University of Chicago

Argonne NATIONAL LABORATORY

Thinking Fast, Thinking Big:
Water Cherenkov and Scintillator Detectors as Optical TPCs

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on behalf of LAPPD and Fast Timing Neutrino Reconstruction Group

Instrumentation Frontier Workshop

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U.S. DEPARTMENT OF ENERGY

Detecting Neutrinos – a numbers game

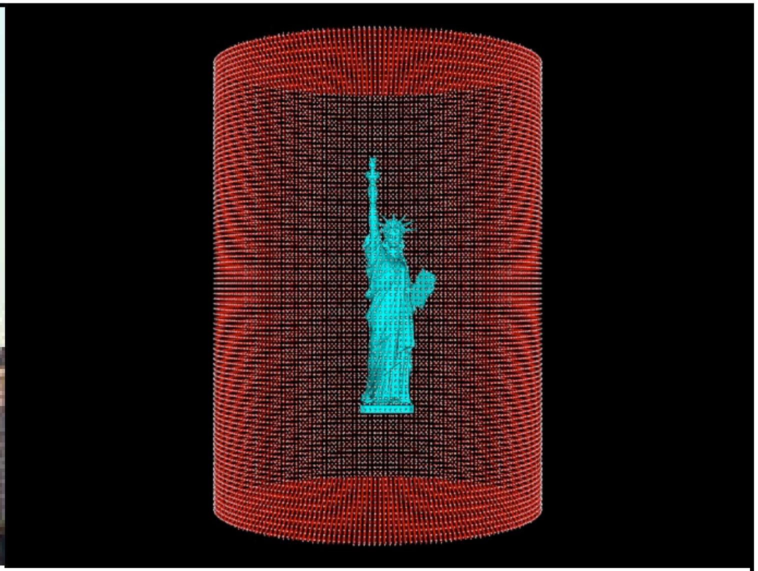
Incredibly small cross sections demand:

- **large fiducial mass**
- time
- high intensity
- low noise

LENA, the proposed European liquid scintillator detector: A nice addition to the Philly skyline?

credit Jürgen Winter

Proposed LBNE Water Cherenkov detector would have comfortably contained the Statue of Liberty



credit Anthony La Torre

Detecting Neutrinos (proton decay) – a numbers game

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- high intensity
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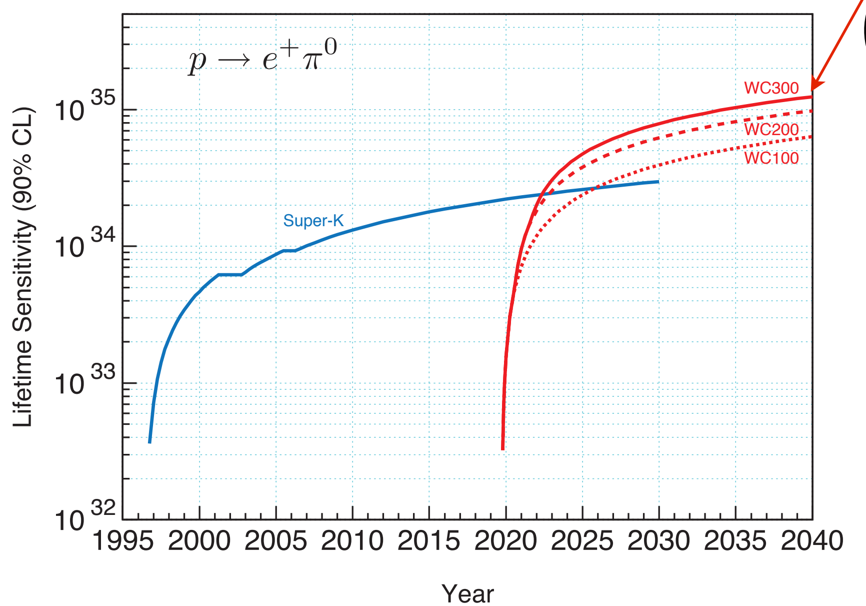
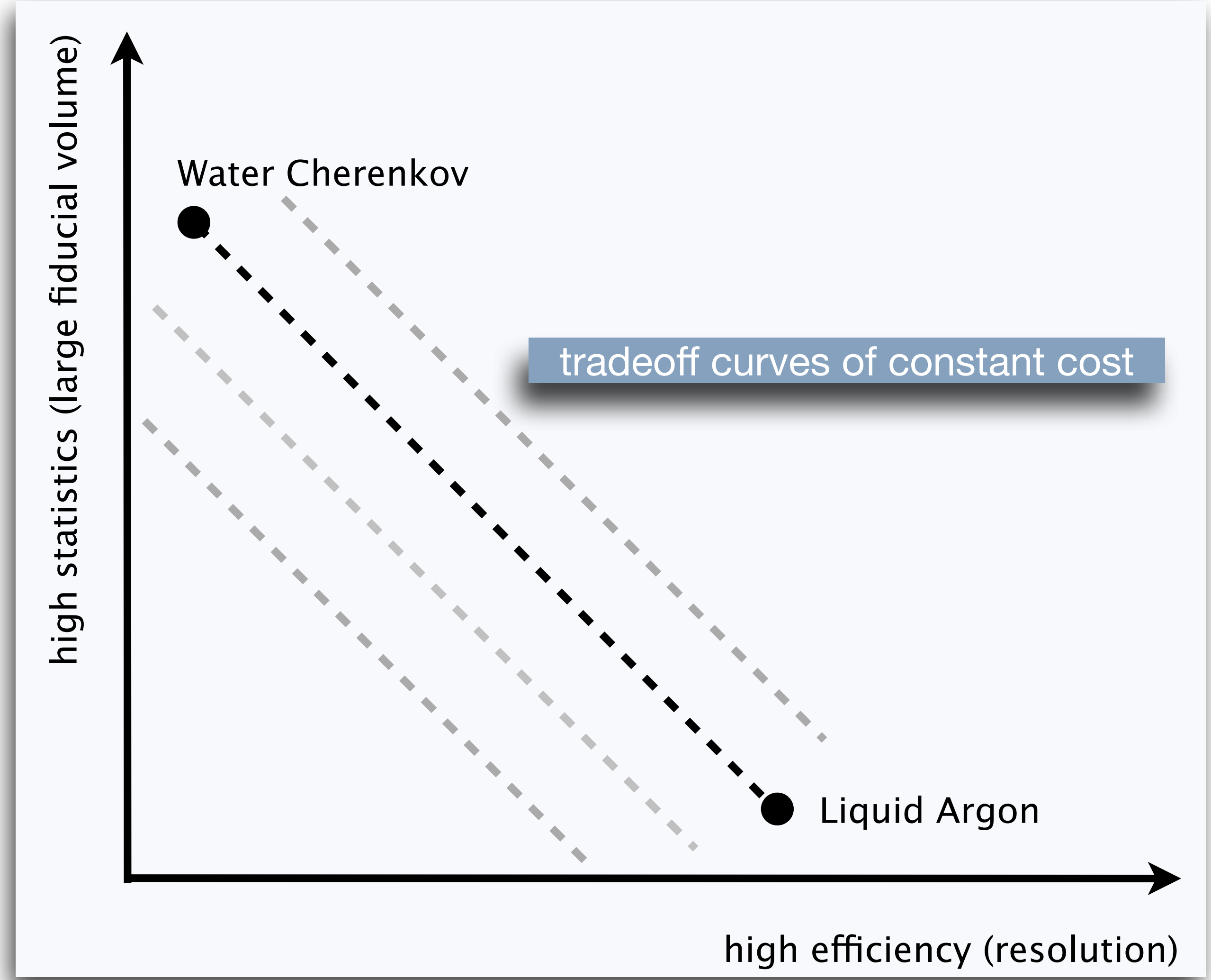
I turn 61 here.



plot by Ed Kearns, BU

The Limits of Thinking Bigger

Neutrino experiments often face tough choices.



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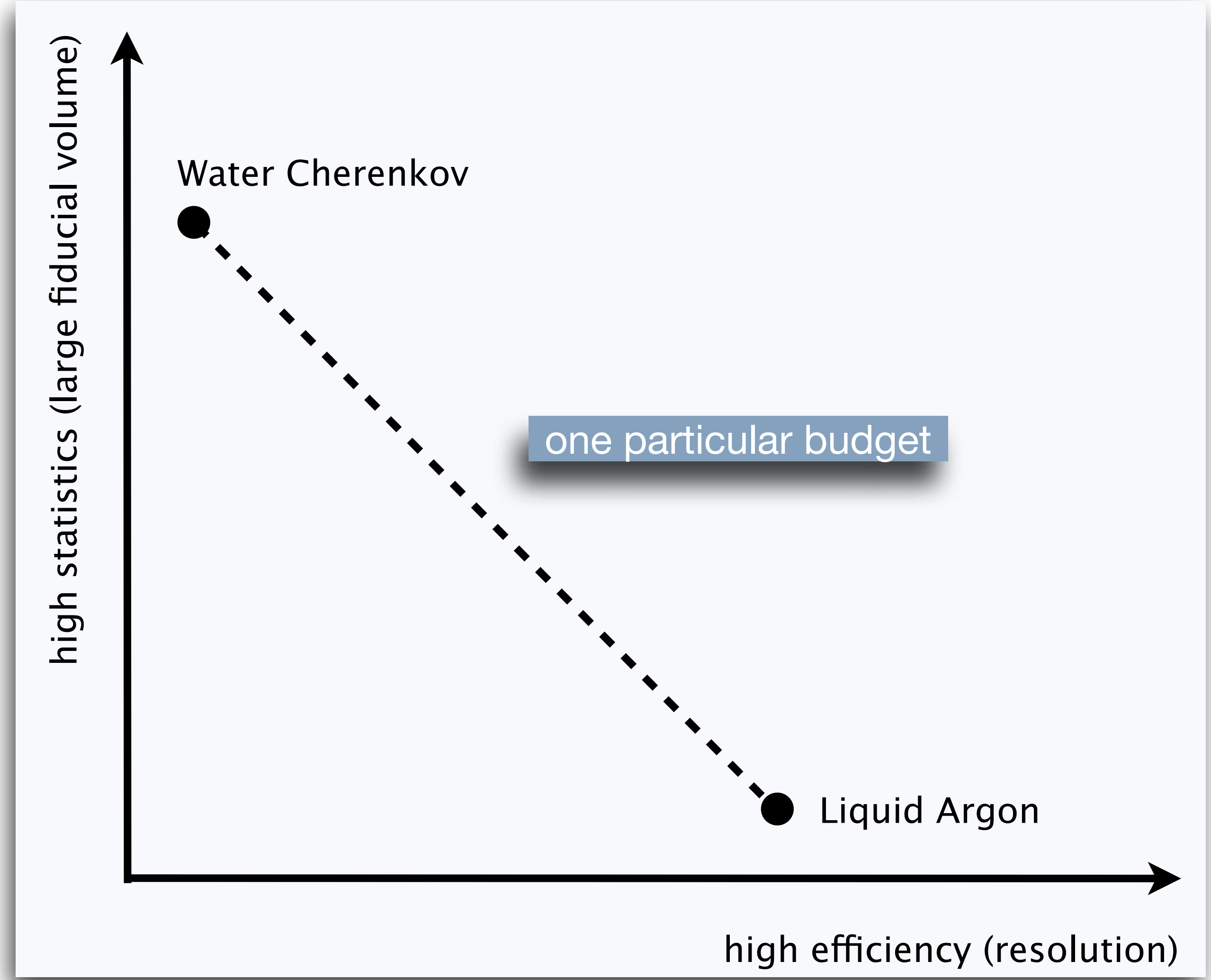
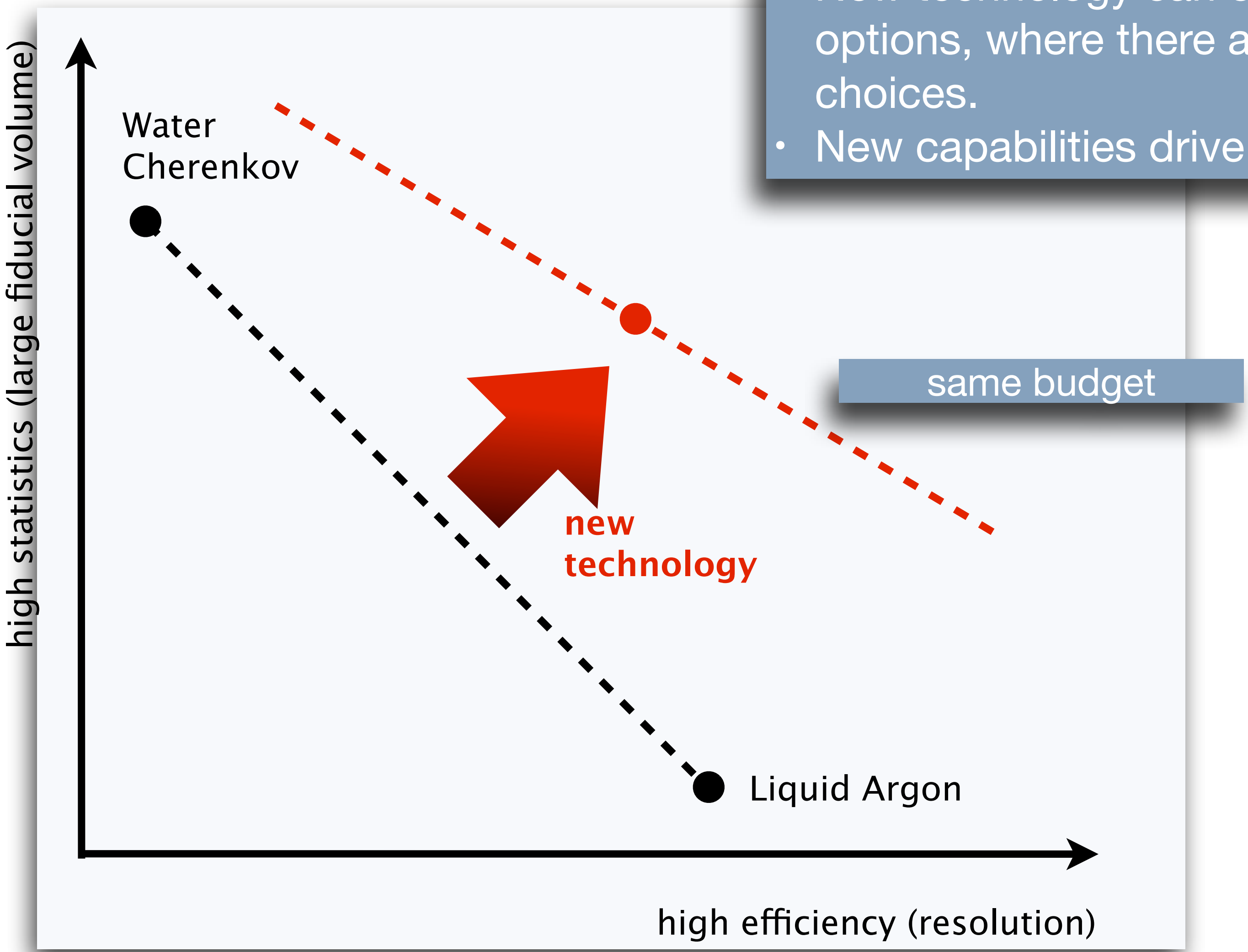
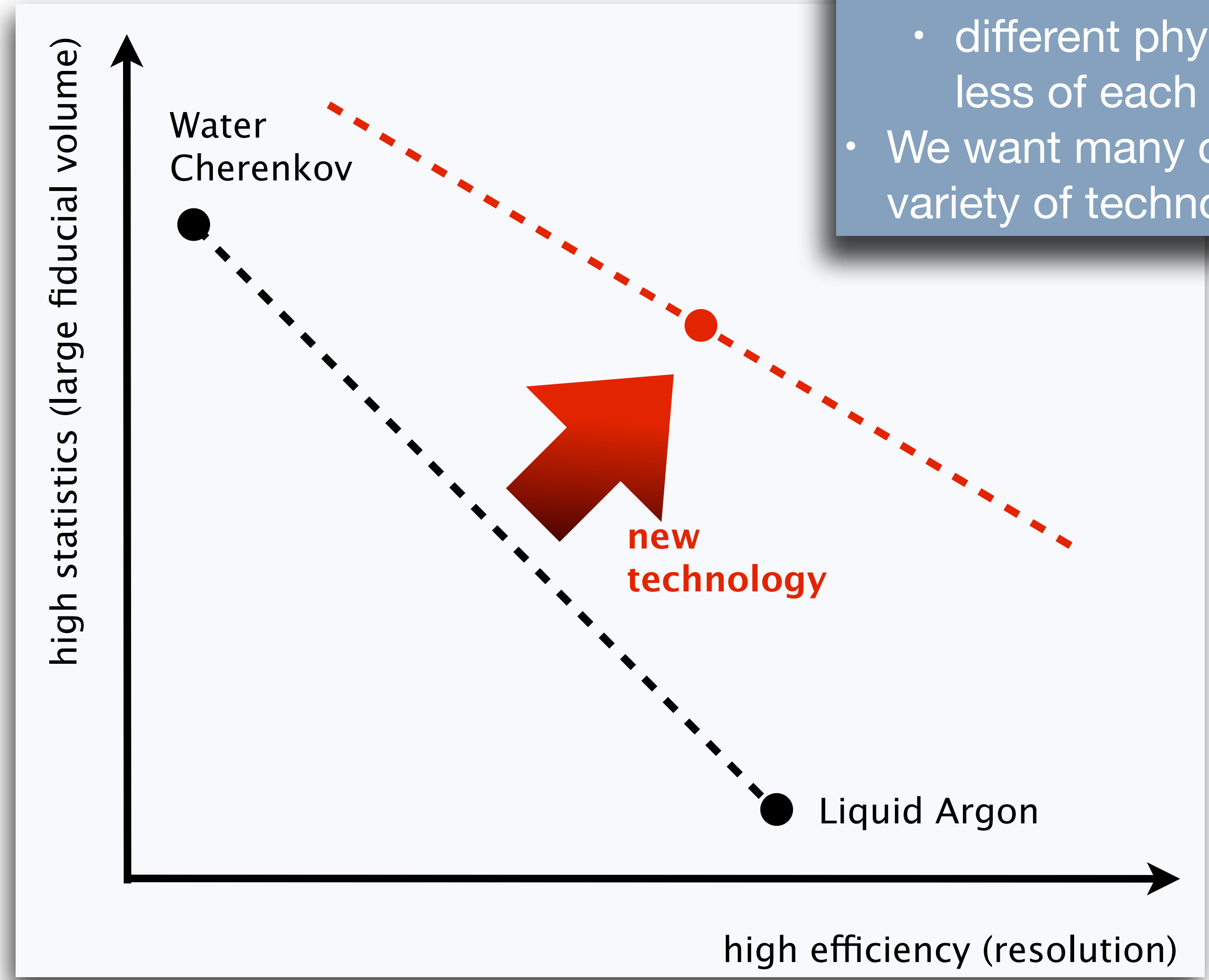


The Limits of Thinking Bigger

- The development of new technology could push this frontier forward.
- New technology can create intermediate options, where there are only a few choices.
- New capabilities drive new physics.



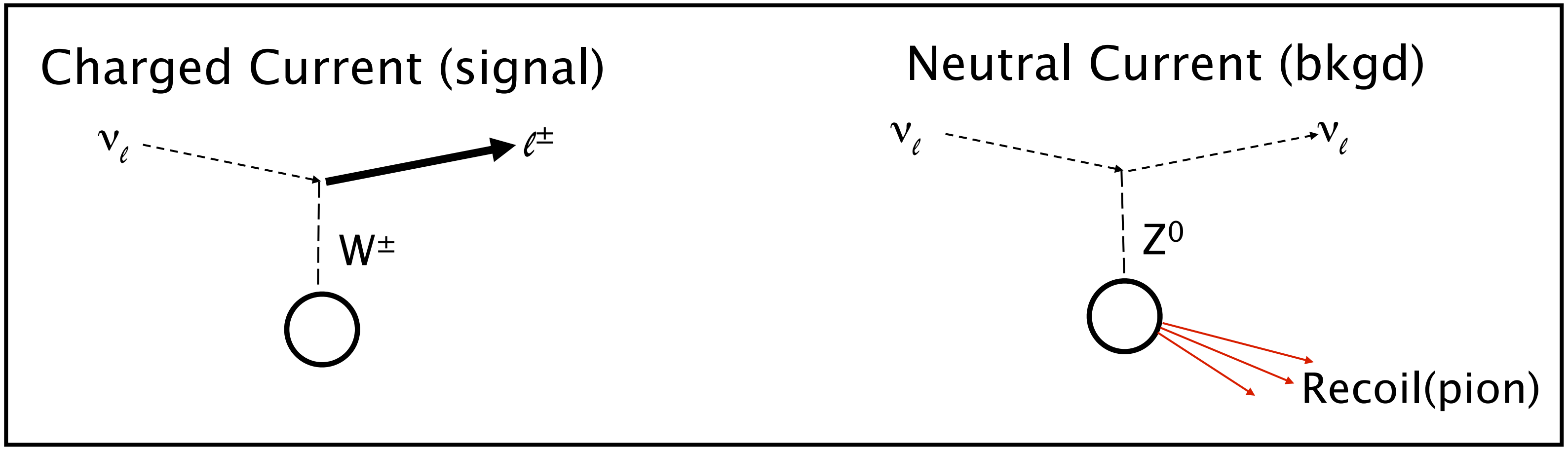
The Limits of Thinking Bigger

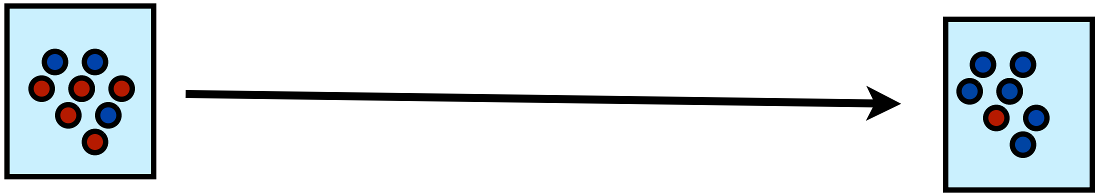


- Other dimensions to this graph:
  - particular target masses have different cross-sections/sensitivity
  - different physics goals need more or less of each capability
- We want many choices and we want a variety of technology options in play

Neutrino Detection Basics

- We detect neutrinos through the products of their interactions with matter.
- Neutrino flavor can be determined by charged-current interactions, which produce charged leptons of like flavor.





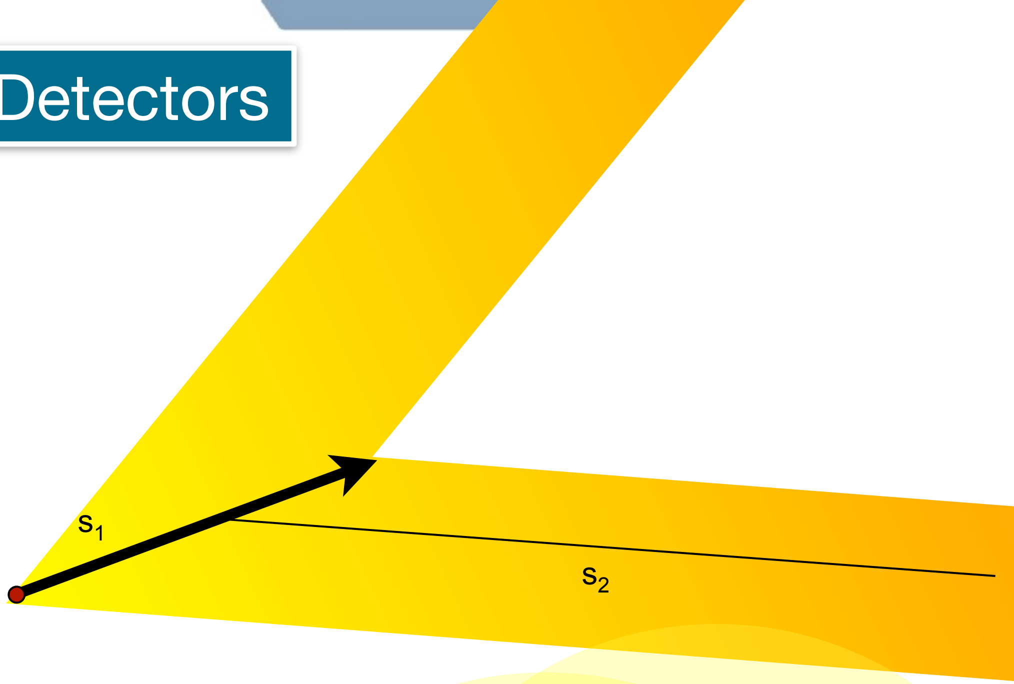
this experiment measures blue appearance and red disappearance.

Typical neutrino oscillation experiments count the relative fractions of leptons of each flavor produced at a near detector, compared with those fractions at a far detector

Light Production In Neutrino Detectors

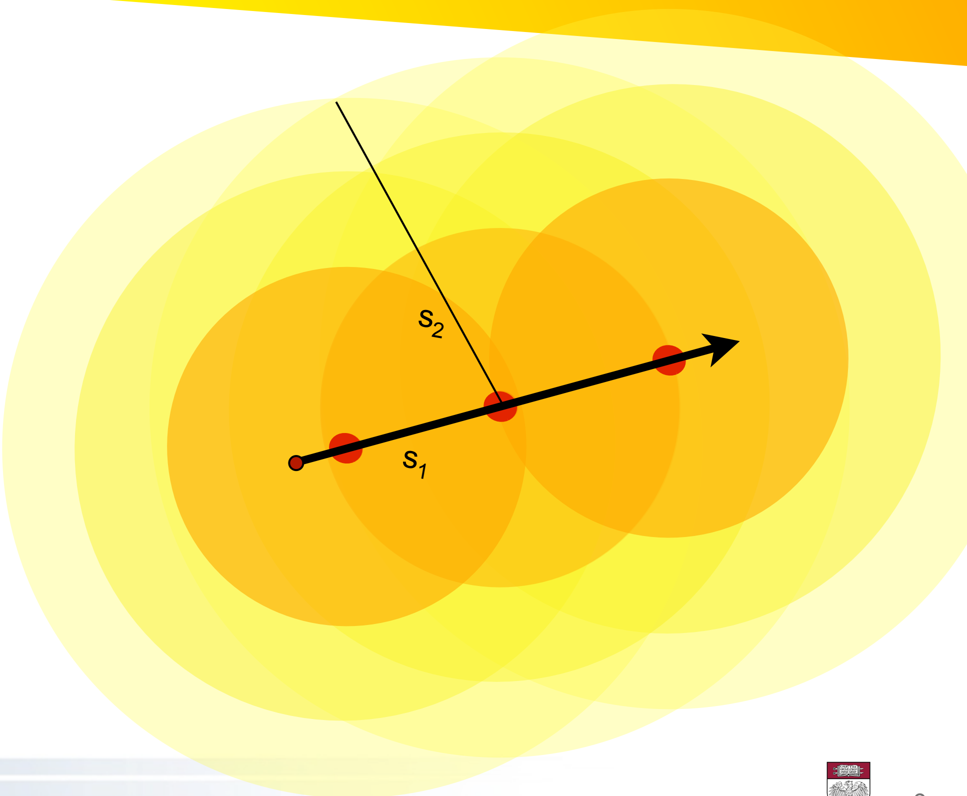
Cherenkov Effect

- An shockwave of optical light is produced when a charged particle travels through a dielectric medium faster than the speed of light in that medium: c/n
- This light propagates at an angle θ_C = acos(1/nβ) w.r.t. the direction of the charged particle…
- Geometry is well-constrained



Scintillation

- Light produced by flourescence of ionized atoms
- Narrower spectral range
- Light yield is much higher
- Energy threshold lower
- But, light is emitted isotropically about emission points along the track
- Emission times are delayed and dispersed



Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

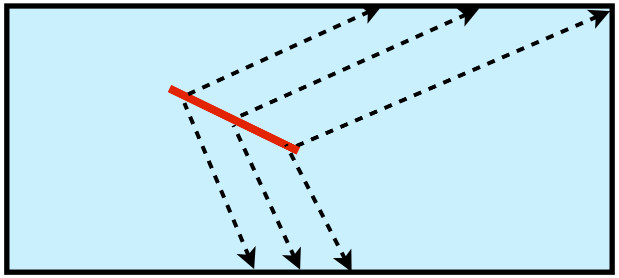
~20 photons/mm (Cherenkov)

2. Drift time

~225,000mm/microsecond

3. Topology

drift distances depend
on track parameters



4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation? Chemical enhancement

2. Drift time

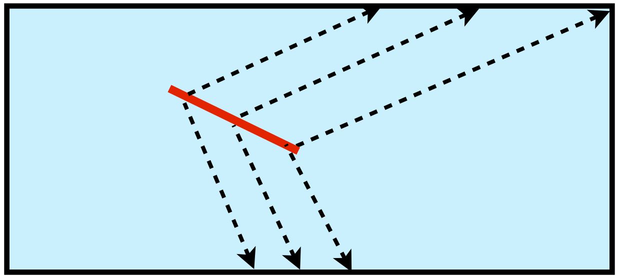
~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution.**

3. Topology

drift distances depend on track parameters

This presents some reconstruction challenges, but not unconquerable.



4. Optical Transport of light in water

Appropriate reconstruction techniques are needed.

Three Needed Improvements in Physics Capabilities

1. Granularity
2. Low E/heavy particle sensitivity
3. Energy Resolution

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1. Granularity
2. Low E/heavy particle sensitivity
3. Energy Resolution

1. Can water Cherenkov/liquid scintillator detectors achieve fine-grained tracking?
   - resolve multiple track event topologies with small opening angles?
   - resolve substructure/systematic differences in EM showers?

2. Can we resolve more kinematic details in "low energy" (O(10) MeV) events, particularly details of nuclear recoil? Can we see heavy charge particles below Cherenkov threshold?

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Three Needed Improvements in Physics Capabilities

1. Granularity
2. Low E/heavy particle sensitivity
3. Energy Resolution

In this talk we will look at

- a few examples of physics questions limited by these 3 capabilities
- ways in which new technology could address these problems

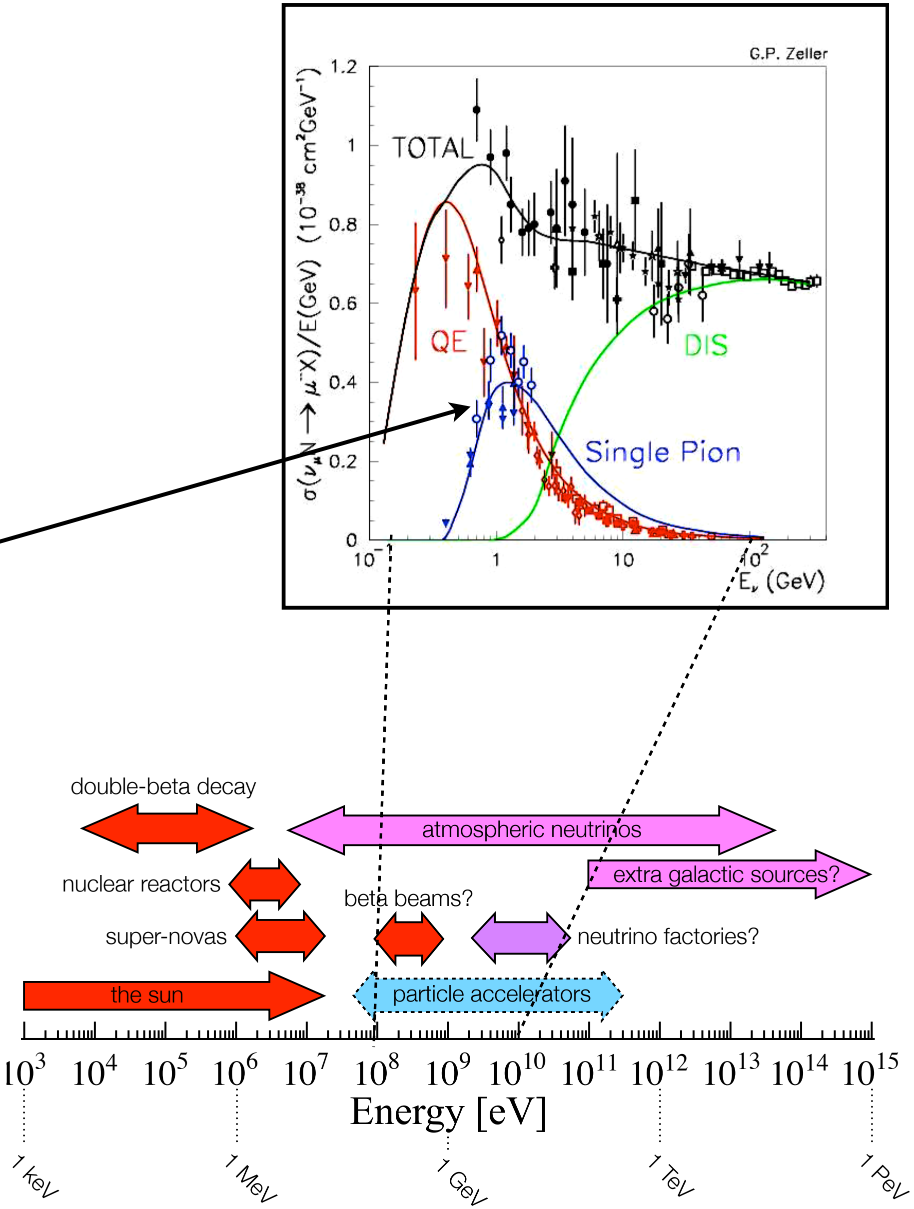
Section I:

A Sampling of Neutrino and PDK Problems Limited by WC Technology

Granularity

Medium energy ranges typical of accelerator and atmospheric neutrino physics fall into the “transition region” between Quasi-elastic scattering and deep inelastic scattering.

Pion production (from excited nuclear states) peaks at these energies.



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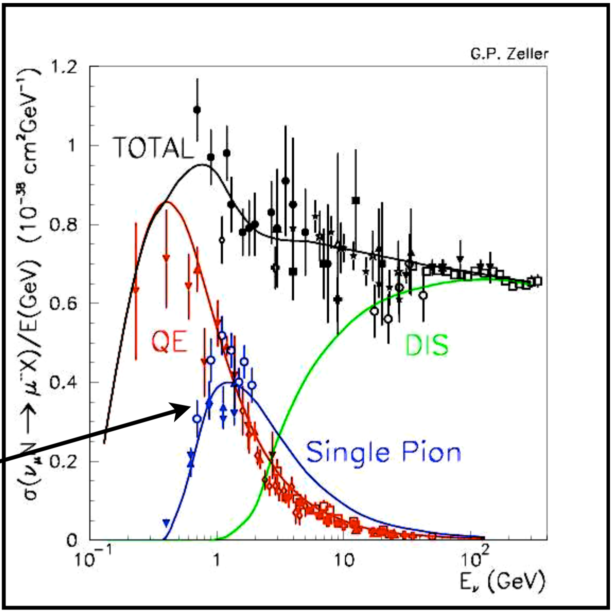

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CC

$$\nu_\mu p \rightarrow \mu^- p \pi^+, \qquad \bar{\nu}_\mu p \rightarrow \mu^+ p \pi^-,$$

$$\nu_\mu n \rightarrow \mu^- p \pi^0, \qquad \bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0,$$

$$\nu_\mu n \rightarrow \mu^- n \pi^+, \qquad \bar{\nu}_\mu n \rightarrow \mu^+ n \pi^-$$

NC

$$\nu_\mu p \rightarrow \nu_\mu p \pi^0, \qquad \bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p \pi^0,$$

$$\nu_\mu p \rightarrow \nu_\mu n \pi^+, \qquad \bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p \pi^+$$

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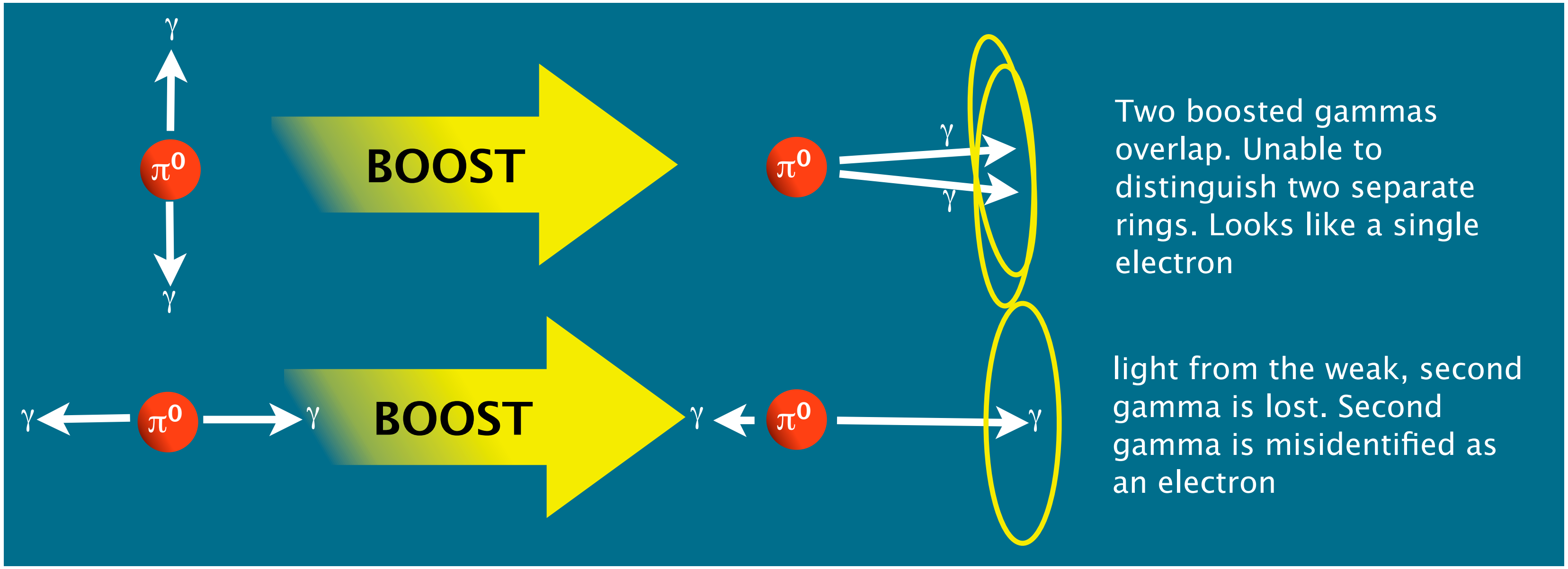
Granularity

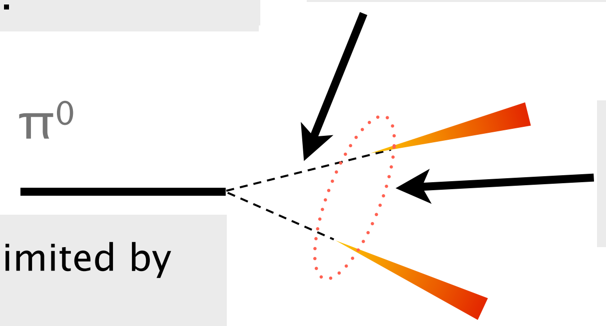


Largest reducible background at ~GeV energies. In WC, in order to achieve a pure electron sample (~1% π^0), one needs harsh quality cuts at the cost of signal efficiency.

There is still a room for significant improvement in the physics capabilities for a given mass of water.

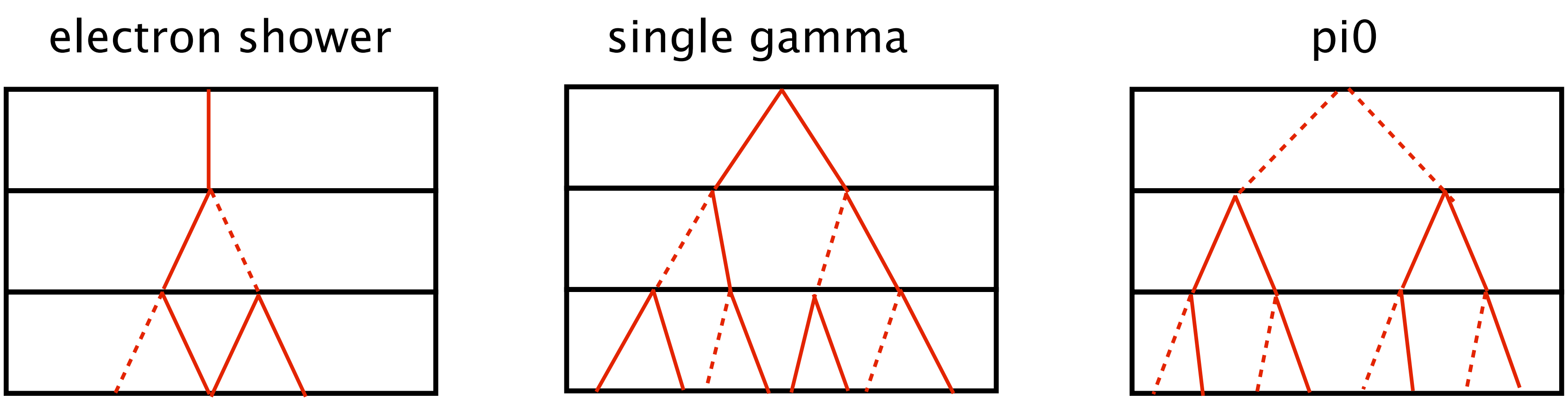
Granularity

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...



- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

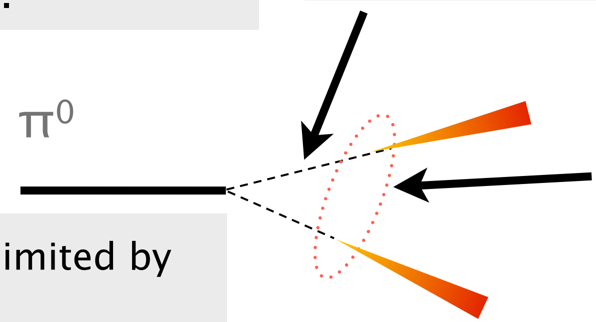
Can we reconstruct the first several stages of an EM shower?



Granularity

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~1.64 nsec



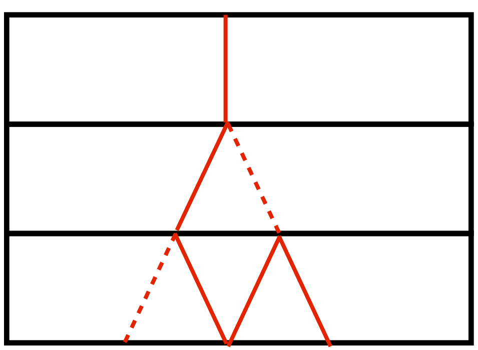
in term of time:
at 7 degrees: ~200 psec
at 15 degrees: ~425 psec

speed of light in water: ~44 psec/cm

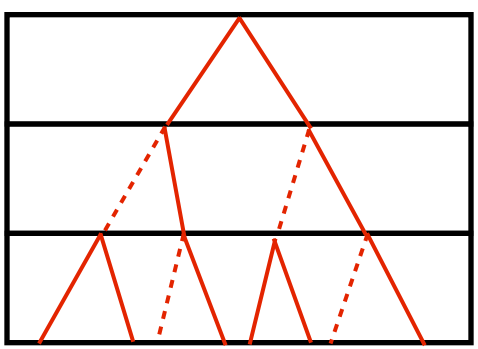
- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

Can we reconstruct the first several stages of an EM shower?

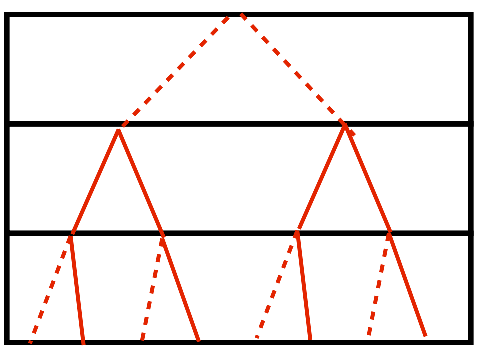
electron shower



single gamma



pi0



Low Energy/Heavy Particle Sensitivity

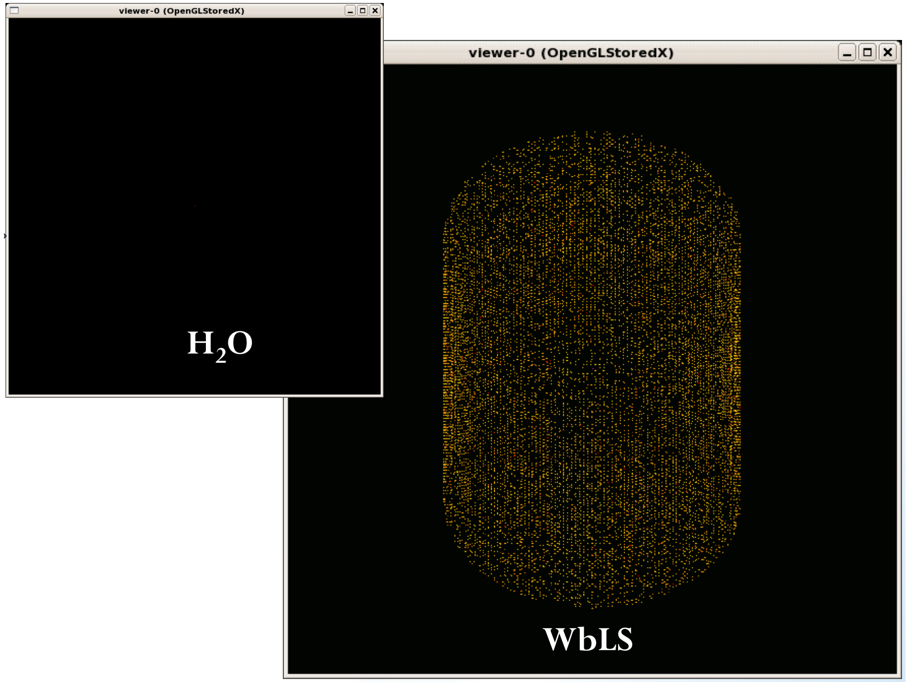
More light/light below Cherenkov threshold

Charged particles only produce Cherenkov light when v > c/n

For massive particles, the threshold for Cherenkov production is >100 MeV

Particle	Threshold
electron	> 0.6 MeV
muon	> 120 MeV
pion	> 160 MeV
kaon	> 563 MeV
proton	> 1070 MeV

K+ in water and liquid scintillator



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	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^+\pi^0$	45%	0.2	45% ?	0.1
$p \rightarrow \nu K^+$	14%	0.6	97%	0.1
$p \rightarrow \mu^+ K^0$	8%	0.8	47%	0.2
n-nbar	10%	21	?	?

SUSY favored proton decay mode:

$$p \rightarrow K^+ \bar{\nu}$$

63.5 % → $\mu^+ \nu$ (152 MeV)

20.7 % → $\pi^0 \pi^+ \rightarrow 2\gamma\ \mu^+ \nu$ (135 MeV, 4 MeV)

Inefficient channel in water. Cannot see the Kaon

Low Energy/Heavy Particle Sensitivity

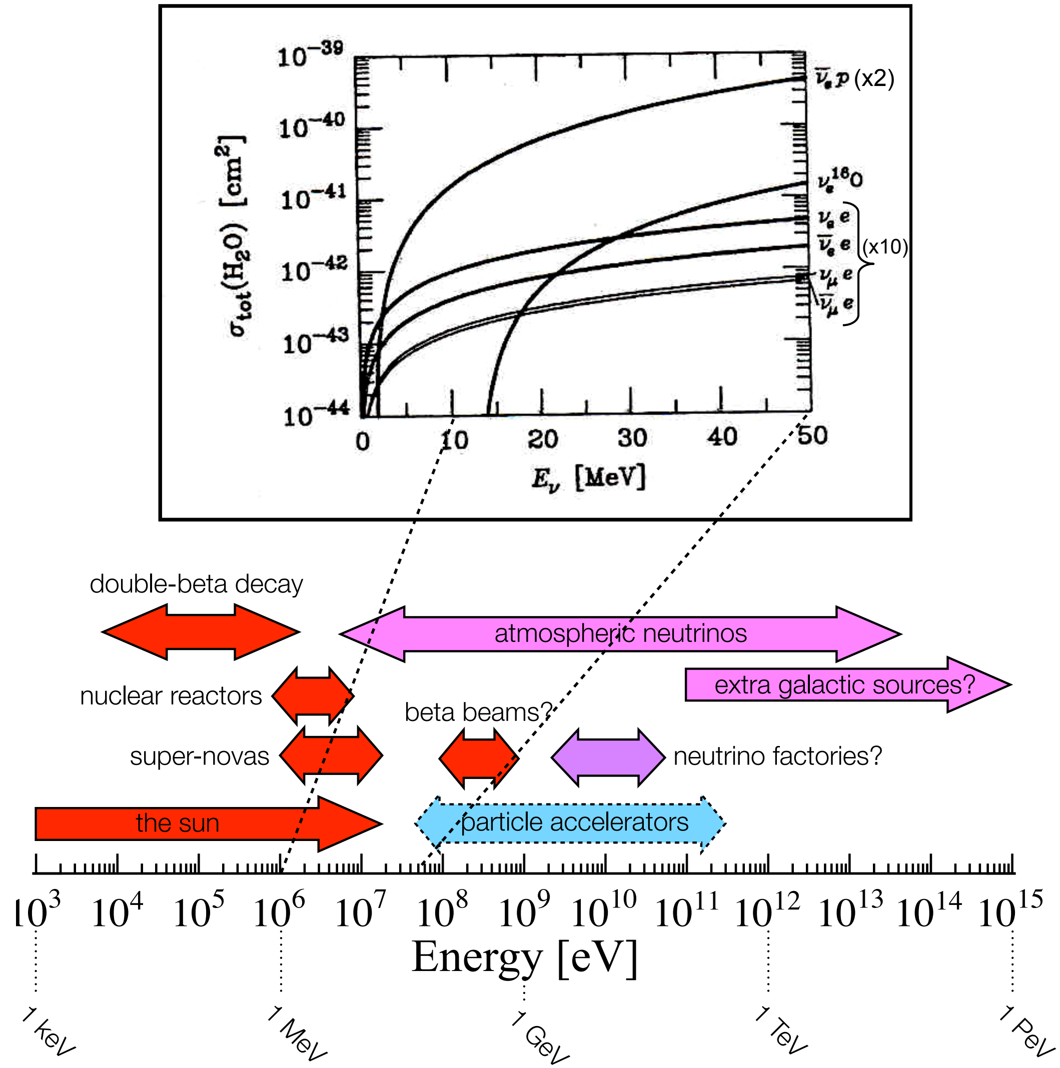
Seeing neutrons

At O(10) MeV energies, inverse beta decay has the largest cross-section in water.

Provides an excellent channel for detecting electron anti-neutrinos in a wide variety of low energy electron anti-neutrino detection contexts:

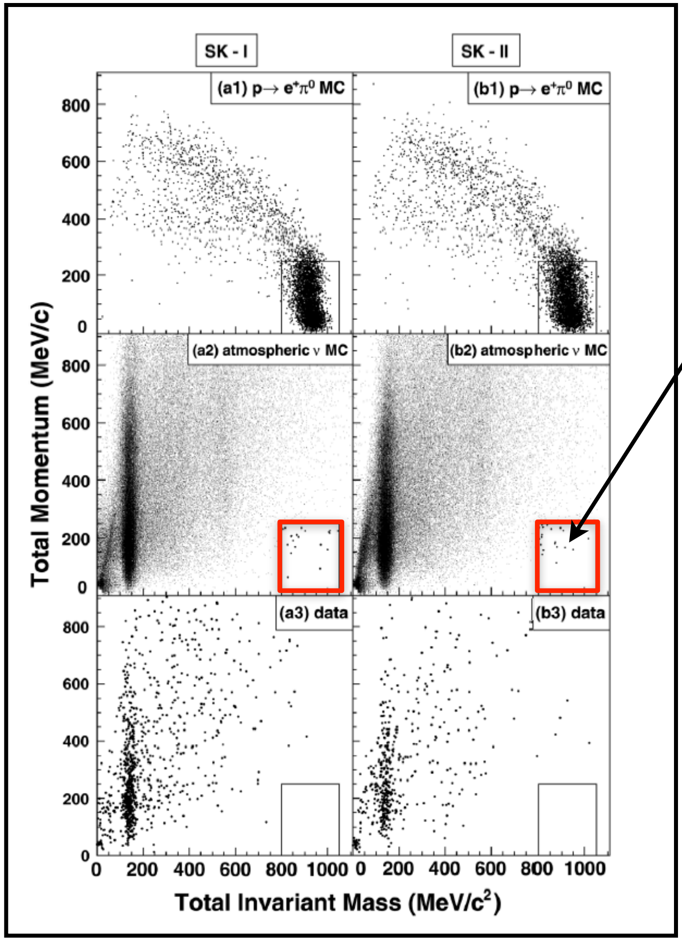
- Supernova neutrinos
- Solar neutrinos
- Geo neutrinos
- Reactor neutrinos

K. Zuber, Neutrino Physics, IOP, 2004



Low Energy/Heavy Particle Sensitivity

Seeing neutrons



Largest reducible background from atmospheric neutrino interactions fall in the signal region for proton decay in the $p \rightarrow e\pi^0$ channel.

This background presents a problem for next generation experiments approaching megaton scales.

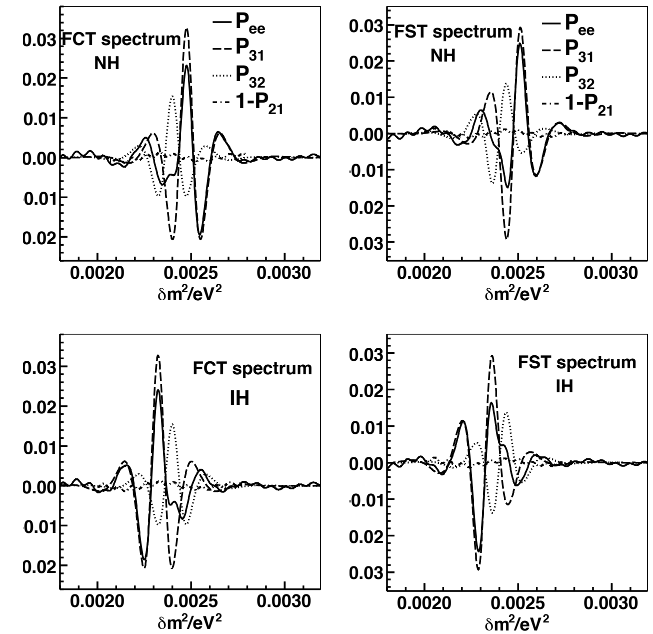
This background is largely reducible if it were possible to see any neutrons produced in the final-state of the neutrino interaction.

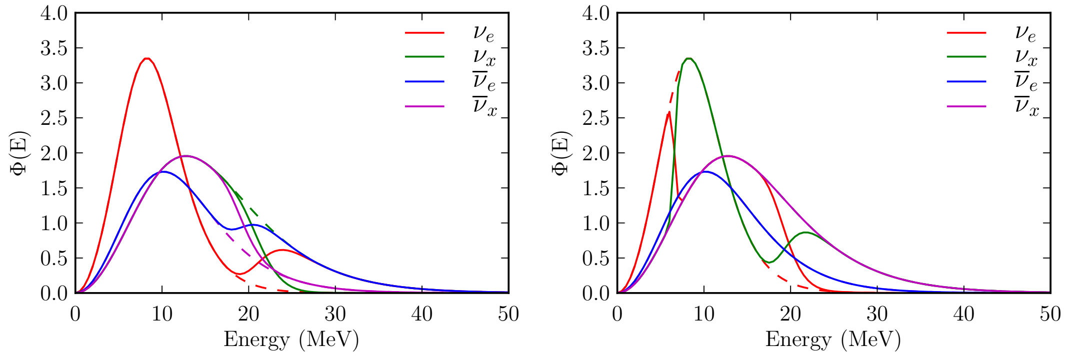
Energy Resolution

Daya Bay II

- Proposed reactor neutrino experiment to determine the neutrino mass hierarchy based on a novel approach.
- 10 kton liquid scintillator detector on a 60 km baseline

Need excellent energy resolutions: 3%/sqrt(E)!





- Core Collapse Supernova
  - the ultimate intensity frontier
    - ~99% of energy is carried away by neutrinos
    - neutrino densities are so high that neutrino–neutrino interactions dominate
  - an experiment we could never afford to build
  - predicted to occur a few times a century in our galaxy

Section II:

Leveraging Technology to Address the Challenges

3 Key Questions ➡ 3 Areas of Technological Improvement

1. Granularity
2. Low E/heavy particle sensitivity
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➡

1. Photodetector Technology
2. Chemical Enhancements to the Target Volume
3. Geometry and Coverage

Reinventing the unit-cell of light-based neutrino detectors

- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

Key Elements of the LAPPD Detector

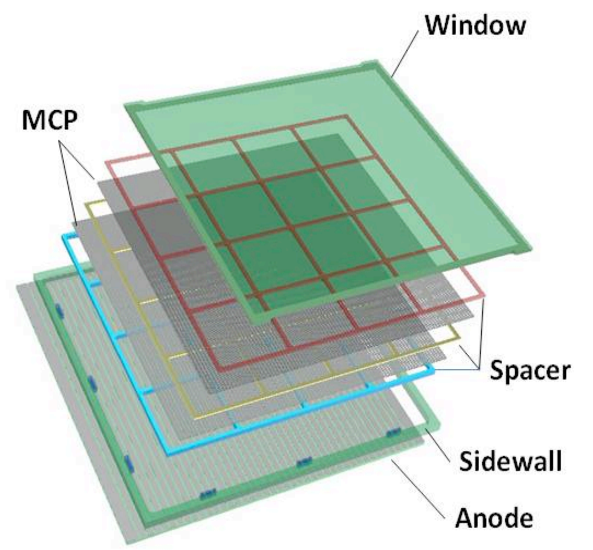
Glass body, minimal feedthroughs

MCPs made using atomic layer deposition (ALD).

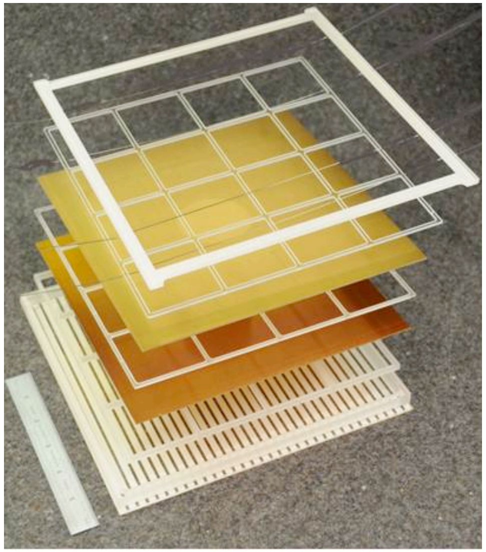
transmission line anode

fast and economical front-end electronics

large area, flat panel photocathodes

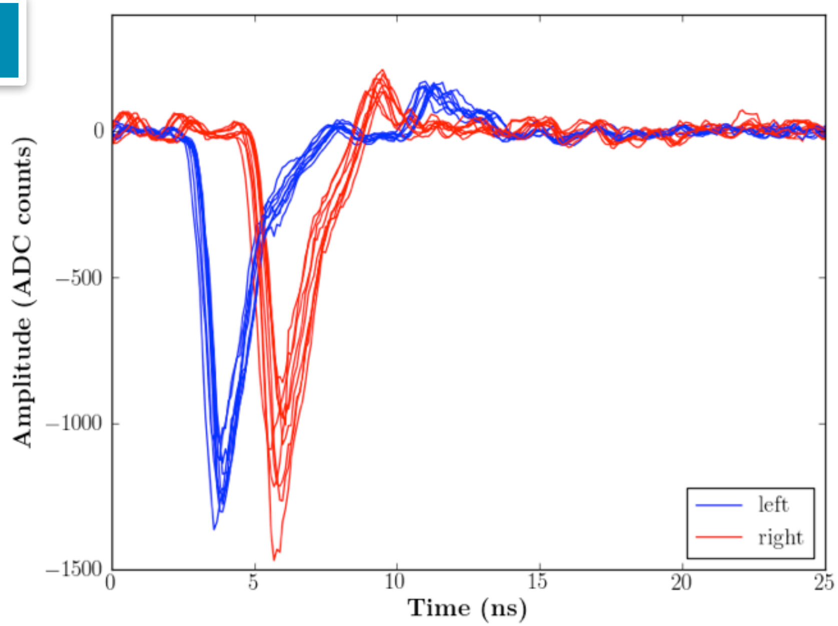


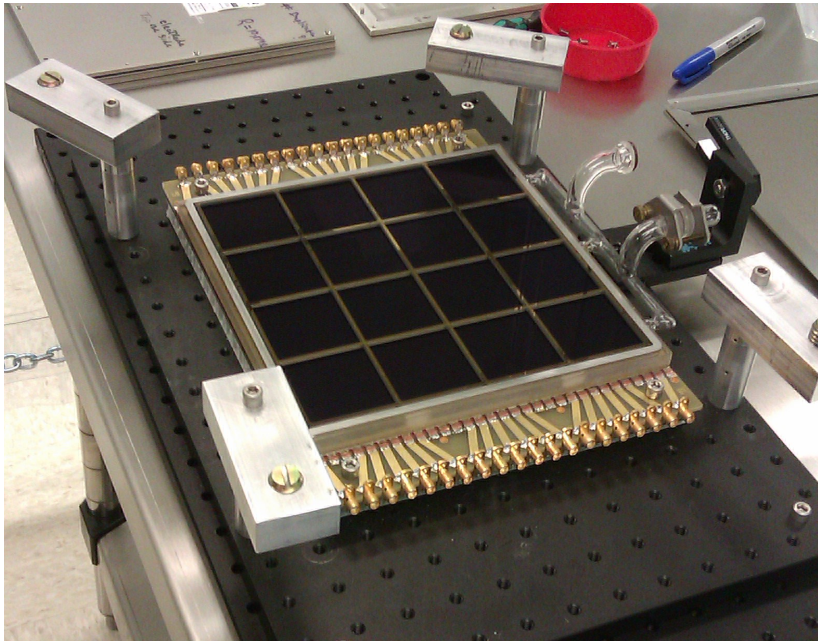
Design Drawing - September 2010

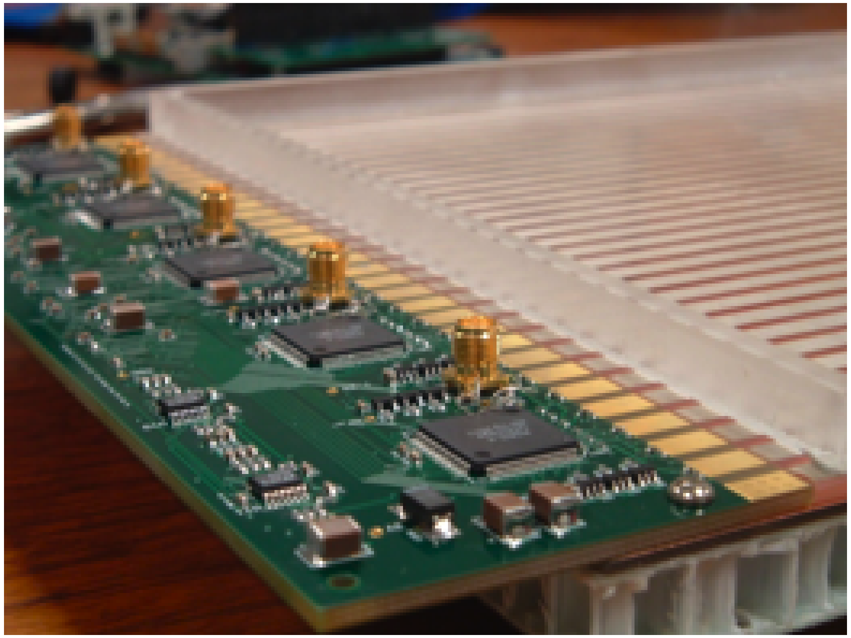


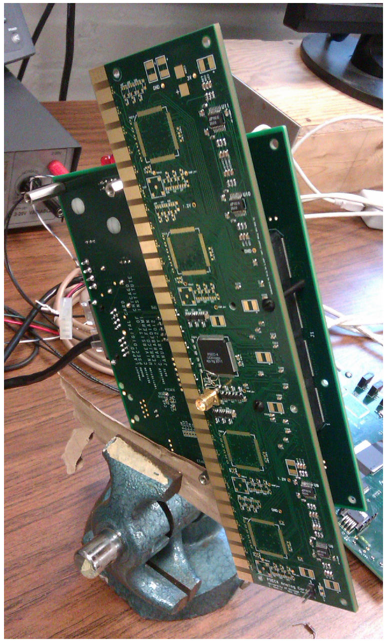
Actual Glass Parts - April 2012

LAPPD



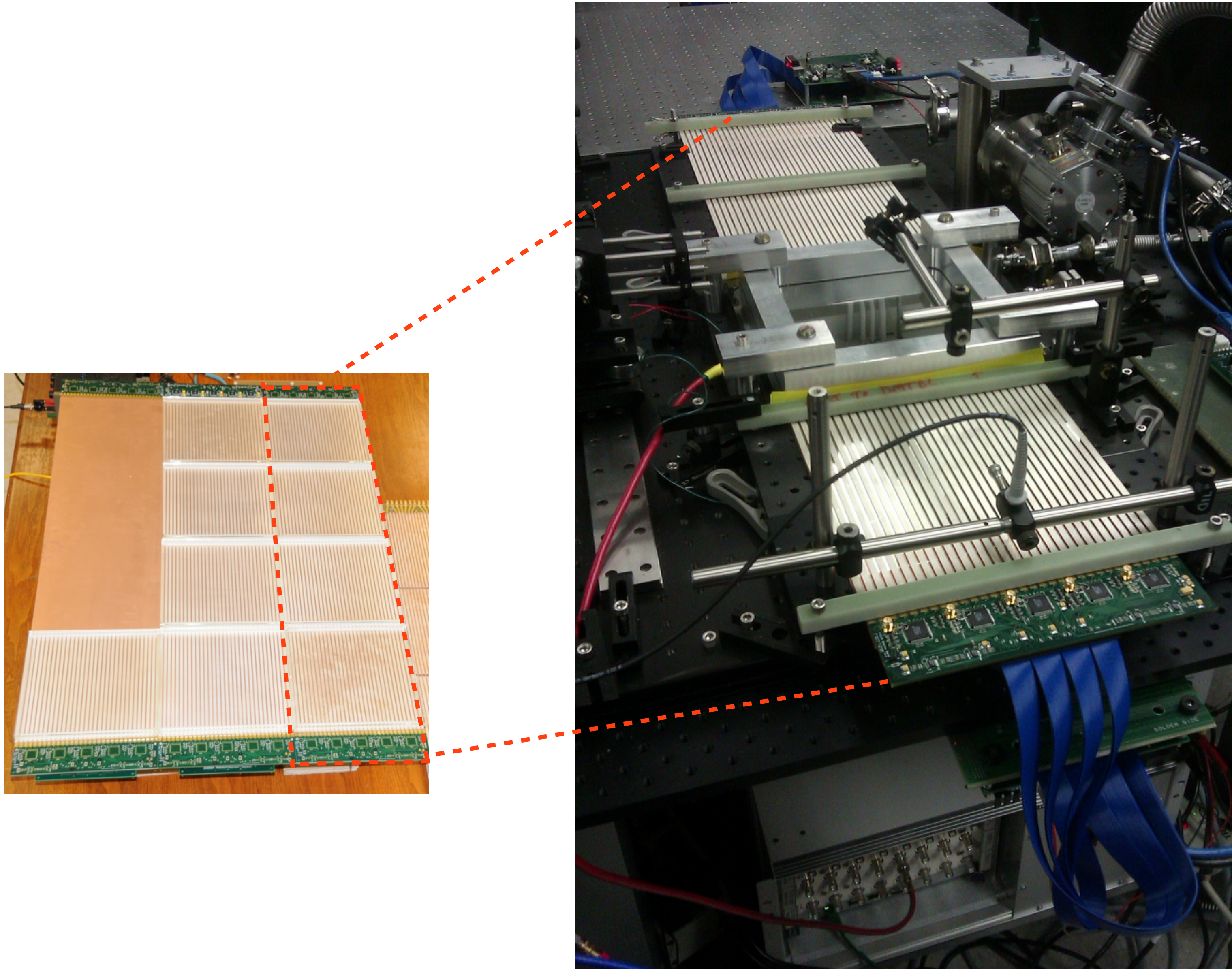






- As an R&D project, the LAPPD collaboration attacked every aspect of the problem of building a complete detector system, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes ("demountable detectors") with resealable top window, robust

LAPPD



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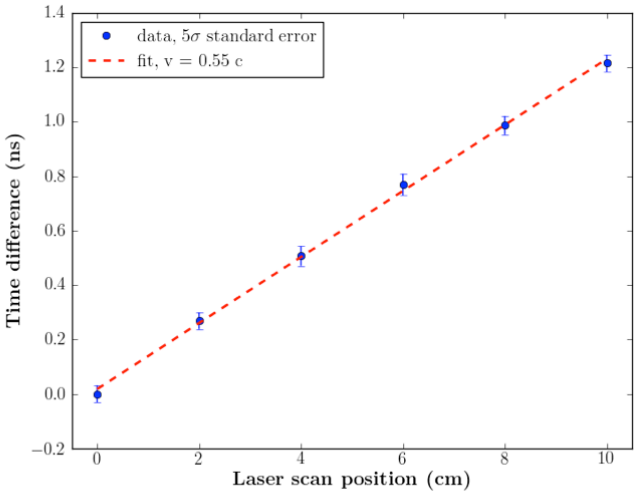
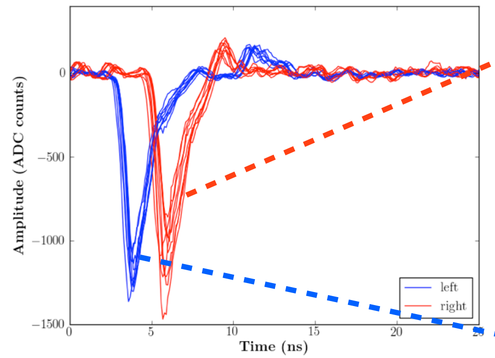
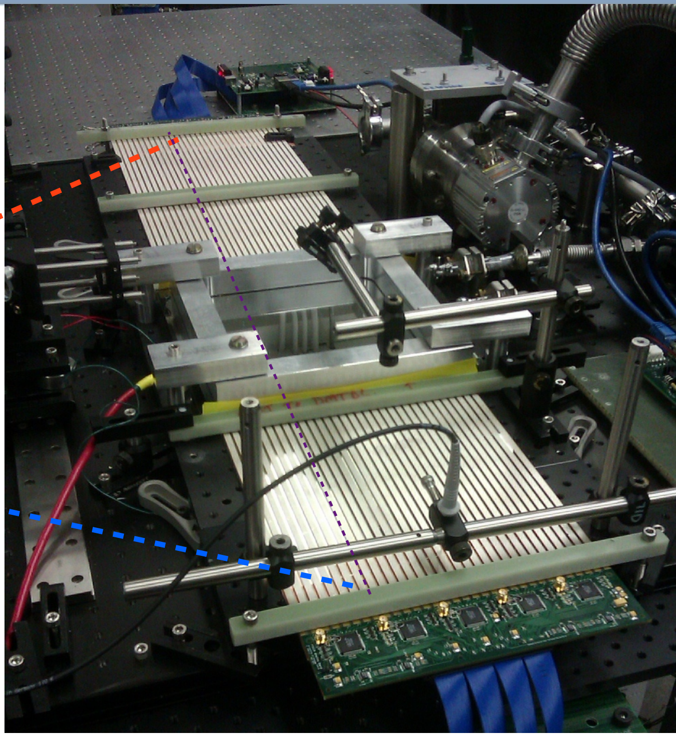
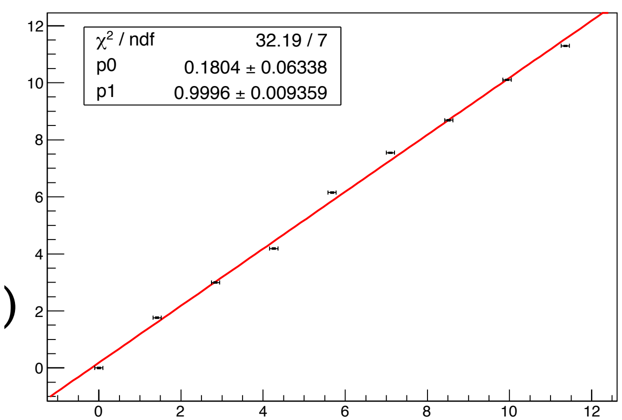






parallel position (wrt striplines)
time different between two end of anode ~2mm



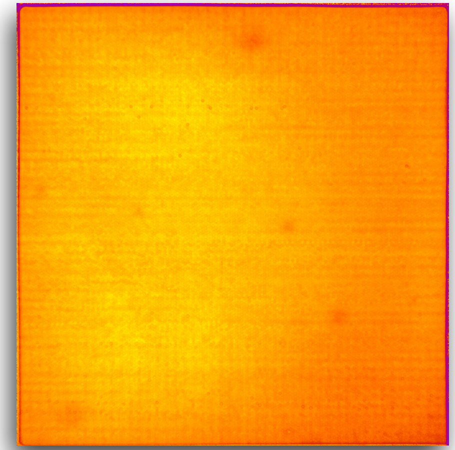
transverse position (wrt striplines)
weighted charge centroid < 1mm

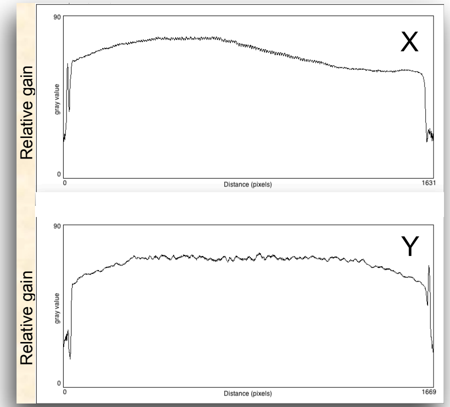
LAPPD

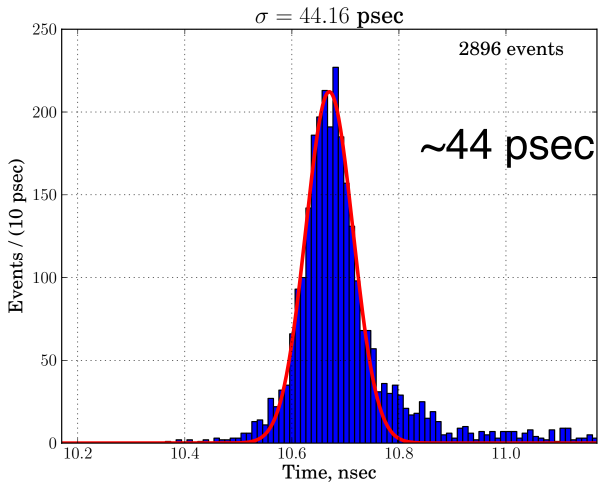
Demonstrated gains of O(10^7)

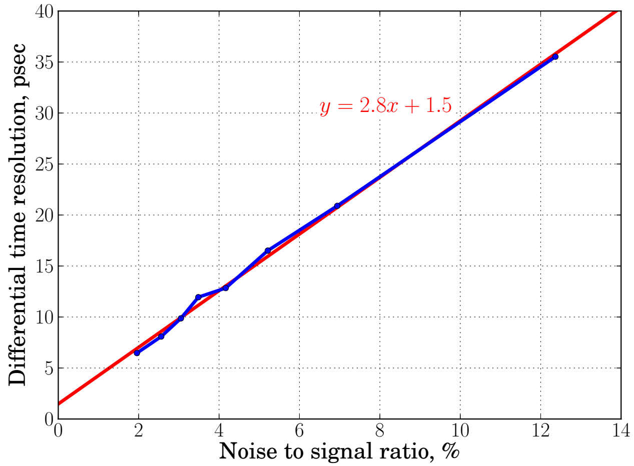
Single photoelectron time resolutions of ~40 picoseconds.

Timing in the many-photoelectron limit approaching single picoseconds









3 Generic Approaches to Event Reconstruction

Fast/parametric

(simple track fits)

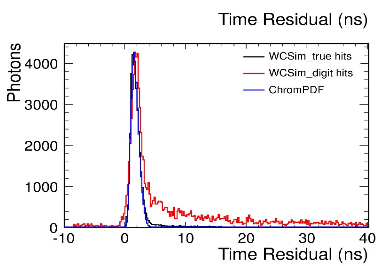
Useful for seed fits and helpful for pedagogical understanding of detector tradeoffs

Limited in Possible Complexity

Work with timing-residual based muon fits to study

- the relationship between vertex resolution and detector parameters
- improvements to track reconstruction with chromatic corrections

T. Xin, I. Anghel (Iowa State)



Working Backward

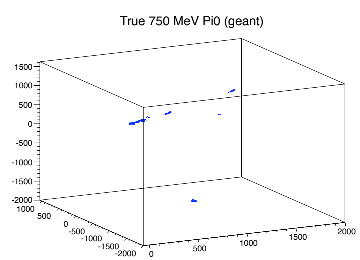
(Generalized Hough Transforms)

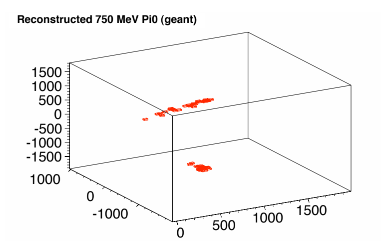
Requires no initial assumptions about event topology

Only makes use of direct light

- Isochron Transform: Causality-based Hough transform for building trakc segments from photon hit parameters
- exploring more detailed reconstruction of EM shower structure

M. Wetstein (U Chicago)





Working forward

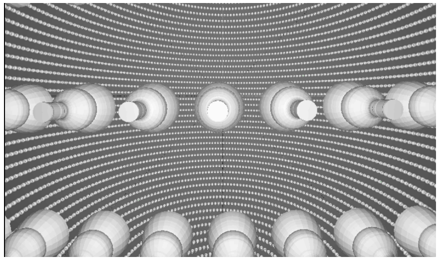
(pattern of light)

Makes fullest use of all photon information, both direct and indirect light

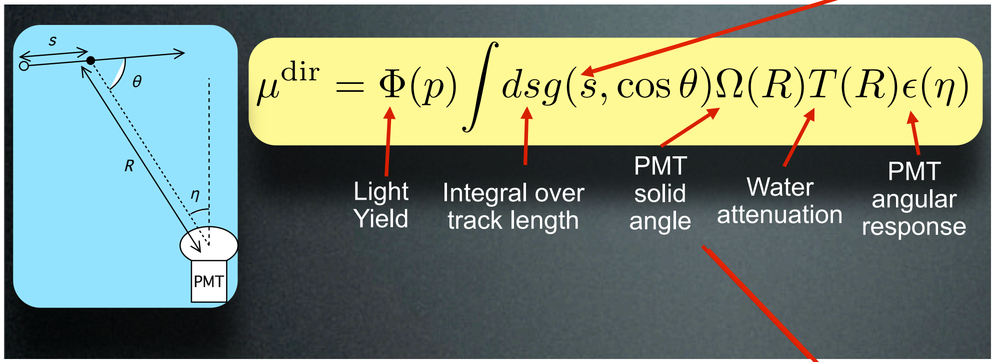
Becomes computationally prohibitive as one tries to resolve finer structure in the event topology

- Chroma: Geant-based, fast photon-tracking MC.
- Capable of rapidly generating large sample MC for a wide variety of detector designs
- Also capable of pattern-of-light fits, where the light pattern for each track hypothesis is generated in real-time.

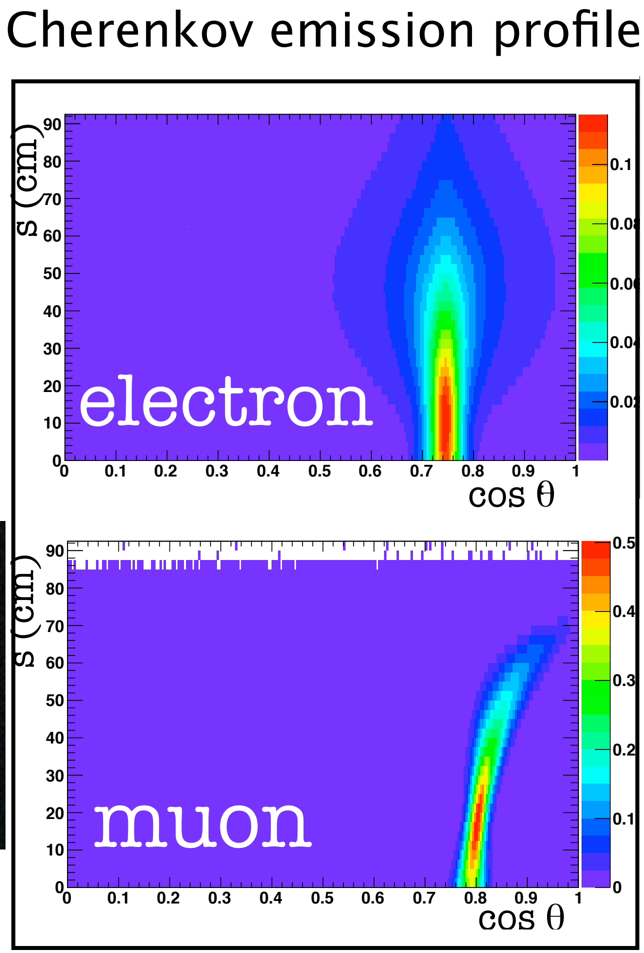
S. Seibert, A. La Torre (U. Penn)

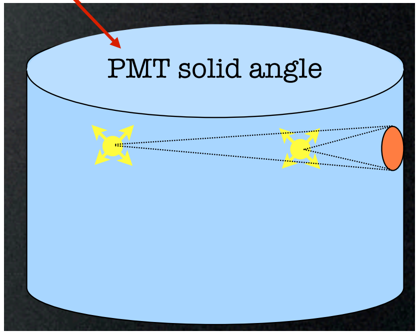


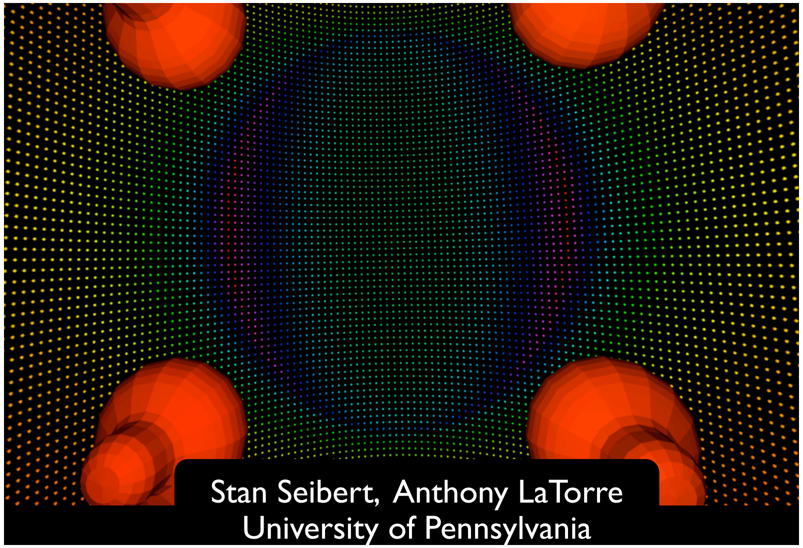
Pattern of Light Fitting



M. Wilking – Triumf

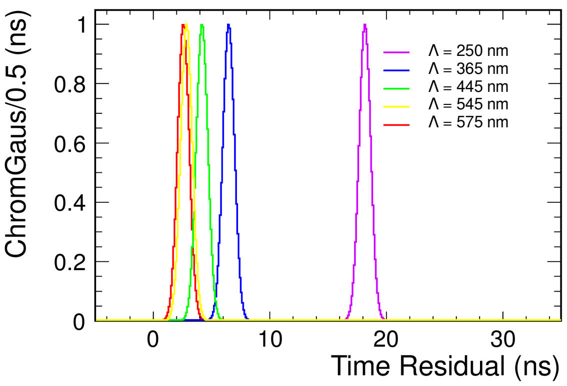


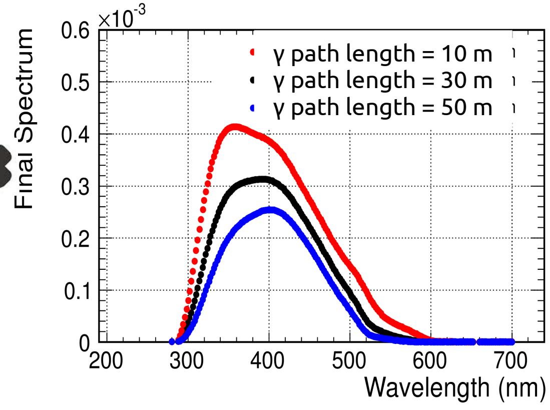


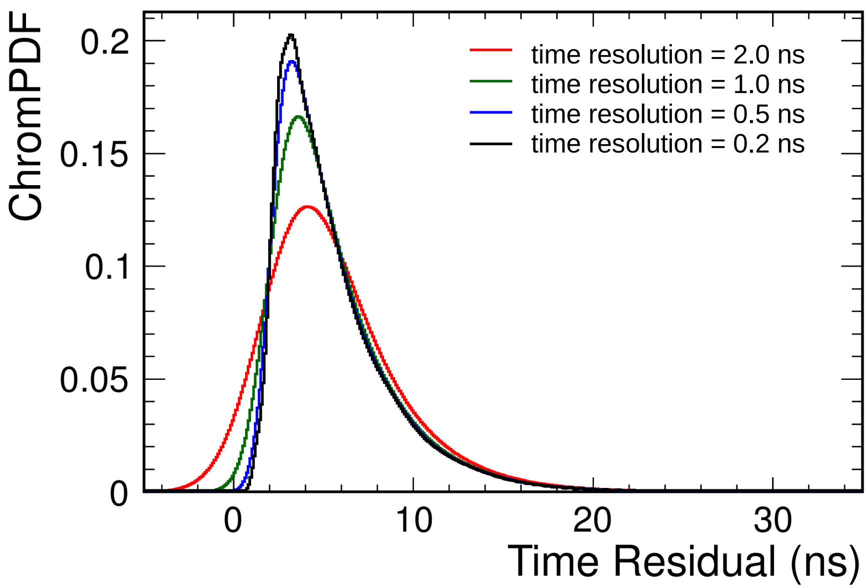


Simple Vertex Reconstruction

- A timing residual-based fit, assuming an extended track.
- Model accounts for effects of chromatic dispersion and scattering.
  - separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits (not factorized in the likelihood).
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.







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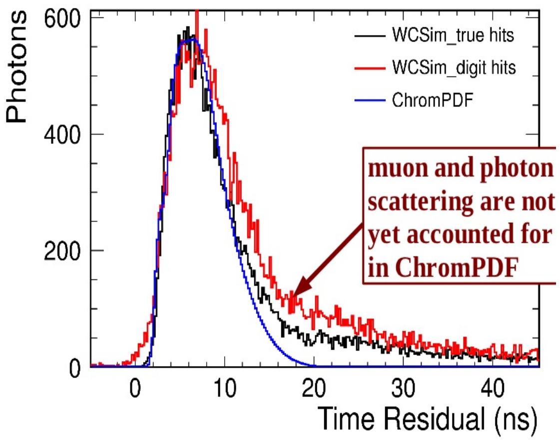
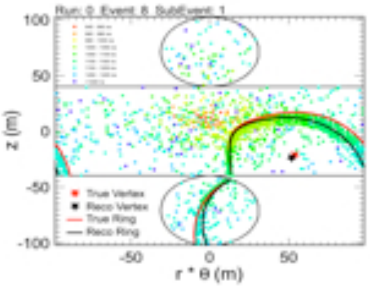
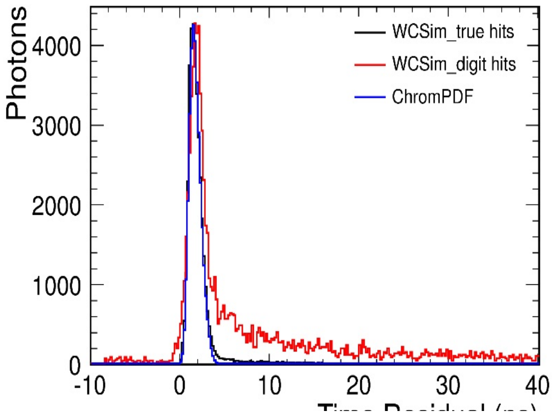
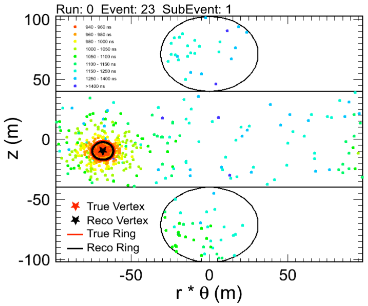




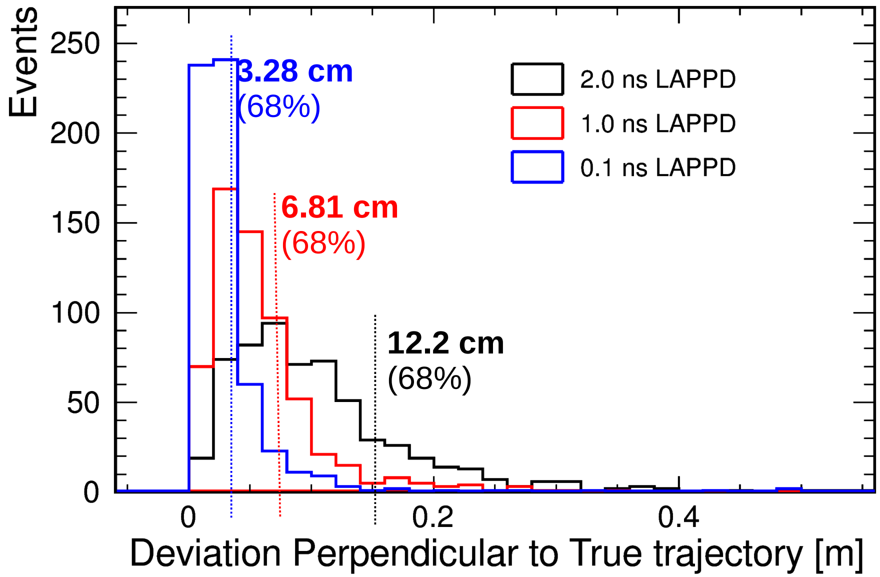




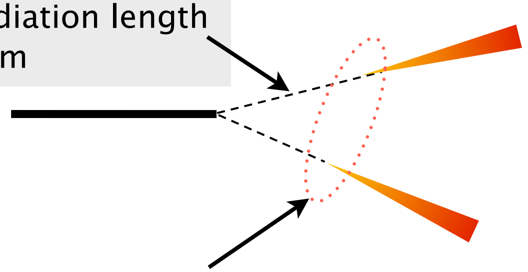
Simple Vertex Reconstruction

Plot Credits: Tian Xin

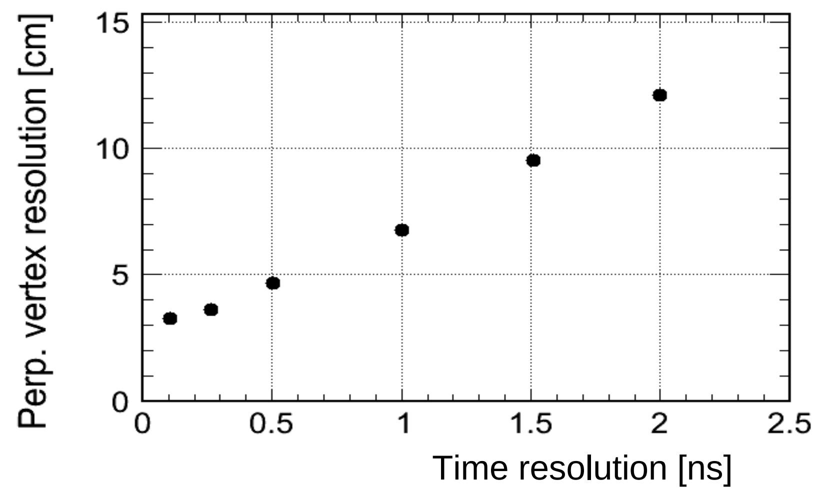
- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.
- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.



~1 radiation length
~37 cm



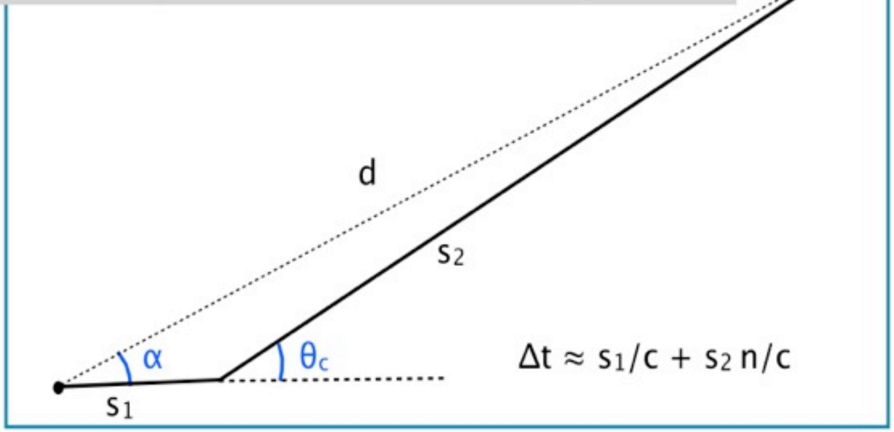
vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm



Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Isochron

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



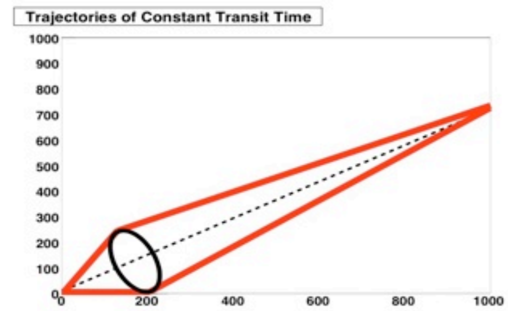
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

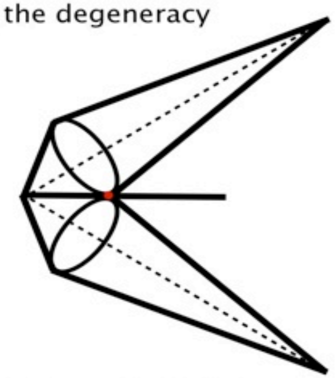
but there are two constraints:

$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

For a single PMT, there is a rotational degeneracy (many solutions).



But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy



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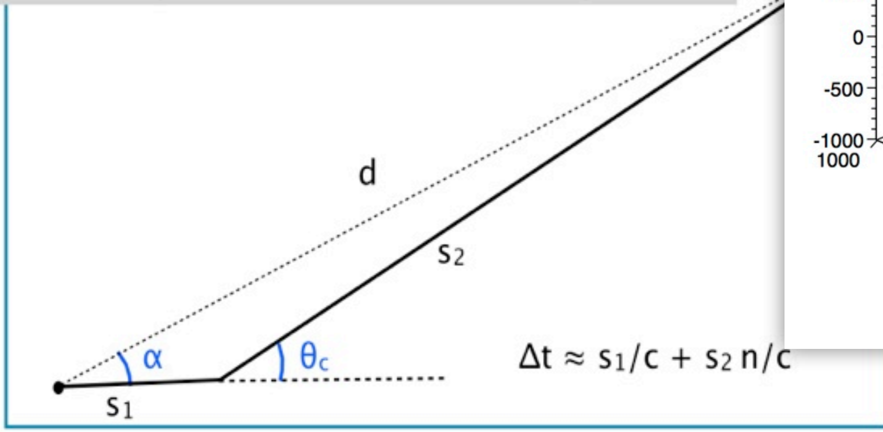

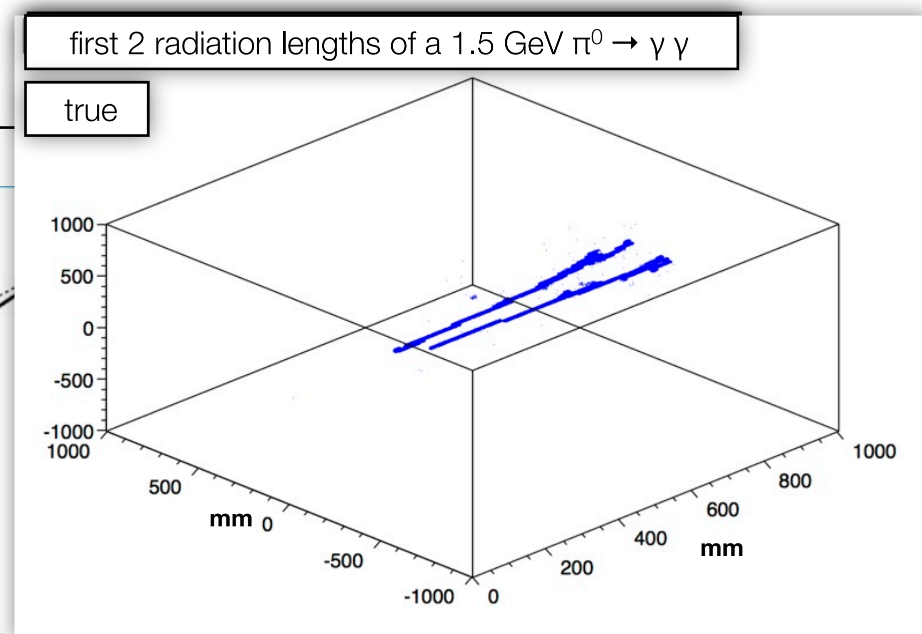

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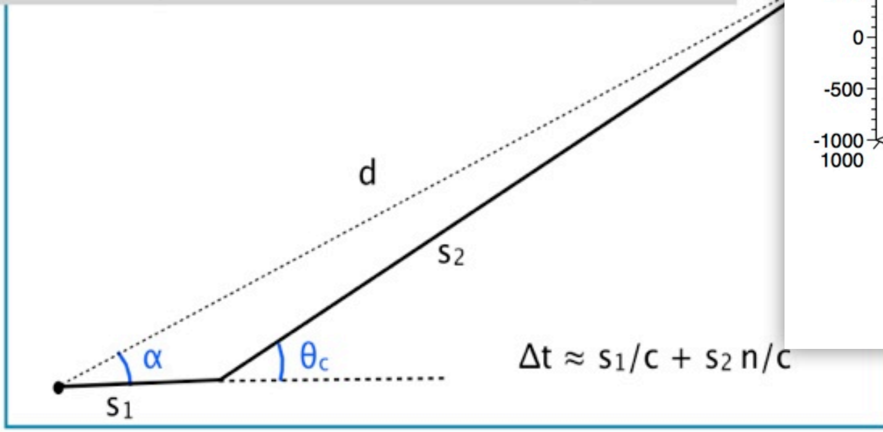

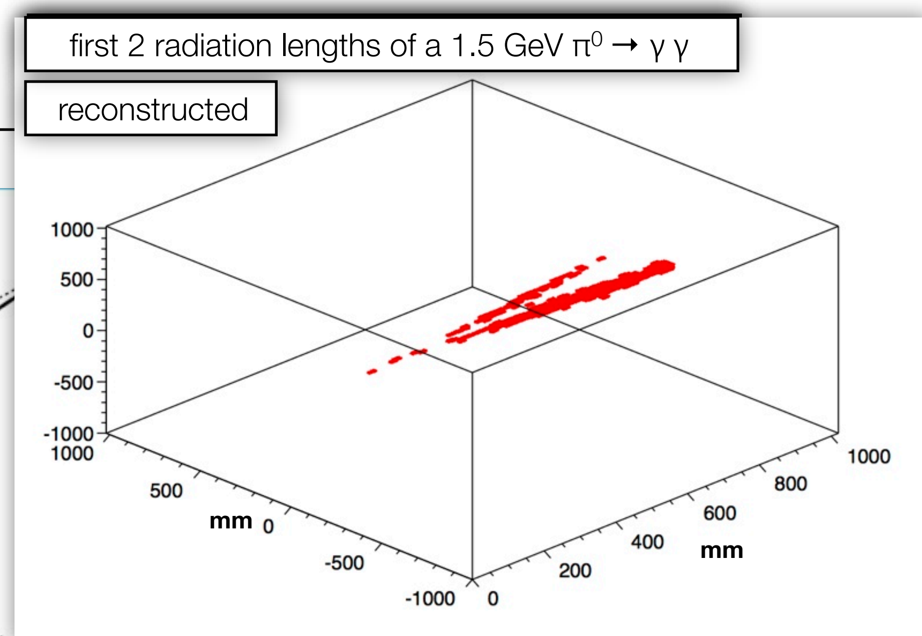

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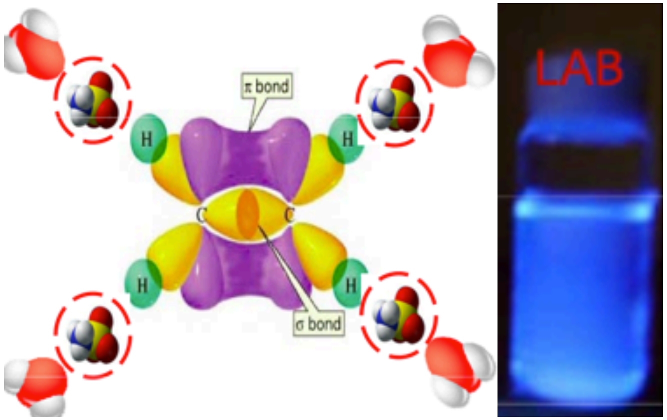
New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

Linear Alkylbenzene (LAB) – Industrial detergent
Key innovations:

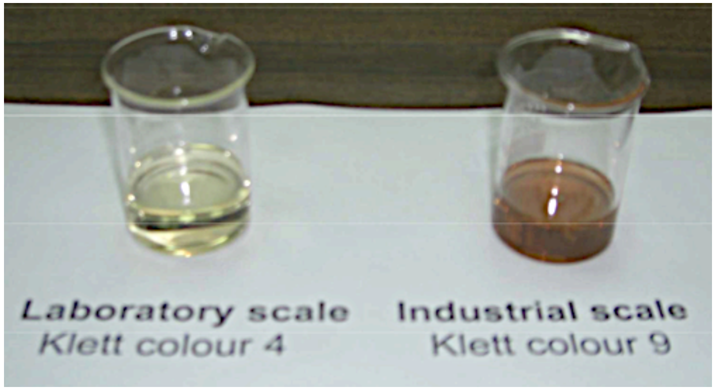
- ability to create stable solutions
- purification to achieve longer attenuation lengths

Minfang Yeh et al, Brookhaven National Lab



Ideal for large scale experiments

- Non-toxic
- Non-flammable
- Stable
- Cheap



The scintillation light might be difficult to resolve with timing, but...

- It may be possible to have both Cherenkov and scintillation light, separated in time
- The spatial/statistical gains would be considerable.

This slide is courtesy of M. Yeh. Special thanks also to Howard Nicholson.

New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

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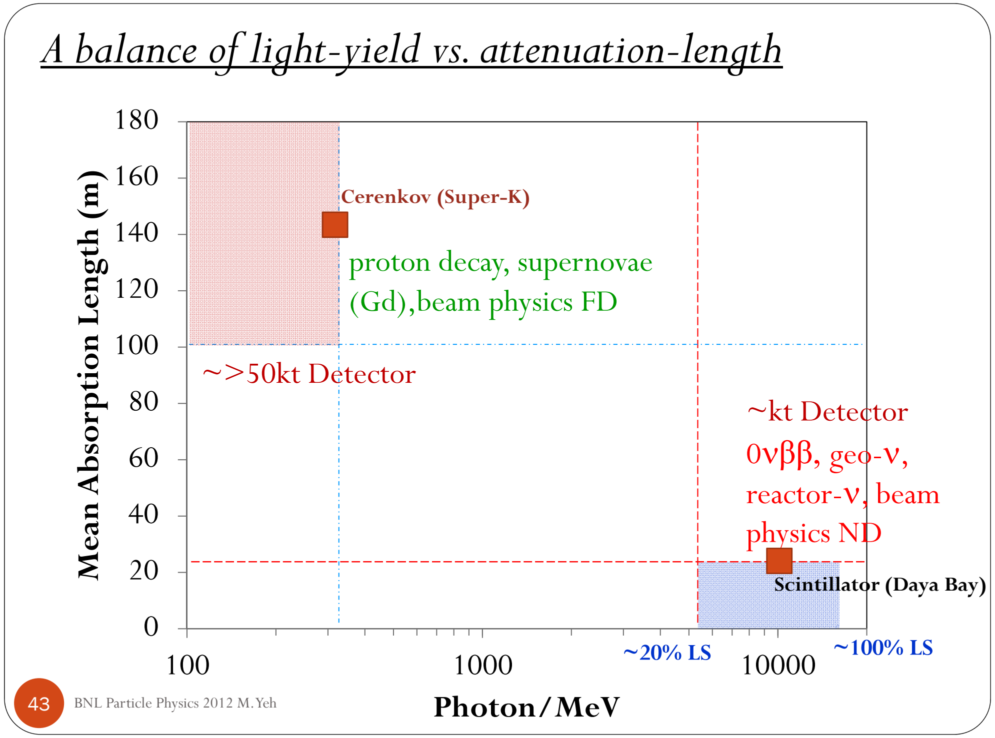

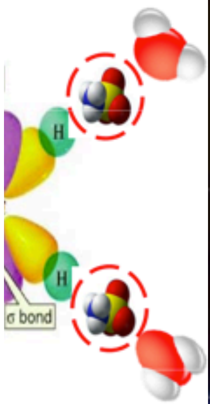

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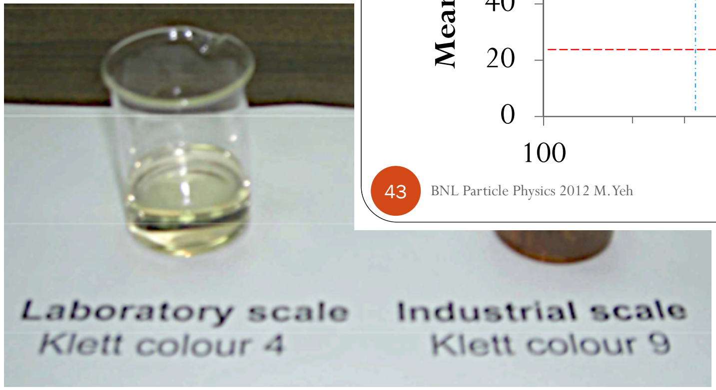

might be difficult , but...

- ve both Cherenkov and ted in time
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This slide is courtesy of M. Yeh. Special thanks also to Howard Nicholson.

Chemical Enhancements to the Target Volume

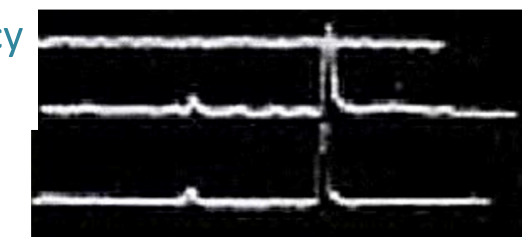
- high energy neutrino events are accompanied by *n*
- assume proton decay is not accompanied by *n*
    - * surely not for free proton
    - * also not for γ-tag states
- consider Gd addition to WC to increase n-capture tag efficiency
- Gadolinium R&D underway at SK

Inverse Beta Decay Detection with Gd

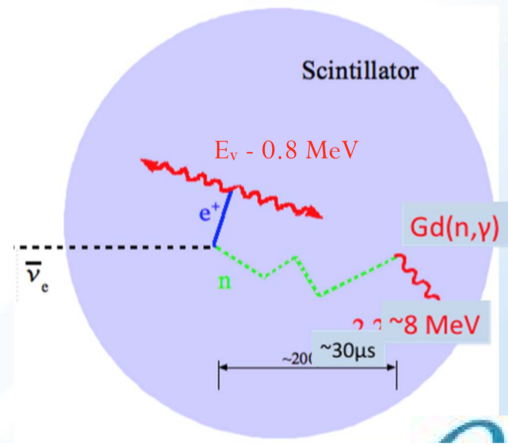
- $E_{threshold} = 1.8\ MeV$
- *'Large' cross section* $\sigma \sim 10^{-42}\ cm^2$
- *Distinctive coincidence signature in a large liquid scintillator detector*

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \gamma' s$$



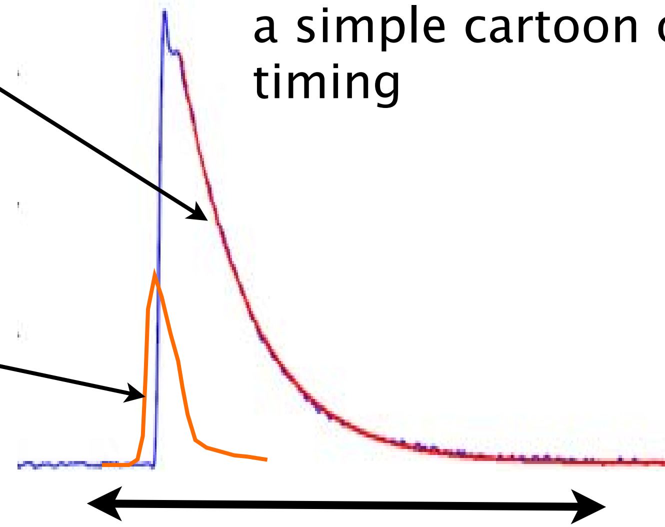
Cowan & Reines, Savannah River 1956



Discriminating Between Scintillation and Cherenkov Light

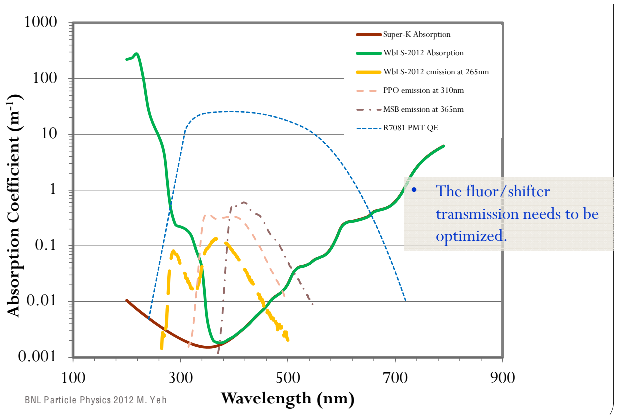
scintillation light more spread out in time

red component of the Cherenkov light arrives O(100) picoseconds earlier than the (blue-ish) scintillation light



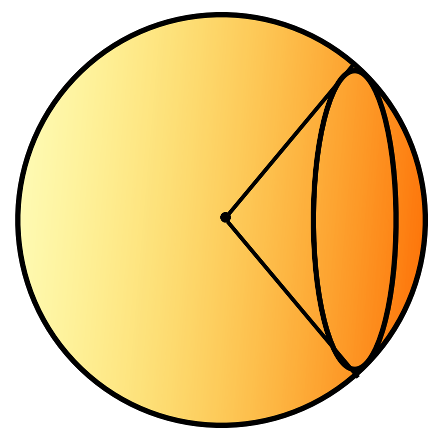
a simple cartoon of the timing

~10s nanoseconds



a simple cartoon of the spatial distribution

scintillation light is spread isotropically, while Cherenkov is constrained to a ~42 degree angle

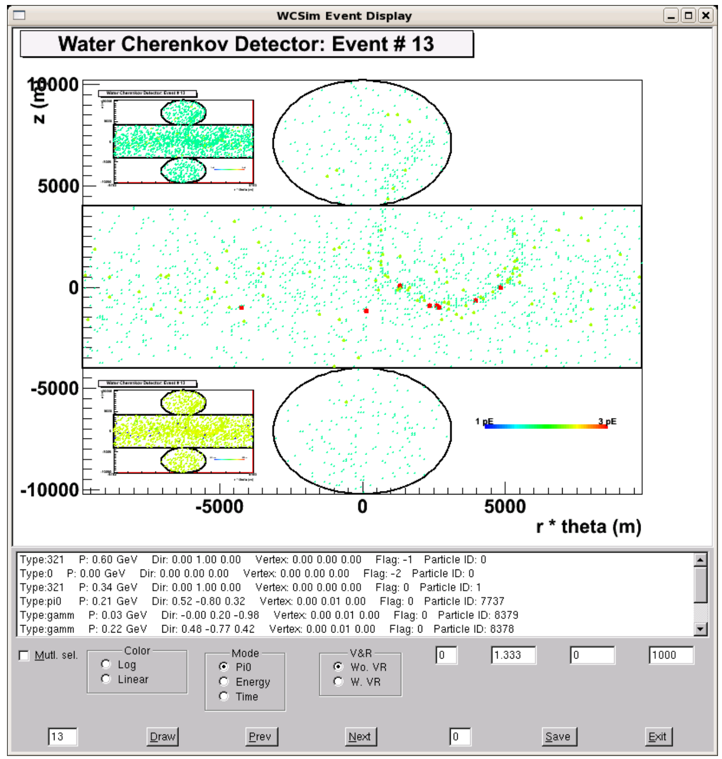


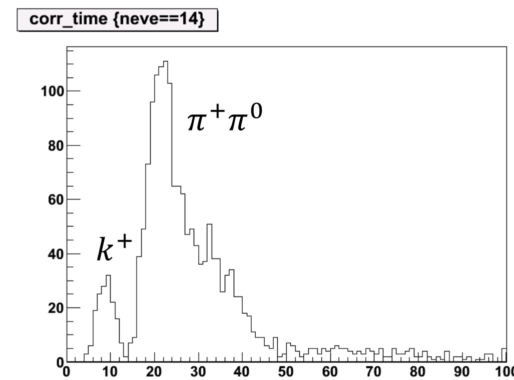
Discriminating Between Scintillation and Cherenkov Light

A quick look of $k^+ \rightarrow \pi^+\pi^0$

Can potentially tune:

relative light yield
wavelength
timing





- Very clear Cerenkov ring even without cut

Energy Resolution

Sen Qian

	KamLAND	Daya Bay II
Detector	~1 kt Liquid Scintillator	➢10 kt Liquid Scintillator
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

More photons, how and how many ?

How?

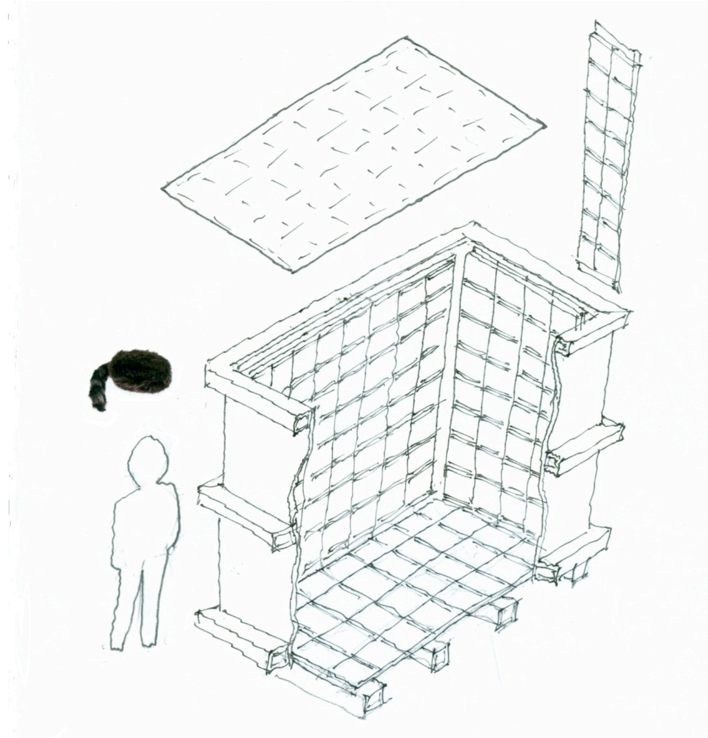
***4.3 –* 5.0 ➔ (3.0 – 2.5)% /√E**

- Increased QE
- Light collection
- Higher Light yield
- Digital photon counting?

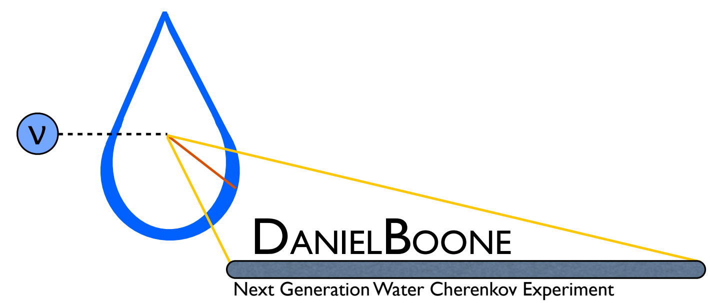
Conclusions

Closing Thoughts

- Radically new technology can come from old ideas
- Often - the enabling technology is not one innovation but the combination of several new ideas
- There is a strong future for advanced WC/ scintillation detectors
- The combination of fine timing and space resolution makes for much improved tracking and analysis capabilities
- The introduction of liquid enhancements (Gd, WbLS, etc) can radically change sensitivities to low energy and high-mass particles
- Need for demonstration experiments over the next few years
- Need for a strong and imaginative community!



Richard Northrop



Thank you

Thanks also to all of my LAPPD and fast timing
colleagues for all of the work presented in this talk