Modeling Pre-Main Sequence Stars

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Plan

- Sources of Uncertainties in the modeling of PMS stars

  1. **Constitutive physics**
     - Equation of State
     - Atmosphere
     - Treatment of the convection
     - Chemical effects (metallicity)

  2. **Physical processes**
     - Rotation
     - Accretion

- Uncertainties in the age and mass determination

  Given the above mentioned error bars in the theoretical models, how does it affect the mass and age determination ?

- Comparisons other works

  How do the different sets of tracks compare with each other ?

- The affects of mass accretion on PMS tracks

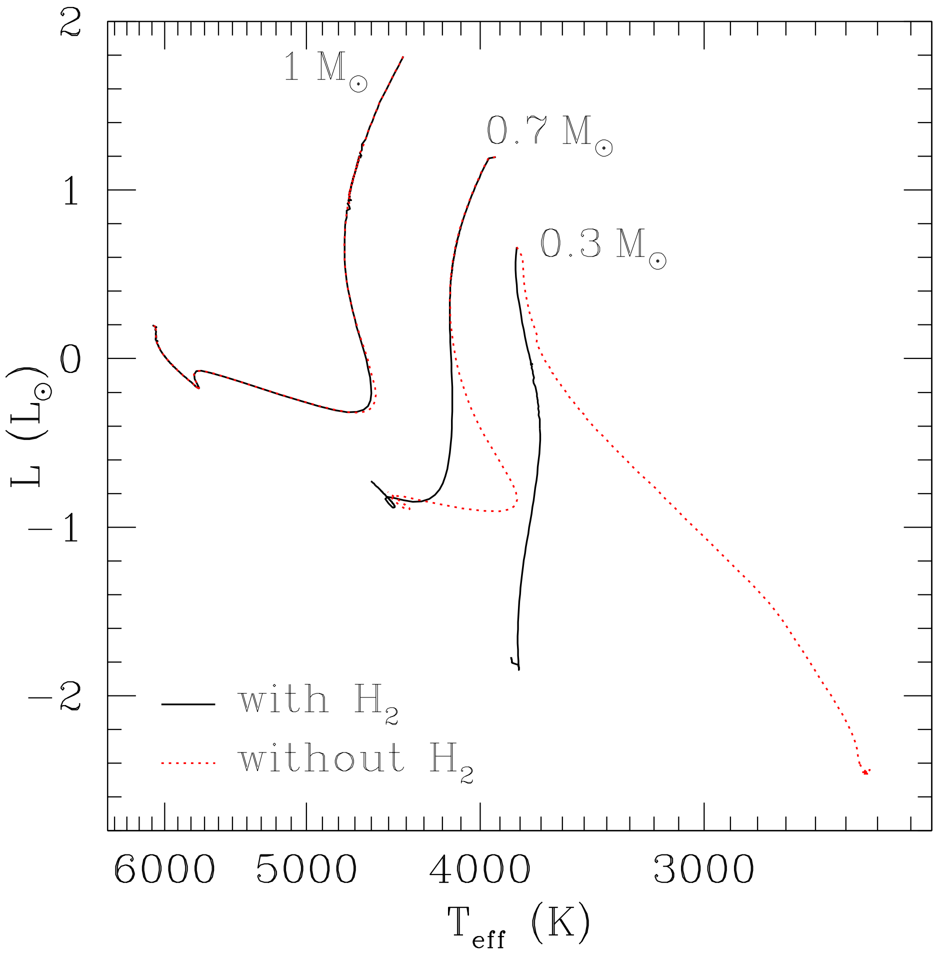
- Conclusion

Uncertainties associated with PMS Modeling

- Equation of state

An accurate treatment of the thermodynamics is particularly required for the modeling of very low mass stars (VLMS, $M \lesssim 0.5\ M_\odot$) where non-ideal effects are large. Non ideal effects include pressure ionization and coulomb shielding, mainly.

Example : Treatment of H_2 in the Saha equations



The presence of H_2 affects mainly stars with $T_{\rm eff} \lesssim 4500$K in which the molecule can form near the photosphere. This lowers the adiabatic gradient and favors convection in the outermost layers

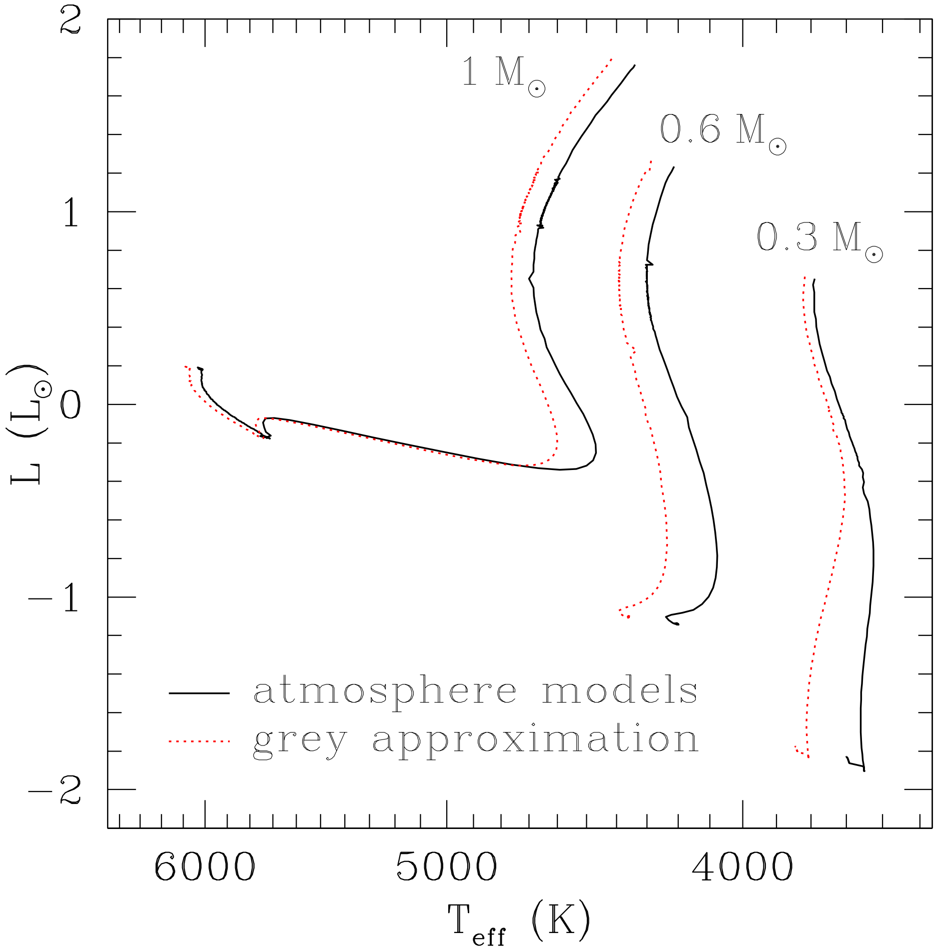
→ strong morphological differences

→ very large shifts in $T_{\rm eff} \sim -100$ to -1300 K

- Atmosphere models

In VLMS, the emergent spectrum differs significantly from a pure black body due to molecular absorption (H_2O, TiO ...) and due to the appearance of convection in the subphotospheric layers.

Grey approximation do not account for these physical processes. In this approximation the atmosphere profile is cooler and denser so that a hotter atmosphere model is required to match the internal structure.



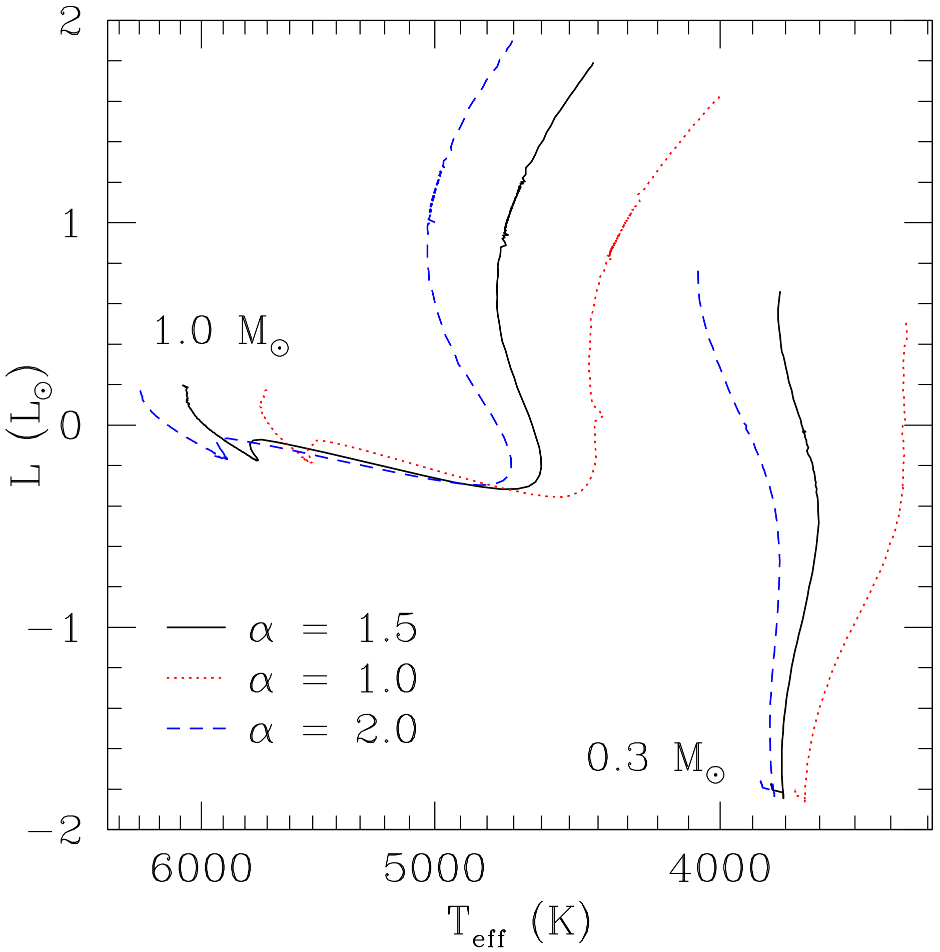
→ **grey models are hotter by $\sim$ 100 – 200 K**, depending on the evolutionary status, metallicity and mass of the star

→ grey atmosphere models remain a good approximation for $T_{\rm eff} \gtrsim$ 4700 K

- Treatment of the convection

A modification to the parameter α in the MLT directly affects the extend of the convective region, i.e. the stellar radius.

A larger value of α allows the energy to be carried out more efficiently. Consequently the stellar radius will be smaller and the effective temperature higher at a given luminosity.



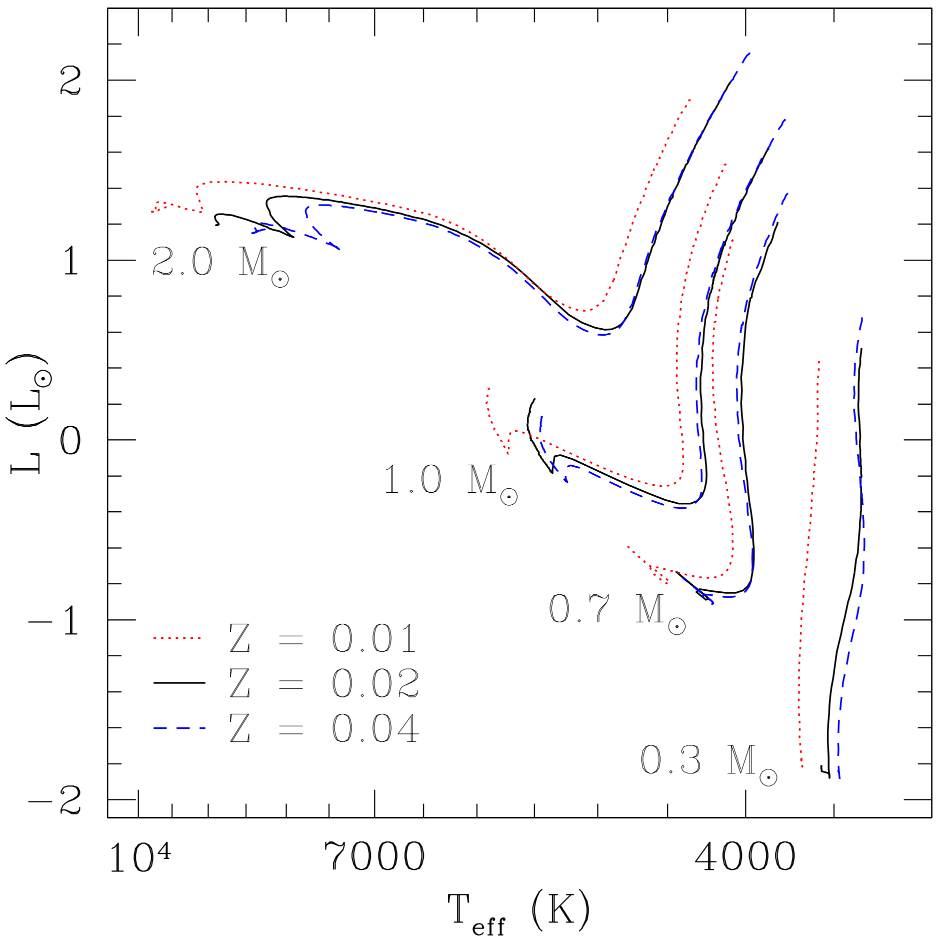
Modification to α of ± 0.5 leads to

$\rightarrow$ differences in $T_{\rm eff}$ of $\sim \pm$ **300 K**

$\rightarrow$ large differences in the surface Li abundance

- Chemical composition

Changing Z modifies the opacity : stars with higher Z (with more metal atoms and thus absorption lines) have a larger opacity $\rightarrow$ they are more opaque to radiation $\rightarrow$ they are less luminous and cooler



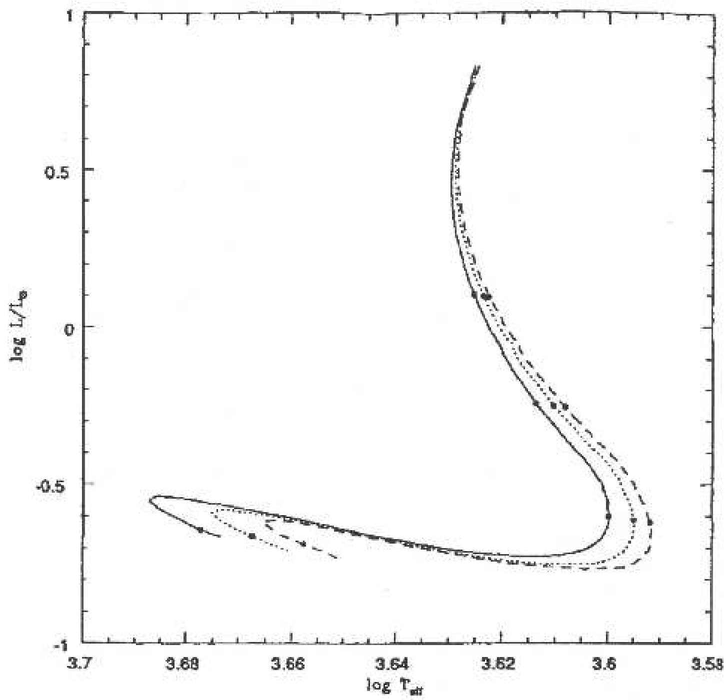
An decrease in Z shifts the tracks towards higher effective temperatures and larger luminosities

$\rightarrow$ For $\Delta Z \approx \pm\, 0.1 \;\rightarrow \Delta T_{\rm eff} \sim \pm\, 300$ K and $\Delta \log L \sim \pm\, 0.2\, \mathrm{L}_\odot$

Note that the effect of increasing or decreasing Z around the solar value is not symmetrical. **Decreasing Z produces a larger shift of the tracks**.

• Rotation

The effect of rotation is to shift the PMS tracks **towards lower effective temperature and luminosity**.



The evolutionary path of the star depends on

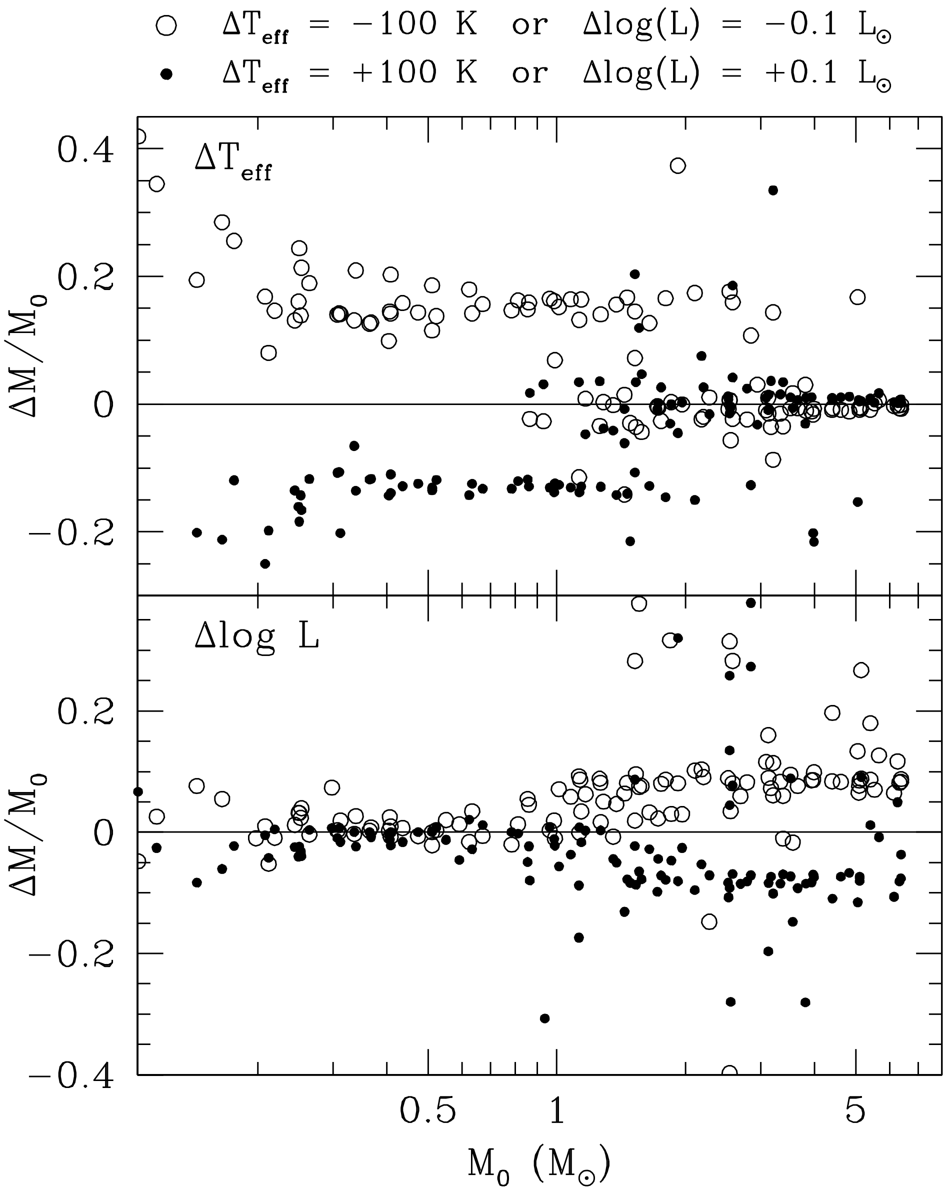
→ the initial angular momentum

→ the adopted angular momentum loss rate.

Typical temperatures differences $\dfrac{\Delta T_{\rm eff}}{T_{\rm eff}} \lesssim 5\%$ ($\sim 300\,{\rm K}$)

The presence of rapid rotation in PMS evolution **can significantly alter the Li depletion**

Uncertainties on the mass determination



General trends :

- **hotter tracks underestimate the stellar mass**

  $\rightarrow |\Delta T_{\rm eff}| = \pm 100\,{\rm K} \rightarrow \dfrac{\Delta M}{M} \sim 20 - 30\,\%$ for $M \lesssim 2M_\odot$

  $\rightarrow$ for **radiative stars**, $\dfrac{\Delta M}{M} \lesssim 5\,\%$

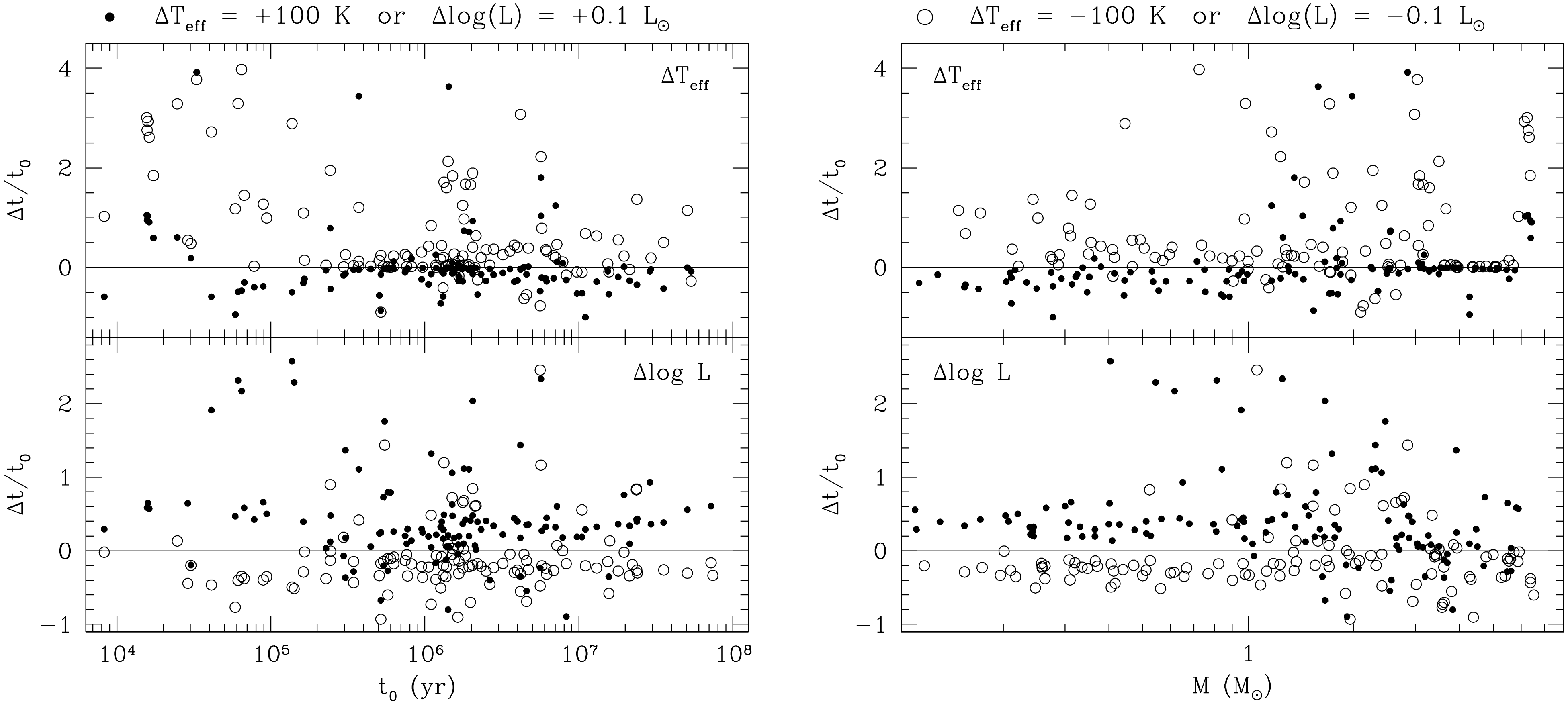
the shifts in $T_{\rm eff}$ mainly affect stars located on the Hayashi line

- **stellar models more luminous underestimate the mass**

  $\rightarrow |\Delta \log L| = \pm\, 0.1\,{\rm L}_\odot \rightarrow \dfrac{\Delta M}{M} \lesssim 10\,\%$

this affects mainly the intermediate mass stars ($M \gtrsim 2M_\odot$) which are more likely located on a radiative track

Uncertainties on the age determination



- **stellar models cooler or more luminous overestimate the age**

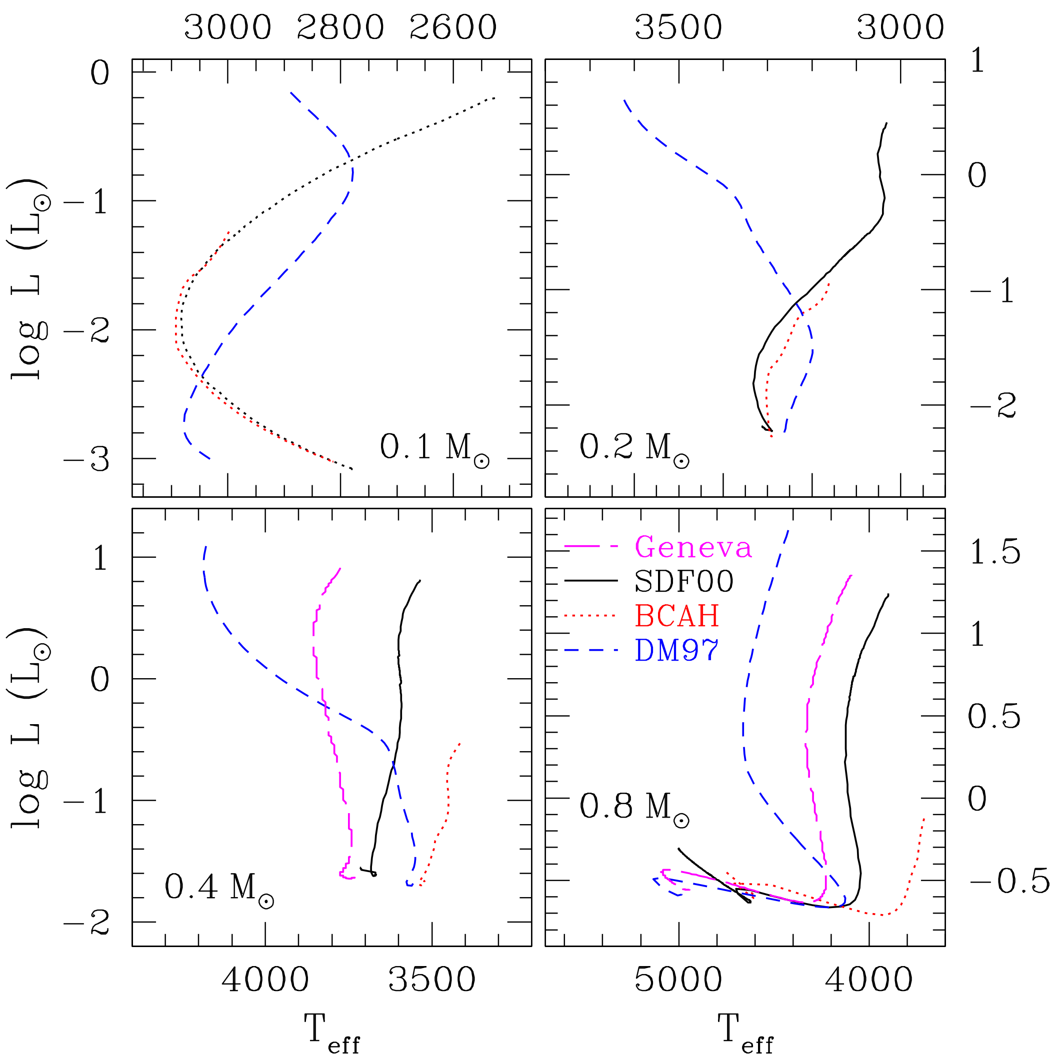
  → *very large uncertainties*, up to a **factor 2-3 in the age estimate for** $\mathbf{t \lesssim 2-3\ 10^6}$ **yr**

  → the uncertainties **decrease with time** (large dispersion before 2-3 Myr)

  → For $\mathbf{M \lesssim 1}$ $M_\odot$, $\frac{\mathbf{\Delta L}}{\mathbf{L}} = \pm\mathbf{10}\,\% \rightarrow \frac{\mathbf{\Delta t}}{\mathbf{t}} \lesssim \mathbf{20}\,\%$ and $\mathbf{\Delta T_{eff}} = \pm\mathbf{100}$K $\rightarrow \frac{\mathbf{\Delta t}}{\mathbf{t}} \lesssim \mathbf{50}\,\%$

Comparison with other sets of tracks

- Morphological differences



The EOS used in these different stellar evolution codes is comparable and appropriate for this modeling

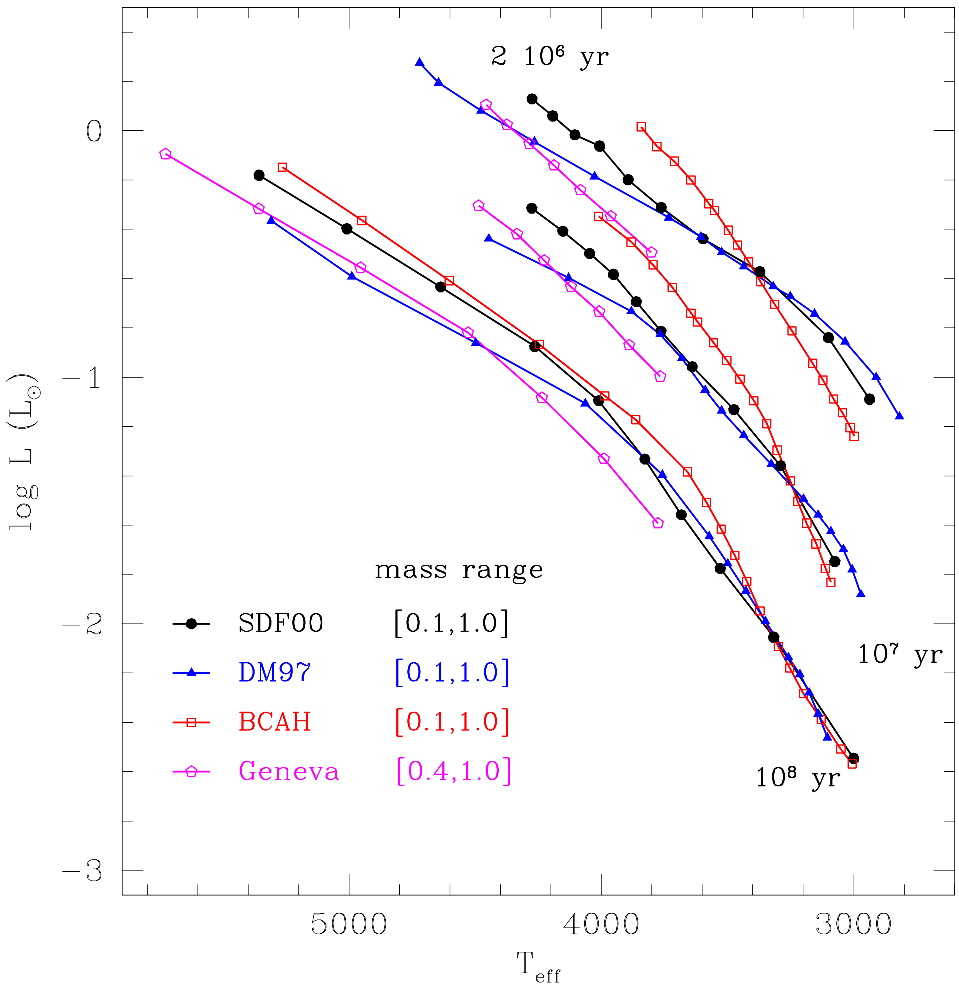
– Below 0.4 $M_\odot$, large discrepancies between the models mainly due to
  - different treatments of convection (DM97 vs others)
  - different boundary conditions (grey vs non-grey models)

– Above 0.6 $M_\odot$, the differences mainly result from different chemical composition and/or values of α since the non ideal effects become small and the grey approximation becomes valid.

$\Longrightarrow$ **ΔT_{eff} can be as large as $\sim$ 500 K !**

SDF00 : Siess, Dufour & Forestin 2000
BCAH : Baraffe, Chabrier, Allard, Hauschildt 1998
DM97 : D'Antona & Mazzitelli 1997
Geneva : Charbonnel, Dappen et al. 1999

• Differences in the isochrones



General comments

BCAH : The slope of the isochrones is different. Their VLMS are less luminous while their low-mass stars are more luminous. The discrepancies vanish when the stars reach the ZAMS.

DM97 : Isochrones very similar in the low mass end. For $M > 0.5\,\mathrm{M}_\odot$ their isochrones are systematically less luminous. Their 2 Myr isochrones would appear as old as 4 Myr with our tracks.

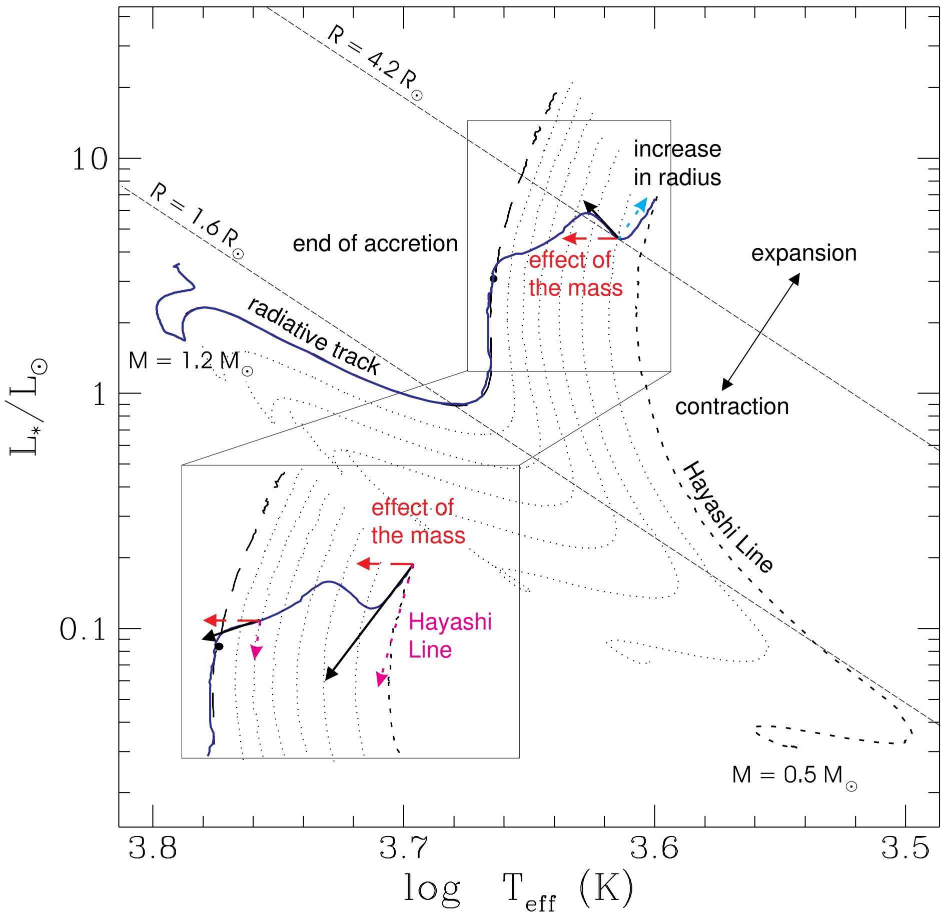
Geneva : Isochrones hotter (grey approx.) by ~ 200 K. In this mass range ($M \gtrsim 0.5\,\mathrm{M}_\odot$) the morphology of the isochrones is very similar. Their 10 Myr isochrones would appear as old as 20 Myr with our tracks

SDF00 : Isochrones intermediate between the DM97 and BCAH98 ones. Morphology very similar to the Geneva isochrones.

→ **Very good agreement of the isochrones for VLMS for t $\gtrsim 10^7$ yr !**

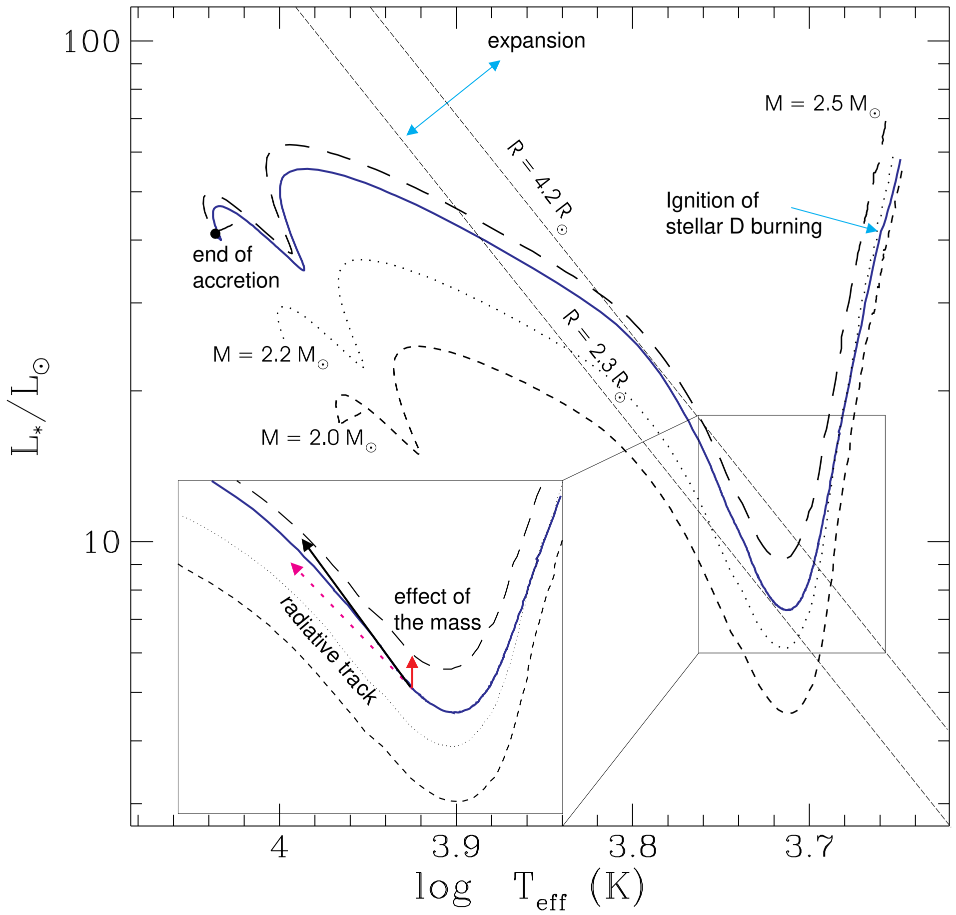
Accreting PMS tracks

- High accretion rates



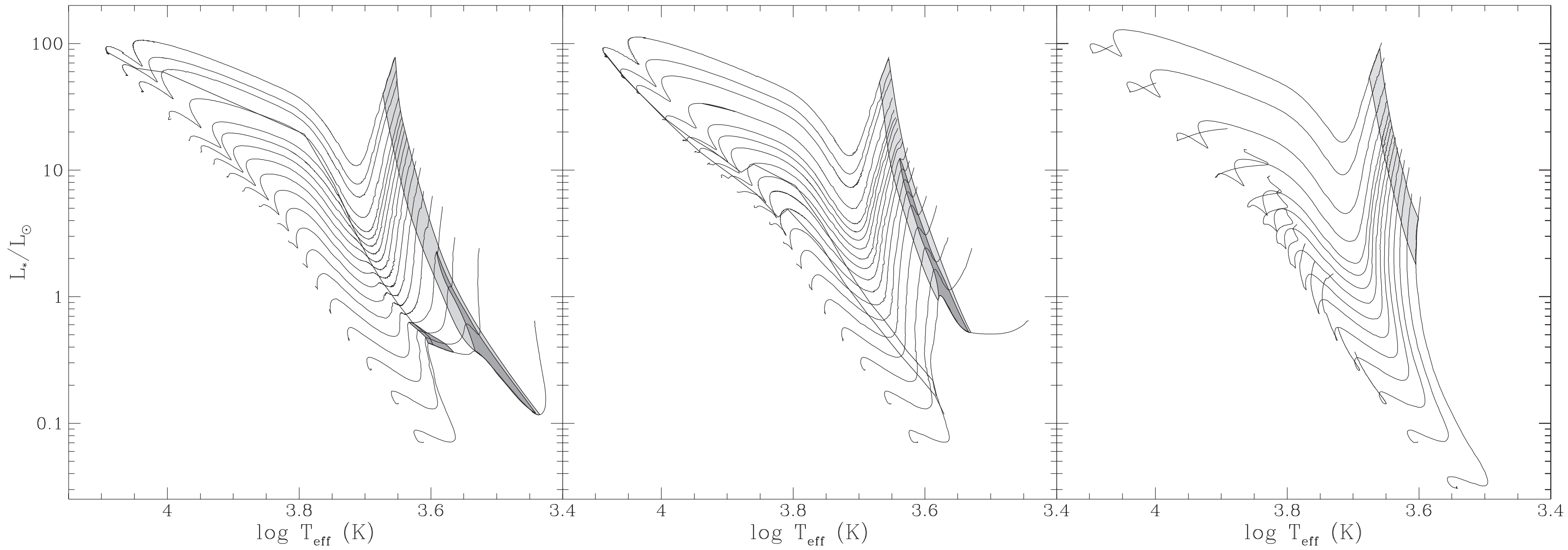
Effects are large because $\tau_{\rm acc} \ll \tau_{\rm KH}$: the star evolves toward higher effective temperatures to reach the Hayashi tracks corresponding to its mass

- Low accretion rates



Effects are small because $L_{\rm acc} \ll L_*$. In this case $\tau_{\rm acc} \gg \tau_{\rm KH}$ and the star follows its Hayashi tracks

Accreting PMS tracks



- Mass determination from accreting tracks
  - As long as the star remains on its Hayashi line, the mass determination is relatively accurate with $\frac{\Delta M}{M} \lesssim 5\,\%$
- Age determination from accreting tracks

  The age determination is more problematic because of the origin of times
  - on their Hayashi tracks, **accreting stars will appear older than they are**. The disparity in the age estimates depends on **the initial state of the star** and of the **accretion history**.
  - on the radiative tracks, **the age of accreting models can be underestimated** as a result of structural readjustments.

  In any case, the determination of ages is relatively **uncertain before 5 Myr**

Conclusion

→ Mass and age determination remain relatively uncertain for VLMS because of the large sensitivity to $\Delta T_{\rm eff}$ and to the accretion effects

→ Below 3-5 Myr, the disparities in ages can be large within a factor of 2-3

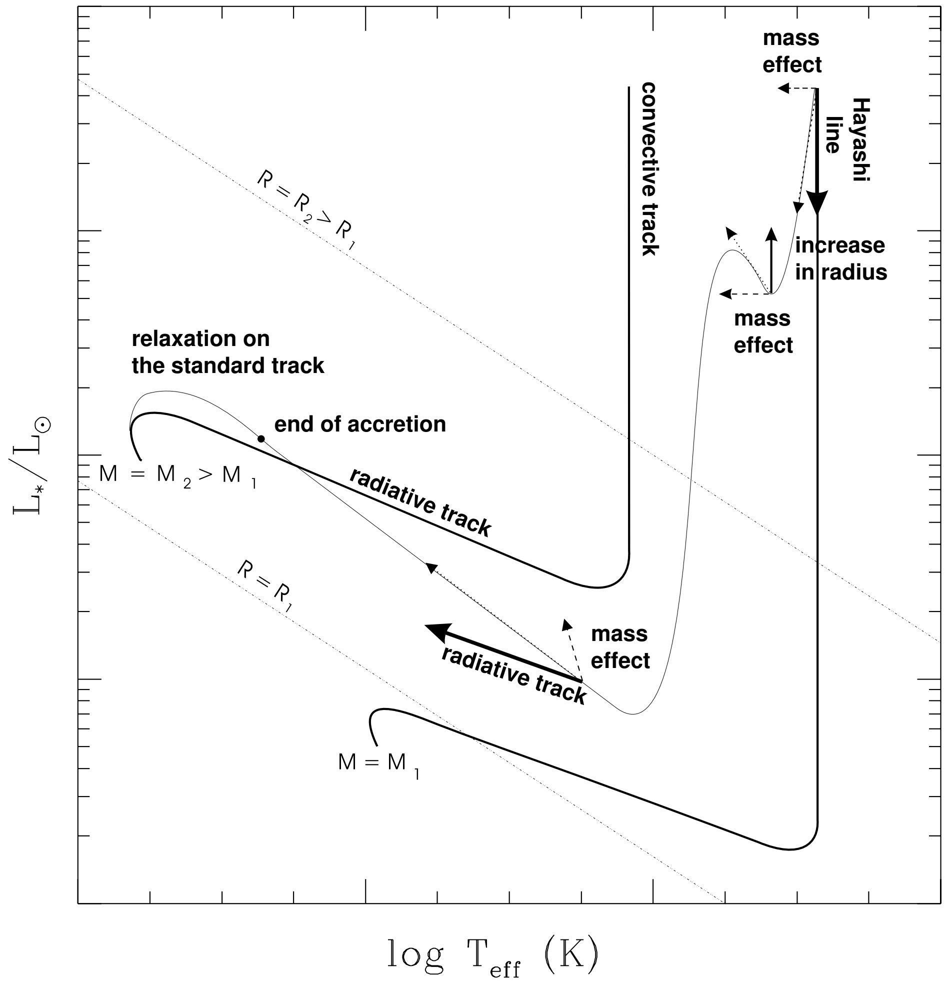
Improving the modeling

- Atmosphere : The computation of inhomogeneous atmosphere, due to the presence of spots (magnetic fields) can modify the position of the star in the HRD
- Convection : Probably the most critical physical ingredient of a stellar evolution code : Why should α be kept constant over the entire evolution and be the same for all stellar masses ?
- Rotation : Needs for a 2D stellar evolution code. A better treatment of rotation will also require a better knowledge of the evolution of the angular momentum
- Accretion : The treatment of accretion also requires 2D simulations
- Constraints : the determination of stellar radii and mass from binary systems can bring strong constraints on PMS stellar models

Improving the mass and age determination

- Accurate **conversion tables** between colors and $T_{\rm eff}$ must be computed from atmosphere models
- A good estimate of the **metallicity** is necessary to derive reliable stellar parameters

Effects of accretion on the PMS tracks



- contraction until deuterium ignites
- burning of the accreted ^{2}H $\rightarrow$ the nuclear luminosity ($L_{\rm nuc} \propto \dot{\rm M}_{\rm acc}$) increases if $L_{\rm nuc} > L_*$, the star expands during its Hayashi phase
- when a thermal equilibrium is reached ($L_* \approx L_{\rm nuc}$), the contraction resumes
- a radiative core develops and due to mass addition, the evolutionary path is "more inclined"

  $\rightarrow$ effects on the age determination mainly
- end of accretion and relaxation of the star