Neutrino Oscillation and Mixing

Alexis Olsho
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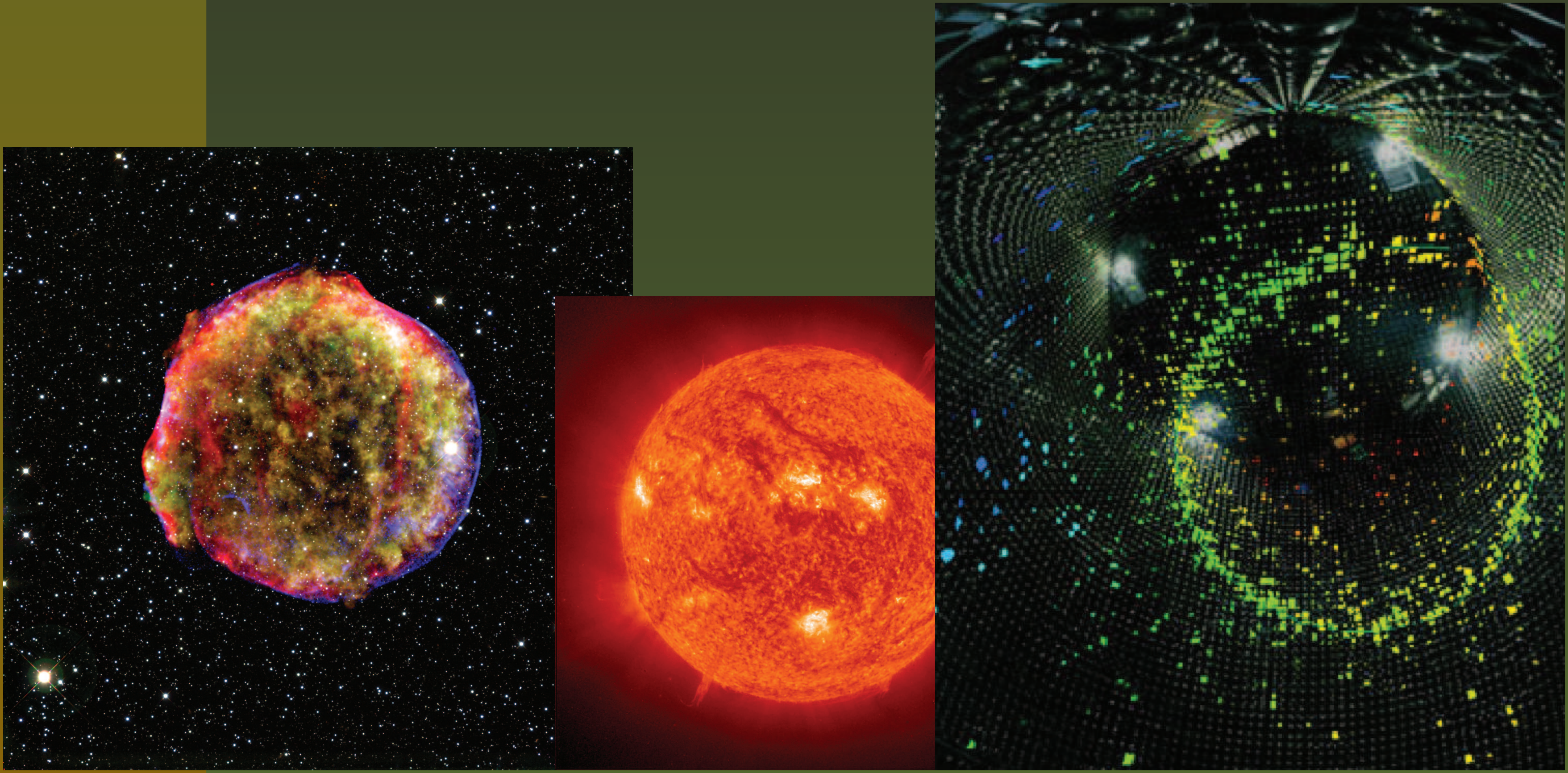
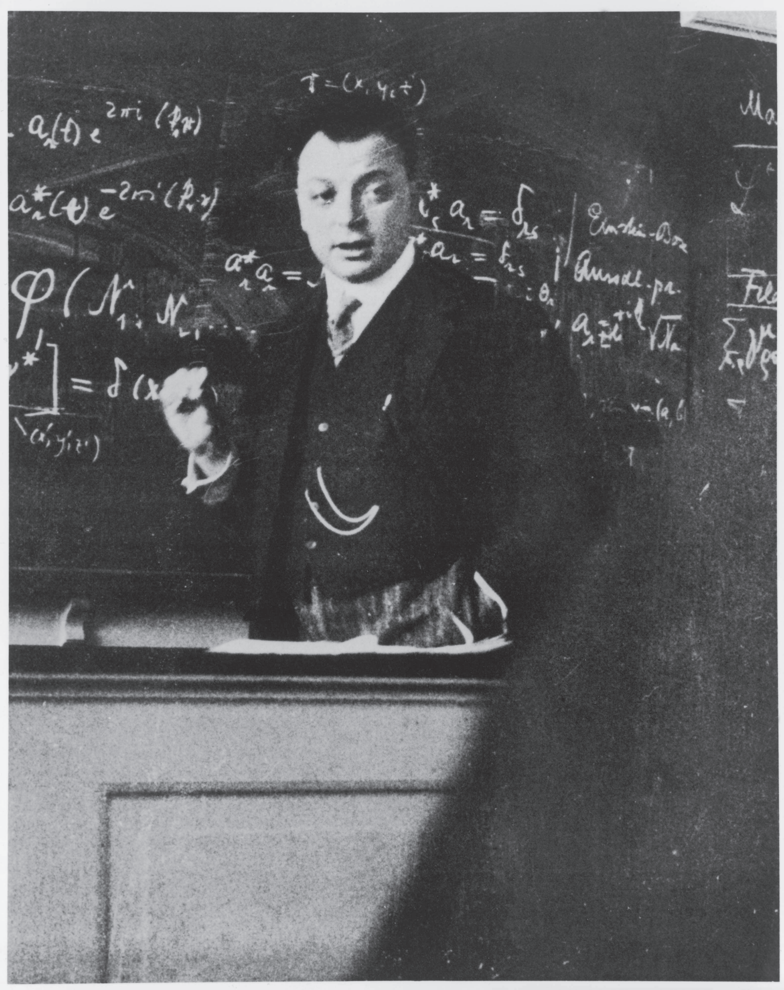


A Problem with Beta Decay



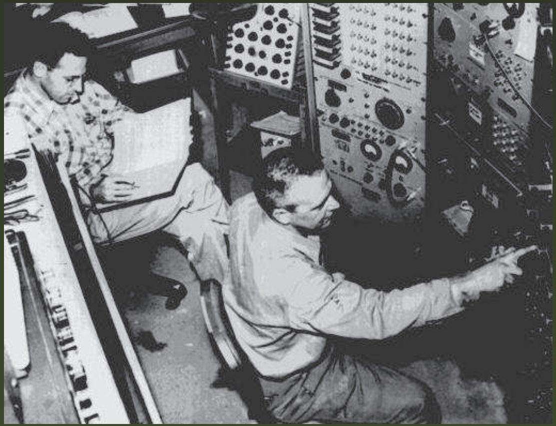
- β^- decay seemed to violate conservation of energy and angular momentum.

- Pauli to the rescue! $n \longrightarrow p + e^- + \nu$

- The neutrino had to be light (massless?), charge-less, and with spin $\frac{1}{2}$.

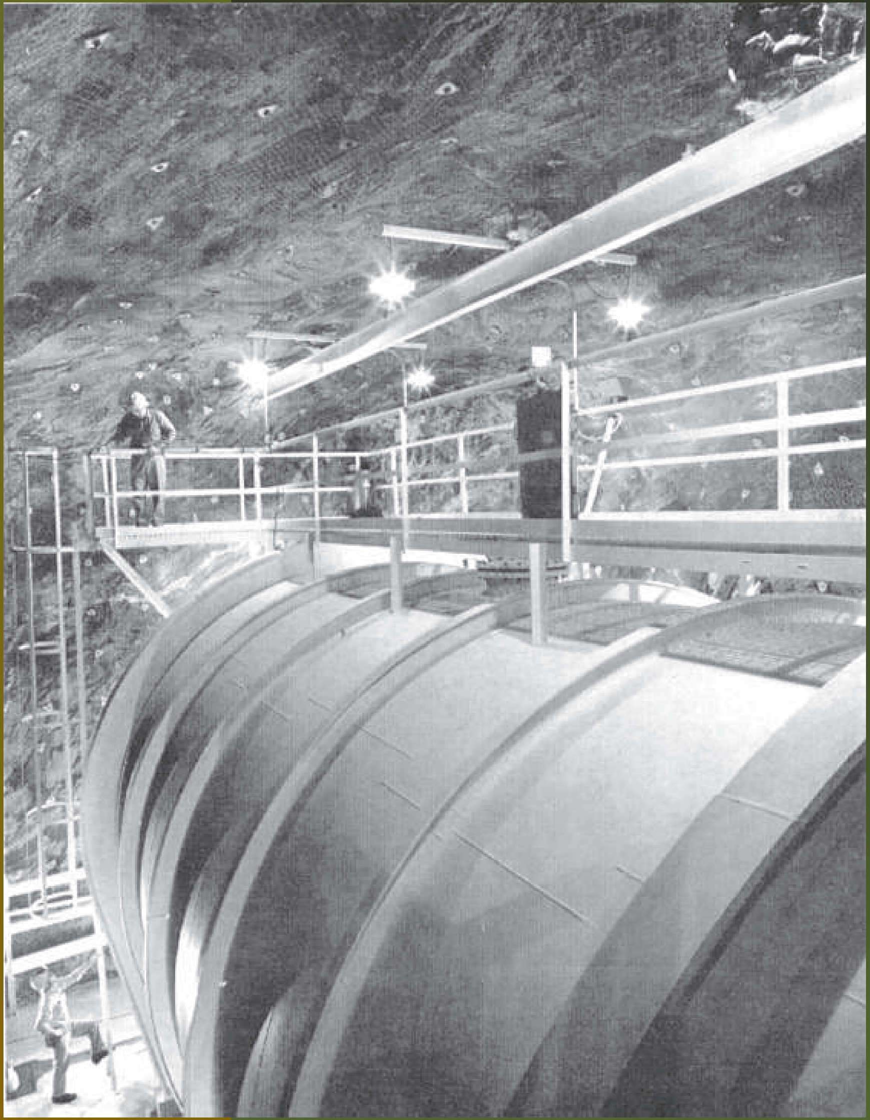
Detection!

- A method for neutrino detection using reverse β decay ($\bar{\nu}_e + p \rightarrow n + e^+$) was suggested by Wang in 1942



- The first antineutrino was detected in 1956 in the Cowan and Reines neutrino experiment.
- Neutrinos: now in three exciting flavors!

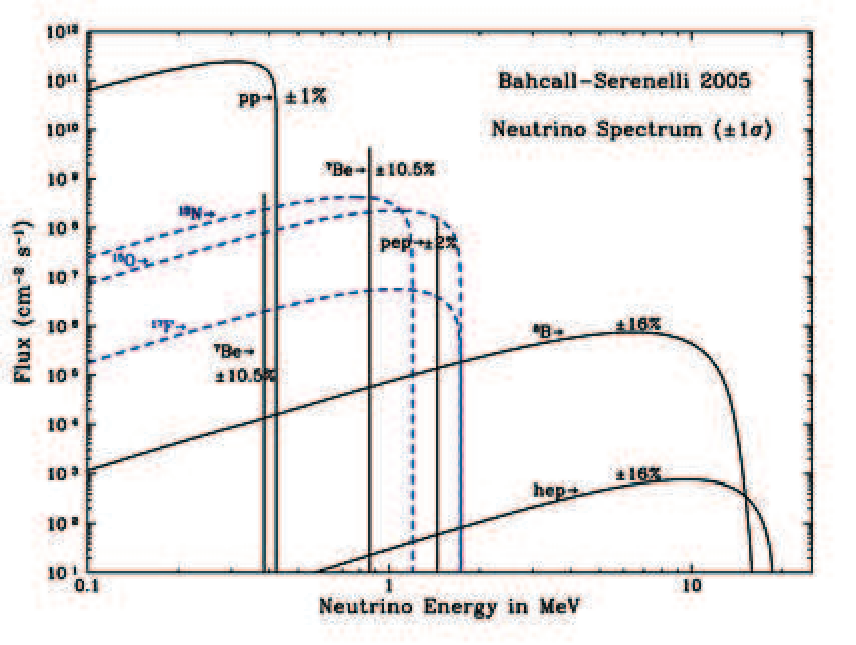
Not Enough Detection!



- Theoretical solar neutrino flux was calculated by John Bahcall.
- Ray Davis: Looking for solar neutrinos (1967). $\nu_e + ^{37}\mathrm{Cl} \longrightarrow e^- + ^{37}\mathrm{Ar}$
- Where have all the electron neutrinos gone? (The Solar Neutrino Problem)

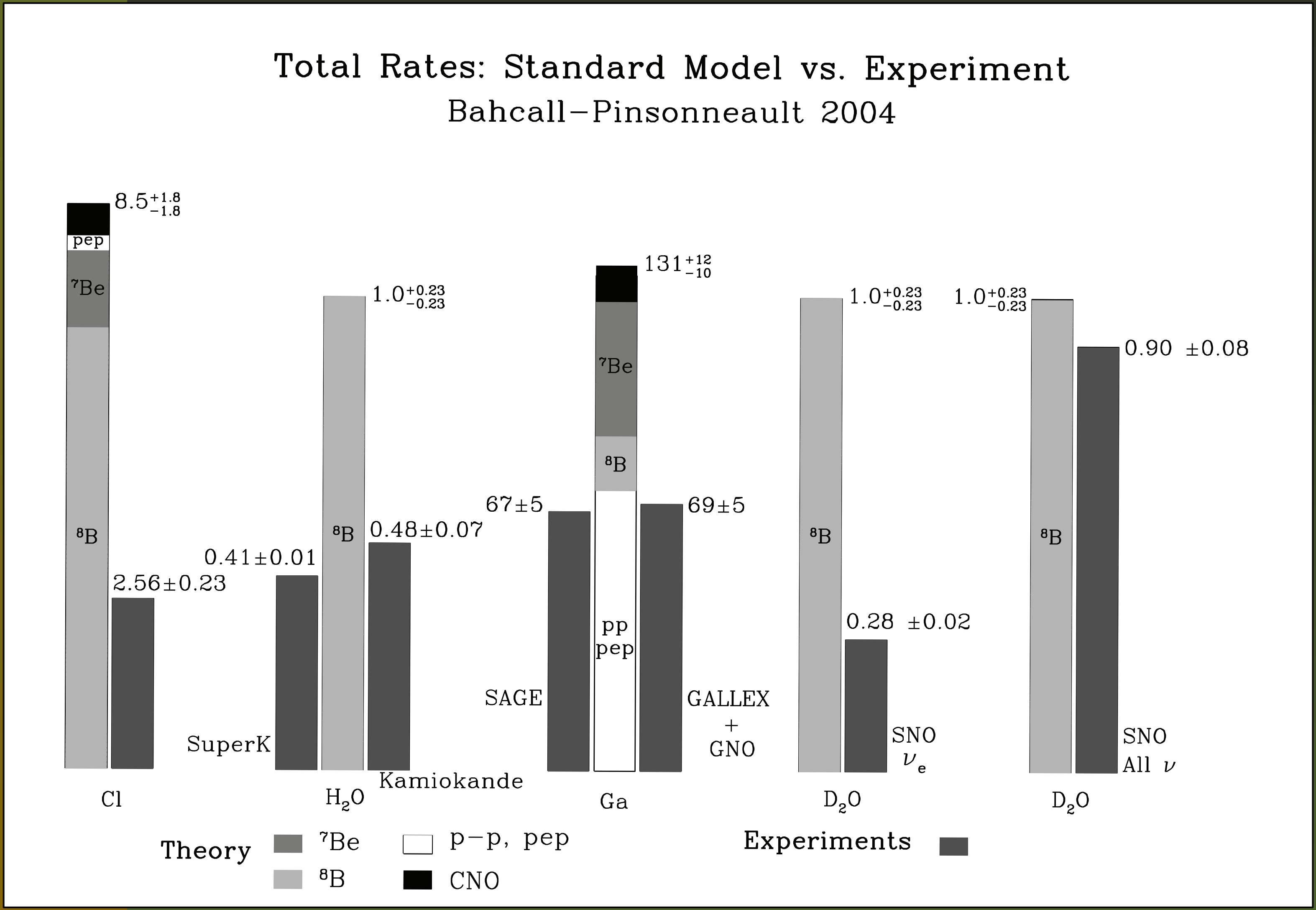
More Missing Neutrinos?

- Other experiments seem to show solar neutrino deficits as well.



- GALLEX, KamiokaNDE, and SNO search for neutrinos of different energies.
- Searches for atmospheric neutrinos (Kamiokande II, Super-K) also show deficits.

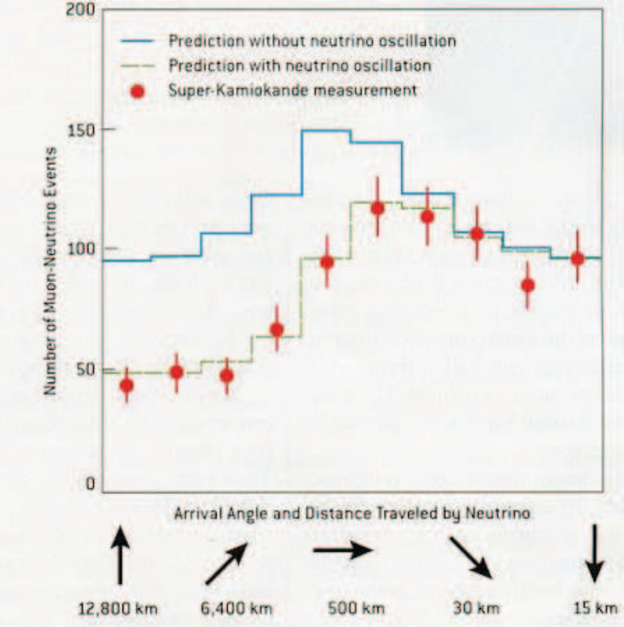
Some Data



Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2004

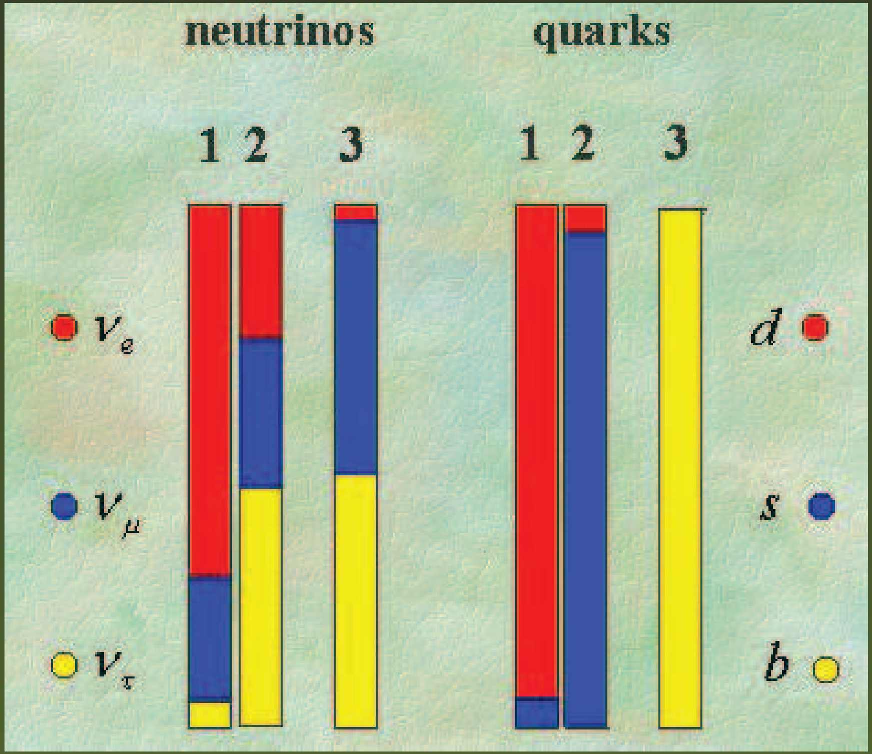
Convincing Evidence



- Data from GALLEX and SNO were particularly compelling.
- GALLEX was able to detect low energy neutrinos with high efficiency
- SNO was the first detector to look for all three flavors of neutrino.

Oscillate Wildly?

- A possible solution: neutrino oscillations.
- Neutrinos in disguise!
- A lesson from quarks.



Massive Implications

- Mixing $\longrightarrow$ mass?
- According to special relativity and quantum mechanics, neutrino oscillation would require $m_\nu > 0$
- The Standard Model does not require neutrinos to be massless.

Neutrino Oscillation

- Consider the three flavor eigenstates (ν_e, ν_μ, and ν_τ) and the three mass eigenstates (ν_1, ν_2, and ν_3) of neutrinos.
- For oscillation to occur, the flavor eigenstates must be different from the mass eigenstates.
- The neutrino flavor state ν_α is a superposition of mass eigenstates:

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

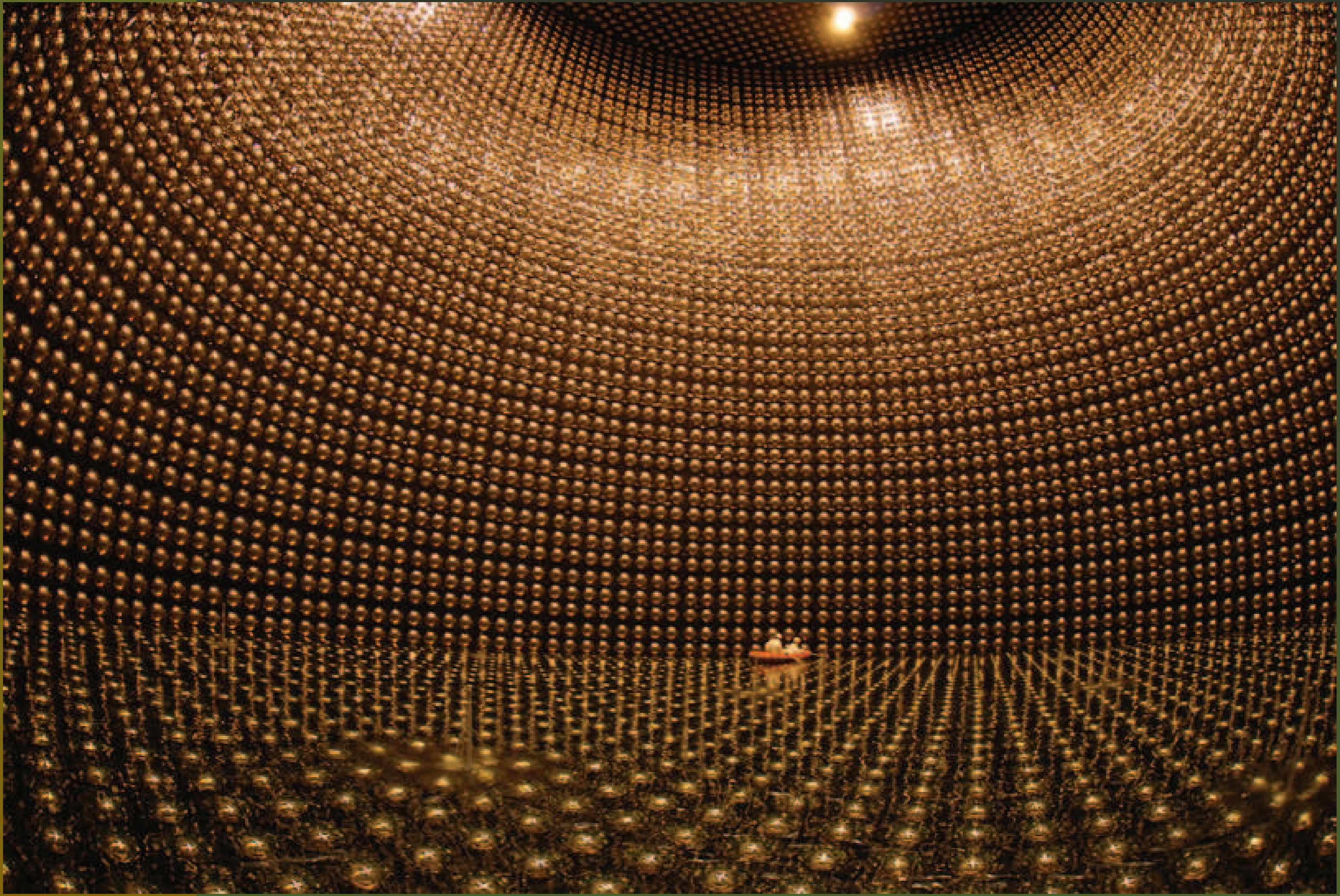
The Mixing Matrix

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

- U is known as the mixing matrix
- For the three eigenstate case, the mixing matrix is

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

Deep Breath



The Mixing Matrix, cont.

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

- The phase factor, δ, is only non-zero if neutrino oscillation violates CP symmetry. (more next time?)

- Oscillations occur because the different mass eigenstates move with different speeds.

Next time

- Upper limits on neutrino mass–why so small?
- What are the implications of neutrino mass?
- What are the mechanisms of neutrino mass, and why does it matter?