Brown dwarfs: Relation to spectral types

Definition of spectral types later than M is discussed in Kirkpatrick et al. (1999, ApJ, 519, 802). Roughly:

- Boundary between M and L is defined by the weakening of TiO and VO bands (important in late M dwarfs), and appearance of metal hydride (FeH and CrH) and neutral alkali metal lines.
- Boundary between L and T is characterized by stronger H_2O and H_2 absorption, and strong methane bands. These features are obvious in the infrared.

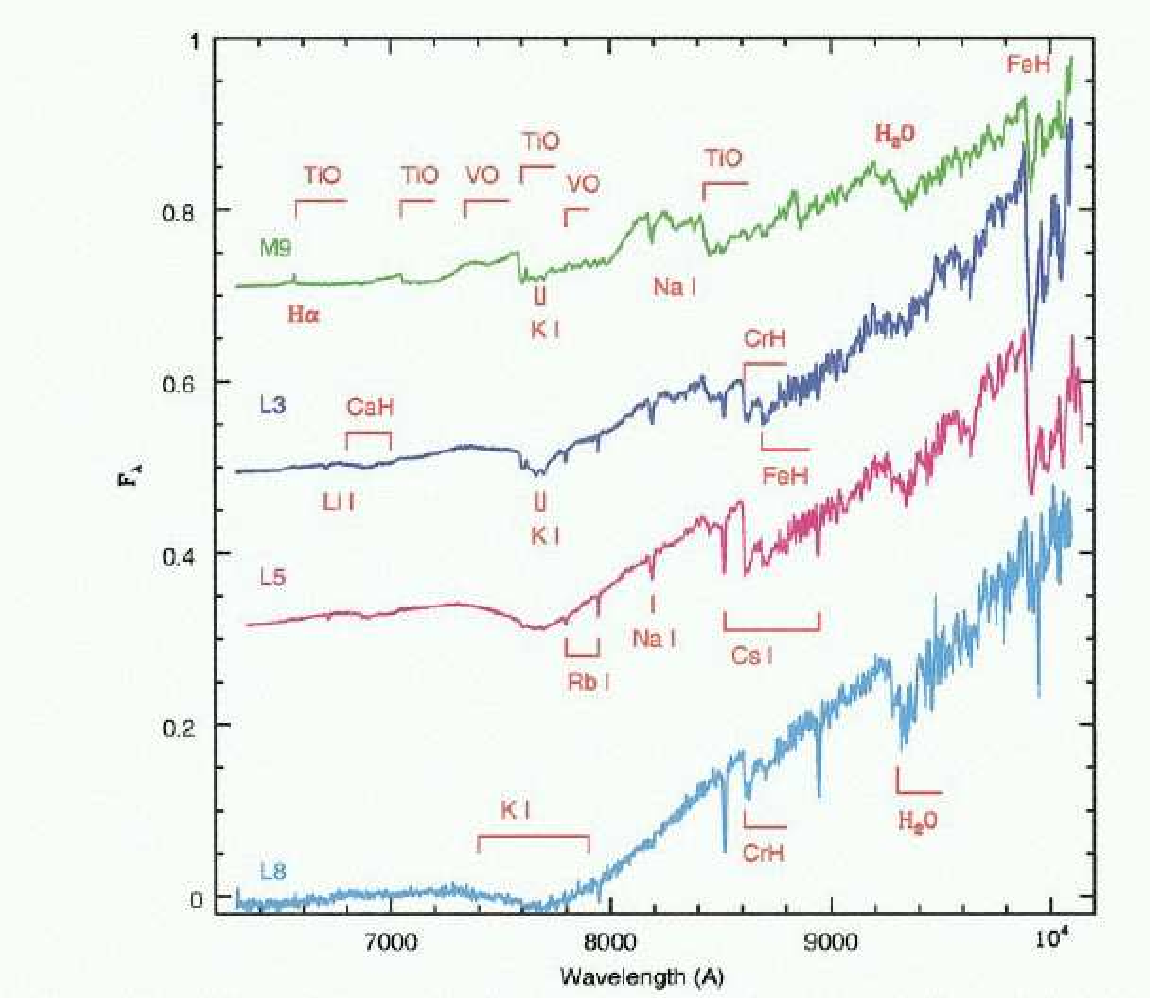
Determining where the substellar boundary lies in spectral type requires:

(i) Establishing the effective temperature that corresponds to a particular type.

(ii) Evolutionary models for $T_e(M, t)$.

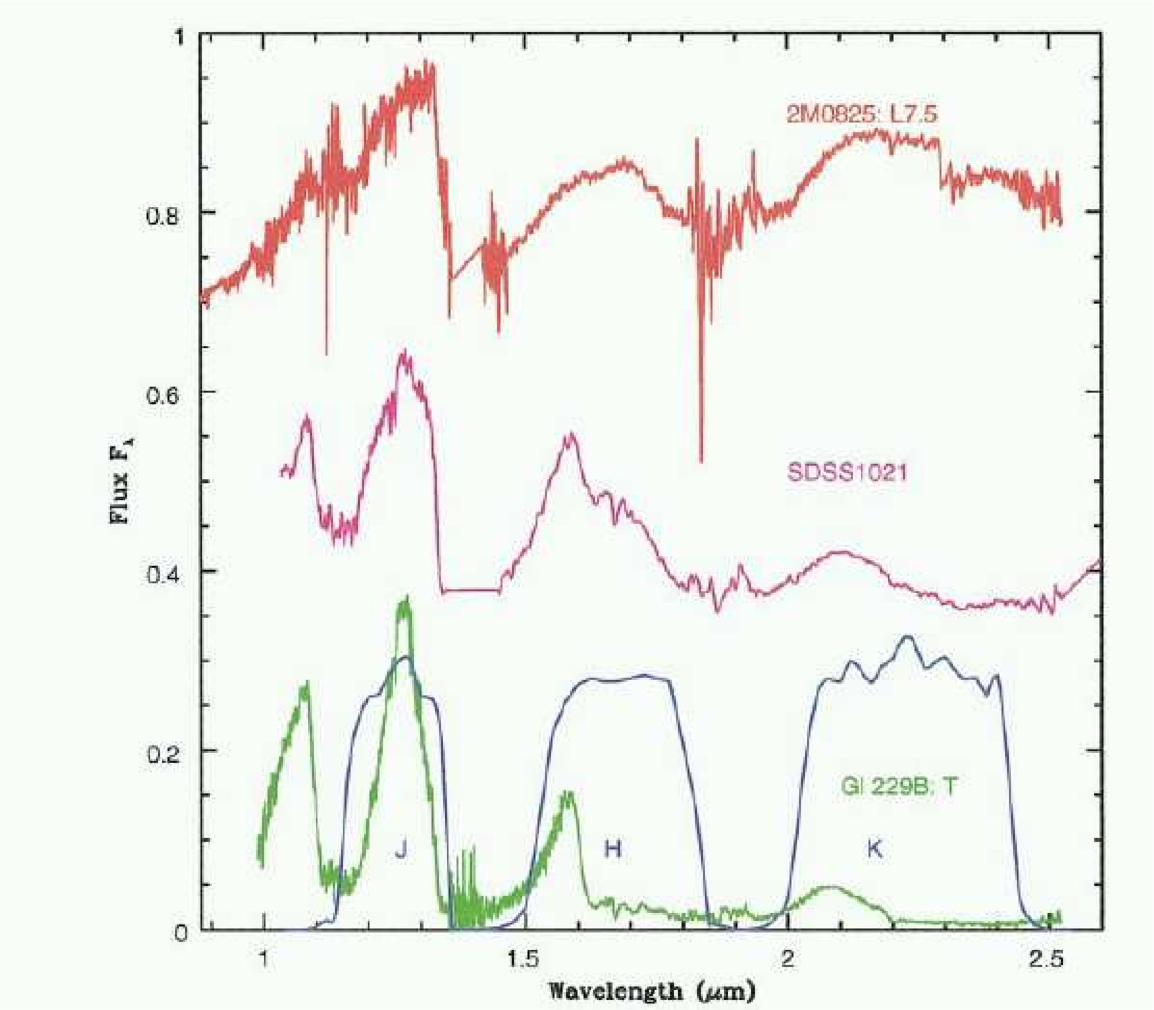
Uncertainty in both these steps.

Spectra of L dwarfs



Range of L dwarfs is estimated to correspond to T_e between 1300 K and 2100 K.

Spectra of T dwarfs



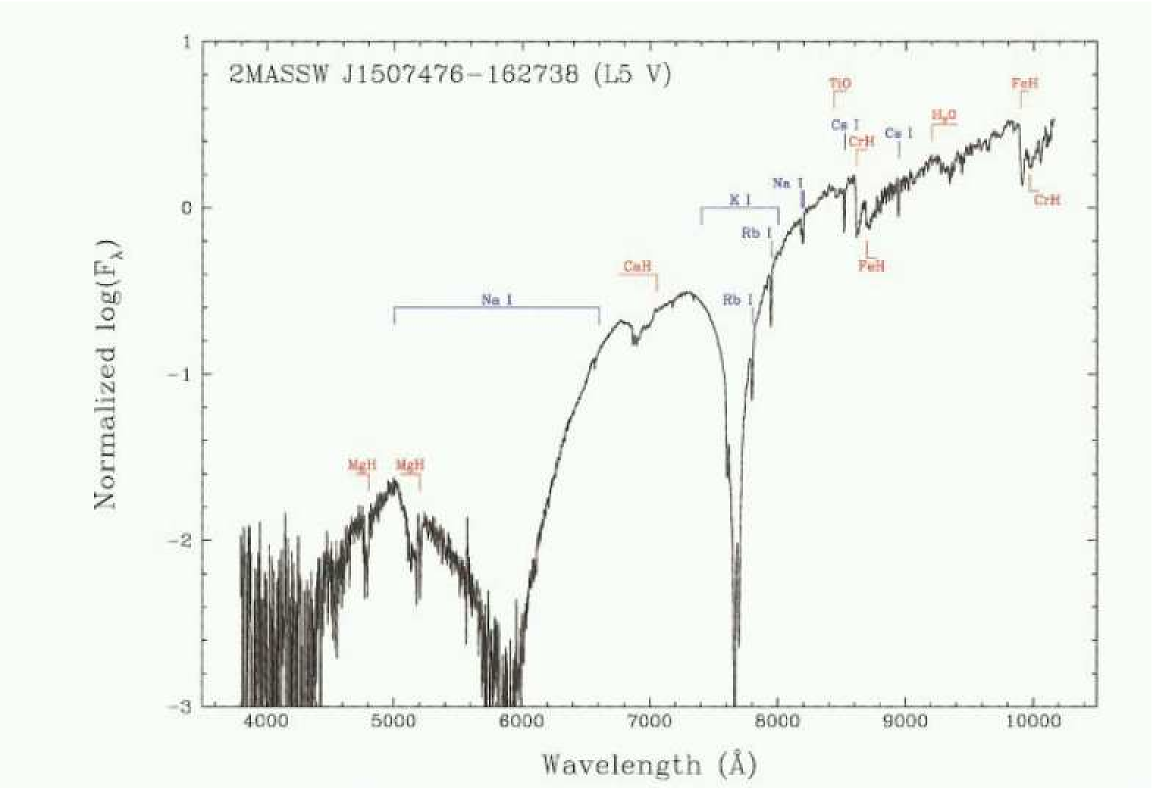
Gl 229B has $T_e \approx 950$ K, $L \sim 7 \times 10^{-6}\ L_\odot$.

Spectrum in this wavelength range is mostly due to water absorption.

T dwarfs may span T_e from 700 K to 1200 K.

At still lower $T_e < 500$ K, predicted that water clouds important in the spectrum.

Optical colors of brown dwarfs

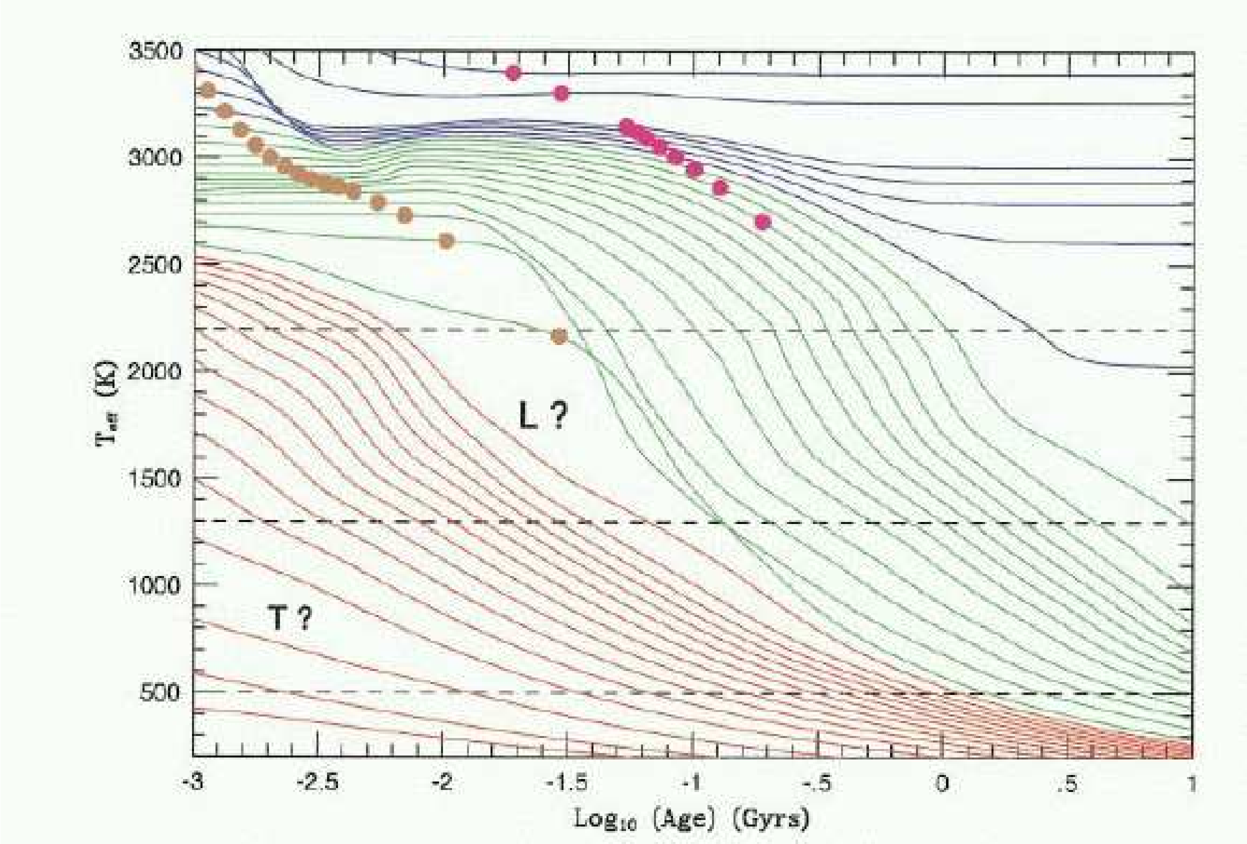


Keck II spectrum of an L5 dwarf. Note:

- Strong absorption in sodium D line.
- K I absorption at 770 nm.
- Appearance of FeH and CrH bands.

Which spectral types are substellar?

Depends upon age and the effective temperature scale.

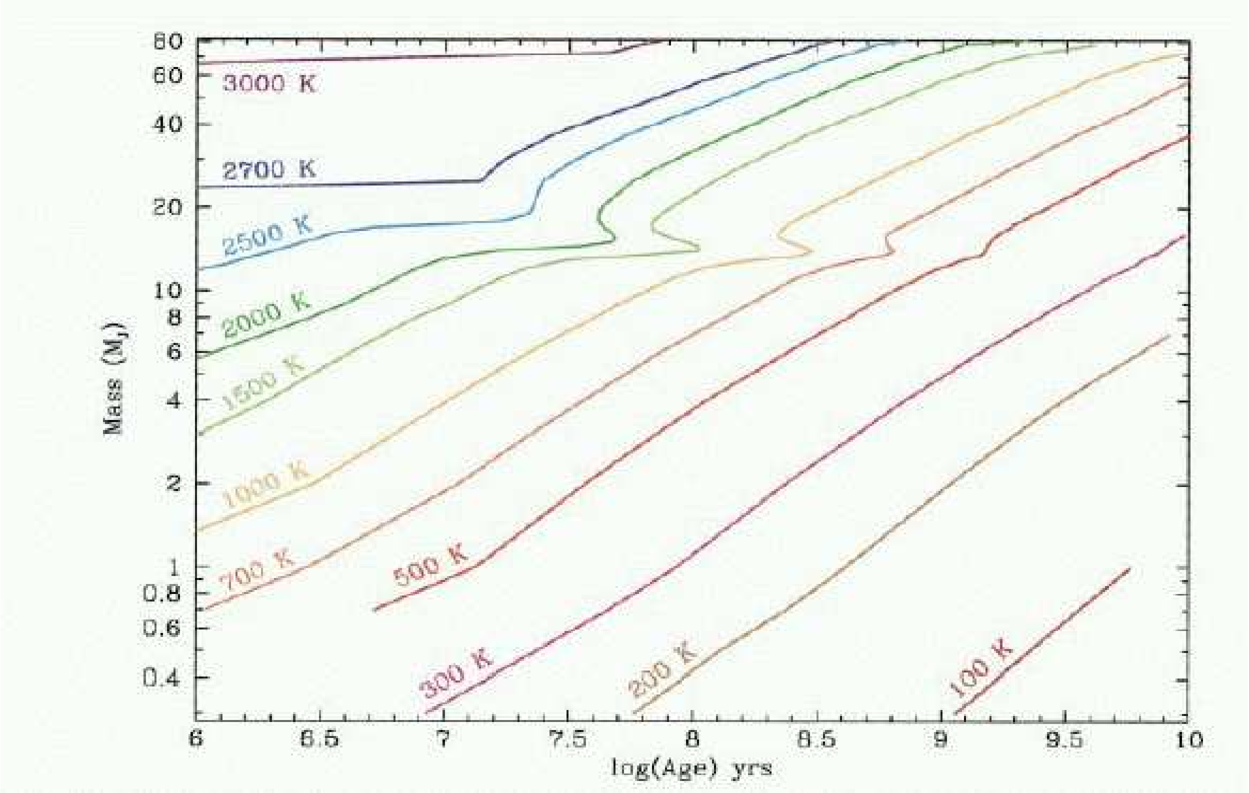


- Edge of the hydrogen burning main sequence at 10 Gyr is an L dwarf.
- All T dwarfs are substellar.
- Most brown dwarfs evolve from M → L → T with increasing age.

Age - mass degeneracy

IR observations of young clusters are sensitive to *extremely* low mass objects (of the order of M_J in Orion assuming an age of a few Myr).

Reliability of mass estimates in clusters correspondingly uncertain.



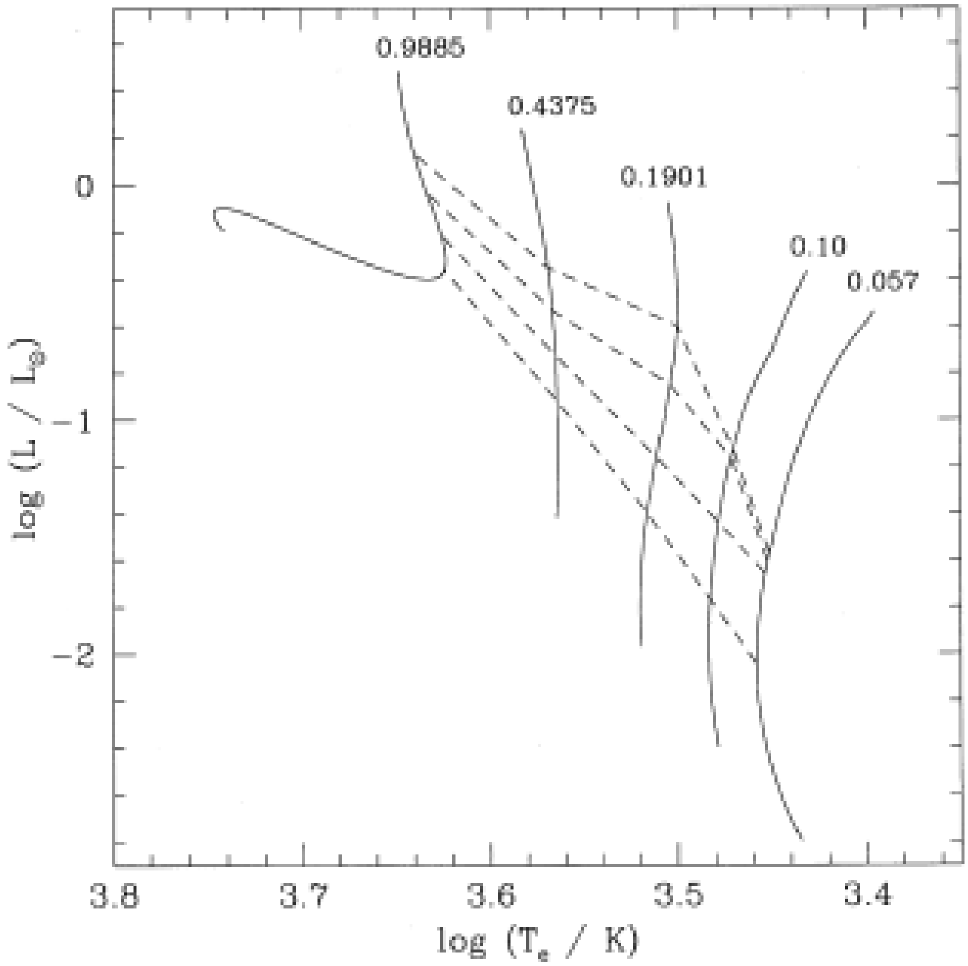
Estimates by Reid et al. (1999) in the field and Luhman et al. (2000) in clusters suggest:

- Brown dwarfs comparable or somewhat more numerous than main sequence stars.
- Contribute to the disk mass density at the $10 - 20\%$ level.

Pre-main-sequence evolution

Non-accreting, pre-main-sequence stars contract along,

- Almost vertical *Hayashi* tracks while fully convective.
- *Henyey* tracks once (if) a radiative core develops.



First goal: show why Hayashi tracks are vertical lines in HR diagram.

Consider a cool star with H$^-$ opacity dominant,

$$\kappa = \kappa_0 \rho^n T^{-s}$$

with $n = 1/2$, $s = -9$. General form of the pressure – density relation in the outer layers is (cf problems on white dwarf cooling and convection),

$$P^{n+1} = \frac{n+1}{n+s+4}\frac{16\pi acGM}{3\kappa_g L} T^{n+s+4}\left[\frac{1-(T_0/T)^{n+s+4}}{1-(P_0/P)^{n+1}}\right]$$

where,

$$\kappa_g = \kappa_0 \left(\frac{\mu}{N_A k}\right)^n$$

and P_0 and T_0 are values at some reference level. Taking this to be the photosphere, then boundary conditions are,

$$\begin{aligned} T_p &= T_e \\ P_p &= \frac{GM}{R^2}\frac{2}{3\bar{\kappa}} \end{aligned}$$

For H$^-$ opacity (details and general expression in *Hansen & Kawaler* §7.3.3), resulting radiative gradient is,

$$\nabla(r) = -\frac{1}{3} + \frac{11}{24}\left[\frac{T_e}{T(r)}\right]^{-9/2} .$$

Since T increases with depth, ∇ increases → onset of convection.

For efficient convection,

$$\nabla = \nabla_{ad} = 0.4.$$

Assume this holds where convection begins. Then for H$^-$ opacity, temperature at onset of convection is,

$$T_f = 1.11 T_e$$

and pressure is,

$$P_f = 2^{2/3} P_p.$$

Interior to this point, for a fully convective star described by an $n = 3/2$ polytrope,

$$P = K' T^{5/2}$$

where K' is related to the polytropic constant K via,

$$K' = \left(\frac{N_A k}{\mu}\right)^{n+1} K^{-n}.$$

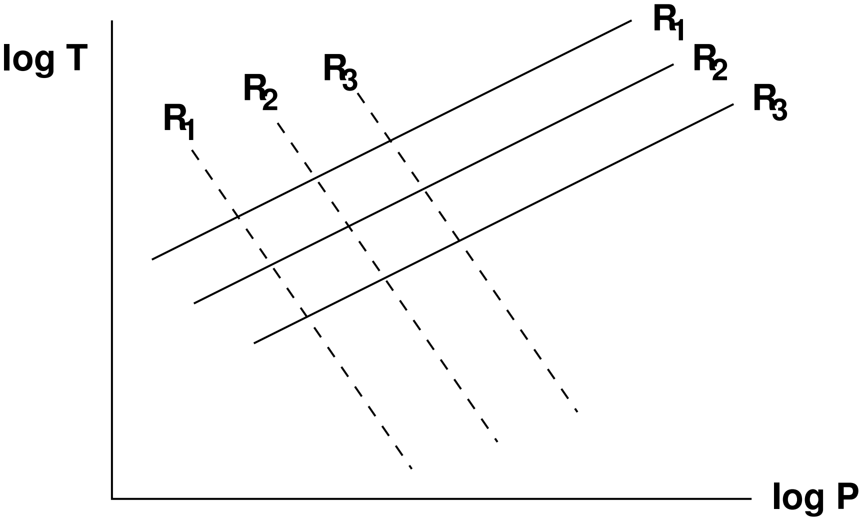
Note: this means that K' is a **known function** of the mass and radius,

$$K' = \frac{0.016}{\mu^{2.5}} \left(\frac{M}{M_\odot}\right)^{-1/2} \left(\frac{R}{R_\odot}\right)^{-3/2}.$$

Pressure and temperature at the onset of convection depend upon the photospheric conditions. Note:

- The pressure P_p depends on the opacity in the atmosphere, and the surface gravity GM/R^2.
- The opacity depends on the photospheric temperature, or equivalently on the luminosity via $L = 4\pi R^2 \sigma T_e^4$.

Demand that P_f and T_f match onto the interior solution – ie for a given mass find the consistent R that works for convective interior and radiative atmosphere.



Find,

$$T_e \approx 2600 \mu^{13/51} \left(\frac{M}{M_\odot}\right)^{7/51} \left(\frac{L}{L_\odot}\right)^{1/102} \text{ K}$$

→ large changes in luminosity lead to almost no change in temperature. Vertical tracks in the HR diagram.