Status of the Solar neutrino problem ~2000

Several different experiments found neutrino fluxes smaller than the theoretical prediction:

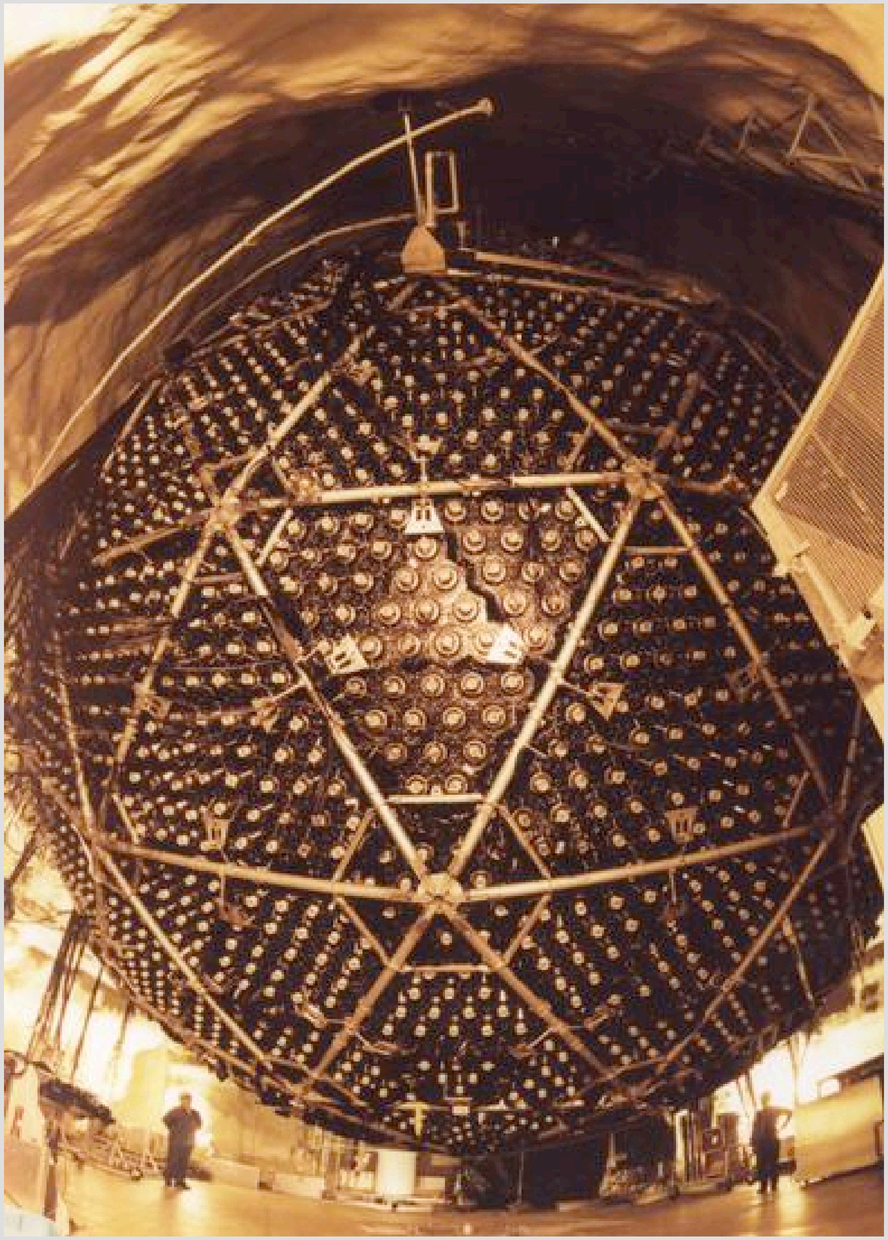
- **Chlorine** (E > 0.8 MeV) - 34%
- **Gallium** (E > 0.2 MeV) - 55%
- **Ordinary water** (E > 5 MeV) - 48%

Two possible explanations:

Sun is producing fewer neutrinos than expected. Gallium results meant that a fairly serious error in Solar structure would have been implied by this…

Electron neutrinos are being produced in the Sun at the \`right' rate, but are being \`lost' on their way to Earth.

Sudbury Neutrino observatory



Water cherenkov radiation detector, but uses heavy water D_2O rather than H_2O.

~1000 tons of D_2O, situated at 7000 foot depth in a mine.

Use of D_2O allows three separate classes of neutrino interaction to be detected:

Charged current $$\nu_e + d \rightarrow p + p + e^-$$

Like the Cl -> Ar reaction (requires changing a neutron into a proton). **Only** works for electron neutrinos.

Elastic scattering $$\nu_x + e^- \rightarrow \nu_x + e^-$$

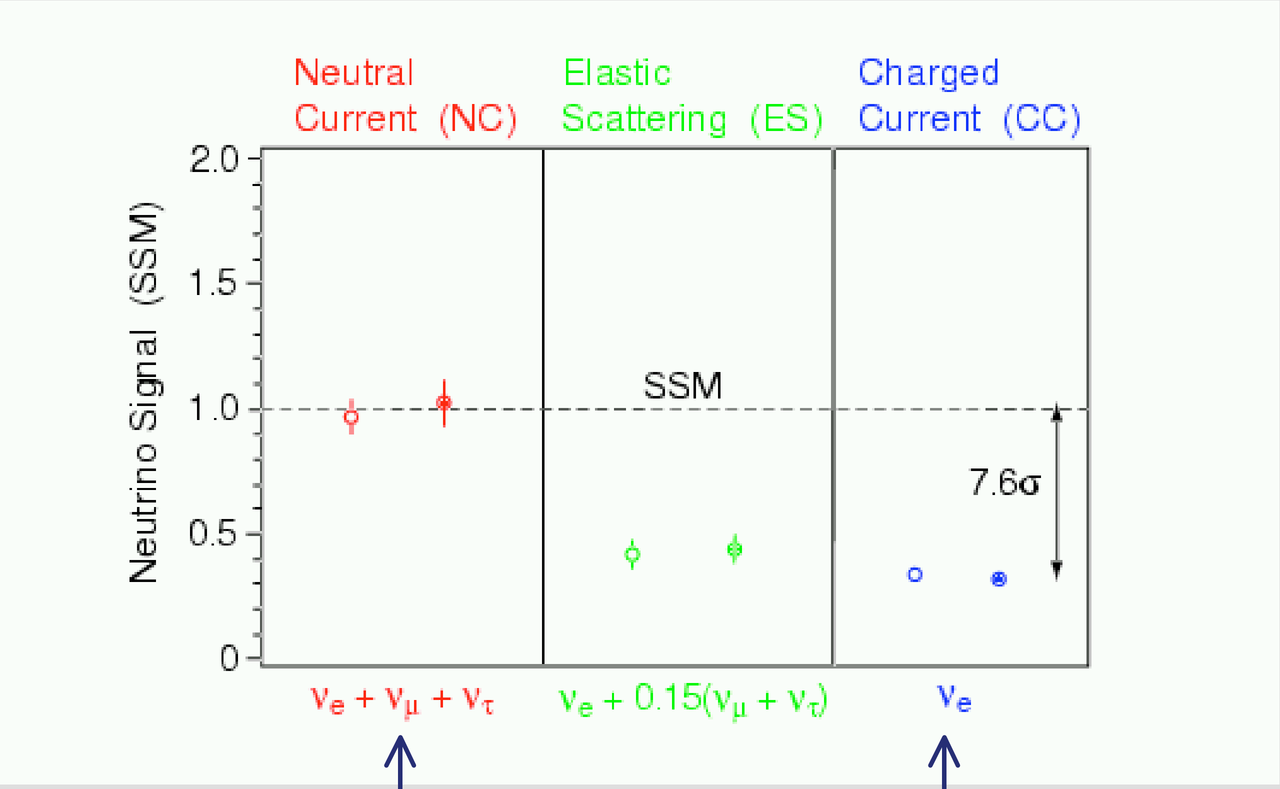
Same reaction as in Super-Kamiokande. Works for all neutrinos, but **much smaller** cross-section (15%) for muon or tau neutrinos as compared to electron neutrinos.

Neutral current $$\nu_x + d \rightarrow \nu_x + n + p$$

New reaction - neutrino breaks up a deuteron. Works equally for all neutrino flavours.

Results from Sudbury neutrino observatory

fraction of expected number of events (based on a Solar model prediction) that are observed



Total number of neutrinos agrees well with the theoretical expectation

Number of ν_e is about one third of number produced in the Sun

Most straightforward interpretation of these results:

1) **Solar models correctly predict the number of electron neutrinos formed in the core of the Sun**

   Evidence: *total* flux of neutrinos at Earth (all three types) measured by SNO is in good agreement with this number.

   Probably do understand the astrophysics of the Solar interior pretty well…

2) **Electron neutrinos are converted into a mix of all three flavours en route to Earth**

   SNO and all other detectors measure a flux of *electron* neutrinos that is much smaller than the predicted Solar flux.

Neutrino oscillations

Basic idea: particles that are created / observed via nuclear interactions (the ν_e, ν_μ, and ν_τ) are linear combinations of `different' particles which propagate through space.

e.g. for only two neutrino flavours can write this as:

particle states that are created or observed via weak interactions →

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

particle states that propagate through space (the `mass eigenstates')

Use factors of cos θ and sin θ for mathematical convenience, these are just constants. Call θ the `mixing angle', measures how different the flavour states are from the mass states.

If the neutrinos (strictly now ν_1 and ν_2) have zero mass, this description does not describe any new physics.

However, if at least one of the masses in non-zero, then the mass eigenstates propagate at *different* speeds. After traveling some distance L, this causes the flavour of the neutrino to oscillate between the two possibilities.

Result is:

Probability that an initially electron neutrino will be subsequently detected as an electron neutrino

$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left[k \left(\frac{\Delta m^2}{\mathrm{eV}^2} \right) \left(\frac{L}{\mathrm{m}} \right) \left(\frac{E}{\mathrm{MeV}} \right)^{-1} \right]$$

- k = constant (k=1.27)
- Δm^2 is the square of the mass difference
- L is distance between source and detector
- E is the energy

Actually, things are (even) more complicated because:

- there are 3 types of neutrino, not 2
- if the neutrinos travel through matter, not a vacuum, the oscillations can be altered

Important point though, is that using a combination of:

- Different Solar neutrino experiments
- Observations of ν_μ created in the Earth's atmosphere

…can measure (most) of the unknown parameters in the theory.

Δm^2 - the mass difference (squared) between neutrino states

θ - the mixing angle(s)

Neutrino oscillations for different energies

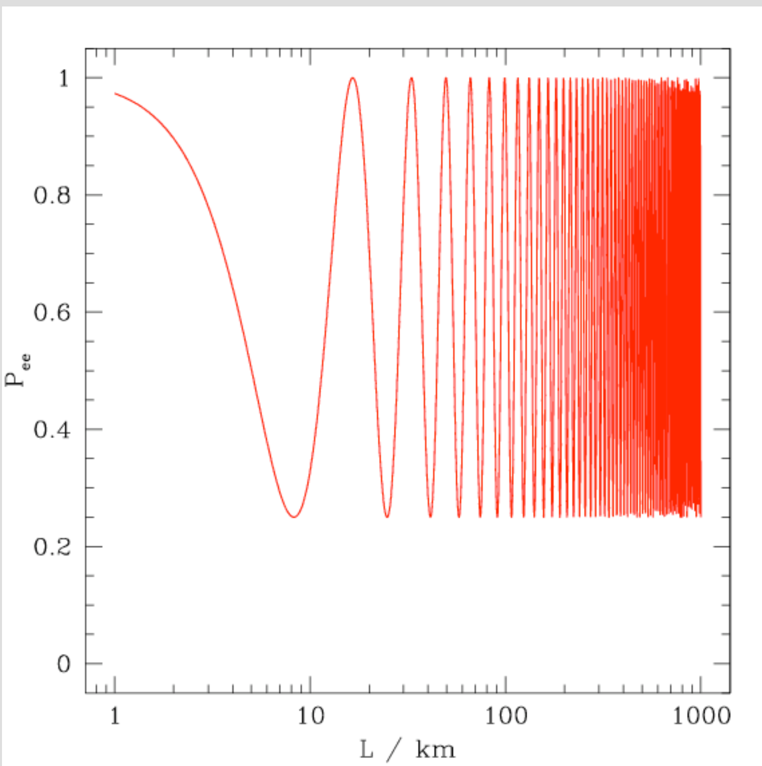
$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left[k \left(\frac{\Delta m^2}{\mathrm{eV}^2} \right) \left(\frac{L}{\mathrm{m}} \right) \left(\frac{E}{\mathrm{MeV}} \right)^{-1} \right]$$

$\theta \approx \pi/6$

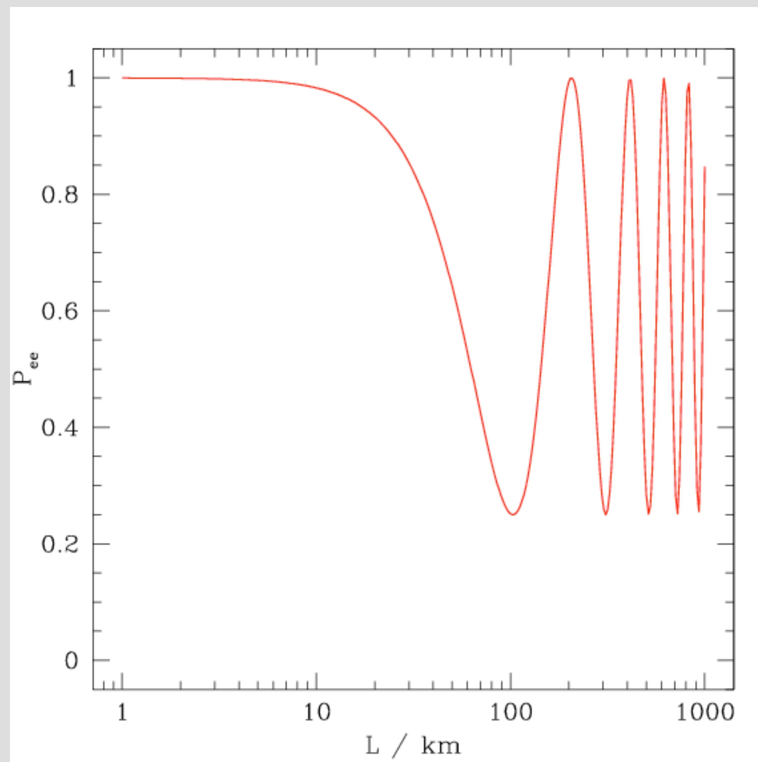
$\Delta m^2 \approx 6 \times 10^{-5}\ \mathrm{eV}^2$

Best-fit parameters to explain Solar neutrino and other experimental data

0.4 MeV



5 MeV



Derived oscillation parameters are accessible to lab experiments. For MeV neutrinos, need to measure the flux as a function of distance over d ~ 100 km. Possible neutrino sources:

- Nuclear reactor (very large power but isotropic emission)
- Particle accelerator (smaller power but narrow beam)

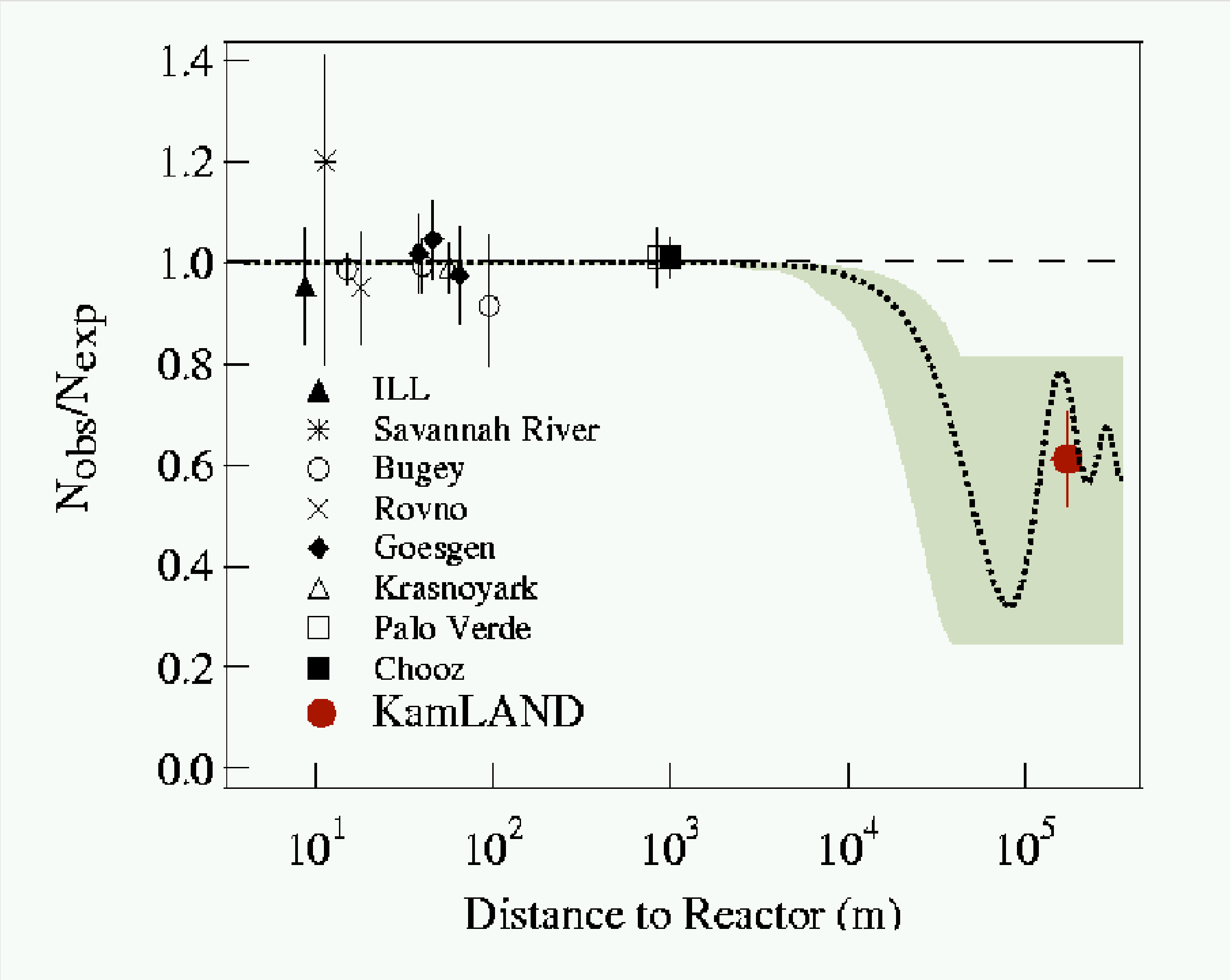
e.g. for a reactor with 1 GW power, each fission releases ~200 MeV. Rate of fissions is ~3 x 10^{19} s^{-1}. Say one neutrino each, then flux is:

- few x 10^{10} cm^{-2} s^{-1} at d = 100 m
- few x 10^{4} cm^{-2} s^{-1} at d = 100 km

⇒ Comparable difficulty to the Solar neutrino experiments for distances of ~100 km

KamLAND experiment

Experiment measured the flux of neutrinos at d = 160 km from a Japanese power station. Found to be ~60% of expected flux.



Very strong evidence for reality of neutrino oscillations.

Implications

Neutrinos have mass:

- So far constrained the mass **difference** between two neutrinos to be ~6 x 10^{-5} eV^2
- Might be `reasonable' to assume the masses are comparable to the mass difference i.e ~10^{-2} eV
- But… this is just a guess, don't know for sure.
- Other limits indicate that the masses are < 1 eV.

Learned more about neutrino physics than about the Sun - all existing data is *consistent* with theoretical models of fusion in the Sun, but enough free parameters in oscillation theory that haven't yet tested the details via neutrinos…