Drifting Photons on Optical Paths, Mirrors, Sub-mm Resolution in Four Dimensions, and Six-Dimensional Phase Space: Exploiting Psec Time Resolution

Henry Frisch
Enrico Fermi Institute and Physics Department
University of Chicago

Abstract

I will discuss MCP-based photo-detector amplification sections and Cherenkov light sources for measurements of charged particles and gamma rays. Sub-psec resolution is predicted for the large pulses such as those produced by a charged particle or electromagnetic shower traversing a photo-detector entrance window. Measuring events with sub-mm resolution in space and time expands the optical phase space from 4 to 6 dimensions, allowing the use of mirrors to minimize expensive instrumented photo-sensitive area.

Three Timing Cases to Distinguish

The factors limiting the ultimate timing resolution are different in each of the following cases:

1. Single optical photons (Scintillation or Cherenkov)
2. Charged Particles above Cherenkov Threshold(H2O,glass)
3. Electromagnetic showers from High Energy photons

I will talk first about #2 and #3, relativistic charged particles and high energy photons, for which psec or sub-psec time resolutions I believe are plausible given certain detection criteria are met, before moving on to #1, for which ultimate resolutions are determined by other factors and are significantly larger.

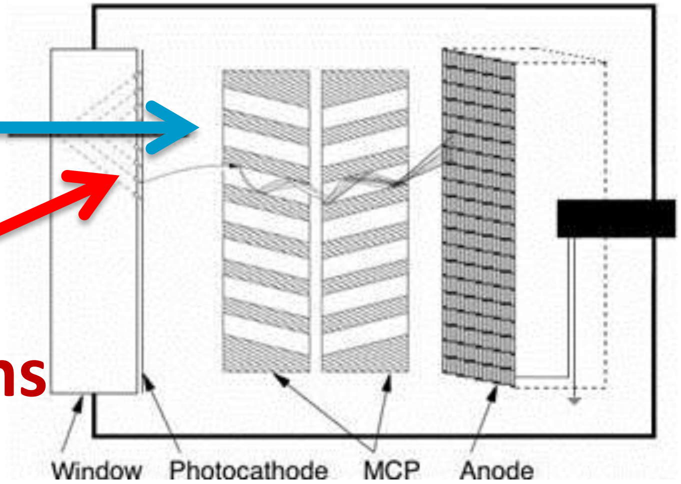
Note: In what follows I treat time and space distances in the same units, i.e. c=1, and 1 psec =300 microns; 1 nsec =1000 psec; 1 nsec =1 foot

Criteria for Sub-Psec Timing-1

Fast Source: A psec source in time-space of many photons in a time-space interval (example: Cherenkov light from a charged particle traversing a radiator or the entrance window of a photodetector);

e, mu, pi, K, p,…

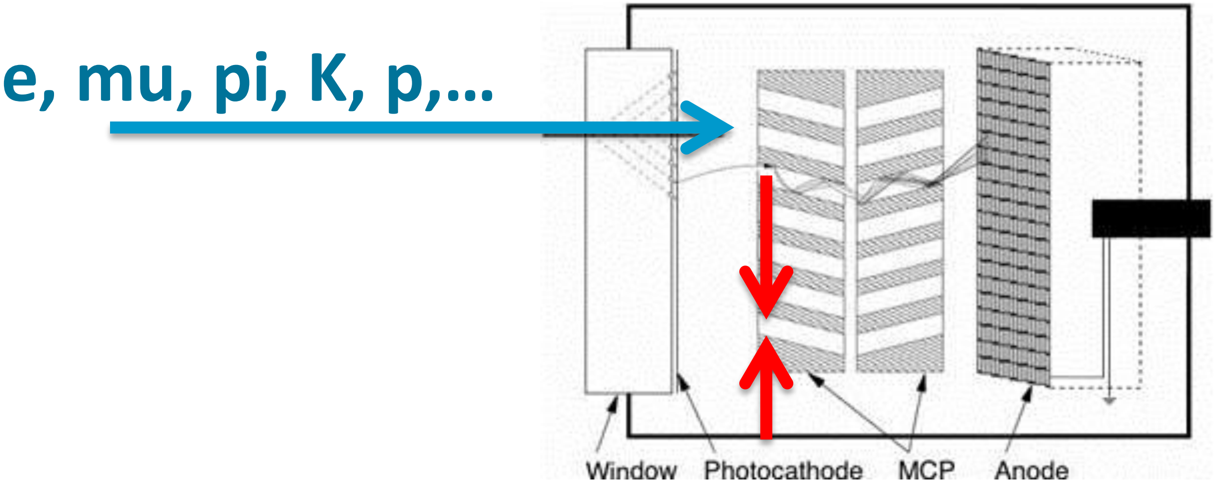
Cherenkov photons



(Or early in an electromagnetic shower such as in a pre-radiator or EM calorimeter (separate discussion));

Criteria for Sub-Psec Timing-2

Psec-level pixel size (example: 10-20 micron pores in an MCP plate)

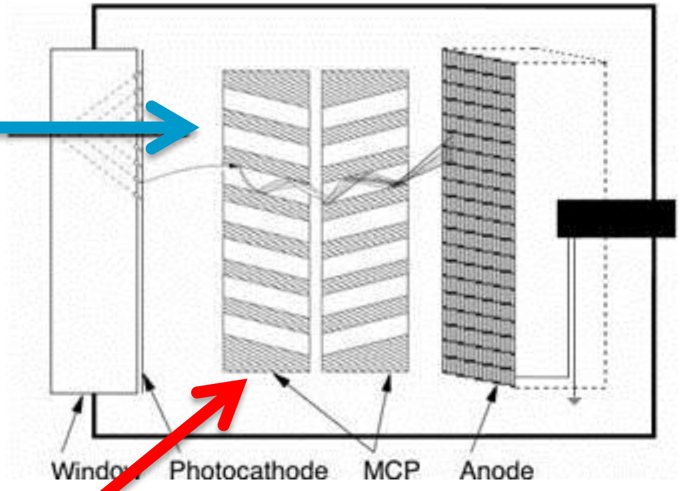


10-20 micron pore

Criteria for Sub-Psec Timing-3

High gain: The gain has to be high enough that a single photon triggers, i.e. the first photon ‘in’ determines the leading edge of the pulse and consequently the timing.

e, mu, pi, K, p,…



Amplification section: Gain-bandwidth, Signal-to-Noise, Power, Cost (eg: two-stages of MgO MCPs give gain >10^7)

Criteria for Sub-Psec Timing-4

Low noise; Voltage jitter under the leading edge translates to time jitter crossing threshold.

noise;

low threshold;

"Either cheer up or take off the hat."

Signal-to-Noise, Rise-time Dependences

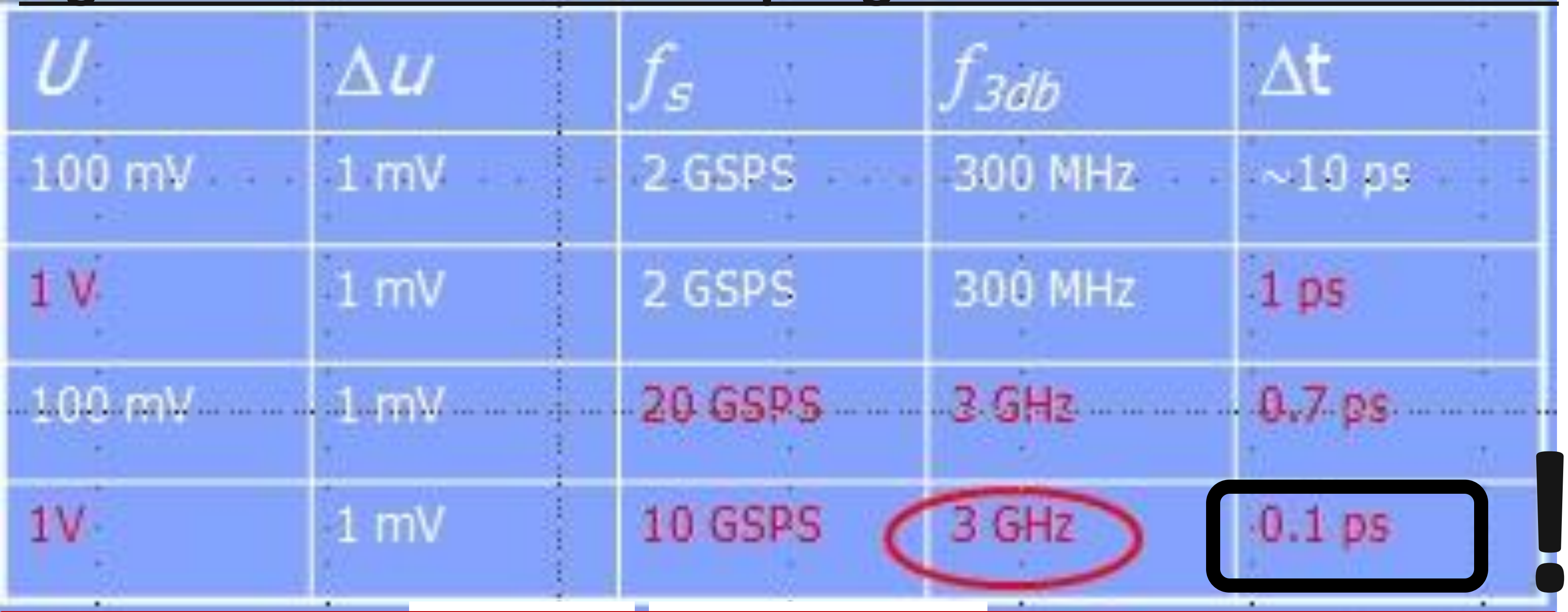
Long discussions (UC workshops) of dependence on analog bandwidth, gain, noise, digitization methods, etc. ;

Answer (S. Ritt) is that at the level of present performance, using waveform sampling, the achievable time resolution is well-described by three parameters: 1) analog band-width (aka rise-time); 2) signal-to-noise; and 3) the sampling rate (assuming sufficient number of bits not to limit).

- **Show typical pulses (Event 0, so not typical, but random)**
- **Show waveform sampling**
- **Show Stefan Ritt's Rule-of-Thumb. For a sampling rate proportional to analog bandwidth it's only 2 parameters.**

Breaking the 1-Psec Barrier?

Stefan Ritt (PSI) table from 2nd Chicago Photocathode Workshop (annotated) (see psec.uchicago/edu/library)

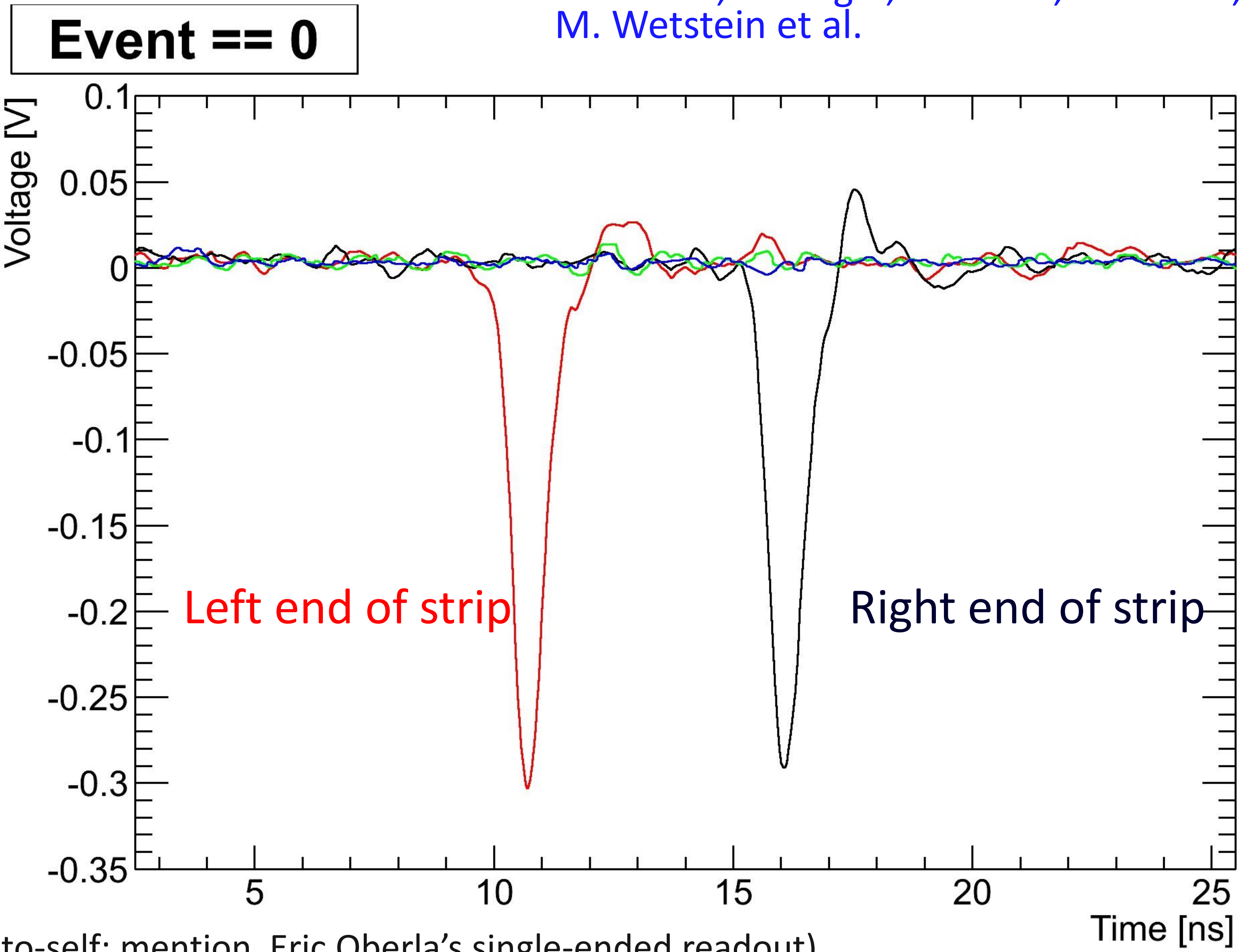


Signal	Noise	Sampling	Bandwidth	Resolution
U	Δu	f_s	f_{3db}	Δt
100 mV	1 mV	2 GSPS	300 MHz	~10 ps
1 V	1 mV	2 GSPS	300 MHz	1 ps
100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
1V	1 mV	10 GSPS	3 GHz	0.1 ps !
LAPPD: 1V	**0.7 mv**	**15 GS/sec**	**1.5 GHz**	**??**

Before 100 fsec something else will surely bite us, but still…

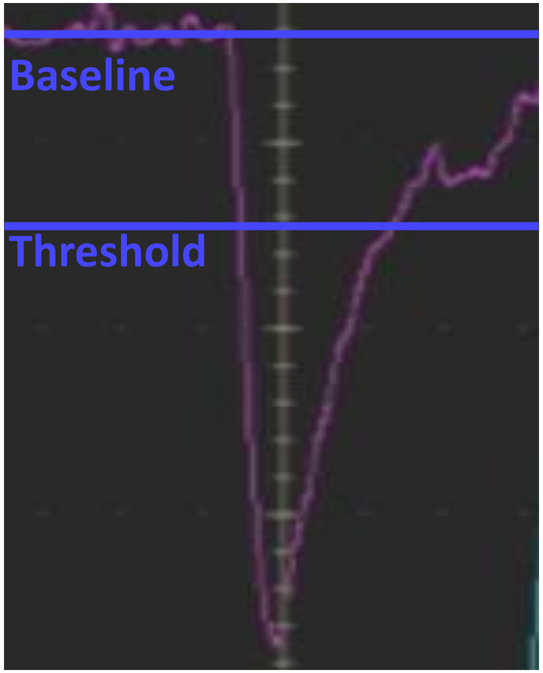
Pulses from a pair of 8” MCP Al2O3 plates

B. Adams, A. Elagin, R. Obaid, E. Oberla,
M. Wetstein et al.

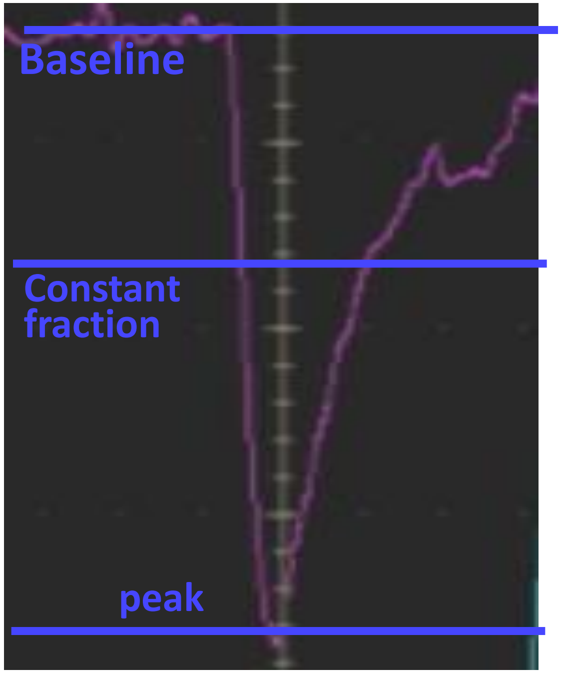


(Note-to-self: mention Eric Oberla’s single-ended readout)

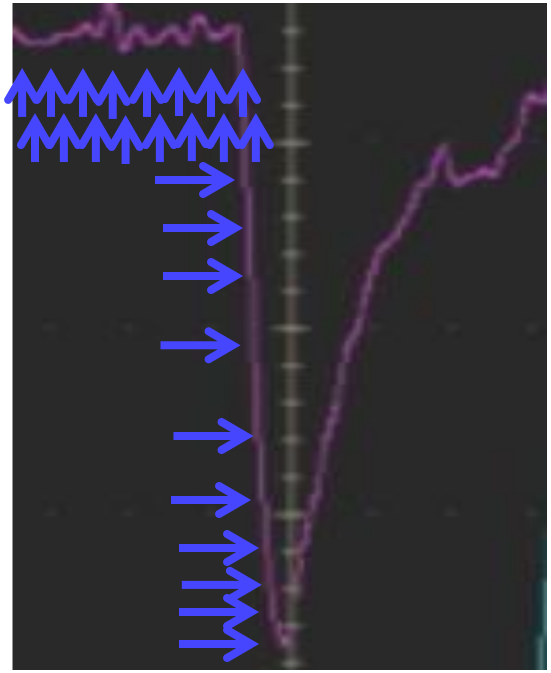
Measuring time t_0 from a pulse



Simple discriminator (single threshold)



Constant Fraction discriminator (CFD)



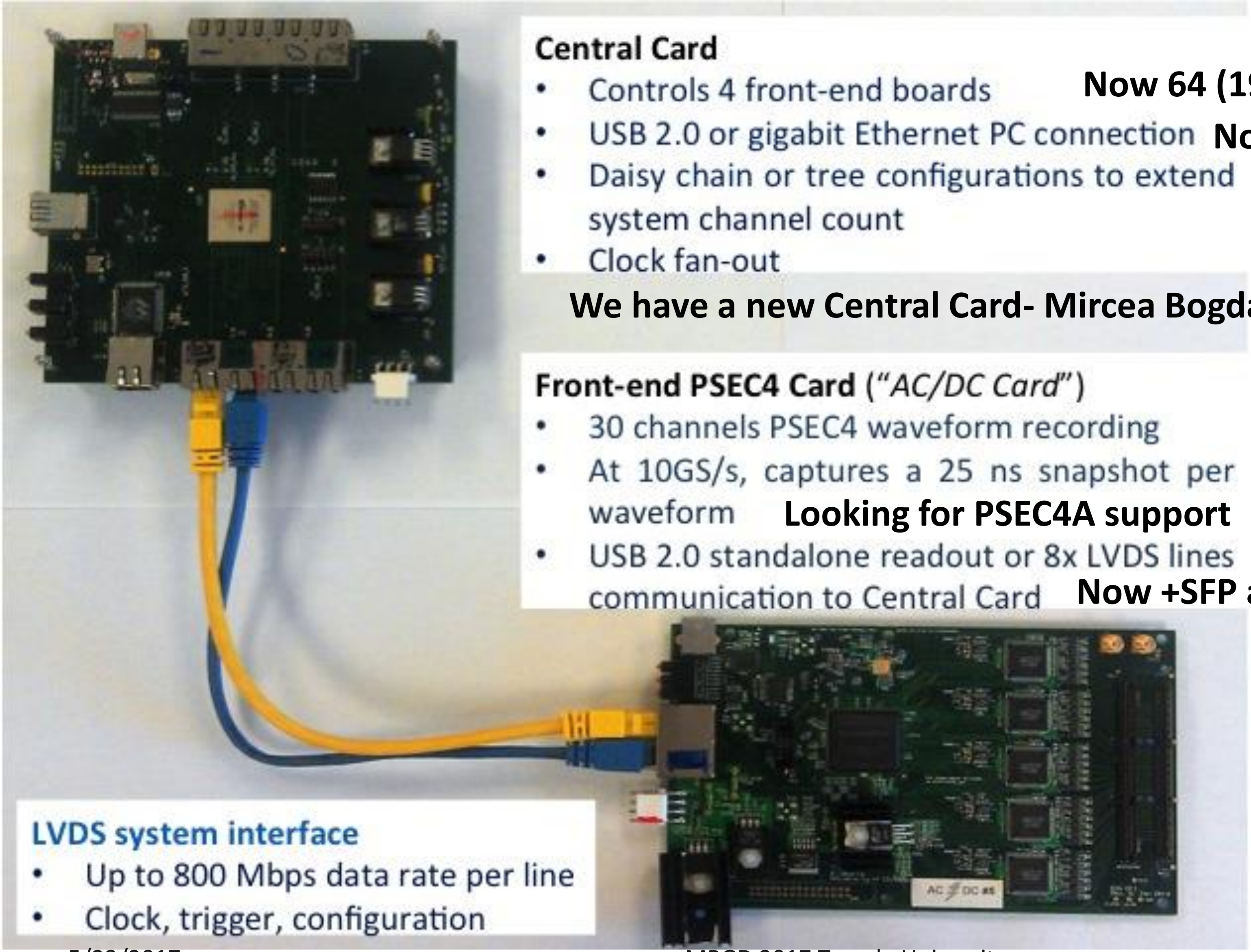
10 GS/sec Waveform Sampling (10 bits/pt PSEC4)

Waveform sampling is basically a fast digital scope on each channel- measures the baseline, pulse shape, pile-up, and allows averaging the noise with N samples on the leading edge (noise can have higher bandwidth than signal, unfortunately)

J.-F. Genat, G.Varner, F. Tang, HJF; *Pico-second Resolution Timing Measurements*; Nucl.Instrum.Meth.A607:387-393,2009; arXiv:0810.5590

`Homebrew' 15 GS/sec CMOS Waveform Sampling System

Eric Oberla's Ph.D thesis



Central Card

- Controls 4 front-end boards **Now 64 (1920 channels)**
- USB 2.0 or gigabit Ethernet PC connection **Now +SFP and VME**
- Daisy chain or tree configurations to extend system channel count
- Clock fan-out

We have a new Central Card- Mircea Bogdan

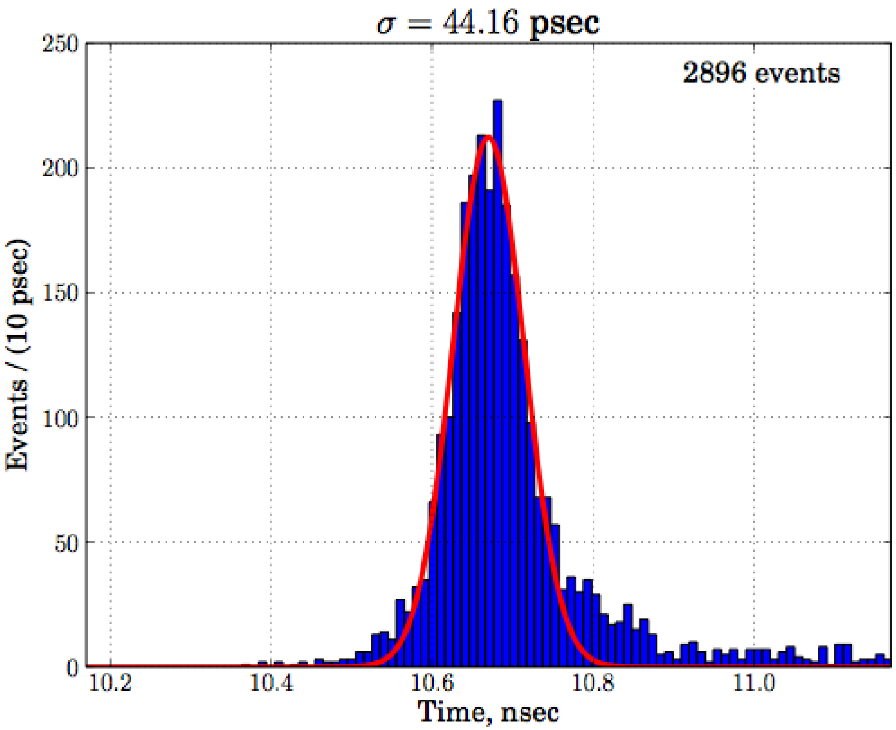
Front-end PSEC4 Card (*"AC/DC Card"*)

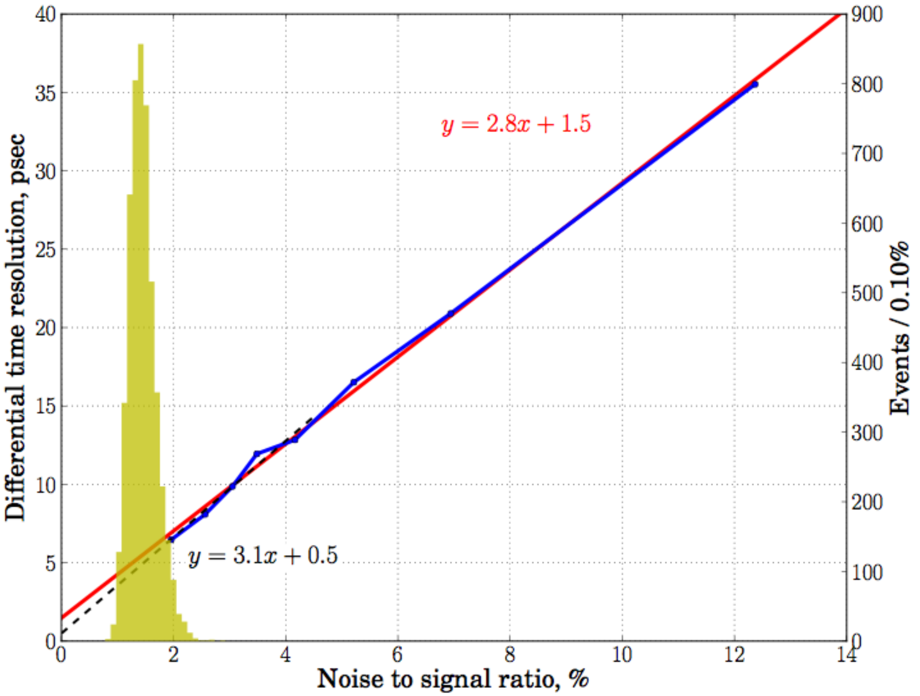
- 30 channels PSEC4 waveform recording
- At 10GS/s, captures a 25 ns snapshot per waveform **Looking for PSEC4A support**
- USB 2.0 standalone readout or 8x LVDS lines communication to Central Card **Now +SFP and VME**

LVDS system interface

- Up to 800 Mbps data rate per line
- Clock, trigger, configuration

Present Time Resolution



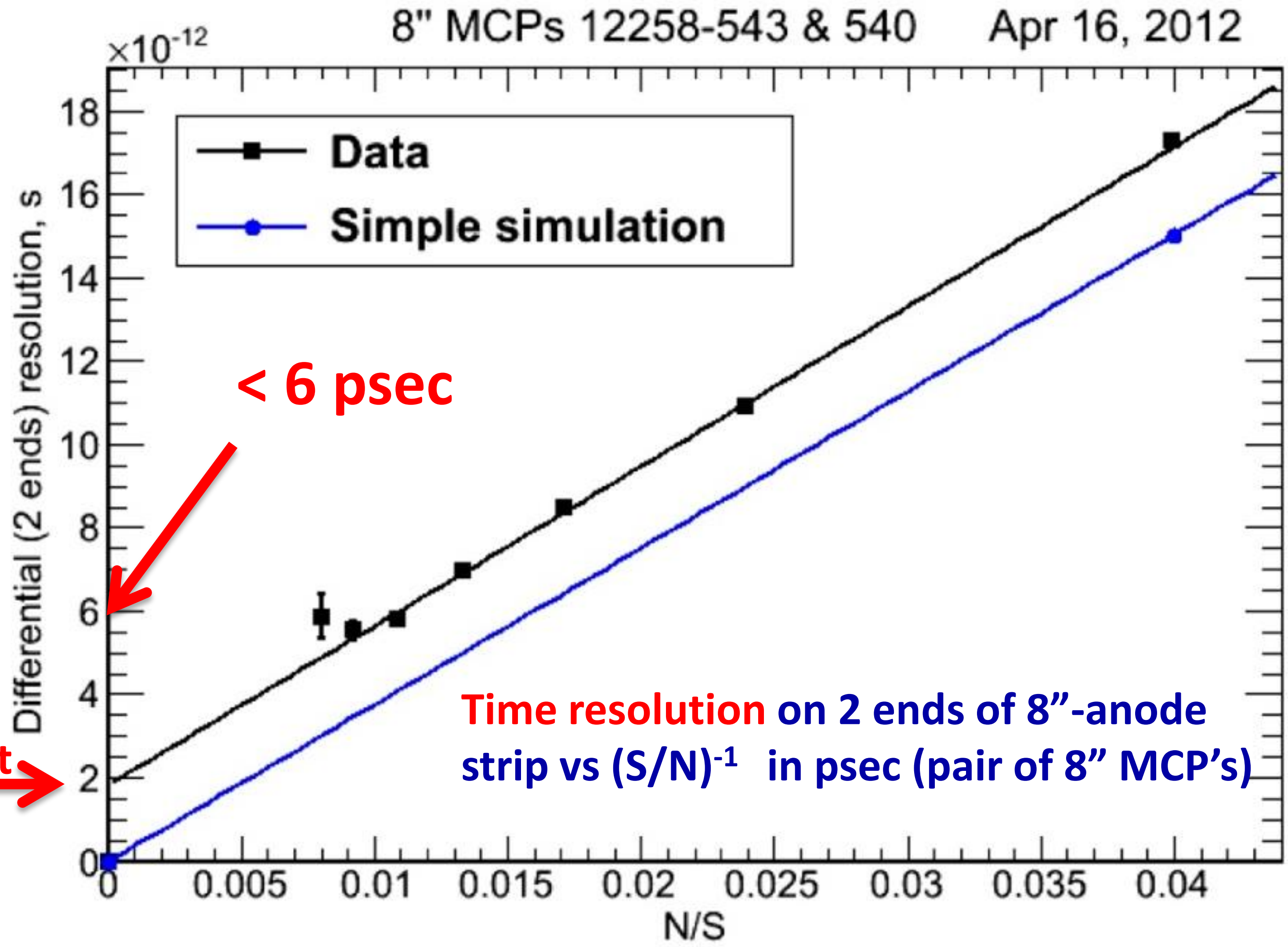


Single Photo-electron
PSEC4 Waveform sampling
Sigma=44 psec

Differential Time Resolution
Large signal Limit
Oscilloscope Readout
Black line is y=3.1x+0.5 (ps)
Red line is y=2.8x +1.5 (ps)
Where the constant term represents the large S/N limit (0.5-1.5 ps)

Highly non-optimized system (!)- could do much better

Timing res. agrees with MC



< 6 psec

Laser spot size

Time resolution on 2 ends of 8”-anode strip vs $(S/N)^{-1}$ in psec (pair of 8” MCP’s)

N = RMS of the noise; S = signal amplitude

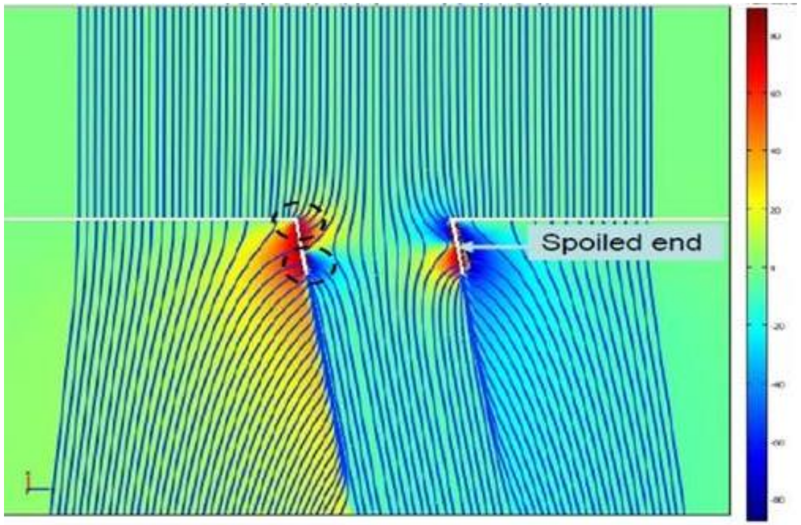
M. Wetstein, B. Adams, A. Elagin, R. Obaid, A. Vostrikov, …

Large-signal Limit Dependence

Does the time resolution go as 1/N or 1/root-N photo-electrons?

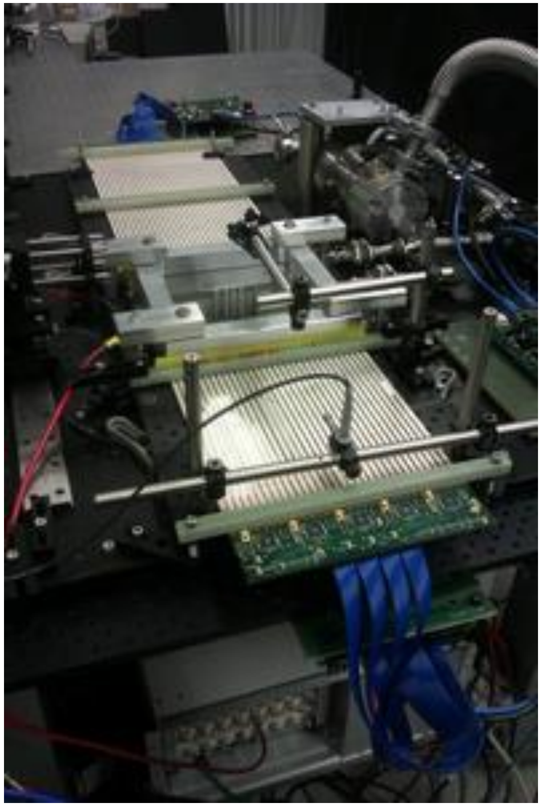
Hypothesis:

- **In an MCP-PMT the time jitter is dominated by the 1st strike- path length to 1st strike varies**
- **Smaller pores, increased bias angle are better**
- **IF gain is such that a single photon shower makes the pulse (e.g. 2E7), time jitter is set by the probability that NO photon has arrived in interval delta-t.**

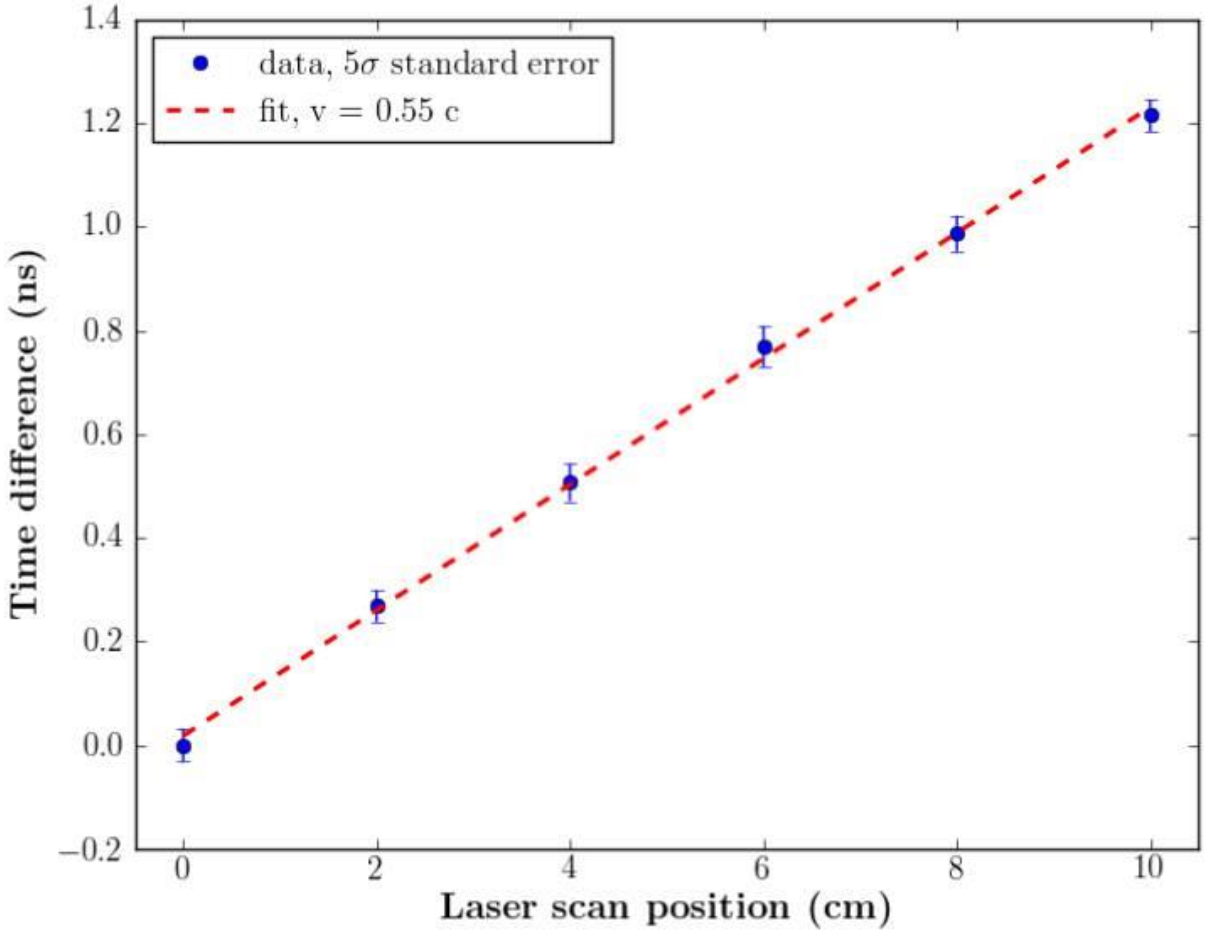


E.g: Cherenk in window- If 50 photoelectrons arrive within 50 psec, the probability that one goes for t psec with NO photon making a first strike goes as e^{-t} => a 1/N

Demonstrated Position Sensitivity



4-tile `tile-row’
of Supermodule

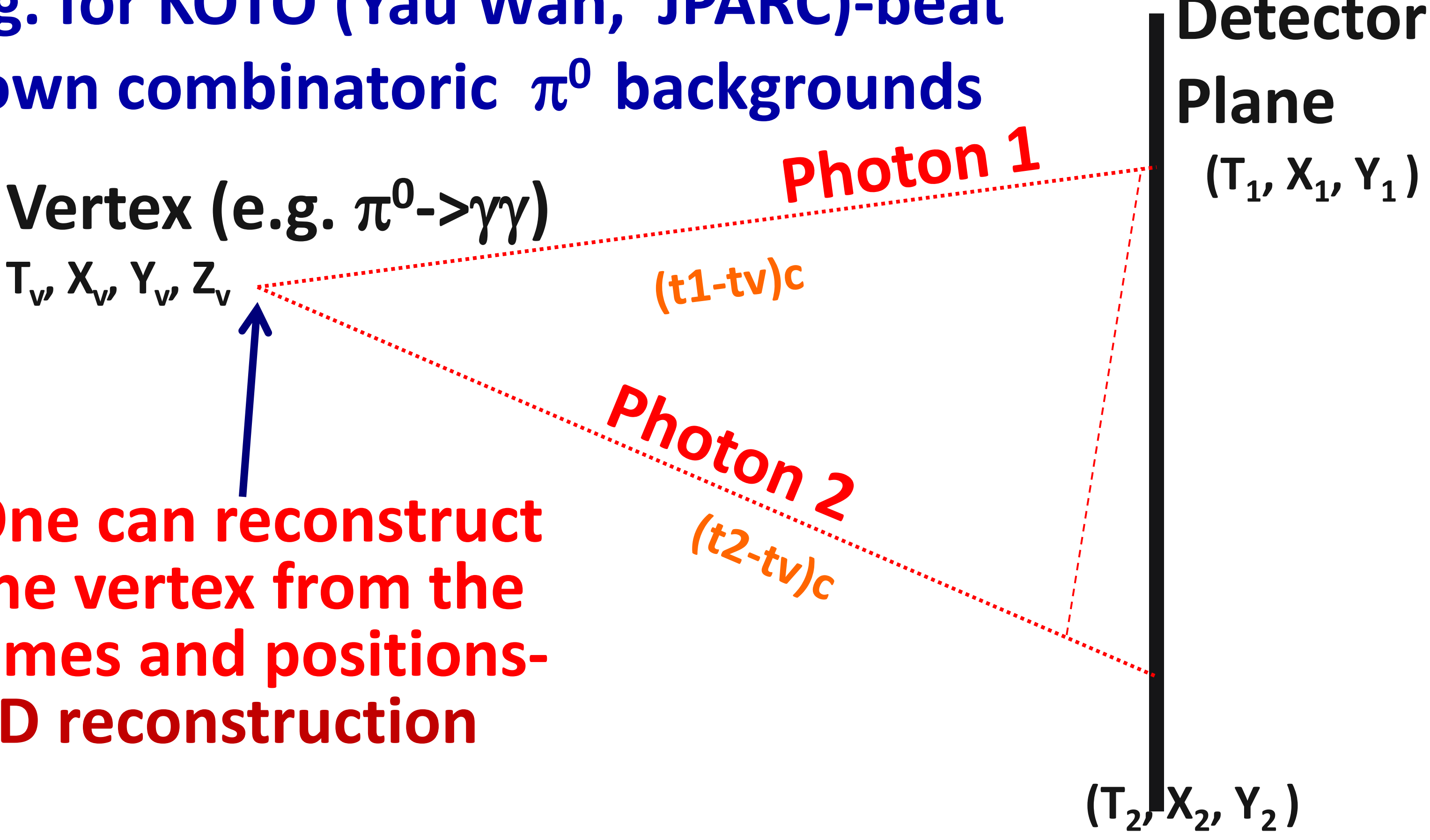


Time difference of 2 ends vs laser position

Applications- 1: Vertexing using arrival 4D-points

E.g. rare Kaon decays- background rejection by reconstructing π^0 vertex space point: (also eta)

E.g. for KOTO (Yau Wah, JPARC)-beat down combinatoric π^0 backgrounds



Detector Plane

Vertex (e.g. $\pi^0 \to \gamma\gamma$)

T_v, X_v, Y_v, Z_v

Photon 1

$(t1-tv)c$

(T_1, X_1, Y_1)

Photon 2

$(t2-tv)c$

(T_2, X_2, Y_2)

One can reconstruct the vertex from the times and positions- 3D reconstruction

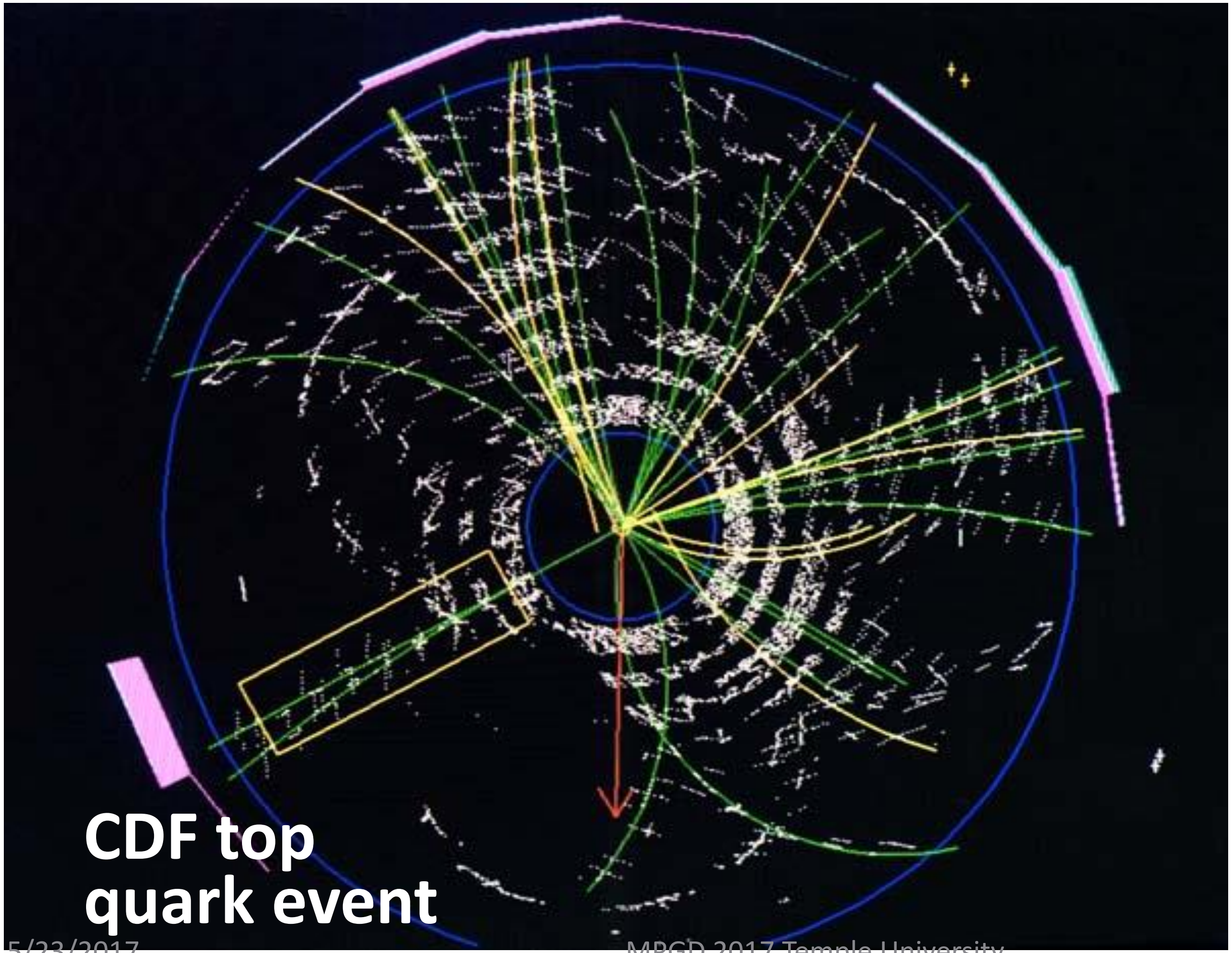
N.B. Photon Drift Velocity is 0.298 mm/psec

Applications: 2--Colliders:

Goals: 1) identify the quark content of charged particles

2) assign tracks to vertices (e.g. CMS forward Ecal.)

3) vertex photons at colliders;



CDF top quark event

Aside: Use photons (and electrons) as reference time- i.e. do differential timing of tracks from the same vertex to eliminate external clock jitter

See Snowmass white paper

The 3rd Case- Optical Photons--Using Light Drift Times for 3D Imaging

- Use time-space photodetectors as a large-area (10-100 m^2) many-pixel ‘camera’ with 25-50 psec resolution to reconstruct images in 3D .
- Analogous to Nygren’s TPC– an `Optical TPC’ (H. Nicholson)- drift photons instead of electrons.
- Current LAPPD microstrip readout gives 700 micron by 700 micron resolution for a 90cm x 20cm anode with cheap CMOS readout- gives $2x10^6$ pixels/m^2
- Resolution in 3rd dimension set by timing: 50 psec = ¾”; 1 psec = 300 microns. Make voxels in 3-space.
- Longitudinal information allows unambiguous use
- of mirrors

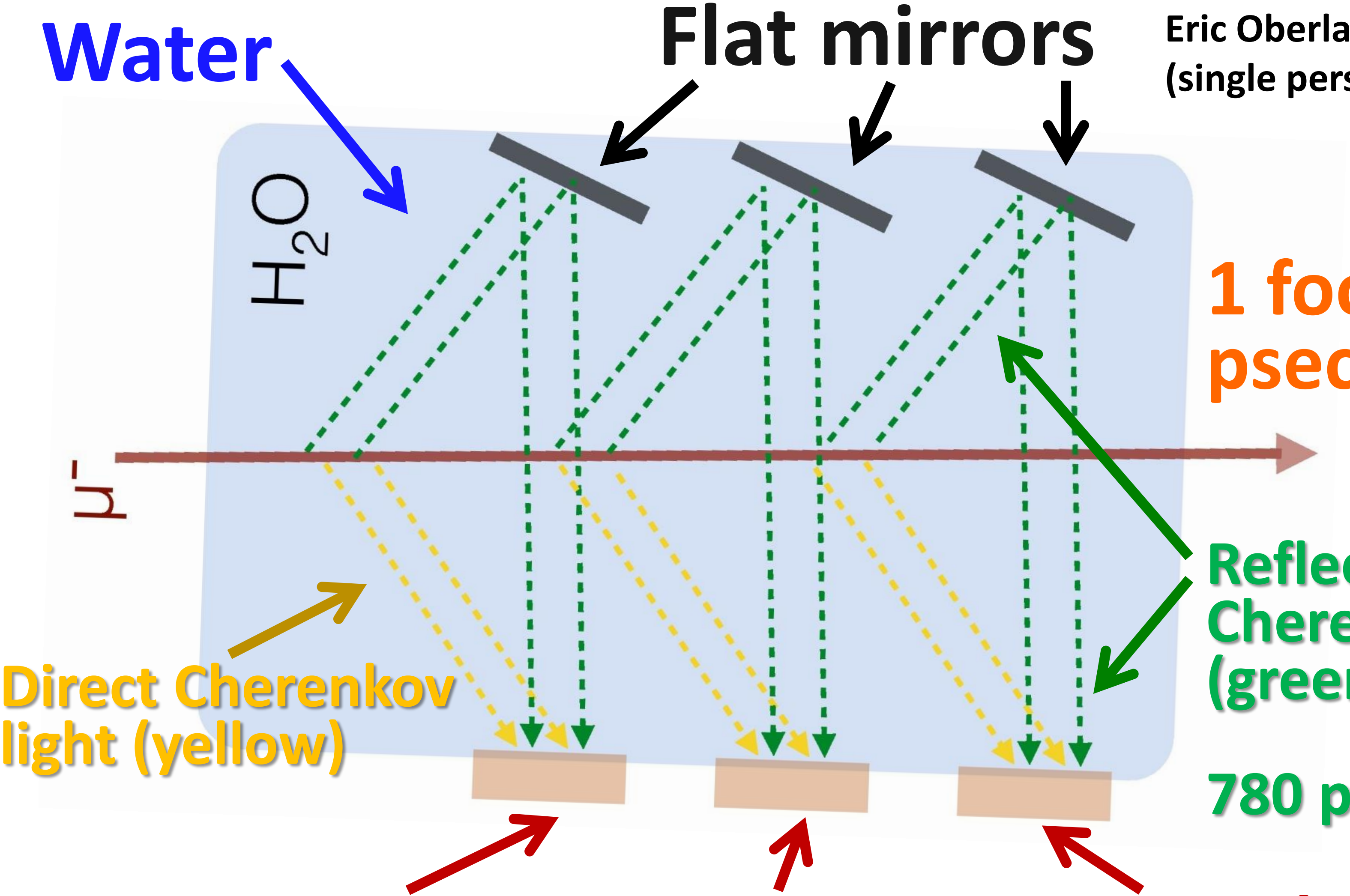
Electron TPC and theOptical TPC

- Drift electrons at constant velocity (E field)
- Limit diffusion with B field
- Charged particles create ionization along track
- Collect position and time at end of drift
- Electrons are used only once (only 1 path in)

- Drift photons at constant velocity
- Limit dispersion by various stratagems (inc. near light)
- Charged particles create Cherenkov light along track
- Collect position and time at end of drift
- Photons can be reflected to increase sensitive area using path length to identify bounce

Build a little prototype and test in a Fermilab test beam (muons)

Eric Oberla's Ph.D thesis
(single person experiment)



Water

Flat mirrors

1 foot/1000 psec muon

Reflected Cherenkov light (green)

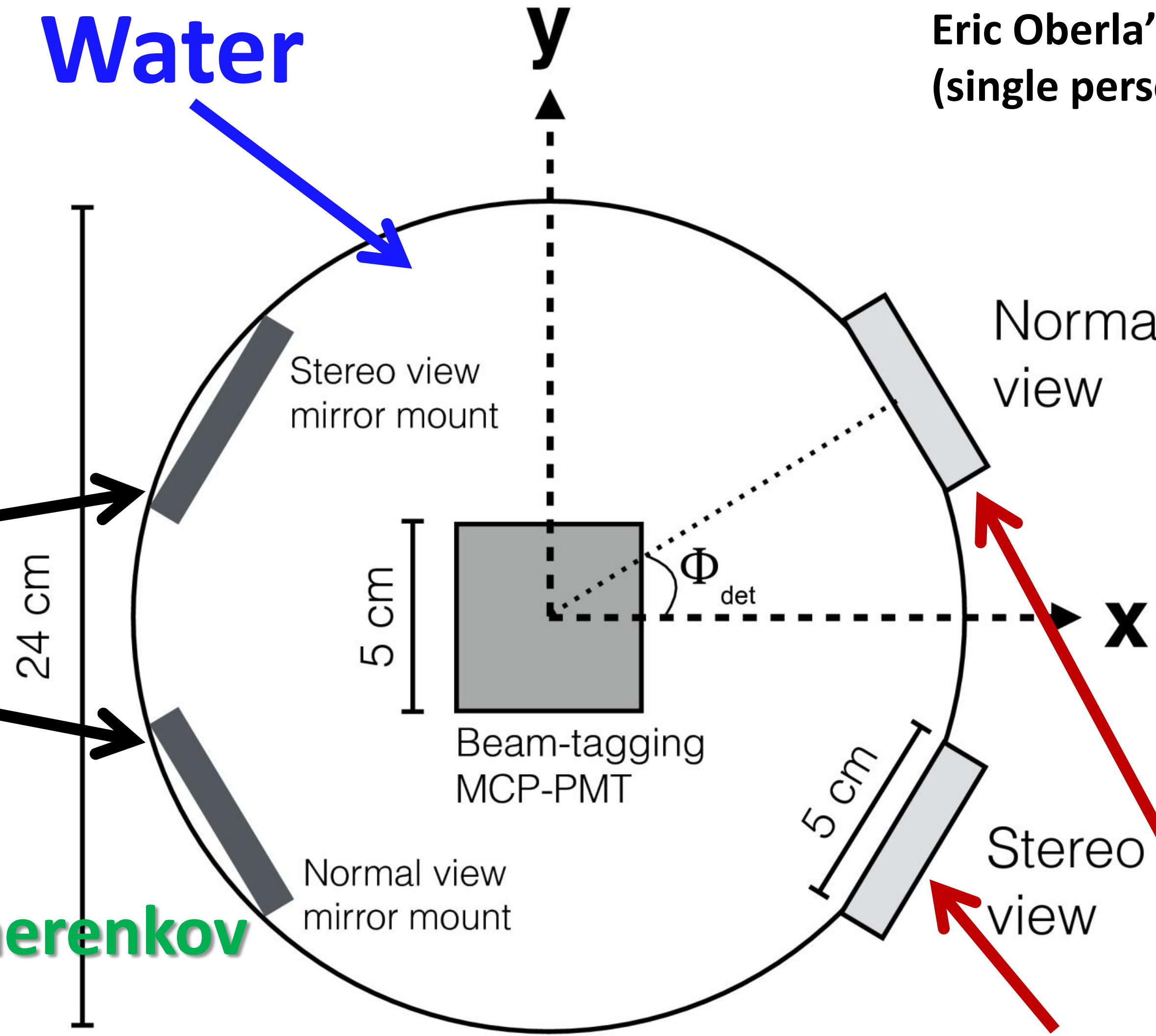
780 psec later

Direct Cherenkov light (yellow)

Photonis MCPs and Chicago striplines/PSEC4

Beam's Eye View of the OTPC

Eric Oberla's Ph.D thesis
(single person experiment)



Water

Flat mirrors

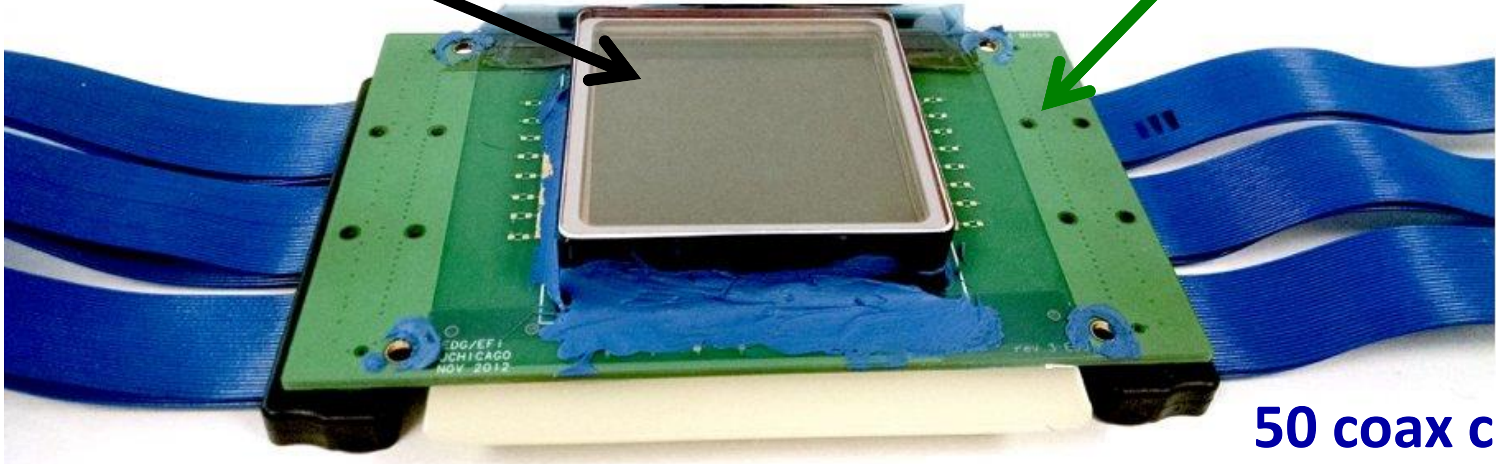
Reflected Cherenkov light arrives 780 psec later depending on position and angle

Photonis MCPs and Chicago striplines/PSEC4

The OTPC Uses Five 2” MCP-PMTs

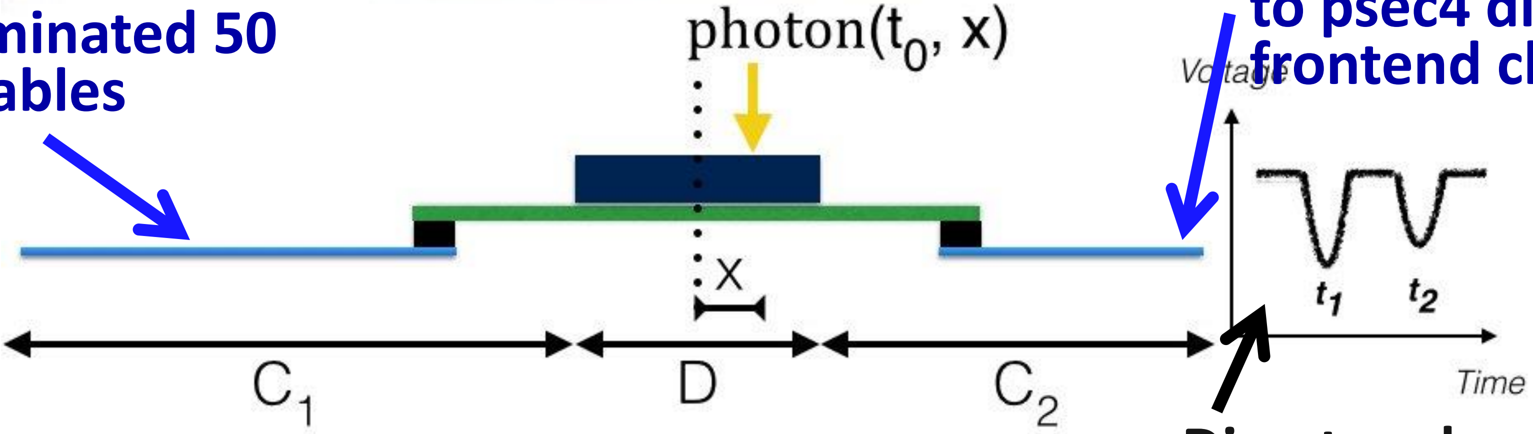
Photonis Planacon with 32x32 anode pad array

PC card with 30 50ohm microstrip transmission lines



Unterminated 50 coax cables

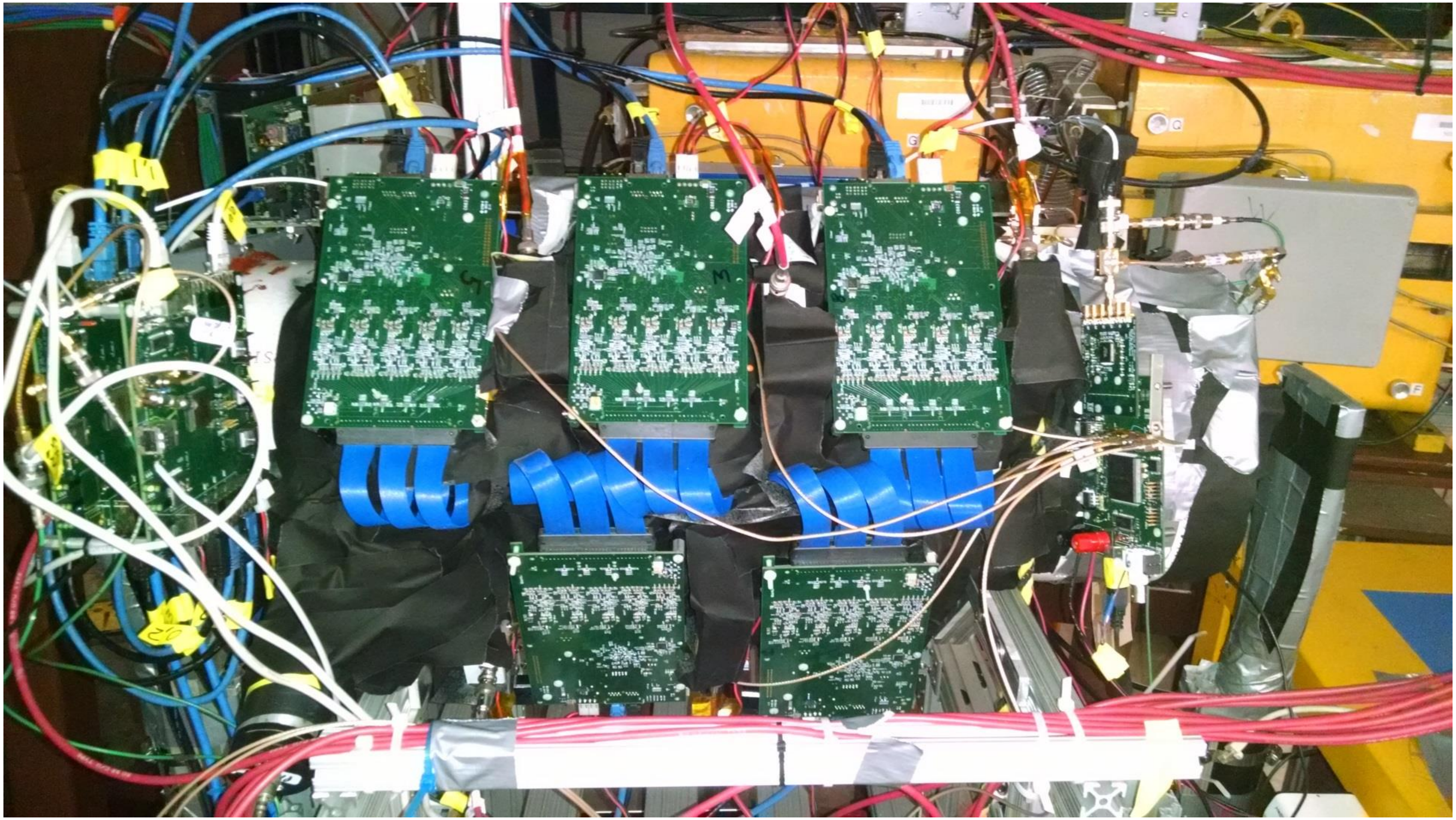
50 coax cables to psec4 digitizing frontend chips



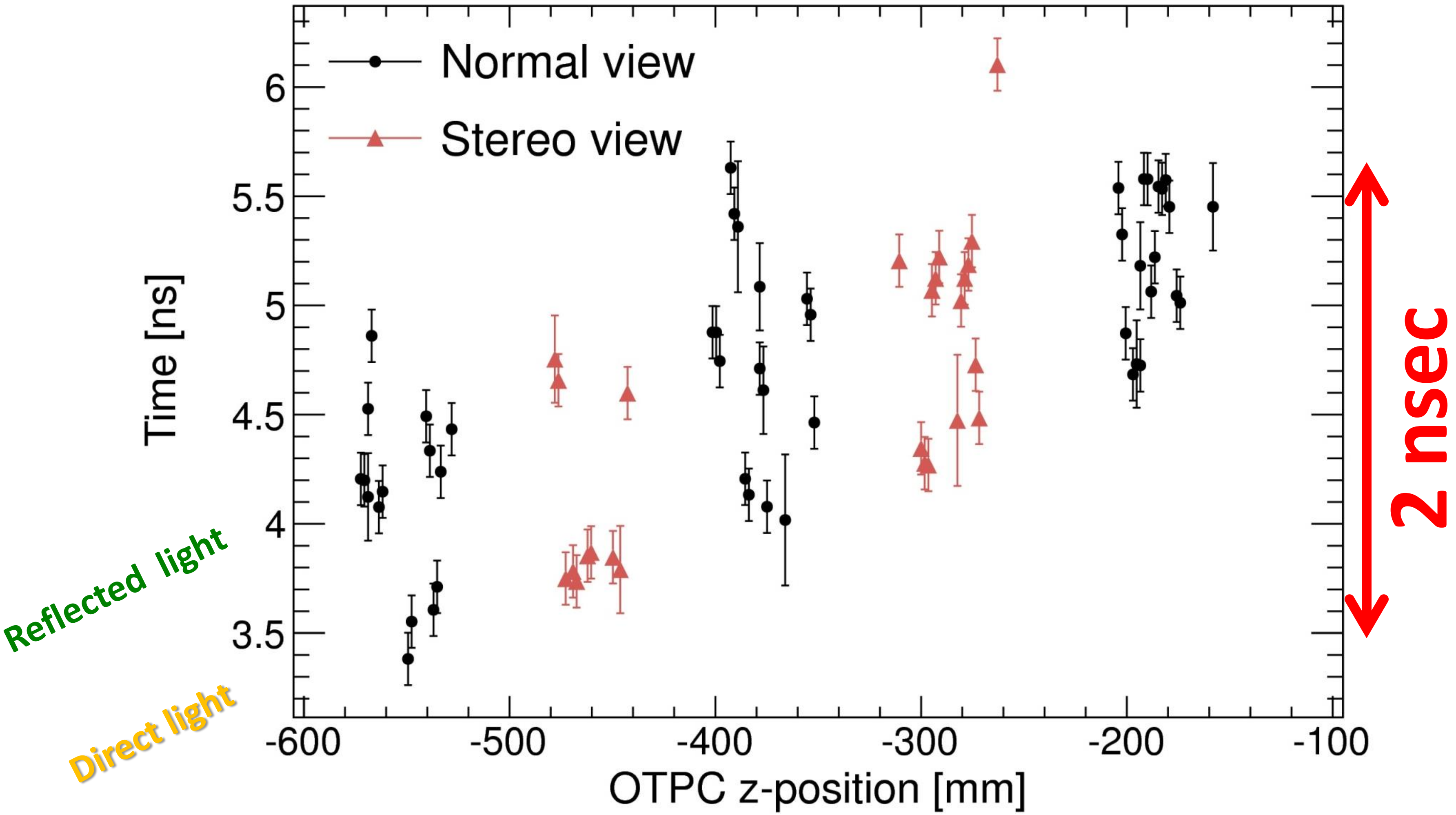
Direct and reflected pulses

Eric Oberla’s Ph.D thesis (single person experiment)

The OTPC prototype installed at Fermilab in the Mcenter test beam



It works: e.g.one event- time vs position



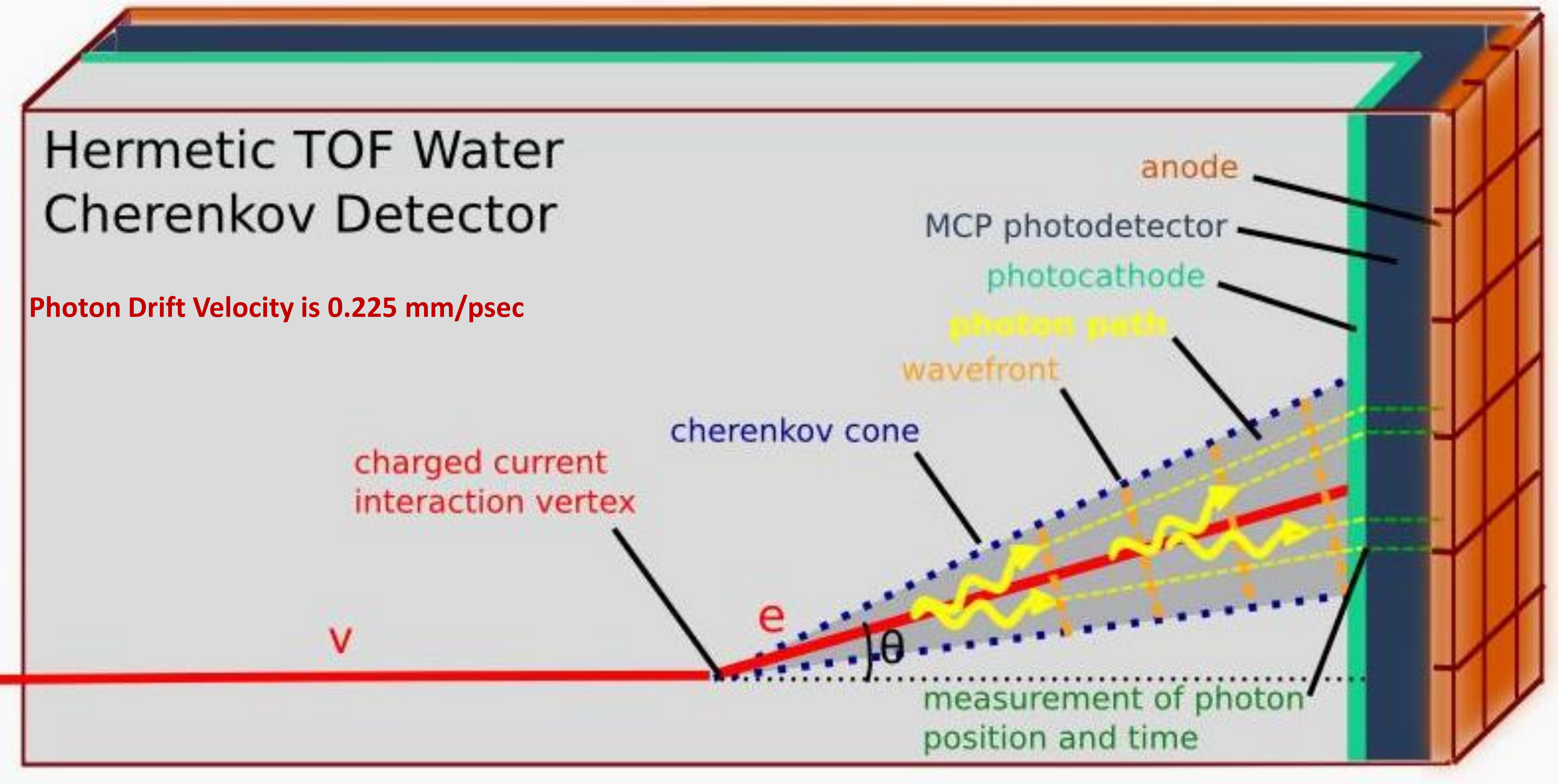
- 60 mrad angular resolution over a lever arm of 40cm
- 1.5 cm spatial resolution (radiation length of H2O is 40cm)
- See 780 psec separation of direct and mirror-reflected light
- More details in Nucl. Instr. Meth. A814, pp19-32 April 1 (2016)

Some Proposed Applications:

- Apply the same principle of coupled time and space arrival coordinates for photons to localize and reconstruct images (3D phase space)
- Uses same hardware for most low-rate applications
- High-rate and high-occupancy applications are a different kettle of fish- PSEC4 and the `Frugal Tile' are not made for these
- Show some to that we've thought about/worked on:

The Optical Time Projection Chamber (OTPC)

- Like a TPC but **drift photons** instead of electrons (no B needed)
- Exploits precise location and time **for each detected photon**
- Would allow **track /vertex reconstruction** in large liquid counters

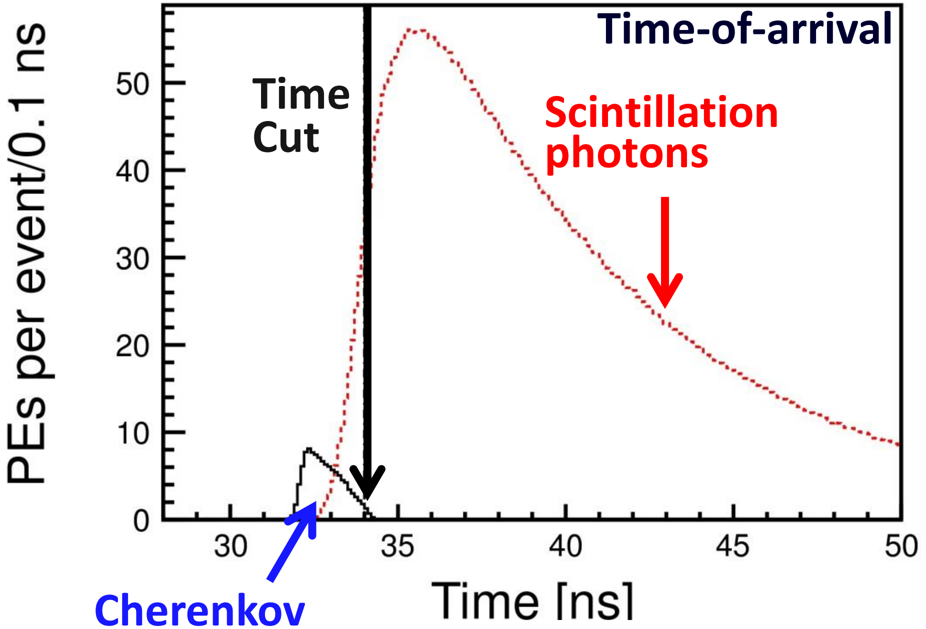


Photon Drift Velocity is 0.225 mm/psec

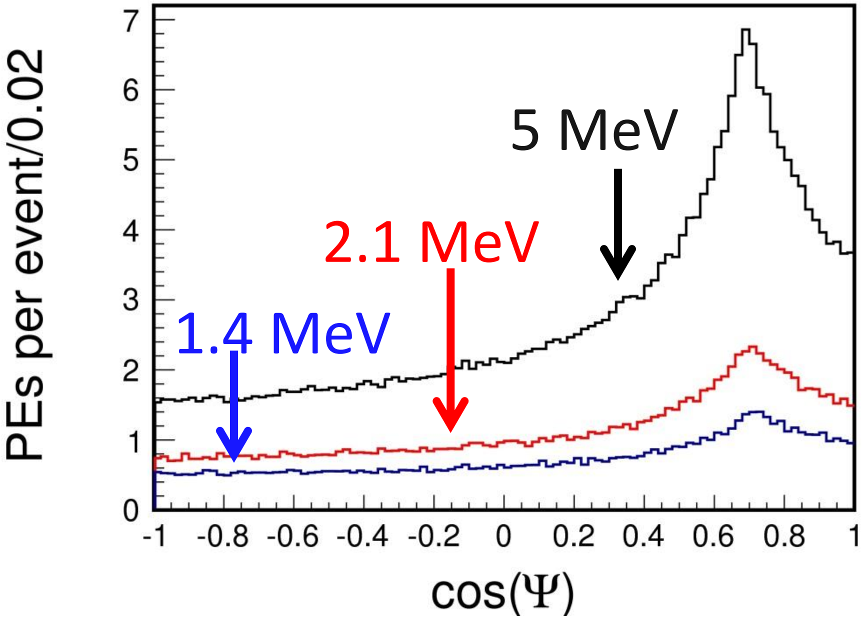
First suggestion of LAPPD’s for DUSEL and the name (OTPC) due to Howard Nicholson

Measuring Directionality in Neutrinoless Double-β Decay

- **Signal has 2 electrons; dominant (non-intrinsic) backgrounds have 1**
- **Cherenkov light retains (some) directionality**
- **Cherenkov light arrives before scintillation, as it's redder (really)**
- **Fast-timing allows selection on the early photons**



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

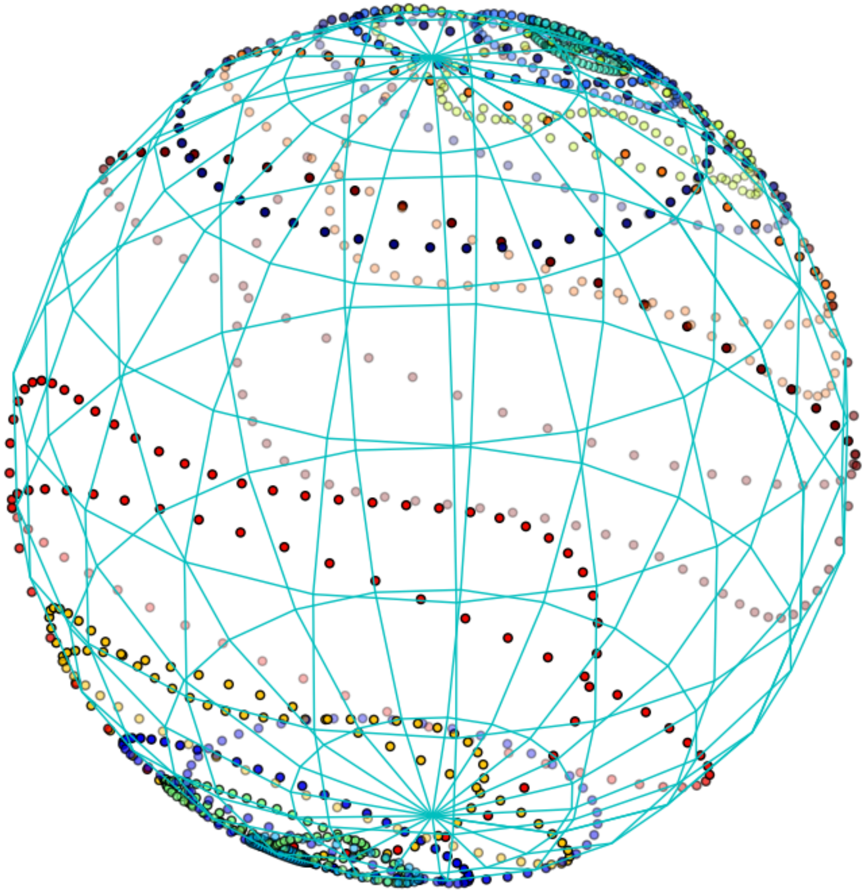


Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.

C. Aberle, A. Elagin, M. Wetstein, L. Winslow, HJF; NIM; arXiv:1307.5813

A. Elagin, H. J. Frisch, B. Naranjo, J. Ouellet, L. Winslow, T. Wongjirad; NIM. (Sept. 2016)

Going beyond a factor of 2 in mirror/cathode ratio



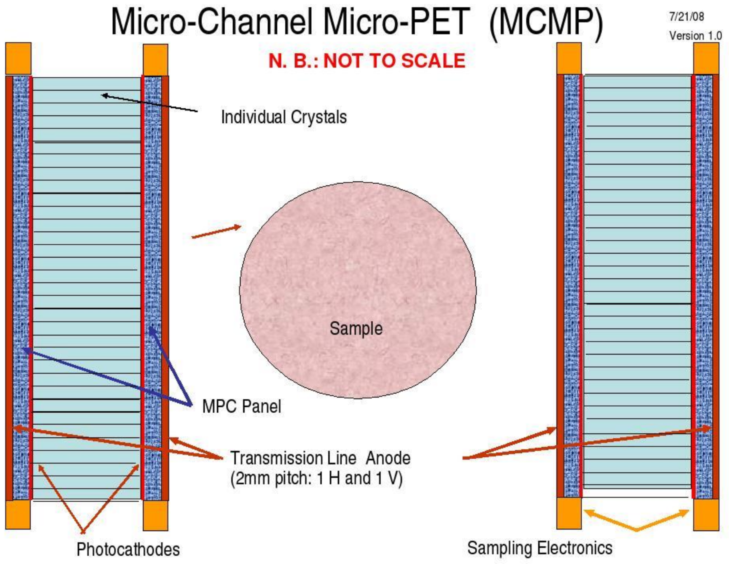
Two parameters for a large detector cost:

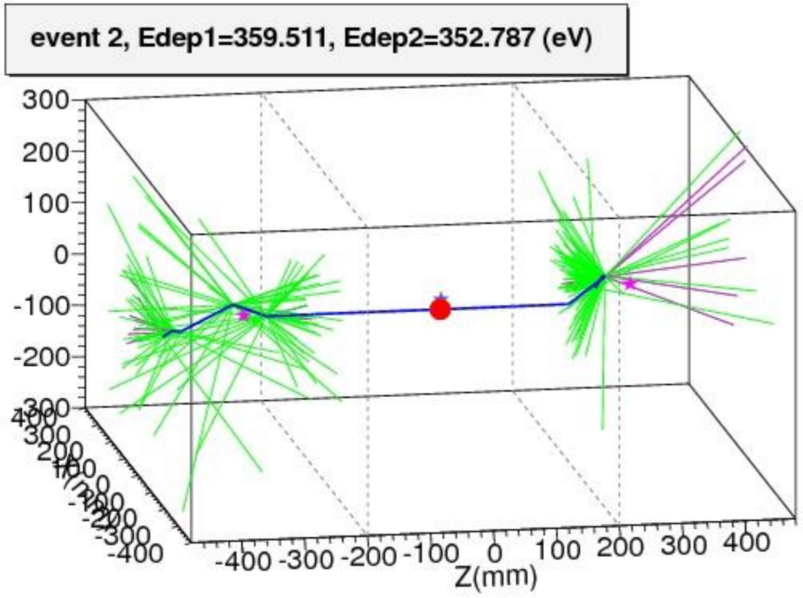
1. Cathode Coverage
2. Mirror/cathode area

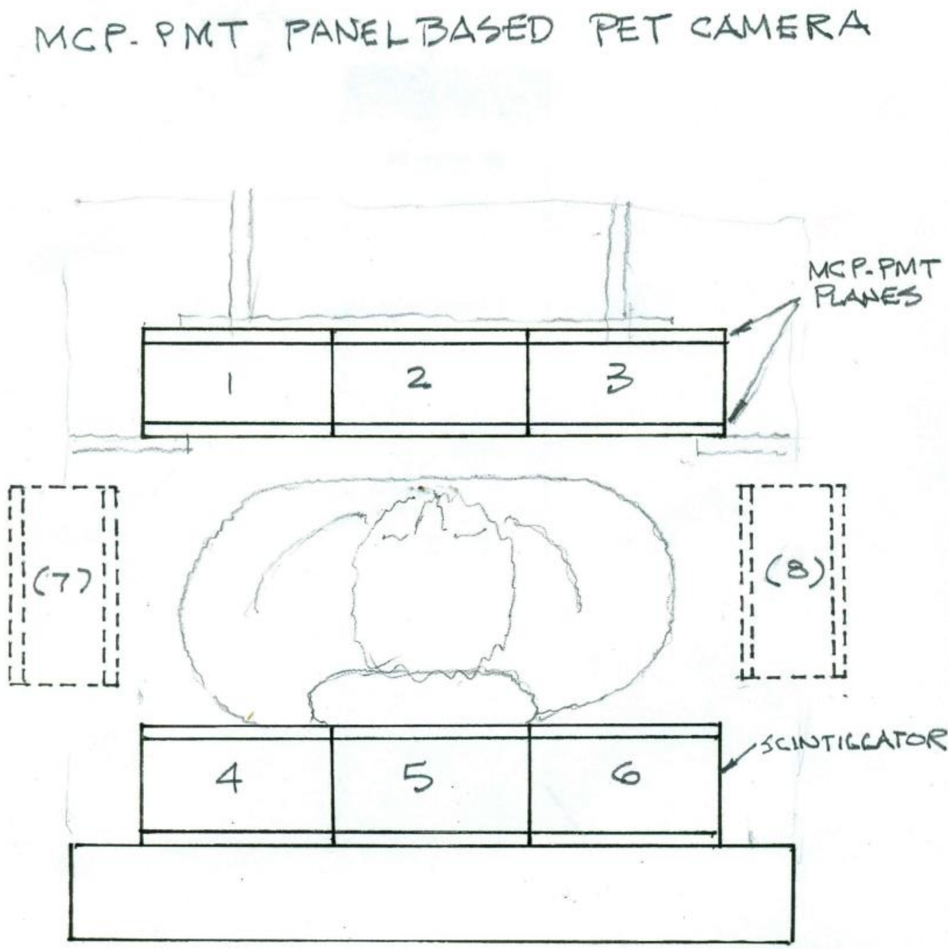
Simulation of reflection points of 20 photons inside a silvered sphere- color-coded by time- E. Angelico

Exploiting the Time Resolution for a Low-Dose Whole-Body Time-of-FlightPET Camera

Carla Grosso-Pilcher







LAPPD^{TM} Status

1. **Being commercialized by Incom, Inc (Charlton MA)- glass substrates, ALD functionalizing, sealed tiles, excellent photocathodes, in progress; (M. Minot, contact);**

2. **Gen-II ceramic body, waiting to hear about DOE Phase-II SBIR (M. Foley, Incom, with UofC);**

3. **Capacitive coupling through metal anode (yes) tested (E. Angelico, T. Seiss, UofC)**

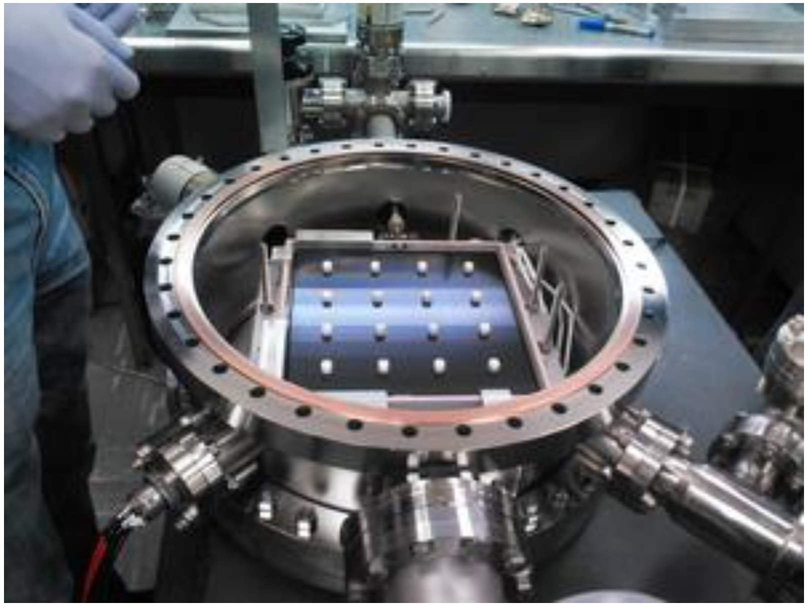
4. **Batch process development going on at UofC (A. Elagin, E. Angelico, E. Spieglan) ;**

5. **PSEC4A- longer/multiple buffer and 8 channels instead of 6 due back from MOSIS soon (E. Oberla);**

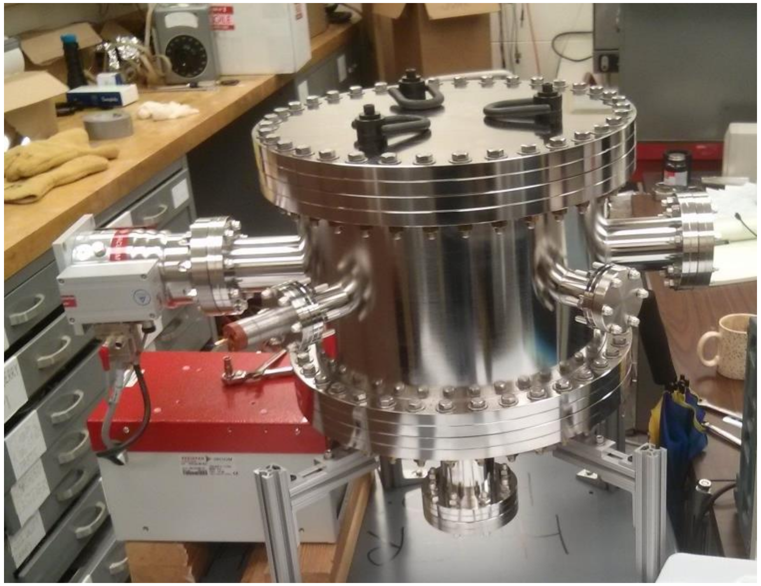
6. **ANNIE control card can handle ~2000 channels per VME crate.**

UofC Batch Process Development

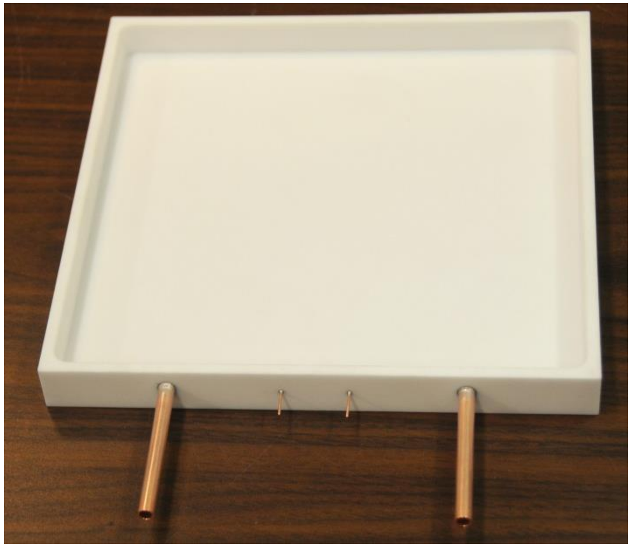
Joe Gregar (ANL) and Andrey Elagin (UofC)



Ceramic Tile being stacked up(UofC)



Gen II Margherita Dual-Vacuum facility



Gen II Ceramic Tile Base (before coating)

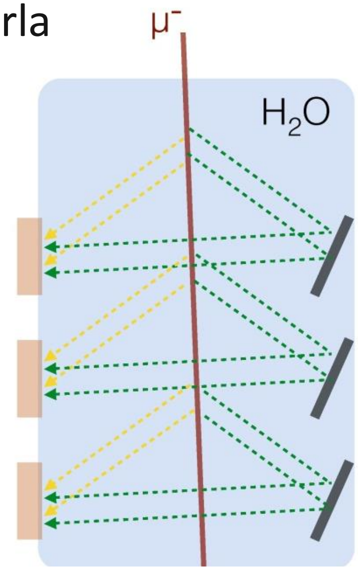
LAPPD Summary

- ✓ Multiple tiles have been sealed
- ✓ Clear pulses
- ✓ Positional information obtained from differential timing
- ✓ Photocathode QE >30% (@365 nm), uniformity >75% over 400 cm^2 area of tile
- ✓ Dark count rates (combined MCPs and PC) < 1 ct/sec/cm^2
- ✓ Seal integrity: 8 months and counting
- ✓ Photocathode stability: 1 month and counting

- Now that we have functional tiles, other design aspects are being optimized
- LAPPDs are currently being tested by collaborators

Lastly, let’s come back to mirrors and the Optical TPC

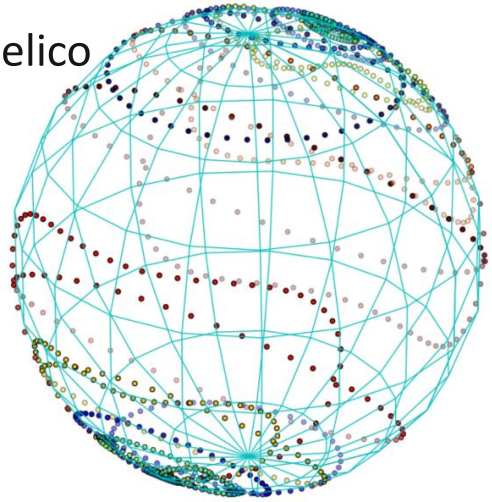
E. Oberla



Adding psec-resolution changes the space in which considerations of Liouville’s Theorem operates from 3dimensional to 4dimensional. In analogy with accelerator physics, we can exchange transverse emittance to longitudinal emittance.

There may be interesting and clever ways to exploit this in large water/scint Cherenkov counters.

E. Angelico

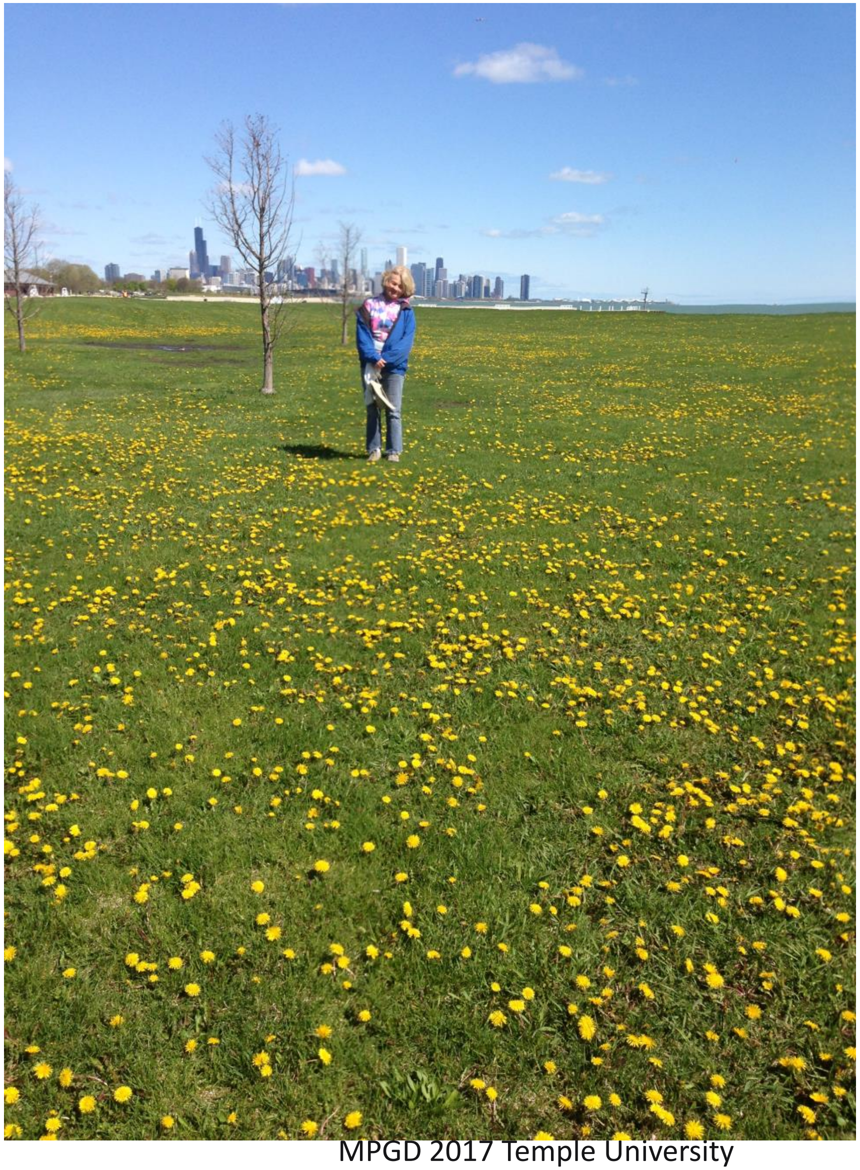


Homage to T. Ypsilantis

Acknowledgements

- My LAPPD Collaborators at ANL, UC-Berkeley SSL, UChicago, Fermilab, Hawaii, and Washington University
- Staff and management at Incom and Arradiance
- Others in the field of fast-timing , with special thanks to T. Ohshima and J. Vavra; and waveform sampling, (special thanks here to D. Breton, E. Delagnes, J.F.-Genat, S. Ritt, and G. Varner)
- H. Marsiske, H. Nicholson and the US DOE Office of Science
- The National Science Foundation

The End



Backup Slides

Recent papers

- E. Angelico, T. Seiss, B. W, Adams, A. Elagin, H. J. Frisch, E. Spieglan;\\{\it Capacitively coupled pickup in MCP-based photo-detectors using a conductive, metallic anode};\\Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)%
- A. Elagin, H. J. Frisch, B. Naranjo, J. Ouellet, L. Winslow, T. Wongjirad;\\{\it Separating Double-Beta Decay Events from Solar NeutrinoInteractions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing};Nucl. Inst. Meth. Phys. Res. A. (Sept. 2016)

recent_refs.tex

- E. Oberla and H.J. Frisch;\\ {\it Charged particle tracking in a water Cherenkov optical time-projection chamber};\\ Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016)% ISSN 0168-9002. arXiv:1510.00947

The LAPPD™

What is it?

A 20cm-square detector of light, sensitive to a single photon, with time resolution < 10 psec and position resolution < 700 microns in 2 dimensions, modular so to be scalable to m^2 systems

Why is it of interest?

Enables a new capability- `imaging in 3D at 15 billion `frames' a second. Light travels ¾" per image.

What are applications?

Neutrino and collider experiments in HEP
Reactor/non-proliferation monitoring
Positron-Emisson Tomography

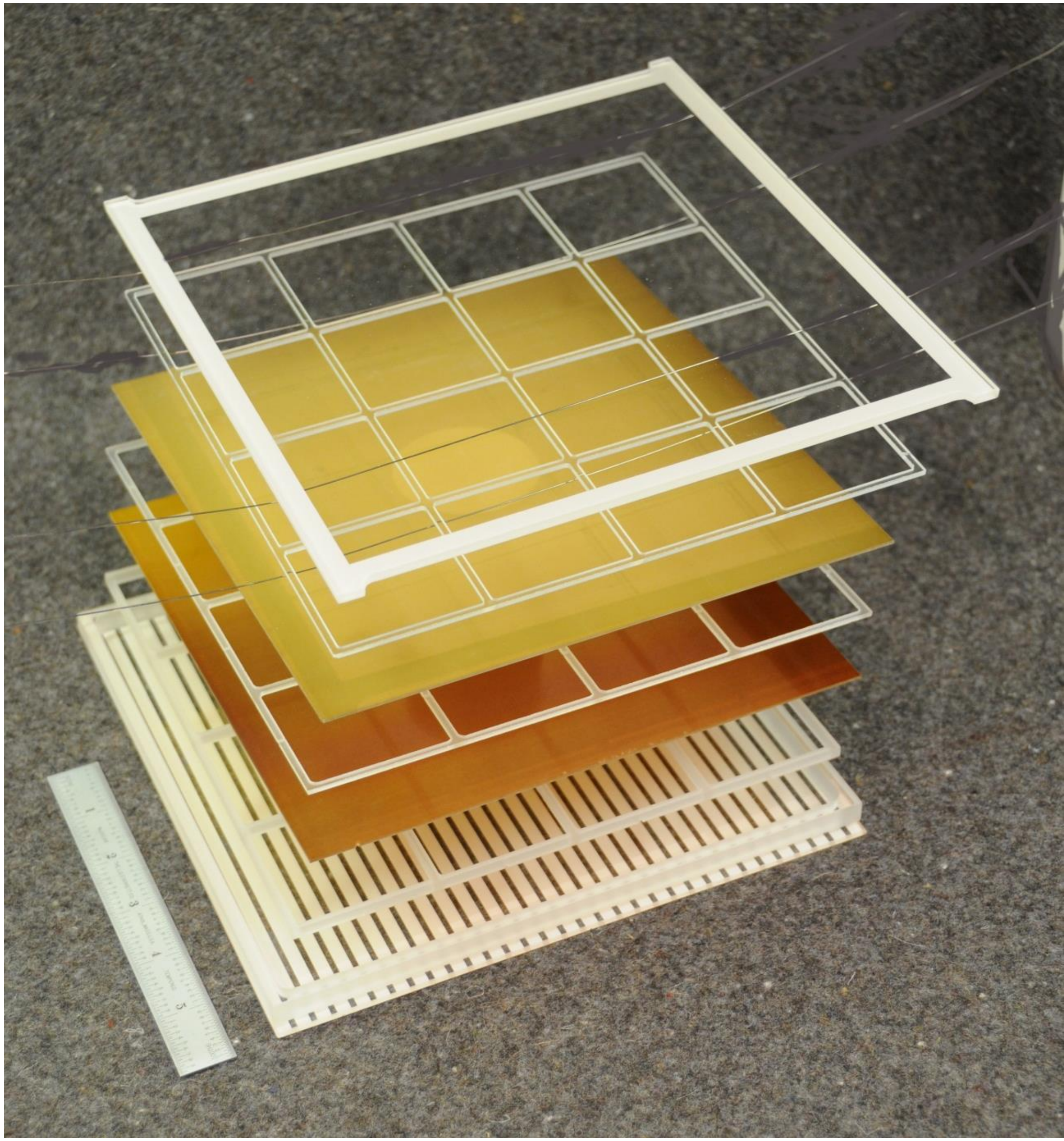
What is the competition?

Silicon PMT's, Resistive-Plate Chambers, smaller MCP-based MCP-PMTs: but none with this gain, bandwidth, and low noise

Keep It Simple- 8 parts

1 topwindow
2 MCP's
3 Spacers
1 Tilebase
1 Getter Necklace
TOTAL: 8 parts

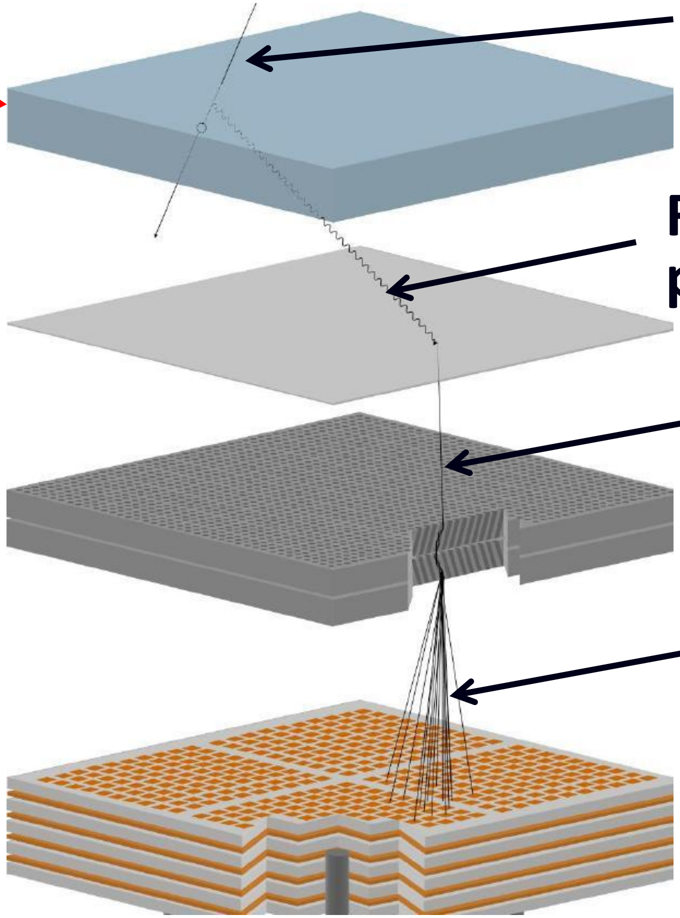
This is the UC Gen-I 'Frugal Tile'- internal HV divider, microstrip anode, indium flat seal. Next is photocathode synthesis: Now working on Gen-II to solve that, improve performance and lower cost.



How Does it Work?

Requires large-area, gain > 10^7, low noise, low-power, long life, $\sigma(t)<10$ psec, $\sigma(x) < 1$mm, and low large-area system cost

Realized that an MCP-PMT has all these but large-area, low-cost: (since intrinsic time and space scales are set by the pore sizes- 2-20μ)



Incoming charged particle

window

Radiated Cherenkov photon

Photocathode on inside of window

Photo-electron from cathode

Pair of micro-channel plates

Output pulse of 10^7 electrons

RF strip-line anode (picture is 2005-version- now we use microstrips)