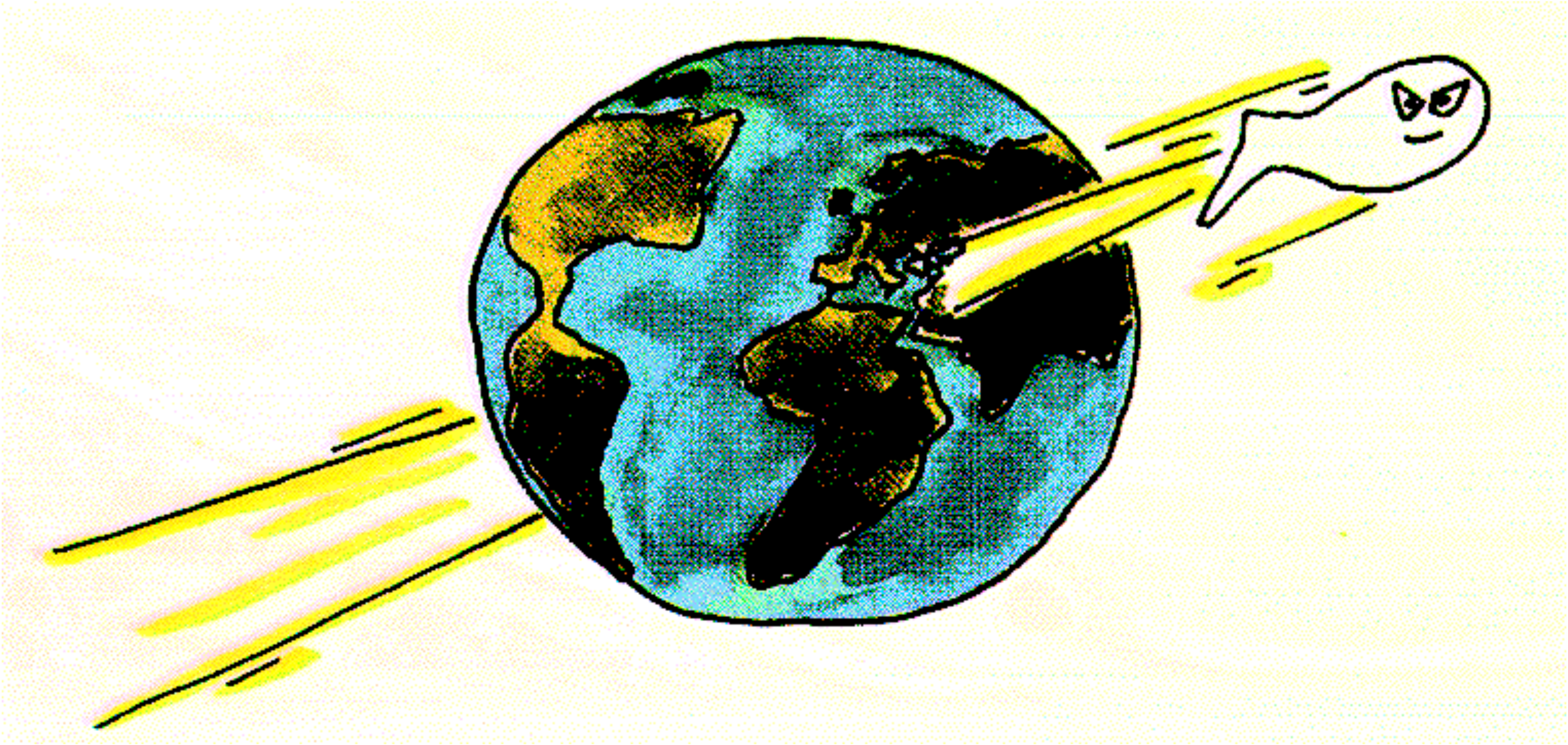
Neutrino Physics

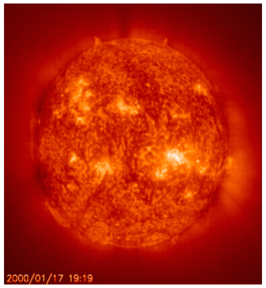


Kate Scholberg, Duke University
NNPSS 2014, Williamsburg, VA

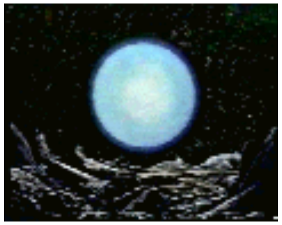
Lecture Plan

Lecture #1: **Neutrino Mass and Oscillations**

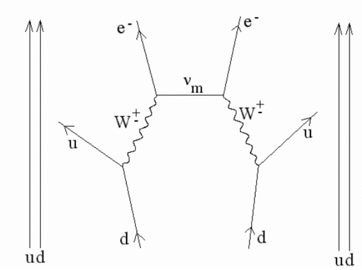
Lecture #2: **Solar Neutrinos**



Lecture #3: **Supernova Neutrinos**



Lecture #4: **Absolute Mass and Neutrinoless Double Beta Decay**



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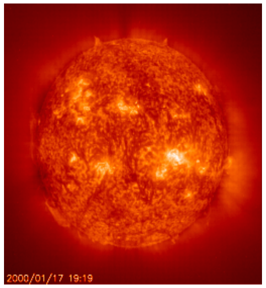
Lecture #2: **Solar Neutrinos**



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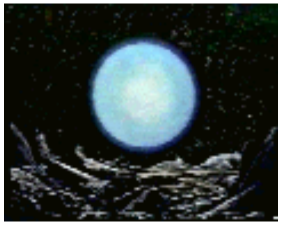

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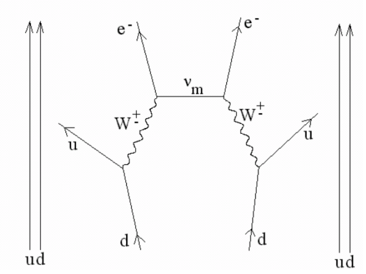
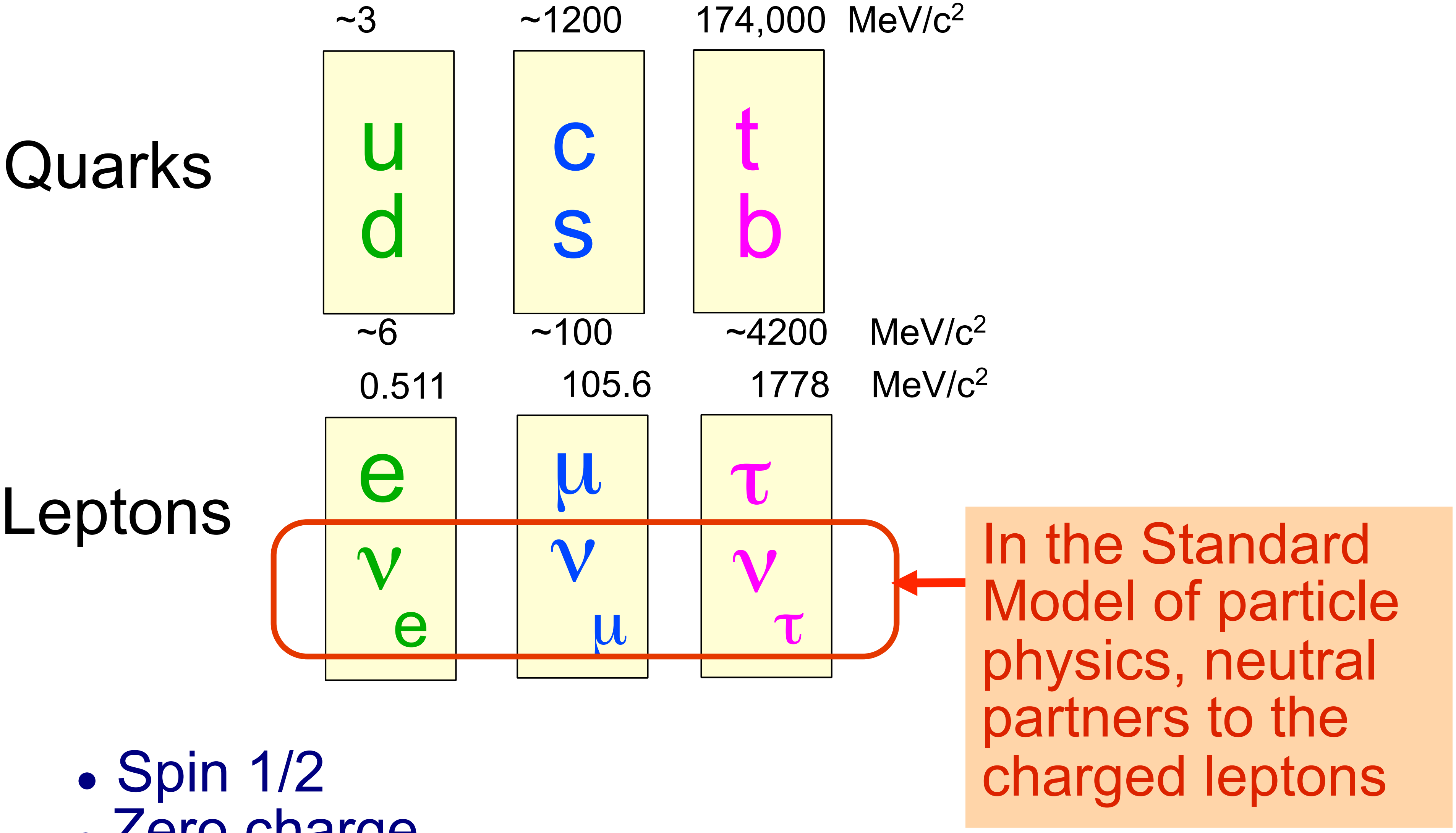


Lecture #1

- 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

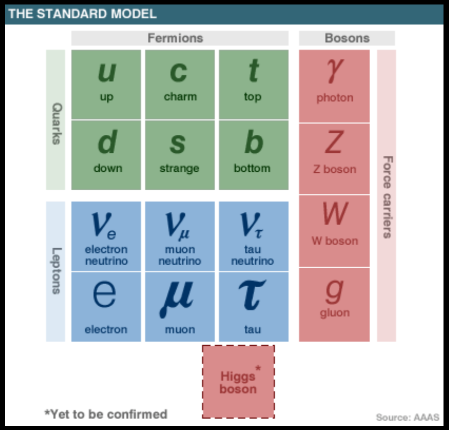


	~3	~1200	174,000	MeV/c^2
Quarks	u	c	t	
	d	s	b	
	~6	~100	~4200	MeV/c^2
	0.511	105.6	1778	MeV/c^2
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	

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!

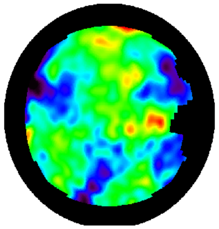
charge conjugation

parity

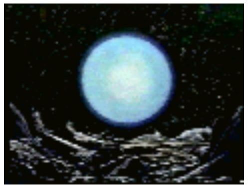
CP violation is likely involved: a difference in behavior between a particle and its mirror-inverted antiparticle: *observed so far in quarks but not leptons*

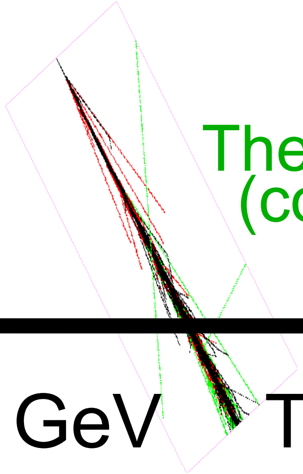
Sources of wild neutrinos

The Big Bang



Super
novae

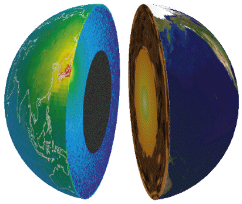


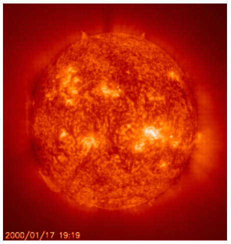


The Atmosphere
(cosmic rays)

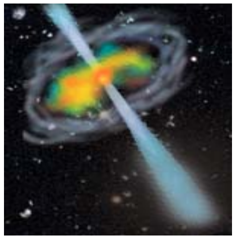
meV eV keV MeV GeV TeV PeV EeV

Radioactive
decay in the
Earth





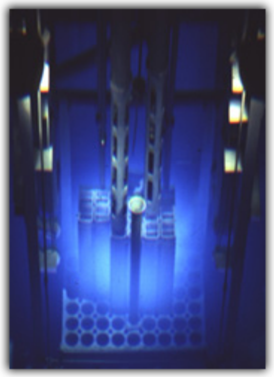
The Sun



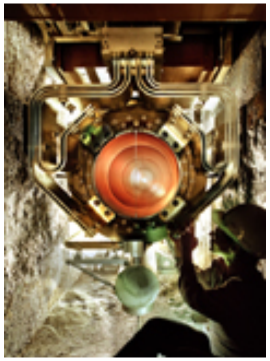
AGN's,
GRB's, ...

Sources of 'tame' neutrinos

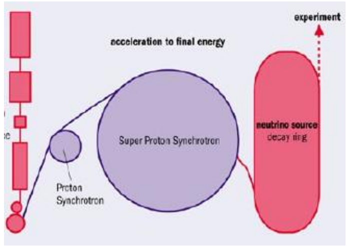
Nuclear reactors



Proton accelerators

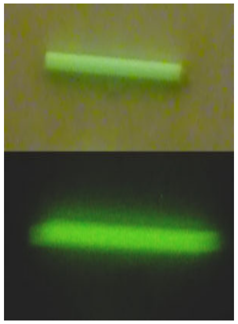


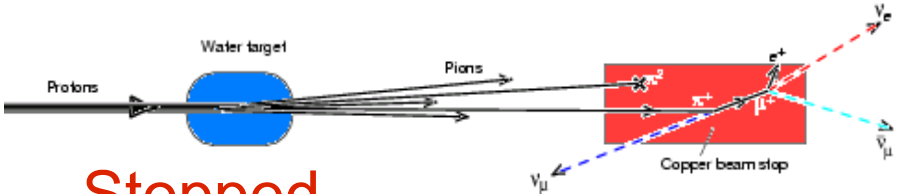
Beta beams



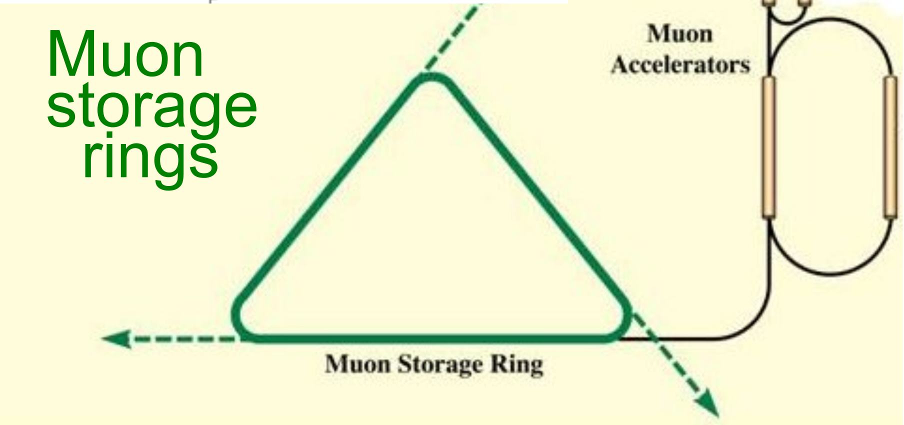
eV keV MeV GeV TeV

Artificial radioactive sources





Stopped pion sources



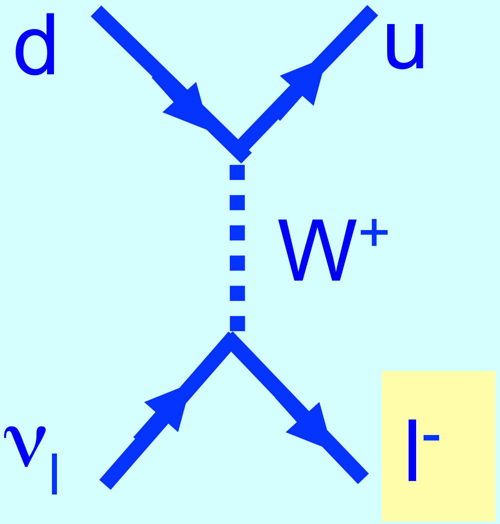
Muon storage rings

Usually (but not always) better understood...

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

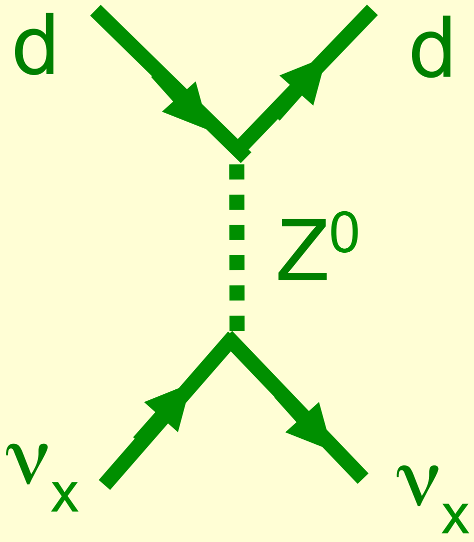


$$\nu_l + N \rightarrow l^{\pm} + N'$$

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:

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

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

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

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

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

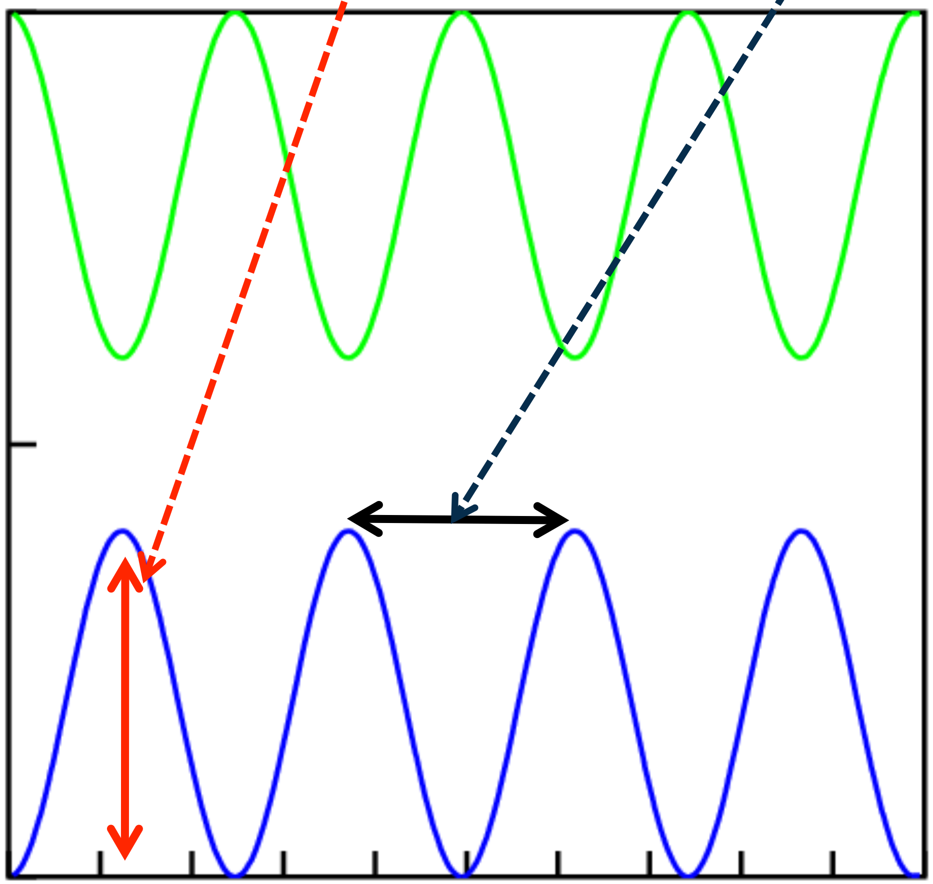
*Note: oscillation depends on mass ***differences***, not absolute masses

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

Appearance: directly see new flavor

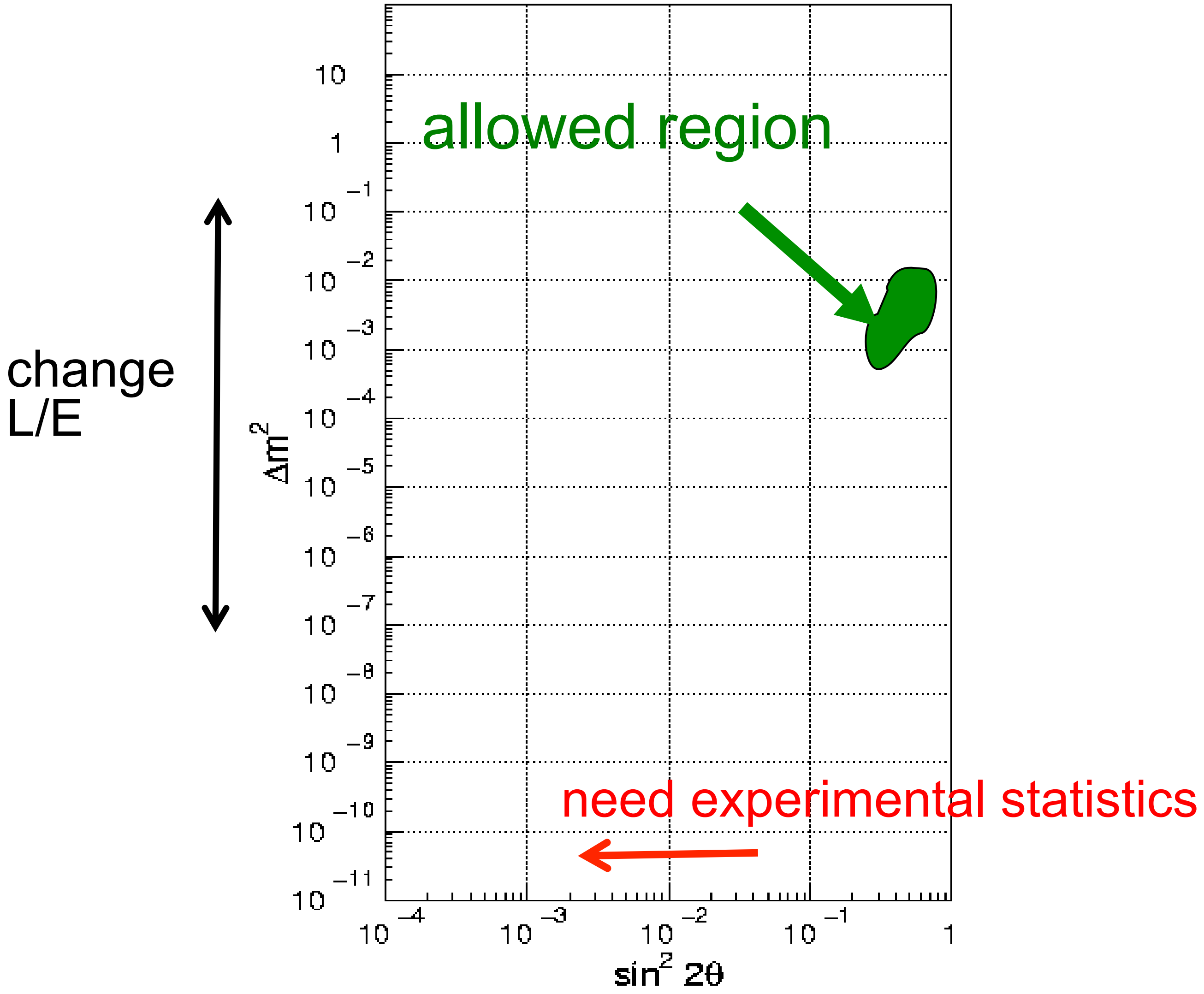
e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV energies

Neutrino 2-flavor oscillation parameter space

amplitude

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

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



allowed region

change L/E

need experimental statistics

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

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

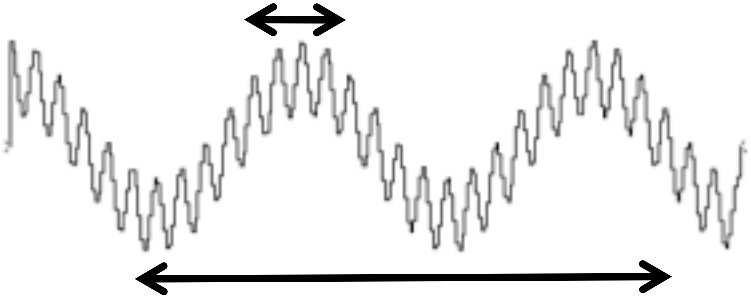
$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

(L in km, E in GeV, m in eV)

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

$$\pm 2 \sum_{i>j} \Im(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \boxed{\sin(2.54 \Delta m^2_{ij} L/E)}$$

oscillatory behavior in L and E



$$|\Delta m^2_{23}| >> |\Delta m^2_{12}|$$ ➔ two frequency scales

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

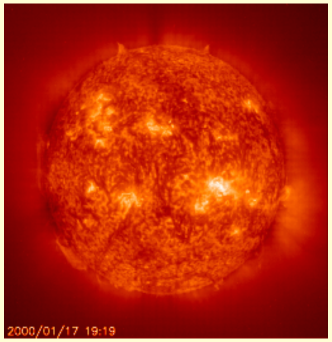
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

We now have strong evidence for flavor oscillations:

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

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

SOLAR NEUTRINOS



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

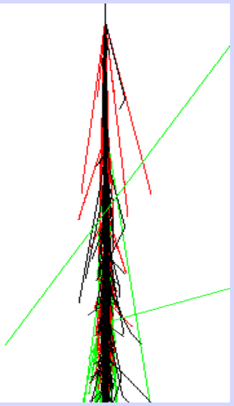
$$\boxed{\nu_e \longrightarrow \nu_\mu, \nu_\tau}$$

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

... now confirmed by a reactor experiment

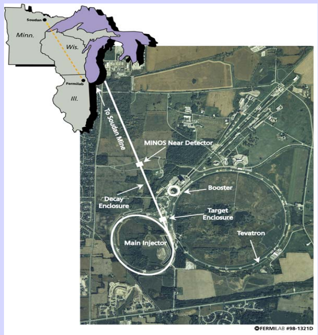
Described by θ_{12}, Δm^2_{12}

ATMOSPHERIC NEUTRINOS



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

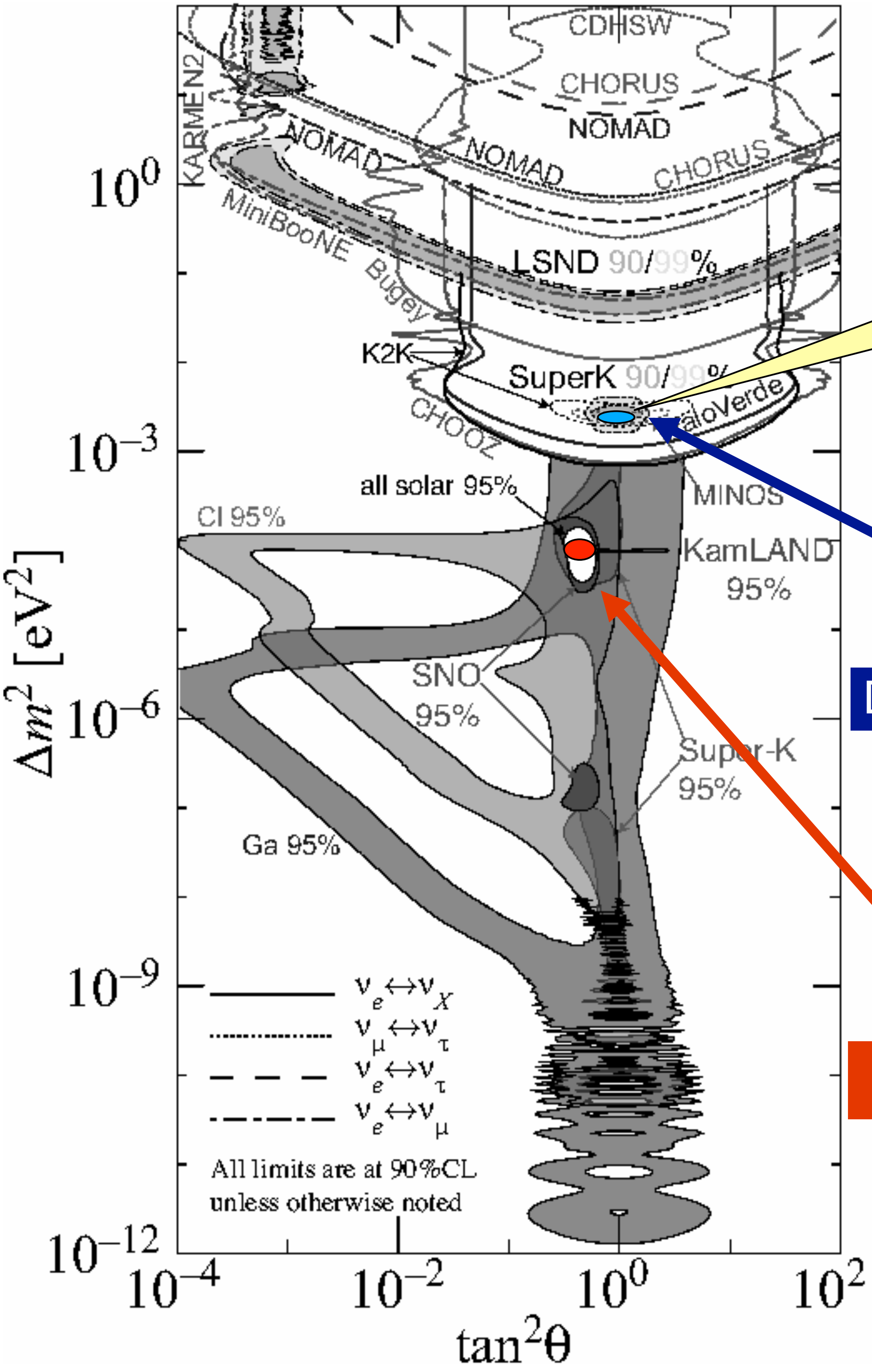
$$\boxed{\nu_\mu \longrightarrow \nu_\tau}$$



...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}

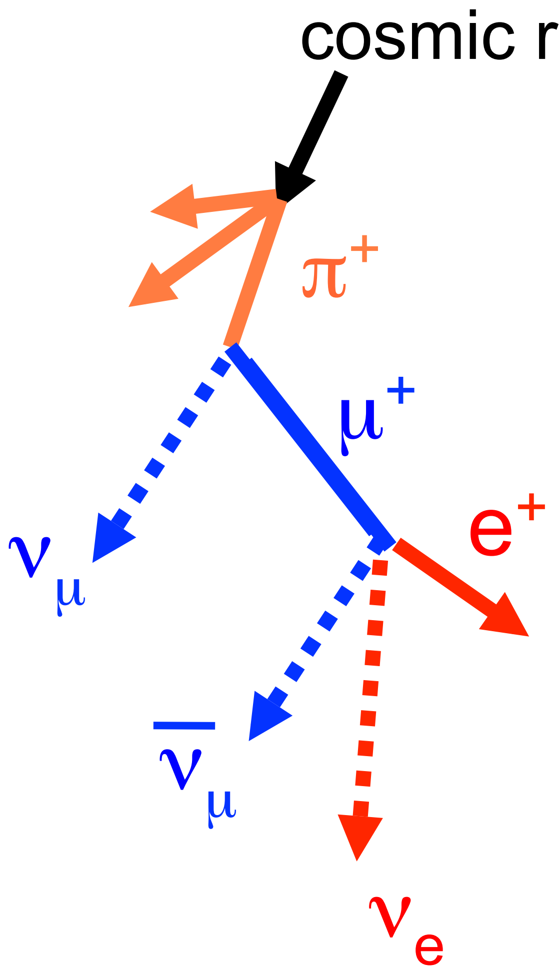
solar/reactor neutrinos

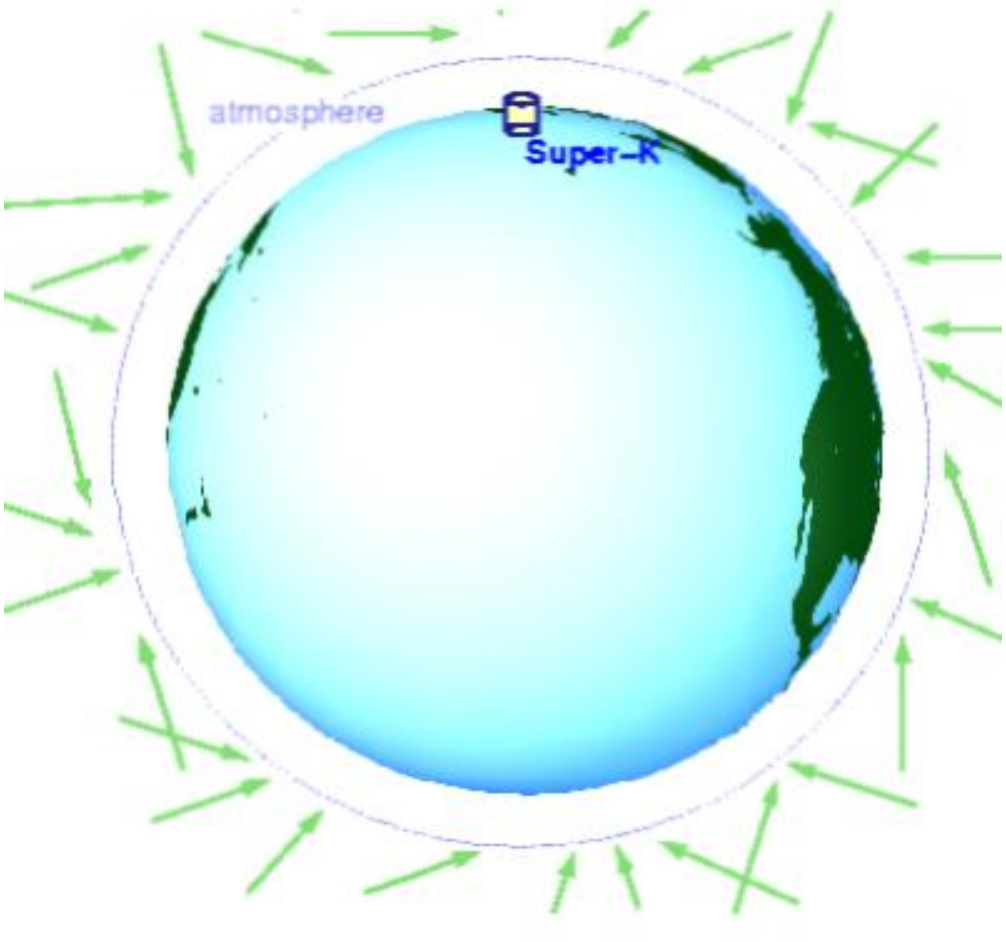
Described by θ_{12}, Δm^2_{12}

this afternoon

Atmospheric Neutrinos

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



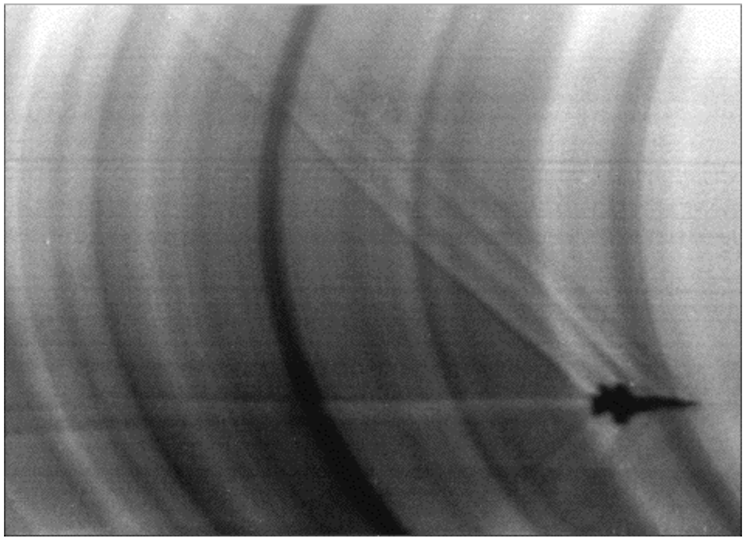


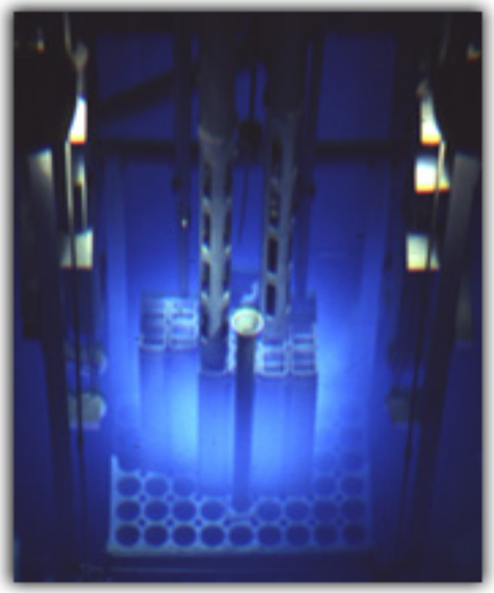
Absolute flux known to ~15%, but *flavor ratio* known to ~5%

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)

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

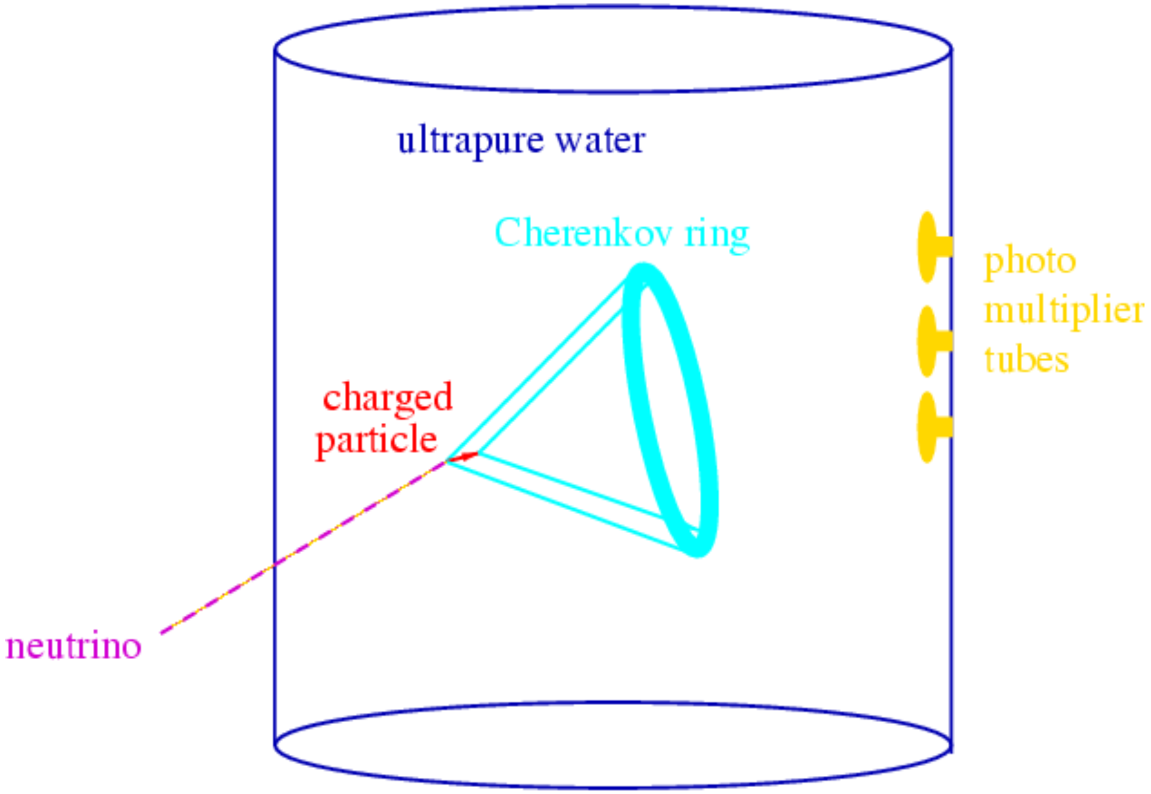
e	0.73
μ	150
π	200
p	1350

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

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

No. of photons ∝ energy loss

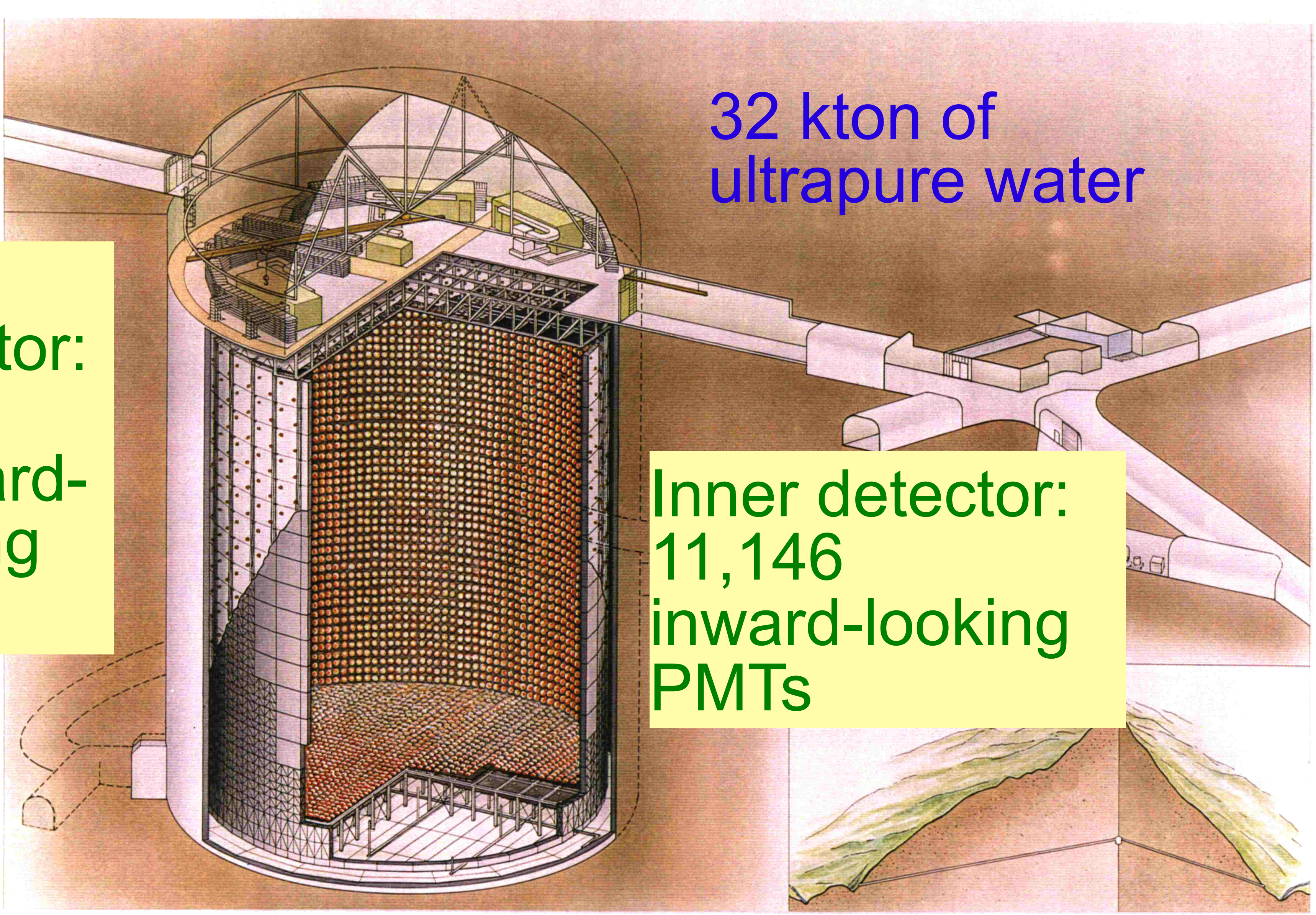
Water Cherenkov ν Detectors



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

Super-Kamiokande

Water Cherenkov detector
in Mozumi, Japan

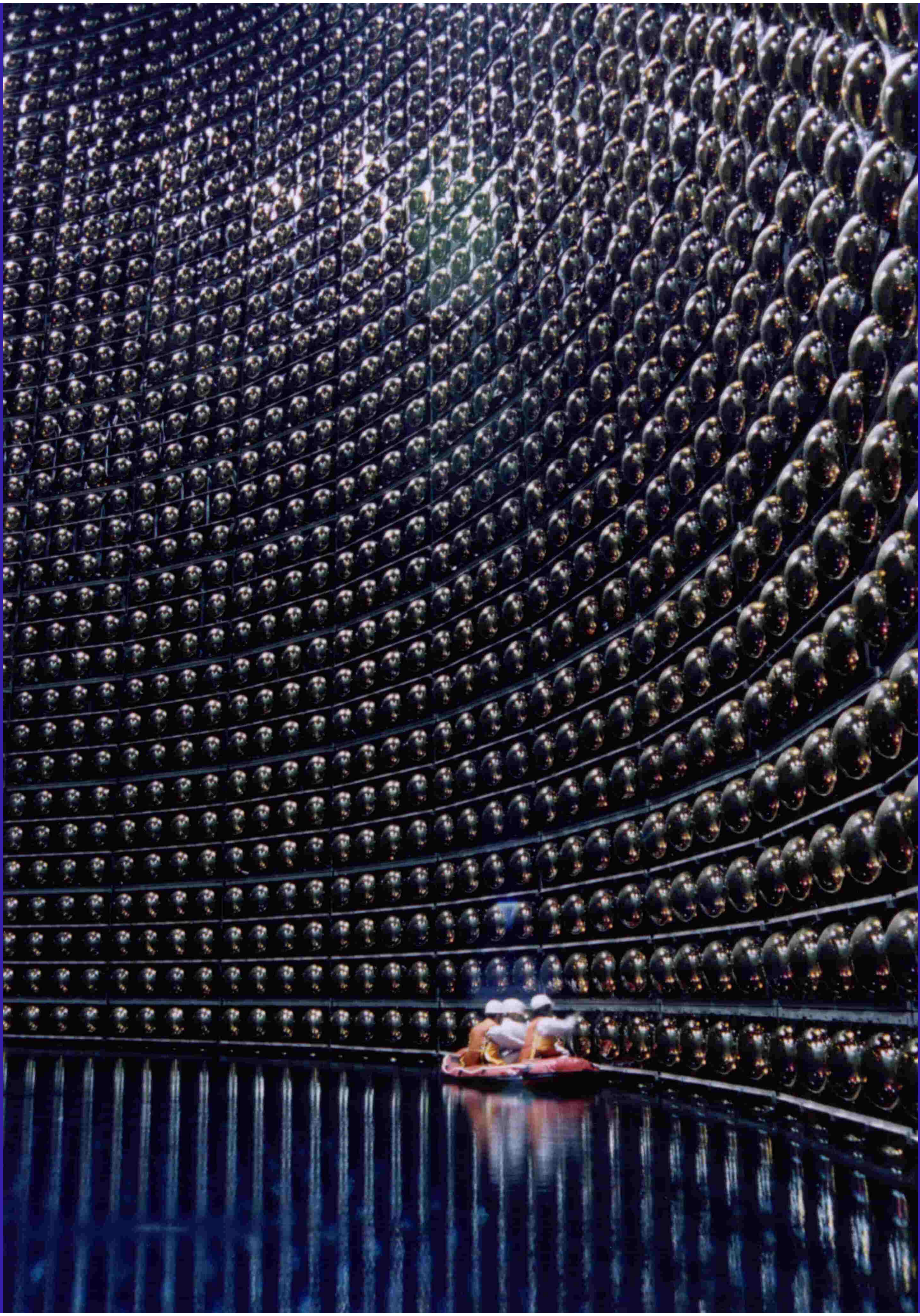


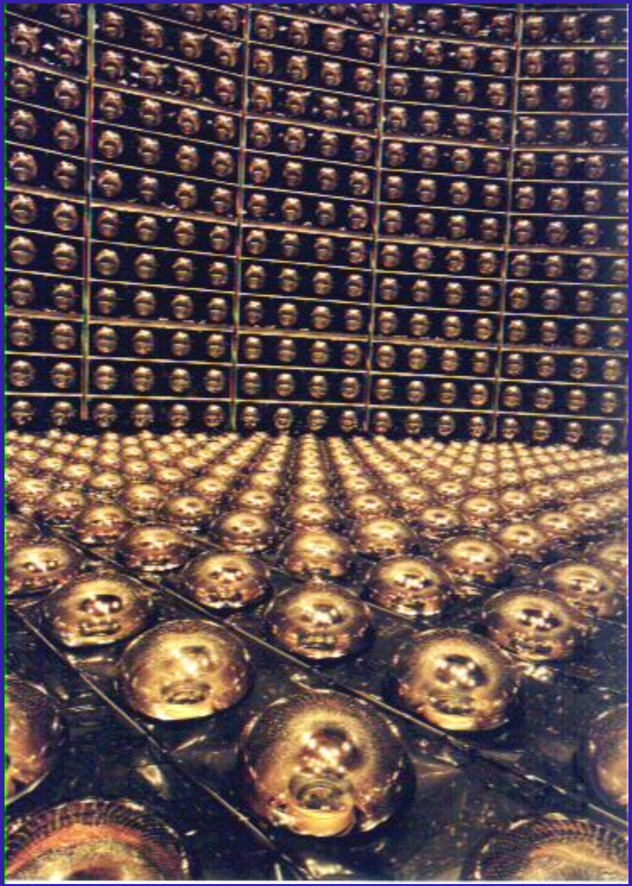
32 kton of
ultrapure water

Outer detector:
1889 outward-looking PMTs

Inner detector:
11,146 inward-looking PMTs

1 km underground to keep away from cosmic rays






DUKE
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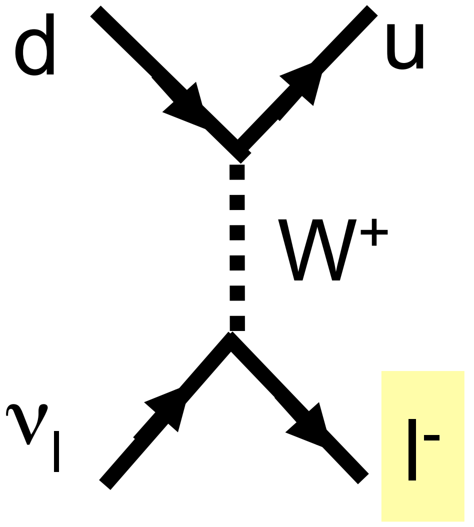
Atmospheric ν's Experimental Strategy

High energy interactions of ν's with nucleons



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

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

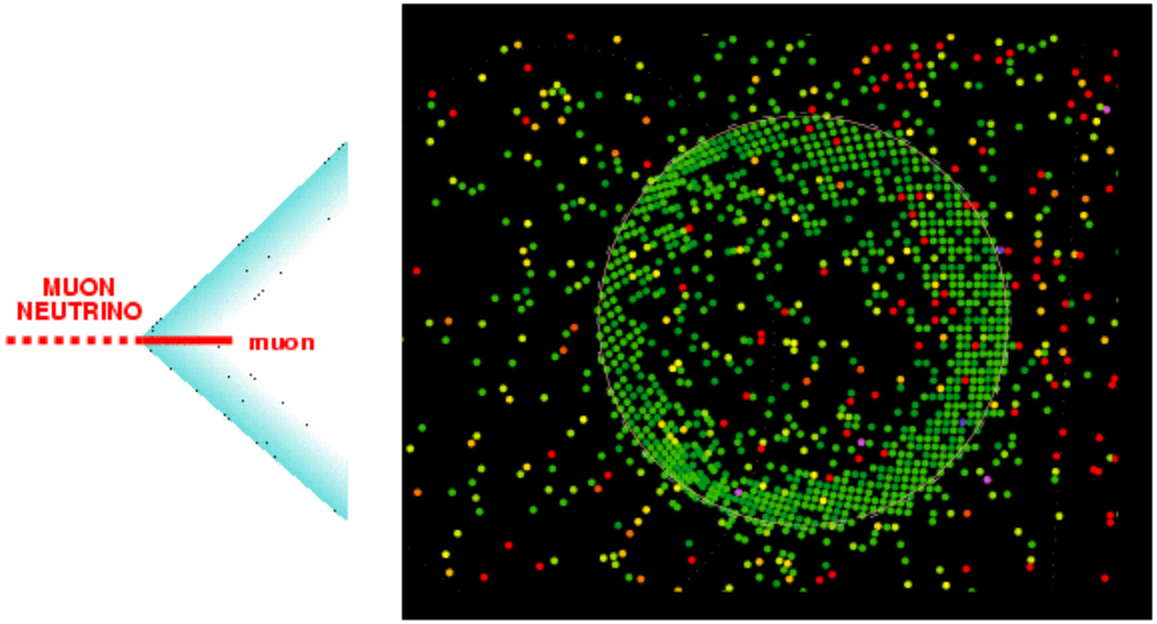
$$\nu_\mu + n \rightarrow \mu^- + p$$

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

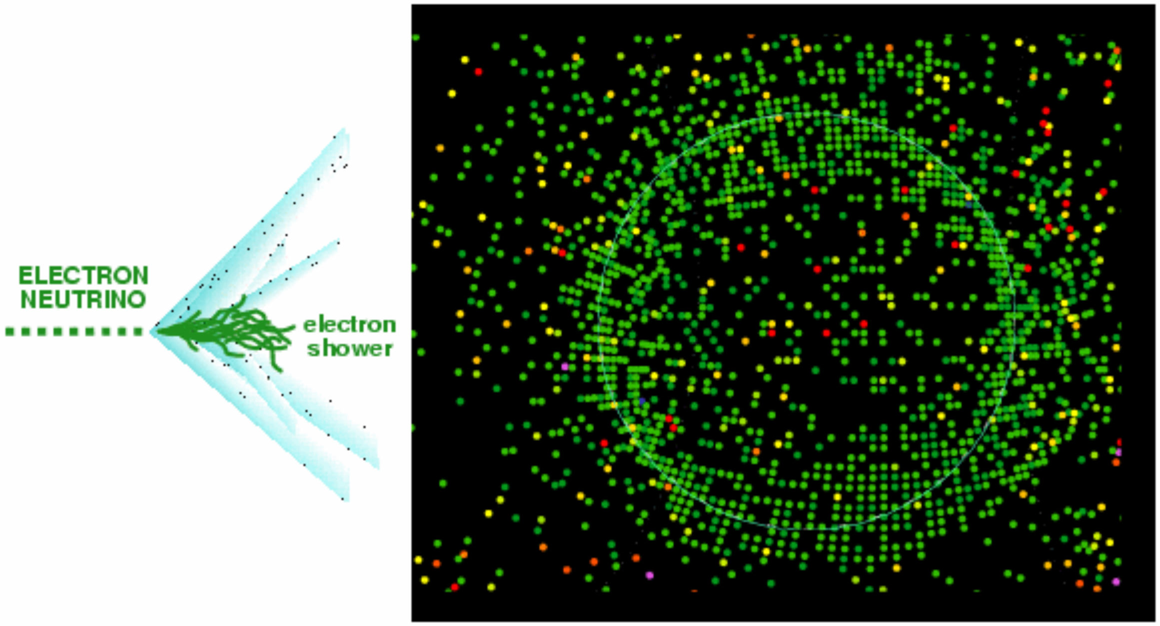
Tag neutrino flavor by flavor of outgoing lepton

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

CC quasi-elastic ("single ring")



Get different patterns in Cherenkov light for e and μ

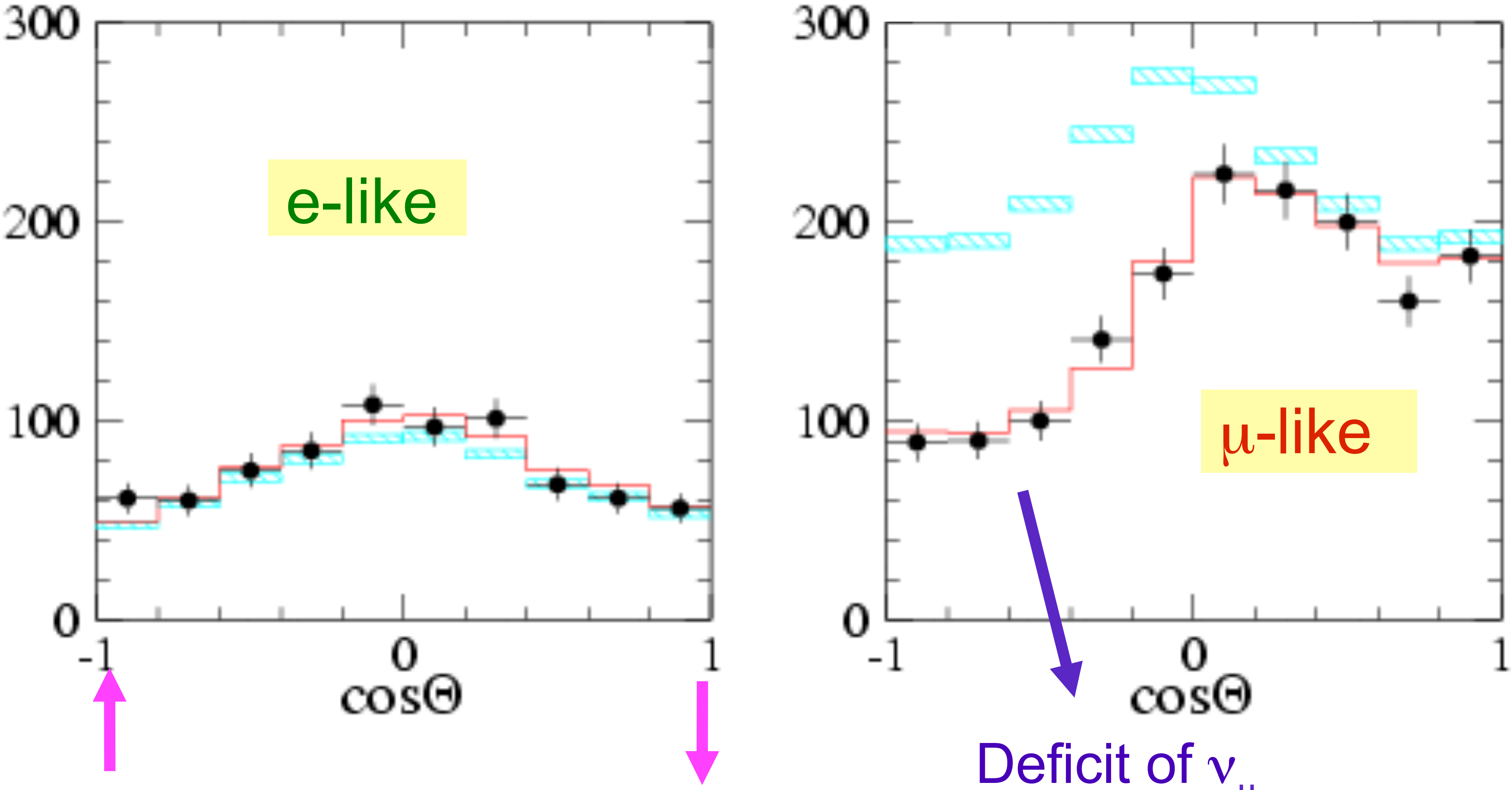


(sim. for other detector types)

From Cherenkov cone get angle, infer pathlength

Zenith angle distribution

1489 days of SK data

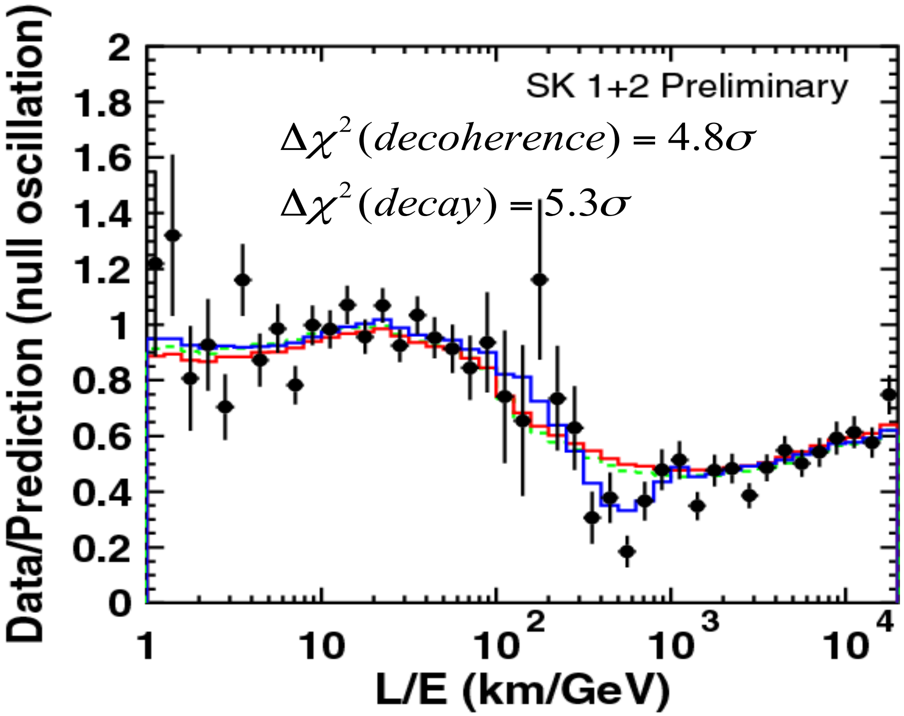


up-going

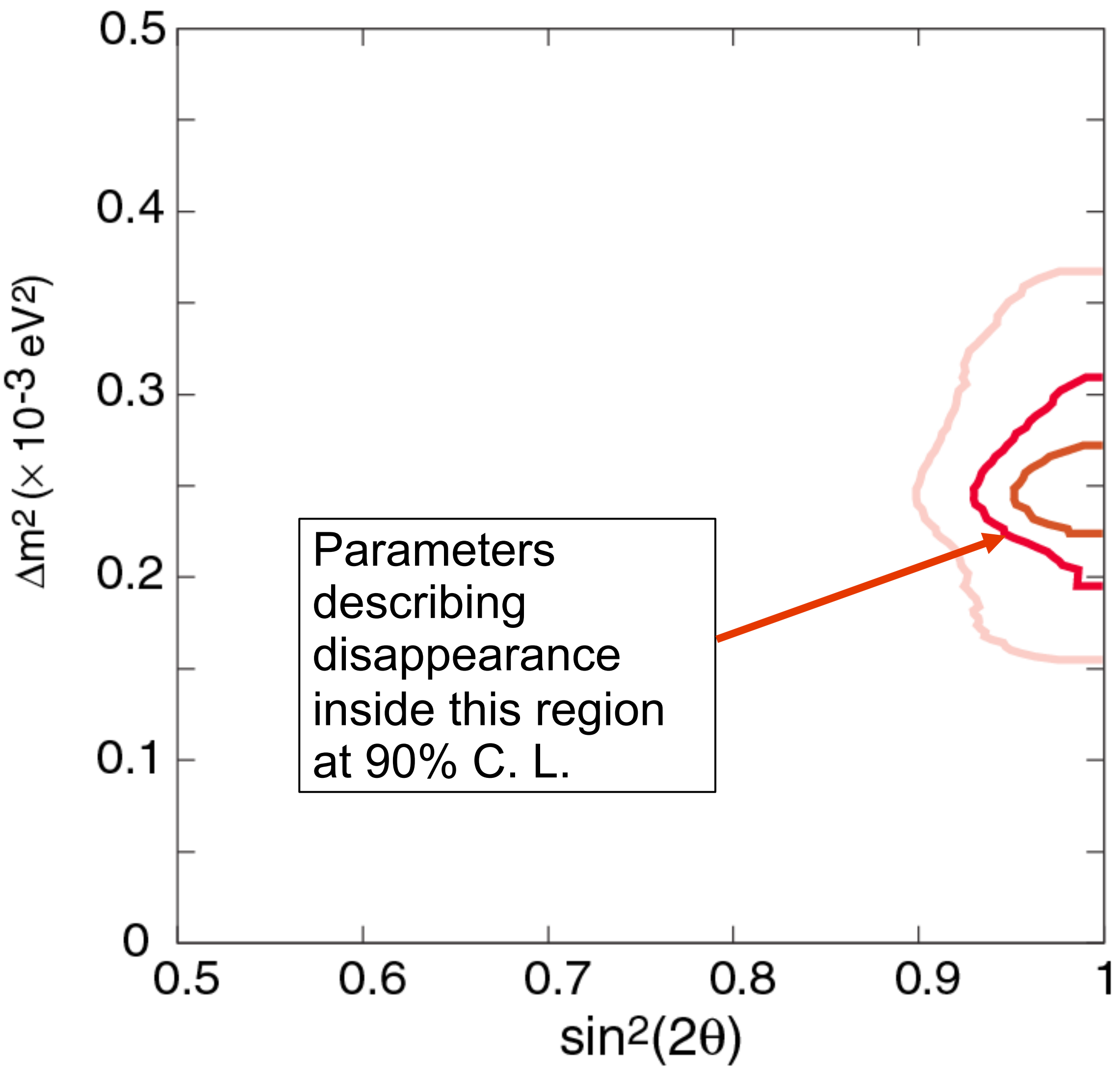
down-going

Deficit of ν_μ
from below
(long pathlength)

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



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



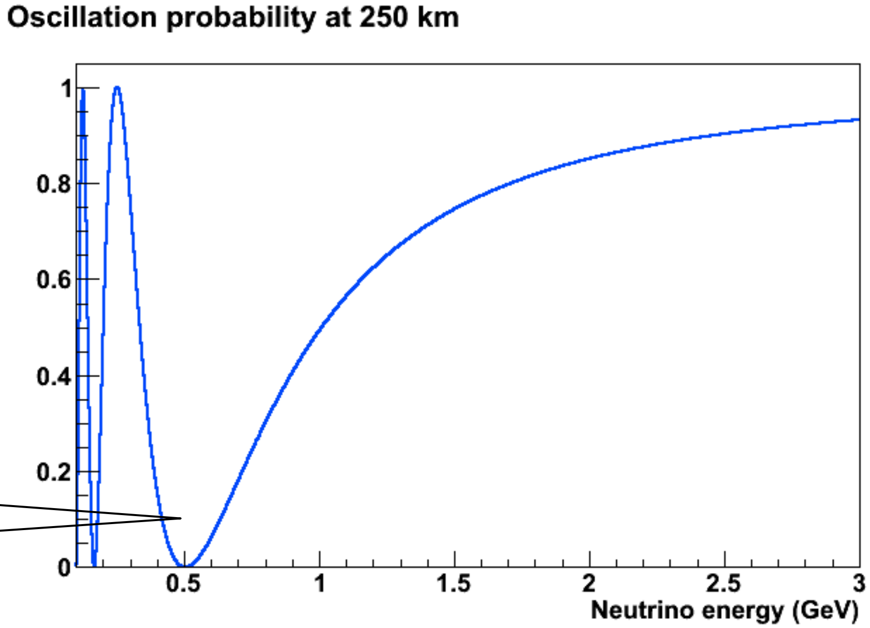
Parameters describing disappearance inside this region at 90% C. L.

Tame the source to confirm & study oscillations with **long-baseline beam experiments**

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

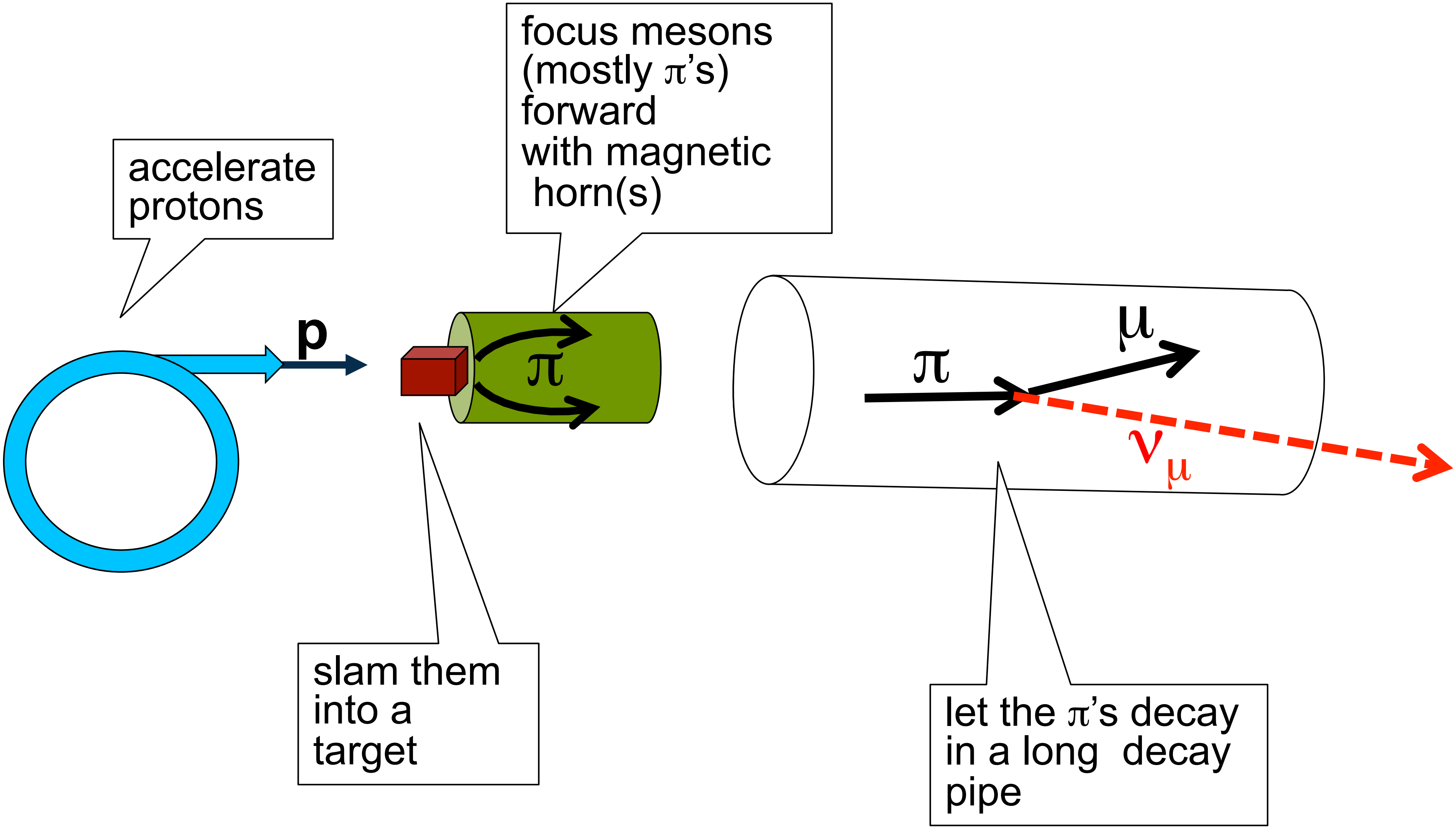
E_ν~ GeV, L~ 100's of km for same L/E

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


Oscillation probability at 250 km

Design your beam at given baseline to cover oscillation peaks

How To Make Tame Neutrinos



accelerate
protons

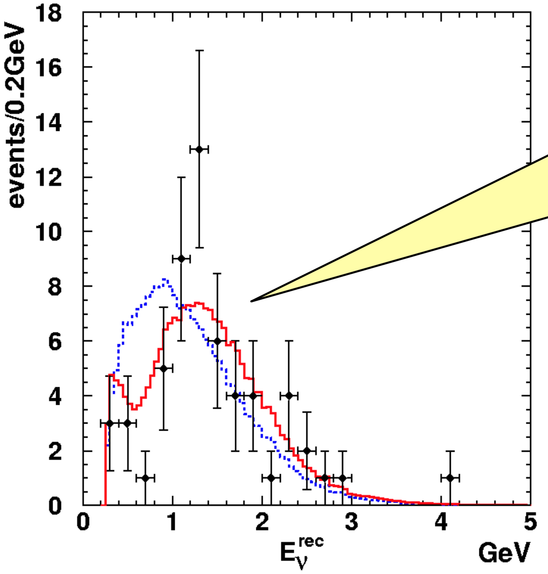
slam them
into a
target

focus mesons
(mostly π's)
forward
with magnetic
horn(s)

let the π's decay
in a long decay
pipe

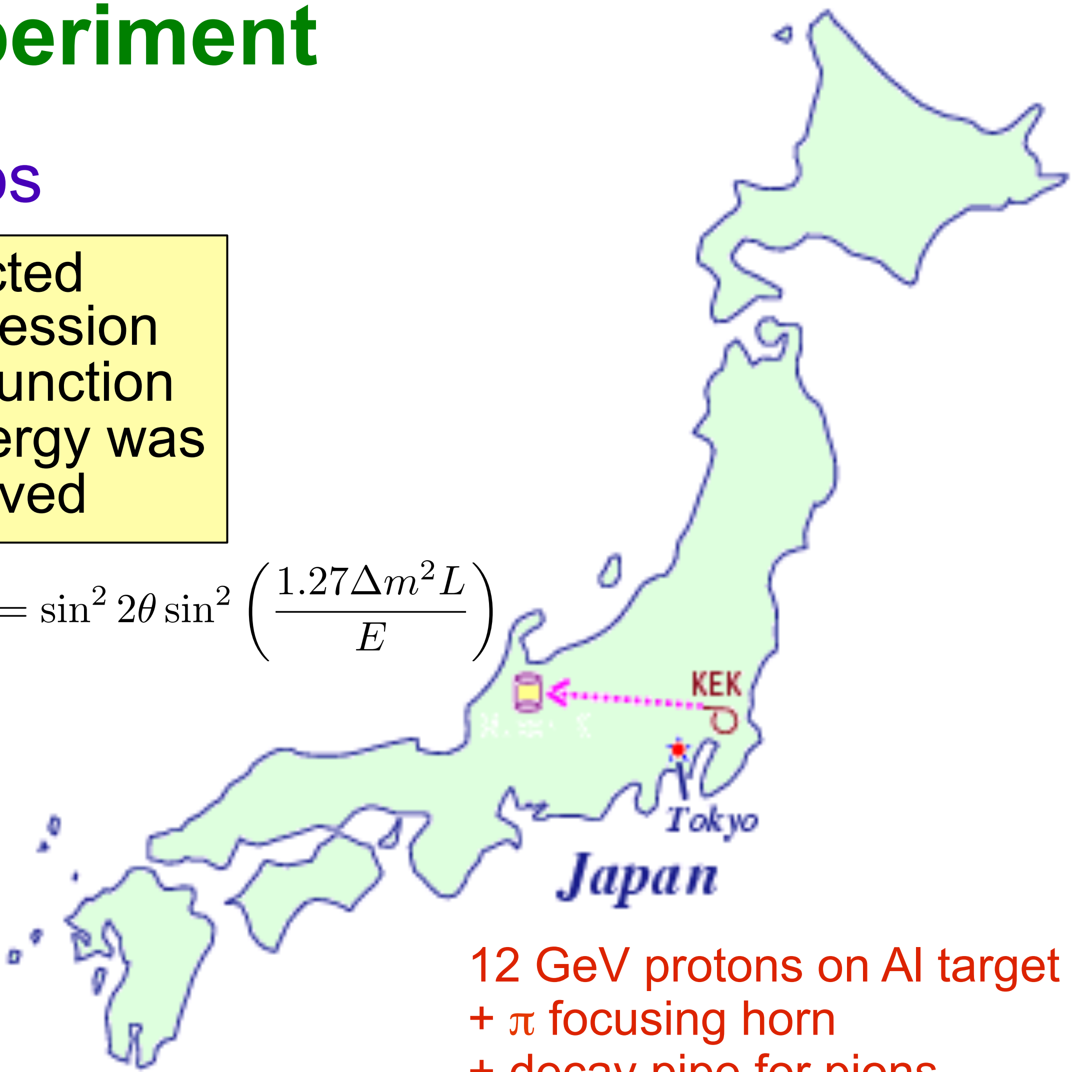
K2K (KEK to Kamioka) Long-Baseline Experiment

~ 1 GeV muon neutrinos



expected suppression as a function of energy was observed

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

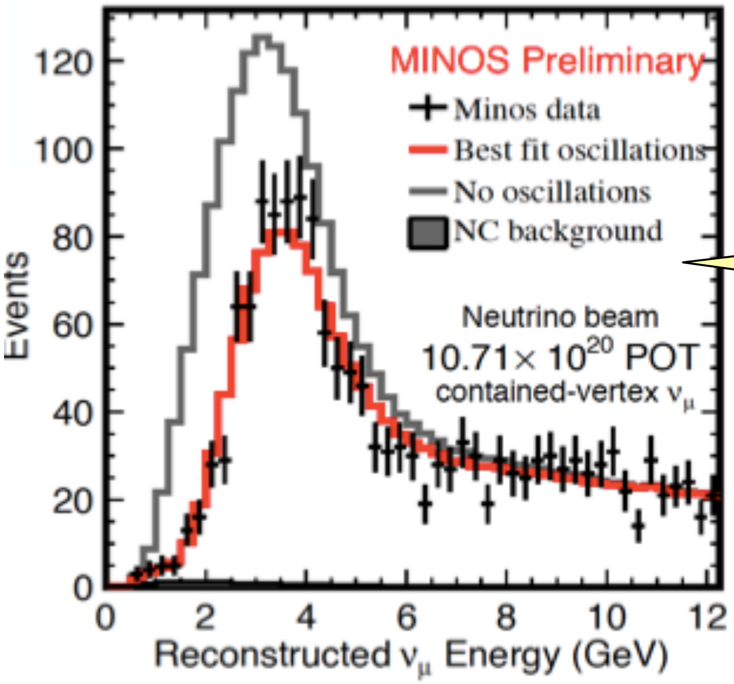


12 GeV protons on Al target
+ π focusing horn
+ decay pipe for pions

MINOS

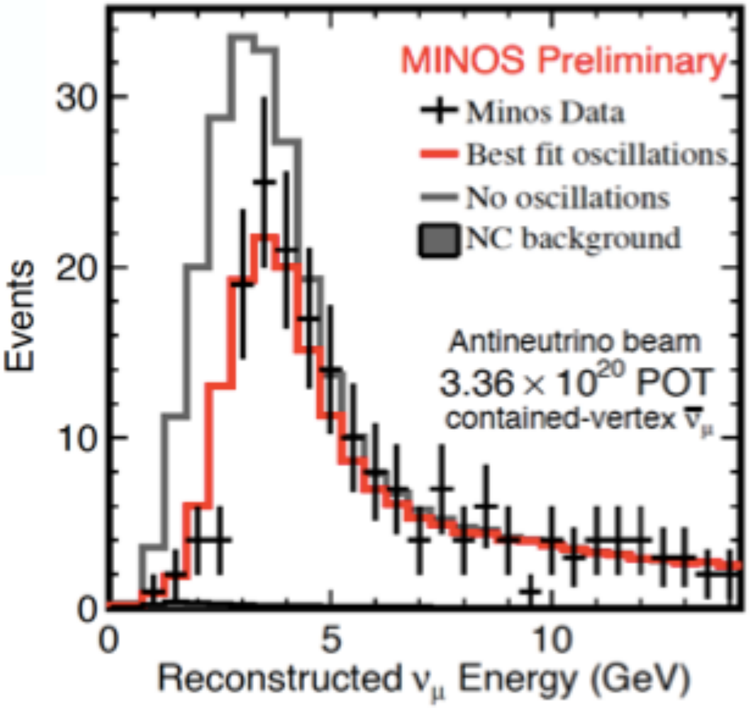
in US making precision measurements of ν_μ disappearance

Neutrinos



suppression of μ-like events

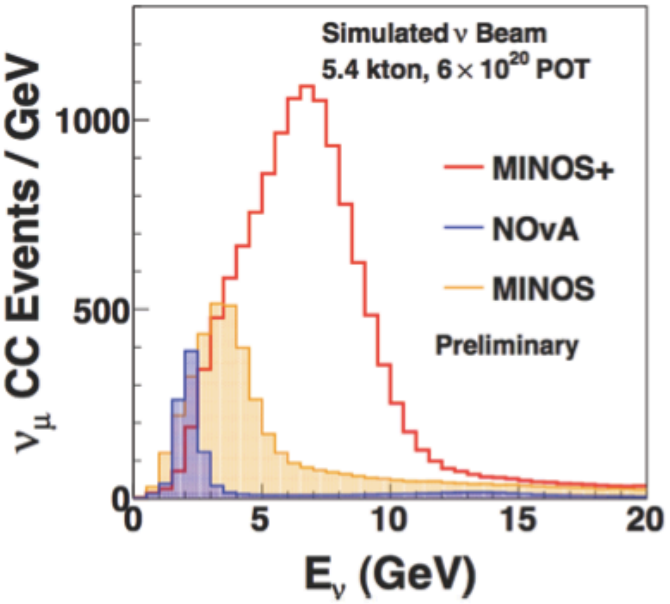
Antineutrinos

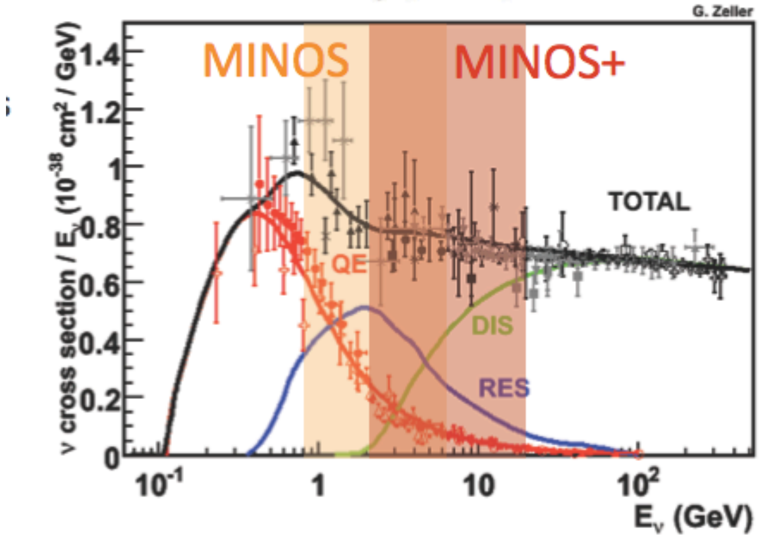


Magnetized iron tracker enables sign selection and event-by-event antineutrino selection

A. Sousa, Neutrino 2014

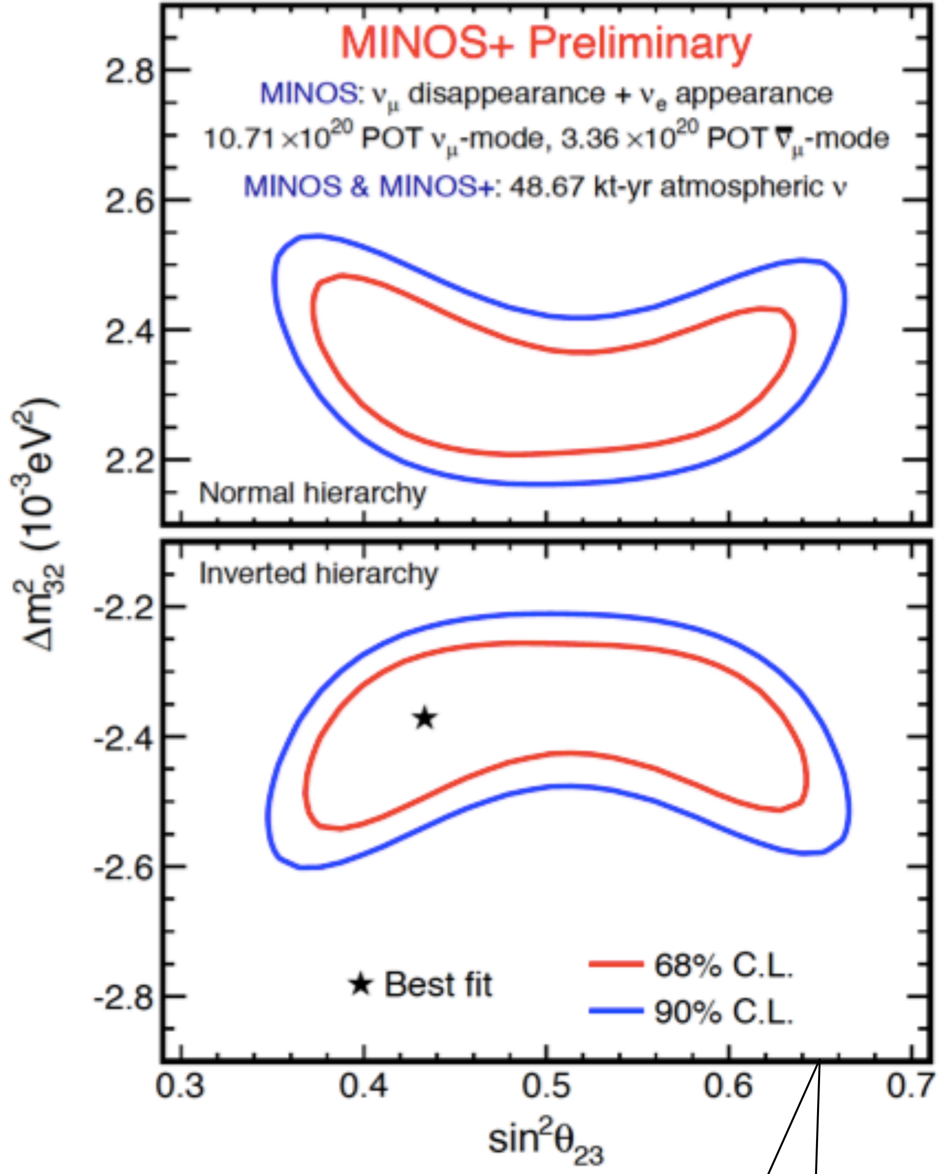
MINOS+





upgraded NuMi beam since 2013
@higher energy

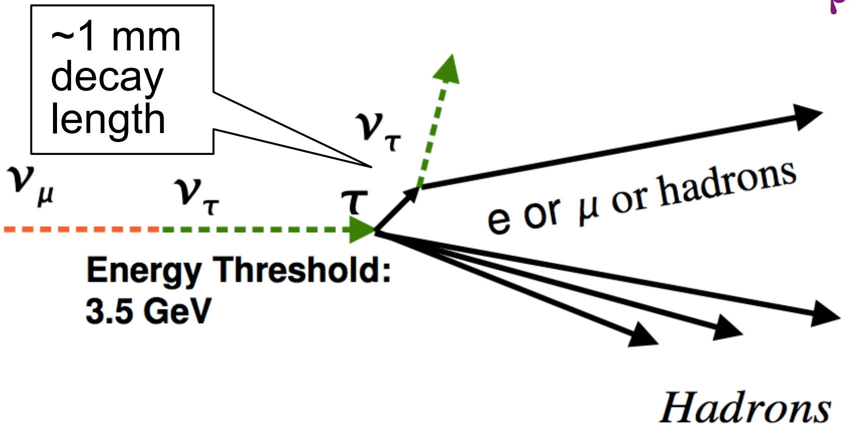
A. Sousa, Neutrino 2014



New results:
three-flavor
oscillations w/
beam &
atmospheric ν's

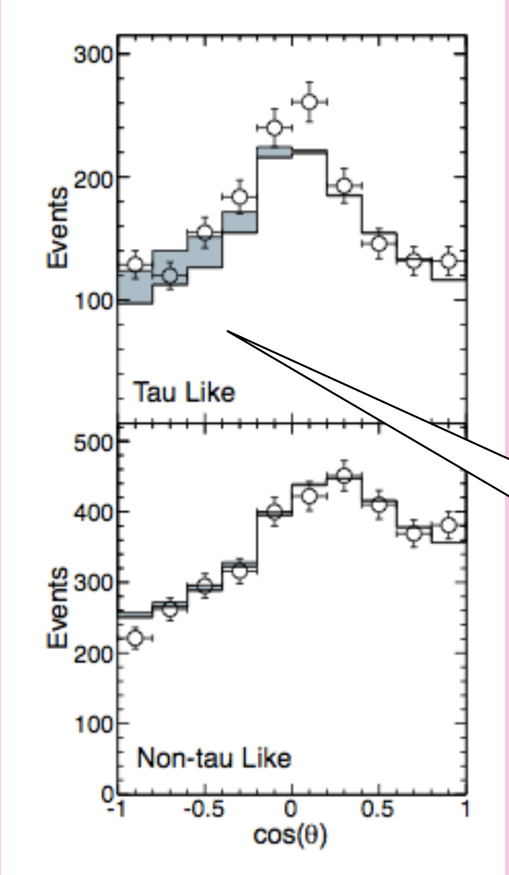
Squeezing
down
$|\Delta m^2_{23}|$!

Is the disappearance $\nu_\mu \rightarrow \nu_\tau$?



Hard to see
τ's explicitly:
require >3.5 GeV,
multiple decay modes

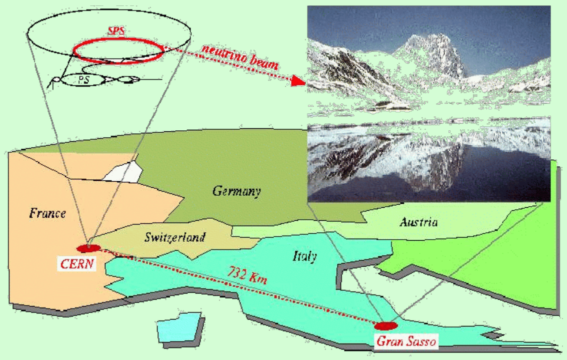
Super-K atmospheric ν's



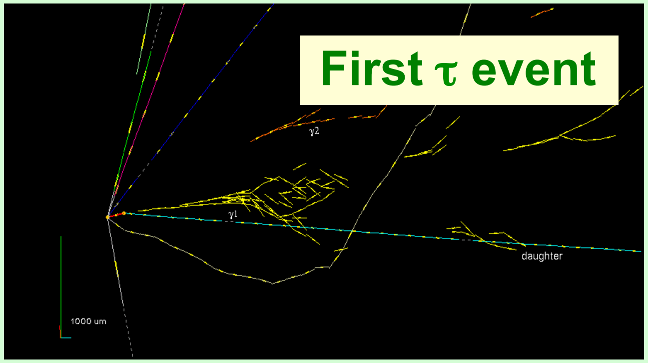
Upgoing
excess of
tau-like
topologies

3.8σ
appearance
result

OPERA @ CNGS



lead/emulsion
sandwich +
active scint.
strip planes +
magnetic
spectrometer,
~17 GeV beam



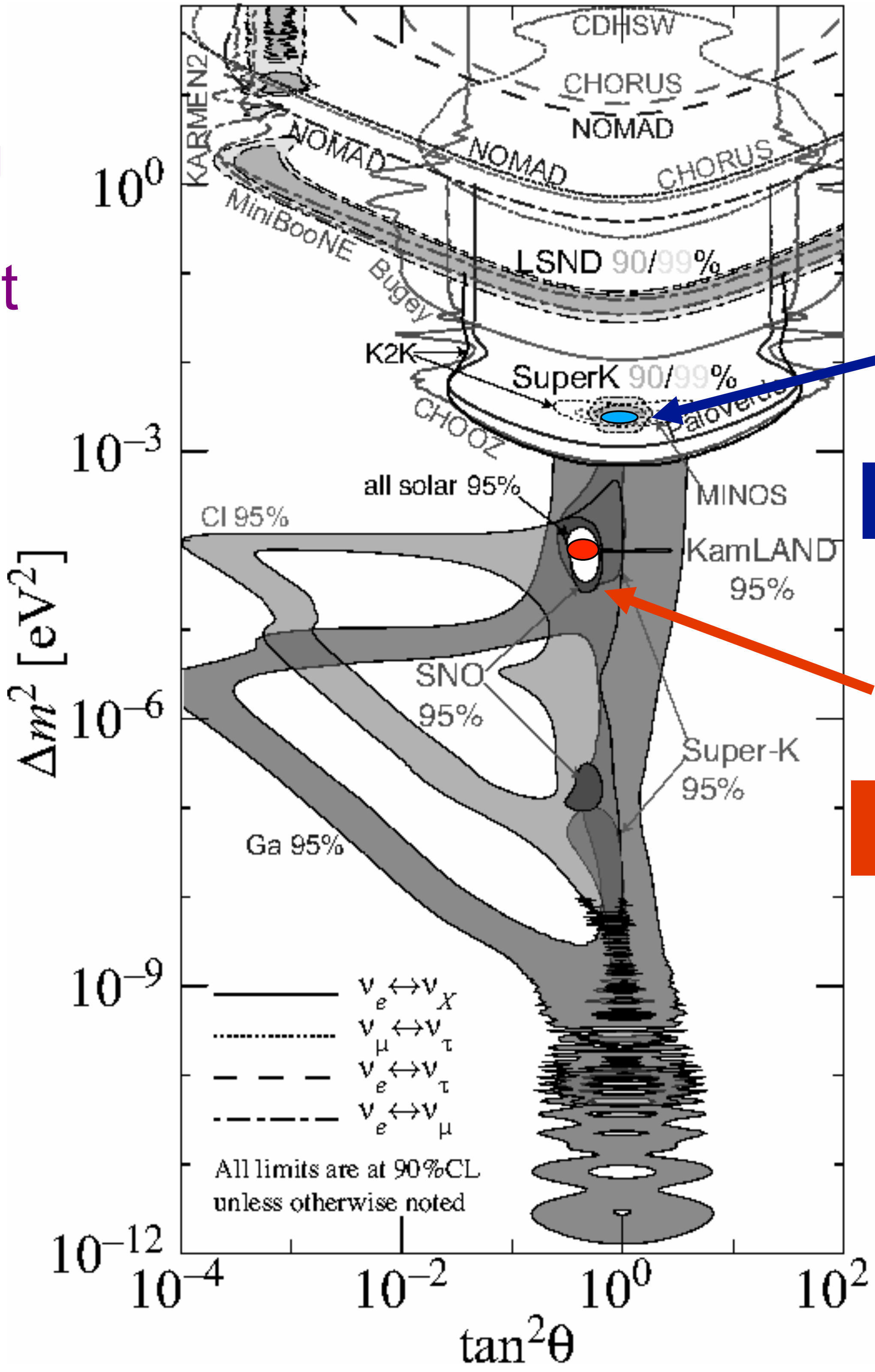
First τ event

NEW

4 τ candidates,
expect
0.23 ± 0.04 bg
(4.2σ)

S. Dusini, Neutrino 2014

Now entering precision measurement era for two-flavor oscillations



atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

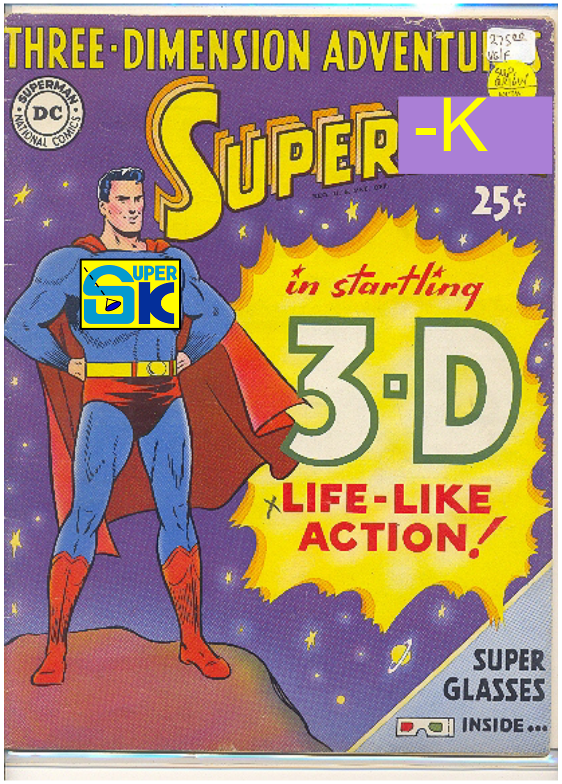
Described by θ_{12}, Δm^2_{12}

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

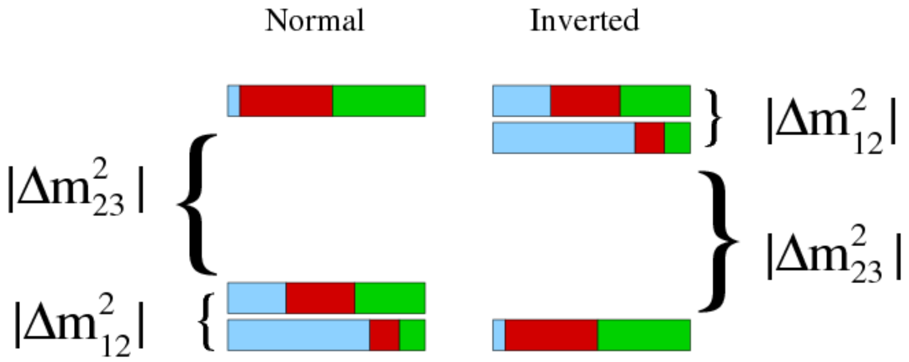
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

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

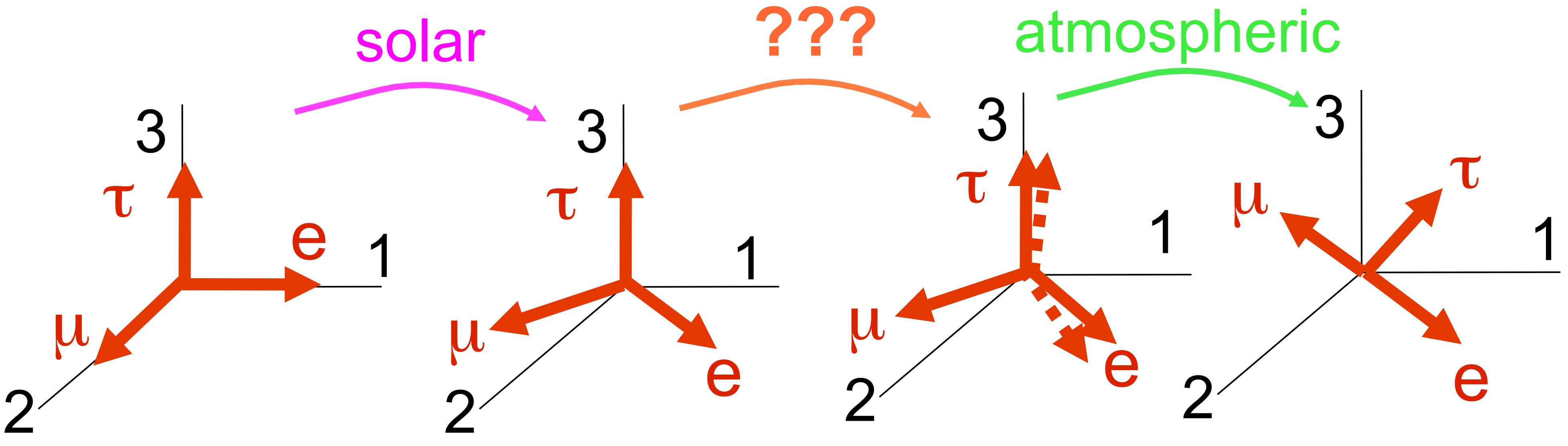


The “last” mixing angle, θ_{13}: 'the twist in the middle'

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

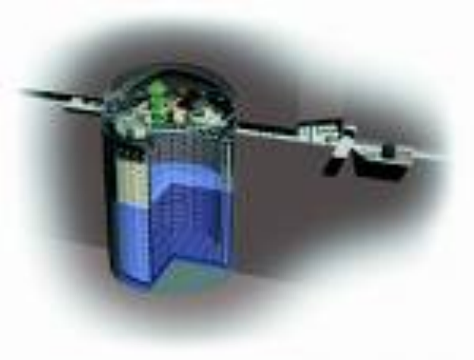
$$\mathrm{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

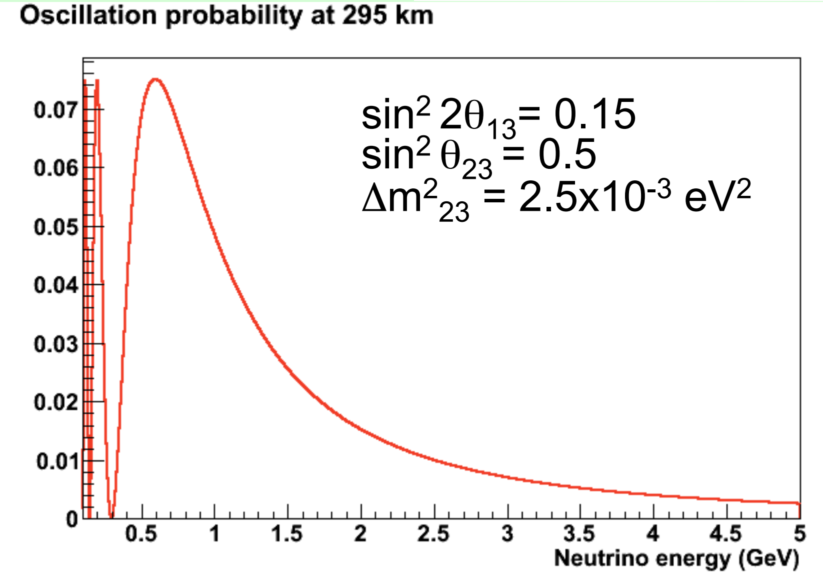
atmospheric ??? solar



Strategies for measuring θ_{13}

Beams

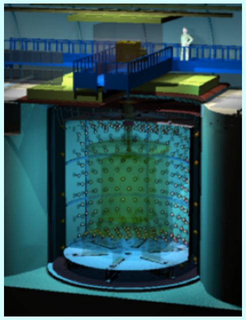


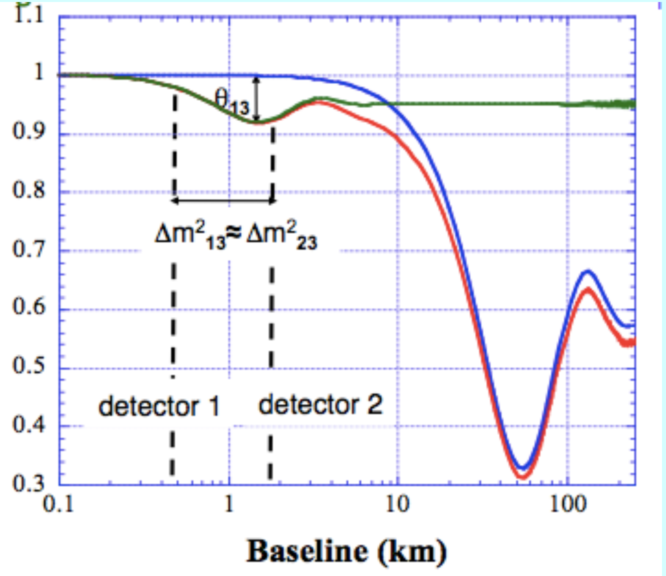


Look for *appearance* of ~GeV ν_e in ν_μ beam on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors



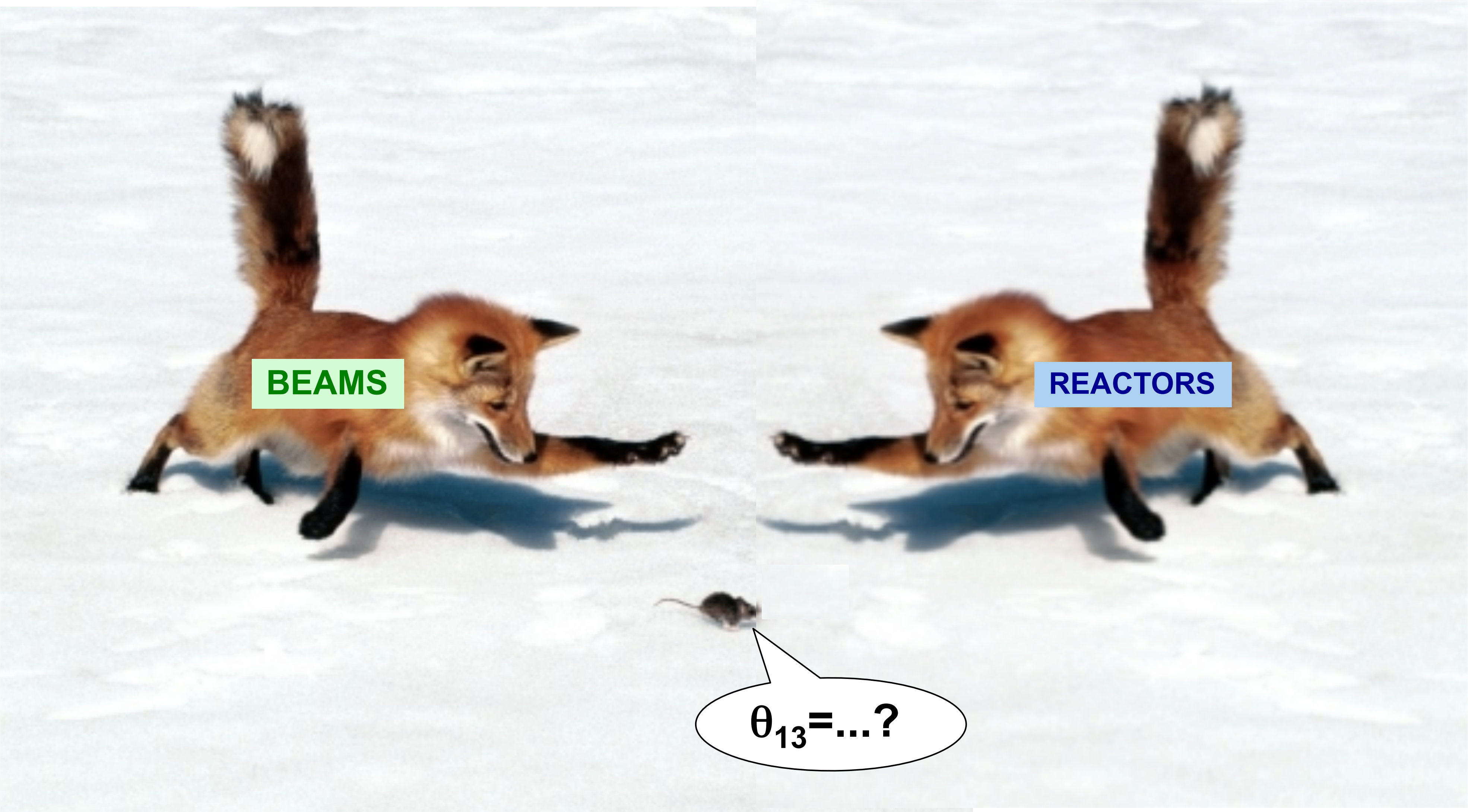


Look for *disappearance* of ~few MeV $\bar{\nu}_e$ on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

A slide from December 2011:

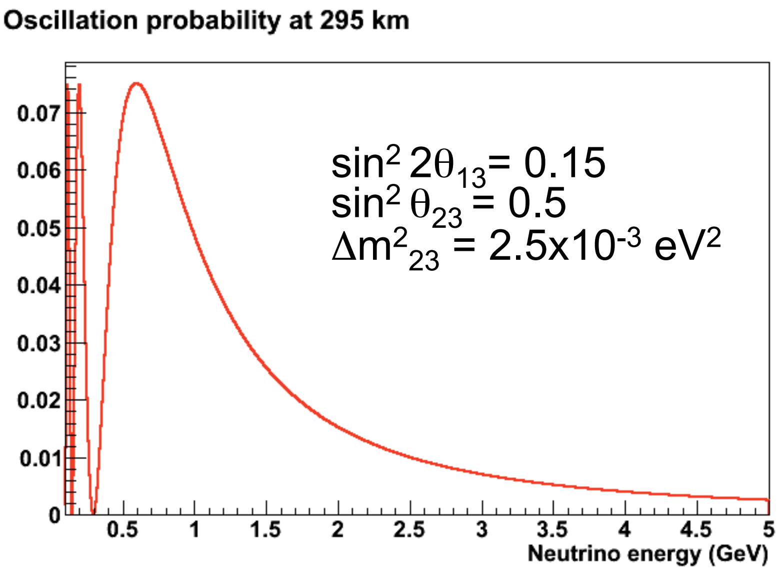
We’re closing in on the answer...



The long-baseline beam approach

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

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



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

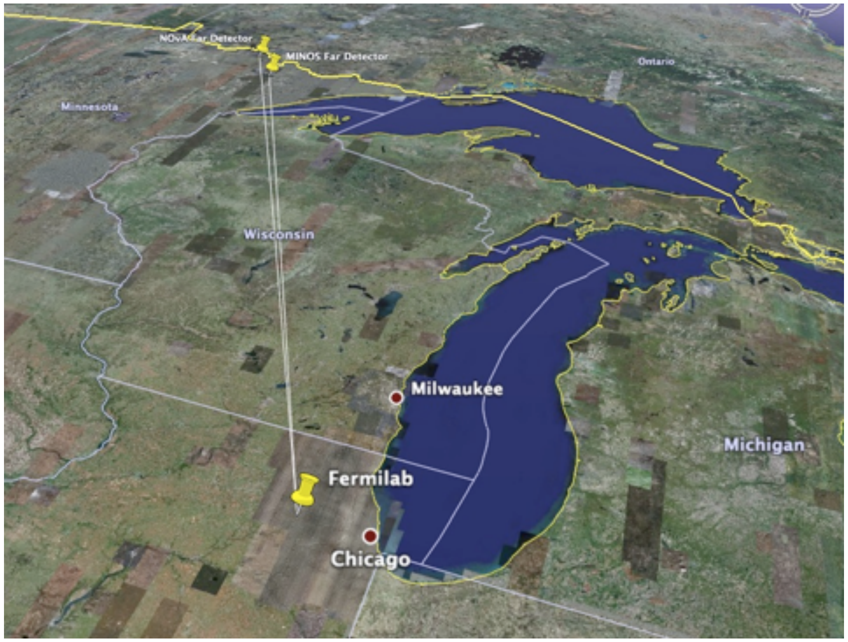
for $\Delta m_{23}^2 >> \Delta m_{12}^2$ and $E_\nu \sim L\Delta m_{23}^2$ (in vacuum), $\delta=0$

Current Long-Baseline Beam Projects

T2K: "Tokai to Kamioka"

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

NOνA at NuMi



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

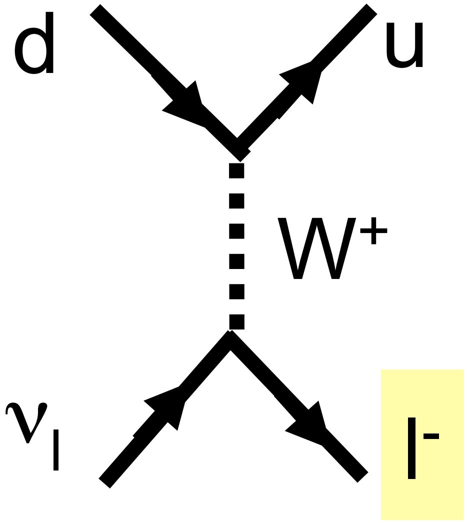
The T2K (Tokai to Kamioka) Experiment

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

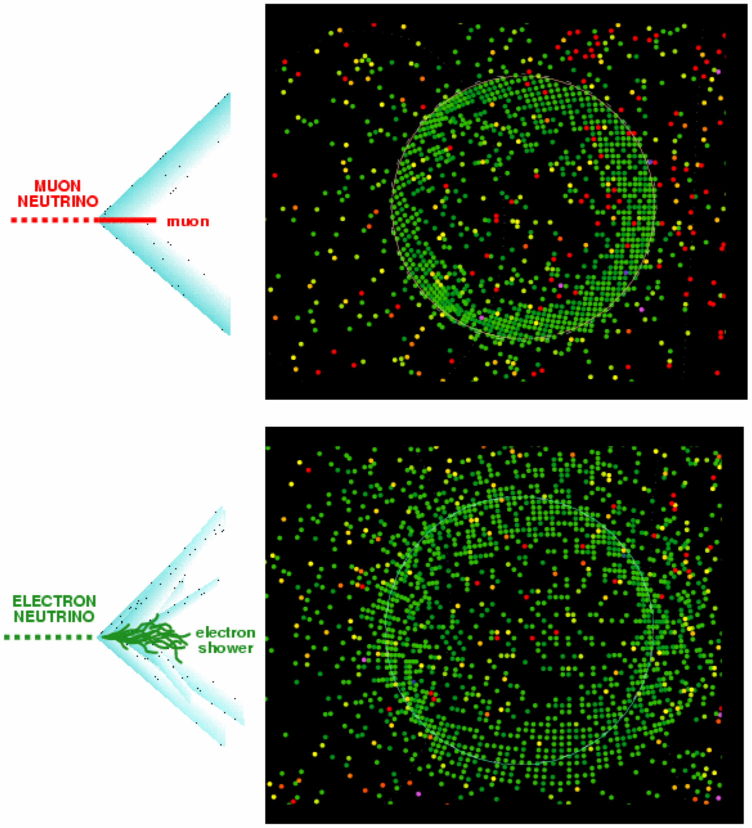
Signature of non-zero θ_{13} at far detector

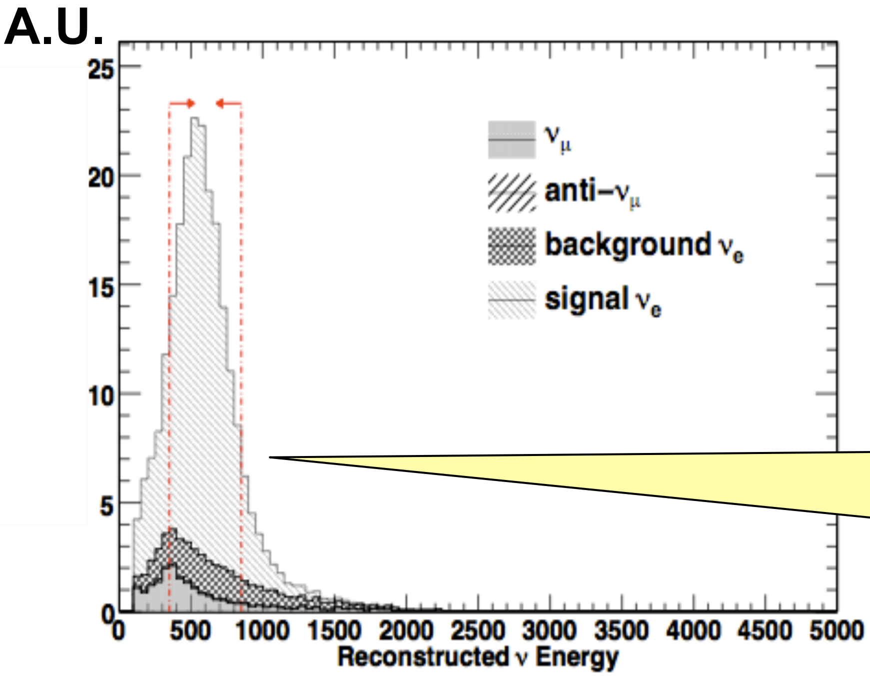


$$\nu_l + N \rightarrow l^\pm + N'$$

select charged-current quasi-elastic events (~single ring);

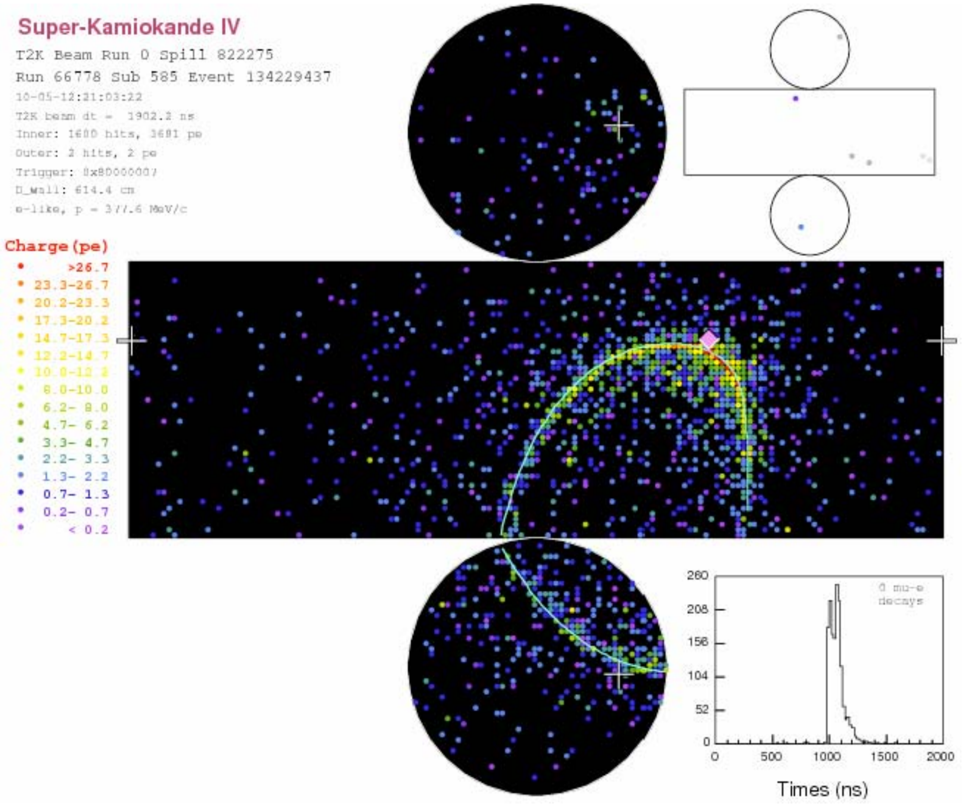
vertex, energy, direction from Cherenkov light



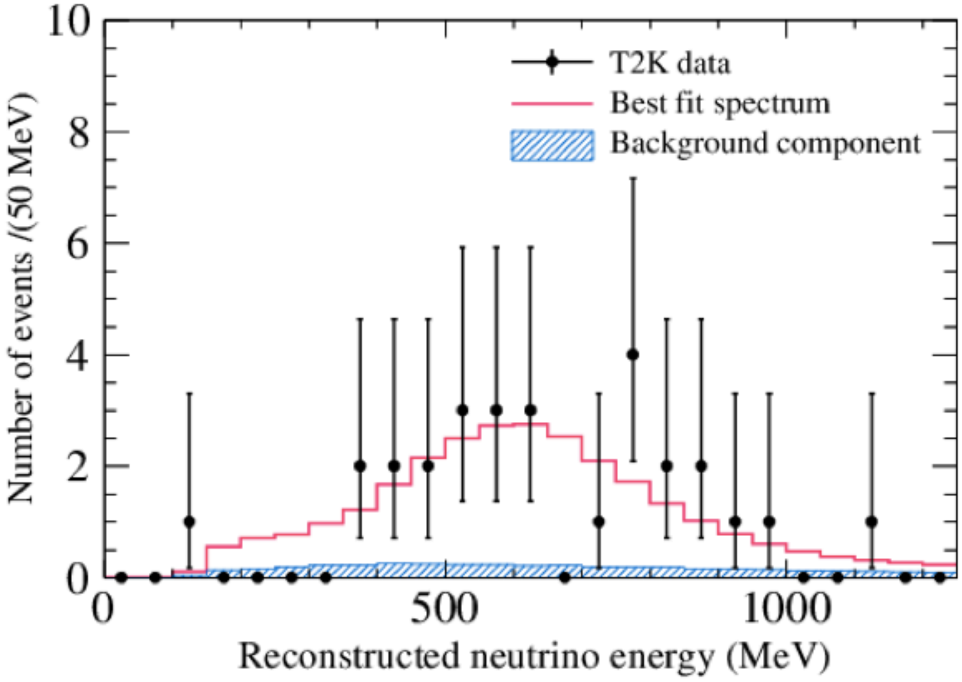


Look for electron appearance:
single fuzzy rings
excess on top of background, with expected spectrum

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

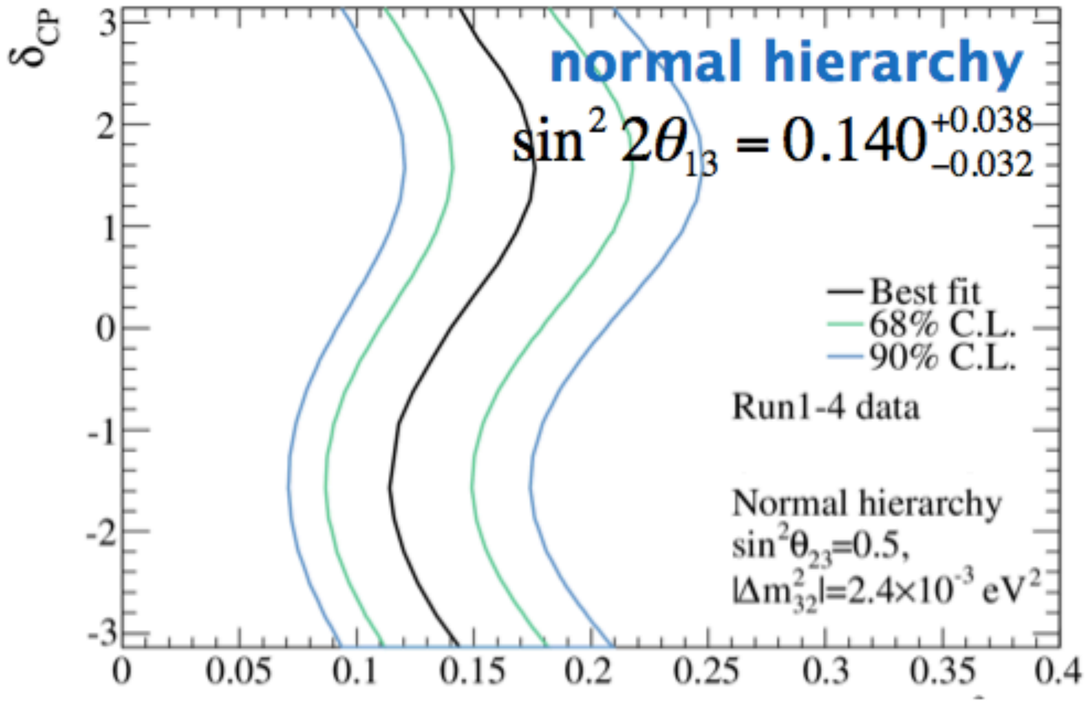


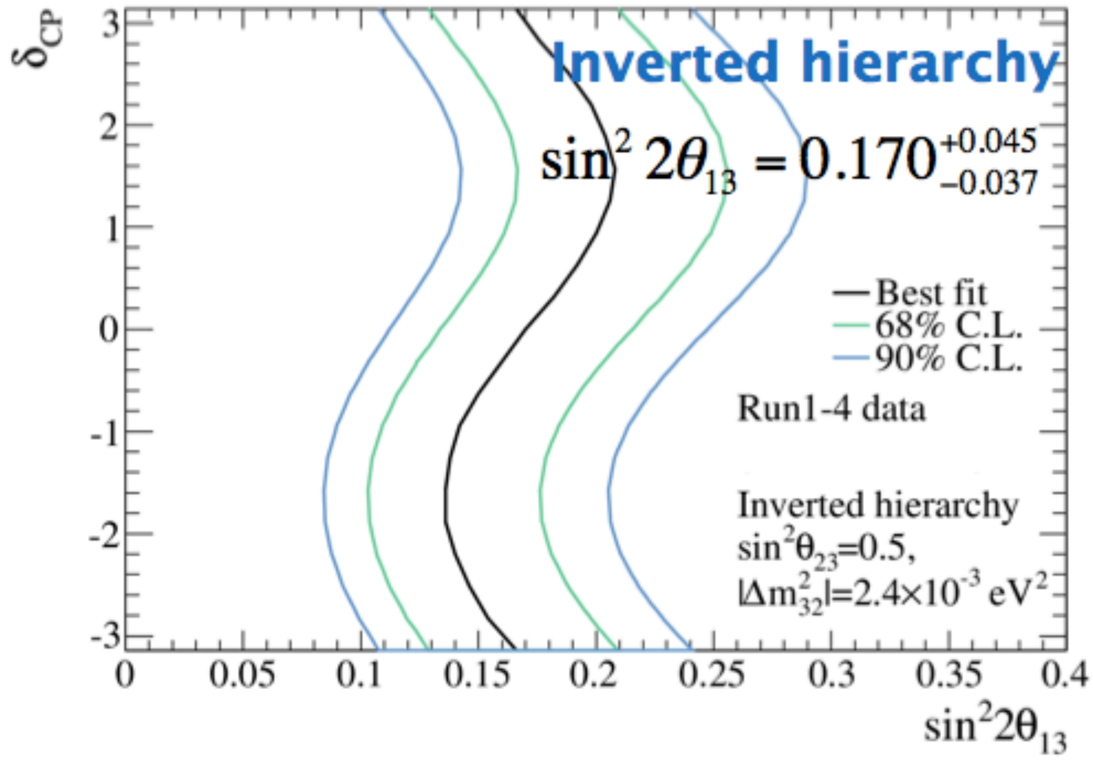
Reconstructed events
after all ν_e cuts



28 ν_e candidate
e-like rings seen,
4.92 ± 0.55 bg expected

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



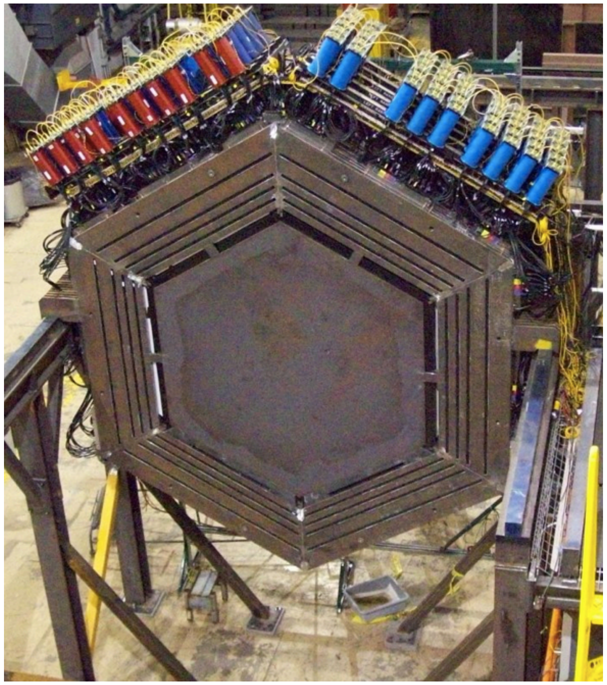


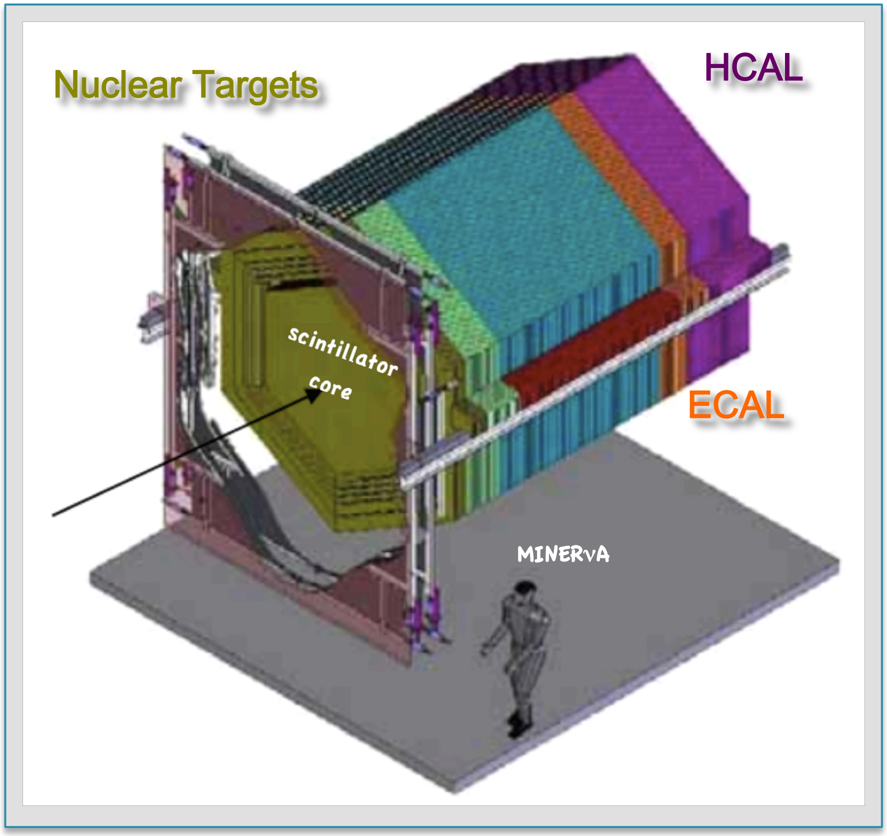
7.3 σ significance for non-zero θ_{13} ...

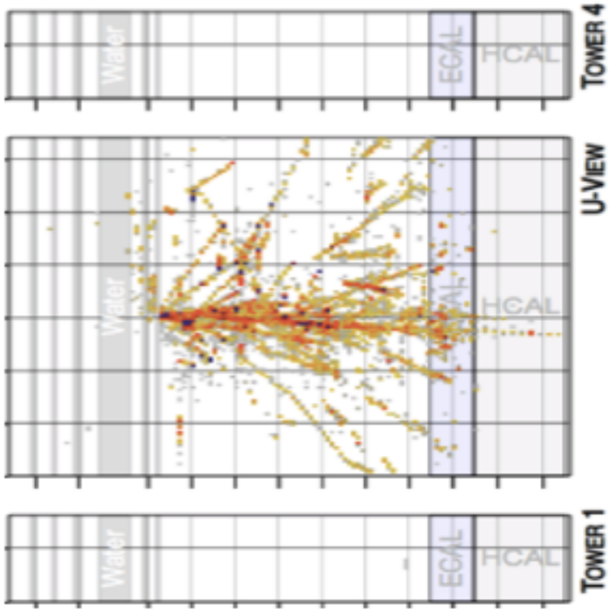
first $>5\sigma$ observation of an appearance channel

Side note: MINERνA

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







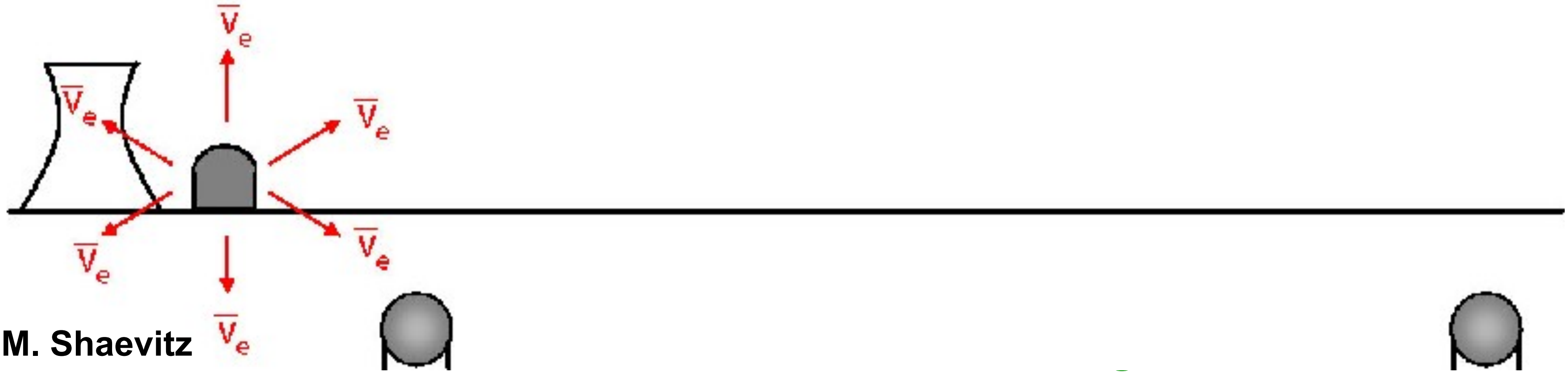
Vital to understand interactions for
interpretation of long baseline
oscillation experiment
backgrounds & systematics!

Measuring θ_{13} with reactor experiments

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

Need <1% systematics!

Cancel systematics w/ 2 identical detectors

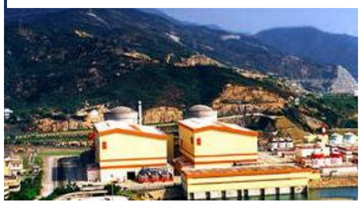


M. Shaevitz

RENO, South Korea

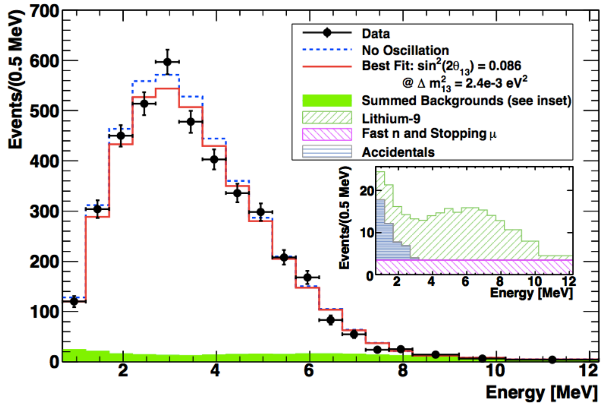
Double Chooz, France

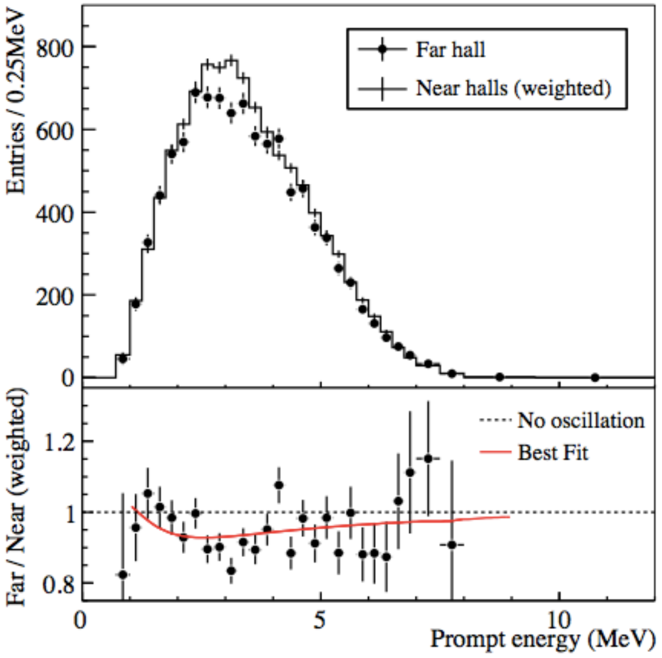
Daya Bay, China

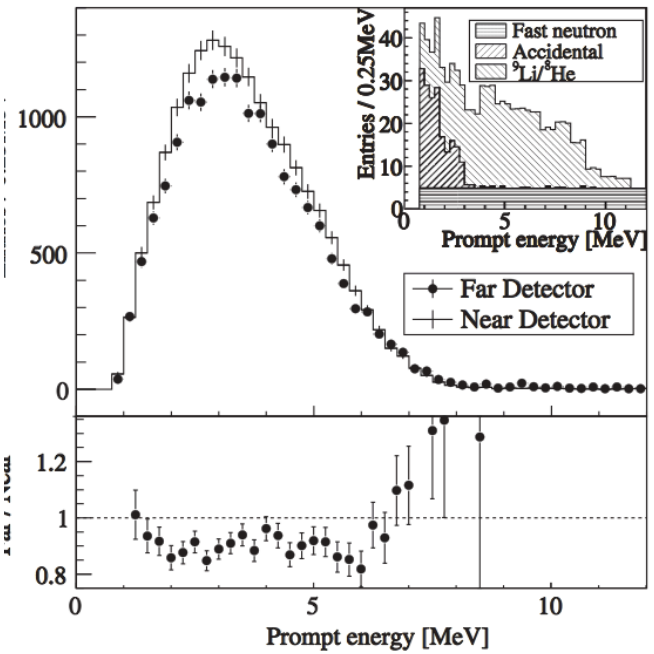


All started taking data in 2011

Results now from all three!

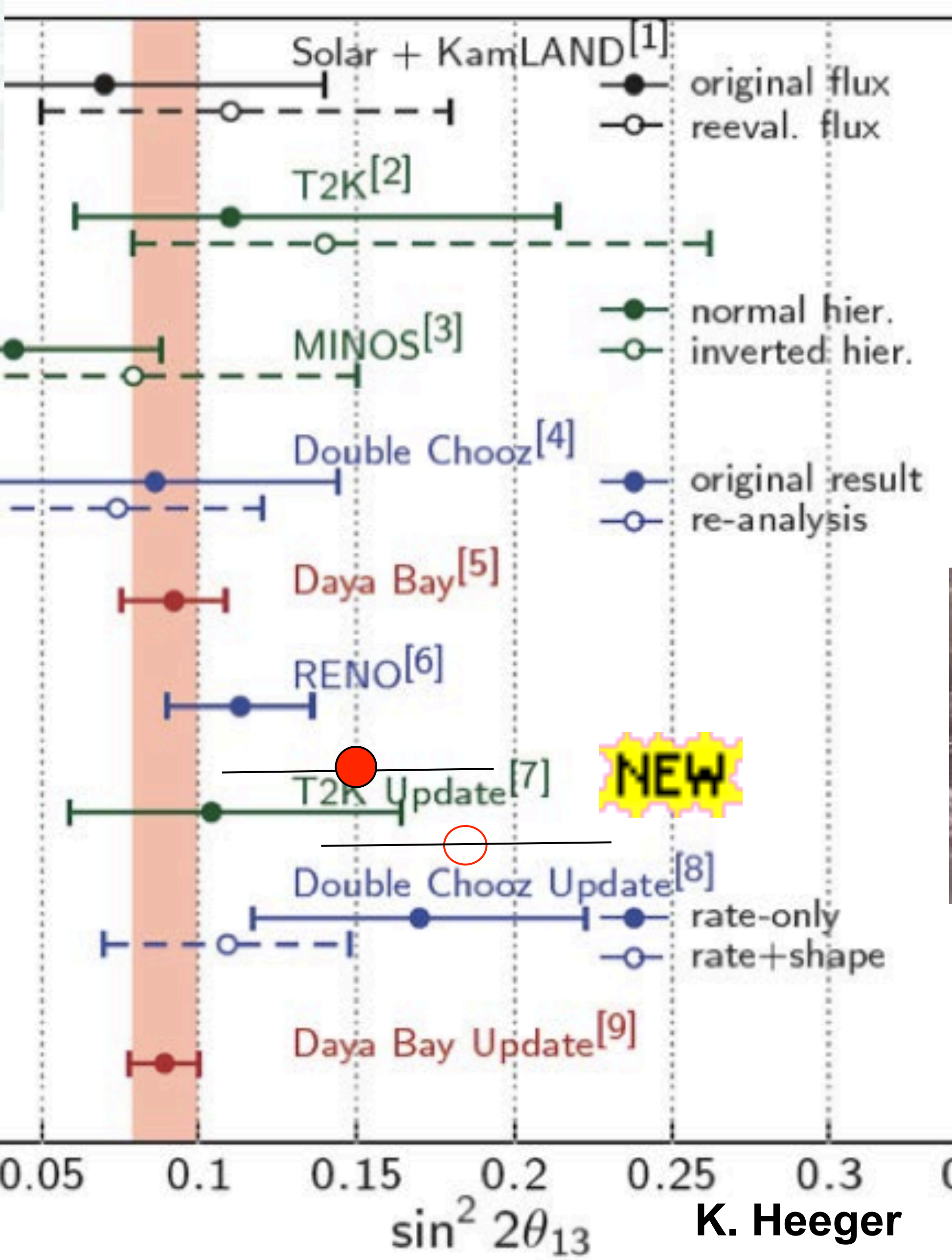






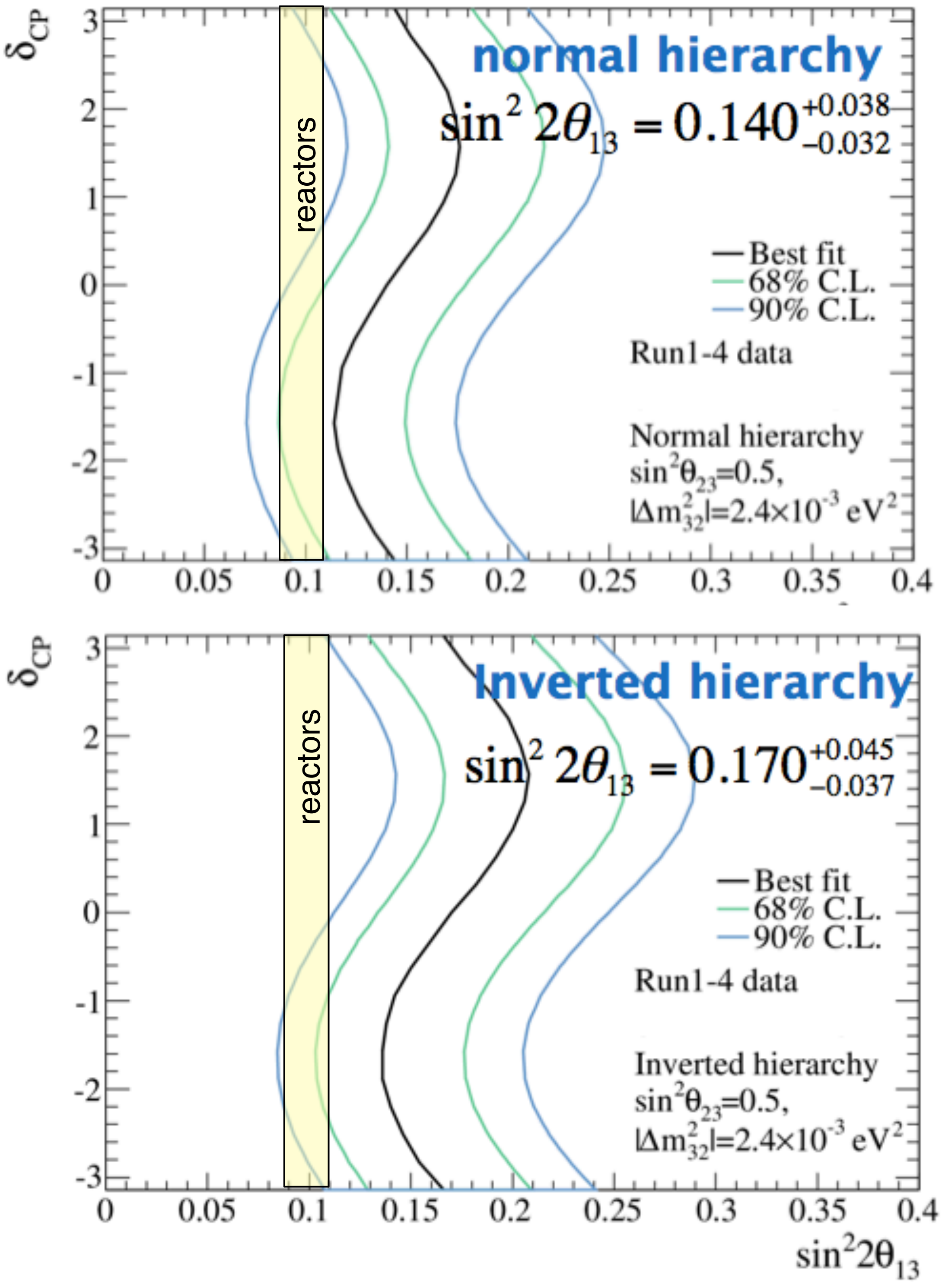
Electron antineutrino deficit and spectral distortion consistent
with non-zero θ_{13}
... in fact now in “precision” regime

We now know that θ_{13} is large!



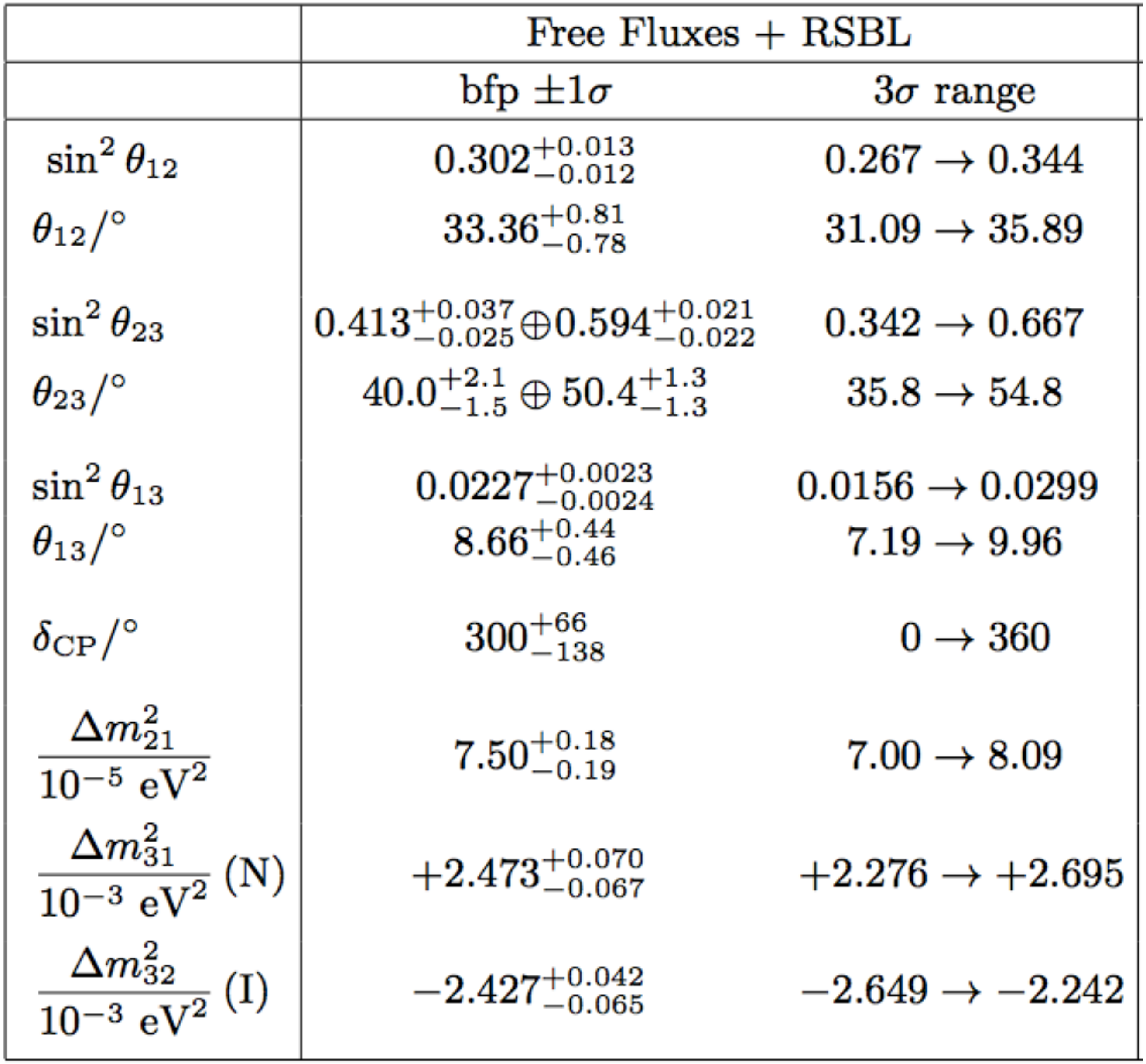
K. Heeger

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



The three-flavor picture fits well

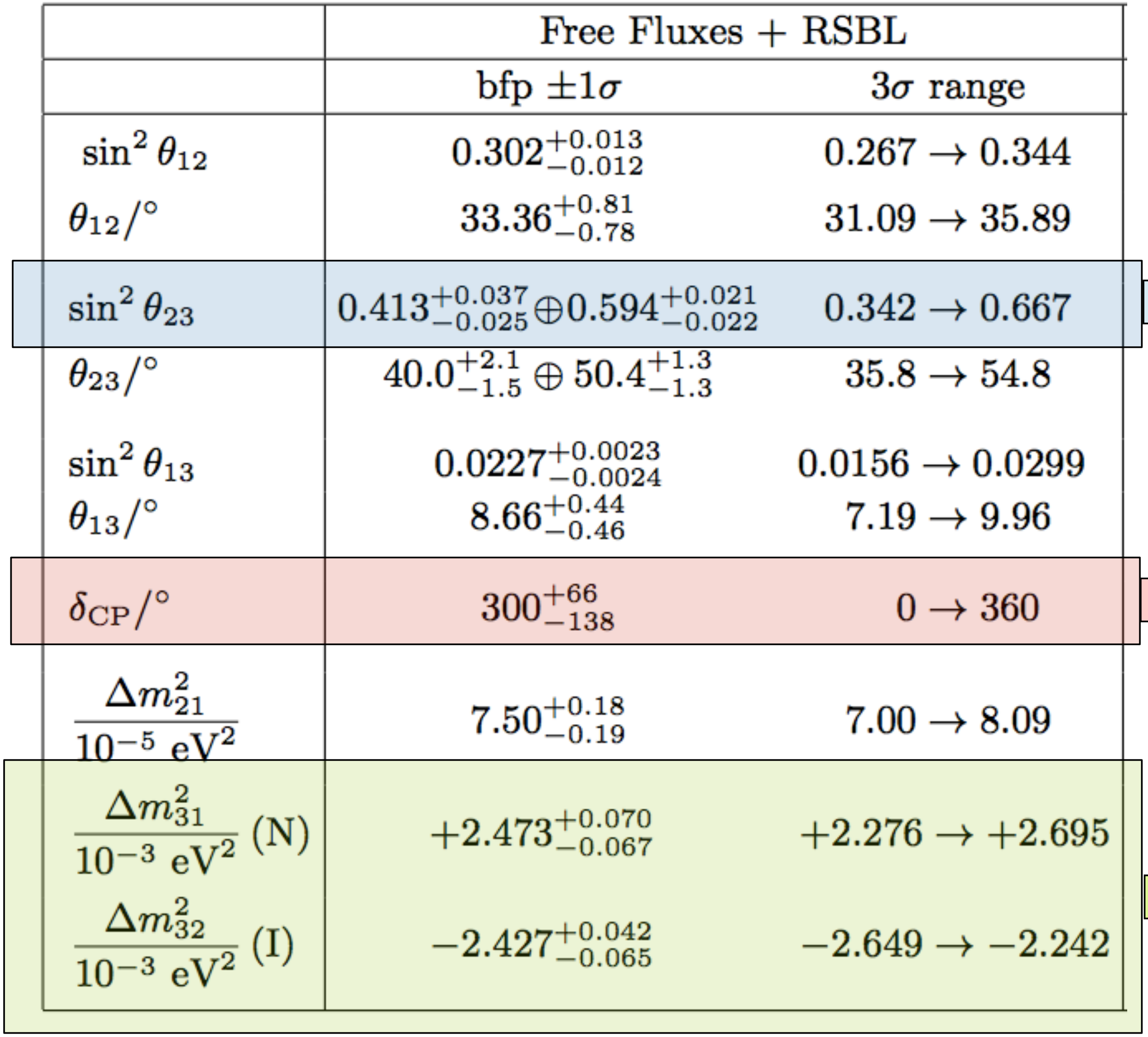
Global three-flavor fits to all data, 2012



	Free Fluxes + RSBL		**3σ knowledge**
	bfp $\pm 1\sigma$	3σ range	
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$	**~14%**
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$	
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$	**~42%**
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$	
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$	**~32%**
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$	
$\delta_{\mathrm{CP}}/^\circ$	300^{+66}_{-138}	$0 \to 360$	**~no info**
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$	**~14%**
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$	**~17%**
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$	

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 10.1007/JHEP12(2012)123

What do we *not* know about the three-flavor paradigm?



	Free Fluxes + RSBL	
	bfp ±1σ	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
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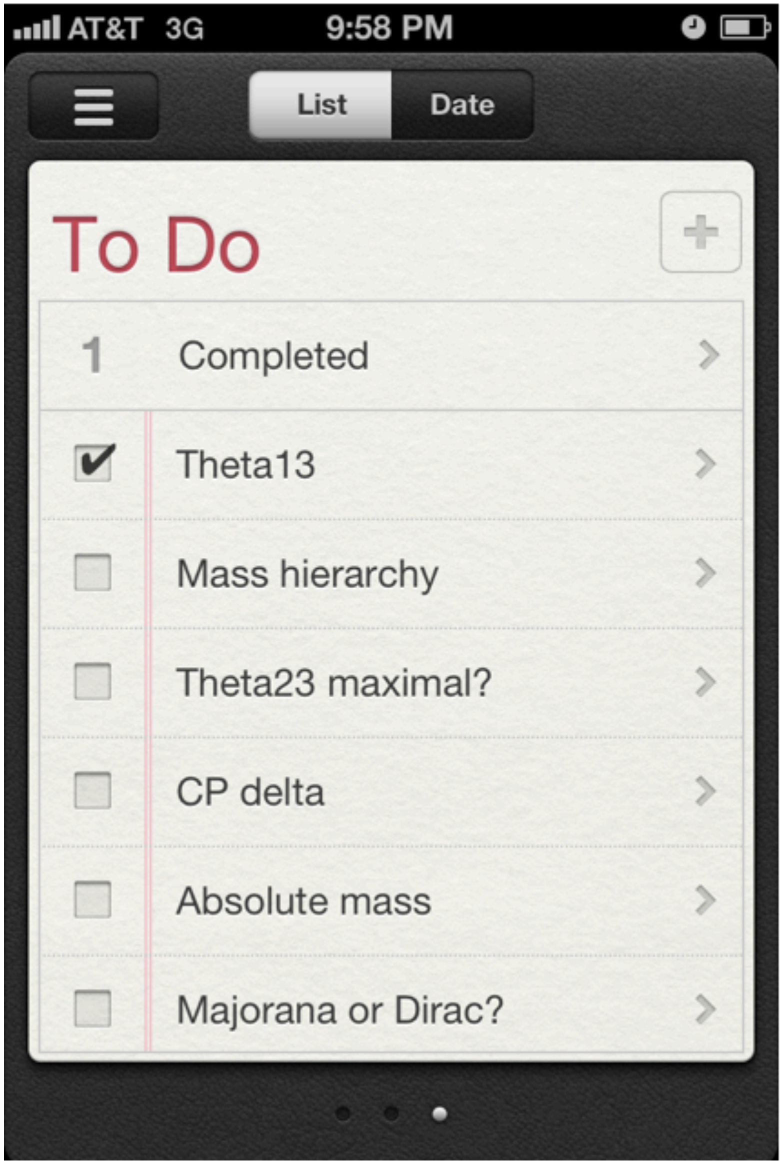
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$

Is θ_{23} non-negligibly greater or smaller than 45 deg?

basically unknown

sign of Δm^2 unknown (ordering of masses)

Why do we care about these parameters?
Is it just a checklist?
What do these parameters tell us?



To Do

1 Completed

- ☑ Theta13
- ☐ Mass hierarchy
- ☐ Theta23 maximal?
- ☐ CP delta
- ☐ Absolute mass
- ☐ Majorana or Dirac?

Non-zero CP violation, could, in principle, inform us on leptogenesis in the context of see-saw neutrino mass models

(or maybe not...)

The God Particle

The God Particle

The Devil Phase?

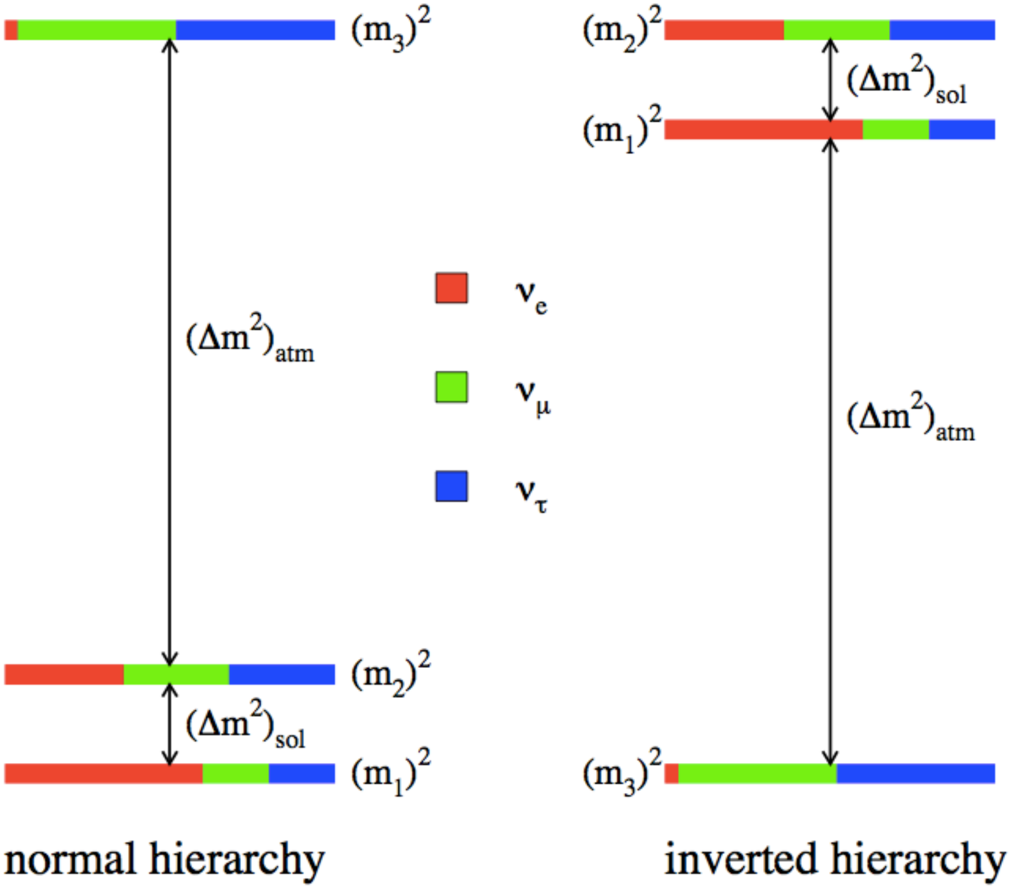
But what it’s really about is *testing the paradigm*...

We need not only to fill in the missing parameters, but make precision measurements of *all* the parameters

Next on the list to go after experimentally:

mass hierarchy

(sign of Δm^2_{32})



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

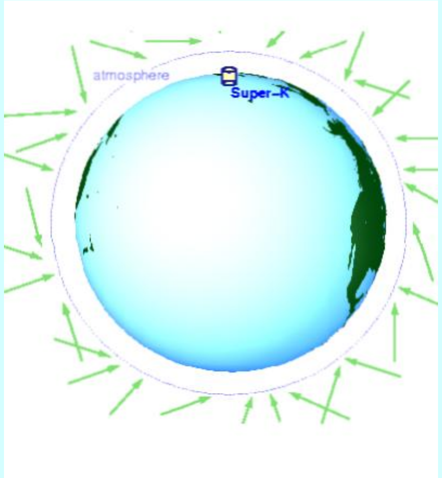
There are many ways to measure the mass hierarchy

They are all challenging...

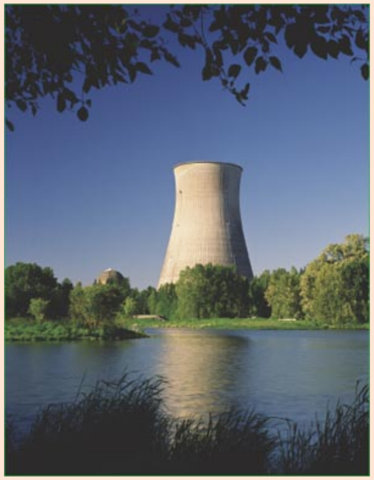
Four of the possible ways to get MH

Long-baseline beams

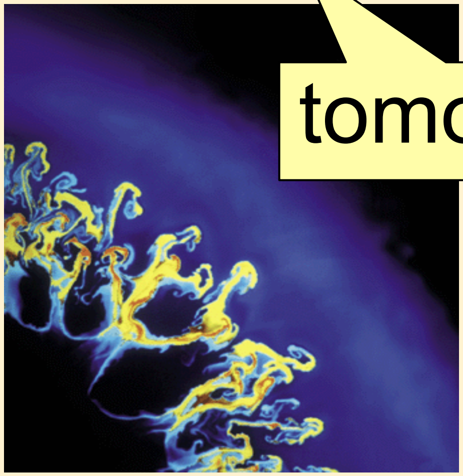
Atmospheric neutrinos



Reactors



Supernovae



tomorrow

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

more this afternoon

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

Change of sign for antineutrinos

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

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

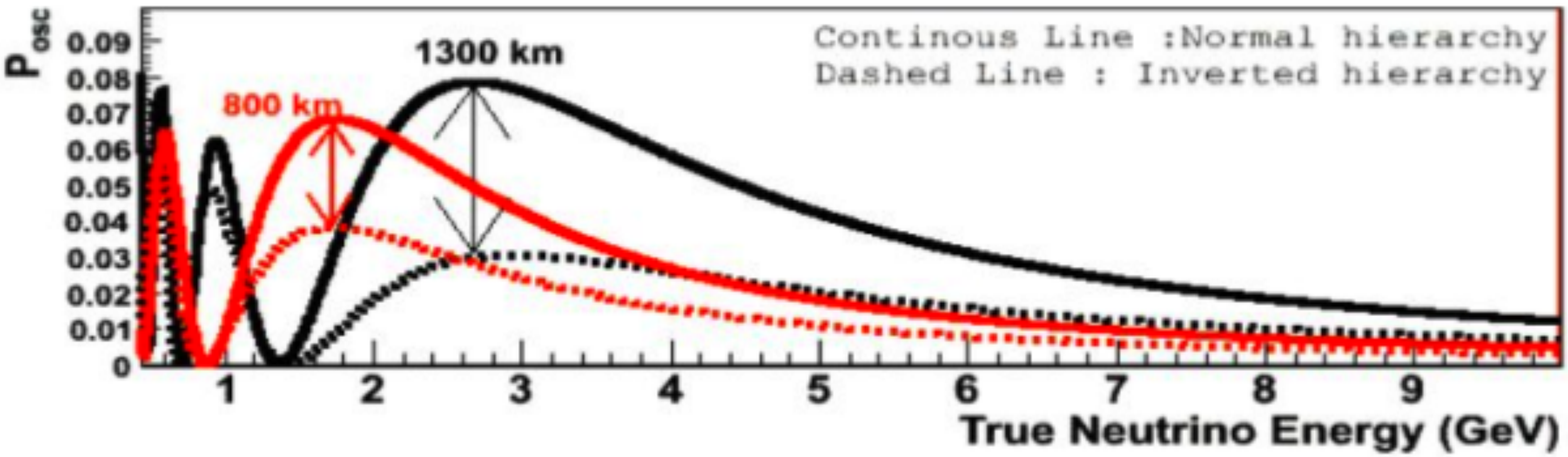
$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

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

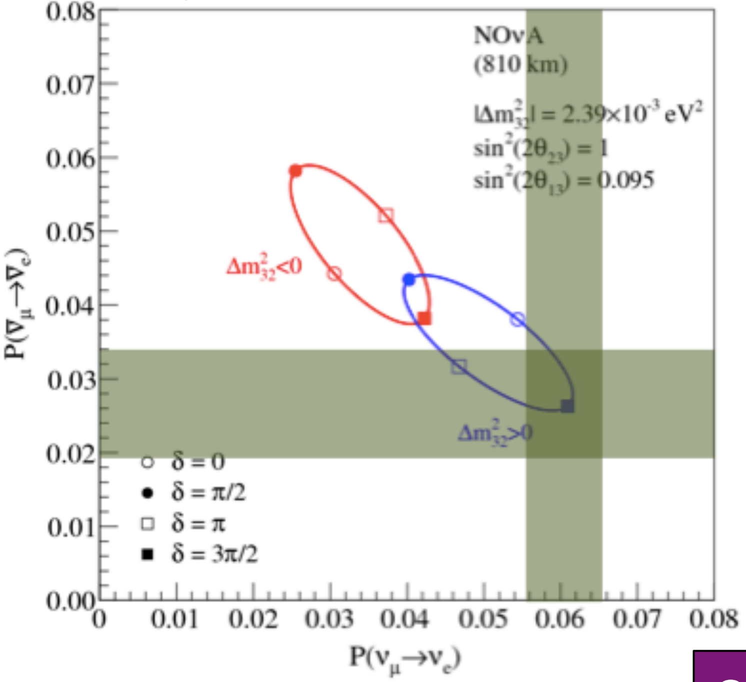
Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

- 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*

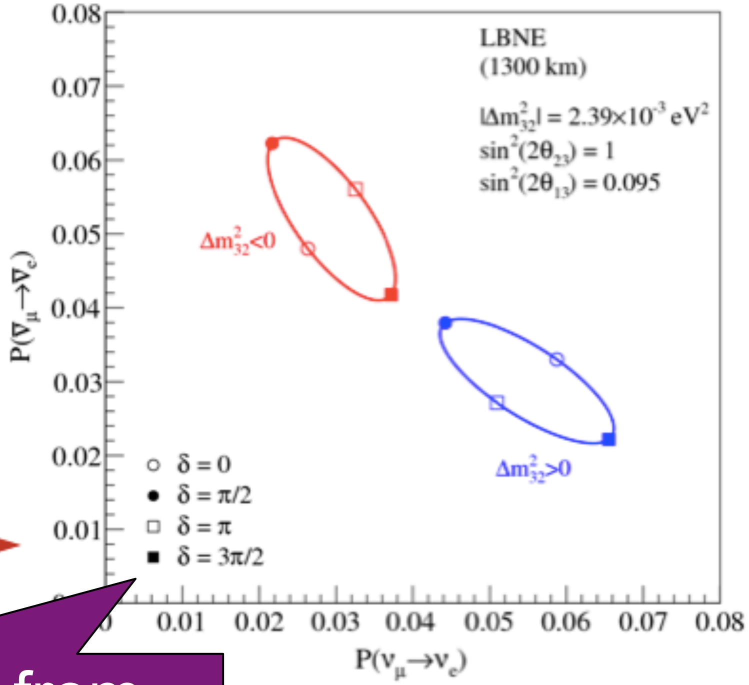
for

both choices of sign(Δm^2)

and for full range of δ_{CP}

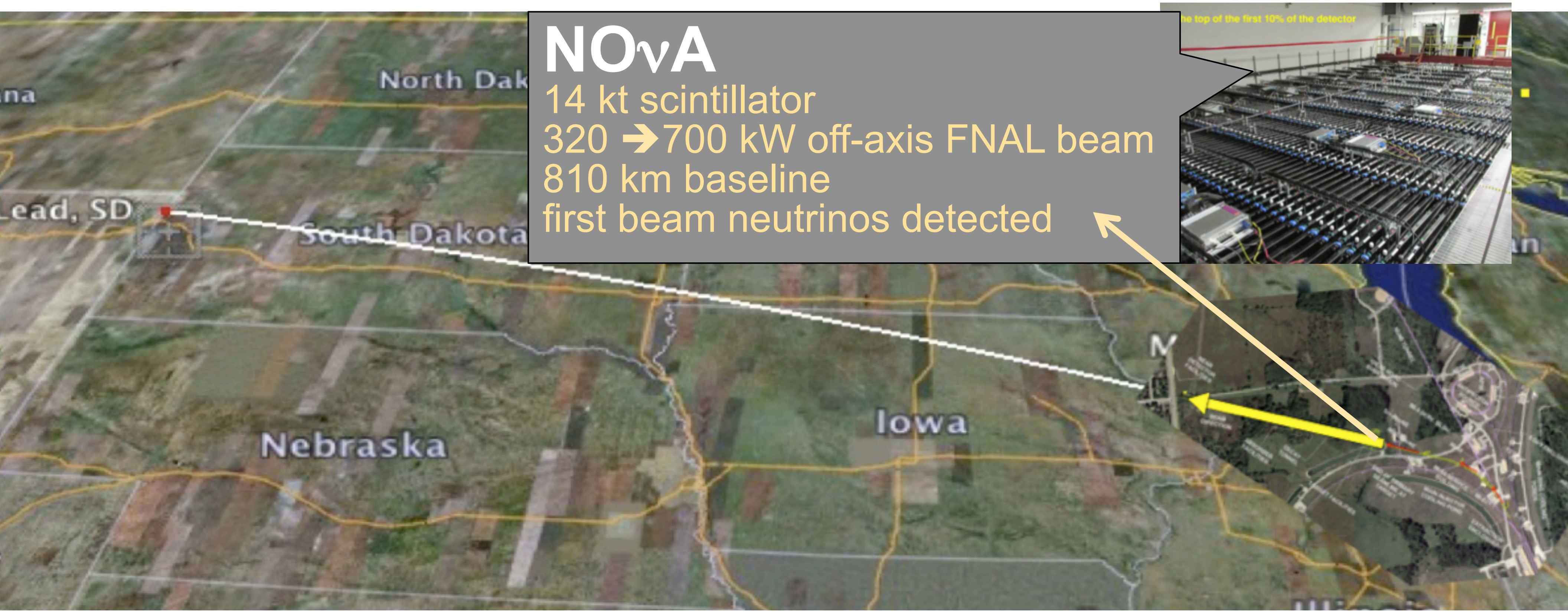
← *810 km*

1300 km →



easier to separate MH from CP effects at long baseline

What's next? NOνA



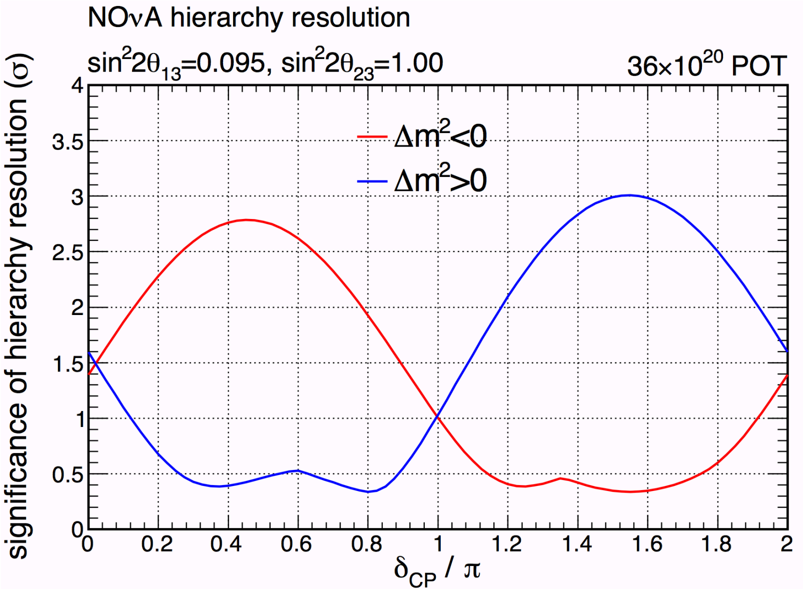
NOνA

14 kt scintillator

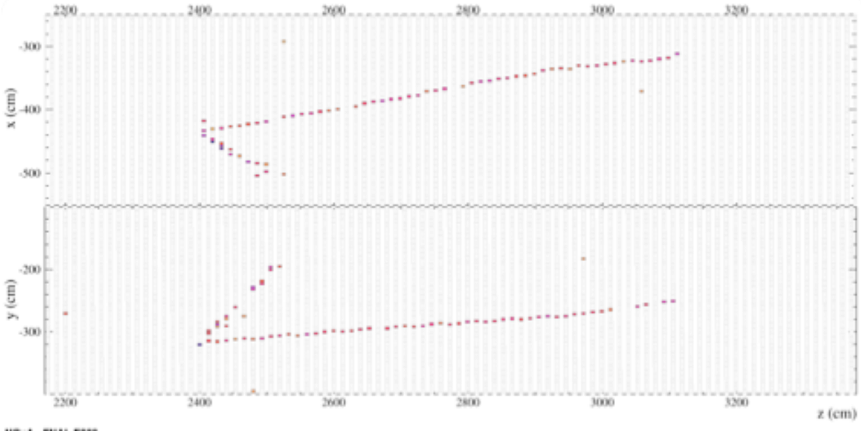
320 → 700 kW off-axis FNAL beam

810 km baseline

first beam neutrinos detected



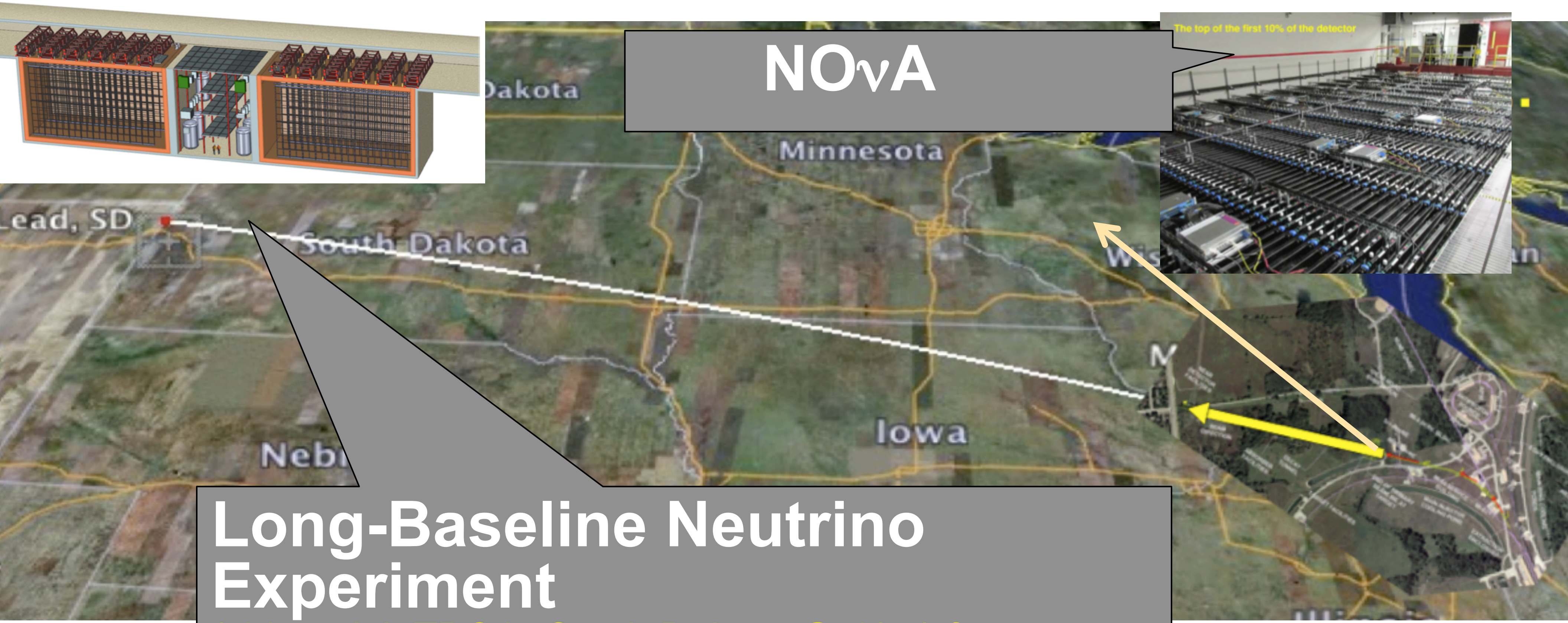
A. Norman, Neutrino 2014



NEW

Detectors complete;
instrumentation will be finished in July
Seeing beam events!

Long-Baseline Neutrino Experiment/Facility



NOνA

Long-Baseline Neutrino Experiment

34 kton LArTPC in South Dakota @ 4850 ft
1300 km baseline
New 1.2 MW beam (PIP-II) ➔ upgradable to 2.3 MW

LBNF (reformulated international collaboration) is highest intermediate term priority in U.S.

Long-Baseline Neutrino Experiment/Facility

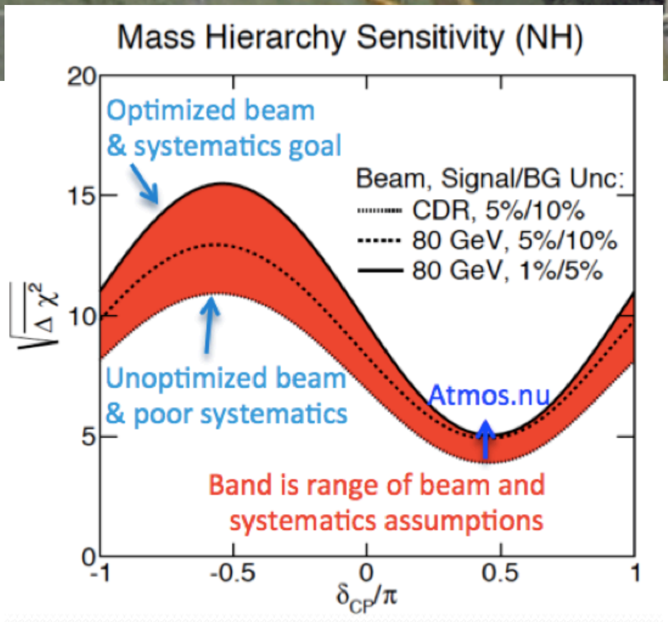
NOνA

Long-Baseline Neutrino Experiment

34 kton LArTPC in South Dakota @ 4850 ft
1300 km baseline
New 1.2 MW beam (PIP-II) ➔ upgradable to 2.3 MW

Very good chance of measuring MH

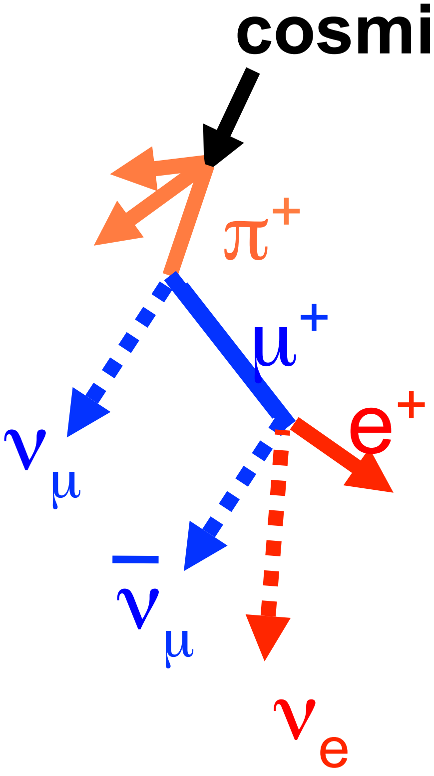
R. Wilson, Neutrino 2014

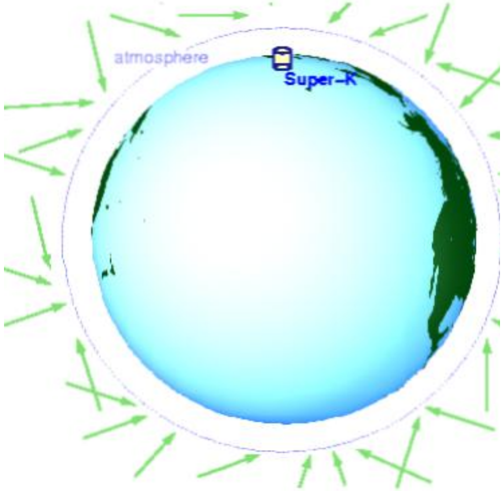


Atmospheric neutrinos: back into the wild

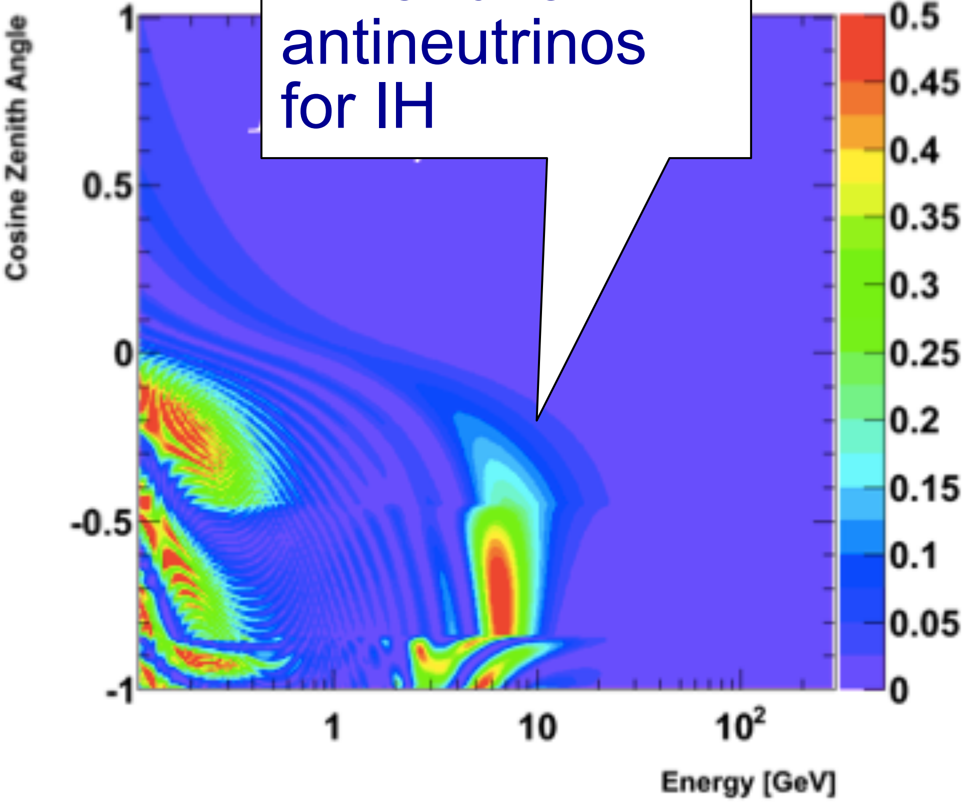
The neutrinos are free, and have a range of baselines & energies,

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





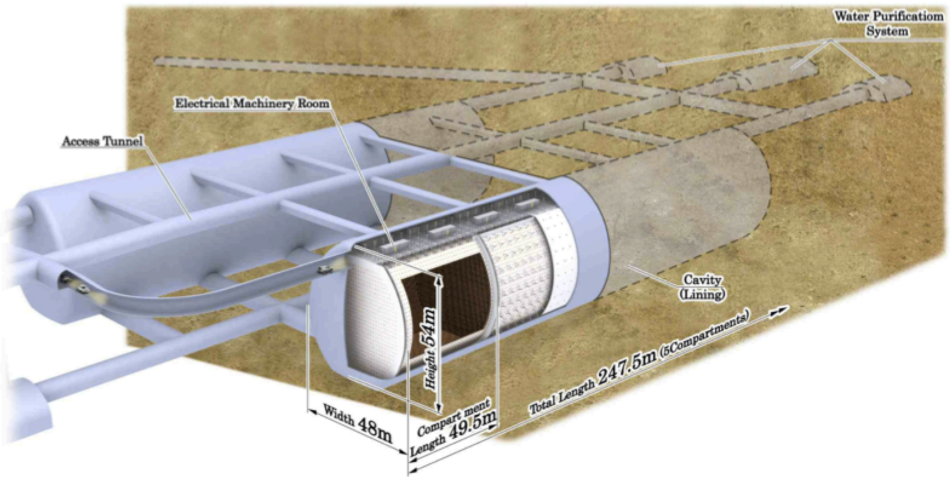
resonance for neutrinos for NH and for antineutrinos for IH



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

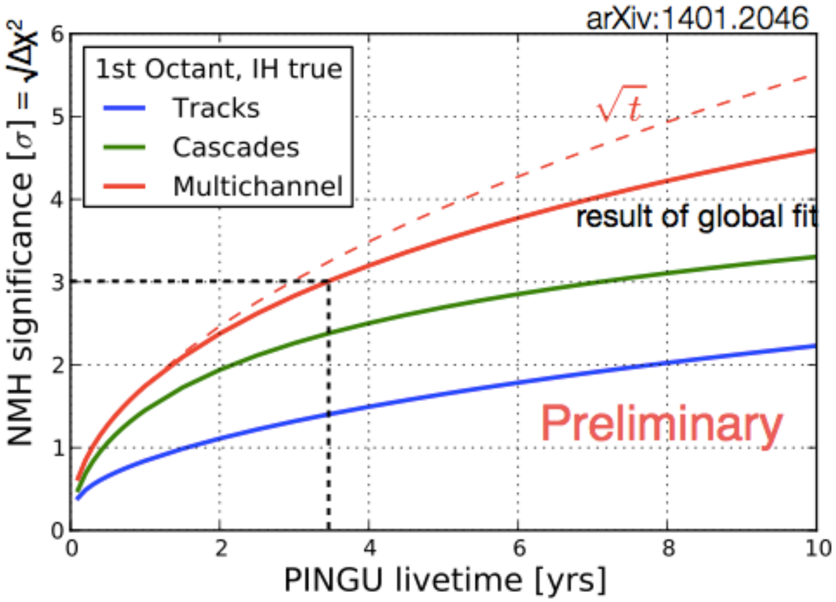
Need both statistics and ability to reconstruct ν energy & direction

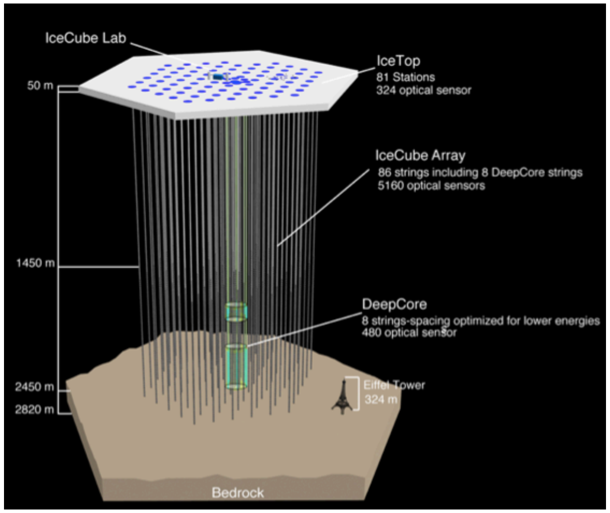
Examples: Hyper-K



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

IceCube DeepCore/PINGU



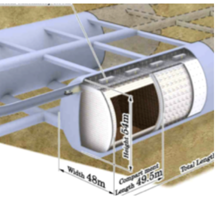


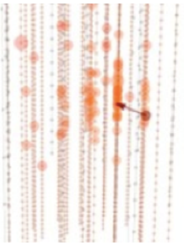
- enormous detector volume & atmnu statistics
- sparse PMTs, so poor reconstruction

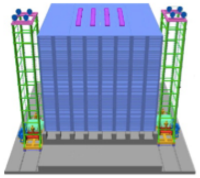
➔ PINGU infill for be reconstruction & lower threshold

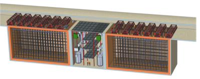
- arXiv:1306.5846

Experiments going after MH with atmnus







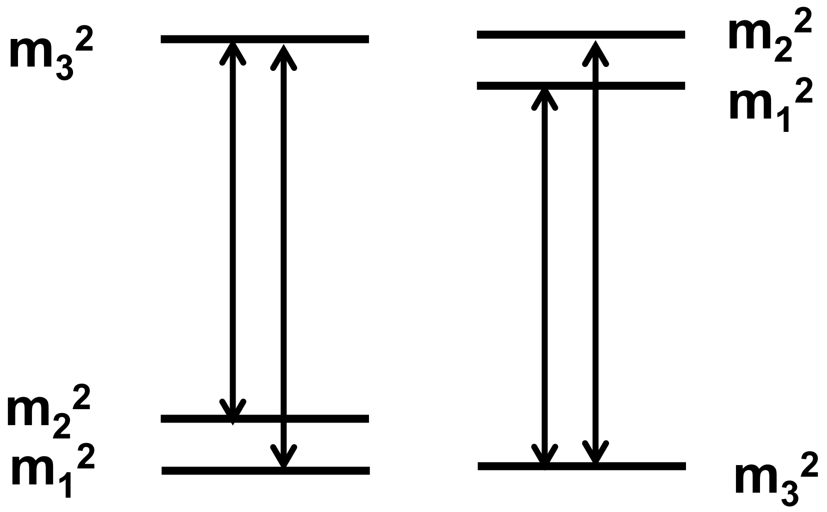


Experiment	**Type**	**Location**	**Reconstruction**	**Mass (kt)**	**Notes**
Super-K	Water Cherenkov	Japan	Good	22.5	Good reconstruction, low stats
Hyper-K	Water Cherenkov	Japan	Good	560	Good reconstruction and stats
IceCube DeepCore	Long String Water Ch.	South Pole	Poor	Mton	Systematics under study, 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/F	LArTPC	USA	Excellent	10-34	Excellent reconstruction
GLACIER	LArTPC	Europe	Excellent	20-100	Excellent reconstruction

The Reactor MH Method

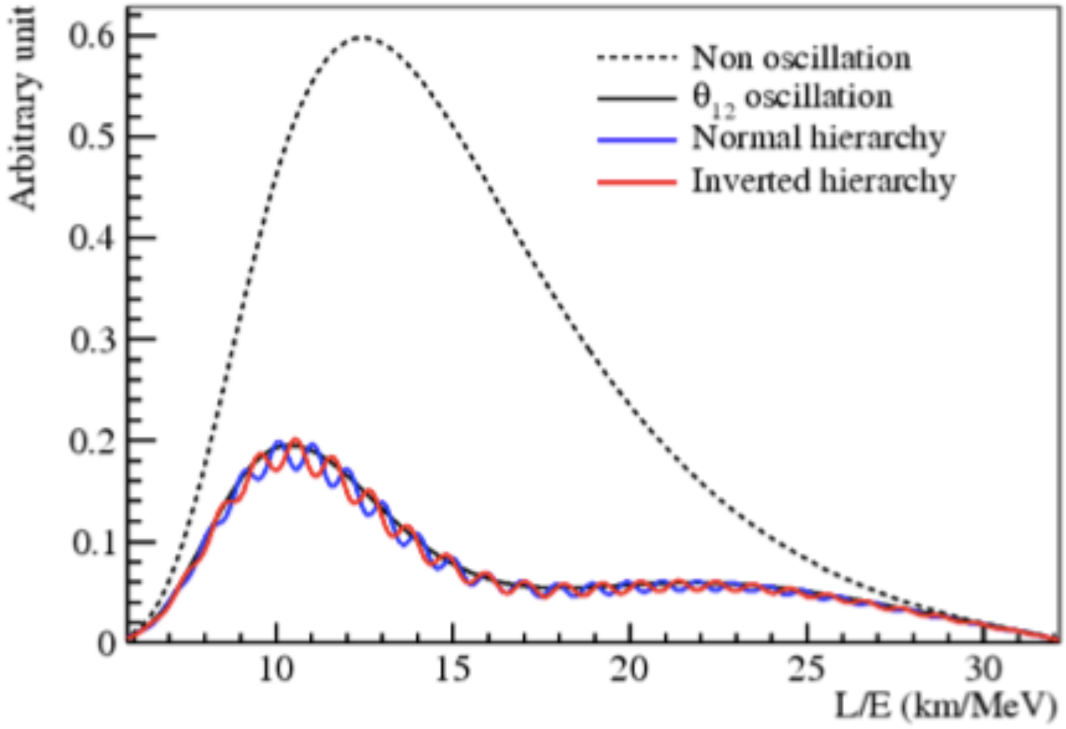
Vacuum oscillation frequencies depend on $\Delta m^2/E_\nu$

Different MH ➔ slightly different frequencies at reactor energies



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

Y. Wang

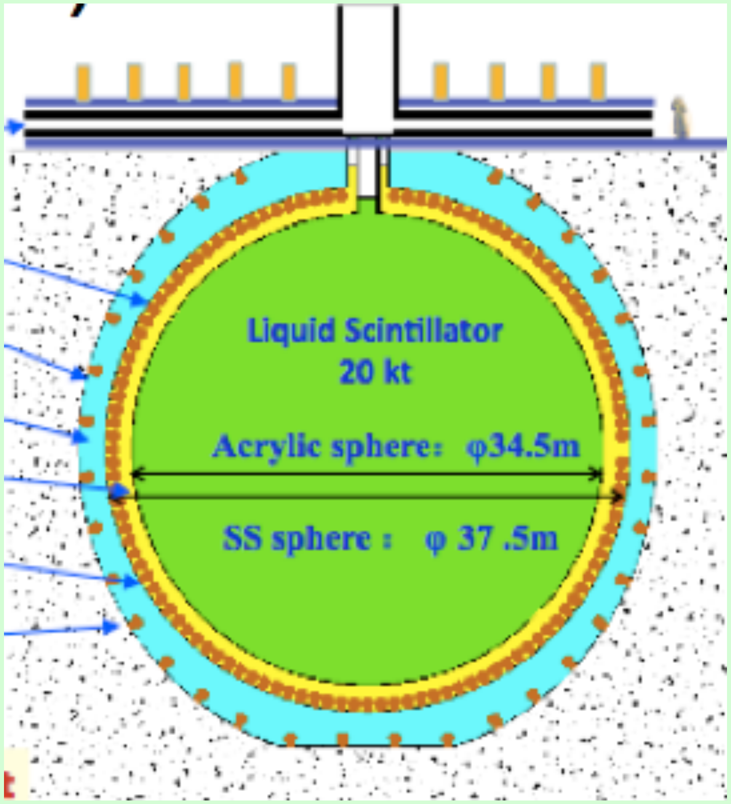


Requires:

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

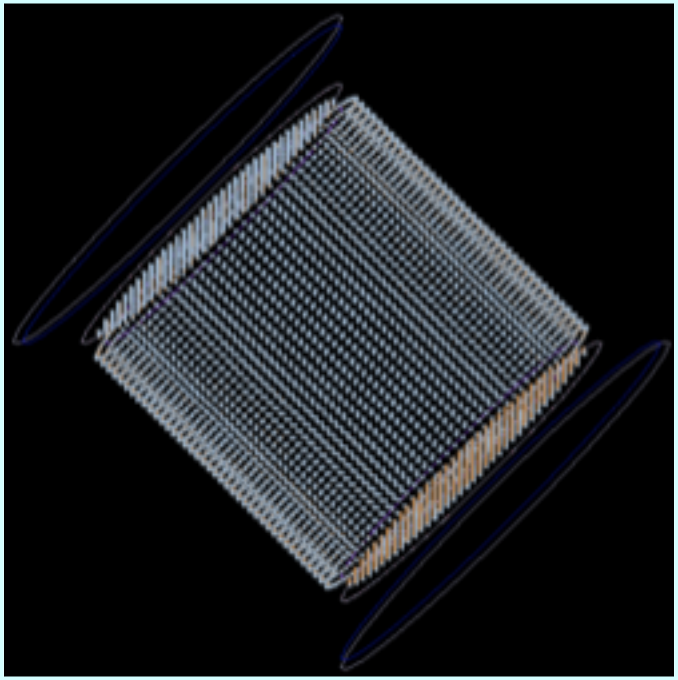
Proposed reactor experiments going after MH

JUNO (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

Measuring CP violation in neutrinos

B. Kayser, PDG

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

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

Flavor transition probability is:

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

From this expression:

$$P(\nu_g \to \nu_f; U) = P(\nu_f \to \nu_g; U^*)$$

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

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

From this expression:

$$P(\nu_g \to \nu_f; U) = P(\nu_f \to \nu_g; U^*)$$

Now if CPT holds,

$$P(\bar{\nu}_f \to \bar{\nu}_g) = P(\nu_g \to \nu_f)$$

Putting this together with the above expression:

$$P(\bar{\nu}_f \to \bar{\nu}_g; U) = P(\nu_f \to \nu_g; U^*)$$

Probability for antinus same as for nus, but with U^*

If U is complex, the 2nd term has opposite sign for antinus, and probabilities differ for nus and antinus

Observation of

$$P(\bar{\nu}_f \to \bar{\nu}_g) \neq P(\nu_f \to \nu_g)$$

is a signature of *intrinsic* CP violation (complex U)

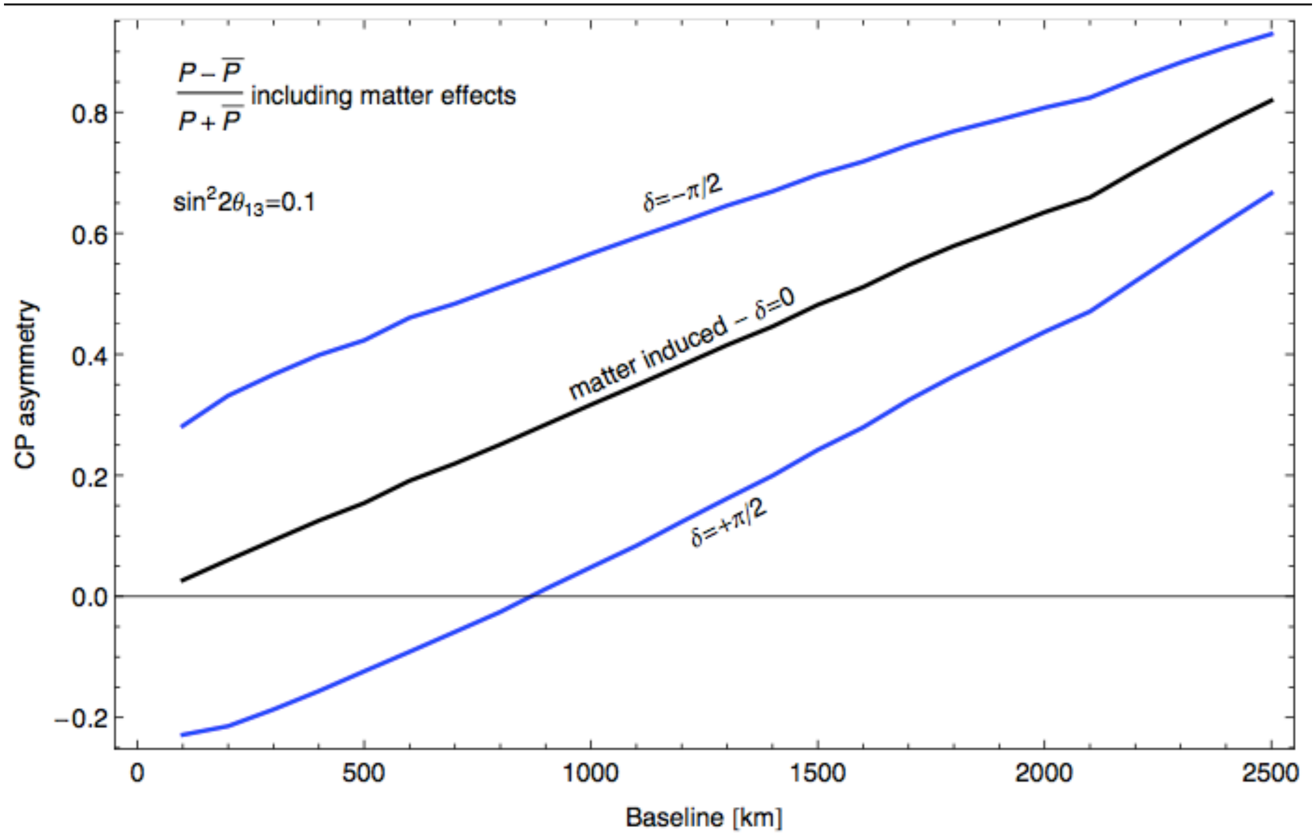
But measurement of CP violation is tangled up with matter effects (depending on MH)...

Matter potential $\nu_\mu \rightarrow \nu_e$ $V_{\mathrm{mat}} = \pm 2\sqrt{2} G_F N_e E$

+ for neutrinos, - for antineutrinos

Earth has electrons, not positrons!

Matter-induced CP asymmetry competes with intrinsic CP asymmetry



P. Huber, NuFact 2013

Long-baseline approach for going after MH *and* CP

Measure transition probabilities for

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

through matter

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = {} & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) \\
& + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right) \\
& + \tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)
\end{aligned}
$$

Change of sign for antineutrinos

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

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

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

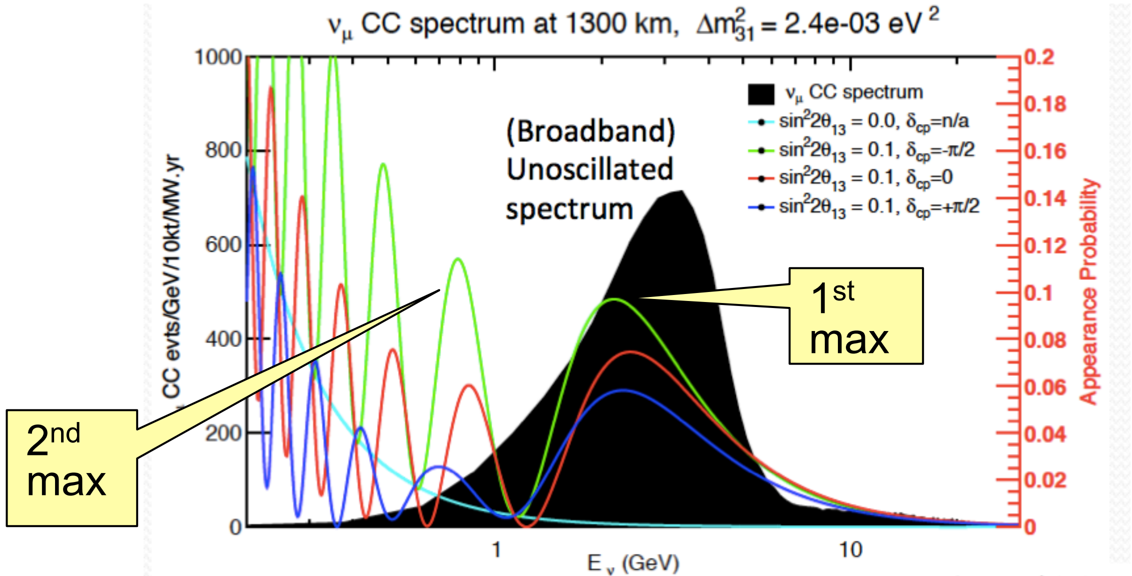
$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

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

- CP δ
- matter density (Earth has electrons, not positrons)

Oscillation probabilities

want
to cover
the wiggles
with your
beam



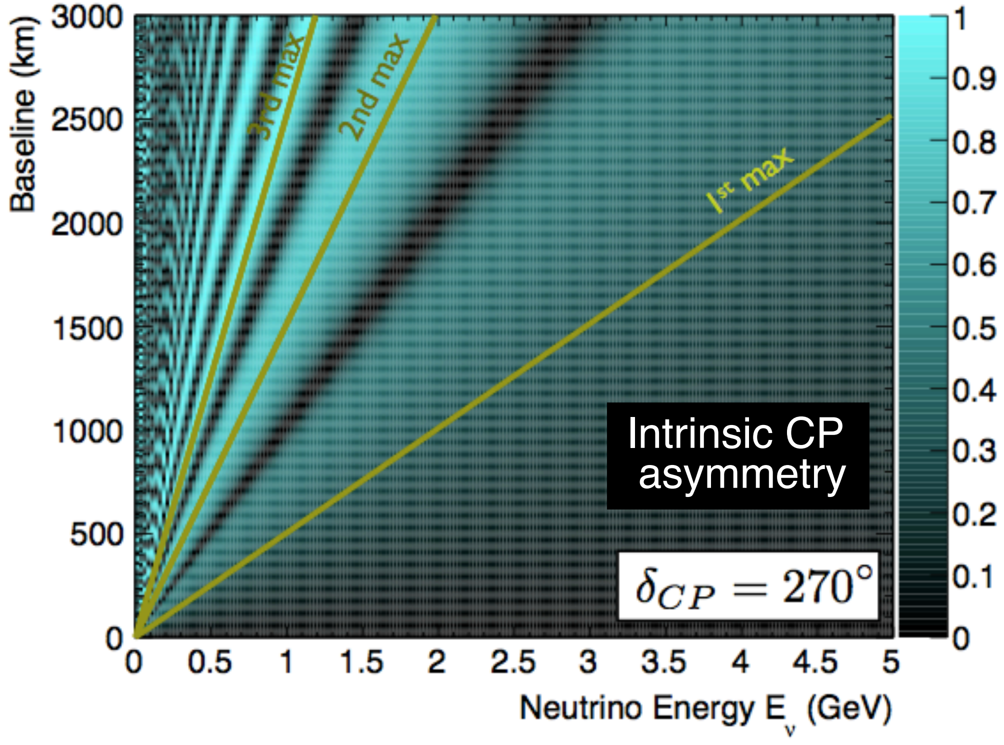
(Broadband) Unoscillated spectrum

2nd max

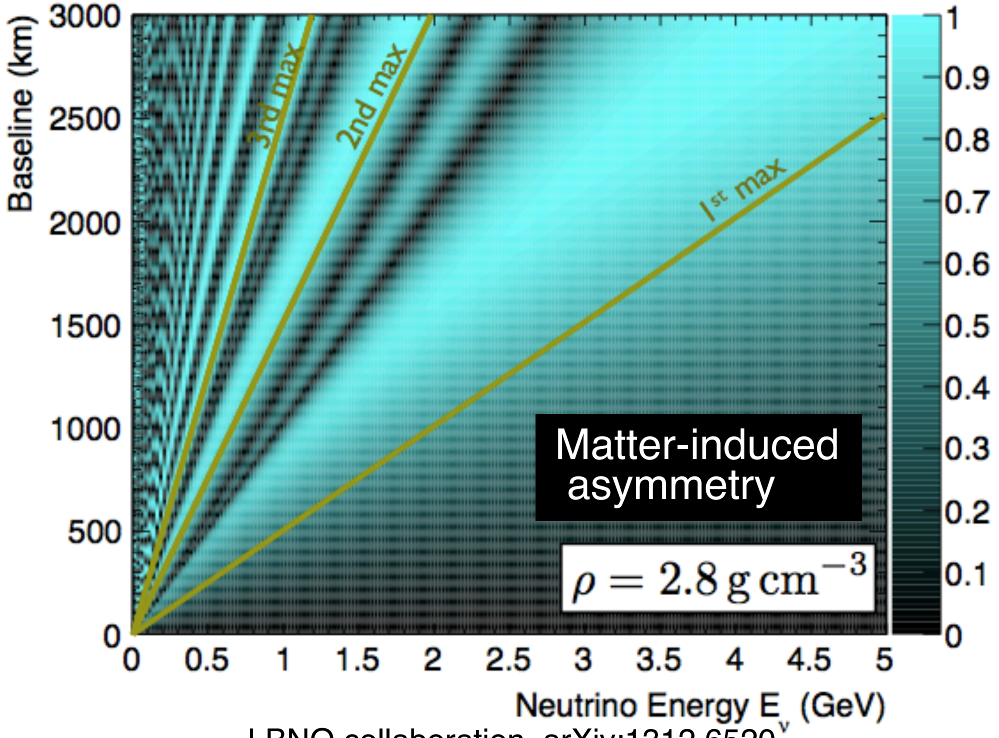
1st max

LBNE collaboration, arXiv:1307.7335

$$\mathcal{A}^{vac}_{CP}(\delta_{CP}) \equiv \left(\frac{P^{vac}(\nu) - P^{vac}(\bar{\nu})}{P^{vac}(\nu) + P^{vac}(\bar{\nu})}\right)$$



$$\mathcal{A}_{CP}(\rho) \equiv \left(\frac{P^{mat}(\nu) - P^{mat}(\bar{\nu})}{P^{mat}(\nu) + P^{mat}(\bar{\nu})}\right)$$



LBNO collaboration, arXiv:1312.6520

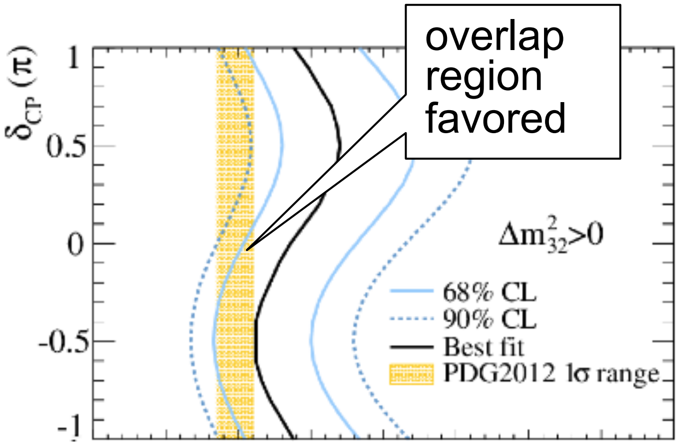
Large intrinsic asymmetry at 2nd max, but still good signal at 1st max

A first hint from T2K NEW

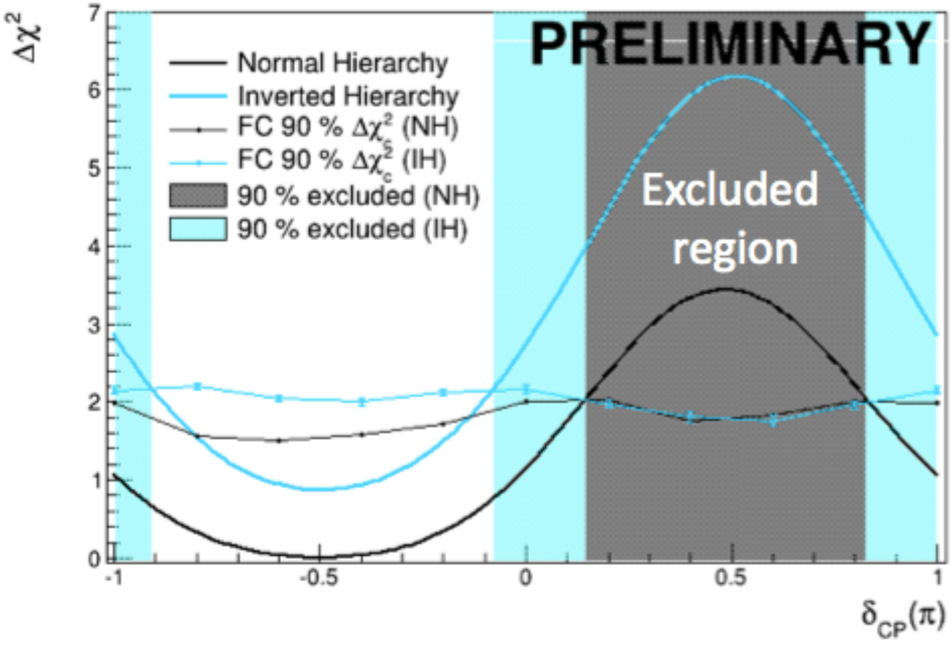
Joint ν_μ, ν_e three-flavor fit,

including reactor constraint on θ_{13}

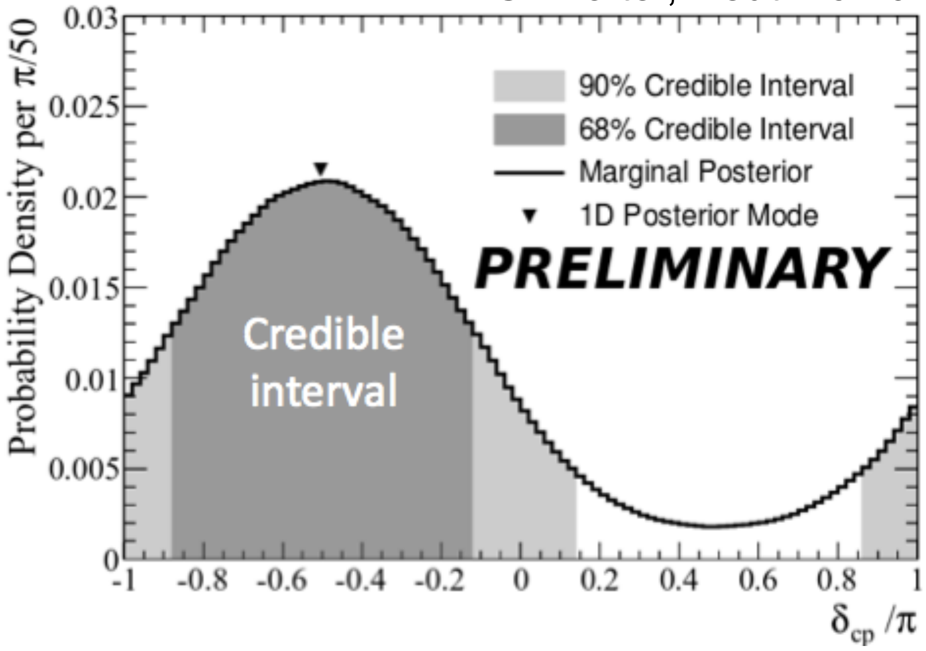
$\sin^2 2\theta_{13} = 0.095 \pm 0.010$



C. Walter, Neutrino 2014



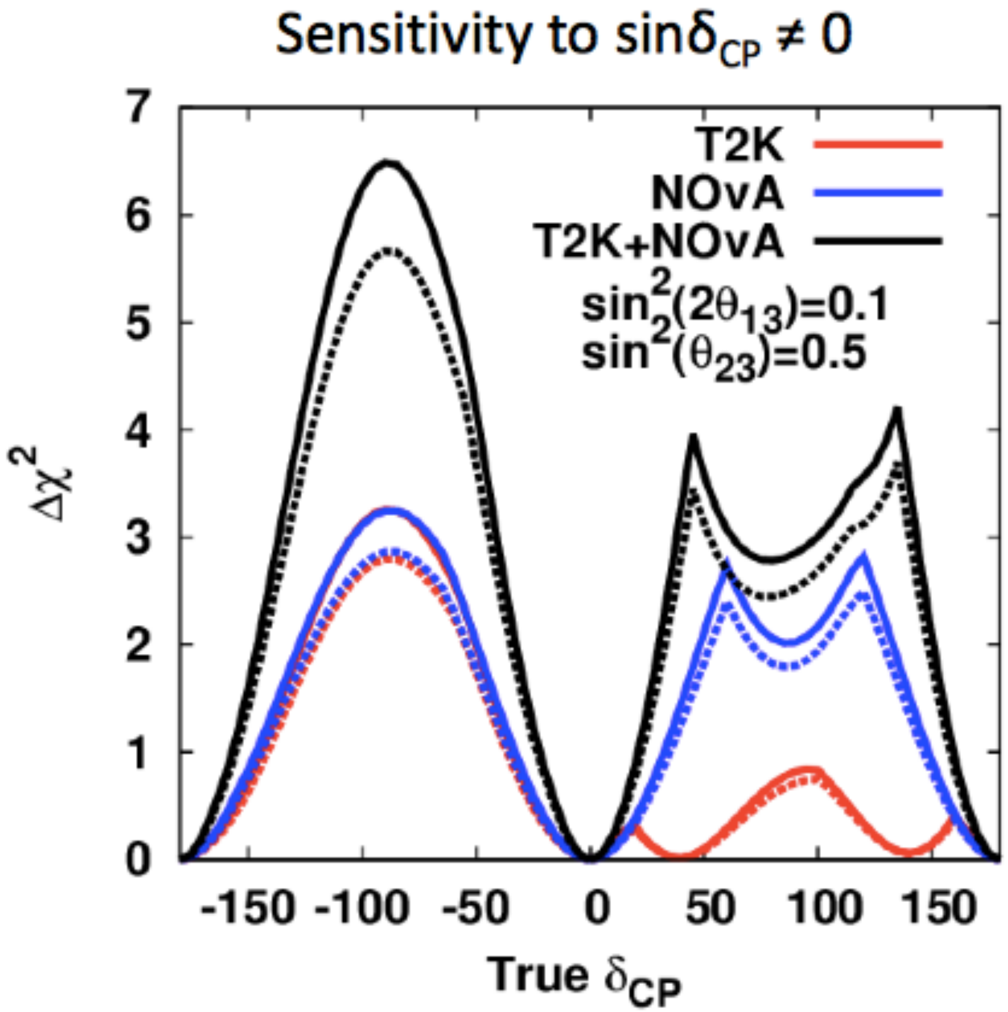
Likelihood ratio fit
w/ Feldman-Cousins
confidence interval



Bayesian analysis w/
Markov Chain Monte Carlo,
marginalize over MH

Both analyses prefer $\delta \sim -\pi/2$

Sensitivity for T2K+NoVA+reactor experiments



$50\%\nu + 50\%\bar{\nu}$

T2K alone

Nova alone

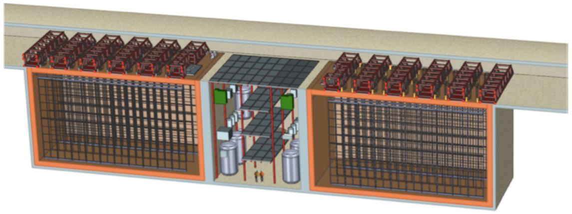
T2K+ Nova

T2K full POT (7.8 x 10^{21}), uses reactor constraint

If parameters are lucky, will get indications of nonzero δ

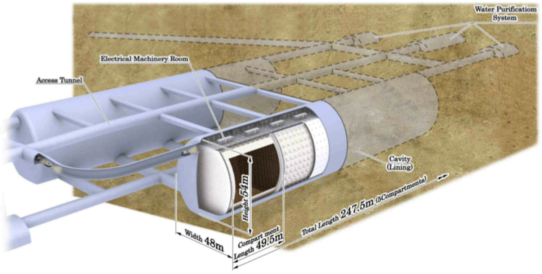
Next superbeam proposals for going beyond

LBNE/F



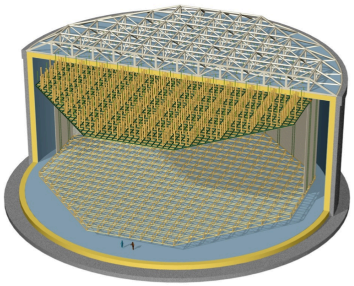
Large argon detector w/ beam from Fermilab

Hyper-K



Large water detector with beam from J-PARC

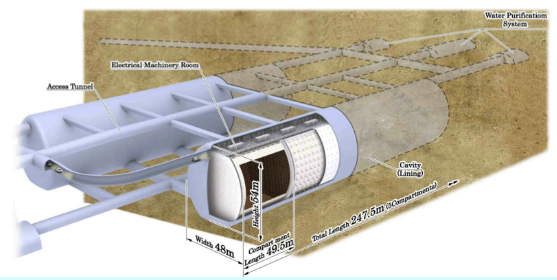
LAGUNA-LBNO

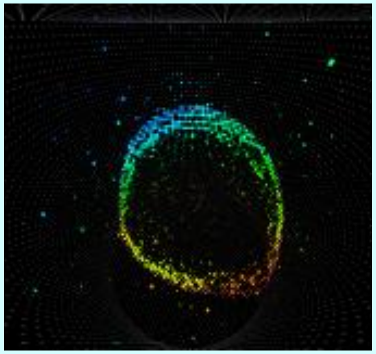


Large detectors (argon or iron) w/ beam from CERN or Protvino

Comments on large detector technologies

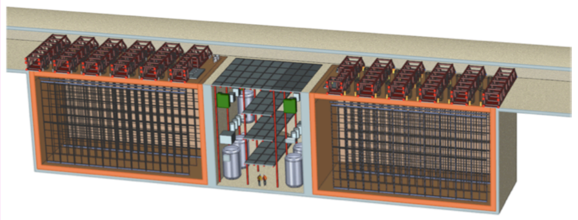
Water Cherenkov

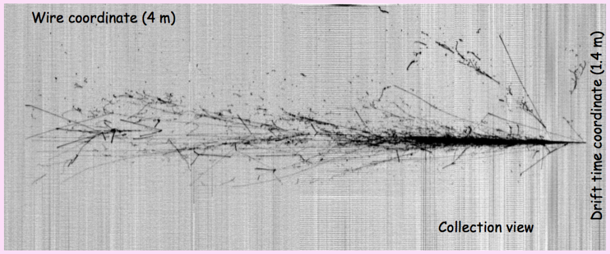




Cheap material,
proven at very
large scale,
but reconstruction
limited by Cherenkov
threshold and photon
collection

Liquid Argon



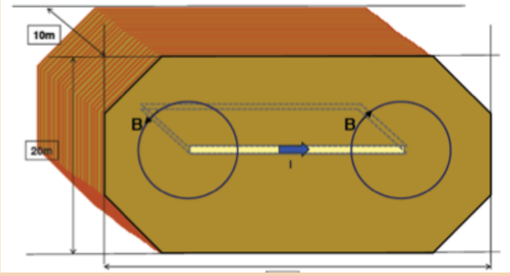


Excellent particle
reconstruction,
but more expensive to
scale to large mass

Liquid Scintillator

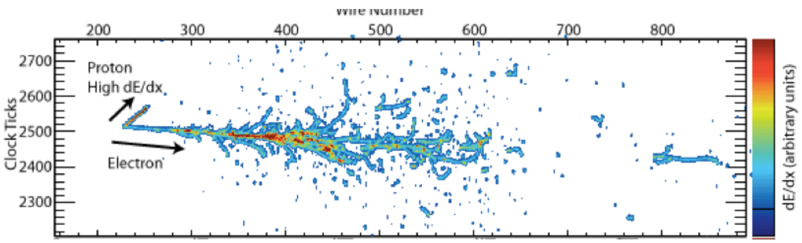
Low energy
threshold
... excellent for
non-accelerator
physics but ~GeV
reconstruction hard

Magnetized Iron



Excellent when
sign selection critical,
e.g., for neutrino factory

Example signal for LBNE/F: ν_e events

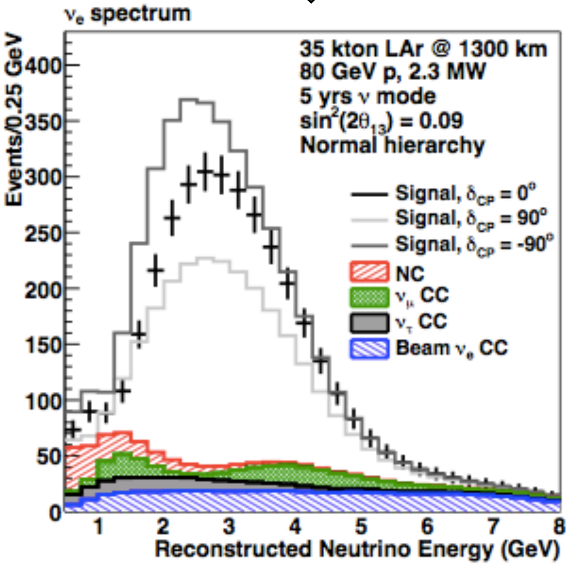


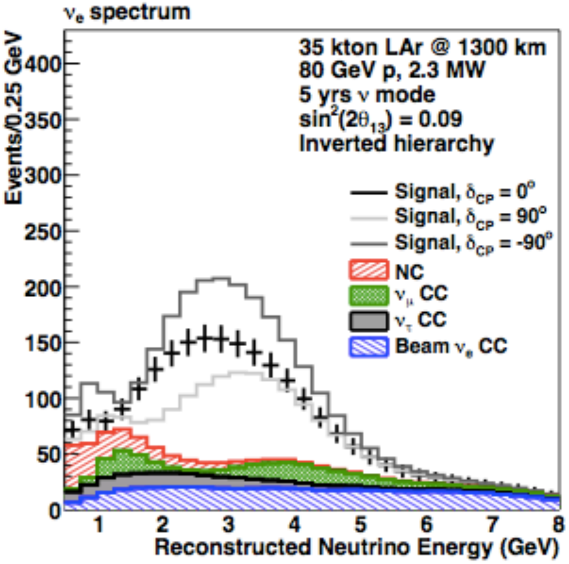
look for ~few GeV em showers in LArTPC

Normal hierarchy

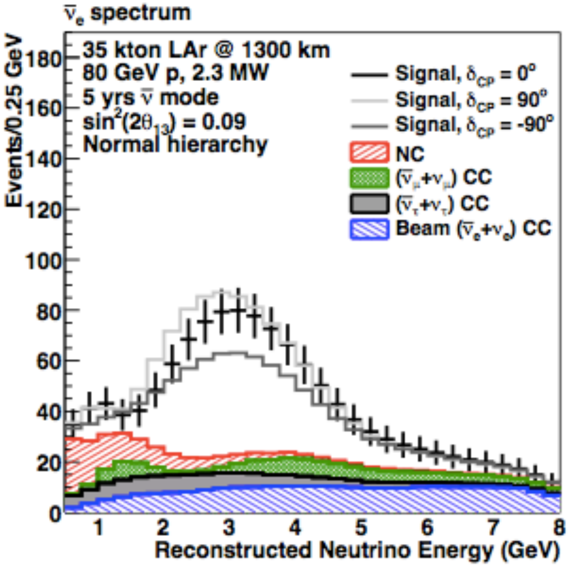
Inverted hierarchy

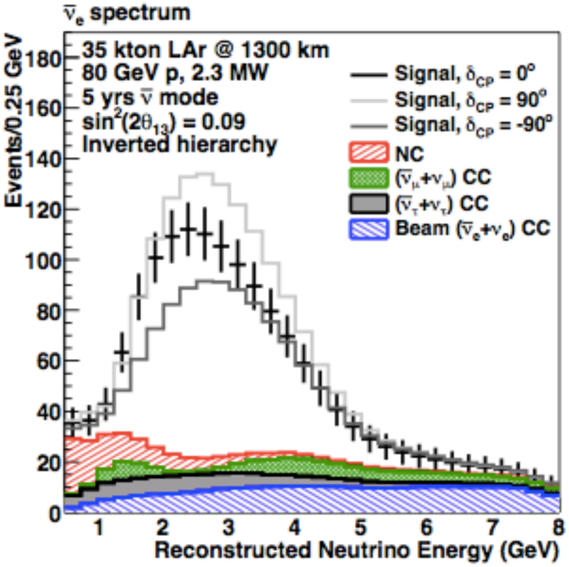
Neutrino beam





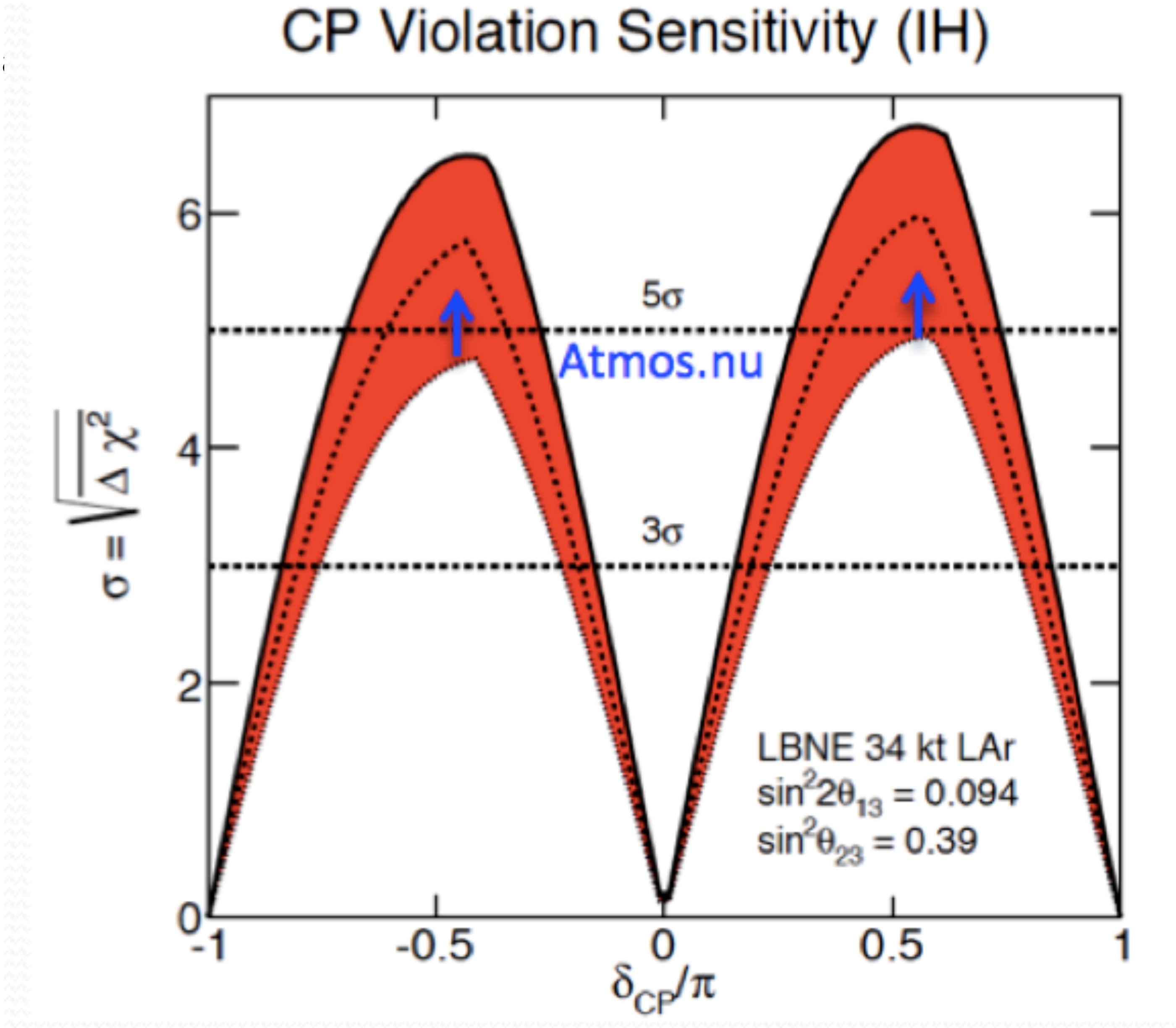
Antineutrino beam





LBNE/F sensitivity to CP δ

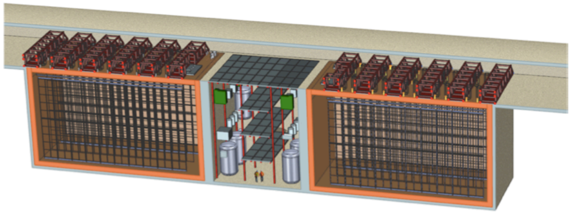
245 kt-MW-yr
[34 kt x 1.2 MW x (3ν+3



R. Wilson, Neutrino 2014

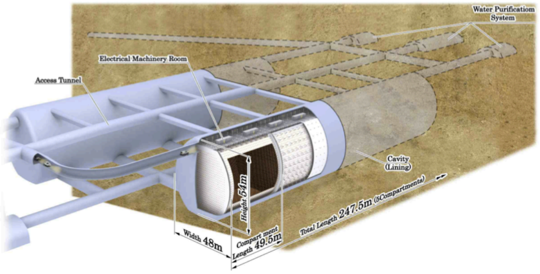
Summary of next superbeam proposals

LBNE/F



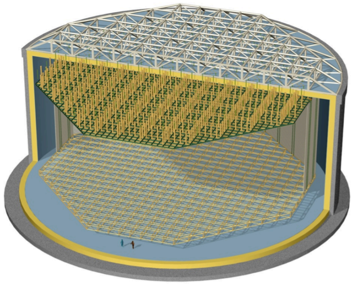
- Wideband beam, medium-energy beam
- 1300 km baseline
- MH and CP sensitivity

Hyper-K



- Narrowband, lower-energy beam
- Huge statistics
- 295 km baseline
- CP sensitivity

LAGUNA-LBNO



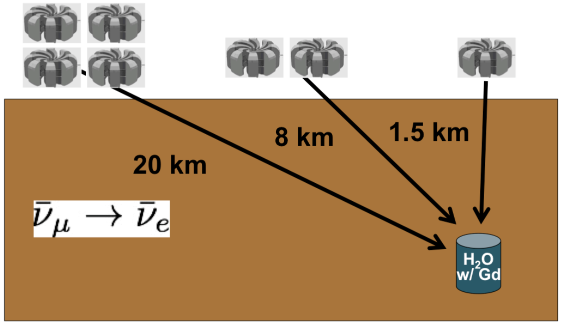
- Wideband beam, higher-energy beam
- 2300 km baseline (in favored option)
- MH and CP sensitivity, focus on 2nd max

Any of them can do the CP job* (decent chance of ~5σ)

*Note: also rich non-accelerator physics (SN, pdk, atmν,...) with different strengths for each detector type

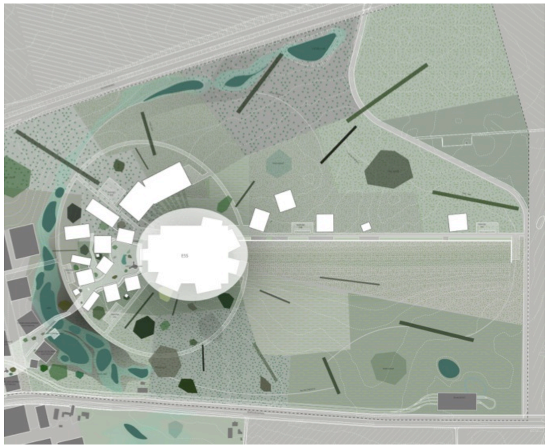
Other ideas for the future

DAEδALUS



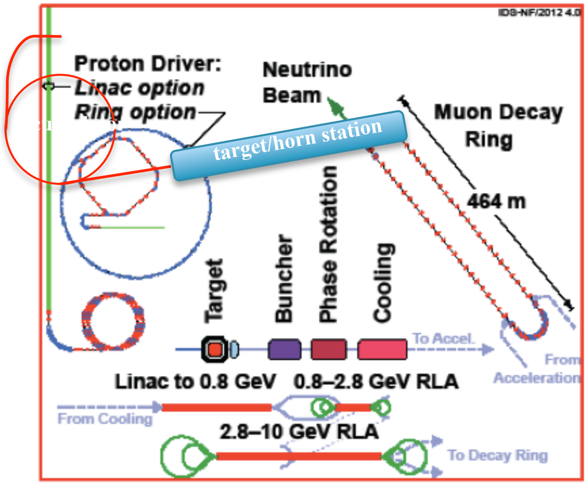
High-power cyclotrons producing pion decay-at-rest neutrinos + large water or scintillator

ESSνSB



Modification of European Spallation Source proton beam + water Ch. detector in Sweden

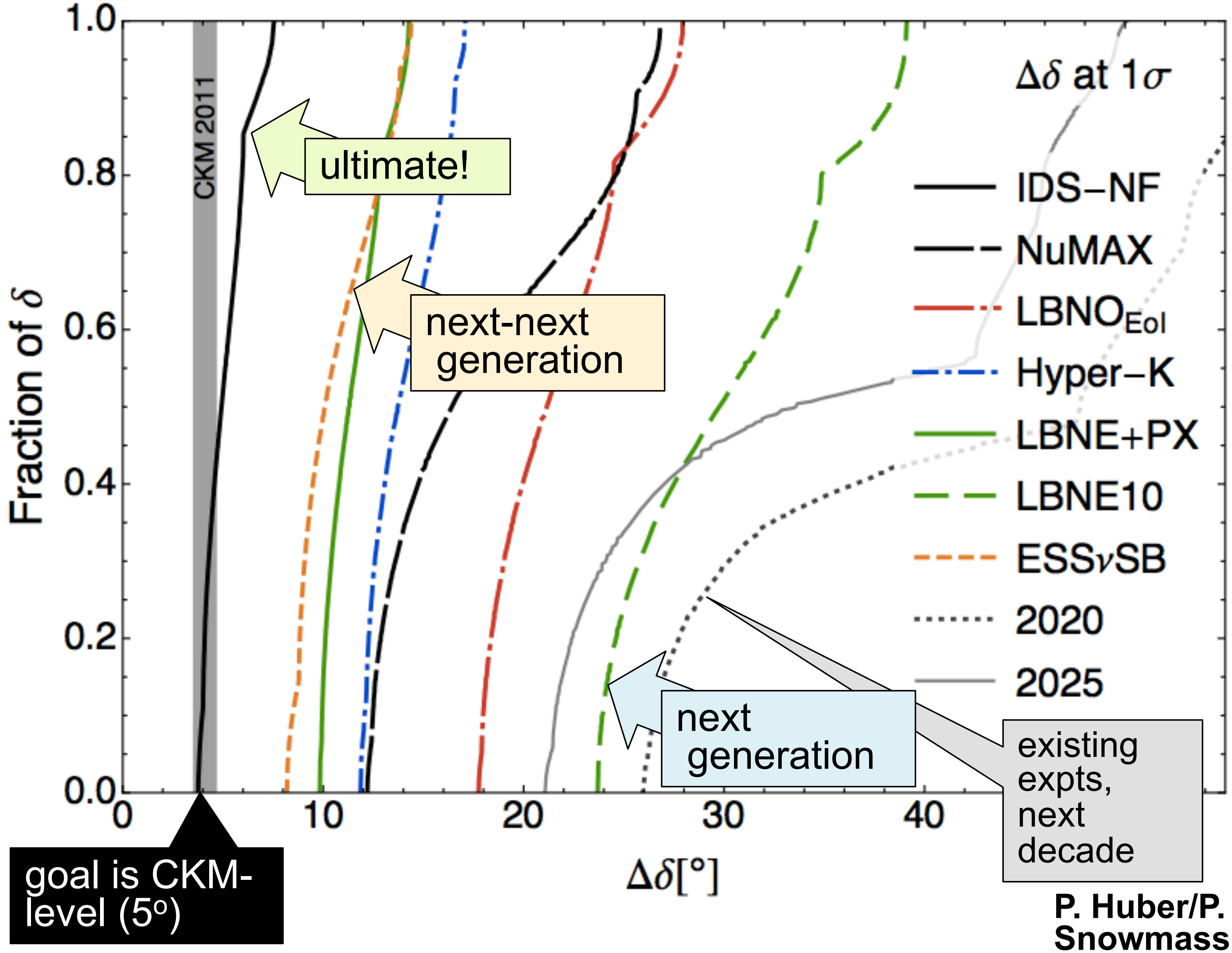
ν factory



Muon storage ring as neutrino source

Summary of long-term long-baseline experiment CP reach

Fraction of CP δ values over which one could attain the specified precision on δ



ultimate!

next-next generation

next generation

existing expts, next decade

goal is CKM-level (5°)

P. Huber/P. Coloma, Snowmass 2013

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

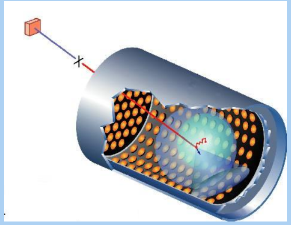
There are already some slightly uncomfortable data that don't fit that paradigm...

Open a parenthesis:

(

Outstanding 'anomalies'

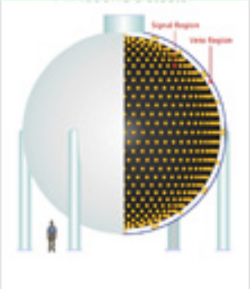
LSND @ LANL (~30 MeV, 30 m)



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

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

MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~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

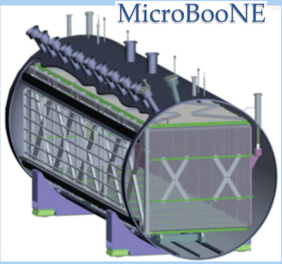
????

more data needed

Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly')
and source ν_e ('gallium anomaly') [cosmology now consistent w/3 flavors]

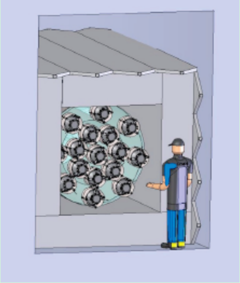
Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle
physics & astrophysics. Or some other new physics??

Ideas to address these anomalies...

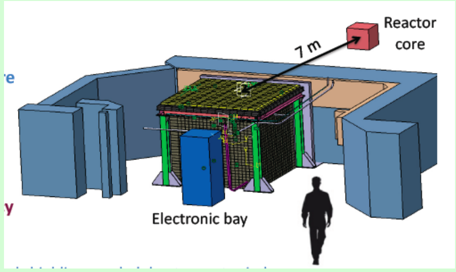


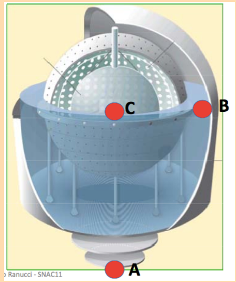
Experiments with beams

(meson decay
in flight and
at rest)

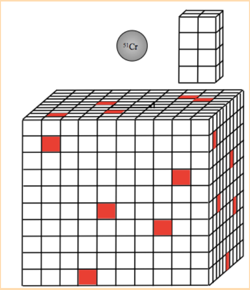


Experiments at reactors





Experiments with radioactive sources



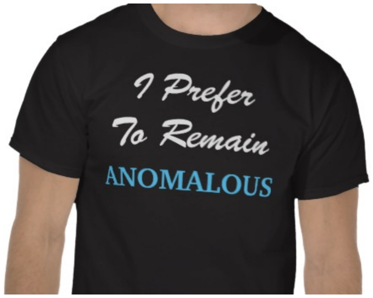
Many more! see e.g., `arXiv:1204.5379`

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

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...