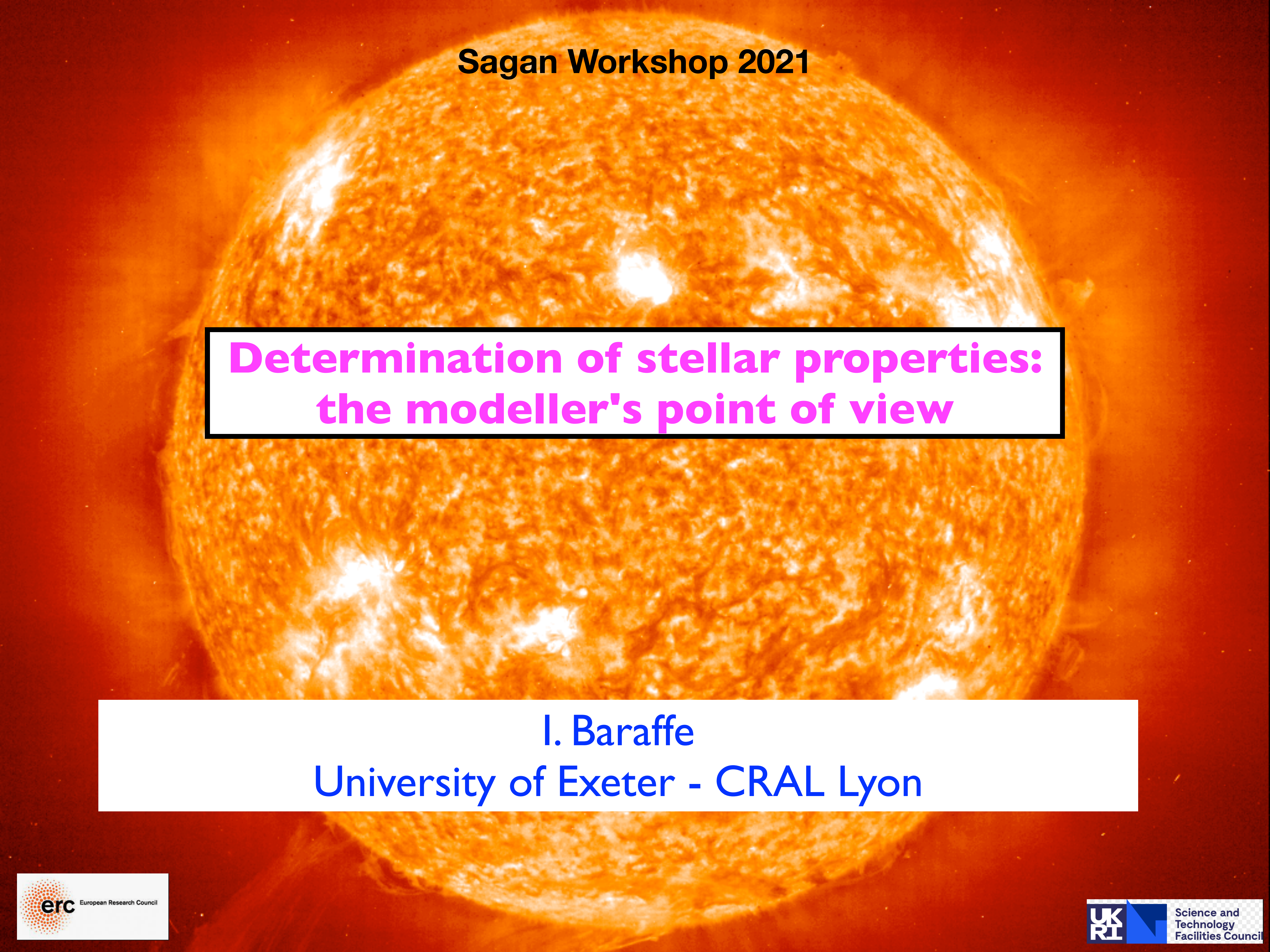

Sagan Workshop 2021

Determination of stellar properties: the modeller's point of view

I. Baraffe
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0) Why do we need stellar models?

I) Basic ingredients for standard stellar models

II) Evolution at very young ages

III) Rotation and magnetic fields

IV) Atmosphere models: a particular challenge

Definitions

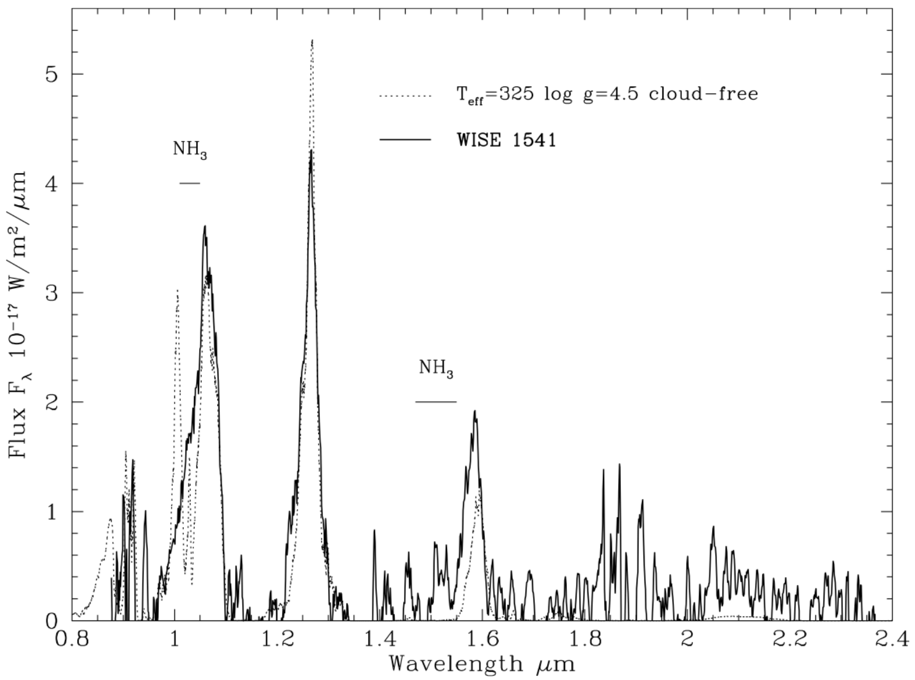
- Stars: $0.07\ M_\odot \rightarrow$ a few $100\ M_\odot$
  - Formation via gravitational collapse of a molecular cloud
  - Different phases of nuclear burning (H, He, C, etc..)
- Brown dwarf: a few $M_J \rightarrow\ \sim 0.07\ M_\odot$
  - most likely form like stars
  - maximum mass: limit for H burning ($T_{central} < 3\ 10^6$ K)
- Planets: $\sim 10\ M_\oplus \rightarrow$ a few M_J
  - Formation in a protoplanetary disk

IAU definition: objects with mass below the deuterium burning minimum mass $M_D=12\ M_J$ *(*$T_{central} < 10^6$ *K)* ☛ **arbitrary**

Why do we need stellar models?

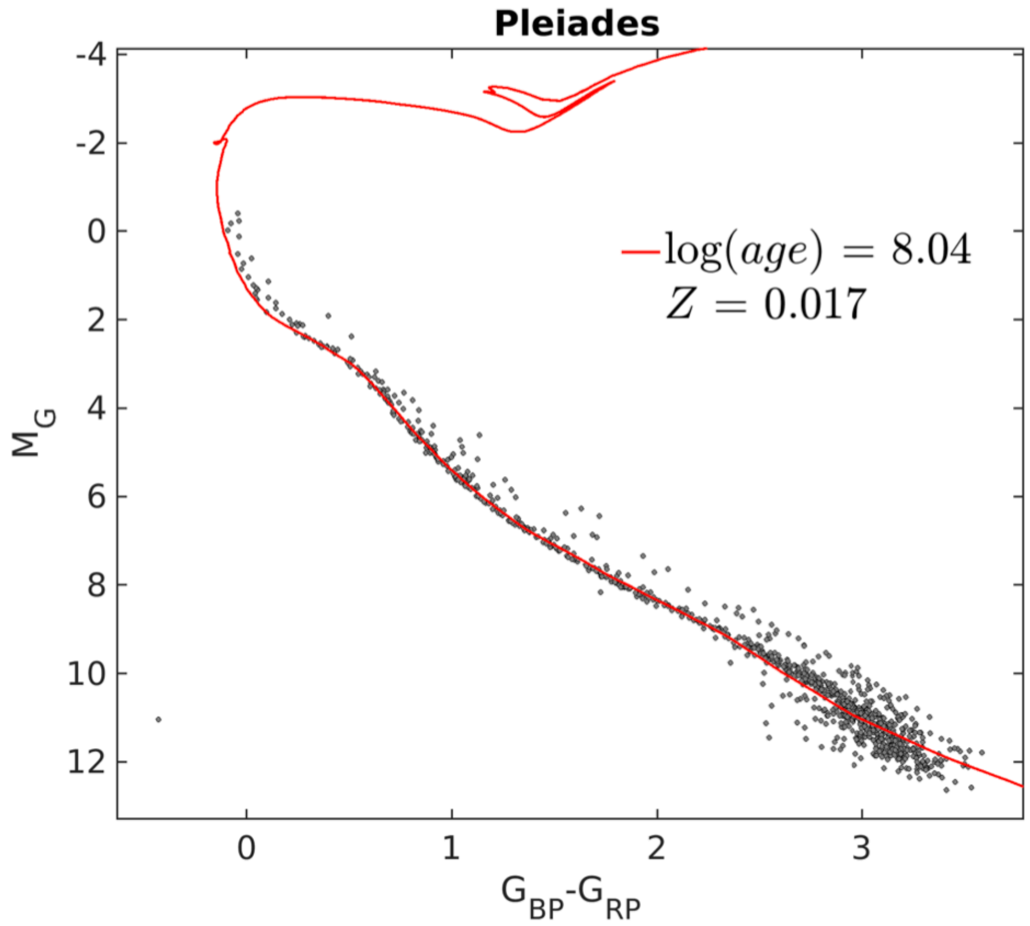
Need models to interpret observations and determine fundamental properties: mass, radius, age, distance, chemical composition

Observed spectra



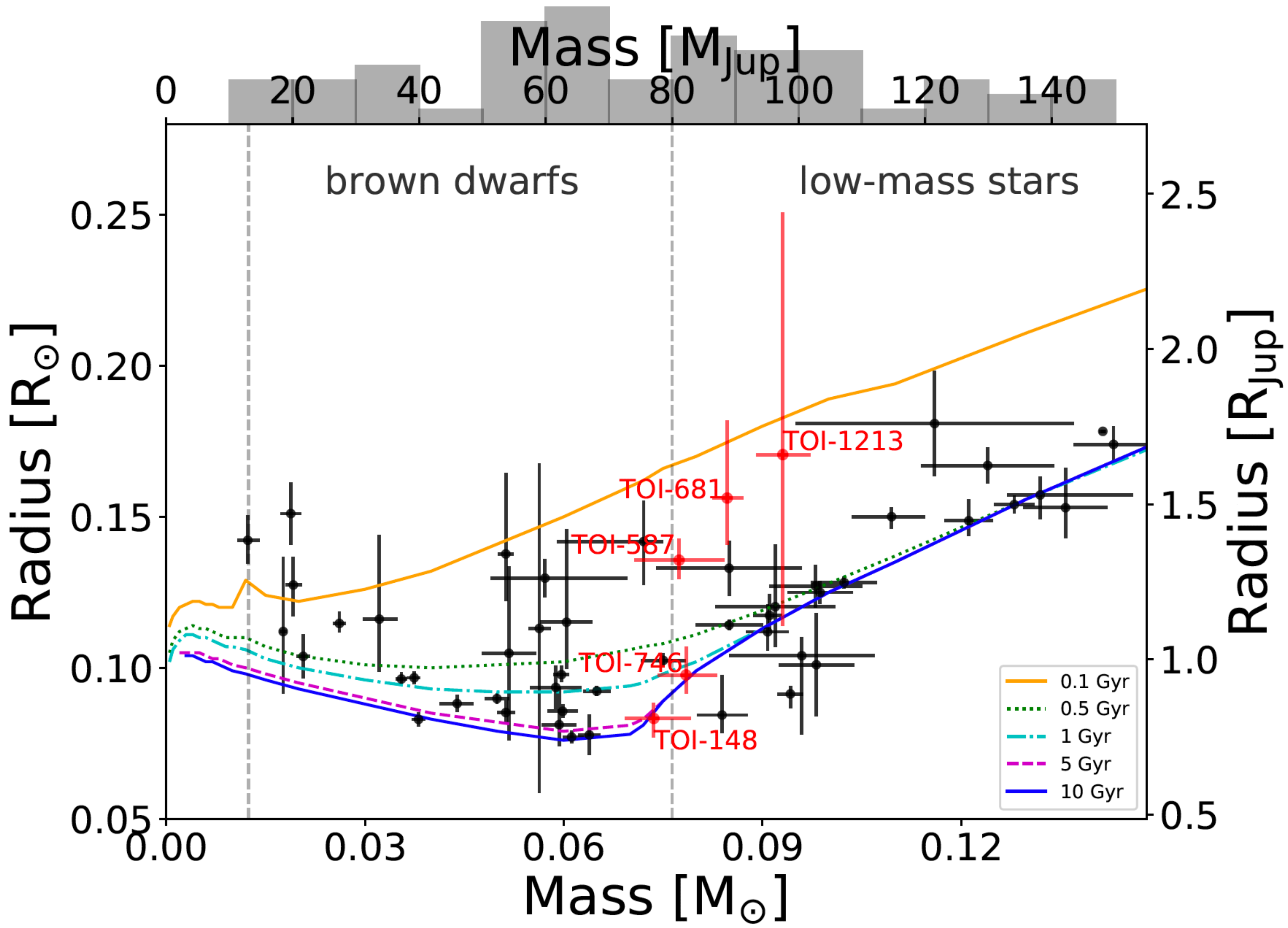
☛ Synthetic spectra provide T_{eff} and gravity g

Color-magnitude diagrams

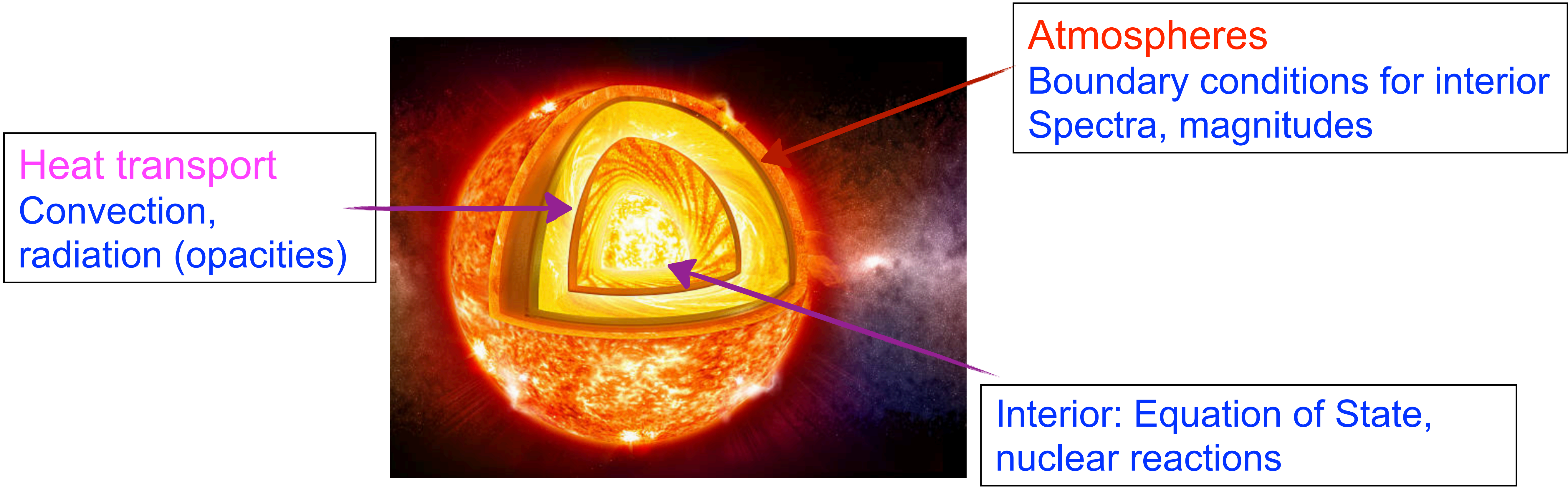


☛ evolutionary models can provide masses and/or ages

Mass-radius relationship



I) Basic ingredients for standard stellar models



Heat transport
Convection,
radiation (opacities)

Atmospheres
Boundary conditions for interior
Spectra, magnitudes

Interior: Equation of State,
nuclear reactions

- Interior structure models

  - **Equation of state** (EOS): thermodynamic properties of main components (H, He, metals Z)
  The EOS is crucial and determines the mechanical structure of an astrophysical body, i.e the M-R relationship

  → Significant progress regarding the EOS for brown dwarfs and giant planets (strong departure from ideal gas *Chabrier and Baraffe 2000, ARAA*)

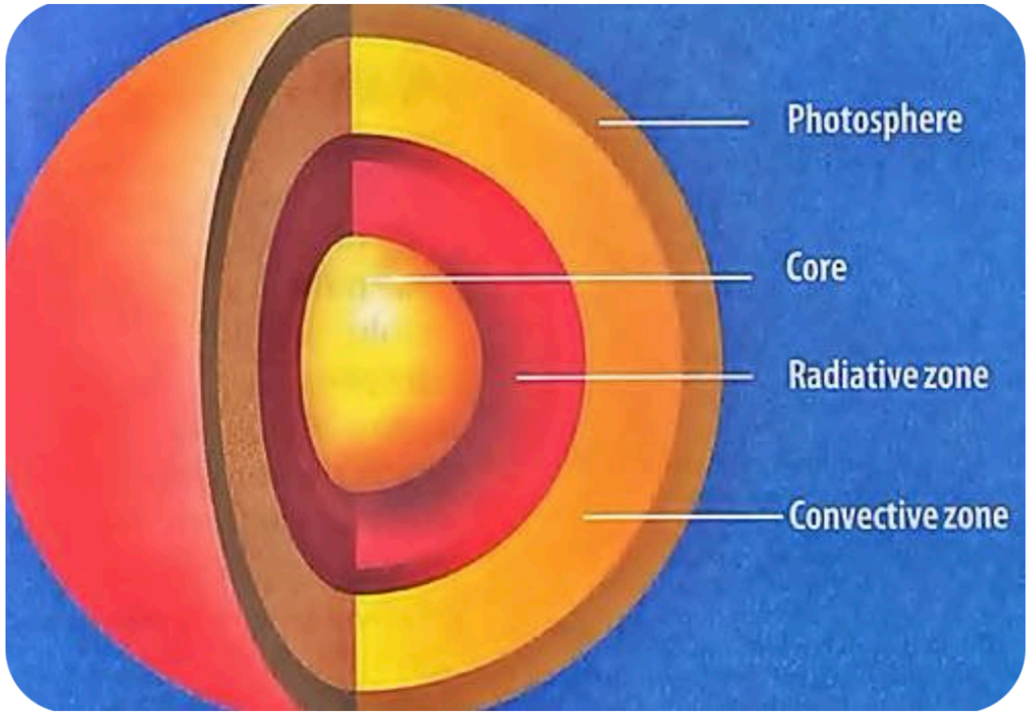
  - **Convection:** described by the Mixing Length Theory (MLT)
  Provide a good description of global heat flux as long as no rotation/magnetic field (see later)

  - **Radiation:** diffusion approximation valid as mean free path of photons << R

$$\mathbf{F_{rad} = - \varkappa \nabla T}$$

radiative conductivity $\varkappa \sim 1/\kappa$ κ opacity of matter

- Atmosphere models



- **Photosphere**: Tiny region (in mass and radius) at the surface where photons escape → optically thin region where diffusion approximation is not valid anymore
  → **modelling decoupled from inner structure calculation**

→ Solve the radiative transfer equation (in 1D i.e plane parallel geometry)
  - Equation of state: perfect gaz
  - Wavelength dependent opacities

Atmosphere models provide the outer boundary to interior structure + synthetic spectra + photometry

- Evolutionary models: combine interior **structure models** and **atmosphere models**

$\downarrow$ $\downarrow$

(M,R) **(T_{eff}, $g=GM/R^2$)**

Profile T(r), ρ(r) **$L = 4\pi R^2 \sigma T_{eff}^4$**

☛**Evolution characterised by nuclear energy production and release of <u>gravitational</u> and <u>internal energy</u> at the rate imposed by L**

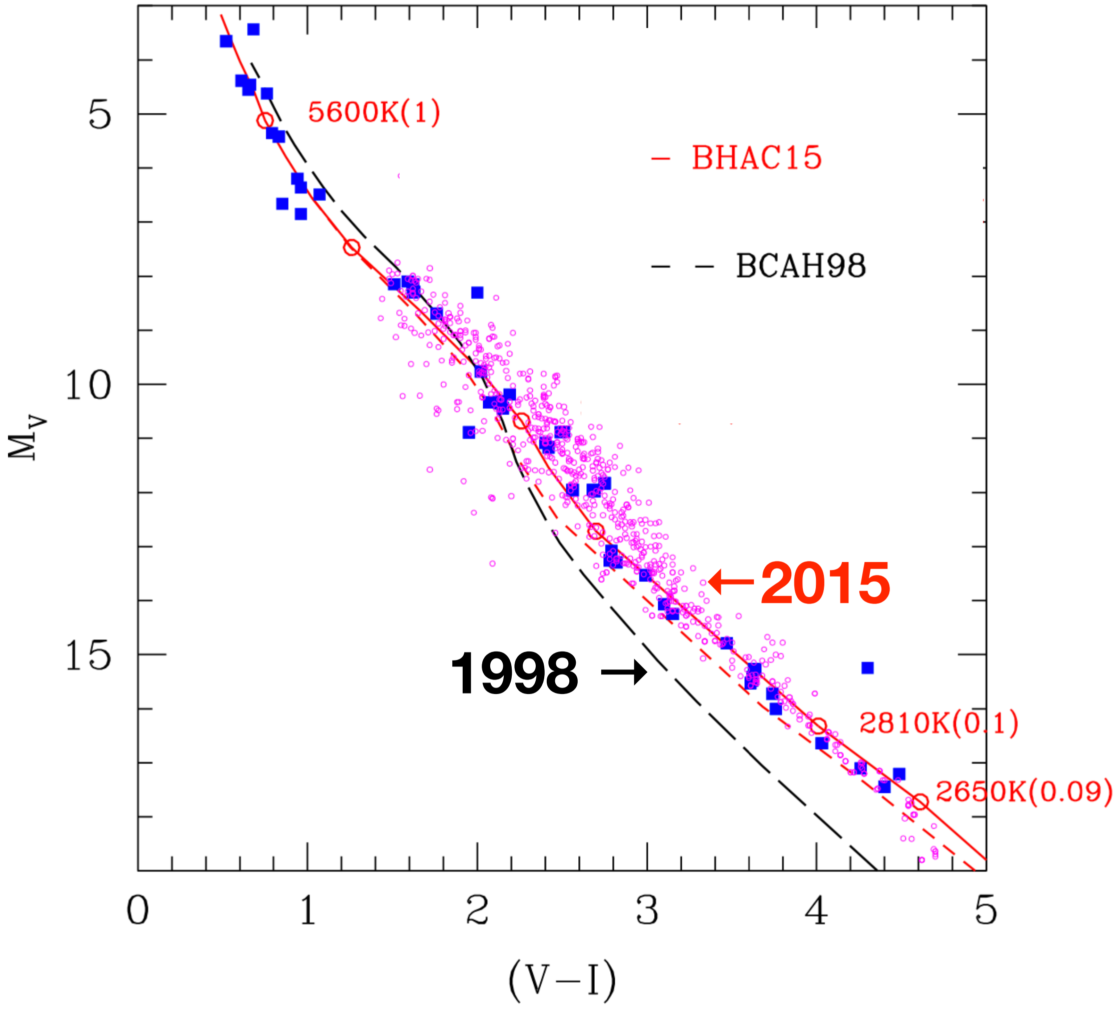
$$L(t) = \boxed{\int_M \epsilon_r} - \boxed{\int_M P \frac{d}{dt}\frac{1}{\rho} dm} - \boxed{\int_M \frac{de}{dt} dm}$$

Evolutionary models provide L(t), R(t), etc...

Huge progress within the past decades:

- Equation of state for H and He
- Molecular opacities (T < 4000 K): H_2, H_2O,TiO, CO, CH_4, NH_3
- Treatment of convective transport in atmopsheres (optically thin medium)

☛ more reliable models and successful comparisons with observations

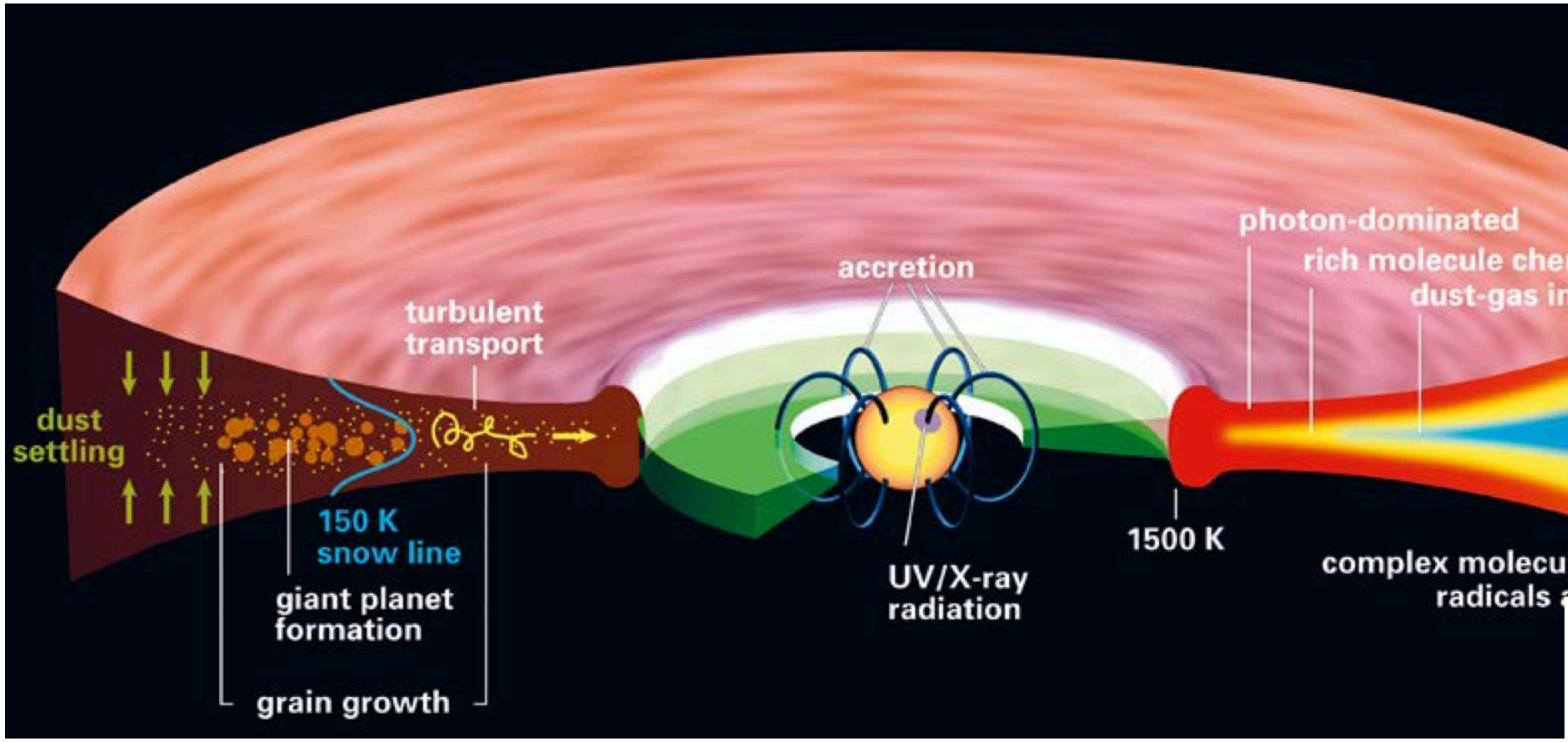


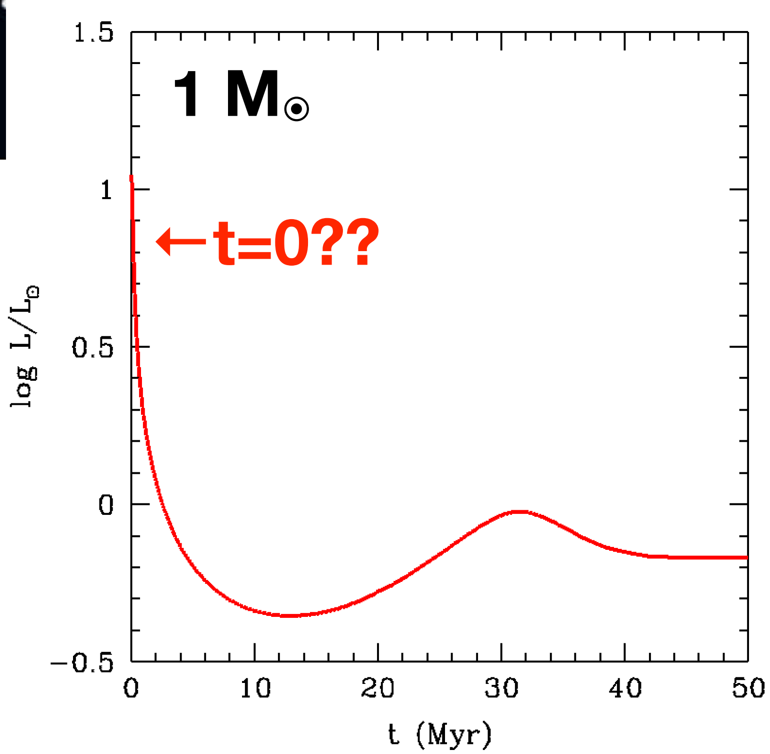
But there are still remaining uncertainties: going beyond standard models

II) Evolution at very young ages: initial conditions

- Ages < 10 Myr, stellar models needed for **age** determination
  → important for the study of **protoplanetary disks** and **planet formation**

→ Ideally early evolution should account for the star formation process: accretion process from a disk





→ What is t=0 for stellar models?? Difficult question....

Modellers have two approaches:

1) Arbitrary initial conditions (no history of star formation process)

Start from very bright and large configurations such that the thermal timescale τ_{kh} is very short (< 1 Myr)

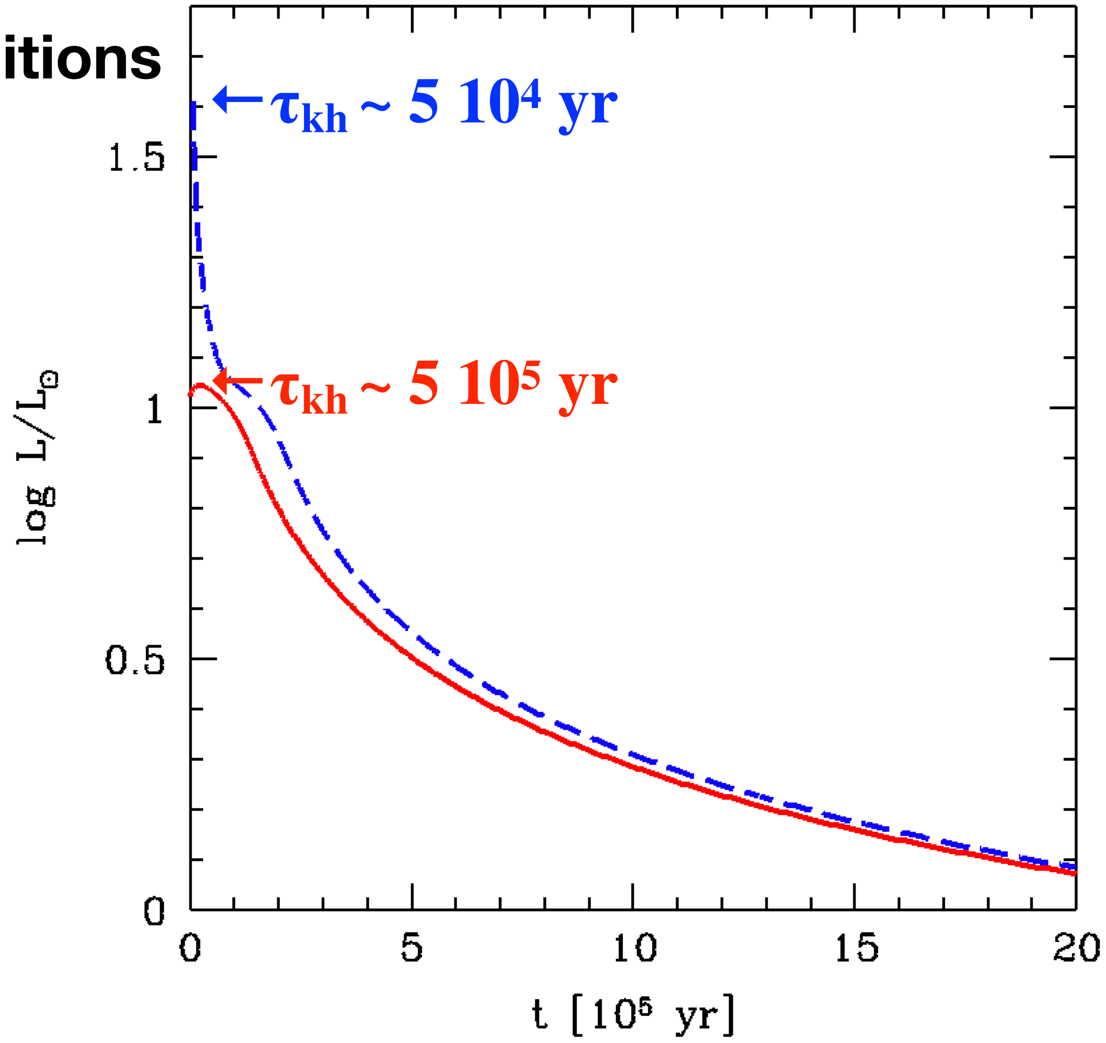
Thermal (or Kelvin-Helmholtz) timescale: $\tau_{kh} \sim G M^2/(RL)$

Characteristic timescale for a star to contract and radiate all its thermal energy

Or characteristic timescale for a star to adjust to a thermal perturbation

After a few τ_{kh} the model forgets its initial conditions

1 $M_\odot$



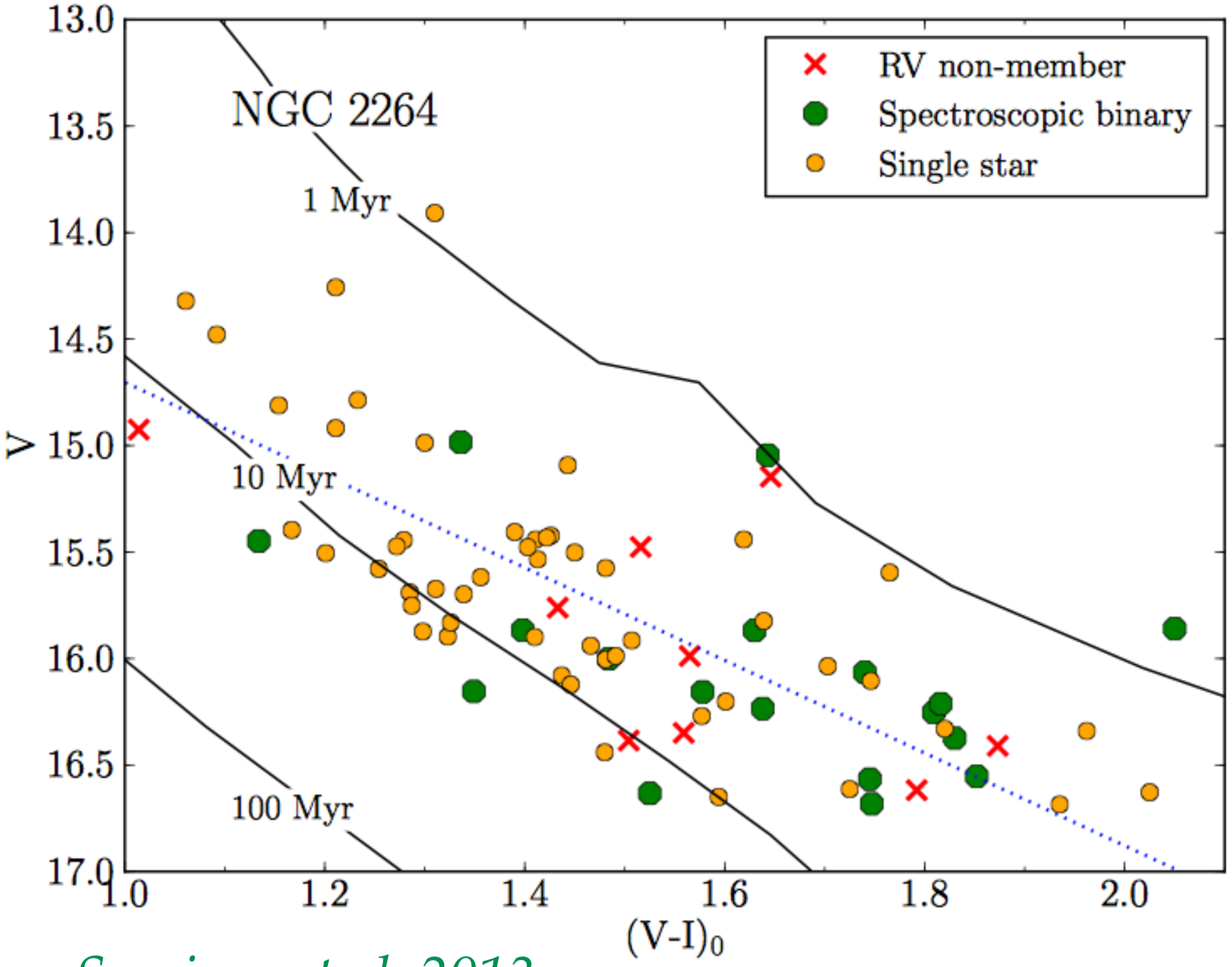
← $\tau_{kh} \sim 5\ 10^4$ yr

← $\tau_{kh} \sim 5\ 10^5$ yr

→ Convenient but unrealistic at ages ≤ 1 Myr

2) Account for accretion (i.e some history of the star formation process)

☛ Motivated to explain a well known puzzle in the field: spread in Teff-L or Color-Magnitude diagrams of young cluster members (1-10 Myr)



Sergison et al. 2013

➡Age spread?

➡Or effect of accretion?

➝ **Accretion at early stages of evolution** can affect the evolution **even after a few Myr** and partly produce the observed HRD spread *(Hartmann et al. 2007; Baraffe et al. 2009, 2010, 2012, 2017; Hosokawa et al. 2011; Kunimoto et al. 2017; Jensen & Haugbolle 2018)*

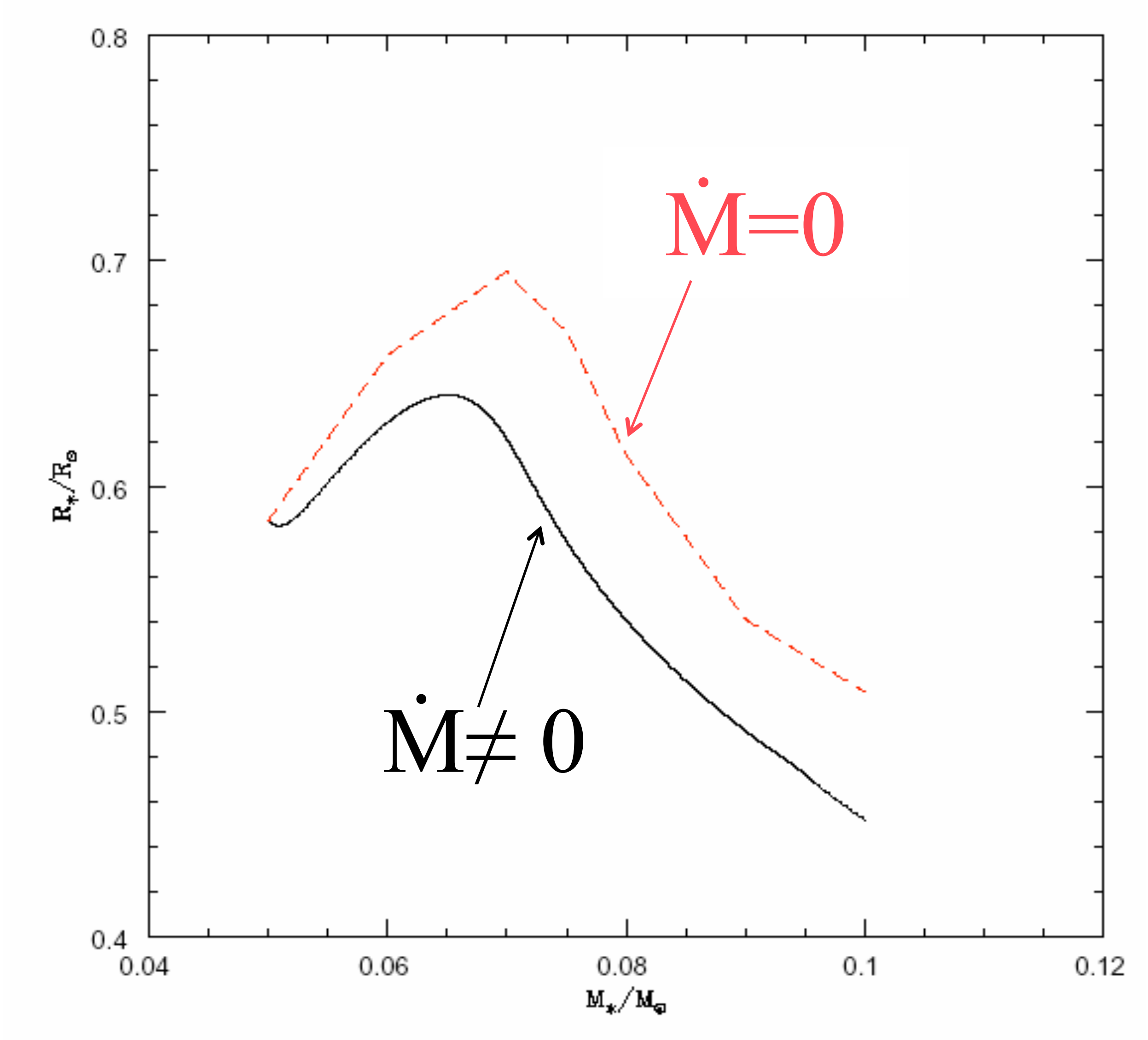
Two major uncertainties:

1) The accretion rate $\dot{M}(t)$ --> depends on star formation model

accreting object contracts faster

structure more compressed than non accreting counterpart

Structure affected if: τ_{acc} **(=M/$\dot{M}$) <<** τ_{kh} **(GM²/RL)**



Agreement between modellers

2) Amount of internal energy accreted $\alpha GM\dot{M}/R$ -> depends on star formation model, on the mass transfer in the accretion disk and the boundary layer disk-protostar

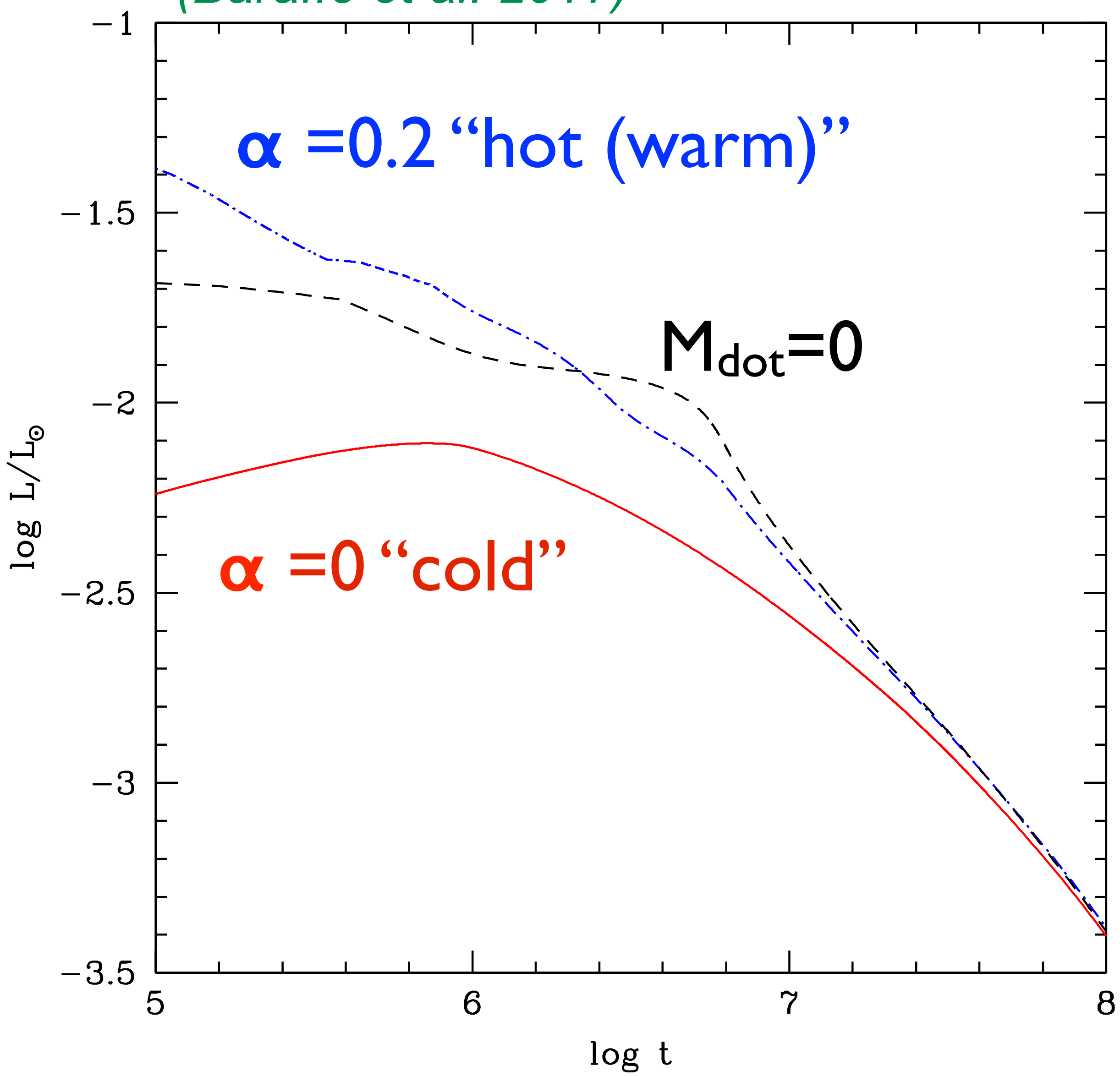
$0 \le \alpha < 1$ free parameter in models

α ≠0 : including accretion energy absorption → less compact structure than with α=0

☛ Accretion can produce young objects with a range of initial luminosities, **depending on M_{dot} and α:**

Brown dwarf of final mass M=0.04 $M_\odot$

(Baraffe et al. 2017)

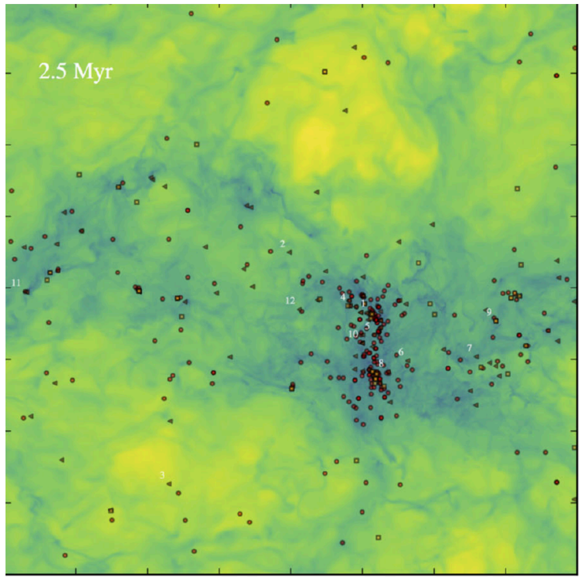


→ Increasing efforts to provide a consistent picture: molecular cloud → prestellar core & disk formation → disk evolution → protostar evolution

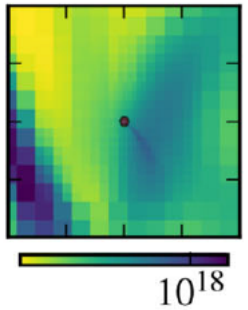
(Baraffe et al. 2012, 2017; Jensen & Haugbolle 2018)

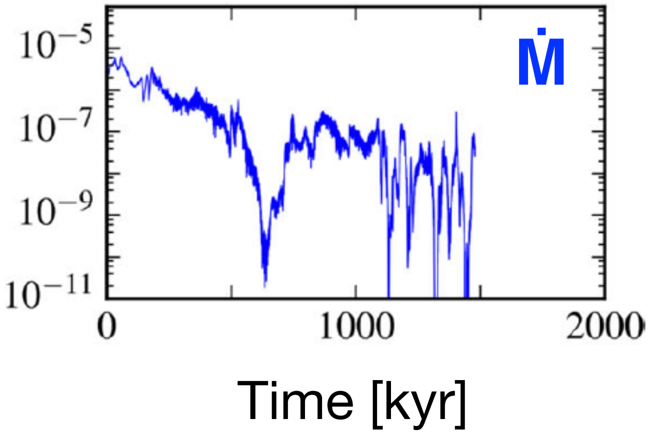
Jensen & Haugbolle 2018

Star formation in a molecular cloud

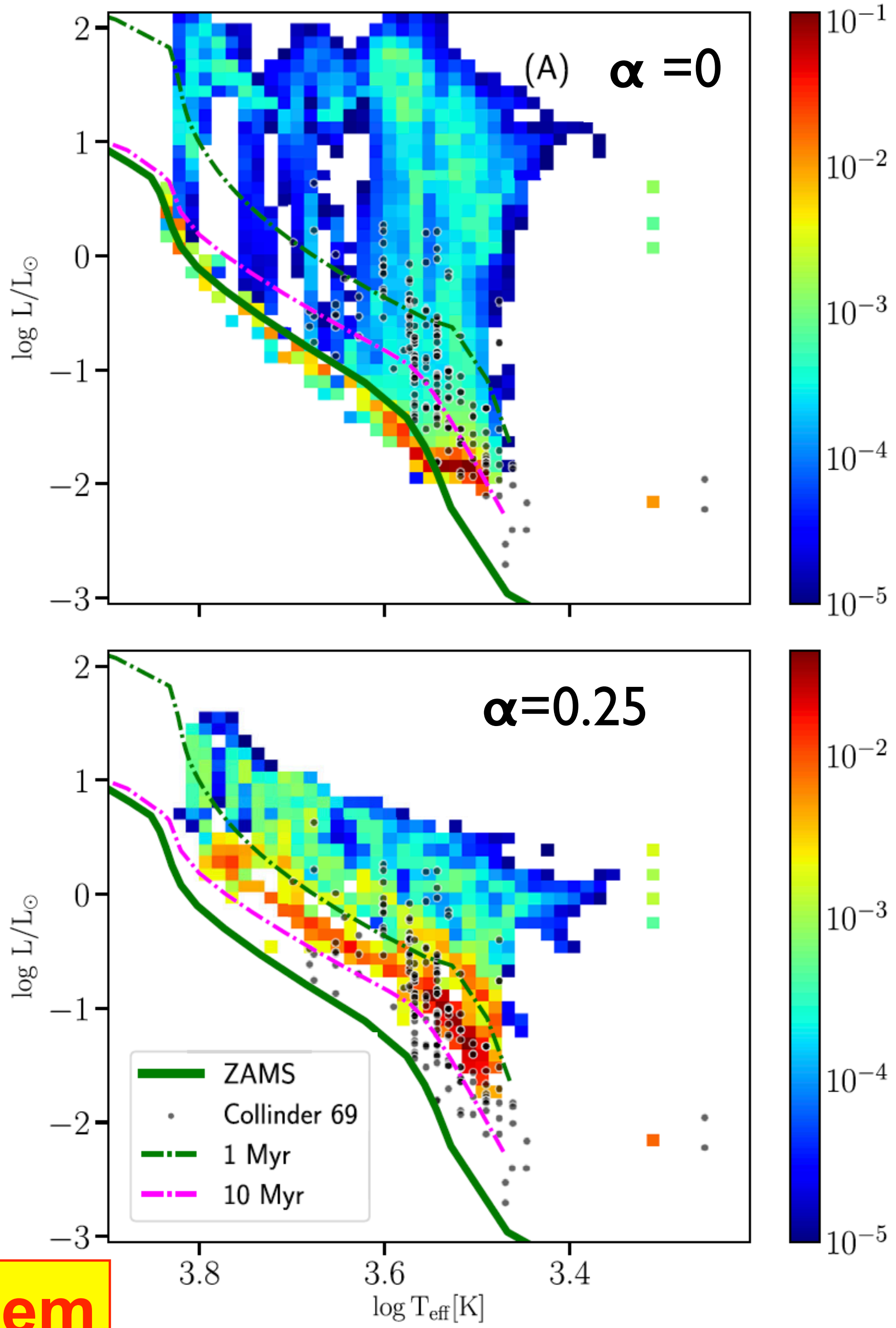


pre-stellar core





Synthetic cluster of young stars



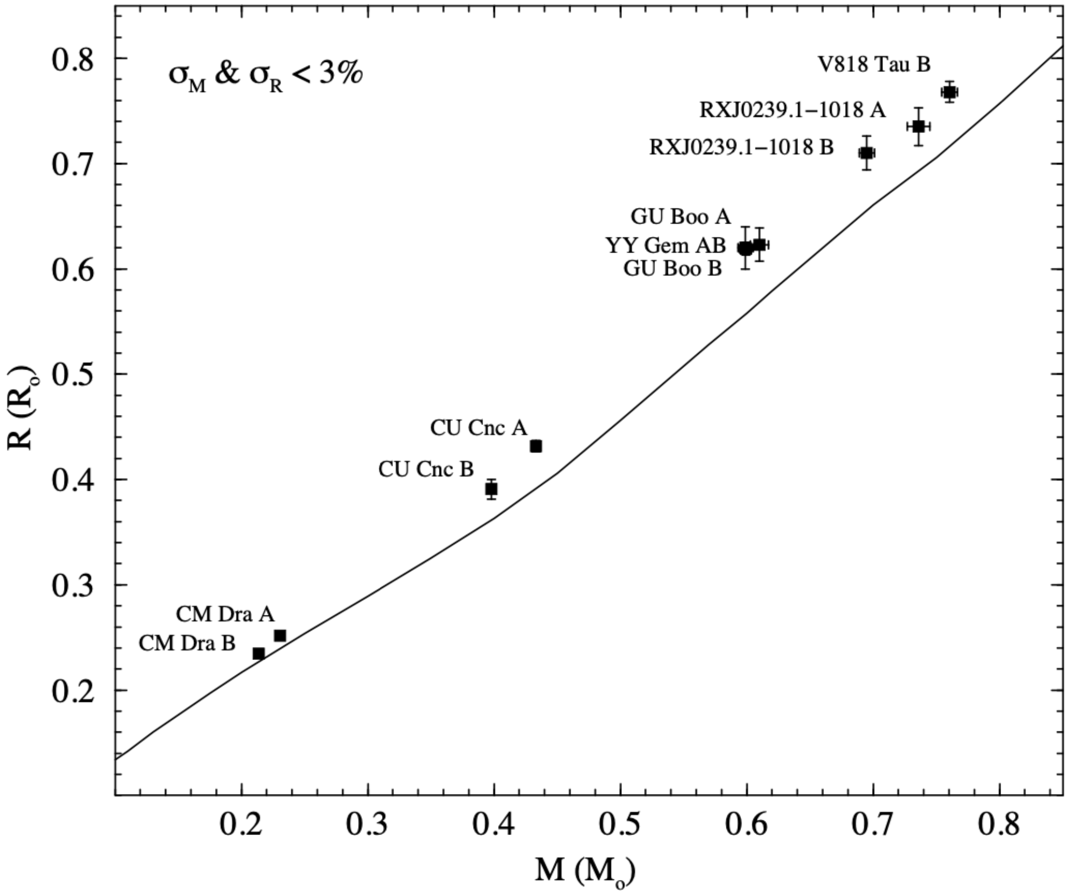
☛ This is a challenging (and exciting) problem

III) Impact of rotation and magnetic fields

From 2000, huge activity to study the effect of **rotation/magnetic** fields on the inner structure of fully convective objects (VLMs and BDs)

☛ Problem driven by key observations:

- Link between magnetic activity and **abnormally large radius** of low mass stars in eclipsing binaries



Eclipsing binaries (fast rotators
And magnetically active)

(Ribas et al. 2006)

- Similar effect on R in single magnetically active late type stars (*Morales et al. 2008)*

☛ Theoretical interpretation:

Strong magnetic fields

(i) suppress or reduce the efficiency of interior convection *(Mullan & MacDonald 2001; Chabrier et al. 2007; Feiden & Chaboyer 2012; Feiden 2016)*

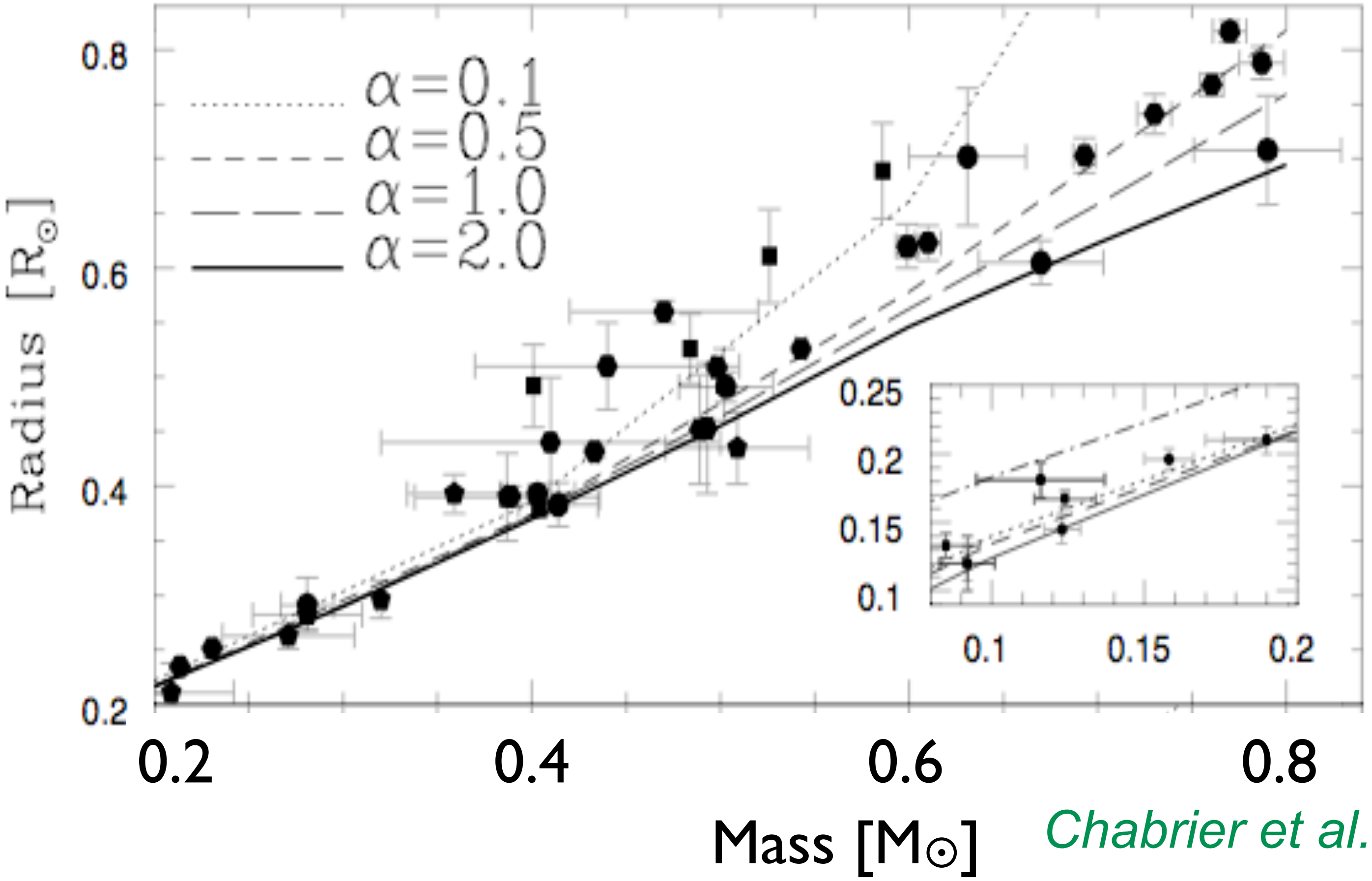
(ii) produce cool surface spots *(Chabrier et al. 2007; Somers & Pinsonneault 2015)*

(i) and/or (ii) ⇒ reduced heat flux ⇒ larger radii and cooler T_{eff}

Phenomenological approach:

(1) Reduced convection efficiency can be **mimicked** by decreasing the mixing length parameter α

$\alpha = l_{mix}/H_P$ (=2 for the Sun)



Chabrier et al. 2007

(2) Effect of spots

- fraction of stellar surface covered by spots $\beta = S_{spots}/S_\star$

-Total flux of the star F:

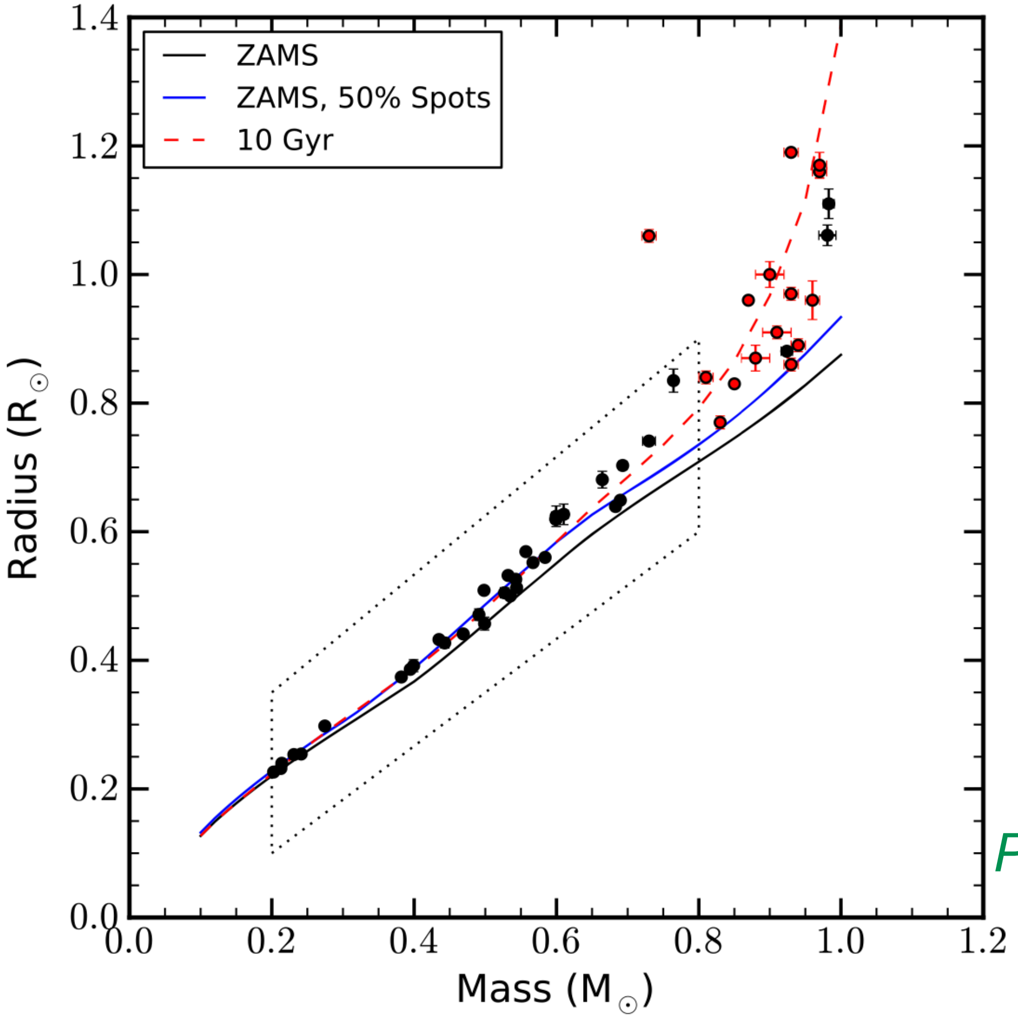
$$F = (1-\beta)\, F_\star + F_{spots}$$

where

$F_\star = \sigma T^4_{eff\star}$ (flux of spot-free star)

F_{spots}= total flux emerging from spots

Cool spots coverage ⇒ $T_{eff} < T_{eff\star}$

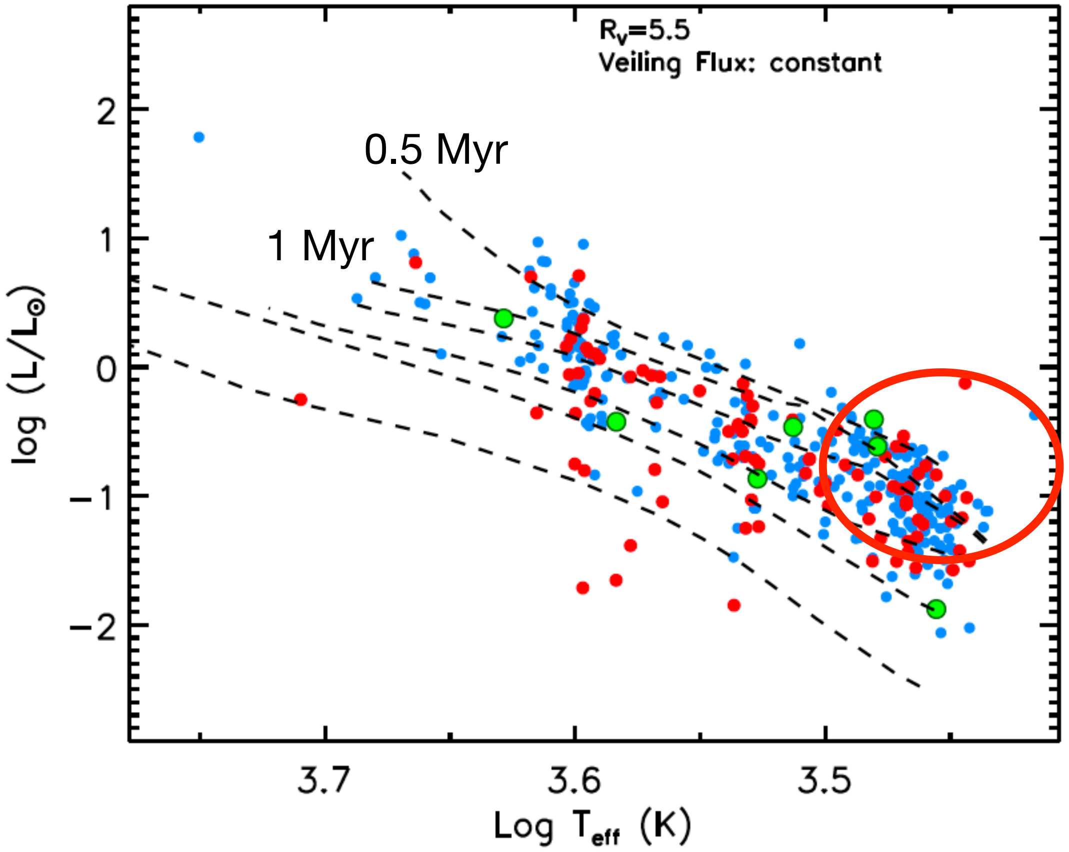


Somers & Pinsonneault 2015

☛ Should we use non standard models?

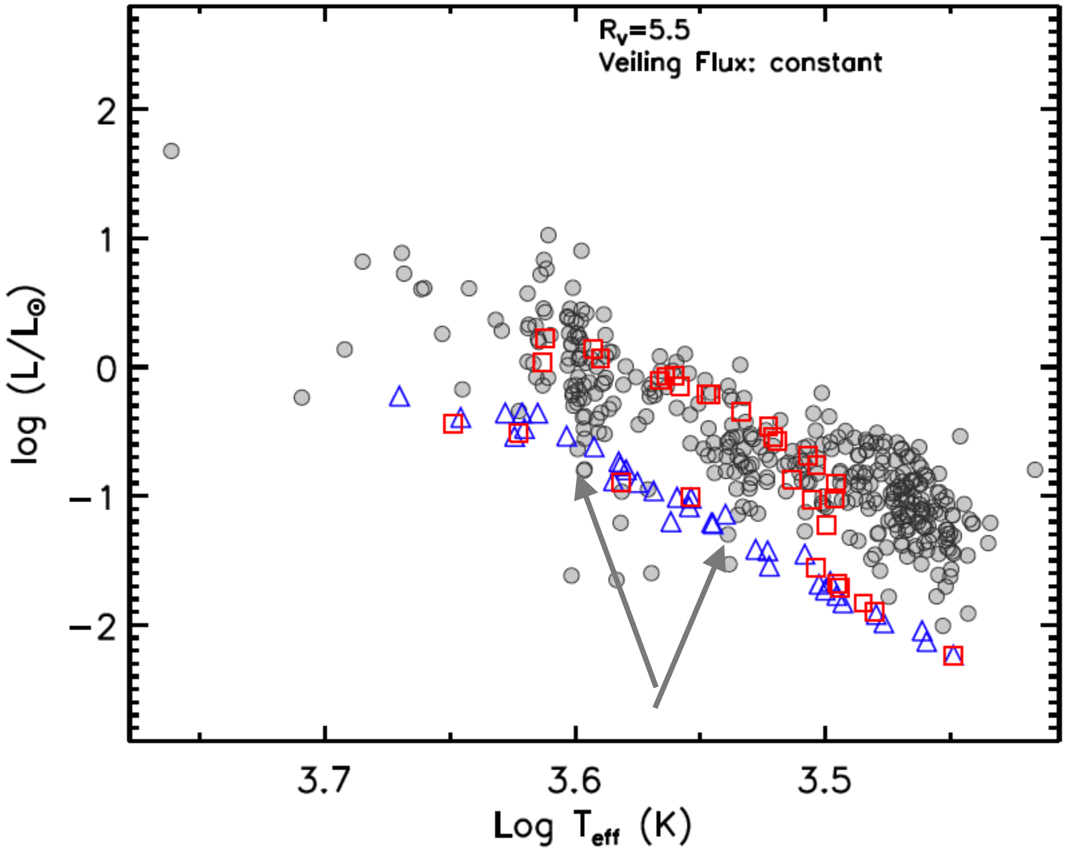
Analysis of the young Orion Trapezium cluster *(Fang et al. 2021, ApJ 908)*

Models with magnetic field *(Feiden 2016)*



→ can better explain *over-luminous* (too cool) low-mass young stars

Models with accretion *(Baraffe et al. 2017)*



→ can explain abnormally faint objects (or high-inclination disks)

☛ But be aware that 1D stellar evolution models rely on phenomenological prescription of 3D effects that still need to be validated.

IV) Atmosphere models: a particular challenge

☛ An uncertainty of particular relevance for the characterisation of young planets (or brown dwarfs...):

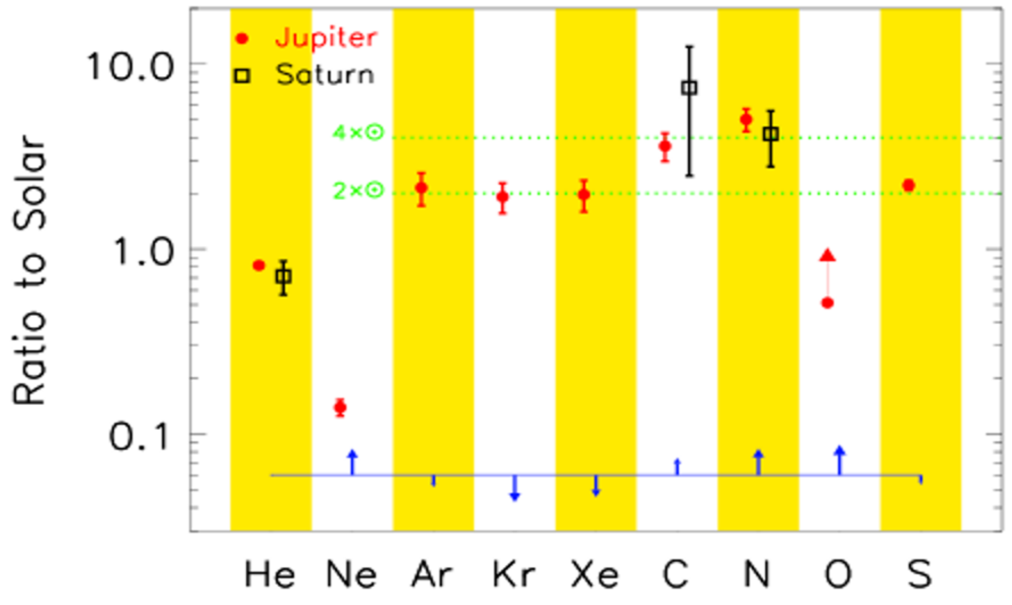
Metallicity versus non equilibrium chemistry

The idea: Measurement of **non solar abundance ratio** in the atmosphere of a young planetary mass object could indicate the formation process (e.g formation in a protoplanetary disk versus stellar-like formation)

Giant planet atmospheres are expected to be **enriched in heavy elements**, as observed in Jupiter and Saturn (inherited during planetesimal accretion as the planet formed):

- **Jupiter:** in situ measurement from Galileo enrichment by a factor 2-4

- **Saturn**:
spectroscopic determination
C (CH4) and N (NH_3)
significantly enriched



Guillot 2005

☛ The question: is it straightforward to measure the metallicity (or abundance ratio)?

No because of non equilibrium chemistry processes

→ if some chemical reactions are very slow → vertical transport via convective motions can lead to departure from equilibrium

Mechanism suggested to operate in Jupiter in 1997 (Prinn & Barshay) and a prevalent feature observed in brown dwarfs (Noll et al. 1997; Griffith & Yelle 1999; Saumon et al. 2000; Geballe et al. 2009; Leggett et al. 2017, Brittany et al. 2020)

Non equilibrium carbon chemistry:

main reaction $CO + 3H_2 \leftrightarrow CH_4 + H_2O$

Below ~ 2000 K, CH_4 becomes the dominant form of C

Transformation CO → CH_4 much slower than inverse reaction

if $t_{mix} << t_{CO \rightarrow CH4}$ $\Longrightarrow$ abundance of CO much larger than predictions based on **local equilibrium chemistry** standard assumption

→ existence of this process confirmed by the detection of large abundances of CO in the atmosphere of a cool brown dwarf GL 229b (T_{eff} ~ 1000 K)

- **Non equilibrium nitrogen chemistry**:

  Same process expected for N: $N_2 + 3H_2 \leftrightarrow 2NH_3$

  Reaction $N_2 \rightarrow NH_3$ much slower than inverse reaction

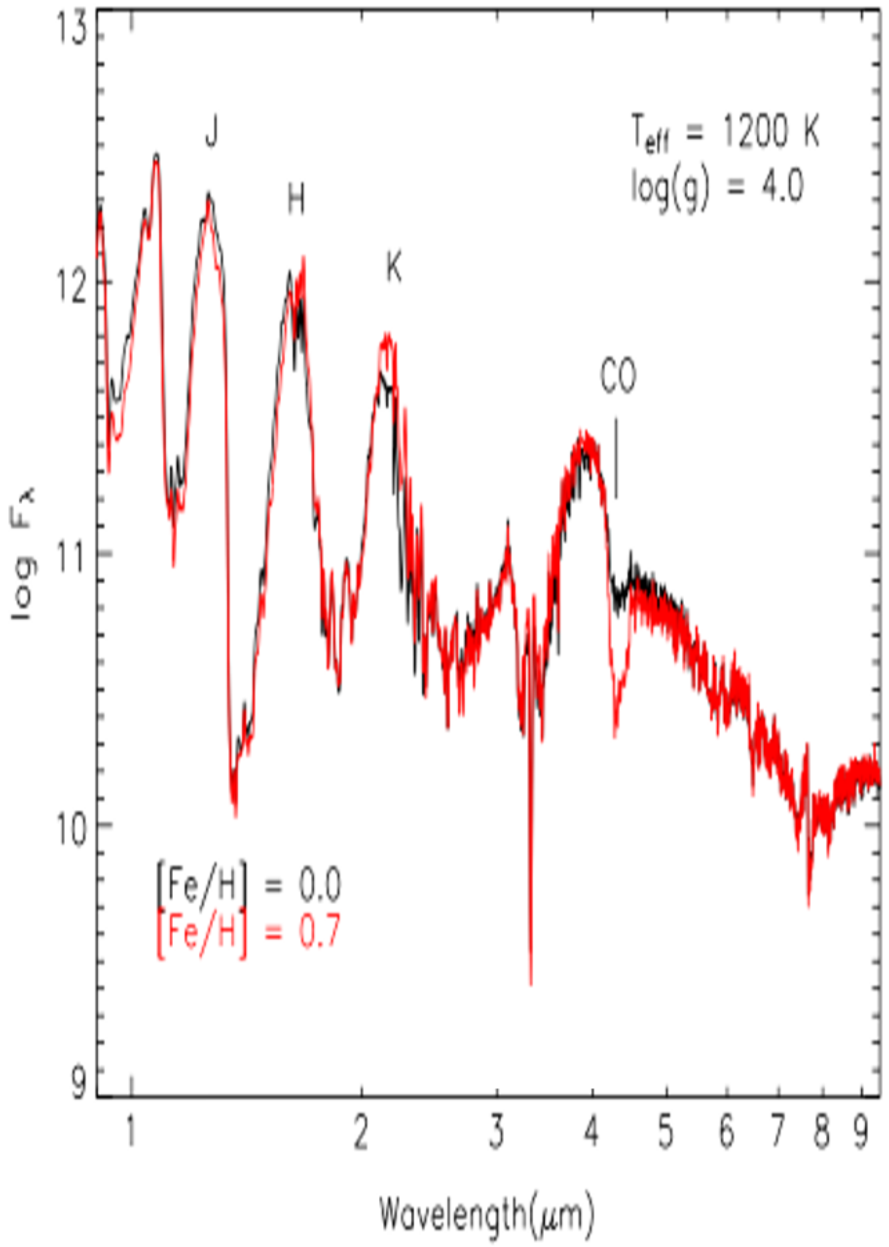
Vertical mixing in atmosphere models is parametrised with the parameter K_{zz}:

$$\tau_{mix} \sim 1/K_{zz}$$

Poor constraints on the eddy diffusion coefficient K_{zz} (10^4 - 10^9 cm^2 s^{-1})

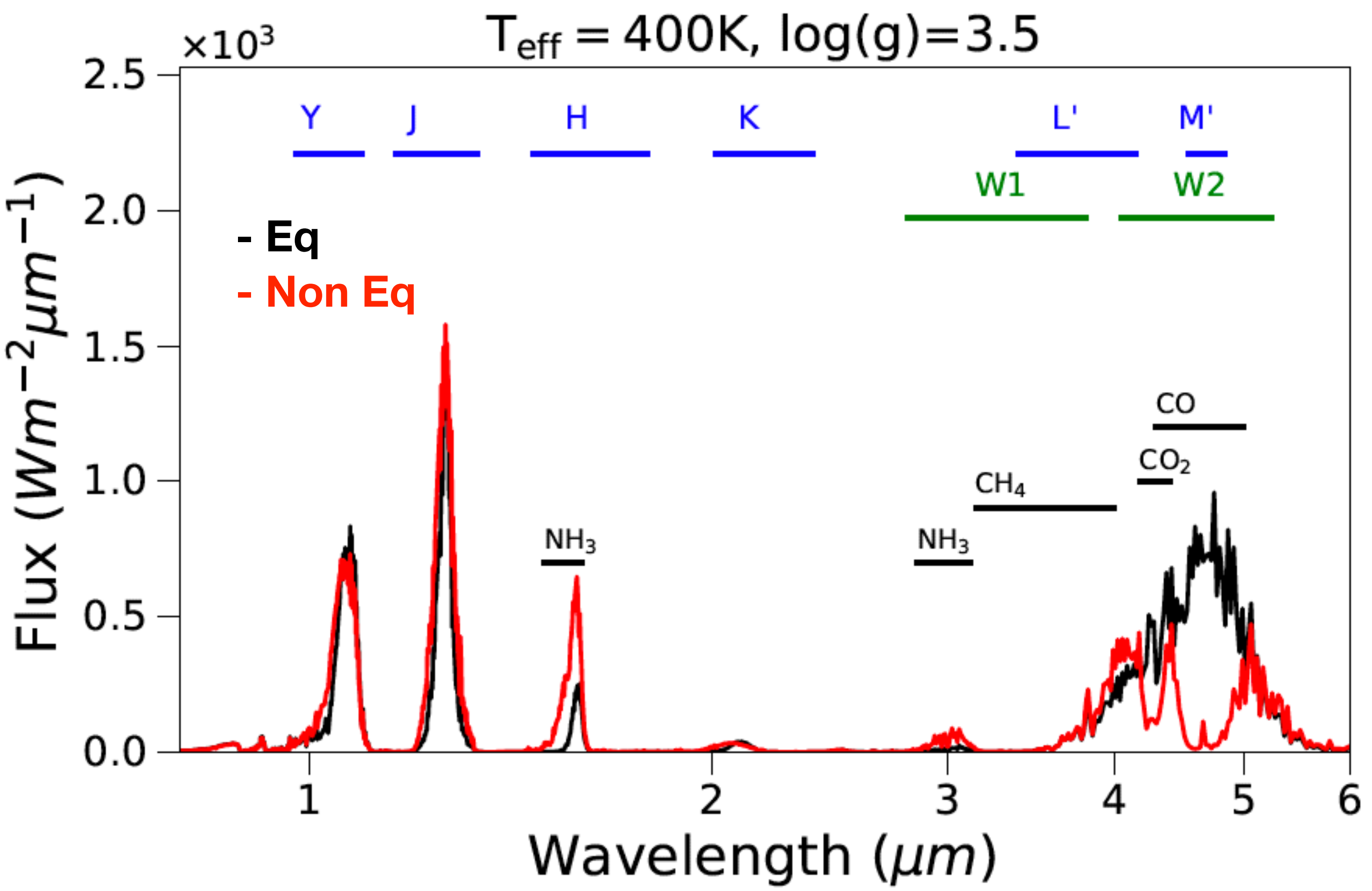
Non equilibrium chemistry could mimic the signature of non solar metallicity

Effect of an increase of metallicity (factor 5)



Barman et al. 2006; Chabrier et al. 2007

Effect of non equilibrium chemistry



Phillips et al. 2020

☛ **Still need to find the best diagnostics to disentangle non equilibrium chemistry versus metallicity effects** *(Marley, Saumon et al.; Phillips,Tremblin et al. etc...)*

Conclusions

- **Uncertainties of stellar models at very young ages: a reality**

  - **Effect of accretion:**
    - **Models:** Further efforts to build a consistent picture molecular cloud collapse → disk evolution → early protostar evolution

  - **Non standard physics (rotation/magnetism):**
    - **Models:** Validation of formalisms from 3D MHD simulations are necessary *(sustained efforts from the stellar MHD community)*

  - **Obervations:** Key to gather multiple information: spectra, magnitudes, activity, rotation lithium abundances, cluster membership, etc...

- **Atmospheric signatures of formation process**

  - **Models:** - Key to find the sweet spots to distinguish metallicity versus non equilibrium chemistry effects
    - Provide constraints on K_{zz} from hydrodynamics simulations

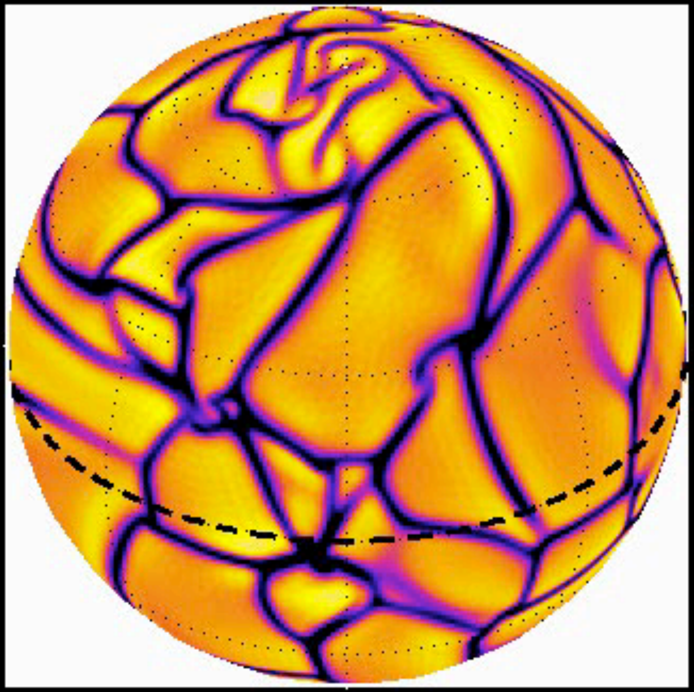
Effect of rotation/magnetic field: The way to go

3D HD simulations: Rotation of fully convective objects

Radial velocity Vr on a surface near the top of a simulation of a slowly rotating M-dwarf.

Up flows are reddish

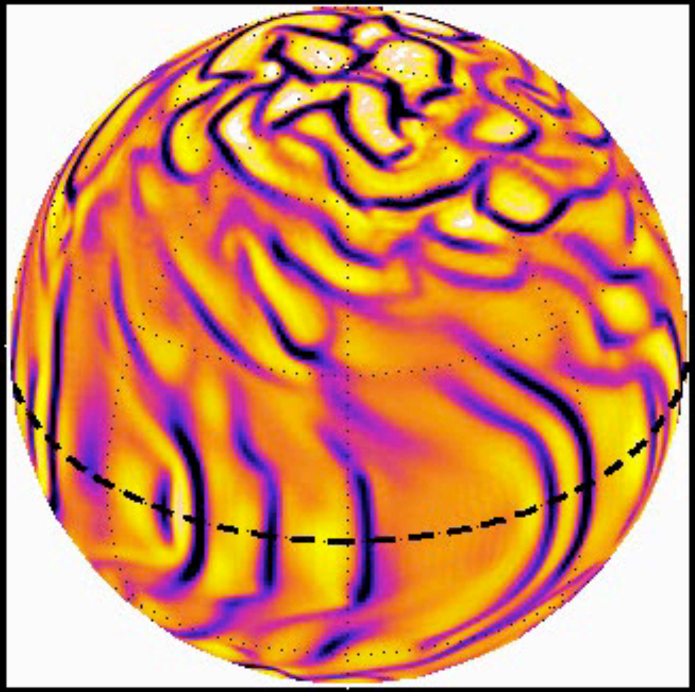
down flows are blue-ish.



More rapidly rotating simulation (10x faster)

The rotation has organised the convection into organised rolls.

(Interior rotation profile constant on cylinders, reflects the Taylor-Proudman constraint)



(Courtesy M. Browning)

Still a long way to go to derive a robust formalism for stellar models...