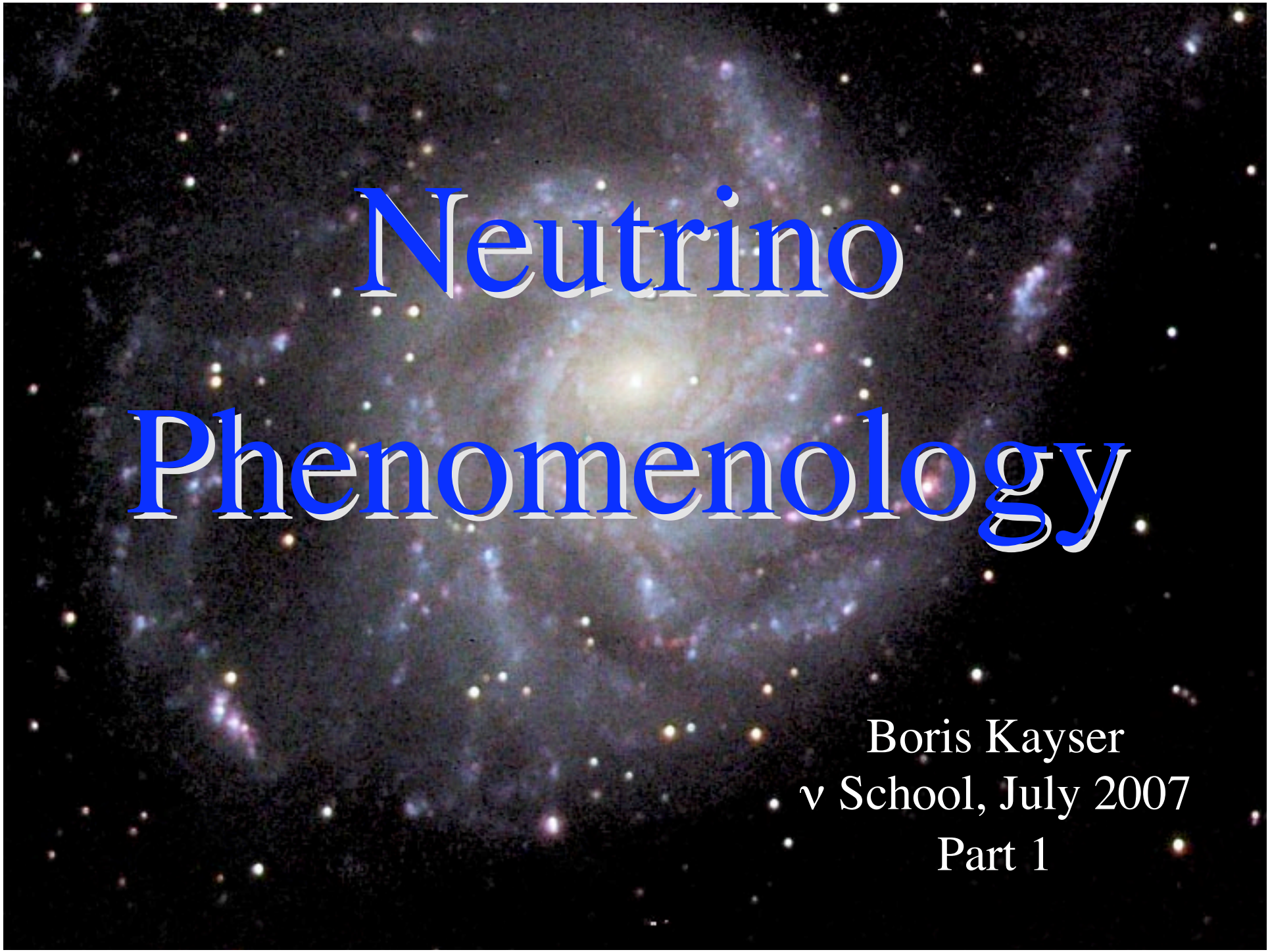

Neutrino
Phenomenology
Boris Kayser
ν School, July 2007
Part 1

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!

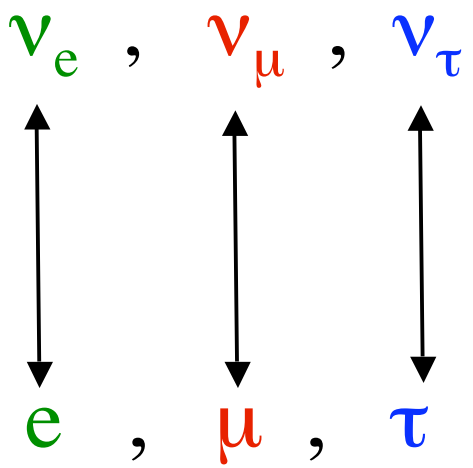
These discoveries come from
the observation of
neutrino oscillation.

The Physics of Neutrino Oscillation

Neutrinos Come in at Least Three Flavors

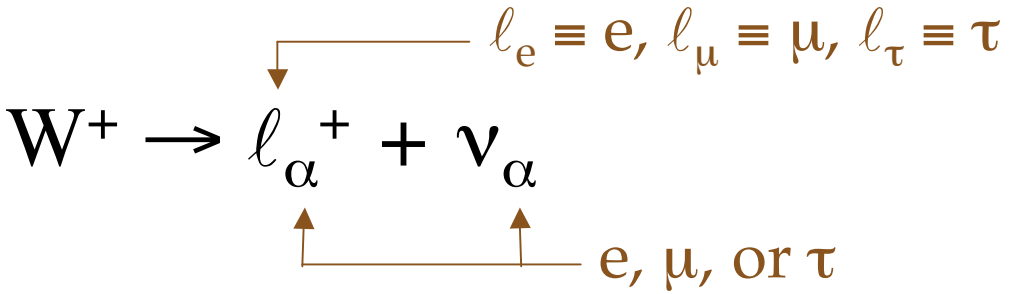
The known neutrino flavors:

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



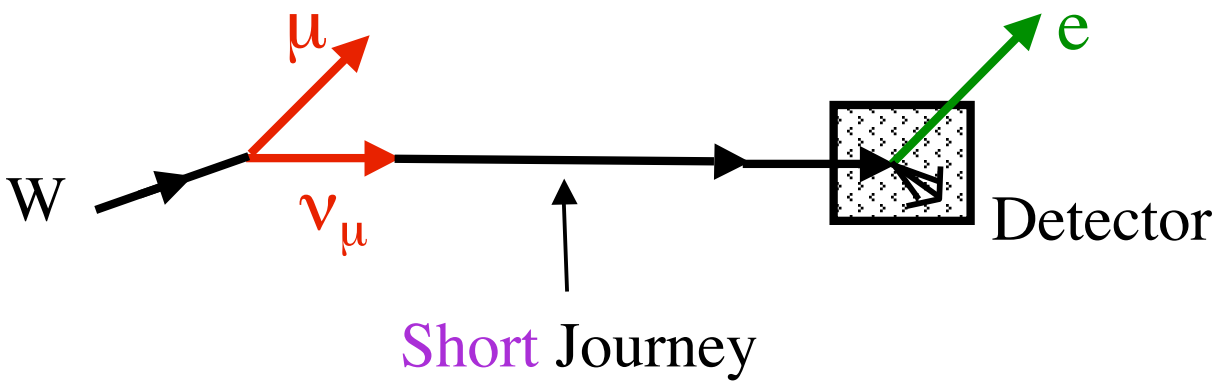
What does *associated* mean?

In leptonic W boson decay —



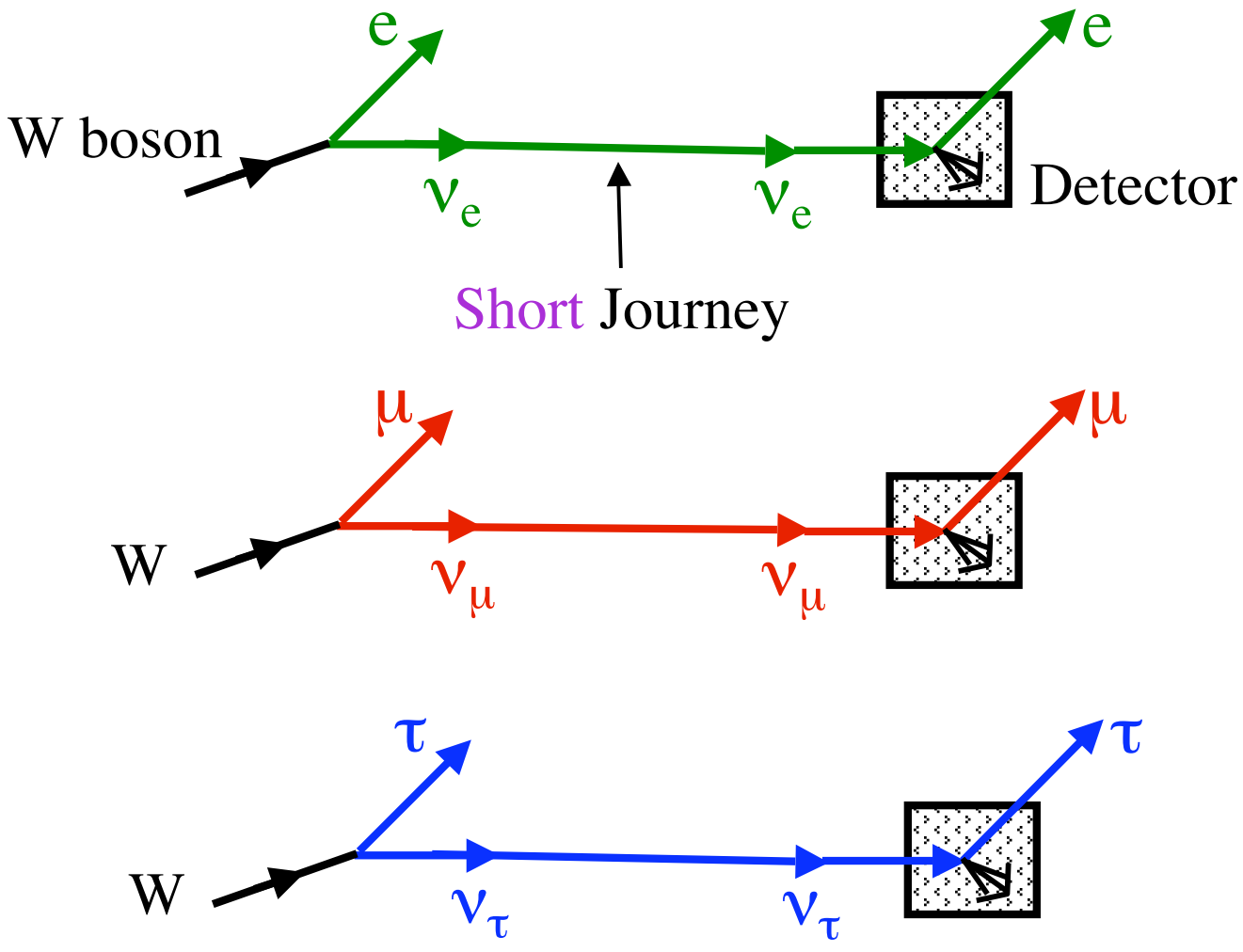
We define ν_α as the neutrino that is emitted together with ℓ_α .

Experiment tells us that ν_e, ν_μ, and ν_τ are ***different*** objects:



Is Not Seen

Rather, what happens is —



The neutrino of flavor α, ν_α, is the one created in W decay together with ℓ_α,

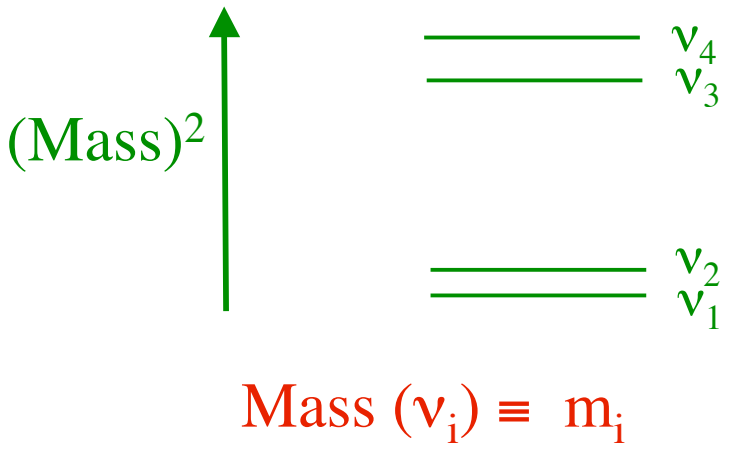
and the one that, when it creates a charged lepton, creates ℓ_α.

But if neutrinos have masses, and leptons mix, then during a ***long*** journey, a neutrino born as ν_α can evolve into something ***different*** that can create a charged lepton ℓ_β of a different flavor from the ℓ_α with which ν_α was born.

Let Us Assume Neutrino Masses and Leptonic Mixing

Neutrino mass —

There is some spectrum of 3 or more neutrino mass eigenstates ν_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

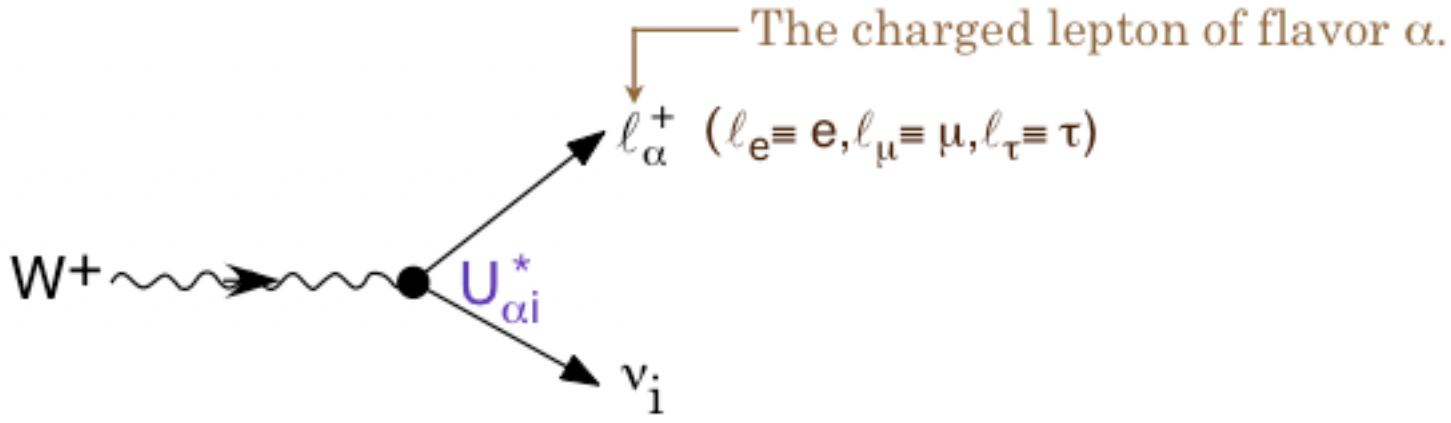
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \ .$$

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.

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

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.

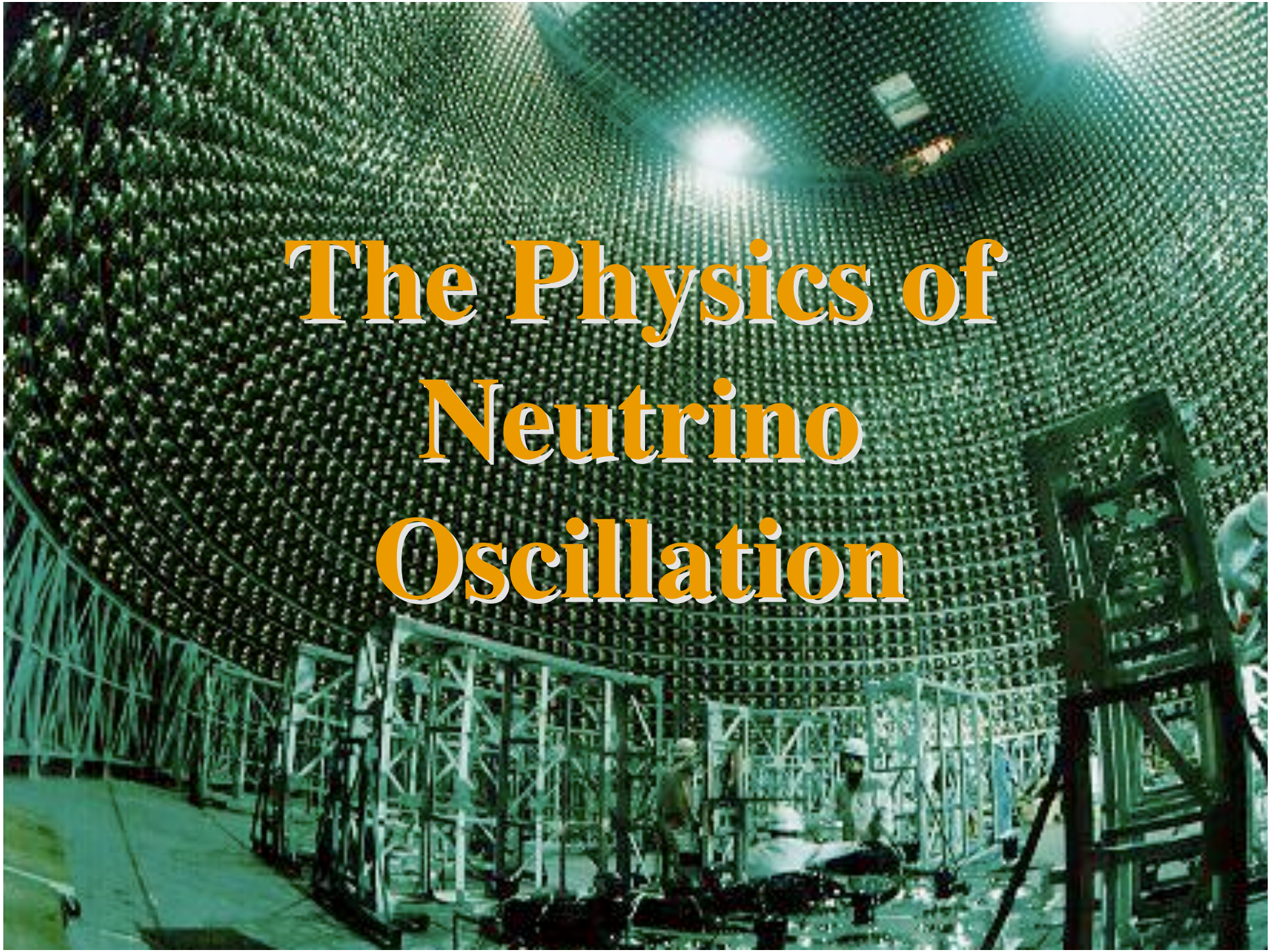
For the lepton couplings to the W boson, we then have —

Left-handed

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

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

Taking mixing into account


The Physics of
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