The Resolution of the Solar Neutrino Problem

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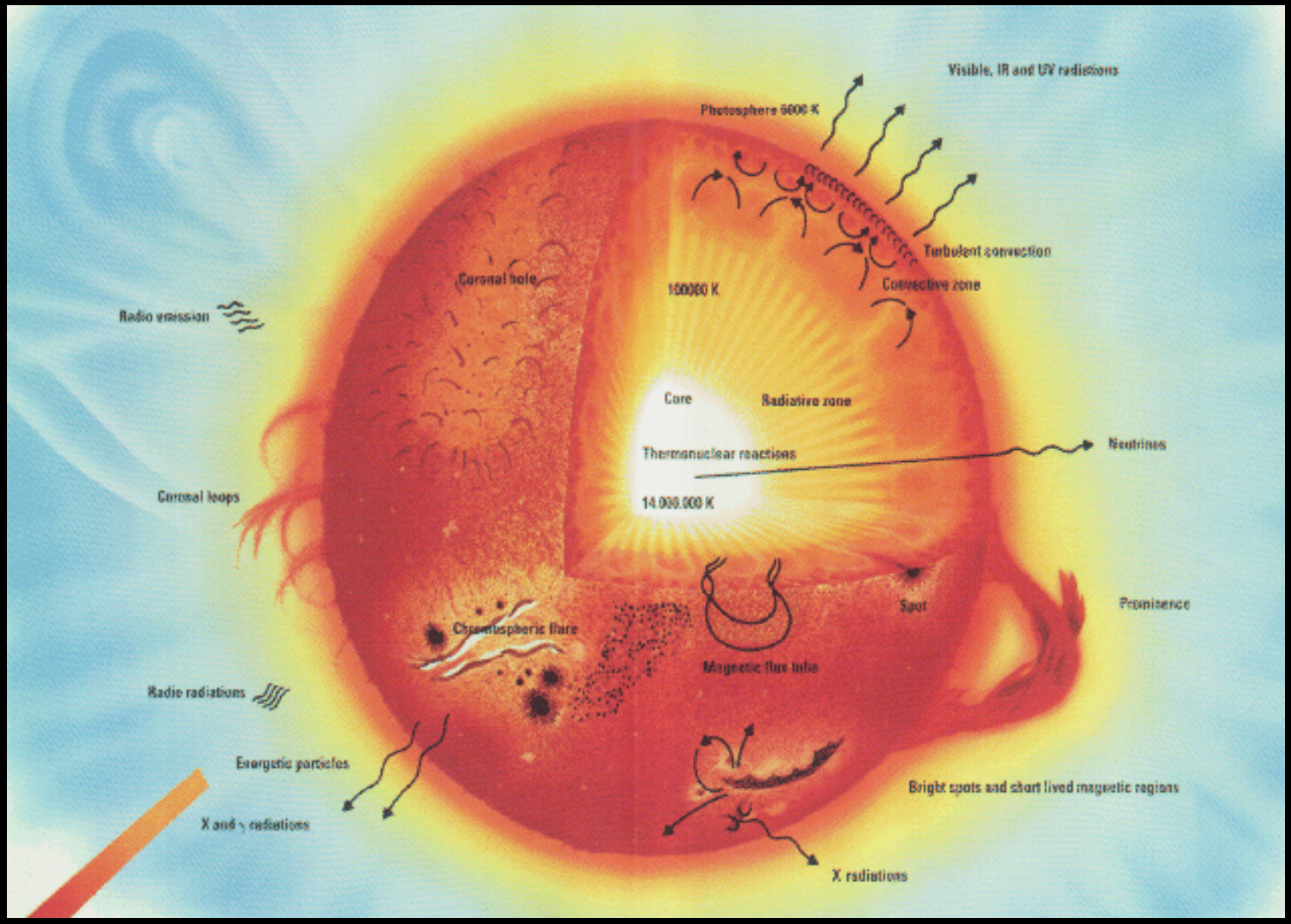
What's the problem?

- Neutrinos are produced in nuclear reactions in the Sun's core.
- From the late 1960s, experiments began to measure the neutrino flux at Earth's surface.
- Solar models overpredicted the measured flux by as much as a factor of 3.
- Later experiments also revealed different suppression at different energies.

The p-p chain

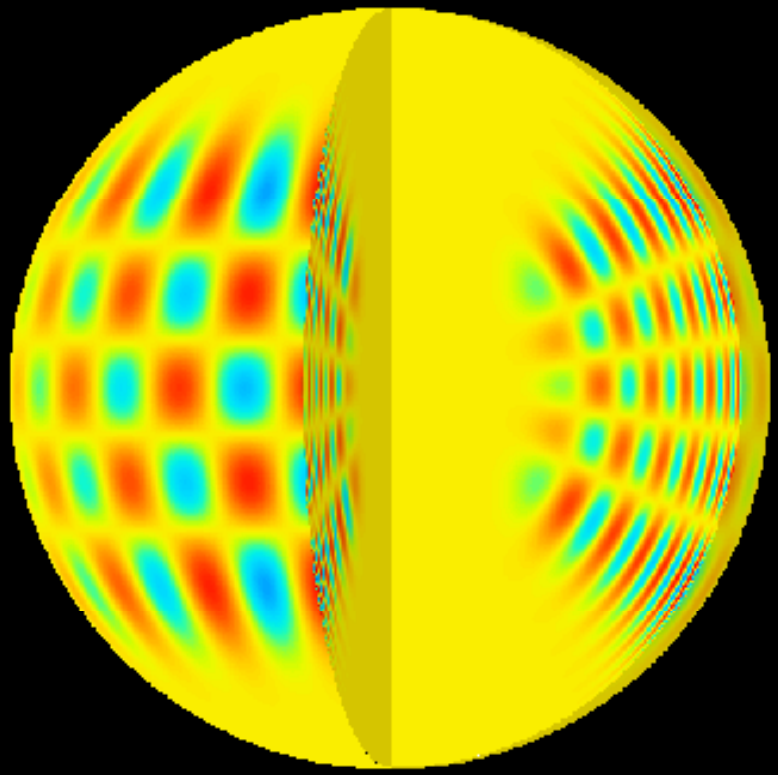
- H + H → D + positron + neutrino
- H + H + electron → D + neutrino
- D + H → He3 + gamma ray
- He3 + He3 → H + H + He4
- He3 + He4 → Be7 + gamma ray
- Be7 + positron → Li7 + neutrino
- Li7 + H → He4 + He4
- Be7 + H → B8 + gamma ray
- B8 → Be8* + positron + neutrino
- Be8* → He4 + He4

Solar structure



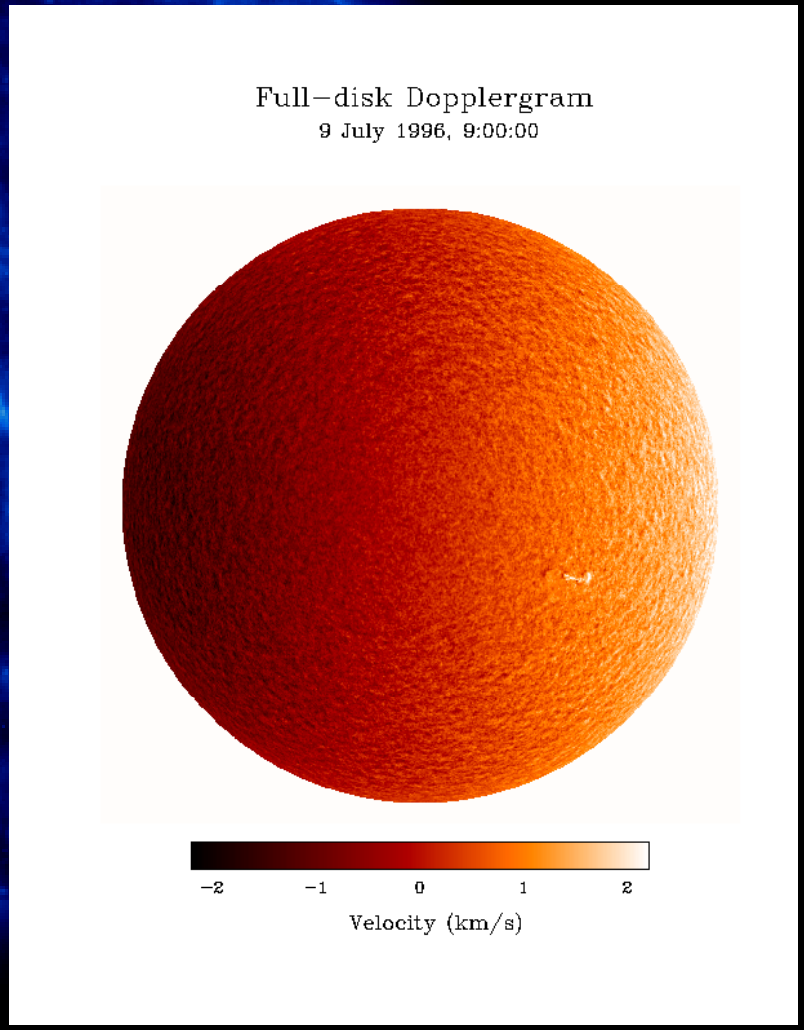
Helioseismology

- Processes in the convective zone continuously excite sound waves.
- Resonant oscillations have periods of about 5 minutes.
- Acoustic p-waves characterised by spherical harmonics.

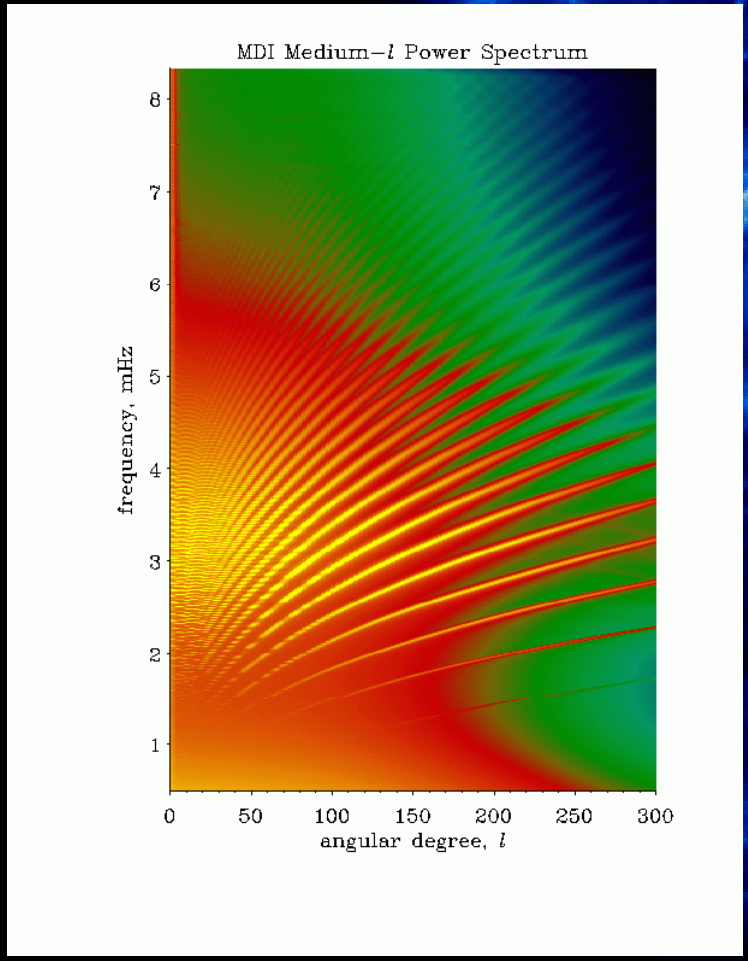


Helioseismology

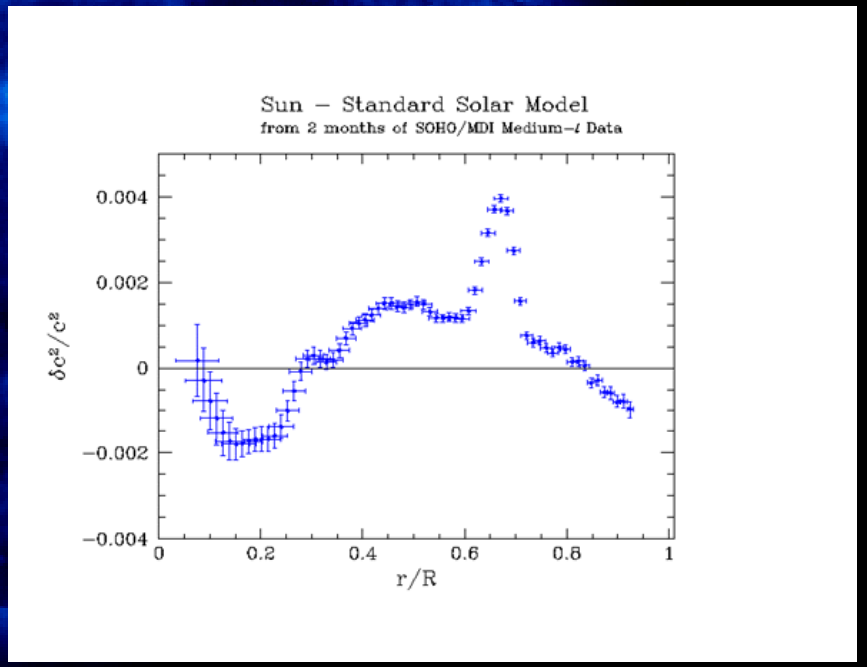
- Individual oscillation modes of amplitude ~0.1 m s^{-1}.
- Measure shifts in spectral lines to an accuracy ~10^{-6} of their width.
- Long contiguous periods of observation required.



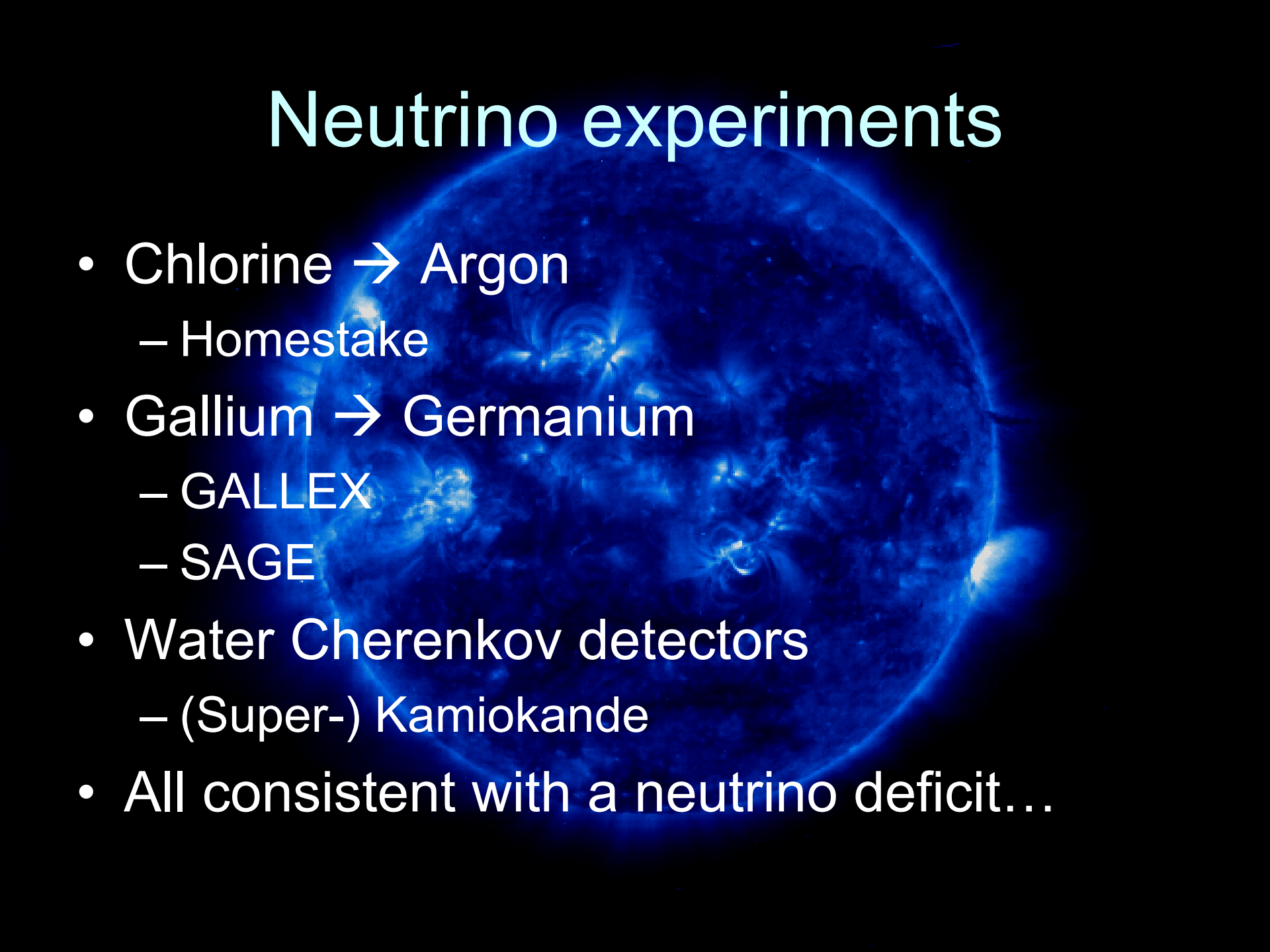
Helioseismology



Solve the inverse problem to obtain sound speeds etc. and compare with models.



Neutrino experiments



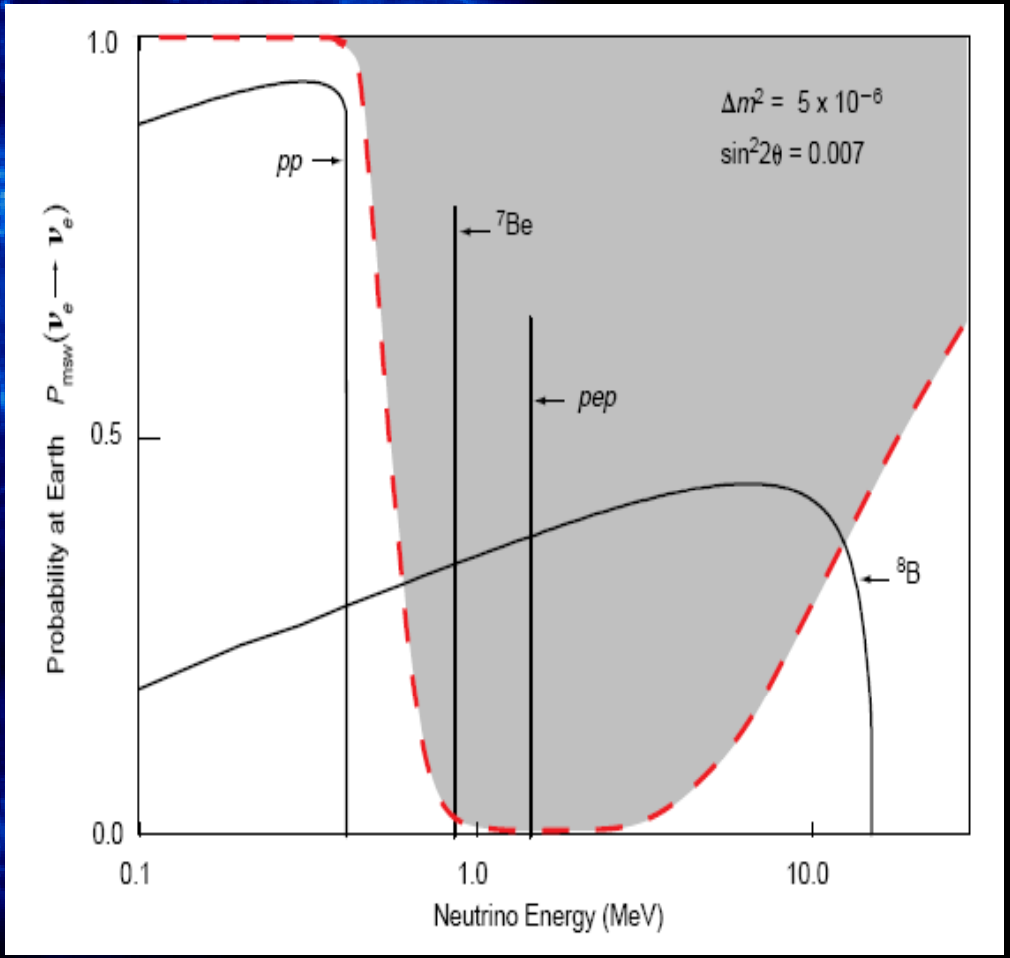
- Chlorine → Argon
  - Homestake
- Gallium → Germanium
  - GALLEX
  - SAGE
- Water Cherenkov detectors
  - (Super-) Kamiokande
- All consistent with a neutrino deficit…

Possible solutions

- Astrophysical solutions lower the Sun's core temperature
  - Mixing – rotation, convection, Helium 3 instability.
  - Different core metallicity.
  - WIMPs.
- Physical solutions invoke changes in particle physics
  - Neutrino oscillations
    - Changes in handedness.
    - Changes in flavour from processes in matter or vacuum.

The MSW effect

- Non-trivial relation between neutrino mass eigenstates and flavour eigenstates.
- Parameterised by a mixing angle θ.
- Oscillation enhanced by high electron density in the Sun.



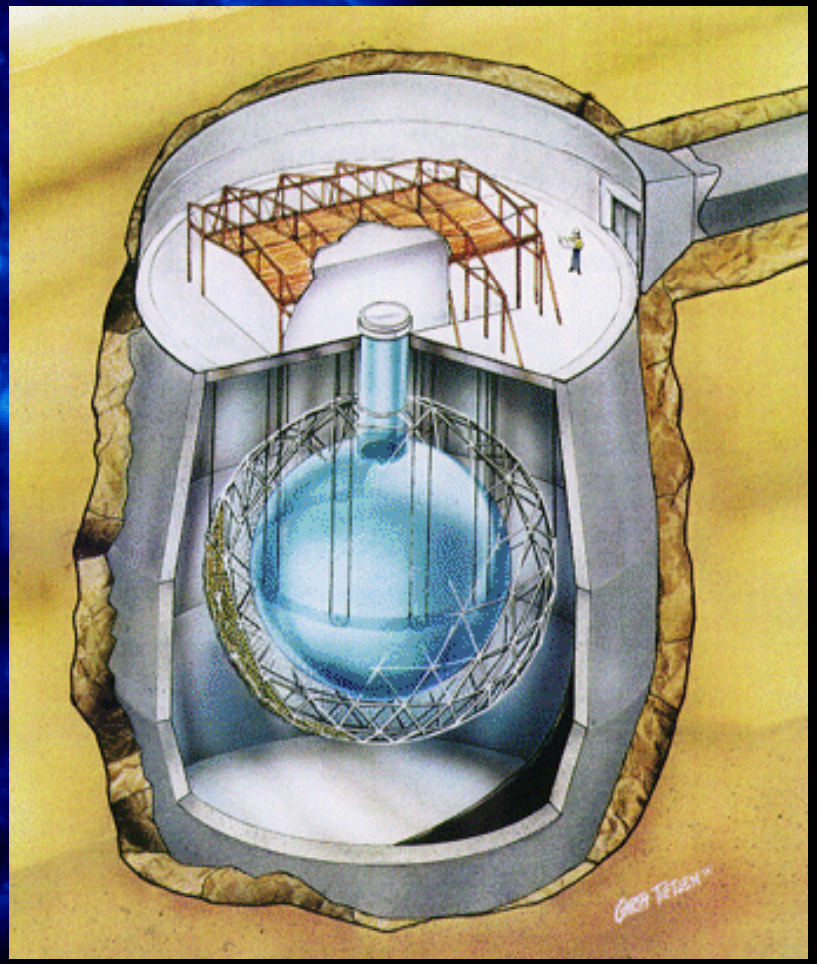
Detecting neutrino oscillations

- Sudbury Neutrino Observatory – a heavy water Cerenkov detector.
- Detects neutrinos via

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

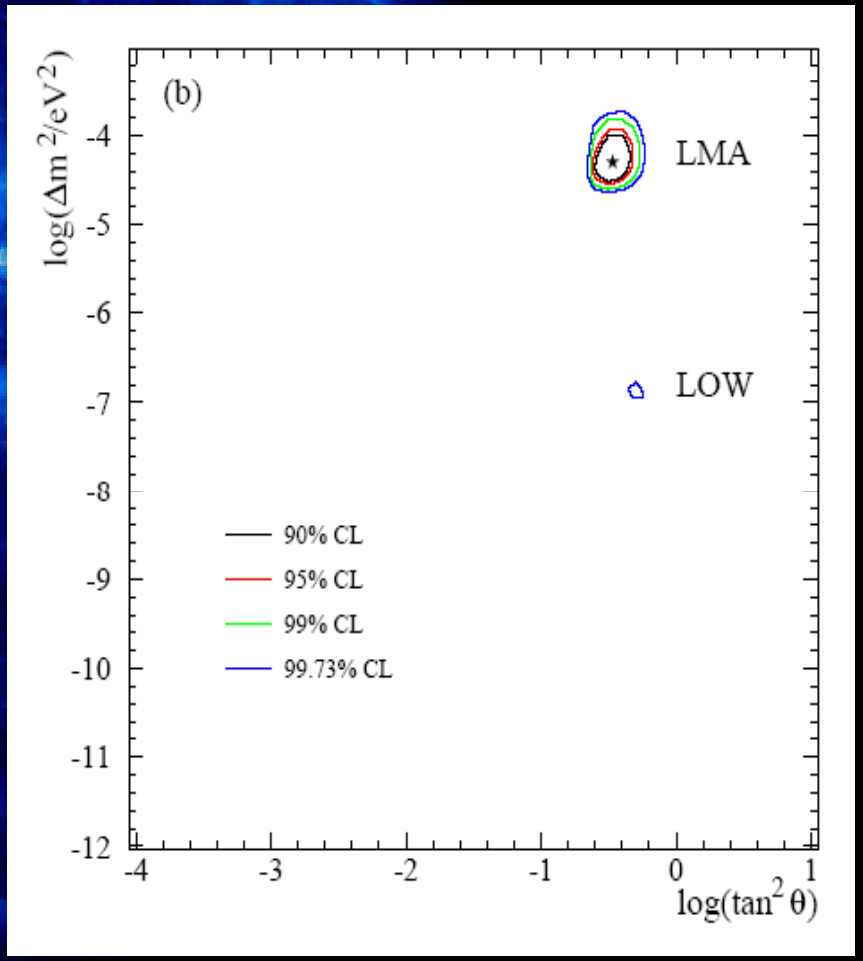
  $\nu_x + d \rightarrow p + n + \nu_x$

  $e^- + \nu_x \rightarrow e^- + \nu_x$
- Directional and energetic information.



Results from SNO

- Confirmation of neutrino oscillations.
- Consistent with the standard solar model.
- Day-night analysis strongly favours a large mixing angle solution and an MSW scenario.



What next for neutrinos?

- Study of oscillations in accelerated neutrinos (K2K) at high energy.
- Borexino will study Be7 solar neutrinos at low energy, probing vacuum oscillations.
- High precision measurements at SNO and SNOLAB.
- Physics beyond the standard model.
- Cosmological consequences of accurate neutrino masses – constraints on Ω_ν.