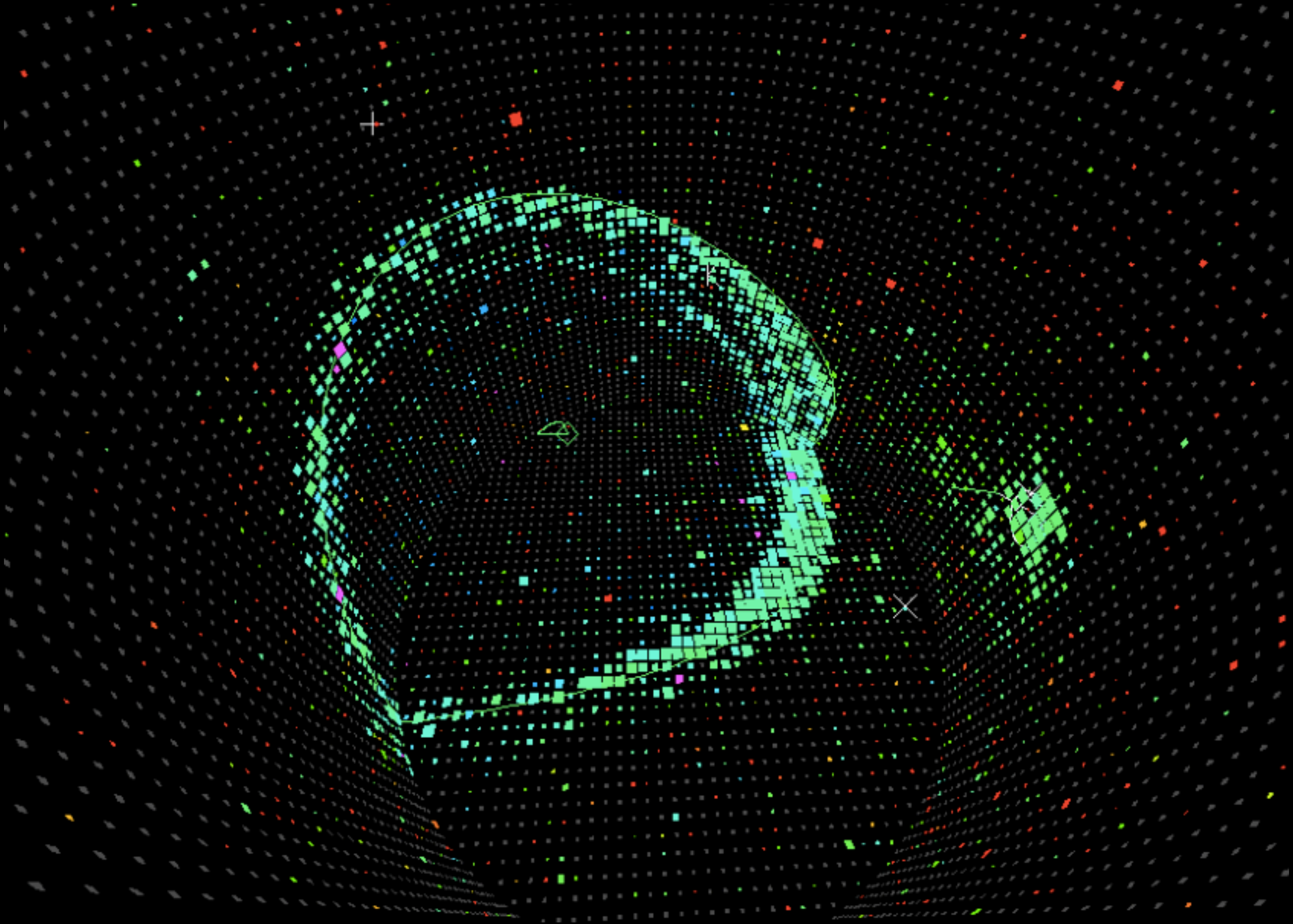
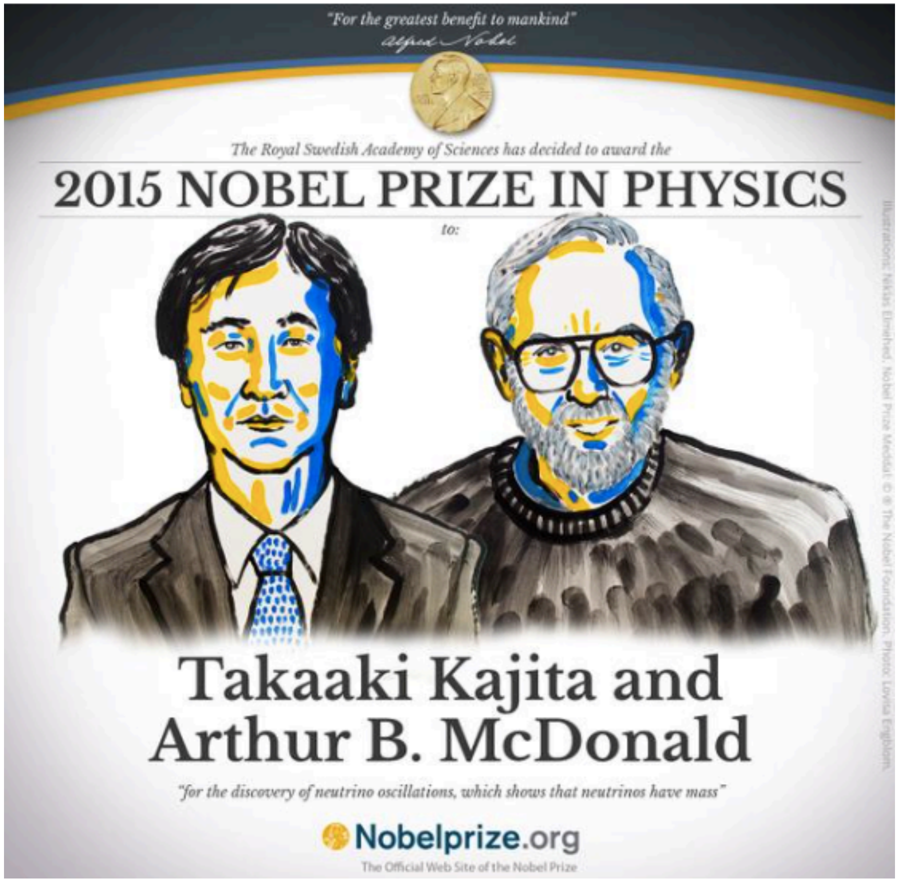
Neutrinos From The Sky and Through the Earth



Kate Scholberg, Duke University

DNP Meeting, October 2016

Neutrino Oscillation Nobel Prize!



The fourth Nobel
for neutrinos:

1988: neutrino flavor
1995: discovery of the neutrino
2002: solar and supernova neutrinos
2015: neutrino oscillations (and mass)

And also: the Breakthrough Prize

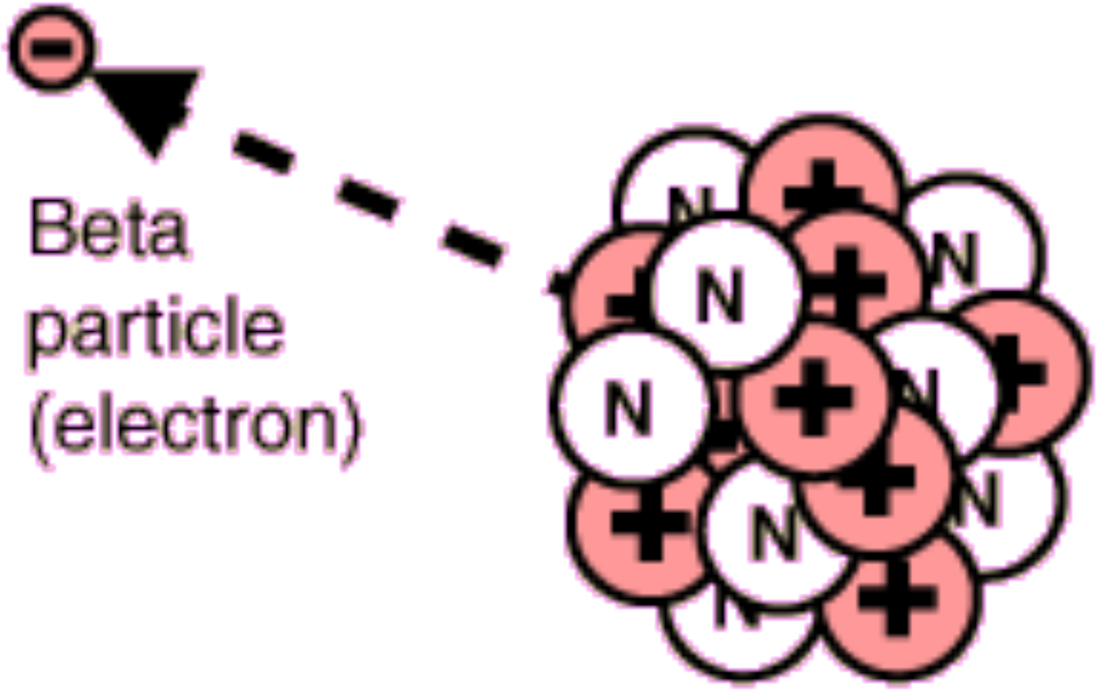
Neutrinos Win Again: More Than 1,300 Physicists Share Breakthrough Prize for Particle Experiments

In October two discoverers of neutrino oscillations won the Nobel Prize. Now their full teams and those of several other experiments on the strange particles share a $3-million award

Recognized also 1300 scientists from 6 collaborations!

A mystery in the early part of last century:

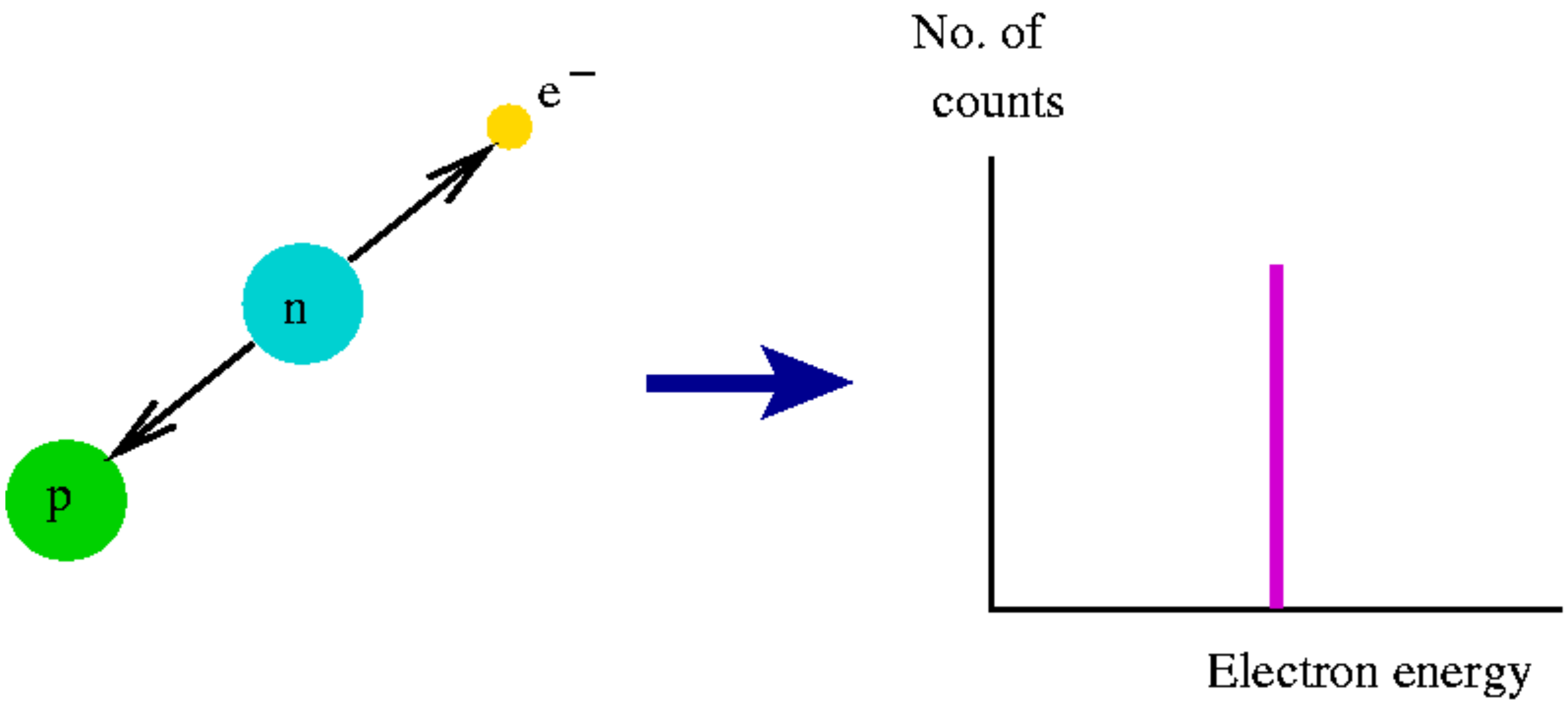
Radioactive beta decay



A nucleus apparently splits into *two pieces*

... it spits off an electron

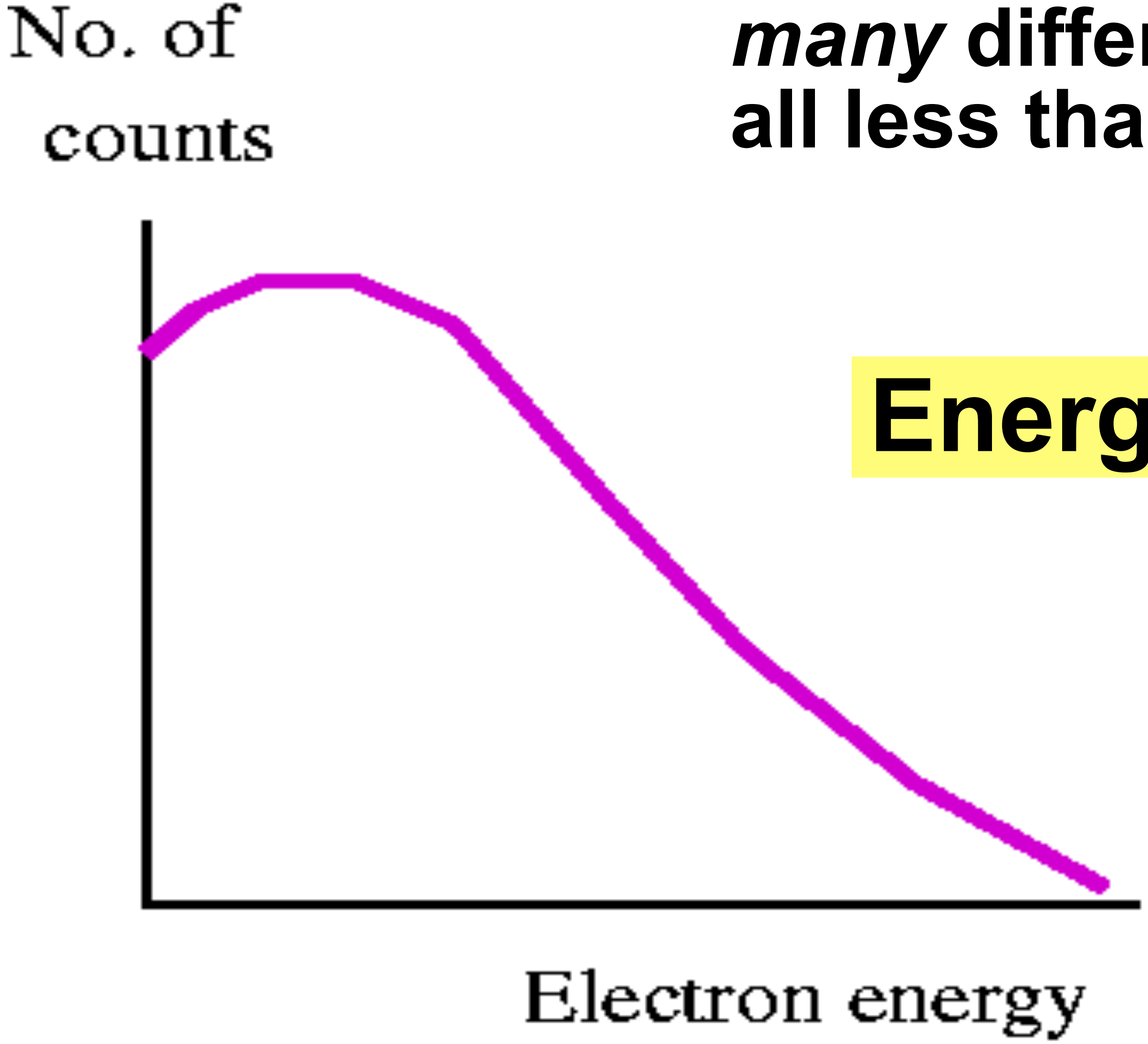
It's actually a neutron inside the nucleus decaying: $\mathbf{n \rightarrow p + e^-}$



Because it's a decay into two particles,
if momentum is conserved,
the p and e$^-$ have *specific energies*

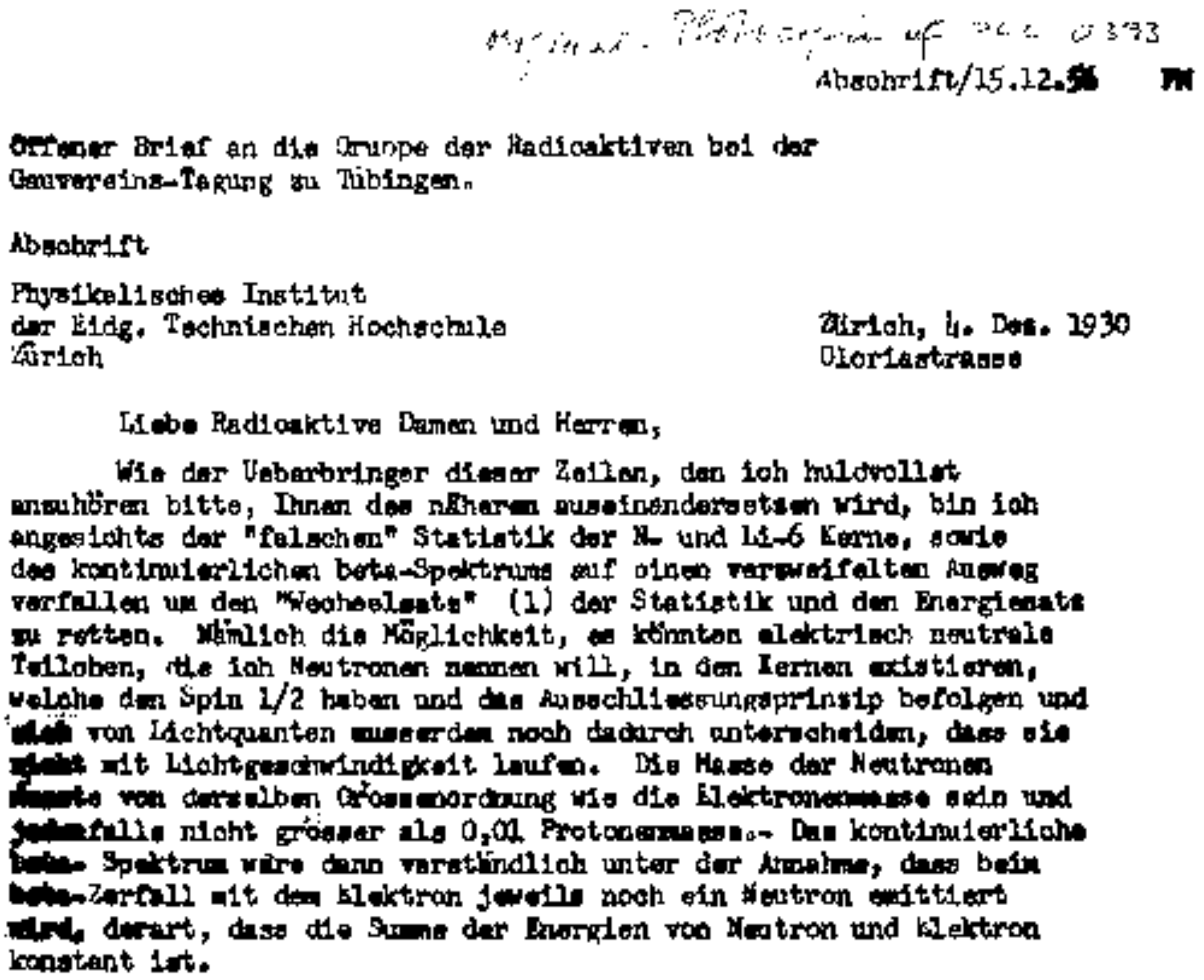
But that's not what's observed!

Instead, electrons have *many* different energies, all less than expected



Energy is missing!!

Wolfgang Pauli, 1930:
"Dear Radioactive Ladies and Gentlemen,
...I have hit upon a desperate remedy..."



Original-Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

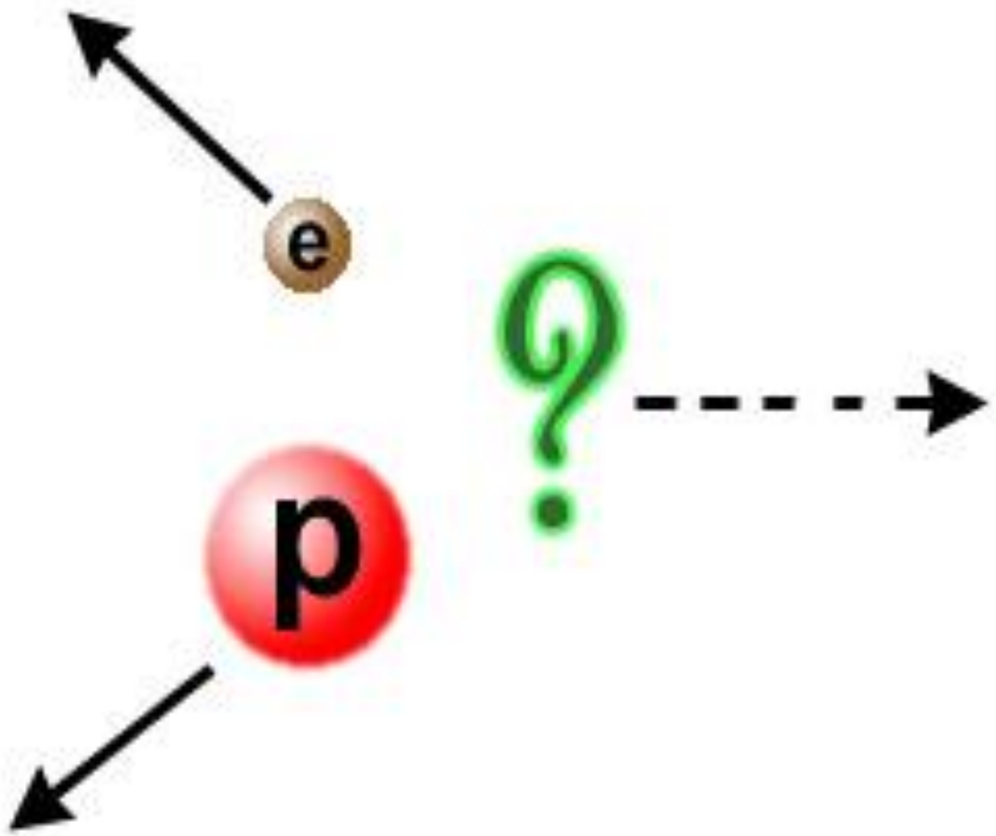
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Pauli's solution: *invisible particle* makes off with the missing energy!

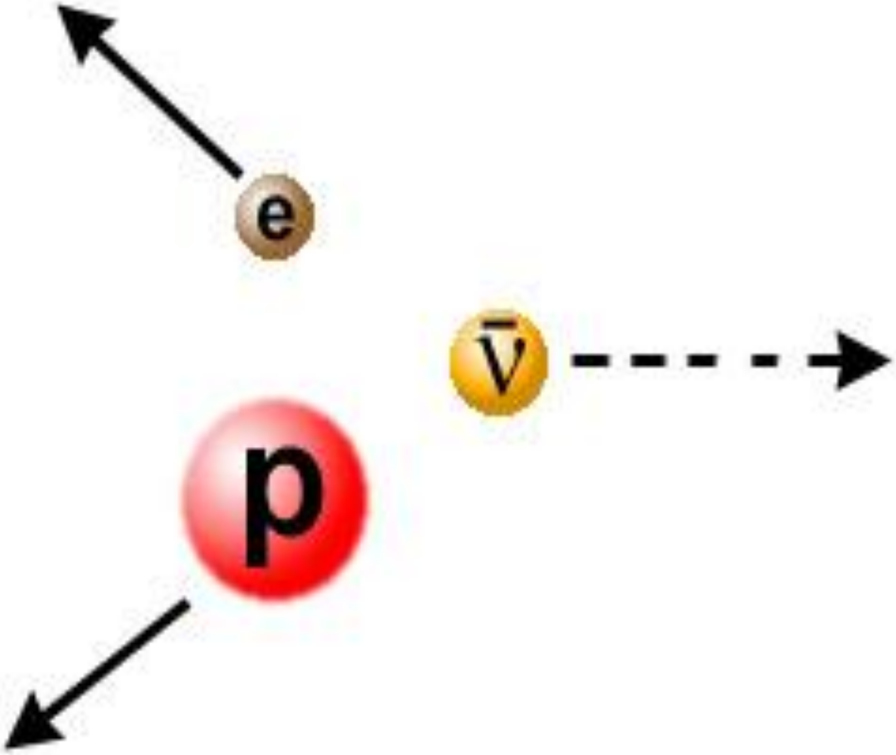


Explains the observed electron energies perfectly

1933 Enrico Fermi named the

NEUTRINO

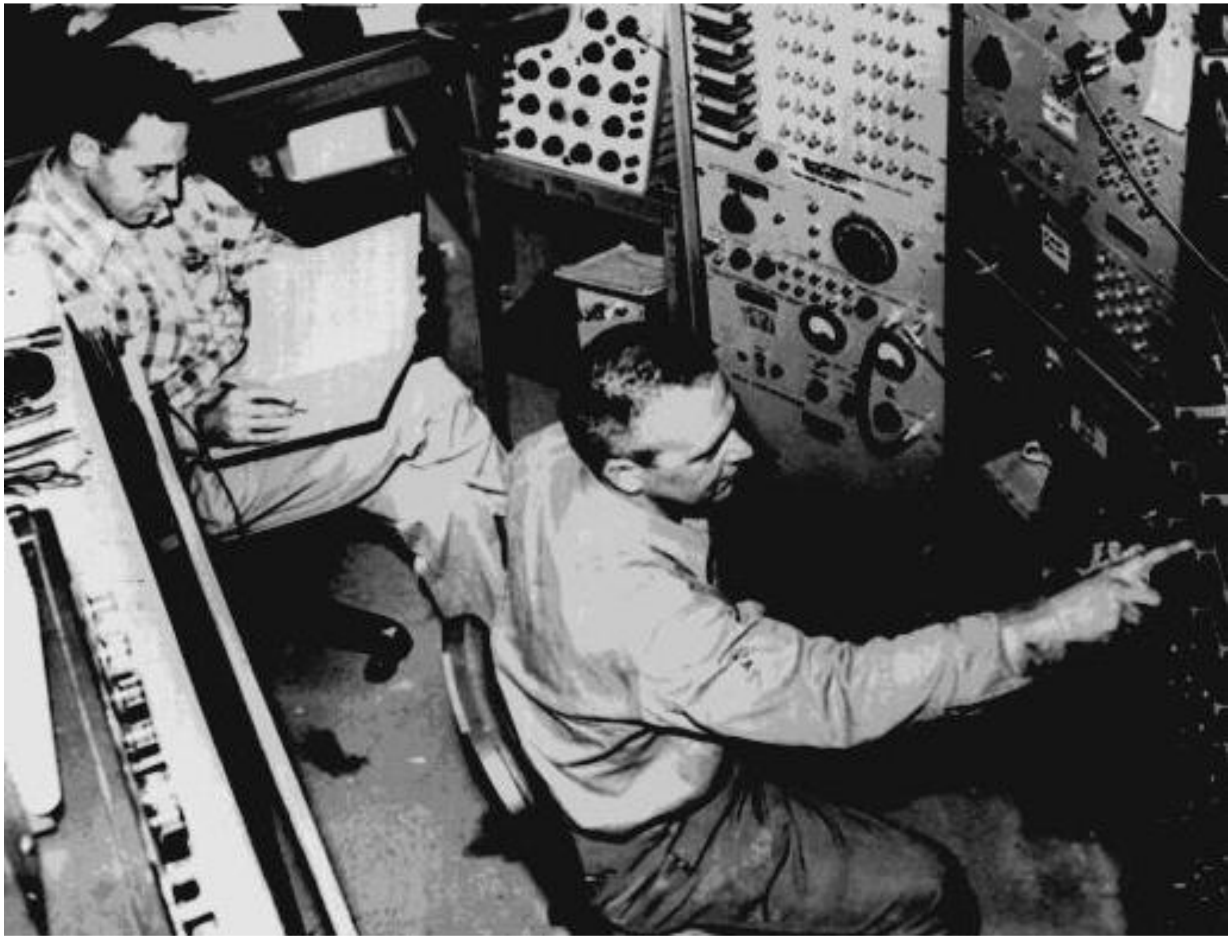
'Little Neutral One'



Zero charge, very small (zero?) mass, interacts **weakly**

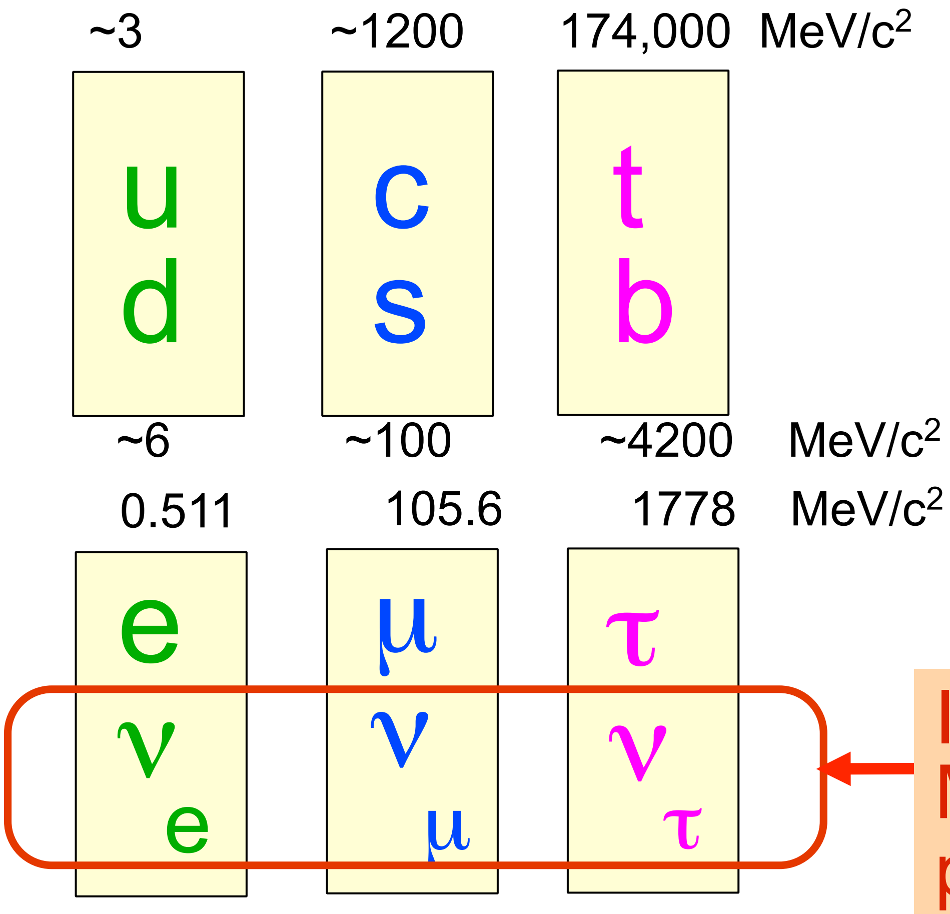
Very hard to detect directly!

Neutrinos do interact with matter to make a charged particle... but very rarely



First neutrinos
(from a nuclear
reactor)
detected
in 1956 by
Reines & Cowan

We now know much more:

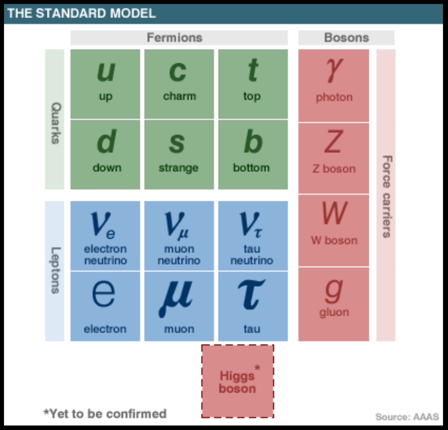


	~3	~1200	174,000	MeV/c^2
Quarks	u	c	t	
	d	s	b	
	~6	~100	~4200	MeV/c^2
	0.511	105.6	1778	MeV/c^2
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	

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

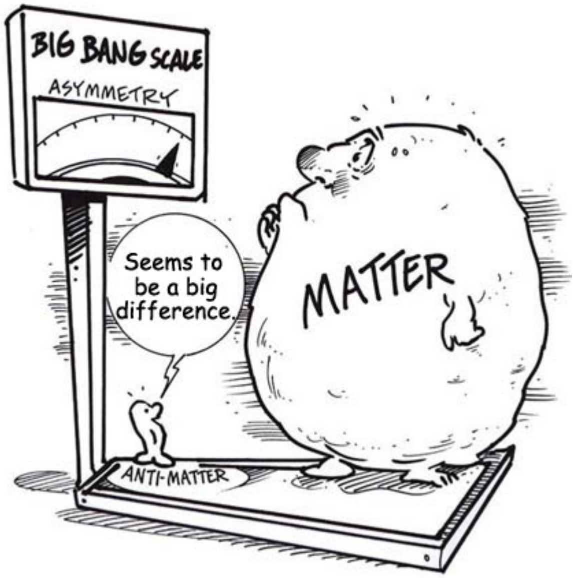
cosmology

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...

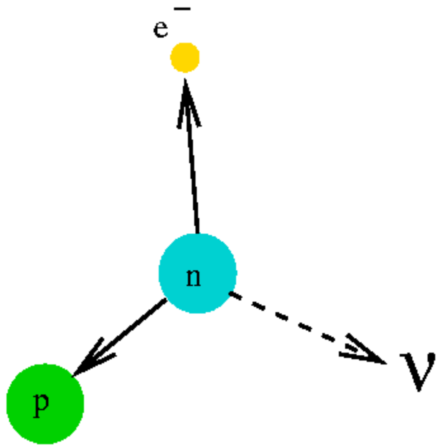
But knowledge of ν properties essential for understanding!

charge

parity

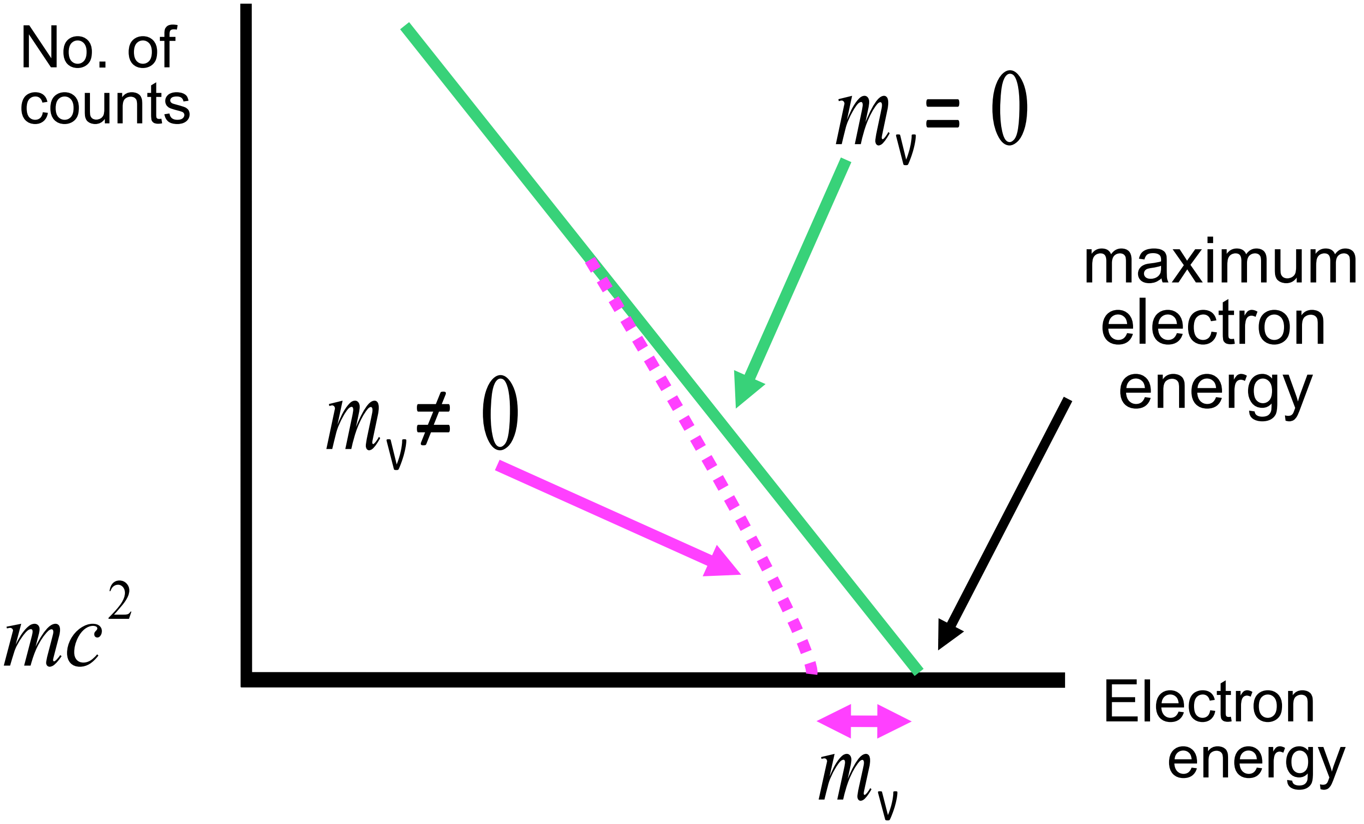
CP violation is likely involved: a difference in behavior between a particle and its mirror-inverted antiparticle, observed so far in quarks but not leptons

Direct Tests for Neutrino Mass



Energy shared by 3 particles

$$E = mc^2$$



Missing energy at the endpoint of the beta decay spectrum ⇒ non-zero neutrino mass

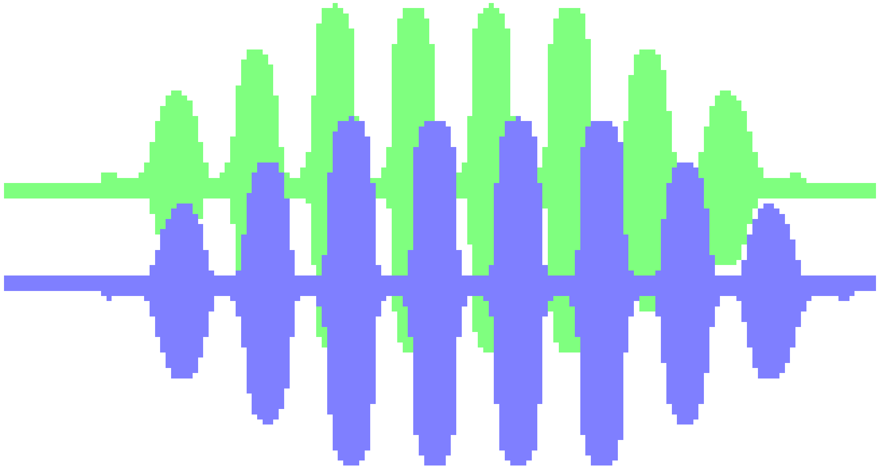
So far nothing found!

Best upper limits: $m_\nu < 1/250{,}000\ m_e$

There's another way of getting at the question of neutrino mass...

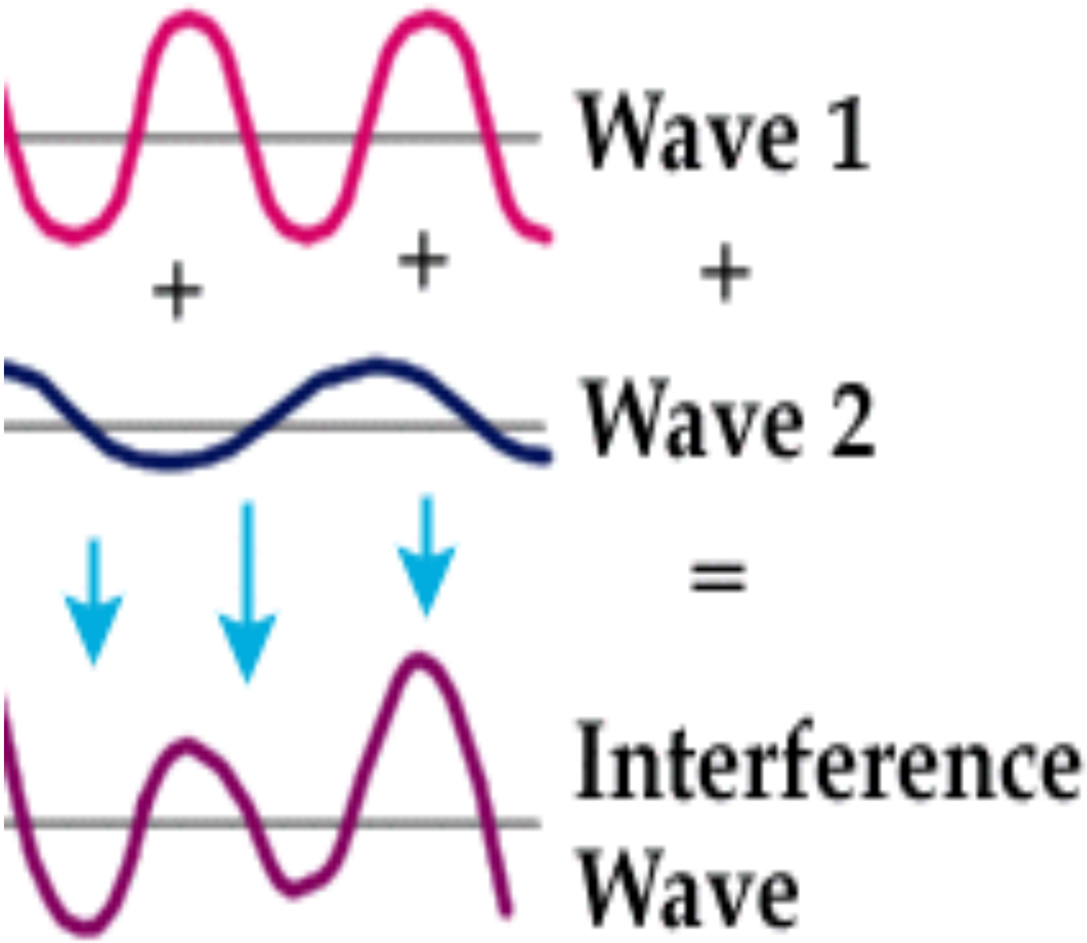
NEUTRINO OSCILLATIONS

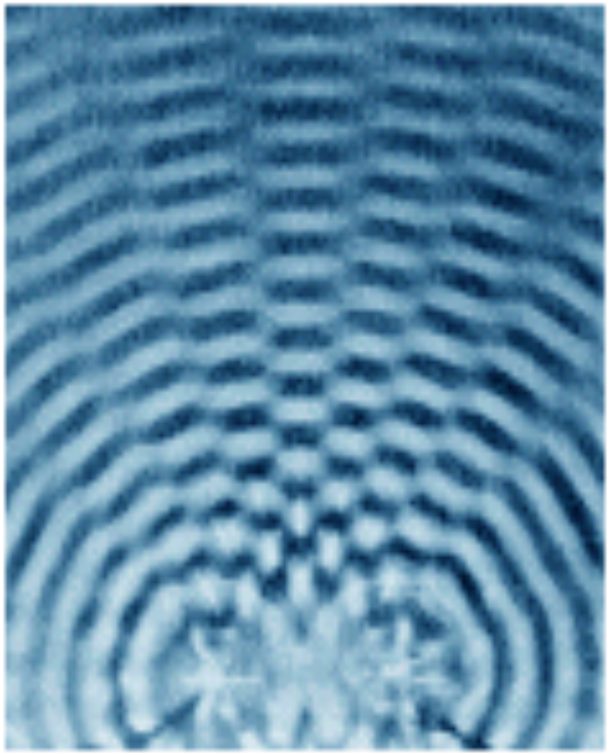
Use the *wave-like* nature of all particles, including neutrinos



Quantum mechanics ⇒ massive neutrinos (as waves) would propagate with different frequencies according to their masses

A neutrino may be made of different "mass states"





The interference of water waves coming from two sources.

The different mass frequencies can **interfere**

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

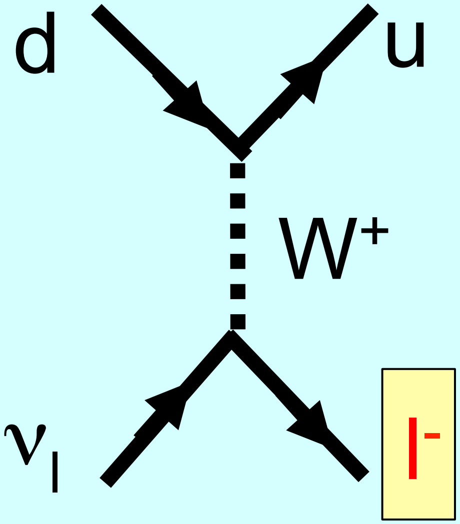
$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

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

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

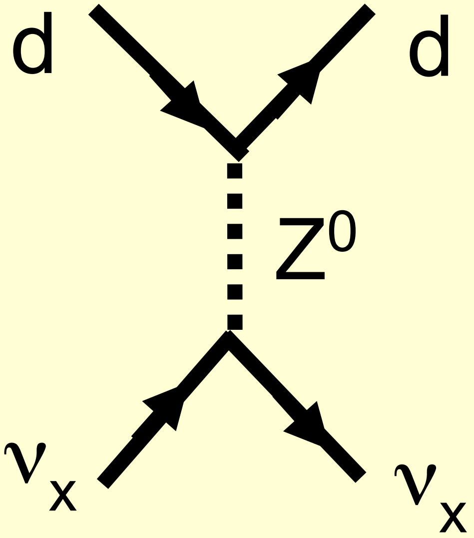


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

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

Neutral Current (NC)



Flavor-blind

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

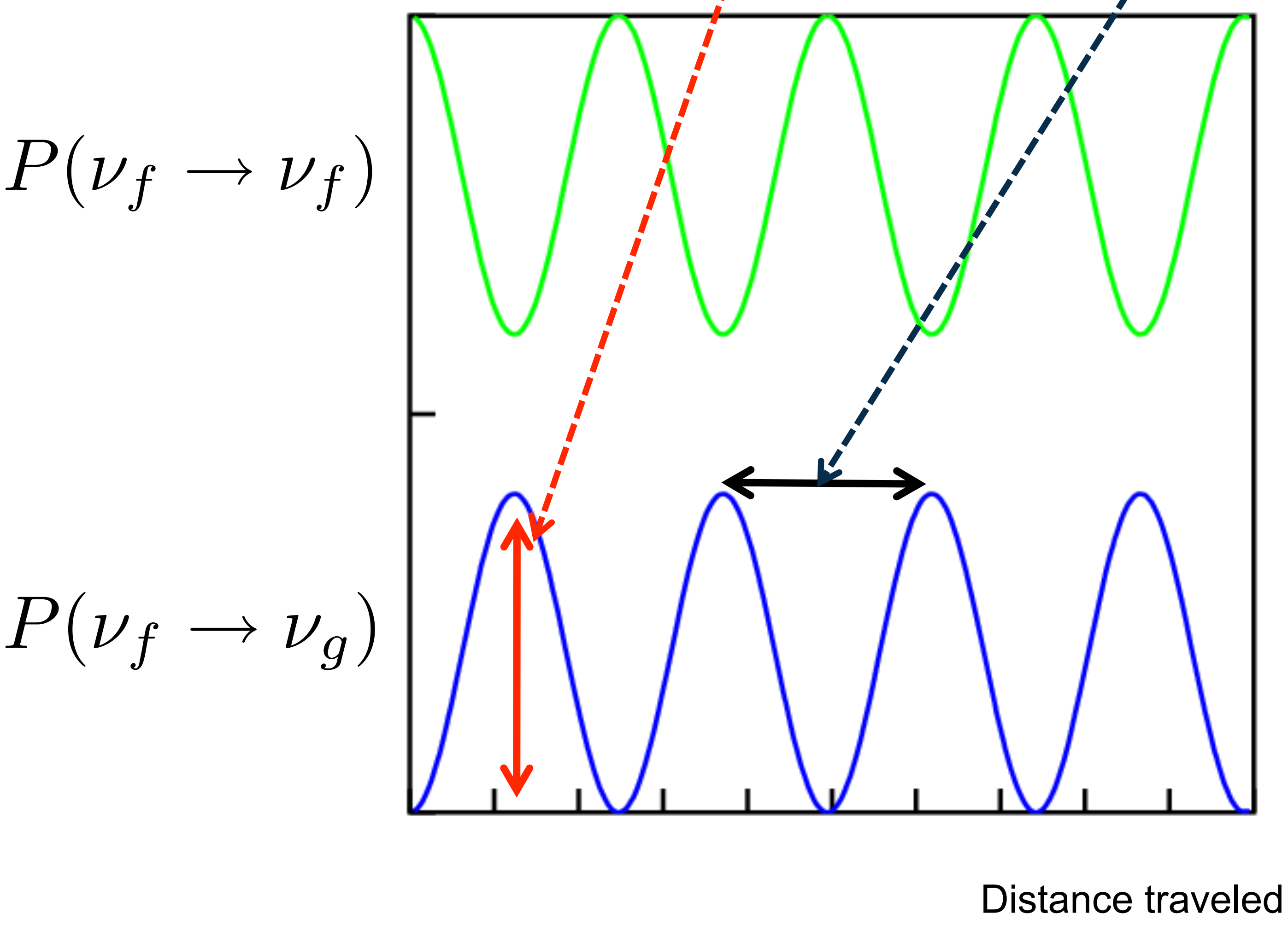
*Note: oscillation depends on mass *differences*, not absolute masses

For 2 flavors:

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

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

Disappearance: ν's oscillate into 'invisible' flavor

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

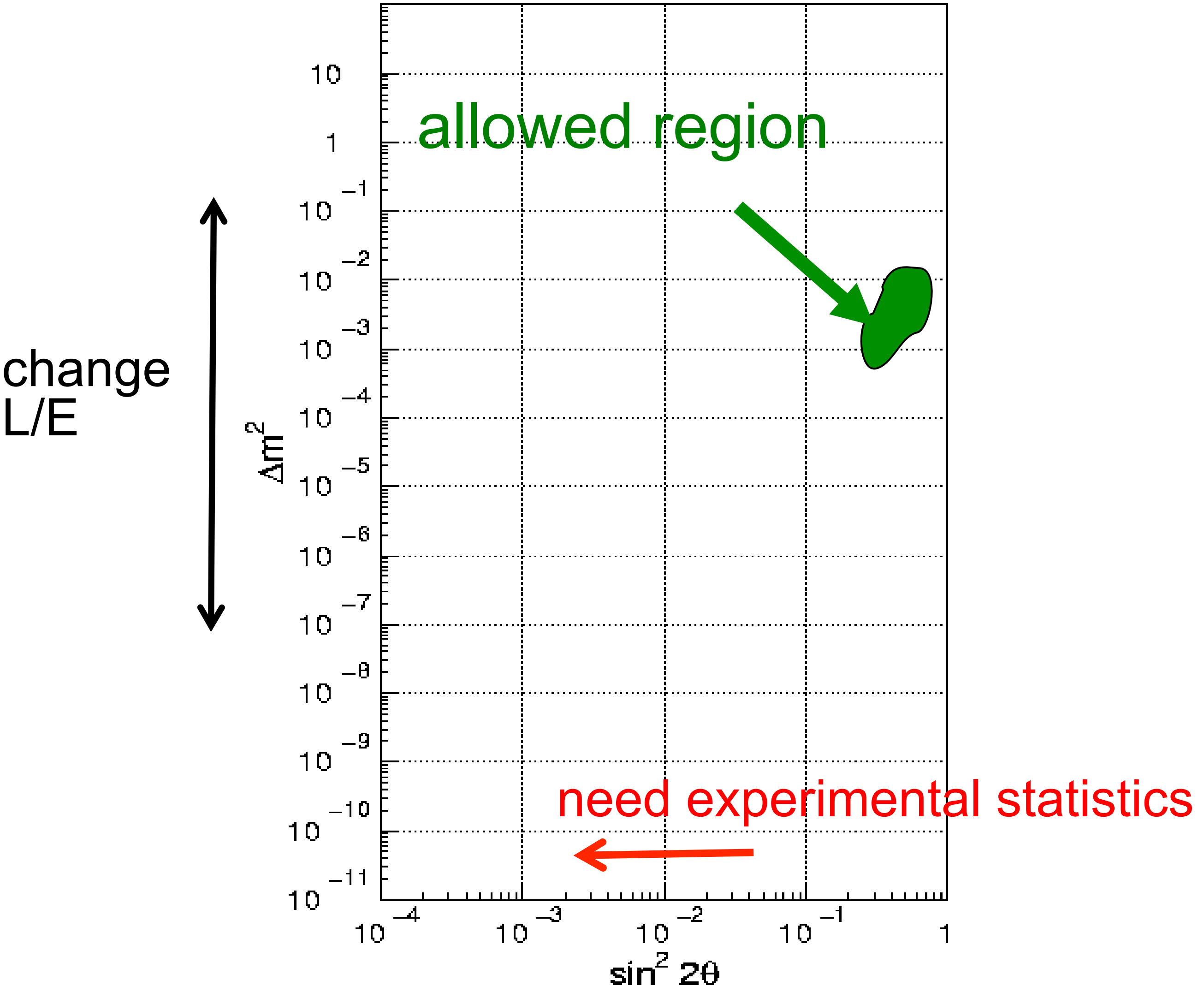
Appearance: directly see new flavor

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

Neutrino oscillation parameter space

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

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

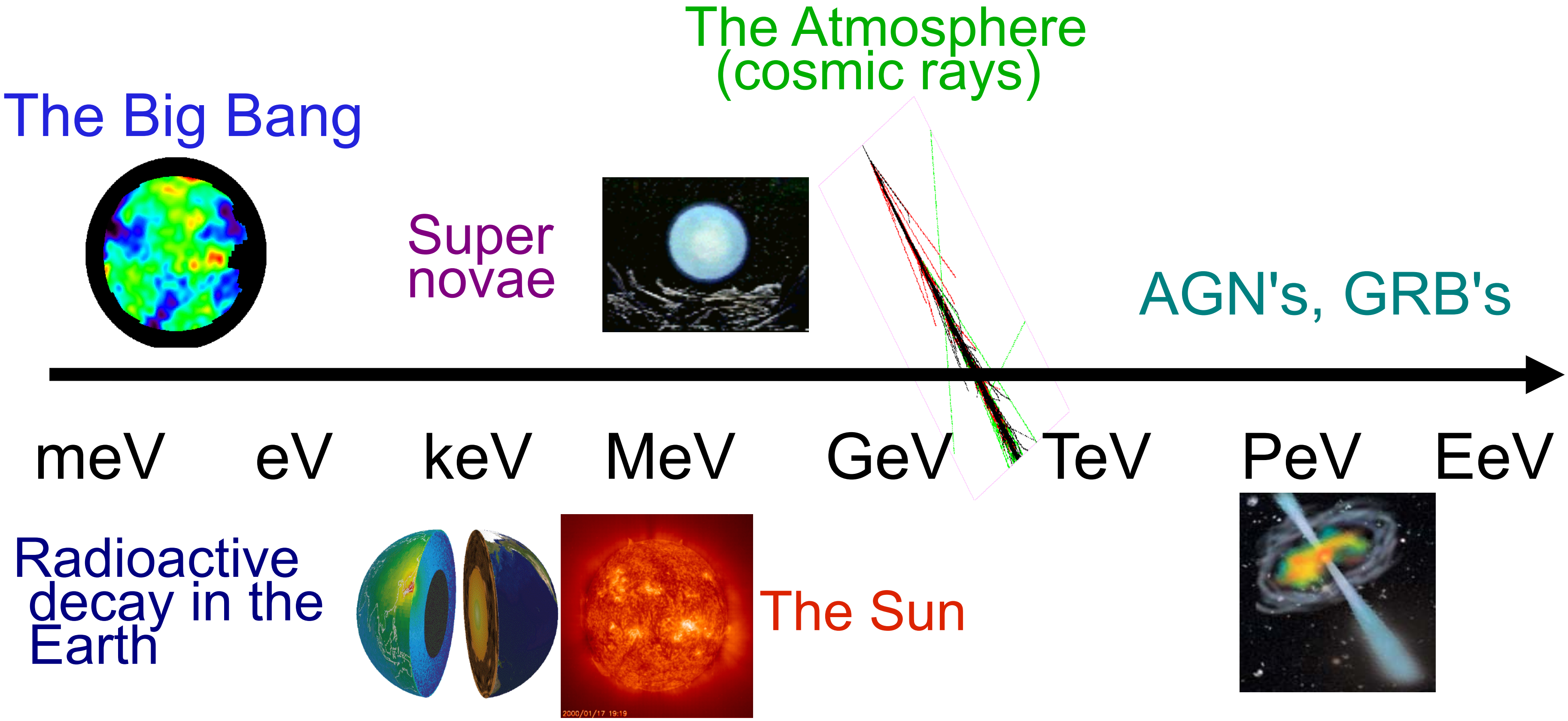


change L/E

allowed region

need experimental statistics

Sources of wild neutrinos



The Atmosphere
(cosmic rays)

The Big Bang

Super
novae

AGN's, GRB's

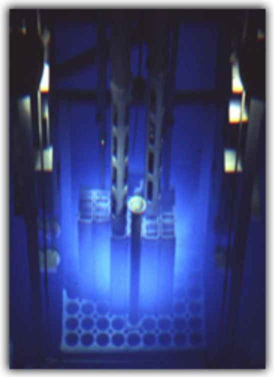
meV eV keV MeV GeV TeV PeV EeV

Radioactive
decay in the
Earth

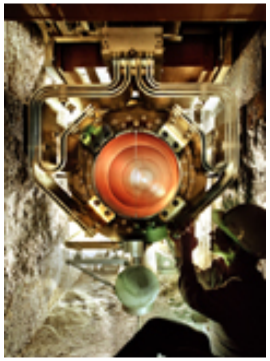
The Sun

Sources of 'tame' neutrinos

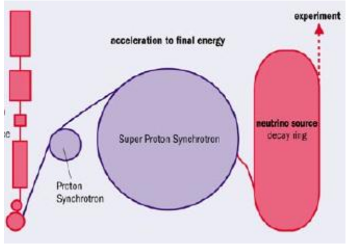
Nuclear reactors



Proton accelerators

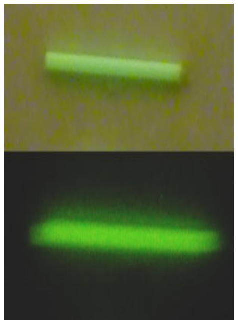


Beta beams

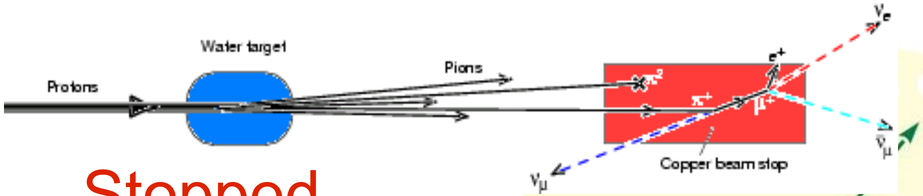


eV keV MeV GeV TeV

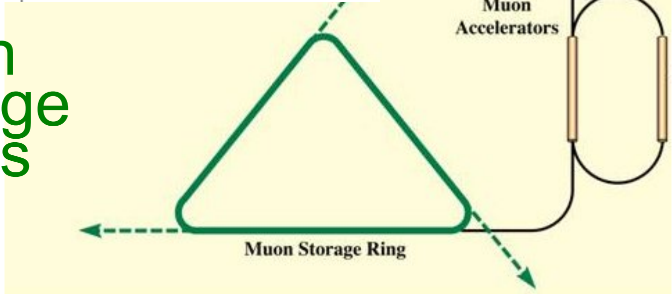
Artificial radioactive sources



Stopped pion sources



Muon storage rings

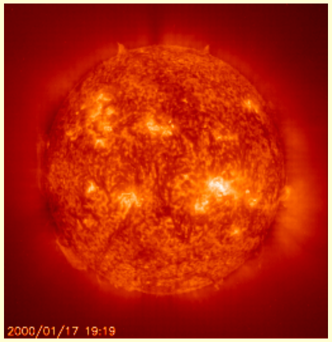


Usually (but not always) better understood...

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...*

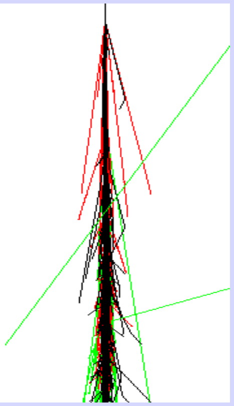
$$\boxed{\nu_e \longrightarrow \nu_\mu, \nu_\tau}$$

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

... now confirmed by a reactor experiment

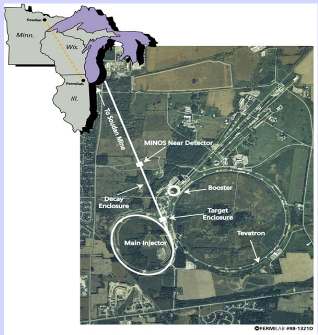
Described by θ_{12}, Δm^2_{12}

ATMOSPHERIC NEUTRINOS



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

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



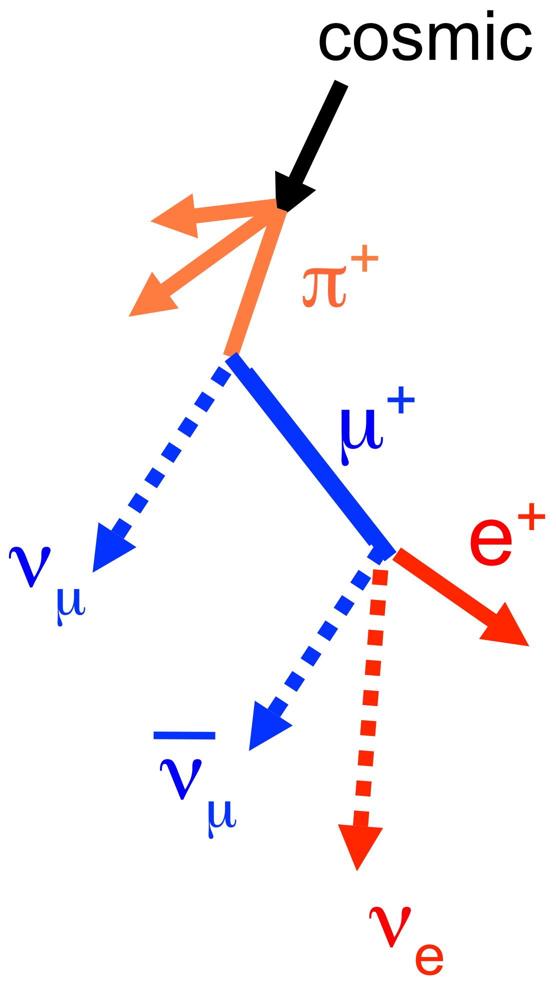
...now confirmed by beam experiments

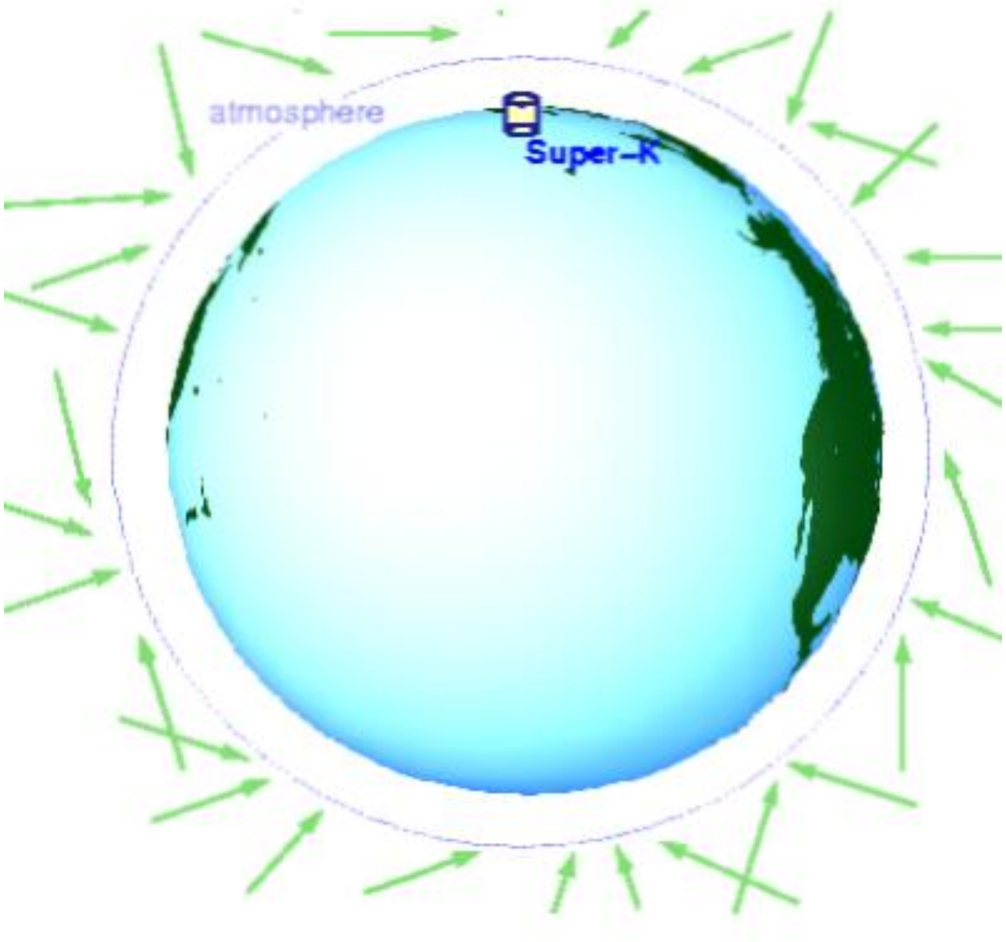
Described by θ_{23}, Δm^2_{23}

Atmospheric Neutrinos

E~ 0.1-100 GeV

L~10-13000 km



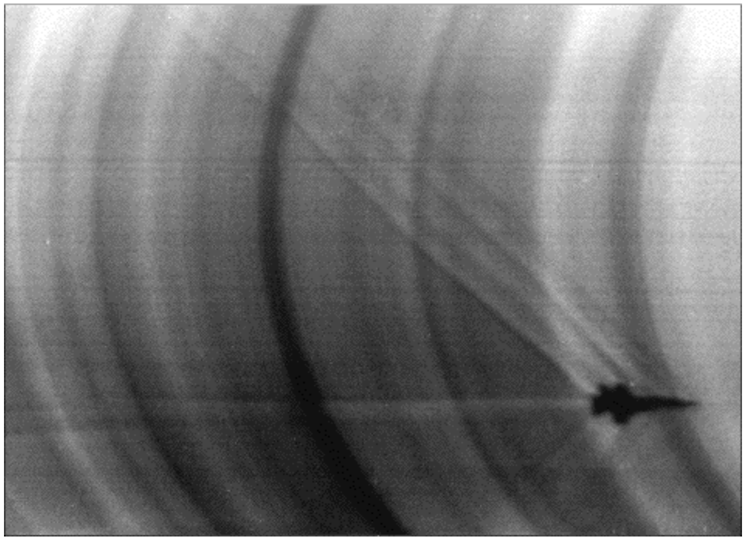


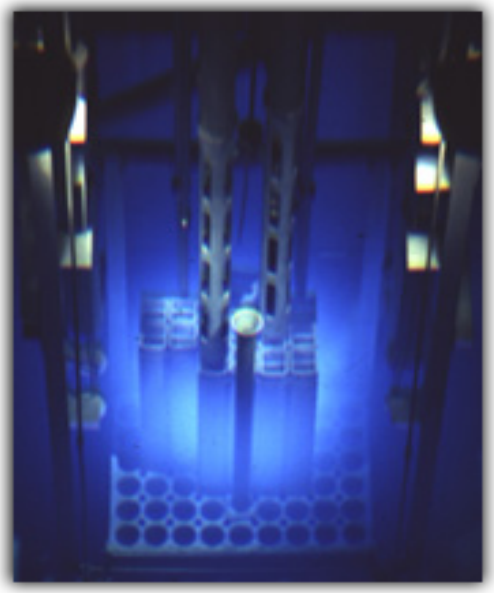
Absolute flux known to ~15%, but ***flavor ratio*** known to ~5%

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)

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

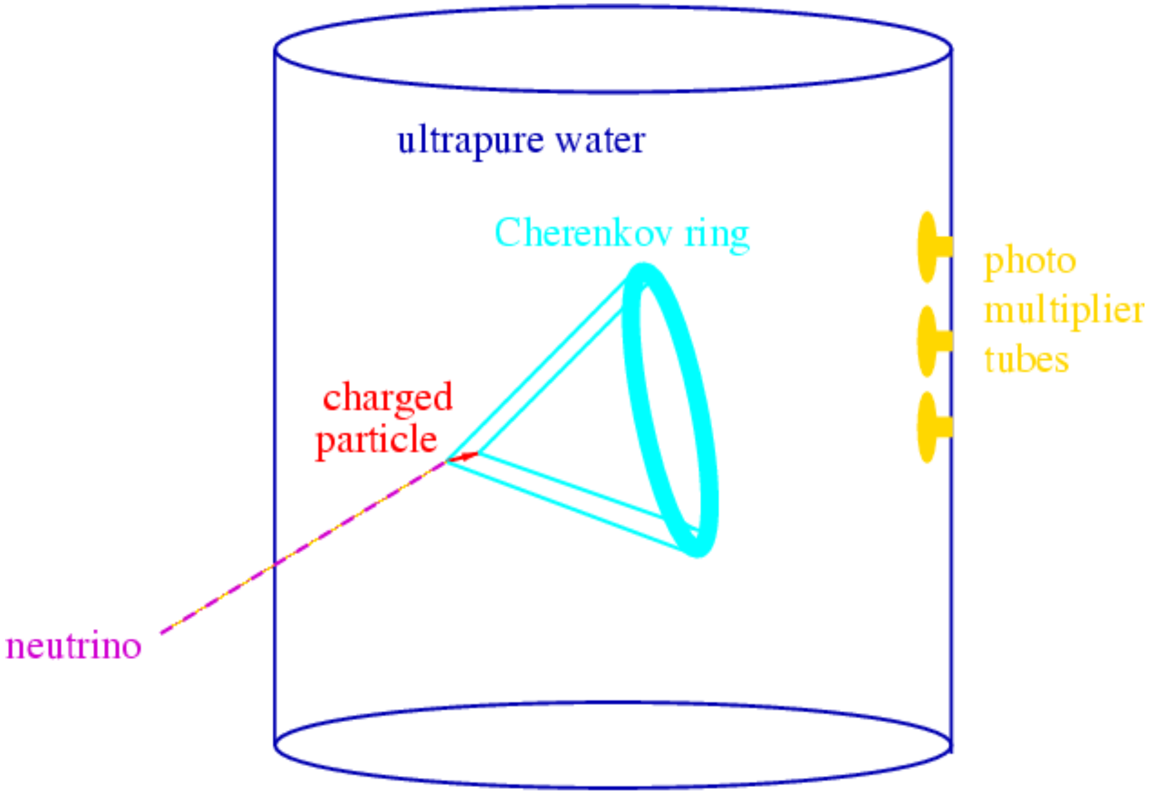
e	0.73
μ	150
π	200
p	1350

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

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

No. of photons $\propto$ energy loss

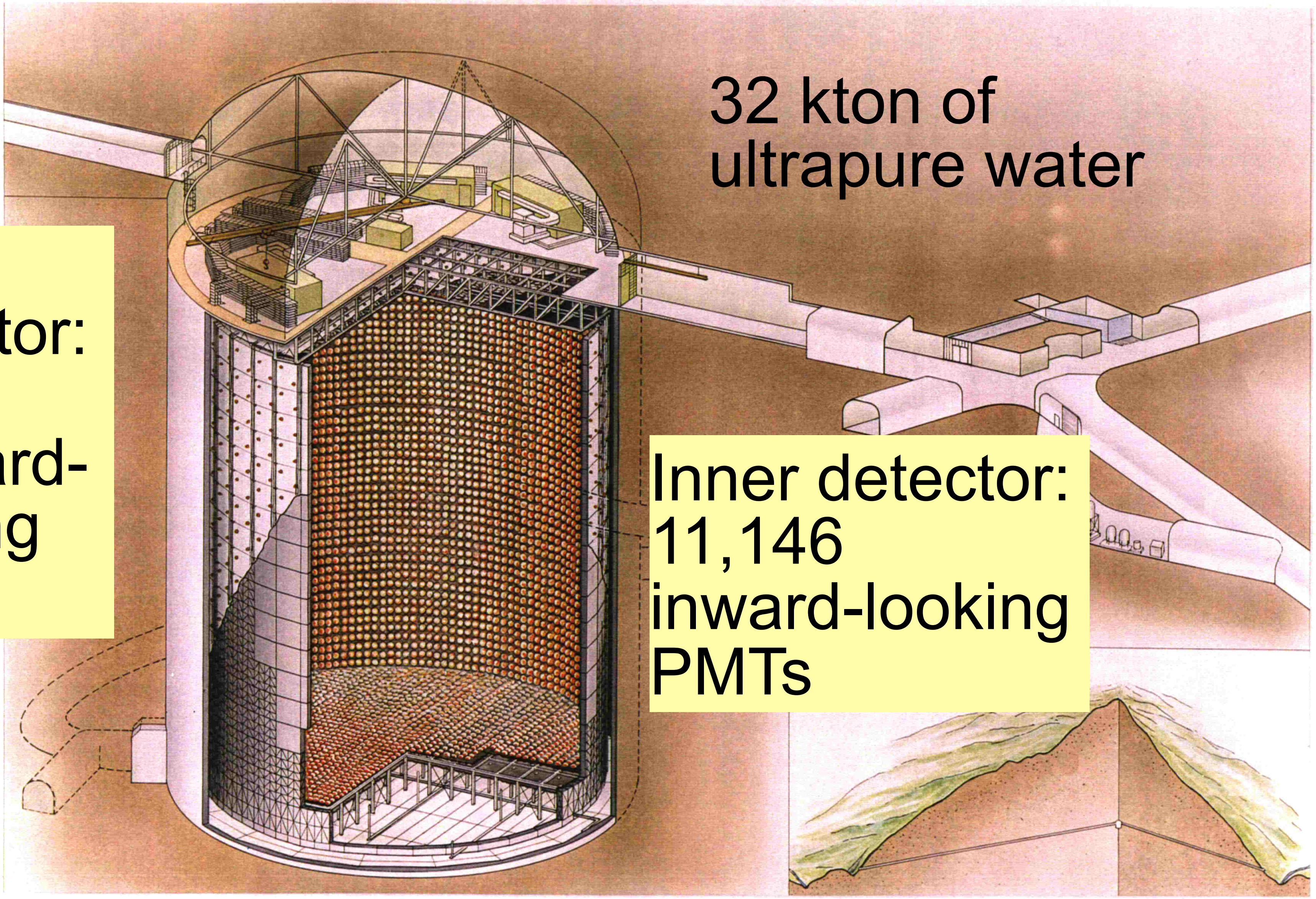
Water Cherenkov ν Detectors



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

Super-Kamiokande

Water Cherenkov detector
in Mozumi, Japan

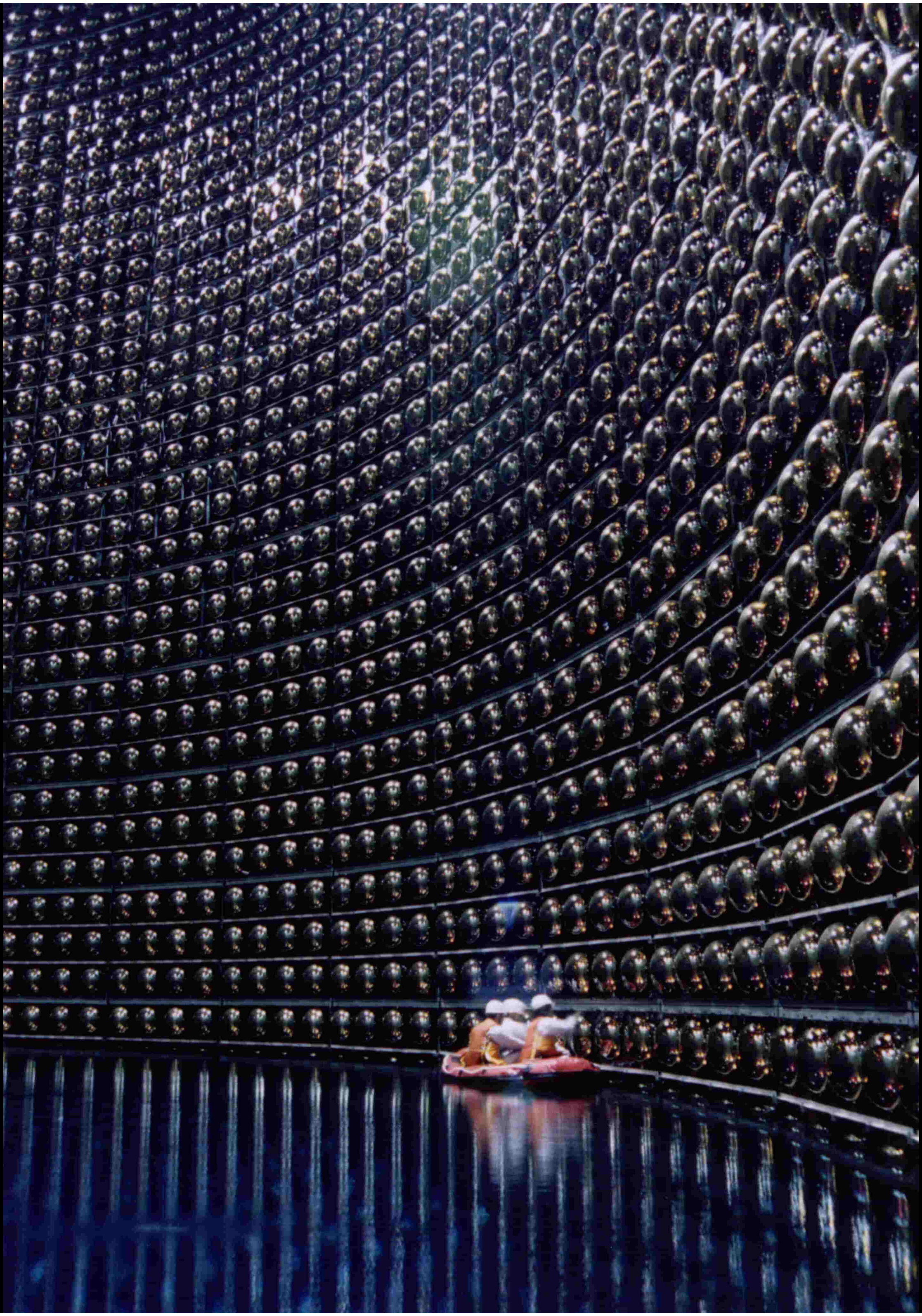


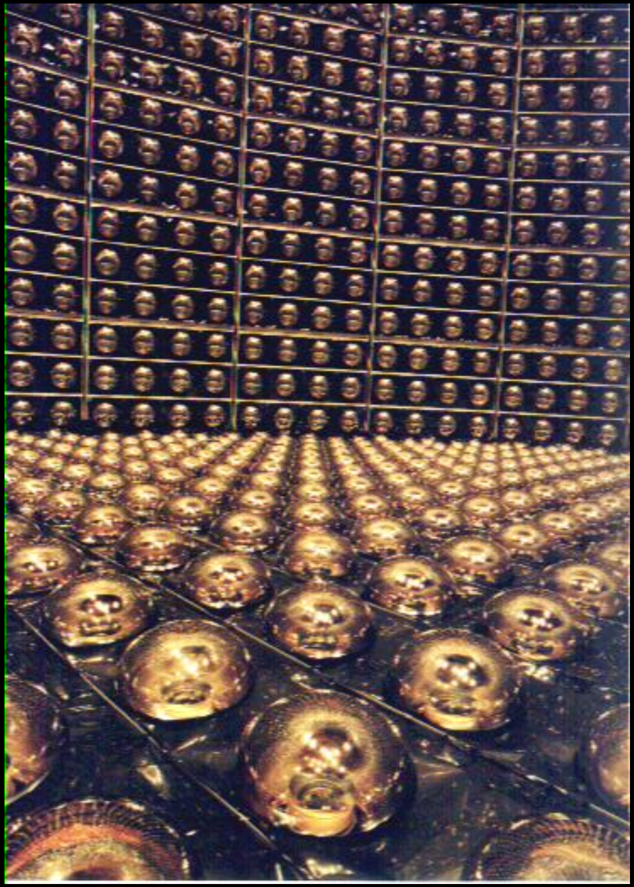
32 kton of ultrapure water

Outer detector: 1889 outward-looking PMTs

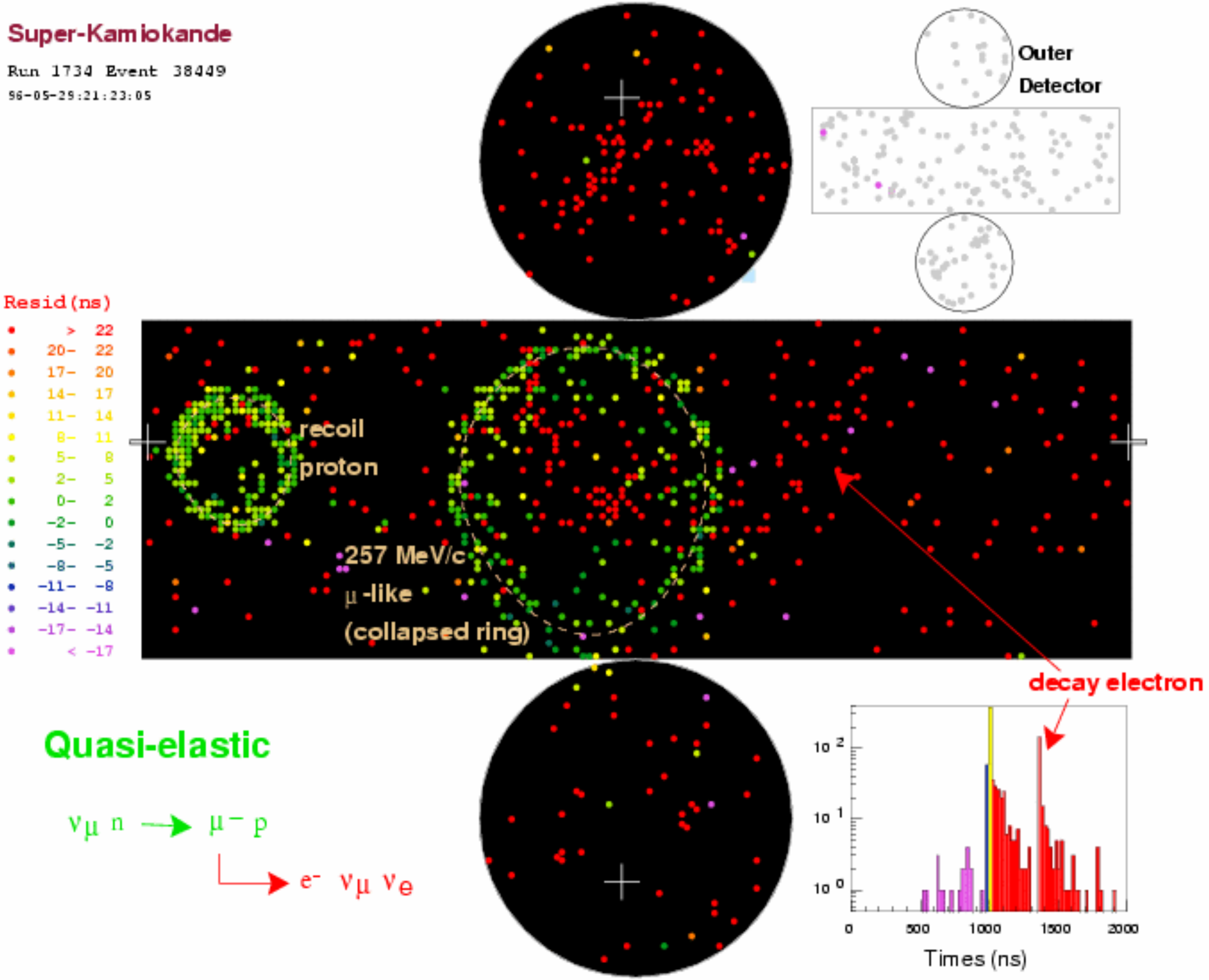
Inner detector: 11,146 inward-looking PMTs

1 km underground to keep away from cosmic rays






DUKE
UNIVERSITY



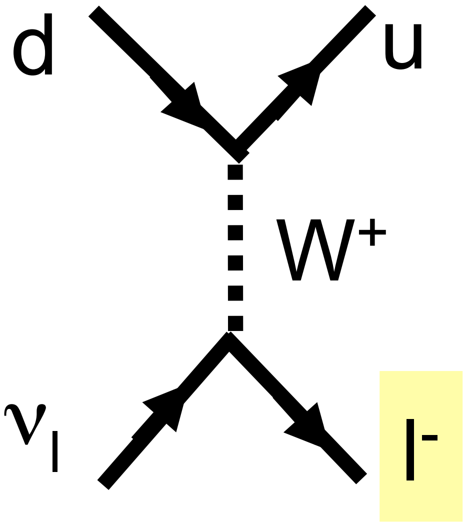
Quasi-elastic

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

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

Atmospheric ν's Experimental Strategy:

High energy interactions of ν's with nucleons



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

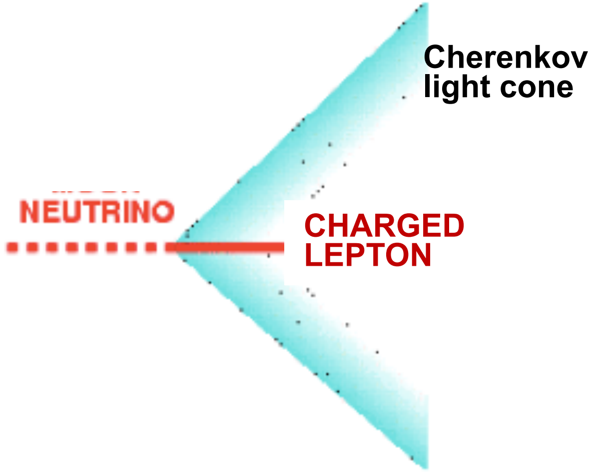
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

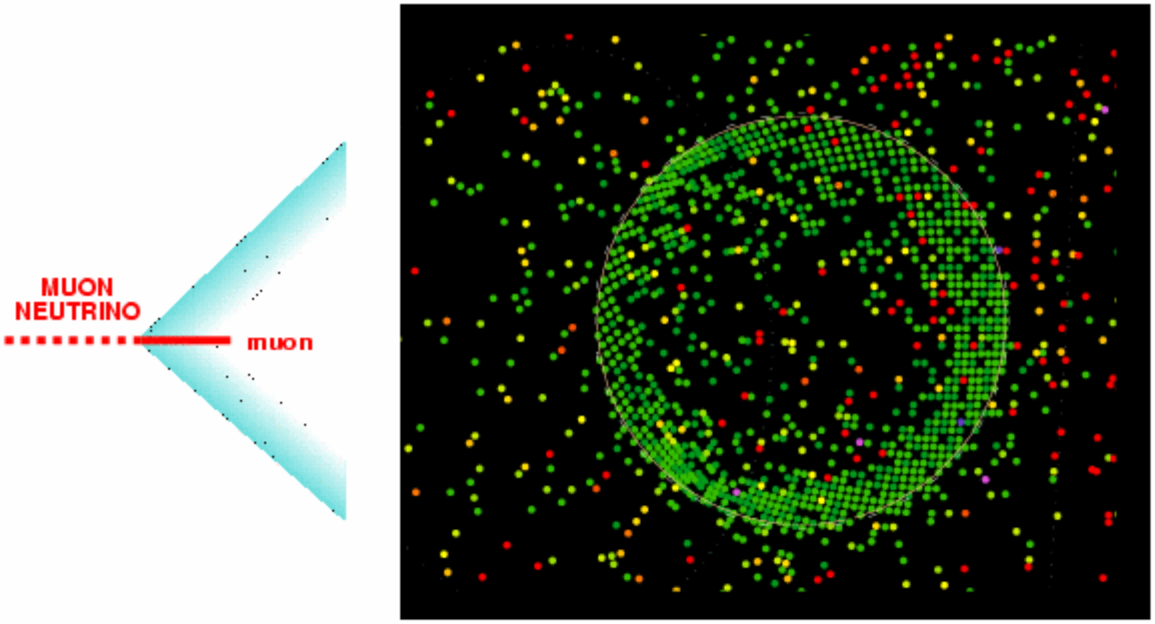
$$\nu_\mu + n \rightarrow \mu^- + p$$

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

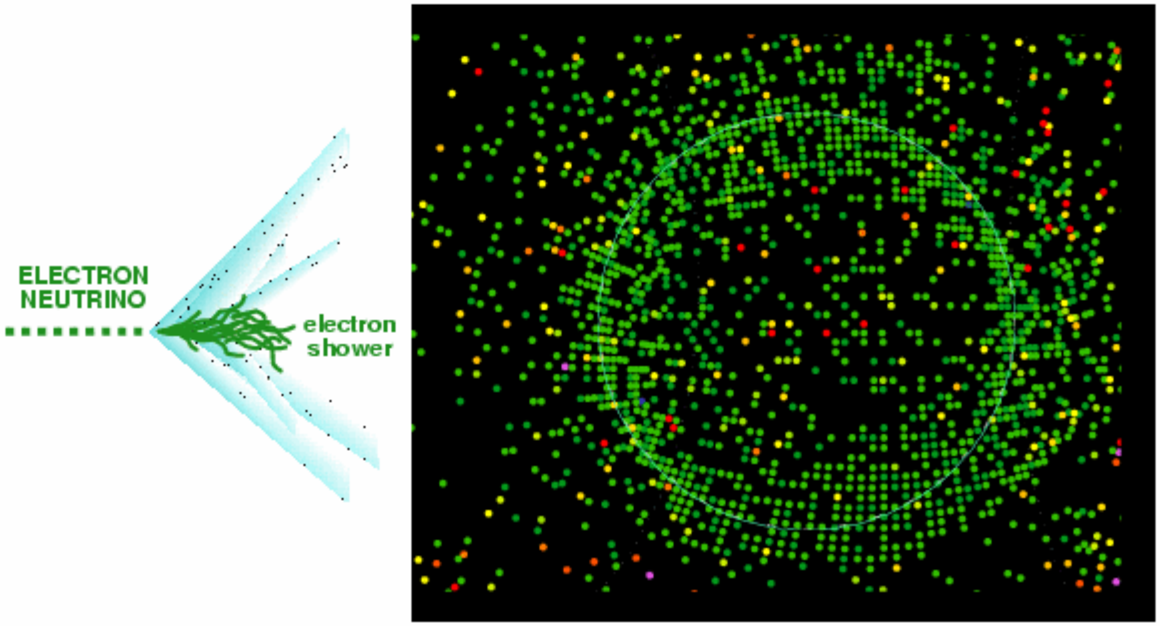
Tag neutrino flavor
by flavor of outgoing lepton

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





Get different patterns in Cherenkov light for e and μ

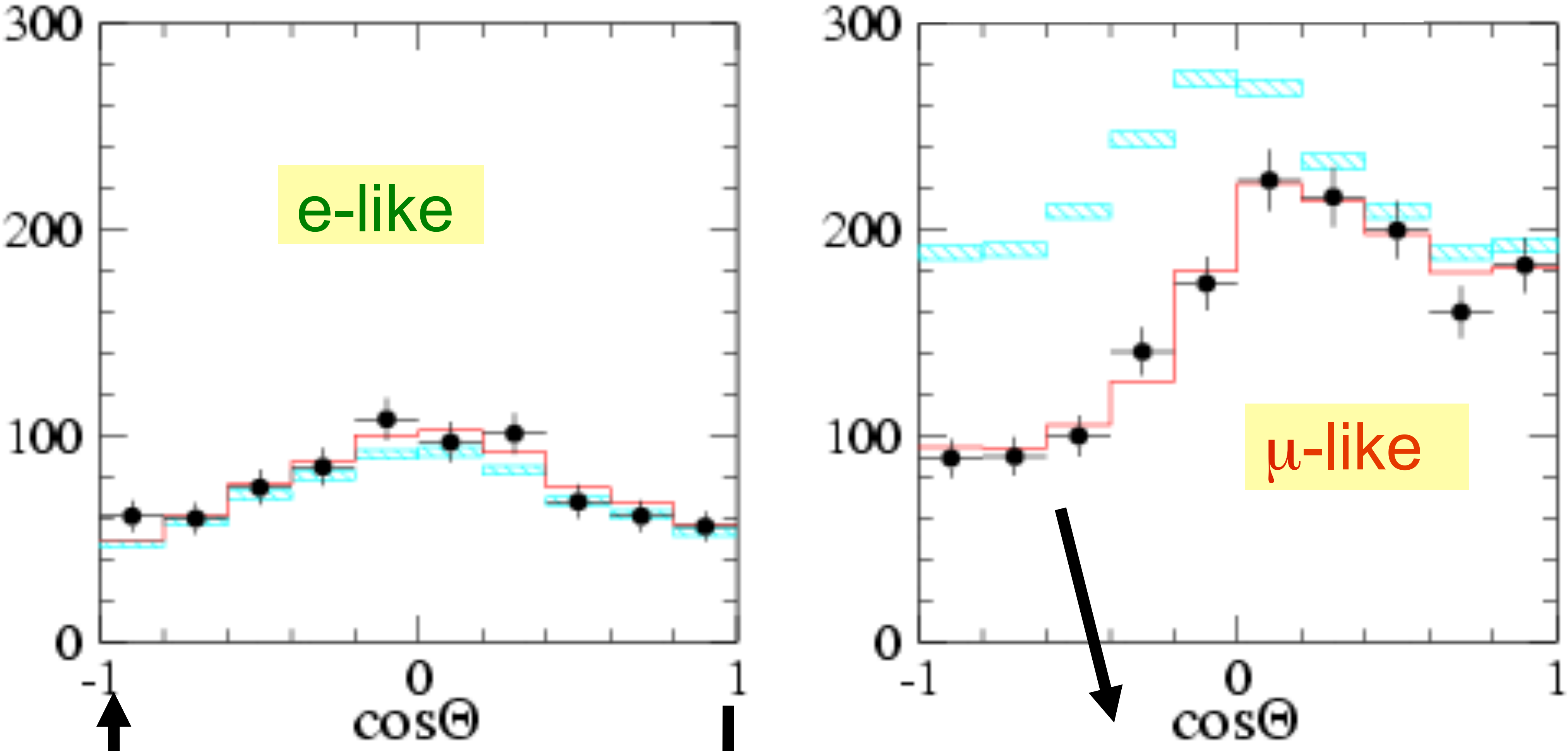


(sim. for other detector types)

From Cherenkov cone get angle, infer pathlength

Zenith angle distribution

1489 days of SK data



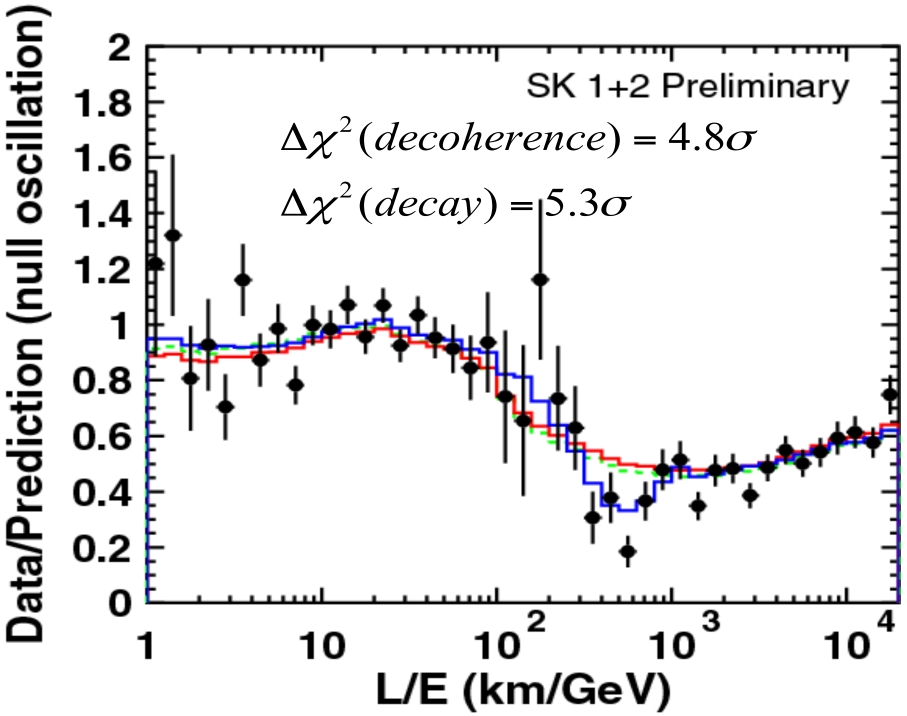
up-going

down-going

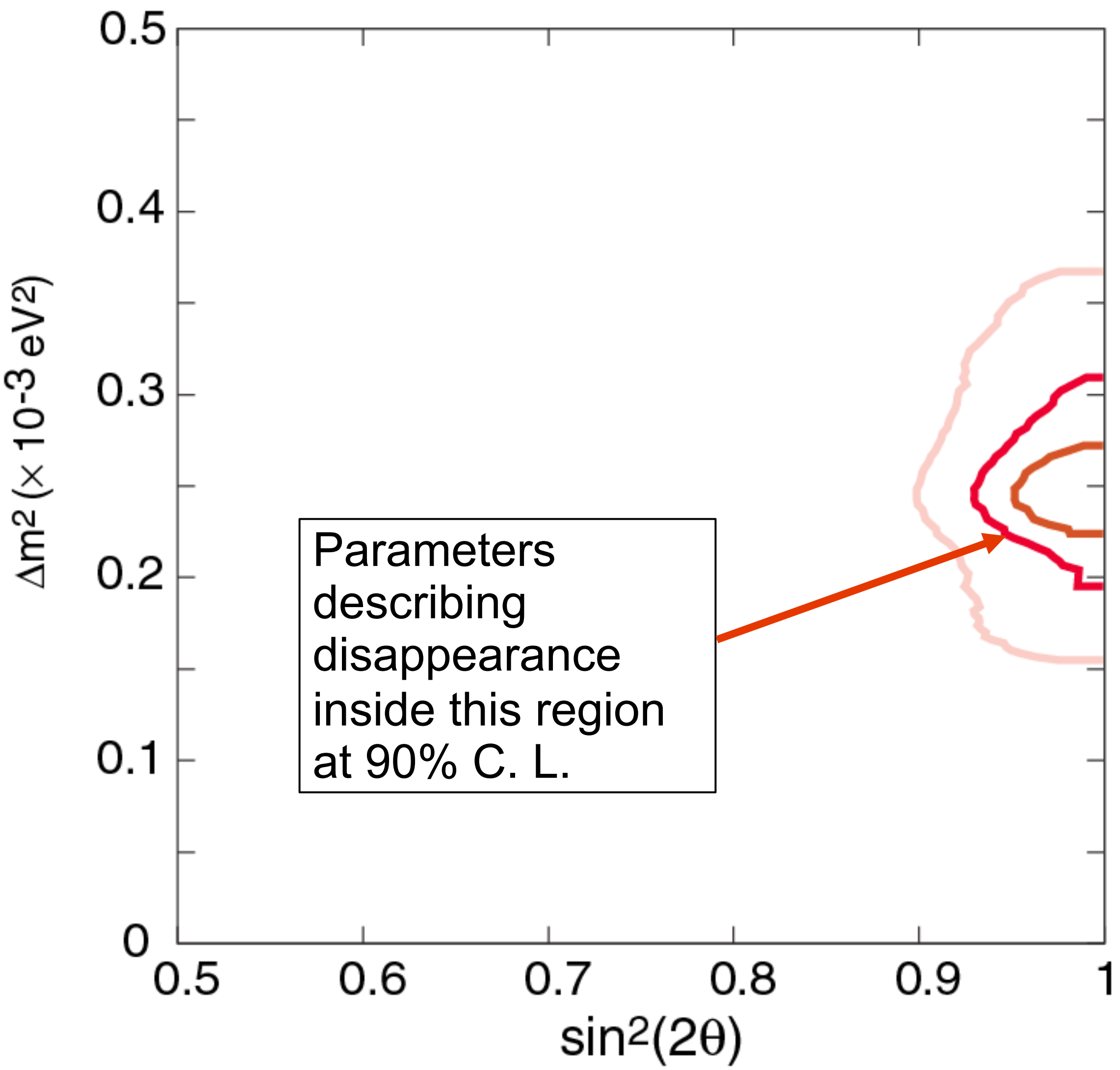
Deficit of ν_μ
from below
(long pathlength)

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

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

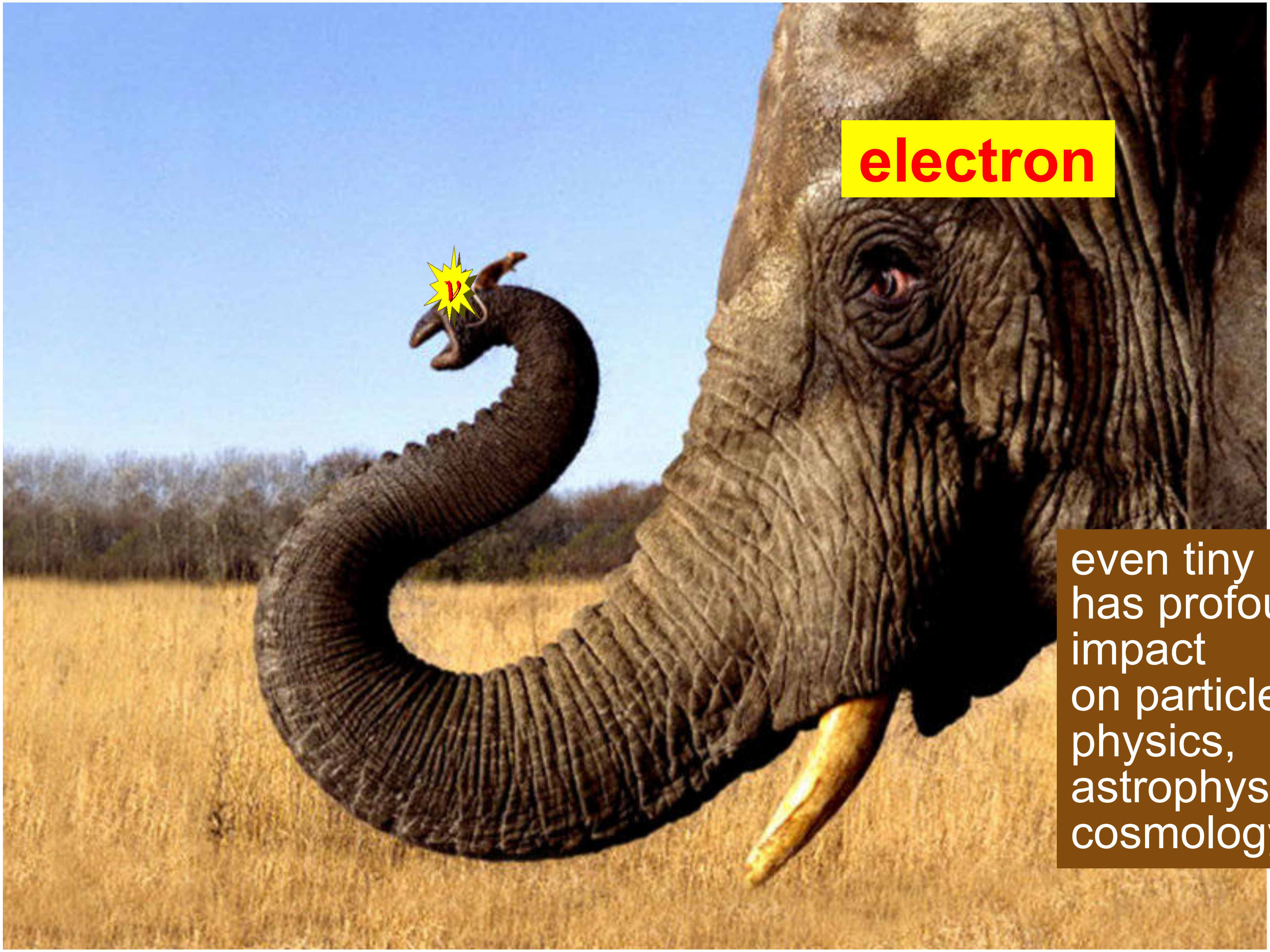


Disappearance consistent with $\nu_\mu \to \nu_\tau$



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

$\Delta m^2 \sim 2.5 \times 10^{-4}\ \mathrm{eV}^2 \Rightarrow$ at least one neutrino state has mass of at least 0.2 eV

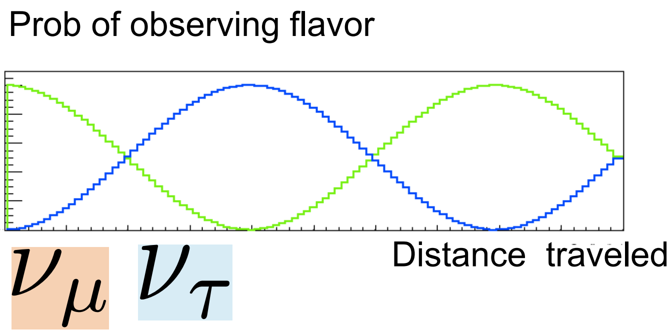


even tiny mass has profound impact on particle physics, astrophysics, cosmology

But there's more!

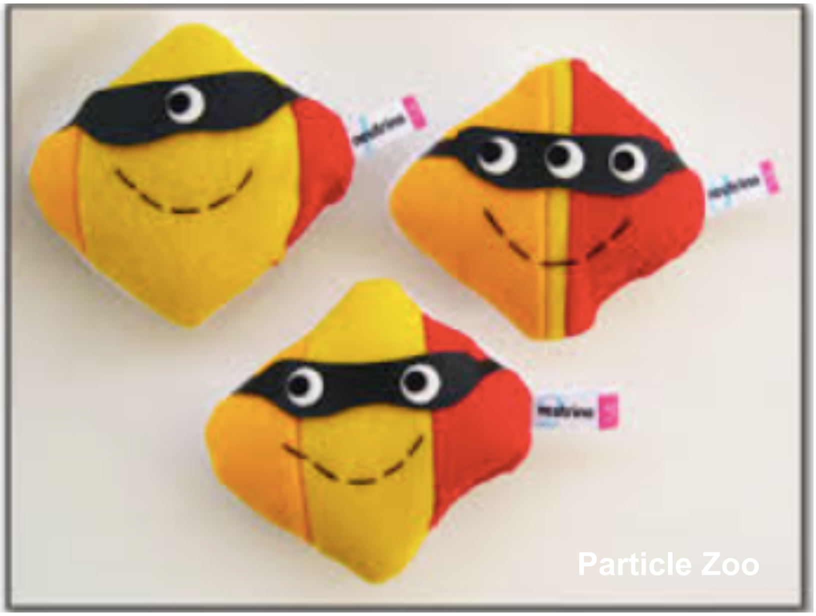
So far have been talking about oscillations of *two* flavors of neutrinos, which describes atmospheric neutrinos well

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$



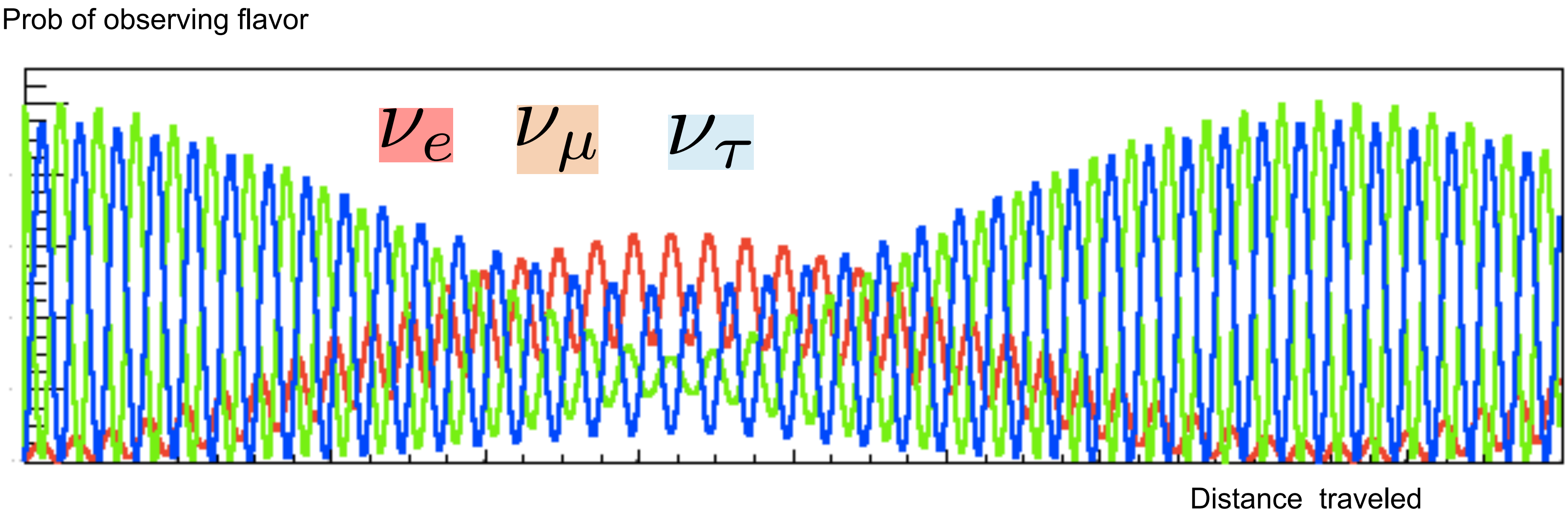
But in fact there are ***three*** flavors, and three mass states

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



Neutrino flavors and masses are mixed and **all three interfere...**

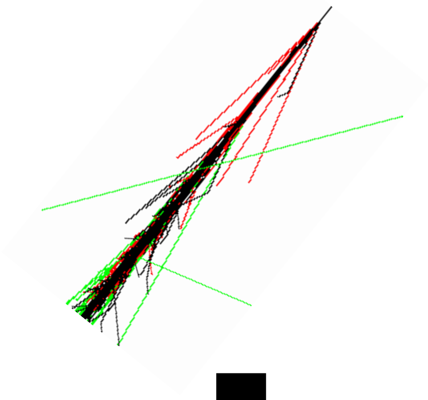
With three flavors,
get more complicated wiggles,
of superposed short and
long wavelengths:



Governed by three “mixing angle” parameters, θ_{12}, θ_{13}, θ_{23}
and mass differences

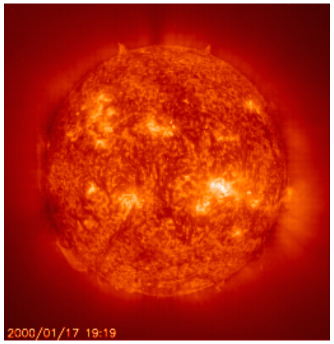
In the past ~15 years, we've been teasing out the hums of 3 neutrinos

atmospheric



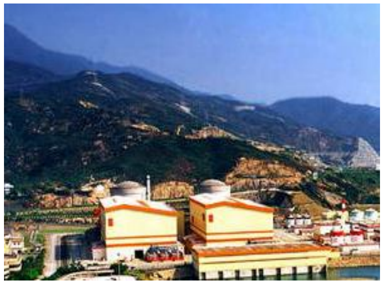
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

solar



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

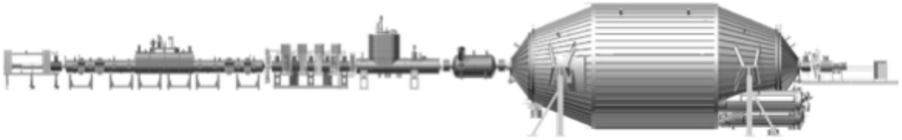
beams

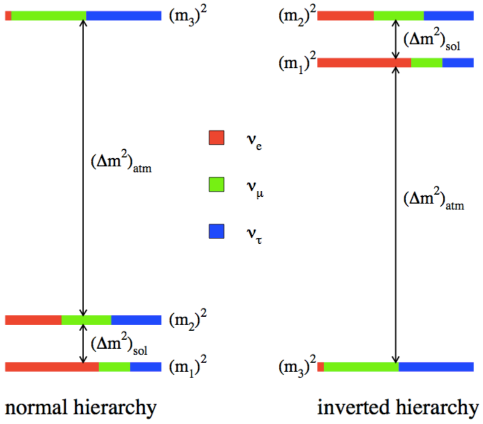


reactor

And there are more questions, and experiments to address them:

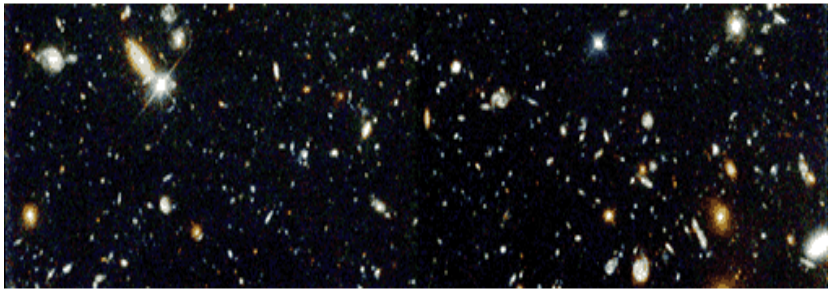
What is the absolute mass scale of the neutrino?

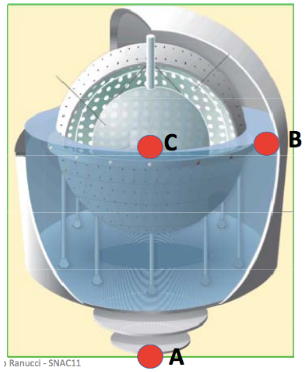




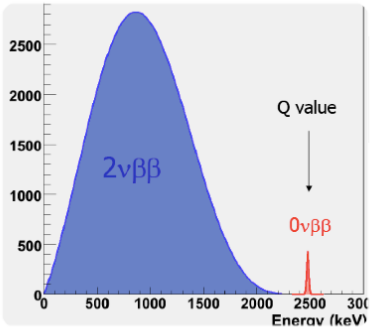
What is the mass pattern?

Do neutrinos violate CP symmetry? Will this help us understand the matter-antimatter asymmetry?



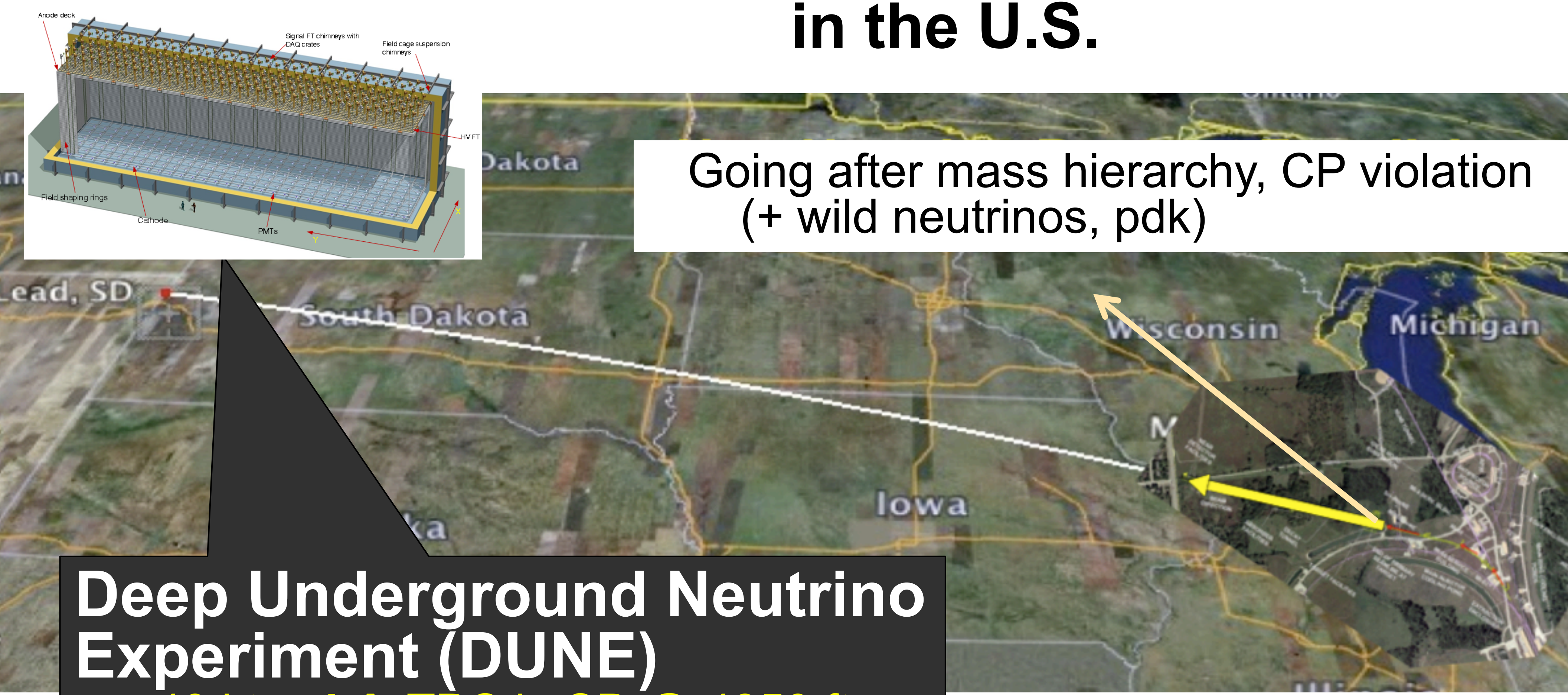


Are there new neutrino states?



Are neutrinos their own antiparticles?

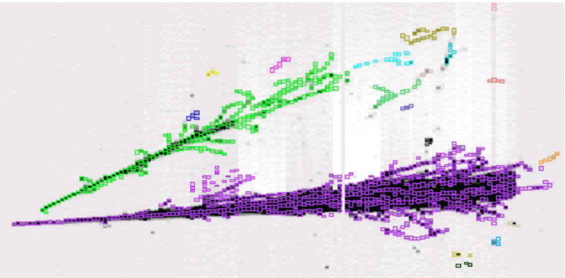
Next-generation long-baseline experiment in the U.S.



Going after mass hierarchy, CP violation
(+ wild neutrinos, pdk)

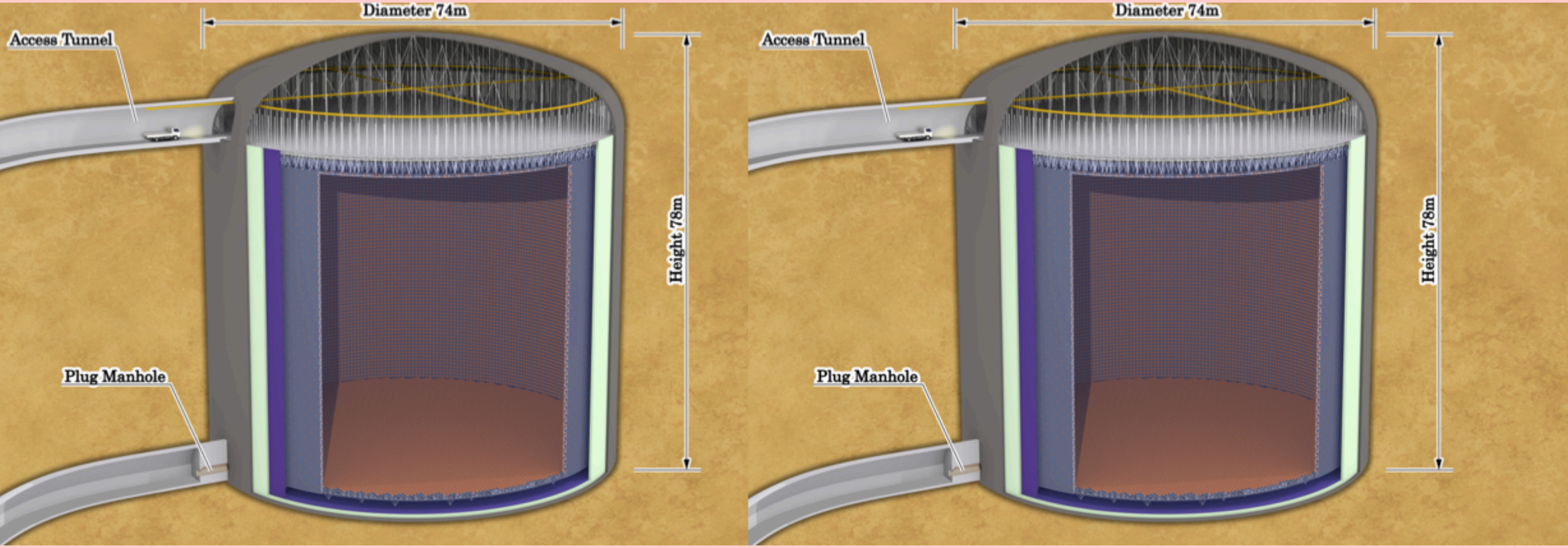
Deep Underground Neutrino Experiment (DUNE)

40 kton **LArTPC** in SD @ 4850 ft
1300 km baseline
New 1.2 MW beam



strength is precision
event reconstruction

Hyper-Kamiokande



379 kton fiducial volume in 2 tanks

Beam from J-PARC 295 km away

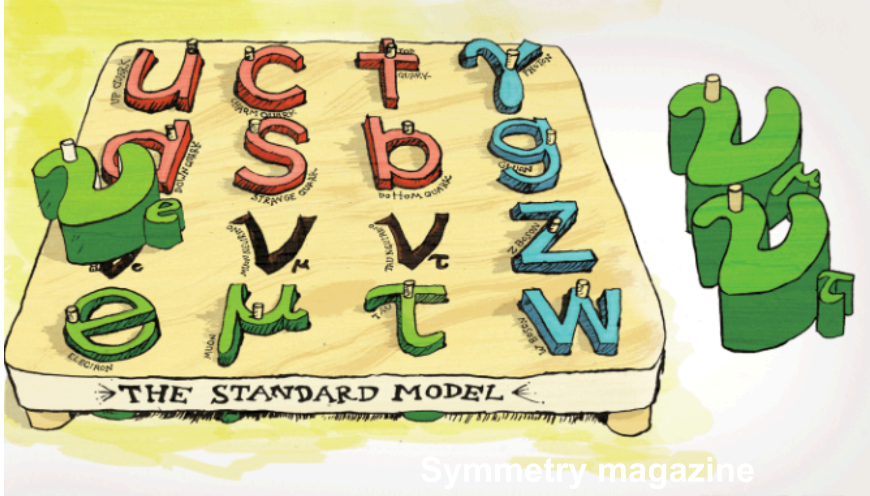
CP violation, atmospheric neutrinos,
supernova neutrinos, proton decay,..

The past two decades have filled in in the three-flavor picture...

But still unknowns! mass pattern, CP violation...

More to ν physics than oscillations... are neutrinos and antineutrinos really the same particle?
What is the absolute mass scale?

And how does it all fit in??
beyond the Standard Model,
matter-antimatter asymmetry,
cosmology....
(neutrinos are weird!
why so light?)



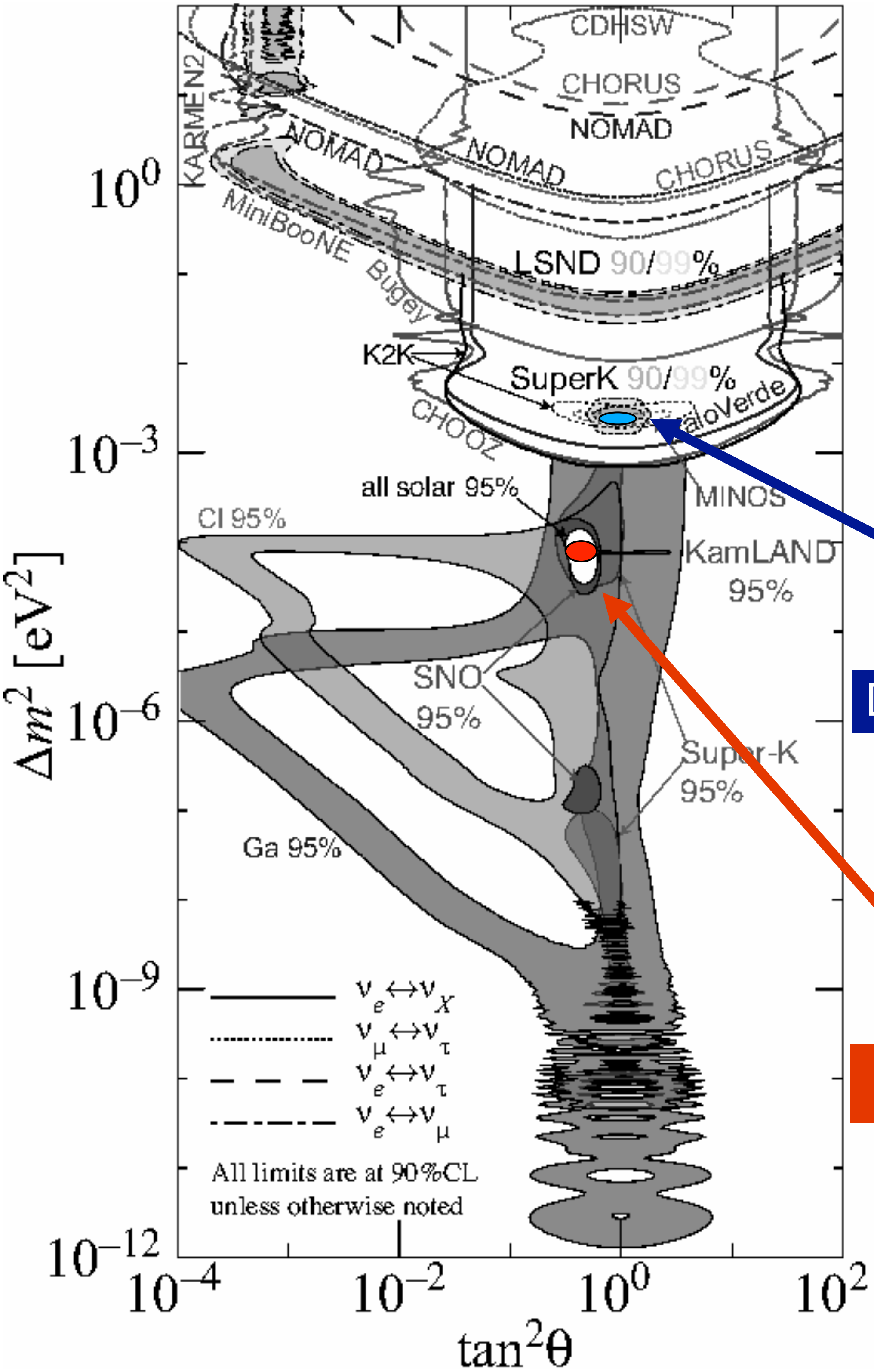
Symmetry magazine

Still many interesting years lie ahead!

On top of the Super-K tank in 1999

Extras/Backups

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



atmospheric/ beam neutrinos

Described by θ_{23}, Δm^2_{23}

solar/reactor neutrinos

Described by θ_{12}, Δm^2_{12}

But there's more!

In the standard picture, we have *three* flavors

$$|\nu_f\rangle = \sum_{i=1}^{3} U^*_{fi} |\nu_i\rangle$$

Parameterize mixing matrix U as:

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

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

So where do we stand in the three-flavor picture?

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

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

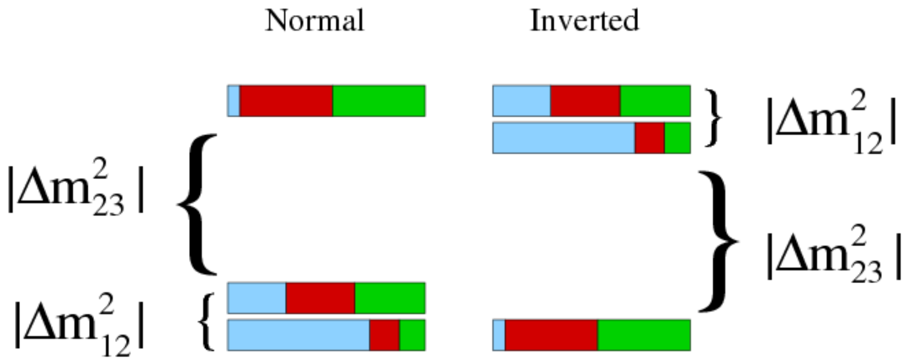
$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

Parameters of Nature

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



Oscillation probability can be computed straightforwardly:

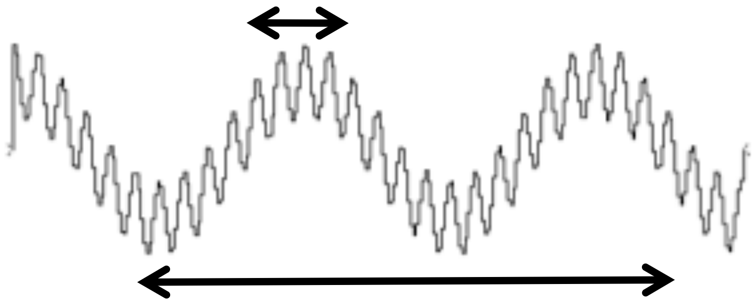
$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \qquad (\mathrm{L\ in\ km,\ \ E\ in\ GeV,\ \ m\ in\ eV})$$

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

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

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

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

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)

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

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

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

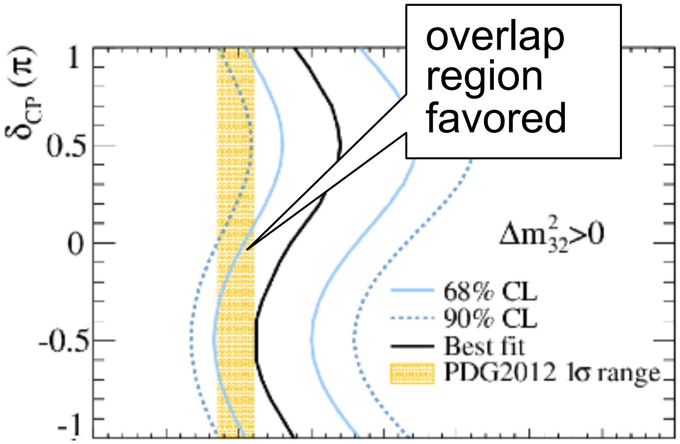
Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

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

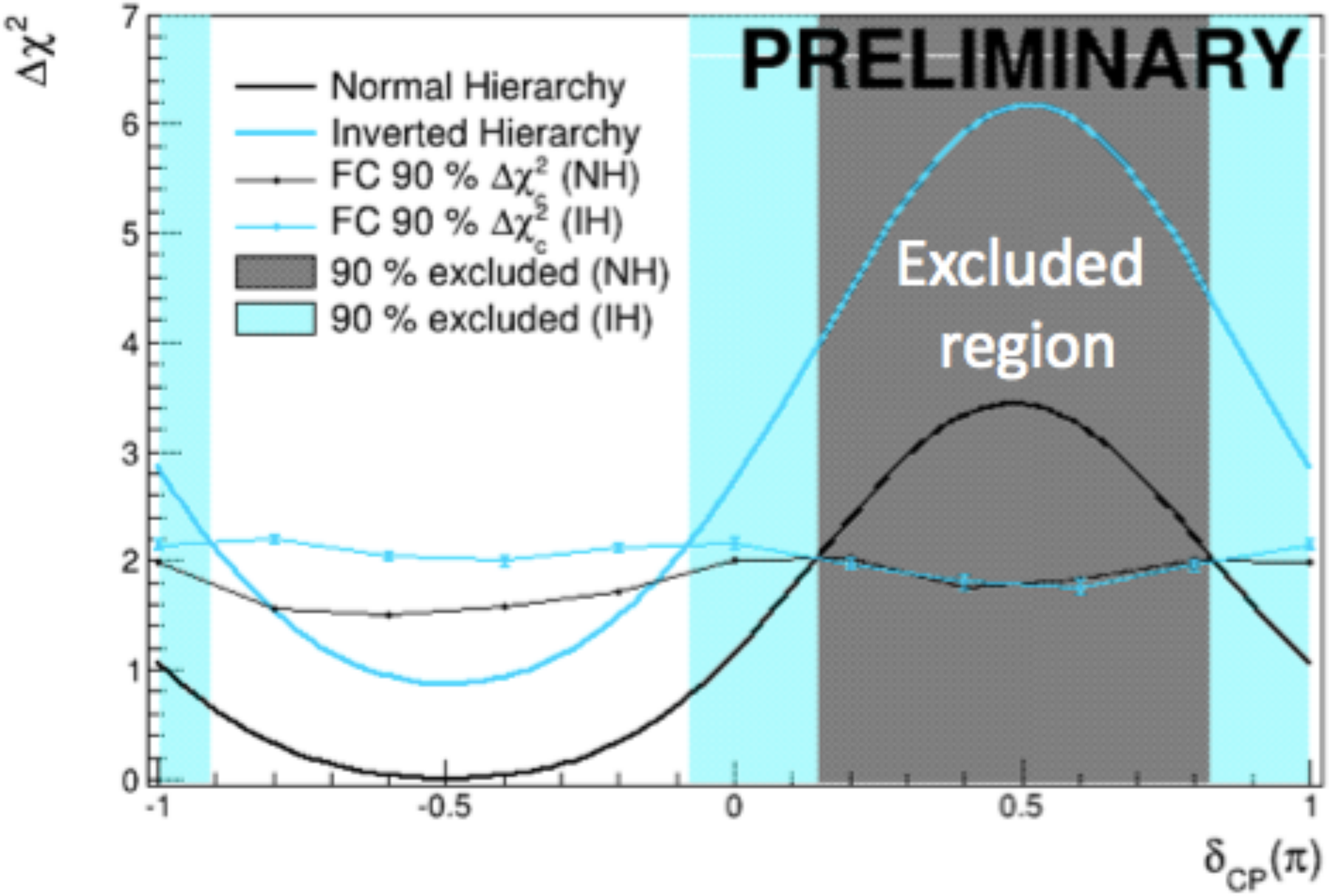
A first hint from T2K

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



Mild preference for $\delta \sim -\pi/2$