Neutrino Detectors II

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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 ν
  - KamLAND, LSND
- **Tracking Detectors**
  - Two ν Experiment
  - NuTeV, MINOS, CHARM II
- **Bubble Chambers**
  - Discovery of Neutral Currents
- **Hybrid Detectors:**
  - MINERνA, NOMAD
  - Discovery of Tau Neutrino

Lecture II: The Challenges for ν_e Appearance

- **Water Cherenkov**
  - Super-Kamiokande
- **Segmented Scintillator**
  - NOνA
- **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? ν_e, ν_μ, ν_τ, 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…

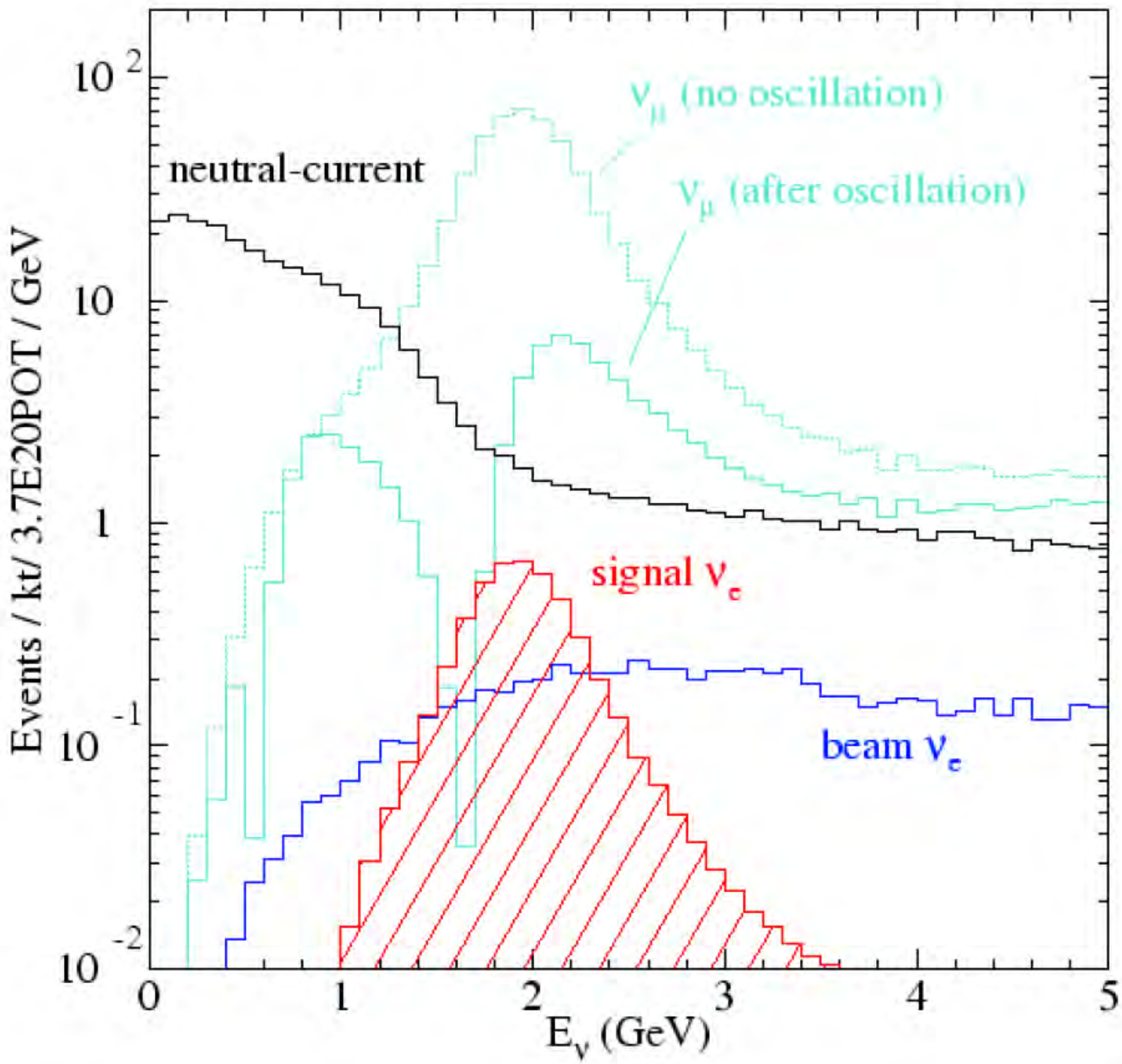
Challenge of ν_e Appearance

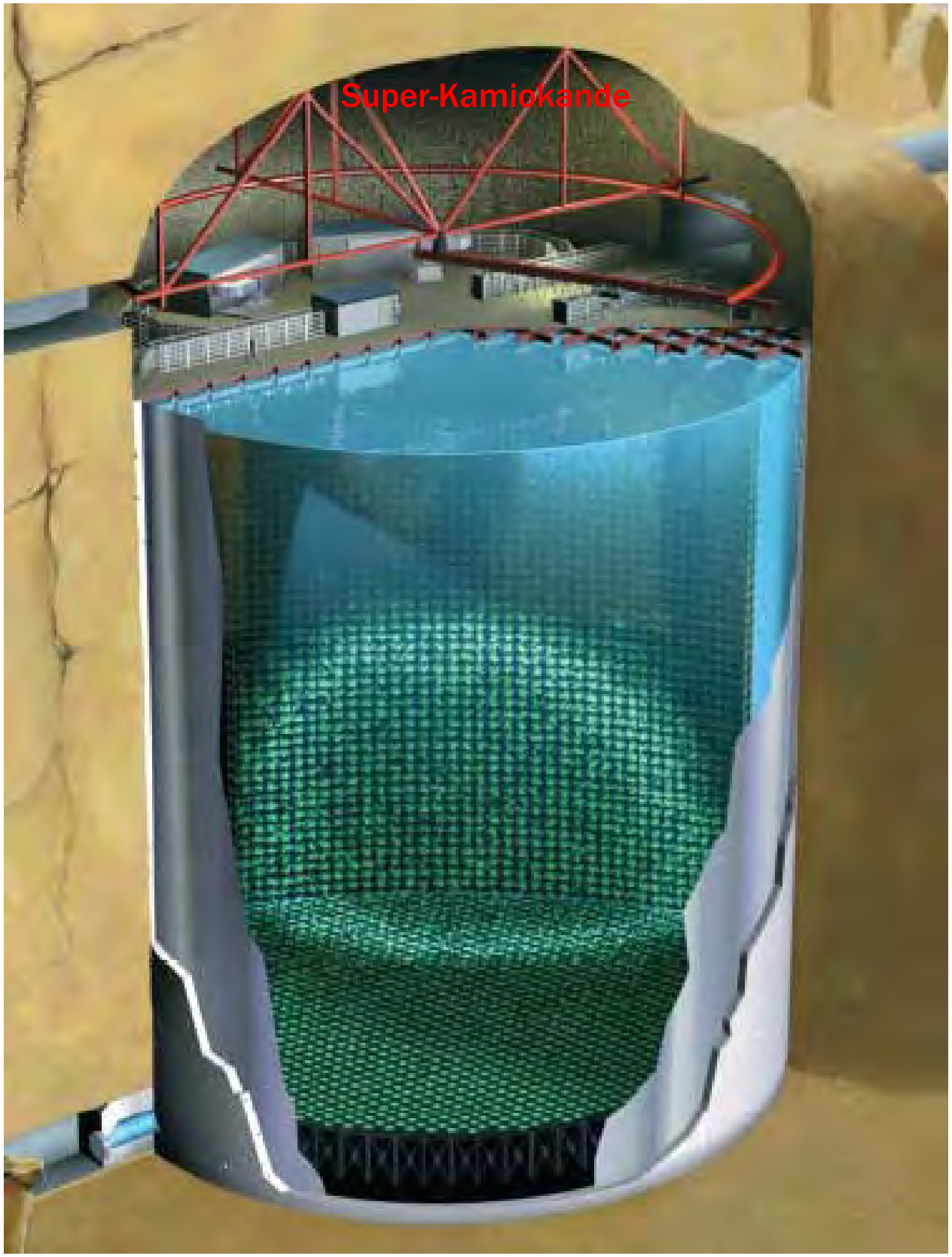
Accelerator beam flux	100×10^6 $\nu/cm^2/5$ yr
Oscillation Probability	1-10%
Event rates: CC ν_μ / NC / ν_e	10K / ~800 / 200 events
Signal Efficiency / BG	40% / 20 events
Mass of detector	22.5 kt

... and something comparable for NOνA.

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

Neutrino Interactions





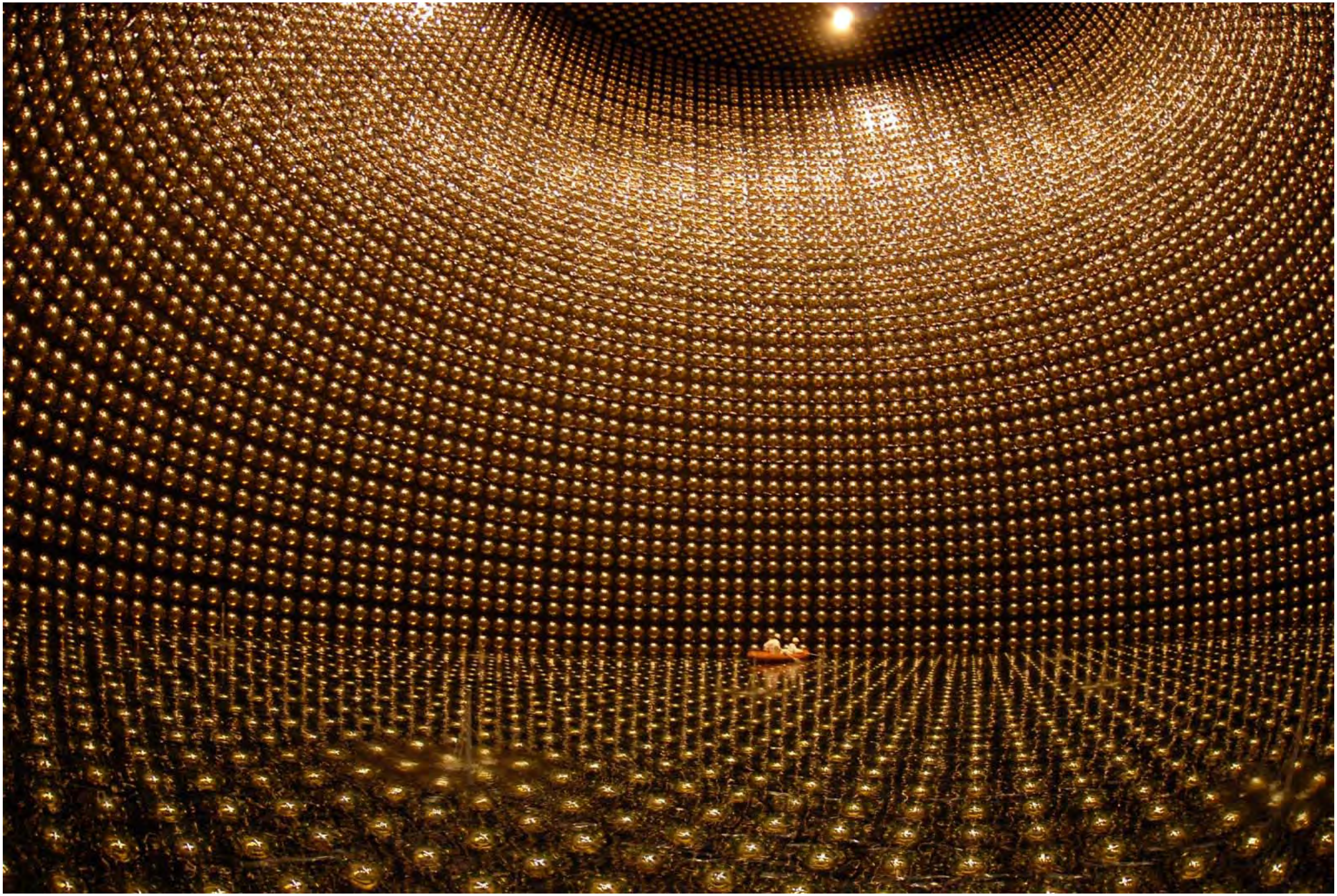
Water Cherenkov

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

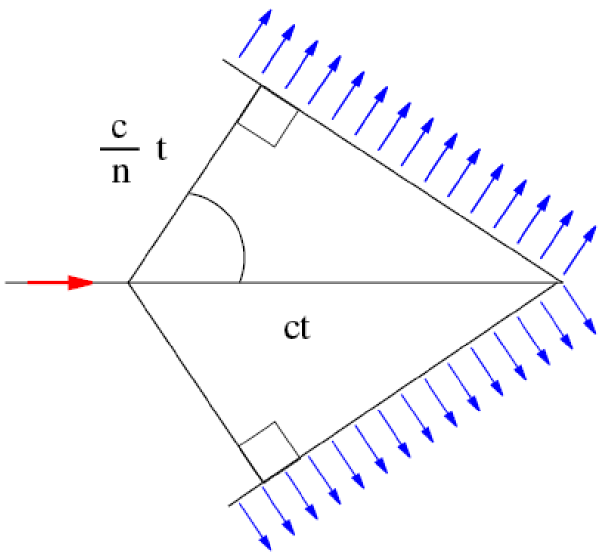
SK-III: May 2006-
Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

SK-future:
Replace all electronics - 2008
Add Gadolinium - 20??



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

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)

$\cos\theta = 1/\beta n$
β threshold = 0.75
$\theta \to 41° = \theta_C$ as $\beta \to 1$

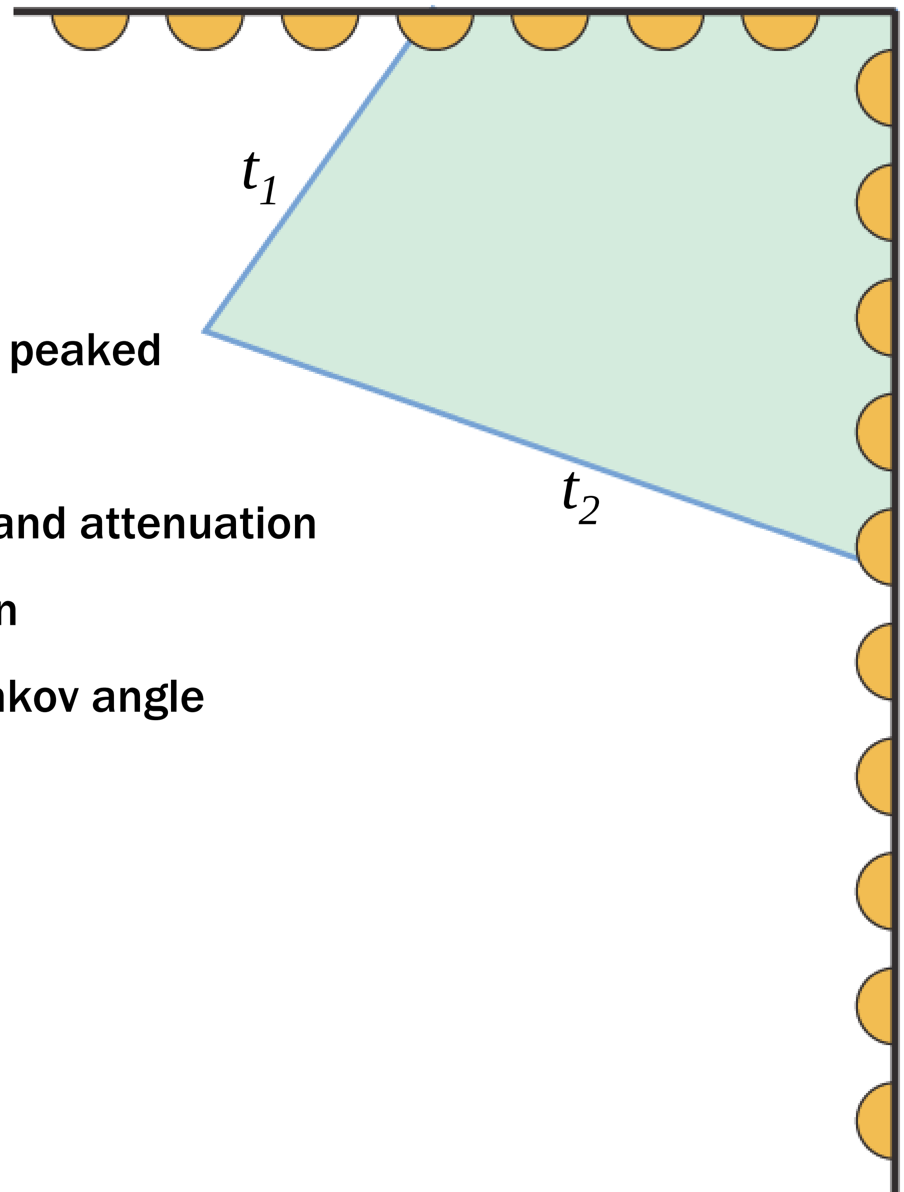
at β=1 ~770 photons/cm emitted (λ 300-600 nm)

	Cherenkov Threshold		
Particle	p(MeV/c)	E(MeV)	T(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"

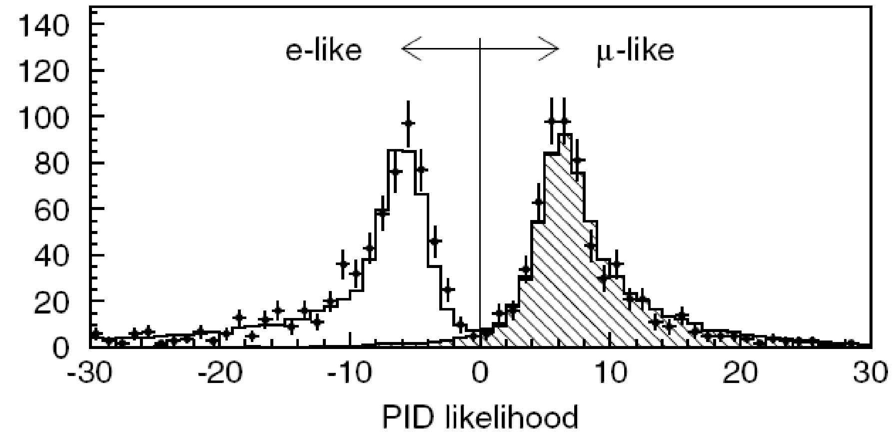
Vertex, direction, momentum

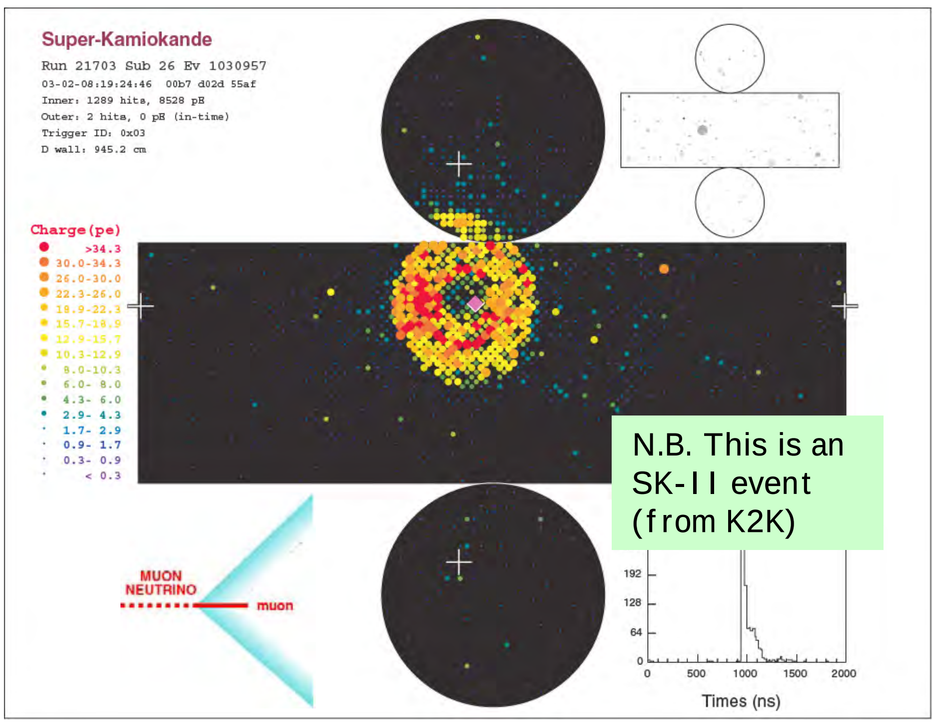
- **Find position where** t_i-TOF(x,y,z) **is most peaked**
- **Correct for length of muon track**
- **Correct for PMT acceptance (#photons) and attenuation**
- **Incorporate PID by expected light pattern**
- **Assign momentum by #pe andfit Cherenkov angle**



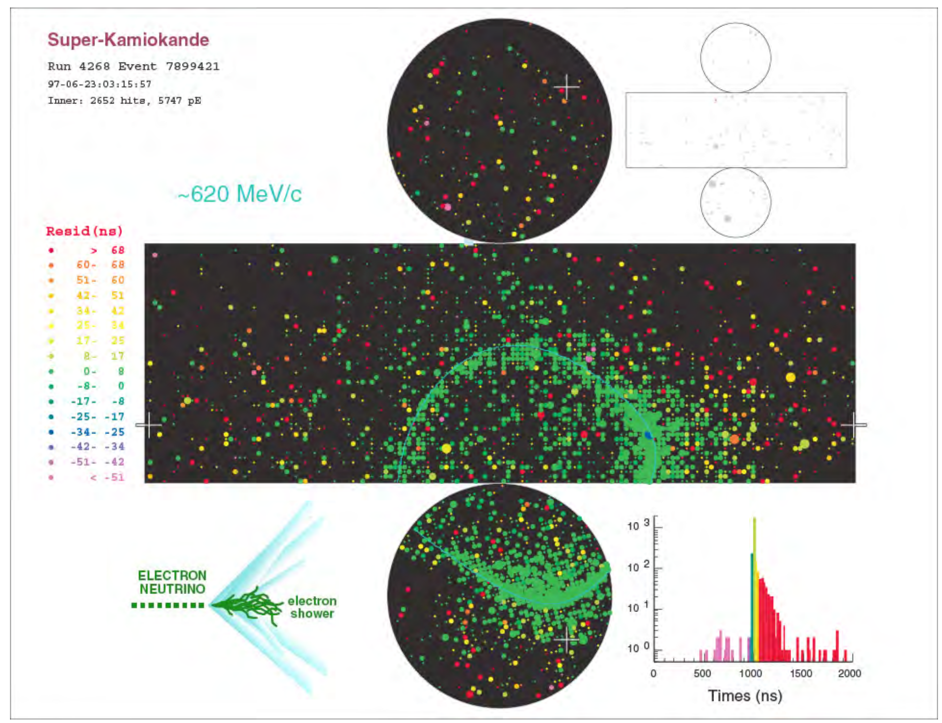
Particle Identification

Compare observed and expected light pattern and Cherenkov angle using likelihood





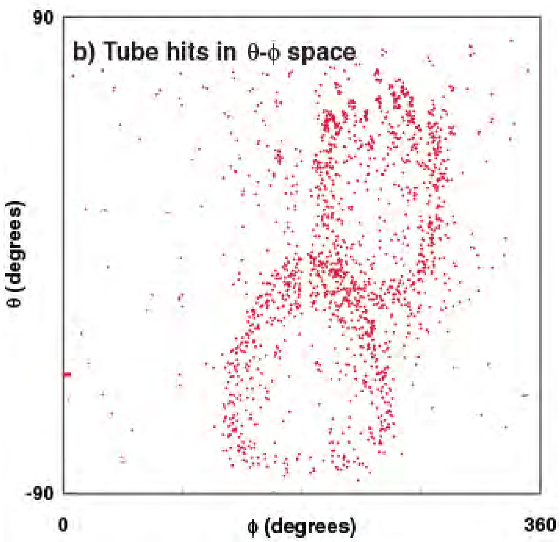
N.B. This is an SK-II event (from K2K)

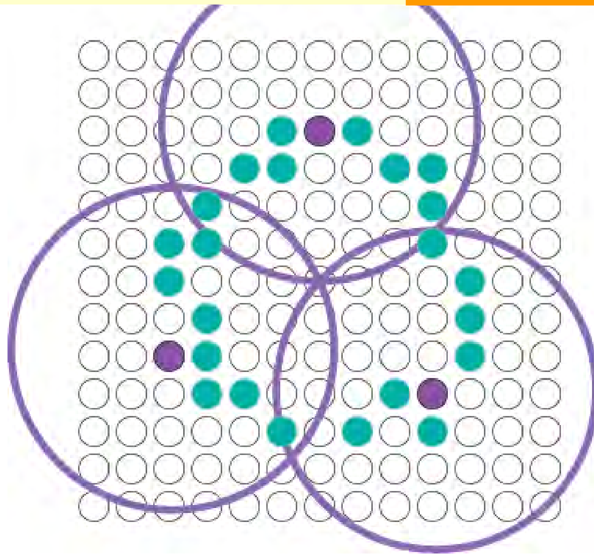


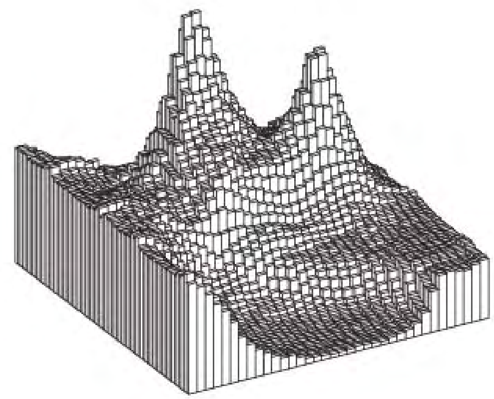
Ring Finding

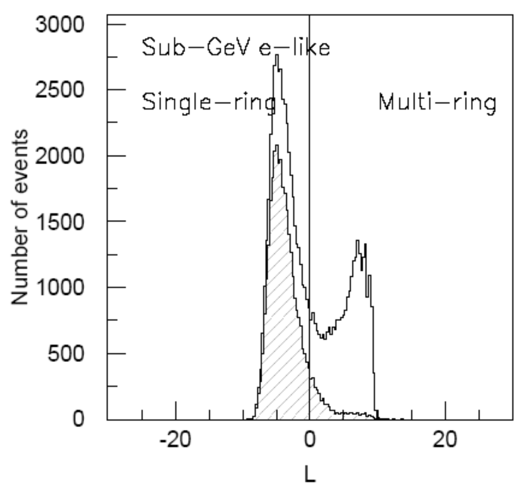
Hough transform

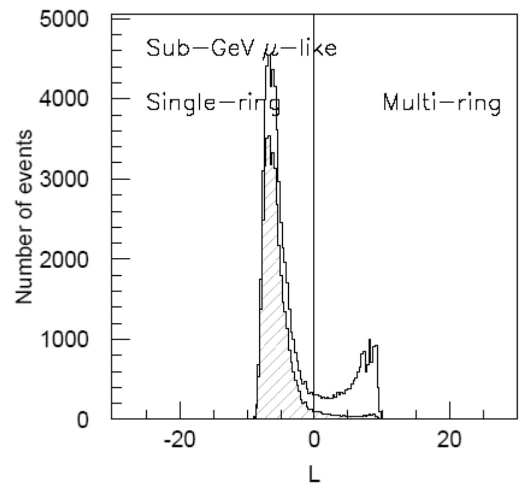
Becomes peak finding problem



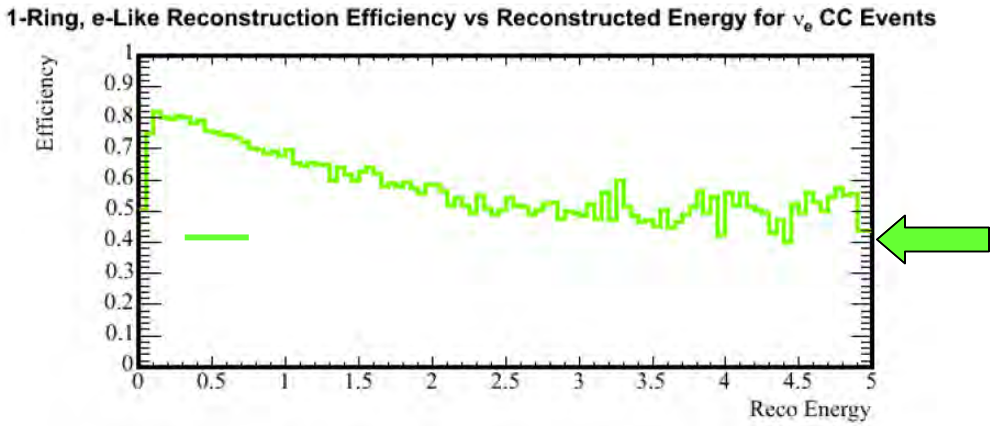


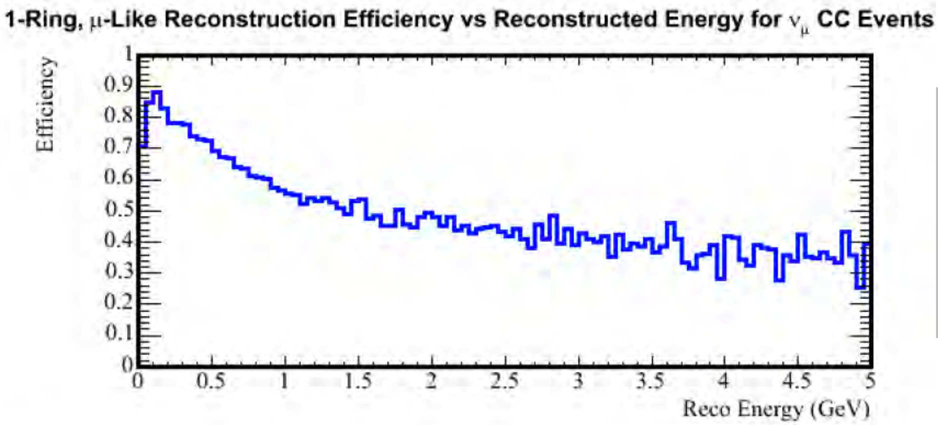


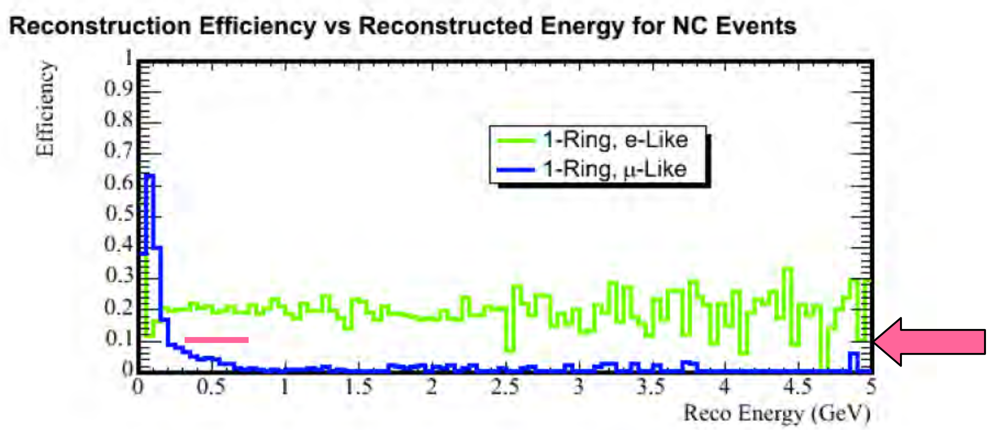




Signal and Background



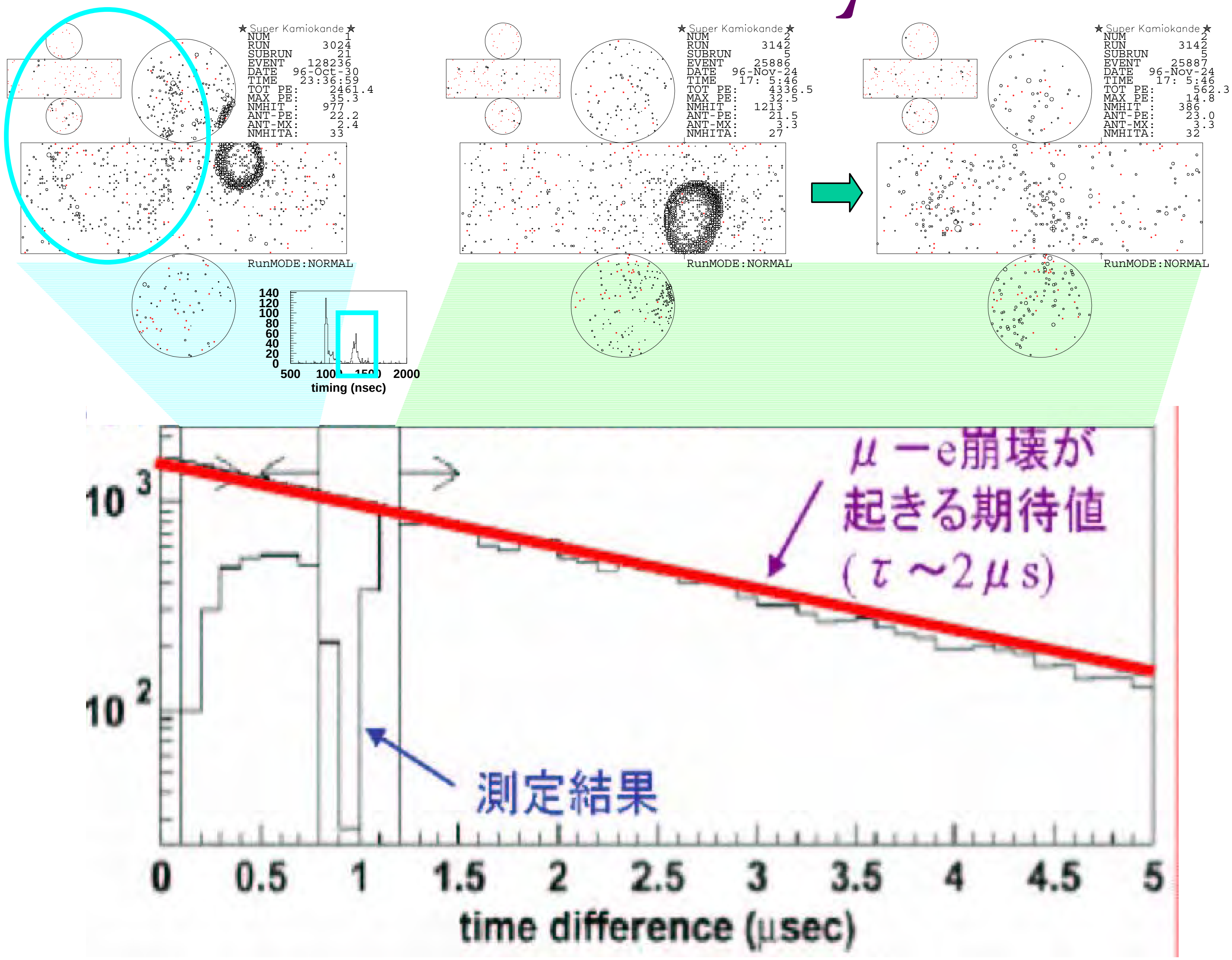




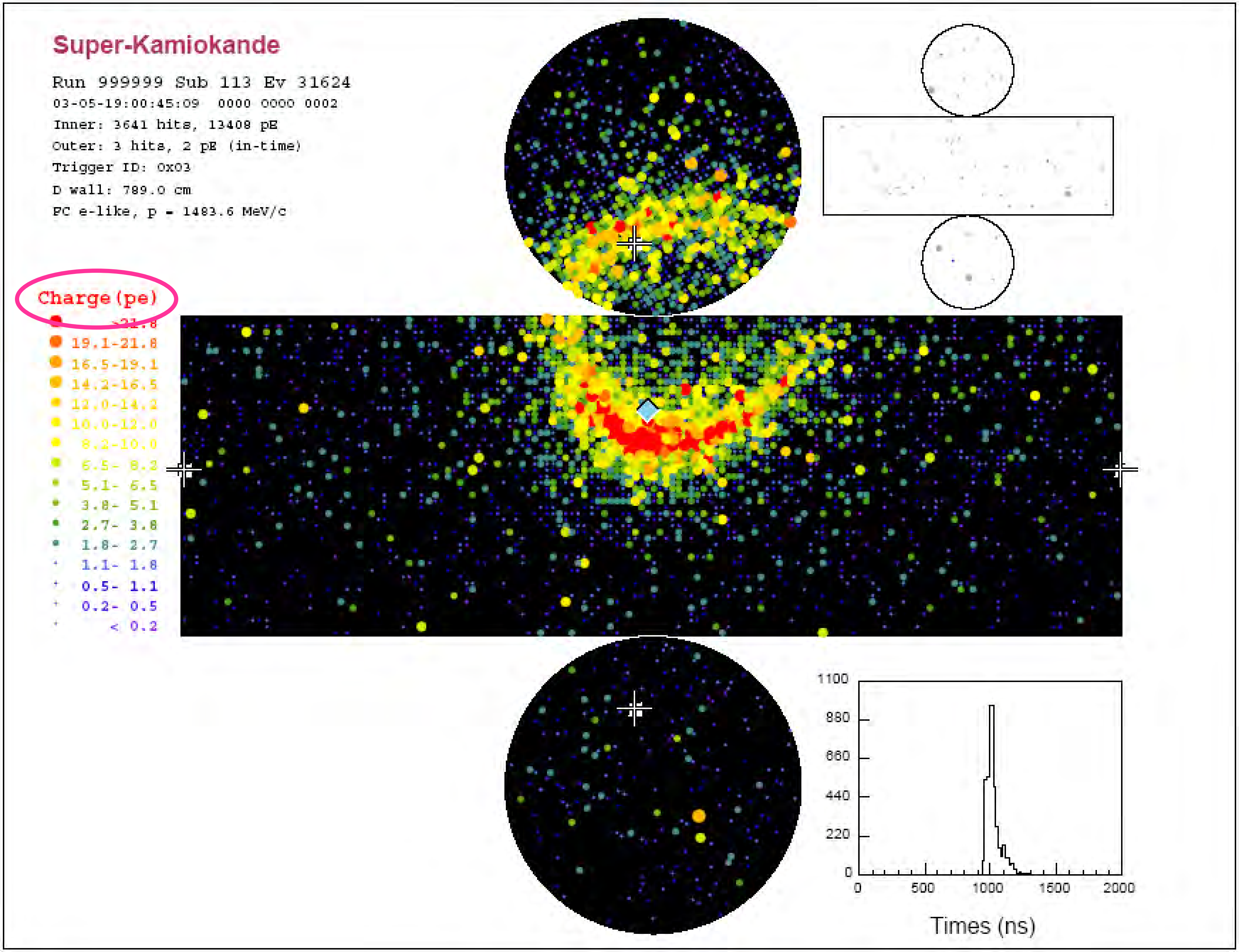
Further cuts:

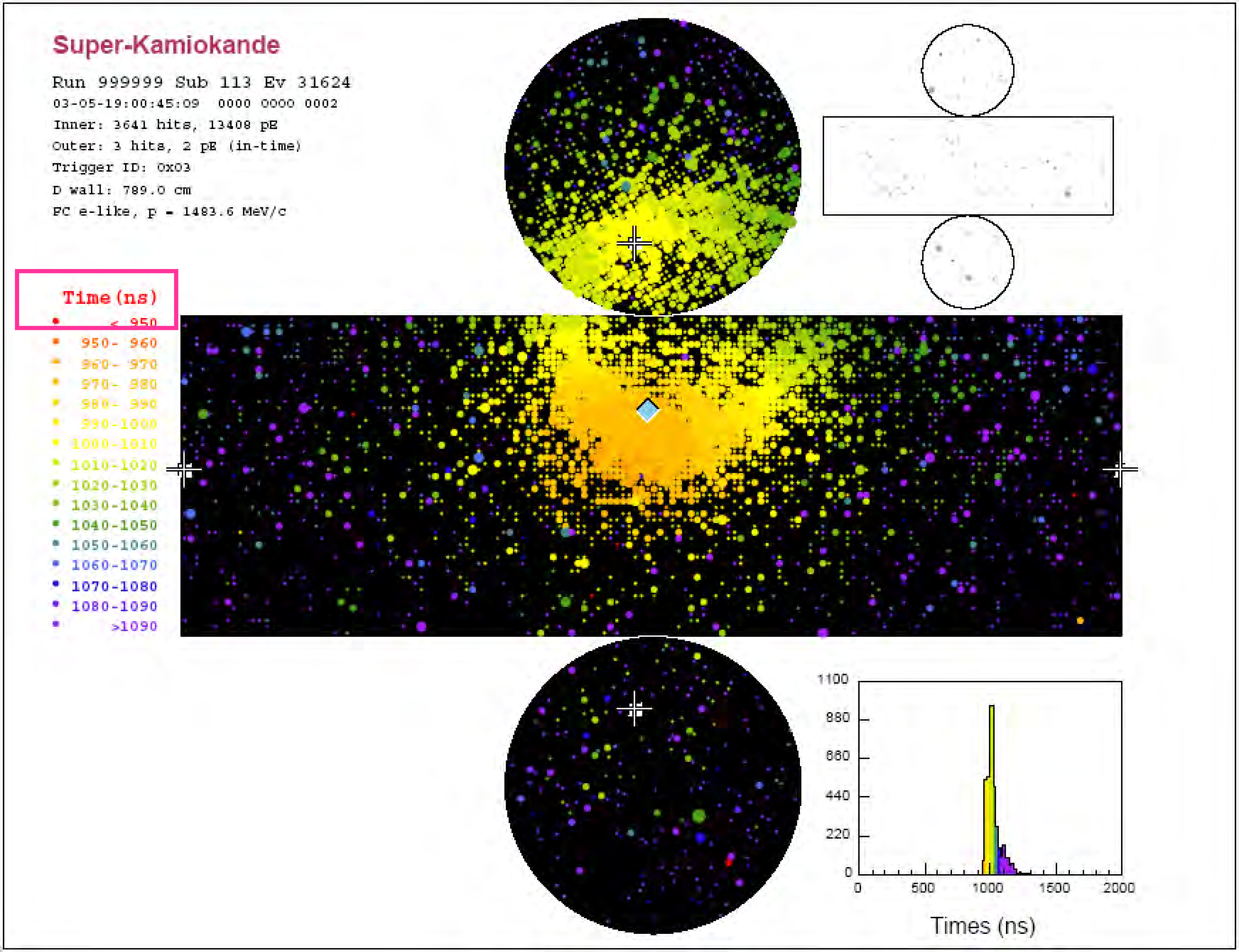
	CC $\nu\mu$	NC	signal
no decay e	14%	19%	76%
E window	1%	16%	58%
pi0 likelihood	0.40%	10%	42%

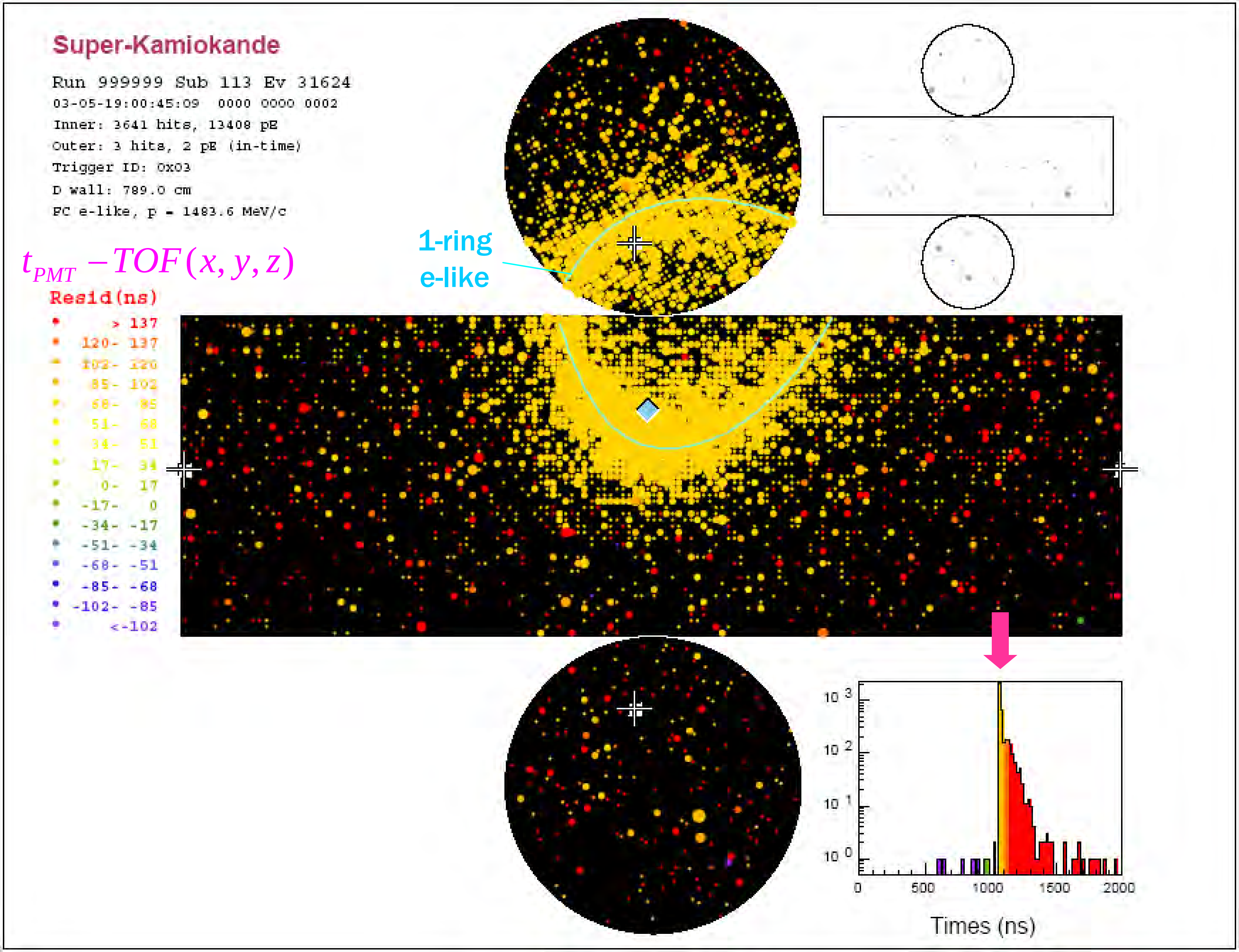
Muon Decay



RunMODE:NORMAL
timing (nsec)
μ ーe崩壊が
起きる期待値
(τ ~2μs)
測定結果
time difference (μsec)

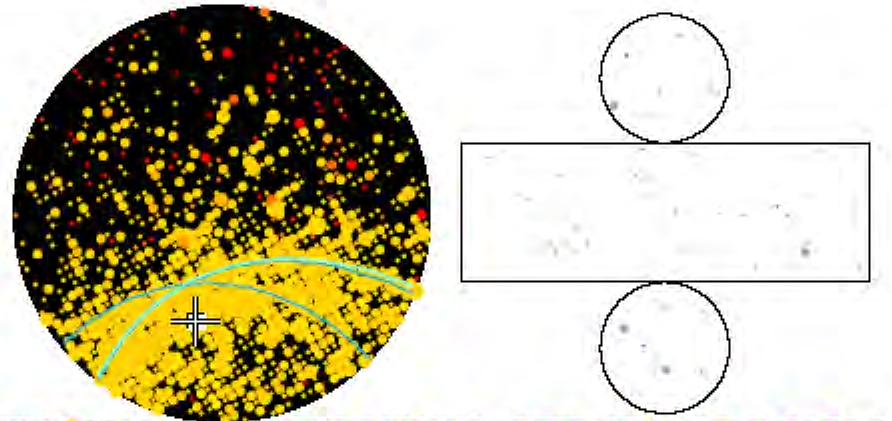

Super-Kamiokande
Run 999999 Sub 113 Ev 31624
03-05-19:00:45:09 0000 0000 0002
Inner: 3641 hits, 13408 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x03
D wall: 789.0 cm
FC e-like, p = 1483.6 MeV/c
Charge (pe)
>21.8
19.1-21.8
16.5-19.1
14.2-16.5
12.0-14.2
10.0-12.0
8.2-10.0
6.5- 8.2
5.1- 6.5
3.8- 5.1
2.7- 3.8
1.8- 2.7
1.1- 1.8
0.5- 1.1
0.2- 0.5
< 0.2
1100
880
660
440
220
0
0
500
1000
1500
2000
Times (ns)

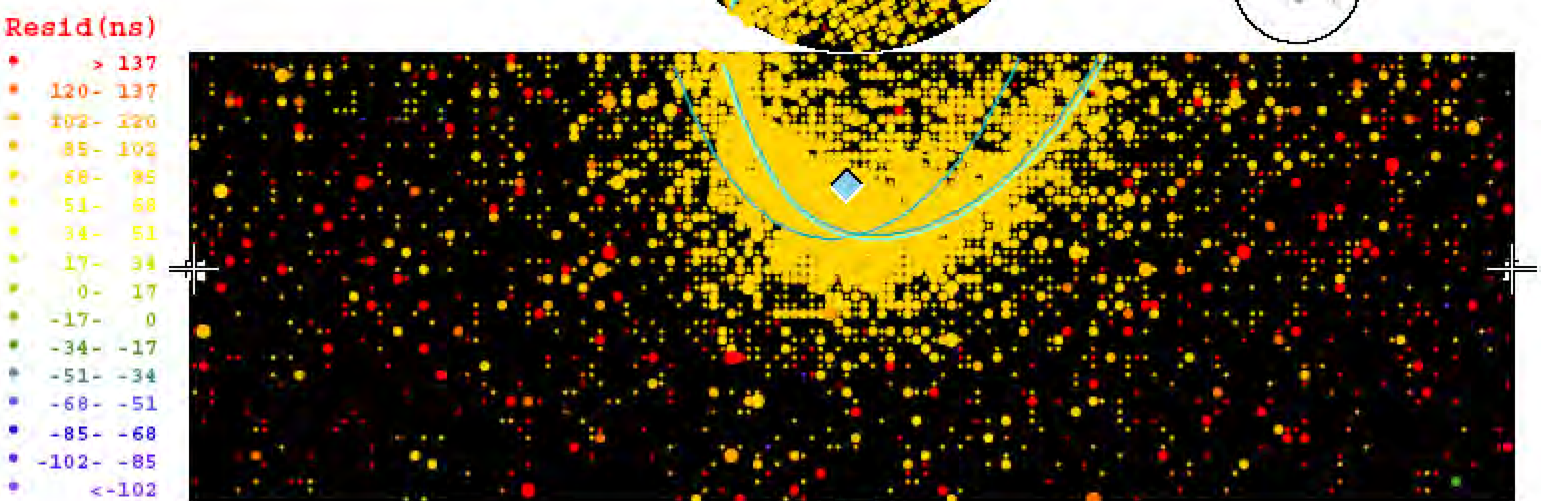

Super-Kamiokande
Run 999999 Sub 113 Ev 31624
03-05-19:00:45:09 0000 0000 0002
Inner: 3641 hits, 13408 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x03
D wall: 789.0 cm
FC e-like, p = 1483.6 MeV/c
Time (ns)
< 950
950- 960
960- 970
970- 980
980- 990
990-1000
1000-1010
1010-1020
1020-1030
1030-1040
1040-1050
1050-1060
1060-1070
1070-1080
1080-1090
>1090
1100
880
660
440
220
0
0
500
1000
1500
2000
Times (ns)

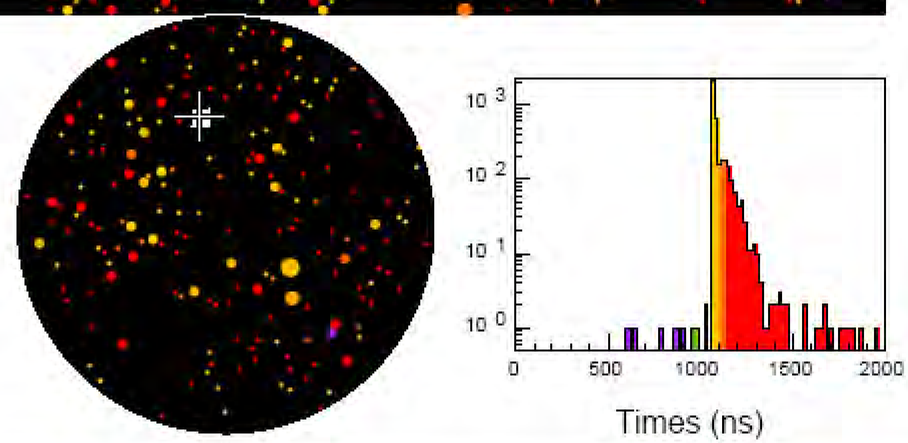


Super-Kamiokande
Run 999999 Sub 113 Ev 31624
03-05-19:00:45:09 0000 0000 0002
Inner: 3641 hits, 13408 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x03
D wall: 789.0 cm
FC e-like, p = 1483.6 MeV/c
$t_{PMT} - TOF(x, y, z)$
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
1-ring
e-like
Times (ns)

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

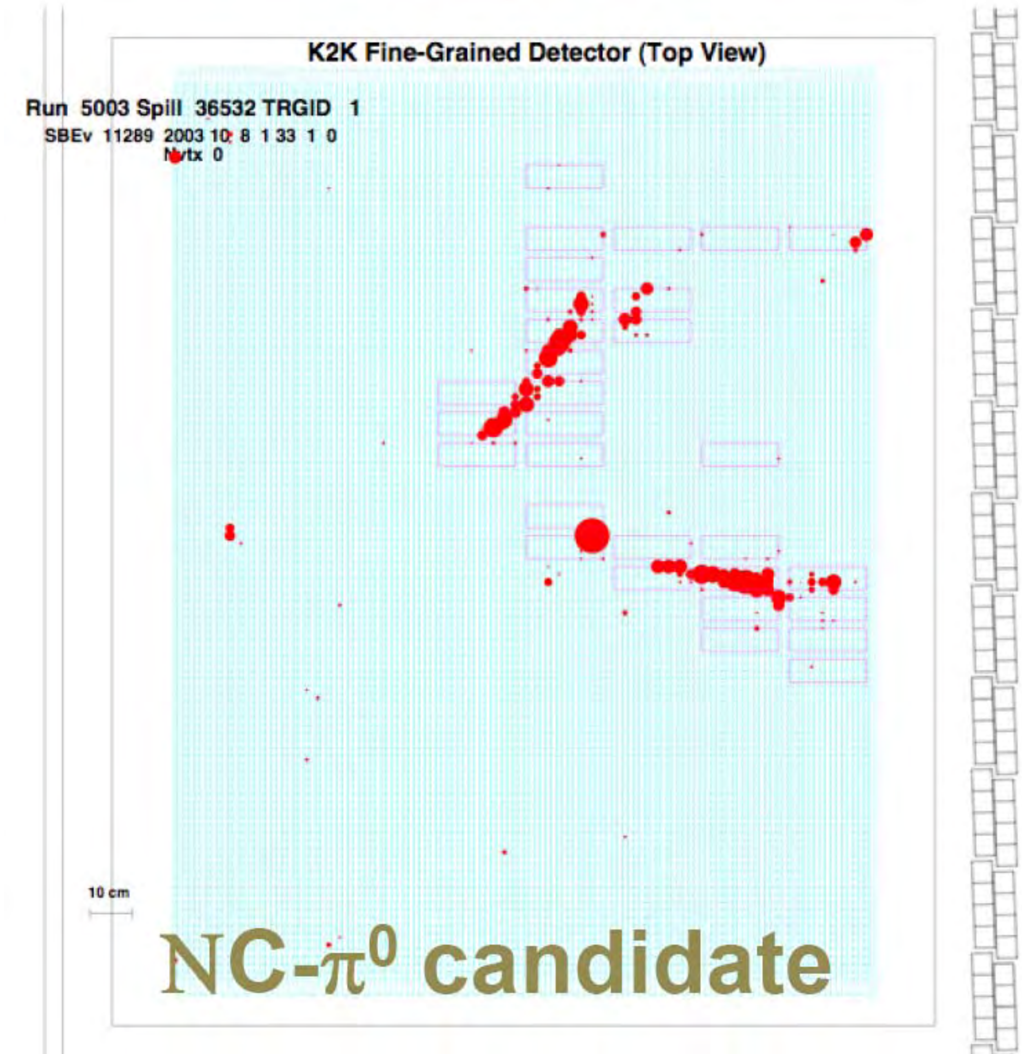






Note: this event is well above the T2K reconstructed energy window (350-850 MeV). But it is in the range for the first maximum at T2KK or FNAL-DUSEL.

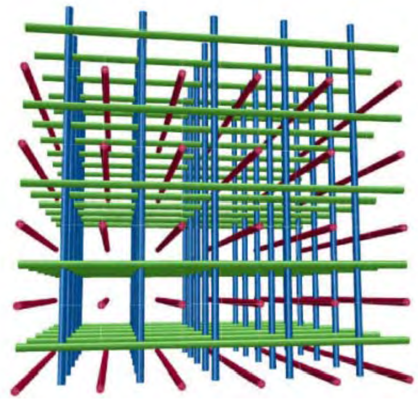
Segmented Scintillator



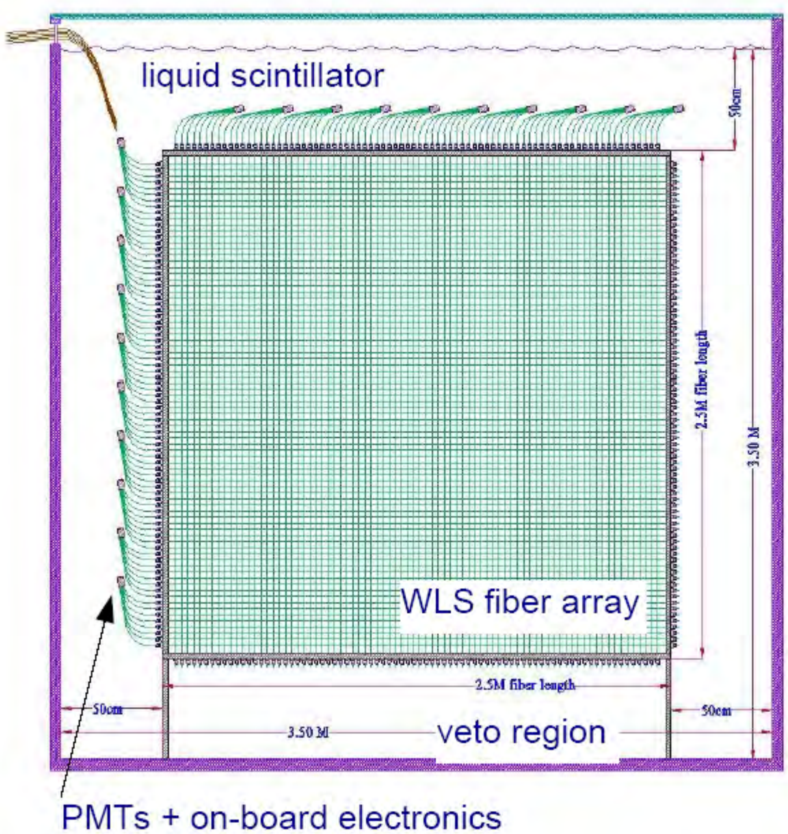
(nearly) *fully active target* and tracking medium

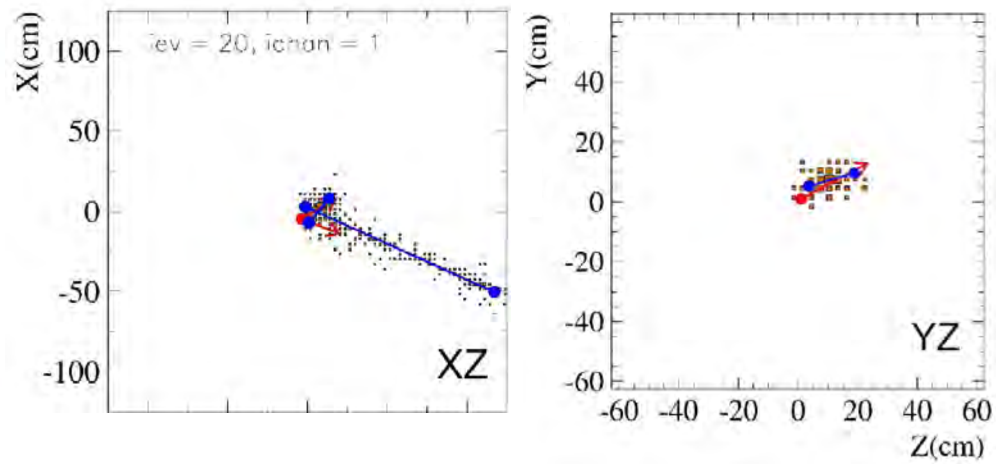
high spatial resolution

SciBath FINeSSE

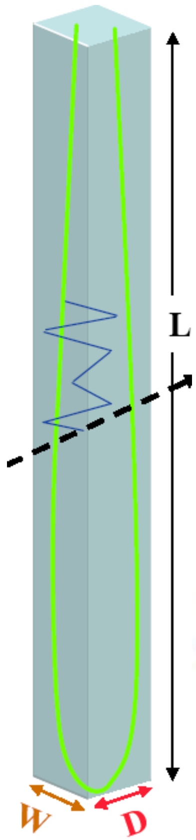


Vertex Detector side view:

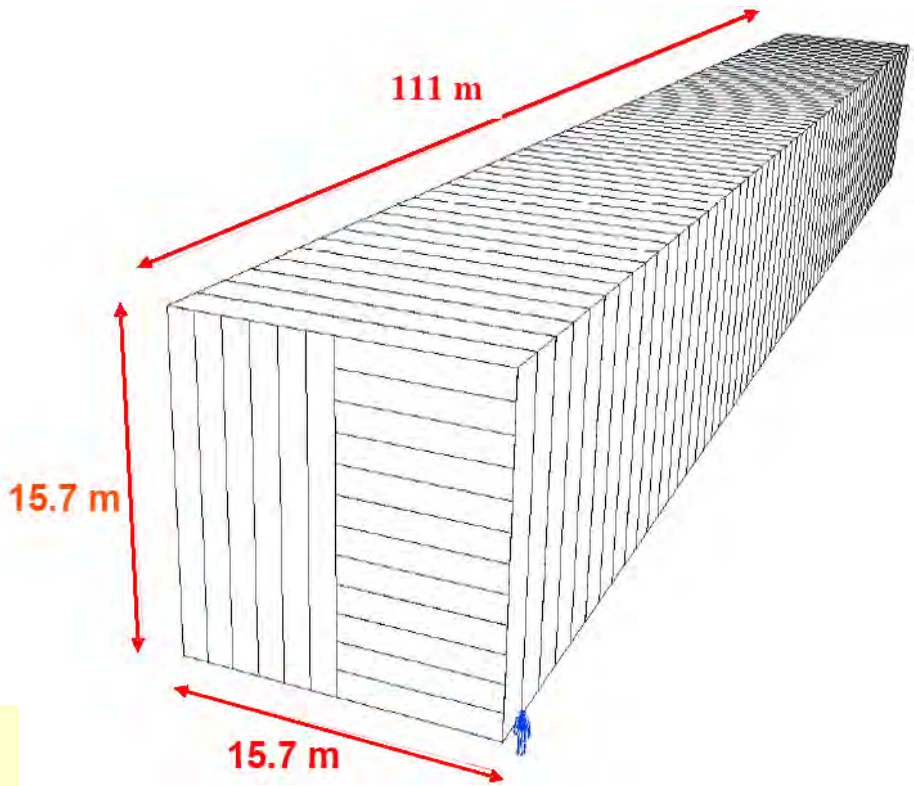




NOvA



4cm×6cm
~ $0.15X_0$



Off-axis from NuMI beam

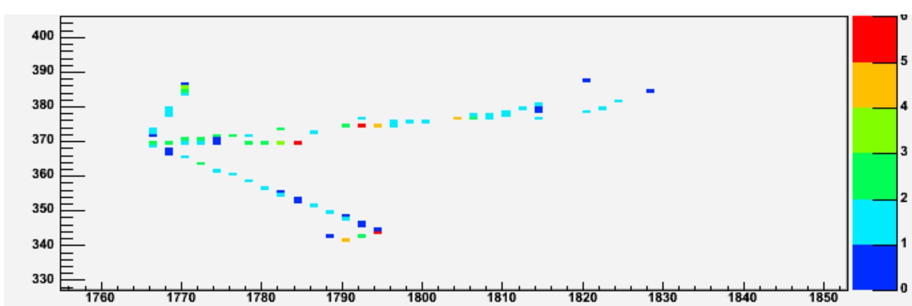
810 km baseline

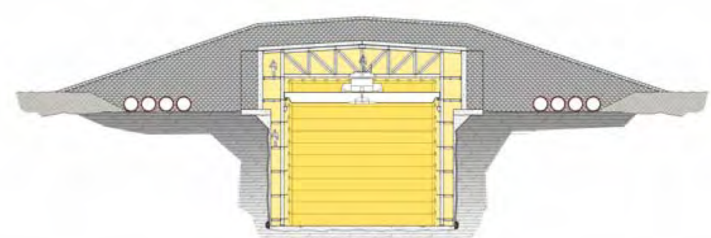
E ~ 2.2 GeV narrow band

~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)

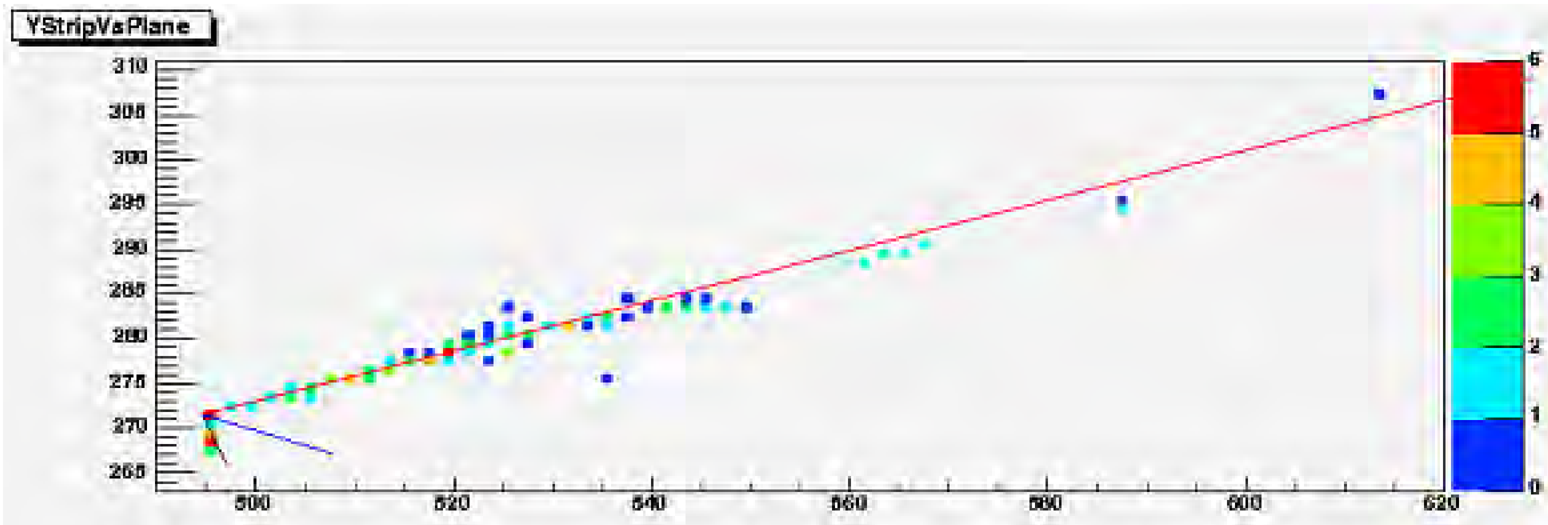


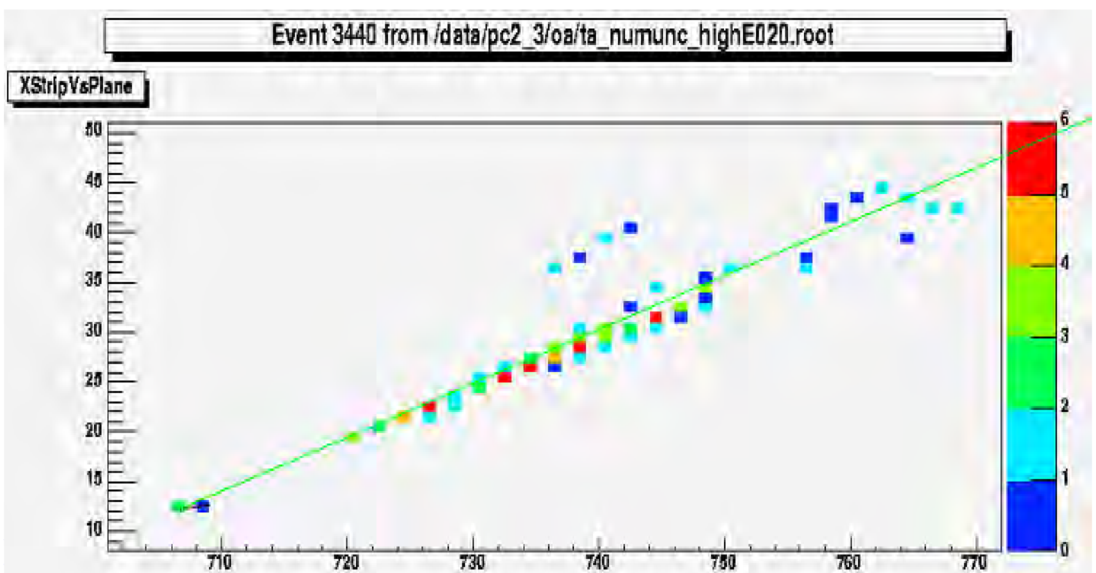


One is Signal, One is Background

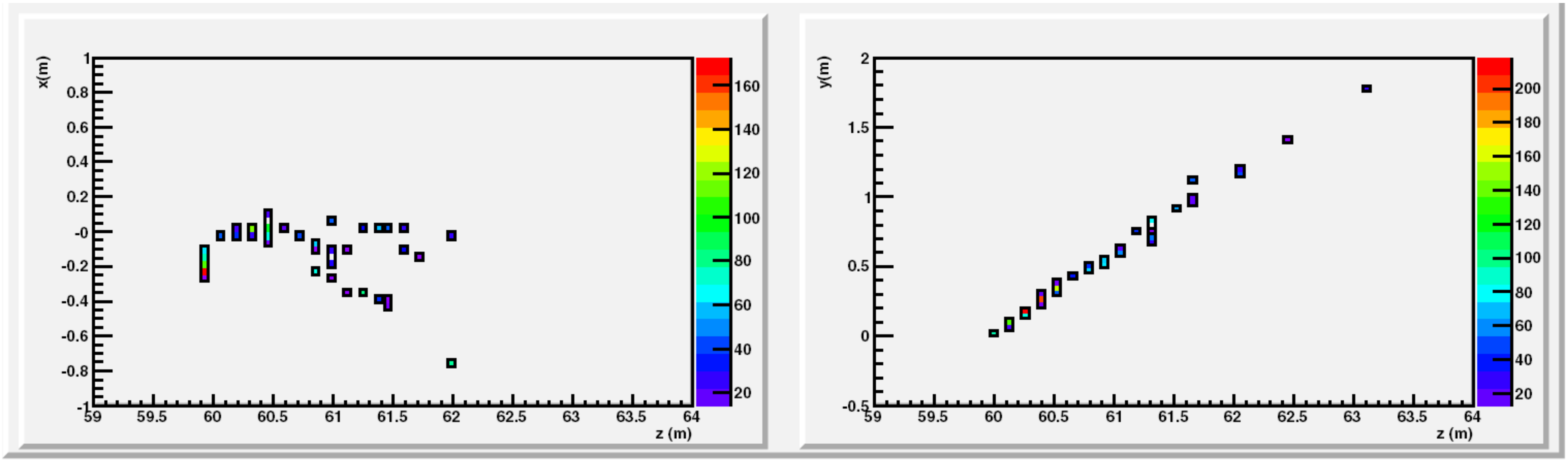
$\nu_e + p \rightarrow e^- + p + \pi^+$

$\nu_\mu + N \rightarrow \nu_\mu + p + \pi^0$



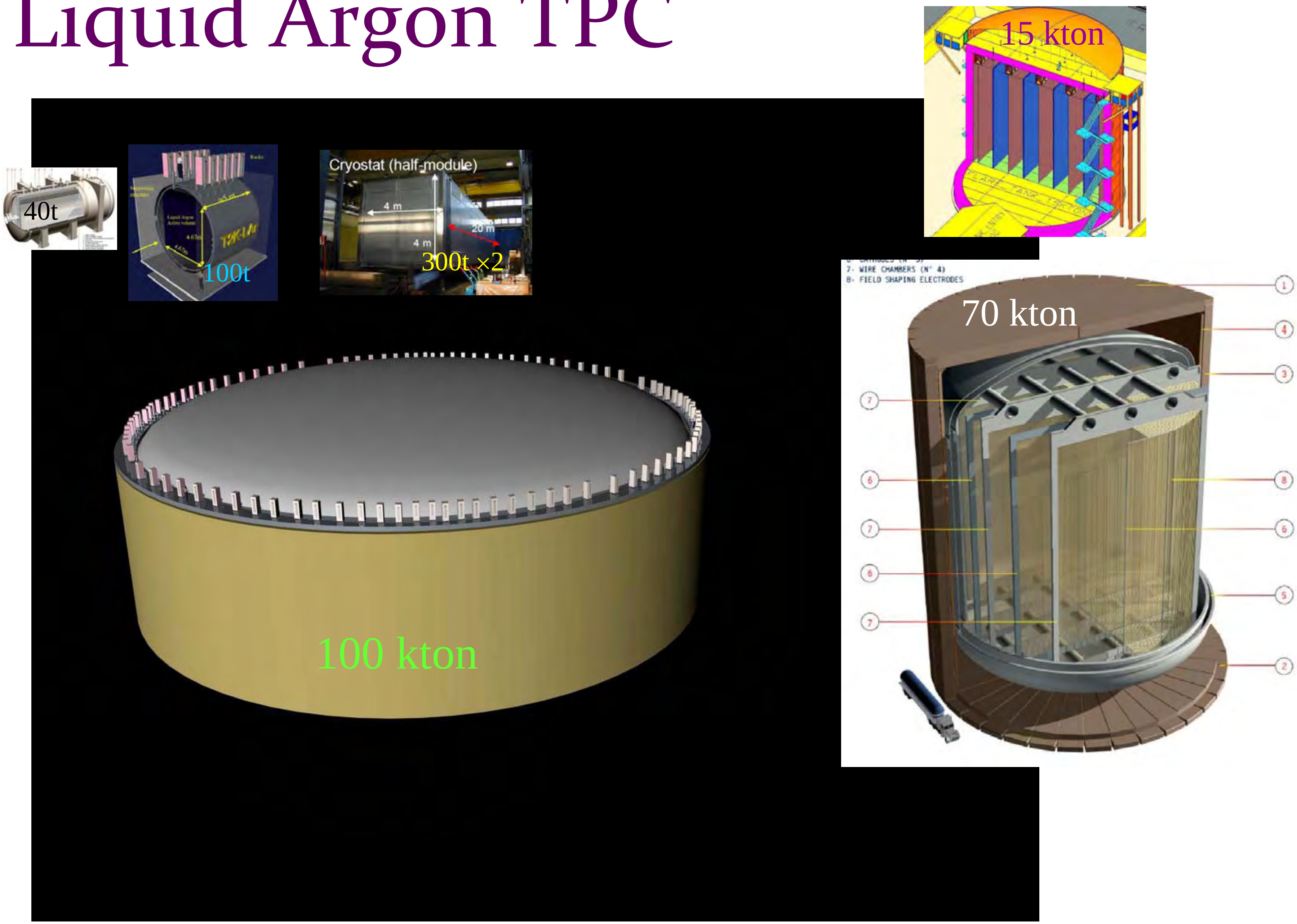


?

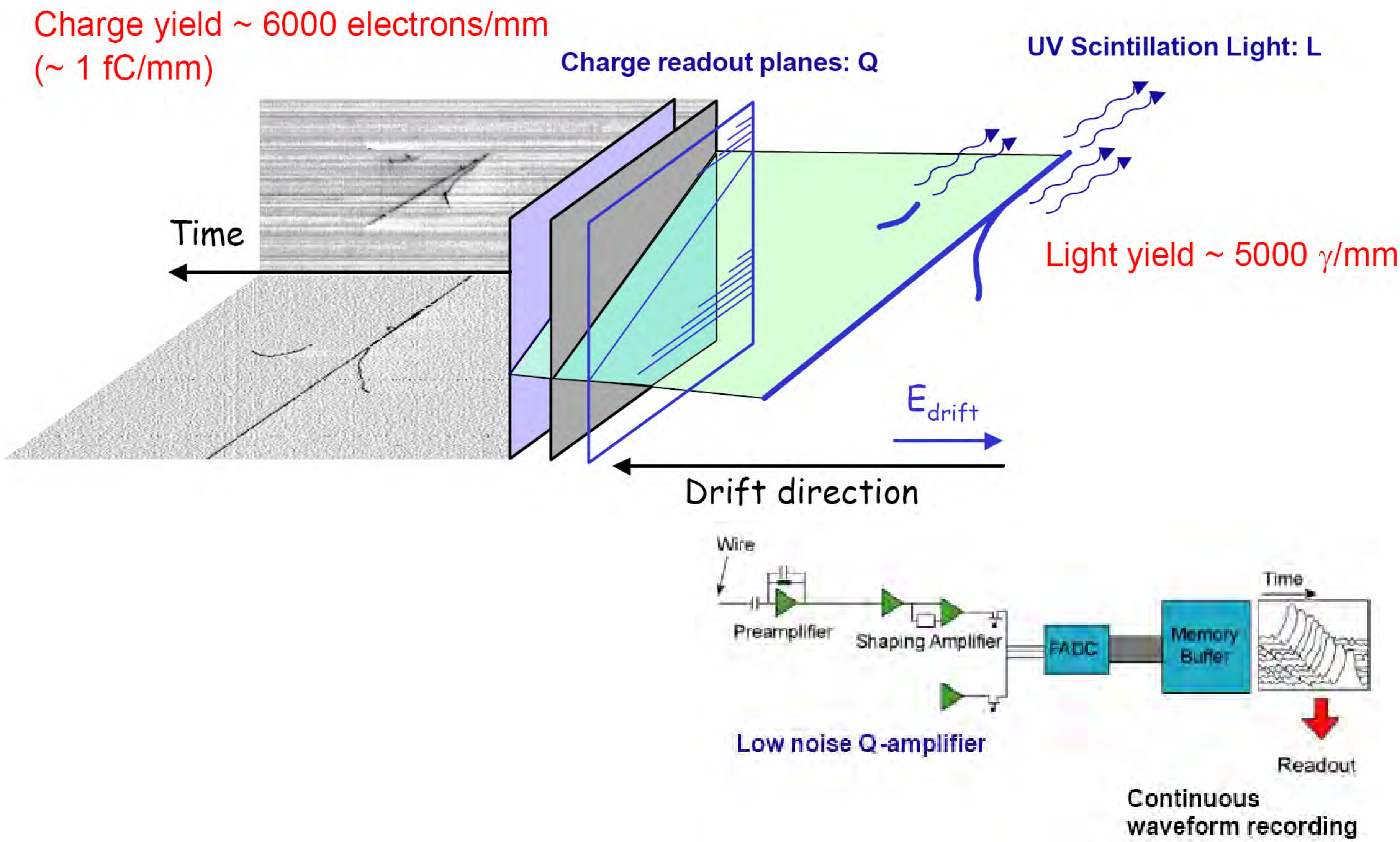


Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c

Liquid Argon TPC



Principle of Operation: LAr TPC



…an electronic bubble chamber

Bubble diameter ~ 3 mm
(diffraction limited)

Bubble size ~ 3x3x0.4 mm^3

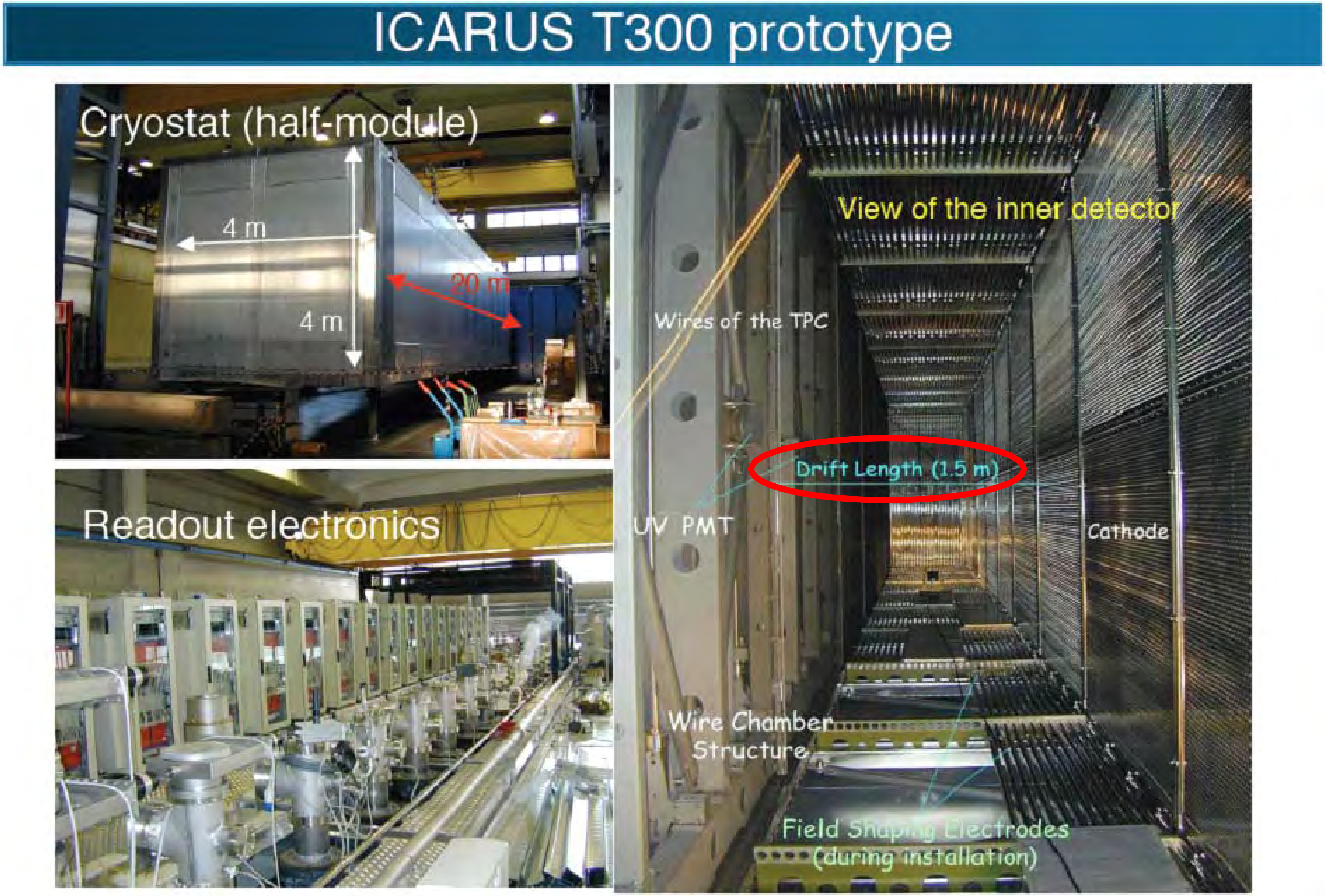
Gargamelle bubble chamber

ICARUS electronic chamber

Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

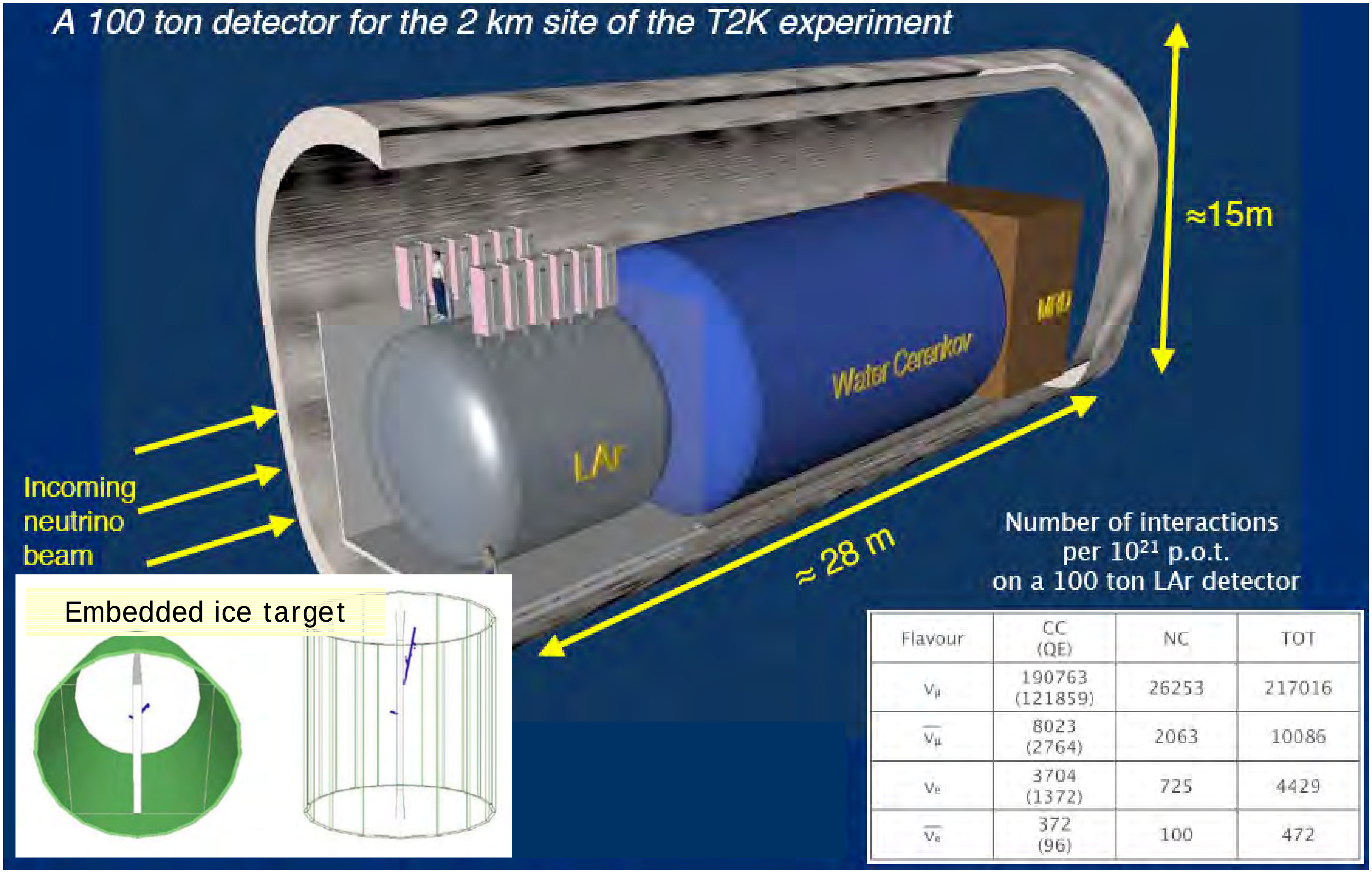
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

ICARUS



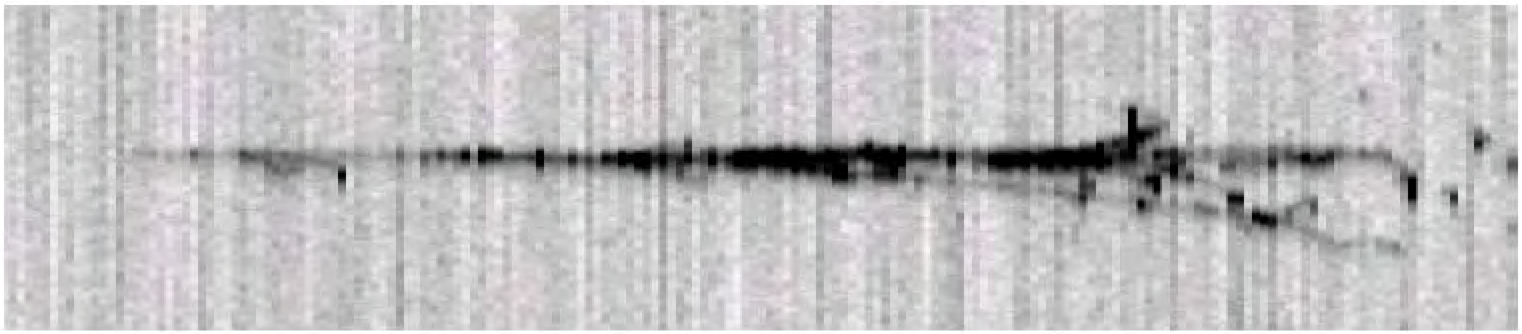
C. Rubbia at Fermilab October 2005 "20 years of liquid Argon technology"

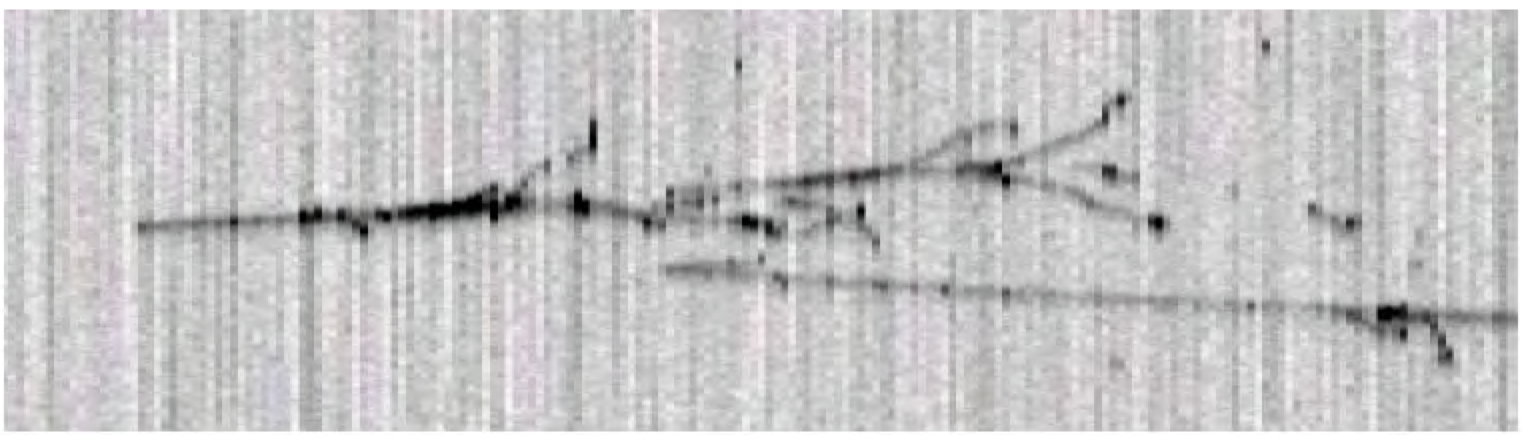
LAr at T2K 2KM (proposed)



Flavour	CC (QE)	NC	TOT
ν_μ	190763 (121859)	26253	217016
$\bar{\nu}_\mu$	8023 (2764)	2063	10086
ν_e	3704 (1372)	725	4429
$\bar{\nu}_e$	372 (96)	100	472

One is signal the other is background





Monte Carlo Vectors	
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gamma	245 MeV/c
gamma	1204 MeV/c

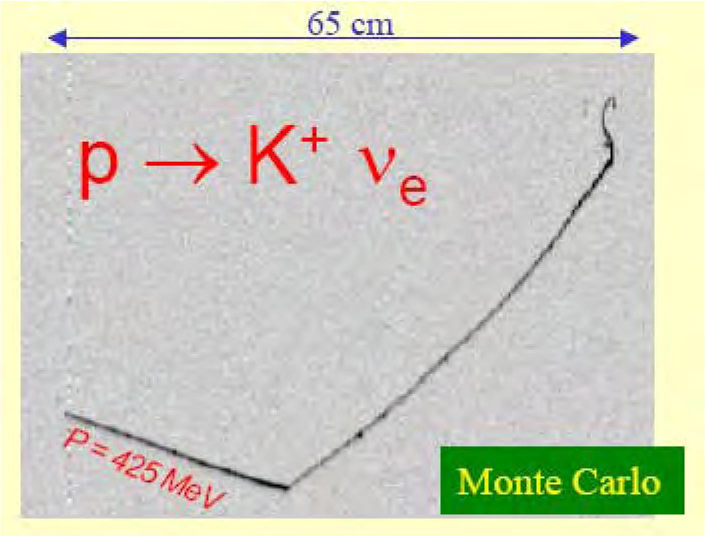
Challenges for Huge LAr TPC

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).

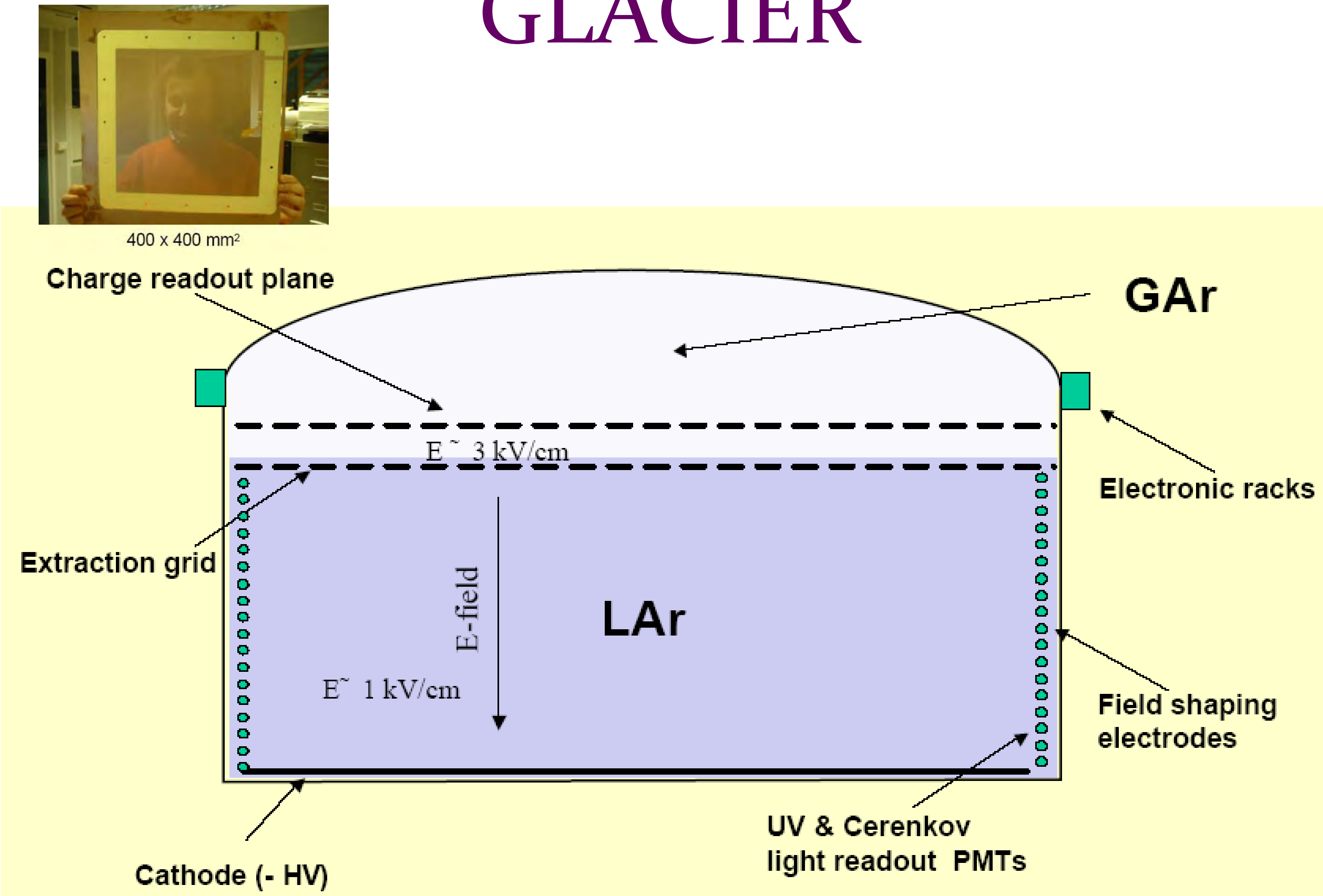
Largest existing detector is 600t ICARUS at Gran Sasso

R&D needed to develop multi-kton detector.
Purification, long drift, (optional) operation in magnetic field, charge amplification, safety …

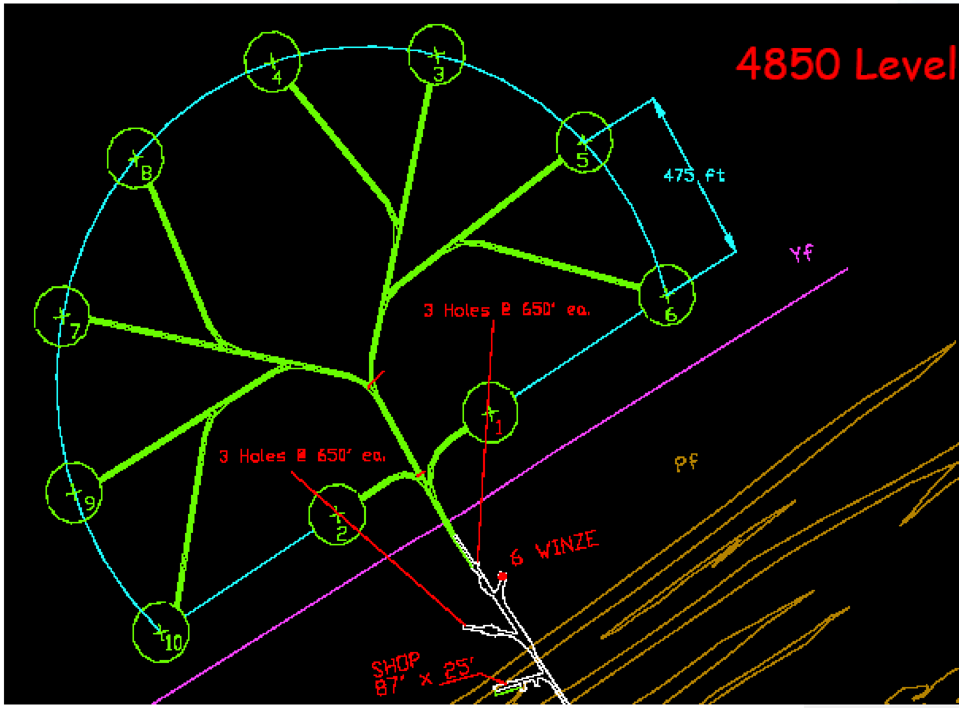


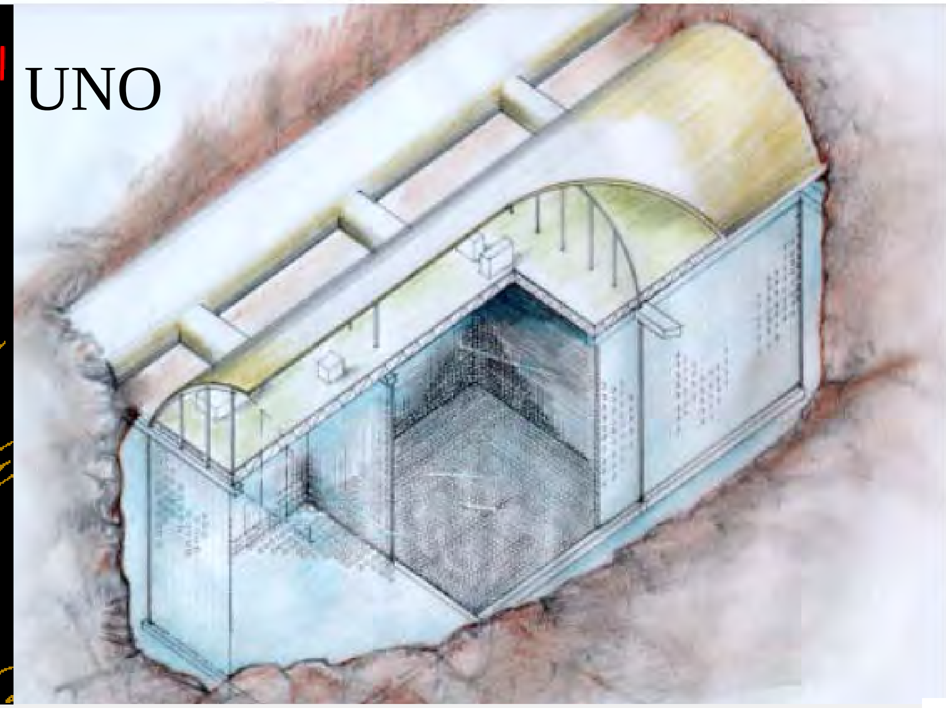
It is generally assumed that 100 kton LAr and 300 kton water Cherenkov are competitive for CP-violation class neutrino experiments. Higher efficiency makes up for lower mass. Water Cherenkov signature performance is good sub-GeV, but becomes worse at higher energies (above few GeV).

GLACIER

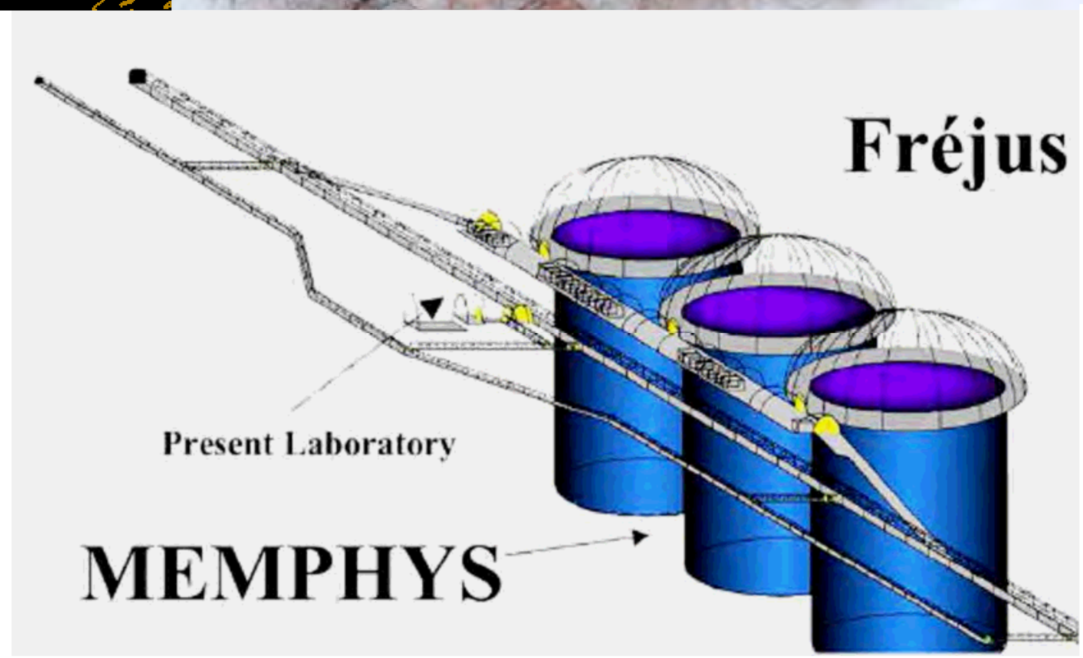


400 x 400 mm2
Charge readout plane
GAr
E ~ 3 kV/cm
Electronic racks
Extraction grid
E-field
LAr
E~ 1 kV/cm
Field shaping electrodes
UV & Cerenkov light readout PMTs
Cathode (- HV)

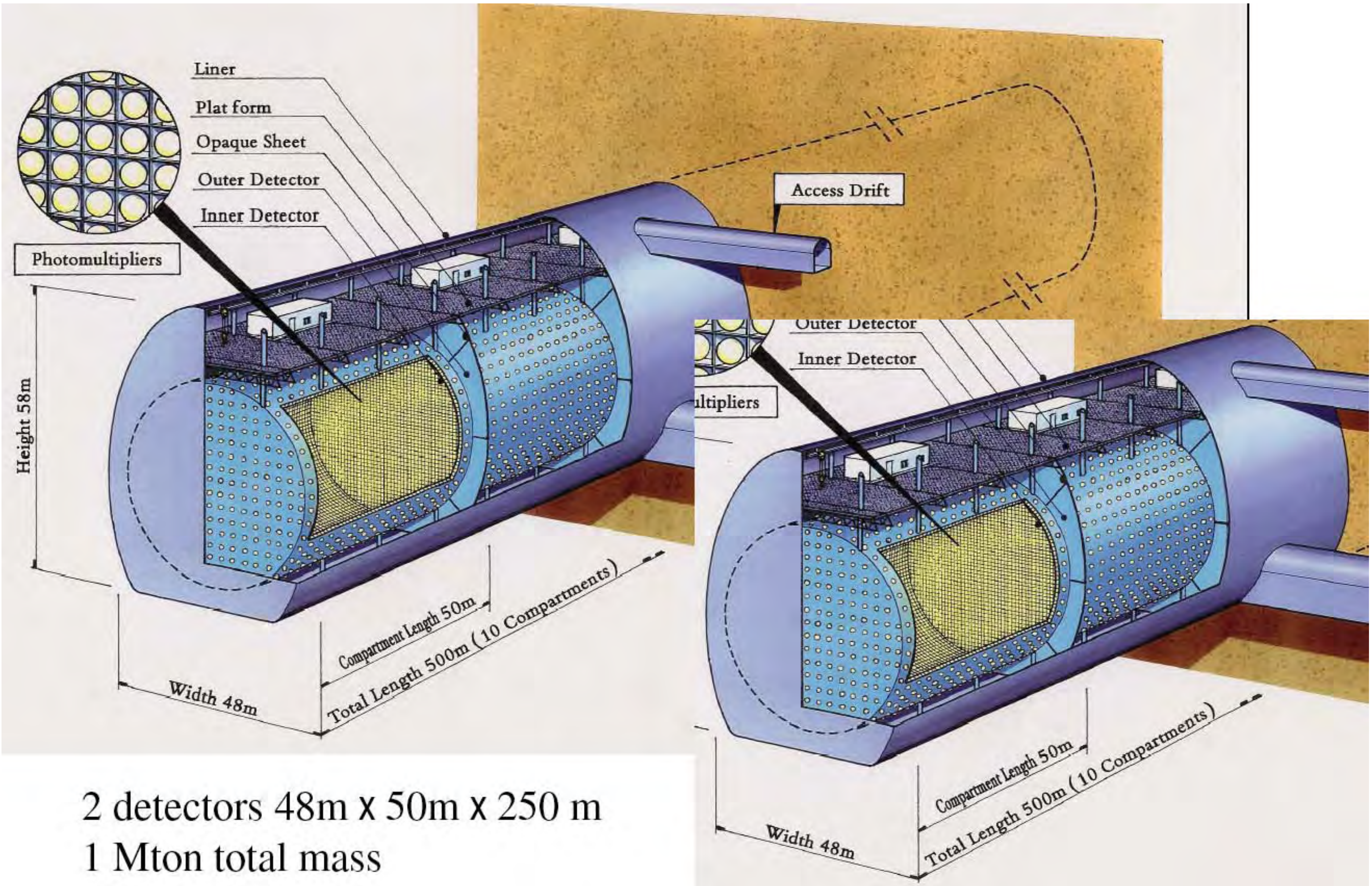




Megaton Scale Water Cherenkov Detectors



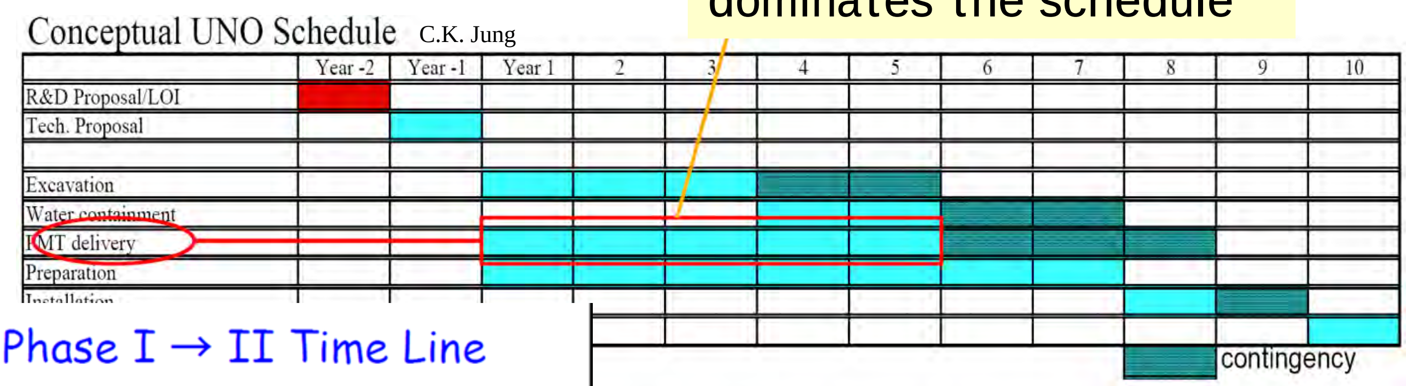
Hyper-Kamiokande

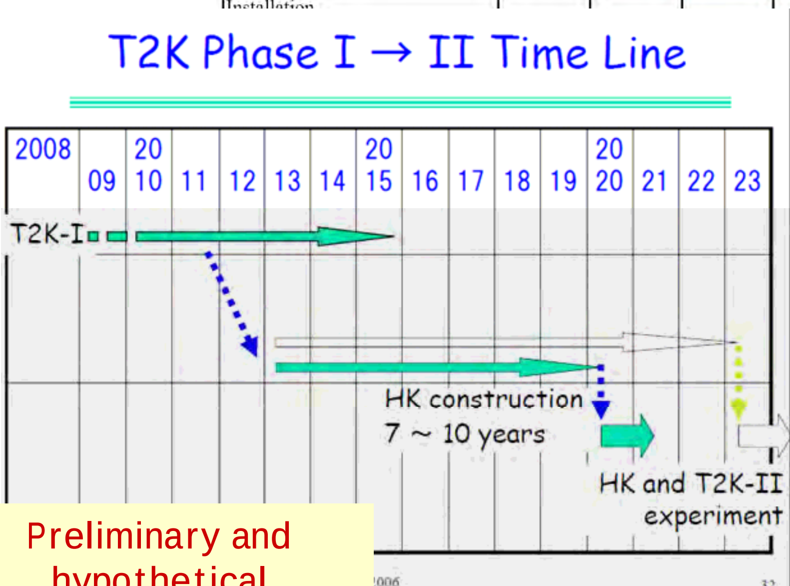


2 detectors 48m x 50m x 250 m
1 Mton total mass

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

(1) PMT fabrication time dominates the schedule





Preliminary and hypothetical

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

40% or 20% Photon Coverage?

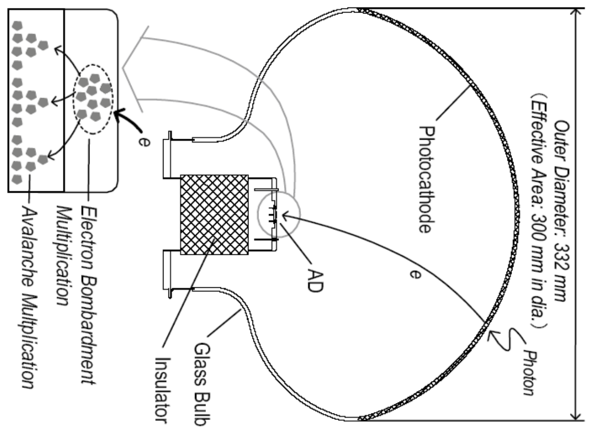
	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm (μ-like)	30 cm (e-like) / 29 cm (μ-like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% (μ-like)	0.69% (e-like) / 0.96% (μ-like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% (μ-like)	6.3% (e-like)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

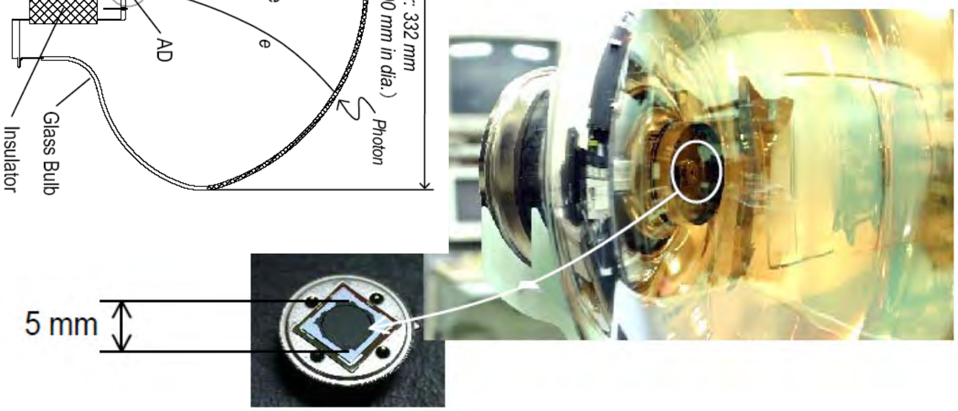
S.T. Clark, Ph.D. Thesis (2006)
F. Dufour, T2KK Workshop (2006)

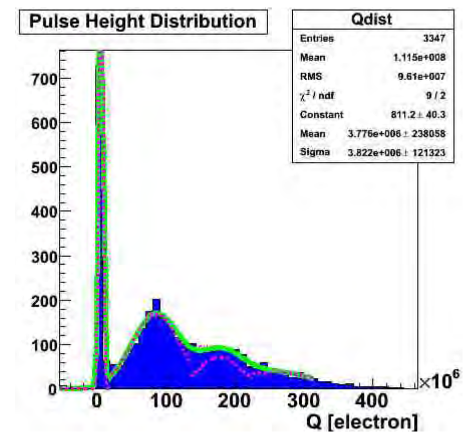
Preliminary numbers, for comparison purposes.
Final published efficiencies and BG may differ.

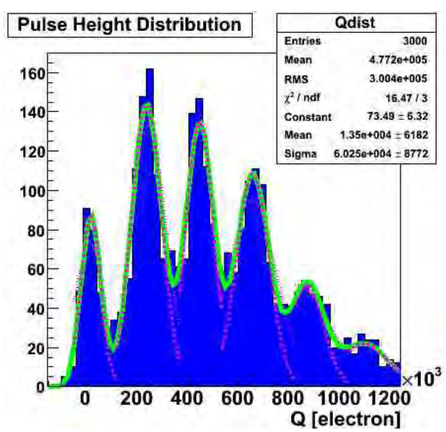
Hybrid Avalanche Photodiode

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 (σ)	190ps	2300ps
Single Photon Energy Resolution	44% (preliminary)	150%
Rise Time	1ns	10ns
Pulse Width	2.2ns	20ns
Dynamic Range (Signal intensity in P.E.)	3000 p.e.	1000 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!

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