Pre-main sequence evolution of low-mass stars: Effects of planet formation on stellar composition

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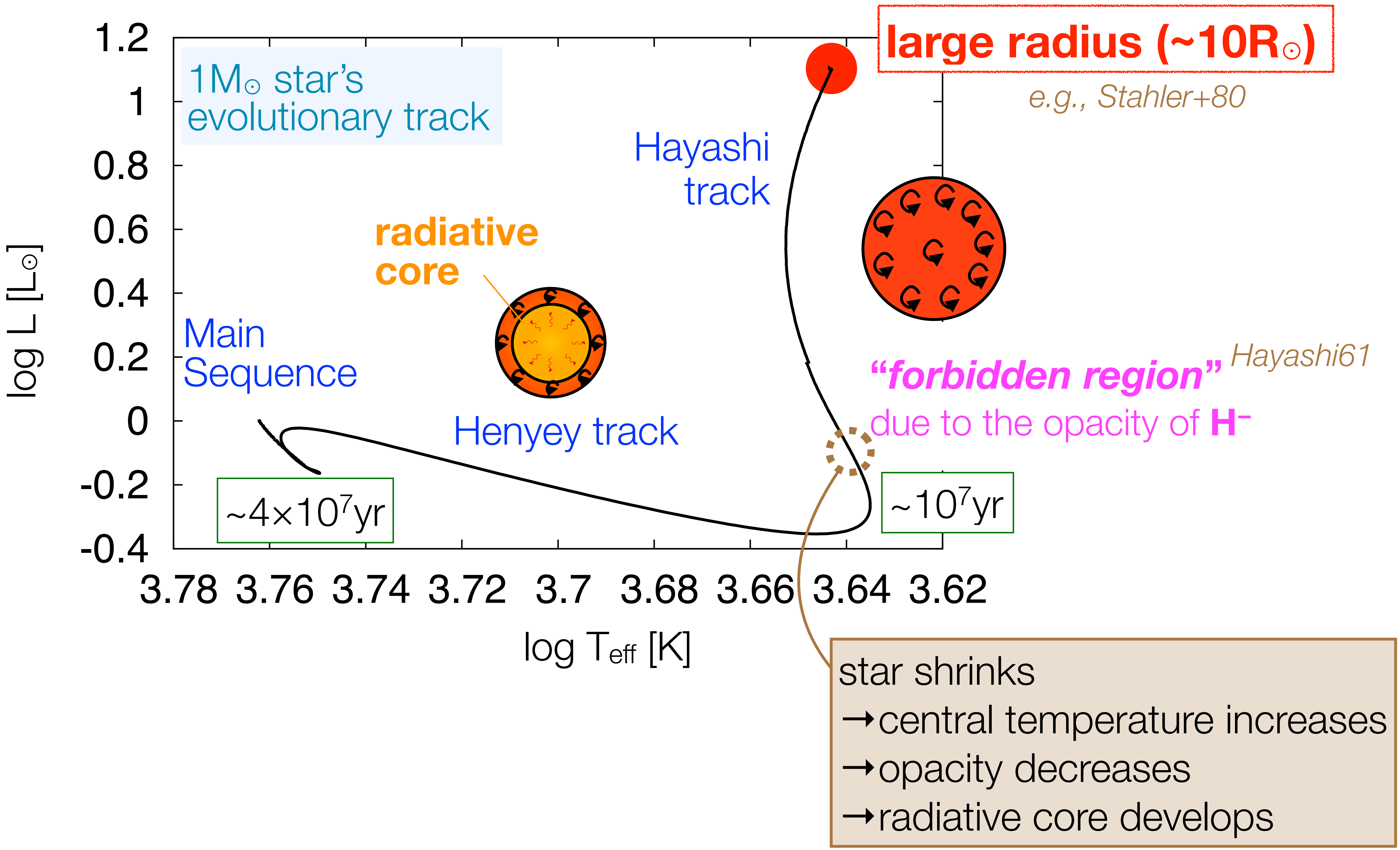
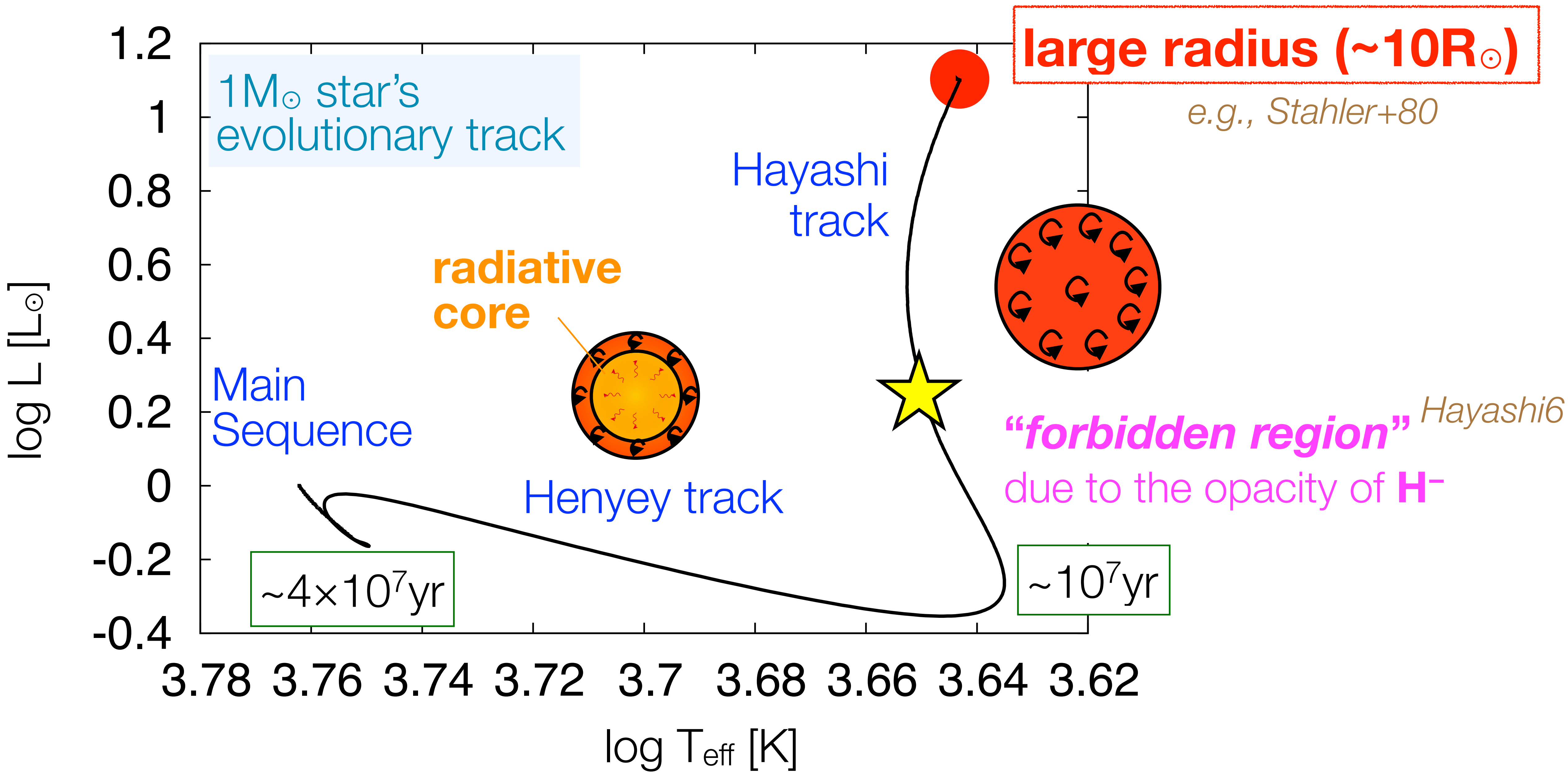
Classical picture of pre-main sequence evolution



Classical picture of pre-main sequence evolution



stellar age and mass are estimated by comparing observed T_{eff} and L with theoretical evolutionary tracks

Classical PMS evolution may not be accurate

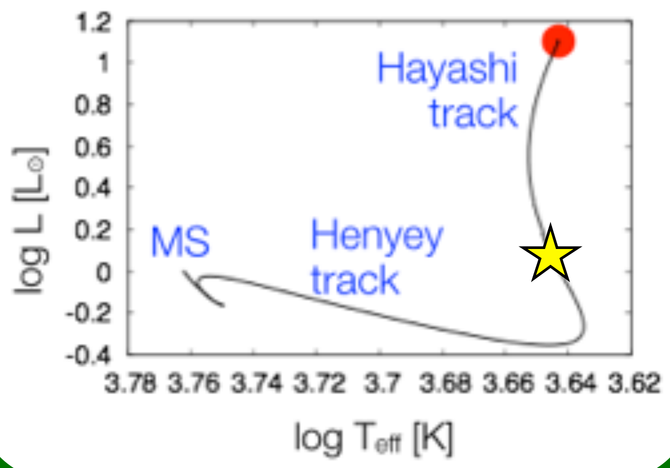
the classical PMS evolution has been called into question
by recent observations:

❖ **mass anomaly of PMS stars** *Stassun+14*

PMS stars' masses estimated with the classical evolutionary tracks are inaccurate up to **50-100%** using eclipsing binary systems

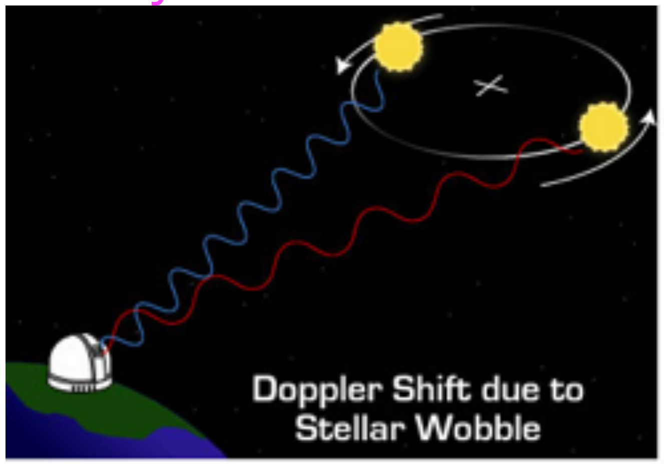
❖ **luminosity (age) spread problem** *Hillenbrand09*

"model mass"

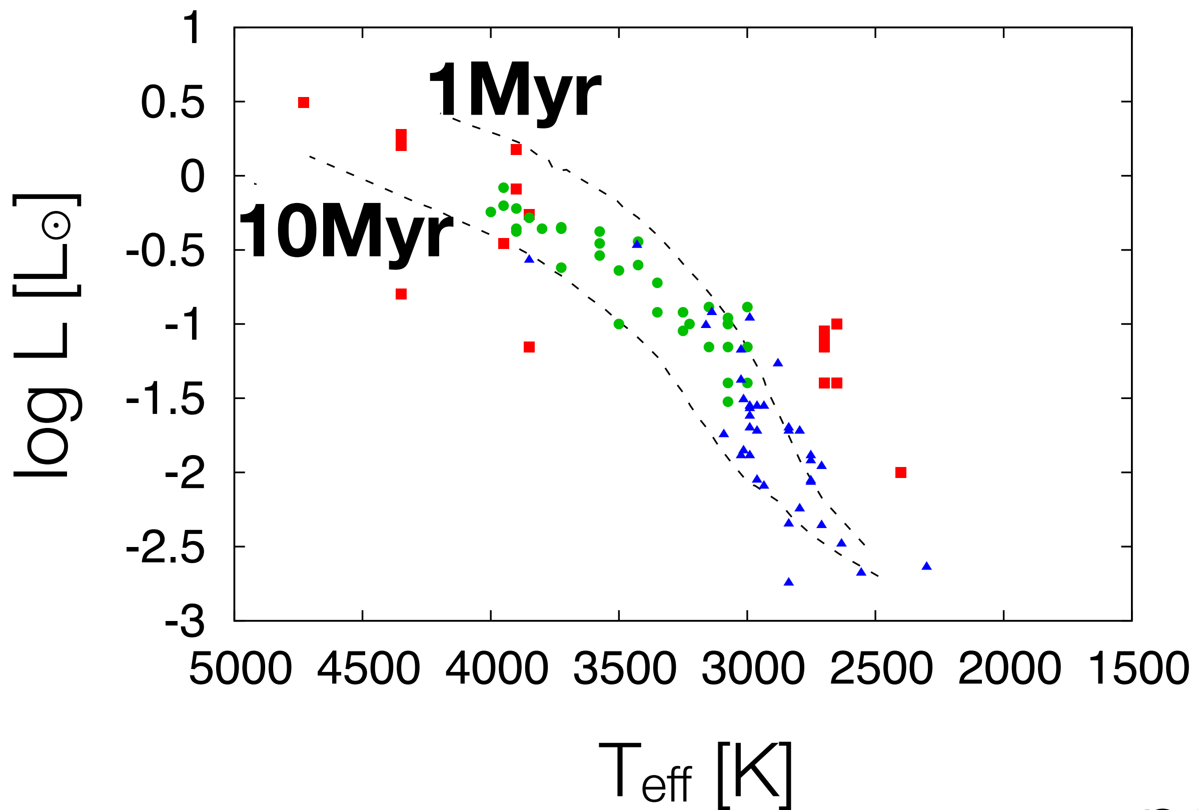


↔

"dynamical mass"



Luminosity (age) spread problem



PMS stars' ages in the same cluster widely spread (~10Myr)
if the classical PMS evolution is used

if stars in a cluster are almost coeval,
this is a big problem

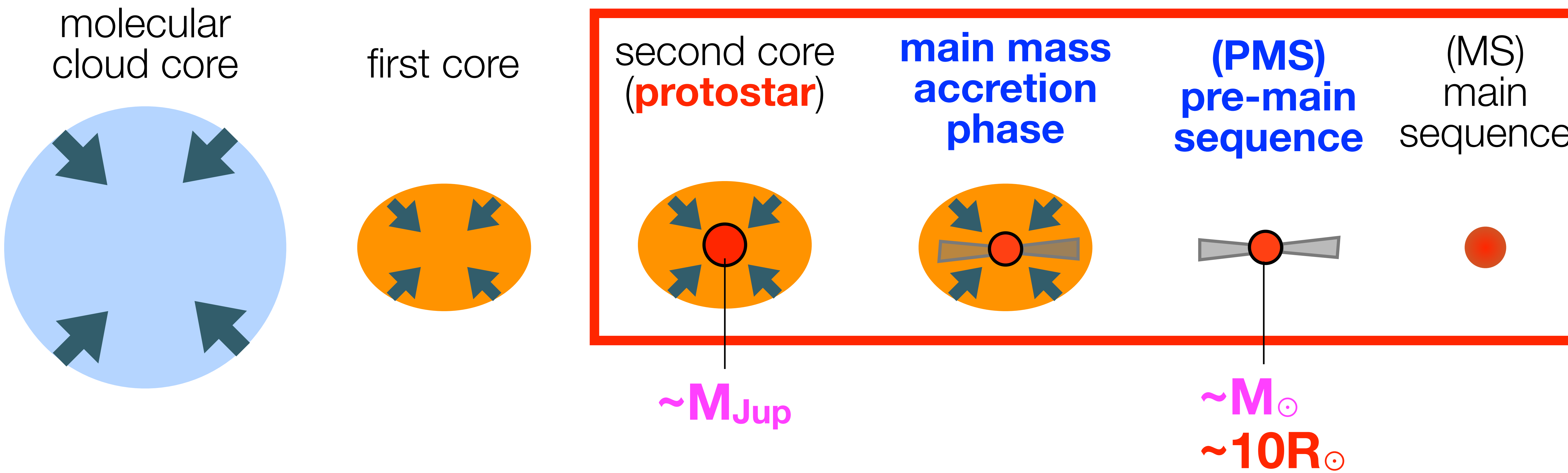
▲Tauras and Chamaeleon I
■ρ Ophiucus
●σ Orionis
— classical isochrone

(Muzerolle+05; Gatti+06,08; Baraffe+98)

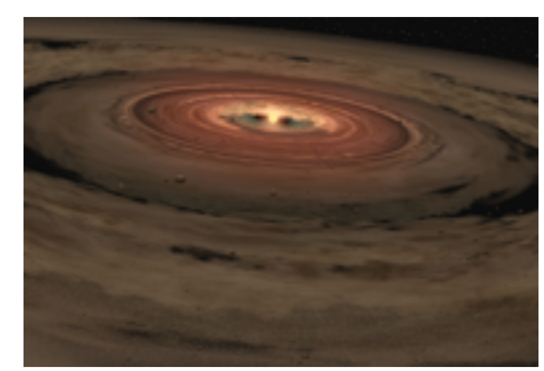
possible solutions:

1. observational error
2. long-lasting star formation in a cluster *(Inutsuka+15)*
3. **classical isochrones are not accurate**

Standard picture of star formation

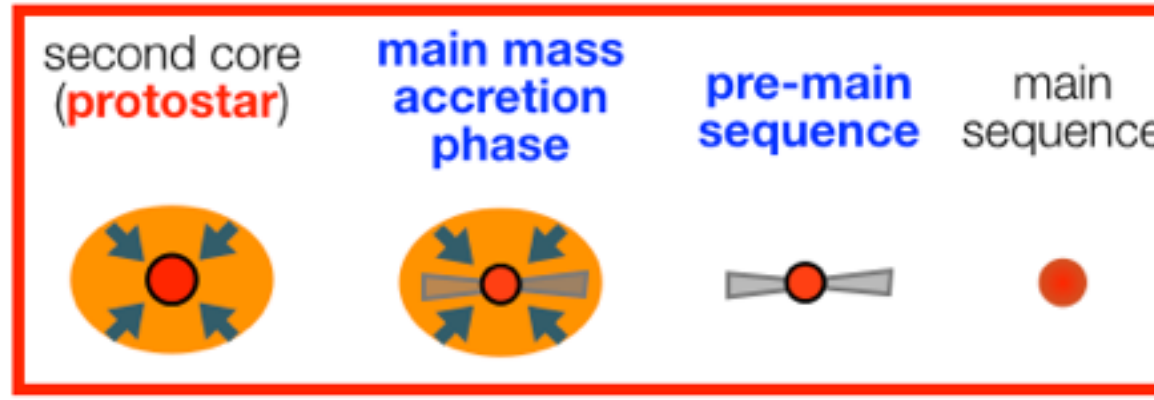


(c) NASA

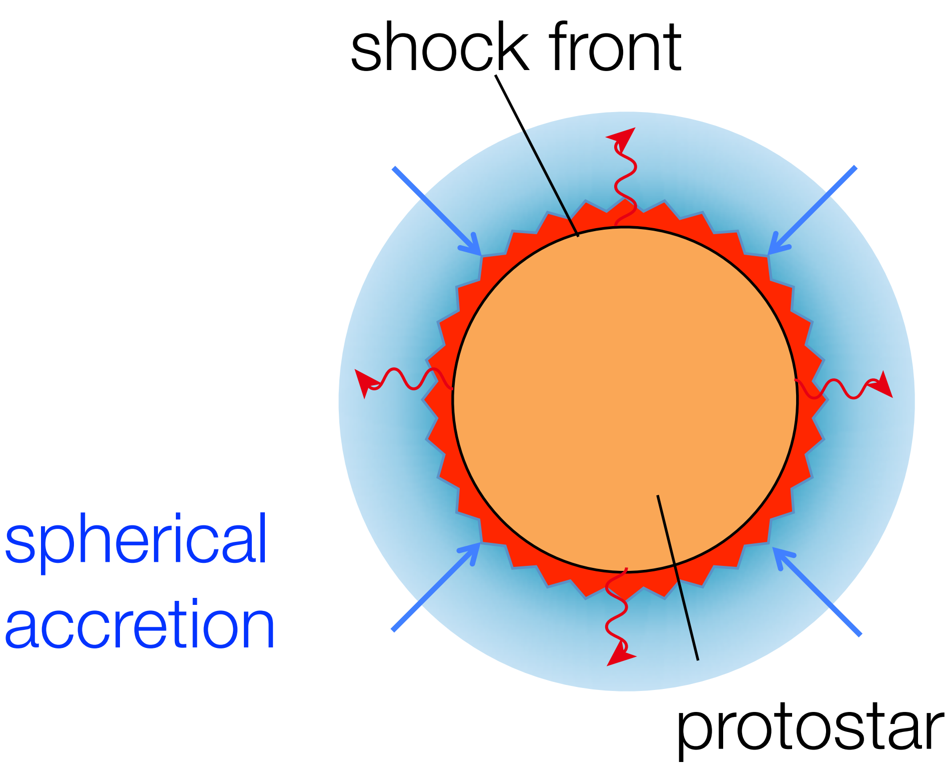


(c) NASA

Configuration of accretion



- ***Classical picture*** *e.g., Stahler+80*



gravitational energy ($GM\dot{M}/R$)

↓

supersonic (free-fall) velocity

↓

thermalized at stellar surface

↓

inefficient radiative cooling

↓

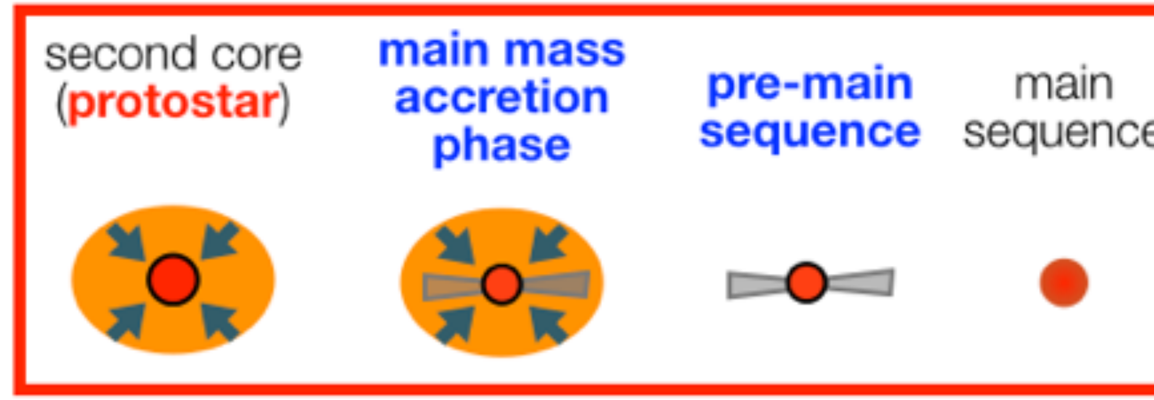
large entropy is carried

inefficient radiative cooling

→**a large amount of entropy** is injected

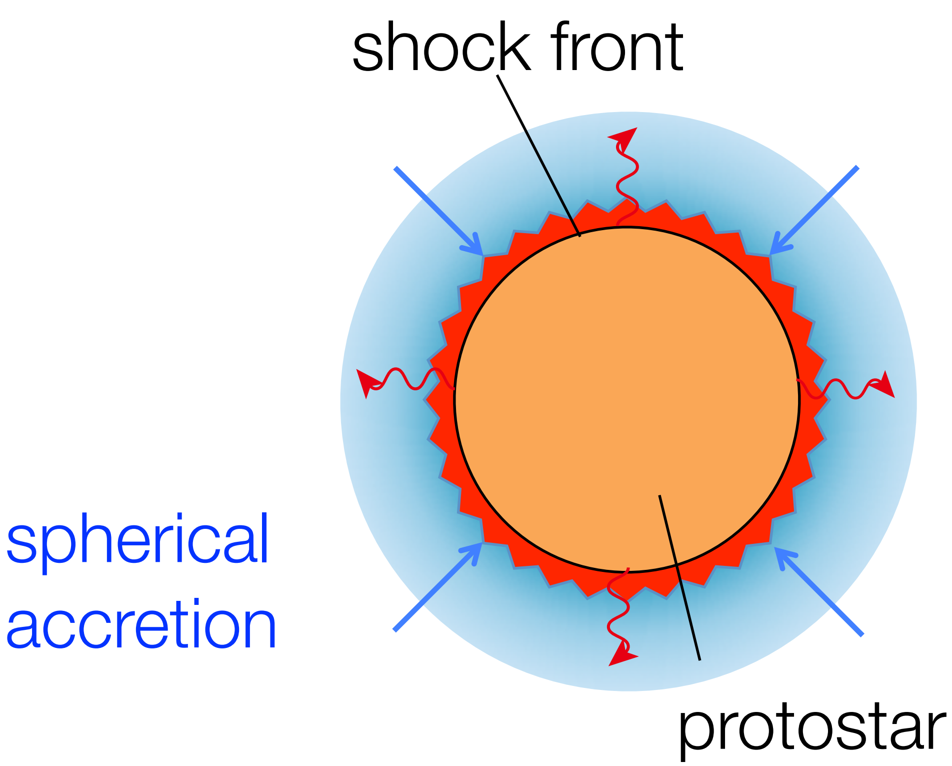
→star is formed with **large radius**

Configuration of accretion



▪*Classical picture*

e.g., Stahler+80



inefficient radiative cooling

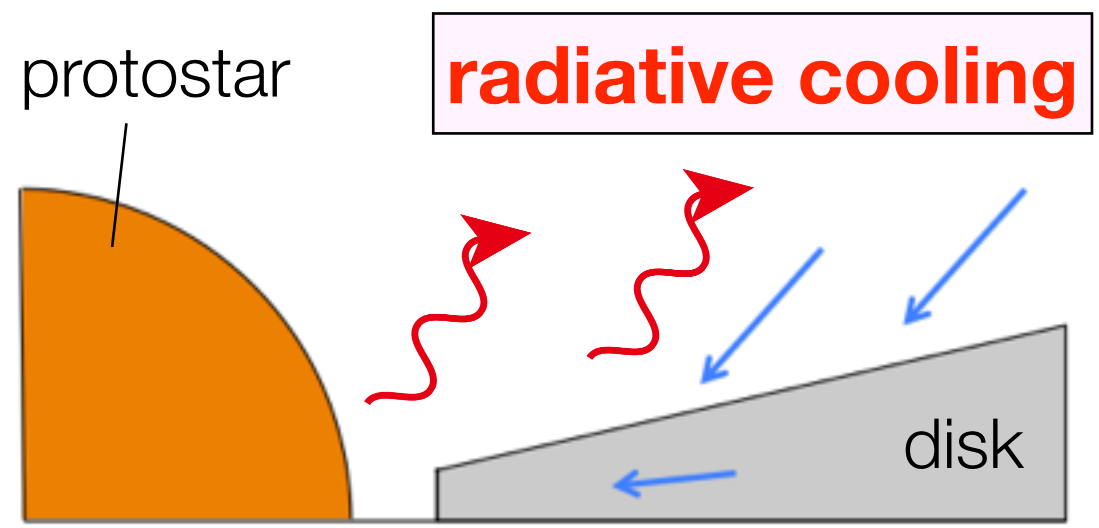
→**a large amount of entropy** is injected

→star is formed with **large radius**

▪*Recent picture*

e.g., Baraffe+09

e.g., Machida+10, Tsukamoto+11, Kratter+10



efficient radiative cooling
from disk's and/or stellar surface
→***low-entropy accretion***

we revisit the PMS evolution with the low-entropy accretion

Computational method

▪Stellar evolution code MESA *Paxton+11,13*

▪Stellar structure equations (1D) **accretion is included**

M_r: mass coordinate

1. **continuity** $$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}$$

2. **momentum** $$\frac{\partial P}{\partial M_r} = -\frac{G M_r}{4\pi r^4}$$ (*hydrostatic equilibrium*)

3. **energy** $$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$

4. **temp. gradient** $$\frac{\partial T}{\partial M_r} = -\frac{G M_r T}{4\pi r^4 P}\nabla$$ $$\nabla = \frac{\mathrm{d}\ln T}{\mathrm{d}\ln P}$$

mixing-length theory, $\alpha_{\rm MLT}$=1.905

(Cox & Giuli68; Henyey+65)

5. **composition** $$\left(\frac{\partial X_i}{\partial M_r}\right)_{M_r} = \frac{m_i}{\rho}\left(\sum_j r'_{ji} - \sum_k r'_{ik}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial X_i}{\partial r}\right)$$

nuclear reaction **diffusion**

composition

X=0.70, Z=0.02

Computational method

▪Effect of the low-entropy accretion

$$\frac{\partial l}{\partial M_r} = \varepsilon_{\rm nuc} - T\frac{\partial s}{\partial t} + \varepsilon_{\rm add}$$

heat injection by accretion

$$L_{\rm add} = \xi G M_\star \dot{M} / R_\star$$

- heating efficiency ξ (=0-1)
  ξ is poorly constrained by RHD simulations

$$\varepsilon_{\rm add} = L_{\rm add} / M_\star$$

- distribute the injected heat uniformly in the entire star

accreting materials' gravitational energy from infinity to star:

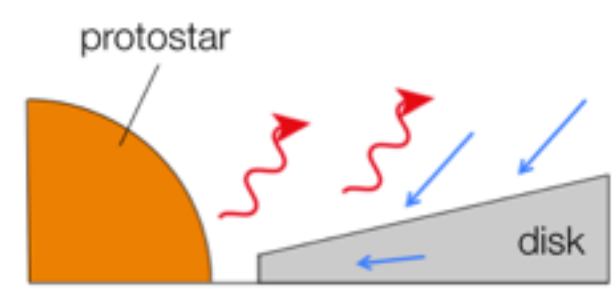
$$L_{\rm acc} = \frac{G M_\star}{R_\star}\dot{M}$$

$$L_{\rm add} = \xi L_{\rm acc}$$

injected to the star

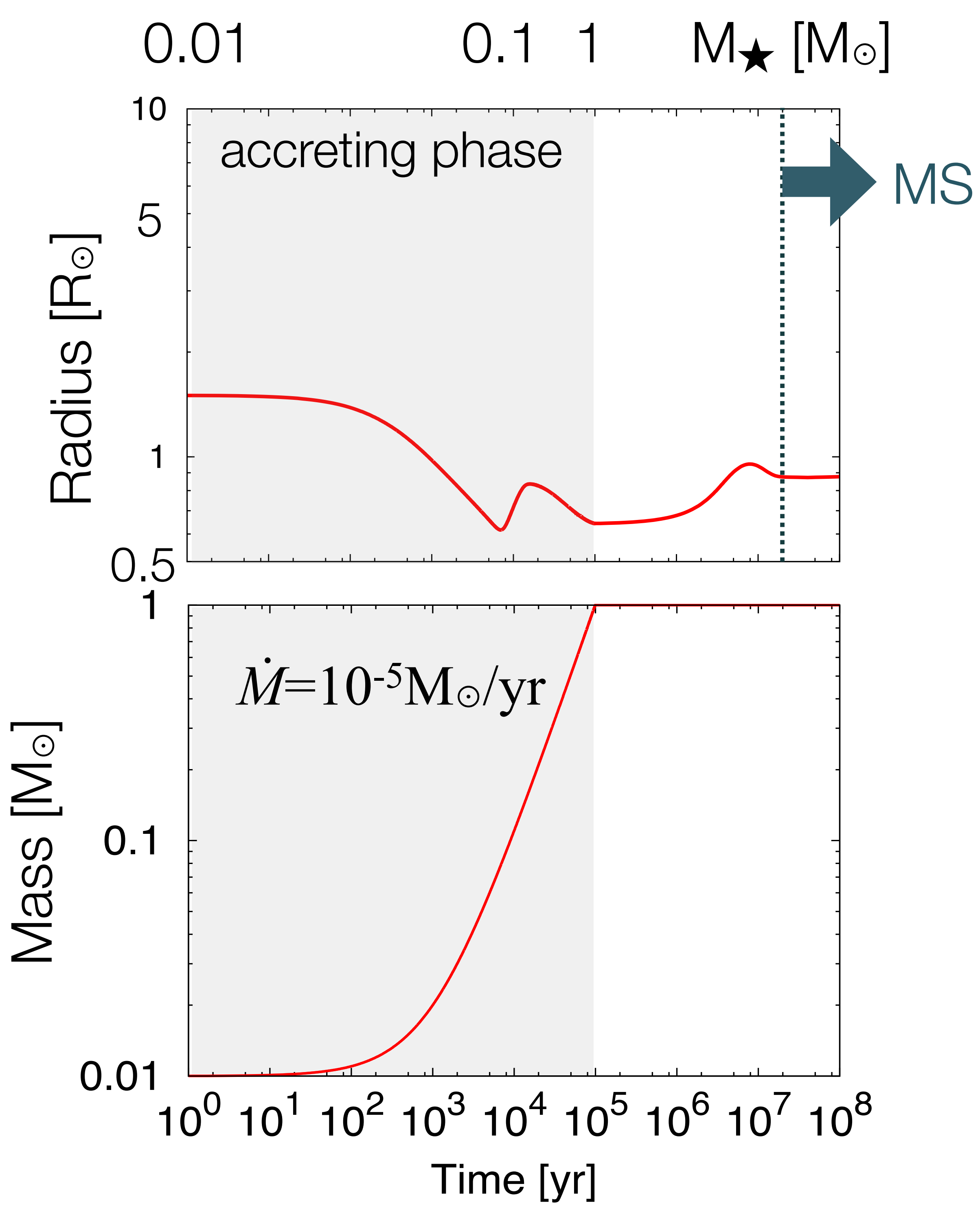
$$L_{\rm rad} = (1-\xi) L_{\rm acc}$$

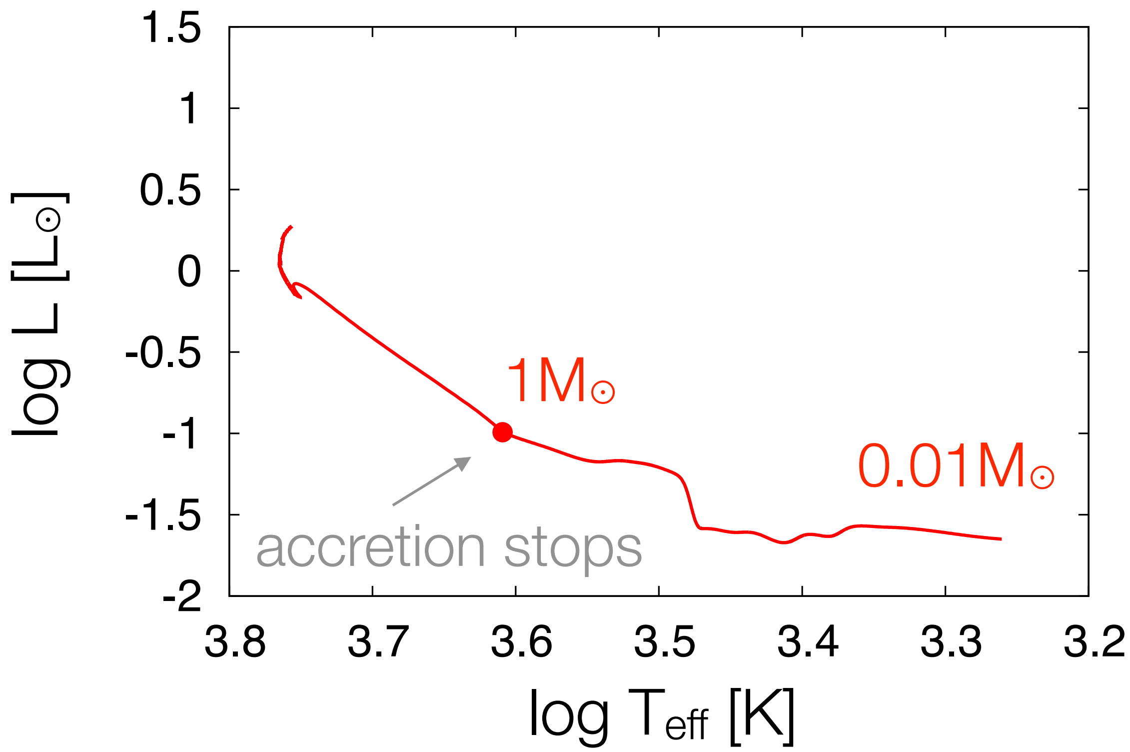
radiated away (+rotation)



PMS evolution with low-entropy accretion

M_{ini}=0.01M⊙
M_{fin}=1M⊙
$\dot{M}$=10^{-5}M⊙/yr
ξ=0, X_D=2.0×10^{-5}

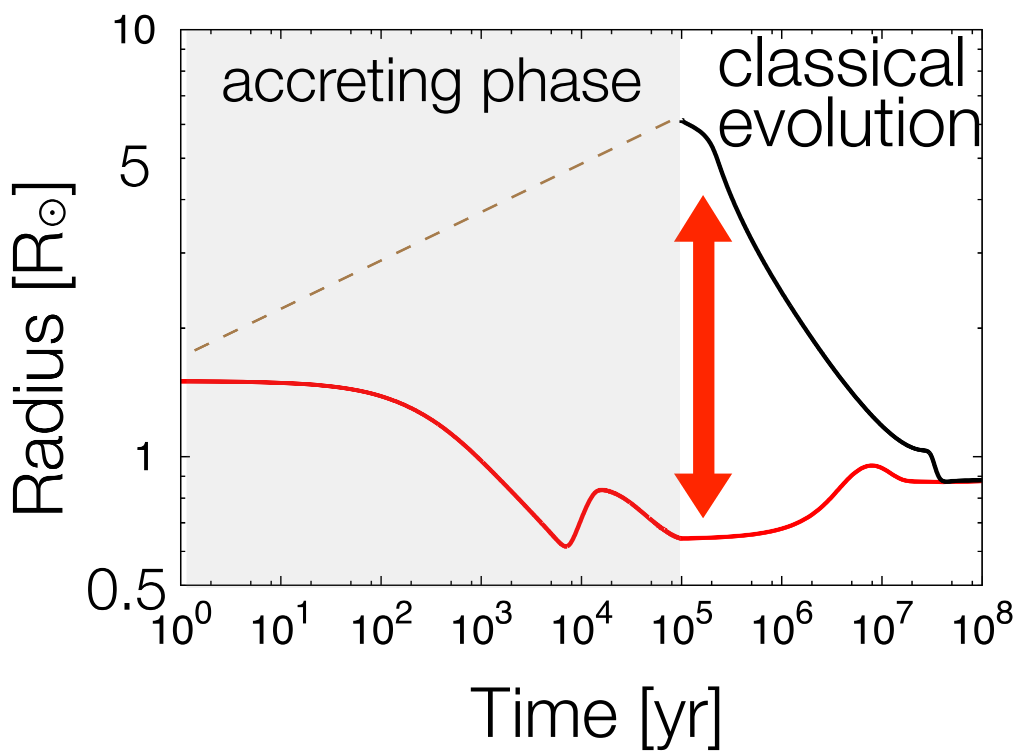




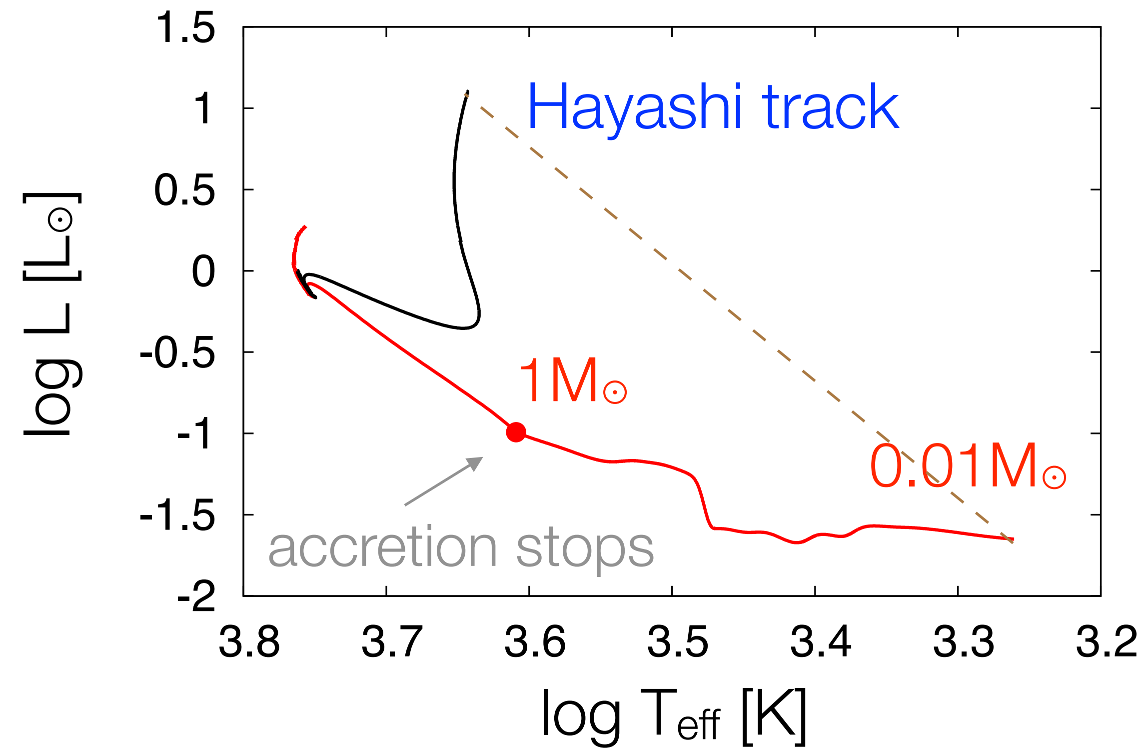
Comparison with classical evolution

M_{ini}=0.01M⊙
M_{fin}=1M⊙
$\dot{M}$=10^{-5}M⊙/yr
ξ=0, X_D=2.0×10^{-5}

■Radius evolution



■Evolutionary track



- **below 1R⊙**
- about one order of magnitude smaller radius

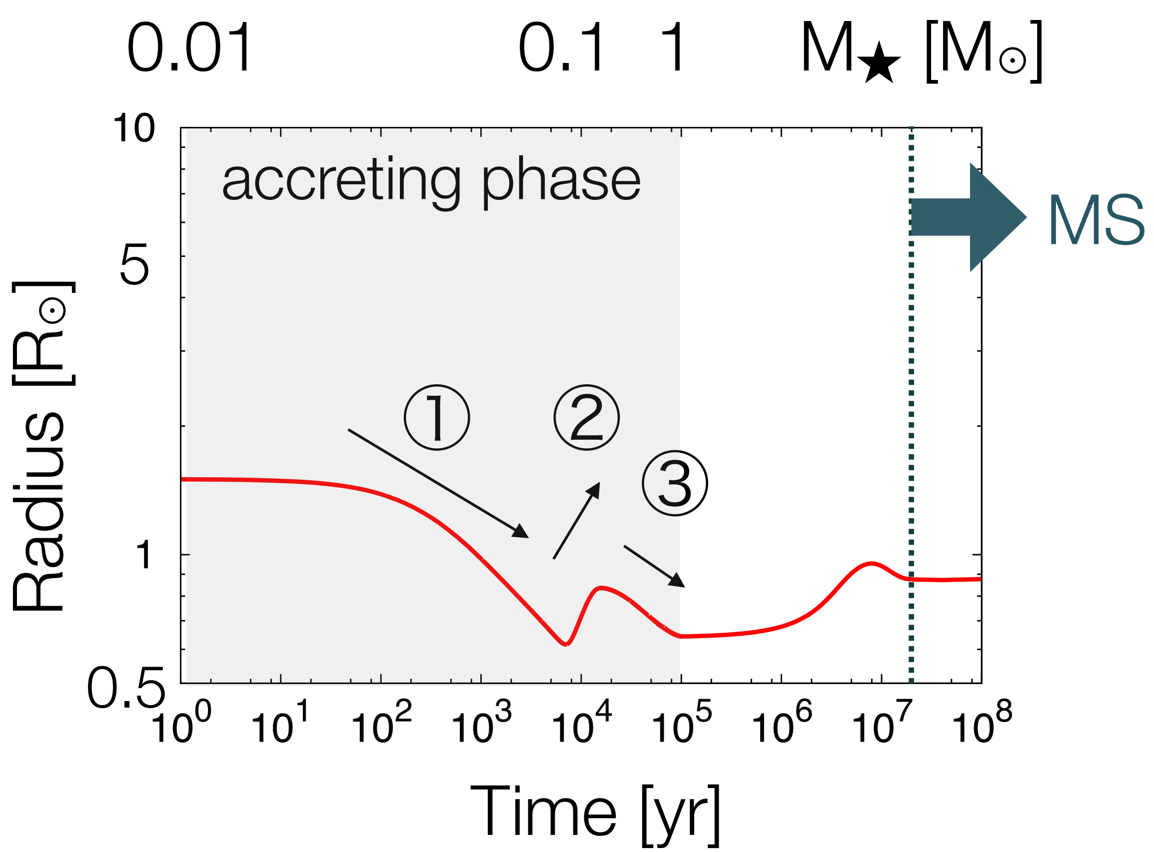
- small luminosity
- **no Hayashi track**

low-entropy accretion → significantly different from the classical evolution

different evolutionary track results in different estimation of M★ and age

PMS evolution with low-entropy accretion

$M_{\rm ini}$=0.01M$_\odot$
$M_{\rm fin}$=1M$_\odot$
$\dot{M}$=10^{-5}M$_\odot$/yr
ξ=0, $X_{\rm D}$=2.0×10^{-5}



stellar radius is determined by **mass** and **entropy**

$$R \propto M^{-1/3} \exp\left[\frac{2}{3}\frac{\mathcal{R}}{\mu}(s - s_0)\right]$$

(fully convective, hydrostatic equilibrium, monoatomic ideal gas)

Chandrasekhar67

①: adiabatic contraction

- constant entropy because ξ=0
- shrink due to the mass accretion

②: deuterium burning

- D+p→^{3}He+**5.5MeV** (T>10^{6}K)
  →**entropy supply**

③: depletion of deuterium

- mass accretion overcomes D-burning

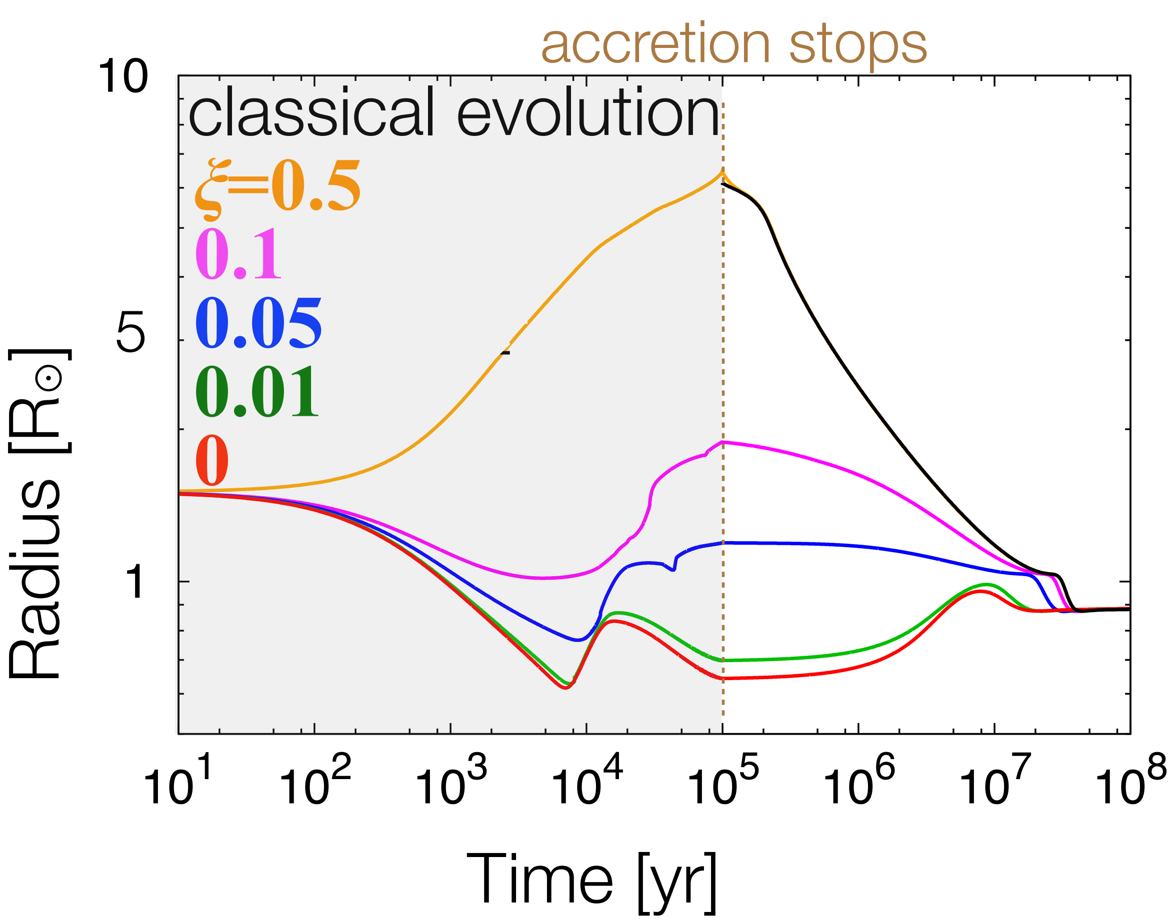
accreting material's entropy and **deuterium content** are important

Dependence on the **heating efficiency** ξ

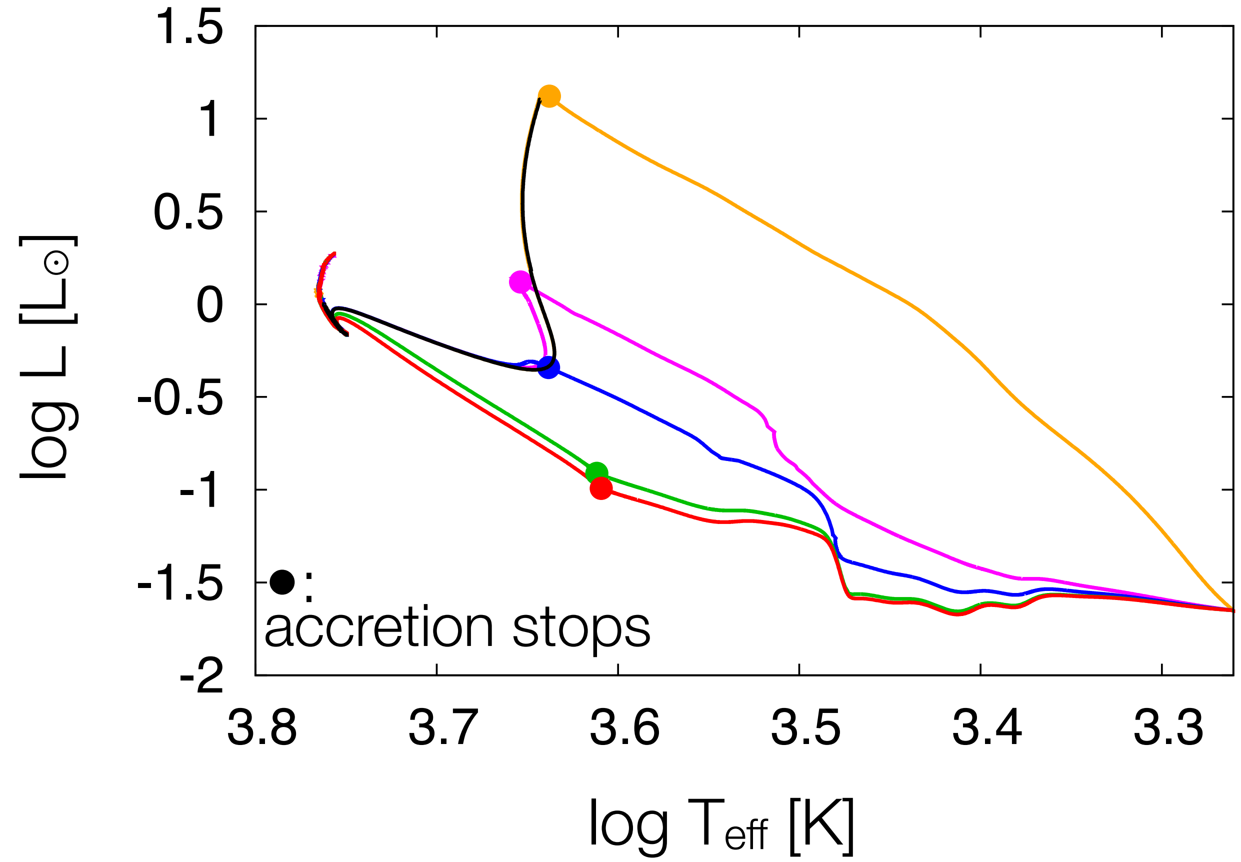
$M_{\rm ini}$=0.01M$_\odot$
$M_{\rm fin}$=1M$_\odot$
$\dot{M}$=10^{-5}M$_\odot$/yr
X_D=2.0×10^{-5}

$$L_{\rm add} = \xi G M \dot{M}/R$$

■Radius evolution



■Evolutionary track



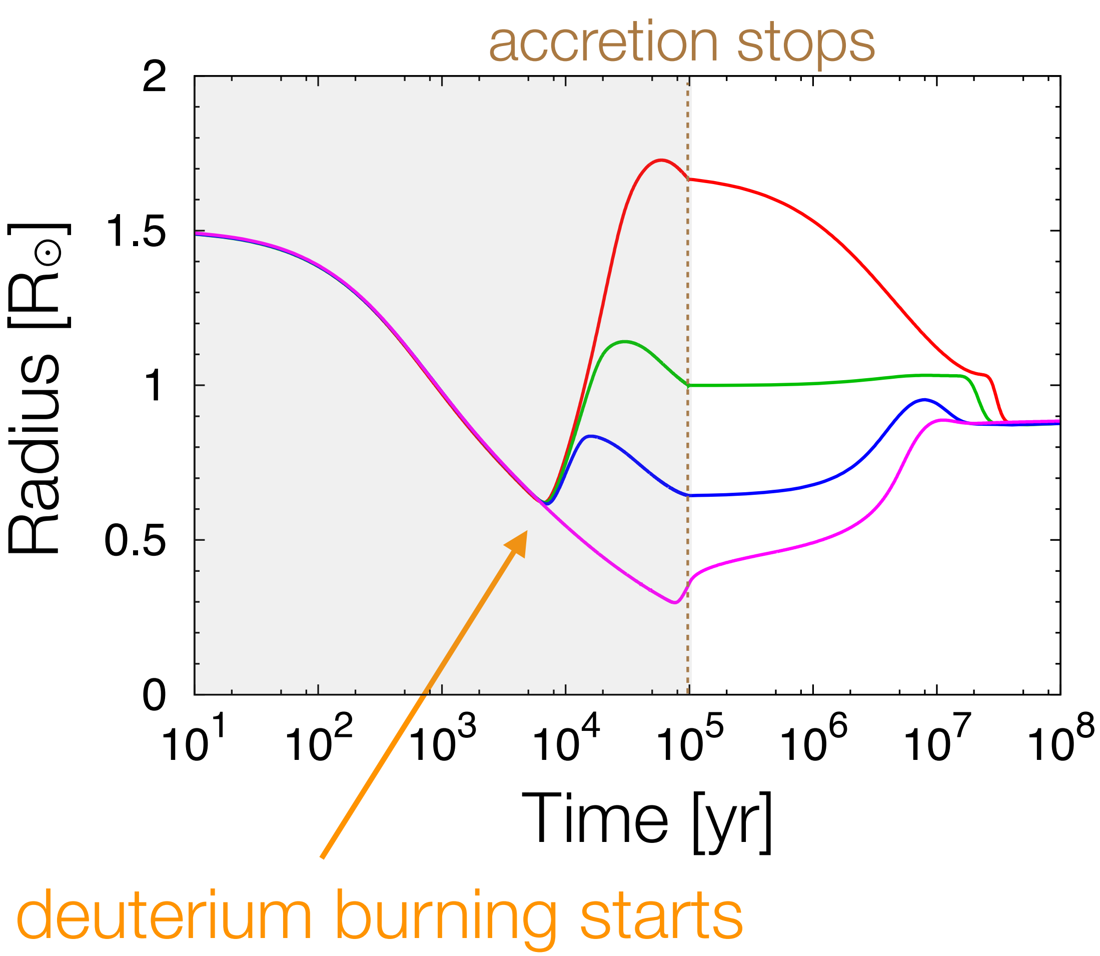
$$R \propto M^{-1/3} \exp\left[\frac{2}{3}\frac{\mathcal{R}}{\mu}(s - s_0)\right]$$

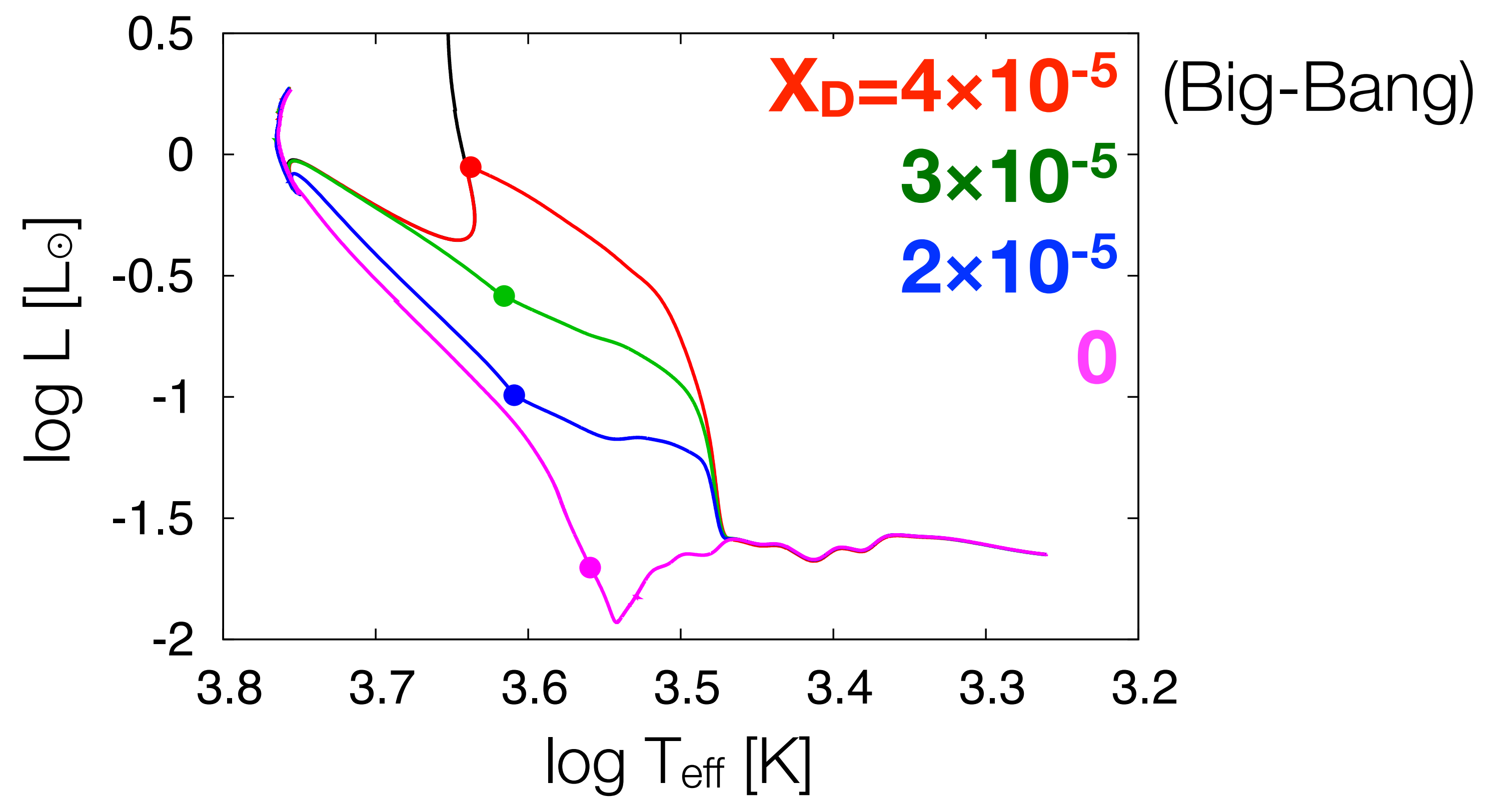
- high entropy injection rate→expansion
- **ξ largely affects the PMS evolution**

Dependence on the **deuterium content X_D**

$M_{ini}=0.01M_\odot$
$M_{fin}=1M_\odot$
$\dot{M}=10^{-5}M_\odot/yr$
$\xi=0$

- Deuterium content **decreases with time** after the Big-Bang
- **It can be different in each star even in the same age**

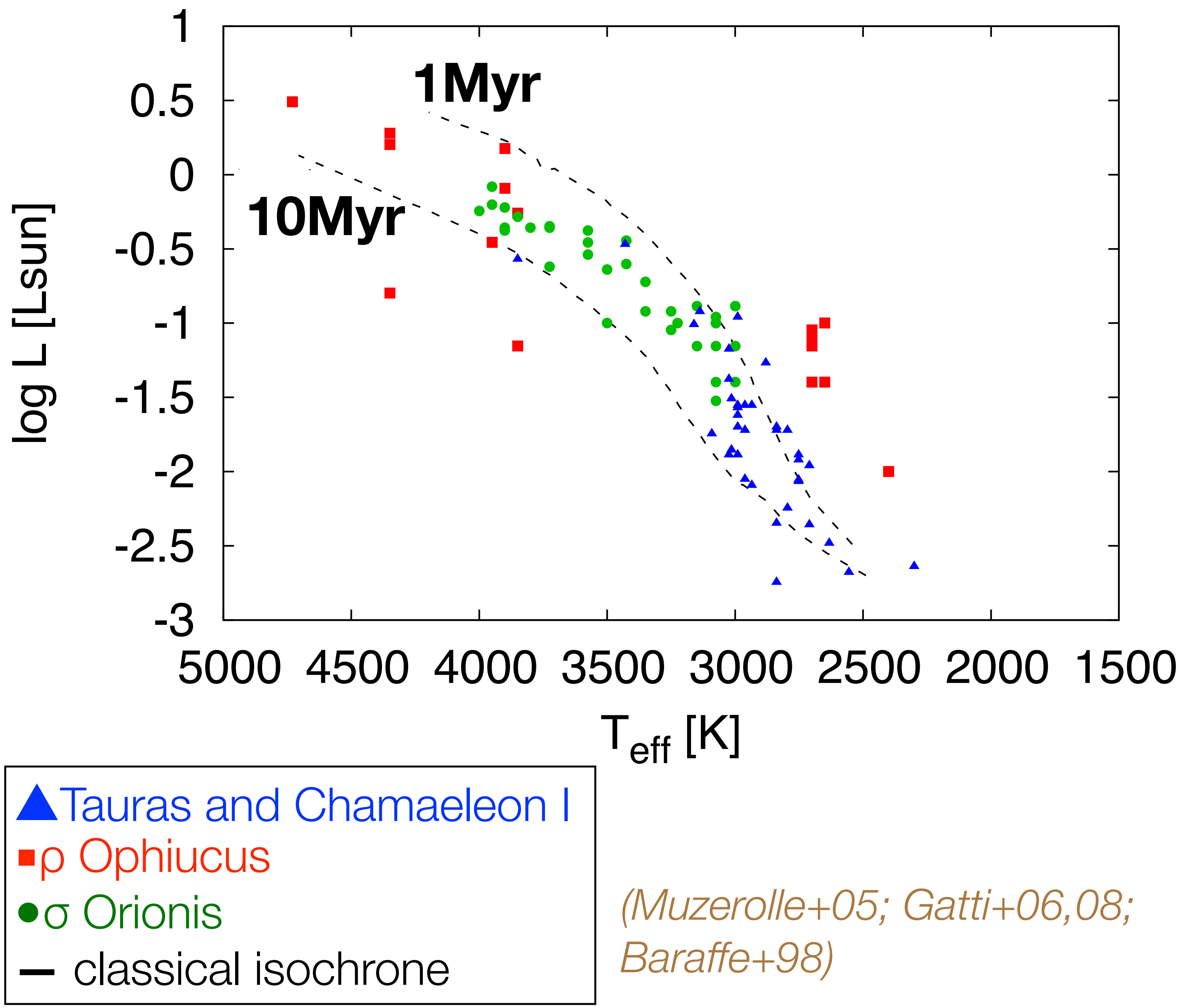




- large deuterium content → lots of entropy is generated → expansion
- **different evolutionary tracks in the high temperature region**

$M_{ini}=0.01M_{\odot}$
$\dot{M}=10^{-5}M_{\odot}/yr$
$X_D=2.0\times10^{-5}$

Impact on the luminosity spread problem

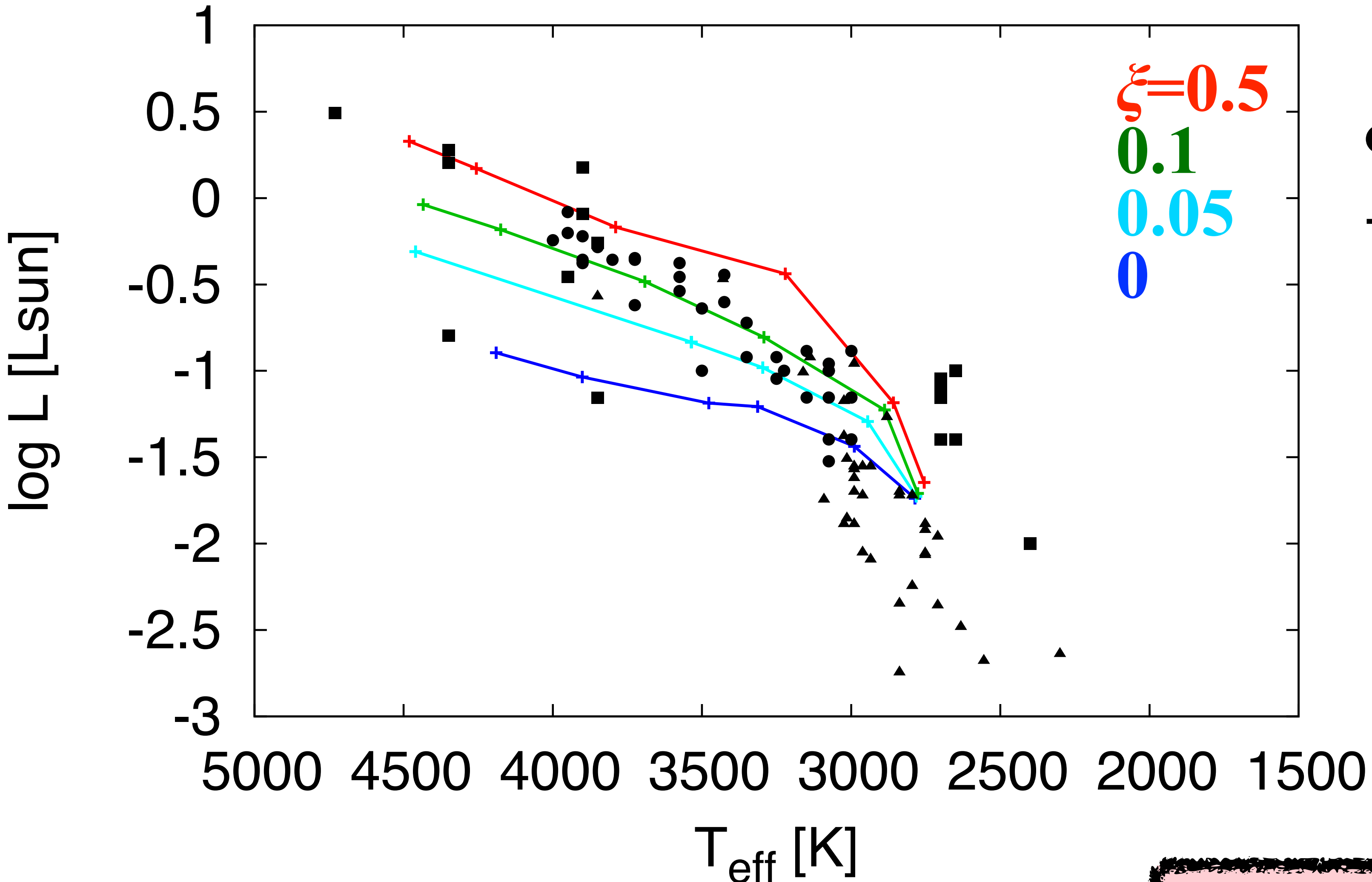


(Muzerolle+05; Gatti+06,08; Baraffe+98)

Impact on the luminosity spread problem

M_{ini}=0.01M$_\odot$
$\dot{M}$=10^{-5}M$_\odot$/yr
X_D=2.0×10^{-5}

1Myr isochrones with different ξ



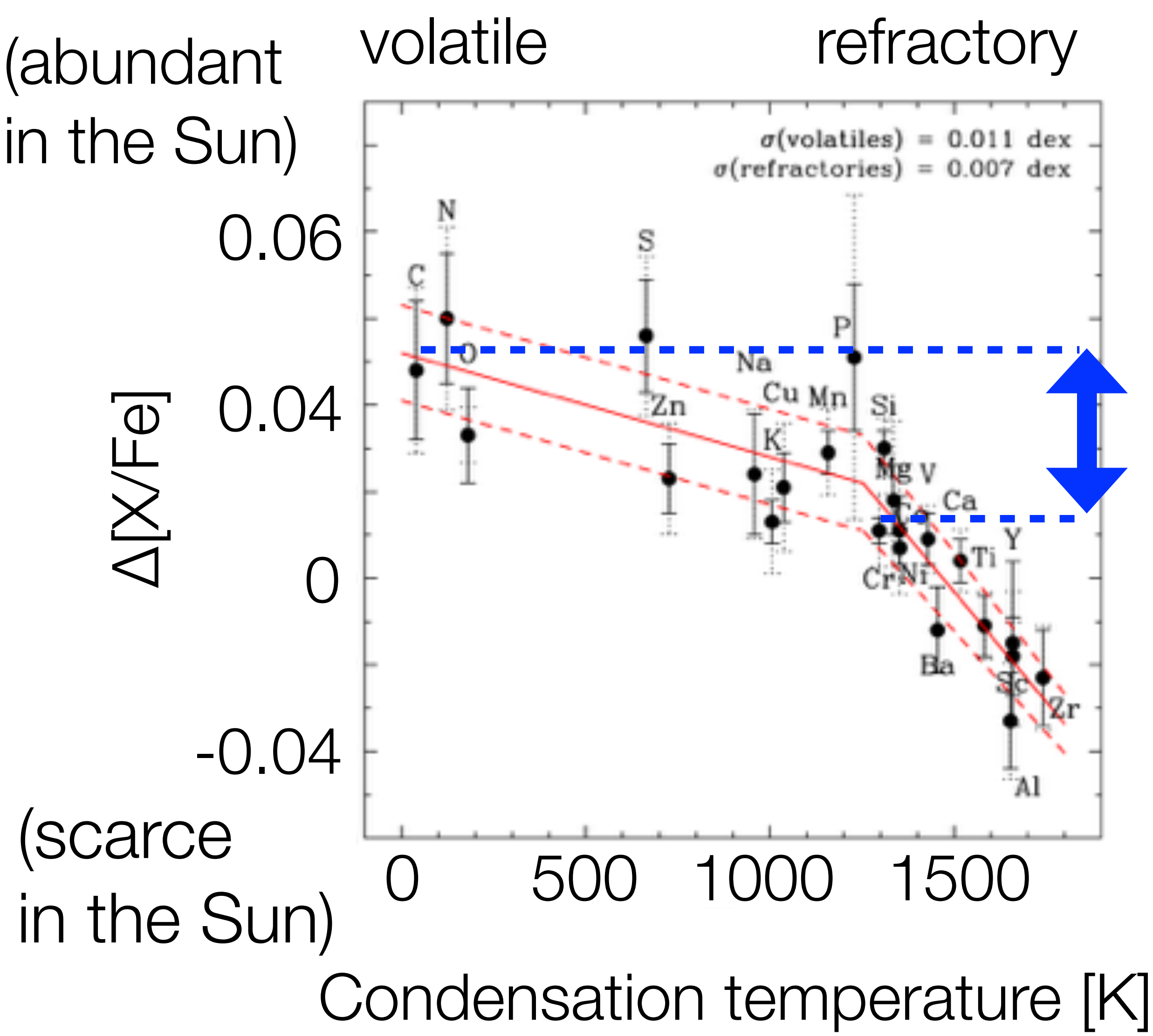
- isochrones spread widely

→**isochrones of different ξ can explain the observed luminosity spread**

Estimation of stellar ages and masses using the classical isochrones is no longer valid

Anomaly of the solar surface composition

Our Sun is a peculiar star



$\Delta[X/Fe] = [X/Fe]_{\odot} - [X/Fe]_{solar\text{-}twins}$

: difference between the Sun and solar-twins

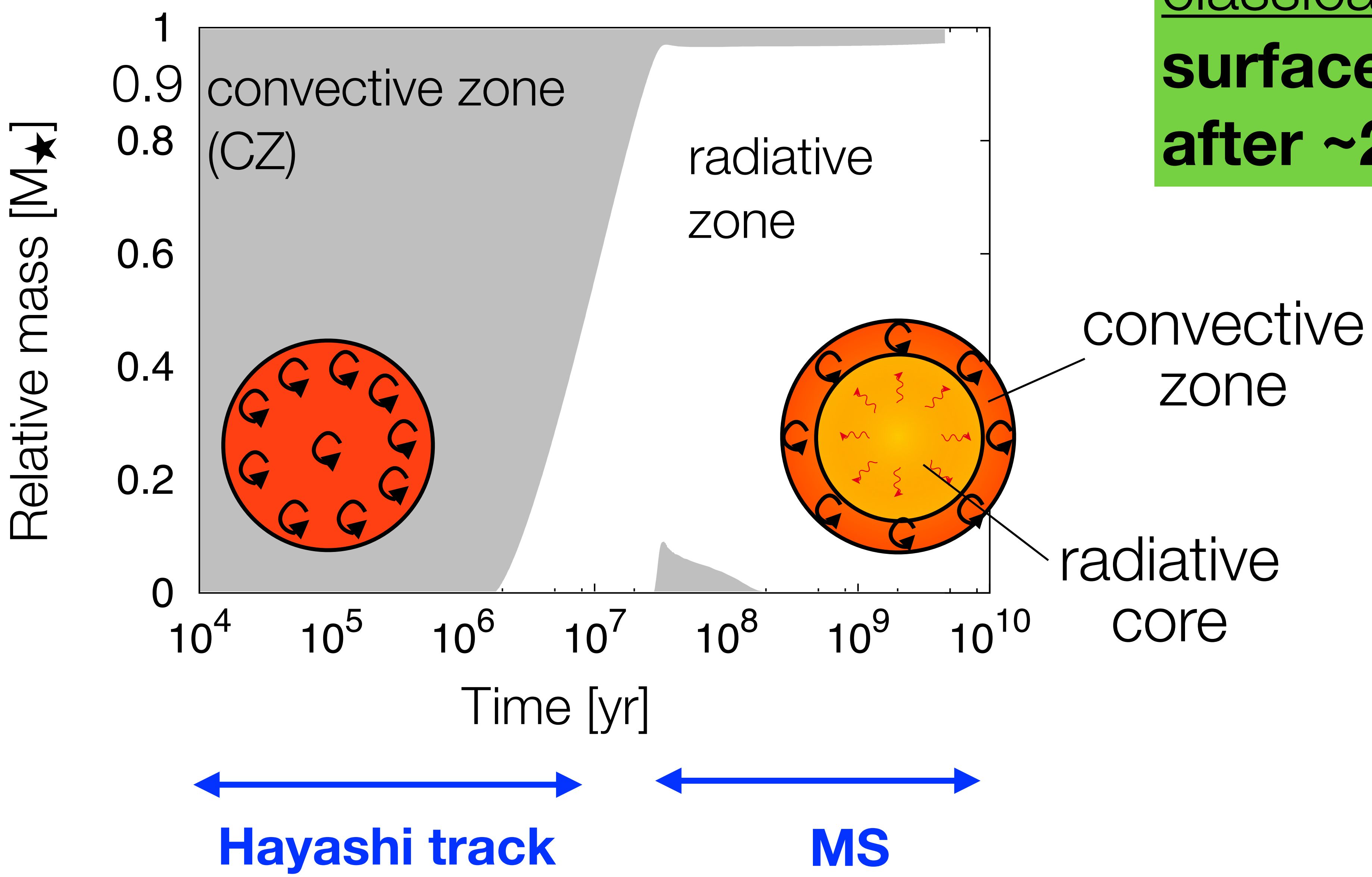
- the Sun is
  -abundant in volatile and
  -scarce in refractory elements
  compared to the solar-twins
- difference: ~0.04dex ~10%

Melendez+09

**solar-twins*: stars with the similar age, metallicity, luminosity and mass to the Sun

Internal structure evolution

■Classical $1M_\odot$ evolution

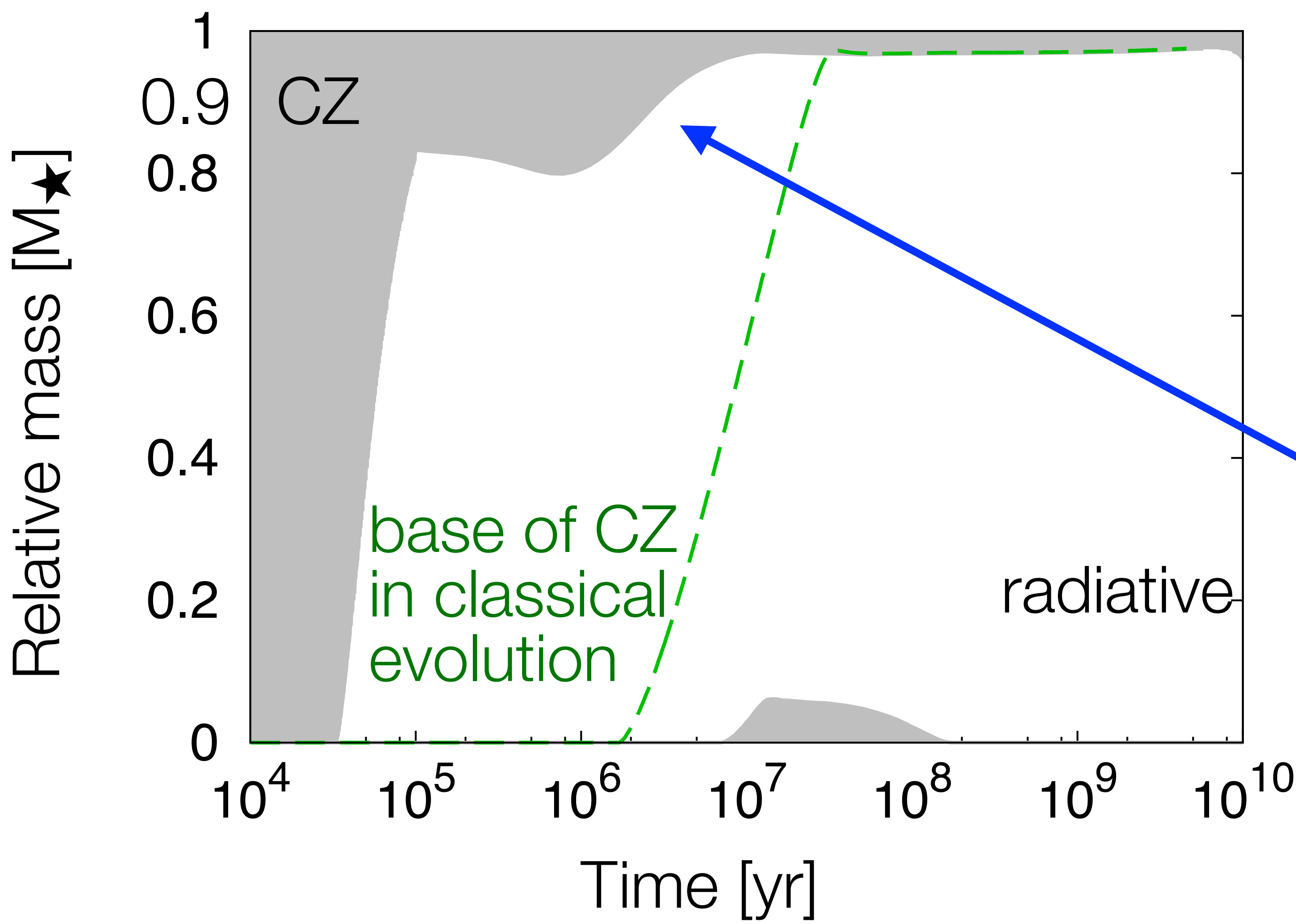


classical evolution:
surface CZ shrinks after ~20 Myr

Internal structure evolution with low-entropy accretion

M_{ini}=0.01M⊙
M_{fin}=1M⊙
$\dot{M}$=10^{-5}M⊙/yr
ξ=0, X_D=2.0×10^{-5}

▪***low-entropy accretion***



classical evolution:
surface CZ shrinks after ~20 Myr

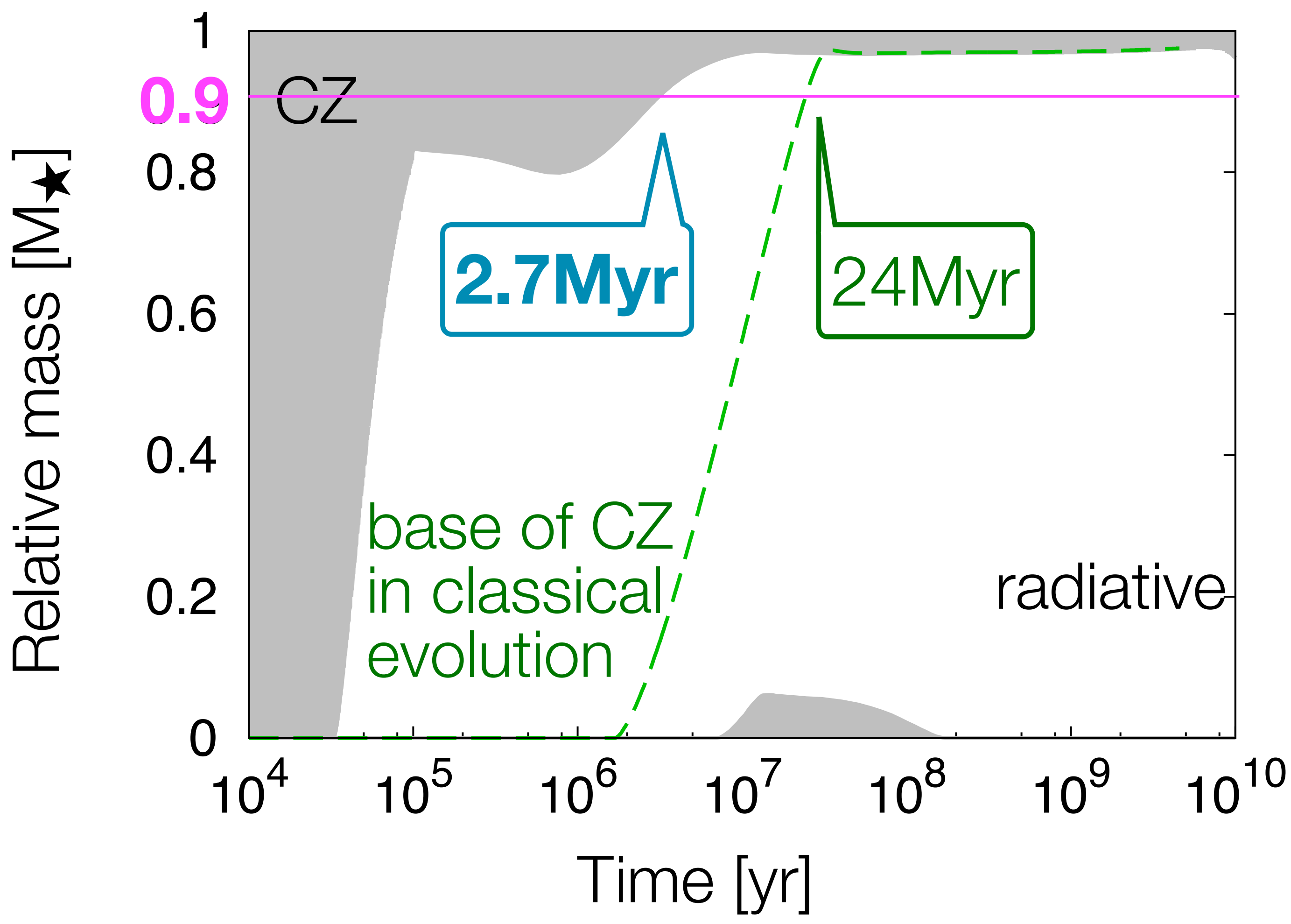
low-entropy accretion:
CZ shrinks much faster

- smaller radius
  → higher internal temperature
  → smaller opacity
  → radiative zone can be developed more easily

Internal structure evolution with low-entropy accretion

M_{ini}=0.01M⊙
M_{fin}=1M⊙
$\dot{M}$=10^{-5}M⊙/yr
ξ=0, X_D=2.0×10^{-5}

▪*low-entropy accretion*



- age when mass in CZ becomes 0.1M⊙
  low-entropy acc.: **2.7Myr**

- ~10 times faster than the classical evolution
- **shorter than the typical disk lifetime (~6Myr)**

Pollution of stellar surface by planet formation

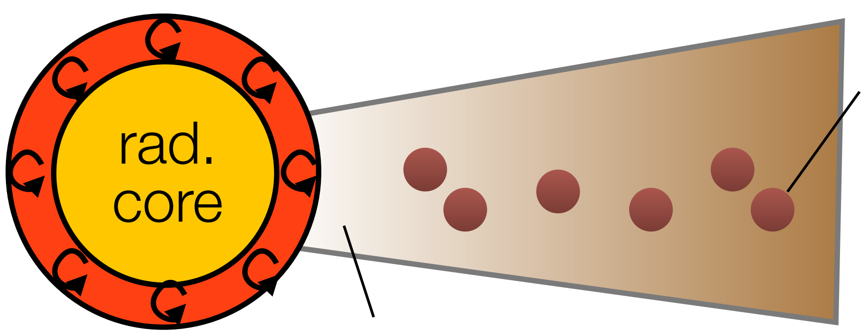
- **thin CZ** within the disk lifetime
- **metal-poor accretion** due to formation of rocky planets

→**stellar surface can be polluted** to be metal-poor composition

accreting materials are mixed only in CZ

(e.g., Chambers10, Ramirez+14)

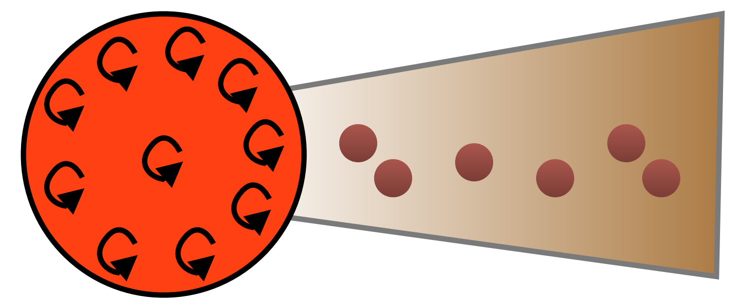
thin surface CZ



rocky objects

metal-poor gas

(e.g.,Guillot, Ida+Ormel 14)



classical evolution: $t_{disk} \ll t_{CZ}$

→pollution to the fully convective star is negligible

Planet formation can affect the host star's surface composition

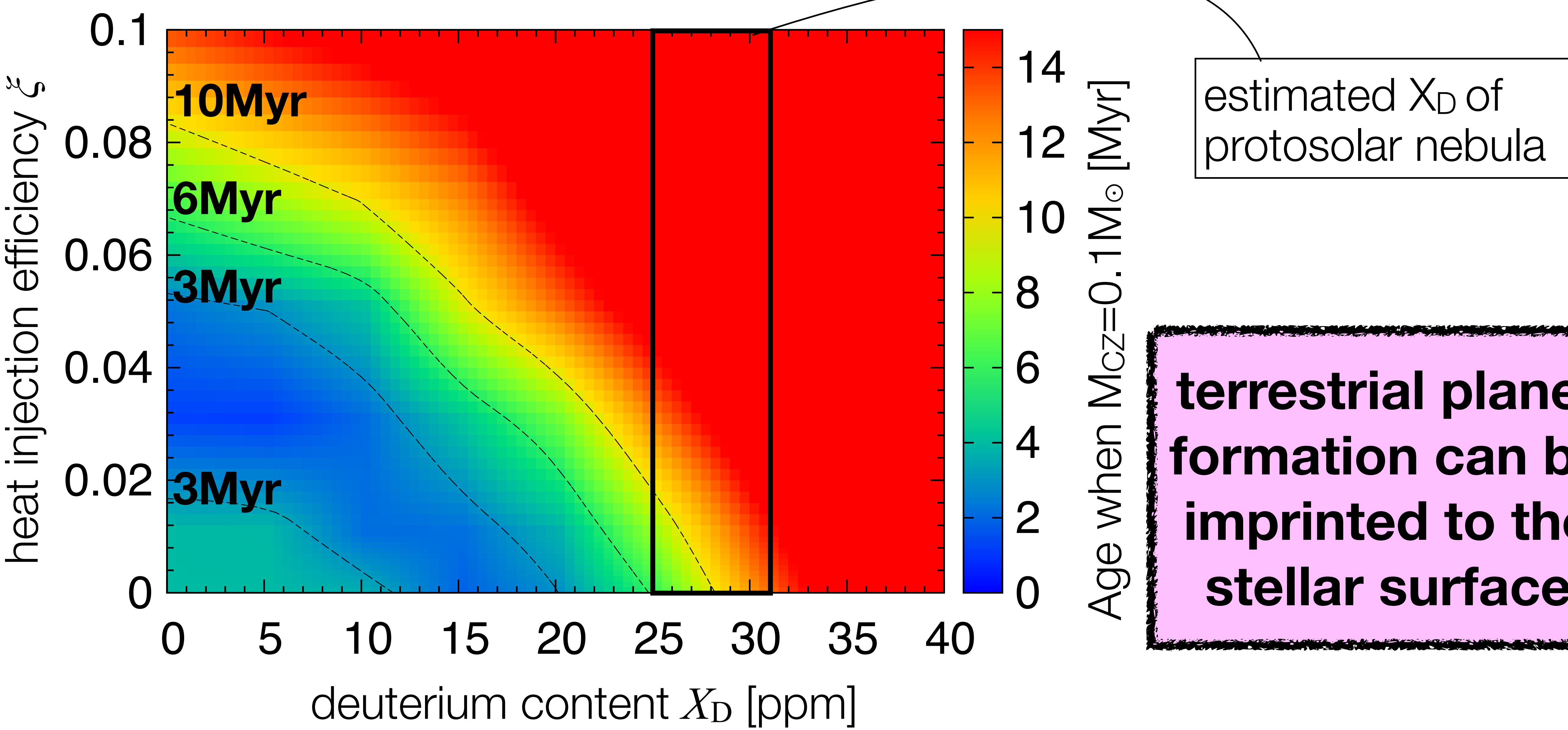
This process may be the solution of

- the solar/stellar anomaly of composition
- the solar metallicity problem

We derive the condition in which this mechanism occurs ($t_{disk} > t_{CZ}$)

Age of CZ shrinkage

M_{ini}=0.01M$_\odot$
M_{fin}=1M$_\odot$
$\dot{M}$=10^{-5}M$_\odot$/yr



terrestrial planet formation can be imprinted to the stellar surface

- CZ shrinks before disk lifetime in low ξ and X_D
- given **low entropy accreted (ξ=0-0.02), the solar surface composition anomaly** can be made by planet formation process

Summary

We calculated PMS evolutions with the low-entropy accretion and found

(1) stars formed by the low-entropy accretion evolve with the much lower radius and luminosity than the classical evolution

→**affects the estimation of stellar mass and age, disk evolution, and planet formation**

(2) the PMS evolution strongly depends on the heat injection efficiency and deuterium content

(3) the luminosity spread problem and the solar composition anomaly can be explained by the low-entropy accretion

(4) multidimensional RHD simulations are needed to determine the accreting materials' entropy