Optical Time Projection Chambers and charged particle tracking in water

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Acknowledgements

Bernhard Adams, Andrey Elagin, Eric Oberla, Henry Frisch, Eric Spieglan

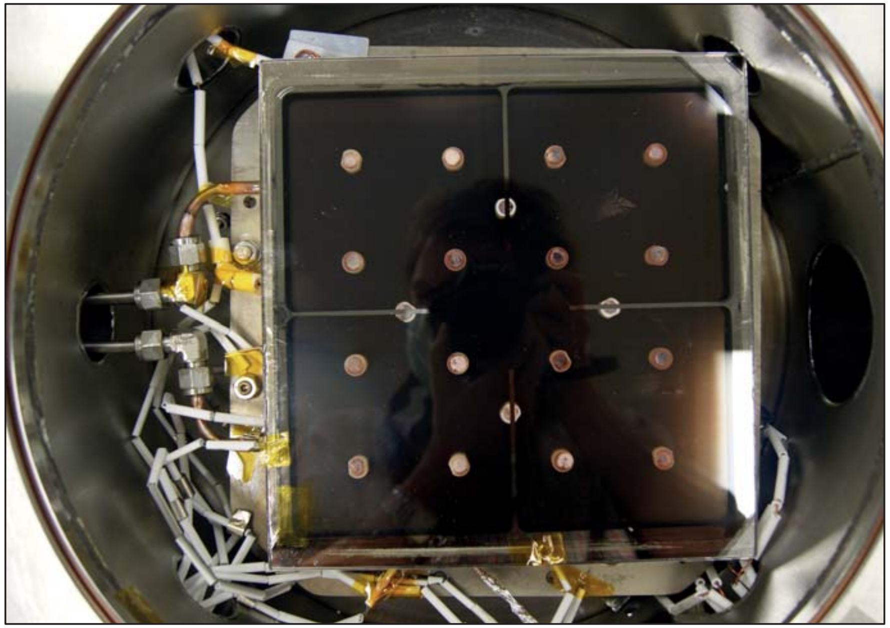
U.S. DEPARTMENT OF ENERGY

Next Generation Instrumentation: Large-Area Psec Photo-detectors (LAMPPDTM) for Charged Particle/Photon TOF and the Next Generation Optical Time Projection Chamber (OTPC)

Incom Phase II SBIR

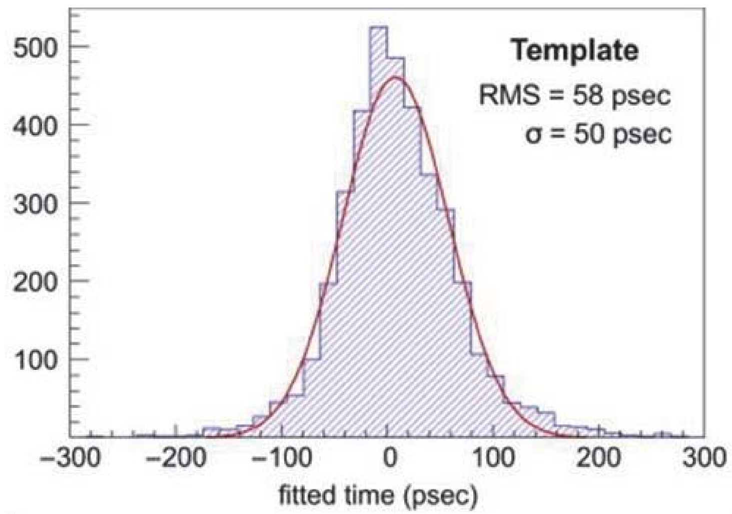
Development of Gen-II LAPPDTM Systems for Nuclear Physics Experiments

LAPPD^{TM} MCP-PMTs



Sealed 20cm x 20cm ceramic LAPPD in the middle of photocathode formation at U of C

Reference: "Timing characteristics of Large Area Picosecond… [NIM A 795, 2015], B. Adams et. al.



single photoelectron absolute time resolution (psec)

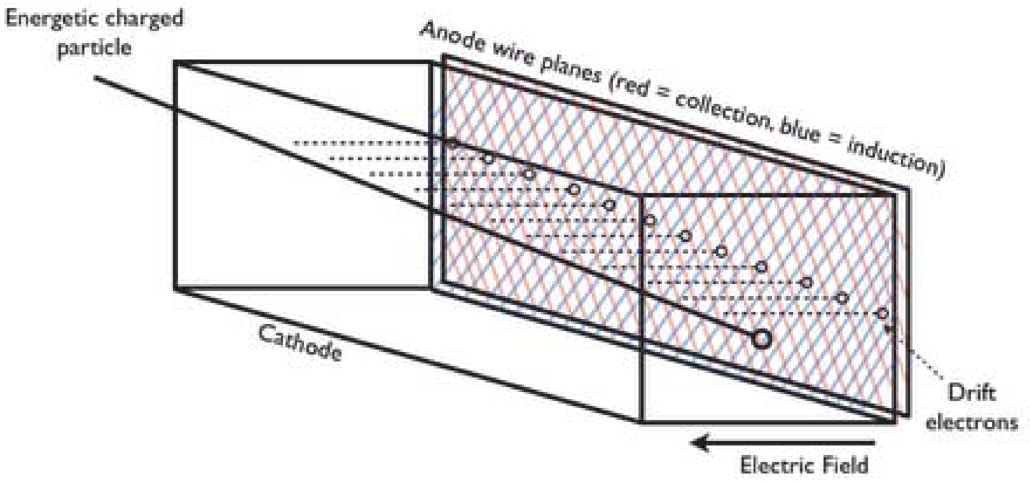
Have demonstrated:

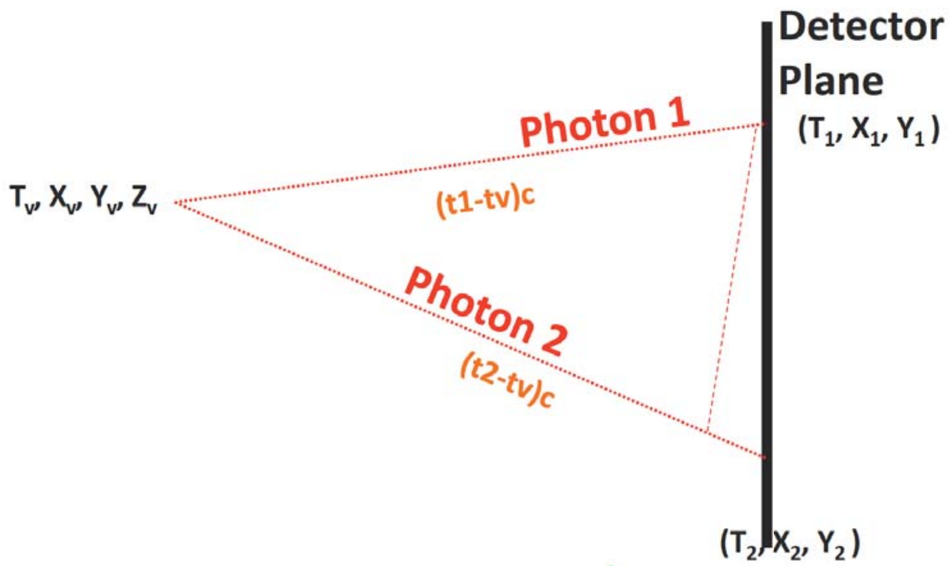
1. Gains of $>10^7$
2. Timing resolution ~50ps on single photon

Fabrication process being studied at U. of C., see talk by Andrey Elagin earlier today

Single photons resolved in 3D (2 space + 1 time)

Arrival time difference > σ_t





Time Projection

3D-vertex reconstruction using 2 space + time coordinates

Prototype OTPC

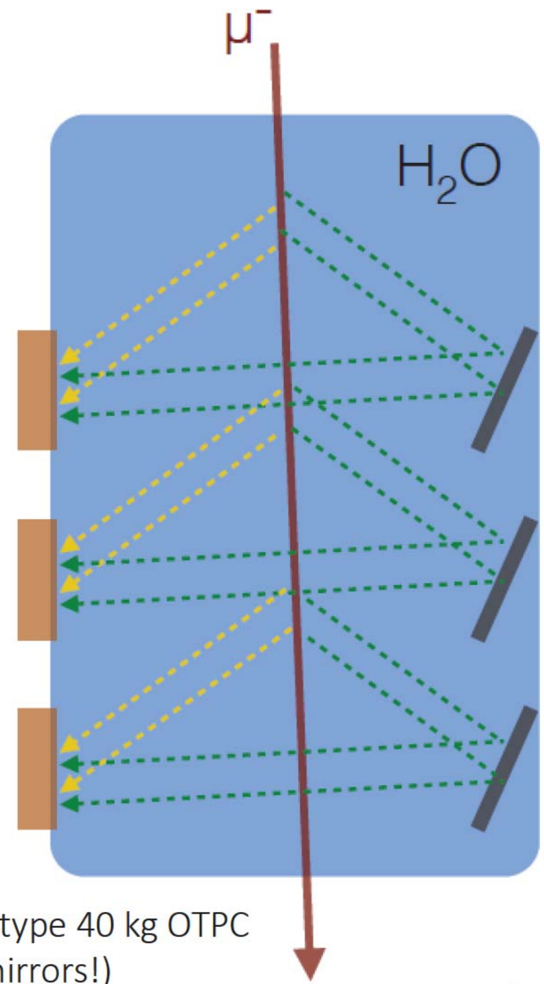
The design and performance of a prototype water Cherenkov optical time-projection chamber

Eric Oberla[a], Henry J. Frisch[a]

[a]Enrico Fermi Institute, University of Chicago; 5640 S. Ellis Ave., Chicago IL, 60637

Fermilab test beam experiment, Eric Oberla's PhD thesis, 2015

- 28 cm diameter, 77 cm long cylindrical detector
- 40 kg of water
- Mirrors bounce photons to lower $$ on PMTs



Prototype 40 kg OTPC
(w/ mirrors!)

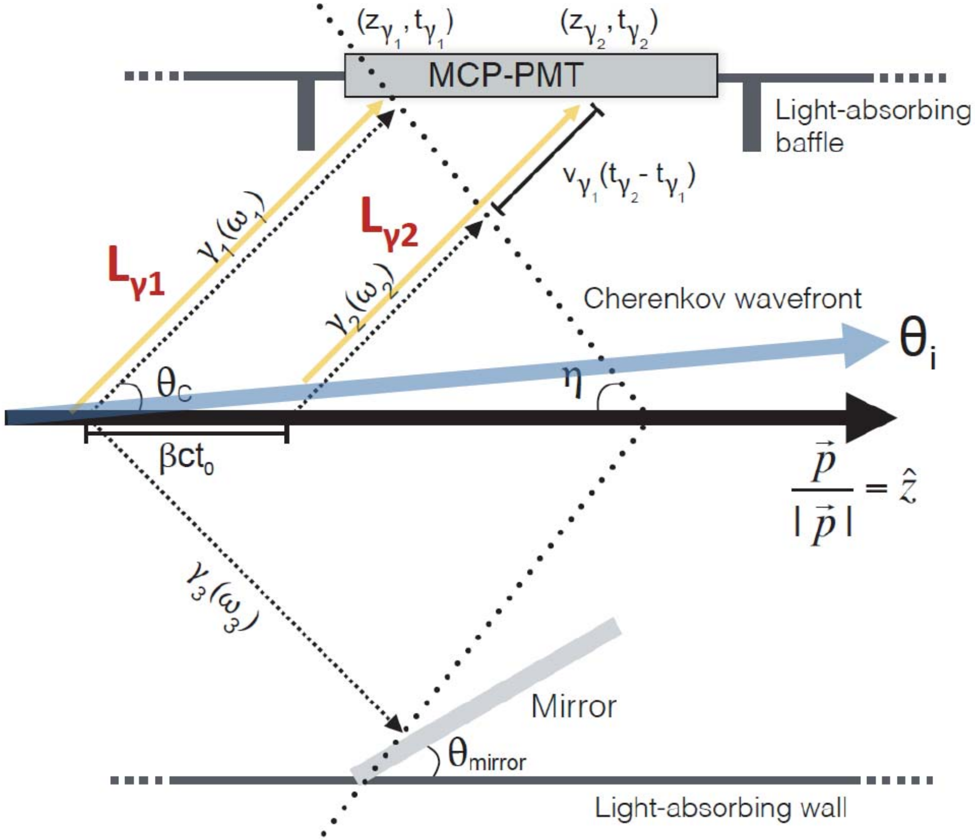
Electron Time Projection

- Drift electrons at a 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)

Optical Time Projection

- Drift photons at constant velocity
- Limit dispersion by various methods (wavelength filtering, etc..)
- 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

In simplest case, track parameters can be solved analytically through ray tracing (ignoring dispersion and scattering)



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

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

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

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

The Cherenkov photons propagate at the group velocity of water. The mean OTPC group velocity $<v_{group}>$ = 218 mm/ns (i.e. the OTPC 'drift speed')

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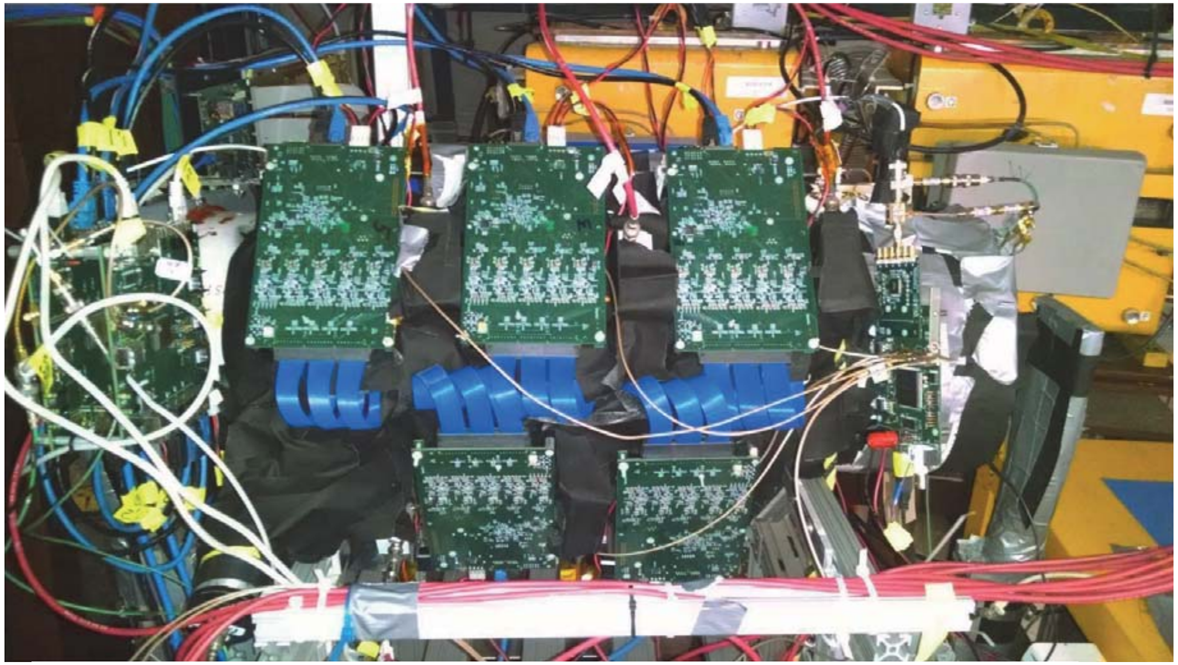
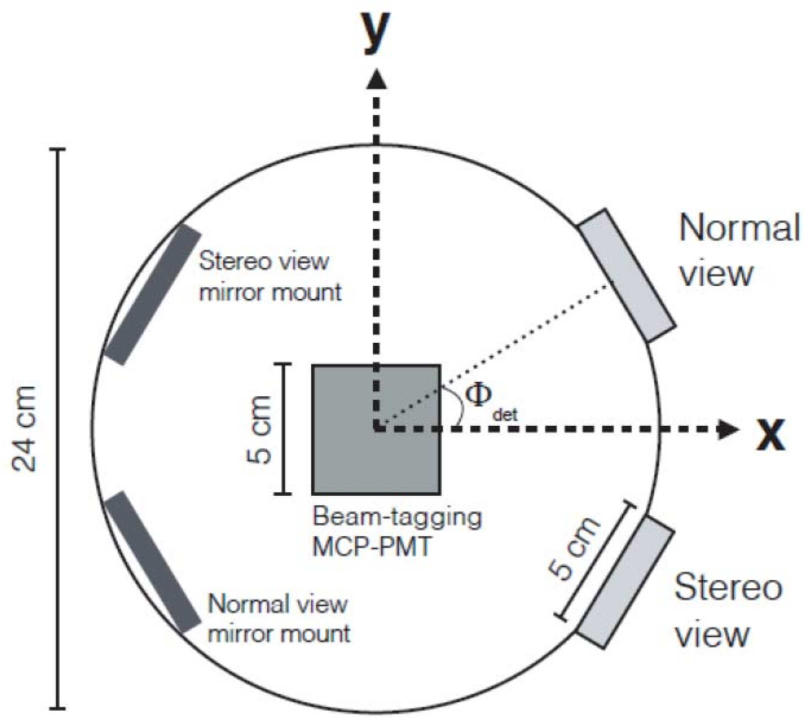
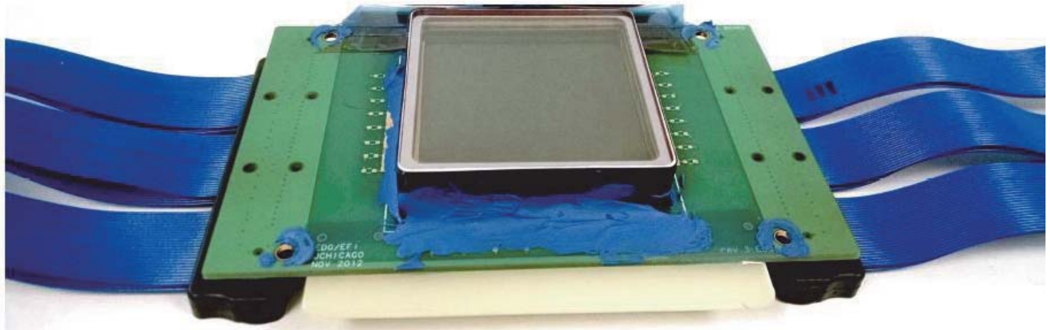
Slide from E. Oberla's talk, ICHEP2016

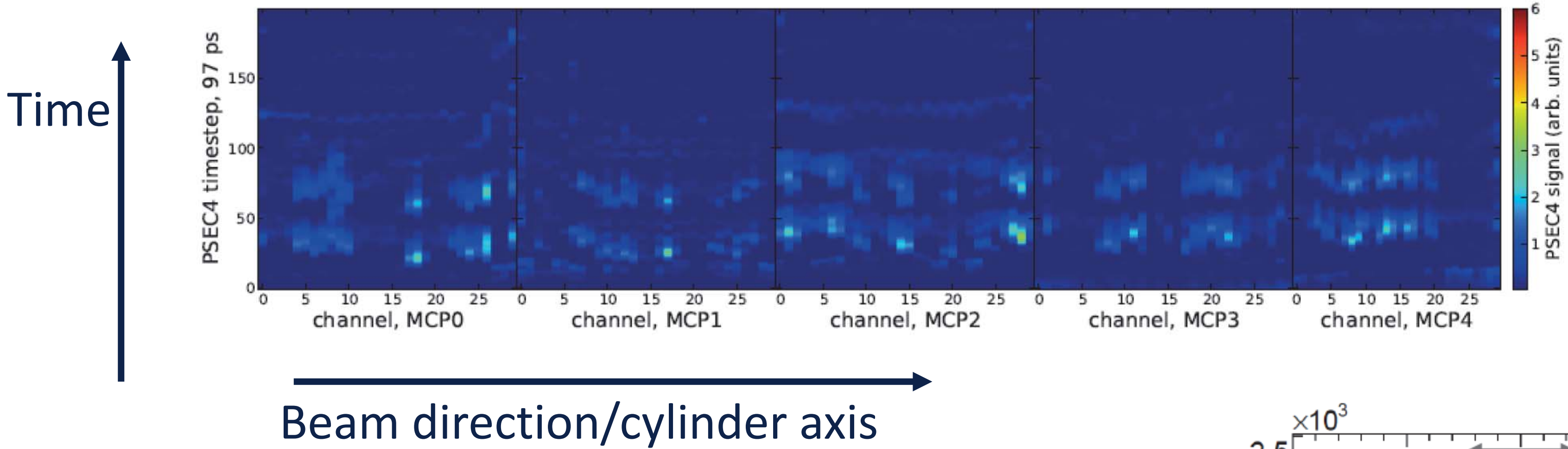
Prototype OTPC



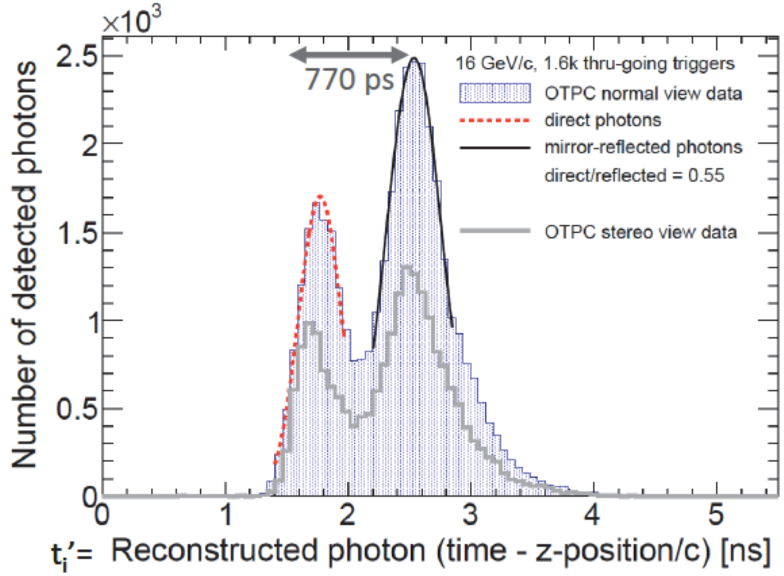




Prototype OTPC

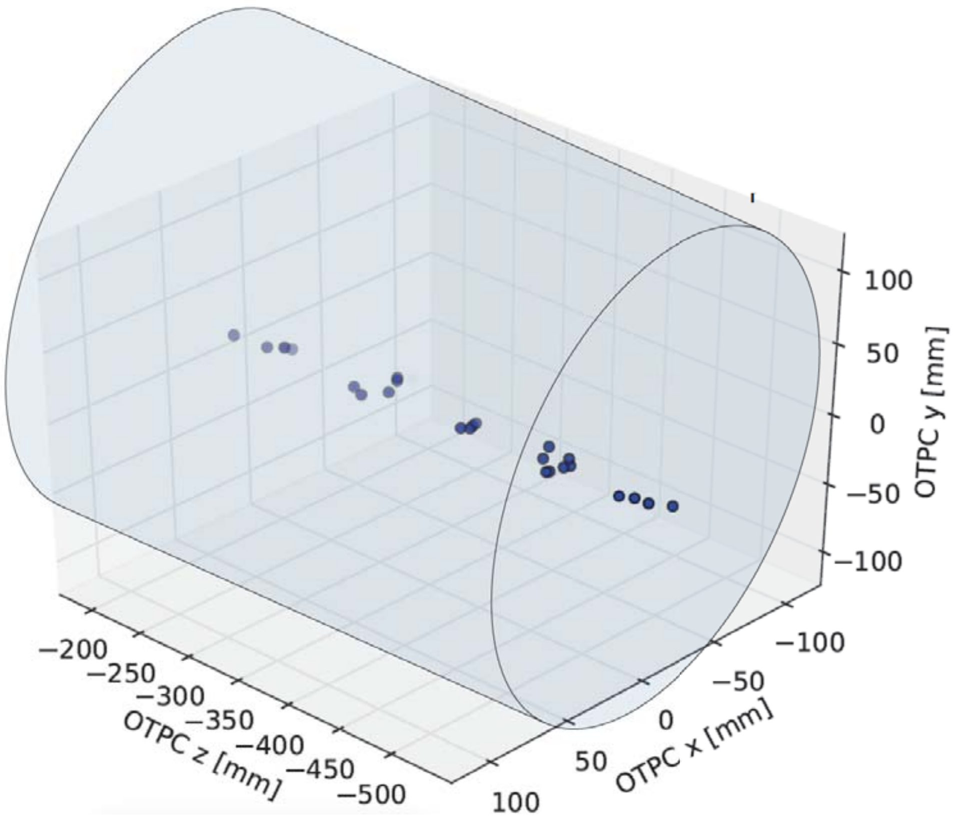


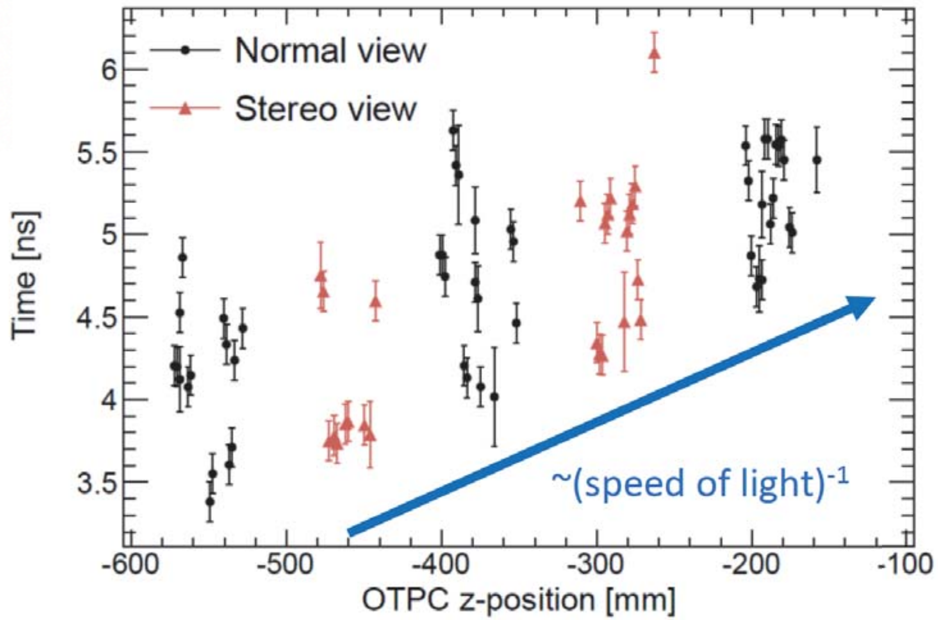
Observe ~770 ps timing separation corresponding to (diameter)/(group velocity)



Prototype OTPC

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

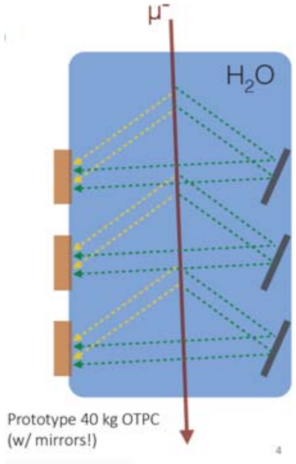




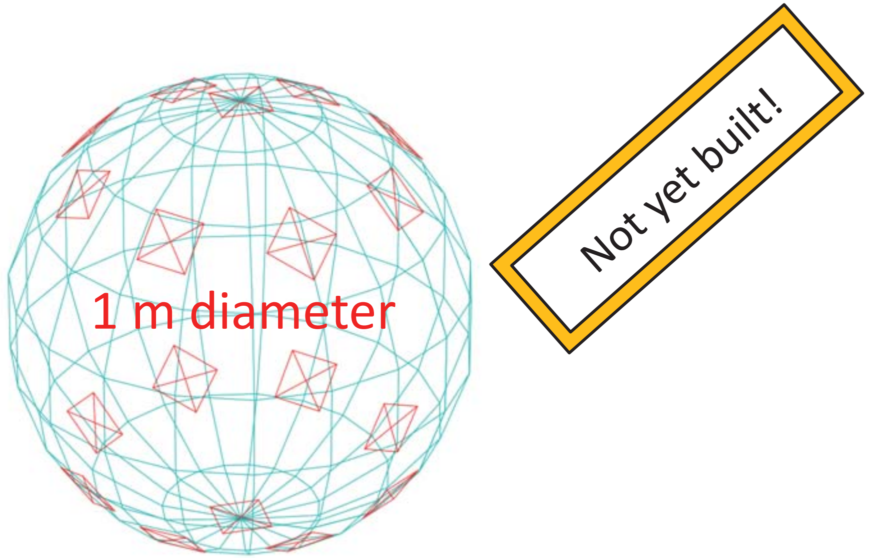
- 60 mrad angular resolution over 40cm lever arm
- 1.5 cm spatial resolution

Charged particle tracking in water!

Scaled up OTPC



40 kg



~1/2 ton

Features:

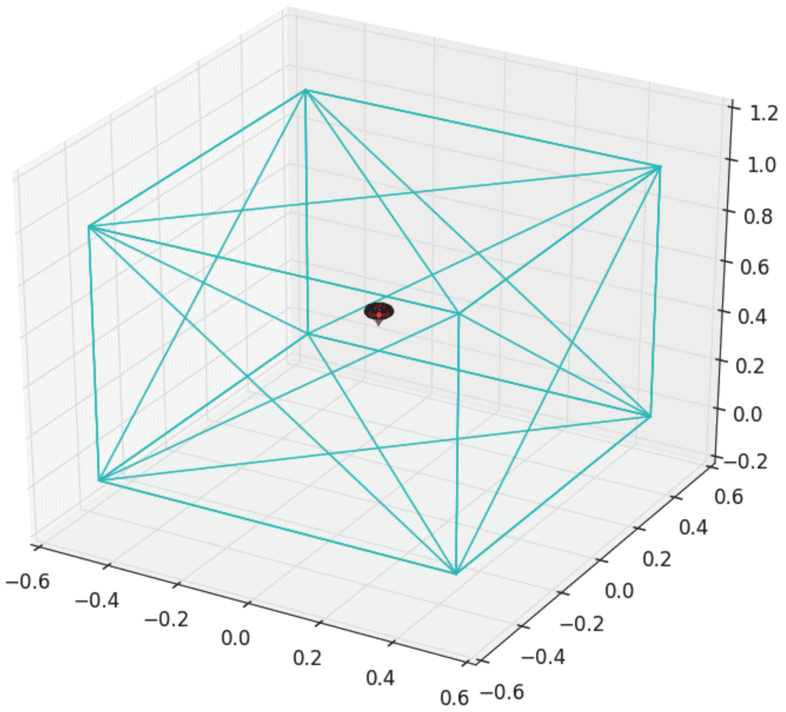
Isotropic sources → Sphere vs. cylinder

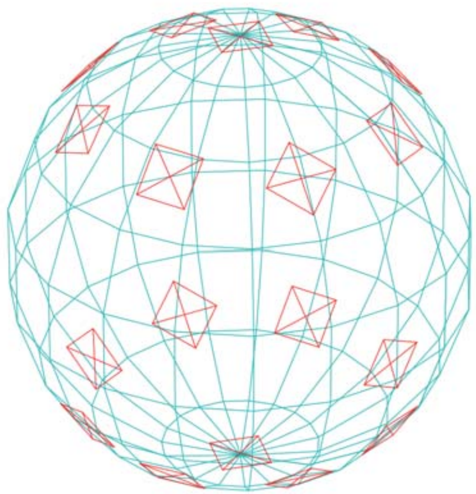
Directionality → Tracking on lengths 3cm – 100cm

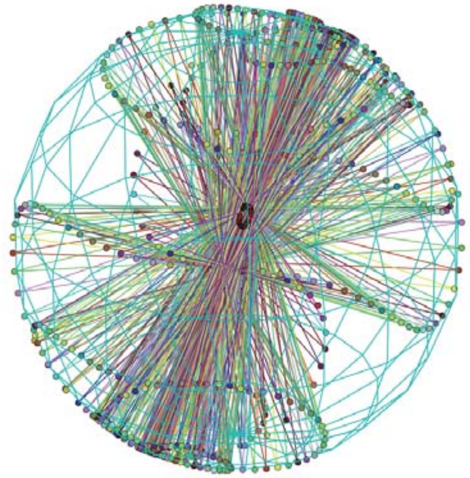
→ Short electron reco. from 0vBB, B^8, SNe, …

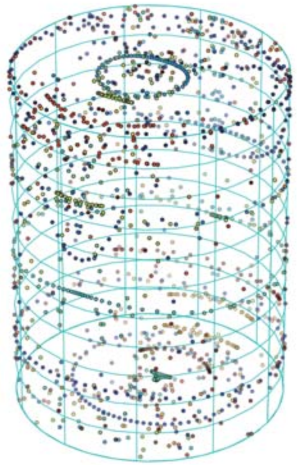
Charged Particle ID → **muons, electrons, showers …**

OTPC Simulation at UC









Python+Geant4 simulation does:

- Ray-tracing/Mirror reflections
- Photodetector resolution (smearing, QE, etc…)
- Track generation (Geant4)
- Dispersion in water
- ANY detector geometry, ANY mirror geometry

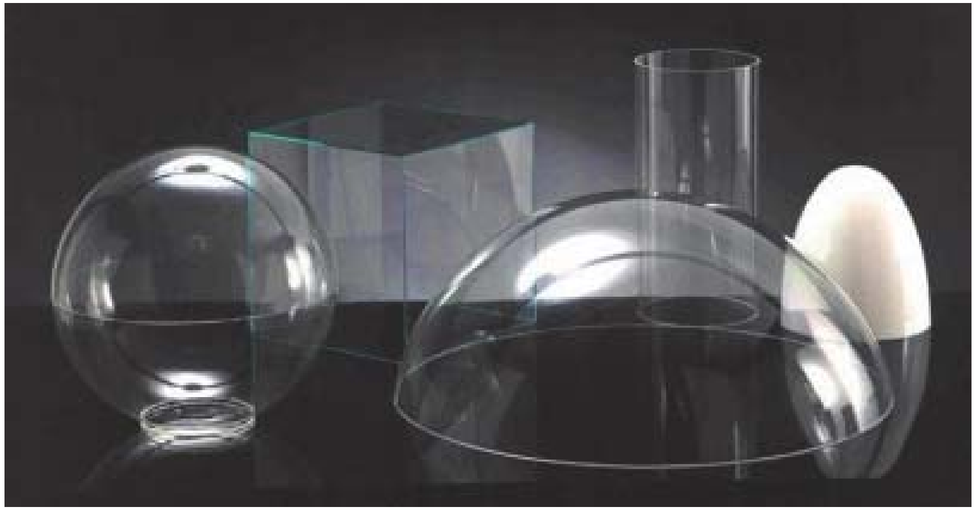
Mirror area/photocathode area = M/C

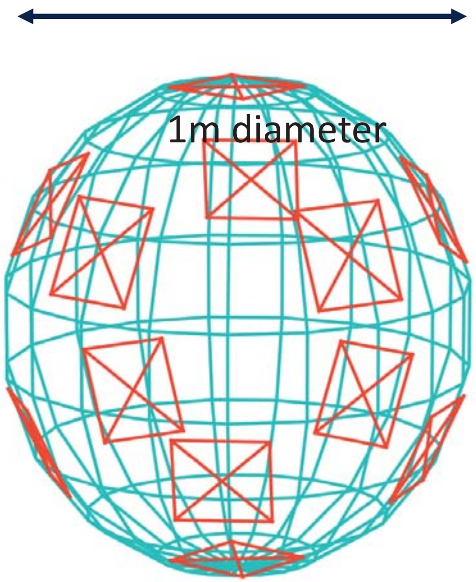
My favorite design thus far

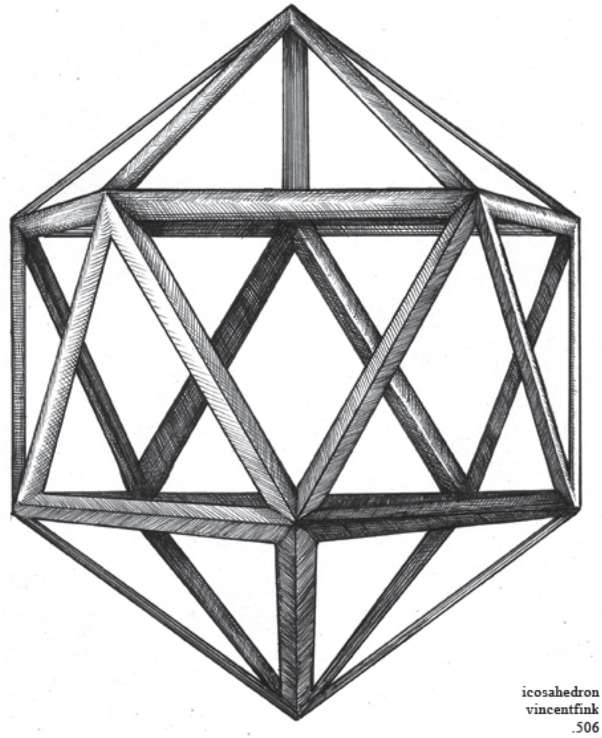
Icosahedron

- Close to equal spacing of detectors on sphere surface
- Low number of LAPPDs (12)
- Close to uniform response from all directions

M/C ~ 83%







Question

How much range in the group velocity (dispersion) can one afford for < 1cm vertex and tracking resolution?

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

$$t_{hit} = \frac{|\vec{x_{track}} - \vec{x_{hit}}|}{v_{group}}$$

Need to choose a reference group velocity

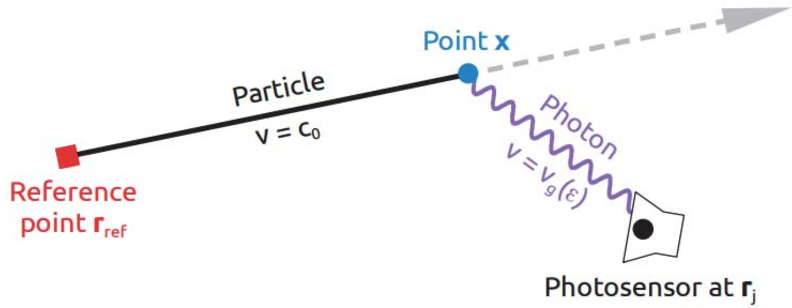
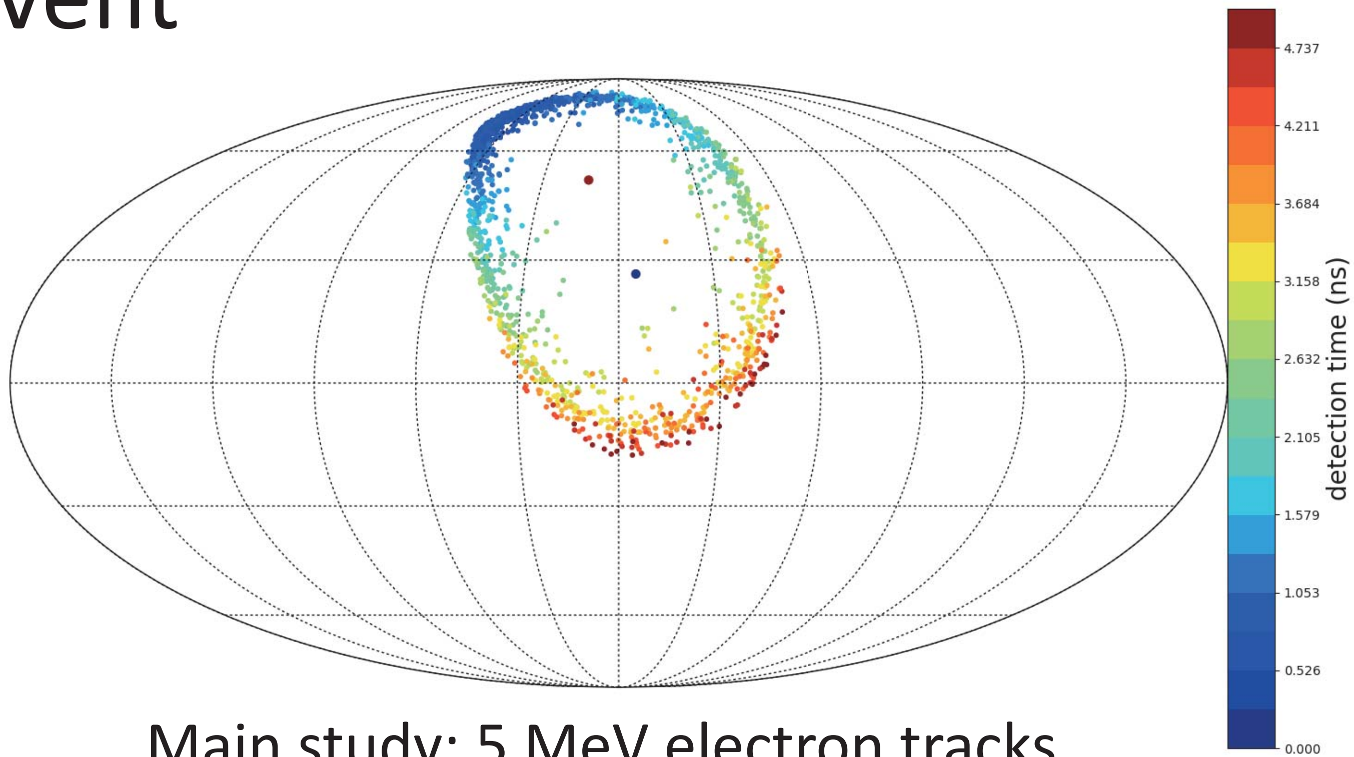


Figure from Sebastian Lorenz thesis dissertation, 2016

M/C = 0 example event

Info:
- Hit time
- Hit position

Truth info:
- Birth point (track points)
- **Wavelength/vgroup**
- …

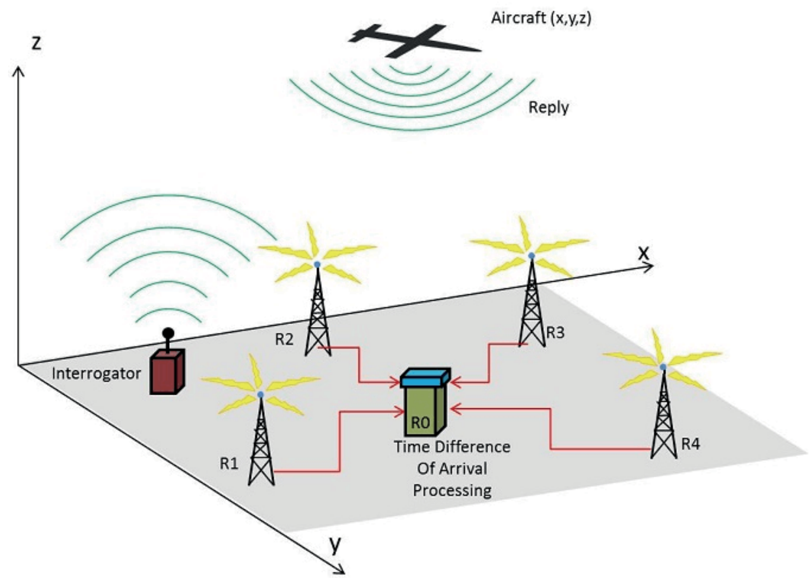


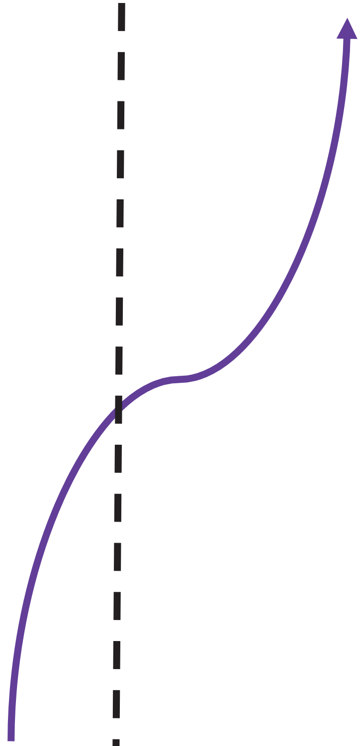
Main study: 5 MeV electron tracks

Starting simple
- Sample is small, 300 isotropic events
- no scattering (straight tracks)
- No mirrors, photocathode everywhere
- Perfect photodetectors (100% QE, perfect timing, …)

4-Lateration

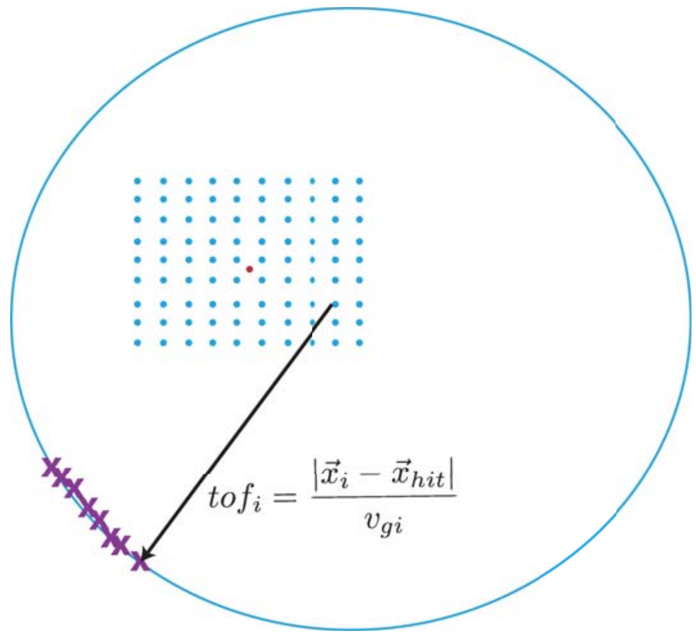
$$(x_0 - x_{hit})^2 + (y_0 - y_{hit})^2 + (z_0 - z_{hit})^2 = v_g^2(t_0 - t_{hit})^2$$





Kamland Zen *(Michinari Sakai thesis disertation 2016)*

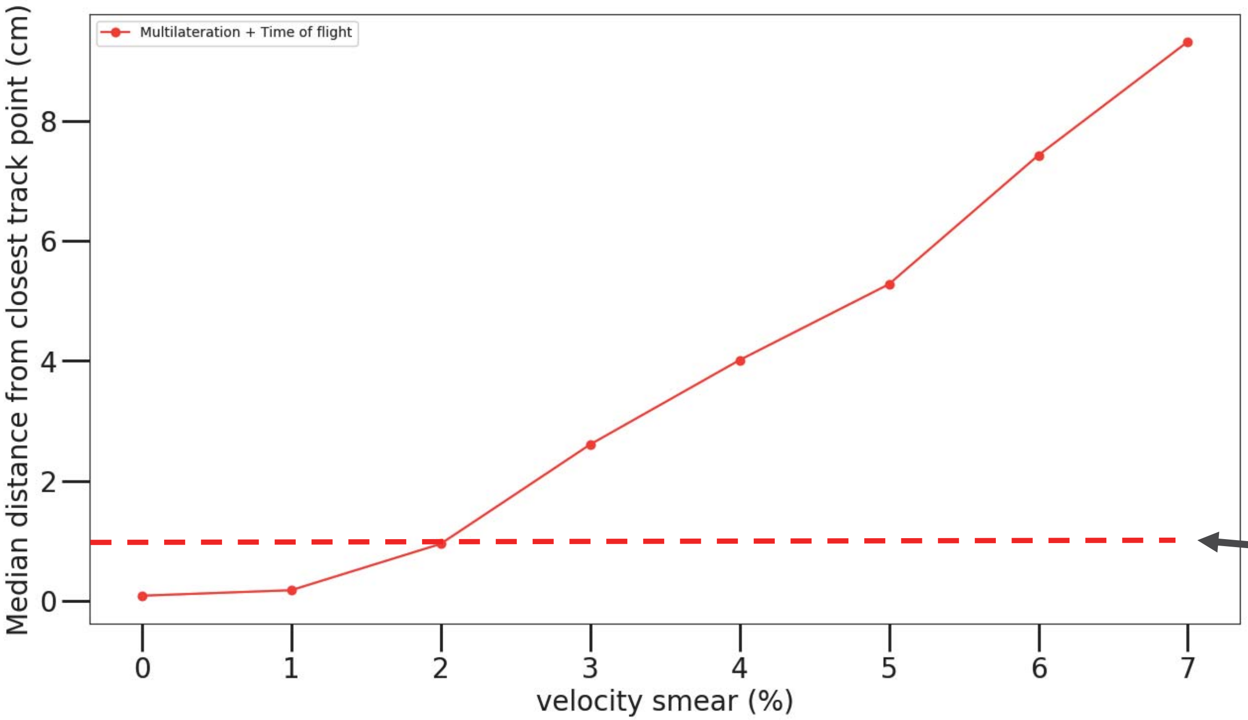
Time of flight



1. Minimize σ in t.o.f. distribution for the set of "test points"
2. Repeat with smaller lattice spacing

Outputs a probable track point

How close does this get to a true point on the track?

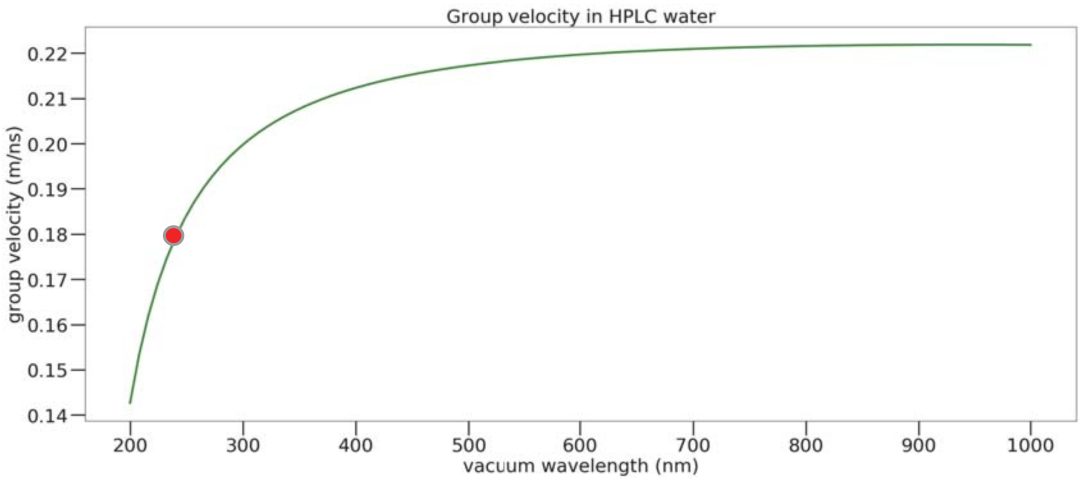


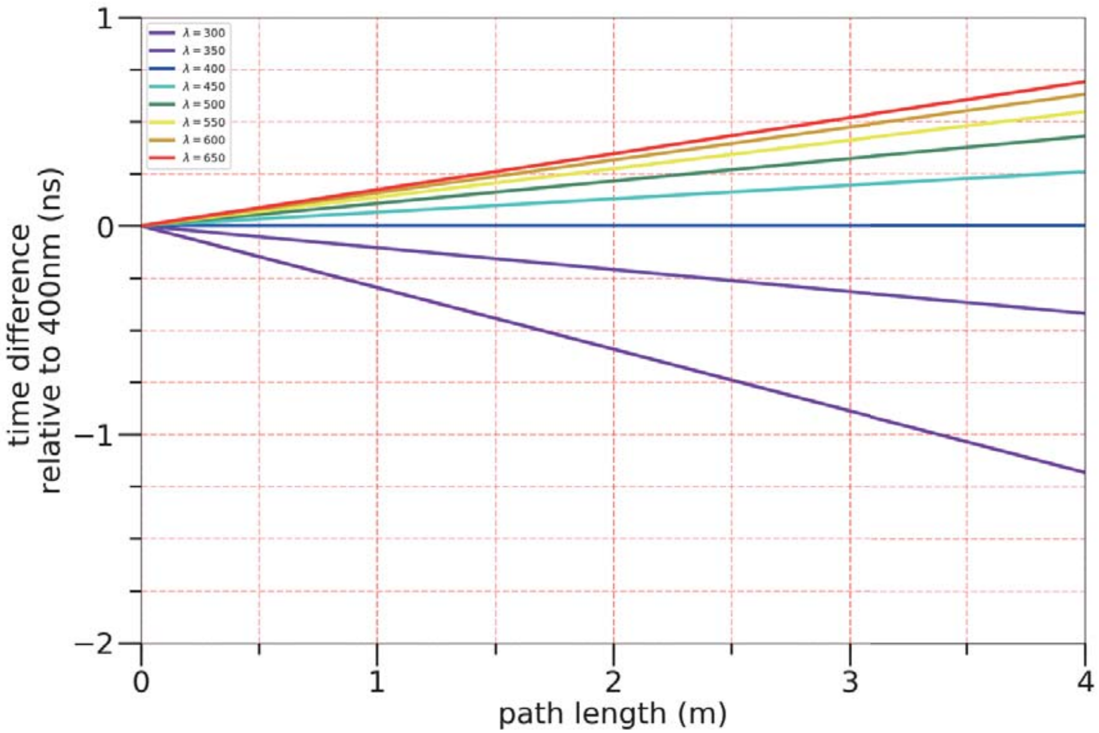
In this simplified scenario I need < 2% smear on group velocity to get 1 cm vertexing

1 cm resolution line

Dispersion

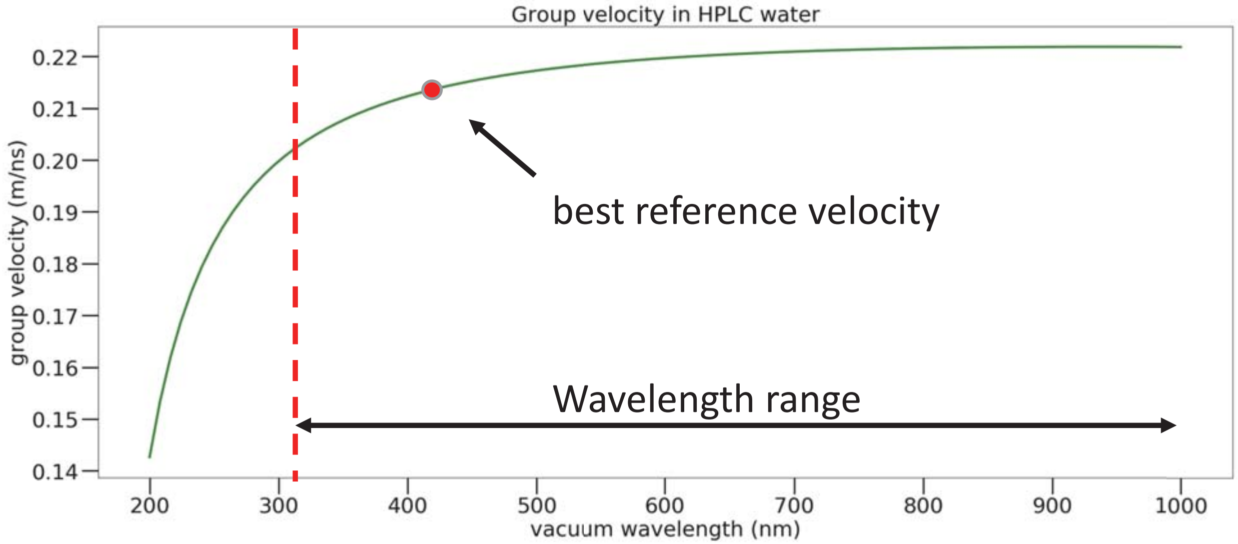
$$v_g(\omega) = \frac{c}{n_g(\omega)} = \frac{c}{n(\omega) \; + \; \omega \; (dn/d\omega)}$$





Dispersion

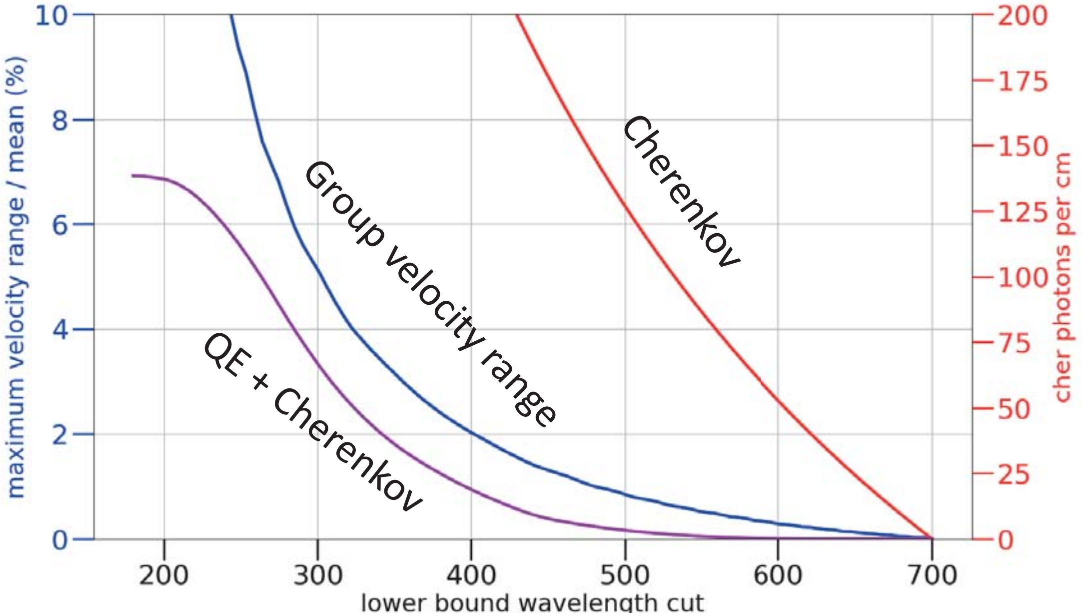
1) Accept only photons in an engineered wavelength range
2) Engineer that range to maximize # Cherenkov photons after QE and minimize group velocity uncertainty

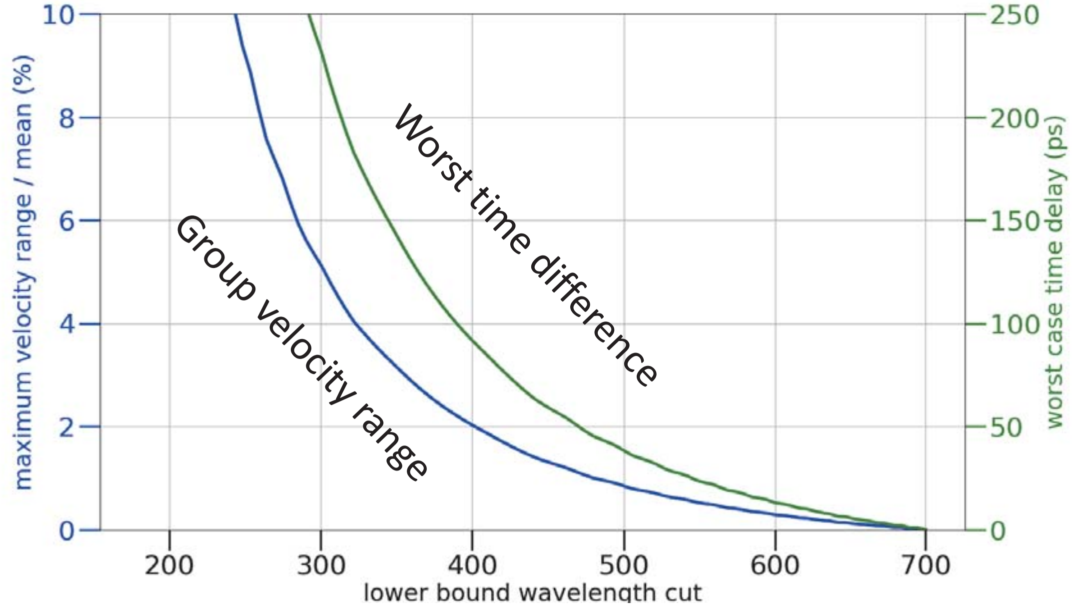


- There is a ”best reference velocity” given a wavelength range
- The velocity range gets smaller as you cut out dispersed photons

Can engineer wavelength acceptance ranges

Engineered wavelength filter



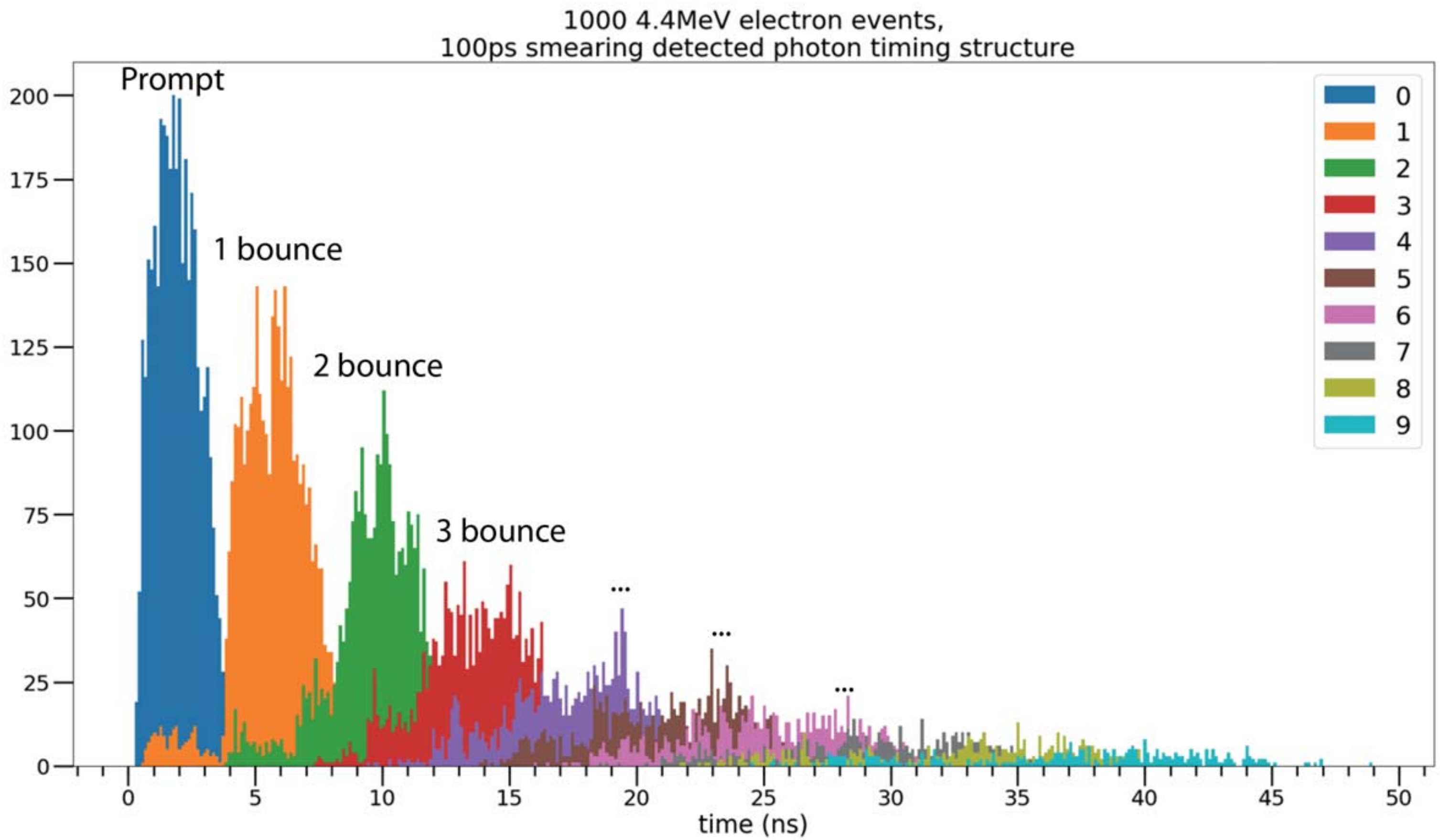


You lose photons

but you don't spoil timing

Dispersion

1) Separate photons into "bounce groups"
2) Assign uncertainties to photons that have traveled longer than others
3) Weight towards earliest light



Can assign uncertainties to photons that have traveled longer than others

Possible particle sources

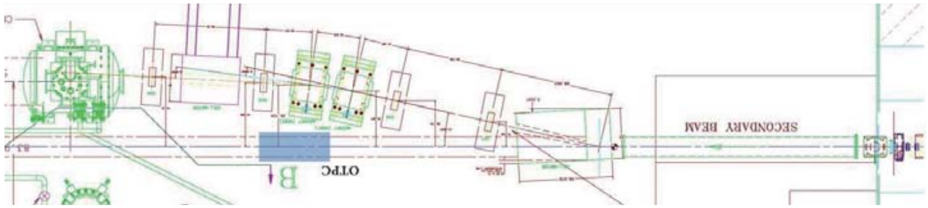
Small, ~5MeV electron tracks

LEAF
Argonne National Laboratory's
Low-Energy
Accelerator Facility

or

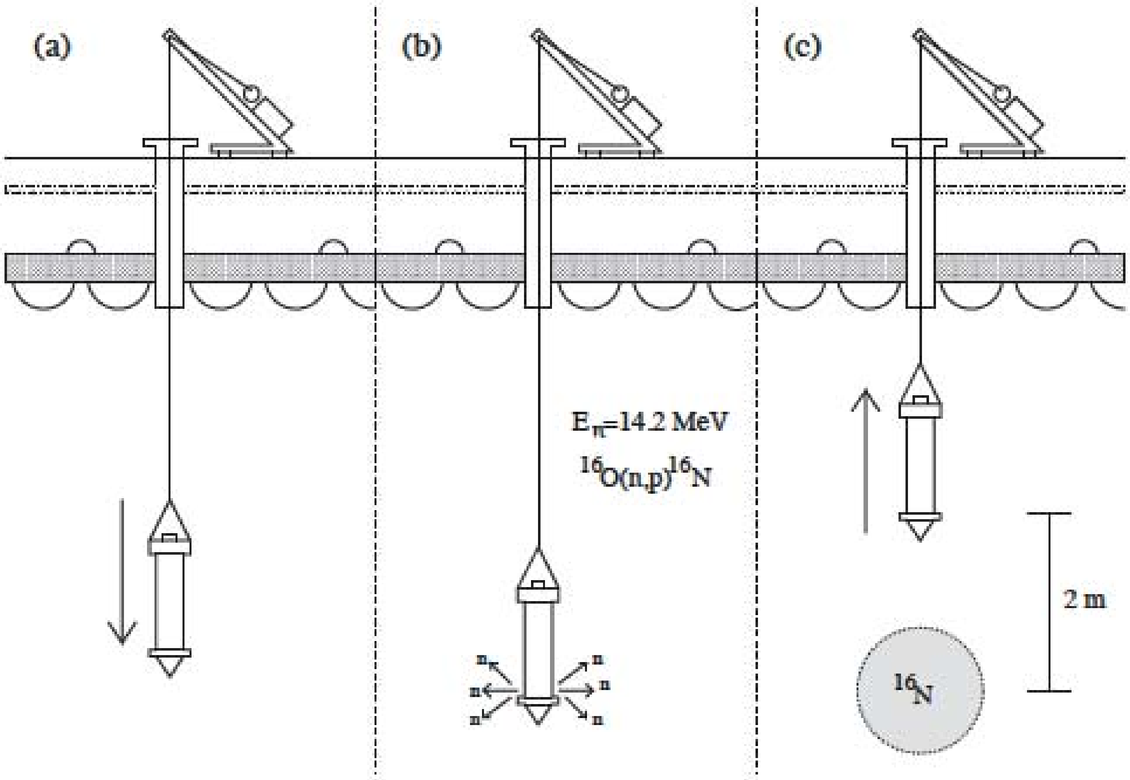
Deuterium-Tritium Neutron Generator

Muons and other particles (particle ID demonstration)



Fermilab test beam

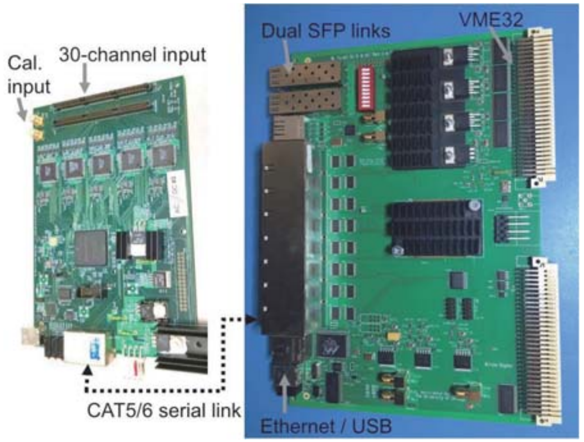
Possible particle sources: Deuterium Tritium Neutron Generator (DTG)



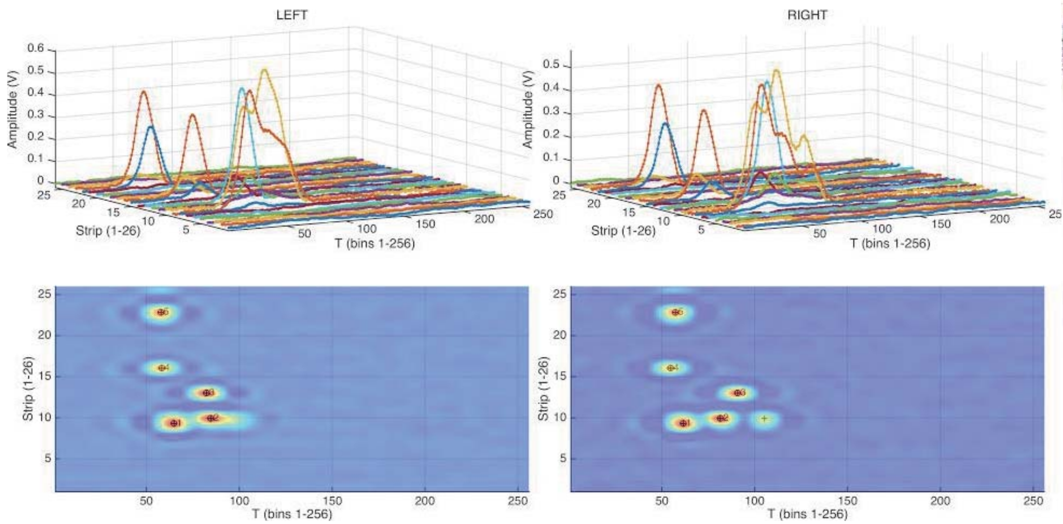
“The decay of N16, with a Q value of 10.4 MeV, is dominated by an electron with a 4.3 MeV maximum energy coincident with a 6.1 MeV gamma ray …”

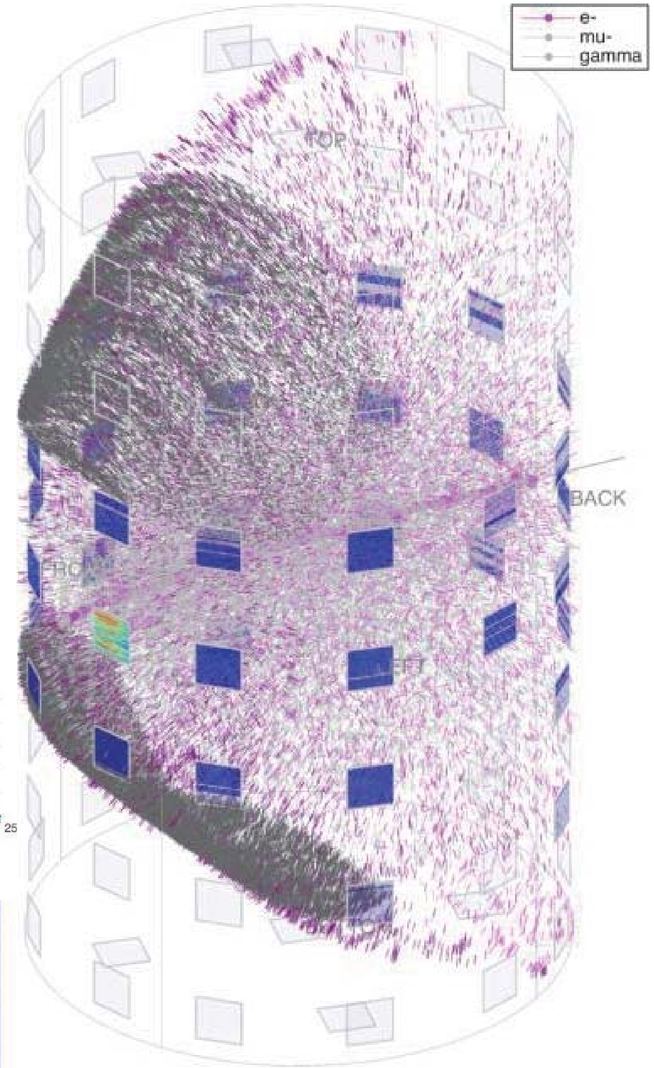
Super-Kamiokande Collaboration, arXiv:0005014v3 (2001)

Lead into ANNIE at FNAL



Experimental overlap in:
- -electronics
- -readout/hit-pattern formation
- -time projection reconstruction
- -water tight hardware
- -...





Questions

1. What is the highest mirror to photocathode ratio for 3cm electron tracking?
   - $$
   - Depends on developing reconstruction methods that use bounces

2. How much dispersion is tolerable in reconstruction?
   - Depends on nphot, algorithm, QE distribution, …

3. How can we beat dispersion down to minimize time uncertainty contribution?
   - How few photons can you reconstruct with?
   - What tricks can we do with wavelength filtering?

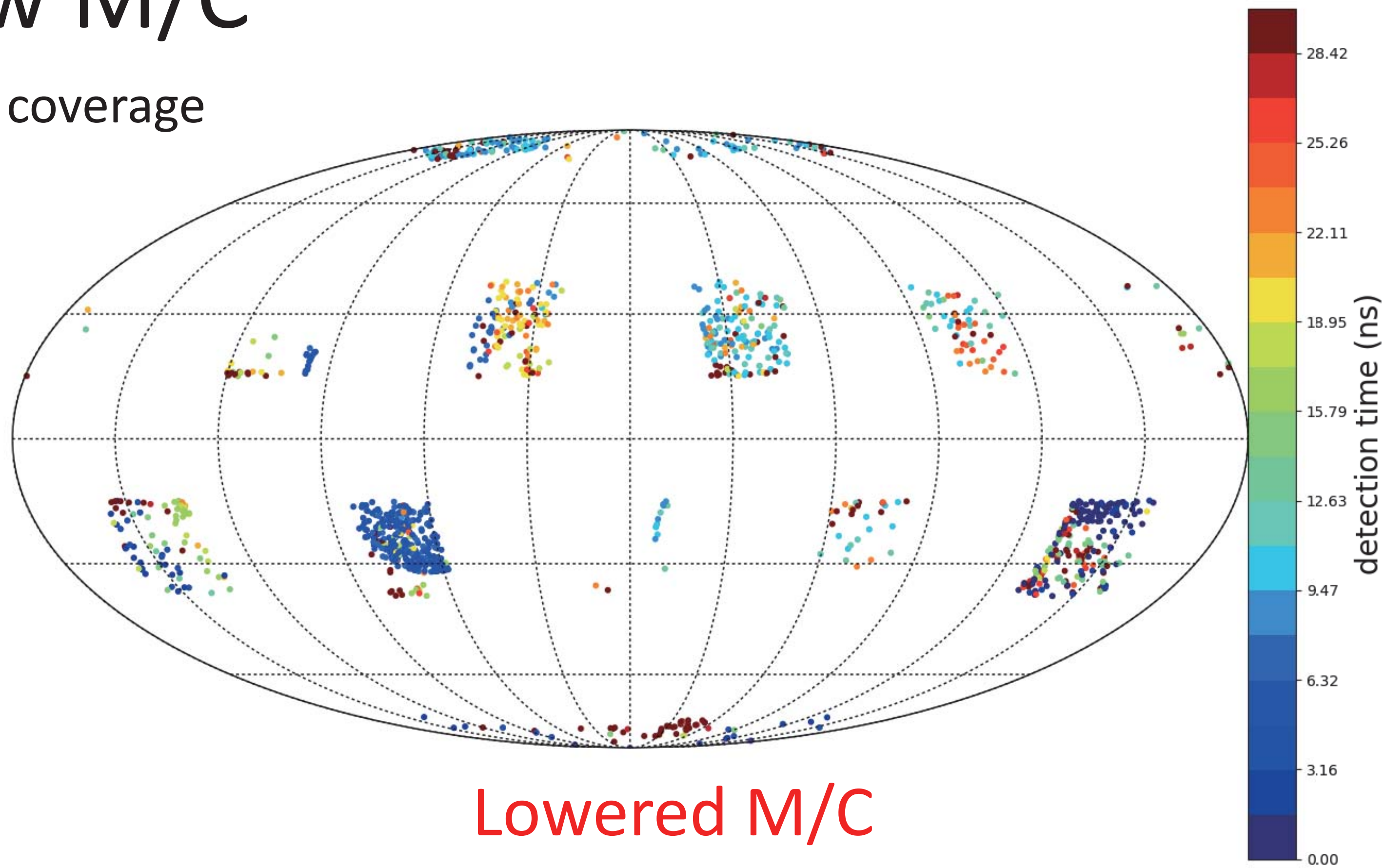
4. What are good calibration sources for 0vBB backgrounds, solar neutrinos, …?

When will we be able to make LAPPDs? This is my 3rd year in the PhD program …

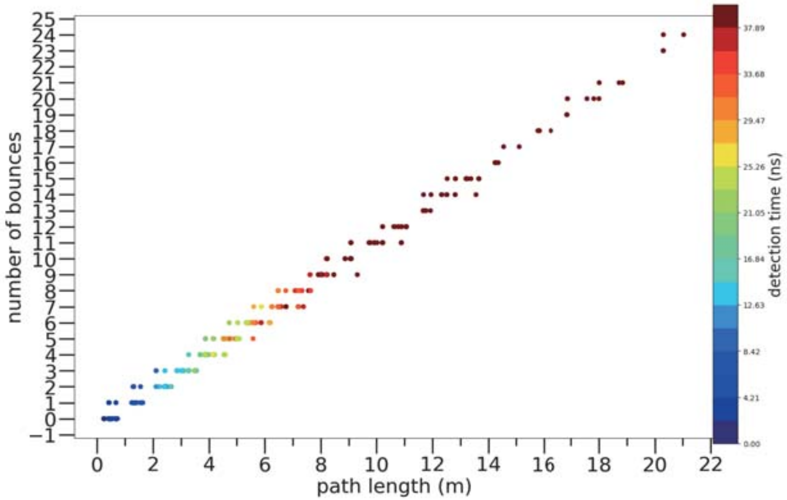
Backup slides

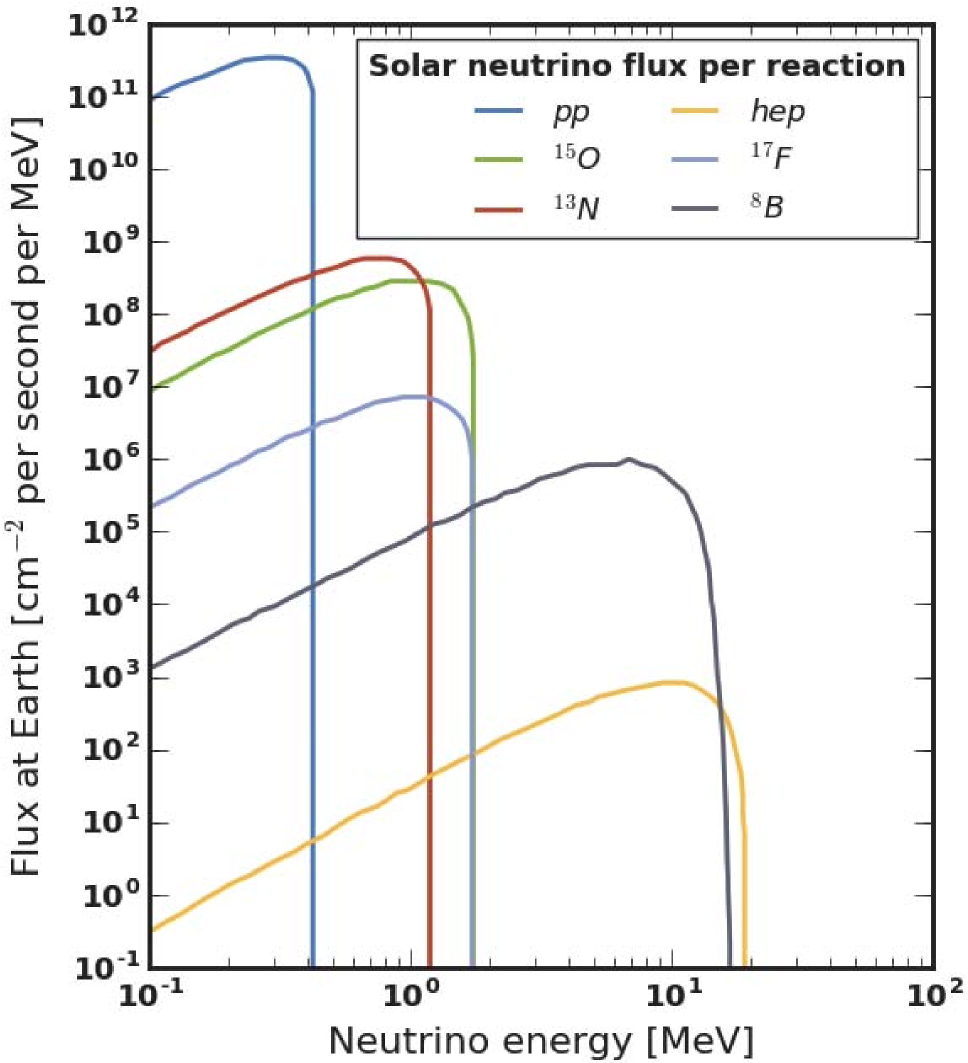
Reconstruction low M/C

1) Start with FULL photocathode coverage
2) Optimize a reconstruction
3) Then increase M/C ratio



Lowered M/C




Solar neutrino flux per reaction
pp
hep
15O
17F
13N
8B
Flux at Earth [cm−2 per second per MeV]
Neutrino energy [MeV]
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1
10^2

Andrey Elagin. “Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing”. NIM A, 2016

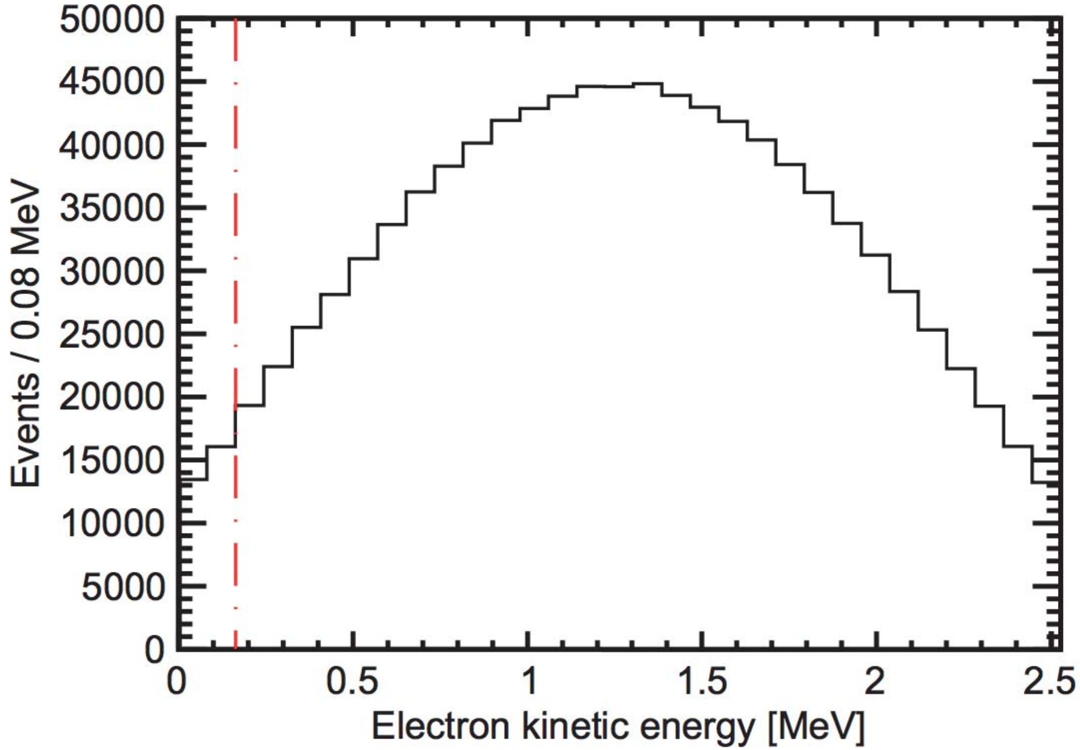
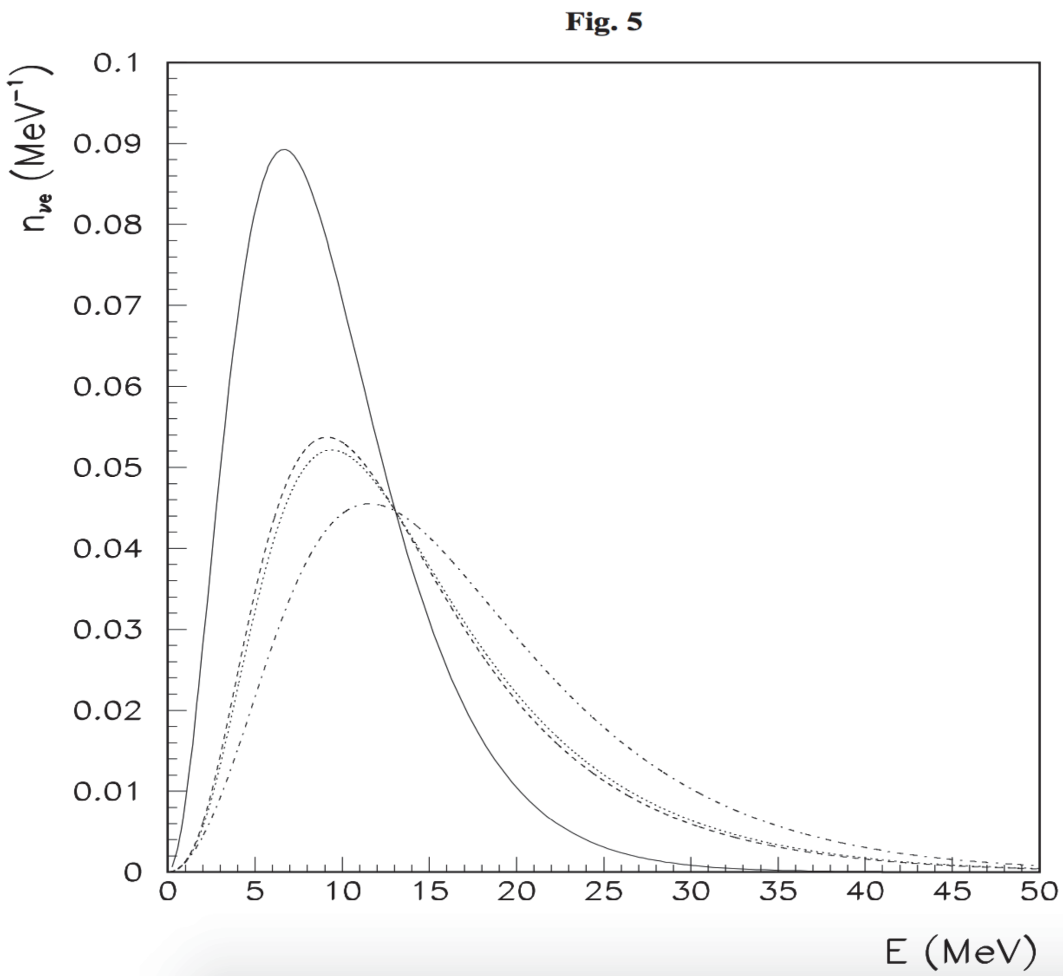


Figure 1: The spectrum in kinetic energy of one of the electrons in $0\nu\beta\beta$- decays of ^{130}Te (endpoint 2.53 MeV). The vertical dashed line indicates the Cherenkov threshold in the liquid scintillator of the detector model. Single electrons from ^{8}B solar neutrinos that are potential background to the $0\nu\beta\beta$-decay search are close in energy to the endpoint and will be above the Cherenkov threshold.



F. Buccella et. al. Supernova Neutrino Energy Spectra and the MSW effect. arXiv:hep-ph/9607226v2