Event Reconstruction Techniques for a (water-based) Liquid Scintillator Detector

Andrey Elagin
University of Chicago

Outline:

- Motivation: next generation of (water-based) liquid scintillator detectors
- Cherenkov / scintillation light separation
- Optical tracking using fast timing
- Event reconstruction algorithms

TAUP2017, Sudbury, July 26, 2017

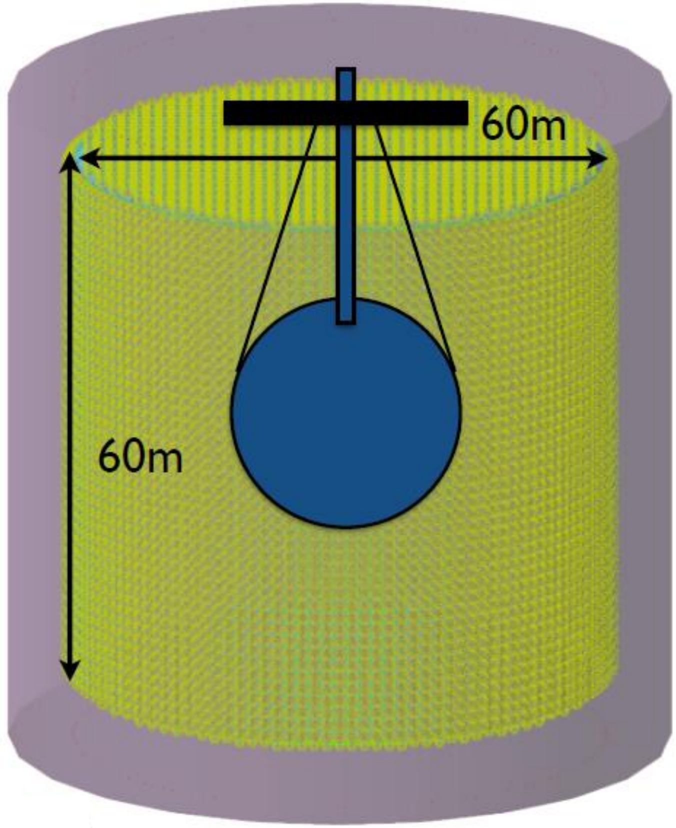
Motivation

- 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



For more on THEIA detector
see talk by Leon Pickard tomorrow

Ability to extract the most information out of each event is crucial
-> need dedicated reconstruction algorithms

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

A Note on Speed of Light

- Light travels one foot in 1 ns (in vacuum)
- 1 ns = 1000 ps
- In 1 picosecond light travels only 300 microns
- Light is slow in picosecond domain -> one can try "drift" photons, much like electrons in a TPC
- 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

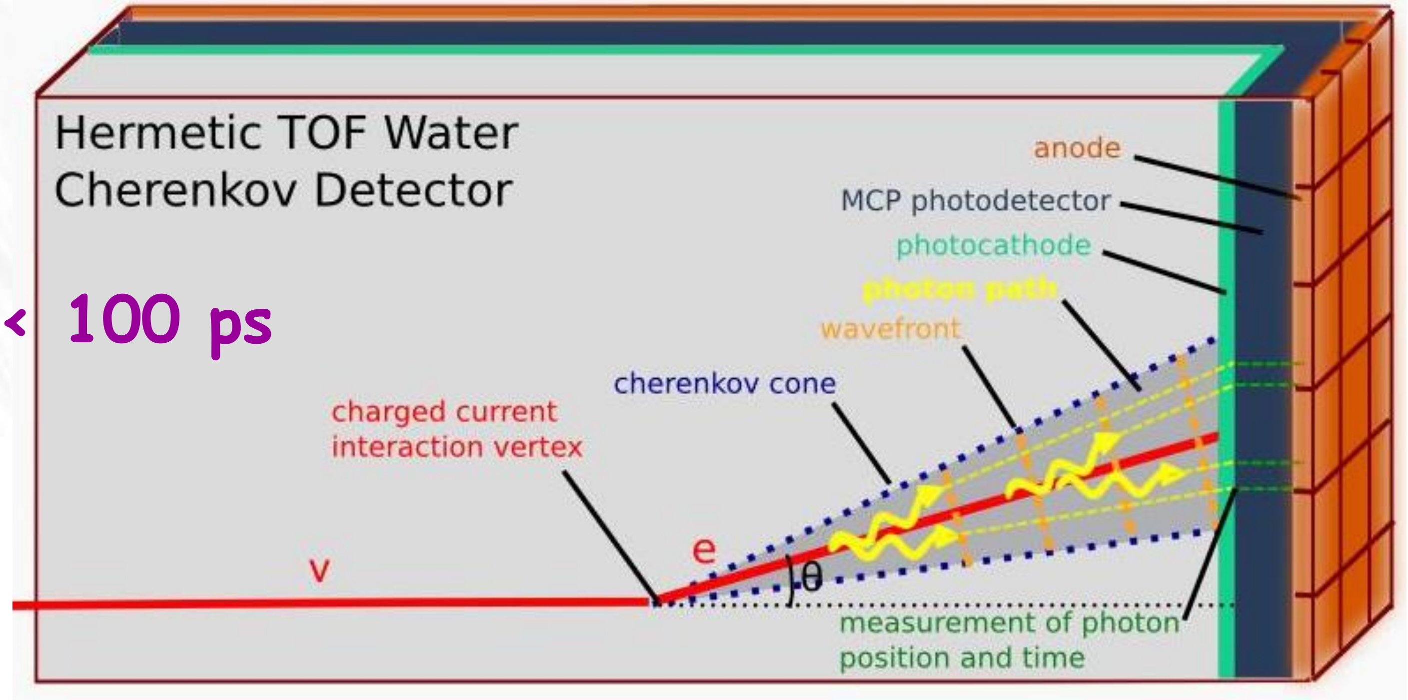
⇨

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

Large-Area Picosecond Photo Detectors (LAPPD) are being developed
"Drifting" photons is one of the key applications of LAPPD

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

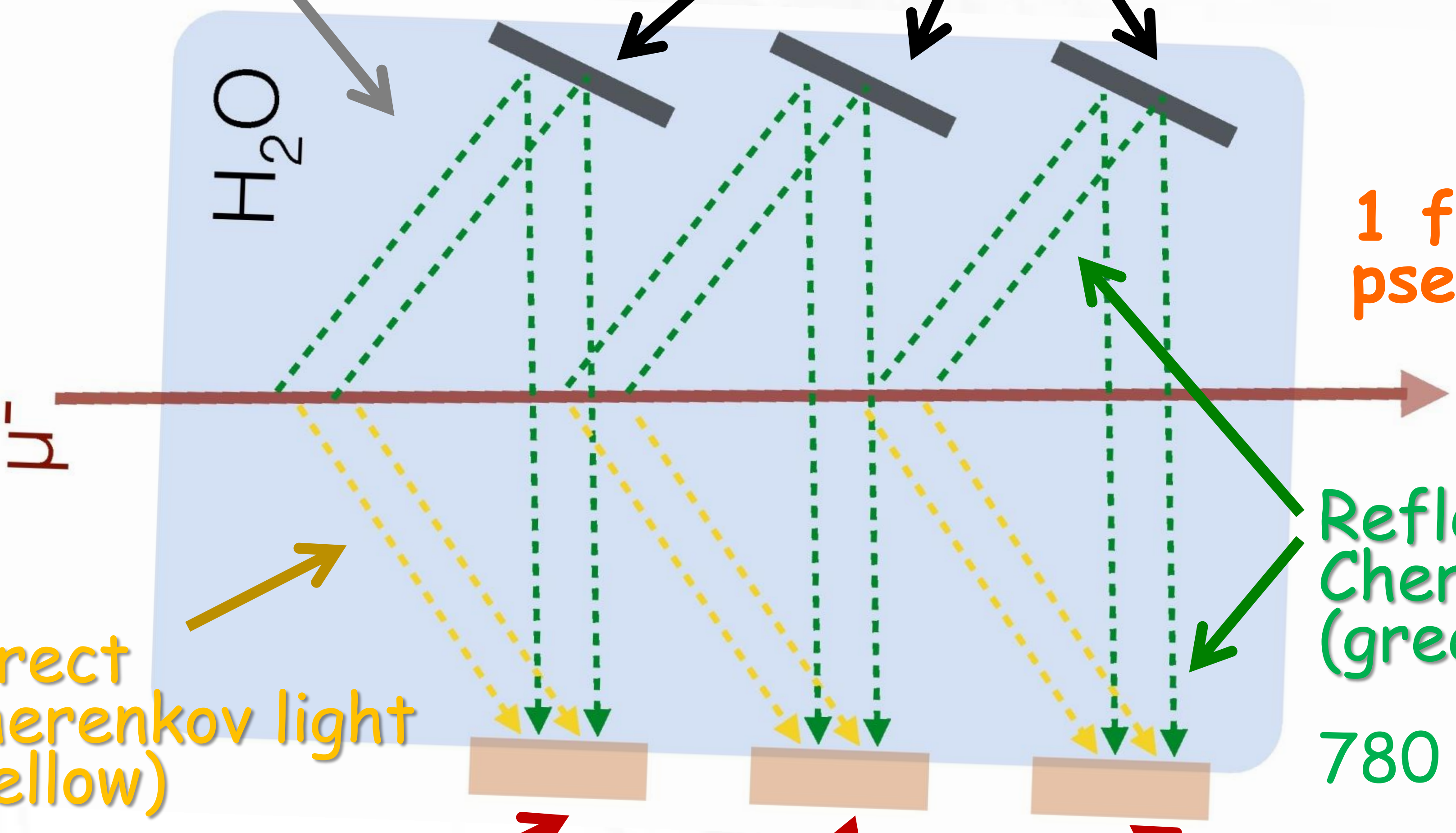
- It doesn't have to be water (use prompt Cherenkov light that arrives early)
- In fact, for long tracks optical tracking should also work using just scintillation

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

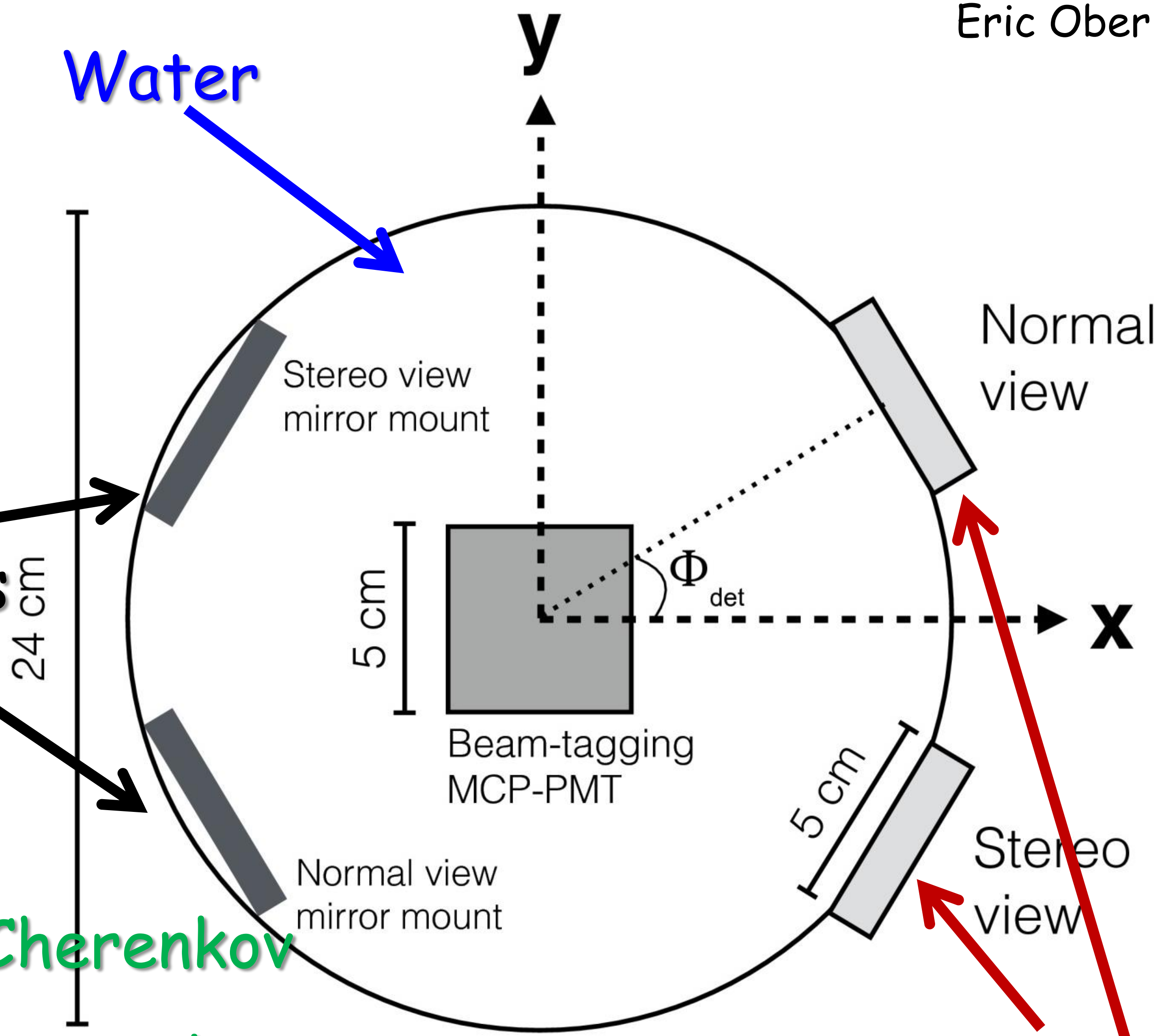
Direct Cherenkov light (yellow)

Photonis MCPs and Chicago striplines/PSEC4

Beam's Eye View of the OTPC

Eric Oberla's Ph.D thesis

Water



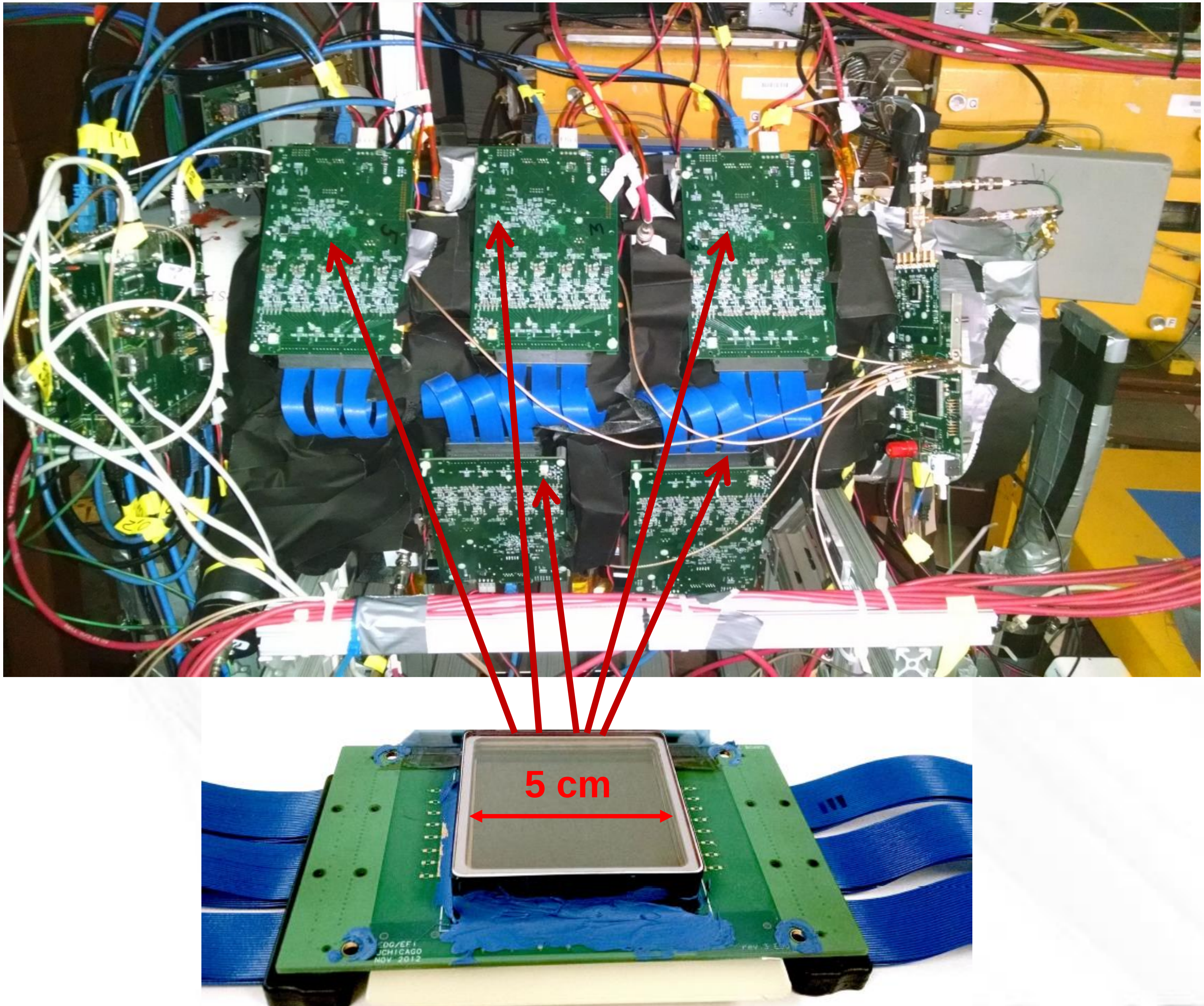
Flat mirrors

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

Photonis MCPs and
Chicago striplines/PSEC4

OTPC at Fermilab Test Beam

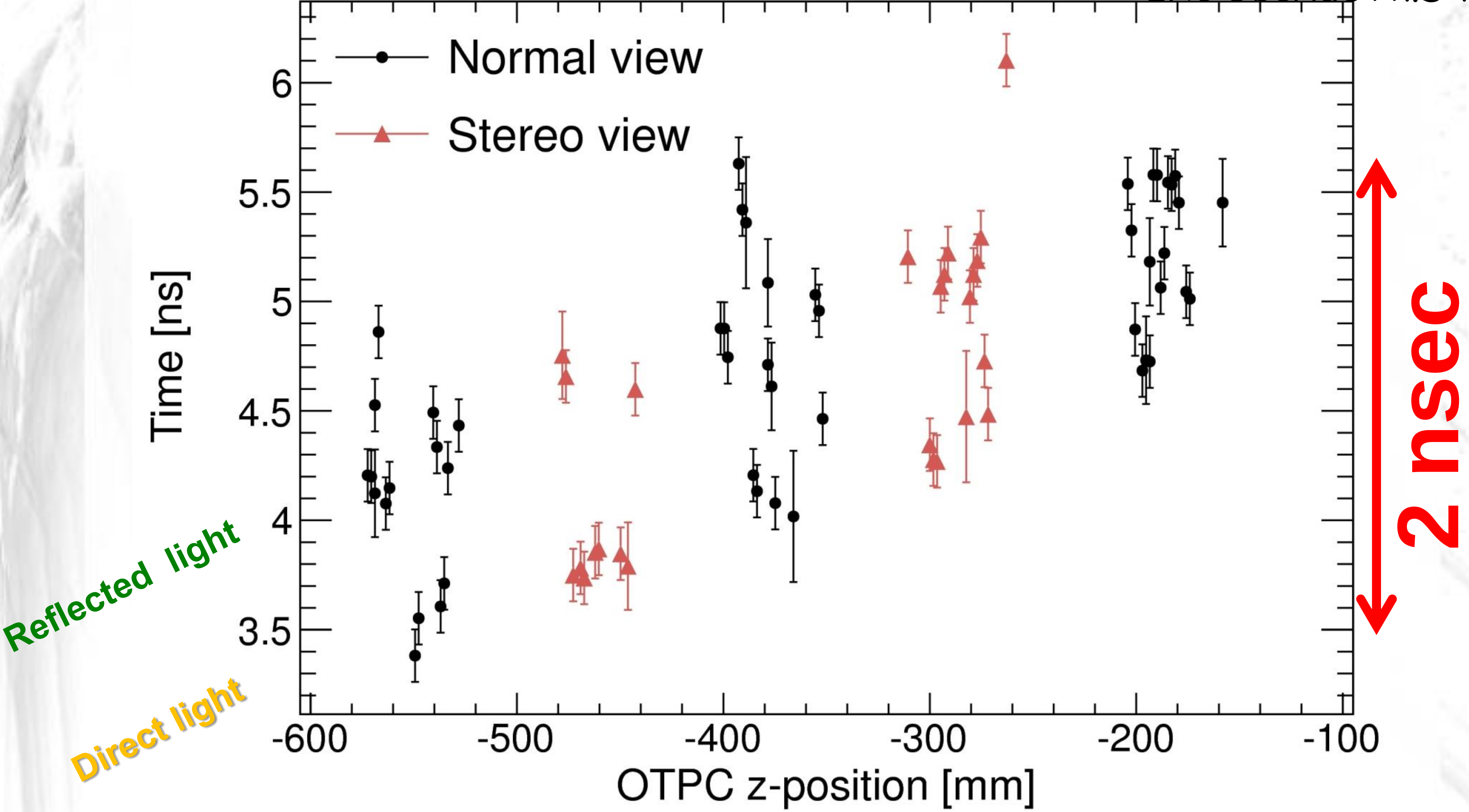
Eric Oberla's Ph.D thesis



Five Photonis Planacons

OTPC Results

Eric Oberla's Ph.D thesis



Reflected light

Direct light

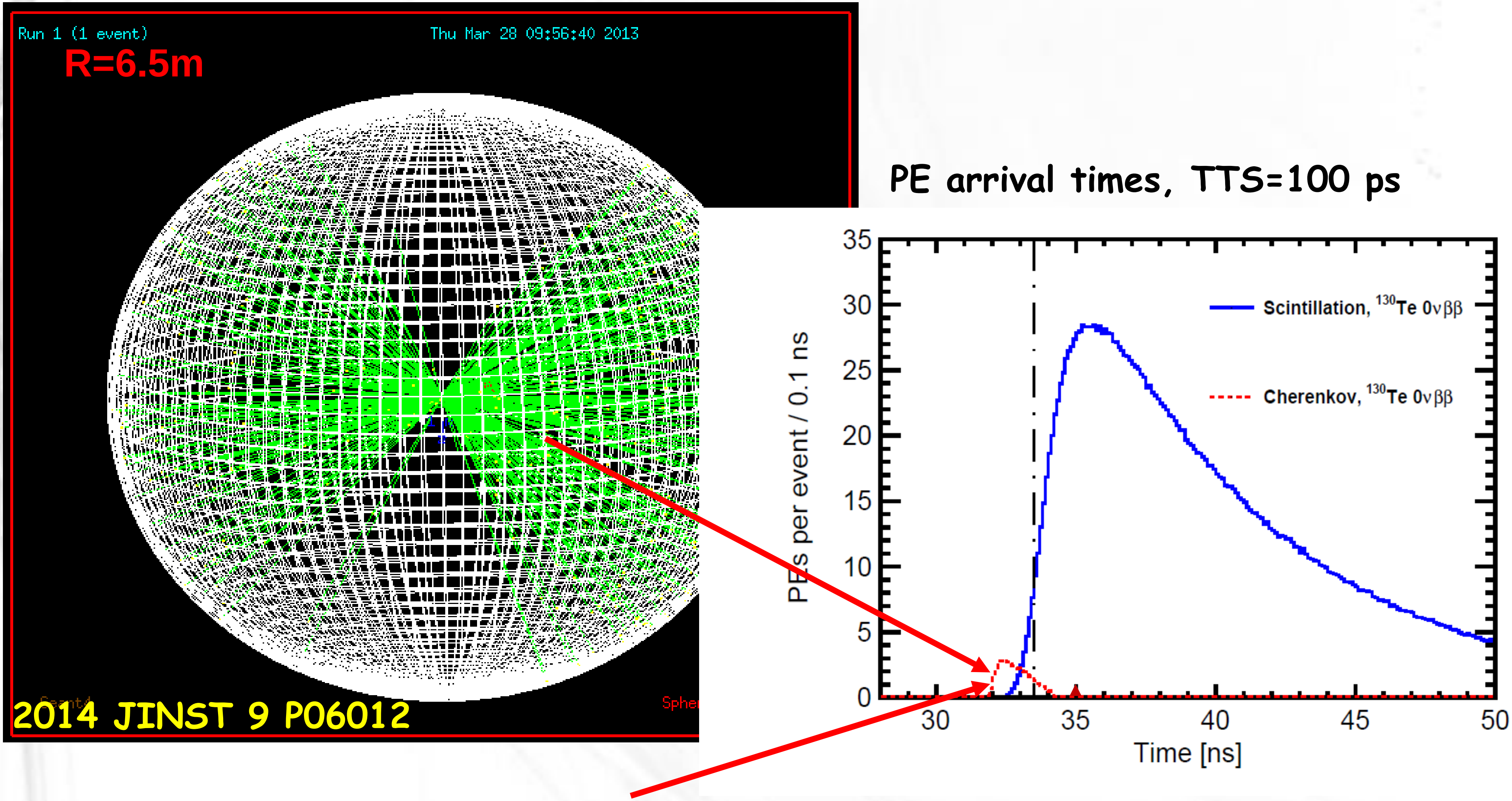
2 nsec

- 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)

Can We See Event Topology in a LS Detector?

Simulation of a $0\nu\beta\beta$ event

(selected event with large angle between electrons)

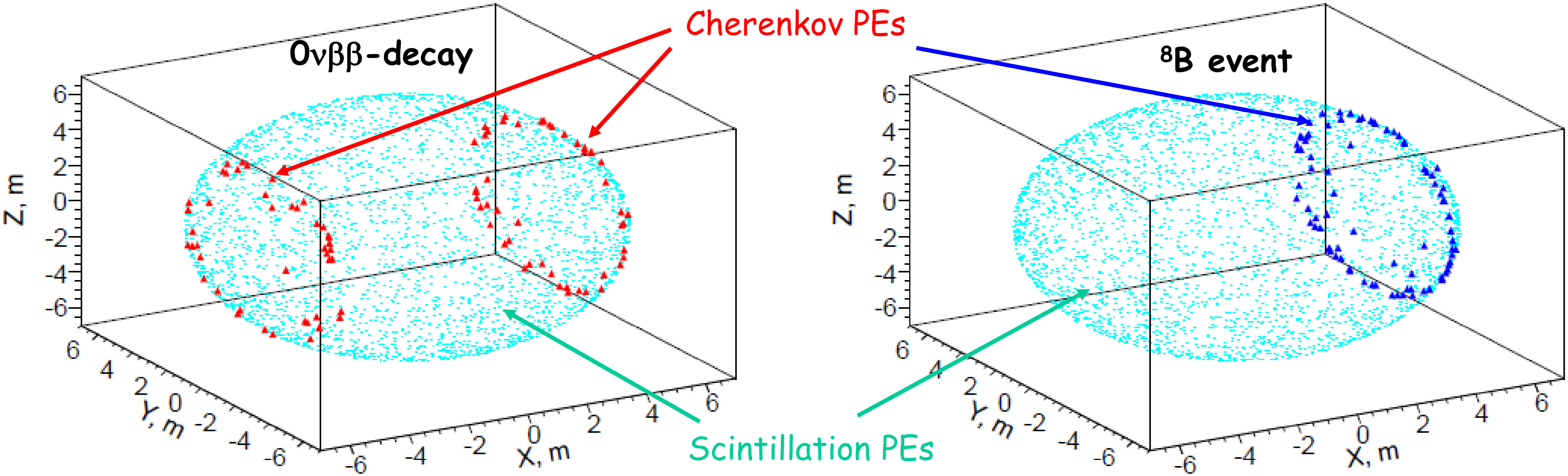


2014 JINST 9 P06012

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

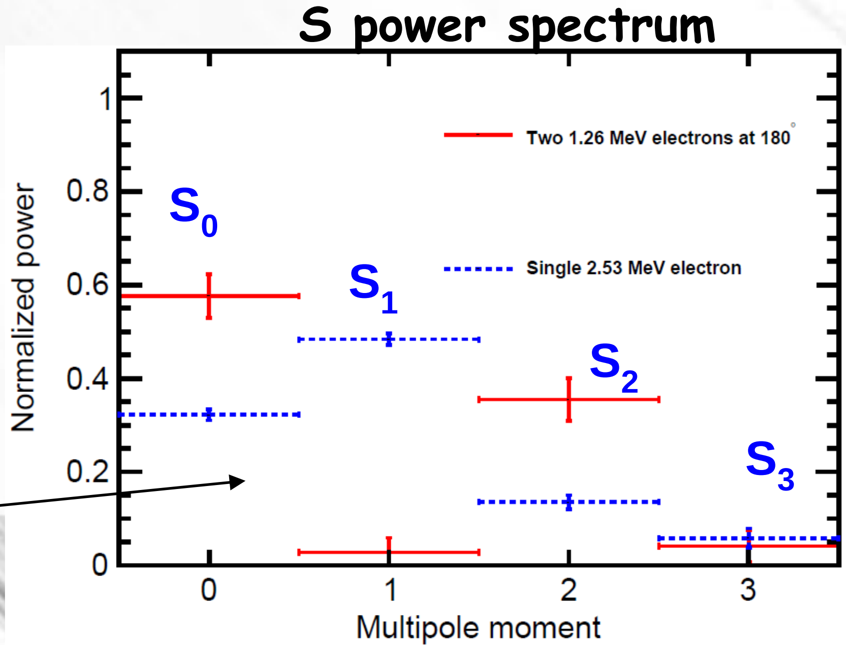
Scintillation PEs

Spherical harmonics analysis

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

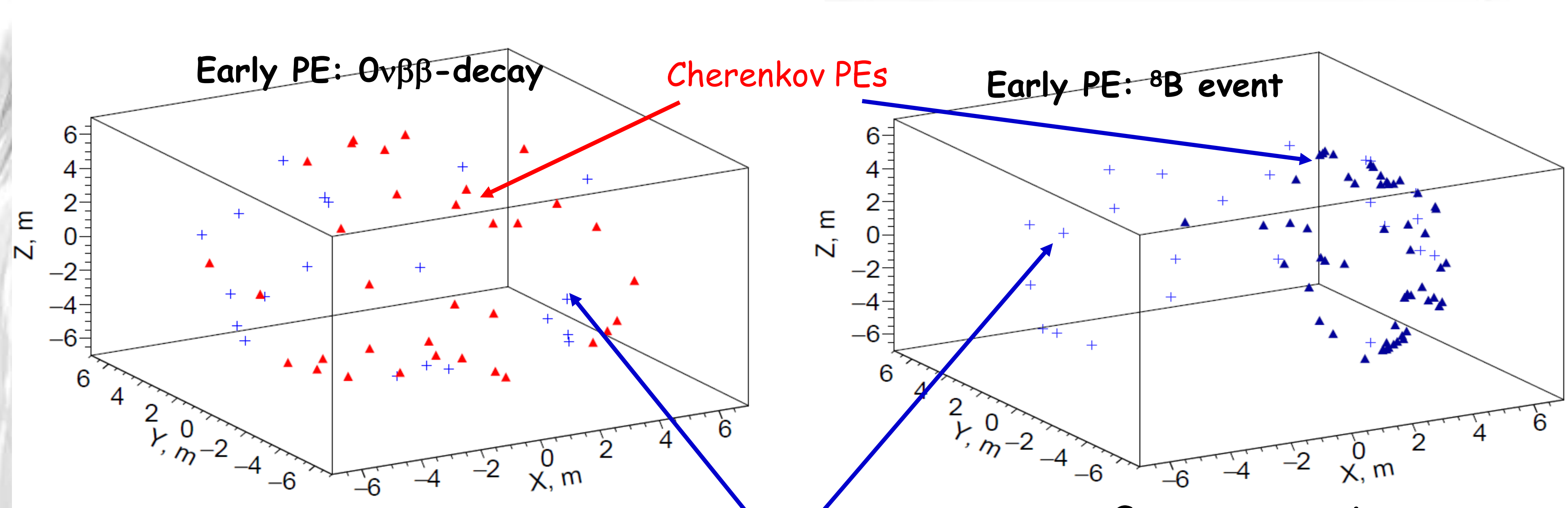
Rotation invariant power spectrum

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



Early Light Topology

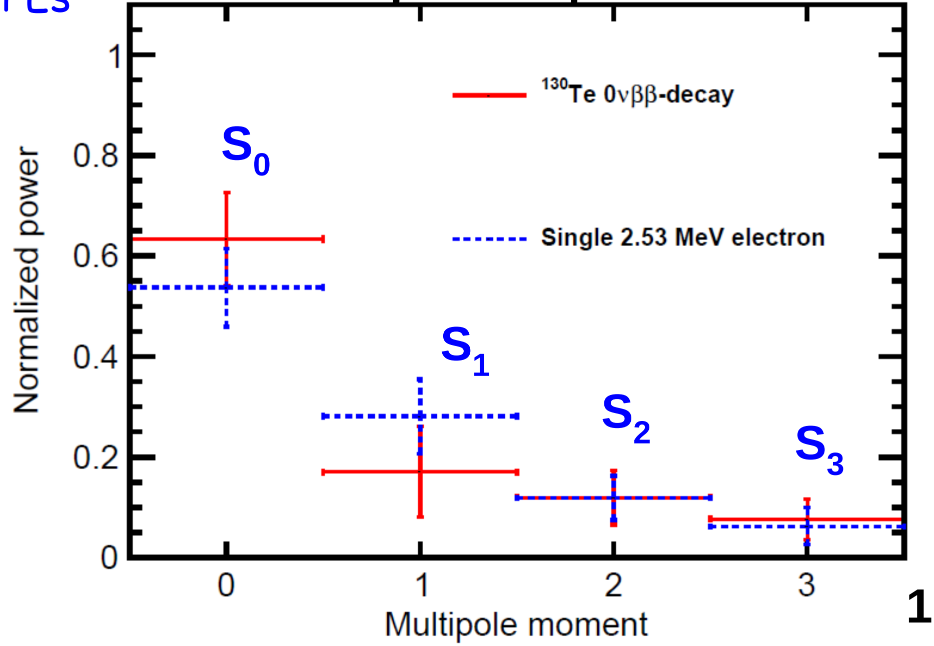
Realistic event displays: early PEs only, KamLAND PMTs QE: **Che~12%**, Sci~23%



NIMA 849 (2017) 102

Scintillation PEs

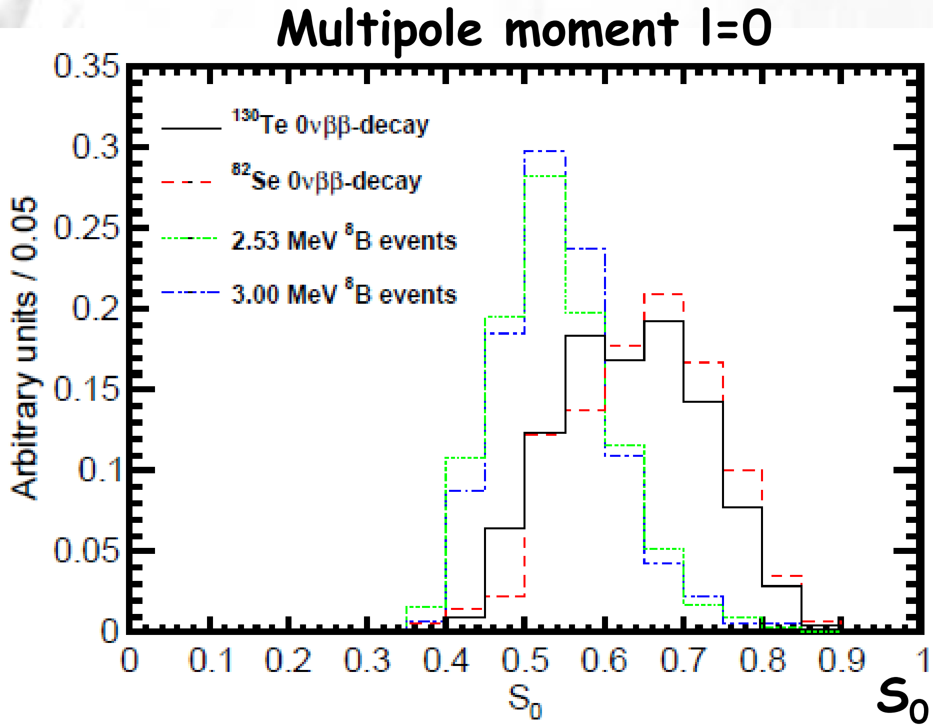
S power spectrum

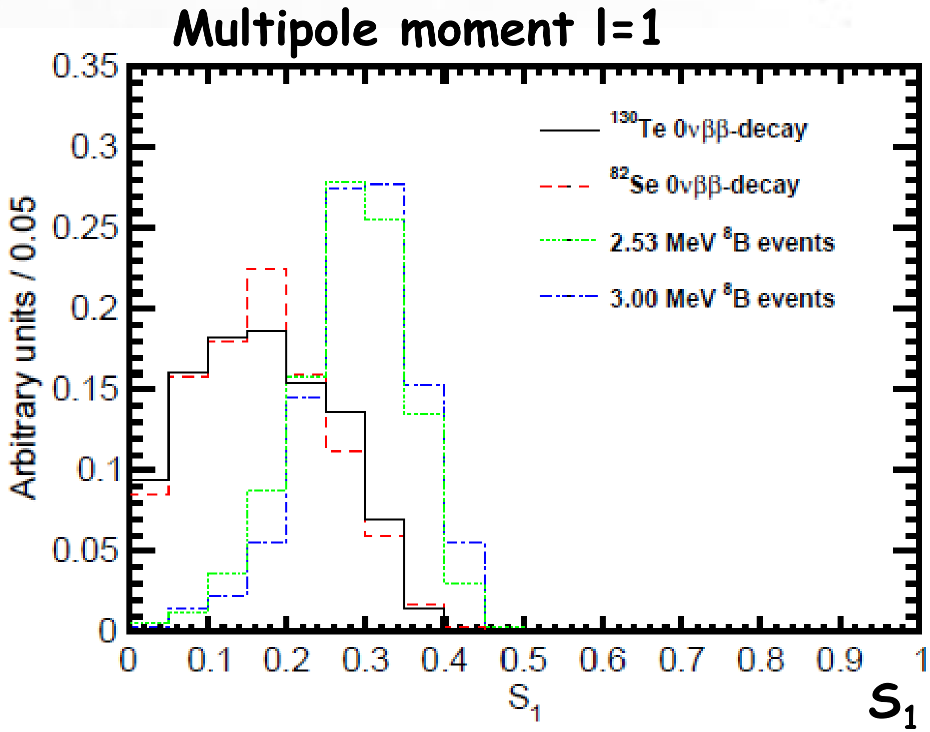


Key parameters determining separation of 0νββ-decay from ^{8}B

- 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

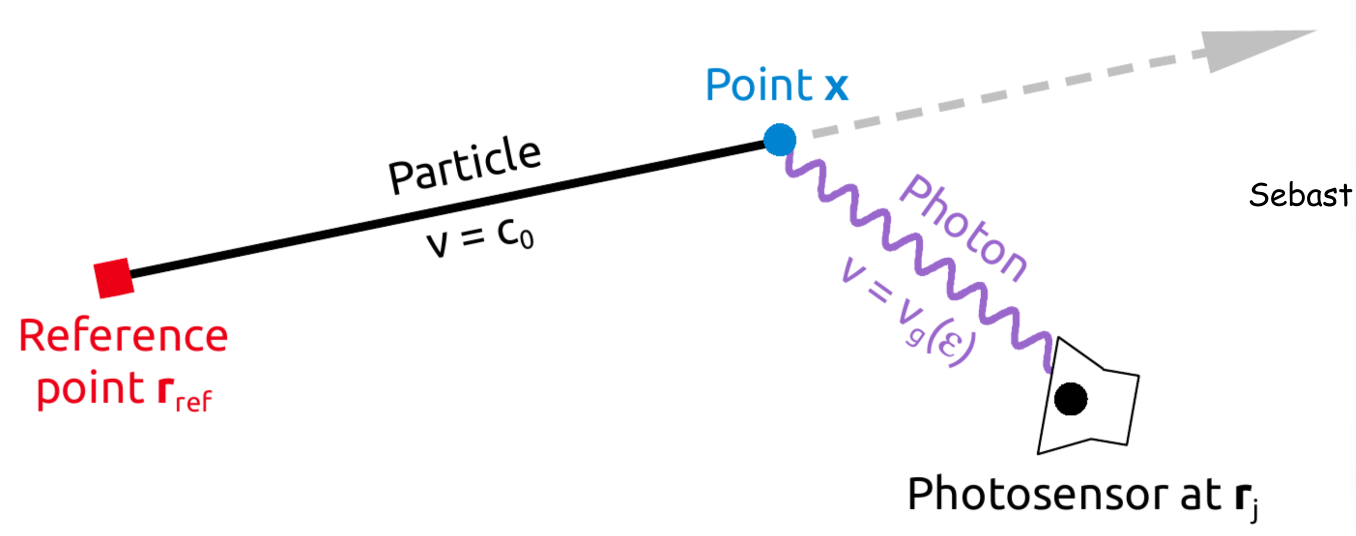
- Spherical harmonics analysis is rather simple, but it doesn't use all available information
- Advanced machine learning techniques looking at 4-vectors of each photon hit should work better (probably makes more sense with a little more progress on the instrumentation front)

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

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

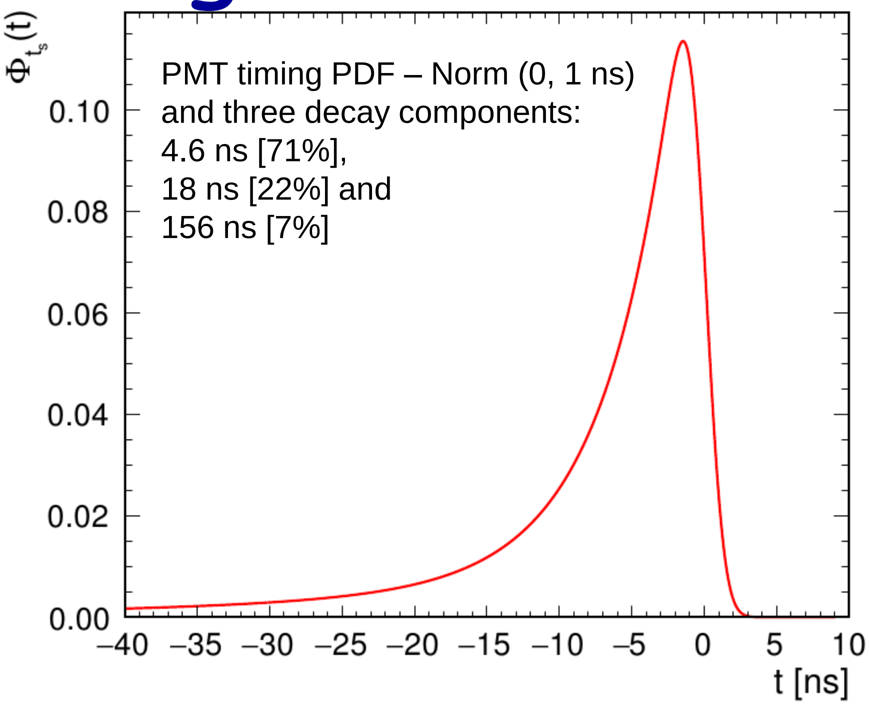
3D Optical Tracking using Scintillation

B. Wonsak et al.

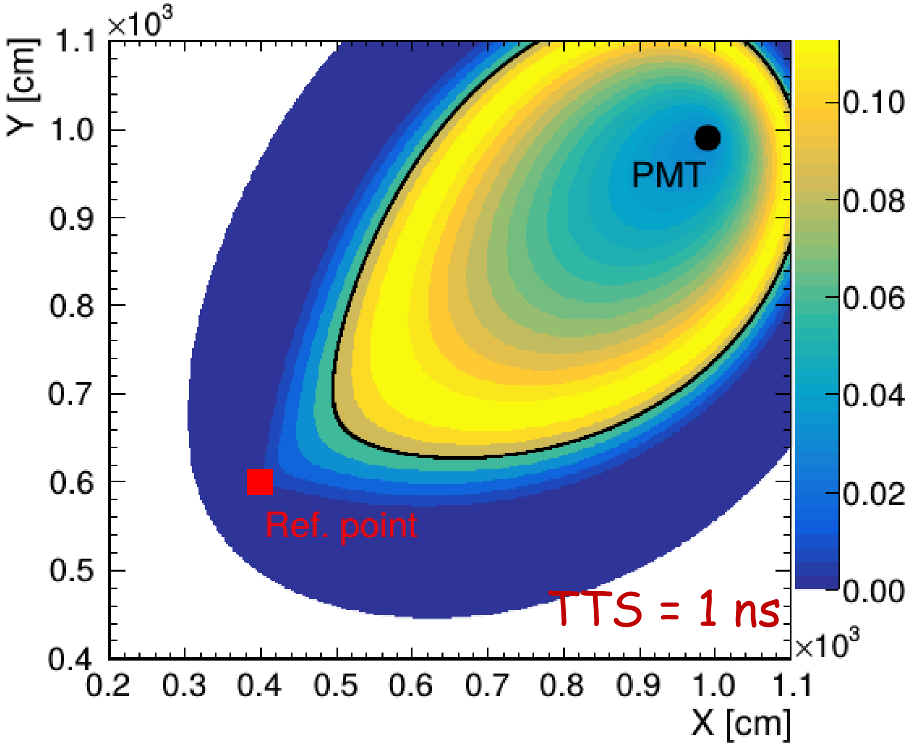
For each photon hit:

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

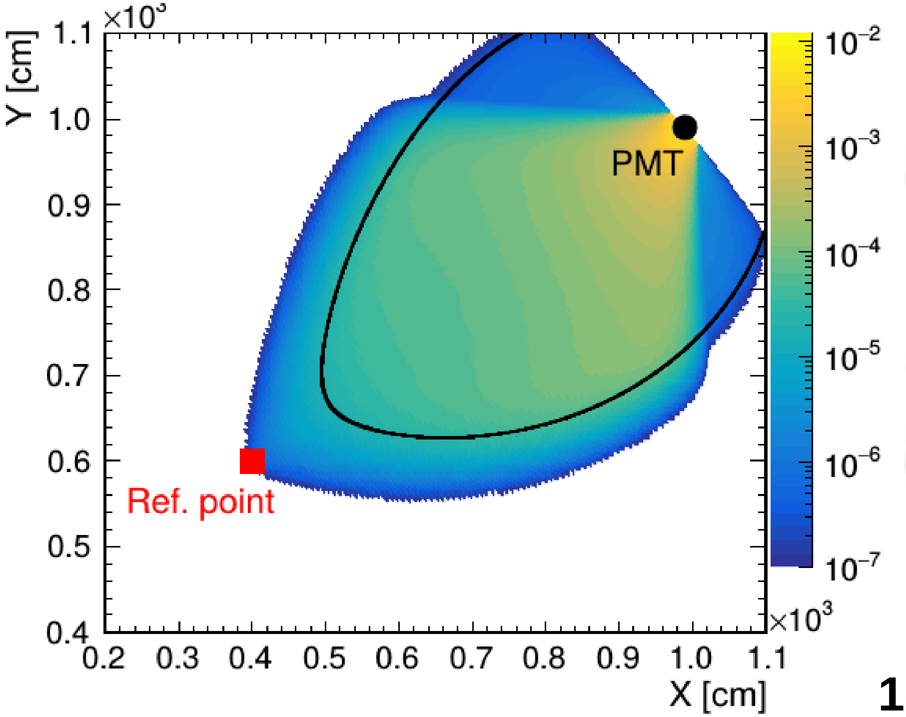
→ spatial p.d.f. for photon emission points



PMT timing PDF – Norm (0, 1 ns)
and three decay components:
4.6 ns [71%],
18 ns [22%] and
156 ns [7%]



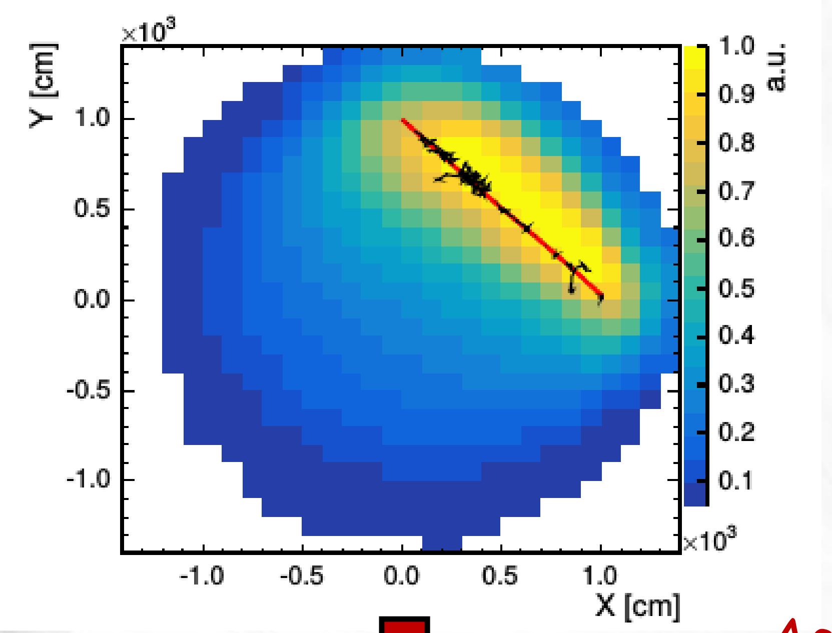
TTS = 1 ns



3D Optical Tracking using Scintillation

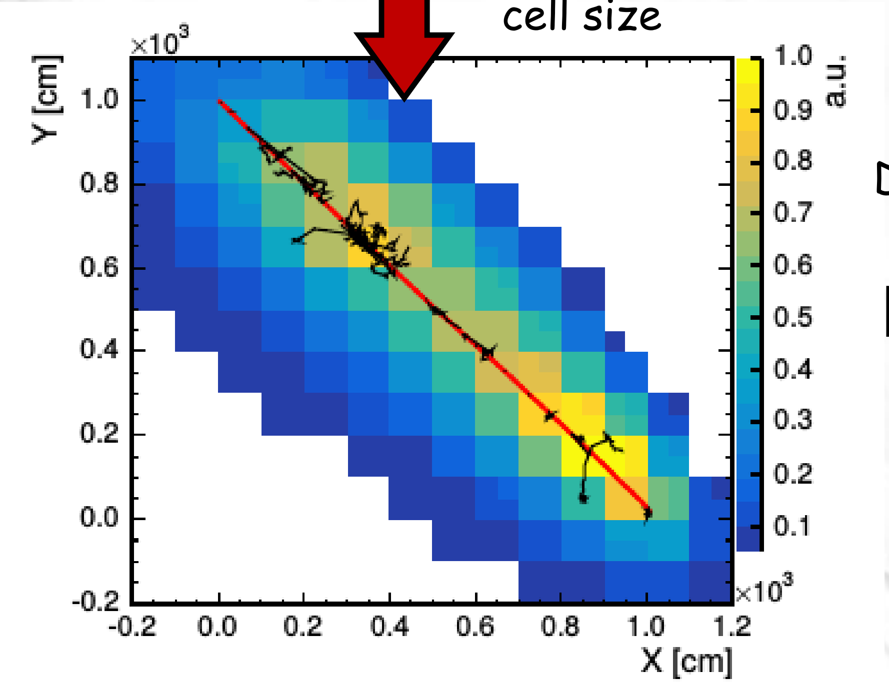
B. Wonsak et al.

- 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



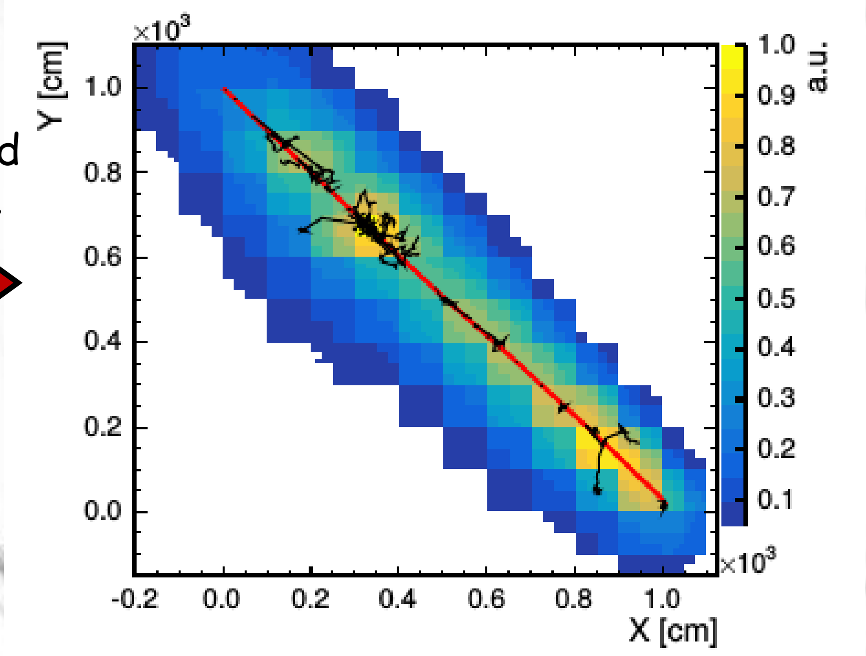
Decreased cell size

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

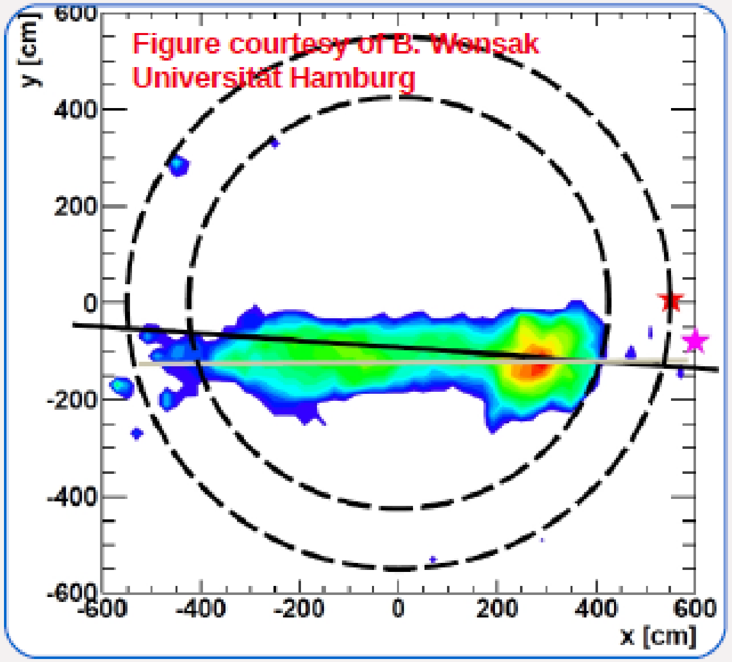
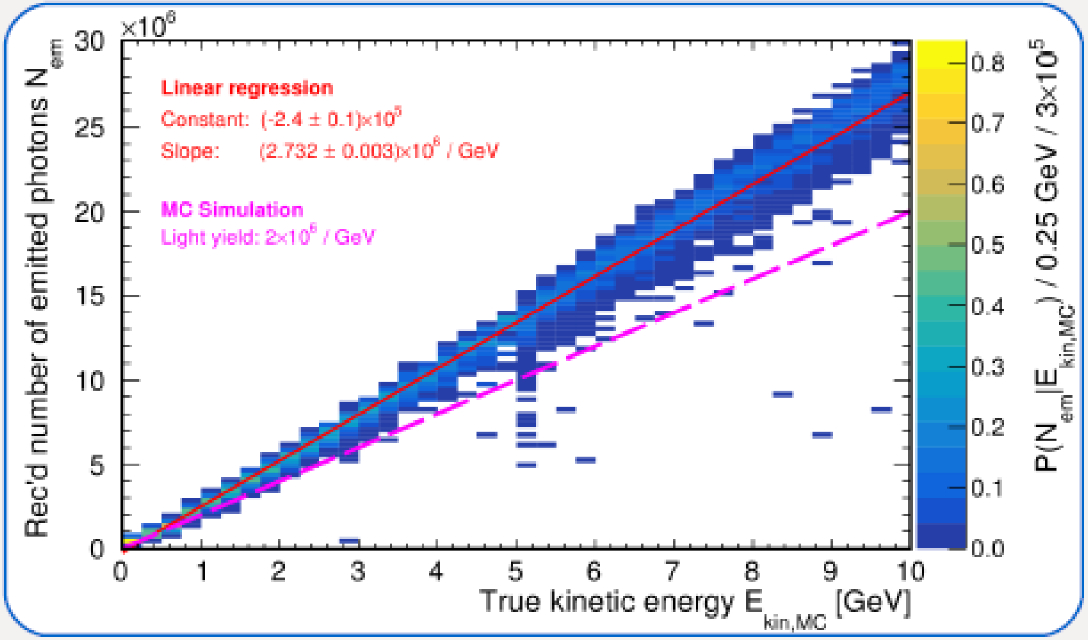
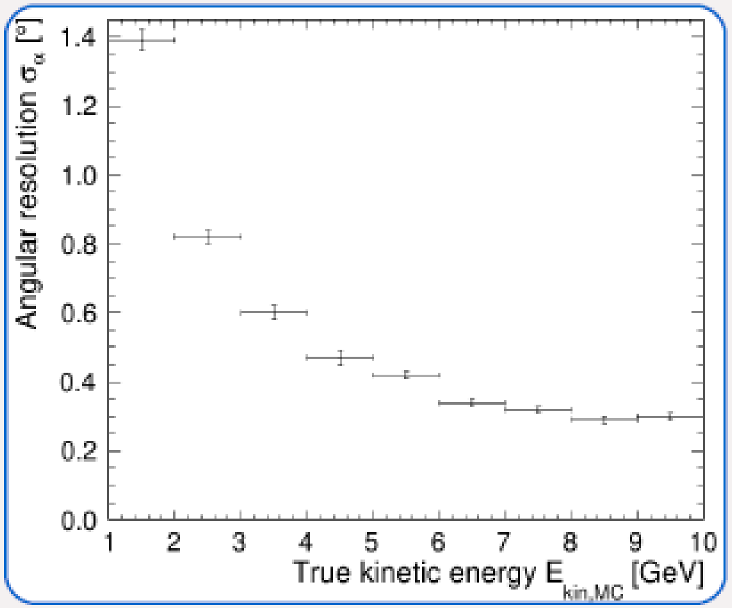


Figure courtesy of B. Wonsak
Universität Hamburg





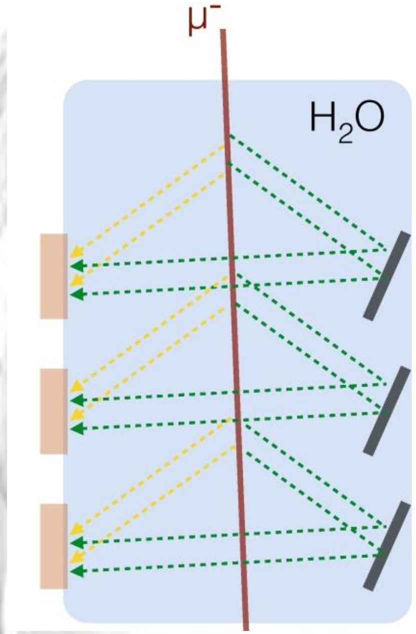
Summary

- Light is slow if measured in picoseconds
- Lots of information can be recovered by 'drifting' photons to a highly segmented photo-detectors
- Using Cherenkov and scintillation light in the same detector is a very attractive option
- New algorithms are being developed for detailed event reconstruction covering MeV to GeV energy range

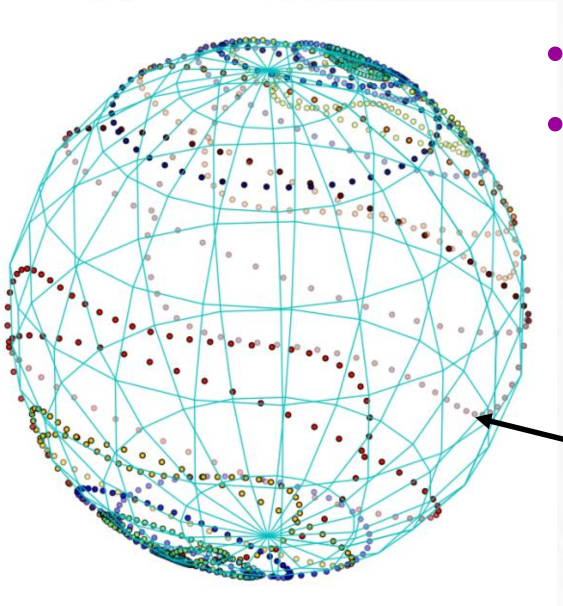
Back-up

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

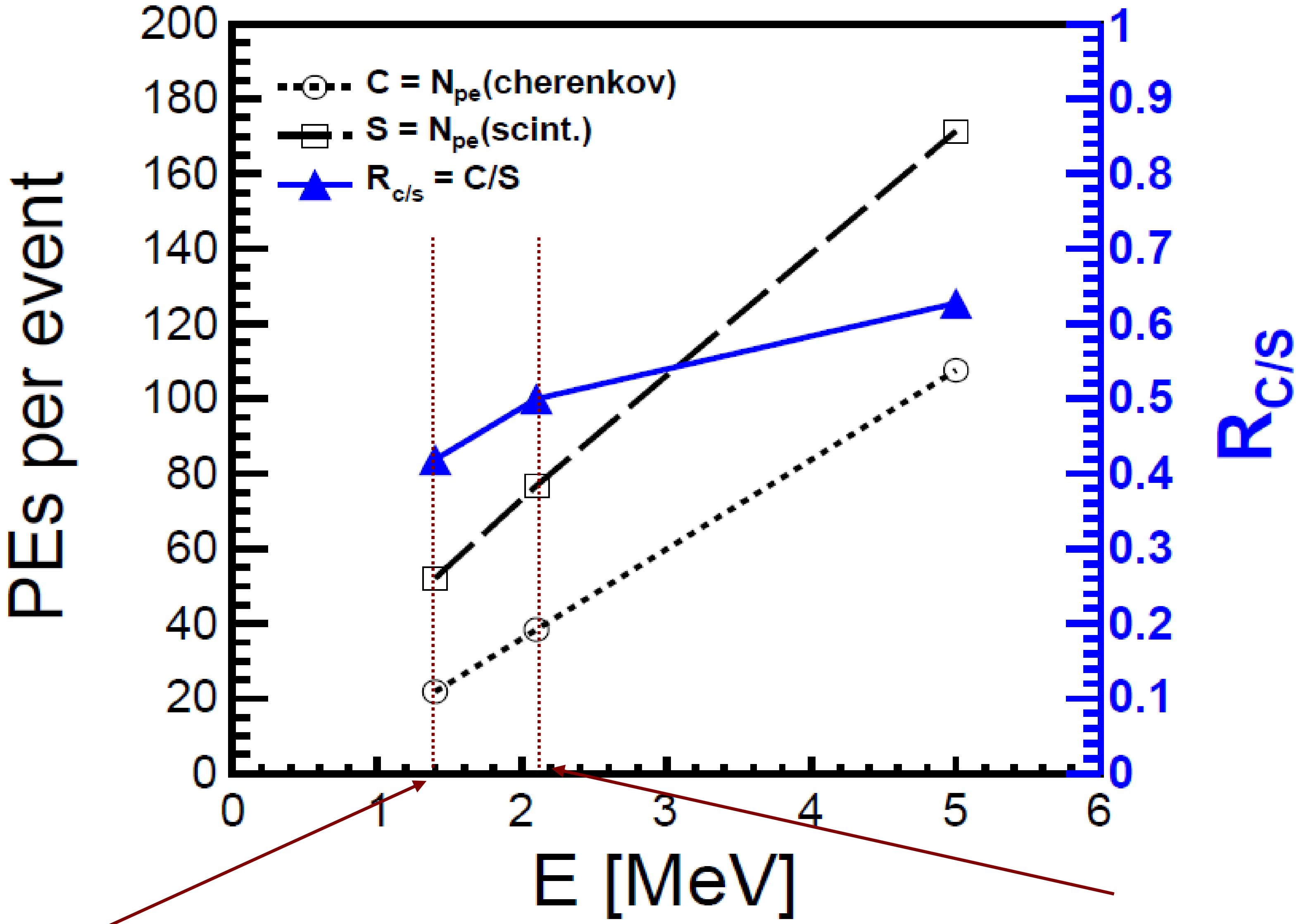
Electron TPC and the Optical TPC

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

OTPC:

- Current LAPPD microstrip readout gives 700 micron by 700 micron resolution for a 90cm x 20cm anode with cheap CMOS readout- gives $2\text{x}10^6$ pixels/m^2
- Resolution in 3rd dimension set by timing: 50 psec = ¾"; 1 psec = 300 microns
- Longitudinal information allows unambiguous use of mirrors

Light yield: Cherenkov vs scintillation



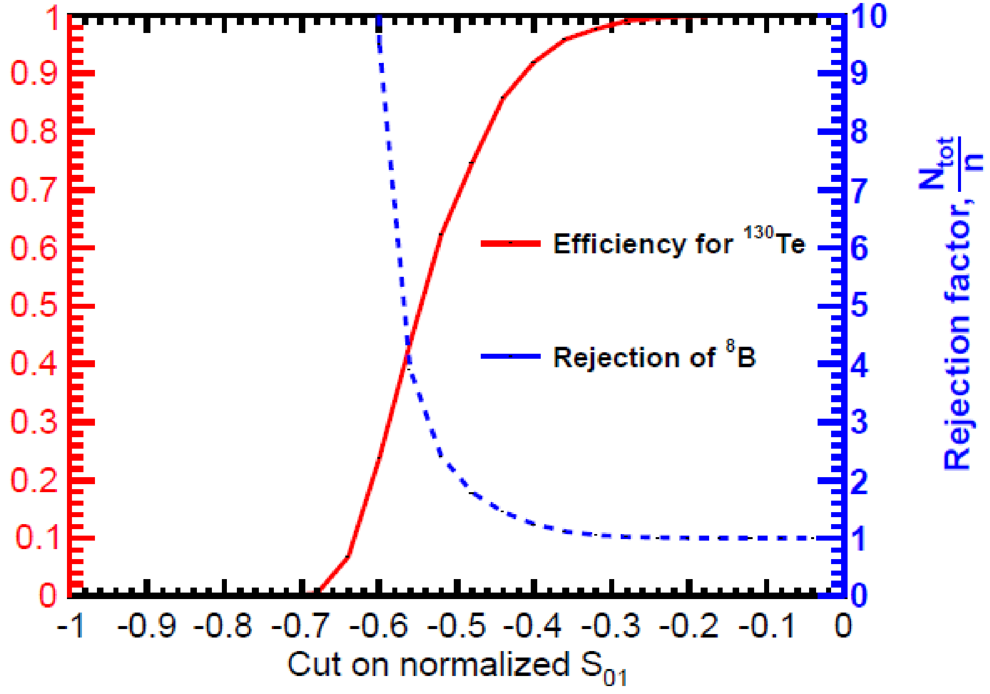
½ Q (^{116}Cd) =1.4 MeV

½ Q (^{48}Ca) =2.1 MeV

$0\nu\beta\beta$ vs ^{8}B

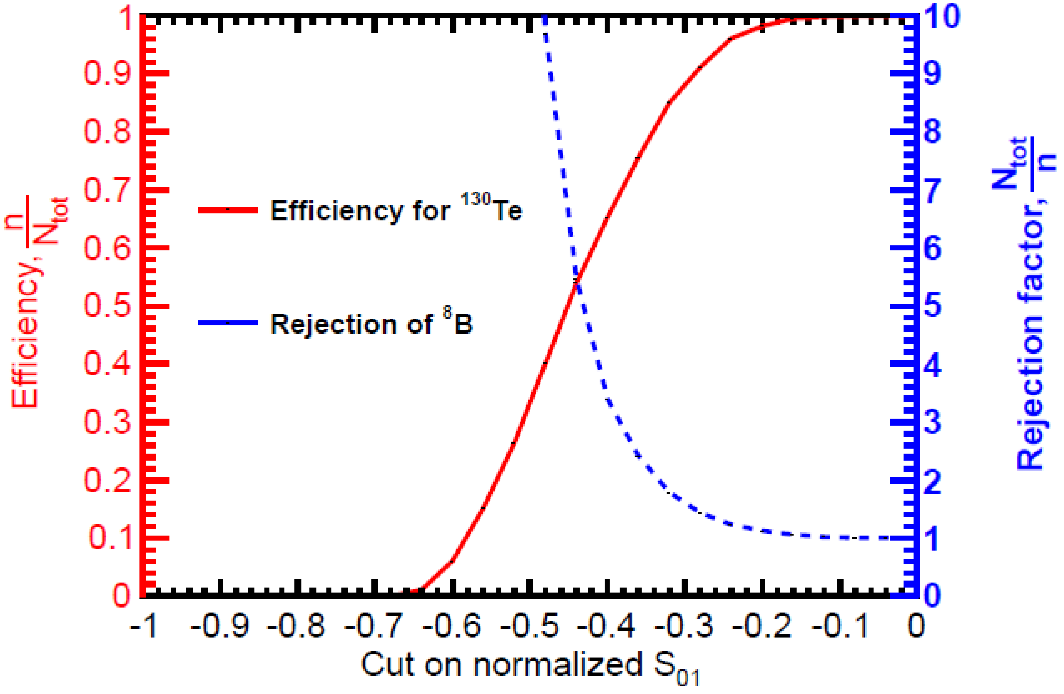
For details see NIM A849 (2017) 102

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



Background rejection factor = 2
@ 70% signal efficiency

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



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

0νββ-decay vs ^{10}C

two-track vs a "complicated" topology

^{10}C decay chain:

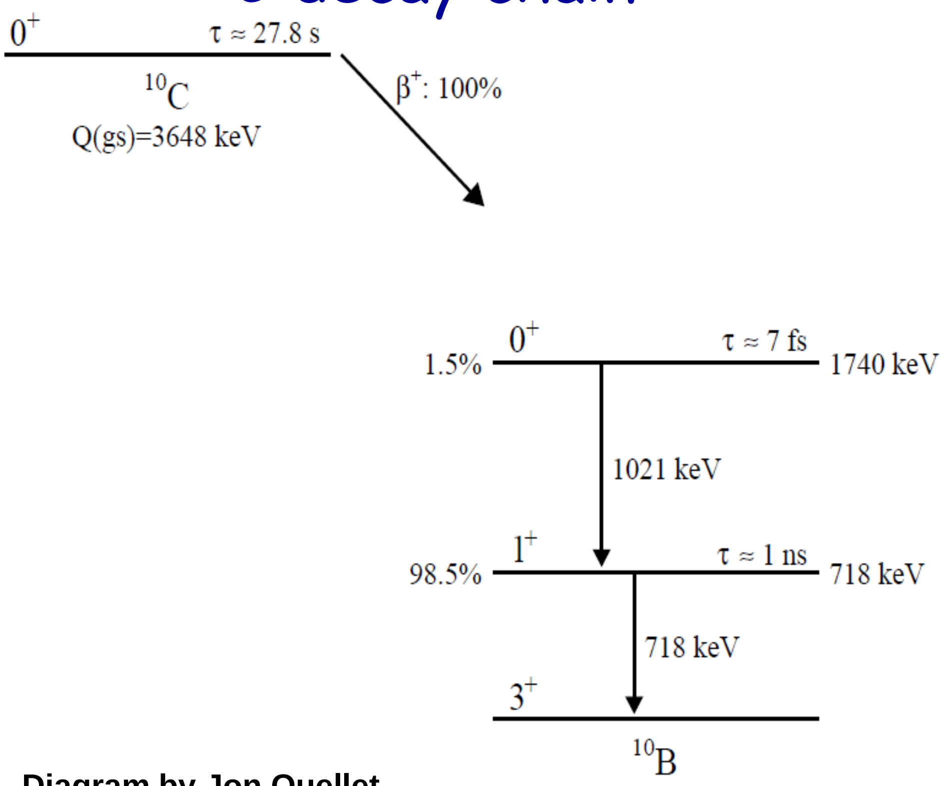
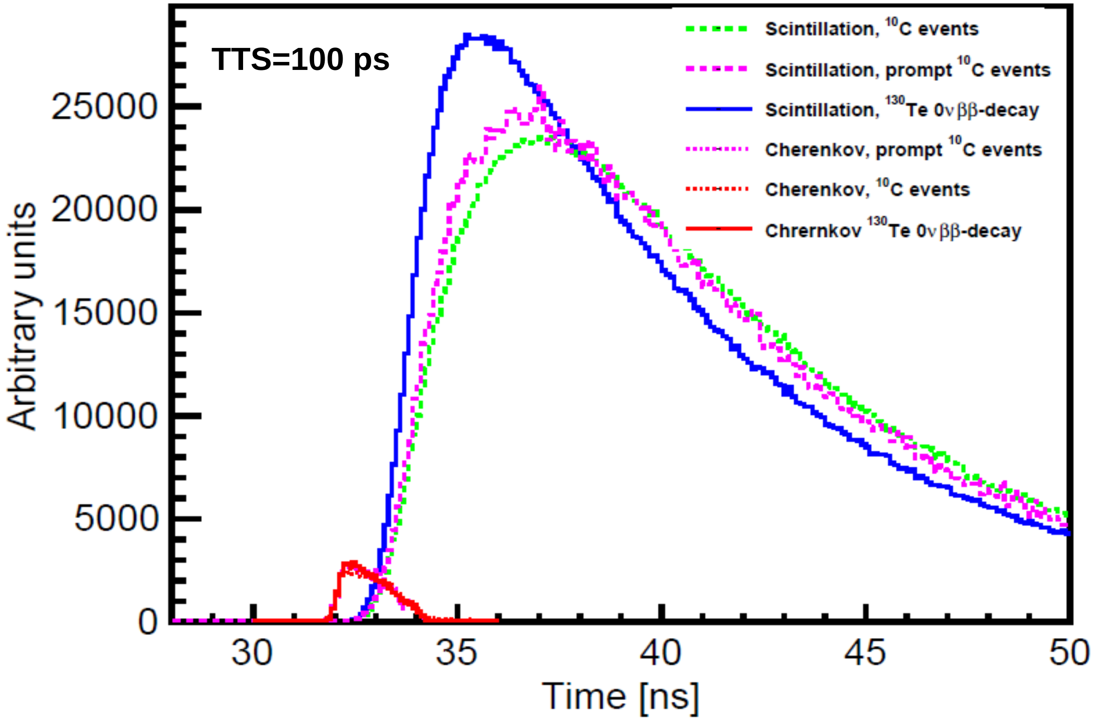


Diagram by Jon Ouellet

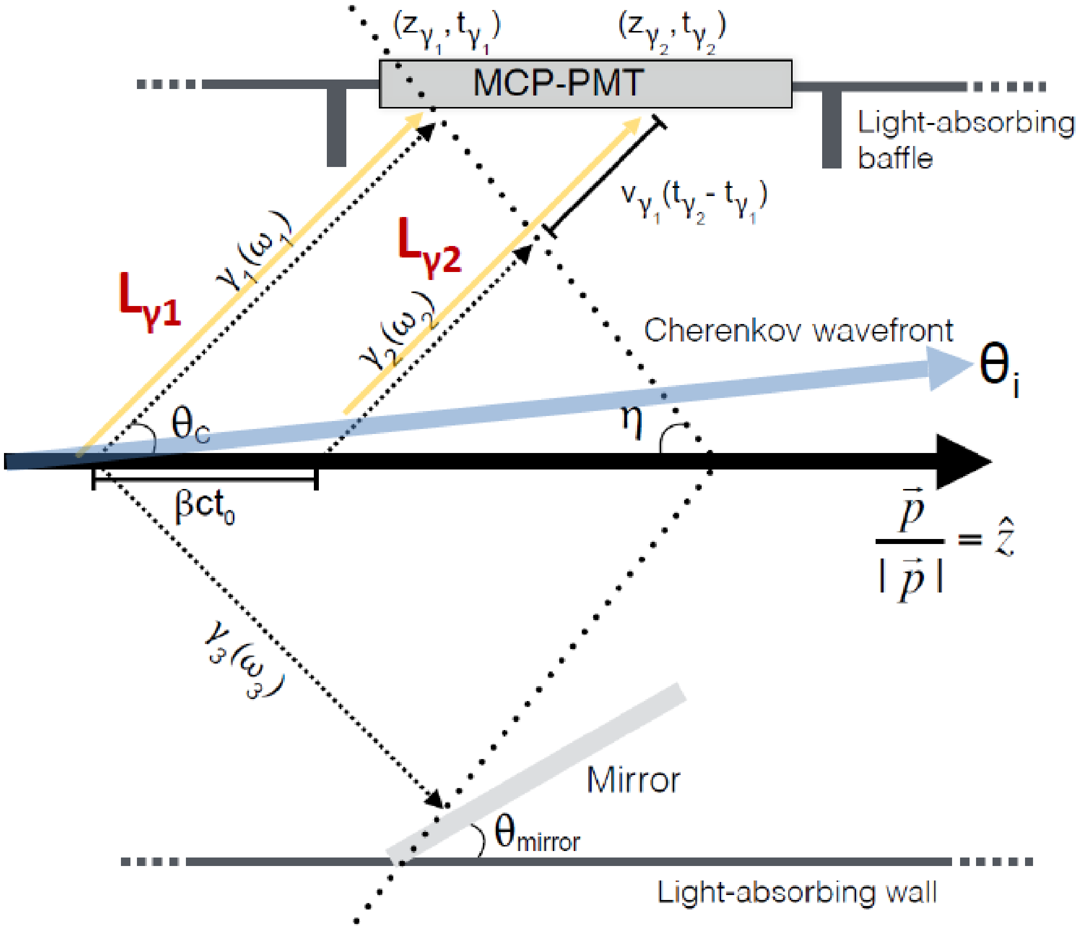
^{10}C vs 0νββ-decay: photons arrival time profile



- ^{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

OTPC Optics – direct light



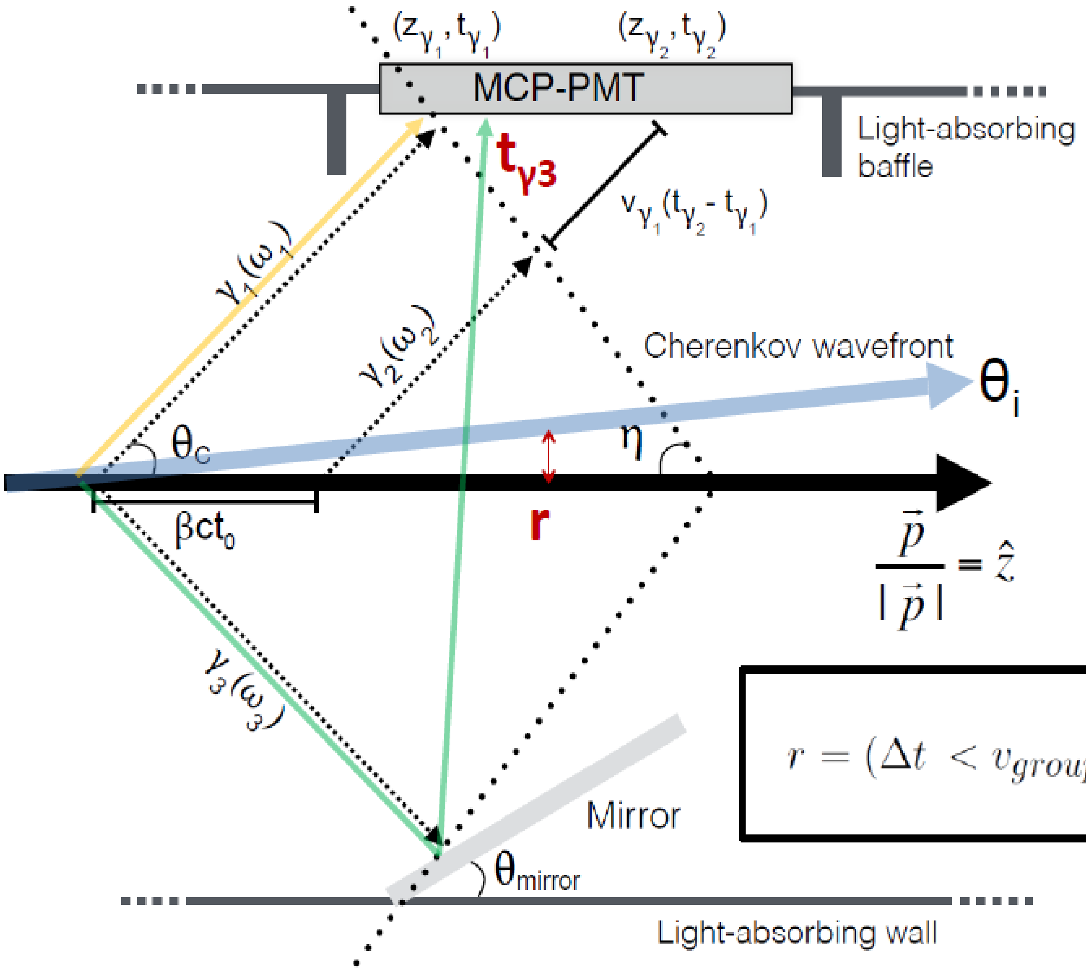
The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle (β) and the particle angle with respect to the OTPC longitudinal axis

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

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

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

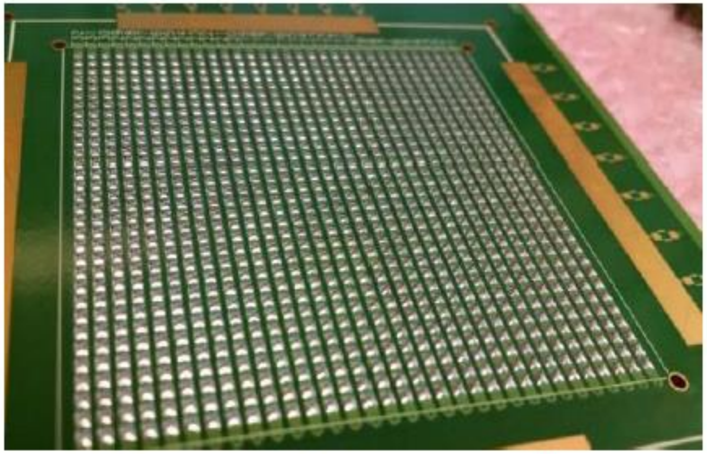
OTPC Optics – direct + reflected light



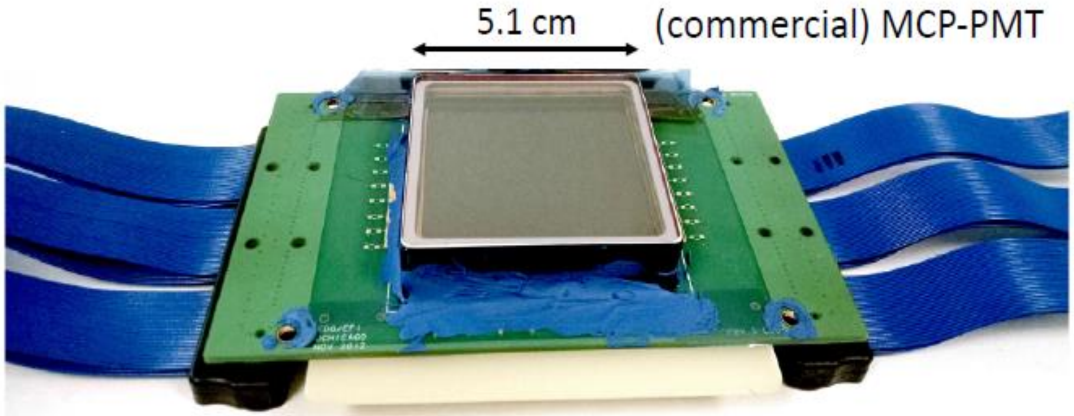
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

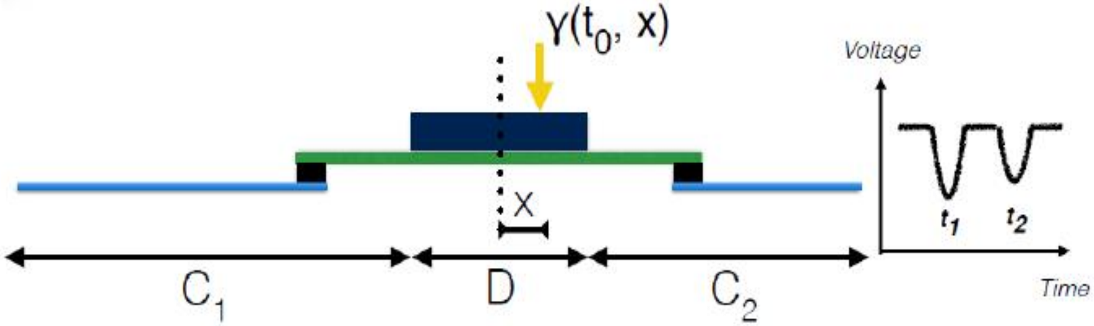
$$r = (\Delta t \; < v_{group} > -D) \, \frac{1}{2} \left(\frac{1}{\sin\theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)} \right)^{-1}$$

OTPC Photodetector Module (PM)

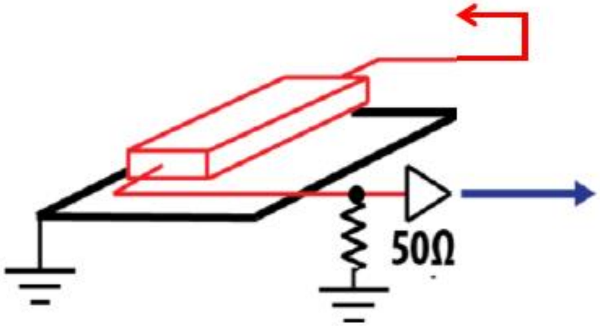


PHOTONIS XP85022
(commercial) MCP-PMT





- 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):



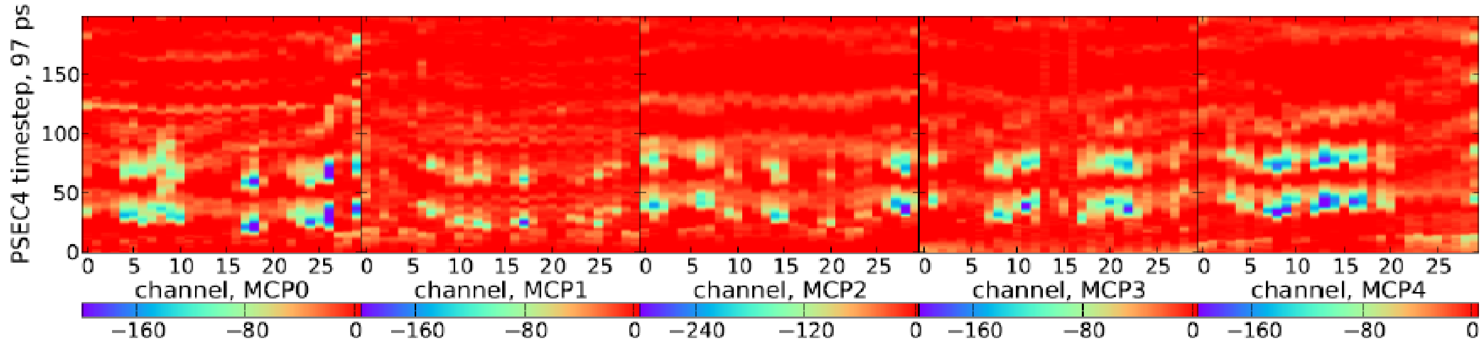
Expressions for the position and time-of-arrival of the detected photon

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

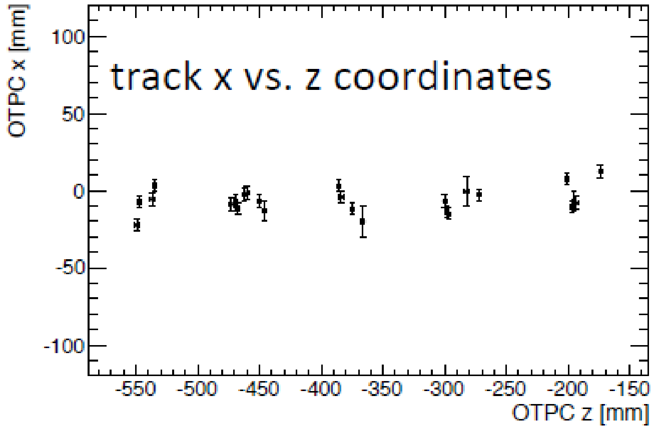
$$t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}}(D + C_2 + C_1)$$

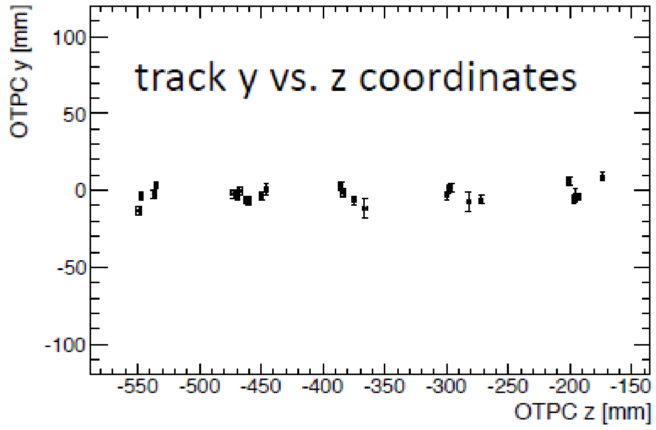
OTPC spatial reconstruction (3)

Example event



Typical event (thru-going μ)





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