Neutrinos

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Fermilab
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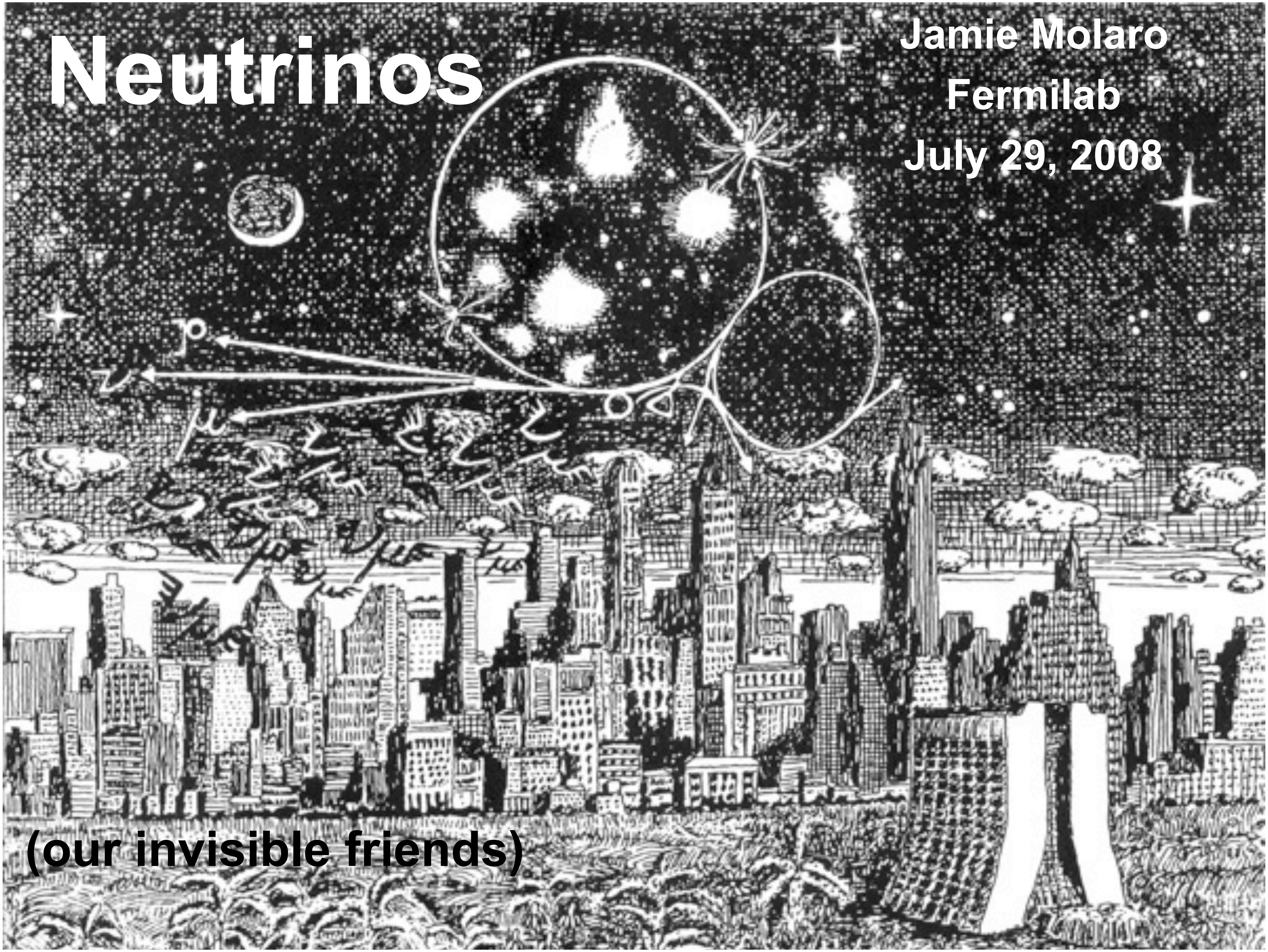
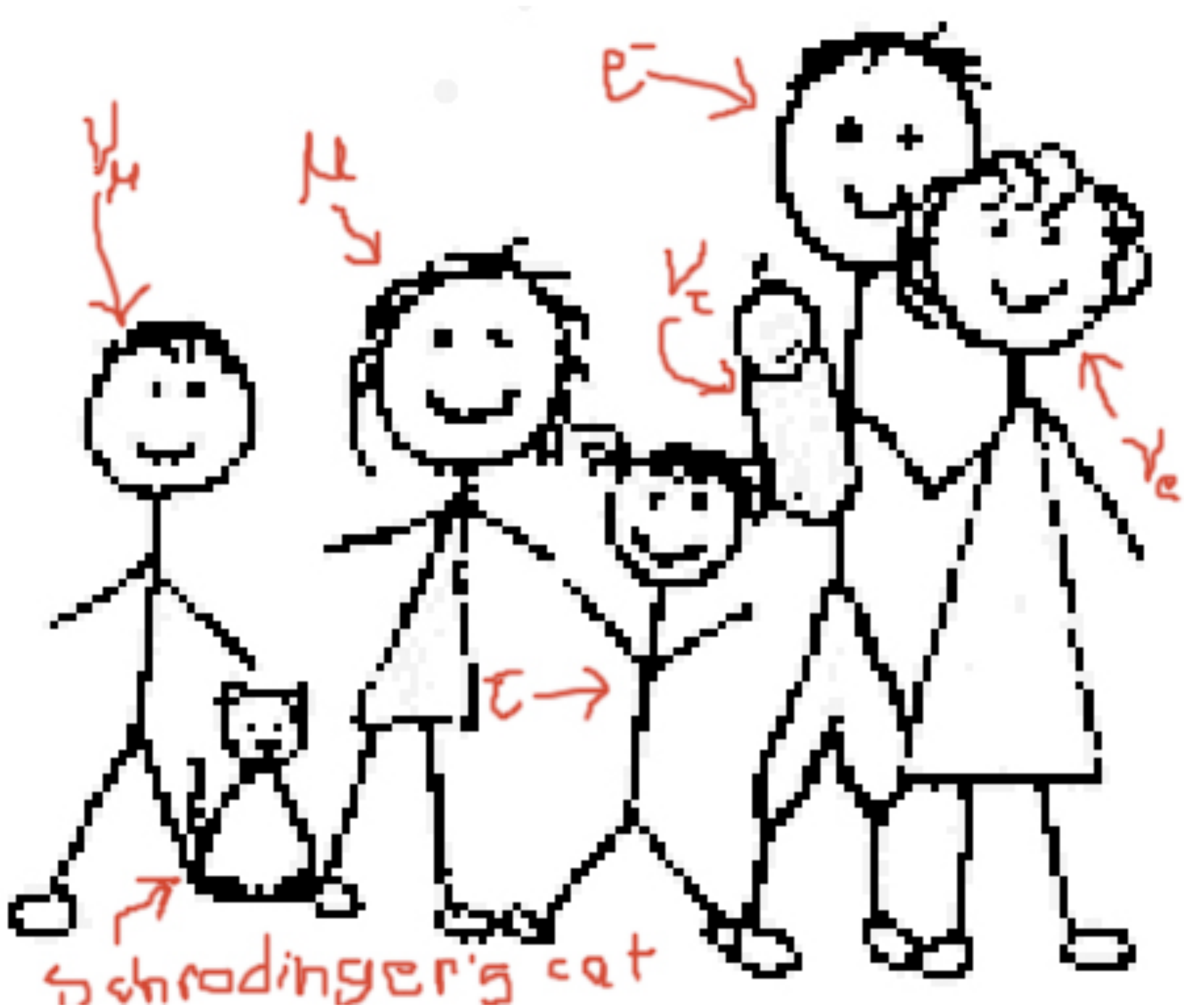


(our invisible friends)

The Lepton Family



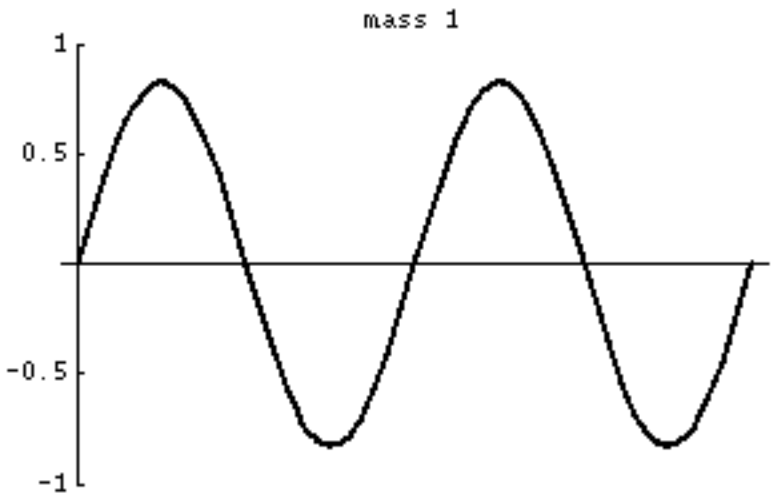
Neutrino Properties

Name:	ν_e	ν_μ	ν_τ
Mass:	<2.2 eV	<170 keV	<15.5 MeV
Charge:	0 (no electric or color charge)		
Spin:	1/2 $\Rightarrow$ Fermions		
Interactions:	Weak, Gravitational		
Antiparticle:	Antineutrinos may be identical to neutrinos.		

Neutrino Oscillations

- The basic idea: a neutrino created as one flavor will change into another flavor as it propagates through space.
- There are 3 flavors and 3 masses. A given neutrino is actually a superposition of these eigenstates.

Creating a superposition:



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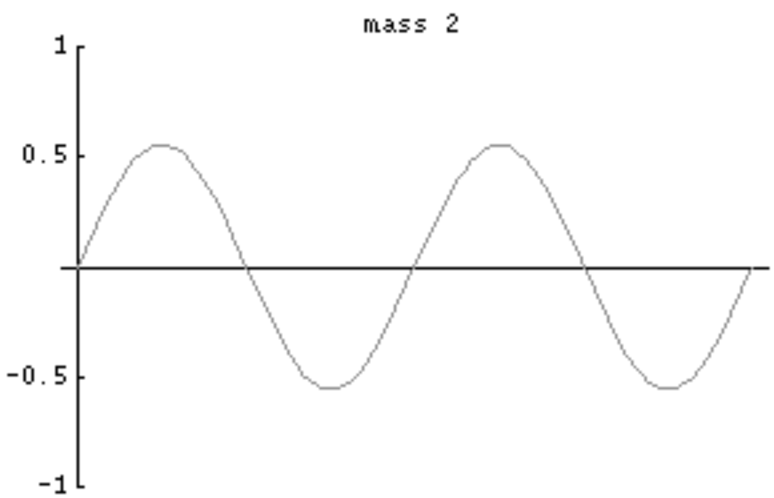

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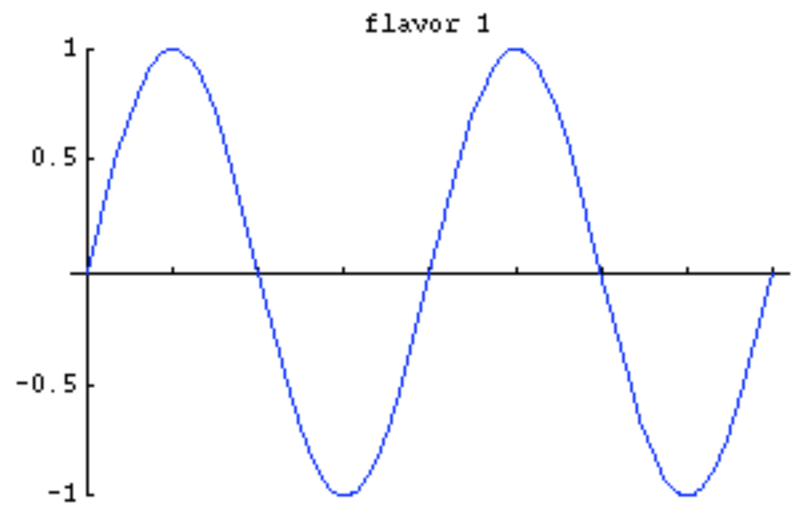
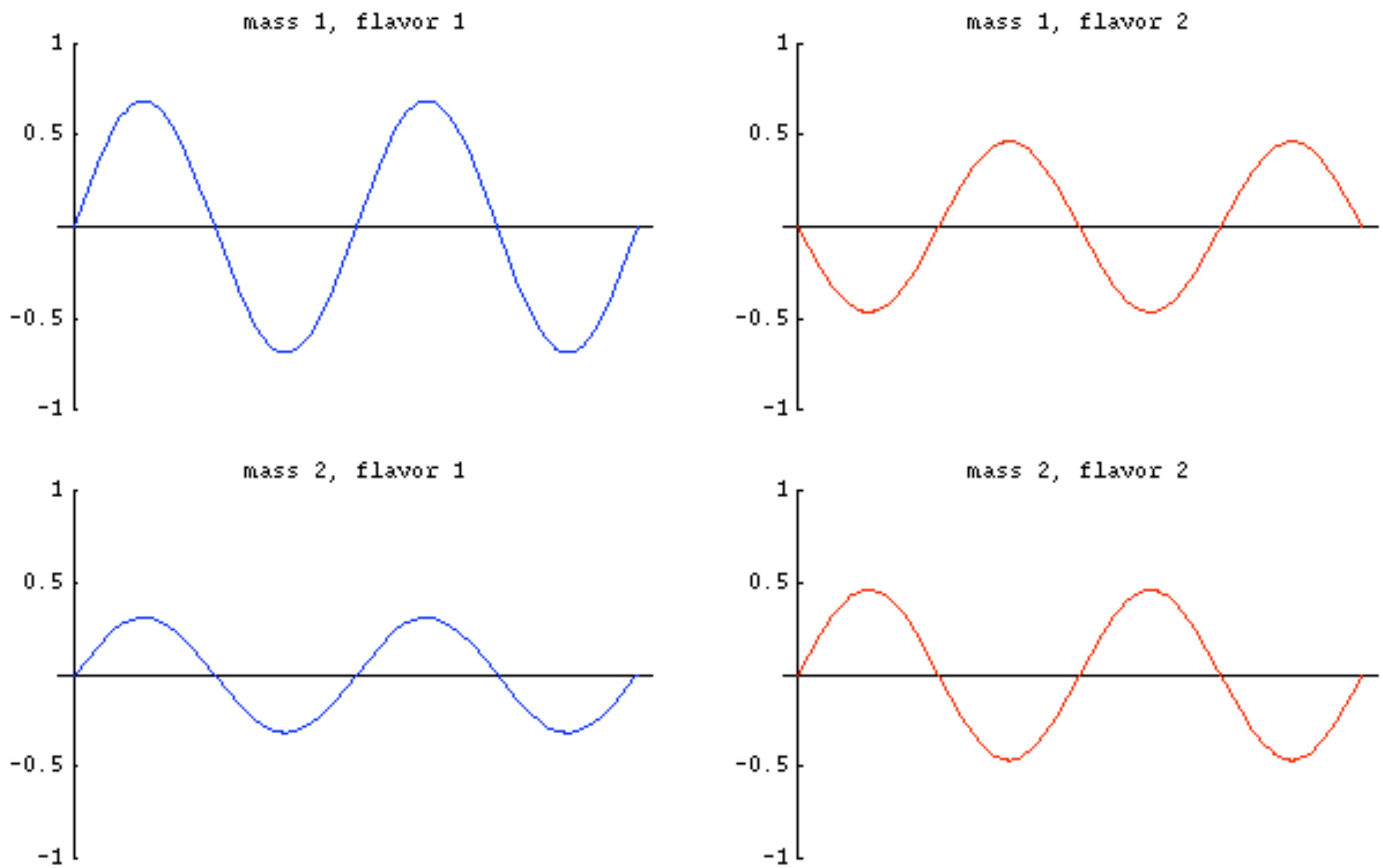
Say flavor 1 is made up of a combination of mass 1 and mass 2 eigenstates



This will be our initial neutrino for this example.

But it's a metasuperposition

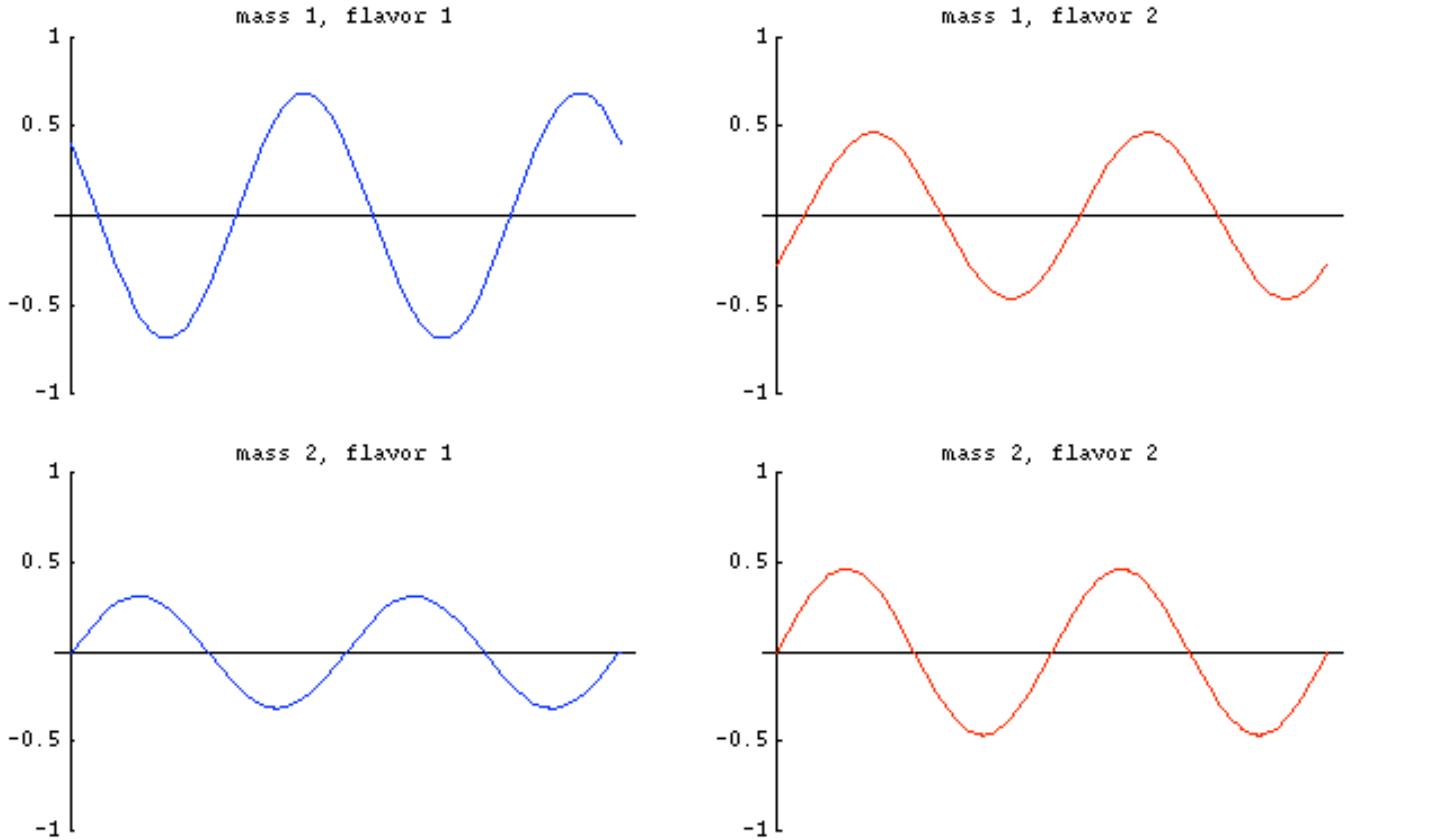
Mass the eigenstates can also be superpositions of flavor eigenstates:



Note that when you add the two flavor 2 mass eigenstates together, they cancel leaving us only with our original, flavor 1 wave.

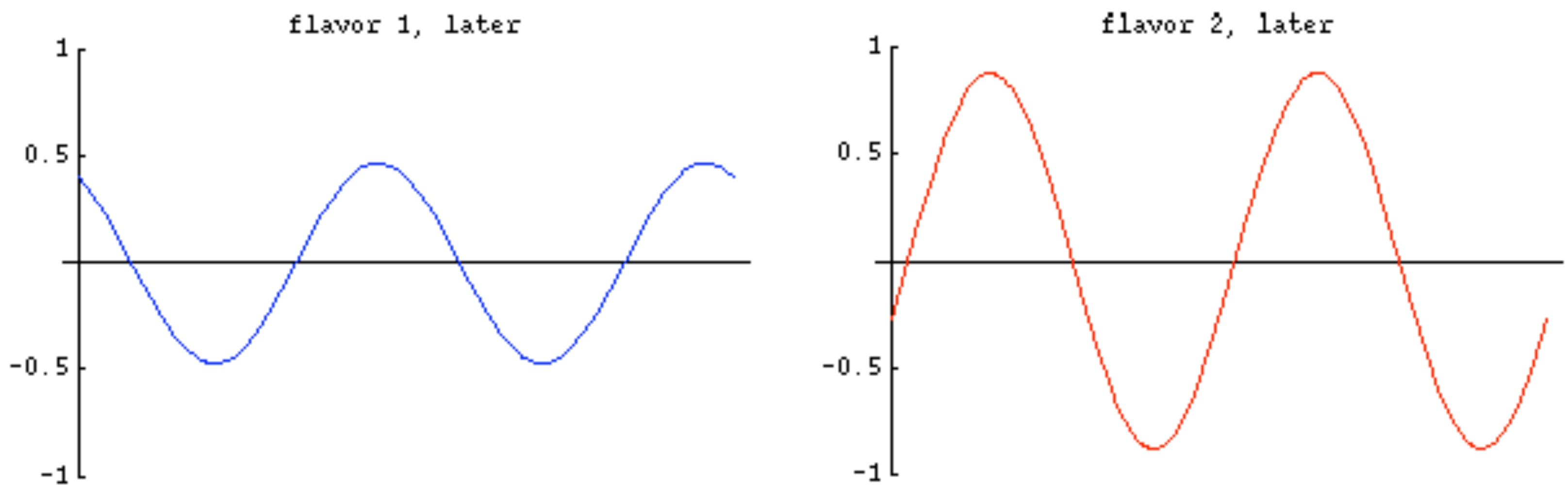
Then time passes

Over time the waves become out of phase with one another…



And our wave changes

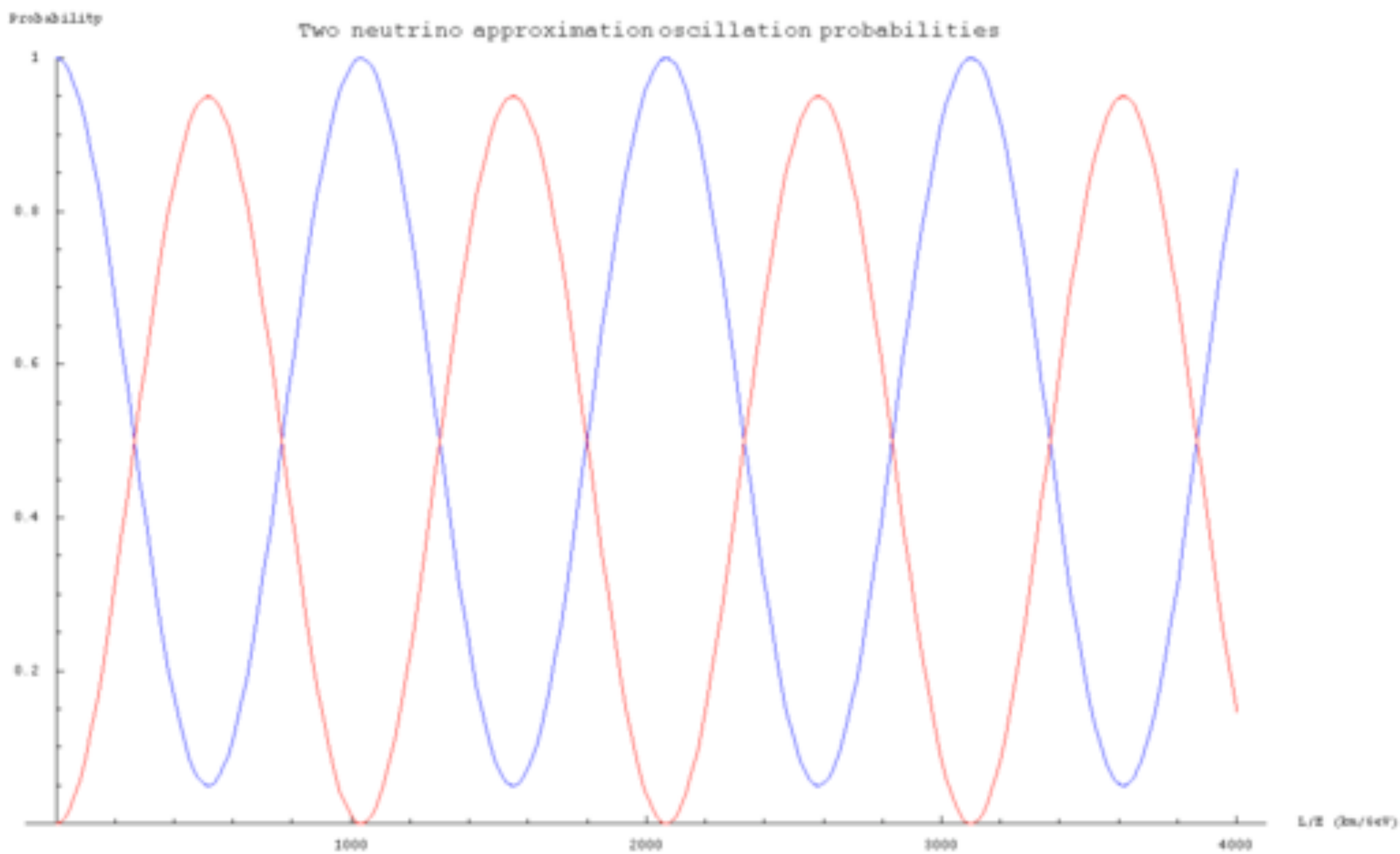
This leaves us with less of flavor 1 and a non-zero amount of flavor 2.



The probability of observing a flavor is equal to the amplitude of the wave squared. If observed at this time, the probability of the neutrino collapsing into flavor 2 is higher than the probability for flavor 1.

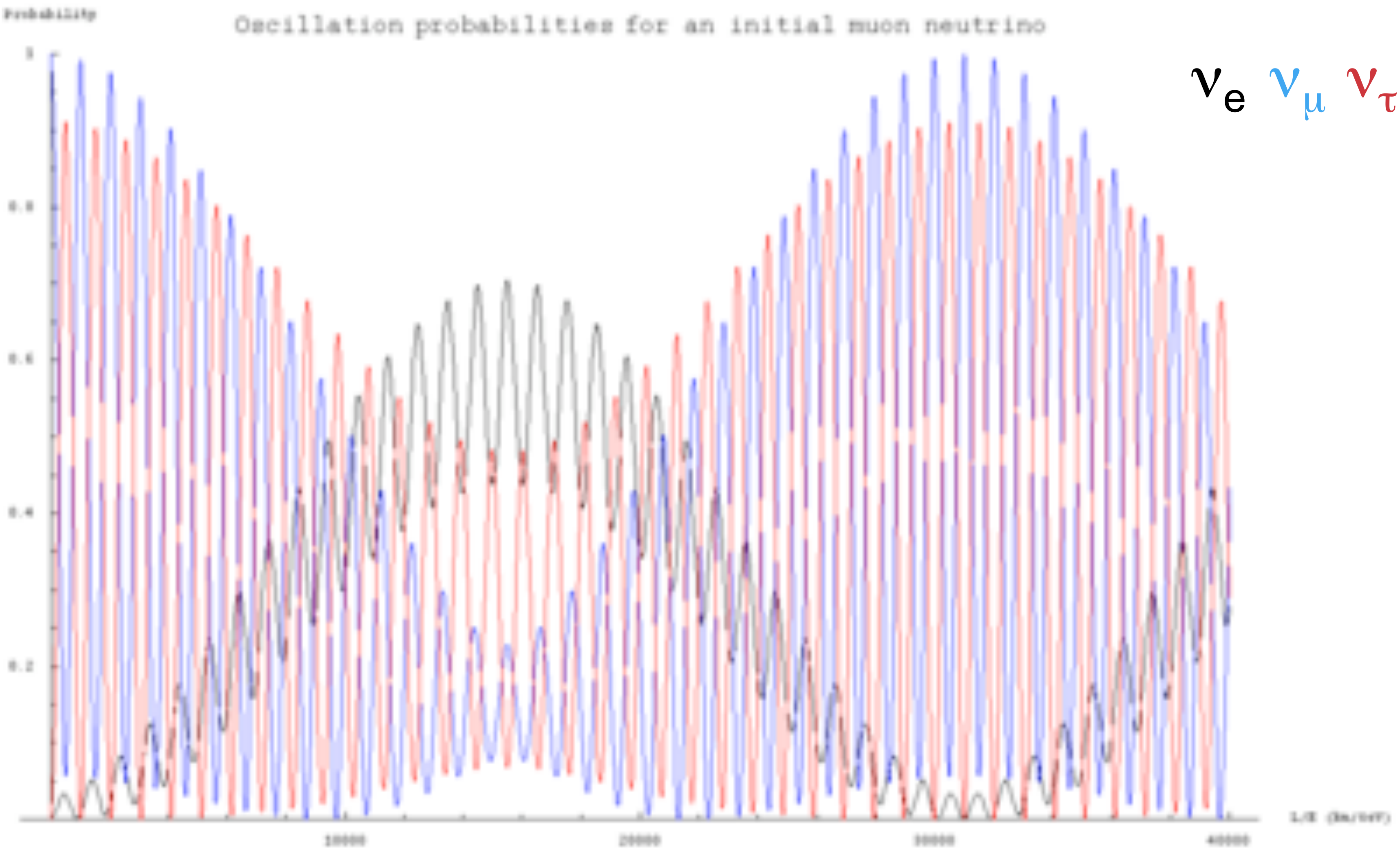
Thus we have an oscillation

The probability of being one flavor or another oscillates back and forth:



And in 3D

Three flavor case, for an initial muon neutrino:



A (very) brief mathematical excursion:

Mathematically, the relationship between the flavor and mass eigenstates is as follows:

$$|\nu_a\rangle = \Sigma_i U_{ai} |\nu_i\rangle$$
$$|\nu_i\rangle = \Sigma_a U_{ai}^* |\nu_a\rangle$$

where the neutrino flavor is given by a = e, μ, τ and the neutrino mass is given by i = 1, 2, 3, and U is the neutrino mixing matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ θ = mixing angle

Oscillation Probability

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{ (natural units)}$$

L = Distance traveled by neutrino

Δm^2 = mass squared difference between mass eigenstates in question

θ = mixing angle

Theta13

- Some terms in U have an additional factor δ. This factor is non-zero only if neutrino oscillation violates CP symmetry. Also notice that each of these terms is proportional to theta13.

- Knowledge of the order of magnitude of theta13 could help guide us in building experiments that probe CP violation in weak interactions.

Family Secrets

- **What is their mass?**
  - Finding oscillation statistics could help us calculate their masses. Determining the mass is important to many things, including dark matter calculations.
- **Are they their own antiparticle?**
  - If neutrinos are their own antiparticles then the neutrinoless double beta decay process is allowed (2n -> 2p +2e instead of 2n -> 2p +2e + 2ν). There are several experiments looking for this.
- **What is the length of each oscillation?**
- **Why is theta13 so small?**
  - What can it tell us about CP violation?

In the future, the lepton family hopes to:

- Discover new physics regarding CP-violation, weak interactions, antimatter and dark matter.
- Teach us more about quantum gravity effects, since it is not affected EM or strong interactions.
- Allow deeper astronomical probing by using sort of "neutrino telescope."
- Go on a family vacation.
- Achieve world peace.

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Image Sources:

Slide 1: http://history.fnal.gov/GoldenBooks/gb_lmlsec.html

Slide 2: http://www.rebekahherzog.com/?p=92

Slide 6-12: http://en.wikipedia.org/wiki/Neutrino_oscillation

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