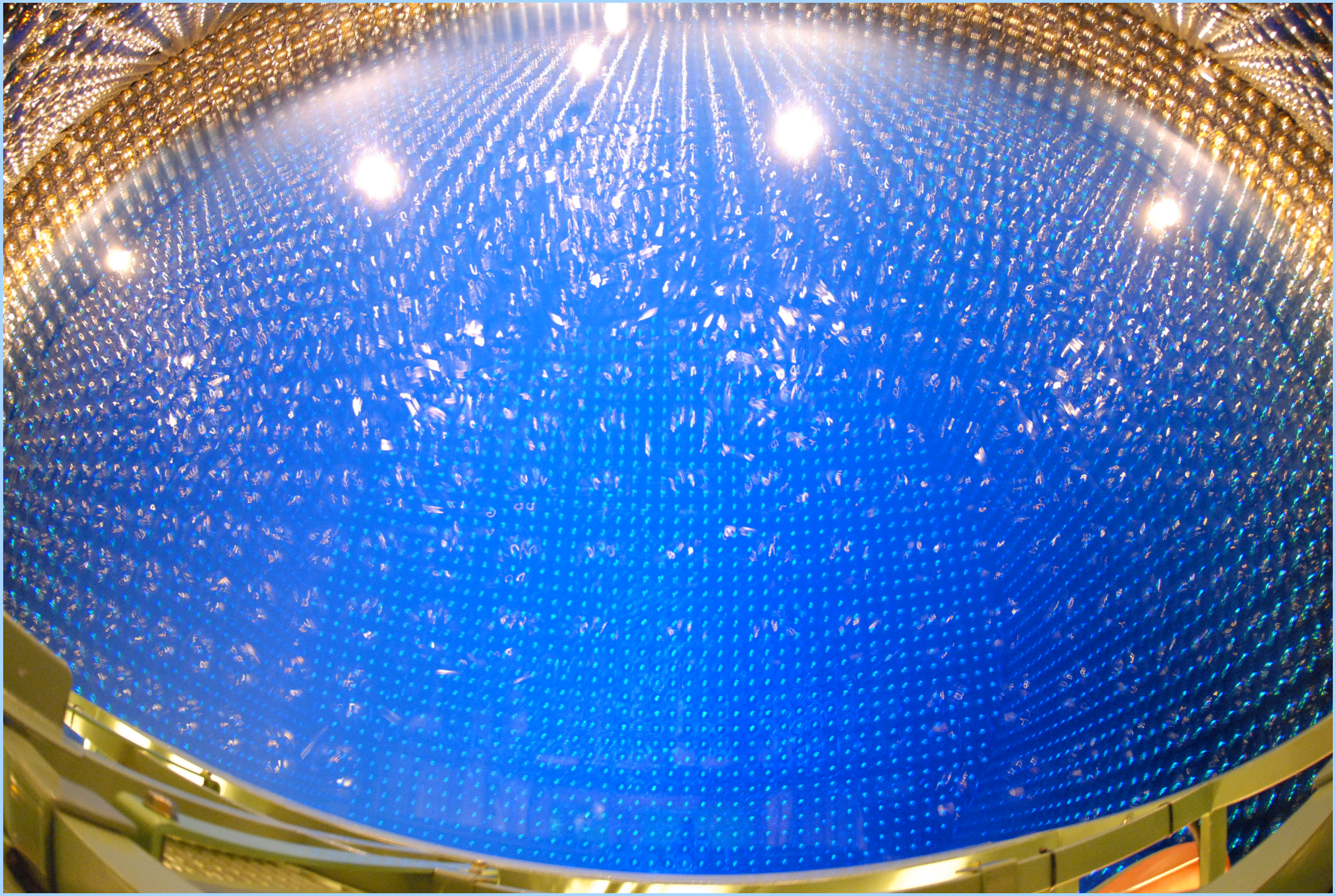
The Factors That Limit Time Resolution for Photon Detection in Large Cherenkov Detectors

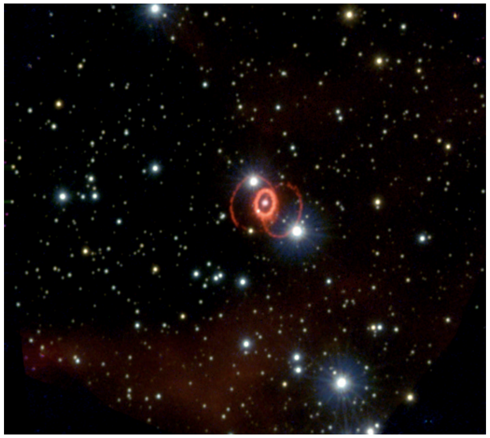


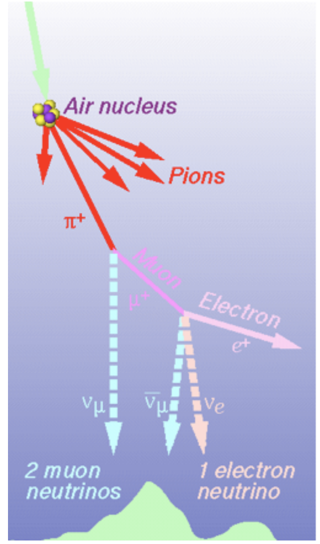
Kate Scholberg, Duke University
Chicago, April 2011

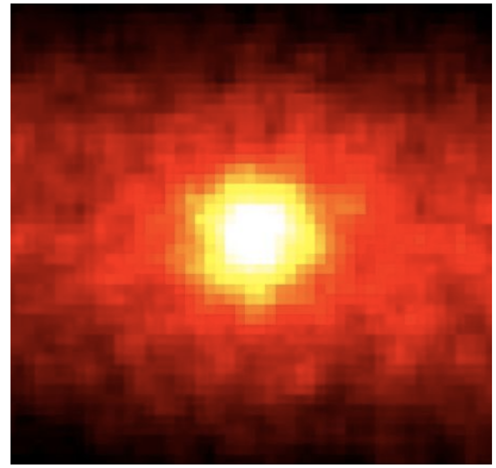
OUTLINE

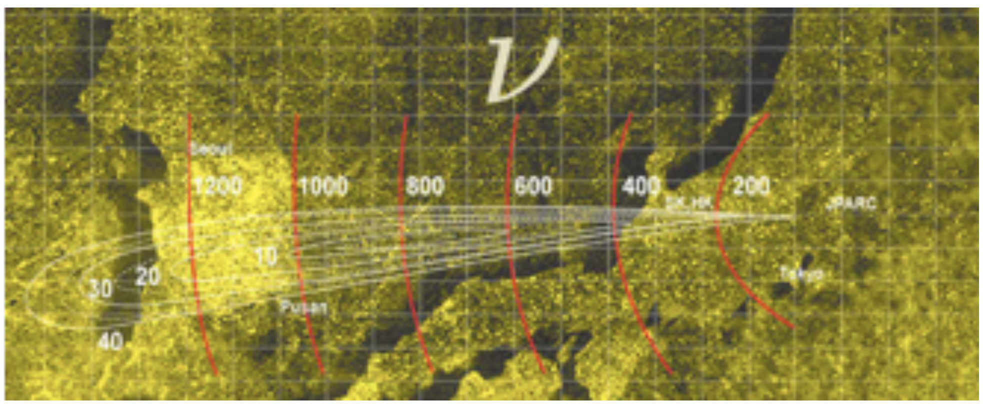
- Overview/physics motivation
- Event reconstruction in water Cherenkov
- Limiting factors (for event reconstruction)
- A toy study with SK reconstruction
- Comments (my personal opinion)

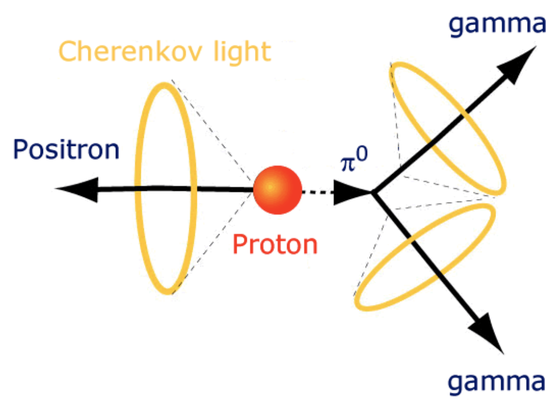
Physics in Large Underground Water Cherenkov Detectors









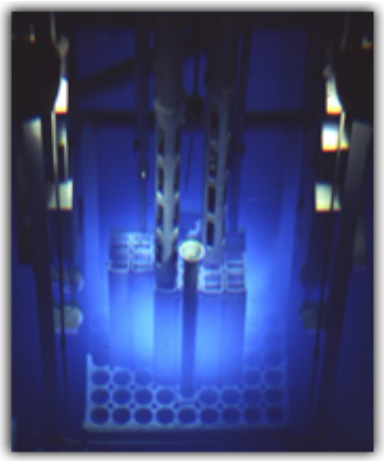


Discovery of ν mass & mixing
Solar neutrino flux
SN1987A
Proton lifetime limits
Indirect WIMP limits ...

→an accomplished past... and more potential for the future!

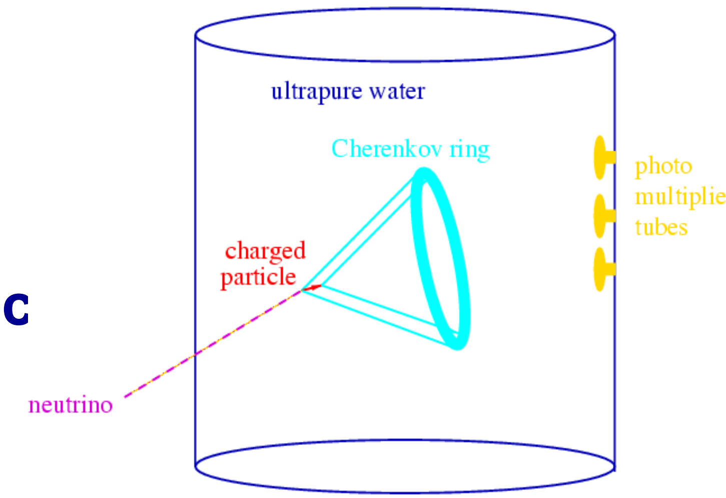
Water Cherenkov Detectors

Charged particles produced in neutrino interactions emit Cherenkov radiation if $\beta > 1/n$



$$\cos\theta_C = \frac{1}{\beta n}$$

$\theta_C = 42^0$ for relativistic particle in water



Thresholds (MeV)

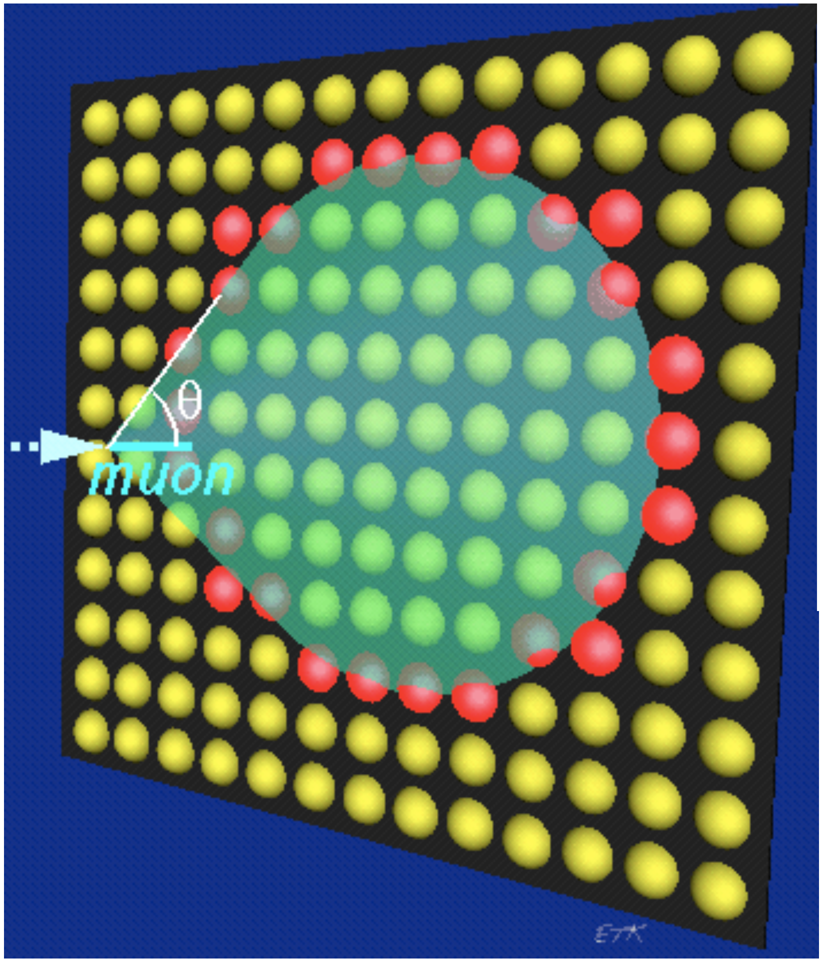
$$E_{th} = \frac{m}{\sqrt{1 - 1/n^2}}$$

e	~0.8 MeV
μ	~160 MeV
π	~210 MeV
p	~1400 MeV

No. photons ∝ energy loss

- cheap detector material! Can make big
- relatively few photons/MeV wrt scintillator (factor of $\sim 10^2$)
- Cherenkov threshold means that heavy particles, and low energy γ's/e's may be invisible
- detector thresholds usually at least ~few MeV

Photomultiplier tubes detect single photons



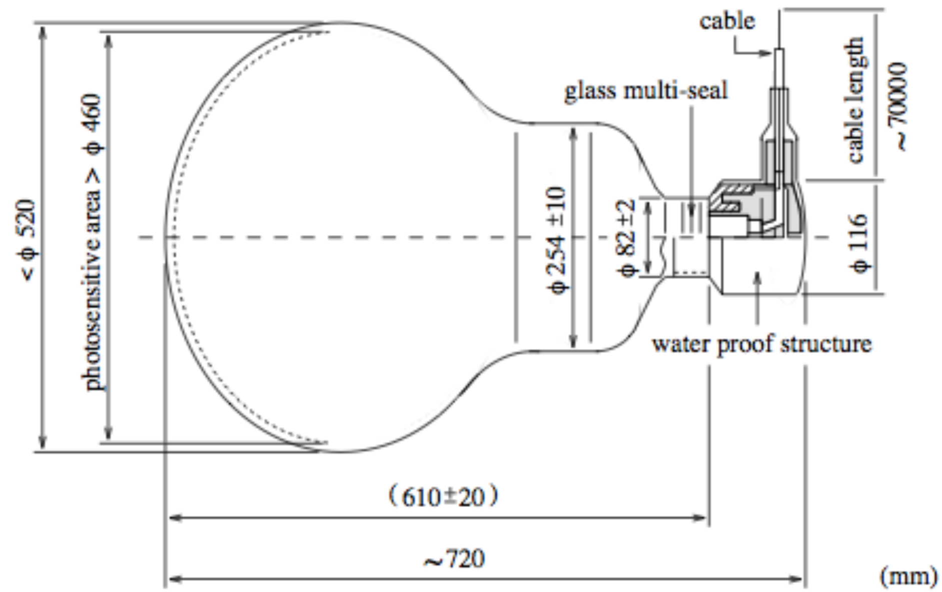
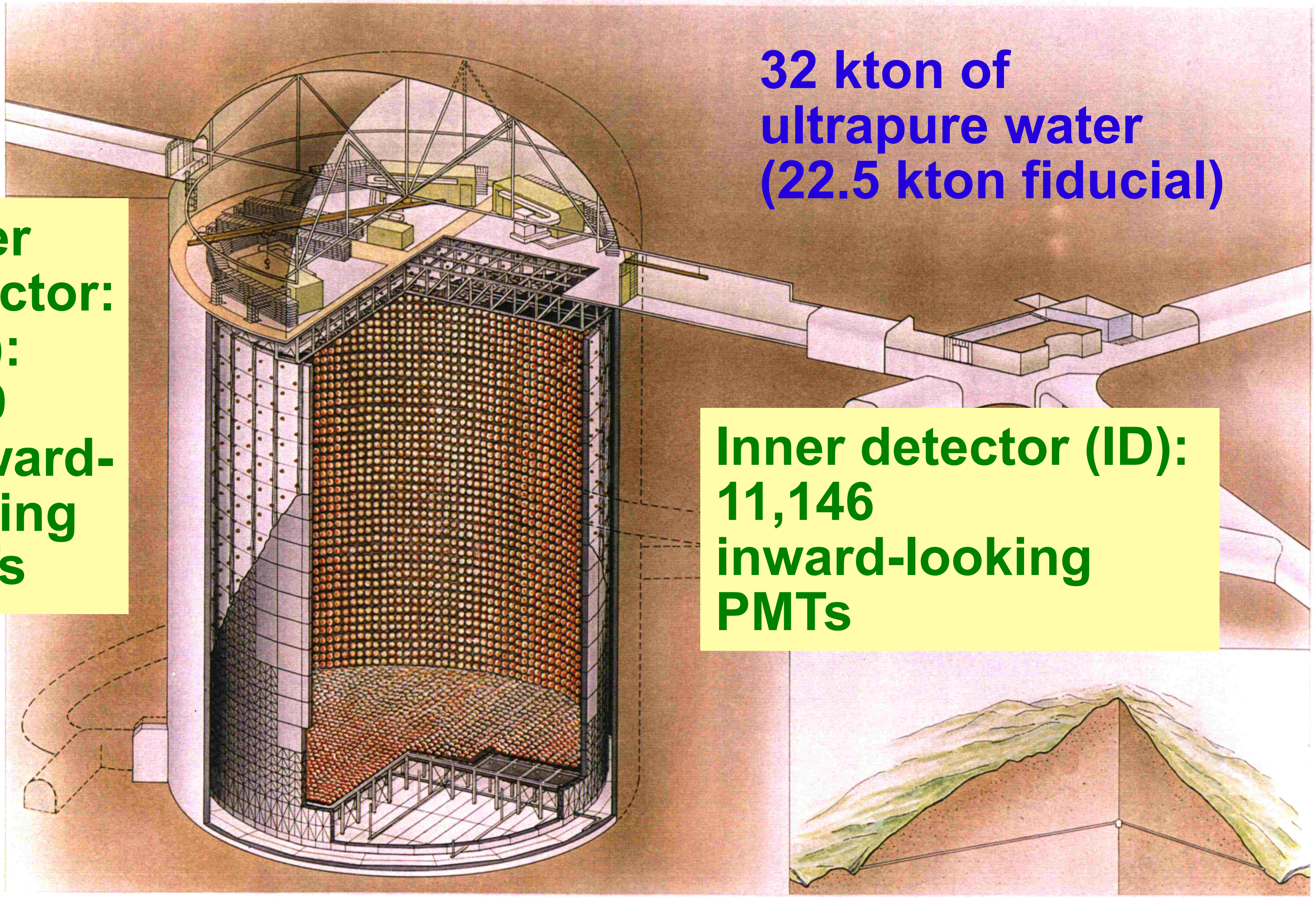


Fig. 7. Schematic view of a 50 cm PMT.

Photons → photoelectrons
→ amplified PMT pulses
→ digitize charge, time
→ reconstruct vertex, energy, direction

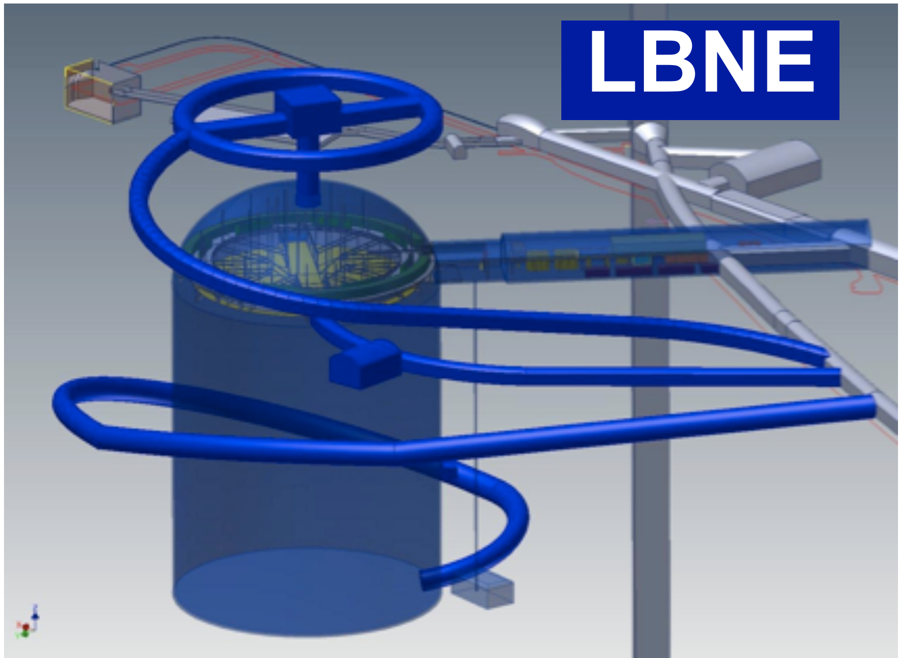
Super-Kamiokande

Water Cherenkov detector in Mozumi, Japan

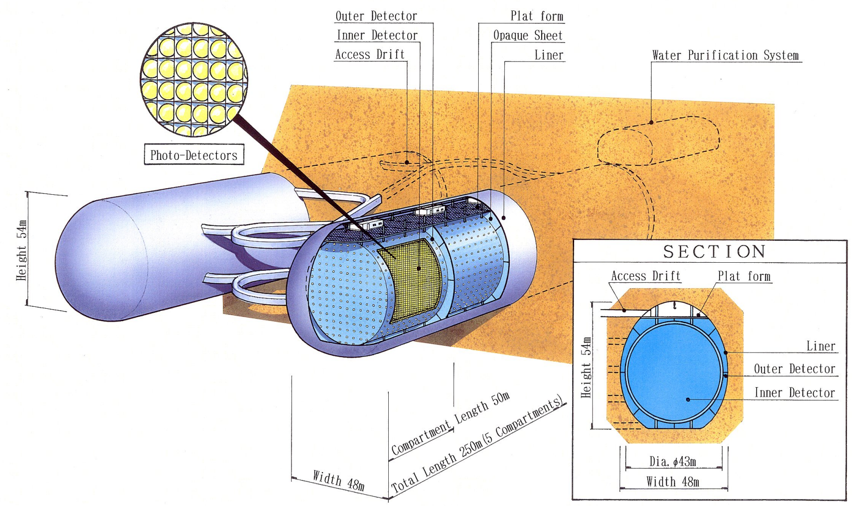


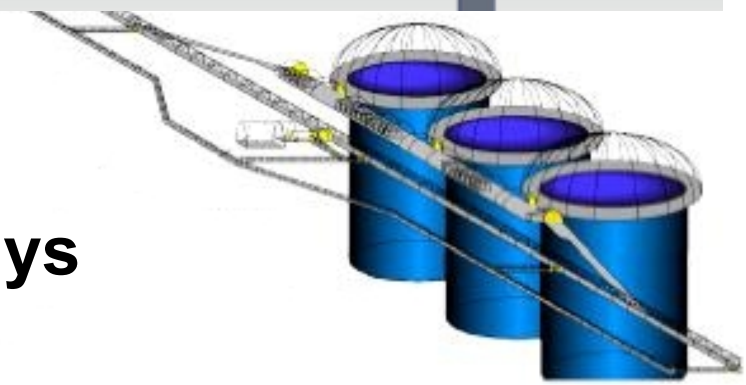
Refurbished in 2008 with new electronics; now running as 'Super-K IV'

Possible future water Cherenkov projects

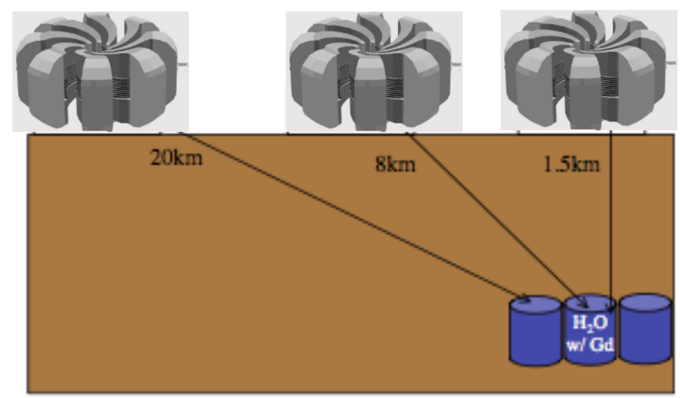


Hyper-K





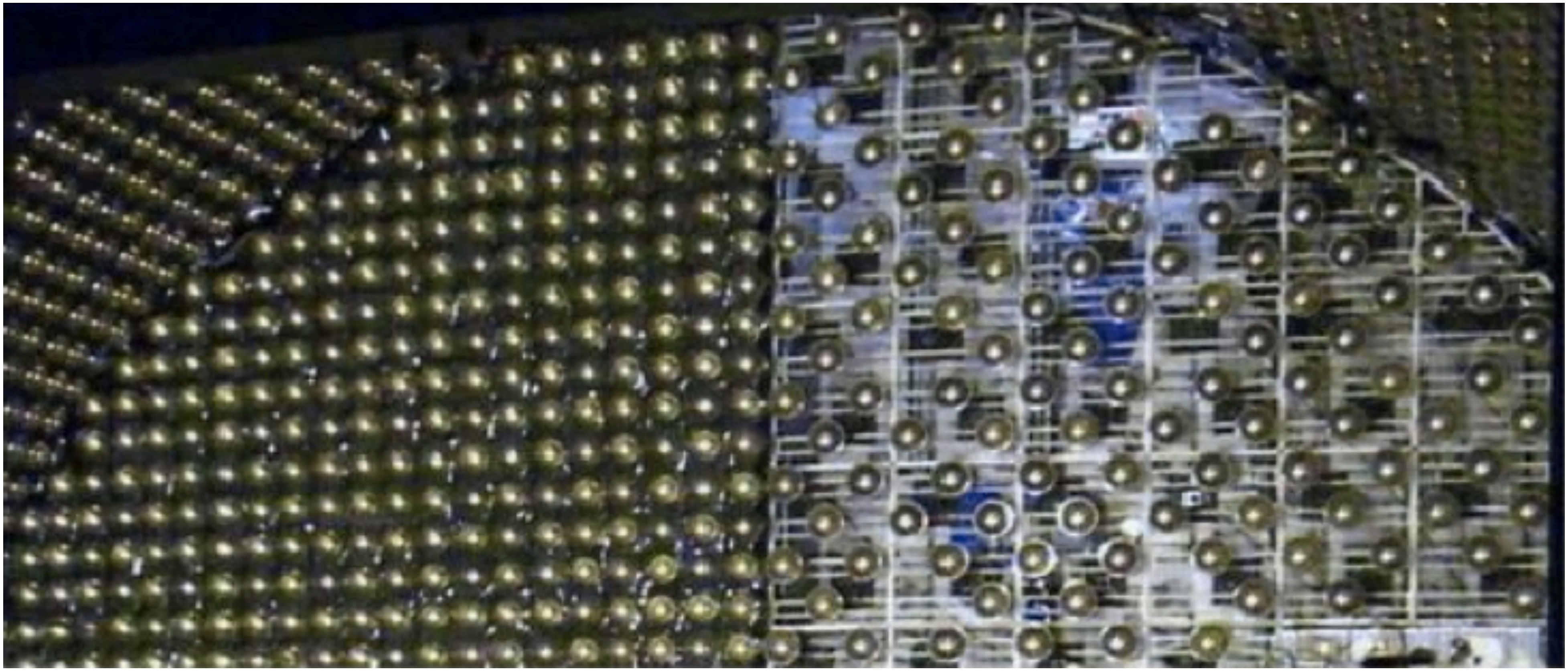
Memphys



DAEδALUS

Require ~few x 10^4-10^5 PMTs: a driving cost!

PMT Coverage

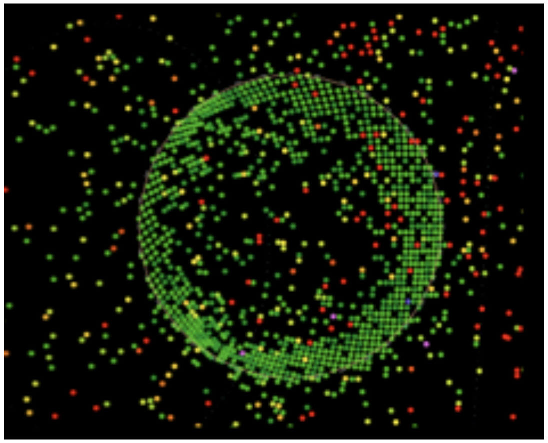


SK I (40%)

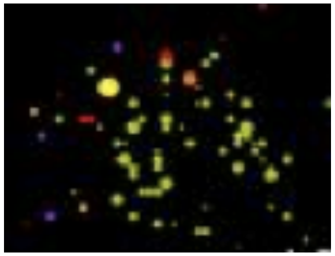
SK II (19%)

More realistic for next generation due to high PMT cost

Physics Goals: SK and next generation water Cherenkov detectors



"High Energy" 50 MeV-100 GeV
- Neutrino physics with long baseline beam
- Proton decay
- Atmospheric neutrinos

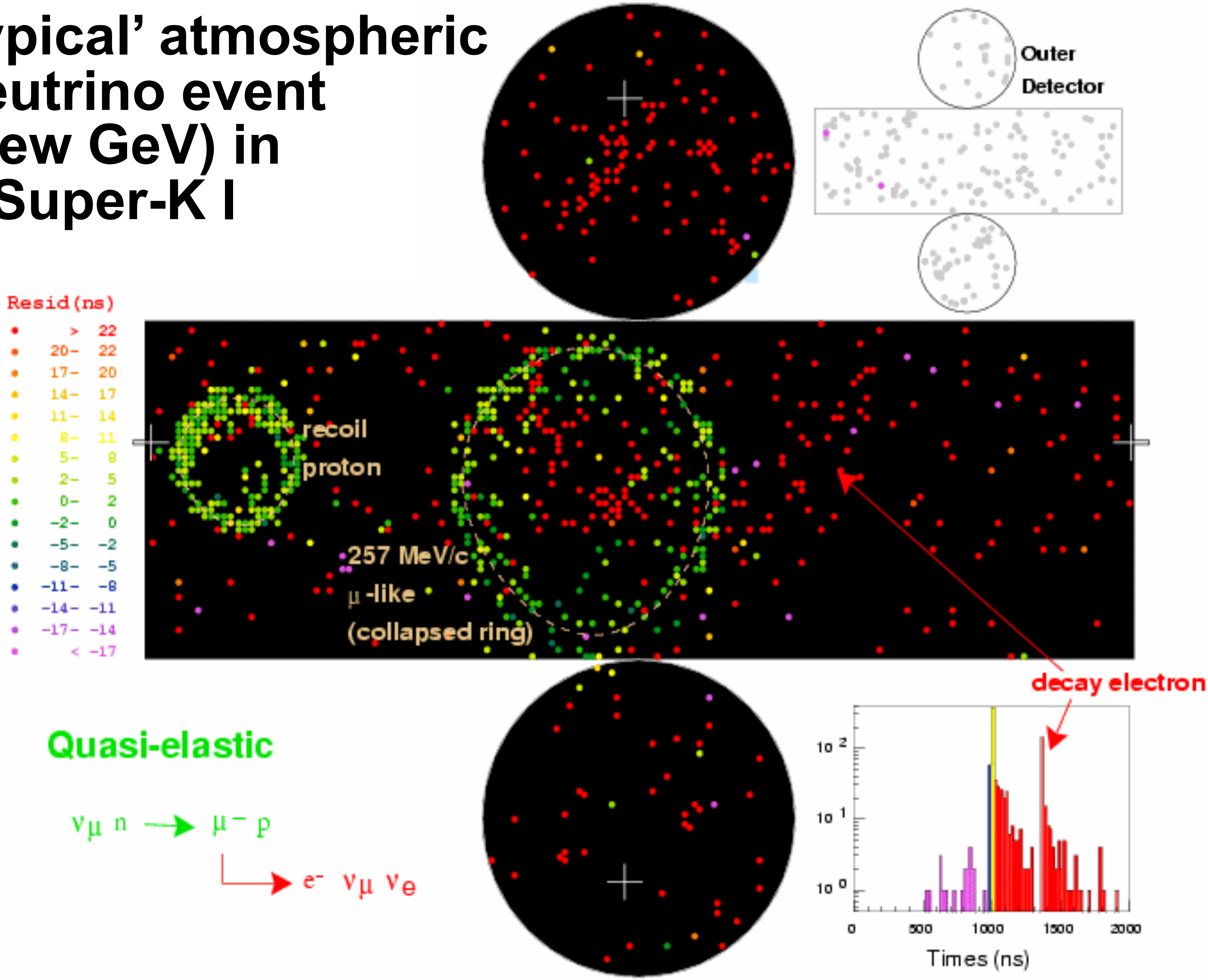


"Low Energy" 5-50 MeV
- Supernova neutrinos: relic and Galactic
- Solar neutrinos
- Neutrino CPV w/DAEδALUS

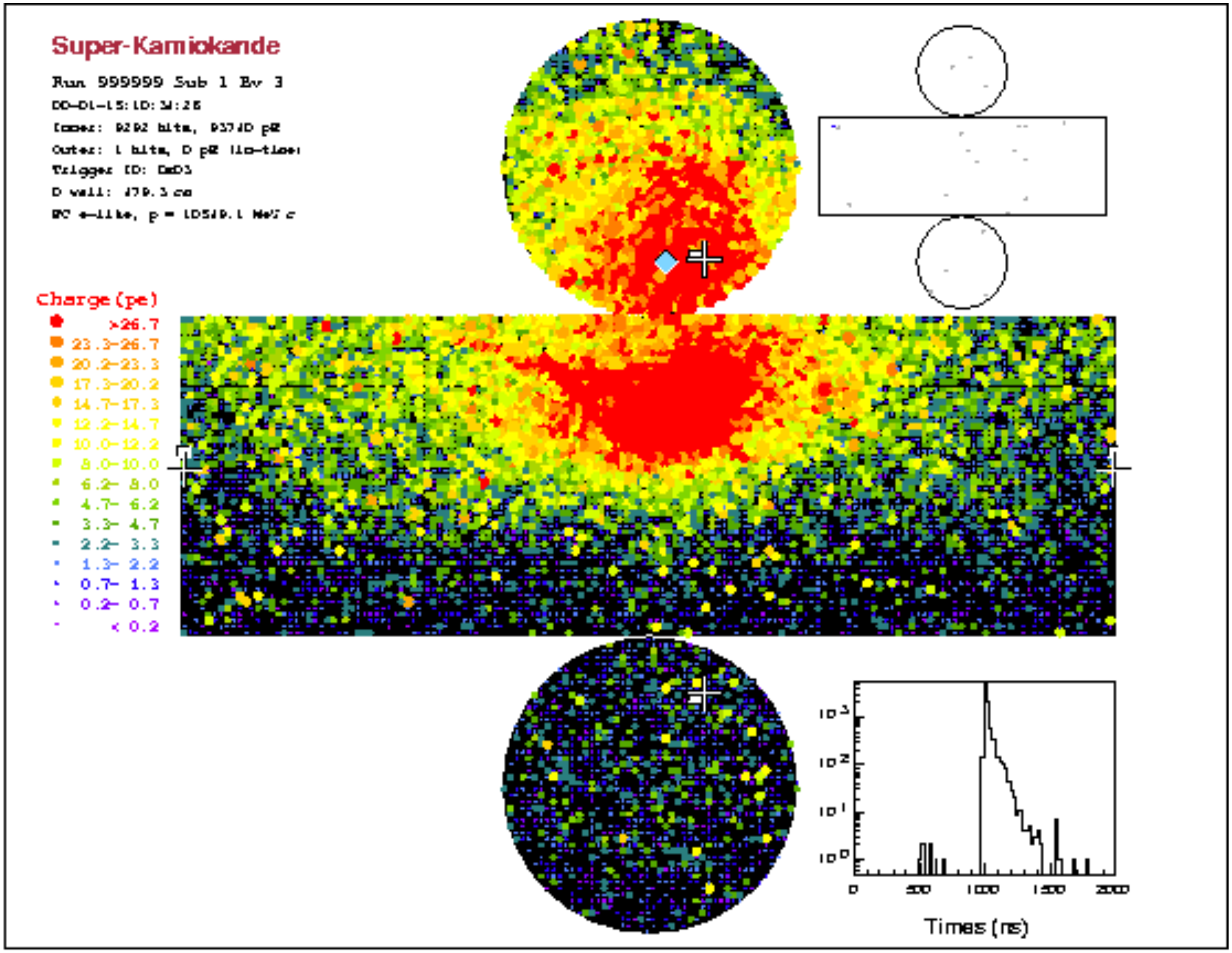
Reconstruction issues tend to be quite different for low and high energy events

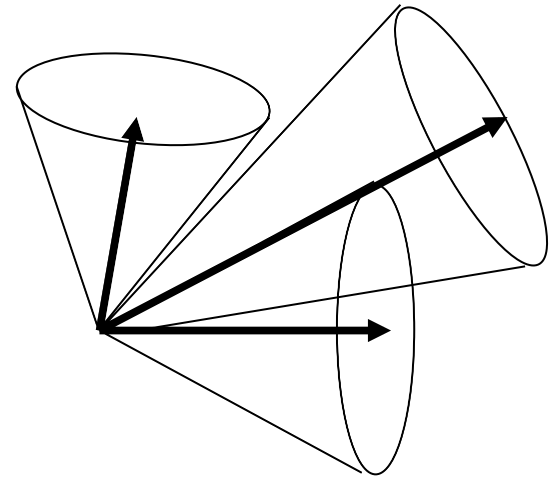
I will zoom in on high energy reconstruction for this talk (important for next generation beams)

‘Typical’ atmospheric neutrino event (~few GeV) in Super-K I



The reconstruction task: vertex, energy, direction, PID; count and fit multiple rings





Many fitters in use for different purposes

High energy neutrino reconstruction

- vertex and direction fit

  by timing residual

- ring counting

  Hough transform for seed,
  likelihood method

- particle ID (e vs μ) for each ring

  likelihood method by
  comparing to expected charge

- precise fitting

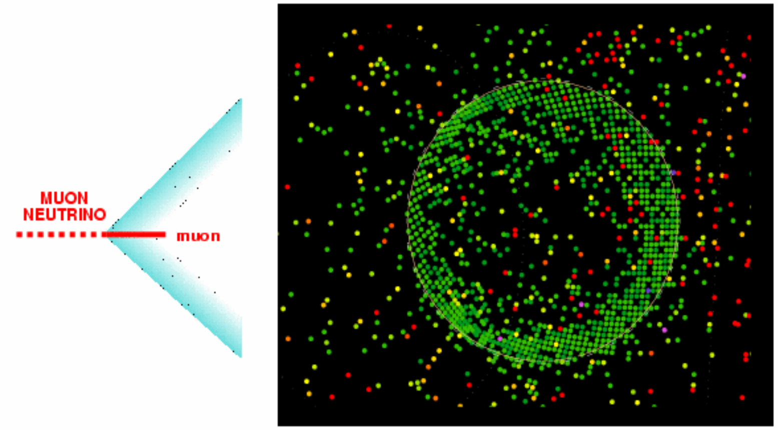
  for 1-ring, using particle ID info

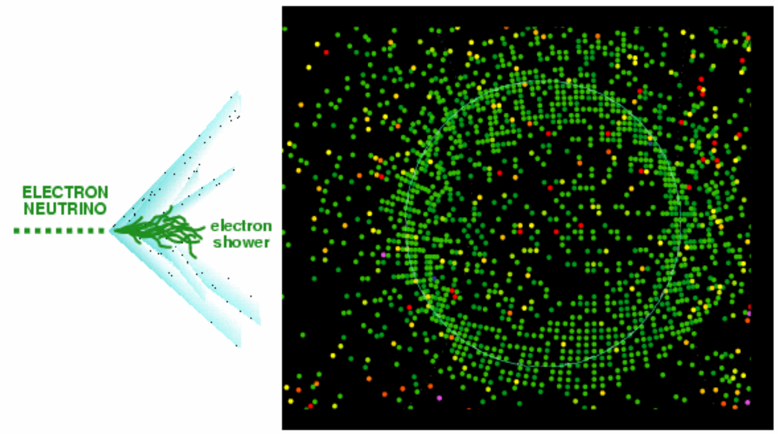
- momentum for each ring

  charge inside Cherenkov cone

- specialized fitters

  e.g. e/π separation





Both time and charge pattern information used

What is limiting us?
Will better timing help? Better pixelization?

Why it's hard to get a simple answer:
reconstruction algorithms tend to be highly tuned to specific detector parameters
... change in detector parameters requires reoptimization of the reconstruction

Definitive answers will require significant simulation work and likely development of new reconstruction algorithms
(LBNE collaborators are working on this!)

For this talk: I took a look at factors limiting reconstruction and did a very simple study with SK reconstruction software

Factors working against us for getting perfect reconstruction from Cherenkov light:

- Nuclear absorption
- Particle scattering
- Secondary production (hadrons, delta rays)
- Cherenkov threshold
- Photon dispersion
- Photon absorption
- Photon scattering (Rayleigh & Mie)

Can't do much about these (other than try to understand them)

- Photon reflection
- (Wavelength shifters)
- PMT dark noise, afterpulsing etc.
- PMT single pe charge resolution
- PMT coverage/light collection
- PMT quantum efficiency
- PMT timing
- Electronics response (dynamic range, cross-talk, noise...)

Potentially improvable

not really limiting
somewhat or possibly limiting
definitely limiting

(for physics with ~GeV events in SK-like detectors; depends a bit on what you are trying to do)

PMT Characteristics

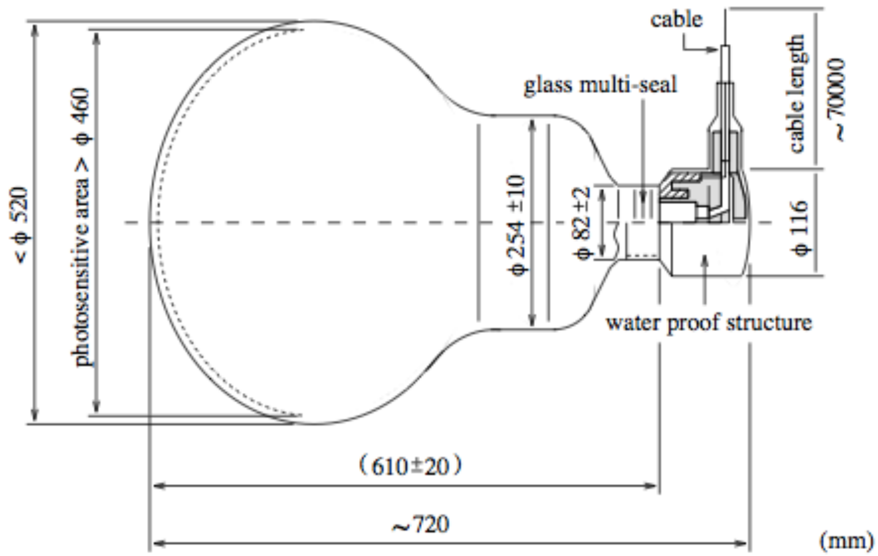
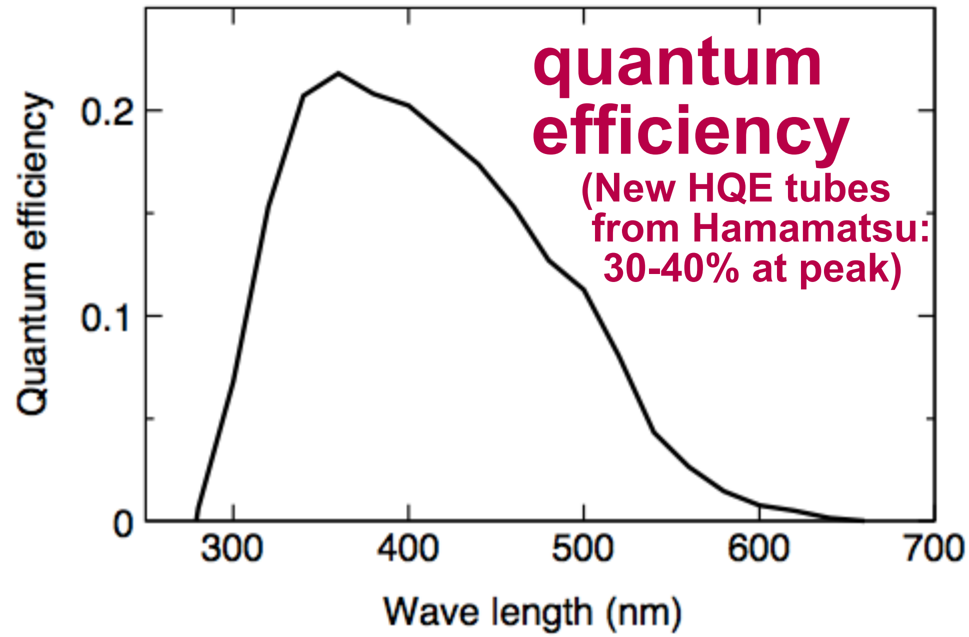
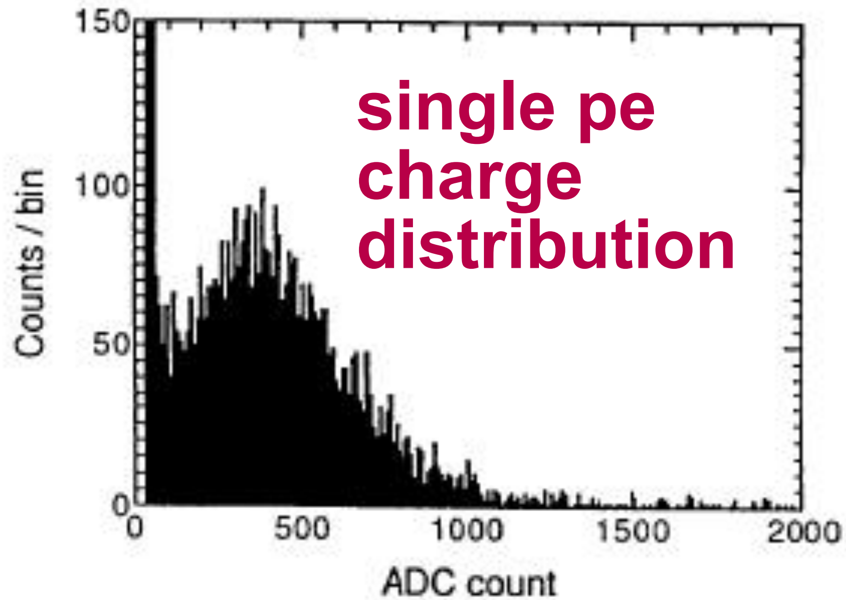
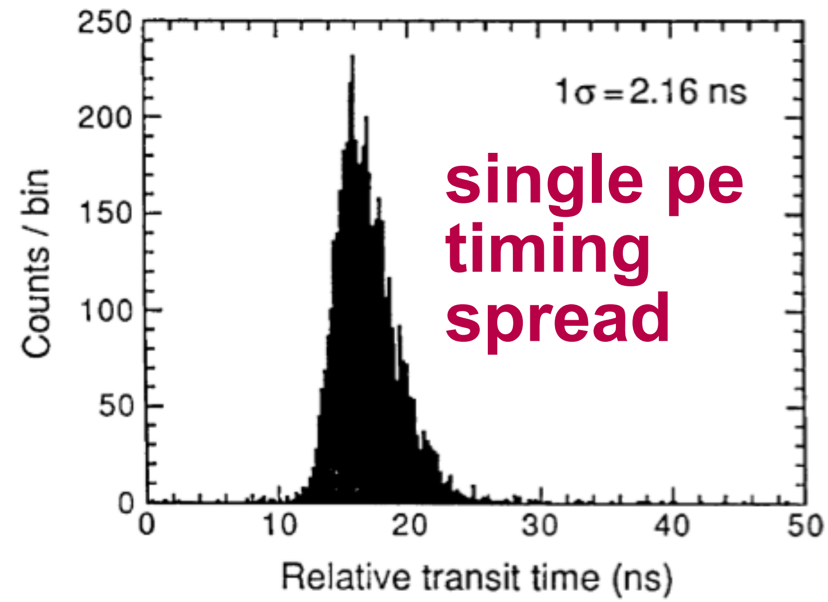


Fig. 7. Schematic view of a 50 cm PMT.

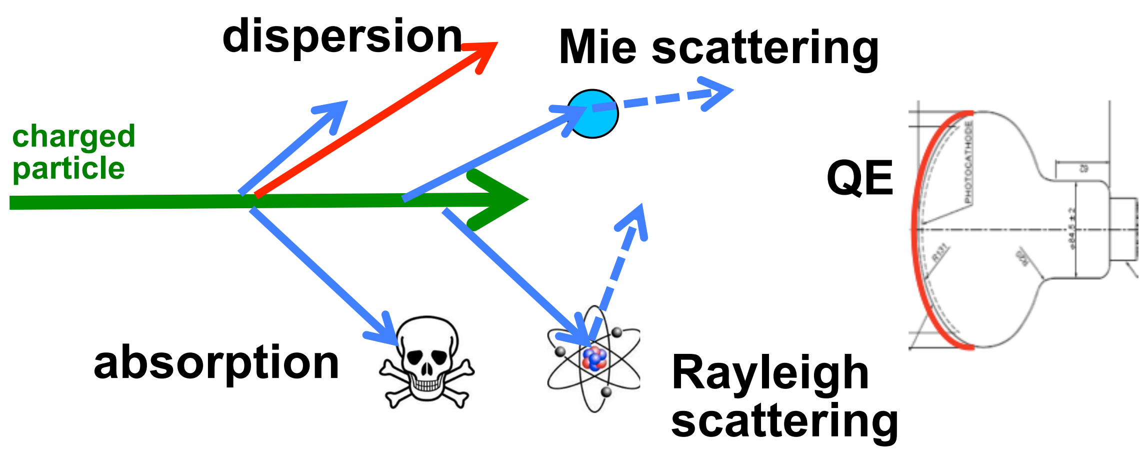


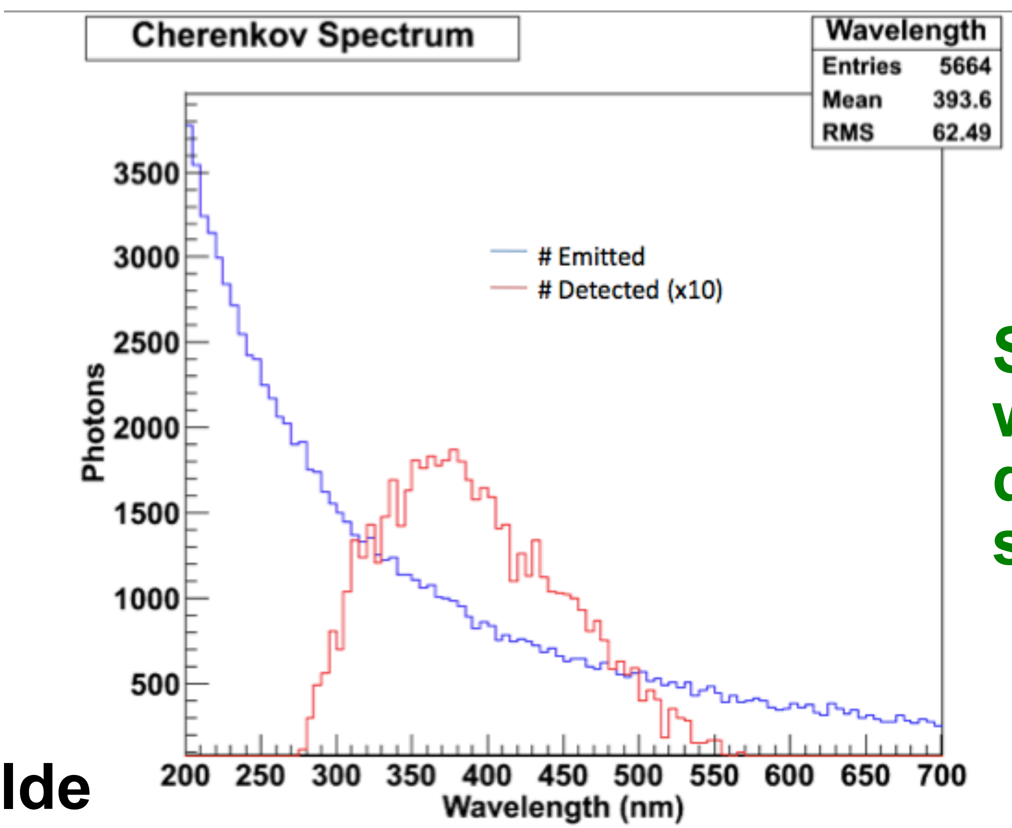
gain ~10^7





Before they get to the PMT the photons must run the gauntlet of interactions with water:



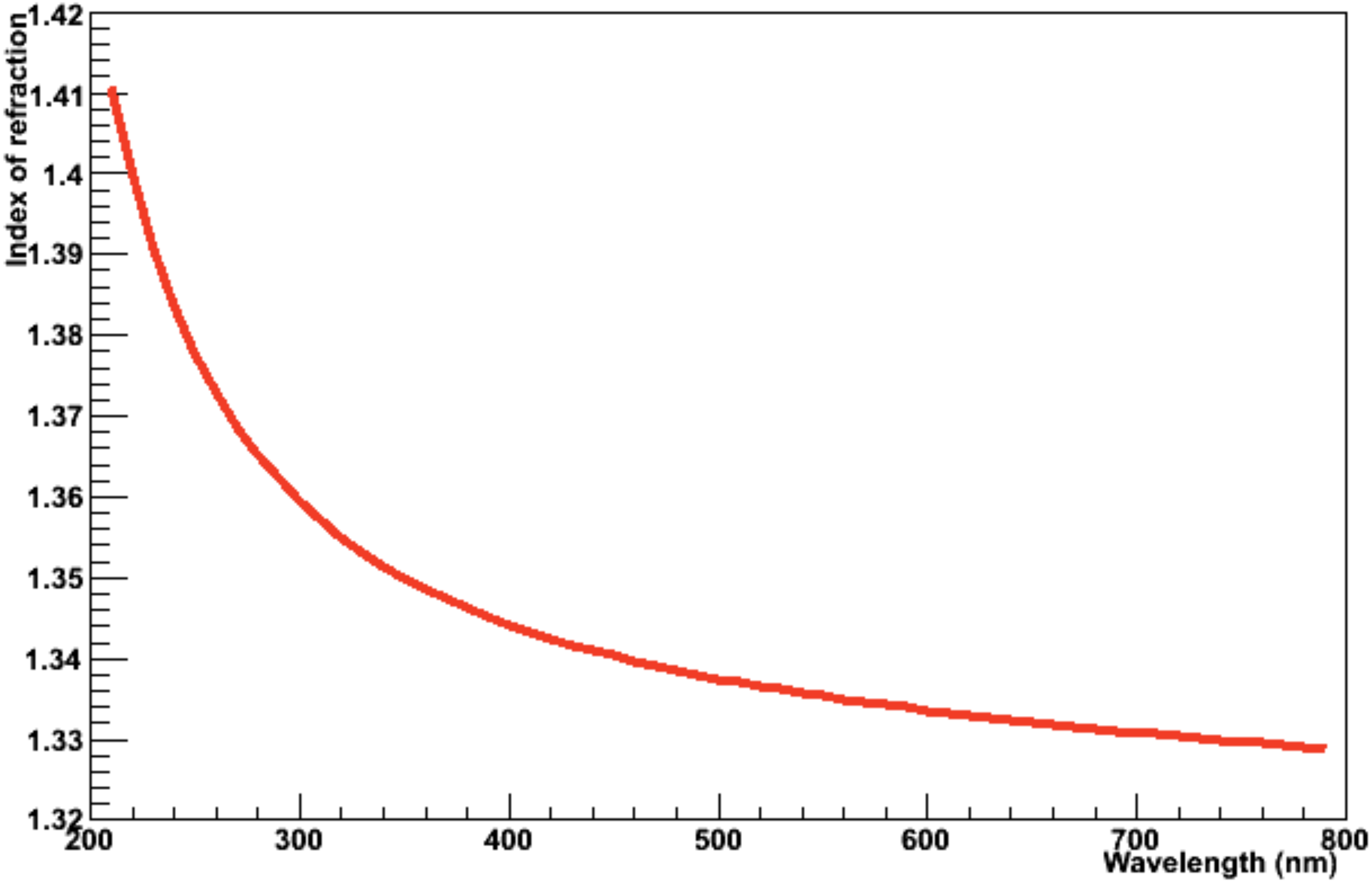


Spectrum and timing will be modified depending on size of detector

From J. Felde

Dispersion

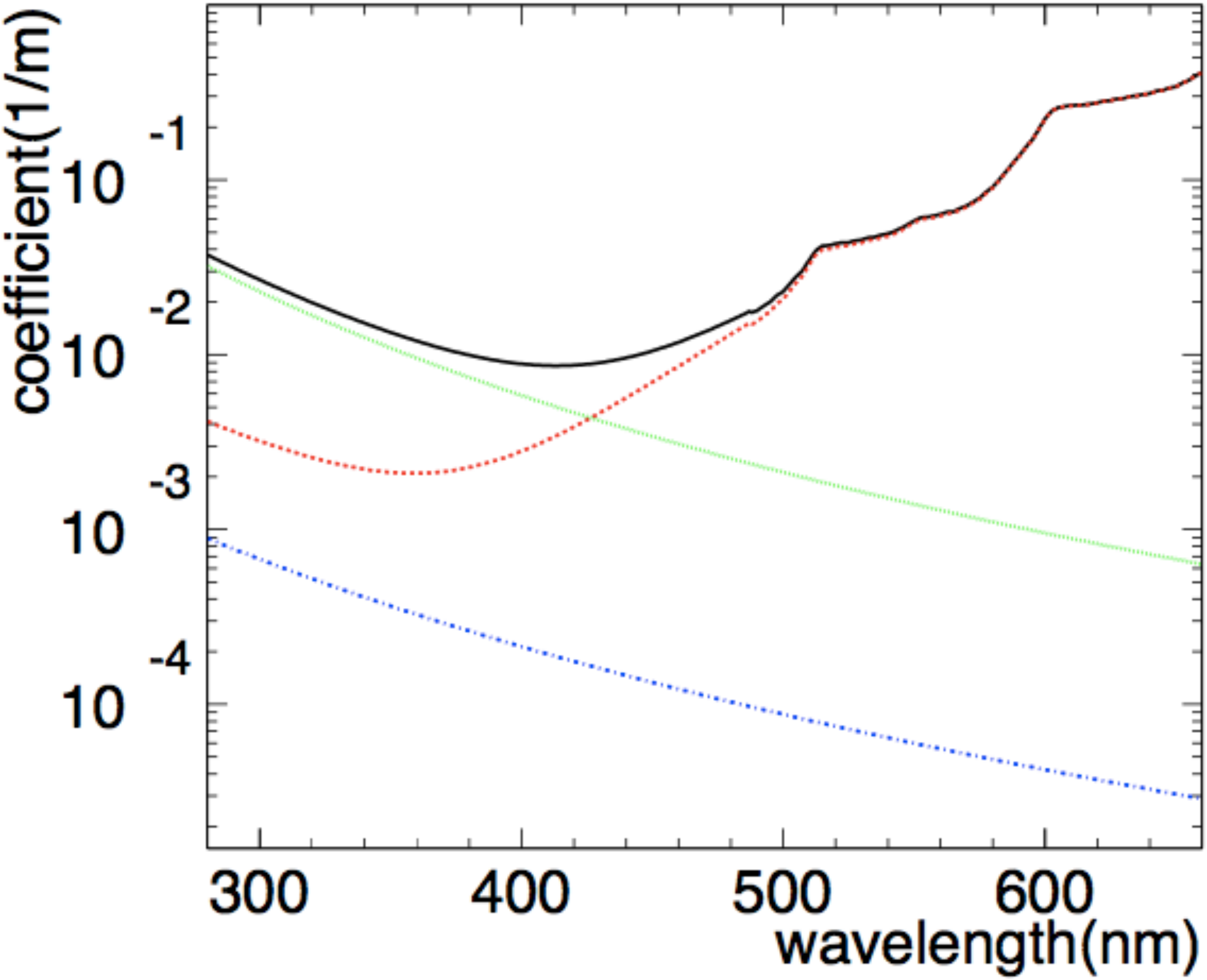
$$v_g = \frac{d\omega}{dk} = \frac{c}{\left[n(\omega) + \omega\left(\frac{dn}{d\omega}\right)\right]}$$



➔time of flight spread

Absorption and scattering

SKIII solar paper, arXiv:1010.0118



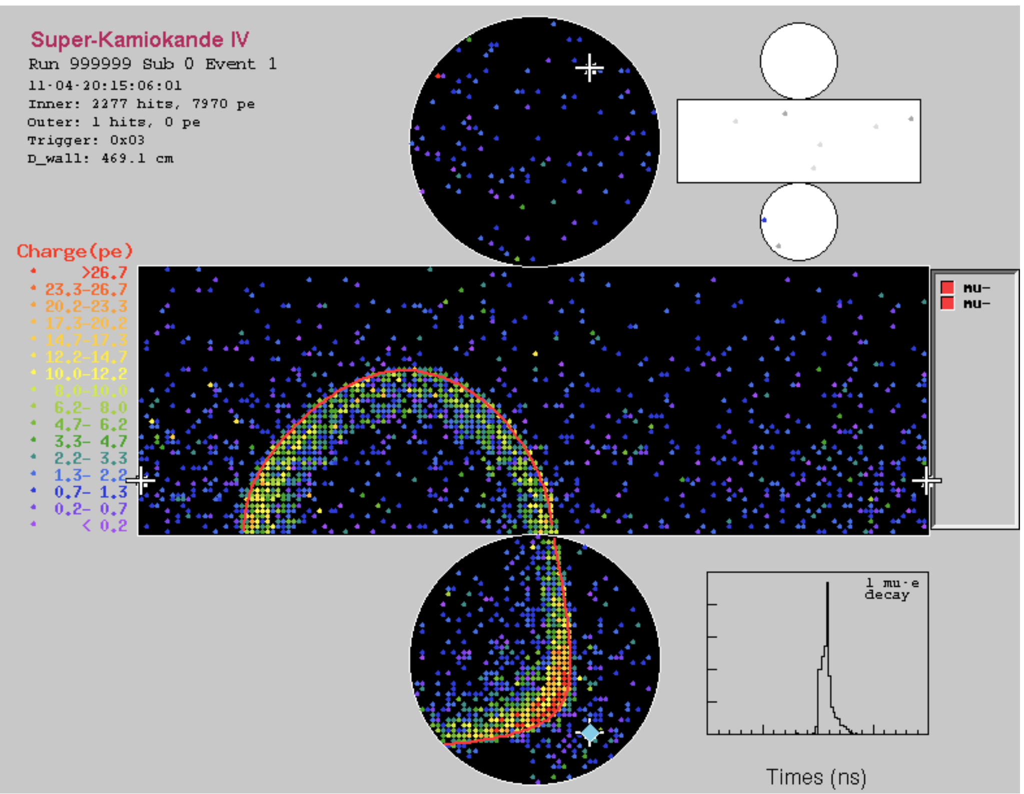
Combined
Rayleigh
Absorption
Mie

In Super-K, measured with laser & cosmics (by tuning MC); absorption is time & position dependent

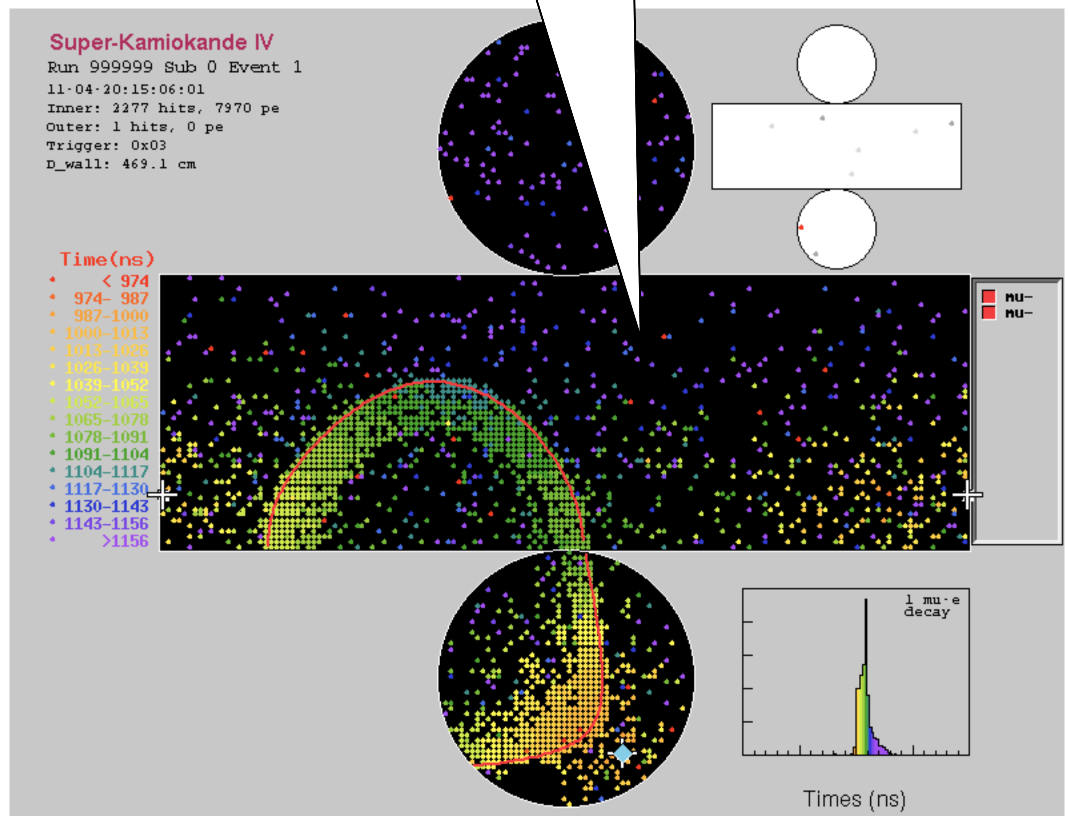
Rayleigh scattering important at low λ
Absorption important at high λ
Mie scattering fairly unimportant (clean water)

Typical high energy muon

Out-of-cone, late scattered light



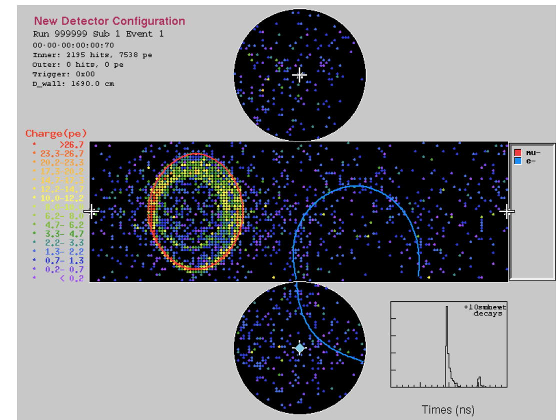
Charge mode

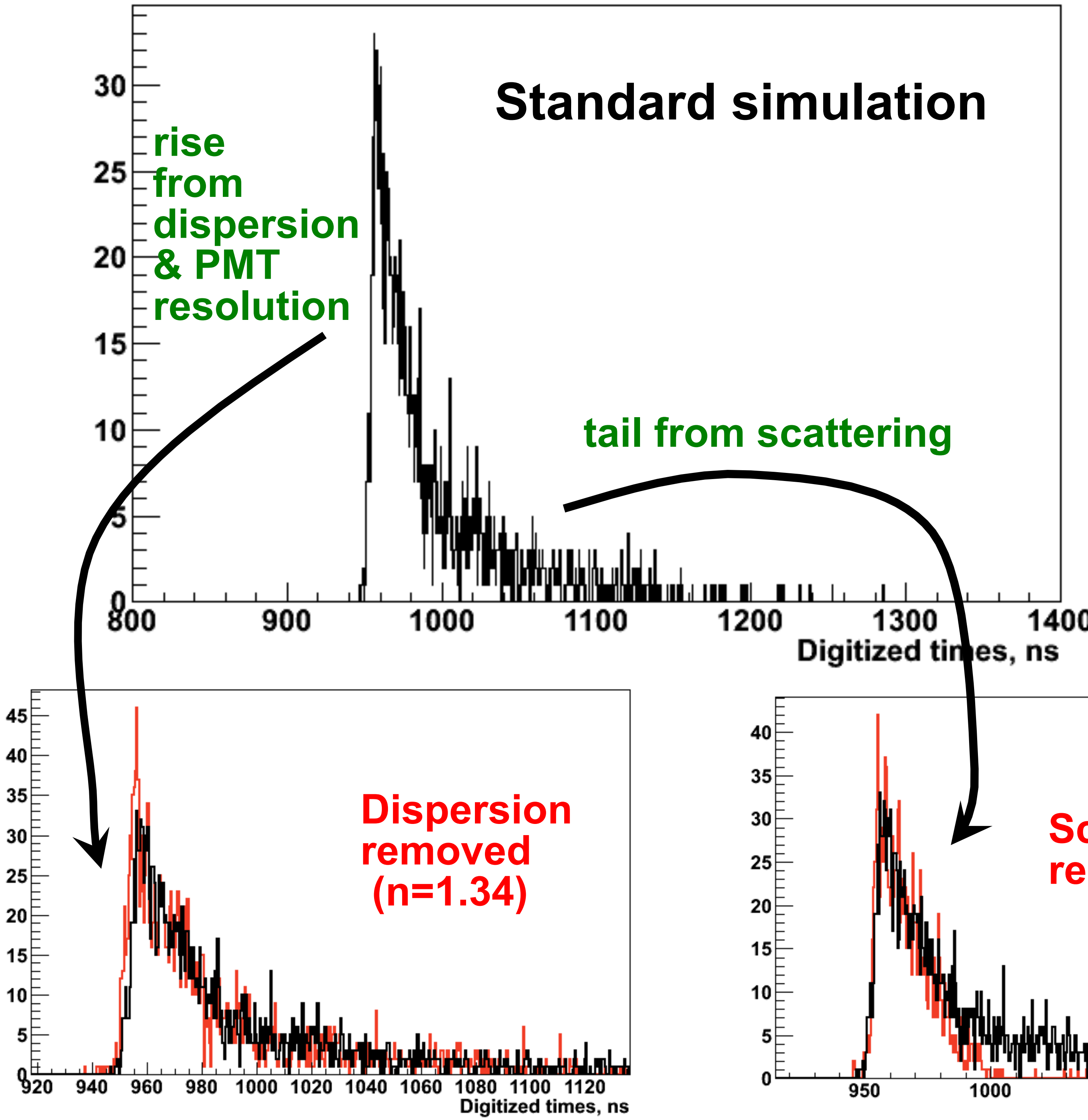


Time mode

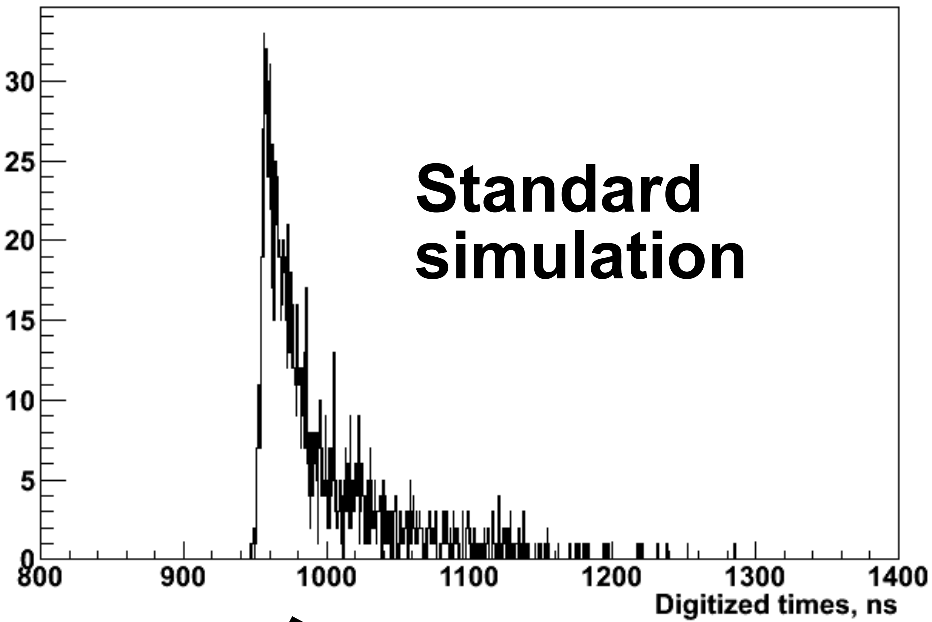
PMT hit time distribution

Single 1 GeV muon shot from center of tank horizontally at wall (times not TOF corrected)

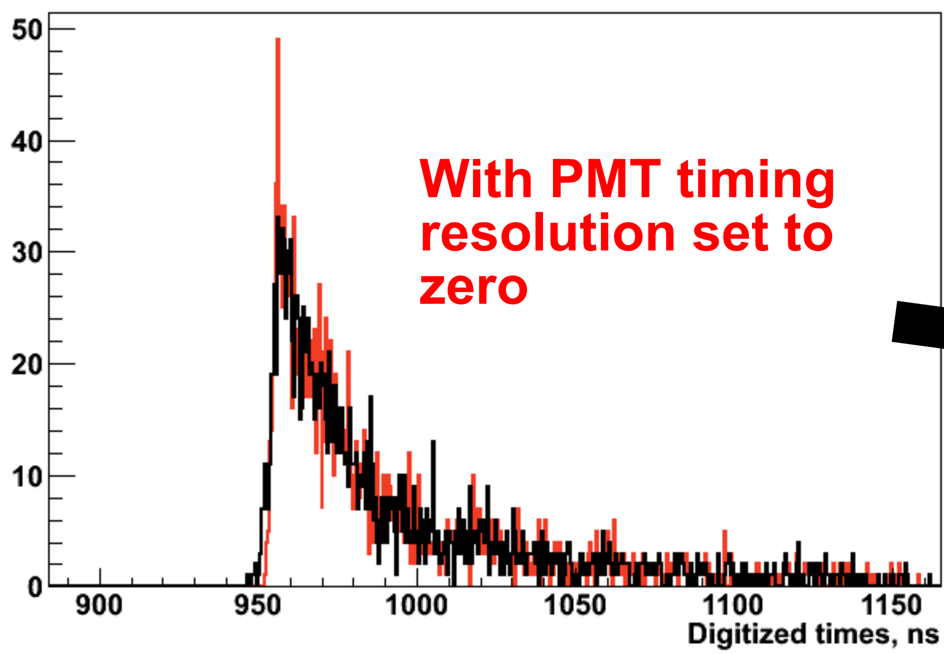


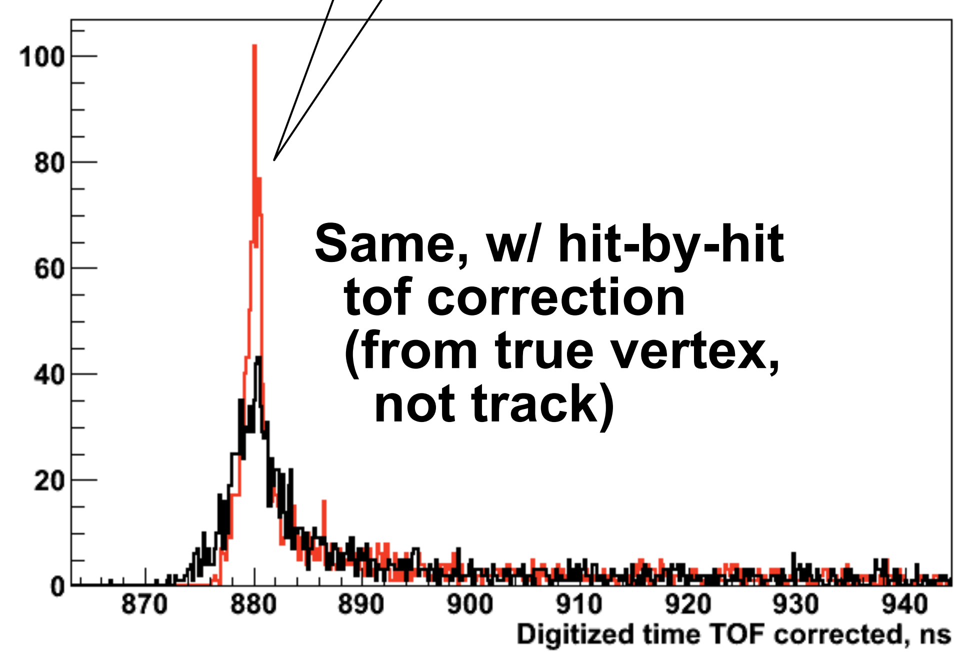


Now look at PMT resolution effect



sharper, as expected... can it be exploited?

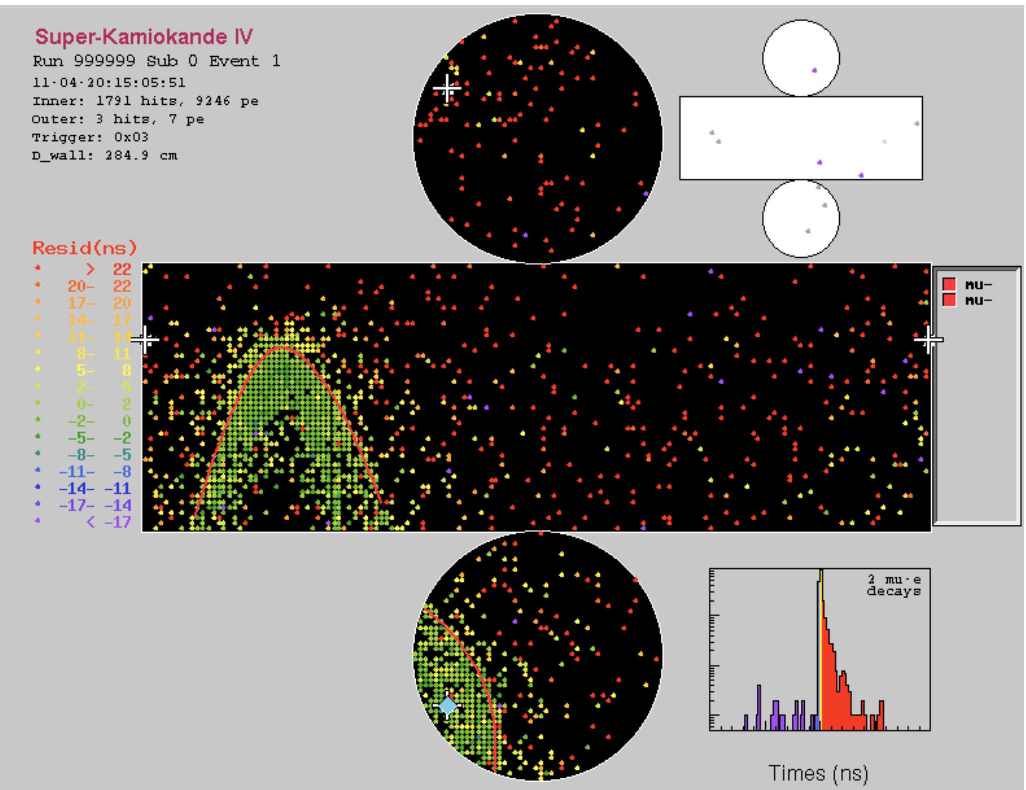




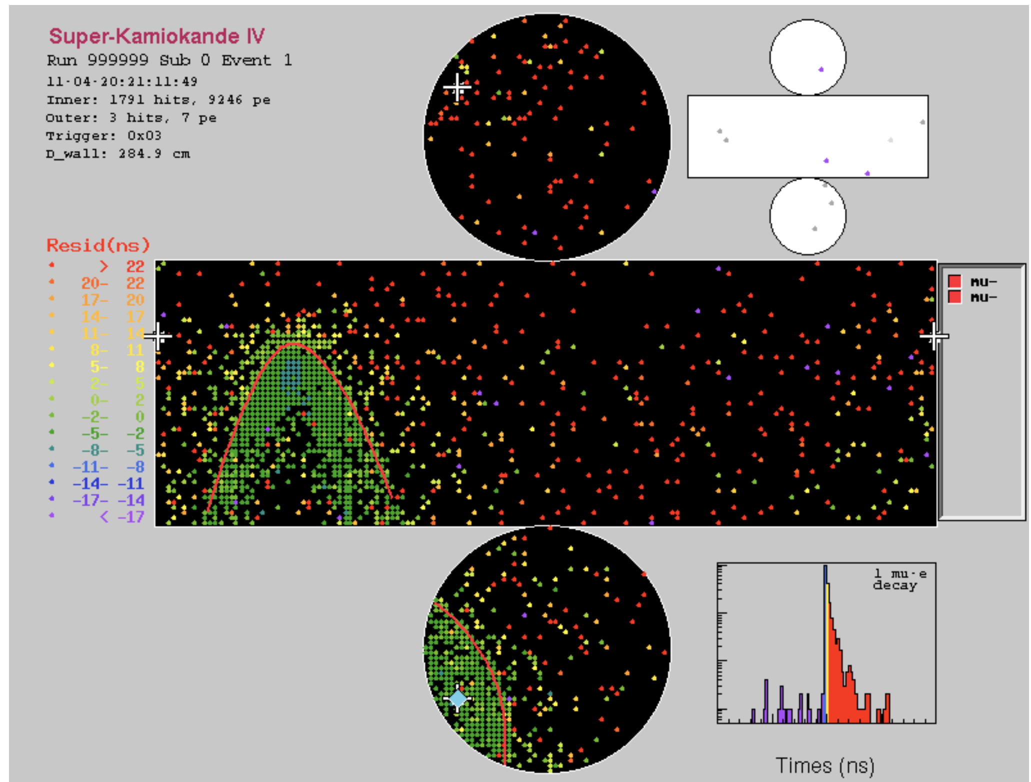
A Simple Study:

change the PMT digitization time spread in the simulation from σ~2.5 ns to 0.2 ns

Normal

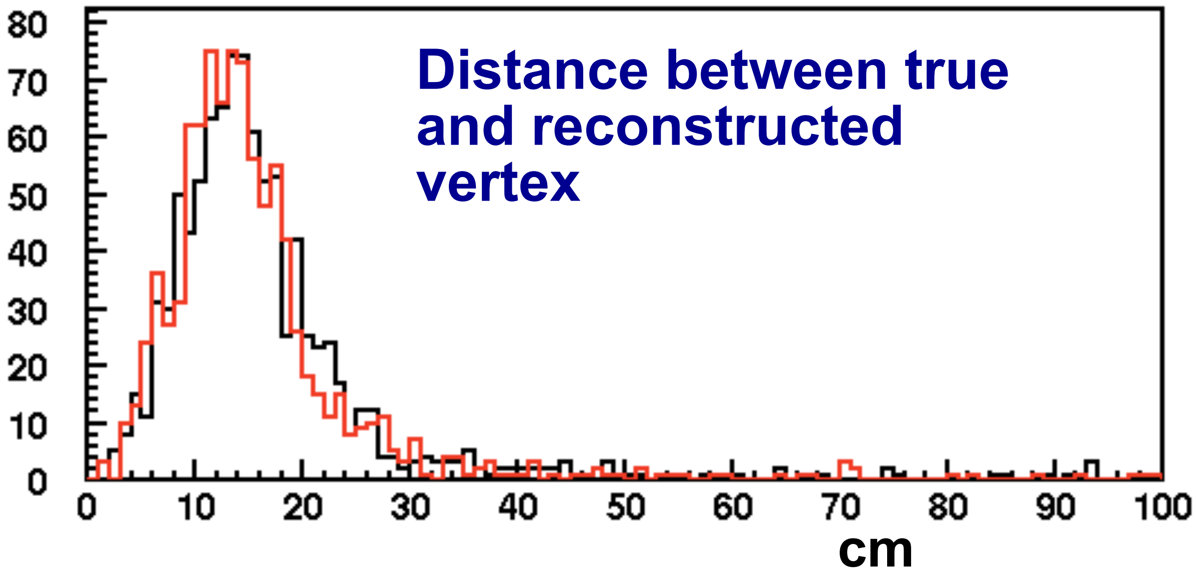


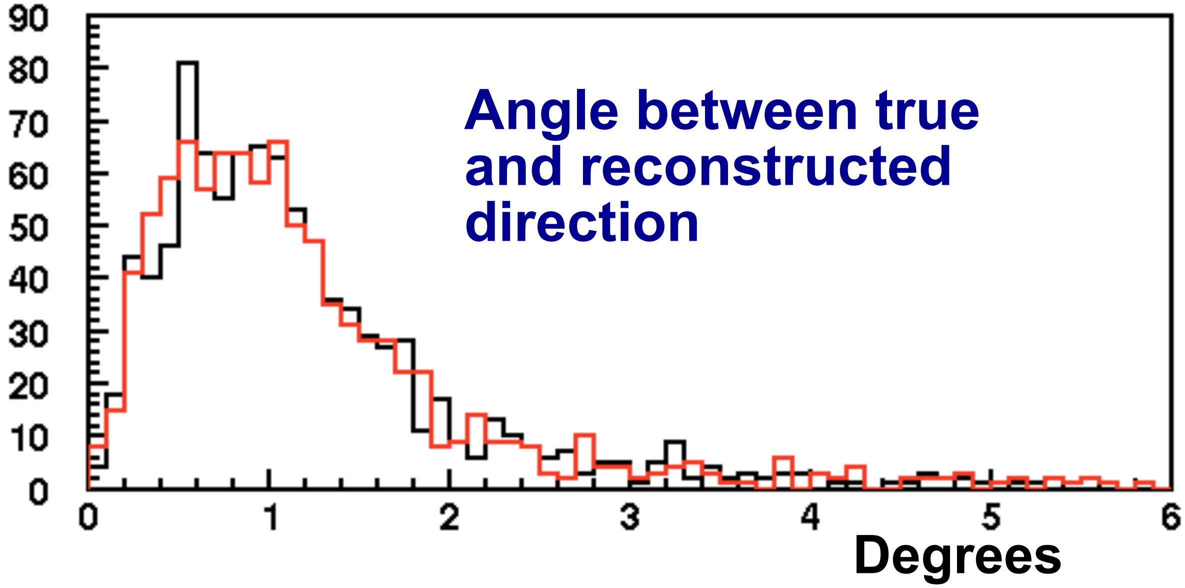
Fast



Hard to see difference in finest event display resolution...

Try SK reconstruction tools on simulated data w/200 ps digitization





1 GeV uniform, isotropic muons

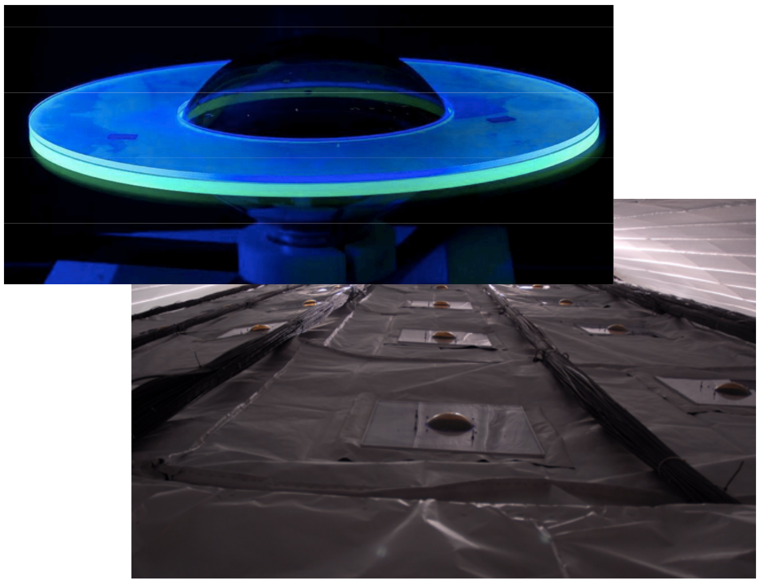
Standard simulation
Sim w/200 ps digitization

Decreased expected time spread in time residual fit goodness, but no other tweaks to reconstruction code

Not much improvement, but can't conclude much because code may not make optimal use of better timing
... *needs more work*
(also: low energy study)

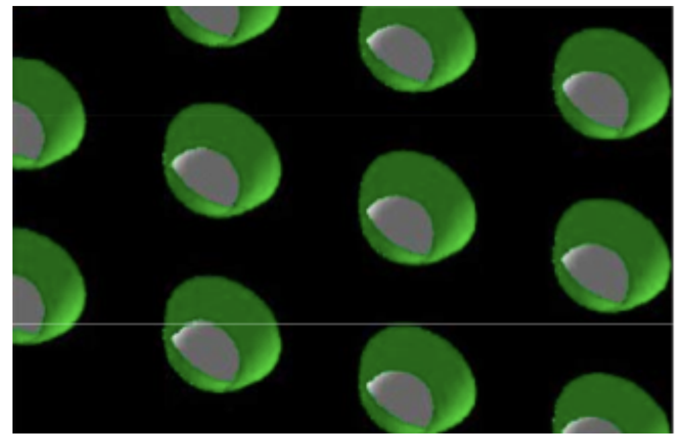
For next-generation experiments, enhanced light collection techniques, including wavelength shifters, are under consideration

wavelength shifter plates



wavelength shifter coatings

Winston cones



These will surely affect time profile and reconstruction; details as yet unknown

R&D underway for LBNE, including simulation studies, to understand effect on reconstruction

My personal opinion:

**For this application, good timing is welcome, but what we mostly want is ... MORE LIGHT!
FOR CHEAP!**

Summary

Cherenkov photons lead a hazardous existence:
dispersion & scattering affect use of timing
for particle reconstruction

Improving photosensor time resolution
(and pixelization?) may lead to
improvements in event reconstruction
... but will require new/reoptimized
reconstruction tools
(work underway in LBNE
collaboration)

Dreaming of more photons...