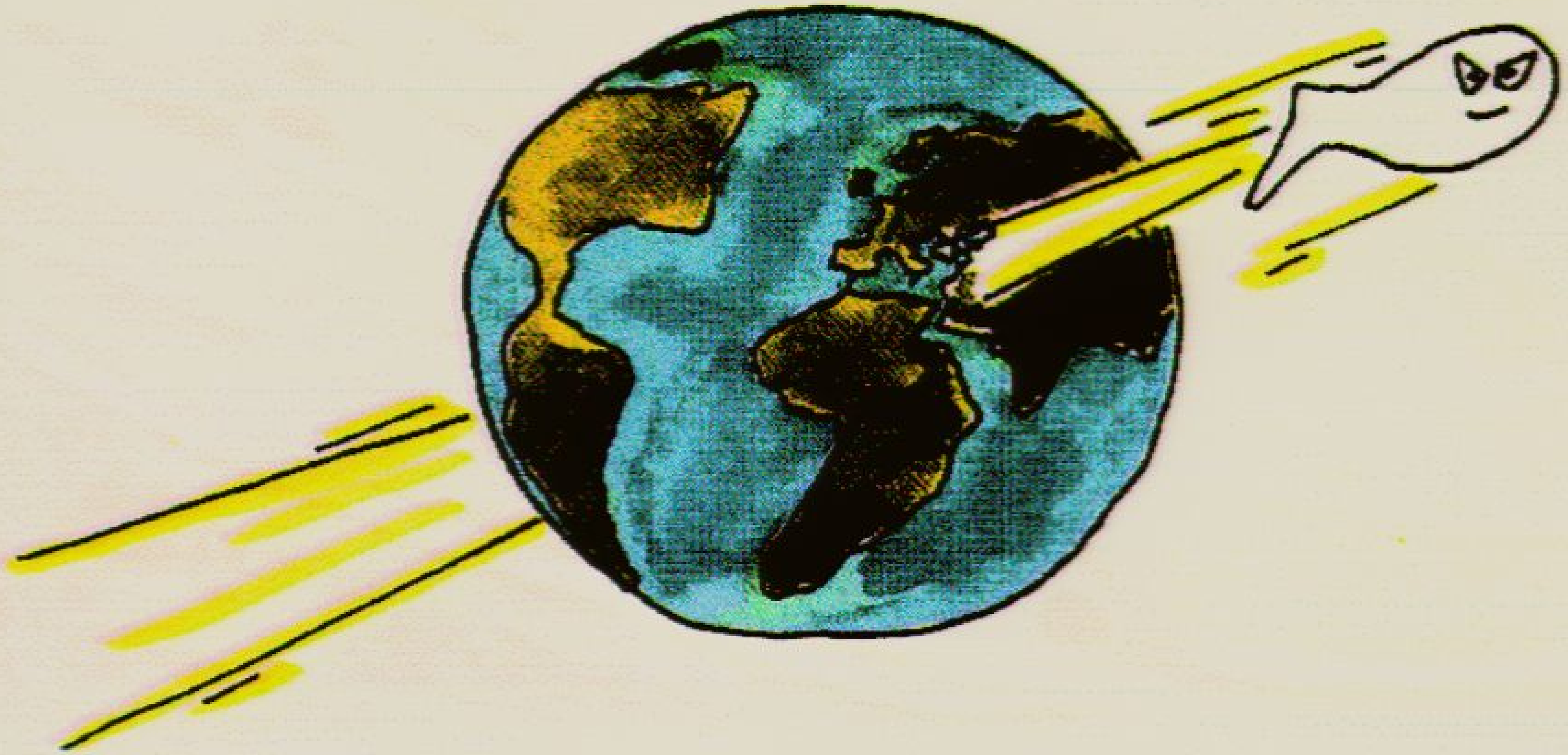
Title: High Energy Neutrinos from the Sky and Through the Earth

Date: May 02, 2007 02:00 PM

URL: http://pirsa.org/07050000

Abstract: The progress in neutrino physics over the past ten years has been tremendous: we have learned that neutrinos have mass and change flavor. I will pick out one of the threads of the story-- the measurement of flavor oscillation in neutrinos produced by cosmic ray showers in the atmosphere, and its confirmation in long distance beam experiments. I will present the history, the current state of knowledge, and how the next generation of high intensity beam experiments will address some of the remaining puzzles.

Neutrinos from the Sky and Through the Earth



Kate Scholberg, Duke University

OUTLINE

- Neutrinos and why they matter
- Neutrino mass and oscillations

- Atmospheric neutrinos
- Super-Kamiokande
- Results from SK and K2K

- Summary of where we stand

- Beyond 2-flavor: θ_{13}, CP violation, hierarchy
- Next generation of experiments: Tokai to Kamioka

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NEUTRINOS

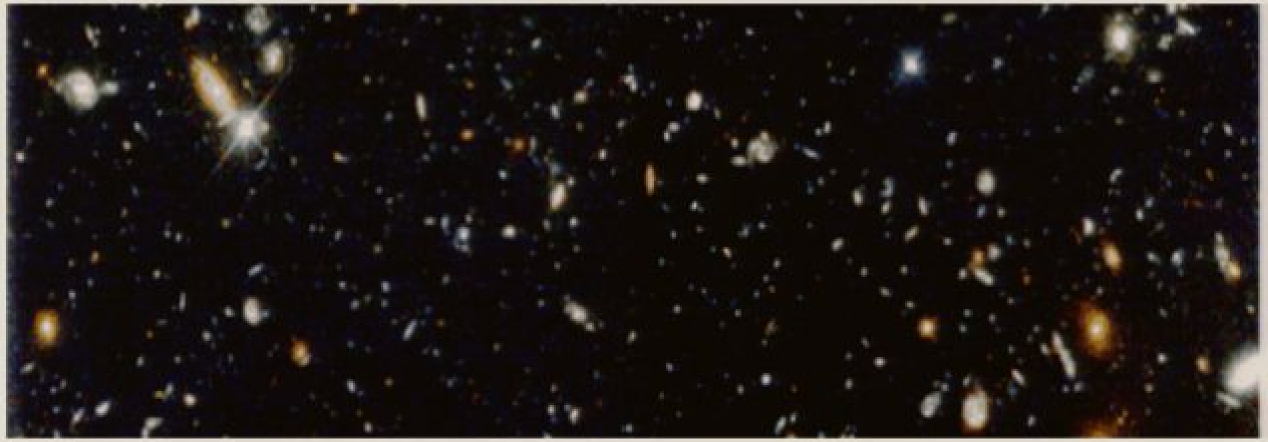
	~3	~1200	174,000	MeV/c^2
Quarks	u	c	t	
	d	s	b	
	~6	~100	~4200	MeV/c^2
	0.511	105.6	1778	MeV/c^2
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	

In the Standard Model of particle physics, neutral partners to the charged leptons

- Spin 1/2
- Zero charge
- 3 flavors (families)
- Interact *only* via ***weak interaction***
- Tiny mass (< 1 eV)

Why Do Neutrinos Matter?

They are a piece of the puzzle: we must understand their properties if we are to understand fundamental particles and their interactions



Neutrinos comprise ~few % of dark matter, but are important in understanding of history of structure formation

We also hope to gain insight into

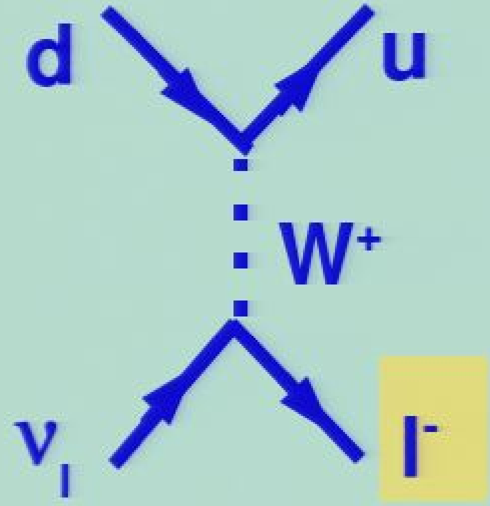
MATTER-ANTIMATTER ASYMMETRY

Observation of CP violation in neutrinos could help understand leptogenesis

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

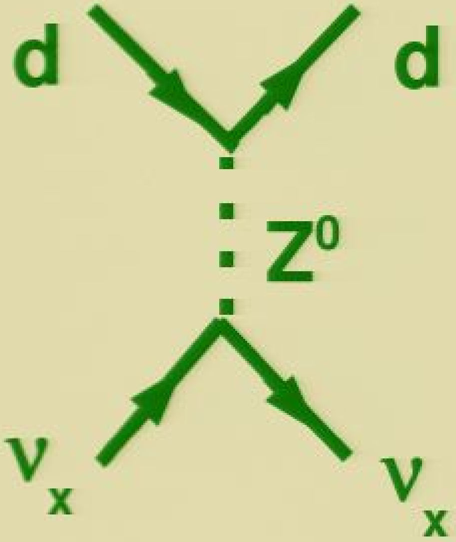


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton with flavor corresponding to neutrino flavor

(must have enough energy to make lepton)

Neutral Current (NC)



Flavor-blind

Neutrino Mass and Oscillations

How can we learn about neutrino mass?

Assume

FLAVOR STATES are superpositions of **MASS STATES**

$|\nu_f>$ $|\nu_m>$

weakly interacting

$$|\nu_f> = \sum_{i=1}^{N} U_{fi} |\nu_i>$$

↓

unitary mixing matrix

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate

(essentially, interference between mass states)

Simple two-flavor case

$$|\nu_f> = \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

$$|\nu_g> = -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

Propagate a distance L:

$$|\nu_i(t)> = e^{-iE_it}|\nu_i(0)> \sim e^{-im_i^2L/2p}|\nu_i(0)>$$

Probability of detecting flavor g at L:

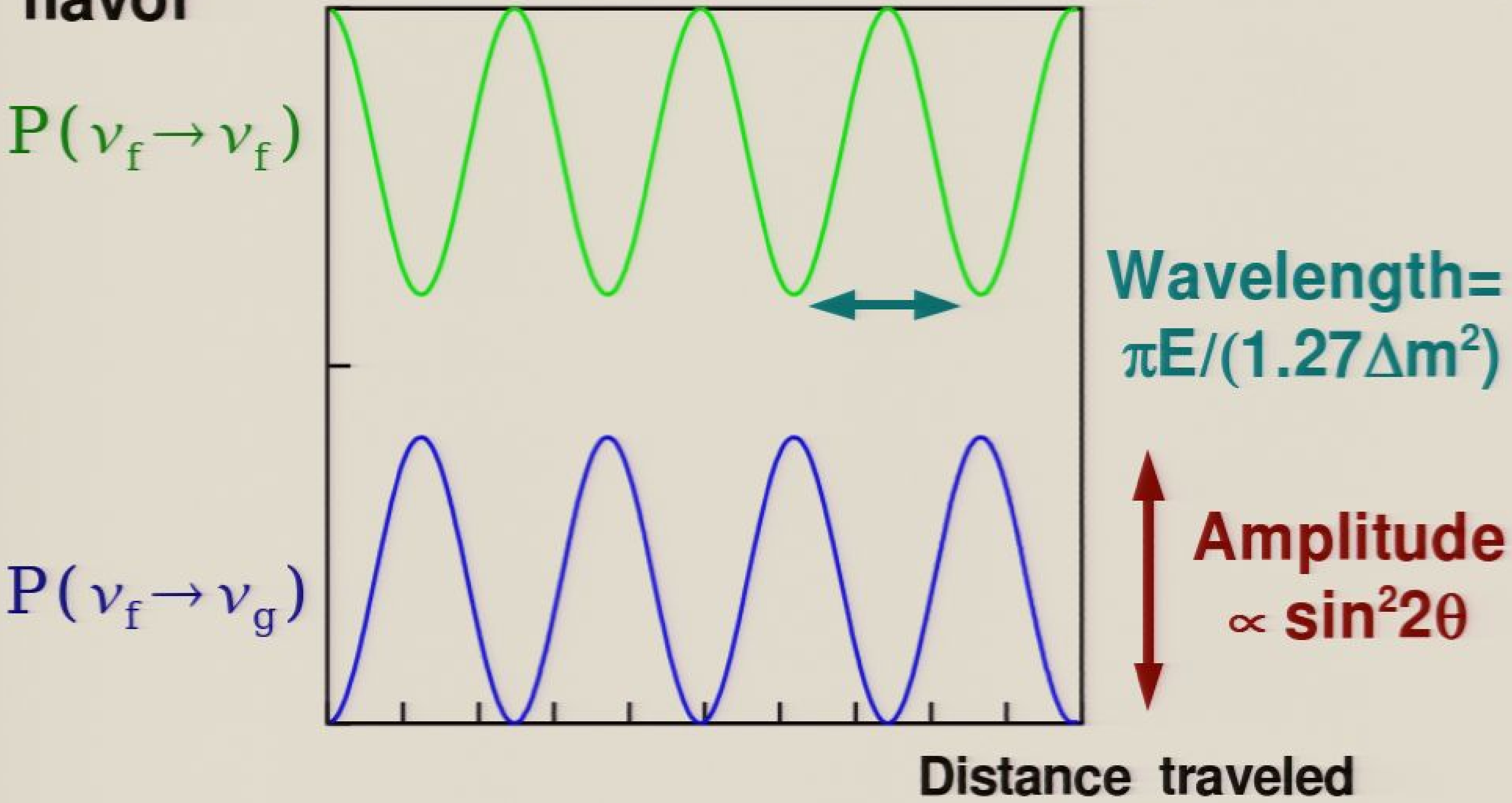
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\boxed{\theta}\sin^2\left(\frac{1.27\boxed{\Delta m^2}L}{E}\right)$$

E in GeV
L in km
Δm^2 in eV^2

Parameters of nature to measure: θ, $\Delta m^2 = m_1^2 - m_2^2$

Probability of changing flavor

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$



Δm^2, $\sin^2 2\theta$ are the parameters of nature;

L, E depend on the experimental setup

The Experimental Game

- Start with some neutrinos (natural or artificial)
- Measure (or calculate) flavor composition and energy spectrum
- Let them propagate
- Measure flavor and energies again

Have the flavors and energies changed?

If so, does the change follow

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right) \; ?$$

Disappearance: ν's oscillate into 'invisible' flavor

e.g. $\nu_e \rightarrow \nu_\mu$ at ~MeV energies

Appearance: directly see new flavor

e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV energies

Oscillation Parameter Space

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

fast wiggle

Twiddle L/E

Frequency $\propto \Delta m^2 L/E$

slow wiggle

Amplitude $\propto \sin^2 2\theta$

Experimental statistics

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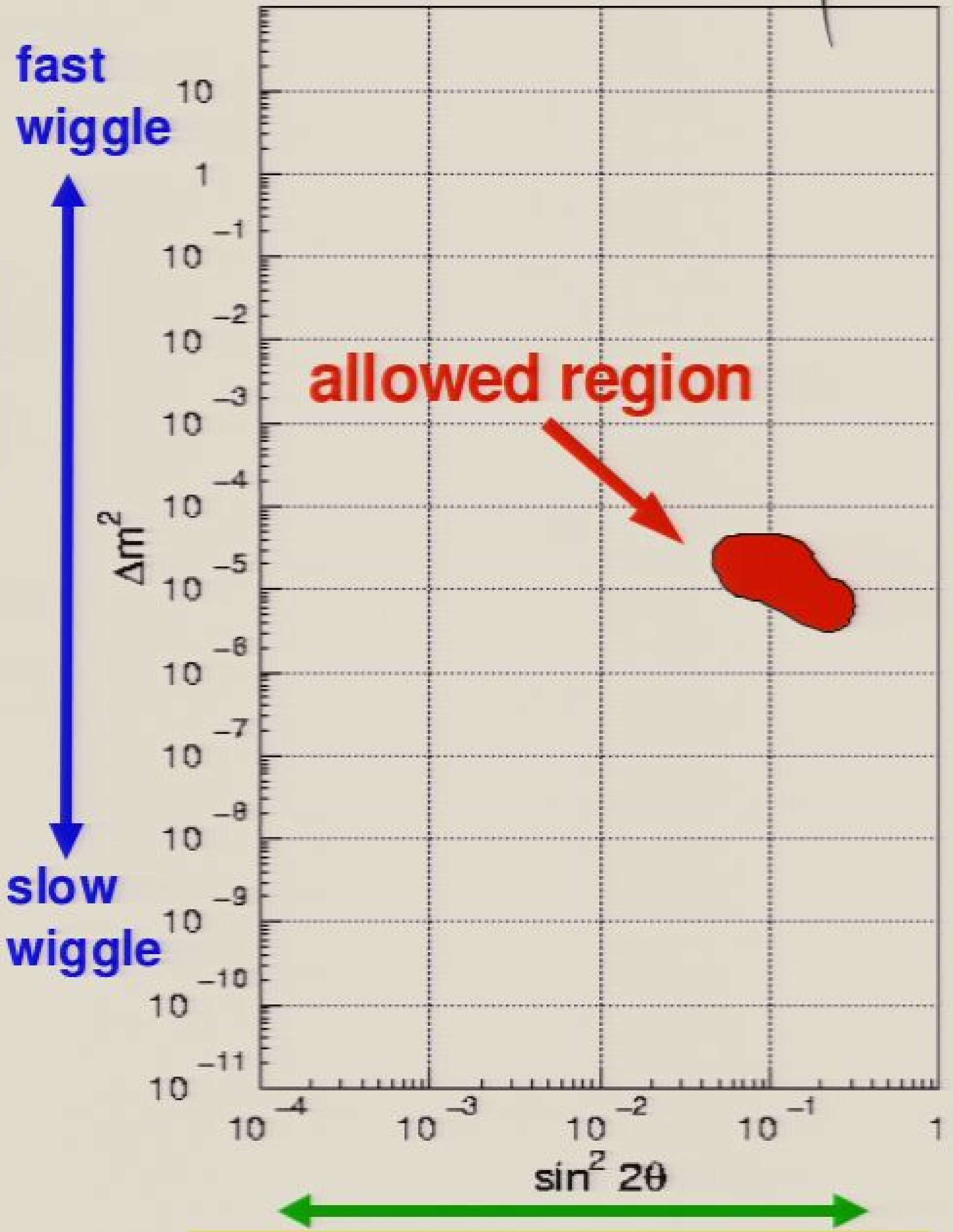

Amplitude $\propto \sin^2 2\theta$

Experimental statistics

More generally, for 3 flavors:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki-Nakagawa-Sakata (MNS) matrix

$$P(\nu_f \rightarrow \nu_g) = \delta_{fg} - 4 \sum_{j>i} \mathrm{Re}(U_{fi} U_{gi} U^*_{fj} U^*_{gj}) \sin^2\left(\frac{1.27\,\Delta m^2_{ij} L}{E}\right)$$
$$\pm 2 \sum_{j>i} \mathrm{Im}(U_{fi} U_{gi} U^*_{fj} U^*_{gj}) \sin\left(\frac{2.54\,\Delta m^2_{ij} L}{E}\right)$$

Frequently, can use 2-flavor approximation
e.g. if $\Delta m_{ij}^2 >> \Delta m_{jk}^2$

Note: 3 flavors ⇒ 2 *independent* Δm_{ij}^2

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fast wiggle

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allowed region

slow wiggle

Amplitude $\propto \sin^2 2\theta$

Experimental statistics

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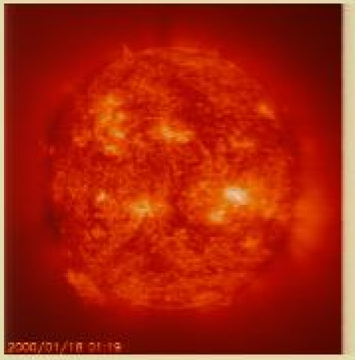
The Three Signals

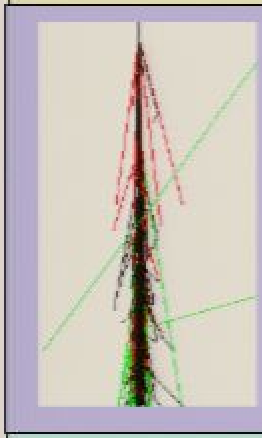
SOLAR NEUTRINOS

$\nu_e \rightarrow \nu_x$

Electron neutrinos from the Sun are *disappearing*

Distance ~ 10^8 km, Energy ~ 0.1-15 MeV



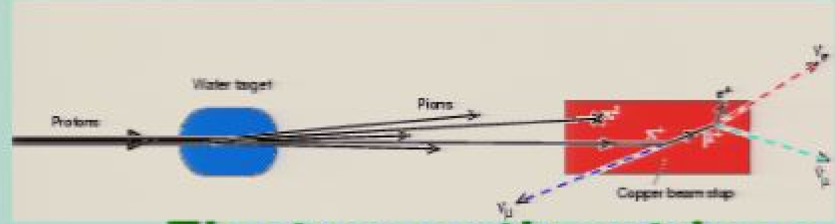


ATMOSPHERIC NEUTRINOS

$\nu_\mu \rightarrow \nu_x$

Muon neutrinos created in cosmic ray showers are *disappearing* on their way through the Earth

Distance ~ 10-13000 km, Energy ~ 0.1-100 GeV



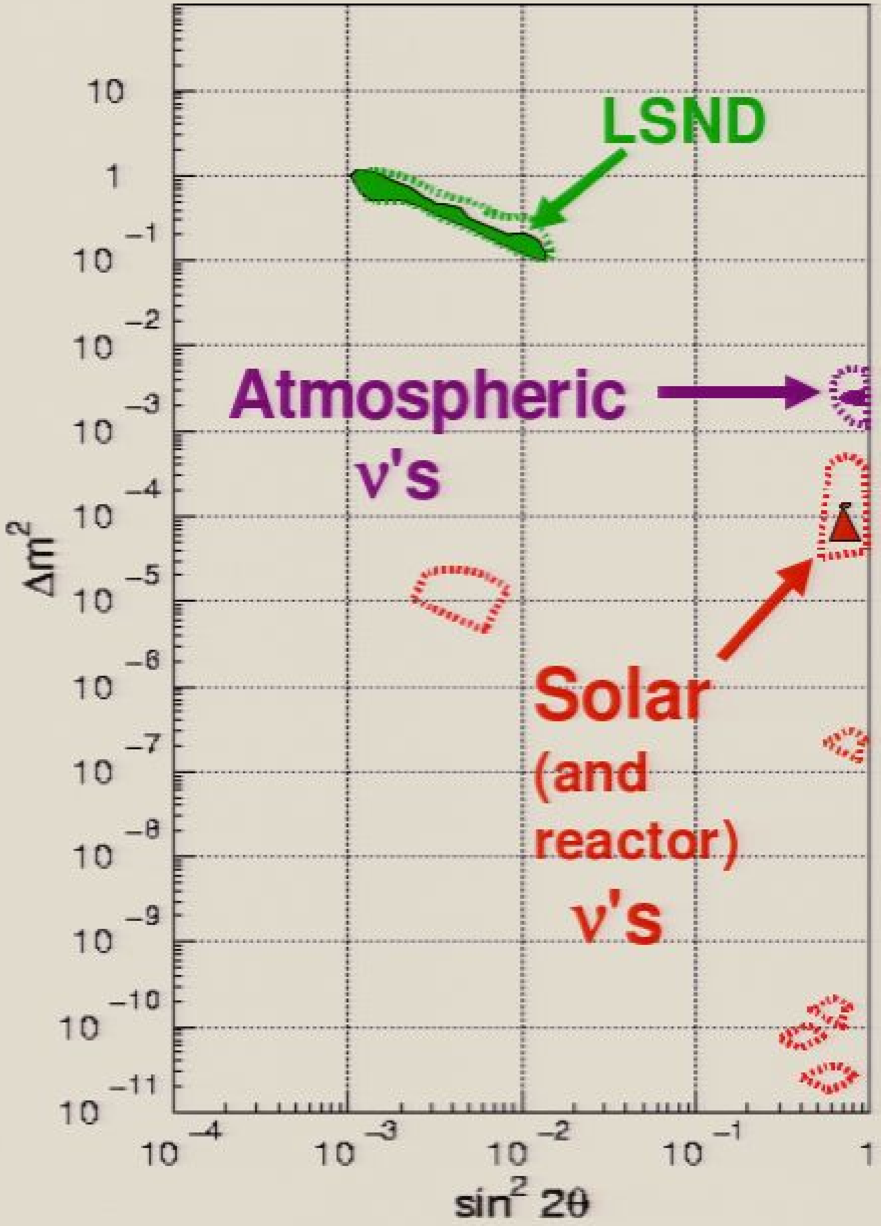
ACCELERATOR NEUTRINOS

Electron antineutrinos *appearing* in a beam of muon antineutrinos at LSND

$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

Distance ~ 30 m, Energy ~ 30-50 MeV

The Three Signals in Parameter Space



$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

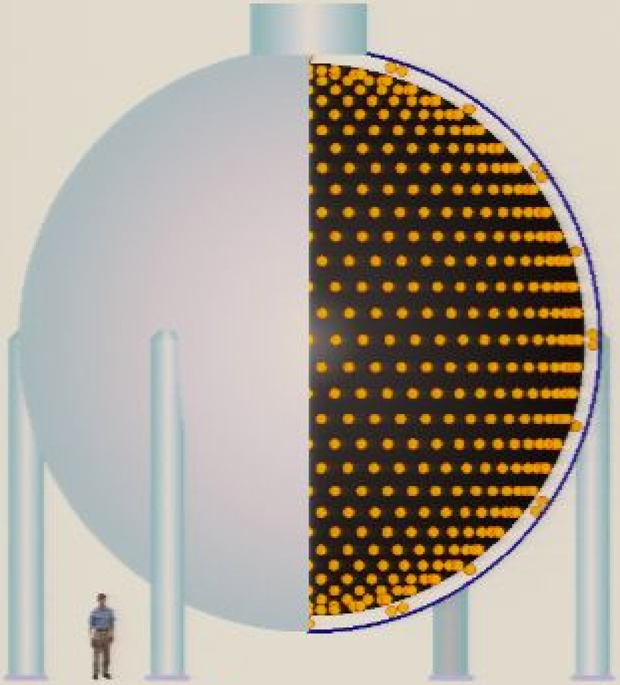
$\nu_\mu \rightarrow \nu_x$

$\nu_e \rightarrow \nu_x$

(Note: can have only 2 independent Δm^2, for 3 neutrinos)

News from MiniBooNE!

Booster Neutrino Experiment at Fermilab



0.8 kton of mineral oil

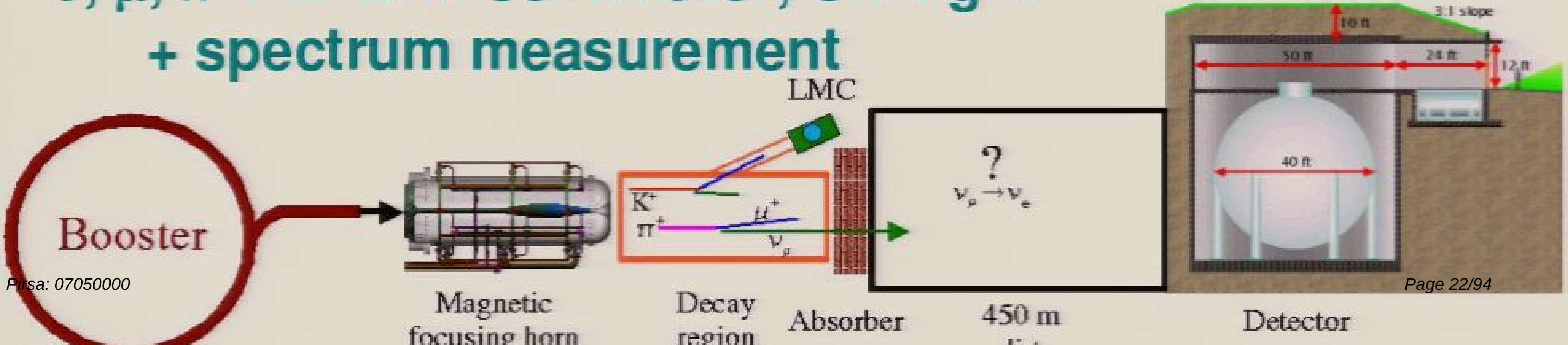
E_ν ~ 1 GeV from 8 GeV booster

L~ 500 m for "mini-BooNE"

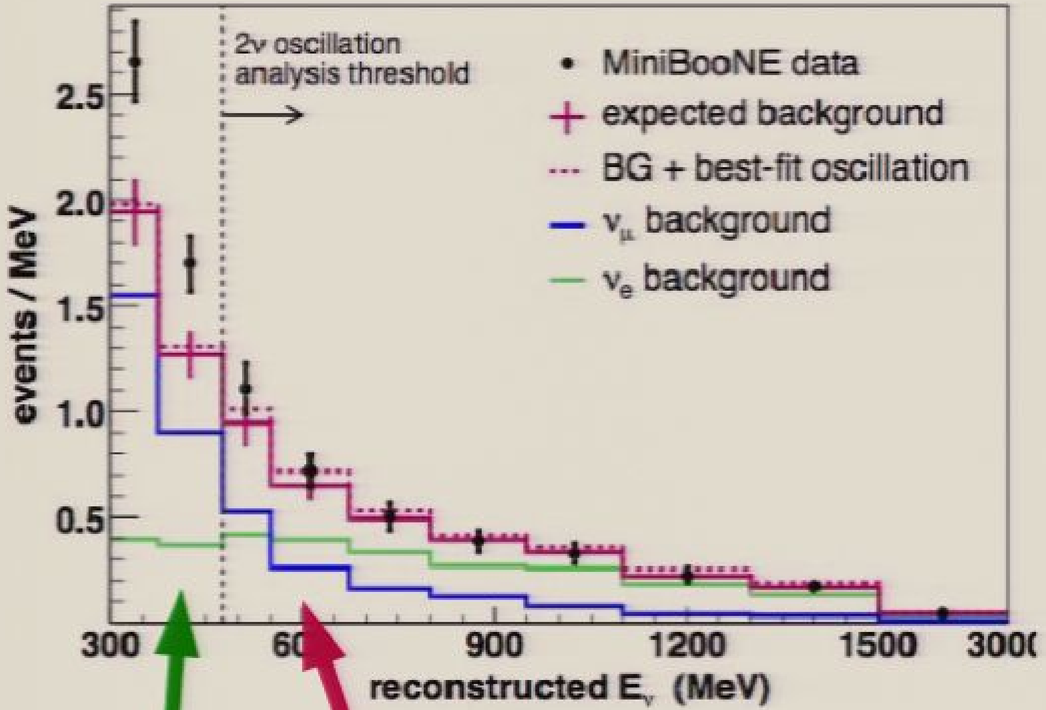
Test $\nu_\mu \rightarrow \nu_e$ at same L/E as LSND

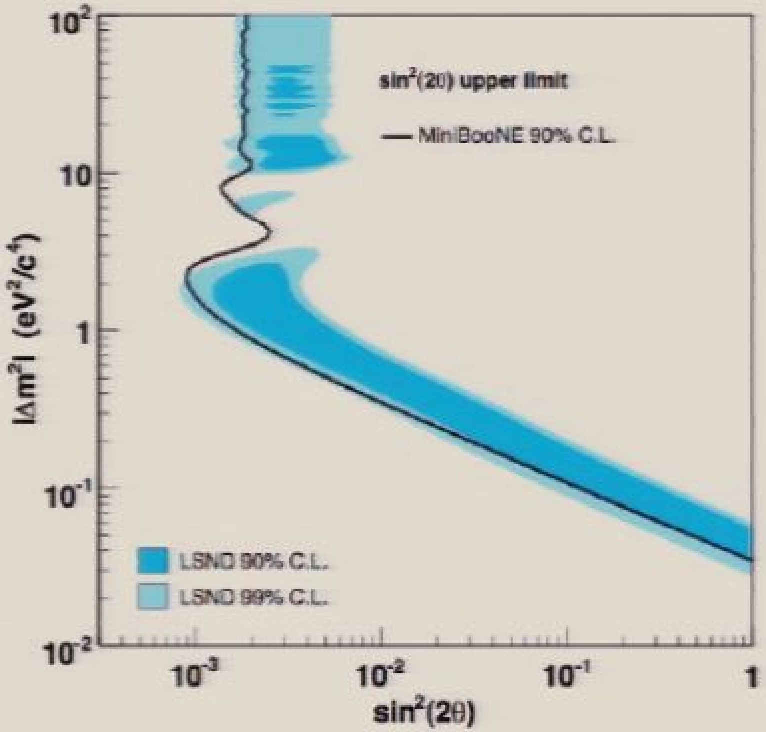
L↑, E↑ : different systematics

e, μ, π^0 PID with scintillator, Ch. light + spectrum measurement



MiniBooNE Results





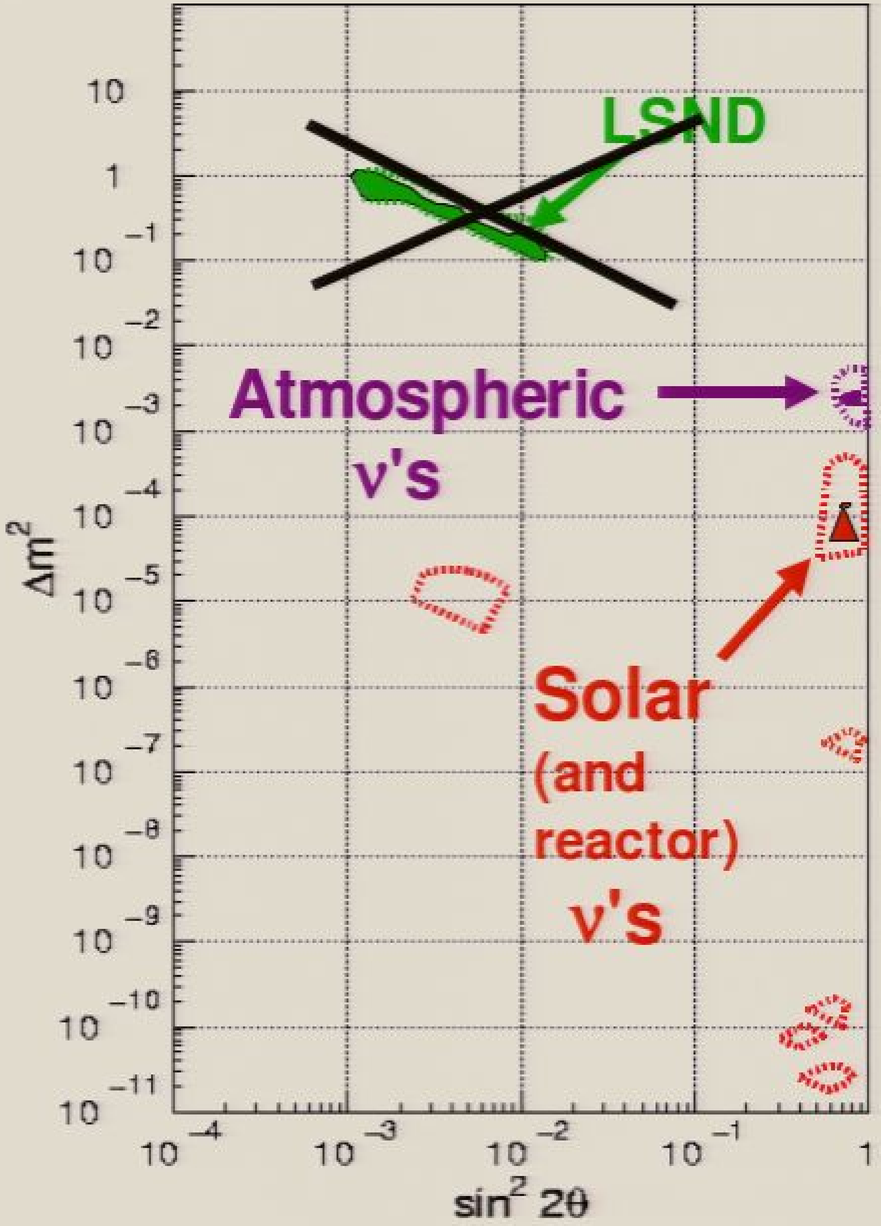
No evidence of energy-dependent excess of ν_e !

Interpreting as two-flavor oscillation: rules out LSND

Some excess at low energy, unconfirmed in alternate analysis & inconsistent with 2 flavor oscillations (may be cross-section or detector issue)

Now running with antineutrinos

The Three Signals in Parameter Space



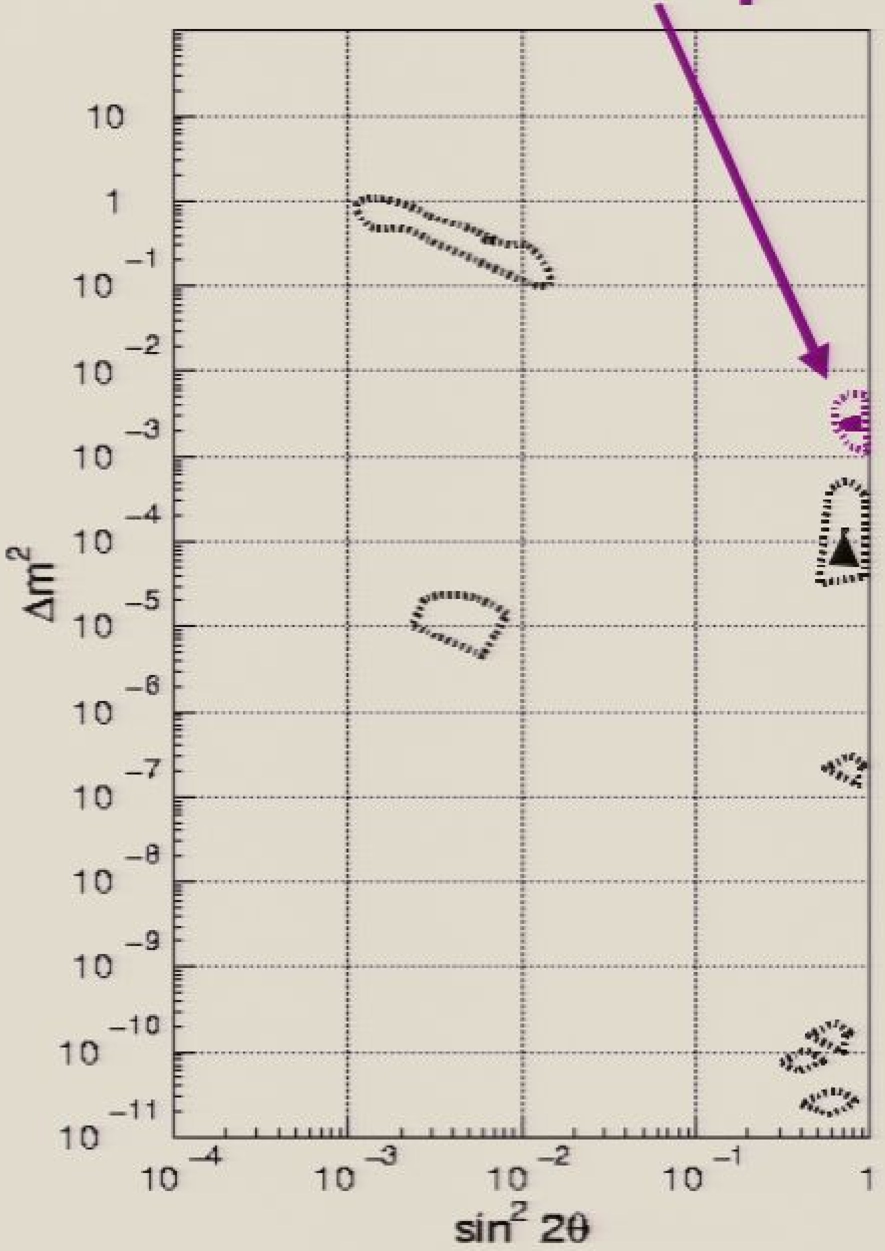
$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

$\nu_\mu \rightarrow \nu_x$

$\nu_e \rightarrow \nu_x$

No more LSND region! (probably...)

We will zoom in to atmospheric ν parameter space

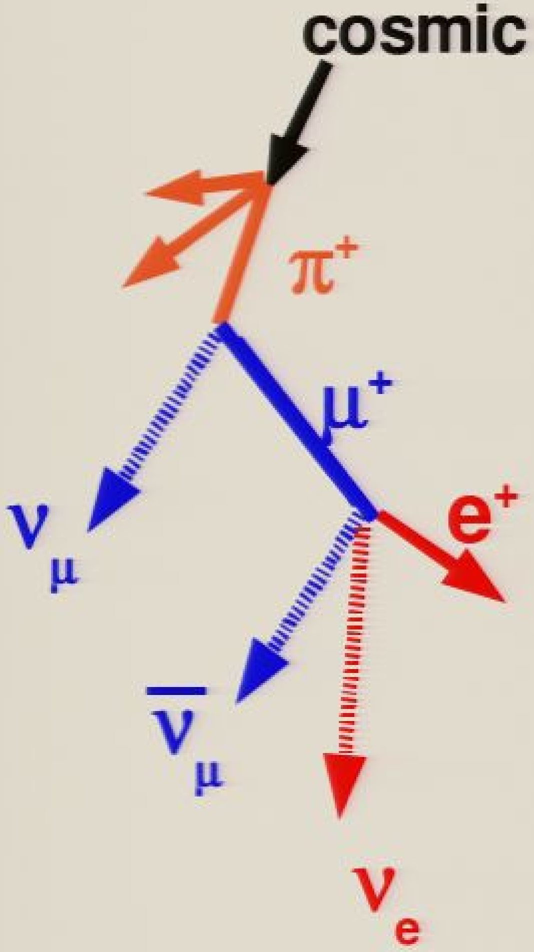


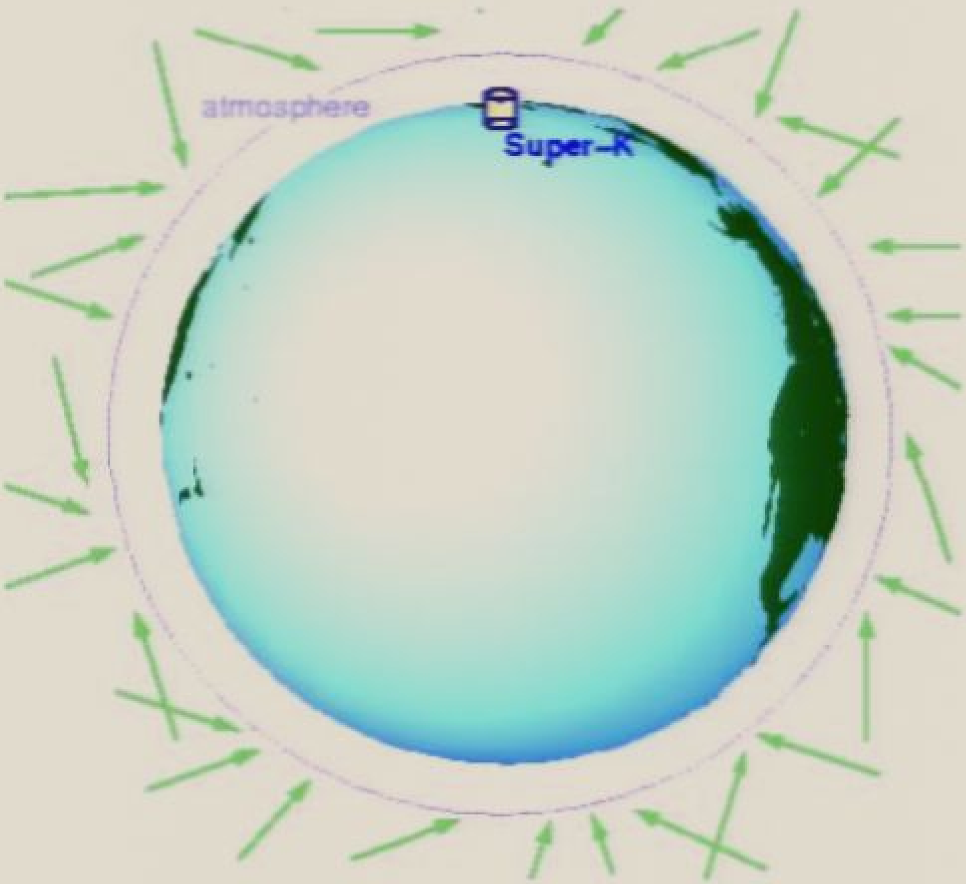
$\nu_\mu \rightarrow \nu_x$

Atmospheric Neutrinos

E~ 0.1-100 GeV

L~10-13000 km



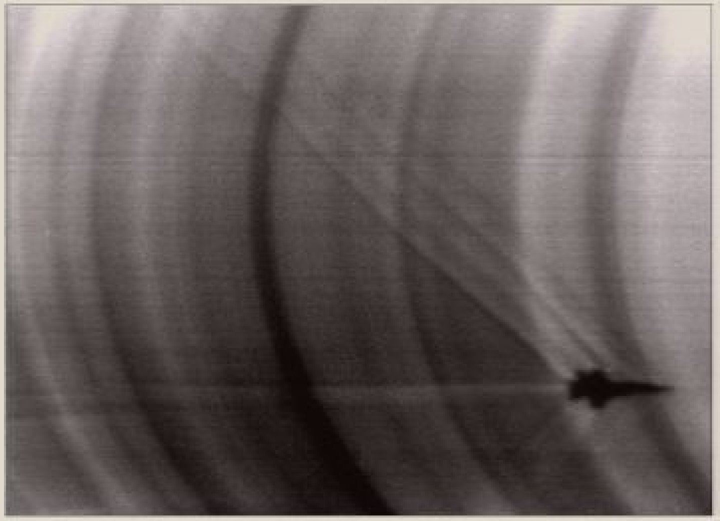


Absolute flux known to ~15%, but *flavor ratio* known to ~5%

By geometry, expect flux with *up-down symmetry* above ~1 GeV (no geomagnetic effects)

Detecting Neutrinos with Cherenkov Light

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



Thresholds (MeV)

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

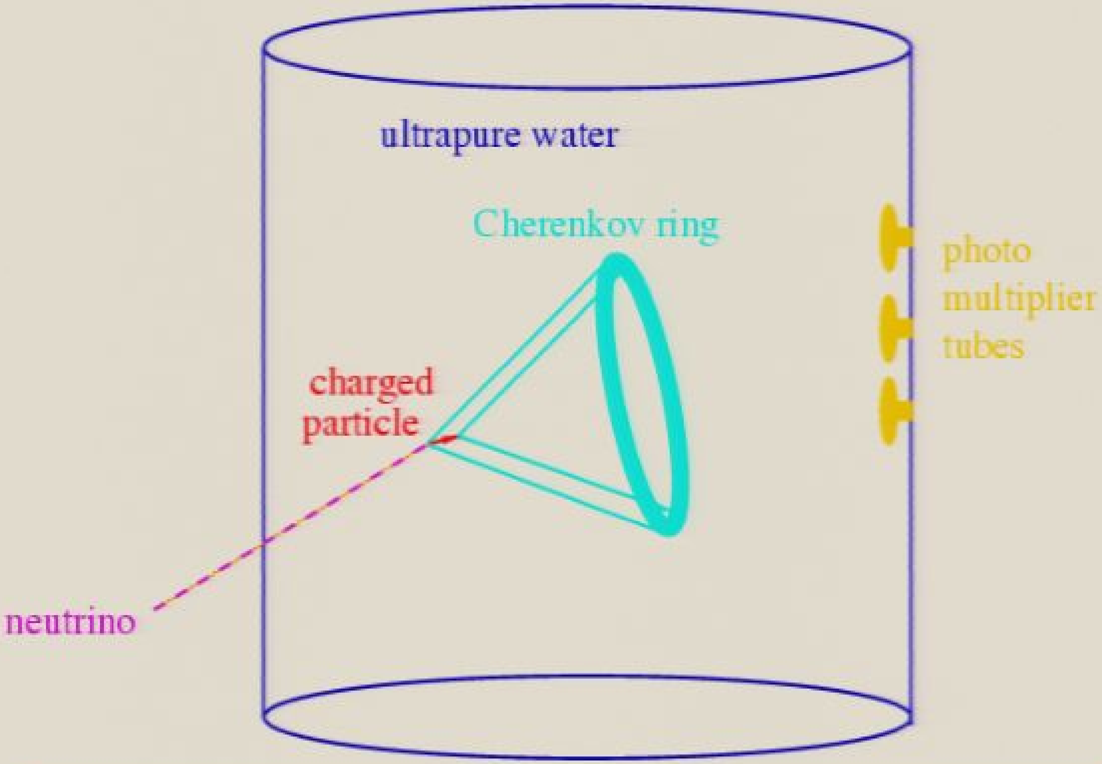
e	0.73
μ	150
π	200
p	1350

Angle: $\cos\theta_c = \frac{1}{\beta n}$

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

No. of photons $\propto$ energy loss

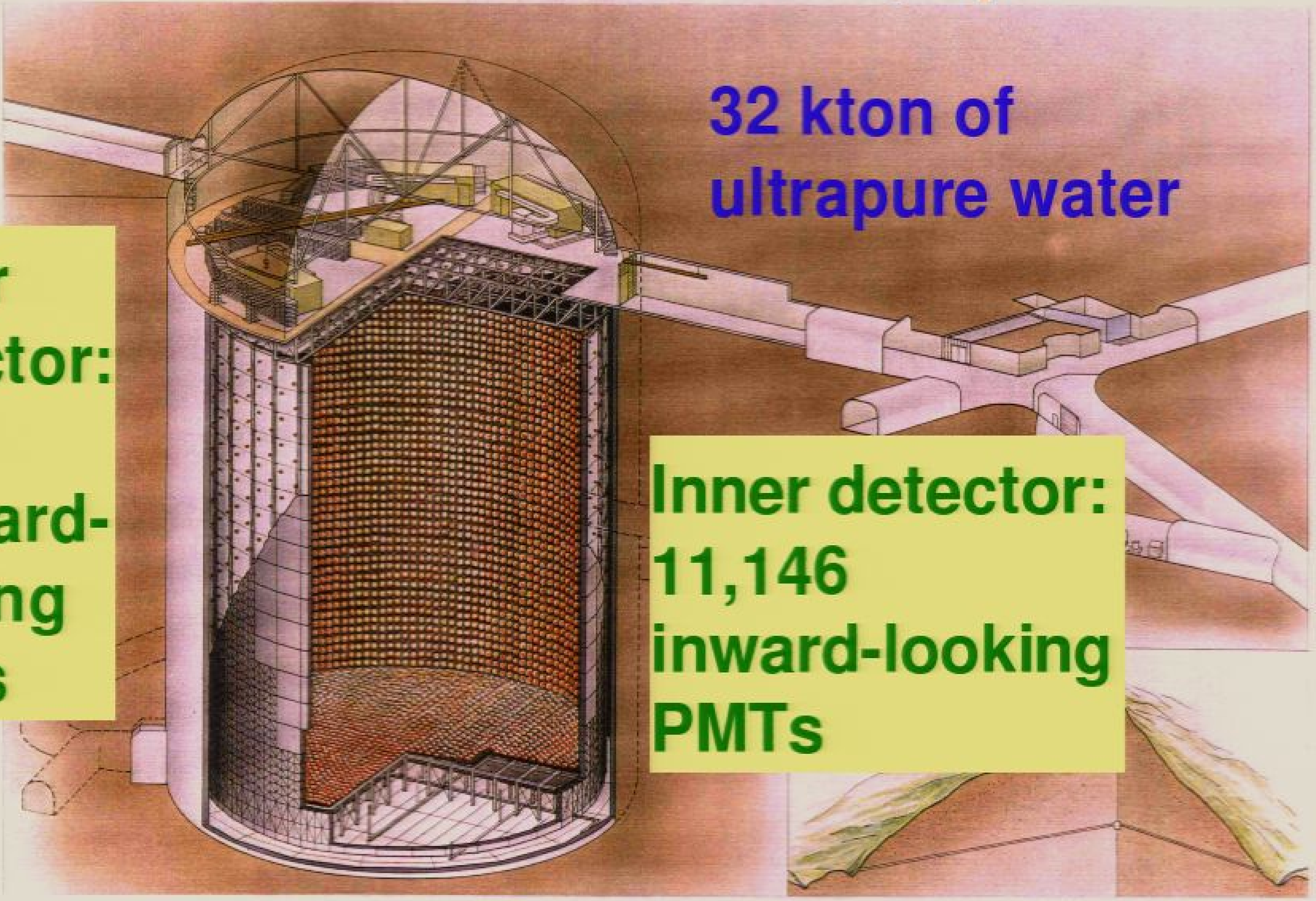
Water Cherenkov ν Detectors



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

Super-Kamiokande

Water Cherenkov detector
in Mozumi, Japan

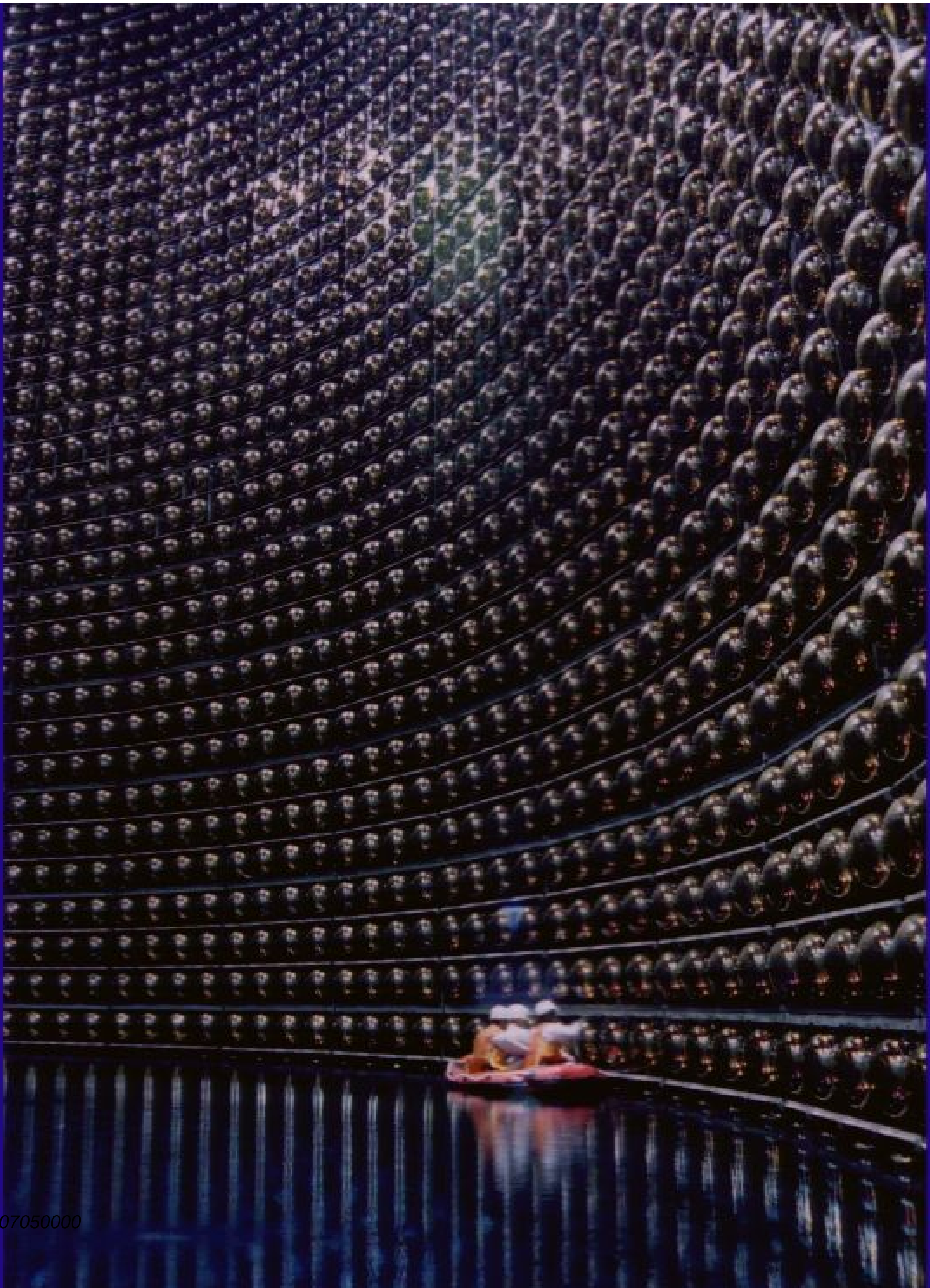


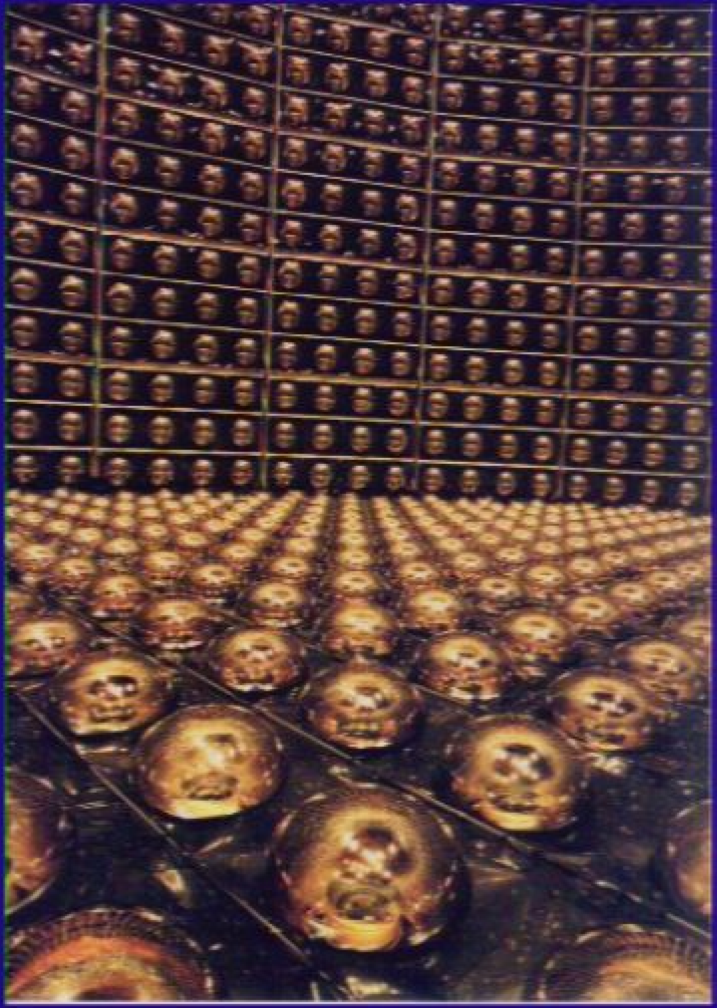
32 kton of
ultrapure water

Outer detector:
1889
outward-looking
PMTs

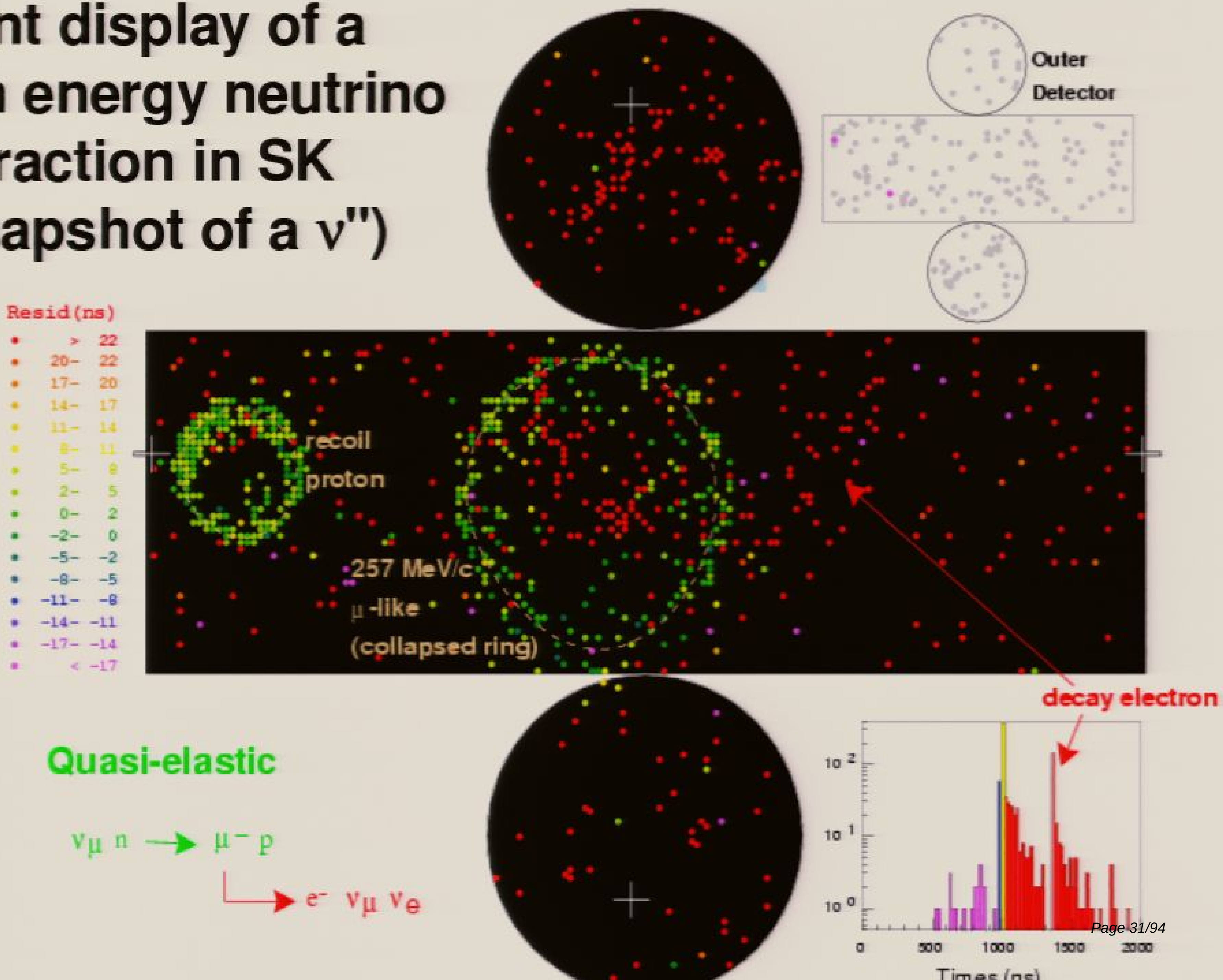
Inner detector:
11,146
inward-looking
PMTs

1 km underground to keep away from cosmic rays





Event display of a high energy neutrino interaction in SK ("snapshot of a ν")



Quasi-elastic

$$\nu_\mu\, n \rightarrow \mu^-\, p$$

$$\hookrightarrow e^-\, \nu_\mu\, \nu_e$$

Super-K Accident November 12, 2001

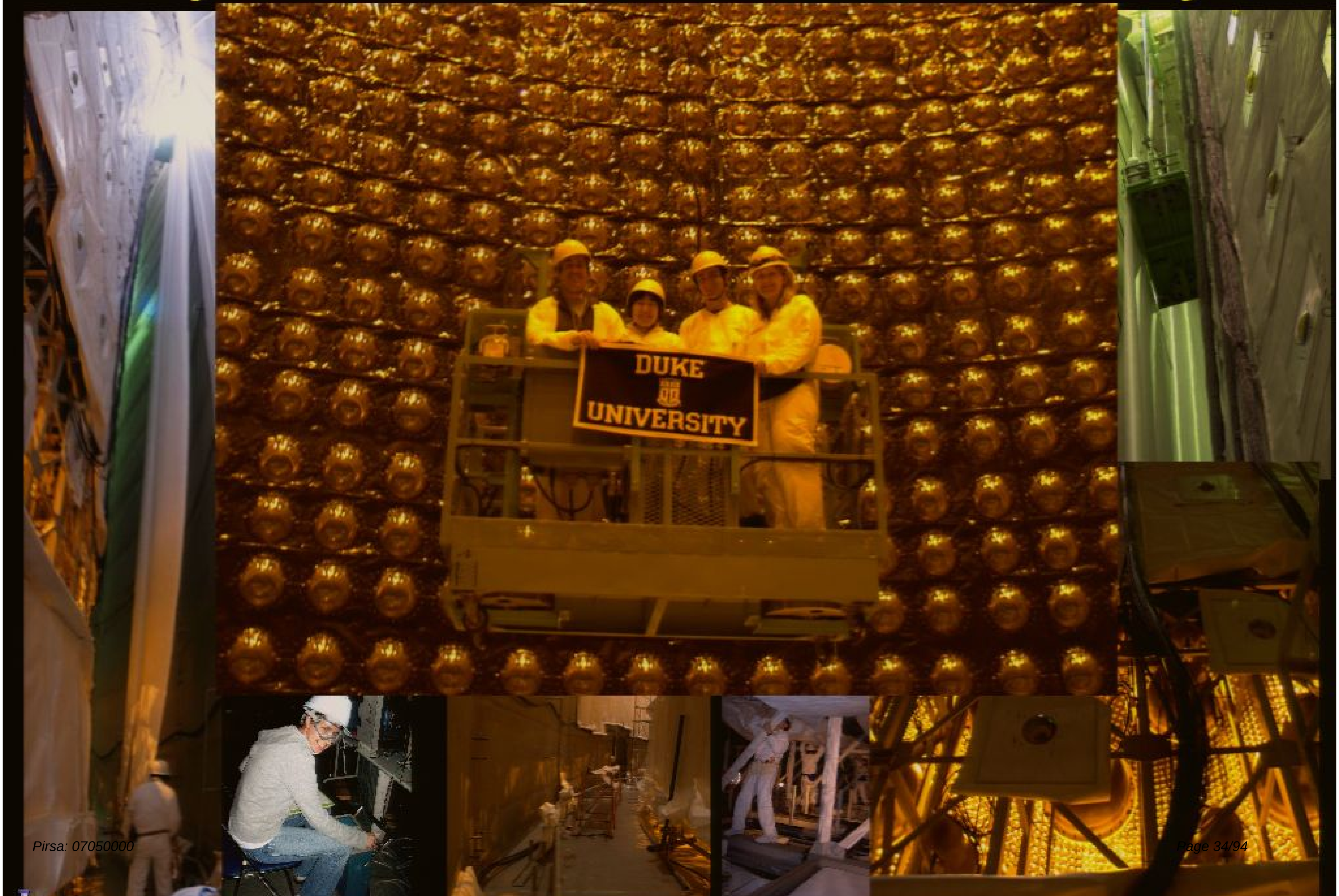
2/3 of PMTs destroyed in chain reaction implosion

Now have acrylic/ fiberglass shells for shock protection

Back online in 2003 with 47% of ID PMTs, full OD (SK II)

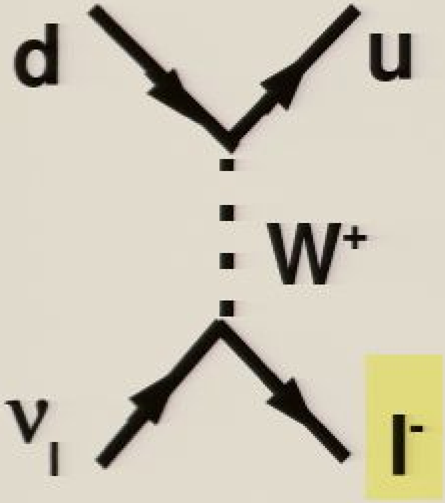
Full reconstruction over winter '05-'06 (SK III)

Super-K Full Reconstruction Photo Gallery



Atmospheric ν's Experimental Strategy:

High energy interactions of ν's with nucleons



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

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

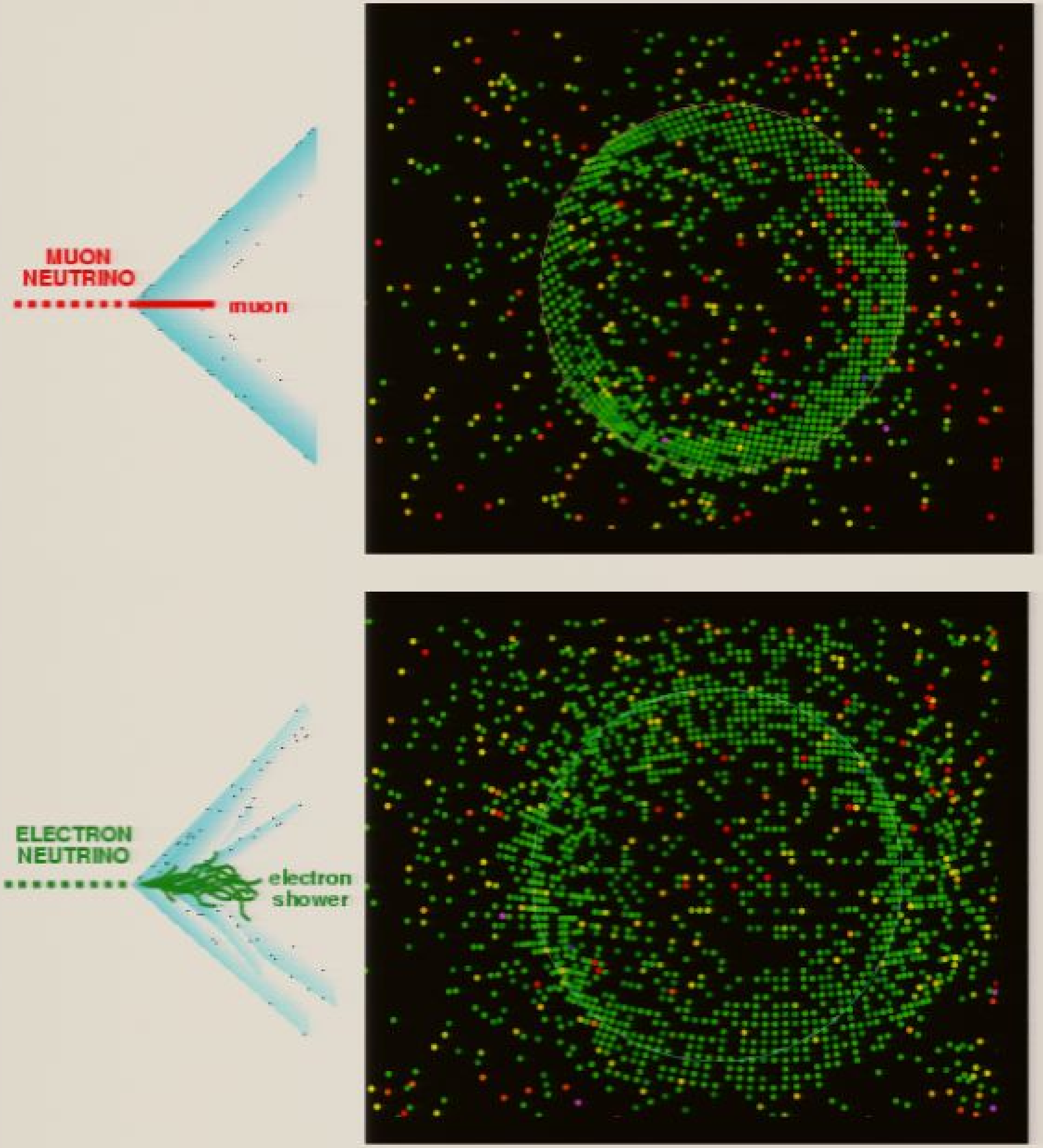
$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Tag neutrino flavor by flavor of outgoing lepton

$$\nu_l + N \rightarrow l^\pm + N'$$

CC quasi-elastic ("single ring")



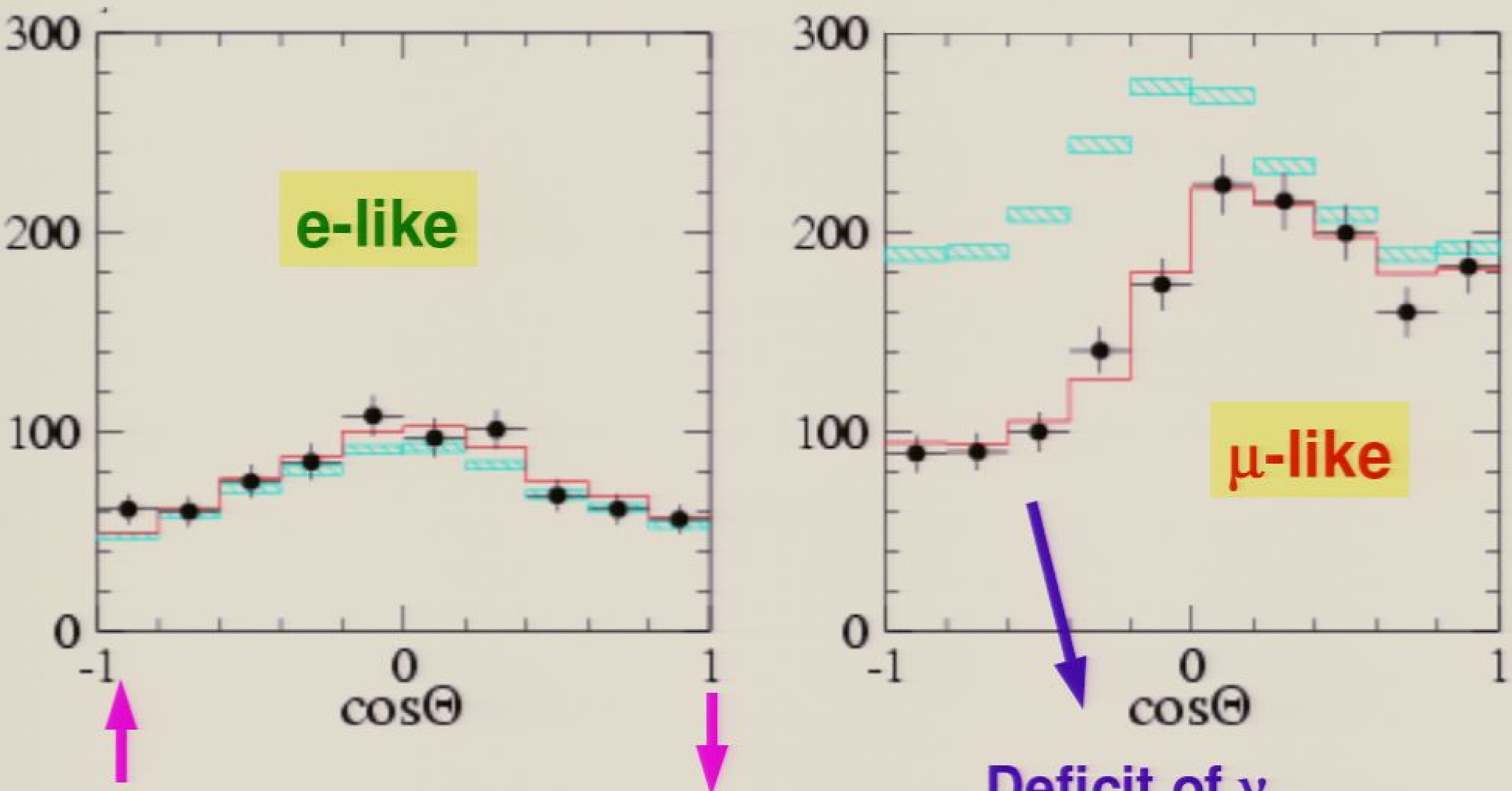
Get different patterns in Cherenkov light for e and μ

(sim. for other detector types)

From Cherenkov cone get angle, infer pathlength

Zenith angle distribution

1489 days of SK data

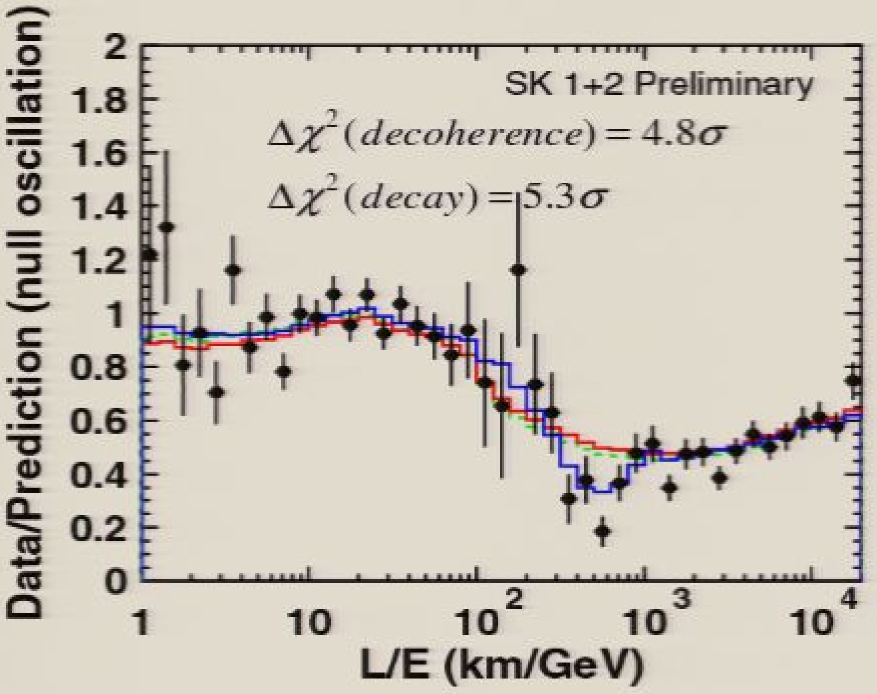


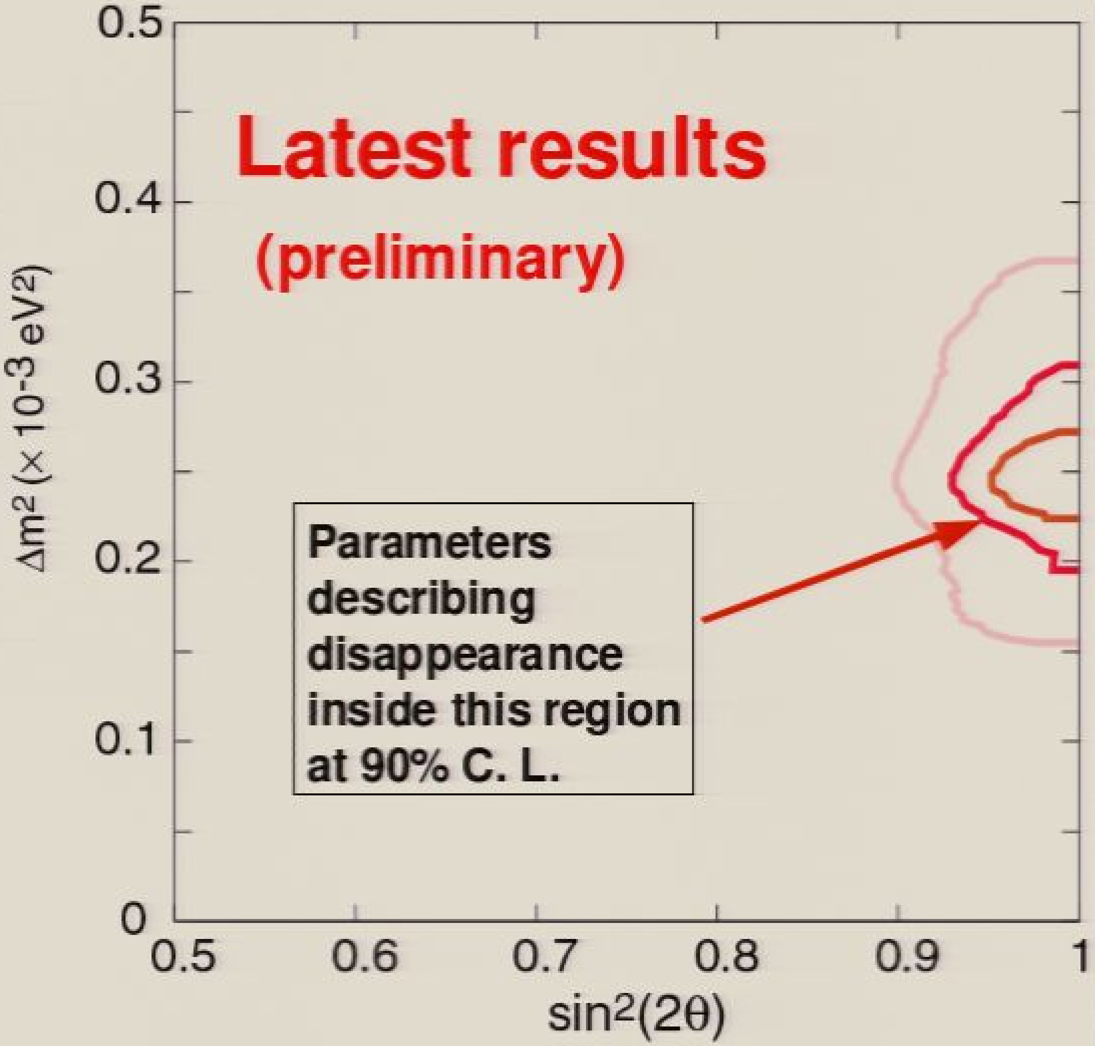
up-going

down-going

Deficit of ν_μ
from below
(long pathlength)

Allowed Parameters $\Delta m^2_{23}, \theta_{23}$





Latest results

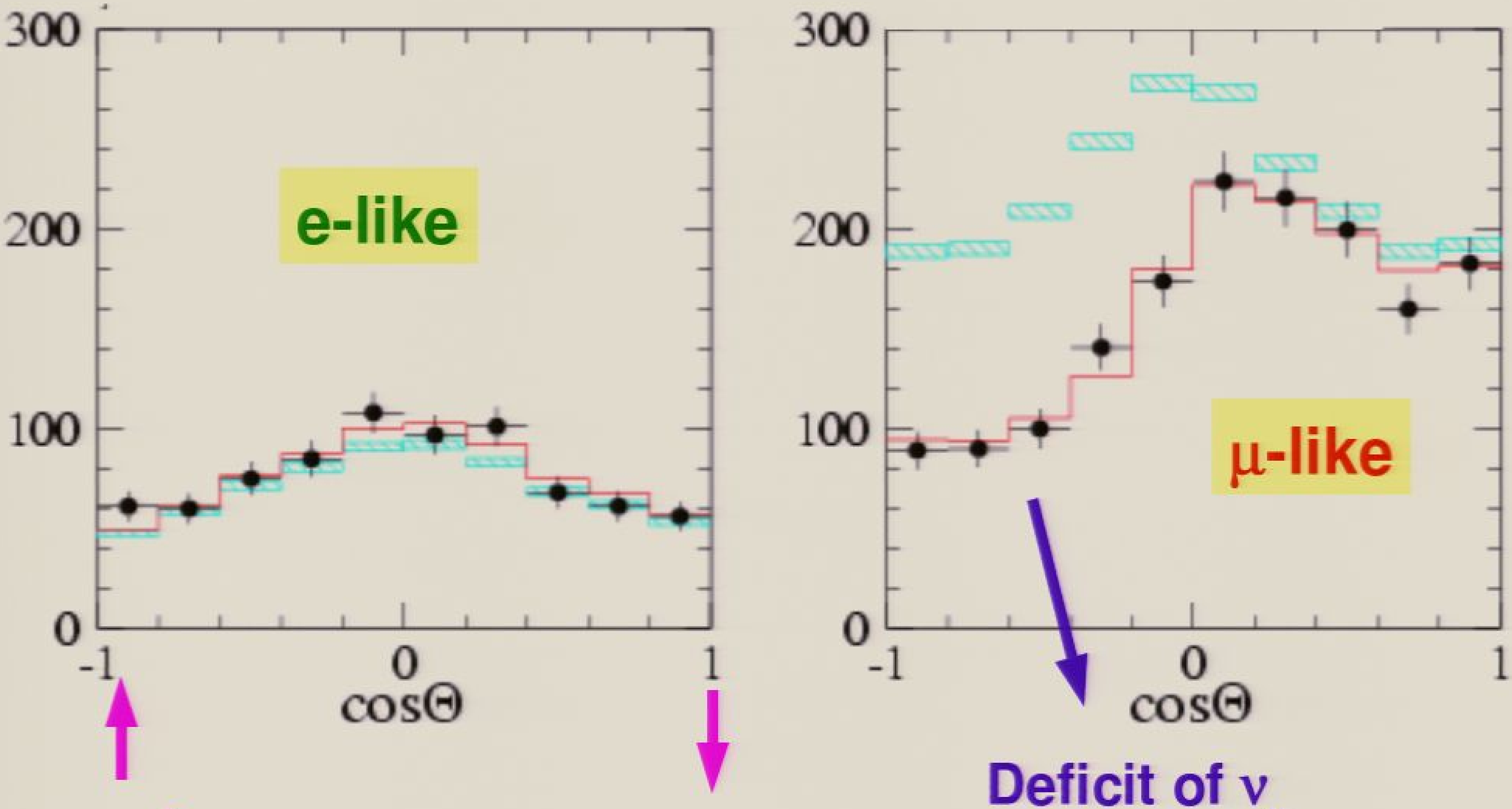
(preliminary)

Parameters describing disappearance inside this region at 90% C. L.

Disappearance consistent with $\nu_\mu \rightarrow \nu_\tau$

Zenith angle distribution

1489 days of SK data



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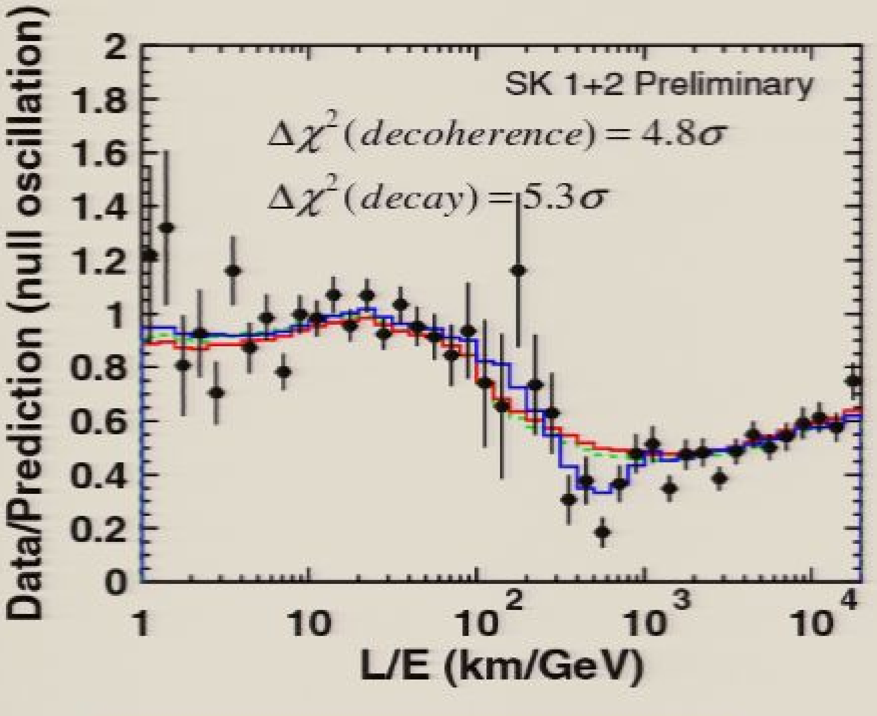

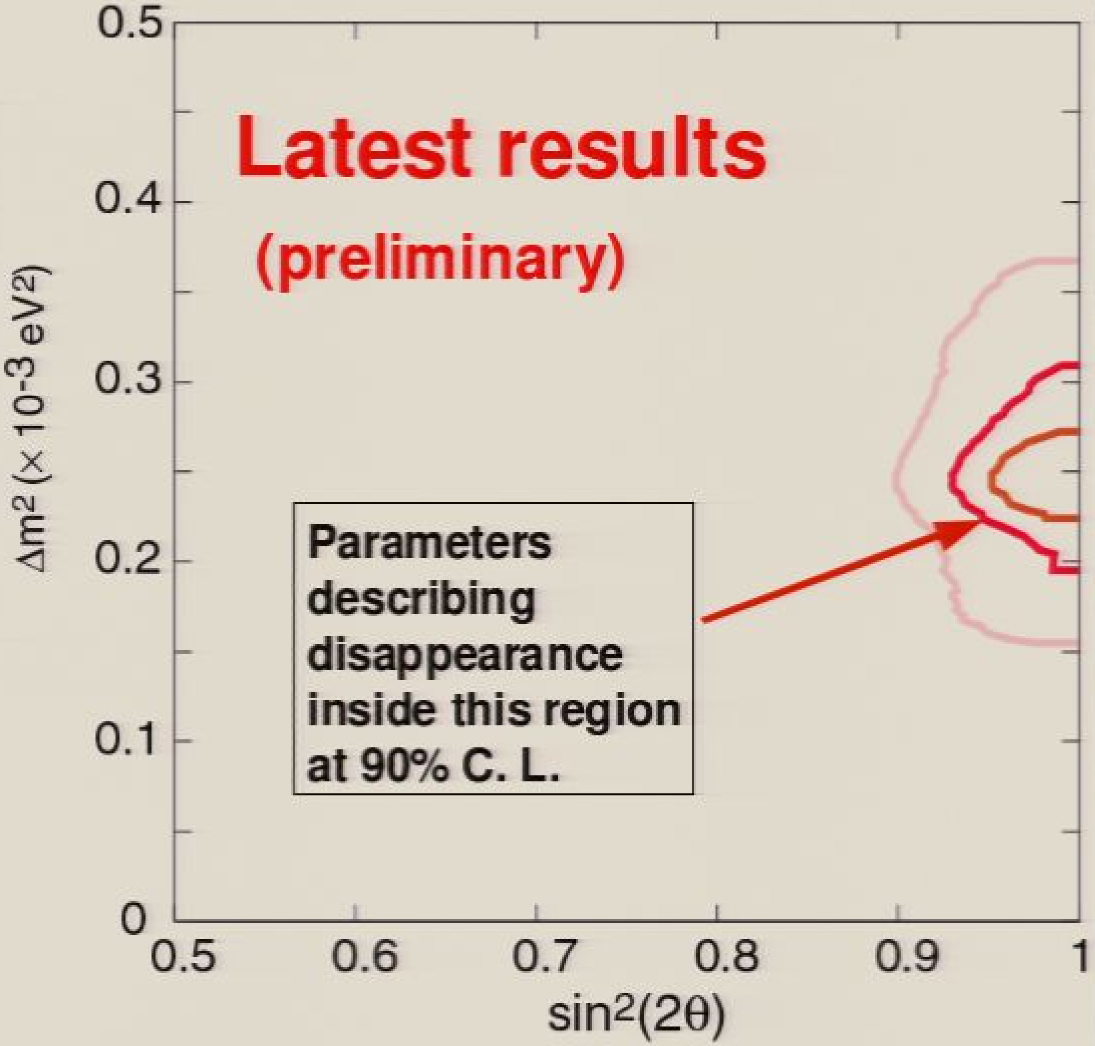

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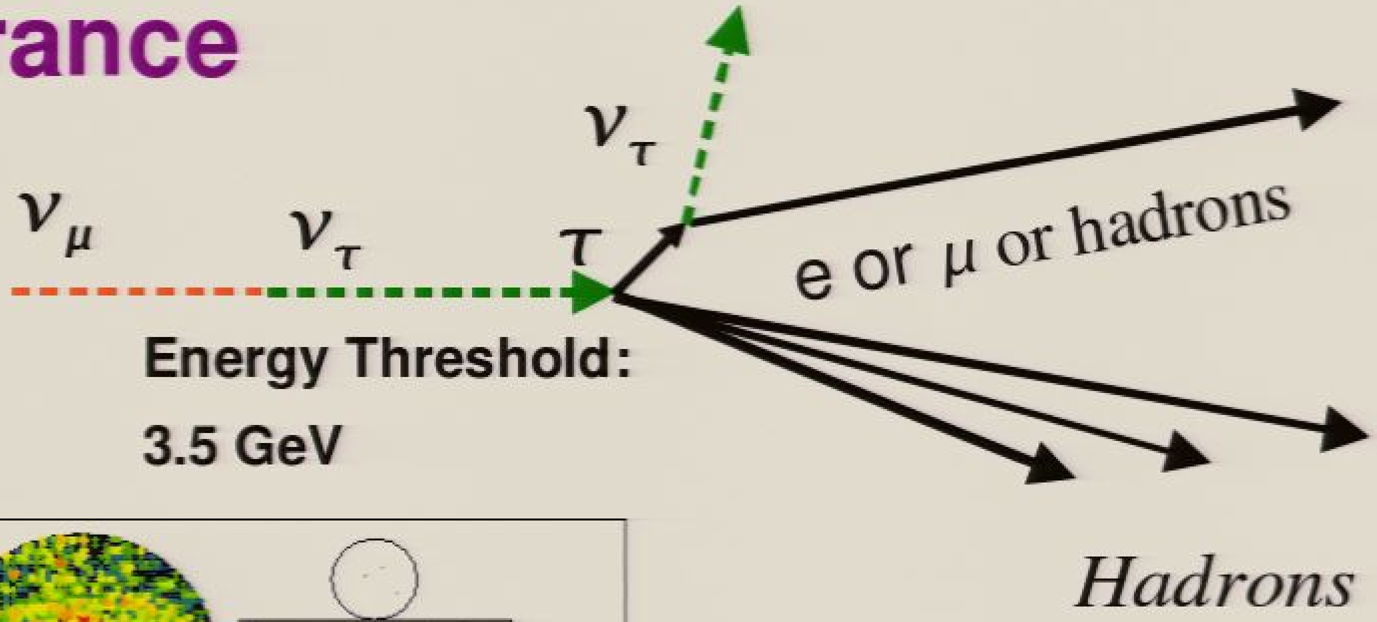
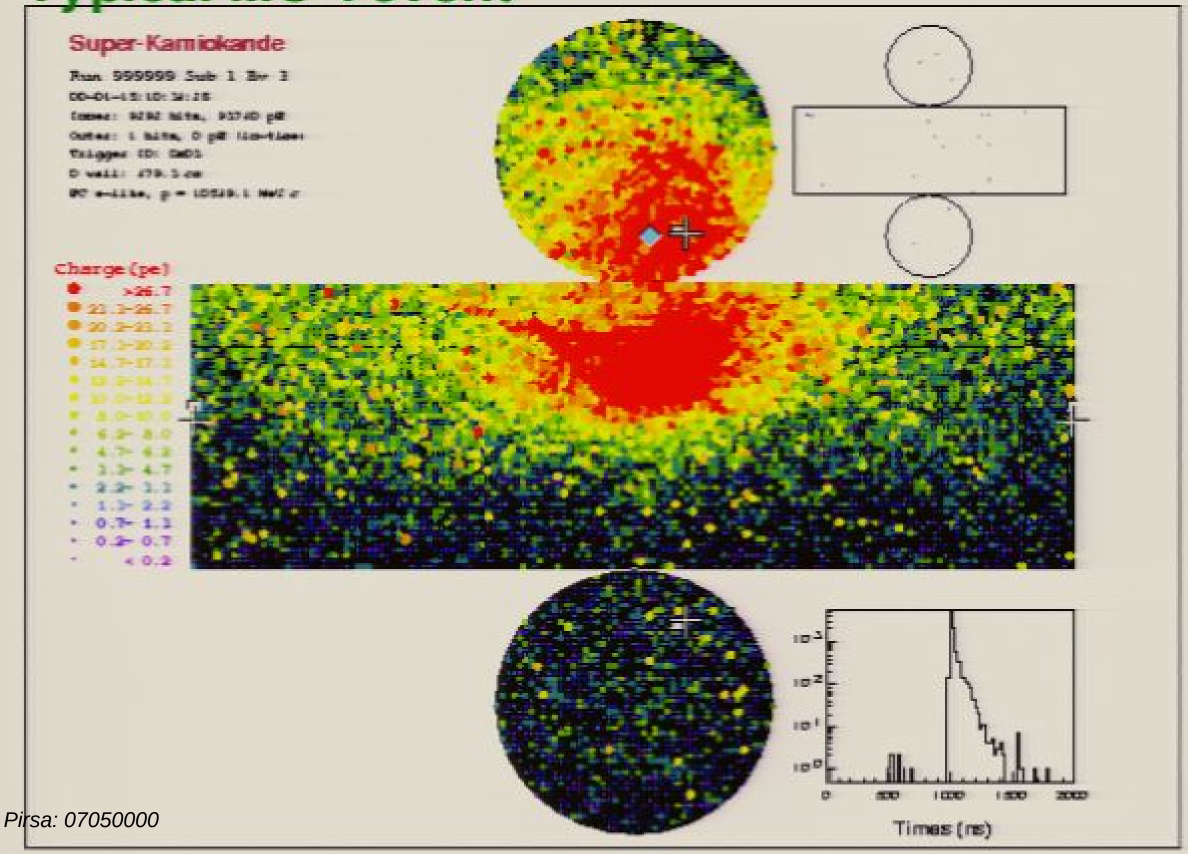
Tau Appearance in Super-K



Energy Threshold:

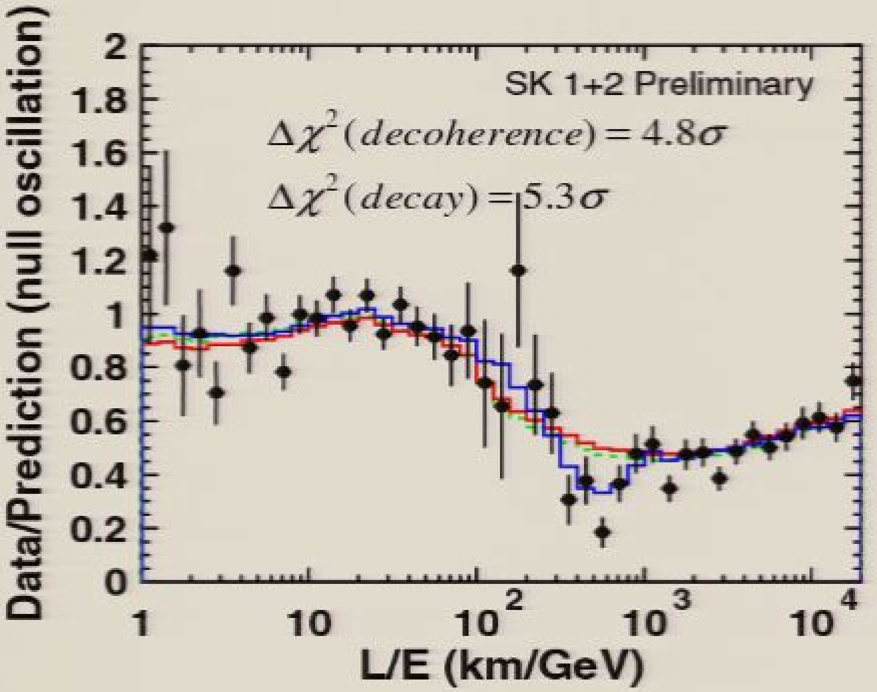
3.5 GeV

Typical MC τ event

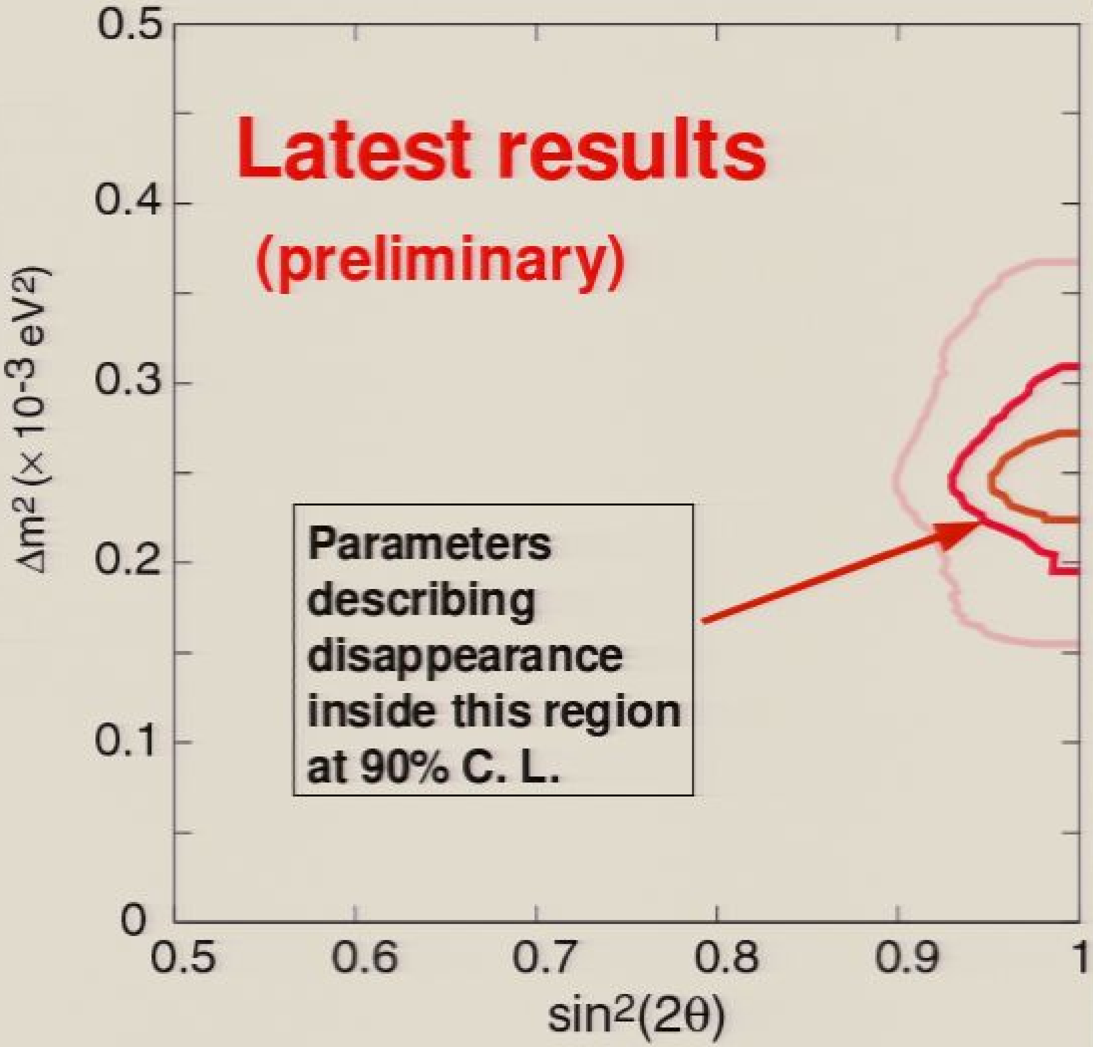


Expect about 80 τ's in SK I sample ... but they are hard to distinguish from other multi-ring ν interaction events

Allowed Parameters $\Delta m^2_{23}, \theta_{23}$



Disappearance consistent with $\nu_\mu \rightarrow \nu_\tau$

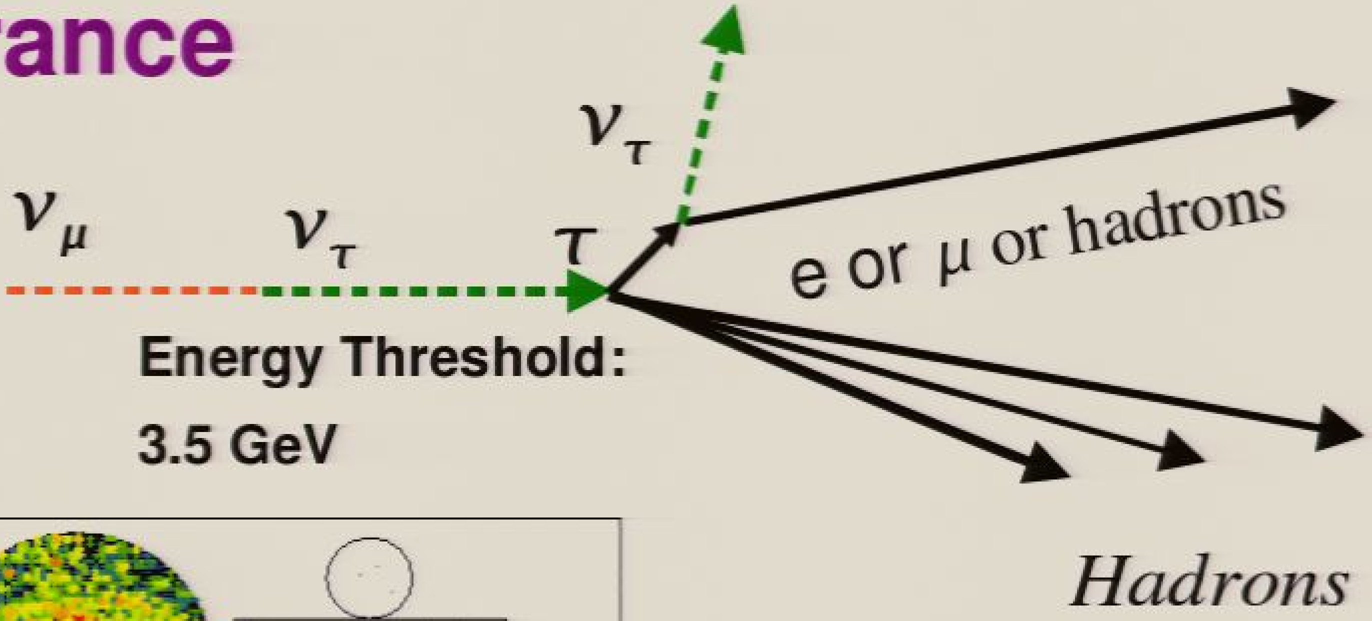


Latest results

(preliminary)

Parameters describing disappearance inside this region at 90% C. L.

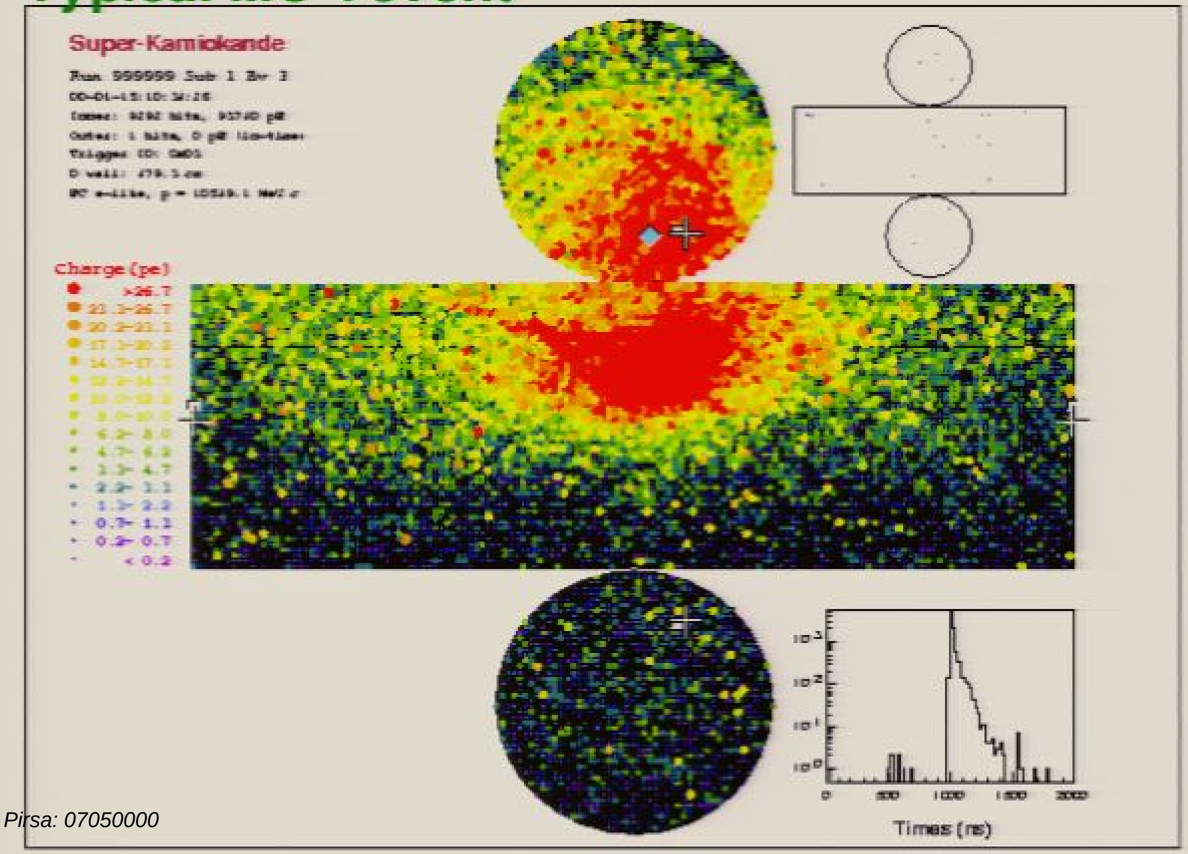
Tau Appearance in Super-K



Energy Threshold:

3.5 GeV

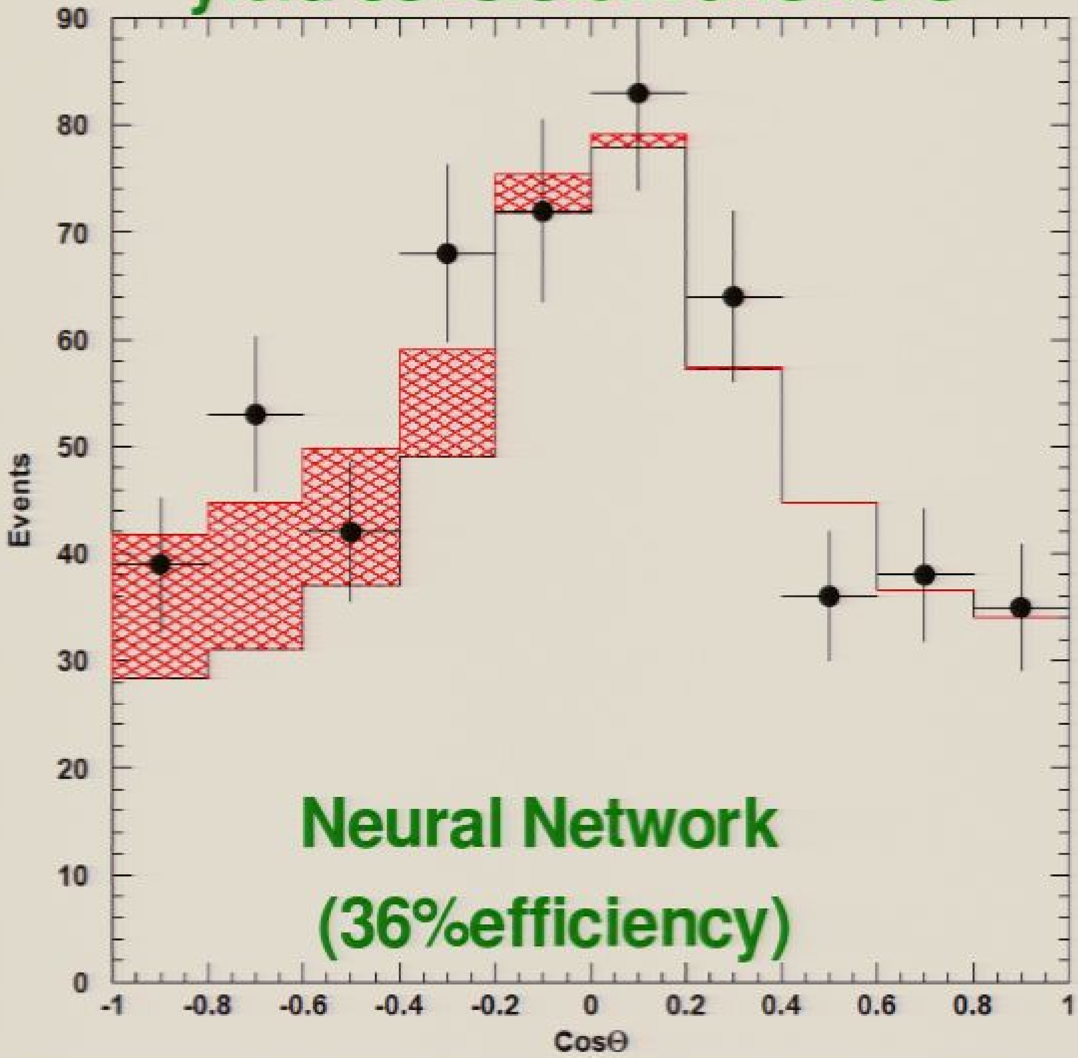
Typical MC τ event



Expect about 80 τ's in SK I sample ... but they are hard to distinguish from other multi-ring ν interaction events

Select τ-like events: (energy, shape, rings, decay electrons)

2 analyses (likelihood and neural network) yield consistent answers



Neural Network (36%efficiency)

MC expectation:

79±31 τ's

From fit to τ-like sample:

(red hatched)

$$152 \pm 47_{stat} \pm^{12.0}_{27.3} \text{ τ's}$$

Consistent with (expected) slight excess of upgoing τ's

Next: INDEPENDENT TEST of atmospheric neutrino oscillations using a well-understood ν beam

$E_\nu \sim$ GeV, $L \sim$ 100's of km for same L/E

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

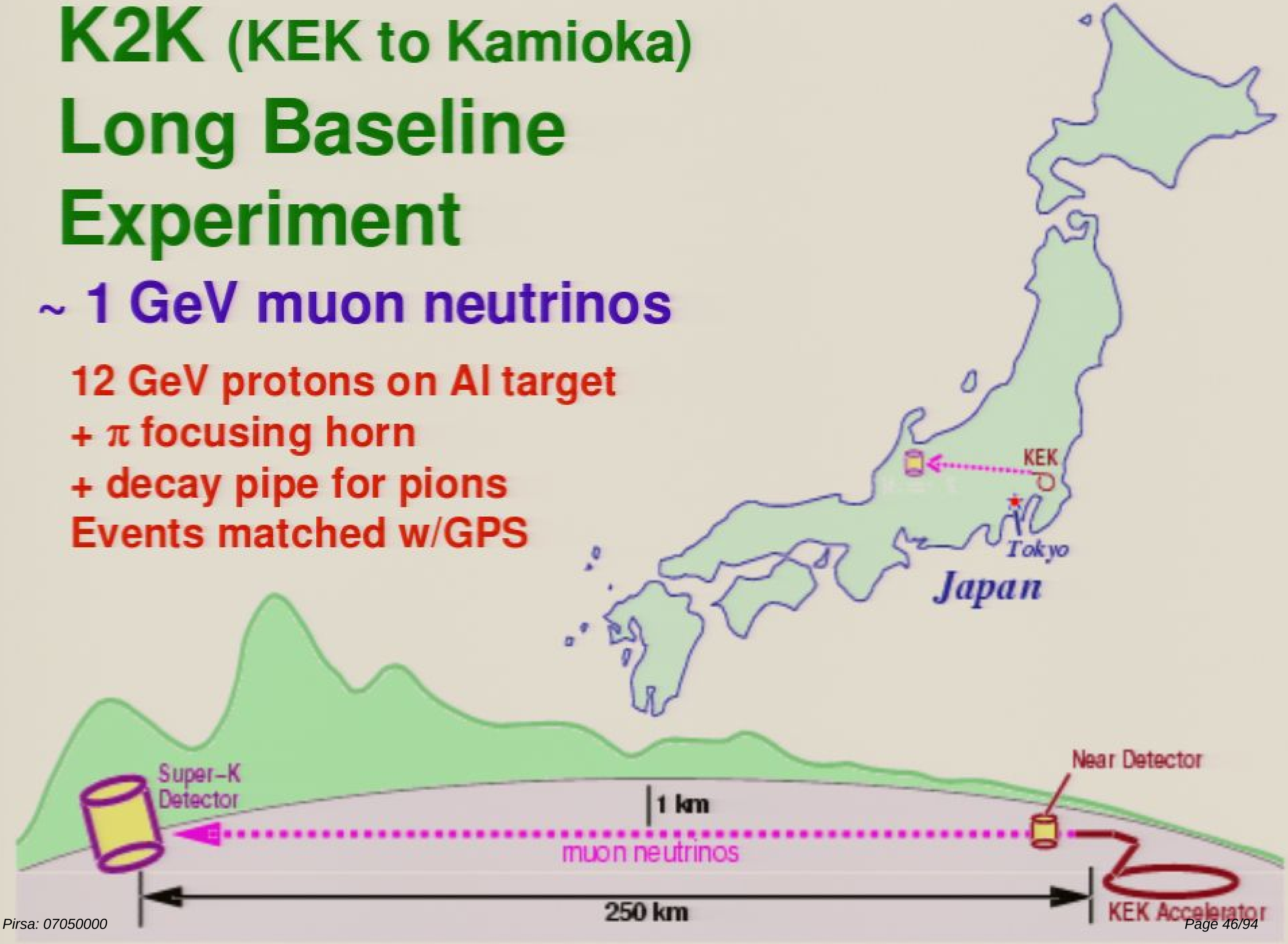
LONG BASELINE EXPERIMENTS

Compare flux, flavor and energy spectrum at near and far detectors

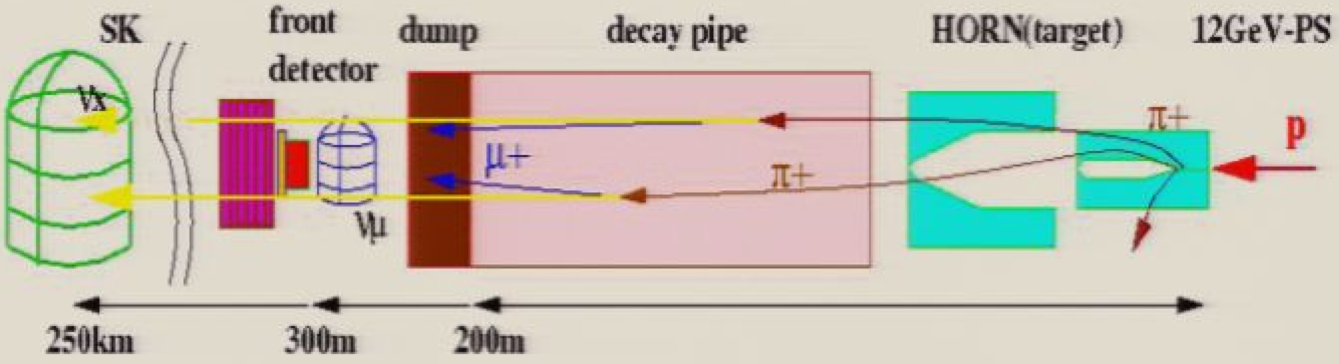
K2K (KEK to Kamioka) Long Baseline Experiment

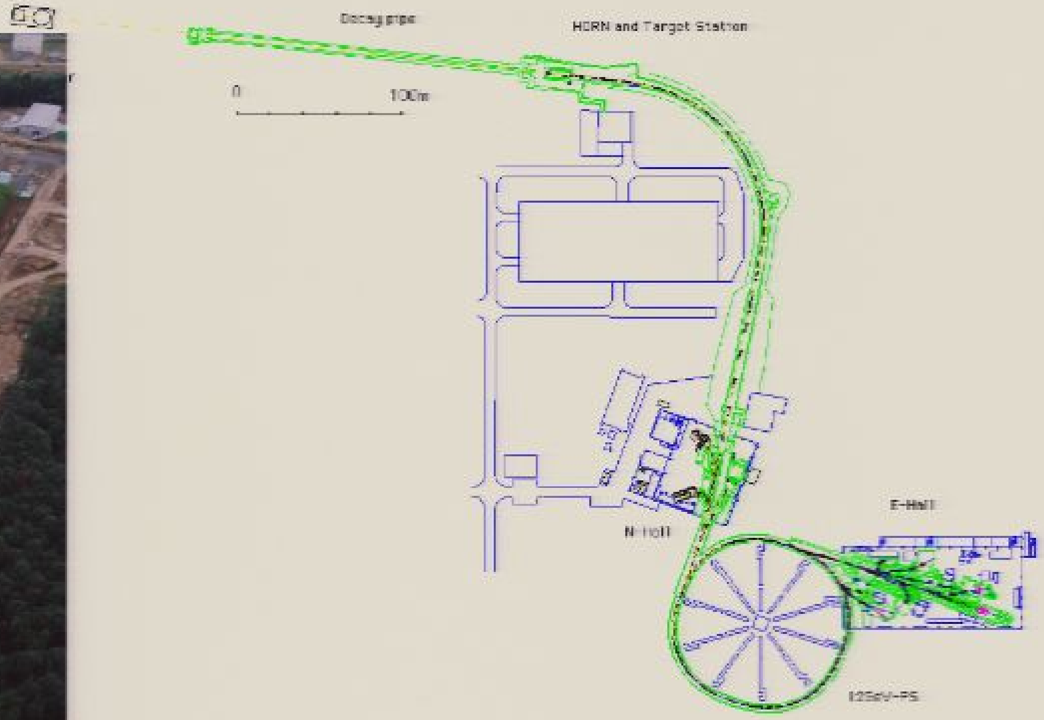
~ 1 GeV muon neutrinos

12 GeV protons on Al target
+ π focusing horn
+ decay pipe for pions
Events matched w/GPS

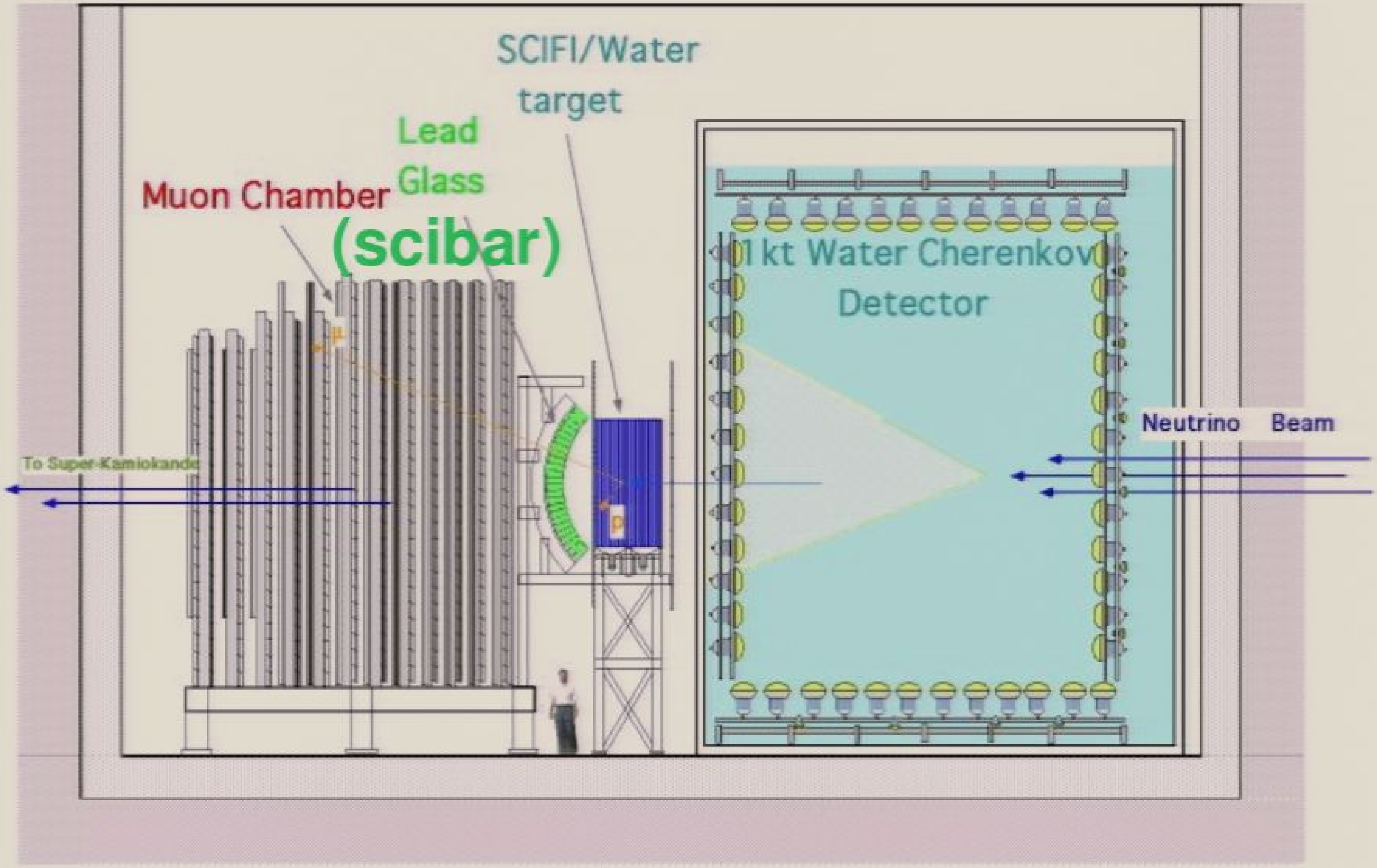


The Neutrino Beamline at KEK



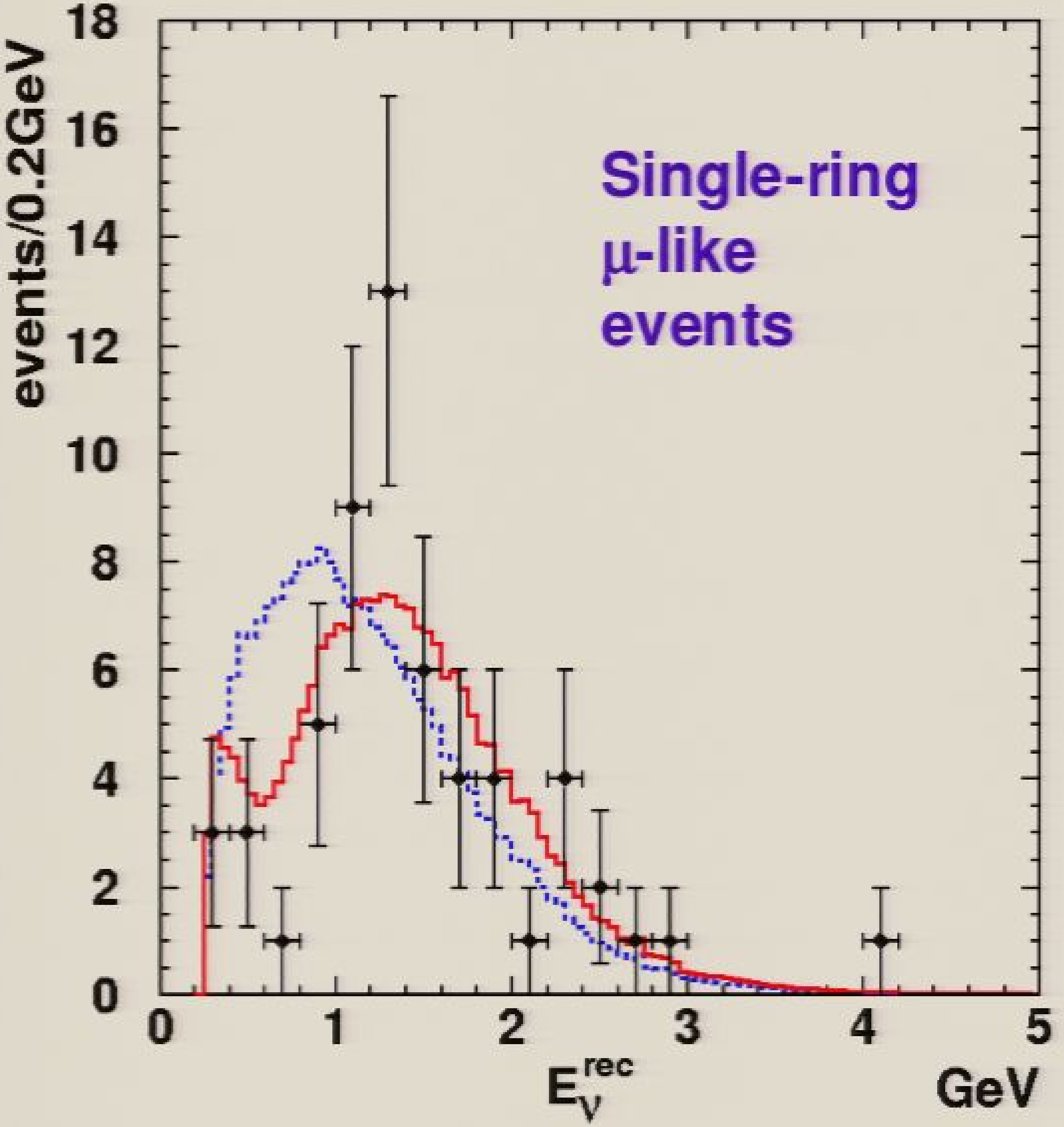


The Near Detector (300 m away)



Characterize the ν beam for extrapolation to SK

Results from K2K: full data sample

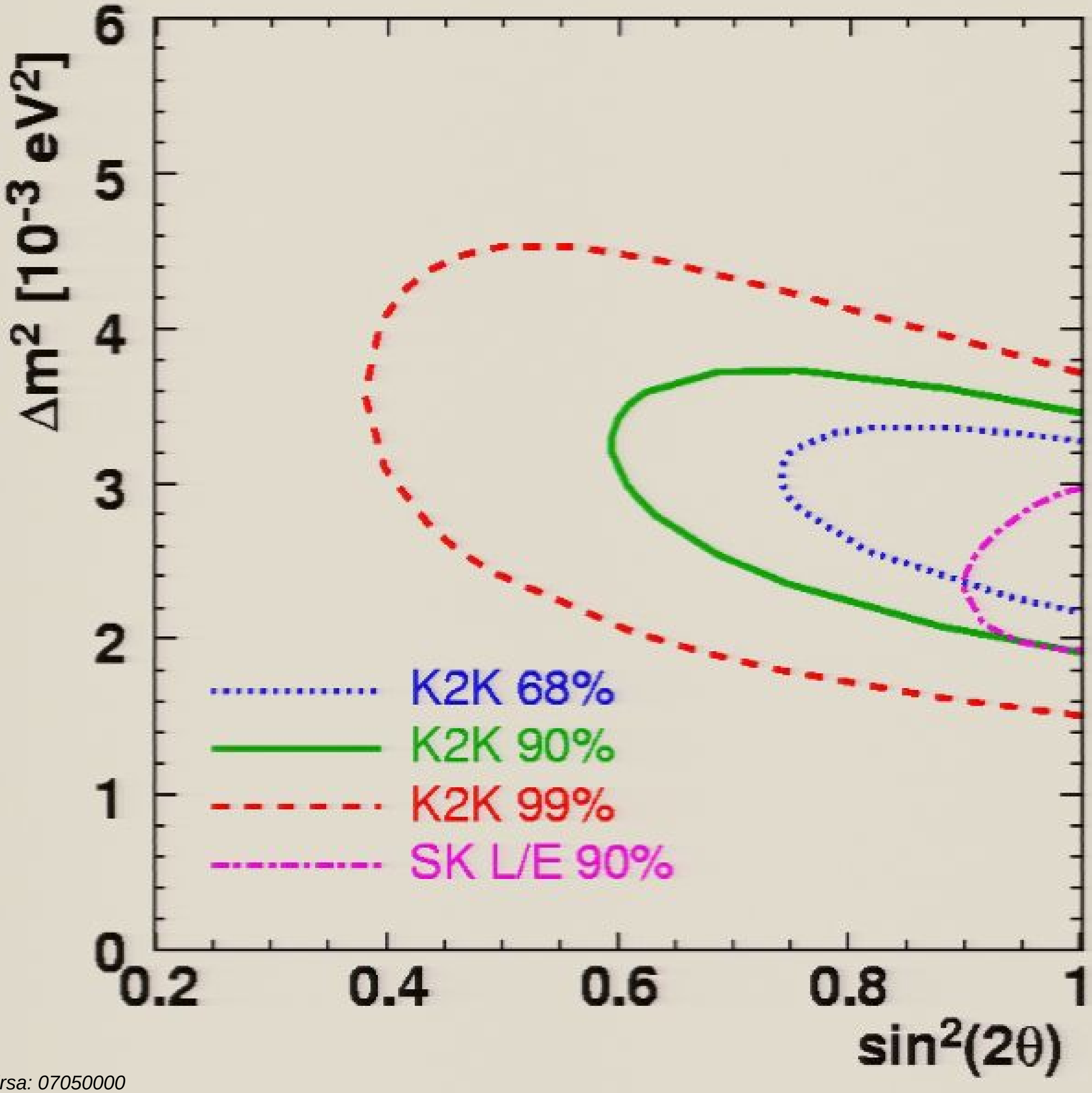


Total 112 beam events observed; expect 158±9

Suppression observed, spectral distortion consistent with oscillations

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

K2K Allowed Oscillation Parameters



Consistent with SK atmospheric ν's !

No-oscillation excluded at $>4\sigma$

Now also confirmed by FNAL's MINOS

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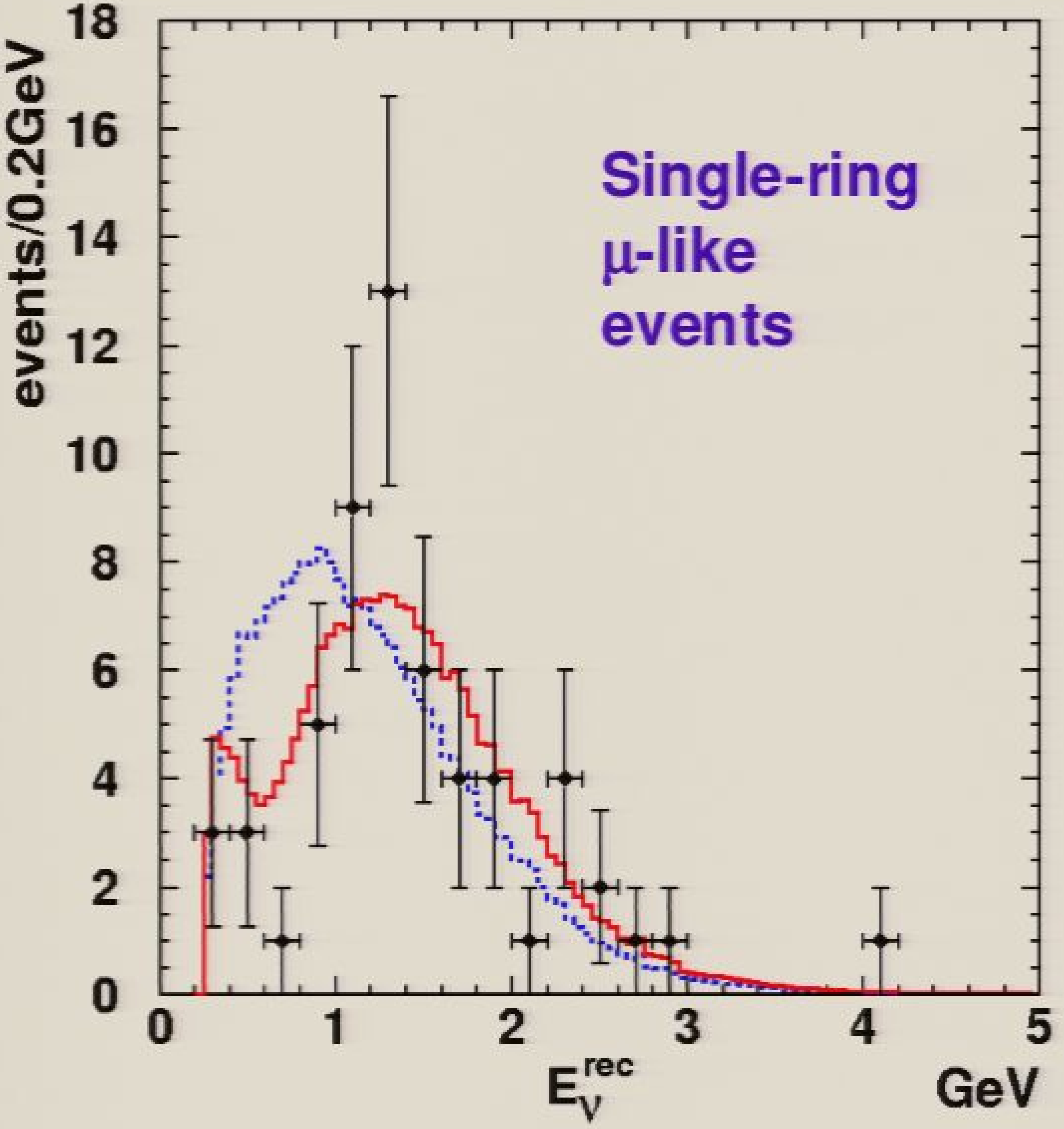

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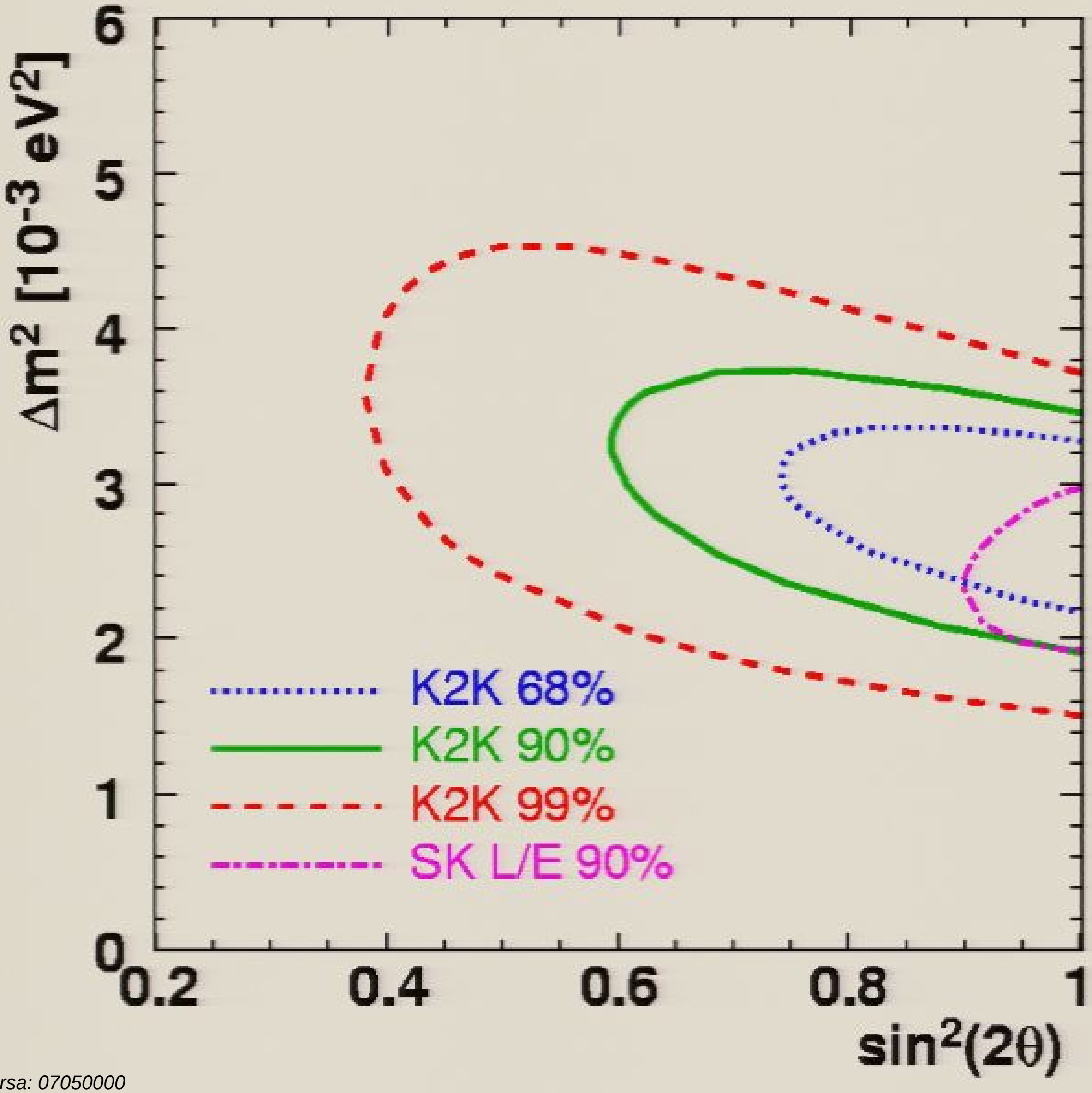

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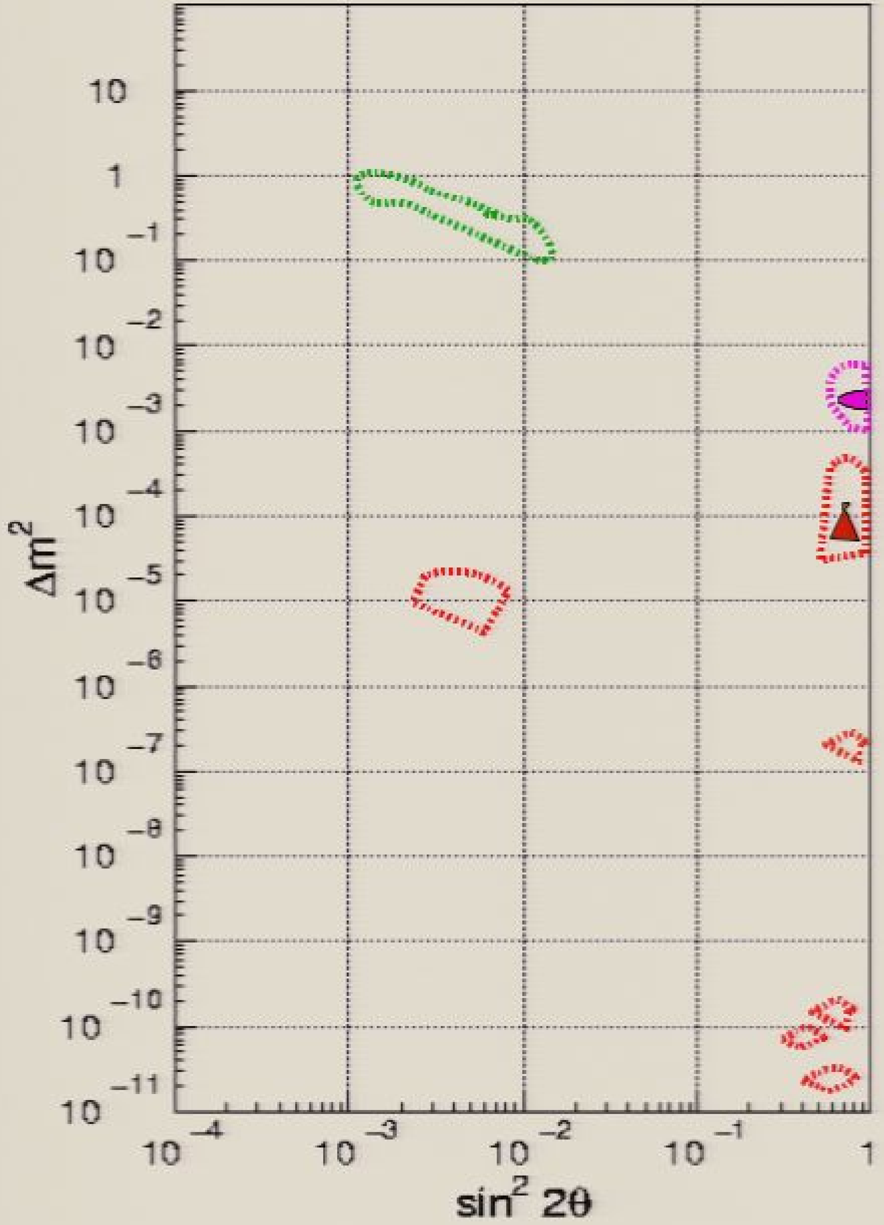
Zooming Back Out: Where Do We Stand Overall?

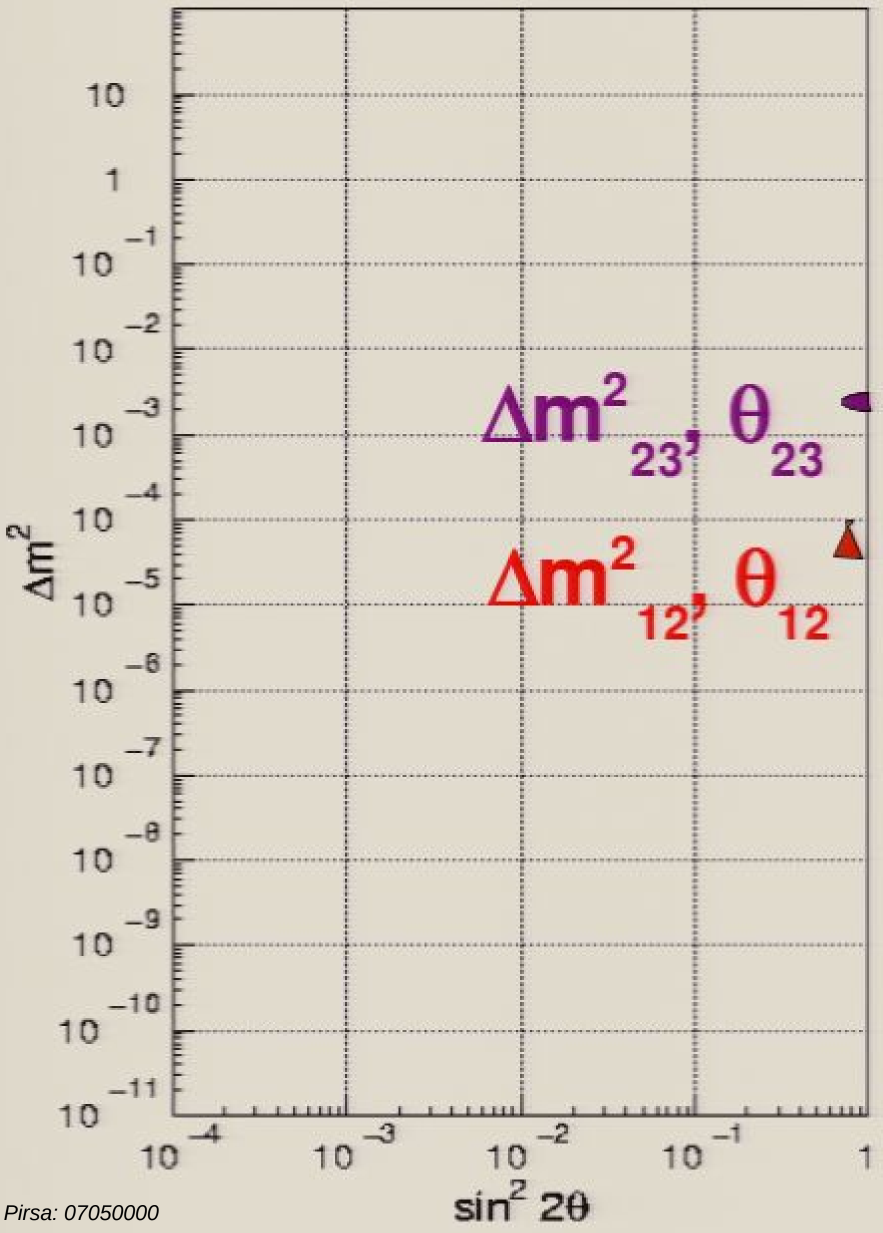


LSND signal gone!
(unless antineutrino signal...)

Atmospheric
signal confirmed
by K2K and MINOS beams,
region shrinking

Solar ν oscillation
confirmed by multiple
experiments, including SNO,
and KamLAND reactor ν's!
Allowed parameters shrunk

What Do We Know About the Mixing Parameters?



Two verified examples of two-flavor mixing

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

Atmospheric/beam

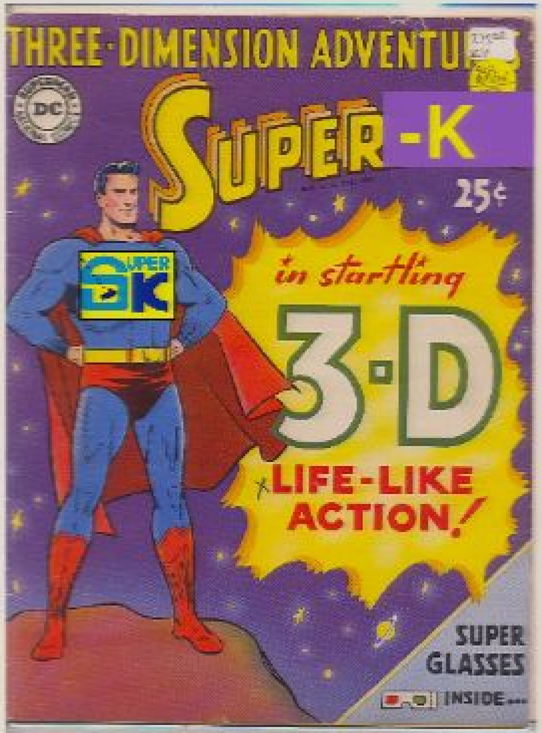
Solar/reactor

2 mixing angles,
2 Δm^2

Allowed parameters getting squeezed down in next generation of experiments

But there's more than just squeezing down 2-flavor parameters ...

Beyond 2-flavor: explore neutrino mixing in a *3-flavor* context



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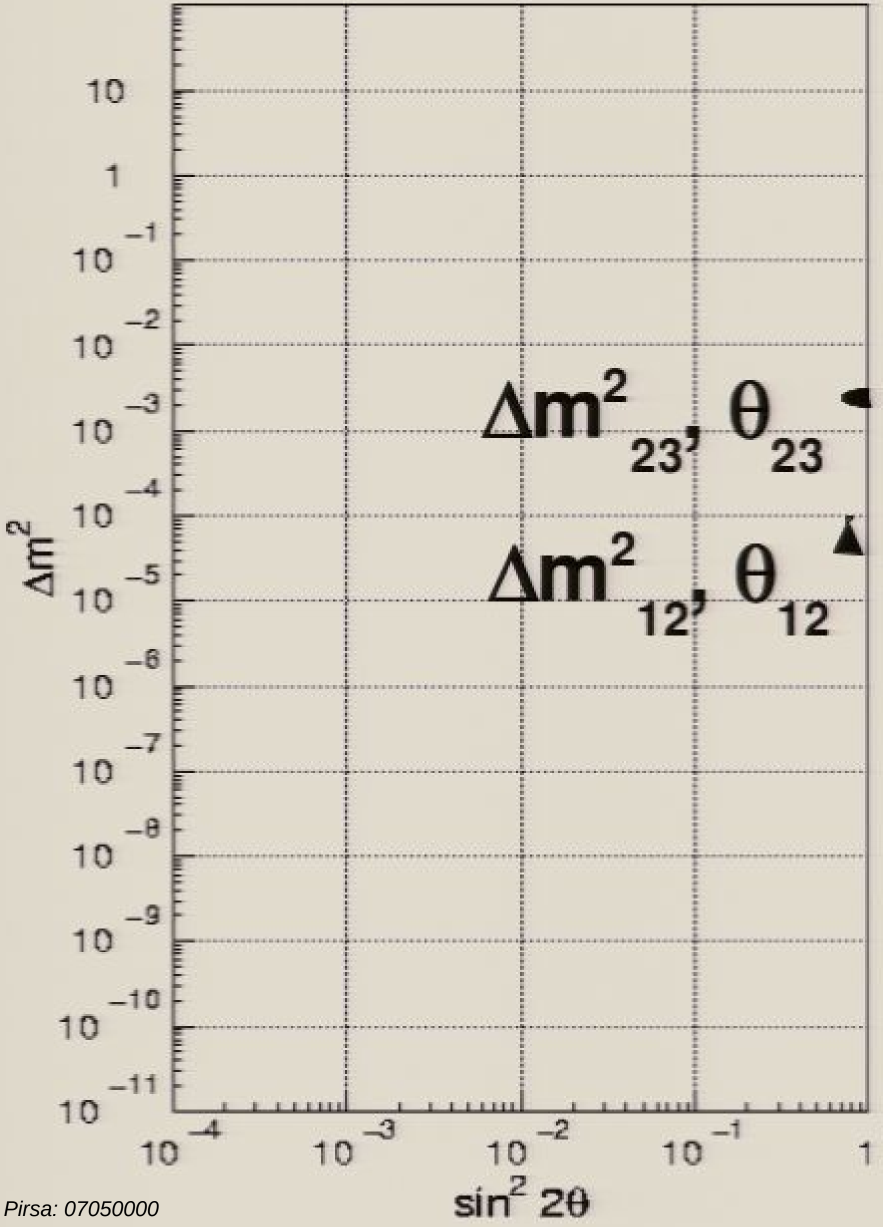


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Described by

- 2 Δm^2 ☑ ☑
- 3 mixing angles (θ_{23},θ_{12},θ_{13})
  ☑ ☑
- CP-violating phase δ

What do we still *not* know?

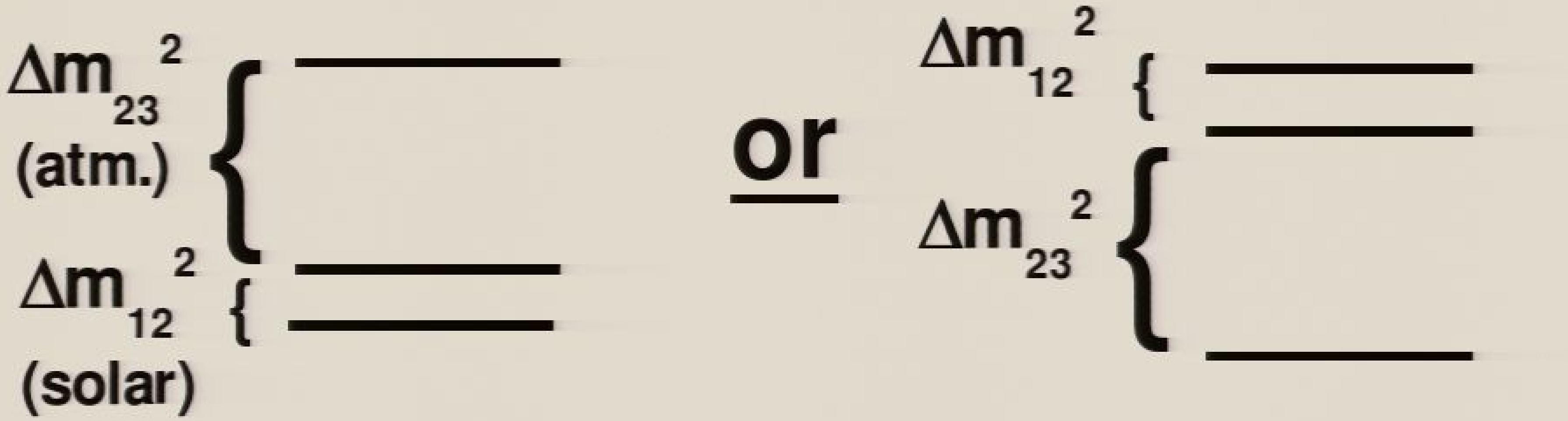
Remaining Questions

(that can be answered by oscillation experiments)

What is the mass hierarchy?

"Normal" hierarchy

"Inverted" hierarchy



- 2 Δm^2 ☑ ☑
- 3 mixing angles (θ_{23}, θ_{12}, θ_{13})
  ☑ ☑ ?

- CP-violating phase δ ?

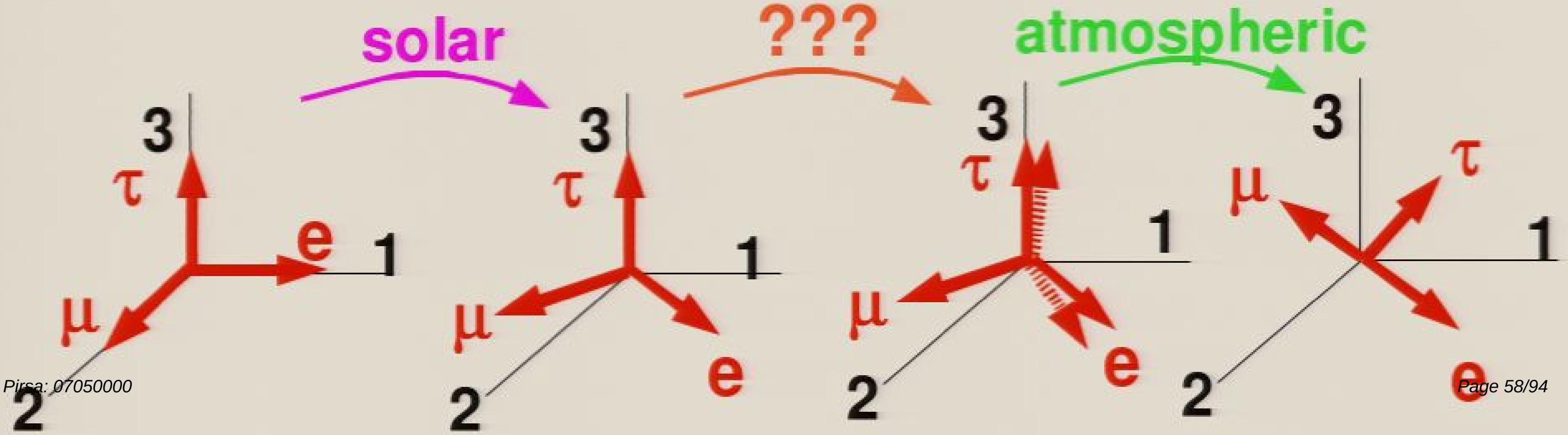
First, θ_{13}: 'the twist in the middle'

$$|\nu_f> = \sum_{i=1}^{N} U_{fi} |\nu_i>$$

MNS mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ??? solar

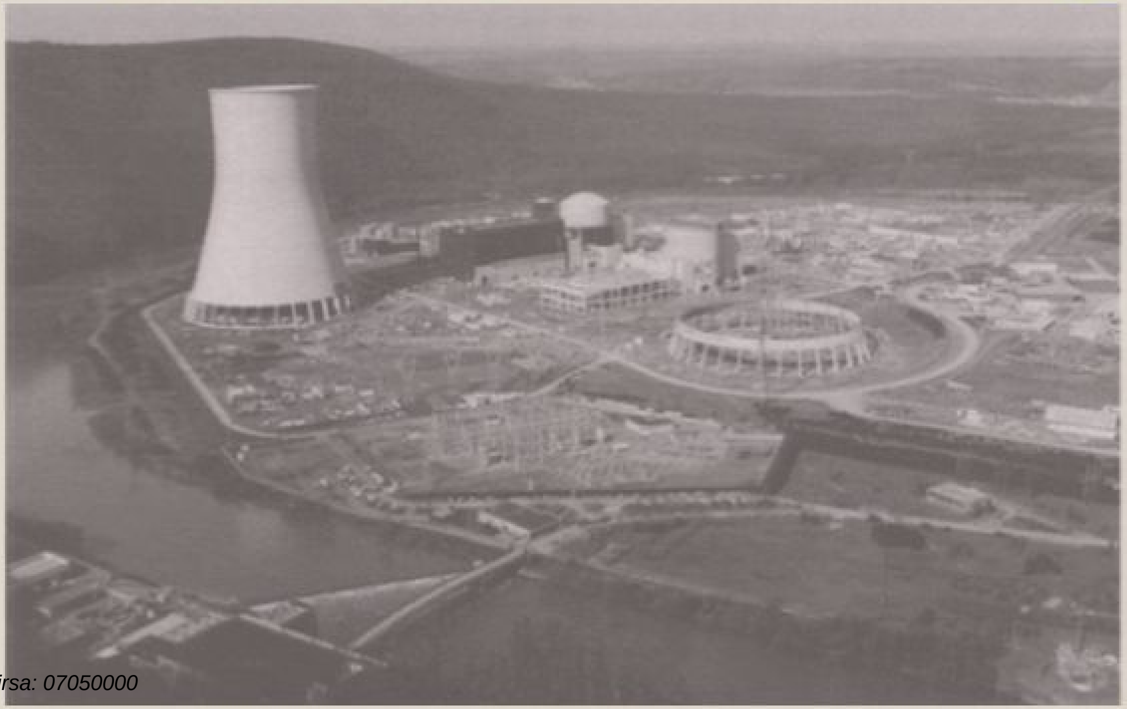


Getting at θ_{13} experimentally: look for disappearance of reactor $\bar{\nu}_e$

(few MeV, ~ km)

$$1\text{-}P(\nu_e \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2(\Delta m^2_{13} L/4E)$$

Current best limits for θ_{13} from CHOOZ



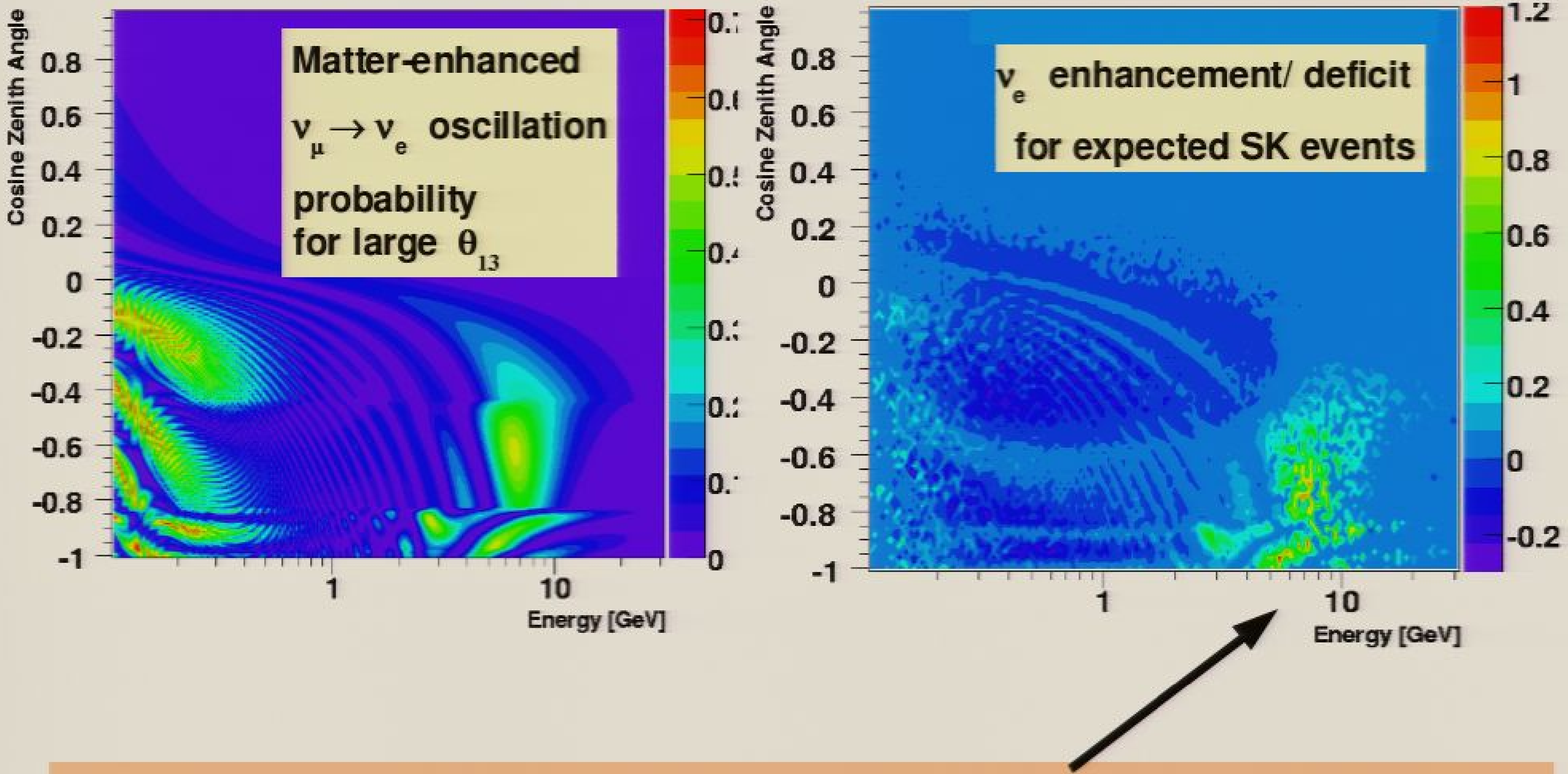
$\bar{\nu}_e \rightarrow \nu_x$

$\Rightarrow$ disappearance amplitude < 5-10%

New experiments (Double CHOOZ, Daya Bay) are trying to go further

Can look for signatures of non-zero θ_{13} in SK atmospheric nus

(Plots by R. Wendell)



Matter-enhanced

$\nu_\mu \rightarrow \nu_e$ oscillation

probability
for large θ_{13}

ν_e enhancement/ deficit

for expected SK events

Expect upgoing multi-GeV ν_e excess: *not seen*

Getting at θ_{13} experimentally: look for disappearance of reactor $\bar{\nu}_e$

(few MeV, ~ km)

$$\boxed{1 - P(\nu_e \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2(\Delta m^2_{13} L/4E)}$$

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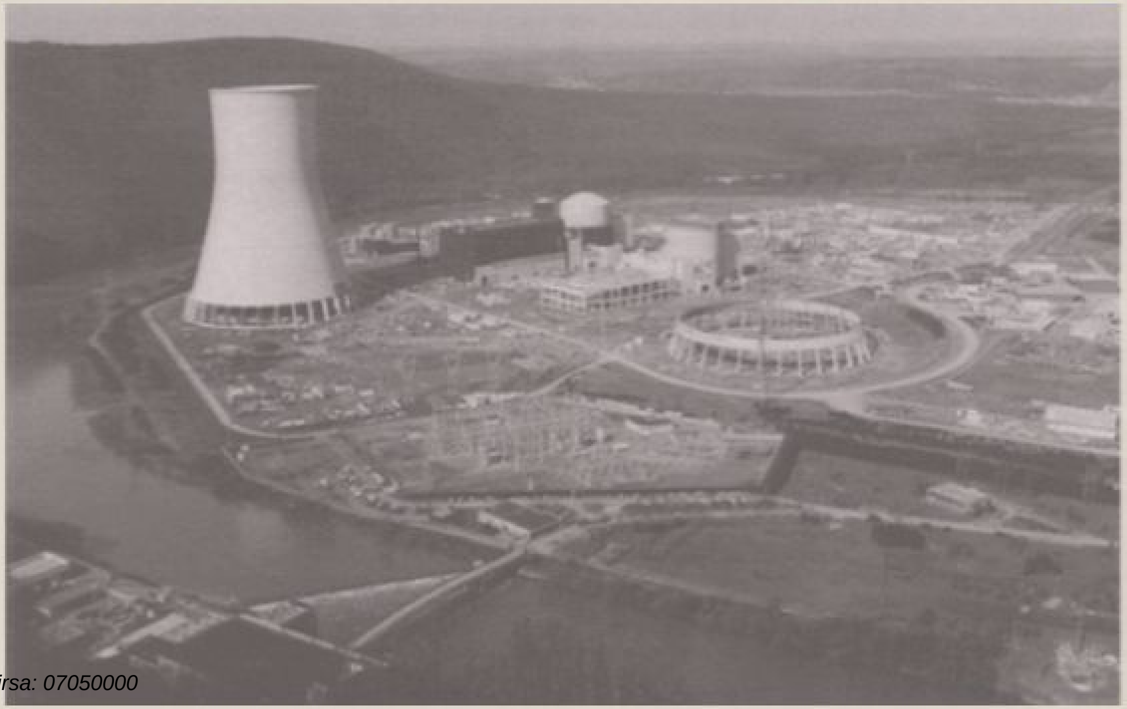

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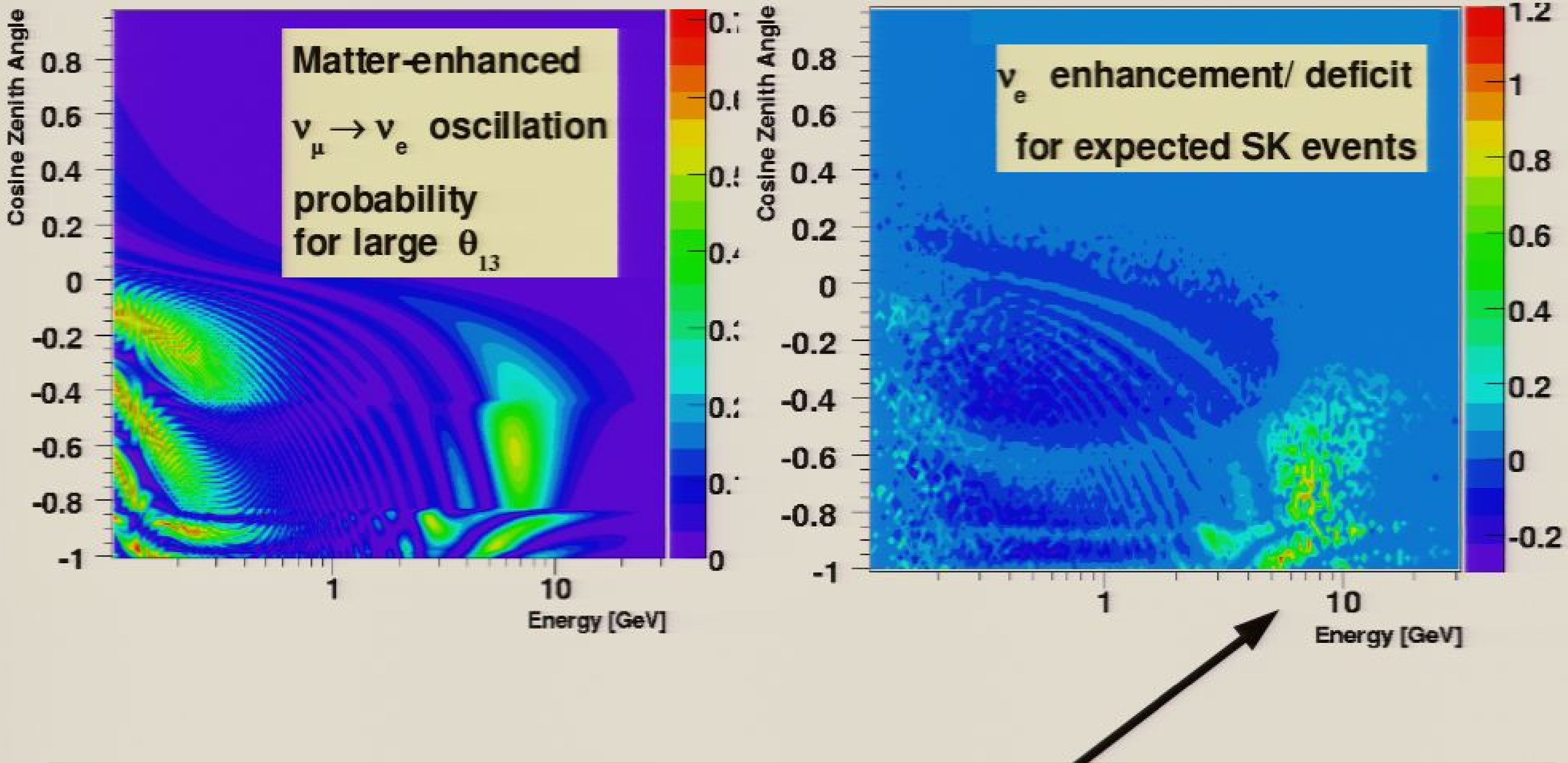
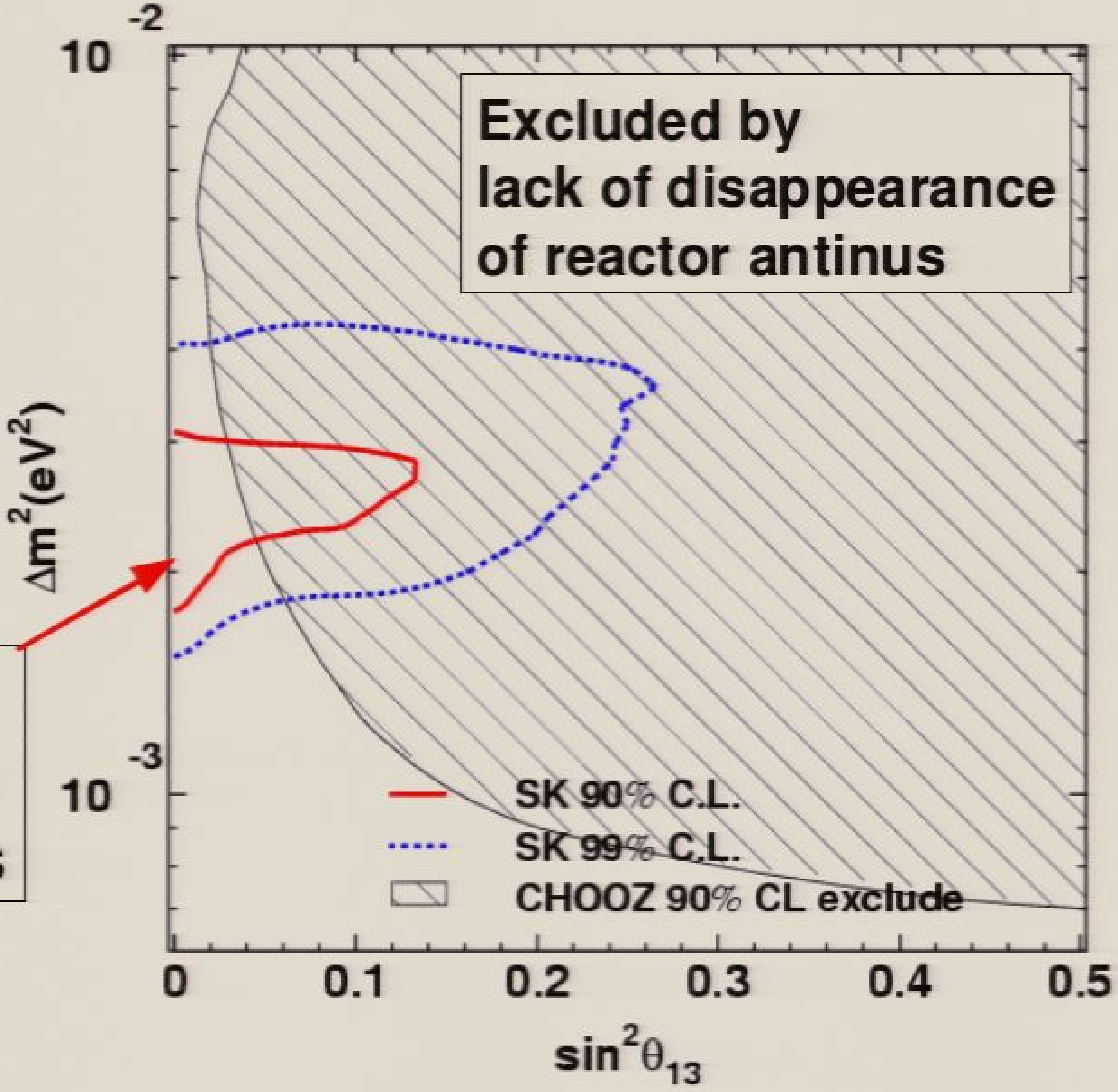


Matter-enhanced $\nu_\mu \rightarrow \nu_e$ oscillation probability for large θ_{13}

ν_e enhancement/ deficit for expected SK events

Expect upgoing multi-GeV ν_e excess: *not seen*

Best knowledge so far about θ_{13}:



Excluded by
lack of disappearance
of reactor antinus

Allowed:
consistent with
atmospheric nus

It's *small* angle, giving *small* modulation!

Another experimental approach:

θ_{13}signature: look for *small ν_e appearance* in a ν_μ beam

$$\begin{tikzcd} \nu_\mu \arrow[r] \arrow[dr, dashed] & \nu_{\mu,\tau} \\ & \nu_e \end{tikzcd}$$

For $\Delta m_{23}^2 >> \Delta m_{12}^2$ and $E_\nu \sim L\Delta m_{23}^2$ (in vacuum):

$$P(\nu_\mu\rightarrow\nu_e) = \underbrace{\sin^2 2\theta_{13}}_{\text{small modulation}} \overbrace{\underbrace{\boxed{\sin^2\theta_{23}}}_{\sim 1/2} \sin^2(\Delta m^2_{23} L/4E)}^{\text{atmospheric-like wiggling}}$$

***Hard* to measure... it's a *small* modulation!**

Need good statistics, clean sample

Future Long Baseline Beam Projects 2009+

Aim for: ~1% on 2-3 mixing, factor of ~10-20 for θ_{13} mixing

T2K: "Tokai to Kamioka"

Existing detector: Super-K
295 km, <1 GeV 0.75 MW beam
Water Cherenkov detector

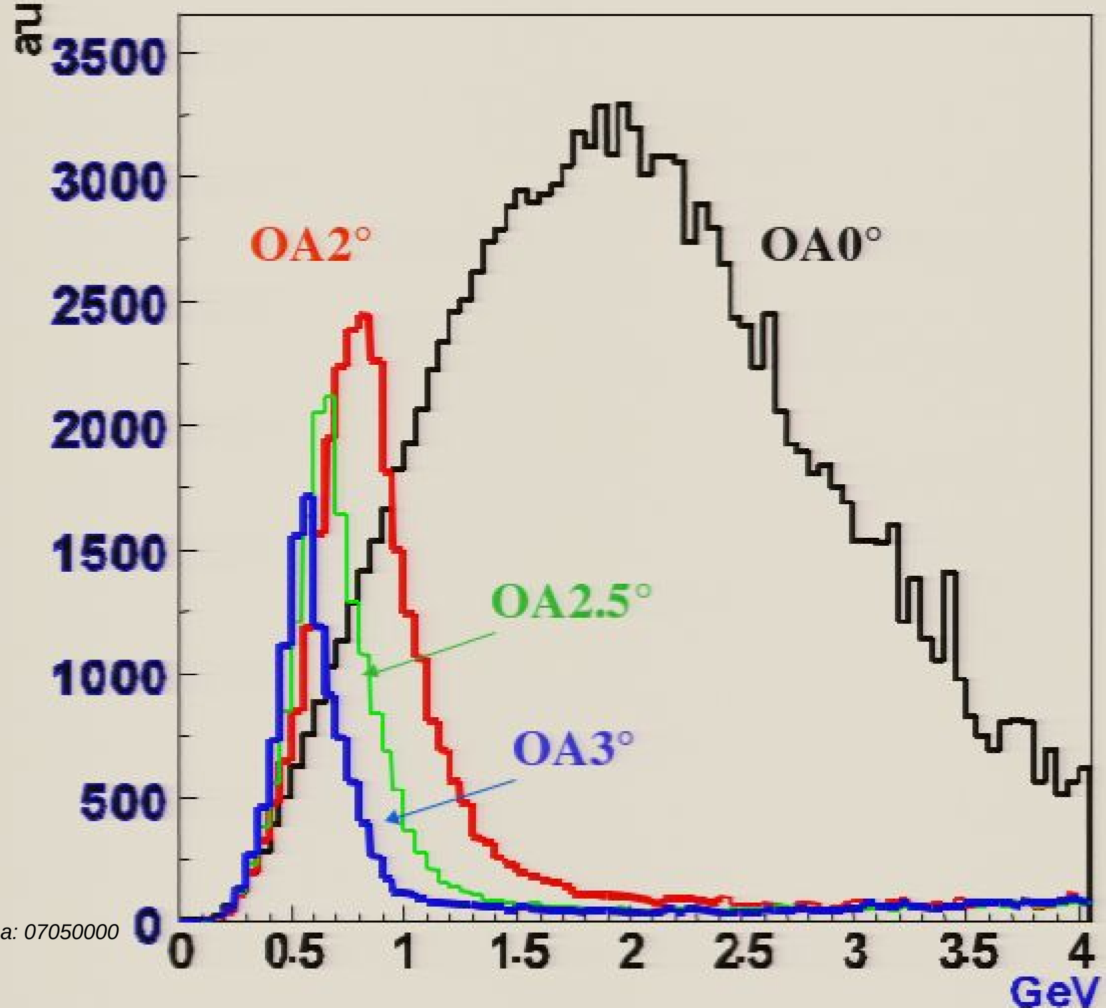
NOνA at NuMi

Existing beam: NuMi
750 km, few GeV beam
Scintillator detector

Detectors will be a few degrees off beam axis

Off-Axis Neutrino Beams

Although you get some reduction in flux, get *more sharply peaked* neutrino energies



Good for background reduction and oscillation fits

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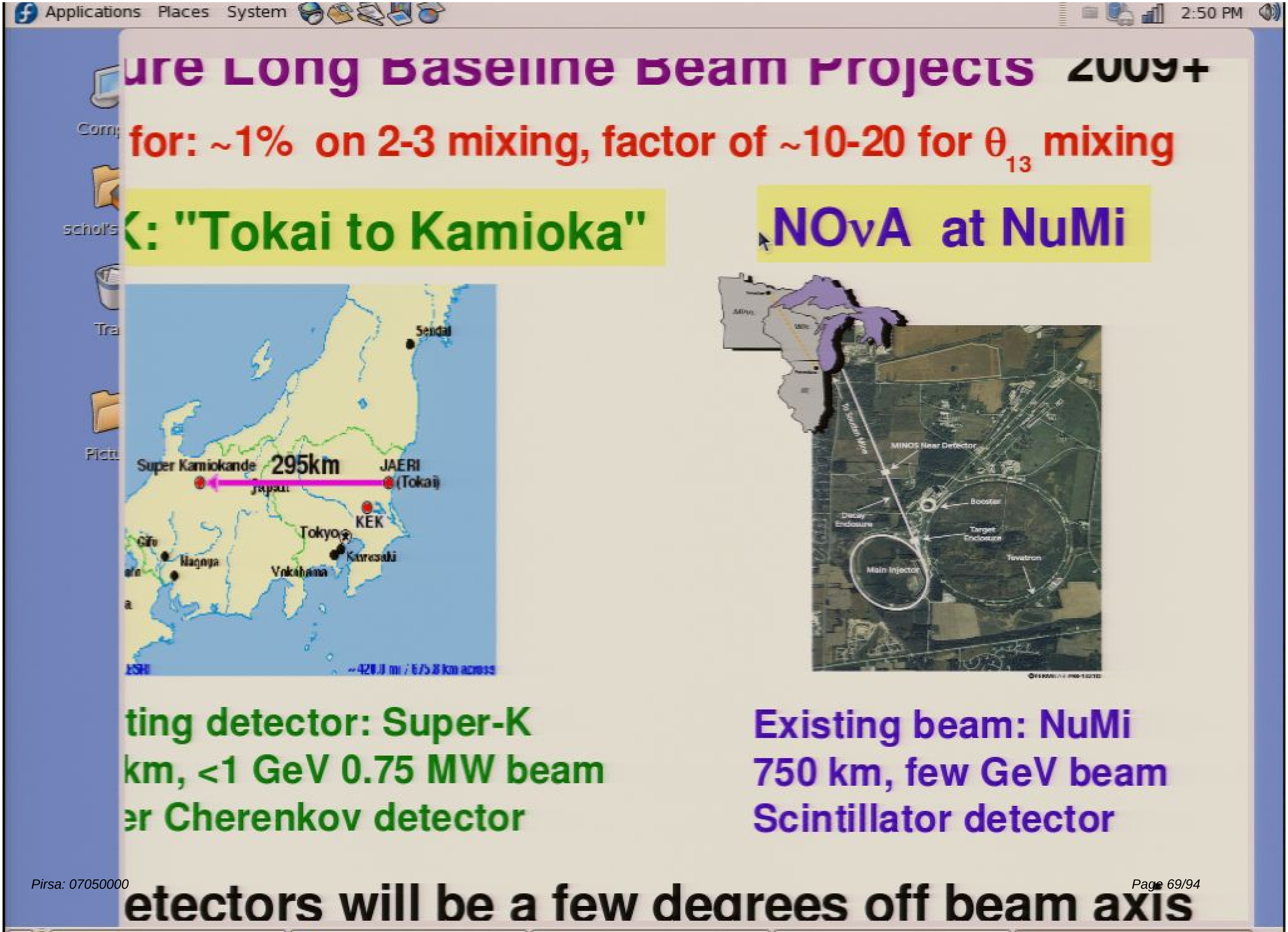

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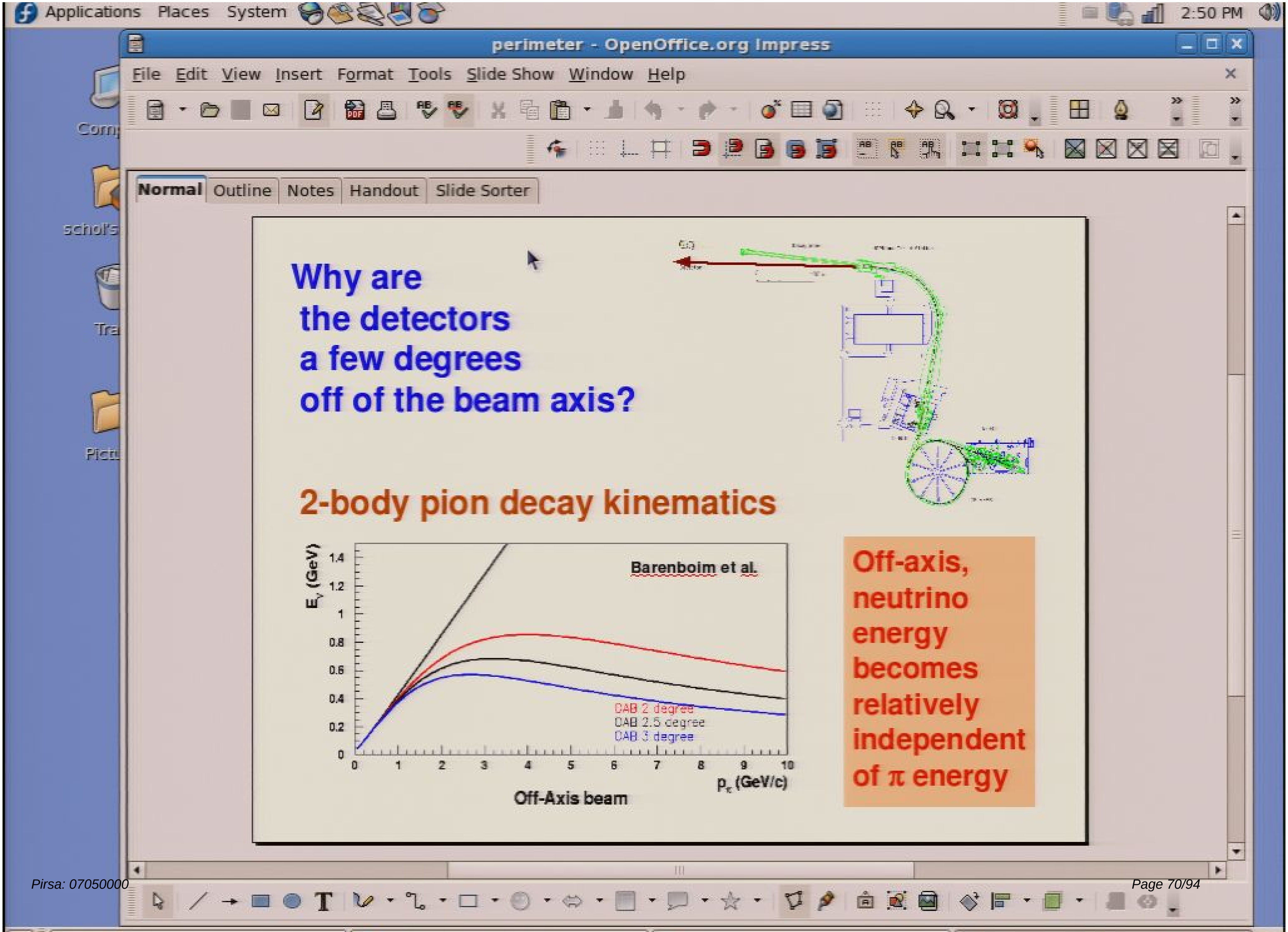


Why are the detectors a few degrees off of the beam axis?

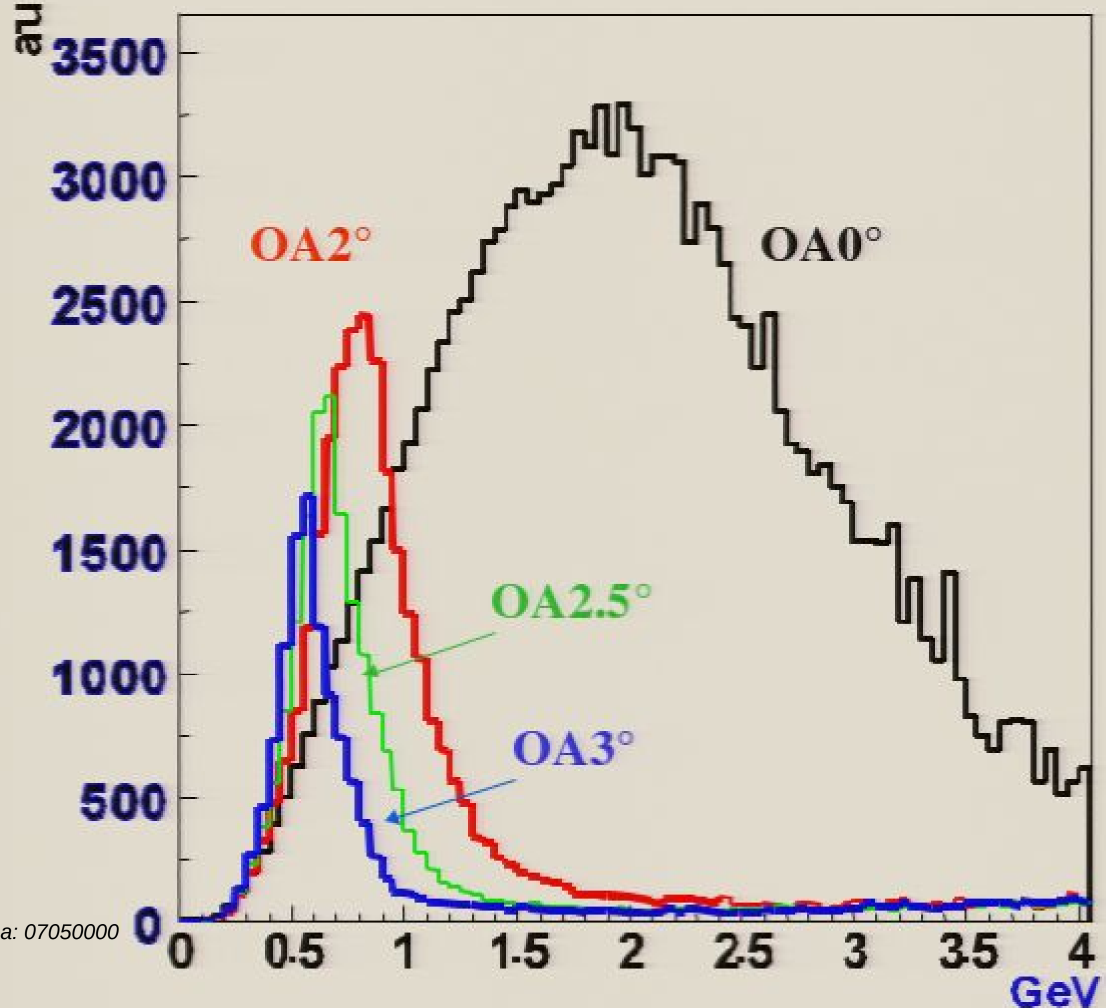
2-body pion decay kinematics

Off-Axis beam

Off-axis, neutrino energy becomes relatively independent of π energy

Off-Axis Neutrino Beams

Although you get some reduction in flux, get *more sharply peaked* neutrino energies



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September, 2005

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T2K Detectors

Far detector: Super-K III (fully rebuilt)

280m detector: fine-grained, high rate detector for beam characterization

2KM detector: water Cherenkov + LAr + MRD

- same ν spectrum as SK
- same target as SK
- same event reconstruction as SK

} cancel systematics

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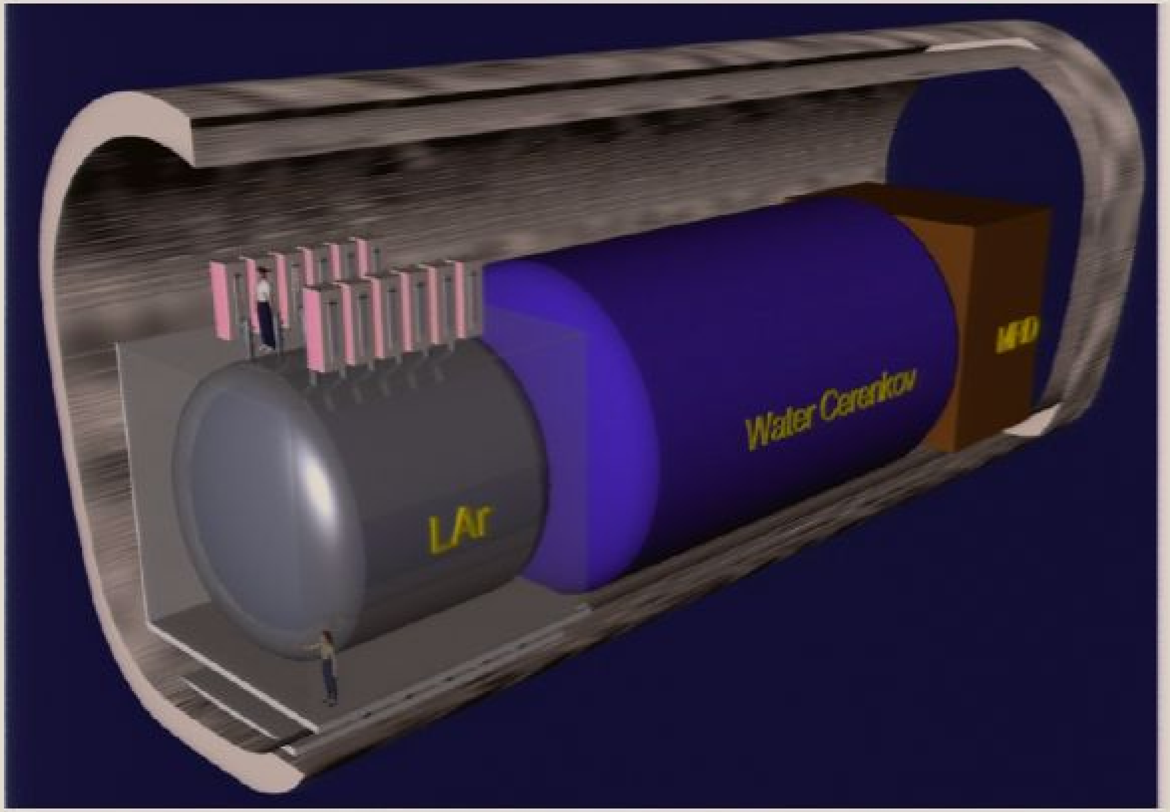

57 m depth

Water Cherenkov: same target, reconstruction as SK
1 interaction/spill/kt, 56t

Liquid Argon: fine grain tracking, no Cherenkov threshold
100 ton Ar + possible ice target

Muon Range Detector: scint + steel plates
high energy tail (ν_e contamination)

And now: getting at CP Violation

Observed for quarks; how about leptons?

phase δ in MNS matrix

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & C_{23} & S_{23}\\ 0 & -S_{23} & C_{23}\end{pmatrix}\begin{pmatrix}C_{13} & 0 & S_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -S_{13}e^{i\delta} & 0 & C_{13}\end{pmatrix}\begin{pmatrix}C_{12} & S_{12} & 0\\ -S_{12} & C_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Compare transition probabilities for
$\nu_\mu \to \nu_e$ **and** $\bar{\nu}_\mu \to \bar{\nu}_e$

But not simple to extract CP violating phase δ...
transition rates depend on all
MNS parameters, plus matter effects...

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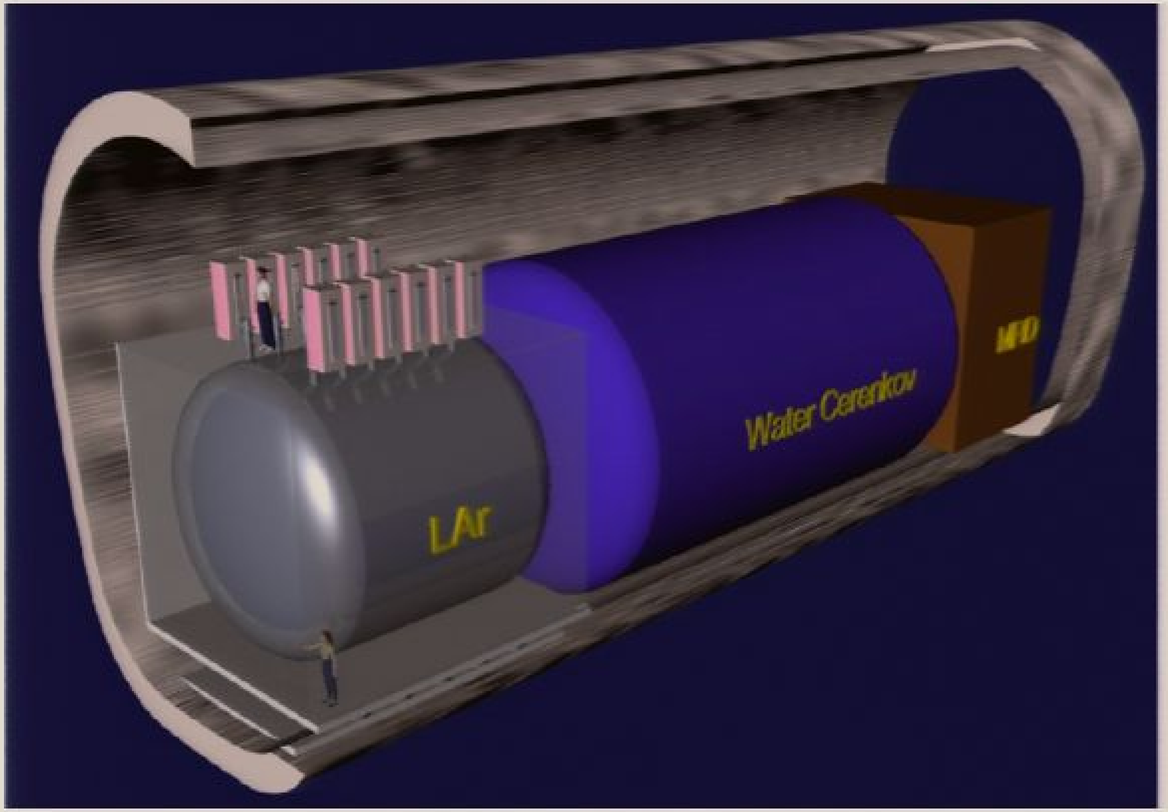

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CP Violating Observables

2nd order in

$$\theta_{13}, \frac{\Delta_{12}}{\Delta_{23}}, \frac{\Delta_{12}}{A}, \Delta_{12}L$$

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

Non-CP terms

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

CP terms

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

Changes sign for $\nu \to \bar{\nu}$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = |A \pm \Delta_{13}|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

A. Cervera et al., Nuclear Physics B 579 (2000)

Mass hierarchy affects nu/nubar via matter effects (need long L)

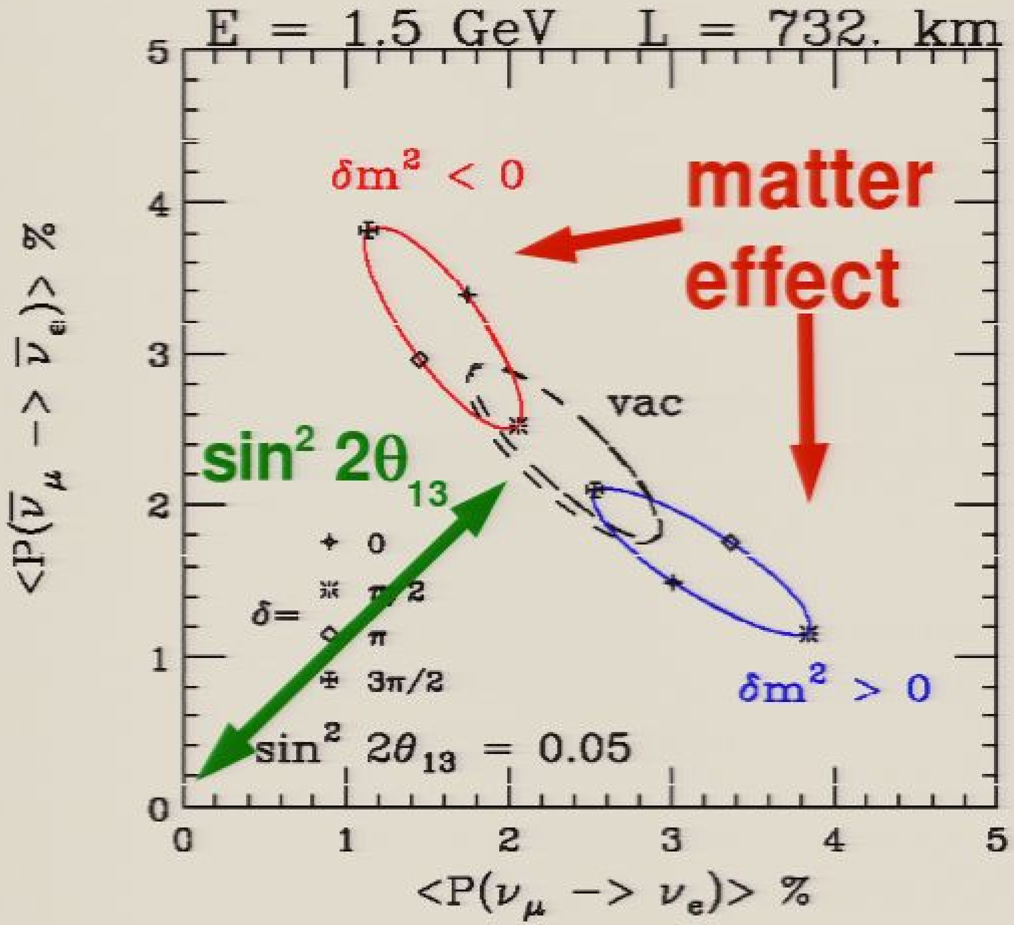
Much messier!

Need precision measurements of parameters

Multiple measurements (ν's and $\bar{\nu}$'s) at long L needed to resolve intrinsic ambiguities

Parameter Ambiguities in CP Observables

Minakata and Nunokawa, hep-ph/0108085



For given $\sin^2 2\theta_{13}$, ellipse corresponds to different δ values

Measured spot on the space could correspond to different δ, $\sin^2 2\theta_{13}$, sign($\Delta m_{23}{}^2$)

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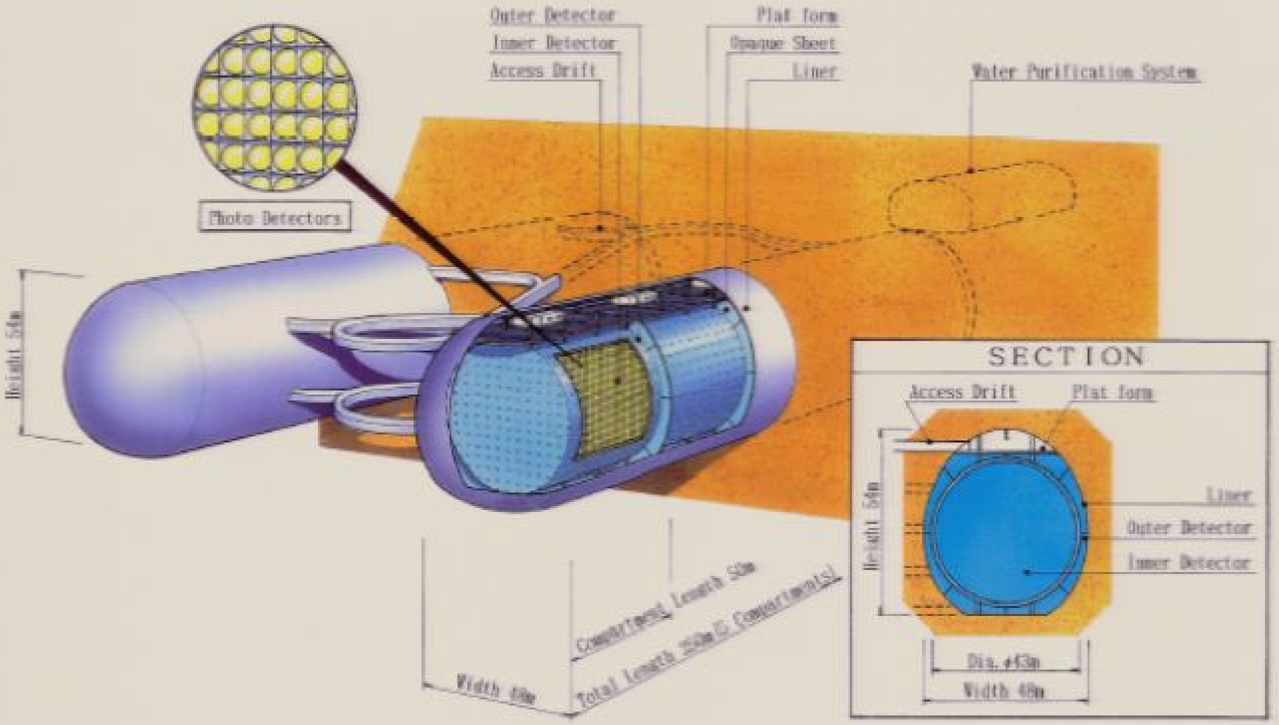
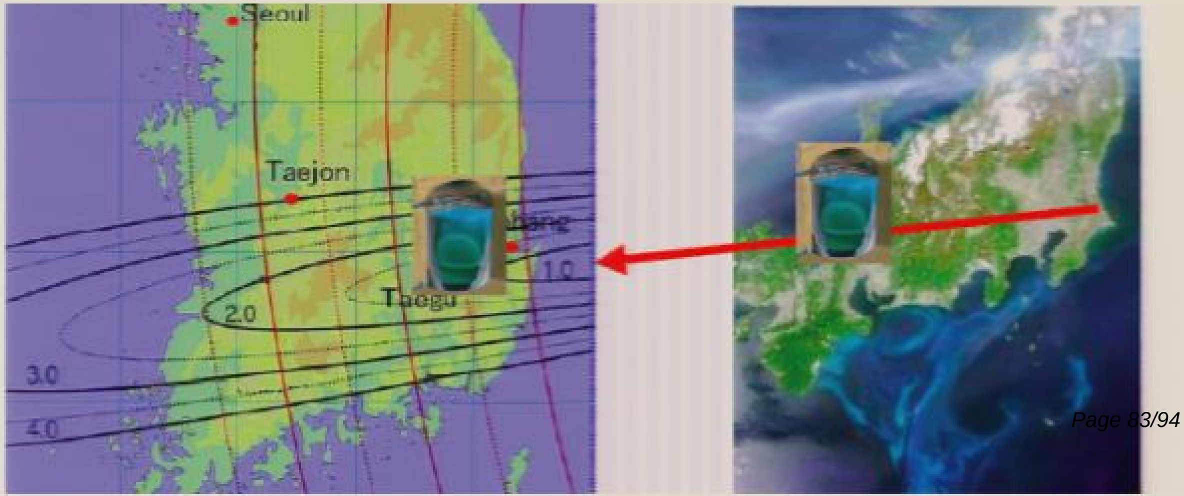
"Phase II" of T2K program: go after CP violation



J-PARC upgrade to 4 MW

Hyper-K ~1 Mton water detector

T2KK: second detector in Korea?



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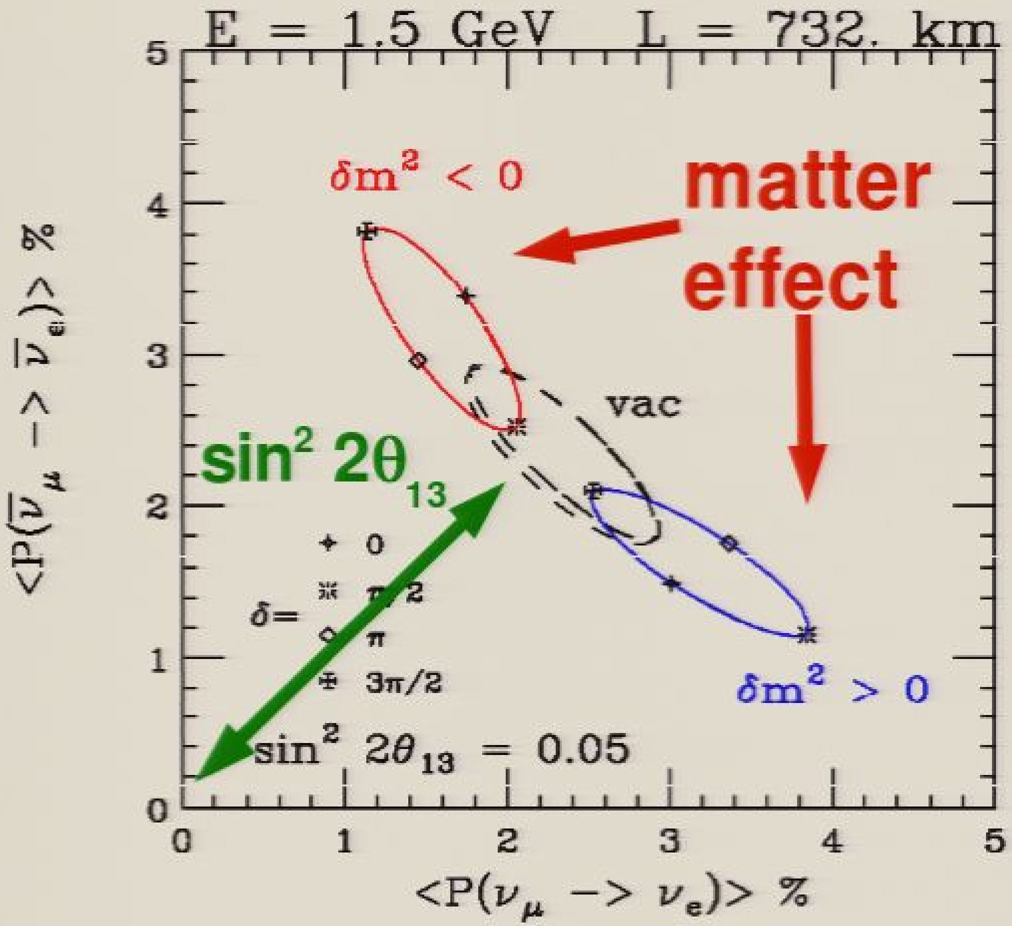

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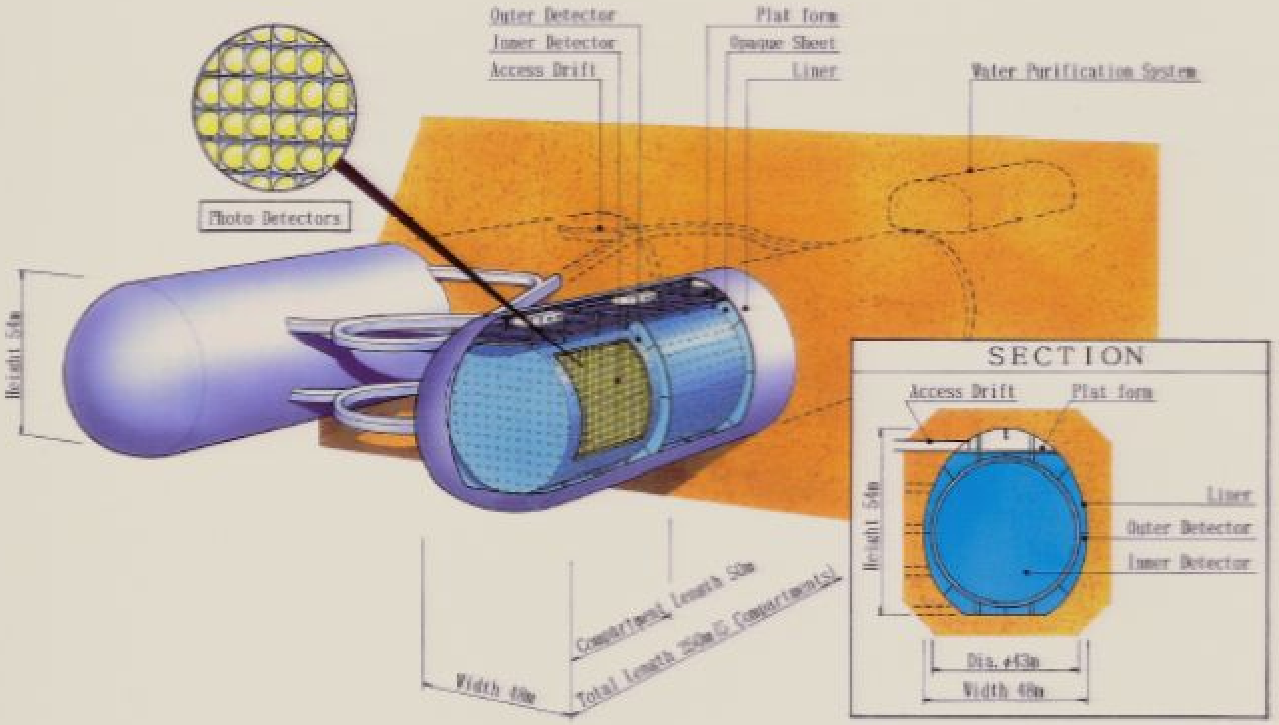
Multiple measurements (ν's and $\bar{\nu}$'s) at long L needed to resolve intrinsic ambiguities

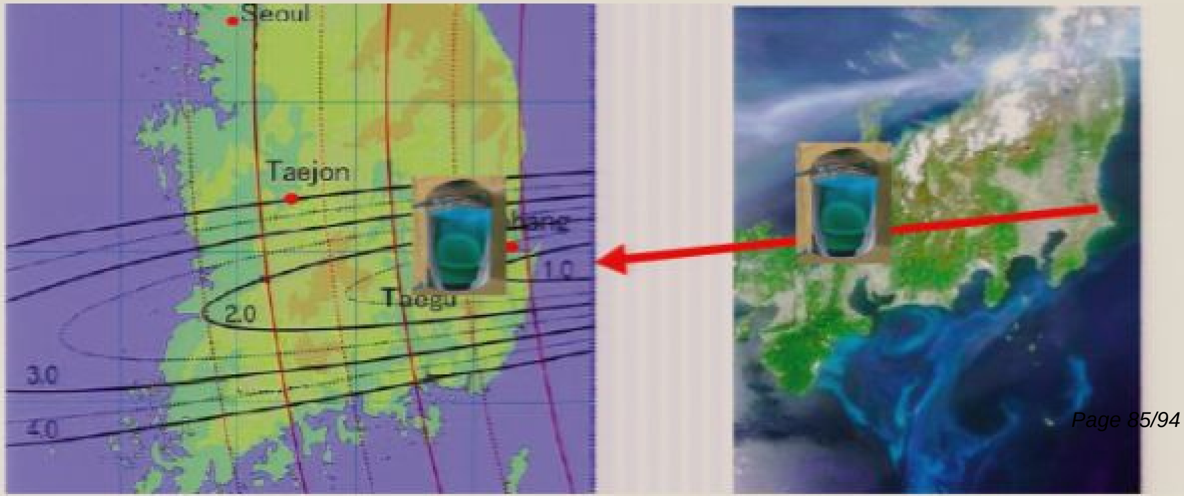
"Phase II" of T2K program: go after CP violation



J-PARC upgrade to 4 MW

Hyper-K
~1 Mton water detector

T2KK: second detector in Korea?

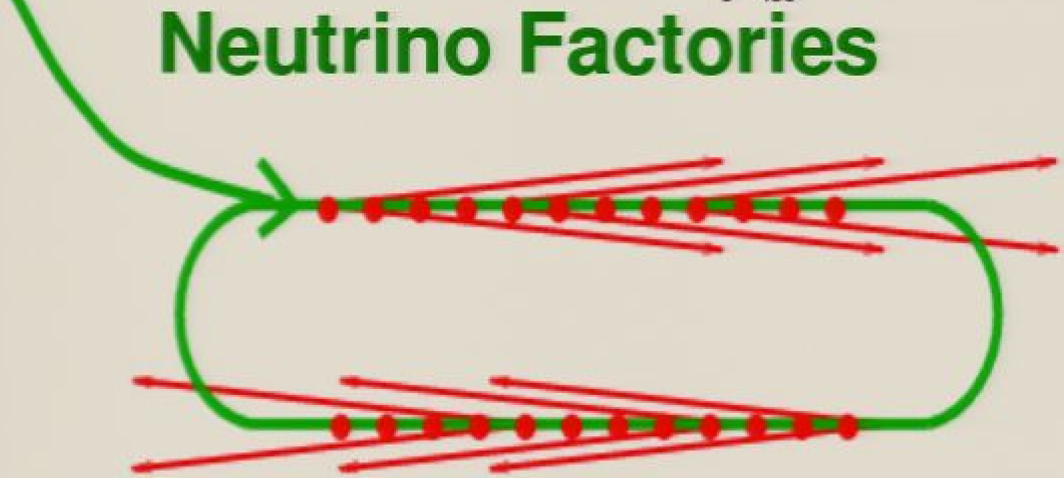


Lots of long-term ideas in global context:

FNAL or Brookhaven super proton driver

Large detector: water?
liquid argon? ...?
New underground lab?

Neutrino Factories



Muon storage ring

~20-50 GeV ν's

L ~3000-7000 km

Also, β-beams: storage ring of radioactive isotope

high intensity antinue/nue source

Summary of "beyond-2-flavor" oscillation physics

Observable	Signature	Next steps*
θ_{13}	Tiny appearance of ν_e in a beam of ν_μ; disappearance of $\bar{\nu}_e$	Next generation beams (T2K, NuMI)  Reactors 
Mass hierarchy sign(Δm_{23}^2)	Matter-induced $\nu/\bar{\nu}$ asymmetry	Superbeams, ν factory 
CPV phase δ	$\nu/\bar{\nu}$ asymmetry	Superbeams, ν factory 

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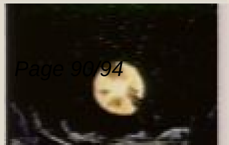

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Will need multiple measurements

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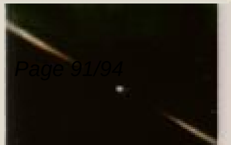


Overall Summary

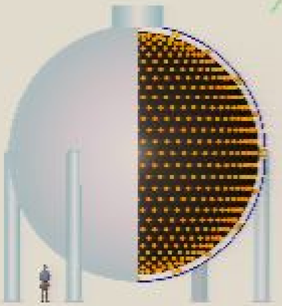
Tremendous progress over the last decade:

Beyond a doubt, neutrinos have mass and mix

Atmospheric oscillations confirmed by beam

Solar oscillations confirmed
by reactor experiments

2- flavor oscillation interpretation
of LSND now disfavored by MiniBooNE!



Parameters getting squeezed down in 3-flavor picture

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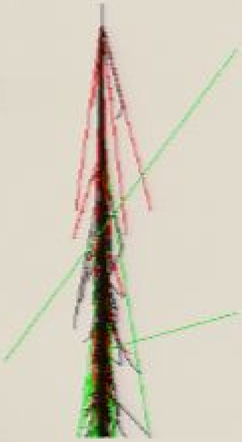

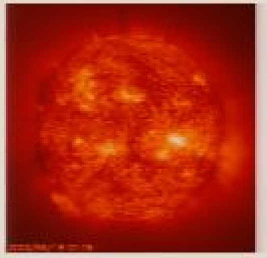

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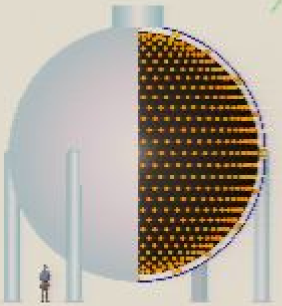

Parameters getting squeezed down in
3-flavor picture

Next quest: θ_{13} , mass hierarchy, CP violation

$\Rightarrow$ new beam and reactor experiments

More to ν physics than oscillations...

Absolute mass scale?

Is the ν its own antiparticle?

$\left\{ \begin{array}{l} \text{Kinematic experiments} \\ \text{Double beta decay} \\ \text{Cosmology} \end{array} \right.$

And how does it all fit in?? beyond the SM, leptogenesis, GUTs, extra dimensions, cosmology...

Many interesting years lie ahead!