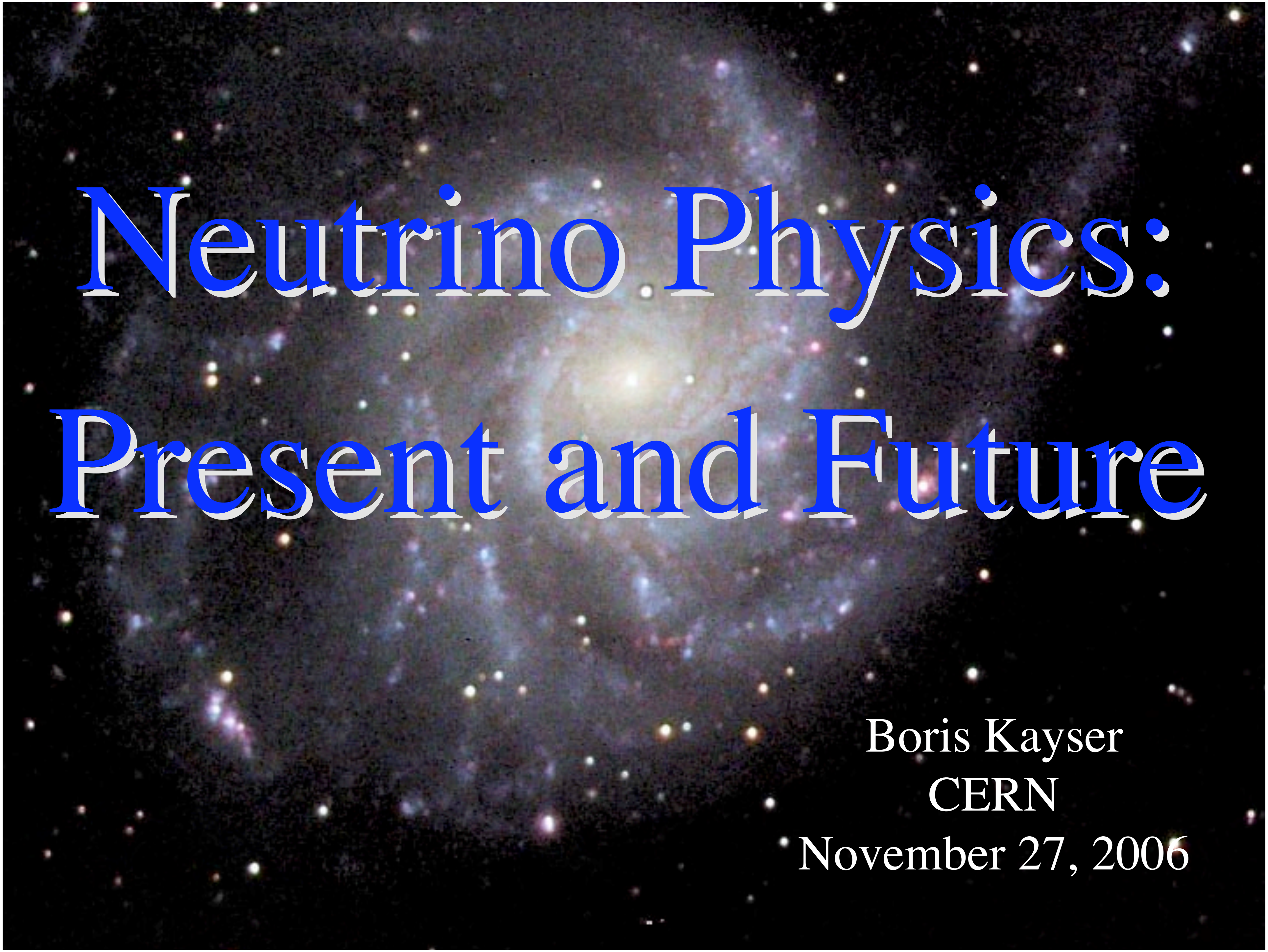

Neutrino Physics: Present and Future

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The Neutrino Revolution
(1998 – ...)

Neutrinos have nonzero masses!

Leptons mix!

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

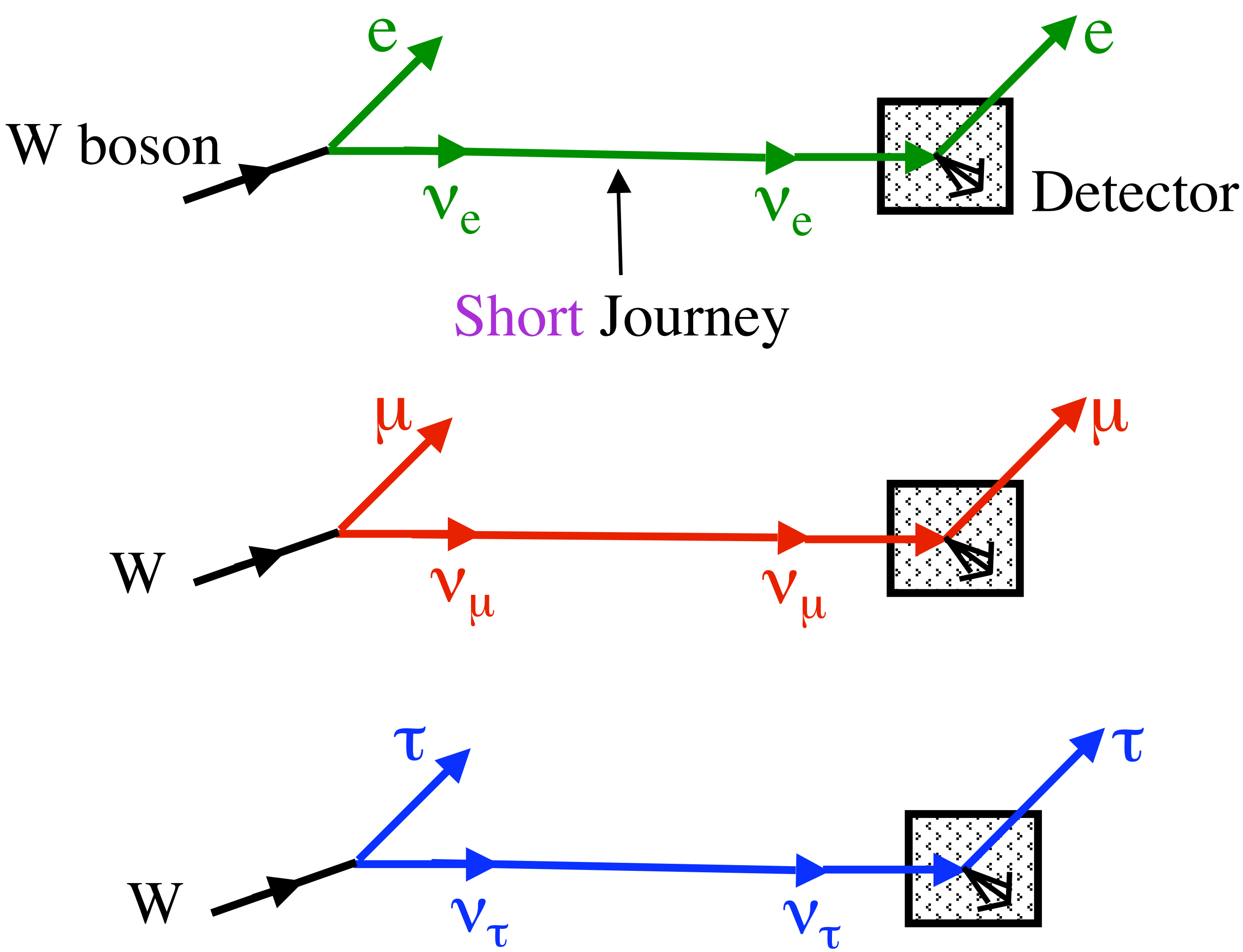
The Physics of Neutrino Oscillation

Neutrinos Come in at Least Three Flavors

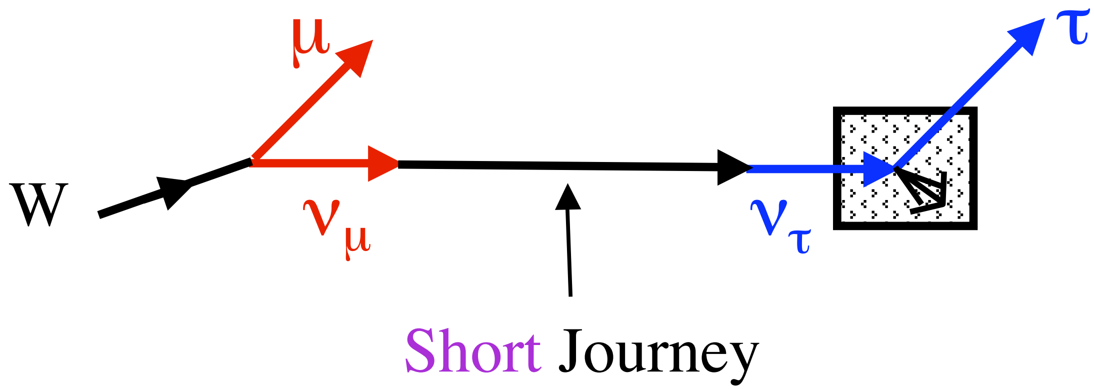
The known neutrino flavors: ν_e , ν_μ , ν_τ

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.



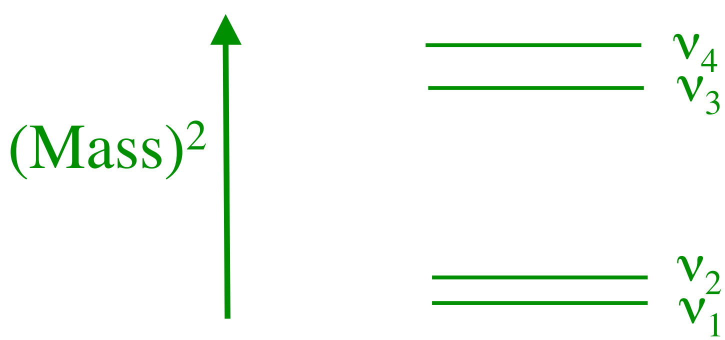
Does Not Occur

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

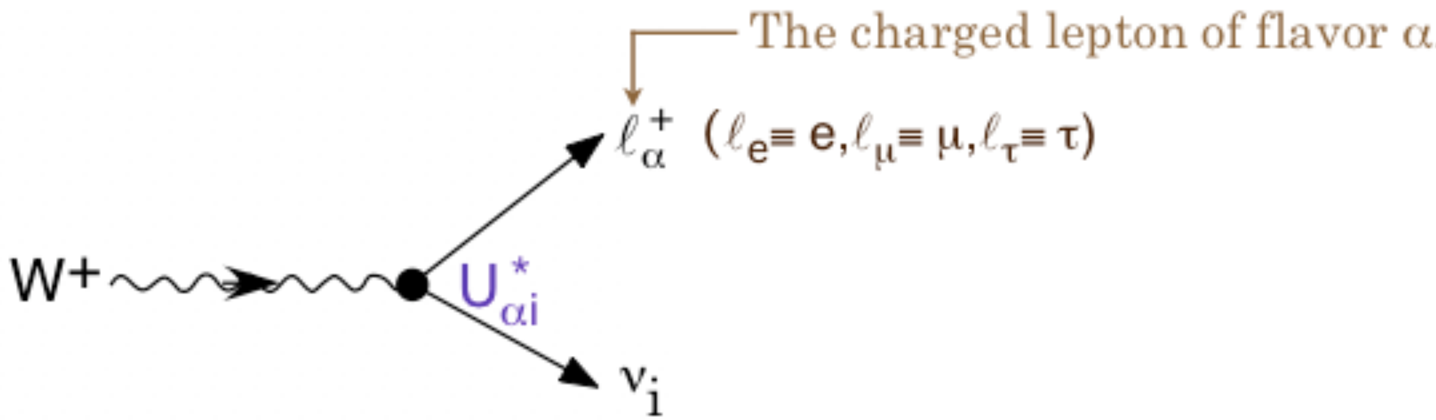
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \ .$$

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.

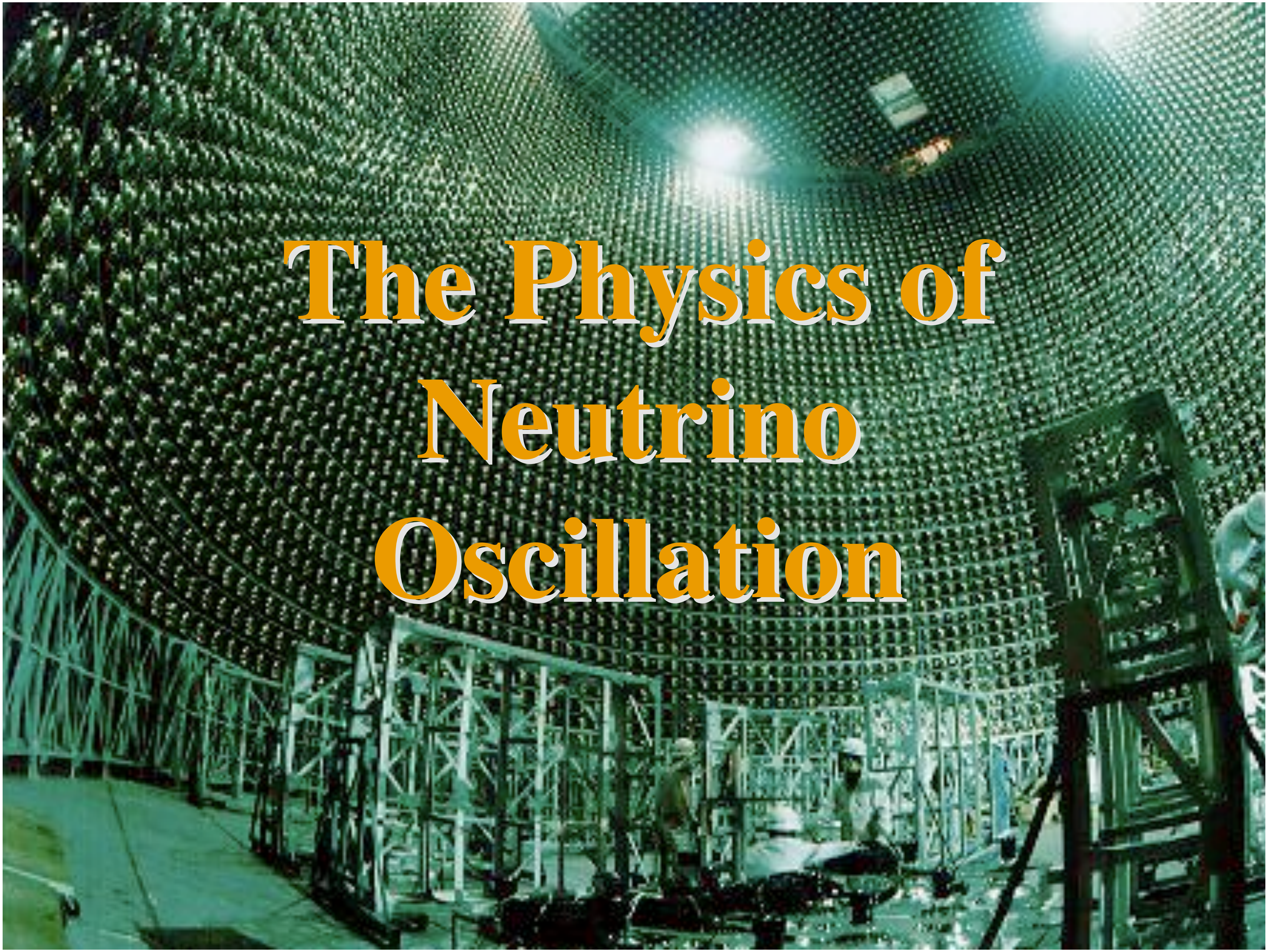
For the lepton couplings to the W boson, we then have —

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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