Using Large-Area Picosecond Photosensors
in Water Cherenkov Detectors

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Motivation

- The next generation of neutrino experiments will require massive detectors to reach the sensitivities needed to measure CP violation in the lepton sector and the neutrino mass hierarchy.

- One or several large water Cherenkov (WCh) detectors provide the mass required for a broad physics program in the US Long Baseline Neutrino Experiment (LBNE) but also for other possibilities such as those in Japan and Europe.

- A challenge for the upcoming WCh will be instrumenting their very large surfaces with current photosensor technology.

- A new technology might open the path to use correlated time and space information for Cherenkov light, possibly boosting the physics performance of these detectors.
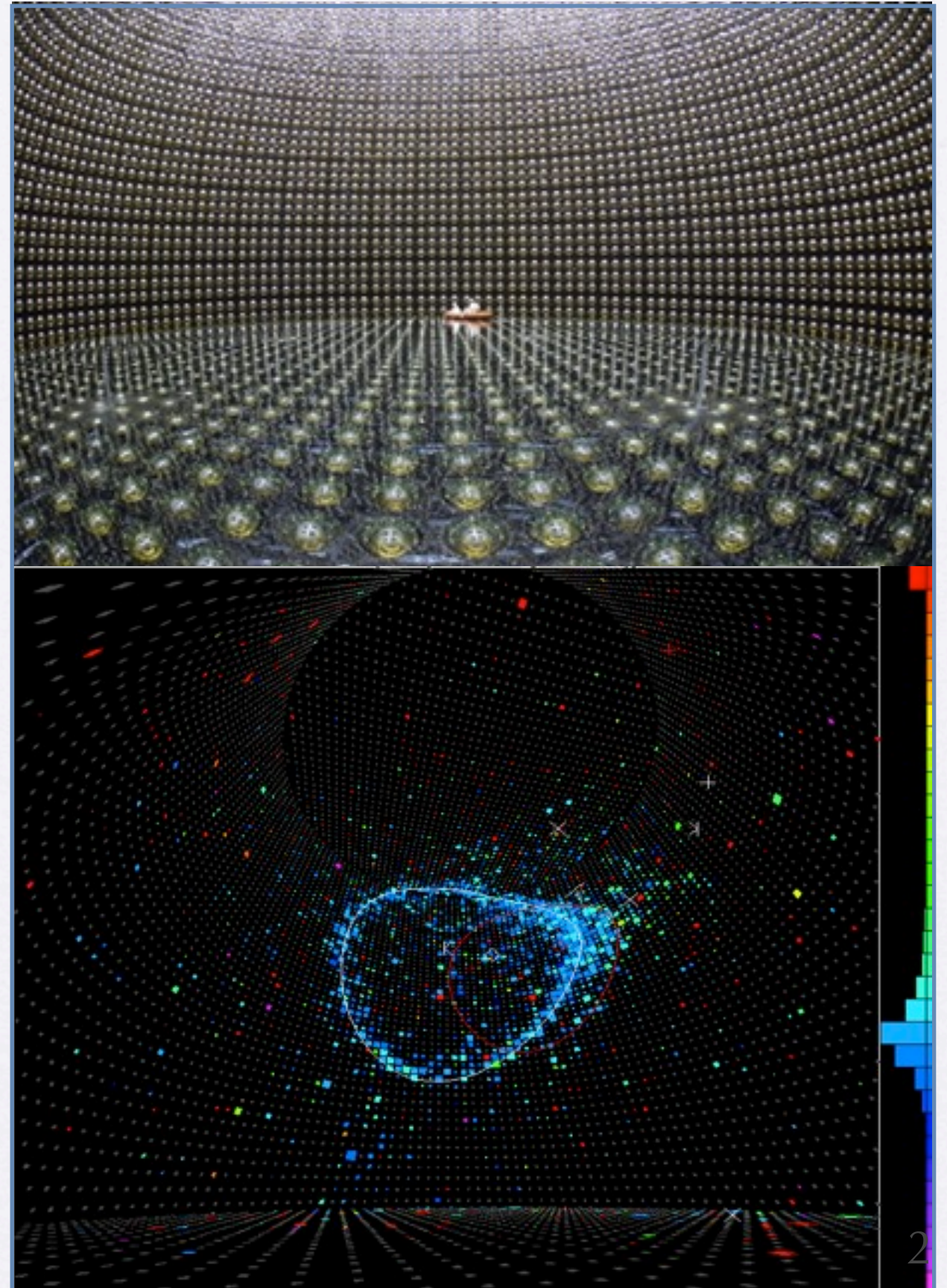
Motivation

- In neutrino physics, there is also a need for smaller and/or higher intensity detectors.

- Recent results have a series of low significance "anomalies" that might need to be resolved and/or measured in a short-baseline beam.

- This could be an excellent opportunity to put a new technology to the test before a large deployment.

- Other interesting uses: a possible Near Detector for LBNE, nuclear non-proliferation, etc.
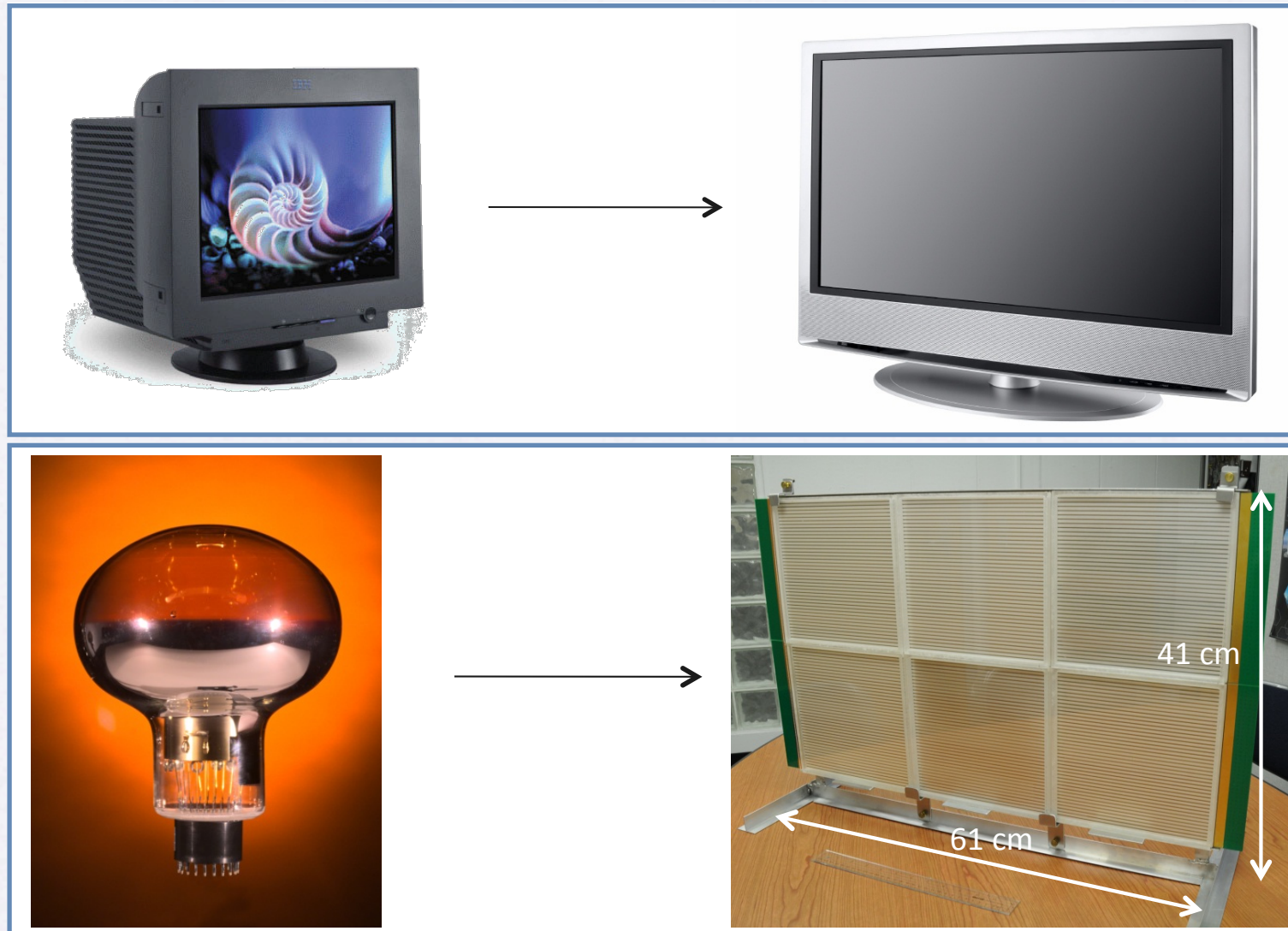
Bill Louis
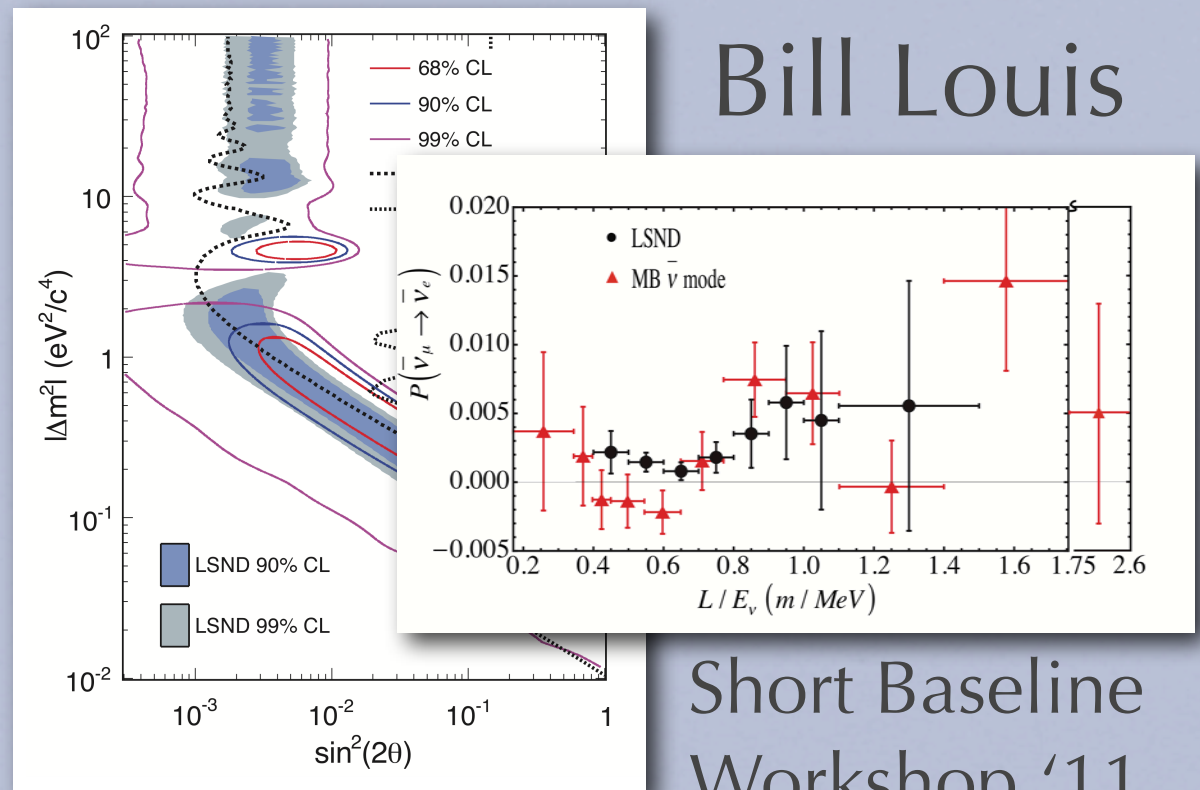
Short Baseline Workshop '11
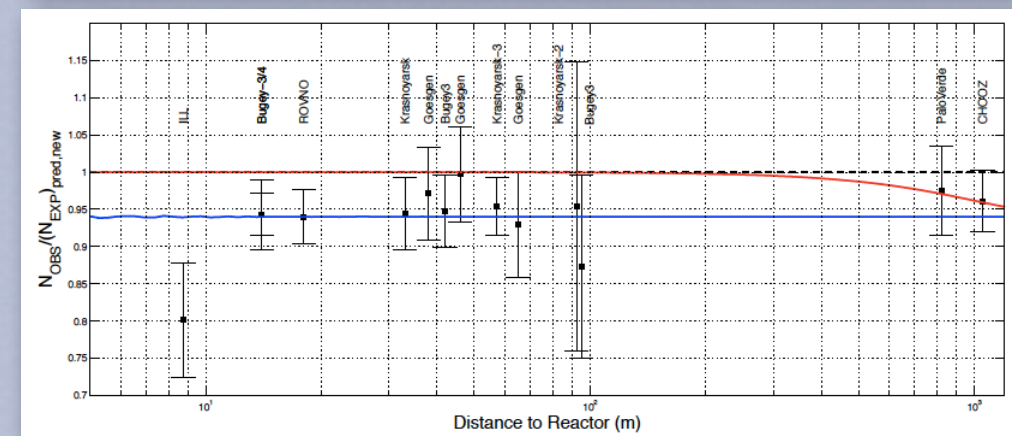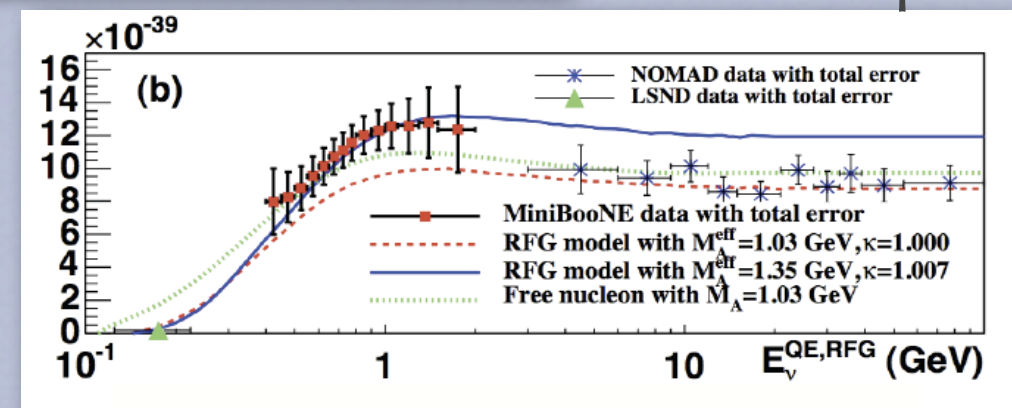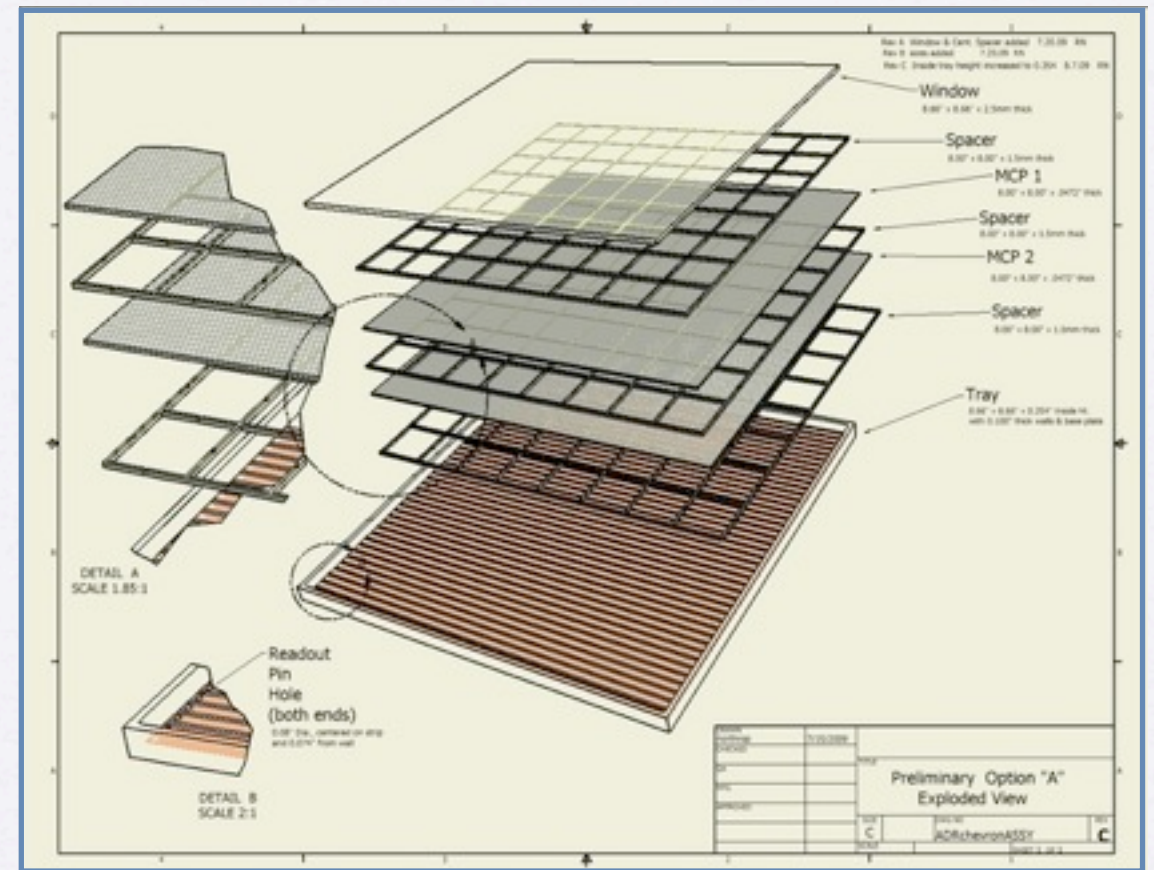
A new technology for neutrinos: LAPPD

- A 3-year DOE project to develop **L**arge **A**rea **P**icosecond **P**hoto-**D**etectors based on microchannel plate (MCP) technology started at ANL August '09.
- The goal is develop cheap, scalable, flat panel photodetectors with precision time resolution, capable of picosecond-level time of flight (TOF) measurements.
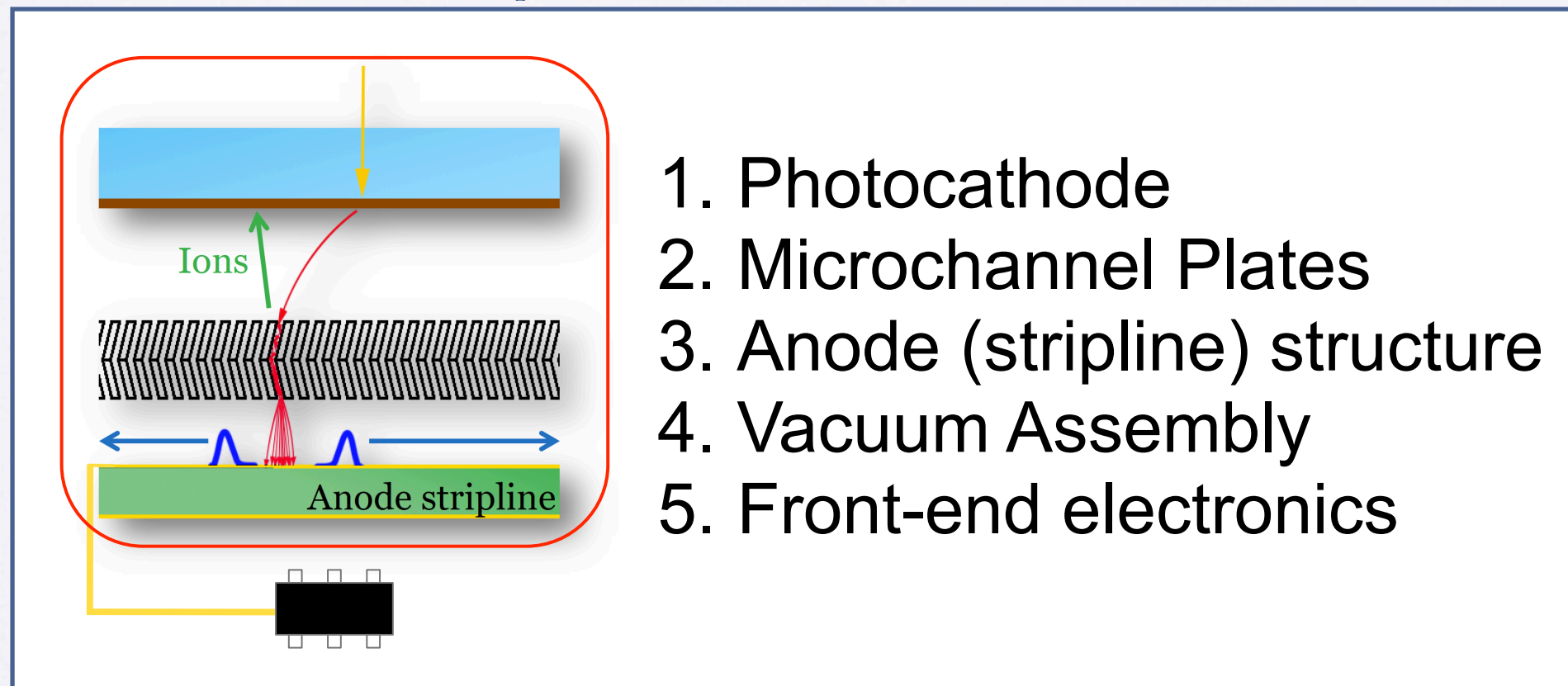
Using Microchannel Plates Photodetectors

- Microchannel Plates are an existing photomultiplier technology known for:
    - Picosecond-level time resolution.
    - Micron-level spatial resolution.
    - Excellent photon-counting capabilities.
    - Being expensive.

- Exploiting advances in material science and electronics, the LAPPD collaboration is designing large-area MCP-PMTs detectors:

    - That preserve time and space resolutions of conventional MCP detectors.

    - At low enough cost per unit area for collider, neutrino and many other applications.

- In collaboration with M. Wetstein, H. Frisch (ANL/UChicago), G. Davies (Iowa State), we are studying the application of these new photosensors to Water Cherenkov detectors.

Anatomy of an MCP-PMT

Ions

Anode stripline

1. Photocathode
2. Microchannel Plates
3. Anode (stripline) structure
4. Vacuum Assembly
5. Front-end electronics

- The LAPPD collaboration is designing each of these elements.
  Th

  - MCP development: use modern fabrication processes (ALD) to control emissivity and resistivity.

  - Readout: use transmission lines and modern chip technologies for high speed cheap low-power high density readout.

  - Development of large area photocathodes: studying techniques for industrial batch processing.

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Microchannel Plate Fabrication

INCOM glass substrates
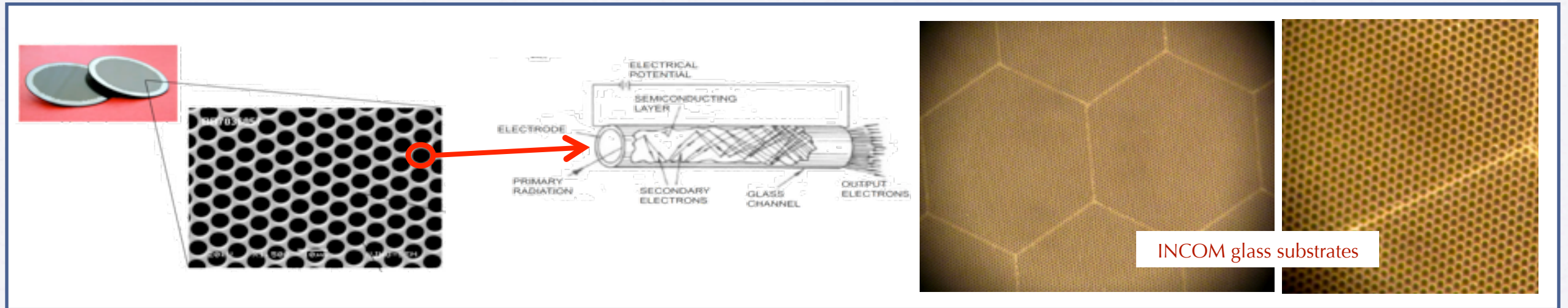
- Conventional MCP Fabrication:

  - Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material.

  - Chemical etching and heating in hydrogen to improve secondary emissive properties.

  - Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties.

- Proposed approach by 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.

J. Elam, A. Mane, Q. Peng, (ANL:ESD/HEP),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)

Achievement: Successful MCP fabrication by ALD on both 33 mm and 8" substrates: able to control resistance and secondary electron yield.

LAPPD Achievements
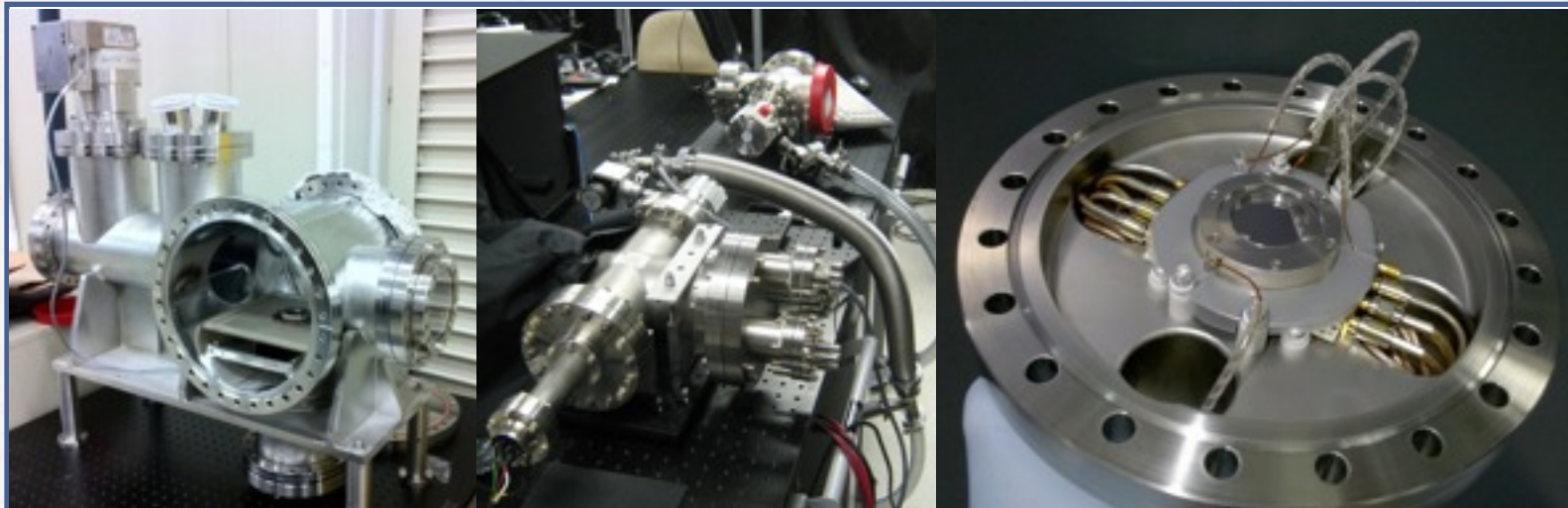
- Demonstrated $> 10^5$ amplification on Argonne-made, 33mm ALD functionalized glass plates.

- Demonstrated better than 200 psec time resolutions for single photoelectrons in ALD MCPs.

- Completion of laser characterization lab for systematic MCP testing in the time domain as well as facilities for characterization of 8" MCPs and lifetime testing.

- Low cost anode design.

- Development of fast, low-cost sampling chips.

- Demonstration of photocathode deposition scalable to 8" panels.

Comparison of ALD MCP Gains w Commercial MCP

- MCP 122
- Avg Mock Tile MCP
- Commercial MCP
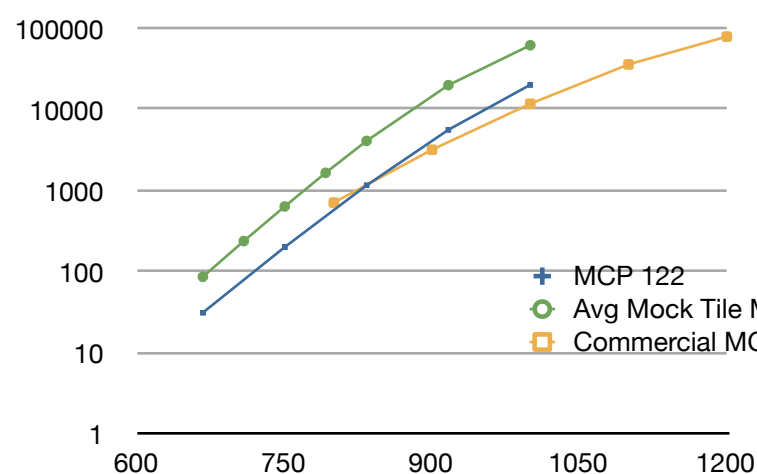
Gain curves for mock tile MCPs

+ 125 ○ 126 □ 127 ✳ 128 △ 129 ◇ 130 + 132 ○ 133 — mean — +50% — -50%
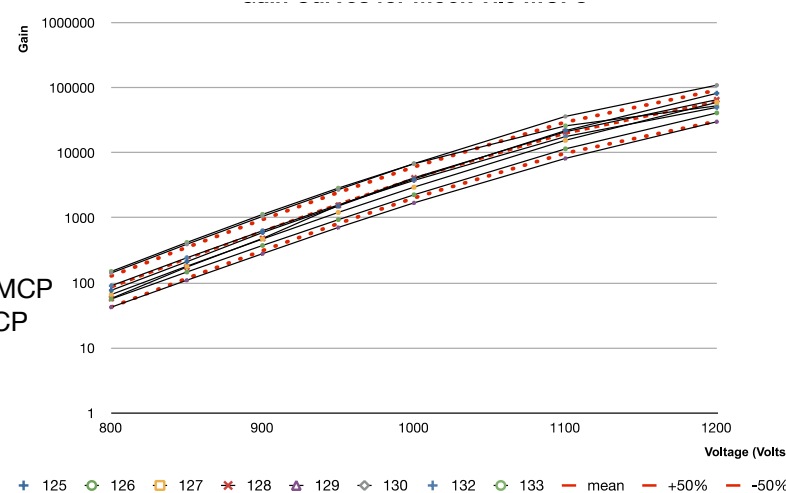
Average pulse shape for single MgO MCP at 1.5 kV, different photocathode voltages
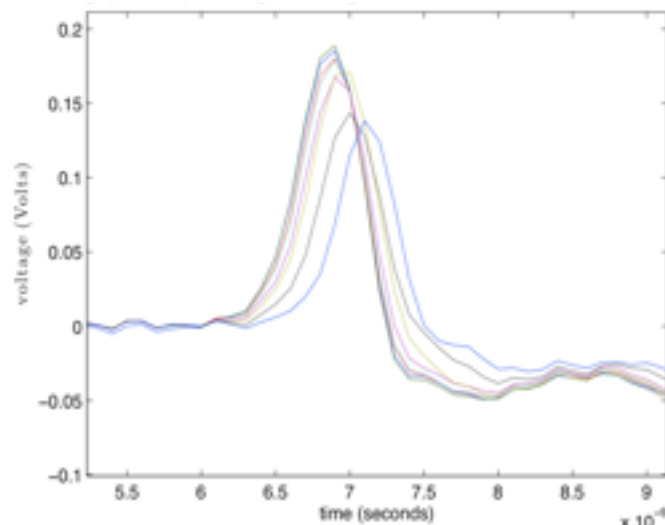
Relative Shift in Mean Arrival Time of Signal Vs Voltge on Anode Gap

M. Wetstein (U Chicago/ANL-HEP), B. Adams, M. Chollet (ANL-APS)

A LAPPD for neutrinos
The proposed design

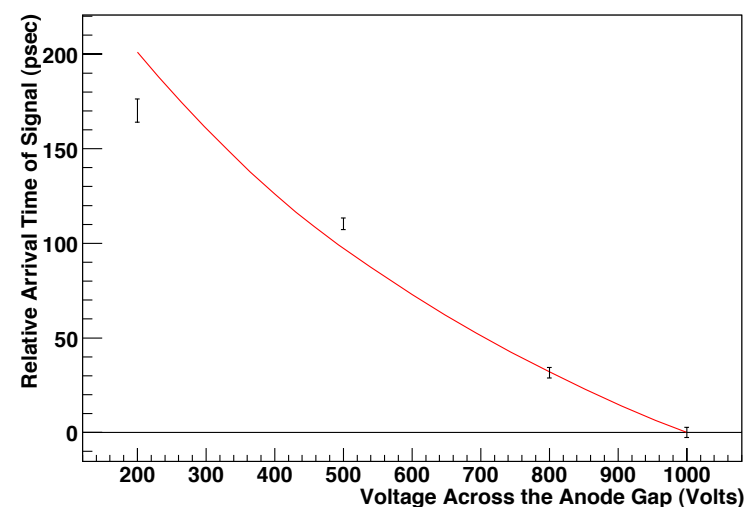- Microchannel plate photosensor in 8x8" tiles arranged in 24x16" super-module.

- Spatial resolution of ~cm, timing resolution of ~100 psec.

- Channel count optimized to large area/ desired granularity.

- Integrated double-sided readout.

- Scaled high QE photocathode. Possible new materials such as nano-structured photocathodes.

- Large-area flat panel provides robust construction. Low internal volume and use of known glass (B33).

- No magnetic susceptibility.
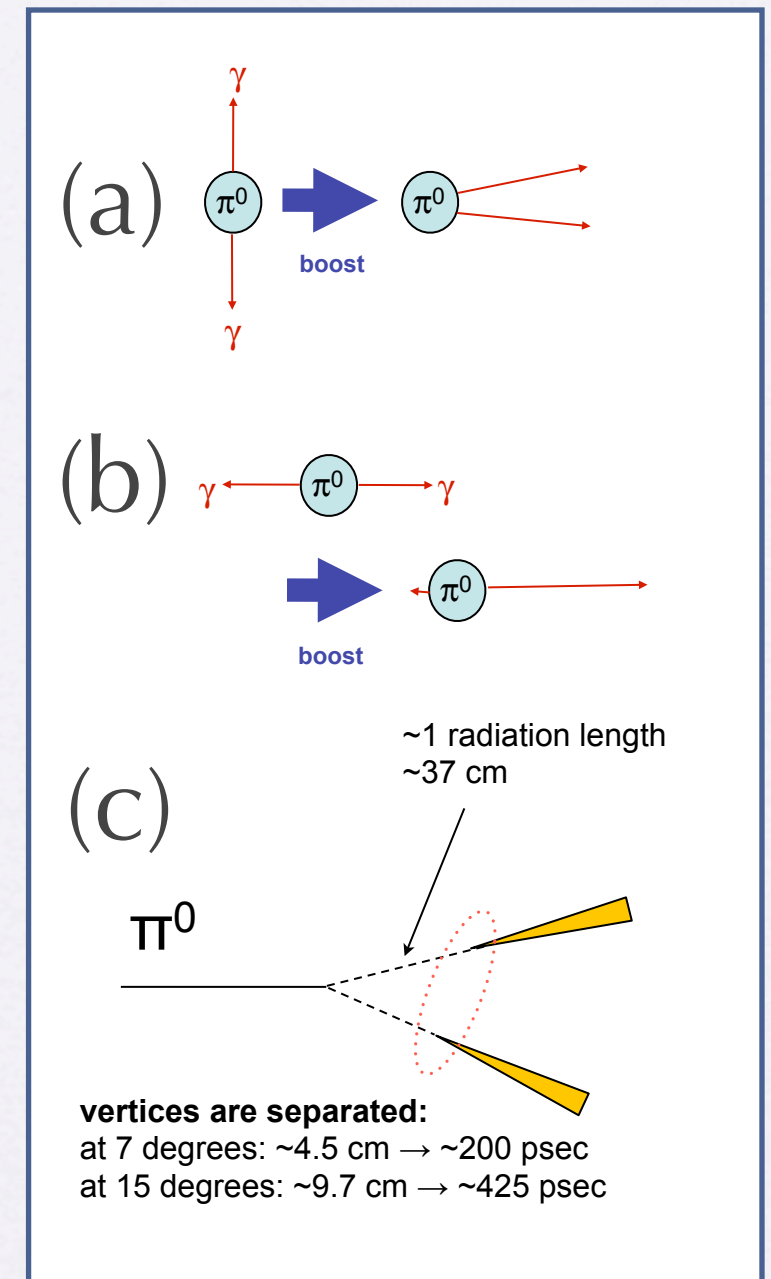

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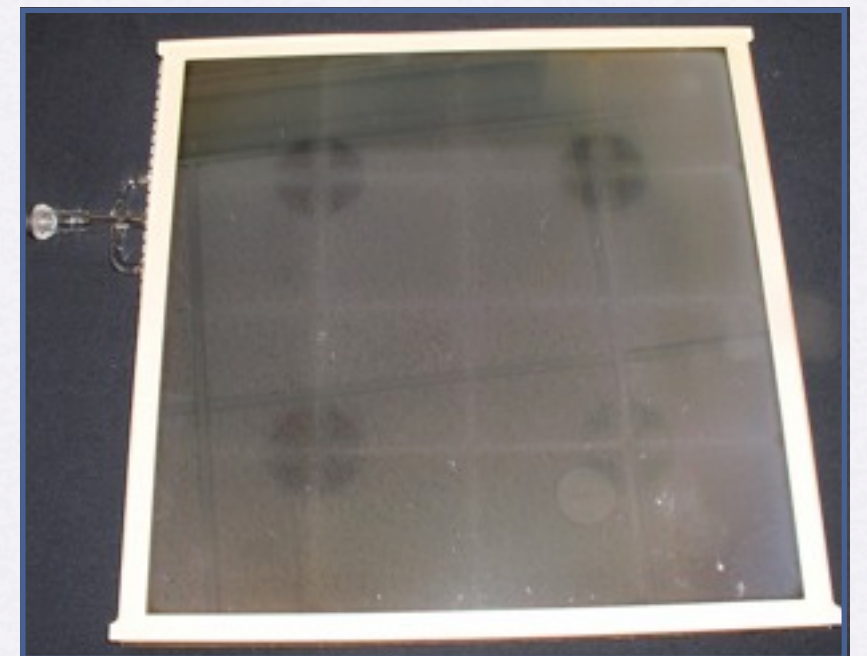
The Neutrino Application

- The application of this new technology for neutrino WCh detectors could enhance background rejection and vertex resolution by **improving spatial and timing information**. It could also broaden the low energy physics capabilities of the detectors by **providing higher coverage** than what is currently planned.

- These benefits need to be demonstrated with simulations, characterization and calibration design for these devices.

- Design of the photosensors is being kept reasonably generic as there are many possible applications.

  - Direct feedback from us to the baseline design of these devices is needed by defining and optimizing the specifications.

- For the LBNE Water Cherenkov detector, this technology is seen as a possible upgrade path.
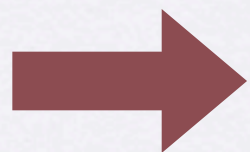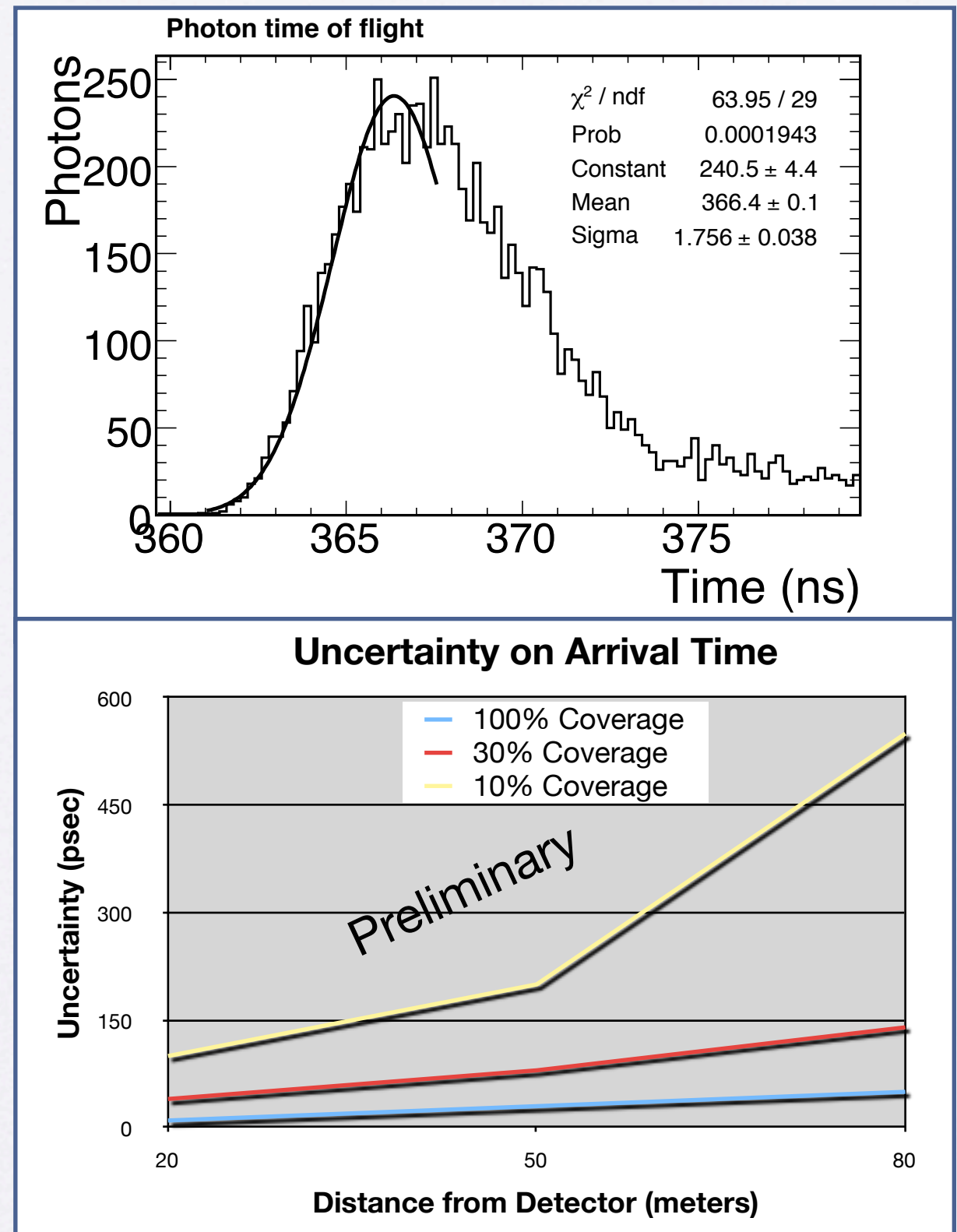
Improving background rejection

- For the long baseline neutrino application, we want to obtain better background rejection:

  (a) Higher granularity and larger coverage improves angular resolution between the two photons in forward π^0 decays (typically smaller than 15˚).

  (b) Larger area coverage/higher QE could increase the efficiency of detecting the less energetic photon in an asymmetric π^0 decay.

  (c) Faster timing can improve vertex resolution down to a few cm, permitting the separation of the conversion points of the π^0 for some events.

(a) γ π^0 **boost** π^0 γ

(b) γ π^0 γ **boost** π^0

(c)

~1 radiation length ~37 cm

π^0

vertices are separated:
at 7 degrees: ~4.5 cm → ~200 psec
at 15 degrees: ~9.7 cm → ~425 psec

Coverage and timing

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

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

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

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

Photon time of flight

χ^2 / ndf	63.95 / 29
Prob	0.0001943
Constant	240.5 ± 4.4
Mean	366.4 ± 0.1
Sigma	1.756 ± 0.038

Photons

Time (ns)

Uncertainty on Arrival Time

Uncertainty (psec)

- 100% Coverage
- 30% Coverage
- 10% Coverage

Preliminary
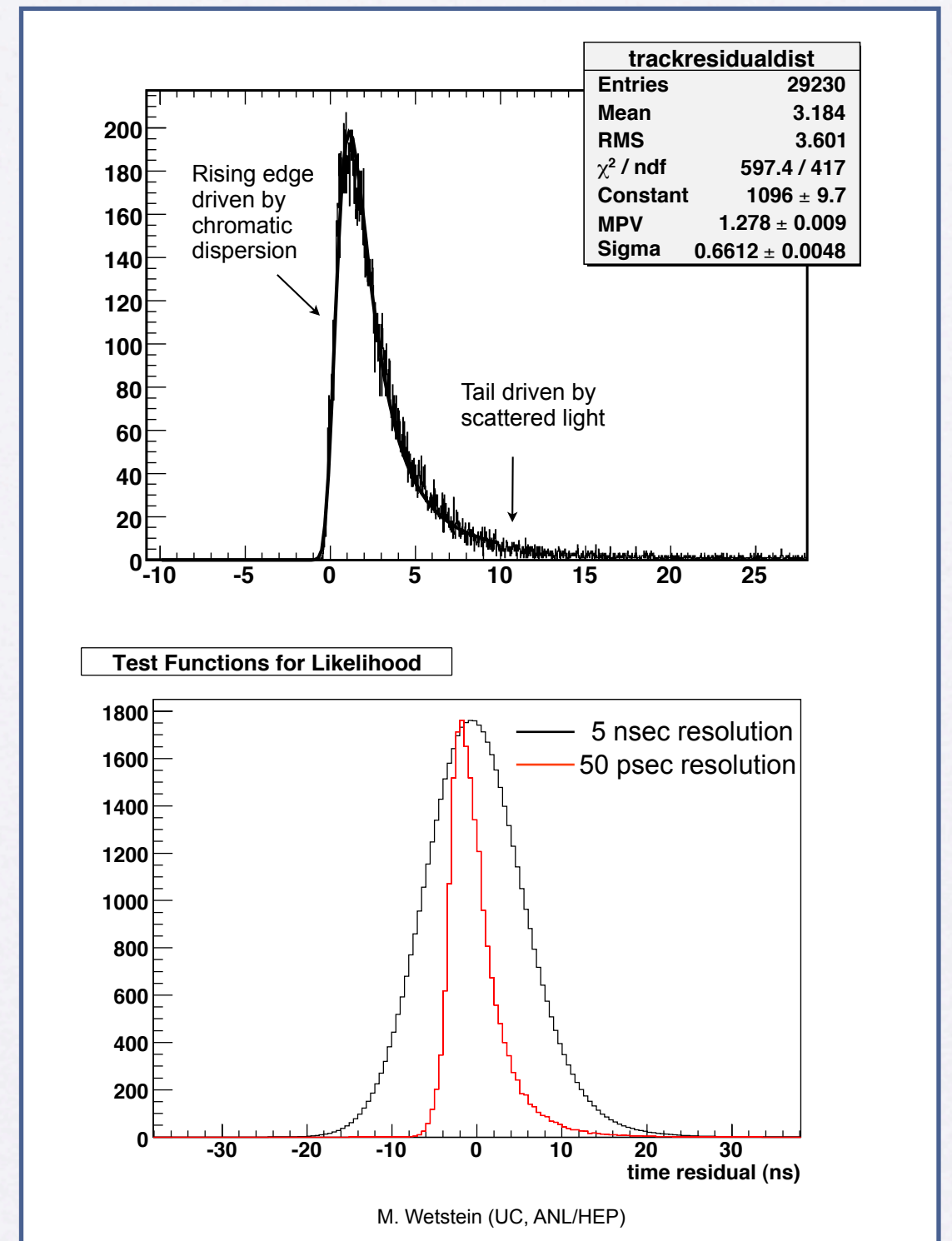
Distance from Detector (meters)

A combined improvement in photodetector coverage and faster timing allows for better use of timing information in Water Cherenkov detectors

First algorithms

- We have produced a new platform for testing algorithms on WCh detectors with interactively n photodetector prop

- These efforts have a promising features such as timing resi potentially be used to improve track reco background

- GEANT-based studies are being done in less idealized conditions: Including effects of temperature, pressure, Mie scattering, higher order chromatic dispersion and wavelength shifting.

M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL),
G. Davies (ISU), T. Xin (ISU)

Argonne
NATIONAL LABORATORY

Wednesday, January 26, 2011

Difficulties in building

Rising edge driven by chromatic dispersion

Tail driven by scattered light

trackresidualdist	
Entries	29230
Mean	3.184
RMS	3.60
Constant	1096 ± 9.7
MPV	1.278 ± 0.009
Sigma	0.6612 ± 0.0048

Test Functions for Likelihood

—— 5 nsec resolution
—— 50 psec resolution

time residual (ns)

M. Wetstein (UC, ANL/HEP)

Argonne

A phased approach

build first something small, then something big

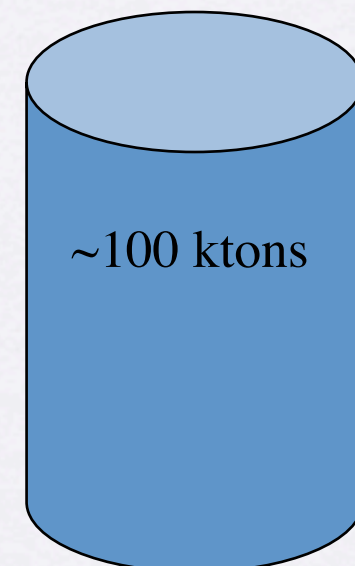- Short term: design, build and operate ~2m^3 detector.
  Application: "proof of principle", homeland security, etc.

  ~1m^3
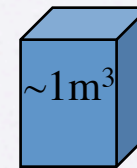
- Intermediate term: build a ~20-ton detector.
  Application: short-baseline neutrino physics (oscillation tests and cross-section measurements), LBNE-like Near Detector, low-background counting facility (if placed underground).
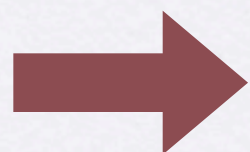
  ~20 ton
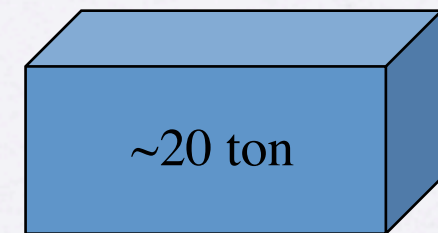
- Long term: apply to large ~100 kton detectors.
  Application: long-baseline neutrino physics, proton decay, super-nova detection, solar neutrinos, etc.

  ~100 ktons

Short term plan

- **Design, build and operate a ~2m^3 detector.**

- *1st stage*: characterize and design LAPPD-based detector: simulate and quantify the benefits of position and time resolution, understand particle ID and background rejection capabilities.

  - Recently there has been progress in producing cheap, high-light yield water-based scintillator (Minfang Yeh/BNL). Thus additional goal characterize water versus water-based liquid scintillator advantages for this application.

- *2nd stage*: Begin building a prototype of such detector with modules available: design the liquid and photodetector containment vessel, understand the LAPPD module/liquid interface and design readout scheme.

- *3rd stage*: Application and operation of LAPPD in various liquids. Initial testing and operation will be done using cosmic rays. Operation in Fermilab test beam. Complete proposal to place in Fermilab neutrino beam.
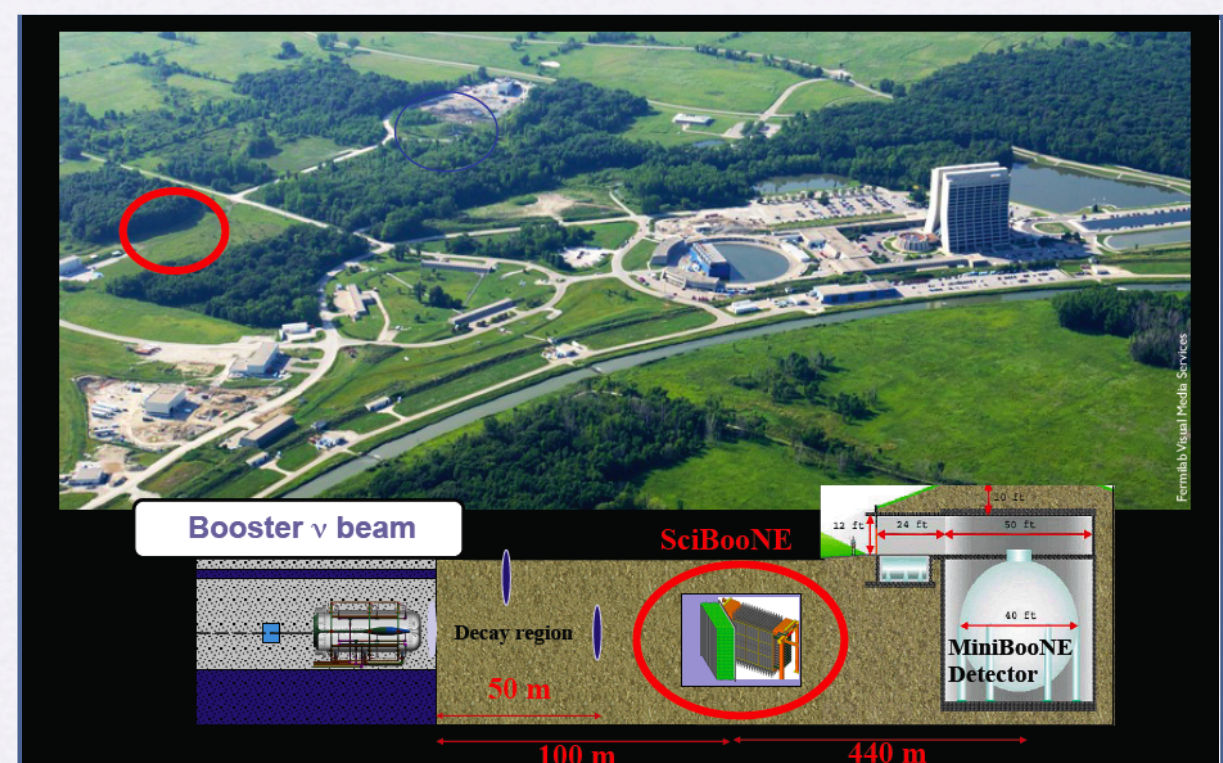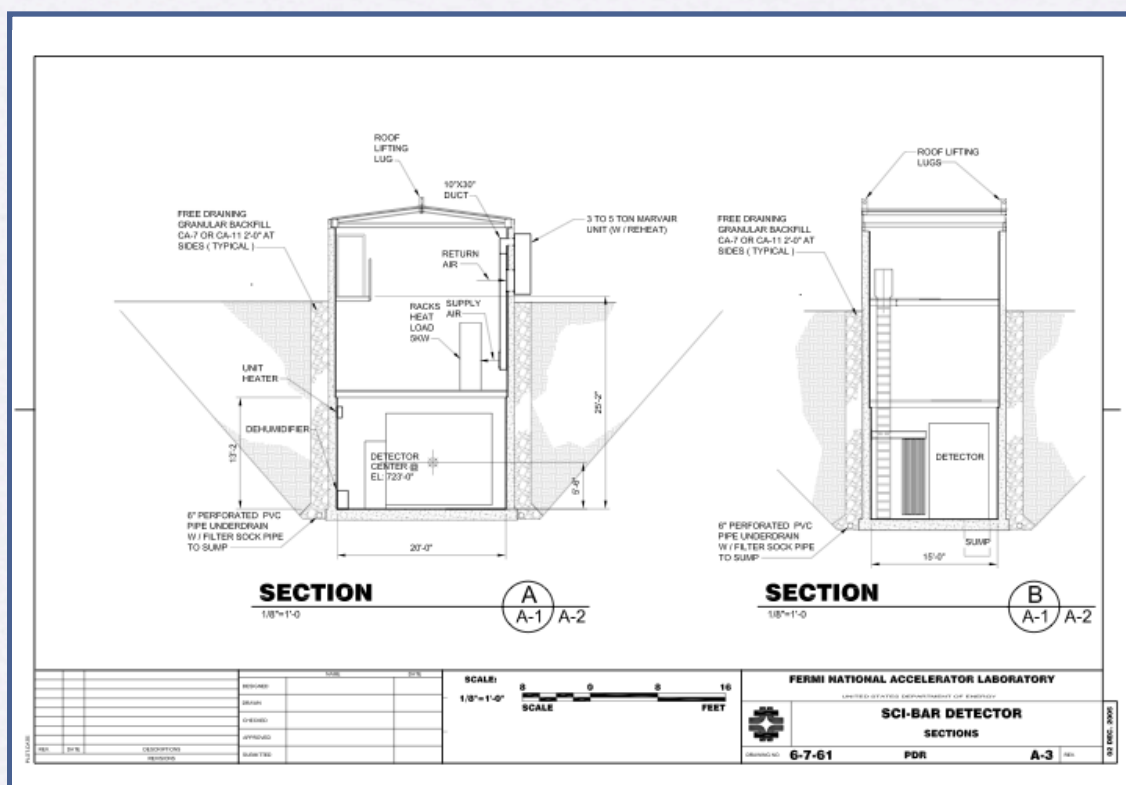
Submitted as LDRD by Djurcic, Demarteau, Frisch, Sanchez, Wetstein.

Intermediate plans

- **Build a ~20-ton detector.**

- Short baseline neutrino workshop 2011 at Fermilab. Discussed recent short-baseline anomalies.

- One idea is using Neutrinos from the Booster beamline in the SciBooNE pit.

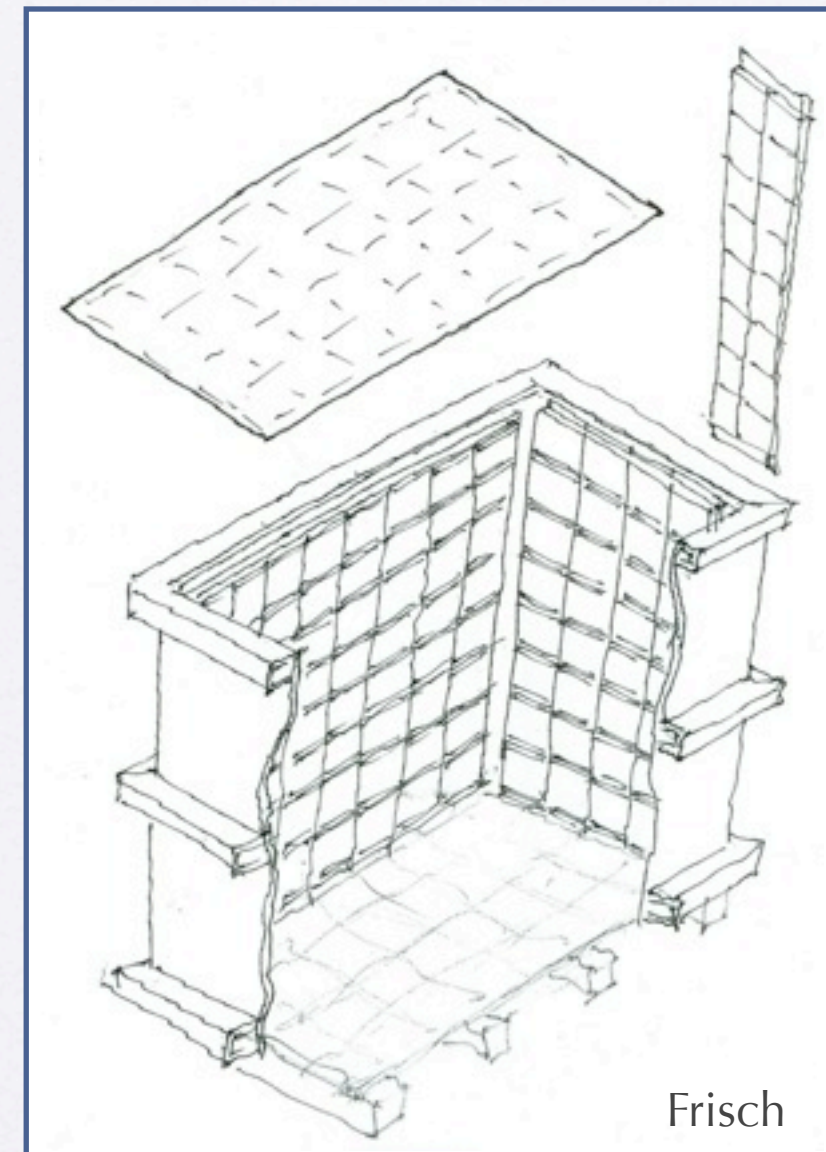- Total neutrinos at this site ~10K/ton/10^{20}POT.

Daniel in the Booster Beam

- Once production ramps up, use modules in a small detector placed in the SciBoone pit at Fermilab, codenamed **Daniel**.

- This is also interesting as a possible test for a water based Near Detector in a project like LBNE.

Frisch

Rates Expected with 1×10^{20} POT exposure at SciBooNE pit

Djurcic

|	Total Events [1/1ton/10^{20}POT]	ν-type	Total (per ν-type)	Charged Current	Neutral Current
Booster Beam (ν-mode, Target = CH_2)	10419	ν_μ	10210	7265	2945
		anti-ν_μ	133	88	45
		ν_e	72	52	20
		anti-ν_e	4.4	3	1.4
Booster Beam (ν-mode, Target = H_2O)	10612	ν_μ	10405	7443	2962
		anti-ν_μ	129	85	44
		ν_e	73	53	20
		anti-ν_e	4.6	3.0	1.6

Z. Djurcic (ANL), M. Demarteau (ANL), H. Frisch (UChicago/ANL), M. Sanchez (ISU/ANL), M. Wetstein (UChicago/ANL)

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Event display: π^0

M. Wetstein (UChicago/ANL)

EventView_after0_hist
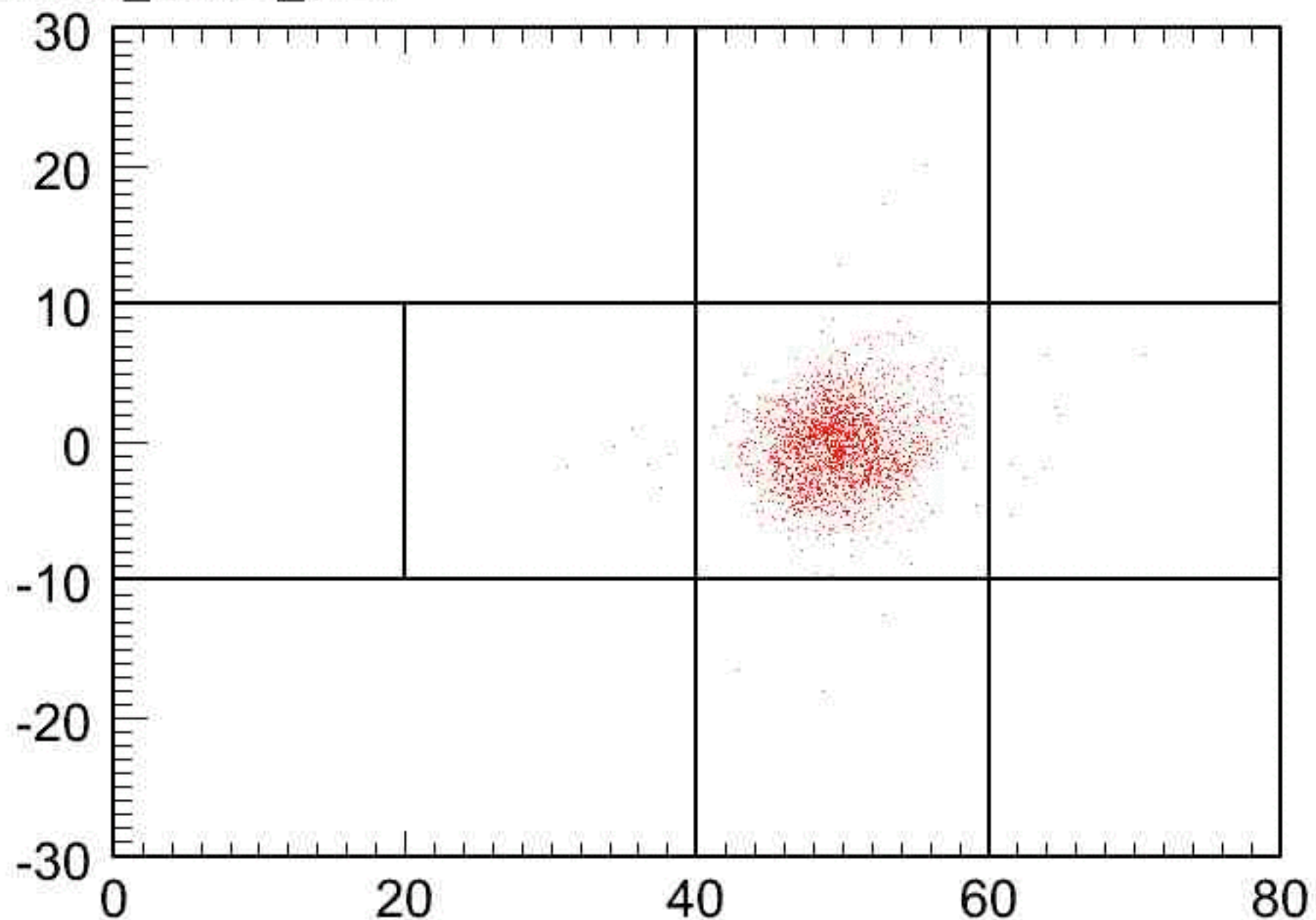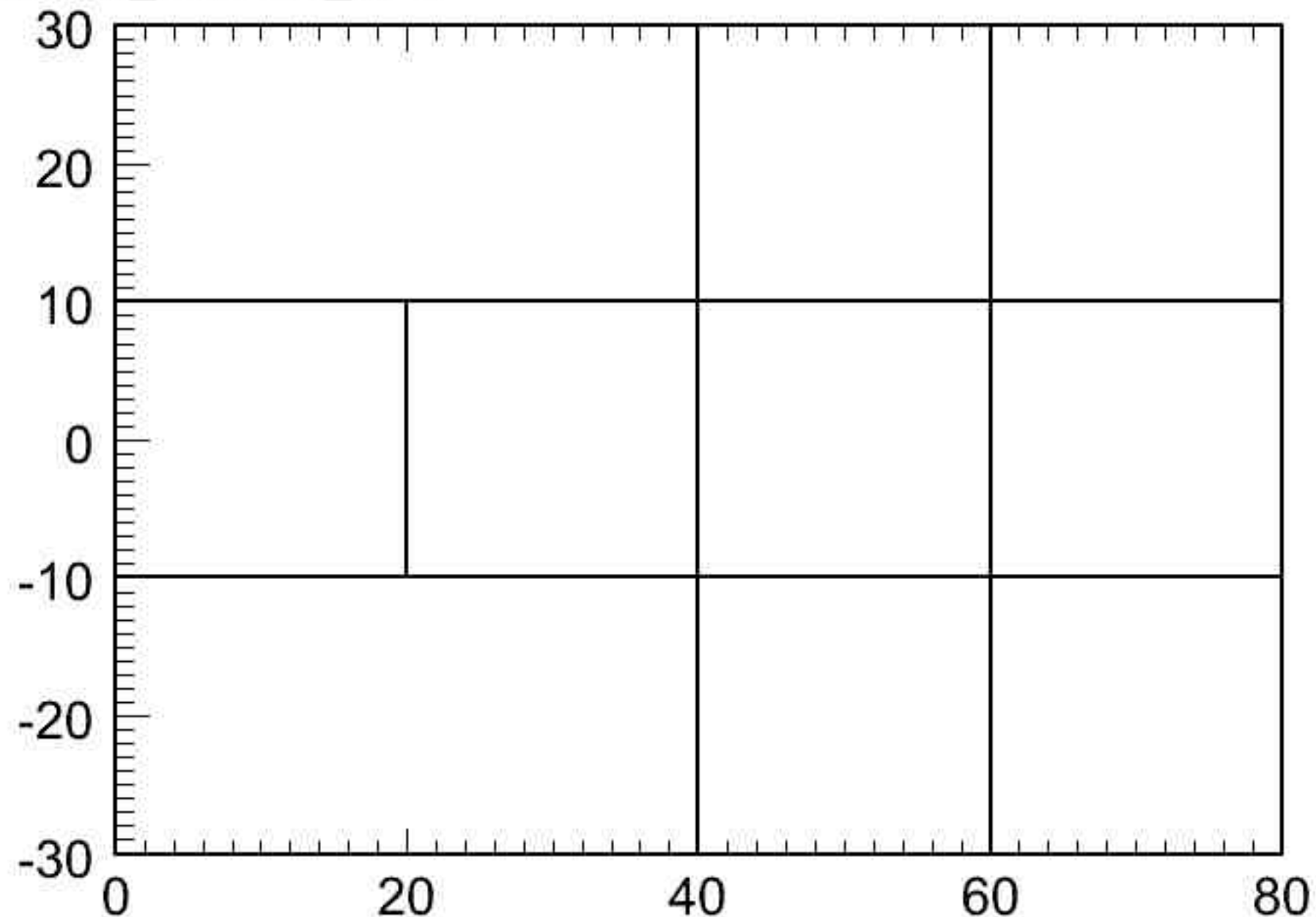
http://www.hep.anl.gov/mcsanchez/EventDisplays/animatedpizero_2ns.gif

Simulation: 750 MeV particle in 2 nsec steps

Event display: π^o

M. Wetstein (UChicago/ANL)

EventView_before0_hist

http://www.hep.anl.gov/mcsanchez/EventDisplays/animatedpizero.gif

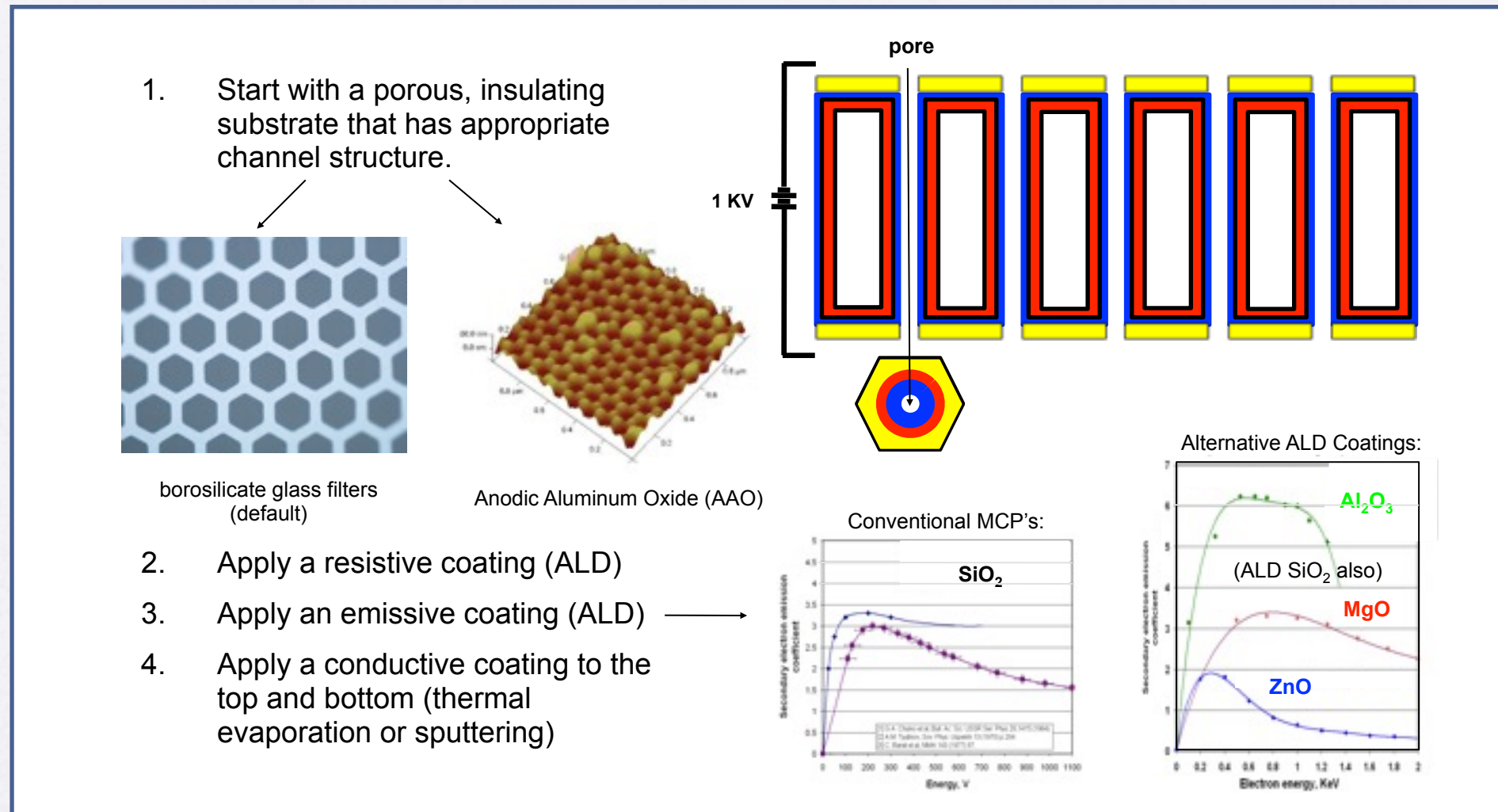Simulation: 750 MeV particle in 100 psec steps

Conclusions

- The LAPPD devices have the potential of improving the physics capabilities of the next generation of Water Cherenkov detectors by providing better timing and higher coverage.

- We have started a program simulating these detectors within the LBNE Water Cherenkov framework as well as developing algorithms that allow us to exploit the features of the new photosensors.

- There is significant work to be done:

  - Complete and test simulations/reconstruction under progressively less ideal conditions. Expand reconstruction to do ring counting and particle ID. Compare to results in latest LBNE WCh design.

  - Provide feedback to the LAPPD collaboration to the design with an eye to improve the physics capabilities of the LBNE WCh detectors.

  - Start a characterization program once prototypes are available and if previous steps are successful develop the necessary calibration design to be able to use these detectors in a realistic scenario.

  - Test in a realistic scenario before commercial product is available, ~m^3 WCh prototype in a neutrino beam.

Backup

Microchannel Plate Fabrication with ALD

1. Start with a porous, insulating substrate that has appropriate channel structure.

pore

1 KV

borosilicate glass filters (default)

Anodic Aluminum Oxide (AAO)

Alternative ALD Coatings:

Conventional MCP's:

2. Apply a resistive coating (ALD)

3. Apply an emissive coating (ALD)

4. Apply a conductive coating to the top and bottom (thermal evaporation or sputtering)

SiO_2

Al_2O_3

(ALD SiO_2 also)

MgO

ZnO

The LAPPD Project

Large Area Picosecond Photodetector Collaboration

John Anderson, Karen Byrum, Gary Drake, Henry Frisch, Edward May, Alexander Paramonov, Mayly Sanchez, Robert Stanek, Robert G. Wagner, Hendrik Weerts, Matthew Wetstein, Zikri Zusof

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David Forbush, Tianchi Zhao

*Department of Physics, University of Washington, Seattle, WA*

- A 3-year DOE project to develop Large Area Fast Photodetectors based on microchannel plate (MCP) technology started at ANL August '09.

- The goals are:
  - To develop cheap, scalable, flat panel photodetectors with precision time resolution, capable of picosecond-level time of flight (TOF) measurements.
  - To get a prototype on the 3 year time scale.

Project ending 2nd year

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Microchannel Plate Fabrication: Atomic Layer Deposition

- A conformal, self-limiting process.

- Allow atomic level thickness control.

- Applicable for a large variety of materials.
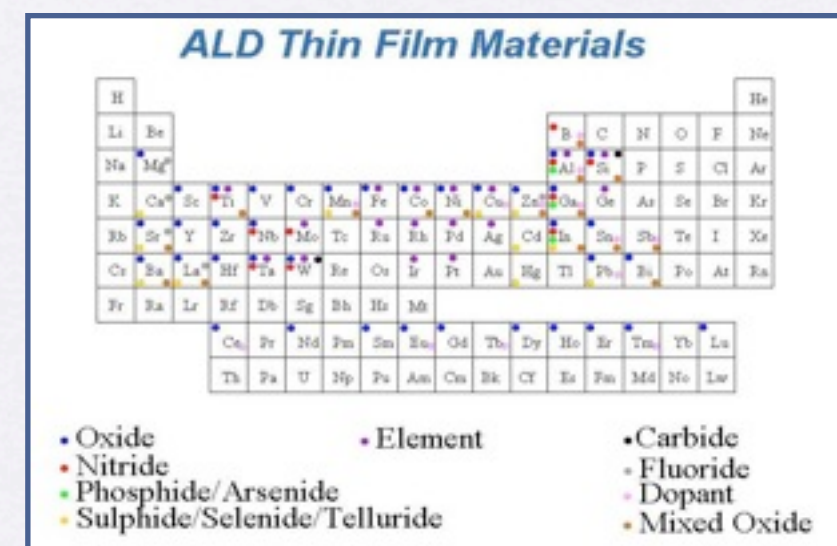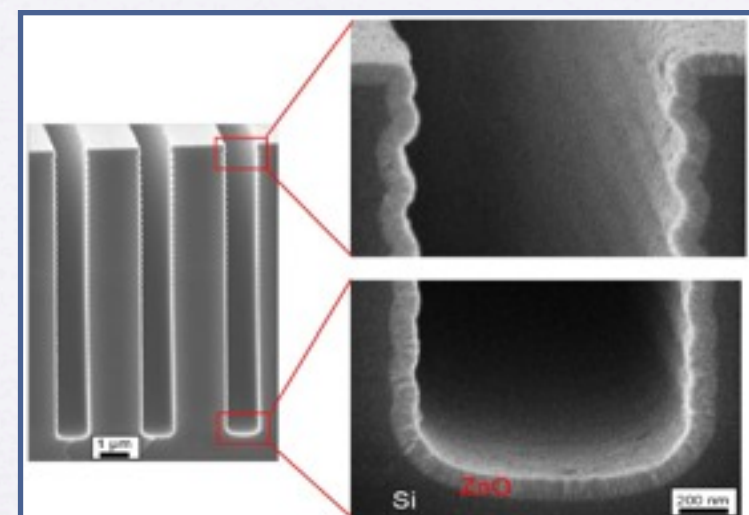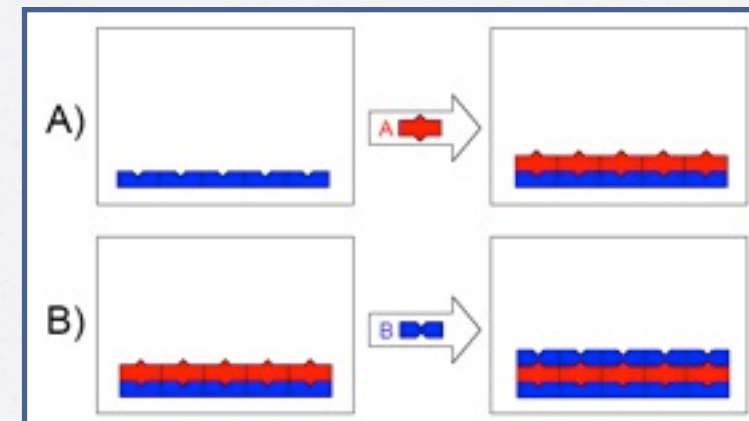
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Device Assembly

- Designing a base-tile 8x8 inches.

- Using sealed glass-panels with integrated FPGA fiber readout.

- The standard 8x8″ tiles can be coupled into a 24x16″ super-module (3x2 tile) for larger area.

- Transmission lines serve as MCP anodes and sampling the line by channel of a waveform sampling chip.

- Coupled into single PC board to produce super-module.

- Parallel effort: use ceramic assemblies similar to those used in conventional MCPs.
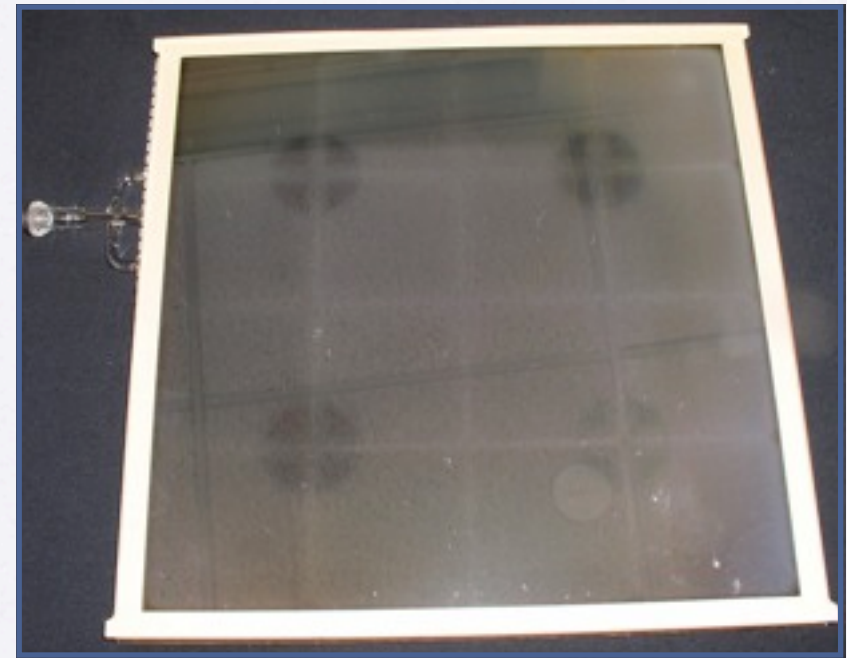
Achievement: First vacuum mock glass tile body assembled successfully.

Device Assembly

- The standard 8x8″ tiles can be coupled into a 24x16″ super-module (3x2 tile) for larger area.

- Coupled into single PC board to produce super-module.

- Integrated FPGA fiber readout. Transmission lines serve as MCP anodes and sampling the line by channel of a waveform sampling chip.
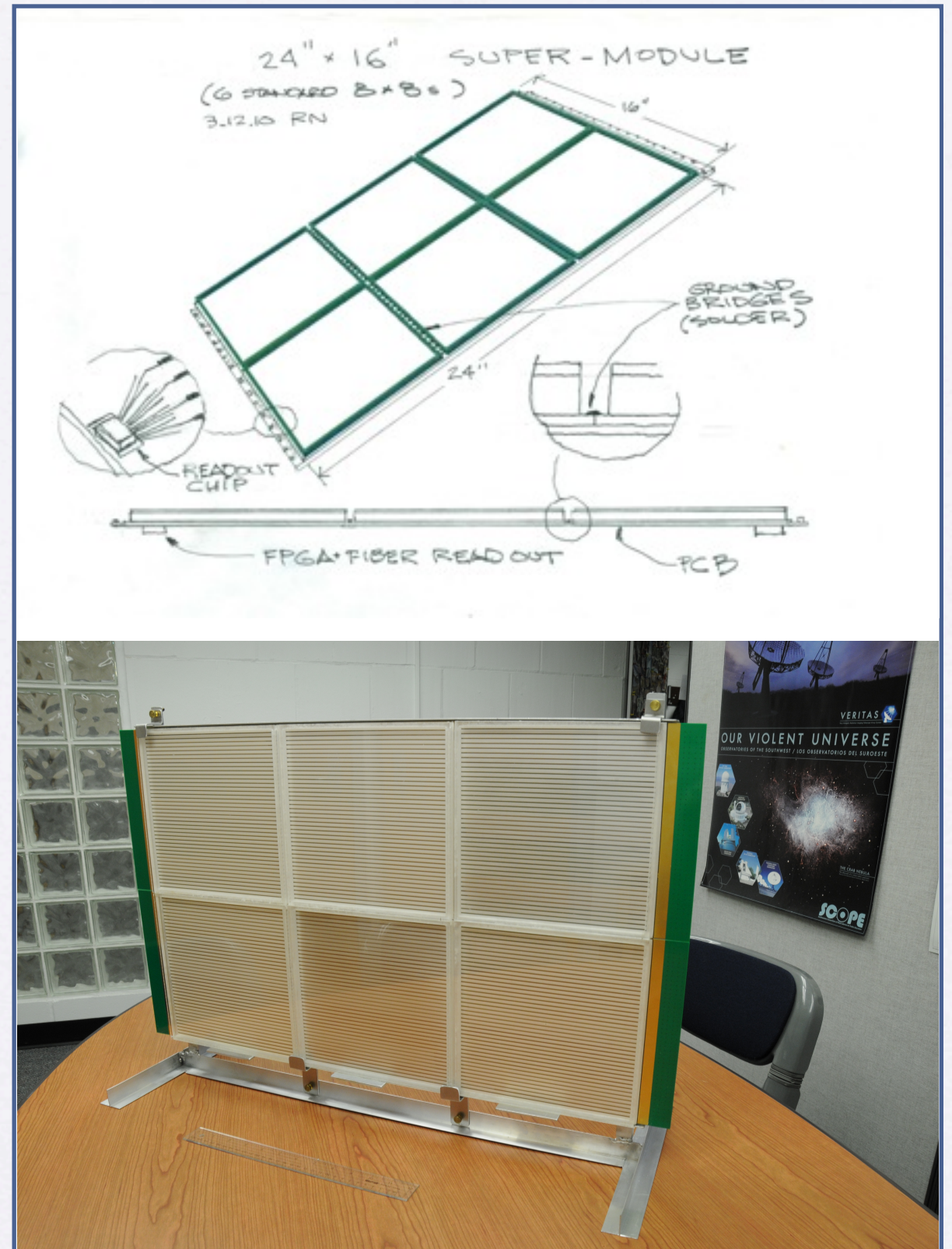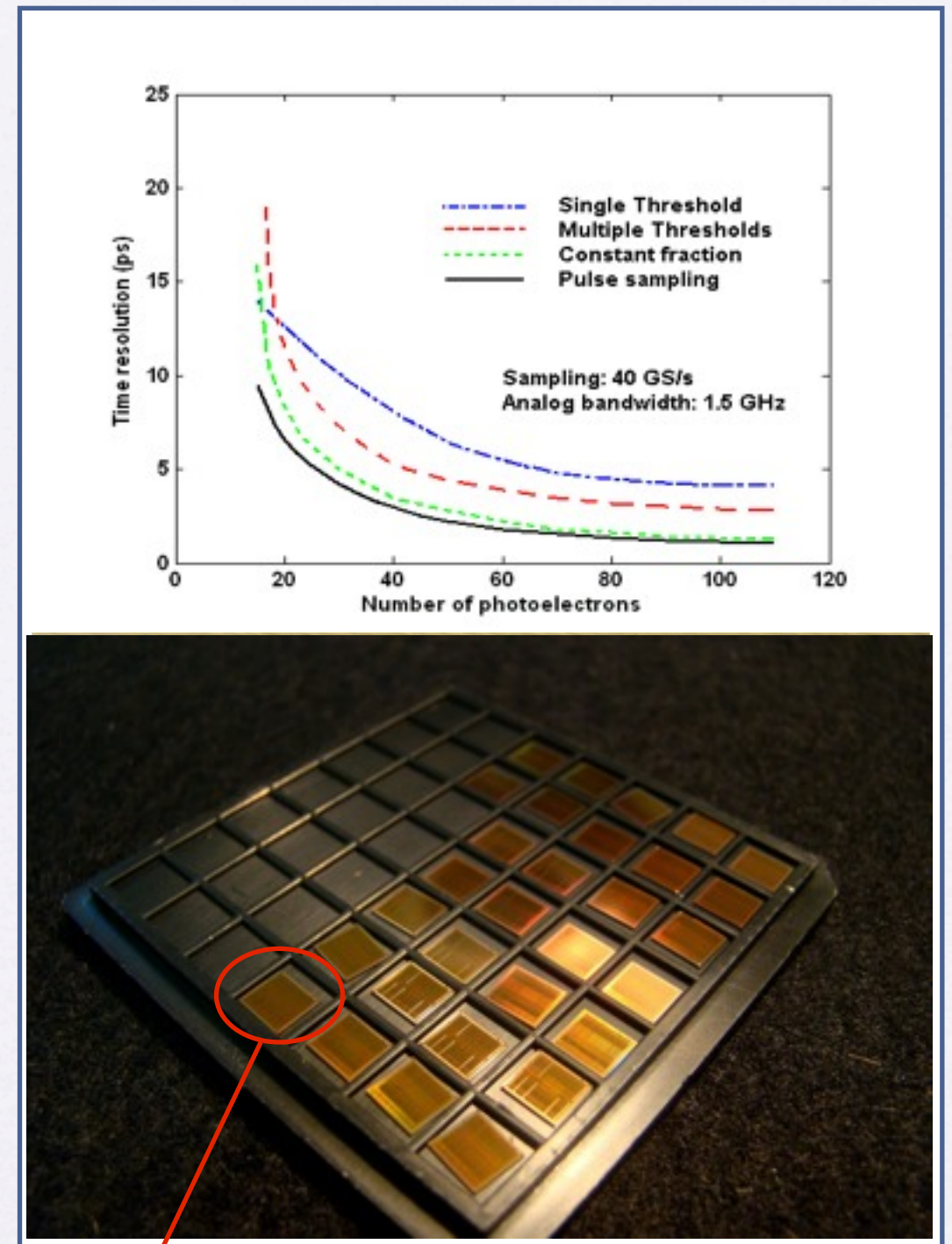
Front End Electronics

- Collaboration between UChicago and Hawaii.

- Resolution depends on number of photoelectrons, analog bandwidth, and signal to noise ratio.

- Transmission lines: readout both ends to provide position and time. Anode is a 50-ohm stripline, scalable to many feet.

  - Simulations indicate that these transmission lines could be scalable to large detectors without severe degradation of resolution.

  - Cover large areas with reduced channel count.

- Wave-form sampling is best and can be implemented in low-power widely available CMOS processes. Low cost per channel.

- For neutrinos a time resolution of ~100 psec should be sufficient.

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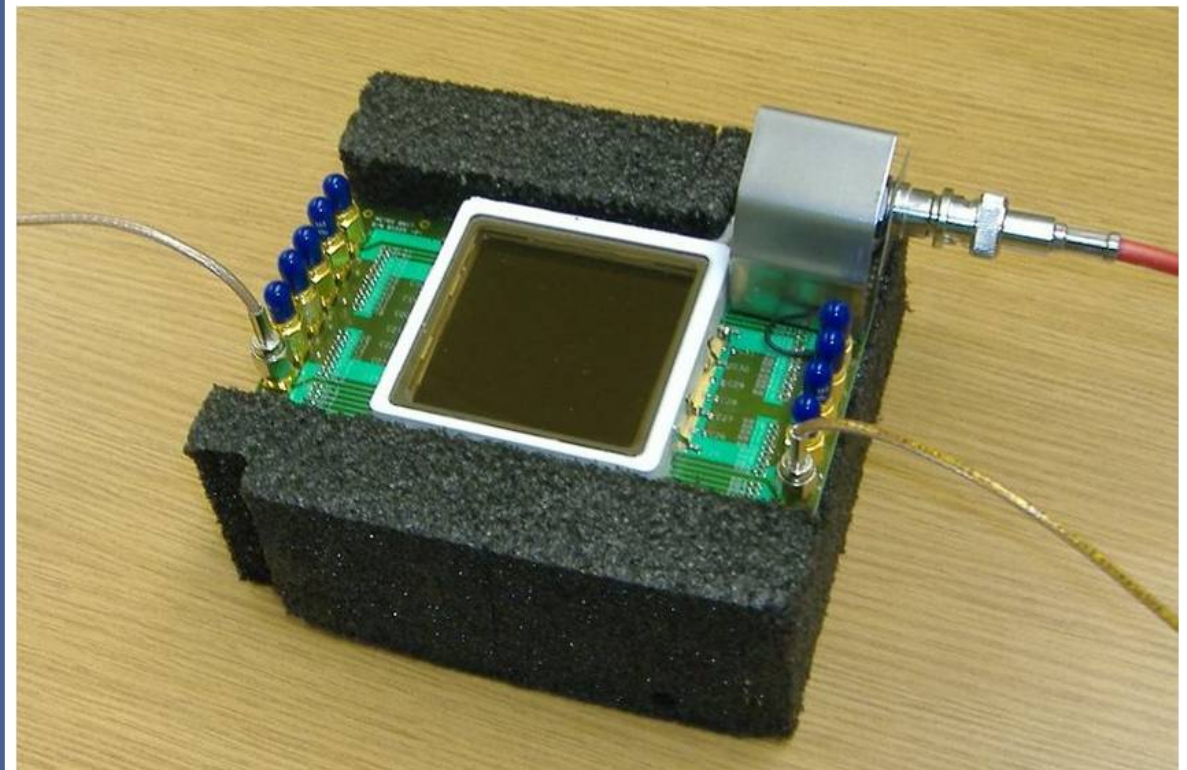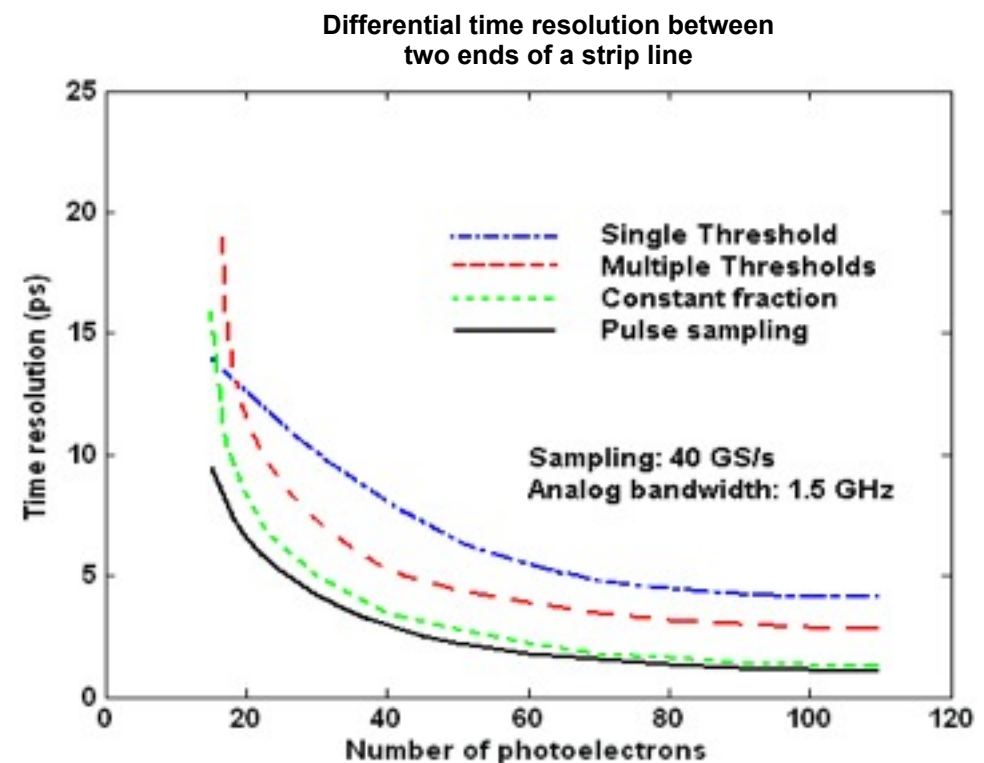

Achievements: Successful testing of PSEC-3 sampling chips (>17 GS/s with <1mV noise). Measured differential resolutions 2-psec and 100 μm on transmission lines.

Front End Electronics

Technical achievement

- Using the electronic front-end and striplines with a commercial Photonis MCP-PMT.

- Coupled 1024 pads to striplines with silver-loaded epoxy.

- Measured 1.95 psec differential resolution, 97 μm position resolution for 158 photoelectrons.

Differential time resolution between two ends of a strip line

Single Threshold
Multiple Thresholds
Constant fraction
Pulse sampling

Sampling: 40 GS/s
Analog bandwidth: 1.5 GHz
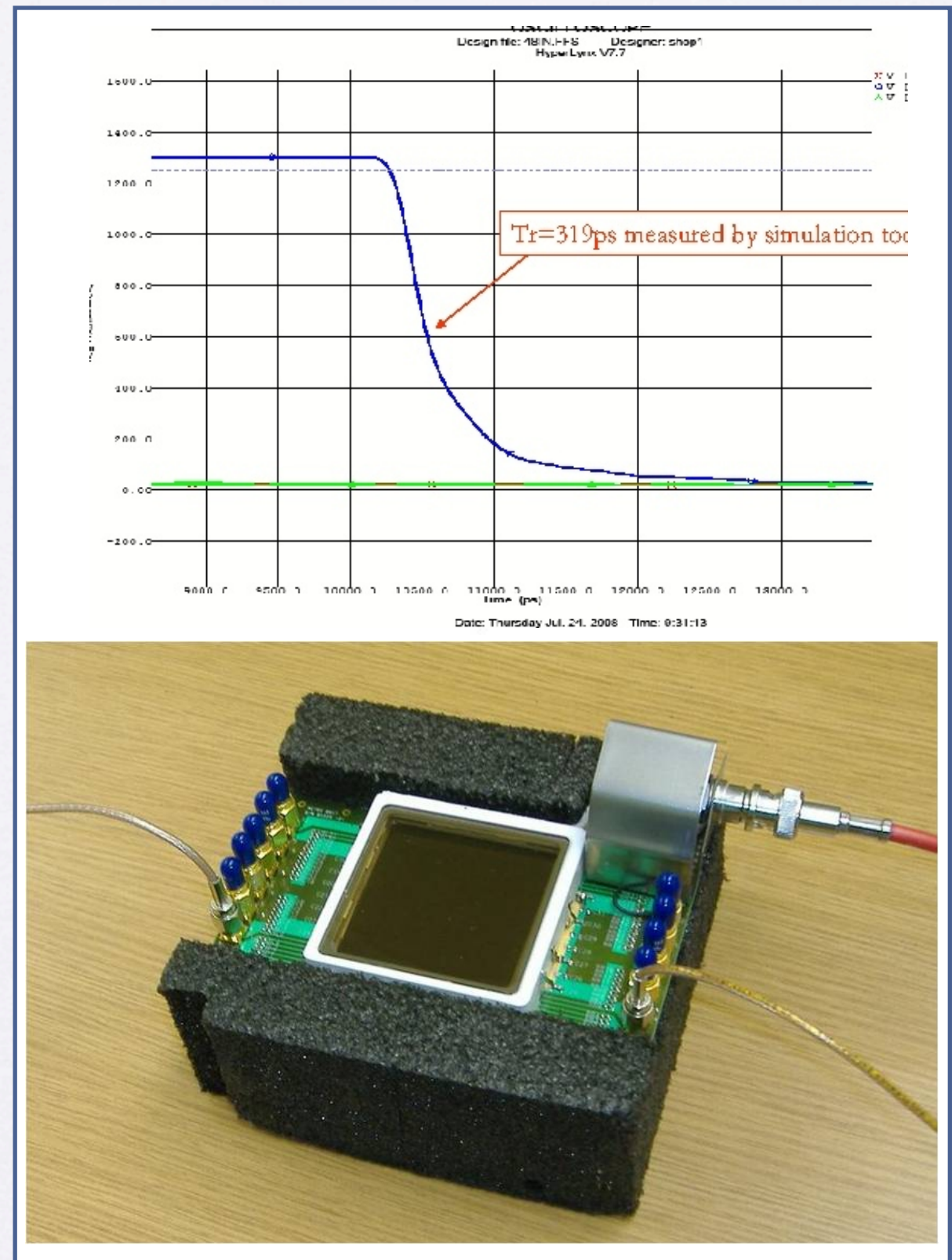
Time resolution (ps) vs Number of photoelectrons

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

Front End Electronics

Technical achievement

- Scaling performance to large area anode simulation.

- A 48-inch transmission line simulation shows 1.1 GHz bandwidth.

- Readout for a 4-foot detector is the same as for a little one.

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

Photocathode fabrication

In-situ QE measurement design update

Al cover
Ceramic insulator
Copper electrode
Holes for LED light

- Two main parallel paths:
  - Scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries and robustness under conditions relevant to industrial batch processing.
  - Could lead to a longer term photocathode program as part of the new ANL detector center
- ANL advanced photocathode lab is under construction.
- 8″ photocathode facility at Berkeley is close to completion.
- Recently acquired commercial photocathode fabrication system is being tested at ANL with plans to modify it for large format photocathodes.

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Photocathode fabrication
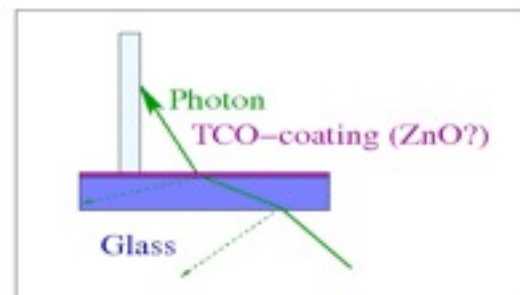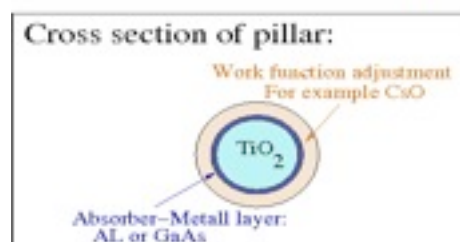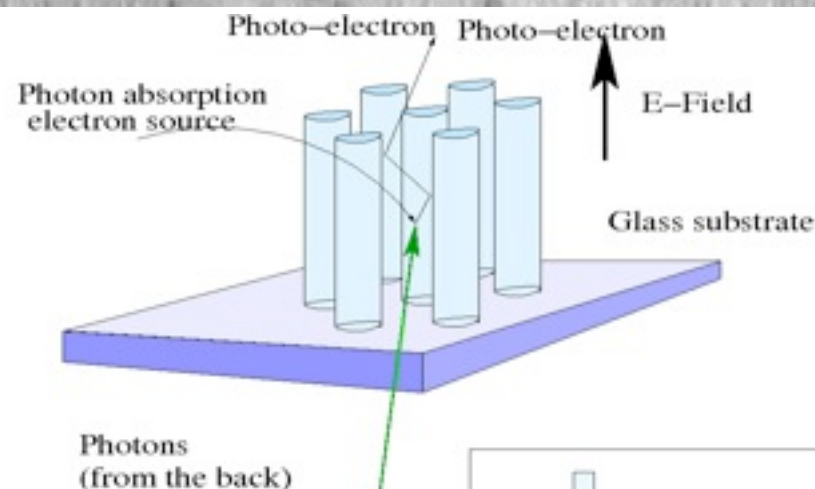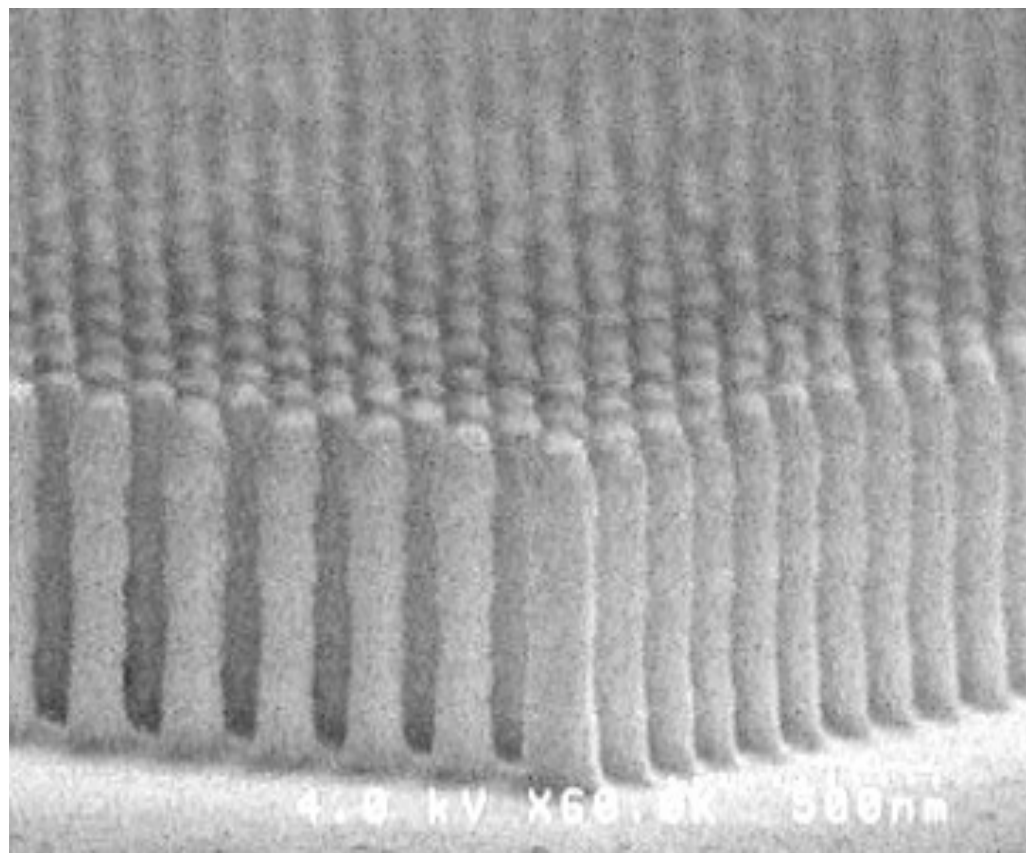
- In parallel with conventional photocathode techniques, pursue more novel photocathode technologies.

- Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries and robustness under conditions relevant to industrial batch processing.

- Nano-structured photocathodes:
  - Reduction of reflection losses (light trap).
  - Heterogeneous structure permits multi-functionality (electrically, optically, electron emission, ion-etching resistant).
  - Increased band-gap engineering capabilities.

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Testing and Characterization

- Testing and characterization is a multi-institution, multidisciplinary effort.

- Done at the microscopic/materials level as well as at the macroscopic/device level.

Microscopic/Materials-Level   **Macroscopic/Device-Level**

Constructing dedicated setup for low-energy SEE and PE measurements of ALD materials/photocathodes.

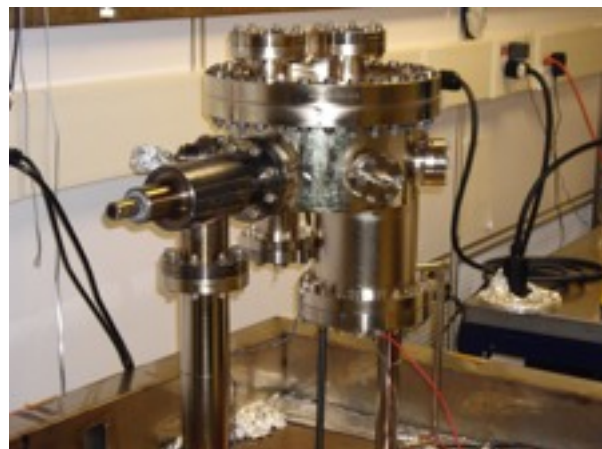Parts-per-trillion capability for characterizing material composition.
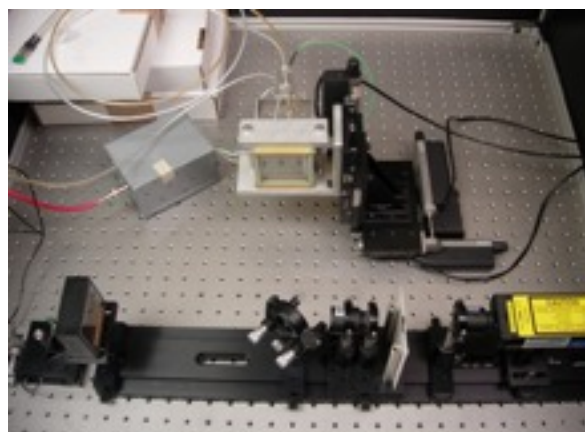
Material Science Division, ANL
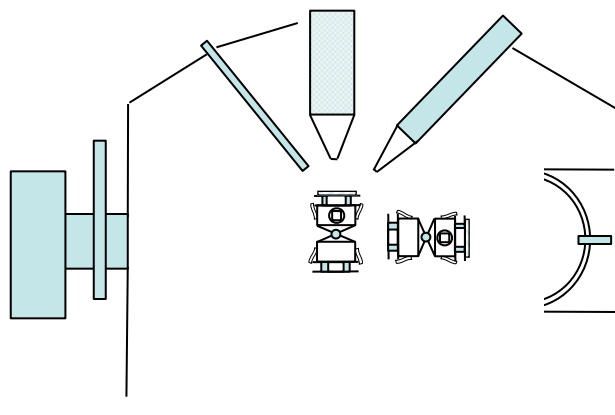
Wide array of equipment for testing individual and pairs of channel plates.

Infrastructure to produce and characterize a variety of conventional photocathodes.

Berkeley SSL

HEP laser test stand

Fast, low-power laser, with fast scope.

Built to characterize sealed tube detectors, and front-end electronics.

Highly Automated

Advanced Photon Source, ANL

Fast femto-second laser, variety of optical resources, and fast-electronics expertise.

Study MCP-photocathode-stripline systems close to device-level. Timing characteristics amplification etc.

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