LAPPDs

in Water and Scintillator Detectors

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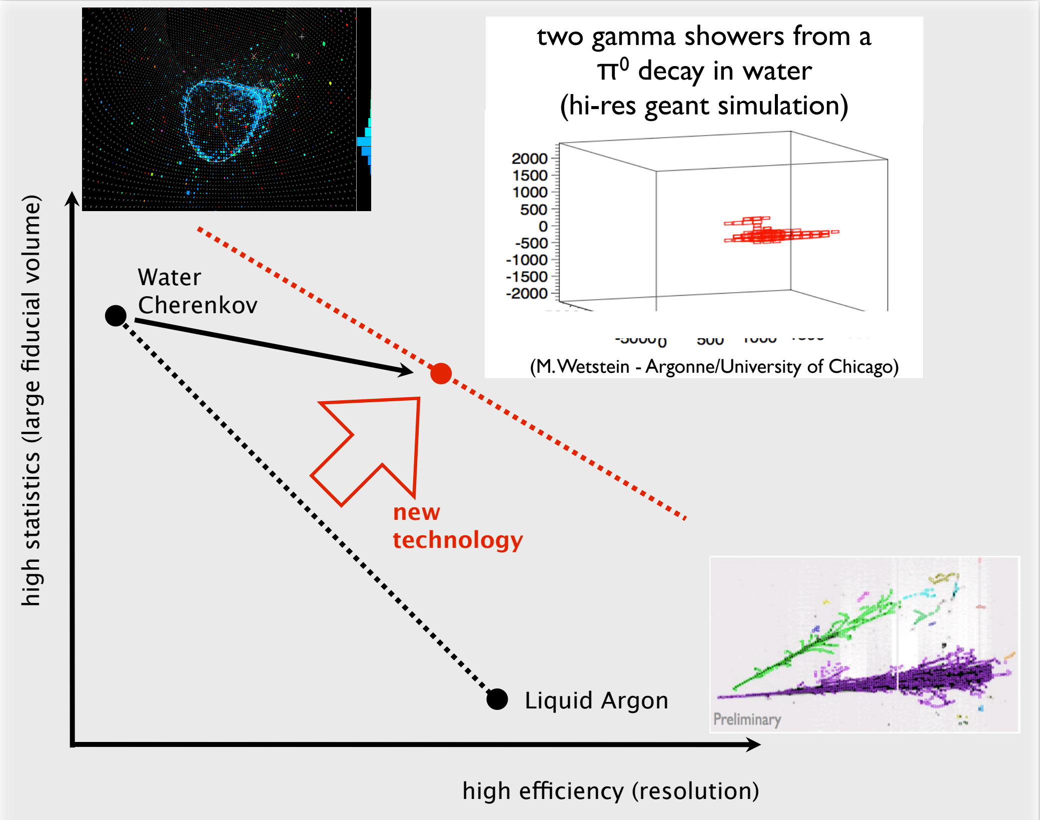
Iowa State University

FroST: Frontiers in liquid Scintillator Technology
March, 2017

U.S. DEPARTMENT OF ENERGY

Introduction

- Photodetectors are a (~80 year old) staple of particle physics
- Photodetection plays and will continue to play critical role in neutrino detectors
- Next generation neutrino experiments are testing the limits of size and cost.
- Advancing photosensor technology is a high-impact way to change technological and economic trade offs



tradeoff curves of constant cost

Moving the Tech Forward

Improving how photosensors perform

- time resolution
- spatial granularity
- quantum efficiency/area coverage
- wavelength dependent response
- photon counting
- cost

Not only

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Moving the Tech Forward

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Improving how photosensors perform

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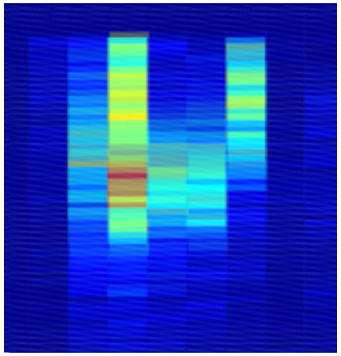
But also

Improving how photosensors are *used*

- light collection
- precision single photon likelihoods (optical TPC)
- dual Cherenkov-scintillation systems (ASDC/THEIA)
- optical imaging (reflective/refractive geometries)

Spatial granularity/ Digital Photon Counting

$$\mathcal{L}(\mathbf{x}) = \prod_{\text{unhit}} (1 - P(i \text{ hit}; \mathbf{x})) \times \prod_{\text{hit}} P(i \text{ hit}; \mathbf{x})\, f_q(q_i; \mathbf{x})\, f_t(t_i; \mathbf{x})$$



with conventional PMTs

- Measure a single time-of-first-light and a multi-PE blob of charge
- Likelihood is factorized into separate time and charge fits
- History of the individual photons is washed out

with hires imaging tubes

- Measure a 4-vector for each individual photon
- Likelihood based on simultaneous fit of space and time light
- one can separately test each photon for it's track of origin, color, production mechanism (Cherenkov vs scintillation) and propagation history (scattered vs direct)

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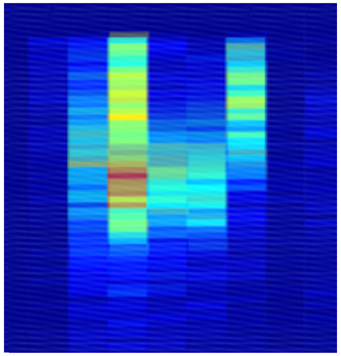
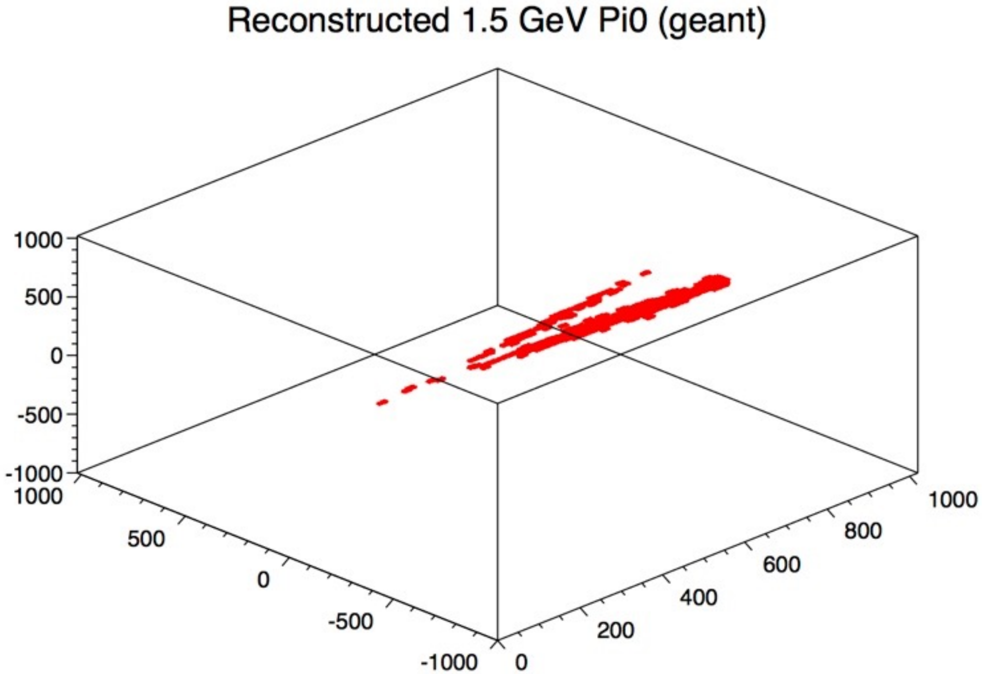
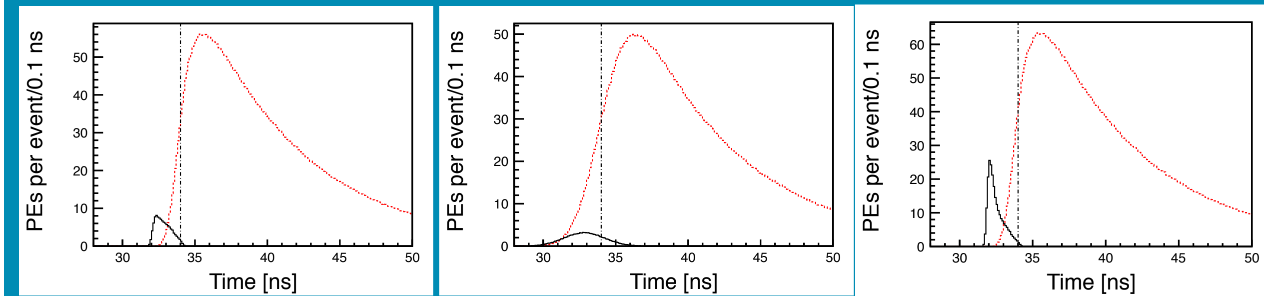




Time reversal algorithms ("working backwards") provide narrow down the details of the event.

Cherenkov - Scintillation Hybrids

Timing to separate between Cherenkov and scintillation light



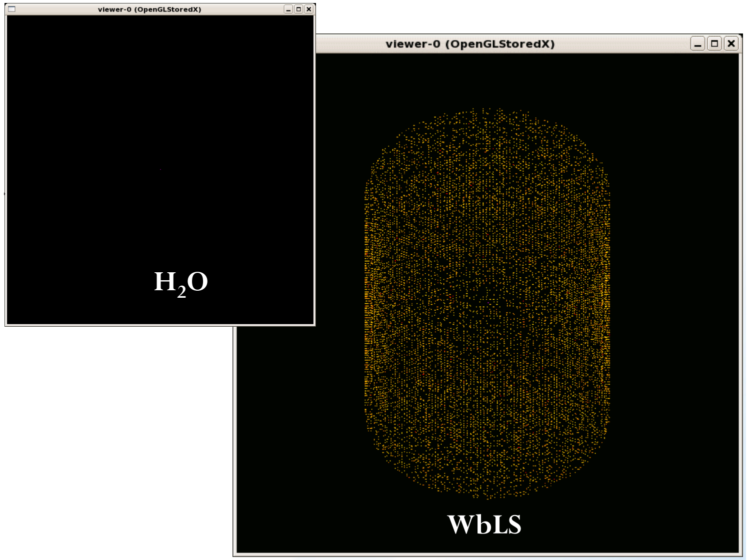
(a) Default simulation. (b) Increased TTS (1.28 ns). (c) Red-sensitive photocathode.

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring *Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;*

arXiv:1307.5813

Cherenkov + scintillation -> tracking + calorimetry

K+ in water and liquid scintillator

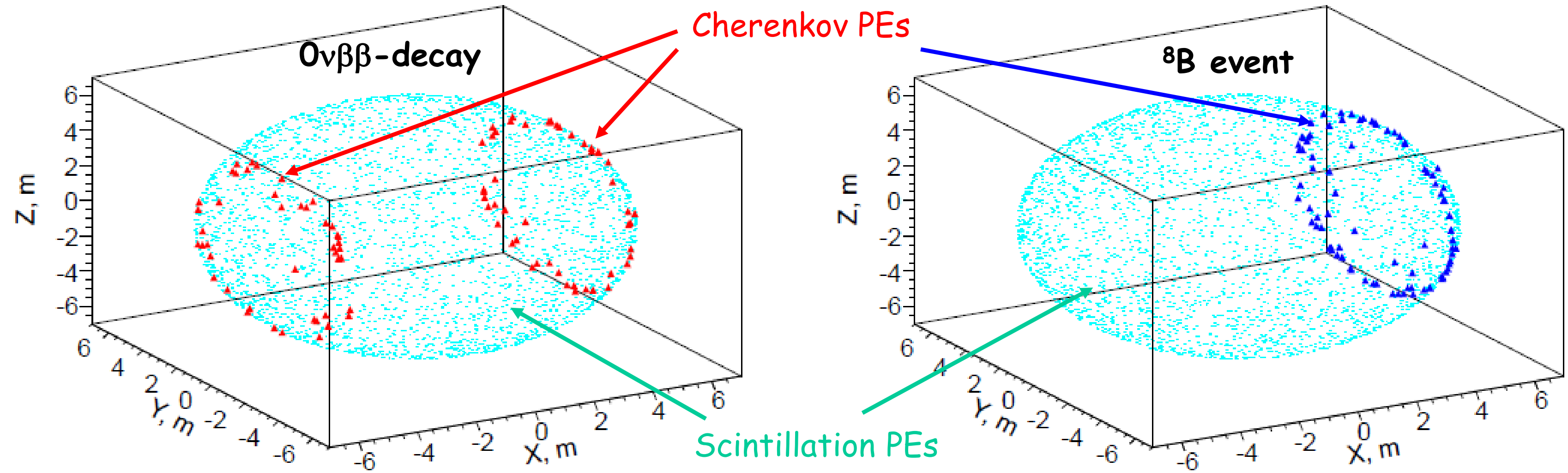


M. Yeh, et al (BNL)

Detecting scintillation light as a means of seeing particles below Cherenkov threshold

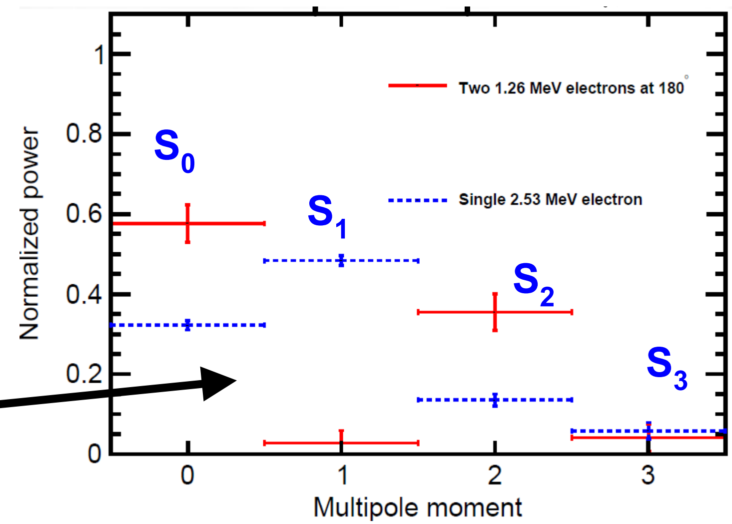
Andrey Elagin (U Chicago)

Idealized event displays: no multiple scattering of electrons, all PEs, QE=30%



$$f(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta,\varphi).$$

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$



Andrey Elagin (U Chicago)

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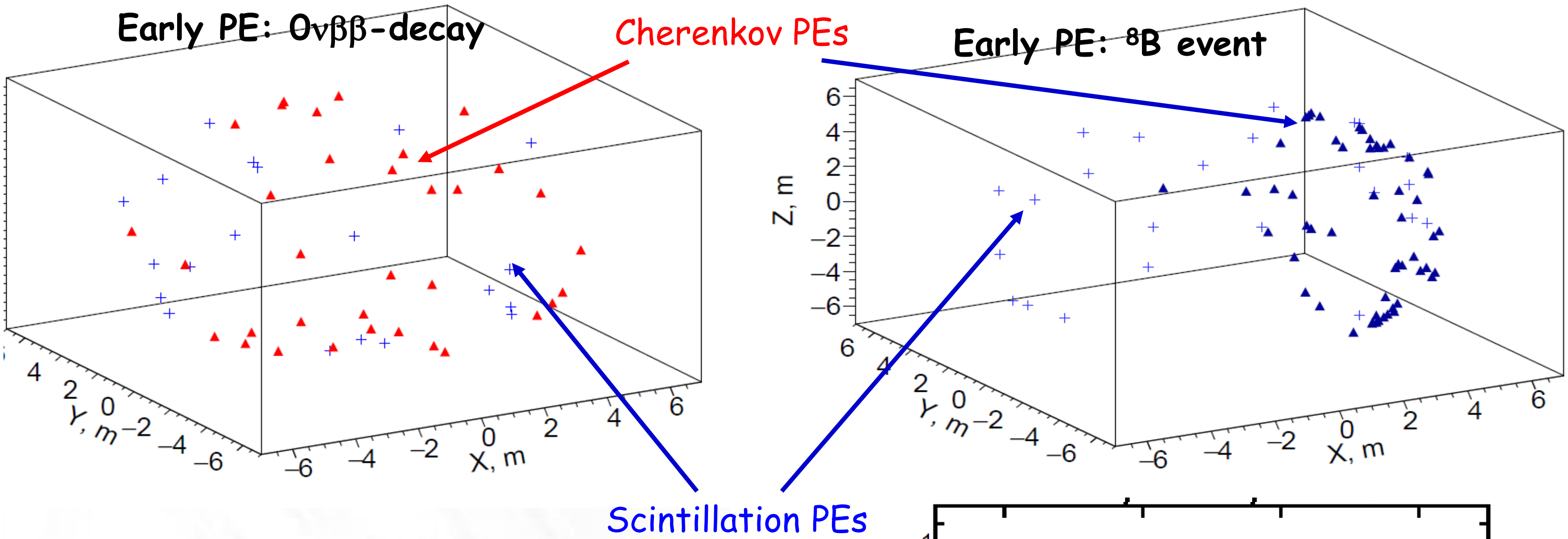
Realistic event displays: early PEs only, KamLAND PMTs QE: Che~12%, Sci~23%



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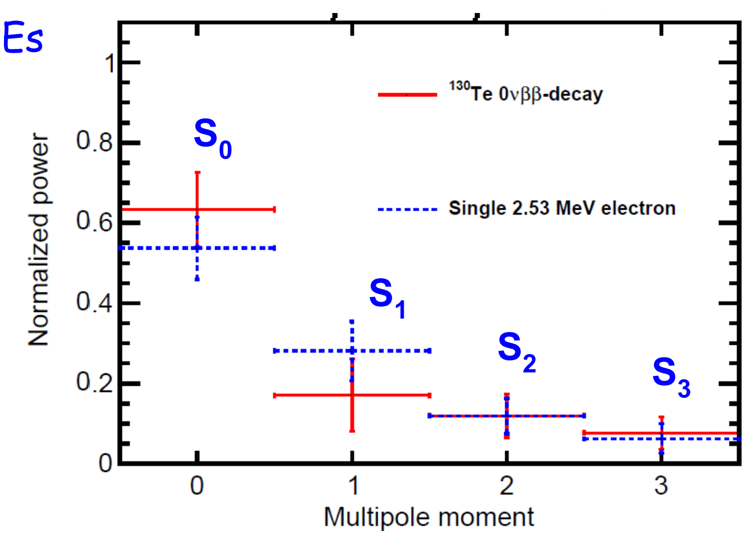
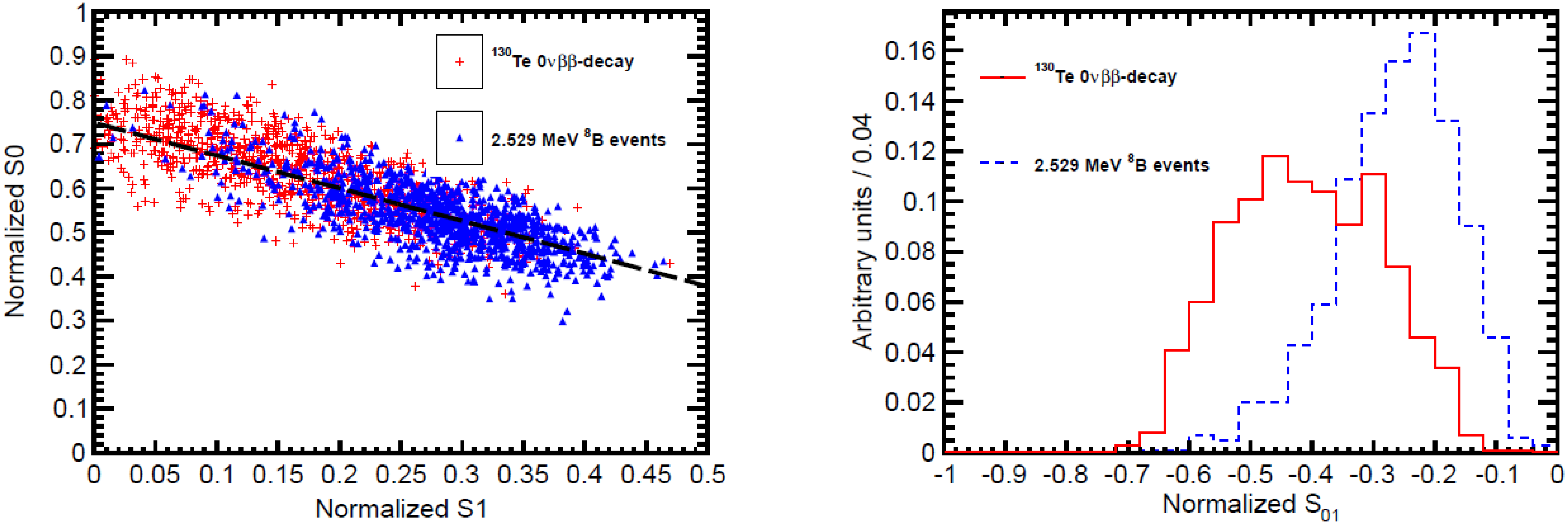


Ideal vertex, central events only, scintillation rise time 1 sec



Key parameters for maximizing separation of 0νββ-decay from ^8B

- Scintillator properties - (narrow spectrum, slow rise time)
- Photodetector properties- (fast, large area, high QE, red sensitive)

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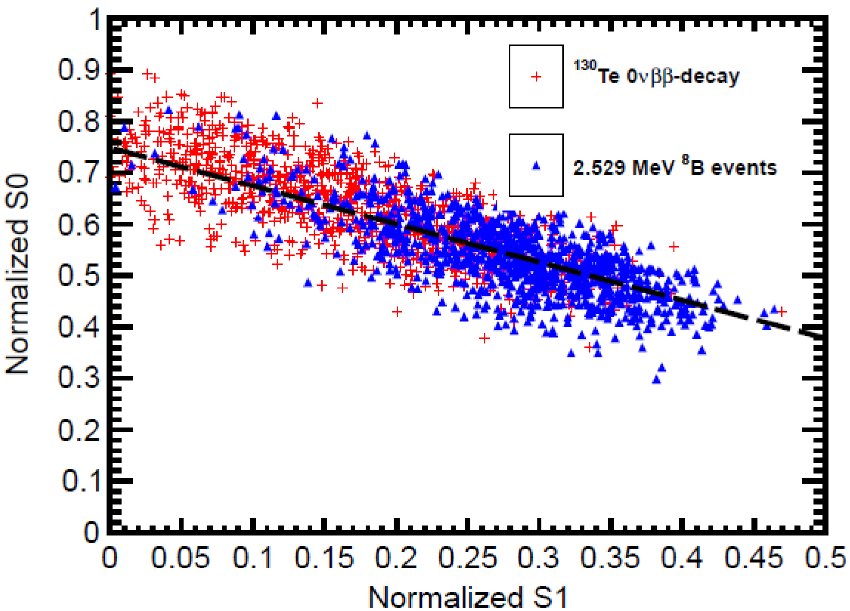

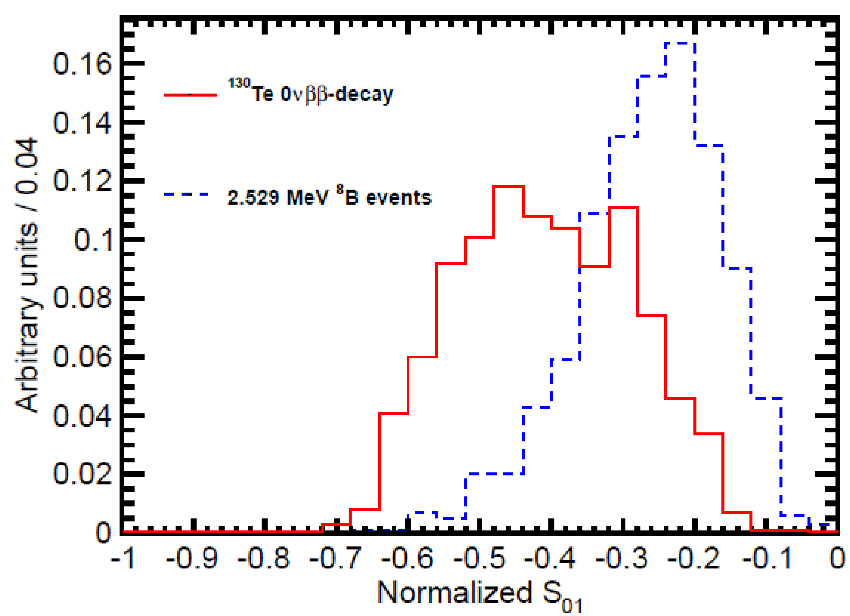

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see NIM A849 (2017) 102

Playing with Phase Space

Imaging a large 2D area onto a smaller 2D area means you lose angular acceptance (Liouville's Theorem).

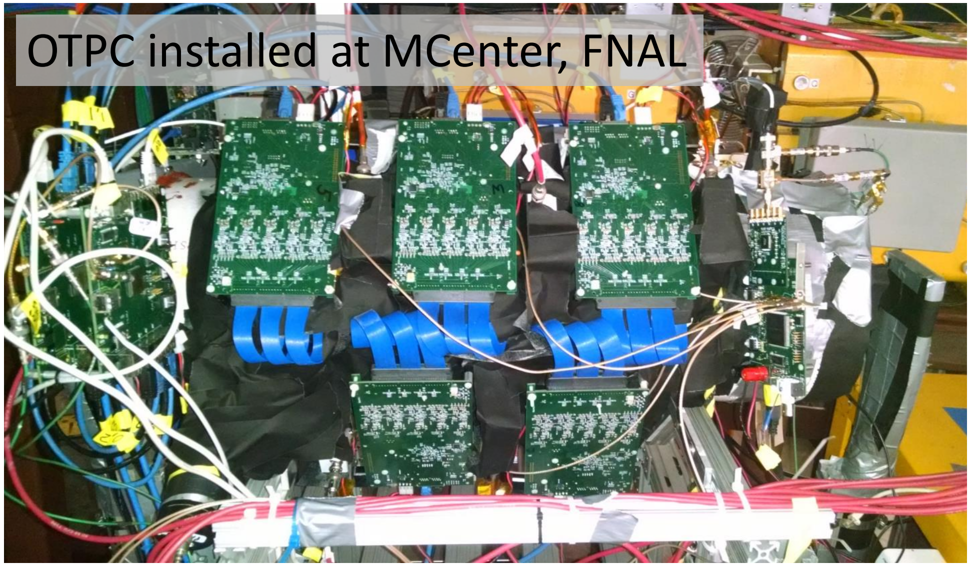
With timing, in addition to 2 spatial directions, you can swap transverse and longitudinal modes (think beam cooling).

You reduce spatial area in exchange for time spreads and measure these with timing detectors...

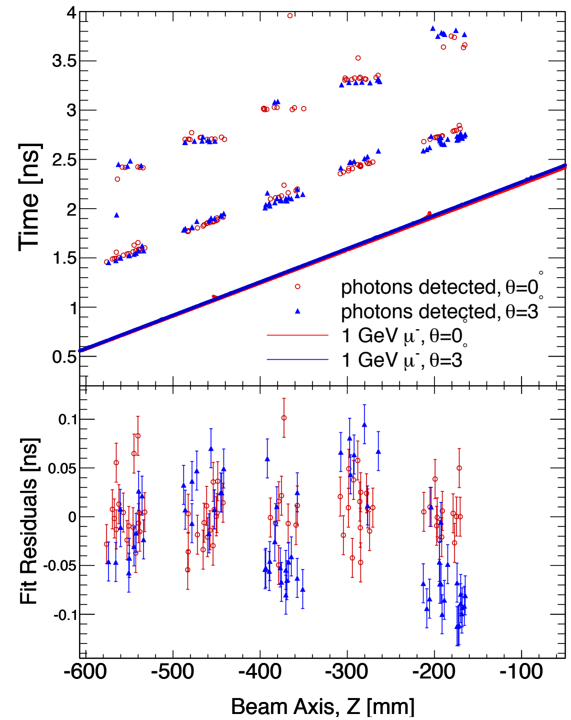
Could this approach work for WCh/wbLS detectors?

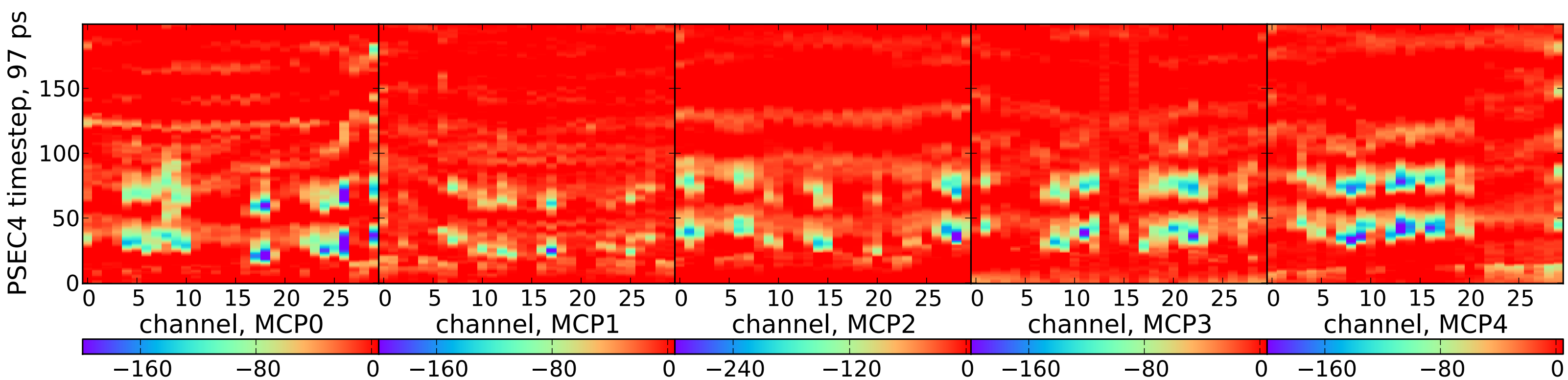
"Optical TPC"

Eric Oberla and Henry Frisch (U Chicago)



180 channel system





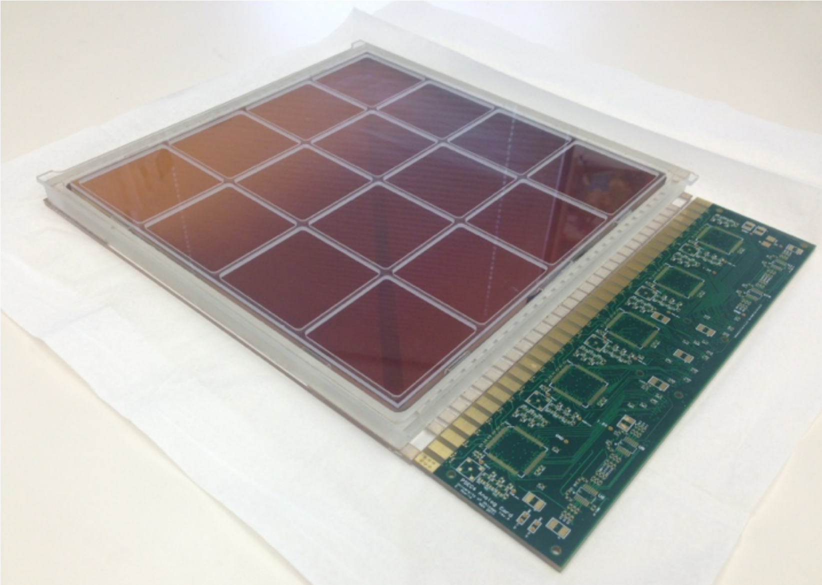
(a)

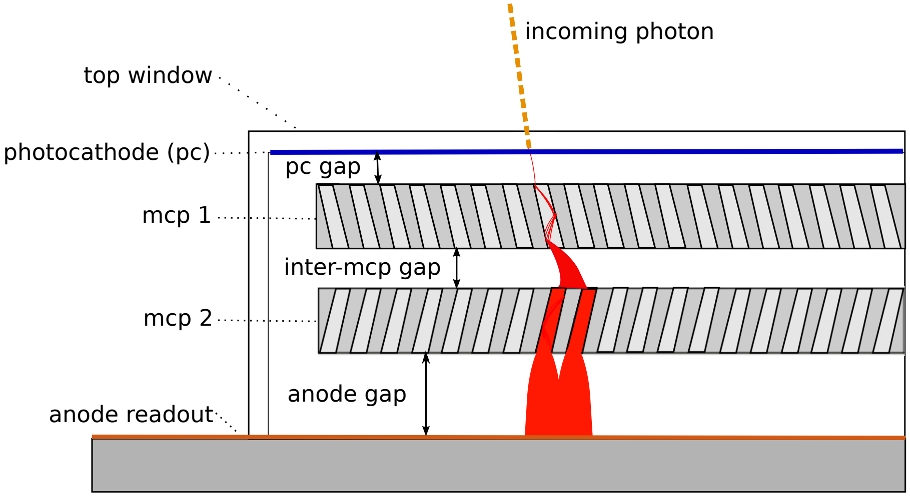
Nucl Inst and Meth 814 pp 19-32 (2016)   arxiv.org/abs/1510.00947

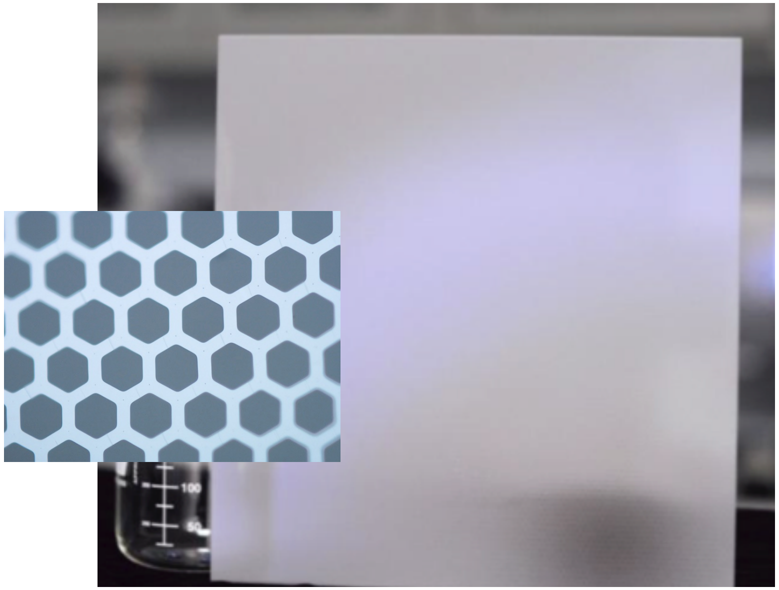
LAPPD project

The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- 50-100 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.







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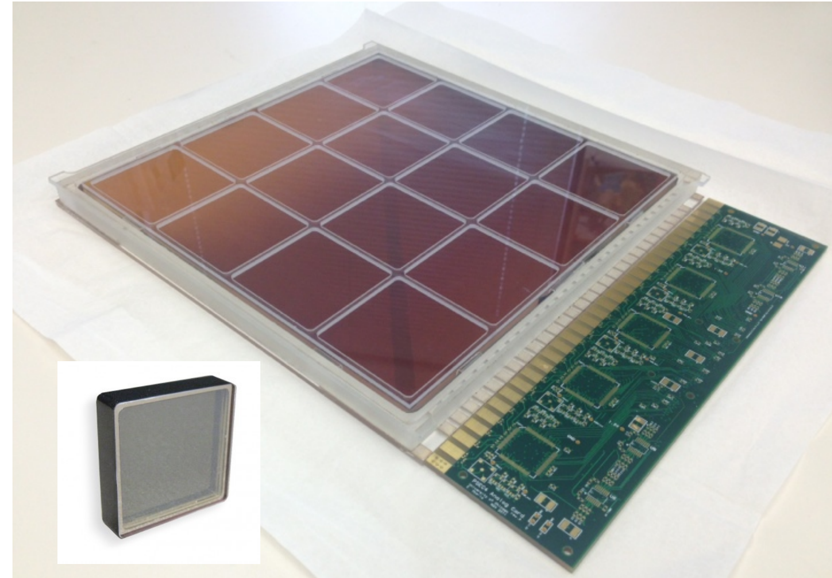
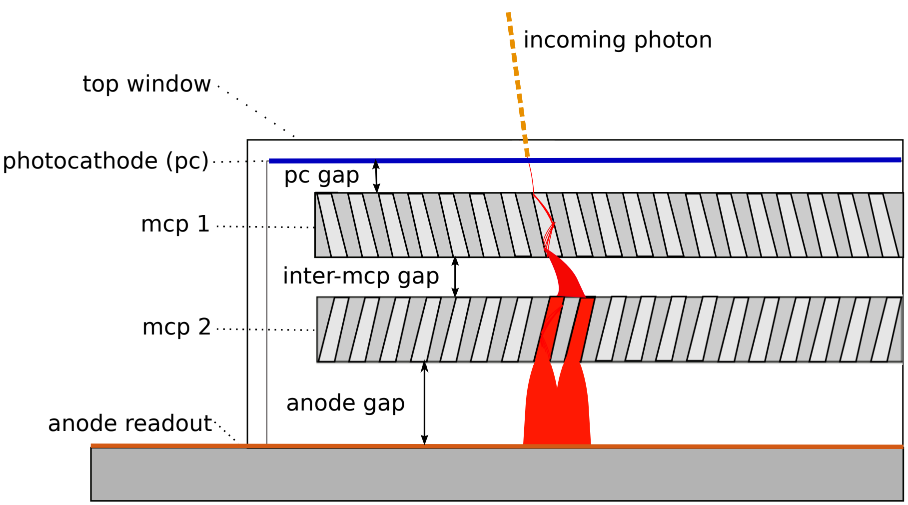
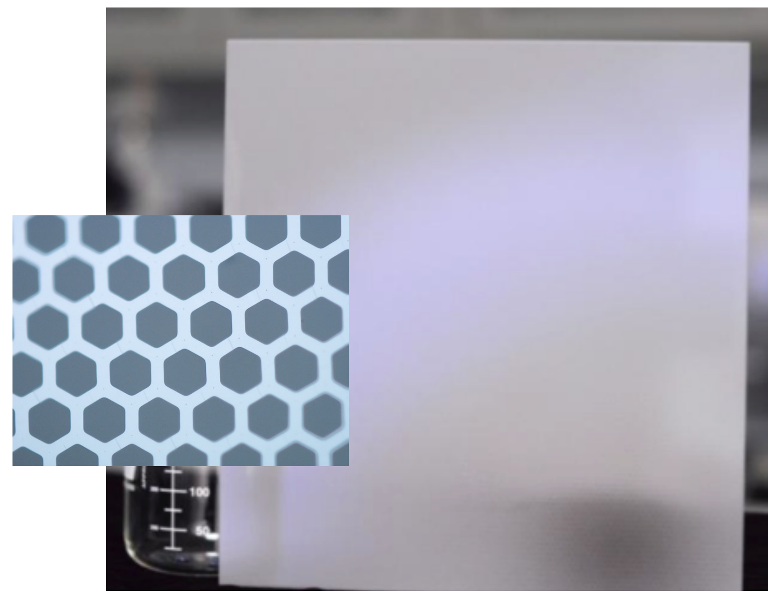
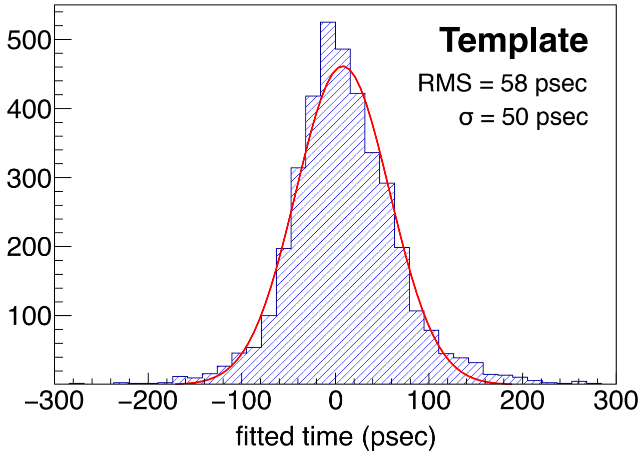


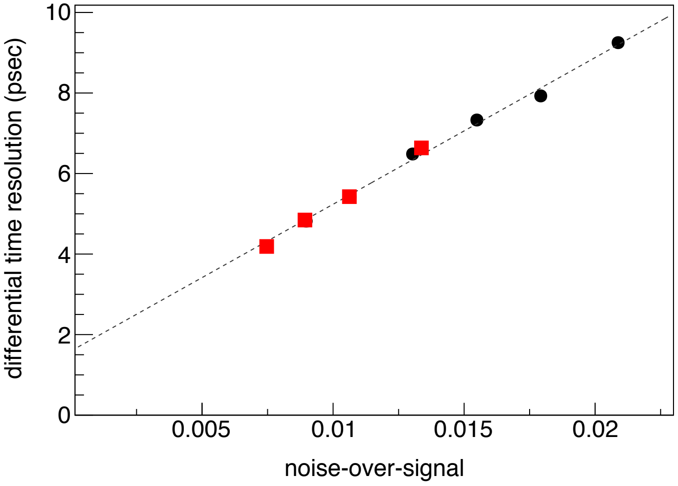


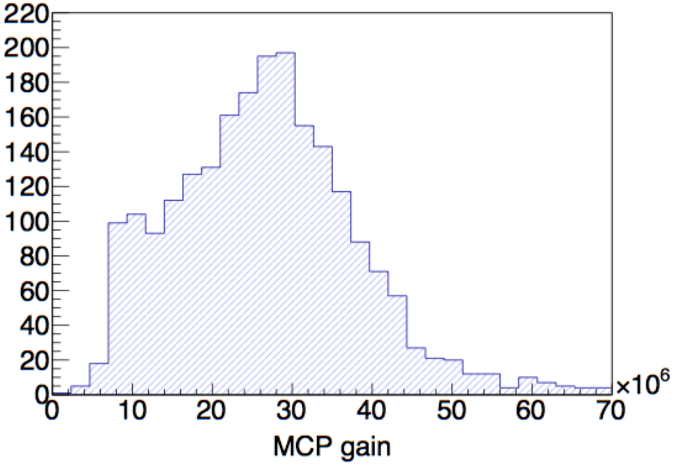


LAPPD Characteristics



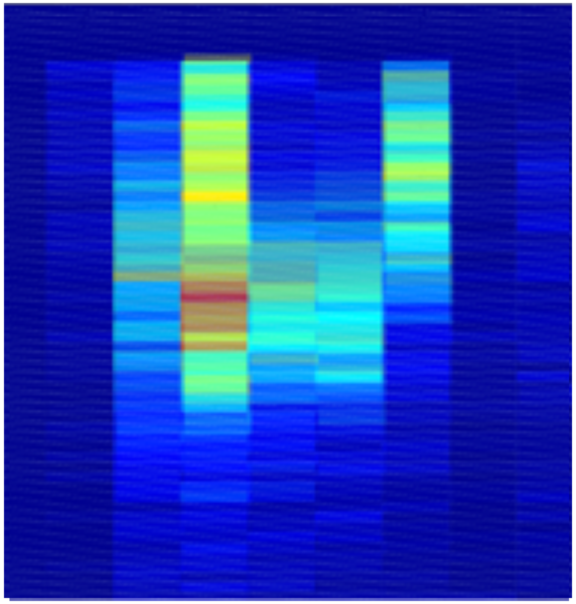
<60 psec, single PE resolutions





10^7 gains

imaging and single photon resolution



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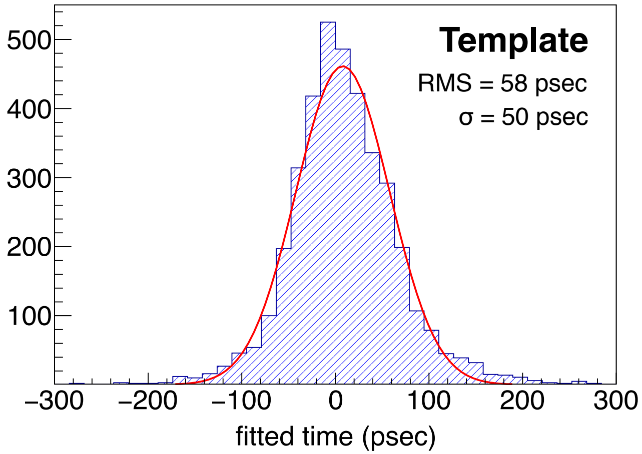

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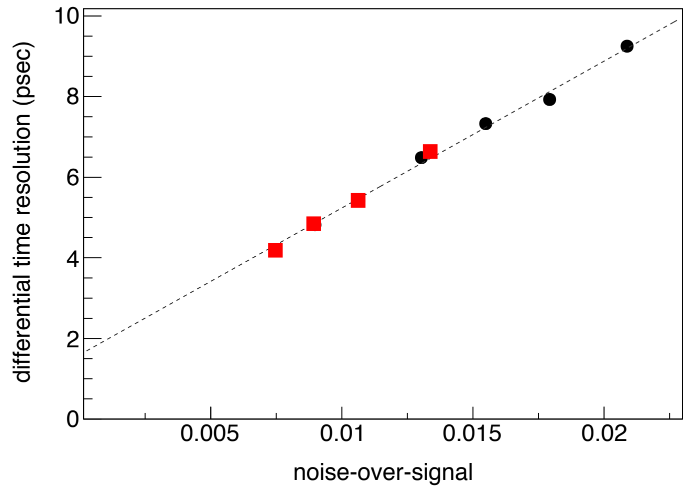

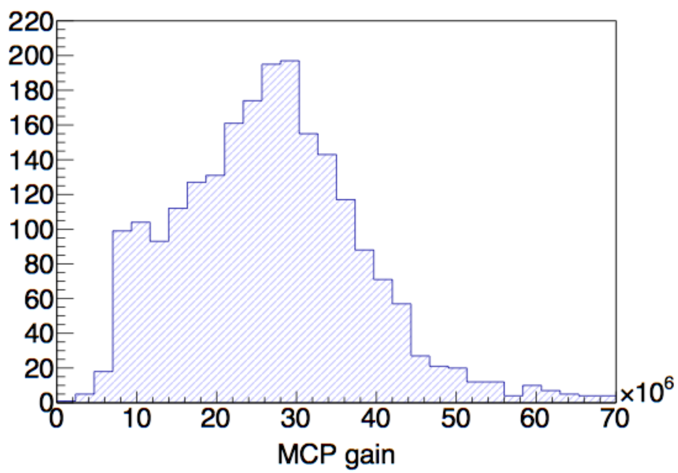

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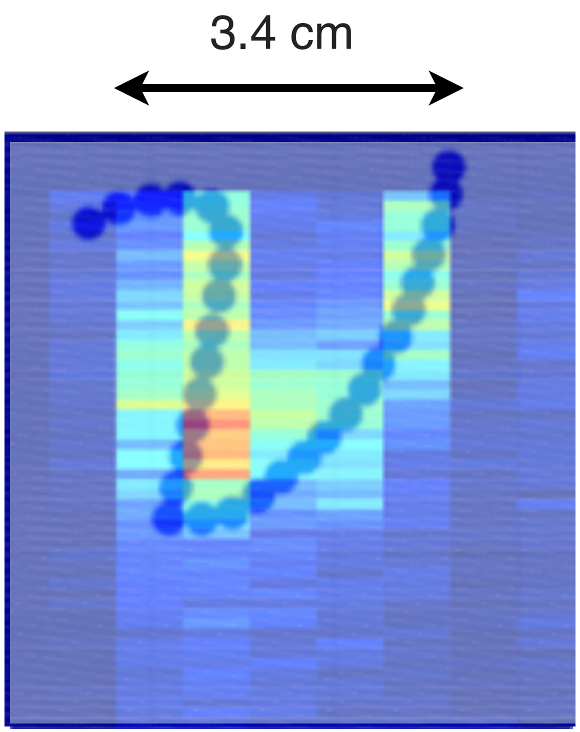

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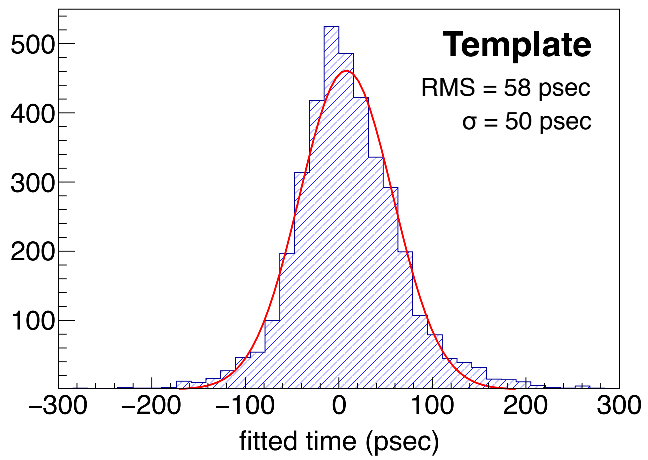

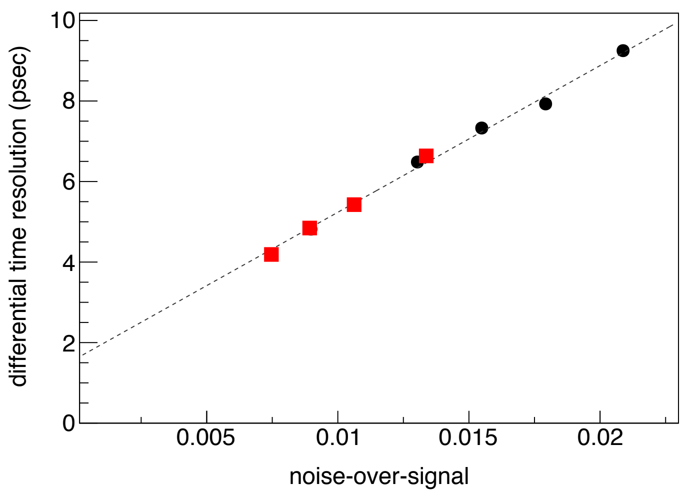

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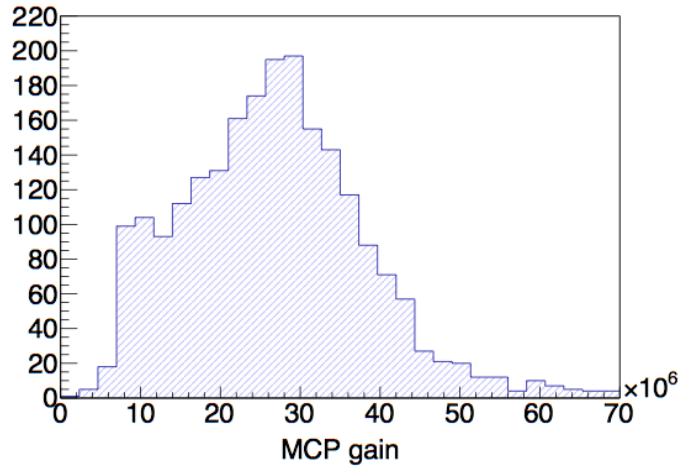
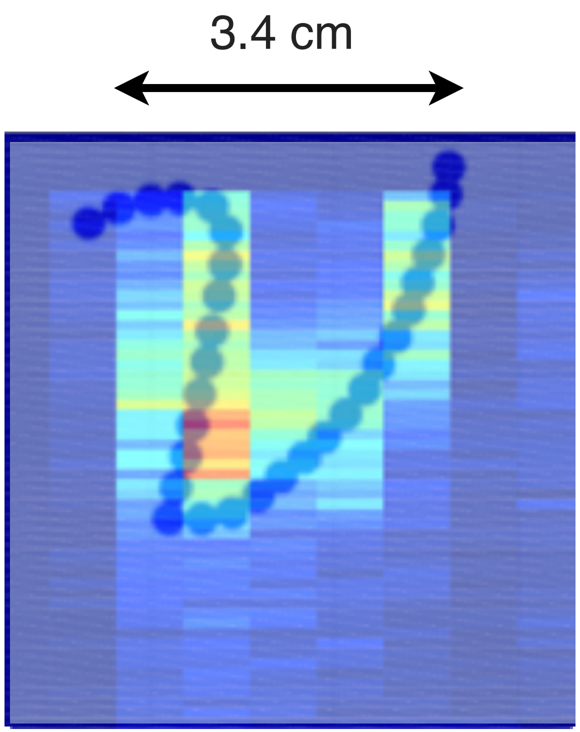
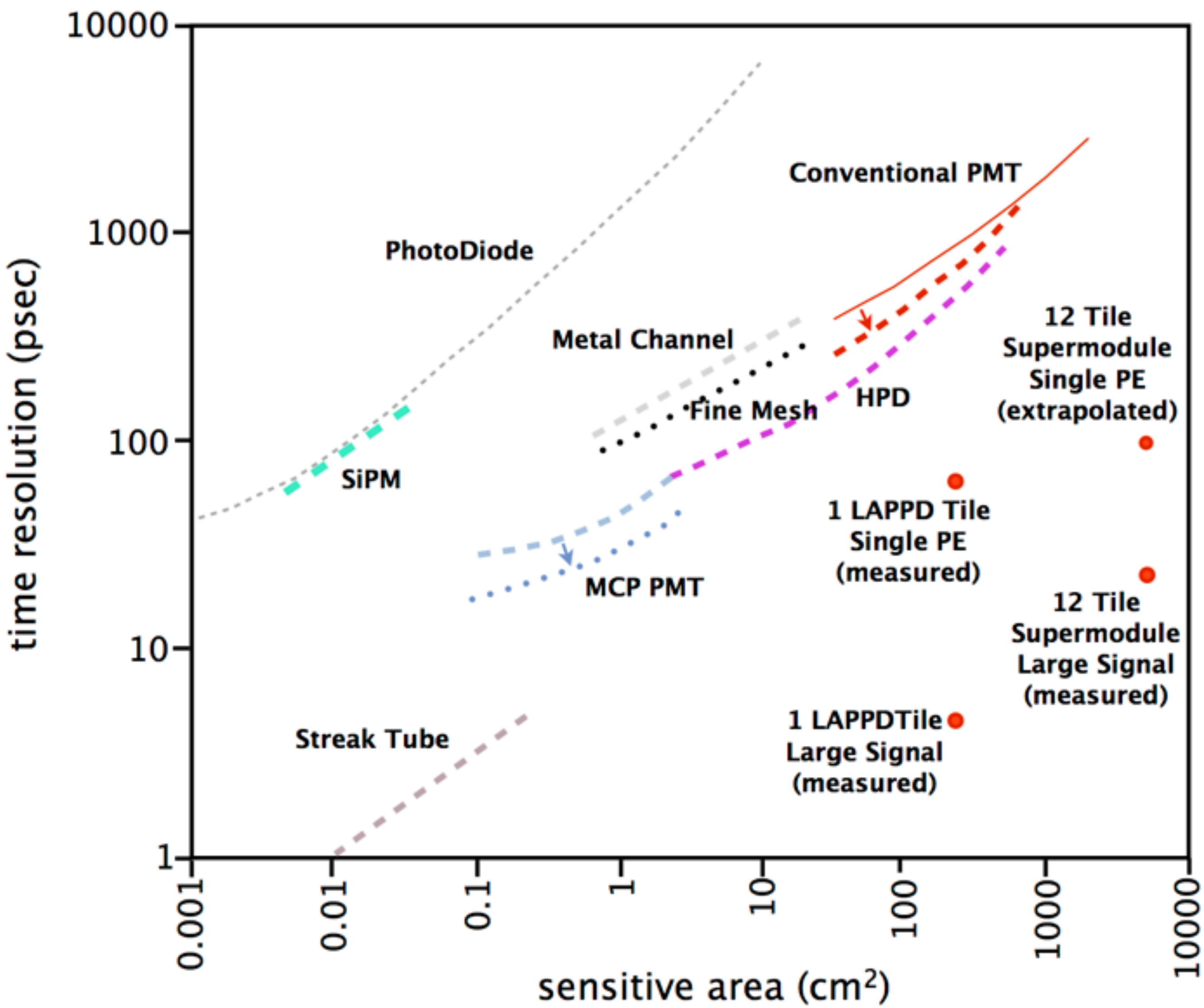


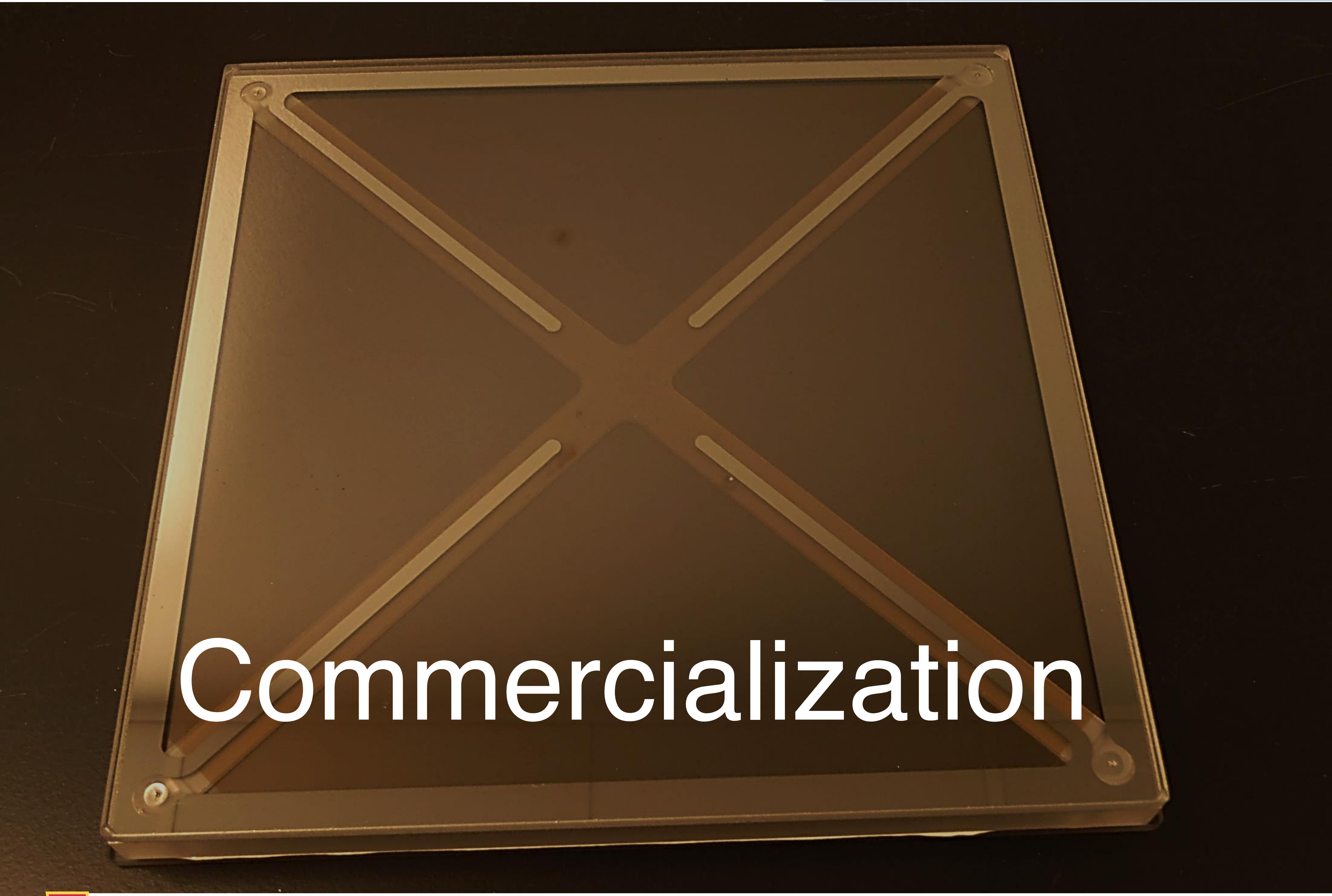


Nucl Inst and Meth, 795, pp 1–11 (2015)

LAPPD capabilities

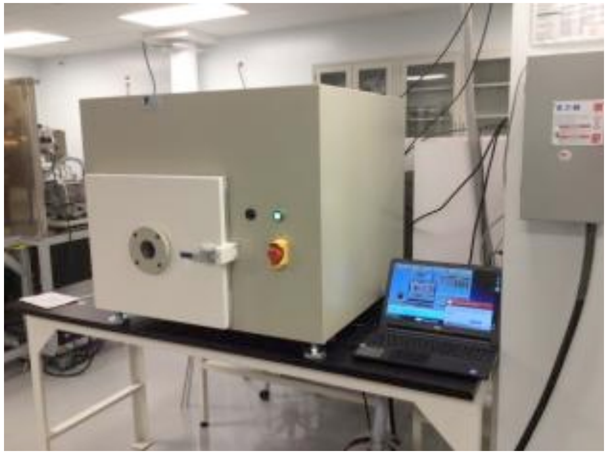


Commercialization



Commercialization Status (Incom)

Plasma cleaner



Vacuum

LAPPD integration and sealing tank

Beneq ALD coater with load-lock

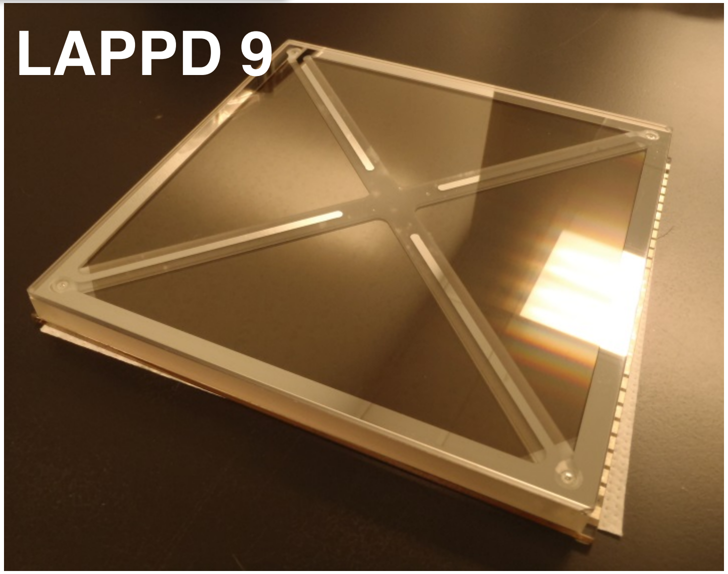
Thermal evaporator

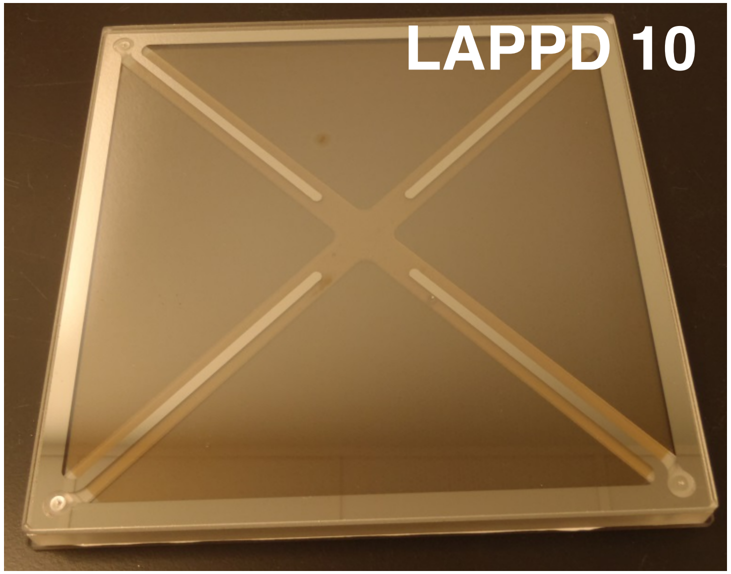
Measurement & test station

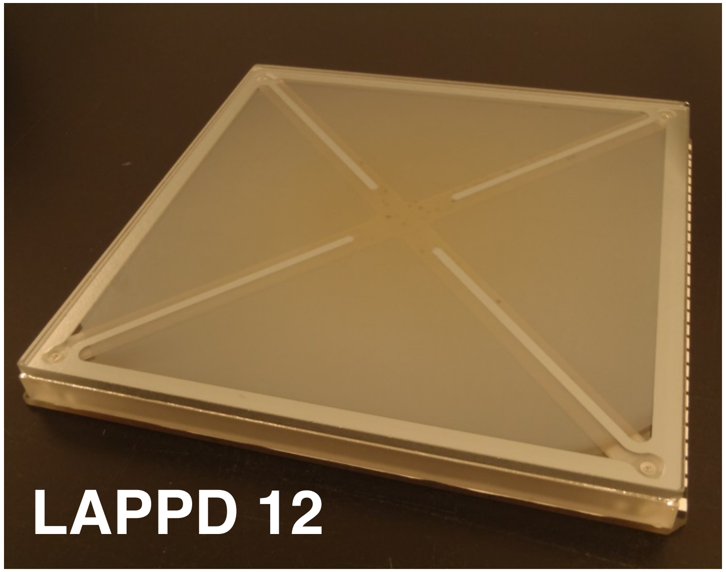
Commercialization Status (Incom)

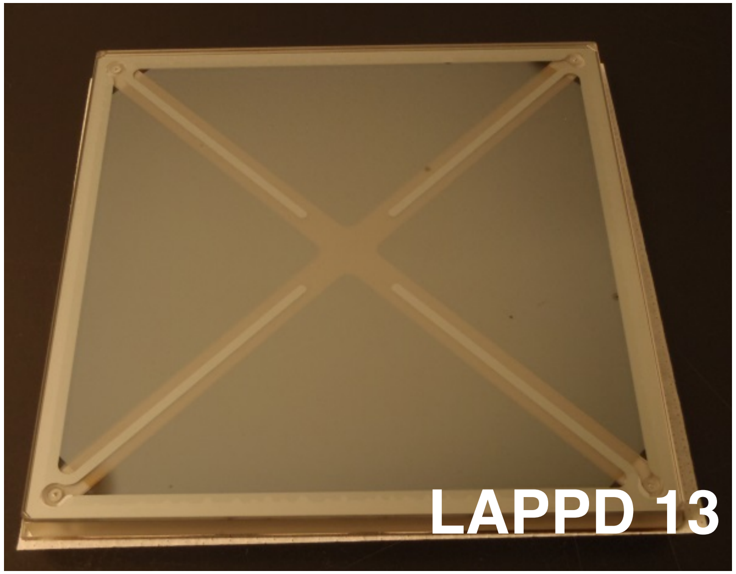
- Funding to create infrastructure and demonstrate a pathway toward pilot production (04/2014)
- Facility operational (11/2015)
- Commissioning trials initiated (12/2015)
  - #9 - Sept 14, 2016, First Sealed Tile – Aluminum Photocathode
  - #10 - Oct. 11, 2016, First Sealed Tile with Bialkali Photocathode
  - #12 - Dec. 21, 2016, QE (365nm Max/Avg/Min) = 16.5%/**<u>11.1%</u>**/6.7%
  - #13 - Jan 26, 2017, QE (365nm Max/Avg/Min) = 31.2%/**<u>24.8%</u>**/17.9%
  - Redesign & Processing Experiments – On-going
- Exploitation (QII 2017)
  - Commit to a baseline design for first run of prototypes
  - Produce prototypes for early adopters
  - Operate Pilot Production on a routine basis

Recent Prototypes

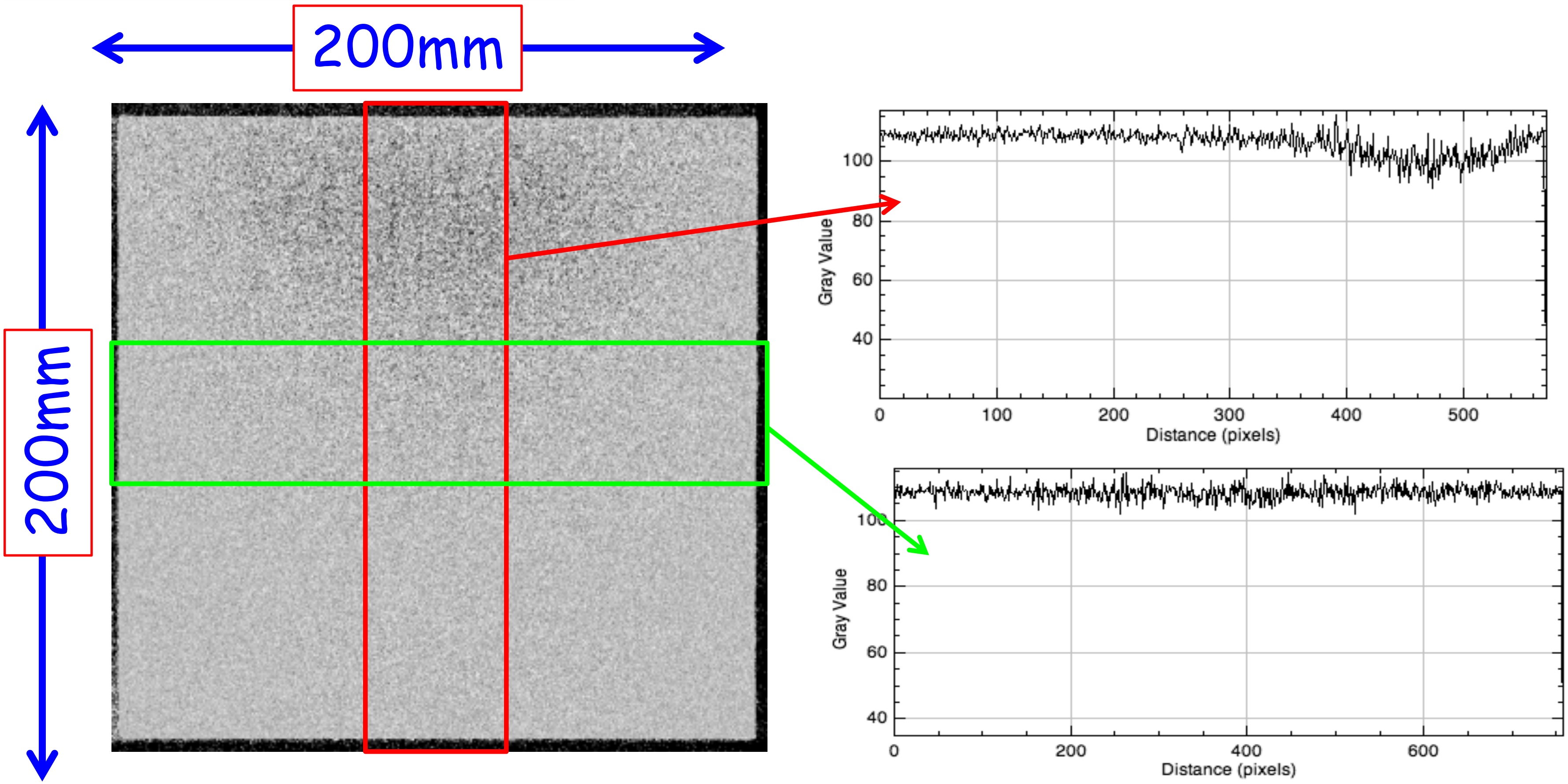








ALD performance (Incom)



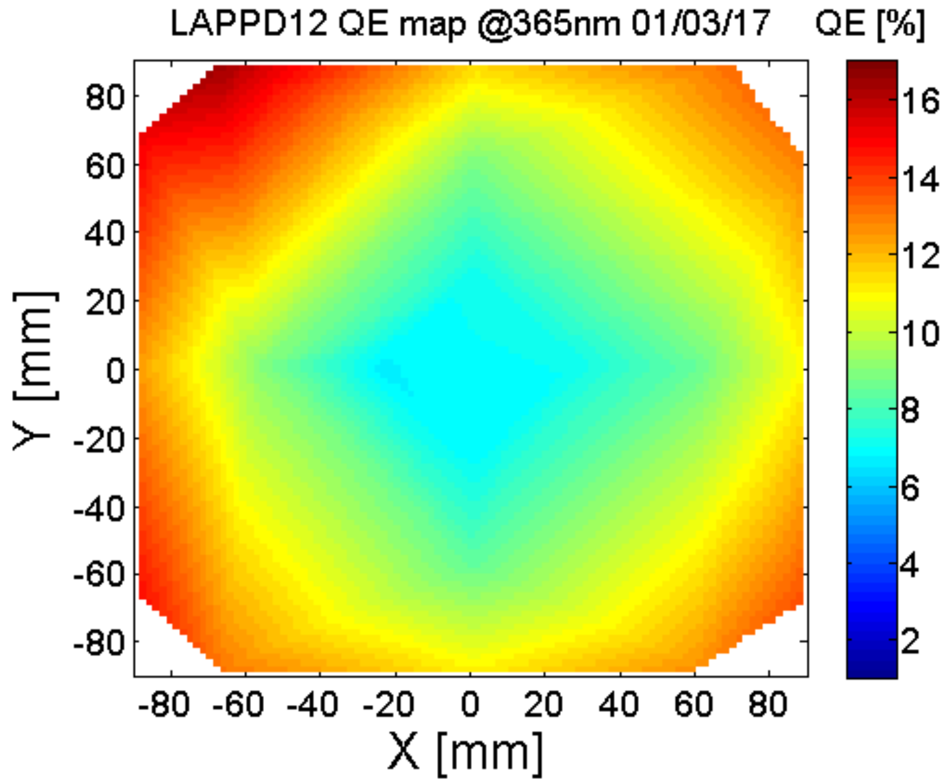
Gain Uniformity Map

20 micron pores

Dark Noise: 0.1 – 1 cts/sec/cm^2

Uniform Gain within ~15% across the area

LAPPD 12 QE map @365nm 10 days after sealing



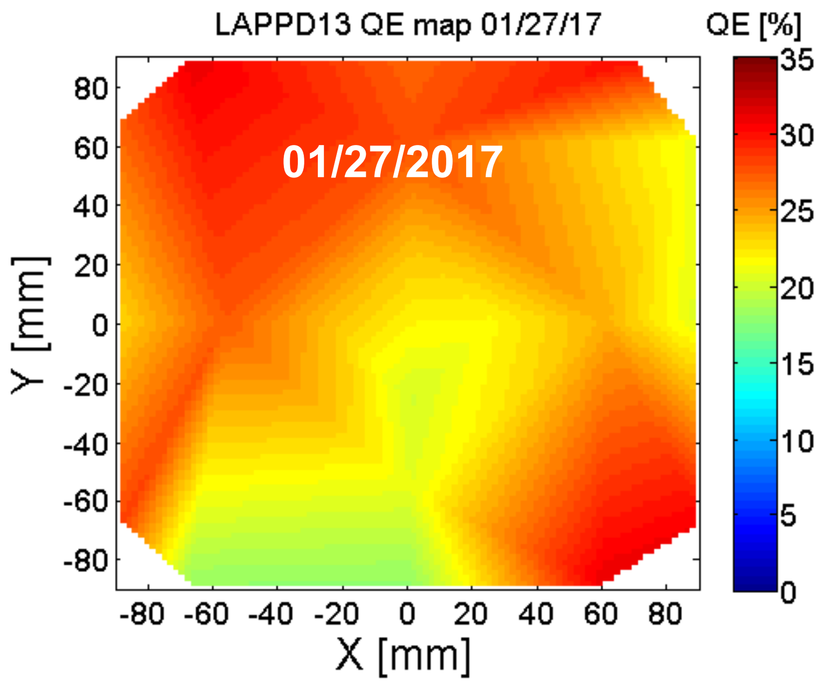
QEmax: 16.5%

Average QE=11.1%

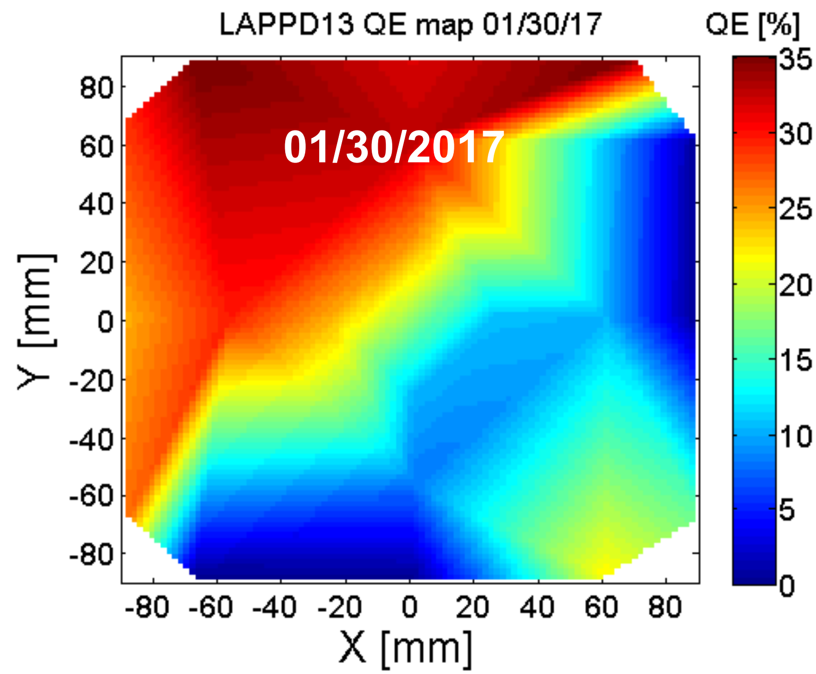
QEmin: 6.7%

Δ (100% - QEmin/QEmax): 60%

LAPPD 13 "EXP" - Addressing QE & Modified Sealing

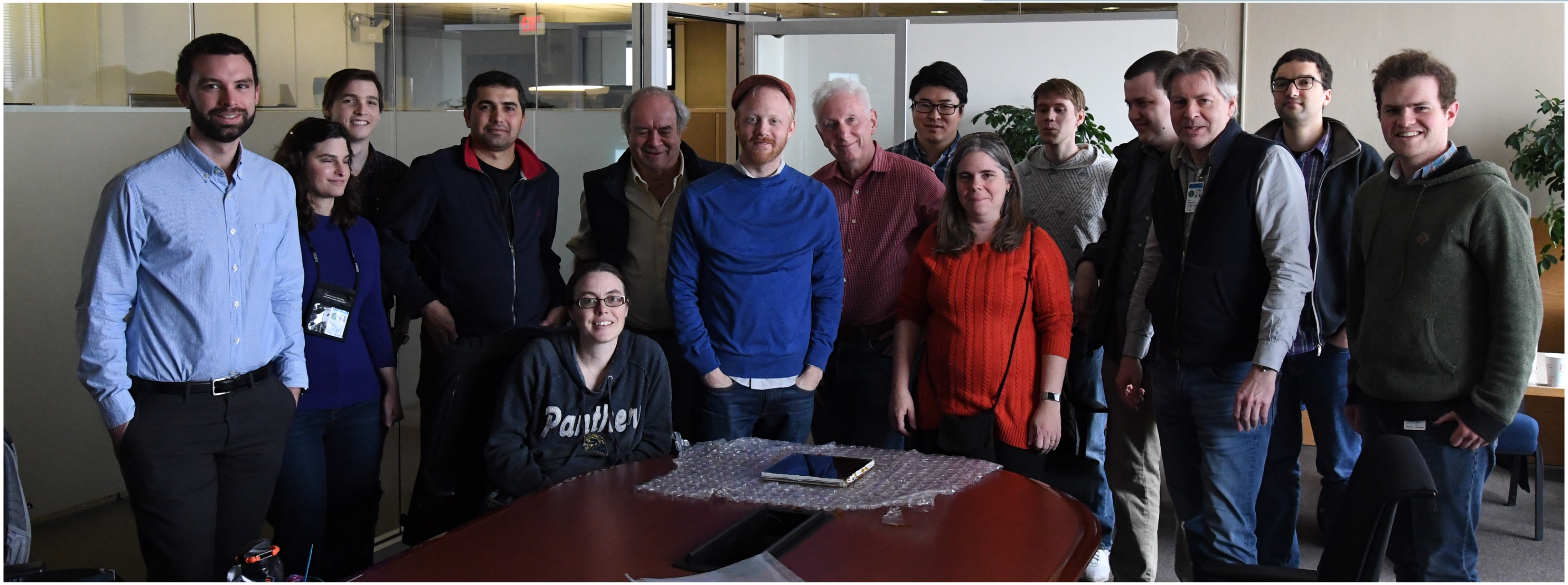


QEmax: 31.2%
Average QE=24.8%
QEmin: 17.9%
Δ (100% - QEmin/QEmax): 42%

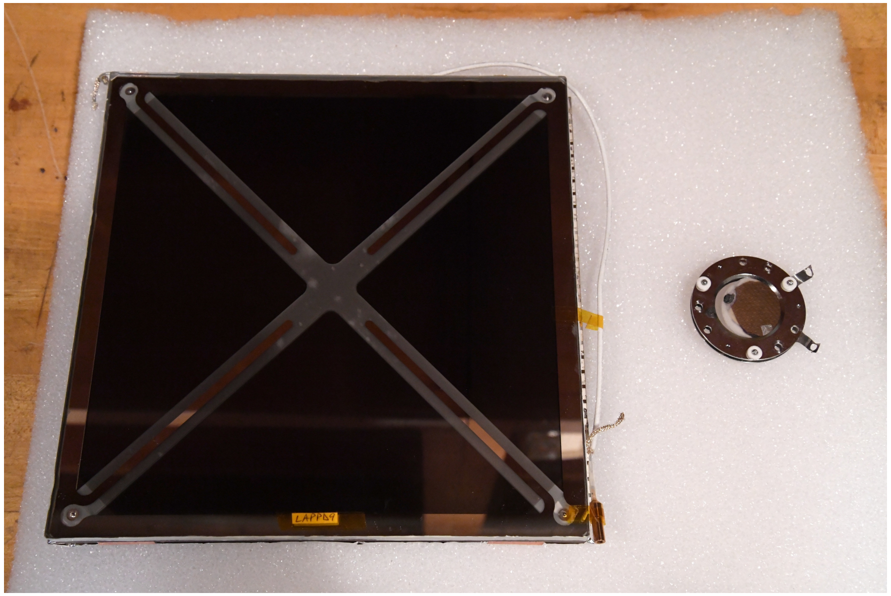


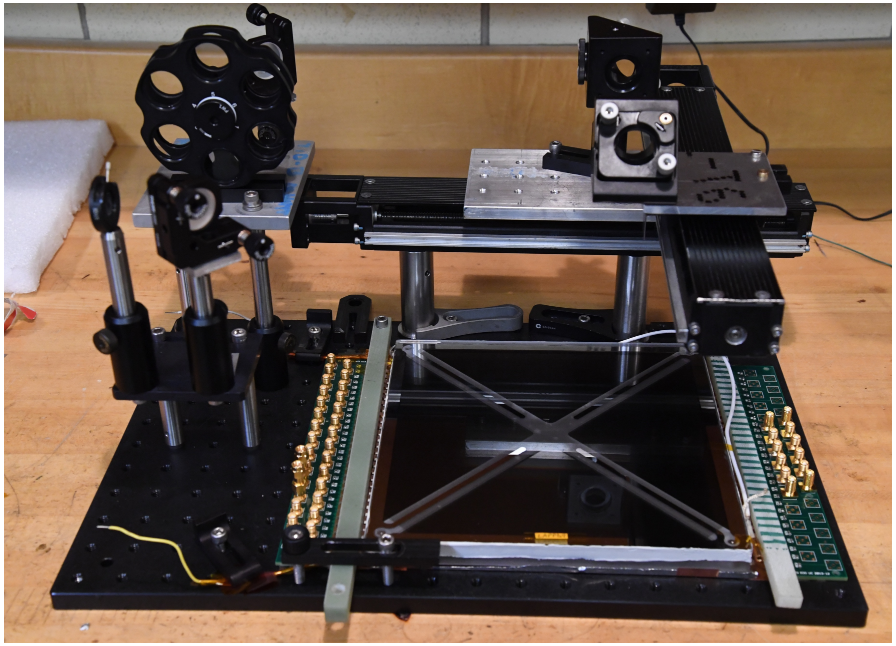
QEmax: 35.3%
Average QE=18.6%
QEmin: 0.01%
Δ (100% - QEmin/QEmax): n/a

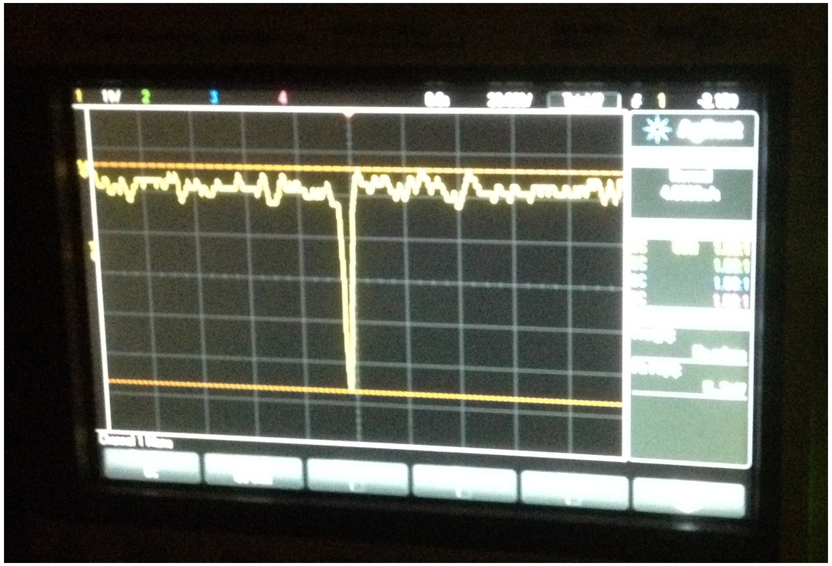
Sealed January 26, 2017, F.S. Window, Internal HV problem, High QE but leak affected QE Uniformity


Panther

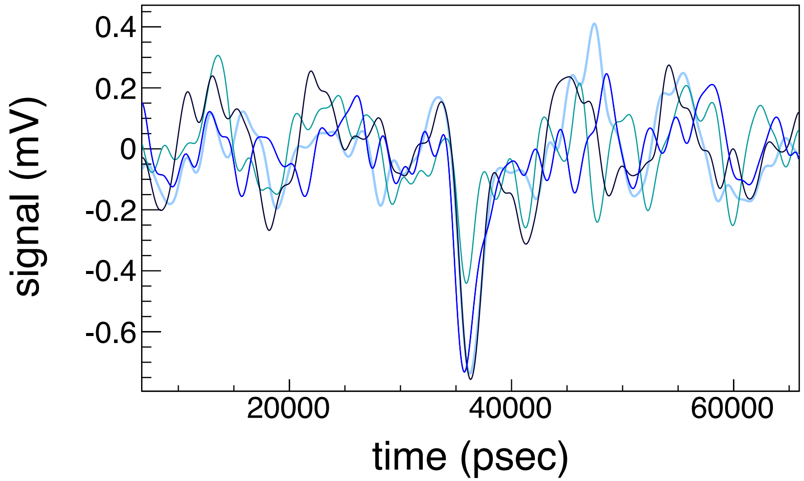

INCOM



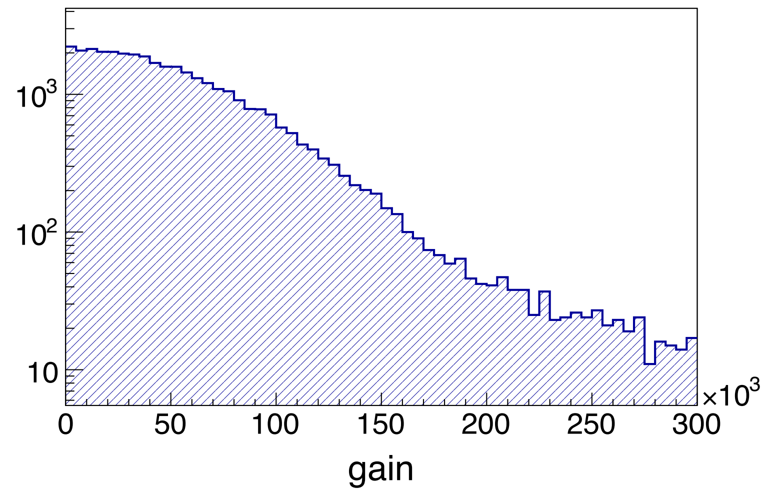




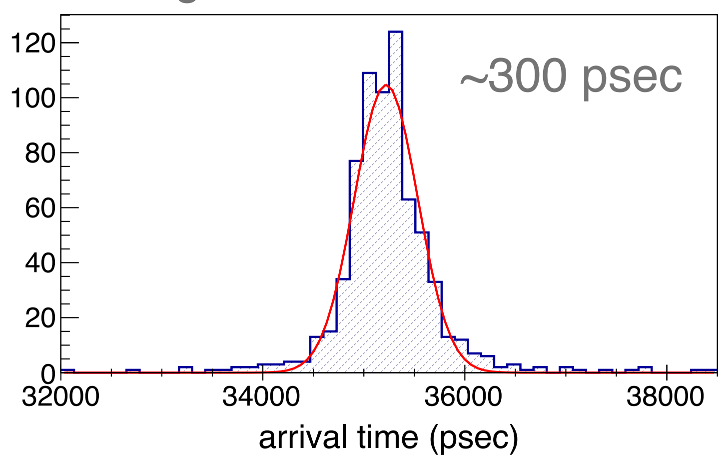
example single-PE pulses



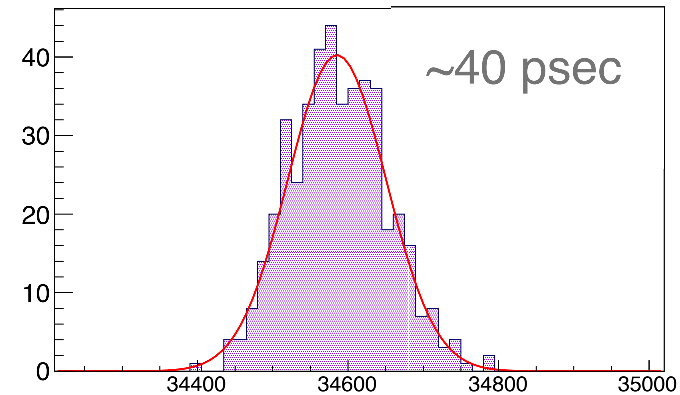
gain distribution



single PE time resolution



multi-PE time resolution



- LAPPD 9 still worked stably and reliably ~6 months after fabrication
- single PE time resolutions of a few hundred picoseconds were observed, limited primarily by gain (this will improve)
- peak gain was observed to be O(10e5) with the caveat that the HV was not optimized
- This can be addressed by pre-amps/optimized HV
- Given that the LAPPD collab has made 10e7 gain, improvement is likely
- LAPPD 12 has arrived and is now installed in the ISU dark box (stay tuned)

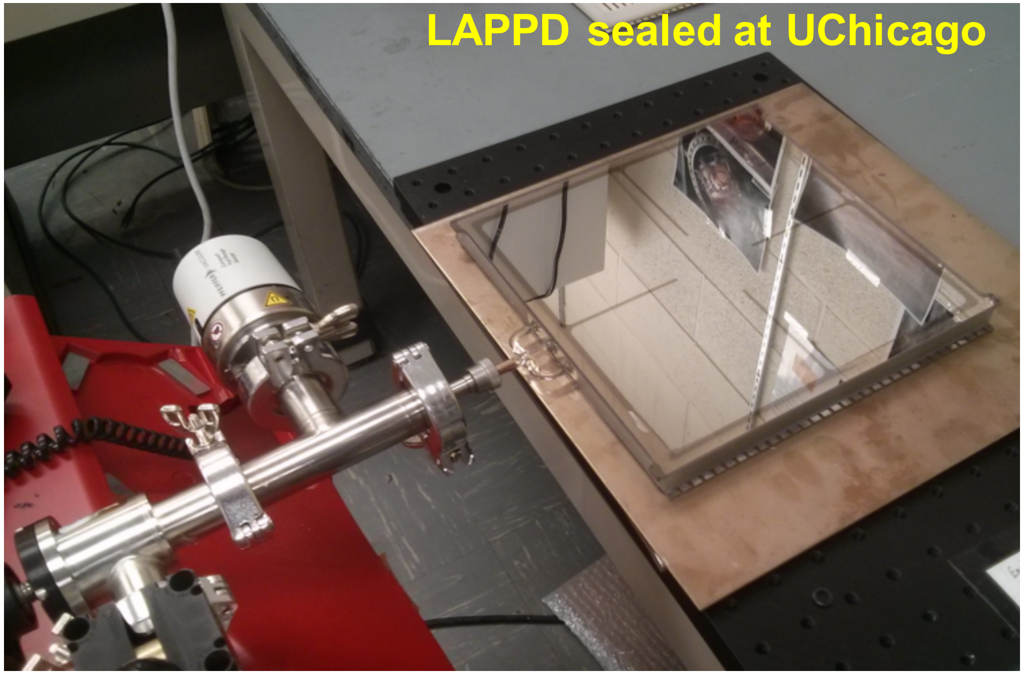
Gen II Development

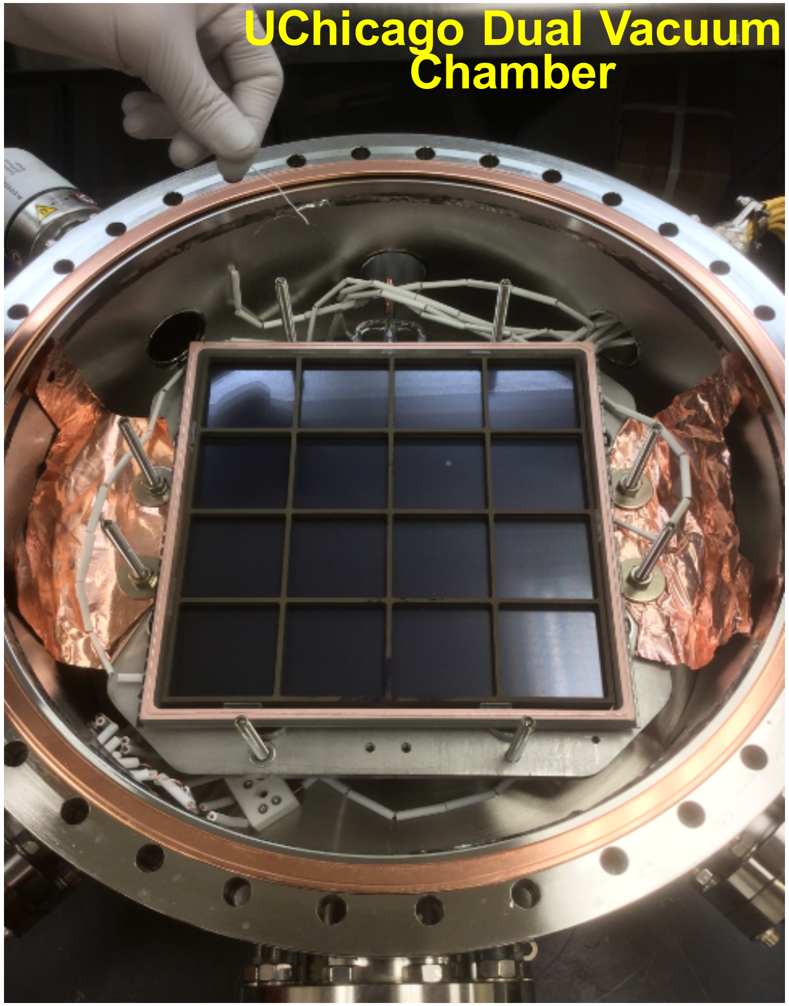
Gen II Development (U Chicago/Incom)

slide credit: Andrey Elagin

To follow closely behind the ramp up of first Incom tiles.

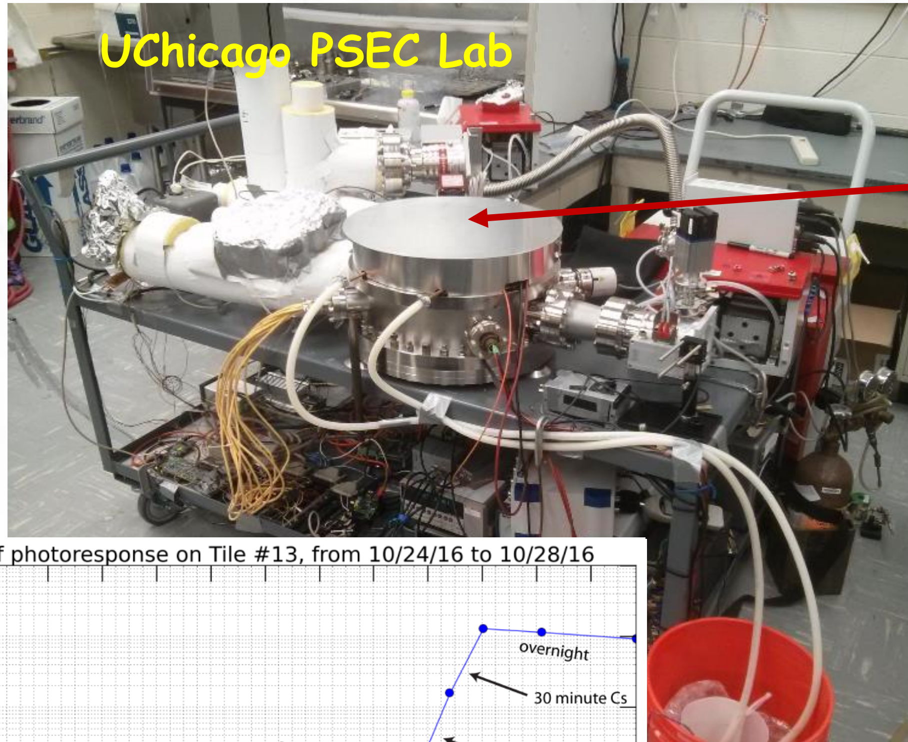
- reduce fabrication costs and increase volume
- improve performance
- Address the vacuum transfer process.
- New approaches to photocathode production
- cheaper and more robust components

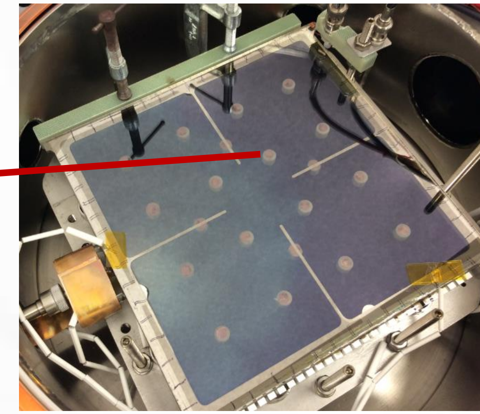


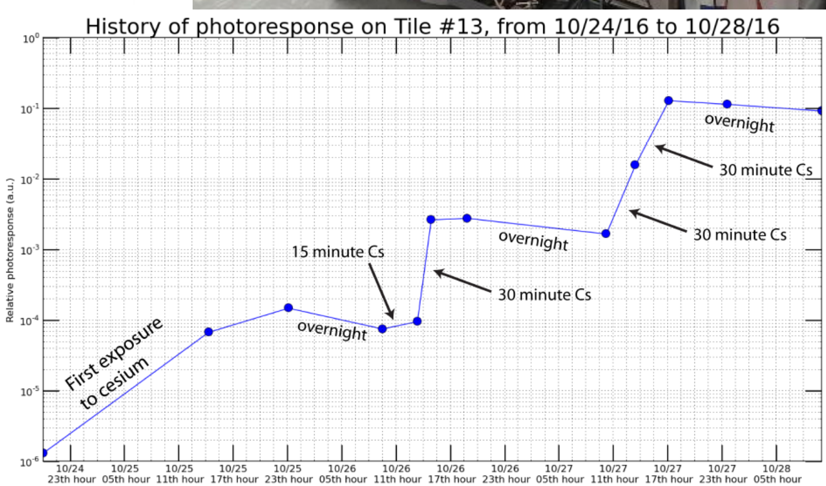


slide credit: Andrey Elagin

Simplify the assembly process by avoiding vacuum transfer:
<u>make photo-cathode after the top seal</u>
(PMT-like batch production)







Heat only the tile not the vacuum vessel

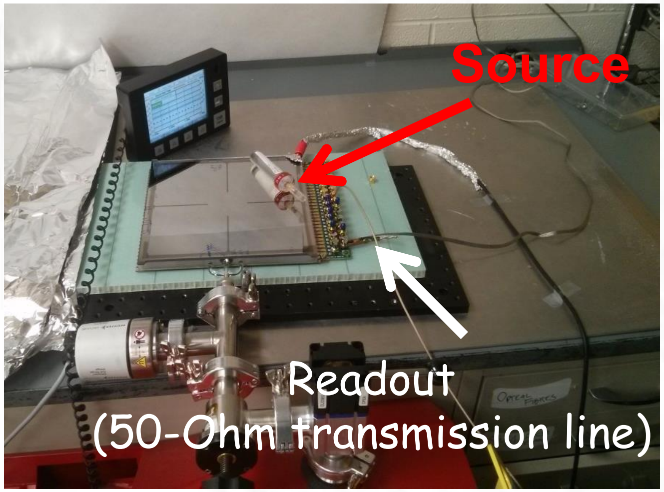
Intended for parallelization

slide credit: Andrey Elagin

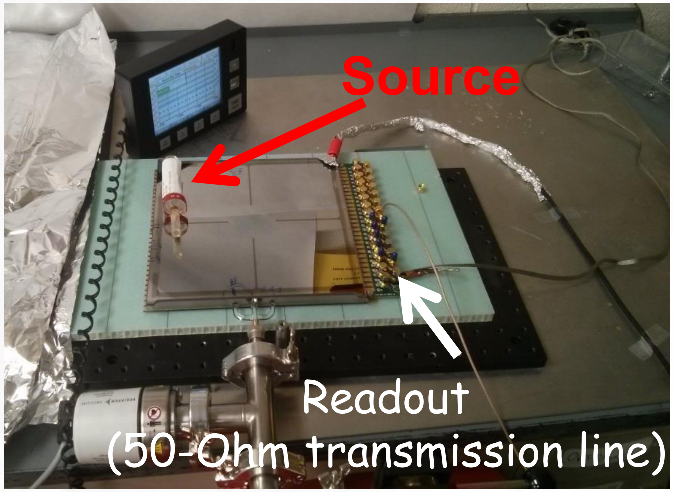
First signals from an In-situ LAPPD

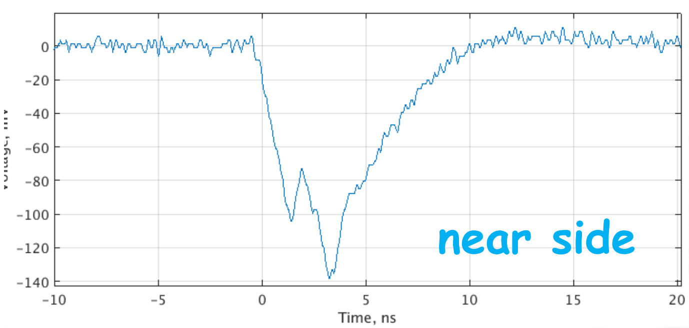
April 2016

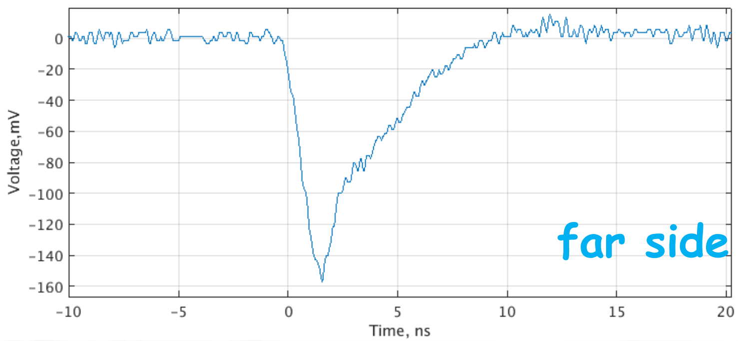
Near side: reflection from unterminated far end



Far side: reflection is superimposed on prompt







The tile is available for QC before the photocathode is shot

slide credit: Andrey Elagin

First Sealed, In-situ LAPPD

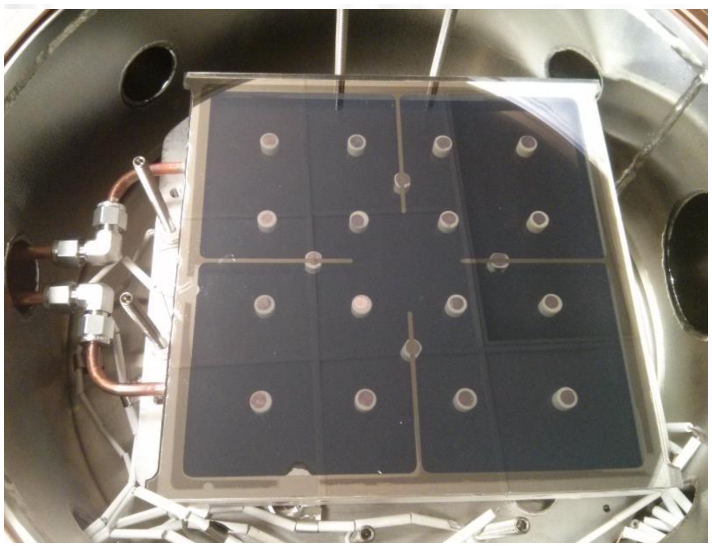
August 18th 2016

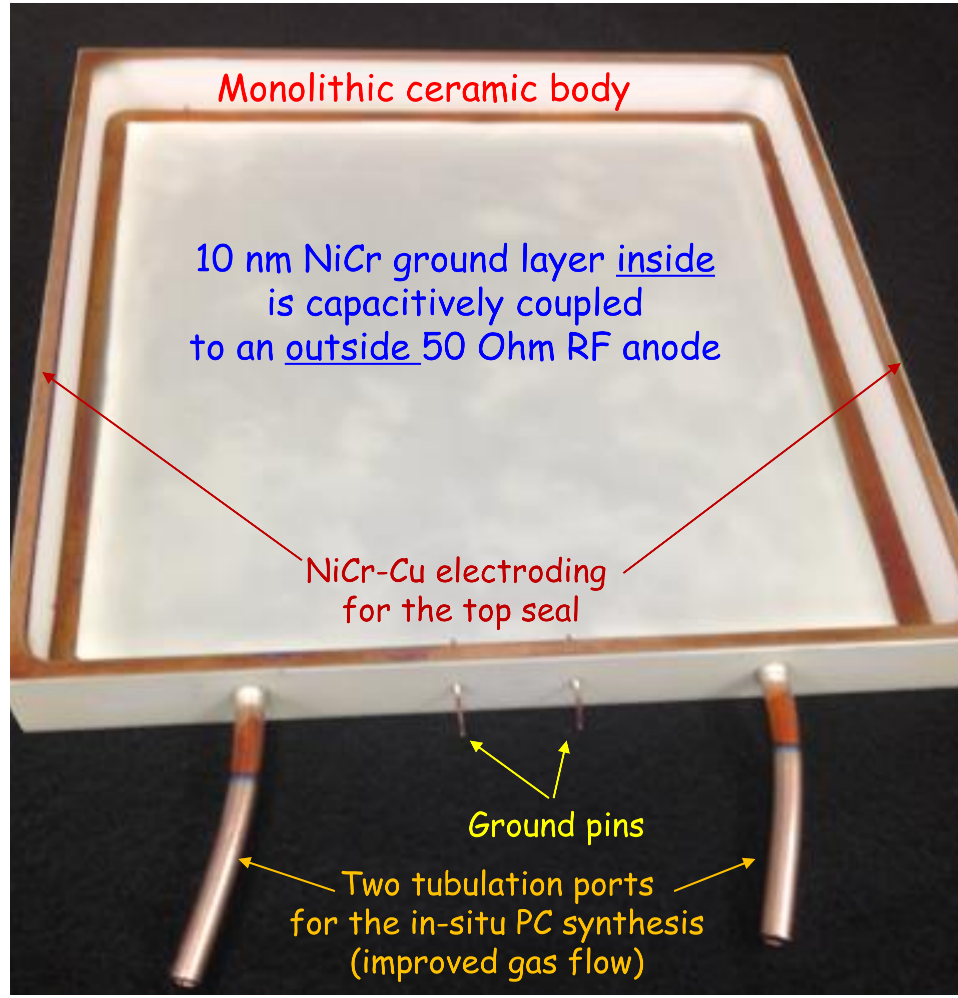
Cs_3Sb photocathode

slide credit: Andrey Elagin

Mechanical Advancements

- Robust ceramic body
- Anode is not part of the vacuum package
- Compatible with current Incom fab
- Also compatible (ideal) for gen II, in situ fab

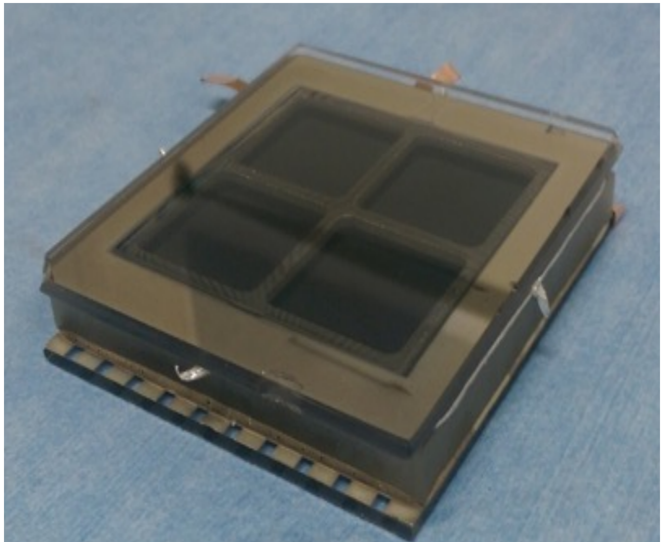




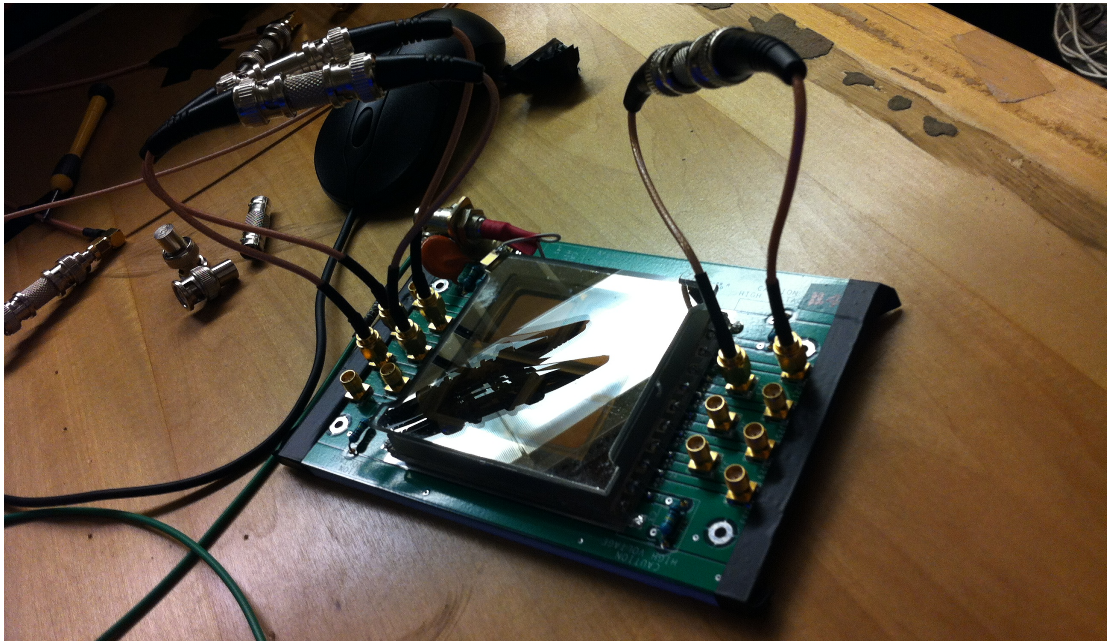
slide credit: Andrey Elagin

ANL 6 cm Tiles

- small format, glass MCP detectors based on the LAPPD concept.
- ANL development facility now producing new tubes regularly and with a high success rate
- slightly low QE (~10%) but high gain and good timing
- a number of long lived prototypes exist, more are on the way and available for testing.



Completed Tube with Photocathode



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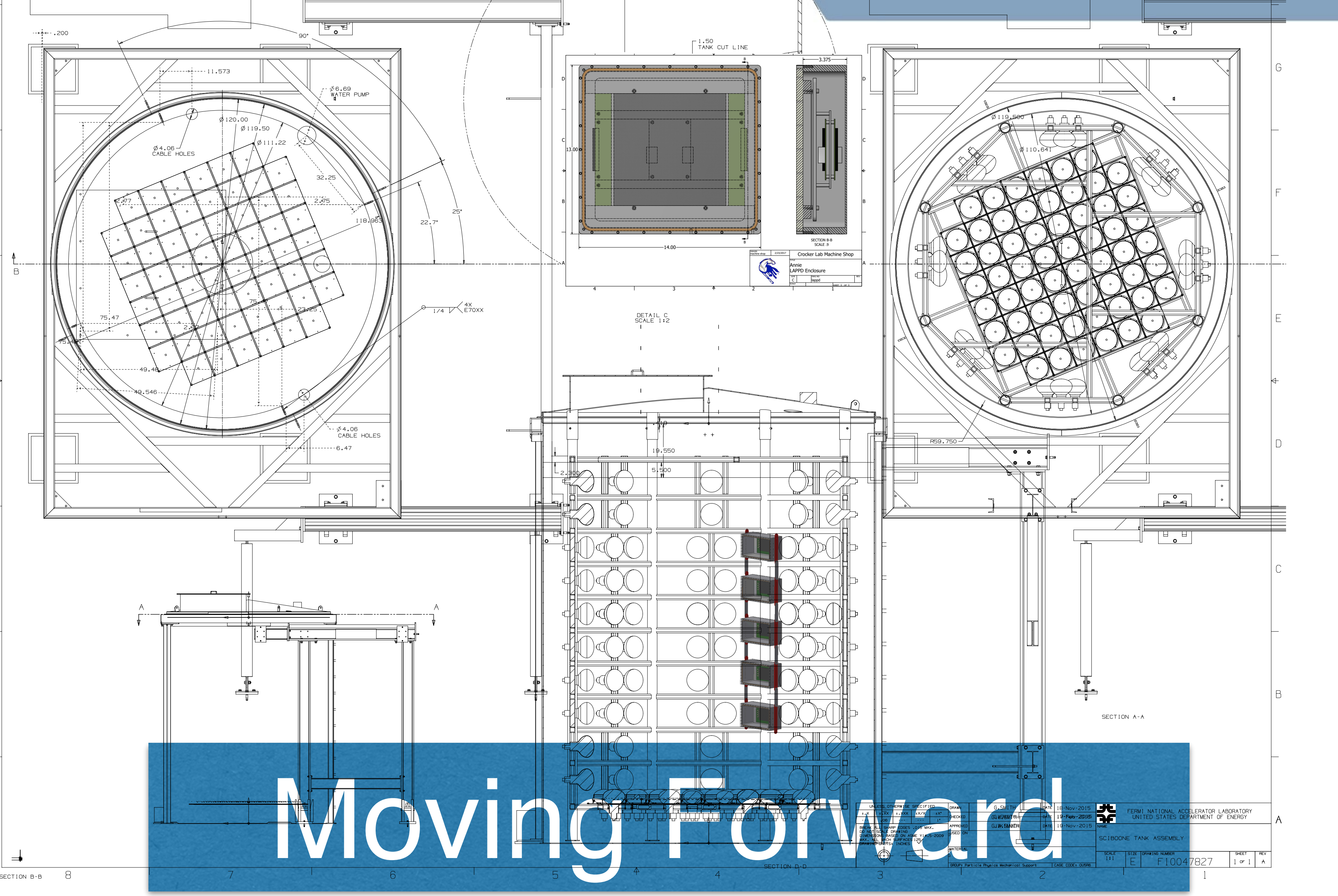


Moving Forward

Early Adopters

First LAPPDs will not be “cheap” (by HEP standards)
- small volumes
- high operational costs
- small market

Even with no further developments, costs are likely to go down with yield, volume, and market size

LAPPD technology is viable outside of particle physics (medical imaging, security, neutron and x-ray imaging, etc)

HEP will benefit from economy of scale.

Gen II could significantly reduce costs.

In the mean time, Incom is very interested in HEP early adopters and is willing to help with costs and availability, *especially* for those who can provide detailed testing/feedback

Successful early demonstrations are critical!

ANNIE - an opportunity

ANNIE -

- a ready built, working WCh neutrino detector
- an opportunity to field test LAPPDs
- there is physics in addition to the R&D

Many future efforts of similar and larger scales to follow

See F. Krennrich's and B. Svoboda's talks

Timeline for ANNIE LAPPD Development

Spring 2016

- continued testing (possible publication) of Incom tiles
- vertical integration test at ISU
  - demonstration of LAPPD + PSEC electronics
  - working together as part of the ANNIE daq
  - credit: Jonathan Eisch ISU, Ben Richards QMUL

Summer 2016

- Reconstruction of cosmic muon direction with a single photodetector
- First full prototype of water-proof housing
- Heat testing of water-proof housing
- Submersion tests

Fall 2017

- First LAPPD(s) in ANNIE

Prototypes and Demonstration Detectors Are Important

- ANNIE has an arrangement with Incom for 20 early production-grade LAPPDs
- It is an important opportunity to demonstrate that LAPPDs are ready and viable for neutrino experiments
- It is a chance to get your hands on some early models

See F. Krennrich's and B. Svoboda's talk

The “BIG” Picture

Over the next 5-10 years, it may be possible to develop new and advanced water and scintillator neutrino detectors concepts

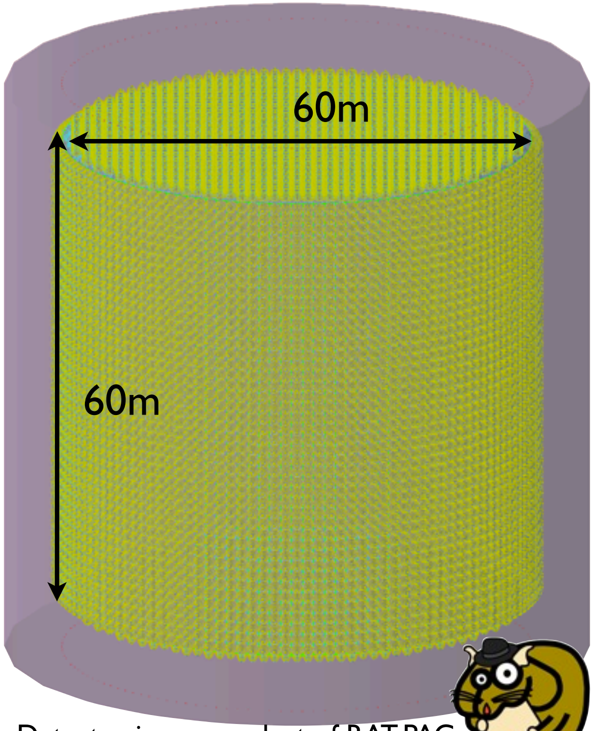
These detectors can bring a much needed scale and physics diversity to neutrino experiments in the US and abroad.

A key ingredient in advancing this technology is the development of advanced photosensors.

New photosensor capabilities open up whole new approaches for detection and reconstruction

Successful early applications and demonstrations will be a crucial next step.

THEIA



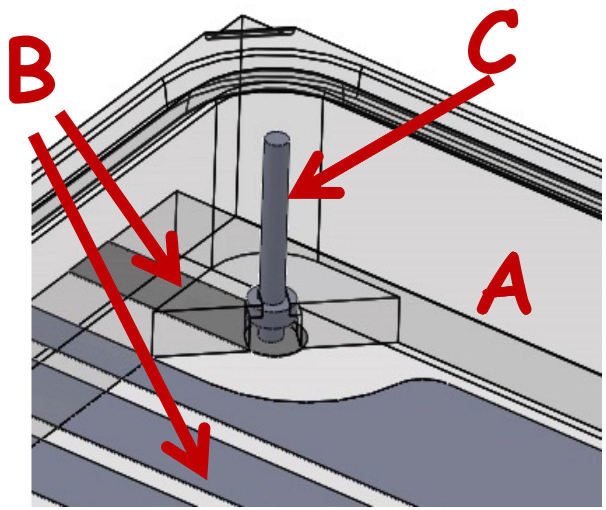
Detector image product of RAT-PAC

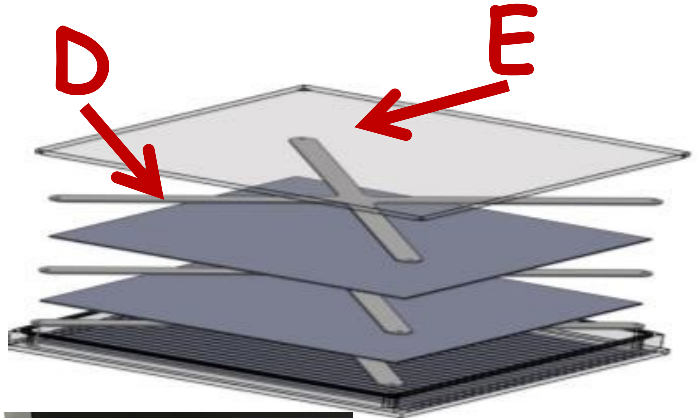
Thank You

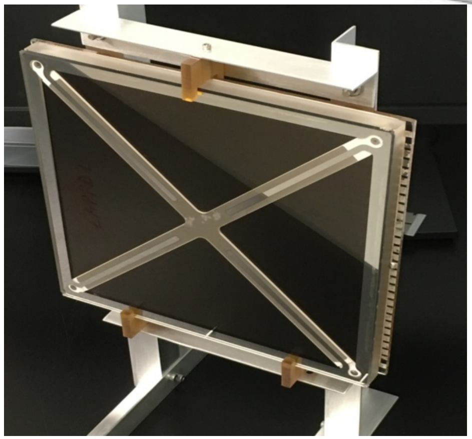
A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration

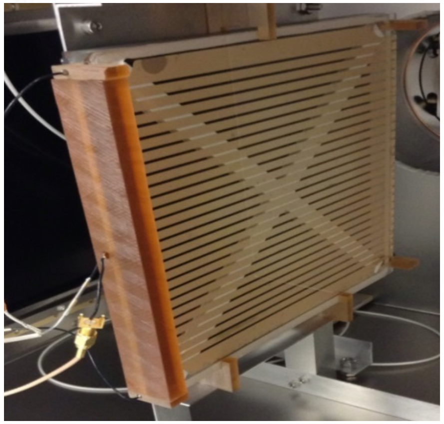
http://arxiv.org/abs/1603.01843

Incom Inc. LAPPD V2.0









A. Lower Tile Assembly (LTA) – Glass or ceramic sidewalls and bottom anode plate, hermetically sealed together,
B. Power & Signal Anode Strips - "penetration free" connection into and out of the tile.
C. Internal Power Pins - deliver voltage to the top and bottom of each MCP
D. X-Spacers – restrain window deflection under pressure, control critical spacing, support getters,
E. Borosilicate or Fused Silica Window – Hermetically sealed to sidewalls

Incom LAPPD Integration & Sealing

Process & Hardware

Process:

- UHV – with Conflat seals, scroll, turbo and ion pump.
- Tile kit components pre-assembled & locked in place .
- Baked to low 10^{-10} torr range
- In-tank operation of tile / scrubbing
- Window Transfer Process
- Multi-alkali Photocathode deposited on underside of window.
- Hot Indium Hermetic Seal – between sidewalls & top window

Hardware:

- Single "Fully Bakeable" Chamber: 30"L X 16"W X 8"H
- Simple window transfer between photocathode deposition & sealing.
- Electrical interconnects for in-process monitoring
- Readily expandable for volume production

LAPPDs

When will they be available?

ANNIE has a quote to get 20 over the next 3 years, with 2 to arrive this fall

How much will the cost?

First prototypes will be expensive
- low yield (a few 10s per year at first)
- high fixed cost

This is not how Incom sees the long term future...

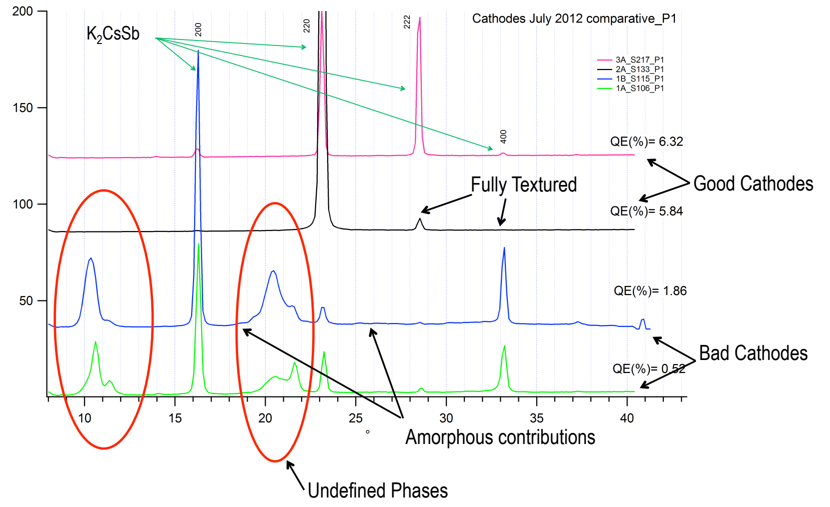
Lots of room for economy of scale, future cost reductions, expanding markets. Need to wait longer to see where prices will head

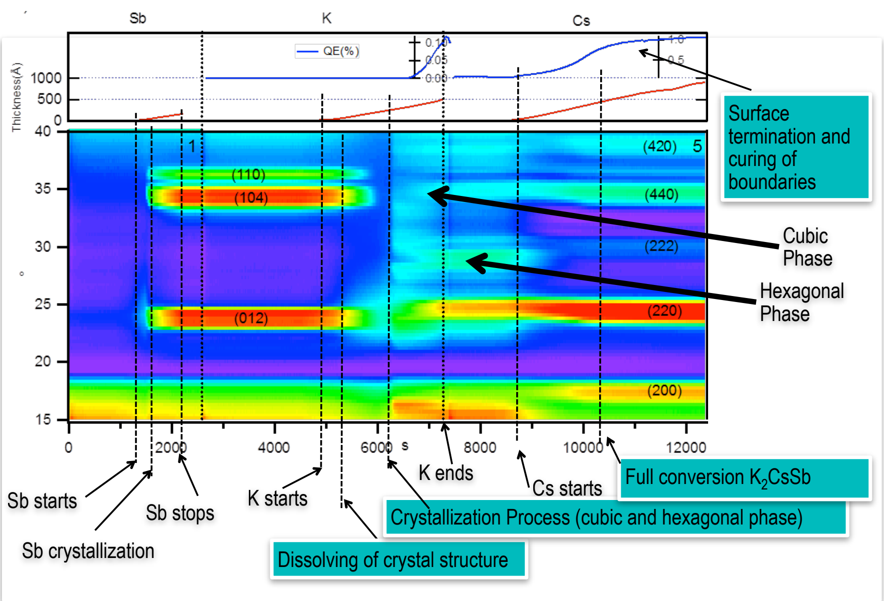
Generic Photocathode Research

Photocathode work: John Smedley (BNL), Howard Padmore (LBNL), RMD, Henry Frisch (University of Chicago), Klaus Attenkofer (BNL)

Understanding of growth recipes

- Characterization tools are established which allows to visualize crystal growth and roughness during processing.
- Sb-metal melting process demonstrated.
- Rough cathode structure is most likely determined by stoichiometry conditions during processing.
- Understanding of p- n-dopants of cathode structures due to alkali deficiencies and surface termination.

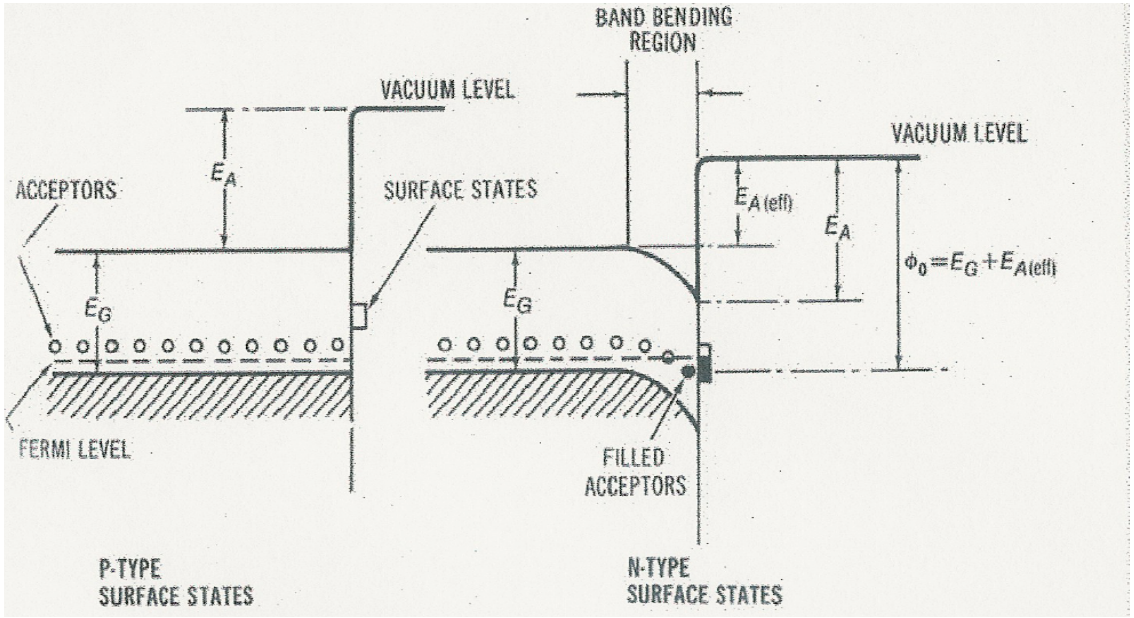




Towards sputtering:

- Macroscopic amount of material can be produced (also allowing bulk measurements like mobility….)
- Target fabrication is successful
- Substitution dopant are under evaluation
- All hardware is currently designed and installed

credit: Klaus Attenkofer (BNL)



A Photocathode is a simplified "pn-junction":

1. Alkali deficiency in the "bulk" provides p-doping of the cathode (indication by XPS data)
2. Excess Cs on the surface creates a N-doped surface resulting in band bending and reduced work function (explains 0.7eV electron affinity)

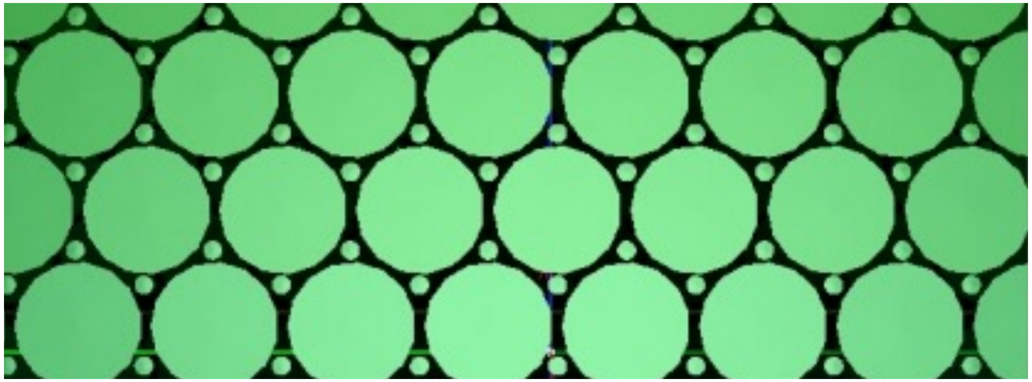
Spatial granularity/ Digital Photon Counting

Lots of small tubes or many large tubes?

Why not both?

Why not also mix technologies?

ANTARES DOM

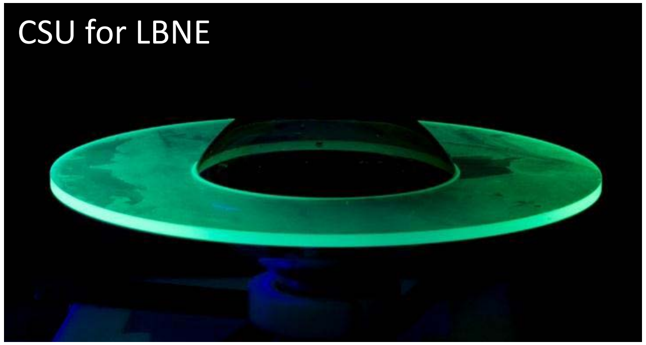


JUNO concept

CHIPS prototype

Light Collection and imaging

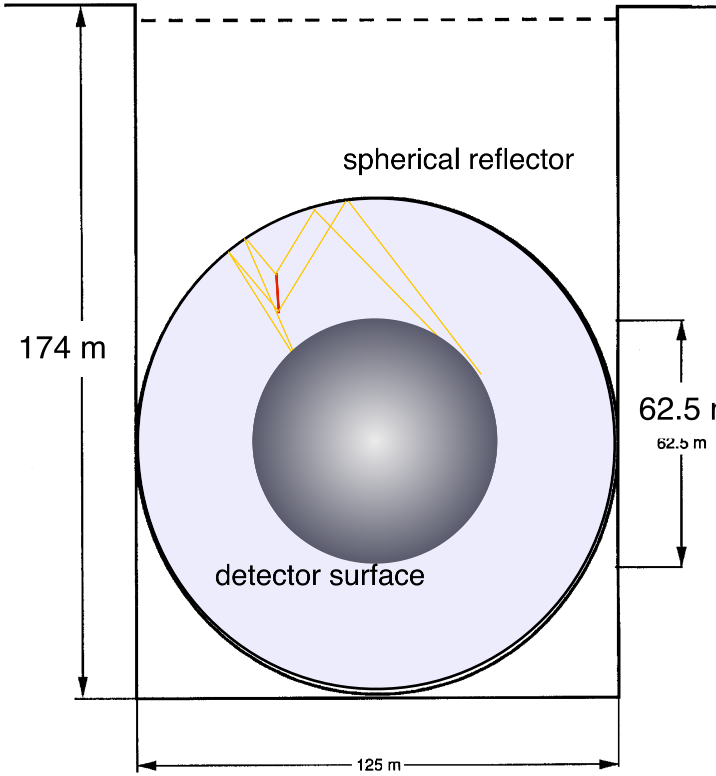
Light collectors can be used to improve collection area per PMT

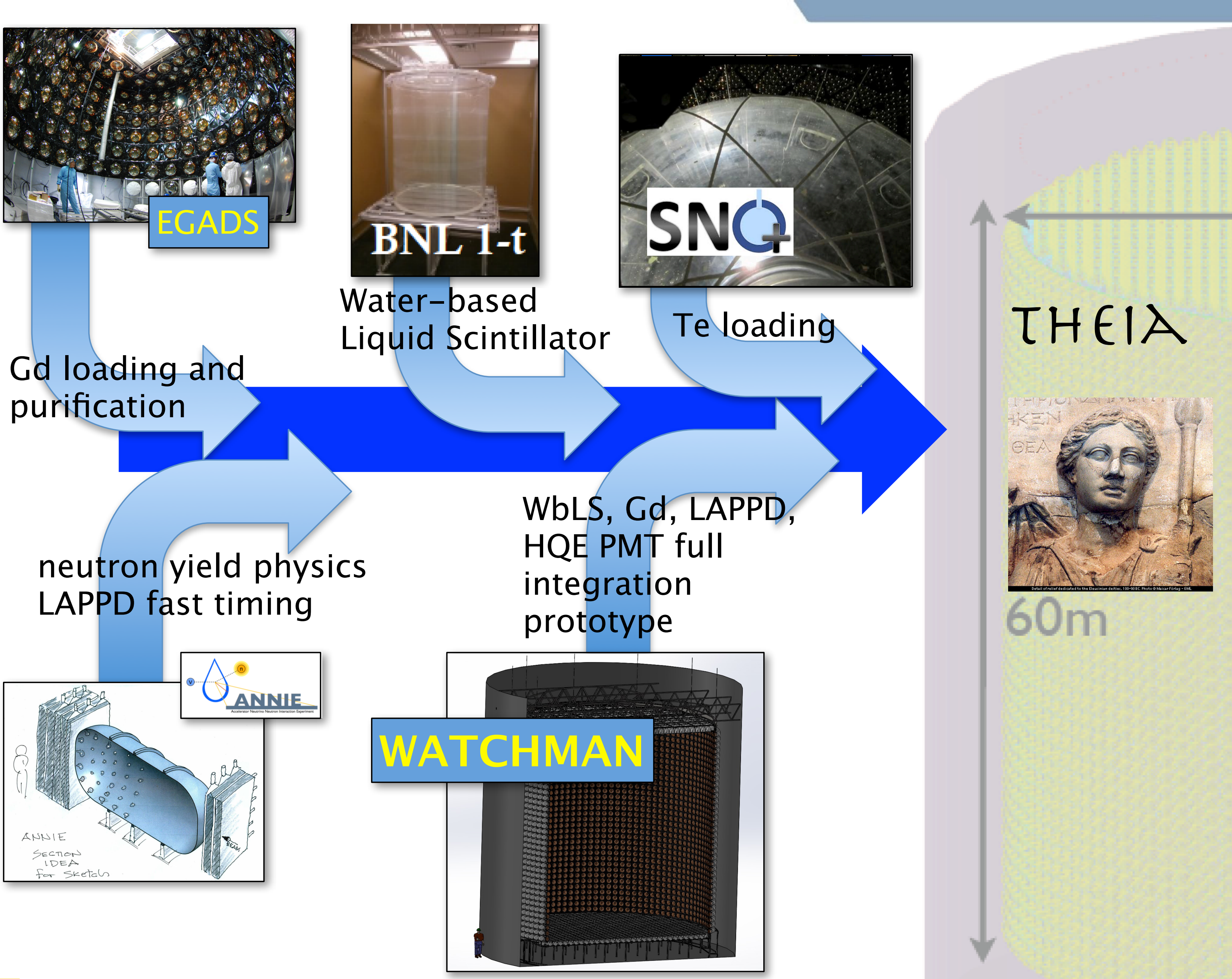


It may be possible to increase light collection through imaging optics, mapping the light onto a smaller surface.

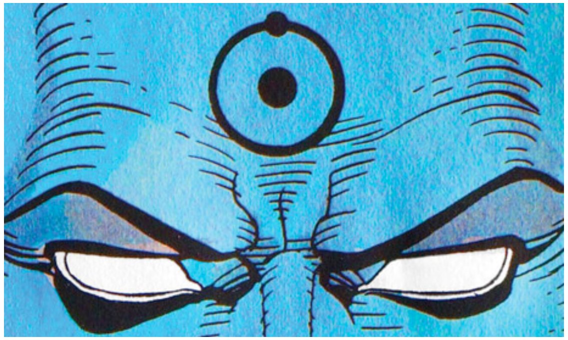
Aqua-RICH

Nuclear Instruments and Methods in Physics Research A 433 (1999) 104}120



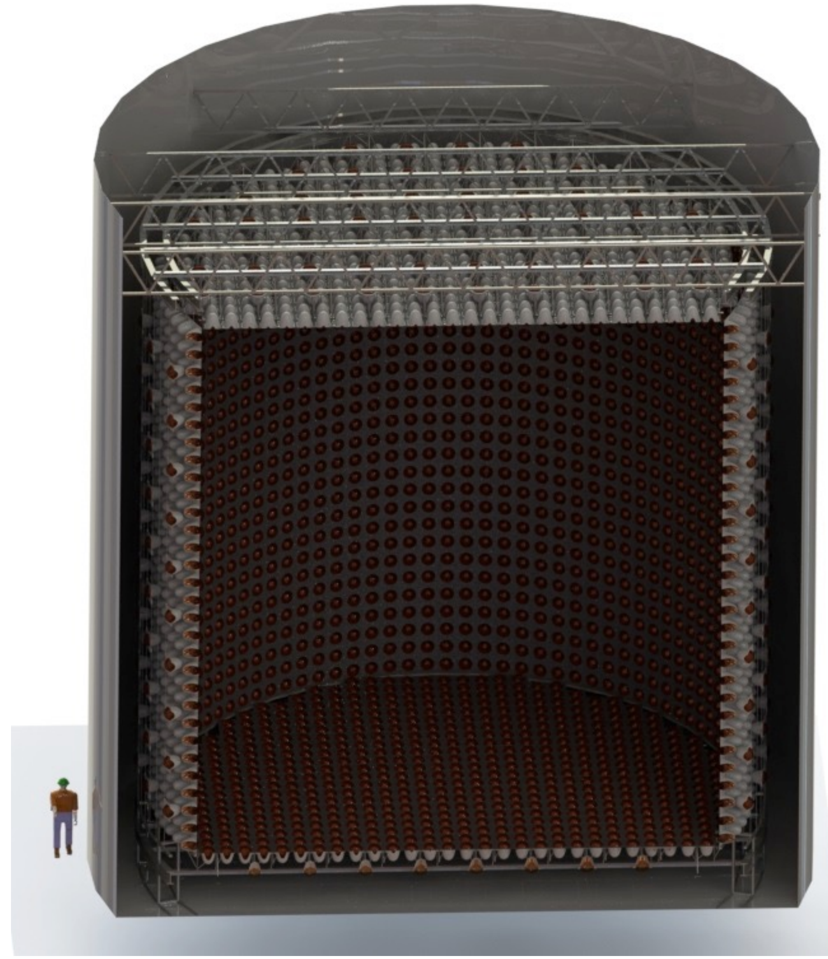

EGADS
BNL 1-t
SNO+
Water-based
Liquid Scintillator
Te loading
Gd loading and
purification
THEIA
60m
neutron yield physics
LAPPD fast timing
WbLS, Gd, LAPPD,
HQE PMT full
integration
prototype
ANNIE
WATCHMAN

WATCHMAN -WATer CHerenkov Monitor of Anti-Neutrinos



A demonstration of remote, neutrino-based reactor monitoring using a Gd-loaded WCh.

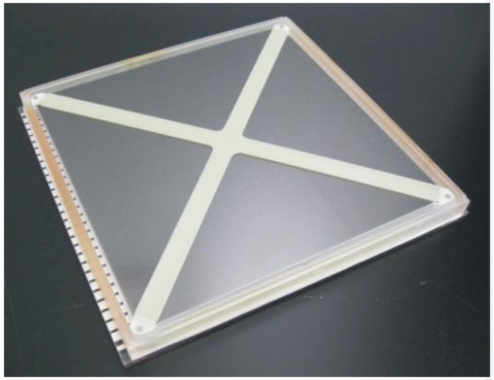
Will be the largest US SN neutrino detector.



Possible oscillation physics program in combination with IsoDar (cyclotron neutrino source).

An opportunity to test LAPPDs in a large scale detector, and with water-based liquid scintillator.

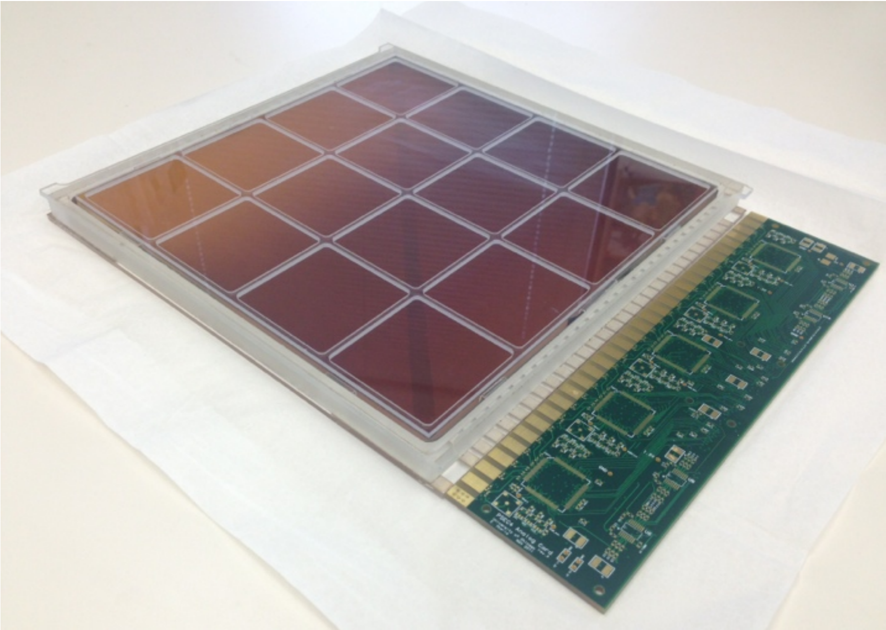
Reinventing the unit-cell of light-based neutrino detectors



- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

What is the LAPPD Concept



LAPPD detectors:

- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:

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

Key Elements of the LAPPD Detector

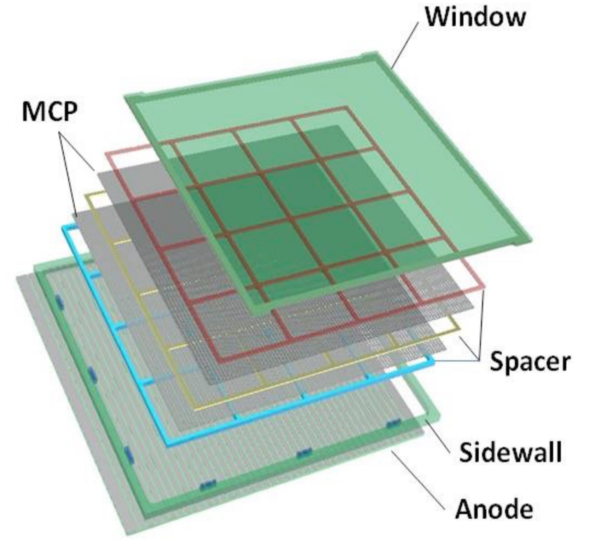
Glass body, minimal feedthroughs

MCPs made using atomic layer deposition (ALD).

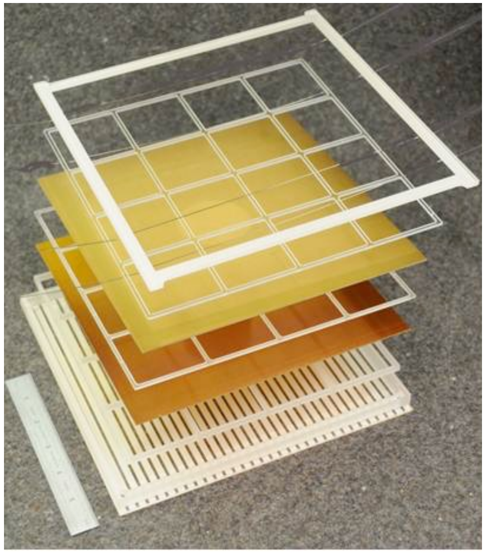
transmission line anode

fast and economical front-end electronics

large area, flat panel photocathodes



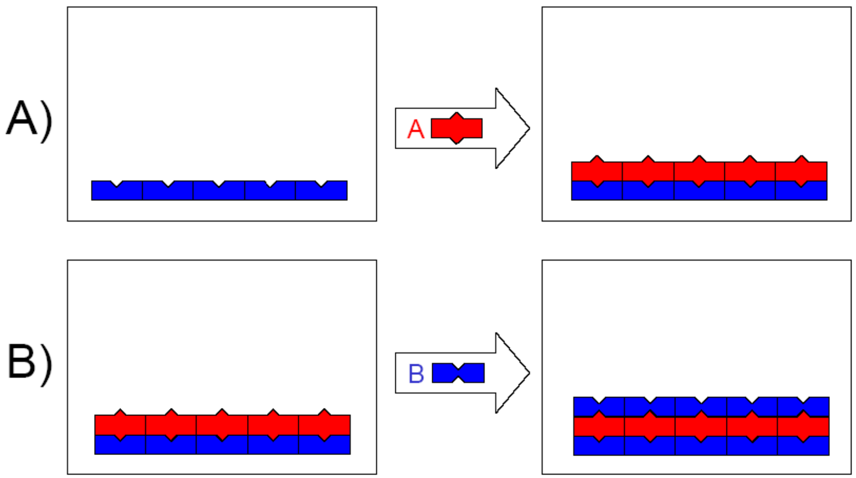
Design Drawing - September 2010



Actual Glass Parts - April 2012

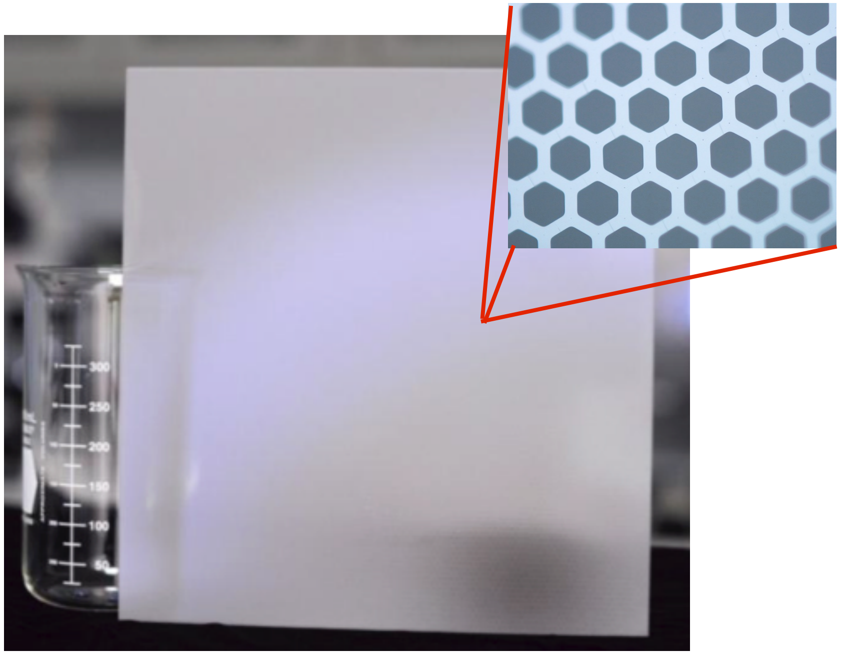
How to Make LAPPDs: Thin Films on Pyrex Glass

Atomic Layer Deposition

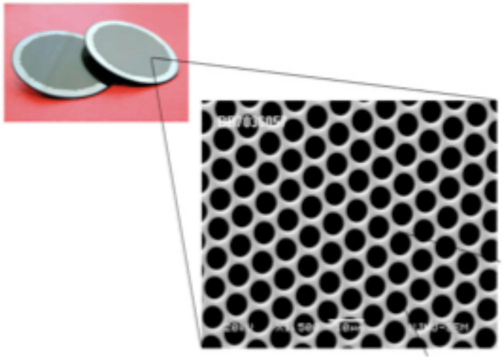


J. Elam, A. Mane

Porous Glass Substrate



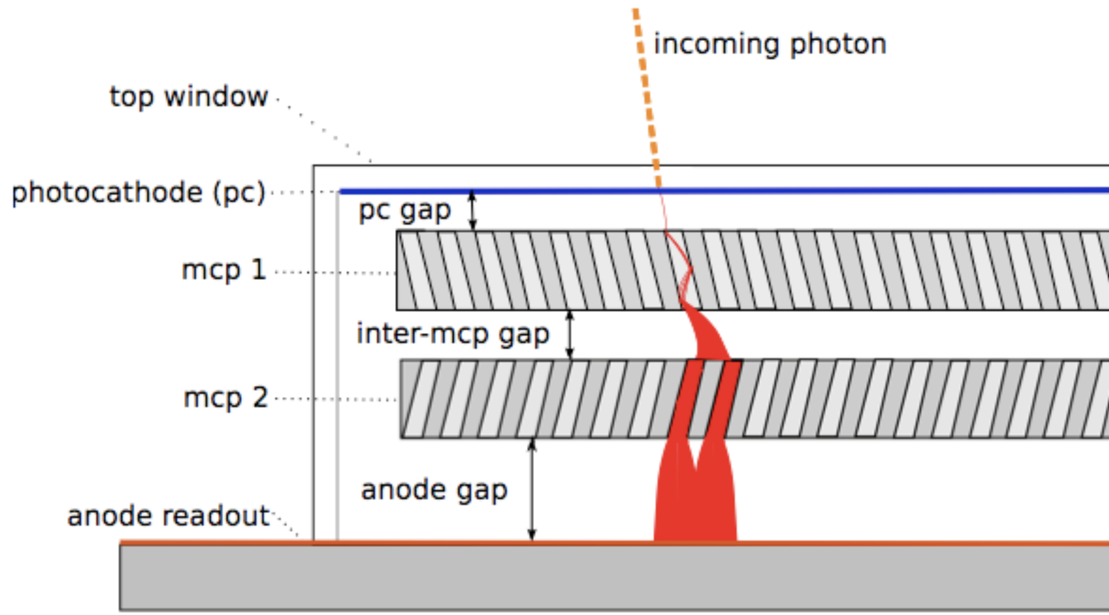
What is an MCP-PMT?



Microchannel Plate (MCP):

- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode

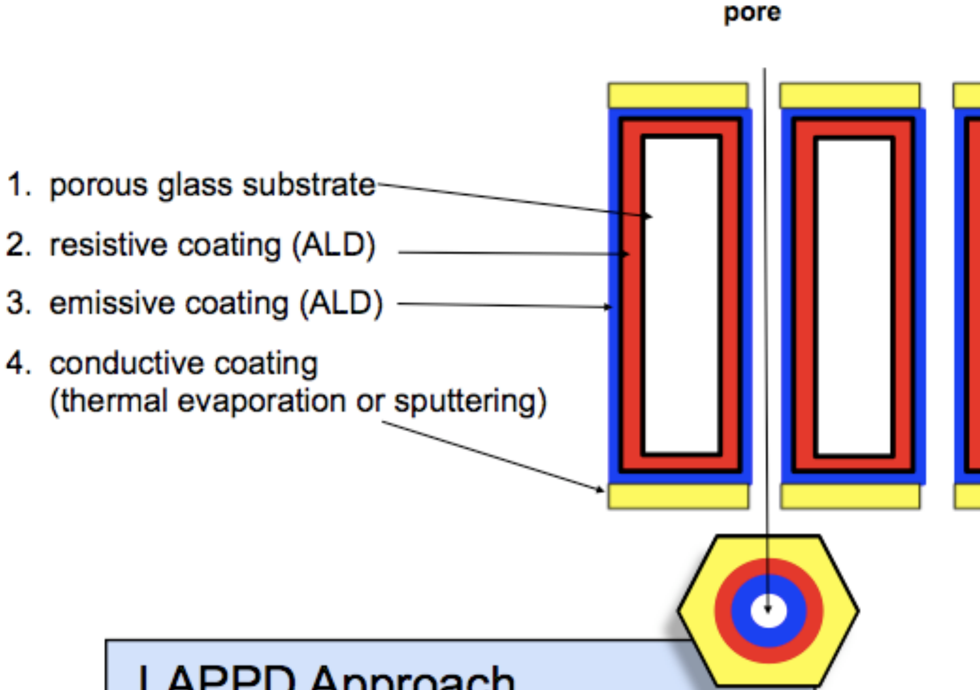


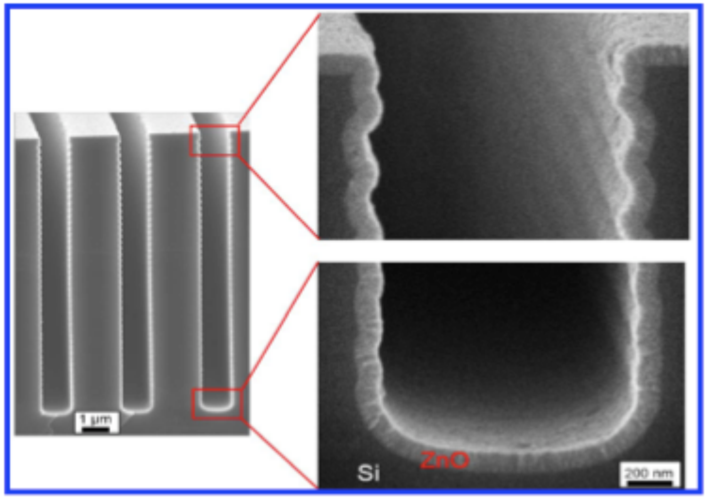
Our Approach

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

Conventional MCP Fabrication

- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material
- Chemical etching and heating in hydrogen to improve secondary emissive properties.
- Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties. (Problems with thermal run-away).





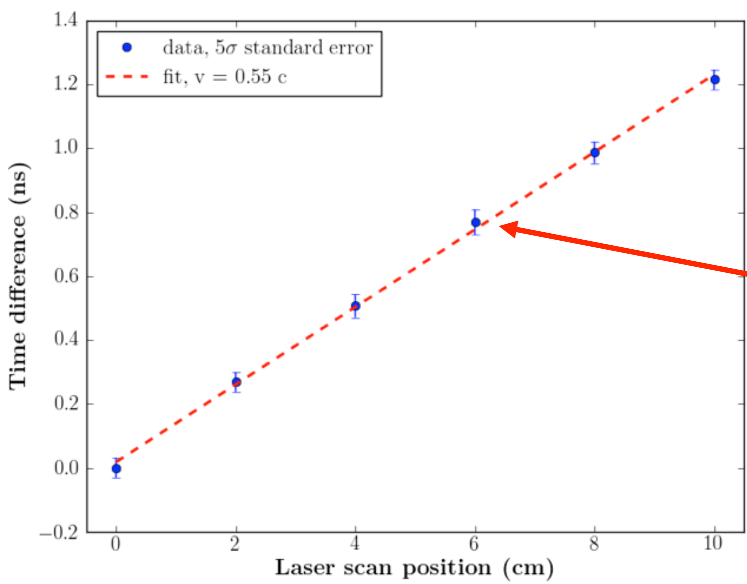
LAPPD Approach

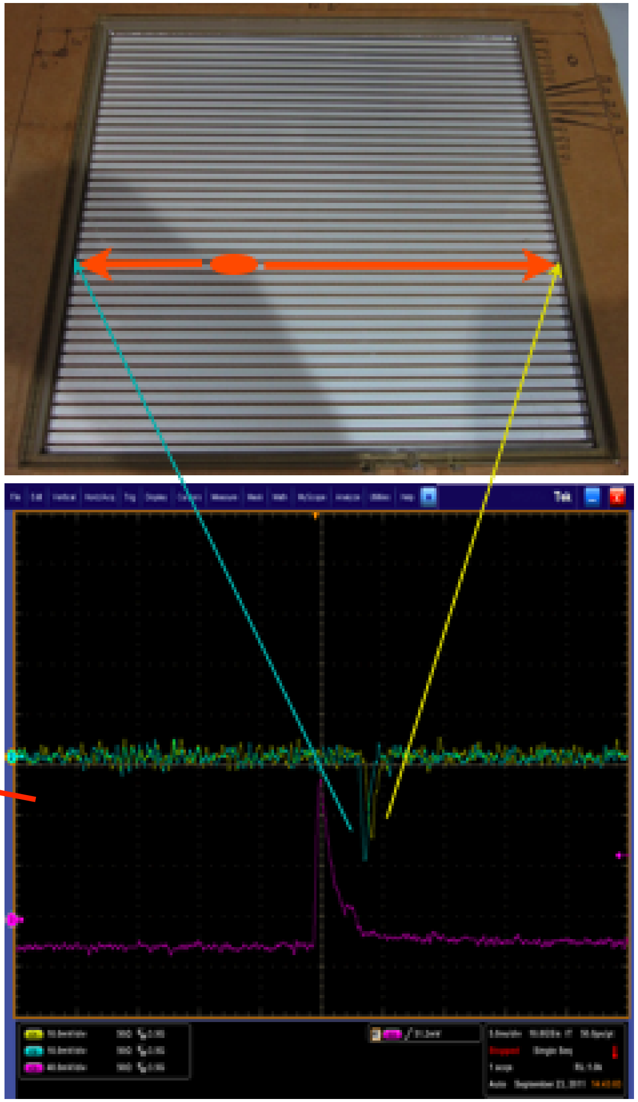
- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

Anode Design: Delay Lines

Channel count (costs) scale with length, not area
Position is determined:

- by charge centroid in the direction perpendicular to the striplines
- by differential transit time in the direction parallel to the strips



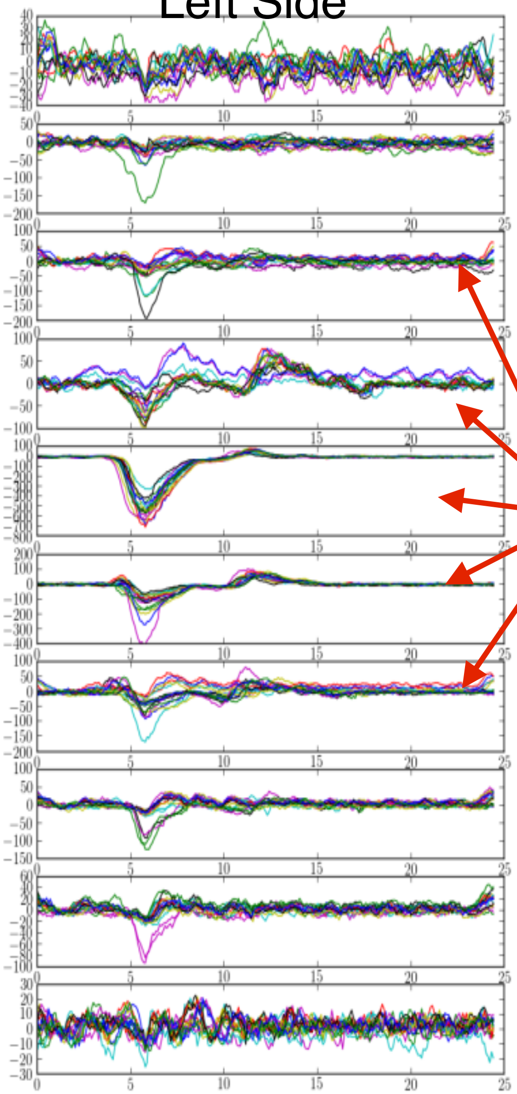


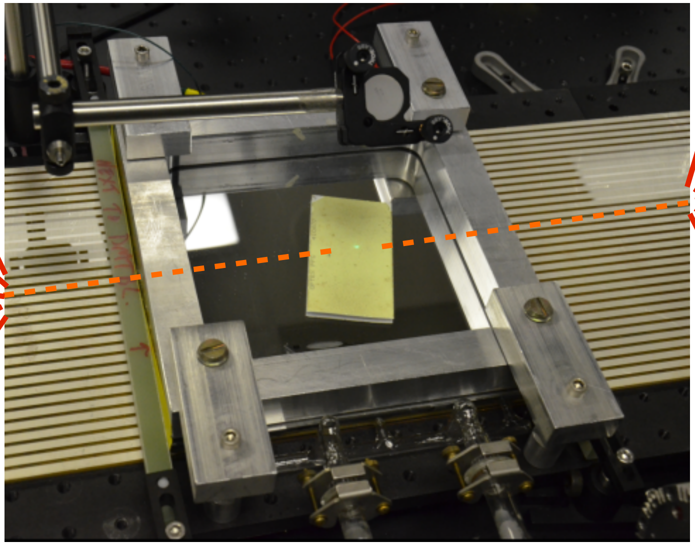
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Anode design

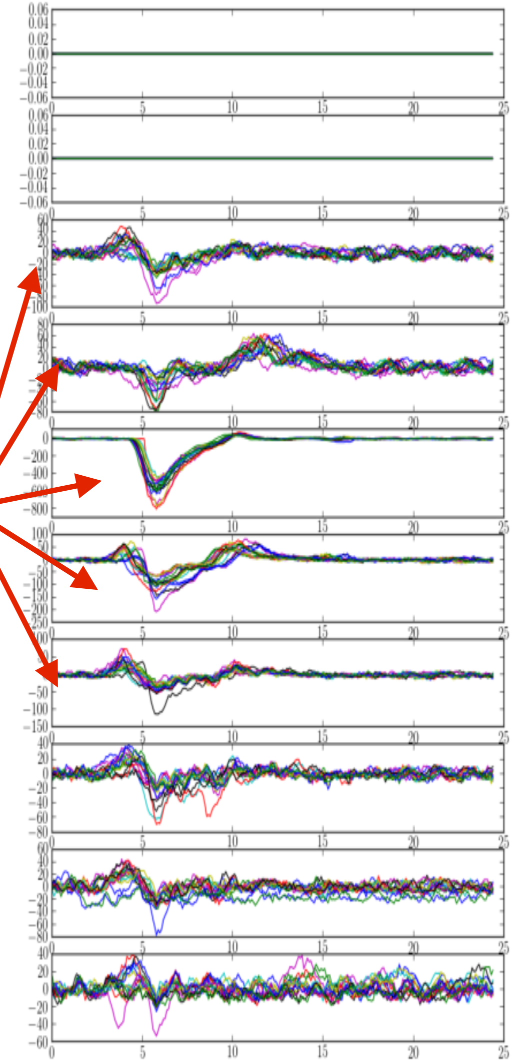
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





Credit: Eric Oberla

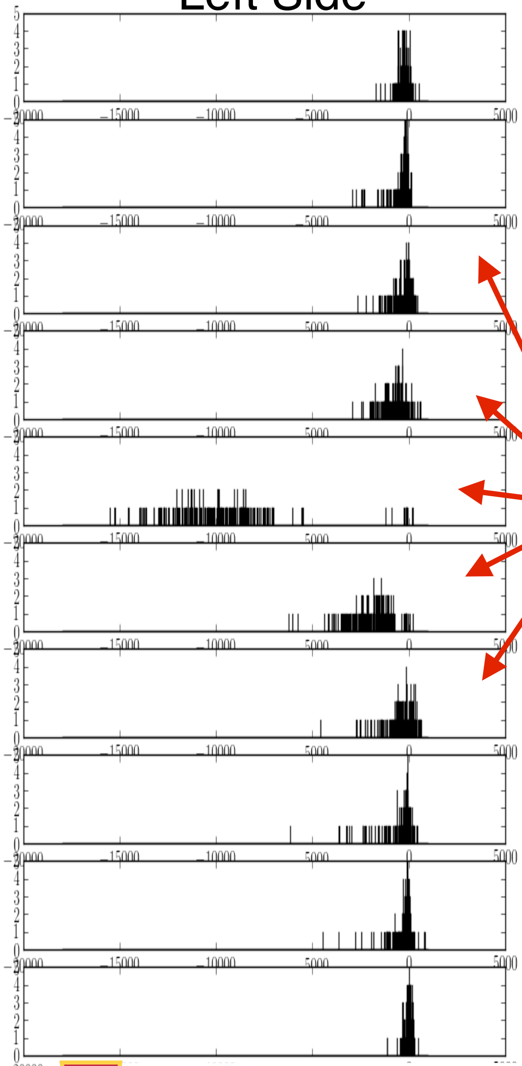


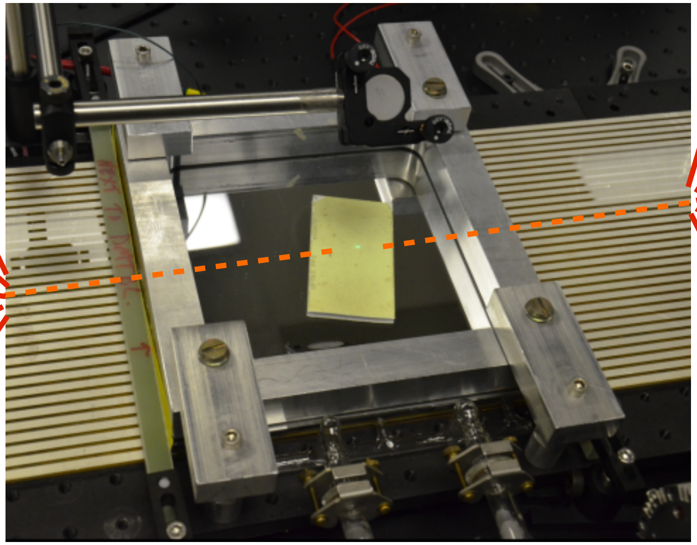
Right Side
Pulses on 10 striplines

Anode design

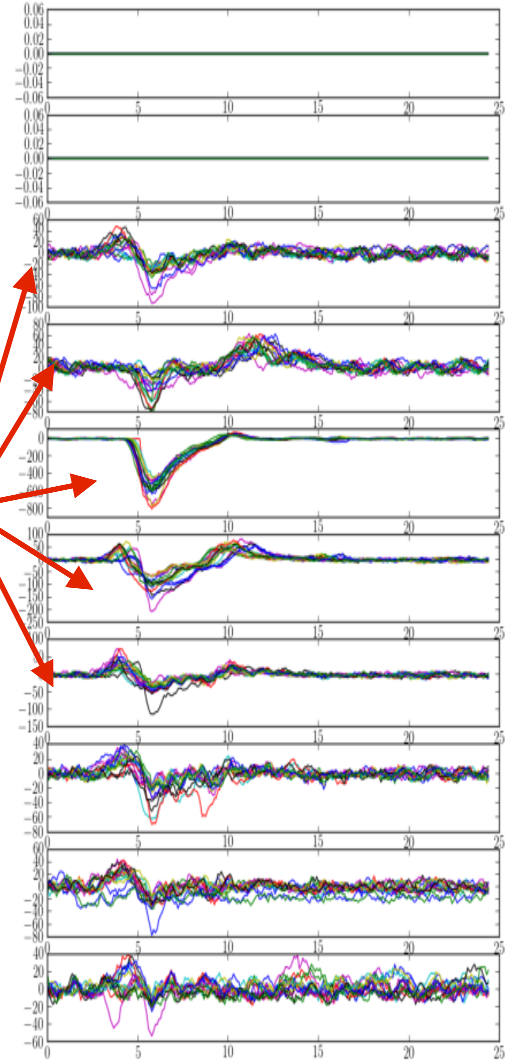
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulse Heights (ADC counts)
Left Side



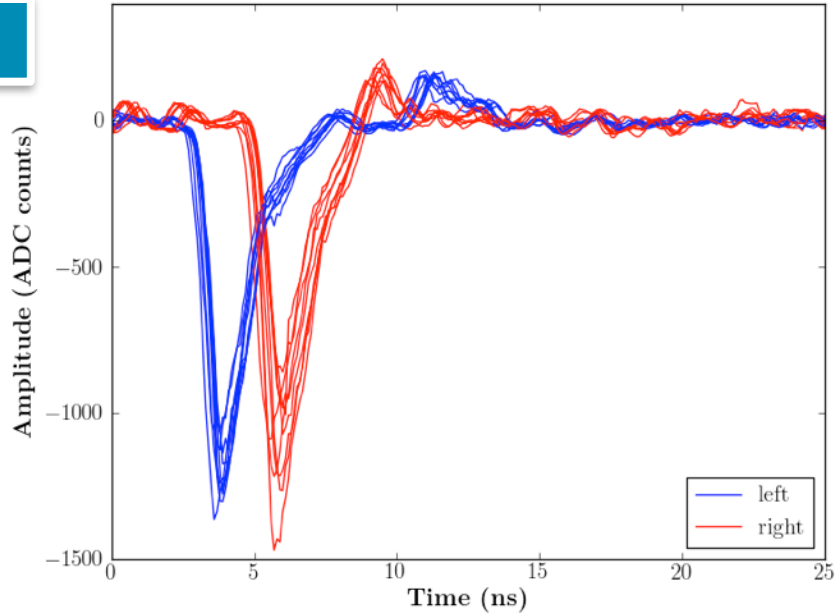


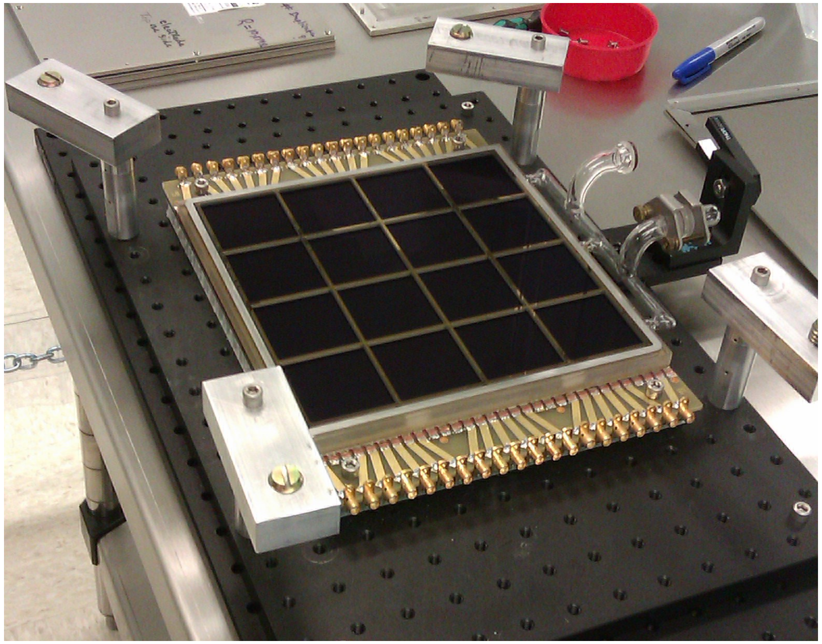
Credit: Eric Oberla

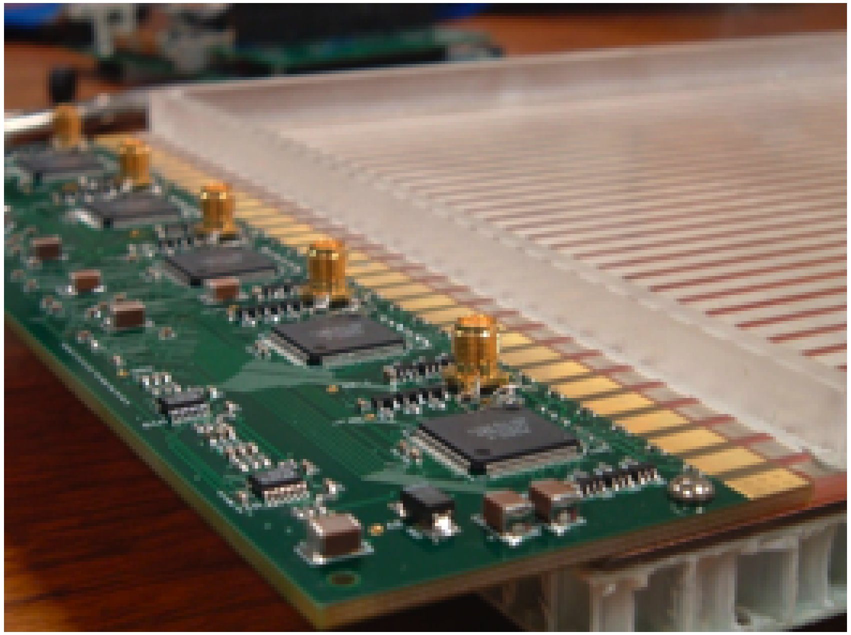


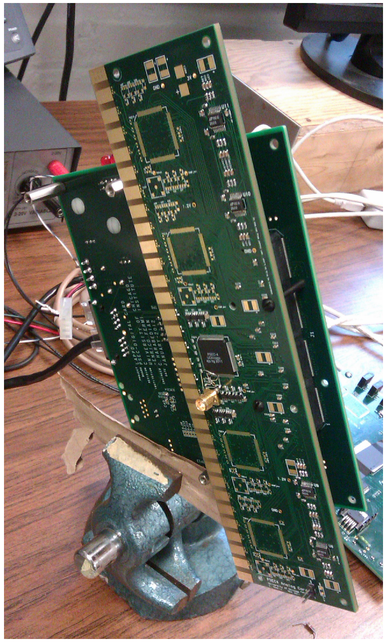
Right Side
Pulses on 10 striplines

LAPPD





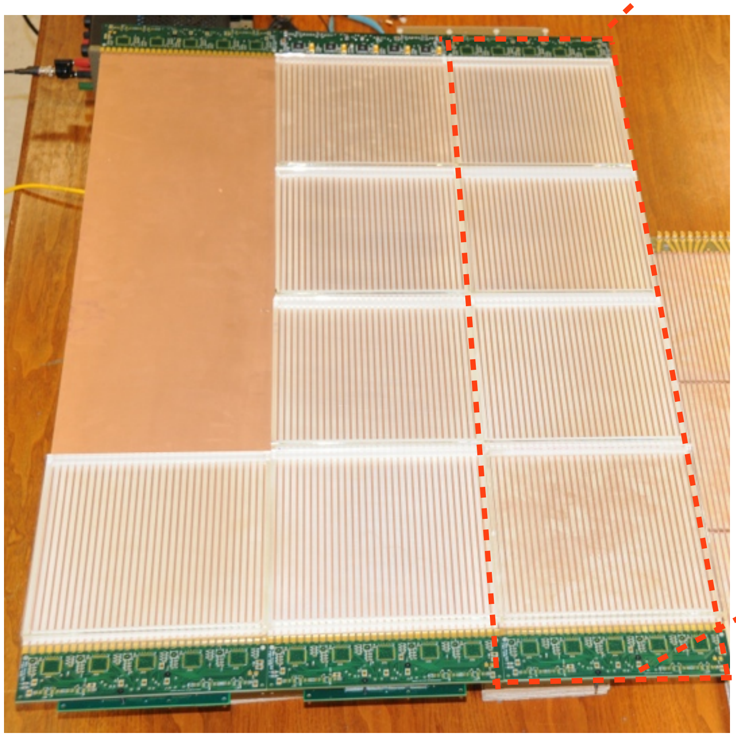


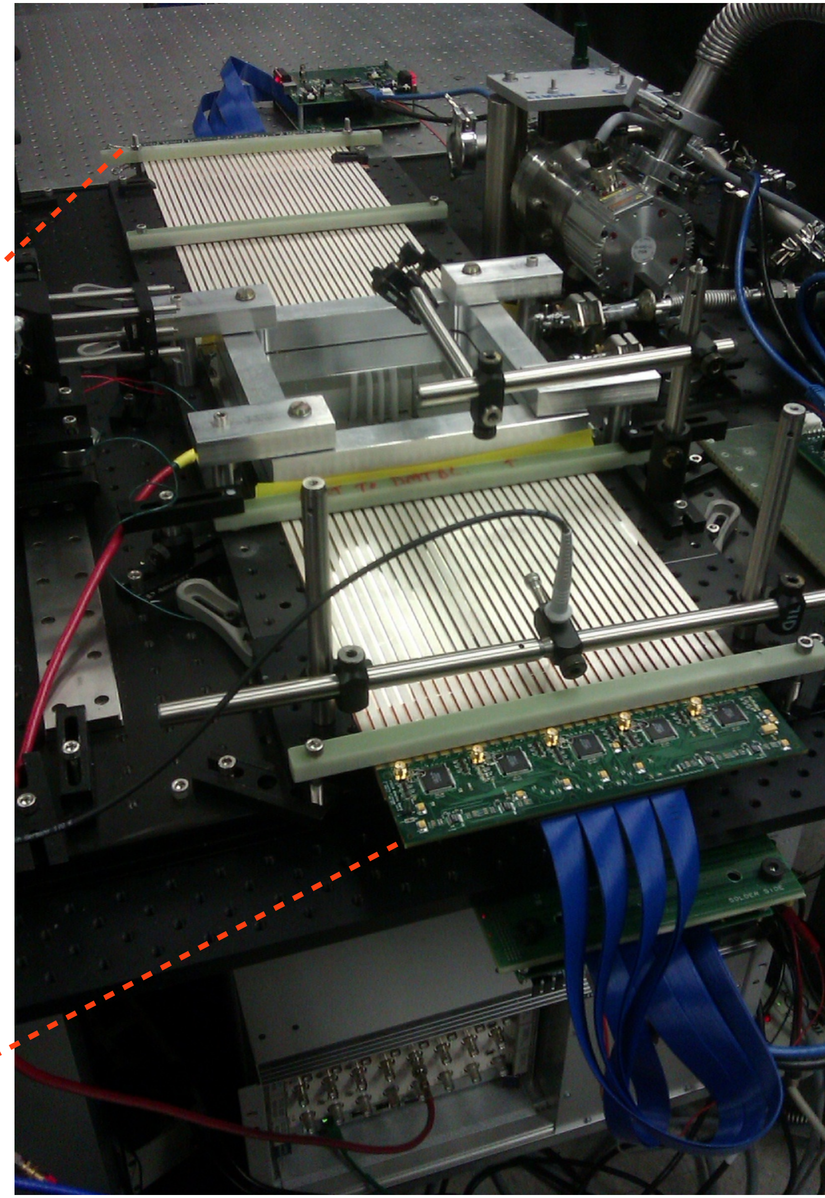


- LAPPD Goal of building a **complete detector system**, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes (“demountable detectors”) with resealable top window, robust aluminum photocathode

“SuMo Slice”

We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system (“SuMo slice”).





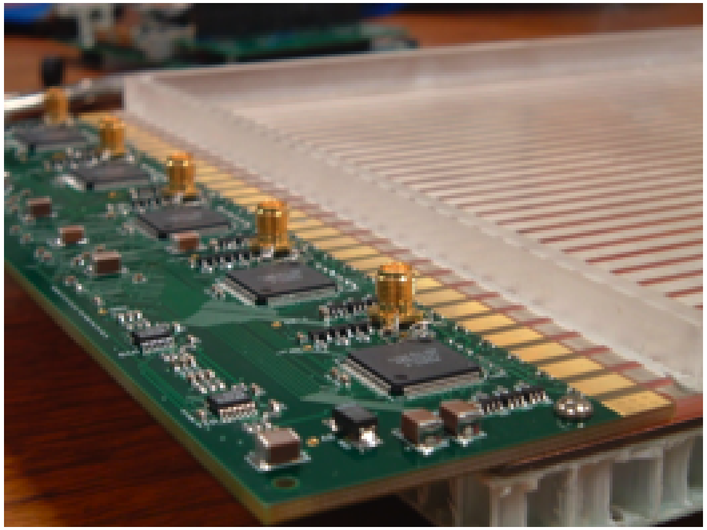
Front-end Electronics

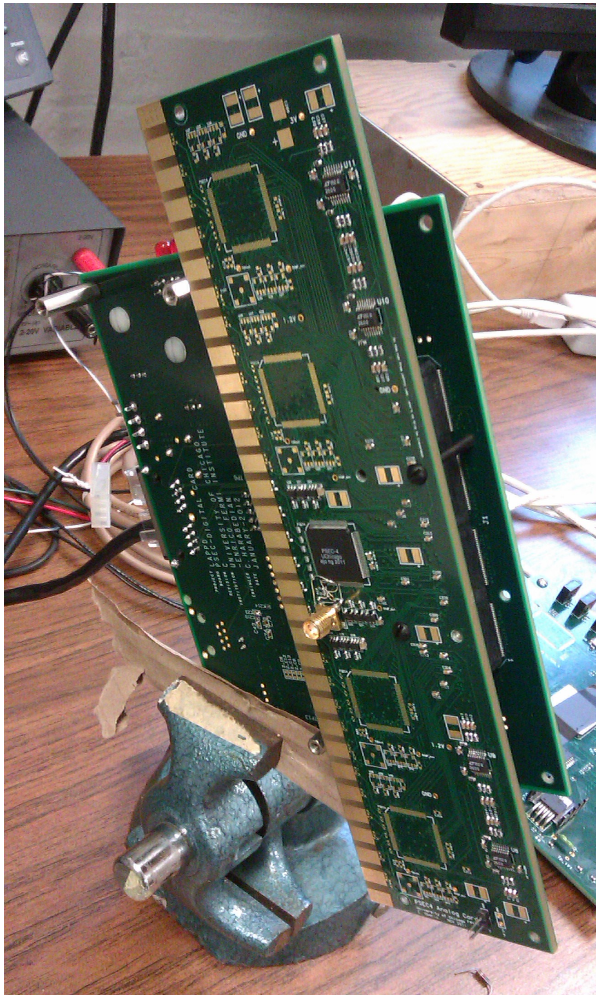
PSEC4 chip: a CMOS-based, low power, waveform sampling chip

- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

LAPPD project covered the whole system, including readout electronics

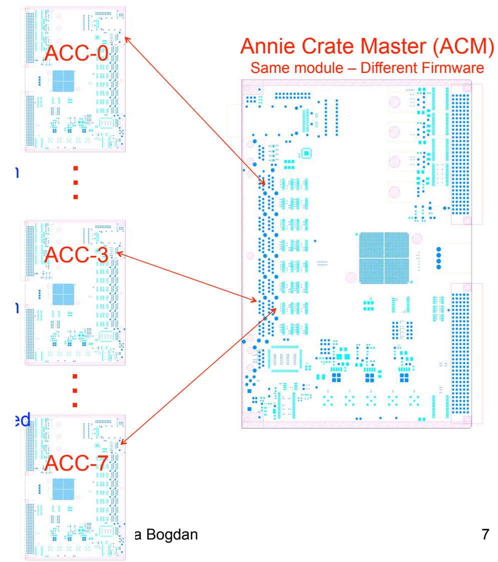
- 180 ch systems have been operated on a test beam.
- The system is being used by a number of groups in several areas of physics.



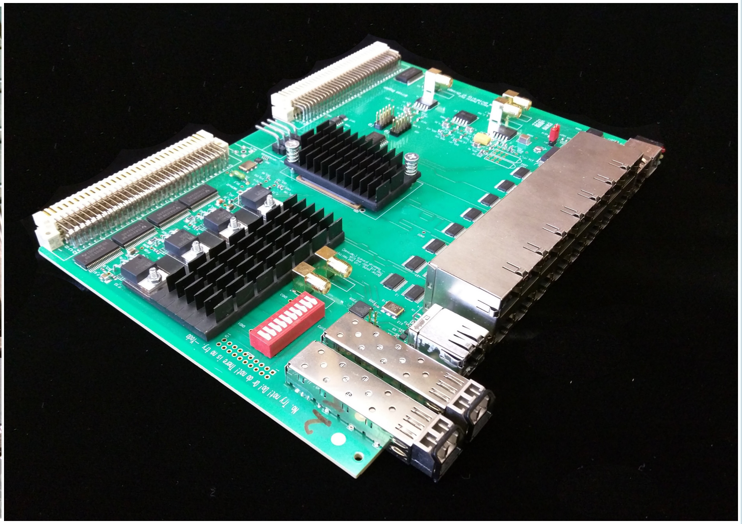


PSEC electronics

- New ANNIE Central Card (ACC) allows the readout of systems with large numbers of LAPPDs (or PMTs).
- Use a similar architecture to the 500 MHz UC cards and will integrate nicely
- We now have 2 ACC cards and the largest single stockpile of PSEC4 chips.



- Work is underway to finish the firmware and merge into our DAQ system.
- Will be tested with 6cm MCPs, this year.



PSEC4 ---> PSEC4a :: overview

credit: E Oberla (UC)

Parameter	PSEC4	PSEC4a
Channels	6	6
Sampling Rate	4-15 GSa/s	2-11 GSa/s
Primary Samples/channel	256	256
Total Samples/channel	256	1024 (or 2048?)
Recording Buffer Time at 10 GSa/s	25.6 ns	100 (or 200) ns continuous OR 4x (or 8x) 25 ns snapshots [*Multi-hit buffering*]
Analog Bandwidth	1.5 GHz	~same, perhaps extended slightly
RMS Voltage Noise	700 μV	~same
DC RMS Dynamic Range	10.5 bits	~same
Signal Voltage Range	1 V	~same (+extend linearity)
ADC on-chip	yes	yes
ADC Clock Speed	1.4 GHz	2 GHz
Readout Protocol	12-bit parallel	same or each ADC bank w/ serial link
Readout Clock Rate	40 MHz	~same or 600MHz serial rate
Average Power Consumption	100 mW	~similar, (higher when ADC running non-stop)
Core Voltage	1.2 V	same, though option to run analog voltage up to 1.4V for more signal range

Main improvement is the moderate increase in sample length = the ability to *multi-hit buffer events that are close in time*. PSEC4a will be able to sample/digitize/readout simultaneously.

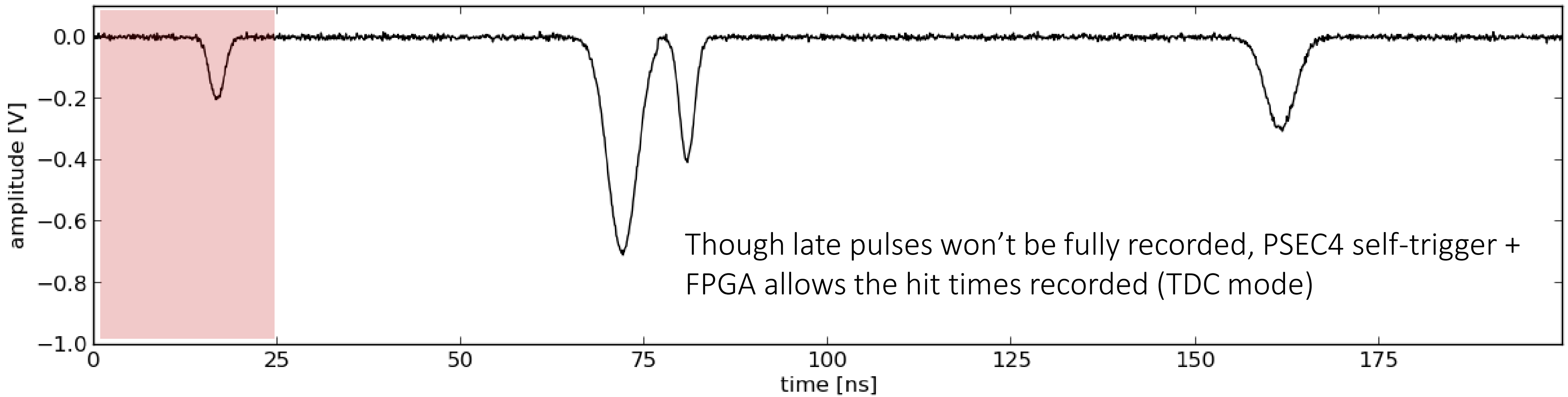
→ **Enables dead-time less operation for a certain experimental event rate (CW+burst)**

PSEC4 -----> PSEC4a

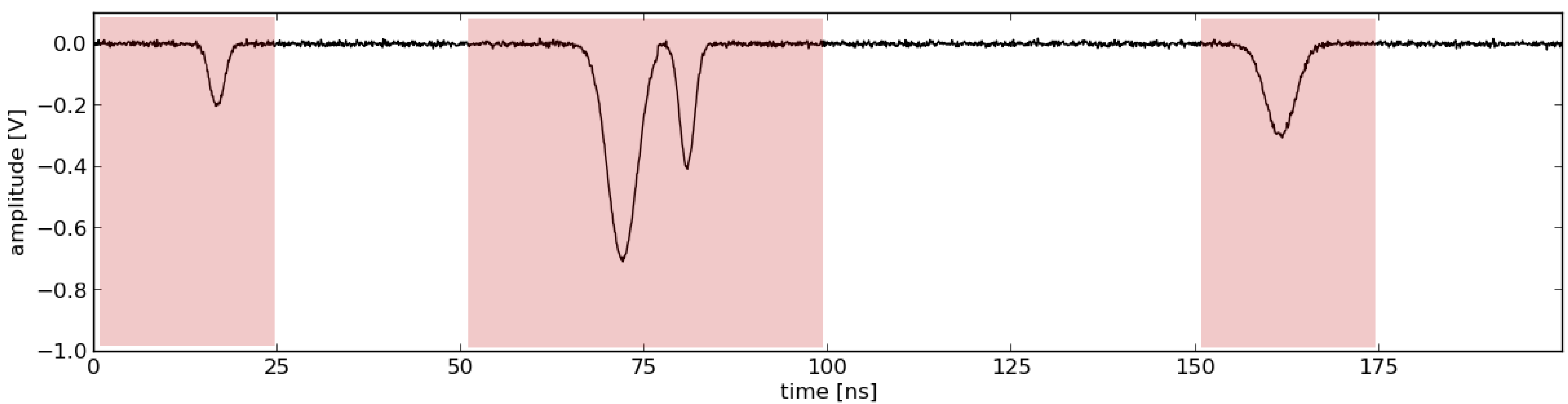
credit: E Oberla (UC)

- Fix the primary PSEC4 limitation: sample depth at 10 GSa/s

PSEC4: red = acquired



PSEC4a: red= acquired

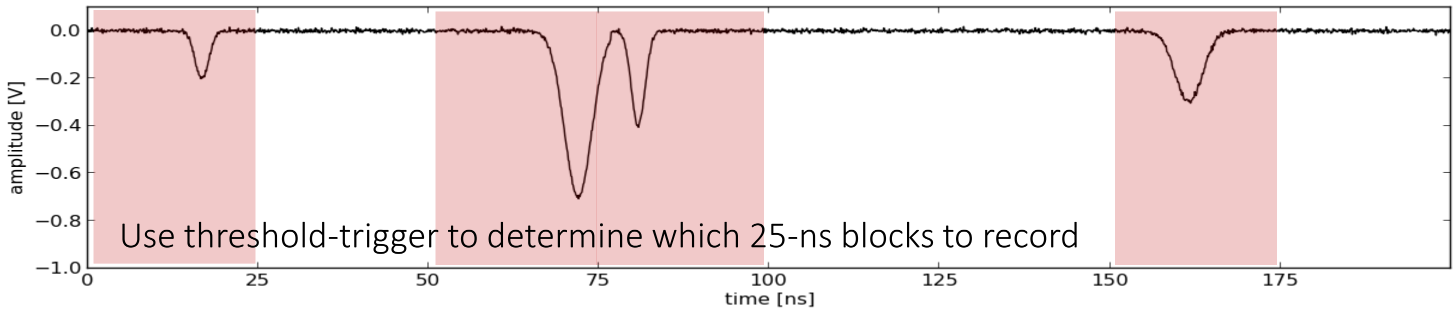


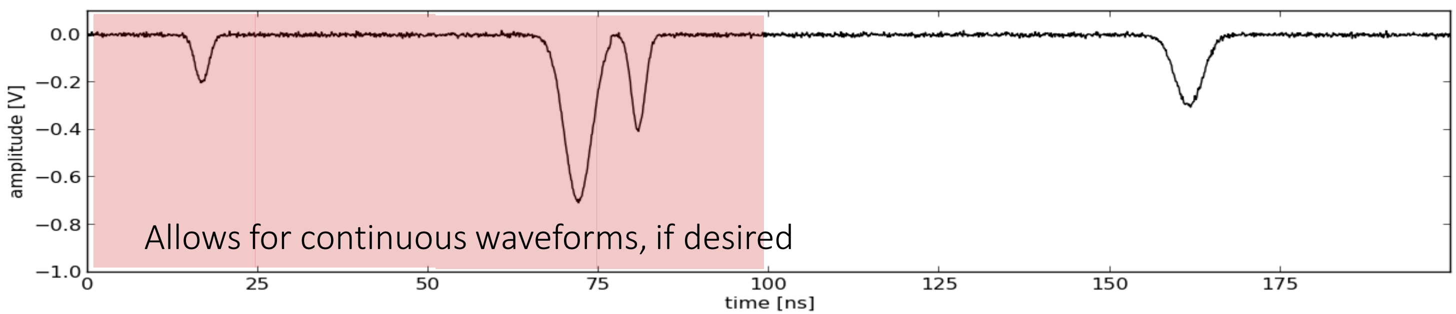
PSEC4a – multi-hit buffering

credit: E Oberla (UC)

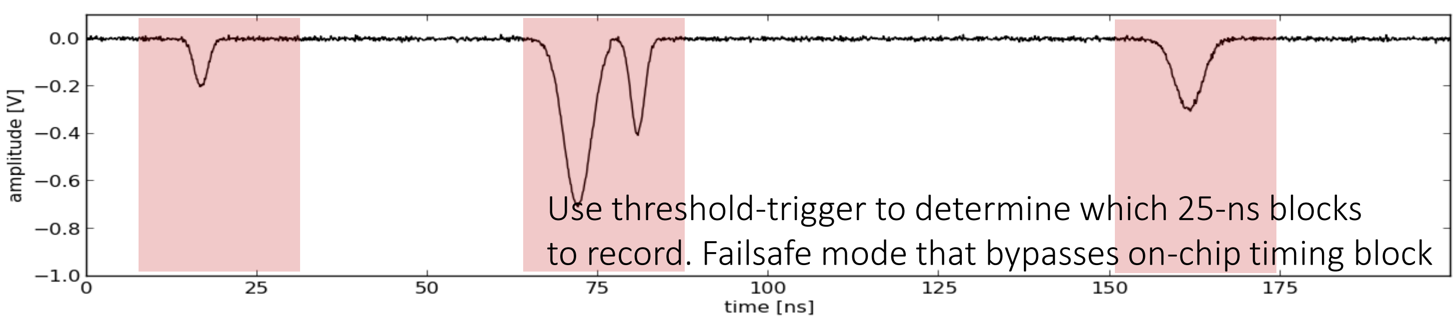
- How many buffers? Considering 2 options: 1024 or 2048 samples per channel
  - Layout space ($) / number of ADC's trade-off vs. typical event occupancy/timing characteristics
- Operation modes:

Clocked addressing: blocks around 40 MHz sample clock. Blocks time-stamped on ASIC





'Trigger-and-transfer': asynchronous blocks, 25 ns wide. (PSEC4-like operation, w/ multi-buffer)



PSEC Costing

PSEC4 chip*

purchased in lots of 40 chips

bulk price/lot (~30 Lots): $3000

price per chip: $75

price per channel: $12.50

	#channels	unit price
ACDC-cards (based on PSEC4)	30	$1,200.00
ANNIE Central Cards	240	$2,500.00

*estimate is for the PSEC4, not the 4A

Full Track Reconstruction: A TPC Using Optical Light?

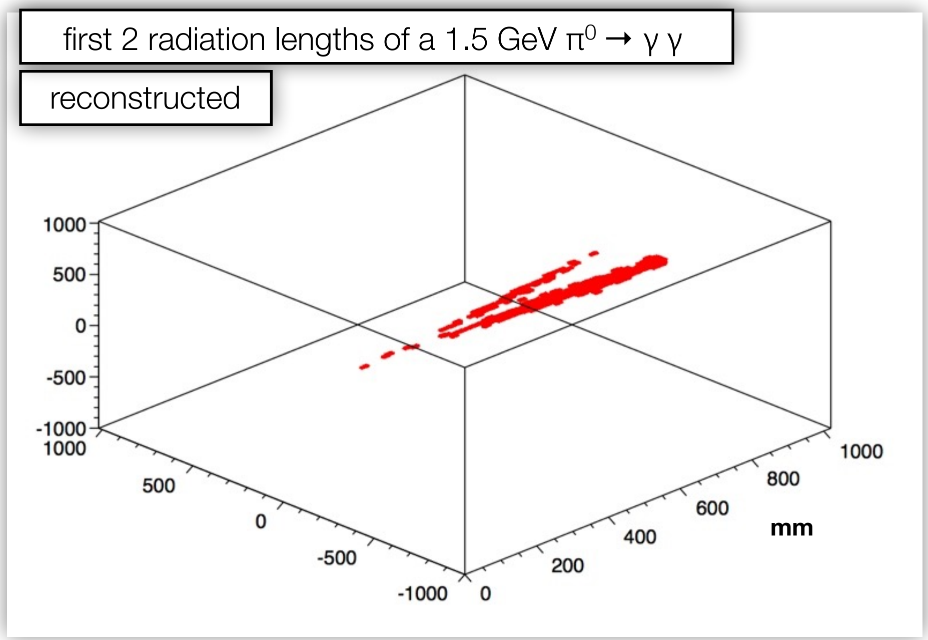


Image reconstruction, using a causal "Hough Transform" (isochron method)

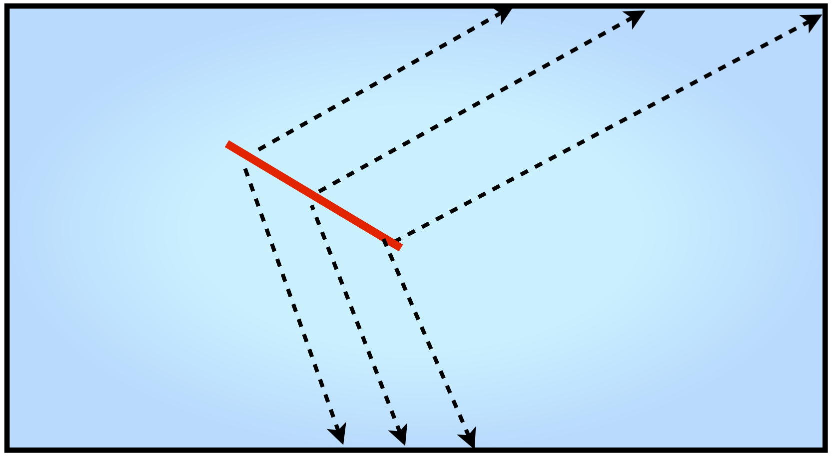
(see ANT13 LAPPD talk)

(see ANT13 mTC talk)

"Drift time" of photons is fast compared to charge in a TPC!

~225,000mm/microsecond

Need fast timing and new algorithms



Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

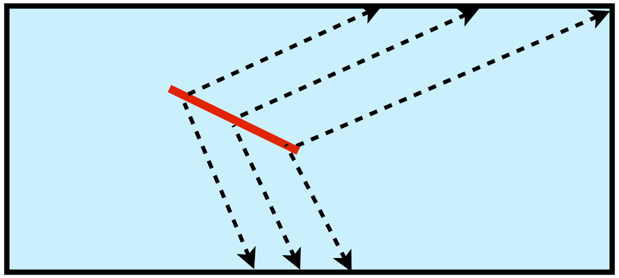
~20 photons/mm (Cherenkov)

2. “Drift time” (photon transit time)

~225,000mm/microsecond

3. Topology

drift distances depend on track parameters



4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation? Chemical enhancement

2. “Drift time” (photon transit time)

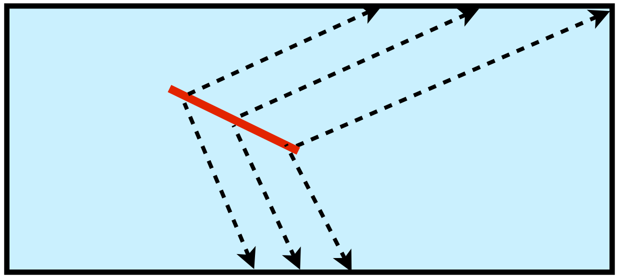
~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution**.

3. Topology

drift distances depend on track parameters

This presents some reconstruction challenges, but not unconquerable.

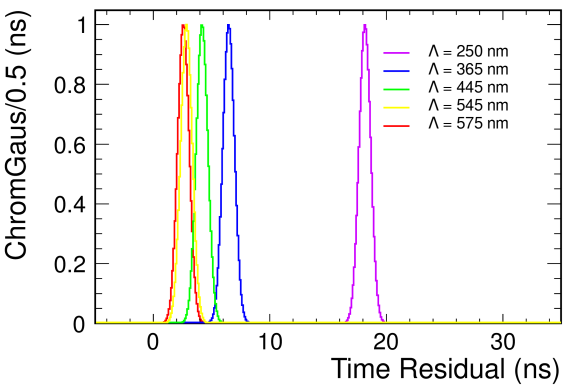


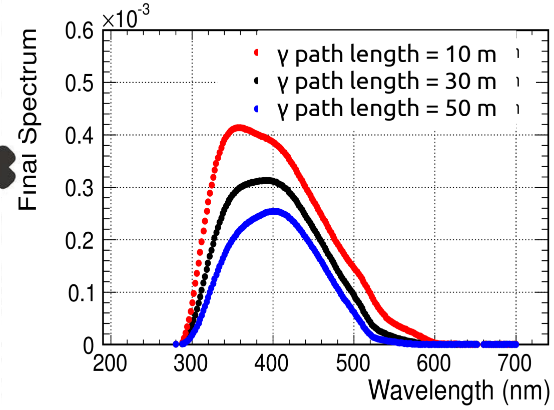
4. Optical Transport of light in water

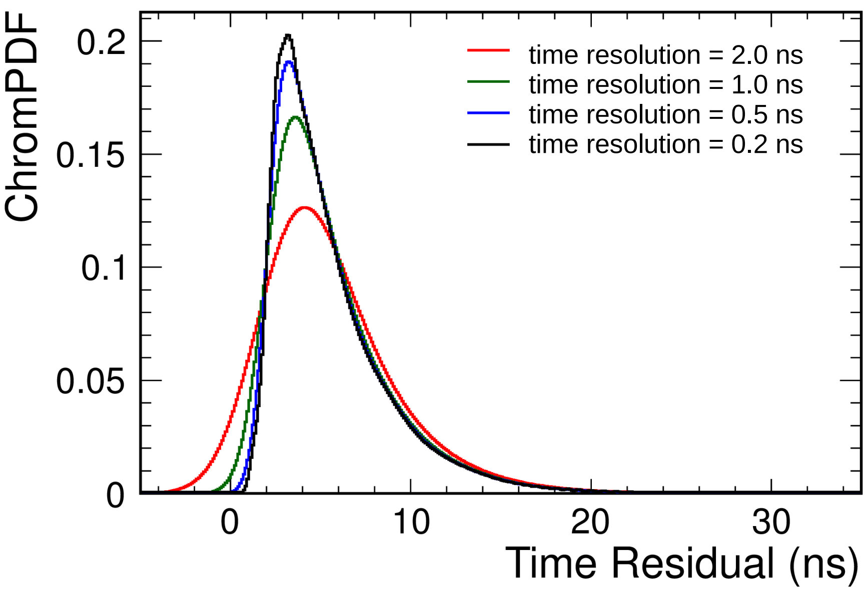
Appropriate reconstruction techniques are needed.

"Simple Vertex" Reconstruction

- A timing residual-based fit, assuming an extended track.
- 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 MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.







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

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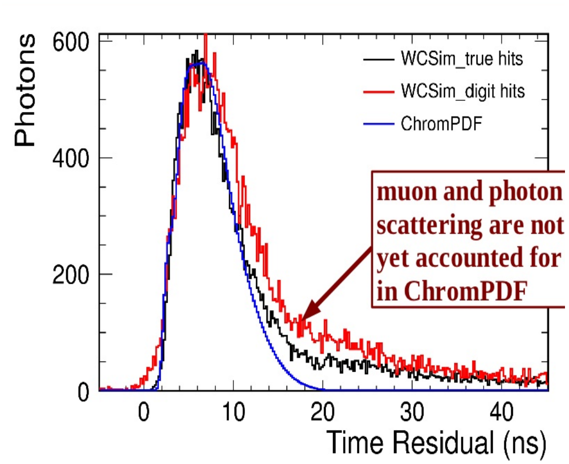
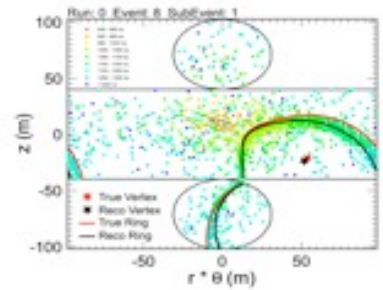
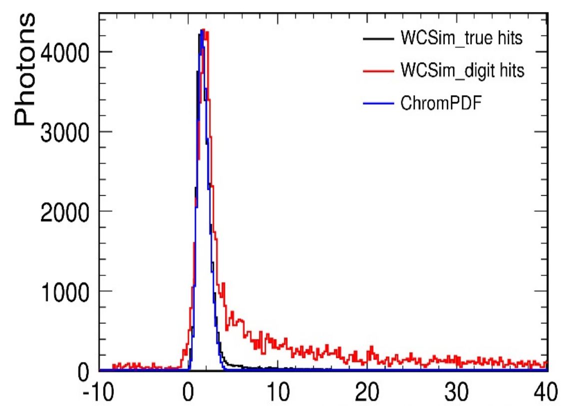
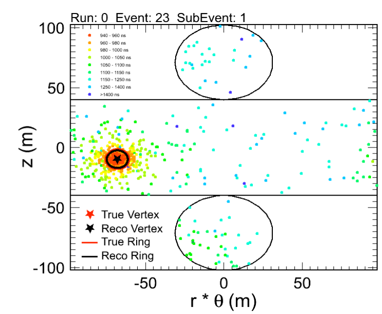






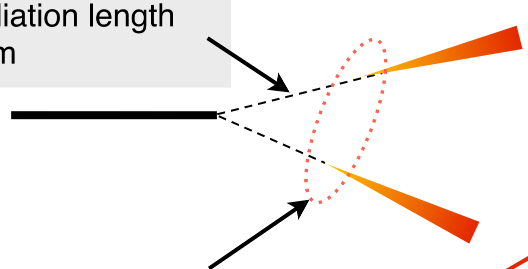


Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Simple Vertex Reconstruction

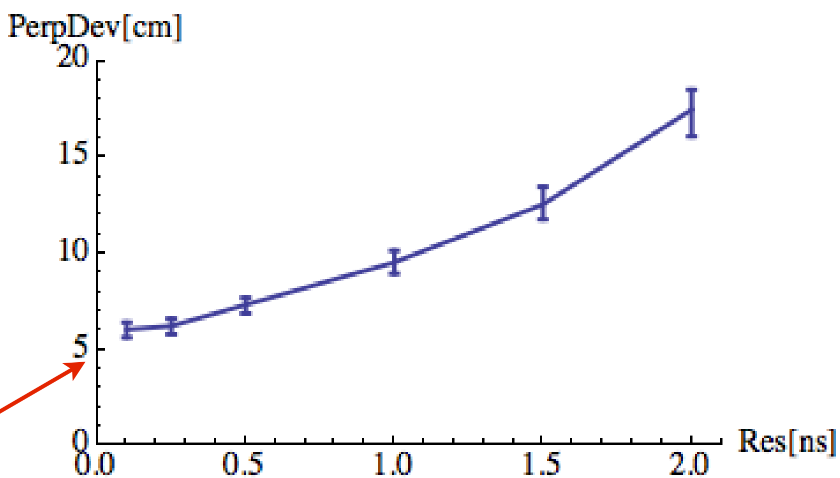
- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.
- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.

~1 radiation length
~37 cm



vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

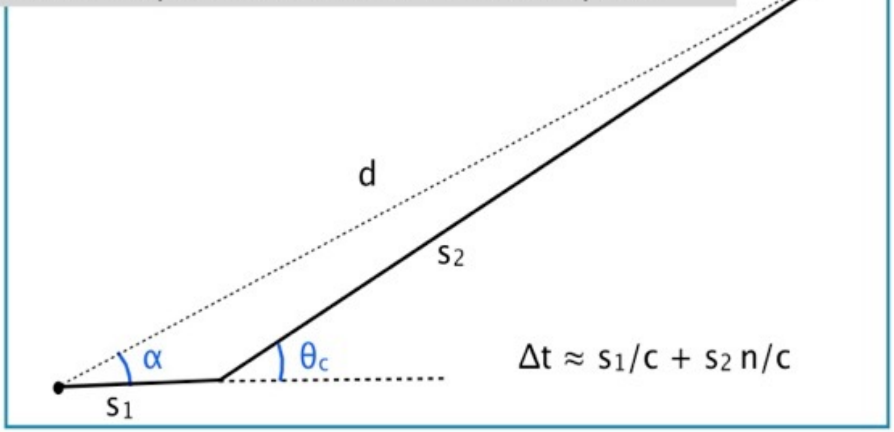
Optical TPCs are scalable to 100s of kilotons



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

Isochron

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



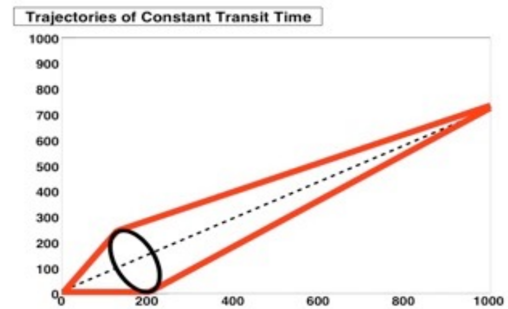
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

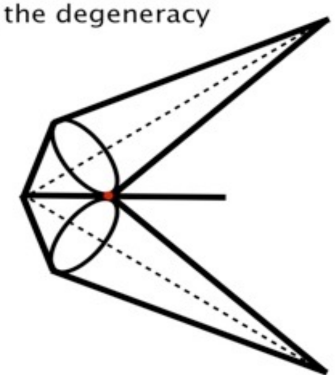
but there are two constraints:

$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

For a single PMT, there is a rotational degeneracy (many solutions).



But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy



M. Wetstein

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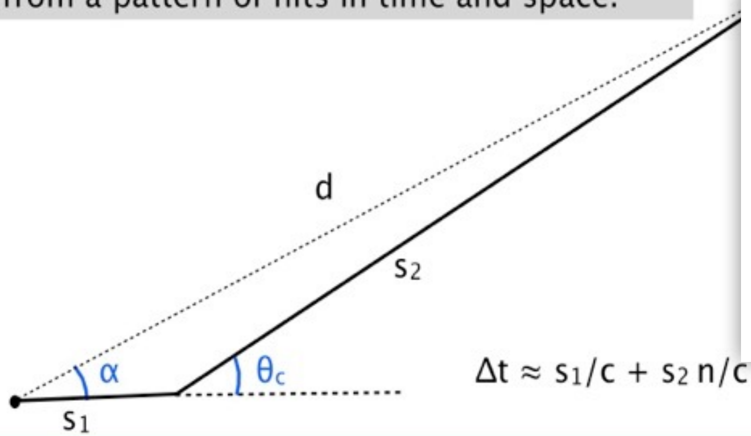

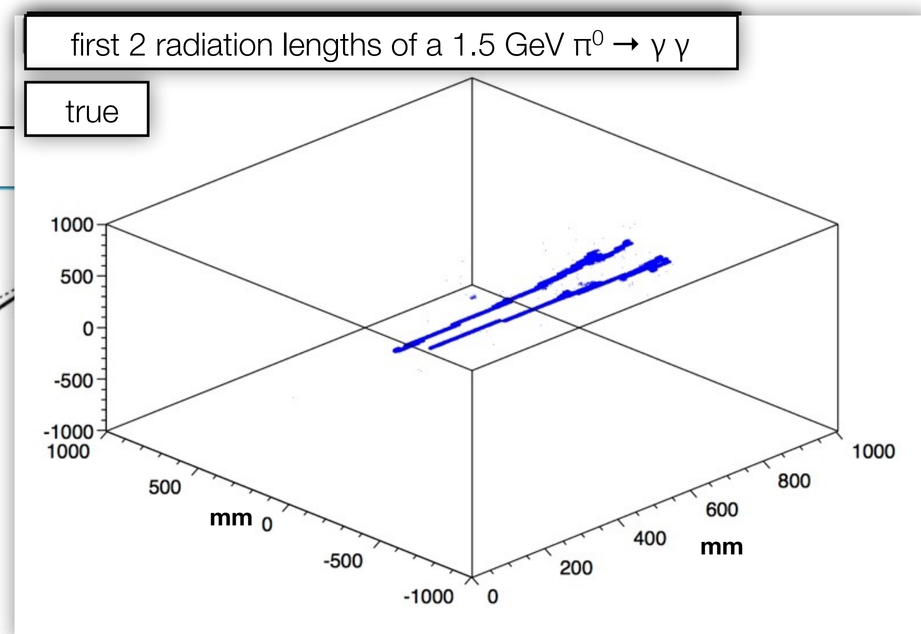

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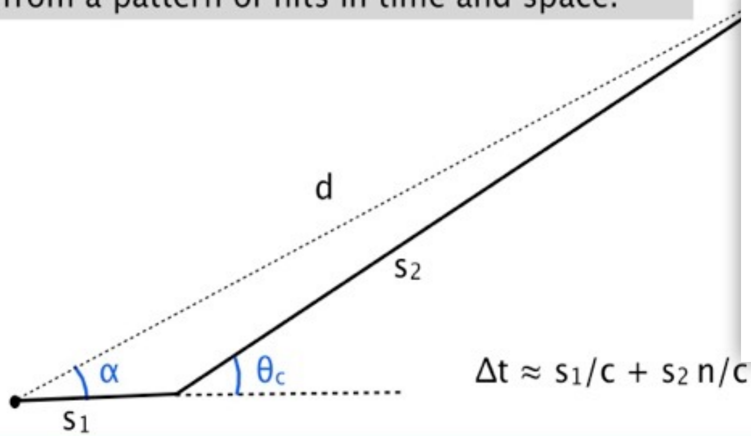

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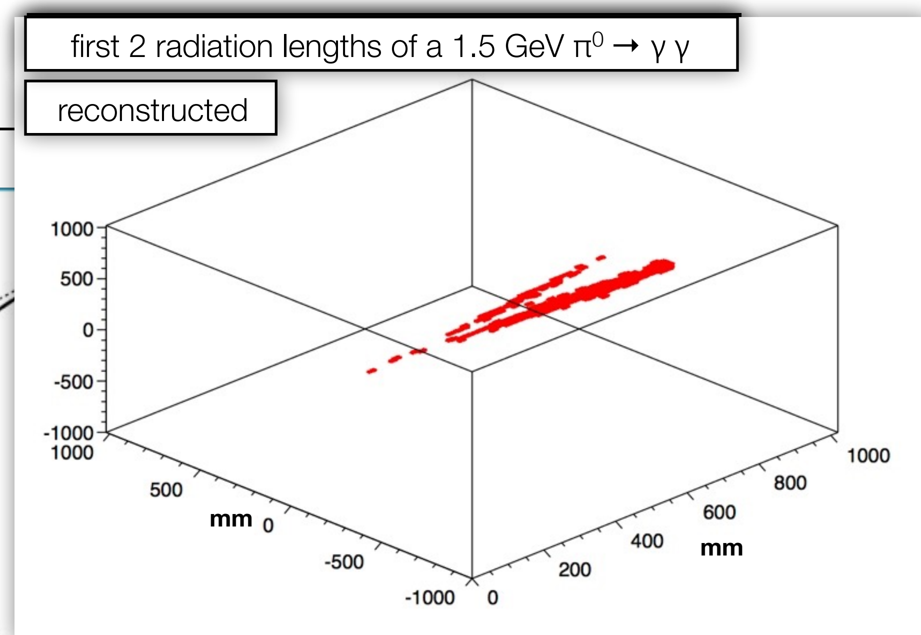
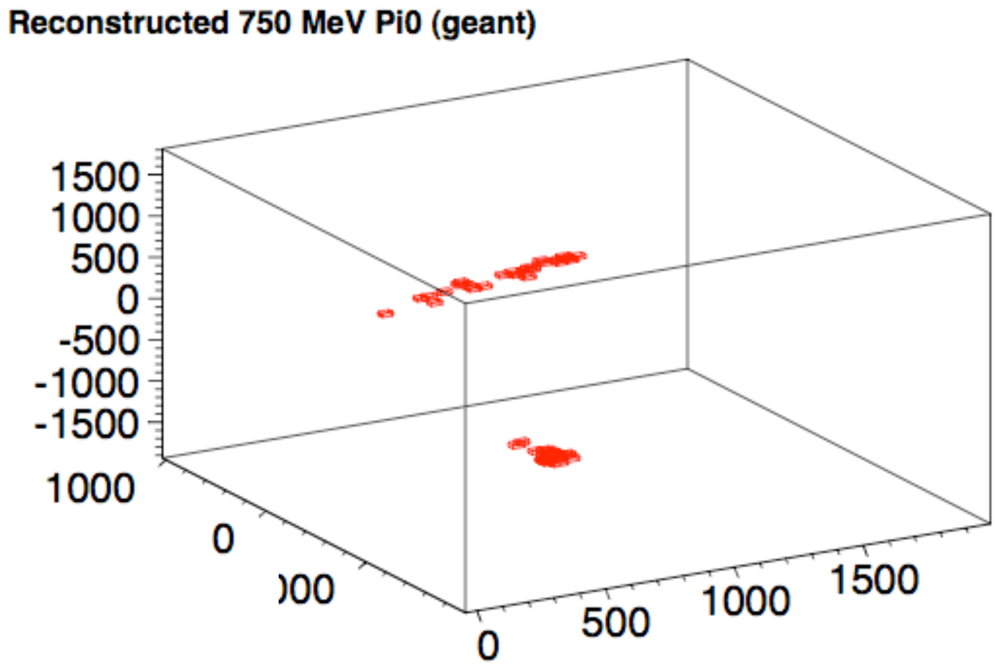
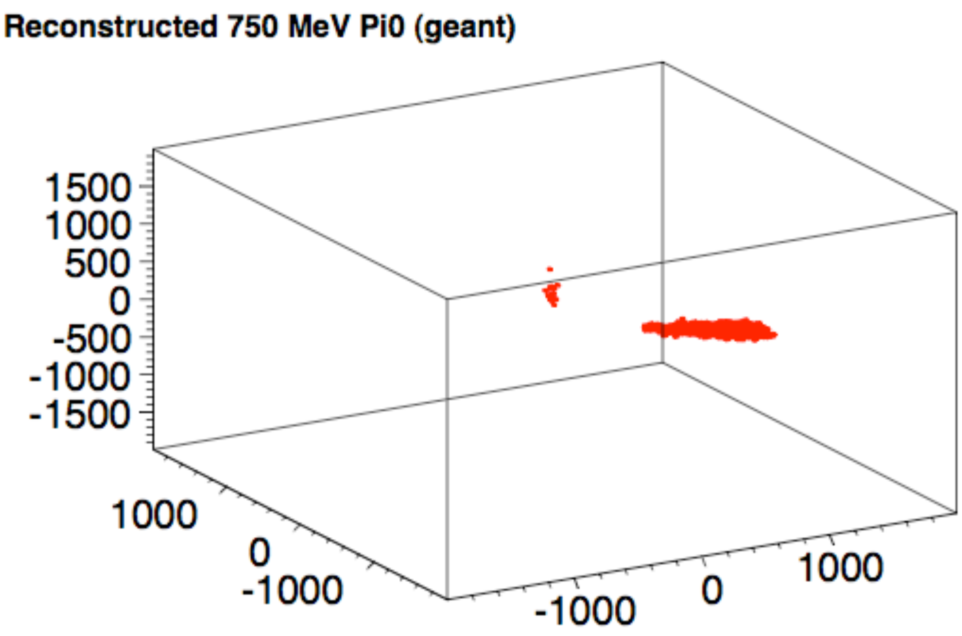


Could be useful for full pattern-fitting approached by providing a seed topology and restricting the phase space of the fit.

M. Wetstein

Comparing Isochron Reconstruction with Truth





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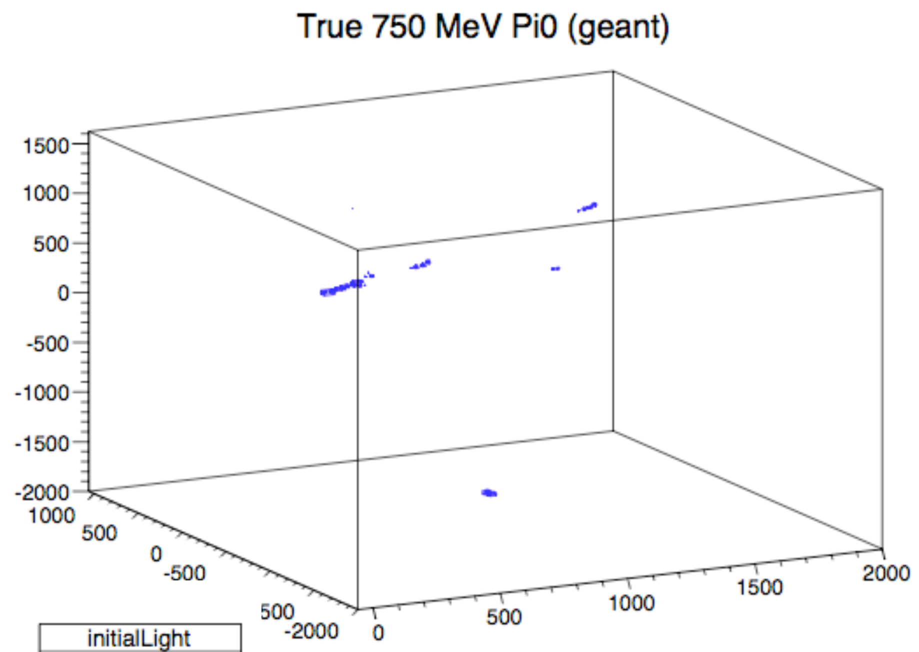
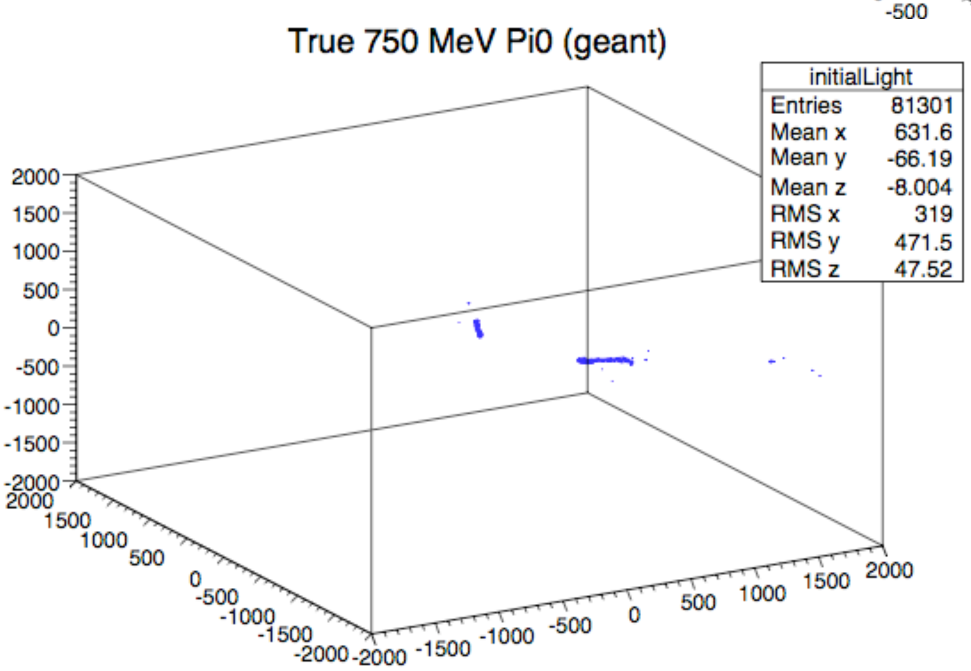
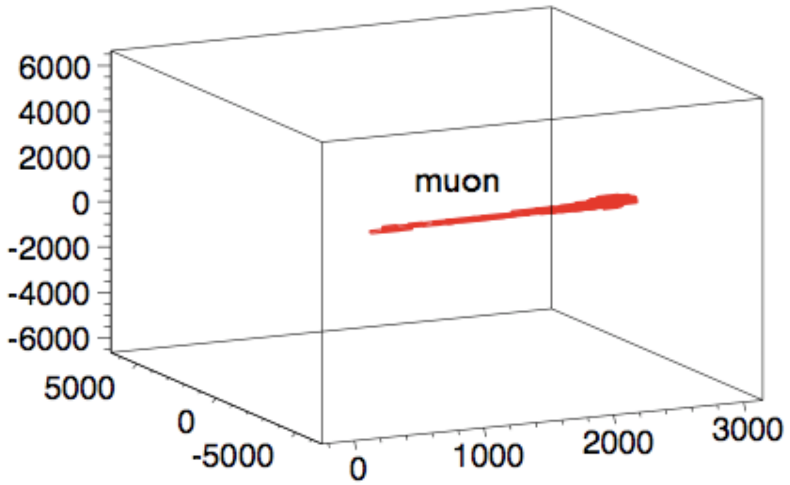
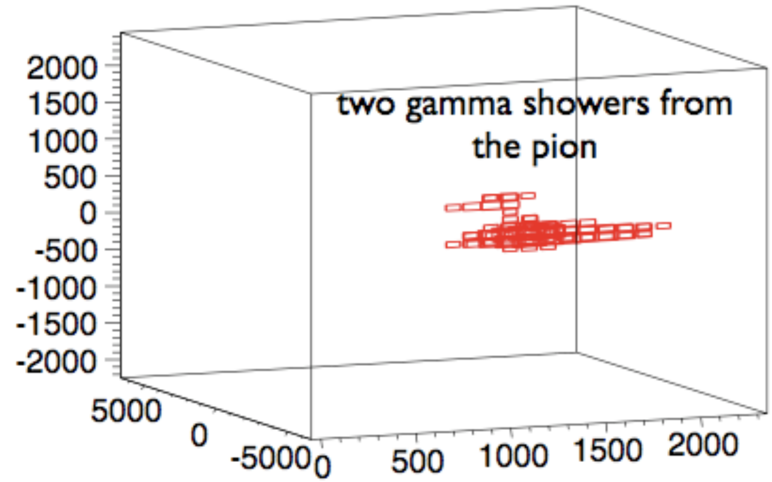
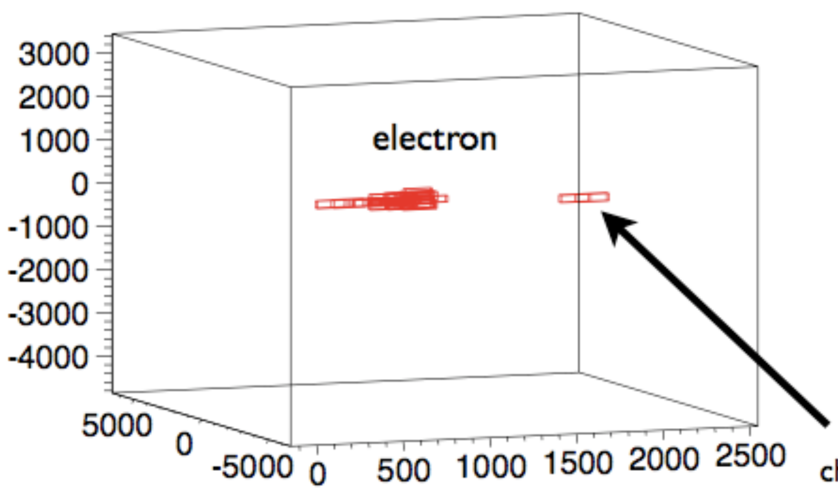




Reconstructing Geant Events







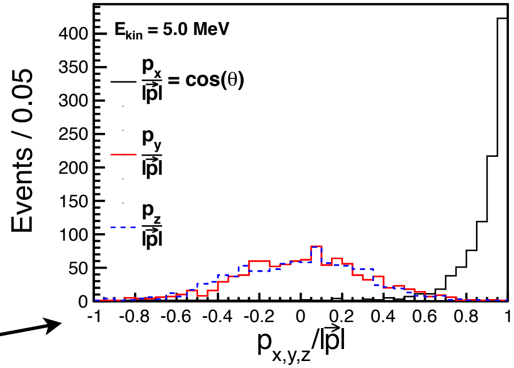
check out the detached shower from the bremstrahlung!!!

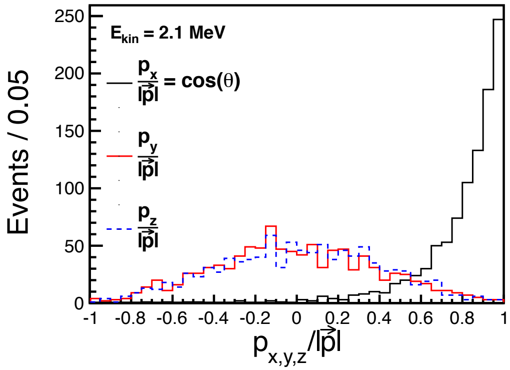
Optical TPC with scintillator

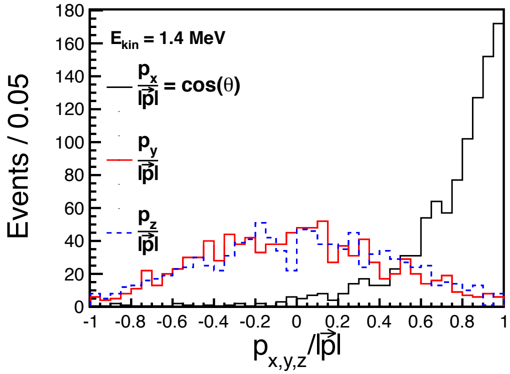
Optical TPC concept is more general than pure Cherenkov.

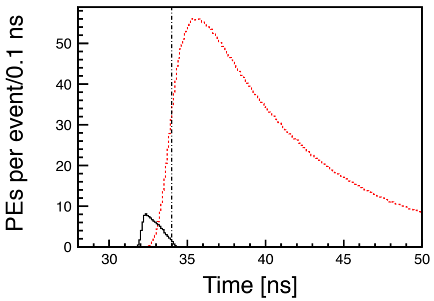
It may be possible to use timing to separate between Cherenkov and scintillation light in liquid scintillator volumes, capitalizing of the advantages of each separately.

One can use the scintillation light for low E sensitivity. <u>And the Cherenkov light for directionality</u>.

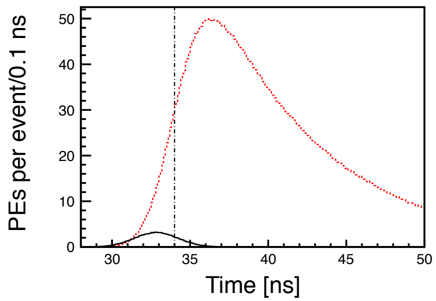




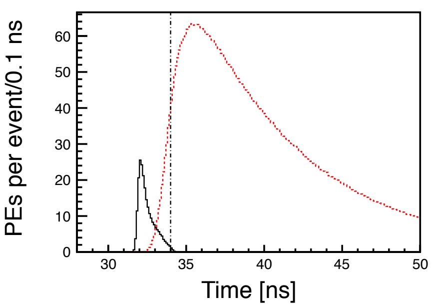




(a) Default simulation.



(b) Increased TTS (1.28 ns).



(c) Red-sensitive photocathode.

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring

Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;

Submitted to JINST, Nov. 2013. e-Print: arXiv:1307.5813

LAPPD2 - What's Next