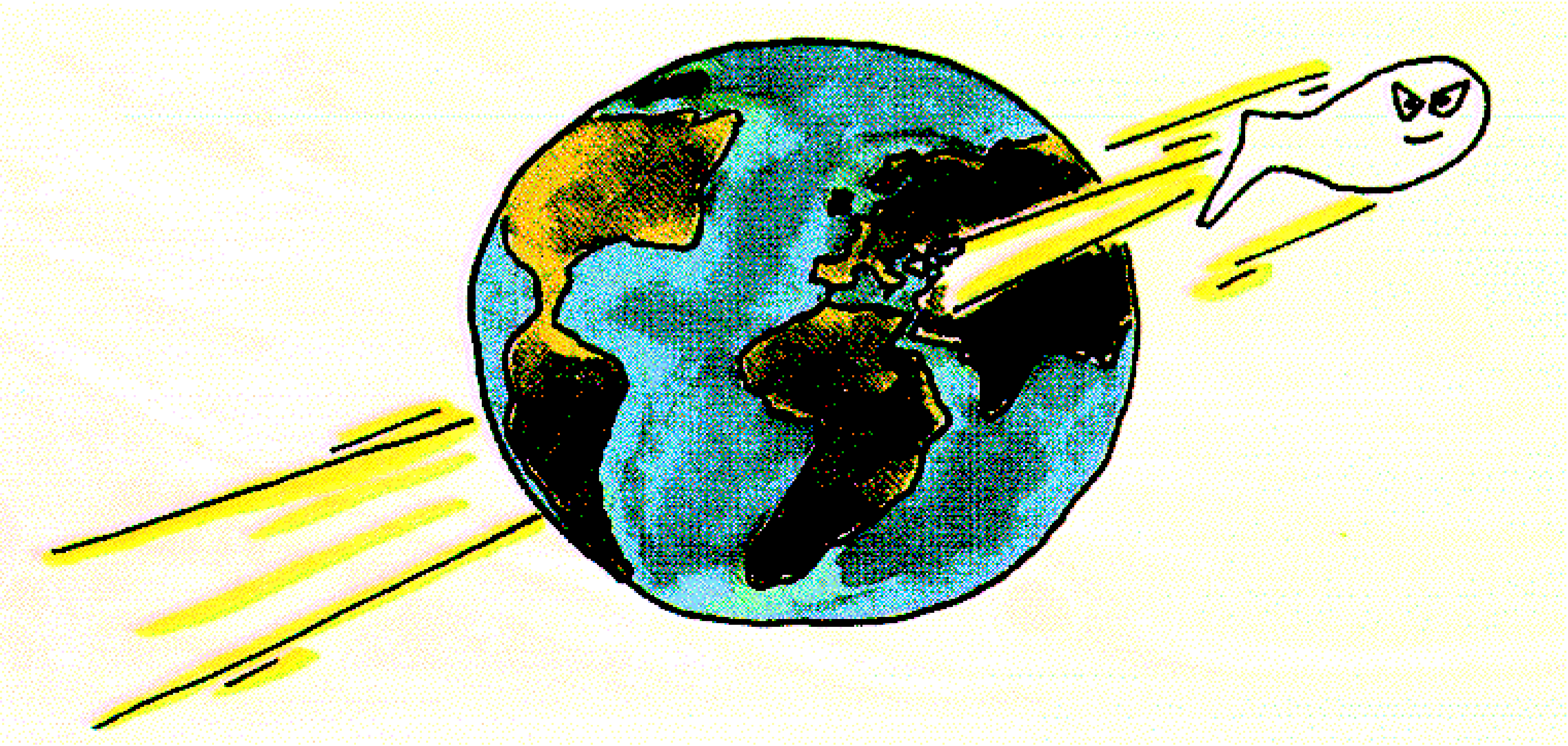
**Today:**

**Part I: Neutrino oscillations intro (SK physics)**

**Part II: Second tutorial: accessing the SK data in a program**

# Super-Kamiokande Physics I: Neutrino Oscillations



# NEUTRINOS

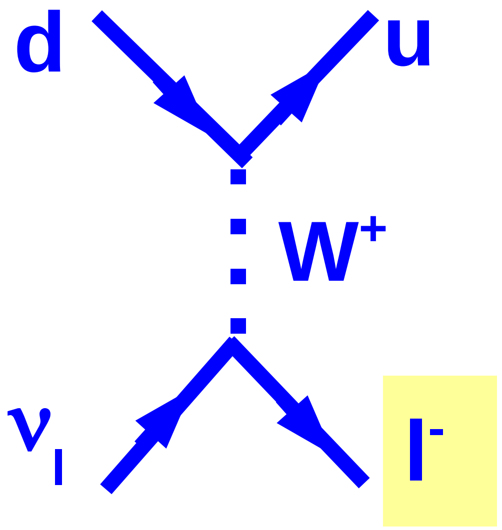
| | | | | |
|---|---|---|---|---|
| | ~3 | ~1200 | 174,000 | $MeV/c^2$ |
| **Quarks** | u | c | t | |
| | d | s | b | |
| | ~6 | ~100 | ~4200 | $MeV/c^2$ |
| | 0.511 | 105.6 | 1778 | $MeV/c^2$ |
| **Leptons** | e | $\mu$ | $\tau$ | |
| | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | |
| | ??? | ??? | ??? | |

**Neutral partners to the charged leptons**

- **Interact only via *weak interaction***
- **Tiny mass (kinematic limits: <~ 2 $eV/c^2$)**

# Neutrino Interactions with Matter

**Charged Current (CC)**

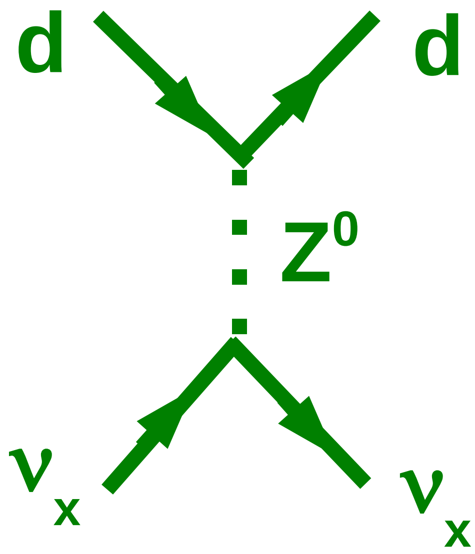



$$\nu_l + N \rightarrow l^{\pm} + N'$$

**Produces lepton with flavor corresponding to neutrino flavor**

**(must have enough energy to make lepton)**

**Neutral Current (NC)**




**Flavor-blind**

# Neutrino Oscillations

Assume

**FLAVOR STATES** $|\nu_f>$ weakly interacting are superpositions of **MASS STATES** $|\nu_m>$

unitary mixing matrix

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

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

# Simple two-flavor case

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

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

**Propagate a distance L:**

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

**Probability of detecting flavor g at L:**

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

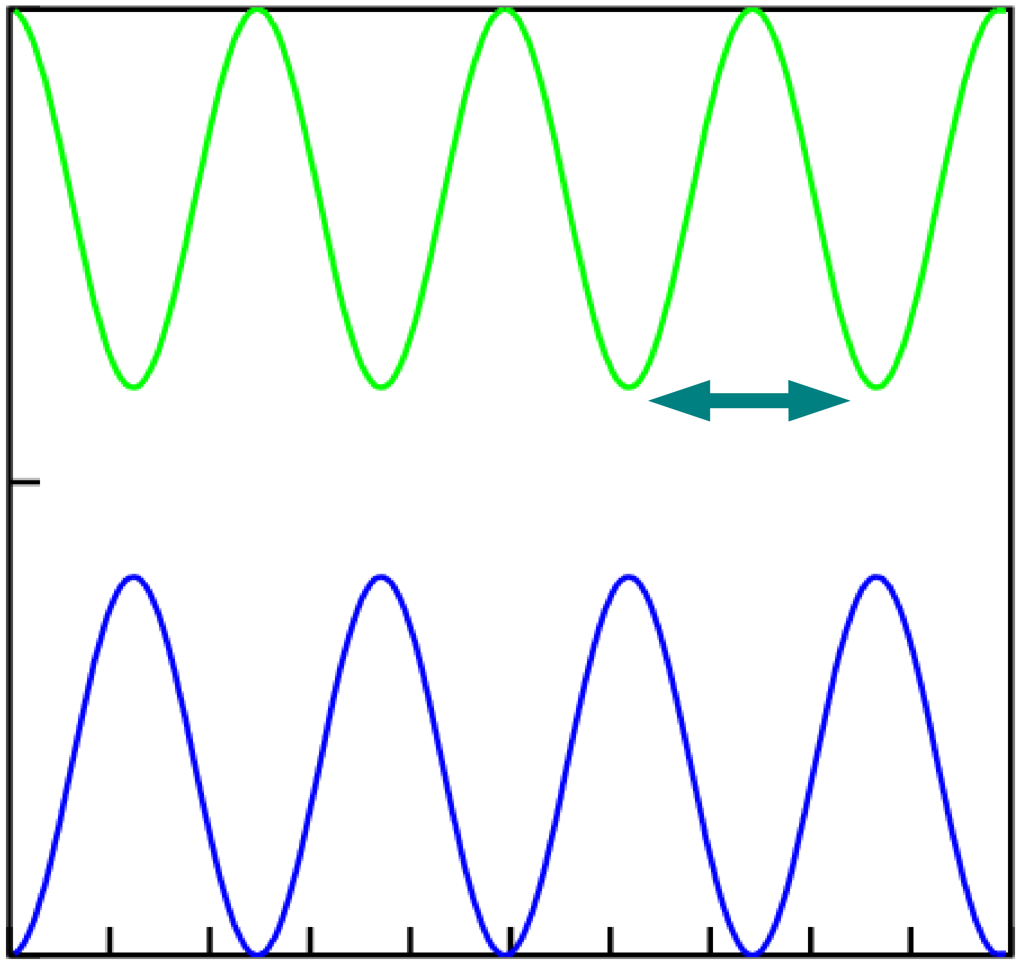
E in GeV
L in km
$\Delta m^2$ in $eV^2$

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

**Probability of changing flavor**

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

$P(\nu_f \rightarrow \nu_f)$



$P(\nu_f \rightarrow \nu_g)$

**Wavelength= $\pi E/(1.27\Delta m^2)$**

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

**Distance traveled**

**$\Delta m^2$, $\sin^2 2\theta$ 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**

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

**?**

**<u>Disappearance</u>: $\nu$'s oscillate into 'invisible' flavor**

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

**<u>Appearance</u>: directly see new flavor**

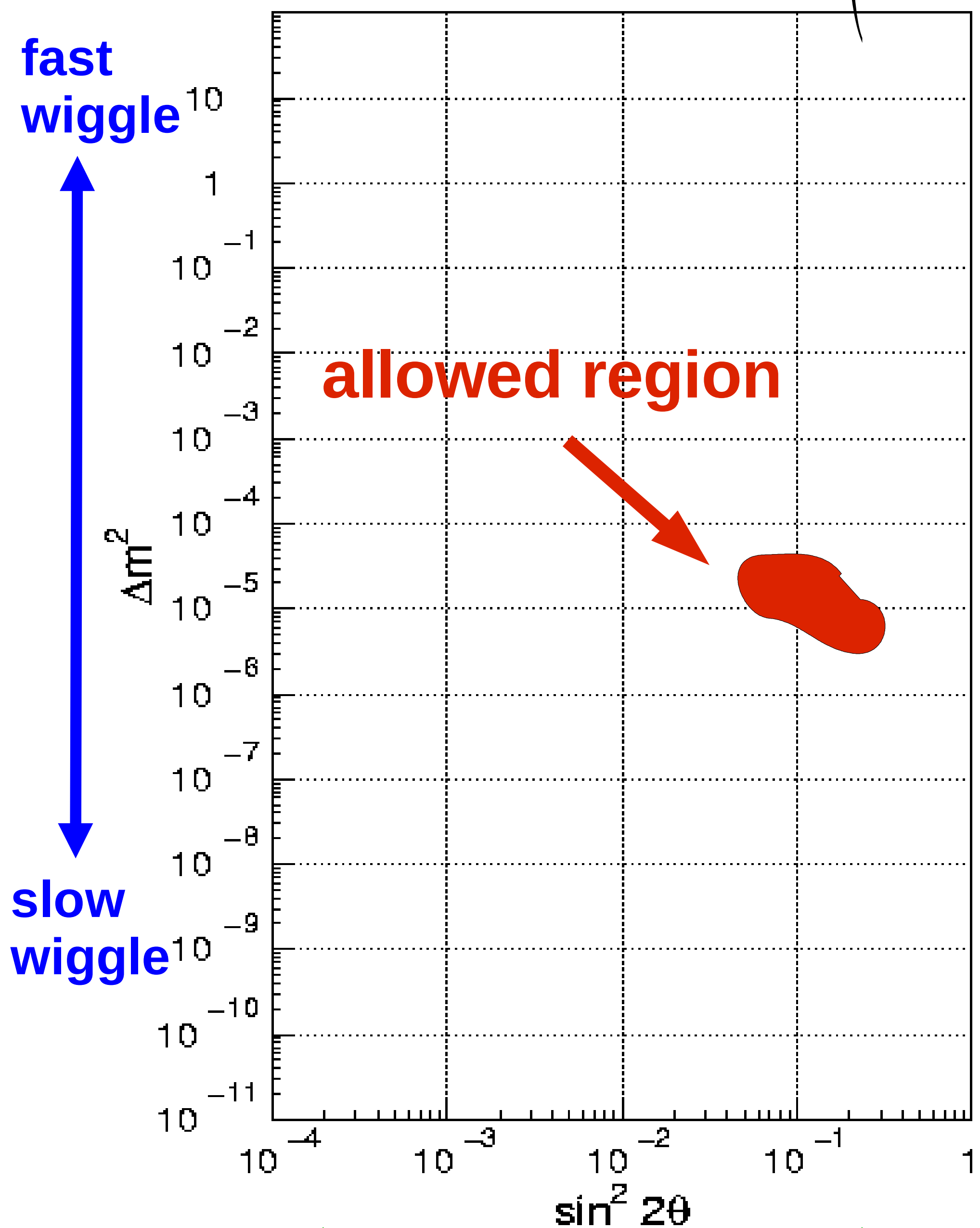
e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV energies

# Oscillation Parameter Space

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

**Twiddle L/E**

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




**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**

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

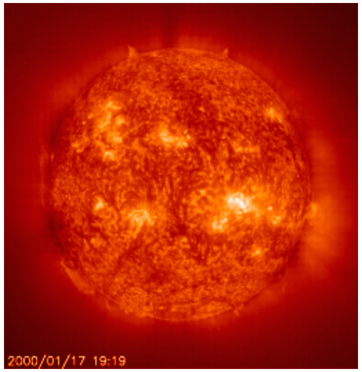
**Frequently, can use 2-flavor approximation**
**e.g. if $\Delta m_{ij}^2 \gg \Delta m_{jk}^2$**

**Notes:**
- **3 flavors ⇒ 2 *independent* $\Delta m_{ij}^2$**
- **sterile ν with no weak interactions?**

# The Three Signals

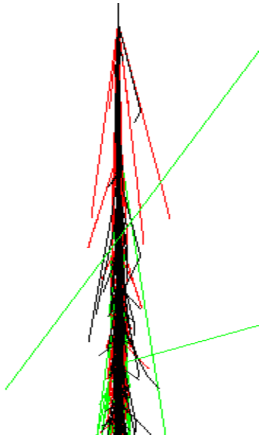
## SOLAR NEUTRINOS

$$\nu_e \rightarrow \nu_x$$




**Electron neutrinos from the Sun are *disappearing...***
**confirmed by KamLAND reactor experiment**

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

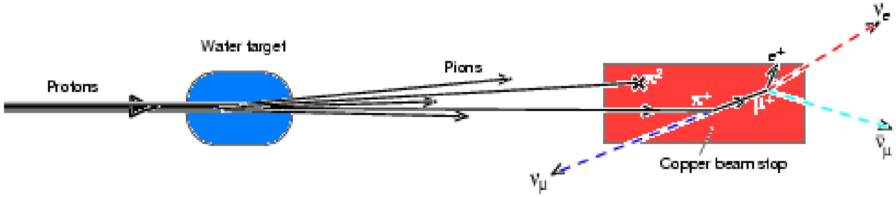


## ATMOSPHERIC NEUTRINOS

$$\nu_\mu \rightarrow \nu_x$$

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

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



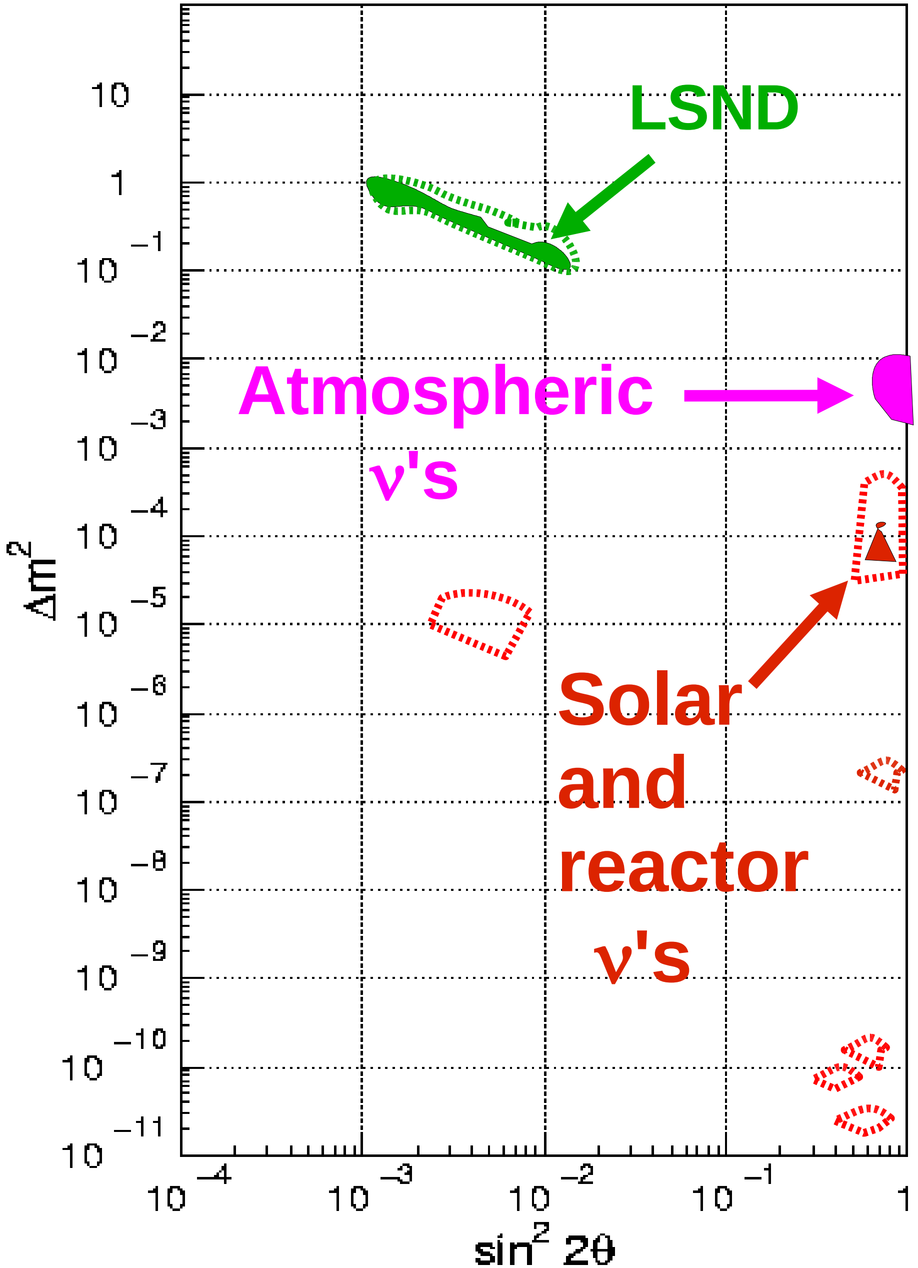

## ACCELERATOR NEUTRINOS

**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

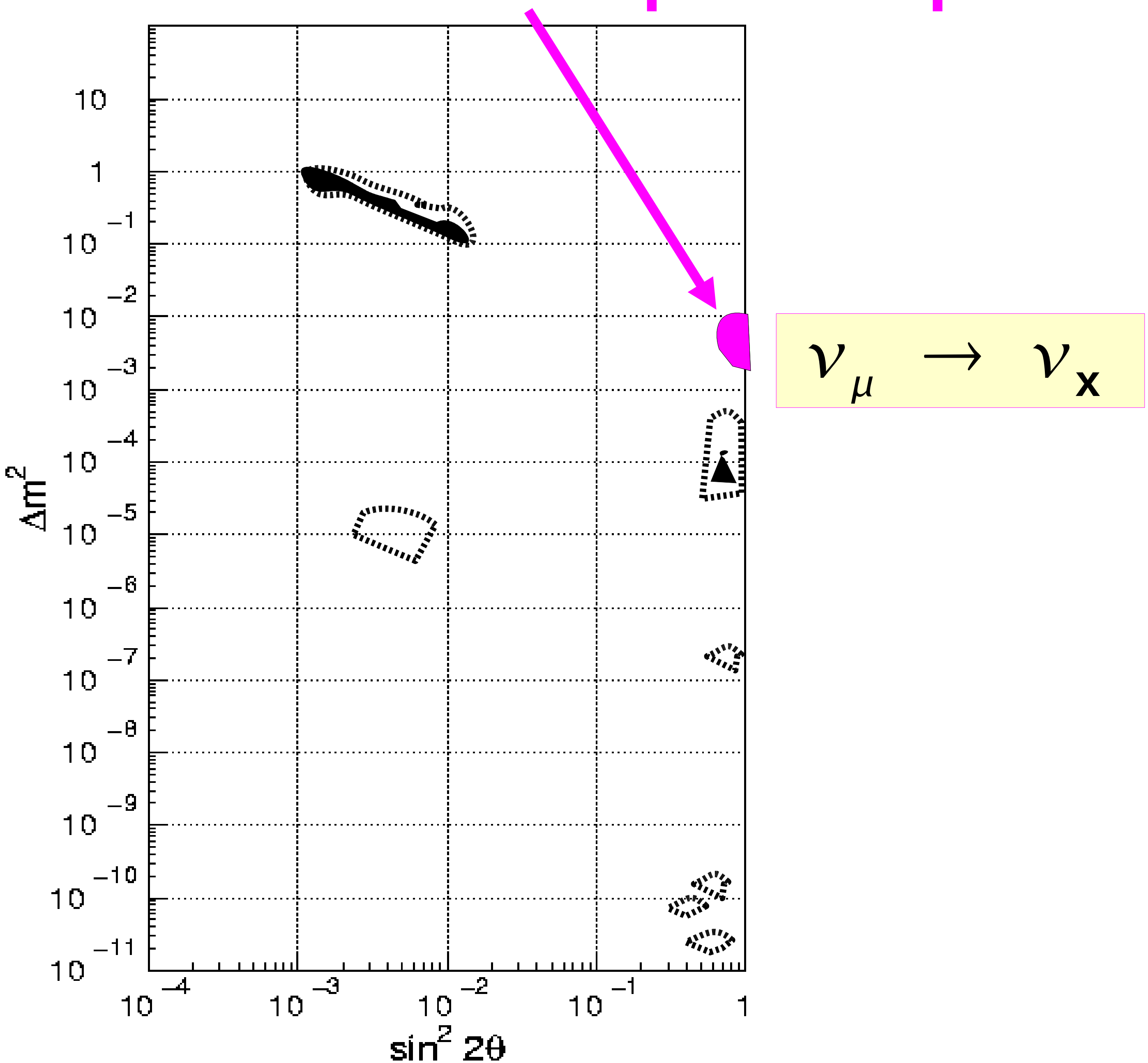



$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\nu_\mu \rightarrow \nu_x$

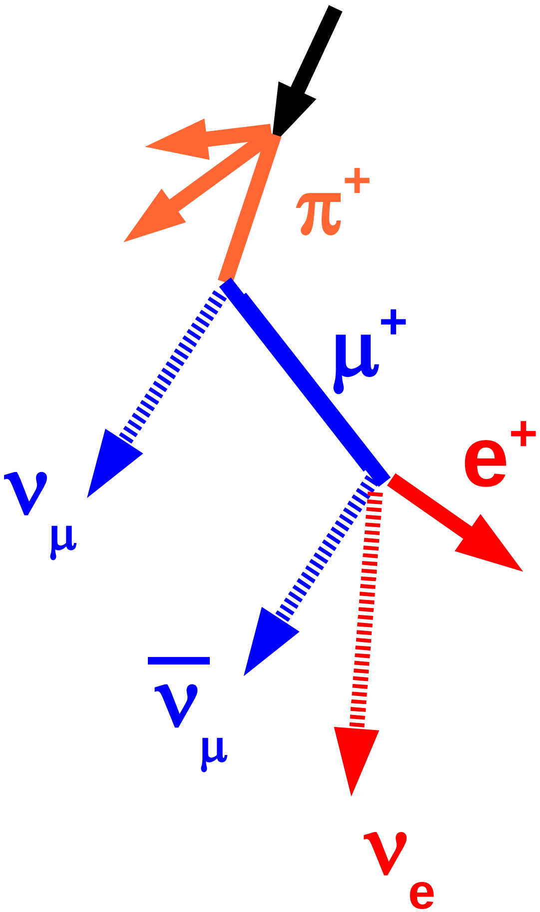
$\nu_e \rightarrow \nu_x$

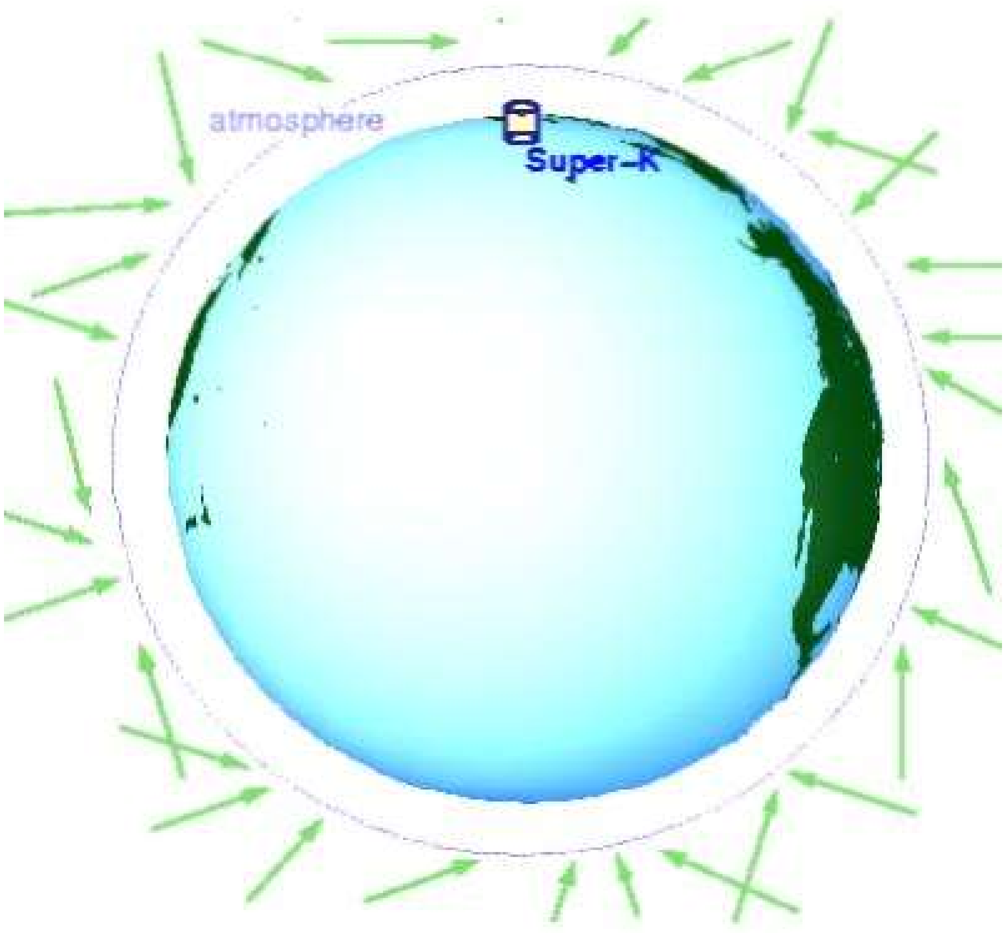
# We will zoom in to atmospheric ν parameter space



# Atmospheric Neutrinos

E~ 0.1-100 GeV
L~10-13000 km



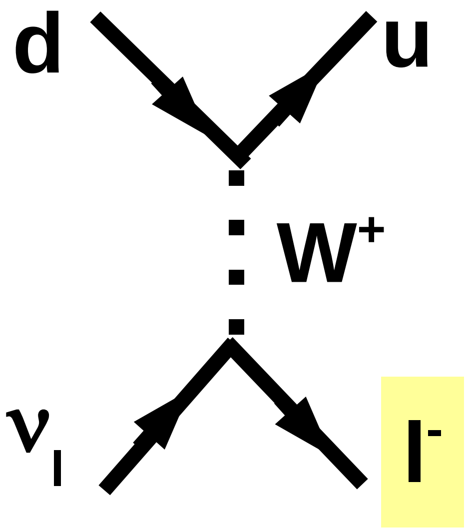




Absolute flux known to ~15%, but *flavor ratio* known to <~5%

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

# Experimental Strategy:

## High energy interactions of ν's with nucleons




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

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

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

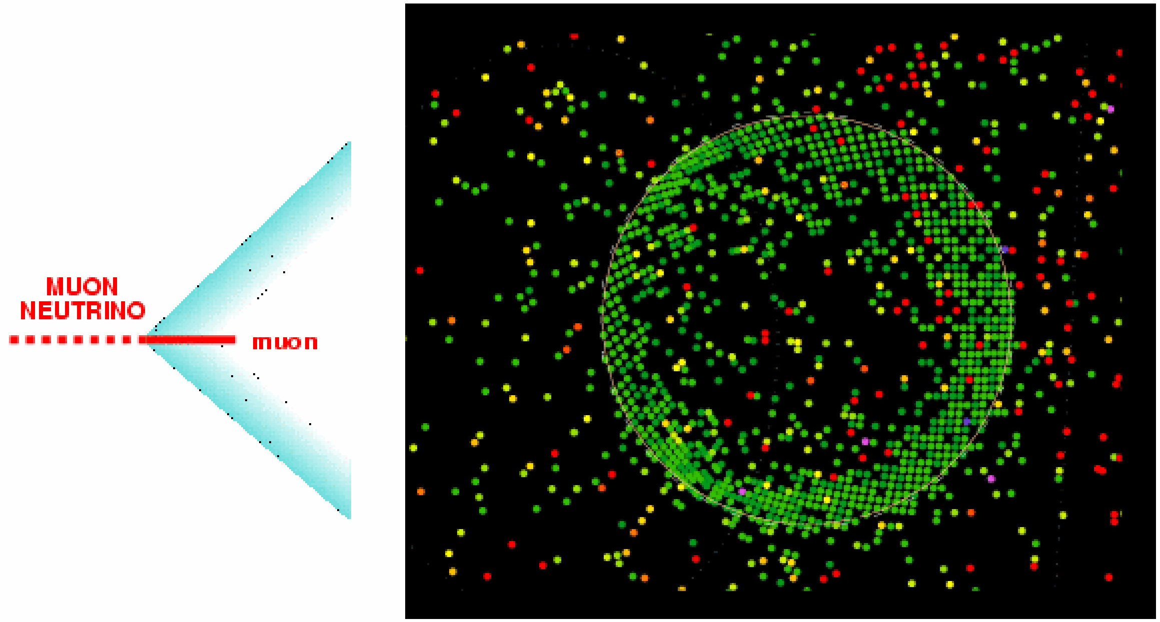
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

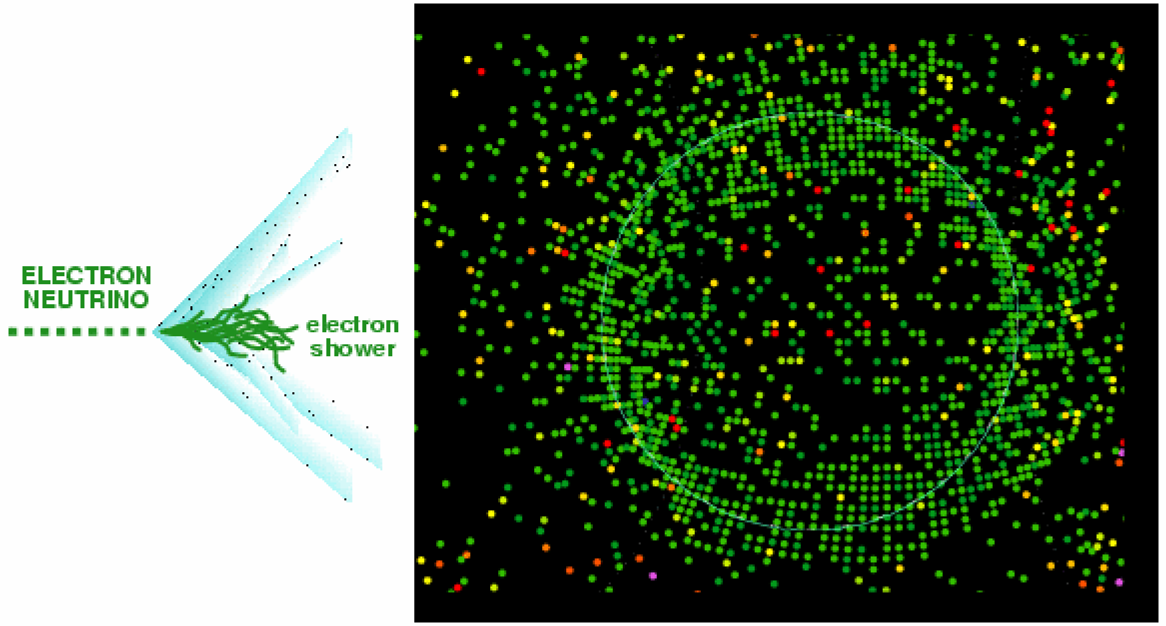
**Tag neutrino flavor by flavor of outgoing lepton**

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

**CC quasi-elastic ("single ring")**

**Also: CC and NC single and multi-π production ("multi-ring")**



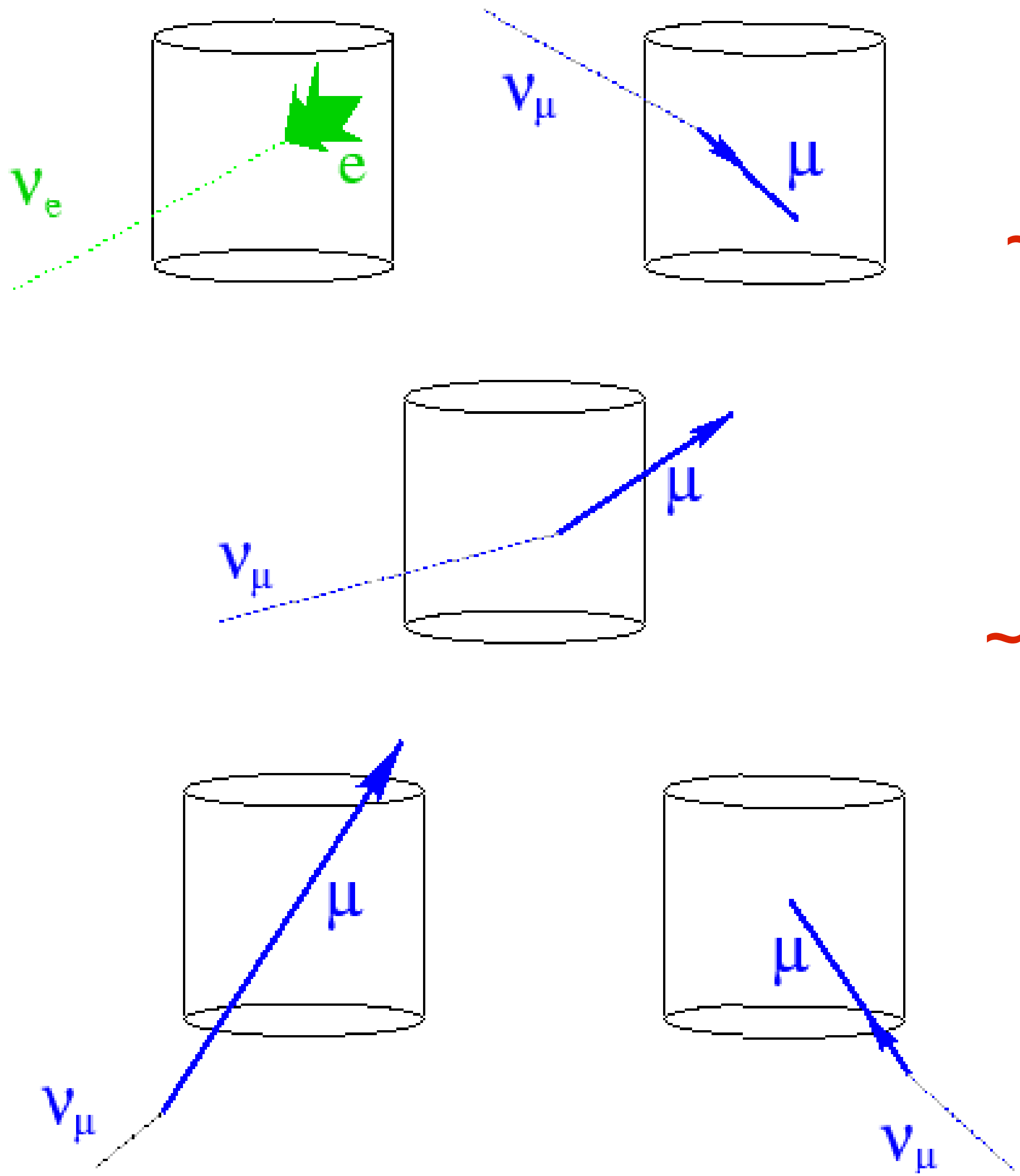




## Get different patterns in Cherenkov light for e and μ

**(sim. for other detector types)**

## From Cherenkov cone get angle, infer pathlength

# High Energy Neutrino Event Topologies




FULLY CONTAINED

~1 GeV

PARTIALLY CONTAINED

~10 GeV

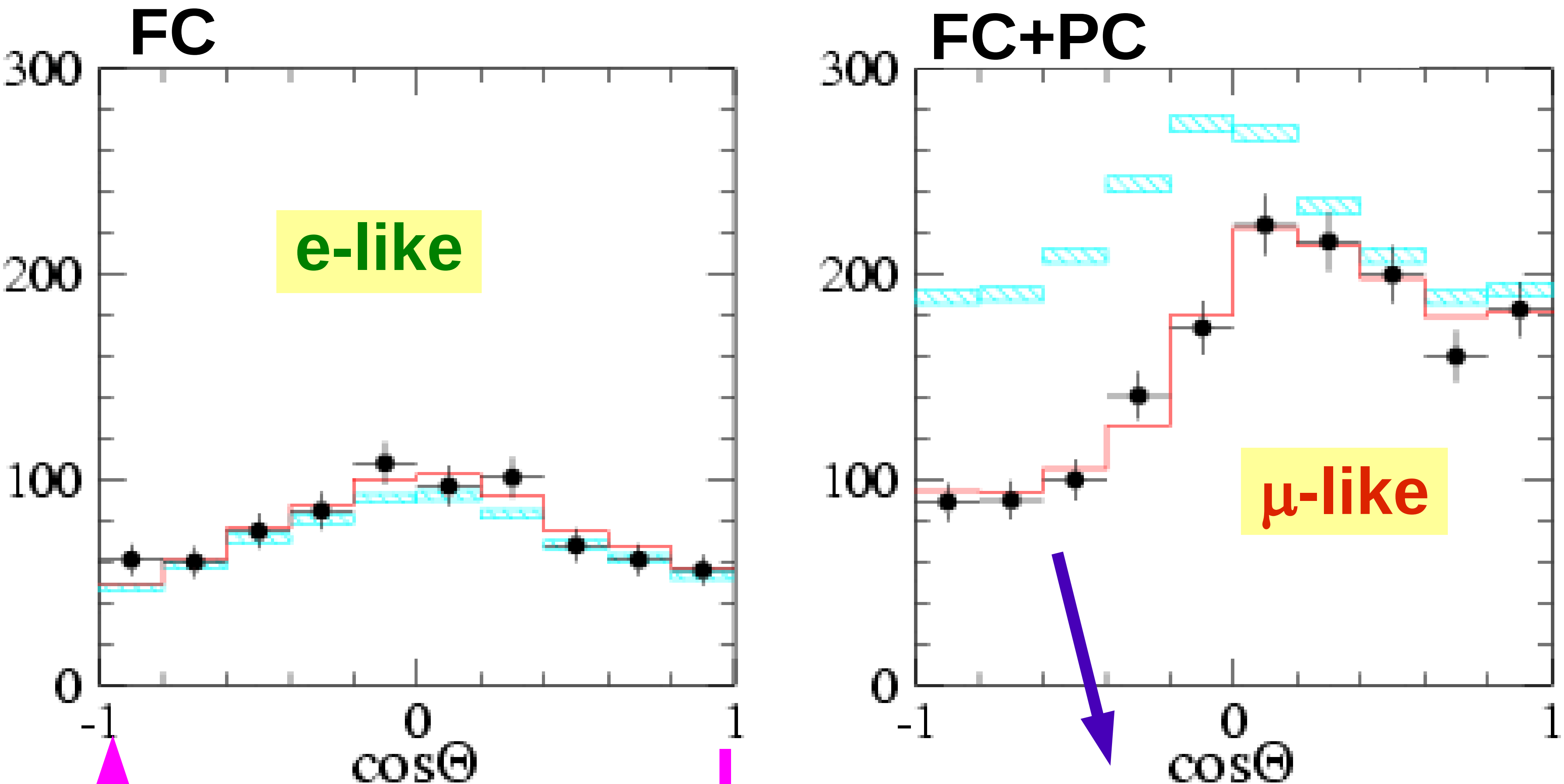
UPWARD GOING MUONS

thru ~100 GeV

stop ~10 GeV

# Zenith angle distribution

**1489 days of SK data (SKI)**

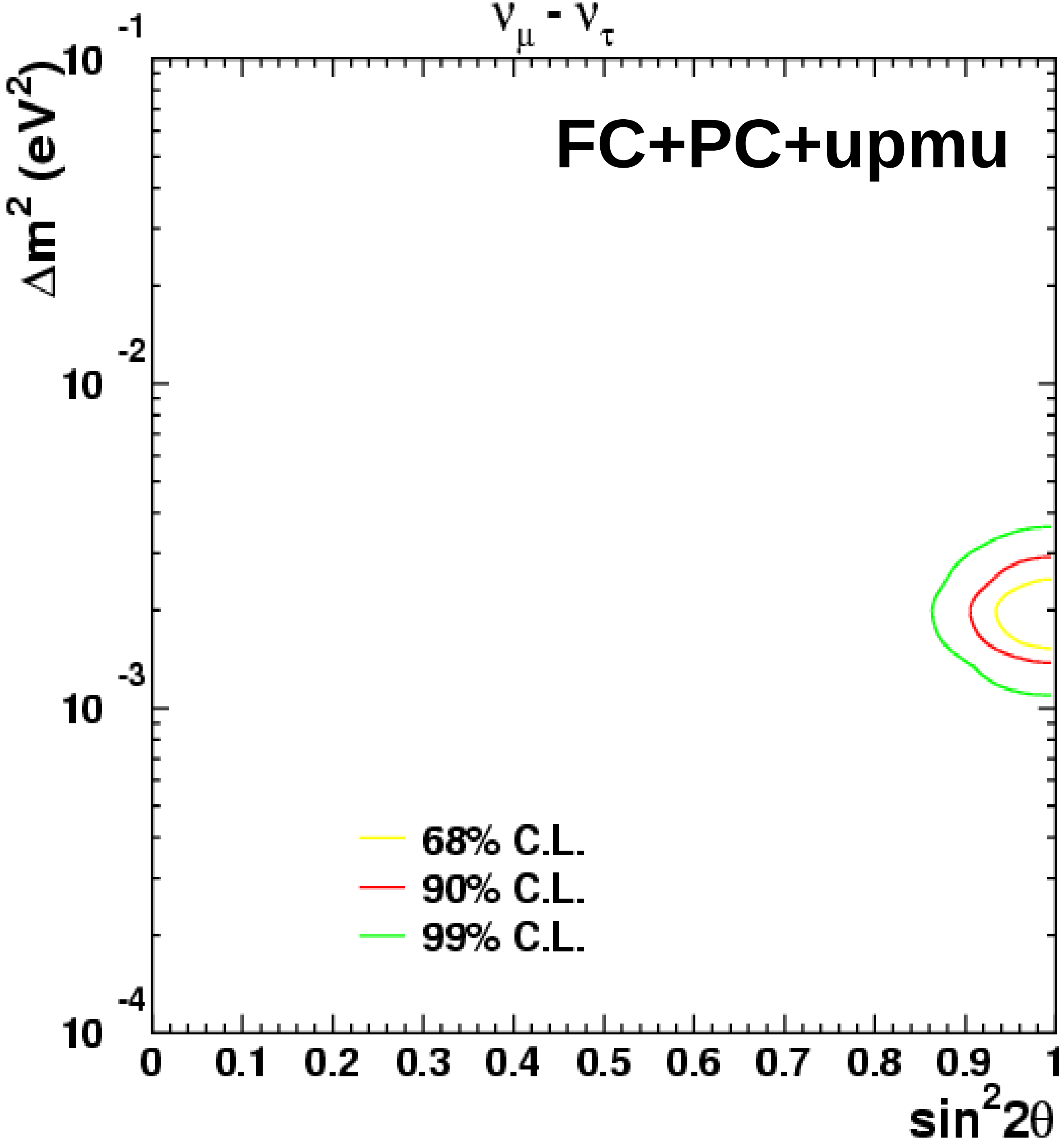



up-going

down-going

**Deficit of $\nu_\mu$**
***from below***
**(long pathlength)**

# Allowed Oscillation Parameters



# Other Atmospheric Neutrino Detectors

## Soudan 2

Minnesota
Iron calorimeter
Contained events
and horizontal muons


## MACRO

Gran Sasso, Italy
Scintillator + streamer tubes

Upward-going muons

**Results are consistent !**

# Summary

**If neutrinos *change flavor* (oscillate), then they *must have mass***

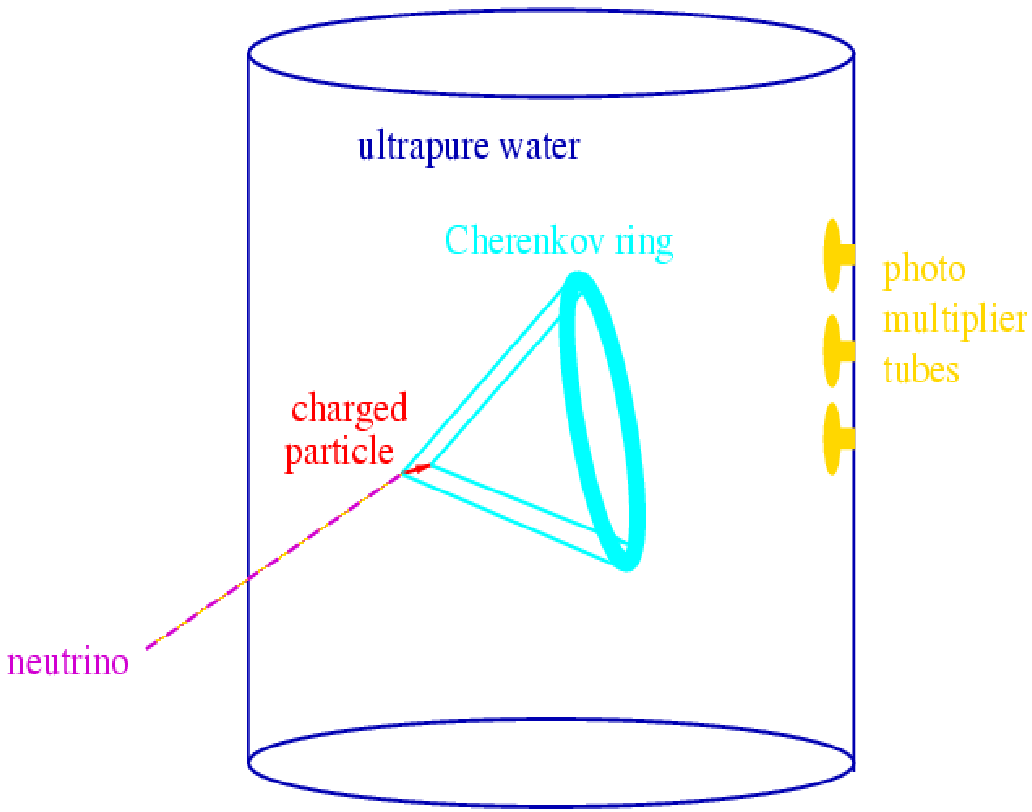
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

**Atmospheric muon neutrinos are changing flavor ('disappearing') as they travel through the Earth:**

**This measurement in SK was the first clear indication of neutrino mass and oscillation**

**The parameters (amplitude and wavelength) are being more precisely measured**

# Reminder from last week:




**Neutrino → Charged particle → Cherenkov light → Photomultiplier tube hit → Digitized pulse (charge, time) → Reconstructed energy, vertex, direction**

## A sample program which accesses the data:

- Open data file (skopenf)
- Loop over events
  - Read one event (skread)
    (information stashed locally)
  - Loop over PMT hits
    - For each hit, fill charge
      and time histograms
- Close data file (skclosef)
- Output histogram

**Later, view histogram with PAW (or Root)**

# First exercises:  (physics Linux cluster)

1. Run superscan to eyeball data files

2.1  Set up and run sample program to look at charges and times for events

TODAY

2.2  Make and view histograms (distributions)

3. Modify program to histogram PMT hit times