

A deep space photograph showing a dense field of stars and distant galaxies, with a bright, hazy region in the center, likely a galaxy cluster or a nebula. The colors are predominantly blue, purple, and white against a black background.

Neutrino Physics: Present and Future

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The Neutrino Revolution

(1998 – ...)

Neutrinos have nonzero masses!

Leptons mix!

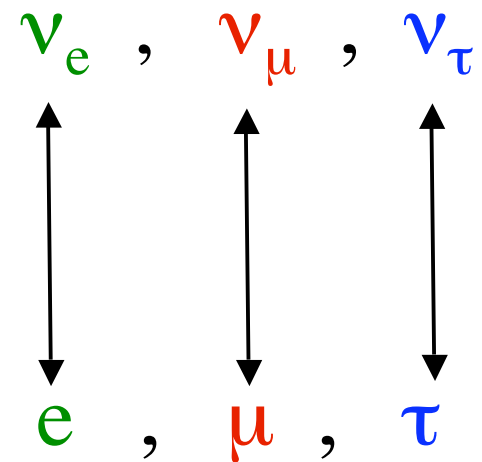
These discoveries come from
the observation of
neutrino oscillation.

The Physics of Neutrino Oscillation

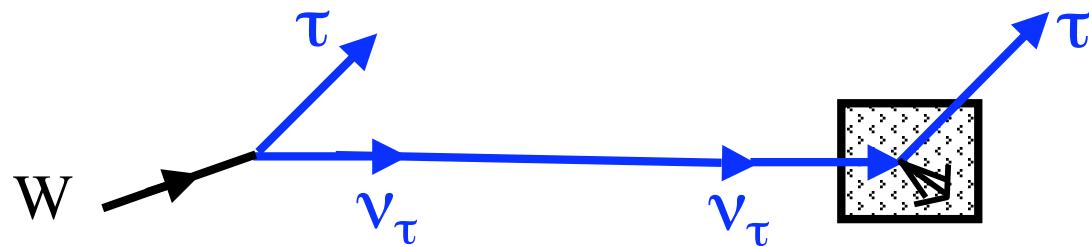
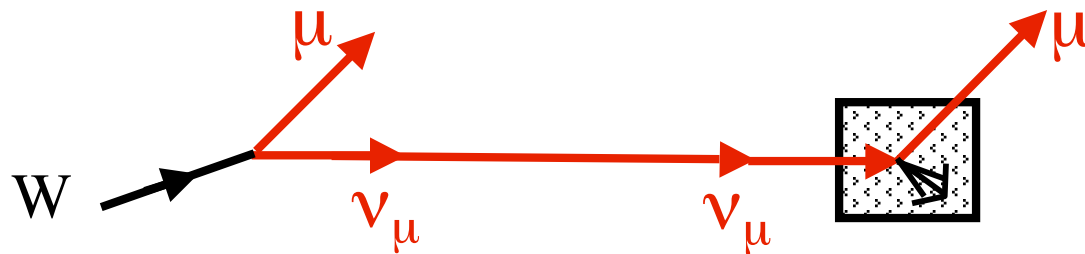
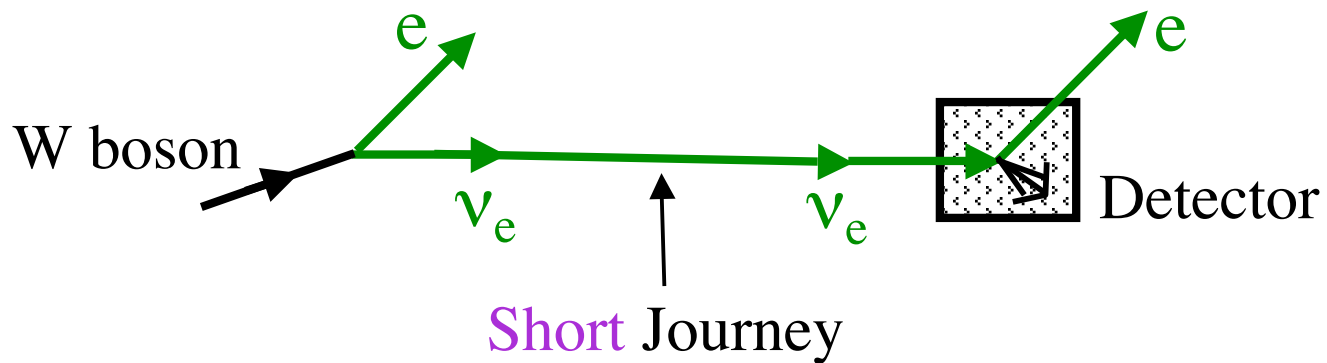
Neutrinos Come in at Least Three Flavors

The known neutrino flavors:

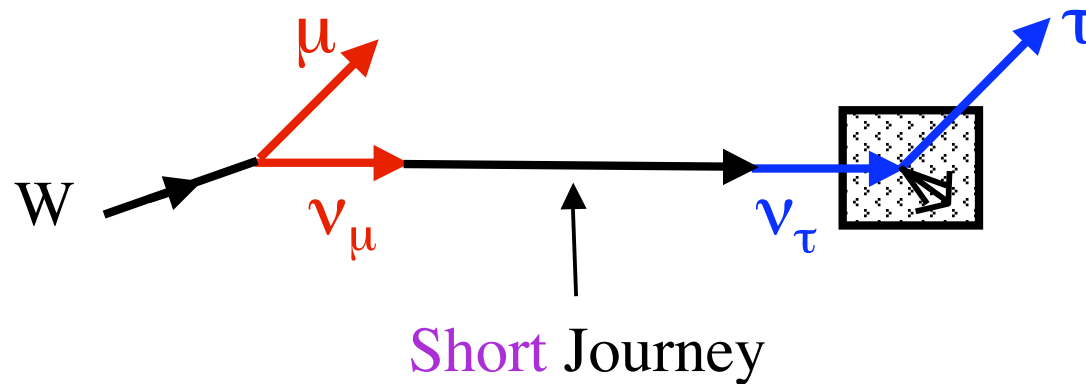
Each of these is associated
with the corresponding
charged-lepton flavor:



The Meaning of this Association



Over short distances, neutrinos do not change flavor.



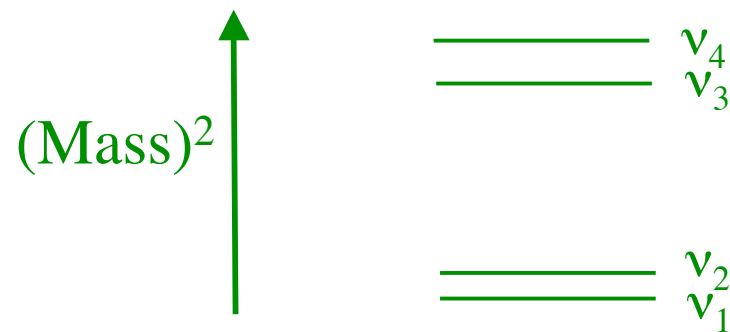
Does Not Occur

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 ν_i :



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

Leptonic mixing —

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

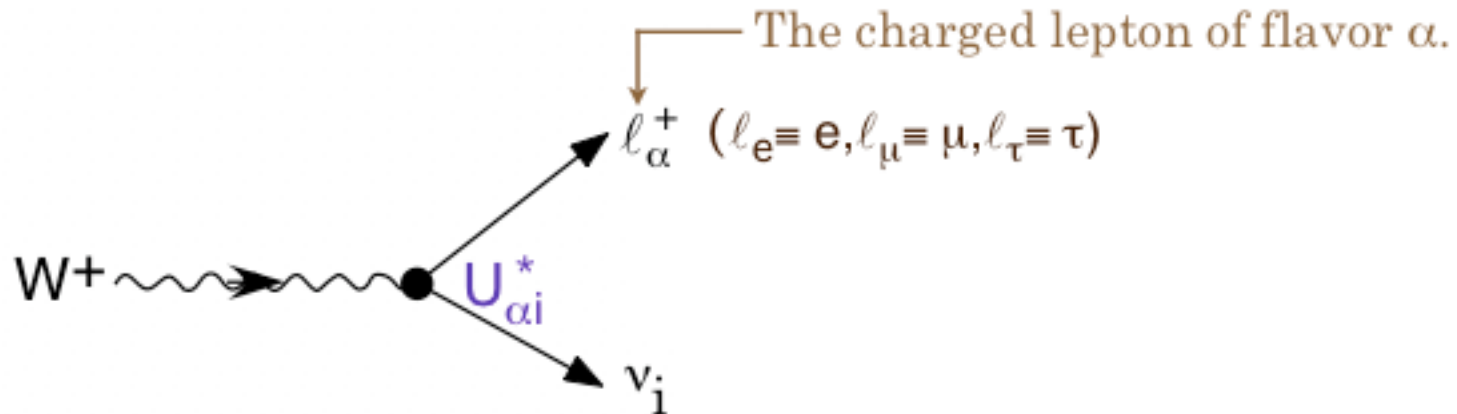
$\ell_e \equiv e, \ell_\mu \equiv \mu, \ell_\tau \equiv \tau$
 $e, \mu, \text{ or } \tau$

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

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

Neutrino of flavor α Leptonic Mixing Matrix Neutrino of definite mass m_i

Another way to look at W decay:



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

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

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

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

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

- The number of different 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 $N \times N$, 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 $|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$ and the unitarity of U ,

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

The flavor- α fraction of ν_i is —

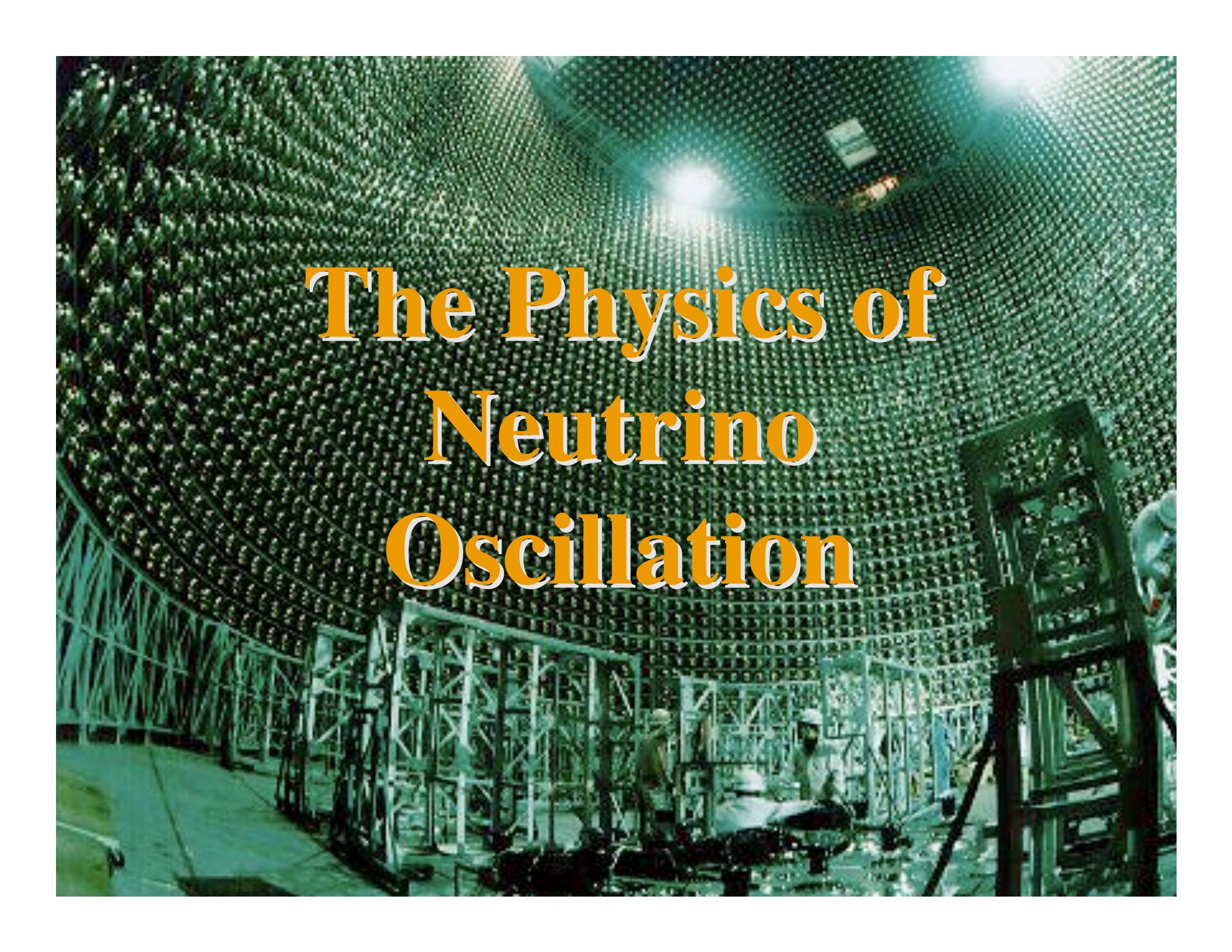
$$|\langle \nu_\alpha | \nu_i \rangle|^2 = |U_{\alpha i}|^2 .$$

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 —

$$\begin{aligned}
 L_{SM} &= -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\overline{\ell}_{L\alpha} \gamma^\lambda \nu_{L\alpha} W_\lambda^- + \bar{\nu}_{L\alpha} \gamma^\lambda \ell_{L\alpha} W_\lambda^+ \right) \\
 &\quad \text{Left-handed} \\
 &= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\overline{\ell}_{L\alpha} \gamma^\lambda U_{\alpha i} \nu_{Li} W_\lambda^- + \bar{\nu}_{Li} \gamma^\lambda U_{\alpha i}^* \ell_{L\alpha} W_\lambda^+ \right) \\
 &\quad \text{Taking mixing into account}
 \end{aligned}$$

The image shows the interior of a large, cylindrical neutrino detector. The walls are covered in a dense grid of photomultiplier tubes, which appear as a textured, greenish surface. In the center, there is a complex structure of metal frames and pipes, likely part of the detector's support system. A bright light source is visible at the top, creating a lens flare effect. The overall atmosphere is industrial and scientific.

The Physics of Neutrino Oscillation