Experimental Particle Astrophysics: Neutrino oscillations experiments

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REU seminar

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For more about projects described, please see:

Super-K: http://www.phys.washington.edu/~superk

T2K: http://neutrino.kek.jp/jhfnu

Outline

- Neutrino FAQ
  - What's a neutrino?
  - How do we detect them?
  - What are neutrino oscillations?
  - Why is all this important?
- Some experiments we are working on currently
  - Super-Kamiokande
    - Large cosmic-ray neutrino detector in Japan
  - T2K
    - Long-baseline neutrino oscillation experiment in Japan

Won't have time here to discuss other UW neutrino projects:

- SNO
- Majorana
- KATRIN

Q: What are neutrinos?

- Neutrinos = subatomic particles with:
  - no electric charge
  - (almost) no mass
  - only weak interactions with matter

Symbol: ν
(Greek letter nu)

That doesn't sound very interesting!

- But…
  - neutrinos are made in (almost) every radioactive decay
  - neutrinos are as abundant as photons in the Universe
    - Several hundred per cm^3 everywhere in the Universe
      - even though they are nearly massless, they make up a significant proportion of the mass in the Universe!
    - You are emitting ~ 40,000 neutrinos/sec right now (^{40}K decays)
    - Neutrinos can penetrate the entire Earth (or Sun) without blinking
      - maybe we can study earth's core with neutrinos?
      - astronomical window into places we can't see with light

How do they fit into our picture of the Universe?

- Standard Model of particle physics:

3 generations of fermions ("matter") | Bosons ("force carriers")

<u>Quarks</u> charge mass (MeV)*	up +2/3 5	charmed +2/3 1350	top +2/3 175000	gluon 0 0
	down -1/3 10	strange -1/3 175	bottom -1/3 4500	photon 0 0
<u>Leptons</u> charge mass (MeV)*	ν_e 0 ~ 10^{-7} ?	ν_μ 0 ~ 10^{-7} ?	ν_τ 0 ~ 10^{-7} ?	Z^0 0 91000
	e -1 0.5	μ -1 105	τ -1 1800	$W^{\pm}$ ± 1 81000

3 'flavors' of leptons

Nucleons are made of 3 quarks:
p = uud
n = udd

antiparticles have opposite charge

*MeV=miliion electron volts
Recall: $E=mc^2$
proton mass = 938 MeV

Q: Where do neutrinos come from?

- Radioactive decays = 'weak nuclear force' in action
  - Example: *beta decay* of neutron
    - 'beta ray' = old term for electron

lepton number = conserved physical property (new kind of 'charge') that only leptons have

neutron (lepton number = 0)

proton (lepton number = 0)

electron (lepton number = +1)

anti-ν (lepton number = -1)
(must be *anti* to conserve lepton #)

  - another example: decay of muon

μ^- (lepton number = +1)

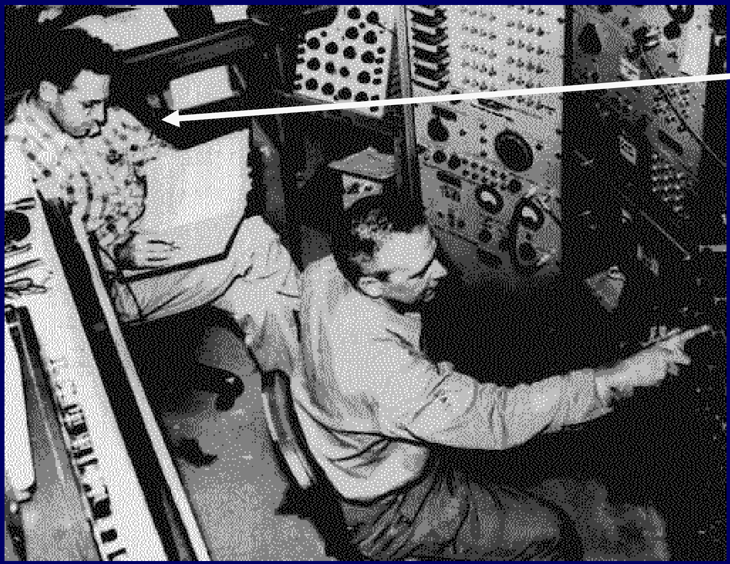
electron (lepton number = +1)

ν (lepton number = +1)

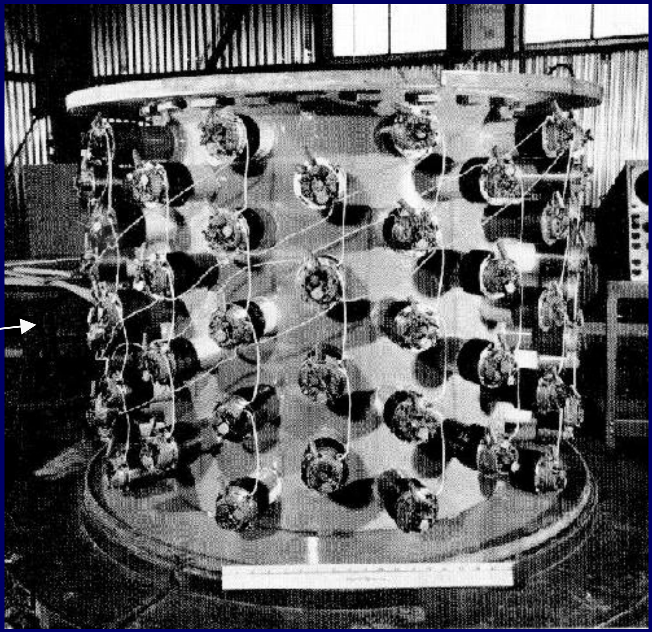
anti-ν (lepton number = -1)

Q: How were they first 'seen'?

- Fred Reines and Clyde Cowan, 1956
  - ν source: initially, nuclear reactor in Hanford, WA (later moved to reactor at Savannah River, S. Carolina)



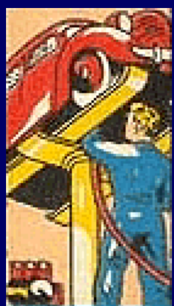
Nobel Prize in Physics 1995
Awarded to Fred Reines "for pioneering experimental contributions to lepton physics"



  - Detector: water with $CdCl_2$
  - *inverse* beta decay: $\bar{\nu} + p \rightarrow n + e^+$

    Observed light flashes from e^+ annihilation followed by decay of neutron

Do neutrinos have mass? Applied QM



- Recall your basic QM (see any textbook for details)

You too can become a quantum mechanic !

1. Particles also behave like waves *(Wave-Particle Duality)*

   where wavelength depends on *momentum* (deBroglie, 1924)

   $$\lambda = \frac{h}{p} \qquad \left(\lambda = \sqrt{\frac{1.5}{E(eV)}},\ nanometers \right)$$

   – p = momentum, h = Planck's constant (a very tiny number)
2. All information about a particle is contained in its *wavefunction* (or *state* function) $\Psi(x,t)$
3. Probability of finding particle at position x at time t is $\left|\Psi(x,t)\right|^2$
   – Ψ itself is *not* a measurable physical quantity
4. Quantum states *evolve* with time: $\Psi(x,t) = \Psi(x,0) \cdot e^{-iEt/\hbar}$
5. All possible wavefunctions for a particle form a 'vector space'

$$\left|V\right\rangle = \sum_i v_i \left|x_i\right\rangle$$

Any quantum state is a *mixture*... ...of basis vectors (or *eigenstates)*

$$\left\langle V \middle| V \right\rangle = \sum_i \left|v_i\right|^2 = 1$$

Probability of *observing* V if state actually *is* V = 1

Quantum mechanics and neutrino flavors

- If m=0 for *all* flavors: momentum *p* ~ energy *E*
- But if $m_\nu > 0$ for *any* flavor:
  - Then mass states are *different* from flavor states
  - So a *flavor* states = *mixtures* of mass states:
    - 1,2=mass states; μ, τ =flavor states

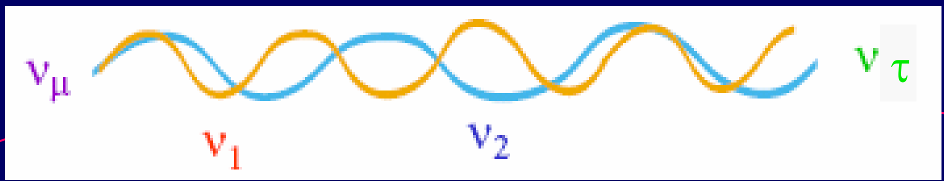
$$\begin{cases} |\Psi_\mu\rangle = a_1|\Psi_1\rangle + a_2|\Psi_2\rangle \\ |\Psi_\tau\rangle = b_1|\Psi_1\rangle + b_2|\Psi_2\rangle \end{cases}$$

(There are 3 neutrino flavors, but we'll pretend only 2 flavors here for simplicity)

- For neutrinos with mass
  - wavelength λ = h/p (de Broglie)

    where $p = (E^2 - m^2)^{1/2}$ (in particle physics units, where c=1)
- So λ *differs* for different mass states *with the same energy*

mixture of mass states that is a muon neutrino



mixture of mass states that is an tau neutrino

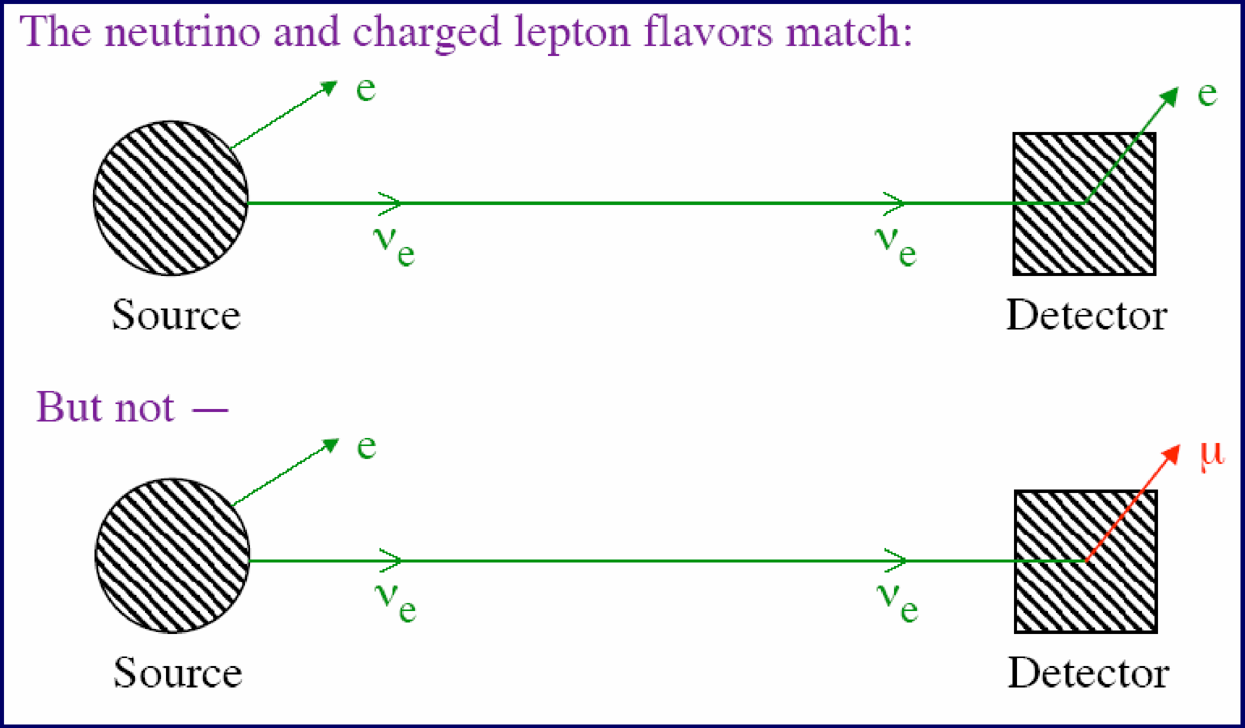
→ Time (∝ distance travelled)

Q: how do we tell a neutrino's flavor?

- We detect and identify neutrinos by observing the *charged leptons* they produce when they interact:

  ν_e + proton $\rightarrow$ e + other stuff

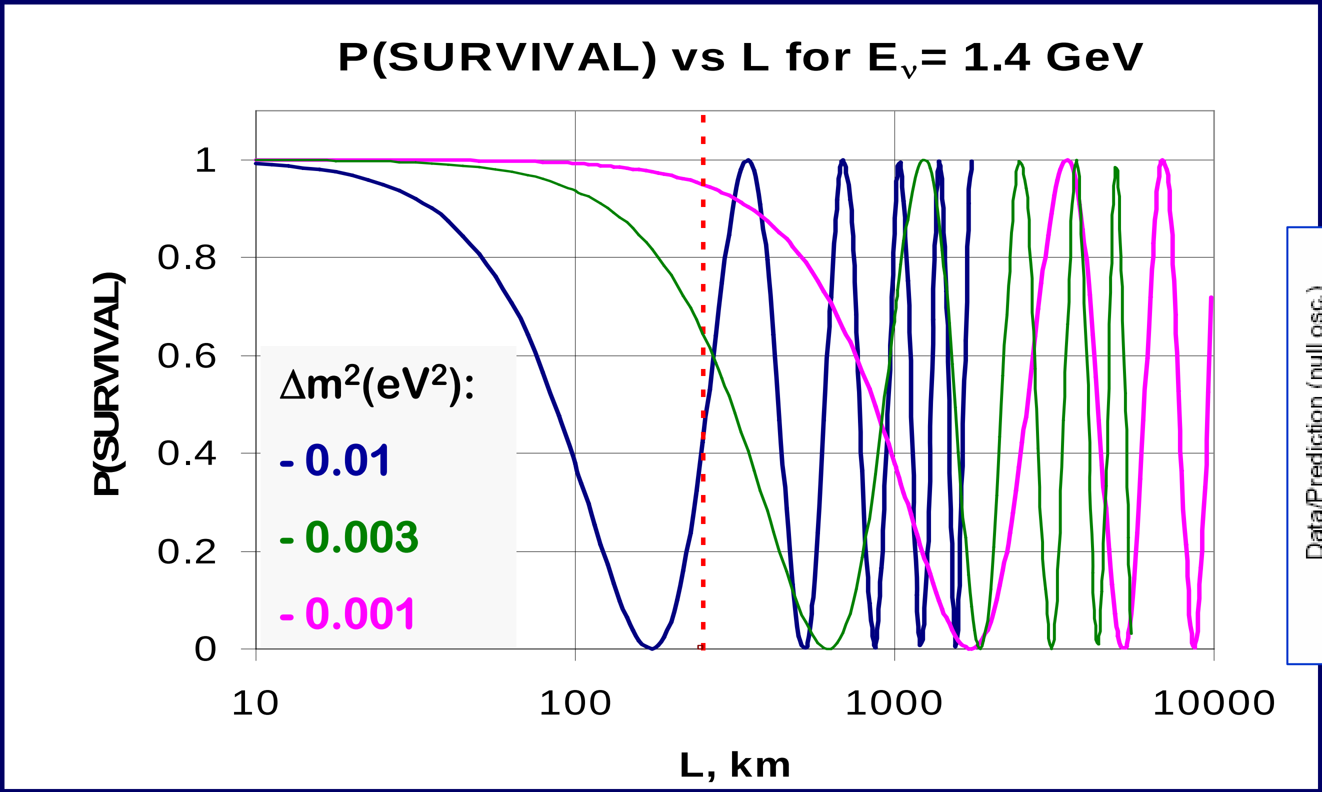
  ν_μ + proton $\rightarrow$ μ + other stuff
- The states $|\nu_\tau\rangle$, $|\nu_\mu\rangle$, $|\nu_e\rangle$ are called neutrino "flavor" states.



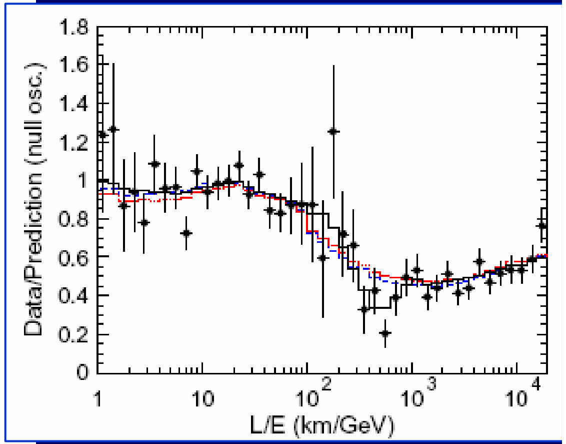
How can we observe neutrino oscillations?

- If we start out with a given flavor = mixture of *mass* states,
  - Probability that a neutrino is detected as the same flavor *oscillates*
  - The relative proportion of each *flavor* will change with time
    - t = *proper time* of neutrino ~ distance travelled from production point

Fraction of muon neutrinos *remaining* vs distance from production point



$$P = 1 - \sin^2 2\theta \sin^2\left(1.2\Delta m^2 \frac{L}{E}\right)$$



Data from Super-K

Neutrino physics experiments

- Super-Kamiokande: multiple physics goals
  - Solar and atmospheric neutrino observatory
  - Far detector for T2K
  - Nucleon decay studies
  - Supernova watch
  - Neutrino astrophysics
    - Search for point sources in high energy data samples
- T2K: neutrino oscillations studies

ν mixing (MNSP) matrix: $\theta_{13} \ll \theta_{12}$, θ_{23}

From Solar, KamLAND:
$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8\times10^{-5}$ [eV^2]

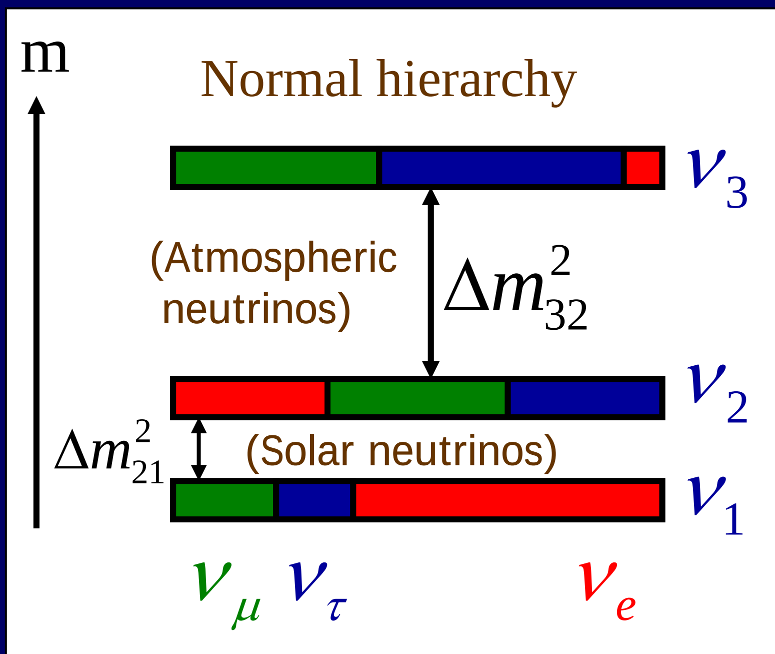
$$\text{Flavor eigenstate}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}\text{Mass eigenstate}$$

From SK Atm., K2K, MINOS
$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ [eV^2]

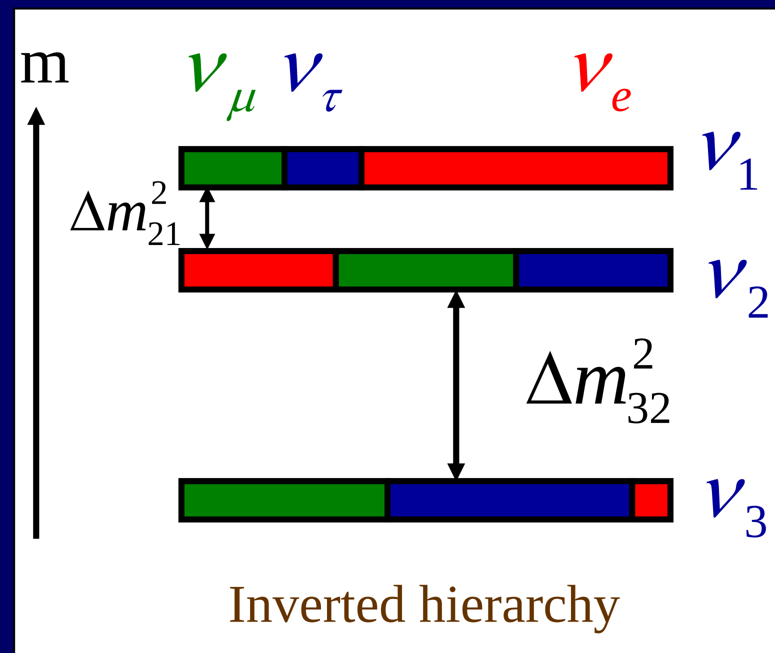
θ_{13} , δ still unknown

What we know so far

- Combine results from Super-K, K2K, SNO, Kamland and earlier experiments:



OR



$\Delta m_{12}{}^2 \sim 10^{-14}\ m_e{}^2$, $\Delta m_{23}{}^2 \sim 10^{-16}\ m_e{}^2$

Experiments to measure neutrino oscillations

- Super-Kamiokande: multipurpose underground detector
  - Neutrino oscillations
  - Proton decay
  - Supernova watch
- K2K (KEK to Kamioka experiment) – now finished
  - Neutrino oscillations using accelerator beam and SK

-- now ↑ future ↓

- T2K = Son of K2K
  - New accelerator at Tokai, 50X higher intensity than KEK
    - Under construction: first beam 2009
- Hyper-Kamiokande
  - 50X size of Super-Kamiokande
    - About 10 km from Super-K site, in Kamioka Town

Super-Kamiokande and K2K

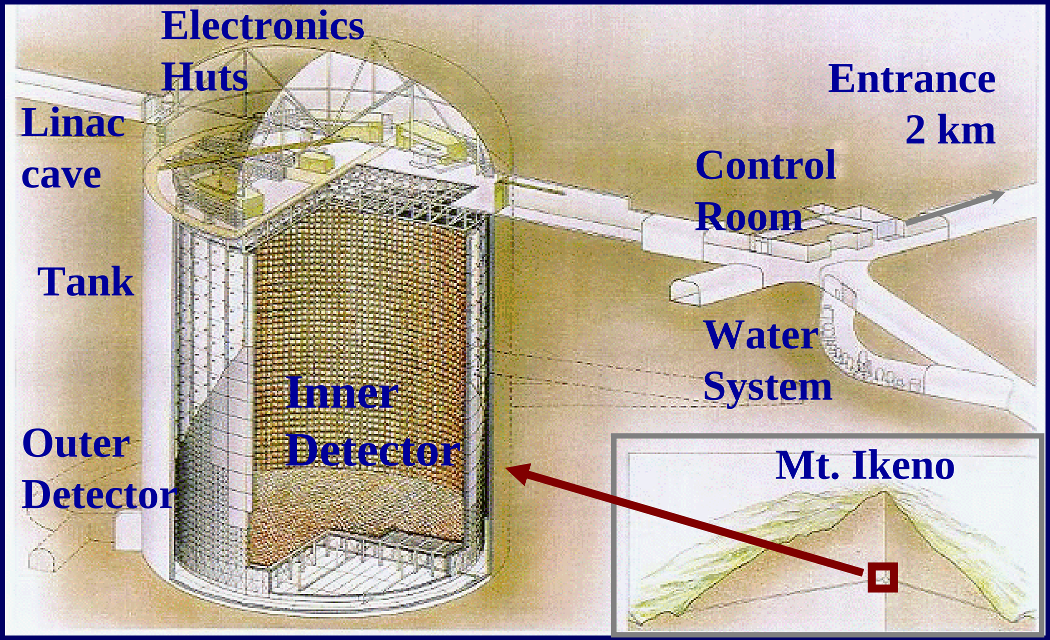
Super-Kamiokande Neutrino Observatory

- In Mozumi mine of Kamioka Mining Co, near Toyama City
- Detects natural (solar, atmospheric) and artificial (K2K) neutrinos

K2K (KEK to Kamiokande) long baseline experiment

- Neutrino beam is generated and sampled at KEK (particle physics lab, near Tokyo)
- Beam goes through the earth to Super-K, 250 km away

Super-Kamiokande



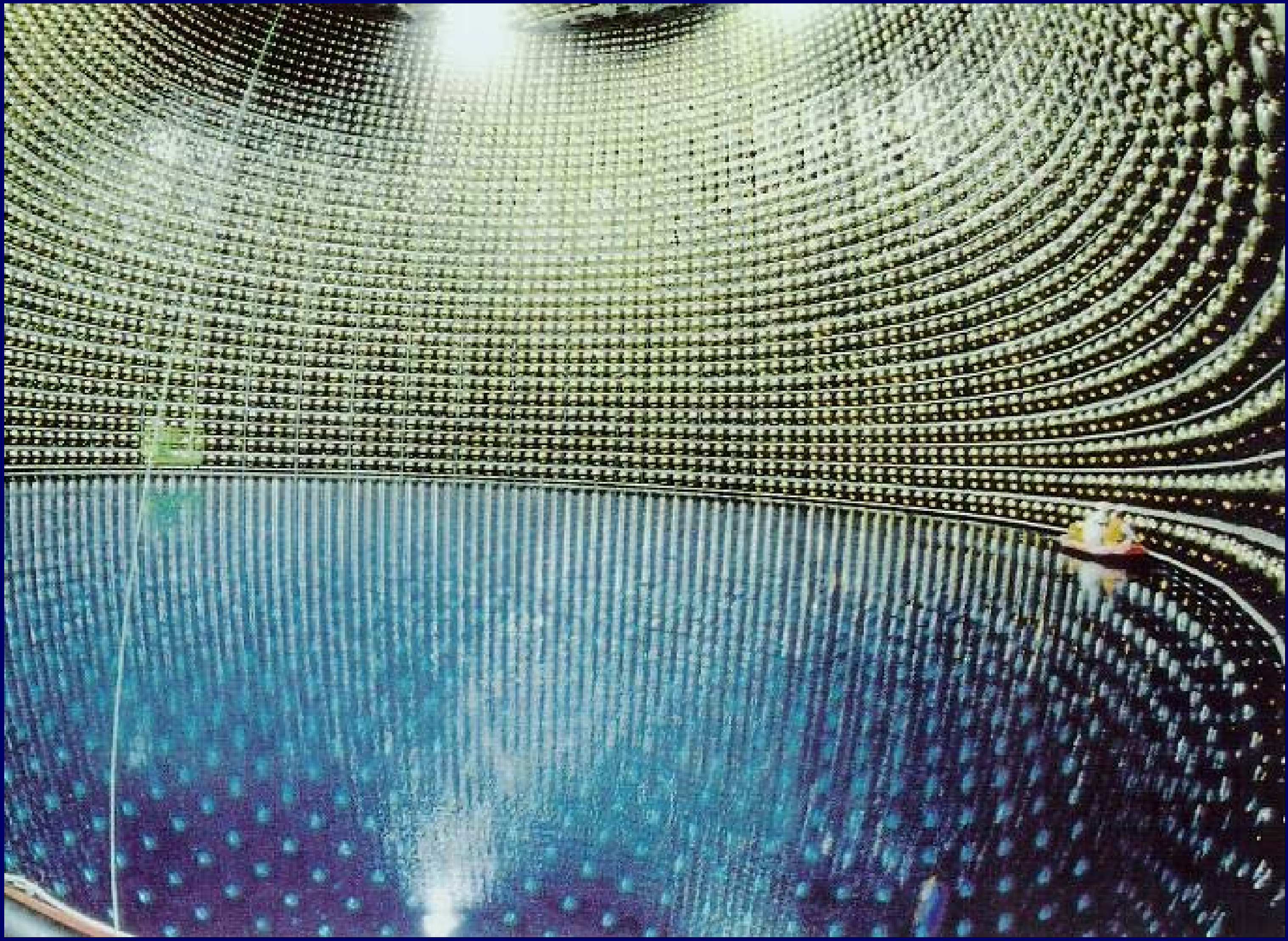
- US-Japan collaboration
- (~100 physicists)
- 50,000 ton ring-imaging water Cherenkov detector
- Inner Detector: 11,146 phototubes, 20” diameter
- Outer Detector: 1,885 phototubes, 8” diameter

- Began operation in April, 1996
- Published first evidence for neutrino mass in June, 1998
- Typically measures neutrino interaction location to within 25 cm, arrival direction to within few degrees
- Typically records about 15 neutrino events per second

See website for more info: http://www.phys.washington.edu/~superk/

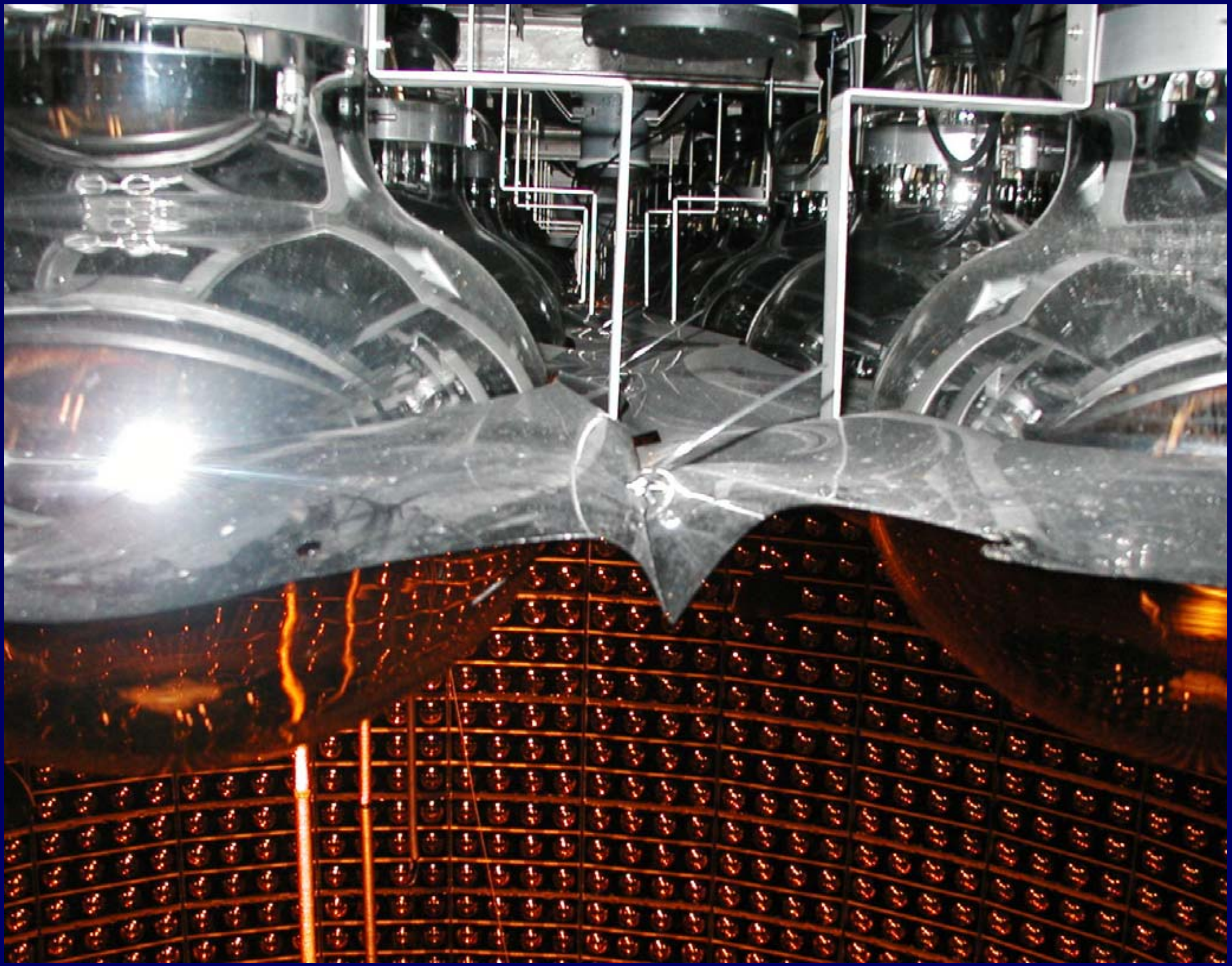
Just how big is Super-K?

- Checking photomultiplier tubes by boat as the tank fills (1996)



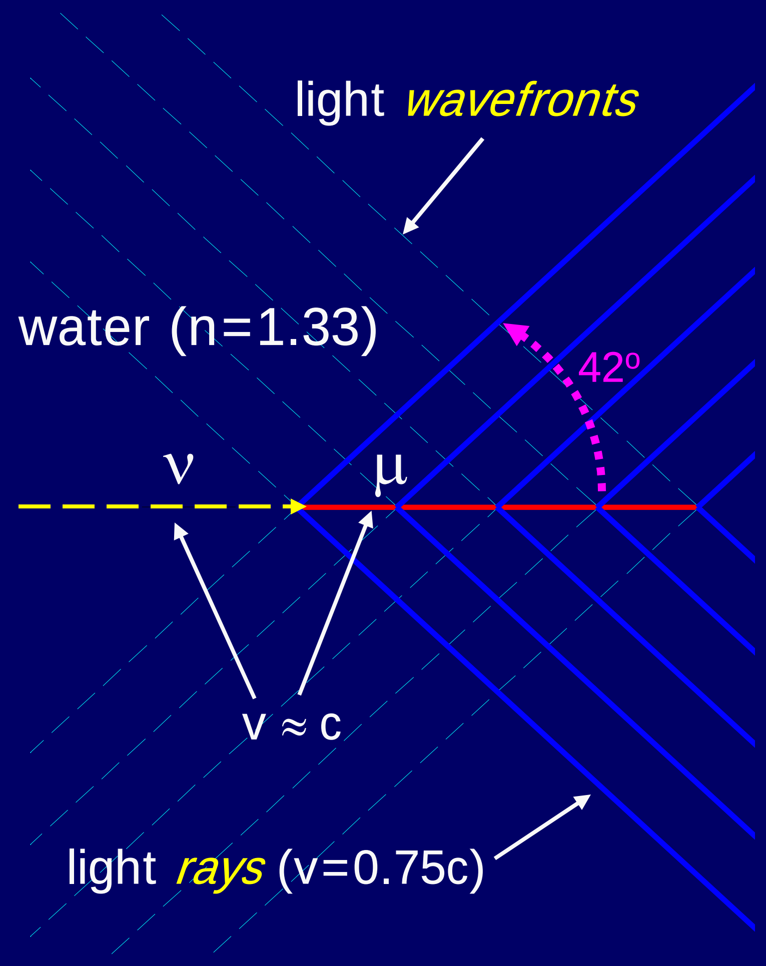
View into Super-K from tank top

- Each photomultiplier tube is 20 inches in diameter!



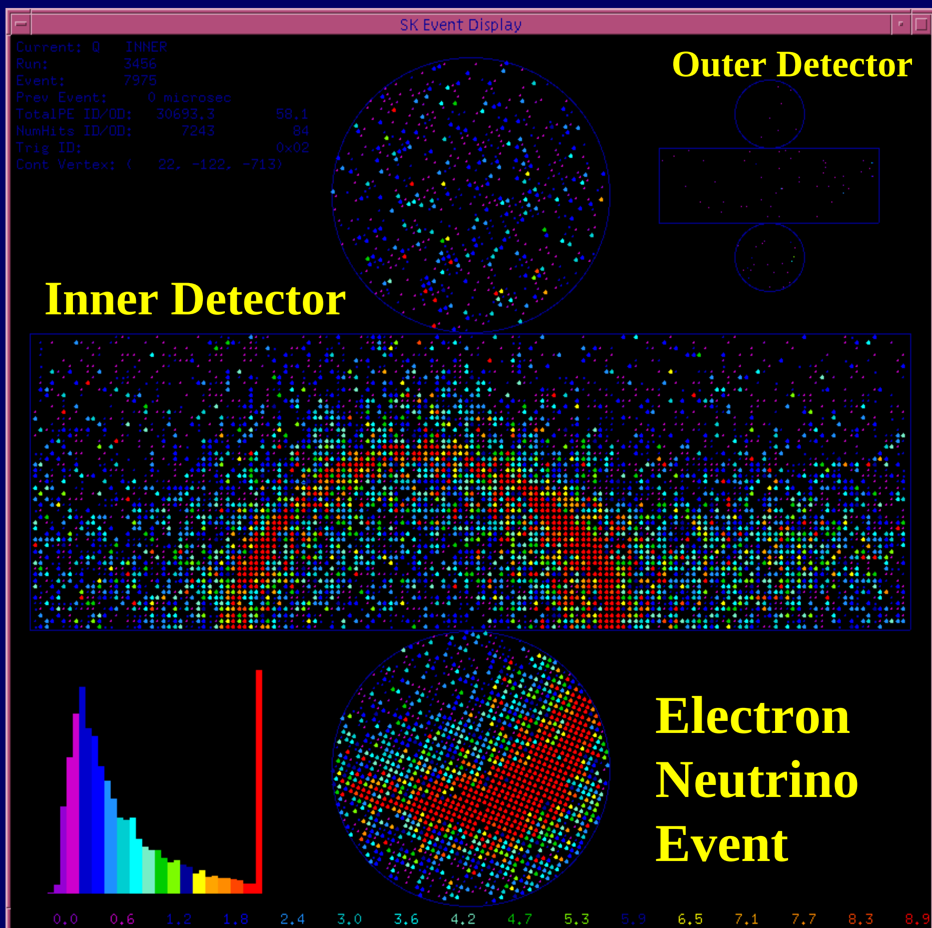
Cherenkov light in water

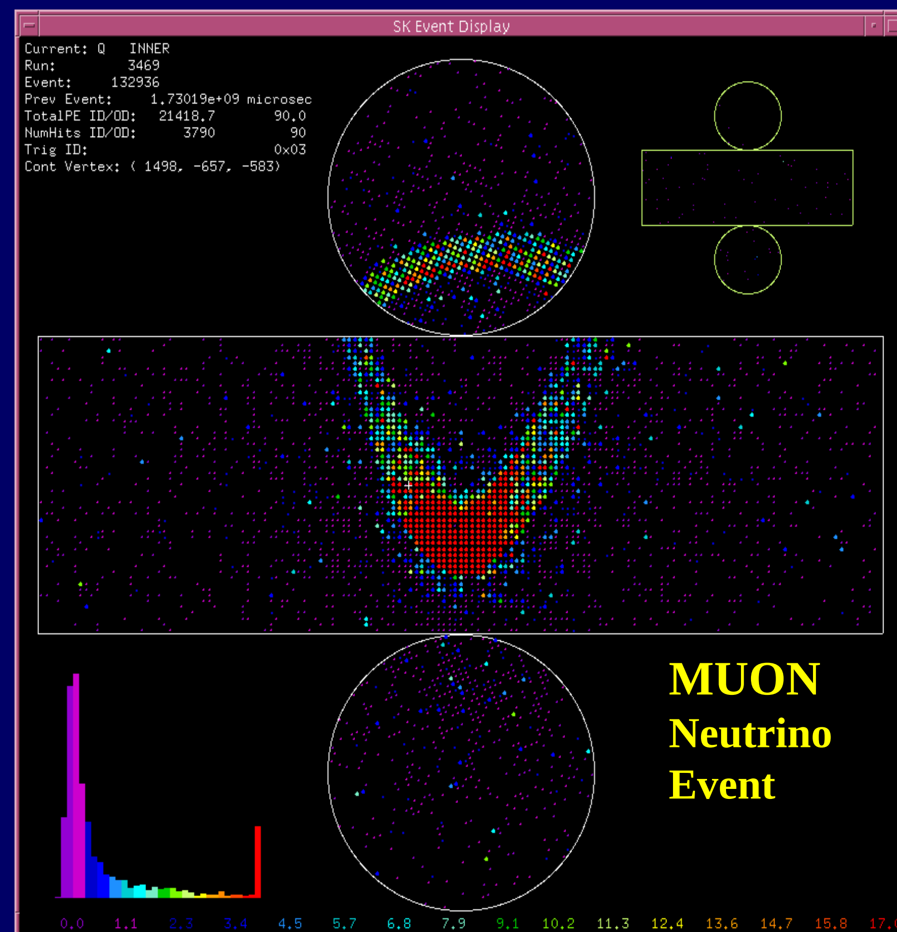
- Neutrino interacts in a nucleus in the water (oxygen or hydrogen)
- Produces a charged muon or electron, which carries an E-M field
  - Tau neutrinos produce a tau which immediately decays into muons and e's
    - Super-K can't identify tau neutrinos
- Muon travels faster than its field can travel in water: "shock wave" builds up
- Cherenkov light is emitted in characteristic 42º rings around the particle direction
- Cherenkov 'rings' are fuzzy for electrons and sharp for muons
  - electrons scatter/shower in the water
  - heavier muons travel in straight paths until very nearly stopped



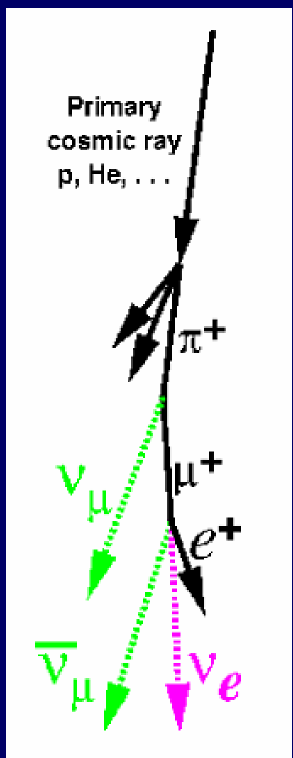
Neutrino “events”: ν_e and ν_μ

Electrons scatter in water and produce fuzzy Cherenkov rings;
Muons travel in straight lines and produce sharp rings





What are atmospheric neutrinos?



Produced by cosmic rays in upper atmosphere (altitude Z=15~20 km)

cosmic ray + air nucleus

$\rightarrow \pi$ mesons $\rightarrow \nu$'s

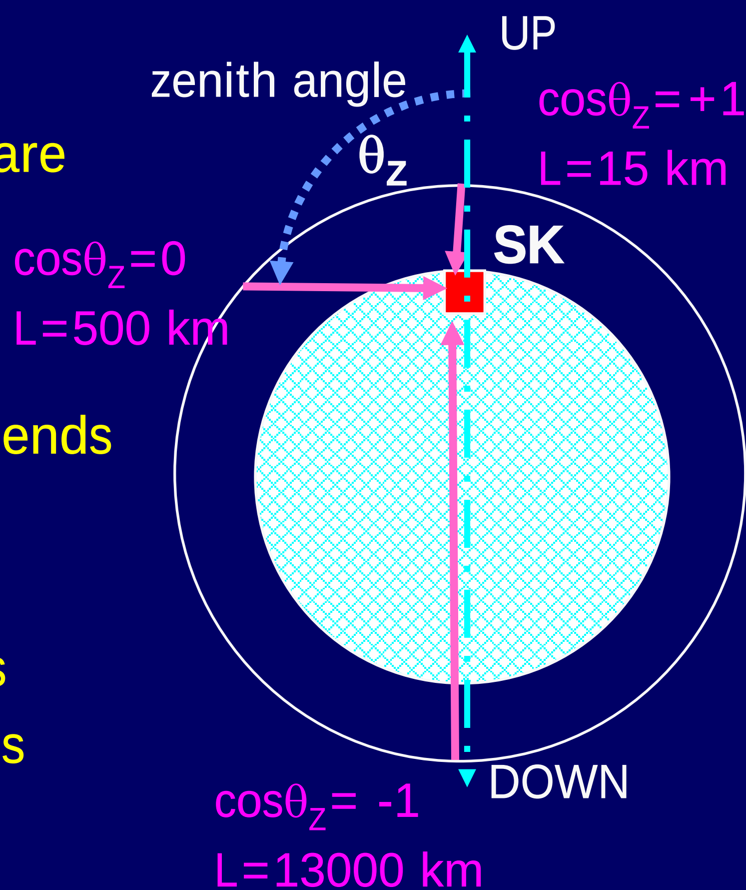
Note: on average, 2 muon ν's are produced for every electron neutrino

Flight path L to SK detector depends on zenith angle θ_Z:

$$L=f(\theta_Z, R, Z)$$

~15 km for downward-going ν's

~13000 km for upward-going ν's



Zenith angle distributions

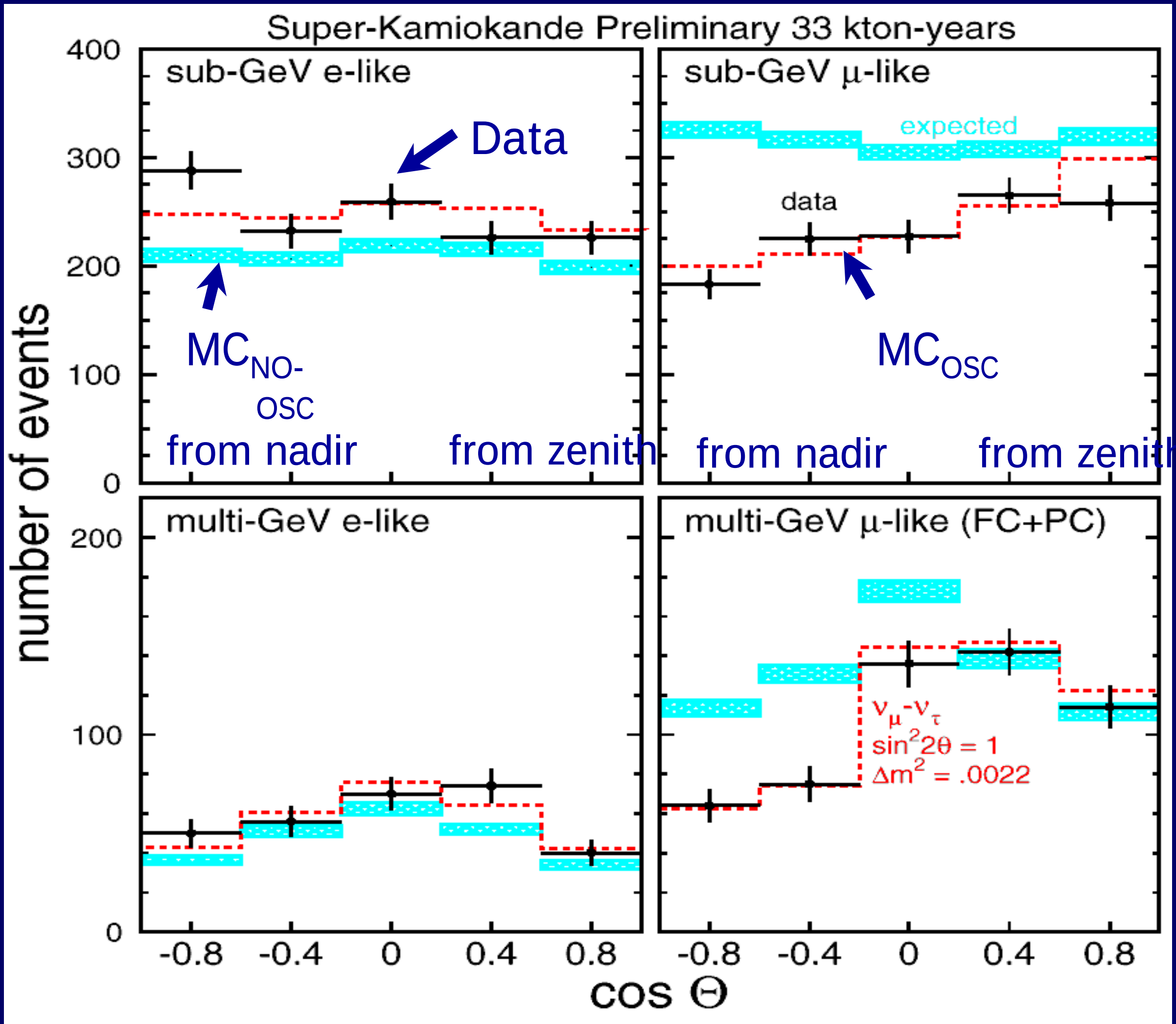
Data (+), MC_{OSC} (-), $MC_{NO\text{-}OSC}$(---)

Use detailed Monte Carlo simulation to calculate what we expect to see

Electron neutrino data are as expected

Muon neutrinos show a strong *up/down asymmetry*, contrary to expectation

Only viable explanation is that ν_μ oscillate into ν_τ (which are not seen in SK)

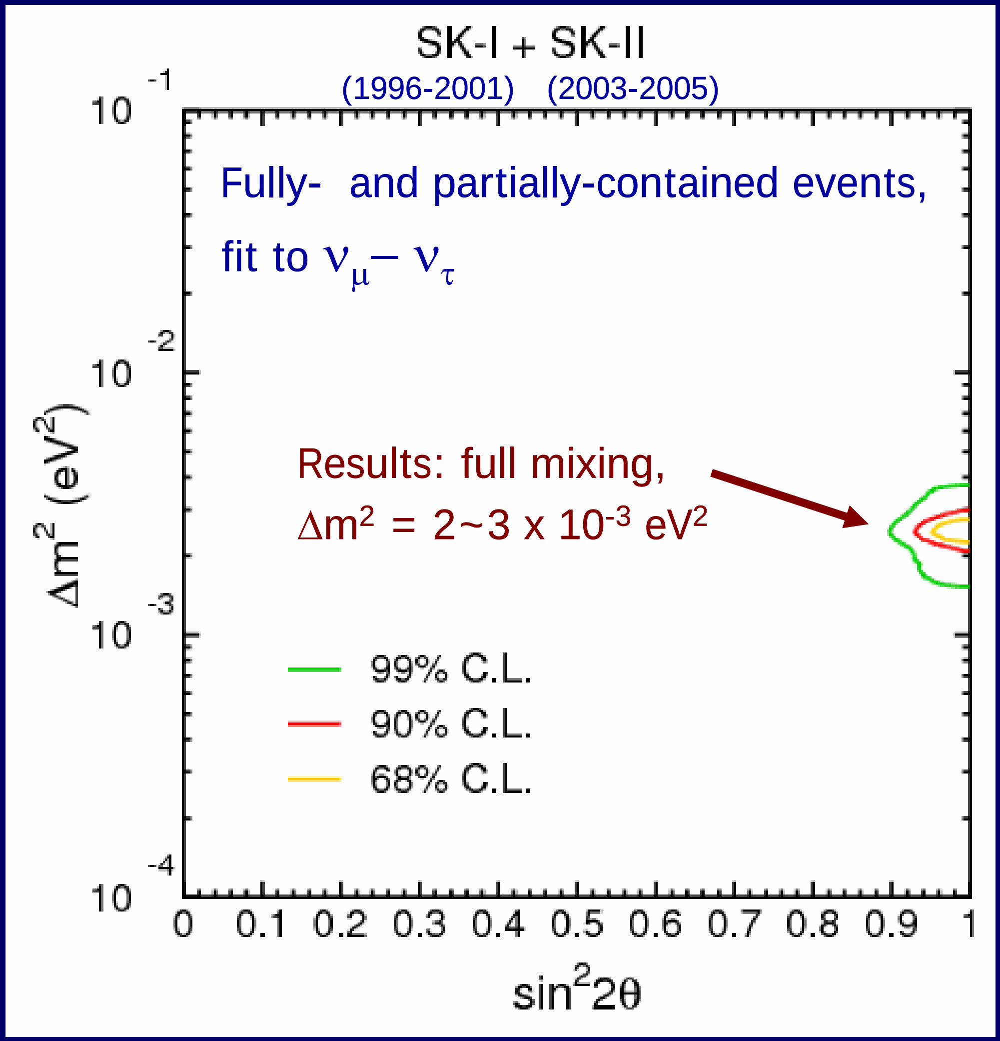


'Allowed region' in parameter space from SuperK

Conclusion: Super-K finds significant evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations from atmospheric neutrino data

Curves show values of Δm^2 and mixing angle θ which are consistent with observations, assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations:

'99% confidence level' means only 1% chance that true values lie outside the region shown due to random statistical fluctuations in data



June 5, 1998: Press clippings...

CNN.com sci-tech > story page

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Scientists in Japan may have discovered secret to the universe's 'missing mass'

The New York Times

NATIONAL DESK | June 5, 1998, Friday

**Mass Found in Elusive Particle; Unive
Never Be the Same**

By MALCOLM W. BROWNE (NYT) 2005 words
Late Edition - Final, Section A, Page 1, Column 1

ABSTRACT - 120 physicists from 23 research ins
Japan and US announce that they have found exi
mass in notoriously elusive subatomic particle c
neutrino; neutrino, particle that carries no electr
is so light that it was assumed for many years to
mass at all; cosmologists will now have to conf
possibility that significant part of mass of unive
be in form of neutrinos; discovery will also con
scientists to revise highly successful theory of c
of matter, Standard Model; finding of mass migh
theories about formation and evolution of galaxi
ultimate fate of universe; if neutrinos have suffi
their presence throughout universe would increa

Clinton praises neutrino discovery

Friday June 5 1:30 PM EDT

CAMBRIDGE, Mass., June 5 (UPI) - President Clinton (Friday) welcomed the discovery by researchers in Japan that neutrinos, the so-called dark matter in the universe, actually have mass. Delivering the commencement address at the Massachusetts Institute of Technology, Clinton called the neutrino discovery another key step in understanding how the world works, and said the Japanese success ``calls into question'' the U.S. government's decision to abandon the Superconducting Super Collider project for examining the tiniest elements of the universe.

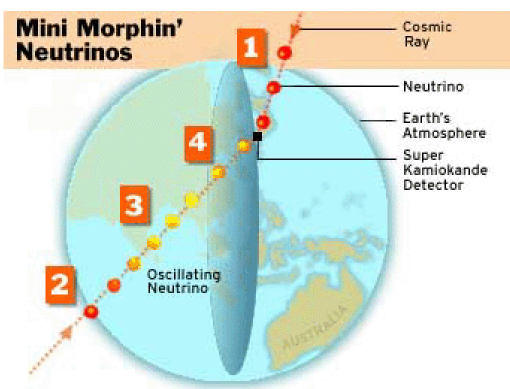
ABCNEWS.com archive **science**

Published on June 9, 1998

Ghostly Neutrinos Possess Smidgen of Mass

The Universe Gains Weight

"This is something that physicists have hoped for and eagerly sought for decades."
— *John Bahcall, Institute for Advanced Studies*



A neutron detector in Japan found more of one flavor of neutrino coming from the sky above than from the earth below—which means they may have mass. Click on the numbers above to follow the zooming neutrinos. (/ABCNEWS .com)

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Front Page

A Neutrino Bombshell: It Has Mass

By Curt Suplee
Washington Post Staff Writer
Friday, June 5, 1998; Page A01

In an old zinc mine 2,000 feet beneath the Japanese Alps, an international team of physicists has discovered that a ubiquitous, ghostly subatomic particle called the neutrino -- previously thought to have no mass at all, like a beam of light -- actually weighs in at about one ten-millionth the mass of the electron.

'Grandfather' of SK won the 2002 Nobel Prize

- Masato Koshiba, U. of Tokyo
  - Leader of predecessor experiment *Kamiokande*;
  - Led effort to design and get support for Super-Kamiokande

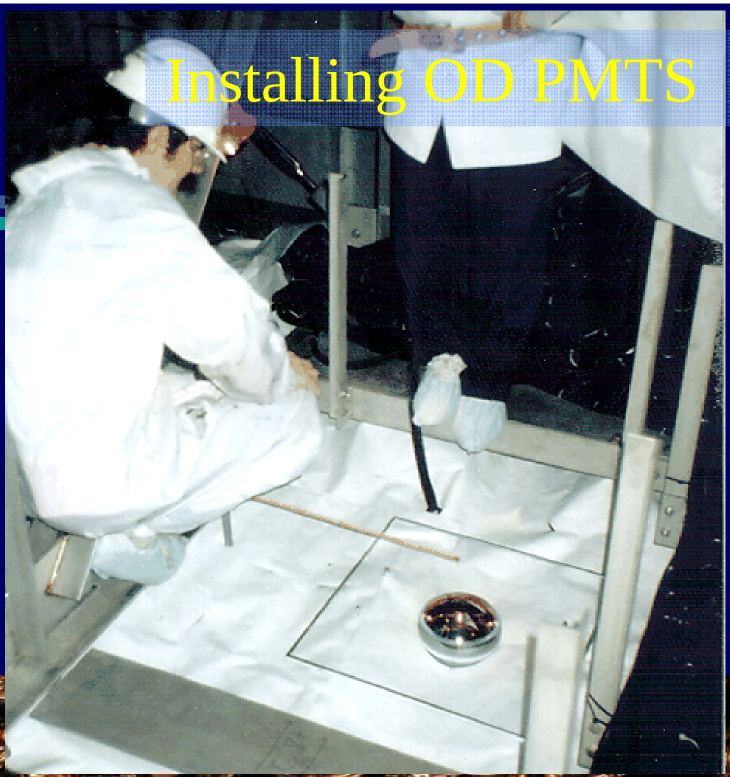
"... for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

M. Koshiba

(with K. Tanaka, winner of 2002 Chemistry prize)

You too can have fun at Super-K

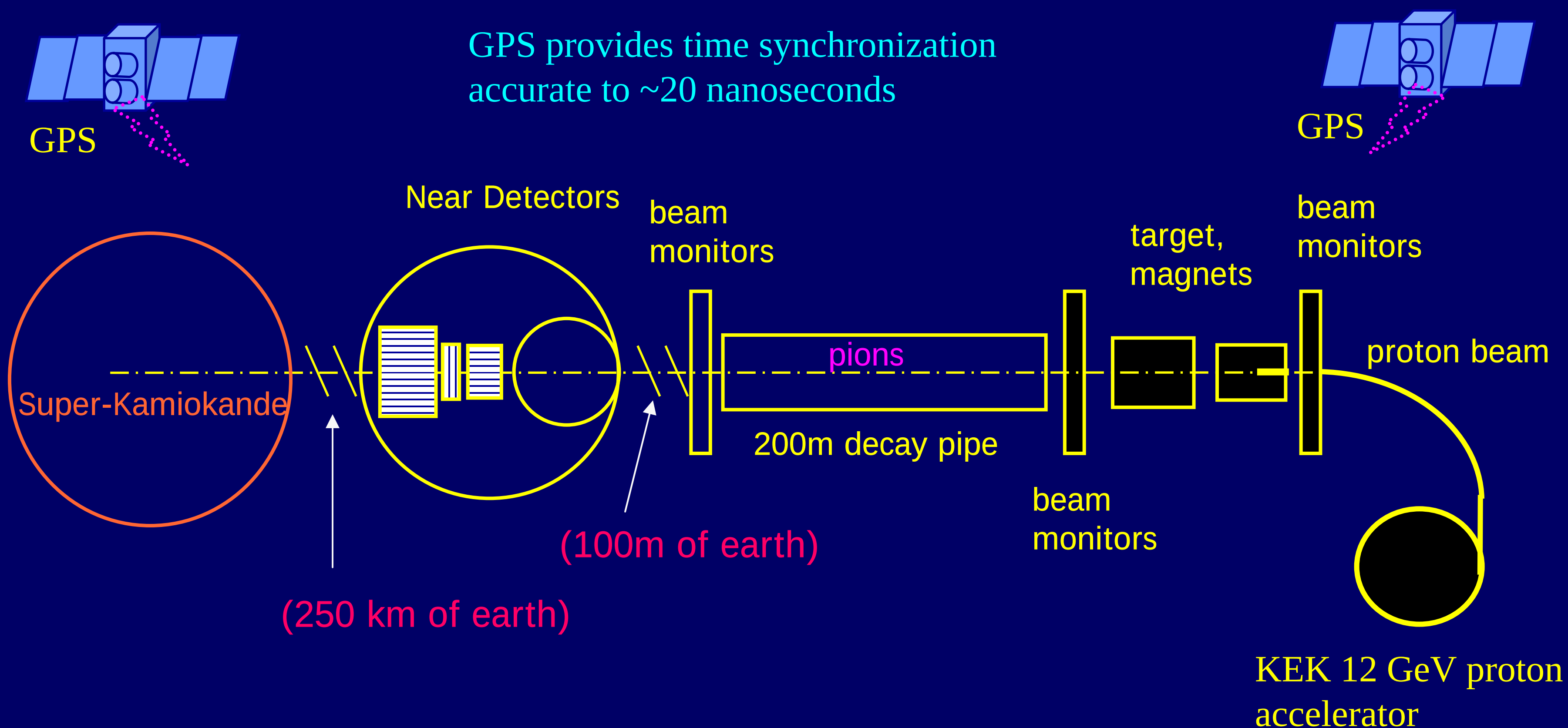
Record snowfalls last year!



Installing OD PMTS

Installing ID PMTS

How do you make a neutrino beam?



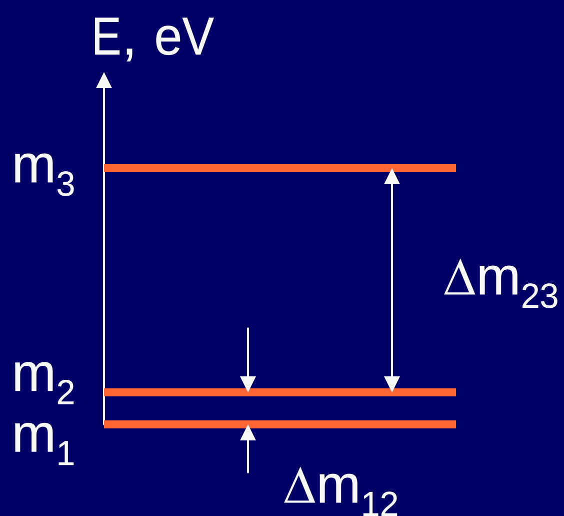
K2K (KEK to Kamioka)

Finished data taking 2001

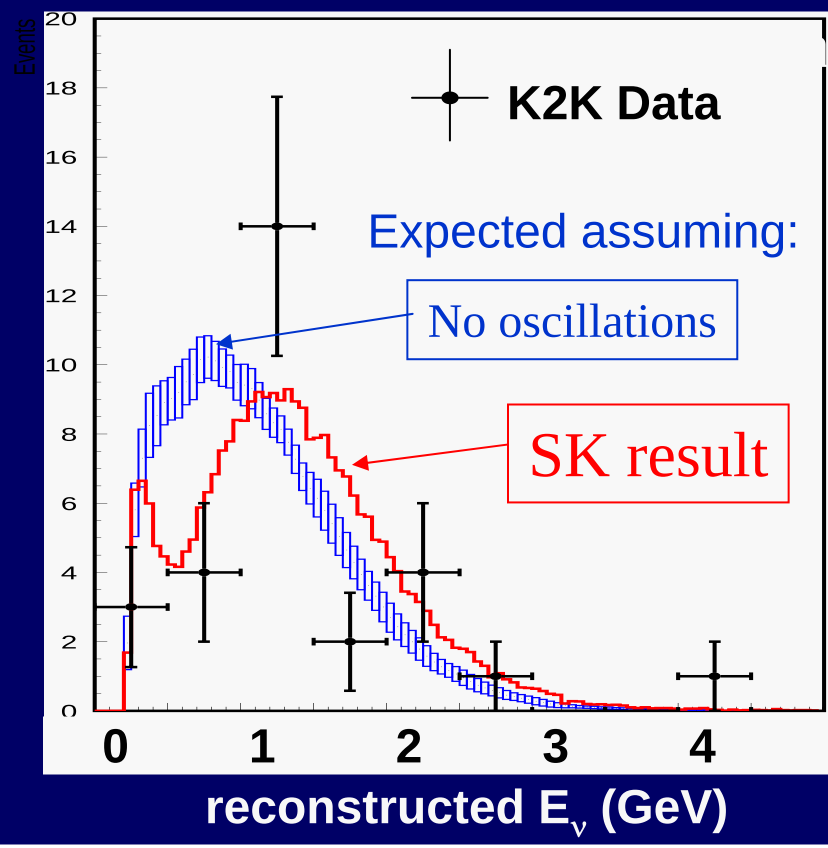
Same plan for T2K (Tokai to Kamioka)

How do you determine neutrino mass from these measurements?

- First: we *don't* measure neutrino mass, only mass *differences* between different mass states:
  - assume there are 3 mass states, one with m ~ 0
  - Solar + atmospheric neutrino data tells us Δm_{12} ~ 0.01 eV and Δm_{23} ~ 0.05 (or vice versa)



K2K data confirmed Super-K:

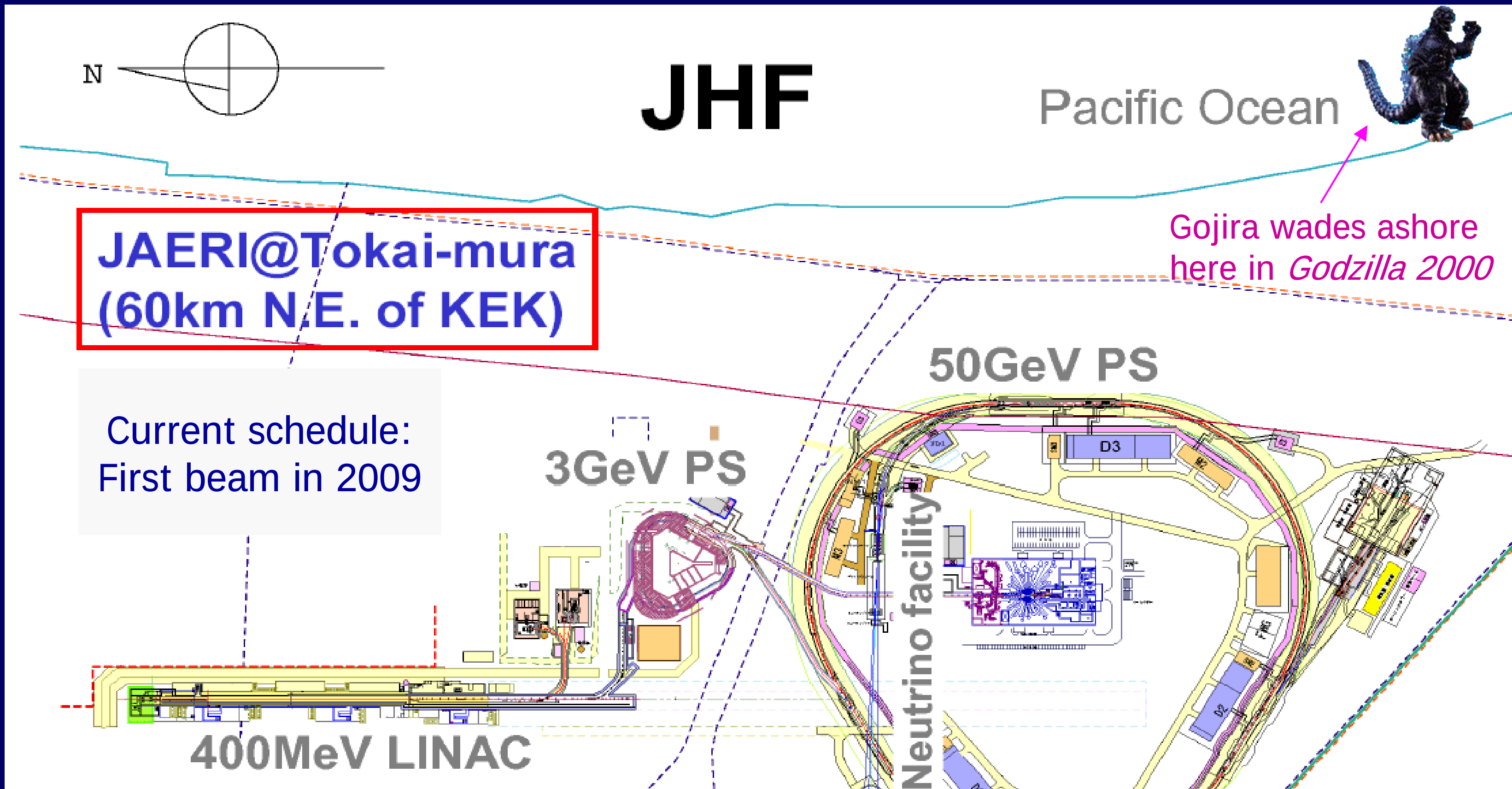


What next?

- “T2K” (Tokai to Kamioka): start taking data 2009
  - New 50 GeV accelerator lab, located 100 km NE of KEK
    - JPARC (Japanese Proton Accelerator Research Center, at Tokai)
    - High intensity proton beam: 0.75 MW !
      - 3.3×10^{14} protons/pulse, 0.3 Hz rep rate
      - Neutrino beam has ~20x increased sensitivity for oscillation effects
      - *Narrow* band, off-axis neutrino beam: ~1 GeV
  - Far detector = Super-Kamiokande again
    - Baseline 295 km
    - Rebuild Super-K to 100% PMT coverage in 2005-6

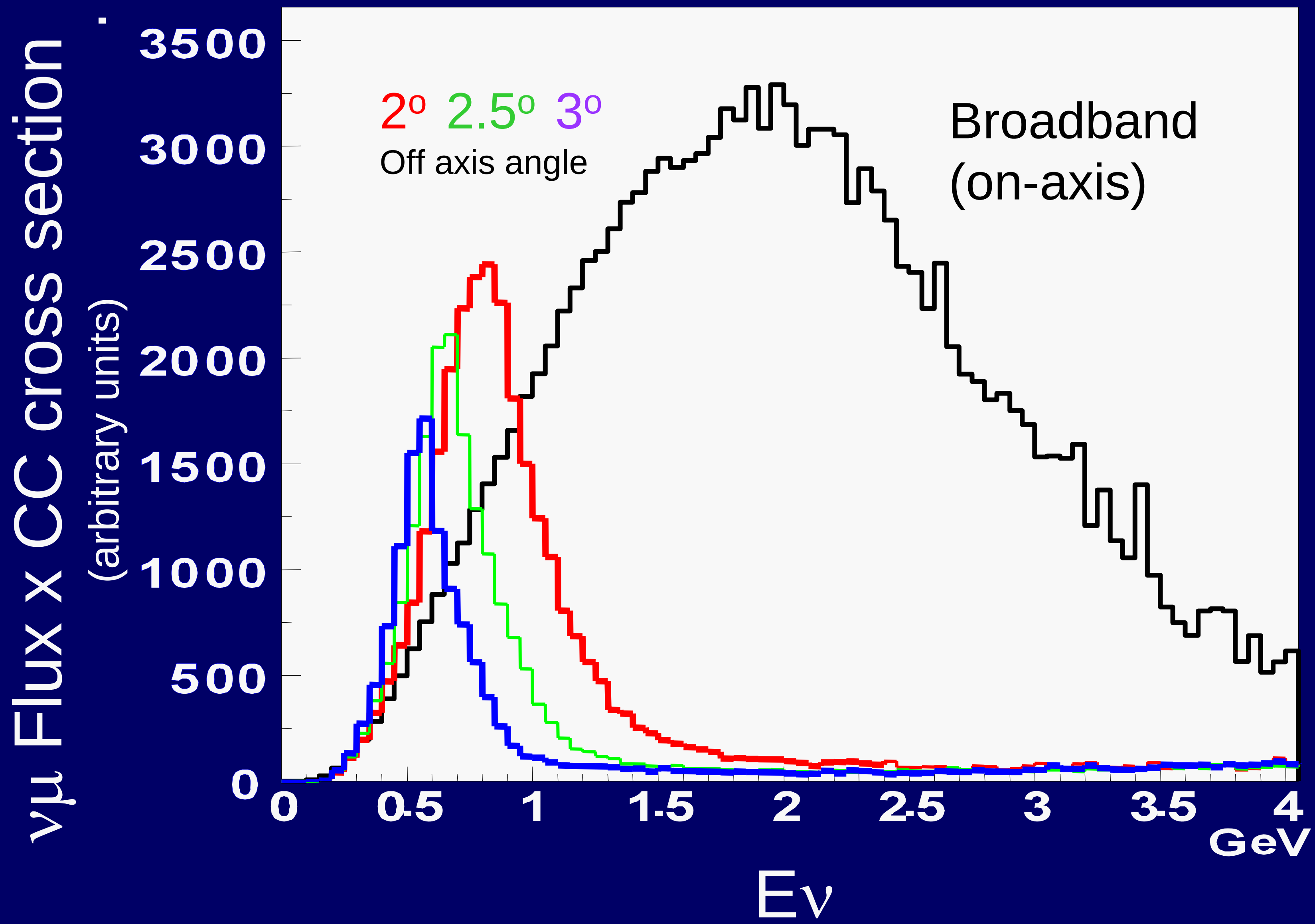
  See http:://neutrino.kek.jp/jhfnu
- Next phase? "Hyper-K": rebuild Super-K, 50 times bigger
  - Can't be done in present mine: new site 10 km away
  - Wait to see if initial results from T2K are promising

JHF accelerator: to be finished in 2008



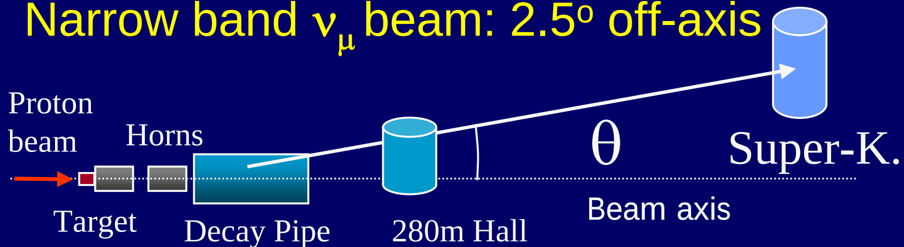
	JHF	MINOS	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.292	0.53	0.45
Power(MW)	0.77	0.41	0.0052

T2K Neutrino E spectra: broadband vs off-axis

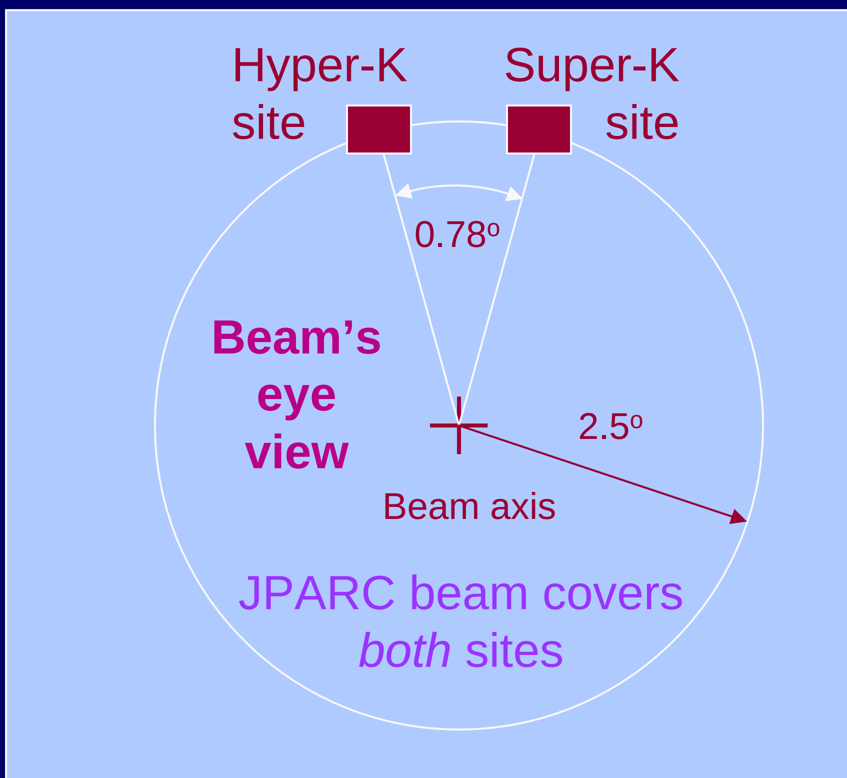


JPARC neutrino beam uses “off-axis” technique

Narrow band ν_μ beam: 2.5° off-axis



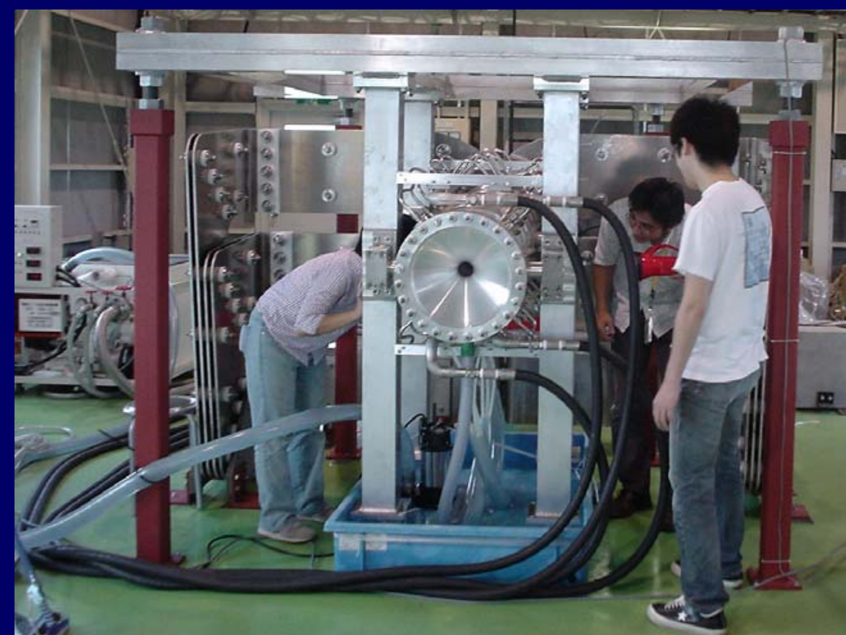
To get anti-neutrinos: reverse horn current



T2K-I event statistics at SK:

(Off axis-2.5 deg, 22.5 kt, per year)

- 2200 total ν_μ events
- 1600 ν_μ CC
- ν_e ~ 0.4% at ν_μ peak E



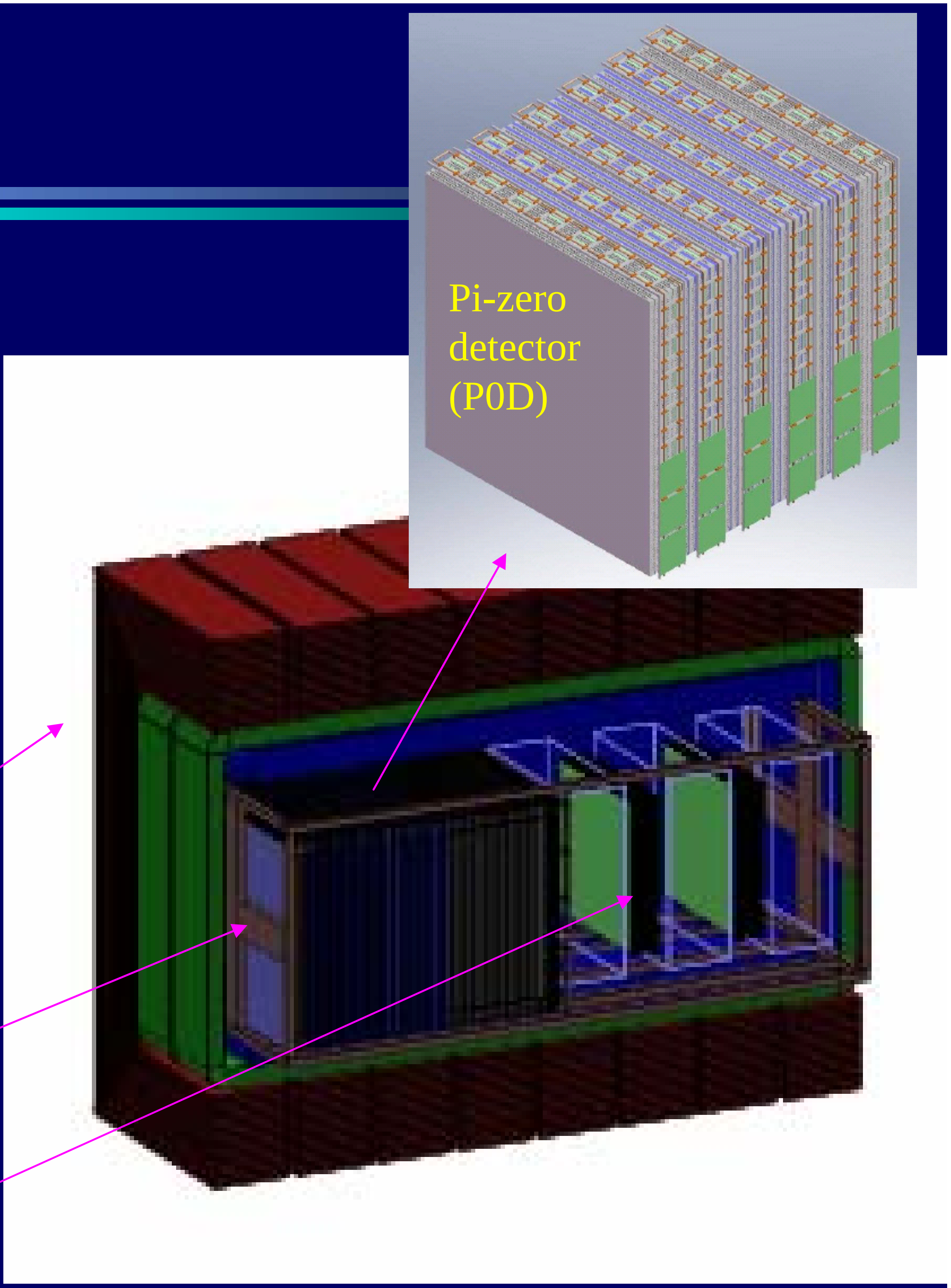
Target/Horn magnet – test setup
Must handle pulses of 100s of kA

T2K Near detector at 280m

- Beamline components (Japan-UW-Colorado)
- On-axis muon monitors (Japan) – not shown
- Off-axis near detectors (US-Canada-Europe)
  - Magnet from CERN
  - P0D = “Pi-zero” detector (US)

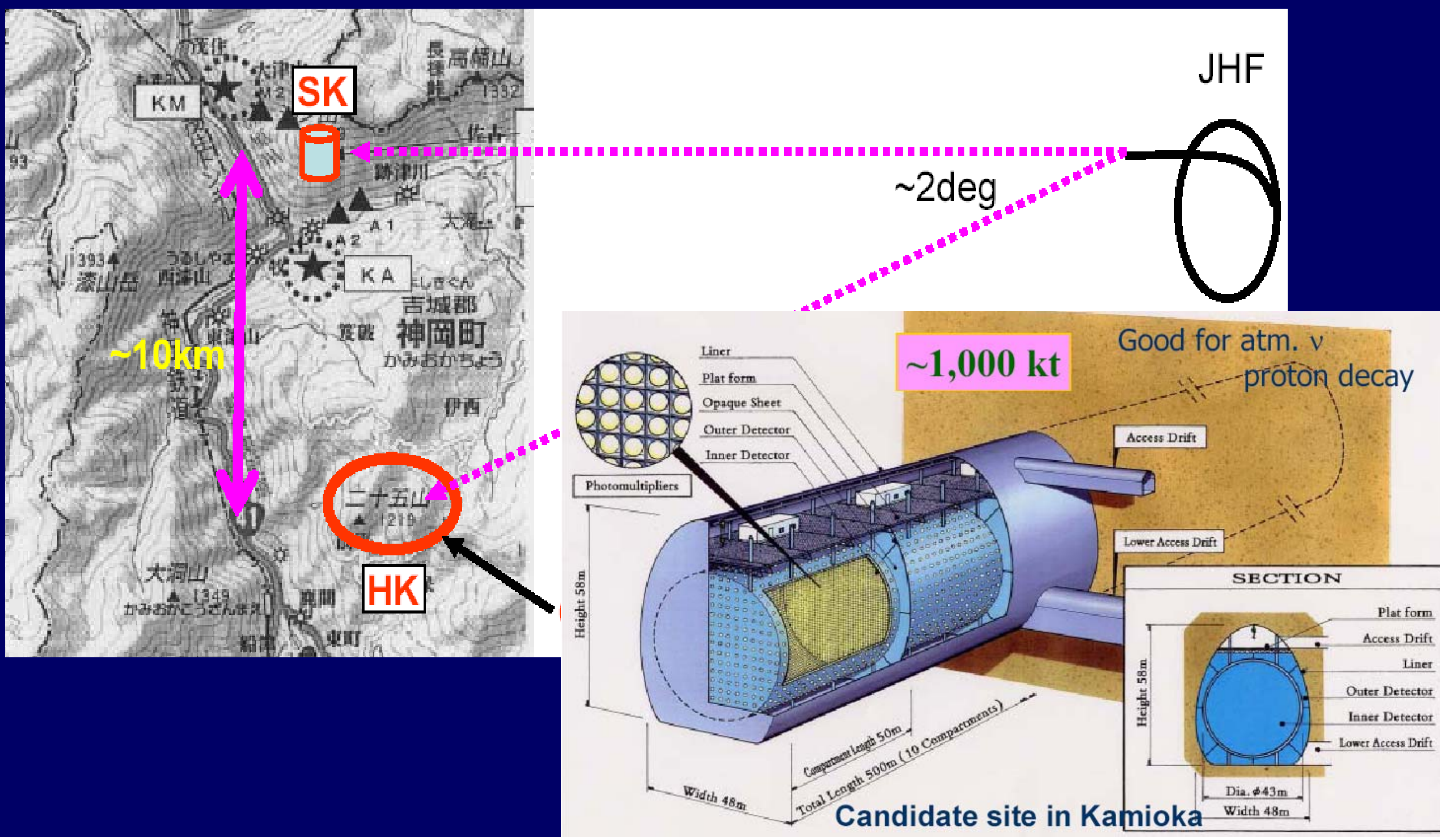
(We’re building parts of P0D here)

  - TPC = Time Projection Chs. (Canada-EU)



Super-K follow-up: Hyper-K?

- Hyper-Kamiokande = million tons of water (probably in several tanks)
- Good Hyper-K site in another mine nearby (same mine owners)
- JHF beam will be able to cover both



Is anyone else working on this?

- Certainly!
  - Need confirmation to have believable results
  - Apologies for not talking about other experiments
- No time here to describe other experiments but you can find out about them on the Web:
  - SNO (in Canada - collaboration includes UW)
  - KamLand (Japan)
  - MINOS (USA)
  - OPERA (Europe)

    - for links see

Super-K: http://www.phys.washington.edu/~superk

K2K: http://neutrino.kek.jp

T2K: http://jnusrv01.kek.jp/public/t2k/