# Instrumentation Development for Optical Tracking in Water and Liquid Scintillator Detectors

Andrey Elagin
University of Chicago

DLNP, JINR, Dubna, October 13, 2017

# Outline

- Ultra-fast timing frontier
- Optical tracking in water
- Optical tracking in liquid scintillator
- Potential application for $0\nu\beta\beta$-decay search
- Large-Area Picosecond Photo-Detectors

## Preface:

- In 1 ns light travels 30cm; 1 ns is 1000 ps; 1ps -> 300 microns
- Light is <u>slow</u> in (sub) picosecond domain
- Speed of light in matter depends on the wavelength

e.g. in a typical scintillator:

v(370 nm) = 0.191 m/ns
v( 600 nm) = 0.203 m/ns

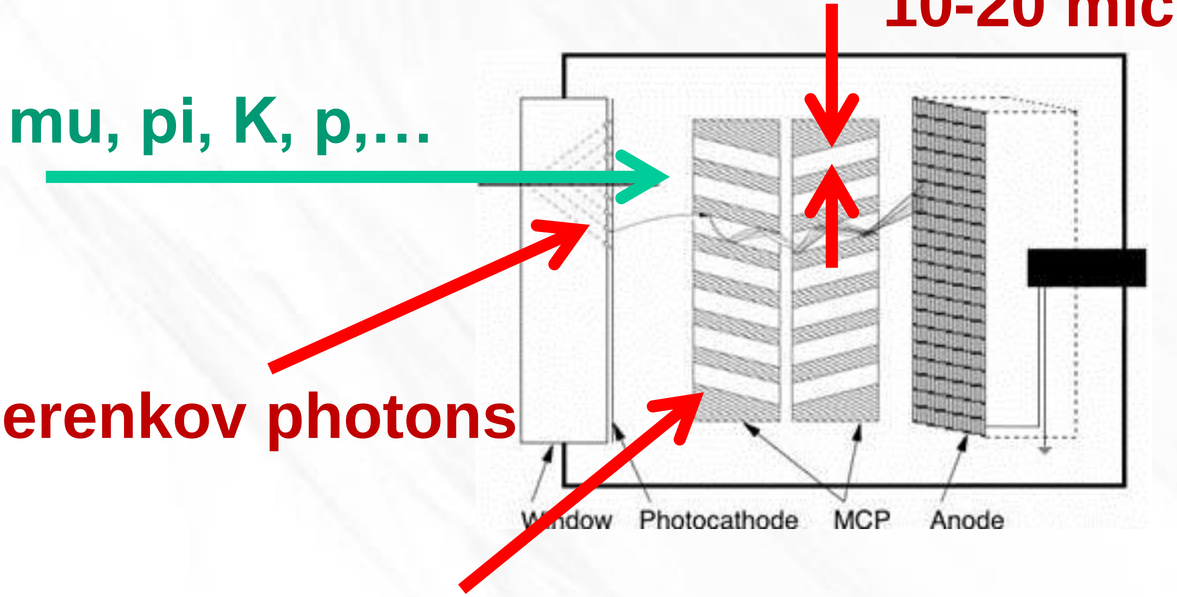
⇨

~2 ns difference over 6.5m distance
(that's a lot of picoseconds)

# Sub-Picosecond Timing Pre-requisites

1) Fast source (e.g. prompt Cherenkov light)
2) Psec-level pixel size (e.g. MCP pores)
3) High gain (e.g. MgO ALD MCPs give >$10^7$)
4) Low noise

Schematic of an MCP-based Photo-Detector



**10-20 micron pore**

**e, mu, pi, K, p,…**

**Cherenkov photons**

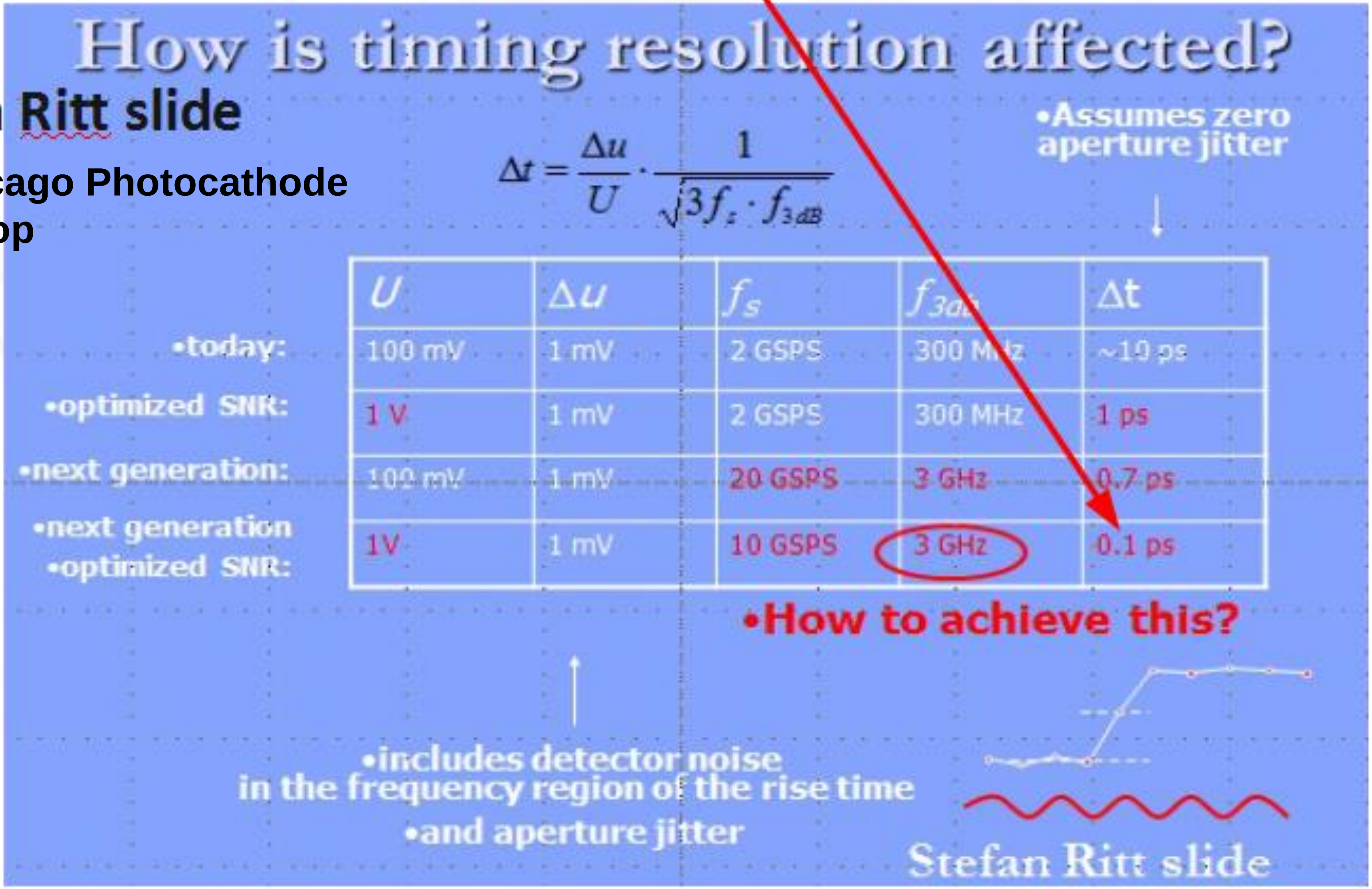
**Amplification section: Gain-bandwidth, Signal-to-Noise, Power, Cost**

# Timing Limits

## Can we achieve sub-picoseconds?

**Stefan Ritt slide**

**2nd Chicago Photocathode Workshop**



# How is timing resolution affected?

$$\Delta t = \frac{\Delta u}{U}\cdot\frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

- Assumes zero aperture jitter

| | $U$ | $\Delta u$ | $f_s$ | $f_{3dB}$ | Δt |
|---|---|---|---|---|---|
| •today: | 100 mV | 1 mV | 2 GSPS | 300 MHz | ~10 ps |
| •optimized SNR: | 1 V | 1 mV | 2 GSPS | 300 MHz | 1 ps |
| •next generation: | 100 mV | 1 mV | 20 GSPS | 3 GHz | 0.7 ps |
| •next generation •optimized SNR: | 1V | 1 mV | 10 GSPS | 3 GHz | 0.1 ps |

- How to achieve this?

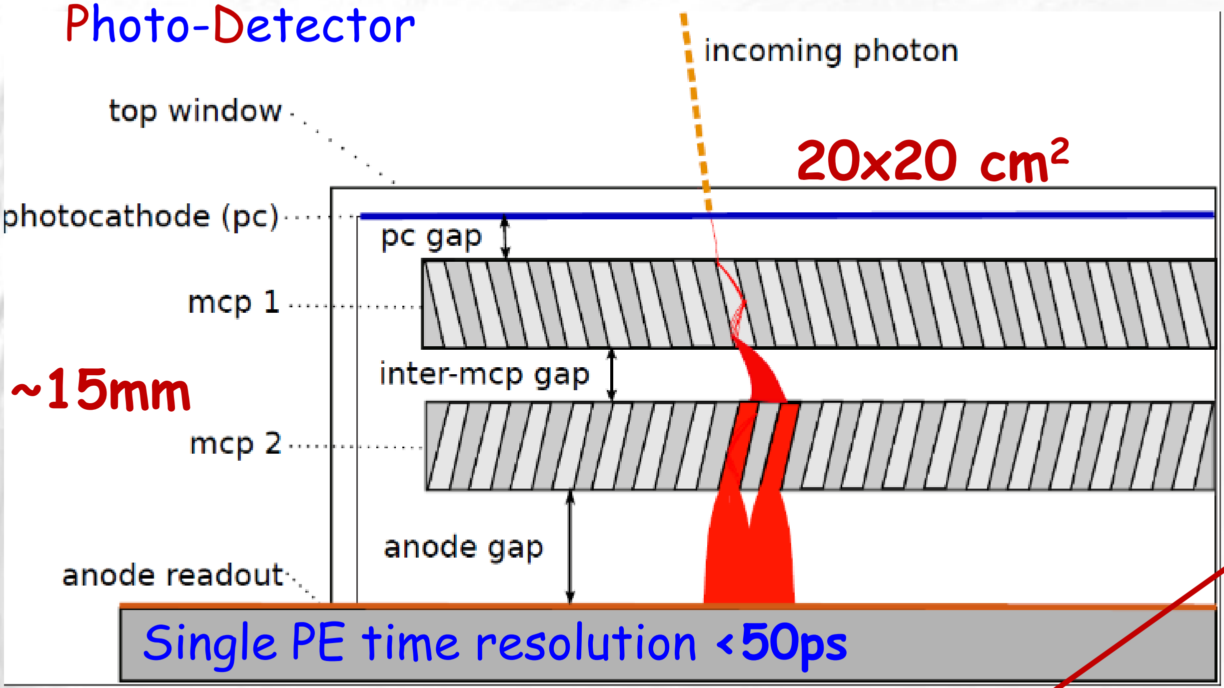
- includes detector noise in the frequency region of the rise time
- and aperture jitter

Stefan Ritt slide

Getting to 100 fs won't be that easy but it's a nice goal to have

# LAPPD™

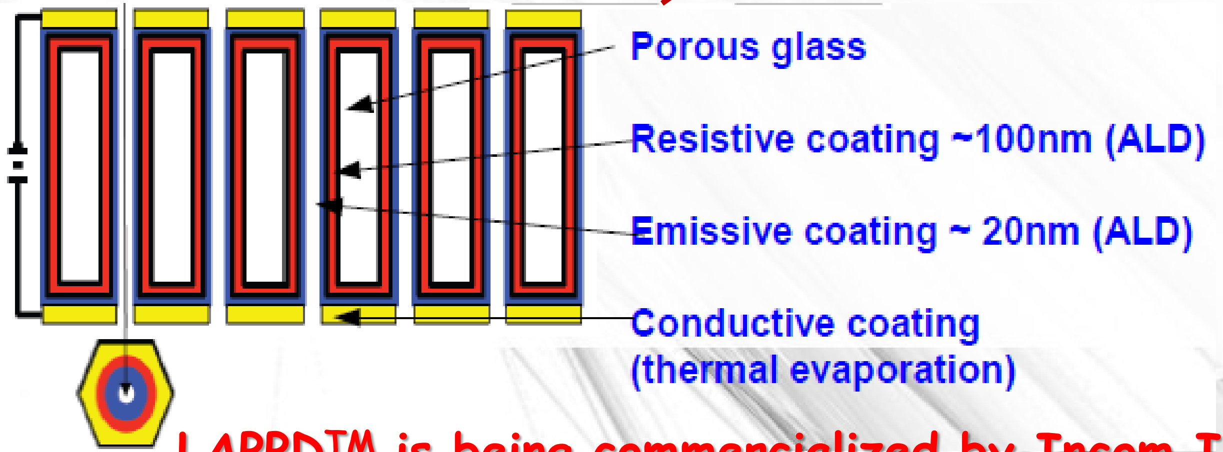
Large-Area Picosecond
Photo-Detector



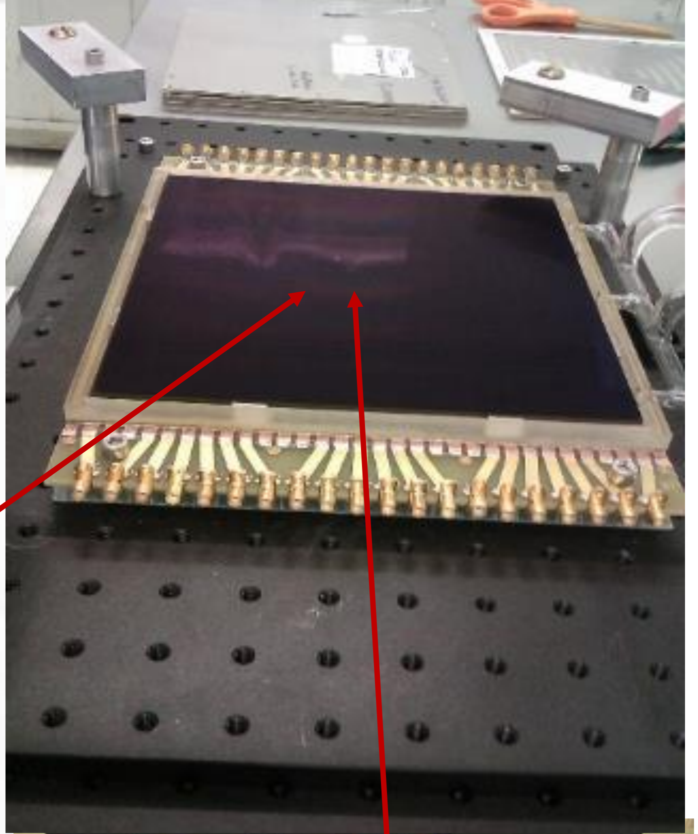
Single PE time resolution <50ps

## Atomic Layer Deposition (ALD)

- J.Elam and A.Mane at Argonne
(process is now licensed to Incom Inc.)
- Arradiance Inc. (independently)



## Micro-Channel Plates (MCPs)

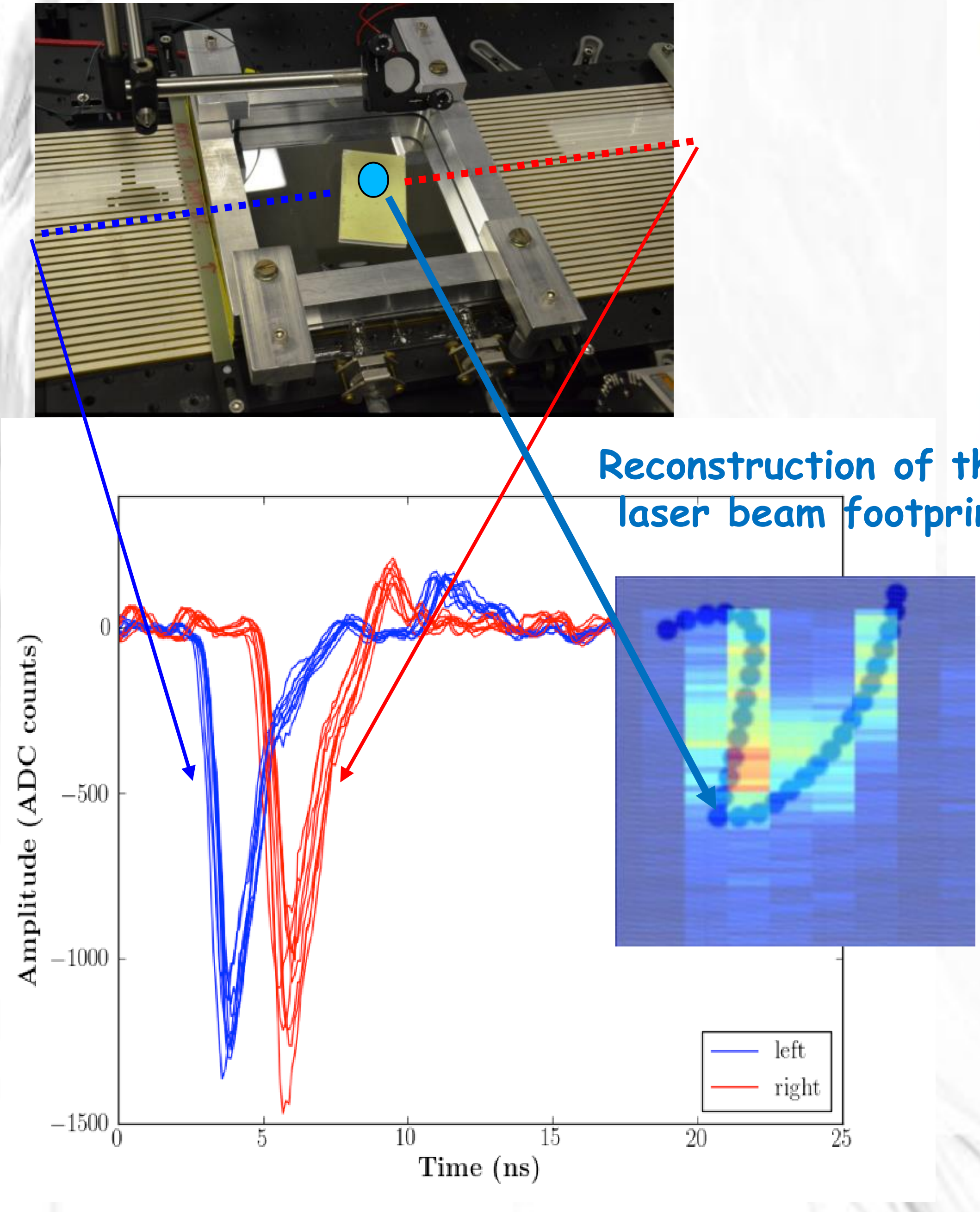


### Micro-Capillary Arrays by Incom Inc.

- Material: borofloat glass
- Area: 8x8"
- Thickness: 1.2mm
- Pore size: 20 μm
- Open area: 60-74%

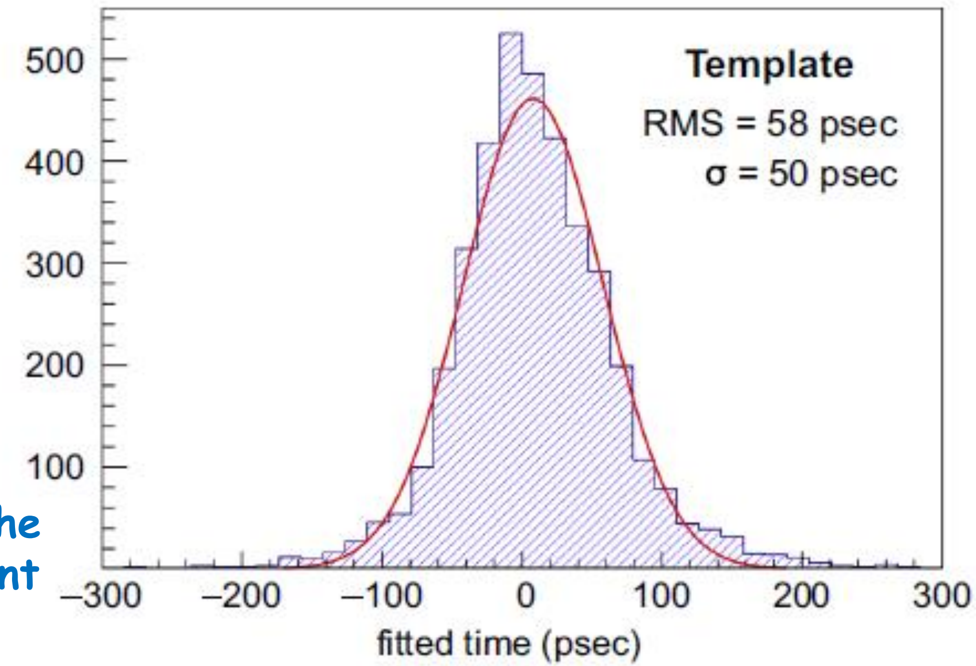
**LAPPD™ is being commercialized by Incom Inc.**

# LAPPD Prototype Testing Results



Reconstruction of the laser beam footprint

Single PE resolution

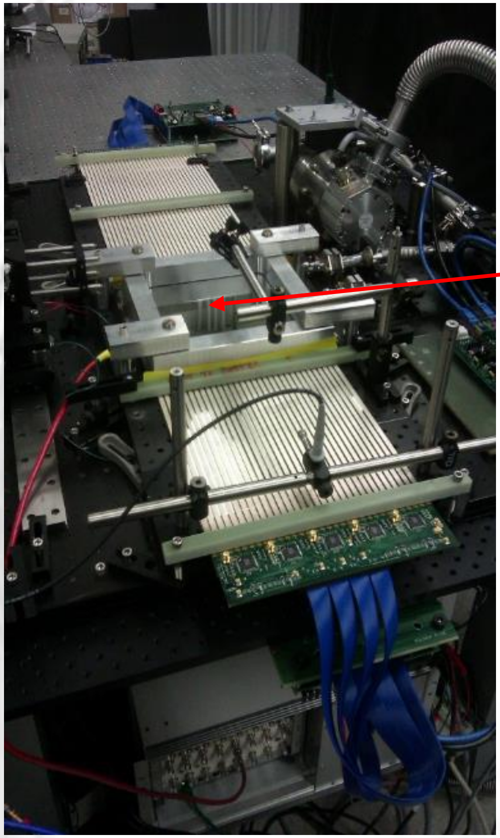


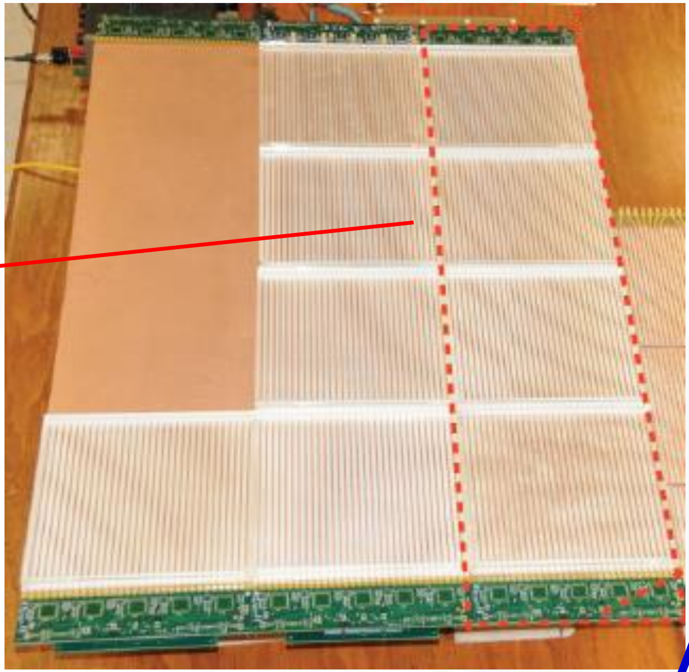
Demonstrated characteristics:
single PE timing ~50ps
multi PE timing ~35 ps
differential timing ~5 ps
position resolution < 1 mm
gain >$10^7$

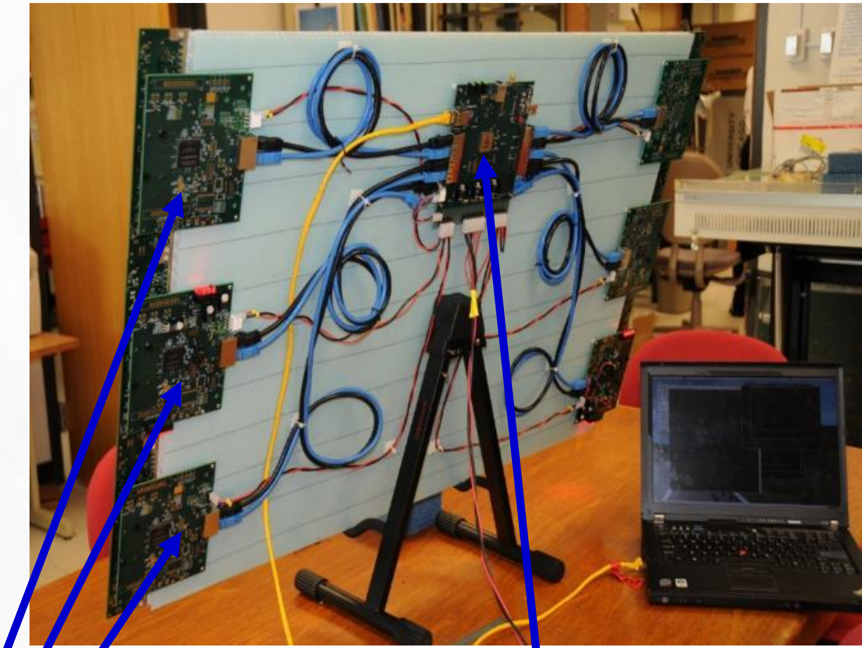
RSI 84, 061301 (2013),
NIMA 732, (2013) 392
NIMA 795, (2015) 1

**See arXiv:1603.01843 for a complete LAPPD bibliography**

# LAPPD Electronics at Chicago







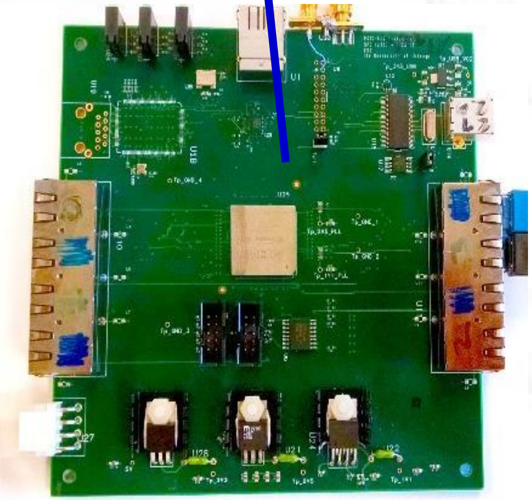
NIM 711 (2013) 124

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

NIM 735 (2014) 452

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

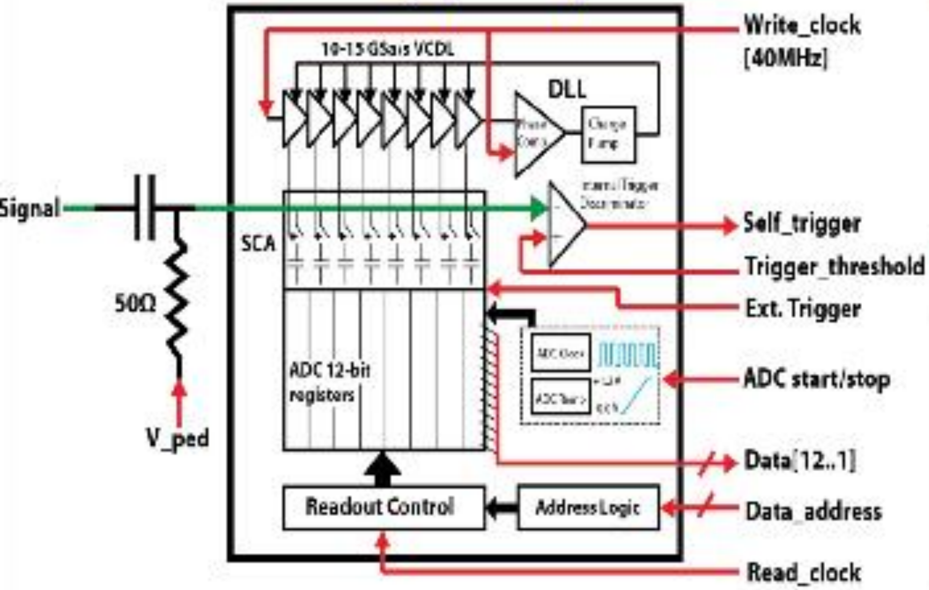
**30-Channel ACDC Card (5 PSEC-4)**

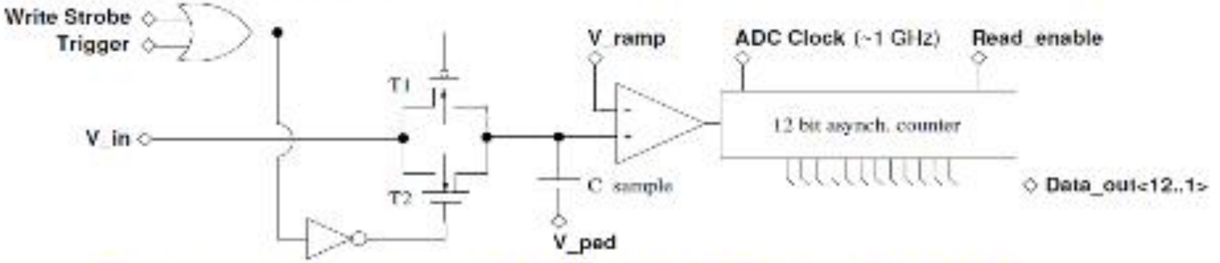


**Central Card (4-ACDC;120ch)**

# PSEC4 ASIC

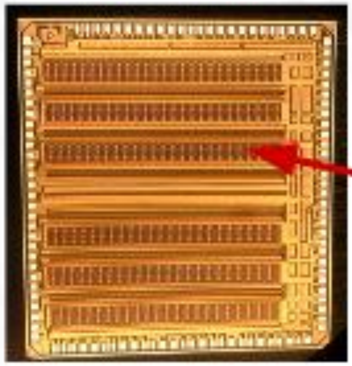
NIMA 735, (2014) 452-461





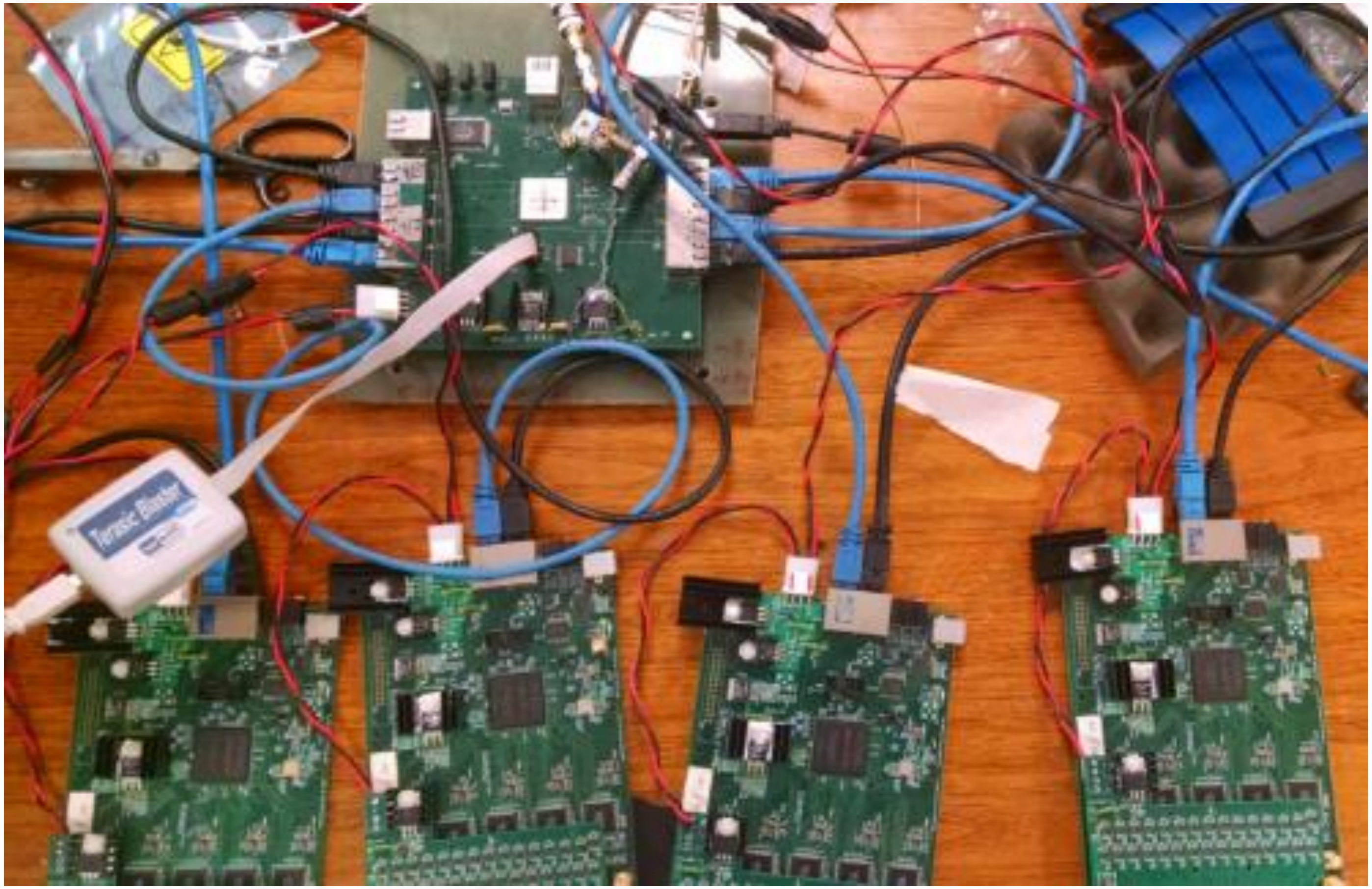
- Fabricated using IBM-8RF 130nm CMOS process
- Each of 6 channels is a switch capacitor array
  - 256 samples deep
  - on-chip ADC
  - sampled of 10's MHz clock using VCDL
- 10Gs/s, 1.5GHz
- Controlled by FPGA

PSEC4 die



Evaluation board

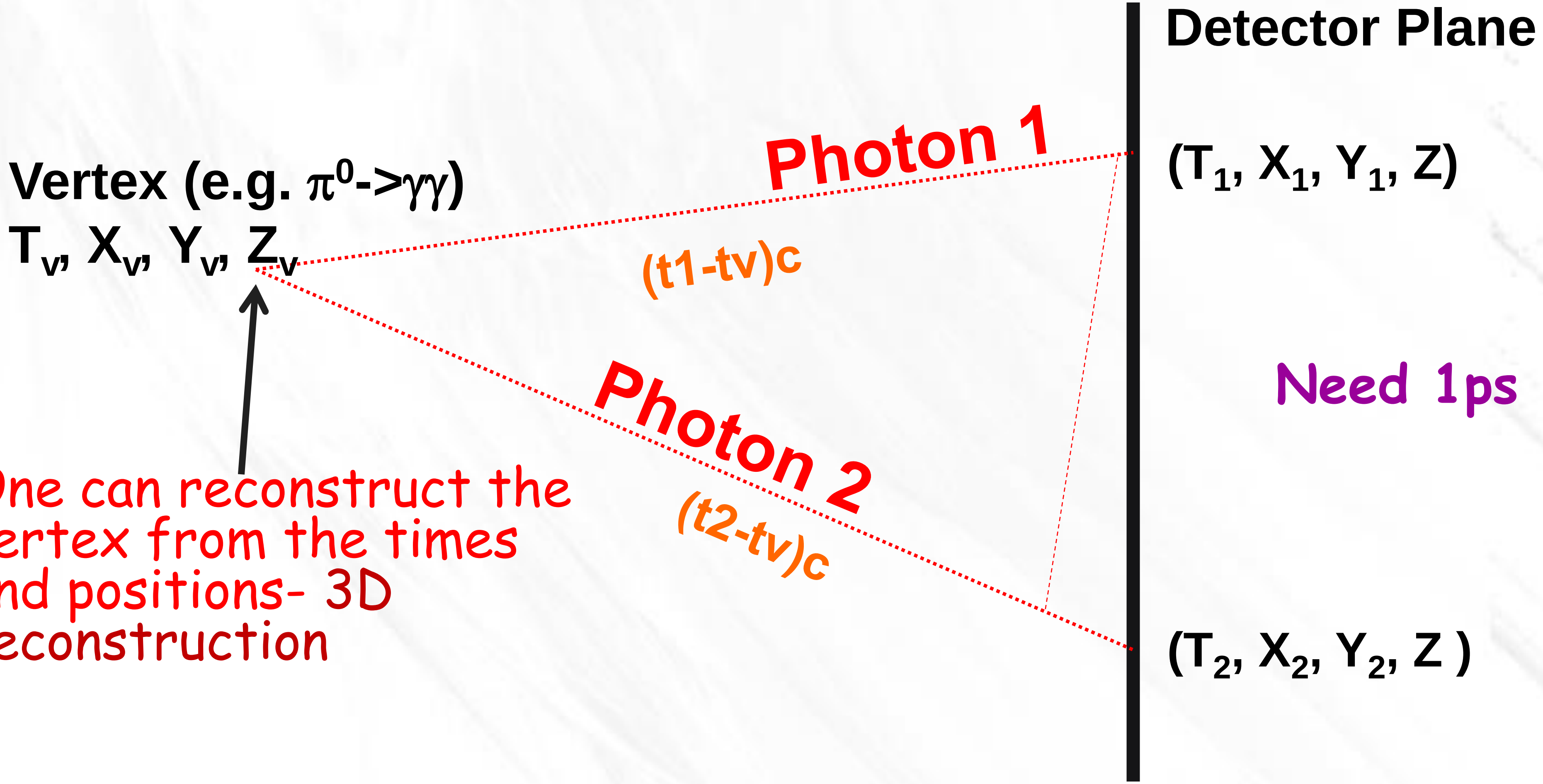
# Multichannel Systems



- 60-channel LAPPD prototype at the ANL Laser Lab
- 180-channel self-triggered Optical TPC at Fermilab
- Central card controls several front end boards
- New central cards by Mircea Bogdan handles 1920 channels

# Vertexing Using Arrival 4D-points

E.g. rare Kaon decays (KOTO at JPARC): background rejection by reconstructing $\pi^0$ vertex space point (beat combinatorics background)



**Detector Plane**

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

$T_V, X_V, Y_V, Z_V$

**Photon 1**

$(t1-tv)c$

$(T_1, X_1, Y_1, Z)$

**Photon 2**

$(t2-tv)c$

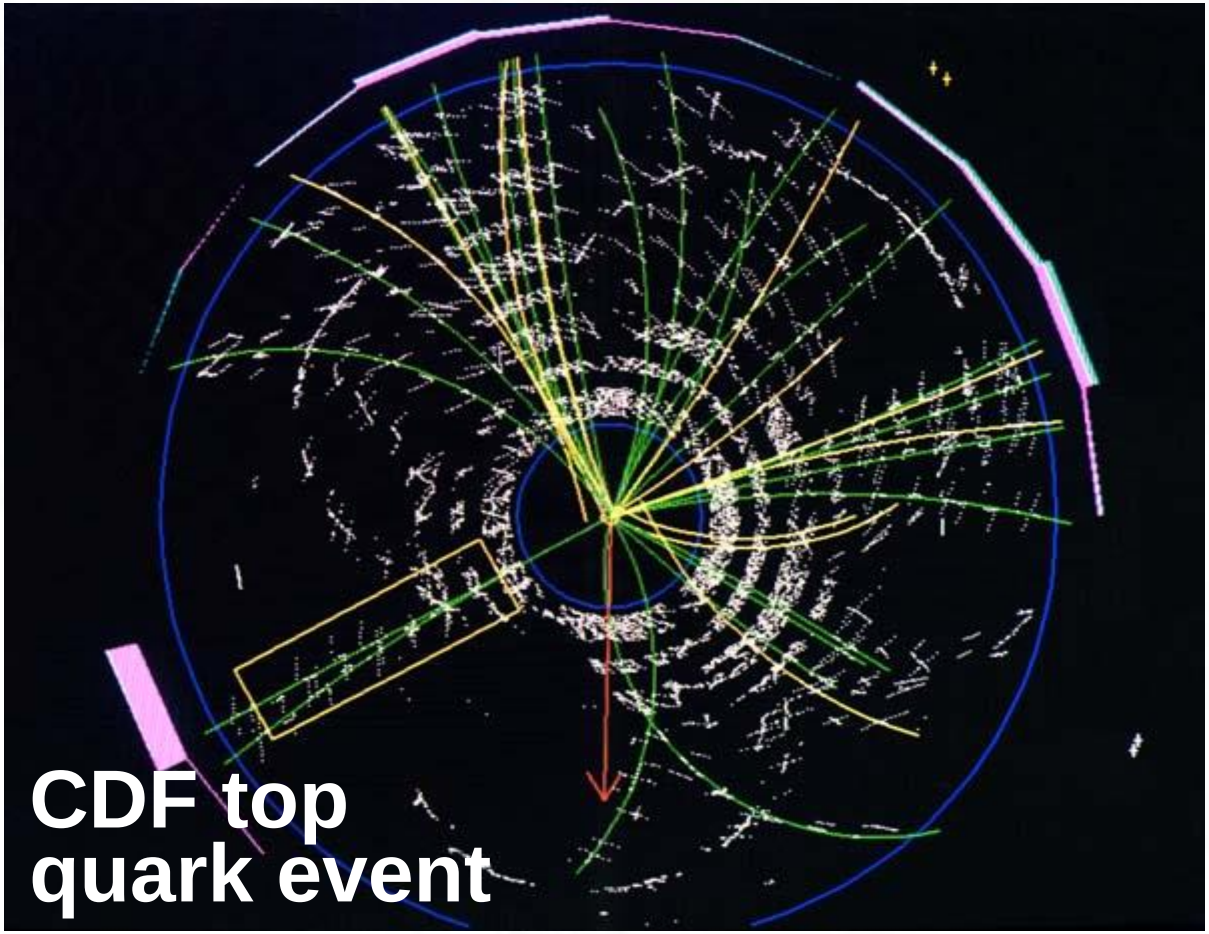
$(T_2, X_2, Y_2, Z)$

Need 1ps

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

# Colliders

- identify the quark content of charged particles
- assign tracks and photons to vertices



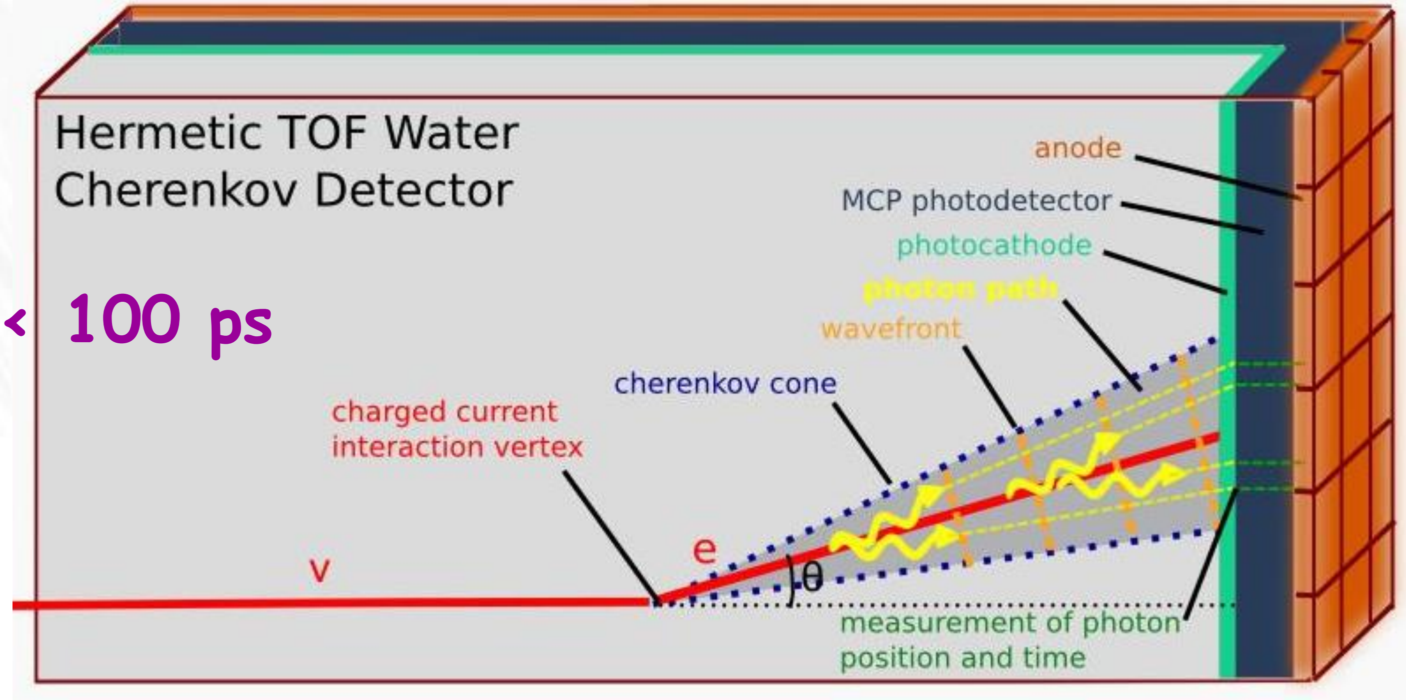
CDF top quark event

Need 1ps

# Optical Time Projection Chamber

- Like a TPC but drifts photons instead of electrons
- Exploits precise location and time for each detected photon
- Would allow track /vertex reconstruction in large liquid counters

**Need < 100 ps**



Suggestion to use LAPPD's for DUSEL and the name (OTPC) due to Howard Nicholson

- It doesn't have to be water (use prompt Cherenkov light that arrives early )
- In fact, for long tracks optical tracking should also work using just scintillation

# Cherenkov vs Scintillation Light

| Cherenkov | Scintillation |
|---|---|
| Prompt emission | Slow emission |
| Directional for each charged track segment | Isotropic for each charged track segment |
| Higher energy threshold | Very low energy threshold |
| Less abundant compared to scintillation light | Abundant: usually completely overshadow Cherenkov light |
| Conventionally used for particle ID, vertexing and "coarse" energy measurements | Conventionally used for vertexing and "precision" energy measurements |

Combining the two should make for a very powerful detector

Very active field:
JINST 7 (2012) P07010; PRD87 (2013) 071301; JINST 9 (2014) 06012; arXiv:1409.5864; NIMA 830 (2016) 303; NIMA 849 (2017) 102; PRC95 (2017) 055801; arXiv:1610.02011

Current status: need fast timing and slow scintillators

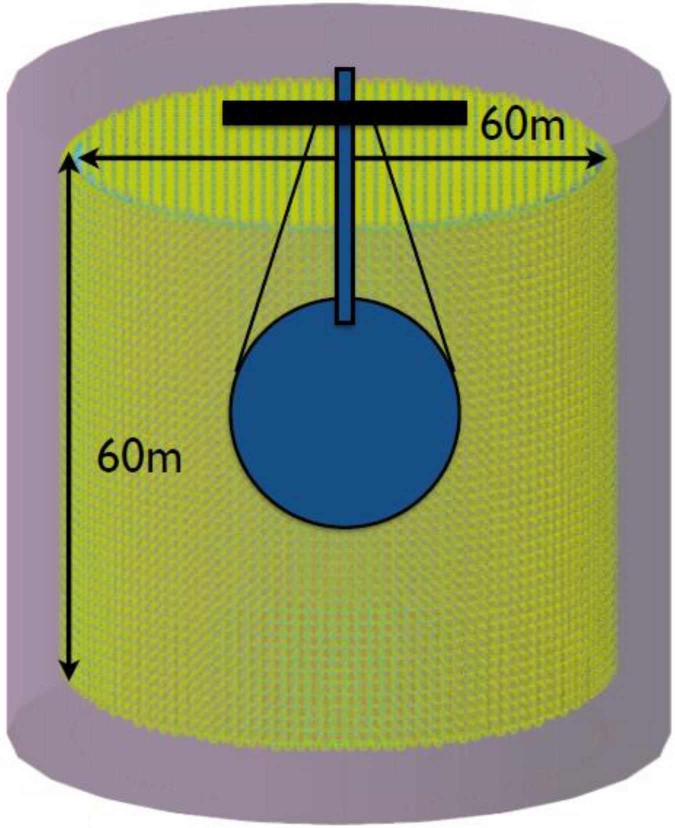
# Large Directional Liquid Scintillator

- Large scintillator detectors and large water-Cherenkov detectors have been very effective in measuring neutrino properties

- Combining the two technologies may allow expanded physics reach of the next generation large neutrino experiments

- Physics Program of THEIA:
  - Neutrinoless double beta decay
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos & DSNB
  - Nucleon decay
  - Long-baseline physics (mass hierarchy, CP-violation)
  - Unexpected surprises

A concept drawing
of the THEIA detector

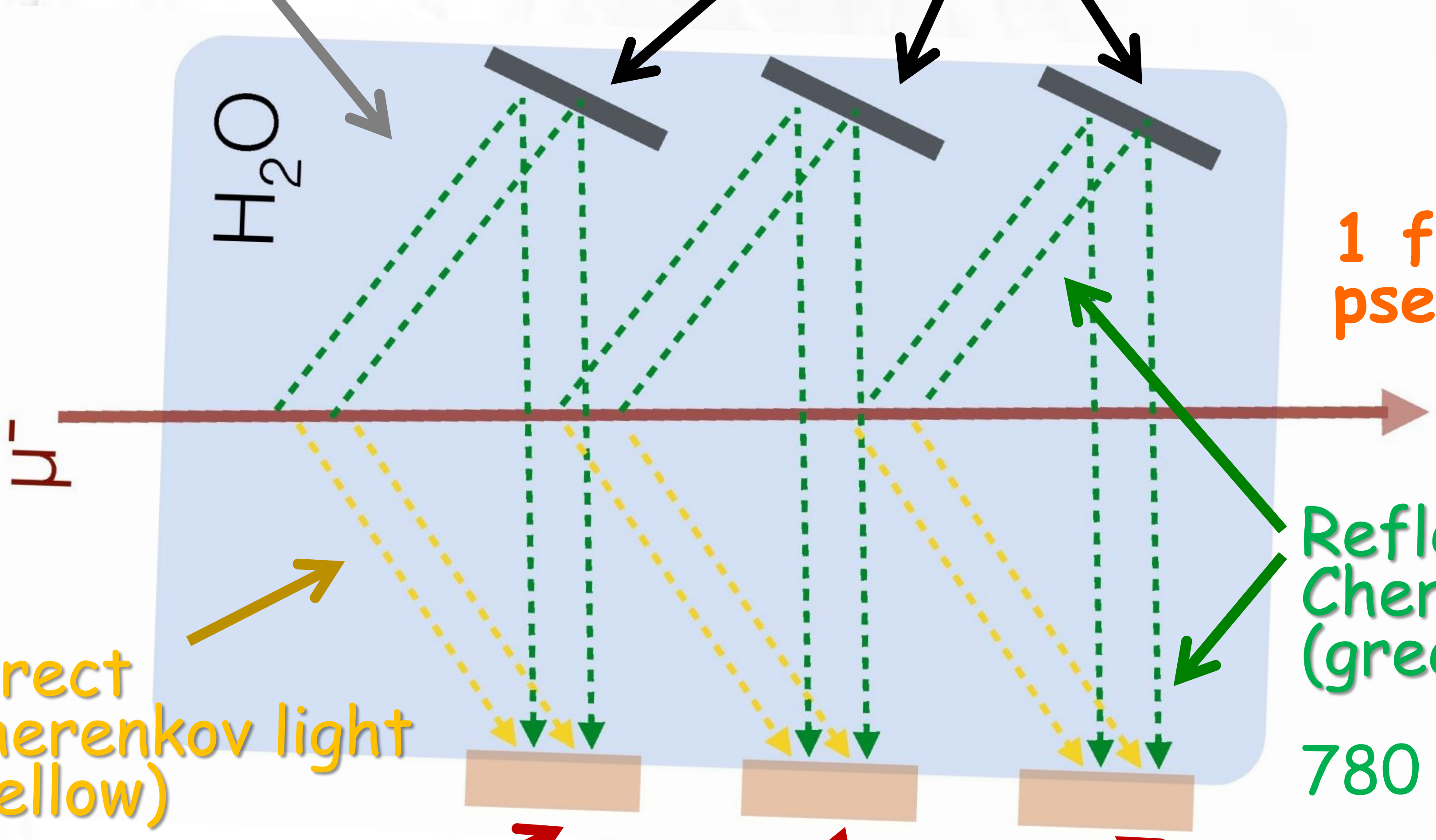


Several design options exist

Cherenkov light provides directionality (background suppression)
Scintillation light provides good energy measurements

# Eric Oberla's Optical TPC

Eric Oberla's Ph.D thesis



Water

Flat mirrors

1 foot/1000 psec muon

Reflected Cherenkov light (green)

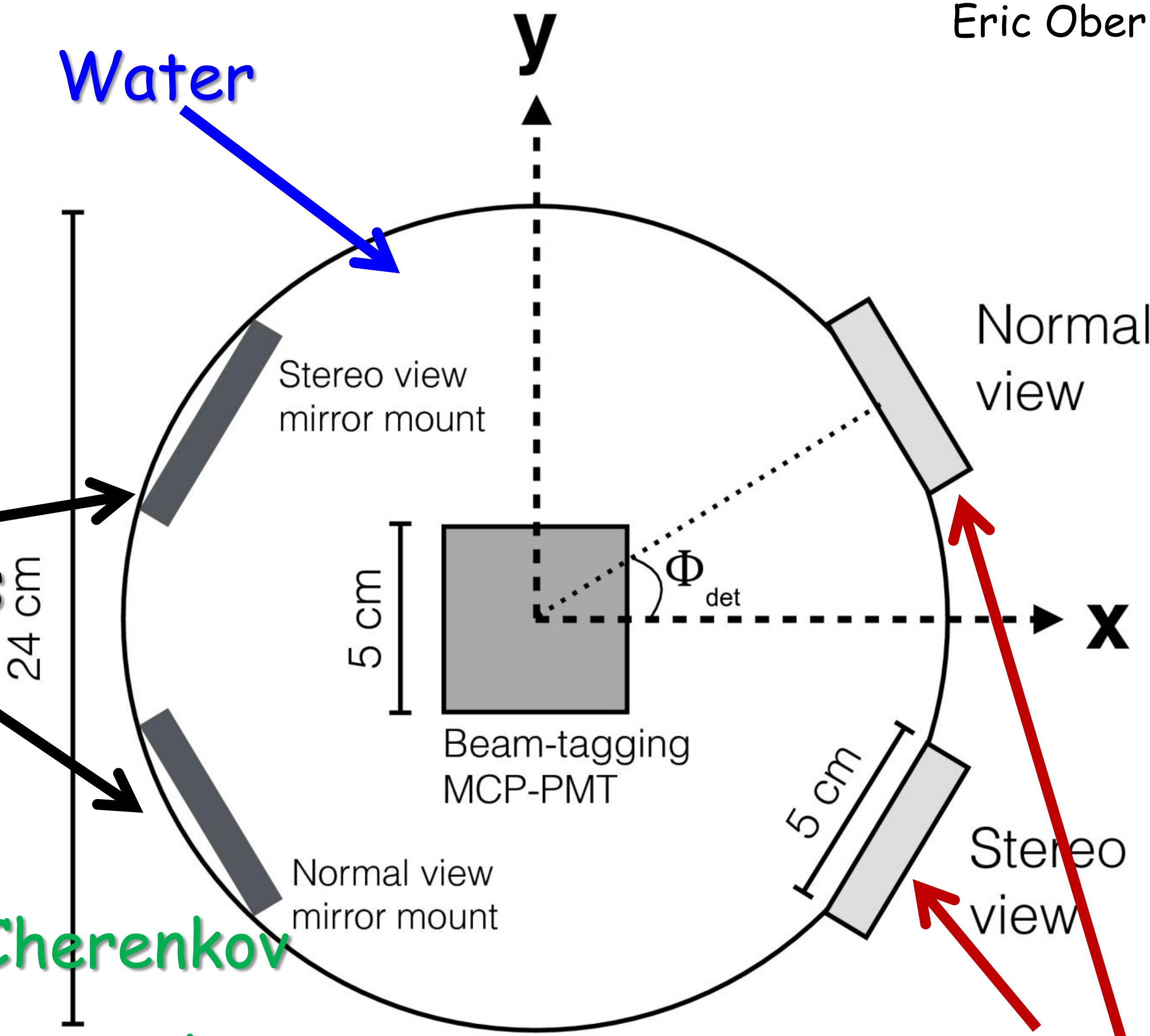
780 psec later

Direct Cherenkov light (yellow)

Photonis MCPs and Chicago striplines/PSEC4

# Beam's Eye View of the OTPC

Eric Oberla's Ph.D thesis



Water

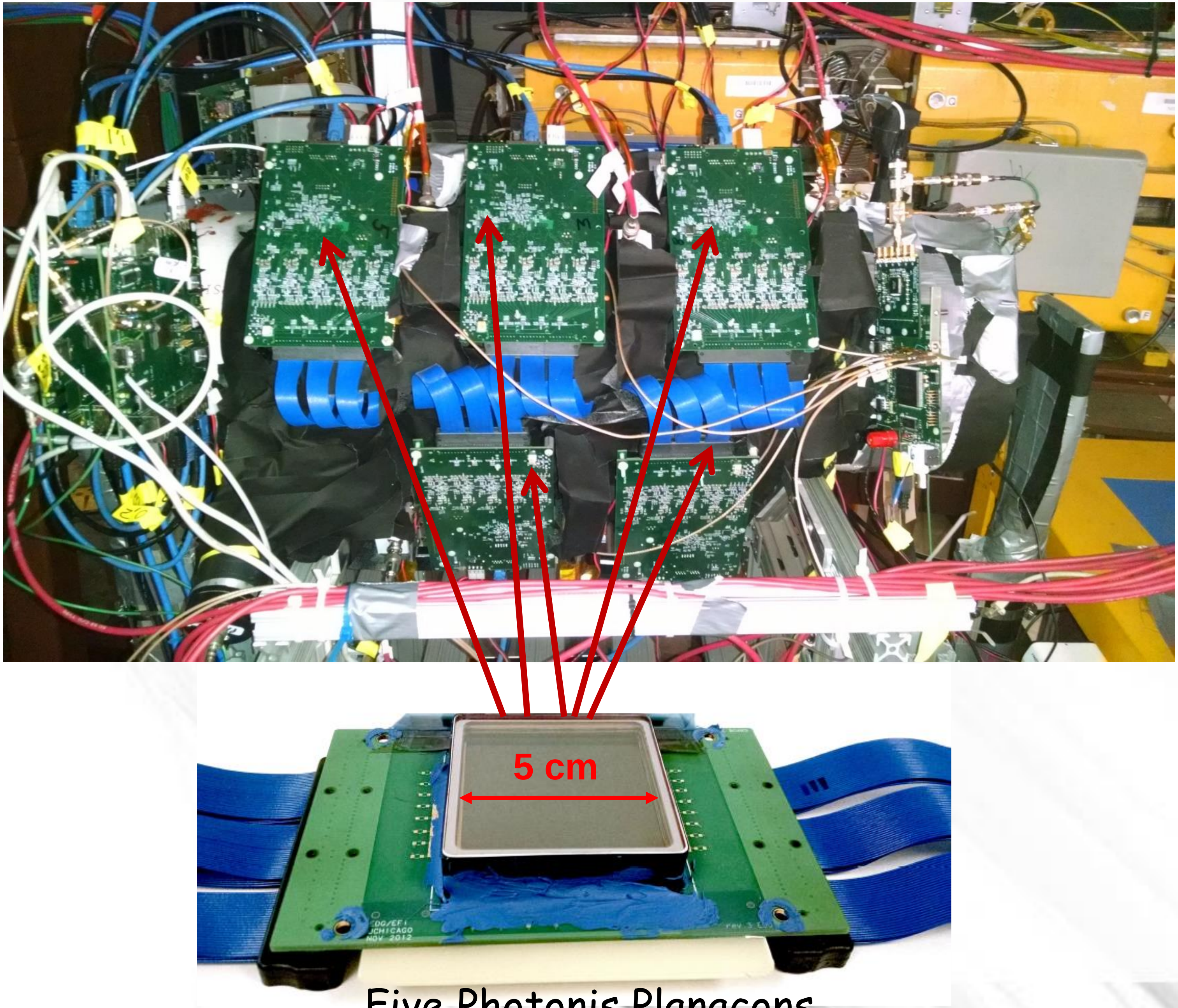
Flat mirrors

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

Photonis MCPs and
Chicago striplines/PSEC4

# OTPC at Fermilab Test Beam

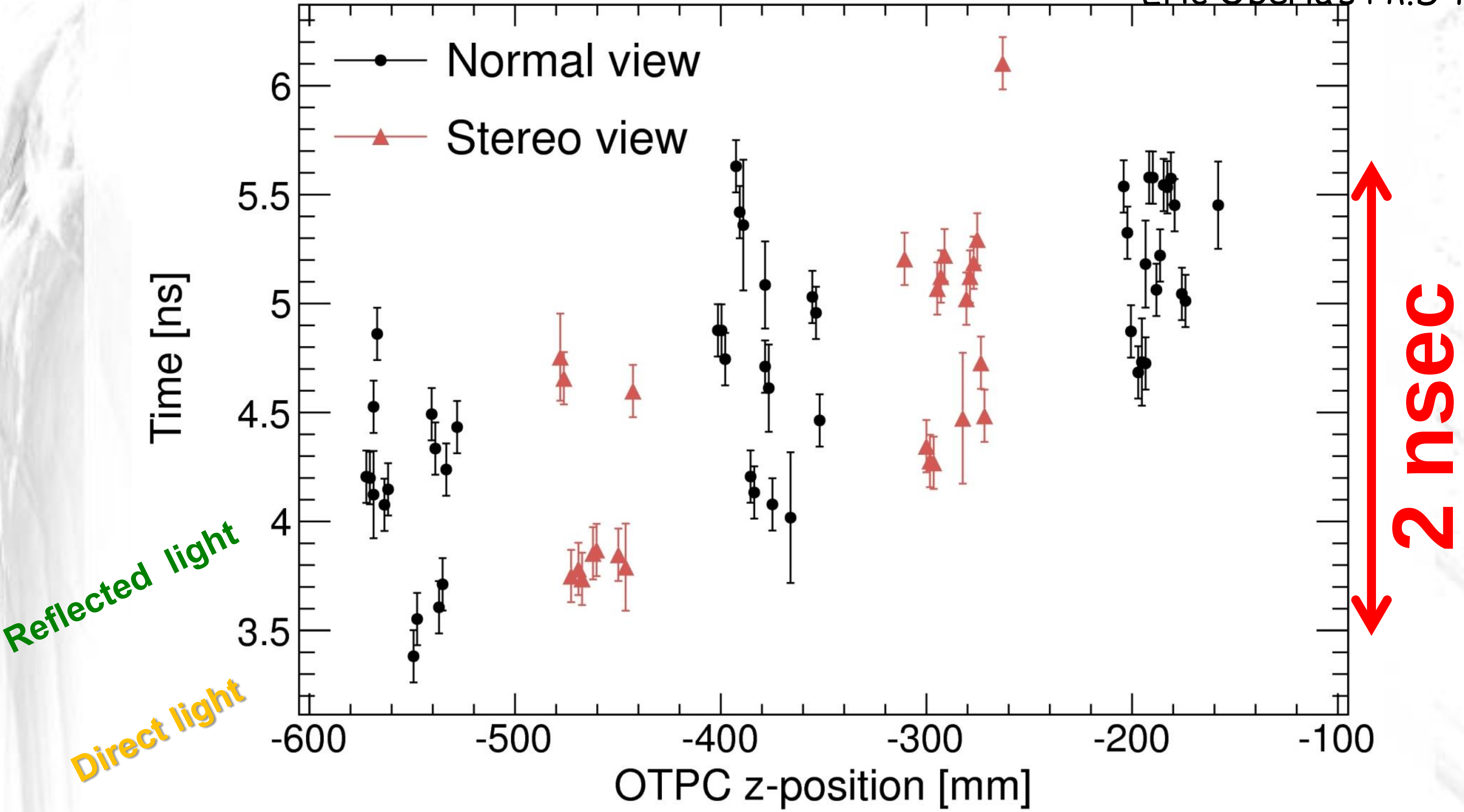
Eric Oberla's Ph.D thesis



Five Photonis Planacons

# OTPC Results

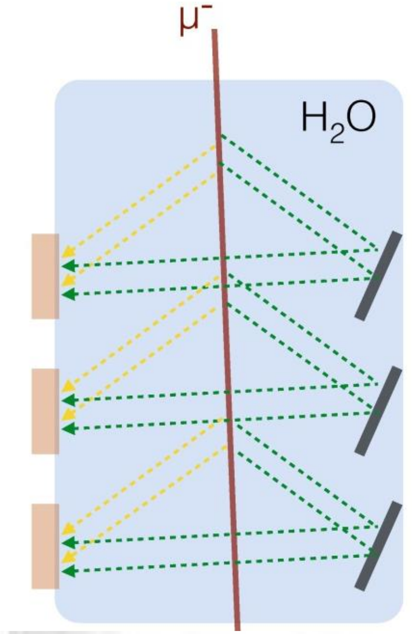
Eric Oberla's Ph.D thesis



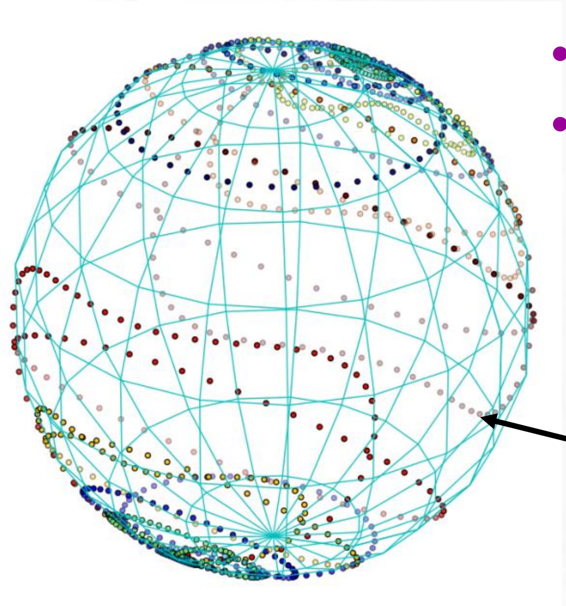
- 60 mrad angular resolution over a lever arm of 40cm
- 1.5 cm spatial resolution (radiation length of H2O is 40cm)
- See 780 psec separation of direct and mirror-reflected light
- More details in Nucl. Instr. Meth. A814, pp19-32 April 1 (2016)

# A Note on Mirrors and the Optical TPC

E. Oberla



E. Angelico



- Photo-cathode coverage is expensive
- Mirrors may help to reduce cost of very large detectors

Simulation of reflection points of 20 photons inside a silvered sphere, color-coded by time

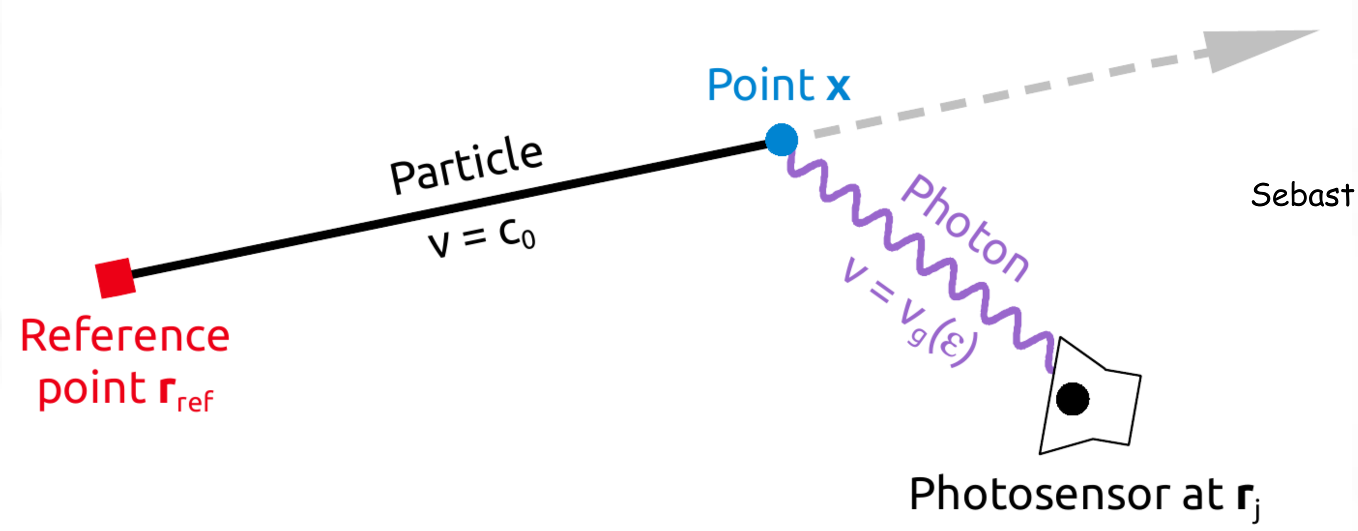
"Adding psec-resolution changes the space in which considerations of Liouville's Theorem operates from 3-dimensional to 4-dimensional. In analogy with accelerator physics, we can exchange transverse emittance to longitudinal emittance.

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

Homage to T. Ypsilantis

# 3D Optical Tracking

Need:
- One reference point (space and time)
- Single photon hit times



Drawing from
Sebastian Lorenz presentation

$$t = t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x}-\mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j-\mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$

Reconstruction algorithms work with Cherenkov or scintillation light
- B. Wonsak et al. Original motivation: LENA scintillator detector
- M. Wetstein et al. Original motivation: water-Cherenkov LBNE detector

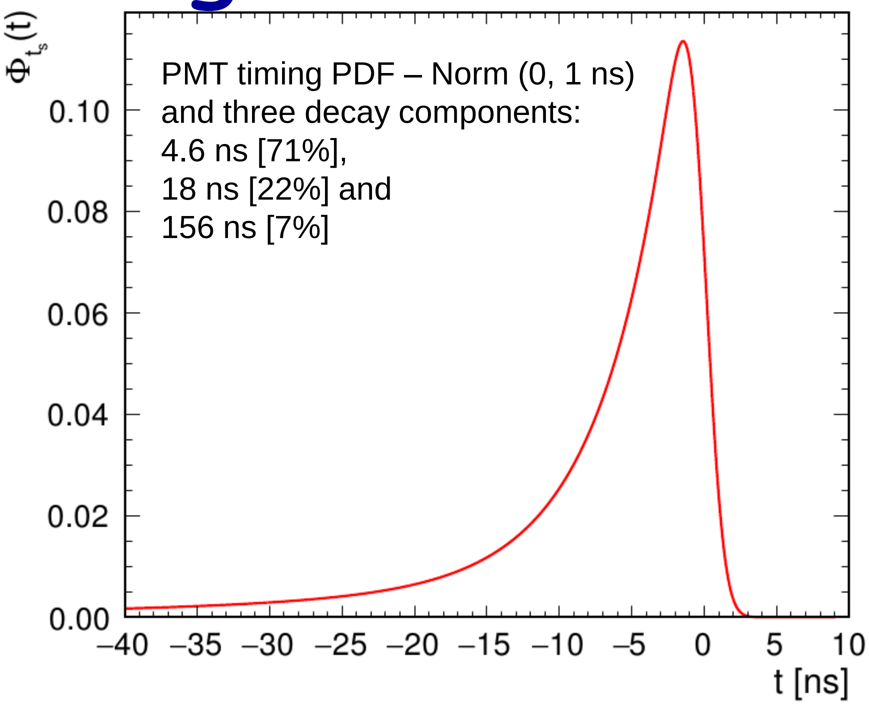
# 3D Optical Tracking using Scintillation

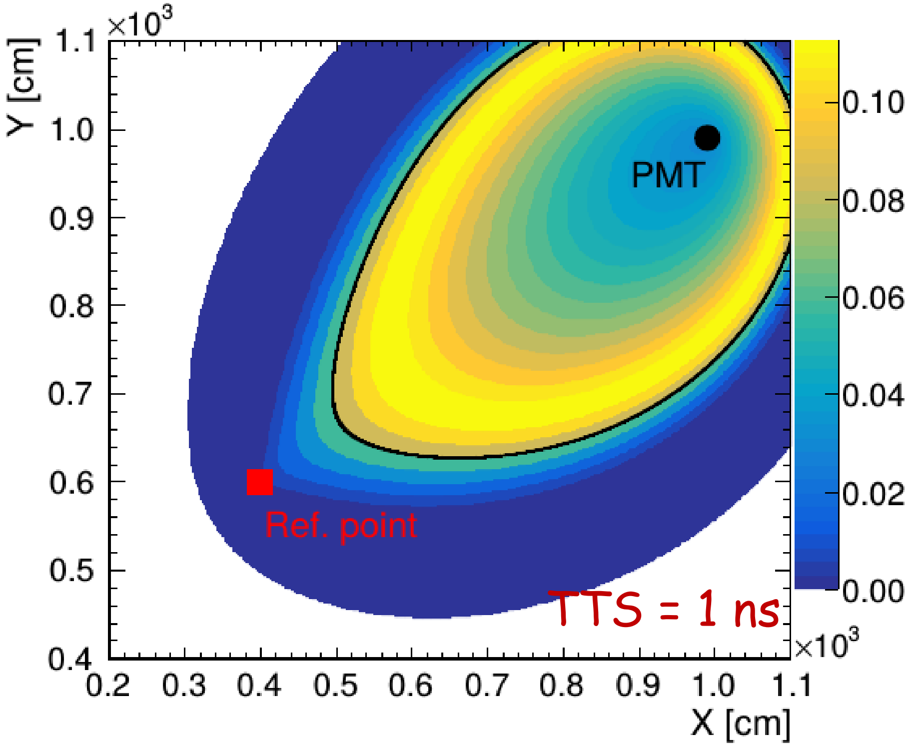
B. Wonsak et al.

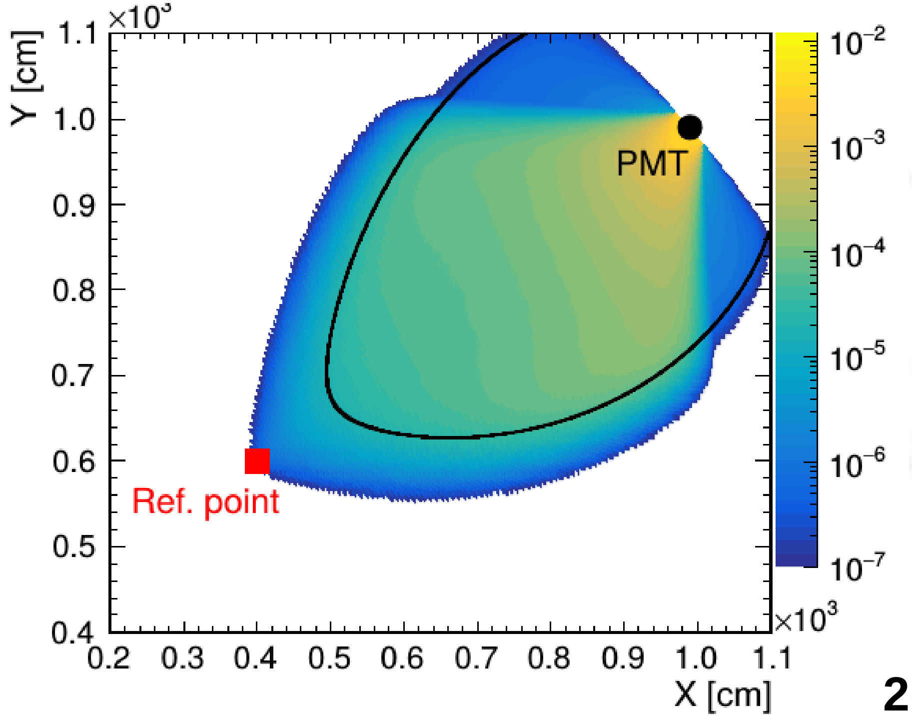
For each photon hit:

- Time defines drop-like surface
- Gets smeared with time profile
  (scintillation & PMT-timing)
- Weighted due to spatial constraints
  (acceptance, optical properties, light concentrator, …)

→ spatial p.d.f. for photon emission points



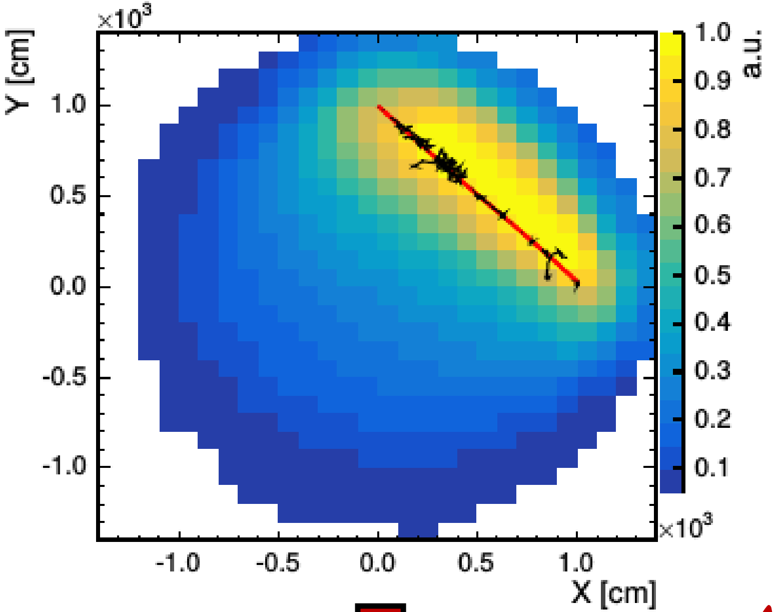




# 3D Optical Tracking using Scintillation

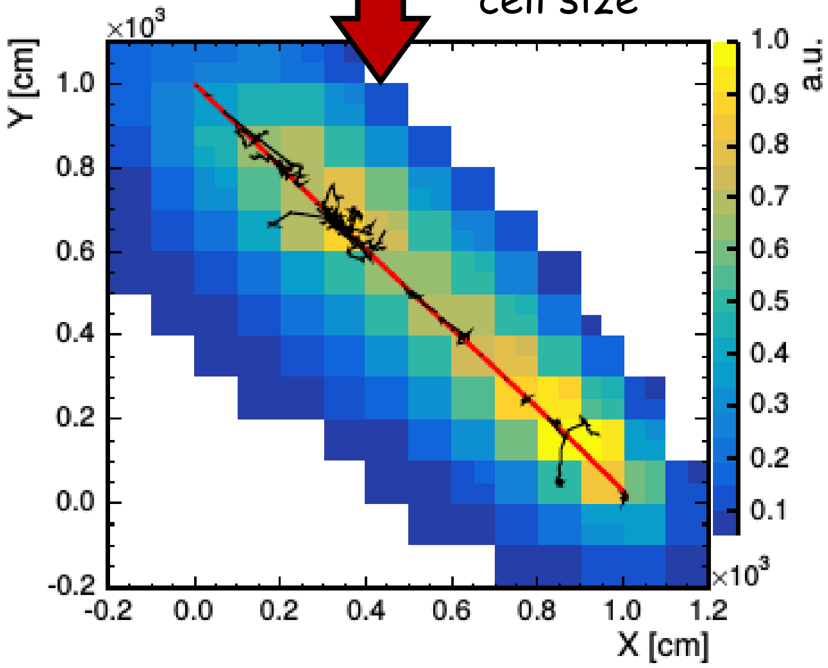
B. Wonsak et al.

- Add up all signals
- Divide result by local detection efficiency
  → Number density of emitted photons
- Use knowledge that all signals belong to same topology to 'connect' their information
  → Use prior results to re-evaluate p.d.f. of each signal



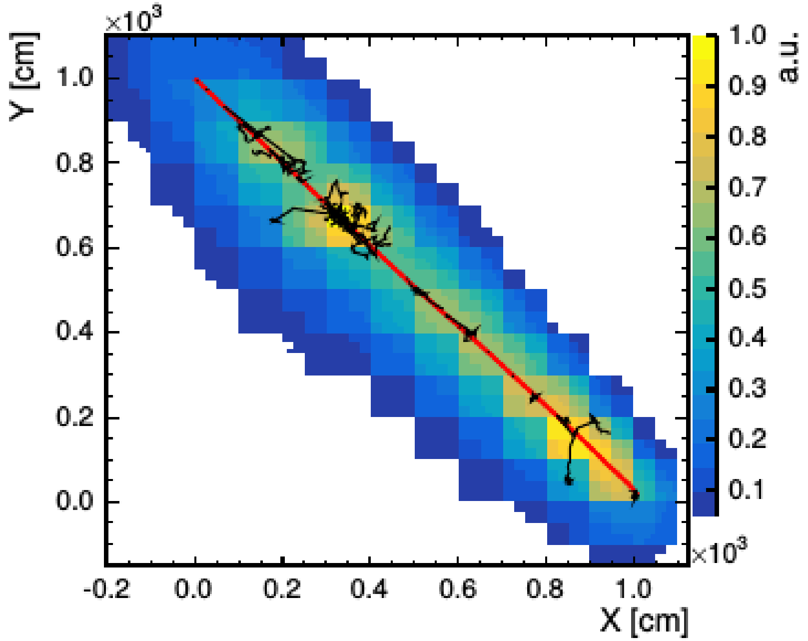
Decreased cell size

Access to dE/dx



Decreased cell size

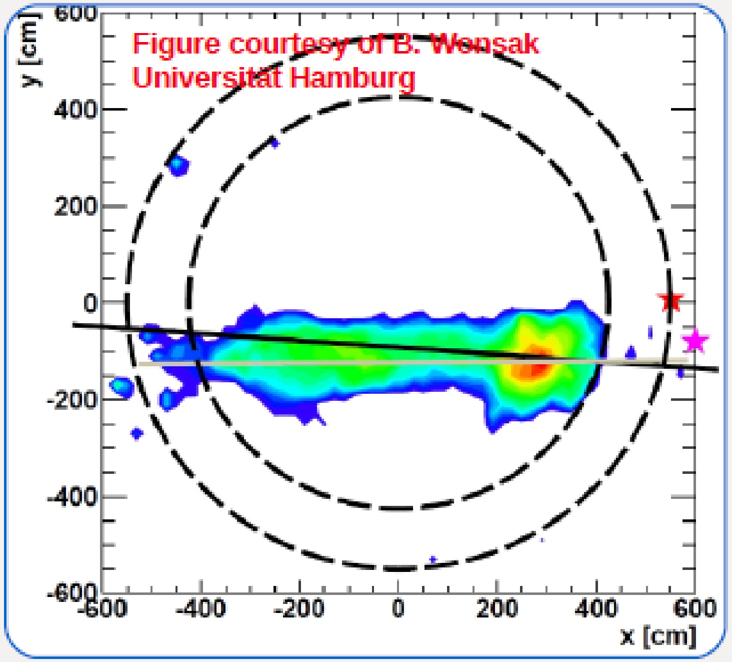
3 GeV muon simulated in LENA

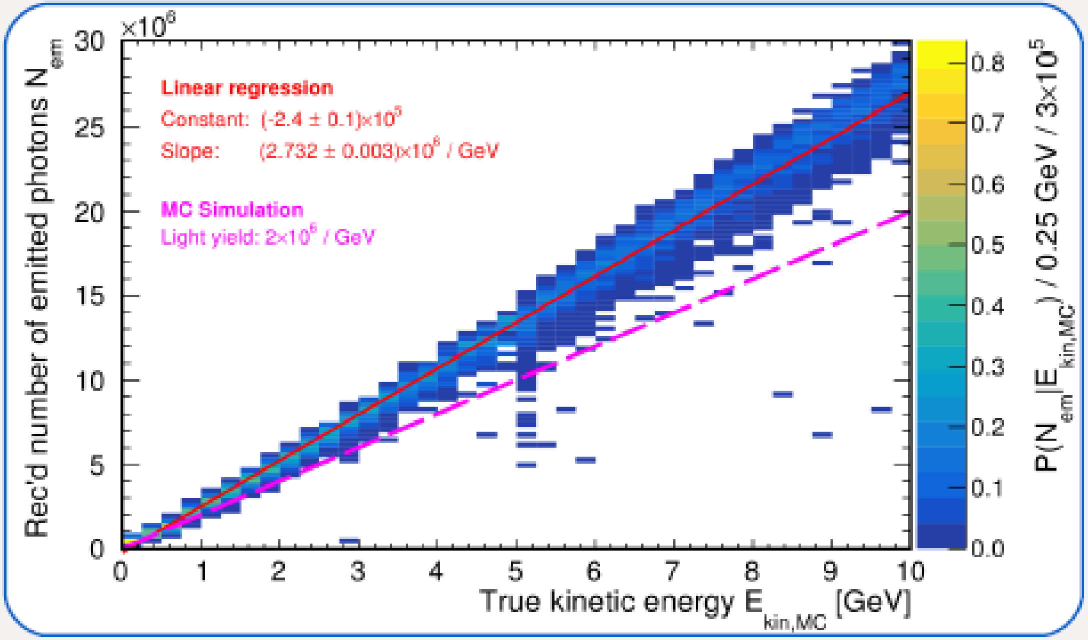


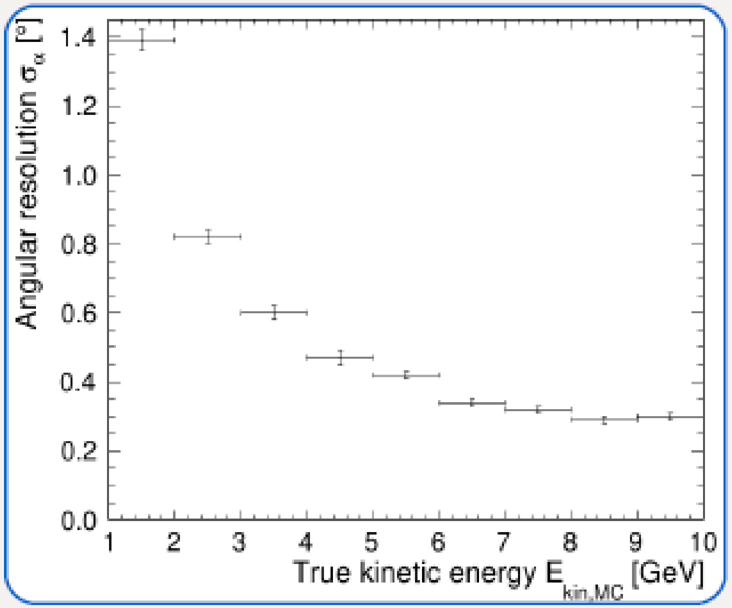
# 3D Optical Tracking using Scintillation

## Current Status (slide by S. Lorenz)

- Early version tested with real Borexino data
- Developed C++ reconstruction framework
  - LENA implemented
  - JUNO implementation ongoing (more complicated optical model)
  - Borexino implementation ongoing (real data!)
- First performance evaluation with fully-contained MC muon events in LENA

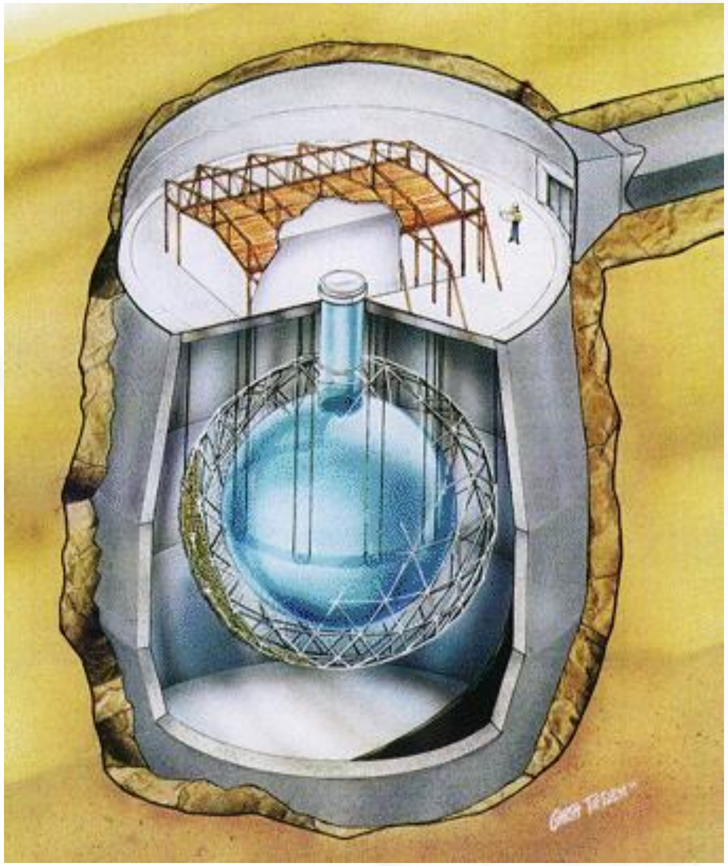




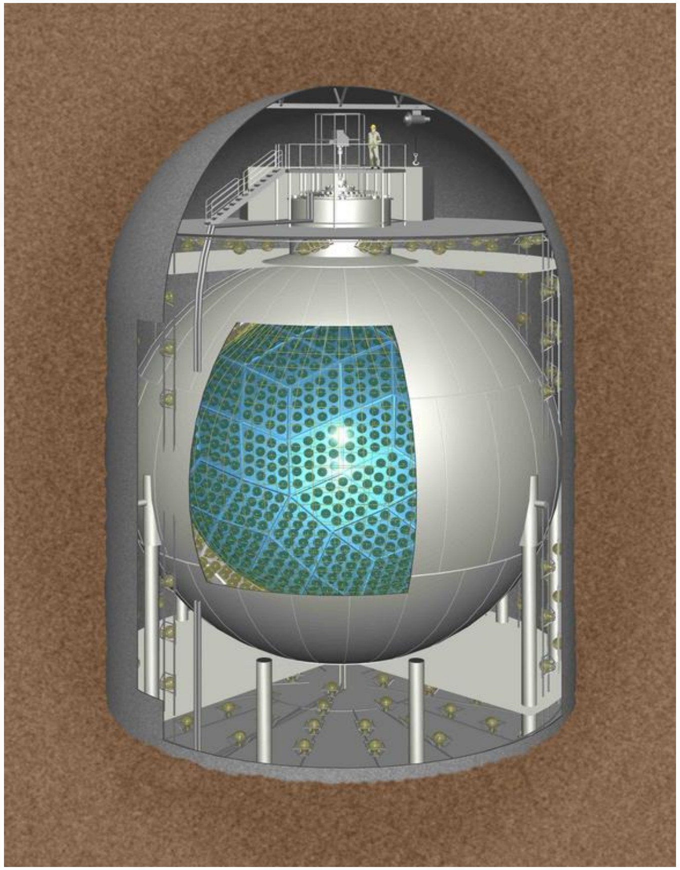


# Liquid Scintillator Detectors

**SNO+: 12 m diameter**

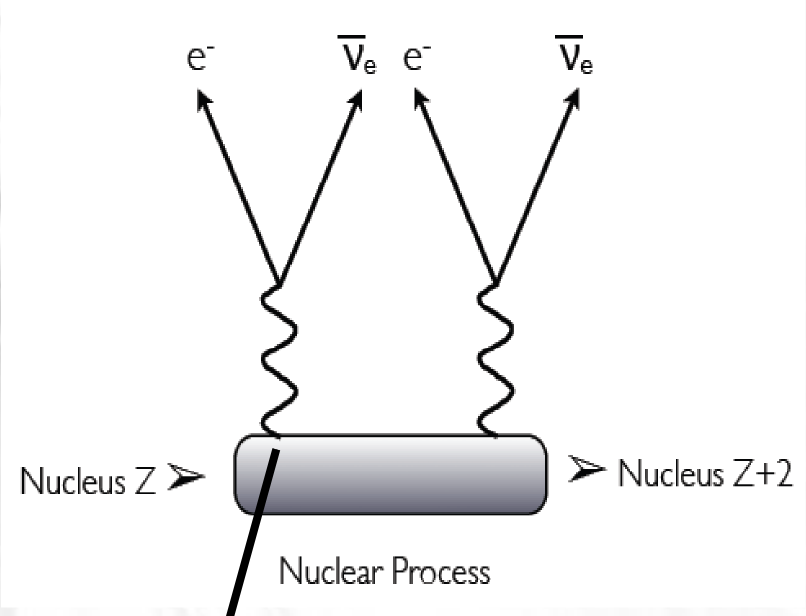


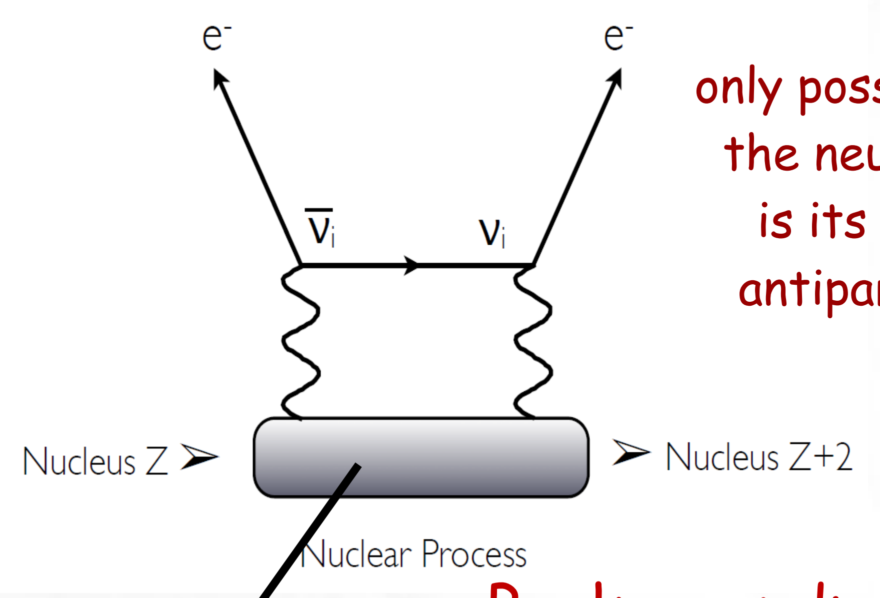
**KamLAND-Zen: 13 m diameter**



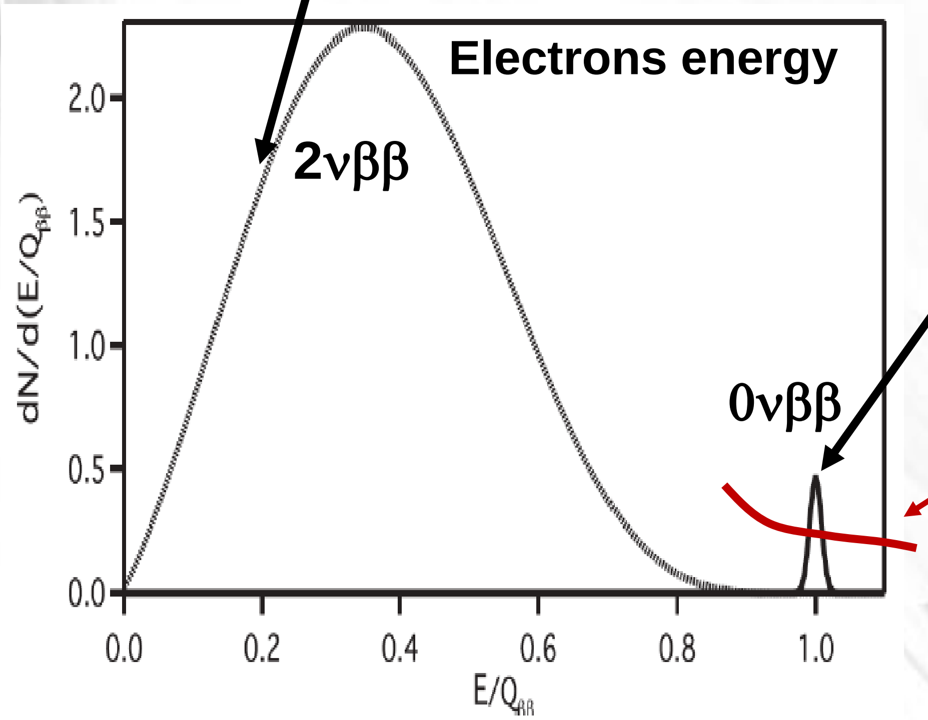
- Both detectors are searching for neutrinoless double beta decay
- Surrounded by slow PMTs for light collection to measure energy

# Double Beta Decay



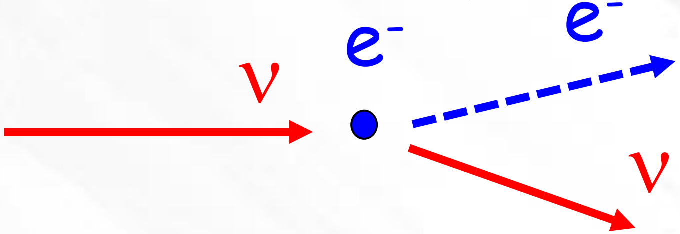


only possible if the neutrino is its own antiparticle



Background:

Electron scattering of neutrinos coming from $^8$B-decays in the sun



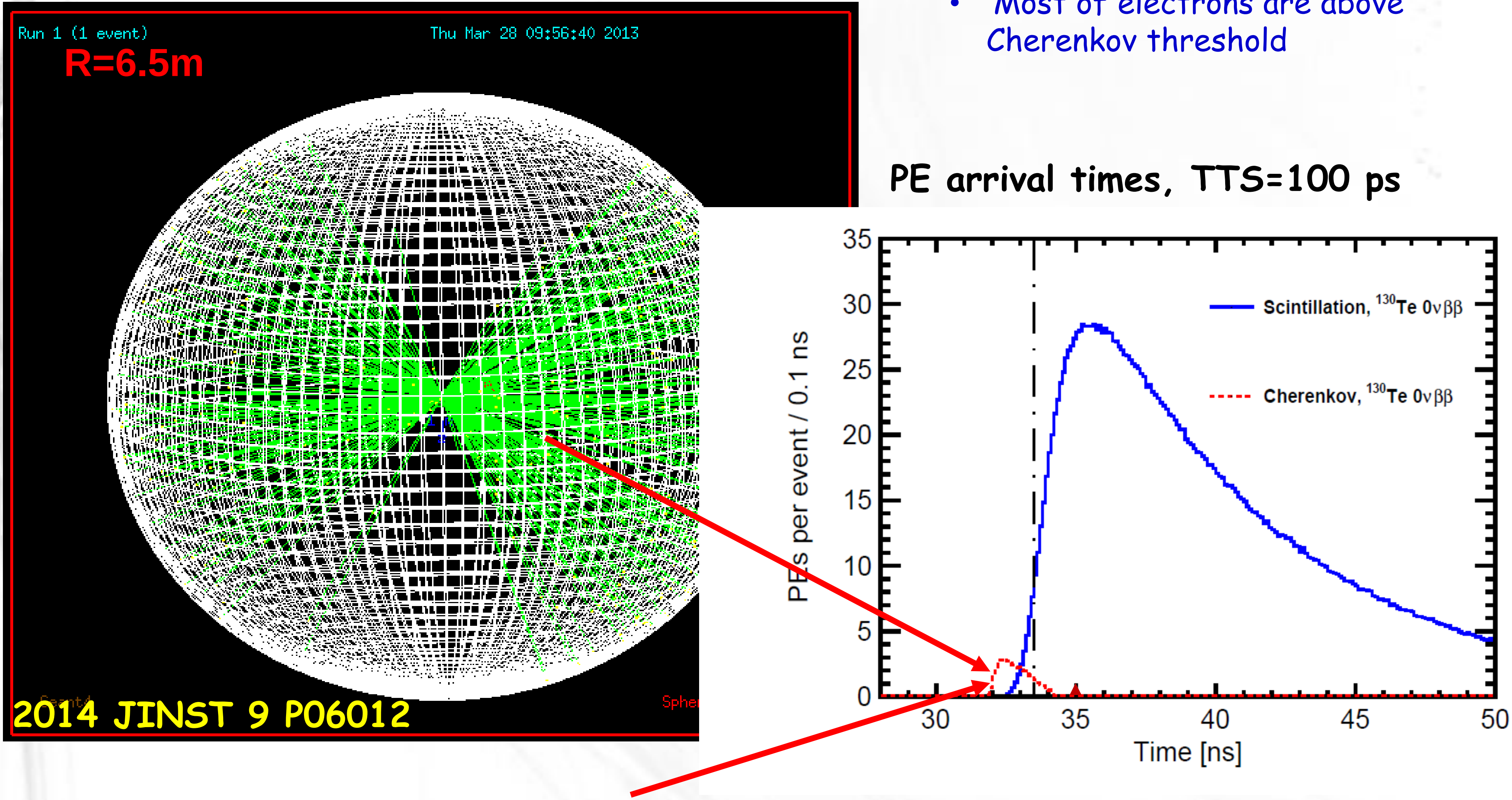
It overlaps with 0νββ-decay energy deposition and therefore this is irreducible background without event topology reconstruction (need two-track vs one-track discriminant)

# Can We See Event Topology in a LS Detector?

Simulation of a $0\nu\beta\beta$ event
(selected event with large angle between electrons)

- Distinct two-track topology with preference to be "back-to-back"
- Most of electrons are above Cherenkov threshold

PE arrival times, TTS=100 ps



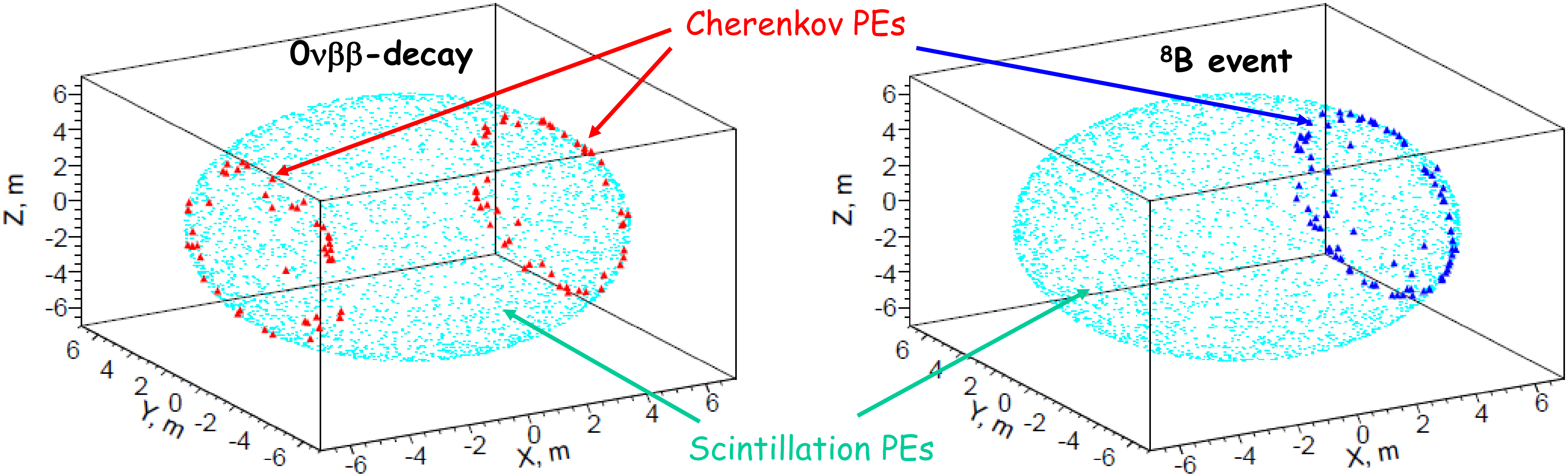
2014 JINST 9 P06012

Fast (arrives early) and directional

- directionality reconstruction
- event topology reconstruction (e.g., 2-track vs 1-track)

# Early Light Topology

Idealized event displays: no multiple scattering, all light after QE=30% cut



Cherenkov PEs

Scintillation PEs

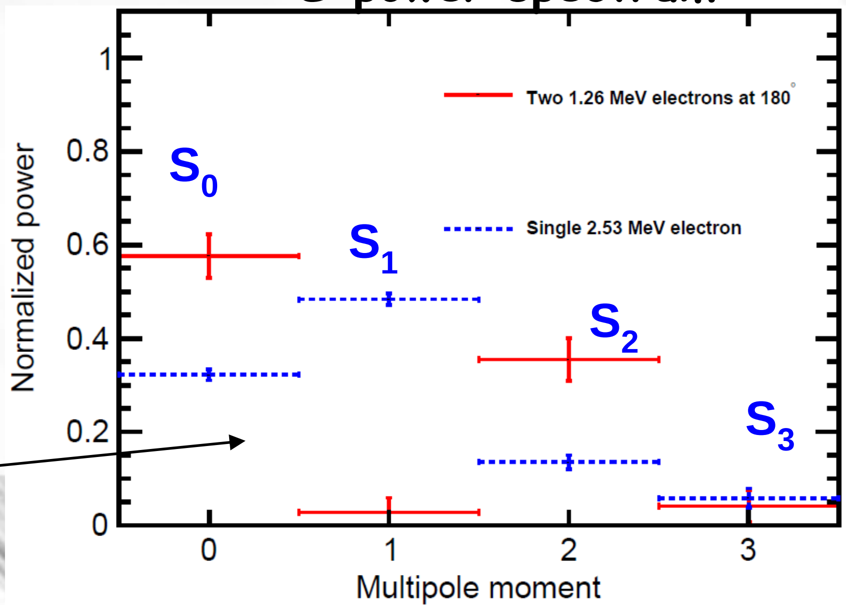
Spherical harmonics analysis

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

Rotation invariant power spectrum

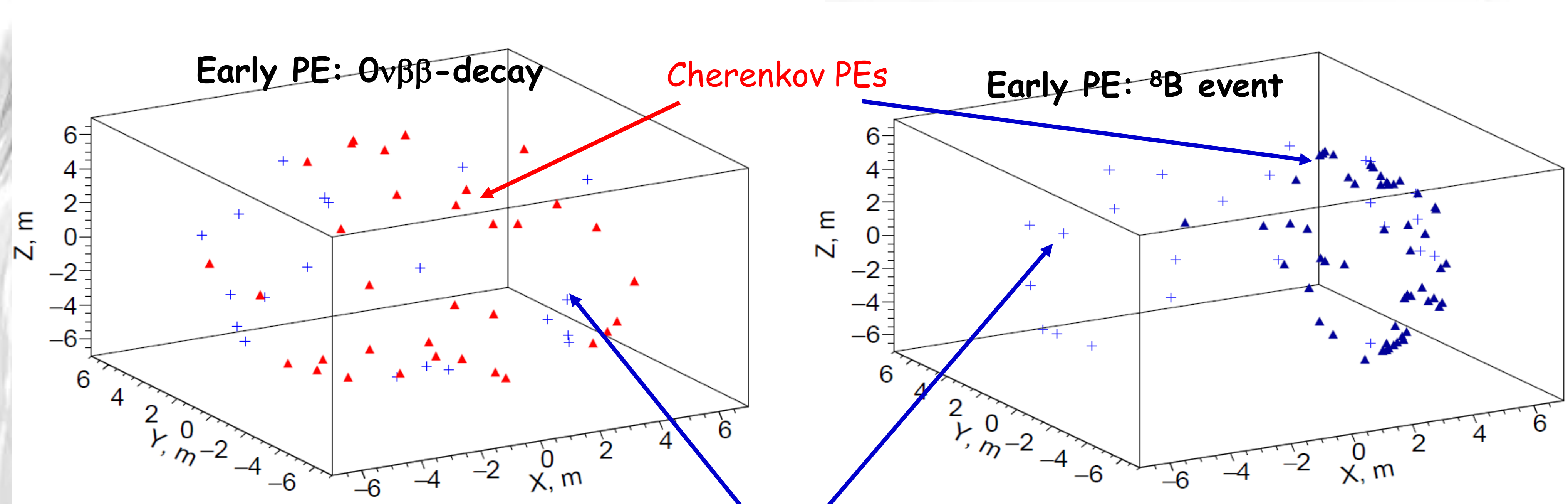
$$\boxed{S_{ff}(\ell)=\sum_{m=-\ell}^{\ell}|f_{\ell m}|^2}$$

S power spectrum



# Early Light Topology

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

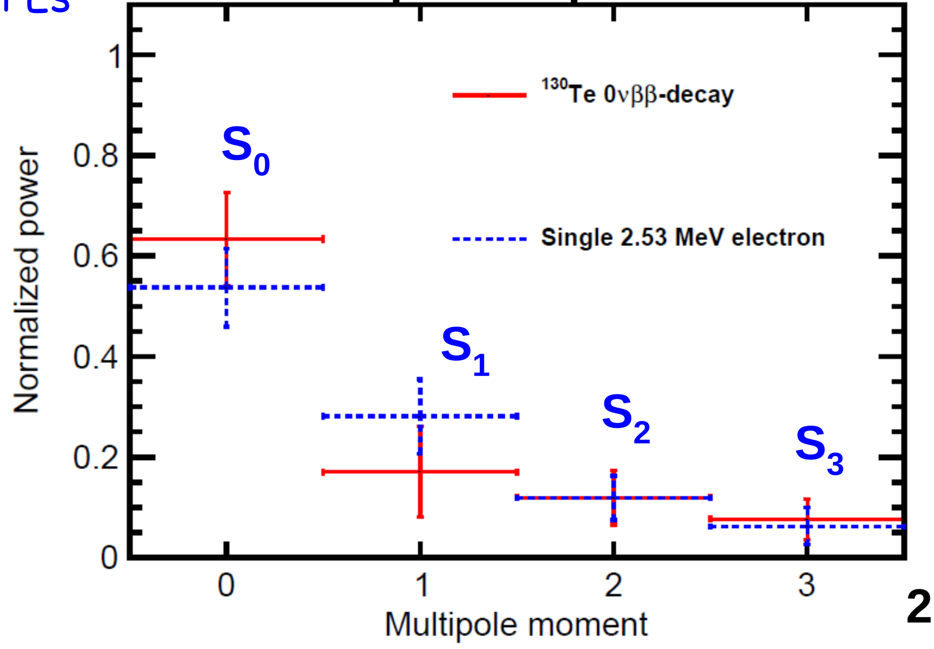


Cherenkov PEs

NIMA 849 (2017) 102

Scintillation PEs

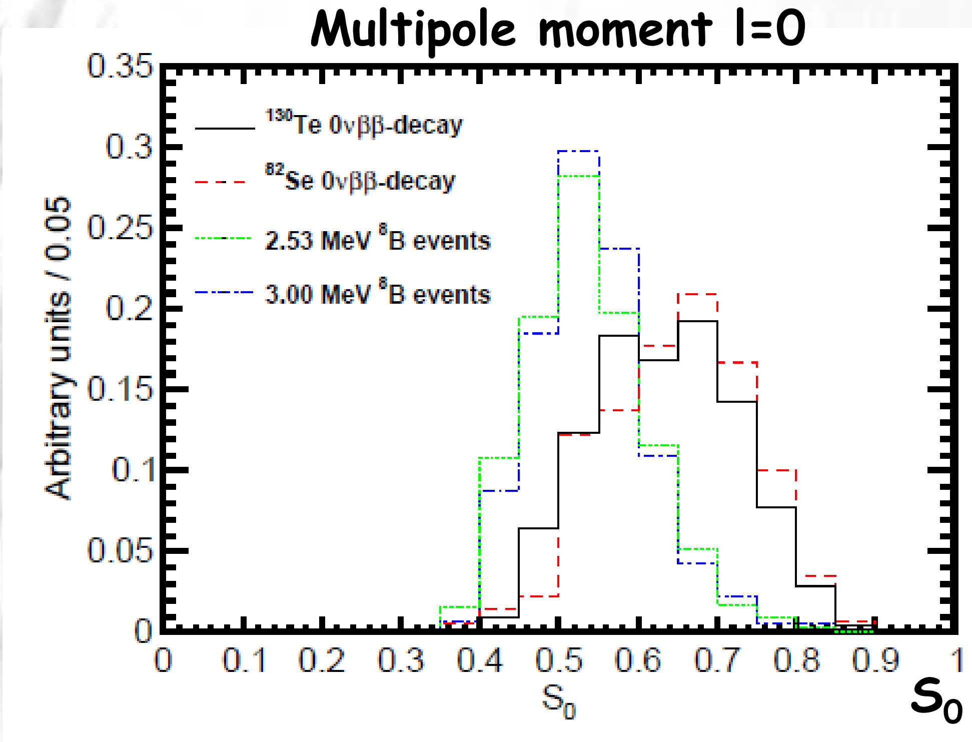
S power spectrum

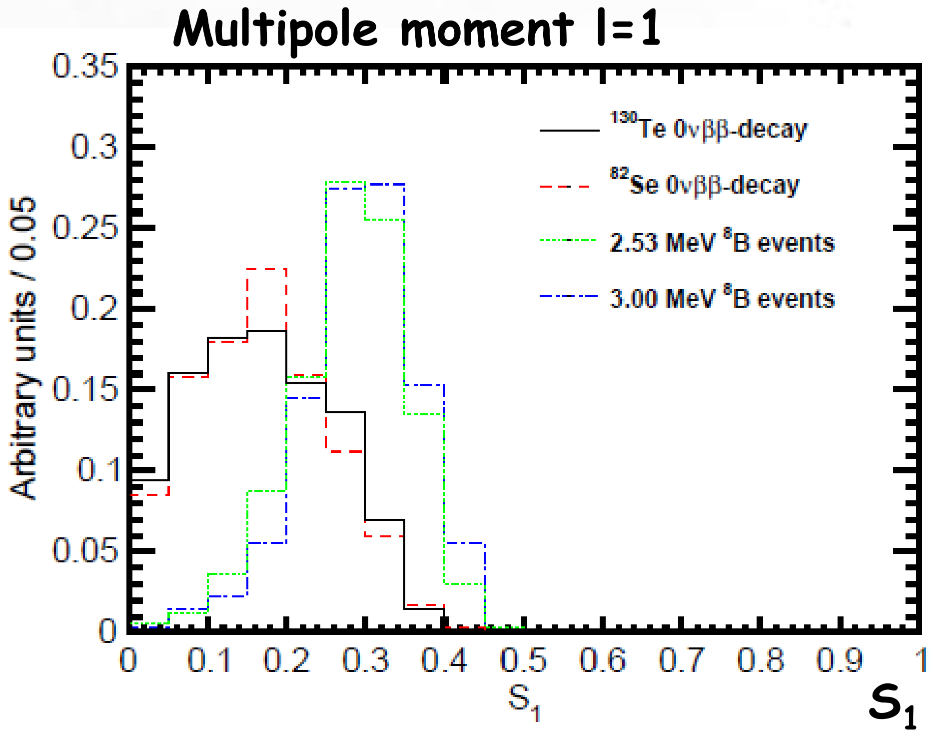


Key parameters determining separation of 0νββ-decay from $^8$B

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

# 2-Track vs 1-Track Event Topology


**Multipole moment l=0**

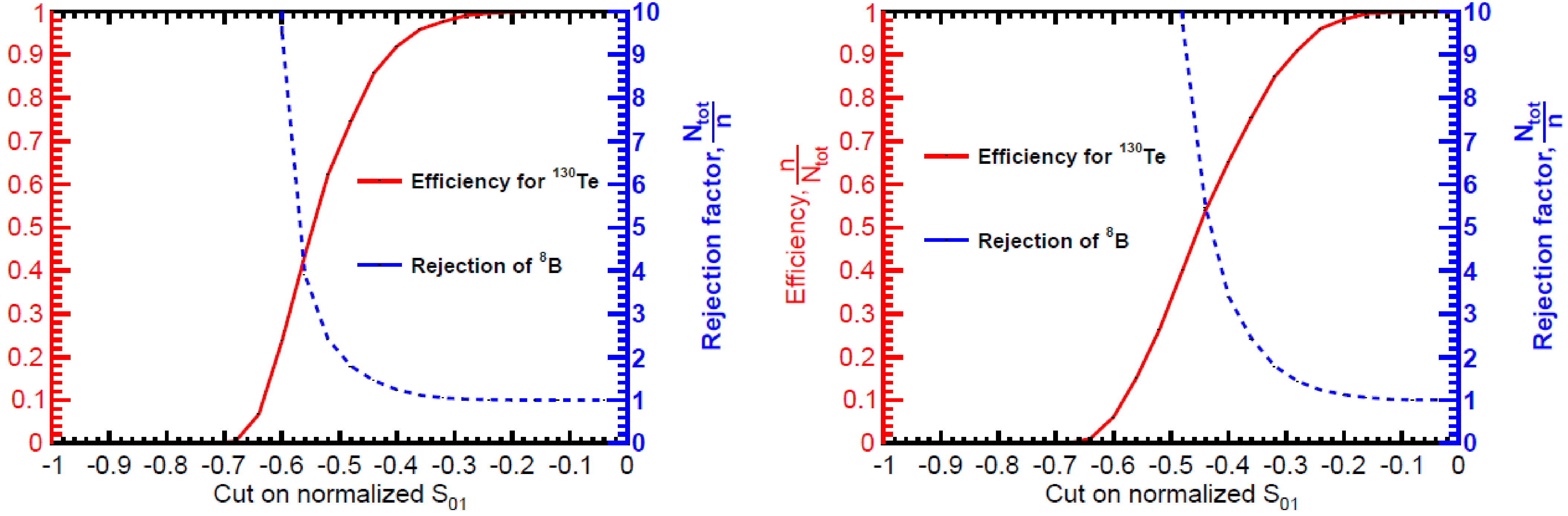

**Multipole moment l=1**

- Spherical harmonics analysis is rather simple, but it doesn't use all available information
- Advanced machine learning techniques looking at 4-vectors of each photon hit should work better (probably makes more sense with a little more progress on the instrumentation front)

Topology reconstruction of MeV events could help against other backgrounds in searches for 0νββ-decay (e.g., $^{10}$C, 2.6MeV gammas)

# $0\nu\beta\beta$ vs $^8B$

For details see NIM A849 (2017) 102



Background rejection factor = 2
@ 70% signal efficiency

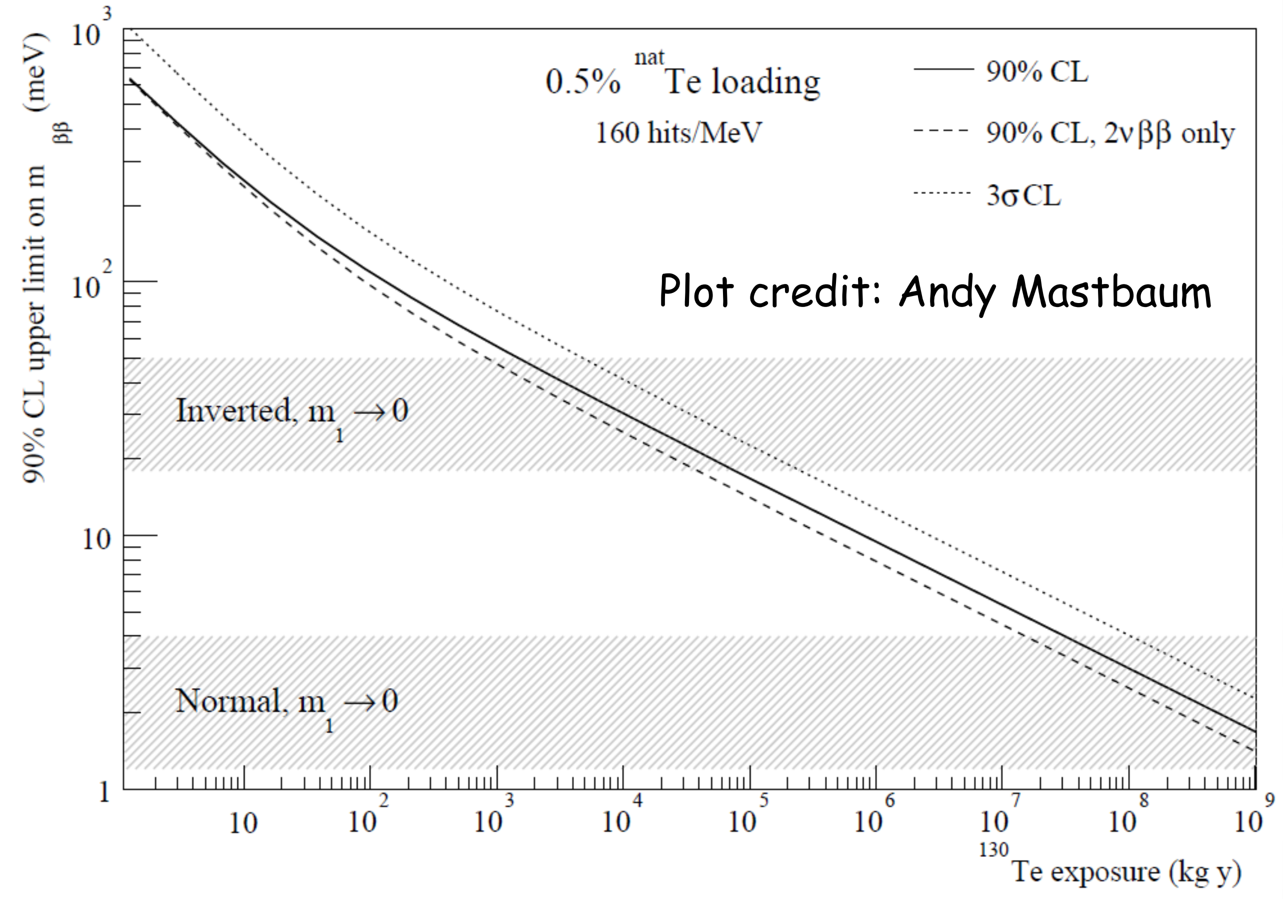
Background rejection factor = 3
@ 70% signal efficiency

Other backgrounds (gammas, alphas, $^{10}$C, etc) also have distinct topologies
Event reconstruction in liquid scintillator would enable new opportunities

# THEIA

Potential for $0\nu\beta\beta$-decay search

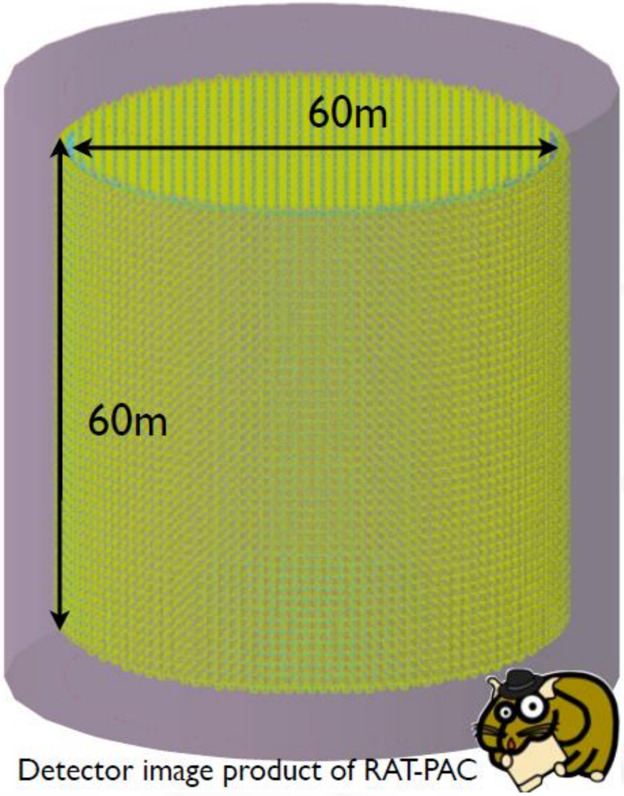
- 50kt detector
- 50% reduction of $^{8}B$
- 0.5% $^{nat}Te$ loading
- 50t $^{130}Te$ after fiducial cuts
- 15 meV after 10 years



Plot credit: Andy Mastbaum

Multipurpose detector
(including neutrino oscillation physics)

Concept paper - arXiv:1409.5864



Detector image product of RAT-PAC

Illustration from a presentation by Gabriel Orebi Gann

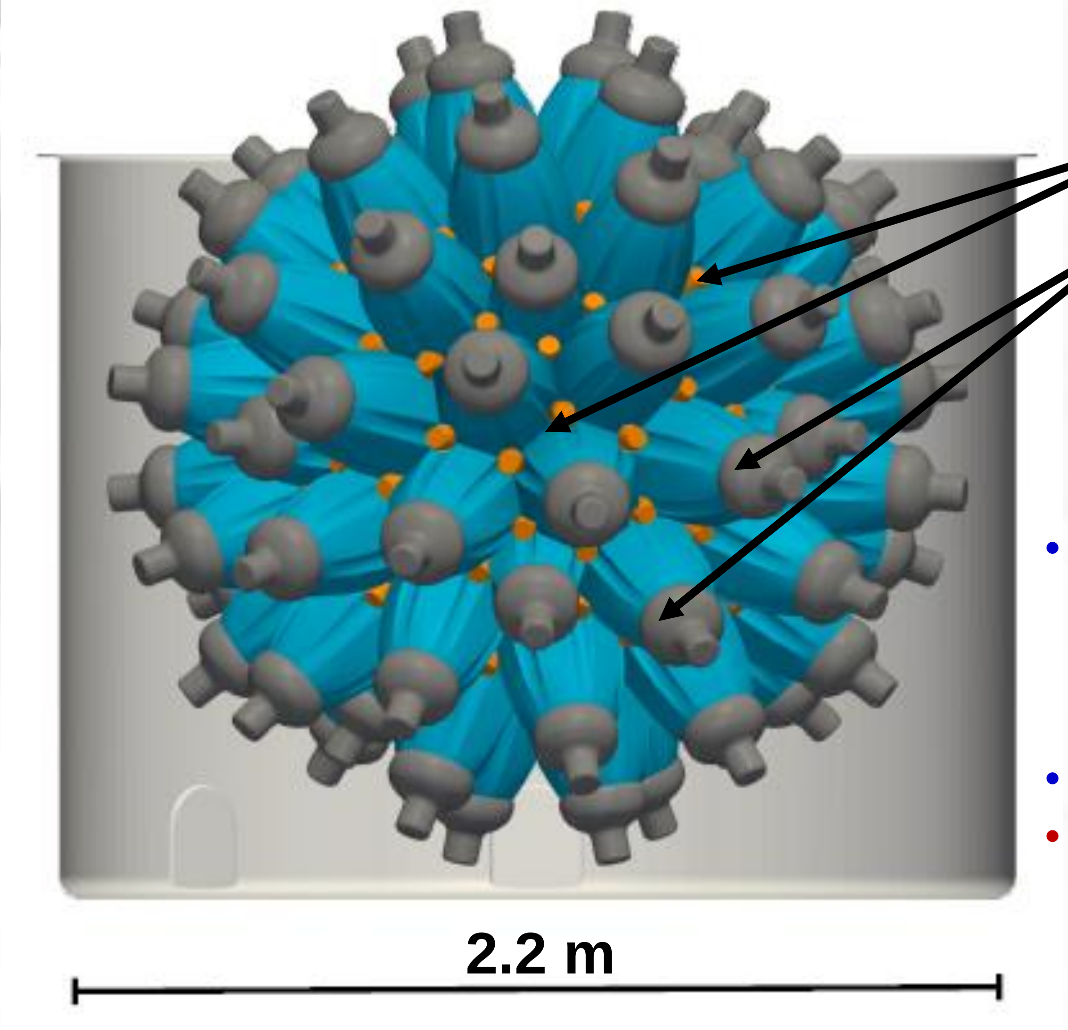
Broad detector R&D program to realize THEIA

# NuDot - Directional Liquid Scintillator

Following up on the ideas discussed in JINST 7 P07010 and JINST 9 06012

R&D Towards Large Scale Detector for $0\nu\beta\beta$-decay

Under construction at MIT, led by L. Winslow



140 2” fast PMTs for timing

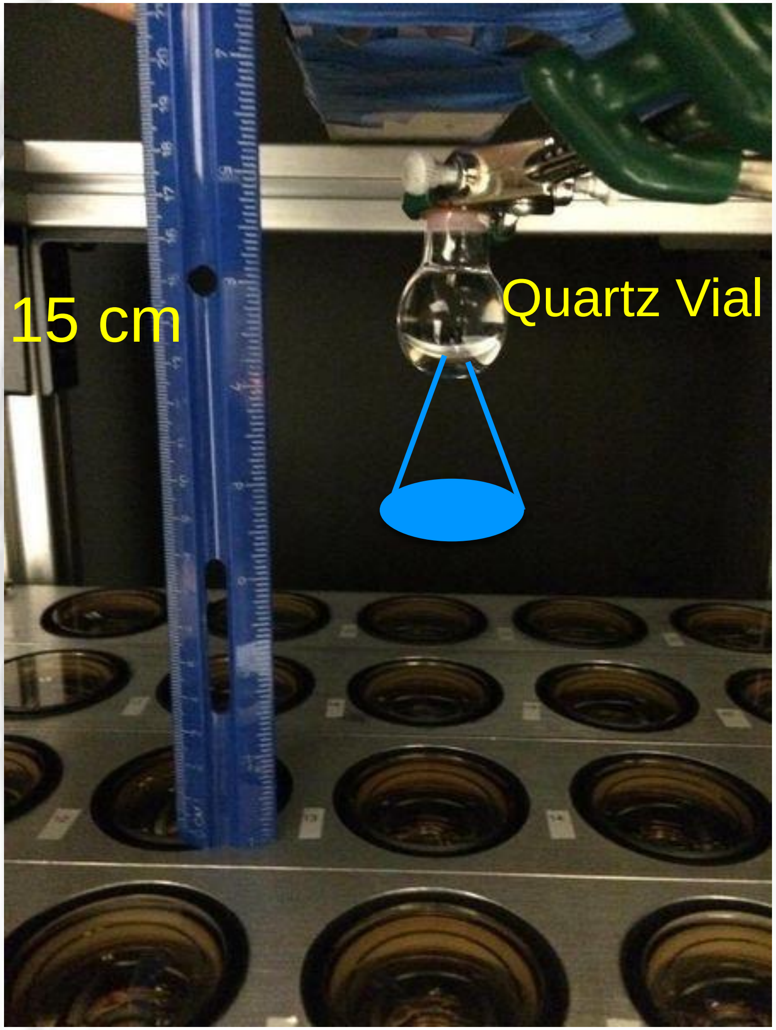
72 10” regular PMTs mounted on Winston Cones for energy resolution

## Goals

- Demonstrate directionality and event topology reconstruction using che/sci separation by fast timing
  - ideally by measuring $2\nu\beta\beta$-decay
- Study scintillators, including quantum dots
- Upgrade 10” PMTs with LAPPDs

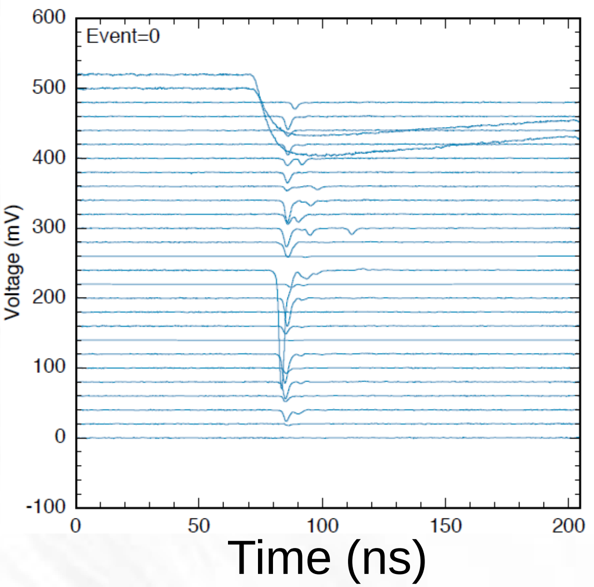
# FlatDot Demonstration

2" PMTs with TTS=300ps

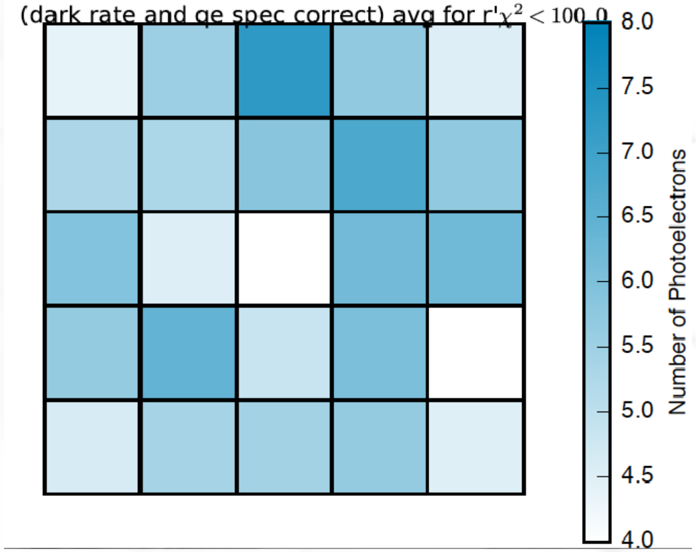


- Intermediate step towards 1m$^3$ spherical NuDot
  - e.g. detection of Cherenkov "rings" from low energy electrons using a tagged Compton source
- Testing different scintillator cocktails (including quantum dots)
- Readout testing

Raw pulses (the top two channels are the trigger)



Event display after corrections

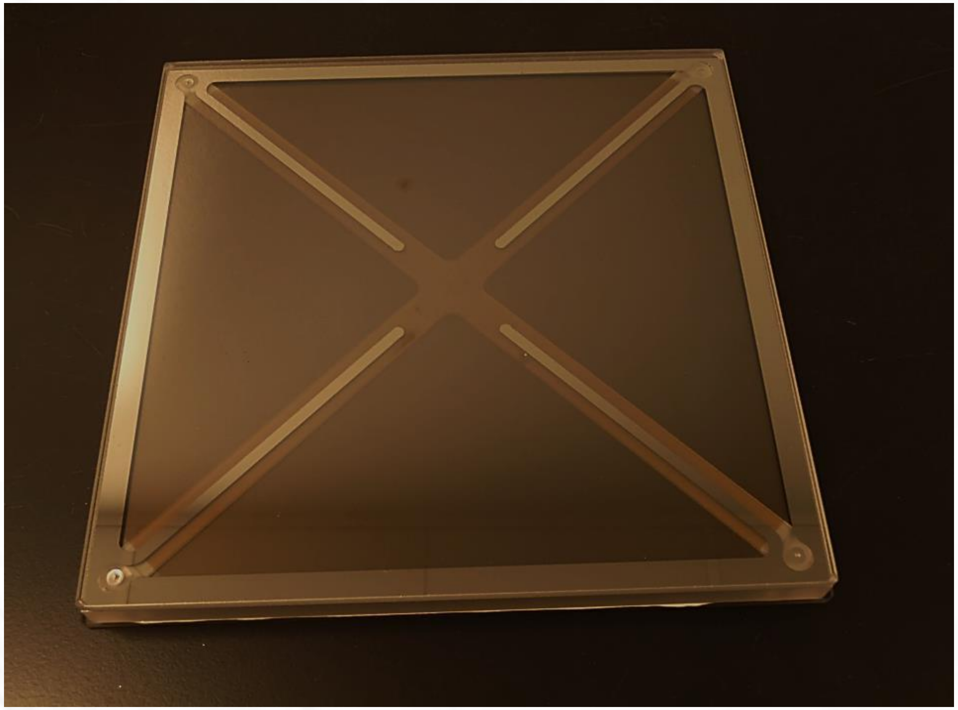


Note: there is an independent effort on Che/Sci light separation - the CHESS experiment at Berkeley by G. Orebi Gann et al., aXiv:1610.02011 and 1610.02029

# LAPPD$^{TM}$ Development

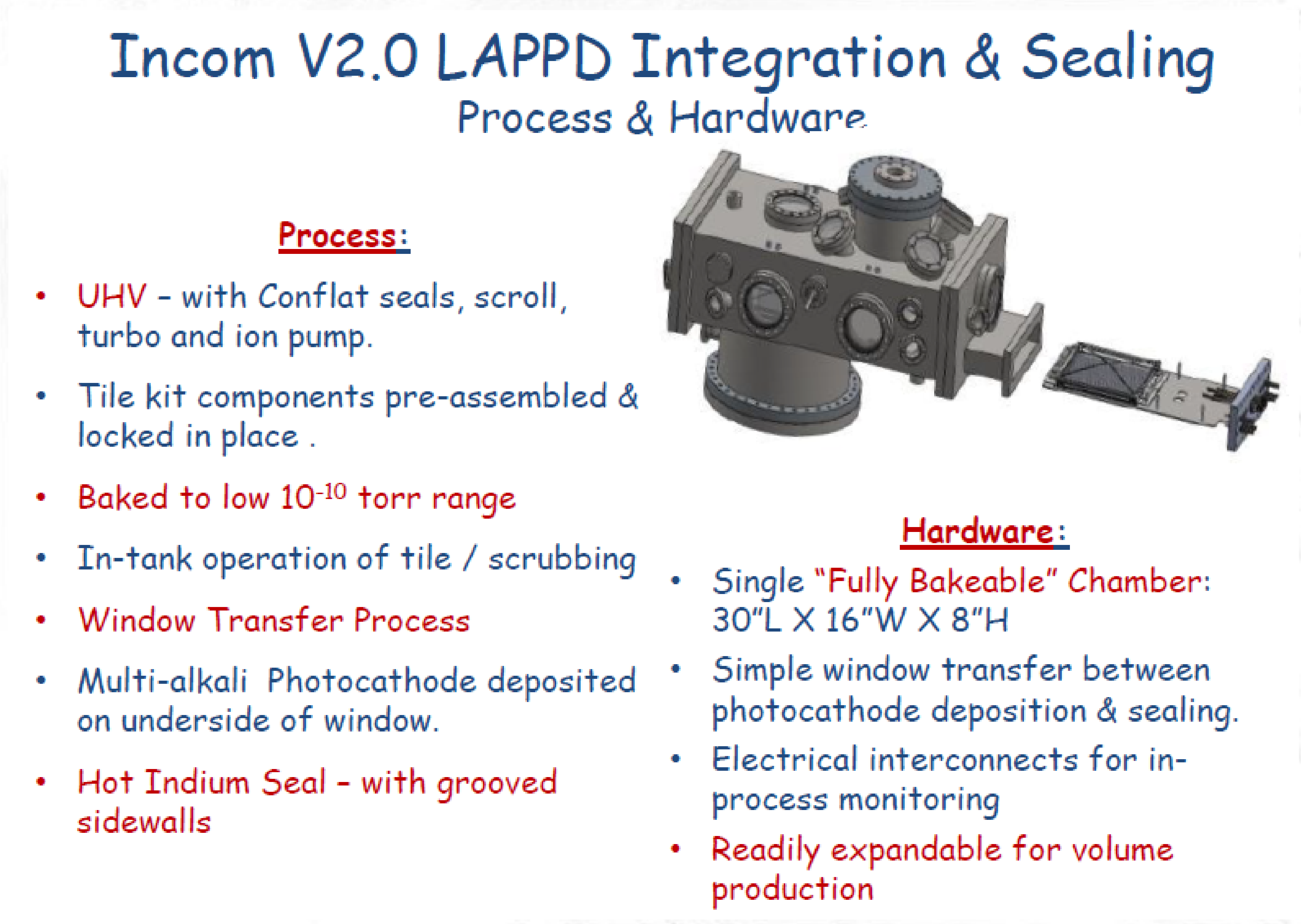
Incom Inc. (Charlton, MA) is working on making LAPPD$^{TM}$ commercially available

Supported by DOE via SBIR grant



- April 2014 - DOE funding to create infrastructure and demonstrate a pathway towards pilot production
- November 2015 – Facility operational
- December 2015 – Commissioning trial initiated
- October 2016 – First Sealed Tile with Bialkali Photocathode
- Now transitioning from “commissioning” to “exploitation” stage

# LAPPD™ @ Incom Inc.



## Incom V2.0 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 Seal - with grooved sidewalls

**Hardware:**

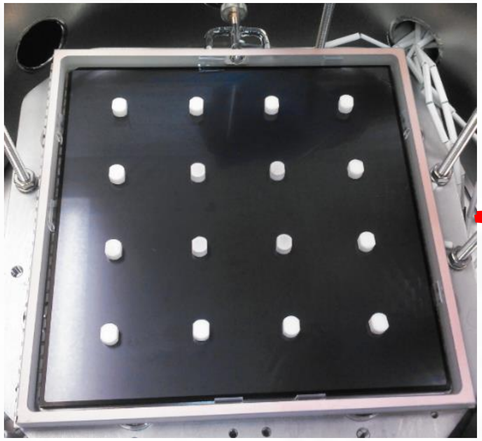
- Single "Fully Bakeable" Chamber: 30"L X 16"W X 8"H
- Simple window transfer between photocathode deposition & sealing.
- Electrical interconnects for in-process monitoring
- Readily expandable for volume production

Slide courtesy of Incom Inc.

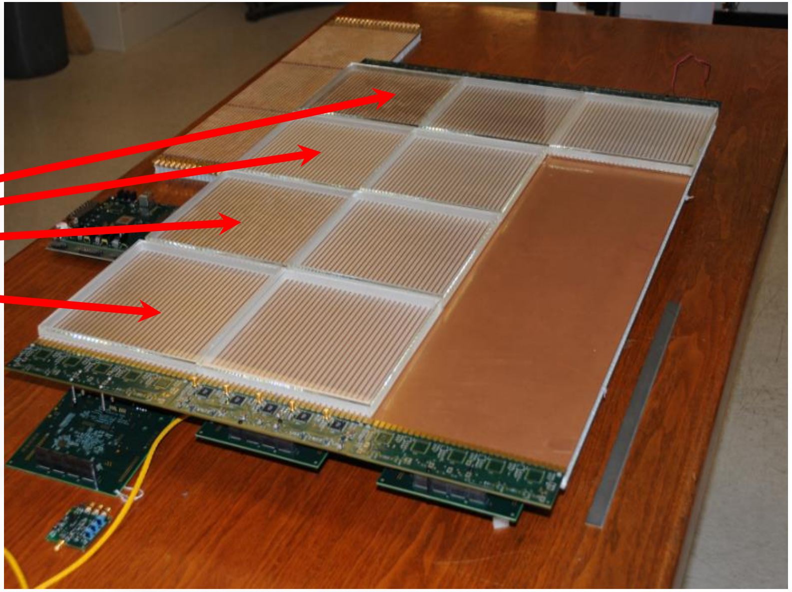
# Goal of the R&D Effort at UChicago

<u>Affordable</u> large-area many-pixel photo-detector systems with picosecond time resolution

LAPPD module 20x20 cm$^2$



Example of a Super Module

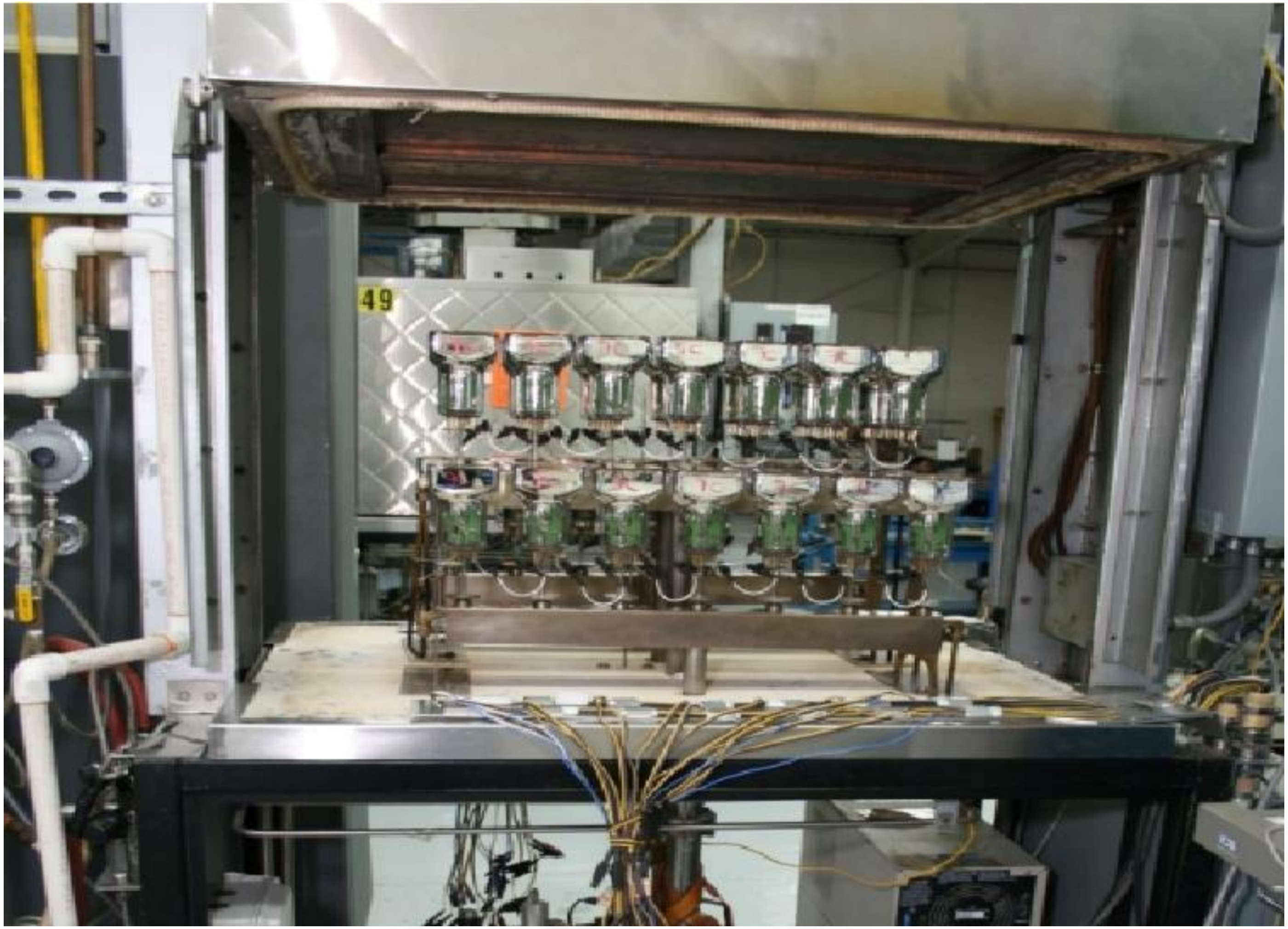


We are exploring if an *<u>In-Situ</u>* process (without vacuum transfer) can be inexpensive and easier to scale for a very high volume production

Production rate of 50 LAPPDs/week would cover 100m$^2$ in one year

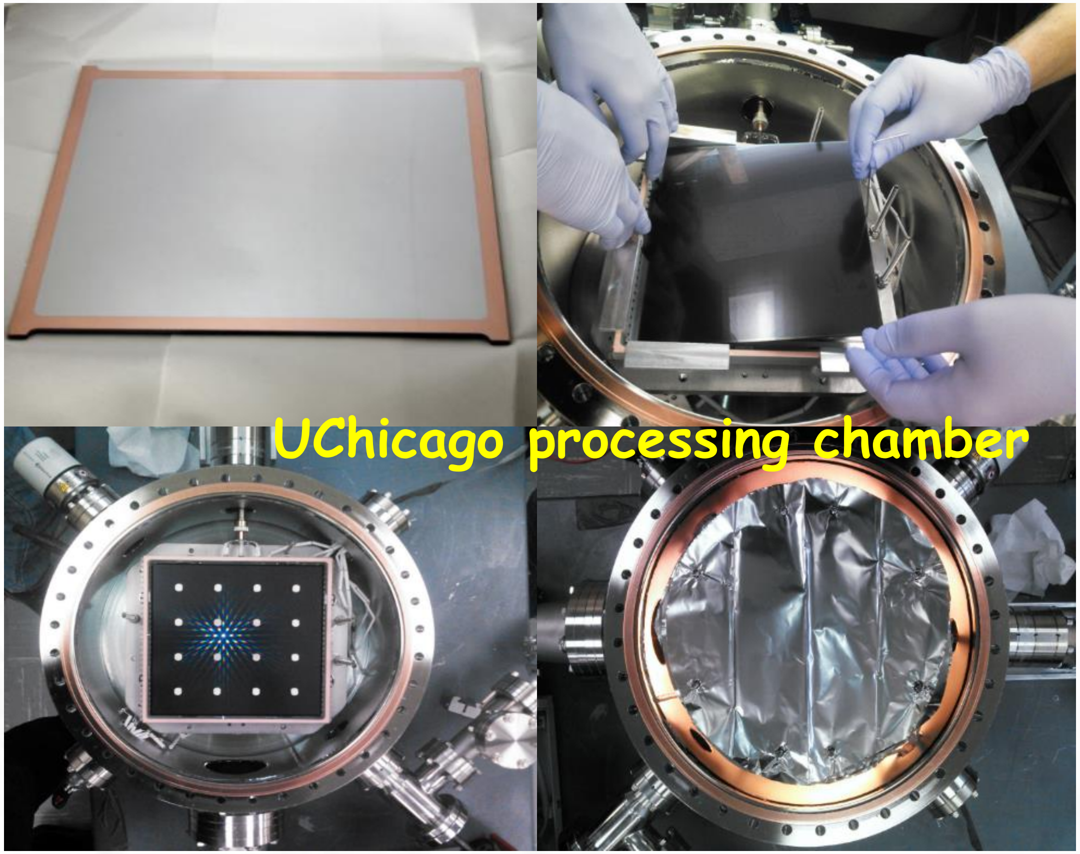
UChicago goal is to develop alternative high volume, scalable, low cost processing options
(in close collaboration with Incom Inc.)

# Can We Make LAPPDs in Batches Like PMTs?



# In-Situ Assembly Strategy

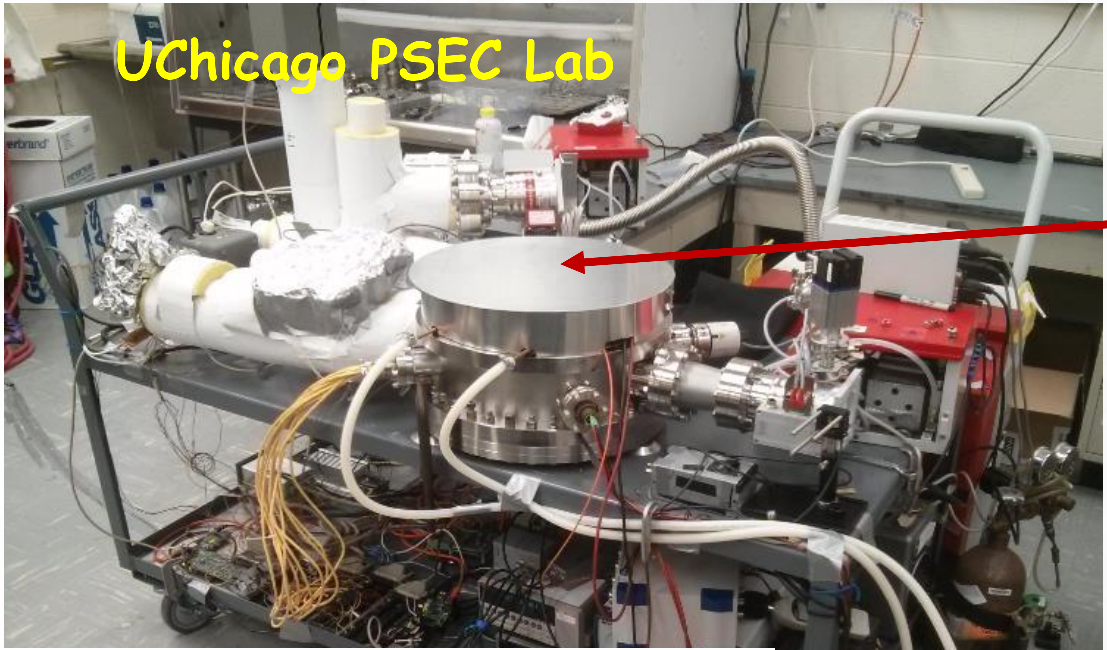
Simplify the assembly process by avoiding vacuum transfer:
make photo-cathode after the top seal
(PMT-like batch production)

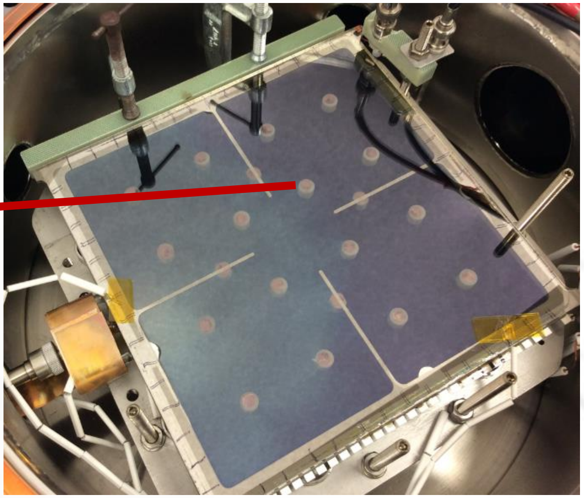


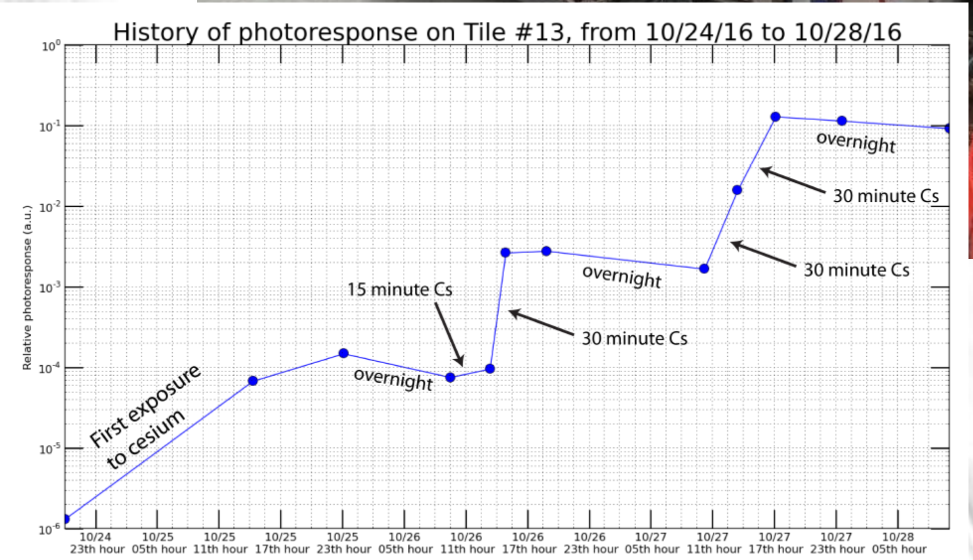
**Step 1:** pre-deposit Sb on the top window prior to assembly
**Step 2:** pre-assemble MCP stack in the tile-base
**Step 3:** **do top seal and bake in the same heat cycle using dual vacuum system**
**Step 4:** bring alkali vapors inside the tile to make photo-cathode
**Step 5:** flame seal the glass tube or crimp the copper tube

# In-Situ LAPPD Fabrication

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







**Heat only the tile not the vacuum vessel**

**Intended for parallelization**

# In-Situ Assembly Facility UChicago

The idea is to achieve volume production by operating many small-size vacuum processing chambers at the same time

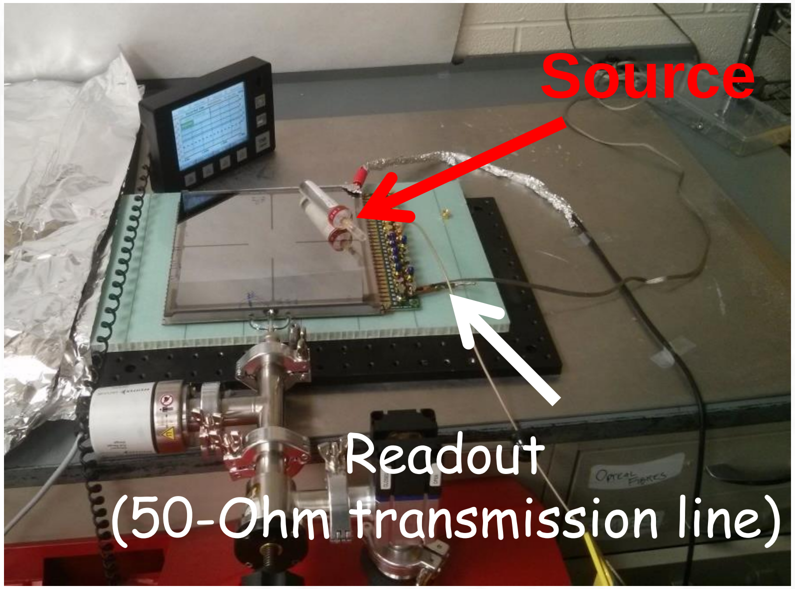
Looking forward towards transferring
the in-situ process to industry

# First Signals from an In-Situ LAPPD

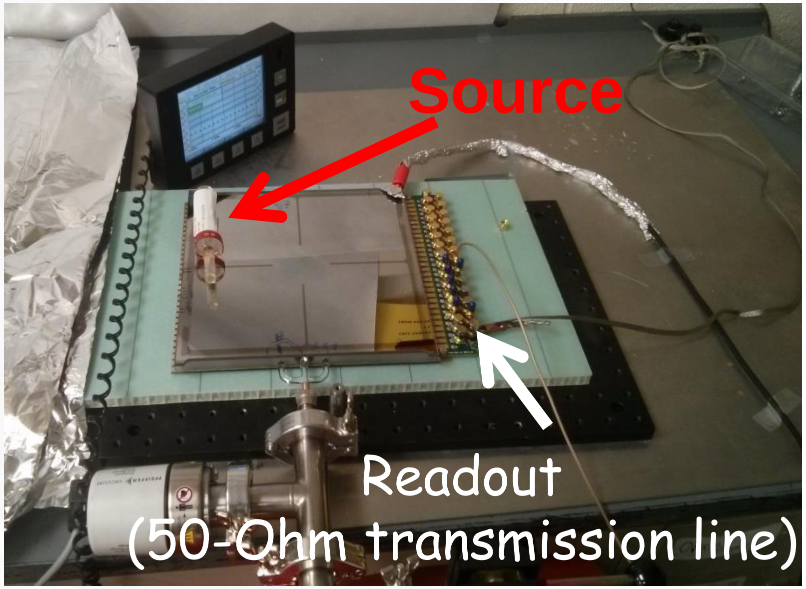
April, 2016

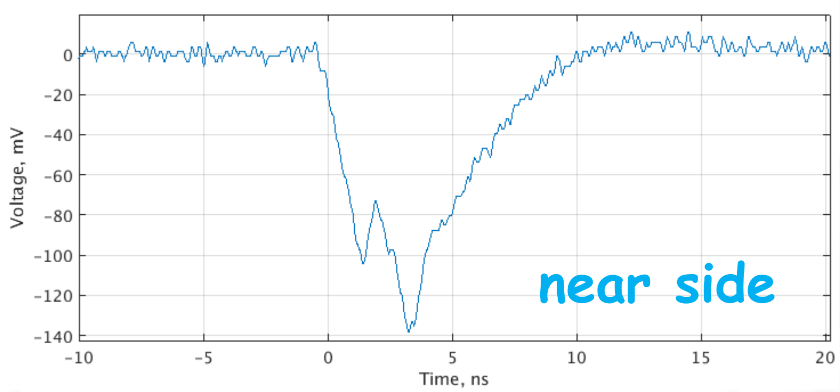
(Sb cathode)

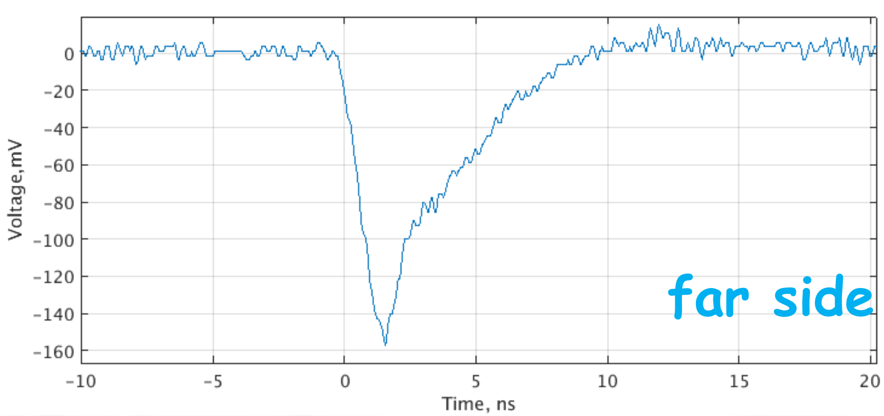
Near side: reflection from unterminated far end



Far side: reflection is superimposed on prompt





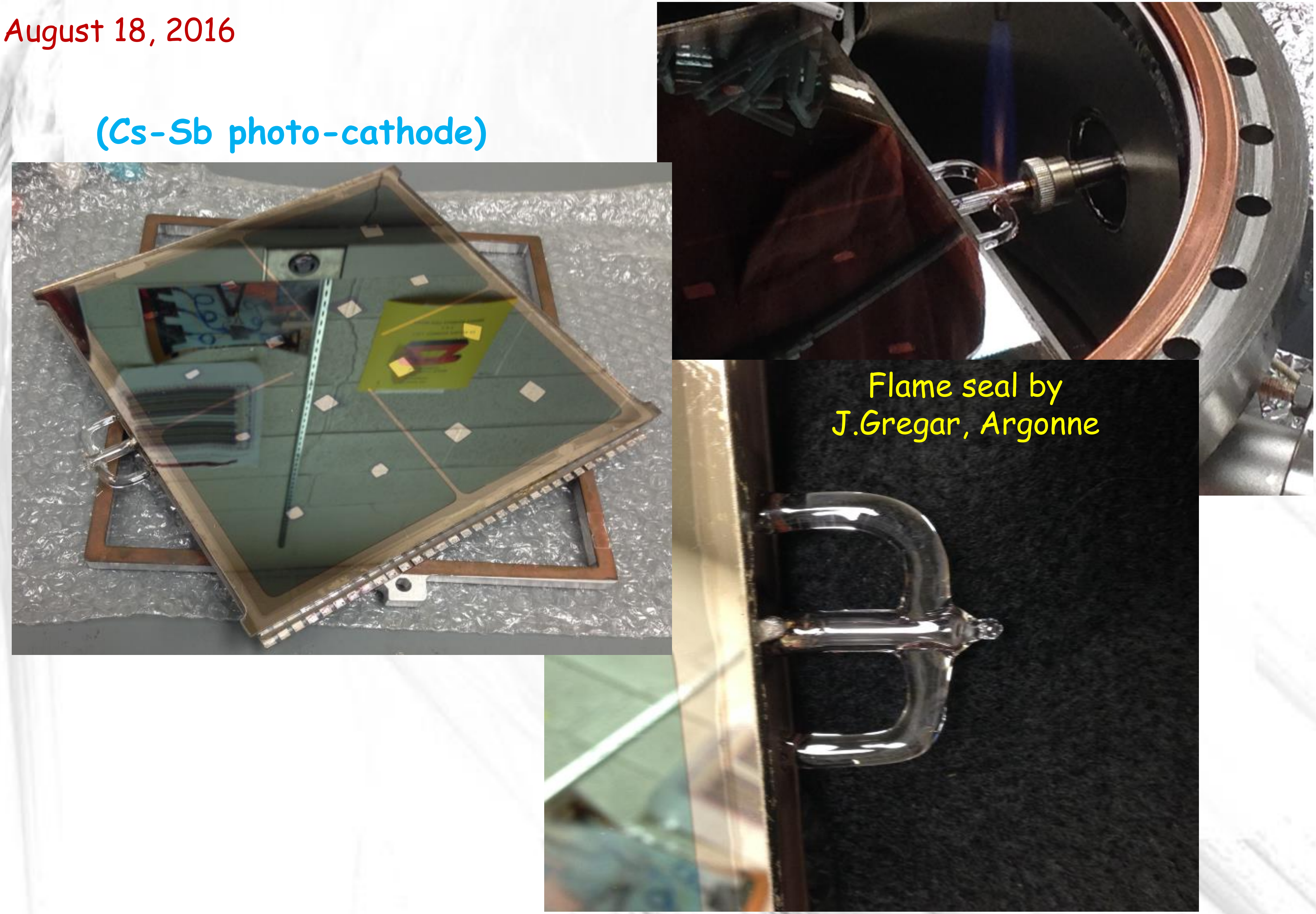


The tile is accessible for QC before photo-cathode shot
This is helpful for the production yield

# First Sealed In-Situ Glass LAPPD

August 18, 2016

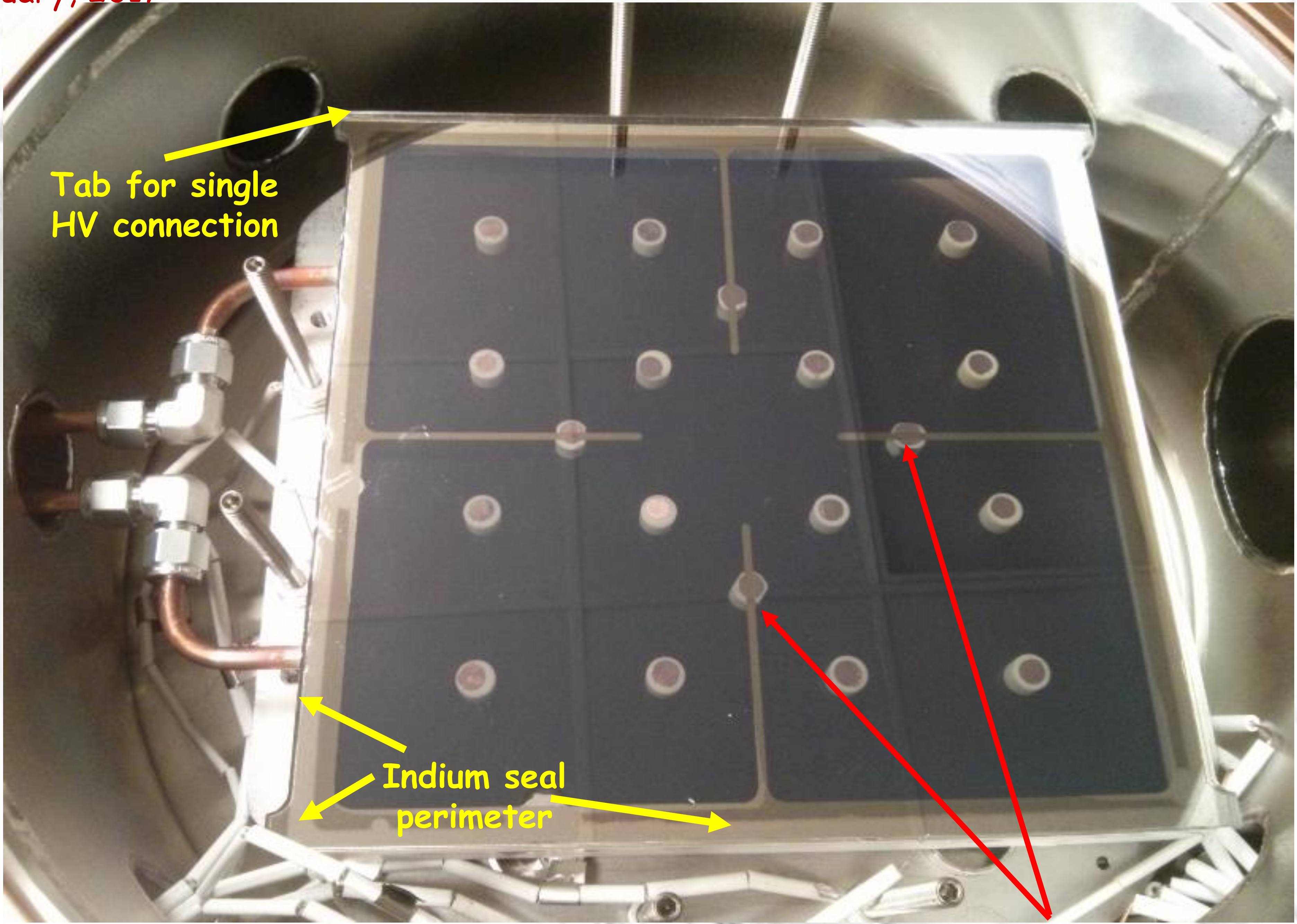
(Cs-Sb photo-cathode)



Flame seal by
J.Gregar, Argonne

# Ceramic Gen-II LAPPD

January, 2017

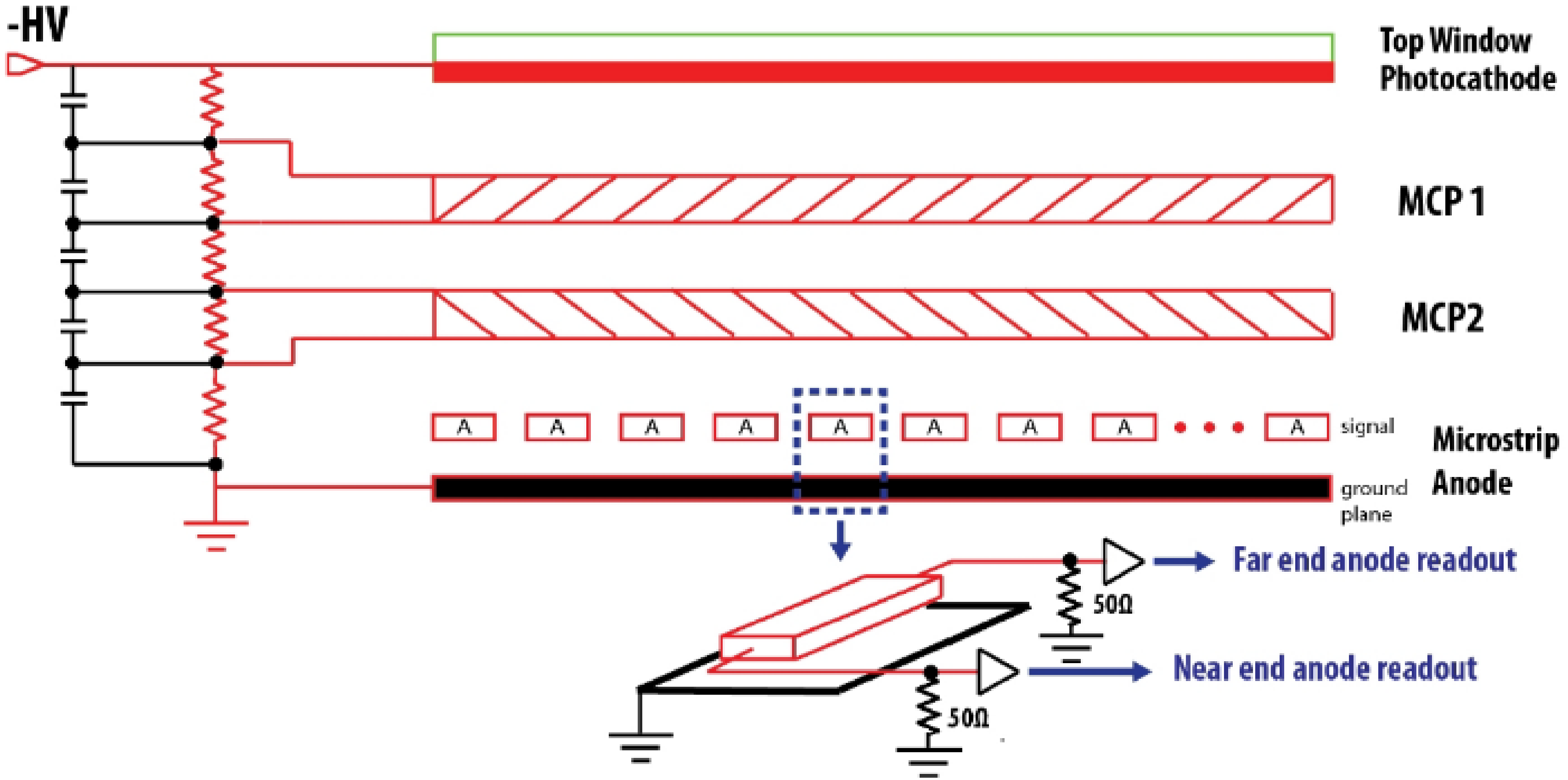


Tab for single HV connection

Indium seal perimeter

Resistive buttons

# Internal HV Divider



# Indium Solder Flat Seal Recipe

## Reliable hermetic seal over a 90-cm long perimeter

### Indium Solder Flat Seal Recipe

Input:

- Two glass parts with flat contact surfaces

Process:

- Coat 200 nm of NiCr and 200 nm of Cu on each contact surface (adapted from seals by O.Siegmund at SSL UC Berkeley)
- Make a sandwich with indium wire
- Bake in vacuum at 250-300C for 24hrs

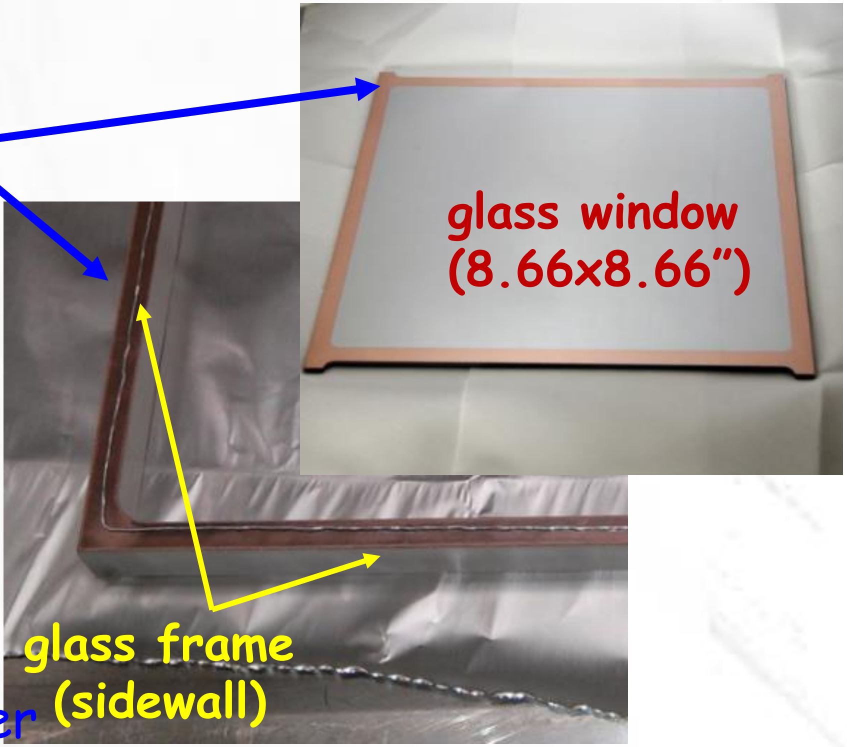
Key features:

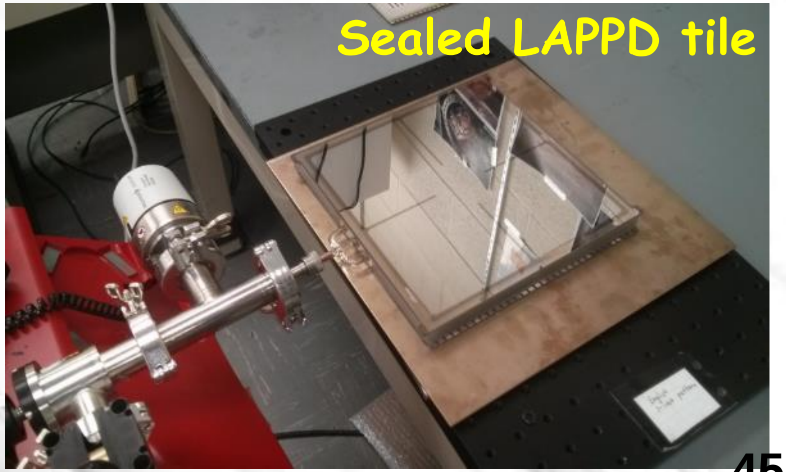
- A good compression over the entire perimeter is needed to compensate for non-flatness and to ensure a good contact
- In good seals indium penetrates through entire NiCr layer (Cu always "dissolves")

This recipe is now understood

It works well over large perimeters

**Metallization and compression are critical**



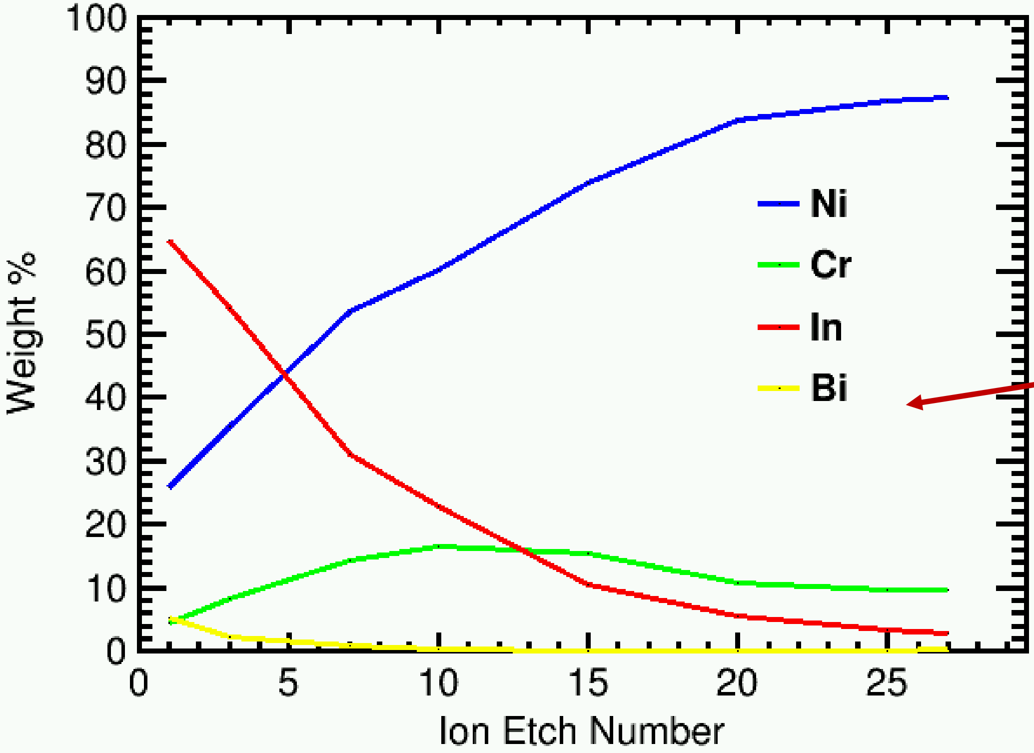


# Metallurgy of the Seal

Moderate temperatures and short exposure time:

- A thin layer of copper quickly dissolves in molten indium
  - Indium diffuses into the NiCr layer

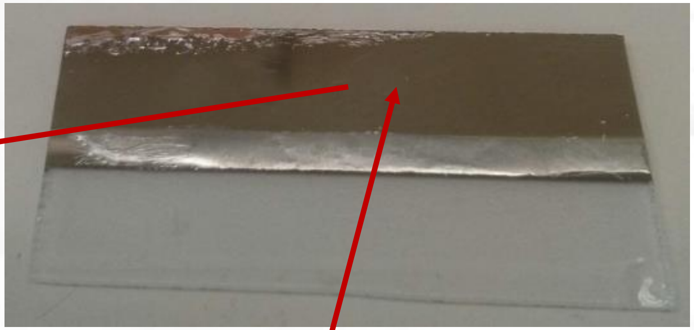
Depth profile XPS



Layer depth (uncalibrated)

Low melting InBi alloy
allows to explore temperatures
below melting of pure In (157C)

Glass with NiCr-Cu metallization
exposed to **InBi** at ~100C for <1hrs
(it seals at these conditions)



InBi was scraped when still
above melting (72C)

The ion etch number is a measure
for the depth of each XPS run

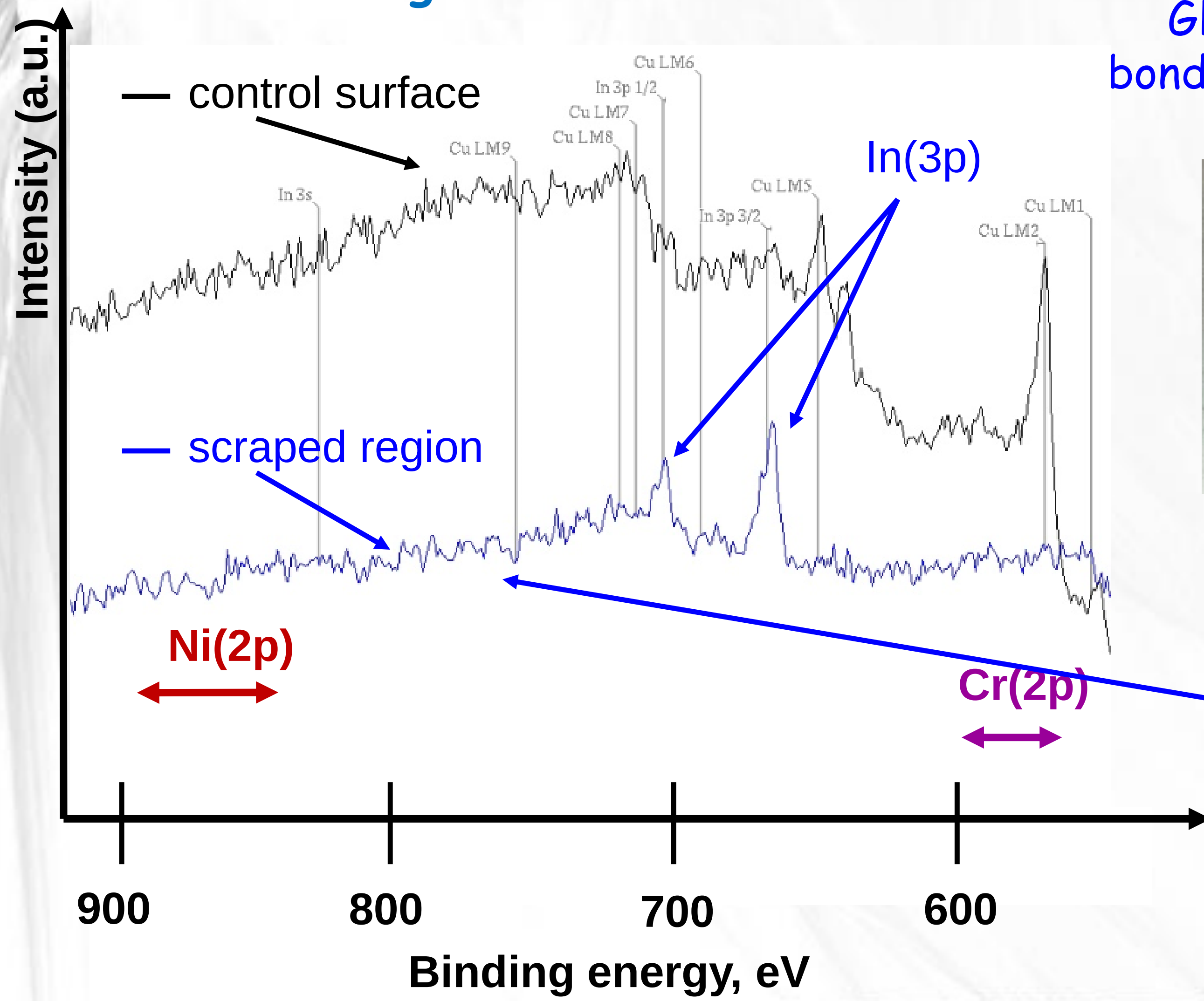
XPS access courtesy of
J. Kurley and A. Filatov at UChicago

# Metallurgy of a Good Seal

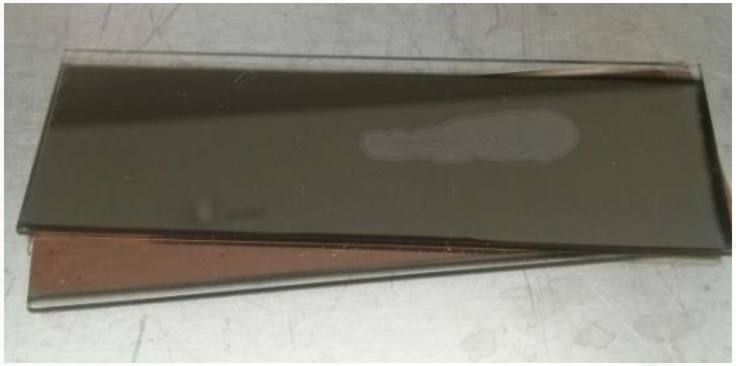
Higher temperatures and longer exposure time

- Indium penetrates through entire NiCr layer

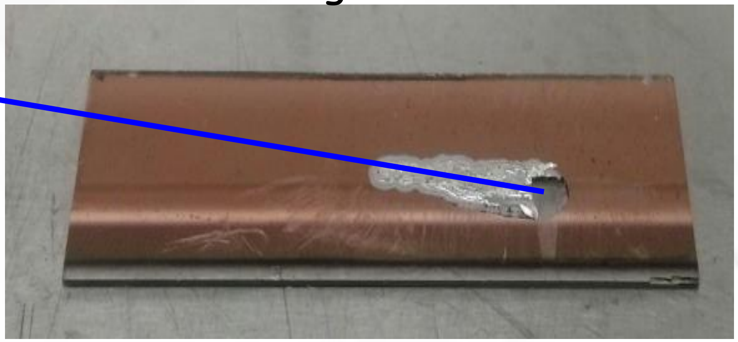
## XPS of the glass side of the interface



Glass with NiCr-Cu metallization bonded by **pure In** at ~350C for 24hrs (it seals at these conditions)



Cut and scrape at the metal-glass interface



We now reliably seal at 250-300C for 12-24hrs

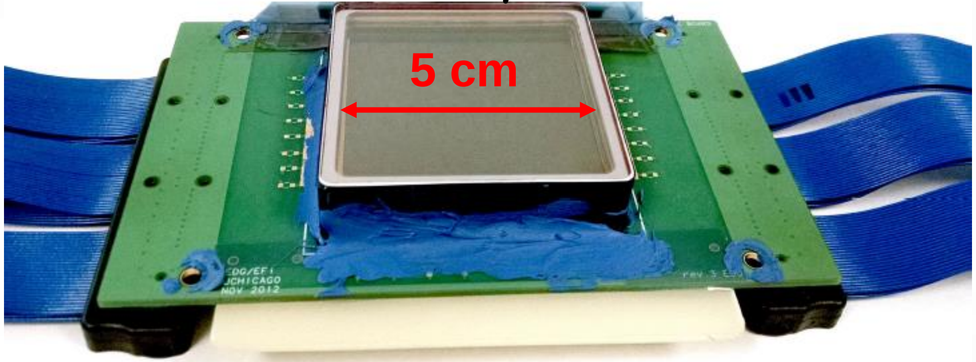
XPS data courtesy of A. Filatov at UChicago

# Indium seal recipes exist for a long time

## Why do we need another indium seal recipe?

PLANACON™

(MCP-PMT by Photonis)



Make larger photo-detectors

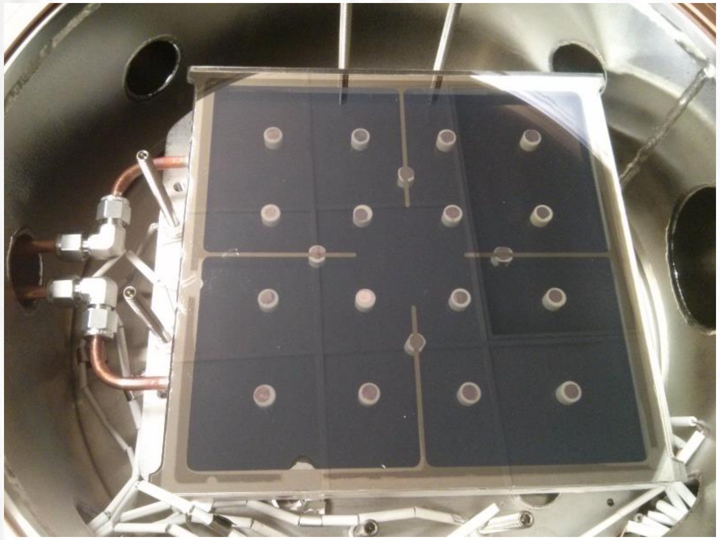
Our recipe scales well to large perimeter

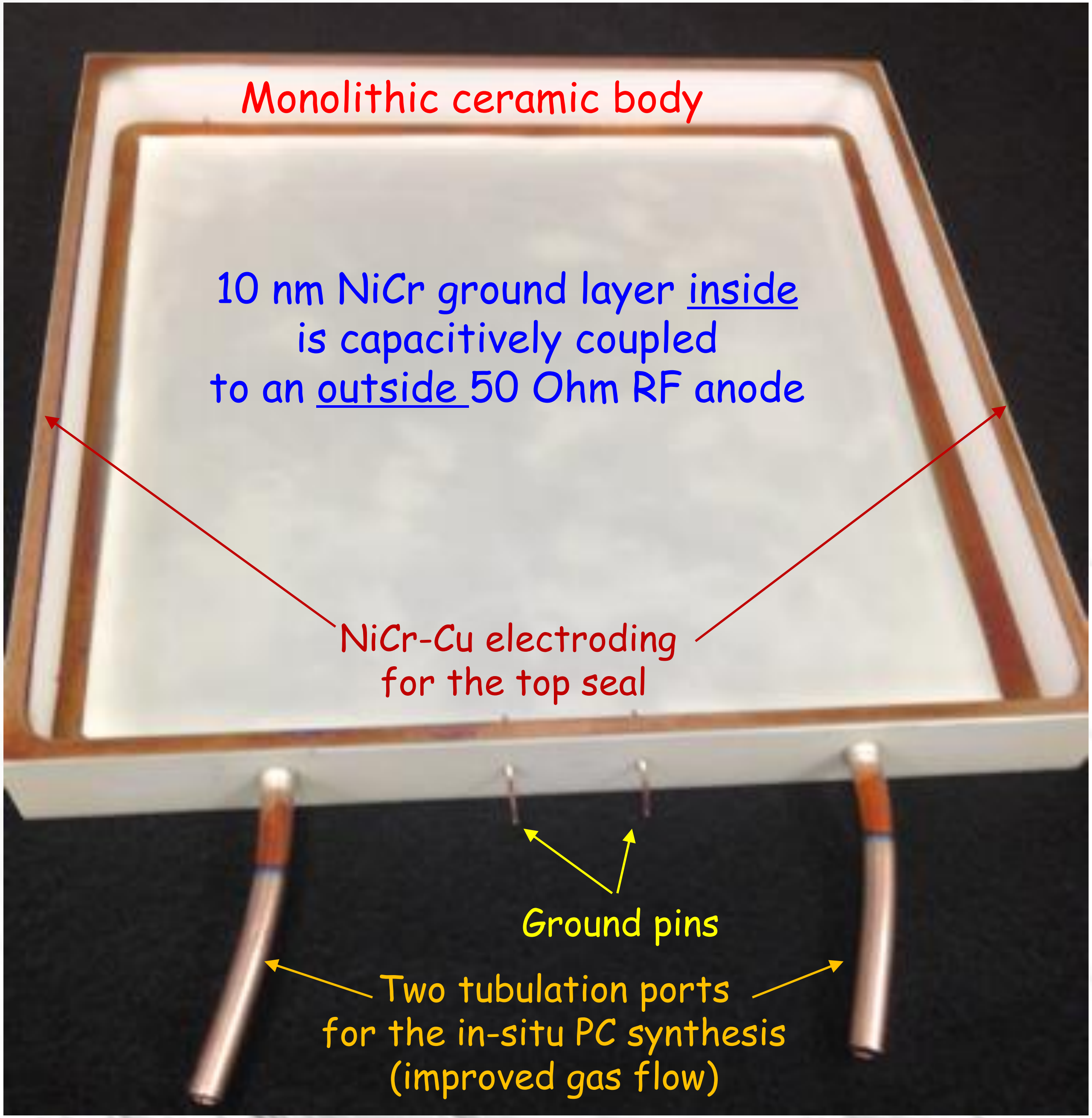
Simplify the assembly process

Our recipe is compatible with PMT-like batch production

# Gen-II LAPPD

- Robust ceramic body
- Anode is not a part of the vacuum package
- Enables fabrication of a generic tile for different applications
- Compatible with in-situ and vacuum transfer assembly processes





Monolithic ceramic body

10 nm NiCr ground layer inside is capacitively coupled to an outside 50 Ohm RF anode

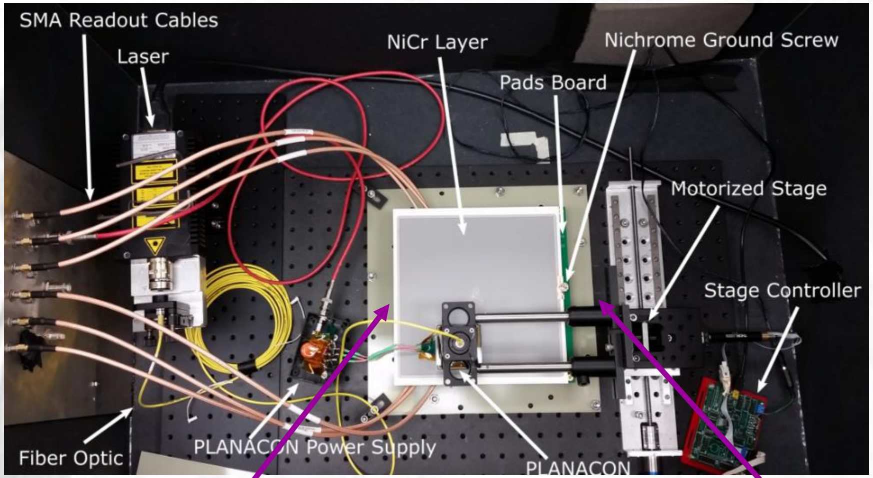
NiCr-Cu electroding for the top seal

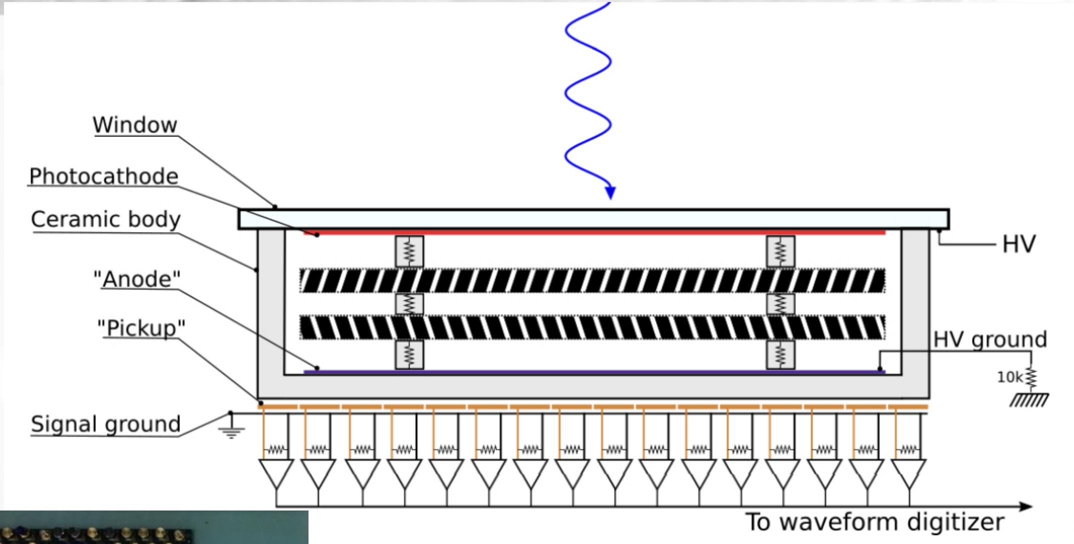
Ground pins

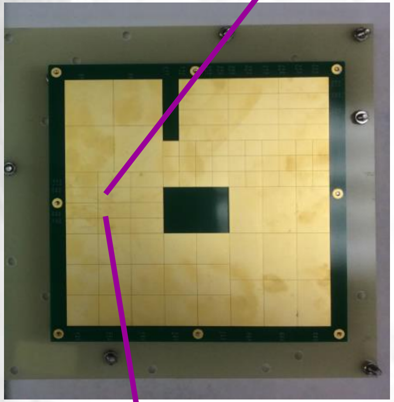
Two tubulation ports for the in-situ PC synthesis (improved gas flow)

Joint effort with Incom Inc. via DOE SBIR

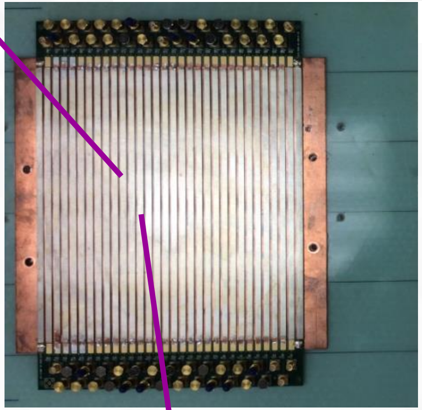
# Gen-II LAPPD: "inside-out" anode



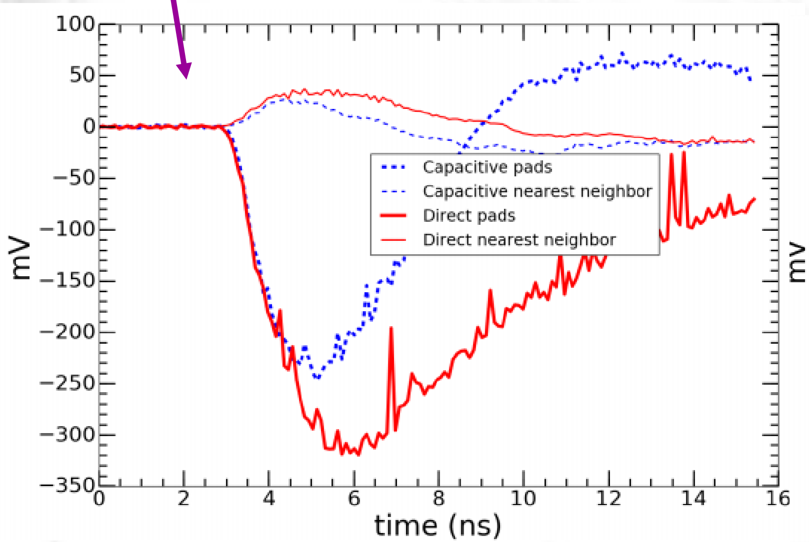


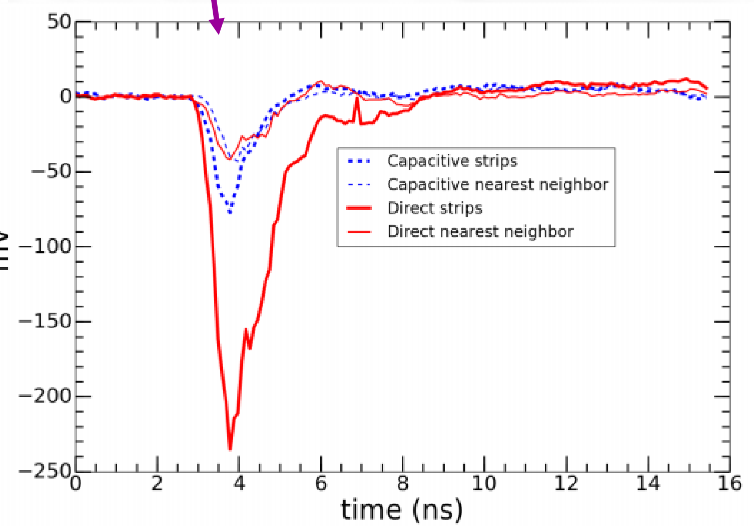


**Chose your own readout pattern**



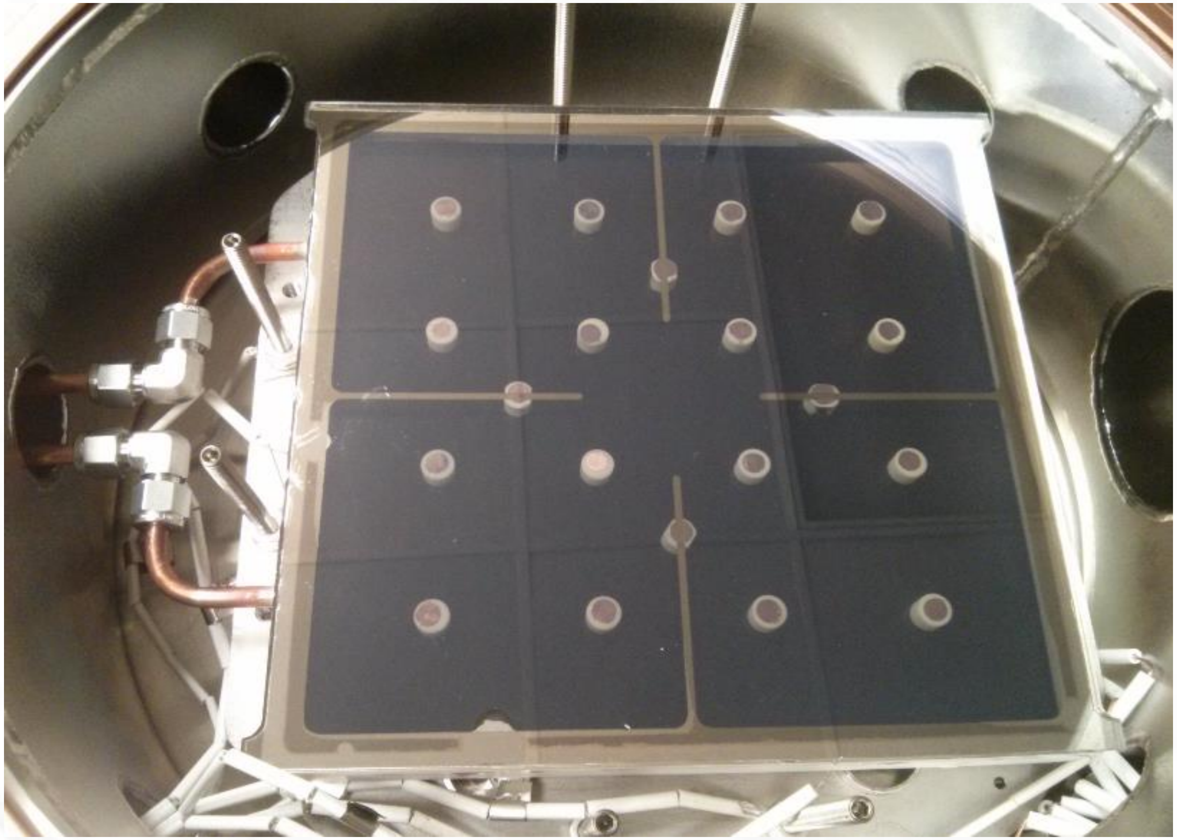
- Custom anode is outside
- Capacitively coupled
- Compatible with high rate applications





**For details see NIMA 846 (2016) 75**

# In-Situ LAPPD: work in progress



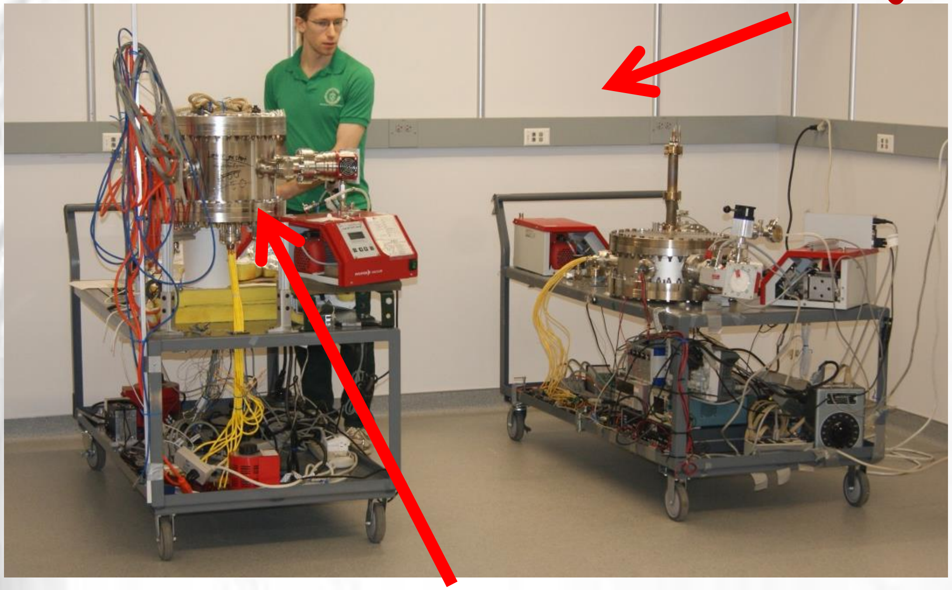
## LAPPD batch production milestones:

- Developed a robust metallurgy scheme for hermetic packaging
- Demonstrated Cs transport from a source outside of the detector package to the entire 20x20 $cm^2$ window surface in the presence of full size MCPs (we did made Cs-Sb photo-cathode)
- Showed that MCP initial resistance can be recovered after Cs-ation (MCPs are NOT permanently damaged or changed)

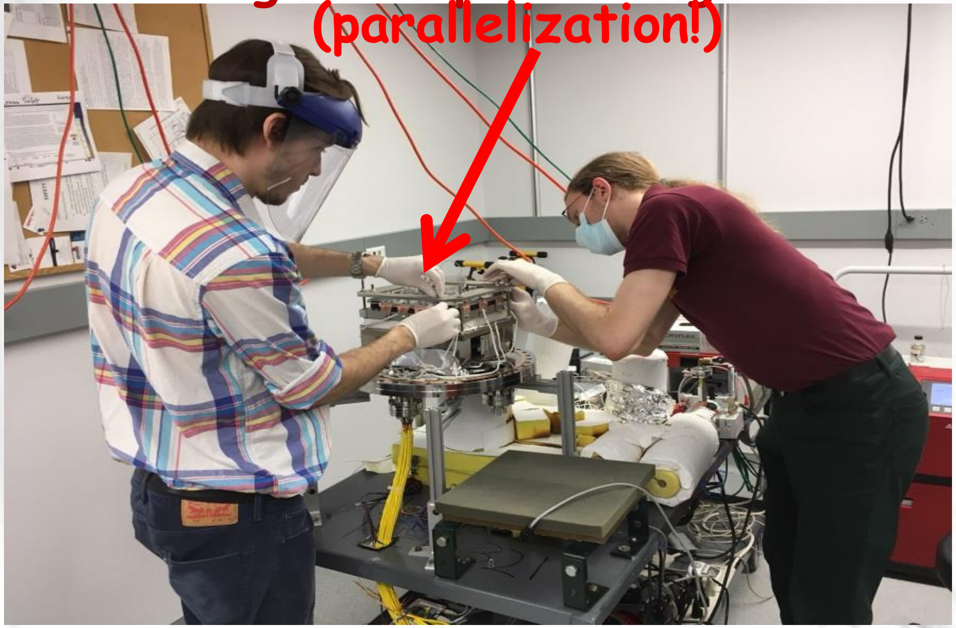
## What's next?

# Going Forward at Full Speed

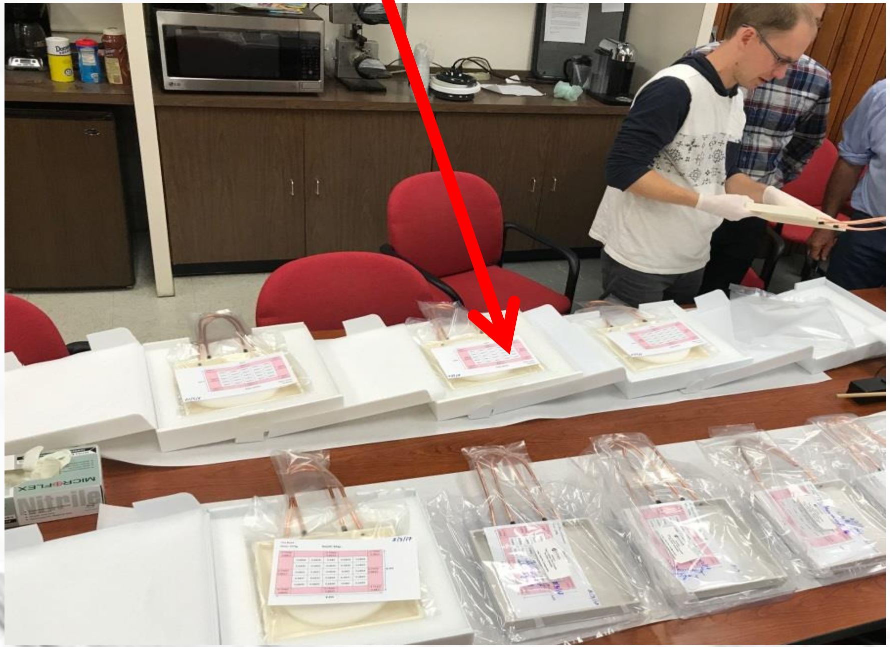
We've just got a new lab



We've got 2nd processing chamber (parallelization!)



We are getting lots of components



# Take Away Message

Light is slow if measured in picoseconds

Lots of information can be recovered
by 'drifting photons' to a highly segmented
photo-detector

Detecting Cherenkov light in a liquid scintillator
detector is very attractive

Large-Area Picosecond Photo-Detectors
are being developed

We really need lots of LAPPDs!
(batch high volume production)

# UChicago PSEC Team

**Evan Angelico, AE, Henry Frisch,**

**Rich Northrop, Carla Pilcher, Eric Spieglan**

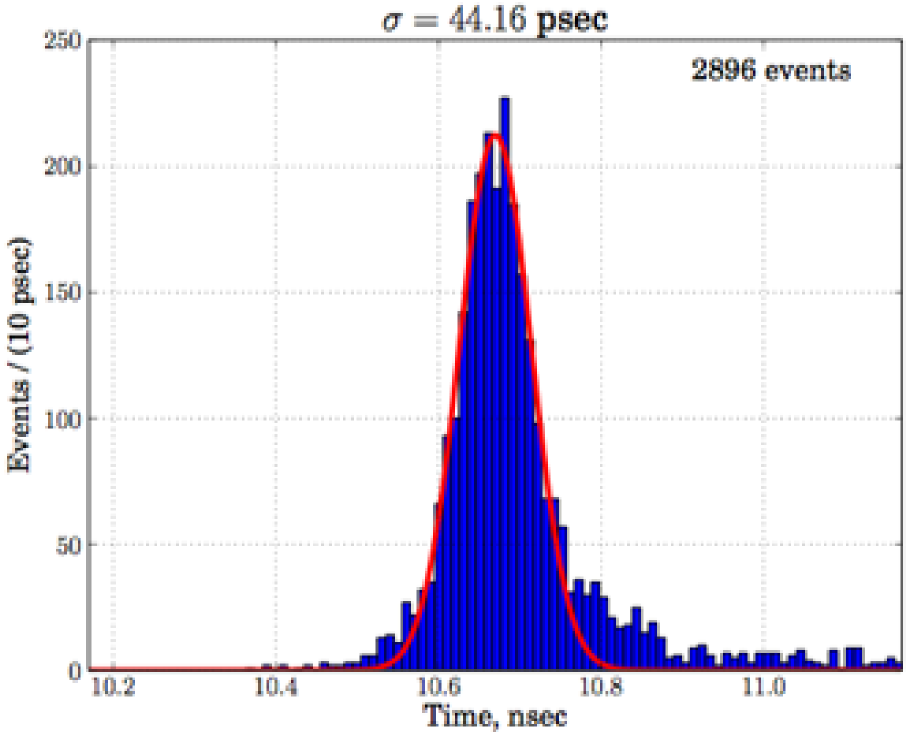
**plus Eric Oberla and Mircea Bogdan on electronics**

**plus 12 high school and undergrad students last summer**

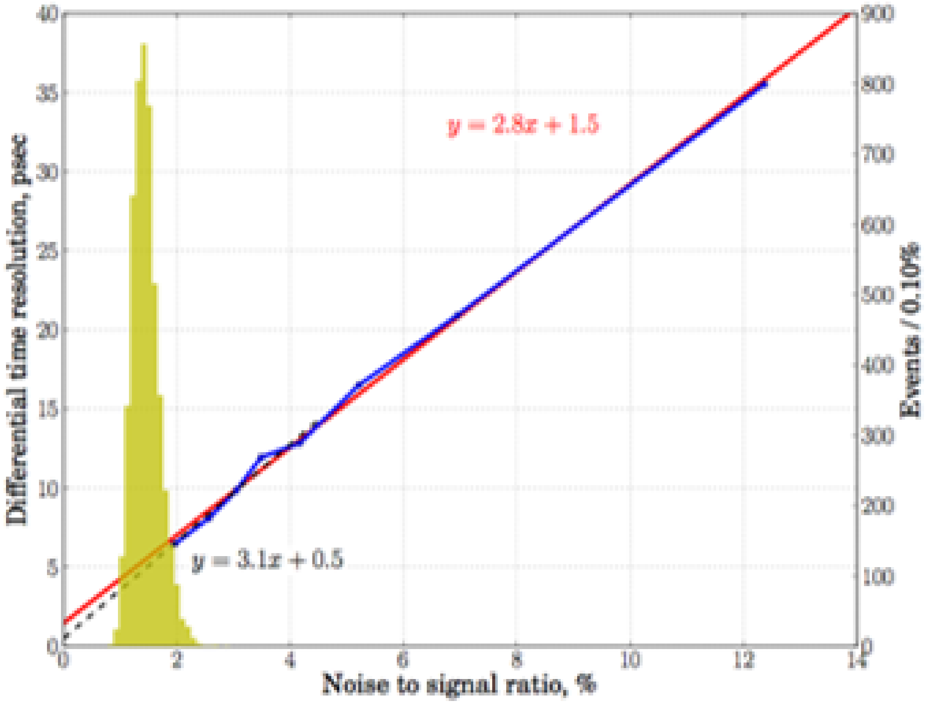
Thank you!

# Back-up

# Present (now old) Time Resolution



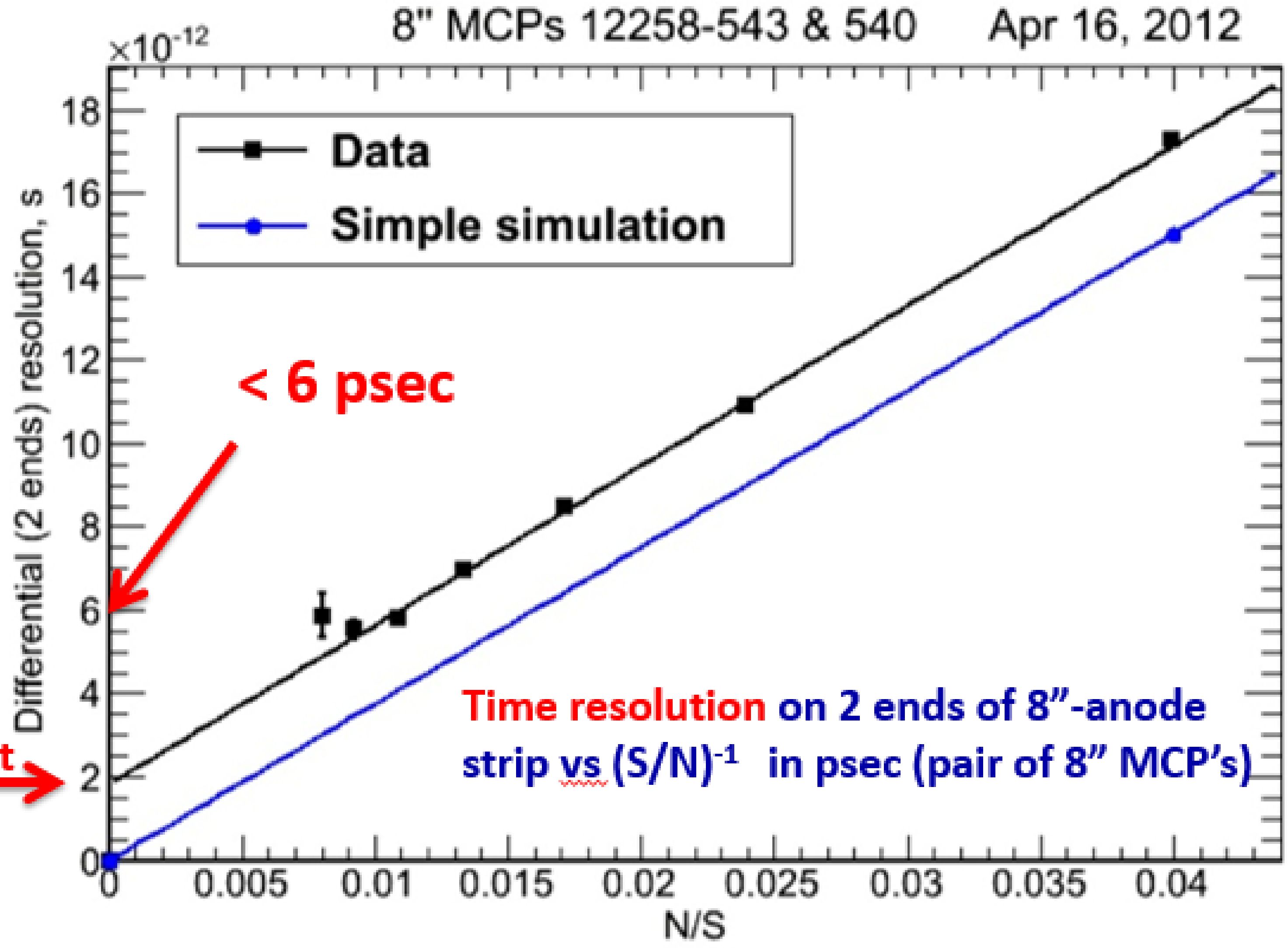
Single Photo-electron
PSEC4 Waveform sampling
Sigma=44 psec



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

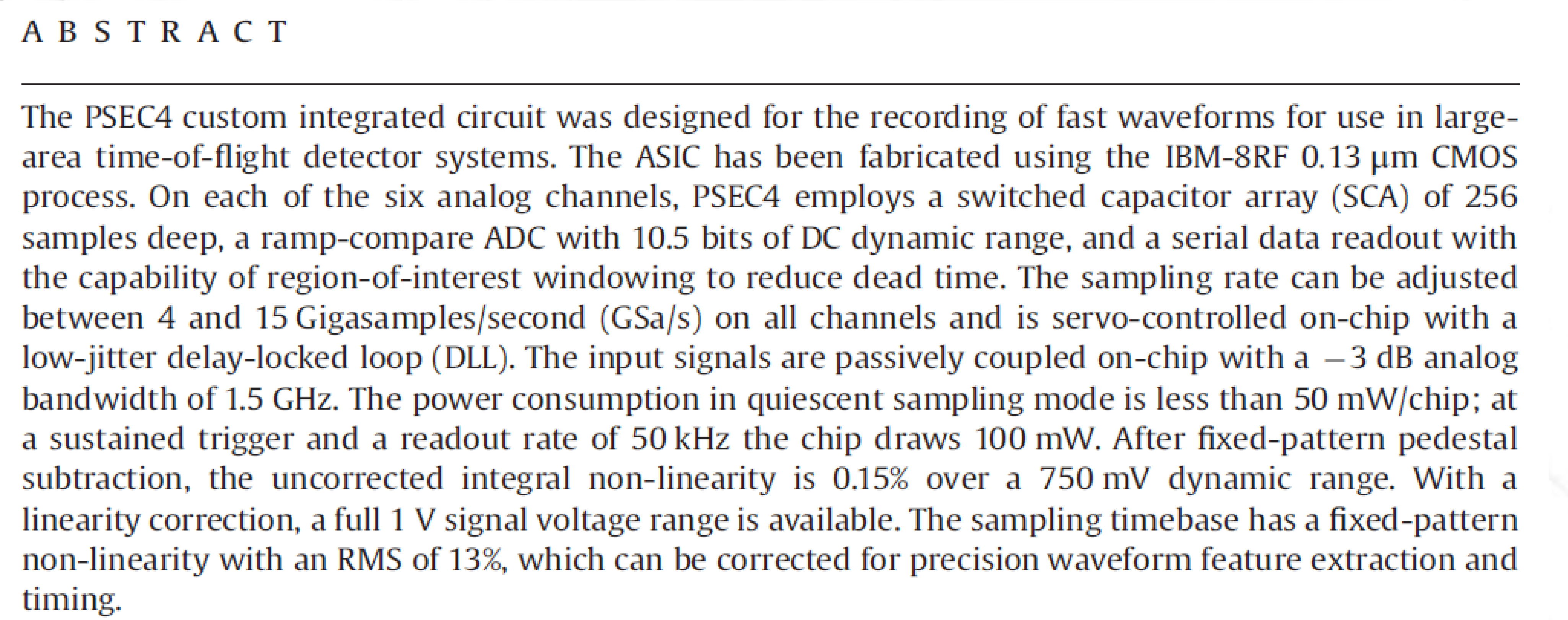
Laser spot size

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, …

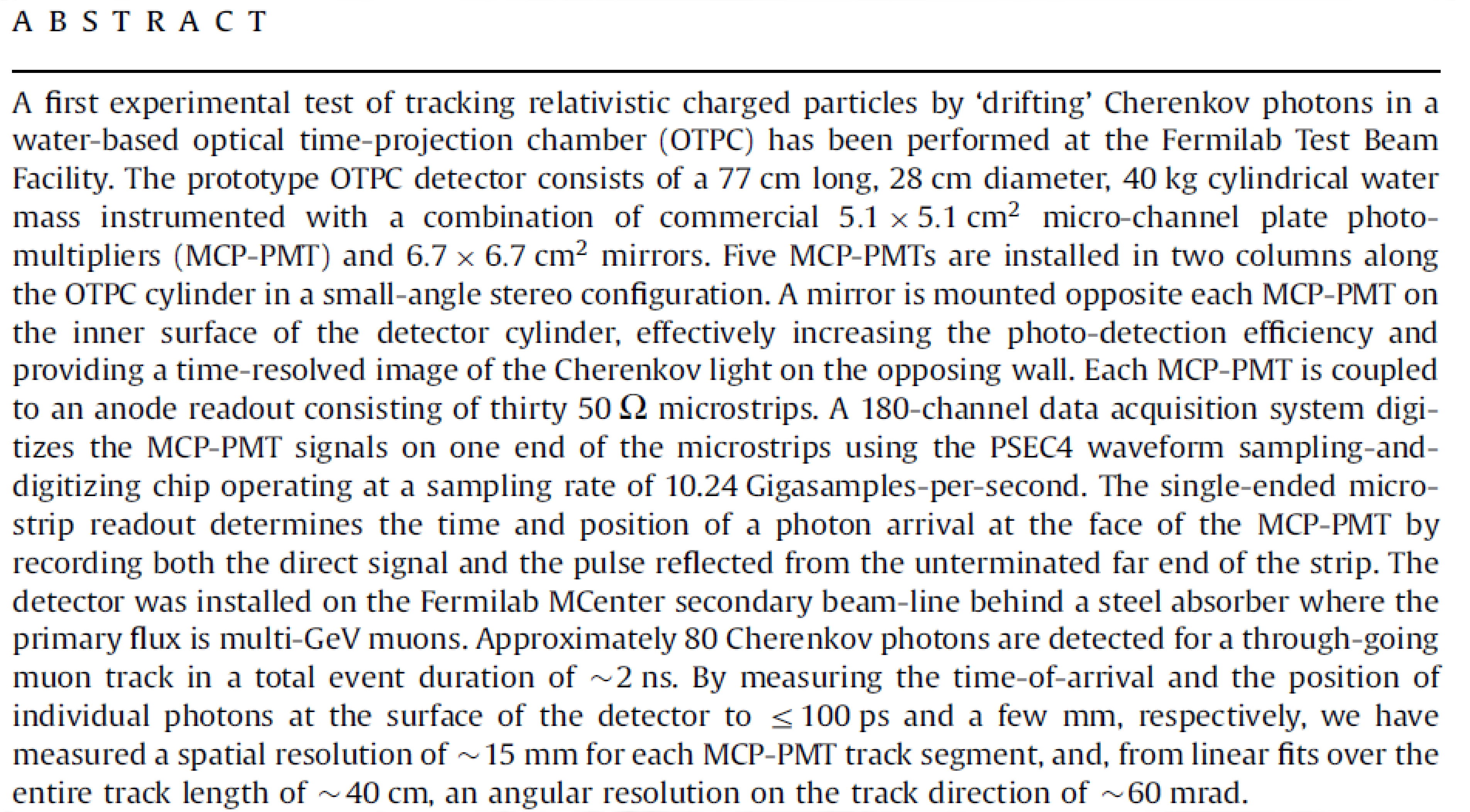
# PSEC4



## A B S T R A C T

The PSEC4 custom integrated circuit was designed for the recording of fast waveforms for use in large-area time-of-flight detector systems. The ASIC has been fabricated using the IBM-8RF 0.13 μm CMOS process. On each of the six analog channels, PSEC4 employs a switched capacitor array (SCA) of 256 samples deep, a ramp-compare ADC with 10.5 bits of DC dynamic range, and a serial data readout with the capability of region-of-interest windowing to reduce dead time. The sampling rate can be adjusted between 4 and 15 Gigasamples/second (GSa/s) on all channels and is servo-controlled on-chip with a low-jitter delay-locked loop (DLL). The input signals are passively coupled on-chip with a −3 dB analog bandwidth of 1.5 GHz. The power consumption in quiescent sampling mode is less than 50 mW/chip; at a sustained trigger and a readout rate of 50 kHz the chip draws 100 mW. After fixed-pattern pedestal subtraction, the uncorrected integral non-linearity is 0.15% over a 750 mV dynamic range. With a linearity correction, a full 1 V signal voltage range is available. The sampling timebase has a fixed-pattern non-linearity with an RMS of 13%, which can be corrected for precision waveform feature extraction and timing.

# OTPC



## ABSTRACT

A first experimental test of tracking relativistic charged particles by ‘drifting’ Cherenkov photons in a water-based optical time-projection chamber (OTPC) has been performed at the Fermilab Test Beam Facility. The prototype OTPC detector consists of a 77 cm long, 28 cm diameter, 40 kg cylindrical water mass instrumented with a combination of commercial $5.1 \times 5.1\ \mathrm{cm}^2$ micro-channel plate photomultipliers (MCP-PMT) and $6.7 \times 6.7\ \mathrm{cm}^2$ mirrors. Five MCP-PMTs are installed in two columns along the OTPC cylinder in a small-angle stereo configuration. A mirror is mounted opposite each MCP-PMT on the inner surface of the detector cylinder, effectively increasing the photo-detection efficiency and providing a time-resolved image of the Cherenkov light on the opposing wall. Each MCP-PMT is coupled to an anode readout consisting of thirty $50\ \Omega$ microstrips. A 180-channel data acquisition system digitizes the MCP-PMT signals on one end of the microstrips using the PSEC4 waveform sampling-and-digitizing chip operating at a sampling rate of 10.24 Gigasamples-per-second. The single-ended microstrip readout determines the time and position of a photon arrival at the face of the MCP-PMT by recording both the direct signal and the pulse reflected from the unterminated far end of the strip. The detector was installed on the Fermilab MCenter secondary beam-line behind a steel absorber where the primary flux is multi-GeV muons. Approximately 80 Cherenkov photons are detected for a through-going muon track in a total event duration of $\sim 2$ ns. By measuring the time-of-arrival and the position of individual photons at the surface of the detector to $\leq 100$ ps and a few mm, respectively, we have measured a spatial resolution of $\sim 15$ mm for each MCP-PMT track segment, and, from linear fits over the entire track length of $\sim 40$ cm, an angular resolution on the track direction of $\sim 60$ mrad.

# In-Situ Cathode Synthesis Trials in Progress

E.g. The black powder from cesiating excess indium

Sealing surface on top of sidewall

Black powder

NiCr anode

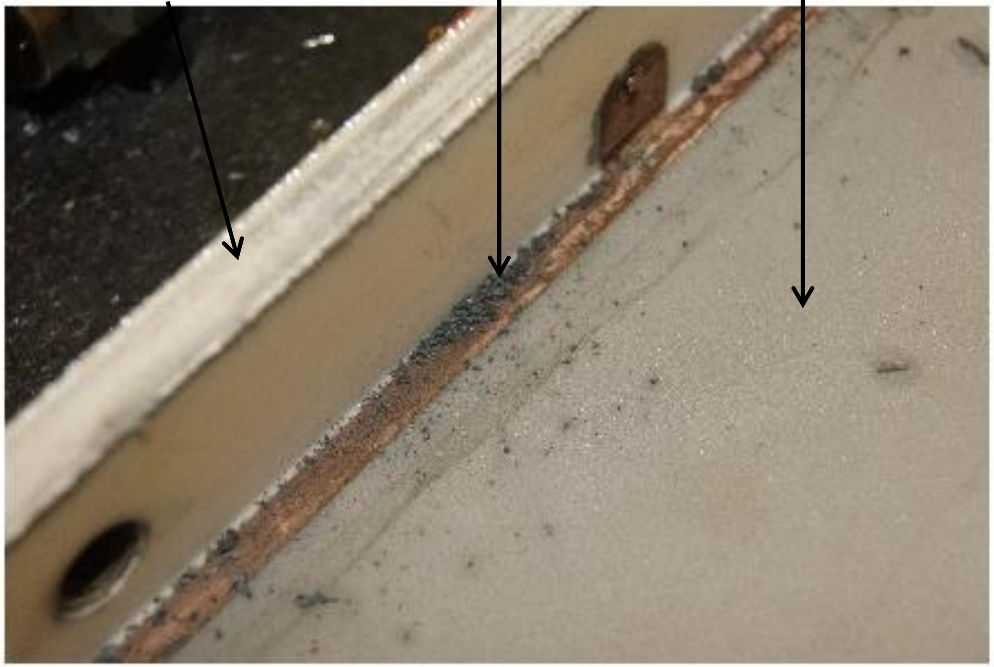


Figure 1: This black dust was found thrown throughout the tile, in crevices and on MCPs and on glass beads. We presume that it came from the window. It was collected from multiple locations and analyzed. This dust is from the window, and flaked everywhere.

(New windows will have no exposed Cu- few weeks away)

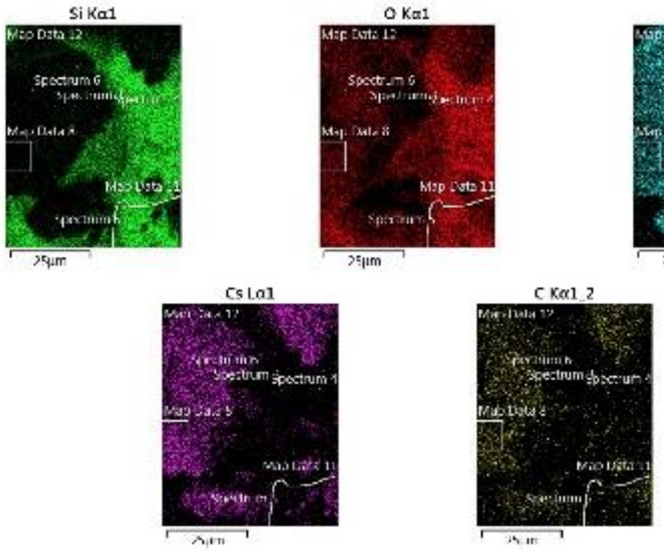


Figure 3: The individual chemical maps from the Figure 2. Notice that the dust specs are mostly Cs and Indium, and the empty space is Si and O. This only confirms that the black dust is some mixture of Cs and Indium, and not its relative composition or homogeneity.

Evan (FIB/SEM
and Andrey (SEM)

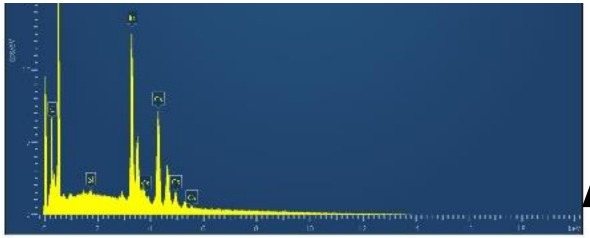


Figure 4: A spectrum from a **dust** fleck shown in the SEM picture above. The peaks indicate the existence of indium and Cs, and not their quantitative relative composition.

Analysis showing it’s a CsIn compound

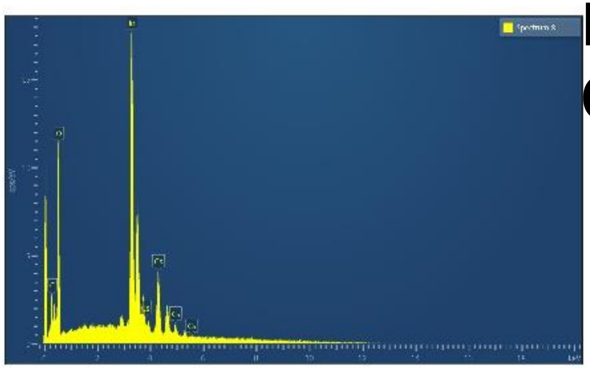
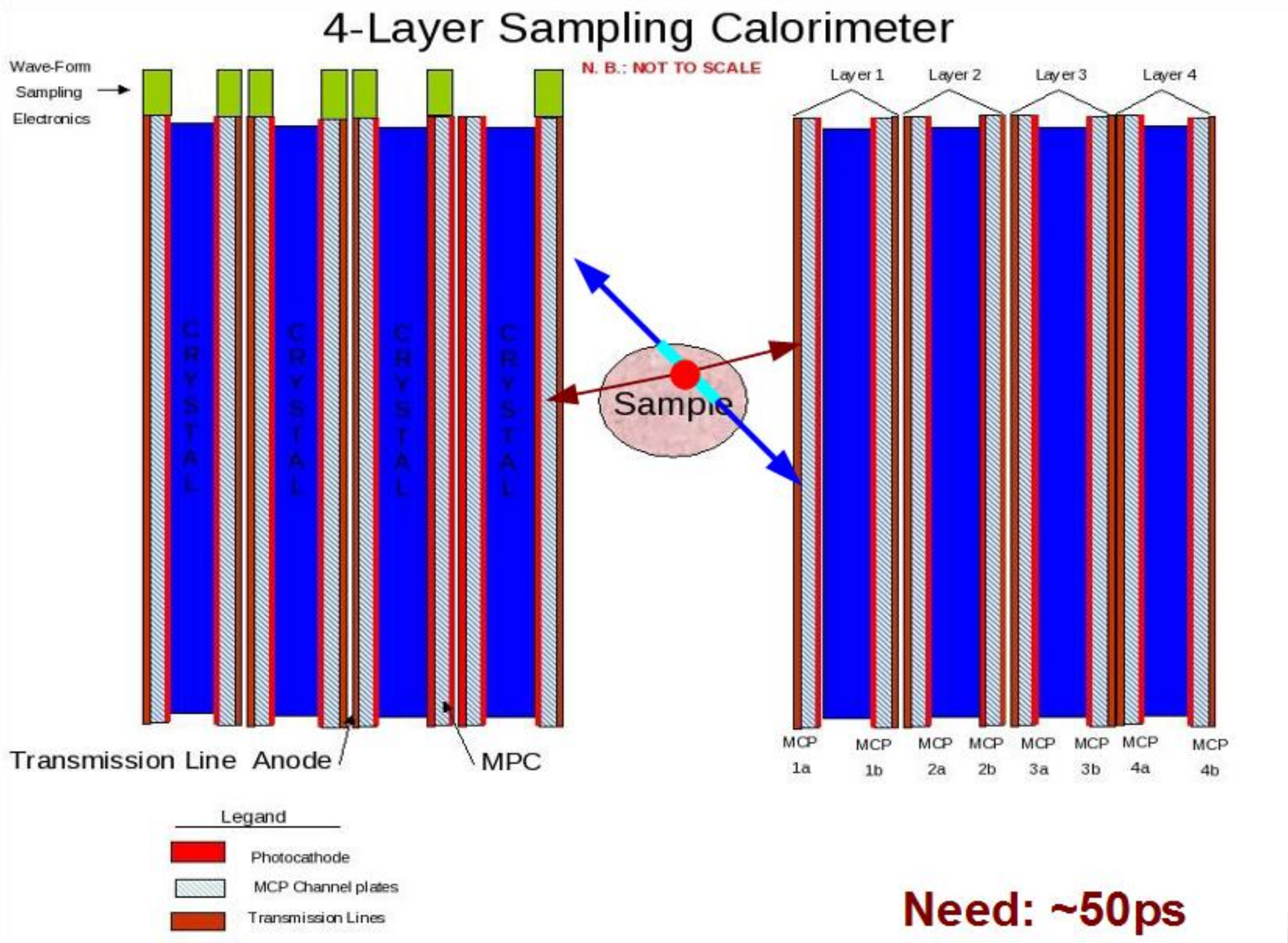


Figure 5: This spectrum is taken from the layer on the **window** that had turned black and flaky. The spectrum looks almost identical to that of the dust flecks.

# Low-Dose Whole-Body PET Camera

Chin-Tu Chen, Henry Frisch, Chien-Min Kao, and Heejong Kim

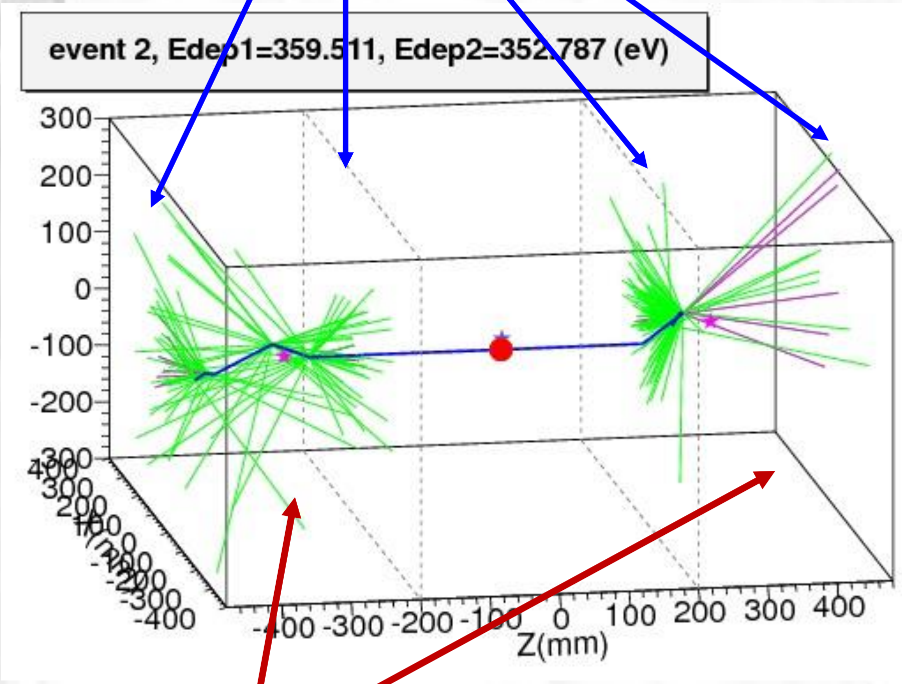


4-Layer Sampling Calorimeter

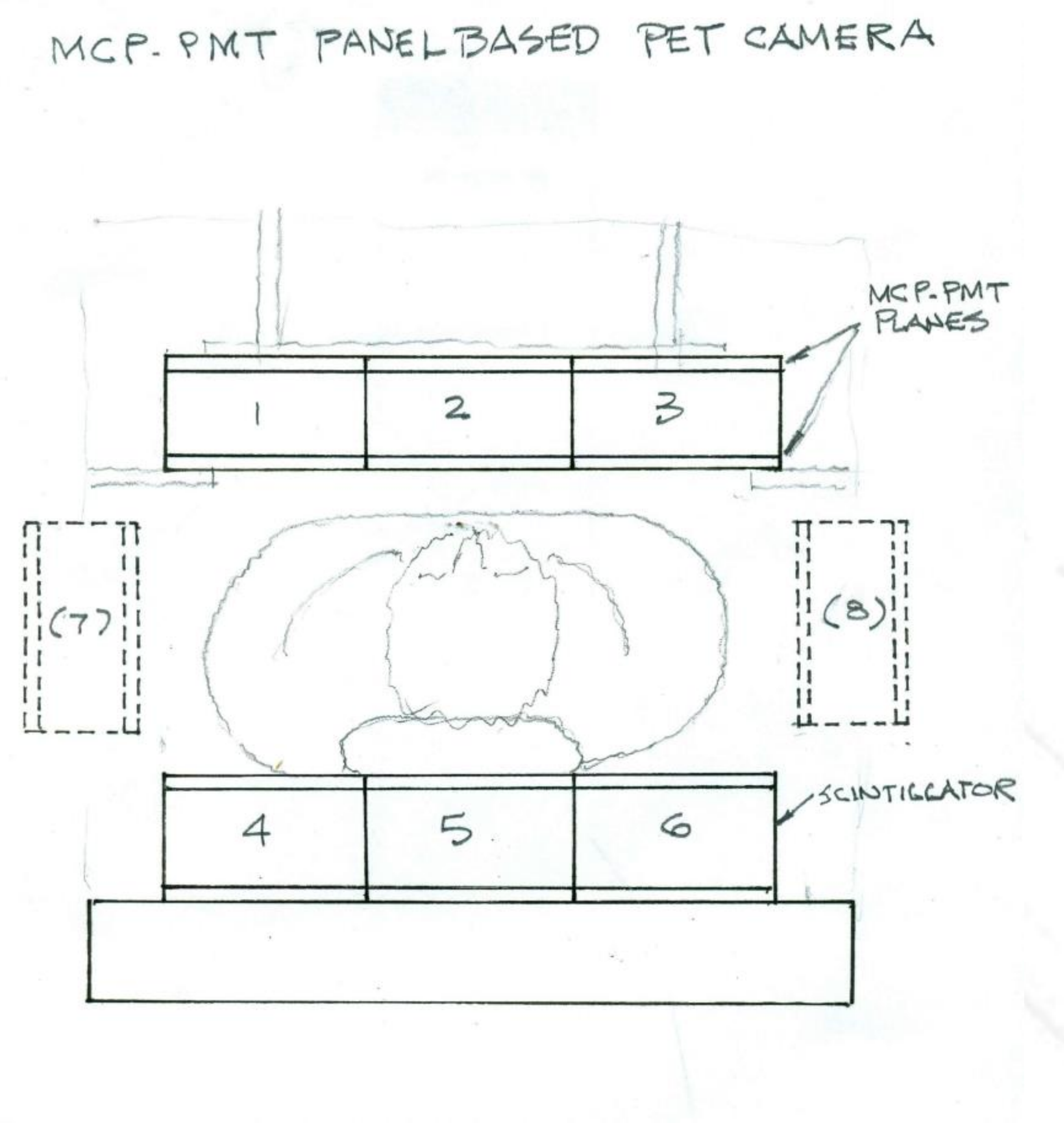
**Need: ~50ps**

# Low-Dose Whole-Body PET Camera

photo-detector planes

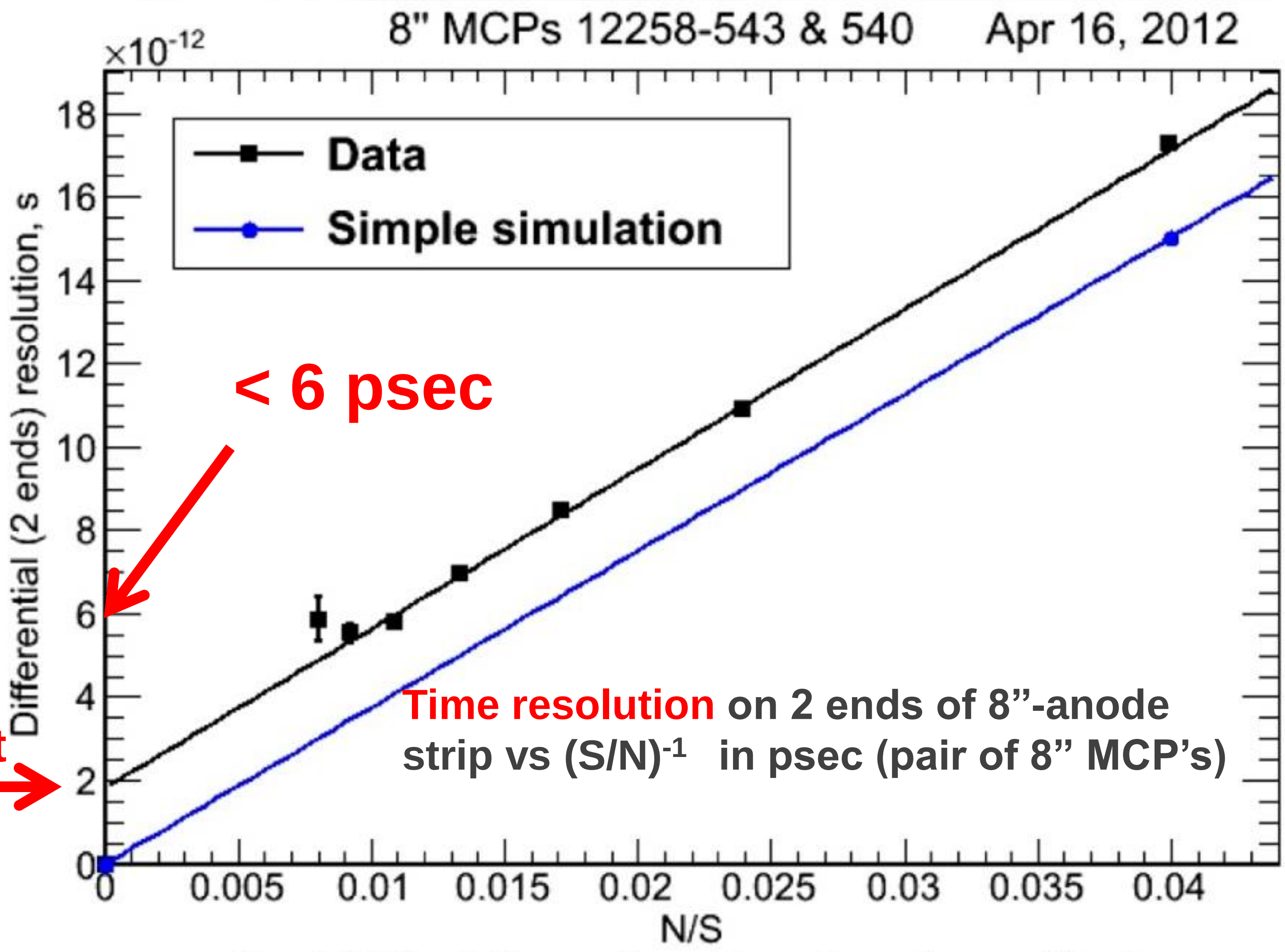


water-based liquid scintillator



Simulation and reconstruction work by Carla Grosso-Pilcher

# Differential Time Resolution



**< 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**

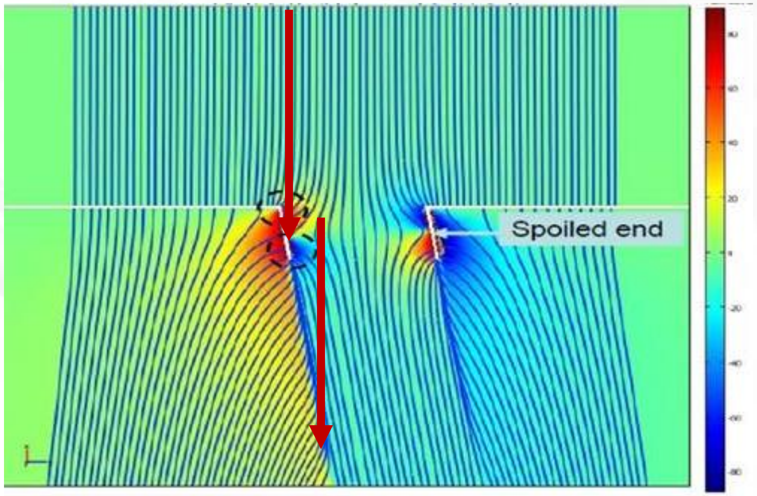
# Large-signal Limit Dependence

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 the 1st strike varies
- Smaller pores, increased bias angle are better
- "IF gain is such that a single photon shower makes the pulse (e.g. $10^7$), time jitter is set by the probability that NO photon has arrived in interval $\delta t$" - H. Frisch

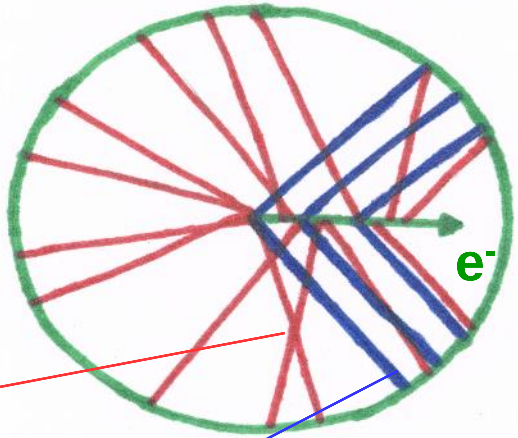
  This assumes that one fits the waveform to determine pulse $T_0$



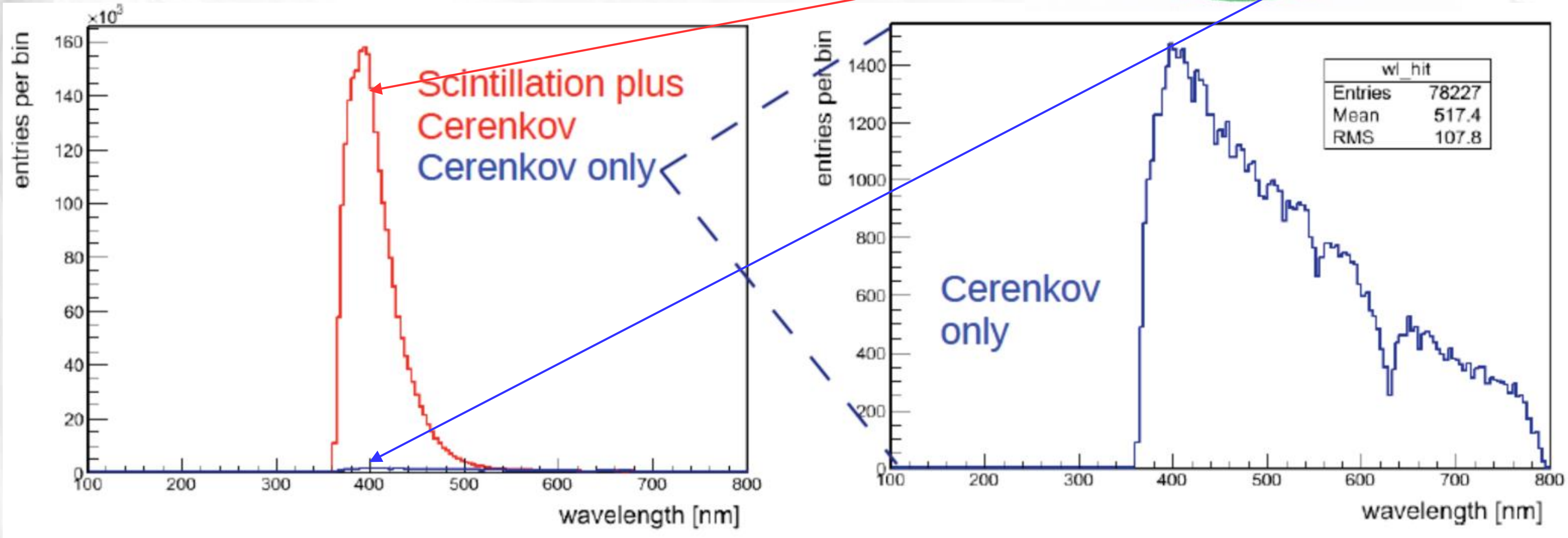
E.g. if 50 photoelectrons (from Cherenkov light in a window) arrive within 50 psec, the probability that one goes for T psec with NO photon making a first strike goes as $e^{-T}$
=> a 1/N dependence

# Can We Detect Cherenkov Light?

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



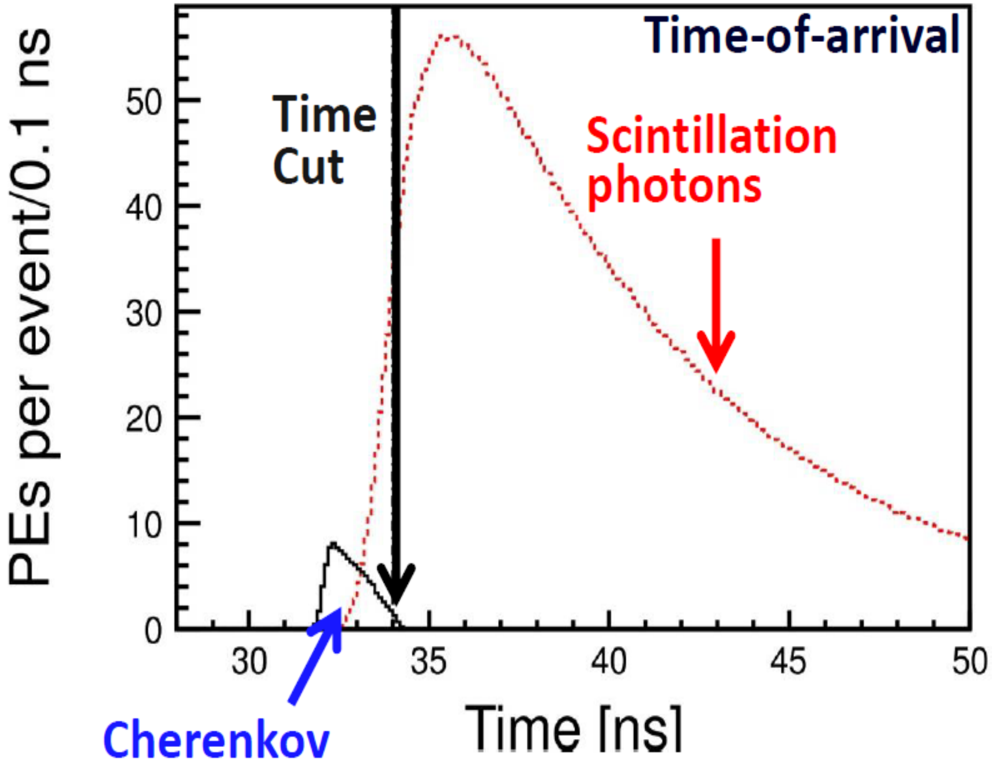
Scintillation model based on KamLAND-Zen simulation



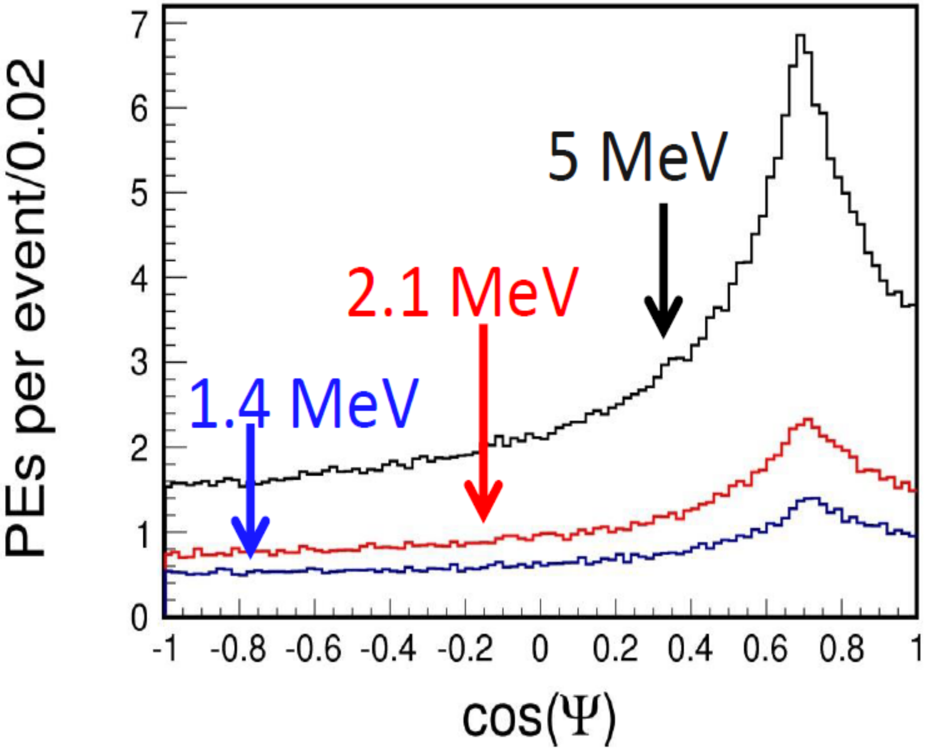
- Scintillation emission is slower
- Longer wavelengths travel faster
- Cherenkov light arrives earlier

370 nm → 0.191 m/ns
600 nm → 0.203 m/ns
~2 ns difference over 6.5m distance

# Directionality of Early Photons



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

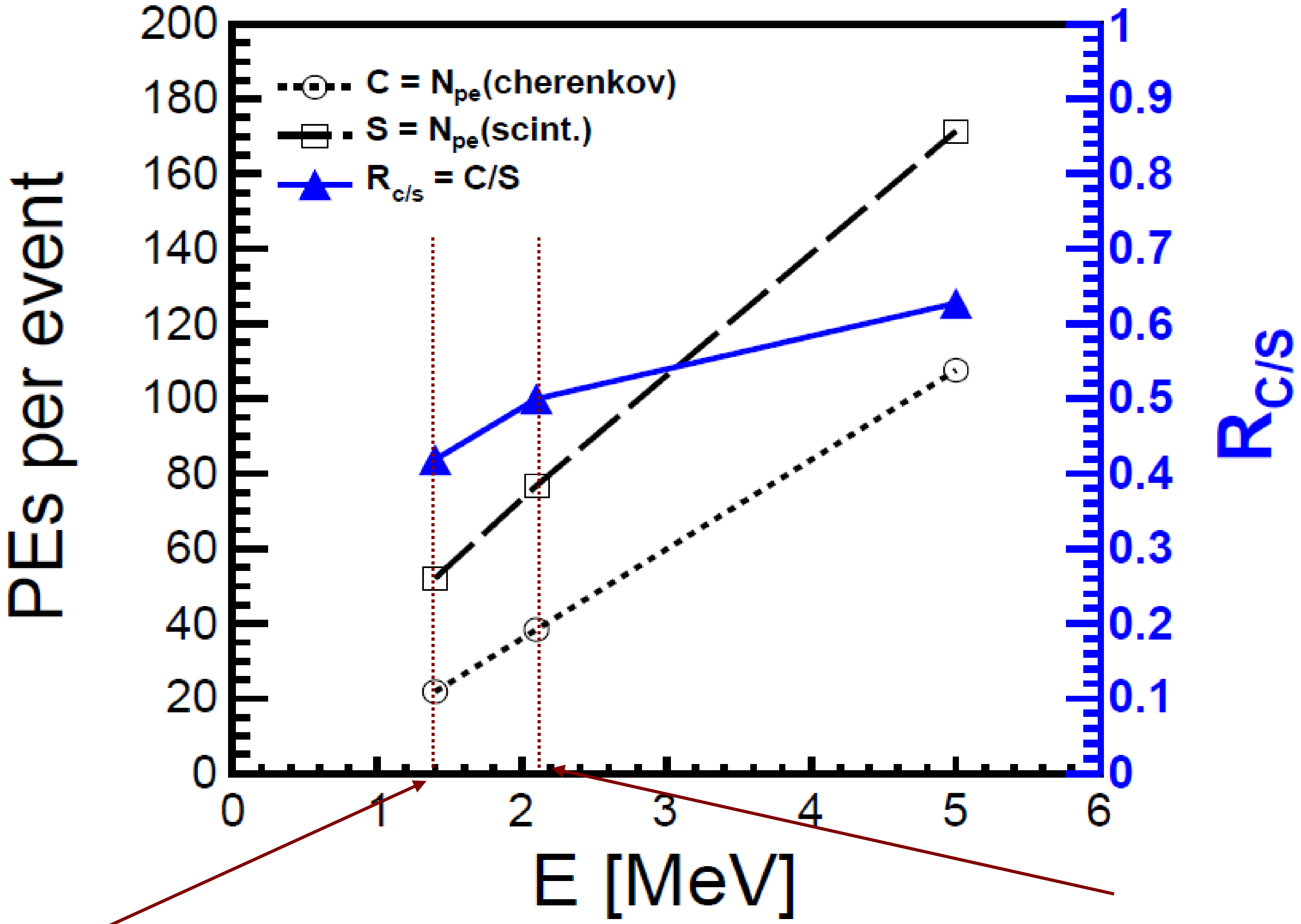


Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.

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

# What About Lower Energies?

**Light yield: Cherenkov vs scintillation**

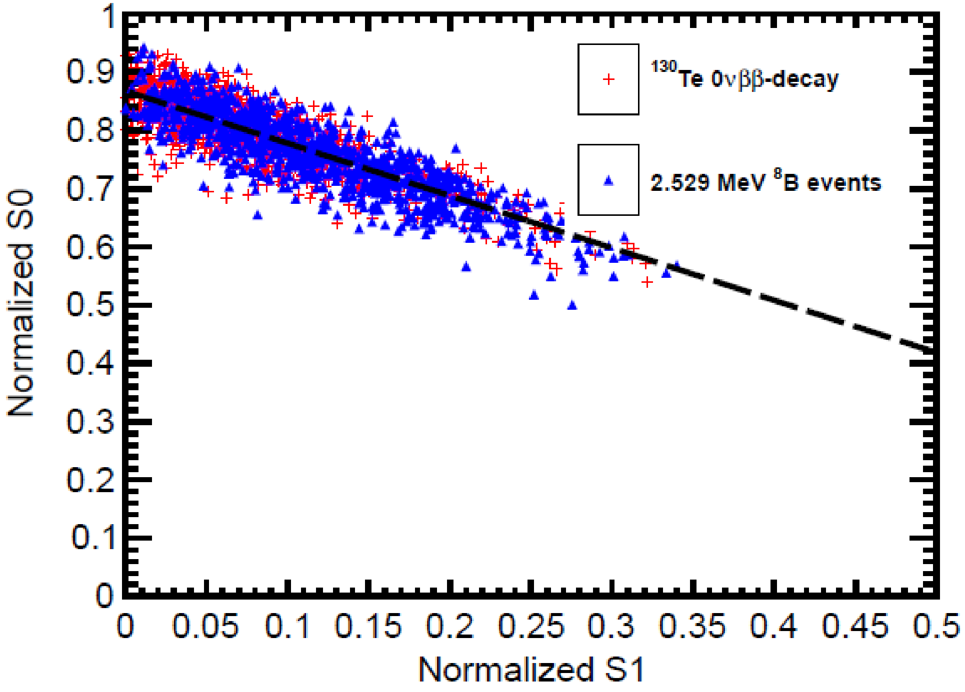


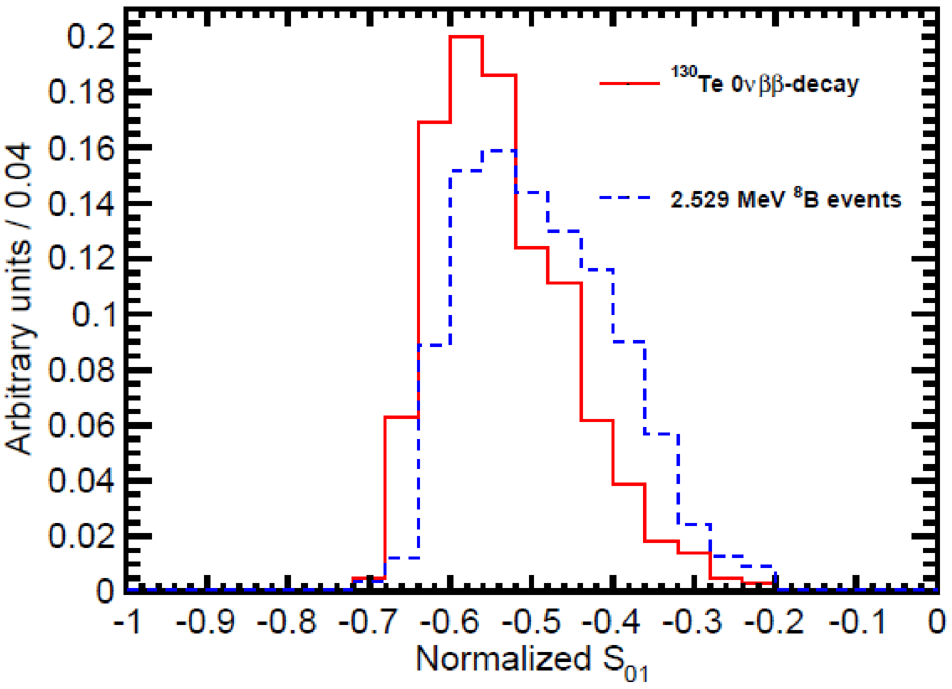
**½ Q ($^{116}$Cd) =1.4 MeV**

**½ Q ($^{48}$Ca) =2.1 MeV**

# $0\nu\beta\beta$ vs $^8$B

Vertex res **5cm**, events within **R<3m**
Sci rise time **1 ns**

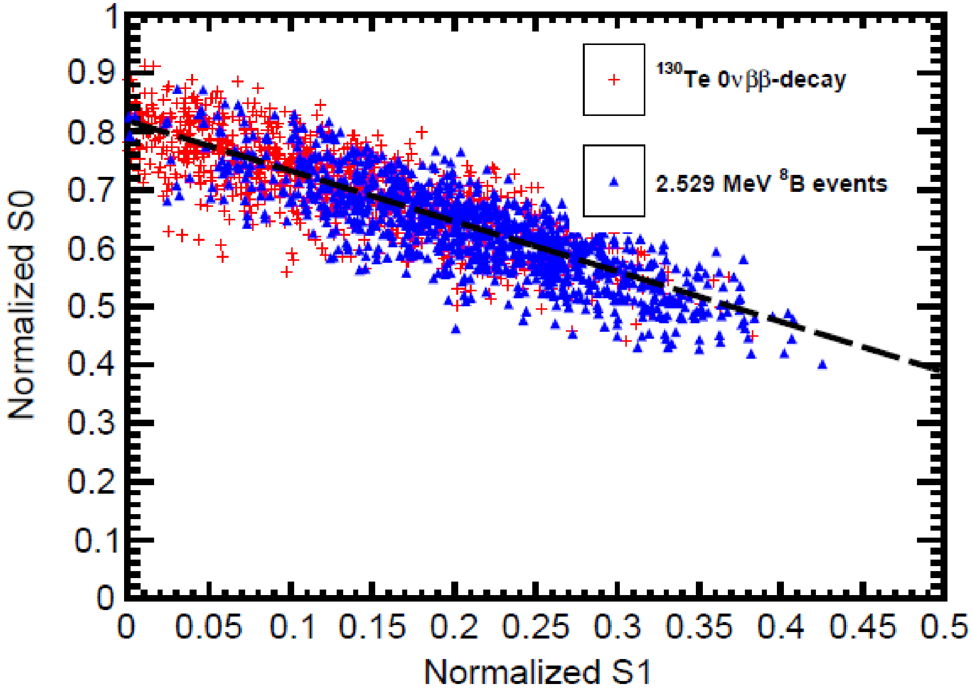


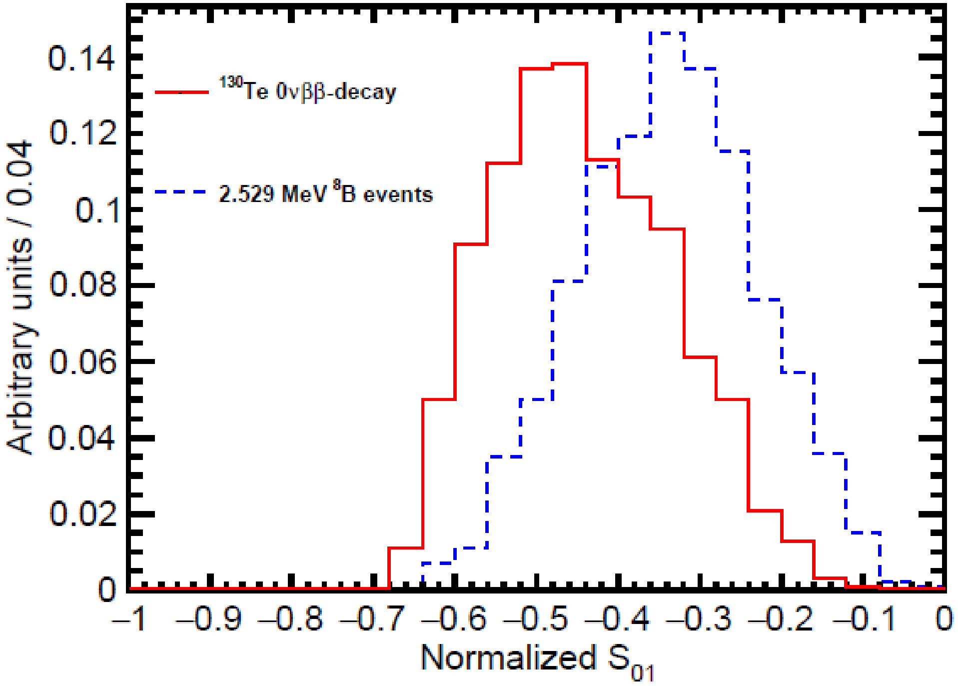


$I_{overlap} = 0.79$

# 0νββ vs $^8$B

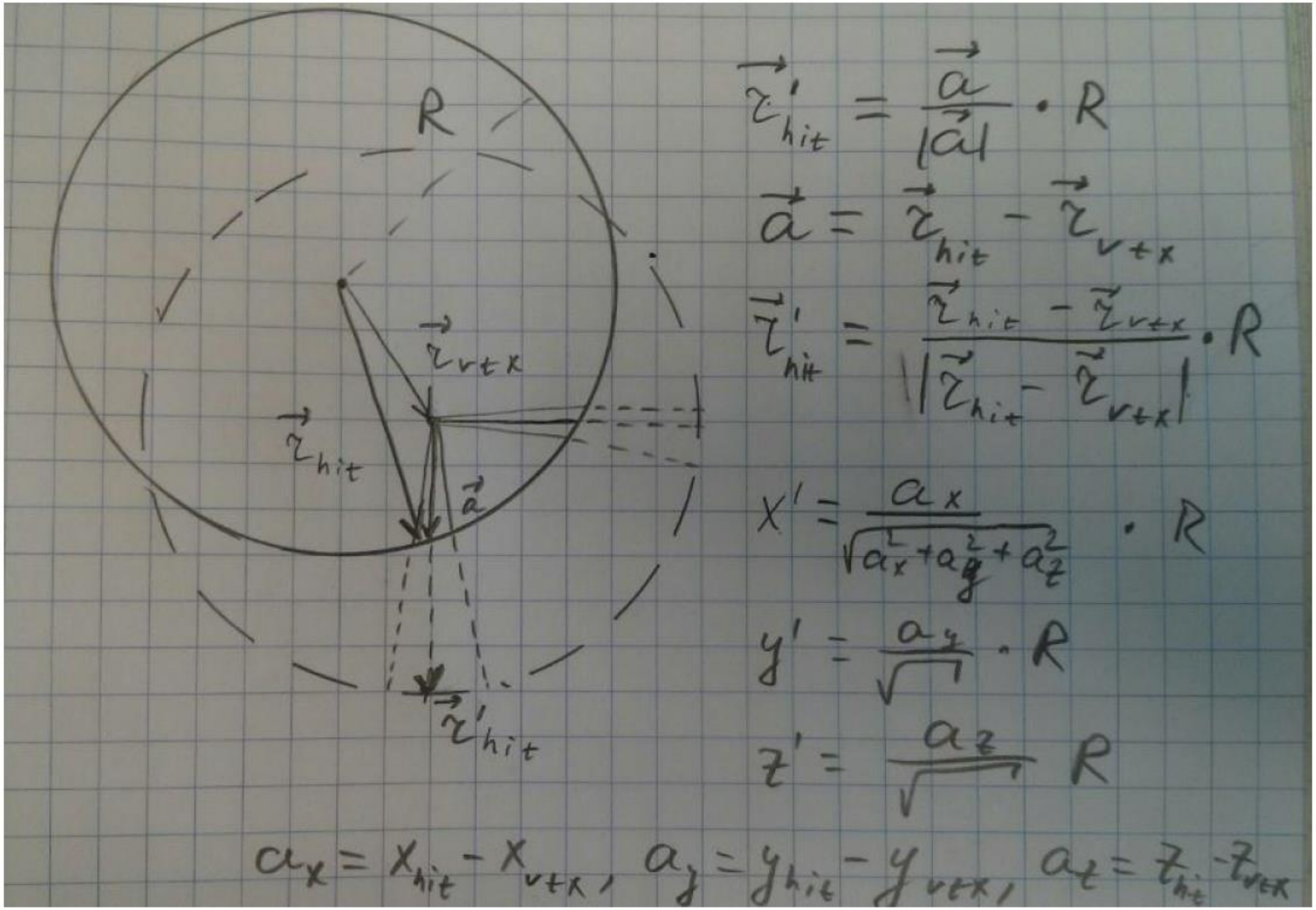
Vertex res **5cm**, events within **R<3m**
Sci rise time **5 ns**





$I_{overlap} = 0.64$

# Off-Center Events



$$\vec{r}'_{hit} = \frac{\vec{a}}{|\vec{a}|}\cdot R$$

$$\vec{a} = \vec{r}_{hit} - \vec{r}_{vtx}$$

$$\vec{r}'_{hit} = \frac{\vec{r}_{hit} - \vec{r}_{vtx}}{|\vec{r}_{hit} - \vec{r}_{vtx}|}\cdot R$$

$$x' = \frac{a_x}{\sqrt{a_x^2 + a_y^2 + a_z^2}}\cdot R$$

$$y' = \frac{a_y}{\sqrt{\ }}\cdot R$$

$$z' = \frac{a_z}{\sqrt{\ }} R$$

$a_x = x_{hit} - x_{vtx}$, $a_y = y_{hit} - y_{vtx}$, $a_z = z_{hit} - z_{vtx}$

# 0νββ-decay vs $^{10}$C

*two-track vs a “complicated” topology*

## $^{10}$C decay chain:

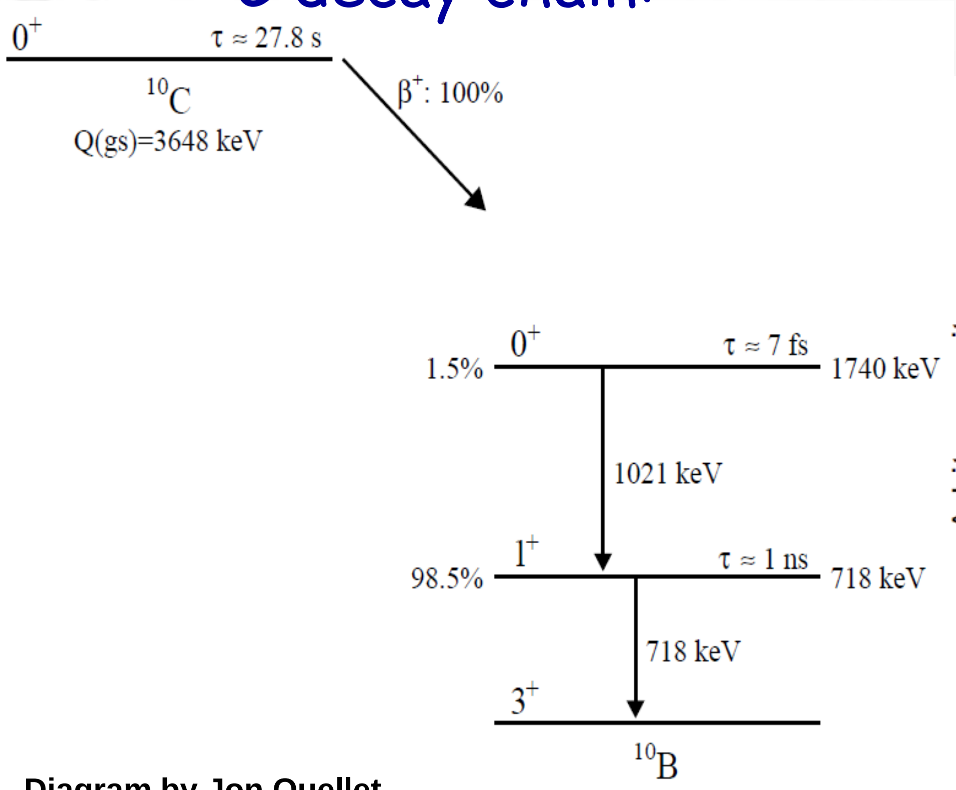
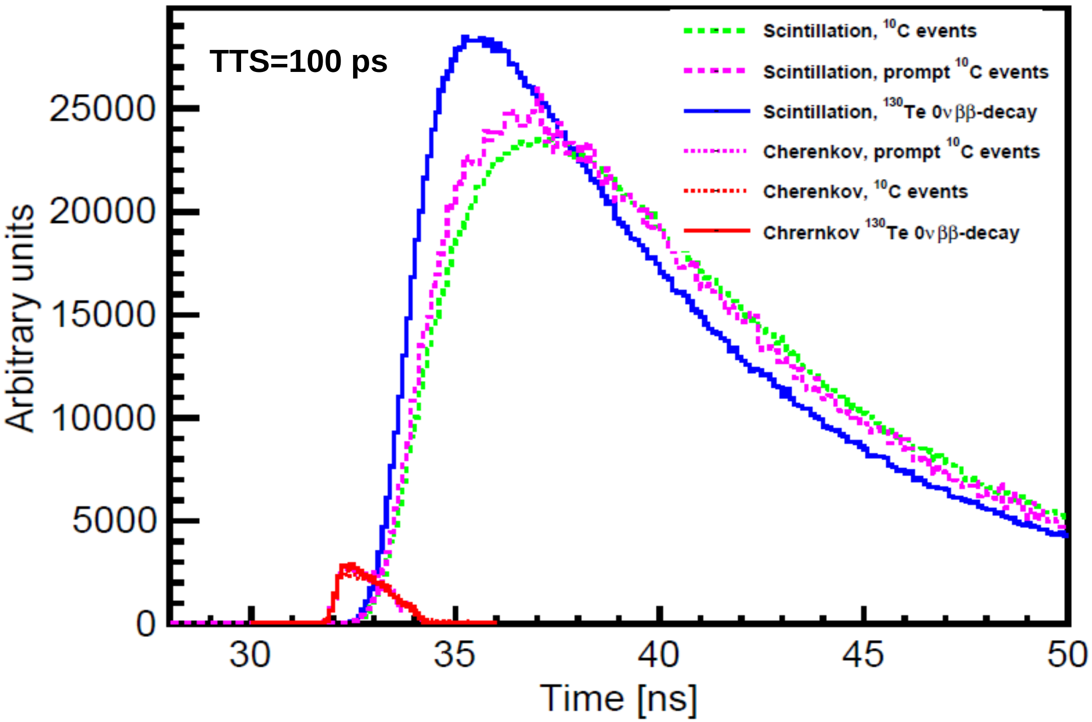


**Diagram by Jon Ouellet**

$^{10}$C vs 0νββ-decay: photons arrival time profile

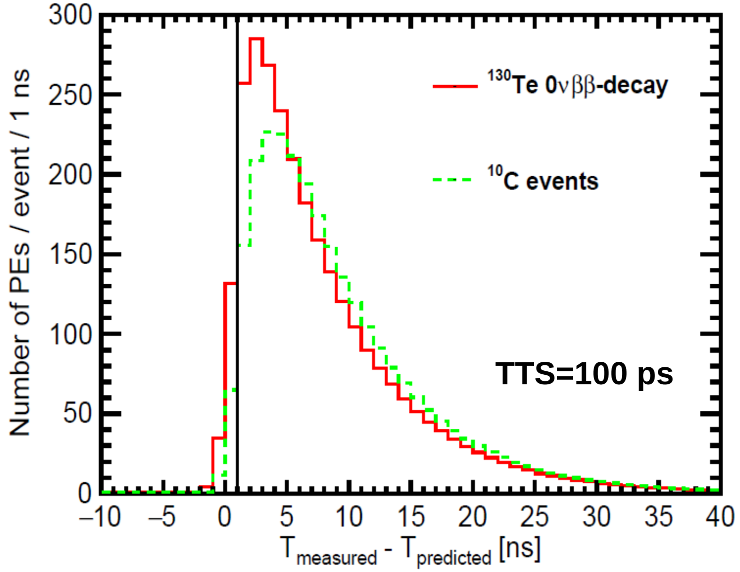


- $^{10}$C final state consist of a positron and gamma (e+ also gives 2x0.511MeV gammas after loosing energy to scintillation)
- Positron has lower kinetic energy than 0νββ electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex

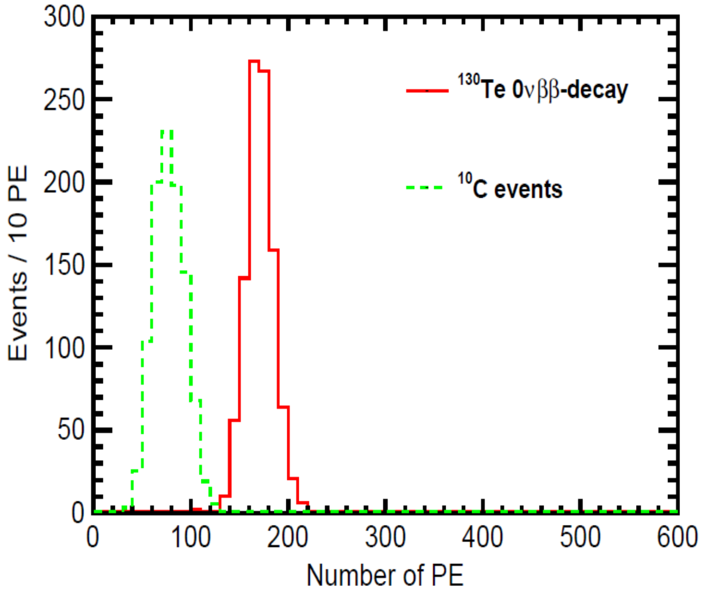
$^{10}$C background can be large at a shallow detector depth

# $0\nu\beta\beta$-decay vs $^{10}$C

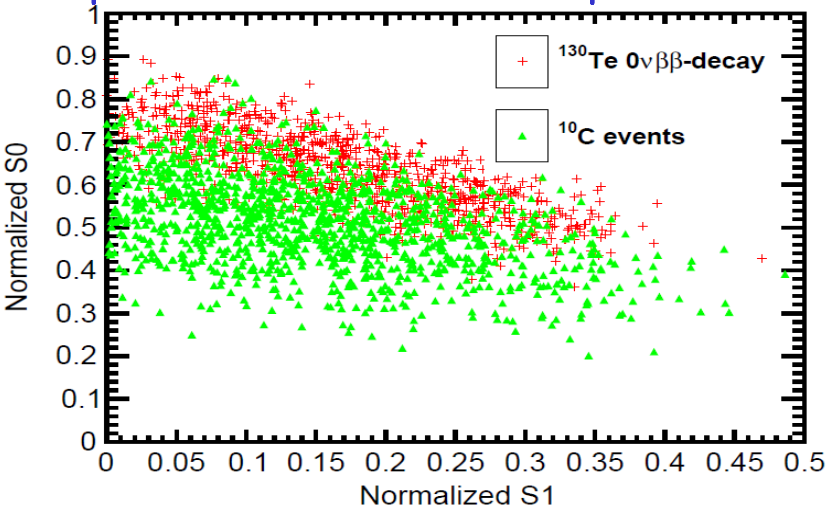
Time profile for events uniformly
distributed within the fiducial volume, R<3m
Vertex resolution of 3cm is assumed



Photons count in early light sample

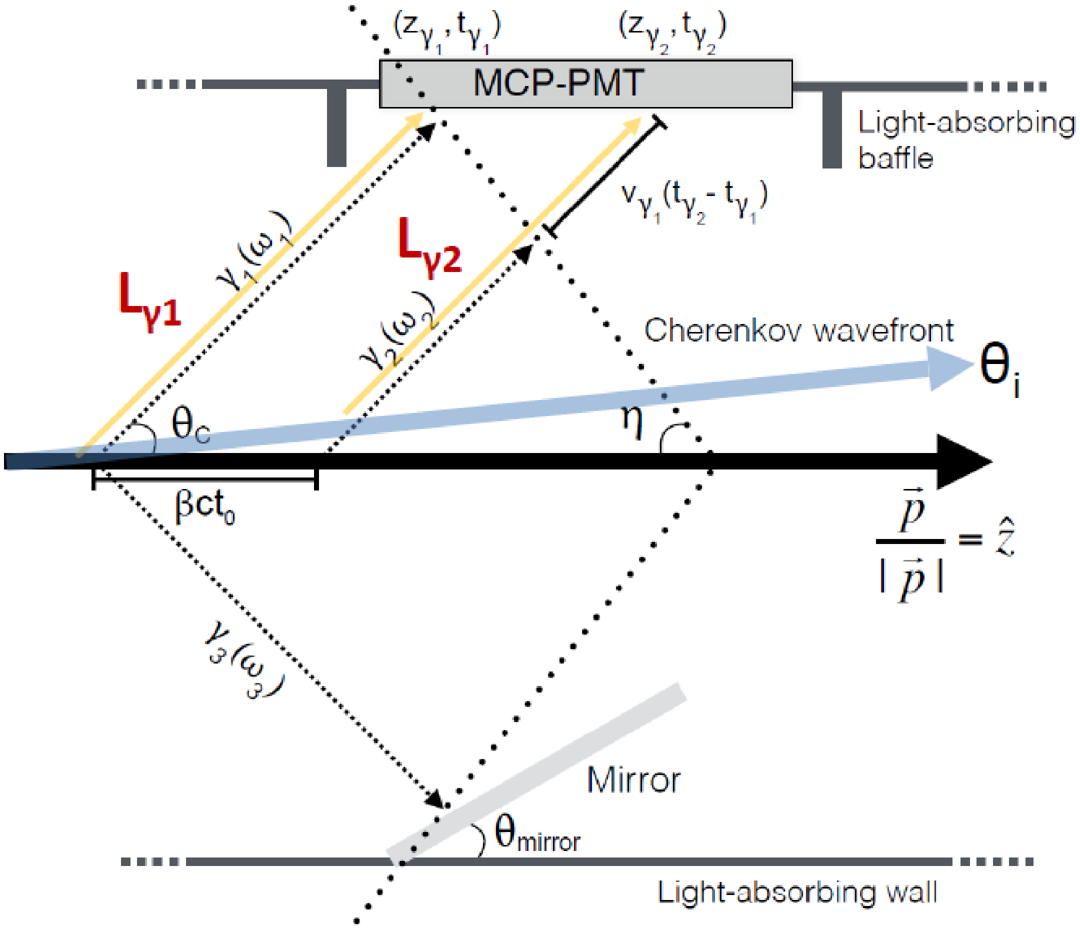


Spherical harmonics help here too



**Disclaimer:** there are other handles on $^{10}$C that are already in use (e.g., muon tag, secondary vertices). Actual improvement in separation power may vary.

# OTPC Optics – direct light



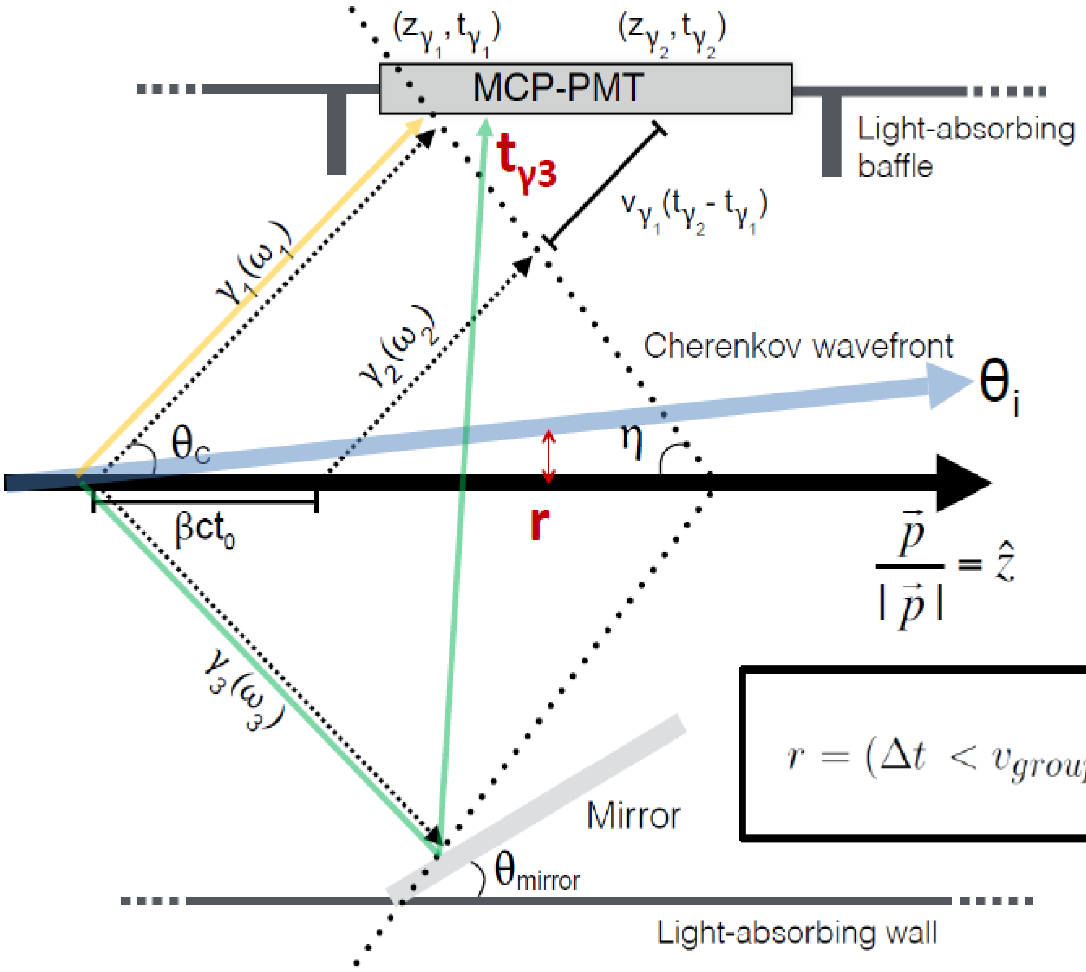
The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle (β) and the particle angle with respect to the OTPC longitudinal axis

$$\Delta t_{\gamma_{21}} = t_o \left(1 - \frac{\beta c}{< v_{group} >} \tan\theta_i\right)$$

$$\Delta z_{\gamma_{21}} = \beta c t_o \cos\theta_i$$

$$\boxed{\frac{dt}{dz} \approx \frac{1}{\beta c} - \frac{\tan\theta_i}{< v_{group} >}}$$

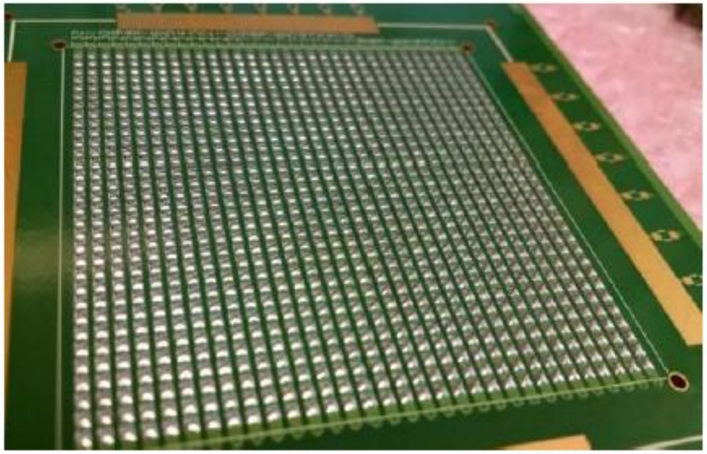
# OTPC Optics – direct + reflected light



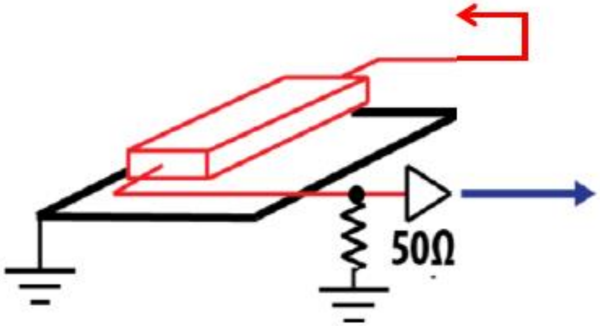
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

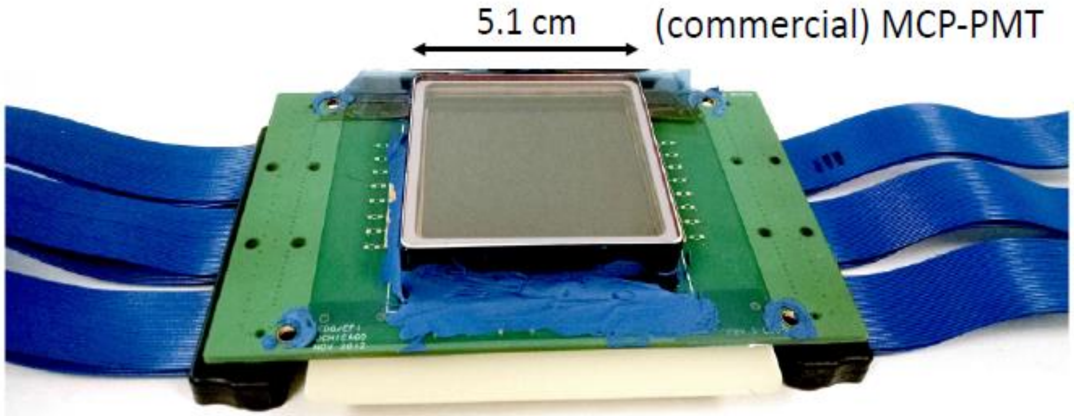
$$\boxed{r = (\Delta t \ < v_{group} > - D)\,\frac{1}{2}\left(\frac{1}{\sin\theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)}\right)^{-1}}$$

# OTPC Photodetector Module (PM)

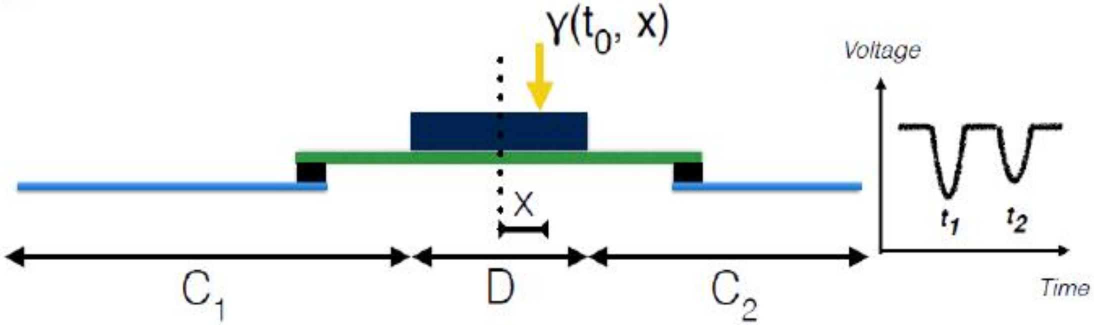


- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- Terminate one end of micro-strip, other end open (high-impedance):





PHOTONIS XP85022 (commercial) MCP-PMT



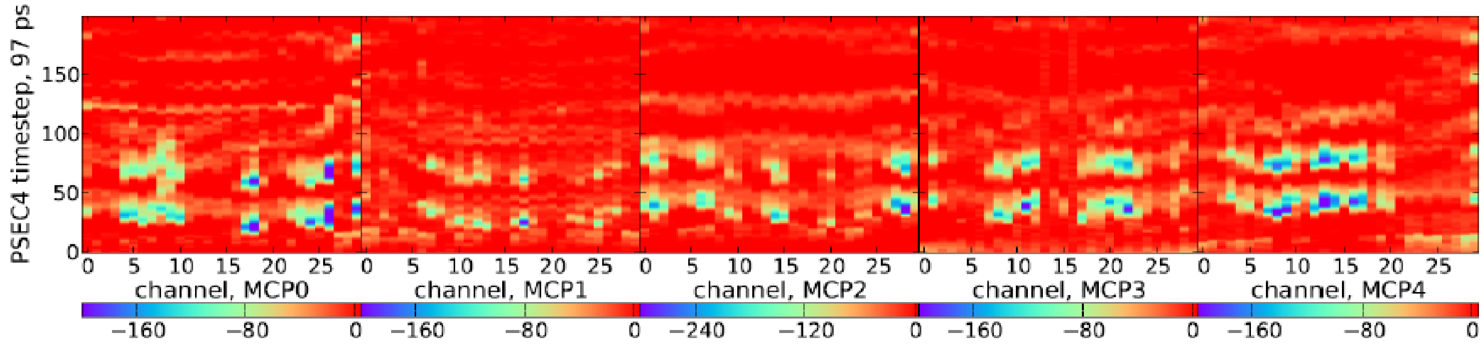
Expressions for the position and time-of-arrival of the detected photon

$$x = v_{prop}\,\frac{t_2 - t_1}{2} - \frac{D + 2\,C_1}{2}$$

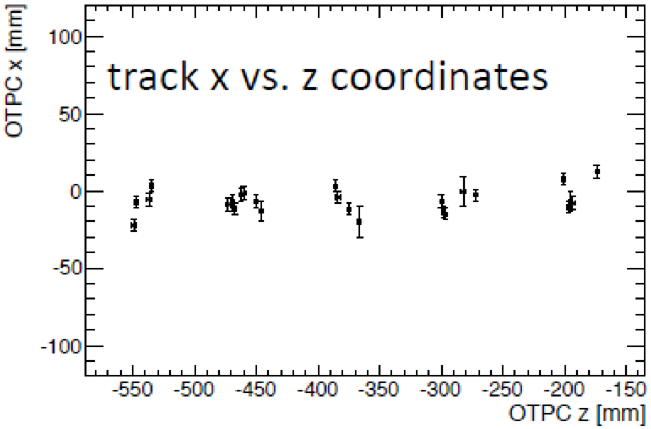
$$t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}}(D + C_2 + C_1)$$

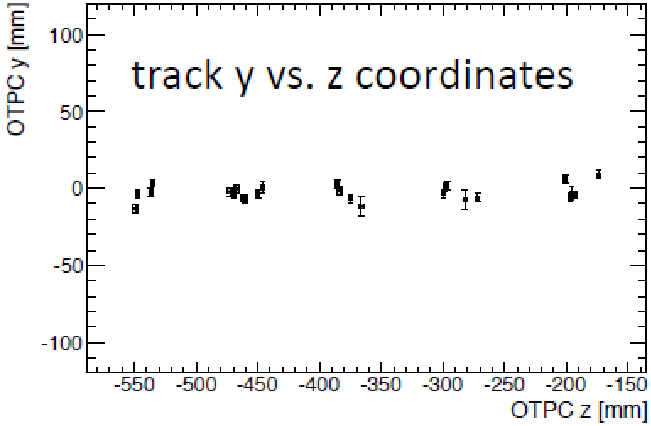
# OTPC spatial reconstruction (3)

Example event



Typical event (thru-going μ)





Projecting the direct photons onto the reconstructed r-coordinate at each PM