8. THE SUN

Matthew Baring – Lecture Notes for ASTR 350, Fall 2021

• The Web site [http://solarscience.msfc.nasa.gov] is an excellent solar physics resource.

1 The Solar Interior

The sun is our best benchmark for stellar structure information. We know it is $X = 0.73$ percent mass fraction of hydrogen, and metallicity $Z = 0.02$ (i.e. above helium) by mass. Clearly, then the sun has been burning hydrogen for most of its life. **C & O, Sec. 11.1**

• The numerical solutions of the structure equations in combination with the nuclear reaction rates have led to the **standard solar model** (SSM).

Plot: Solar Interior and Historic Evolution

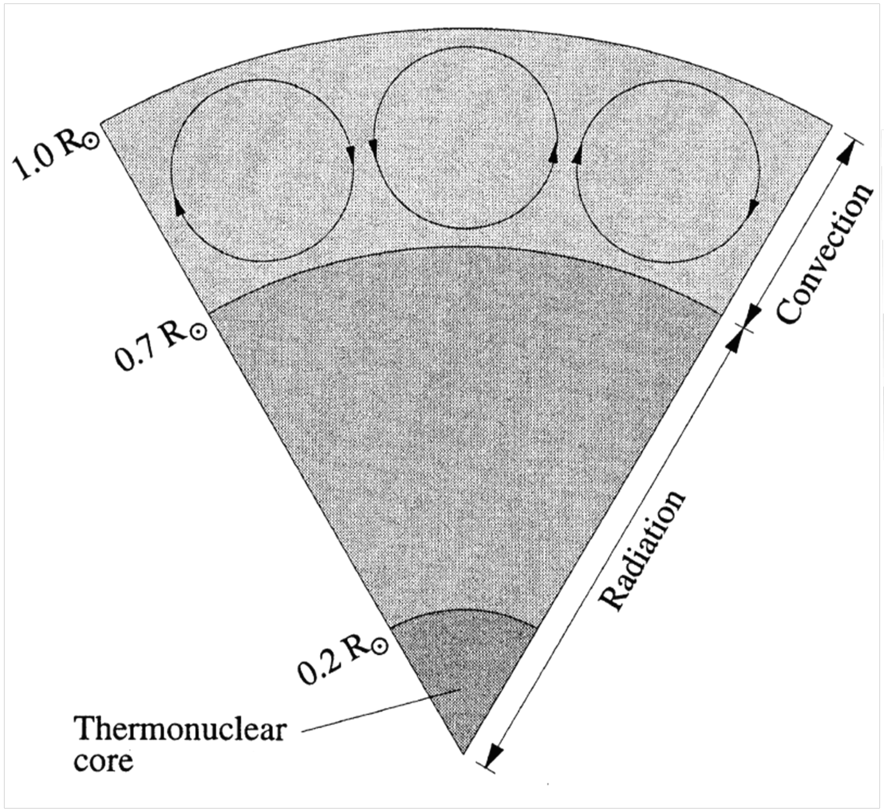
• Stellar evolution calculations, plus radioactive dating of meteorites and Moon rocks indicate that the solar age is $4.5\,\text{Gyr}$.

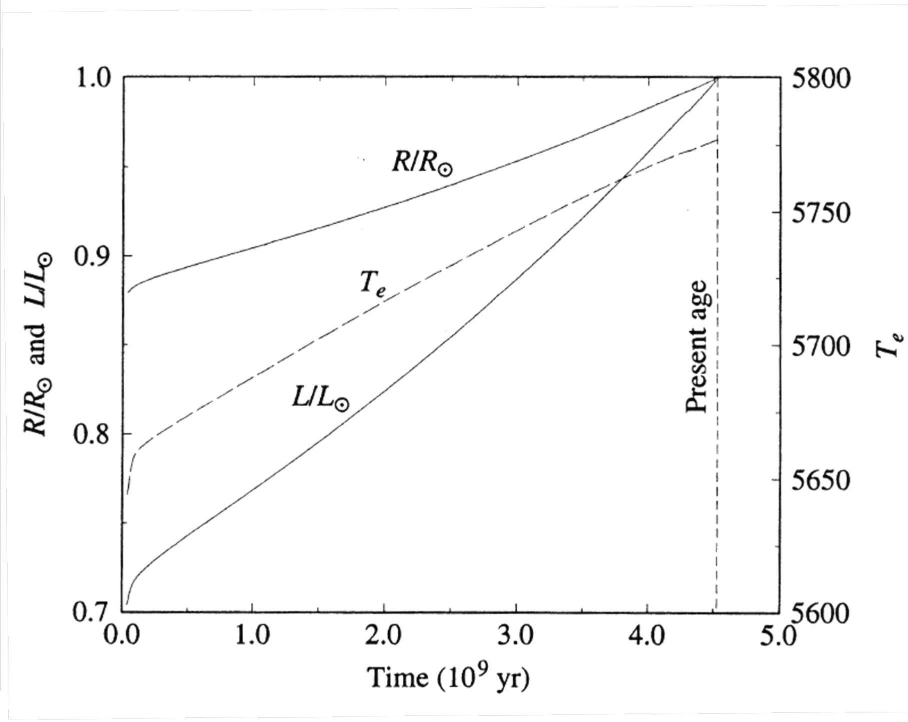
• The sun has had only modest evolution during its lifetime.

The SSM has lead to complicated details about the solar interior:

Plot: Profiles of the Solar Interior

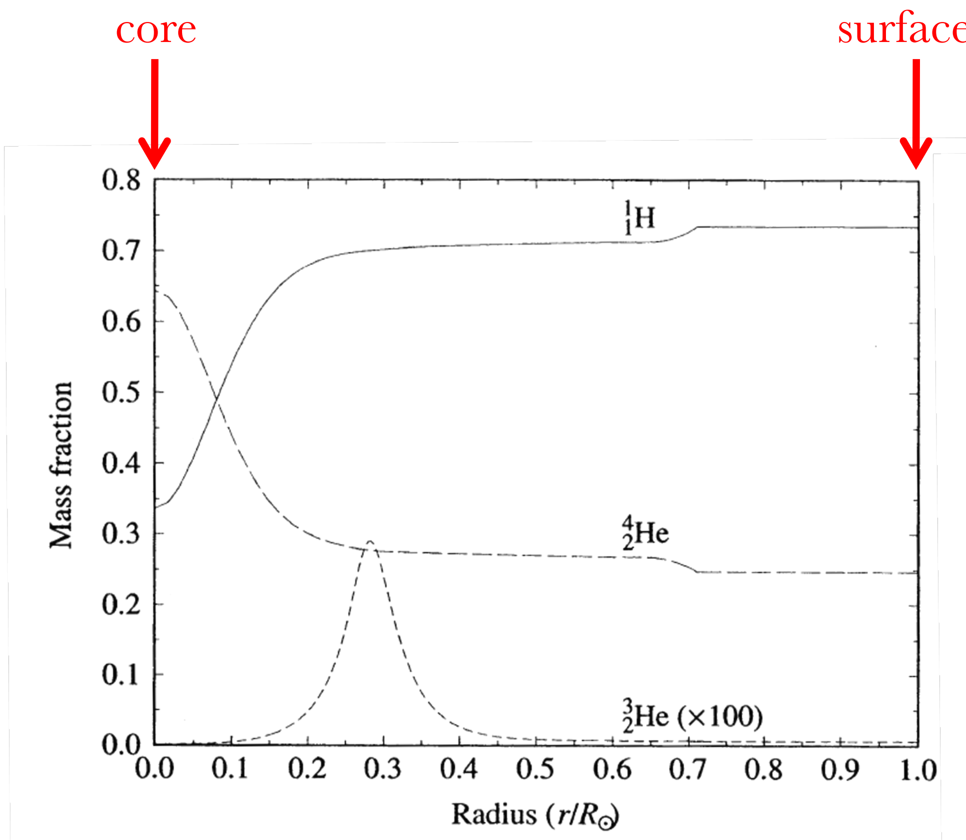
Solar Interior and Historic Evolution

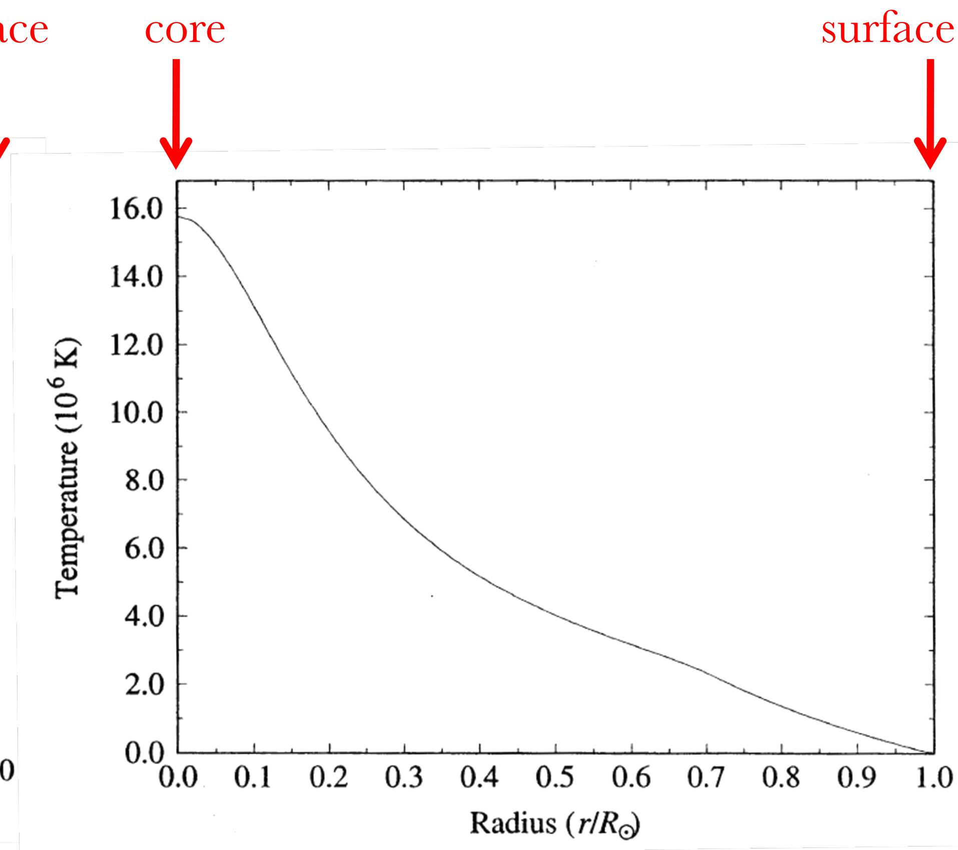




- *Left*: schematic of the solar interior (from Carroll+Ostlie).
- *Right*: evolution of radius, temperature and luminosity as the sun has aged.

Profiles of the Solar Interior





- *Left*: abundances in the solar interior (from Carroll+Ostlie).
- *Right*: distribution of temperature inside the sun.

1.1 Solar Neutrino Problem

While most properties were understood, the region least understood is the solar convection zone, and the most distressing issue has been the **solar neutrino problem**. This dilemma existed for two and a half decades. **C & O, pp. 356–9**

• Ray Davis (Nobel Prize, 2002) began measuring solar neutrino fluxes in the Homestake Gold Mine, South Dakota with a tank of perchloroethylene (C_2Cl_4), sampling the neutrino-induced reaction

$$ {}^{37}_{17}Cl + \nu_e \;\leftrightarrow\; {}^{37}_{18}Ar + e^- \quad . \tag{1} $$

This reaction has a threshold of 0.814 MeV, below most relevant reactions in the PP chain, with the exception of the fusion of two hydrogen nuclei.

$*$ While many neutrinos are produced in the PP chain, the detector is most sensitive to the reaction

$$ {}^{8}_{5}B \;\to\; {}^{8}_{4}Be + e^+ + \nu_e \quad . \tag{2} $$

This accounts for only about 0.02% of PP chain-generated electron neutrinos.

Plot: Solar Neutrino Flux Predictions and Experimental Domains

$*$ Davis and successors measure fluxes in **solar neutrino units**, or SNU (1 SNU $= 10^{-36}$ reactions per target atom per second).

Plot: Davis' Homestake Time History of Solar Neutrino Flux

• The anticipated yield from the SSM is 7.9 SNU, while the experimental determination was 2.26 ± 0.26 SNU. This discrepancy defines the **solar neutrino problem**.

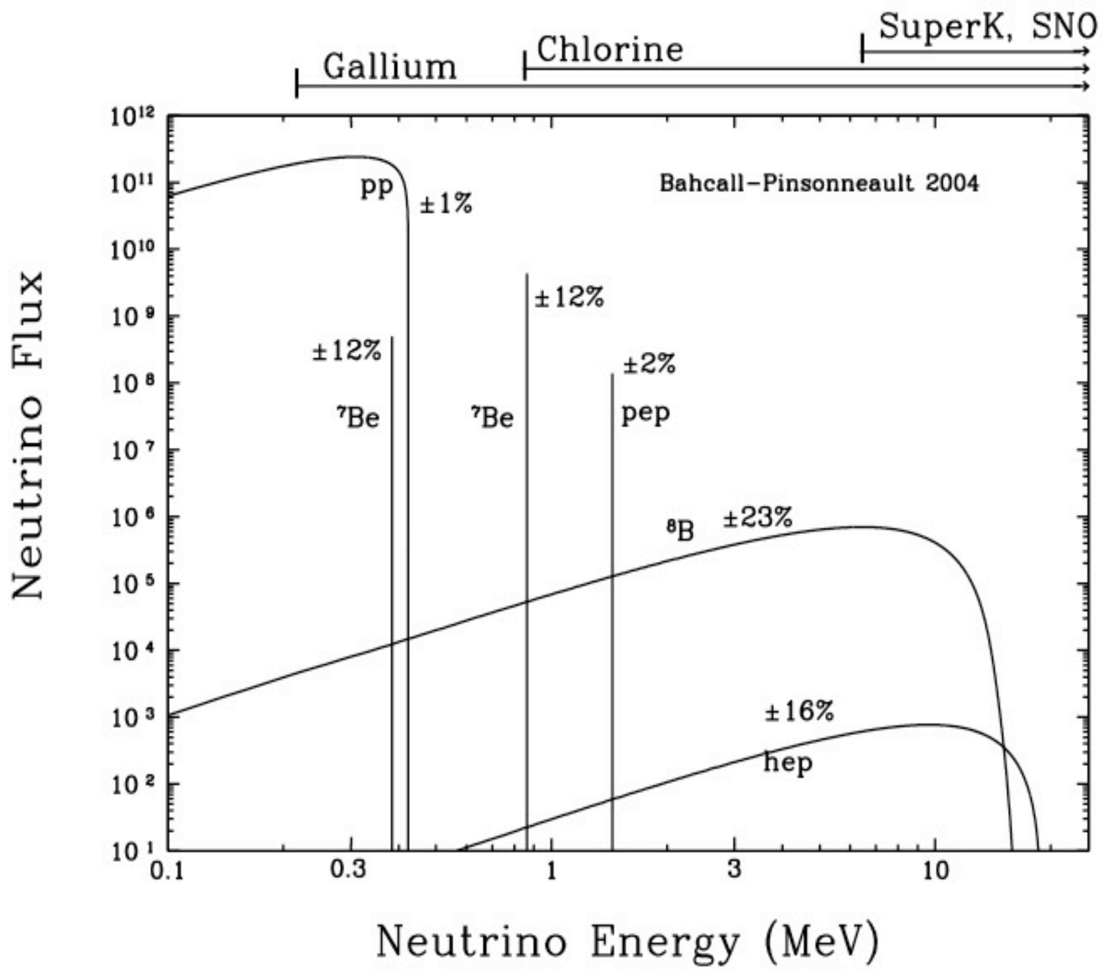
$*$ It has been confirmed by other neutrino detectors such as SAGE, GALLEX and KAMIOKANDE.

Plot: Solar Neutrino Experiment/Theory Summary Comparison

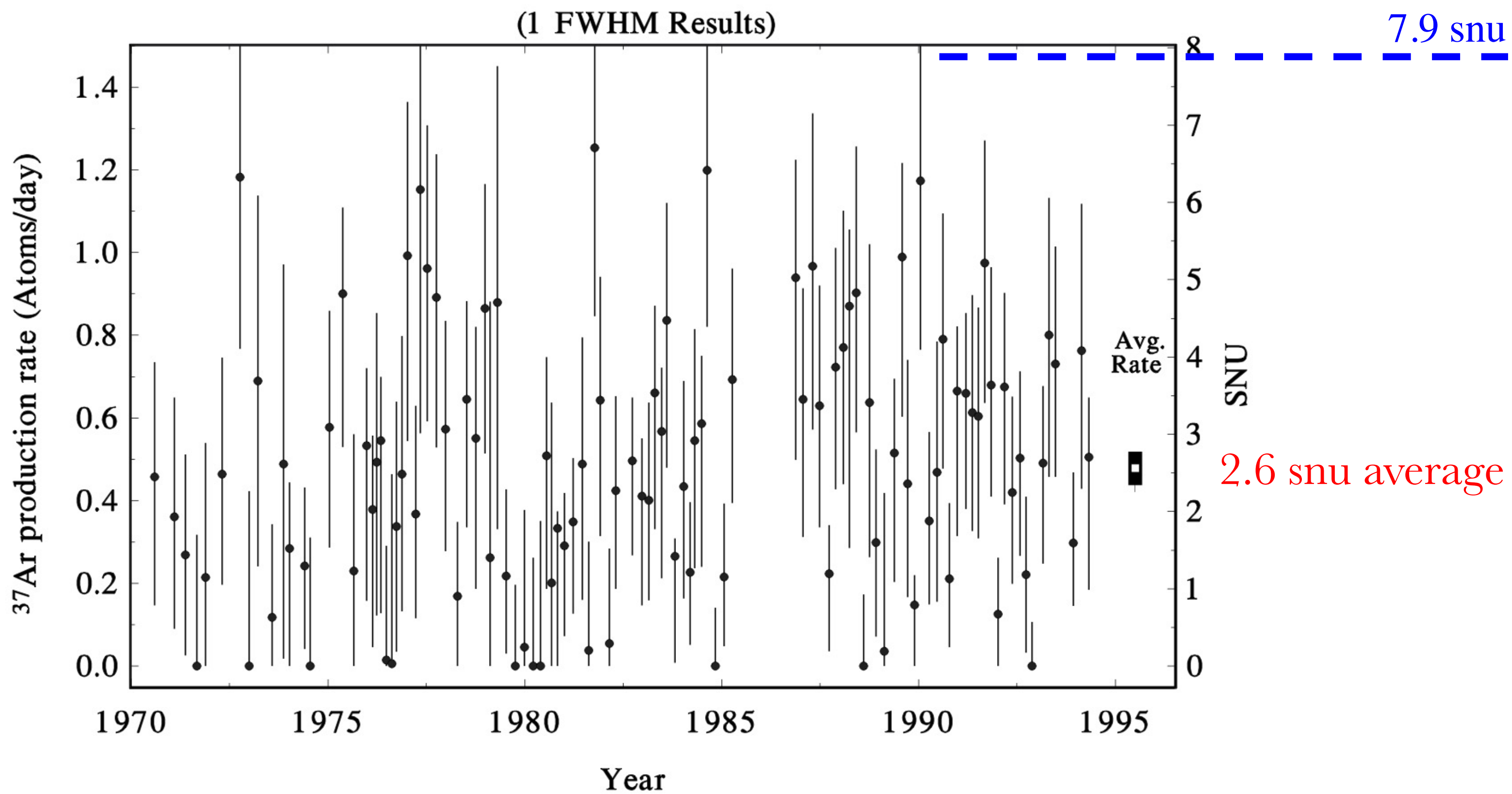
• While the solar neutrino problem originally called the SSM into question, it has led to a fascinating new piece of physics, leaving the SSM intact.

http://www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html

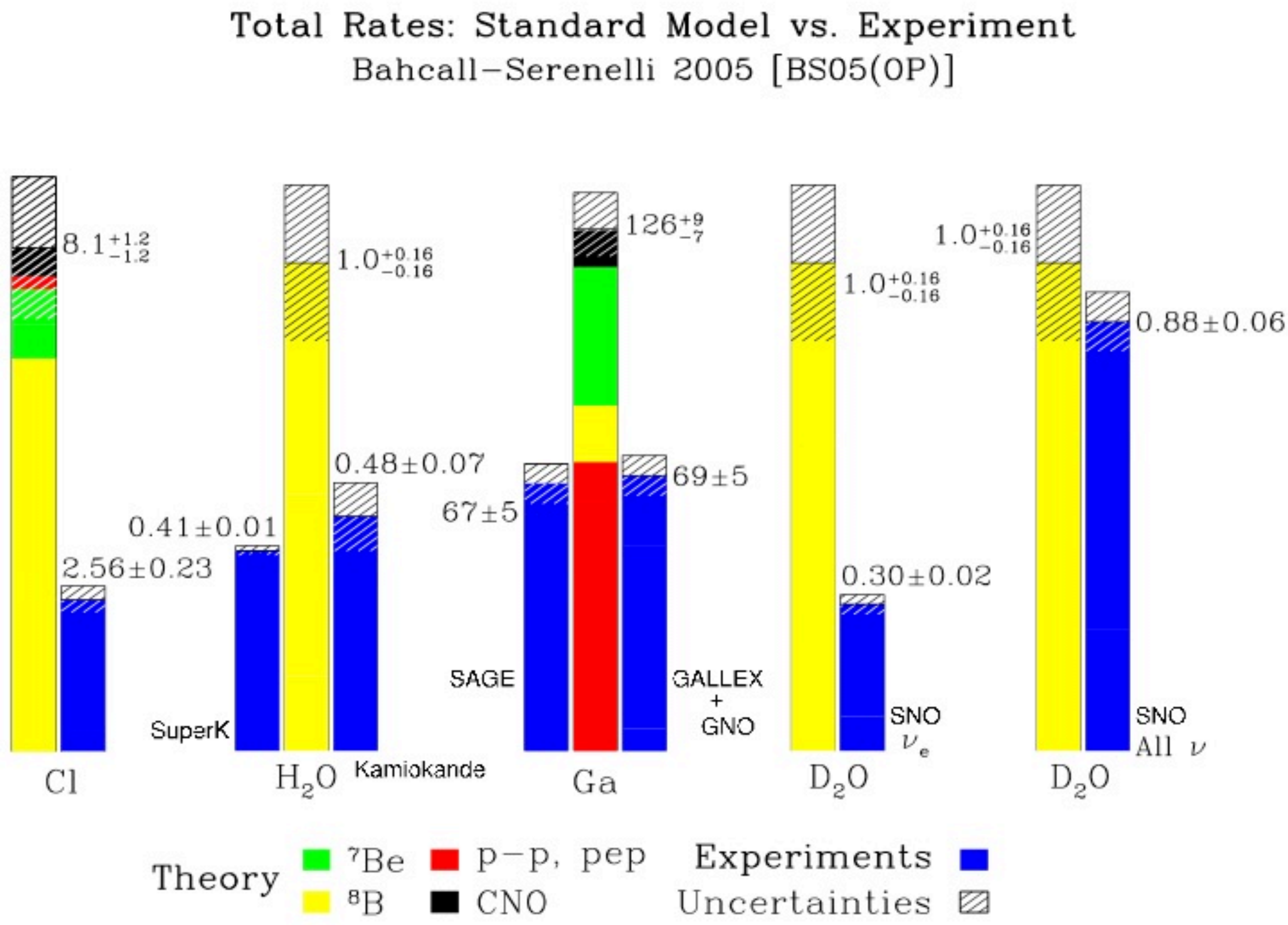
Solar neutrino flux predictions



Davis' Homestake Solar Neutrino Fluxes



- Fluxes from the Davis solar neutrino experiment from 1970-1994. Data are binned in roughly 3 month intervals. Error bars are large.
- From Cleveland et al., Astrophys. J. **496**, 505 (1998).
- The blue dashed line marks the SSM predicted ν flux.



http://www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html

• A solution proposed years before resolution of the problem was that the low signal was due to **neutrino oscillations**. One of the predictions of *electroweak theory* is that there are three different flavors of neutrinos accompanying the three types of leptons in electroweak interactions: the electron neutrino ν_e, the muon neutrino ν_μ and the tau neutrino ν_τ.

• It was proposed that a neutrino state is actually an admixture of these pure states with some specified mixing angle θ_{ew}, so that over time or distance, neutrinos could transform between different neutrino states. This oscillation is called the **Mikheyev-Smirnov-Wolfenstein (MSW)** effect.

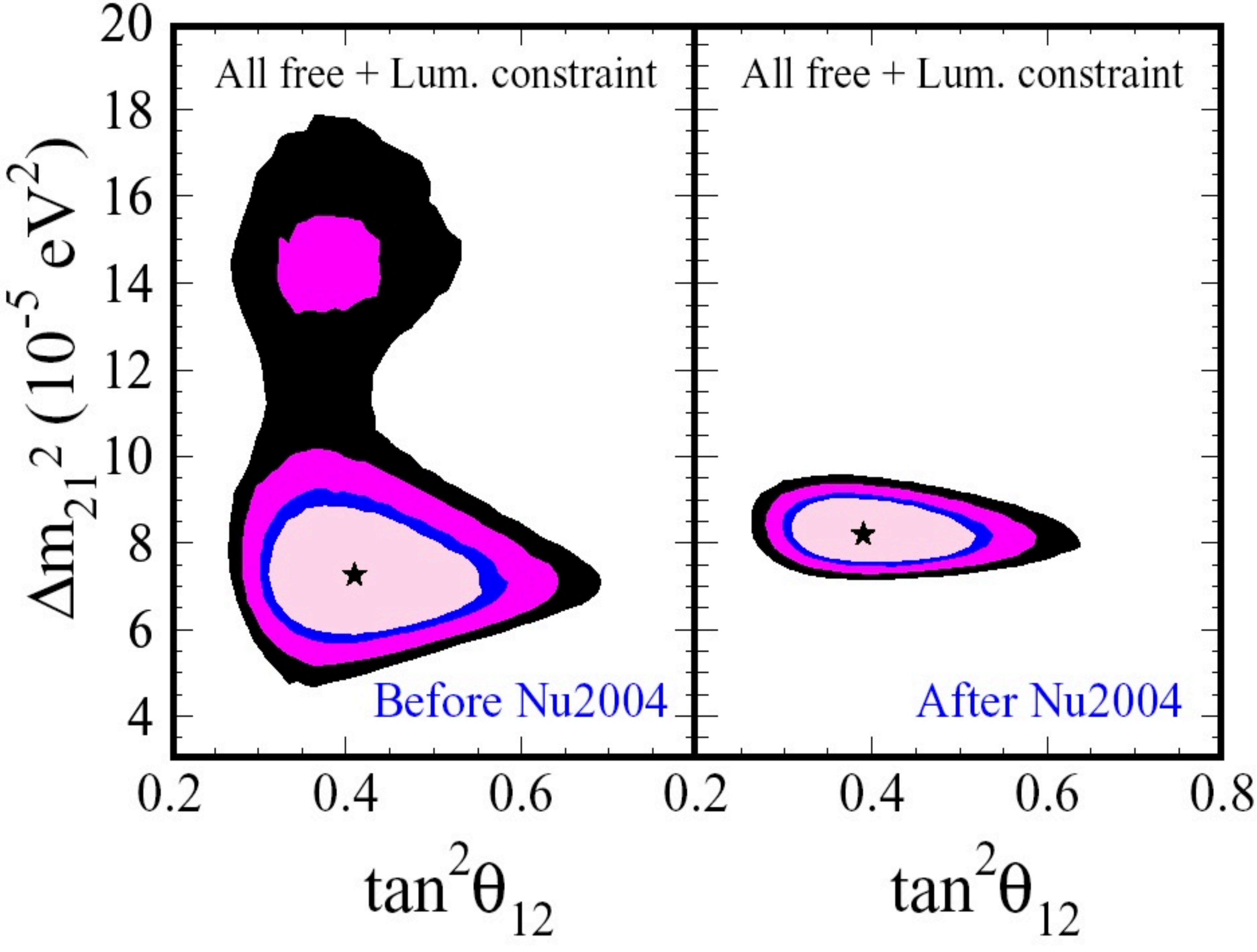
• If the oscillation length is somewhat less than 1 AU, then ν_e produced in the PP chain will only present in terrestrial detectors at 1/3 of the flux. Only the electron neutrinos can be detected in the Davis experiment. Hence, this would explain nearly all of the solar neutrino discrepancy.

$\ast$ The mixing is contingent upon a mass difference between the different neutrino flavors, i.e. that neutrinos are massive. Experimental bounds of $m(\nu_e) \lesssim 7\,\text{eV}$ had been established over the last decade.

• This solution was proven with the discovery of neutrino oscillations by the Super-Kamiokande water Cherenkov experiment.

Plot: Neutrino Oscillation Phase Space

• An excellent Web resource for solar physics and the neutrino problem can be found at [`http://www.talkorigins.org/faqs/faq-solar.html`].



All free + Lum. constraint
All free + Lum. constraint
Before Nu2004
After Nu2004
Δm_{21}^2 (10^{-5} eV^2)
20
18
16
14
12
10
8
6
4
0.2
0.4
0.6
0.2
0.4
0.6
0.8
$\tan^2\theta_{12}$
$\tan^2\theta_{12}$

2 The Solar Surface and Exterior

The lowest layer in the atmosphere, which extends down to one optical depth is called the **photosphere**, within which much of the emergent blackbody temperature is established. **C & O, Sec. 11.2**

• The fact that the blackbody corresponds to just a single temperature, as opposed to a convolution of temperatures, implies that the scalelength for temperature gradients far exceeds the diffusive mean free path.

∗ The photosphere is around 500km thick.

• At the base of the photosphere, we see a patchwork of bright and dark regions that constantly change on timescales of 5-10 minutes. This effect is known as **granulation**, corresponding to spatial extents of 500-1000km.

Plot: SOHO UV Observations

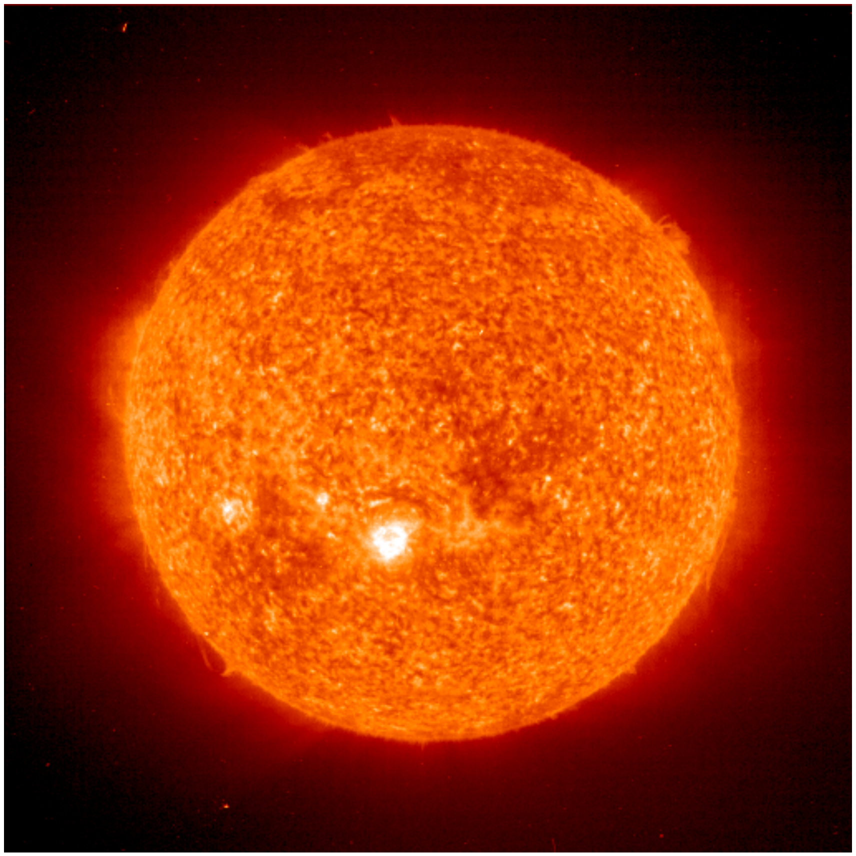
Granulation could occur on smaller scales, but we are limited by arcsecond resolution. Doppler shifting of spectral absorption lines in these granules on these variation timescales indicates rising (brighter) and falling (darker) bubbles at speeds of $0.4\,\text{km/sec}$. *This signals convective energy exchange.*

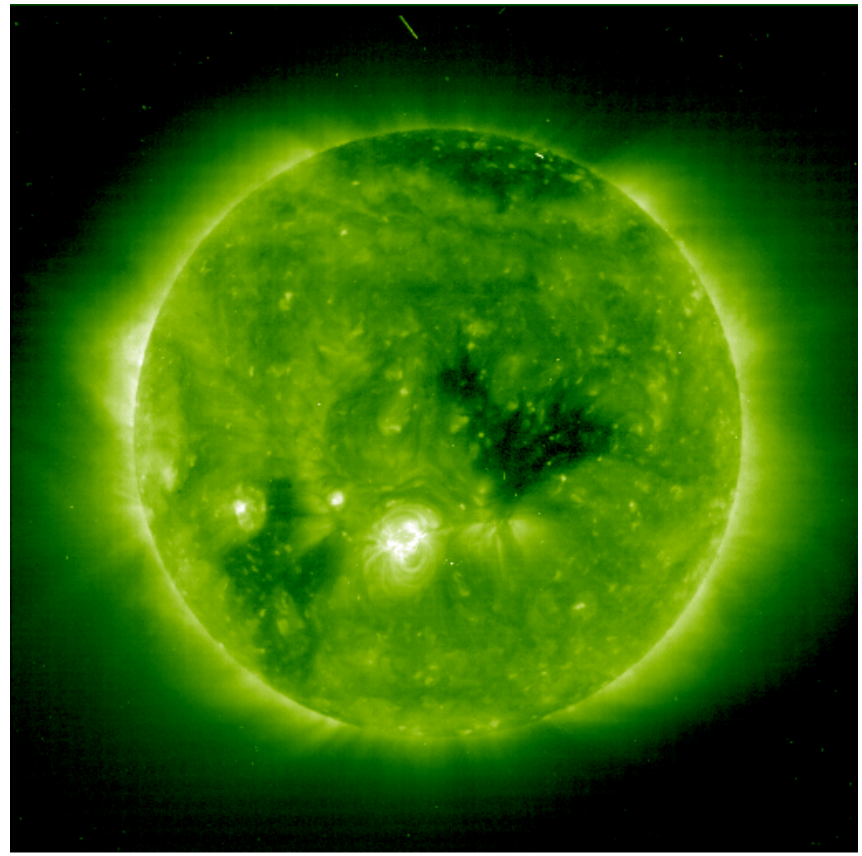
• The photosphere also contains a rather unique ion, H^-, where a second electron is loosely bound with an energy of $0.75\,\text{eV}$. Such an ion can be neutralized by collisional stripping by photons blueward of 17,000 Å.

∗ This source of continuum opacity is primarily responsible for the smoothness of the solar spectrum in the visible and infra-red. Only about 1 in 10^7 hydrogen atoms exist as H^- in the photosphere.

• Above the photosphere are regions called the **chromosphere**, where the gas becomes somewhat hotter yet much more tenuous, at number densities of around 10^9 atoms per cubic centimeter. Then at heights above around 3000 km, there is the **corona**, where large and transient magnetic loops can drive plasma heating to X-ray and even soft gamma-ray temperatures.

Sun in UV: SOHO Observations





- Left panel: He lines showing convective granulation
- Right panel: Fe emission exhibiting coronal activity