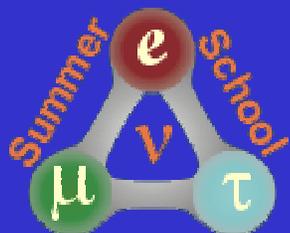


# Neutrino Detectors II

**Ed Kearns**  
**Boston University**

Lecture notes version: some annotations added and slides/overlays condensed with respect to the version shown during the school.



**The Neutrino Physics Summer School**  
**Fermilab, July 2-13, 2007**

## Lecture I: Broad Survey of Past Detectors

### \* Inverse Beta Decay

Discovery of the  $\bar{\nu}$   
KamLAND, LSND

### \* Tracking Detectors

Two  $\nu$  Experiment  
NuTeV, MINOS, CHARM II

### \* Bubble Chambers

Discovery of Neutral Currents

### \* Hybrid Detectors:

MINER $\nu$ A, NOMAD

Discovery of Tau Neutrino

## Lecture II: The Challenges for $\nu_e$ Appearance

### \* Water Cherenkov

Super-Kamiokande

### \* Segmented Scintillator

NO $\nu$ A

### \* Liquid Argon TPC

ICARUS & future experiments

Mixed throughout: fundamental physics of particle interactions, principles of operation of detector elements. Lots of diagrams, photos, and event displays.

# So, you want to build a neutrino detector?

- How many events do you need to detect?

This determines detector mass.

- What kind of interaction?  $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ , NC?

- What do you want to measure: Energy? Final states?

This influences detector technology.

- What sorts of backgrounds do you expect?

How much can you tolerate?

More influence on detector technology, maybe conflicting.

- How much money do you have?

Detector technology, mass, time...

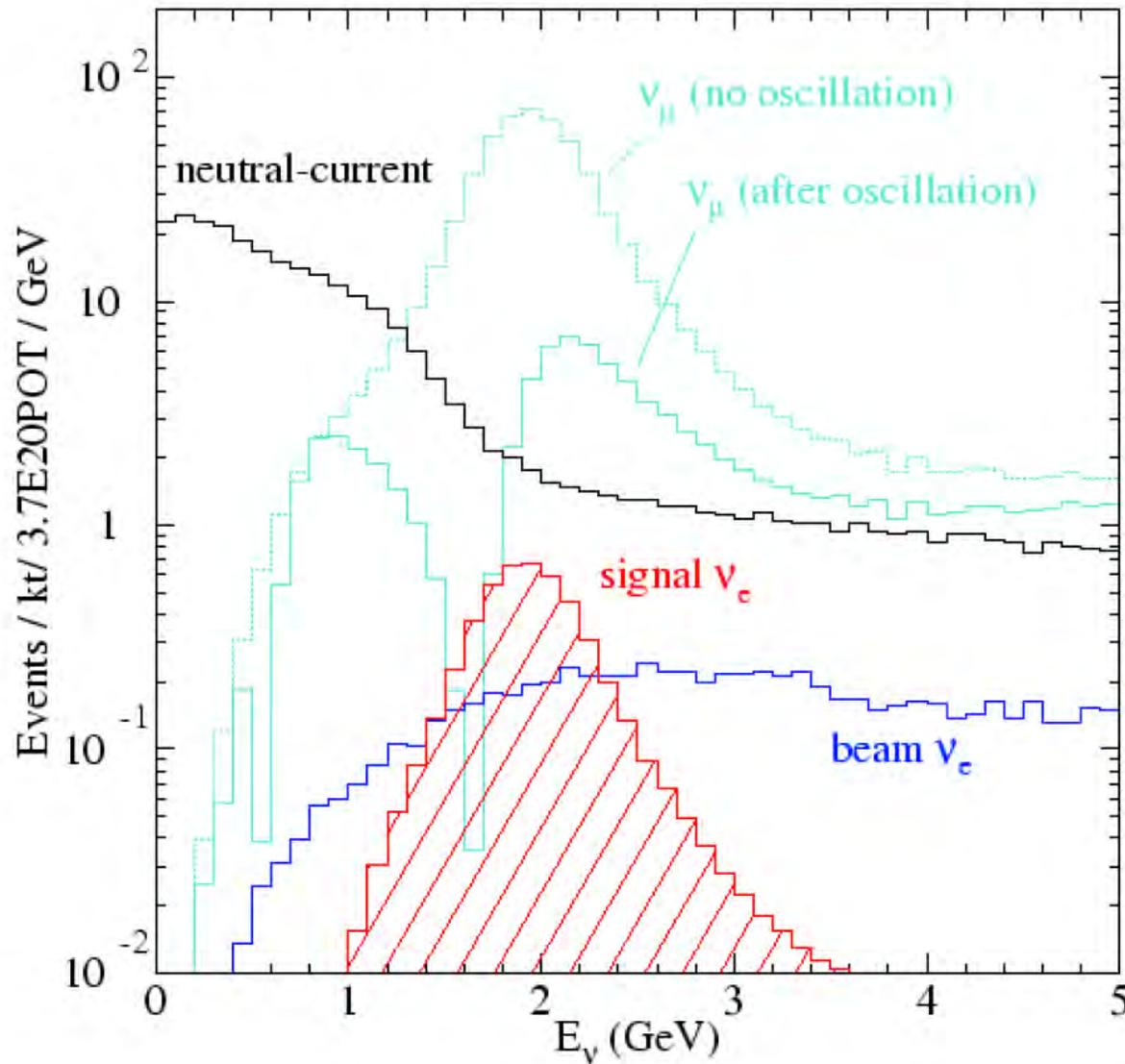
# Challenge of $\nu_e$ Appearance

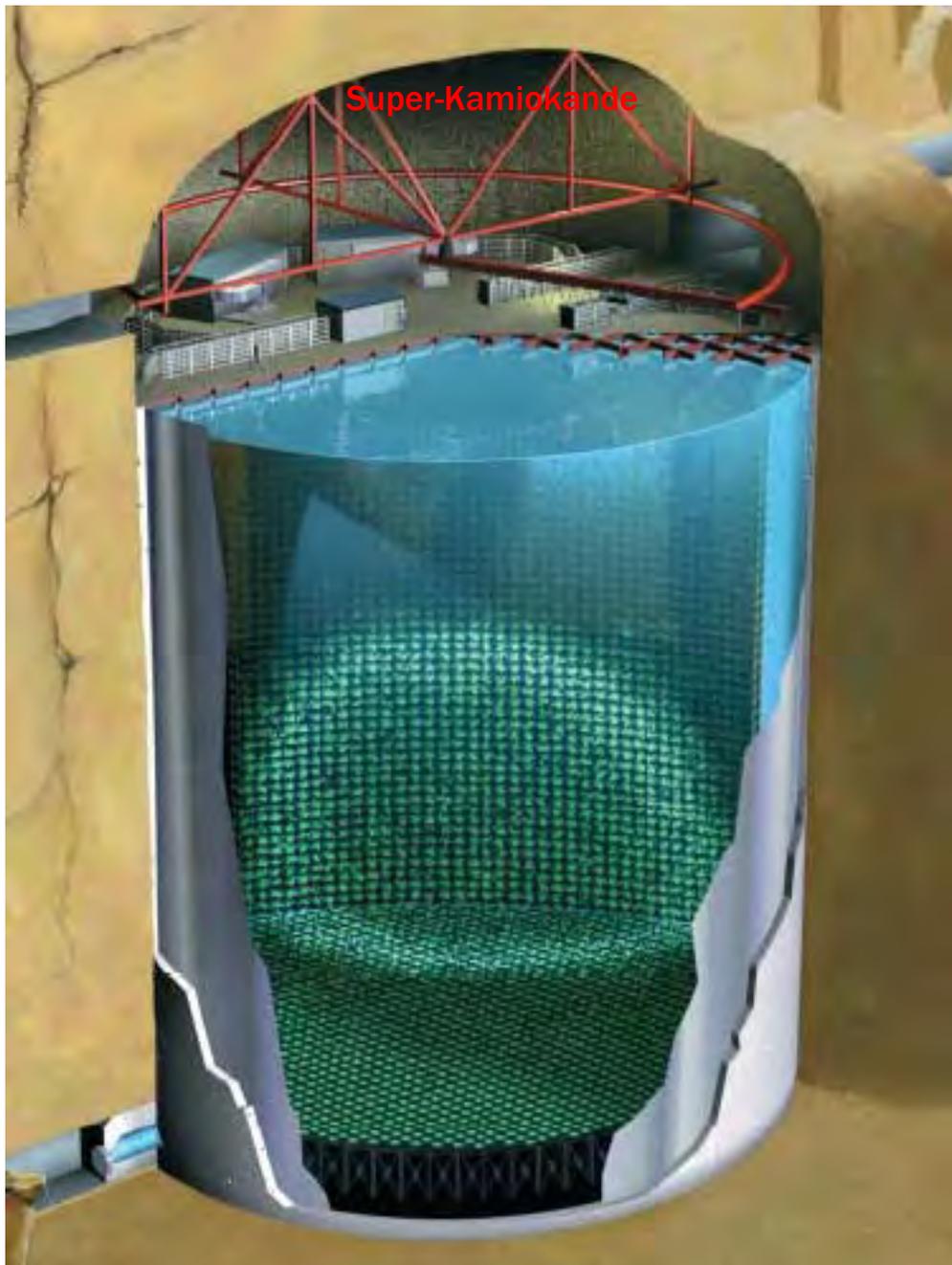
Accelerator beam flux	$100 \times 10^6 \nu/\text{cm}^2/5 \text{ yr}$
Oscillation Probability	1-10%
Event rates: CC $\nu_\mu$ / NC / $\nu_e$	10K / $\sim 800$ / 200 events
Signal Efficiency / BG	40% / 20 events
Mass of detector	22.5 kt

... and something comparable for  $\text{NO}\nu\text{A}$ .

And then... let's in the future try to measure a difference in  $\nu_e$  versus anti- $\nu_e$  appearance to demonstrate CP violation. Need more intense beam and bigger detector. See strategy lectures.

# Neutrino Interactions





# Water Cherenkov

## **SK-I: 1996-2001**

22.5 kton fiducial volume (2m from wall)  
11146 50-cm inner PMTs , 40% coverage  
1885 20-cm outer PMTs

## **SK-II: Jan 2003-Oct 2005**

Recovery from accident  
5182 50-cm inner PMTs  
Acrylic + FRP protective  
Outer detector fully restored

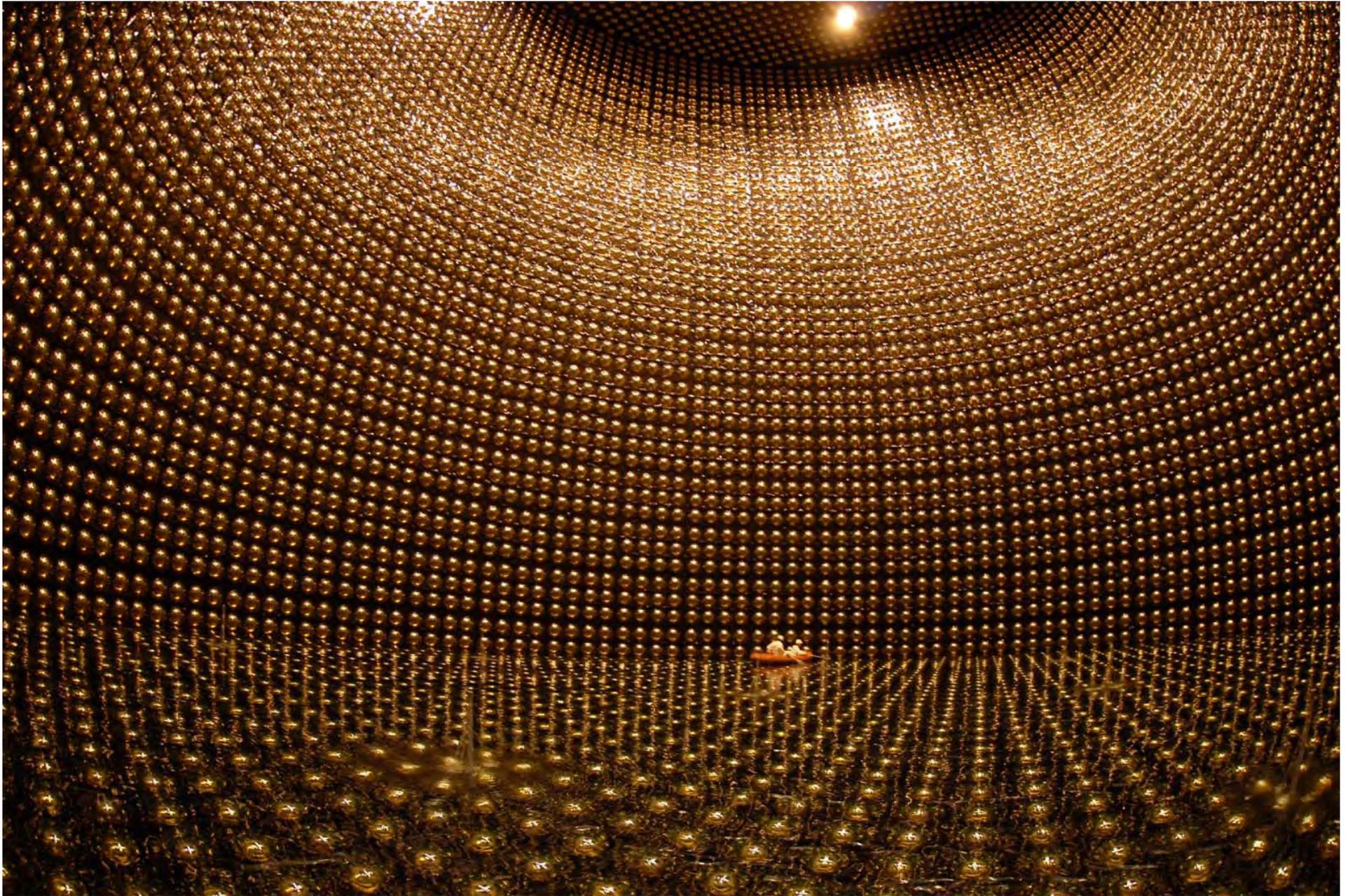


## **SK-III: May 2006-**

Restored 40% coverage  
Outer detector segmented (top | barrel | bottom)

## **SK-future:**

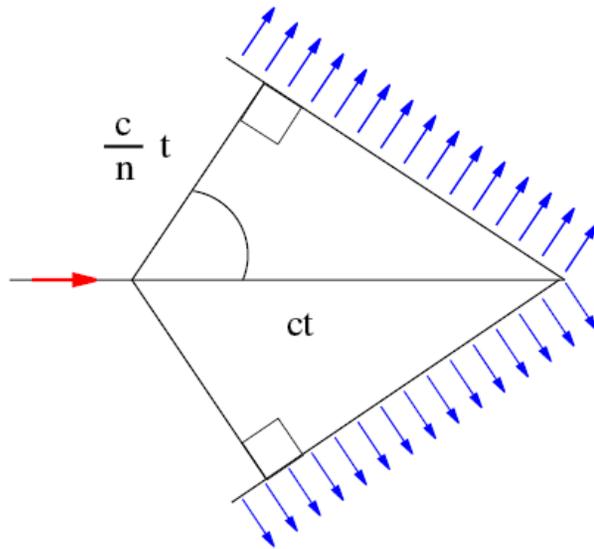
Replace all electronics - 2008  
Add Gadolinium - 20??



Super-Kamiokande III (newly rebuilt, filling in May 2006)

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007

# Cherenkov Effect



## Applications:

- ▶ Calorimetry - water, lead glass
- ▶ Threshold counters (adjust  $n$ )
- ▶ Air Cherenkov - gamma ray astronomy
- ▶ Particle ID by Cherenkov angle + momentum

## Cherenkov Radiation in Water ( $n = 1.33$ )

$\cos \theta = 1/\beta n$   
 $\beta$  threshold = 0.75  
 $\theta \rightarrow 41^\circ = \theta_c$  as  $\beta \rightarrow 1$

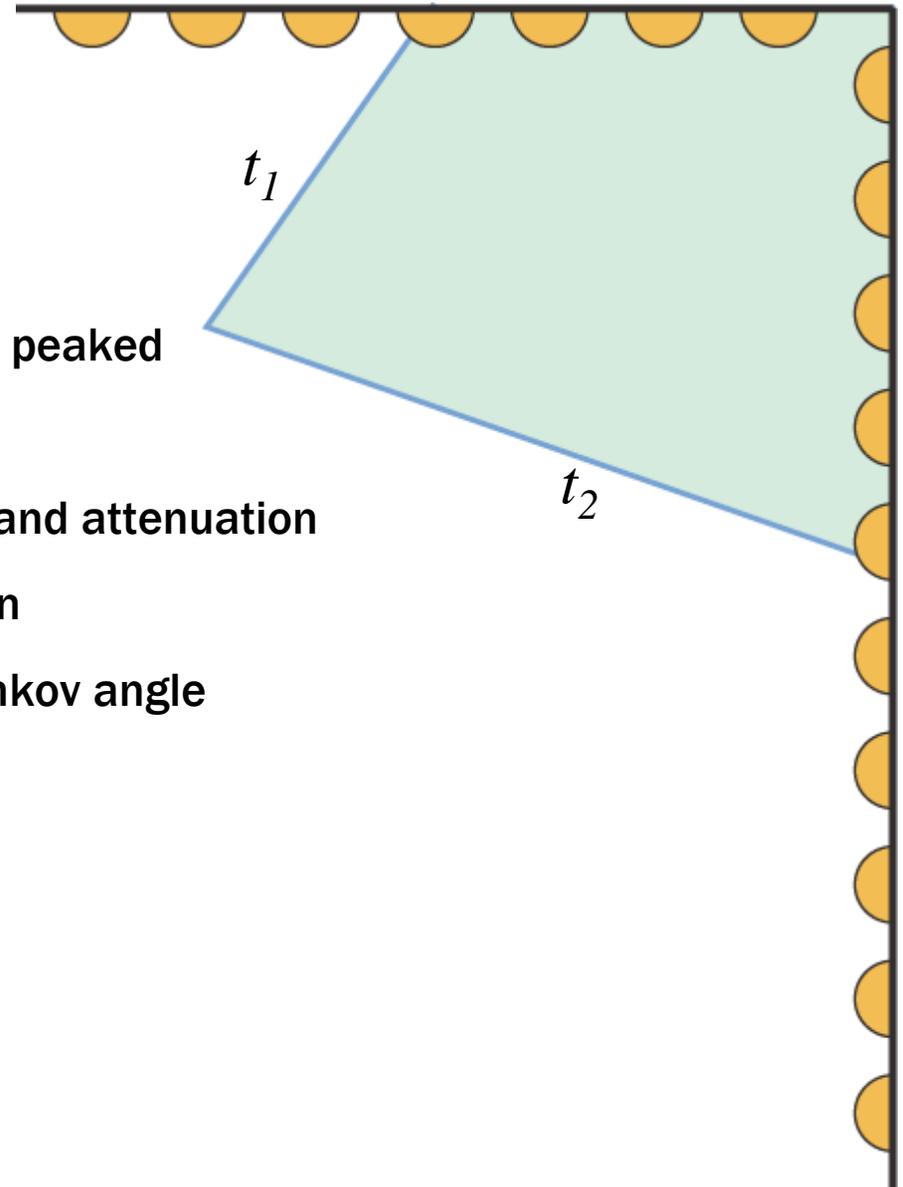
at  $\beta=1$  ~770 photons/cm emitted ( $\lambda$  300-600 nm)

Particle	Cherenkov Threshold		
	$p(\text{MeV}/c)$	$E(\text{MeV})$	$T(\text{MeV})$
electron	0.58	0.77	0.26
muon	119.	159.	54.1
pion	158.	211.	71.5
kaon	560.	746.	253.
proton	1063.	1419.	480.

# “Tracking”

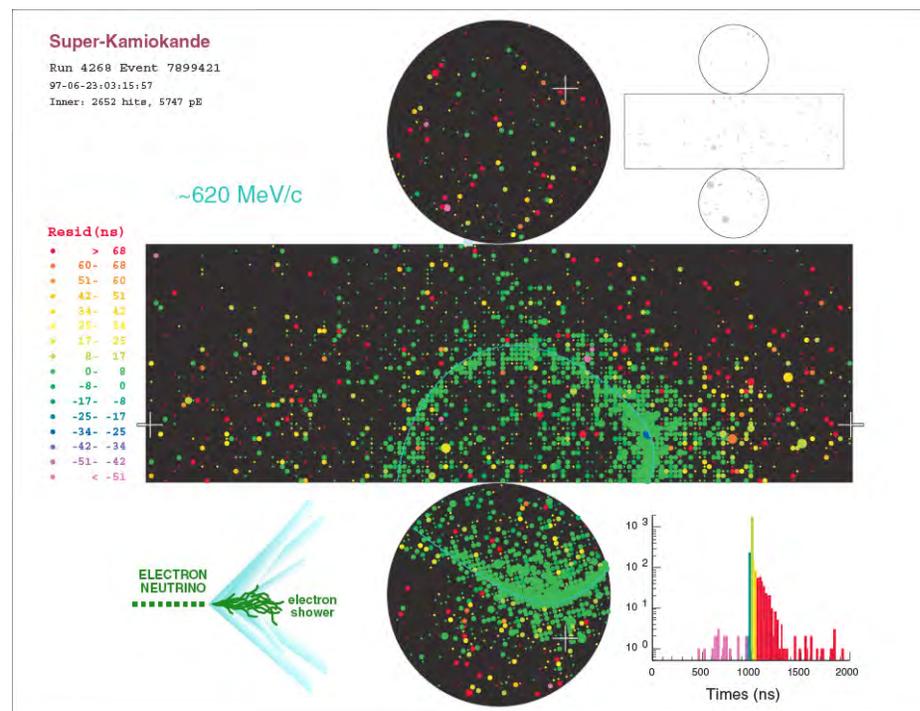
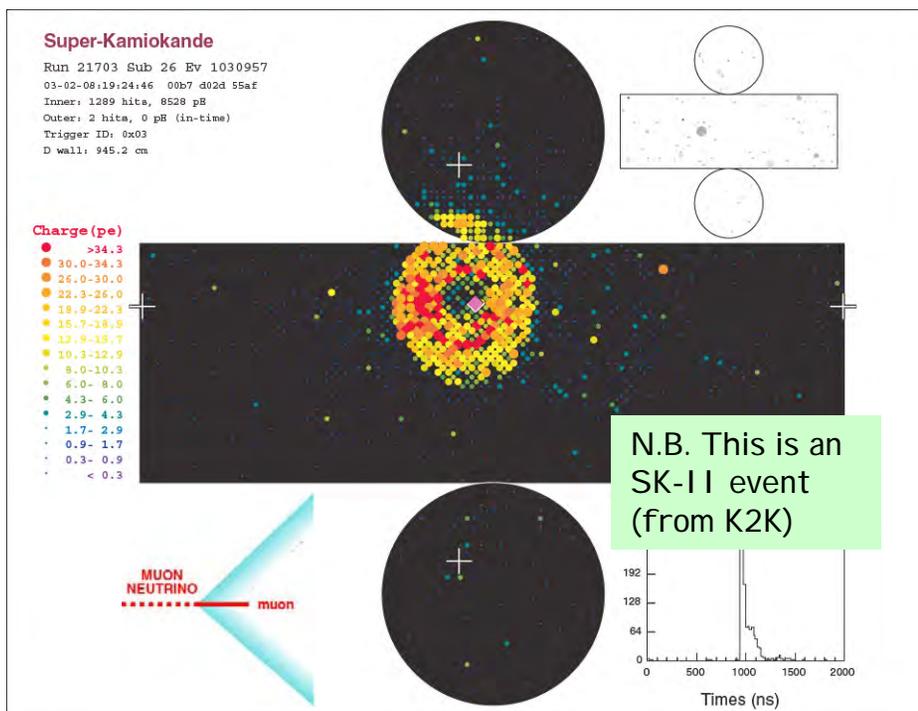
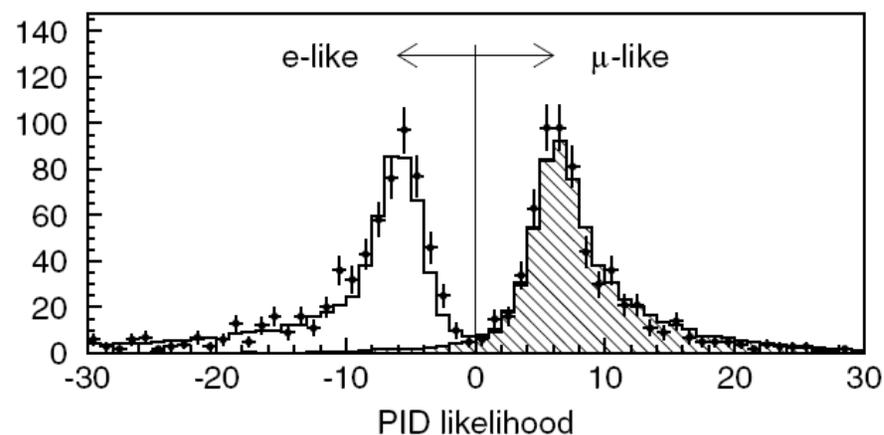
Vertex, direction, momentum

- Find position where  $t_i$ -TOF( $x,y,z$ ) is most peaked
- Correct for length of muon track
- Correct for PMT acceptance (#photons) and attenuation
- Incorporate PID by expected light pattern
- Assign momentum by #pe and fit Cherenkov angle



# Particle Identification

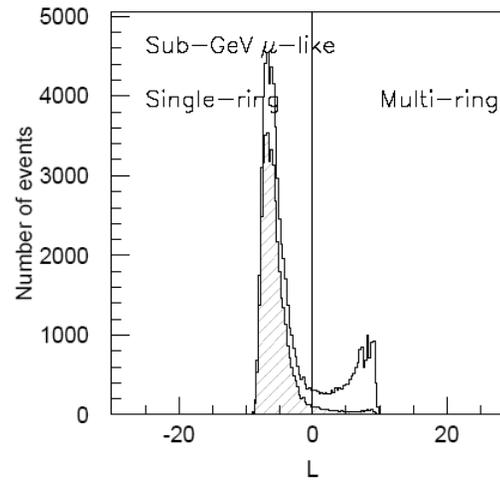
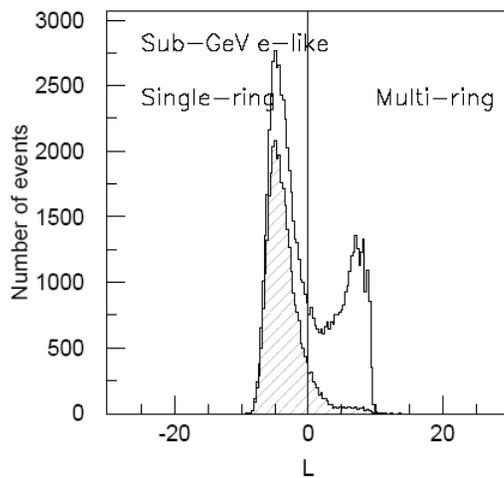
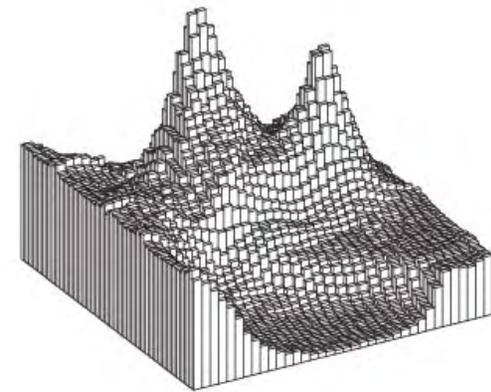
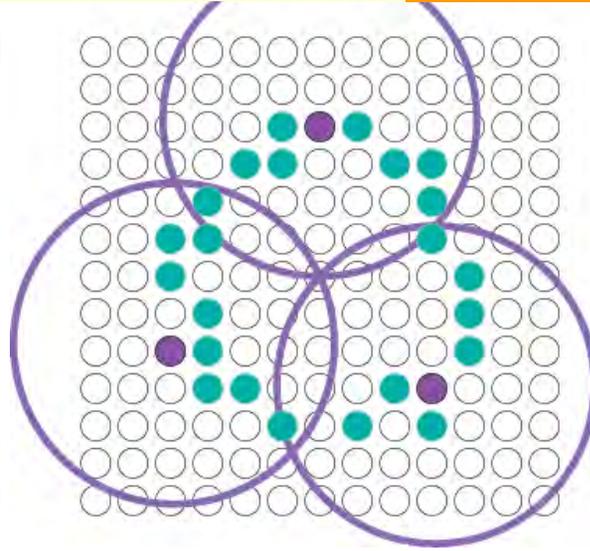
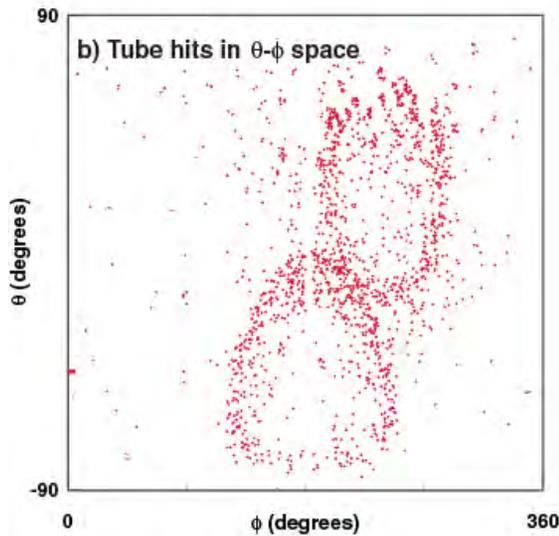
Compare observed and expected light pattern and Cherenkov angle using likelihood



# Ring Finding

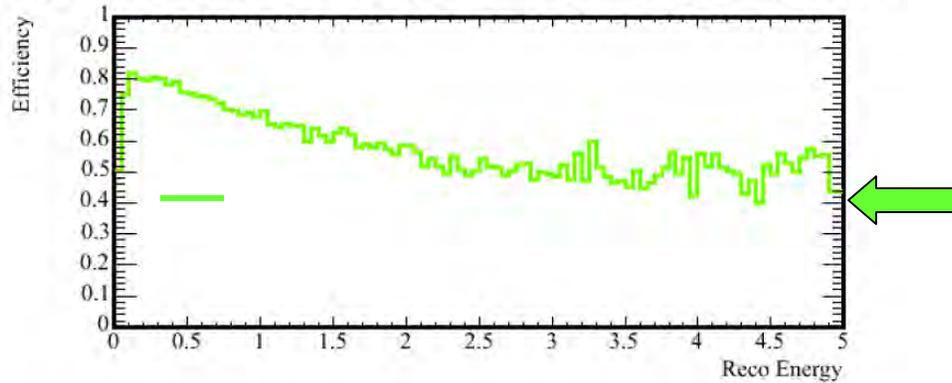
Hough transform

Becomes peak finding problem

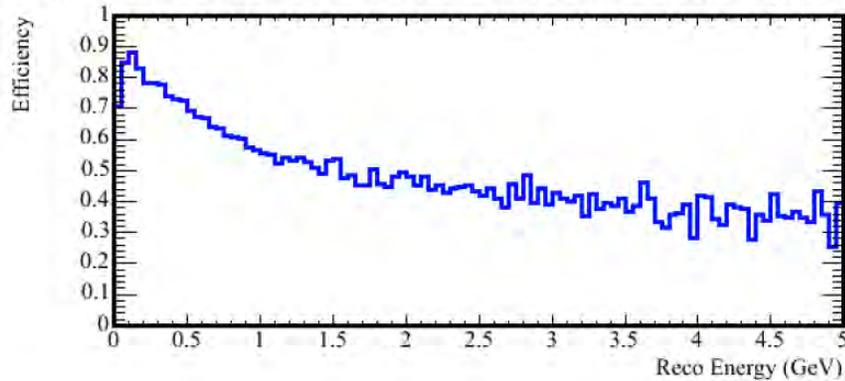


# Signal and Background

1-Ring, e-Like Reconstruction Efficiency vs Reconstructed Energy for  $\nu_e$  CC Events



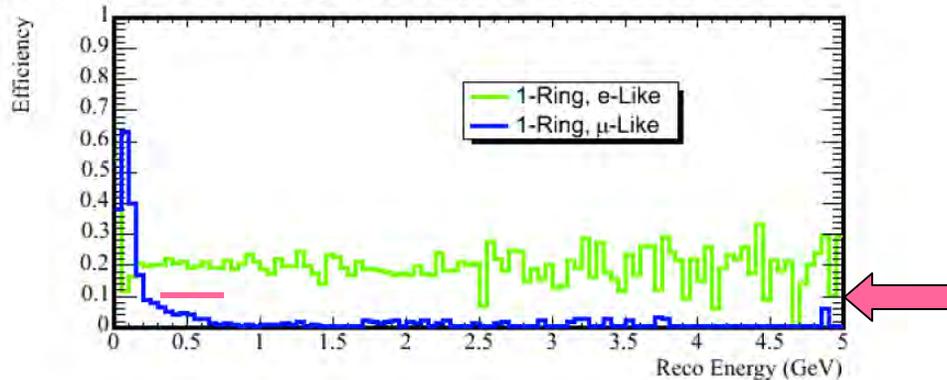
1-Ring,  $\mu$ -Like Reconstruction Efficiency vs Reconstructed Energy for  $\nu_\mu$  CC Events



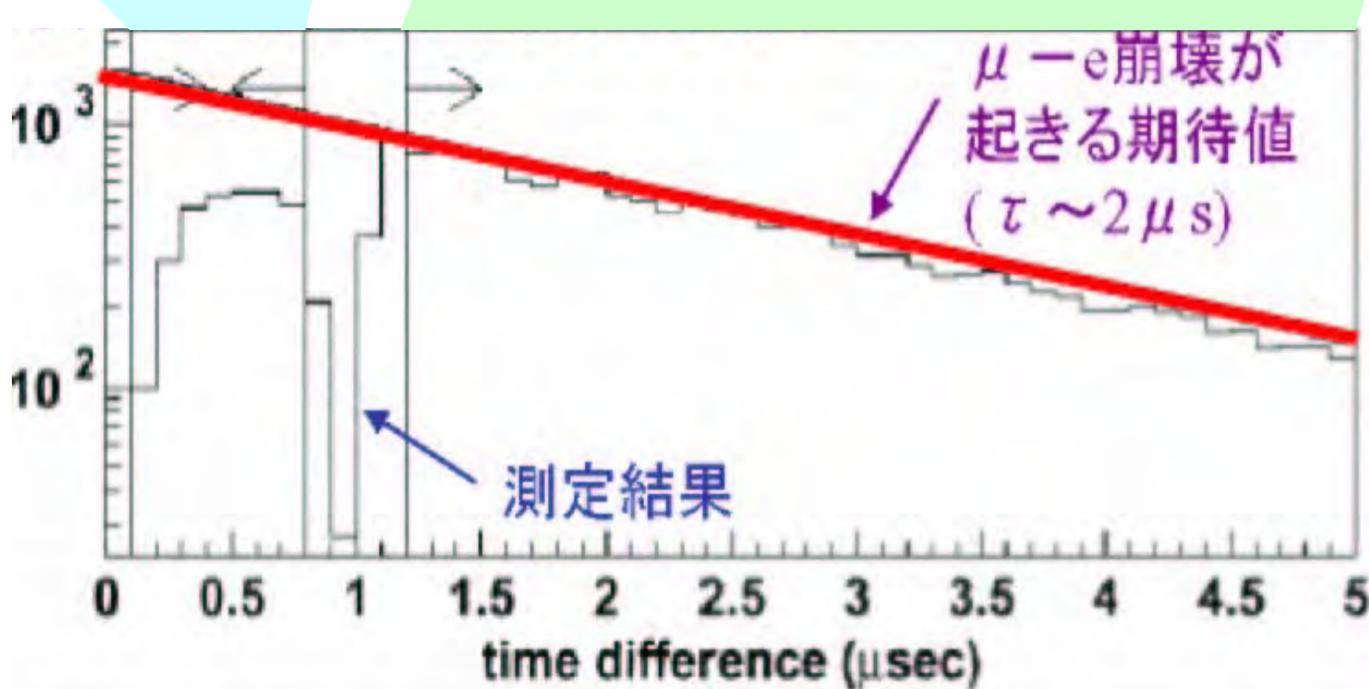
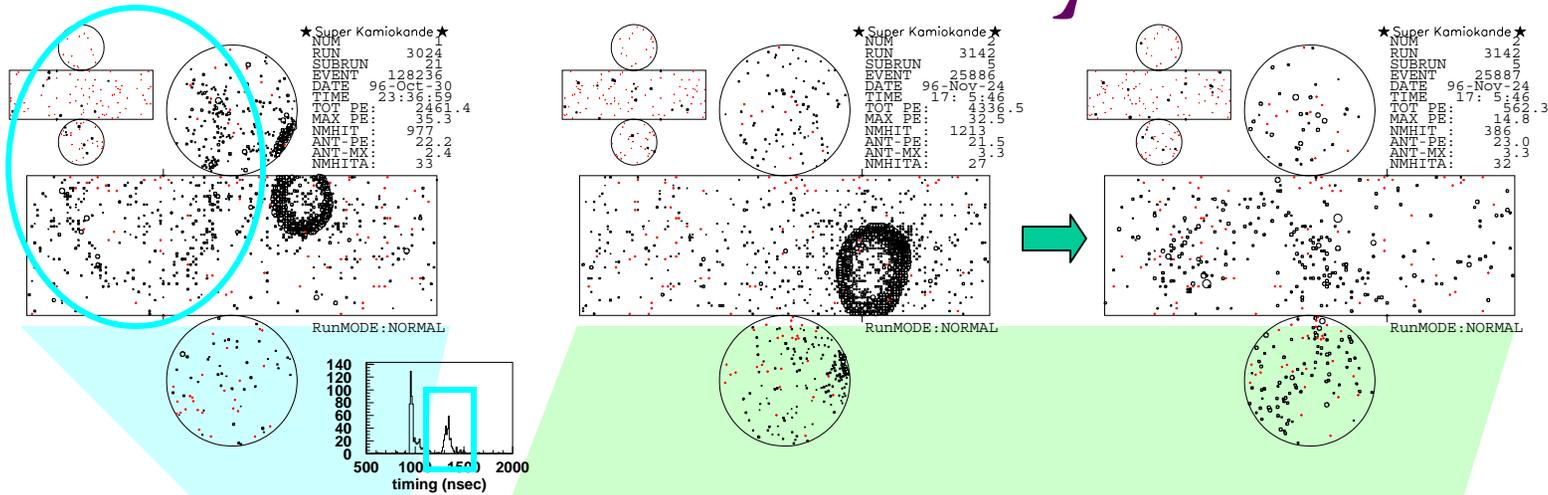
Further cuts:

	CC $\nu_\mu$	NC	signal
no decay e	14%	19%	76%
E window	1%	16%	58%
pi0 likelihood	0.40%	10%	42%

Reconstruction Efficiency vs Reconstructed Energy for NC Events

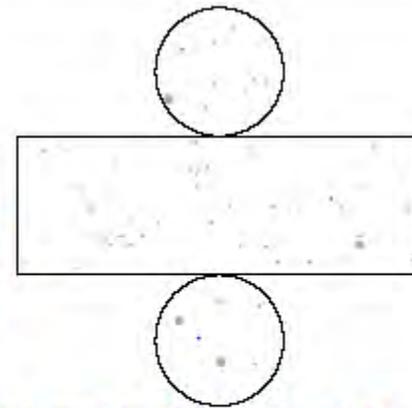
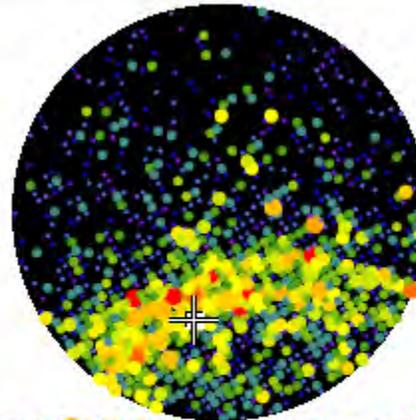


# Muon Decay



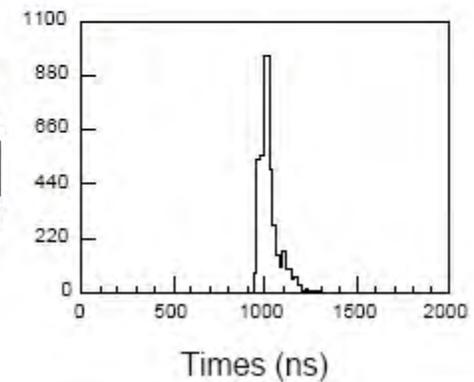
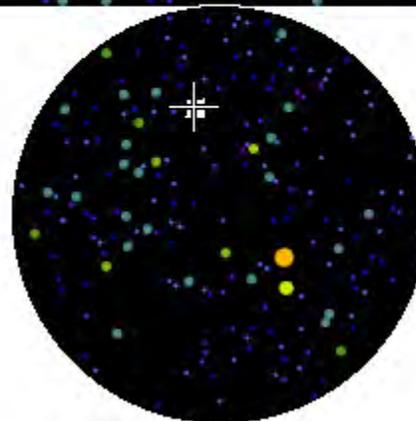
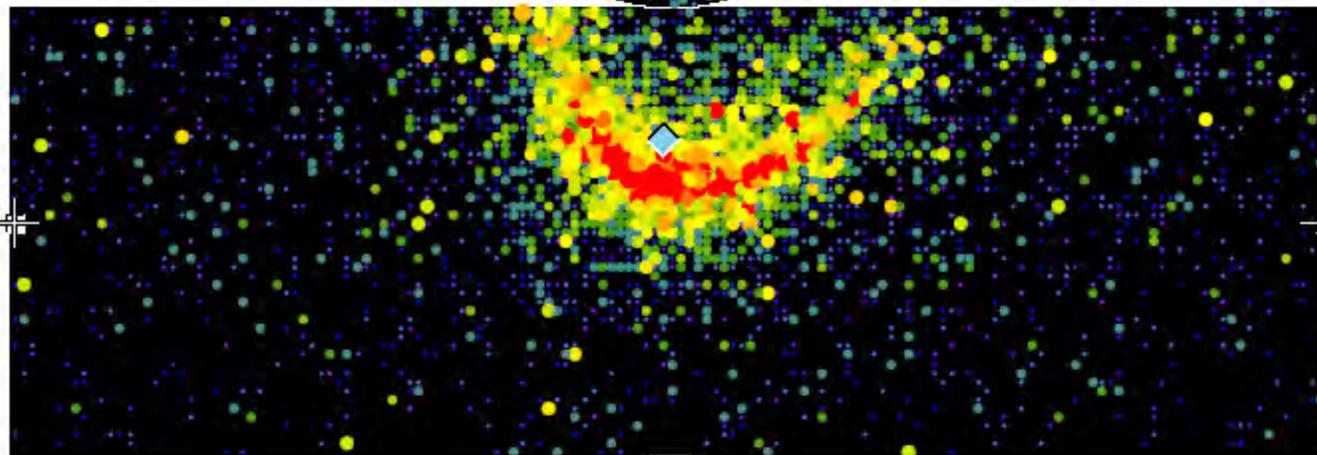
## Super-Kamiokande

Run 999999 Sub 113 Ev 31624  
03-05-19:00:45:09 0000 0000 0002  
Inner: 3641 hits, 13408 pE  
Outer: 3 hits, 2 pE (in-time)  
Trigger ID: 0x03  
D wall: 789.0 cm  
FC e-like, p = 1483.6 MeV/c



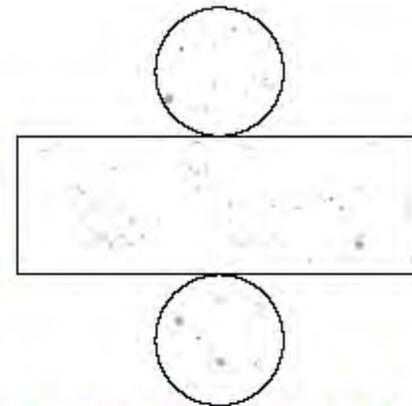
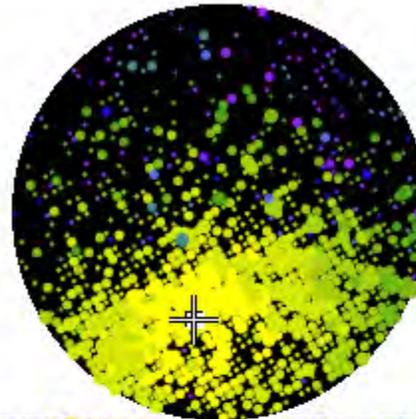
### Charge (pe)

- >21.8
- 19.1-21.8
- 16.5-19.1
- 14.2-16.5
- 12.0-14.2
- 10.0-12.0
- 8.2-10.0
- 6.5- 8.2
- 5.1- 6.5
- 3.8- 5.1
- 2.7- 3.8
- 1.8- 2.7
- 1.1- 1.8
- 0.5- 1.1
- 0.2- 0.5
- < 0.2



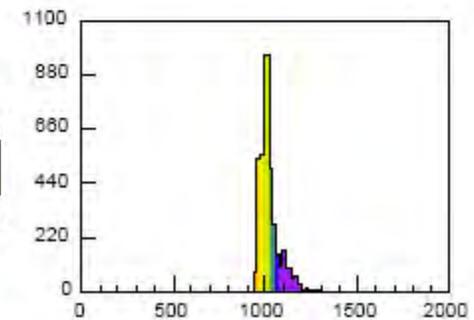
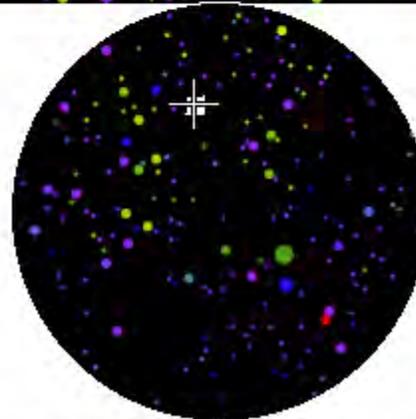
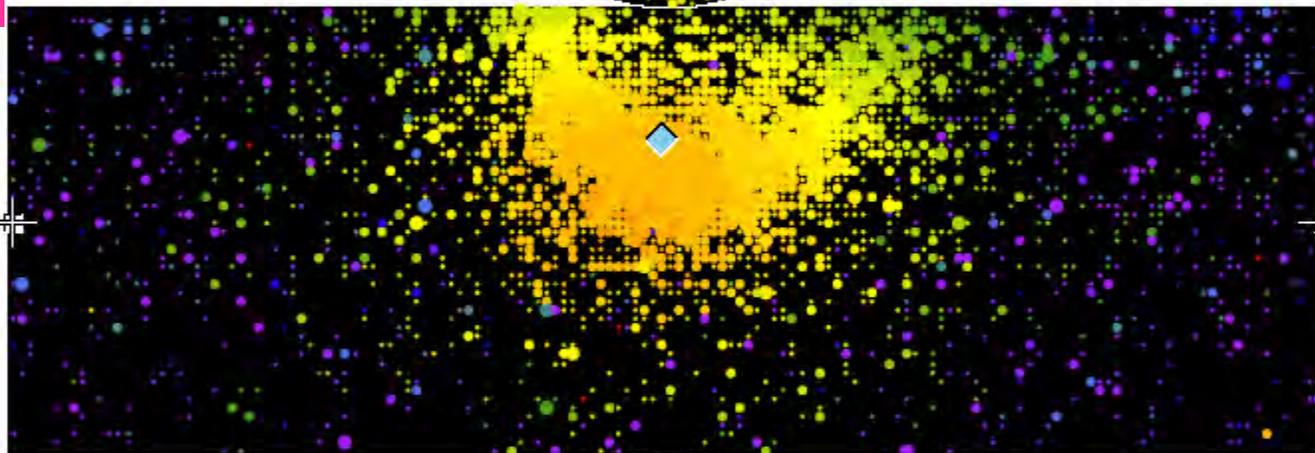
## Super-Kamiokande

Run 999999 Sub 113 Ev 31624  
03-05-19:00:45:09 0000 0000 0002  
Inner: 3641 hits, 13408 pE  
Outer: 3 hits, 2 pE (in-time)  
Trigger ID: 0x03  
D wall: 789.0 cm  
FC e-like, p = 1483.6 MeV/c



### Time (ns)

- < 950
- 950- 960
- 960- 970
- 970- 980
- 980- 990
- 990-1000
- 1000-1010
- 1010-1020
- 1020-1030
- 1030-1040
- 1040-1050
- 1050-1060
- 1060-1070
- 1070-1080
- 1080-1090
- >1090



Times (ns)

# Super-Kamiokande

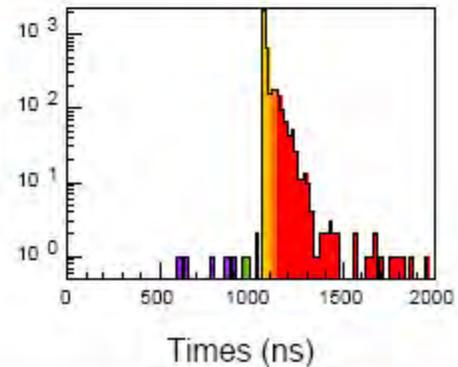
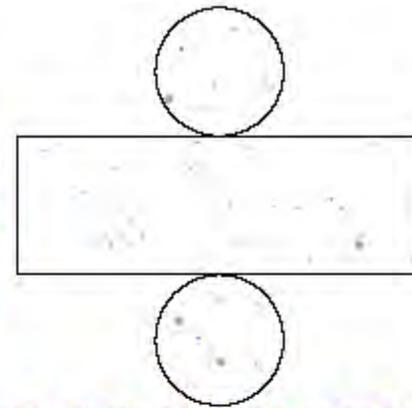
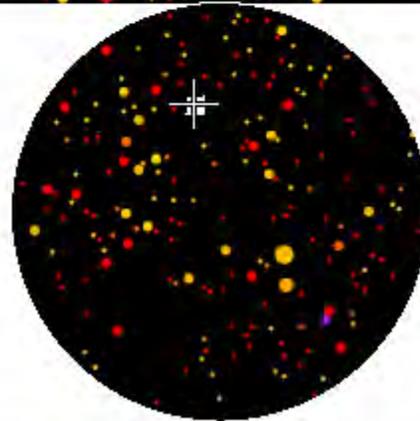
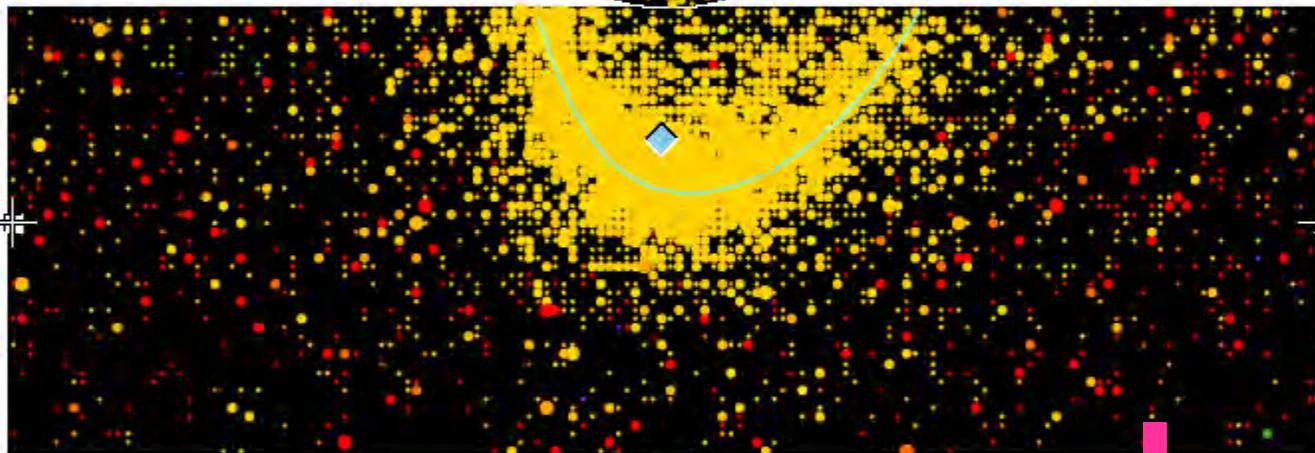
Run 999999 Sub 113 Ev 31624  
03-05-19:00:45:09 0000 0000 0002  
Inner: 3641 hits, 13408 pE  
Outer: 3 hits, 2 pE (in-time)  
Trigger ID: 0x03  
D wall: 789.0 cm  
FC e-like, p = 1483.6 MeV/c

$$t_{PMT} - TOF(x, y, z)$$

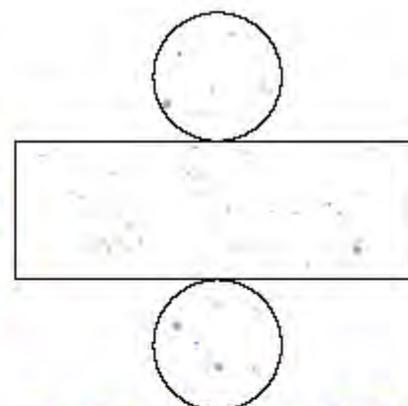
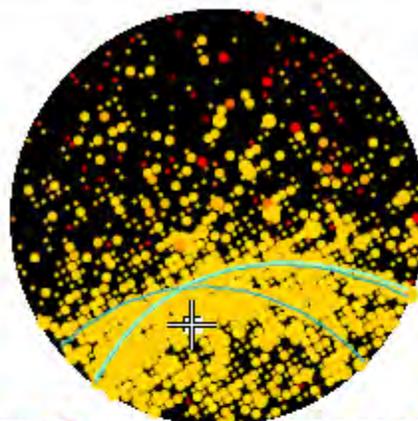
Resid(ns)

- > 137
- 120- 137
- 102- 120
- 85- 102
- 68- 85
- 51- 68
- 34- 51
- 17- 34
- 0- 17
- -17- 0
- -34- -17
- -51- -34
- -68- -51
- -85- -68
- -102- -85
- < -102

1-ring  
e-like

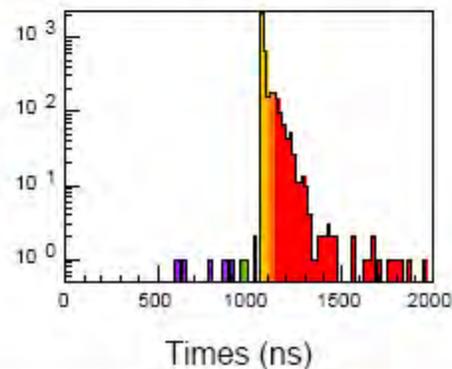
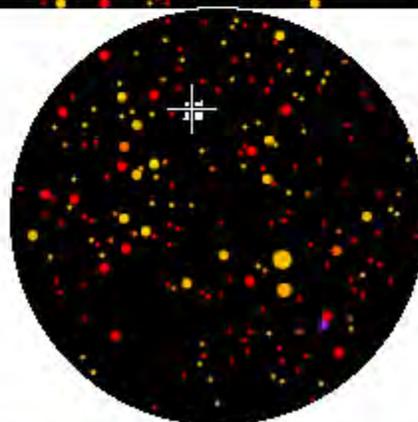
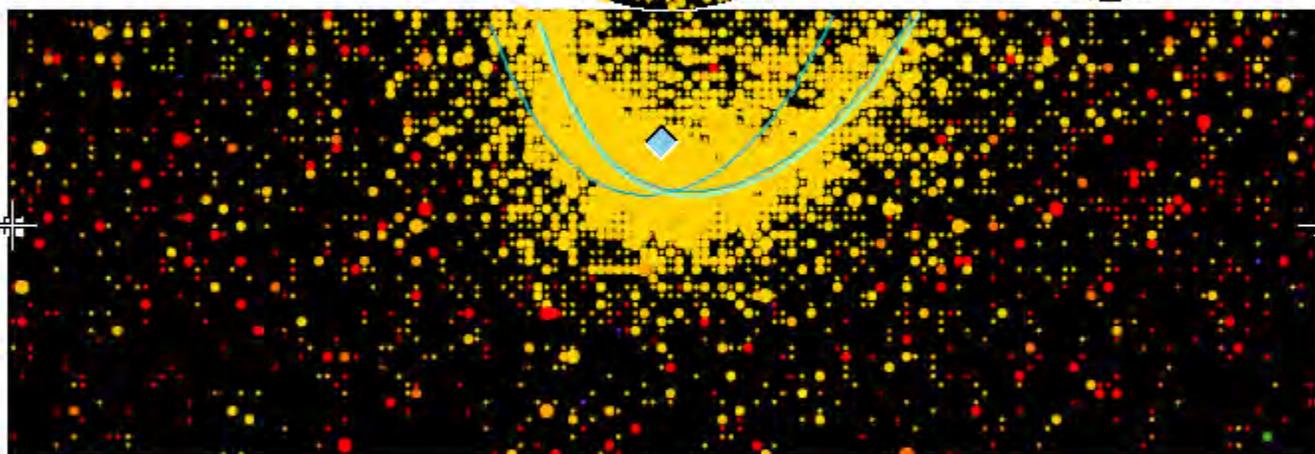


Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c
1-ring e-like E reconstructed	1.7 GeV



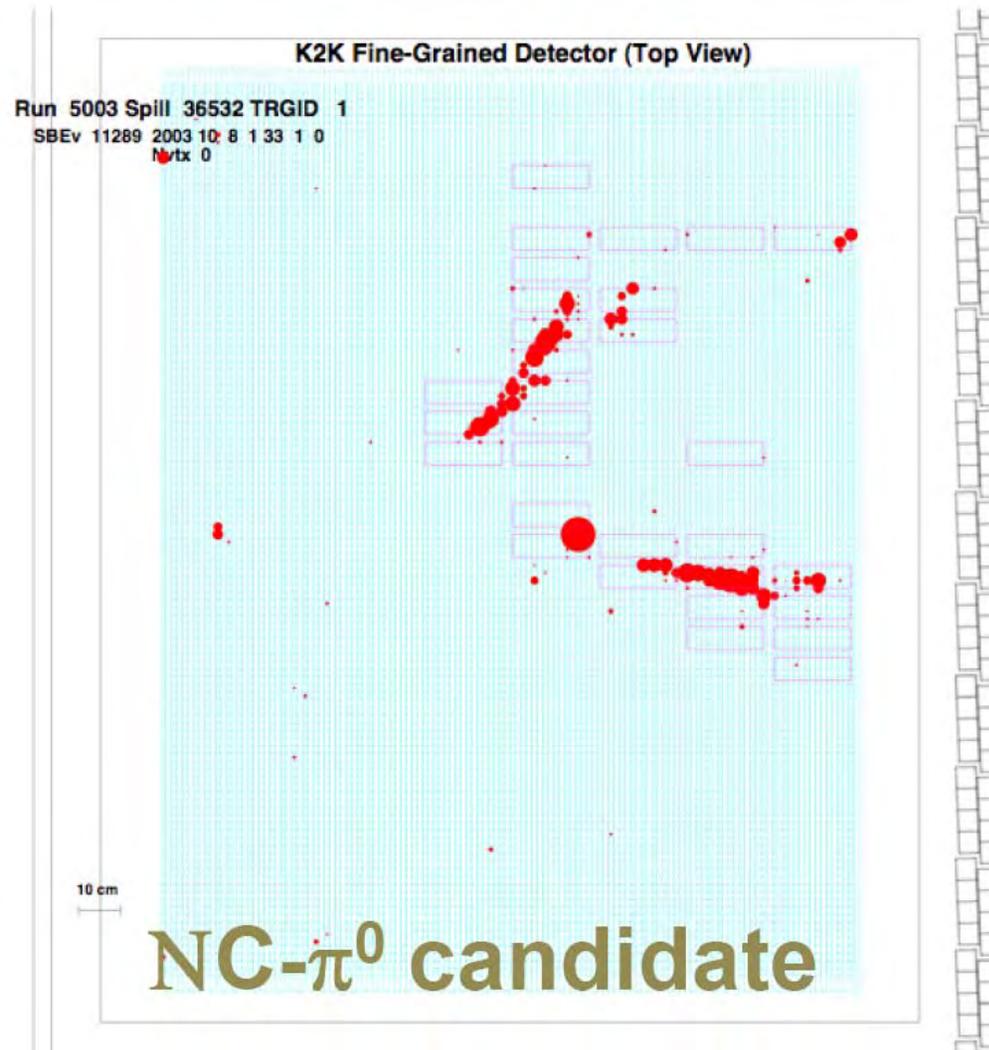
Resid(ns)

- > 137
- 120- 137
- 102- 120
- 85- 102
- 68- 85
- 51- 68
- 34- 51
- 17- 34
- 0- 17
- -17- 0
- -34- -17
- -51- -34
- -68- -51
- -85- -68
- -102- -85
- < -102



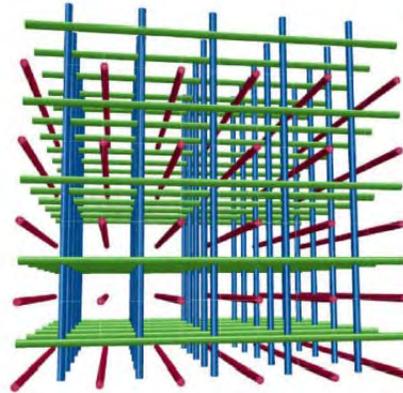
Note: this event is well above the T2K reconstructed energy window (350-850 MeV). But it is in the range for the first maximum at T2KK or FNAL-DUSEL.

# Segmented Scintillators



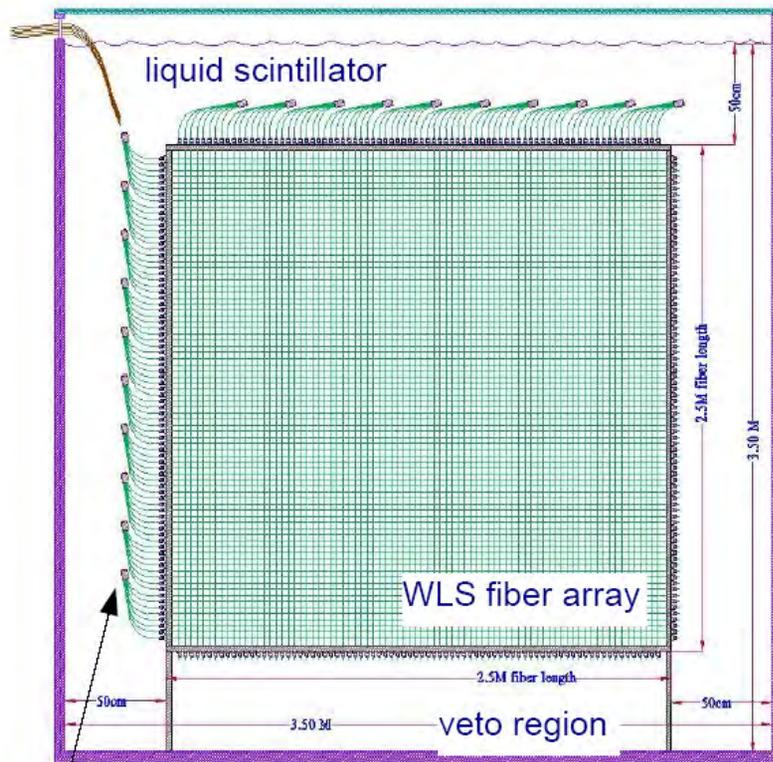
(nearly) *fully active target* and tracking medium  
high spatial resolution

# SciBath

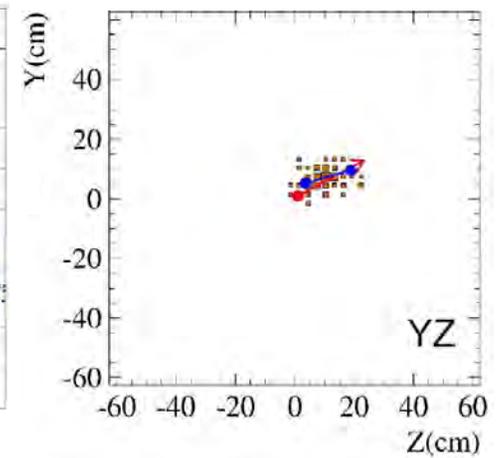
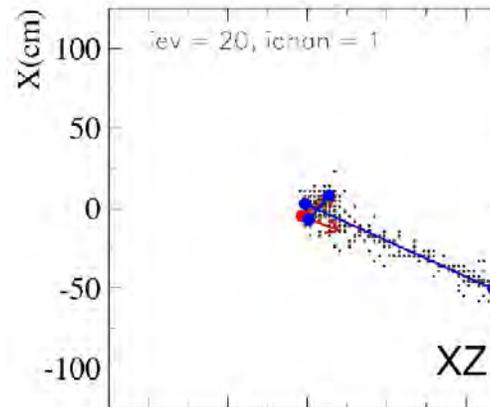


# FINeSSE

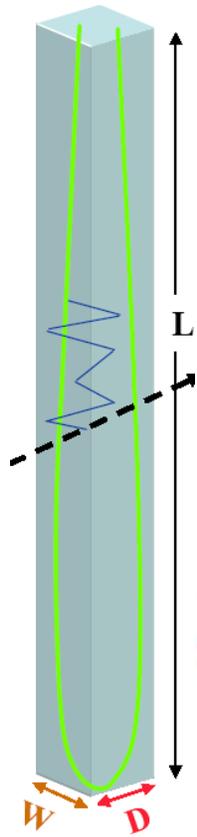
Vertex Detector side view:



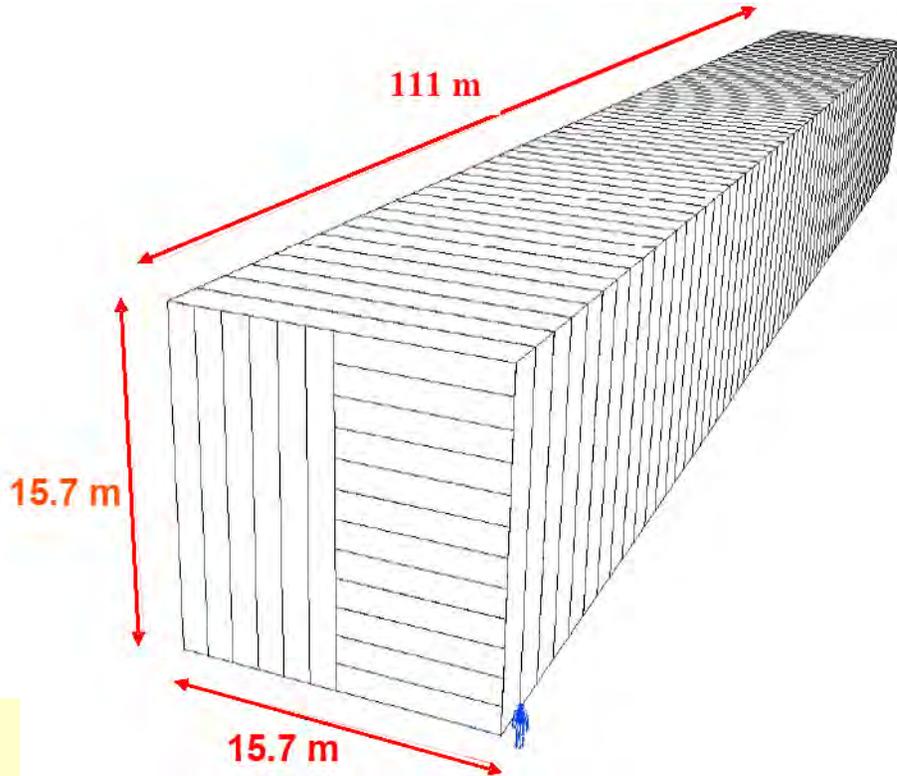
PMTs + on-board electronics



# NOvA



4cm×6cm  
~ 0.15X<sub>0</sub>



Off-axis from NuMI beam

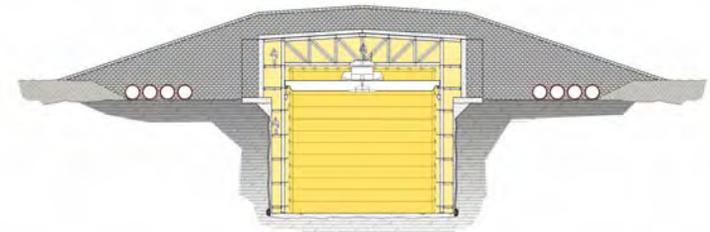
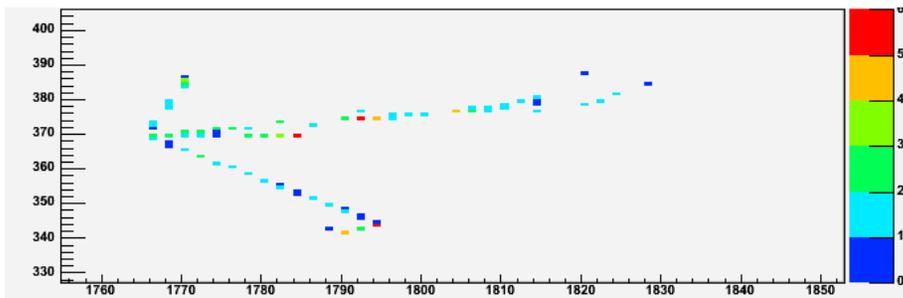
810 km baseline

E ~ 2.2 GeV narrow band

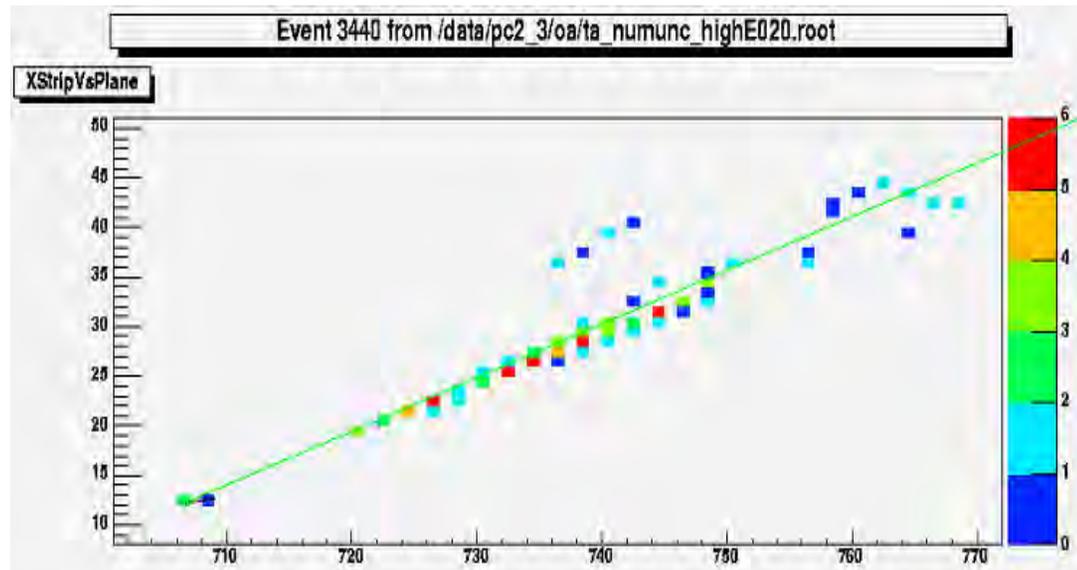
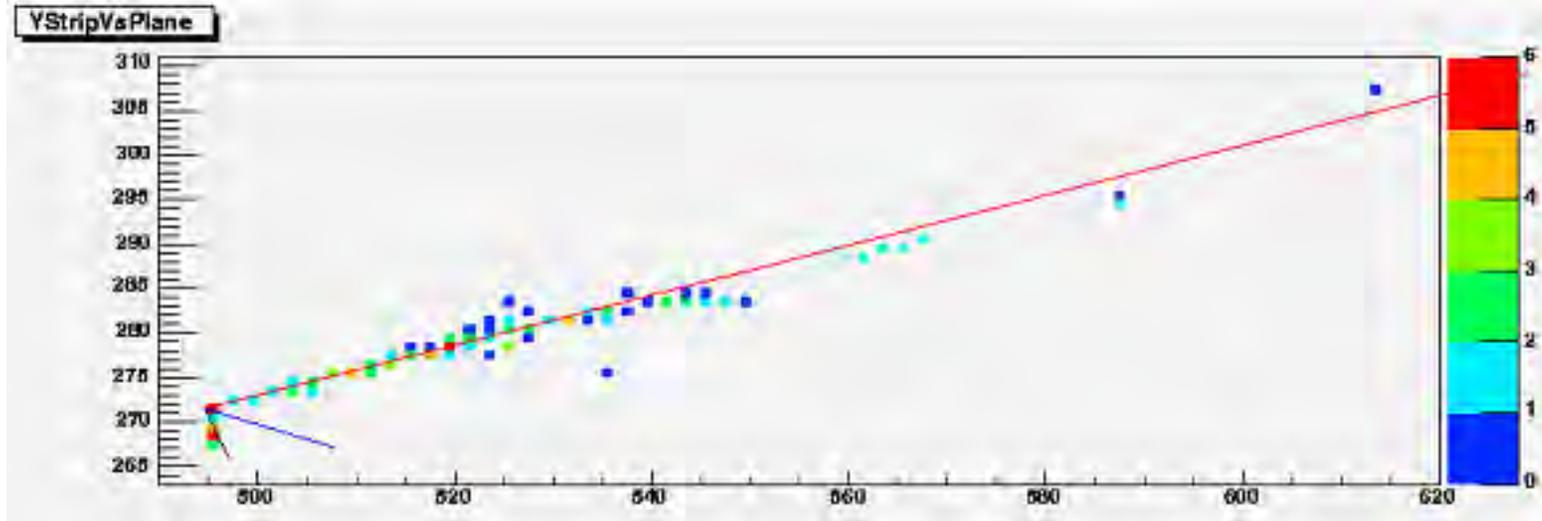
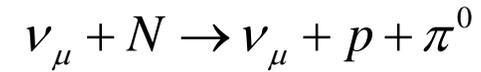
~20 kton totally active detector  
*(build as much as can afford)*

Planes of liquid scintillator  
(mineral oil) read by WLS fiber  
and APD

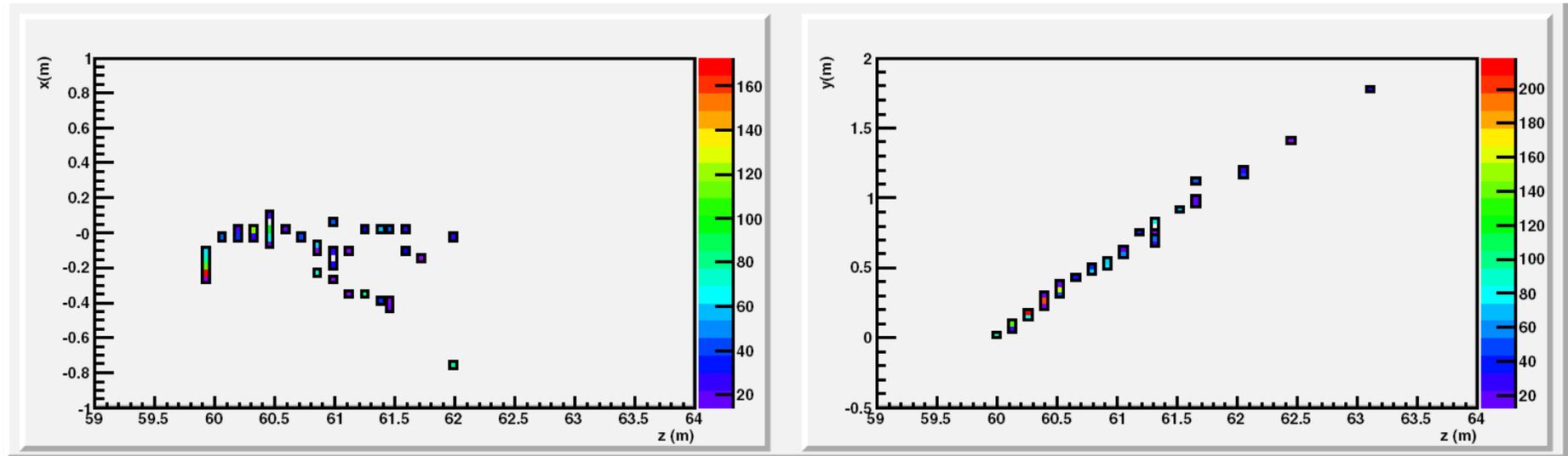
Surface detector with small  
overburden (below)



# One is Signal, One is Background

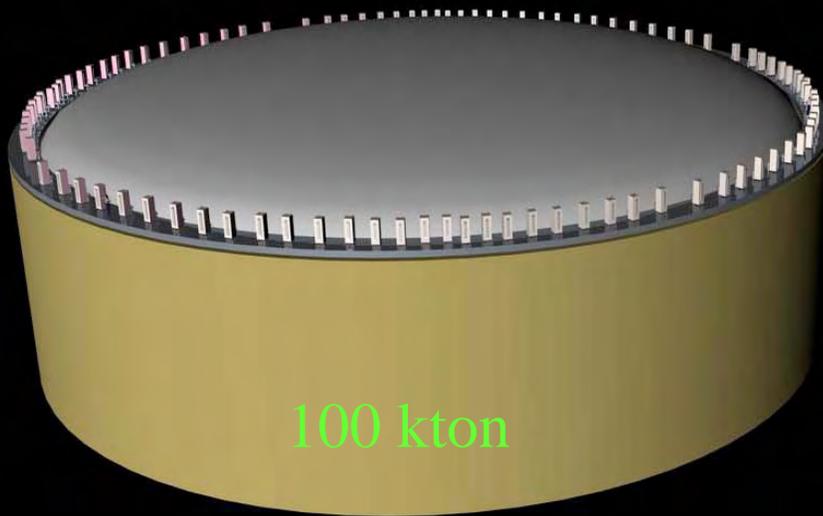
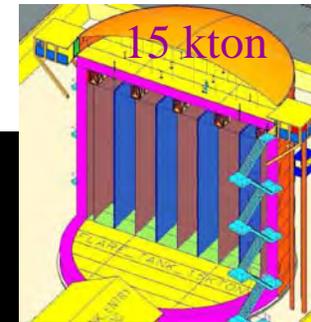
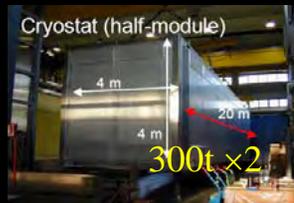
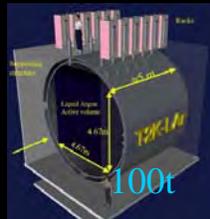


?



Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c

# Liquid Argon TPC

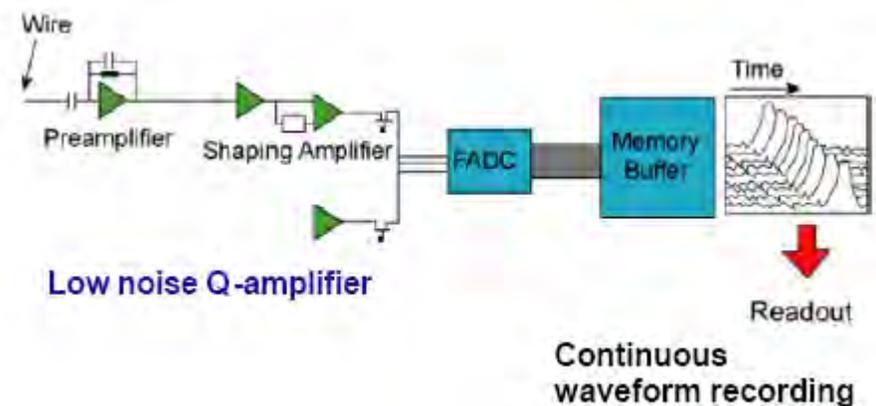
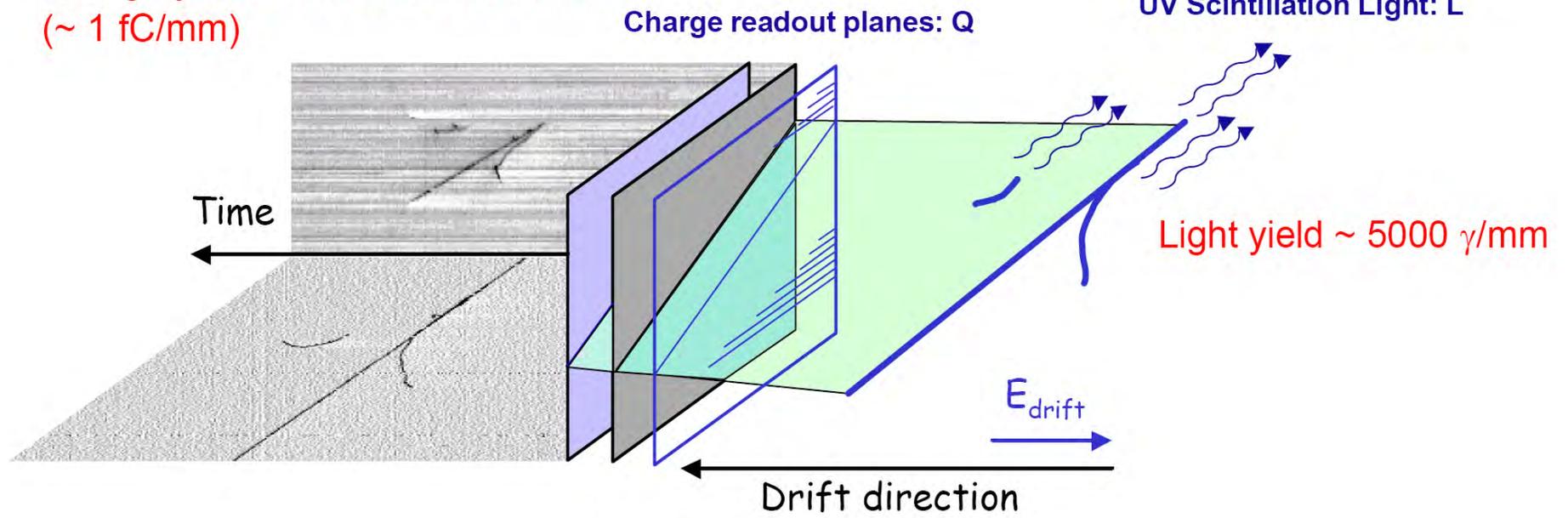


# Principle of Operation: LAr TPC

Charge yield  $\sim 6000$  electrons/mm  
( $\sim 1$  fC/mm)

UV Scintillation Light: L

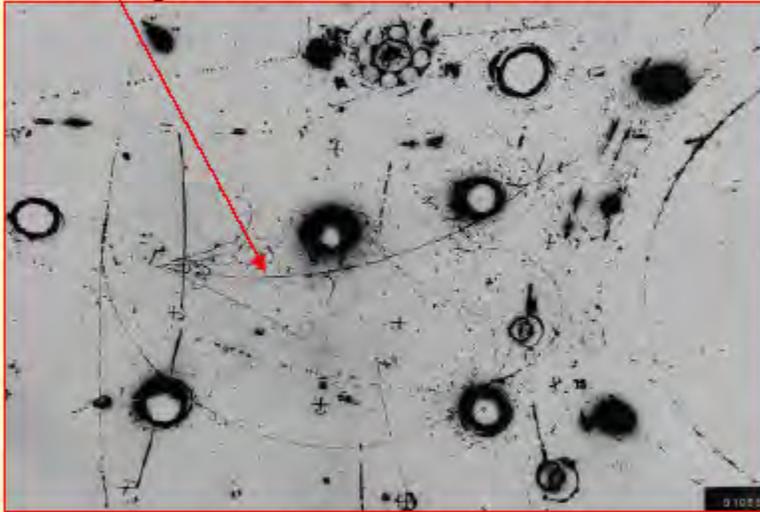
Light yield  $\sim 5000$   $\gamma$ /mm



## ...an electronic bubble chamber

Bubble diameter ~ 3 mm  
(diffraction limited)

Gargamelle bubble chamber

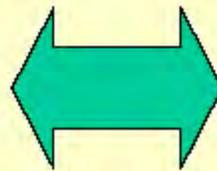


Bubble size ~ 3x3x0.4 mm<sup>3</sup>

ICARUS electronic chamber



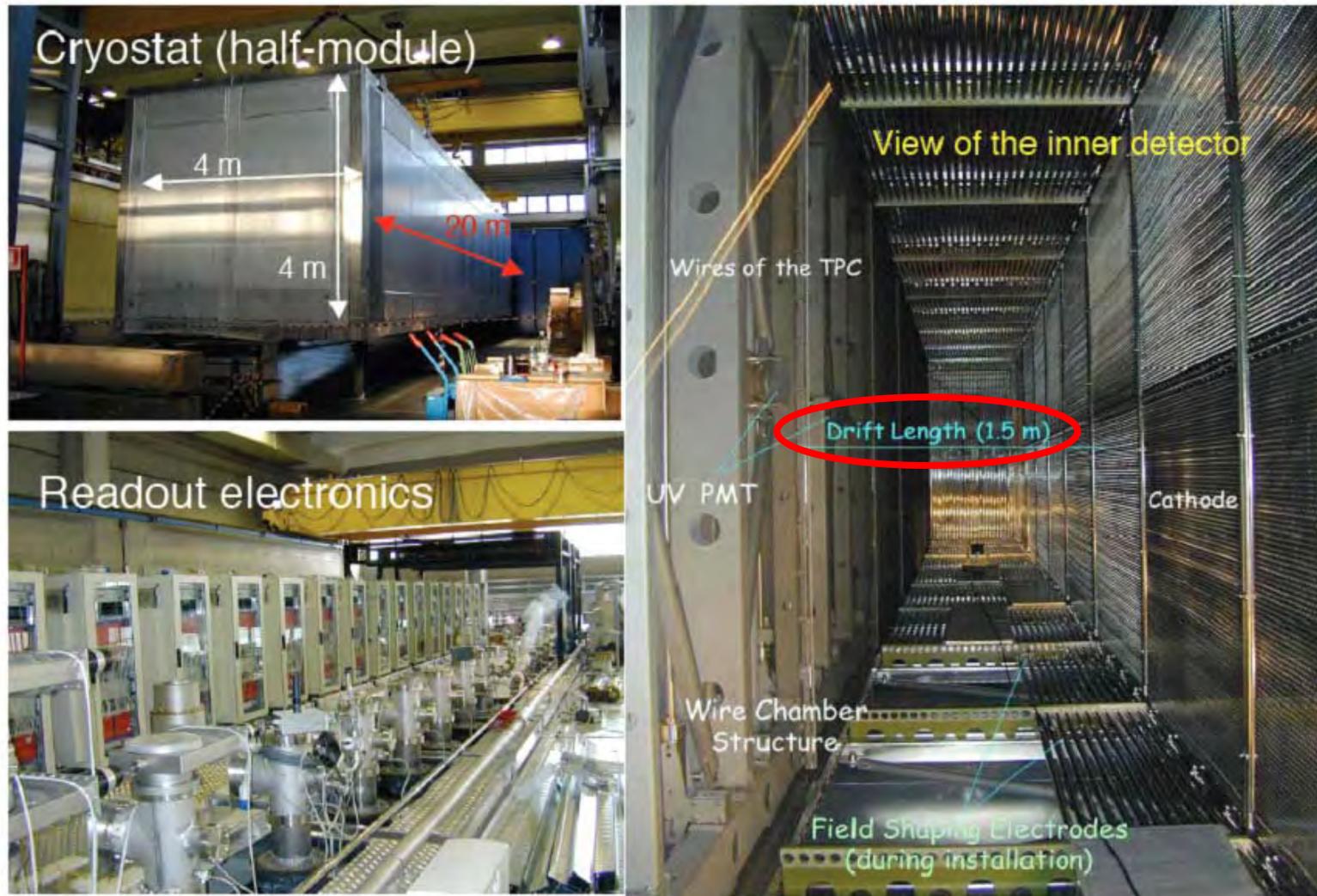
Medium	<i>Heavy freon</i>
Sensitive mass	3.0 ton
Density	1.5 g/cm <sup>3</sup>
Radiation length	11.0 cm
Collision length	49.5 cm
dE/dx	2.3 MeV/cm



Medium	<i>Liquid Argon</i>
Sensitive mass	Many ktons
Density	1.4 g/cm <sup>3</sup>
Radiation length	14.0 cm
Collision length	54.8 cm
dE/dx	2.1 MeV/cm

# ICARUS

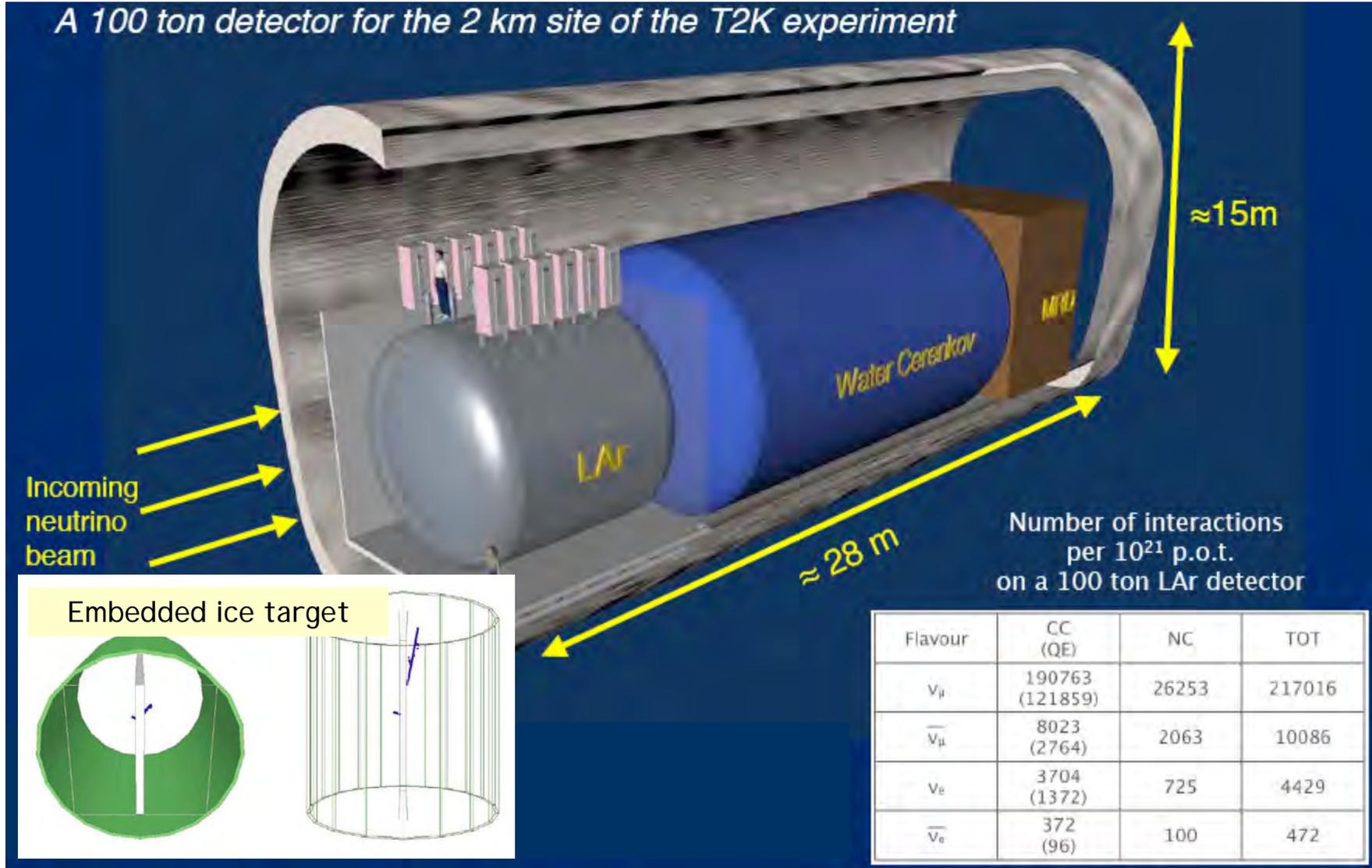
## ICARUS T300 prototype



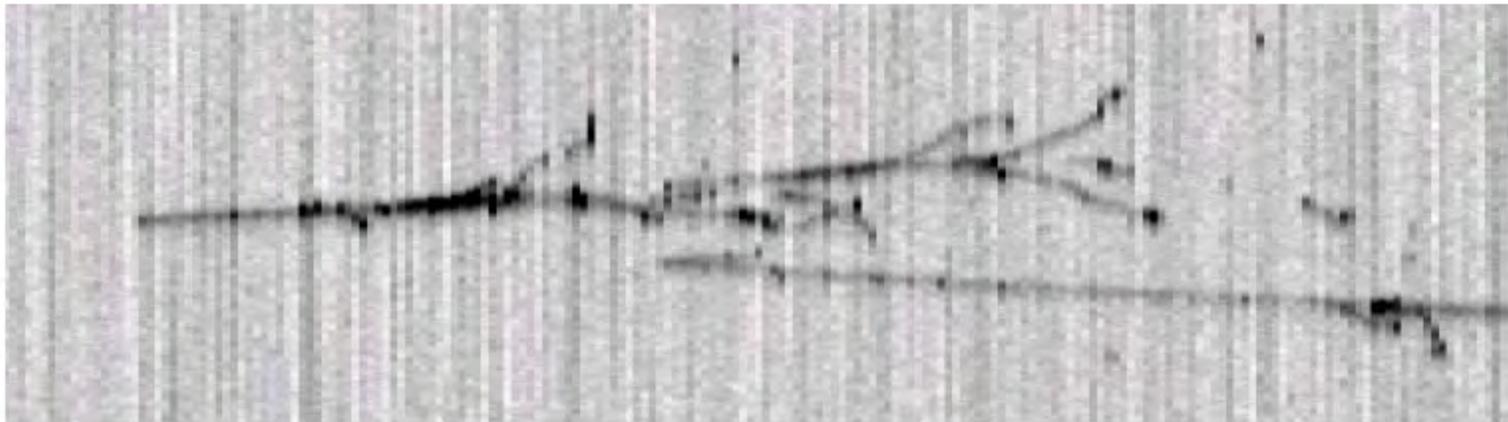
C. Rubbia at Fermilab October 2005 "20 years of liquid Argon technology"

# LAr at T2K 2KM (proposed)

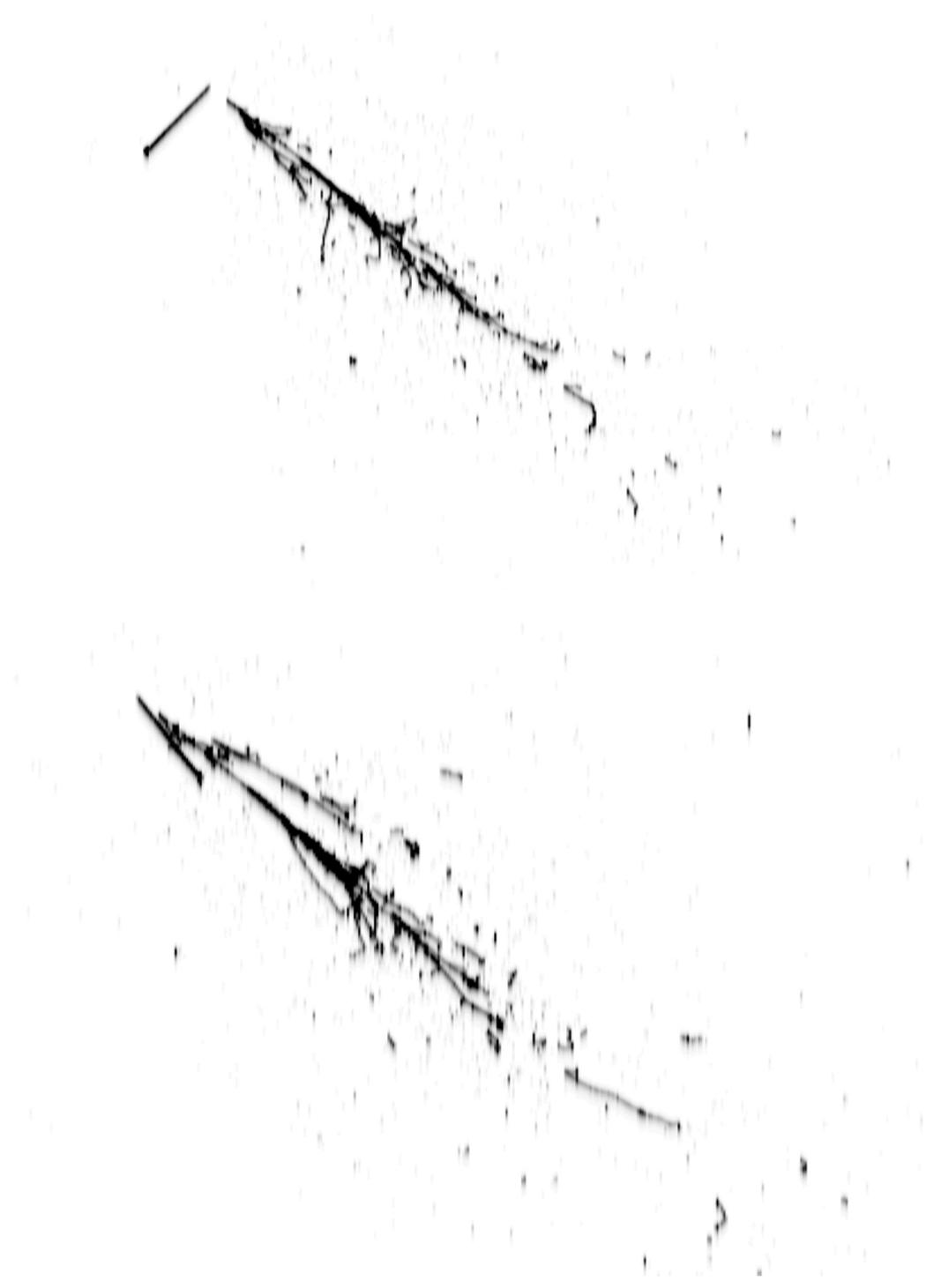
A 100 ton detector for the 2 km site of the T2K experiment



One is signal the other is background



Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c



# Challenges for Huge LAr TPC

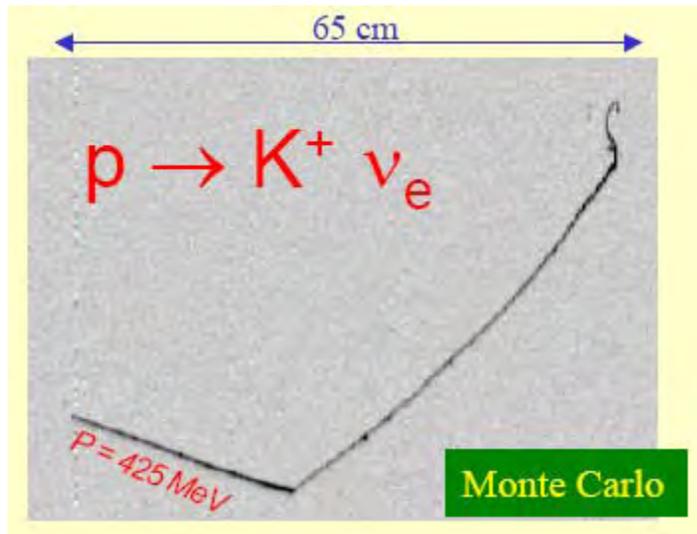
Goal is ~100 kton for CP-violation class experiments

Highly desirable to be underground to also search for proton decay ( $p \rightarrow K^+ \nu$  especially promising).

Largest existing detector is 600t ICARUS at Gran Sasso

R&D needed to develop multi-kton detector.

Purification, long drift, (optional) operation in magnetic field, charge amplification, safety ...

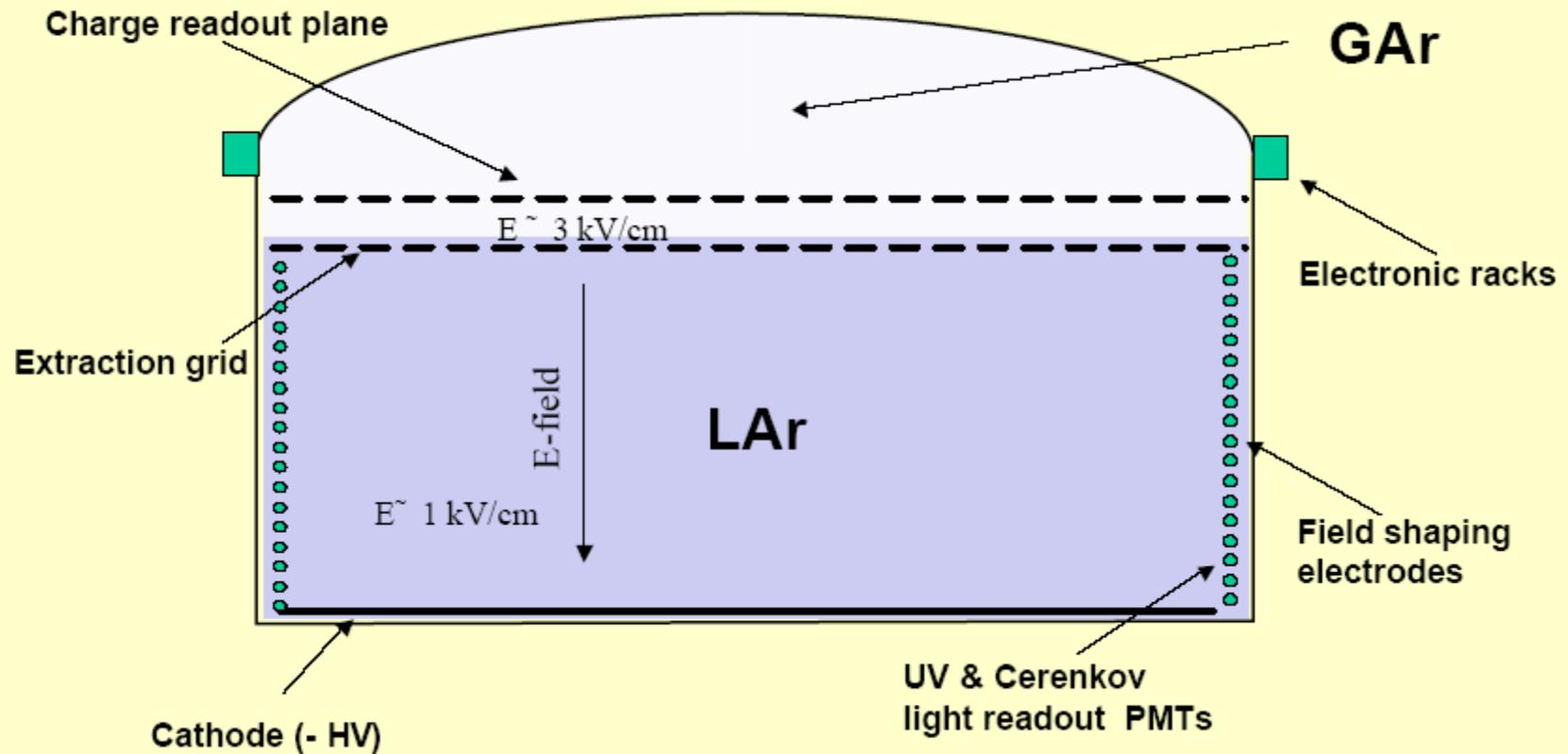


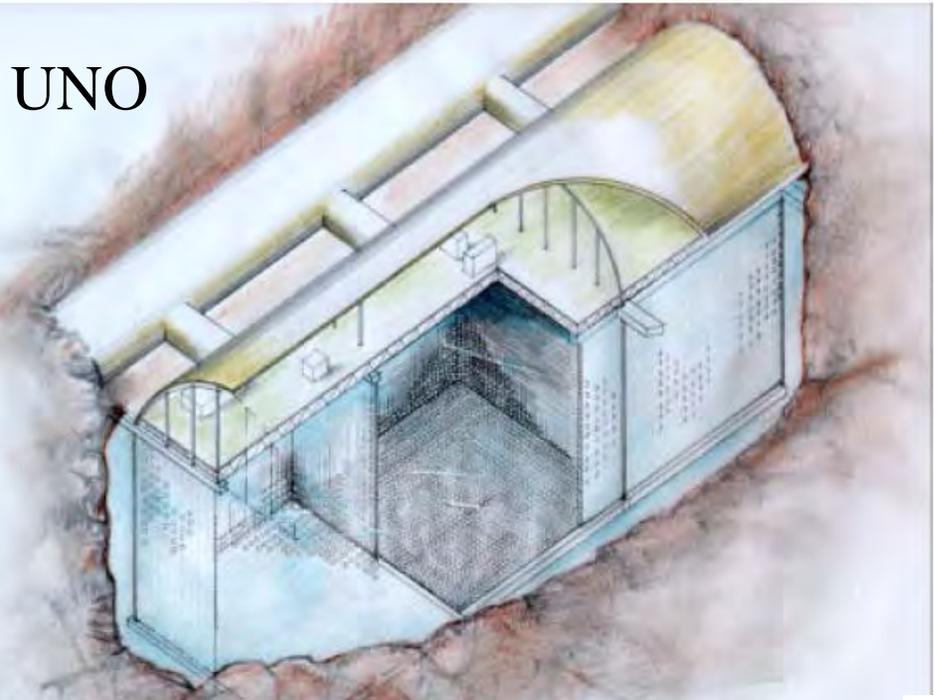
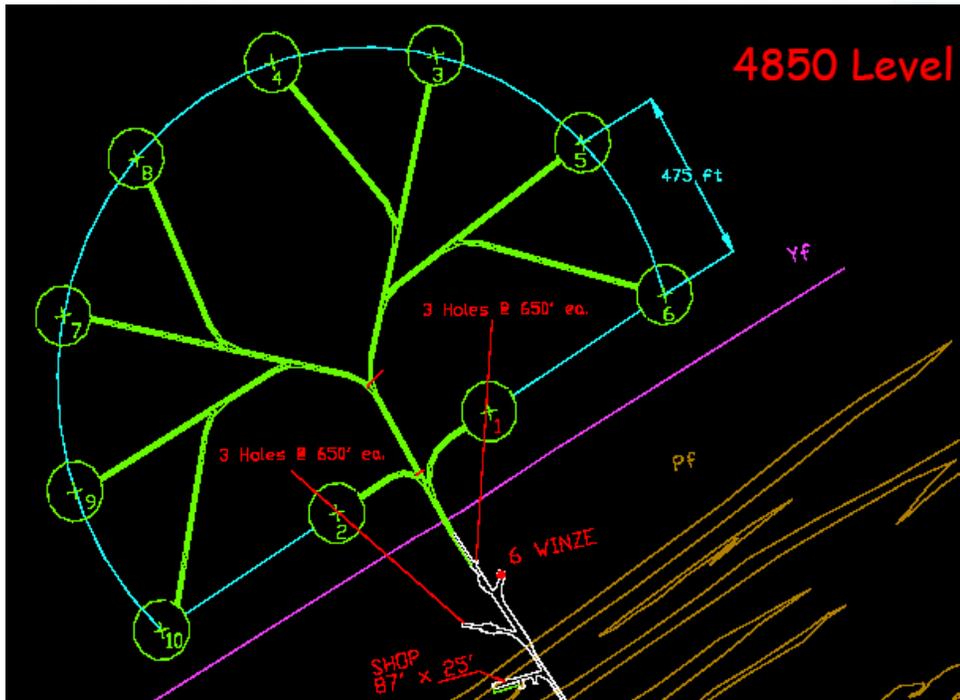
It is generally assumed that 100 kton LAr and 300 kton water Cherenkov are competitive for CP-violation class neutrino experiments. Higher efficiency makes up for lower mass. Water Cherenkov signature performance is good sub-GeV, but becomes worse at higher energies (above few GeV).

# GLACIER



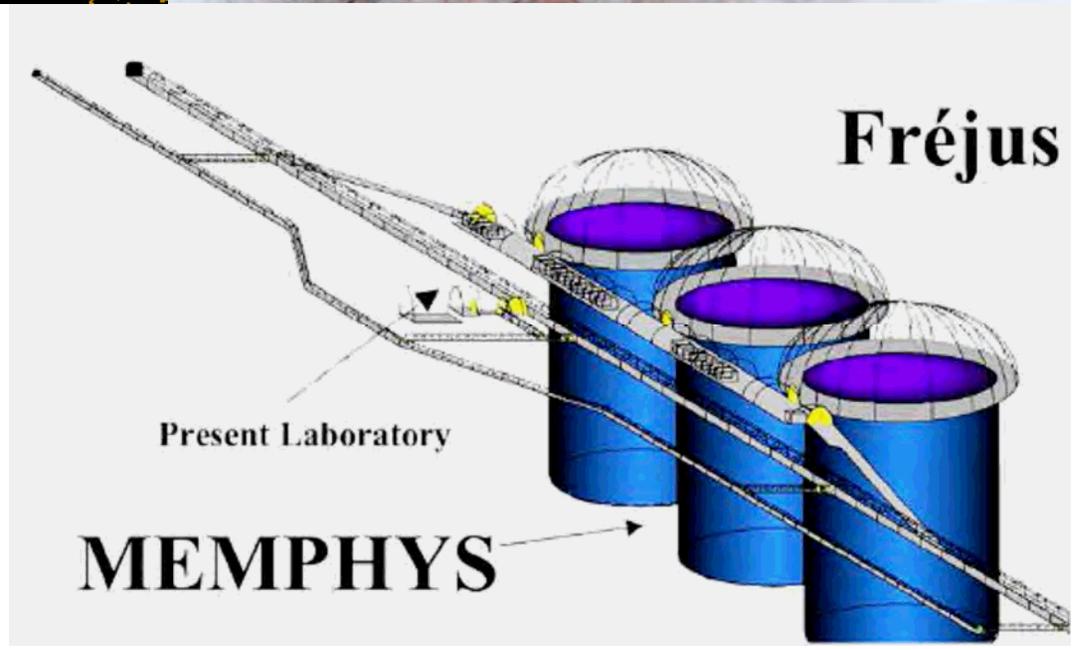
400 x 400 mm<sup>2</sup>





UNO

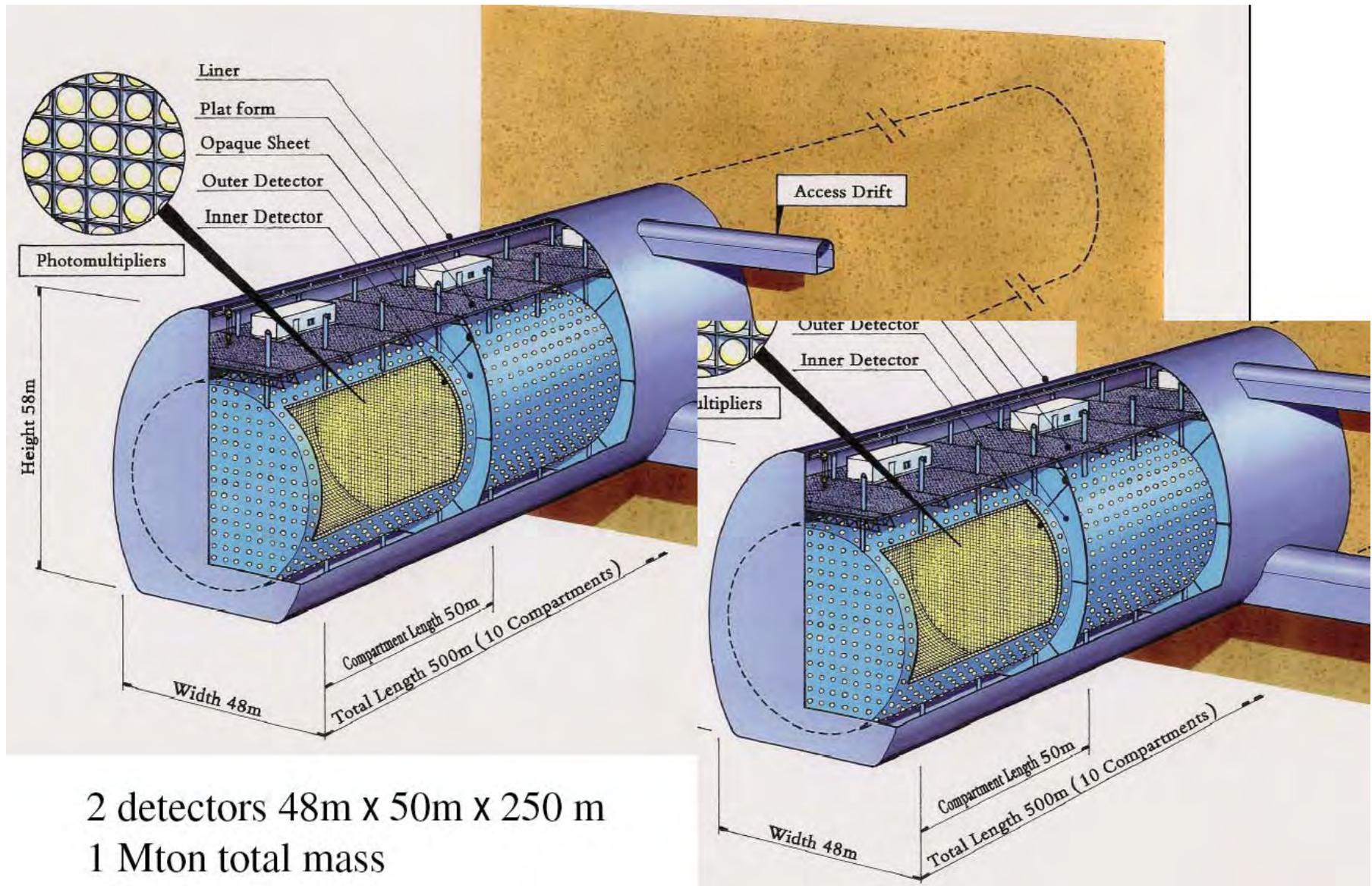
# Megaton Scale Water Cherenkov Detectors



Fréjus

MEMPHYS

# Hyper-Kamiokande

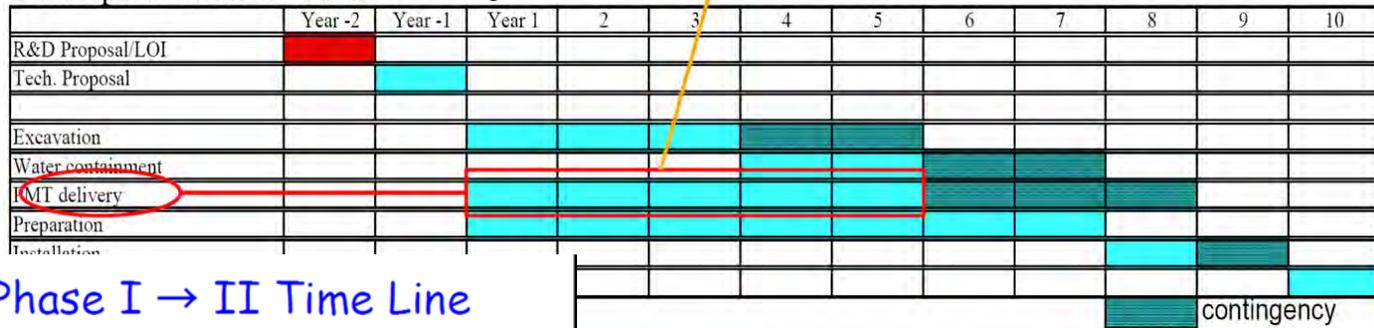


2 detectors 48m x 50m x 250 m  
1 Mton total mass

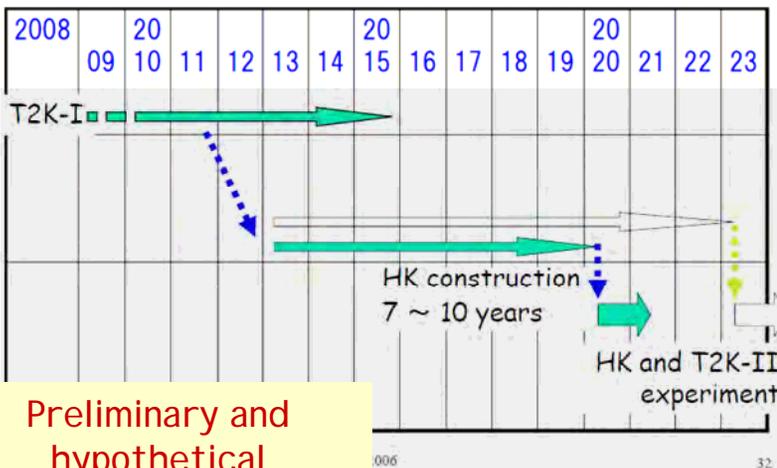
# What's stopping us from making even bigger water Cherenkov detectors?

(1) PMT fabrication time dominates the schedule

Conceptual UNO Schedule C.K. Jung



T2K Phase I → II Time Line



Preliminary and hypothetical

(2) Cost: scaling from SK with no savings, 100K tubes ~ 300M\$

# 40% or 20% Photon Coverage?

	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm ( $\mu$ -like)	30 cm (e-like) / 29 cm ( $\mu$ -like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% ( $\mu$ -like)	0.69% (e-like) / 0.96% ( $\mu$ -like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% ( $\mu$ -like)	6.3% (e-like) / 4.0% ( $\mu$ -like)
$p \rightarrow e^+ \pi^0$ signal efficiency	$40.8 \pm 1.2 \pm 6.1\%$	$42.2 \pm 1.2 \pm 6.3\%$
$p \rightarrow e^+ \pi^0$ background	0.39( $\pm 35\%$ ) events/100kty	0 events/100kty
$p \rightarrow K^+ \nu, \gamma$ tag signal efficiency	$8.4 \pm 0.1 \pm 1.7\%$	$4.7 \pm 0.1 \pm 1.0\%$
$p \rightarrow K^+ \nu, \gamma$ tag background	0.72( $\pm 28\%$ ) events/100kty	1.4( $\pm 30\%$ ) events/100kty
$p \rightarrow K^+ \nu, \pi^+ \pi^0$ signal efficiency	$5.5 \pm 0.1 \pm 0.7\%$	$5.7 \pm 0.1 \pm 0.4\%$
$p \rightarrow K^+ \nu, \pi^+ \pi^0$ background	0.59( $\pm 28\%$ ) events/100kty	1.0( $\pm 30\%$ ) events/100kty
T2K $CC\nu_e$ likelihood effic.	83.7% ( $\pm 0.1\%$ stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

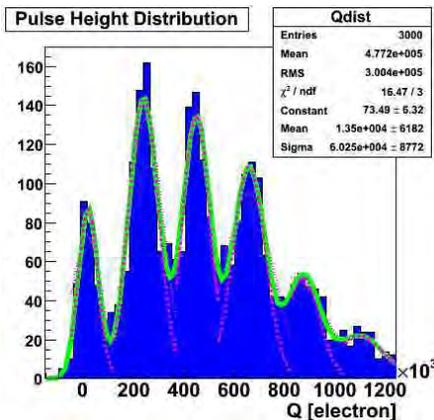
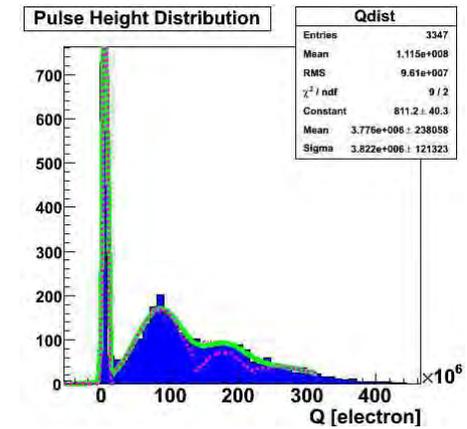
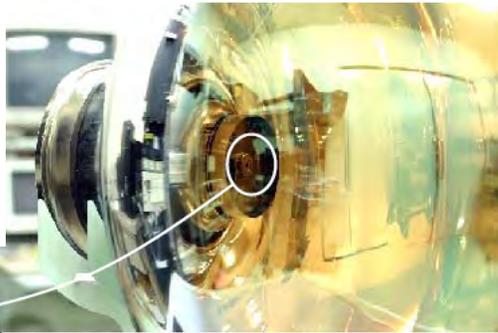
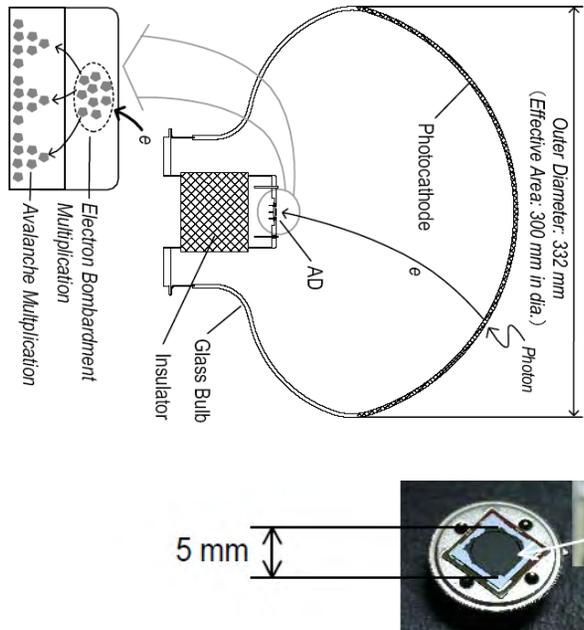


S.T. Clark, Ph.D. Thesis (2006)  
F. Dufour, T2KK Workshop (2006)

**Preliminary numbers, for comparison purposes.**  
**Final published efficiencies and BG may differ.**

# Hybrid Avalanche Photodiode

R&D: U. Tokyo/KEK/Hamamatsu/ICRR <http://www-conf.kek.jp/rd-photon2006/>



Parameters	13-inch HPD	20-inch PMT (R3600-02)
Order of Gain	$10^5$	$10^7$
Single Photon Time Resolution ( $\sigma$ )	190ps	2300ps
Single Photon Energy Resolution	44% (preliminary)	150%
Rise Time	1ns	10ns
Pulse Width	2.2ns	20ns
Dynamic Range	3000 p.e.	1000 p.e.
(Signal intensity in P.E.)		

# Conclusions

Neutrino detectors:

What do you want from the final state?  
What does your experiment demand in terms  
of signal, background, event reconstruction?

Design based on interplay of:  
Mass - Granularity - Cost

Next generation (+100 kton) will likely be:  
Water Cherenkov (cheap, so to speak)  
Liquid Argon (if we can learn how)

Thanks for all the good questions,  
let's go to the barbecue!

*Special thanks to: F. Dufour, M. Ishitsuka, B. Lundberg, A. Meregaglia, M. Messier, J. Morfin, J. Raaf, S. Willocq.*