Large-Area Picosecond Photo-Detectors

and their application in a directional liquid scintillator detector

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University of Chicago

CPAD Instrumentation Frontier Meeting, University of Texas at Arlington, October 6, 2015

Outline

- Large-Area Picosecond Photo-Detectors (LAPPD)
  - design concept
  - key results from first prototype (demountable LAPPD)
- Post- R&D stage: path to industrialization
- Some applications
  - Directional Liquid Scintillator and Cherenkov / scintillation light separation to search for $0\nu\beta\beta$-decay
  - Optical TPC (Eric Oberla PhD thesis) → next talk

arXiv:1510.00947

Large-Area Picosecond Photo-Detectors (LAPPD)

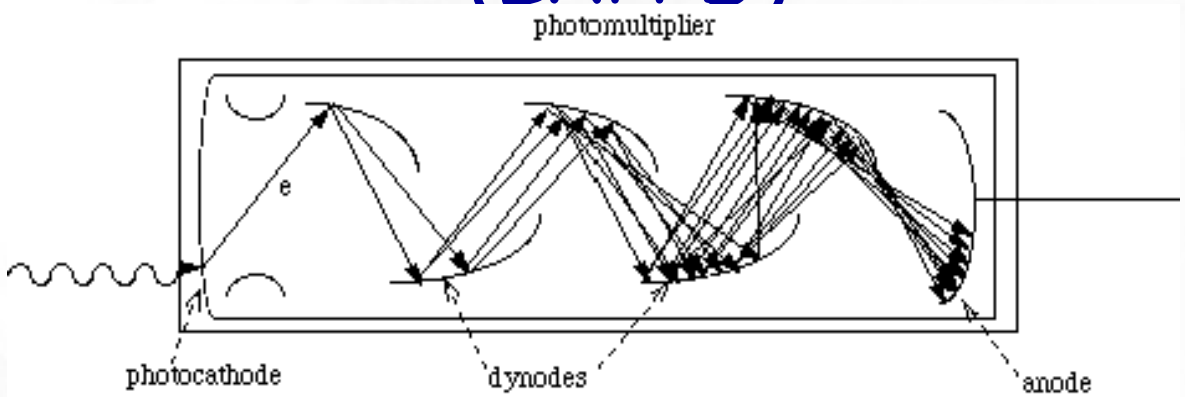
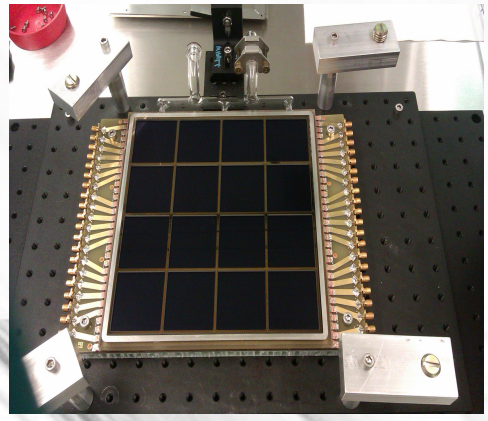


Photo-Multiplier Tube (PMT) is a classical example of a photo-detector

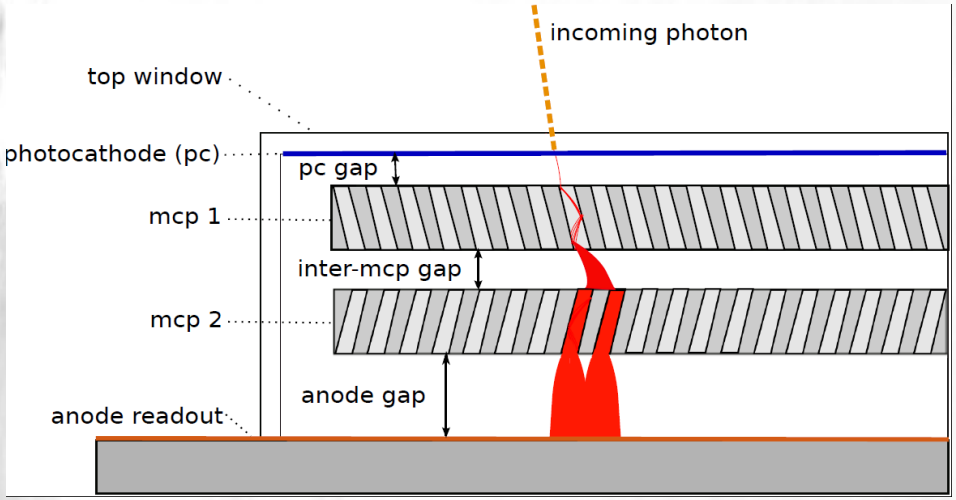
- use photo-electric effect to convert a photon to an electron
- use secondary electron emission (SEE) to amplify the signal

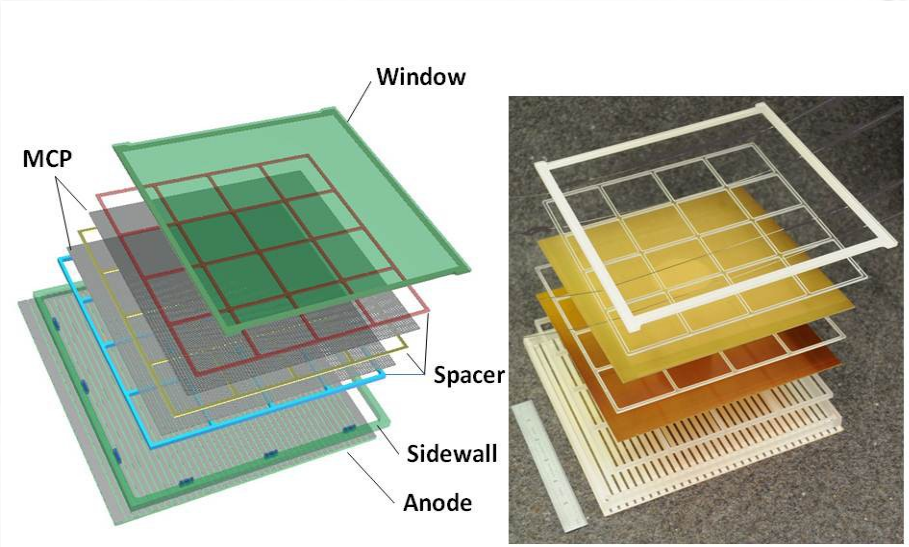
Uncertainty on the electron path causes uncertainty on the signal timing

The shorter the electron path the better the time resolution



LAPPD Glass Package (20x20 cm^2)

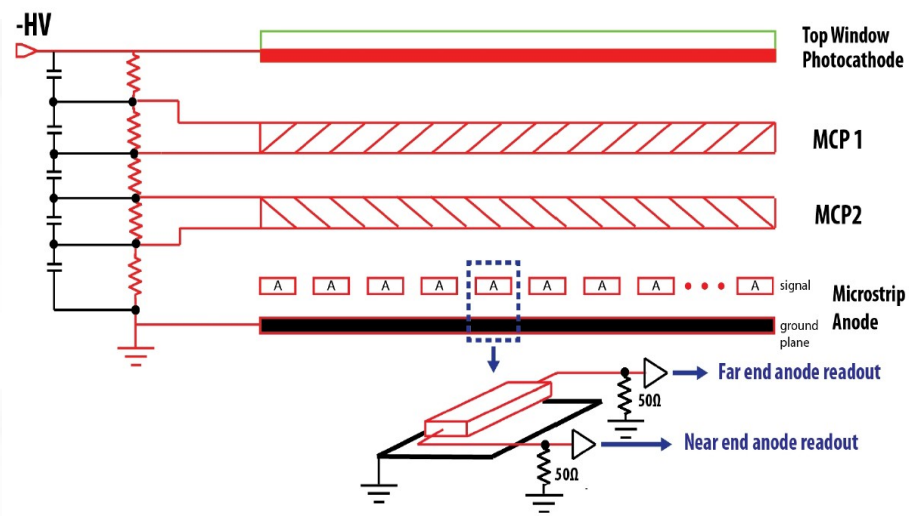




Design Drawing - September 2010

Actual Glass Parts - April 2012

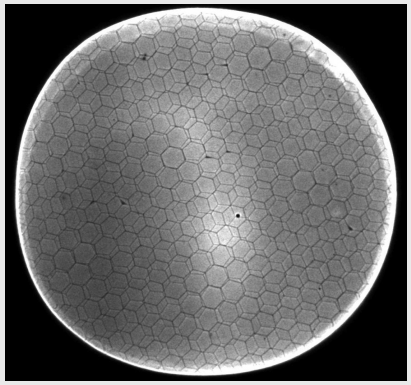
The Frugal Tile



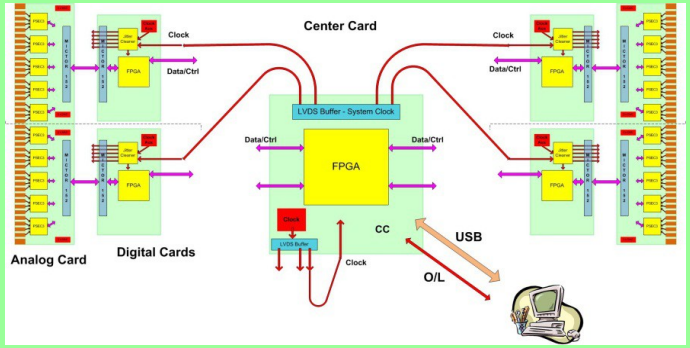
- Borofloat glass
- Silk-screened anode
- Flat panel
- No pins, single HV cable
- Modular design

LAPPD Components

MicroChannel Plates

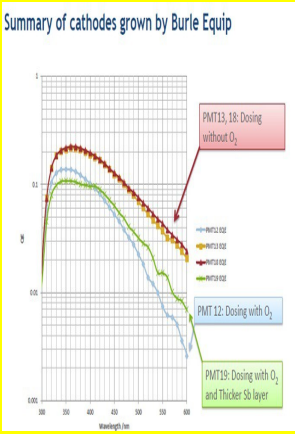


Electronics/Integration

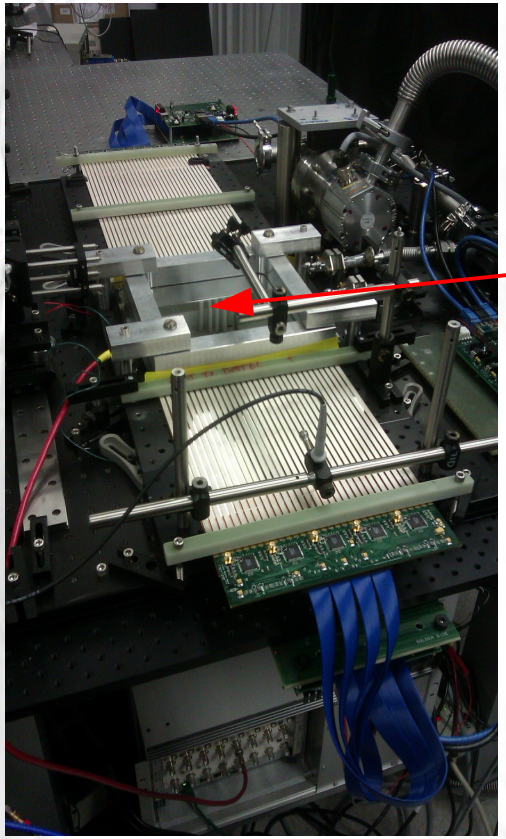


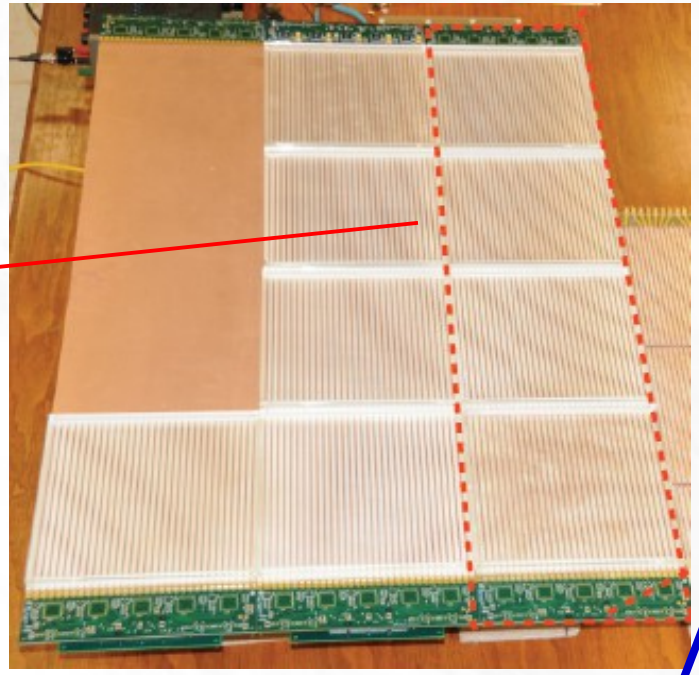
Hermetic Packaging

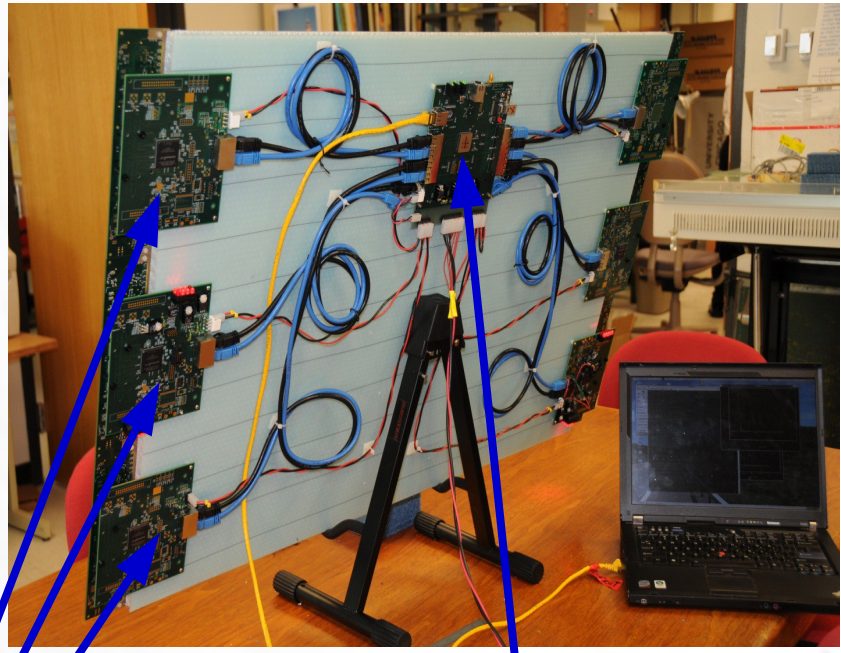
Photocathodes



Large Area Readout Electronics

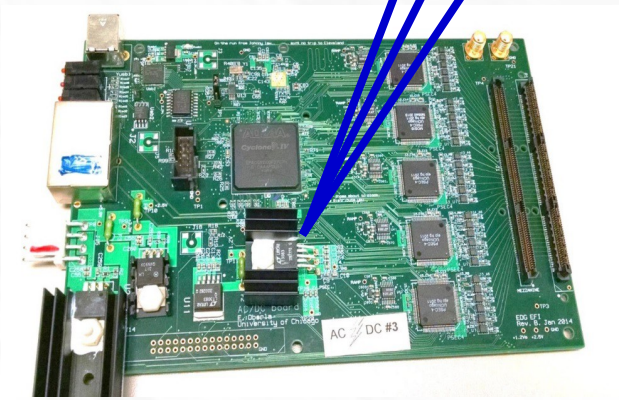




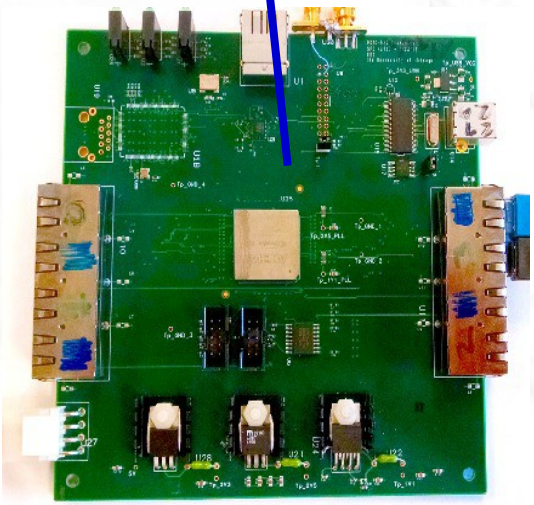


Delay-line anode:
- 1.6 GHz bandwidth
- number of channels
  scales linearly with area

PSEC-4 ASIC chip:
- 6-channel, 1.5 GHz, 10-15 GS/s

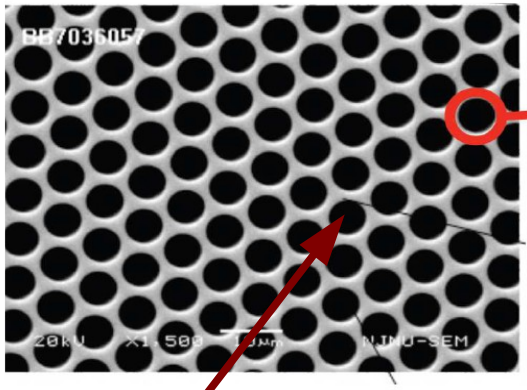


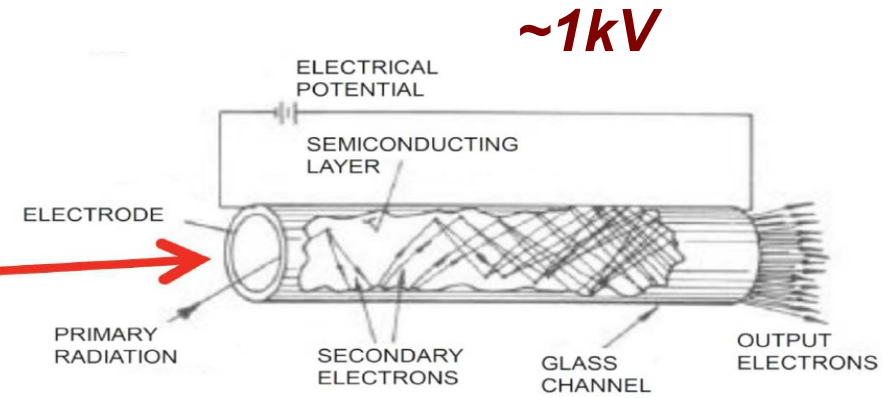
30-Channel ACDC Card (5 PSEC-4)

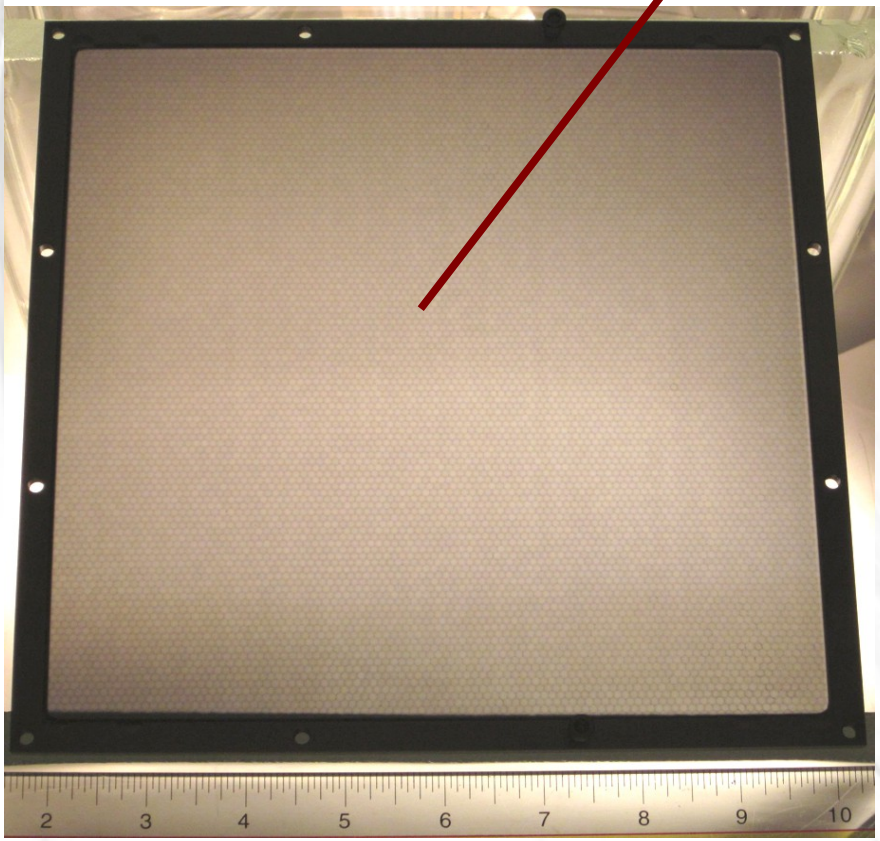


Central Card (4-ACDC;120ch)

Micro-channel Plates





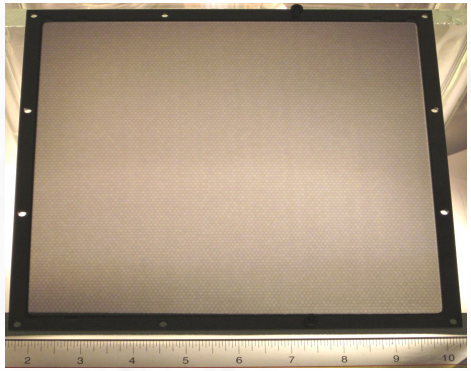


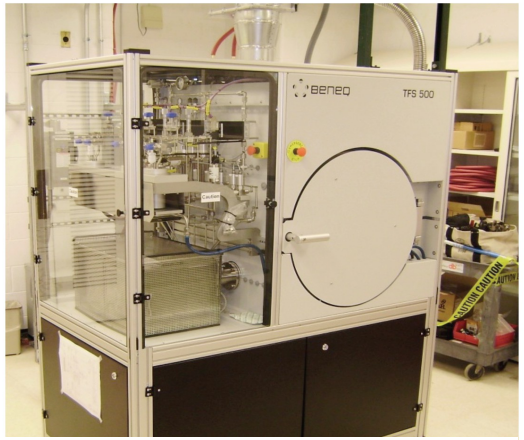
Micro-Capillary Arrays by Incom Inc.

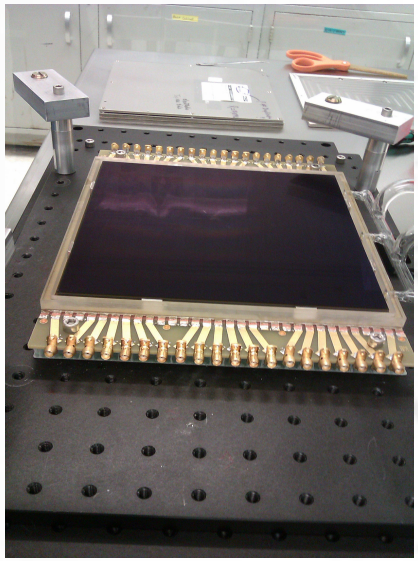
- ***Material:*** ***borofloat glass***
- ***Area:*** ***8x8”***
- ***Thickness:*** ***1.2mm***
- ***Pore size:*** ***20 μm***
- ***Open area:*** ***60-80%***

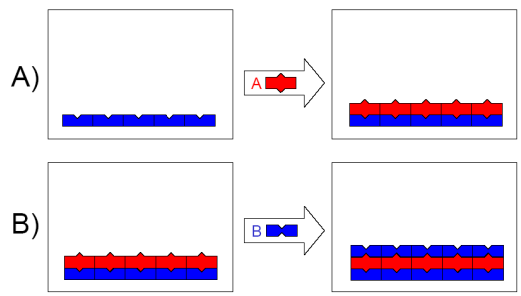
Atomic Layer Deposition

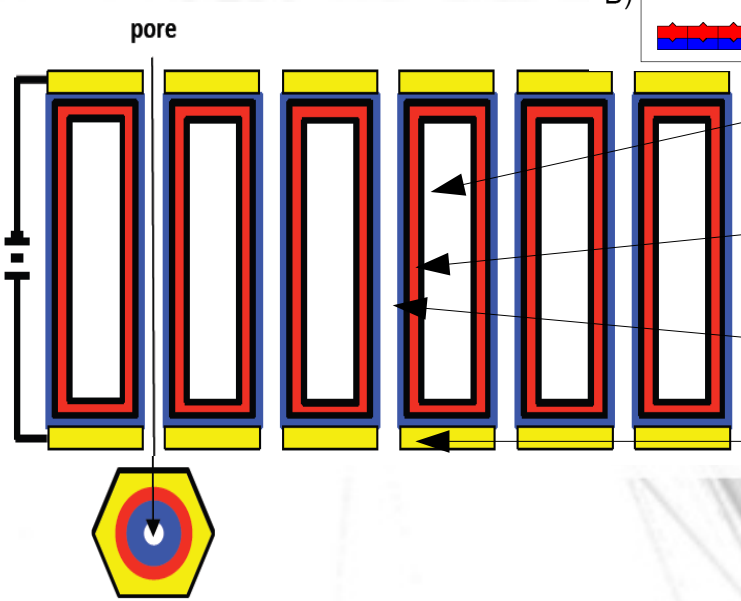
ALD Process for MCP Coating
by A.Mane, J.Elam
and independently by Arradiance Inc.











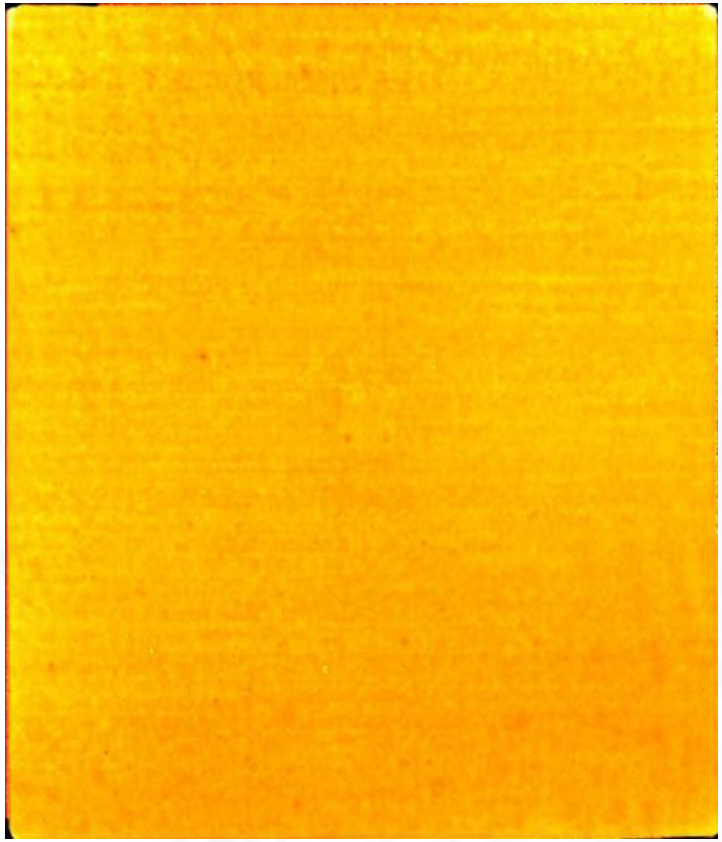
Porous glass

Resistive coating ~100nm (ALD)

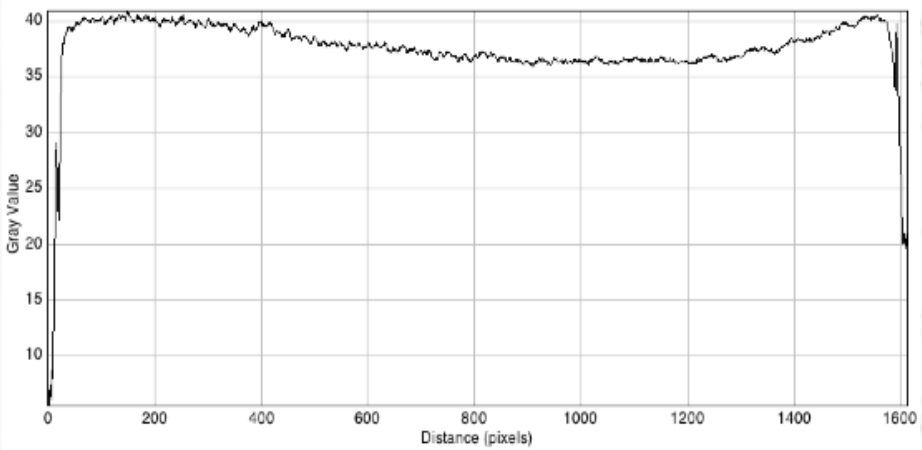
Emissive coating ~ 20nm (ALD)

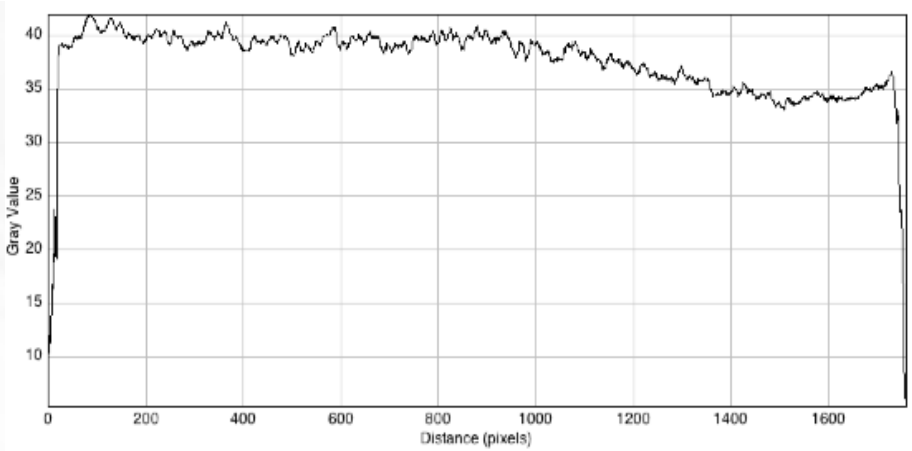
Conductive coating
(thermal evaporation)

Gain Uniformity



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



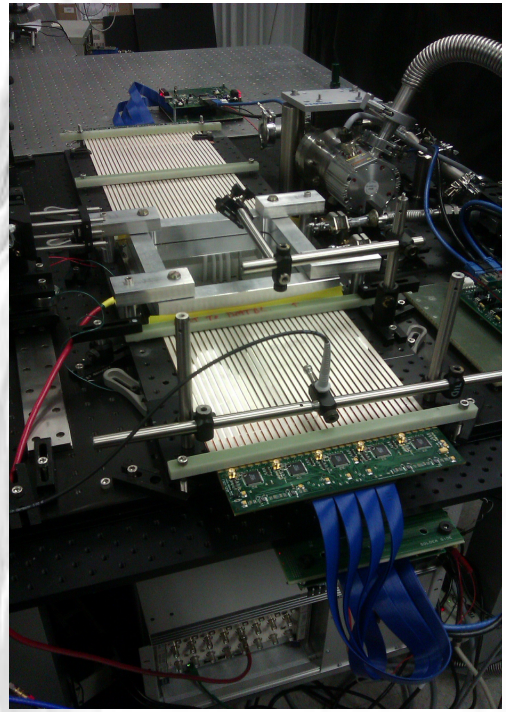


Gain is uniform within ~15% across full 20 x 20 cm^2 area

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

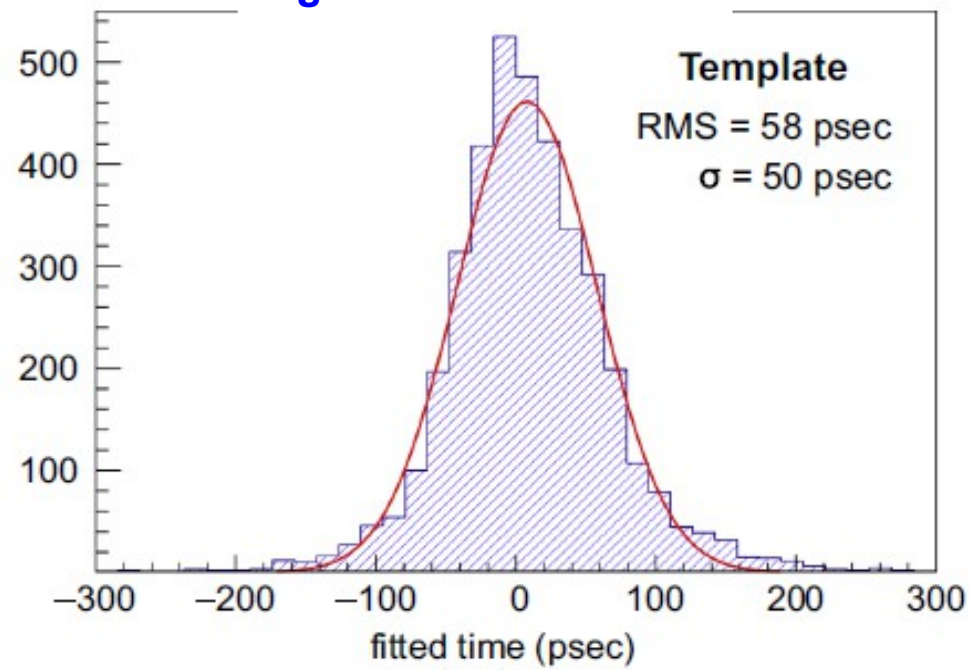
Noise <0.1 counts cm^{-2} s^{-1}

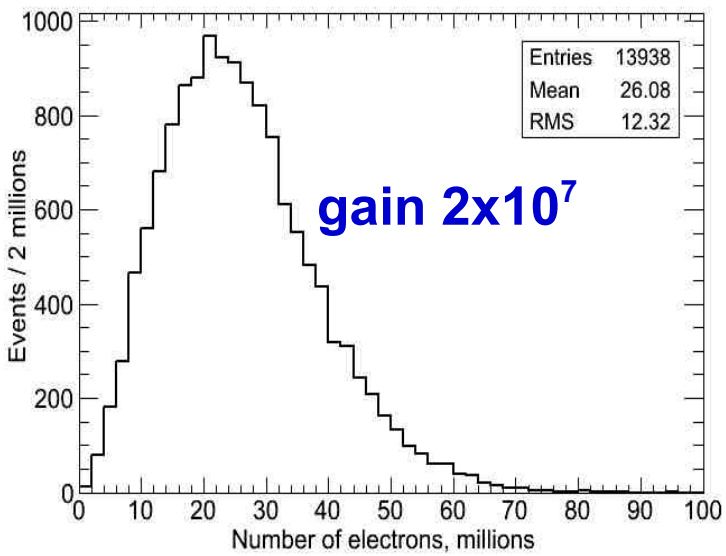
LAPPD Prototype Testing Results



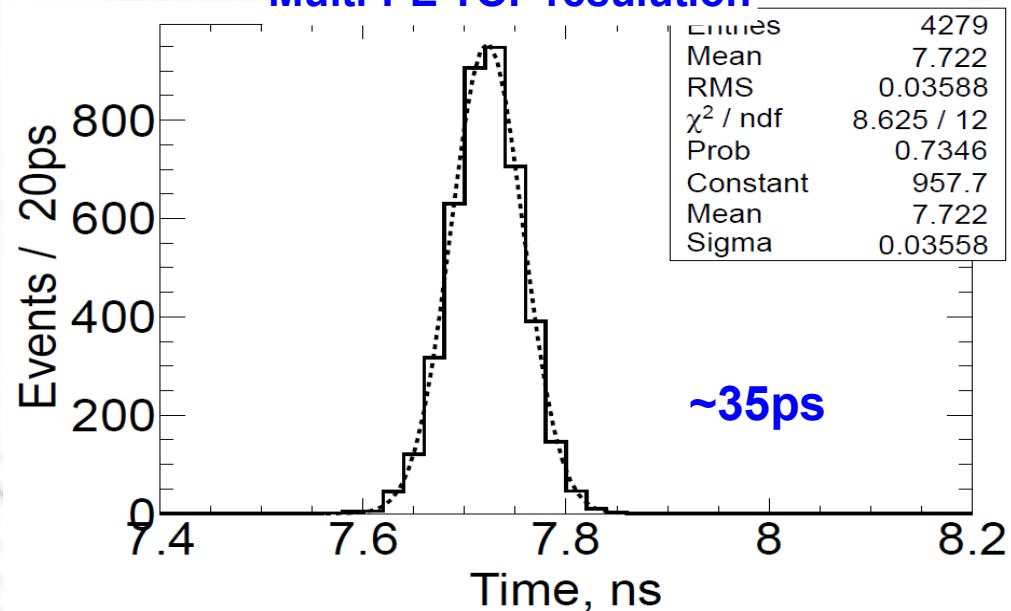
NIMA 732, (2013) 392
NIMA 795, (2015) 1

Single PE TOF resulution

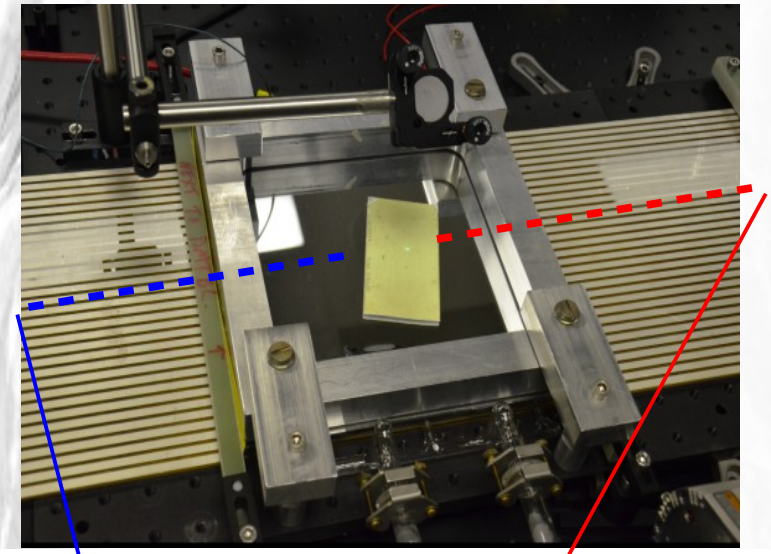


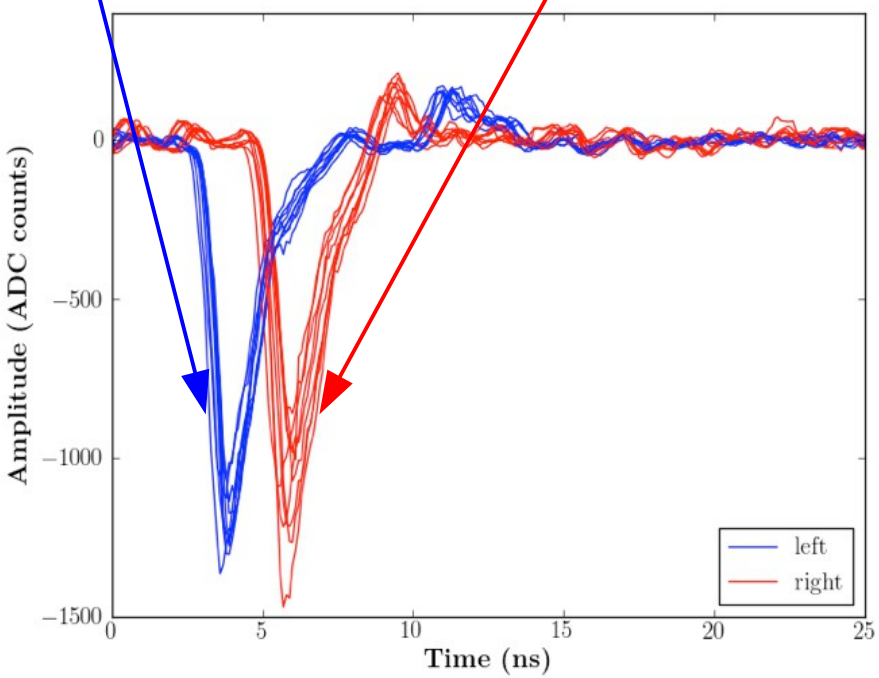


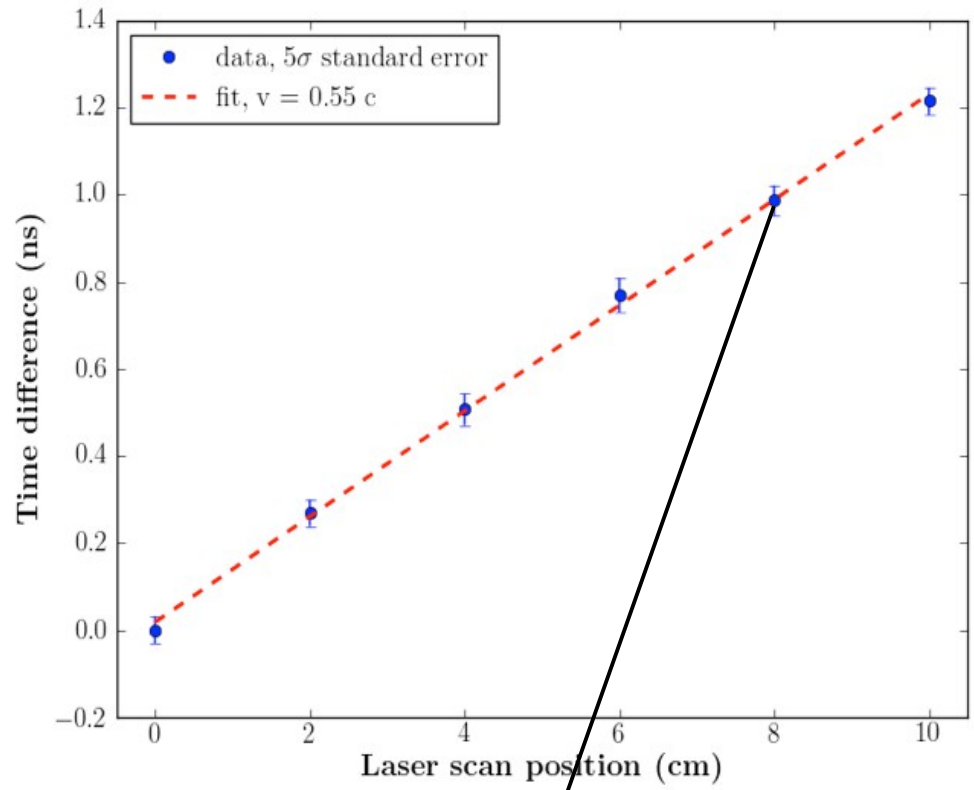
Multi-PE TOF resulution



LAPPD Prototype Testing Results







Longitudinal δX
(differential timing)

4 tiles (90-cm anode): ΔT=~18ps → **δX=~1.8mm**

1 tile (20-cm anode): ΔT=~5ps → **δX=~0.5mm**

Transverse δX=~0.7mm
(charge sharing profile)

Key R&D Questions have been resolved

- **Substrate: glass or AAO (downselect made-AAO patented)**
- **Secondary-emission layer- measure SEY's from ALD**
- **ALD resistive layer on micropores**
- **MCP performance: gain, uniformity, stability, lifetime**
- **Good QE uniform 20-cm photocathode deposition**
- **Photocathode lifetime on B33 glass**
- **Smaller feature (130nm process) analog wave-form ASIC**
- **Psec level system development (clock, multichannel)**
- **High bandwidth low channel-count readout system**
- **Packaging- anode to sidewall seal (fritting)**
- **Packaging- sidewall to window seal (top seal)**

Many of these could have been a showstopper. All of these have been done.

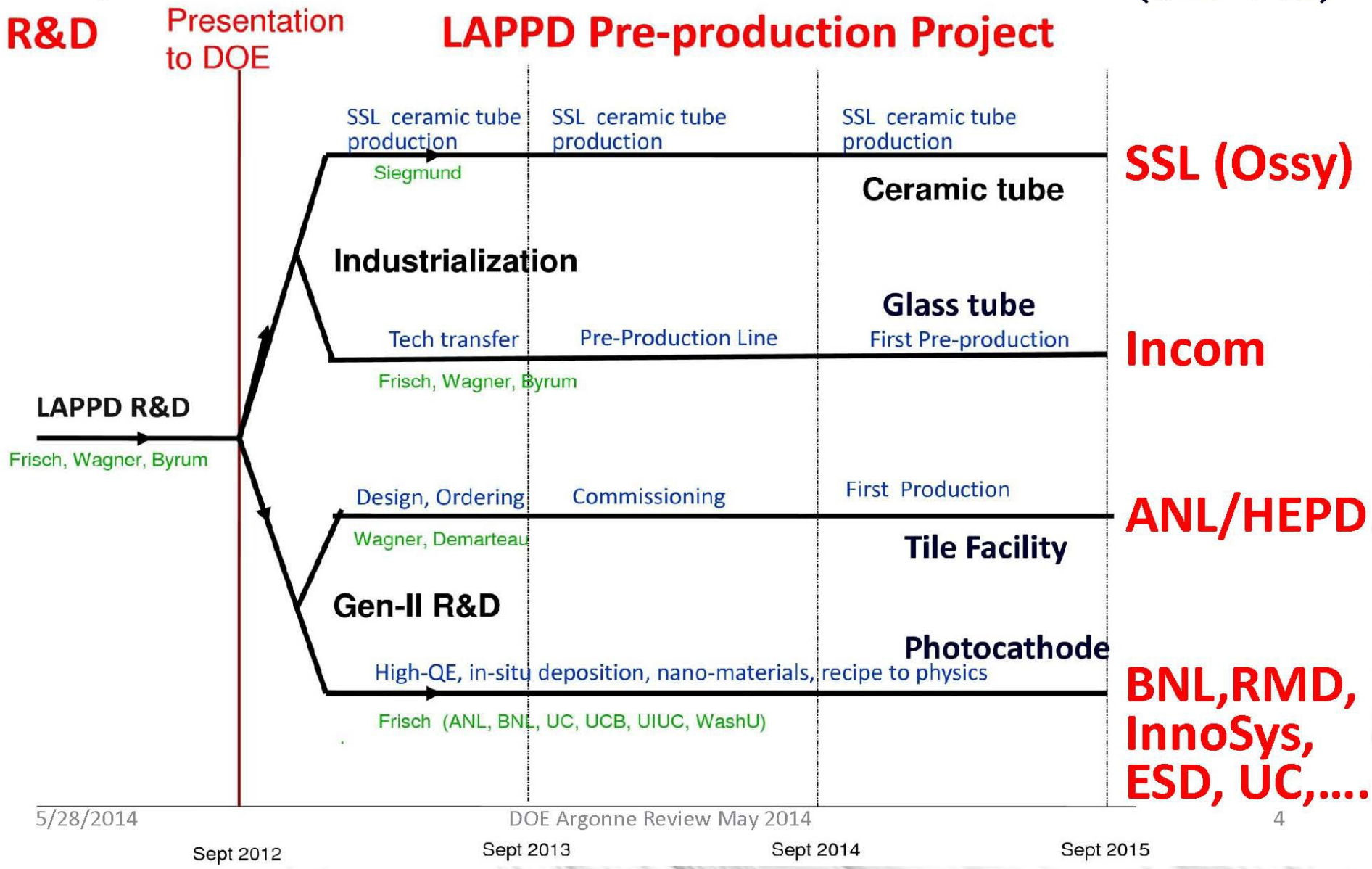
*** There are R&D questions for alternative, possibly better, solutions, but an adequate solution has been demonstrated for each of these individually**

Slide credit: Henry Frisch

The 2013 Transition from LAPPD to Production: The 4 Parallel Paths

Dec 12, 2012 Presentation to DOE

(a UC view)

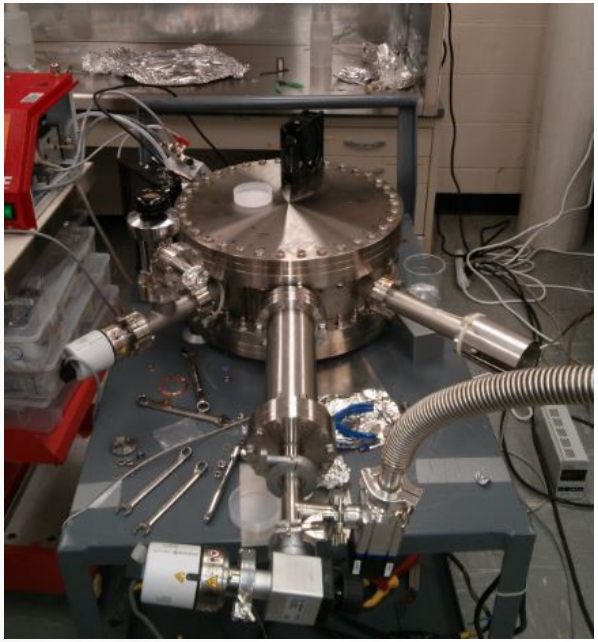


Slide credit: Henry Frisch

4 Parallel Paths (from the previous slide)

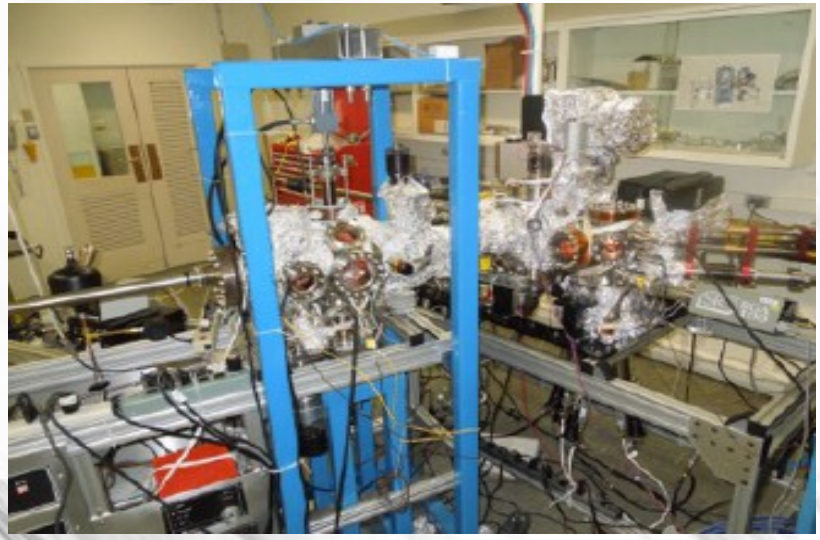
SSL vacuum transfer assembly

UChicago ultra-lightweight "in-situ" assembly

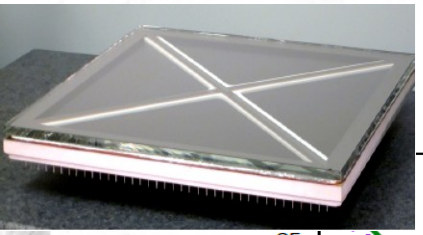


Incom integration and sealing tank

ANL small tile processing chamber

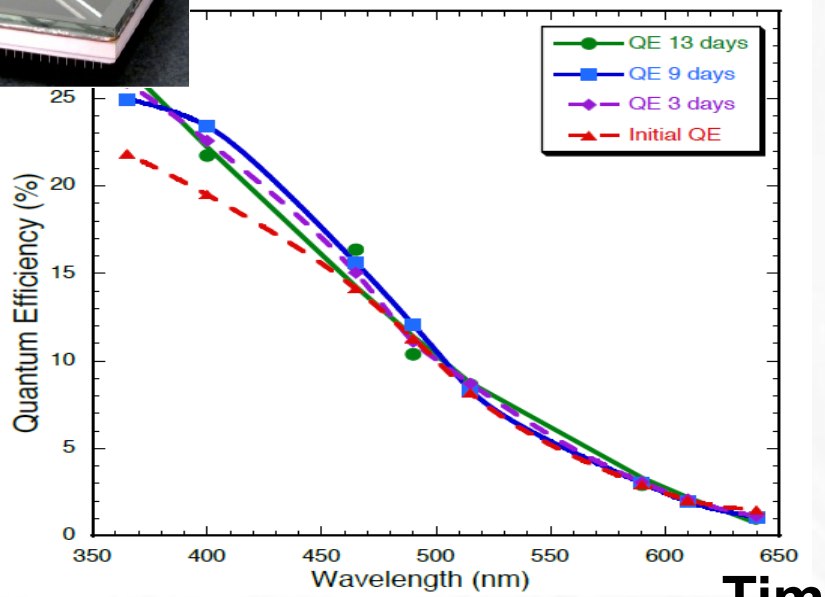


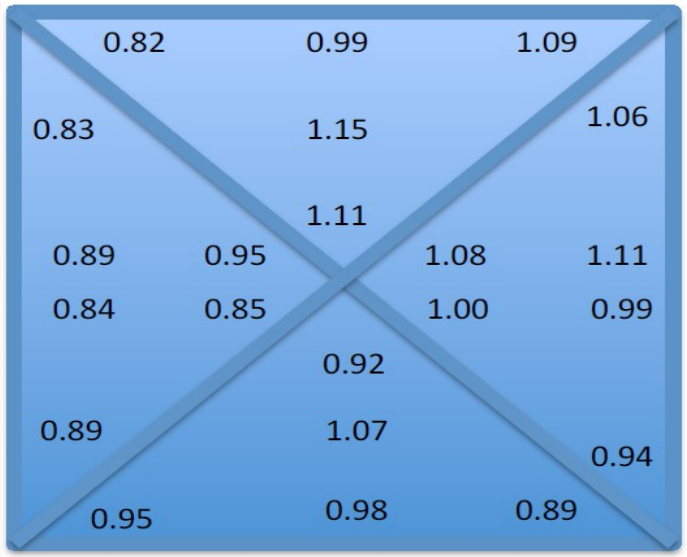
SSL Ceramic LAPPD Tile Results



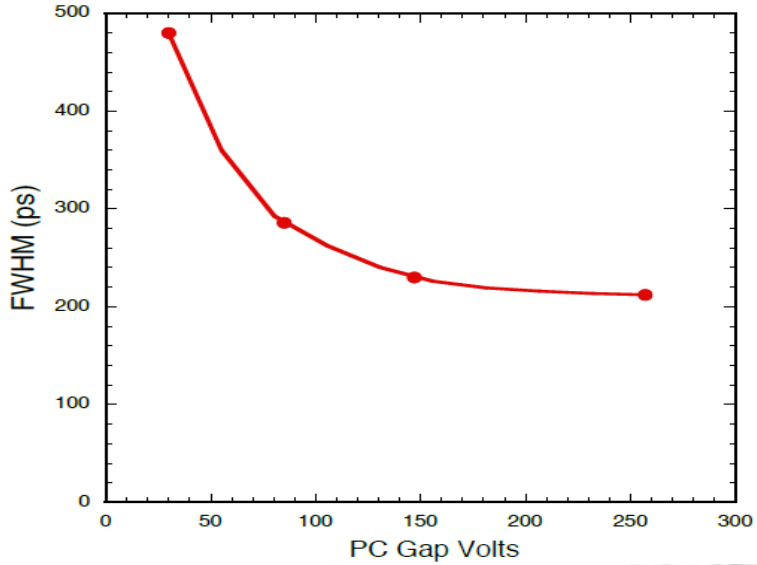
Measurements after full processing cycle inside the vacuum chamber

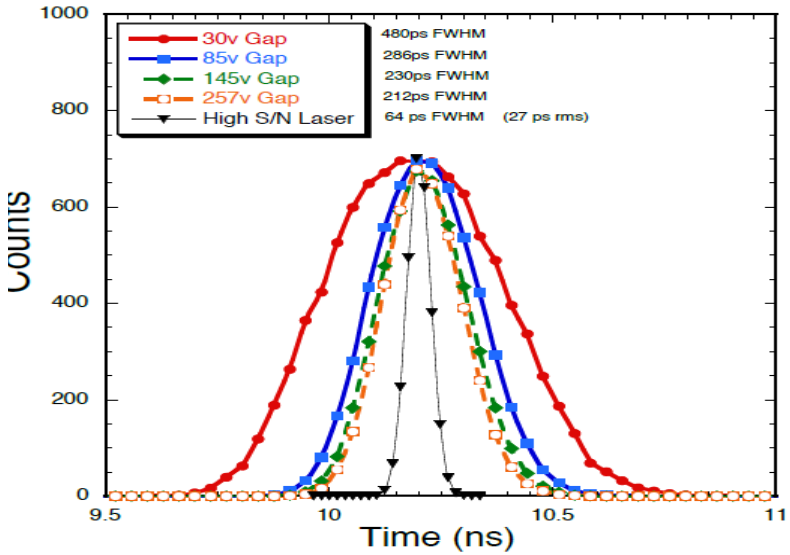
QE





Timing





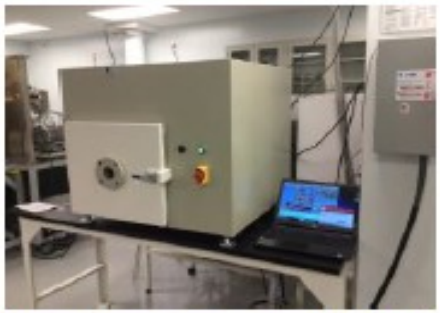
2014 JINST 9 C04002

Incom Inc. Effort

INCOM

Bright Ideas in Fiberoptics

Recent Incom Equipment Installations



Plasma cleaner rec'd 9/2015

Vacuum oven due 10/2015

LAPPD integration and sealing tank rec'd 9/2015

Beneq ALD coater with load-lock installed 6/2015

Thermal evaporator commissioned 12/2014

Measurement & test station, commissioned 8/2015

Vacuum oven is final major piece of equipment needed for fabrication of LAPPDs at Incom

Slide credit: Chris Craven

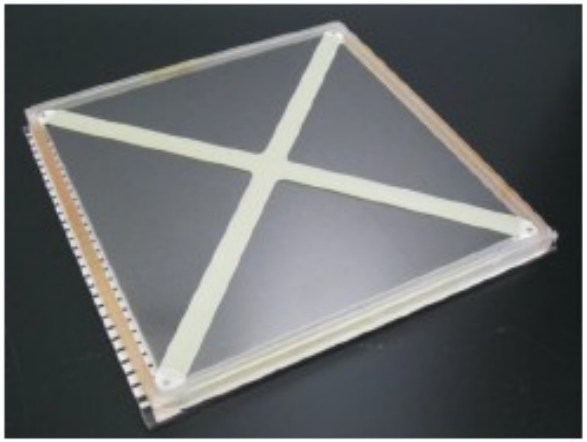
Incom Inc. Effort

INCOM

Bright Ideas in Fiberoptics

Status, Schedule

- Plasma cleaner
  - To clean GCAs before coating
  - To clean tile components before sealing
- Vacuum oven
  - To bake GCAs prior to coating
  - To post-anneal MCPs after ALD
  - To condition indium for LAPPD sealing
- Thermal evaporator
  - For electroding MCPs and metalizing LAPPD components
  - Commercial coating service, e.g. for Argonne and UChicago
- ALD coater
  - Optimizing reaction chamber for SEE layer coating
  - Coating of 20 cm (8") MCPs in November
- Measurement & test station
  - Now measuring resistance & gain on 33 mm MCPs
  - Installing cross delay-line readout, 20 cm format testing, timing measurement capability
- Integration and sealing station
  - Now installing subsystems for internal movement, tile scrubbing, photocathode deposition



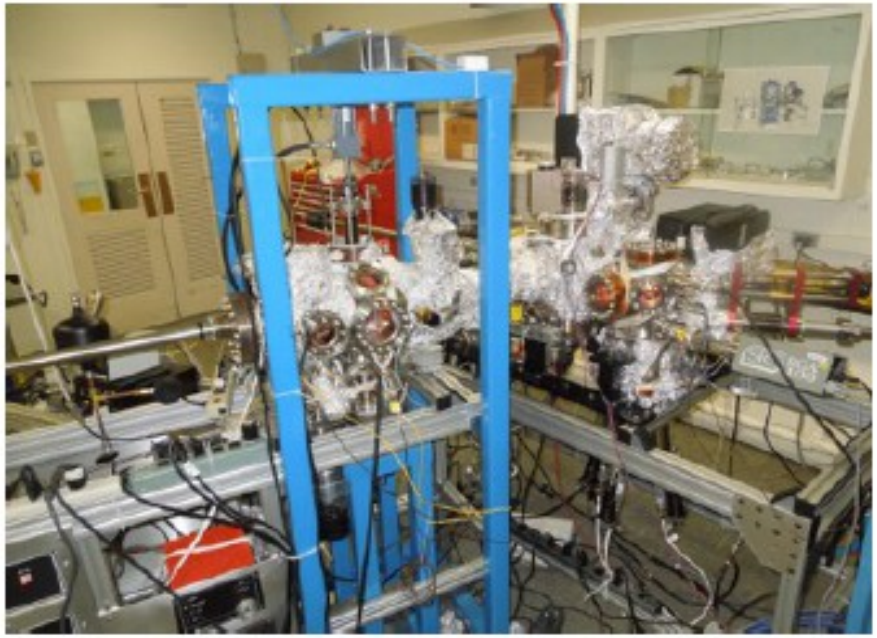
- Major funding provided by DOE under TTO and SBIR grants.
- Extensive technical support from Argonne National Laboratory, University of Chicago, and UC Berkeley, Space Sciences Laboratory

Targeting first functional LAPPD tile produced at Incom by 12/31/15

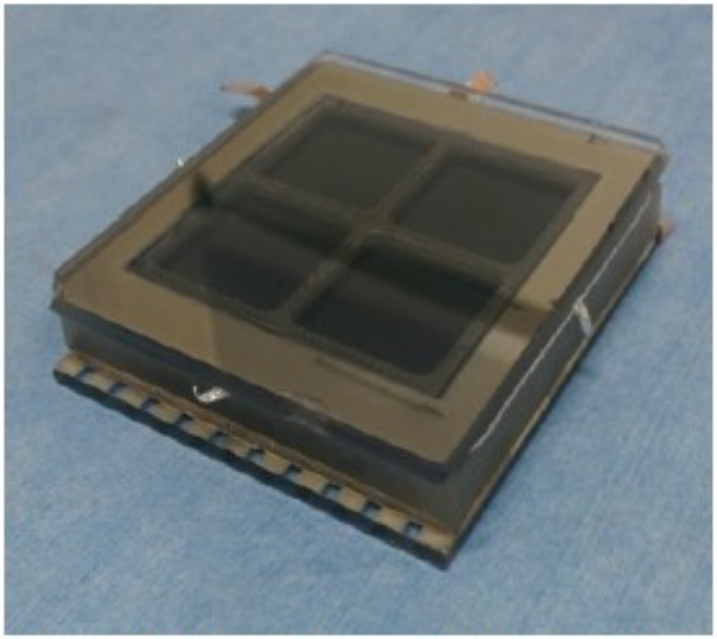
Slide credit: Chris Craven

ANL Effort

6cm × 6cm MCP Production at Argonne



Argonne Small Single Tube Processing System (SmSTPS)



Completed Tube with Photocathode
Thermopressure Indium top window seal
Strip line readout

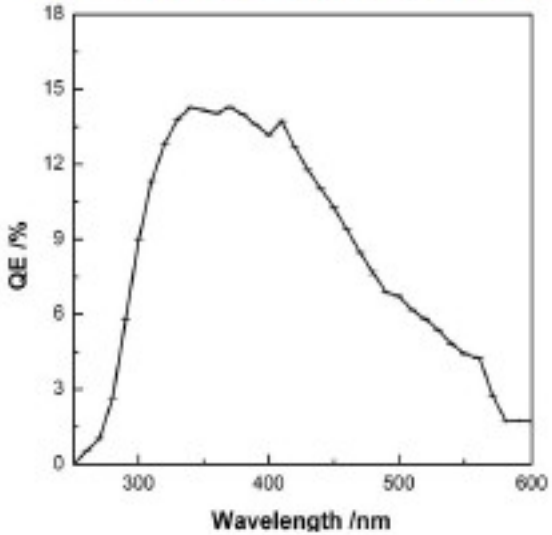
- Argonne SmSTPS is UHV transfer system for complete fabrication of 6cm × 6cm MCP Photodetectors
  - Bialkali photocathode
  - Two MCPs with 20μm pores
  - MCP functionalized with atomic layer deposition resistive layer & MgO secondary emission layer
- Produced 6 functional tubes with internal resistive chain for biasing
  - limited flexibility: no QE measurement possible, need to finely match MCP resistance
- Improved designed allows individual MCP bias; eliminates internal chain
  - 4 functional tubes produced; on track for 10 by end of 2015
  - Good timing and position resolution; working to improve QE to ≥ 20%

Slide credit: Bob Wagner

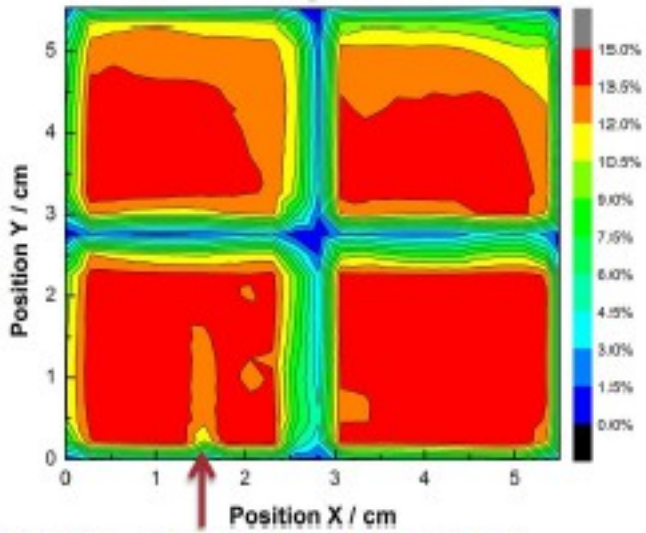
ANL Effort

Argonne 6cm × 6cm MCP-PMT Performance

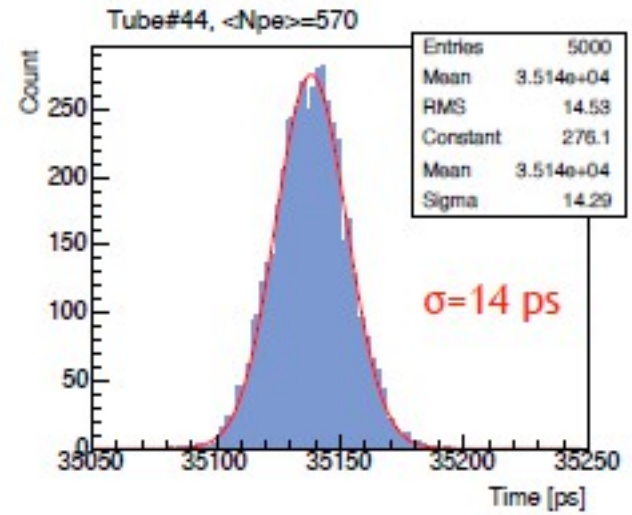
Tube 47 QE~15% at 350nm

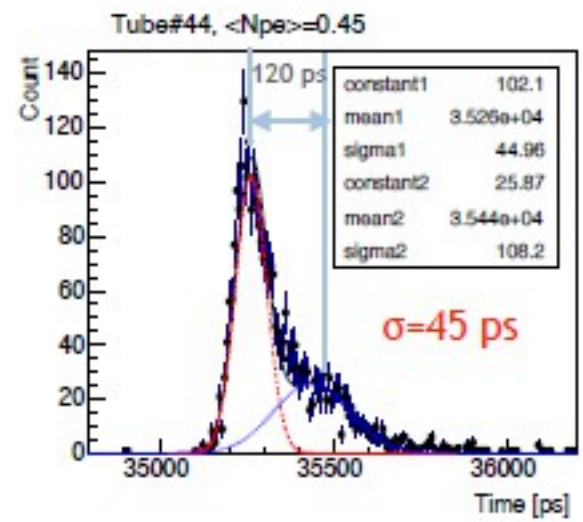


QE uniformity map



Photocurrent meas. pin shadow



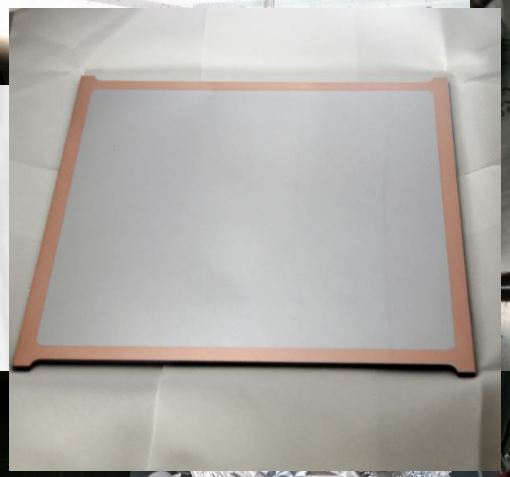


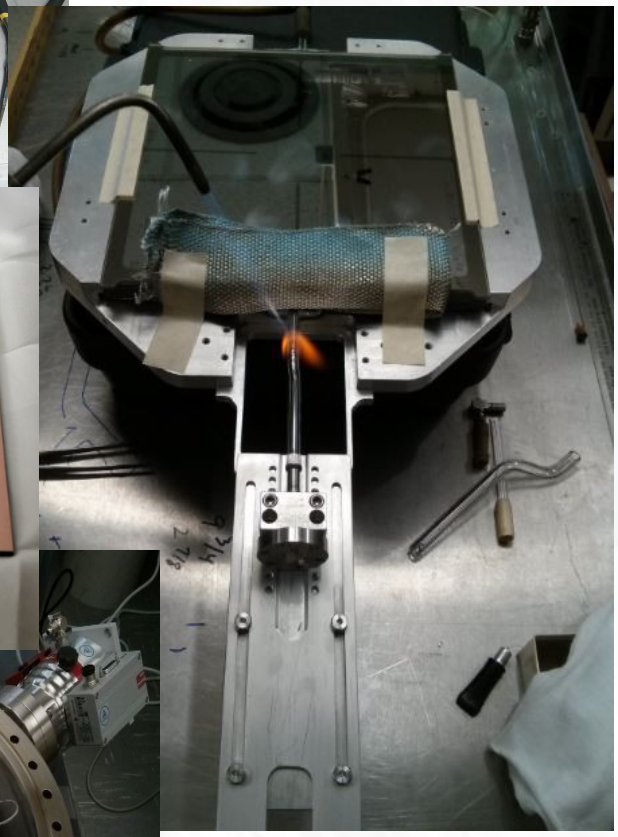
- Typical gain of tubes @ 1000V/MCP is 10^7
- Single pe time resolution < 50ps
- Multi-pe time resolution < 15ps
- Spatial resolution ~ 1mm

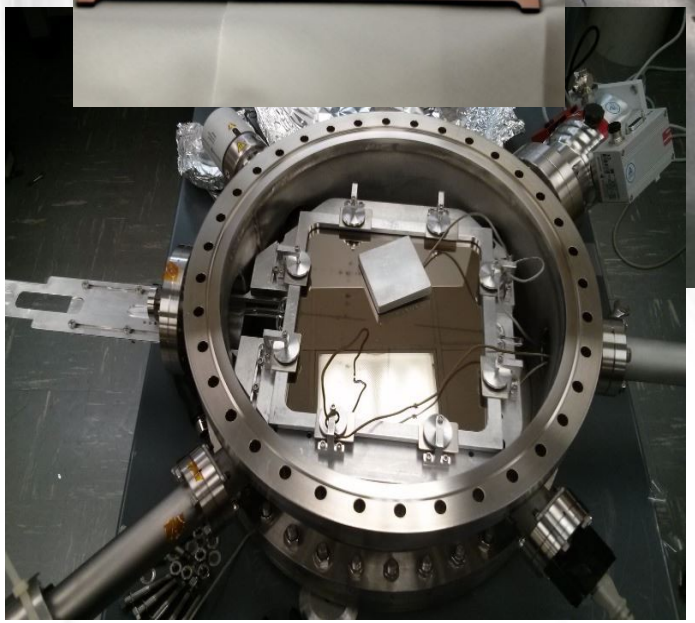
Slide credit: Bob Wagner

UChicago Effort

„In-Situ“ LAPPD assembly at UChicago







The goal is to avoid vacuum transfer process and do PMT-style photo-cathode activation through a glass tube after the detector is sealed.

Step 1: deposit Sb on the top window (air stable, very thin oxide layer forms on the surface)

Step 2: complete hermetic packaging via indium seal using metallization along the perimeter of the glass-body detector

Step 3: bake at high temperature (350C)

Step 4: activate Sb layer by bringing Cs/K vapors through a small glass tube attached to the detector body

Step 5: flame seal the glass tube

- Light-weight processing chamber
- Potentially high production yield (using multiple chambers)
- High risk high reward path

"In-Situ" Critical Component #1

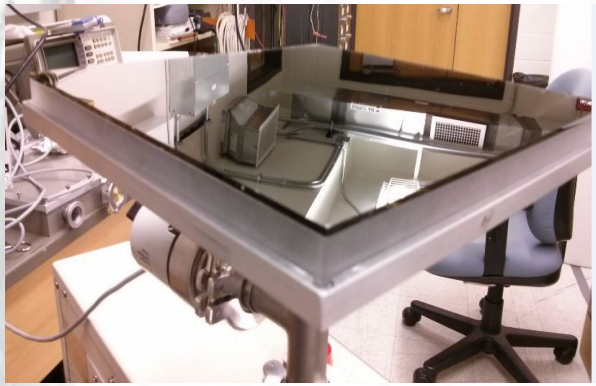
Top Seal

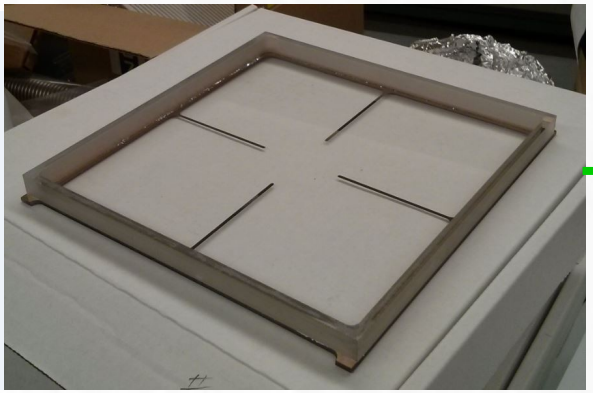
Developed two recipes to make solder seal between flat glass surfaces

I) InBi alloy seal in the inert atmosphere

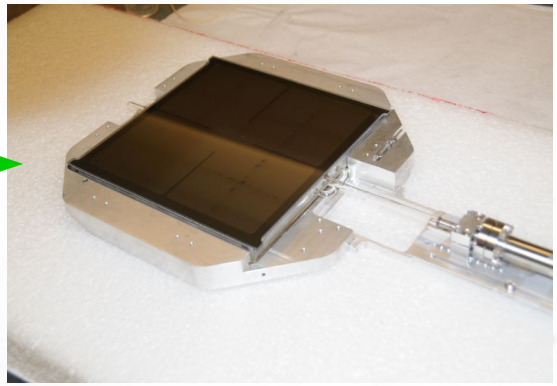
- low temperature seal, done in the N2 filled glove box

Test seals



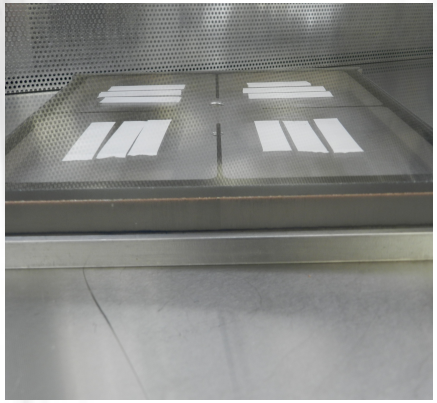


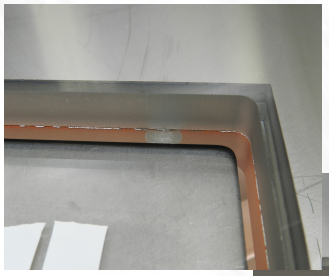
Sealed LAPPD tile

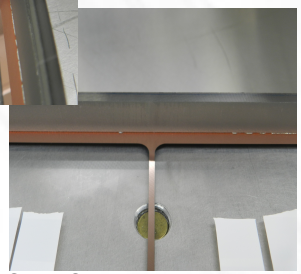


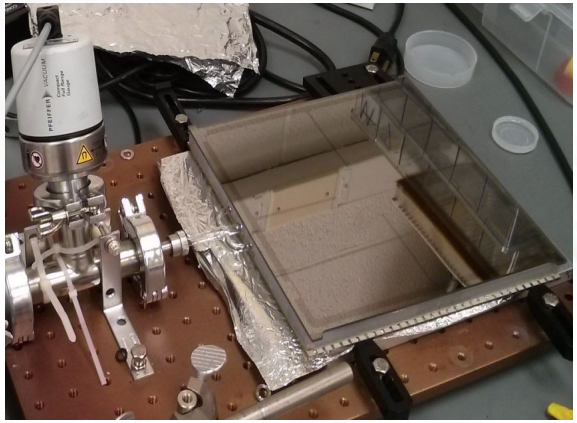
II) Pure indium seal in vacuum

- high temperature seal, done in the processing chamber during the bake







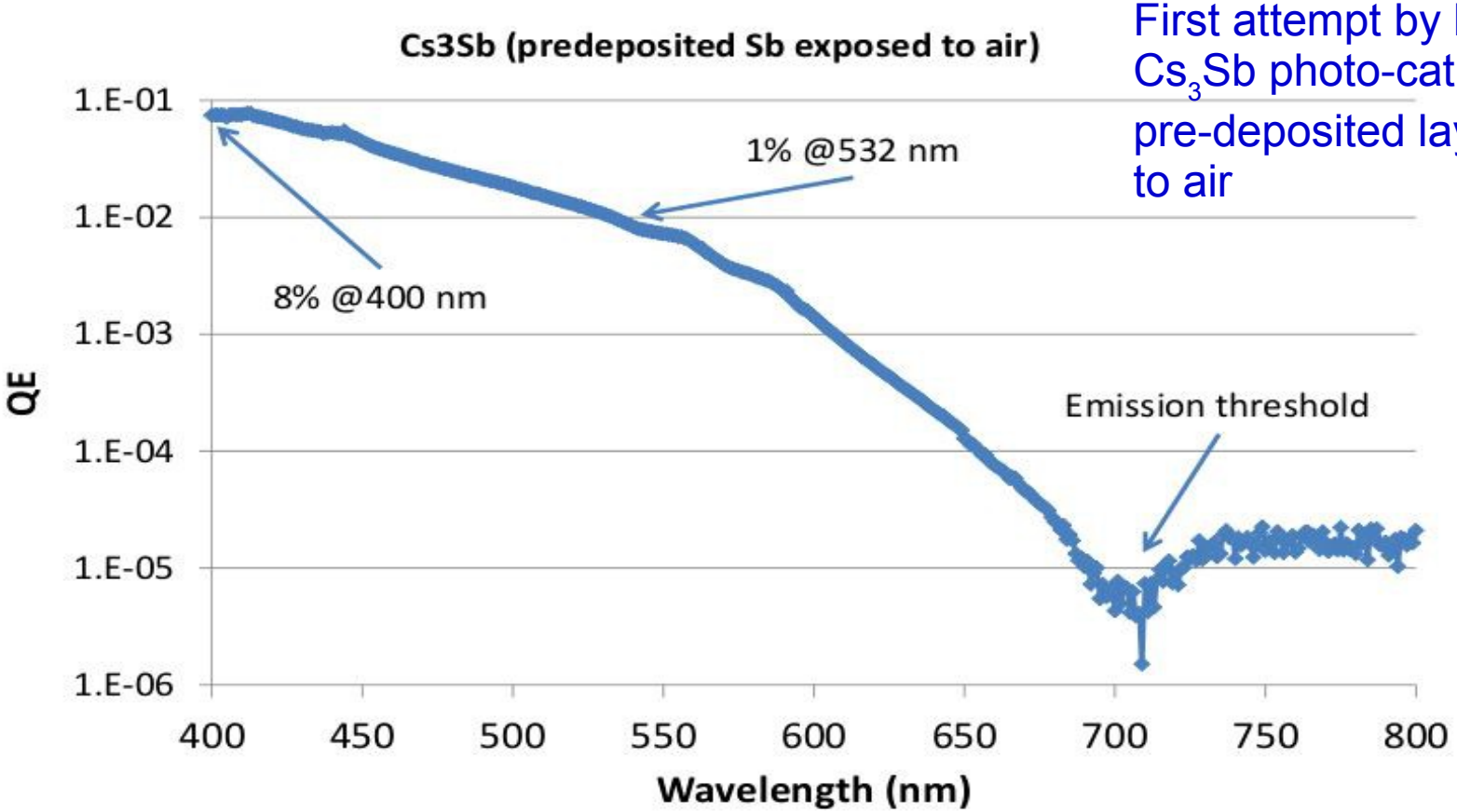


Transition along the green arrows is far from being trivial: e.g., high tolerances over large area
There is always room for improvement (e.g. metallurgy of the seal during high temperature bake out), but I believe the hermetic packaging is in good shape: it seals and stays sealed (6+ months now)

"In-Situ" Critical Component #2

Photo-cathode: can we make one after Sb exposed to air?

Working closely with Cornell group (Luca Cultera and Ivan Bazarov) to optimize photo-cathode activation step



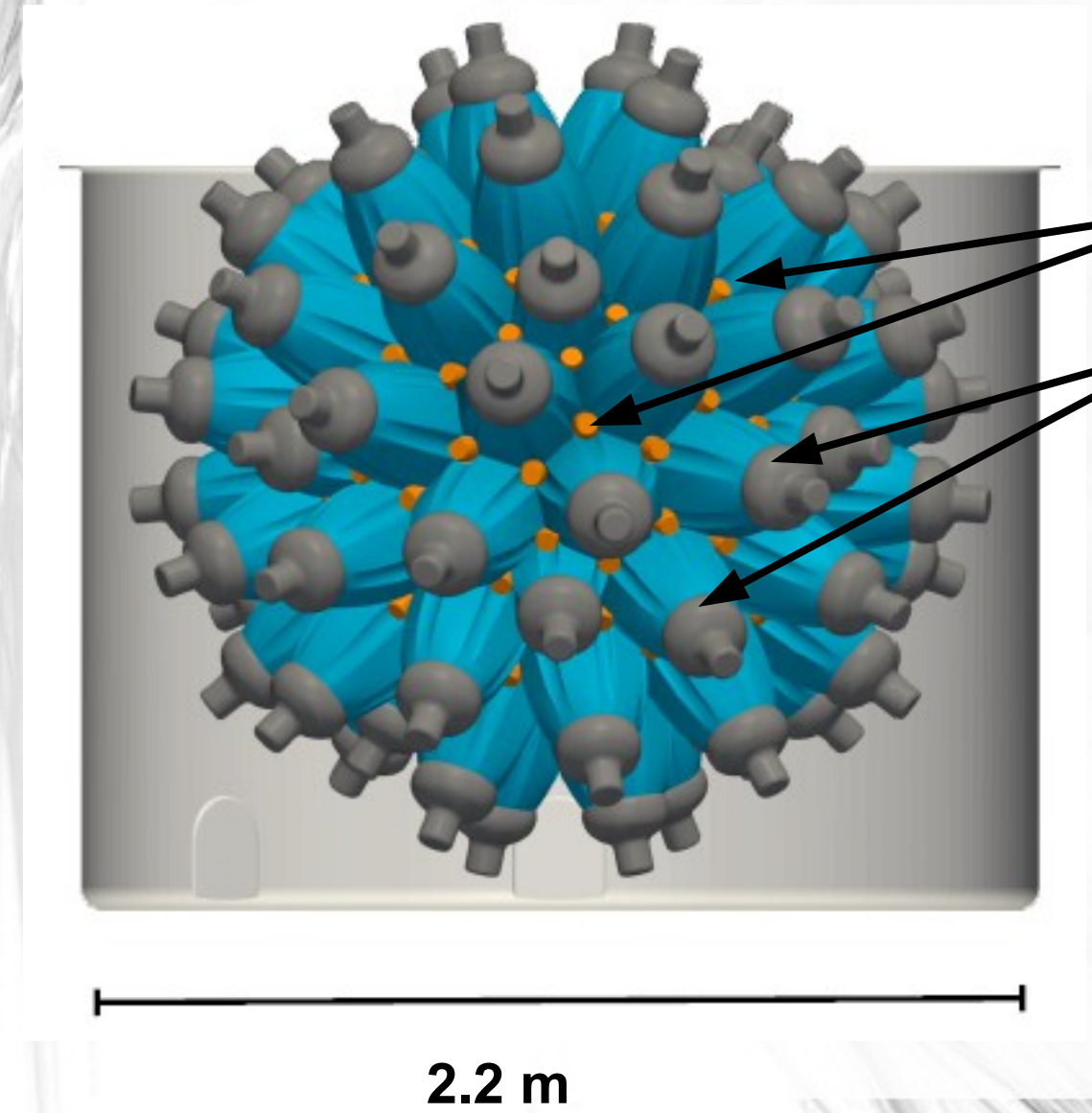
First attempt by L.Cultera to make Cs_3Sb photo-cathode using pre-deposited layer of Sb exposed to air

LAPPD Summary

- R&D stage is over (almost)
- All individual components have been reliably demonstrated
- Focus is on commercialization through Incom Inc.
- Thinking hard about production yield
- Work continues on optimization of individual components

Directional Liquid Scintillator

NuDot prototype detector is being built at MIT



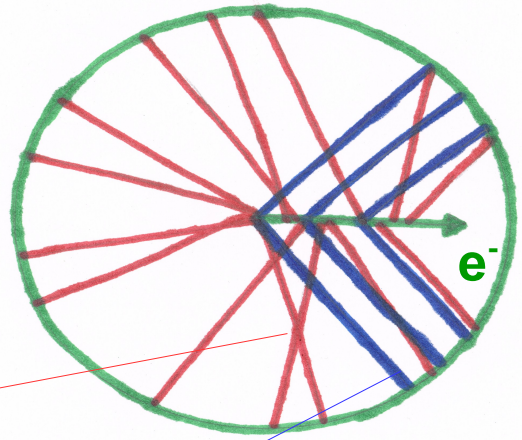
140 2” fast PMTs for timing

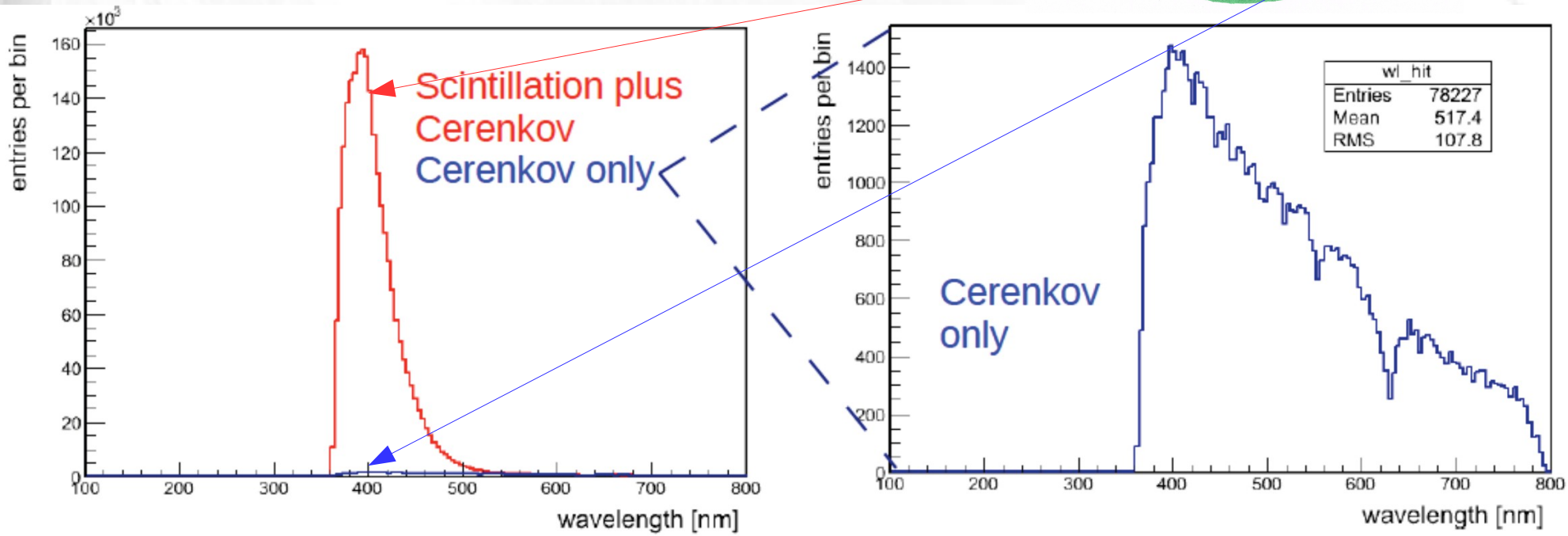
72 10” regular PMTs mounted on Winston Cones for energy resolution
To be upgraded with LAPPDs

- Possibility to scale to large detector mass
- Variety of topics including:
  - Geoneutrinos
  - Solar neutrinos
  - Supernova neutrinos
  - Neutrinoless double beta decay

Can We See Cherenkov Light in a LS Detector?

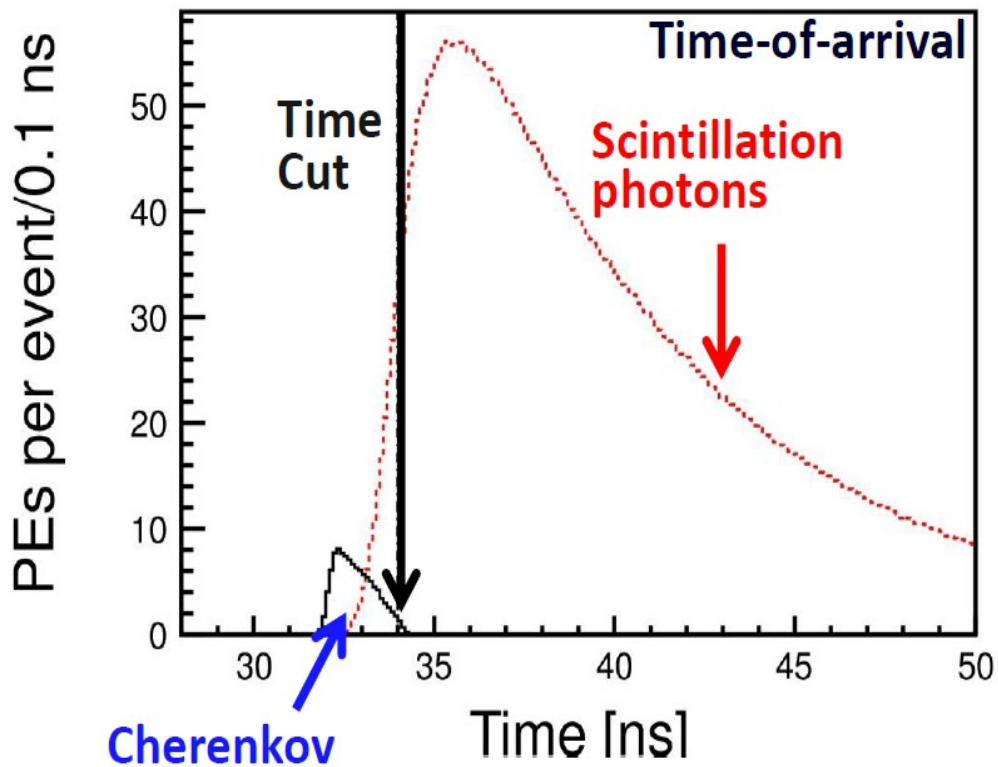
Scintillation light is more intense
Cherenkov is usually lost in liquid scintillator detectors



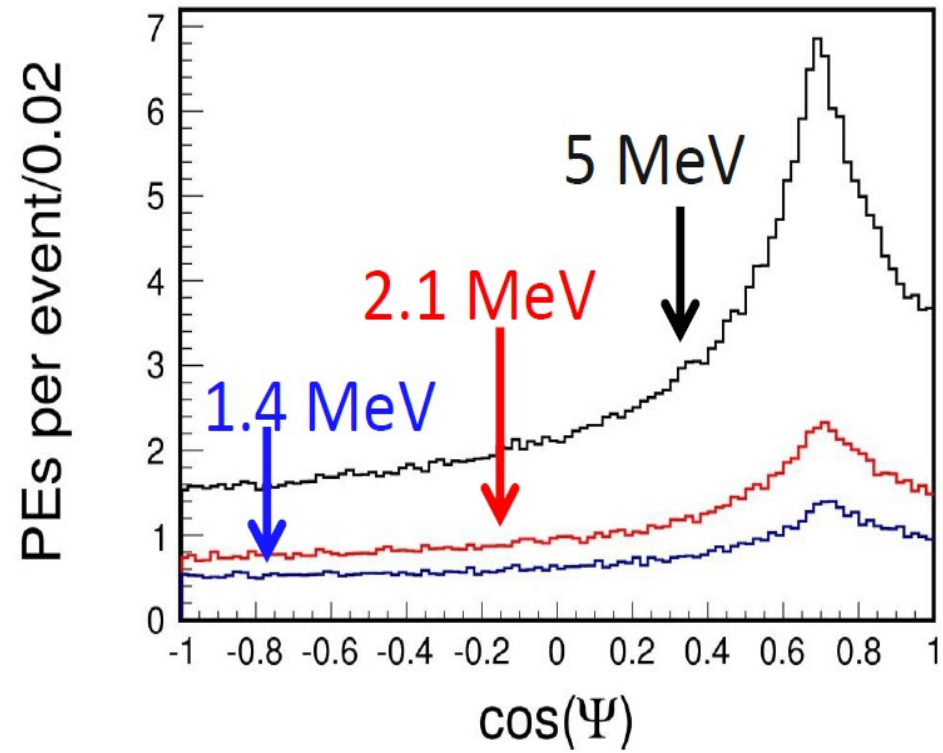


- Longer wavelengths travel faster
- Scintillation process is slow
- Cherenkov light arrives earlier

Directionality of Early Photons



Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec



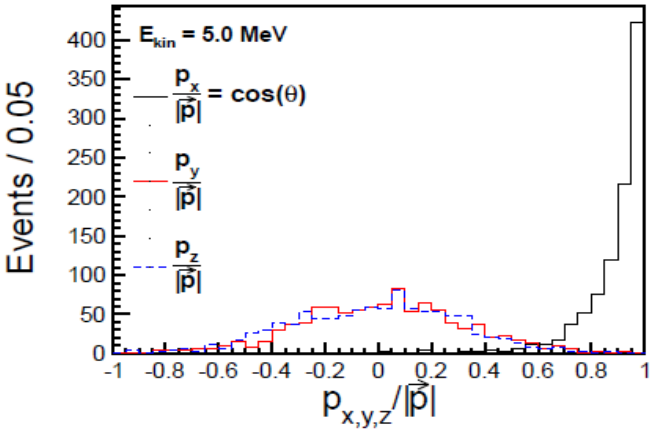
Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.

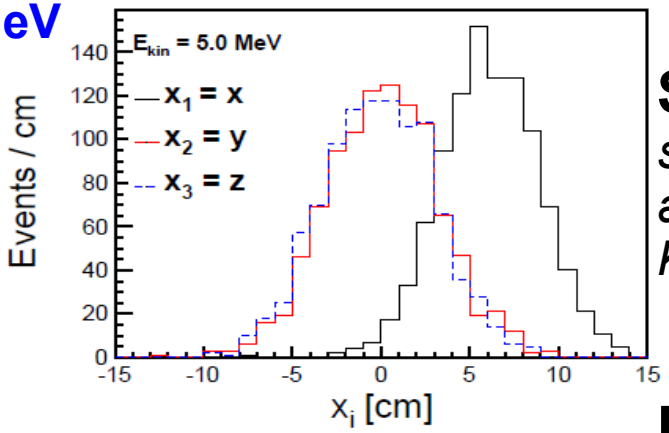
C.Aberle, A.Elagin, H.Frisch, M.Wetstein, L.Winslow
2014 JINST 9 P06012

Directionality and Vertex Reconstruction

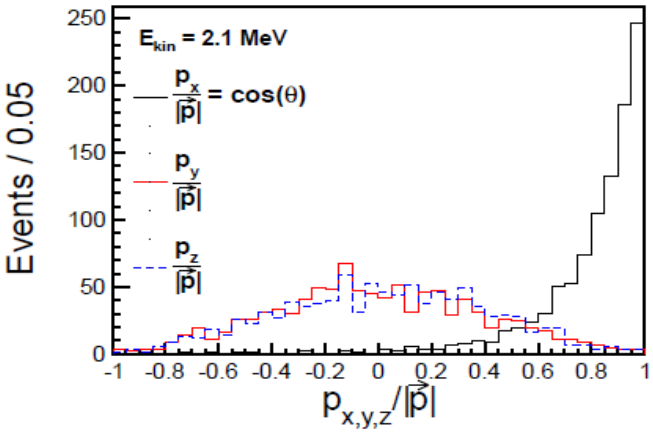
Directionality **Vertex**

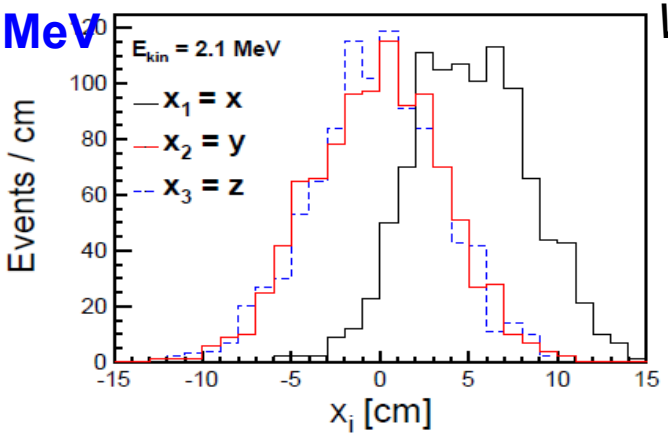
5 MeV



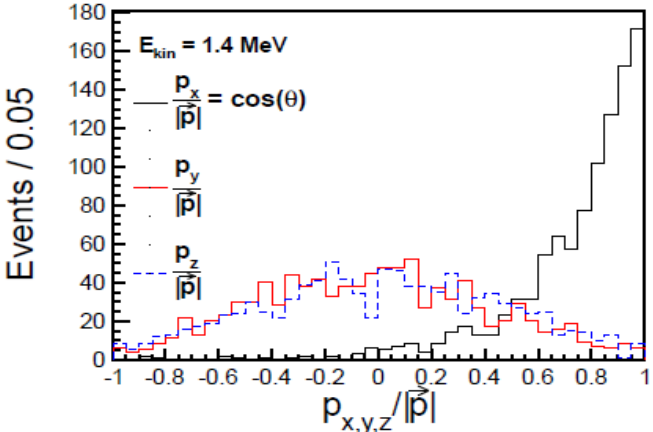


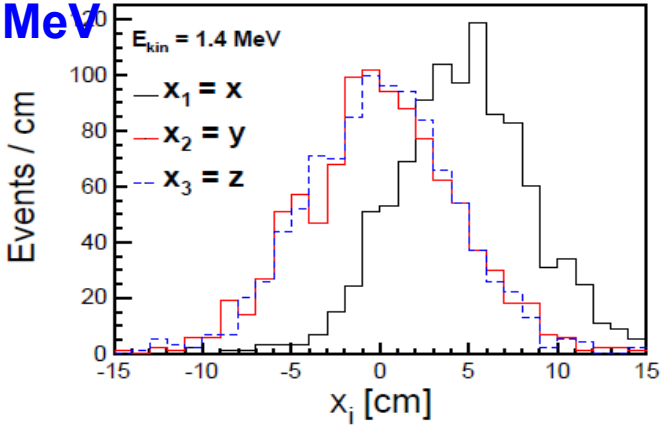
2.1 MeV





1.4 MeV





Simulation:
single electrons along X-axis at the center of 6.5m sphere KamLAND scintillator

Reconstruction:
WCSim adapted for low energy

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

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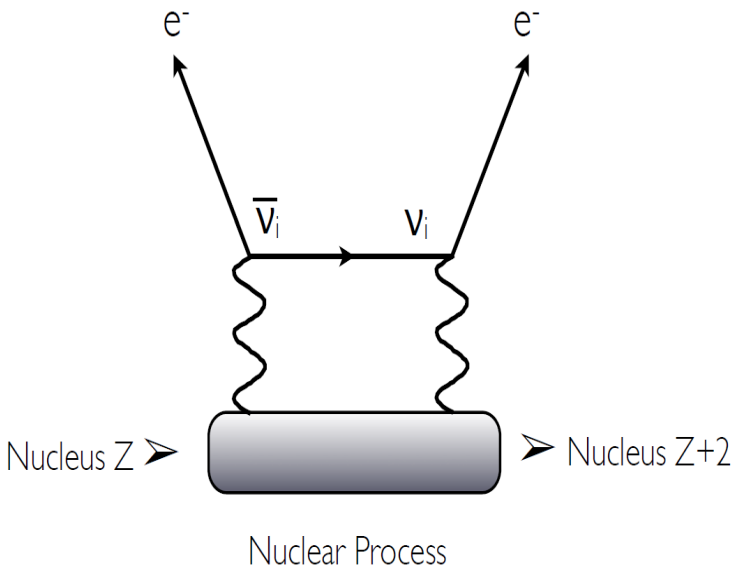
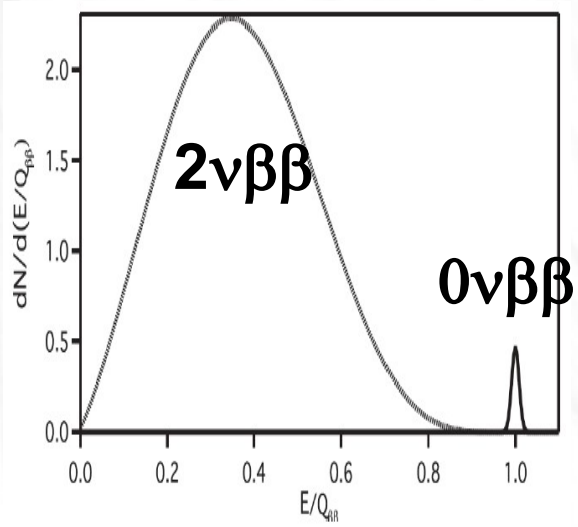
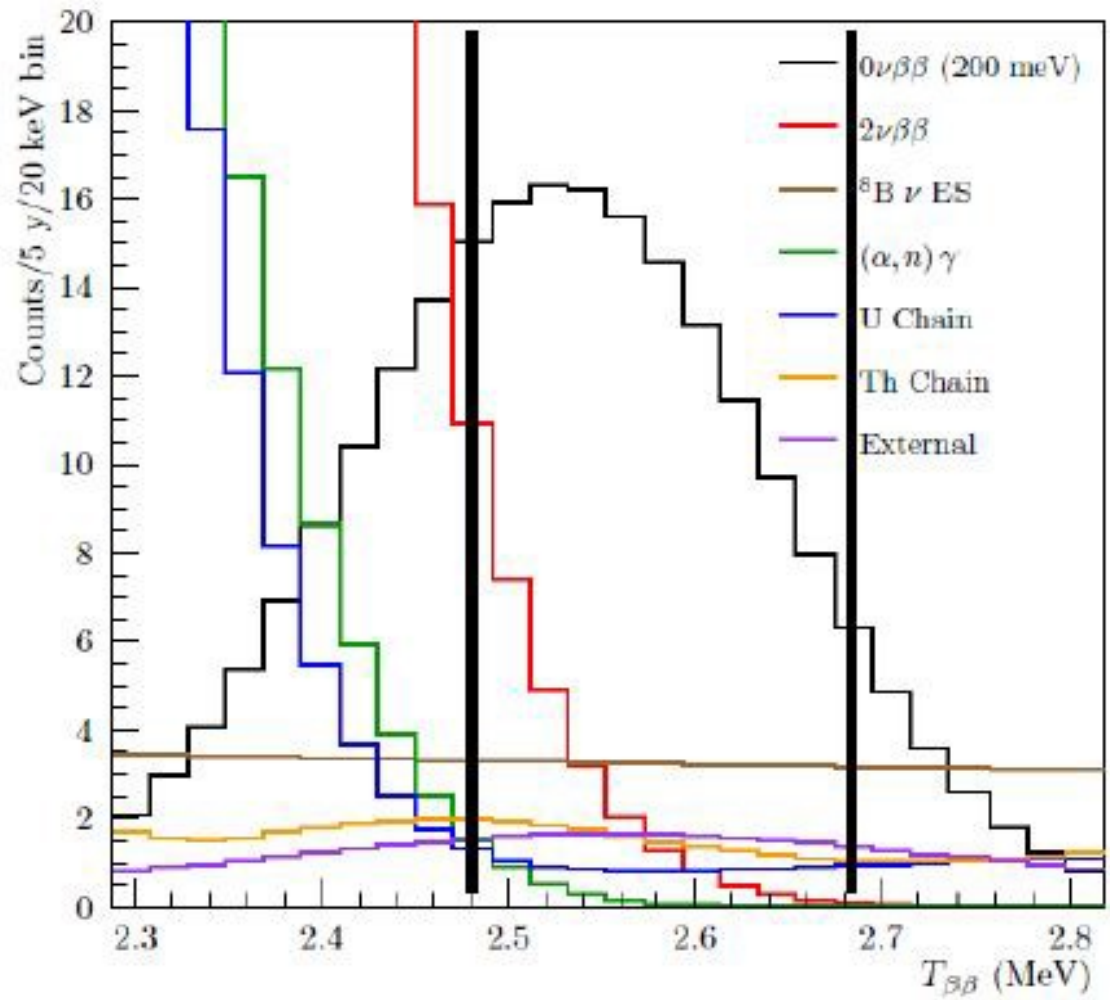
Fast Timing for 0νββ-decay





SNO+ expected energy spectrum

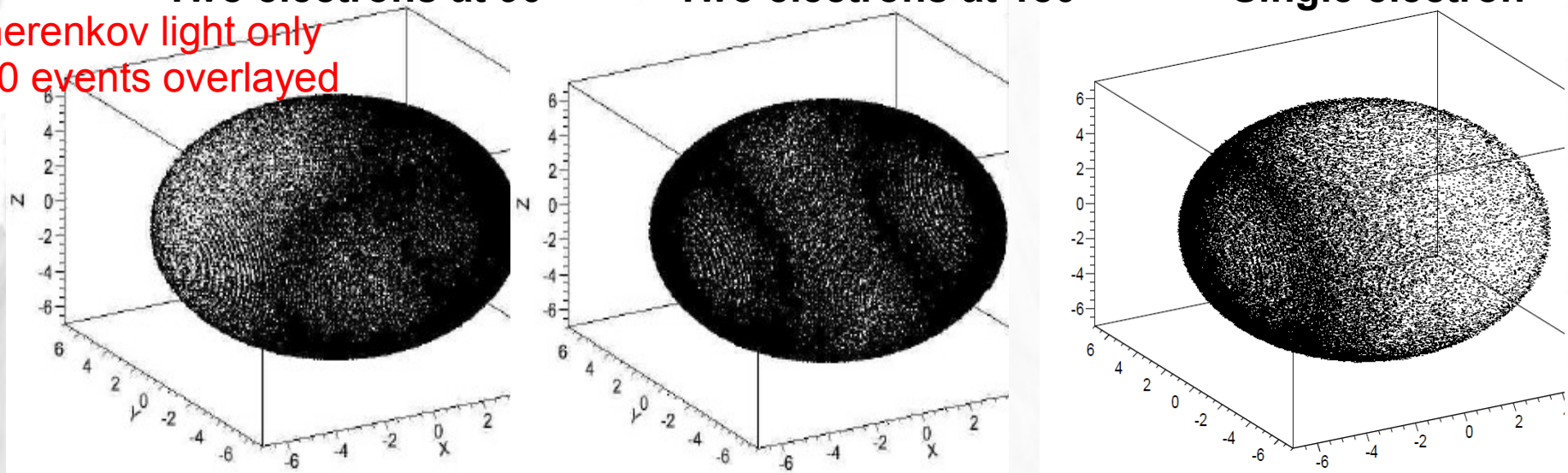


- ^{8}B solar neutrino is 2nd largest background
- It has only 1 electron

Directionality or Topology?

5 MeV
Cherenkov light only
100 events overlayed

Two electrons at 90° **Two electrons at 180°** **Single electron**



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

$$N_{(\ell,m)} \equiv \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}\,.$$

$$f_\ell^m = \int_\Omega f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi)\, d\Omega = \int_0^{2\pi} d\varphi \int_0^{\pi} d\theta \sin\theta f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi).$$

L2 norm

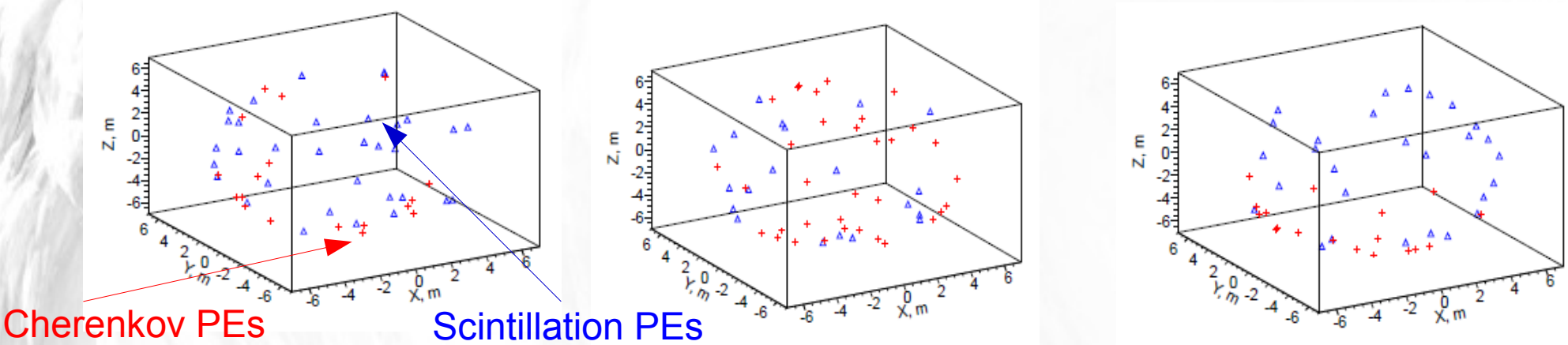
$$\int_\Omega |f(\Omega)|^2 d\Omega = \sum_{\ell=0}^{\infty} S_{ff}(\ell)$$

„Power“ (rotation invariant)

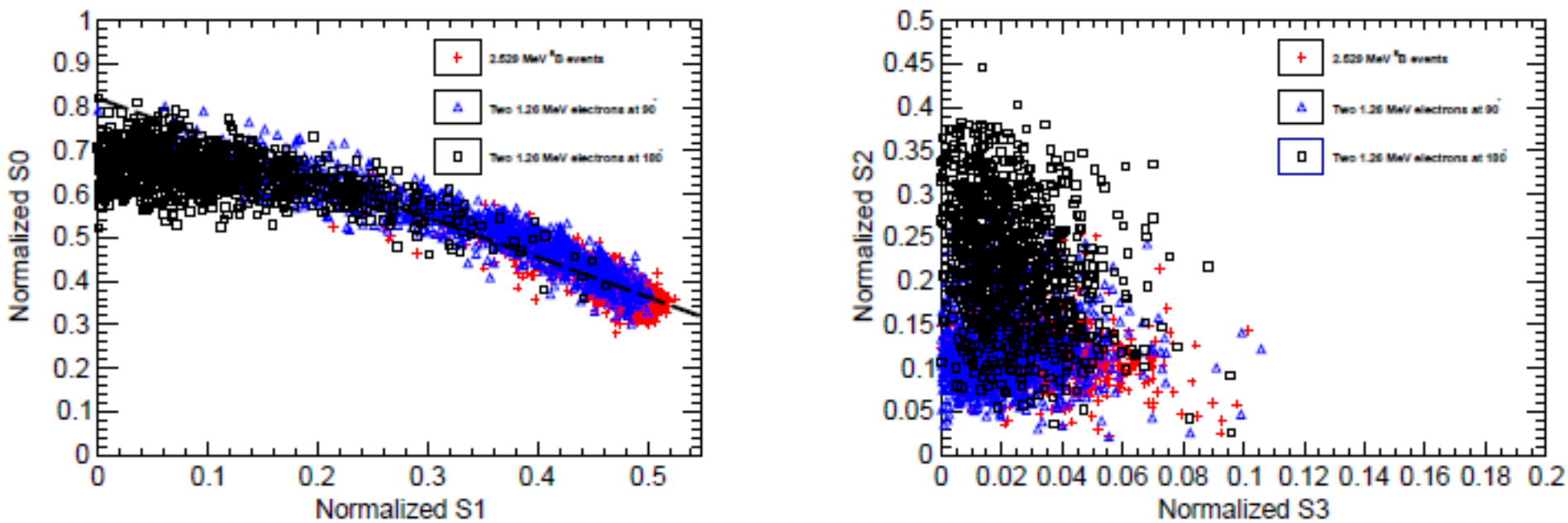
$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$

Early Light Spherical Harmonics

2x1.26 MeV electrons at 90° **2x1.26 MeV electrons at 180°** **Single 2.53 MeV electron**

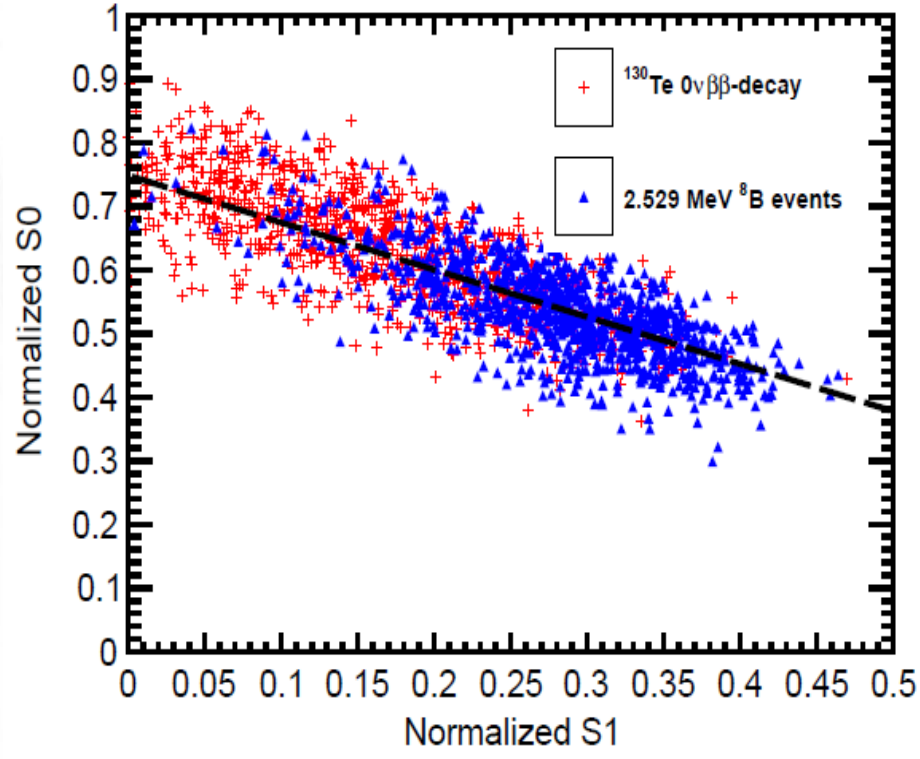


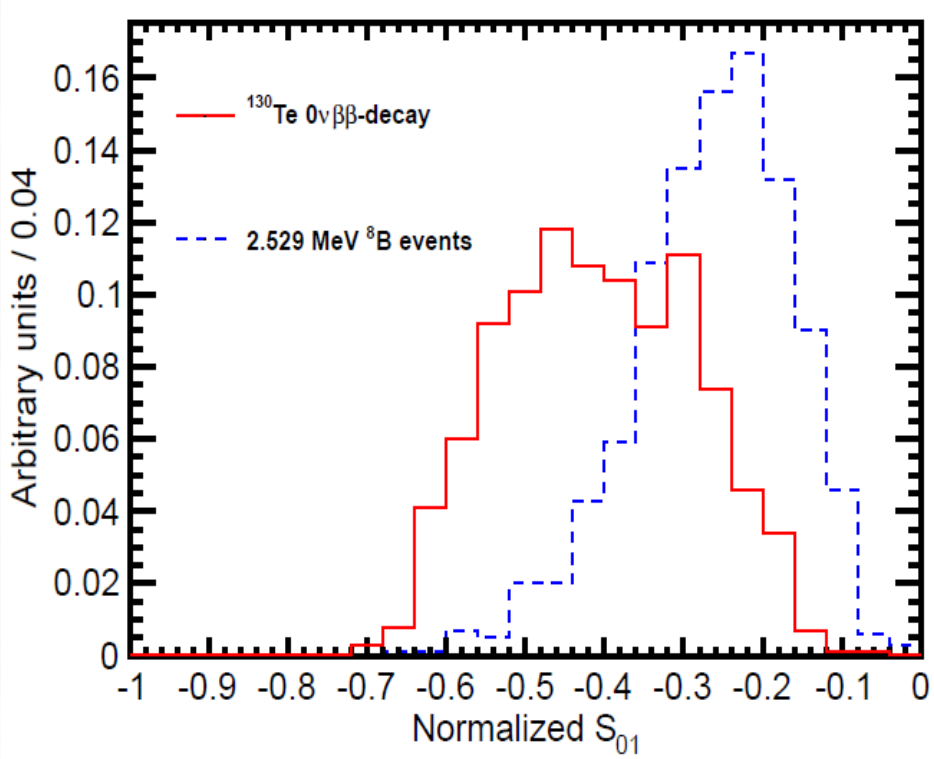
Power spectrum components SI calculated for Cherenkov light only



^{130}Te 0νββ-decay vs ^{8}B

2 tracks vs single track topology





Simulation details:

- Events are generated at the center of 6.5m spherical detector
- Scintillation spectrum and QE is taken from KamLAND simulation
- TTS=100 ps, 100% area coverage
- Early photons (both Cherenkov and scintillation) within 33.5 ns time window are considered
- Ideal vertex reconstruction is assumed

Key elements for maximum separation

- Slow emission of the scintillation light
- Good vertex reconstruction

Can we ever detect colors of individual photons?

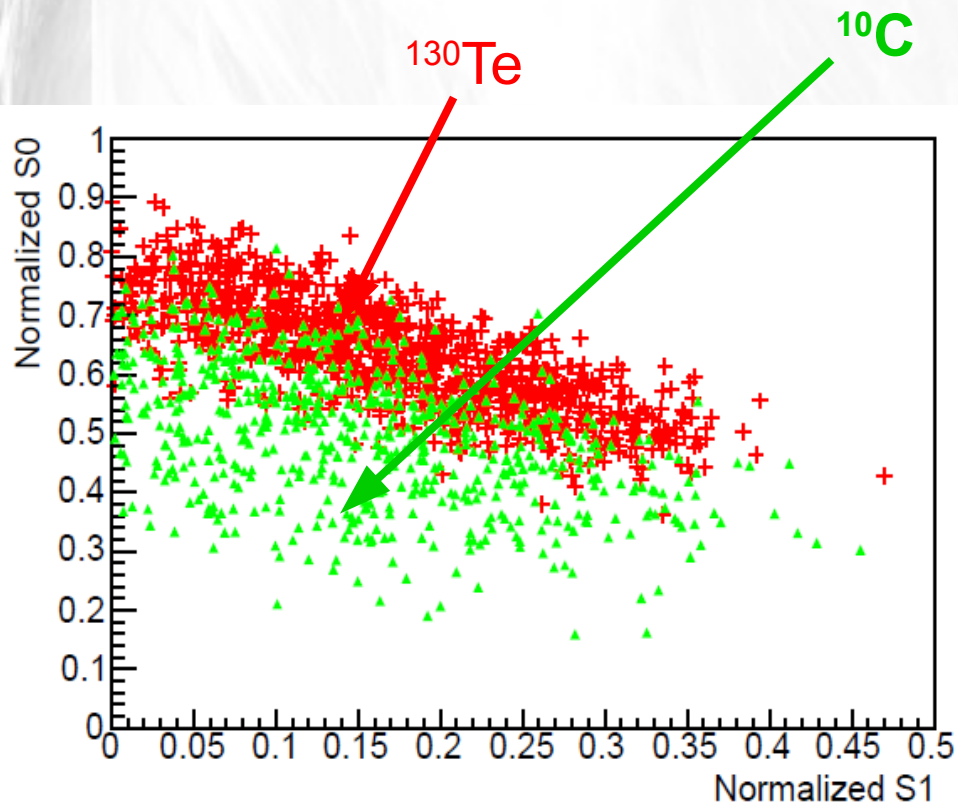
^{130}Te 0νββ-decay vs ^{10}C

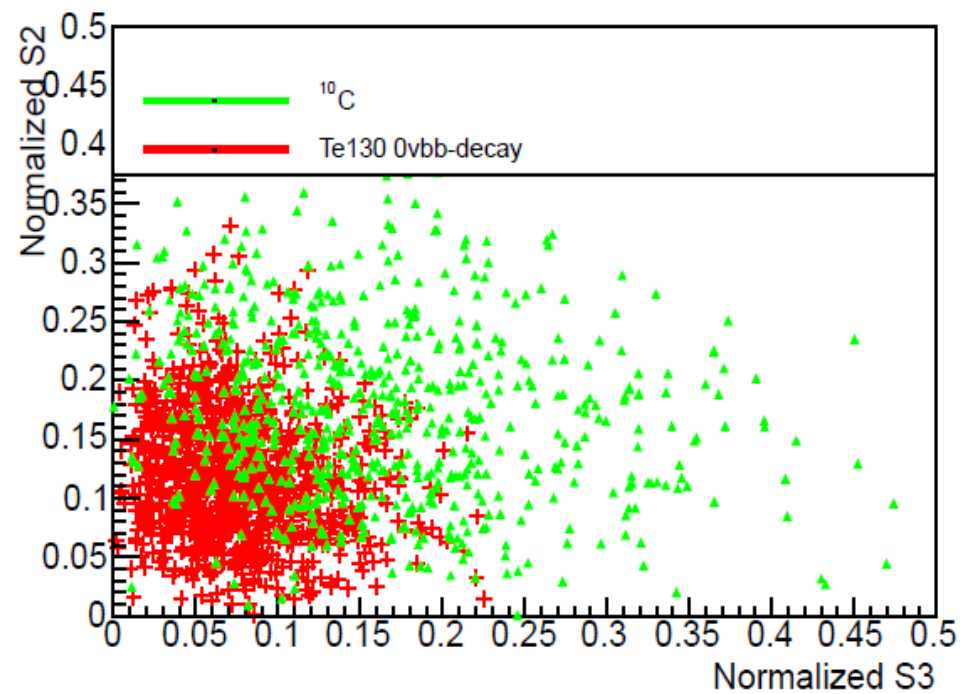
2 tracks vs a "complicated" topology

^{10}C decay modes:

[98.6%] $^{10}C \rightarrow {}^{10}B(718) + e^{+} \rightarrow {}^{10}B(0) + \gamma$ **T(1/2) ~ 1 ns**

[1.4%] $^{10}C \rightarrow {}^{10}B(1740) + e+ \rightarrow {}^{10}B(718) + \gamma$ **T(1/2) ~ ps**



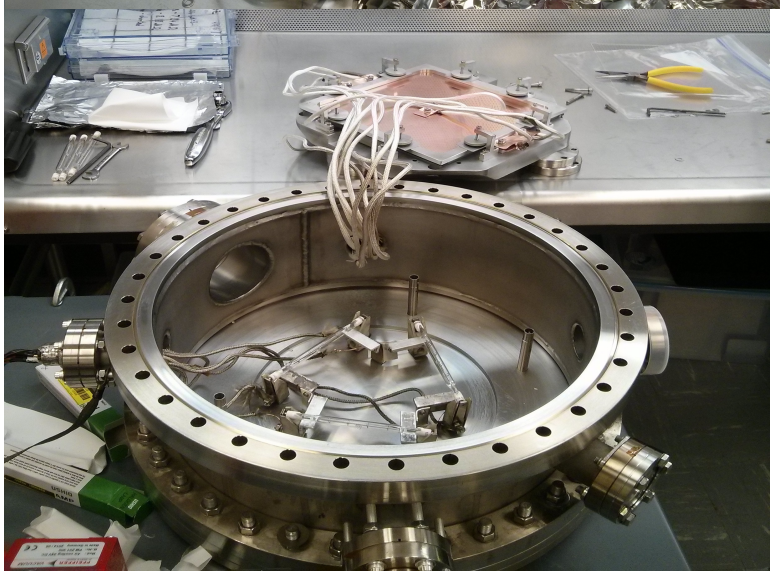


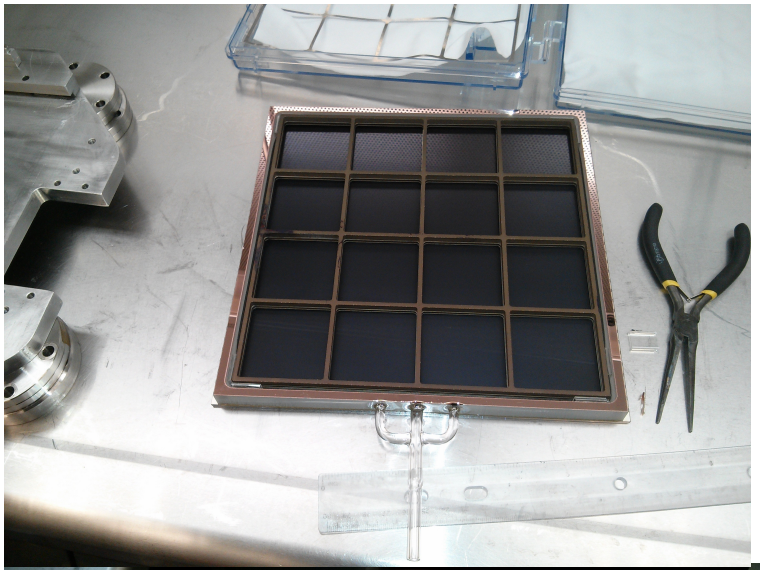
^{10}C would be dominant background at shallow depth

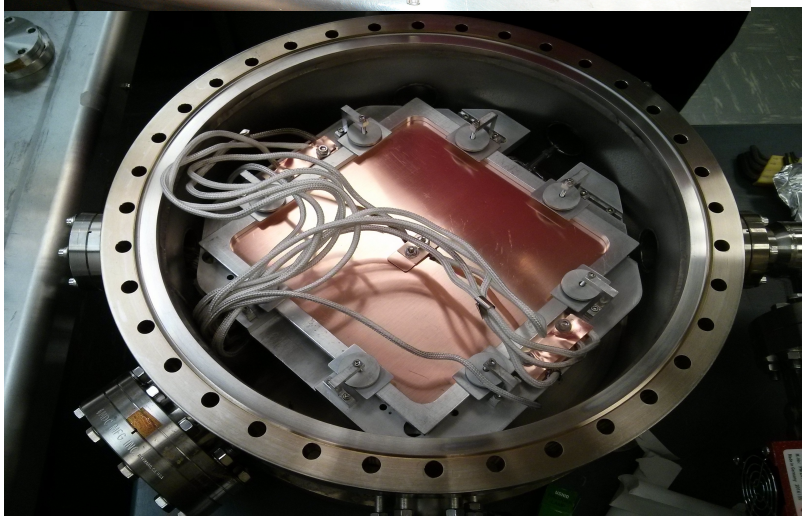
Thank you

Back Up

Back-up: more details on the vacuum chamber





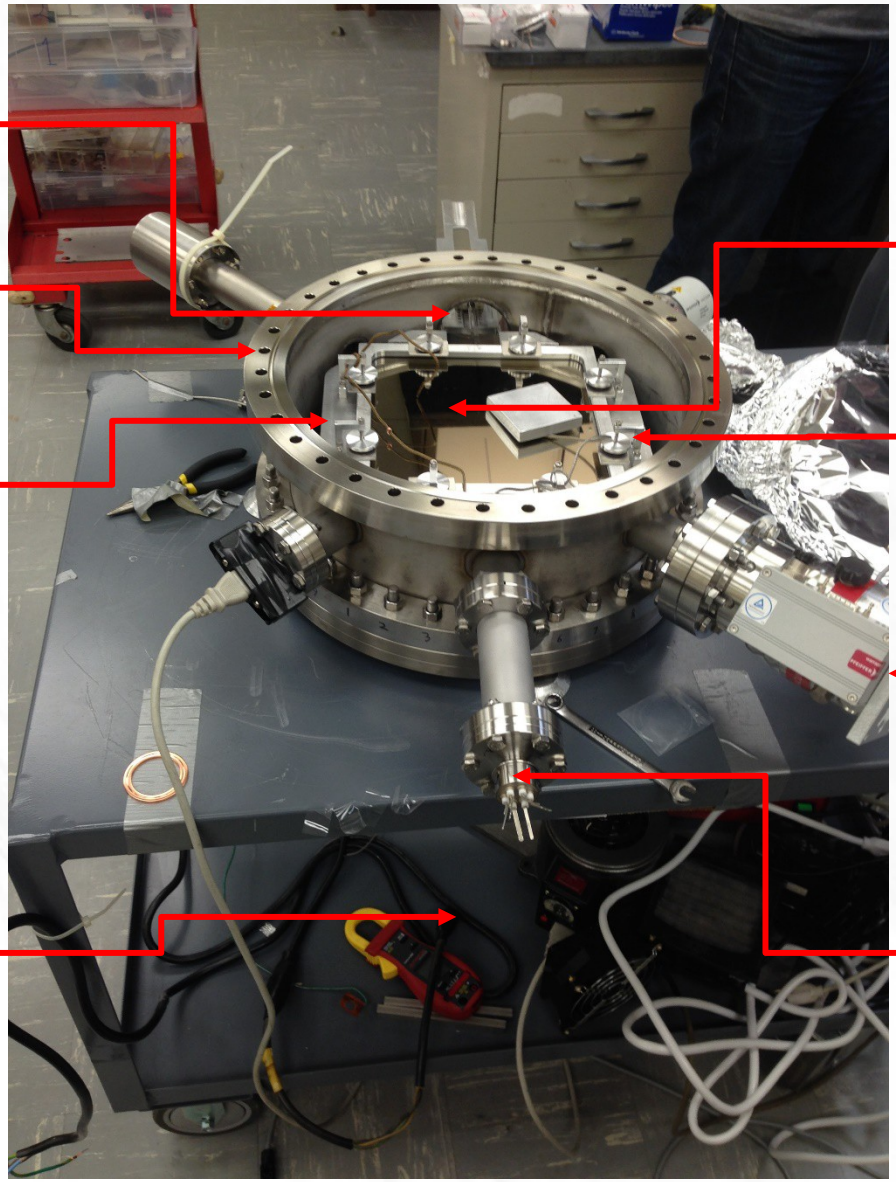


Inner vacuum to tile and for bi-alkali vapor

Standard 16.5” ConFlat flange

Tile fixture heated (350C) by quartz lamps underneath

Raspberry Pi process data logger- temperatures (10), pressures, RGA,…



Sealed tile (no getter this shot)

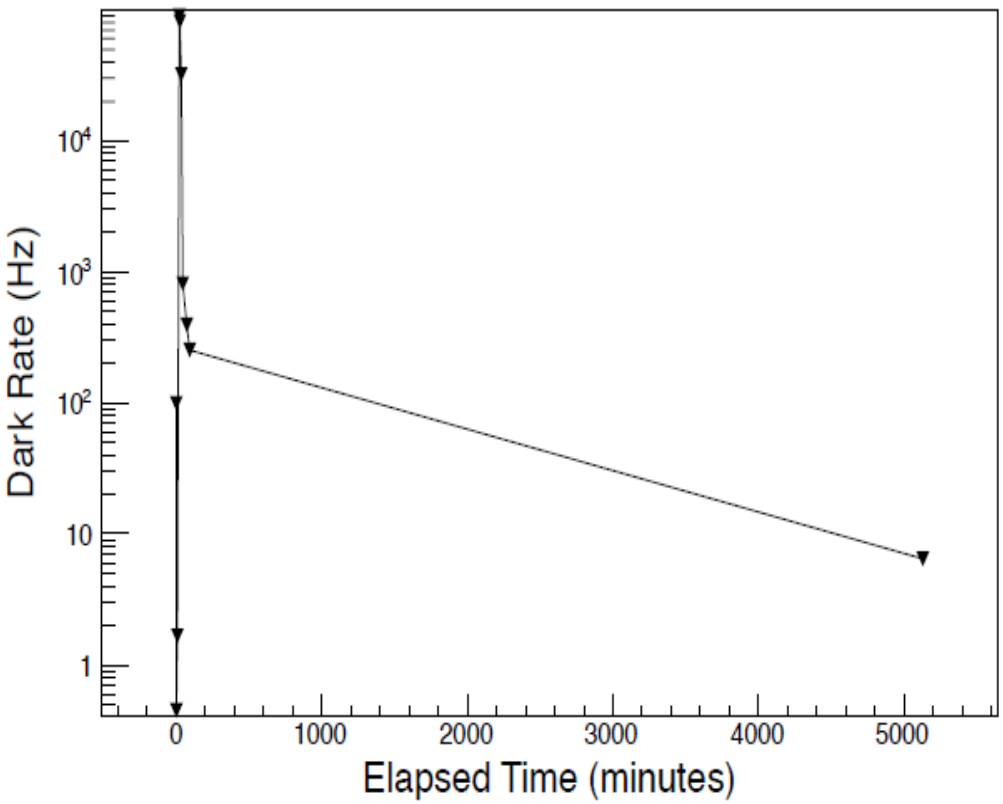
Precision load and positioning fixture for seal

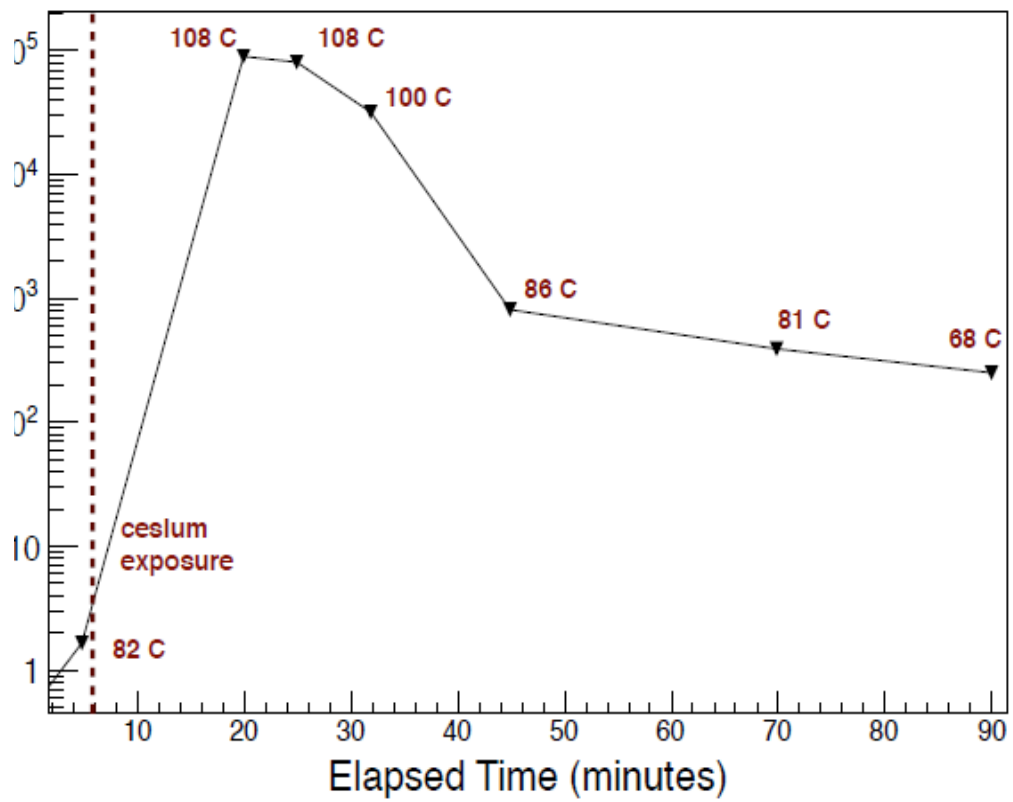
Outer vacuum for seal process

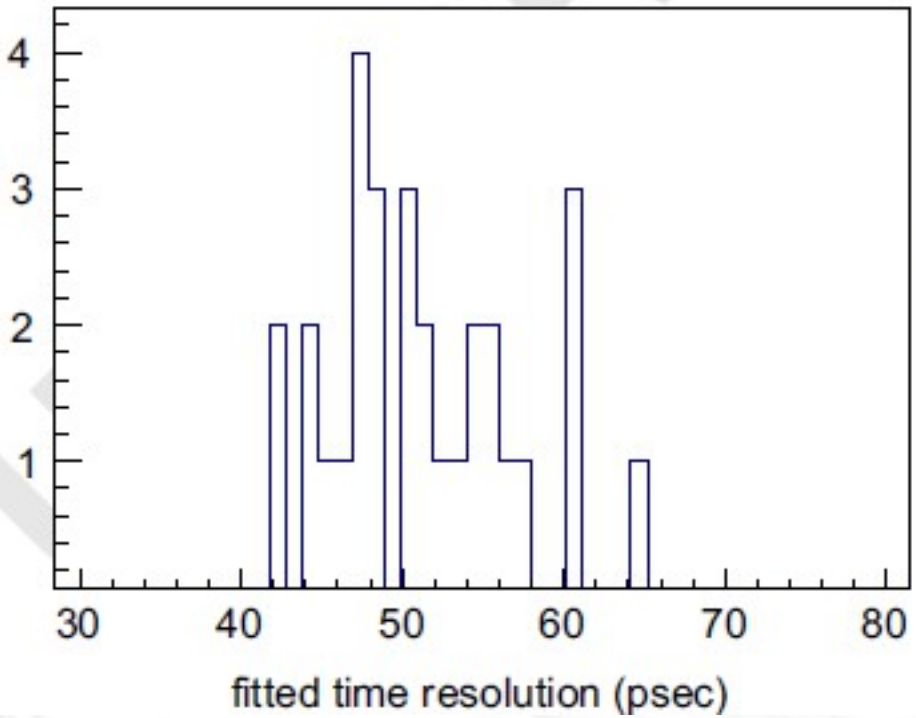
Thermocouples feedthrough

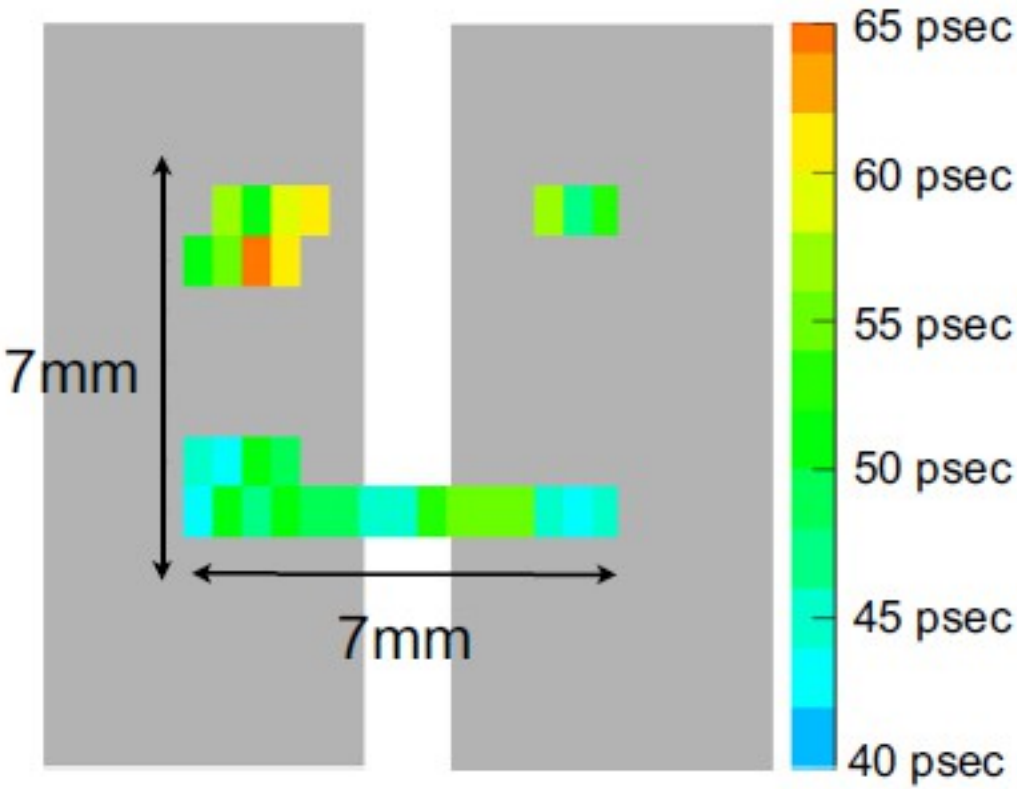
„In-Situ“ LAPPD assembly at UChicago
Critical component #2: in-situ photo-cathode activation

Studied effect of exposing the MCPs to Cs vapors
- MCP become noisy at first, but then go back to normal



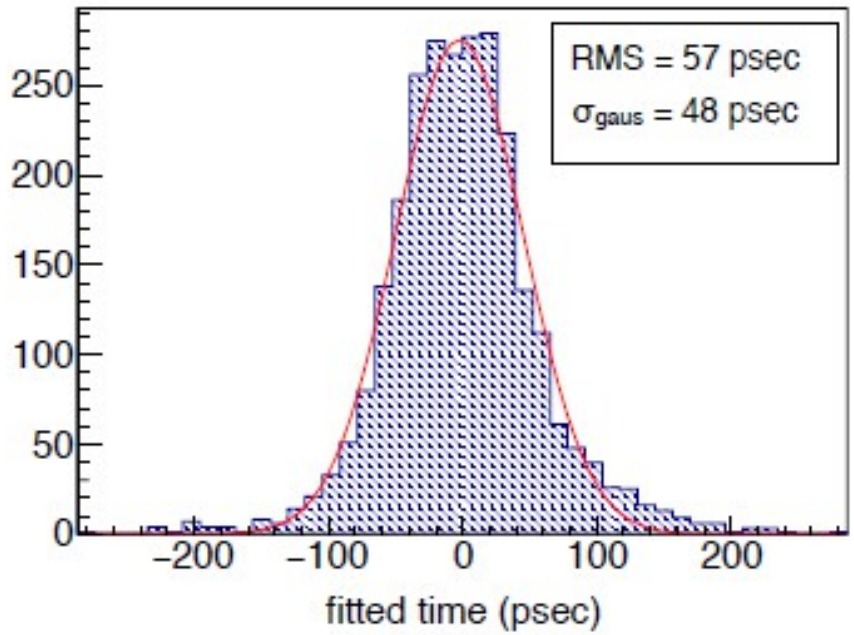



4
3
2
1
30
40
50
60
70
80
fitted time resolution (psec)

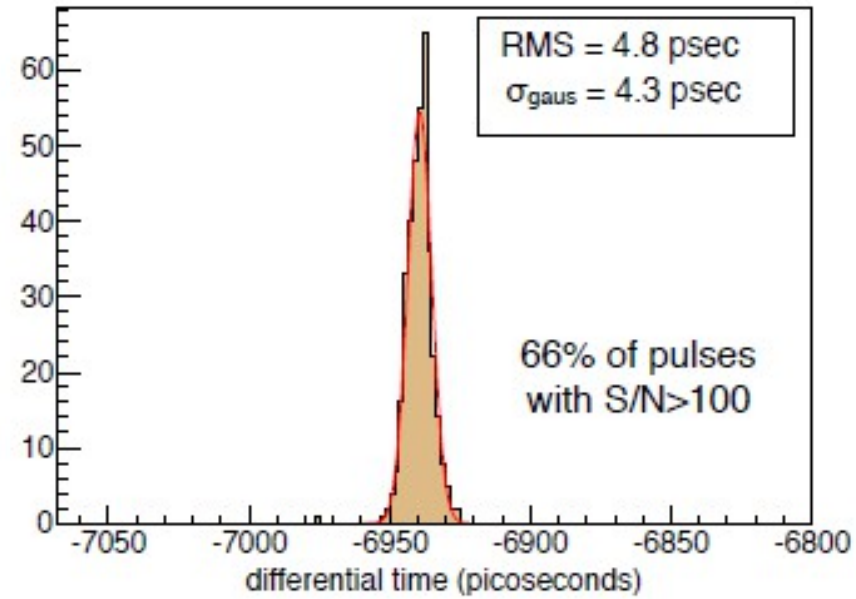

7mm
7mm
65 psec
60 psec
55 psec
50 psec
45 psec
40 psec

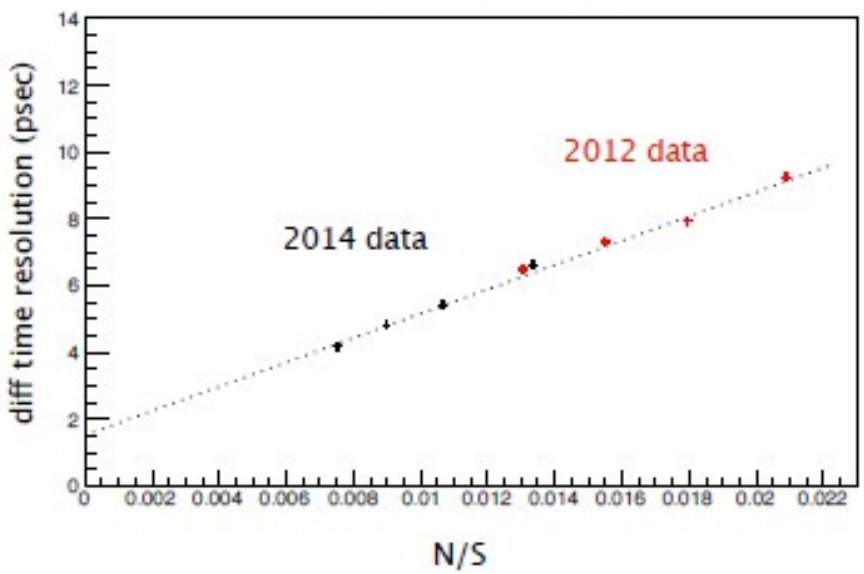
LAPPD capabilities

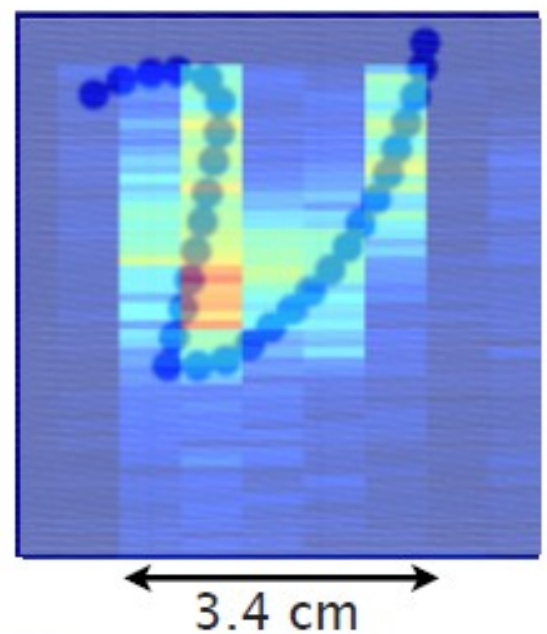
single photoelectron absolute time resolution



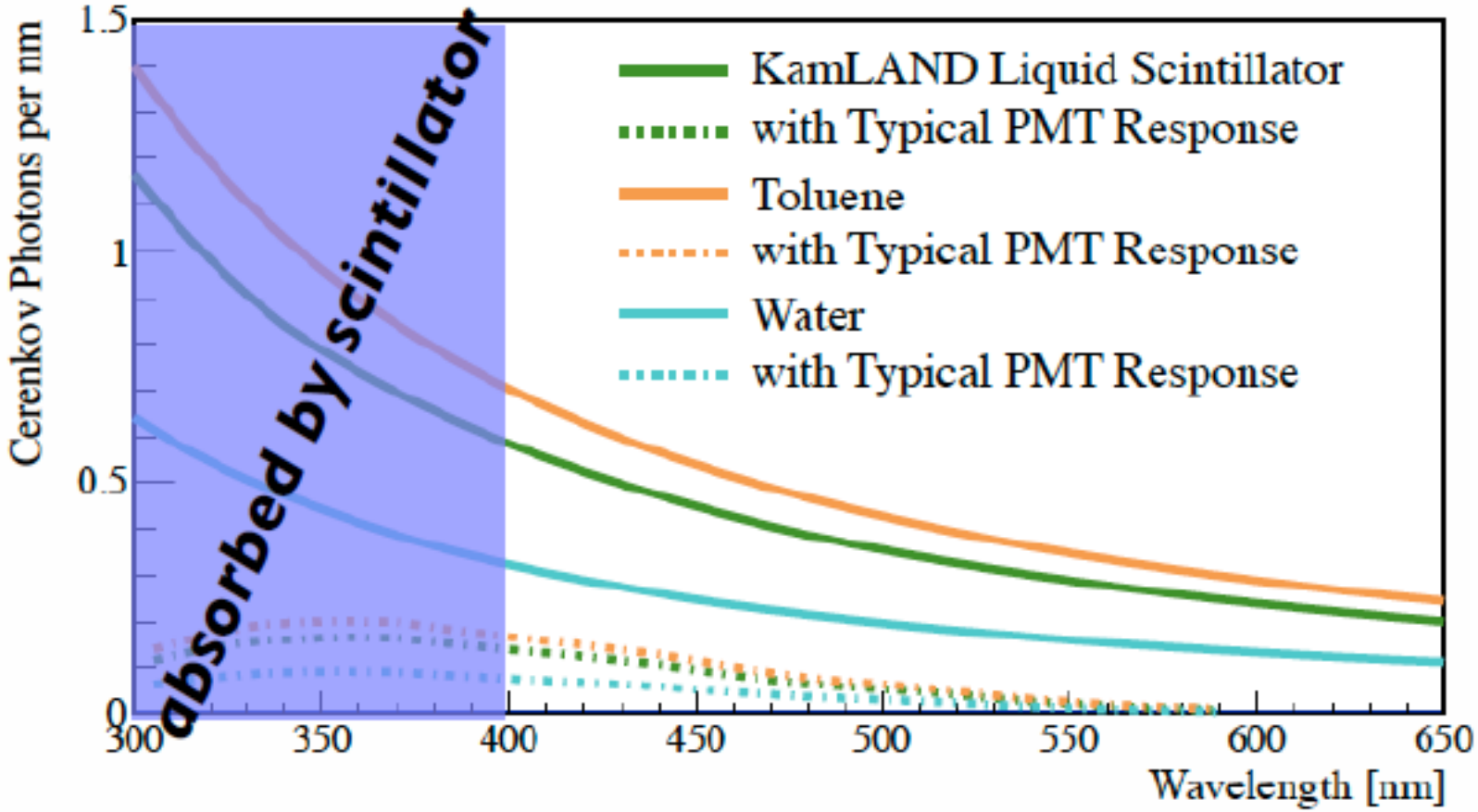
differential time resolution between 2 ends of stripline





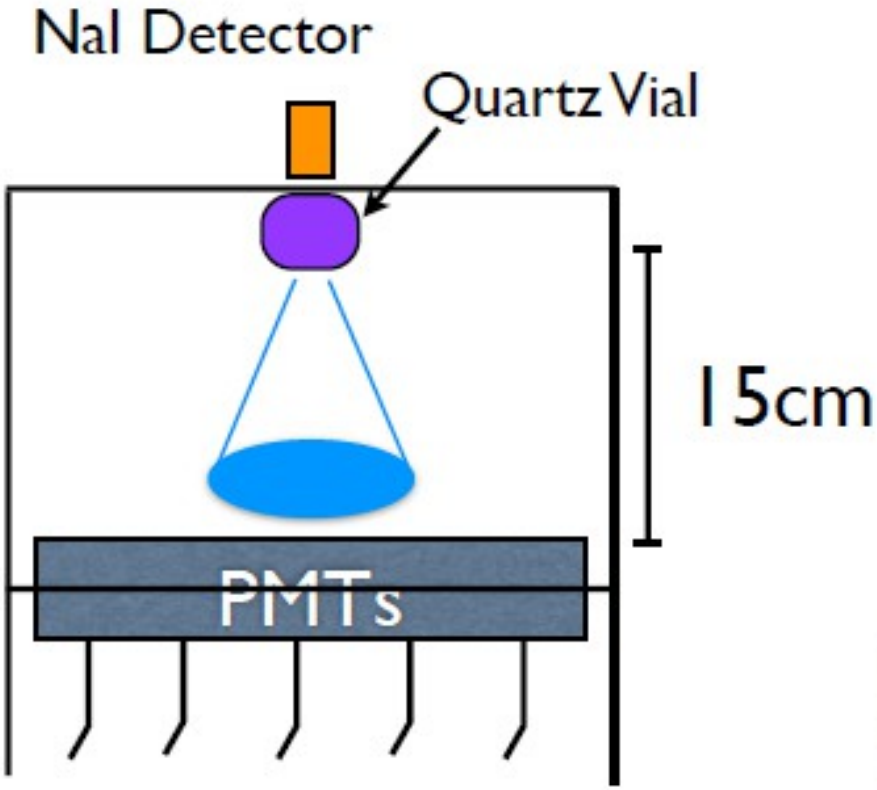


Number of Cherenkov Photons for a 1MeV e-

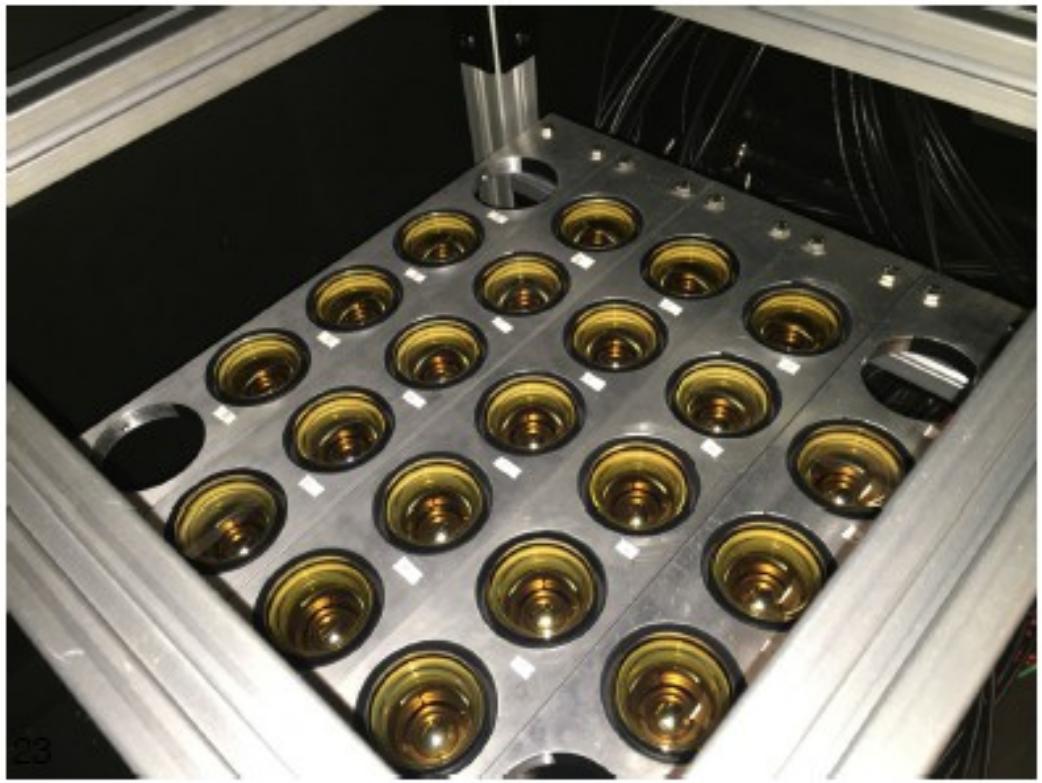


Retains directional information!

Demonstration of Cherenkov/ scintillation separation using tagged Compton source.

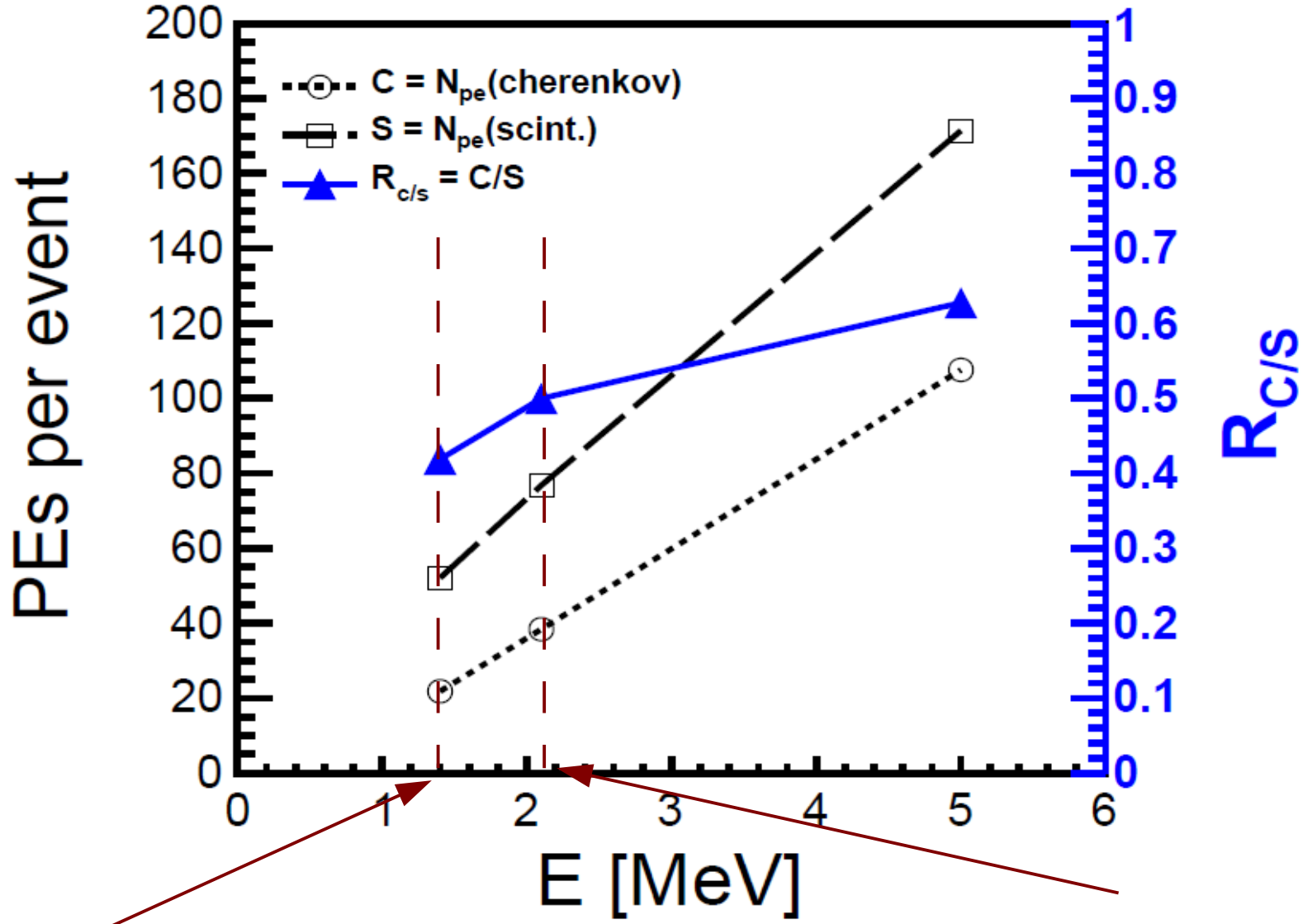


In additions, excellent system for testing new data acquisition system and testing different scintillator cocktails.

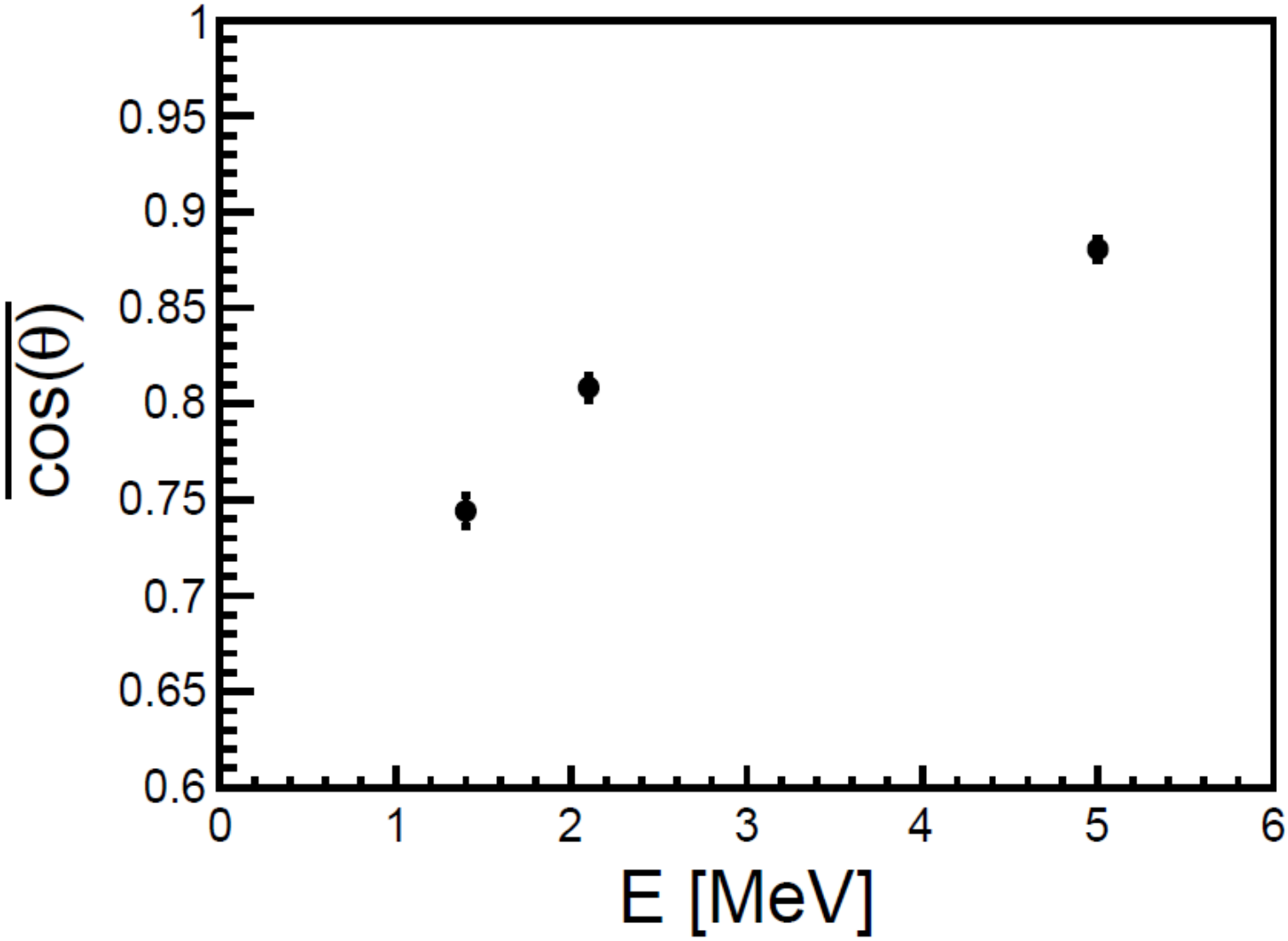


What About Lower Energies?

Light yield: Cherenkov vs scintillation



½ Q (^{116}Cd) =1.4 MeV

½ Q (^{48}Ca) =2.1 MeV

What About Lower Energies?