

# Neutrino Phenomenology

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# The Neutrino Revolution

(1998 – ...)

Neutrinos have nonzero masses!

Leptons mix!

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

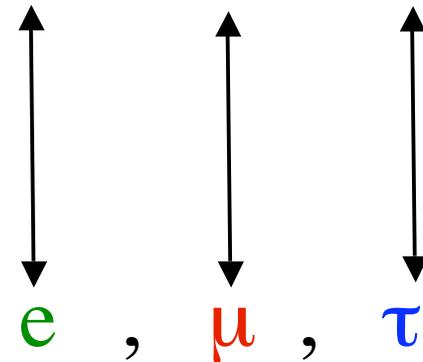
# The Physics of Neutrino Oscillation

# Neutrinos Come in at Least Three Flavors

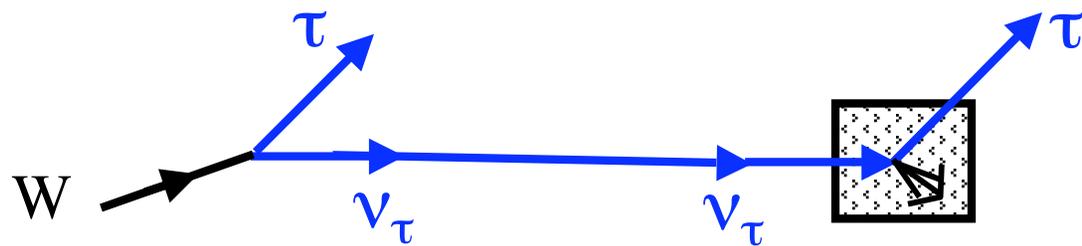
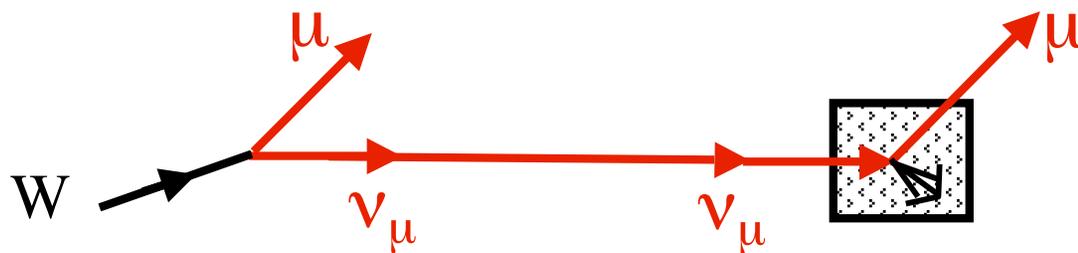
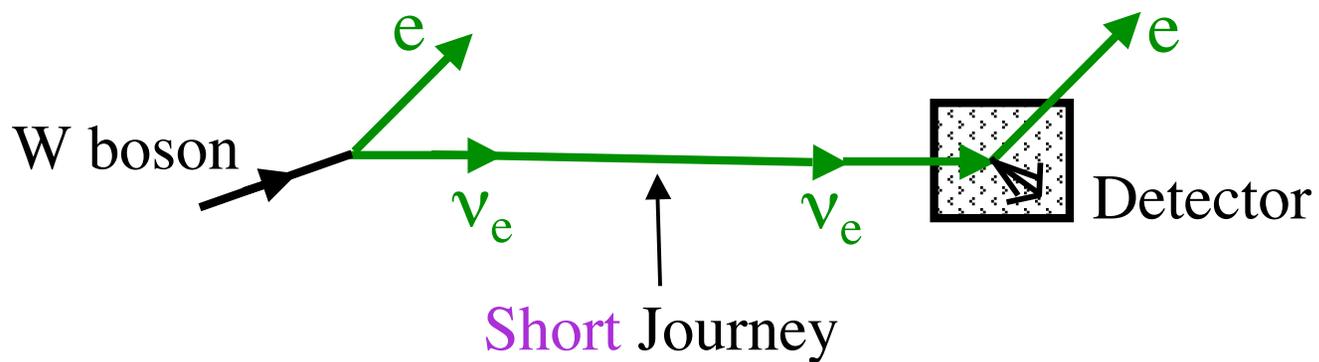
The known neutrino flavors:

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

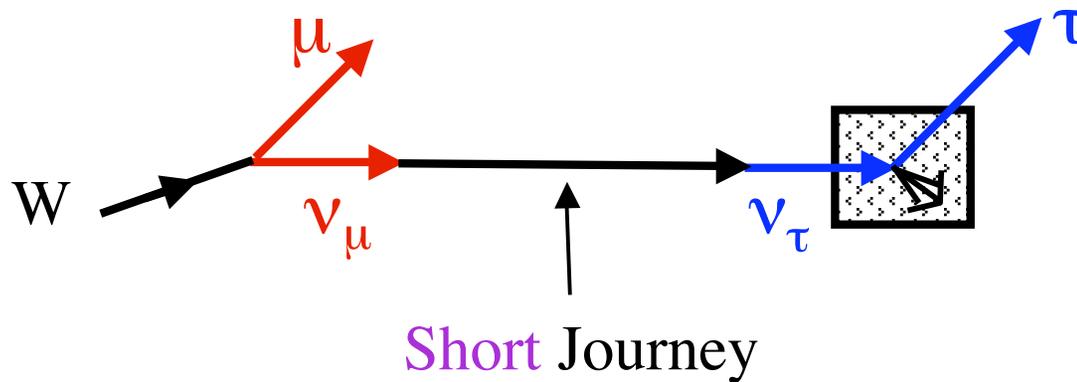
Each of these is associated  
with the corresponding  
charged-lepton flavor:



# The Meaning of this Association



Over short distances, neutrinos do not change flavor.



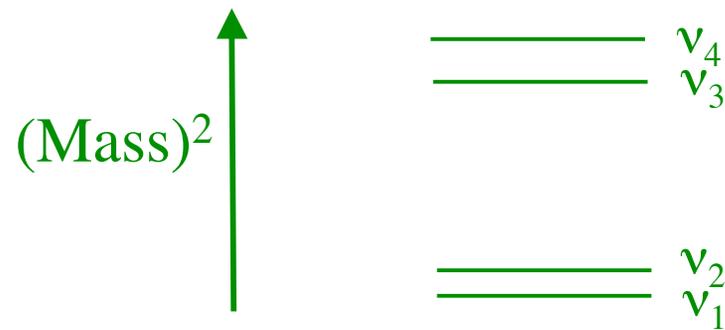
Does Not Occur

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  $\nu_i$ :



$$\text{Mass}(\nu_i) \equiv m_i$$

# Leptonic mixing —

When  $W^+ \rightarrow l_\alpha^+ + \nu_\alpha$  ,

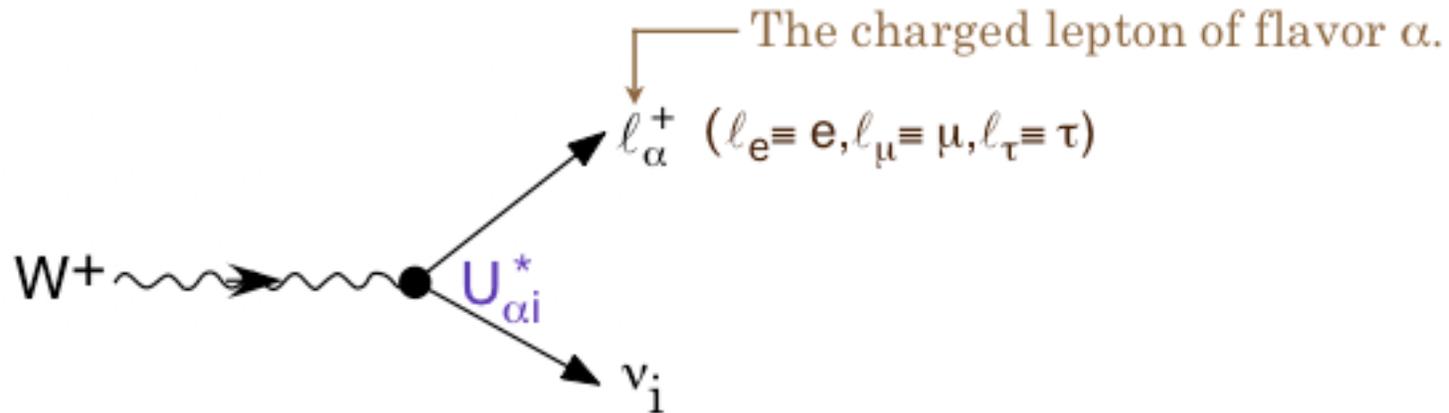
$l_e \equiv e, l_\mu \equiv \mu, l_\tau \equiv \tau$   
 $e, \mu, \text{ or } \tau$

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

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle .$$

Neutrino of flavor  $\alpha$                       Neutrino of definite mass  $m_i$   
 Leptonic Mixing Matrix

Another way to look at W decay:



A given  $l_{\alpha}^{+}$  can be accompanied by *any*  $\nu_i$ .

$$\text{Amp}(W^{+} \rightarrow l_{\alpha}^{+} + \nu_i) = U_{\alpha i}^{*}$$

The neutrino state  $|\nu_{\alpha}\rangle$  produced together with  $l_{\alpha}^{+}$

$$\text{is } |\nu_{\alpha}\rangle = \sum_i U_{\alpha i}^{*} |\nu_i\rangle .$$

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

- The number of different  $\nu_i$  is the same as the number of different  $\ell_\alpha$  (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  $N > 3$   $\nu_i$ , and  $U$  is  $N \times N$ , but still unitary.

Just as each neutrino of definite flavor  $\nu_\alpha$  is a superposition of mass eigenstates  $\nu_i$ , so each mass eigenstate is a superposition of flavors .

From  $|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$  and the unitarity of U,

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle .$$

The flavor- $\alpha$  fraction of  $\nu_i$  is —

$$|\langle \nu_\alpha | \nu_i \rangle|^2 = |U_{\alpha i}|^2 .$$

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.

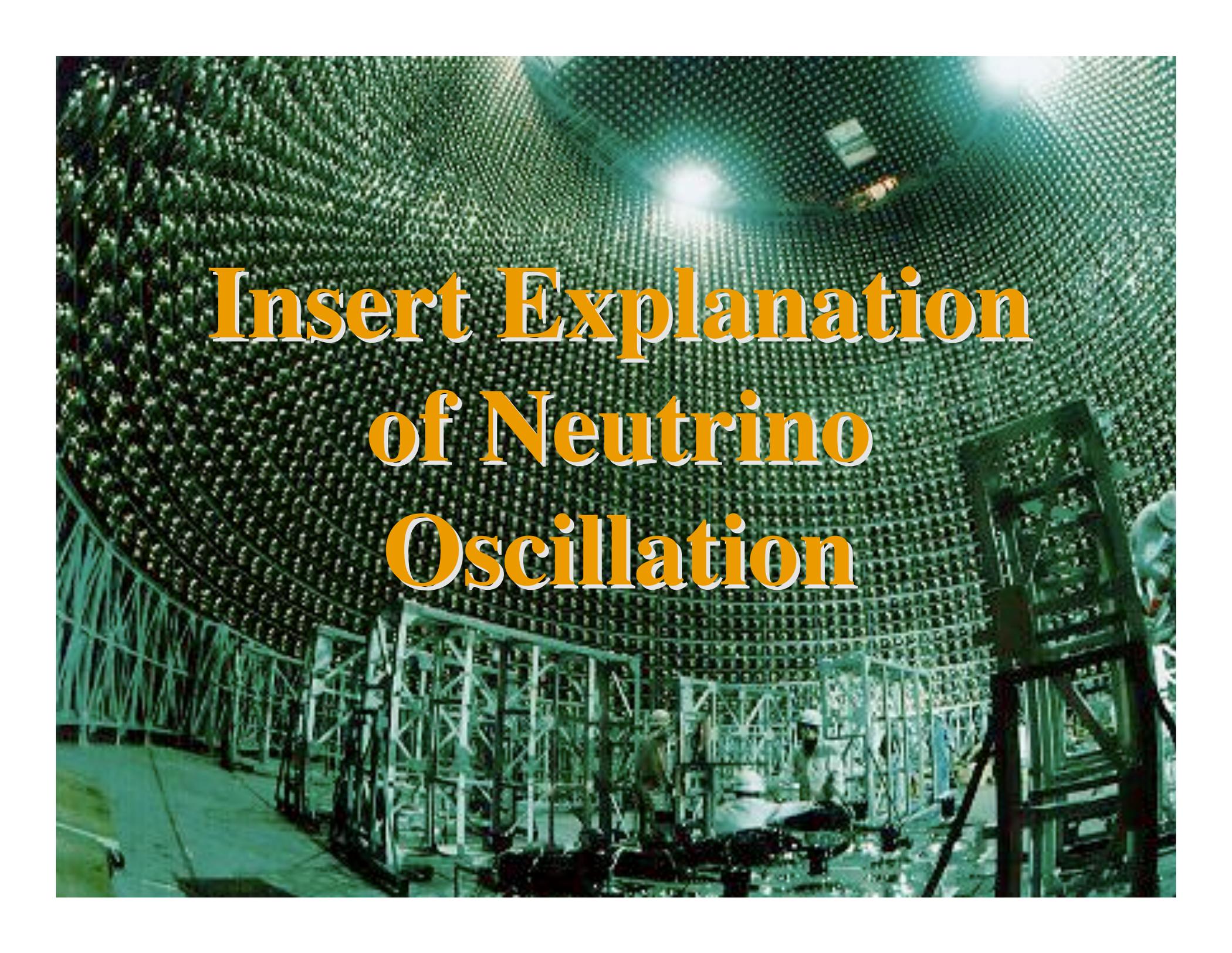
For the lepton couplings to the W boson, we then have —

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

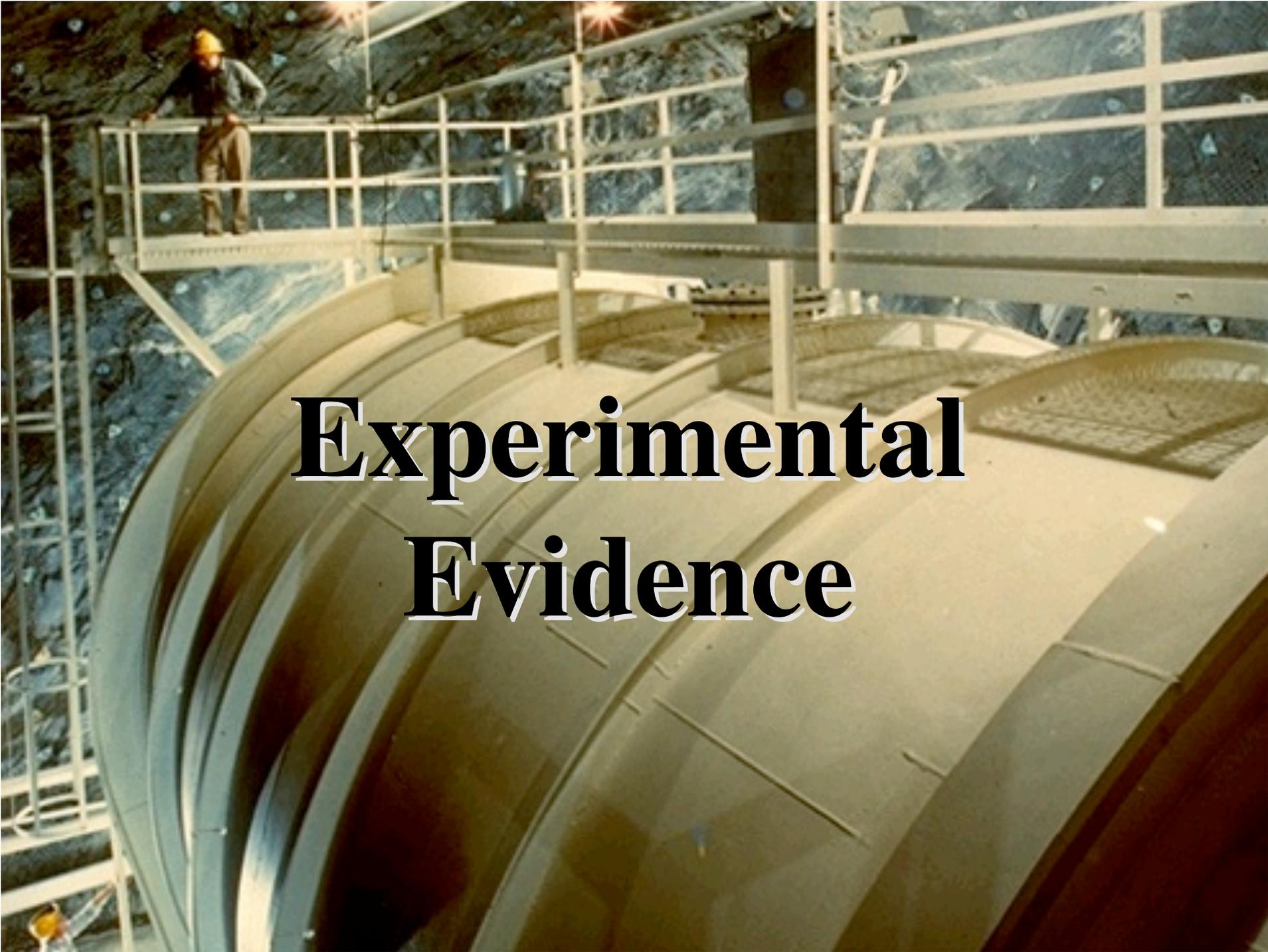
Left-handed

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

Taking mixing into account

The image shows the interior of a large, cylindrical particle detector. The walls are covered in a dense, green, grid-like pattern of small, square-shaped elements. The floor is a light-colored, possibly concrete or metal, surface. In the center, there is a complex structure of metal beams and supports, likely part of the detector's internal framework. The lighting is somewhat dim, with a few bright spots, possibly from overhead lights or the detector's own illumination system. The overall atmosphere is technical and industrial.

# Insert Explanation of Neutrino Oscillation

A photograph of a large industrial facility, possibly a water treatment plant. In the foreground, there are large, curved, metallic structures that appear to be part of a filtration or sedimentation process. In the background, a worker wearing a yellow hard hat and a dark jacket is standing on a metal walkway or platform. The scene is illuminated by bright lights, creating a high-contrast environment. The overall color palette is dominated by metallic grays and blues, with the yellow of the worker's hard hat providing a focal point.

# Experimental Evidence

# Evidence For Flavor Change

## Neutrinos

## Evidence of Flavor Change

Solar

Compelling

Reactor

Compelling

( $L \sim 180$  km)

Atmospheric

Compelling

Accelerator

Compelling

( $L = 250$  and  $735$  km)

Stopped  $\mu^+$  Decay

Unconfirmed

( LSND  
( $L \approx 30$  m)

# What Happens To Solar Neutrinos

Solar  $\nu_e \rightarrow \nu_\mu / \nu_\tau$  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  ${}^8\text{B}$  neutrinos, not the low-energy pp neutrinos.

Since  $\nu_3$  couples at most feebly to electrons (to be discussed), and solar neutrinos are born  $\nu_e$ , the solar neutrinos are mixtures of just  $\nu_1$  and  $\nu_2$ .

This is a 2-neutrino system.

Convention:  $\nu_2$  *heavier* than  $\nu_1$ .

Solar neutrino flavor change is  $\nu_e \rightarrow \nu_x$ , where  $\nu_x$  is some combination of  $\nu_\mu$  and  $\nu_\tau$ .

In the sun,

$$H = \frac{\Delta m_{sol}^2}{4E} \begin{bmatrix} -\cos 2\theta_{sol} & \sin 2\theta_{sol} \\ \sin 2\theta_{sol} & \cos 2\theta_{sol} \end{bmatrix} + \sqrt{2} G_F N_e \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{matrix} \nu_e & \nu_x \\ \nu_e & \nu_x \end{matrix}$$

At the center of the sun,

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

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

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

The interaction term in H dominates, and  $\nu_e$  is approximately an eigenstate of H.\*

\*For the ( $E \sim 0.2\text{MeV}$ ) pp neutrinos,  $H_{Vac}$  dominates.

The  $^8\text{B}$  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  $H_{\text{vac}}$ ,  $\nu_2$ .\*

It stays  $\nu_2$  until it reaches the earth. **Nothing “oscillates”!**

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

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

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