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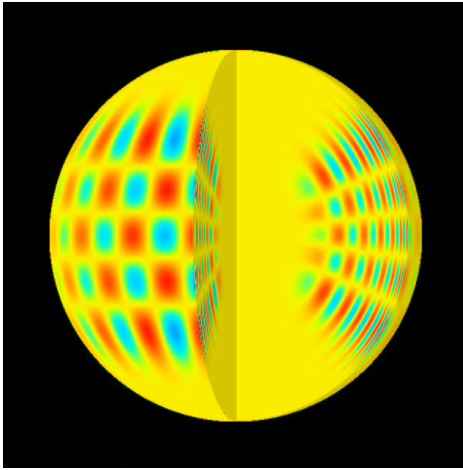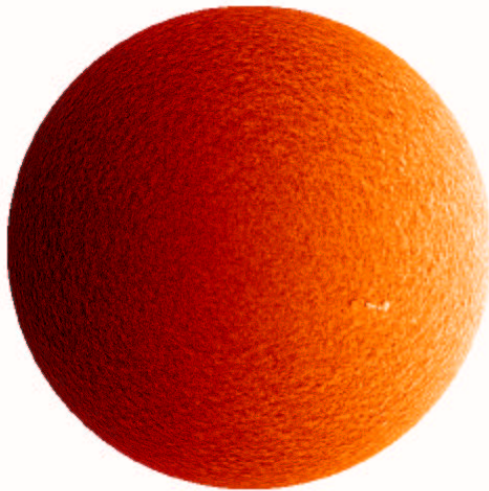in the Sun
(p mode
n=14, l -20)**

**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:* $\sim 0.1\,m/s$

- need to measure *Doppler shifts* in spectral lines relative to their width to an accuracy of $1{:}10^6$

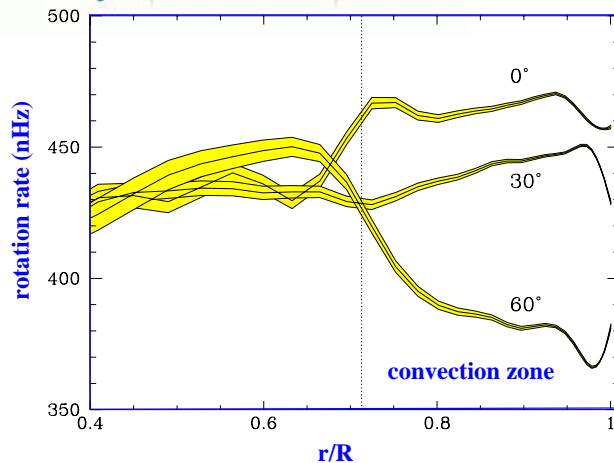 ▷ possible with good spectrometers and long integration times (to average out noise)
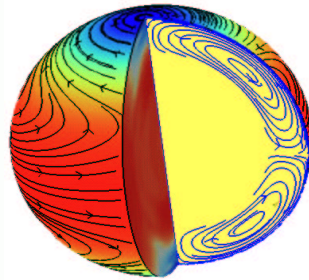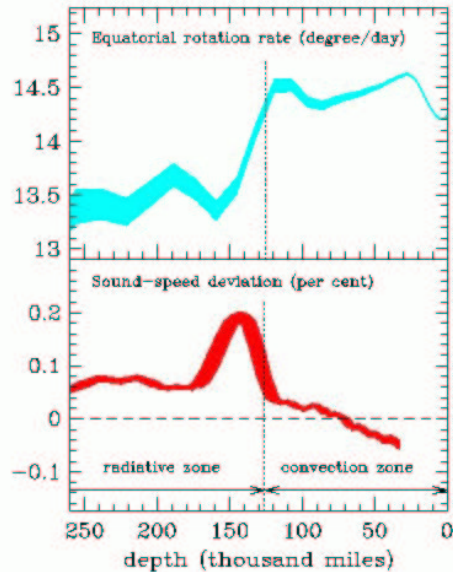
Results

- *density* structure, *sound speed*

- depth of outer *convective zone:* $\sim 0.28\,\mathrm{R_\odot}$

- *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)

The Sun's Interior Rotation and Structure from the SOHO data

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* $\rightarrow$ *direct probe of the solar core*

- neutrino-emitting reactions (in the pp chains)

$$^1\mathrm{H} +\,^1\mathrm{H} \;\rightarrow\; ^2\mathrm{D} + \mathrm{e}^+ + \nu \qquad \mathrm{E}_\nu^{\max} = 0.42\,\mathrm{Mev}$$
$$^7\mathrm{Be} + \mathrm{e}^- \;\rightarrow\; ^7\mathrm{Li} + \nu \qquad\quad \mathrm{E}_\nu^{\max} = 0.86\,\mathrm{Mev}$$
$$^8\mathrm{B} \;\rightarrow\; ^8\mathrm{Be} + \mathrm{e}^+ + \nu \qquad \mathrm{E}_\nu^{\max} = 14.0\,\mathrm{Mev}$$

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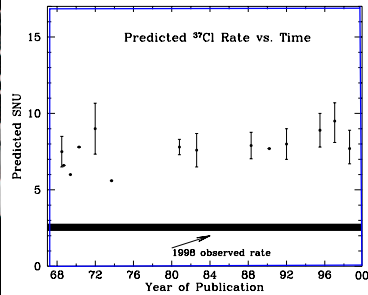
The Homestake experiment (Davis)

- *neutrino detector:* underground tank filled with 600 tons of Chlorine ($\mathrm{C}_2\,\mathrm{Cl}_4$: dry-cleaning fluid)

- some neutrinos react with Cl

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

- rate of absorption $\sim 3 \times 10^{-35}\,\mathrm{s}^{-1}$ per $^{37}\mathrm{Cl}$ 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 $^8\mathrm{B}$ reaction (only minor reaction in the Sun)
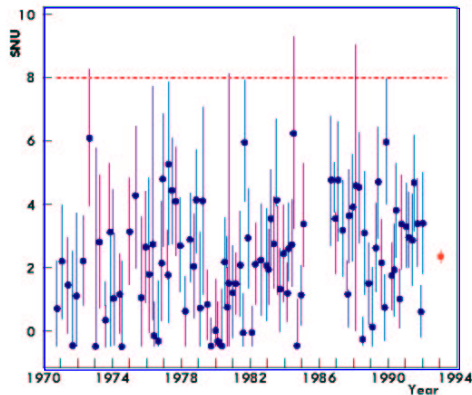
The Davis Neutrino Experiment

Model Predictions

Predicted ^{37}Cl Rate vs. Time

Predicted SNU

15

10

5

0

1998 observed rate

68 72 76 80 84 88 92 96 00
Year of Publication

**Homestake Mine
(with Cl tank)**

SNU

10

8

6

4

2

0

1970   1974   1978   1982   1986   1990   1994
Year

Results

Proposed Solutions to the Solar Neutrino Problem

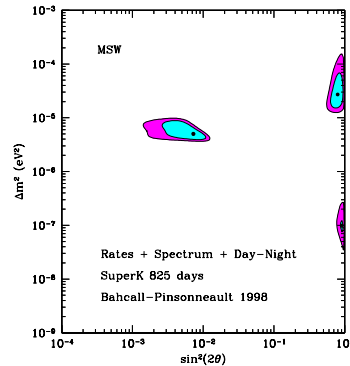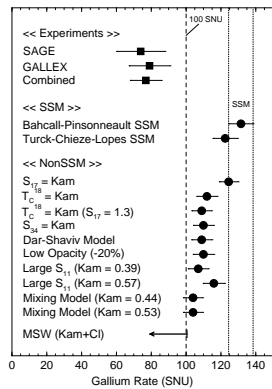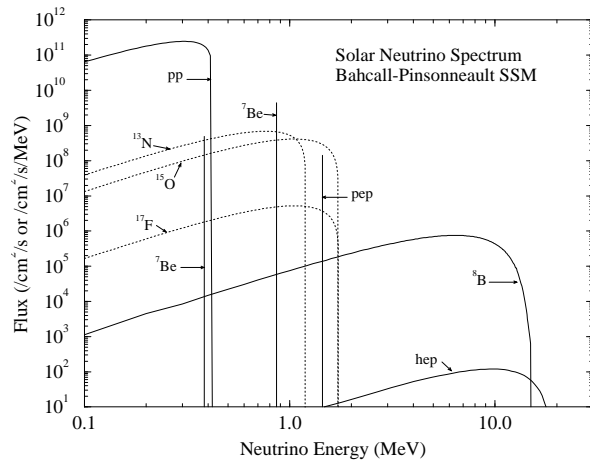- dozens of solutions have been proposed

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 → 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 Neutrino Spectrum
Bahcall-Pinsonneault SSM

Flux (cm^2/s or /cm^2/s/MeV)

10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}

pp
^{7}Be
^{13}N
^{15}O
pep
^{17}F
^{7}Be
^{8}B
hep

0.1   1.0   10.0
Neutrino Energy (MeV)

100 SNU

<< Experiments >>
SAGE
GALLEX
Combined

<< SSM >>
Bahcall-Pinsonneault SSM
Turck-Chieze-Lopes SSM

<< NonSSM >>
S_{17} = Kam
T_C^{18} = Kam
T_C^{18} = Kam (S_{17} = 1.3)
S_{34} = Kam
Dar-Shaviv Model
Low Opacity (-20%)
Large S_{11} (Kam = 0.39)
Large S_{11} (Kam = 0.57)
Mixing Model (Kam = 0.44)
Mixing Model (Kam = 0.53)

MSW (Kam+Cl)

SSM

0   20   40   60   80   100 120 140
Gallium Rate (SNU)

10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

MSW

Δm^2 (eV^2)

Rates + Spectrum + Day-Night
SuperK 825 days
Bahcall-Pinsonneault 1998

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
$\sin^2(2\theta)$

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
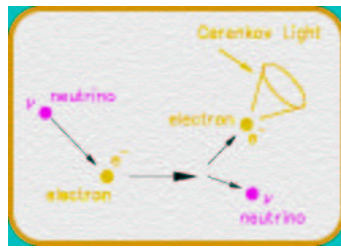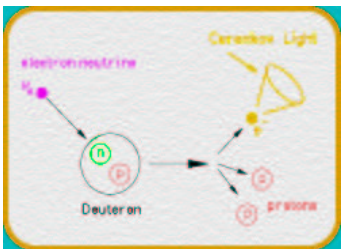
1) *The Kamiokande experiment* (also super-Kamiokande)

▷ uses 3000 tons of ultra-pure water (680 tons active medium) for $\nu + e^- \rightarrow \nu + e^-$ (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?)
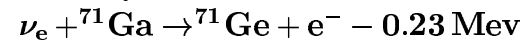
The Sudbury Neutrino Observatory
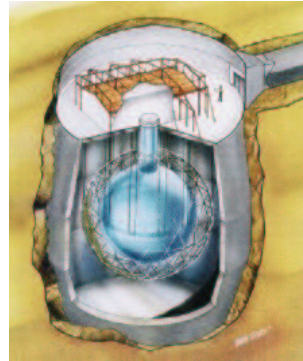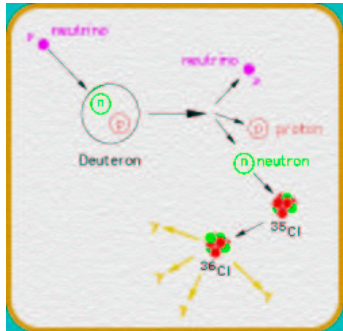
1000 tons of heavy water

2) *The Gallium experiments* (GALLEX, SAGE)

   ▷ uses Gallium to measure low-energy *pp neutrinos* directly
$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^- - 0.23\,\mathrm{Mev}$$

   ▷ *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)?*