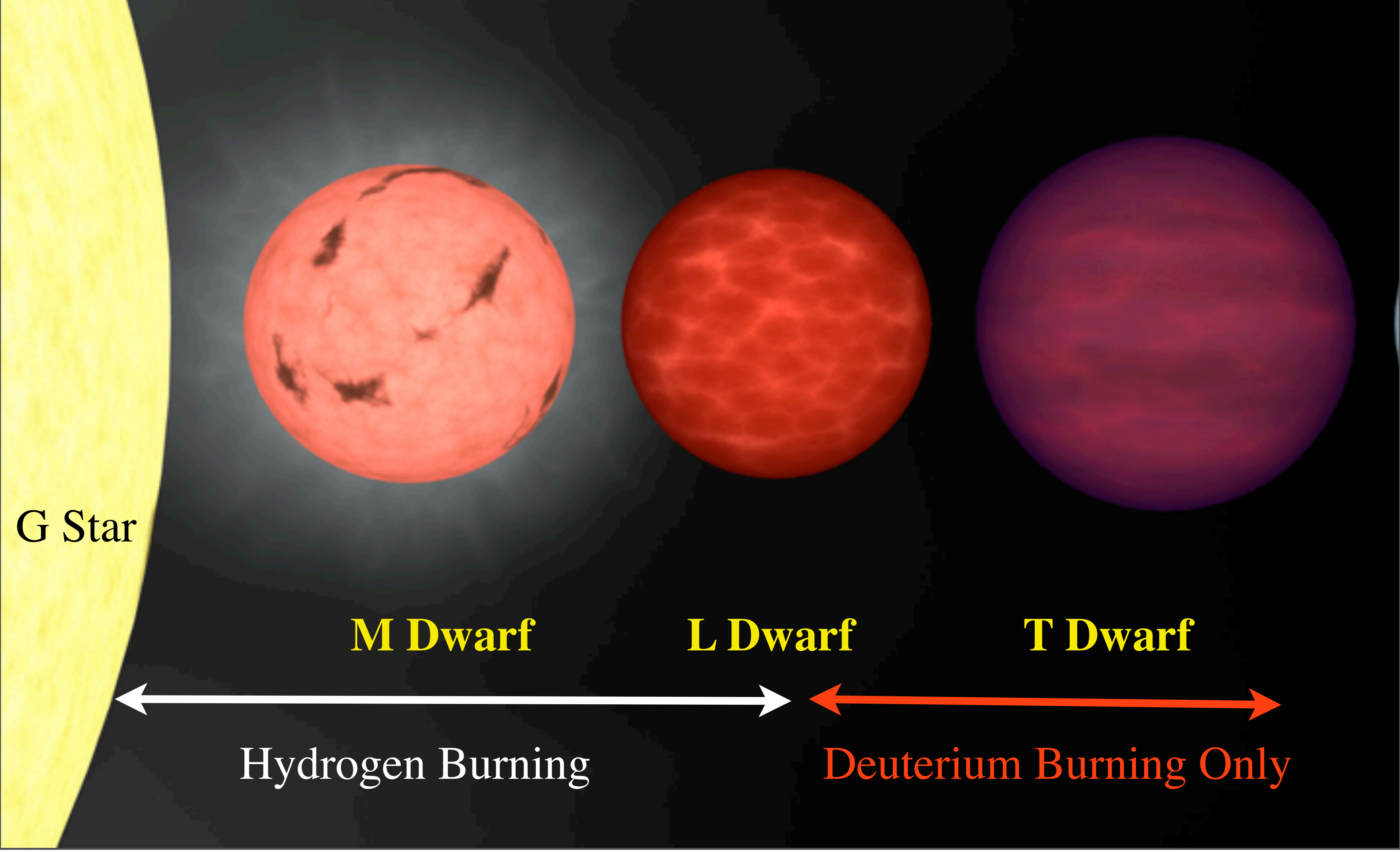
Lecture 20: Deuterium Burning and Hydrogen Burning



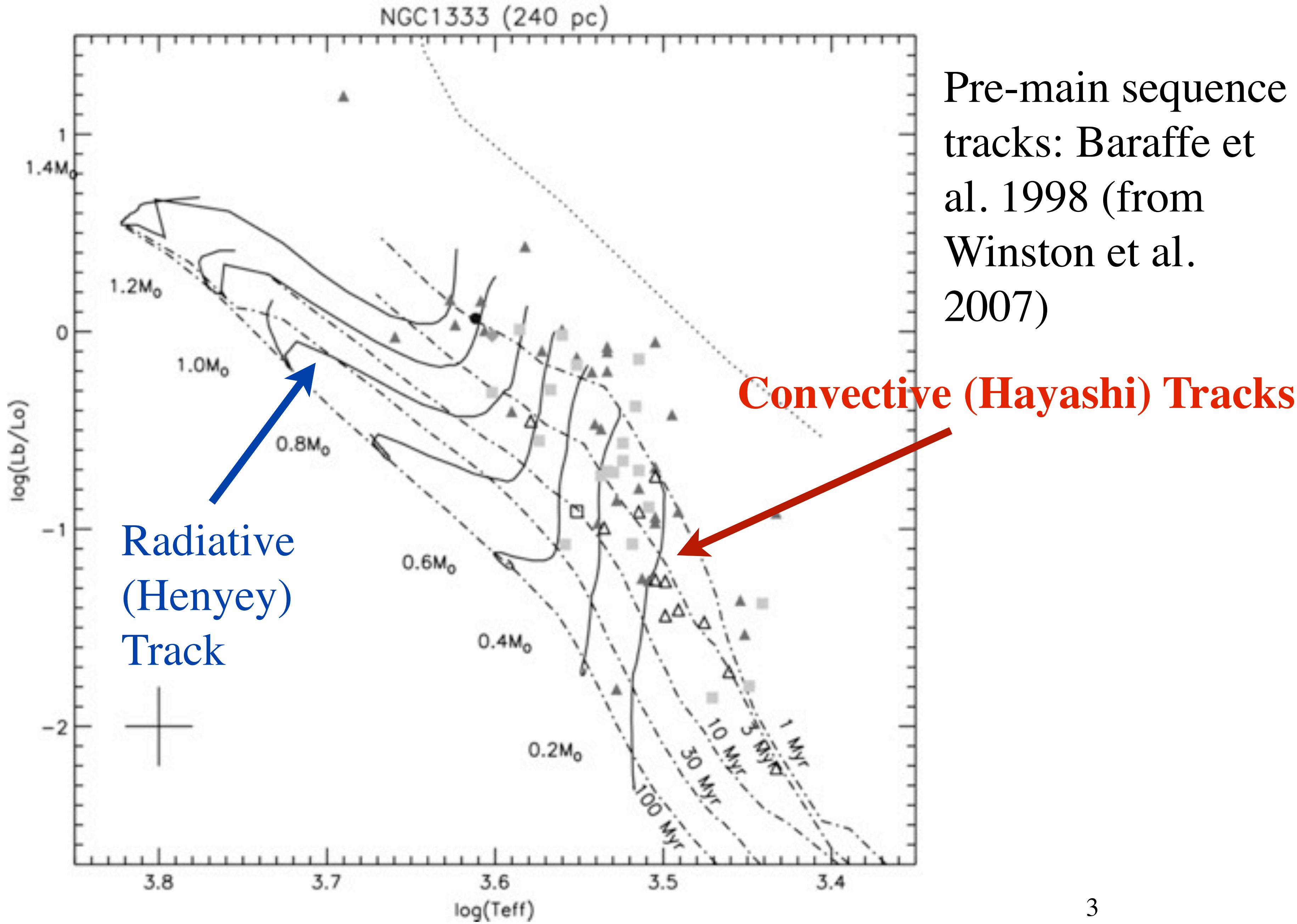
Decreasing Luminosity

Increasing Time

Protostars: **Accretes mass throughout protostellar phase. Can undergo Deuterium fusion (for low mass stars) and Hydrogen fusion (high mass stars). Accretion onto star with a disk. Must overcome magnetic pressure, resulting in magnetospheric accretion for low mass stars. Must overcome photon pressure for high mass stars.**

Pre-Main Sequence Star: **only happens for low to intermediate stars. Star contracts and center heats up. Deuterium fusion possible.**

Main Sequence Stars: **hydrogen fusion. Long period of stable luminosity and radius.**



Pre-main sequence tracks: Baraffe et al. 1998 (from Winston et al. 2007)

Nuclear Burning Before the Main Sequence:

Deuterium Burning in Pre-Main Sequence Stars

Deuterium Burning

Before the onset of Hydrogen burning, Deuterium can be fused with Hydrogen at a temperature of a 1×10^6 K. The reaction for Deuterium burning is:

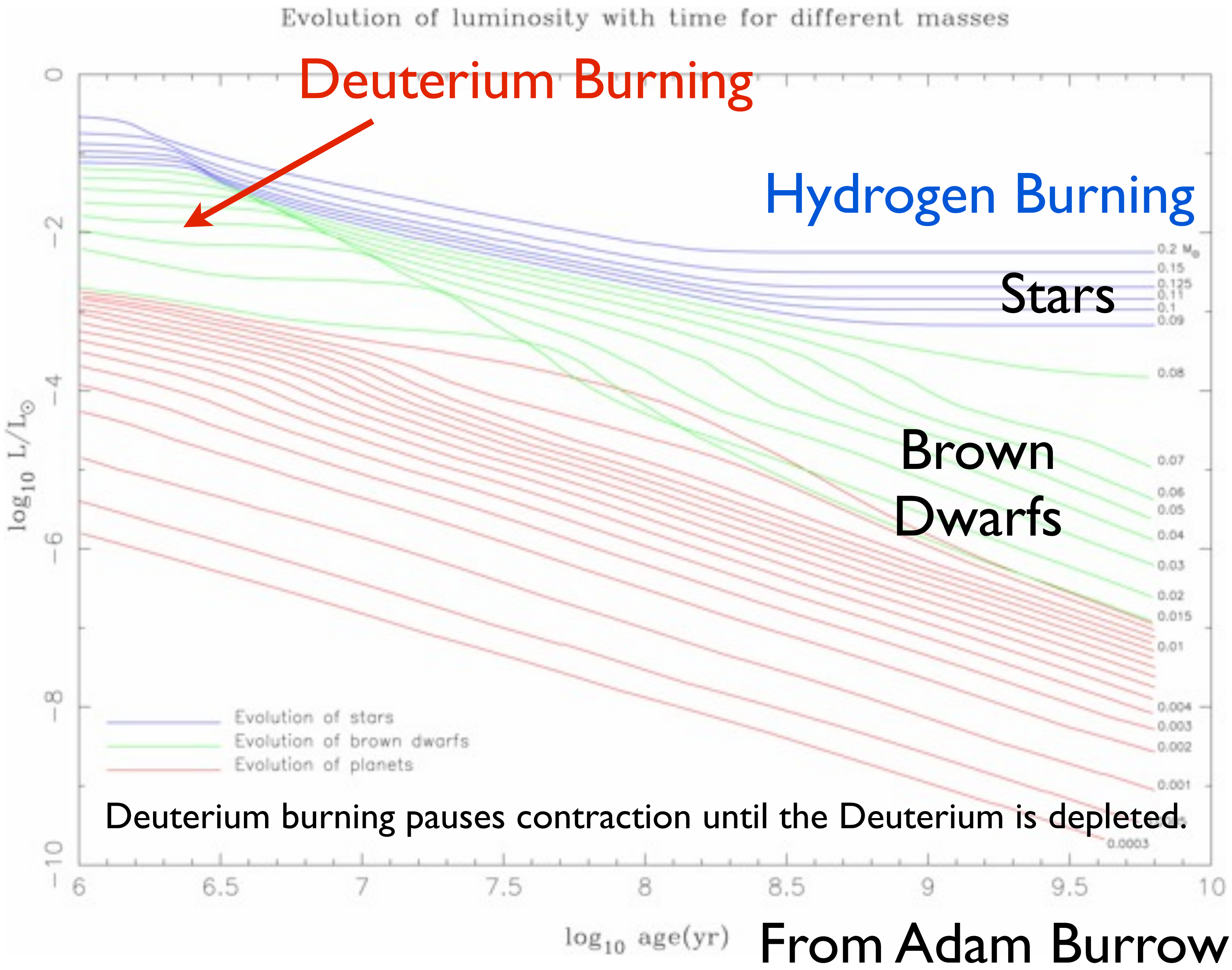
$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma \tag{45}$$

The resulting equation produces $\Delta E_D \equiv 5.5$ MeV. The onset of Deuterium burning is at 1×10^6 K, as opposed to 1×10^7 K for the proton-proton chain. The energy generation is

$$\epsilon_D = \left[\frac{D}{H}\right] \epsilon_0 \left(\frac{\rho}{1\ g\ cm^{-3}}\right) \left(\frac{T}{1 \times 10^6\ K}\right)^{n_D} \tag{46}$$

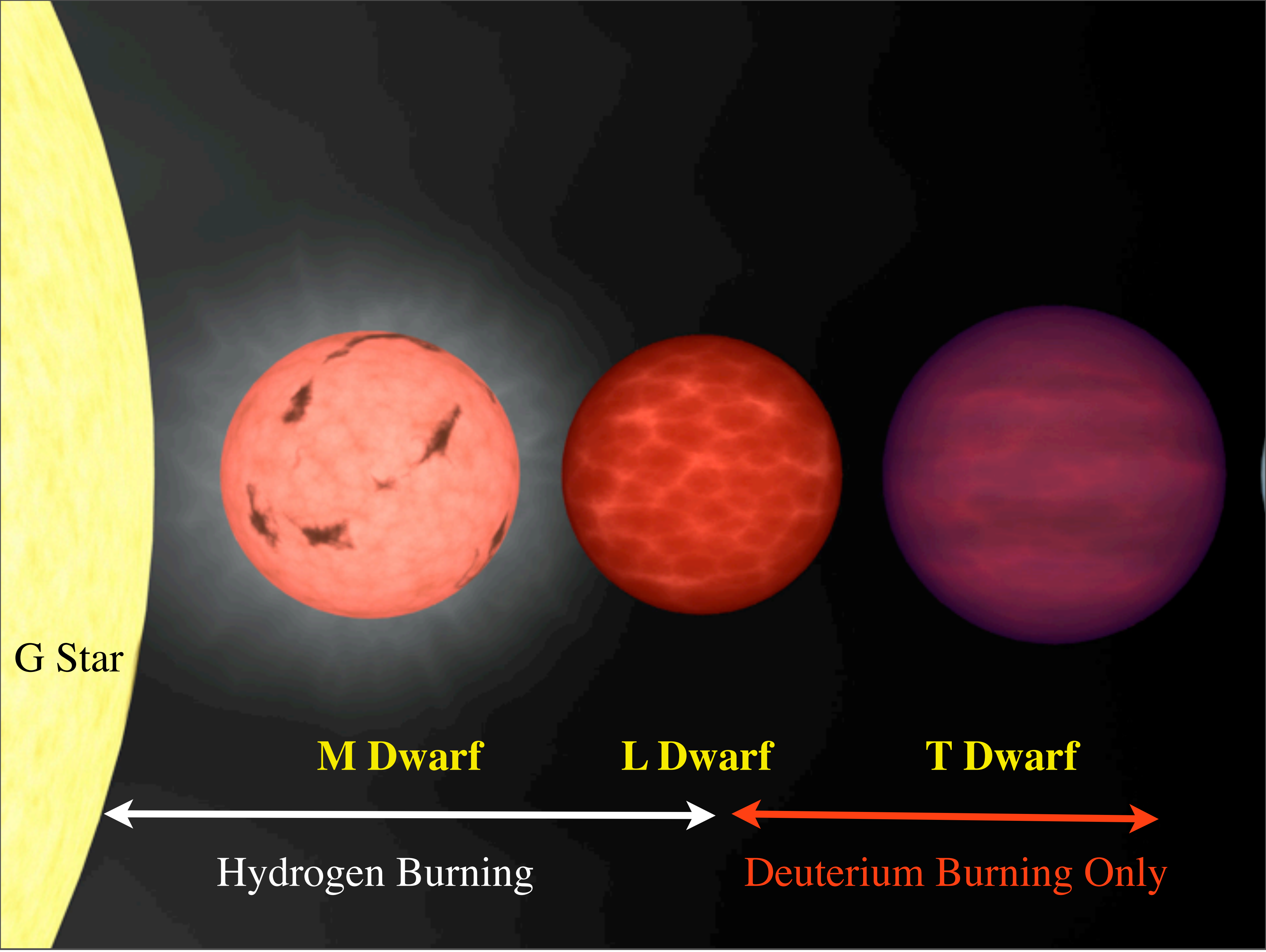
where $n_D = 11.8$ and $\epsilon_0 = 4.19 \times 10^7$ erg g^{-1} s^{-1}.

The Deuterium Burning in Brown Dwarfs



Deuterium burning pauses contraction until the Deuterium is depleted.

From Adam Burrow


G Star
M Dwarf
L Dwarf
T Dwarf
Hydrogen Burning
Deuterium Burning Only

Nuclear Burning in Protostars:
Deuterium Burning During the Accretion Phase

Deuterium Burning

The luminosity for Deuterium burning was calculated by Stahler (1988) for a convective star ($n = 3/2$ polytrope)

$$L_D = 1.92 \times 10^{17} f \left[\frac{D}{H}\right] \left(\frac{M}{M_\odot}\right)^{13.8} \left(\frac{R}{R_\odot}\right)^{-14.8} L_\odot \qquad (47)$$

where [D/H] is the interstellar Deuterium abundance (2.5×10^{-5}) and f is the fraction of Deuterium left relative to the interstellar abundance. During protostellar evolution, the amount of Deuterium is quickly used up, unless more is brought in. The change in the mass of Deuterium is determined by the equation:

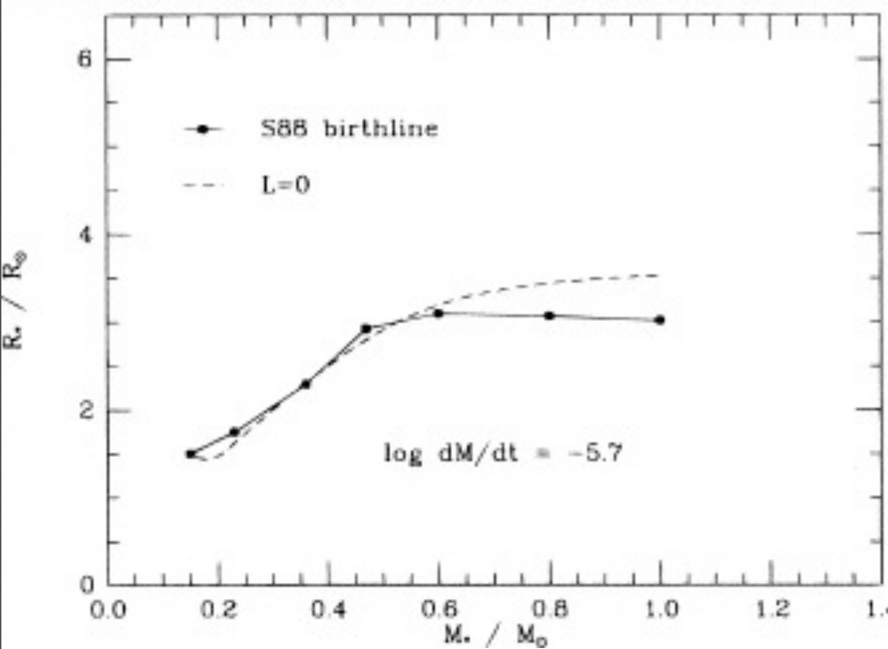
$$\frac{df\,M}{dt} = \dot{M} - \frac{L_D}{\beta_D} \qquad (48)$$

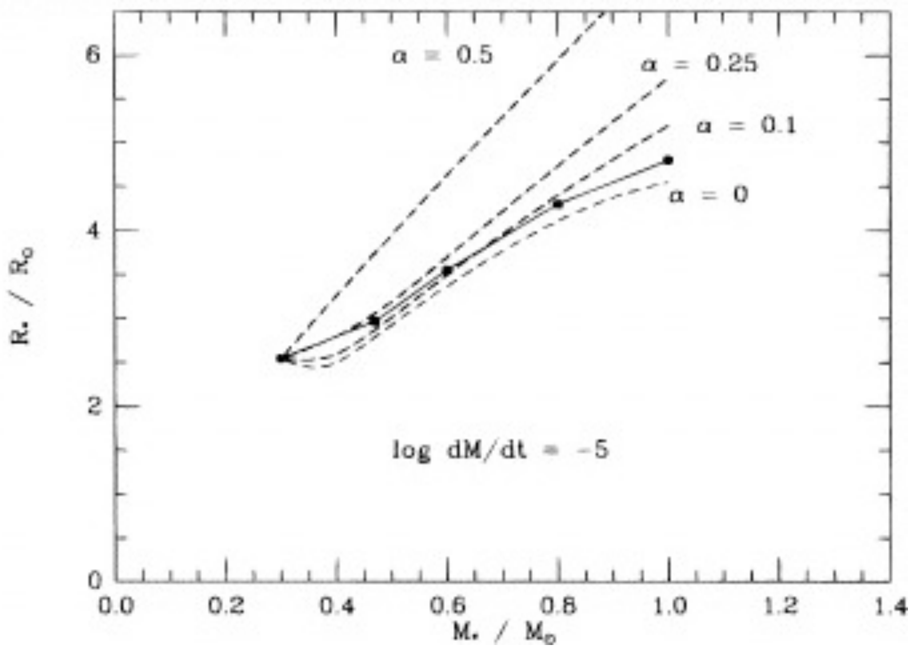
where β_D is the energy available per gram of gas with a typical [D/H] ratio (9.2×10^{13} ergs gm^{-1}). If $L_D = \dot{M}\beta_D$, then an equilibrium is achieved. A higher luminosity will deplete the Deuterium.

The Stellar Birthline (see last lecture)

Birthline for L=0

Hartmann et al 1997

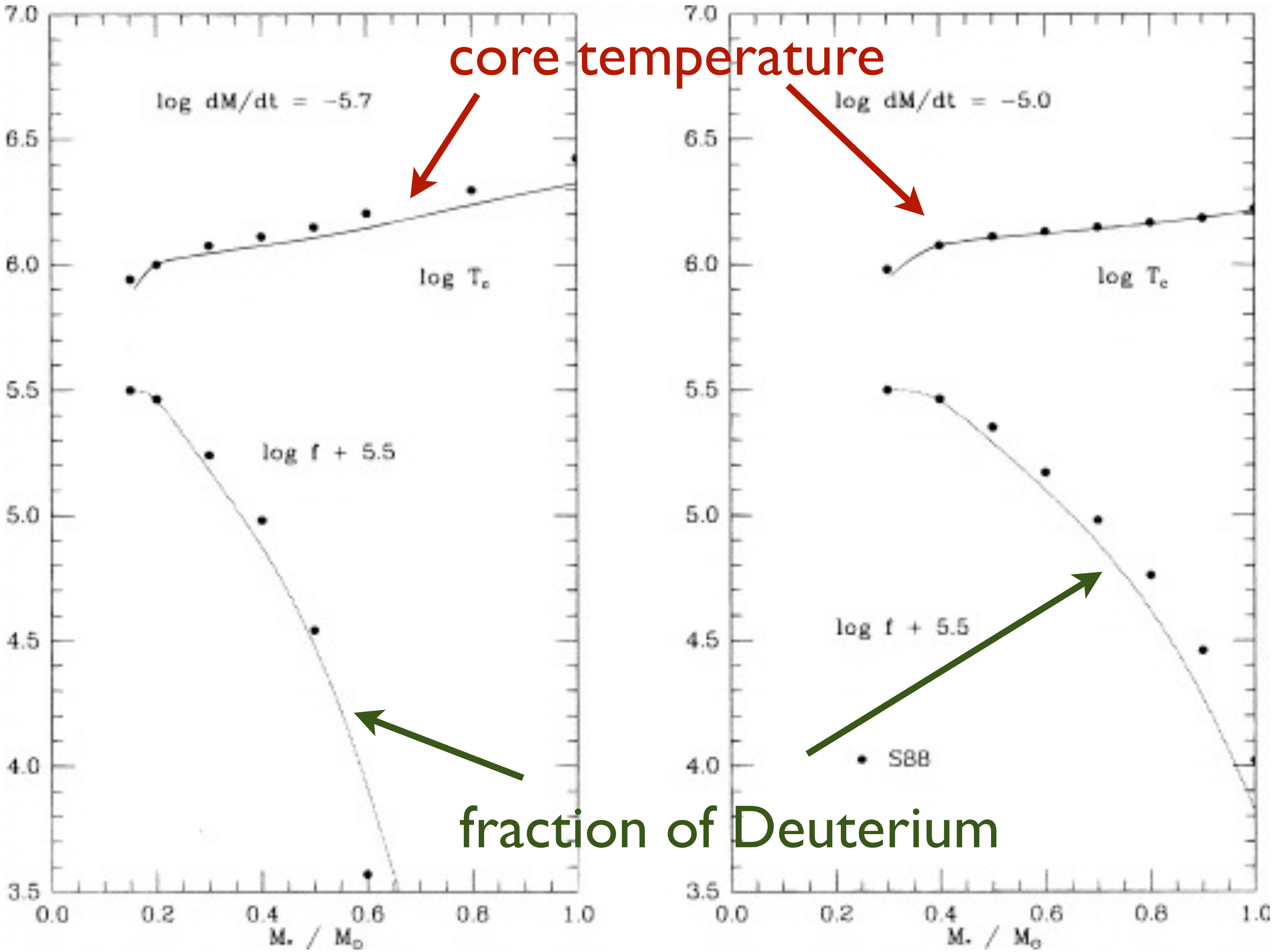




The birthline gives the evolution of protostellar mass and radius for a given accretion rate.

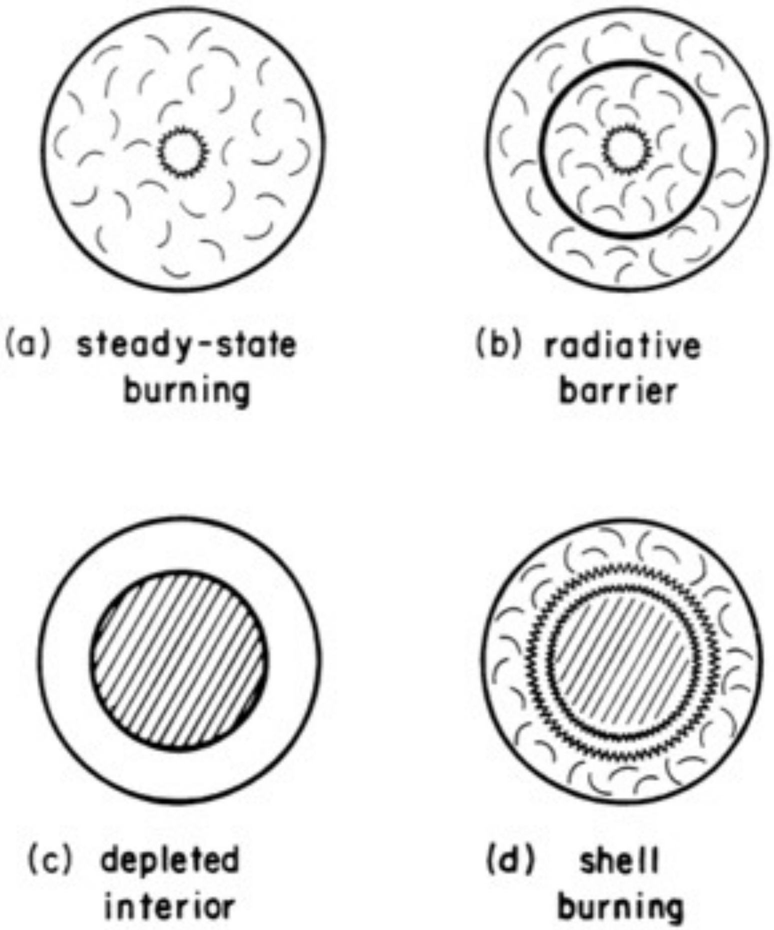
Stellar birthline for total luminosity L=0

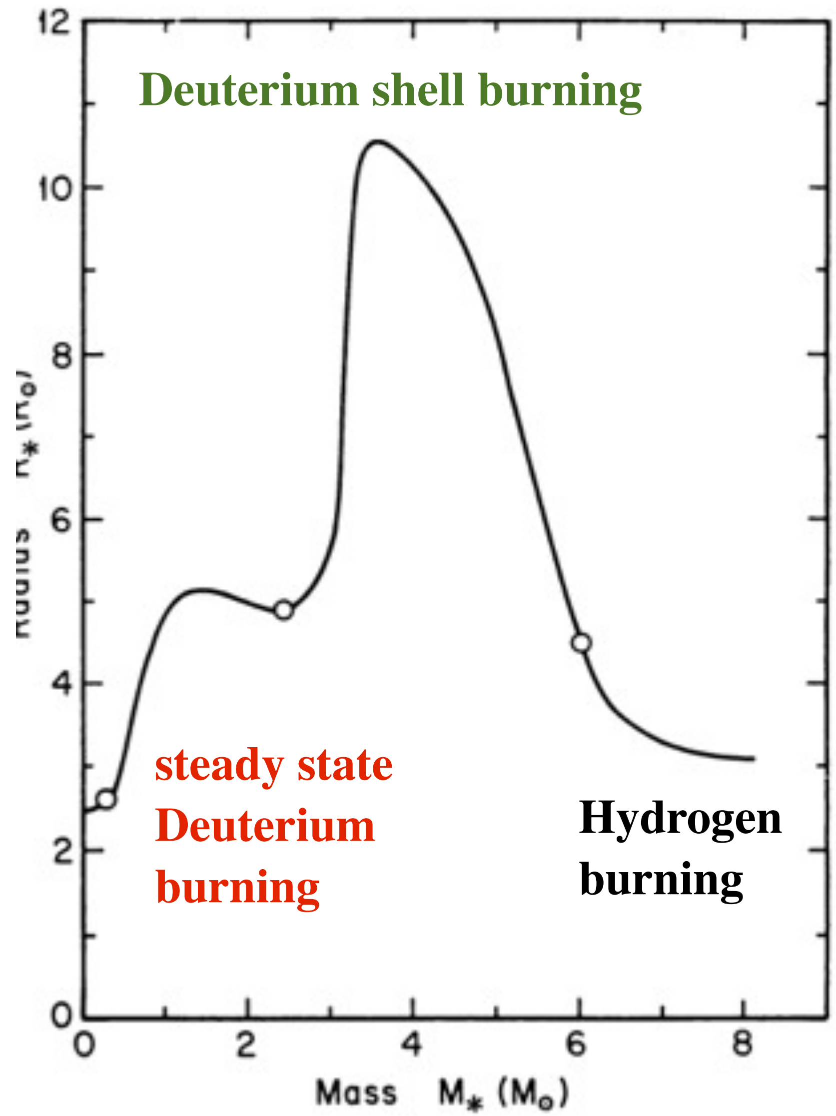
This shows the evolution of central temperature and f, the fraction of D/H (relative to the interstellar abundance.)



Hartmann et al 1997

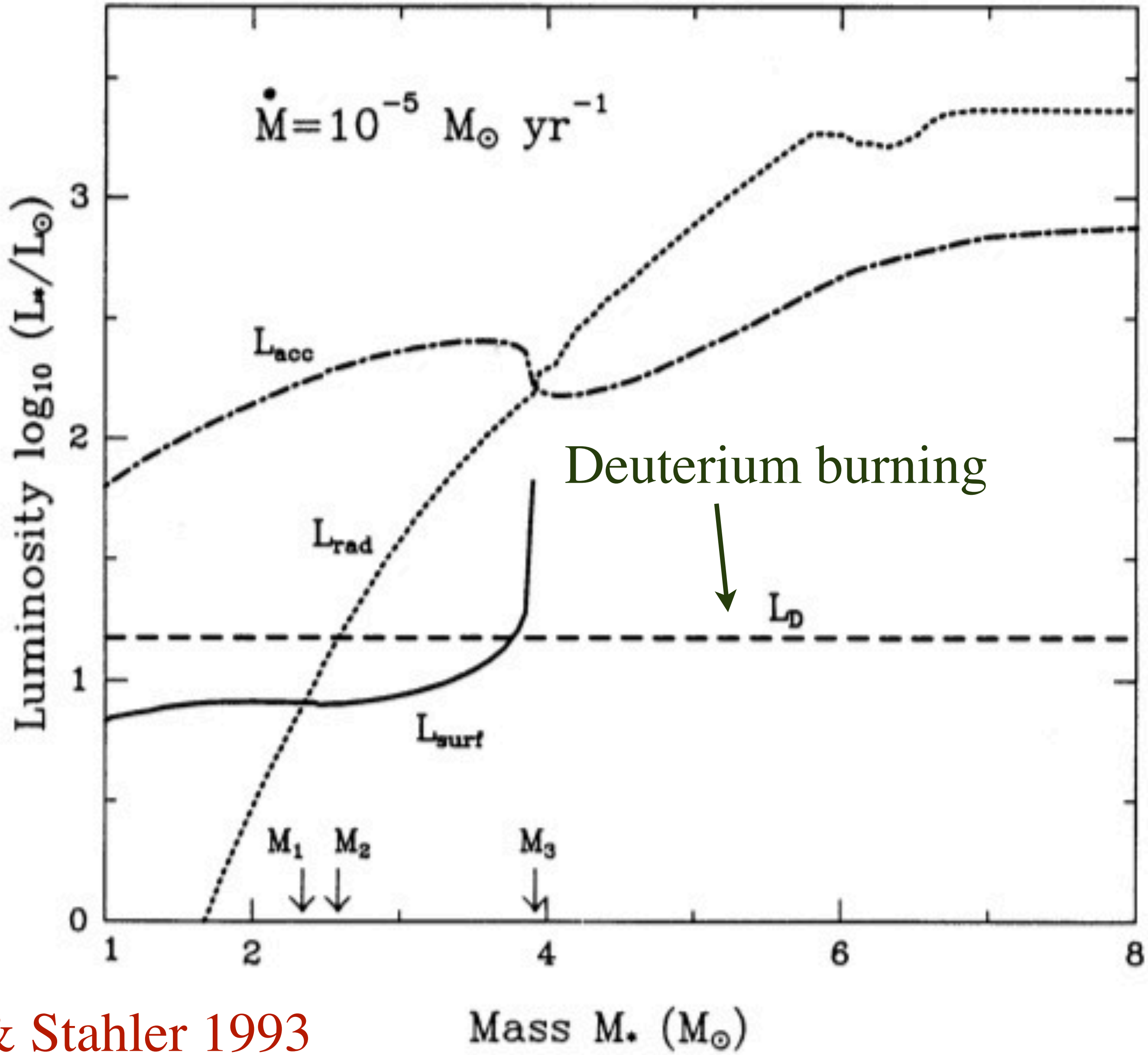
Deuterium Shell Burning





Palla & Stahler 1990

Contribution due to deuterium burning



Palla & Stahler 1993

Deuterium Burning: Pre-main sequence or Protostellar?

The initial core temperatures at the birthline, T_c, may exceed 1×10^6 K, thus Deuterium burning can start before the pre-main sequence phase.

Deuterium burning in protostars may significantly deplete the amount of Deuterium by the time the pre-main sequence phase starts.

This has never been verified experimentally.

This may not happen for the lowest mass stars and brown dwarfs, which start Deuterium burning later.

Review: Hydrogen Burning on the Main Sequence

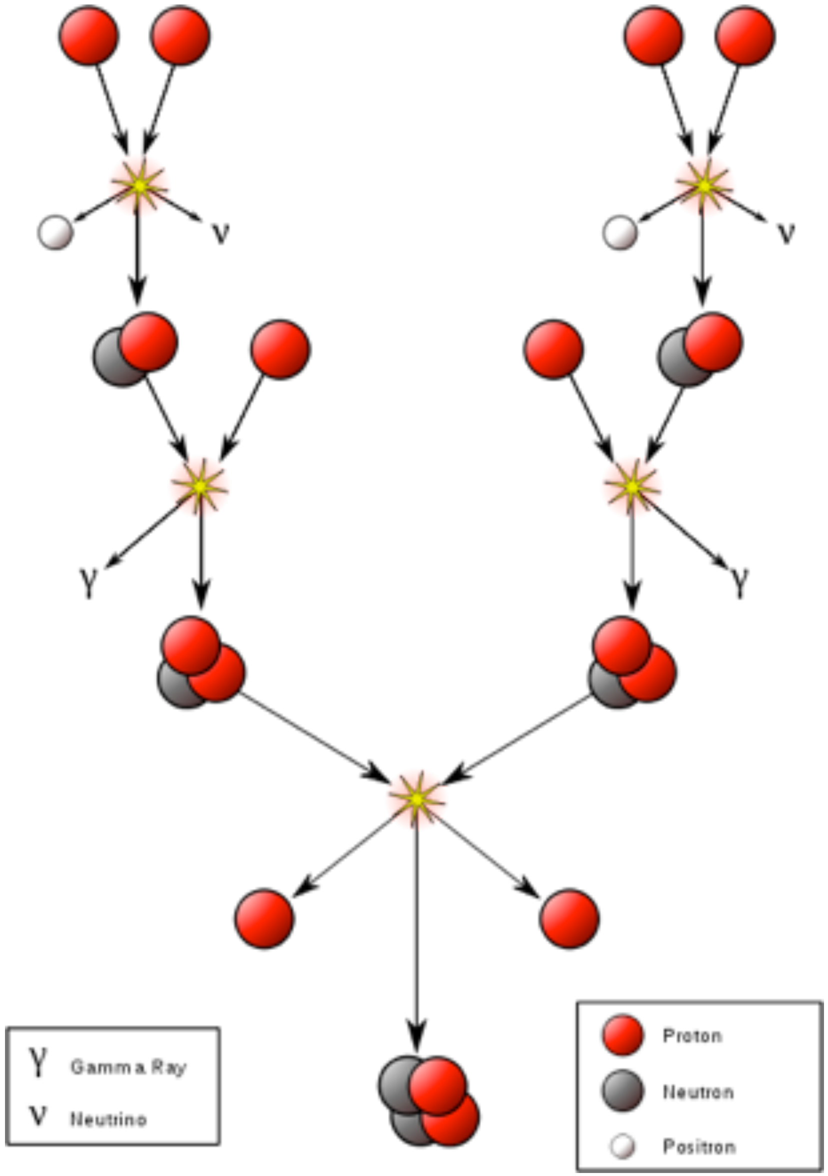
Review: Types of Nuclear Burning

The energy generation per unit volume goes as the density squared. Thus, we can write the energy generation per mass, equivalent to the energy per volume divided by density, as

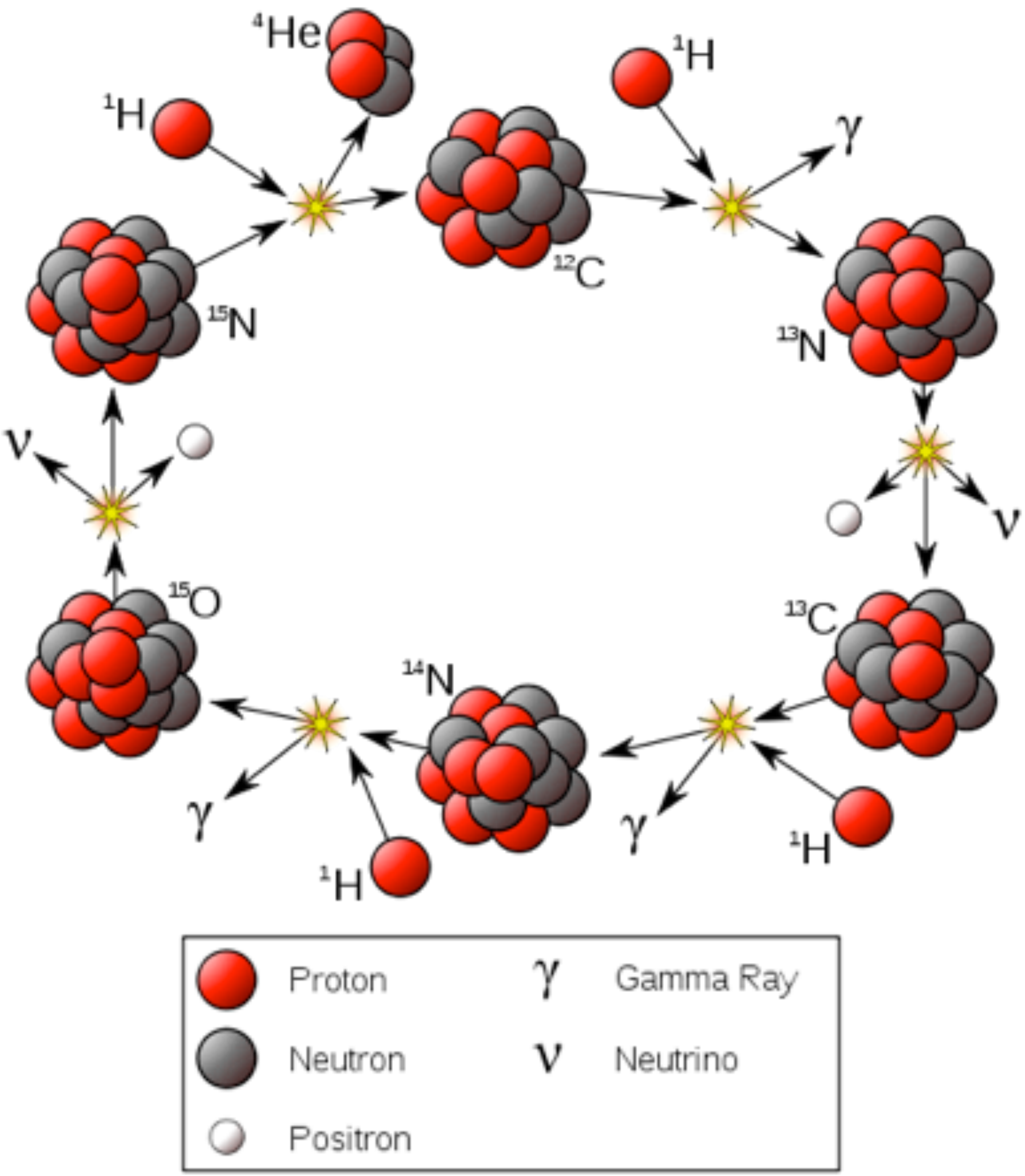
$$\epsilon \propto \rho T^n \tag{1}$$

$n = 4$ for the P-P chain, $n = 11.8$ for Deuterium burning, $n = 17$ for the CNO cycle.

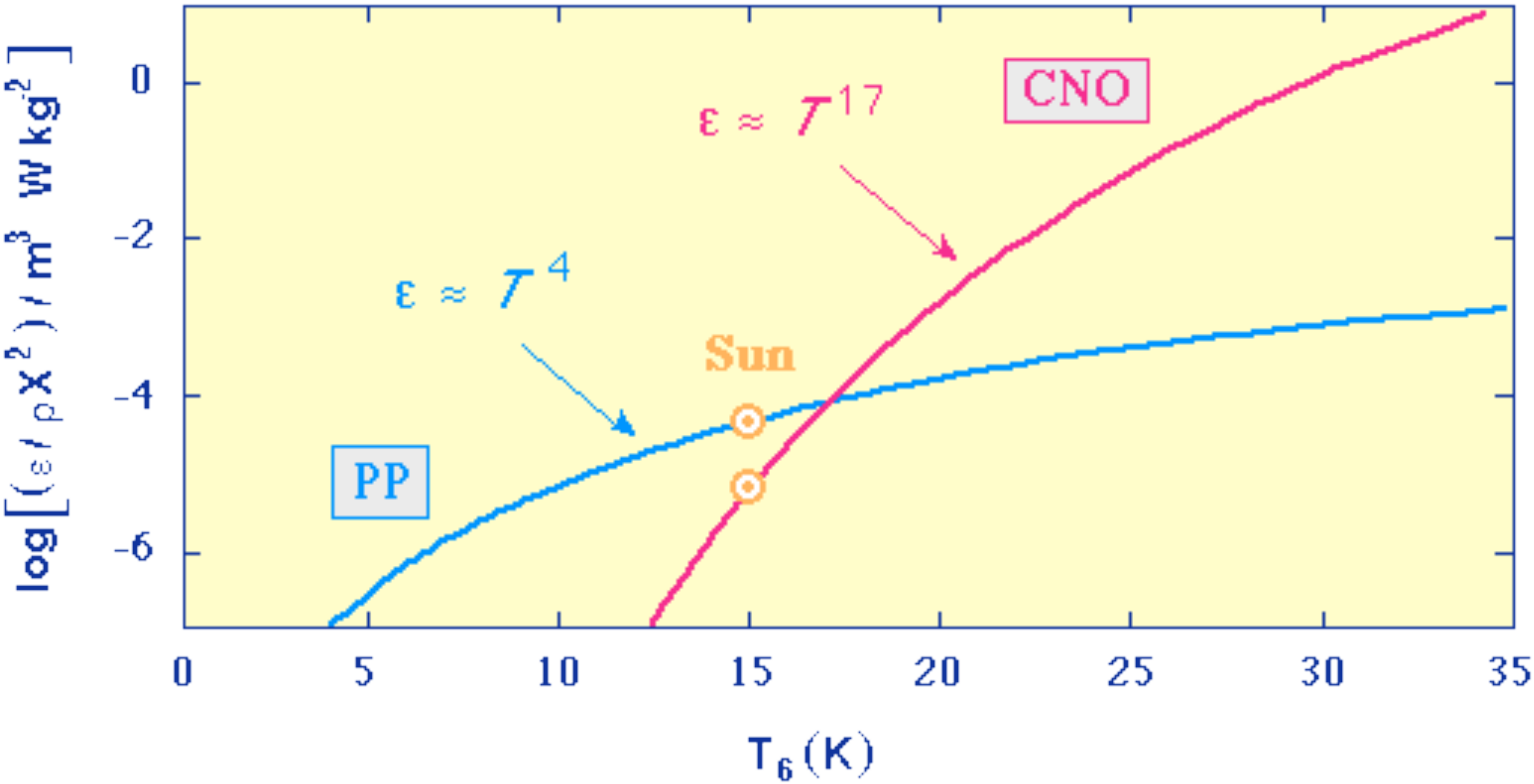
The P-P Chain pp 1 branch



The CNO Cycle



P-P Chain vs CNO Cycle



http://csep10.phys.utk.edu/astr162/lect/energy/cno-pp.html

Review: Pressure and the Internal Energy of a Gas

Last semester, we found that the Internal energy of a gas (per unit mass) is given by

$$P = (\gamma - 1)u\rho \qquad (2)$$

where $\gamma = C_P/C_V$, the ratio of the specific heats. Thus, for an ideal gas, $\gamma = 5/3$, and:

$$u = \frac{3}{2}\frac{P}{\rho} \qquad (3)$$

For radiation $\gamma = 4/3$ and

$$u_{rad} = 3P \qquad (4)$$

where for a radiation of a temperature T

$$u_{rad} = 3P = \frac{4\sigma}{c}T^4 = aT^4 \qquad (5)$$

Review: The Virial Theorem

The Virial Equilibrium of Stars: One More Time

Let's start with the Virial Theorem recast in the following form:

$$-3\int \frac{P}{\rho} dm = \Omega \tag{6}$$

where $dV = dm/\rho$. In the case of an ideal gas, we can write:

$$\frac{P}{\rho} = \frac{kT}{\mu m_H} \tag{7}$$

and

$$u_{gas} = \frac{3}{2}\frac{kT}{\mu m_H} \tag{8}$$

So the Virial equation does give $U = -1/2\Omega$, as expected. Let us try to generalize the equation to include radiation. Since we are interested in stars, and not clouds, the surface pressure term and magnetic field term are not important. Following an analysis in Prialnik:

$$\frac{P}{\rho} = \frac{P_{gas}}{\rho} + \frac{P_{rad}}{\rho} = \frac{kT}{\mu m_H} + \frac{aT^4}{3\rho} = \frac{2}{3}u_{gas} + \frac{1}{3}u_{rad} \quad (9)$$

where u_{gas} and u_{rad} are the specific internal energy (energy per mass). We can now express the virial equation as

$$U_{gas} = -\frac{1}{2}(\Omega + U_{rad}) \quad (10)$$

Note that radiation pressure effectively reduces the the gravitational attraction, with $\Omega + U_{rad}$ being an effective gravitational potential energy. The total energy is then:

$$E = \frac{1}{2}(\Omega + U_{rad}) = -U_{gas} \quad (11)$$

and the change in energy is given by:

$$\dot{E} = L_{nuc} - L \quad (12)$$

Thus, pre-main sequence contraction stops when $L_{nuc} = L$

Summary

Deuterium burning requires a core temperature of only 1×10^6 K, thus it can occur in the pre-main sequence or protostellar phase.

The abundance of Deuterium is low and it is rapidly depleted, unless it is continually replenished by accretion.

In the pre-main sequence phase, Deuterium burning can slow the contraction of stars.

In the protostellar phase, Deuterium burning may increase the radius of the star as it accretes and significantly alter the birthline.

In convective protostars, Deuterium burning occurs in the core, but in intermediate mass stars that start to develop radiative zones on the birthline, Deuterium burning may occur in a shell. This shell burning may swell the radius.

Hydrogen burning requires temperatures of 1×10^7 K. The PP chain occurs for lower temperatures, but the CNO cycle dominates at higher temperatures.

Nuclear energy may balance losses from radiation, stopping the contraction of the star. The long period of equilibrium created by Hydrogen burning is the main sequence.