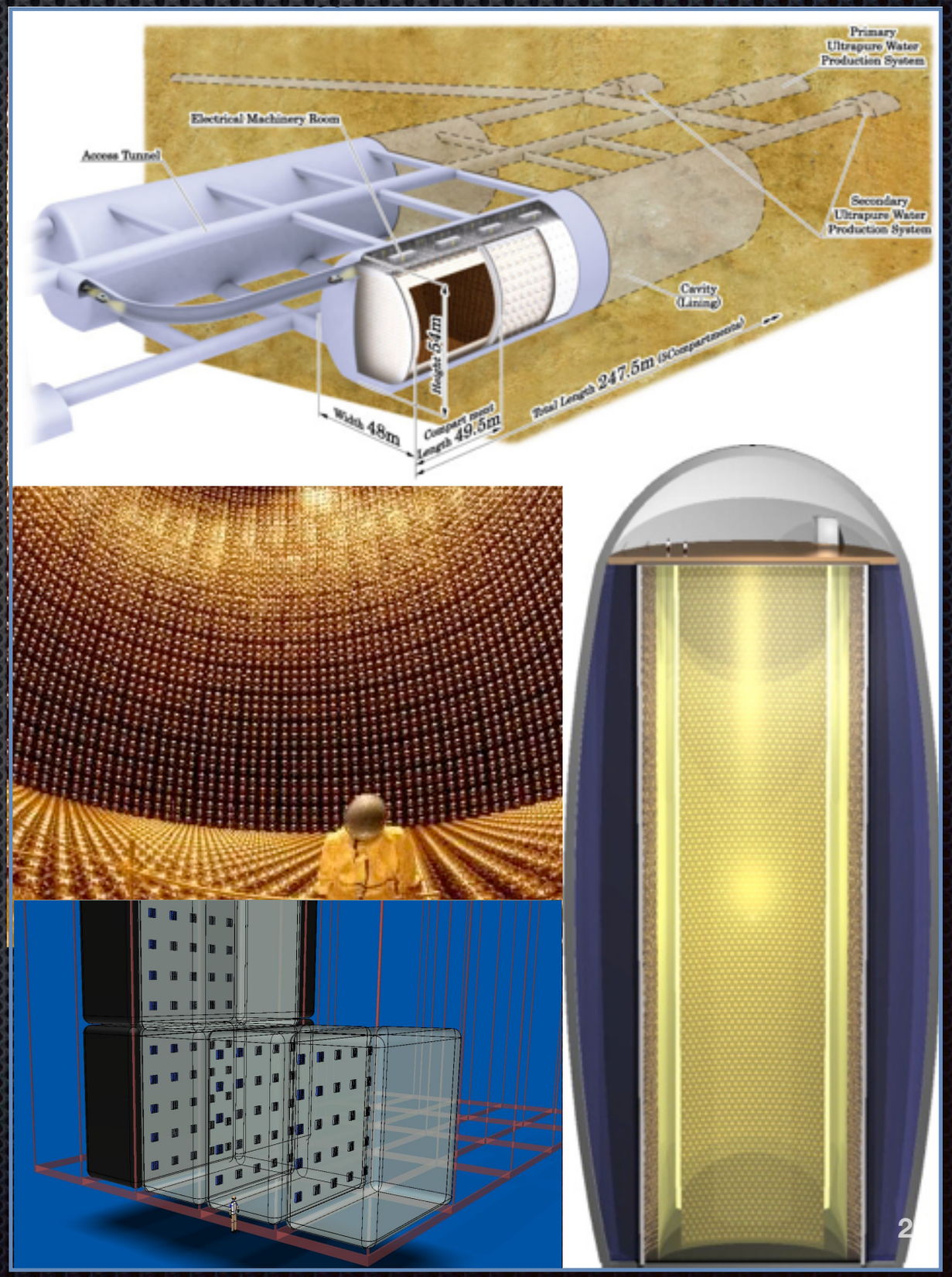
Iowa State University /
Argonne National Laboratory



TAUP 2015 - Torino, ITALY - September 8, 2015

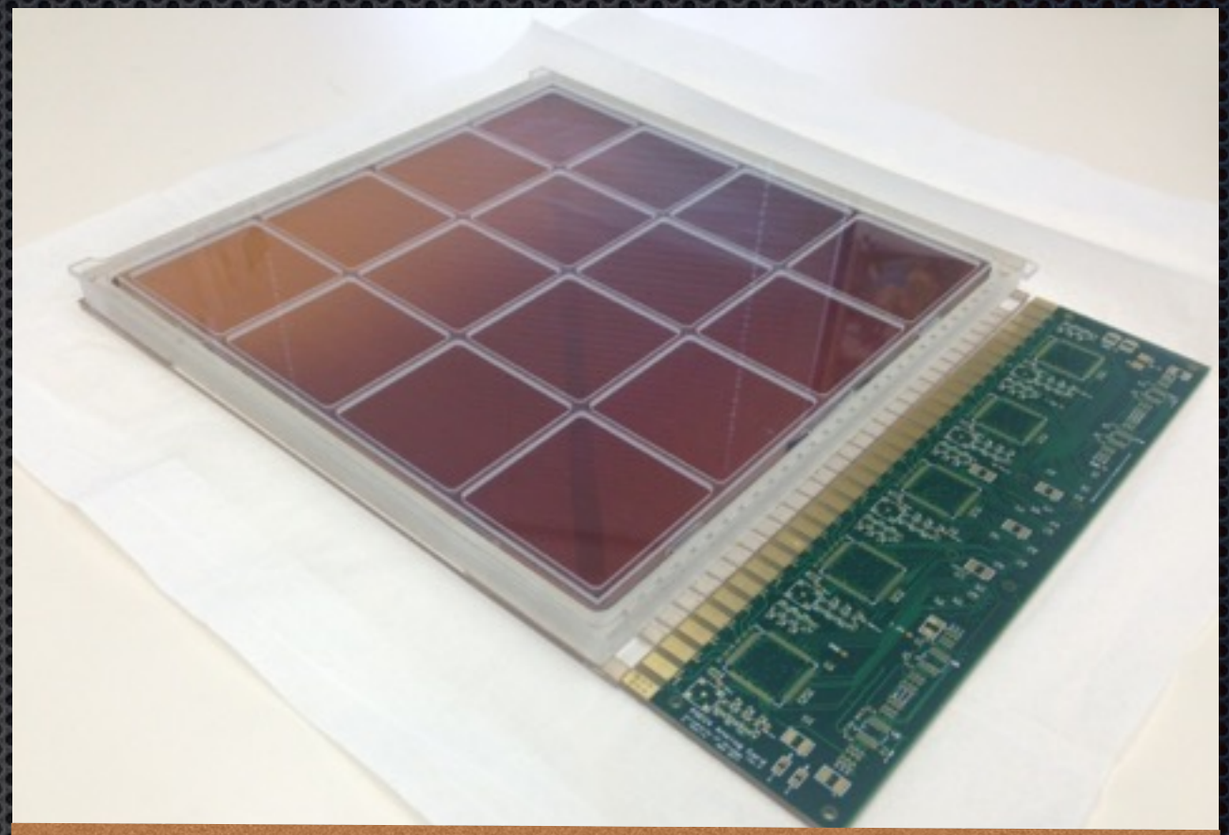
The next generation neutrino detectors

- The **next generation of neutrino experiments** will require massive detectors to reach the sensitivities needed to measure CP violation, the mass hierarchy, the θ_{23} octant, nucleon decay and supernova relic neutrinos.
- One or several **large detectors,** can provide the mass required for these experiments.
- A challenge will be instrumenting the **very large volumes/surfaces**.
- Another challenge will be making **multi-purpose detectors** to enable a broader physics program.



Using LAPPDs for neutrinos

- **Large-area picosecond photodetectors (LAPPD)** based on microchannel plates are being developed by collaboration of US universities, labs and private companies.
- Microchannel technology makes electron path very small allowing for excellent timing.
- For a **neutrino application**, the characteristics of these can be tuned to:
  - Timing resolution of **~100 psec**
  - Spatial resolution of **~1cm**

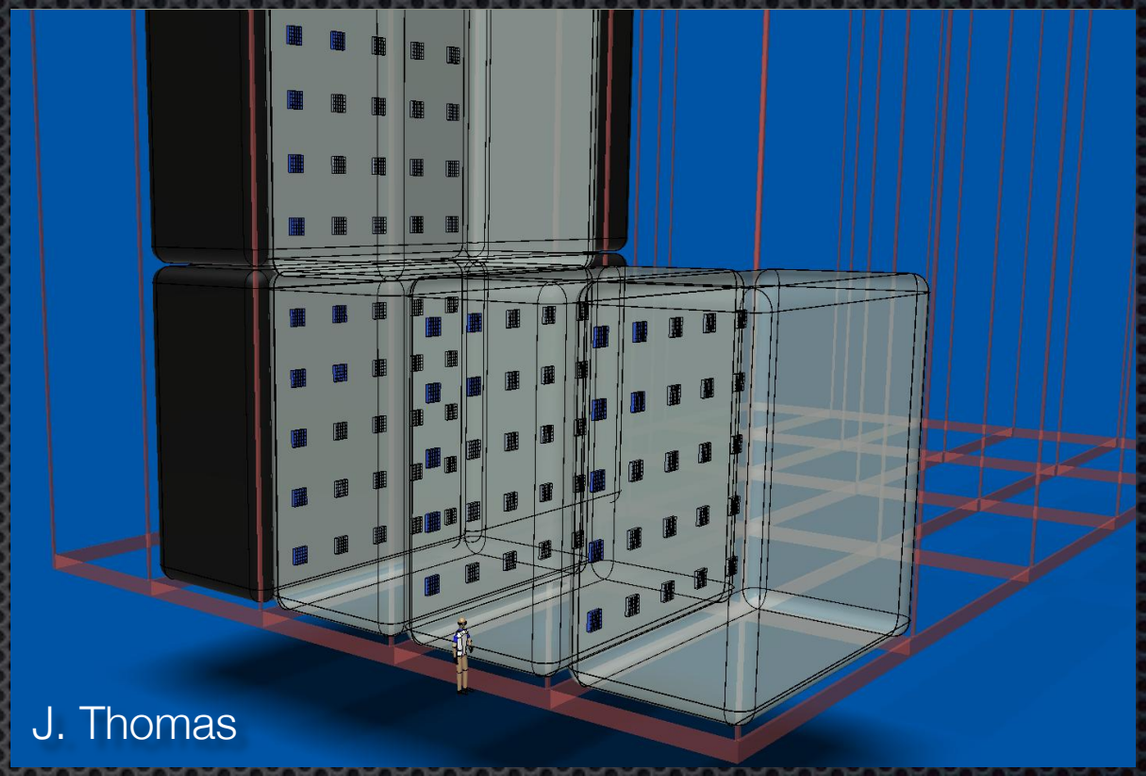


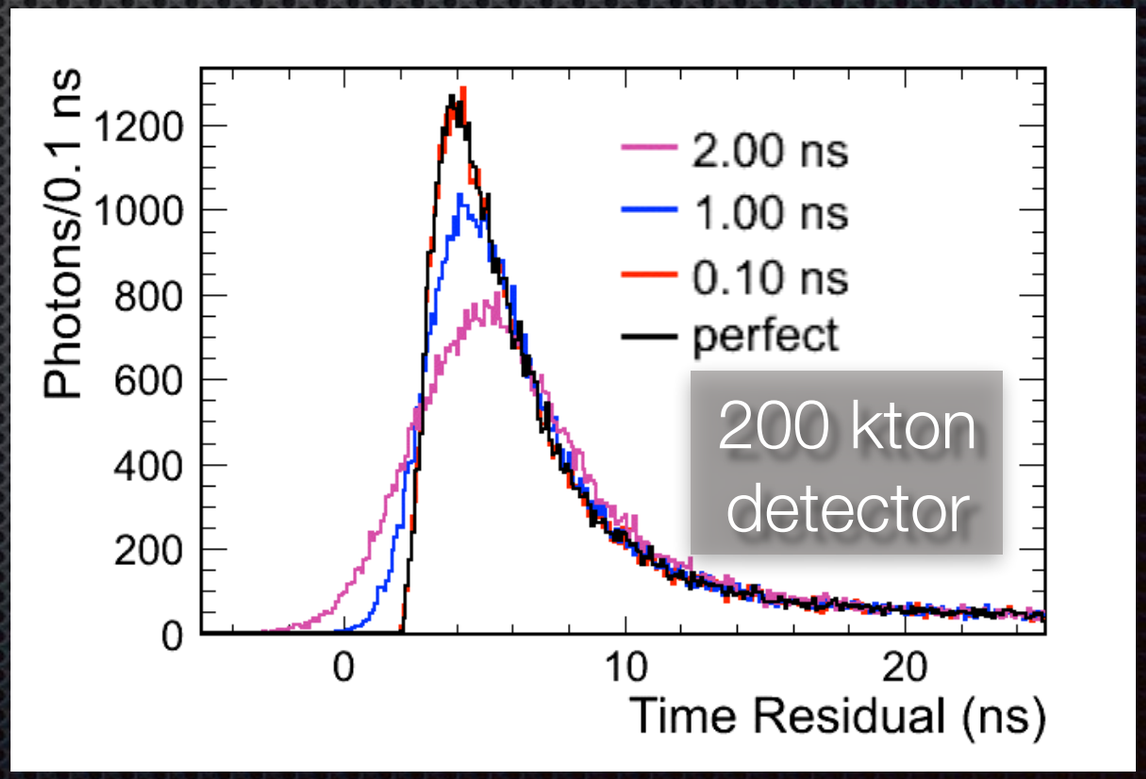
- A pilot production line is being built at Incom Inc as part of a 3 year technology transfer program.
- On track for first prototypes in 2016.

http://psec.uchicago.edu

Using LAPPDs for neutrinos

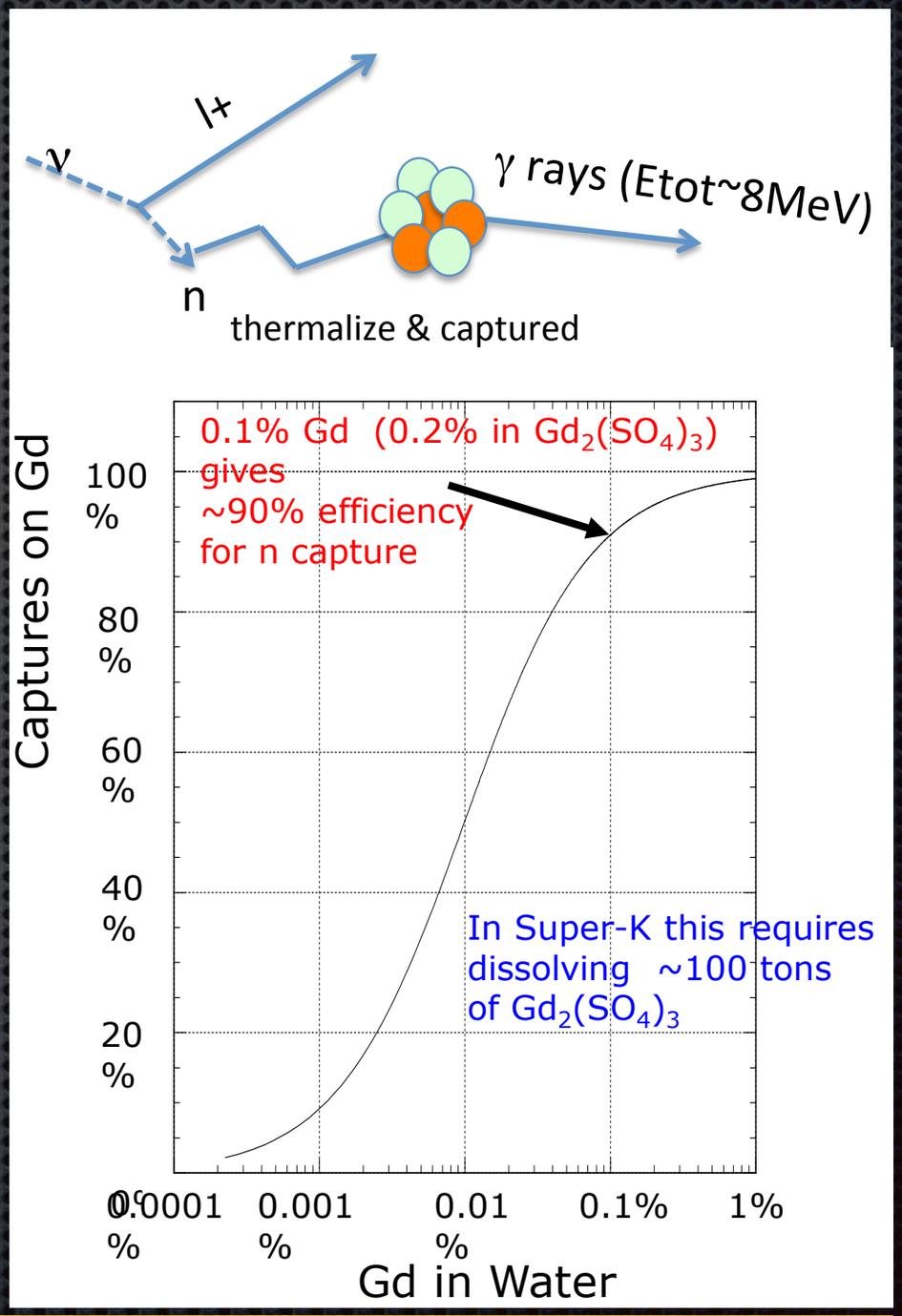
- This new technology applied to **Water Cherenkov detectors** could open the door to better background rejection and vertex resolution as well as high intensity (near det.) situations.
- Potential impact of LAPPDs:
  - Does **better timing information** improve vertex resolution for interactions in Water Cherenkov detectors?
  - Does **improved granularity and/or coverage** improve particle ID?





Using Gd for neutrinos

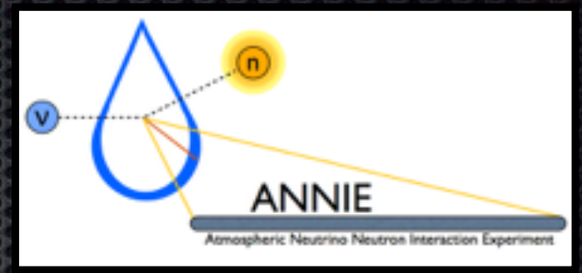
- Dissolving gadolinium (Gd) in water as neutron absorber has been proposed: Beacom and Vagins PRL93, 171101.
- Increasing the cross section of the neutron capture and shortening the time delay of the capture reduces the background for several physics measurements:
  - Supernova relic neutrino
  - Proton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



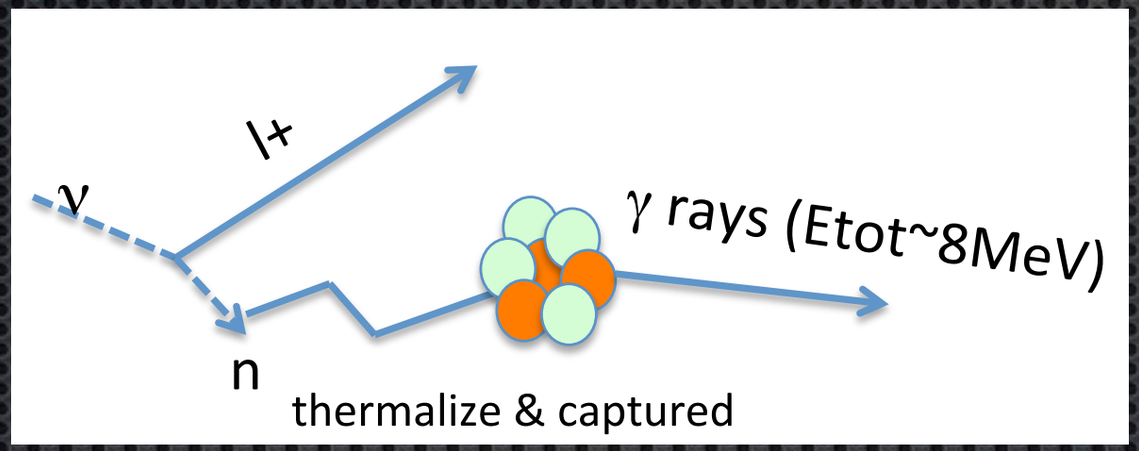
Super-K has decided on June 27, 2015 it will add Gd

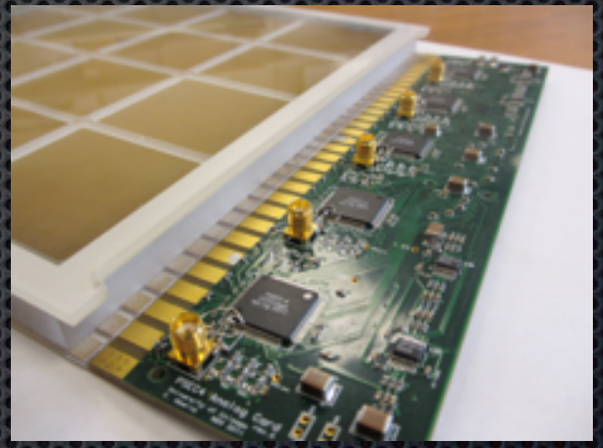
see Sekiya-san's talk - TAUP 2015

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!**

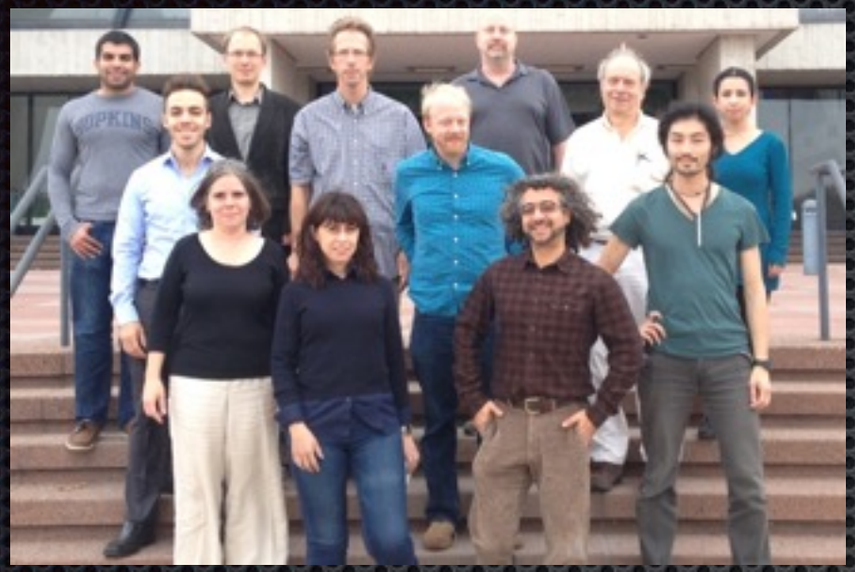




- A key physics measurement in understanding the nature neutrino-nucleus interactions.
- Application of a promising technology for detecting neutrinos.

Phase 1 - neutron background measurement - approved
Phase 2 - physics measurement - proposed

The ANNIE collaboration

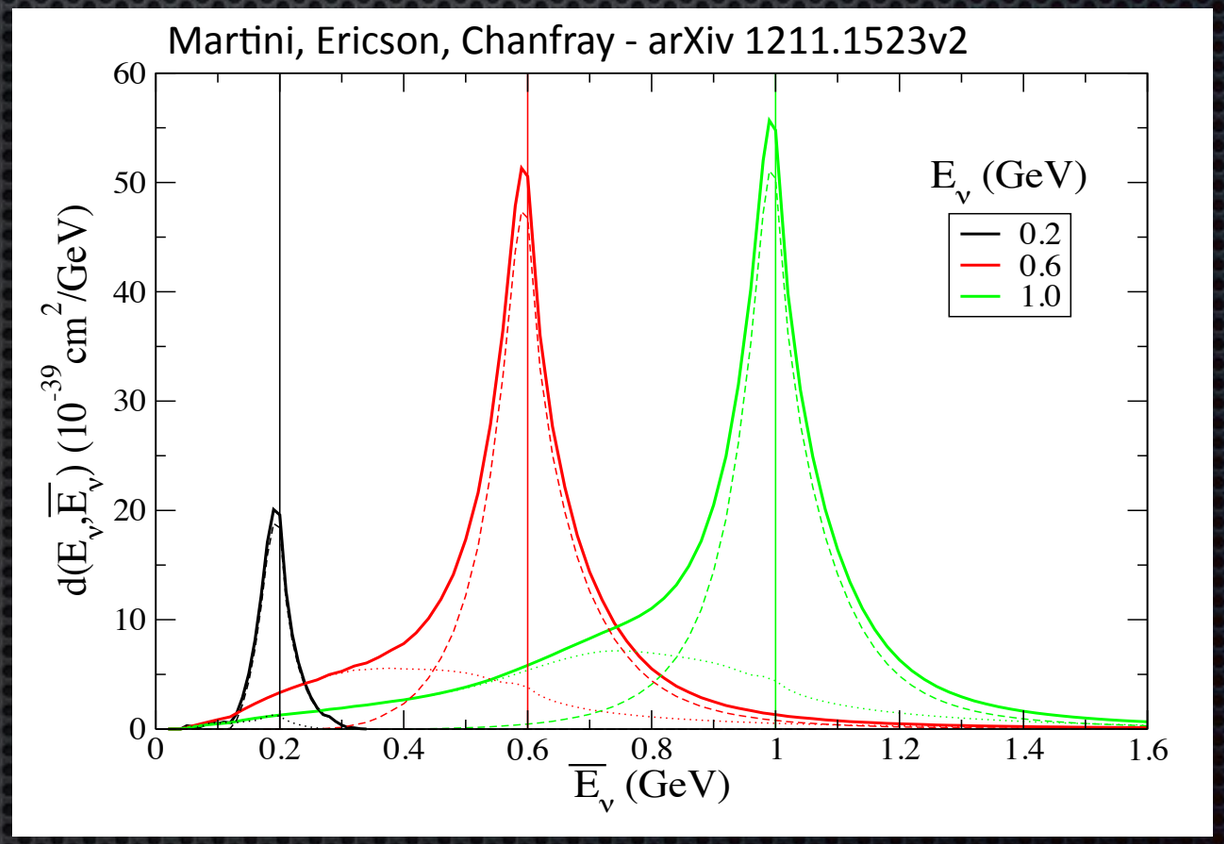


Argonne National Laboratory
Brookhaven National Laboratory
Fermi National Laboratory
University of California at Berkeley
University of California at Davis
University of California at Irvine
University of Chicago
Iowa State University
Ohio State University
University of Sheffield
Queen Mary University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

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

Studying neutrino-nucleus interactions

- Neutrino nucleus interactions are a **hot topic** for upcoming oscillation measurements.
- The recent interest in multi-nucleon and MEC processes results from high statistics data confronted with models of neutrino-nucleus interactions.
- The average bias of the wrong np-nh modeling uncertainty on T2K $\sin^2\theta_{23}$ is 3%, target 1%. M. Hartz - Nufact 2015

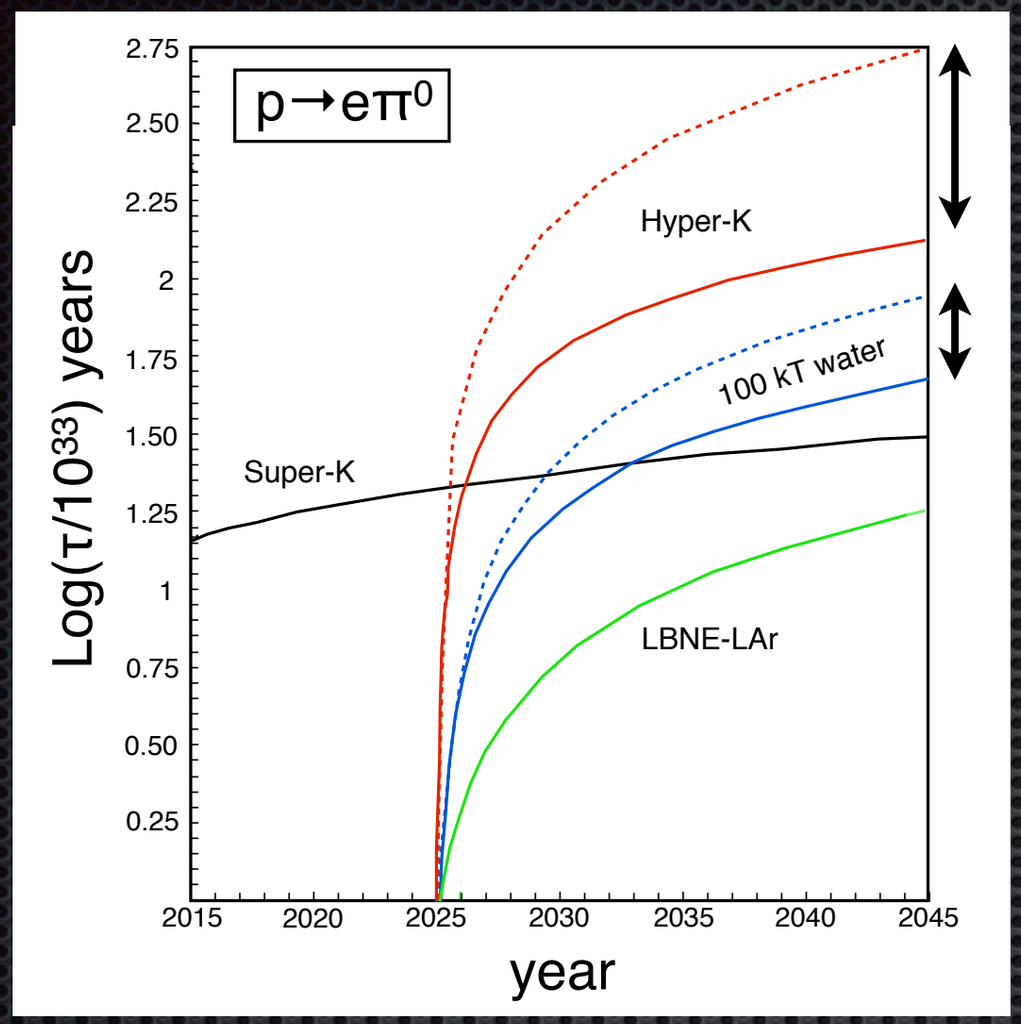


M. Martini - Nufact 2015

A variety of new neutrino data focused on understanding neutrino-nucleus interactions is needed

ANNIE is a final-state X + Nn measurement that complements X + Np in LAr

Discovering proton decay



- Next-generation proton decay (PDK) experiments will be background limited (from atmospheric neutrinos) at a rate of:

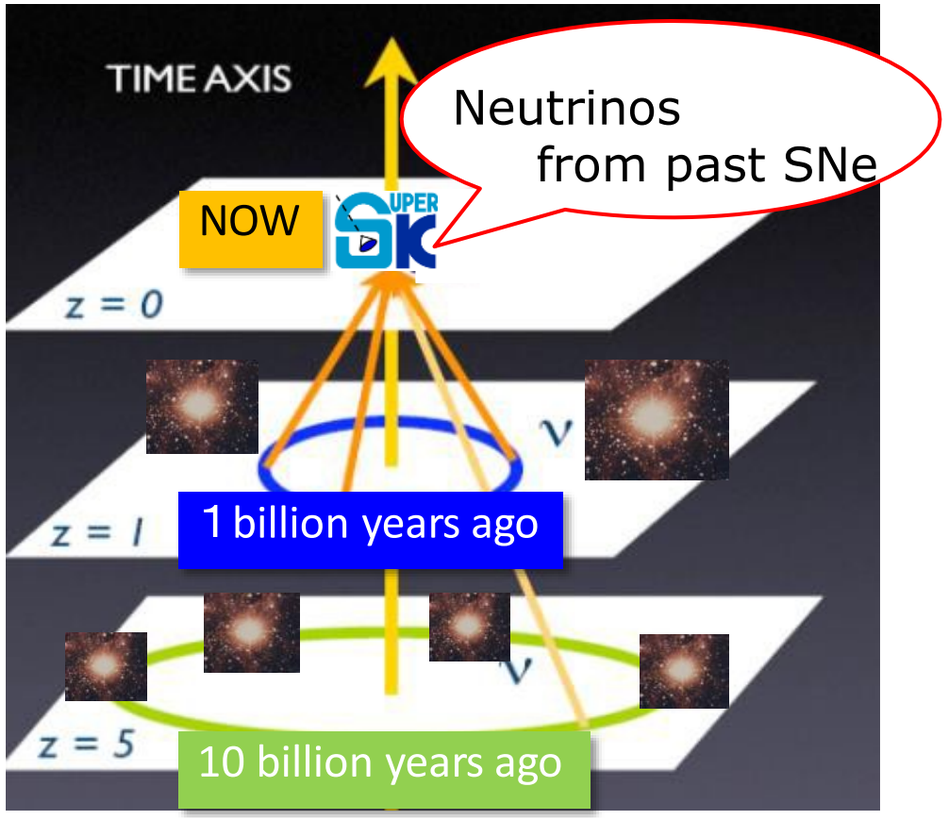
$$1.63^{+0.42}_{-0.33}(\text{stat})^{+0.45}_{-0.51}(\text{syst})\ \text{events/Megaton}\cdot\text{year}$$

- It is expected that these backgrounds would produce final-state neutrons, whereas PDKs would not.
- The presence of neutrons detected with Gd-loaded water can then be used to reject the atmospheric neutrino background.
- However this introduces a systematic uncertainty from the unknown neutron multiplicity in atmospheric neutrino interactions.

Uncertainty can be reduced by beam experiments like ANNIE

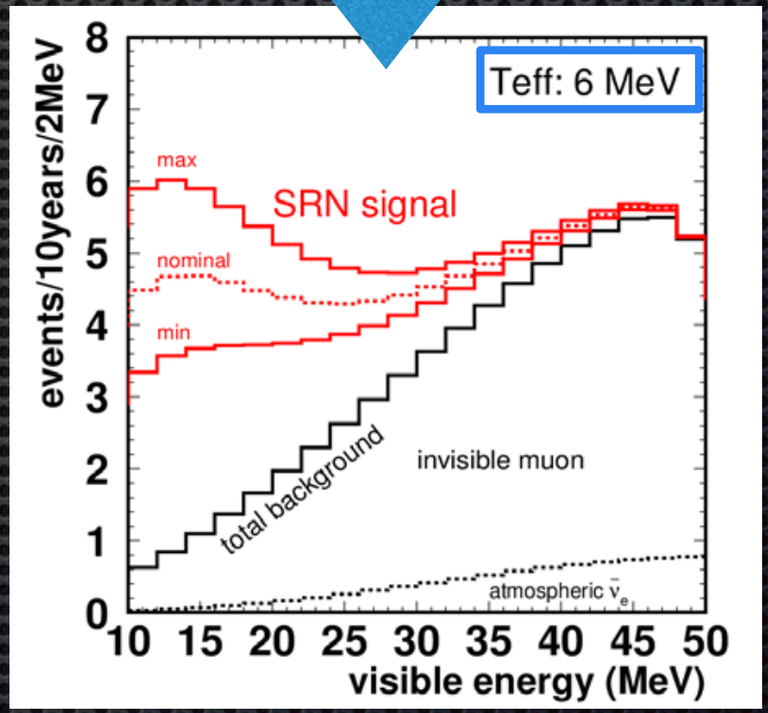
Discovering supernova relic neutrinos

- Search window for SRN at SK : From ~10MeV to ~30MeV
- Limited by BG. More than 1 order reduction is needed.



Data on the neutron yield of neutrino interactions helps estimate background.

with Gd

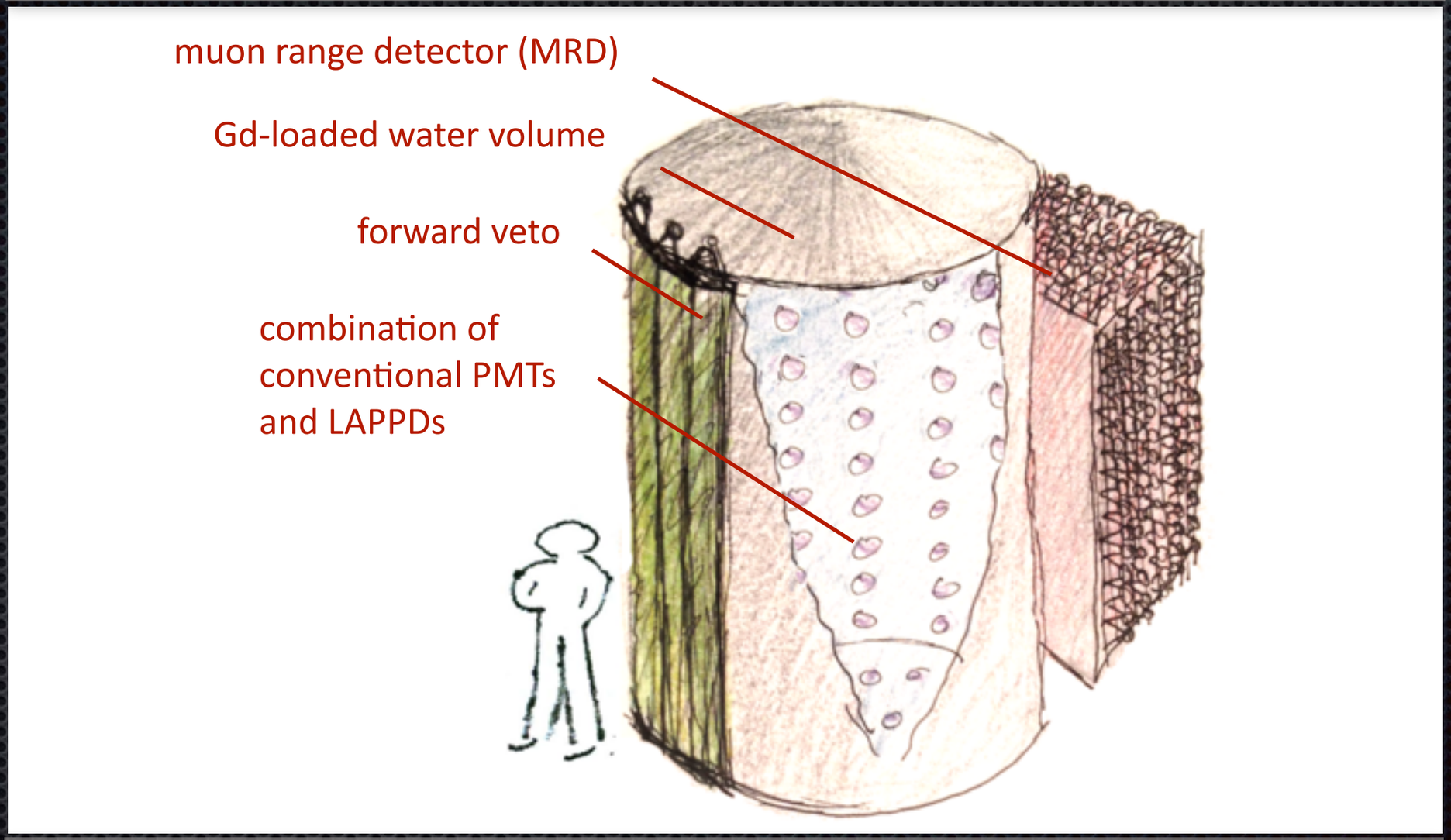


Assumption
- n capture efficiency: 90%
- Gd γ detection efficiency: 74%.
- 35% of the SK-IV invisible muon BG
  - By n-tagging

see Sekiya-san's talk - TAUP 2015

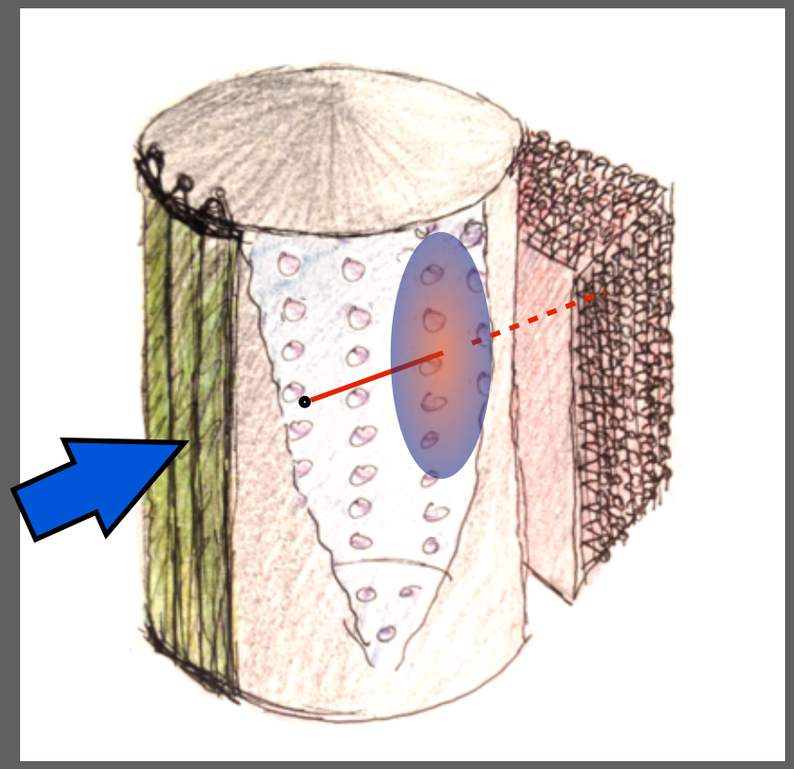
The ANNIE concept

A 23-ton tank filled with Gd-loaded water

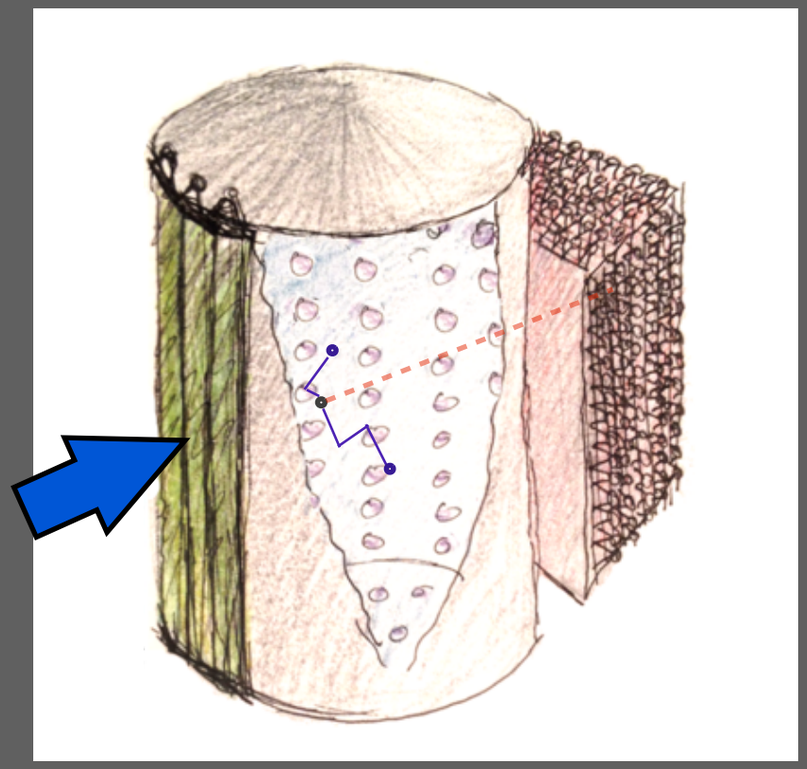


The tank diameter is 2.7 m and height is 4 m.

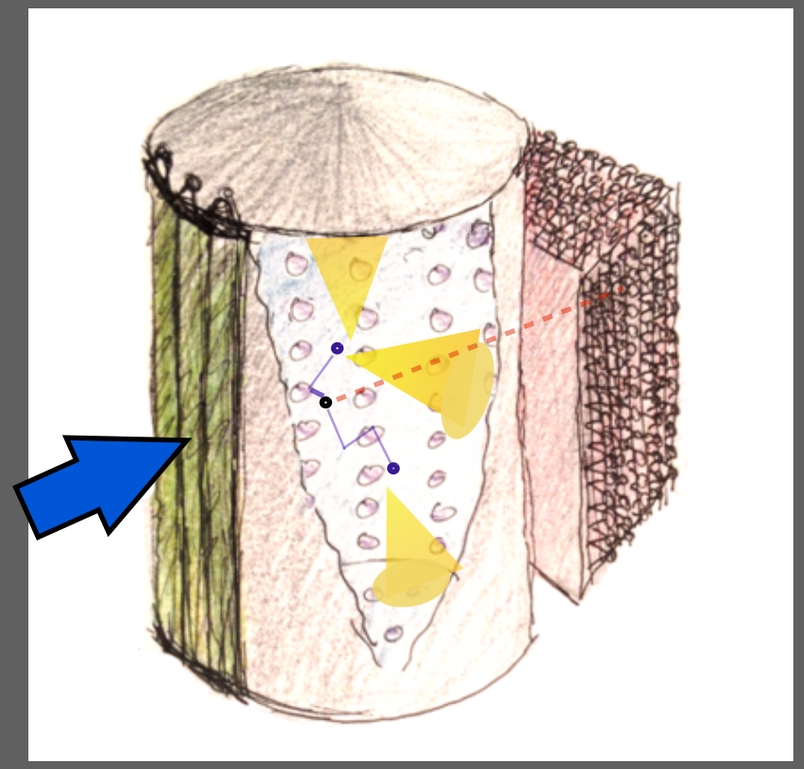
The ANNIE concept



Prompt muon tracks through water volume, ranges in MRD



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

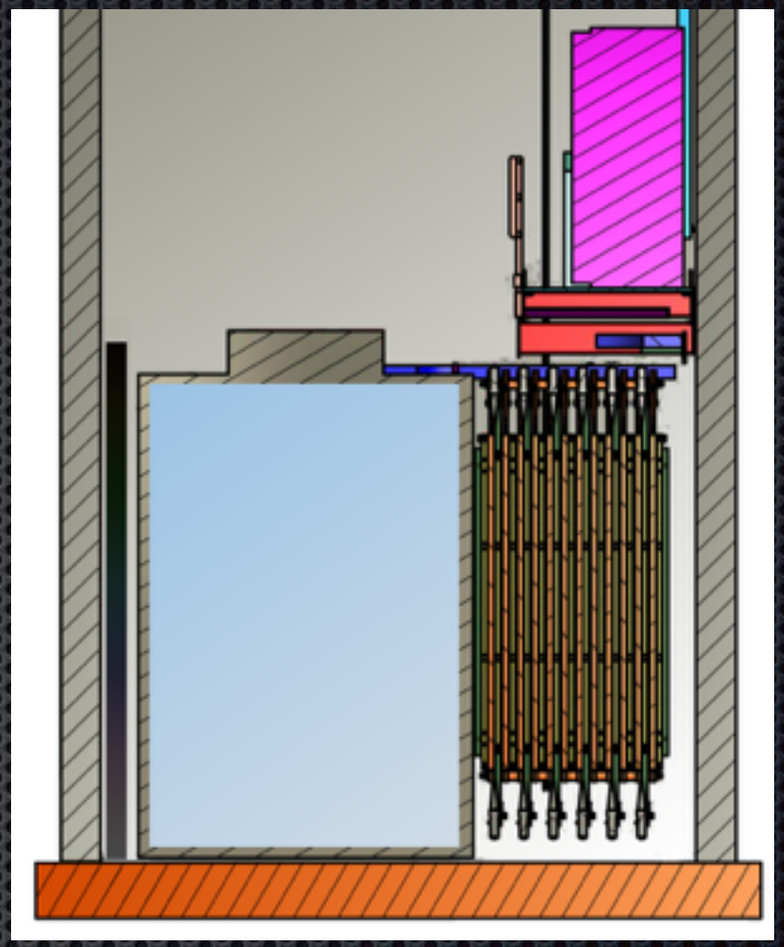


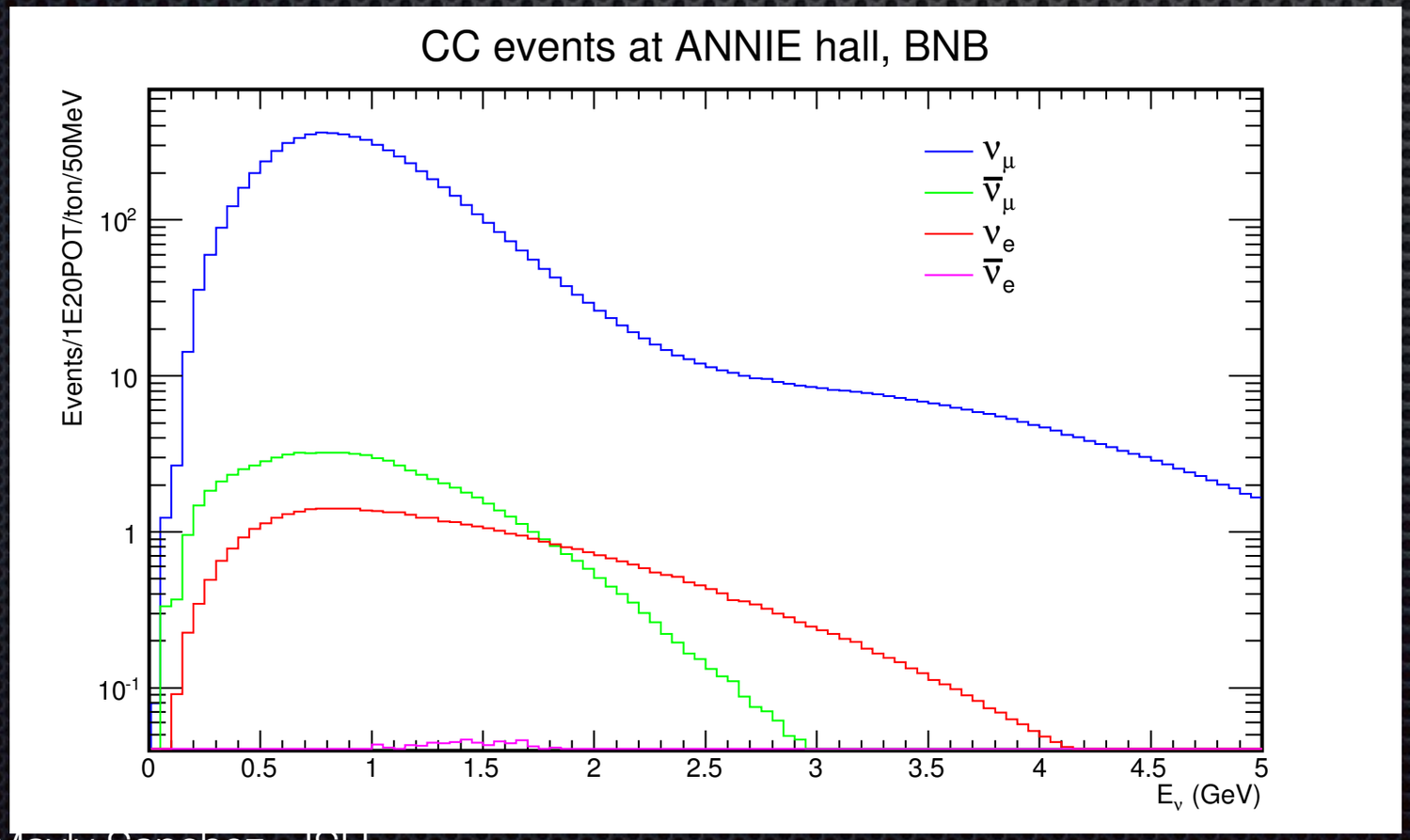
neutrons thermalize and capture on Gd, flashes of light are detected by PMTs

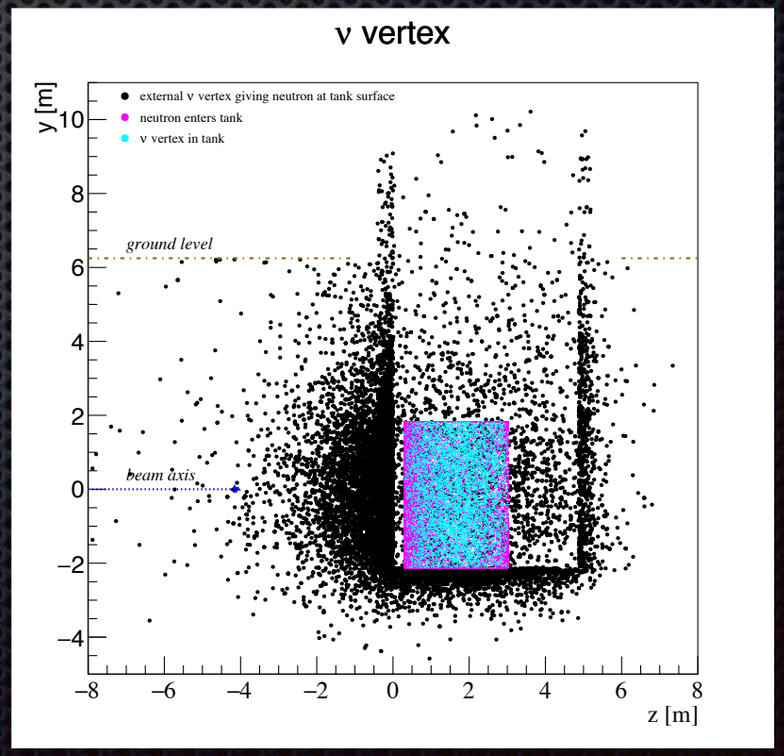
ANNIE elements

- Tank to be placed in the SciBooNE hall.
- Use existing Booster Neutrino Beam (BNB) running for MicroBooNE and the short baseline program at Fermilab.
- Neutron background from beam is estimated to be small.

SciBooNE hall section

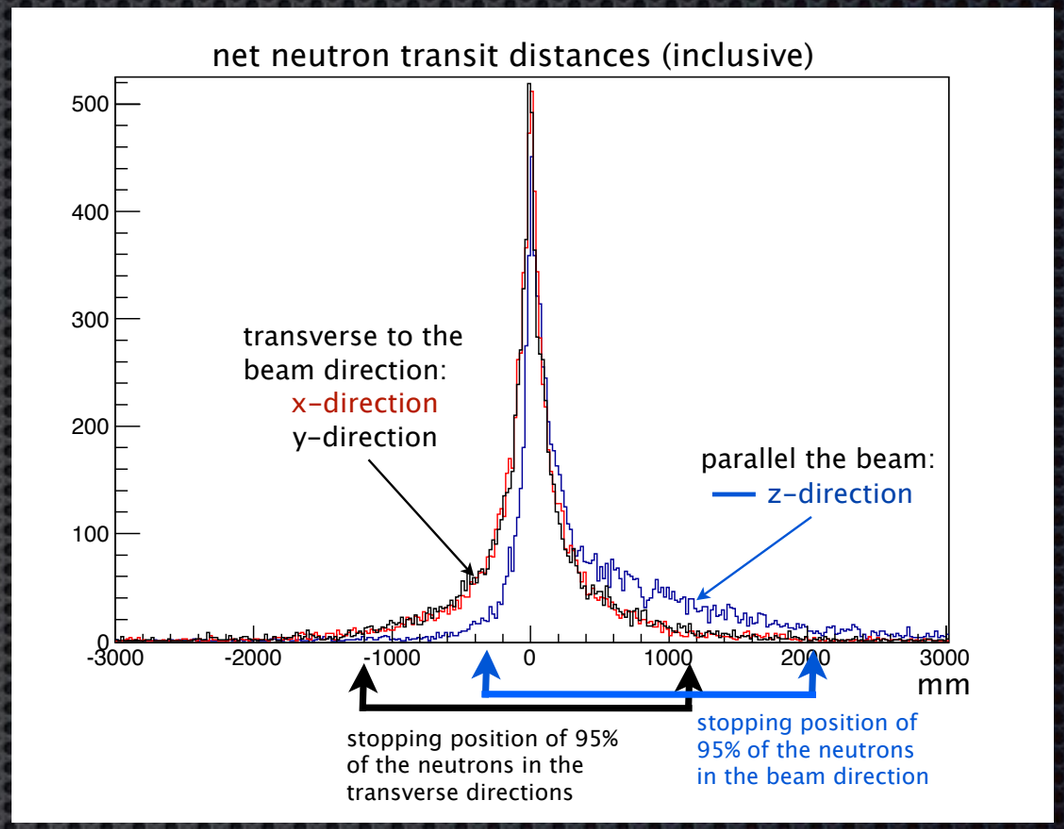


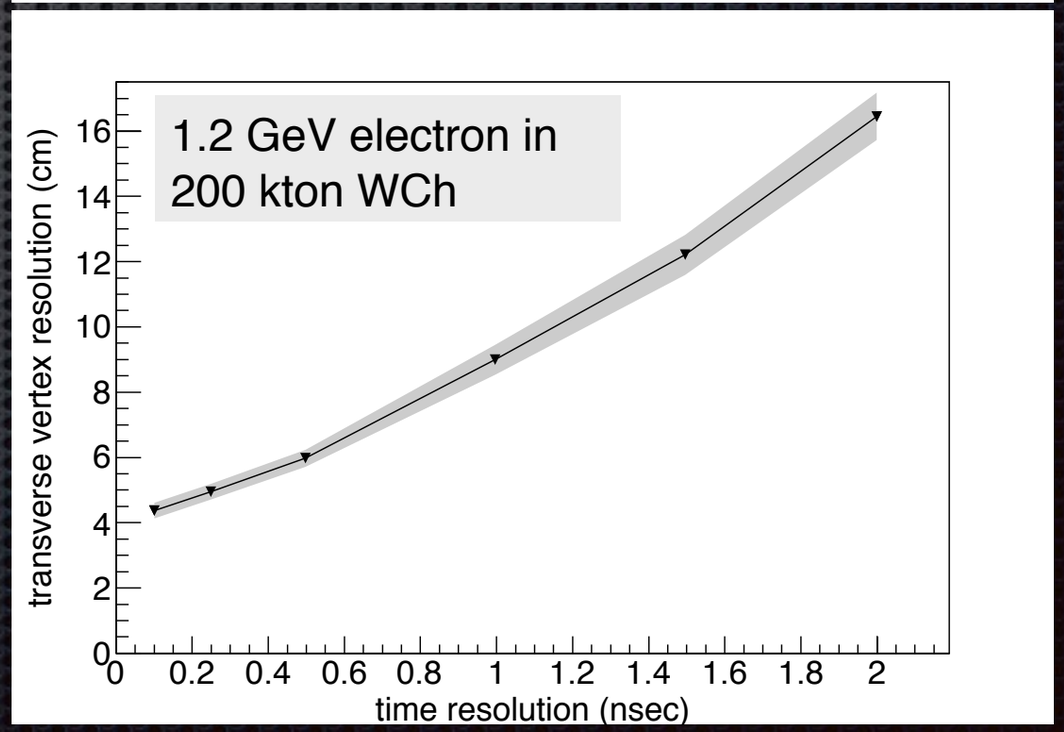




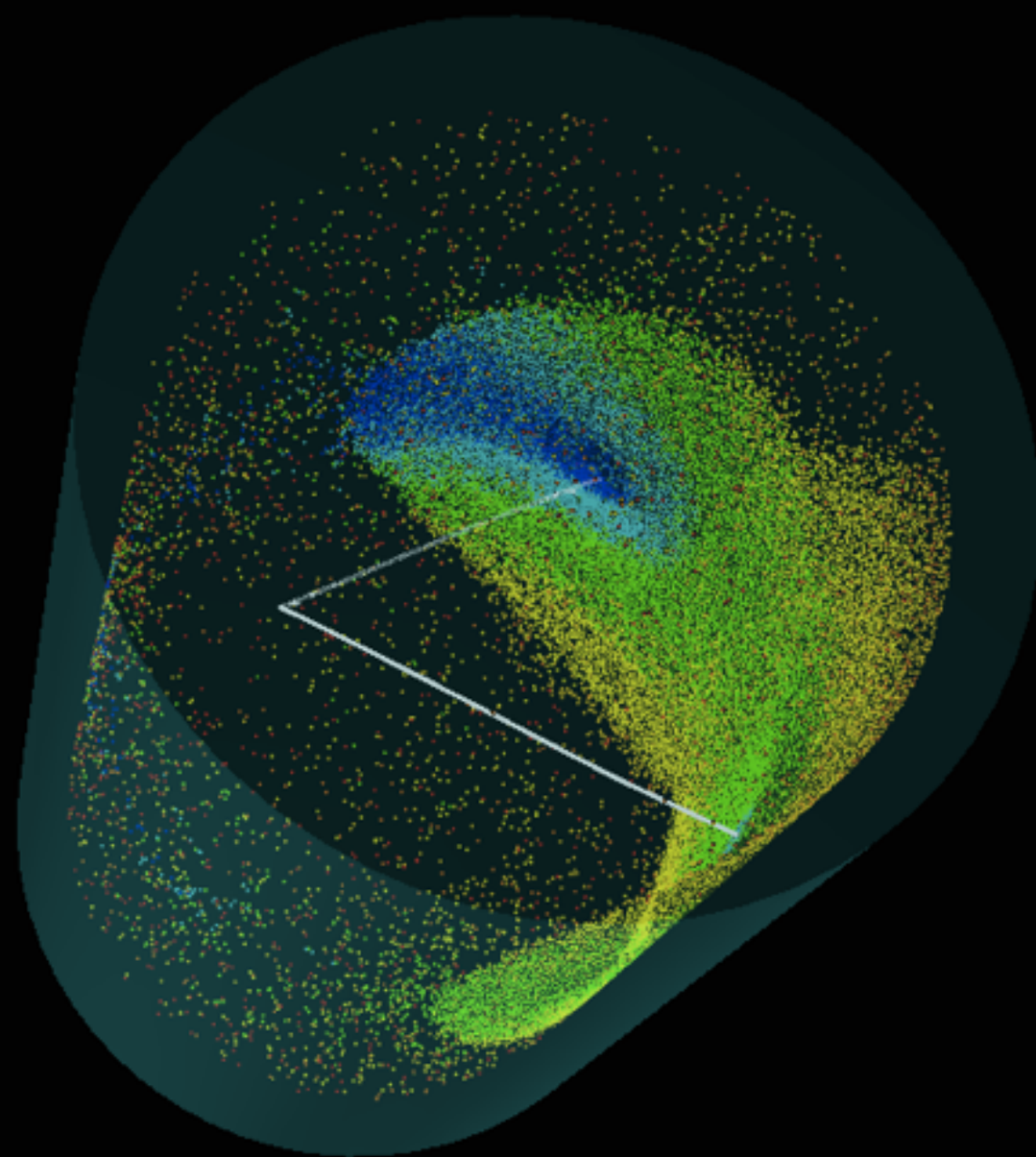
Using LAPPDs for ANNIE

- 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.



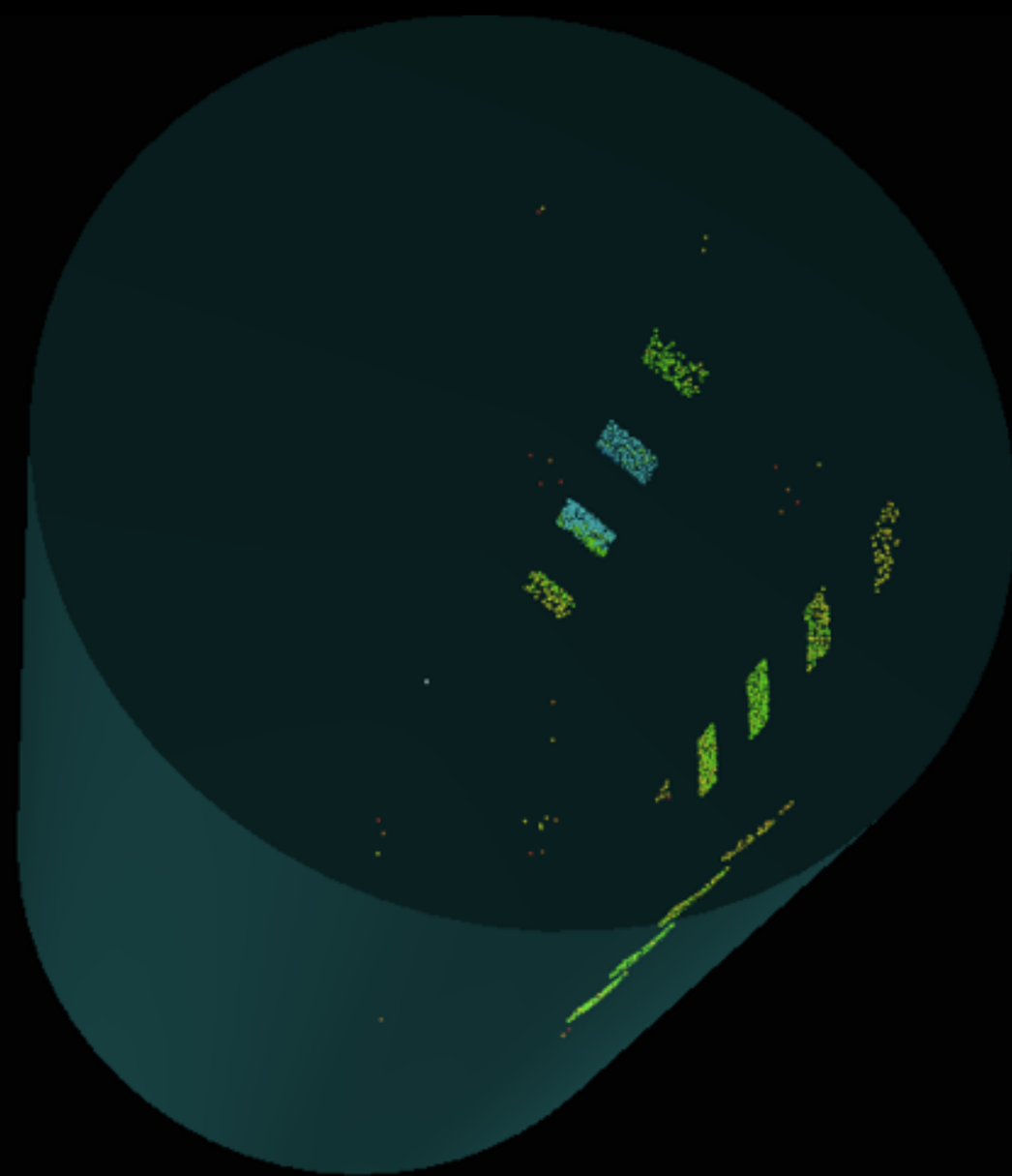


A 2-prong (muon/pion) neutrino interaction in ANNIE



All hits

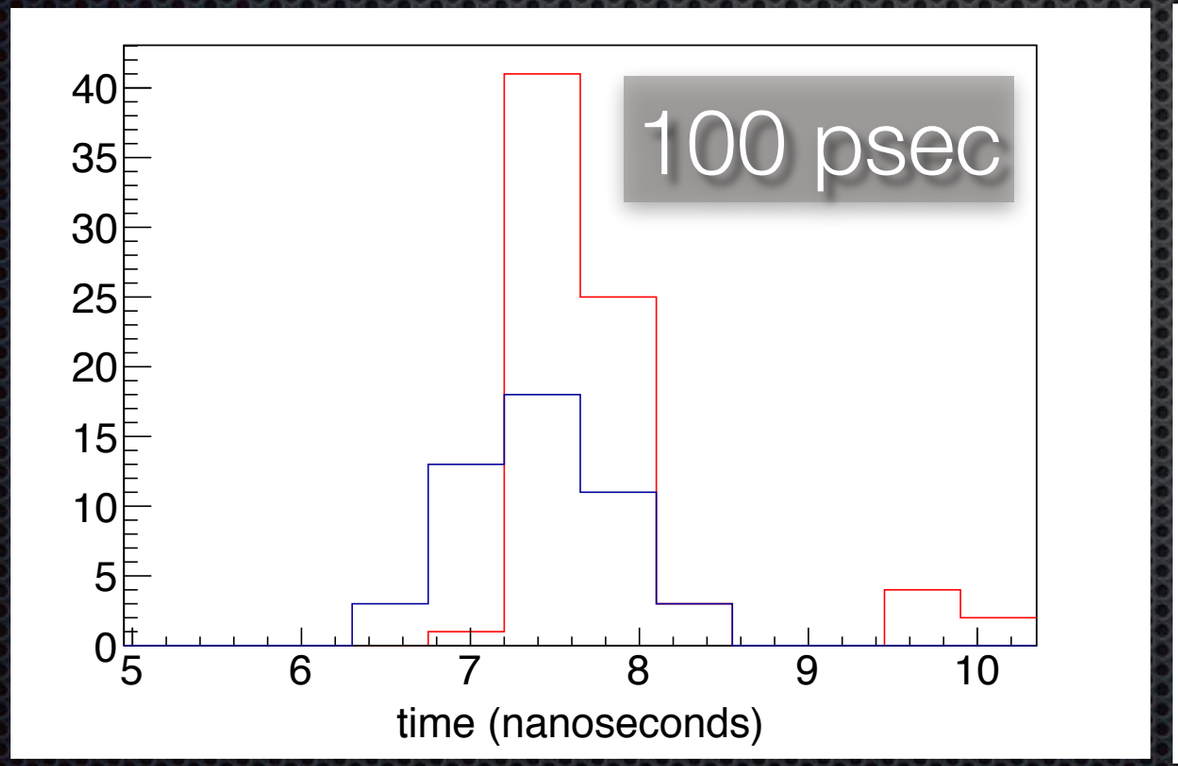
A 2-prong (muon/pion) neutrino interaction in ANNIE

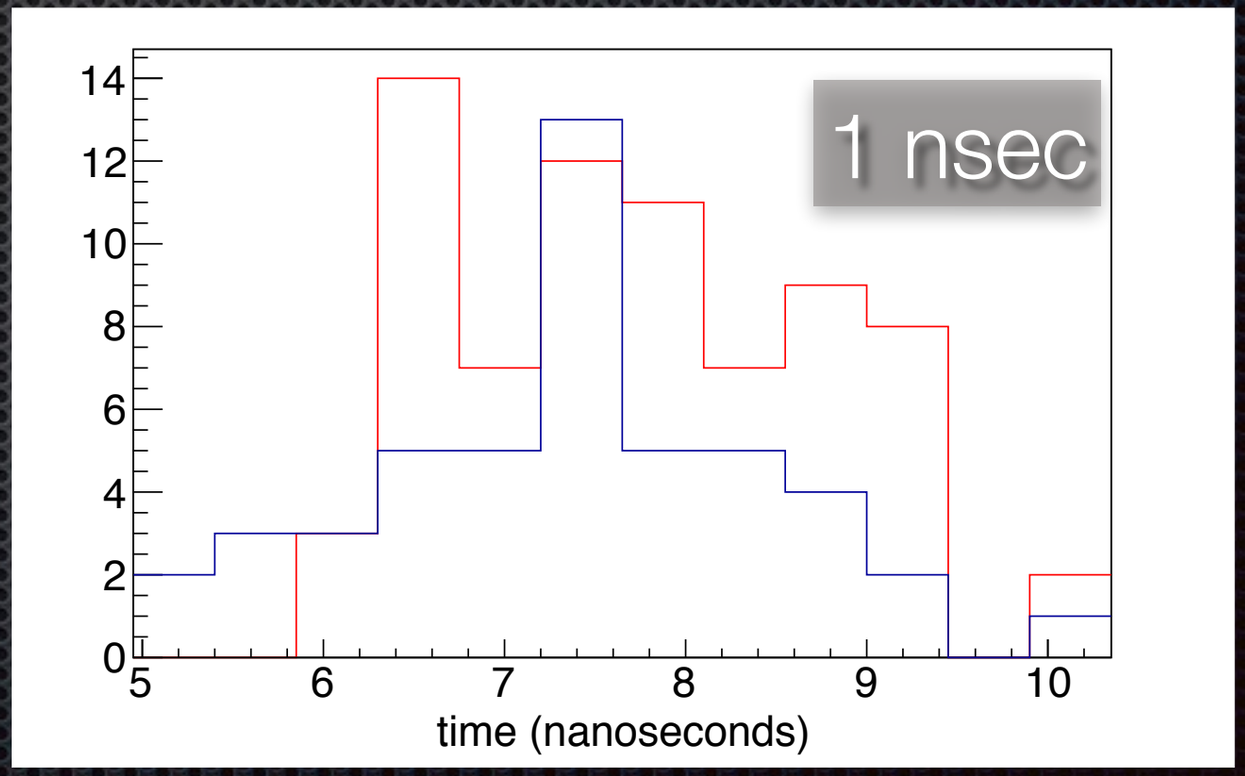


20 LAPPDs

Using LAPPDs for ANNIE

- Fine granularity and timing can help even under limited photosensor coverage.
- In a small detector fast timing can help separate light between two tracks (pion = blue, muon red).





Phased approach

Fall 2015

to Jun 2016

to Jun 2017

to Jun 2018

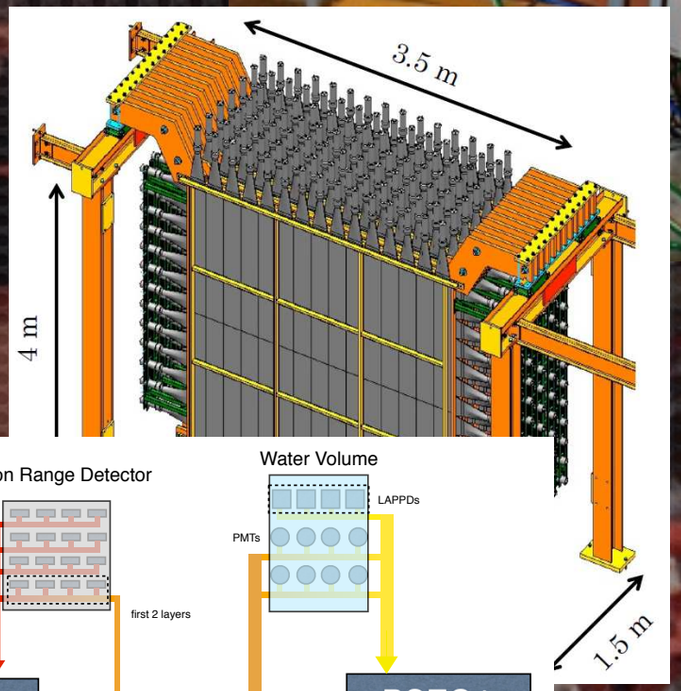
to Mar 2021

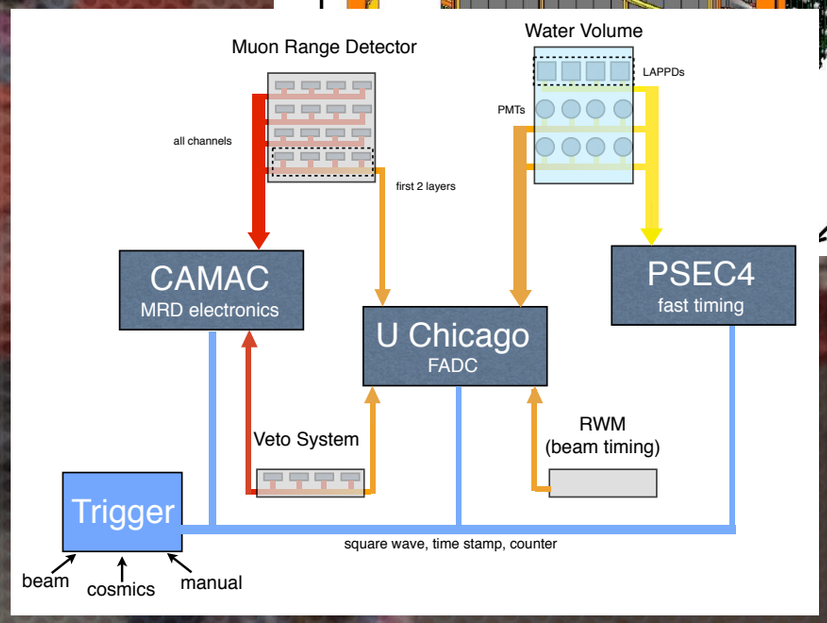
on-going

- 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
- R&D, procurement, construction, commissioning
- Phase II - First physics run (1 year):
  limited LAPPD coverage (up to 8), enhanced PMT coverage, focus on CCQE-like events
- Second physics run (2 years):
  full LAPPD coverage (up to 20 LAPPDs)
  more detailed event reconstruction
  compare neutron yields for CC, NC, and inelastic

Status of ANNIE

- The forward veto has been completed! The tank is purchased and is to be deployed this month.
- Work is underway to recommission the MRD, design the electronics, procuring PMT coverage.
  - Work on the inner volume is planned to occur over next few months.
- Water filling and commissioning is to begin mid-fall. Booster Neutrino Beam (BNB) turns back on in mid-October.





Neutron background data taken by June 2016

Summary

- A new generation of fast timing photodetectors is in development.
  - This technology enables next generation detectors with better vertex resolution and particle ID.
- Chemical enhancements to water detectors broaden the physics of current and next generation experiments.
- A program for demonstrating these new capabilities is developing.
  - A detailed understanding neutrino nucleus interactions is necessary to meet the demands of future precision neutrino measurements: **ANNIE is set to contribute to the X + Nn measurements.**
  - A demonstration of techniques that open the path to physics beyond neutrino oscillations: **Proton decay and supernova relic measurements will benefit from neutron yield measurements by ANNIE.**

Thanks !

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."

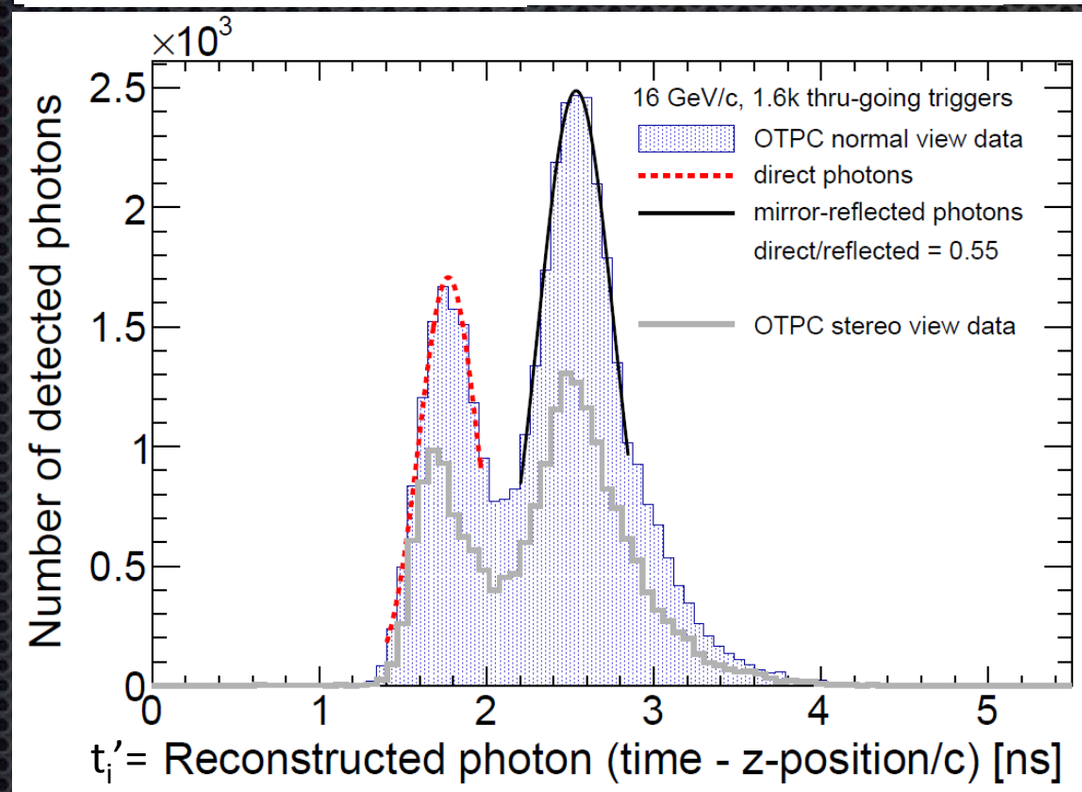
- ANNIE has been approved for Phase I construction by the Fermilab directorate and is on schedule.
- Fermilab and the community have provided significant support.
- A proposal for the Intermediate Neutrino Program FOA is under preparation for Phase II.

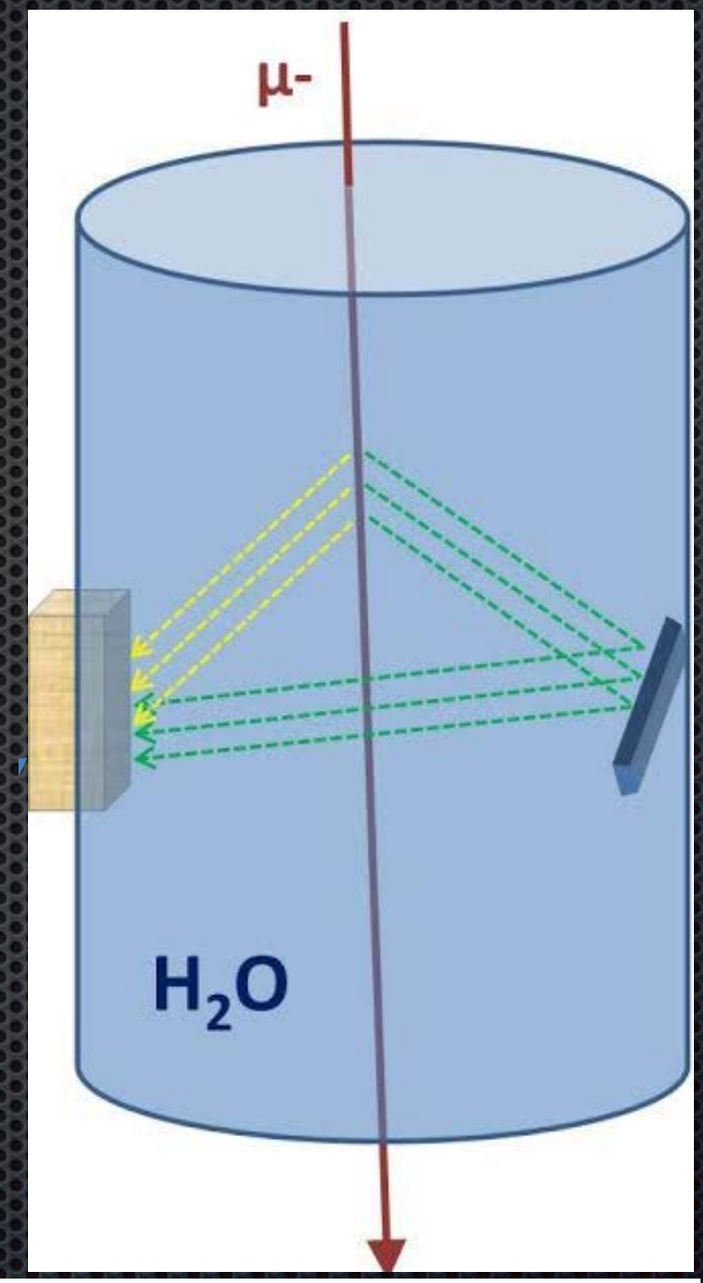
New collaborators are welcome!

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





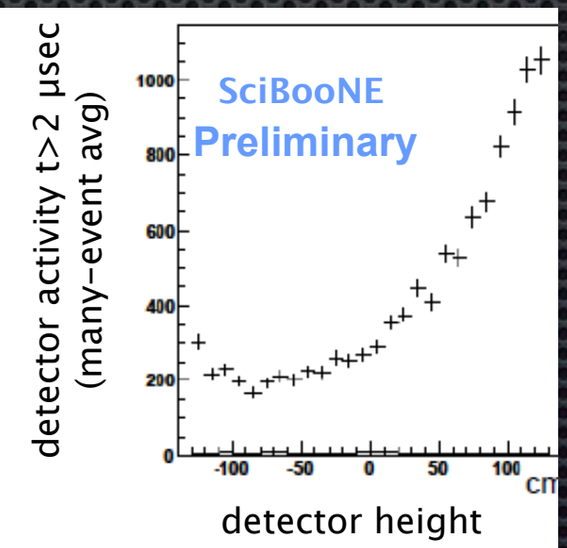
By time and space resolving, we measure an angular resolution of a few degrees (50 mrad) and a spatial resolution on particle tracks of 15 mm

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

ANNIE phase I

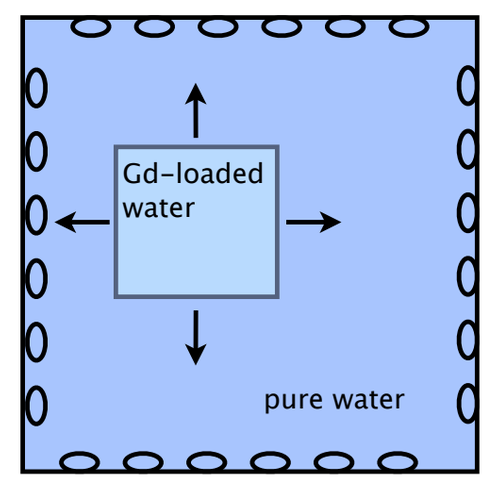
ANNIE will see neutron backgrounds from 2 sources:

- **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.

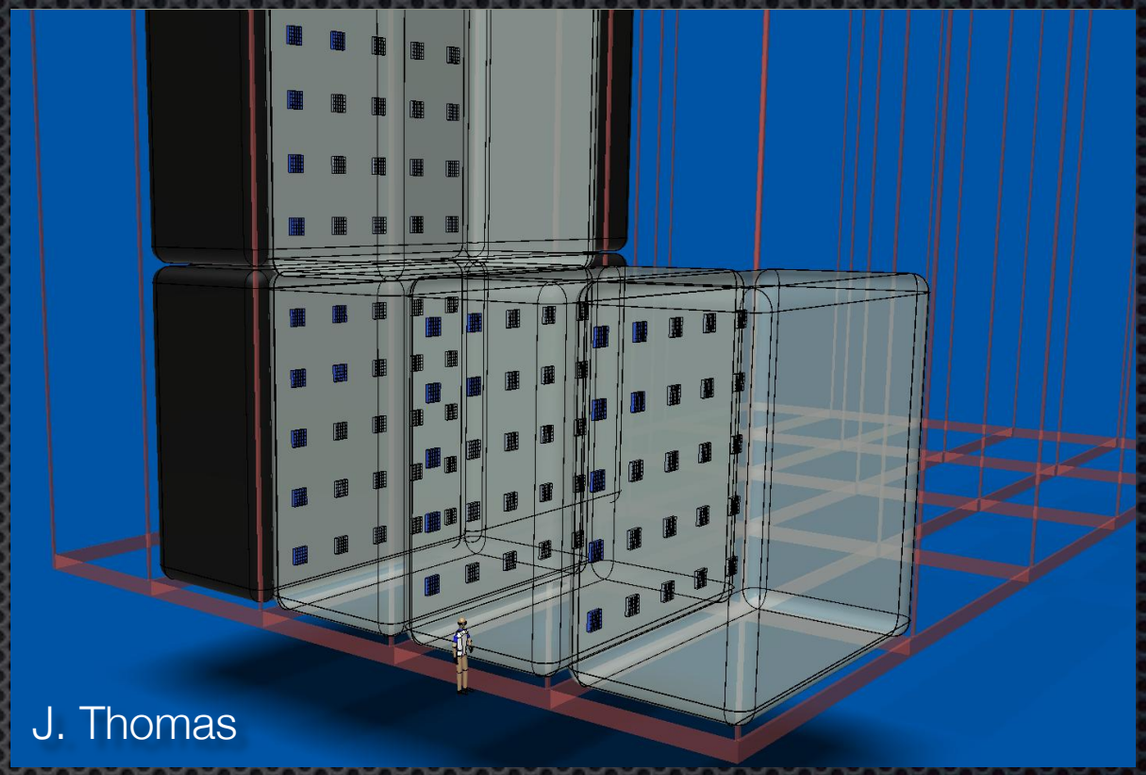
With a Phase I detector, we can test the first LAPPDs submerged in water, as they become available.

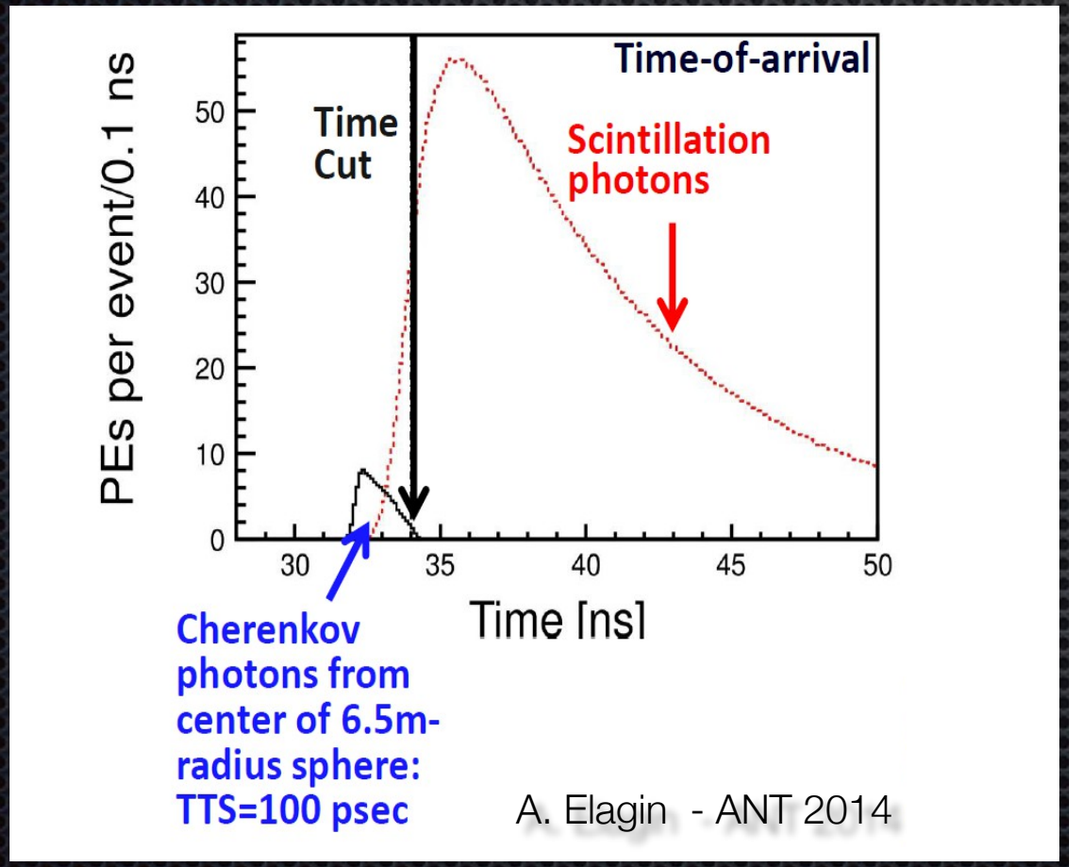


Requires input and coordination with Fermilab.

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**.



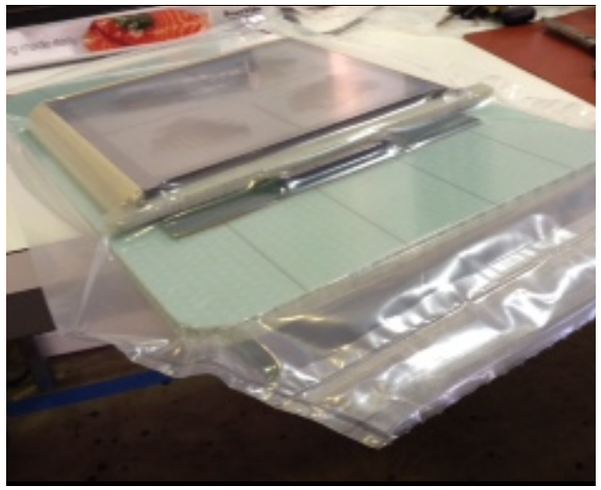


- For water-based liquid scintillator detectors it could help separate Cherenkov from scintillation light.

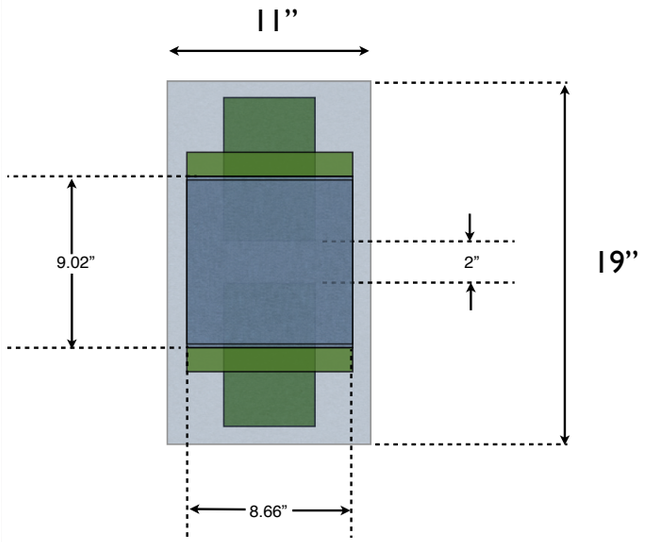
(not described this talk)

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.

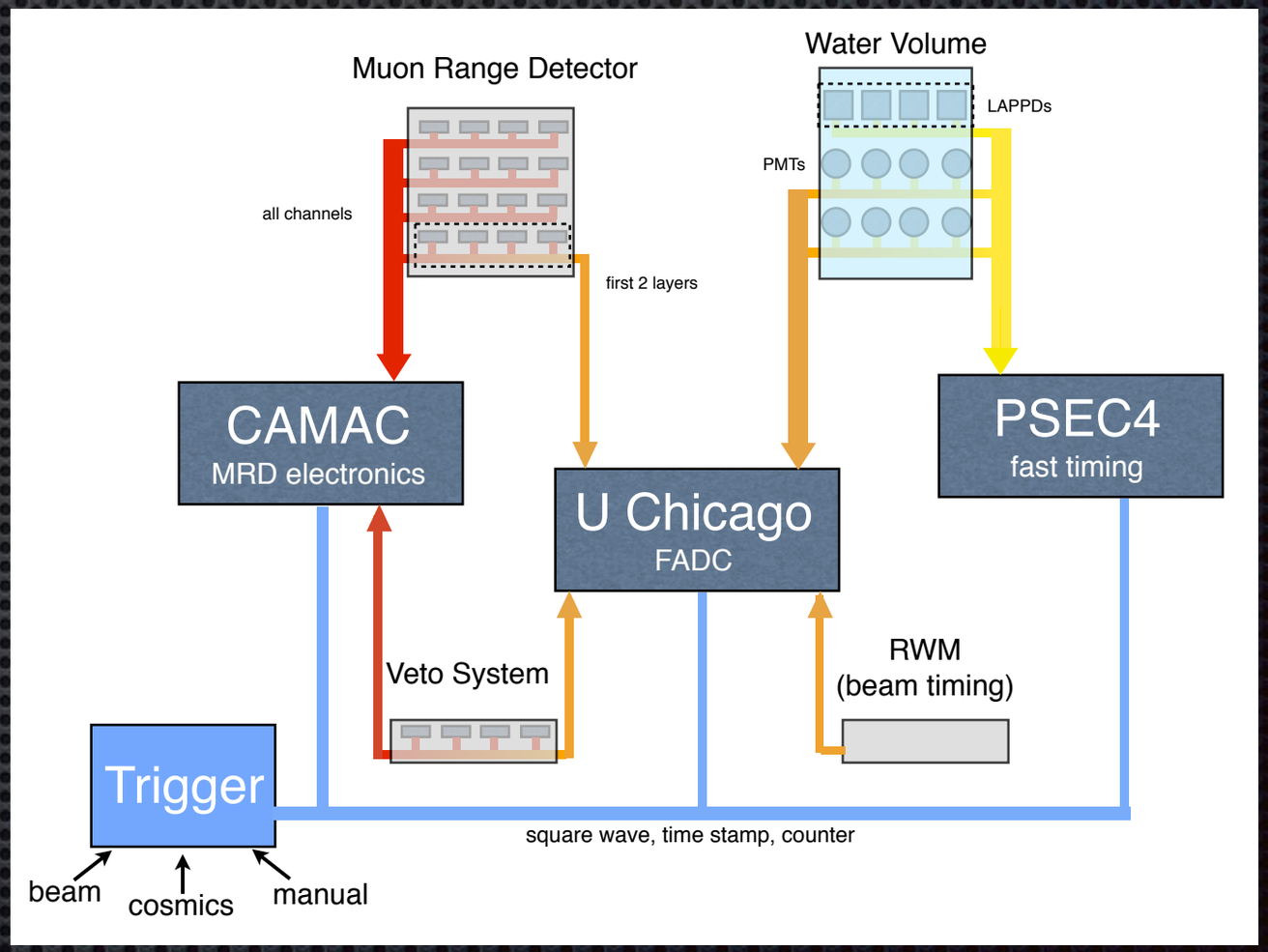


credit: Brooke Adams



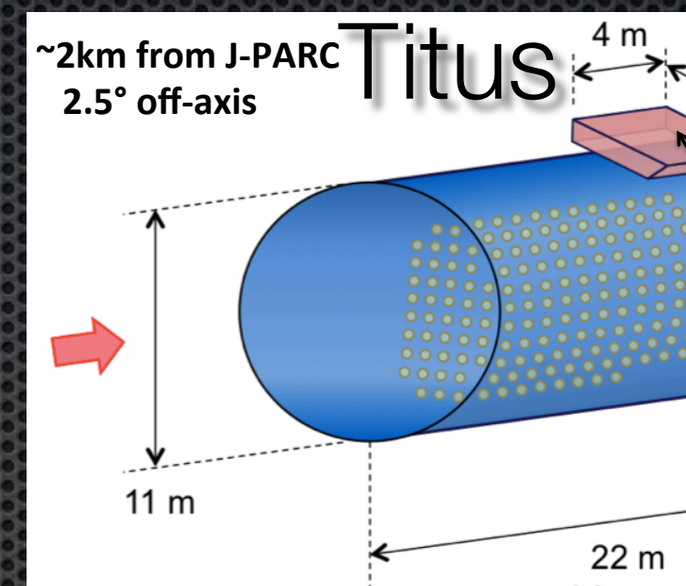
LAPPD R&D for ANNIE and beyond

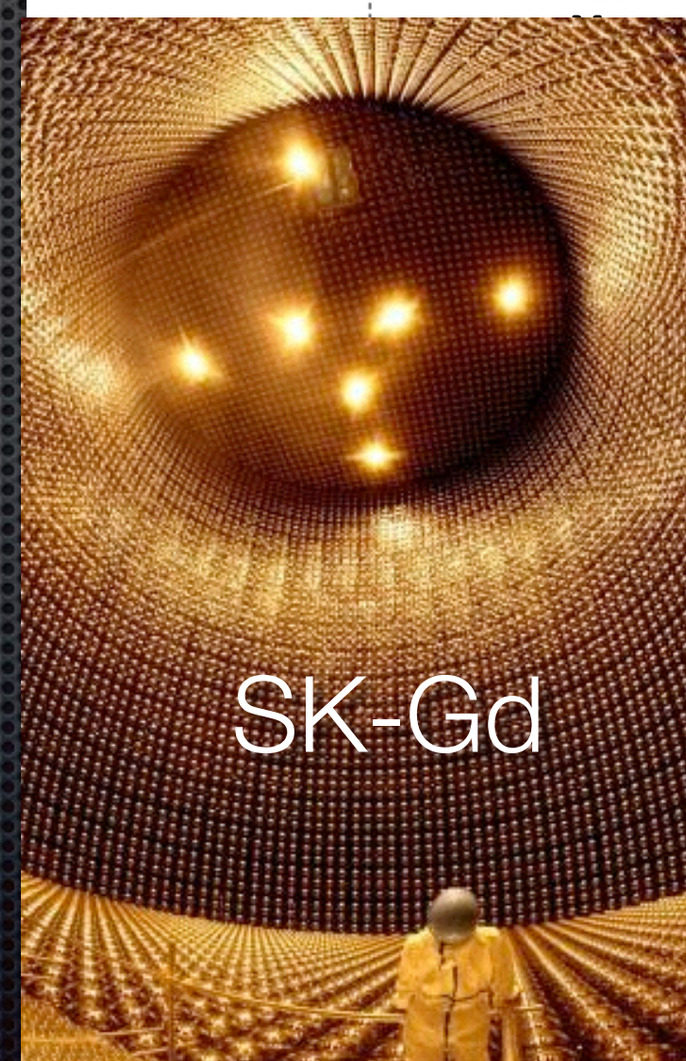
- A working 240 channel DAQ system with self-triggering already exists, thanks to the U Chicago optical TPC (E. Oberla, H. Frisch, M. Bogdan).
- The next step is to generalize to higher channel counts and integrate LAPPDs with more complicated detector systems.
- The ANNIE electronics group (ISU, UChicago,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

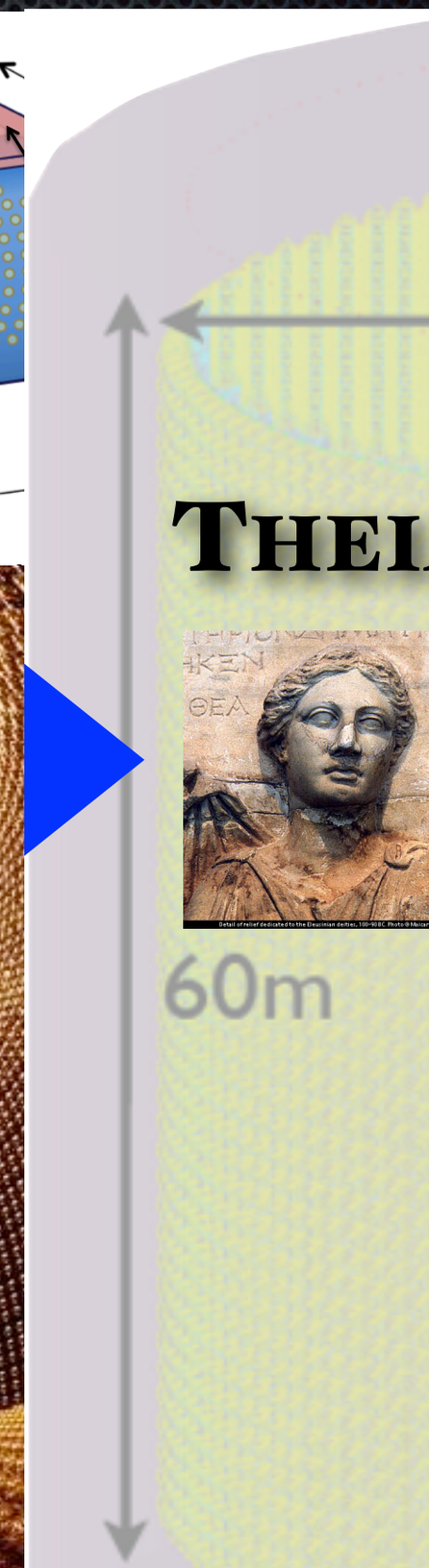


ANNIE and then…

- 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.



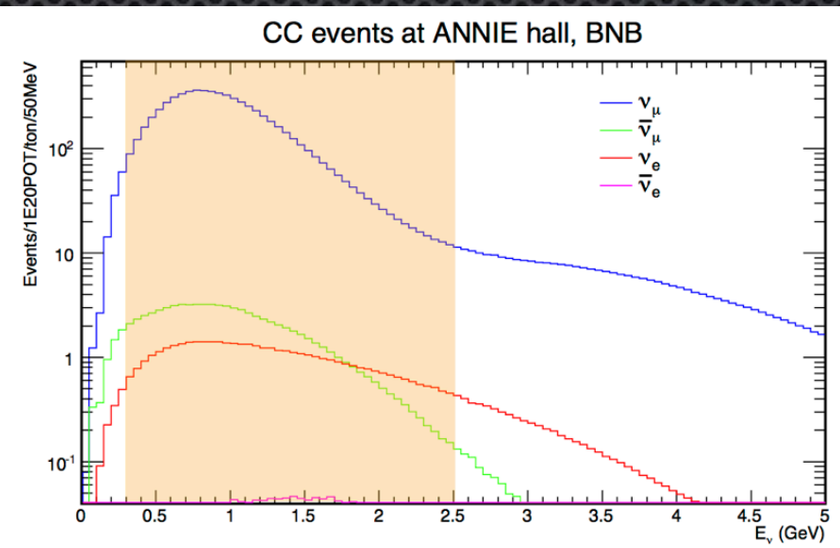




Beam rates and requirements

We need 3 things in a beam:

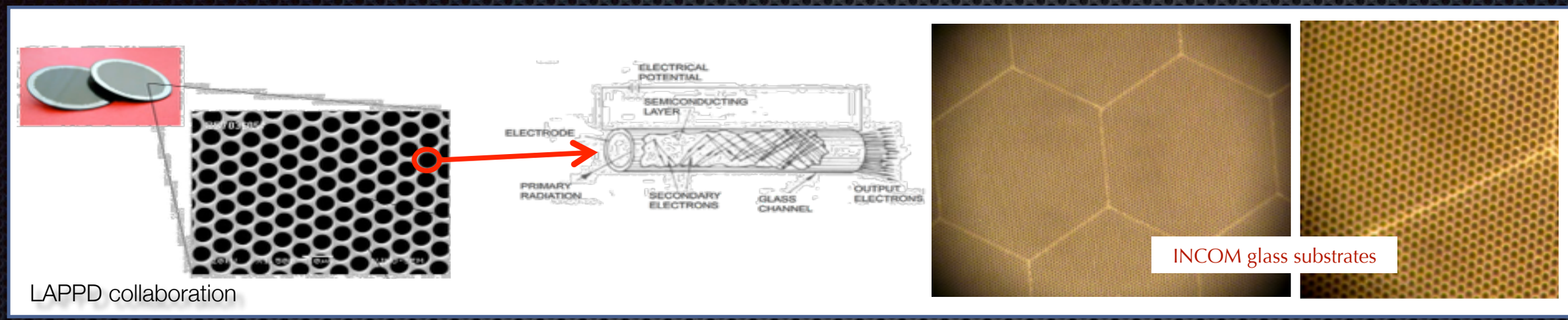
- Energy peaked in the range of the proton mass/atmospheric neutrino flux (1-2.5 GeV)
- Statistics
- Low pileup rate



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



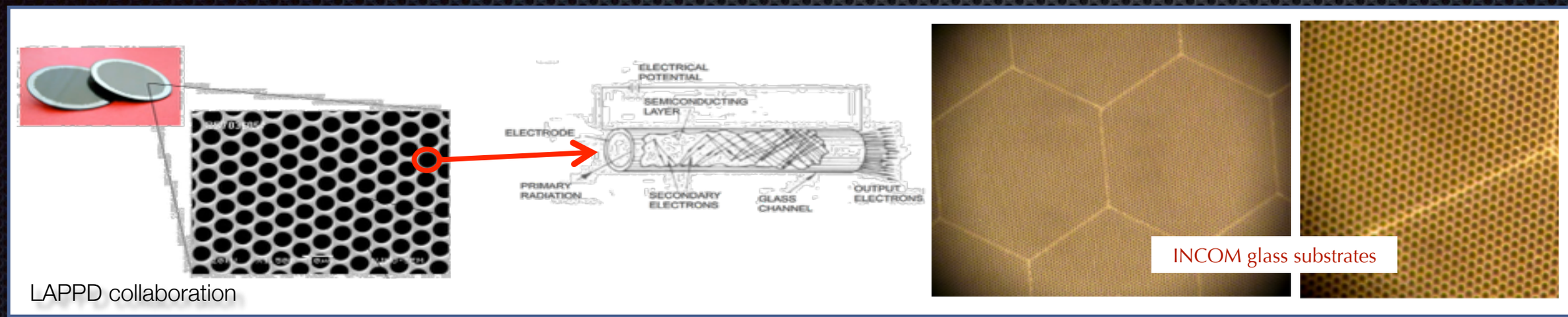
LAPPD collaboration

- 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.

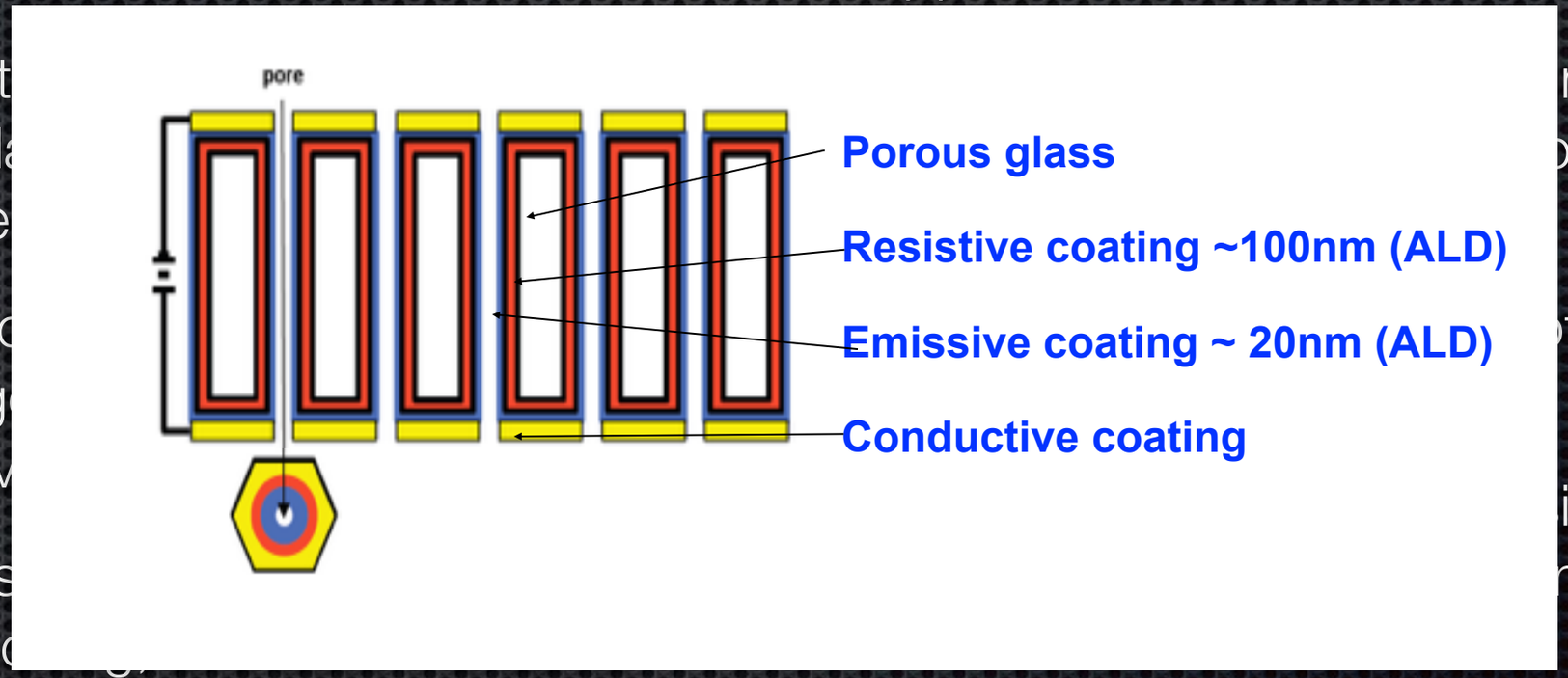
Approach demonstrated for 8-inch tiles

Key innovation: large micro-channel plates



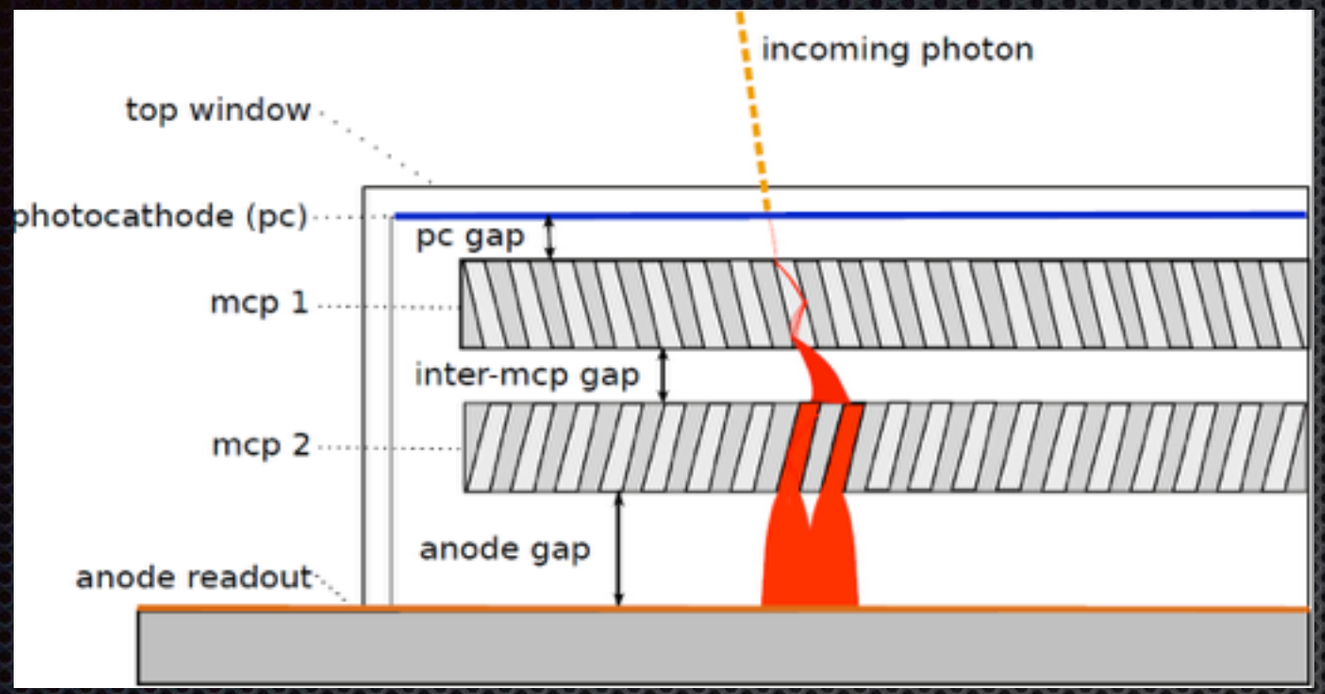
LAPPD collaboration

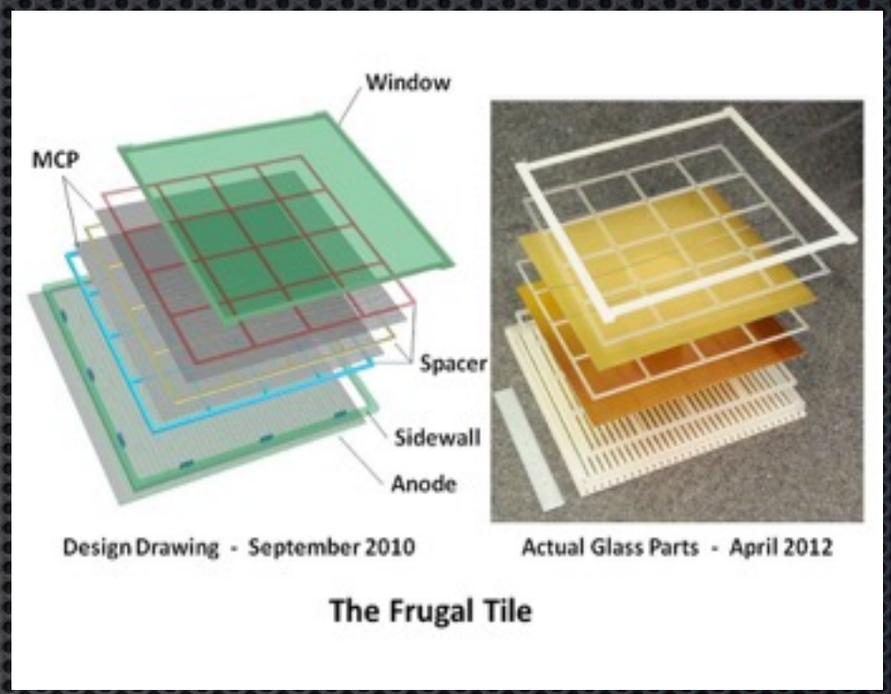
- Conventional MCP Fabrication:
  - Pore st… nctions: lead-gla… onductive also se…
  - Chemic… timize hydrog… emissiv…
  - Expens… ition (ALD), conditi… method. material for resistive and secondary emissive properties.
- Approach for LAPPD:



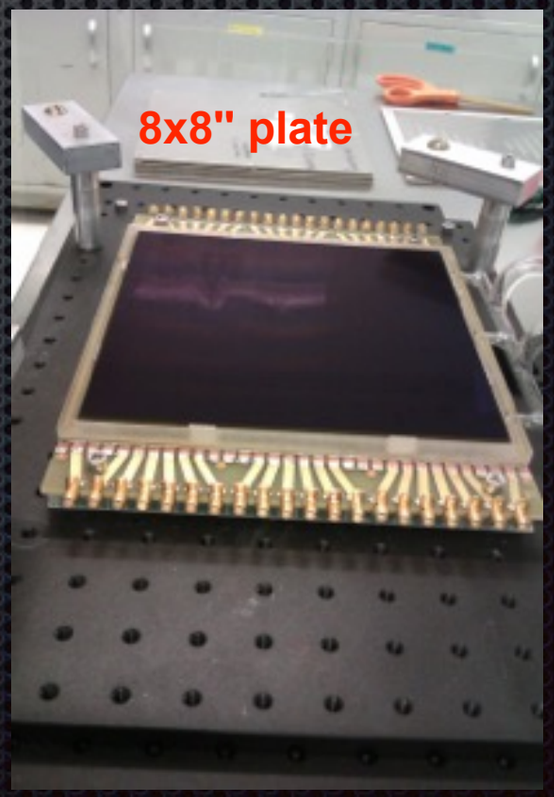
Approach demonstrated for 8-inch tiles

The 8-inch LAPPD glass tile





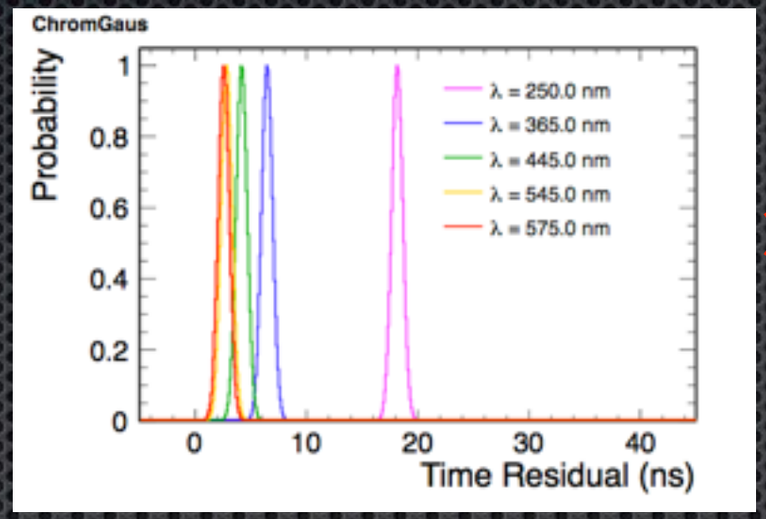
- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- Designed for fast timing
- Alternative more traditional ceramic packaging developed at Berkeley/SSL.

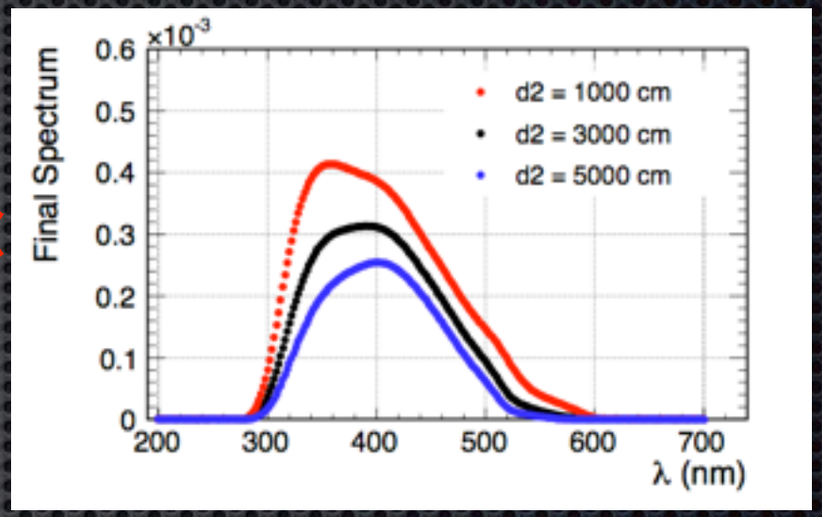


Packaging is to some extent application specific

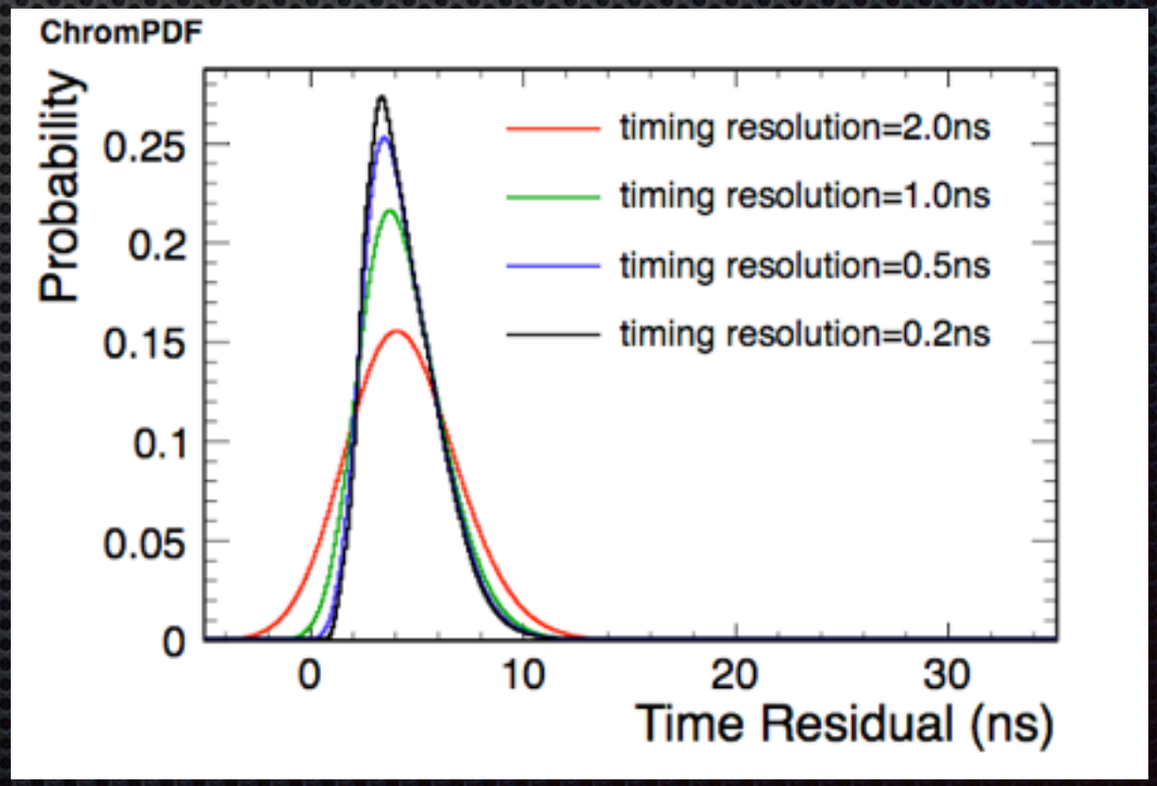
Using Time Residuals

- 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.





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

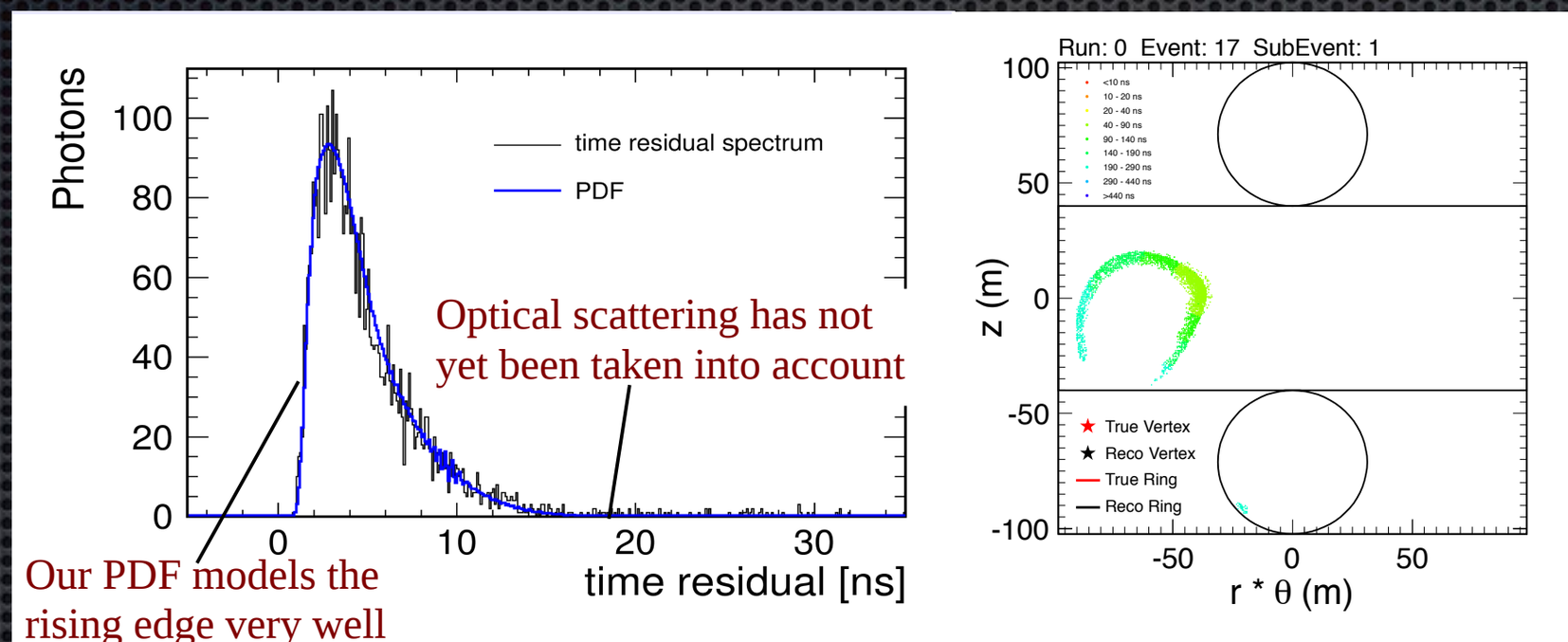


T. Xin, I. Anghel, M. Sanchez, M. Wetstein

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



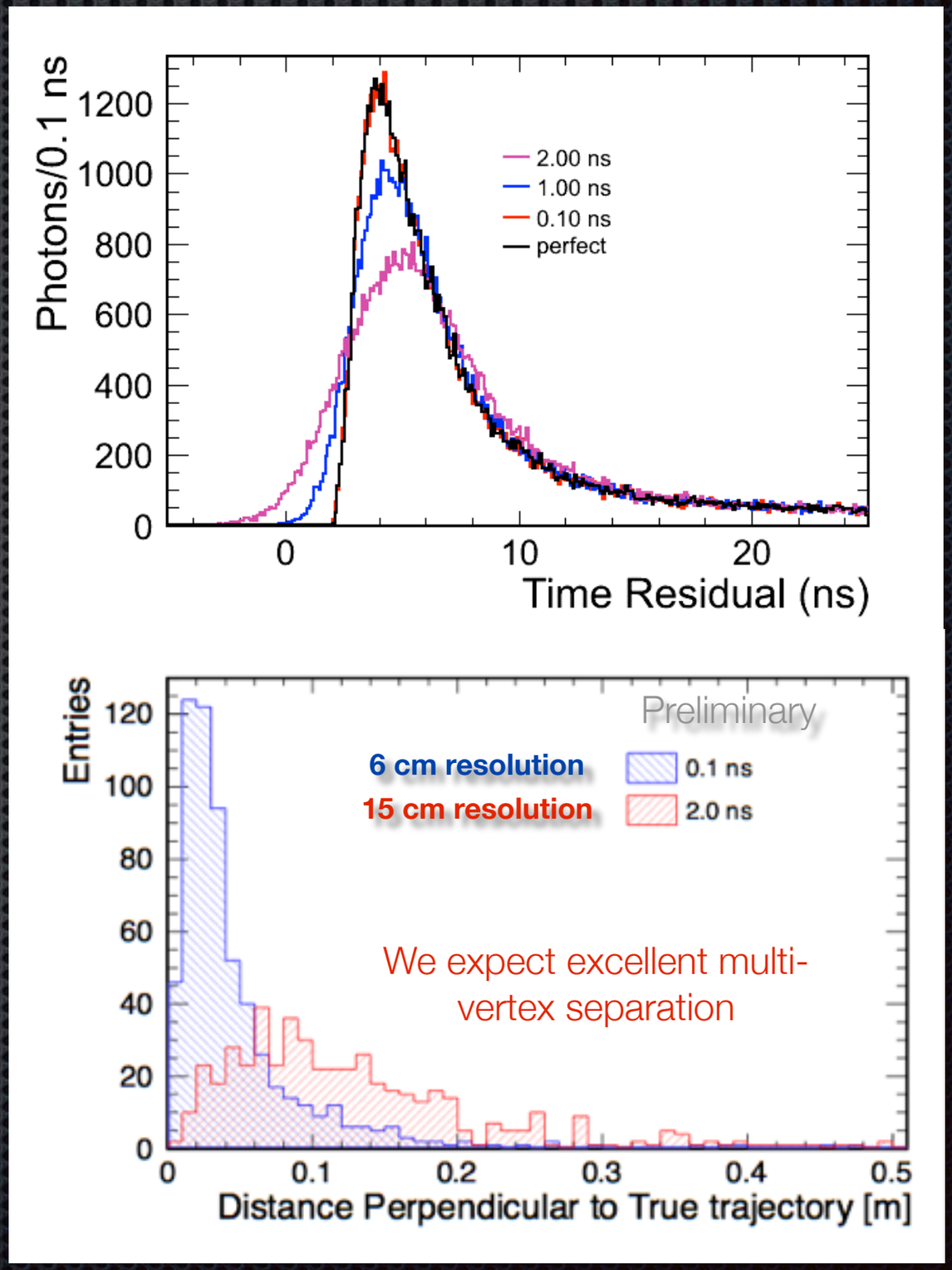
- It is not as sophisticated as full pattern-of-light fitting.
- However in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.

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.

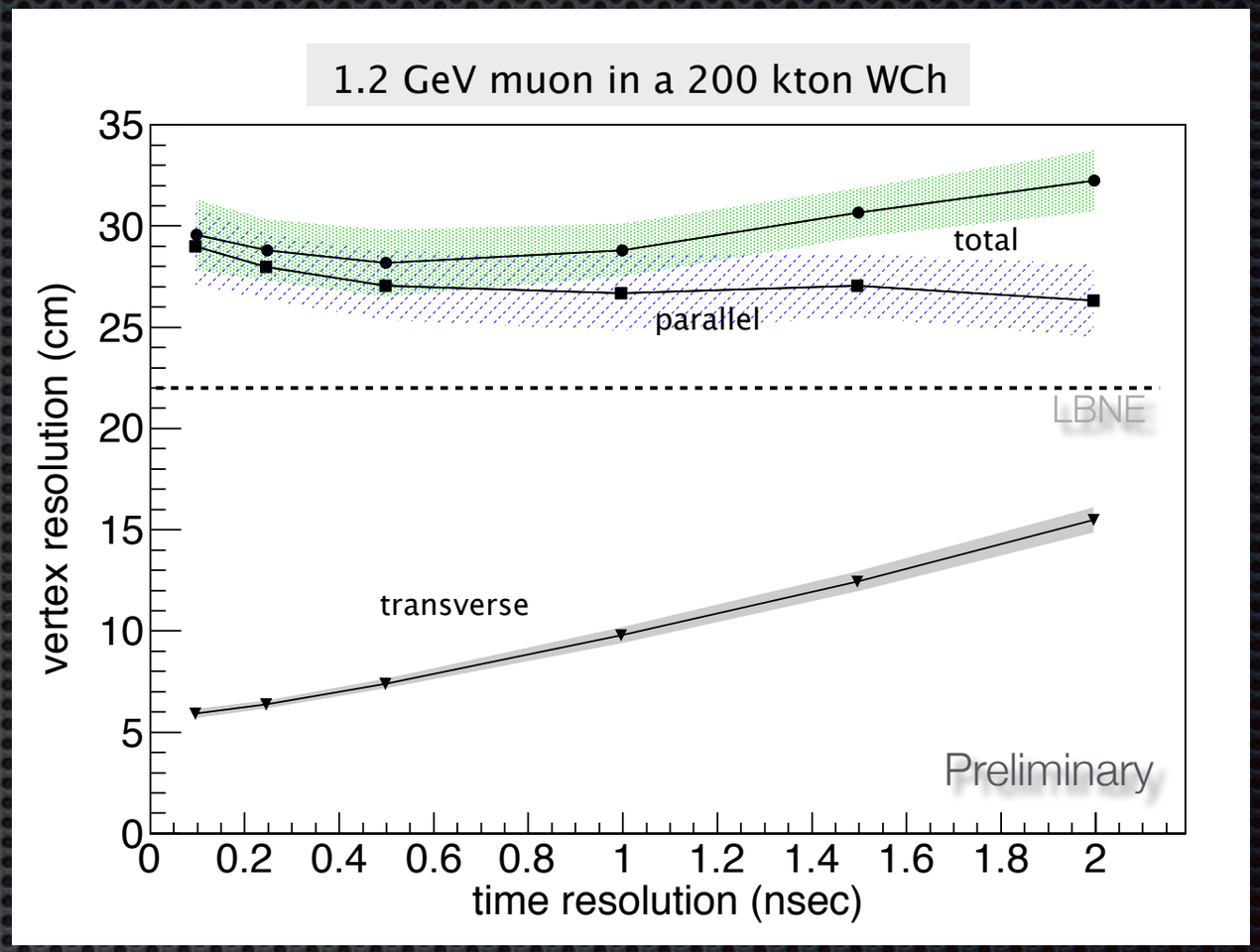
- If we use a 200 kton simulated detector with 13% photodetector coverage.
  - 1.2 GeV muons uniformly distributed.
  - Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.



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

More Time Residuals results

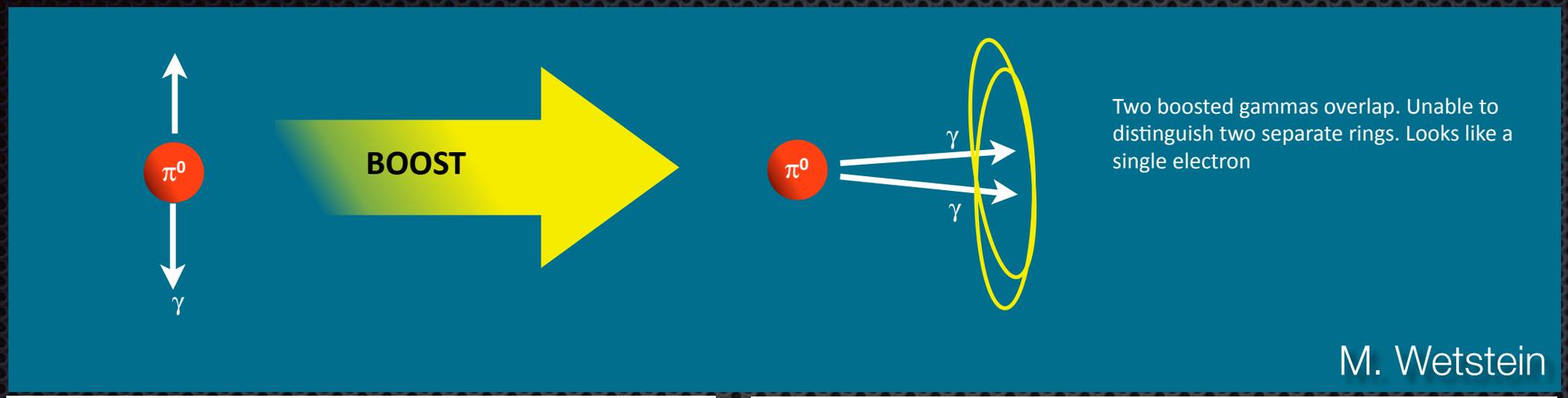
- Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.
  - Compare this vertex resolution to ~22 cm for LBNE WCh design using similar fits with no chromatic corrections and standard digitization.

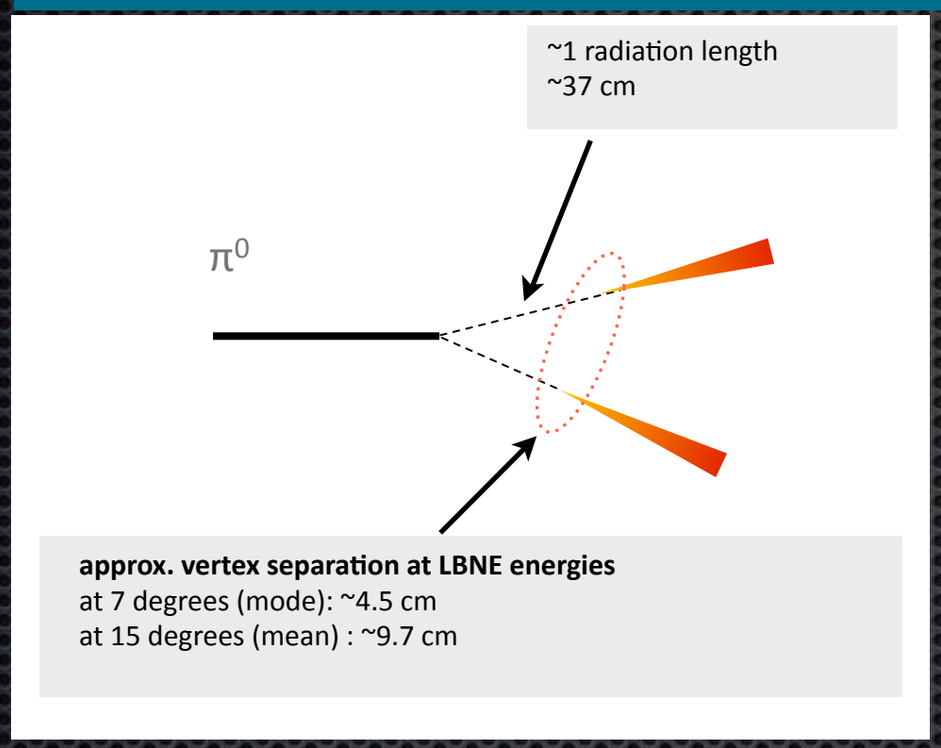


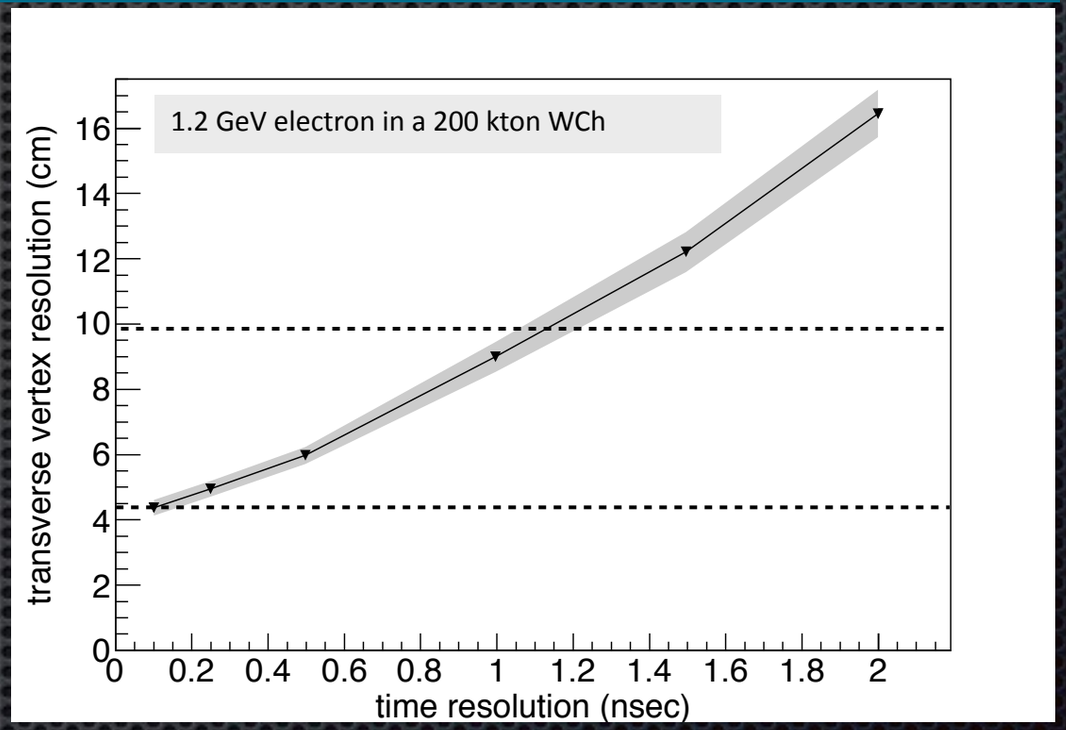
- Based on pure timing, vertex position along the direction parallel to the track is unconstrained.
  - Must use additional constraint: fit the "edge of the cone" (first light).
  - Better algorithms using full pattern of light with better spatial resolution could help here.

- 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



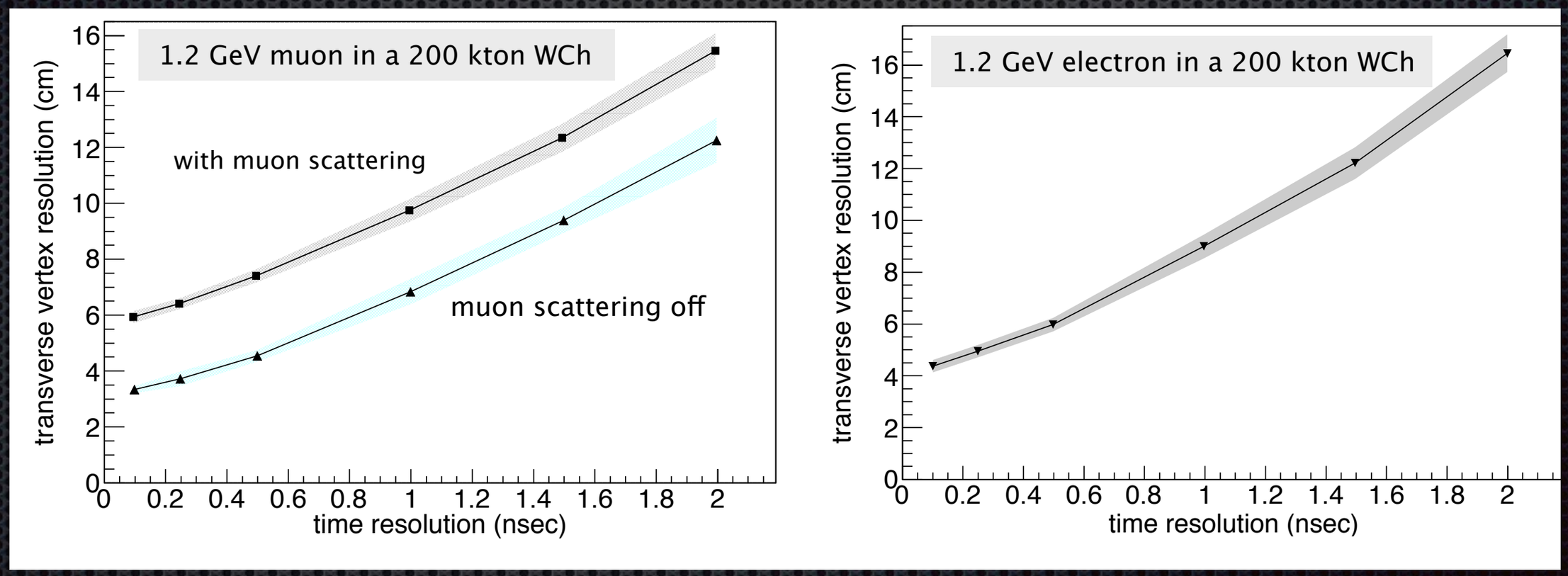




- Transverse vertex resolution is useful in rejection boosted neutral pions.
- Better time resolutions could help to cut deeper into this background.

Transverse vertex resolution

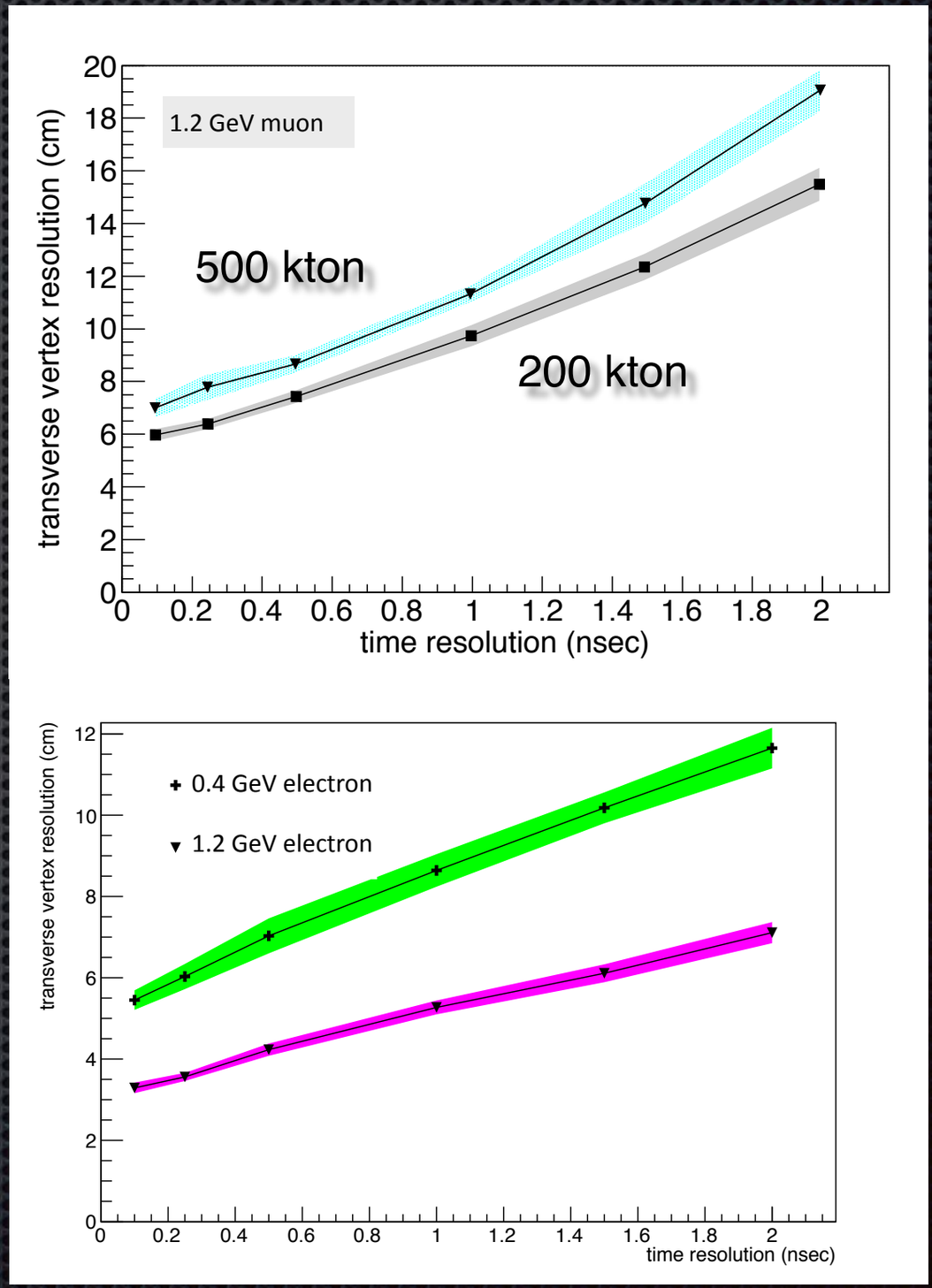
- Muon scattering is not a limiting factor for the gains observed.
- Electrons show slightly better vertex resolutions.



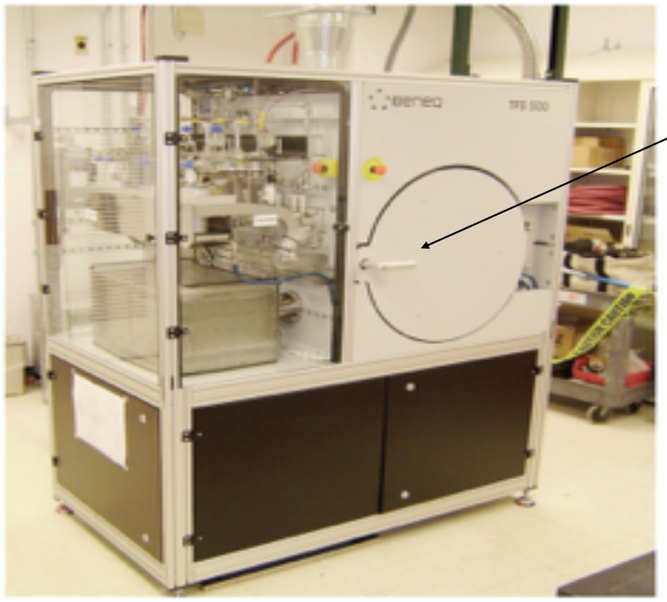
Other detector configurations

- 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.

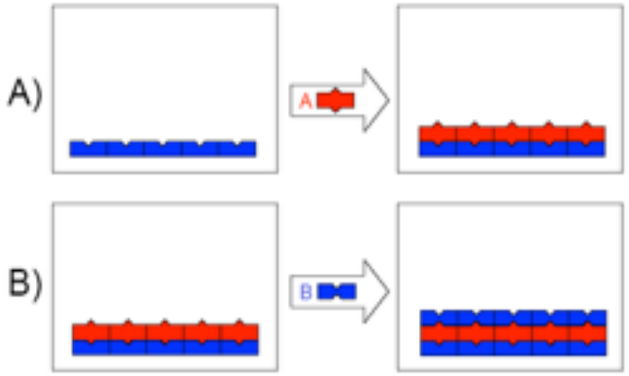
publication coming soon!

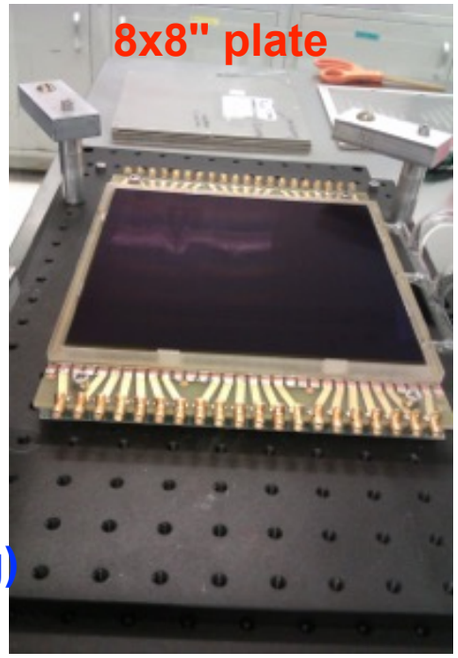


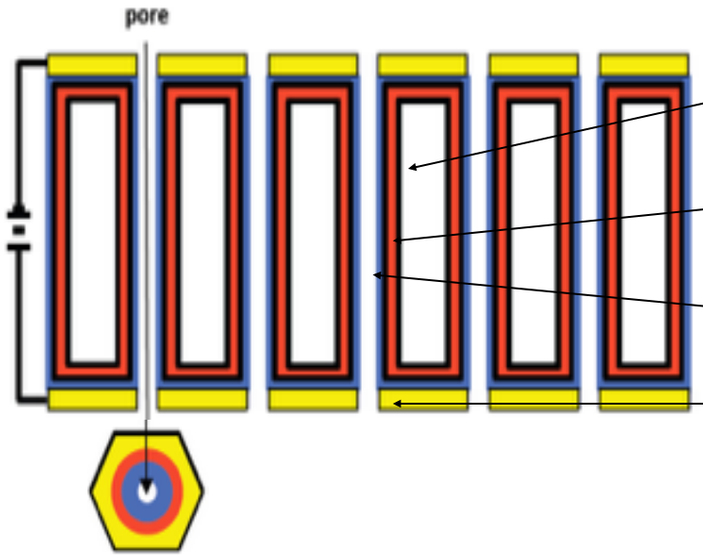
The MCP using Atomic Layer Deposition (ALD)



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







Porous glass

Resistive coating ~100nm (ALD)

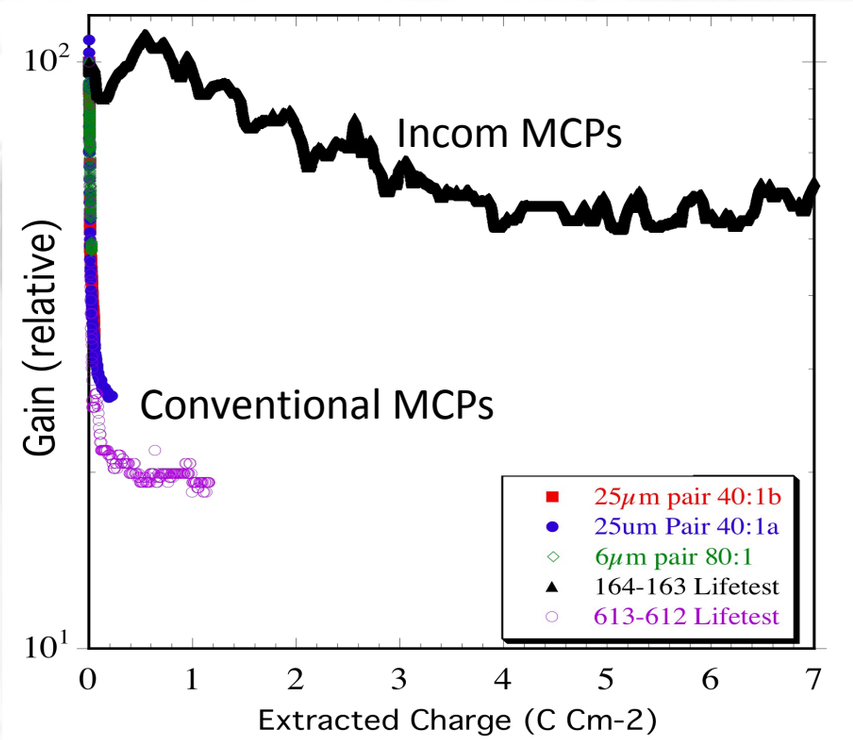
Emissive coating ~ 20nm (ALD)

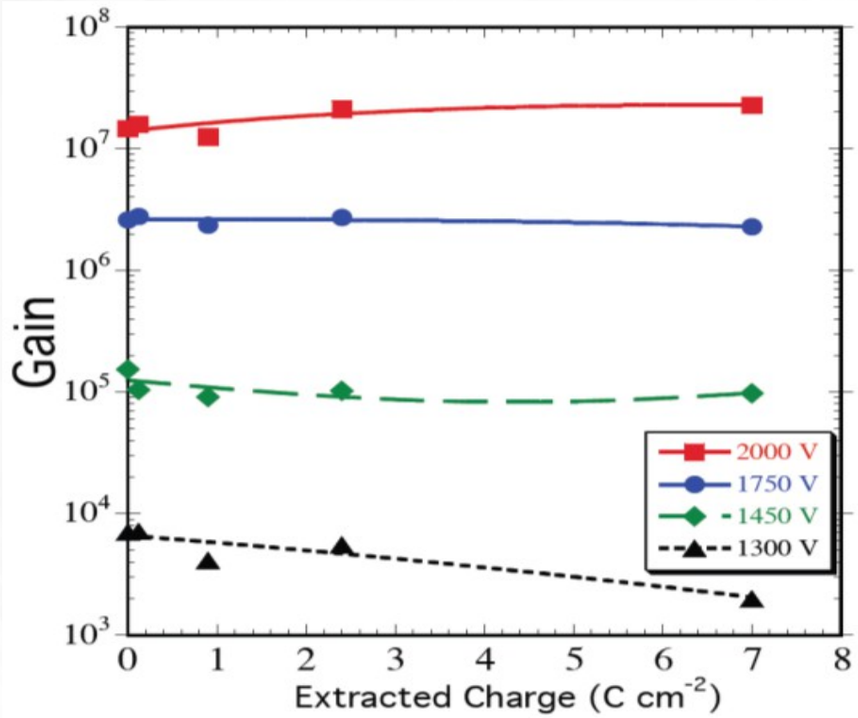
Conductive coating
(thermal evaporation or sputtering)

A. Elagin

Gain Stability

A. Elagin - ANT 2014





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

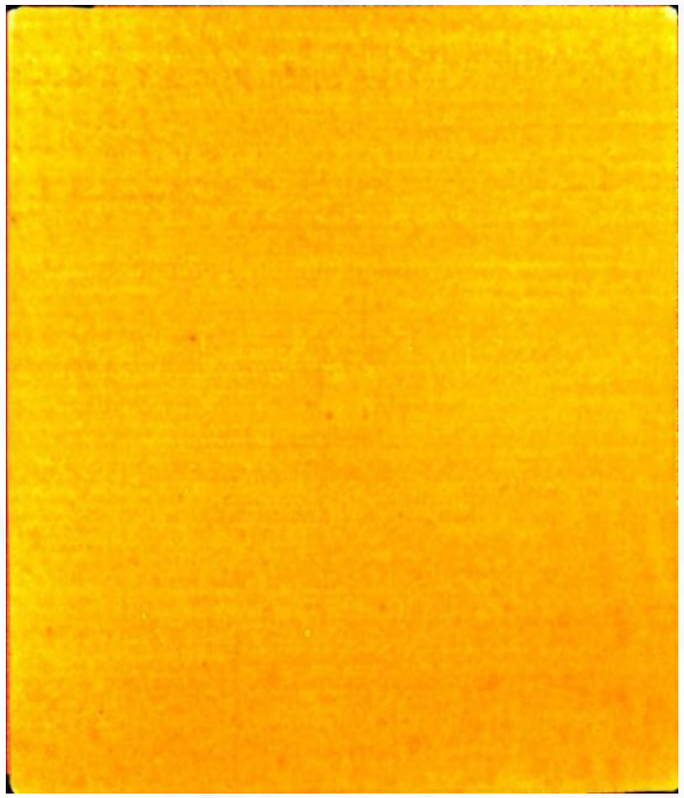
O.H.W. Siegmund, J.B. McPhate, S.R. Jelinsky, J.V. Vallerga, A.S. Tremsin, R.Hemphill, H.J. Frisch, R.G. Wagner, J. Elam, A. Mane and the LAPPD Collaboration, "Development of Large Area Photon Counting Detectors Optimized for Cherenkov Light Imaging with High Temporal and sub-mm Spatial Resolution," 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.

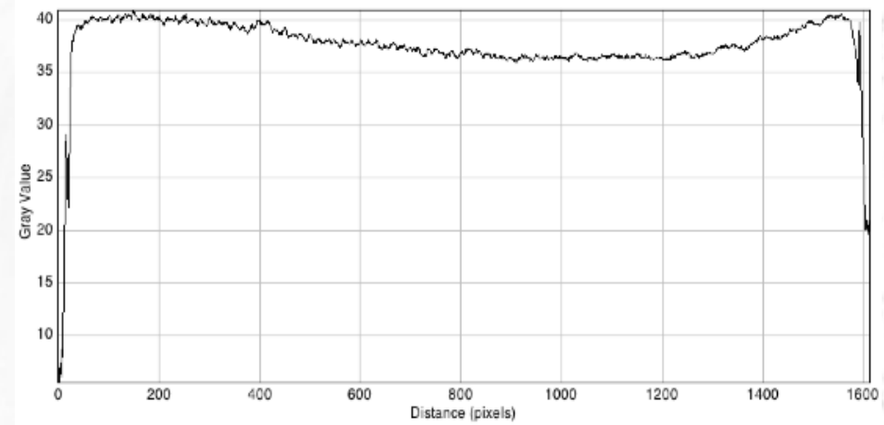
Oswald H. W. Siegmund, John V. Vallerga, Anton S. Tremsin, Jason B. McPhate, Xavier Michalet, Shimon Weiss, Henry Frisch, Robert Wagner, Anil Mane, Jeffrey Elam, Gary Varner, "Large Area and High Efficiency Photon Counting Imaging Detectors with High Time and Spatial Resolution for Night Time Sensing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

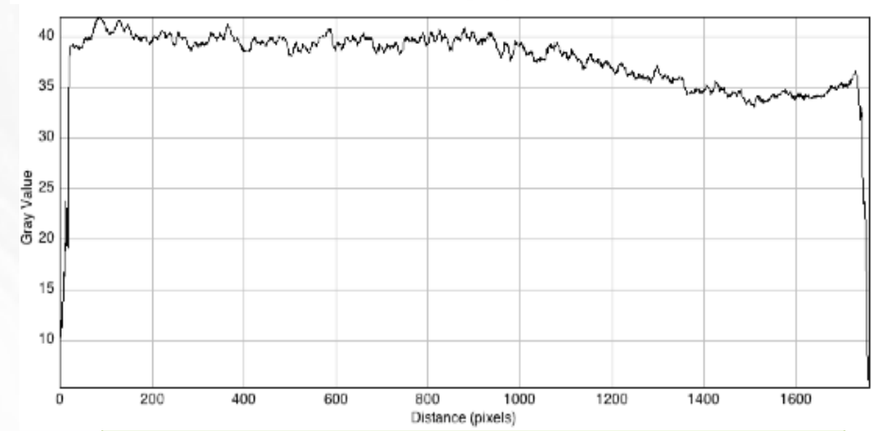
Gain Uniformity

A. Elagin - ANT 2014



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 cm² area

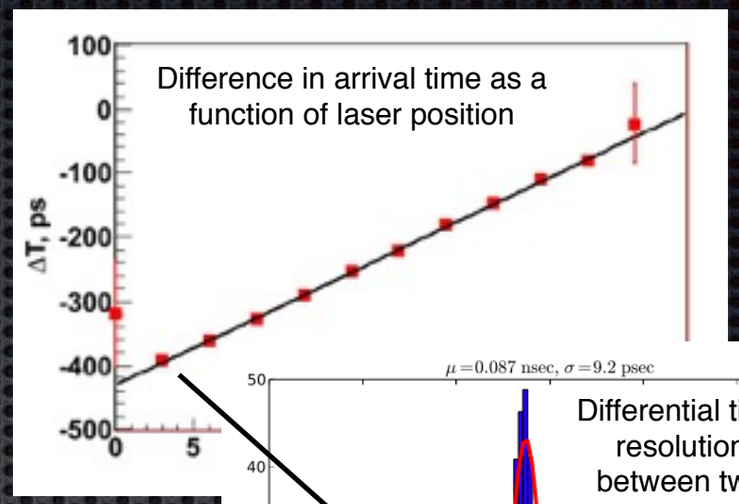
O.H.W. Siegmund, N. Richner, G. Gunjala, J.B. McPhate, A.S. Tremsin, H.J. Frisch, J. Elam, A. Mane, R. Wagner, C.A. Craven, M.J. Minot, "Performance Characteristics of Atomic Layer Functionalized Microchannel Plates" Proc. SPIE 8859-34, in press (2013).

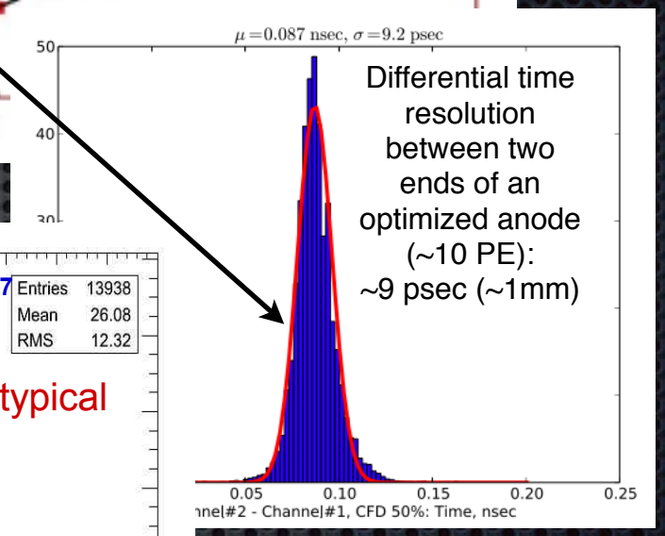
Also, very low noise: <0.1 counts cm^{-2} s^{-1}

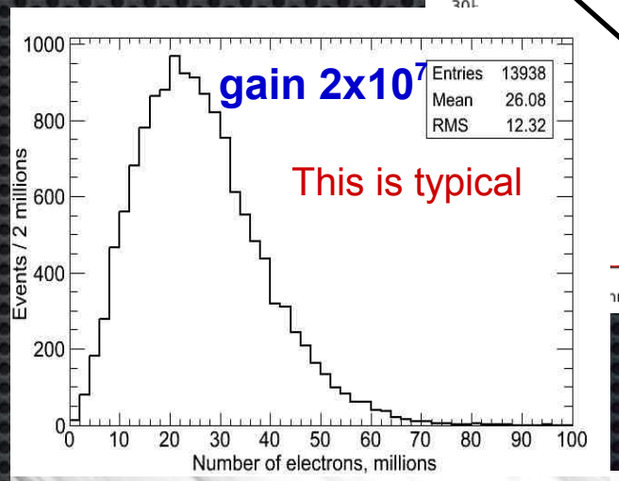
a factor of ~4 lower compared to conventional MCPs

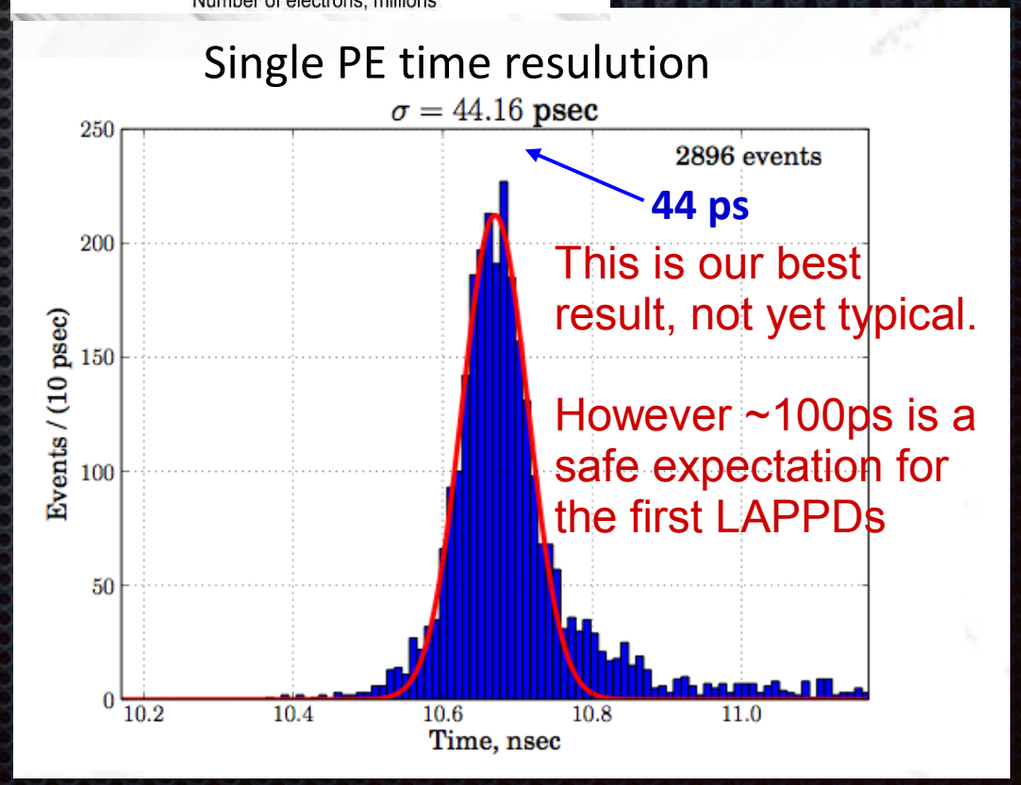
LAPPD Status

- 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.



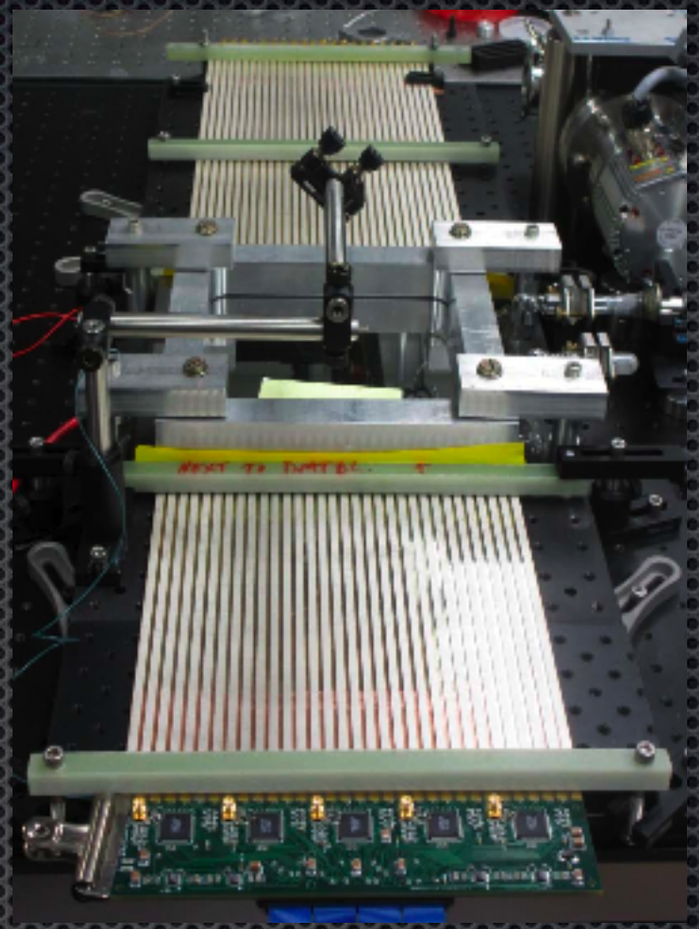




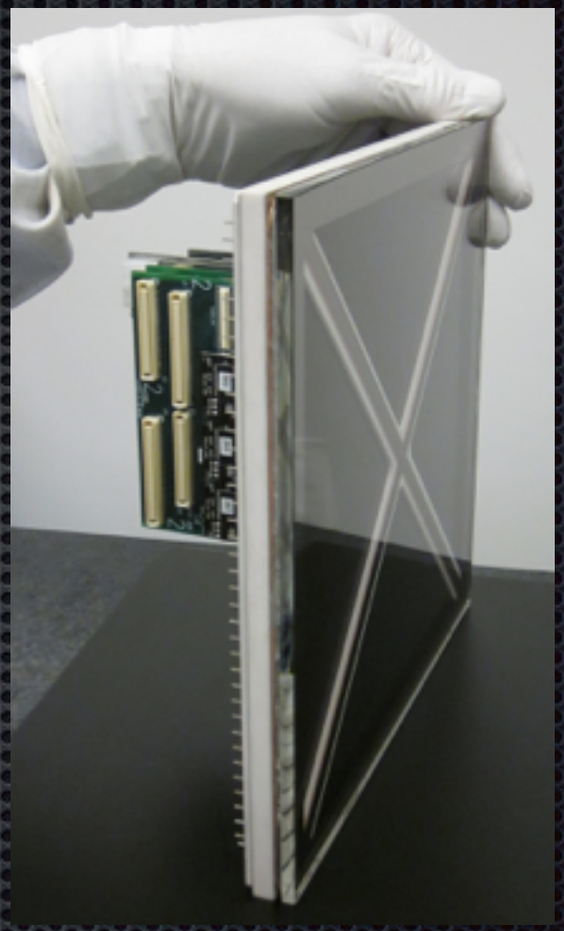


LAPPD Status

- 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



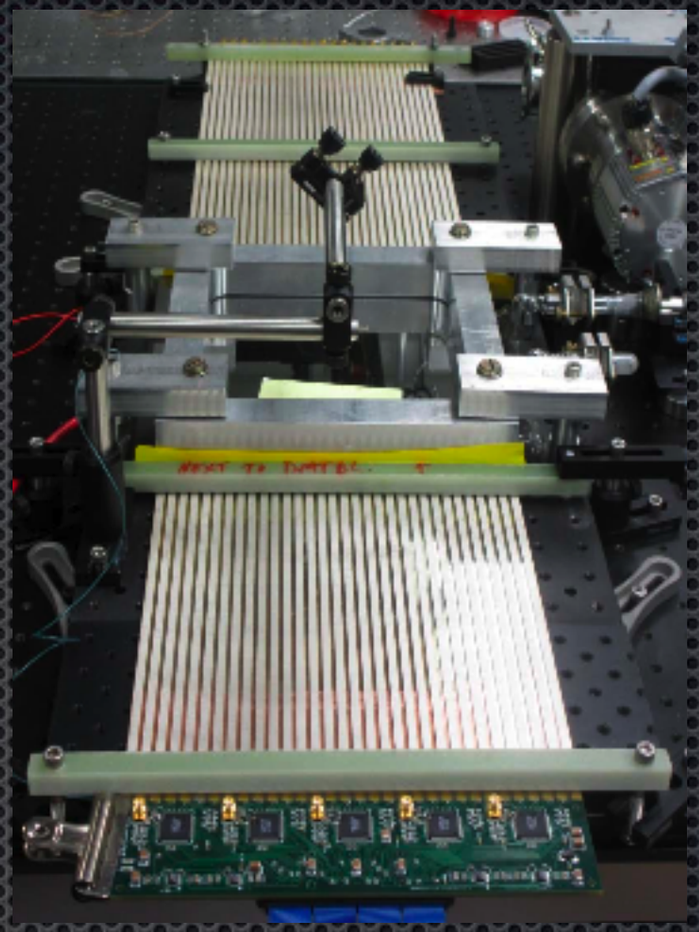
Berkeley SSL detector system- ceramic body LAPPD

UChicago lightweight in-situ assembly

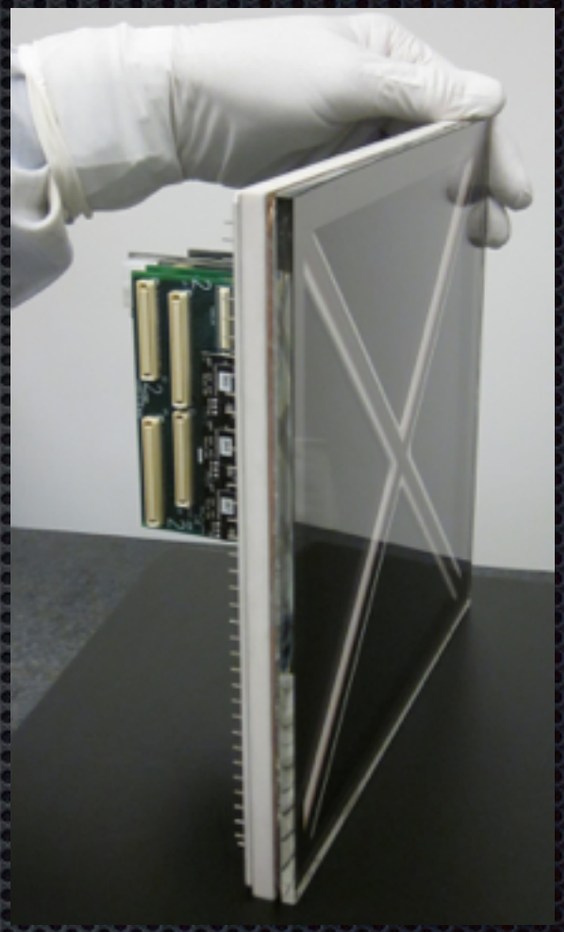
Berkeley SSL Sealed-Tube Processing Tank

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.

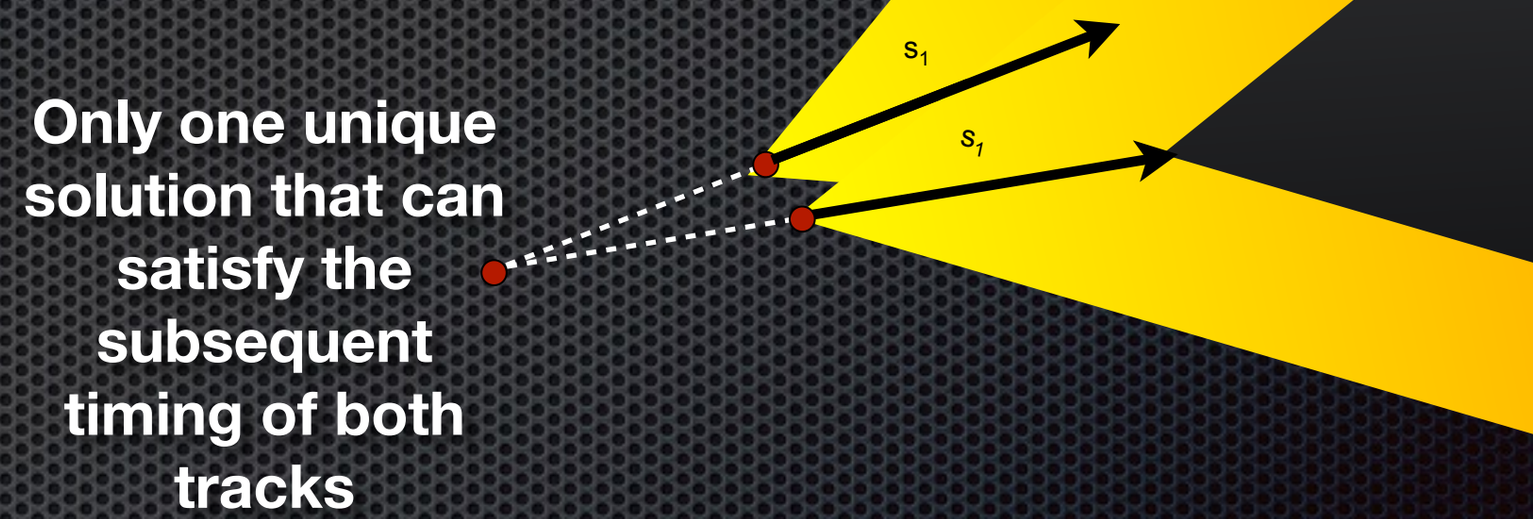
UChicago lightweight in-situ assembly

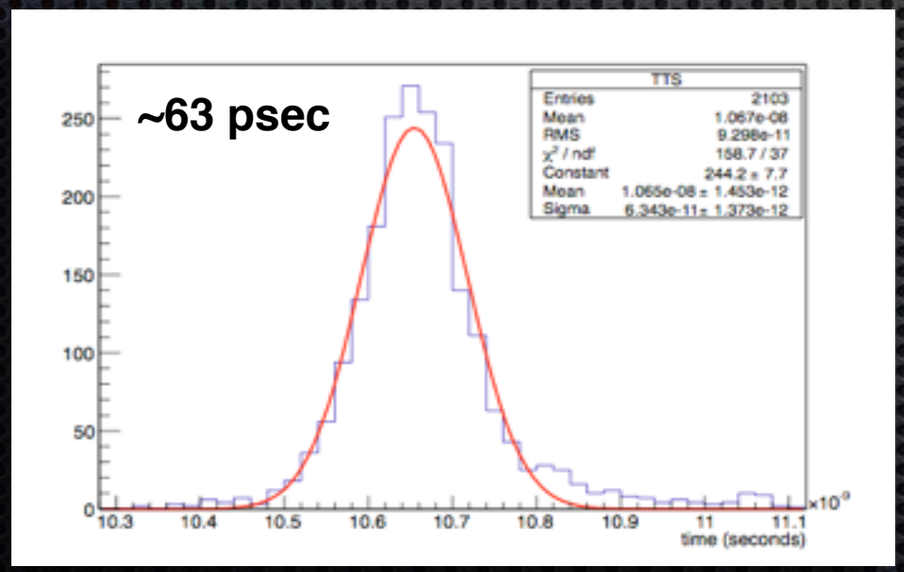
Berkeley SSL Sealed-Tube Processing Tank

Timing-based vertex fitting

Fortunately, multi-vertex separation is a differential measurement.

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

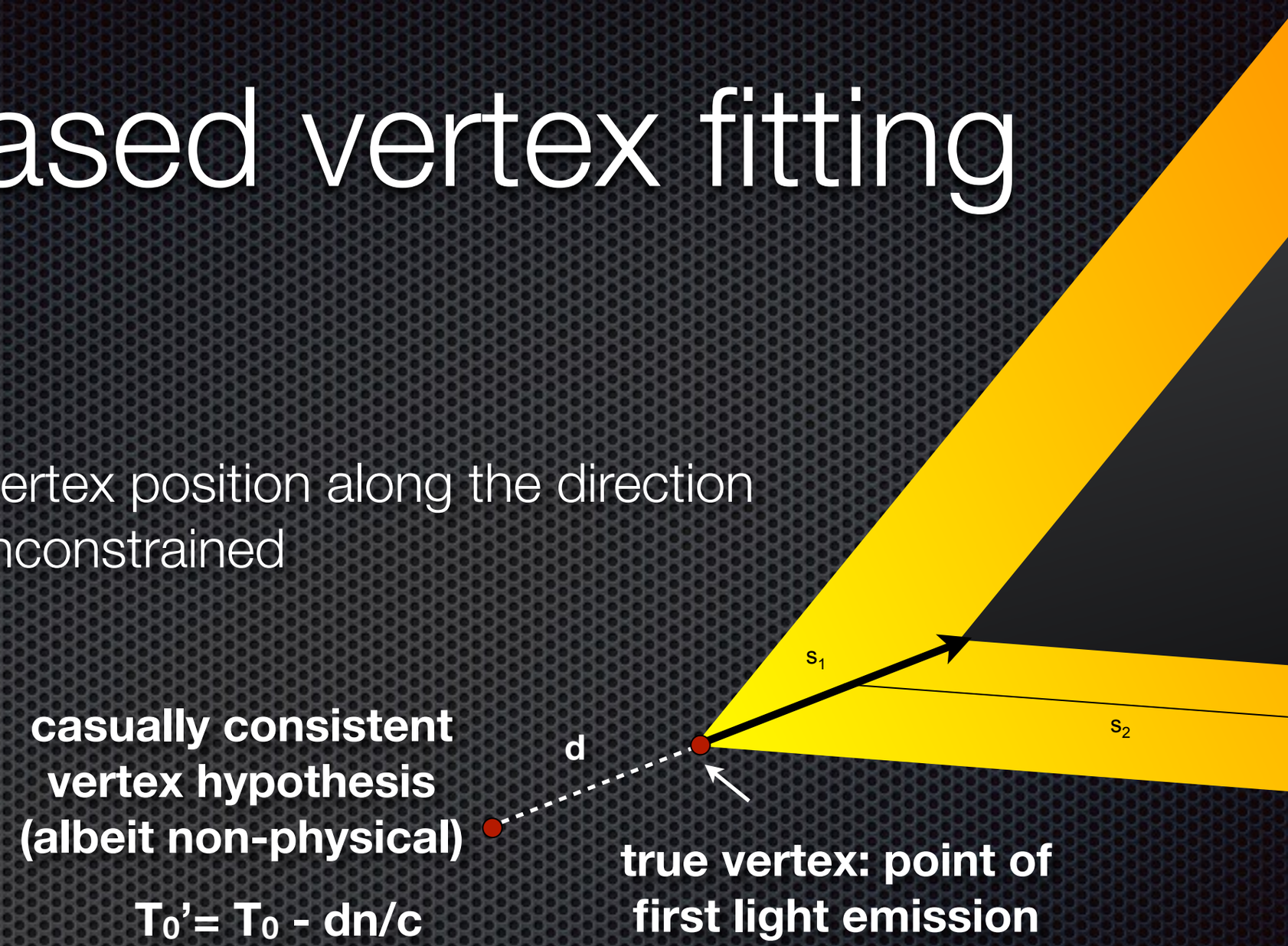




100 picoseconds ~ 2.25 centimeters

Timing-based vertex fitting

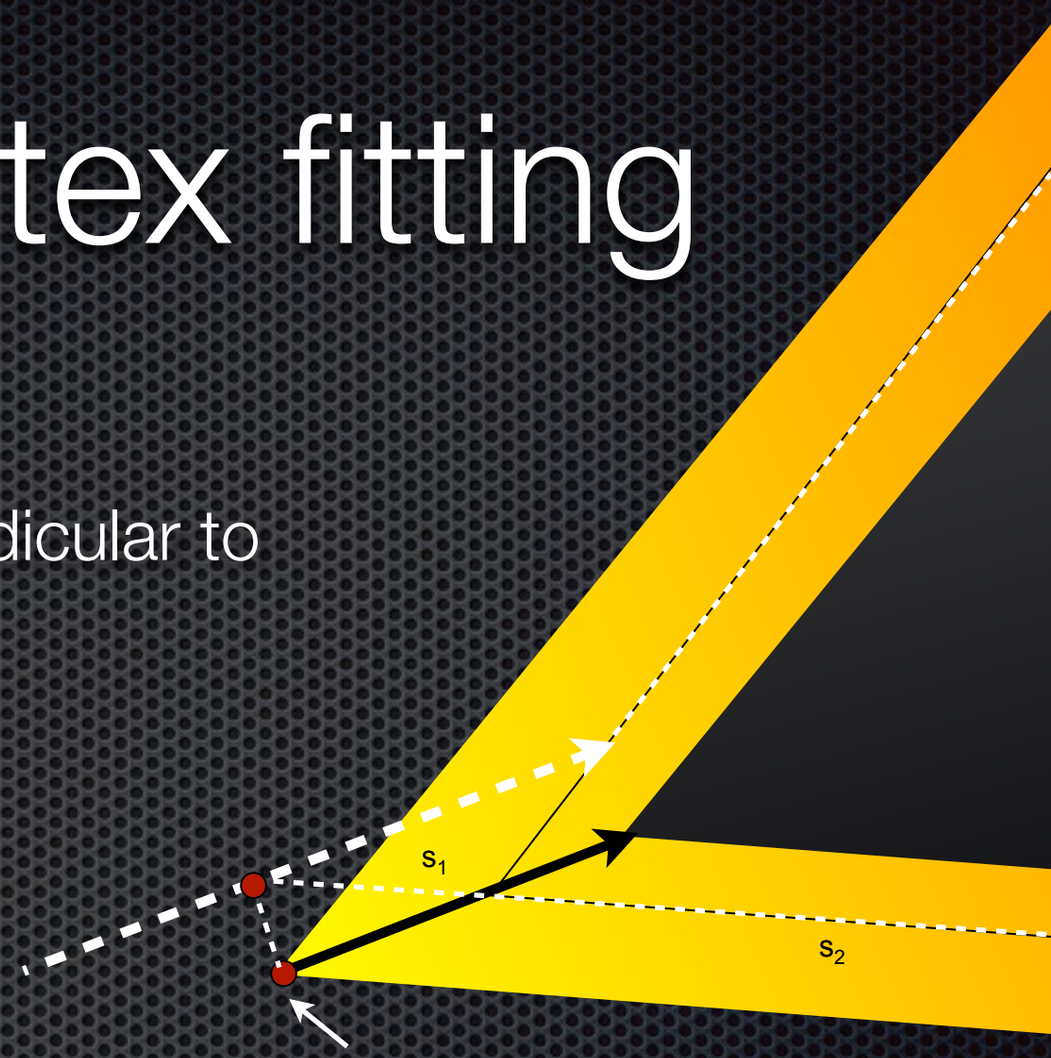
Based on pure timing, vertex position along the direction parallel to the track is unconstrained



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)

$T_0' = T_0 - dn/c$

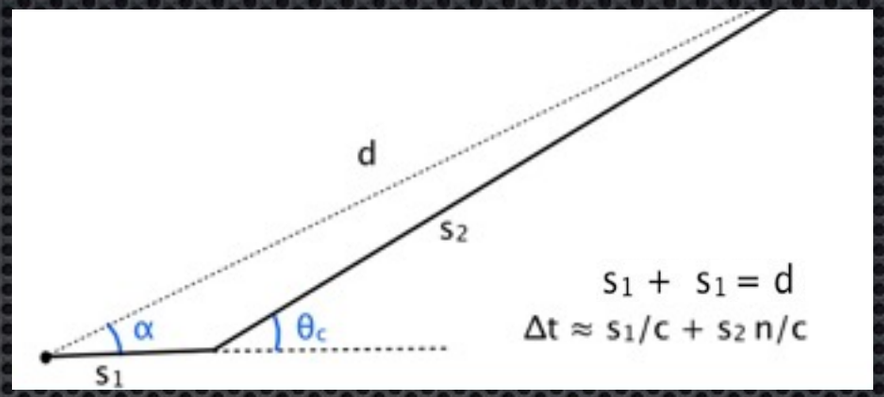
true vertex: point of first light emission

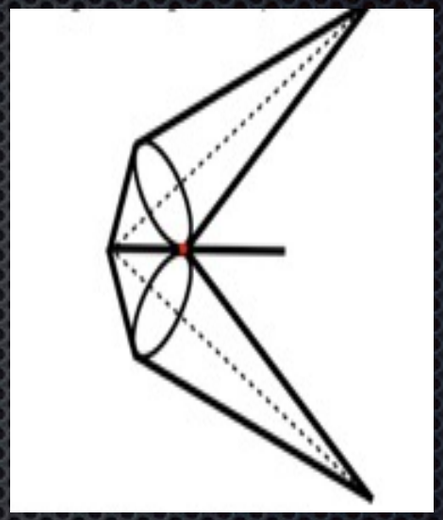
For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

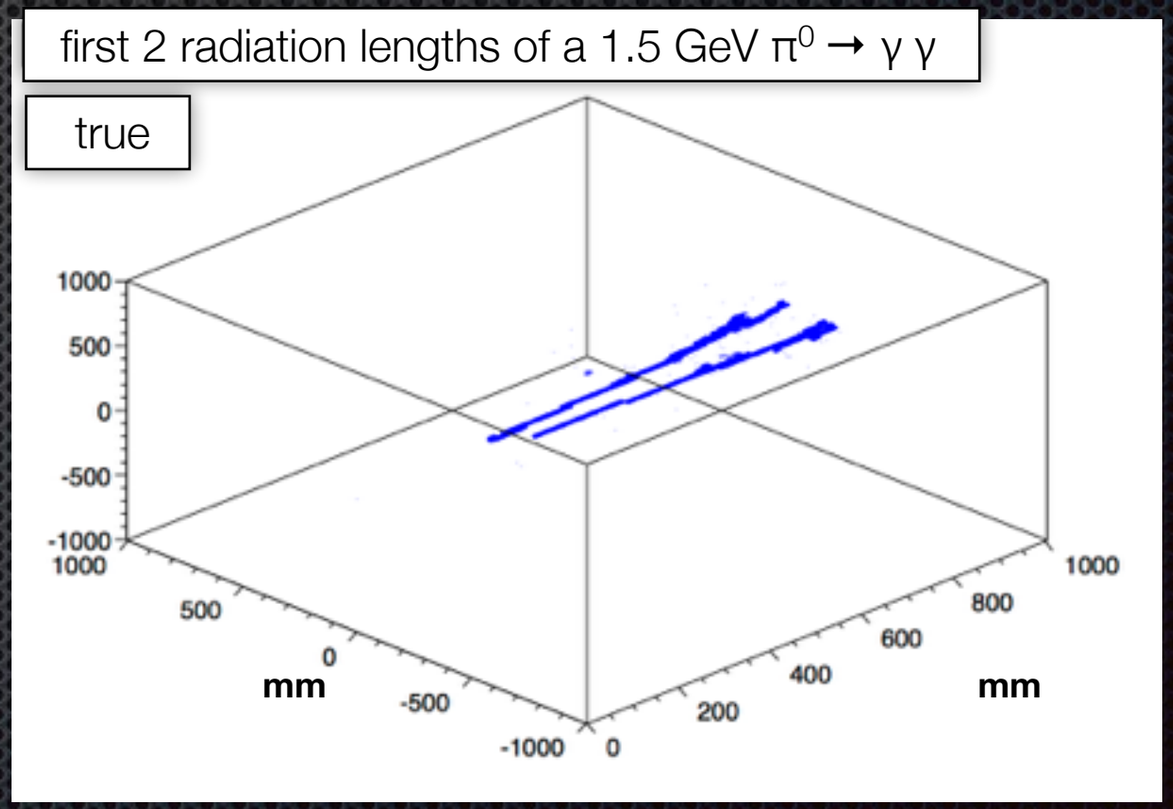
100 picoseconds ~ 2.25 centimeters

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.



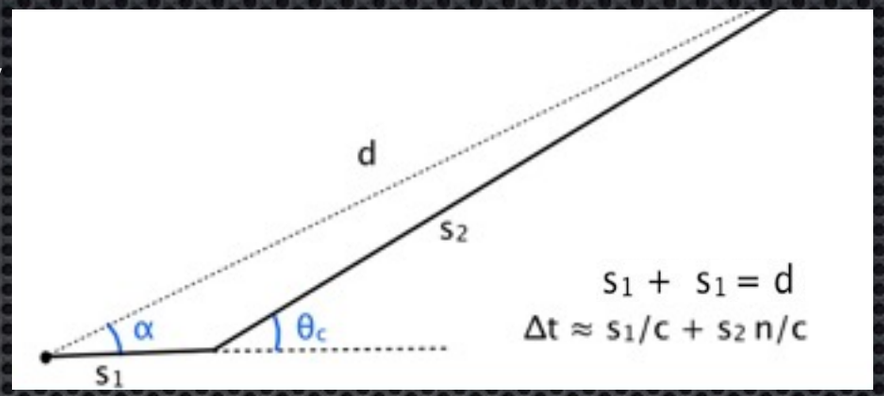


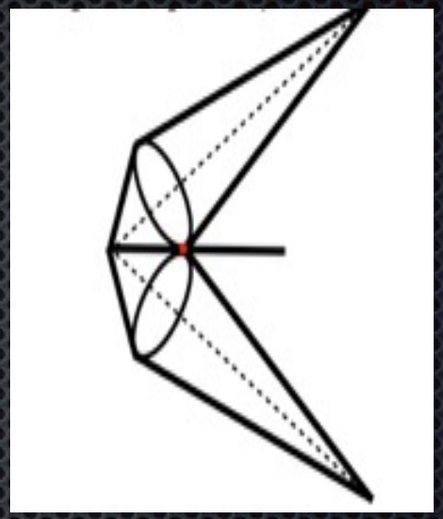


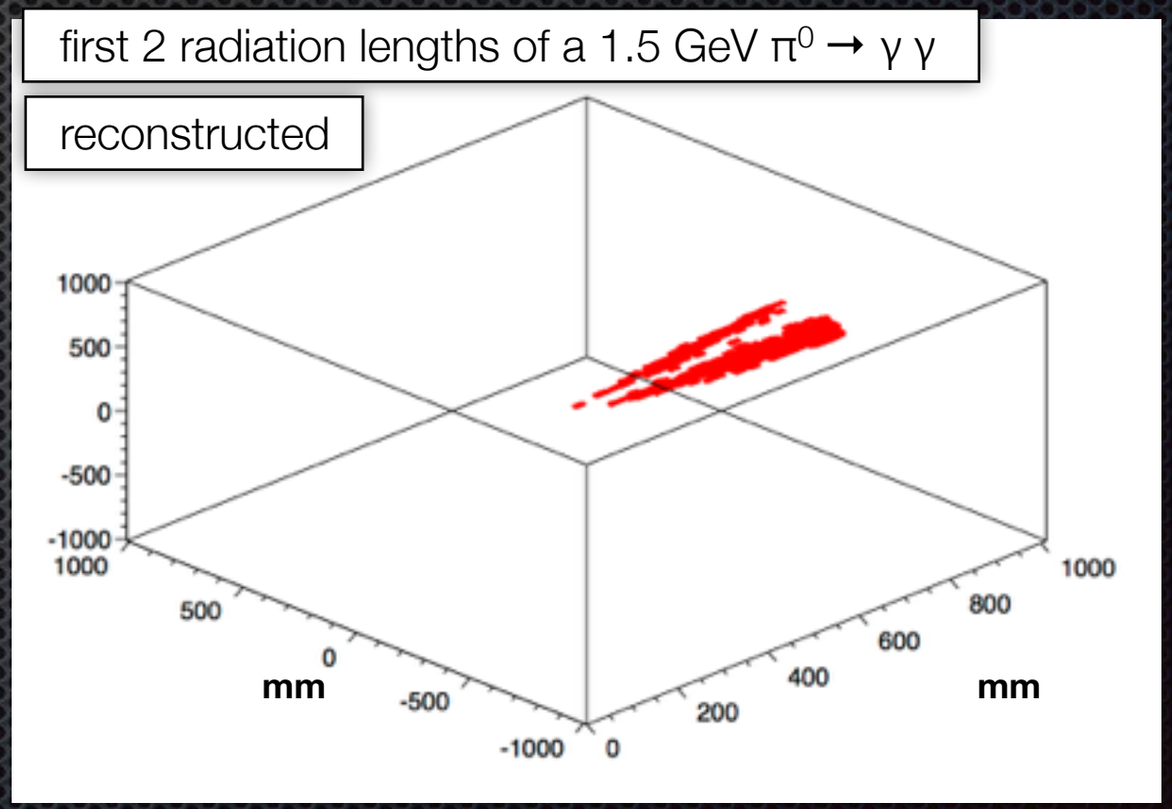
M. Wetstein

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.







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.