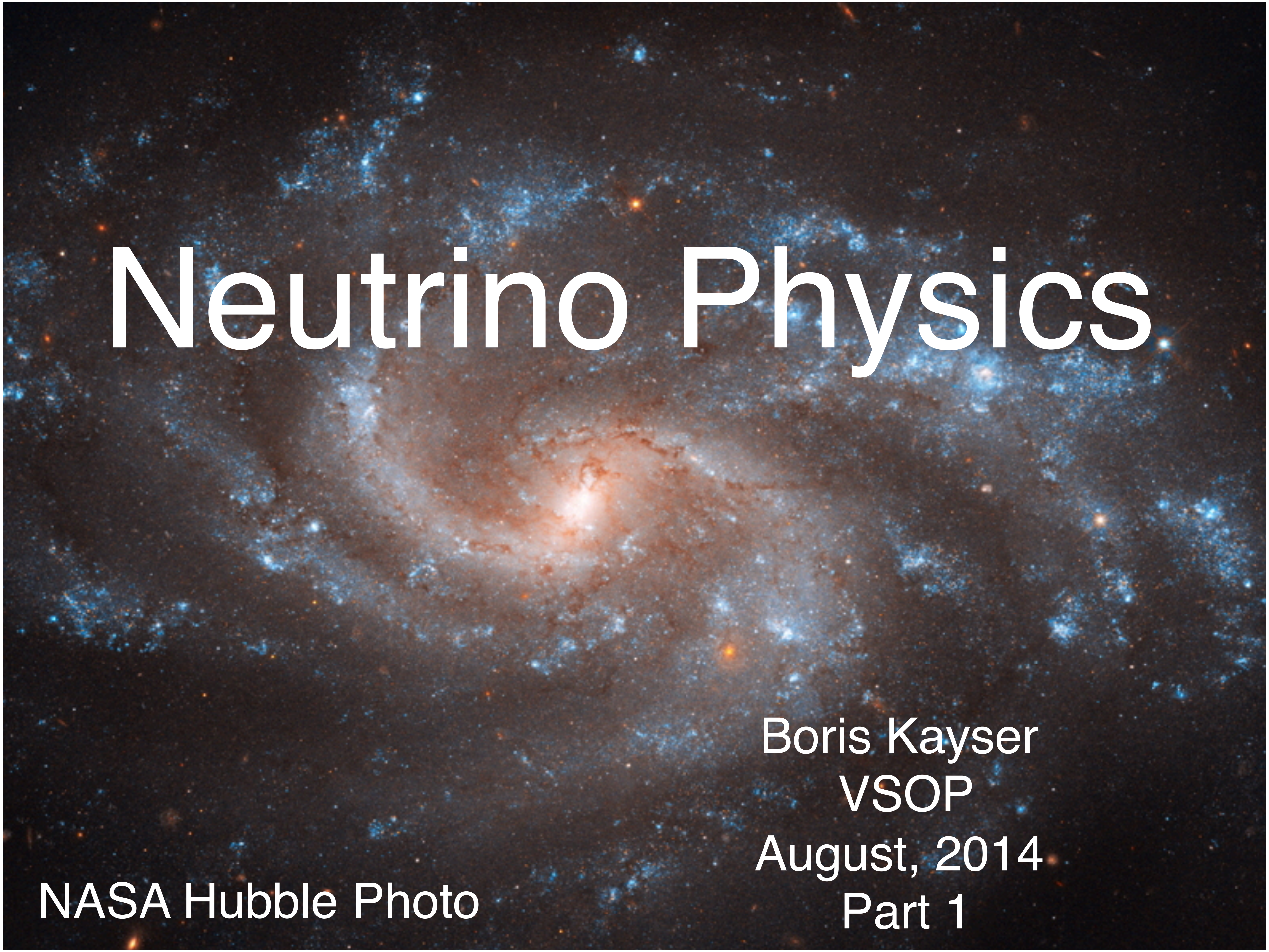


Neutrino Physics

Boris Kayser
VSOP
August, 2014
Part 1

NASA Hubble Photo

What Are Neutrinos Good For?

Energy generation in the sun starts with the reaction —

$$p + p \rightarrow d + e^{+} + \nu$$

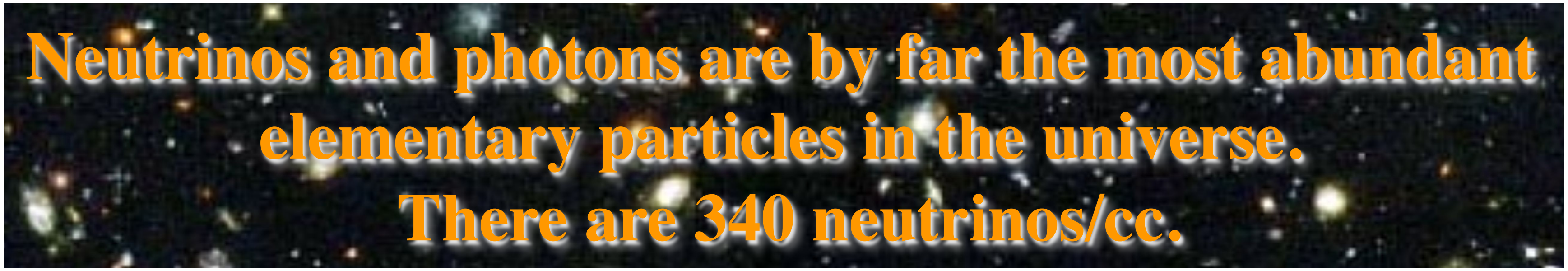
Spin: $\frac{1}{2}$ $\frac{1}{2}$ 1 $\frac{1}{2}$ $\frac{1}{2}$

Without the neutrino, angular momentum would not be conserved.

Uh, oh ……

We would not be here!

The Neutrinos



Neutrinos and photons are by far the most abundant elementary particles in the universe.
There are 340 neutrinos/cc.

The neutrinos are spin – 1/2, electrically neutral, leptons.

The only known forces they experience are the weak force and gravity.

This means that their interactions with other matter have very low strength.
Thus, neutrinos are difficult to detect and study.

Their weak interactions are successfully described by the Standard Model.

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!

The Origin of Neutrino Mass

The fundamental constituents of matter
are the ***quarks***, the ***charged leptons***,
and the ***neutrinos***.

Most theorists strongly suspect that the origin of the neutrino masses is different from the origin of the quark and charged lepton masses.

The Standard-Model ***Higgs*** may still be involved,
but not in the same way
as for the quarks and charged leptons.

More later ……….

The discovery of neutrino mass
and leptonic mixing
comes from the observation of
neutrino flavor change
(neutrino oscillation).

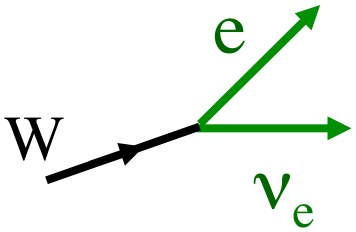
Introduction to Neutrino Oscillation

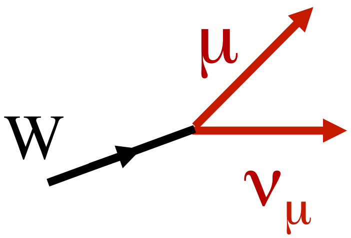
The Neutrino Flavors

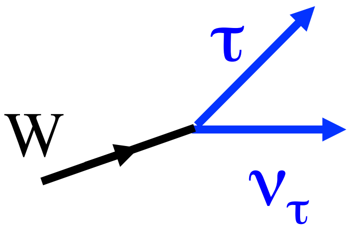
There are three flavors of charged leptons: e , μ , τ

There are three known flavors of neutrinos: ν_e, ν_μ, ν_τ

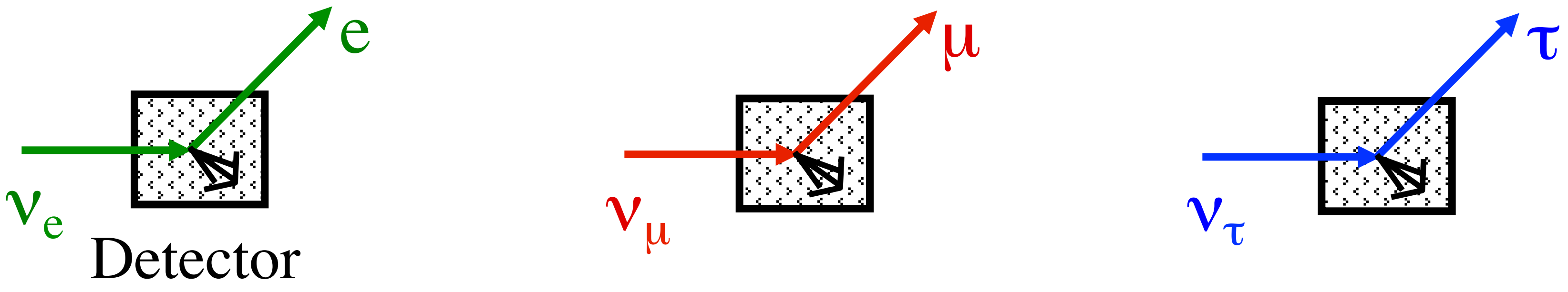
We ***define*** the neutrinos of specific flavor, ν_e, ν_μ, ν_τ, by W boson decays:



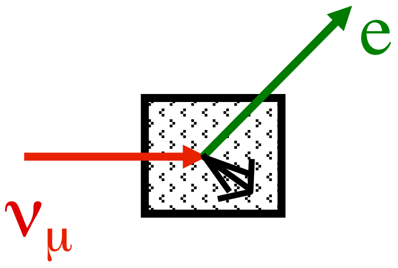




As far as we know, when a neutrino of given flavor interacts and turns into a charged lepton, that charged lepton will always be of the same flavor as the neutrino.



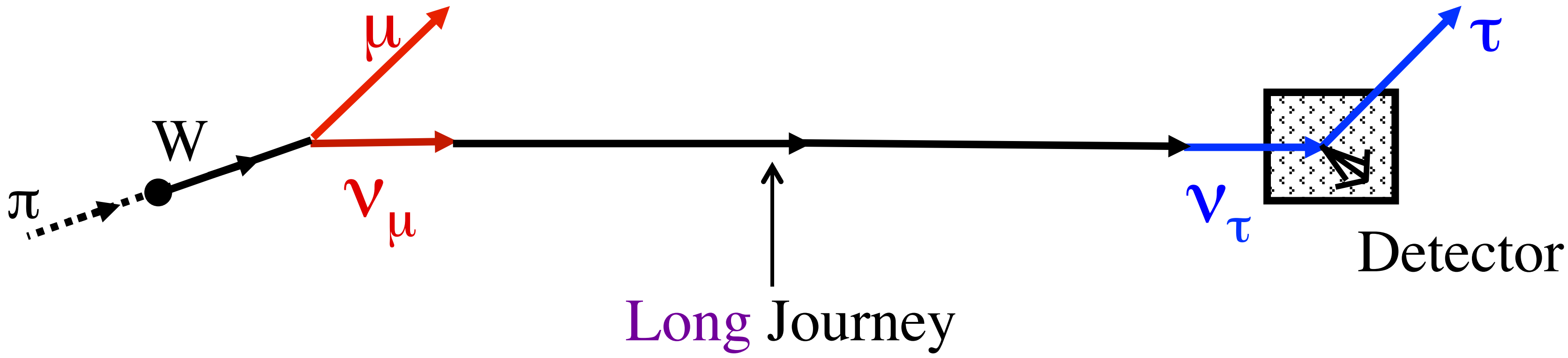
but not



Lederman
Schartz
Steinberger

Neutrino Flavor Change ("Oscillation")

If neutrinos have masses, and leptons mix, we can have —



Give a ν time to change character, and you can have

for example: $\nu_\mu \longrightarrow \nu_\tau$

The last 16 years have brought us compelling evidence that such flavor changes actually occur.

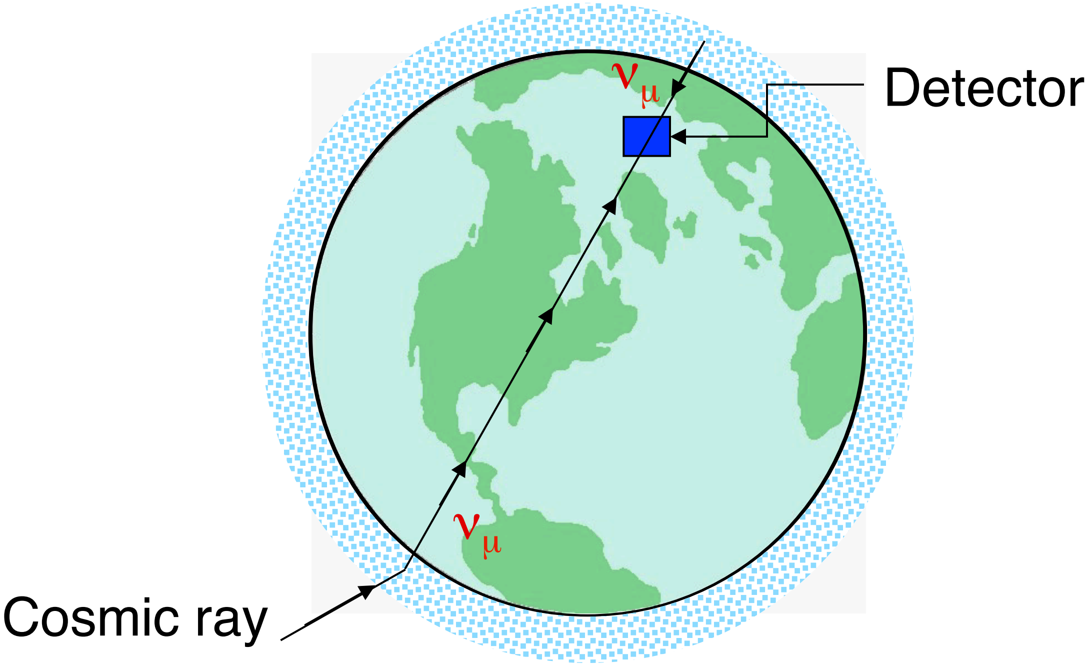
Flavor ***change*** does not add neutrinos to a beam — it just changes the flavor of those already present.

If some of the neutrinos in a beam born as ν_μ are turning into ν_τ, there must be fewer ν_μ left in the beam.

Disappearance of some of the old flavor

→ ***Appearance*** of some of the new flavor

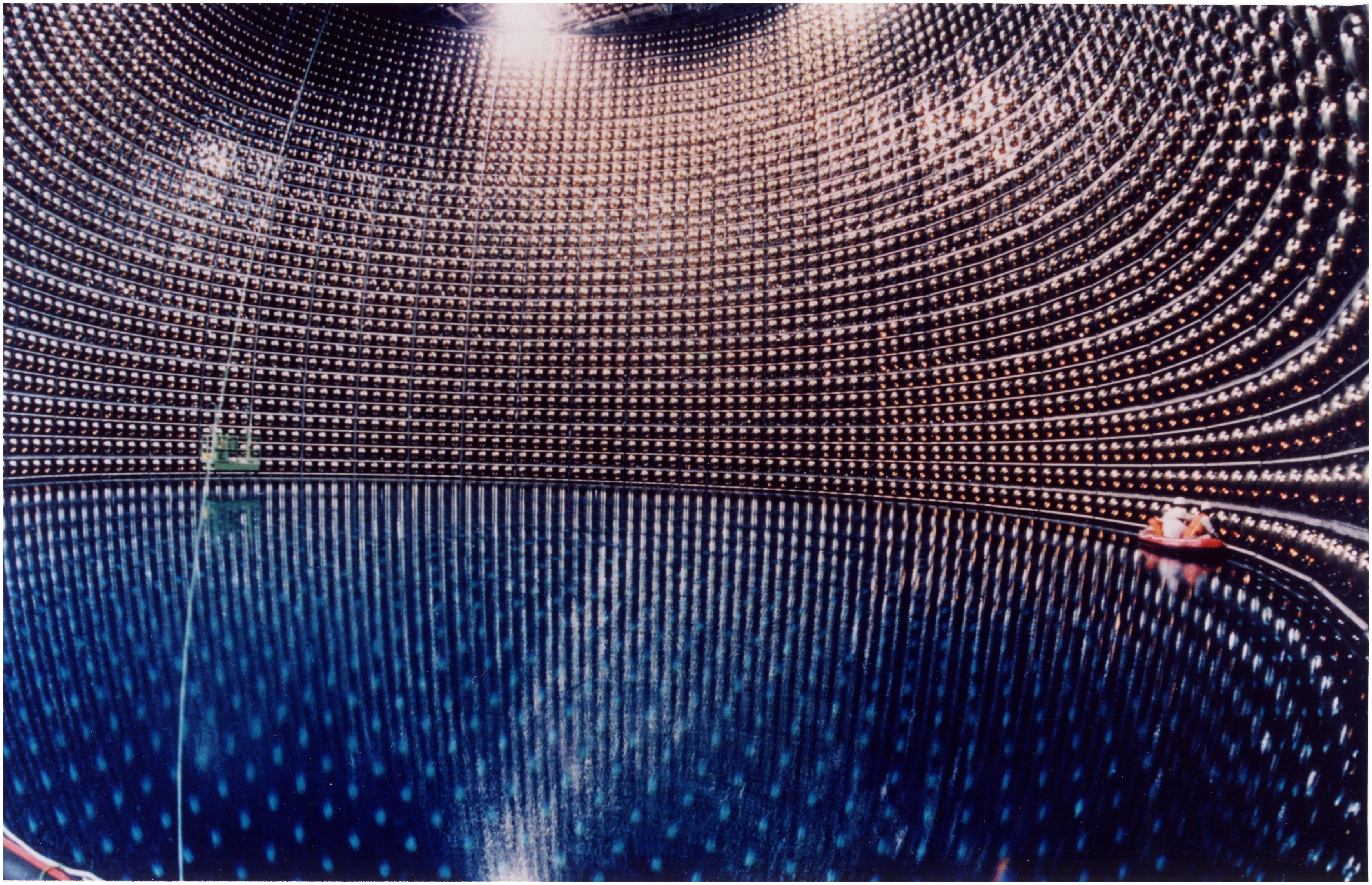
— Atmospheric Neutrinos —
The First Compelling Evidence



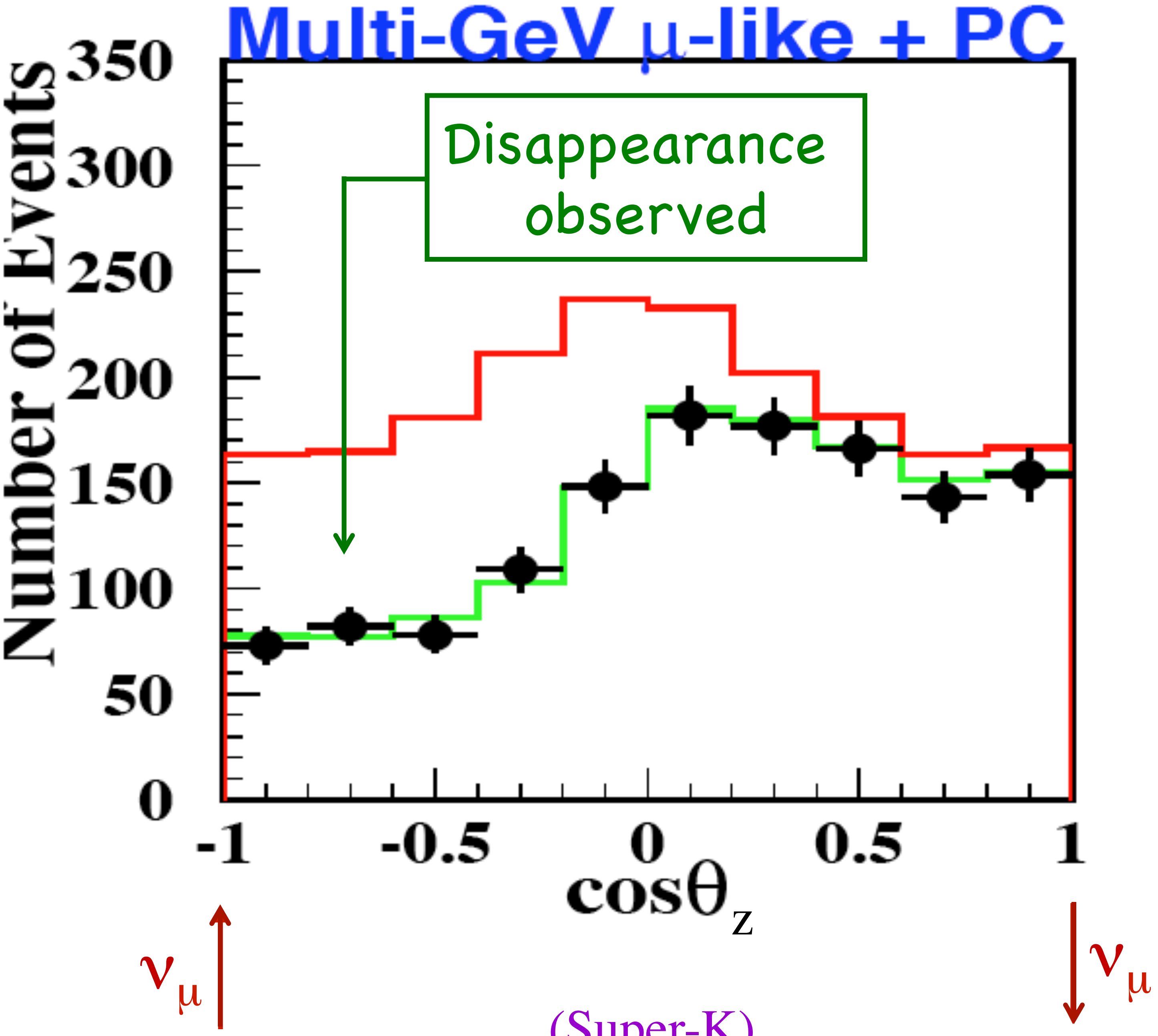
Isotropy of the $\gtrsim 2$ GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Rightarrow \quad \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 \ .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV, $\dfrac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} \cong 1/2$.



Super-Kamiokande: 50 ktons of water, surrounded by 11k phototubes that detect Cerenkov light from a μ or e



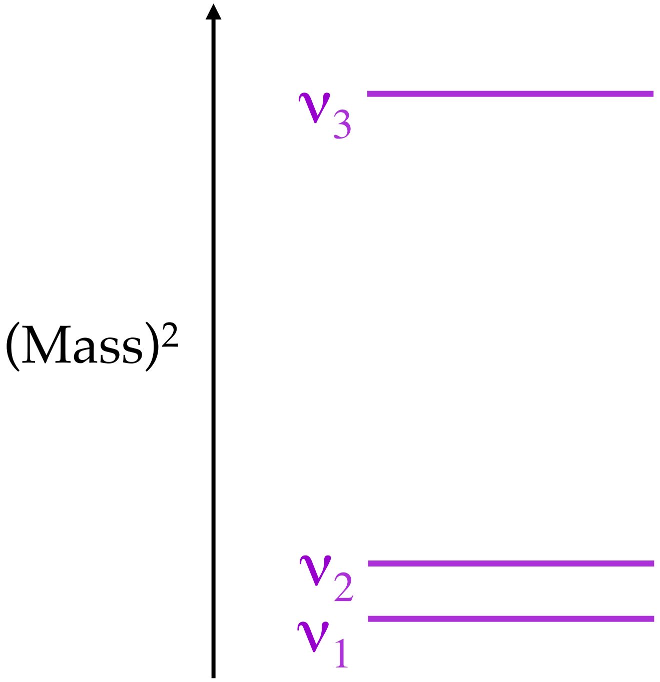
Disappearance observed

(Super-K)

The Physics of Neutrino Oscillation

Flavor Change Requires ***Neutrino Masses***

There must be some spectrum of neutrino mass eigenstates ν_i:



Mass $(\nu_i) \equiv m_i$

Flavor Change Requires ***Leptonic Mixing***

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

($W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau$)

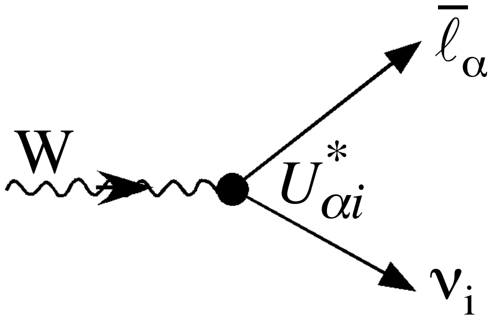
are superpositions of the neutrinos of definite mass:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} \, |\nu_i> \quad .$$

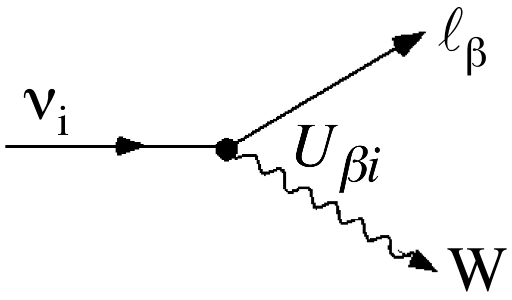
Neutrino of flavor
$\alpha = e, \mu$, or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i



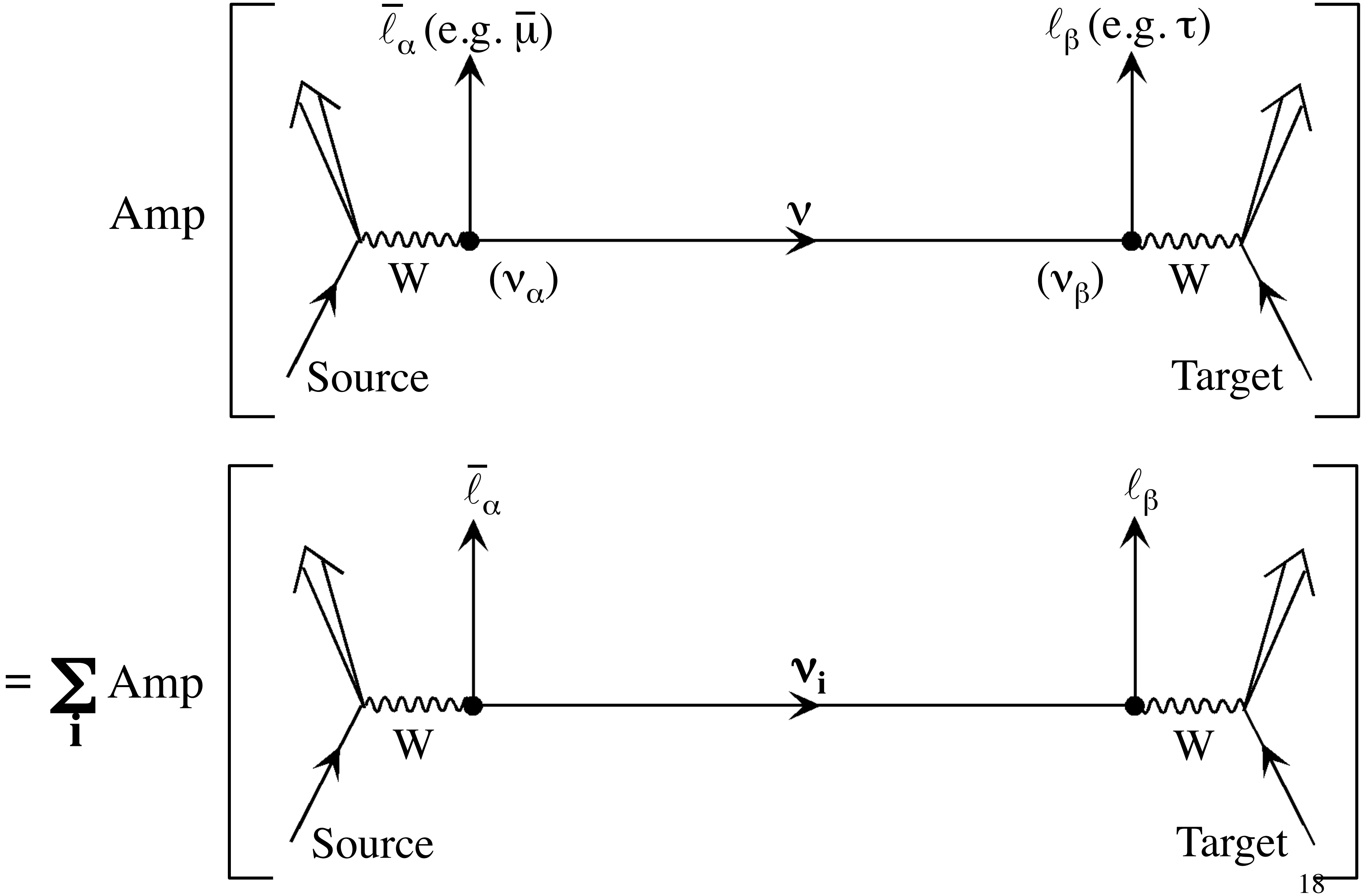
and



ℓ_α is a charged lepton ($\ell_e \equiv e$, $\ell_\mu \equiv \mu$, $\ell_\tau \equiv \tau$).

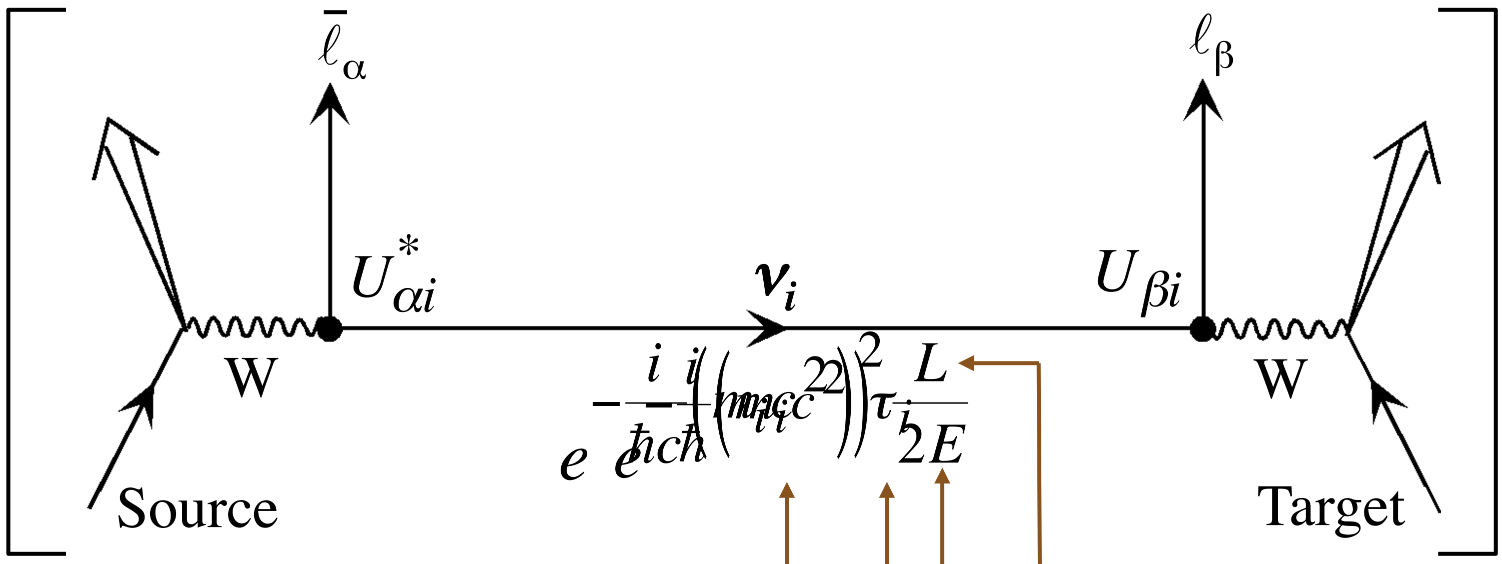
Neutrino Flavor Change ("Oscillation")

(Approach of BK and L. Stodolsky)



$$\mathrm{Amp}\left(\nu_\alpha \to \nu_\beta\right)$$

$$= \sum_{\mathbf{i}} \mathrm{Amp}$$



Rest energy

Energy

Proper time

Distance

$$= \sum_i U^*_{\alpha i}\, e^{-\frac{i}{\hbar c}\left(m_i c^2\right)^2 \frac{L}{2E}}\, U_{\beta i}$$

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\mathrm{Amp}\left(\nu_\alpha \to \nu_\beta\right)\right|^2$$

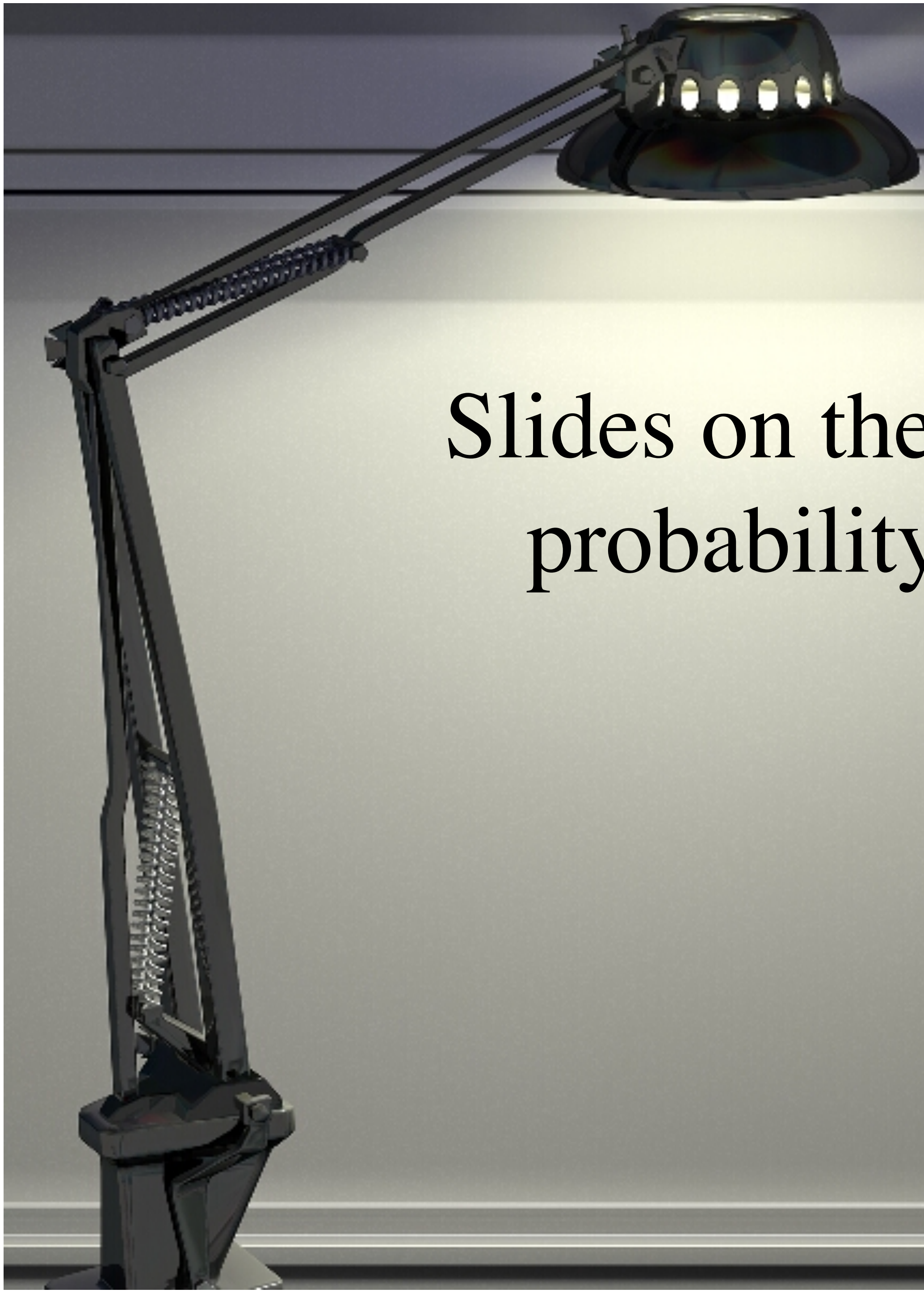
Probability

Why does $e^{-\frac{i}{\hbar}\left(m_i c^2\right)\tau_i}$ describe neutrino propagation?

If, in the lab. frame, a neutrino ν of mass m,
with momentum p and energy E,
travels a distance L in time t,
its wave function picks up a factor —

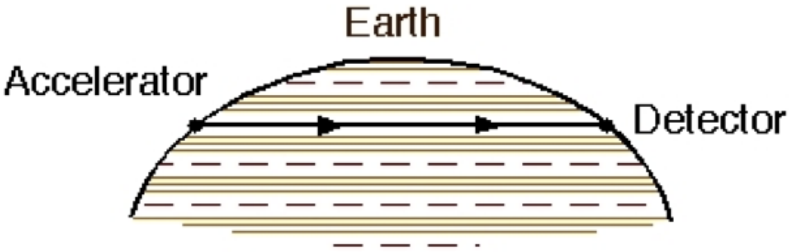
$$\exp\left[\frac{i}{\hbar}\left(pL - Et\right)\right] \underset{\uparrow}{=} \exp\left[-\frac{i}{\hbar}\left(mc^2\right)\tau\right]$$

By the Lorentz
transformation

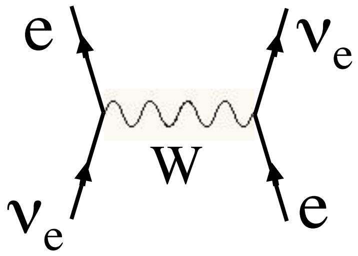


Slides on the oscillation probability go here.

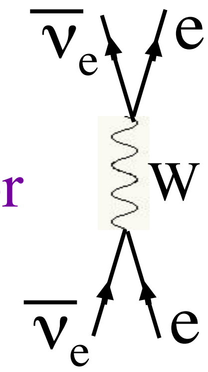
Neutrino Flavor Change In Matter



involves



or



Coherent forward scattering via this
W-exchange interaction leads to
an extra interaction potential energy —

$$V_W = \begin{cases} +\sqrt{2}G_F N_e, & \nu_e \\ -\sqrt{2}G_F N_e, & \bar{\nu}_e \end{cases}$$

Fermi constant

Electron density

This raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

The fractional importance of matter effects on an oscillation involving a vacuum splitting Δm^2 is —

$$\overbrace{[\sqrt{2}G_F N_e]}^{\text{Interaction energy}} \,/\, \overbrace{[\Delta m^2/2E]}^{\text{Vacuum energy}} \equiv x\ .$$

The matter effect —

- — Grows with neutrino energy E
- — Is sensitive to Sign(Δm^2)
- — Reverses when ν is replaced by $\bar{\nu}$

This last is a “fake CP violation”, but
the matter effect is negligible when $x << 1$.

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (Long-Baseline)	Compelling
Atmospheric	Compelling
Accelerator (Long-Baseline)	Compelling
Accelerator & Reactor (Short-Baseline)	“Interesting”

Further Highlights of the History

Solar Neutrinos

History –

Nuclear reactions in the core of the sun produce ν_e. Only ν_e.

Theorists, especially John Bahcall, calculated the produced ν_e flux vs. energy E.

Ray Davis' Homestake experiment measured the higher-E part of the ν_e flux ϕ_{ν_e} that arrives at earth.

The Homestake experiment could detect only ν_e. It found:

$$\frac{\phi_{\nu_e}(\text{Homestake})}{\phi_{\nu_e}(\text{Theory})} = 0.34 \pm 0.06$$

The Possibilities:

The theory was wrong.

The experiment was wrong.

Both were wrong.

Neither was wrong. Two thirds of the ν_e flux changes into a flavor or flavors that the Homestake experiment could not see.

The Resolution —

Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\, p\, p \;\Rightarrow \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \qquad (\nu \text{ remains a } \nu)$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.301 \pm 0.033$$

Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos change flavor.

For solar neutrinos, $P(\nu_e \rightarrow \nu_e) = 0.3$.

Change of flavor does not change the total number of neutrinos.

The total flux, $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$, should agree with Bahcall's prediction.

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (5.54 \pm 0.32 \pm 0.35) \times 10^6/\mathrm{cm}^2\mathrm{sec}$

Theory*: $\phi_{\mathrm{total}} = (5.69 \pm 0.91) \times 10^6/\mathrm{cm}^2\mathrm{sec}$

*Bahcall, Basu, Serenelli

John Bahcall and Ray Davis both stuck to their results for several decades, and both were ***right*** all along.

KamLAND Evidence for Oscillatory Behavior

The KamLAND detector studied $\overline{\nu}_e$ produced by Japanese nuclear power reactors ~ 180 km away.

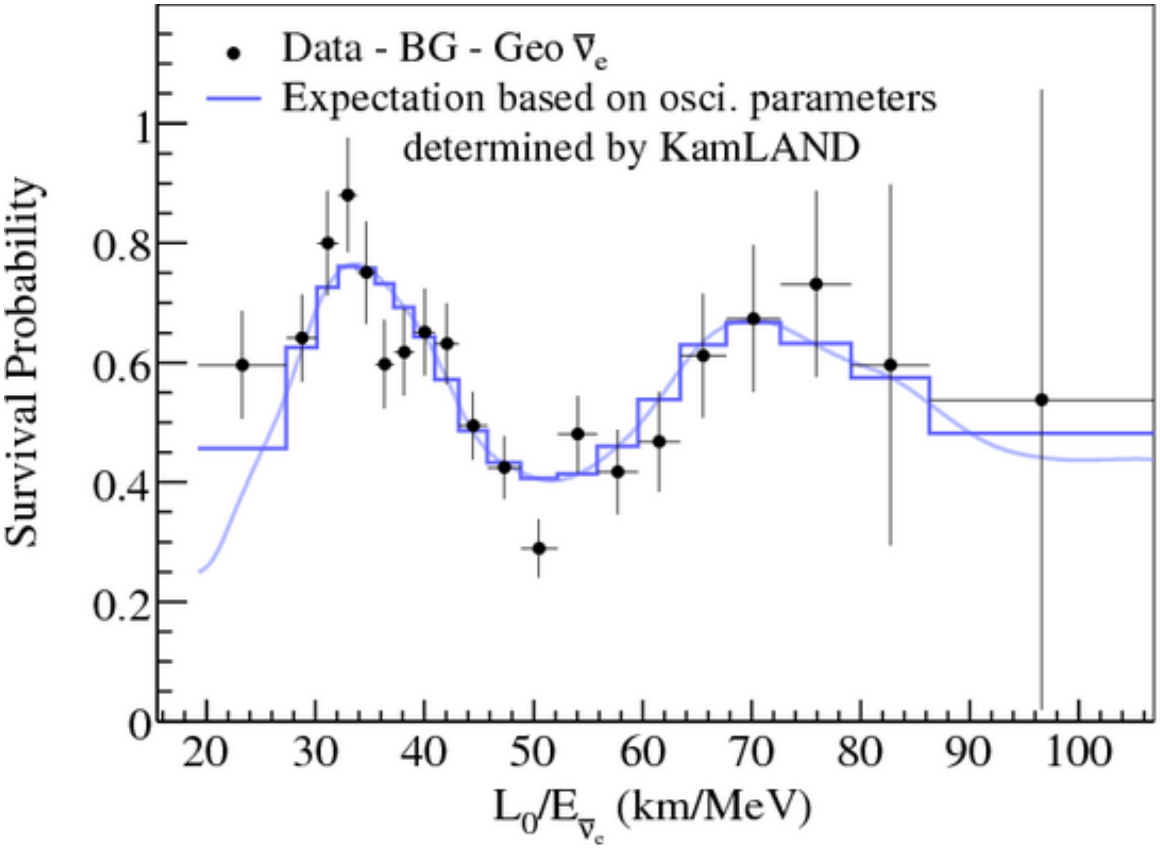
For KamLAND, $x_{\text{Matter}} < 10^{-2}$. Matter effects were negligible.

The $\bar{\nu}_e$ survival probability, $P(\bar{\nu}_e \to \bar{\nu}_e)$, should oscillate as a function of L/E following the vacuum oscillation formula.

In the two-neutrino approximation, we expect —

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right].$$

Survival probability $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ of reactor $\overline{\nu}_e$



L_0 = 180 km is a flux-weighted average travel distance.

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ actually oscillates!

The End — Part 1