SOLAR NEUTRINOS

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INSS18, Mainz

PROGRAM: 2 LECTURES

First Lecture

1A) How does the Sun shine? A few stories and heroes (before 1989)

1B) Standard Solar Models (quick tour by A. Serenelli)

1C) Solar Neutrino fluxes at the Earth

Second Lecture

2D) How does the Sun shine? A few stories and heroes I (after 1989)

2E) Solar Neutrino Experiments and Lessons in Neutrino Physics

2F) Roadmap of future solar neutrino research

HOW DOES THE SUN SHINE? A global effort !

- XIX century: Debate on the Age of the Sun

Radioactivity (1896), Theory of relativity (1905).

- Ernest Rutherford (1904) proposed radioactivity as the source of Solar power.
- Francis Aston (1920) discovery: ^{4}He is lighter than 4 ^{1}H
- Arthur Eddington (1920) propose burning of ^{1}H into ^{4}He
- Cecilia Payne (1925): The Sun is made mostly of H and He

Quantum mechanics (1925)

- George Gamov (1928): quantum tunnelling
- Bethe-Weizsäcker-Zyklus (1938) : CNO cycle
- Hans Bethe (1939): pp chain and CNO cycle

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York
(Received September 7, 1938)

The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$\mathrm{H}+\mathrm{H}=\mathrm{D}+\epsilon^{+}. \qquad (1)$$

The deuteron is then transformed into He^{4} by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} \mathrm{C}^{12}+\mathrm{H}=\mathrm{N}^{13}+\gamma, & \mathrm{N}^{13}=\mathrm{C}^{13}+\epsilon^{+} \\ \mathrm{C}^{13}+\mathrm{H}=\mathrm{N}^{14}+\gamma, & \\ \mathrm{N}^{14}+\mathrm{H}=\mathrm{O}^{15}+\gamma, & \mathrm{O}^{15}=\mathrm{N}^{15}+\epsilon^{+} \\ \mathrm{N}^{15}+\mathrm{H}=\mathrm{C}^{12}+\mathrm{He}^{4}. & \end{array} \qquad (2)$$

SOLAR NEUTRINO PROBLEM

After WWII:

- Willy Fowler et al: calculate and measure the most important cross sections of pp chain and CNO cycle

In the late 1950s, pp chain is identified as the main mechanism of energy generation.

$$4\,{}^{1}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + \text{energy}$$

First solar Model Calculation (1962)

- Ray Davis (1964) Solar Neutrinos: Experimental
- John Bahcall (1964) Solar Neutrinos: Experimental

"proposal to verify that nuclear reactions power the Sun"

- Homestake experiment (since 1968): Fewer neutrinos than predicted

Solar Neutrino Problem identified

Solar Neutrino Problem solutions proposed

- Pontecorvo (1960s) - Neutrino oscillations
- Lincoln Wolfenstein(1978) Matter effects in neutrino propagation
- Stanislav Mikheiev, Alexei Smirnov (1985) Resonant conversion-MSW effect
- Masatoshi Koshiba, Kamiokande experiment (since 1986): Fewer neutrinos
- 1989 "Neutrino Astrophysics" book by John Bahcall
- Since 1990s: Helioseismology and new neutrino experiments

A LOOK INSIDE STANDARD SOLAR MODELS

Stellar structure basic assumptions:

self-gravitating spherically symmetric object with no rotation nor magnetic field

1. Hydrostatic equilibrium $$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$$

2. Mass Conservation $$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$

3. Energy Balance $$\frac{\partial L_m}{\partial m} = \varepsilon_n - \varepsilon_\nu - T\frac{ds}{dt} \equiv \varepsilon_n - \varepsilon_\nu + \varepsilon_g$$

4. Energy transport $$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\begin{cases}\nabla_{rad} \\ \nabla\end{cases}$$

5. Composition changes $$\frac{dn_i}{dt} = \left.\frac{\partial n_i}{\partial t}\right|_{nuc} + \left.\frac{\partial n_i}{\partial t}\right|_{conv} + \left.\frac{\partial n_i}{\partial t}\right|_{diff} ; i = 1,\ldots, N$$

6. Microphysics: Equation of State, Radiative Opacities, Nuclear Cross Sections

Stellar structure – Hydrostatic equilibrium 1/2

1D Euler equation – Eulerian description (fixed point in space)

$$\rho \left.\frac{\partial v}{\partial t}\right|_r + \rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} + f$$

Numerically, Lagrangian description (fixed mass point) is easier (1D)

$$\left.\frac{\partial}{\partial t}\right|_m = \left.\frac{\partial}{\partial t}\right|_r + \left.\frac{\partial r}{\partial t}\right|_m \frac{\partial}{\partial r}$$

here m denotes a concentric mass shell

and using $f = -\frac{Gm}{r^2}$ and $\delta m = 4\pi r^2 \rho \delta r$ Euler equation becomes

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2} \left.\frac{\partial^2 r}{\partial t^2}\right|_m$$

Stellar structure – Hydrostatic equilibrium 2/2

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2}$$

Hydrodynamic time-scale τ_{hydr}:

$$P = 0 \Rightarrow \frac{Gm}{r^2} \approx \frac{r}{\tau^2_{hydr}} \Rightarrow \tau_{hydr} \approx \frac{1}{2}\left(G\bar{\rho}\right)^{1/2} \approx 27\,\mathrm{min}$$

τ_{hydr} << any other time-scale in the solar interior:

hydrostatic equilibrium is an excellent approximation

$$\boxed{\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}} \qquad (1)$$

Stellar structure – Energy equation 1/2

L_m is the energy flux through a sphere of mass m; in the absence of energy sources

$$\frac{\partial L_m}{\partial m} dt = -dq$$

where $dq = du + PdV$.

Additional energy contributions (sources or sinks) can be represented by a total specific rate ε (erg g^{-1} s^{-1})

$$\frac{\partial L_m}{\partial m} = \varepsilon - \frac{dq}{dt}$$

Possible contributions to ε: nuclear reactions, neutrinos (nuclear and thermal), axions, etc.

Stellar structure – Energy equation 2/2

In a standard solar model we include nuclear and neutrino contributions (thermal neutrinos are negligible):

$\varepsilon = \varepsilon_n - \varepsilon_\nu$ (taking $\varepsilon_\nu > 0$)

$$\frac{\partial L_m}{\partial m} = \varepsilon_n - \varepsilon_\nu - T\frac{ds}{dt} \equiv \varepsilon_n - \varepsilon_\nu + \varepsilon_g \qquad (3)$$

In the present Sun the integrated contribution of ε_g to the solar luminosity is only ~ 0.02% (theoretical statement)

Solar luminosity is almost entirely of nuclear origin $\Rightarrow$

Luminosity constrain: $L_\odot = \int \frac{\partial L_m}{\partial m} dm \approx \int (\varepsilon_n - \varepsilon_\nu) dm$

Stellar structure – Energy transport
Radiative transport 1/2

Mean free path of photons $l_{ph}=1/\kappa\rho$ (κ opacity, ρ density)

Typical values $<\kappa>=0.4\text{cm}^2\text{g}^{-1}$, $<\rho>=1.4\ \text{g cm}^{-3} \Rightarrow l_{ph}\approx 2\text{cm}$

$l_{ph}/R_\odot \approx 3\times10^{-11} \Rightarrow$ transport as a diffusion process

If D is the diffusion coefficient, then the diffusive flux is given by

$$\vec{F} = -D\vec{\nabla}U$$

and in the case of radiation $D = \frac{1}{3}cl_{ph}$ and $U = aT^4$ where c is the speed of light and a is the radiation-density constant and U is the radiation energy density.

In 1-D we get

$$F = -\frac{4ac}{3}\frac{T^3}{\kappa\rho}\frac{\partial T}{\partial r}$$

Stellar structure – Energy transport

Radiative transport 2/2

The flux F and the luminosity L_m are related by $F = \frac{L_m}{4\pi r^2}$

and the transport equation can be written as

$$\frac{\partial T}{\partial r} = -\frac{3}{16\pi ac}\frac{\kappa\rho L_m}{r^2 T^3}$$

or, in lagrangian coordinates $\boxed{\frac{\partial T}{\partial m} = -\frac{3}{64\pi^2 ac}\frac{\kappa L_m}{r^4 T^3}}$

Using the hydrostatic equilibrium equation, we define the radiative temperature gradient as

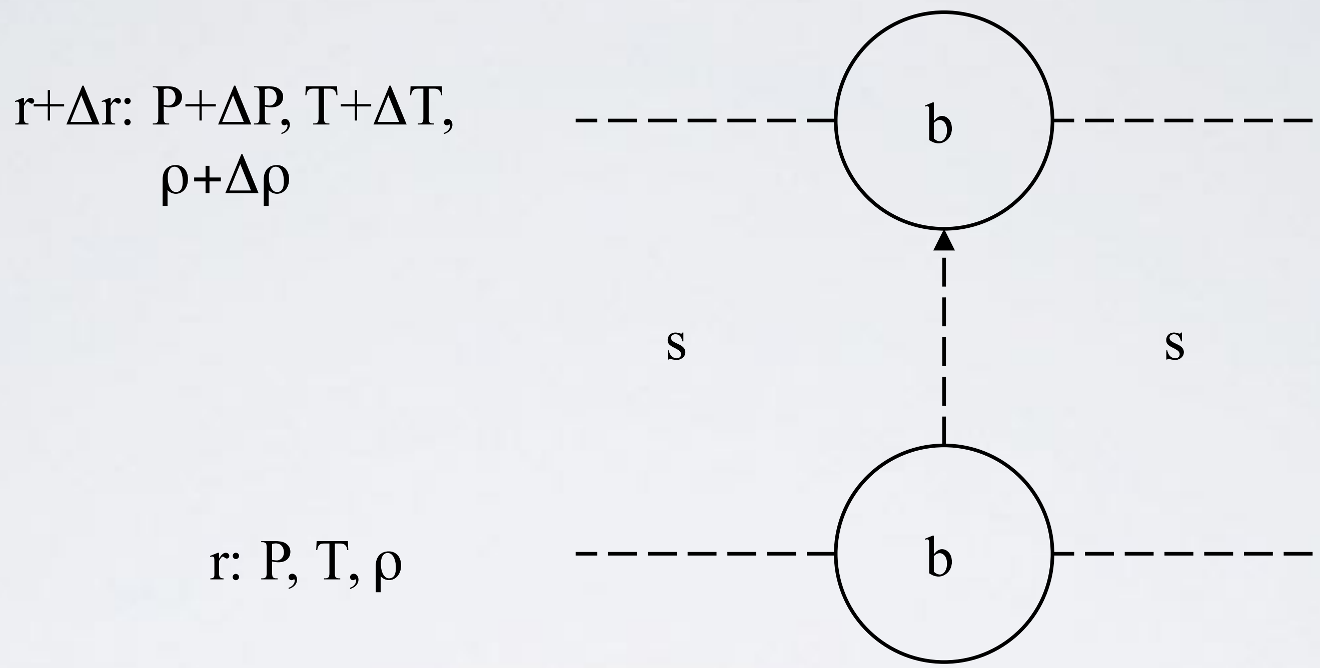
$$\nabla_{rad} \equiv \left.\frac{d\ln T}{d\ln P}\right|_{rad} = \frac{3}{16\pi acG}\frac{\kappa L_m P}{mT^4}$$

and finally

$$\boxed{\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla_{rad}} \qquad (4)$$

Stellar structure – Energy transport
Convective transport 1/3

Adiabactic displacement



Stability condition: $$\Delta\rho_b < \Delta\rho_s \Rightarrow \left.\frac{d\ln\rho}{dr}\right|_b \Delta r < \left.\frac{d\ln\rho}{dr}\right|_s \Delta r$$

Using hydrostatic equilibrium, and $$d\ln\rho = \alpha d\ln P - \delta d\ln T$$

$$\left.\frac{d\ln T}{dr}\right|_b > \left.\frac{d\ln T}{dr}\right|_S \Rightarrow \left.\frac{d\ln T}{dr}\right|_{ad} > \left.\frac{d\ln T}{dr}\right|_{rad}$$

Stellar structure – Energy transport

Convective transport 2/3

Divide by $\dfrac{d\ln P}{dr}$ and get

$$\boxed{\left.\frac{d\ln T}{d\ln P}\right|_{ad} > \left.\frac{d\ln T}{d\ln P}\right|_{rad} \equiv \nabla_{ad} > \nabla_{rad} \quad \text{Schwarzschild criterion for dynamical stability}}$$

When does convection occur?

$$\nabla_{rad} = \frac{3}{16\pi acG}\frac{\kappa L_m P}{mT^4} \Rightarrow \begin{cases} \text{large } L_m \text{ (e.g. cores of stars } M_* > 1.3 M_\odot\text{)} \\ \text{regions of large } \kappa \text{ (e.g. solar envelope)} \end{cases}$$

Stellar structure – Energy transport

Convective transport 3/3

Using definition of ∇_{rad} and $F = \dfrac{L_m}{4\pi r^2}$ we can write

$$F = \frac{4acG}{3}\frac{T^4 m}{\kappa P r^2}\nabla_{rad}$$ and, if there is convection: $F=F_{rad}+F_{conv}$

where $$F_{rad} = \frac{4acG}{3}\frac{T^4 m}{\kappa P r^2}\nabla$$

∇ is the actual temperature gradient and satisfies $\nabla_{ad} < \nabla < \nabla_{rad}$

F_{conv} and ∇ must be determined from convection theory (solution to full hydrodynamic equations)

Easiest approach: Mixing Length Theory (involves 1 free param.)

Energy transport equation $$\boxed{\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla} \qquad (4b)$$

Stellar structure – Composition changes 1/4

Relative element mass fraction: $X_i = \frac{n_i m_i}{\rho}; \sum_i X_i = 1$

X hydrogen mass fraction, Y helium and "metals" $Z = 1 - X - Y$

The chemical composition of a star changes due to

- Convection
- Microscopic diffusion
- Nuclear burning
- Additional processes: meridional circulation, gravity waves, etc. (not considered in SSM)

Stellar structure – Composition changes 2/4

Convection (very fast) tends to homogenize composition

$$\left.\frac{\partial n_i}{\partial t}\right|_{conv} = \frac{\partial}{\partial m}\left(\left(4\pi r^2 \rho\right)^2 D_{conv} \frac{\partial n_i}{\partial m}\right)$$

where D_{conv} is the same for all elements and is determined from convection treatment (MLT or other)

Microscopic diffusion (origin in pressure, temperature and concentration gradients). Very slow process: $\tau_{diff} >> 10^{10}$yrs

$$\left.\frac{\partial n_i}{\partial t}\right|_{diff} = \frac{\partial}{\partial m}\left(4\pi\rho r^2 n_i w_i\right)$$

here w_i are the diffusion velocities (from Burgers equations for multicomponent gases, Burgers 1969)

Dominant effect in stars: sedimentation H↑ – Y & Z ↓

Stellar structure – Composition changes 3/4

Nuclear reactions (2 particle reactions, decays, etc.)

$$\left.\frac{\partial n_i}{\partial t}\right|_{nuc} = -\sum_j \frac{n_i n_j}{1+\delta_{ij}} <\sigma v>_{ij} + \sum_{kl} \frac{n_k n_l}{1+\delta_{kl}} <\sigma v>_{kl} + \text{e.t.}$$

here $<\sigma v> = \int_0^\infty v\sigma(v)\Phi(v)dv$

$\Phi(v)$ is the relative velocity distrib. and $\sigma(v)$ is cross section

Sun: main sequence star → hydrogen burning

low mass → pp chains (~99%), CNO (~1%)

Basic scheme: $4p \rightarrow {}^4He + 2\beta^+ + 2\nu_e + \sim 25/26$ MeV

hydrogen burning – pp chains

$$\begin{cases} p + p \rightarrow {}^2H + e^+ + \nu_e + \gamma \\ p + p + e^- \rightarrow {}^2H + \nu_e \end{cases}$$

Q=1.44 MeV, <Q$_\nu$>=0.265 pp neutrinos

Q=Q$_\nu$=1.44 pep neutrinos

$${}^2H + p \rightarrow {}^3He + \gamma$$

Q=5.49

$$\underbrace{{}^3He + {}^3He \rightarrow {}^4He + 2p + \gamma}_{\substack{\text{ppI} \\ 88\text{-}89\%}}$$

Q=12.86

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

Q=1.59

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e$$

Q=Q$_\nu$=0.86 (90%)-0.38 (10%)

^{7}Be neutrinos

$$\underbrace{{}^7Li + p \rightarrow {}^4He + {}^4He + \gamma}_{\substack{\text{ppII} \\ 10\%}}$$

Q=17.35

$${}^7Be + p \rightarrow {}^8B + \gamma$$

Q=0.137

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e + \gamma$$

^{8}B neutrinos Q=17.98, <Q$_\nu$>=6.71

$$\underbrace{{}^8Be \rightarrow {}^4He + {}^4He}_{\substack{\text{ppIII} \\ 1\%}}$$

Marginal reaction:

$${}^3He + p \rightarrow {}^4He + e^+ + \nu_e + \gamma$$

Q=19.795, <Q$_\nu$>=9.625 hep neutrinos

hydrogen burning – CNO cycle

CN-cycle

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$ Q=1.94

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e + \gamma$$ Q=2.22, $\langle Q_\nu \rangle$=0.707 ^{13}N neutrinos

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$ Q=7.55

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$ Q=7.30

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e + \gamma$$ Q=2.75, $\langle Q_\nu \rangle$=0.996 ^{13}N neutrinos

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He + \gamma$$ Q=4.97

NO-cycle

$$^{15}N + p \rightarrow {}^{16}O + \gamma$$ Q=12.13

$$^{16}O + p \rightarrow {}^{17}F + \gamma$$ Q=0.600

$$^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e + \gamma$$ Q=2.76, $\langle Q_\nu \rangle$=0.999 ^{17}F neut.

$$^{17}O + p \rightarrow {}^{14}N + {}^{4}He + \gamma$$ Q=1.19

CNO cycle is regulated by ^{14}N+p reation (slowest)

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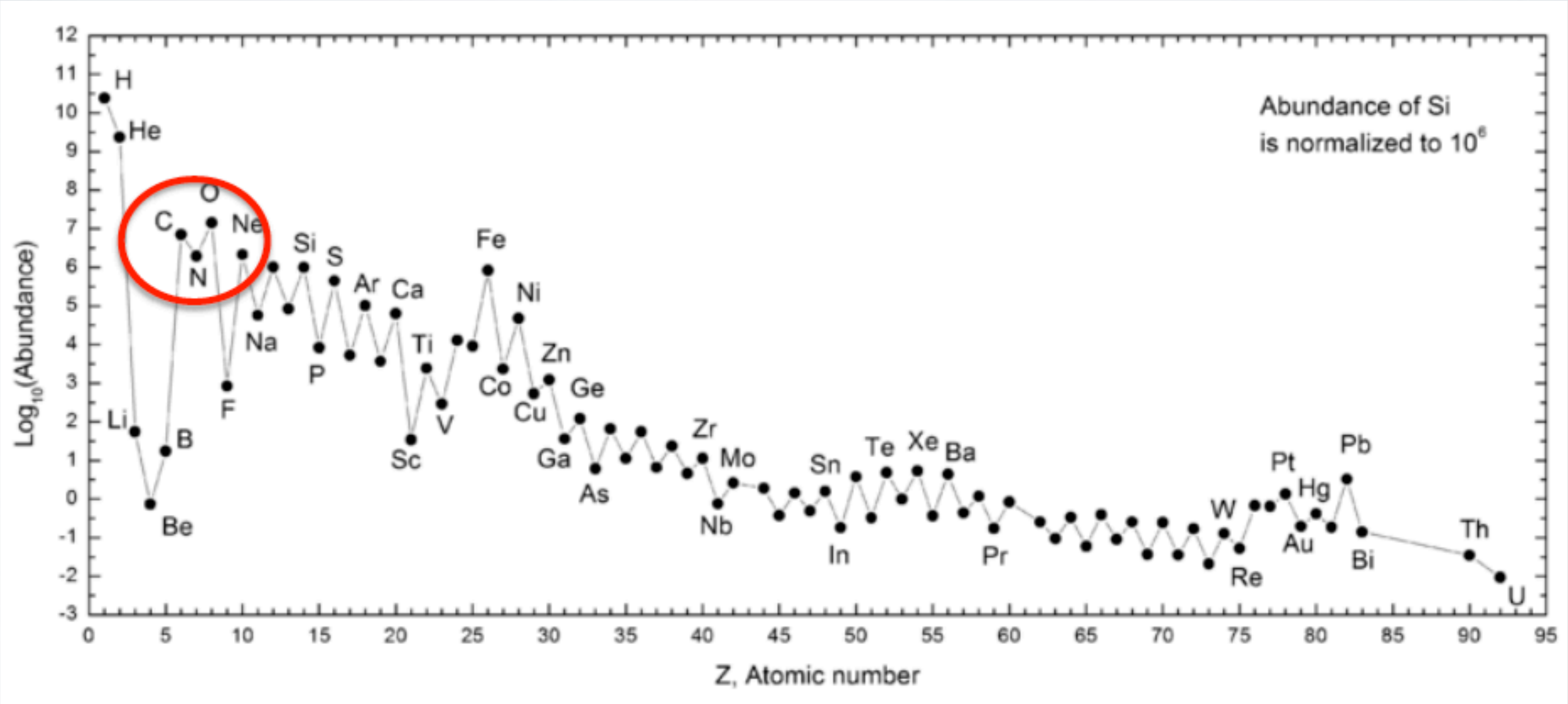
6. Microphysics: Equation of State, Radiative Opacities, Nuclear Cross Sections

Other Inputs



Meteoritic abundances

- CI Chondrites

✓ Mass spectroscopy very accurate!

✓ But volatile elements (form gaseous components) are depleted

H, He, C, N, O and Ne

need a conversion factor from the solar to meteoritic scale

Meteoritic abundances

- CI Chondrites

depleted in **H** → coupling meteoritic abundances to astronomical scale using **Si**

A (el) = const + log N (el)

assuming A(Si) = 7.54
const = 1.54 to match Si abundance on both scales

Grevesse & Sauval (1989)

- 1D hydrostatic solar model
- LTE

old 1D LTE

Asplund, Grevesse, Sauval, Scott, 2009, ARAA

- 3D hydrodynamical solar model
- NLTE, where available

new 3D NLTE

Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

Significantly lower solar **metal mass fraction Z**

- **Z=0.0169** (GS 1998)
- **Z=0.0134** (AGSS 2009)

Other Inputs

Qnt.	Central value	σ (%)	Ref.
$^3\mathrm{He}(^3\mathrm{He},2\mathrm{p})^4\mathrm{He}$	5.21 MeV b	5.2	1
$^3\mathrm{He}(^4\mathrm{He},\gamma)^7\mathrm{Be}$	$5.6 \cdot 10^{-4}$ MeV b	5.2	1
$^7\mathrm{Be}(\mathrm{e}^-,\nu_\mathrm{e})^7\mathrm{Li}$	Eq (40) SFII	2.0	1
$^3\mathrm{He}(\mathrm{p},\mathrm{e}^+\nu_\mathrm{e})^4\mathrm{He}$	$8.6 \cdot 10^{-20}$ MeV b	30.2	1
$^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}$	$1.06 \cdot 10^{-2}$ MeV b	7.6	1
$\tau_\odot$	$4.57 \cdot 10^9$ yr	0.44	2
diffusion	1.0	15.0	2
$L_\odot$	$3.8418 \cdot 10^{33}$ erg s^{-1}	0.4	2

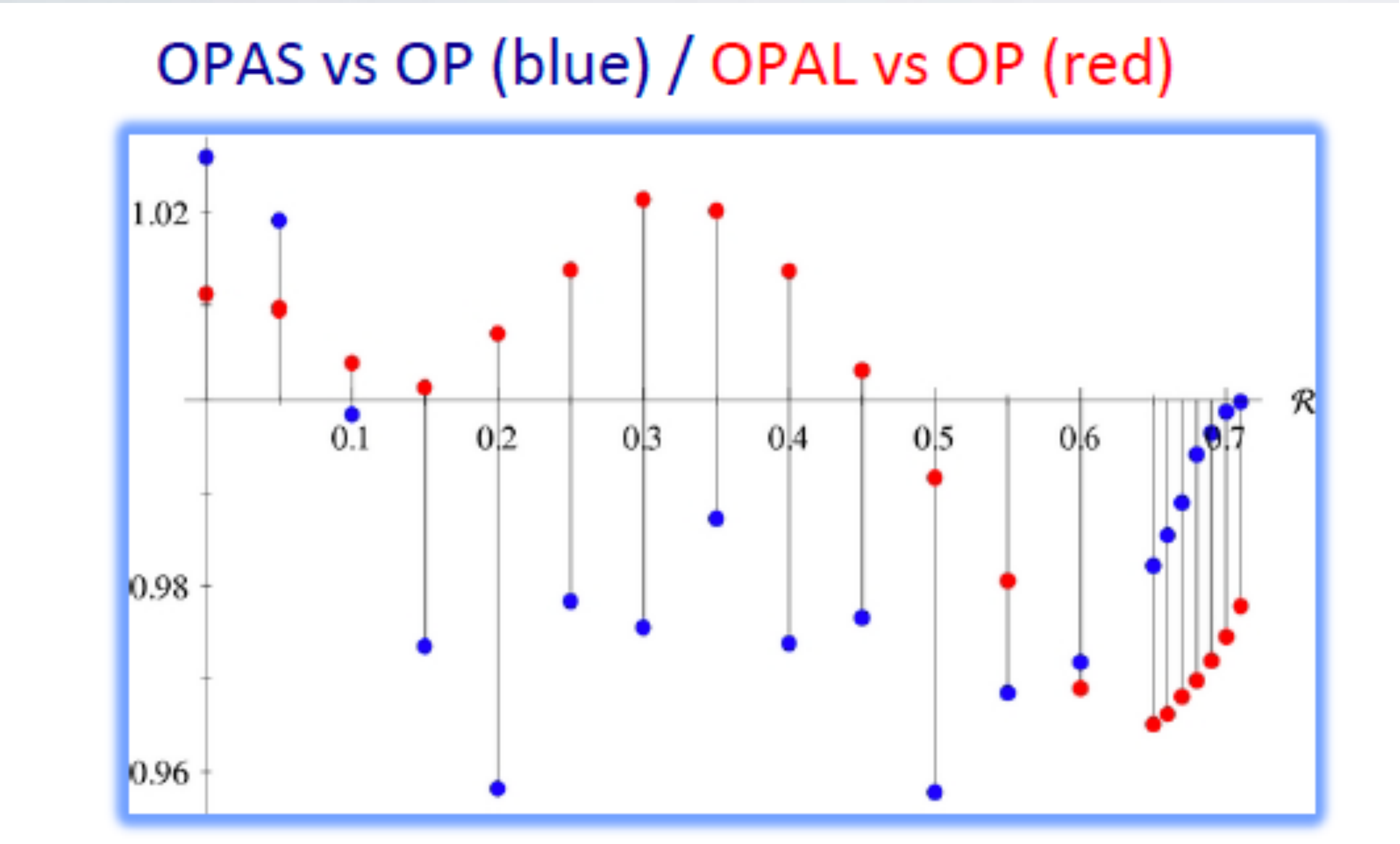
	$S(0)$	Uncert. %	$\Delta S(0)/S(0)$	Ref.
S_{11}	$4.03 \cdot 10^{-25}$	1	0.5%†	1,2,3
S_{17}	$2.13 \cdot 10^{-5}$	4.7	+2.4%	4
S_{114}	$1.59 \cdot 10^{-3}$	7.5	-4.2%	5

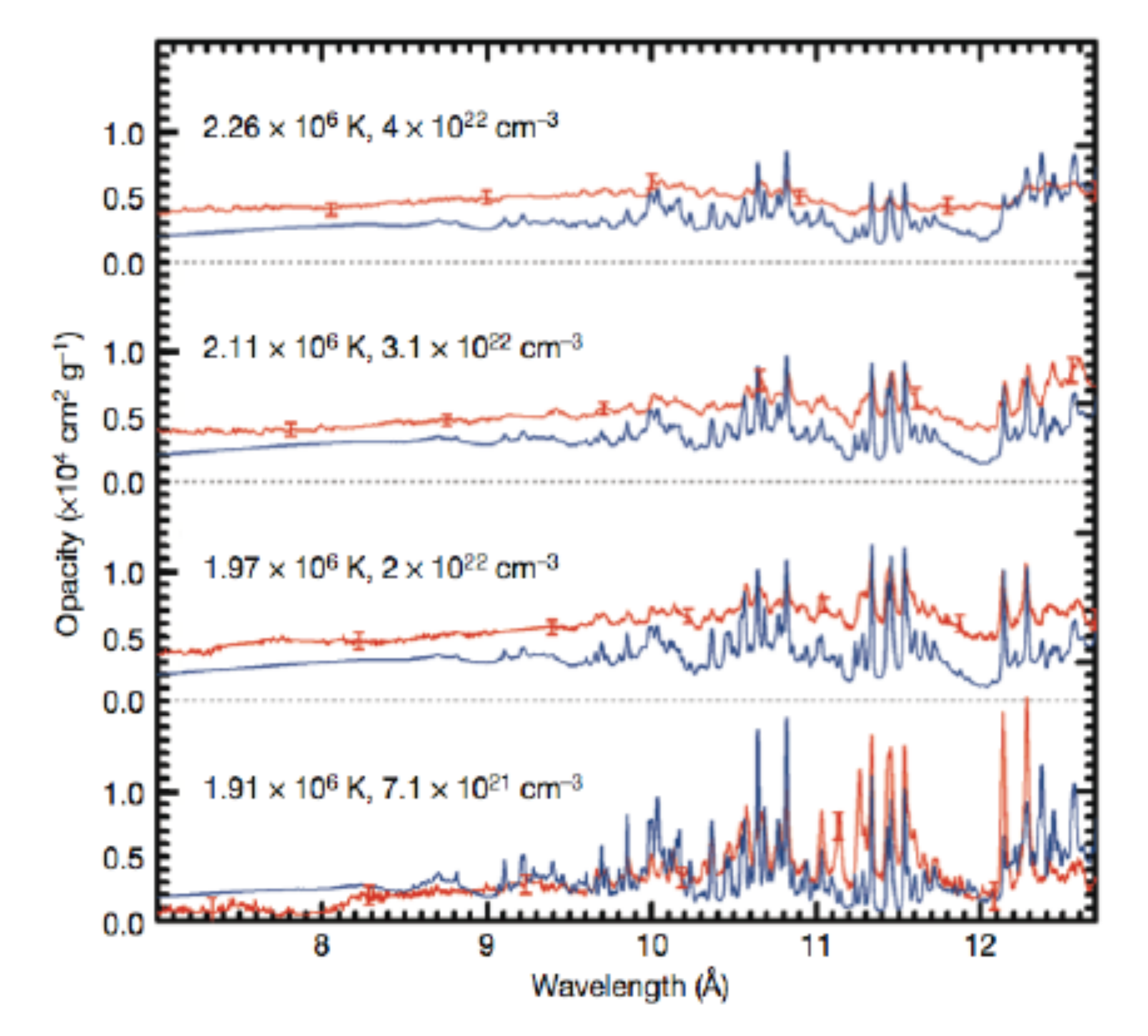
Nuclear Cross Sections

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Ne	8.08 ± 0.06	7.93 ± 0.10
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Ar	6.40 ± 0.06	6.40 ± 0.13
Fe	7.50 ± 0.01	7.45 ± 0.01
$(Z/X)_\odot$	0.02292	0.01780

Solar Abundances in log(Z/A) +12

Other Inputs





Opacity tables (calculations)

Iron opacity (1/4 solar density)
Sandia Lab

Standard Solar Model – What we do 1/2

Solve eqs. 1 to 5 with good microphysics, starting from a Zero Age Main Sequence (chemically homogeneous star) to present solar age

Fixed quantities		
Solar mass	$M_\odot=1.989\times10^{33}$g 0.1%	Kepler's 3rd law
Solar age	$t_\odot=4.57\times10^{9}$yrs 0.5%	Meteorites

Quantities to match		
Solar luminosity	$L_\odot=3.842\times10^{33}$erg s^{-1} 0.4%	Solar constant
Solar radius	$R_\odot=6.9598\times10^{10}$cm 0.1%	Angular diameter
Solar metals/hydrogen ratio	$(Z/X)_\odot= 0.0229$	Photosphere and meteorites

- Dating the Solar System
  - Ratio $^{238}U/^{235}U$ known and constant (in space, not in time) in solar system material
  - Primordial isotopic composition of lead (Pb) known from meteoritic samples with very low abundances of U or Th
- Measure the ratio $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ in your sample, and, taking into account that ^{204}Pb does not change, write

$$^{206}Pb^* = \left[\left(\frac{^{206}Pb}{^{204}Pb}\right) - \left(\frac{^{206}Pb}{^{204}Pb}\right)_{PRIM}\right] {}^{204}Pb_{PRIM} = {}^{238}U\left[e^{\lambda_{238}T} - 1\right]$$

$$^{207}Pb^* = \left[\left(\frac{^{207}Pb}{^{204}Pb}\right) - \left(\frac{^{207}Pb}{^{204}Pb}\right)_{PRIM}\right] {}^{204}Pb_{PRIM} = {}^{235}U\left[e^{\lambda_{235}T} - 1\right]$$

$$\frac{^{206}Pb^*}{^{207}Pb^*} = \frac{^{238}U}{^{235}U}\left[\frac{e^{\lambda_{238}T} - 1}{e^{\lambda_{235}T} - 1}\right]$$ is only function of T

Standard Solar Model – What we do 2/2

3 free parameters:

- Convection theory has 1 free parameter: α_{MLT} determines the temperature stratification where convection is not adiabatic (upper layers of solar envelope)
- 2 of the 3 quantities determining the initial composition: X_{ini}, Y_{ini}, Z_{ini} (linked by $X_{ini}+Y_{ini}+Z_{ini}=1$). Individual elements grouped in Z_{ini} have relative abundances given by solar abundance measurements (e.g. GS98, AGS05)

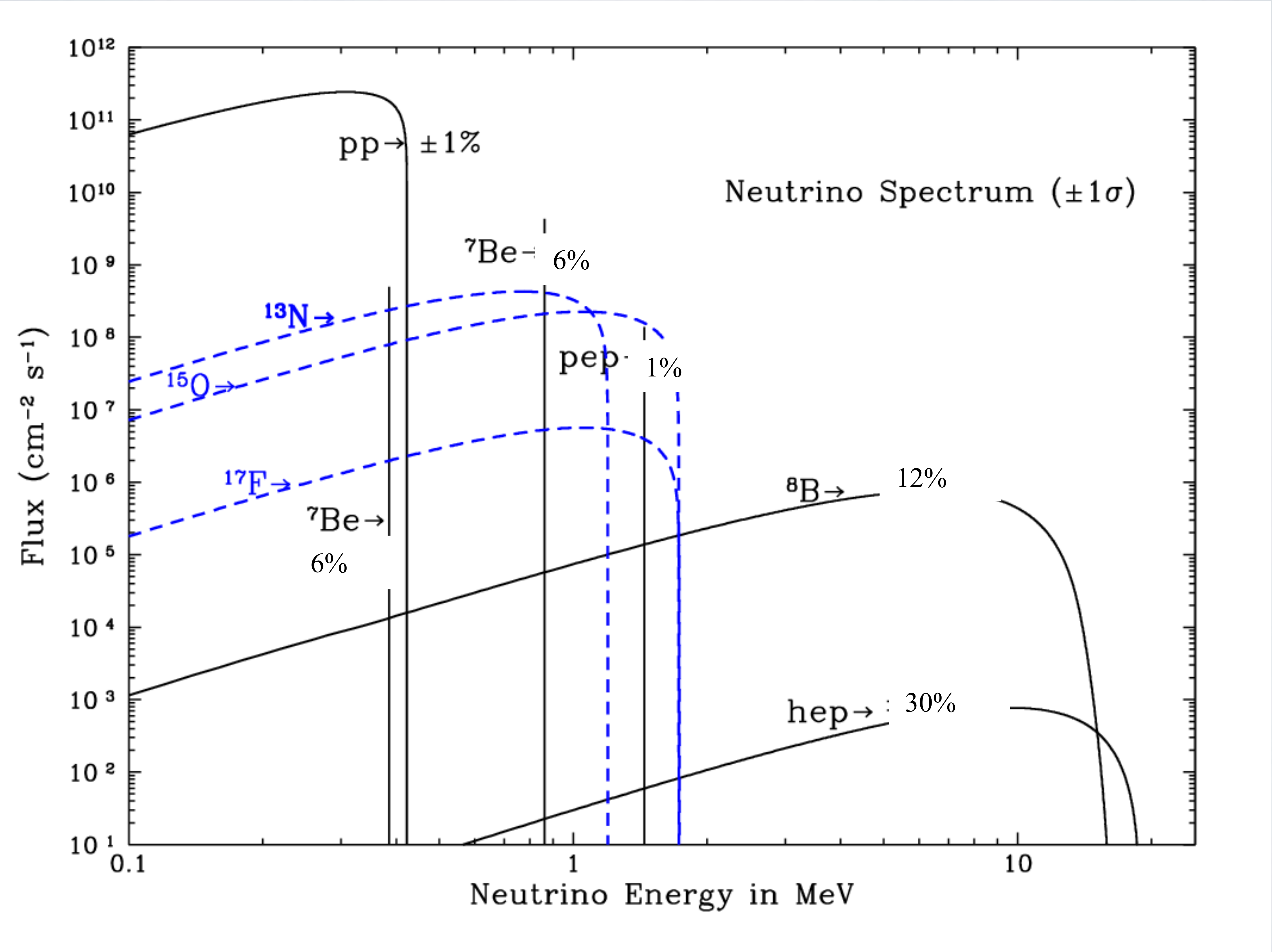
Construct a $1M_\odot$ initial model with X_{ini}, Z_{ini}, ($Y_{ini}=1- X_{ini}-Z_{ini}$) and α_{MLT}, evolve it during $t_\odot$ and match $(Z/X)_\odot$, $L_\odot$ and $R_\odot$ to better than one part in 10^{-5}

Standard Solar Model – Predictions

- Eight neutrino fluxes: production profiles and integrated values.
- Chemical profiles $X(r)$, $Y(r)$, $Z_i(r)$ $\rightarrow$ electron and neutron density profiles (needed for matter effects in neutrino studies)
- Thermodynamic quantities as a function of radius: T, P, density (ρ), sound speed (c)
- Surface helium Y_{surf} (Z/X and $1=X+Y+Z$ leave 1 degree of freedom)
- Depth of the convective envelope, R_{CZ}

Standard Solar Model

Solar neutrino spectra

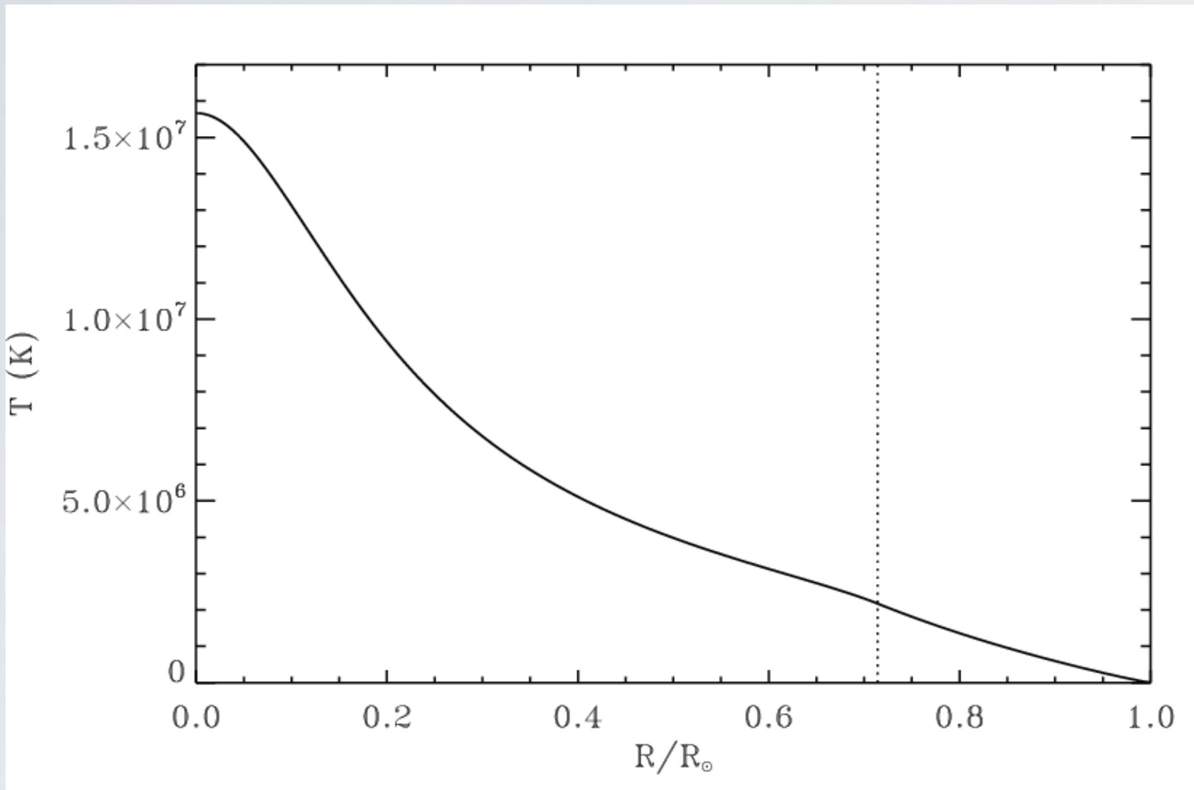


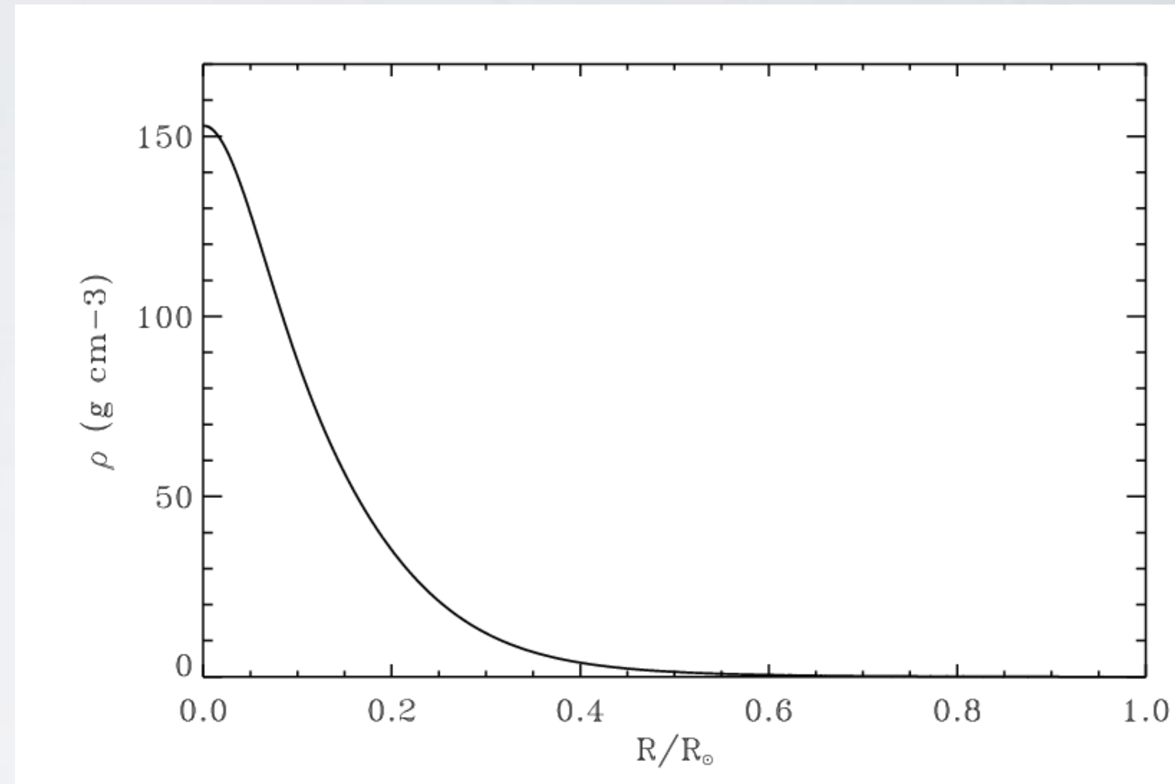
Flux	B16-GS98	B16-AGSS09met	Solar^a
$\Phi(\mathrm{pp})$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(\mathrm{pep})$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(\mathrm{hep})$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7\mathrm{Be})$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8\mathrm{B})$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}\mathrm{N})$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}\mathrm{O})$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}\mathrm{F})$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

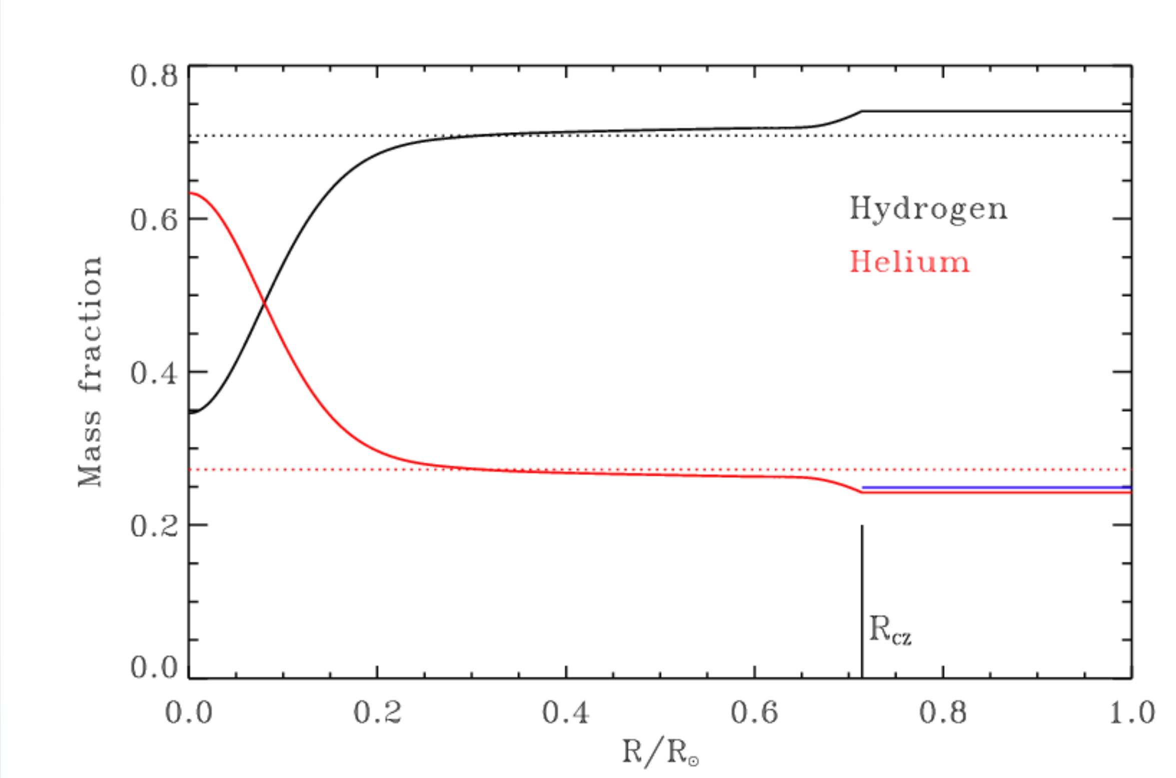
Table 6. Model and solar neutrino fluxes. Units are: 10^{10} (pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6 (^{8}B, ^{17}F) and 10^3(hep) cm^{-2}s^{-1}. ^{a}Solar values from Bergström et al. (2016).

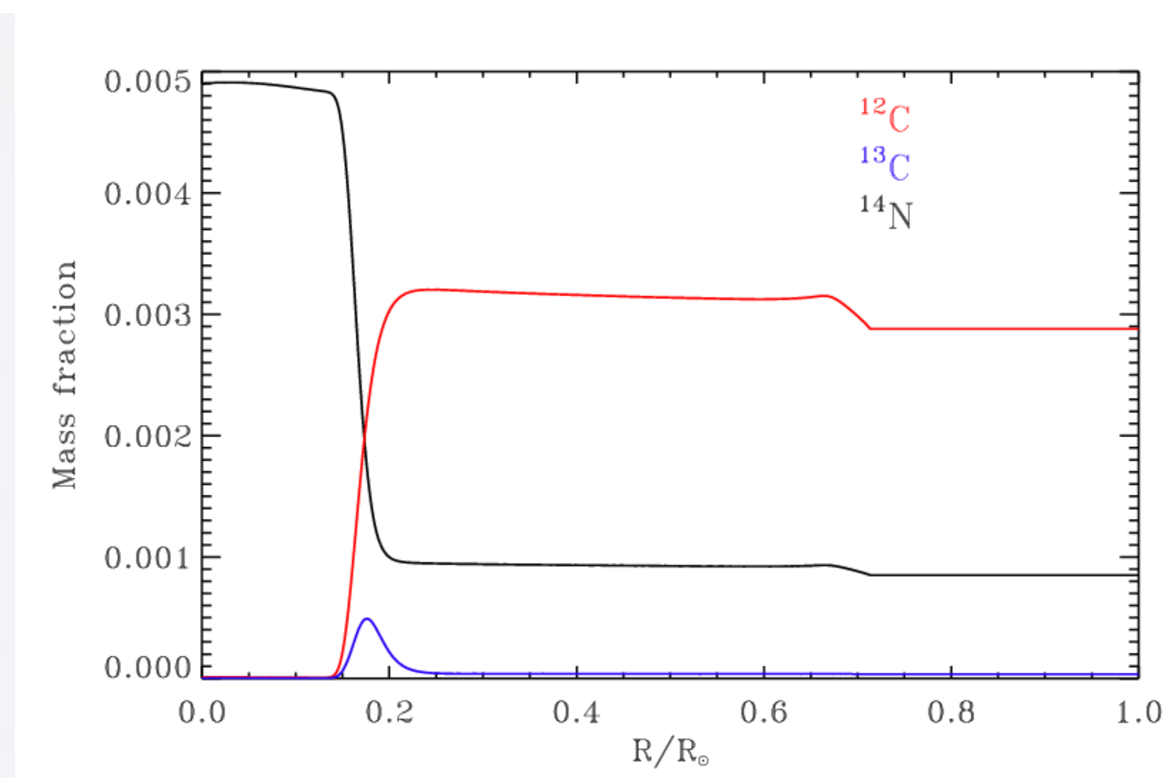
Standard Solar Model

Internal structure



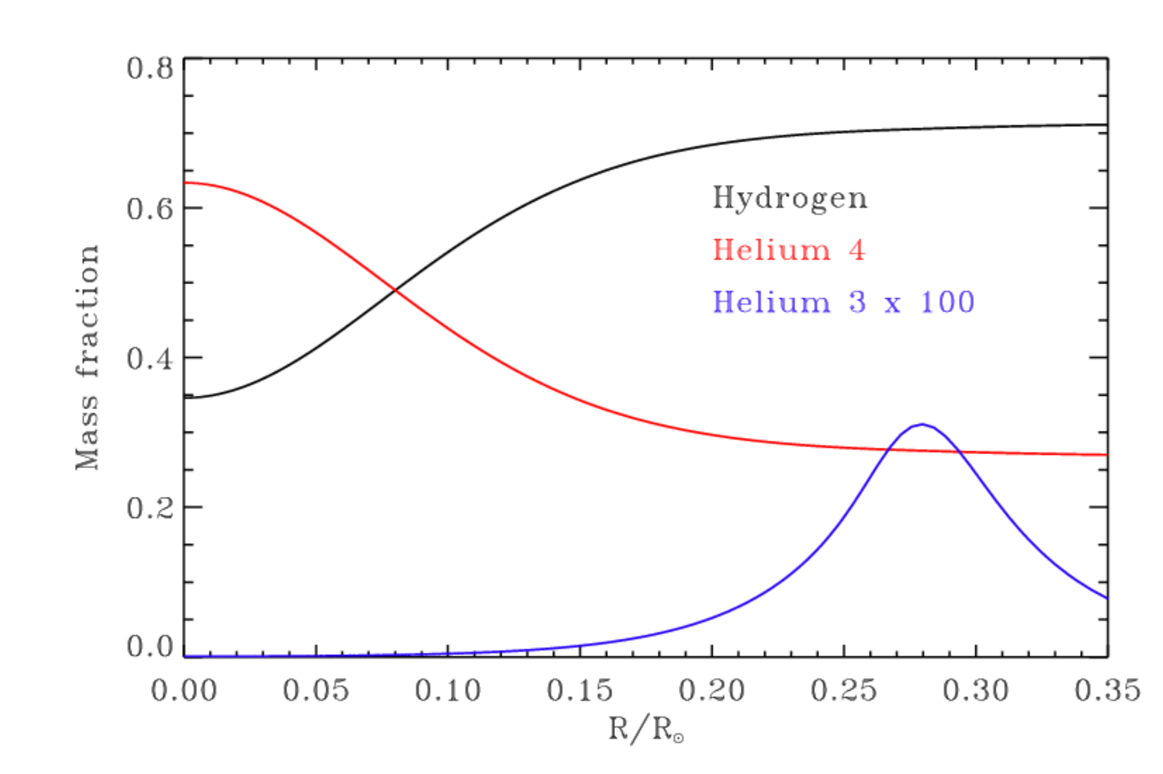






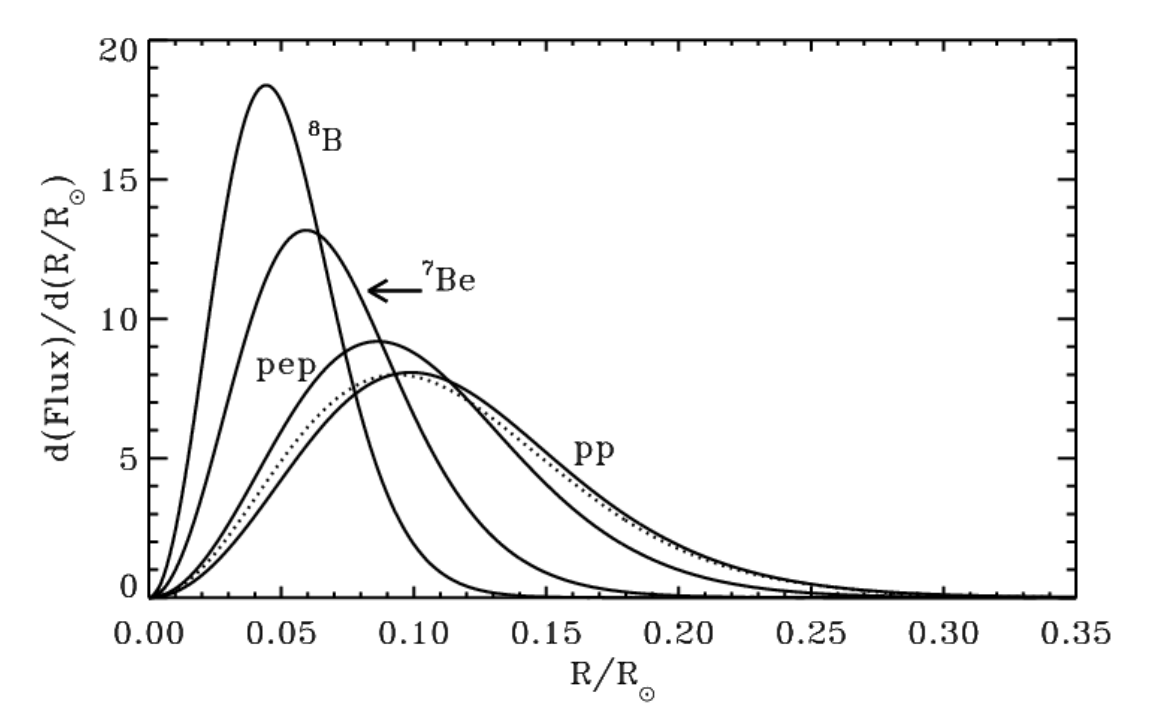
Standard Solar Model
Neutrino production

$$
\text{ppI}\begin{cases} p + p \rightarrow {}^2H + e^+ + \nu_e + \gamma \\ {}^2H + p \rightarrow {}^3He + \gamma \\ {}^3He + {}^3He \rightarrow {}^4He + 2p + \gamma \end{cases}
$$



Distribution of neutrino fluxes

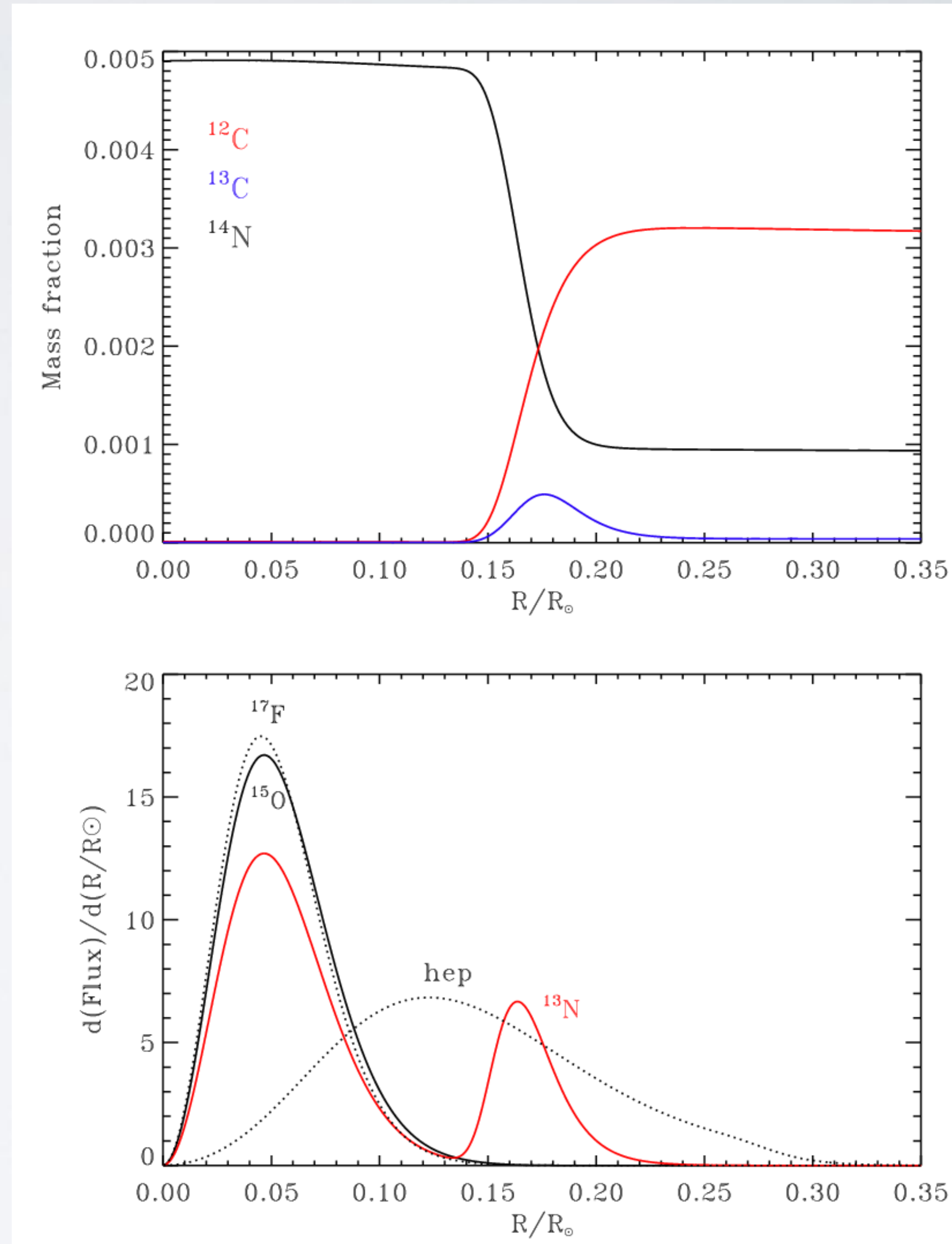
$$
\frac{d(Flux)}{d(R/R_\odot)} = N_F 4\pi r^2 \rho \phi
$$



Standard Solar Model
Neutrino production

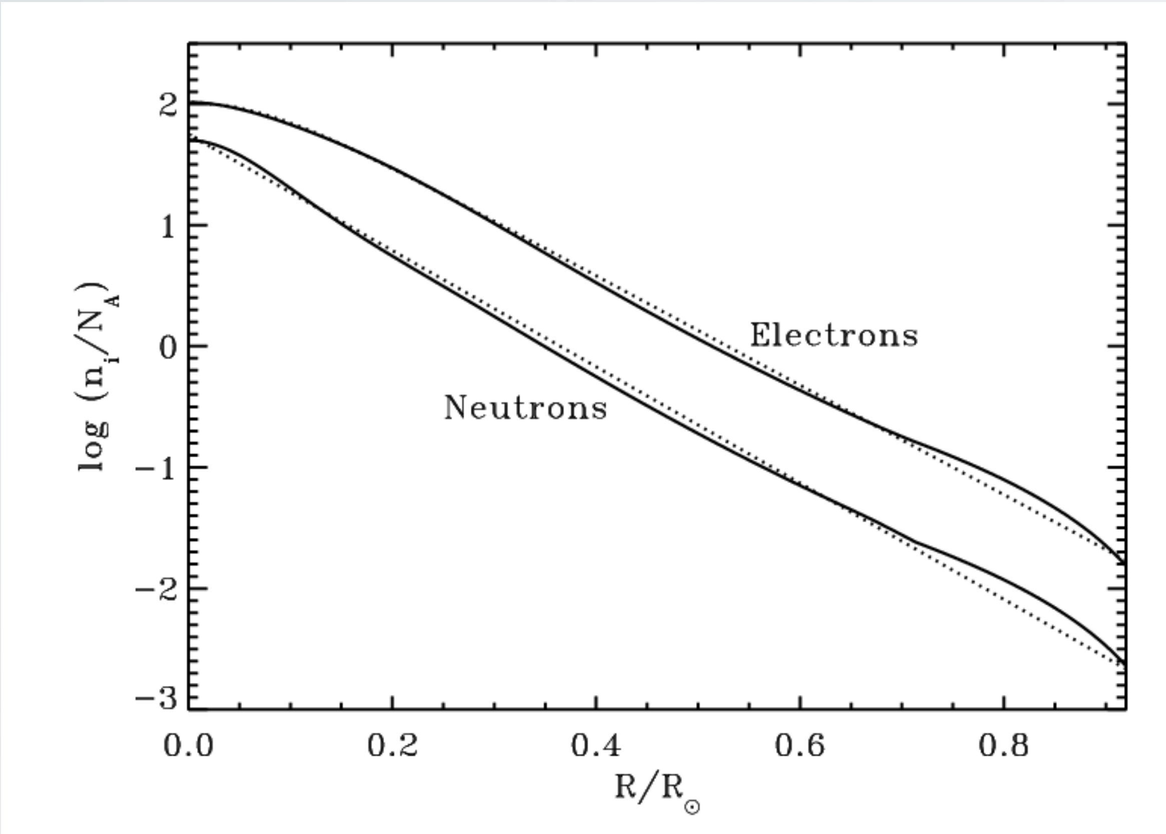
$$^{12}C + p \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e + \gamma$$
$$\text{CN-cycle} \quad {}^{13}C + p \rightarrow {}^{14}N + \gamma$$
$$^{14}N + p \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e + \gamma$$
$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He + \gamma$$

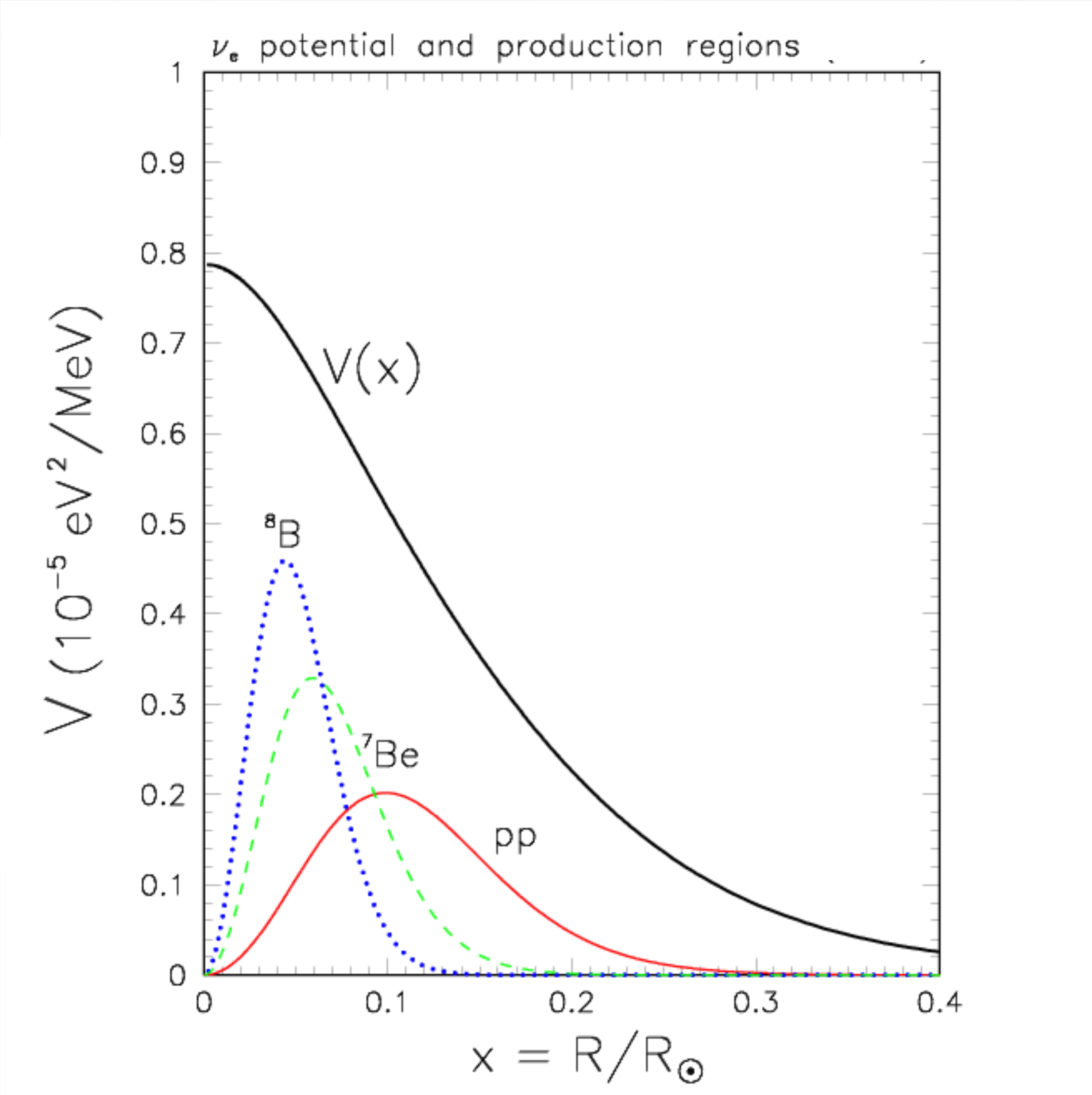
C+N (+O) = Const.



Standard Solar Model

Solar neutrinos and matter effects



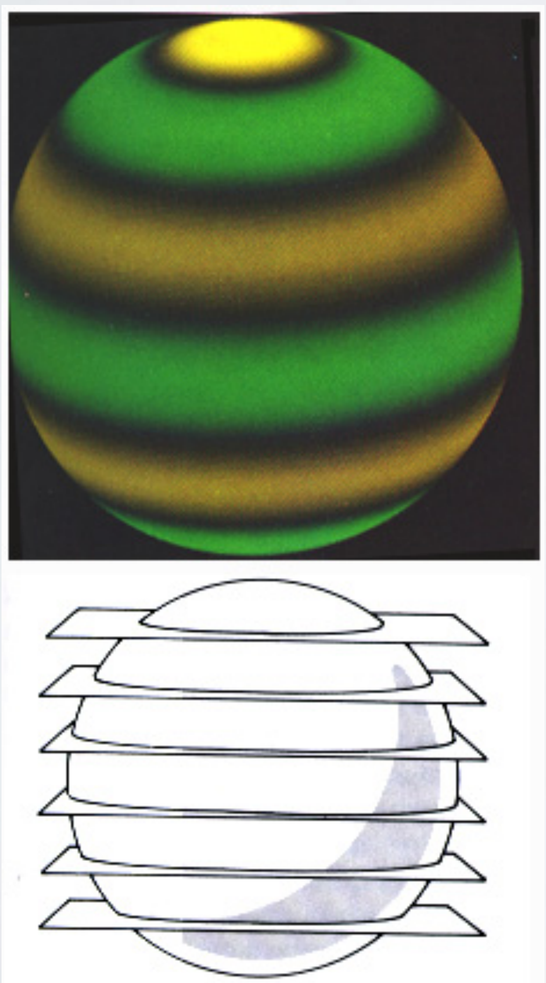


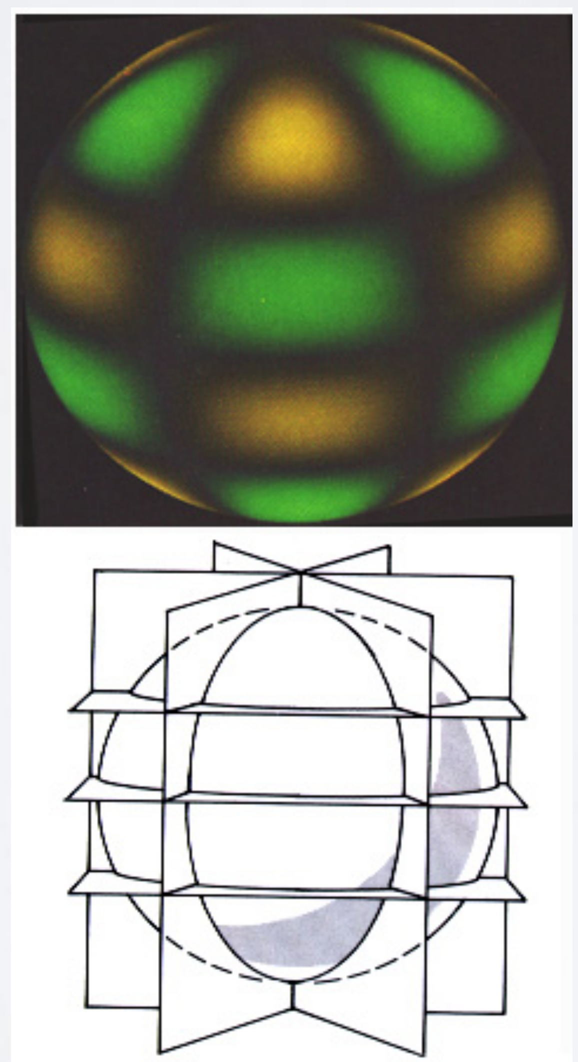
$$V(x) = \sqrt{2} G_F n_e(x)$$

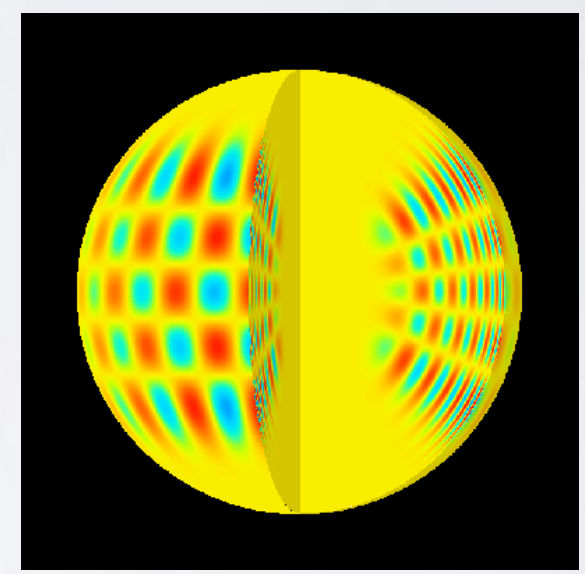
Neutrino fluxes are created in different matter potentials

The Sun as a pulsating star - Overview of Helioseismology 1/4

- Discovery of oscillations: Leighton et al. (1962)
- Sun oscillates in > 10^5 eigenmodes
- Frequencies of order mHz (5-min oscillations)
- Individual modes characterized by radial *n*, angular *l* and longitudinal *m* numbers





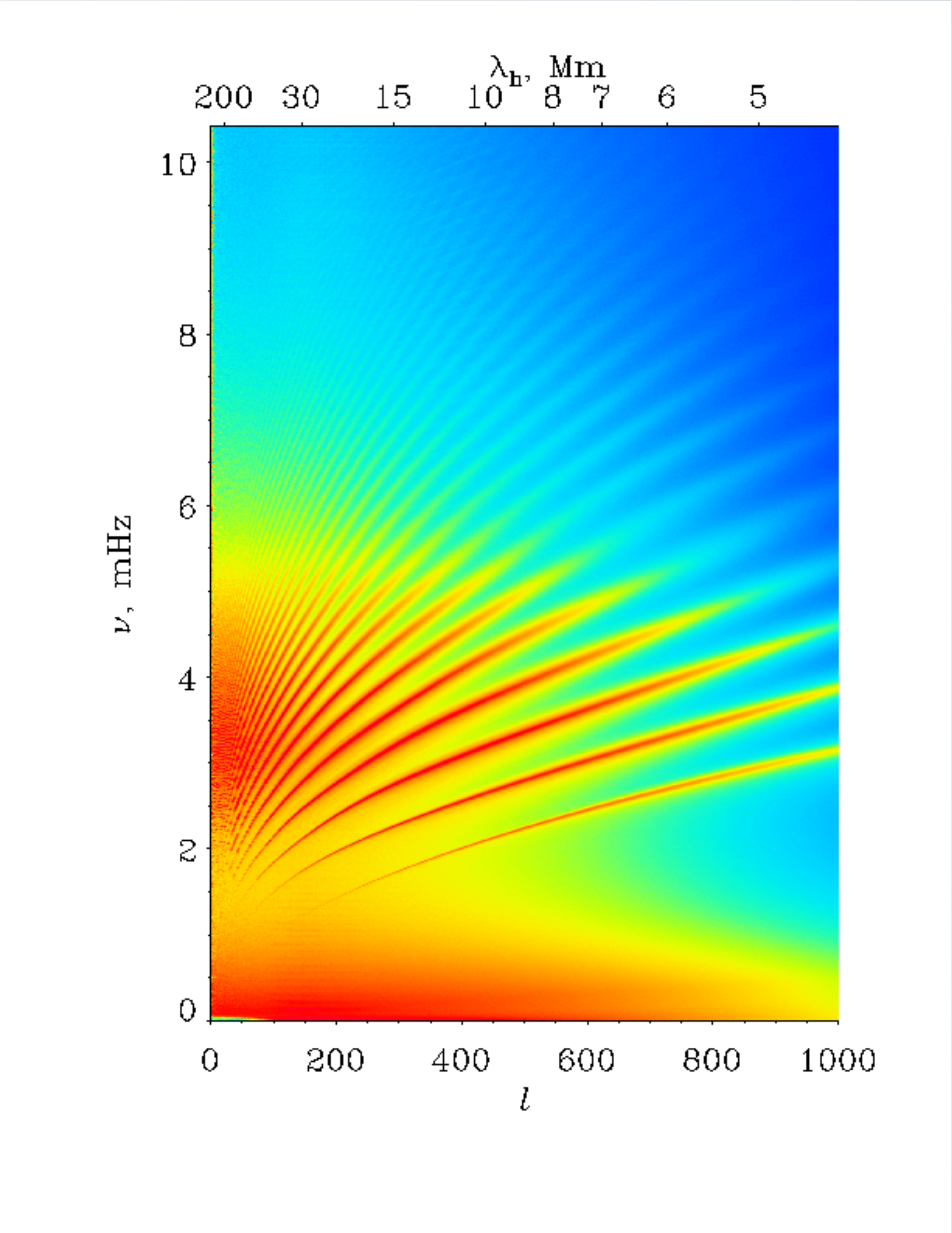


The Sun as a pulsating star - Overview of Helioseismology 2/4

• Doppler observations of spectral lines: velocities of a few cm/s are measured

• Differences in the frequencies of order μHz: very long observations are needed. BiSON network (low-*l* modes) has data collected for ~ 5000 days

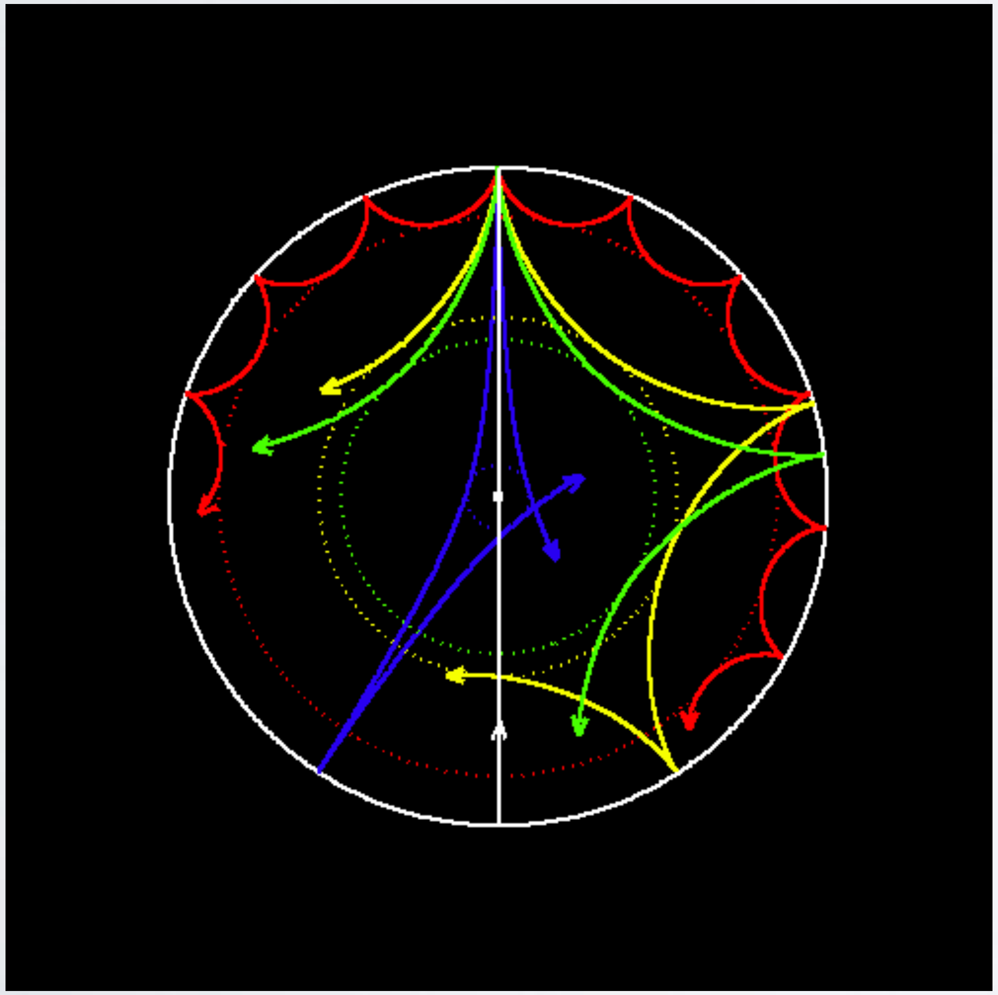
• Relative accuracy in frequencies 10^{-5}



The Sun as a pulsating star - Overview of Helioseismology 3/4

• Solar oscillations are acoustic waves (p-modes, pressure is the restoring force) stochastically excited by convective motions

• Outer turning-point located close to temperature inversion layer. Inner turning-point varies, strongly depends on *l* (centrifugal barrier)



Credit: Jørgen Christensen-Dalsgaard

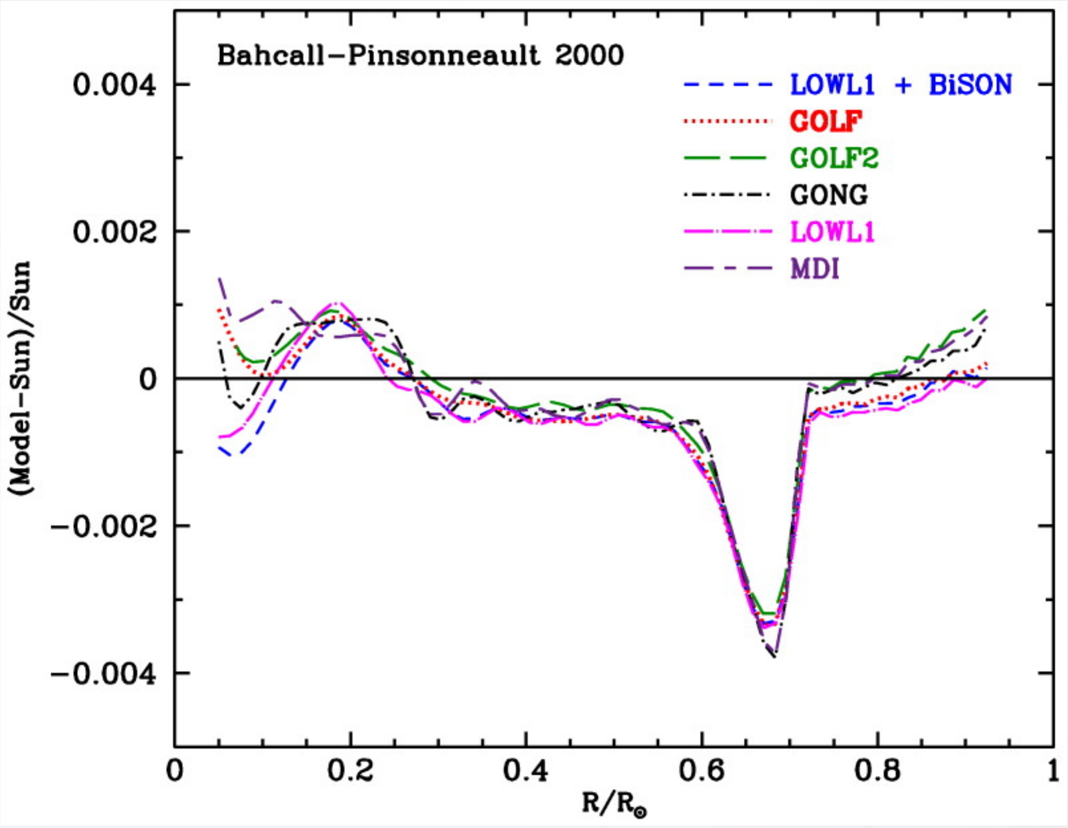
The Sun as a pulsating star - Overview of Helioseismology 4/4

- Oscillation frequencies depend on ρ, P, g, c
- Inversion problem: using measured frequencies and from a reference solar model determine solar structure

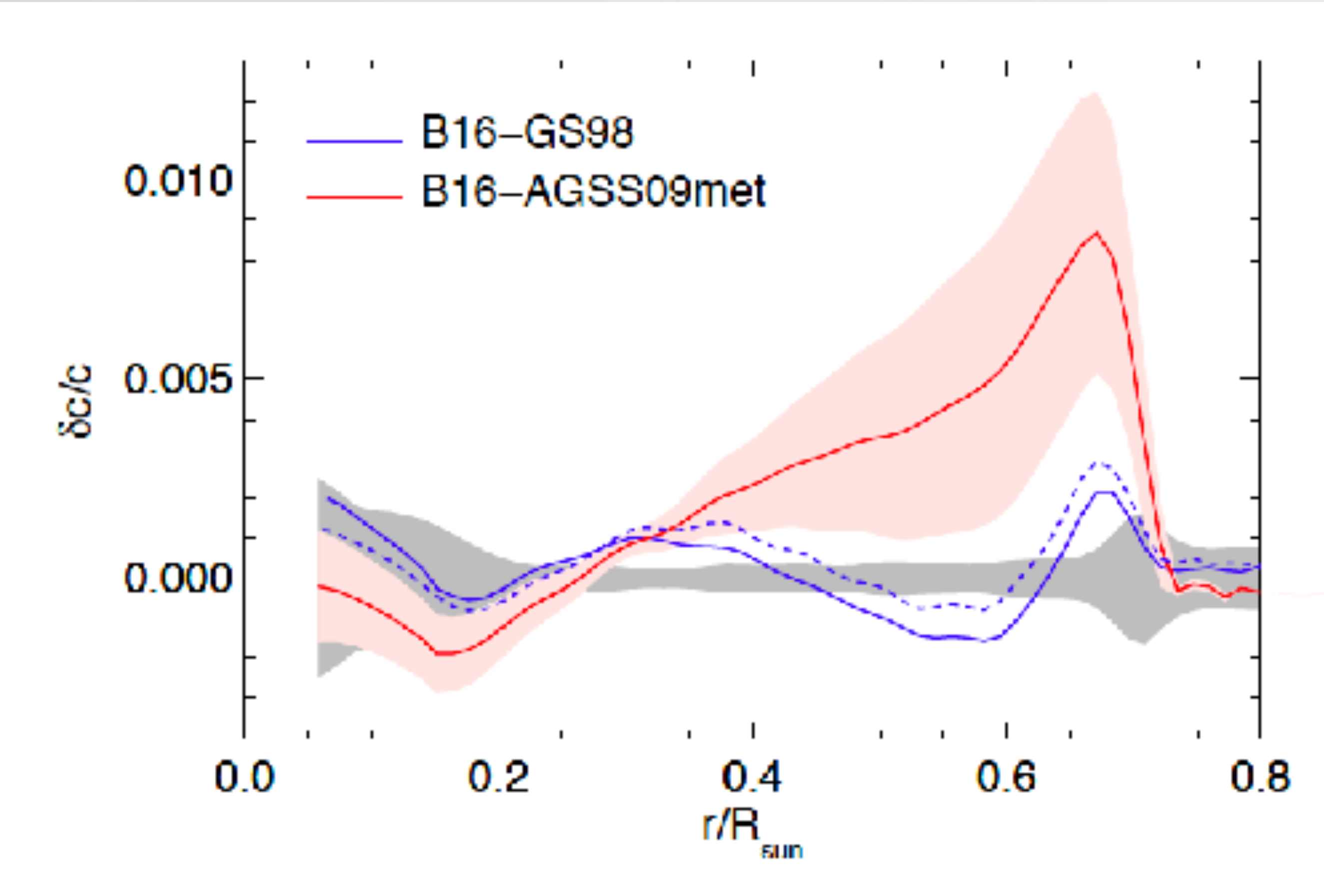
$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + F_{surf}(\omega_i)$$

Output of inversion procedure: $\delta c^2(\mathrm{r})$, $\delta\rho(\mathrm{r})$, R_{CZ}, Y_{SURF}

Relative difference of c between Sun and BP00



Standard Solar Model
Helioseismology



Solar Abundances Problem

	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0^a
α_{MLT}	2.18 ± 0.05	2.11 ± 0.05	-
Y_{ini}	0.2718 ± 0.0056	0.2613 ± 0.0055	-
Z_{ini}	0.0187 ± 0.0013	0.0149 ± 0.0009	-
Z_S	0.0170 ± 0.0012	0.0134 ± 0.0008	-
Y_C	0.6328 ± 0.0053	0.6217 ± 0.0062	-
Z_C	0.0200 ± 0.0014	0.0159 ± 0.0010	-

Best determinations of solar abundances lead so a wrong beating solar model

PROGRAM: 2 LECTURES

First Lecture

1A) How does the Sun shine? A few stories and heroes (before 1989)

1B) Standard Solar Models (quick tour by A. Serenelli)

1C) Solar Neutrino fluxes at the Earth

Second Lecture

2D) How does the Sun shine? A few stories and heroes I (after 1989)

2E) Solar Neutrino Experiments and Lessons in Neutrino Physics

2F) Roadmap of future solar neutrino research