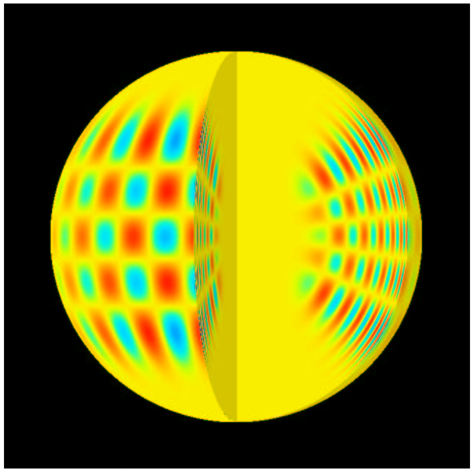
HELIOSEISMOLOGY (I)

acoustic mode
in the Sun
(p mode
n=14, l -20)



full-disk
Dopplergram

velocity (km/s)

STRUCTURE OF THE SUN

- The Sun is the only star for which we can measure internal properties → test of stellar structure theory
- Composition (heavy elements) from meteorites
- Density, internal rotation from helioseismology
- Central conditions from neutrinos

HELIOSEISMOLOGY

- The Sun acts as a resonant cavity, oscillating in millions of (acoustic, gravity) modes (like a bell)

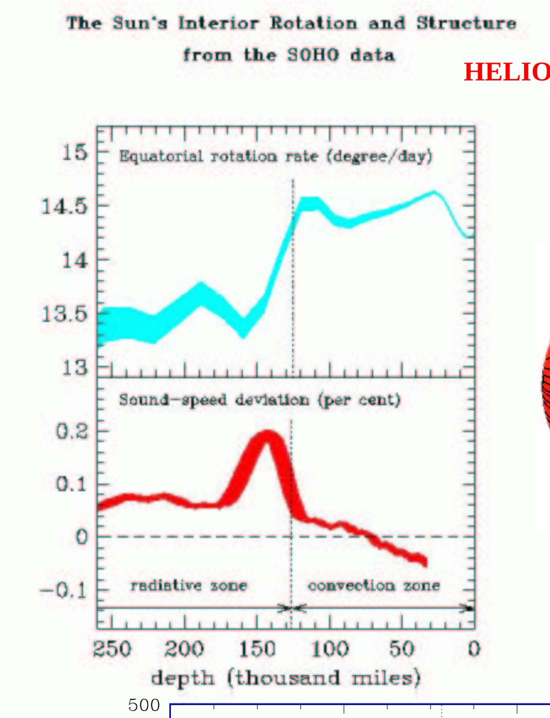
→ can be used to reconstruct the internal density structure (like earthquakes on Earth)

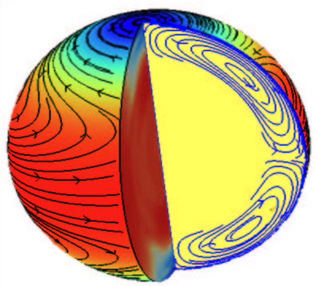
- oscillation modes are excited by convective eddies
- periods of typical modes: 1.5 min to 20 min
- velocity amplitudes: $\sim 0.1\,\mathrm{m/s}$
- need to measure Doppler shifts in spectral lines relative to their width to an accuracy of $1{:}10^6$
  - ▷ possible with good spectrometers and long integration times (to average out noise)

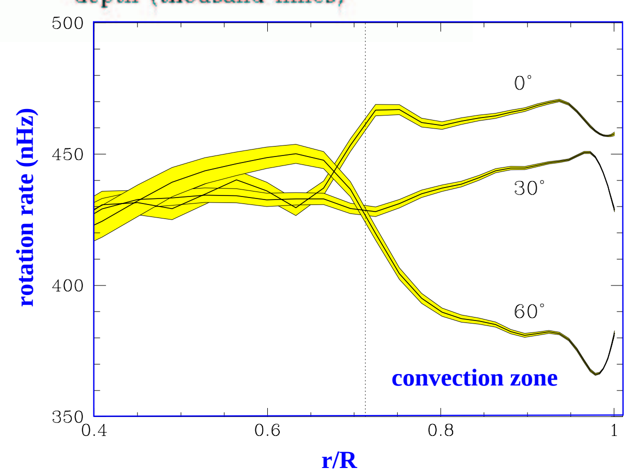
Results

- density structure, sound speed
- depth of outer convective zone: $\sim 0.28\,R_\odot$
- rotation in the core is slow (almost like a solid-body) → the core must have been spun-down with the envelope (efficient core–envelope coupling)

HELIOSEISMOLOGY (II)







SOLAR NEUTRINOS

- Neutrinos, generated in solar core, escape from the Sun and carry away $2-6\,\%$ of the energy released in H-burning reactions
- they can be observed in underground experiments $\to$ direct probe of the solar core
- neutrino-emitting reactions (in the pp chains)

$$
\begin{array}{rclr}
{}^{1}\mathrm{H}+{}^{1}\mathrm{H} & \to & {}^{2}\mathrm{D}+\mathrm{e}^{+}+\nu & \mathrm{E}_{\nu}^{\max}=0.42\,\mathrm{Mev} \\
{}^{7}\mathrm{Be}+\mathrm{e}^{-} & \to & {}^{7}\mathrm{Li}+\nu & \mathrm{E}_{\nu}^{\max}=0.86\,\mathrm{Mev} \\
{}^{8}\mathrm{B} & \to & {}^{8}\mathrm{Be}+\mathrm{e}^{+}+\nu & \mathrm{E}_{\nu}^{\max}=14.0\,\mathrm{Mev}
\end{array}
$$

- The Davis experiment (starting around 1970) has shown that the neutrino flux is about a factor of 3 lower than predicted $\to$ the solar neutrino problem

The Homestake experiment (Davis)

- neutrino detector: underground tank filled with 600 tons of Chlorine ($C_2\,Cl_4$: dry-cleaning fluid)
- some neutrinos react with Cl

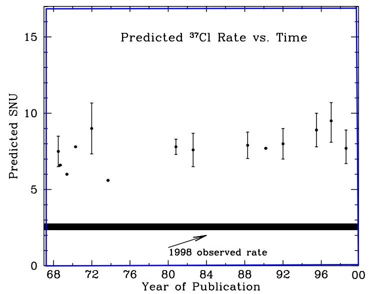
$$\nu_{\mathrm{e}}+{}^{37}\mathrm{Cl}\to{}^{37}\mathrm{Ar}+\mathrm{e}^{-}-0.81\,\mathrm{Mev}$$

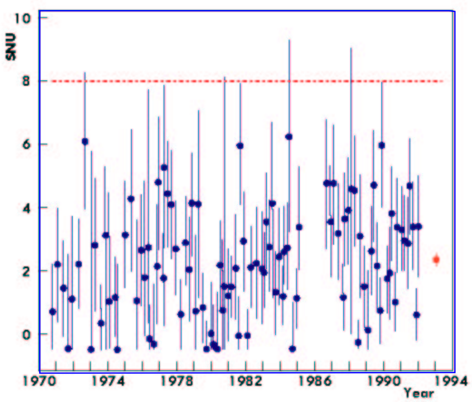
- rate of absorption $\sim 3\times10^{-35}\,\mathrm{s}^{-1}$ per ^{37}Cl atom
- every 2 months each ^{37}Ar atom is filtered out of the tank (expected number: 54; observed number: 17)
- caveats
  - ▷ difficult experiment, only a tiny number of the neutrinos can be detected
  - ▷ the experiment is only sensitive to the most energetic neutrinos in the ^{8}B reaction (only minor reaction in the Sun)

The Davis Neutrino Experiment

Homestake Mine
(with Cl tank)

Model Predictions





Results

Proposed Solutions to the Solar Neutrino Problem

- dozens of solutions have been proposed

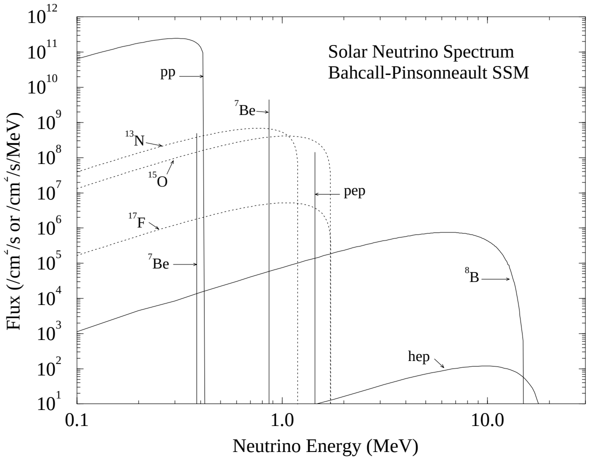
1) Astrophysical solutions

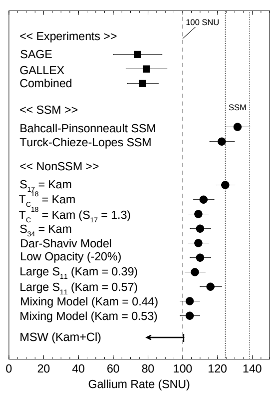
- ▷ require a reduction in central temperature of about 5 % (standard model: 15.6×10^6 K)
- ▷ can be achieved if the solar core is mixed (due to convection, rotational mixing, etc.)
- ▷ if there are no nuclear reactions in the centre (inert core: e.g. central black hole, iron core, degenerate core)
- ▷ if there are additional energy transport mechanisms (e.g. by WIMPS = weakly interacting particles)
- ▷ most of these astrophysical solutions also change the density structure in the Sun $\rightarrow$ can now be ruled out by helioseismology

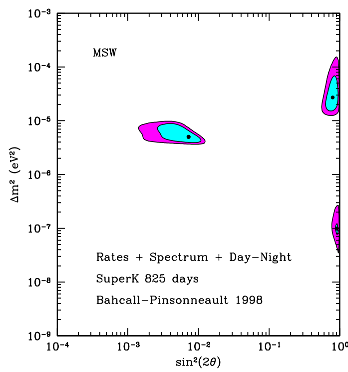
2) Nuclear physics

- ▷ errors in nuclear cross sections (cross sections sometimes need to be revised by factors up to ~ 100)
- ▷ improved experiments have confirmed the nuclear cross sections for the key nuclear reactions

Solar Neutrinos







3) Particle physics

- ▷ all neutrinos generated in the Sun are electron neutrinos
- ▷ if neutrinos have a small mass (actually mass differences), neutrinos may change type on their path between the centre of the Sun and Earth: neutrino oscillations, i.e. change from electron neutrino to μ or τ neutrinos, and then cannot be detected by the Davis experiment
- ▷ vacuum oscillations: occur in vacuum
- ▷ matter oscillations (MSW [Mikheyev-Smirnov--Wolfenstein] effect): occur only in matter (i.e. as neutrinos pass through the Sun)

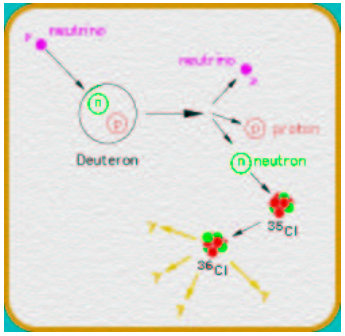
RECENT EXPERIMENTS

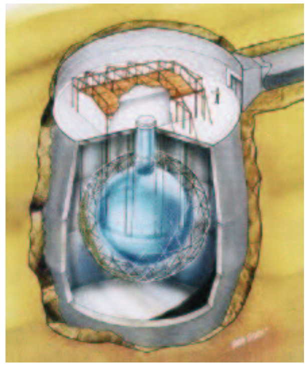
- resolution of the neutrino puzzle requires more sensitive detectors that can also detect neutrinos from the main pp-reaction

1) The Kamiokande experiment (also super-Kamiokande)

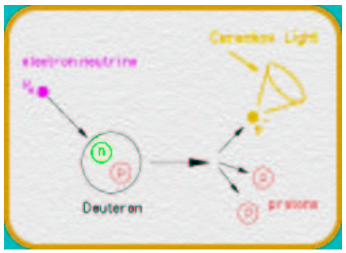
- ▷ uses 3000 tons of ultra-pure water (680 tons active medium) for $\nu + e^- \to \nu + e^-$ (inelastic scattering)
- ▷ about six times more likely for ν_e than ν_μ and ν_τ
- ▷ observed flux: half the predicted flux (energy dependence of neutrino interactions?)

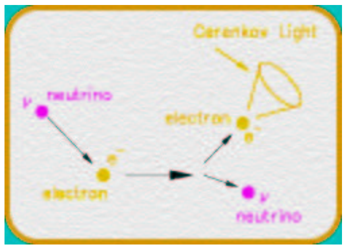
The Sudbury Neutrino Observatory

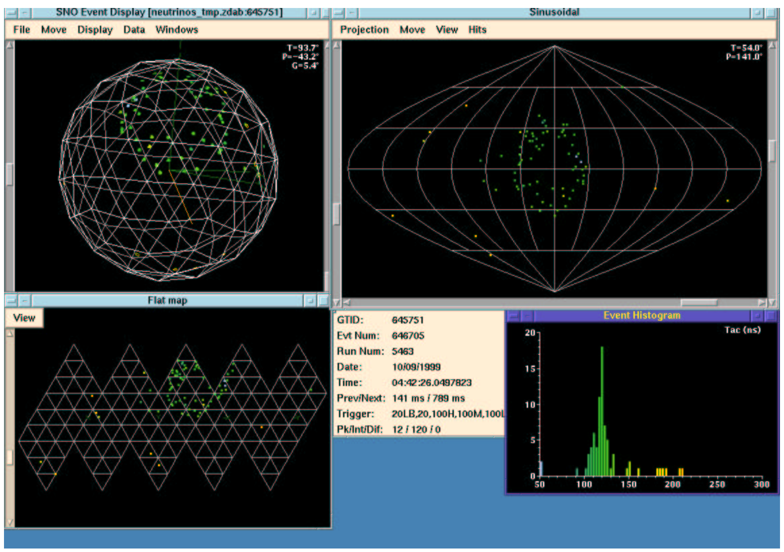




1000 tons of heavy water







2) The Gallium experiments (GALLEX, SAGE)

- ▷ uses Gallium to measure low-energy pp neutrinos directly
  $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^- - 0.23\,\mathrm{Mev}$
- ▷ results: about 80 ± 10 SNU vs. predicted 132 ± 7 SNU (1 SNU: 10^{-36} interactions per target atom/s)

3) The Sudbury Neutrino Observatory (SNO)

- ▷ located in a deep mine (2070 m underground)
- ▷ 1000 tons of pure, heavy water (D_2O)
- ▷ in acrylic plastic vessel with 9456 light sensors/photo-multiplier tubes
- ▷ detect Cerenkov radiation of electrons and photons from weak interactions and neutrino-electron scattering
- ▷ results (June 2001): confirmation of neutrino oscillations (MSW effect)?