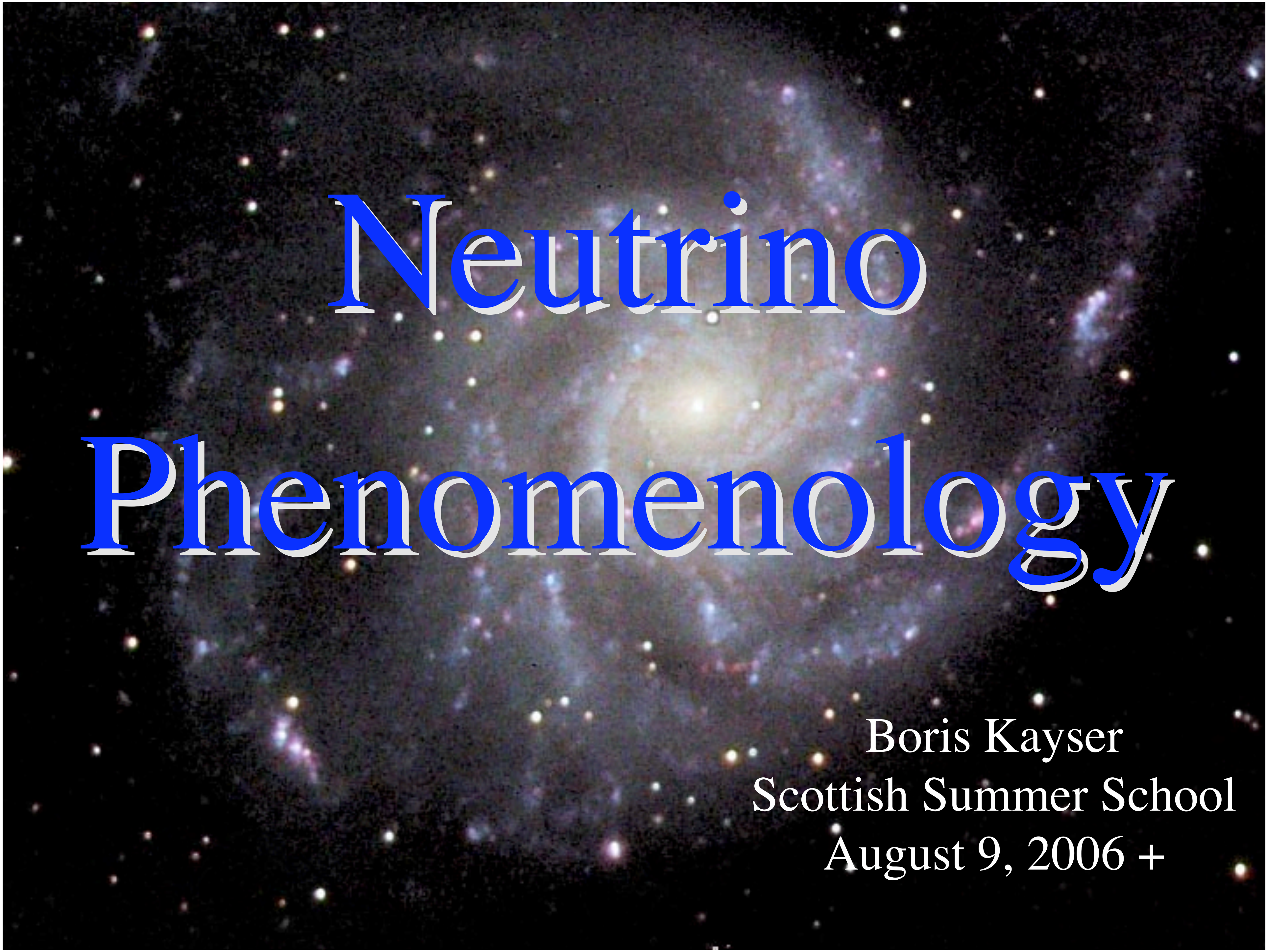
Neutrino
Phenomenology
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Scottish Summer School
August 9, 2006 +

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!

These discoveries come from the observation of ***neutrino oscillation***.

The Physics of Neutrino Oscillation

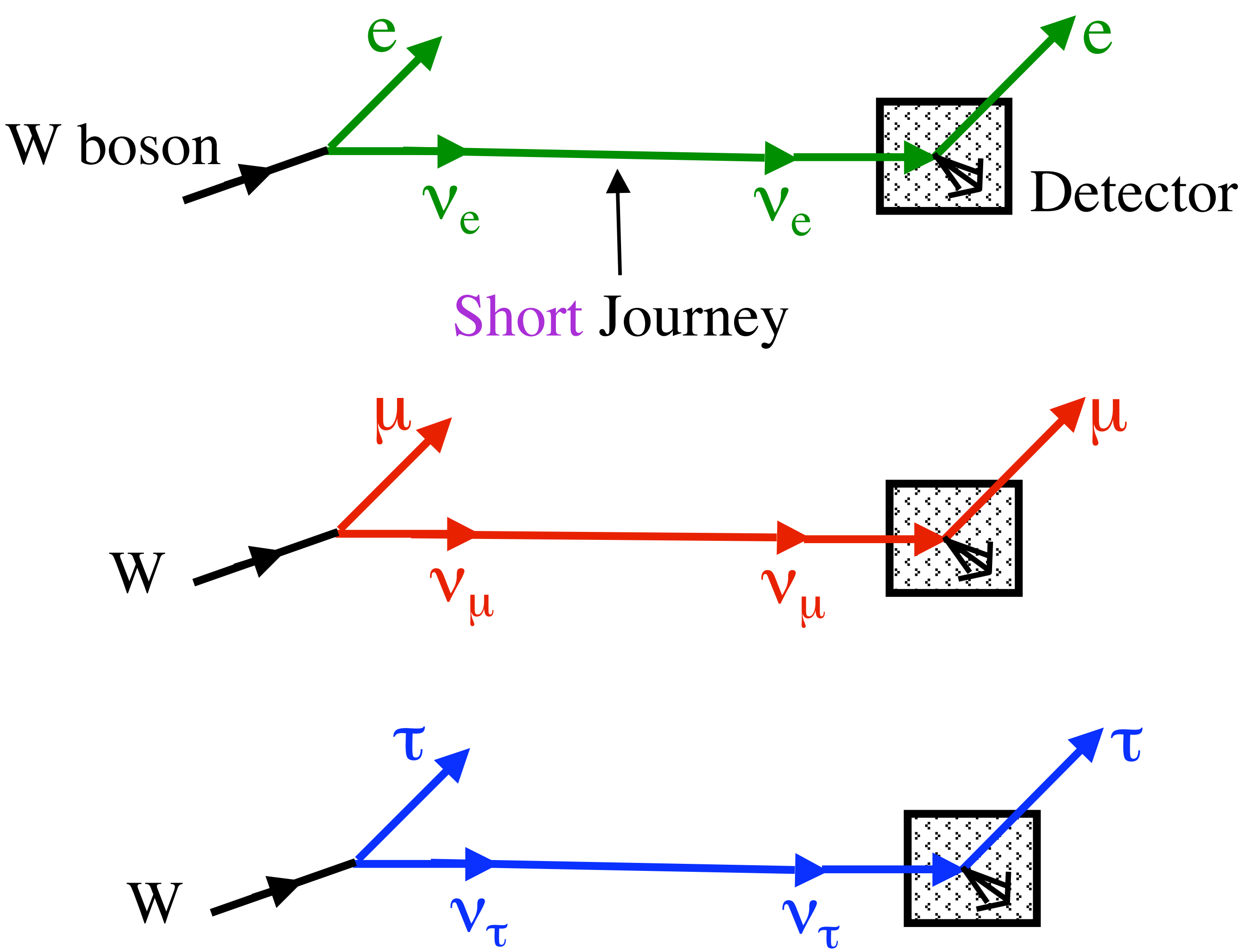
Neutrinos Come in at Least Three Flavors

The known neutrino flavors: ν_e , ν_μ , ν_τ

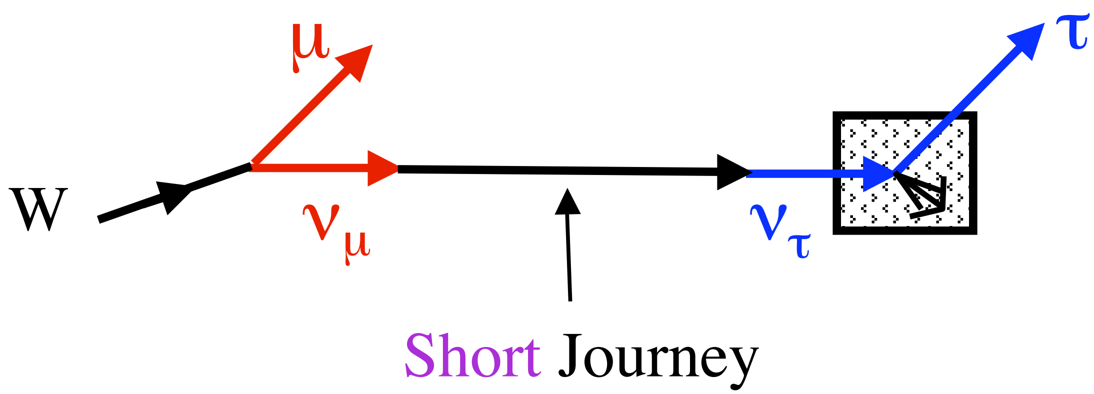
↕ ↕ ↕

Each of these is associated with the corresponding charged-lepton flavor: e , μ , τ

The Meaning of this Association



Over short distances, neutrinos do not change flavor.



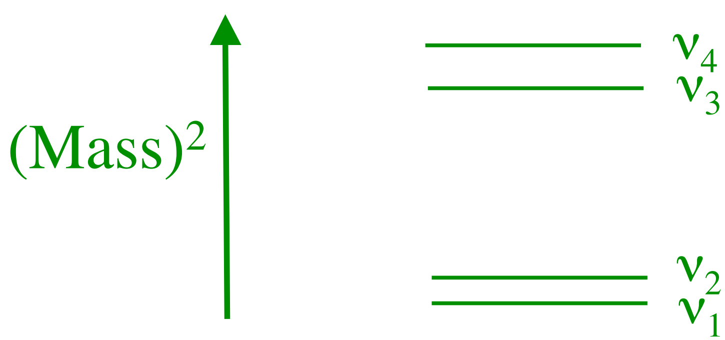
Does Not Occur

But if neutrinos have masses, and leptons mix, neutrino flavor changes do occur during ***long*** journeys.

Let Us Assume Neutrino Masses and Leptonic Mixing

Neutrino mass —

There is some spectrum of 3 or more neutrino mass eigenstates ν_i:



Mass $(\nu_i) \equiv m_i$

Leptonic mixing —

$\ell_e \equiv e,\ \ell_\mu \equiv \mu,\ \ell_\tau \equiv \tau$

When $W^+ \rightarrow \ell_\alpha^{\,+} + \nu_\alpha$,

e, μ, or τ

the produced neutrino state $|\nu_\alpha\rangle$ is

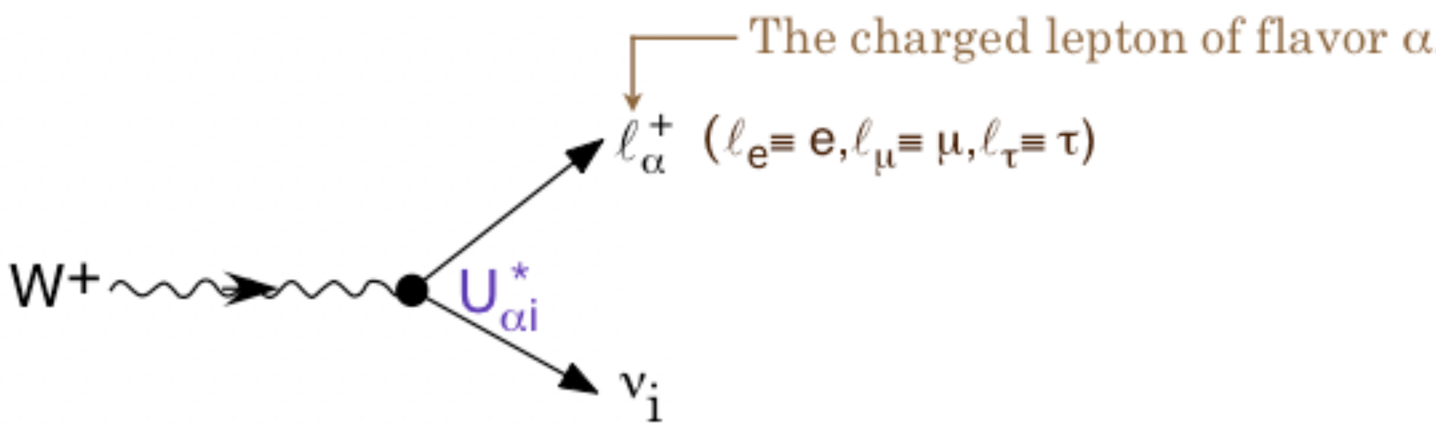
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \ .$$

Neutrino of flavor α

Neutrino of definite mass m_i

Leptonic Mixing Matrix

Another way to look at W decay:



A given ℓ_α^+ can be accompanied by *any* ν_i.

$$\mathrm{Amp}(W^+ \rightarrow \ell_\alpha^+ + \nu_i) = U^*_{\alpha i}$$

The neutrino state $|\nu_\alpha>$ produced together with ℓ_α^+

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

According to the Standard Model, extended to include neutrino mass and leptonic mixing —

- The number of different ν_i is the same as the number of different ℓ_α (3).
- The mixing matrix U is 3 x 3 and unitary:

$$UU^\dagger = U^\dagger U = 1.$$

Some models include "sterile" neutrinos — neutrinos that experience none of the known forces of nature except gravity.

In such models, there are N > 3 ν_i, and U is N x N, but still unitary.

Just as each neutrino of definite flavor ν_α is a superposition of mass eigenstates ν_i, so each mass eigenstate is a superposition of flavors .

From $|\nu_\alpha> = \Sigma_i\, U^*_{\alpha i}\, |\nu_i>$ and the unitarity of U,

$$|\nu_i> = \Sigma_\alpha\, U_{\alpha i}\, |\, \nu_\alpha> .$$

The flavor-α fraction of ν_i is —

$$|<\nu_\alpha|\nu_i>|^2 = |U_{\alpha i}|^2 .$$

The Standard Model (SM) description of neutrino *interactions* (not masses or leptonic mixing) is well-confirmed.

We will assume it is true, and extend it to include mixing.

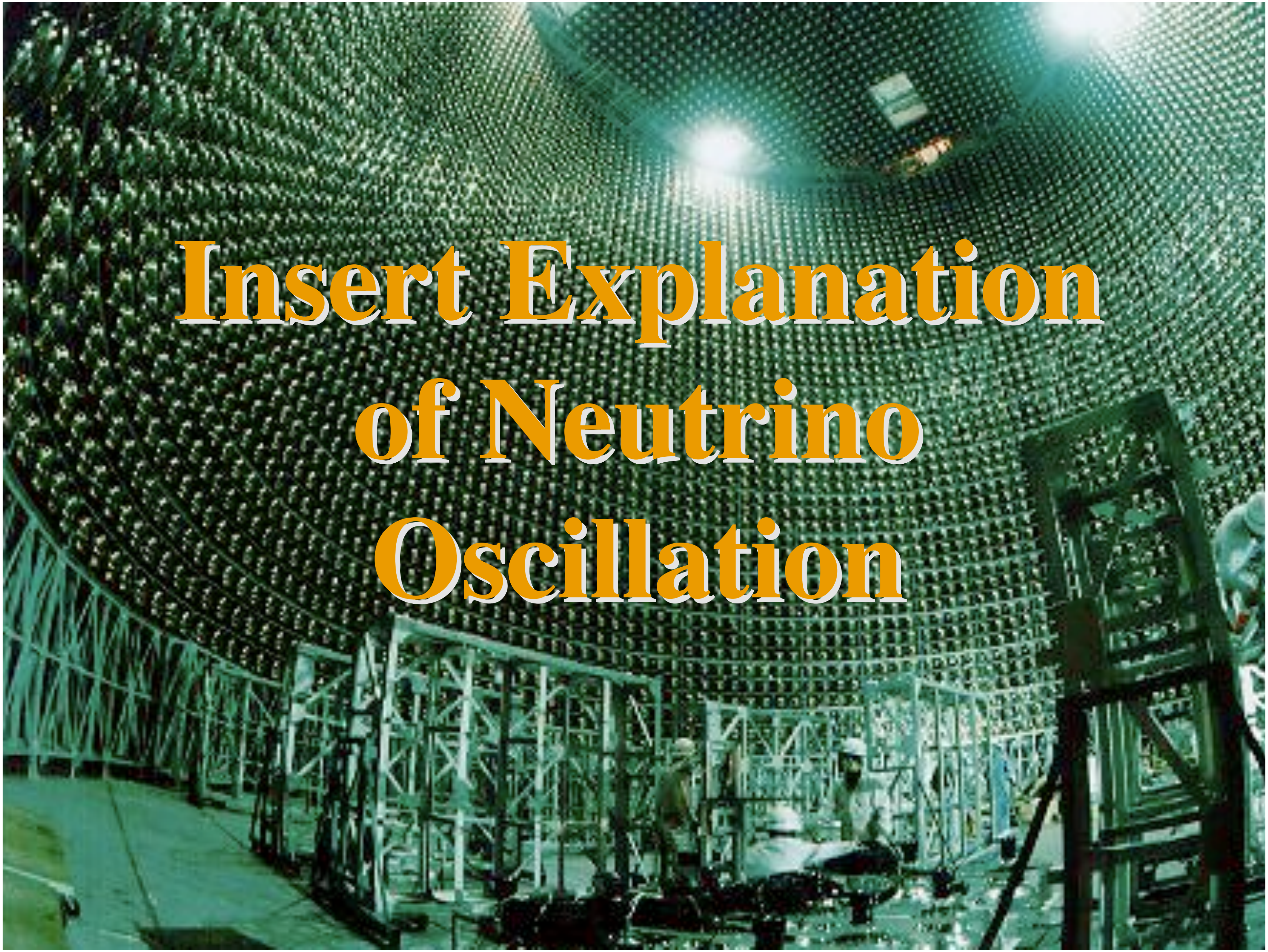
For the lepton couplings to the W boson, we then have —

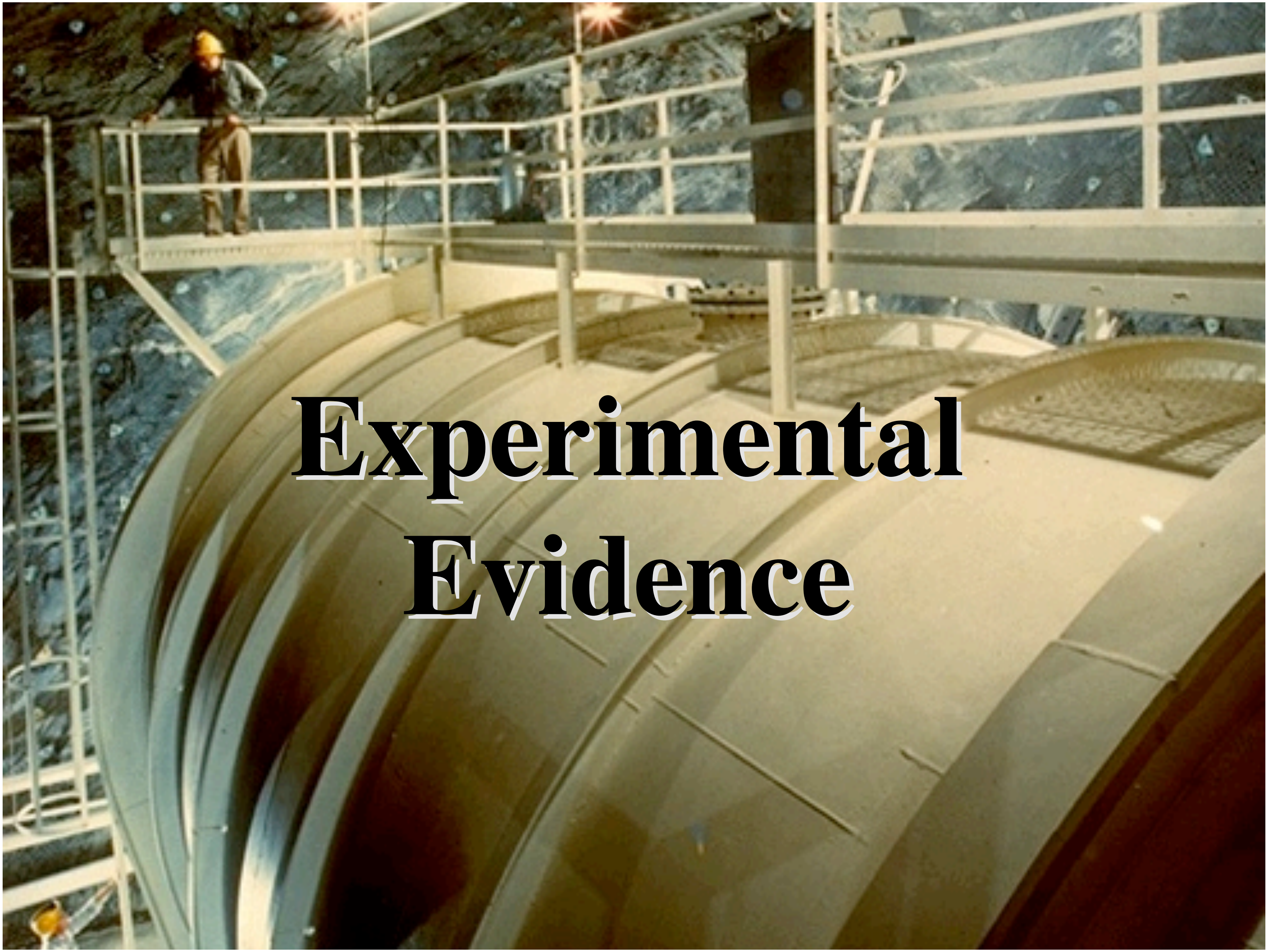
Left-handed

$$L_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\overline{\ell}_{L\alpha} \gamma^{\lambda} \nu_{L\alpha} W_{\lambda}^{-} + \overline{\nu}_{L\alpha} \gamma^{\lambda} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\overline{\ell}_{L\alpha} \gamma^{\lambda} U_{\alpha i} \nu_{Li} W_{\lambda}^{-} + \overline{\nu}_{Li} \gamma^{\lambda} U_{\alpha i}^{*} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

Taking mixing into account


Insert Explanation
of Neutrino
Oscillation


Experimental
Evidence

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay (LSND, $L \approx 30$ m)	Unconfirmed

What Happens To Solar Neutrinos

Solar $\nu_e \rightarrow \nu_\mu$ / ν_τ is now well established.

The mechanism for this flavor conversion is the —

Large Mixing Angle version of the —

Mikheyev Smirnov Wolfenstein

— Effect.

This occurs as the neutrinos stream outward through solar material. It requires both interactions with matter and neutrino mass and mixing.

How Does the Large Mixing Angle MSW Effect Work?

The solar *matter effect* is important for the high-energy ^8B neutrinos, not the low-energy pp neutrinos.

Since ν_3 couples at most feebly to electrons (to be discussed), and solar neutrinos are born ν_e, the solar neutrinos are mixtures of just ν_1 and ν_2.

This is a 2-neutrino system.

Convention: ν_2 *heavier* than ν_1.

Solar neutrino flavor change is $\nu_e \rightarrow \nu_x$, where ν_x is some combination of ν_μ and ν_τ.

In the sun,

$$H = \frac{\Delta m^2_{sol}}{4E}\begin{bmatrix} -\cos 2\theta_{sol} & \sin 2\theta_{sol} \\ \sin 2\theta_{sol} & \cos 2\theta_{sol} \end{bmatrix} + \sqrt{2} G_F N_e \begin{array}{c} \begin{array}{cc} \nu_e & \nu_x \end{array} \\ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \end{array} \begin{array}{l} \\ \nu_e \\ \nu_x \end{array}$$

At the center of the sun,

$$\sqrt{2}\, G_F N_e \approx 0.75 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

For $\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2 and typical ^{8}B neutrino energy of ~ 8 MeV,

$$\Delta m^2_{sol} / 4E \approx 0.25 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

The interaction term in H dominates, and ν_e is approximately an eigenstate of H.*

*For the (E ~ 0.2MeV) pp neutrinos, H_{Vac} dominates.

The ^8B solar neutrino propagates outward adiabatically.

It remains the slowly - changing heavier eigenstate of the slowly - changing H.

It emerges from the sun as the heavier eigenstate of H_{Vac}, ν_2.*

It stays ν_2 until it reaches the earth. Nothing "oscillates"!

Since $\nu_2 = \nu_e \sin\theta_{sol} + \nu_x \cos\theta_{sol}$, (See 2 × 2 U matrix)

Prob[See ν_e at earth] $= \sin^2\theta_{sol}$.

*Good to 91% (Nunokawa, Parke, Zukanovich-Funchal)