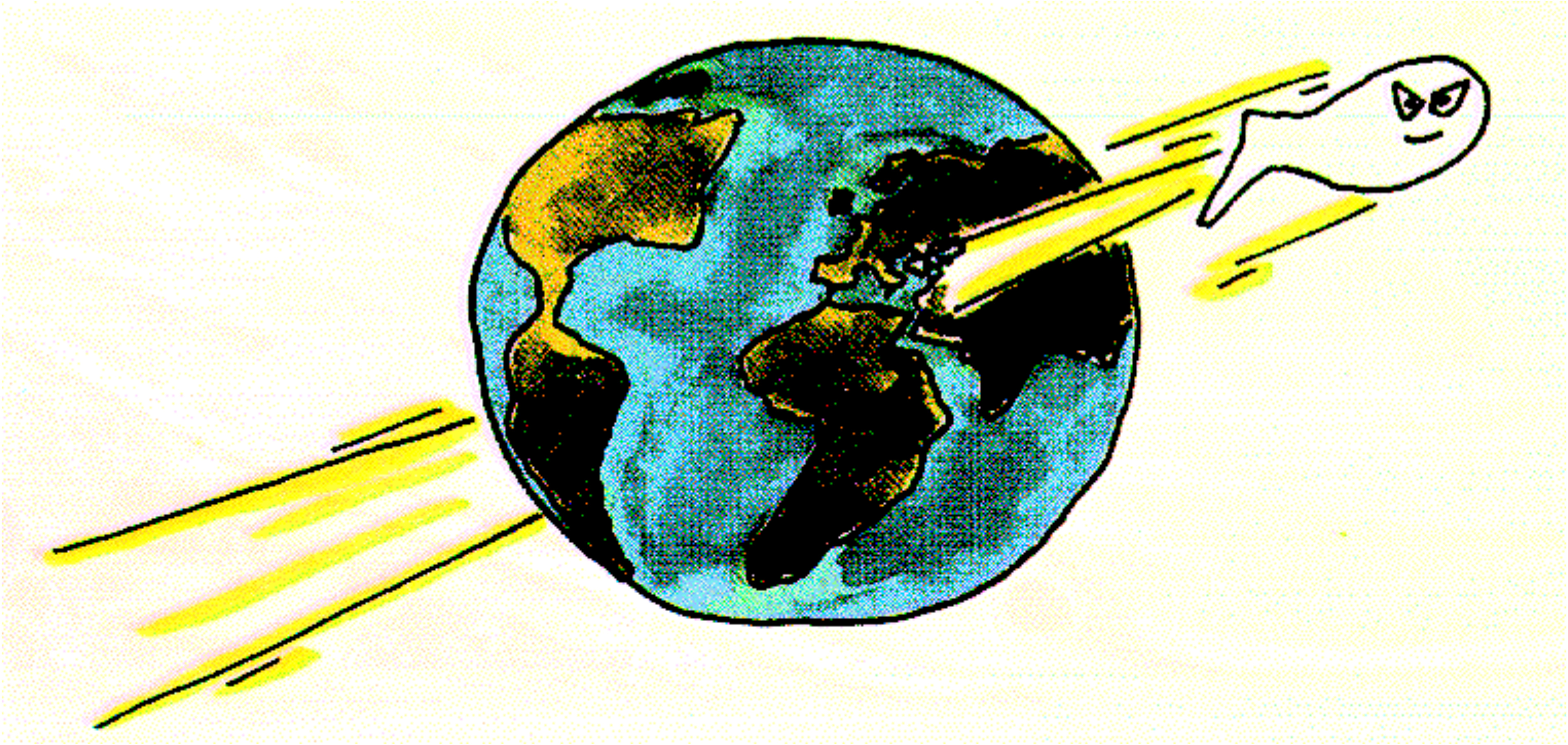
Neutrino Physics

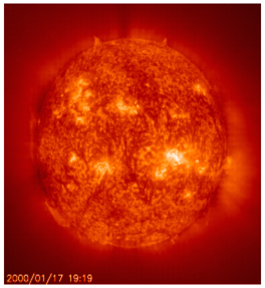


Kate Scholberg, Duke University

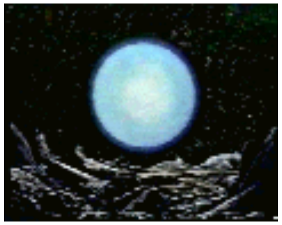
Lecture Plan

Lecture #1: Neutrino Mass and Oscillations

Lecture #2: Solar Neutrinos



Lecture #3: Supernova Neutrinos



Lecture #1

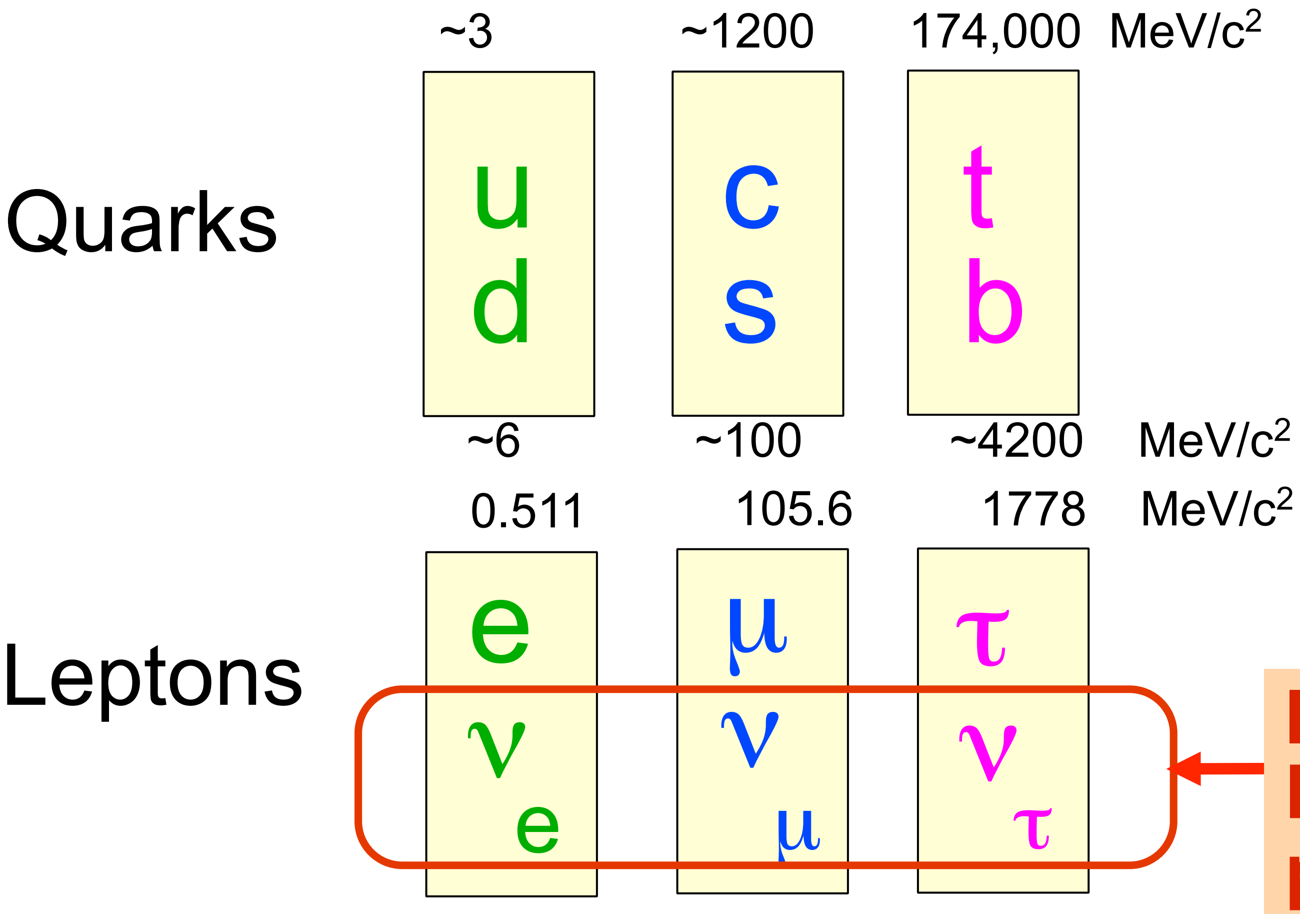
- Neutrinos and why they matter
- Neutrino mass and oscillations

- Atmospheric neutrinos
- Long-baseline beam experiments

- Beyond 2-flavor: θ_{13}, CP violation, hierarchy
- Next questions and generation of experiments

- Hunting down anomalies

NEUTRINOS

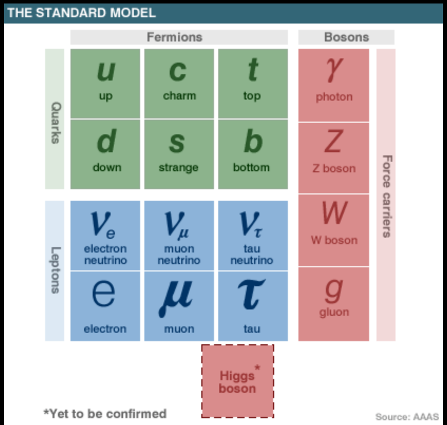


	~3	~1200	174,000	MeV/c^2
Quarks	u	c	t	
	d	s	b	
	~6	~100	~4200	MeV/c^2
	0.511	105.6	1778	MeV/c^2
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	

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* (& gravity)**
- **Tiny mass (< 1 eV)**

Why do neutrinos matter?



THE STANDARD MODEL

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
		Higgs* boson			

*Yet to be confirmed

Source: AAAS

fundamental particles and interactions

astrophysical systems

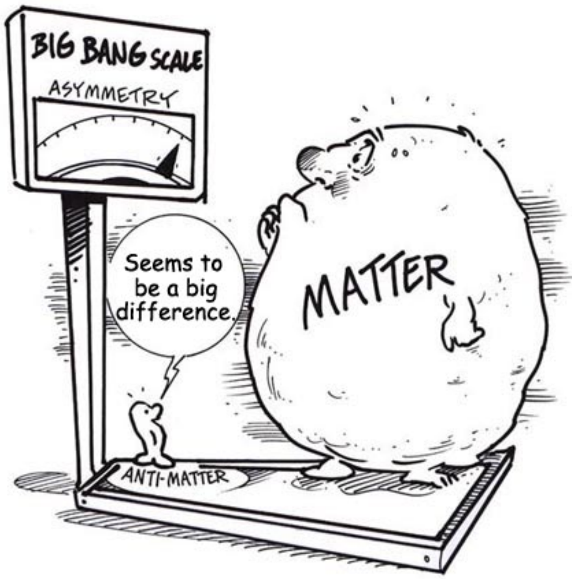
cosmology

nuclear physics

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

And in particular: understanding of neutrino parameters may give insight into the origin of

MATTER-ANTIMATTER ASYMMETRY



$$\eta = \frac{(\eta_b - \eta_{\bar{b}})}{\eta_\gamma} = \frac{\eta_B}{\eta_\gamma} \sim 10^{-10}$$

Mechanism of asymmetry generation not known...

But knowledge of ν properties essential for understanding!

charge conjugation

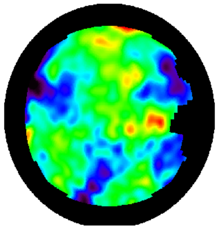
parity

CP violation is likely involved: a difference in behavior between a particle and its mirror-inverted antiparticle: *observed so far in quarks but not leptons*

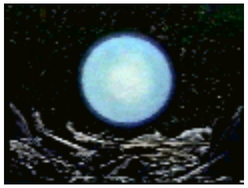
Sources of wild neutrinos

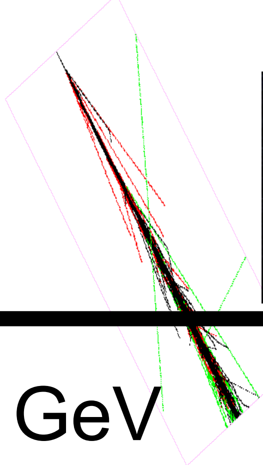
The Atmosphere (cosmic rays)

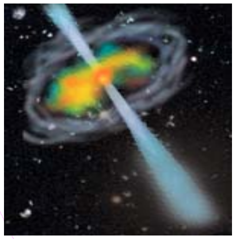
The Big Bang



Super novae



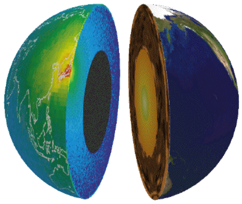


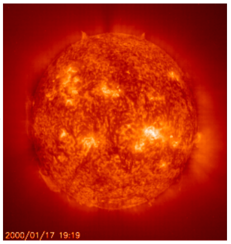


AGN's, GRB's

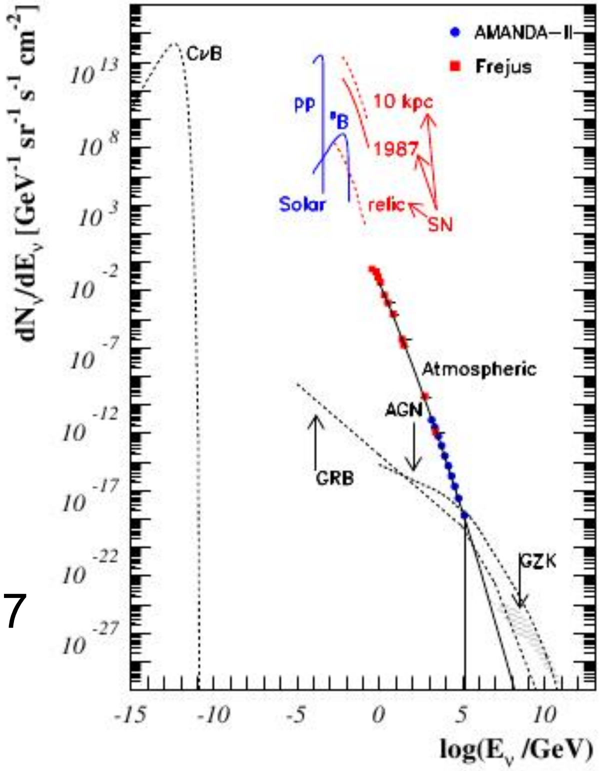
meV eV keV MeV GeV TeV PeV EeV

Radioactive decay in the Earth





The Sun

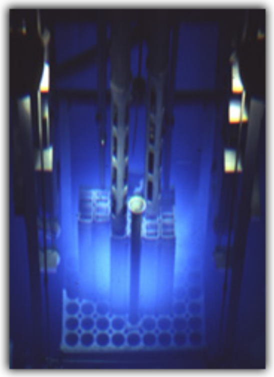


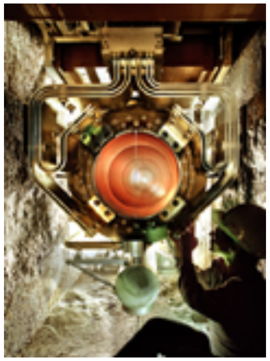
J. Becker, arXiv:0710.1557

Sources of 'tame' neutrinos

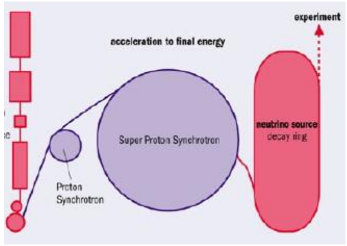
Proton accelerators

Nuclear reactors



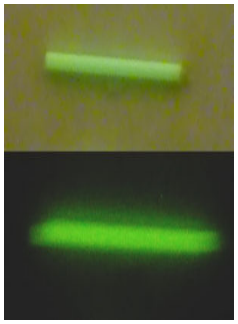


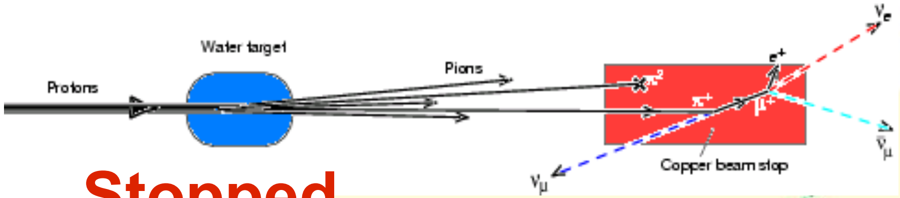
Beta beams



eV keV MeV GeV TeV

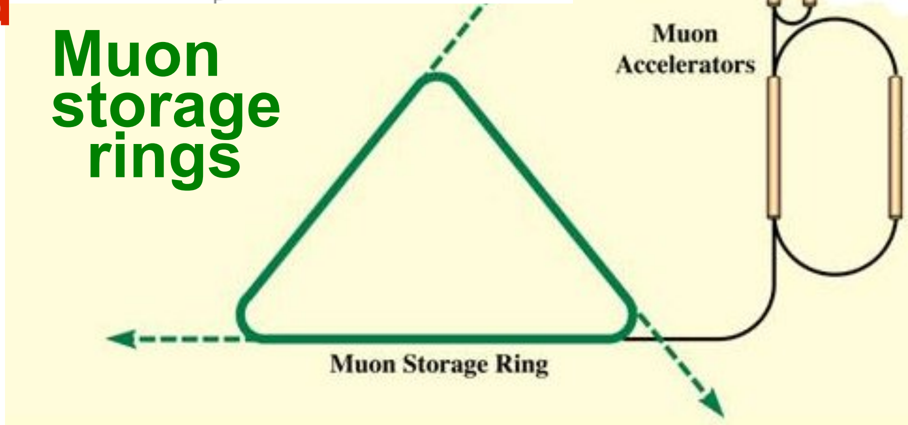
Artificial radioactive sources





Stopped pion sources

Muon storage rings

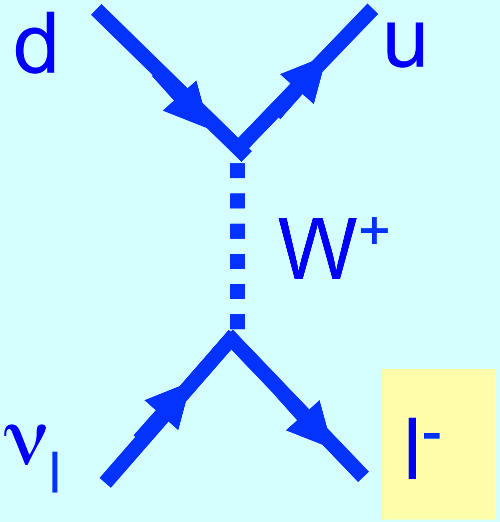


Usually (but not always) better understood...

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

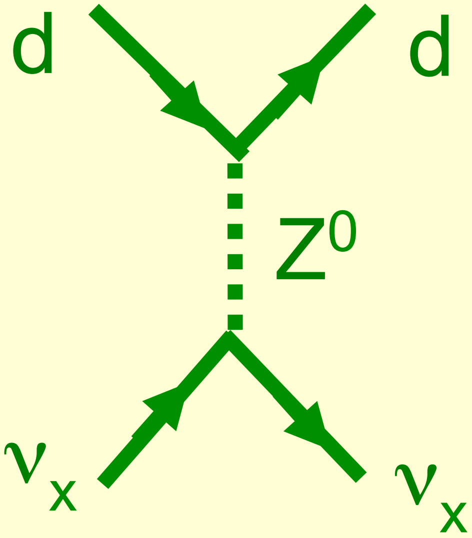


$$\nu_l + N \rightarrow l^{\pm} + N'$$

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?

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate (essentially, interference between mass states)

Simple two-flavor case

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

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

Propagate a distance L:

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

Probability of detecting flavor g at L:

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

E in GeV
L in km
Δm^2 in eV^2

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

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

$\Delta m^2 = m_1^2 - m_2^2$

If **flavor oscillations are observed, *then* there must be at least one non-zero mass state**

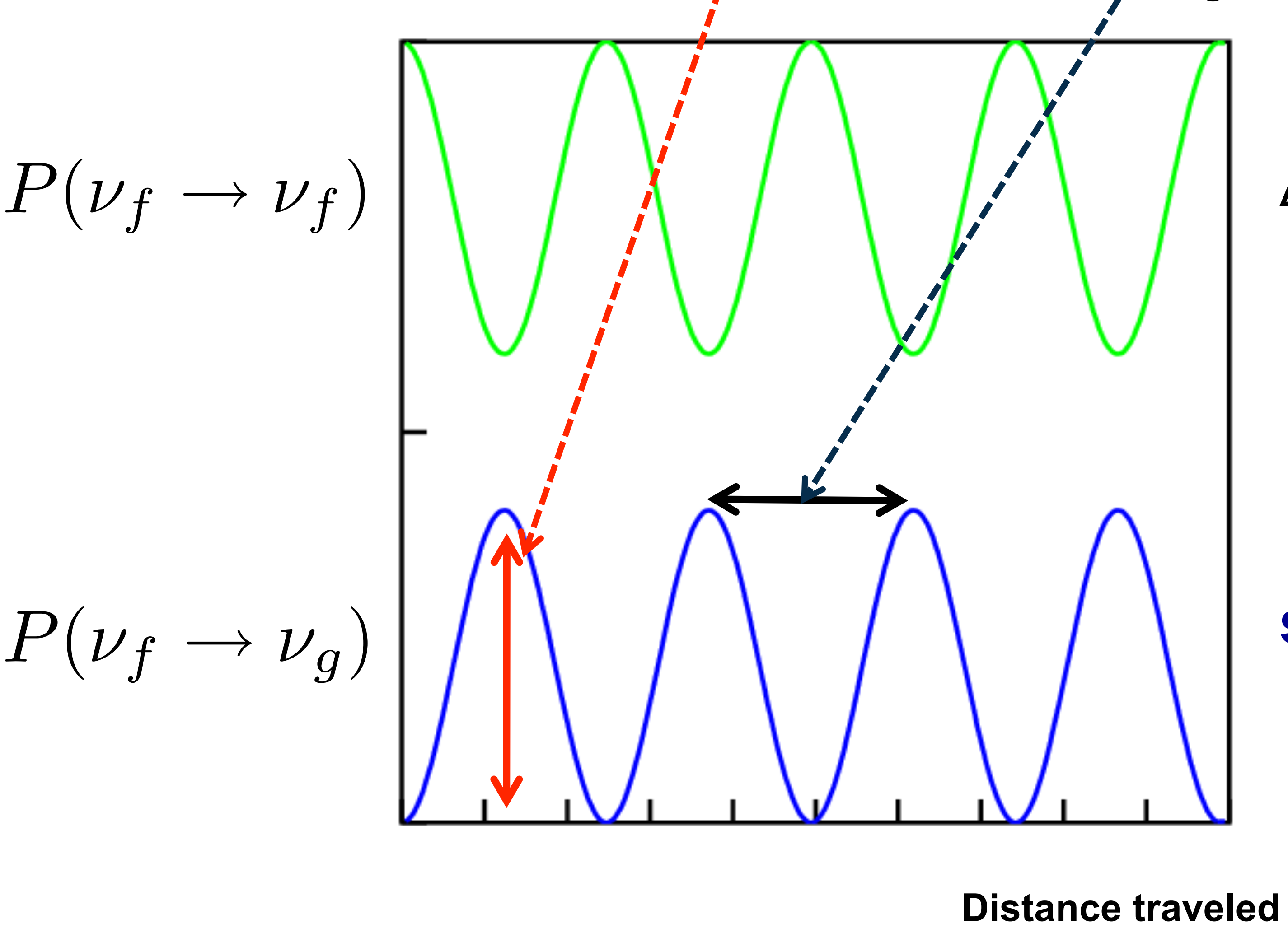
***Note: oscillation depends on mass *differences*, not absolute masses**

In 2-flavor approximation:

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

amplitude

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



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 (wild or tame)
- 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 $P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$**?**

Disappearance: ν's oscillate into 'invisible' flavor

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

Appearance: directly see new flavor

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

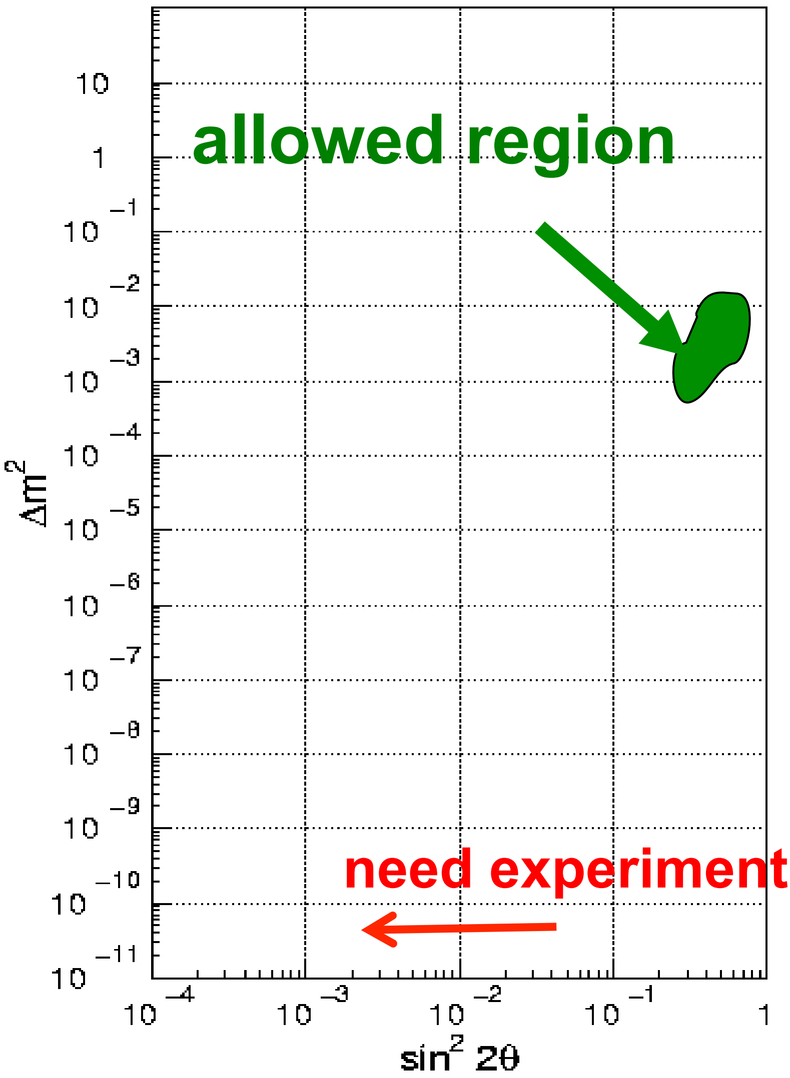
Neutrino oscillation parameter space

amplitude

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

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

change L/E



allowed region

need experimental statistics

But we have *three* flavors: oscillation probability can be computed straightforwardly

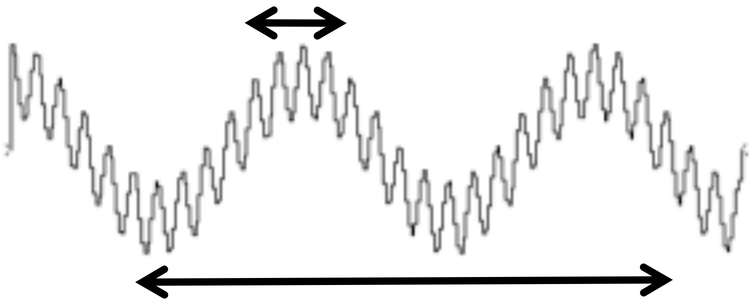
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad (\mathrm{L\ in\ km,\ \ E\ in\ GeV,\ \ m\ in\ eV})$$

$$P(\nu_f \rightarrow \nu_g) = \delta_{fg} - 4\sum_{j>i} \mathrm{Re}(\mathrm{U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*}})\boxed{\mathrm{sin}^2(1.27\Delta \mathrm{m_{ij}^2 L/E_\nu})}$$

$$\pm 2\sum_{j>i} \mathrm{Im}(\mathrm{U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*}})\boxed{\mathrm{sin}^2(2.54\Delta \mathrm{m_{ij}^2 L/E_\nu})}$$

oscillatory behavior in L and E



$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ **two frequency scales**

For appropriate L/E (and U_{ij}), oscillations “decouple”, and probability can be described the two-flavor expression

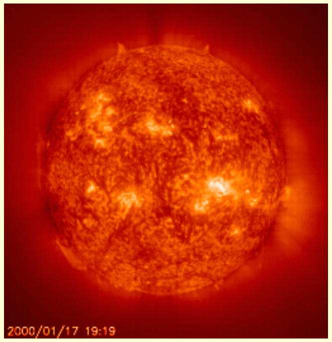
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

We now have strong evidence for flavor oscillations:

In each case, first measurement with ‘wild’ ν’s was confirmed and improved with ‘tame’ ones

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

SOLAR NEUTRINOS



Electron neutrinos from the Sun are *disappearing*...

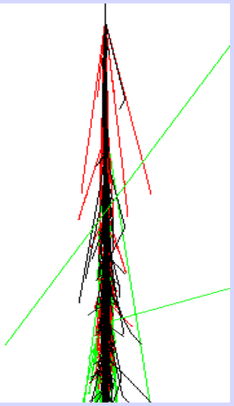
$$\nu_e \longrightarrow \nu_\mu, \nu_\tau$$

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

... now confirmed by a reactor experiment

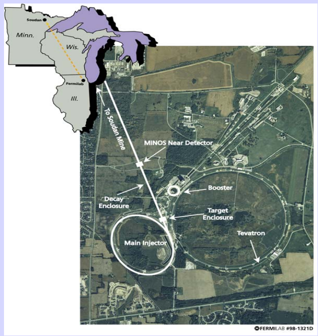
Described by θ_{12}, Δm^2_{12}

ATMOSPHERIC NEUTRINOS



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

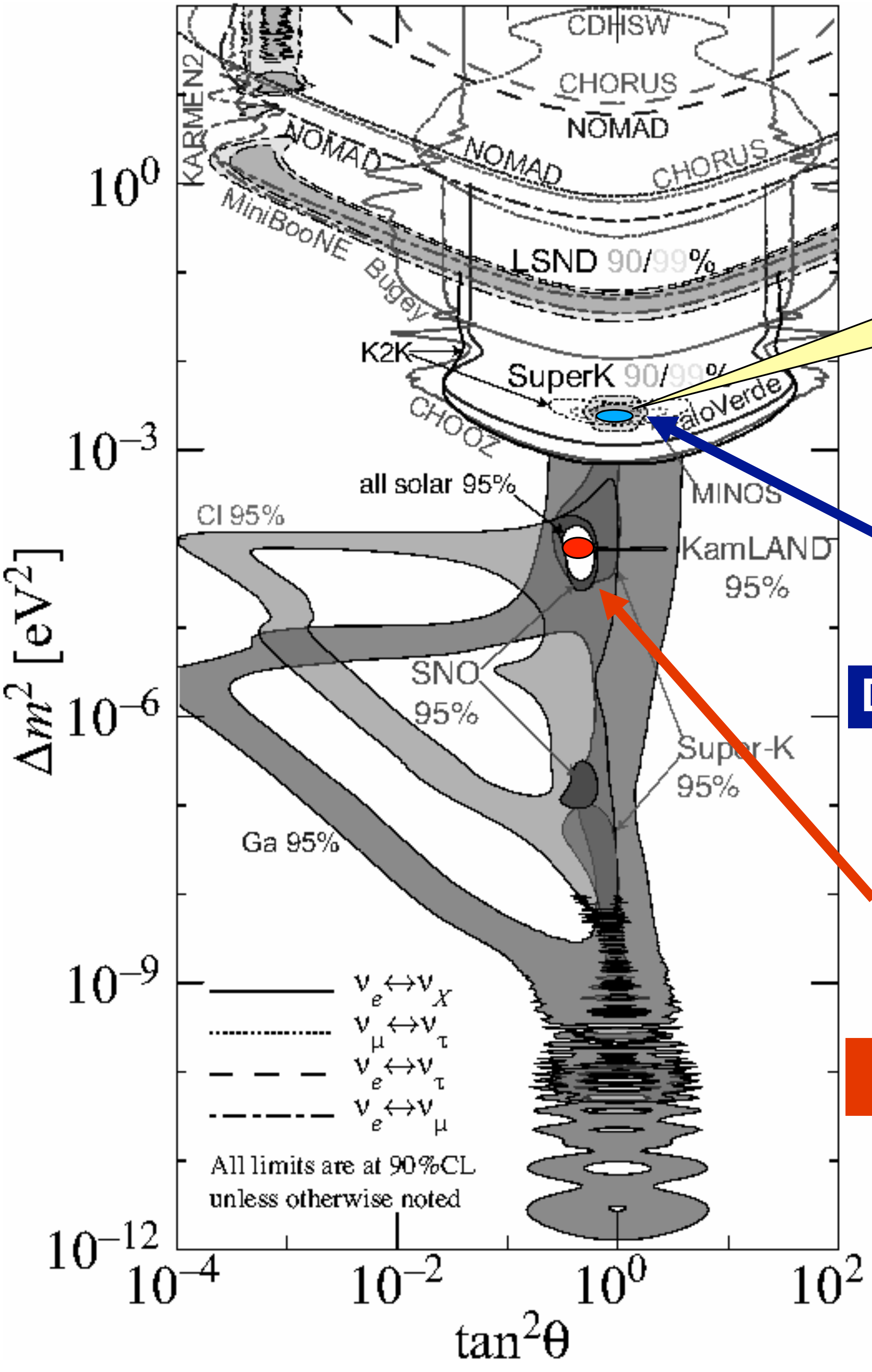
$$\nu_\mu \longrightarrow \nu_\tau$$



...now confirmed by beam experiments

Described by θ_{23}, Δm^2_{23}

In fifteen years parameters have been shrunk down many orders of magnitude!



zoom in here

atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

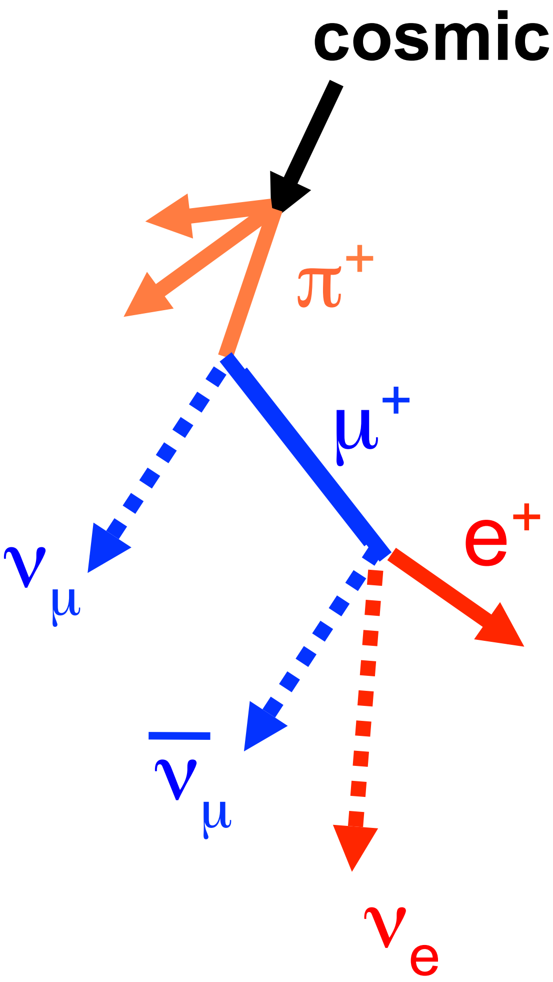
Described by θ_{12}, Δm^2_{12}

tomorrow

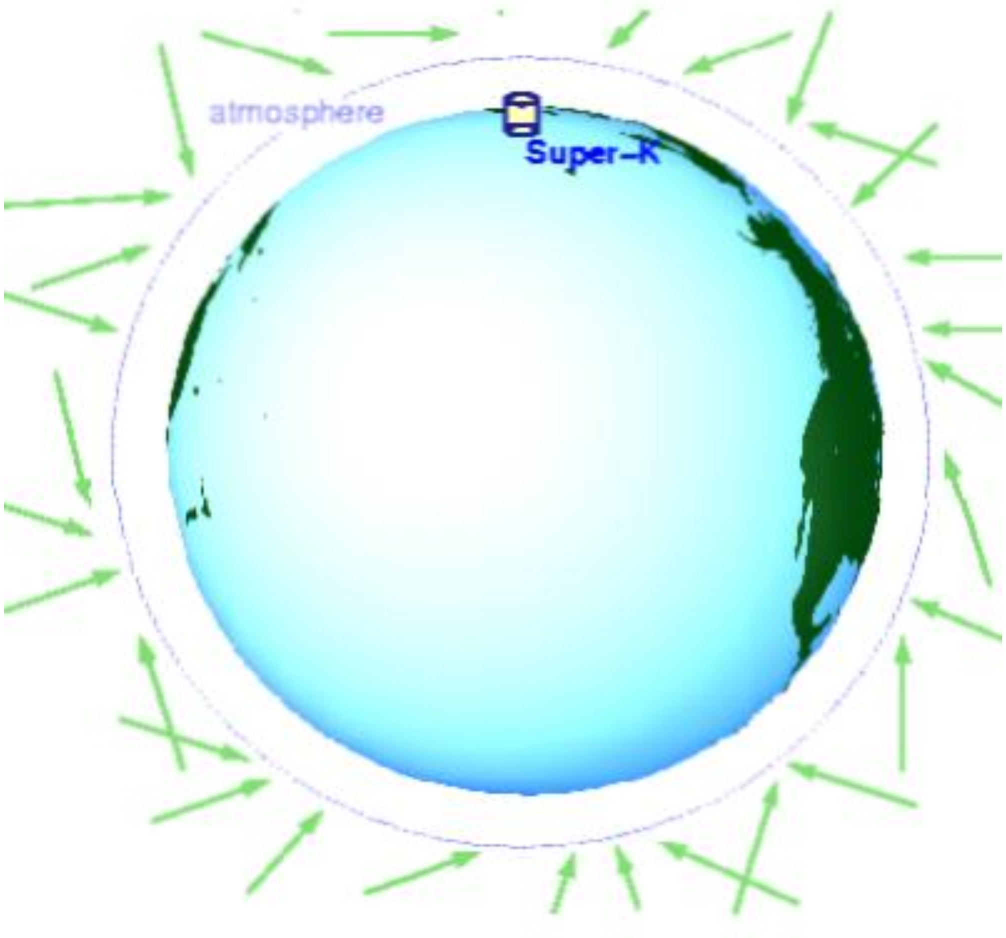
Atmospheric Neutrinos

E~ 0.1-100 GeV

L~10-13000 km



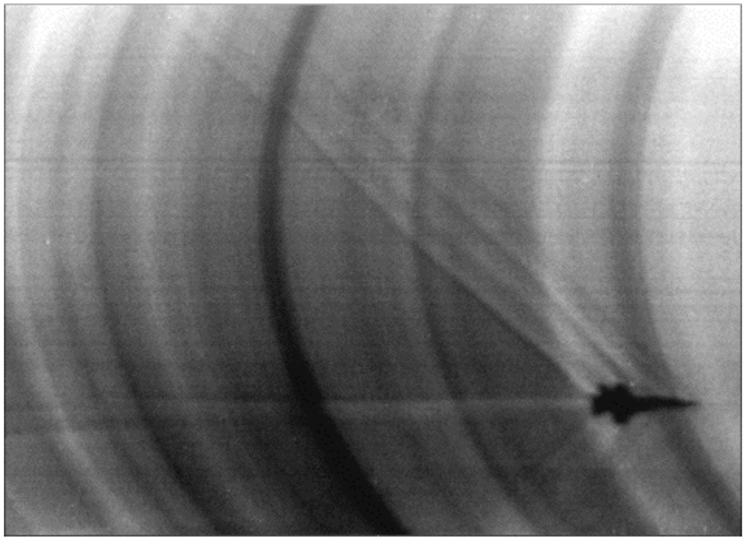
Absolute flux known to ~15%, but *flavor ratio* known to ~5%

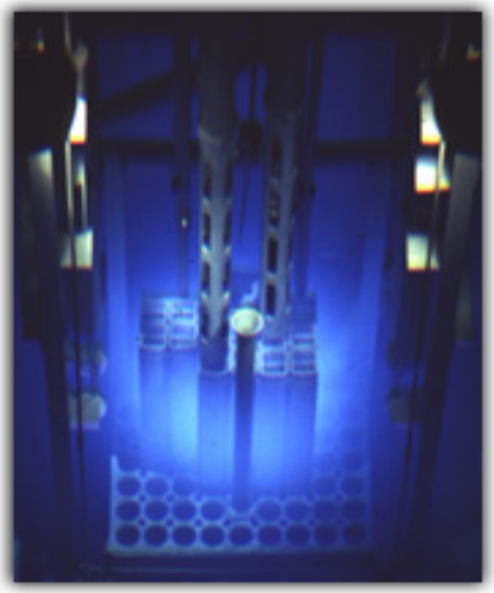


By geometry, expect flux with *up-down symmetry* above ~1 GeV (no geomagnetic effects)

Detecting Neutrinos with Cherenkov Light

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





Thresholds (MeV)

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

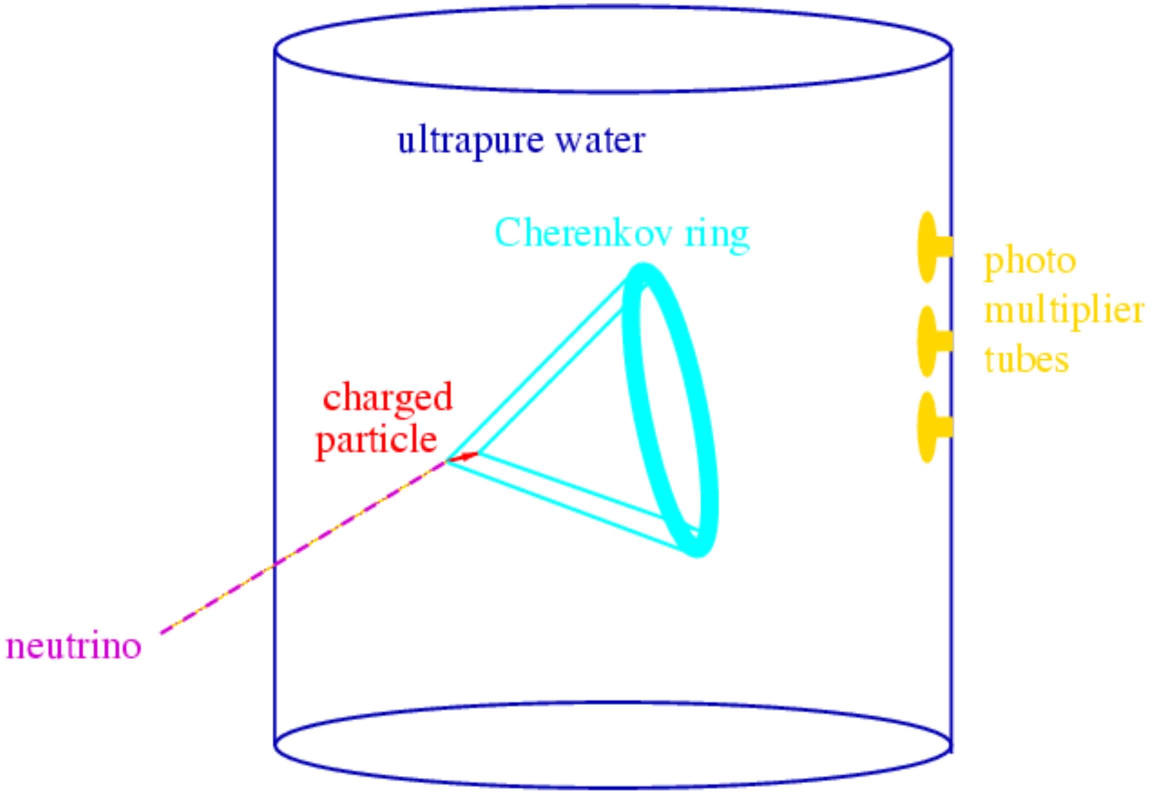
e	0.73
μ	150
π	200
p	1350

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

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

No. of photons ∝ energy loss

Water Cherenkov ν Detectors



Photons

⇨ **photoelectrons**

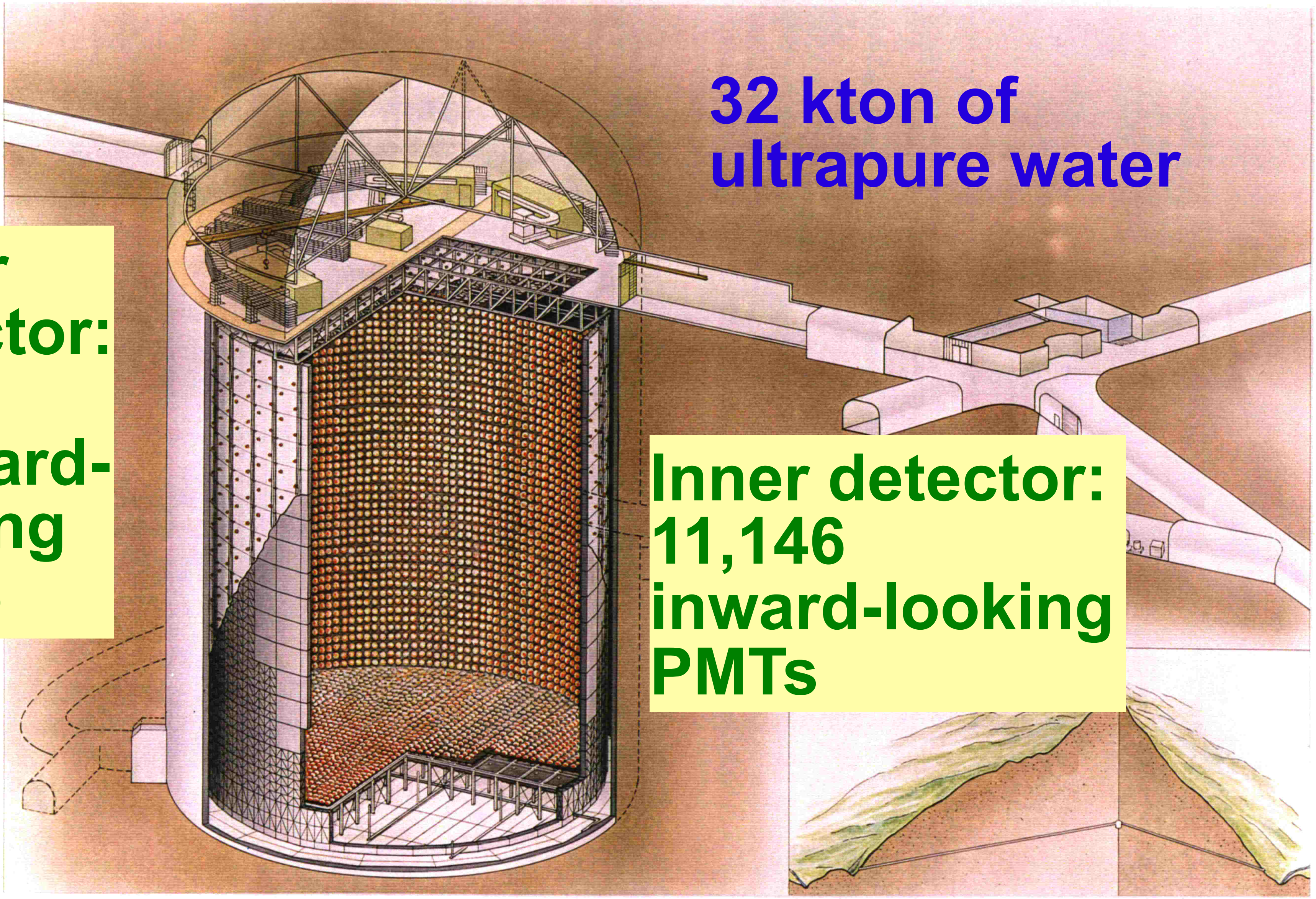
⇨ **PMT pulses**

⇨ **digitize charge, time**

⇨ **reconstruct energy, direction, vertex**

Super-Kamiokande

Water Cherenkov detector
in Mozumi, Japan

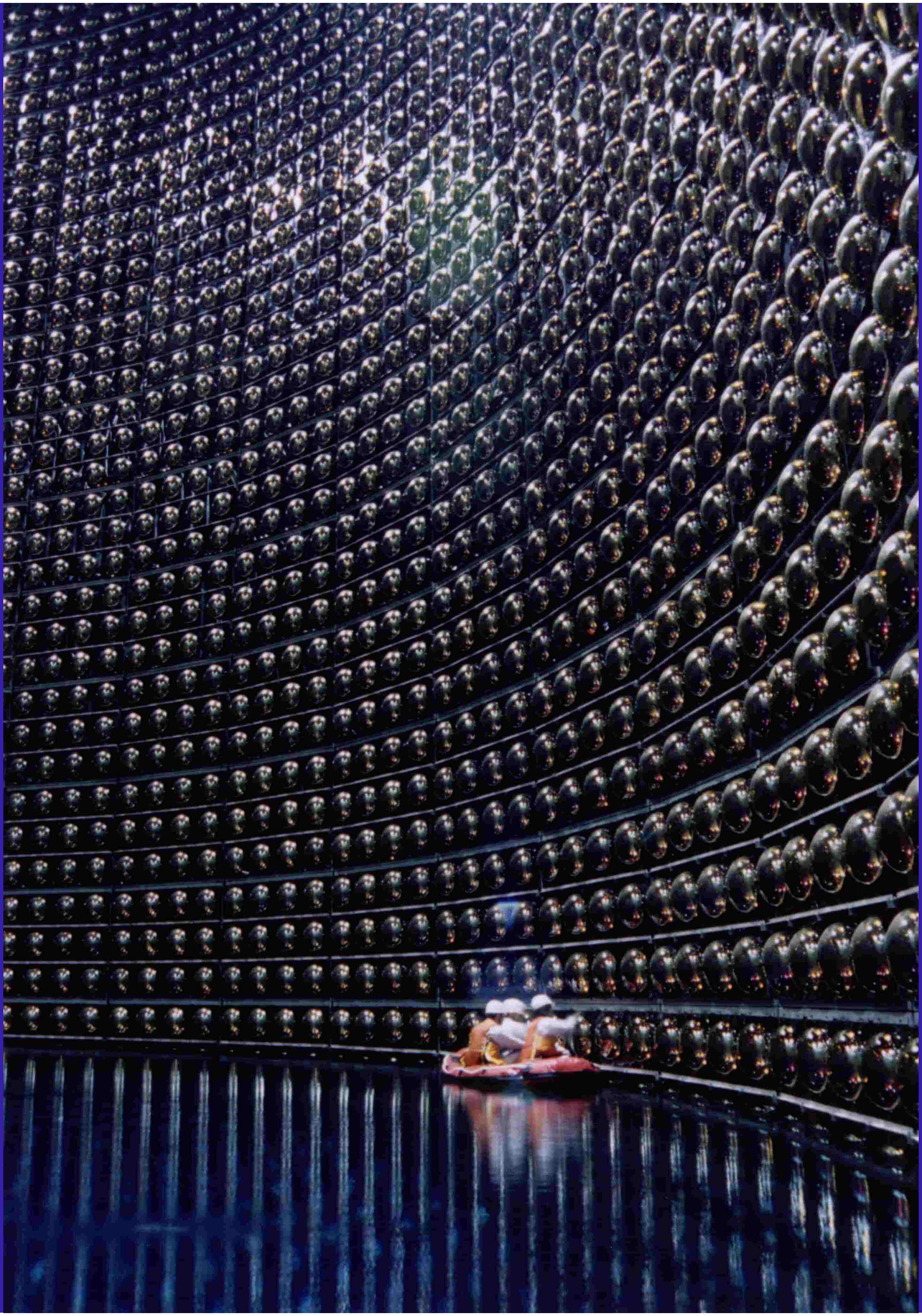


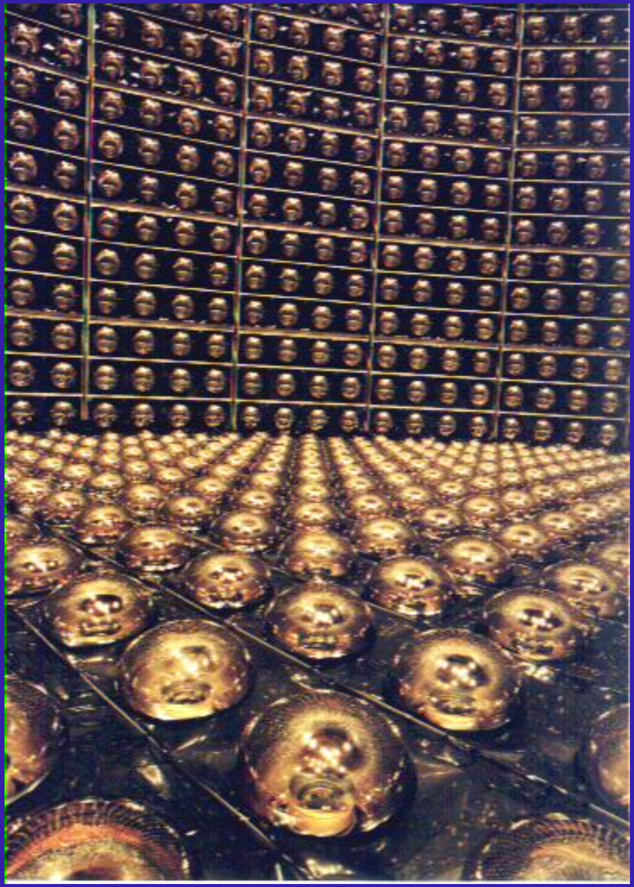
32 kton of
ultrapure water

Outer detector: 1889 outward-looking PMTs

Inner detector: 11,146 inward-looking PMTs

1 km underground to keep away from cosmic rays



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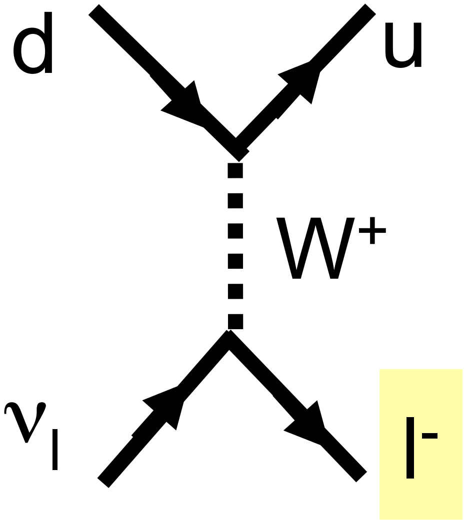
Atmospheric ν's Experimental Strategy:

High energy interactions of ν's with nucleons



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

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

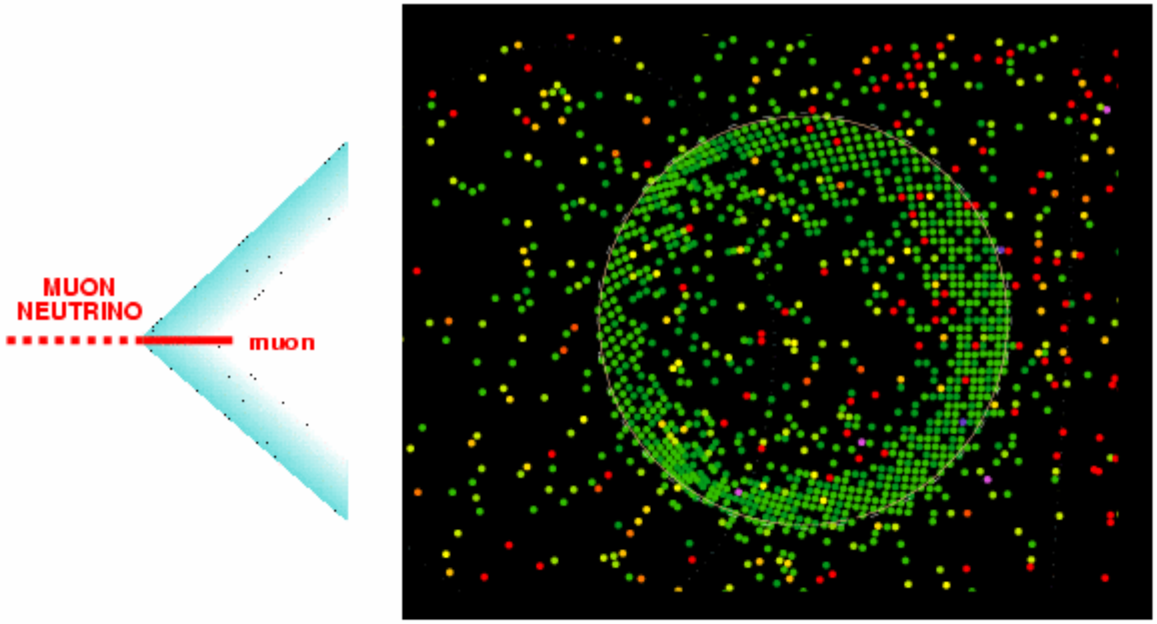
$\nu_\mu + n \rightarrow \mu^- + p$

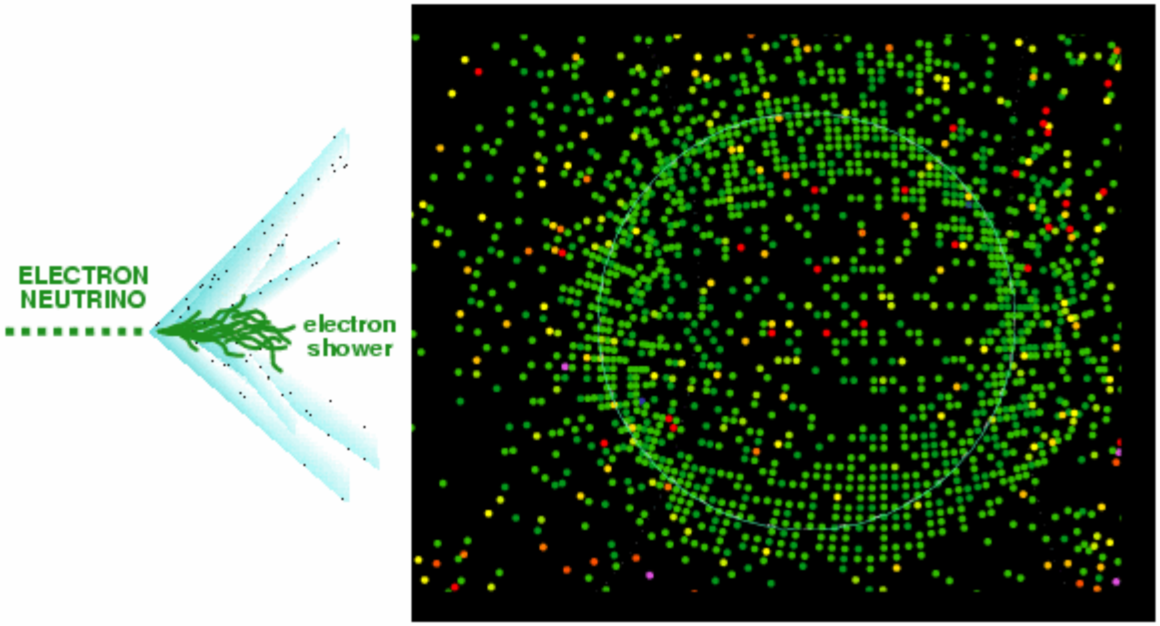
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

Tag neutrino flavor by flavor of outgoing lepton

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

CC quasi-elastic ("single ring")





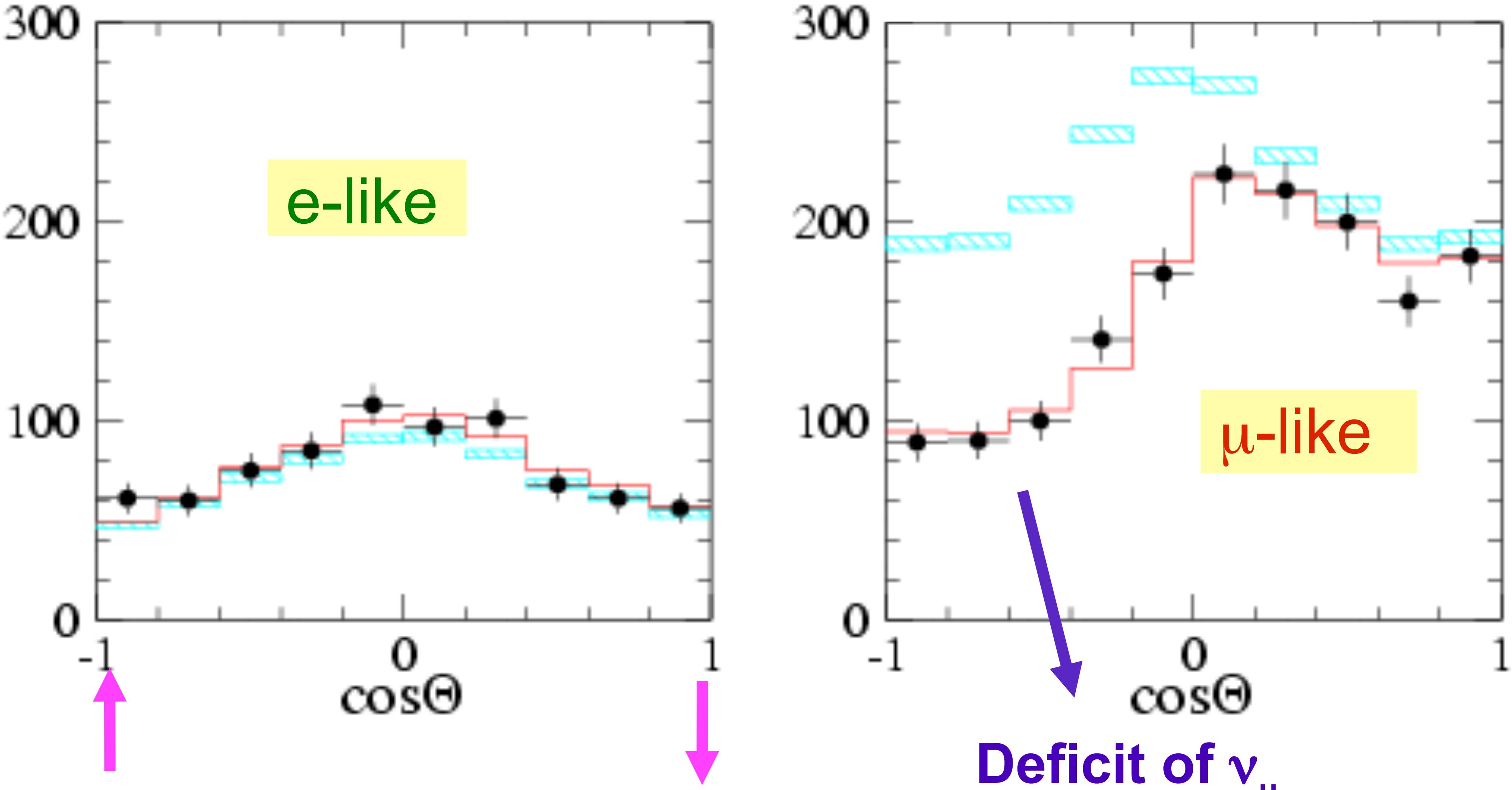
Get different patterns in Cherenkov light for e and μ

(sim. for other detector types)

From Cherenkov cone get angle, infer pathlength

Zenith angle distribution

1489 days of SK data



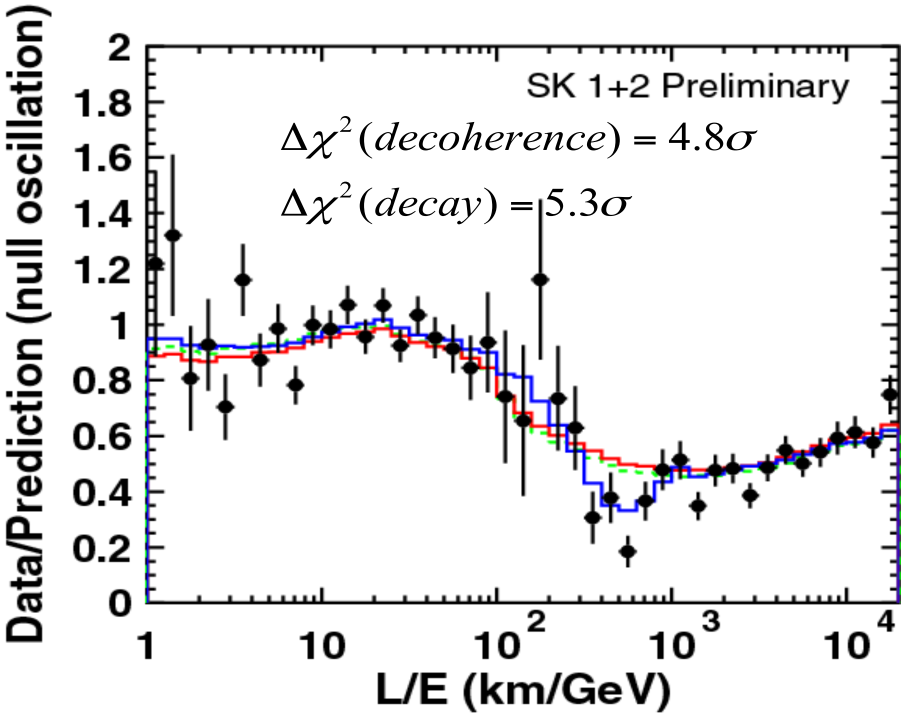
up-going

down-going

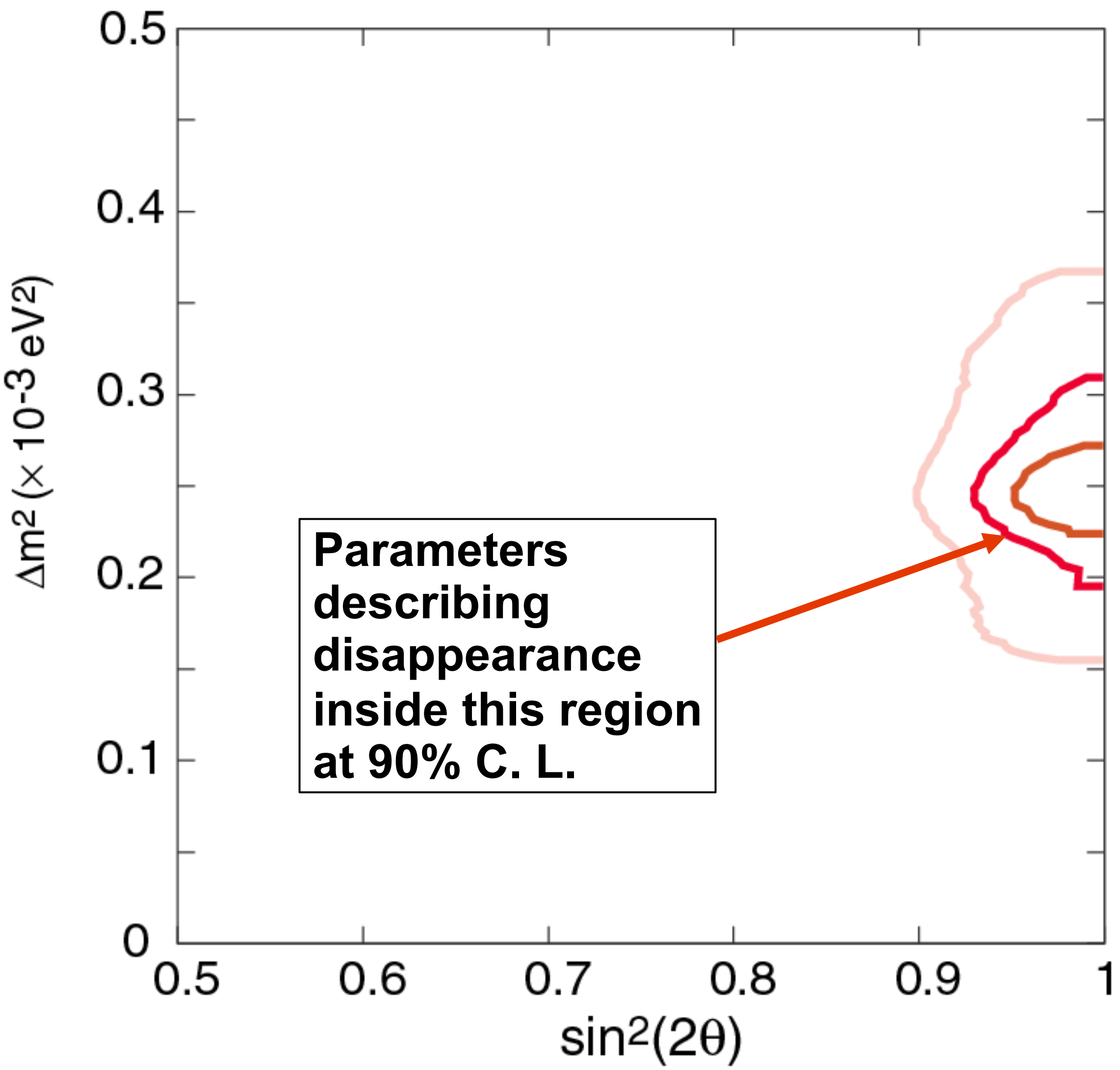
Deficit of ν_μ
from below
(long pathlength)

Allowed Parameters

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



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



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

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

E_ν~ GeV, L~ 100's of km for same L/E

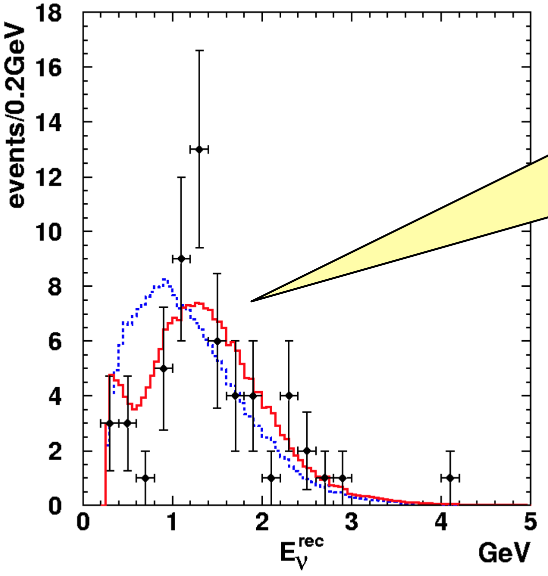
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

LONG-BASELINE EXPERIMENTS

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

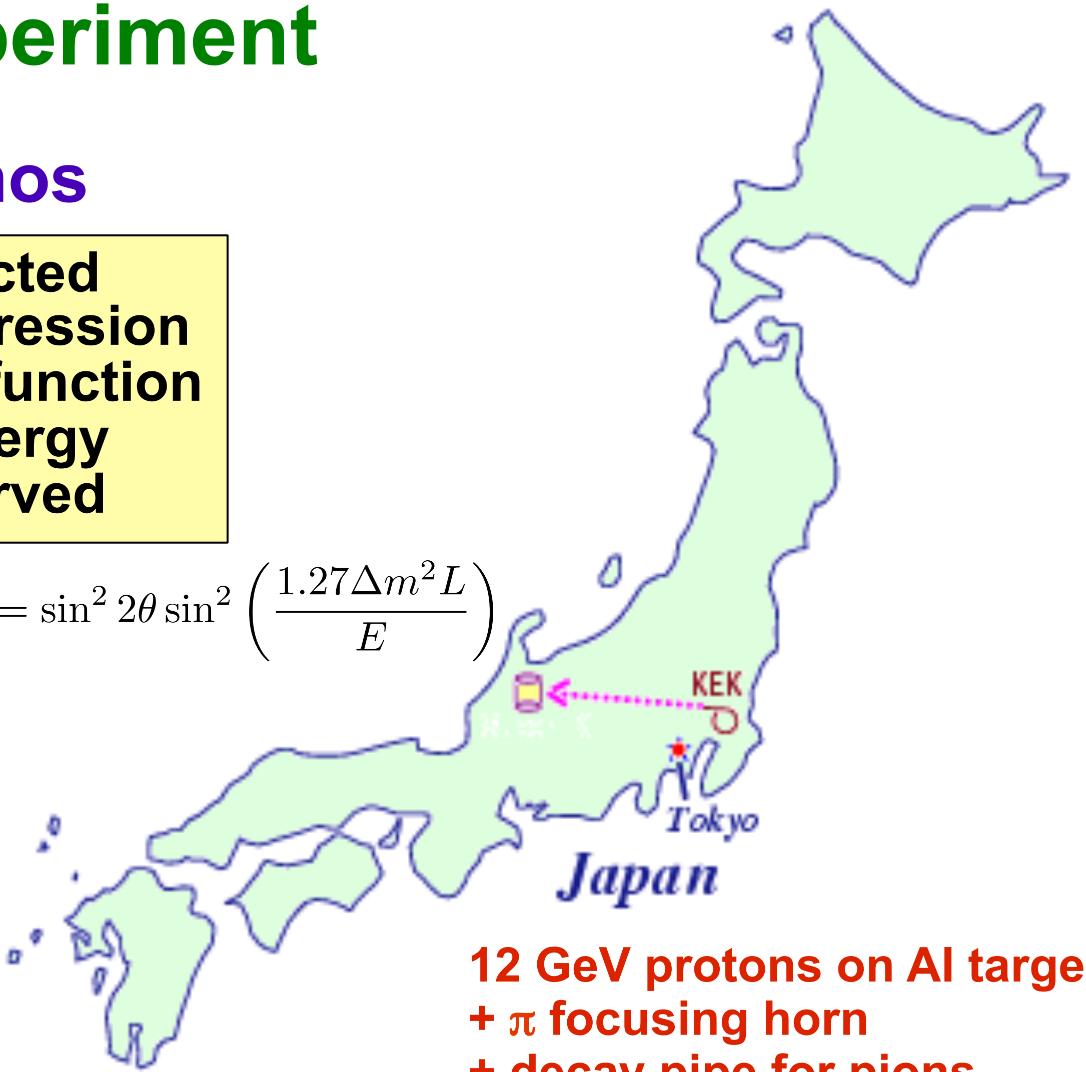
K2K (KEK to Kamioka) Long-Baseline Experiment

~ 1 GeV muon neutrinos



expected suppression as a function of energy observed

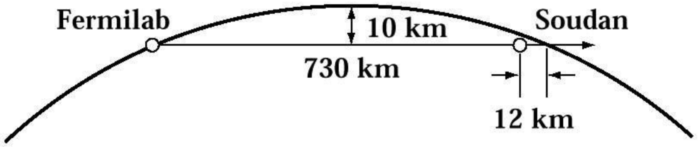
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

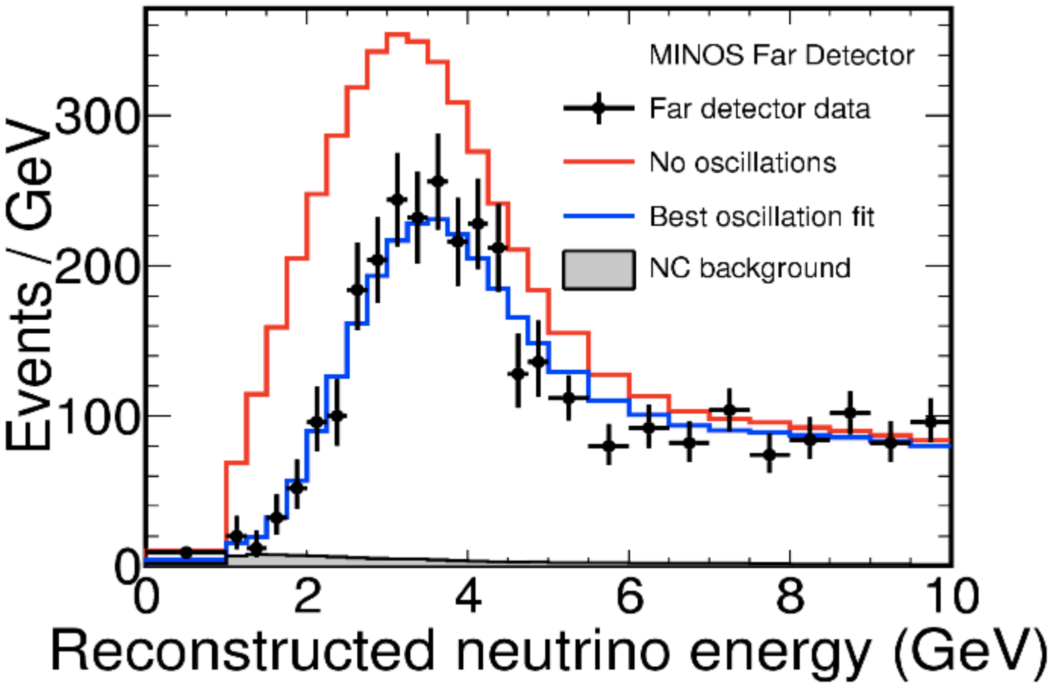


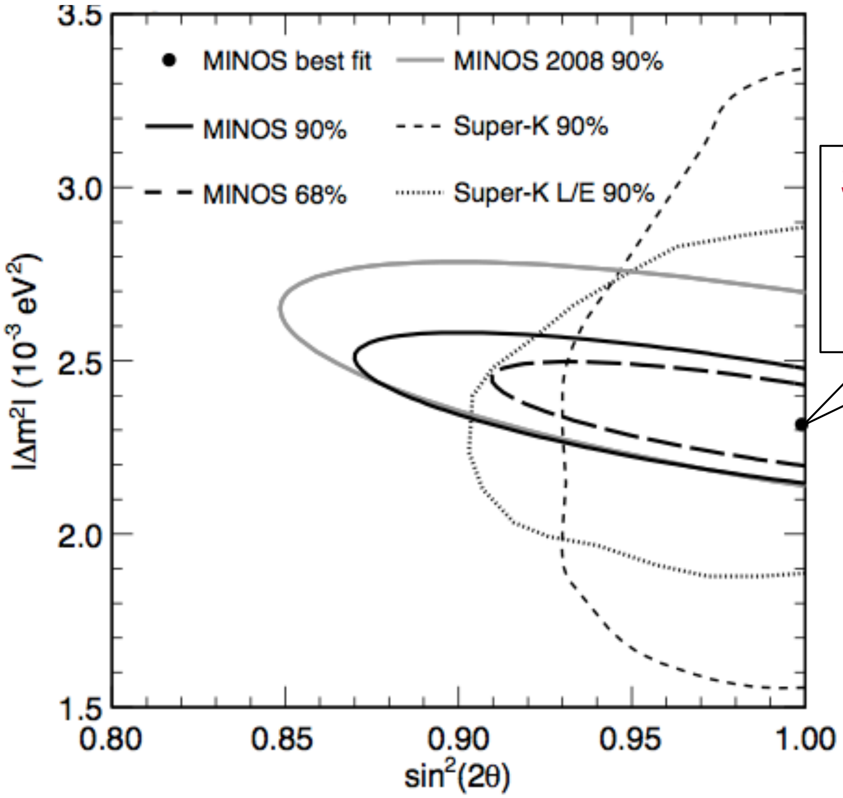
12 GeV protons on Al target
+ π focusing horn
+ decay pipe for pions

MINOS

in US making precision measurements of ν_μ disappearance

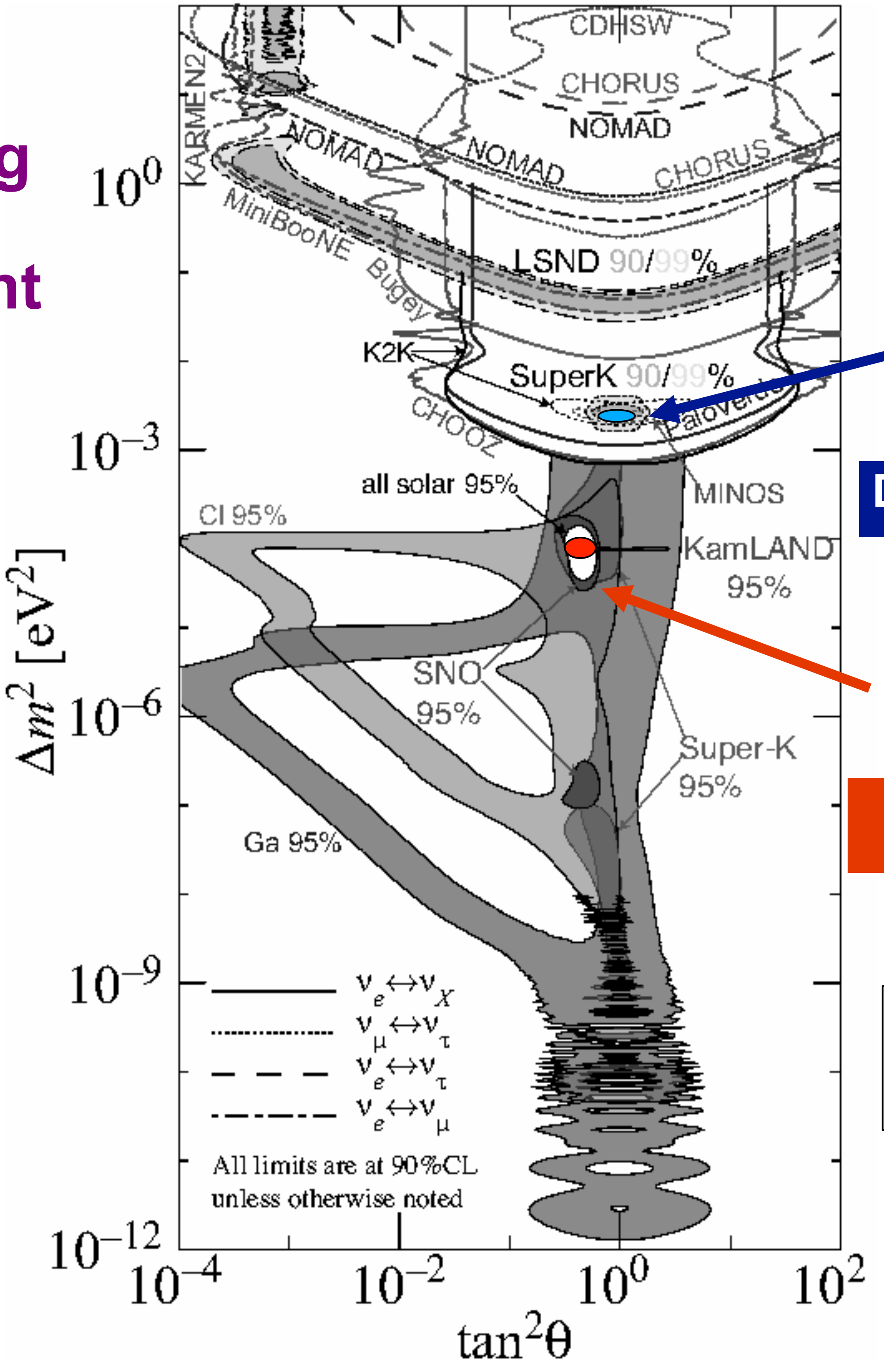






Squeezing down Δm^2_{23} !

Now entering precision measurement era for two-flavor oscillations



atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

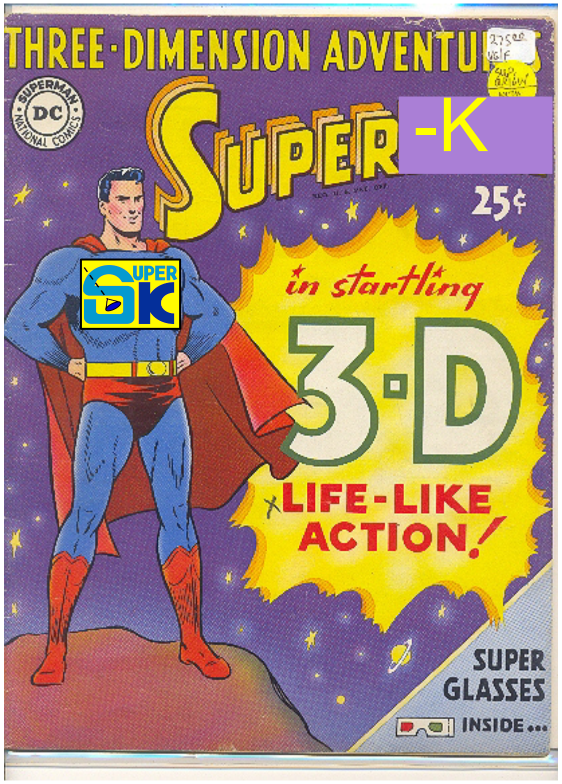
Described by θ_{12}, Δm^2_{12}

tomorrow's story

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

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Three flavor mixing

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

Parameterize mixing matrix U as

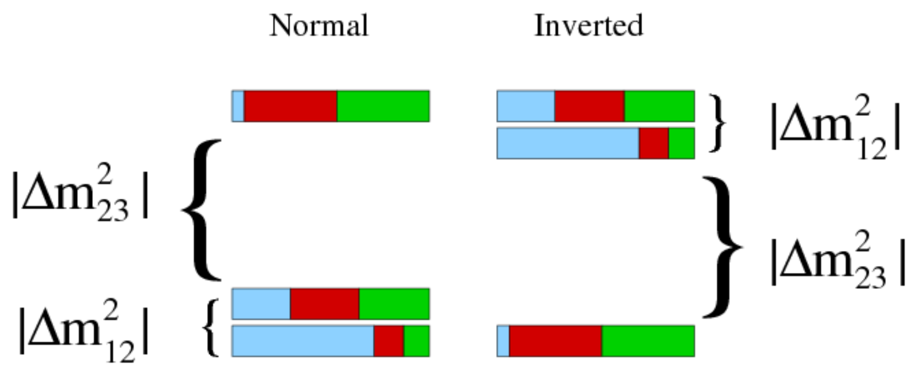
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



After 15 years of oscillation measurements, remaining unknowns in the 3-flavor picture:

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

atmospheric/beam ? **solar/reactor**

Masses

$$m_1,\ m_2,\ m_3 \leftrightarrow \Delta m^2_{12}, |\Delta m^2_{23}|, sign(\Delta m^2_{23}), m_i$$

☑ ☑ ? ?

Angles

(plus Majorana phases)

$$\theta_{12},\quad \theta_{23},\quad \theta_{13},\quad \delta$$

☑ ☑ ... ?

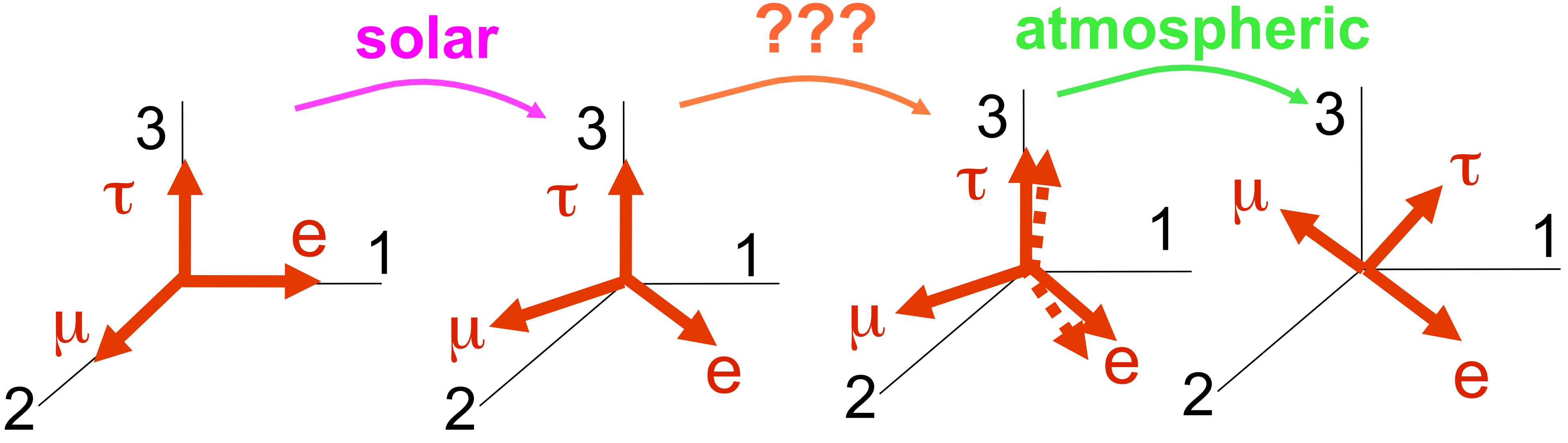
maximal?

First, θ$_{13}$: 'the twist in the middle'

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

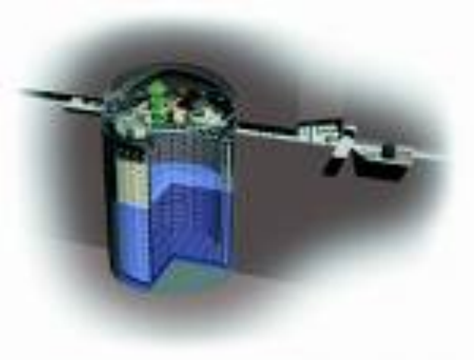
$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

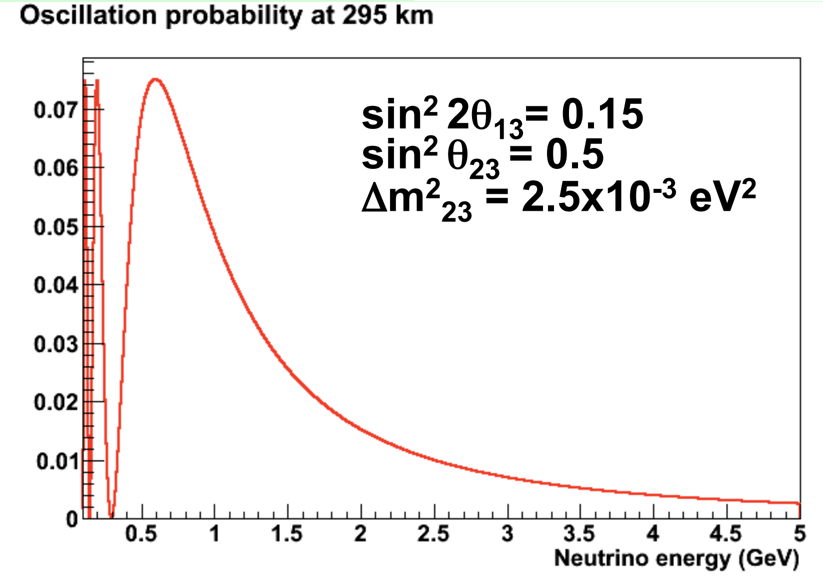
atmospheric ??? solar



Strategies for determining θ_{13}

Beams

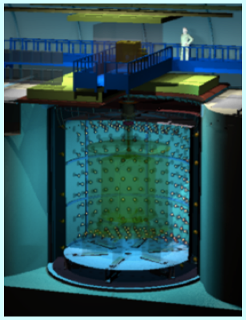


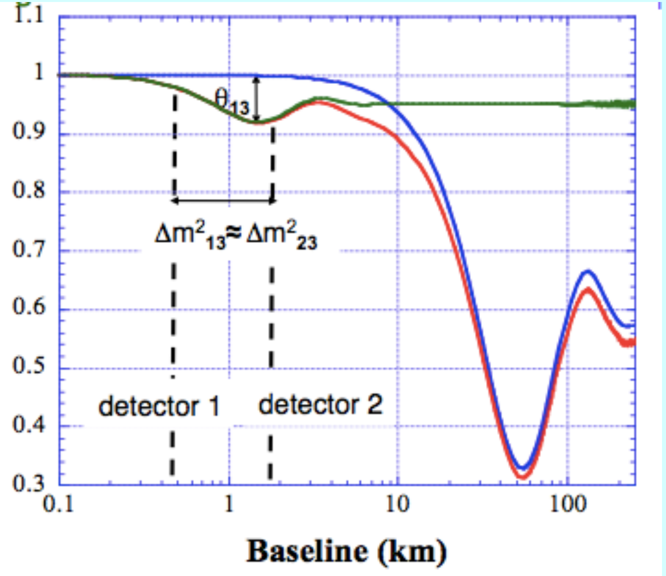


Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors



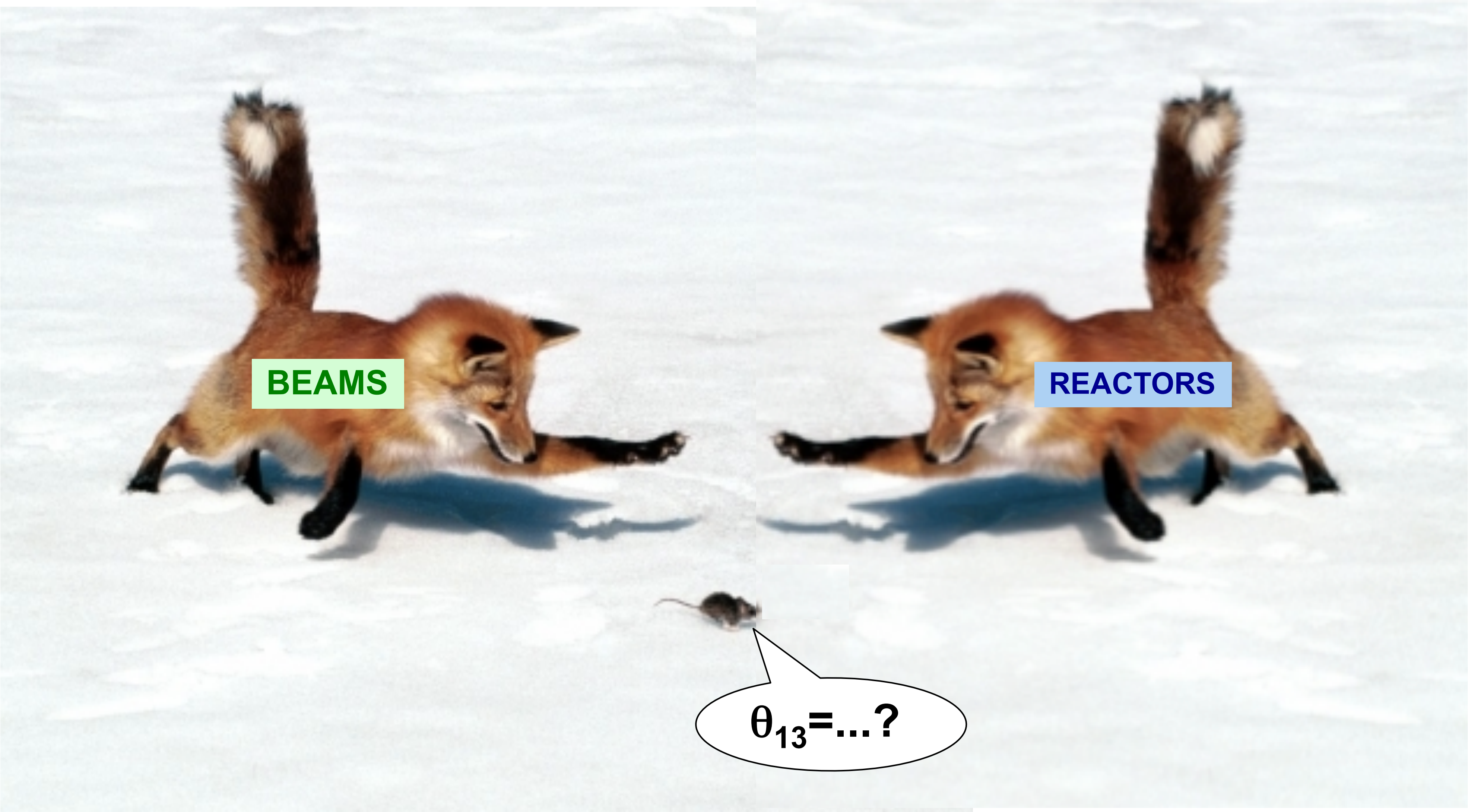


Look for *disappearance* of ~few MeV $\bar{\nu}_e$ on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

A slide from December 2011:

We’re closing in on the answer...

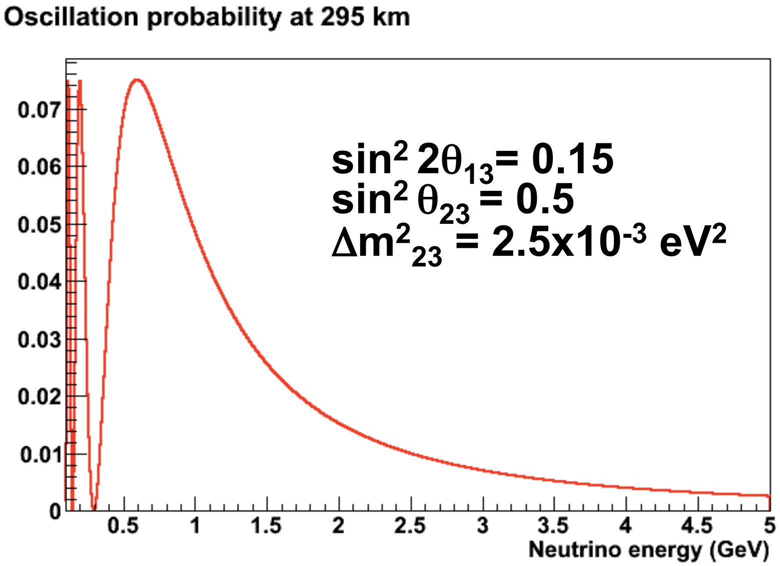


The long-baseline beam approach:

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

$$\nu_\mu \rightarrow \nu_{\mu,\tau}$$

$$\nu_\mu \dashrightarrow \nu_e$$


Oscillation probability at 295 km

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

for $\Delta m^2_{23} >> \Delta m^2_{12}$ and $E_\nu \sim L\Delta m^2_{23}$ (in vacuum), $\delta=0$

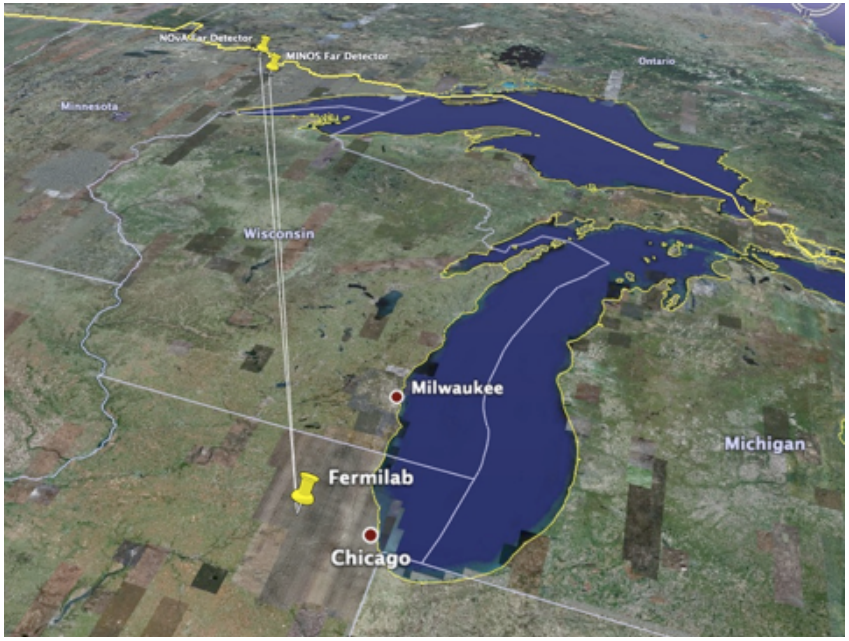
Hard to measure... known from the CHOOZ reactor experiment that it's a *small* modulation! Need good statistics, clean sample

Current Long Baseline Beam Projects

Physics goals : precision 2-3 mixing, non-zero θ_{13} search

T2K: "Tokai to Kamioka"

NOνA at NuMi



Pre-existing detector: Super-K
New beam from J-PARC
295 km baseline
Water Cherenkov detector

Pre-existing beam:
Fermilab NuMi upgrade
810 km baseline
Scintillator detector

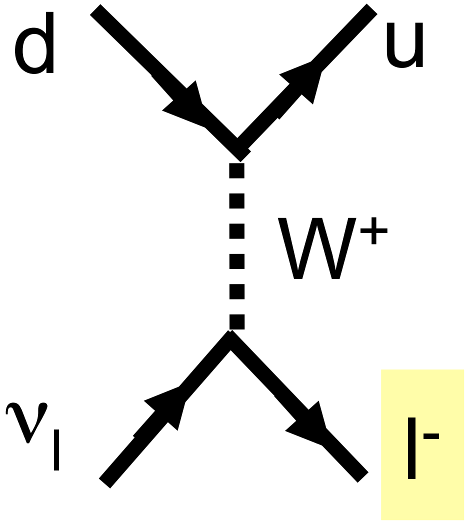
The T2K (Tokai to Kamioka) Experiment

Super-K

J-PARC

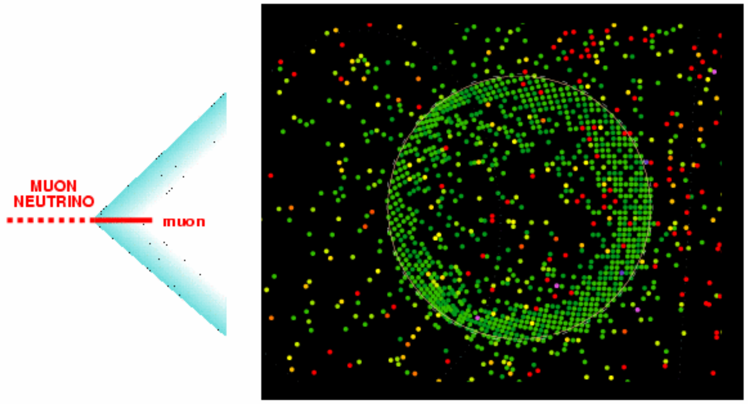
- second-generation long baseline experiment (following K2K, MINOS)
- high-intensity (750 kW) 2.5° off-axis ν_μ beam from J-PARC 295 km to Super-K, a large water Cherenkov detector
- collaboration of ~500 people, ~60 institutes, 12 countries

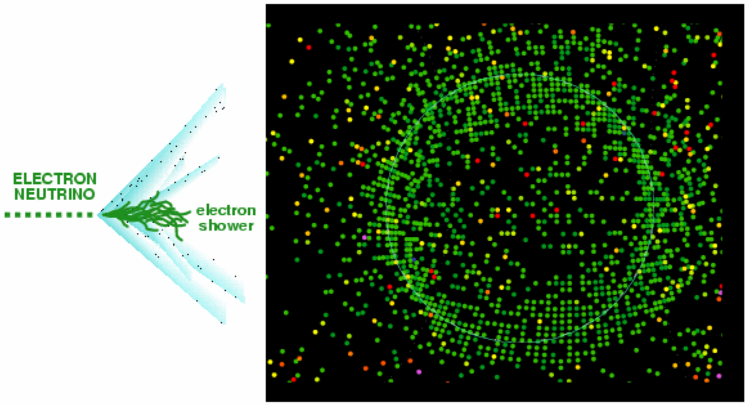
Signature of non-zero θ_{13} at far detector

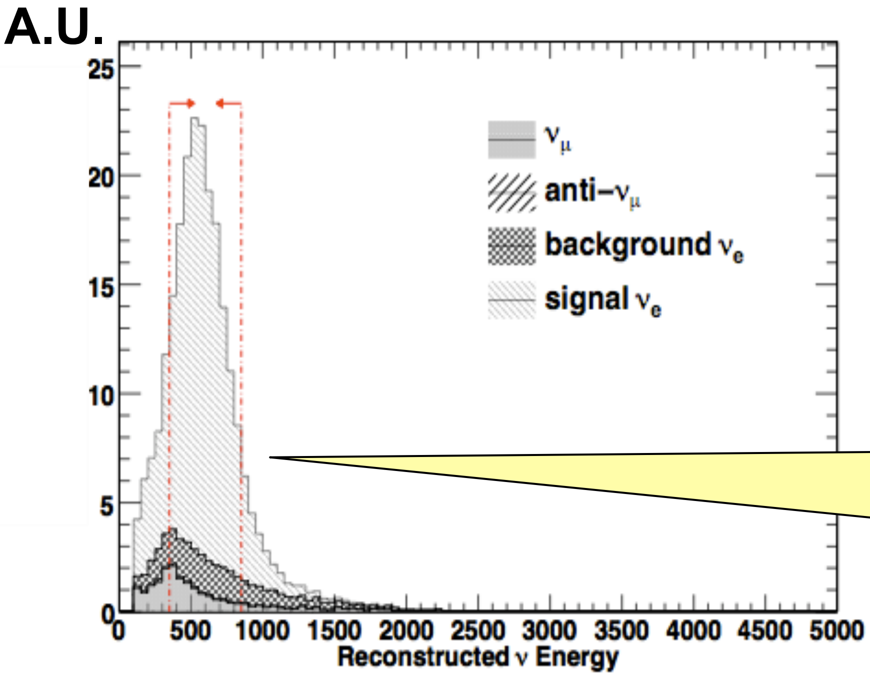


select charged-current quasi-elastic events (~single ring);
vertex, energy, direction from Cherenkov light

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

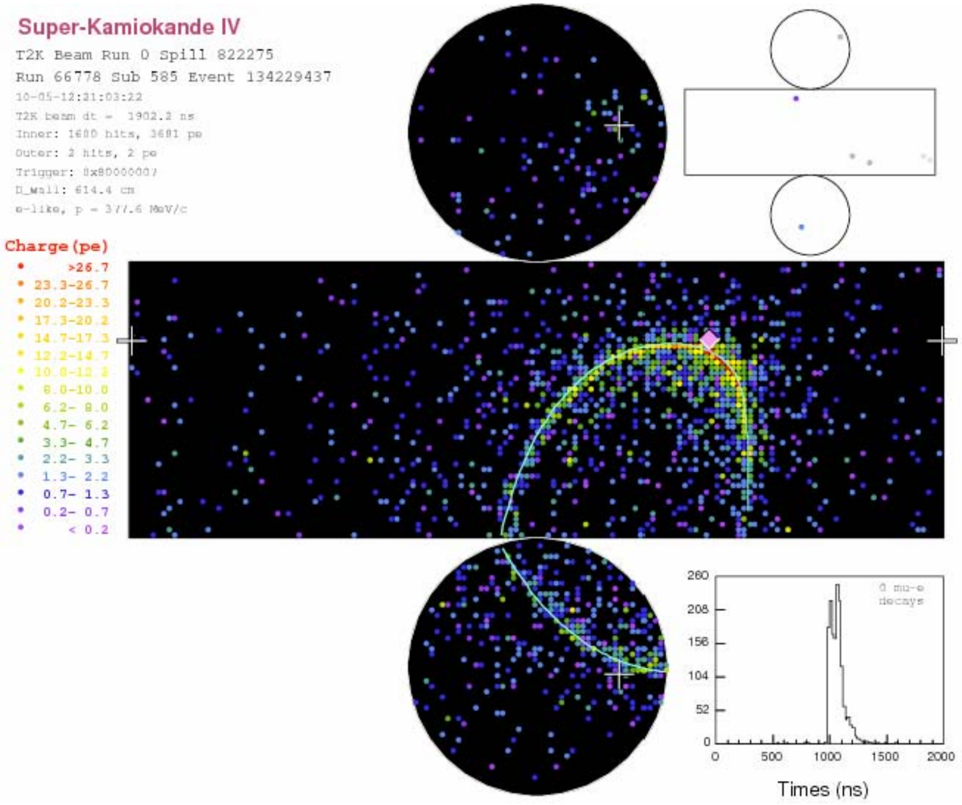




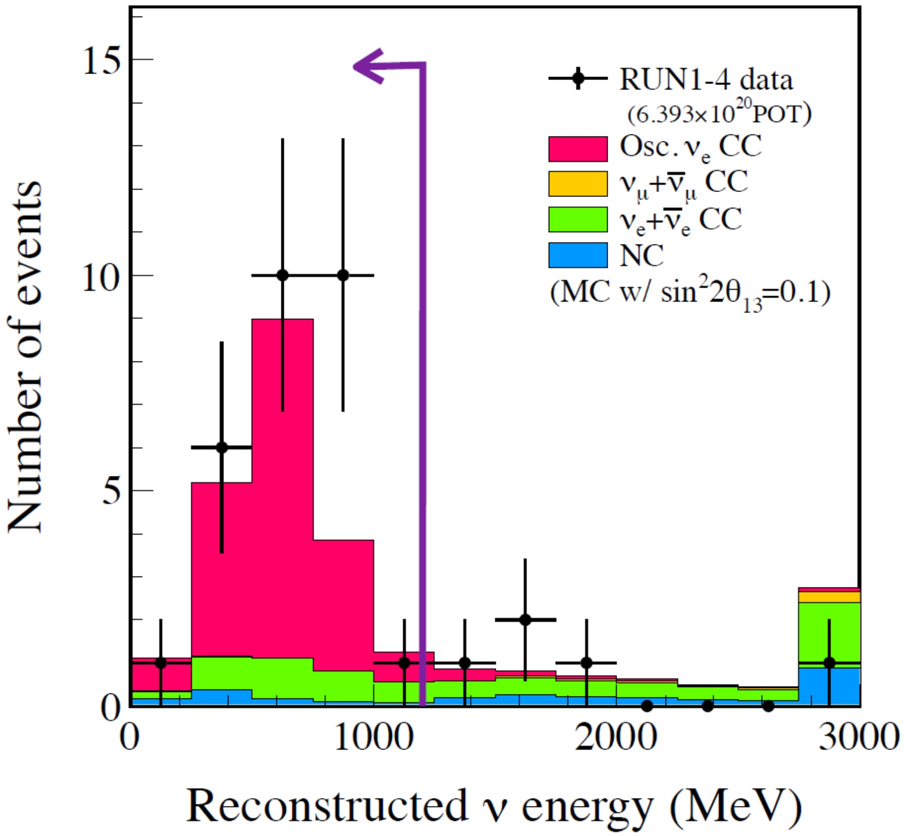


**Look for electron appearance:
single fuzzy rings excess on top of background, with expected spectrum**

Excess of ν_e -like events seen in T2K, consistent with non-zero θ_{13}



Reconstructed events after all ν_e cuts



28 ν_e candidate e-like rings seen, 4.64 ± 0.52 bg expected

NEW

T2K allowed region in $\sin^2 2\theta_{13}$ and CP δ

Best fit w/ 68% C.L. error @ $\delta_{CP}=0$

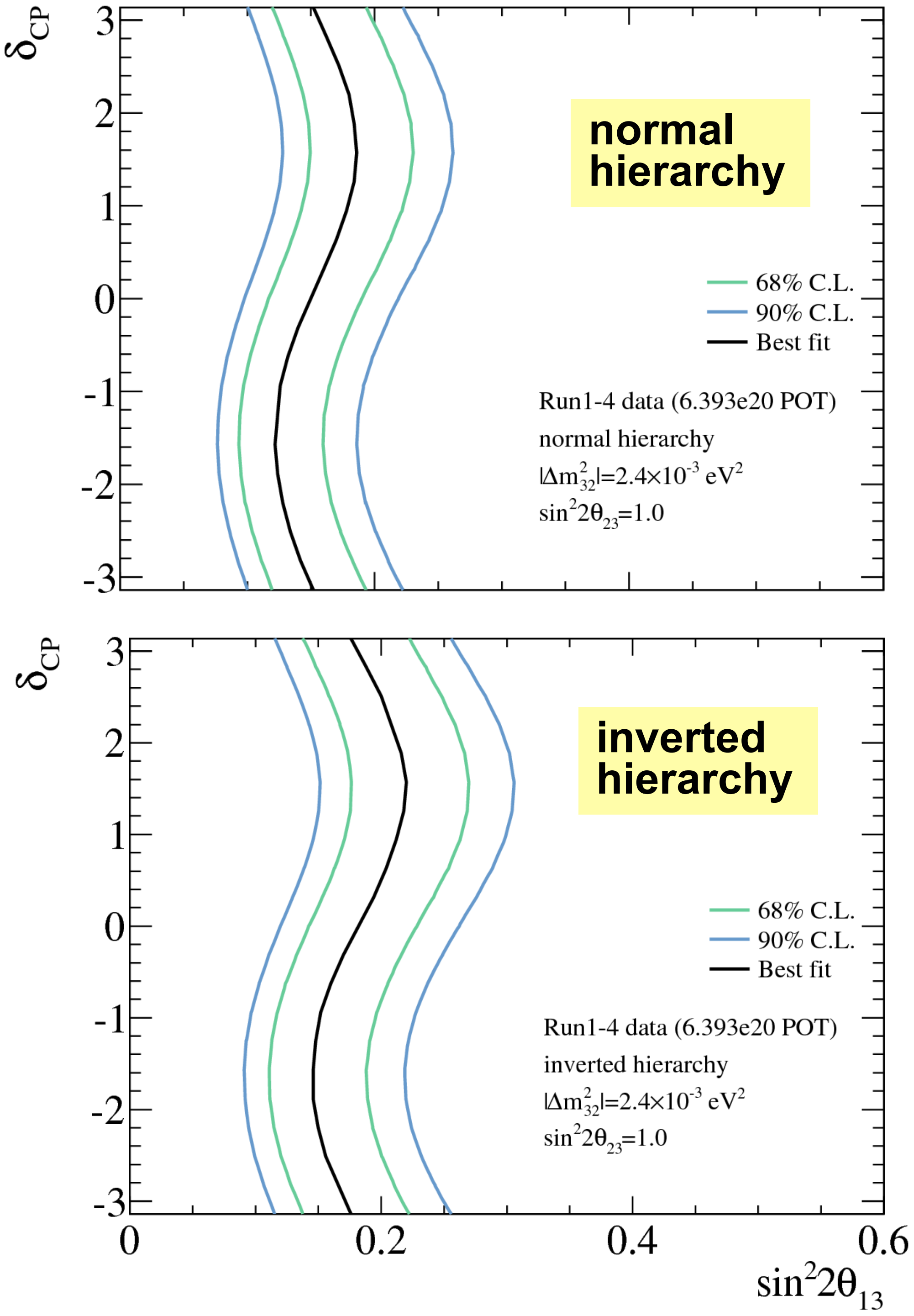
normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

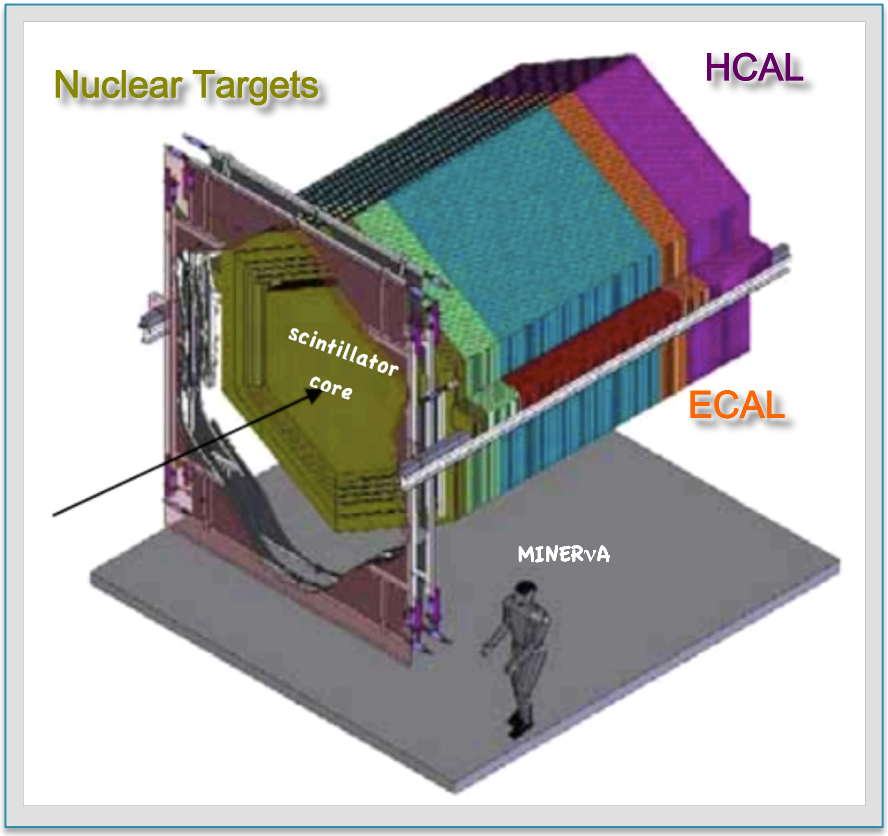
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

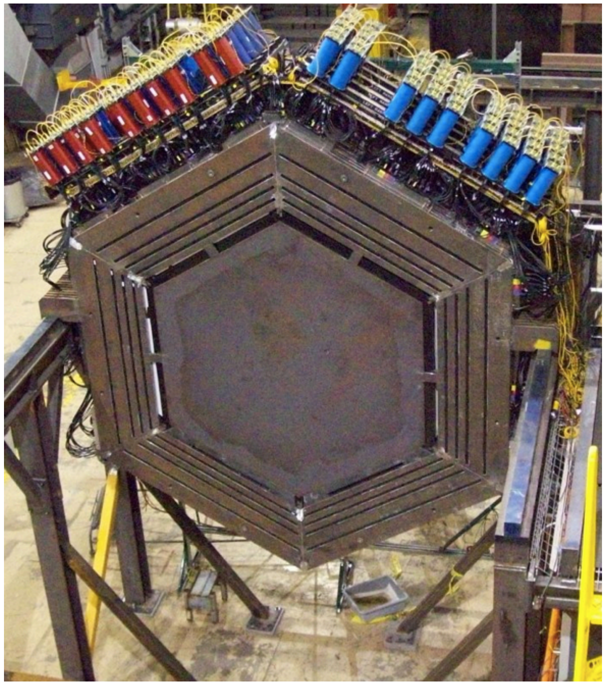
Assuming
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2
$\sin^2 2\theta_{23}=1.0$

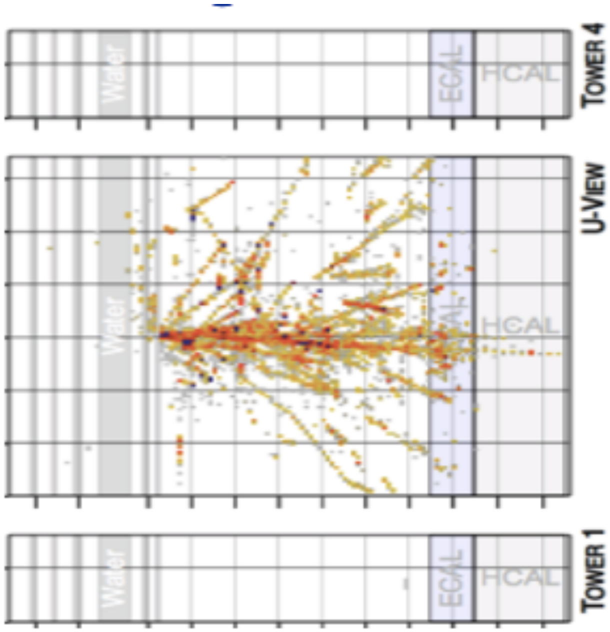


Side note: MINERνA

**Detector at NuMI (Fermilab)
to measure cross-sections of
~GeV neutrinos on nuclear targets**
(finely-segmented scintillator
+ em& hadronic calorimeters)







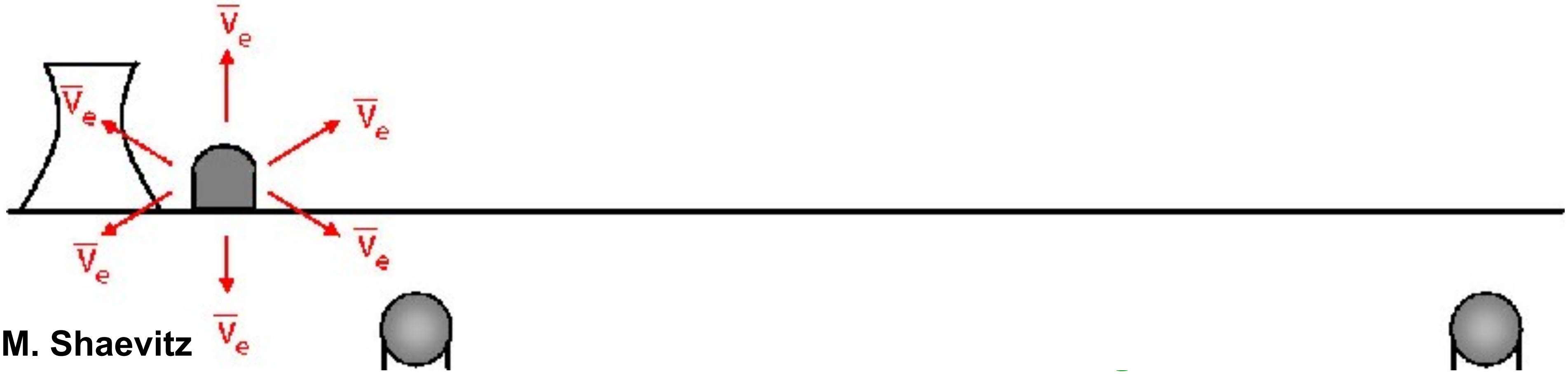
Vital to understand interactions for interpretation of long baseline oscillation experiment backgrounds & systematics!

Measuring θ_{13} with reactor experiments

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)$$

Need <1% systematics!

Cancel systematics w/ 2 identical detectors

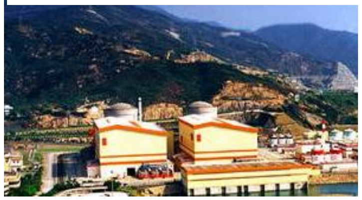


M. Shaevitz

RENO, South Korea

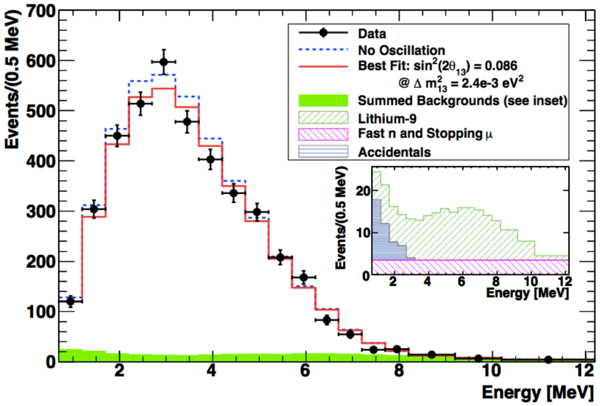
Double Chooz, France

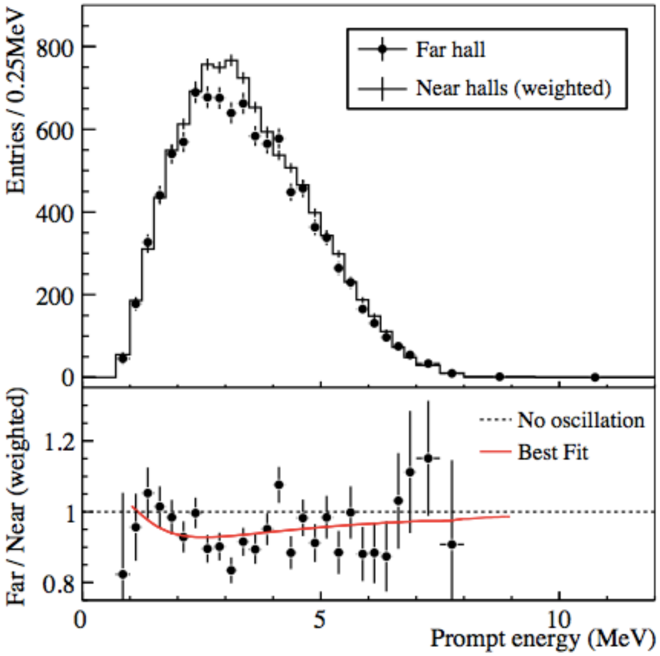
Daya Bay, China

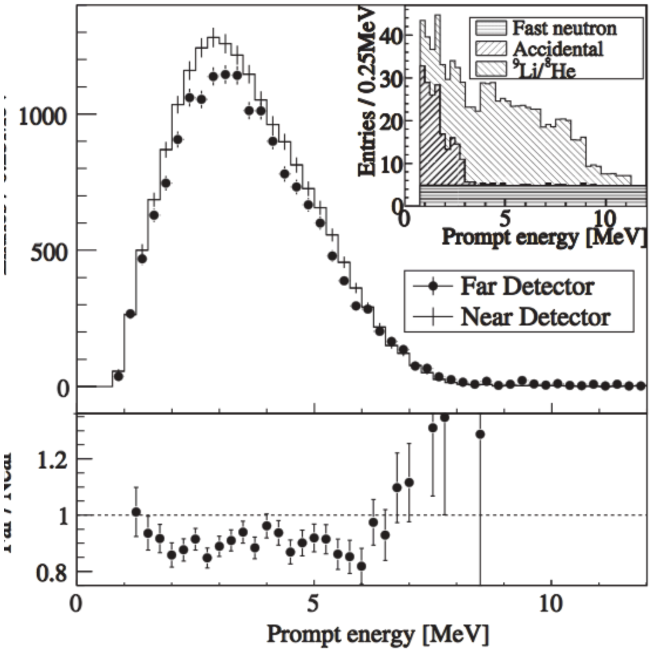


➡ All taking data in 2011

Results now from all three!



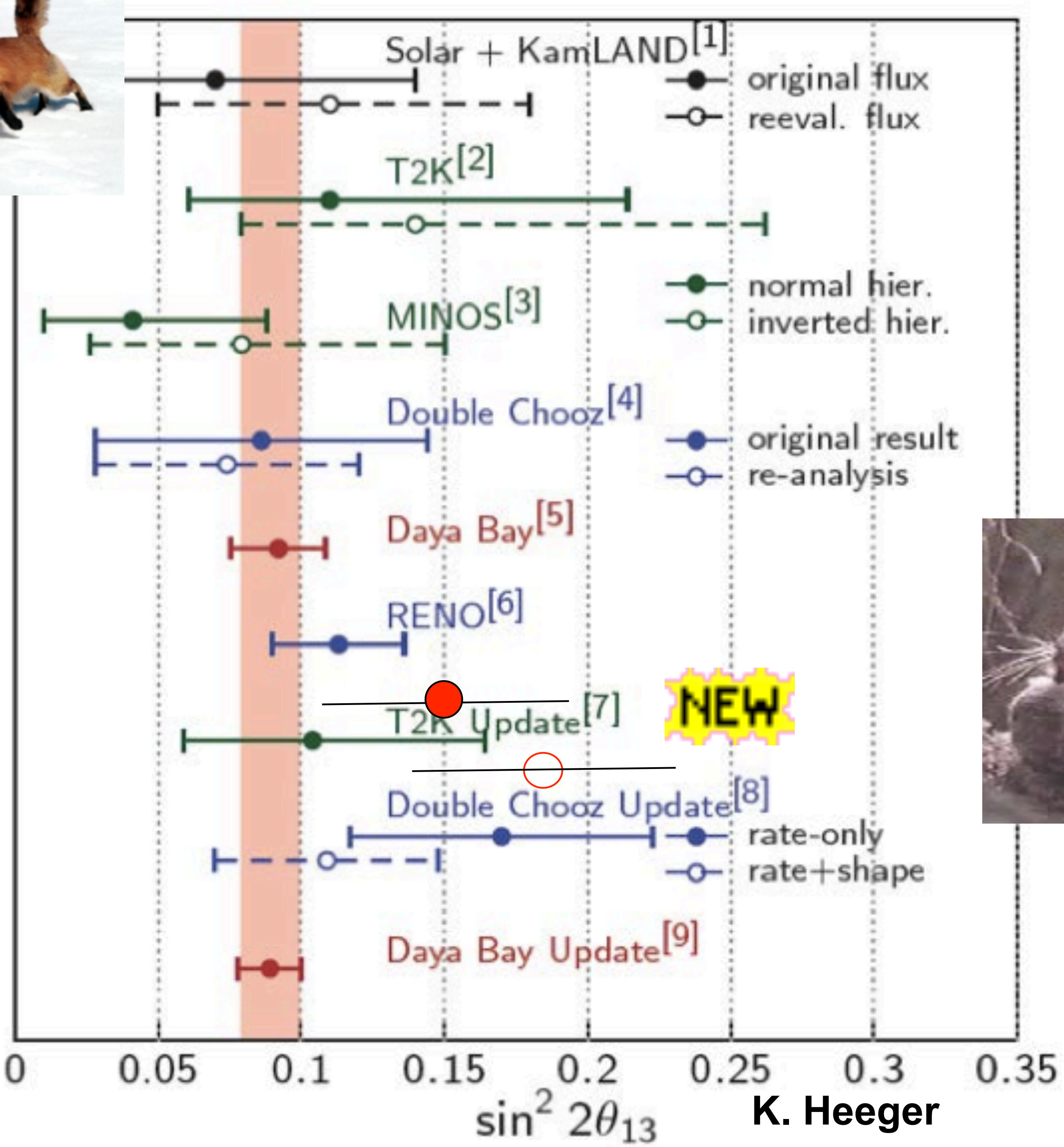




Electron antineutrino deficit and spectral distortion consistent
with non-zero θ_{13}

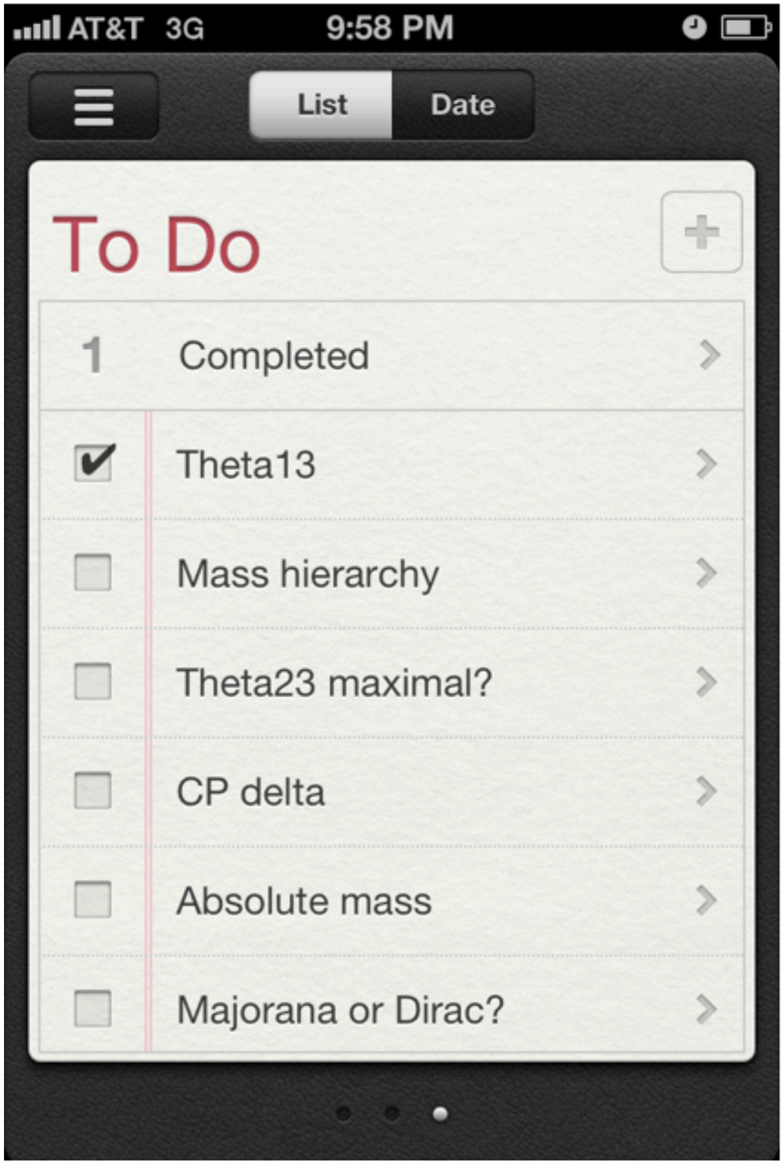
... in fact now in "precision" regime

We now know that θ_{13} is large!



K. Heeger

We need to keep testing the model!



☑ Theta13

☐ Mass hierarchy

☐ Theta23 maximal?

☐ CP delta

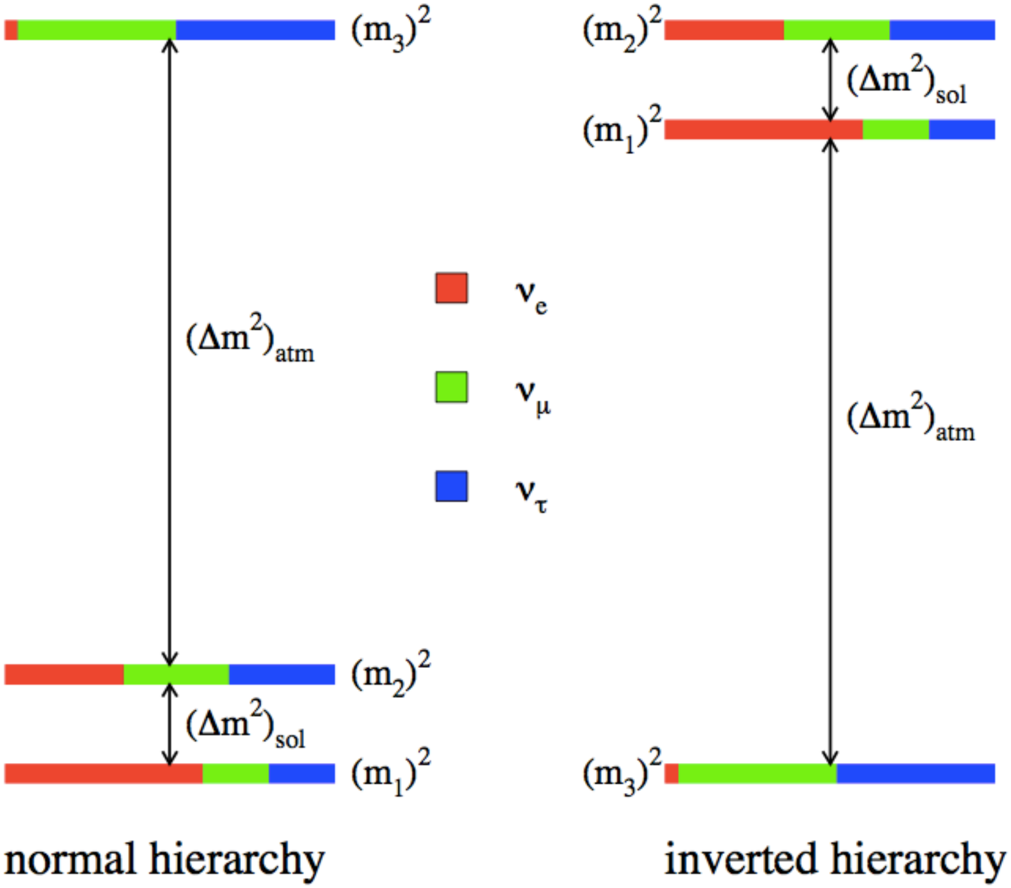
☐ Absolute mass

☐ Majorana or Dirac?

Next on the list to go after experimentally:

mass hierarchy

(sign of Δm^2_{32})



normal hierarchy

inverted hierarchy

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

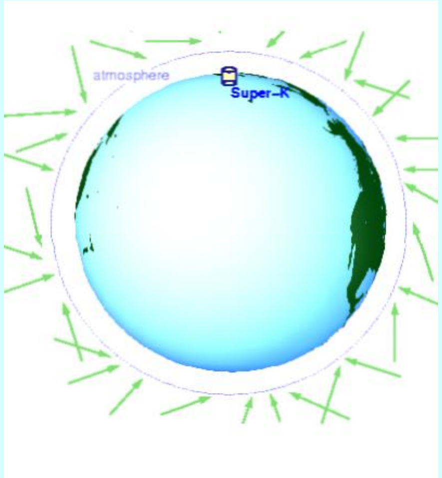
There are many ways to measure the mass hierarchy

They are all challenging...

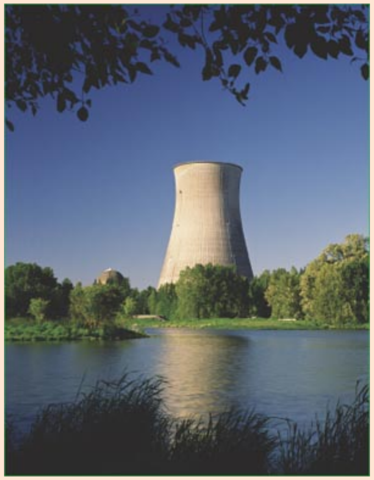
Four of the possible ways to get MH

Long-baseline beams

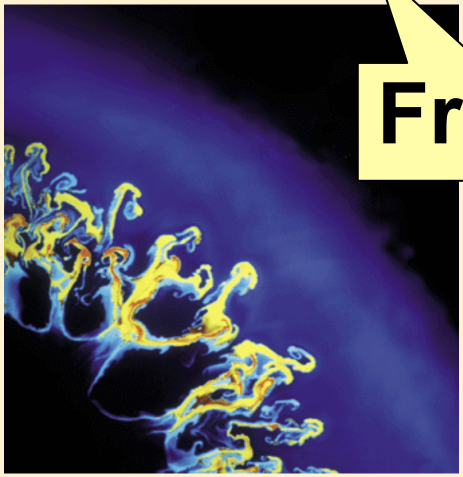
Atmospheric neutrinos



Reactors



Supernovae



Friday

Determining the MH with long-baseline beams

The basic strategy

Compare transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

through matter

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right)$$

Change of sign for antineutrinos

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

A. Cervera et al., Nucl. Phys. B 579 (2000)

$\tilde{J} \equiv c_{13}\,\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$

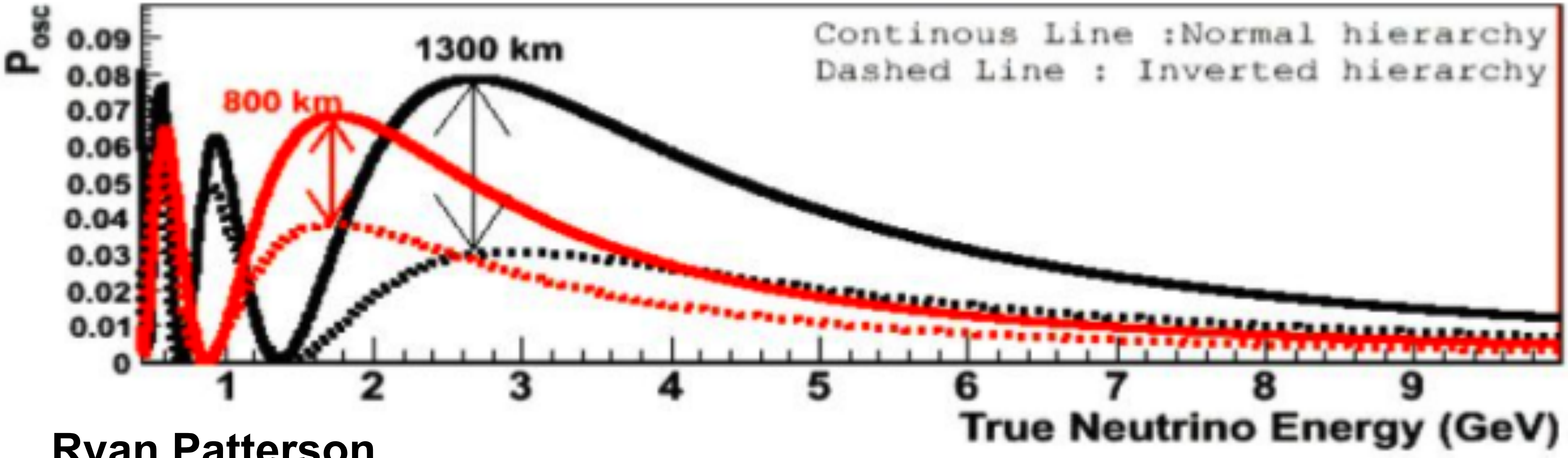
$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}$, $\tilde{B}_\mp \equiv |A \mp \Delta_{13}|$, $A = \sqrt{2}G_F N_e$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

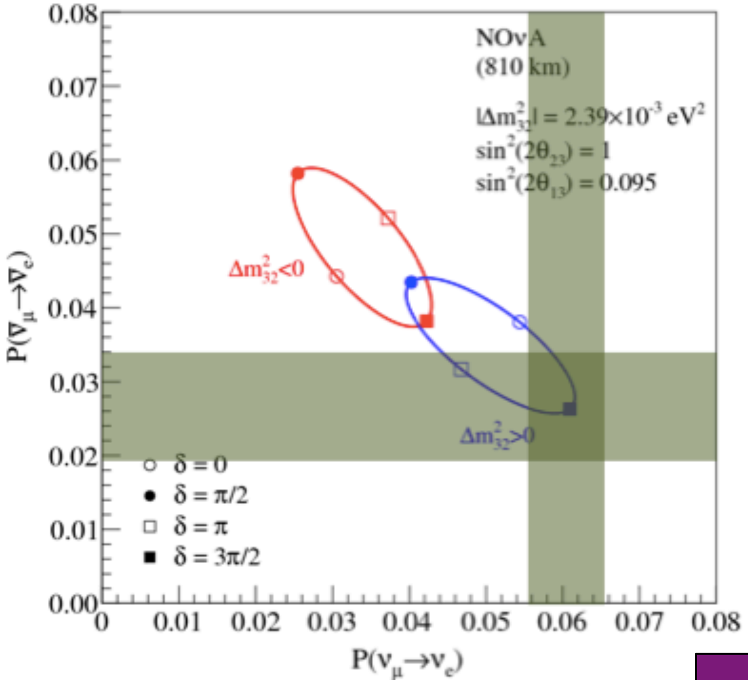
Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

- **CP δ (more later on that)**
- **matter density (Earth has electrons, not positrons)**

The baseline matters:



Ryan Patterson



$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ *vs.* $P(\nu_\mu \to \nu_e)$

shown at a particular *L/E*

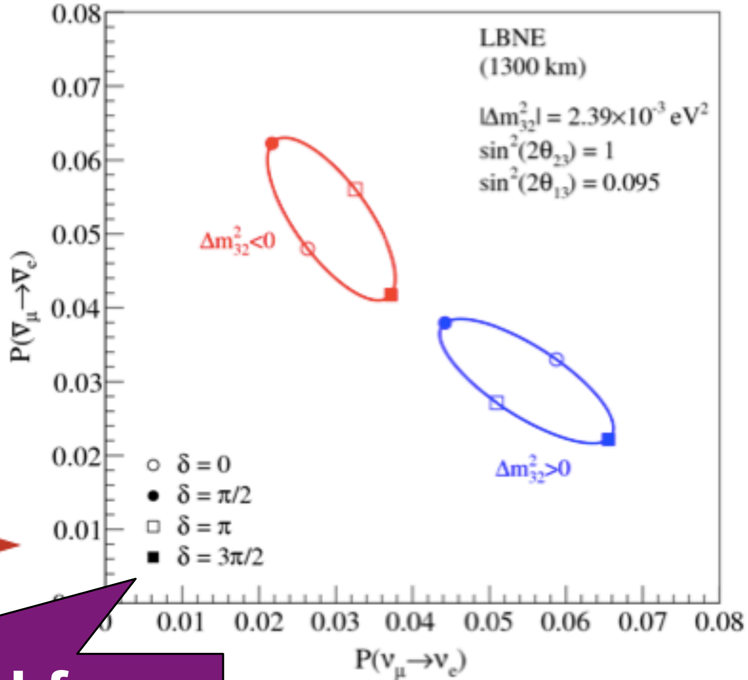
for

both choices of sign(Δm^2)

and for full range of δ_{CP}

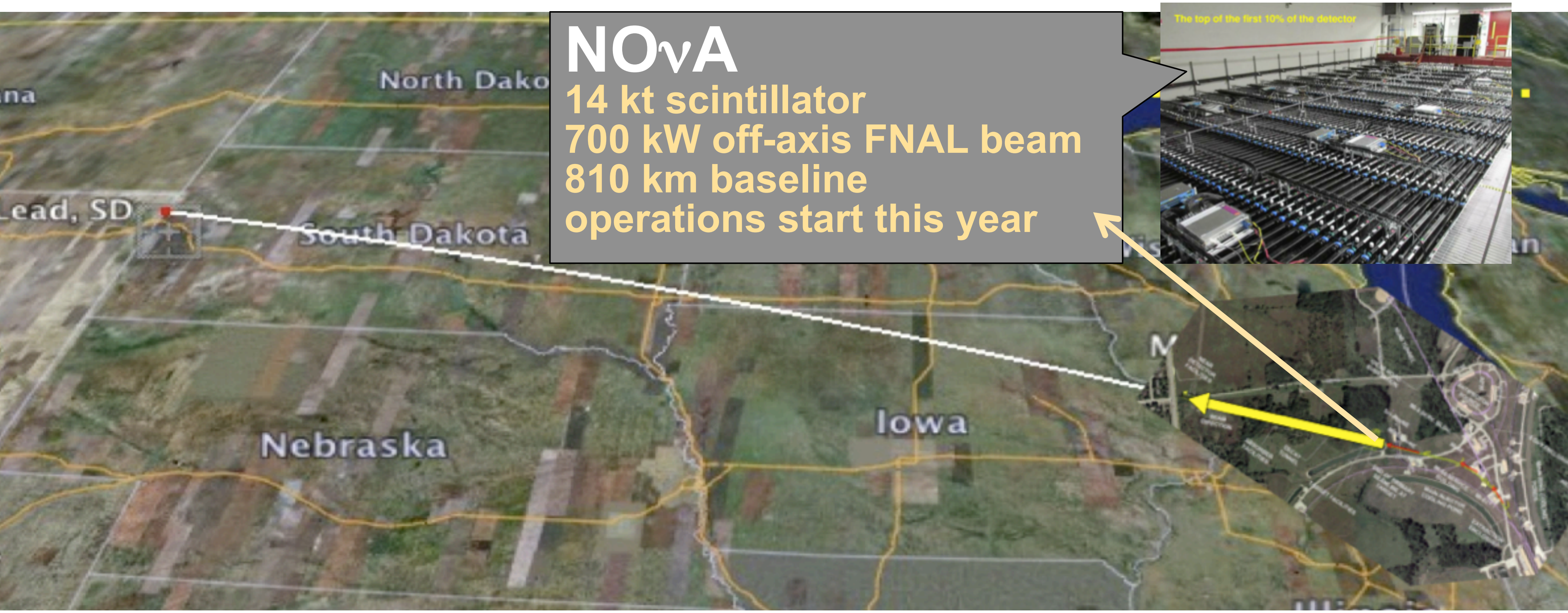
810 km ←

→ *1300 km*



easier to separate MH from CP effects at long baseline

New U.S. long-baseline experiments



NOνA

14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline
operations start this year

New U.S. long-baseline experiments

NOνA

14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline
operations start this year

Long-Baseline Neutrino Experiment

34 kton LArTPC in SD @ 4850 ft
1300 km baseline
New 700 kW beam

New U.S. long-baseline experiments

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34 kton LArTPC in SD @ 4850 ft
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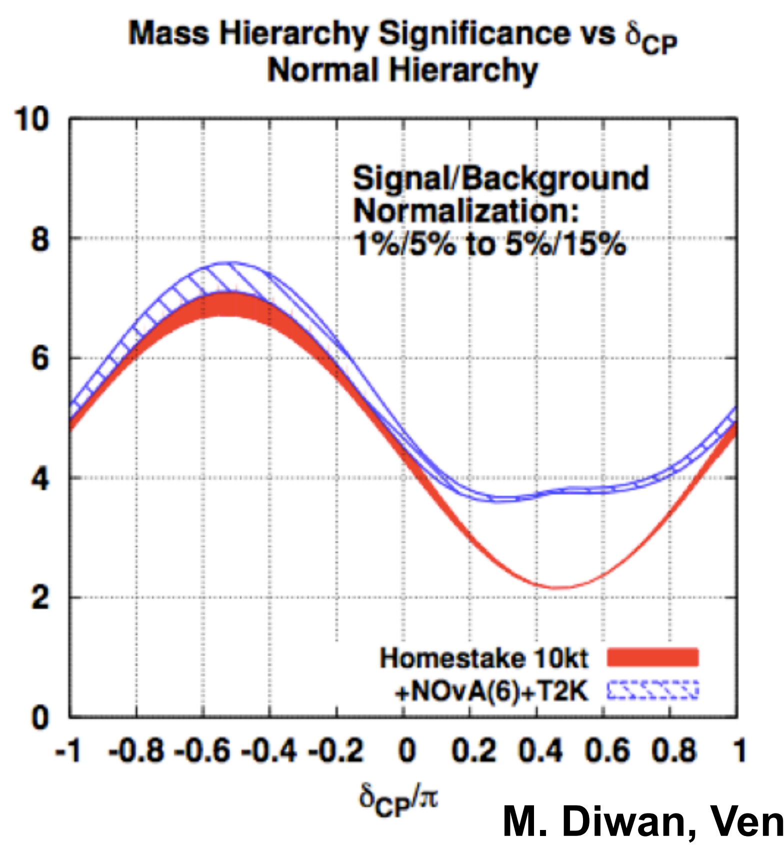


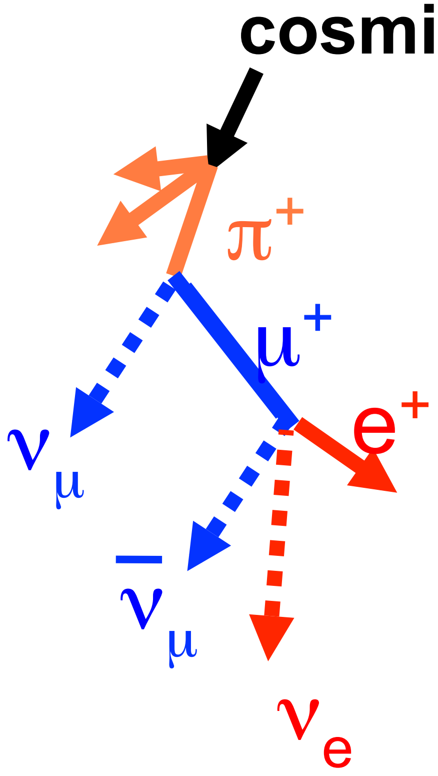
good combined reach, and improvement with more mass or beam (e.g. Project X at FNAL)

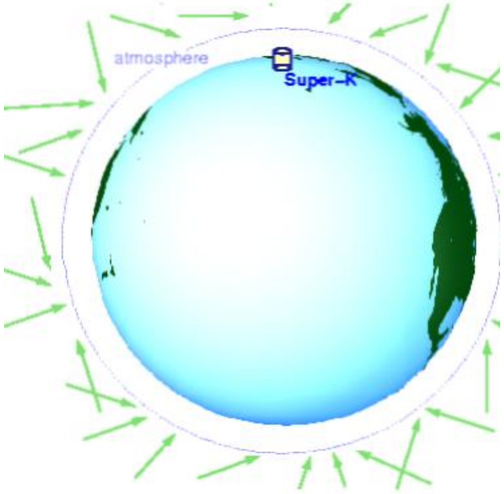
M. Diwan, Venice, Mar 2013

Atmospheric neutrinos: back into the wild

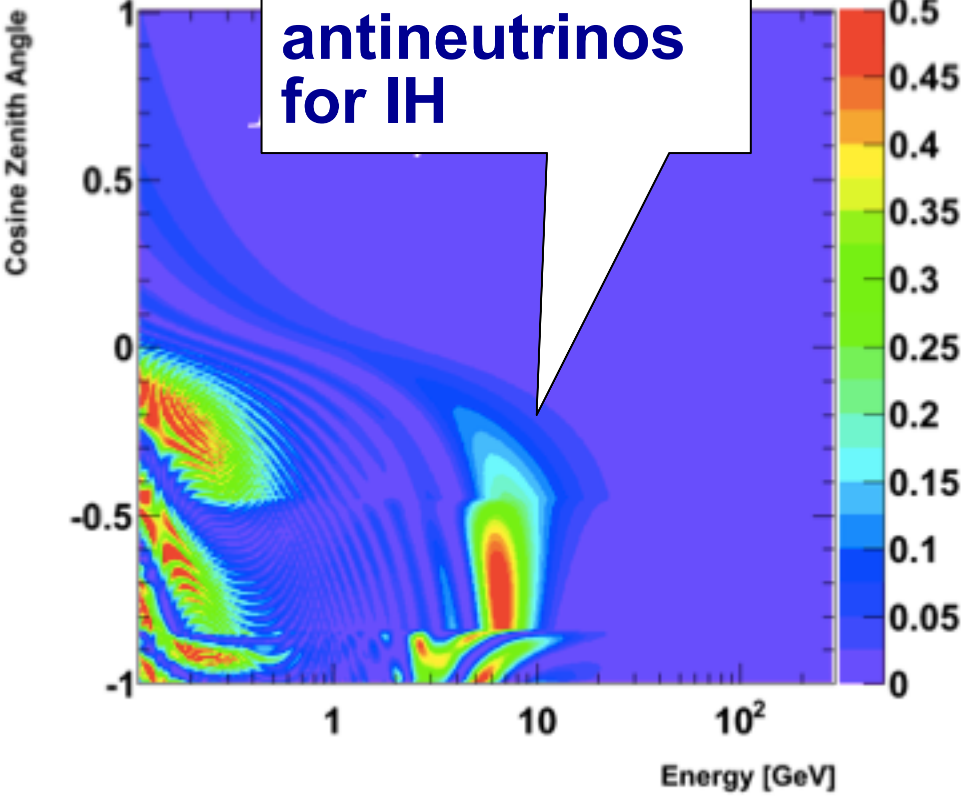
The neutrinos are free, and have a range of baselines & energies,

.... but they do what they damn well please





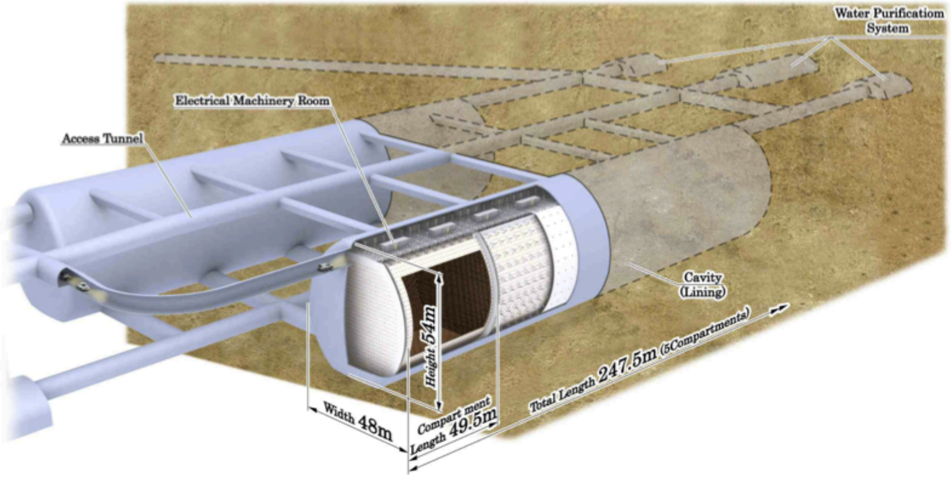
resonance for neutrinos for NH and for antineutrinos for IH



$$P(\nu_\mu \to \nu_e)$$

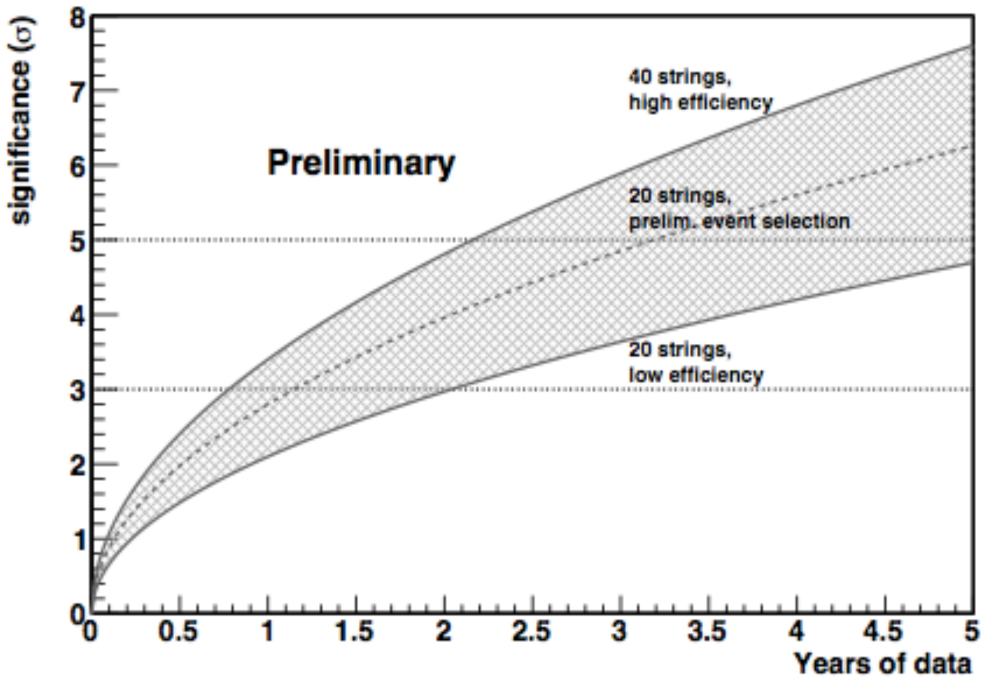
Need both statistics and ability to reconstruct ν energy & direction

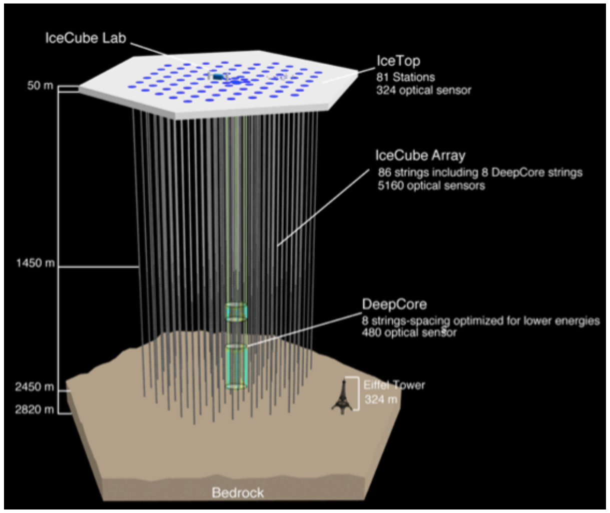
Examples: Hyper-K



- Tochibora mine, near Kamioka;
  (1500-1750 mwe)
- 560 ktons (25 x SK)
- LOI on arXiv:1109.3262

IceCube DeepCore/PINGU



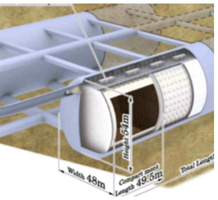


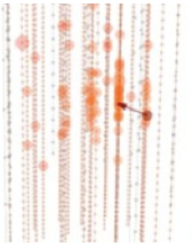
- enormous detector volume & atmnu statistics
- sparse PMTs, so poor reconstruction

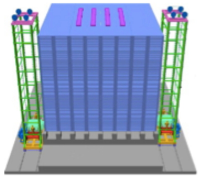
➔ PINGU infill for be reconstruction & lower threshold

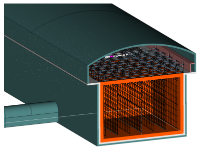
- arXiv:1306.5846

Experiments going after MH with atmnus







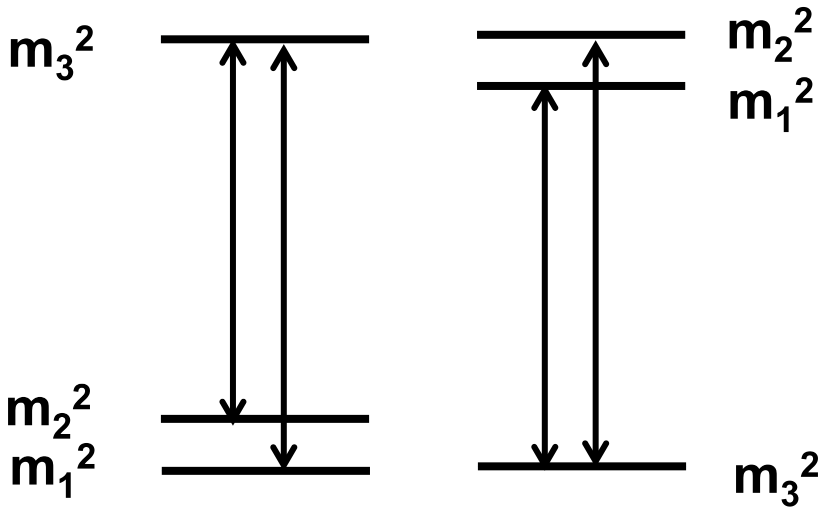


Experiment	Type	Location	Reconstruction	Mass (kt)	Notes
Super-K	Water Cherenkov	Japan	Good	22.5	Good reconstruction, low stats
Hyper-K	Water Cherenkov	Japan	Good	560	Good reconstruction and stats
IceCube DeepCore	Long String Water Ch.	South Pole	Poor	Mton	Systematics under study, huge stats
PINGU	Long String Water Ch.	South Pole	Improved	Mton	Systematics under study, huge stats
ORCA	Long String Water Ch.	Europe	Poor	Mton	Systematics under study, huge stats
ICAL@INO	Iron Calorimeter	India	Good	50	Magnetized → lepton sign selection
LBNE	LArTPC	USA	Excellent	10-34	Excellent reconstruction
GLACIER	LArTPC	Europe	Excellent	20-100	Excellent reconstruction

The Reactor MH Method

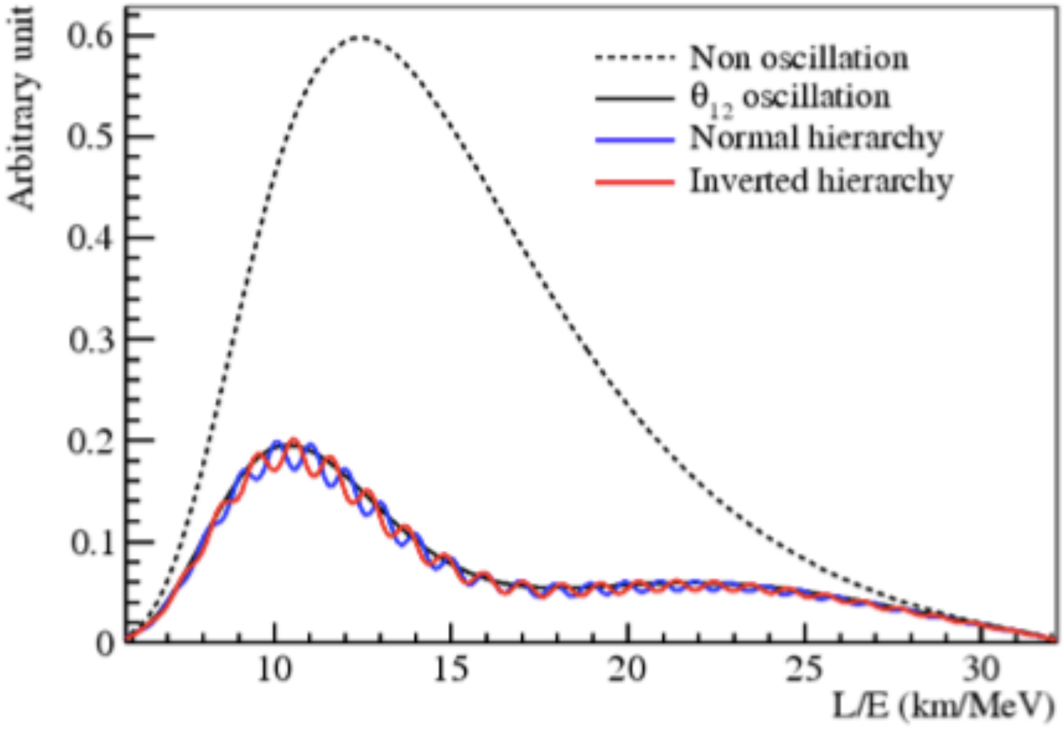
Vacuum oscillation frequencies depend on $\Delta m^2/E_\nu$

Different MH ➔ slightly different frequencies at reactor energies



$$\mathrm{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\mathrm{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

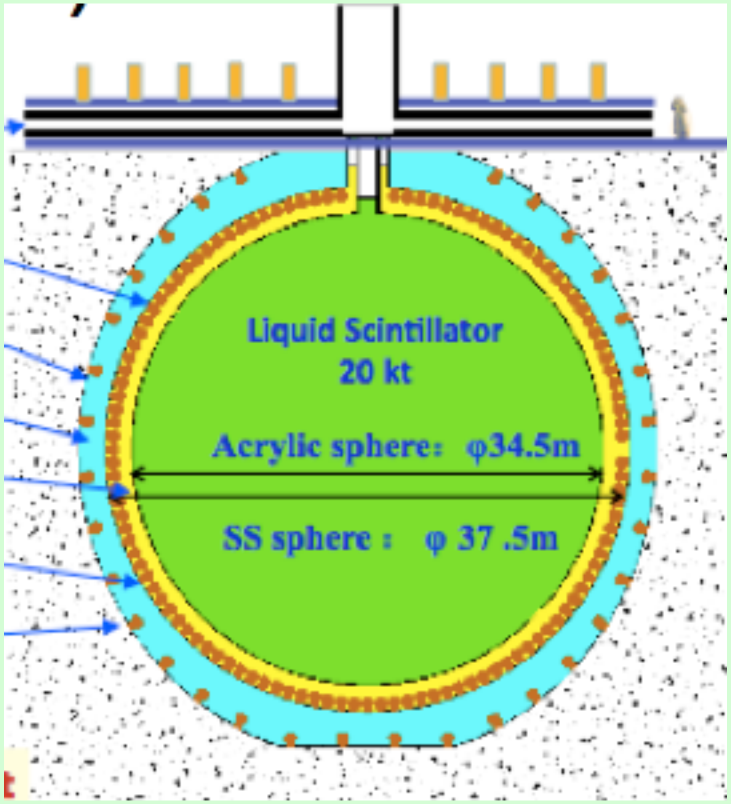
Y. Wang



Requires:
- **good energy resolution** (~3%)
- **excellent understanding of energy scale** (fraction of a percent)

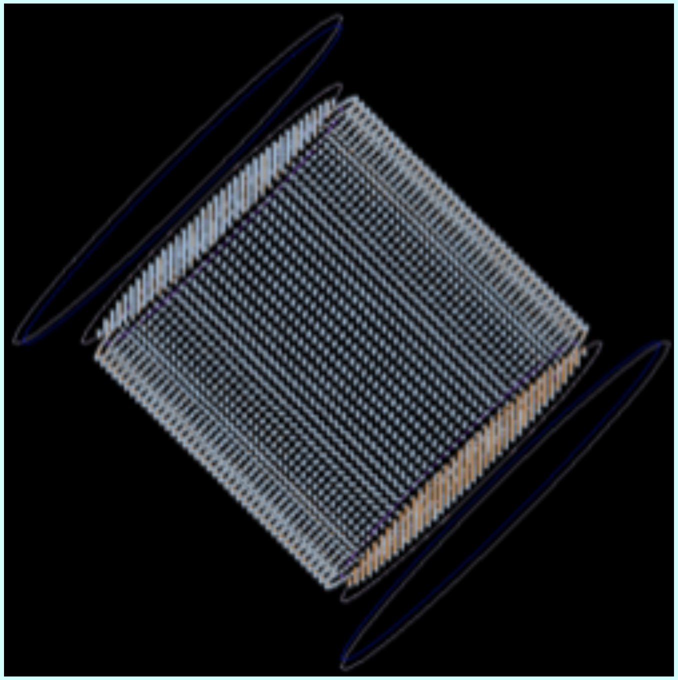
Proposed reactor experiments going after MH

Daya Bay II (China)



- 20 kt detector at 55-60 km
- ~ 40 GW_{th} power
- ~700 m underground
- < 3% resolution @ 1 MeV
- ~0.2% energy calibration

RENO-50 (South Korea)



- 18 kt detector at 47 km
- 16.8 GW power (Yonggwang)
- >500 m underground
- similar detector requirements

Next: CP violation

Compare transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ **and** $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

(matter effects understood, or absent)

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$

$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\enclose{circle}{\pm\delta} - \frac{\Delta_{13} L}{2}\right)$$

Change of sign for antineutrinos

$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$

$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \; \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \; A = \sqrt{2} G_F N_e$

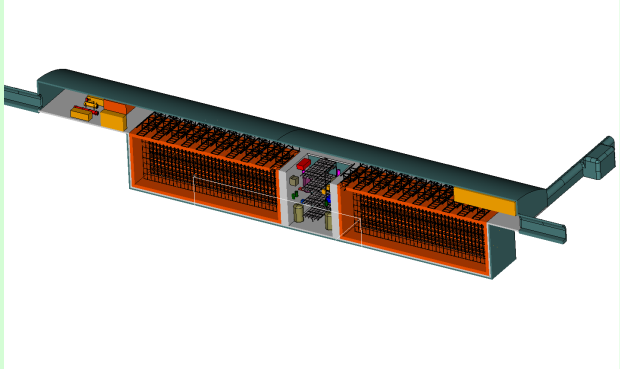
$\theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13}$ are small

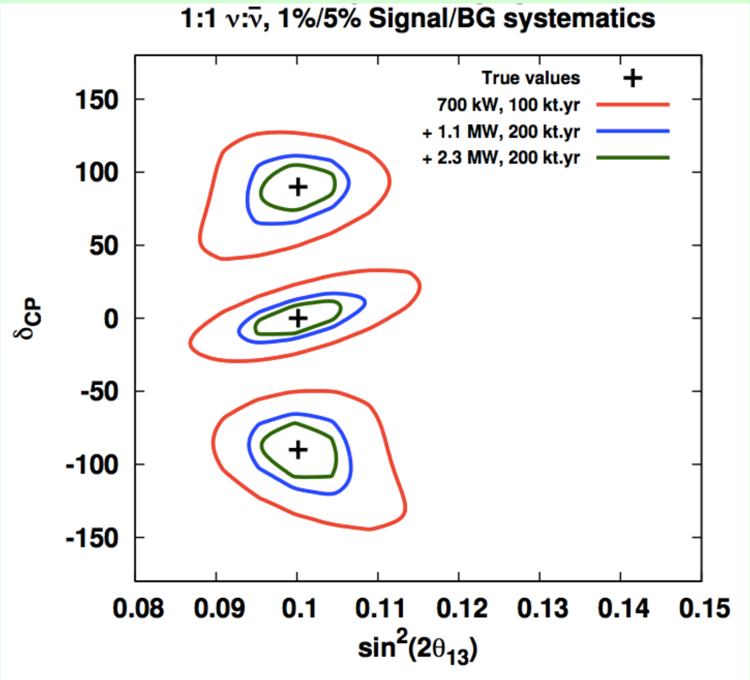
A. Cervera et al., Nuclear Physics B 579 (2000)

The Next Generation of CP Searches

LBNE (U.S.)

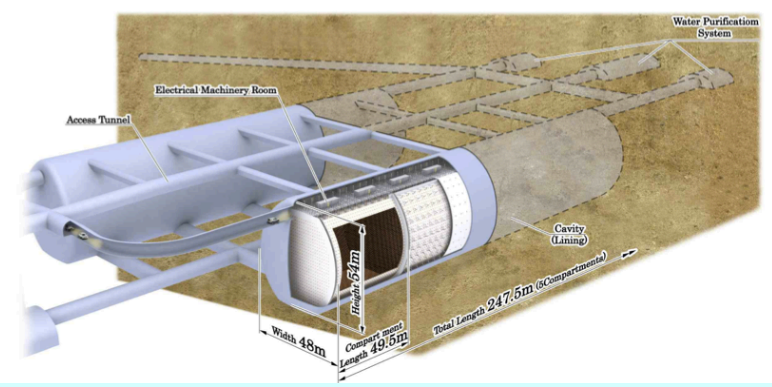
new FNAL 700 kW beam
+ eventual PX (1300 km)

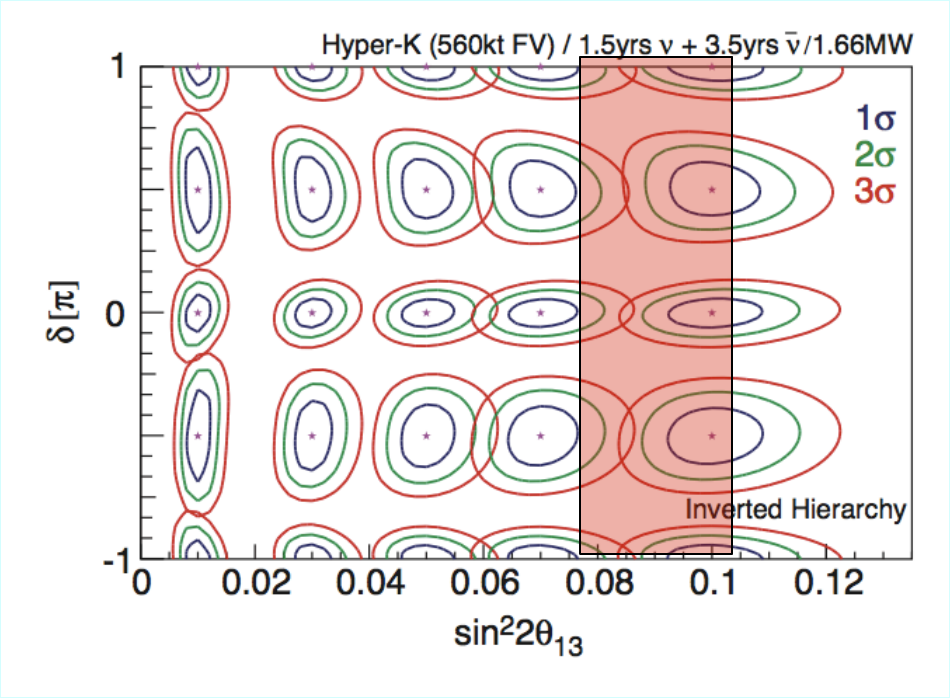




Hyper-K (Japan)

upgraded (x50) T2K beam
from J-PARC (300 km)





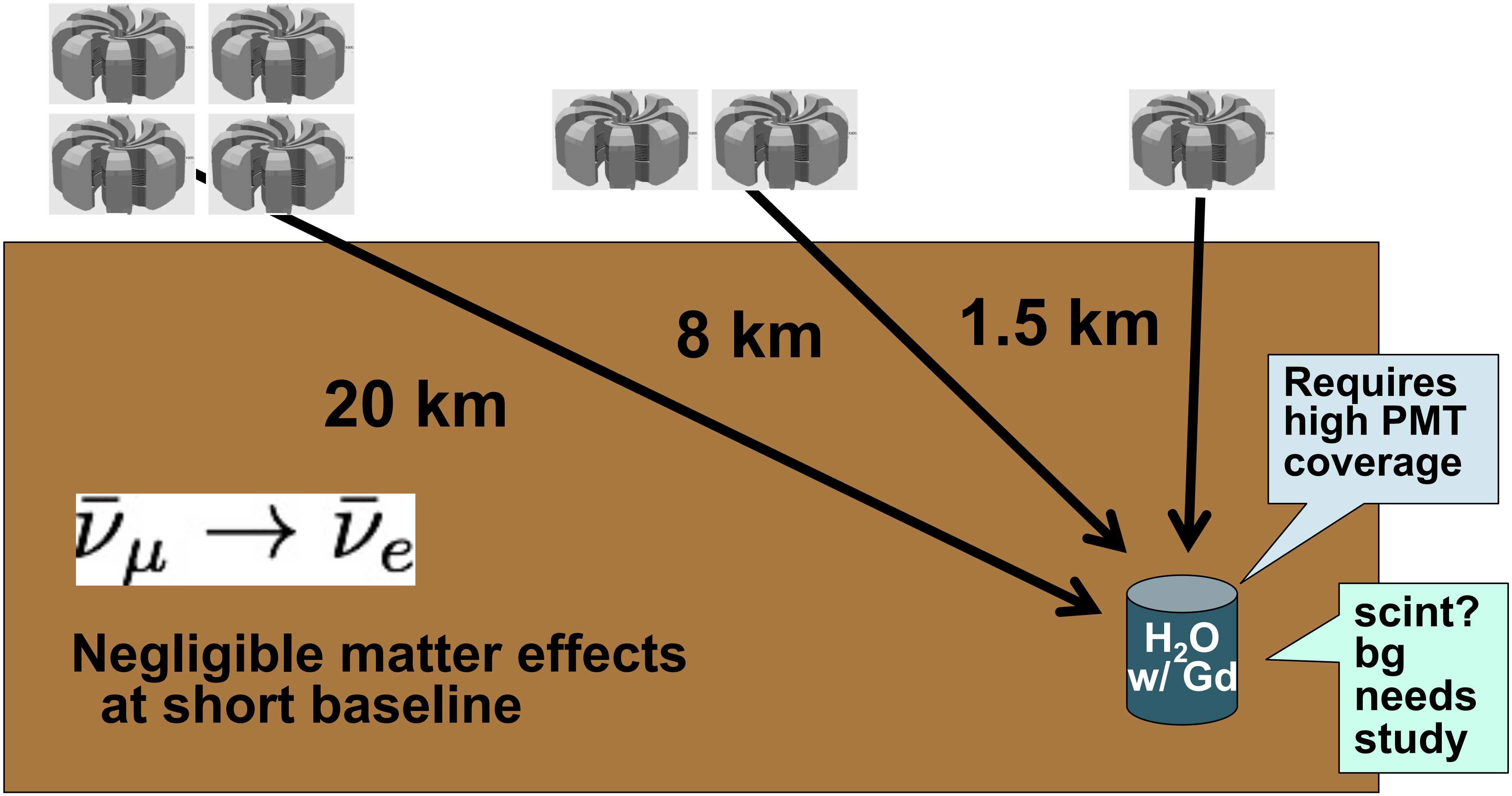
**Farther future: new accelerator techologies:
cyclotrons (DAEδALUS), neutrino factories,...**

A different approach for ν CPV: DAEδALUS

Multiple stopped-pion neutrino sources:

L ~1.5-20 km
E ~10-50 MeV

$$\frac{L}{E} \sim \frac{1000\ \mathrm{km}}{3000\ \mathrm{MeV}} \sim \frac{10\ \mathrm{km}}{30\ \mathrm{MeV}}$$



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

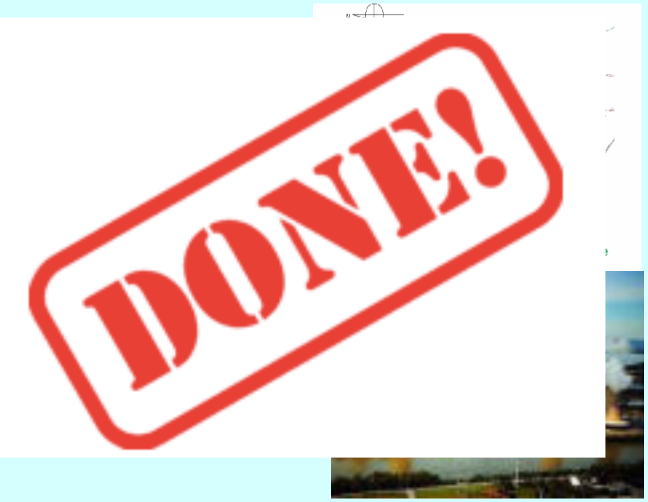
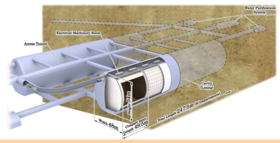
Negligible matter effects at short baseline

Requires high PMT coverage

scint? bg needs study

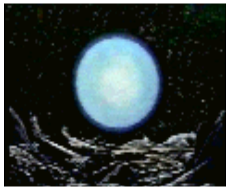
J. Conrad & M. Shaevitz, Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys. Rev. Lett. 104, 141802 (2010)

Summary of "3-flavor" oscillation physics

Observable	Signature	Next steps*
θ_{13}	Tiny appearance of ν_e in a beam of ν_μ; disappearance of $\bar{\nu}_e$	Ne be (T2 R 
Mass hierarchy sign(Δm_{23}^2)	Matter-induced $\nu/\bar{\nu}$ asymmetry, oscillation distortion	Superbeams, atmospheric, reactors 
CPV phase δ	$\nu/\bar{\nu}$ asymmetry	Superbeams, atmospheric ν, cyclotrons 

Will need multiple measurements

*Super nova



All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

There are already some slightly uncomfortable data that don’t fit that paradigm...

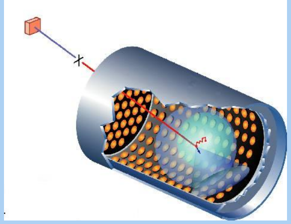
Open a parenthesis:

(

Outstanding 'anomalies'

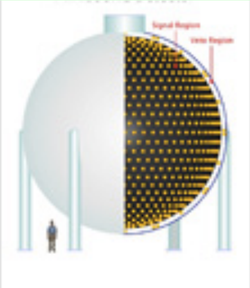
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ \mathrm{eV}^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL (ν,$\overline{\nu}$ ~1 GeV, 0.5 km)



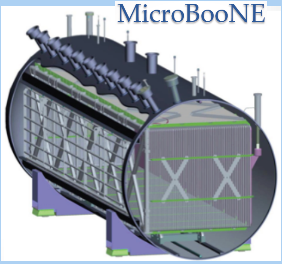
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

????
more data needed

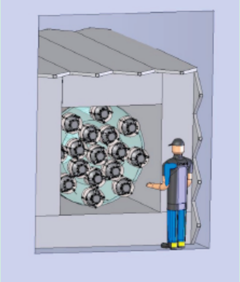
Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly')
and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle physics & astrophysics. **Or some other new physics??**

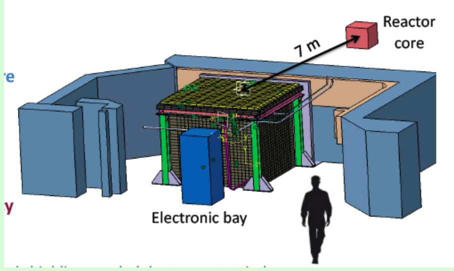
Ideas to address these anomalies...

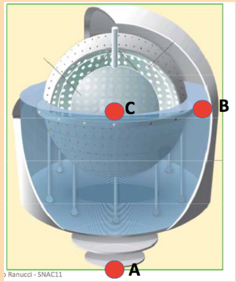


Experiments with beams (meson decay in flight and at rest)

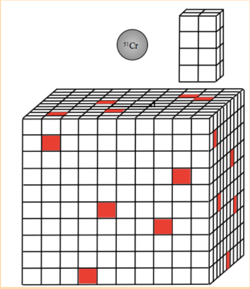


Experiments at reactors





Experiments with radioactive sources



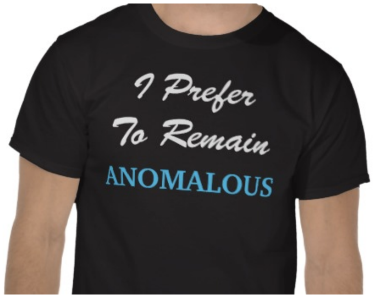
Many more! see e.g. `arXiv:1204.5379`

Parenthesis is not closed...

Possible futures

exciting new world to explore!

anomalies confirmed



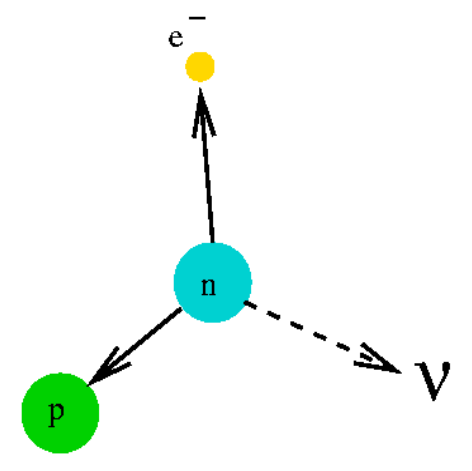
fill in the 3-flavor parameters and keep pushing on the paradigm

anomalies go away

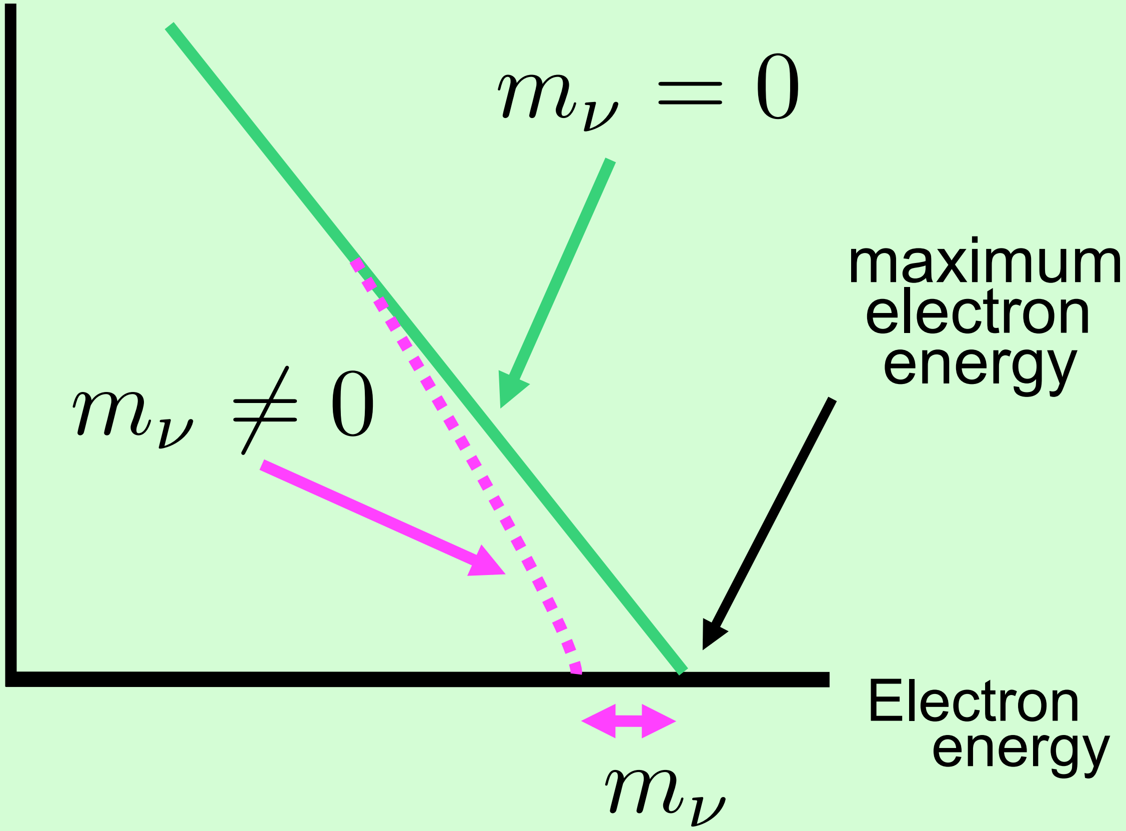
What about the absolute neutrino mass scale?

Kinematic experiments for absolute neutrino mass

(oscillation experiments only inform on mass *differences*)



No. of counts



$m_\nu = 0$

maximum electron energy

$m_\nu \neq 0$

Electron energy

m_ν

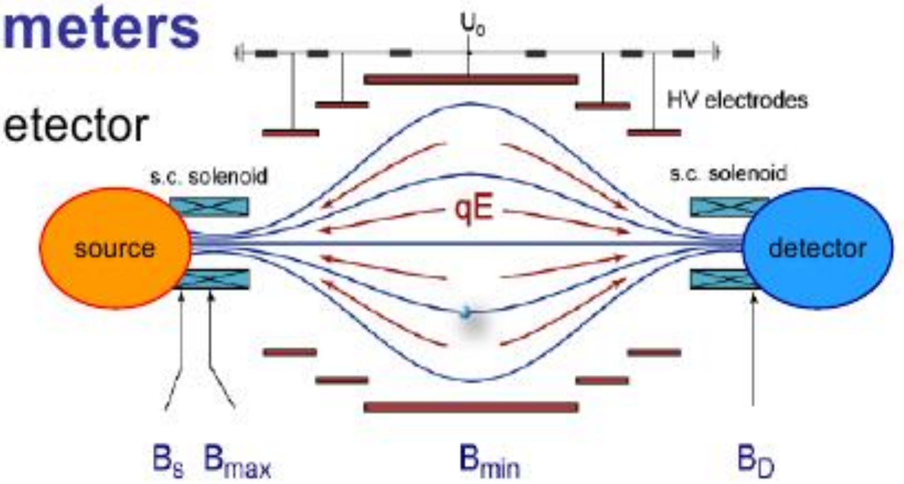
Look for distortion of β-decay spectrum near endpoint

Current best limits: Mainz, Troitsk: m_ν < 2.2 eV

Experimental approaches: aiming for sub-eV sensitivity

Spectrometers

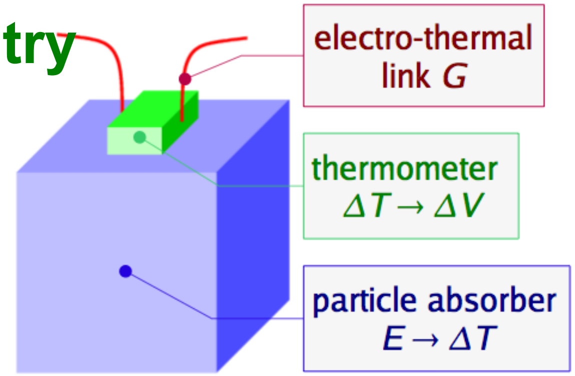
Source≠Detector



$$^3\mathrm{H} \rightarrow {}^3\,\mathrm{He} + e^- + \bar{\nu}_e$$

18.6 keV endpoint
Mainz, Troitsk➔ KATRIN
(0.2 eV expected)

Thermal calorimetry

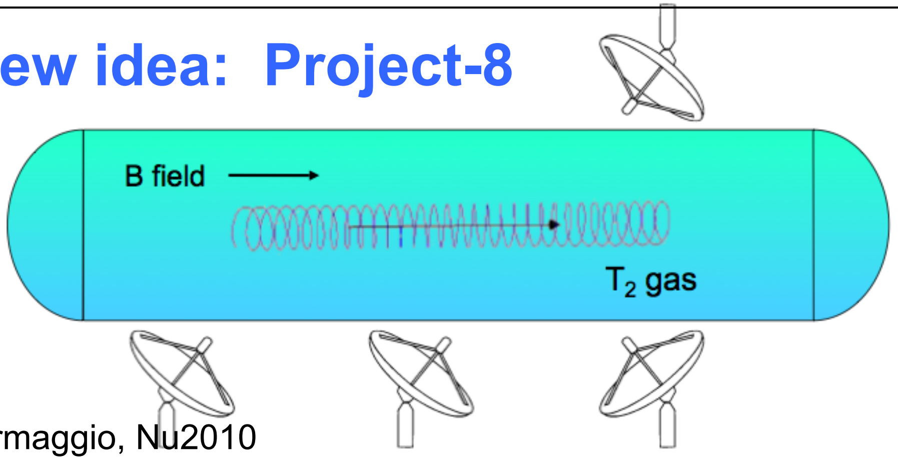


A. Nucciotti, Nu2010

$$^{187}\mathrm{Re} \rightarrow {}^{187}\,\mathrm{Os} + e^- + \bar{\nu}_e$$

2.5 keV endpoint
MARE

New idea: Project-8



J. Formaggio, Nu2010

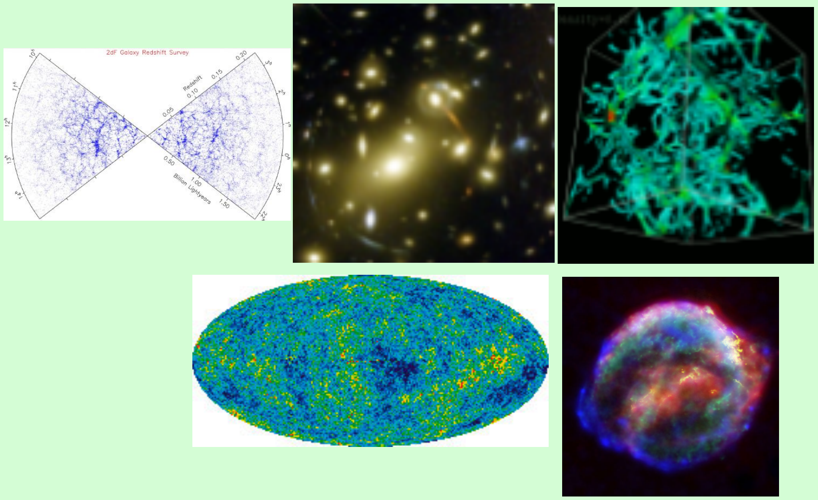
$$^3\mathrm{H} \rightarrow {}^3\,\mathrm{He} + e^- + \bar{\nu}_e$$

Measure energy via cyclotron frequency

Another way of getting at absolute neutrino mass

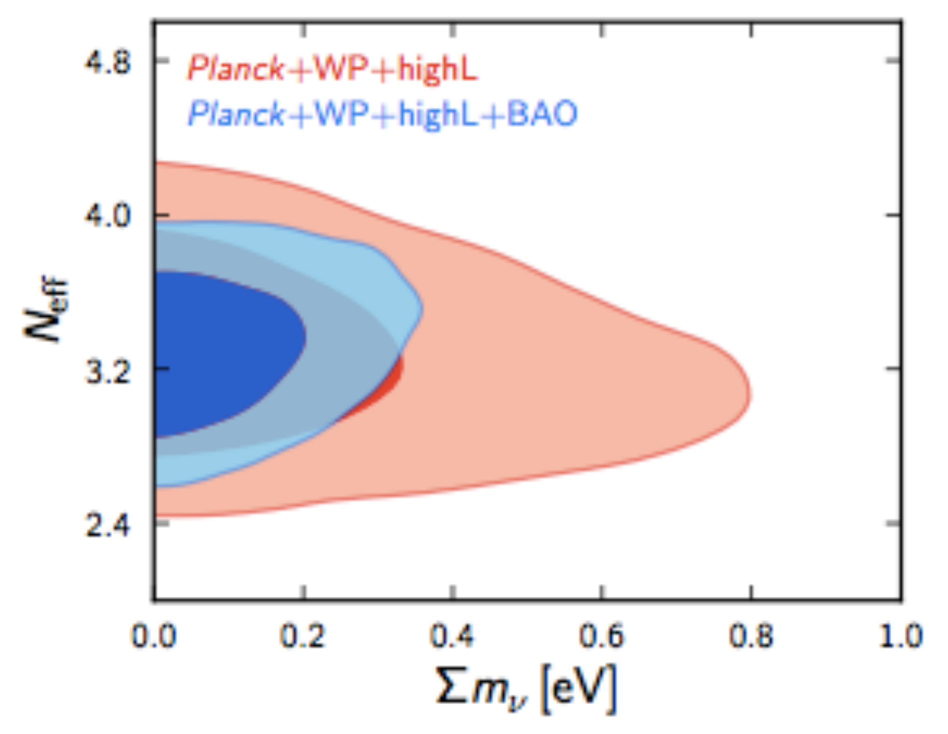
Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...

(model-dependent)



from Planck

$$\sum m_i <\sim 0.6 \text{ eV}$$



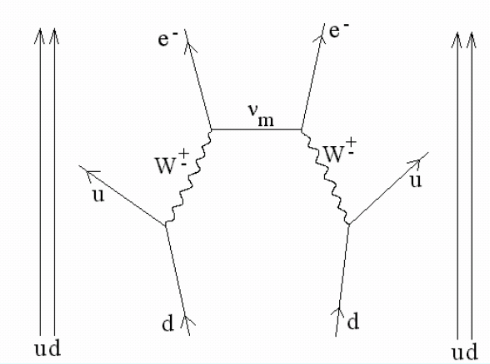
And some giant questions I will omit...

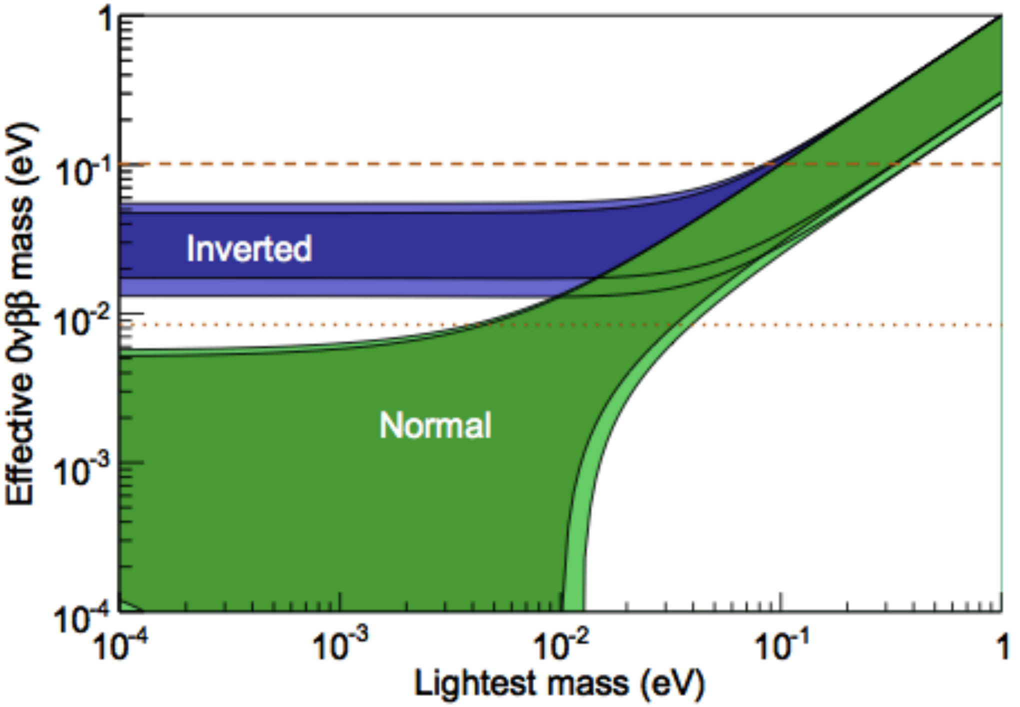
How do we add the masses to the SM?

Are neutrinos Majorana or Dirac?

Neutrinoless Double Beta Decay

$$\langle M_{\mathrm{eff}}\rangle^2 = |\sum_i U_{ei}^2 M_i|^2$$





Lecture #1 Summary

We now have a pretty robust, simple 3-flavor neutrino paradigm, describing most of the data

Still a few unknown parameters in this picture, notably MH and CP δ, but clear steps to take

- **MH: multiple approaches (all challenging but conceivable)**
- **CP δ: standard LBL approach is promising**

and plenty of long-term ideas....

→need to push on the paradigm w/ precision measurements

Anomalies are still out there...
they may or may not go away...