Stellar evolution from the Pre Main Sequence to the Zero Age Main Sequence

Alessandro Bressan

International School for Advanced Studies (SISSA) Trieste

Collaborators
G. Costa, C.T. Nguyen - SISSA
Y. Chen, P. Marigo - Padova University
X. Fu - Kavli Institute Peking University
L. Girardi - INAF OAPD

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Outline

- Standard PARSEC PMS Models
- The Zero Age Main Sequence
- New PARSEC PMS Models with accretion
- An application to Herbig Ae/Be stars
- Conclusions

Basic Ingredients of *PARSEC*

PAdova TRieste Stellar Evolution Code

- **High-temperature opacity** **log(T) : 4.2 - 8.7**
  Opacity Project At Livermore (OPAL, Iglesias & Rogers 96)
  Conductive opacities are included following Itoh et al. 08
- **Low temperature opacity** **log(T): 3.2 - 4.1**
  AESOPUS (Marigo & Aringer2009)
- **EOS is the FreeEOS by A.W. Irwin**
  (GPL licence http://freeeos.sourceforge.net/)

Interpolation in 4 dimensions: T R (= ρ/T6) X Z or Y-C-O Z

Solar abundance

Z = 0.0152 Z/X = 0.0209 Caffau et al. 2011

Z = 0.017 Z/X = 0.023 Grevesse & Sauval 98 (GS98)

Z = 0.0134 Z/X = 0.0181 Asplund et al. 2009 (A+09)

Basic Ingredients of *PARSEC*

PAdova TRieste Stellar Evolution Code

- **NUCLEAR REACTIONS**
  p-p chains   CNO tri-cycle   Ne–Na   Mg–Al chains α-capture α-n reactions
  recommended rates: **JINA reaclib database** Cyburt et al. 10 (**updated to 2016**)

- Convective energy transport
  Mixing Length: calibration with the Solar Model = 1.74 Hp
- Mixing
  Core overshooting and envelope overshooting
  Turbulent diffusion implemented
  Microscopic diffusion included (coefficients Thoul+ 94)
- *Rotation: geometry and mixing (Costa+19)*
- *Boundary conditions (see later)*

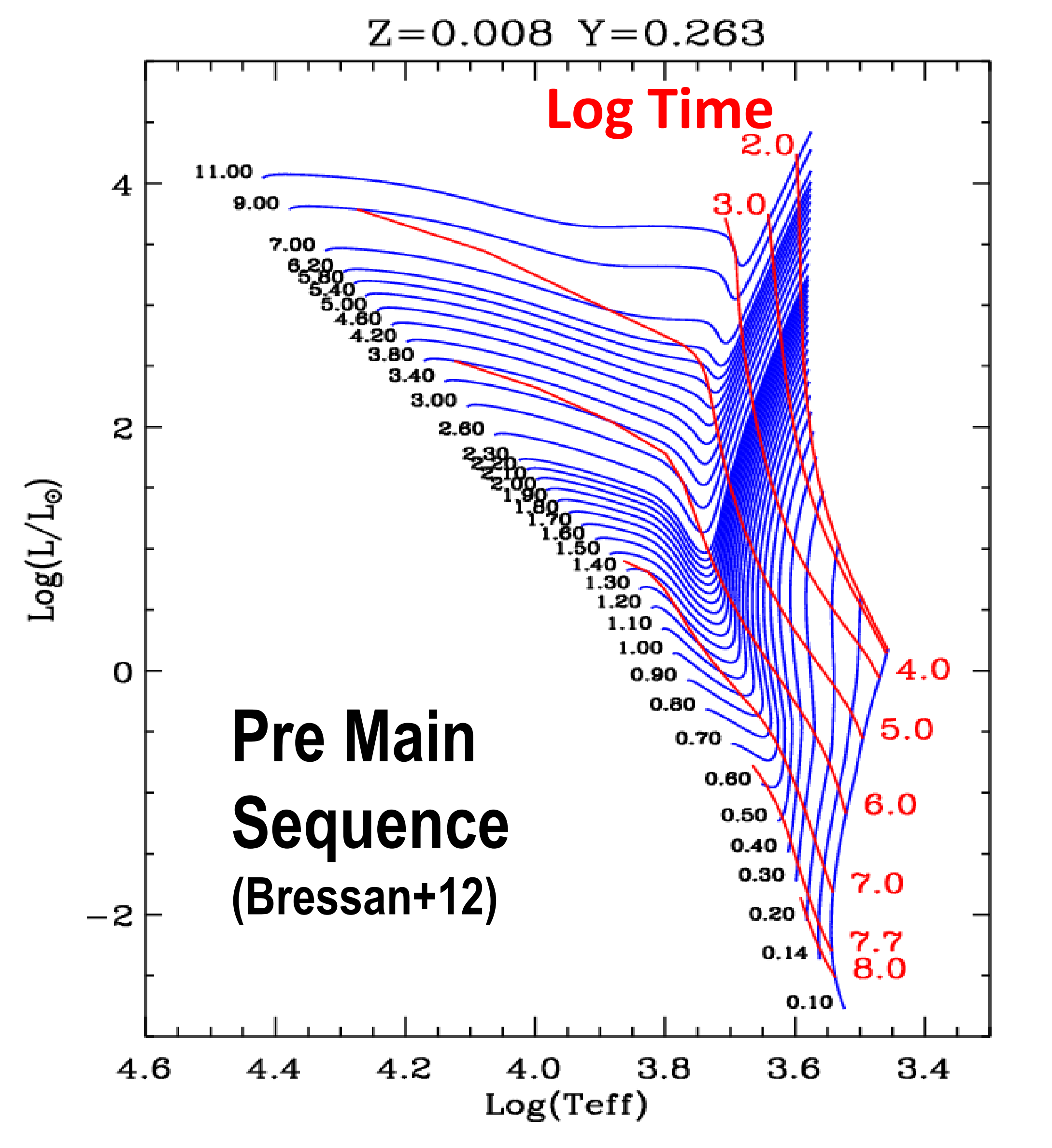
PMS Evolution

Standard : constant mass

Starting Model:
an inflated configuration with central Tc=10^5K

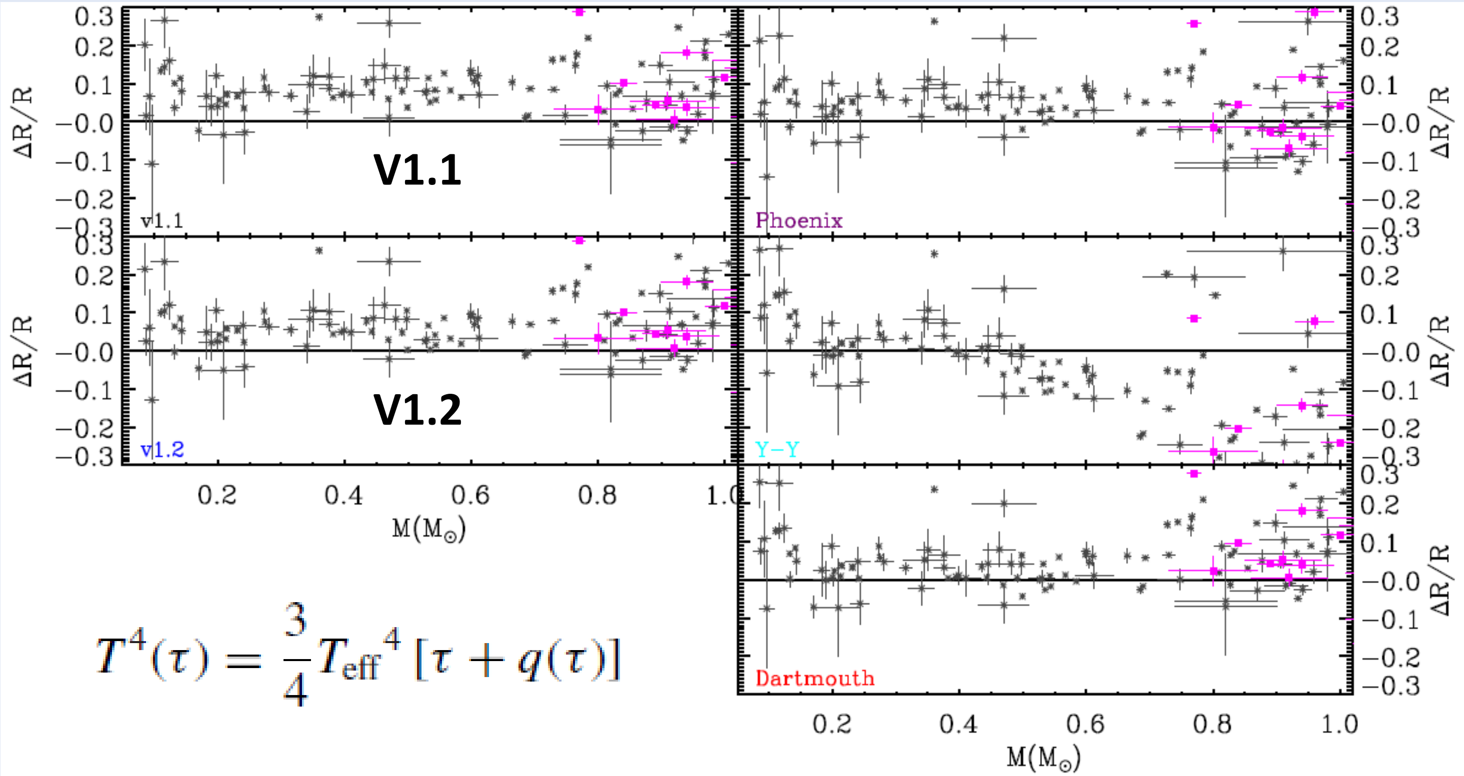
The star is let to contract under the effects of gravity

ZAMS: the point, after central D-burning where, contraction stops under the effects of main nuclear reactions (Lg = 0)



The Zero Age Main Sequence

To characterize PMS phase in the CMD, a well behaved ZAMS is needed. LMS models show a discrepancy with the observed mass-radius of dwarf stars. *In PARSEC V1.1 DR/R ~ 8% (Chen+14)*

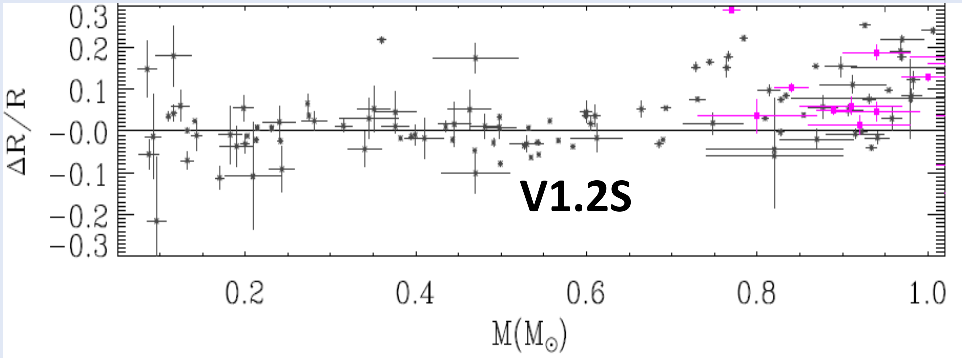


$$T^4(\tau) = \frac{3}{4} T_{\mathrm{eff}}{}^4 \left[\tau + q(\tau)\right]$$

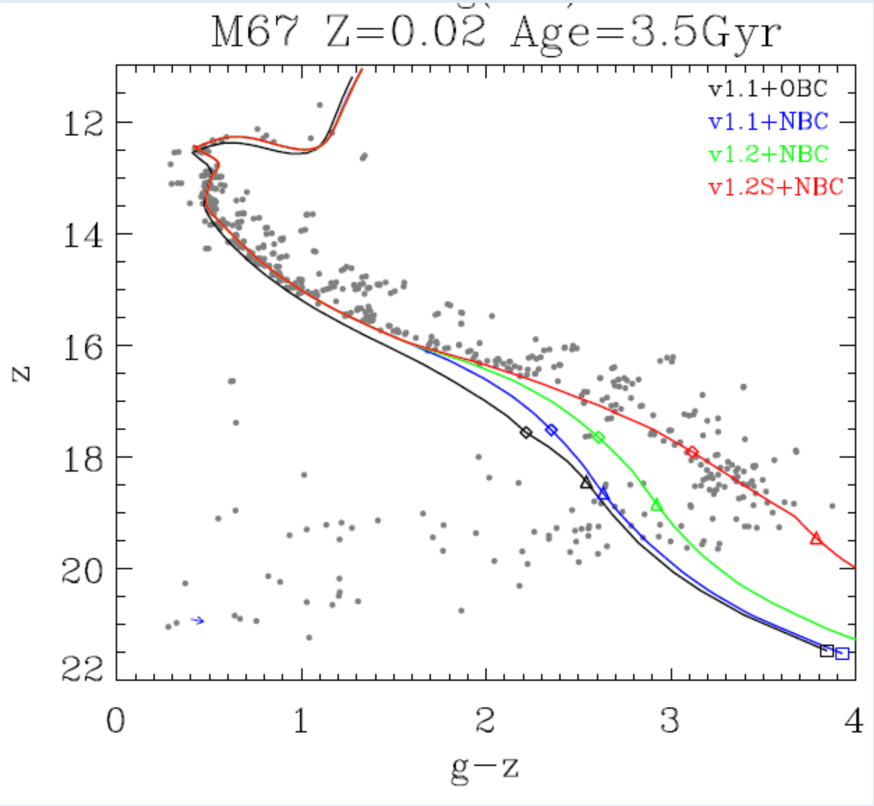
Implementing boundary conditions (T-τ relations Te, g) from PHONIX BT-Settl models, reduce DR/R to 5% (PARSEC V1.2).

The Zero Age Main Sequence

With shifted T-tau relations (from 0 at Teff=4730K to 14% at Teff = 3160 K) models may reproduce the observed mass-radius relation for dwarf stars.

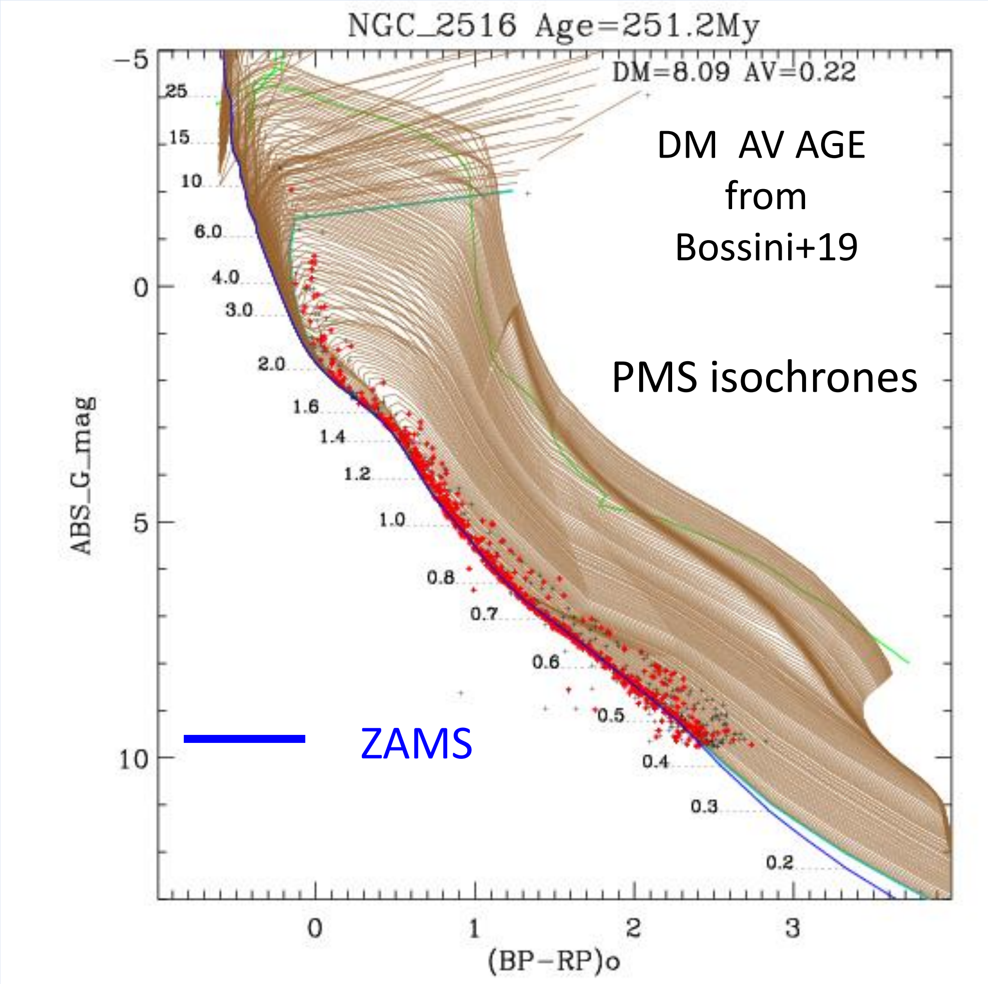


Use the shift as a “calibrated T-tau relation” (PARSEC V1.2S, Chen+14))

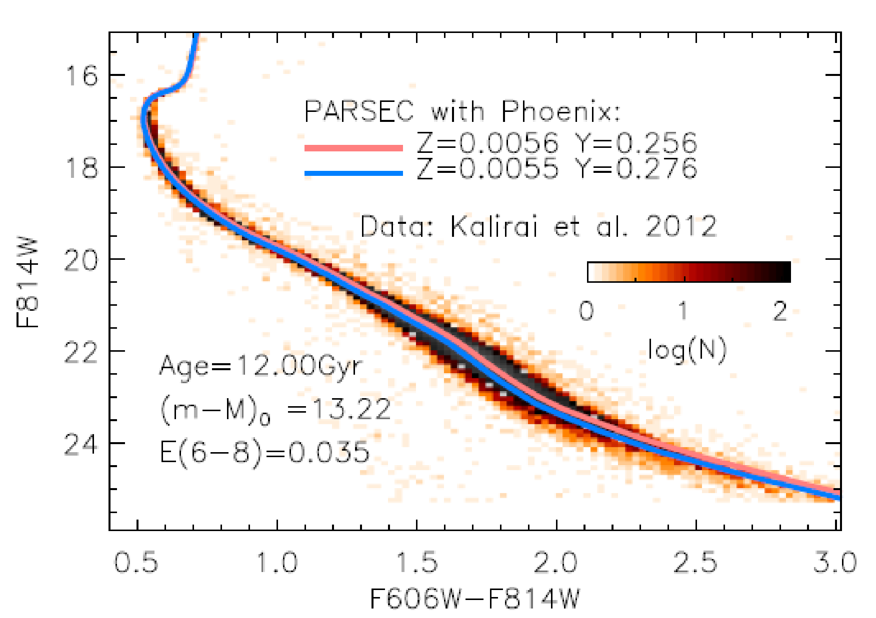


The Zero Age Main Sequence

The model ZAMS matches that of Gaia DR2 Open Clusters ($Z_\odot$, Bossini+19)



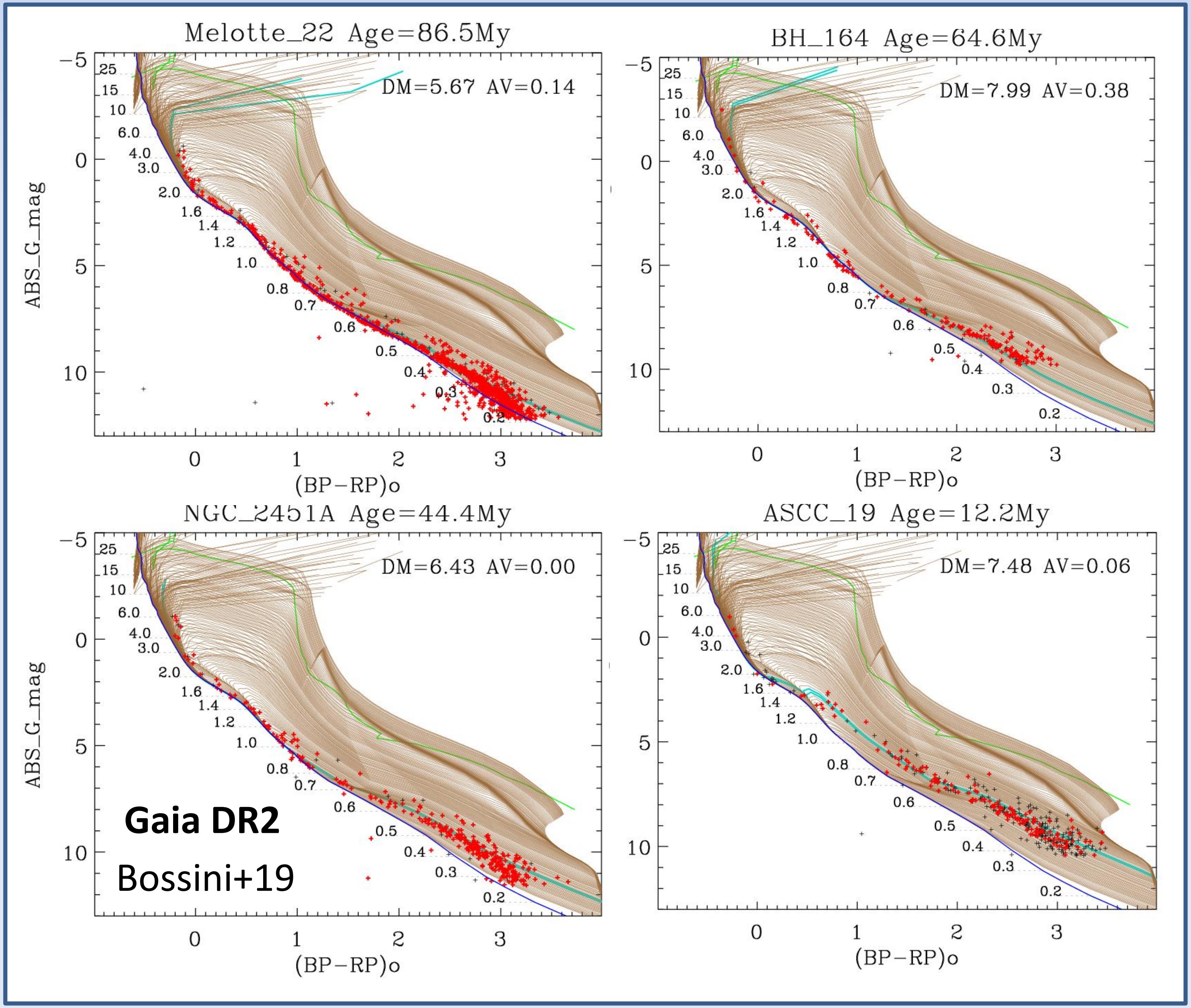
But that of metal poor systems as well
47Tuc (Fu+18)



Brown lines: PARSEC PMS tracks

Cyan line: PARSEC PMS track at Bossini+19 age

ZAMS & PMS Evolution



Models with Accretion

- accreting matter specific entropy = that of star surface
  (Hartmann+97; but see Stahler, Shu & Taam 1980, Stahler, Palla, Salpeter 1986)

  accretion luminosity $L_{acc} = \frac{GM\dot{M}}{R}(1 - \frac{R*}{R_{in}})$

- $L_{add} = \xi \frac{GM\dot{M}}{R}$ ξ: heat injection efficiency $0 \leq \xi \leq 1$ (Baraffe+09,12)
- $\frac{\partial L}{\partial M_r} = \varepsilon_n - T \frac{\partial S}{\partial t}|_{M_r} + \varepsilon_{add}$

- $\varepsilon_{add}(r) = \frac{L_{add}}{M} \times \max\left[0, \frac{2}{A^2}\left(\frac{M_r}{M} - 1 + A\right)\right]$ $0 \leq A \leq 1$

  $\varepsilon_{add} =$ 0 from the center to $\frac{M_r}{M} = 1-A$

  $\varepsilon_{add} \sim \frac{M_r}{M}$ from $\frac{M_r}{M} = 1-A$ to M

(Kunitomo+ 17)

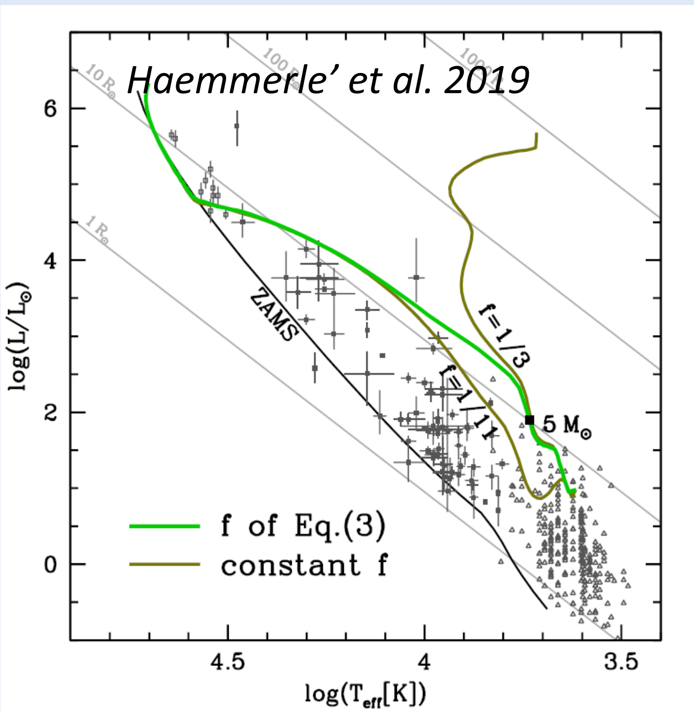
The accretion rate $\dot{M}$

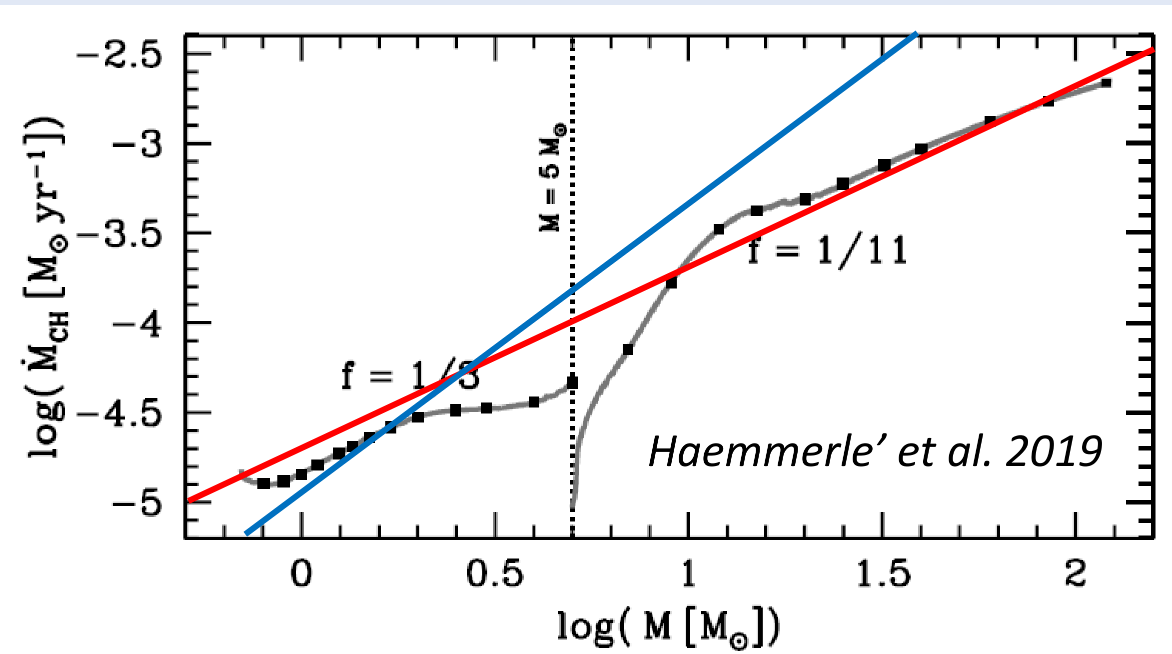
- Empirical relation between outflow and the bolometric luminosity L of source

CH:Churchwell(1999)-Henning(2001)

- Mass accretion rate □ to the mass outflow
- Calibration against observations provide *f* (Haemmerle' et al. 2019)

$$\dot{M} = f\,\dot{M}_{\rm disc} = \frac{f}{1-f}\,\dot{M}_{\rm out}$$





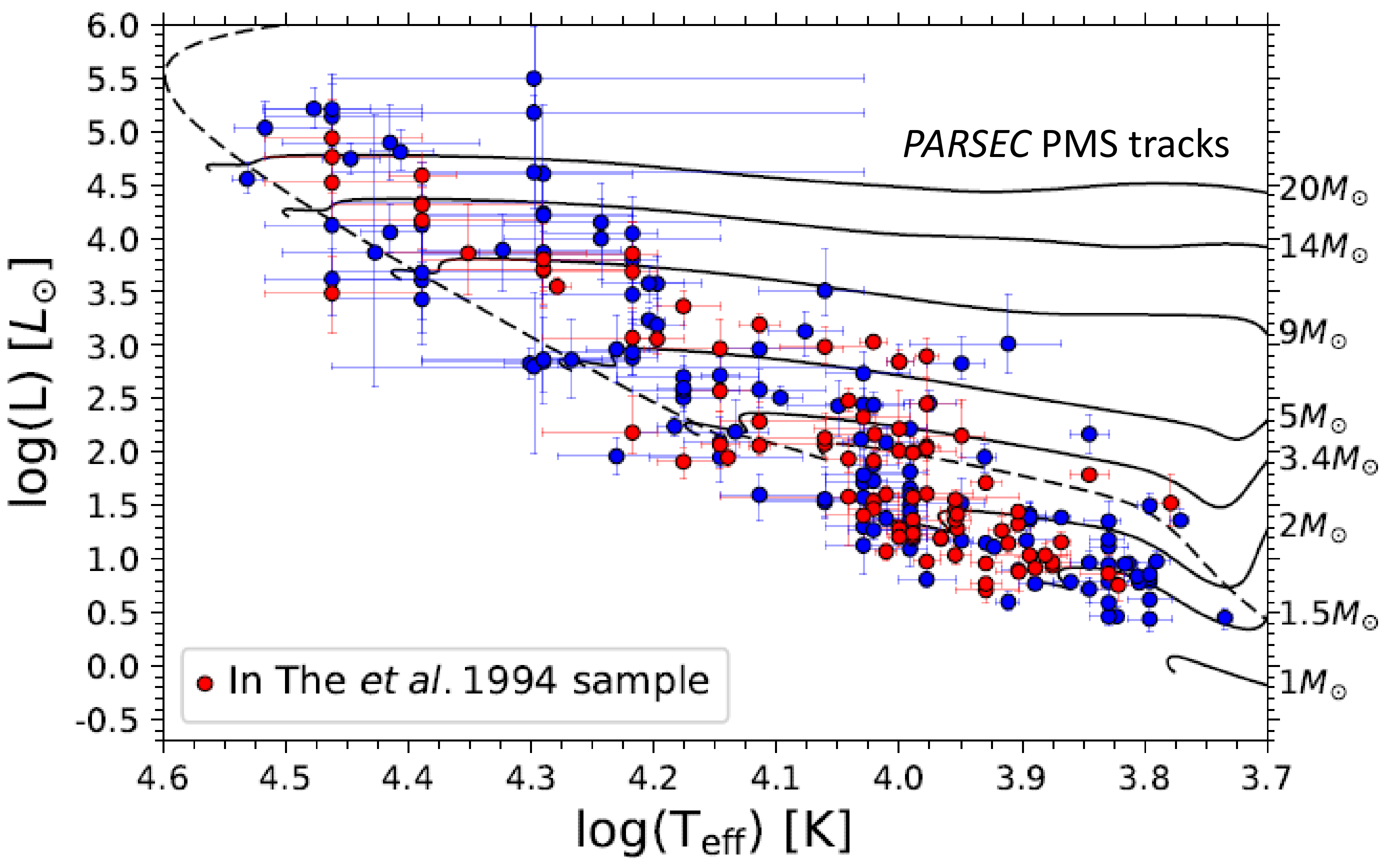
$\dot{M}$= 2 10^{-5} x M (e.g. Barentsen et al 11 ~ $M^{1.1}$)

- ❑ Adopted here:

$\dot{M}$= 10^{-5} x $M^{1.6}$ (Muzerolle +03; Natta+ 06 ~ M^2)

Gaia DR2 sample of Herbig Ae/Be stars

M. Vioque[1,2], R. D. Oudmaijer[1], D. Baines[3], I. Mendigutía[4], and R. Pérez-Martínez[2] 2018



Pre Main Sequence tracks

- The initial model is a hydrostatic contracting core with

  $M = 0.05\ M_\odot$

  $T_c \sim 10^5 K$

  $\rho_c \sim 0.03 g/cm^3$

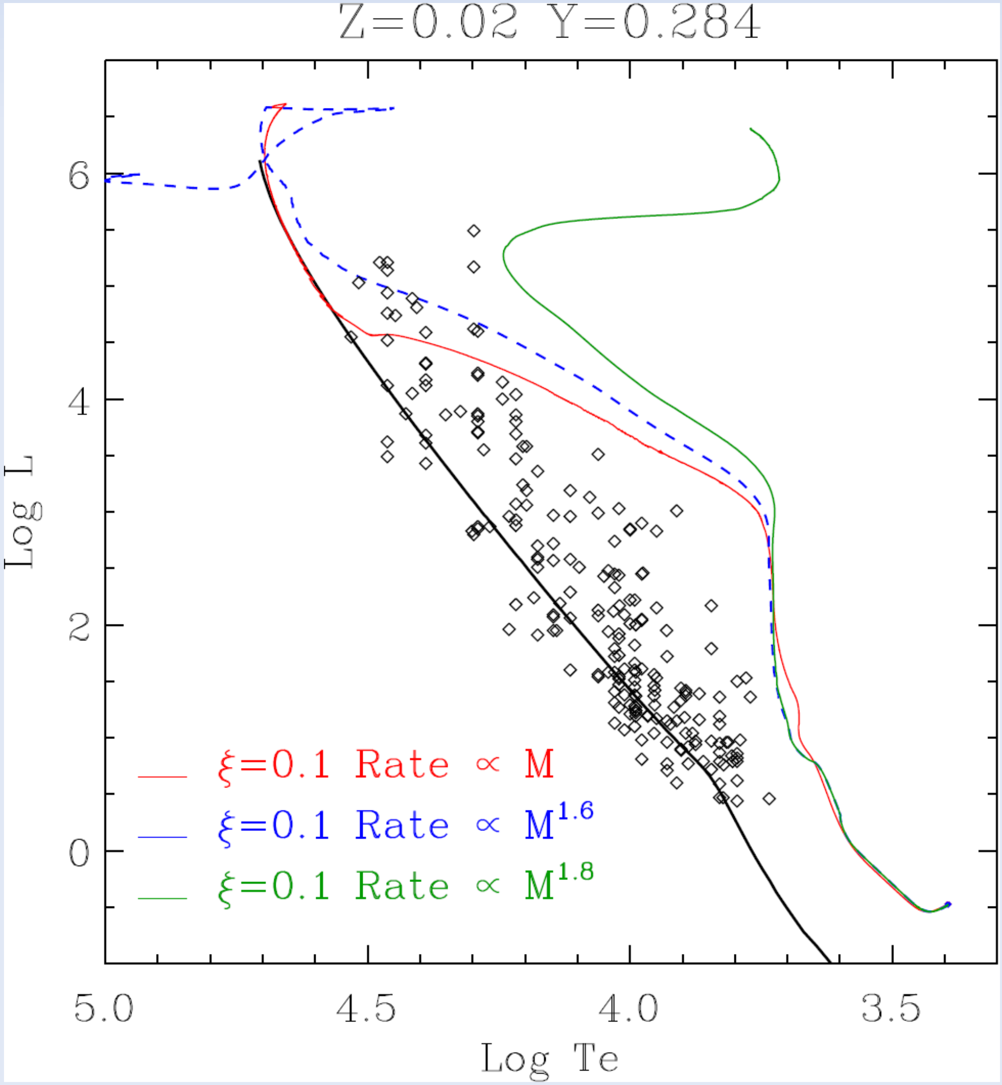
  $R \sim 3 R_\odot$

- The final mass of the sequence is $\sim$ 200 $M_\odot$

- Three values adopted for the exponent of the $\dot{M} \sim M^\alpha$ law:

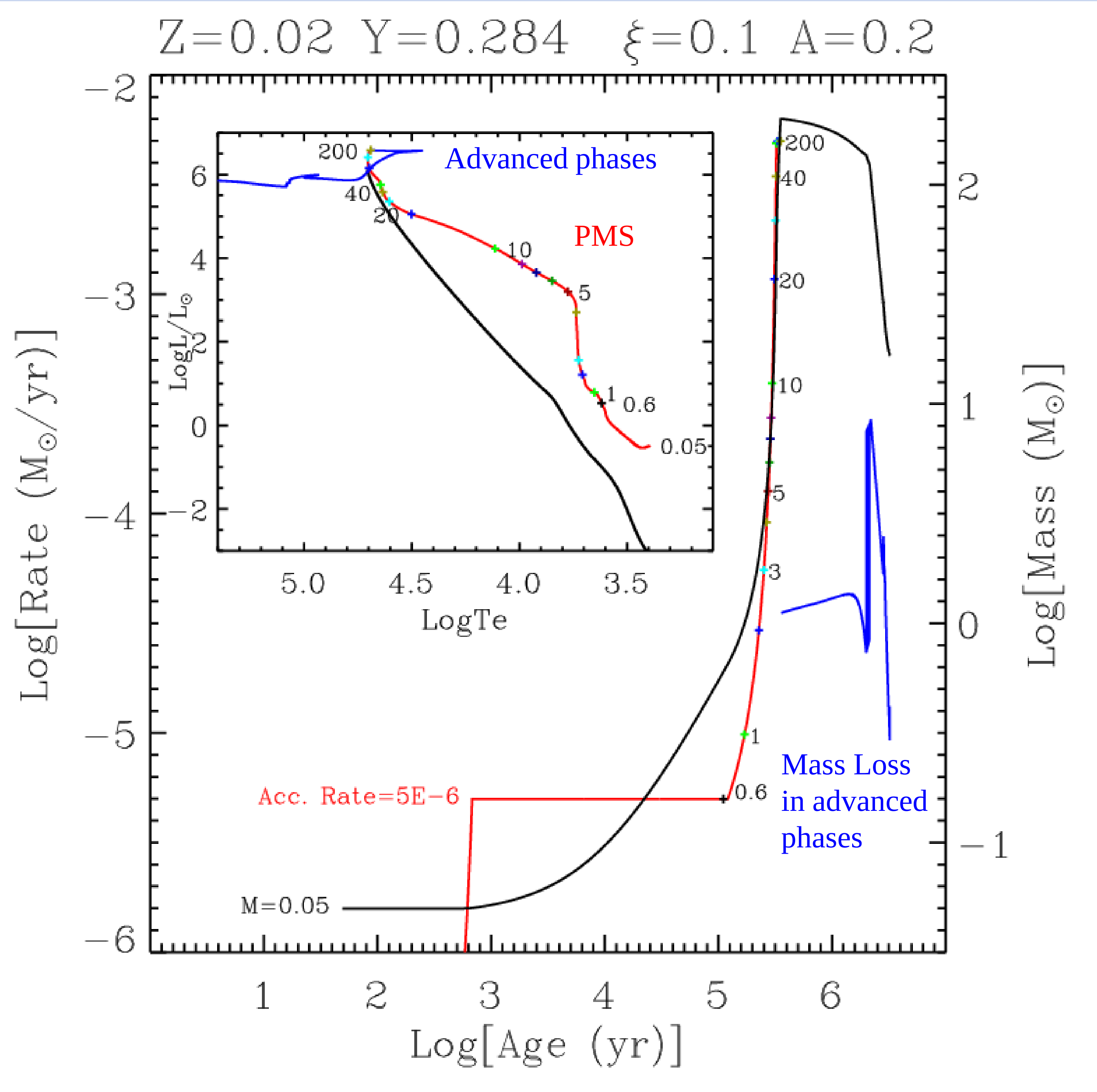
  α = 1, 1.6, 1.8

- ξ =0.1 $\quad L_{add} = \xi \dfrac{GM\dot{M}}{R}$

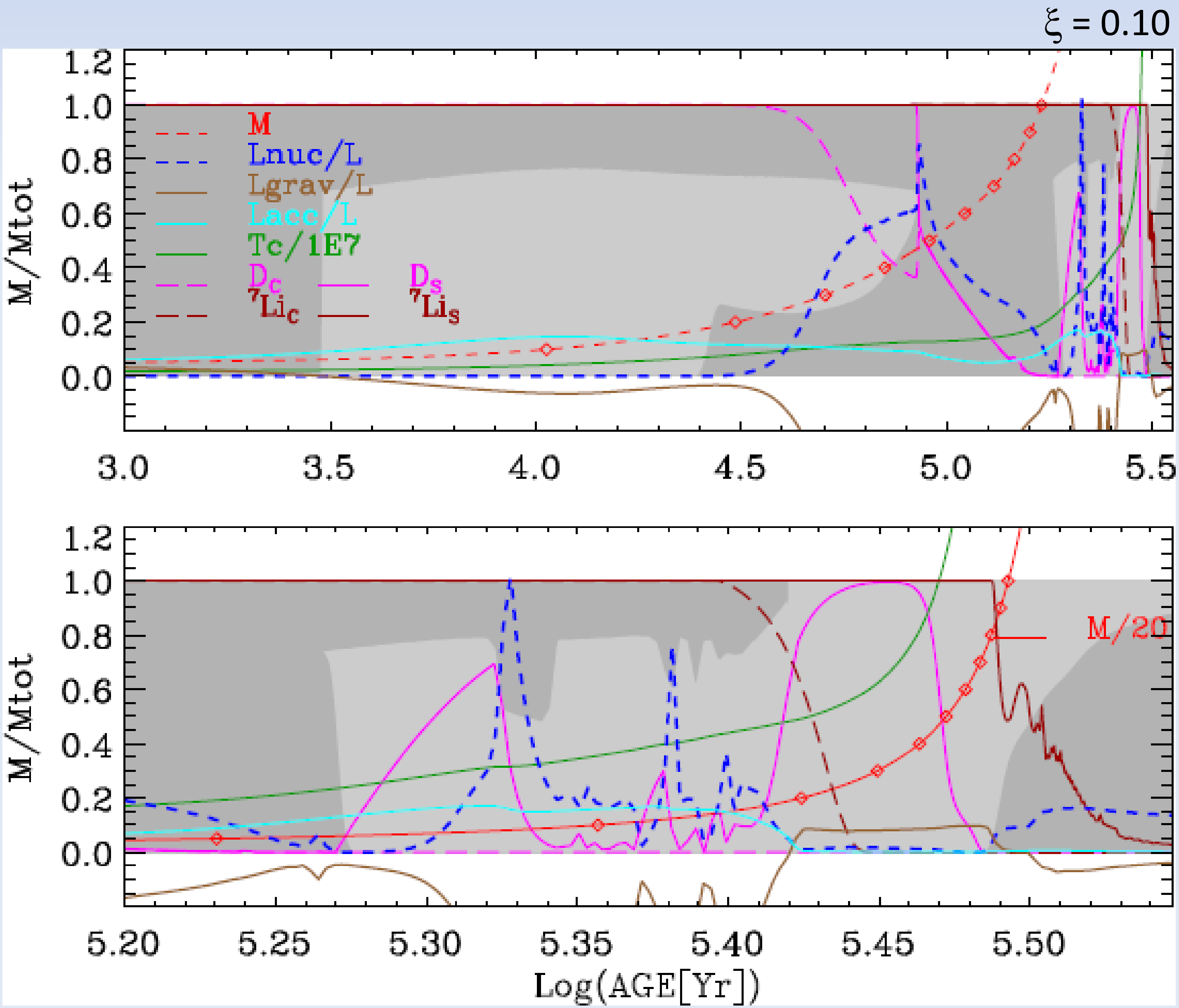


PMS:
accretion rate
and mass
as a function of time

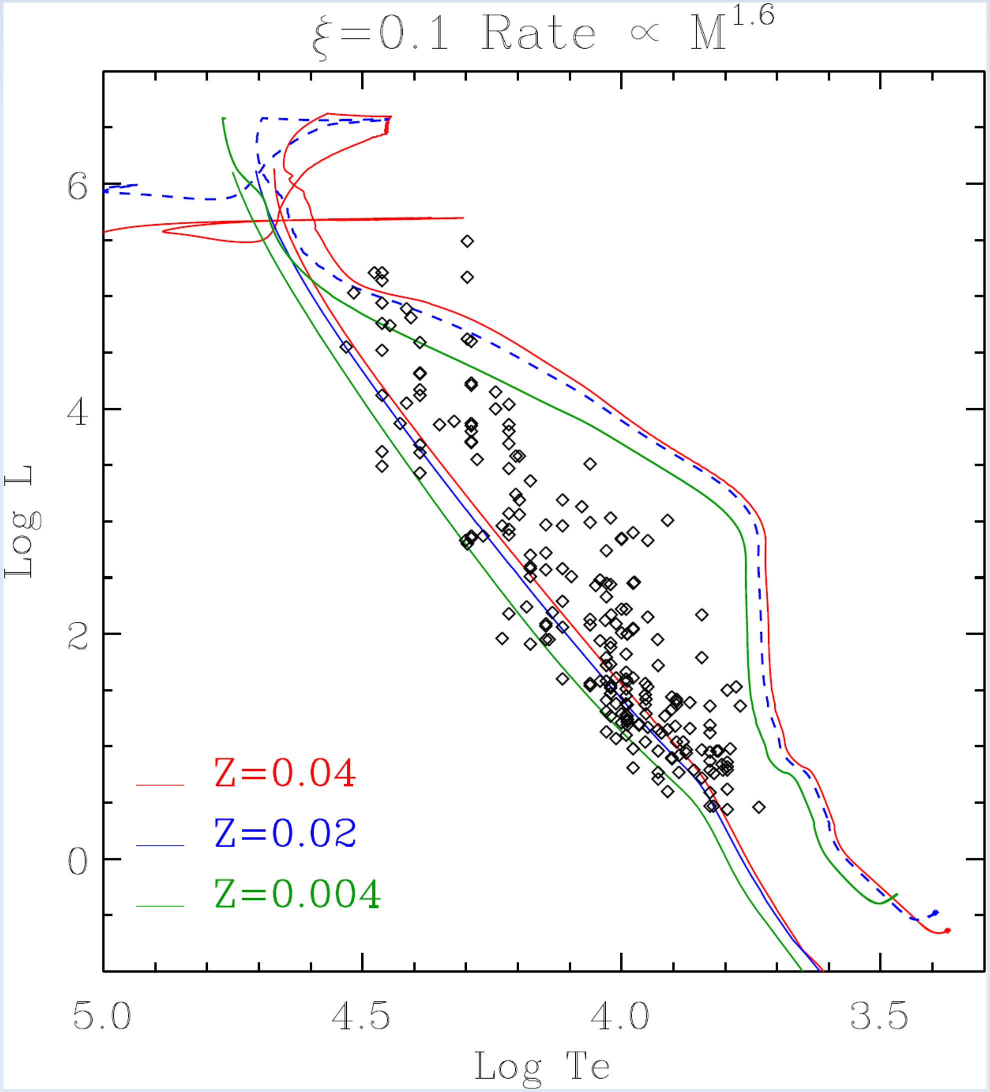
case with ξ =0.1



The internal structure



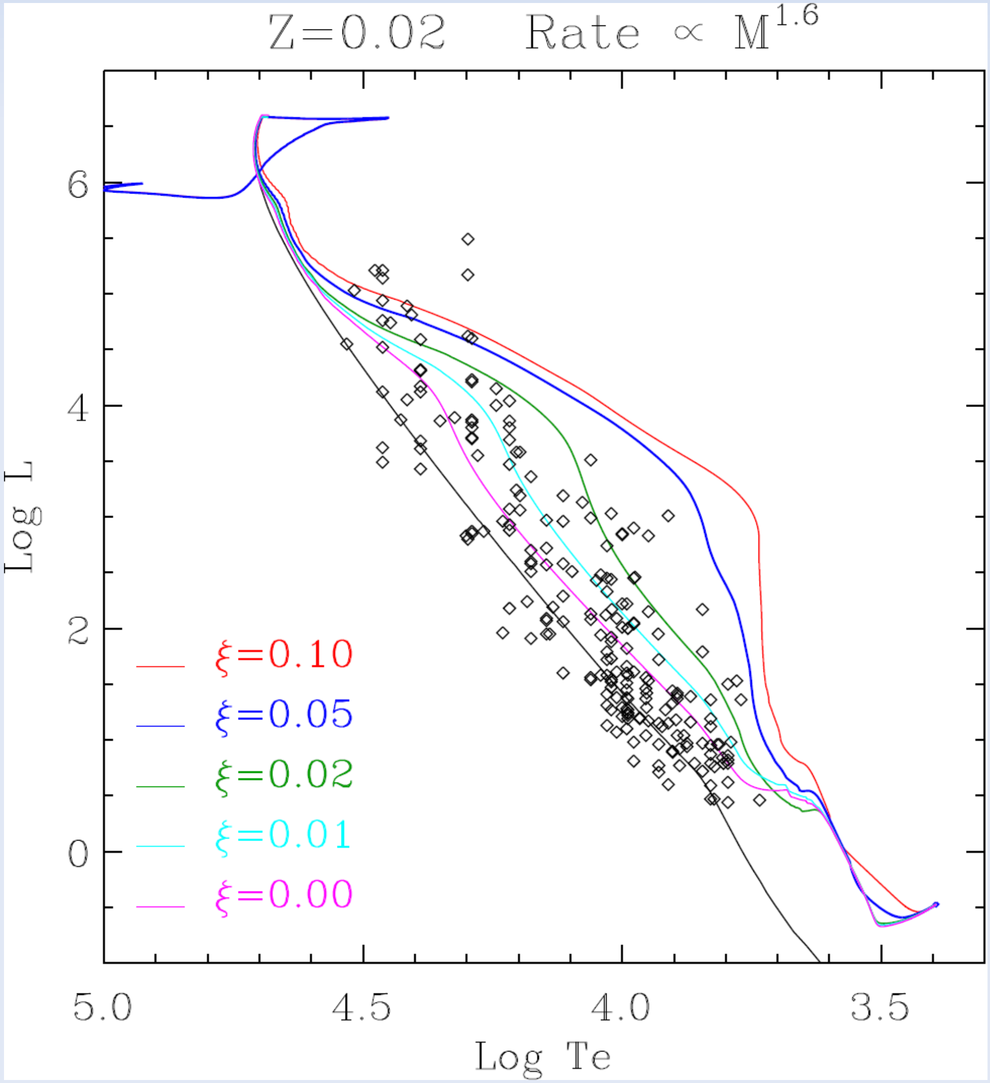
Metallicity Effects



Varying the heat injection efficiency ξ

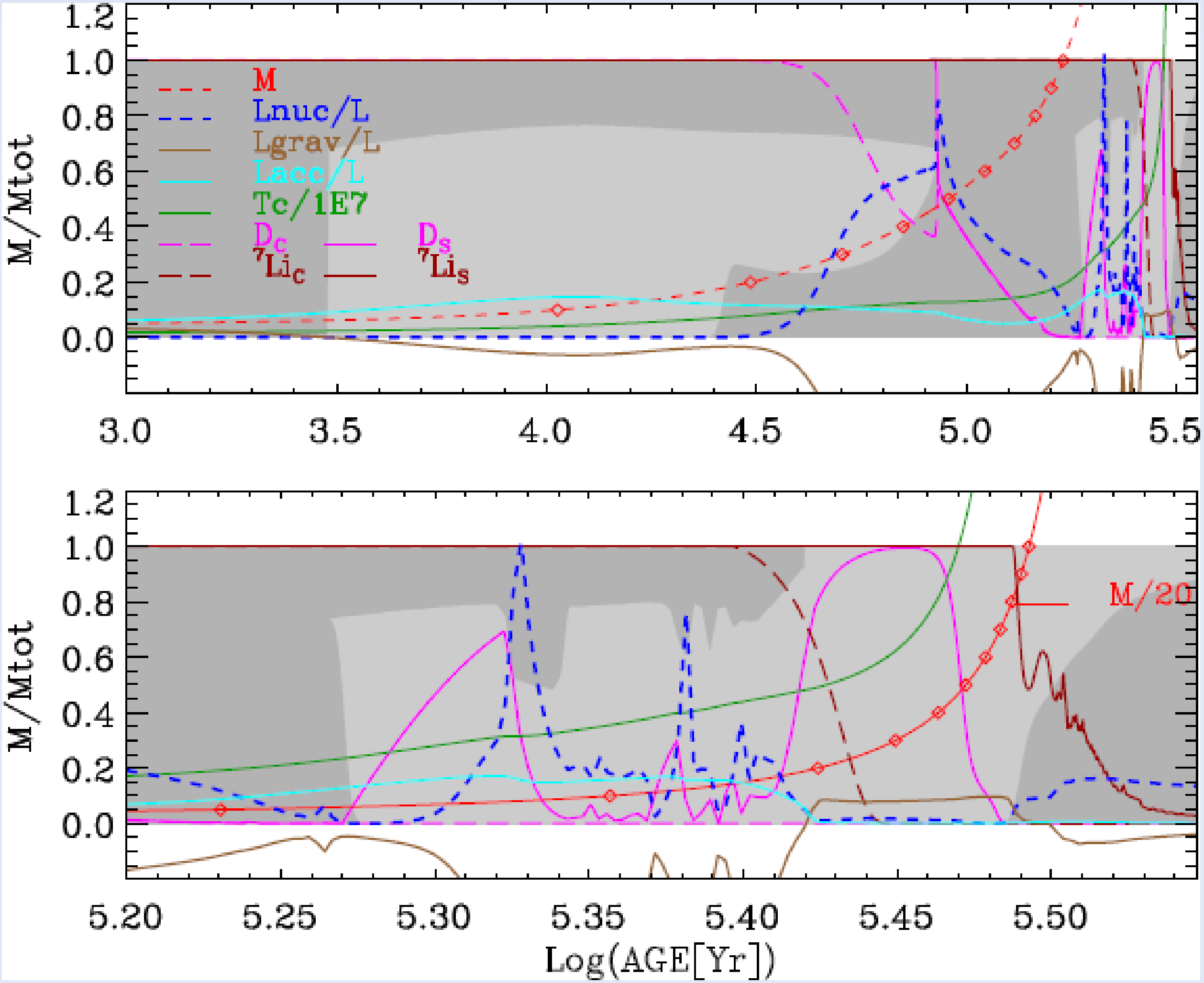
$$L_{add} = \xi \frac{GM\dot{M}}{R}$$

- Varying ξ changes the amount of heat absorbed by the star.
- The accretion rate is unaffected and so the rate of mass growth.
- The star reaches its final structure in the same time but its path in the HR diagram and internal structure are different.
- A better modelling should account for eventual feedback effects on the accretion rate, ξ and A.



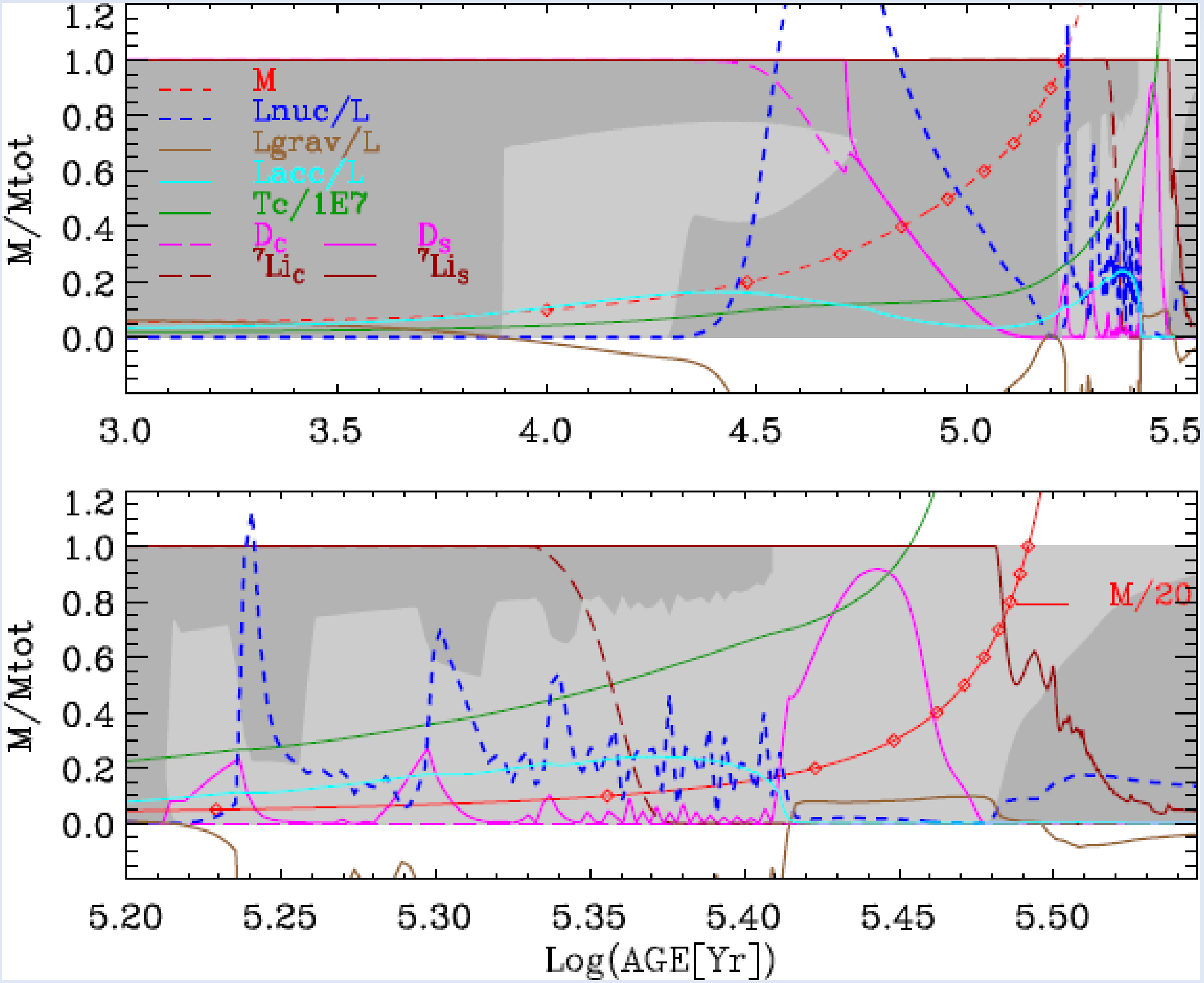
Varying the heat injection efficiency ξ

$\xi = 0.10$



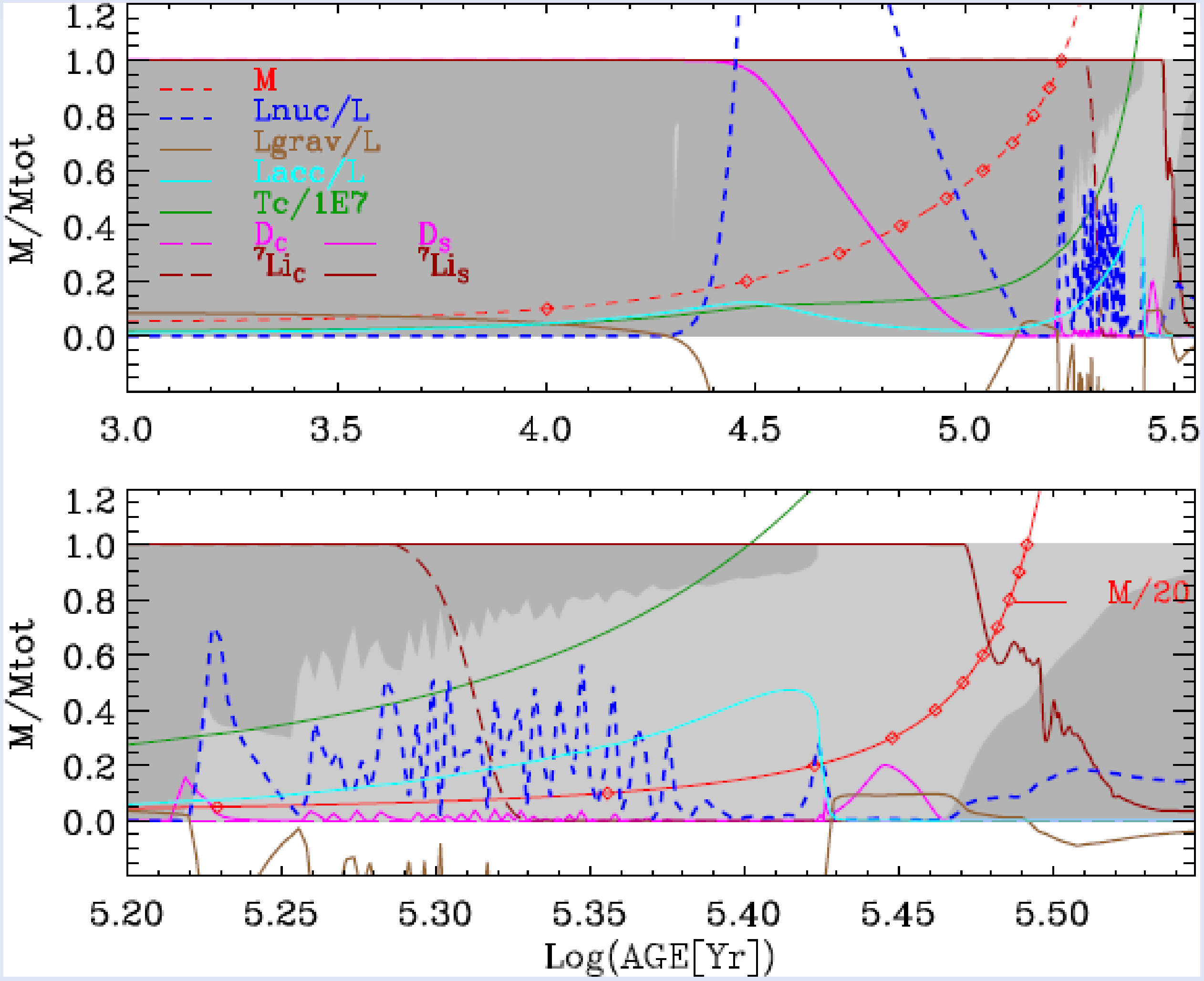
Varying the heat injection efficiency ξ

$\xi = 0.05$



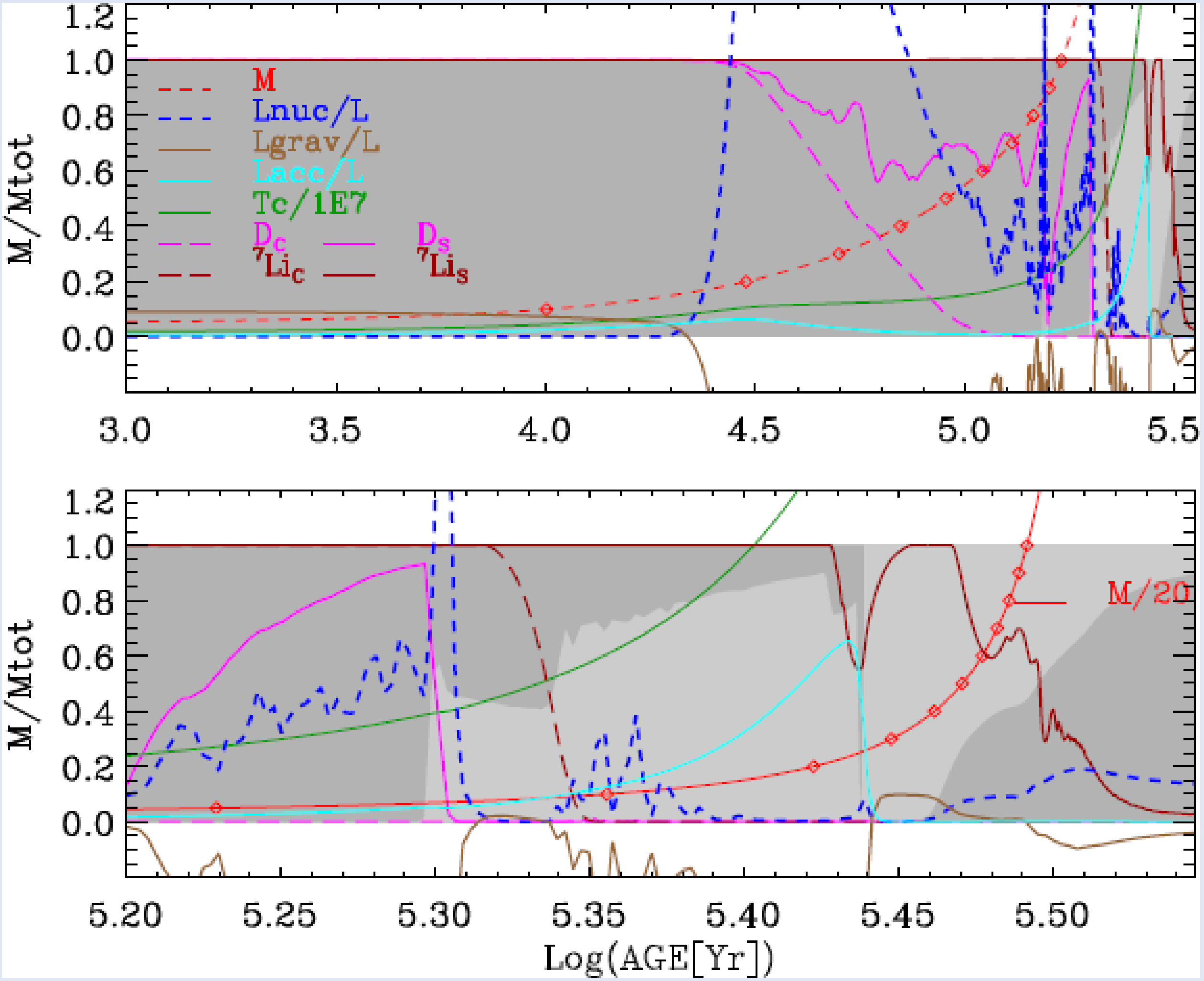
Varying the heat injection efficiency ξ

$\xi = 0.02$



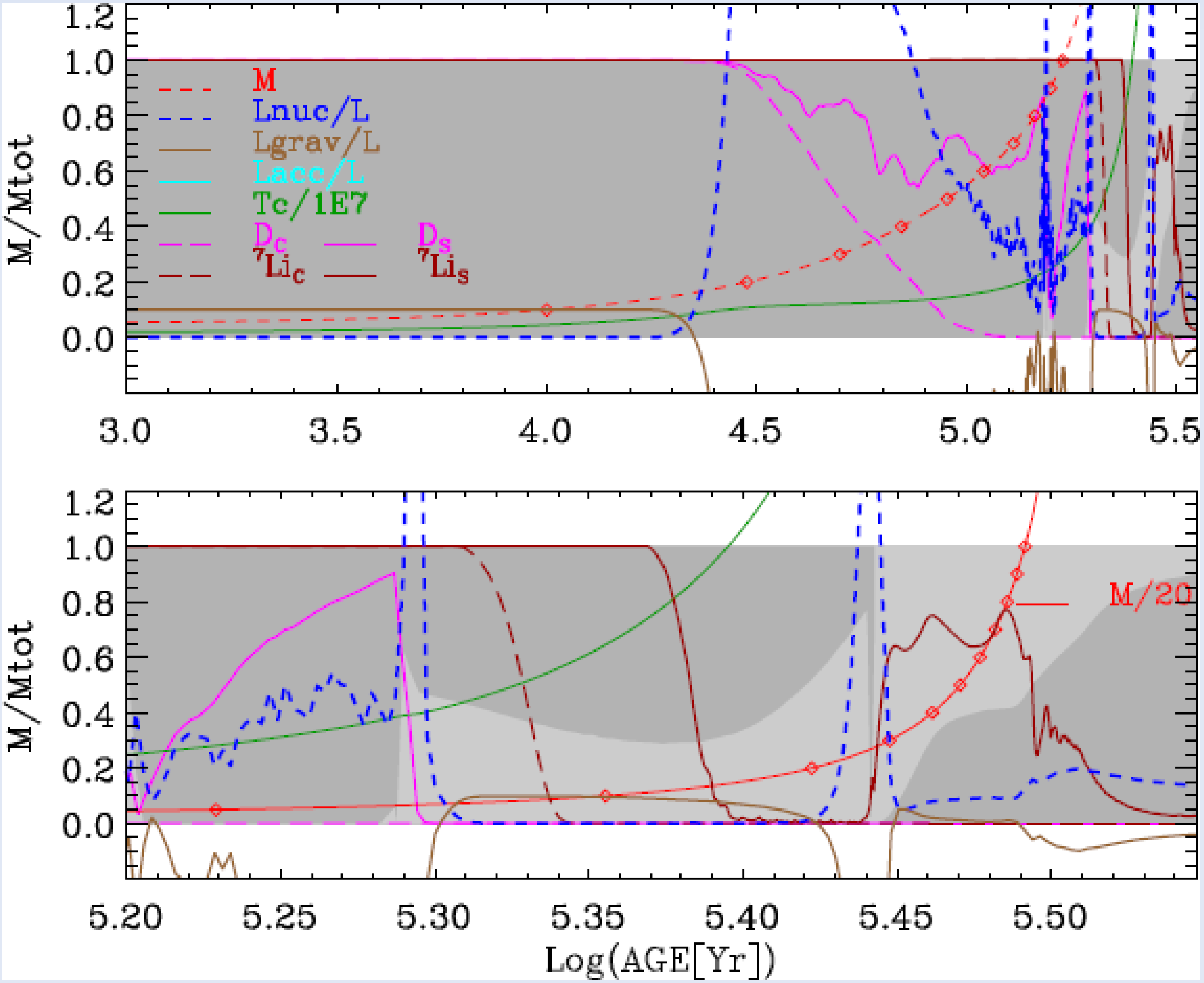
Varying the heat injection efficiency ξ

ξ = 0.01



Varying the heat injection efficiency ξ

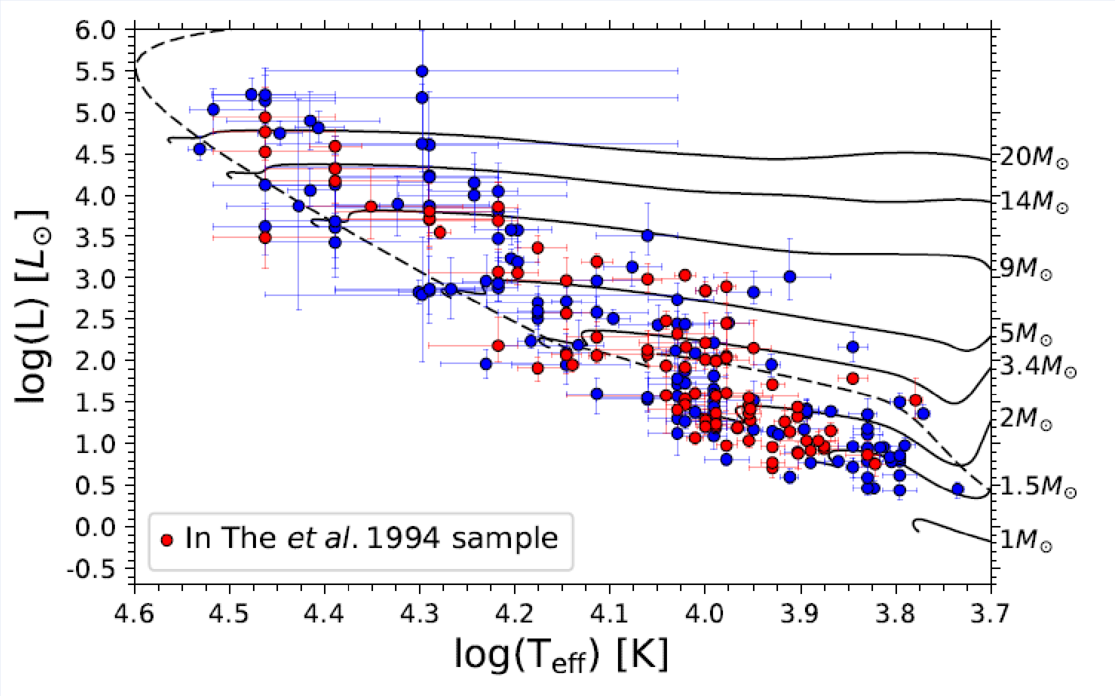
$\xi = 0$



What can be said on the evolutionary status of Herbig Ae/Be stars ?

Are constant mass models adequate to determine properties of such PMS stars?

Variation of accretion parameters may affect the location in the CMD.
Thus the derived properties could be different when accretion models are used.



From the PMS to the ZAMS

A typical path in presence of accretion

- PMS stars follow an accretion sequence until they reach critical conditions for accretion quenching, at a time t_b
- At this stage the PMS stars leave the accretion sequence
- Following evolution, toward ZAMS, determined by the time scale of the accretion quenching
- Assume an exponential decay of the accretion rate

$$\dot{M} = \dot{M}_b \; e^{-(t-tb)/\tau}$$

t_b **is the age on the birth line**

- By construction, this model requires to select the rightmost PMS sequence that surrounds all the observed data (with α = 1.6)
- Grids of evolutionary sequences with

α = 1.6

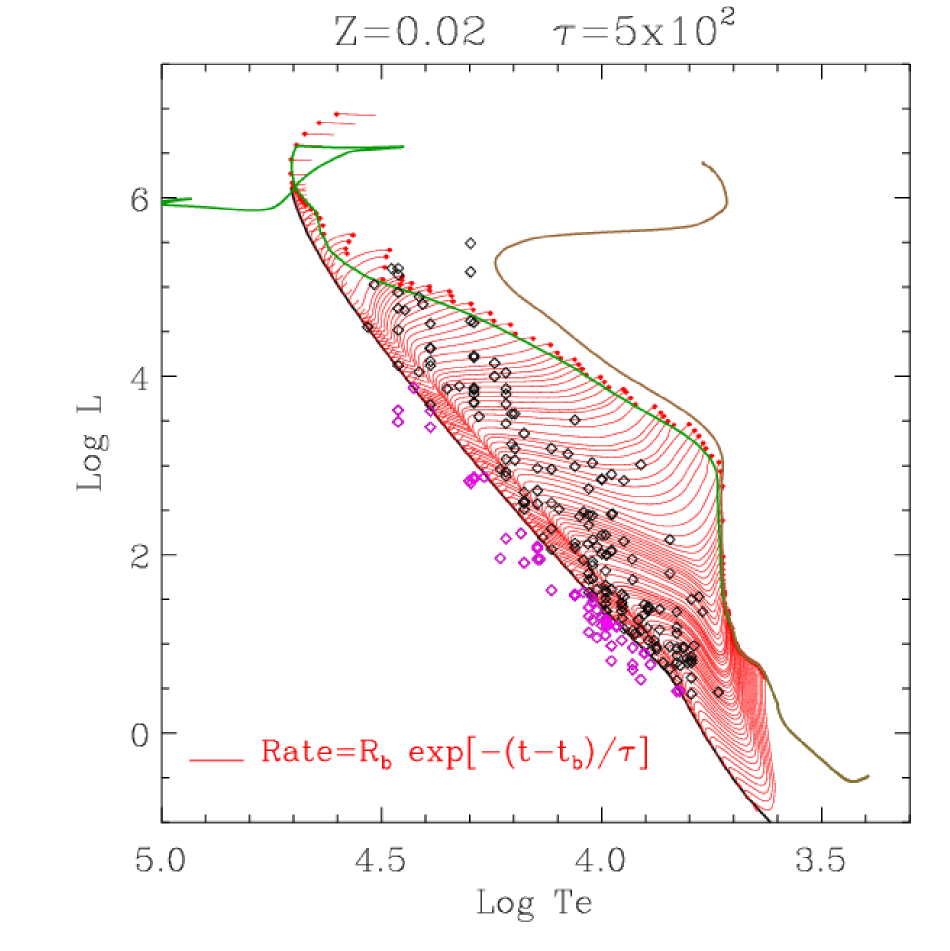
t_b from 5 10^2 yr to 10^6 yr

Z=0.02

From the PMS to the ZAMS

Grids of evolutionary sequences sufficiently populated to allow parameter extraction from best fits to data

Very simple algorithm for the best fit: nearest object because grid fine enough (wrt errors shown by Vioque+18)



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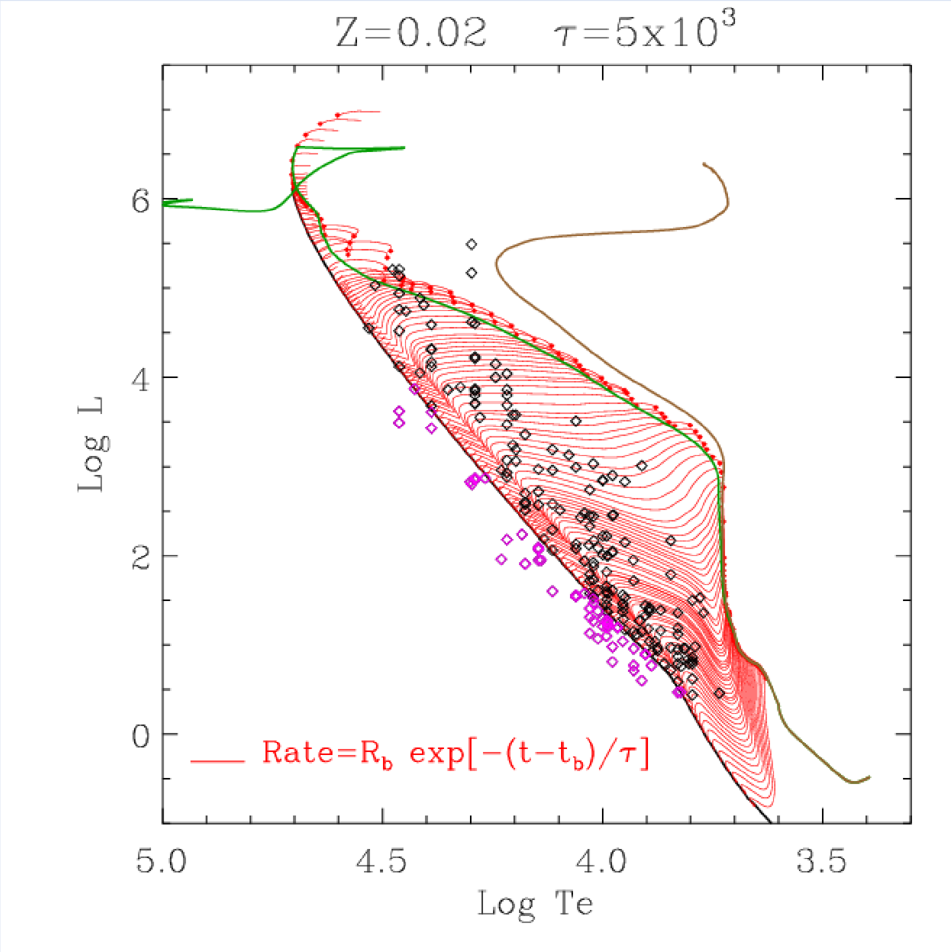

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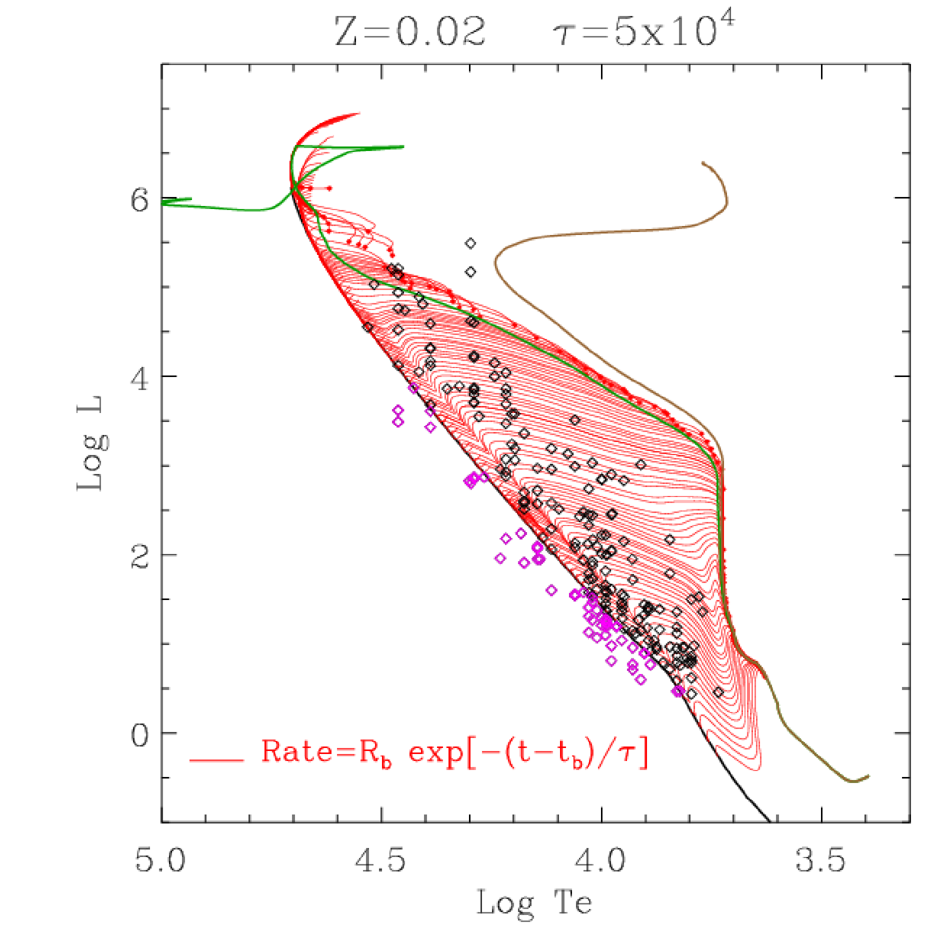

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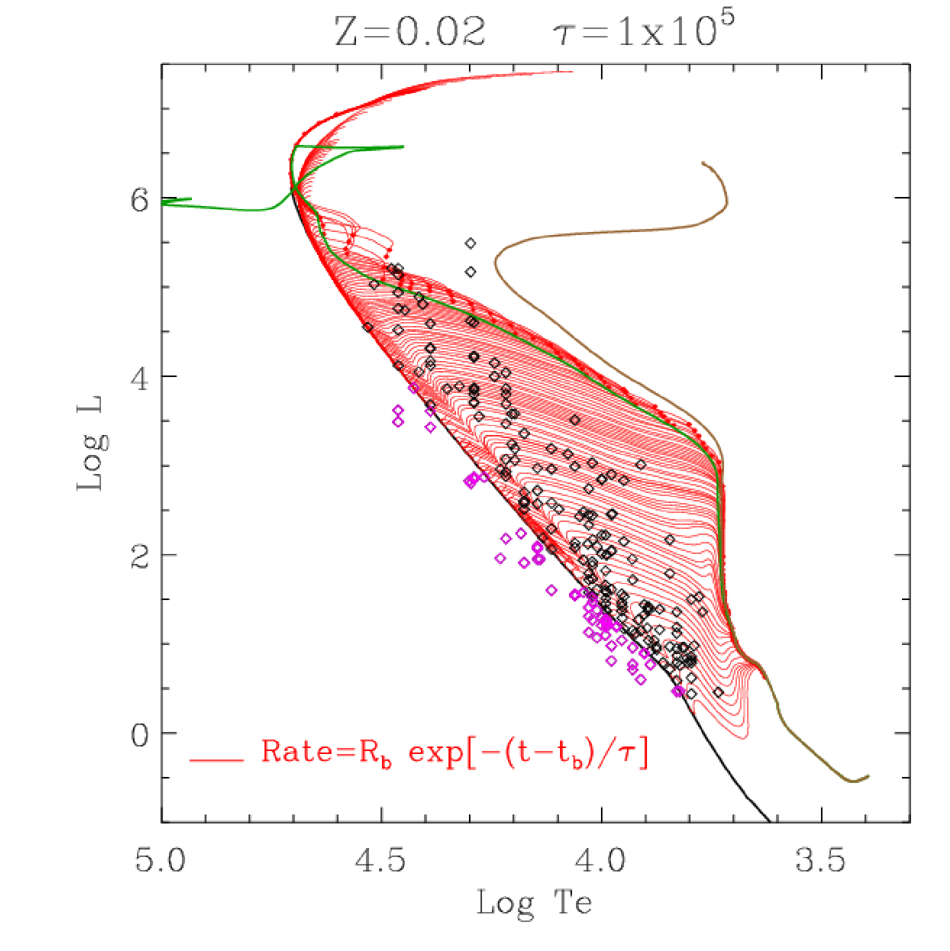

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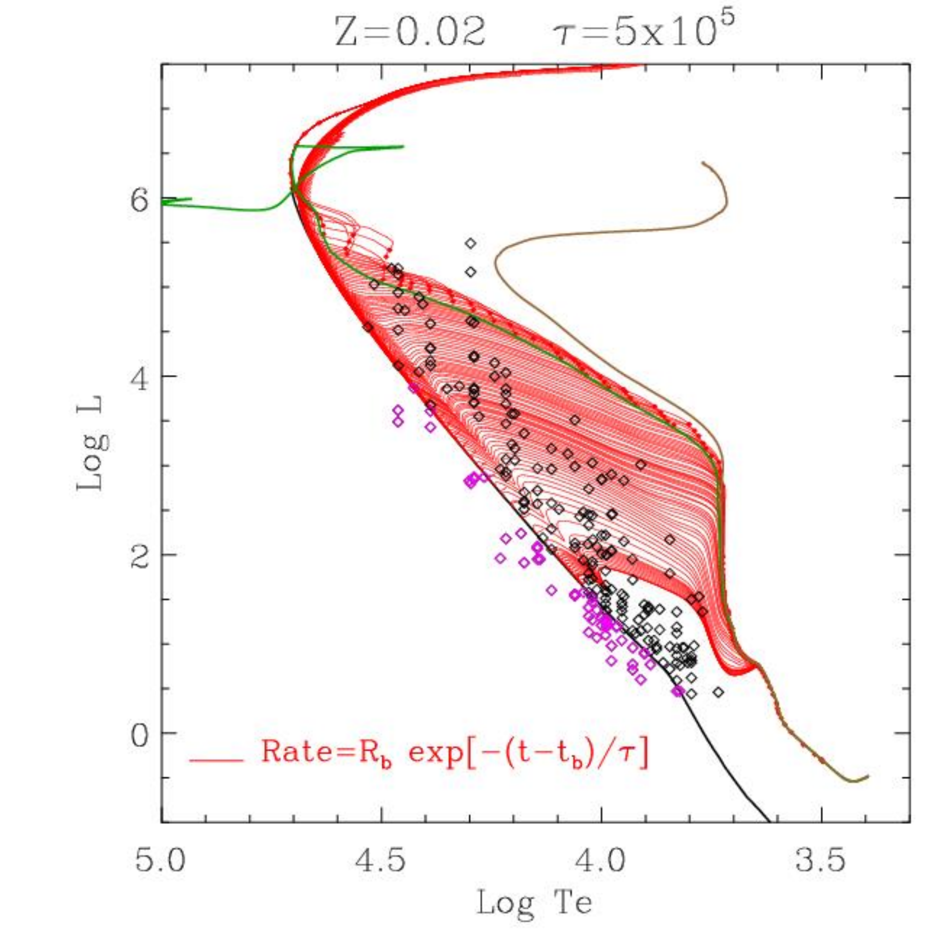
At the largest values of τ, models cannot overlay the data in spite of many additional models of lower mass added to the grid



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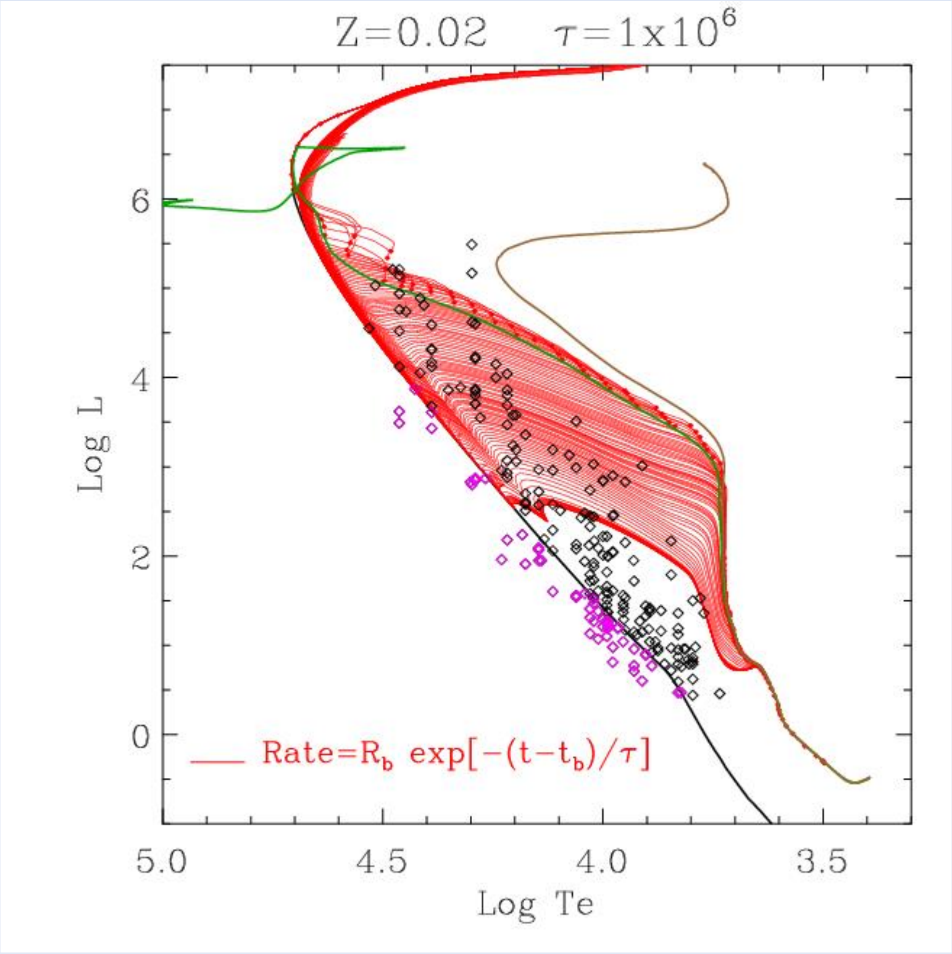
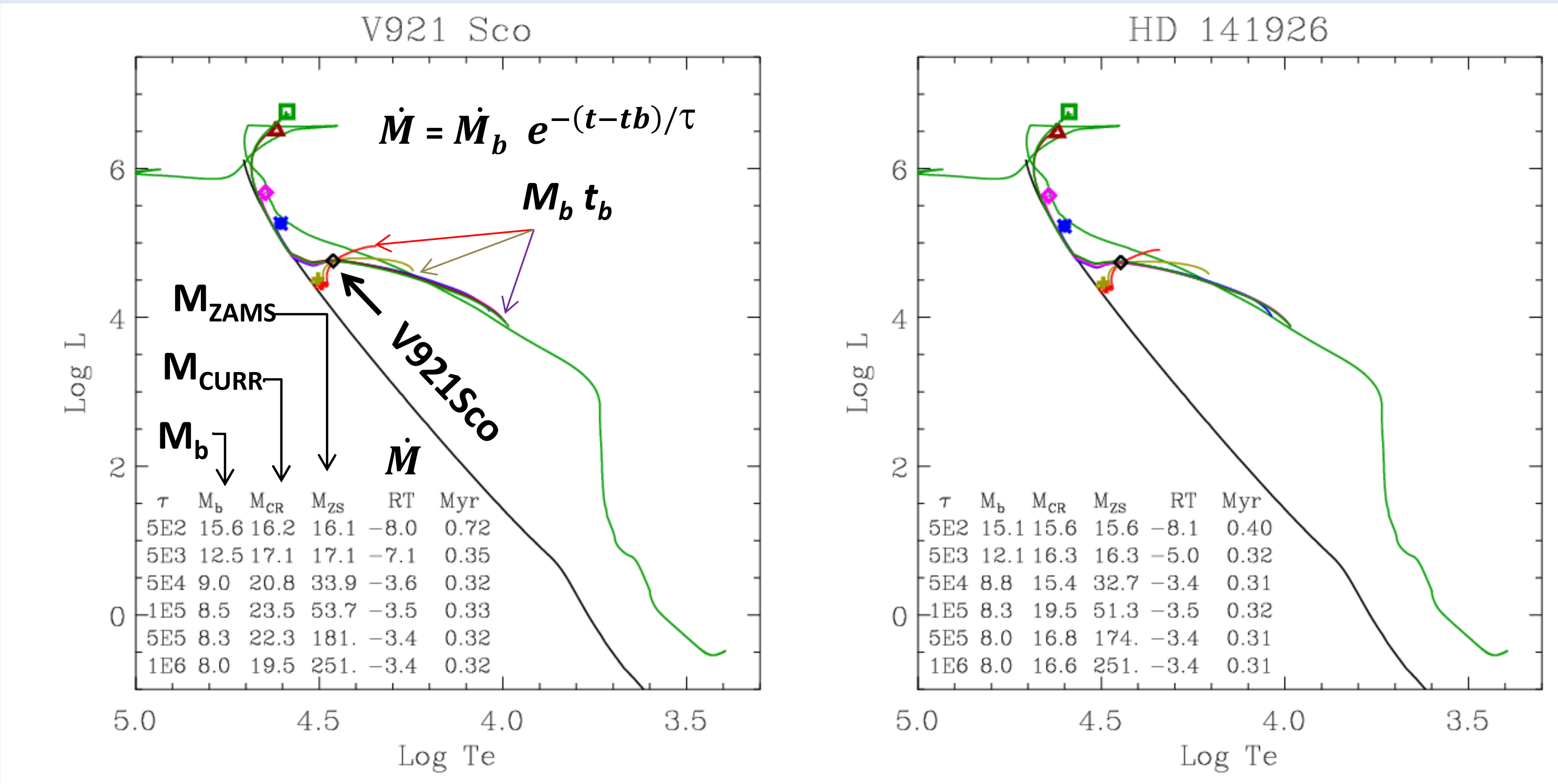


A few selected fits …



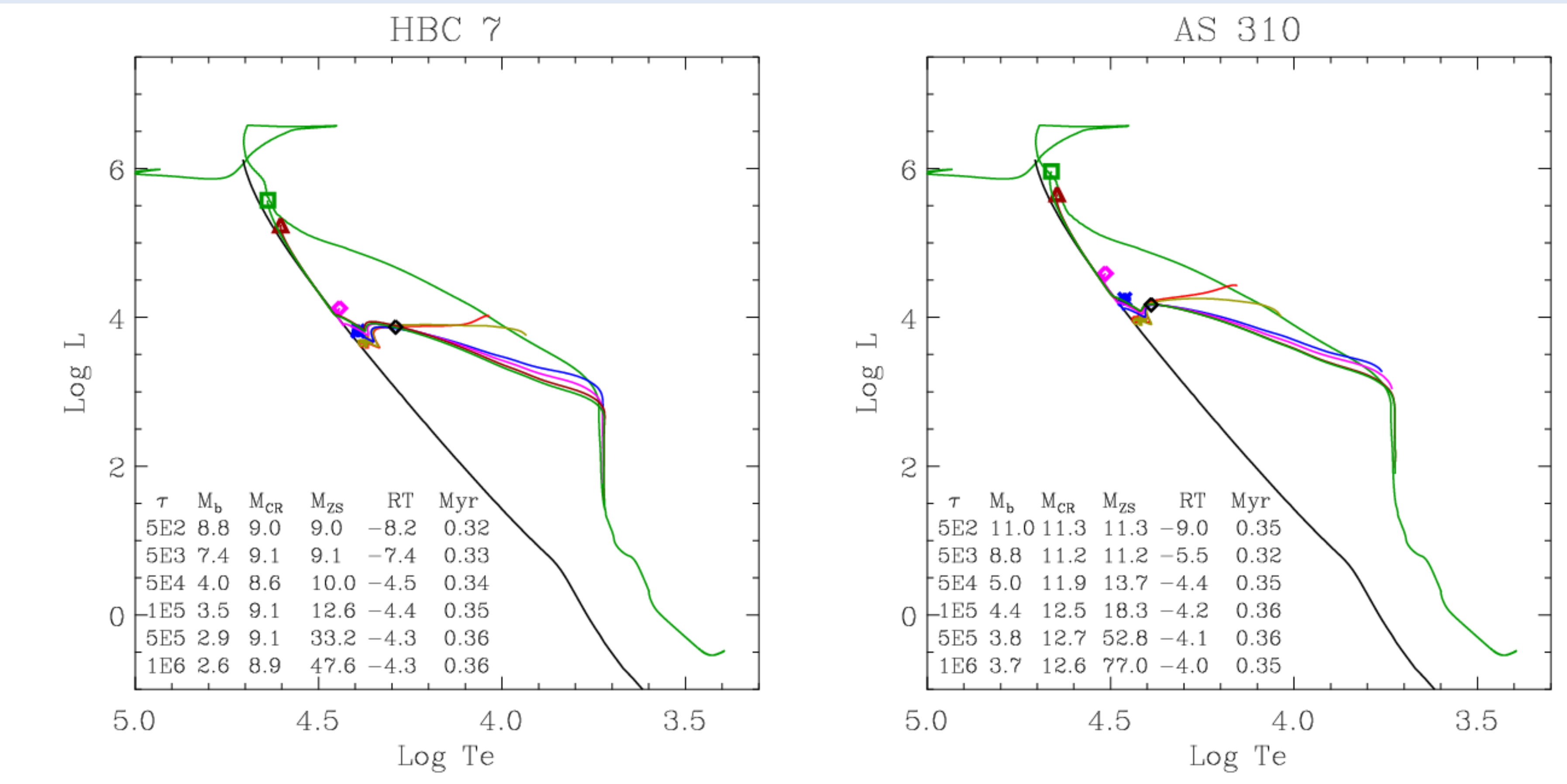
V921 Sco:

τ	M_b	M_{CR}	M_{ZS}	RT	Myr
5E2	15.6	16.2	16.1	−8.0	0.72
5E3	12.5	17.1	17.1	−7.1	0.35
5E4	9.0	20.8	33.9	−3.6	0.32
1E5	8.5	23.5	53.7	−3.5	0.33
5E5	8.3	22.3	181.	−3.4	0.32
1E6	8.0	19.5	251.	−3.4	0.32

HD 141926:

τ	M_b	M_{CR}	M_{ZS}	RT	Myr
5E2	15.1	15.6	15.6	−8.1	0.40
5E3	12.1	16.3	16.3	−5.0	0.32
5E4	8.8	15.4	32.7	−3.4	0.31
1E5	8.3	19.5	51.3	−3.5	0.32
5E5	8.0	16.8	174.	−3.4	0.31
1E6	8.0	16.6	251.	−3.4	0.31

A few selected fits …



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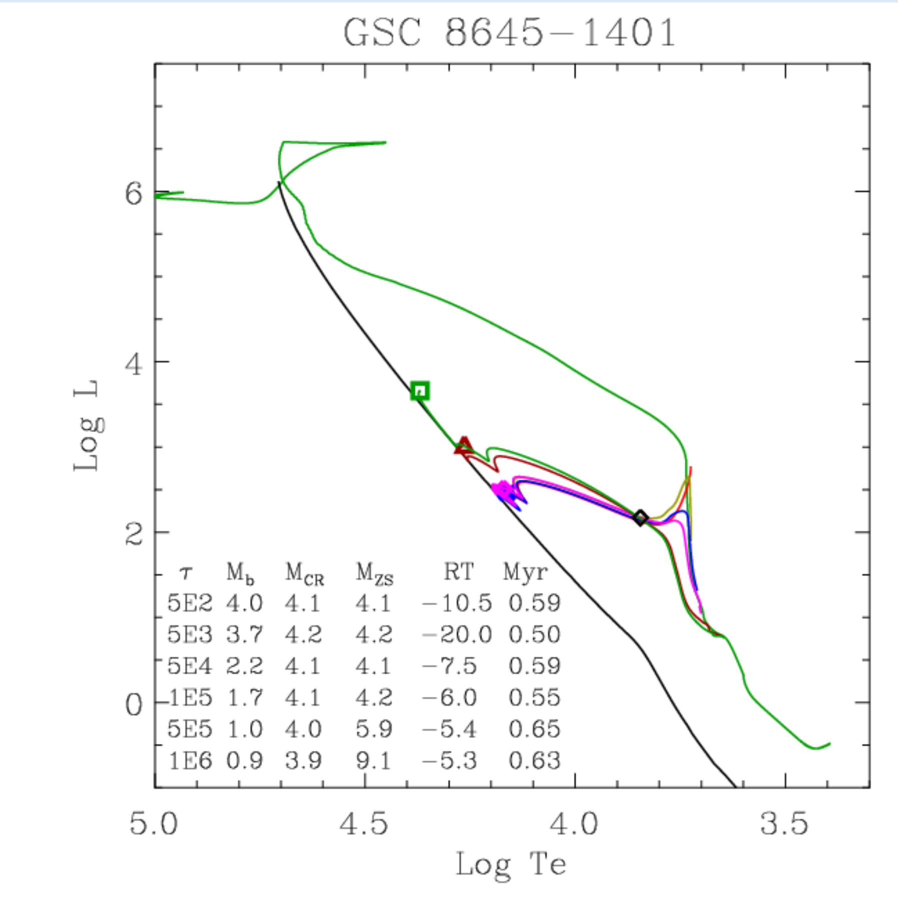
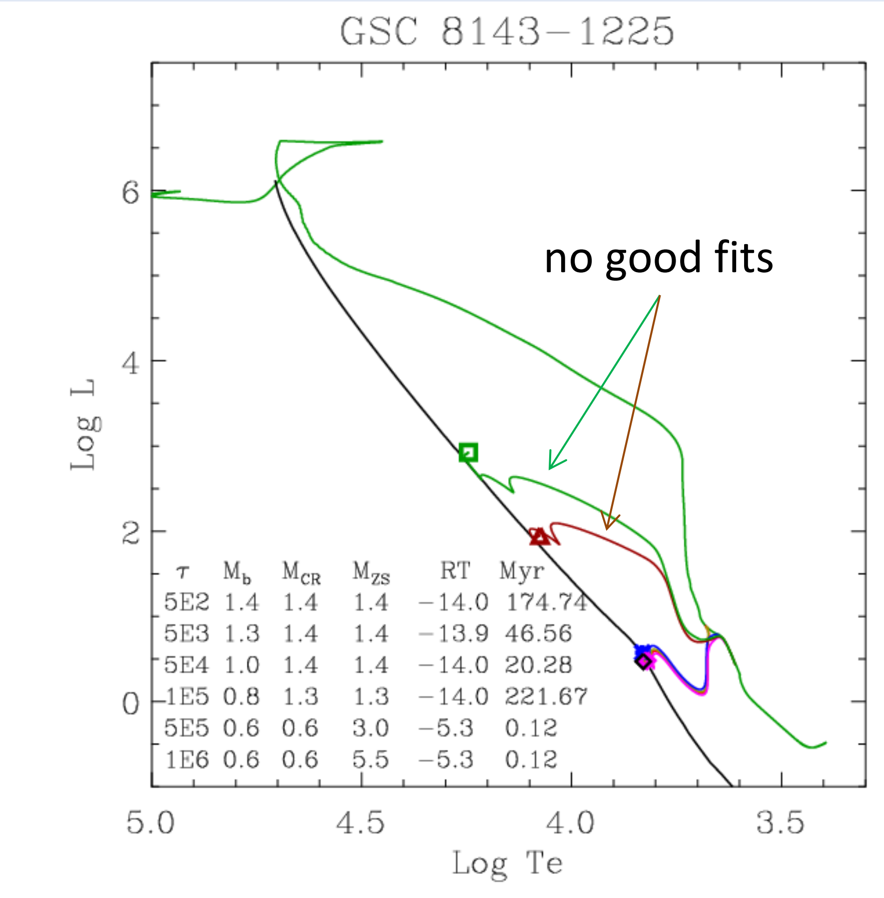




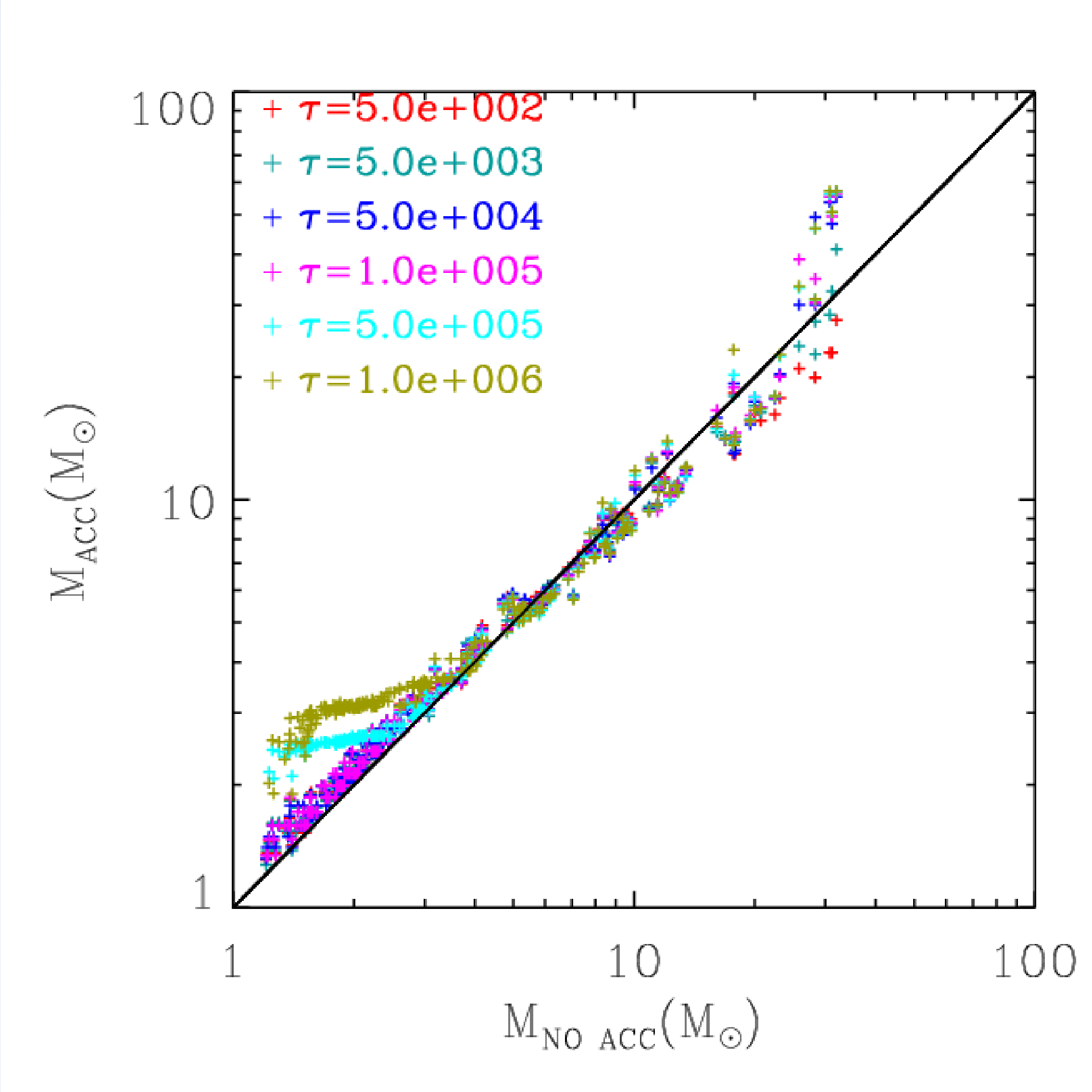
Accretion vs Standard models

Current Masses (M_{curr})

$M_{NO\ ACC}$: values are taken from compilation of Vioque+18 (PARSEC/no acc/Z=0.01)

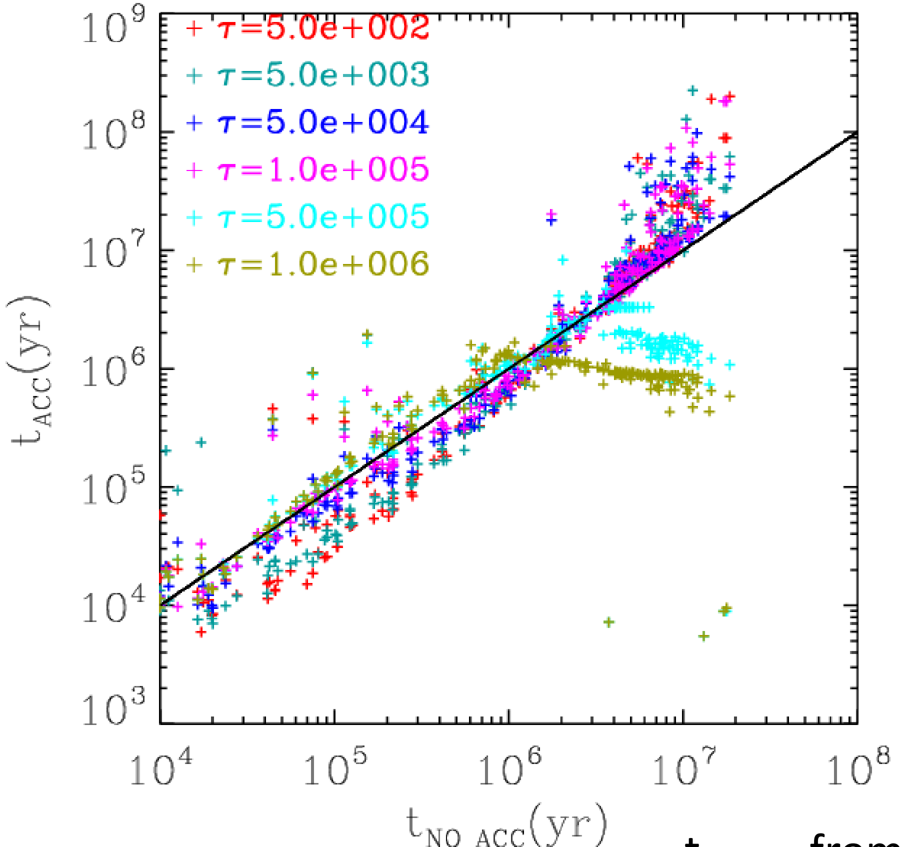
M_{ACC} : our estimates with new PARSEC models with accretion

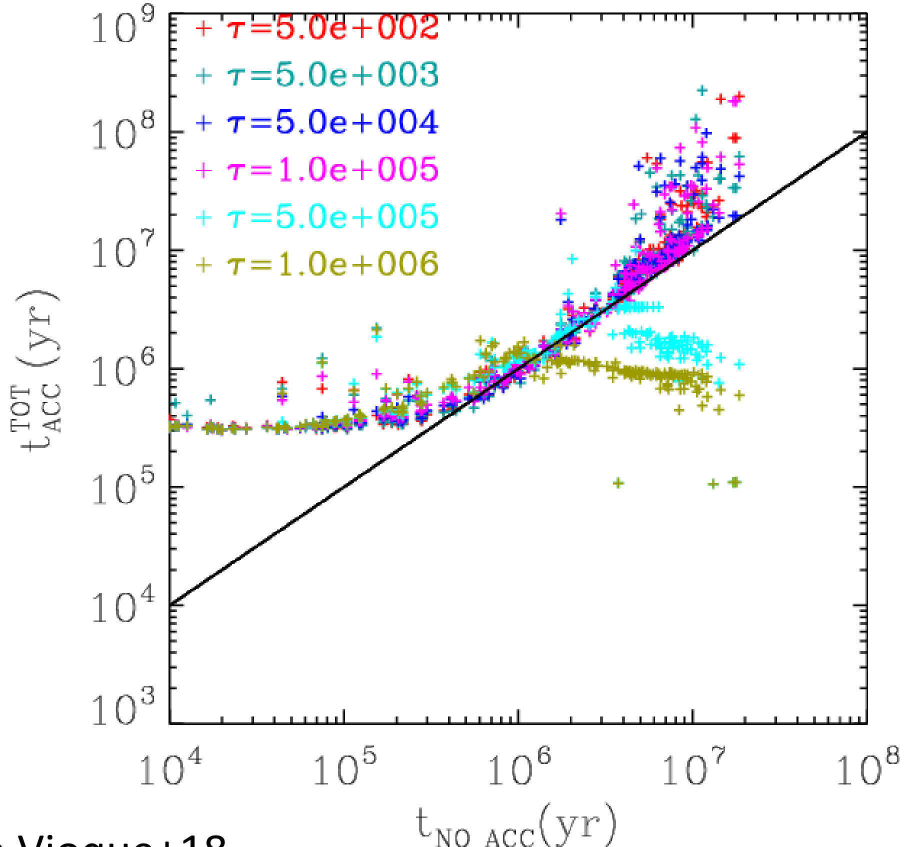
Mass estimates from different models are in fairly good agreement !



Accretion vs Standard models
AGES

$t_{ACC} = t - t_b$ $\qquad$ $t^{TOT}_{ACC} = (t - t_b) + t_b$





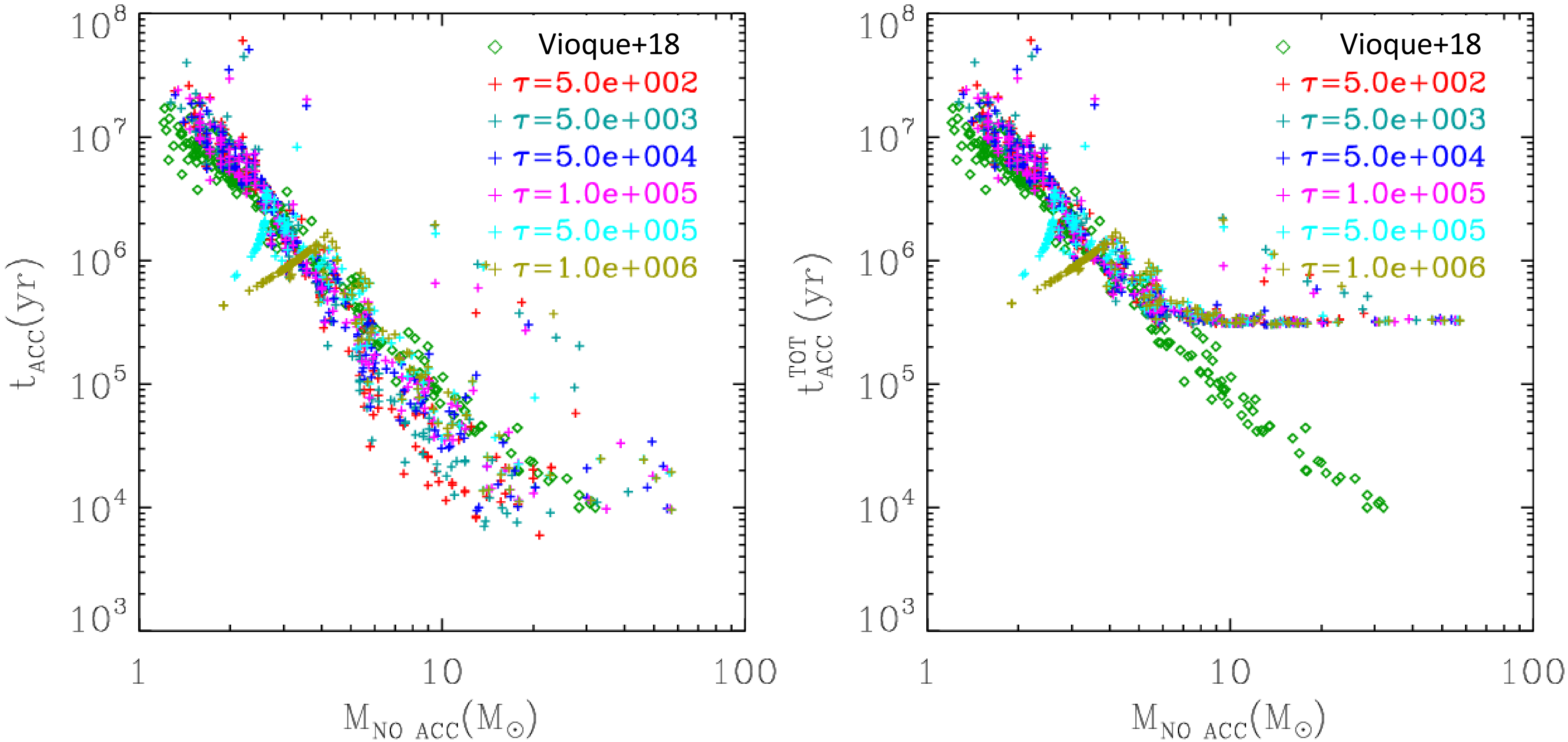
$t_{NO\ ACC}$ from Vioque+18

Accretion vs Standard models

Age vs MASS

$t_{ACC} = t - t_b$

$t_{ACC}^{TOT} = (t - t_b) + t_b$



Predicted vs Observed Hα Luminosity

- **Model Hα** luminosity derived from the accretion rate inverting existing empirical relationships (see also magnetospheric accretion models e.g. Hartmann+94, Muzerolle+98)

$$Log\left(\frac{Lacc}{L_\odot}\right) = a + b * Log\left(\frac{LH\alpha}{L_\odot}\right)$$

a	b		
2.09 ± 0.06	1.00 ± 0.05	Herbig Ae/Be stars	(Fairlamb+17)
1.50 ± 0.26	1.12 ± 0.07	CTTs	(Alcala' +14)
1.93 ± 0.23	1.13 ± 0.07	CTTs	(Barentsen+11)

- Accretion rates for individual objects fitted by evolutionary models depend on the rates decay law (e.g. e-folding time)

Observed Hα Luminosity of Vioque+18 objects obtained from:

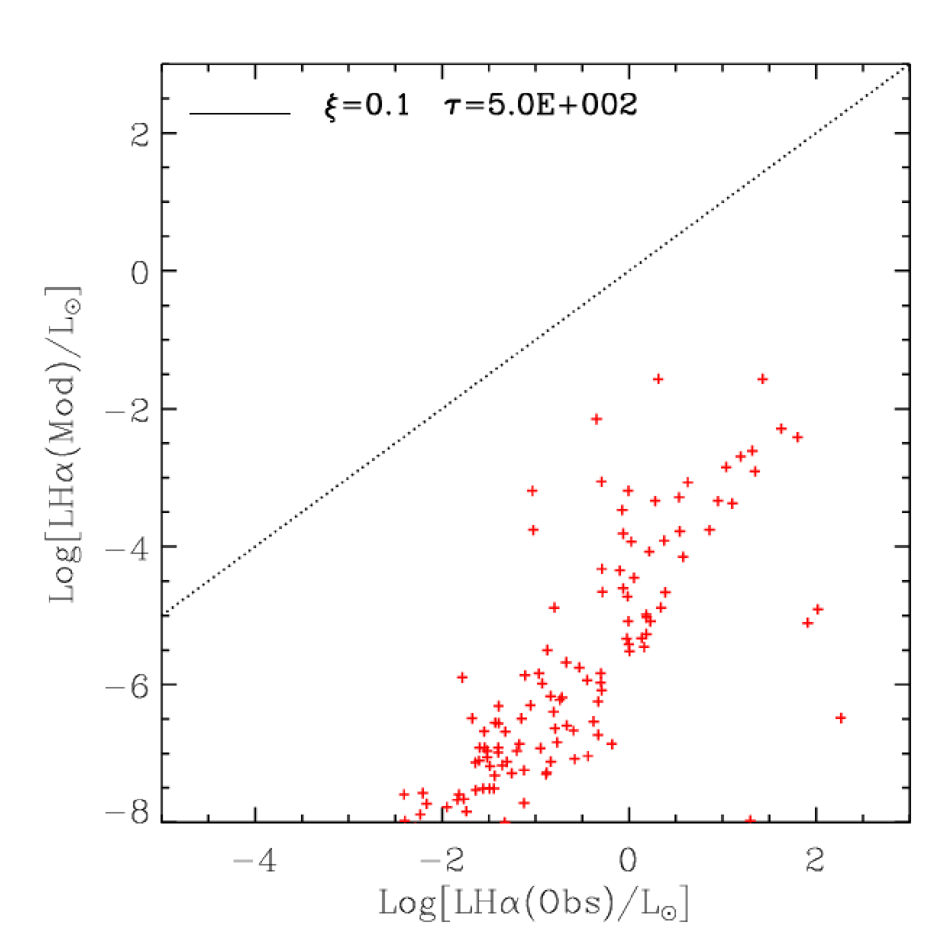
- EW(Hα) -corrected for photospheric absorption (Fairlamb+17, Vioque+18)-
- Hα continuum from SPECTRA(Teff, g, Lum) e.g. Lejeune+96; Munari+05

Predicted vs Observed Hα Luminosity

Adopted relation is Fairlamb+17:

$$Log\left(\frac{LH\alpha}{L_\odot}\right)_{model} = -2.1 + Log\left(\frac{Lacc}{L_\odot}\right)$$

Very similar results using Barentsen+11



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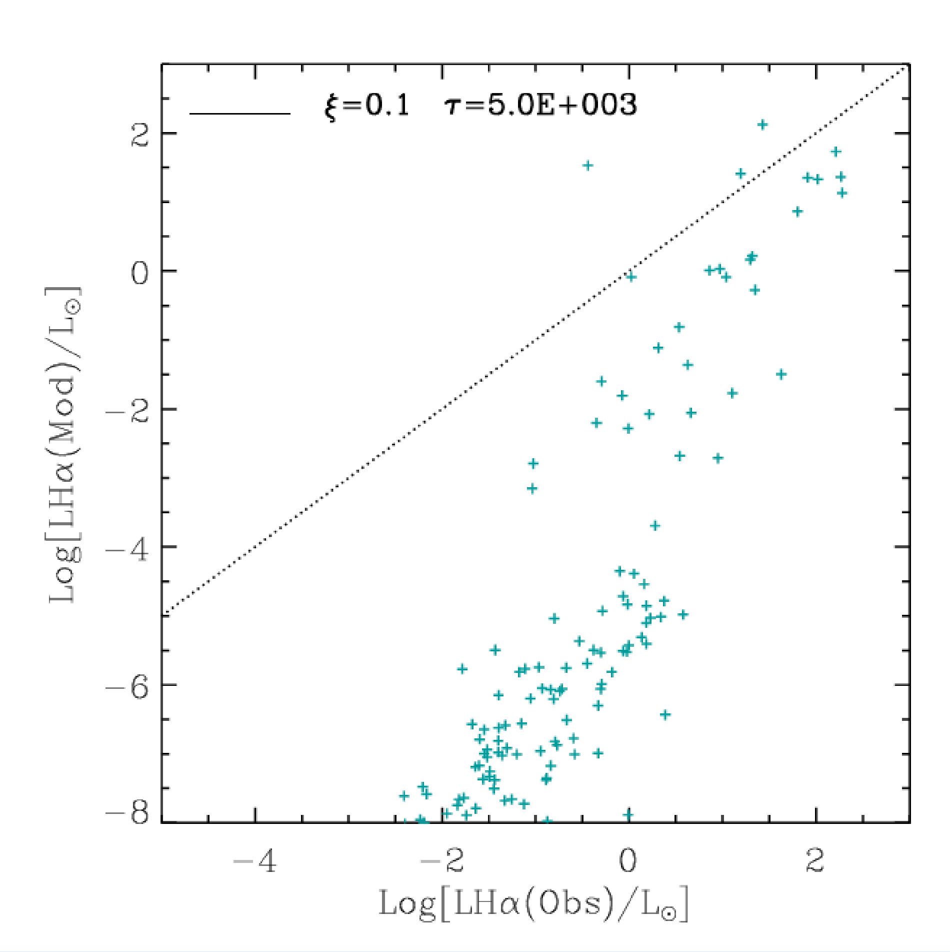

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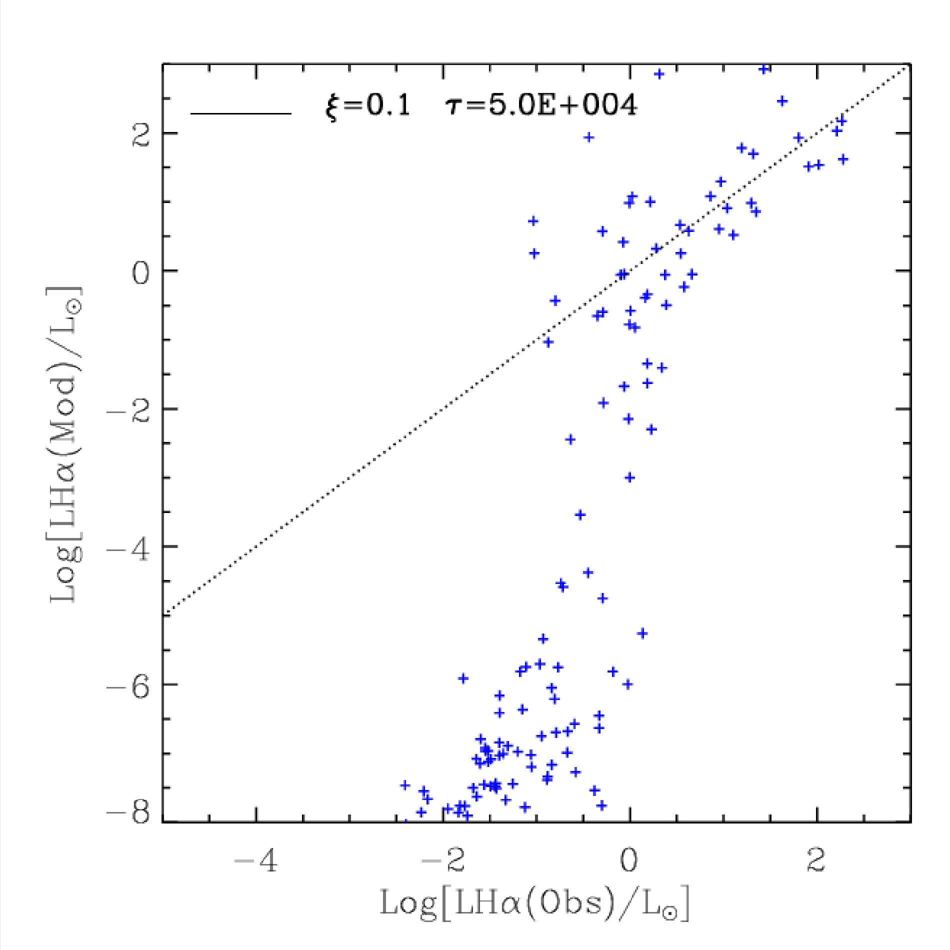

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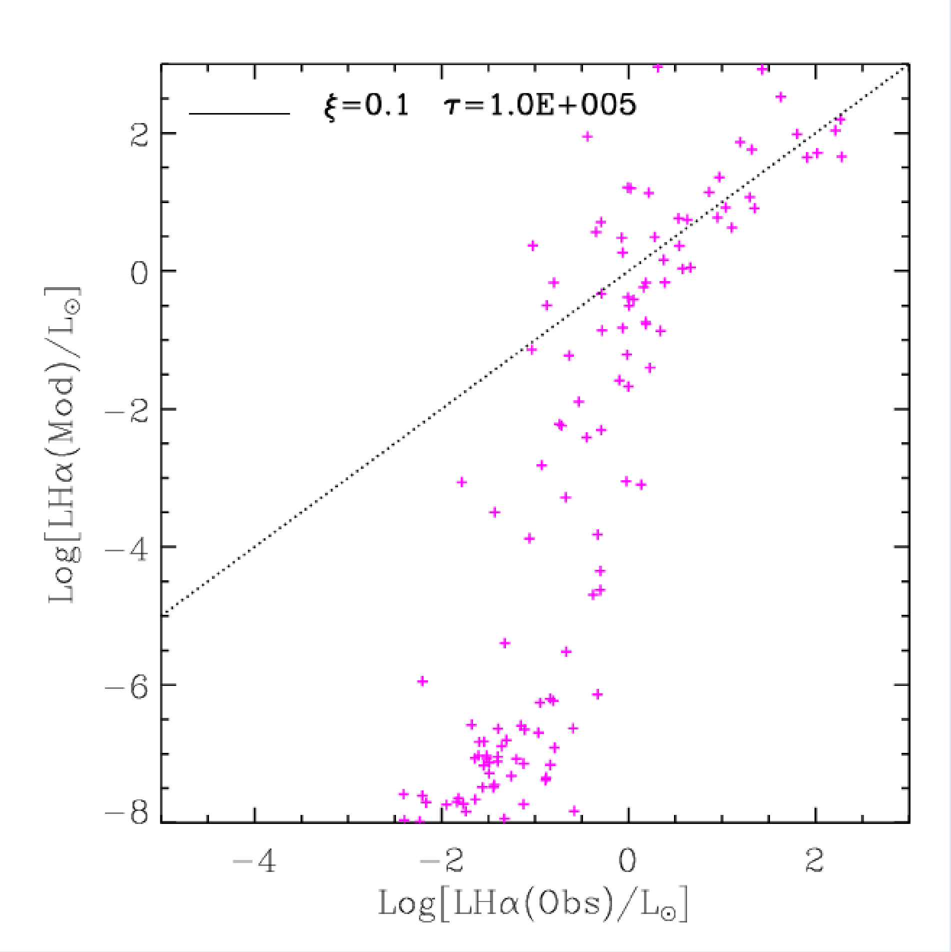

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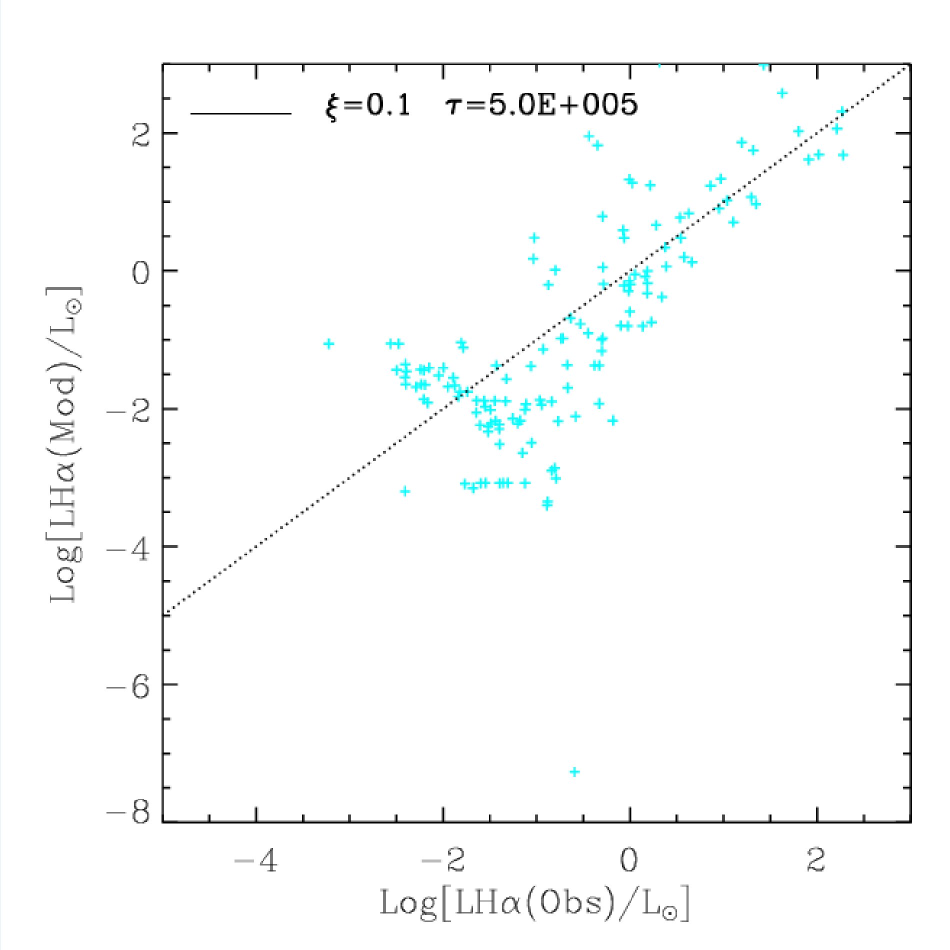

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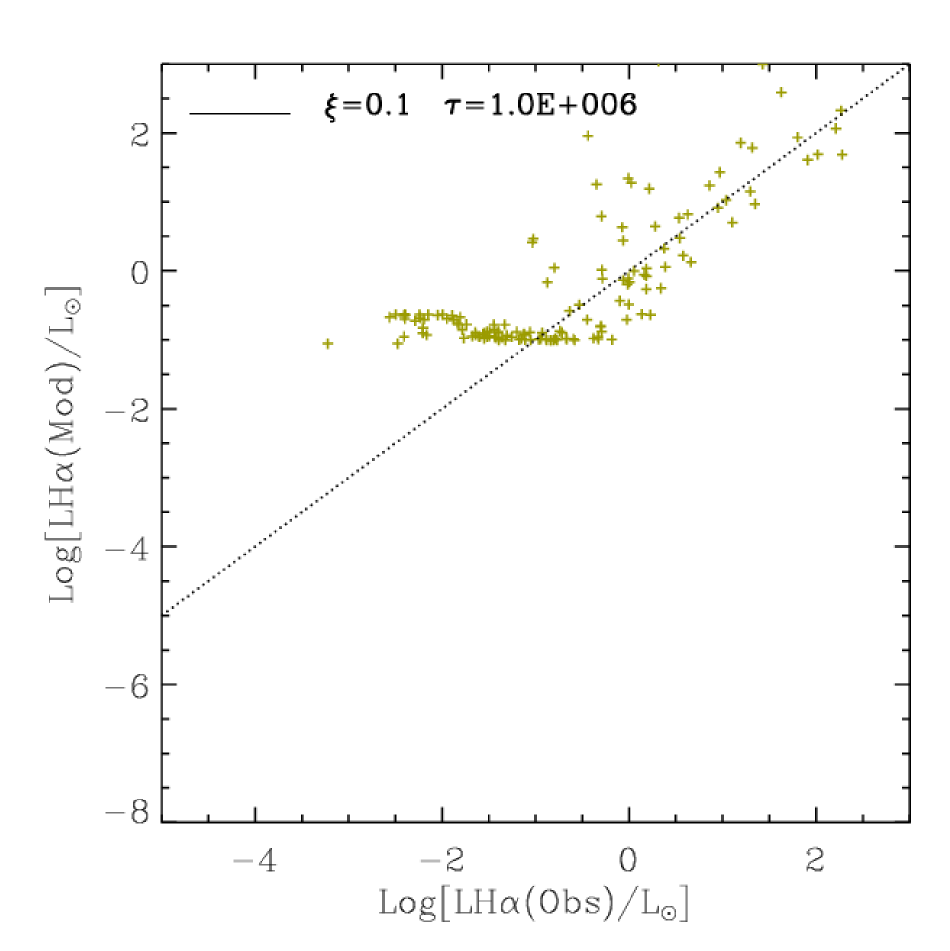
$$Log\left(\frac{LH\alpha}{L_{\odot}}\right)_{model} = -2.1 + Log\left(\frac{Lacc}{L_{\odot}}\right)$$

Very similar results using Barentsen+11



Main challenge of these models

Using

- stellar birth-line with ξ = 0.10 and $\dot{M}$=10^{-5} x $M^{1.6}$
- exponential decay

$$\dot{M} = \dot{M}_b \; e^{-(t-tb)/\tau}$$

$H\alpha$ in Objects with luminosity

$Log\left(\frac{L}{L_\odot}\right) < 2$

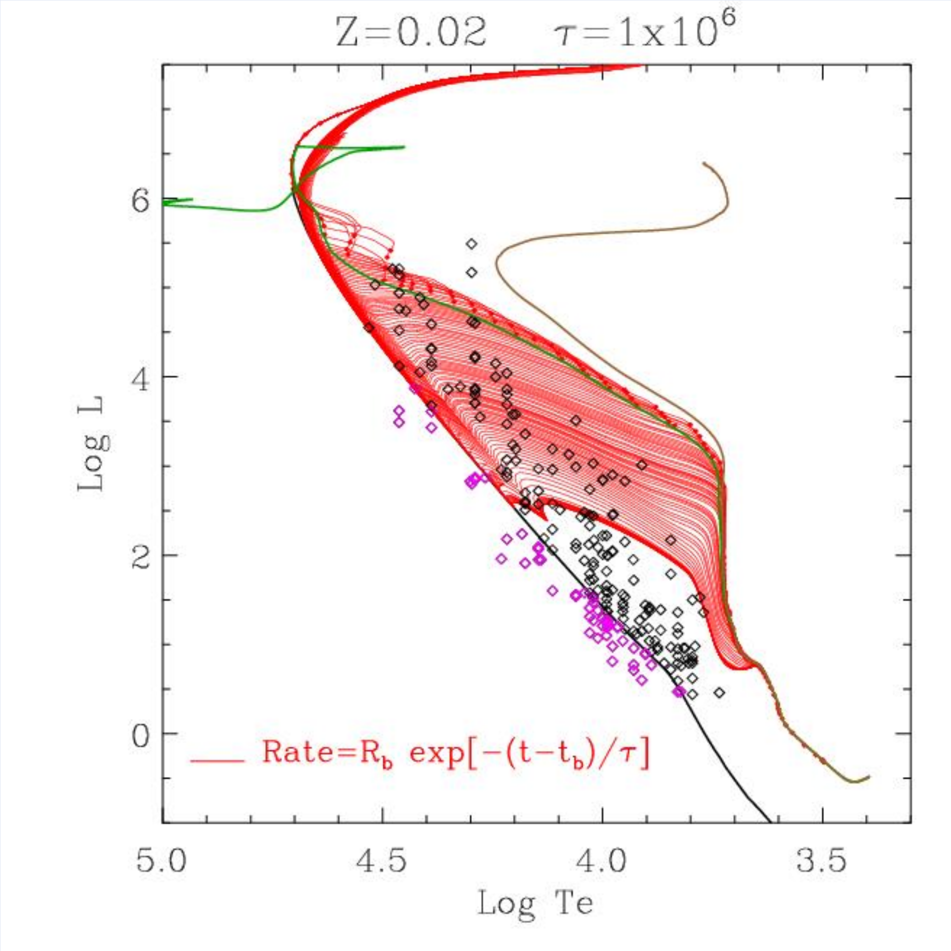
cannot be reproduced

Observed $H\alpha$ luminoisty reproduced

- only using τ ~ 0.5-1.0 x 10^5yr
- only in more luminous objects

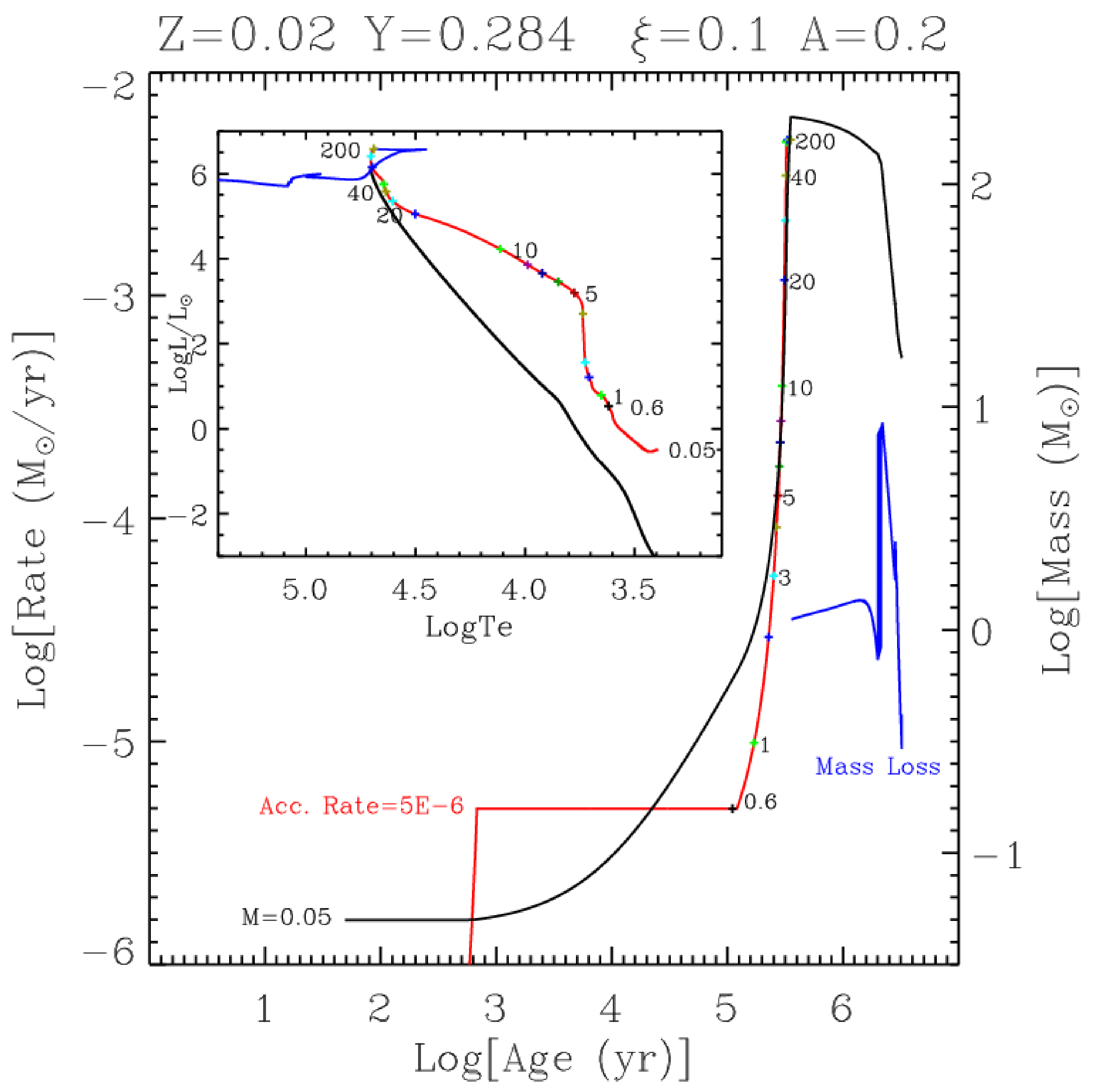
$Log\left(\frac{L}{L_\odot}\right) > 2$

$Log\left(\frac{LH\alpha}{L_\odot}\right)_{observed} > -0.5 - 0$



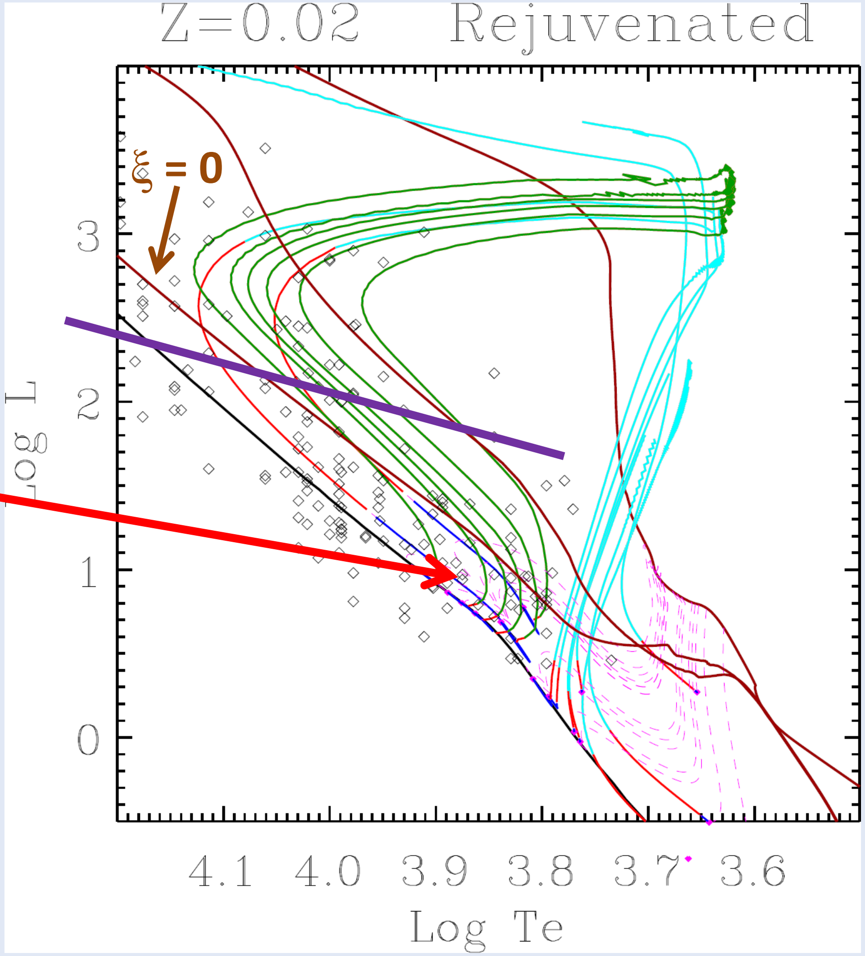
Accretion rate
and mass
as a function of time.

Case with ξ =0.1



Ways out

1) Rejuvenated models (hot): accretion resumes while the star is already on the ZAMS:
too short lifetime near the ZAMS: models spend most of the time above cold accretion (ξ = **0**) path!

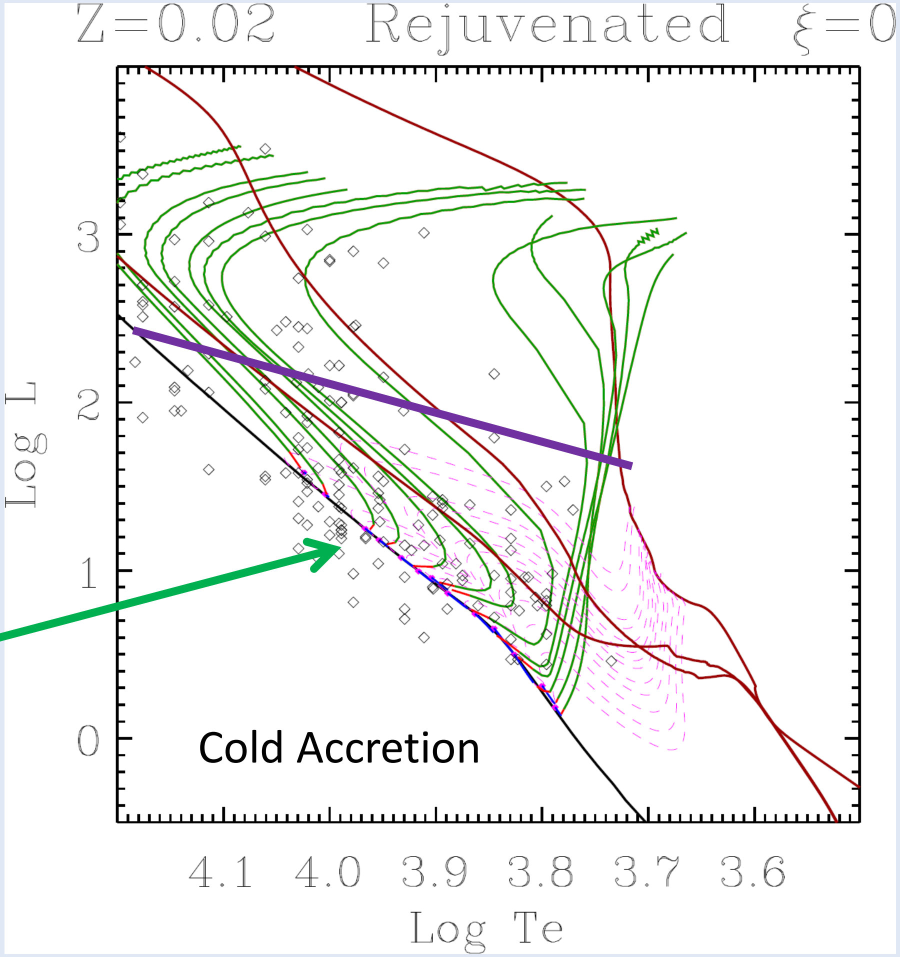


Ways out

1) Rejuvenated models (hot): accretion resumes while the star is already onthe ZAMS: too short lifetime near the ZAMS: models spend most of the time above cold accretion (ξ **= 0**) path!

2) Rejuvenated models but with **cold accretion**

3) Intermittent cold-hot accretion



CONCLUSIONS

- PARSEC ZAMS is well calibrated and nicely fits also GAIA DR2 CMDs of Open Clusters
- In GAIA DR2, PMS of young clusters well defined and generally sharp
  - very well fitted by non accreting PMS models
  - same age must reproduce

    evolution away from ZAMS at TURNOFF

    evolution toward ZAMS in PMS
- New PARSEC models with accretion were presented: will be soon available but after exploitation and calibration of main parameters
- Accretion models compared with Herbig Ae/Be stars:
  - current mass determination fairly independent from accretion
  - Ages ?
  - envisaged evolution scenarios not able to reproduce observed Hα data of fainter objects: possible explanations call for rejuvenation, cold accretion or both
- too many parameters: observations will likely have the last word