Zero Age Main Sequence

Once star has collapsed and nuclear fusion has started: zero age main sequence (ZAMS) is reached

> The Main Sequence is the result of steady state fusion (“burning”) of hydrogen into helium in stellar centers.

. . . longest phase of stellar evolution (10 billion years for Sun)

Stellar structure defined by balance between pressure inwards due to gravitation and pressure outwards due to energy release (“hydrostatic equilibrium”).

Stellar Structure

Stellar structure governed by four coupled differential equations:

Mass structure

(mass conservation)

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \rho(r)$$

Pressure structure

(hydrostatic equilibrium)

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)\frac{GM(r)}{r^2}$$

Temperature structure

(energy transport)

$$\frac{\mathrm{d}T}{\mathrm{d}r} = -\frac{3}{4ac}\frac{\kappa\rho(r)}{T^3}\frac{L(r)}{4\pi r^2}$$

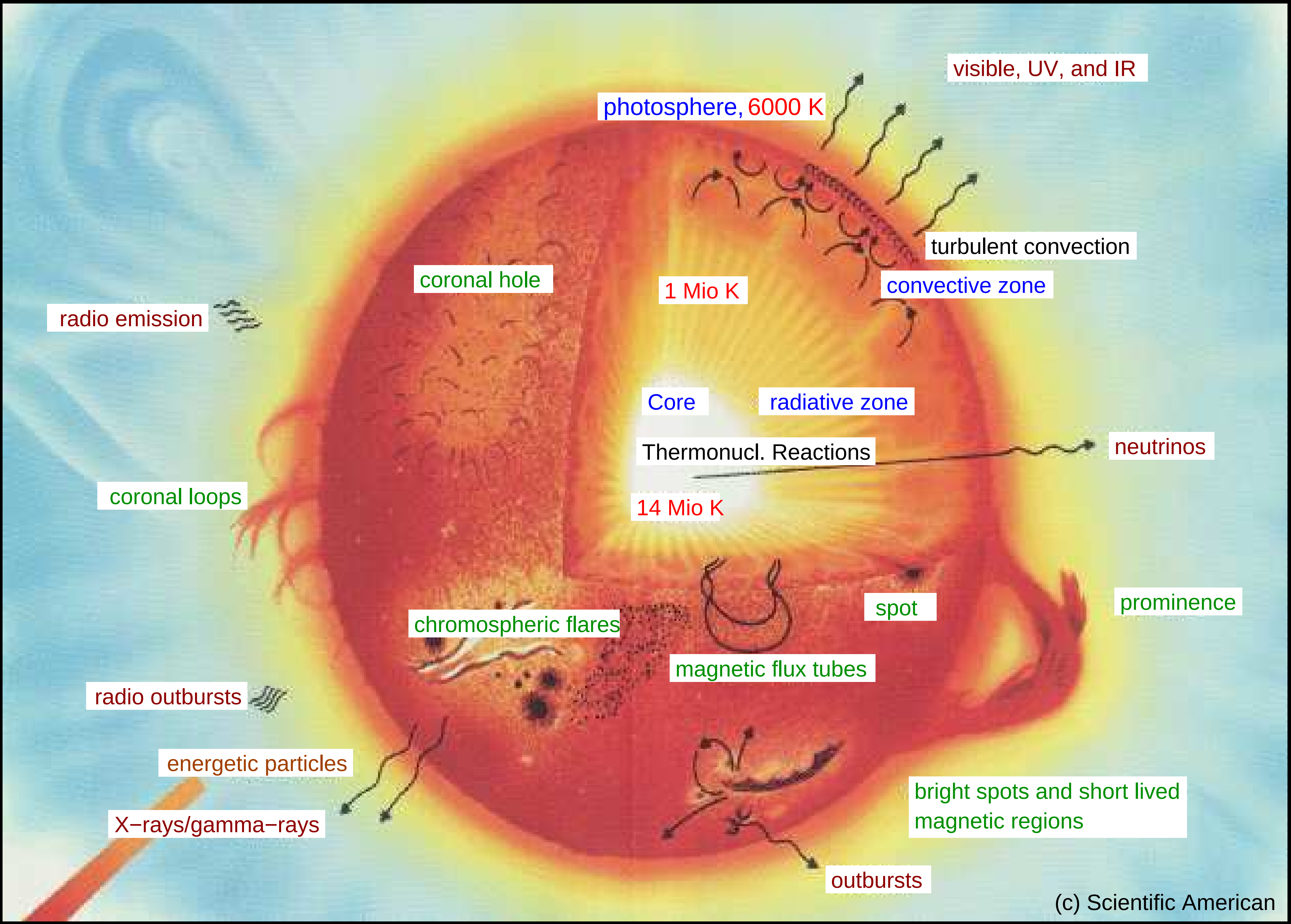
Energy conservation

(energy transport)

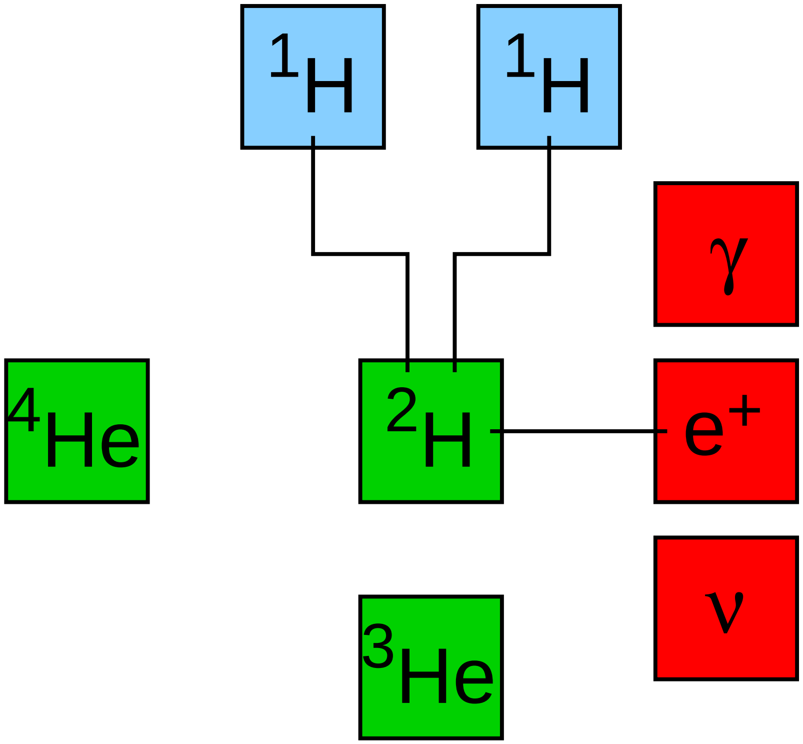
$$\frac{\mathrm{d}L}{\mathrm{d}r} = 4\pi r^2 \rho(r)\epsilon(r)$$

plus “equation of state” ($P = P(T, \rho)$), energy generation ($\epsilon = \epsilon(T, \rho, Z)$),...

Stellar model: numerical solution of stellar structure equations.


visible, UV, and IR
photosphere, 6000 K
turbulent convection
convective zone
coronal hole
1 Mio K
radio emission
Core
radiative zone
Thermonucl. Reactions
neutrinos
coronal loops
14 Mio K
spot
prominence
chromospheric flares
magnetic flux tubes
radio outbursts
energetic particles
X−rays/gamma−rays
bright spots and short lived magnetic regions
outbursts
(c) Scientific American

Energy generation: Proton-Proton chain



For moderate central temperatures, He is produced using the proton proton chain.

First, two protons create a deuteron:

$$^1\mathrm{H} + {^1\mathrm{H}} \longrightarrow {^2\mathrm{H}} + \mathrm{e}^+ + \nu_\mathrm{e} \tag{2.1}$$

This process is slow (happens once for a nucleon per 10^{10} years)

Then an additional proton is attached:

$$^2\mathrm{H} + {^1\mathrm{H}} \longrightarrow {^3\mathrm{He}} + \gamma \tag{2.2}$$

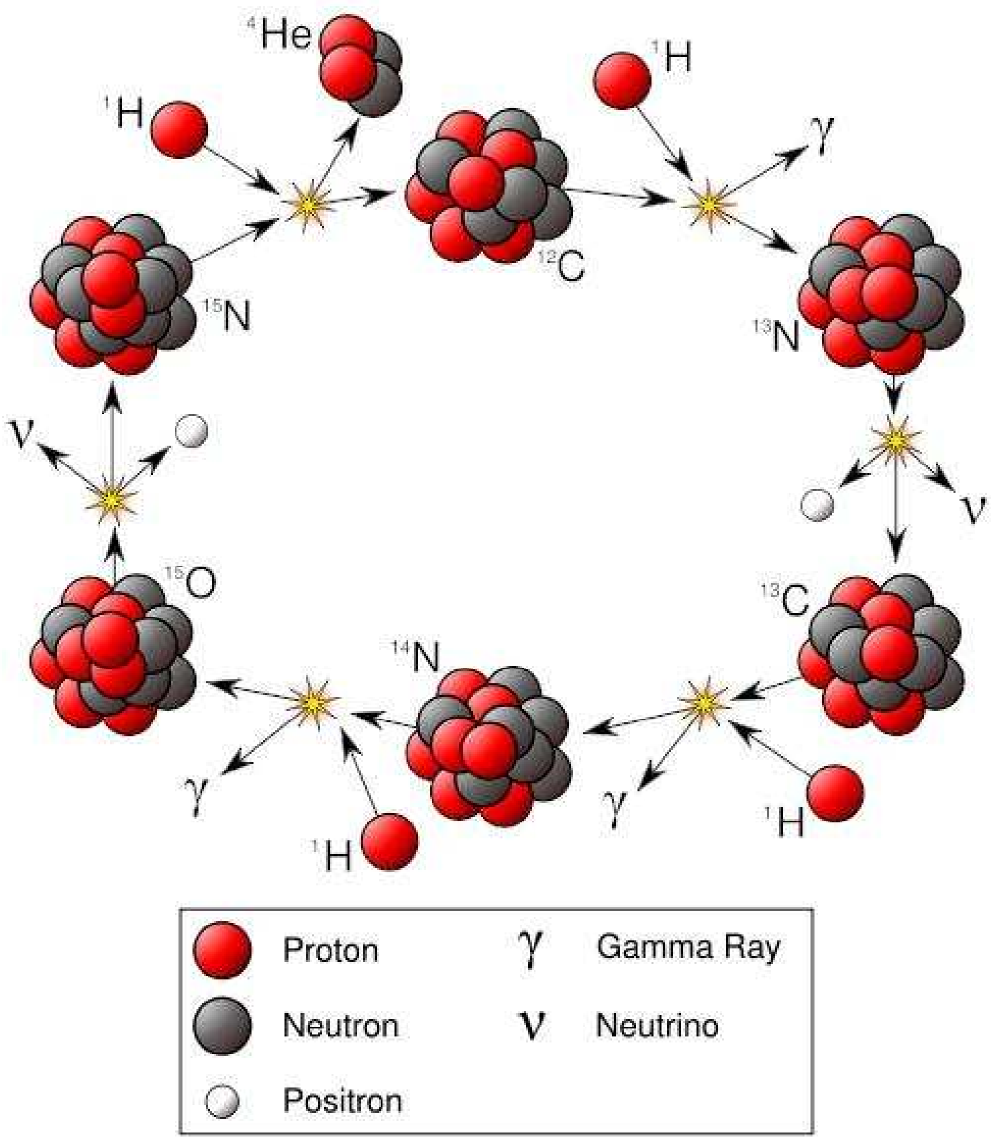
and two helium nuclei can form an alpha particle:

$$^3\mathrm{He} + {^3\mathrm{He}} \longrightarrow {^4\mathrm{He}} + 2{^1\mathrm{H}} \tag{2.3}$$

This is the so called pp I-cycle, minor variations of the theme exist (pp II, pp III cycles), but pp I dominates.

pp chain dominates for $T \lesssim 2 \times 10^7$ K, $\epsilon_\mathrm{pp} \propto T^5$;
Sun: 98.4%.

Energy generation: CNO cycle



The CNO cycle (Bethe-Weizsäcker-cycle) requires the presence of C, N, and O isotopes as catalysts.

CNO cycle has slightly smaller energy release than pp-cycle because of higher neutrino losses.

Reaction $^{14}\text{N} + p \longrightarrow {}^{15}\text{O} + \gamma$ is th slowest reaction (one million years).

CNO cycle dominates above 2×10^{7} K, $\epsilon_{\text{CNO}} \propto T^{17}$; Sun: 1.6%.

Wikipedia

Solar Structure

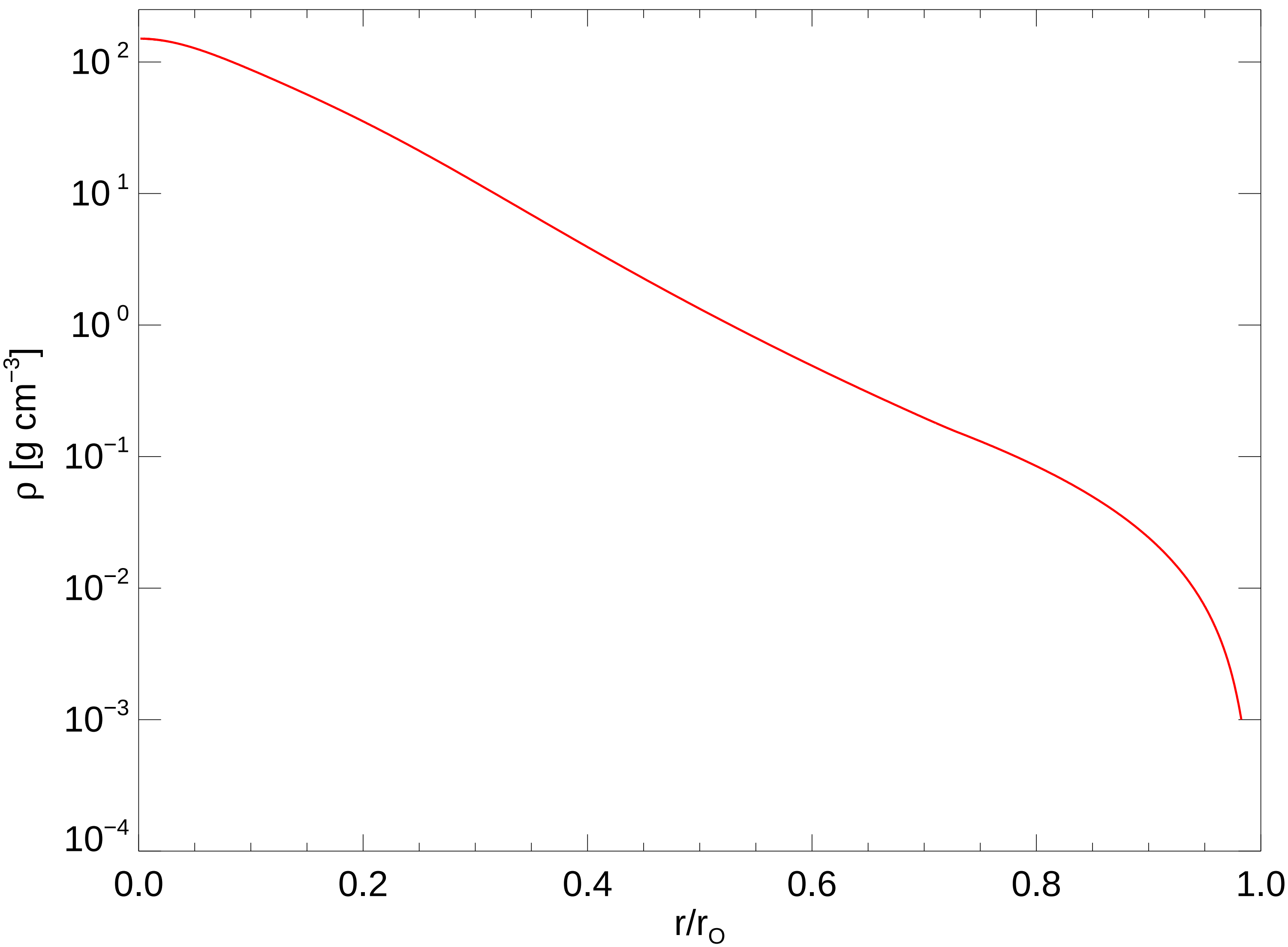
Based on observations of

- Solar Mass: $1\,M_\odot = 1.997 \times 10^{30}\,\mathrm{kg} = 1.997 \times 10^{33}\,\mathrm{g}$
- Solar Luminosity: $1\,L_\odot = 3.127 \times 10^{26}\,\mathrm{W} = 3.127 \times 10^{33}\,\mathrm{erg\,s^{-1}}$
- Solar chemical composition (=elemental abundances): 75% H, 24% He, 1% metals (by mass)

it is possible to use the equations of stellar structure to determine a model for the structure of the Sun, i.e., M_r, L_r, $\rho(r)$, $T(r)$, abundances(r).

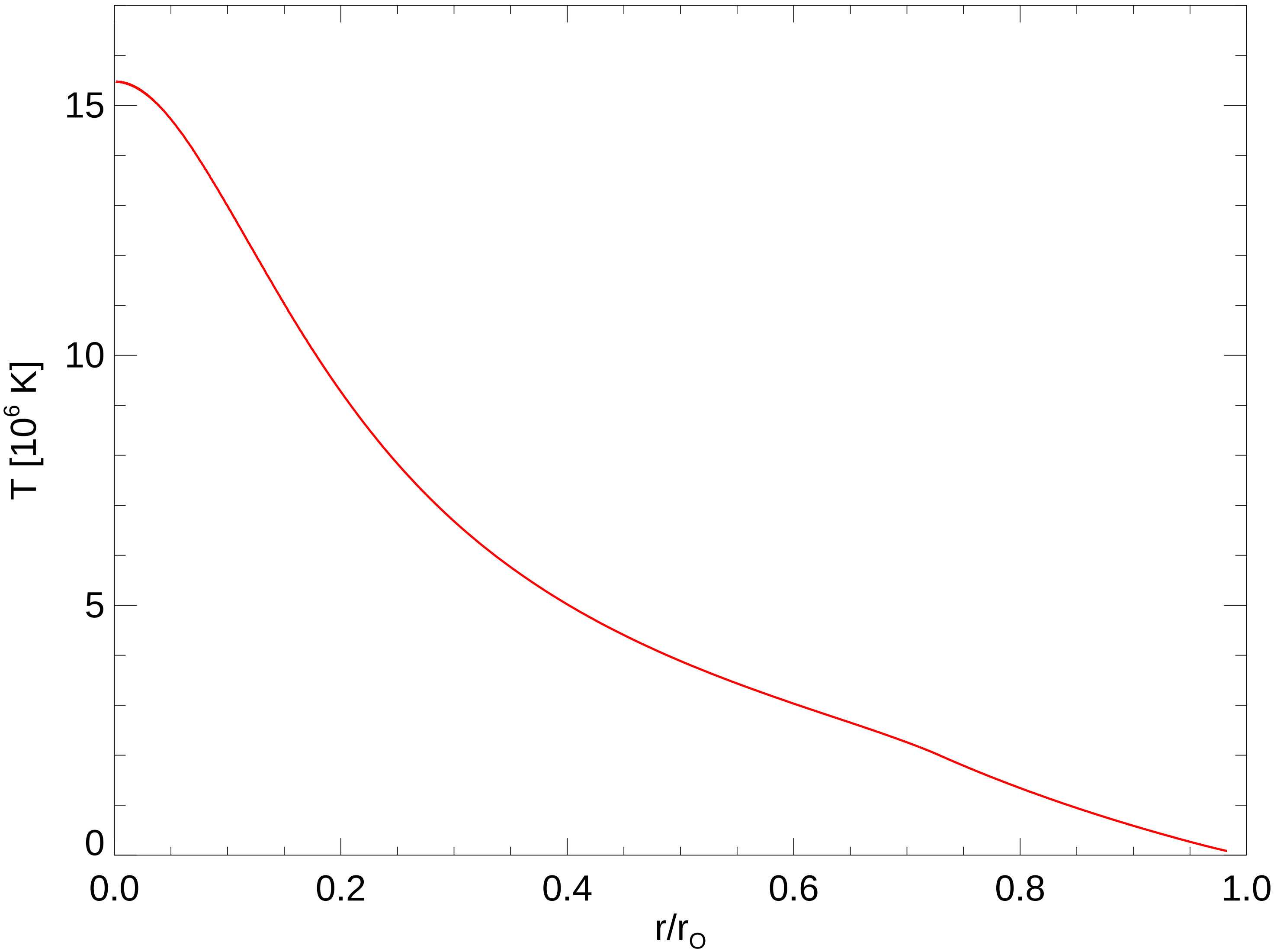
The best models available are called “standard models”.

Standard Solar Model, I



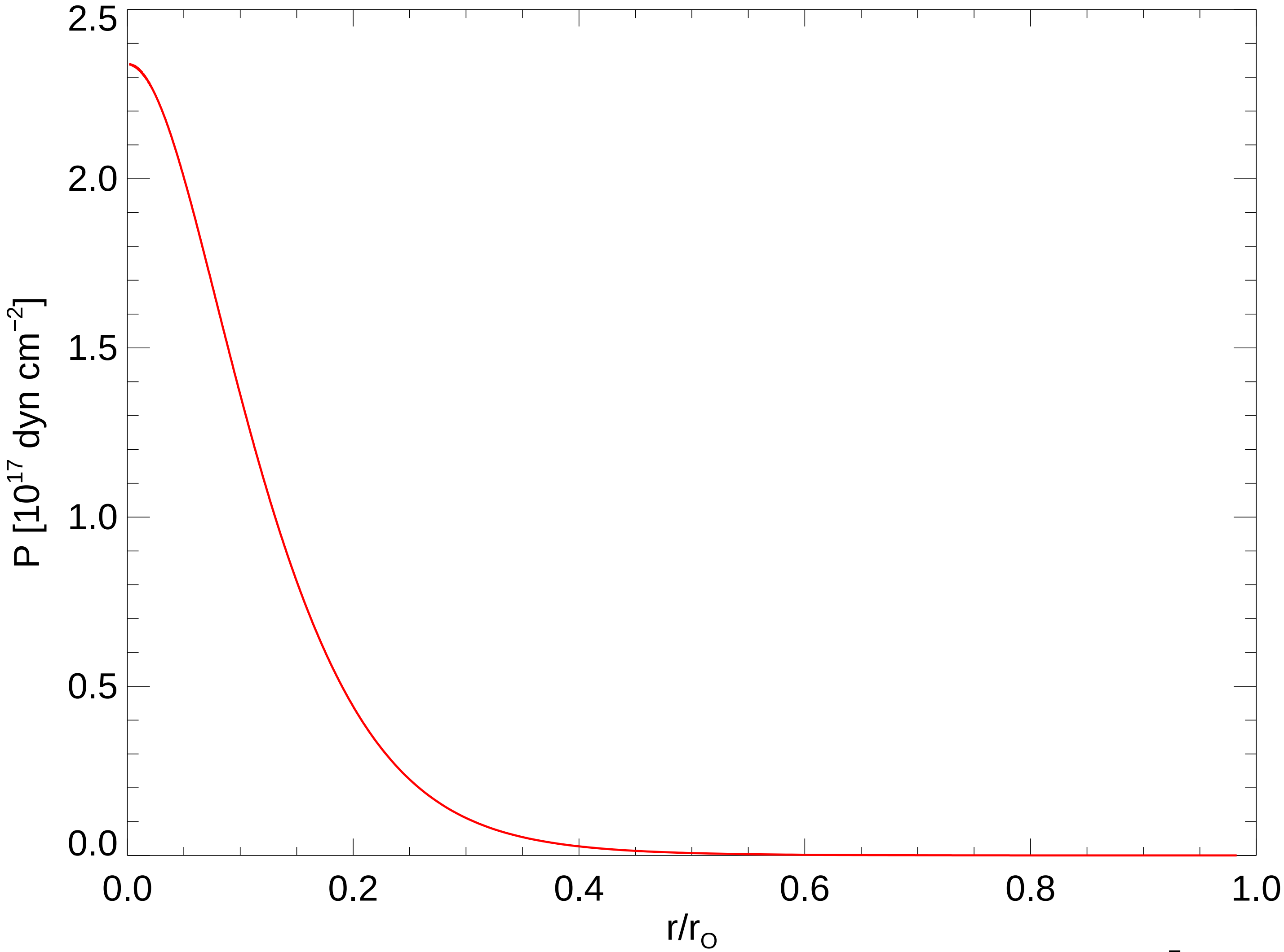
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model, II



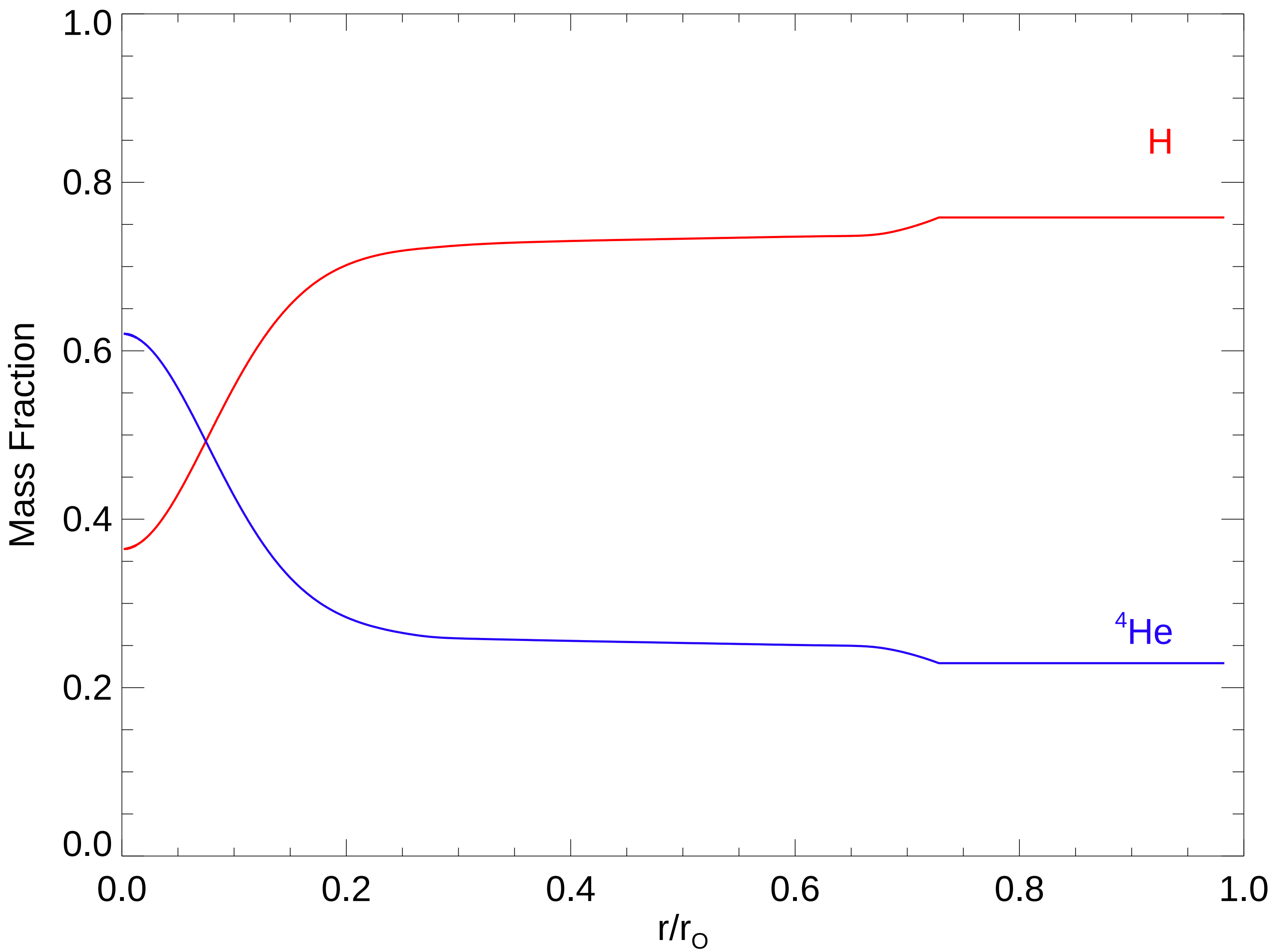
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model, III



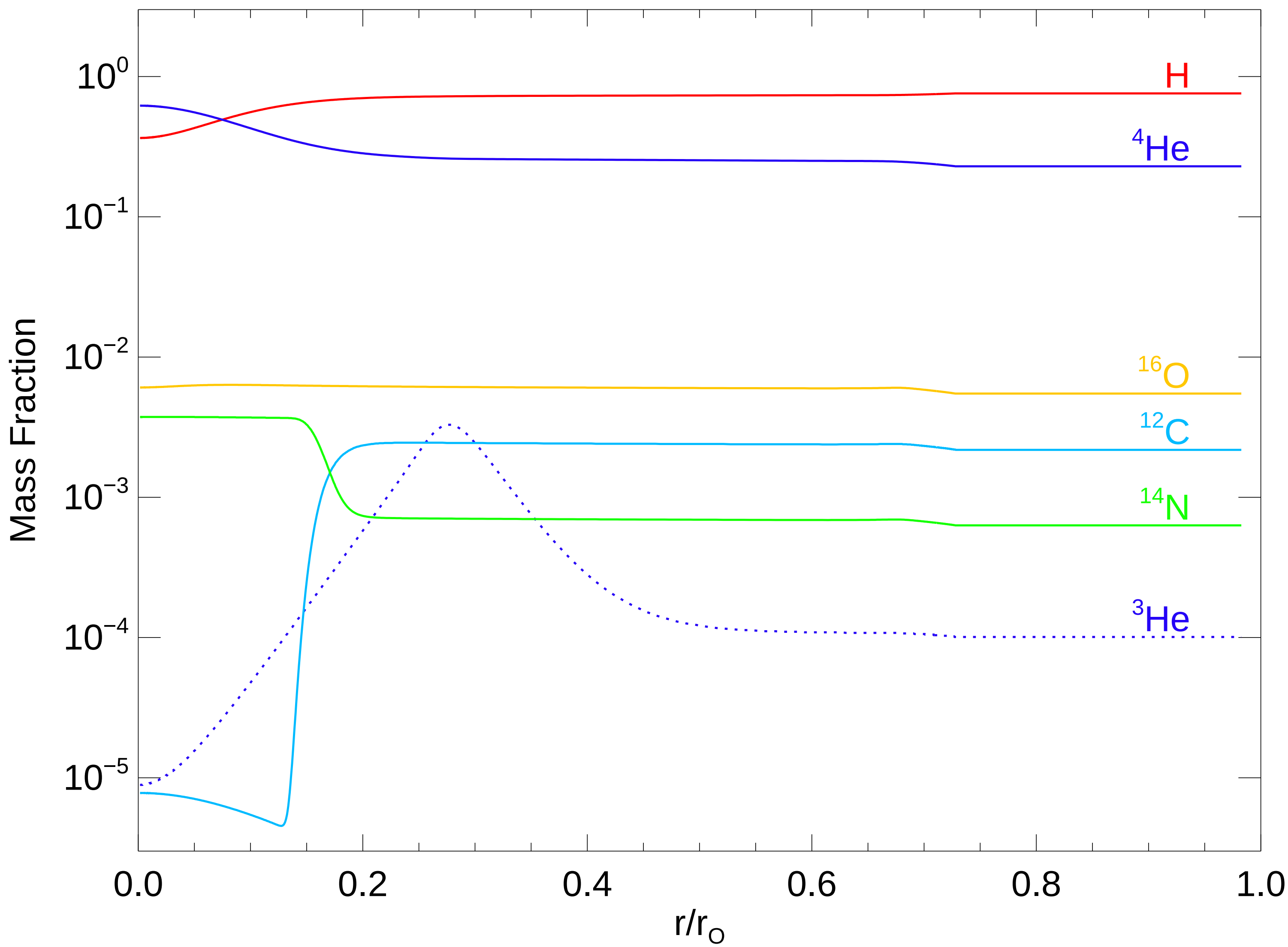
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530; 1 dyn $= 10^{-5}$ N, 1 dyn cm^{-2} $= 0.1$ Pa)

Standard Solar Model, IV



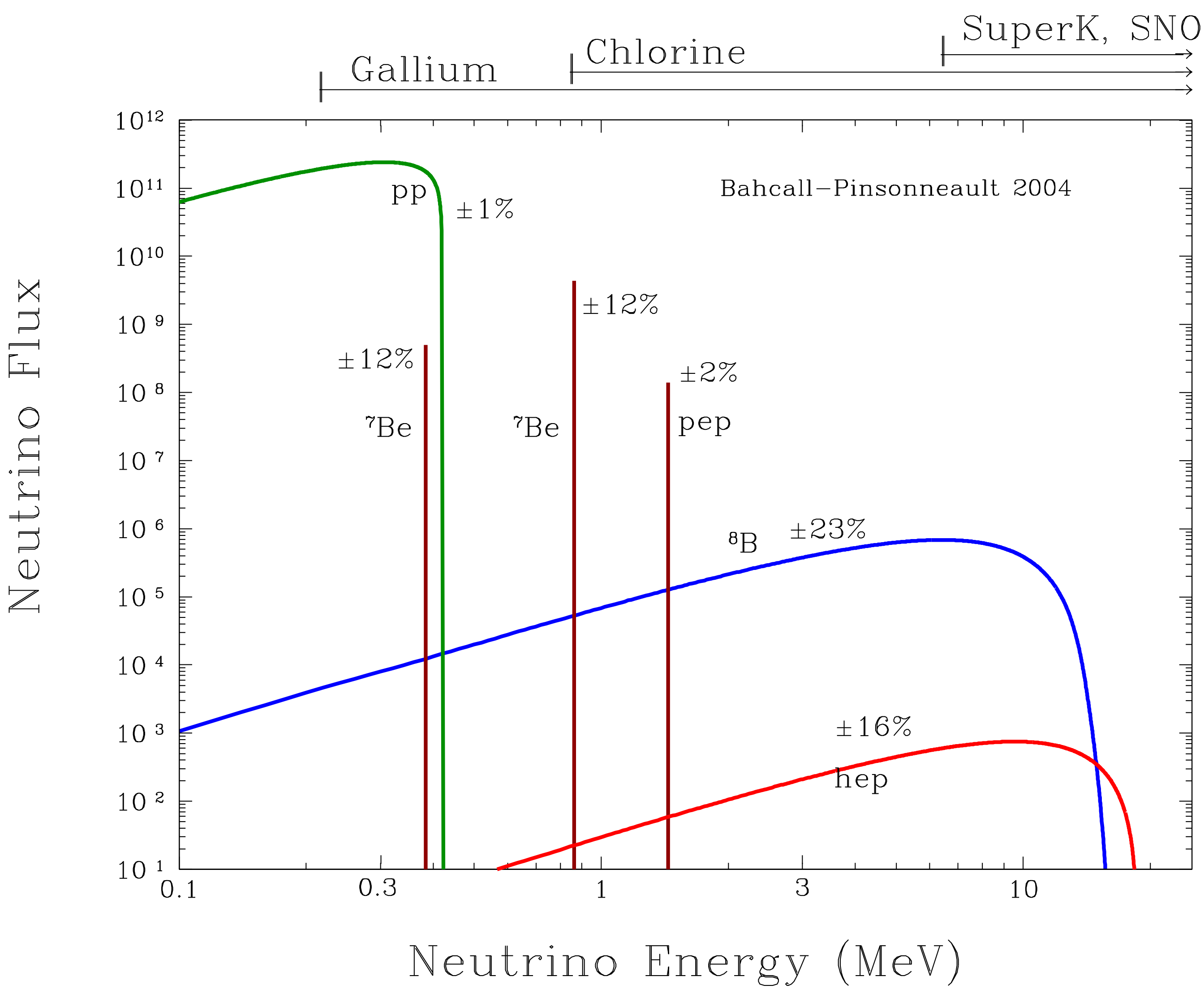
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Standard Solar Model, V



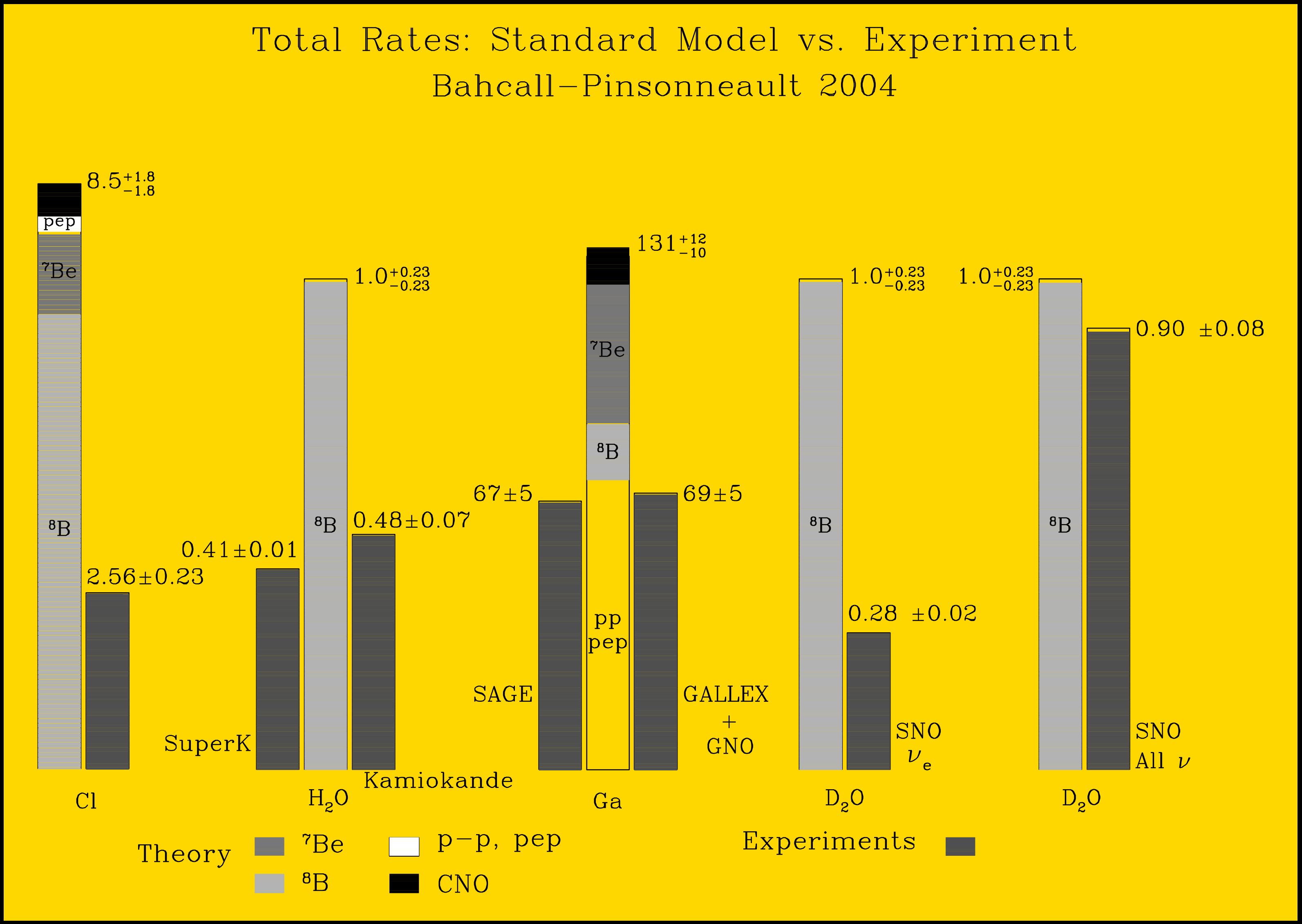
Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

Solar Neutrinos



The solar model predicts a solar neutrino spectrum that can be compared with Earth based measurements. This is the most direct test of theory of stellar structure known.

after Bahcall



SNO (2001): When taking *all* neutrino flavors into account, i.e., take into account that solar neutrinos change their flavor on the way from the Sun to us, the measured and predicted neutrino fluxes agree.

Stars: Evolution