Neutrino Mass and the Evolution of the Universe

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The Story So Far

- Neutrinos were proposed as a solution to problems with β-decay.
- For years, the three varieties neutrinos were presumed to be massless.
- Eventually, it was found that neutrinos can change their flavor, indicating that they must have some mass.
- Neutrino oscillation is described by the "mixing matrix":

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

The Mixing Matrix

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

- The mixing matrix describes the probability of a neutrino with a definite mass (1, 2 or 3) to be in a particular flavor eigenstate (e, μ or τ).
- The matrix depends on the phase δ, and three mixing angles: θ_{12}, θ_{23}, and θ_{13}. θ_{12} and θ_{23} are known (approximately):

$$\theta_{12} \sim 32^\circ \quad \text{and} \quad \theta_{23} \sim 45^\circ$$

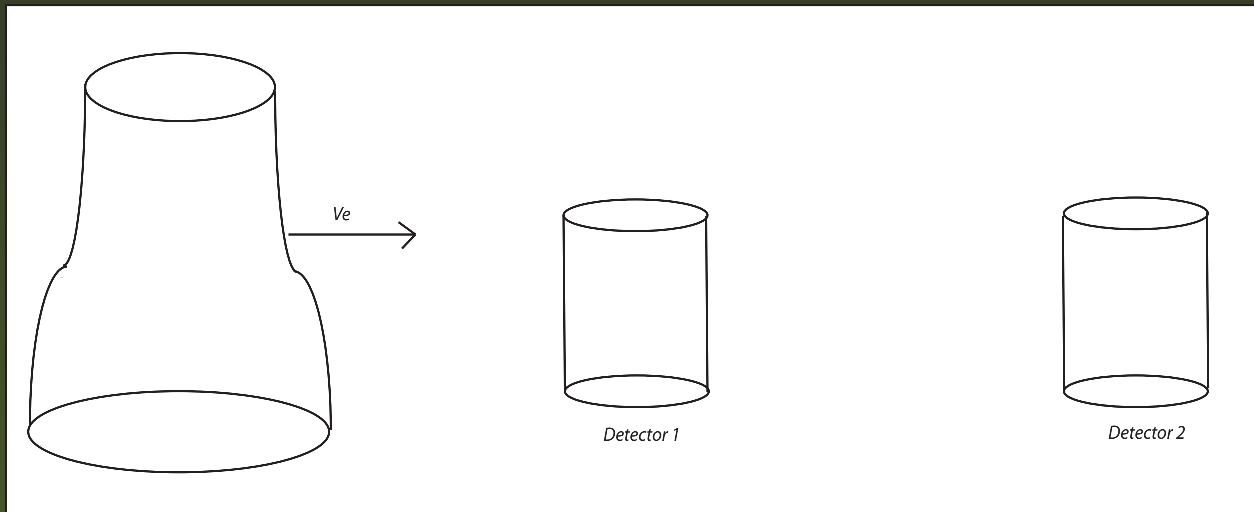
- The mixing angle θ_{13} is not known, but is believed to be much smaller ($< 3.2^\circ$)

Finding θ_{13}

- Determining a value of θ_{13} will complete our knowledge of mixing
- The other two mixing angles are measured by solar neutrinos (θ_{12}) and atmospheric neutrinos (θ_{23})
- There are two major types of experiments being done in the attempt to find θ_{13}: accelerator experiments and reactor experiments.
- I'll focus on two of the reactor experiments: Daya Bay (China) and Double Chooz (France)

Reactor Experiments

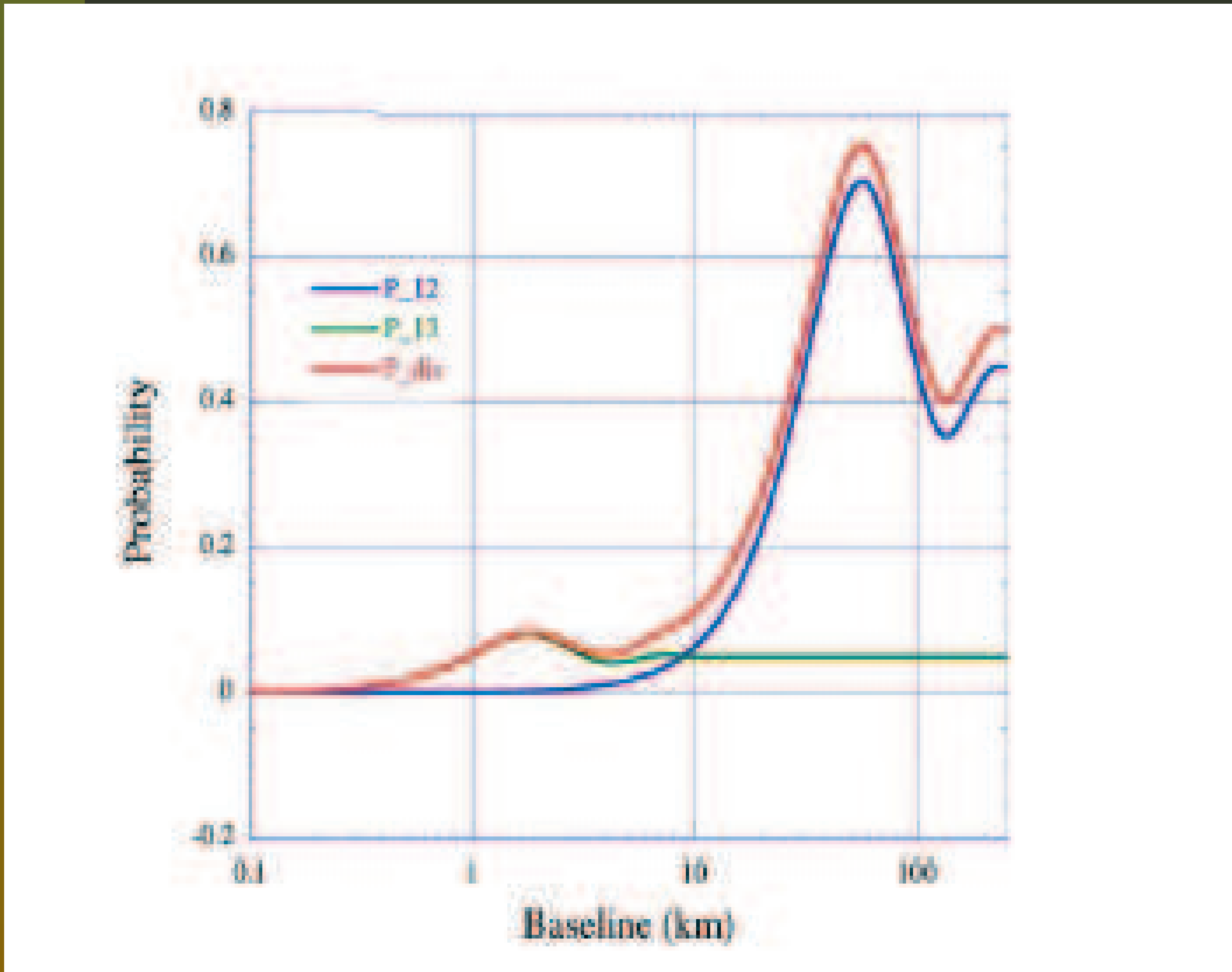
- In reactor experiments, physicists look for a change in flux of electron antineutrinos over some distance.



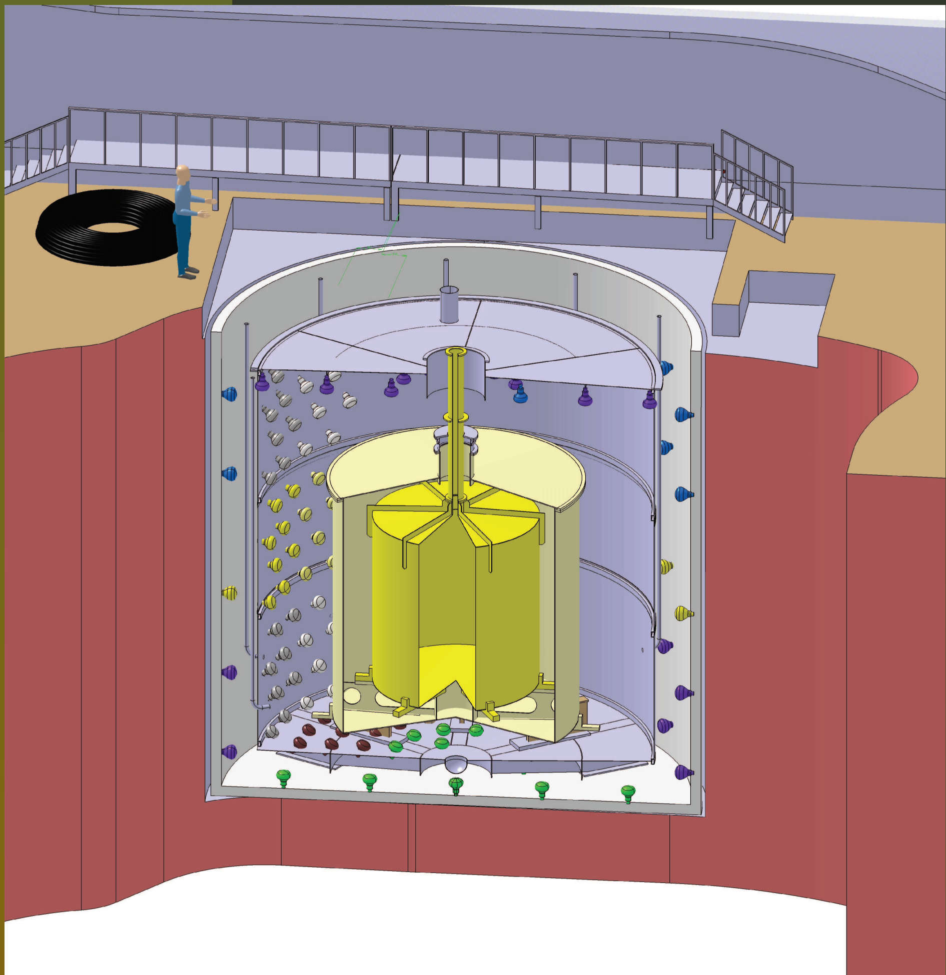
- The survival probability of reactor antineutrinos is described approximately by

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

Reactor Experiments



Detecting Neutrinos



- Detectors are filled with Gd-doped fluid that "detects" reverse β-decay: $\bar{\nu}_e + p \longrightarrow n + e^+$
- Researches look for distinctive γ-ray "double-burst" from $e^- + e^+$ and n capture

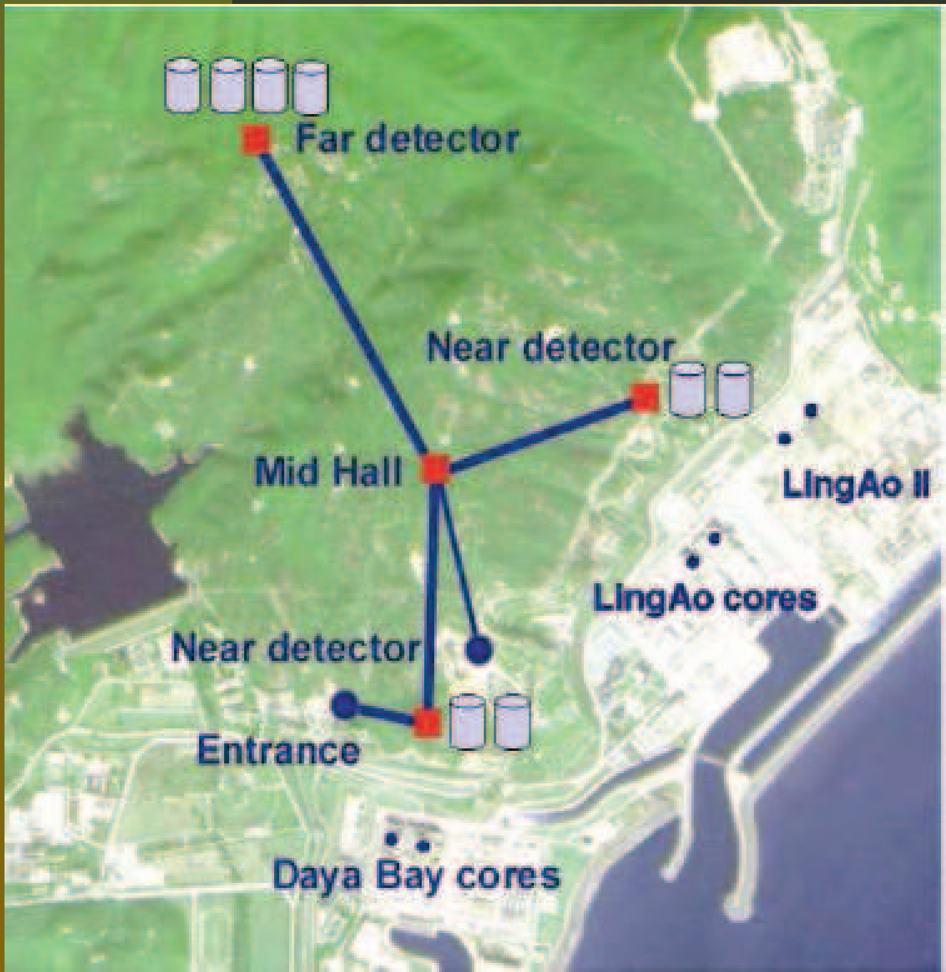
Daya Bay

http://dayabay.bnl.gov/

- Being constructed in China, outside of Hong Kong; data collection starts in June 2010.

- Will detect antineutrinos from two (eventually three) nearby plants: Daya Bay and LingAo (total power 11.6 GW), with a third plant (with an additional 5.8 GW power) being commissioned by 2010.

Daya Bay



Daya Bay Proposal, Daya Bay Collaboration

- Three detector sites with a total of 8 identical detectors
- After 3 years of data collection, experimenters hope to have a value of $\sin^2 2\theta_{13}$ with a sensitivity of 0.008

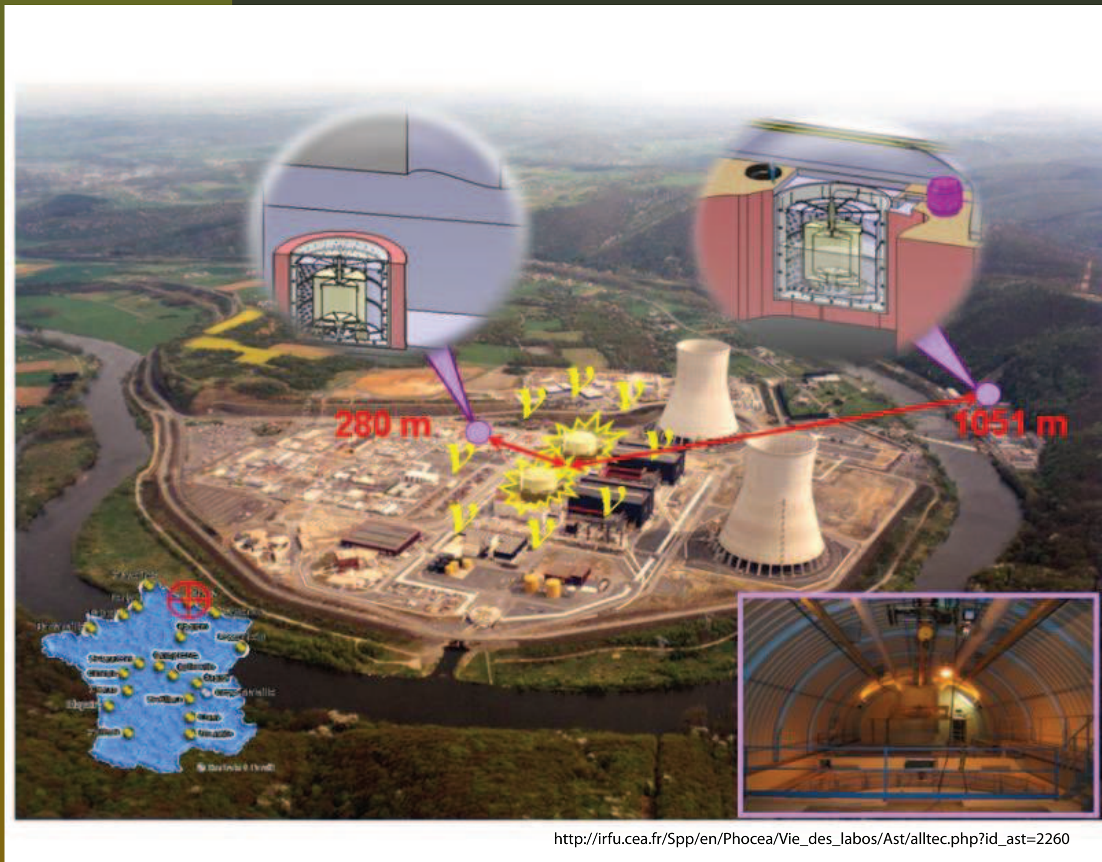
Double Chooz

http://doublechooz.in2p3.fr/Scientific/Photos/vue_laterale_Centrale_Chooz.jpg

- Detecting antineutrinos from a pair of reactor cores at Chooz nuclear power plant, in France.

- Total output of power plant is ~ 8.6 MW.

Double Chooz



- Two sites with near-identical detectors
- After three years of data collection, experimenters expect to have a value of $\sin^2 2\theta_{13}$ with a sensitivity of 0.025.

θ_{13} and CP violation

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

- A non-vanishing value of θ_{13} would imply that neutrino oscillation is CP violating, which would be the first evidence of leptonic CP violation.
- If the reactor experiments put an upper bound of < 0.01 on θ_{13}, then CP violation in neutrinos would be essentially insignificant.
- Even if neutrino oscillations are found to be CP violating, it's possible that it's not the CP violation for which we are seeking.

Neutrino mass and the evolution of the universe

- “What are the masses of the neutrinos and how have they shaped the evolution of the universe?”
- The universe has an apparent “overabundance” of matter, and “deficit” of antimatter.
- It is known that CP violation in quarks contributes to this matter/antimatter imbalance, but it is also known that their contribution is not large enough to explain the imbalance
- If neutrino oscillations are significantly CP violating, we have another candidate to help explain the imbalance.