Evolutionary models and age determinations

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Also

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New release of stellar evolutionary tracks and isochrones in Padova

- ***PADOVA TRIESTE STELLAR EVOLUTION CODE* (*PARSEC*)**

  (Bressan, Marigo, Girardi, Salasnich, Dal Cero, Rubele & Nanni 2012)

  - **Input Physics**
  - **Comparison with previous tracks**
- **Some caveats on age determinations**

Reference Solar Abundances

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

Element	AY=log(*N*Y/*N*H)+12	Reference	GS98	A+09	AGS05
Li	1.03	Caffau et al. (2011)			
C	8.50	Caffau et al. (2010)	8.52	8.43	8.39
N	7.86	Caffau et al. (2009)	7.92	7.83	7.78
O	8.76	Caffau et al. (2008)	8.83	8.69	8.66
P	5.46	Caffau et al. (2007)			
S	7.16	Caffau & Ludwig (2007)			
K	5.11	Caffau et al. (2011)			
Fe	7.52	Caffau et al. (2011)			
Eu	0.52	Mucciarelli et al. (2008)			
Hf	0.87	Caffau et al. (2008)			
Os	1.36	Caffau et al. (2011)			
Th	0.08	Caffau et al. (2008)			

For all other species we adopt Grevesse & Sauval (1998)

Compare with:

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

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

Opacity

High-temperature opacity log(T) : 4.2 - 8.7

Opacity Project At Livermore (OPAL, Iglesias & Rogers 96)

interactive web mask http://opalopacity.llnl.gov

specify the partitions, Xi/Z of 19 heavy elements

C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Ti, Cr, Mn, Fe, Ni

Low temperature opacity log(T): 3.2 - 4.1

AESOPUS (Marigo & Aringer2009)

interactive web mask http://stev.oapd.inaf.it/aesopus

92 elements from H to U and ~ 800 chemical species

300 neutral atoms and ions up to 5th ionization stage

500 molecular species

Conductive opacities are included following Itoh et al. 08

2D GRID

Log T **3.2** *0.01* **3.7** *0.02* **8.7**

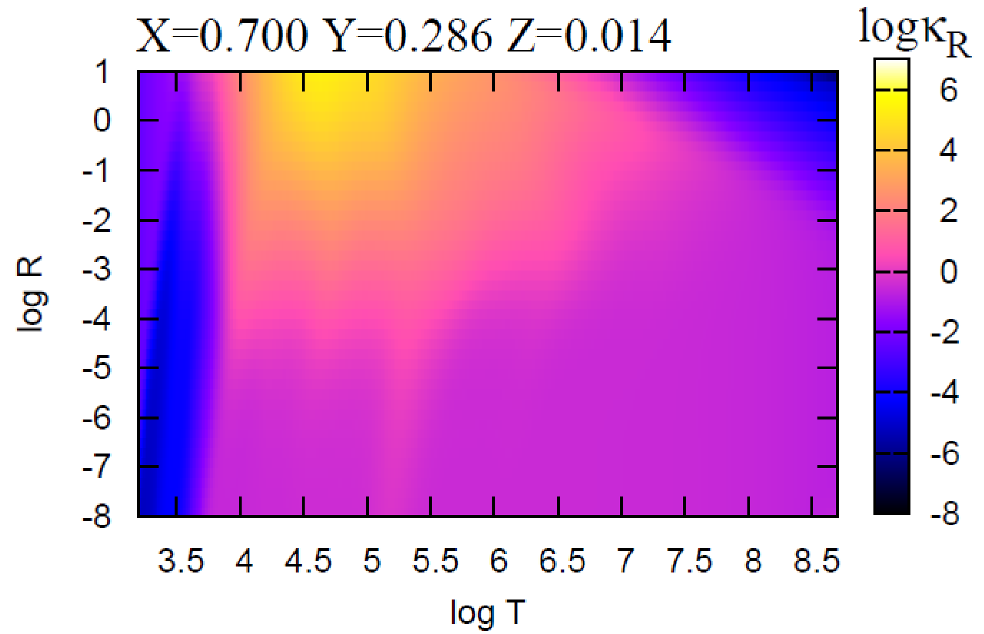
log R -8 *0.2* 1 R = ρ/T6

H-rich tables

4 dimensions **T R X Z**

- bilinear in T R
- parabolic X Z

(**10 Z tables loaded at once**)



H-free tables

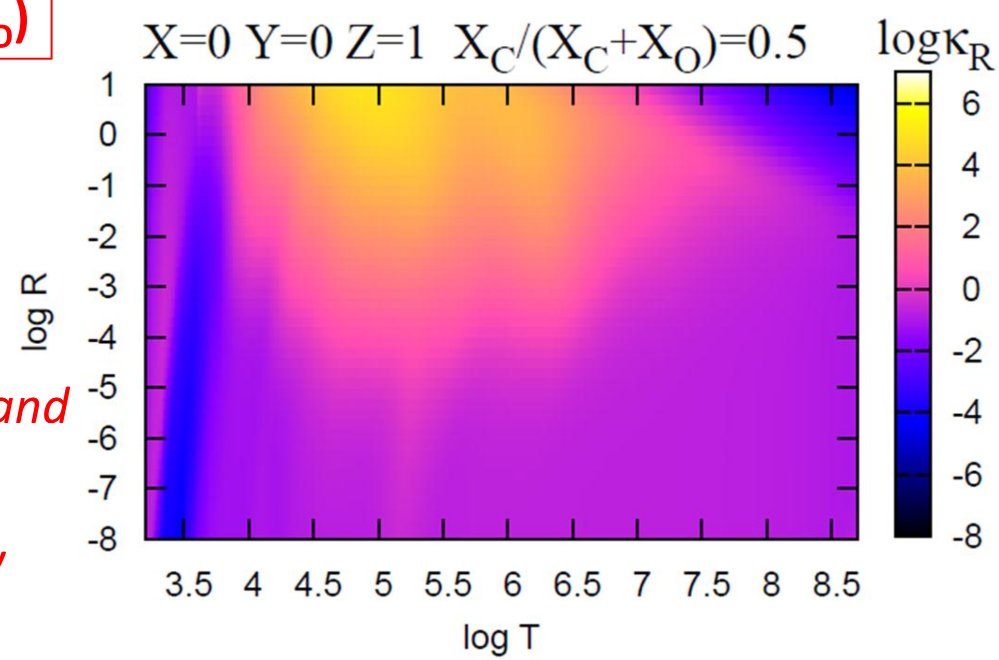
$R_C=X_C/(X_C+X_O)$

5 dimensions **T R Y R_C Z**

- bilinear R T
- linear R_C (3 values per table)
- parabolic Z

Partial derivatives wrt T & R computed and stored at load time over the same grid.

With the same algorithm obtain opacity and derivatives at once



Equation Of State

- **EOS is the FreeEOS by A.W. Irwin**

  (available under the GPL licence http://freeeos.sourceforge.net/)

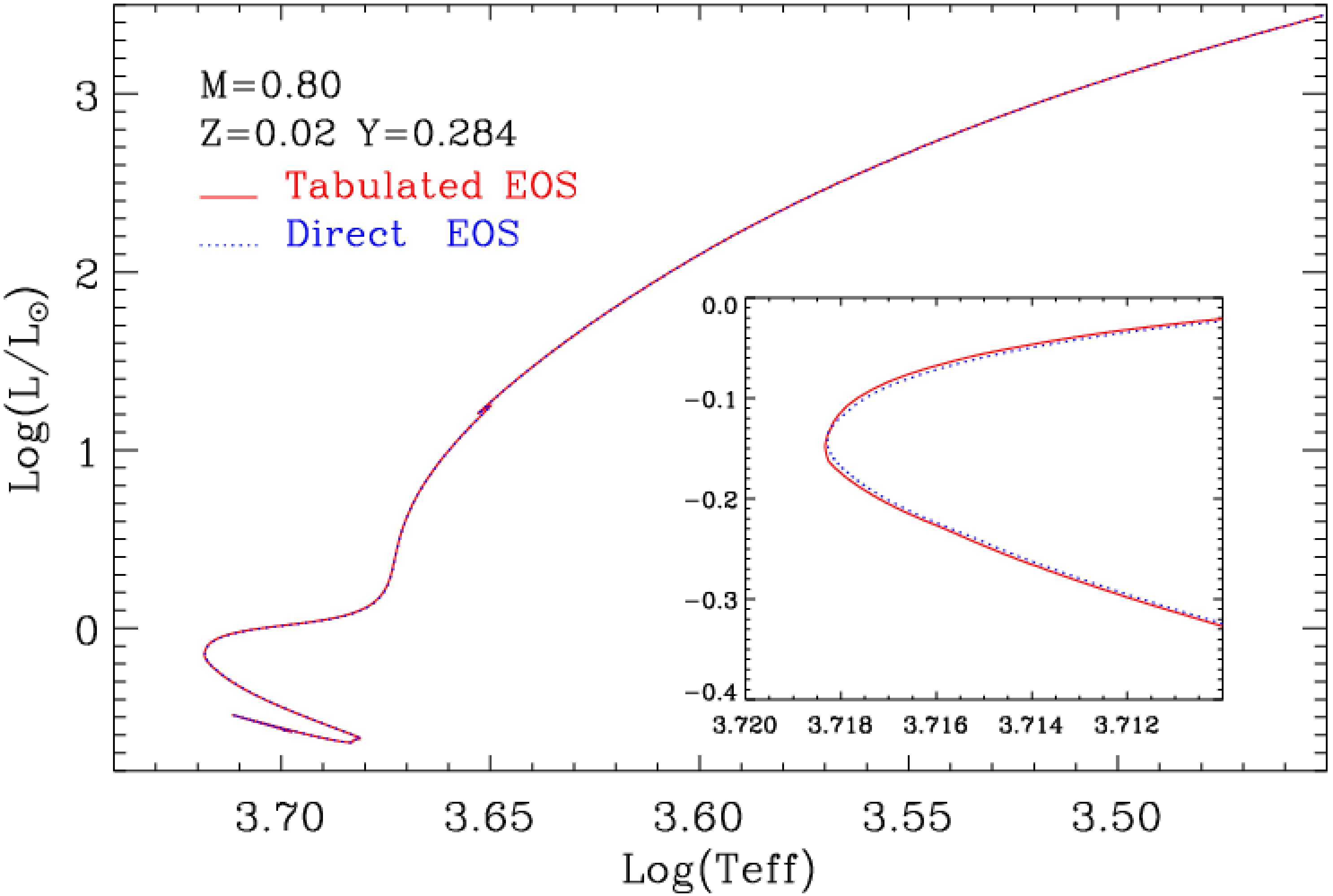
FreeEOS package fully implemented: may be used ``on-the-fly'' for different approximations and levels of accuracy.
EOS accounts for 20 elements:
H, He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, Ca, Ti, Cr, Mn, Fe, Ni

For speed purposes we use a very accurate pre-tabulated version:

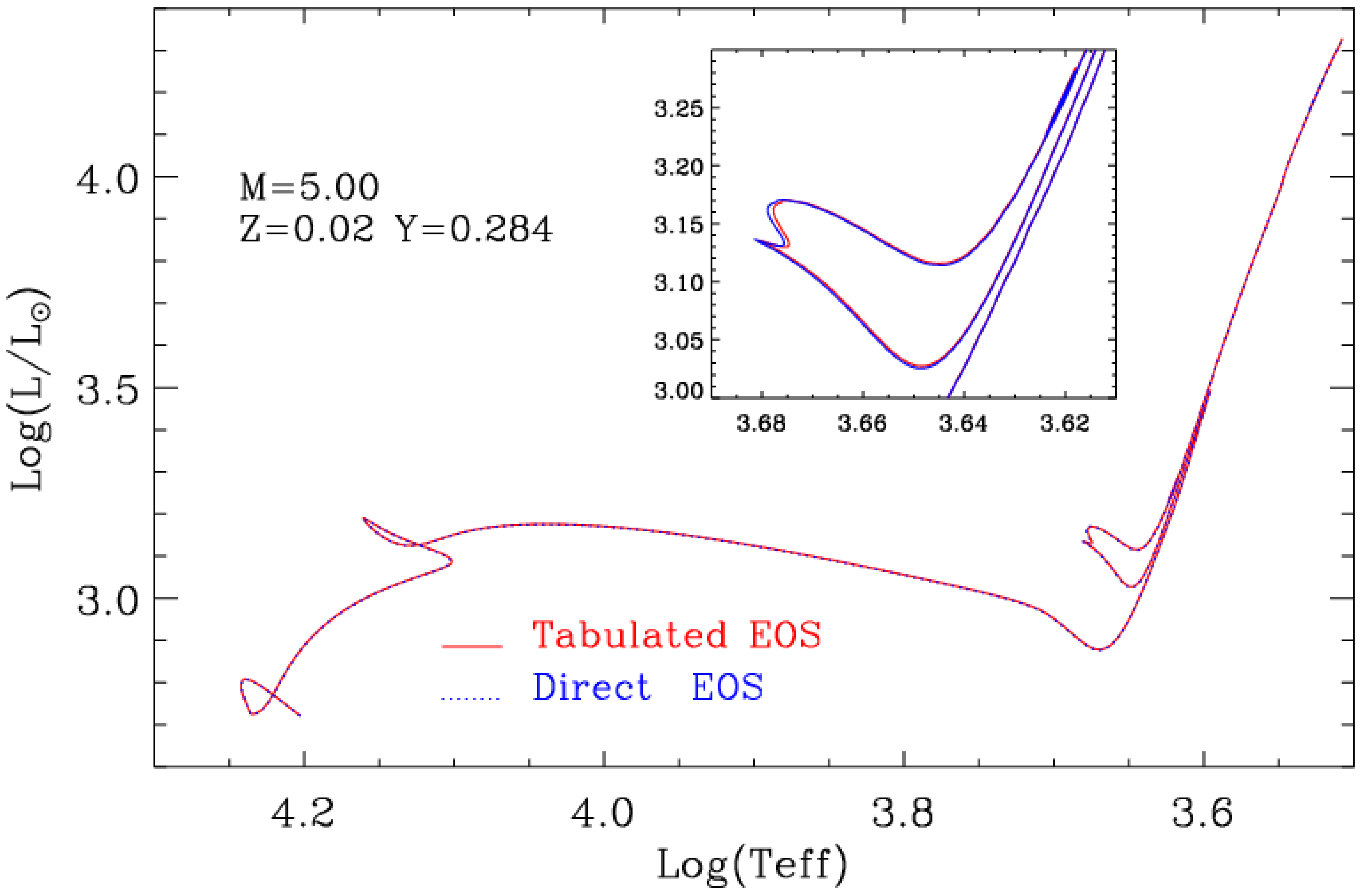
- for any partition Z_i/Z consider several metallicities Z
- for each Z, pre-compute EOS tables in T, P grid:
  - H-rich set 10 tables 10 Xs
  - H-free set 31 tables: 10 Ys x 3 RC s + (X=0,Y=1-Z) table

- Use the same interpolation scheme adopted for opacity

EOS Interpolation



EOS Interpolation



NUCLEAR REACTIONS, e-SCREENING & NEUTRINO LOSSES

- **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
- electron screening: Dewitt et al. 73 & Graboske et al. 73
- Neutrino losses : Munakata et al. 85, Itoh &Kohyama 83, Haft et al. 94 (plasma)

$p(p,\beta^+\nu)D$	Cyburt et al. (2010)	$p(D,\gamma)\,^3He$	Descouvemont et al. (2004)
$^3He(^3He,\gamma)2p+^4He$	Angulo et al. (1999)	$^4He(^3He,\gamma)\,^7Be$	Descouvemont et al. (2004)
$^7Be(e^-,\gamma)\,^7Li$	Caughlan & Fowler (1988)	$^7Li(p,\gamma)\,^4He+^4He$	Descouvemont et al. (2004)
$^7Be(p,\gamma)\,^8B$	Angulo et al. (1999)	$^{12}C(p,\gamma)\,^{13}N$	Angulo et al. (1999)
$^{13}C(p,\gamma)\,^{14}N$	Angulo et al. (1999)	$^{14}N(p,\gamma)\,^{15}O$	Imbriani et al. (2005)
$^{15}N(p,\gamma)\,^4He+^{12}C$	Angulo et al. (1999)	$^{15}N(p,\gamma)\,^{16}O$	Angulo et al. (1999)
$^{16}O(p,\gamma)\,^{17}F$	Angulo et al. (1999)	$^{17}O(p,\gamma)\,^4He+^{14}N$	Chafa et al. (2007)
$^{17}O(p,\gamma)\,^{18}F$	Chafa et al. (2007)	$^{18}O(p,\gamma)\,^4He+^{15}N$	Angulo et al. (1999)
$^{18}O(p,\gamma)\,^{19}F$	Angulo et al. (1999)	$^{19}F(p,\gamma)\,^4He+^{16}O$	Angulo et al. (1999)
$^{19}F(p,\gamma)\,^{20}Ne$	Angulo et al. (1999)	$^{20}Ne(p,\gamma)\,^{21}Na$	Angulo et al. (1999)
$^{21}Ne(p,\gamma)\,^{22}Na$	Iliadis et al. (2001)	$^{22}Ne(p,\gamma)\,^{23}Na$	Hale et al. (2002)
$^{23}Na(p,\gamma)\,^4He+^{20}Ne$	Hale et al. (2004)	$^{23}Na(p,\gamma)\,^{24}Mg$	Hale et al. (2004)
$^{24}Mg(p,\gamma)\,^{25}Al$	Iliadis et al. (2001)	$^{25}Mg(p,\gamma)\,^{26}Al^g$	Iliadis et al. (2001)
$^{25}Mg(p,\gamma)\,^{26}Al^m$	Iliadis et al. (2001)	$^{26}Mg(p,\gamma)\,^{27}Al$	Iliadis et al. (2001)
$^{26}Al^g(p,\gamma)\,^{27}Si$	Iliadis et al. (2001)	$^{27}Al(p,\gamma)\,^4He+^{24}Mg$	Iliadis et al. (2001)
$^{27}Al(p,\gamma)\,^{28}Si$	Iliadis et al. (2001)	$^4He(2\,^4He,\gamma)\,^{12}C$	Fynbo et al. (2005)
$^{12}C(^4He,\gamma)\,^{16}O$	Buchmann (1996)	$^{14}N(^4He,\gamma)\,^{18}F$	Görres et al. (2000)
$^{15}N(^4He,\gamma)\,^{19}F$	Wilmes et al. (2002)	$^{16}O(^4He,\gamma)\,^{20}Ne$	Angulo et al. (1999)
$^{18}O(^4He,\gamma)\,^{22}Ne$	Dababneh et al. (2003)	$^{20}Ne(^4He,\gamma)\,^{24}Mg$	Angulo et al. (1999)
$^{22}Ne(^4He,\gamma)\,^{26}Mg$	Angulo et al. (1999)	$^{24}Mg(^4He,\gamma)\,^{28}Si$	Caughlan & Fowler (1988)
$^{13}C(^4He,n)\,^{16}O$	Angulo et al. (1999)	$^{17}O(^4He,n)\,^{20}Ne$	Angulo et al. (1999)
$^{18}O(^4He,n)\,^{21}Ne$	Angulo et al. (1999)	$^{21}Ne(^4He,n)\,^{24}Mg$	Angulo et al. (1999)
$^{22}Ne(^4He,n)\,^{25}Mg$	Angulo et al. (1999)	$^{25}Mg(^4He,n)\,^{28}Si$	Angulo et al. (1999)

Internal Mixing

Convection

- *mixing length (calibration with the Solar Model)*
- *core overshoot (see below)*
- *envelope overshoot (")*

Diffusion

- *Microscopic diffusion included as in Salasnich 99, for all elements (assumed fully ionized)*
- *Diffusion coefficients calculated following Thoul et al. 94*
- *Turbulent diffusion also implemented*
- *Second order differential equations solved together with the chemistry equation network, at the end of equilibrium models*

No Rotation (being implemented as diffusive mixing)

Solar Calibratiom

The comparison with the solar data is a necessary step to check the quality of the input physics and to calibrate some parameters that cannot be derived from the theory

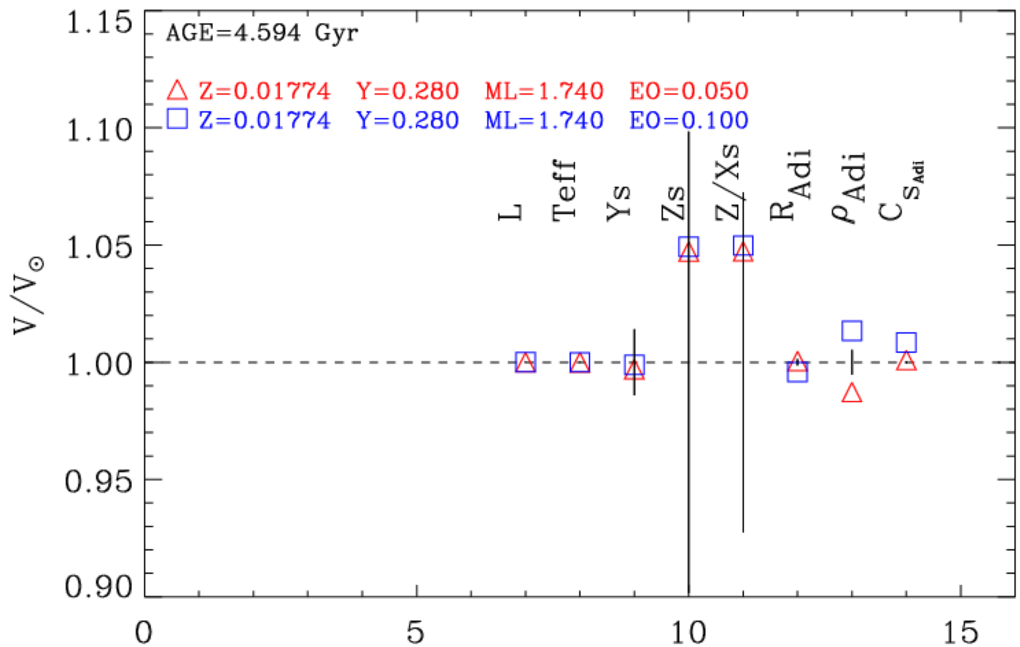
Parameter	Value	error	source
$L_\odot$ (10^{33}erg s^{-1})	3.846	0.005	Guenther et al. (1992)
$R_\odot$ (10^{10} cm)	6.9598	0.001	Guenther et al. (1992)
$T_{\rm eff,\odot}$ (K)	3.7617	-	from $L_\odot$ & $R_\odot$
$Z_\odot$	0.0152	0.0015	Caffau et al. (2011)
$Y_\odot$	0.2485	0.0035	Basu & Antia (2004)
$(Z/X)_\odot$	0.0207	0.0015	from $Z_\odot$ & $Y_\odot$
$R_{\rm ADI}/R_\odot$	0.713	0.001	Basu & Antia (1997)
$\rho_{\rm ADI}$	0.190	0.0001	Basu et al. (2009)
$C_{\rm S,ADI}/10^7$	2.235	0.0001	Basu et al. (2009)

Solar Model

$L_\odot$ (10^{33} erg s^{-1})	3.846	Guenther et al. (1992)
$R_\odot$ (10^{10} cm)	6.9598	Guenther et al. (1992)
$T_{\mathrm{eff},\odot}$ (K)	3.7617	from $L_\odot$ & $R_\odot$
$Z_\odot$	0.0152	Caffau et al. (2011)
$Y_\odot$	0.2485	Basu & Antia (2004)
$(Z/X)_\odot$	0.0207	from $Z_\odot$ & $Y_\odot$
$R_{\mathrm{ADI}}/R_\odot$	0.713	Basu & Antia (1997)
ρ_{ADI}	0.190	Basu et al. (2009)
$C_{\mathrm{S,ADI}}/10^7$	2.235	Basu et al. (2009)

(Derived values)

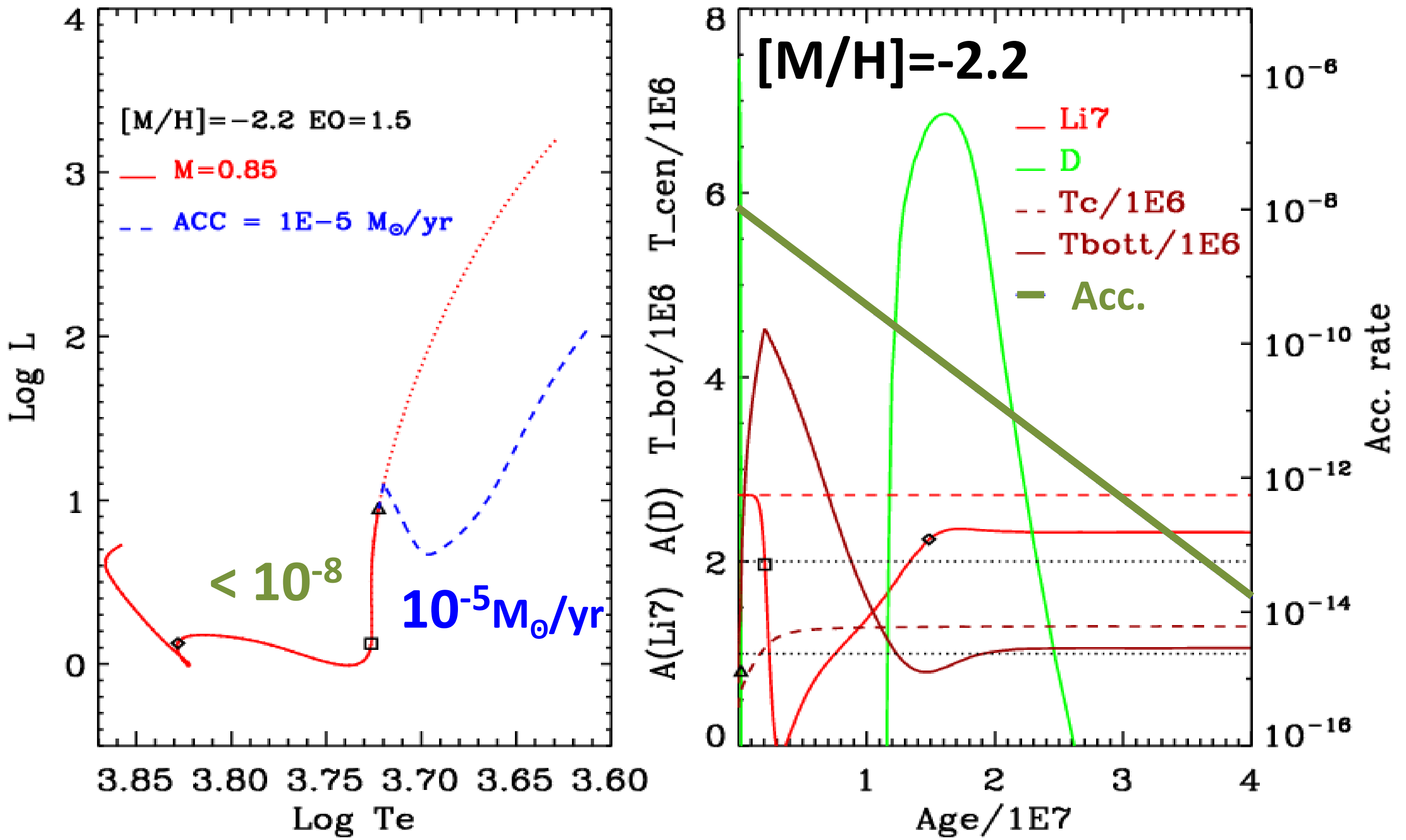
Age(Gyr)	4.594
Z_{Initial}	0.0177
Y_{Initial}	0.28
MLT	1.74



$$\frac{\delta Y}{\delta Z} \sim 1.78$$

Yp = 0.2485 from 7-yr WMAP (*Komatsu et al. 11*)

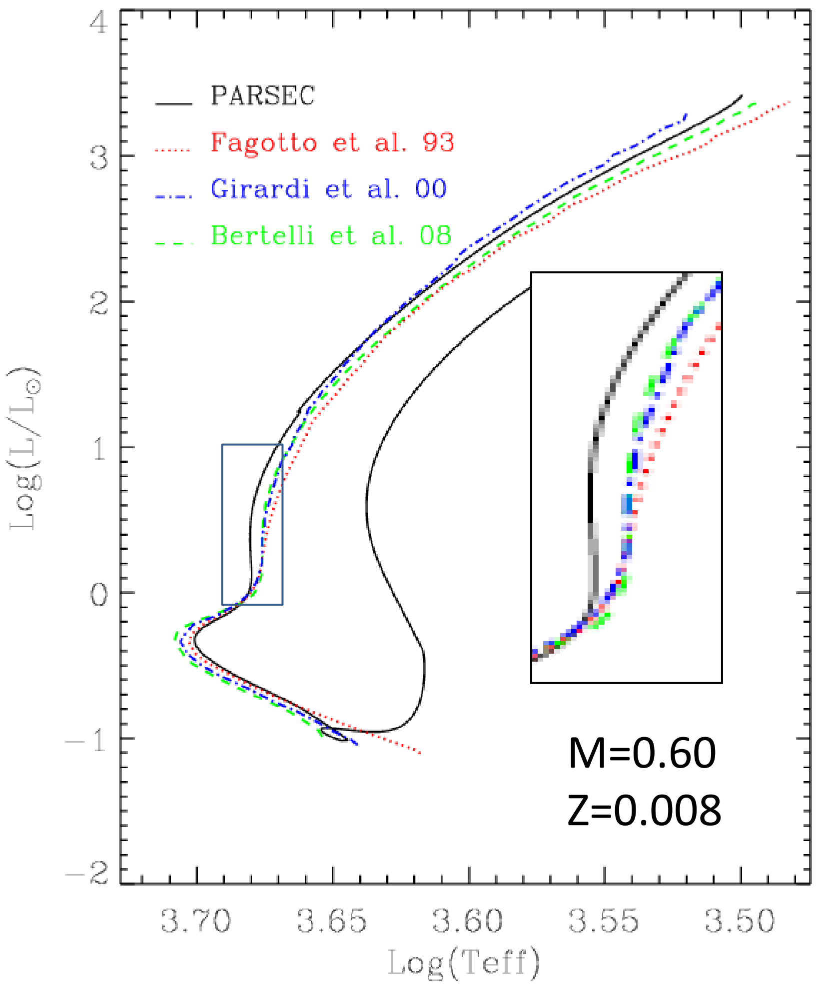
➢ Pre Main Sequence Evolution

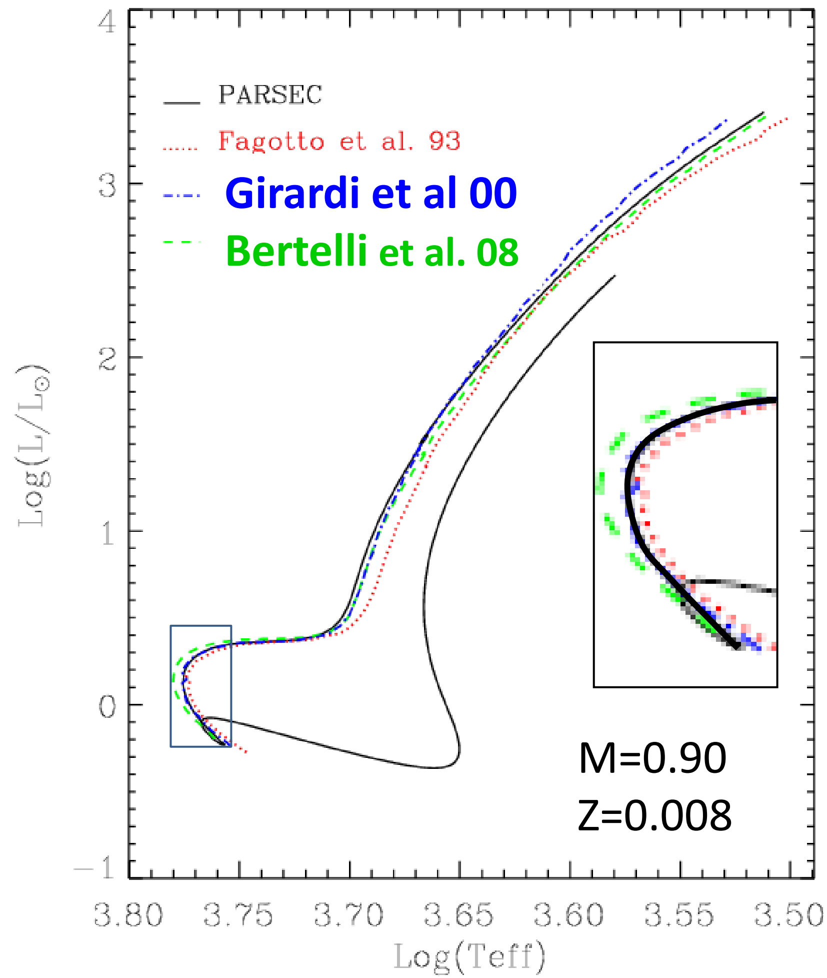


Li abundance (*Molaro et al. 2012)*

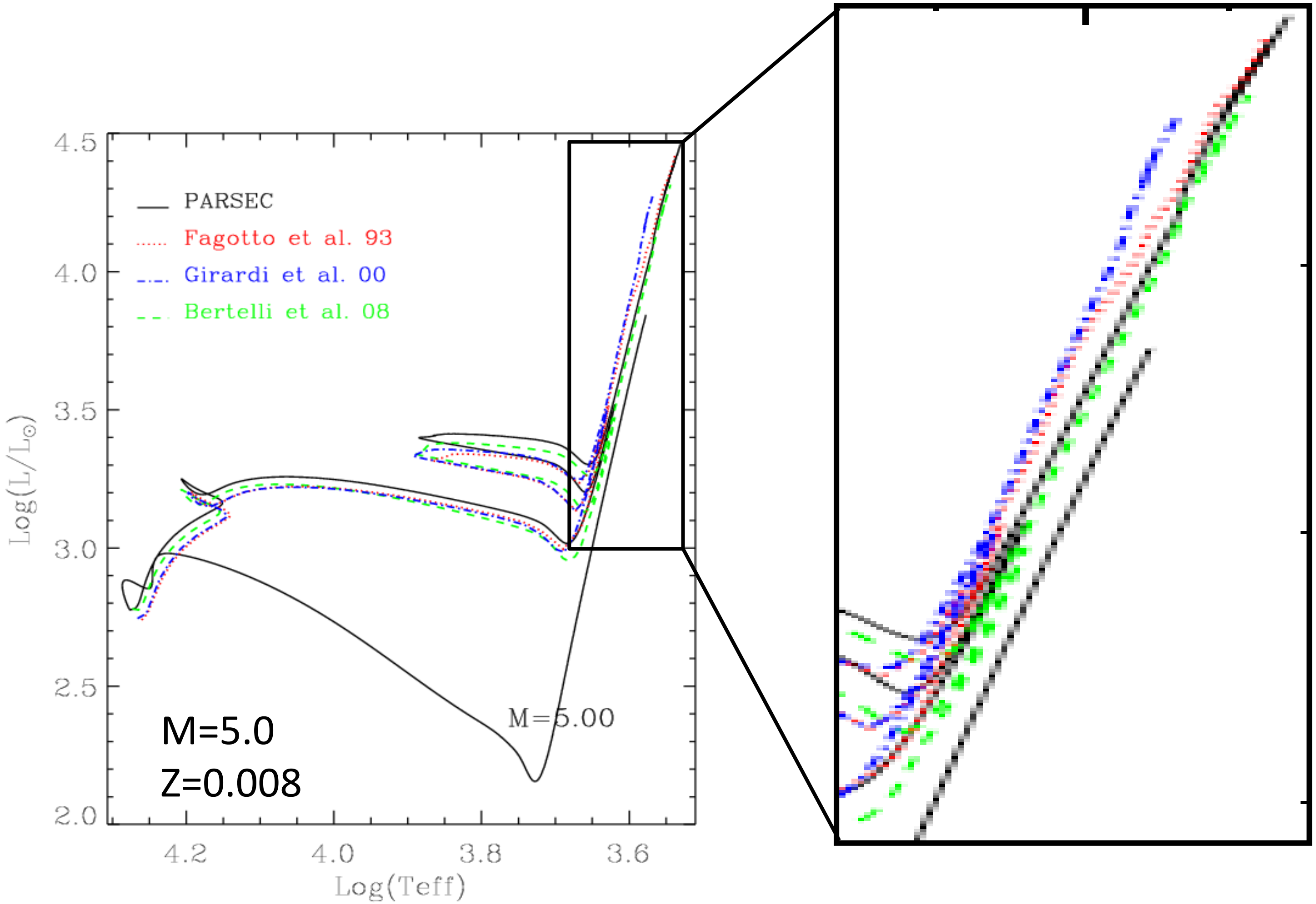
effects of EO + residual accretion rate (< **10^{-8}**$M_{\odot}$/yr: *De Marchi et al 2011*)

➢ Comparison with previous Padova Tracks





- **Hotter RGB base**
- **Cooler Turn-Off (diffusion)**

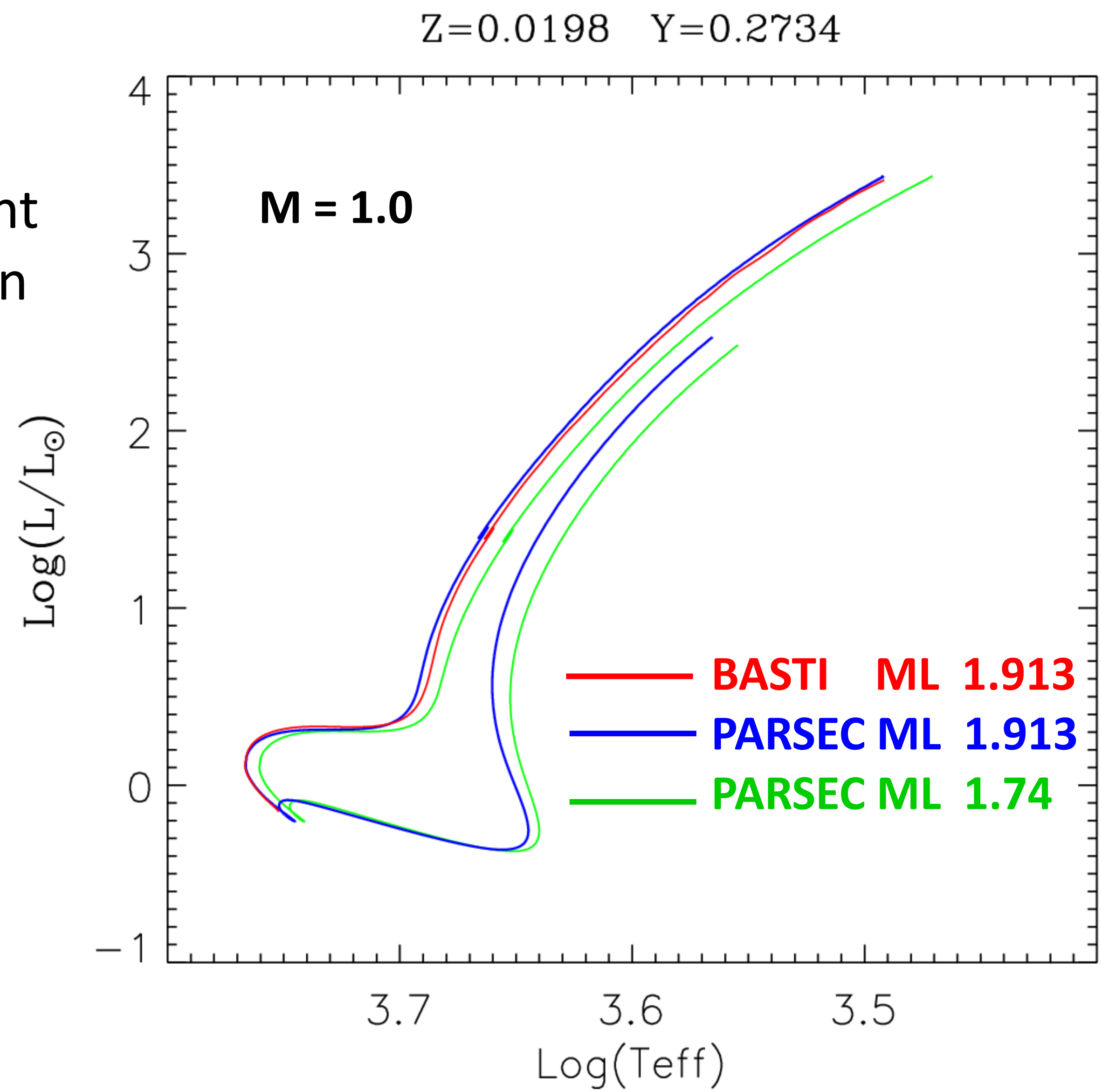


- **Cooler RGB TIP at the fixed luminosity**

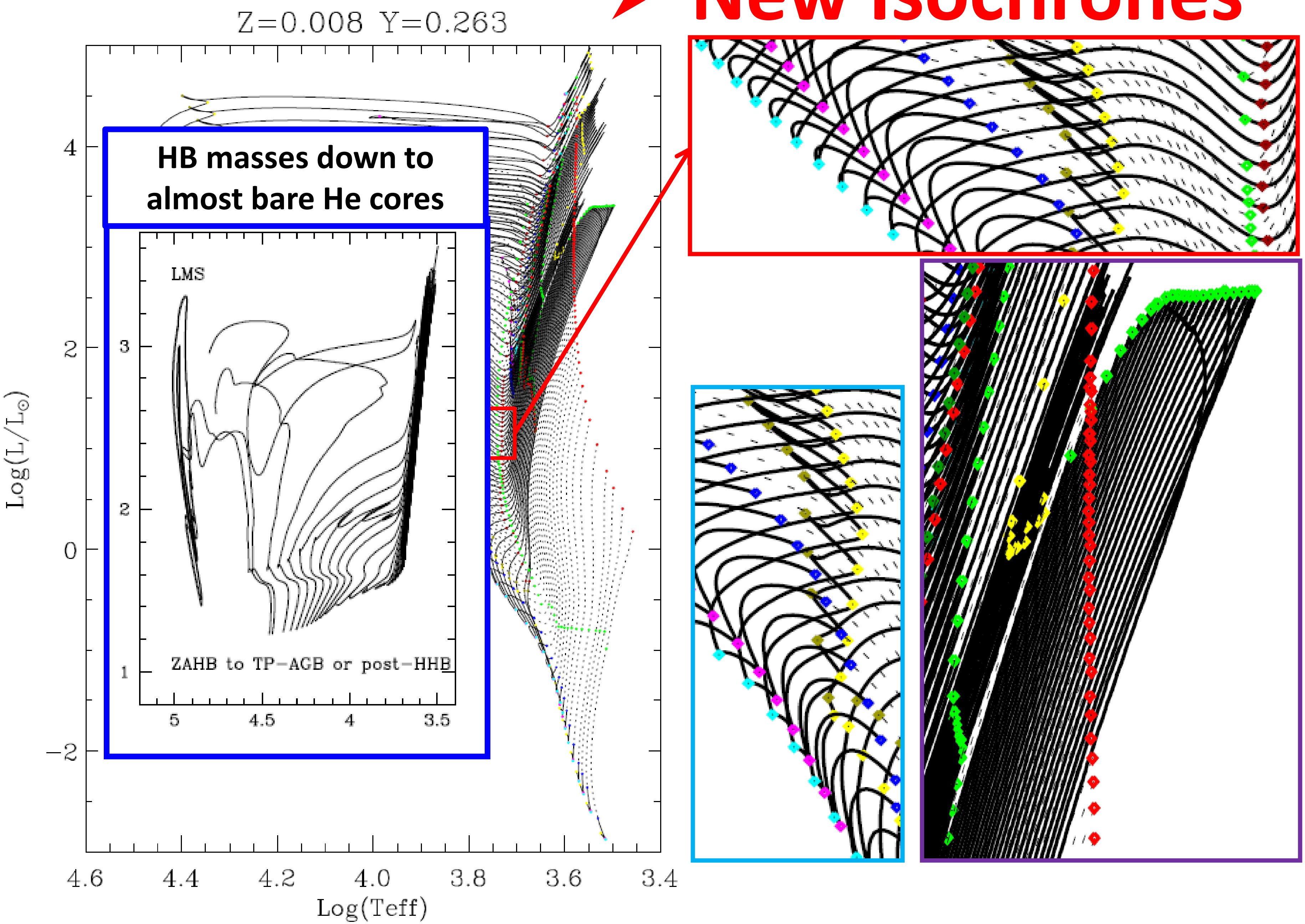
PARSEC vs BaSTI

&

the effects of current surface composition of the Sun



➢ New Isochrones

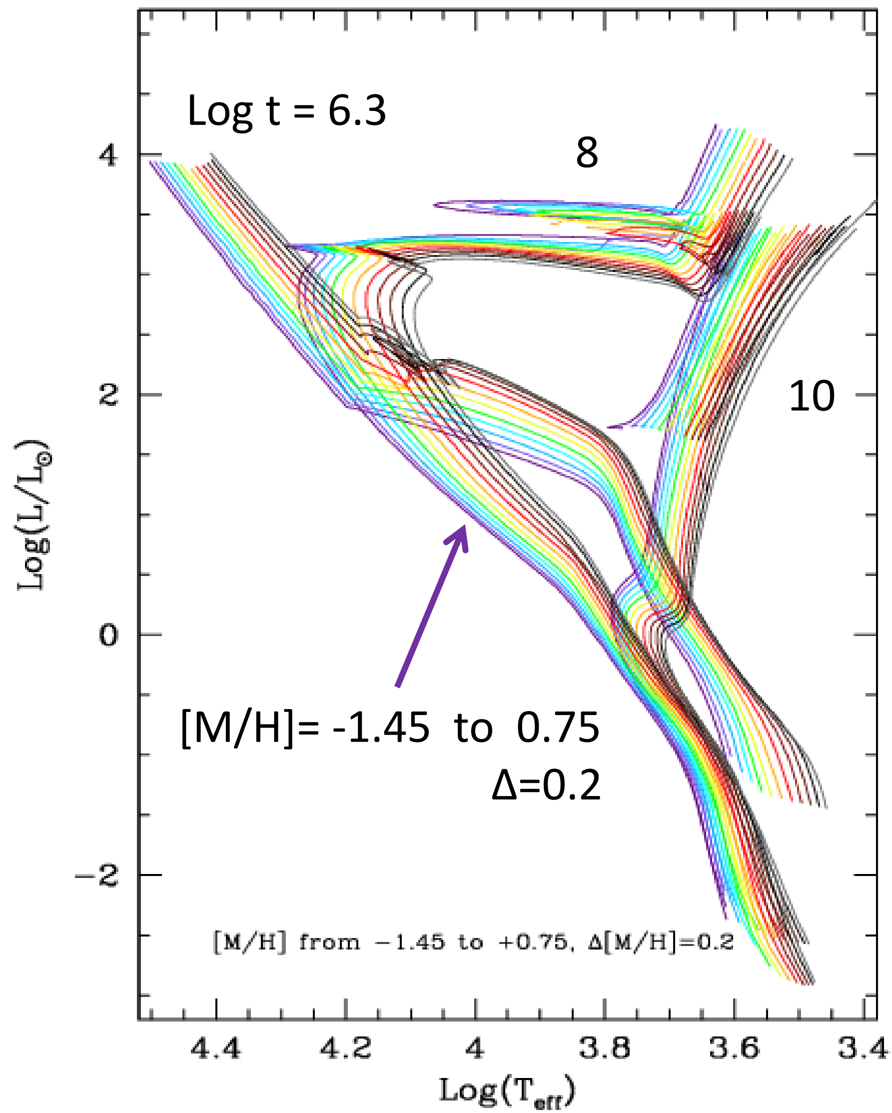


➢ DATA SETS (now)

from Solar model $\frac{\delta Y}{\delta Z} \sim 1.78$

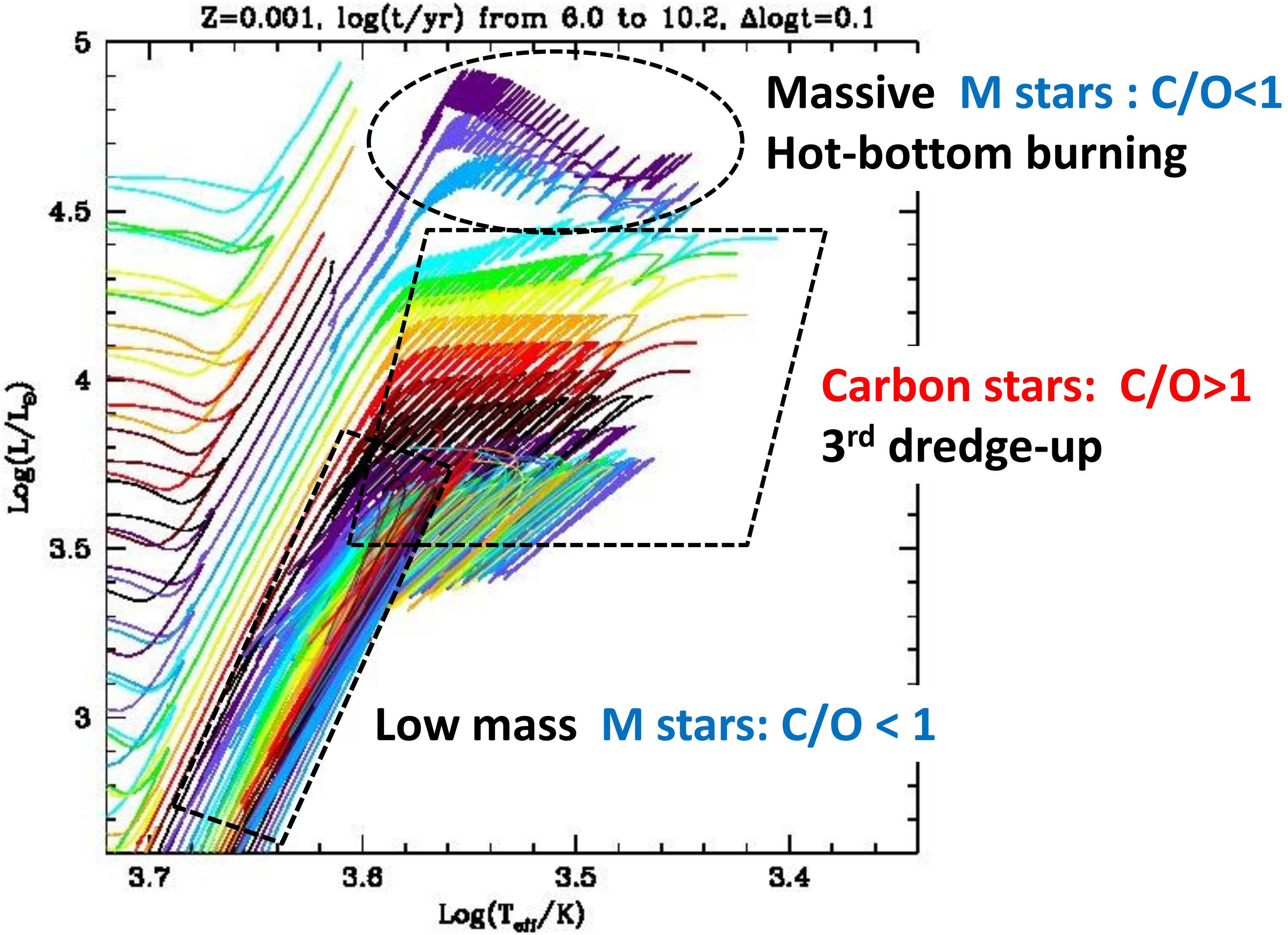
Z	Y	[M/H][a]	[α/Fe] (dex) 0	+0.2	+0.4
0.0005	0.2485	−1.49	×	×	
0.001	0.250	−1.19	×	×	
0.004	0.256	−0.58	×	×	
0.005	0.258	−0.48			×
0.006	0.259	−0.40	×	×	
0.008	0.263	−0.28	×	×	
0.010	0.267	−0.18	×	×	×
0.010	0.263	−0.18		×	
0.014	0.273	−0.02	×		
0.015	0.276	−0.01		×	
0.017	0.279	+0.06	×	×	
0.017	0.350	+0.11	×		
0.017	0.400	+0.15	×		
0.02	0.284	+0.14	×	×	×
0.03	0.302	+0.34	×	×	
0.04	0.321	+0.48	×	×	
0.05	0.339	+0.60	×	×	
0.06	0.356	+0.70	×	×	×
0.07	0.375	+0.78	×	×	

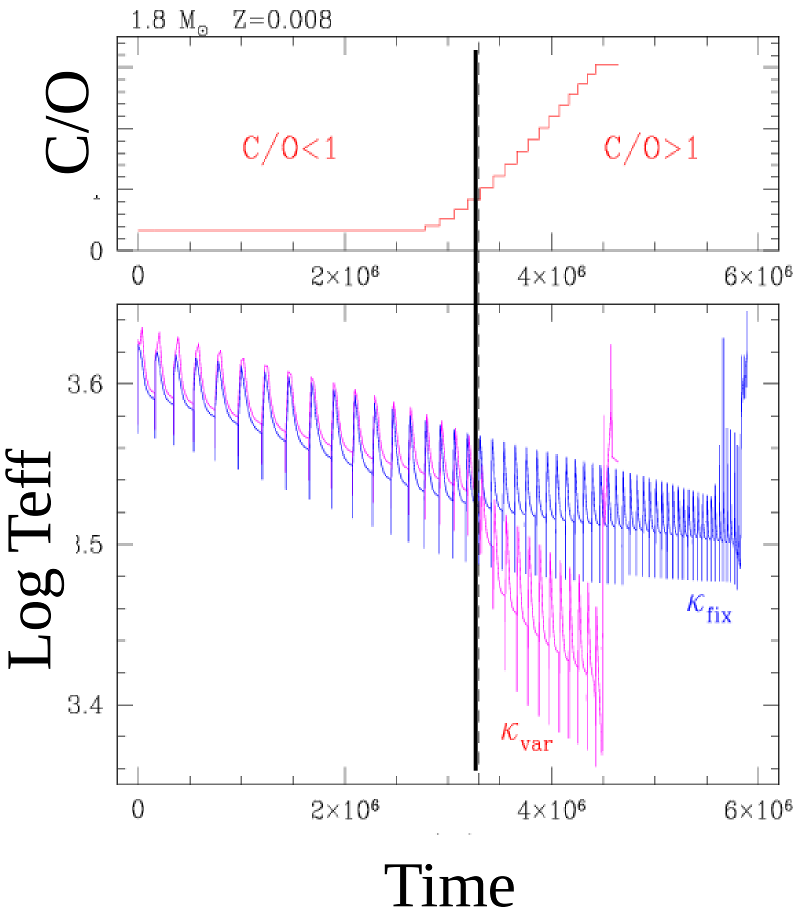
$$Y = 0.2485 + 1.78\,Z$$



➢ New isochrones with detailed TP-AGB phase

(Marigo, Bressan, Girardi, Nanni in prep.)





EFFECTIVE TEMPERATURE
from envelope integrations

Molecular opacities consistent with the current surface C/O ratio, in place of tables valid for solar-scaled compositions (Marigo 2002)

NEW IMPROVEMENT:
ÆSOPUS (Marigo & Aringer 09)

Photospheric **cooling effect** in C-rich AGB models
Consistent with observed Teffs and colors of carbon stars

➢ Photometric Systems

Photometric systems listed in
http://stev.oapd.inaf.it/~lgirardi/cmd_2.3/photsys.html
Girardi et al. (2002, 2005, 2008); Marigo et al. (2008), Aringer et al. (2009)

For the GAIA G, G_BP and G_RP passbands:
Vallenari private comm. (Jordi et al. 2010)

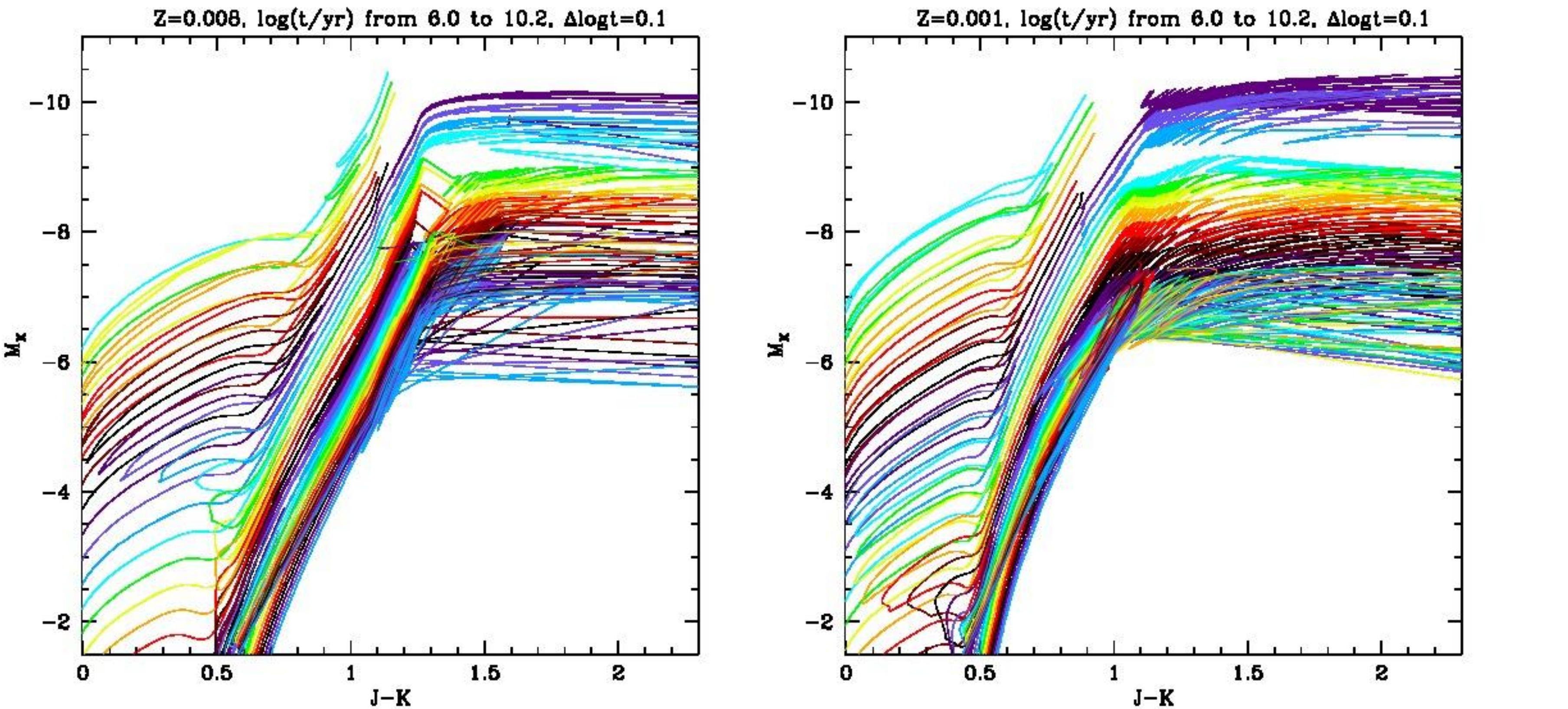
- ATLAS9 stellar atmospheres from Castelli & Kurucz (2003)

***T*eff: 4000K to 50 000 K   log g: −2 to 5**
scaled-solar metallicities [M/H] of between −2.5 and +0.5.
(also α-enhanced partitions)

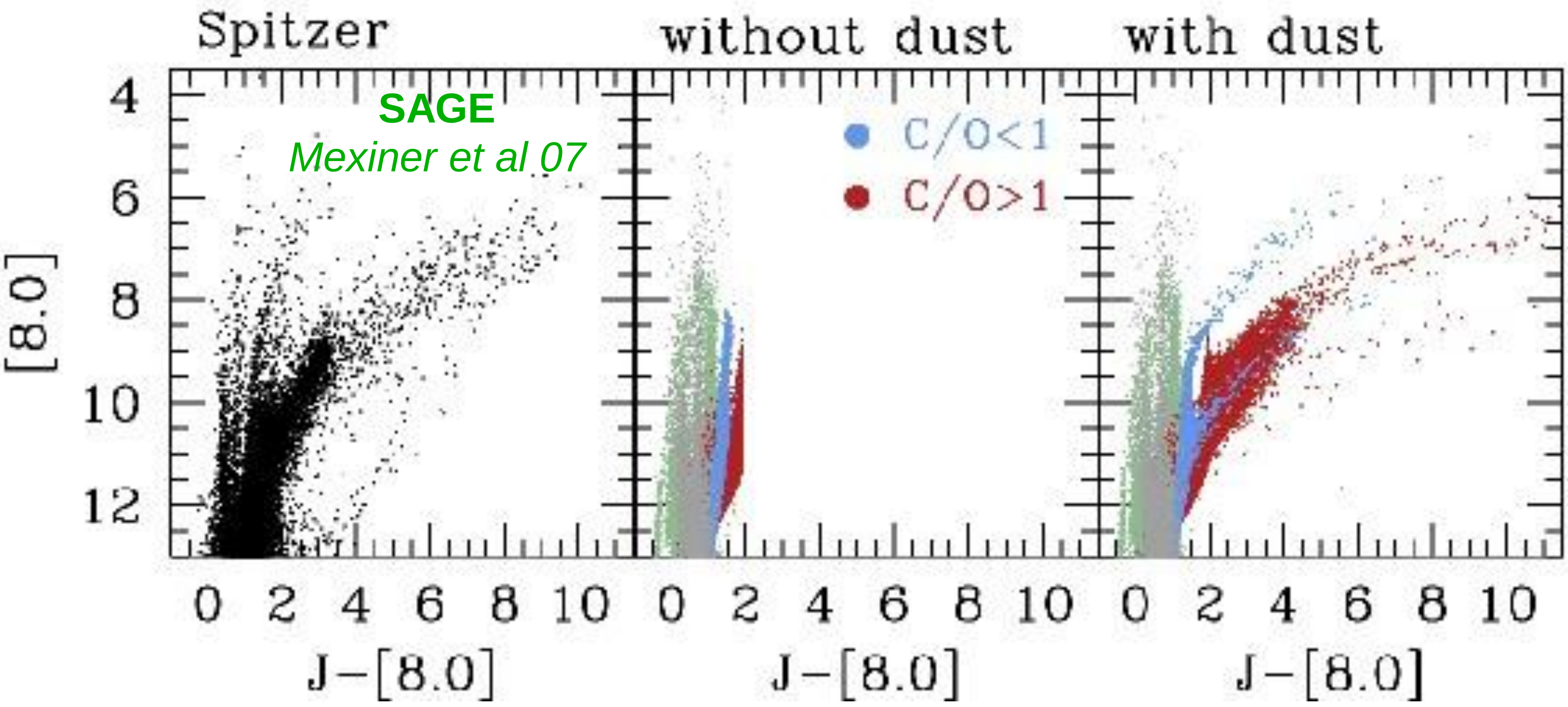
- M giants from Fluks et al. (1994)
- Carbon stars from Loidl et al. (2001) or Aringer et al. (2009)
- M, L, and T dwarfs from Allard et al. (2000)

➢ Dusty isochrones

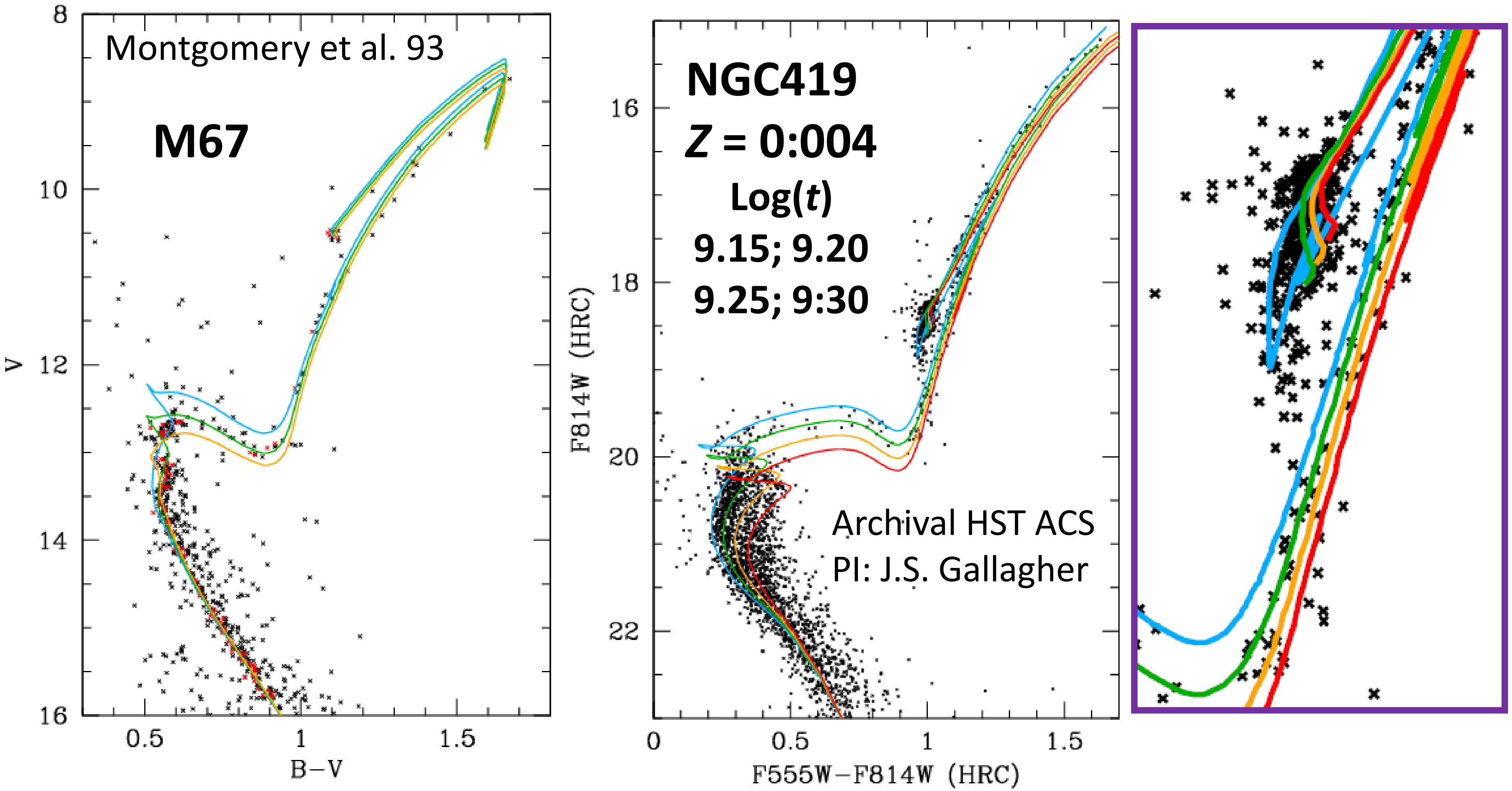
Inclusion of circumstellar dust from mass-losing AGB stars
Dust yields consistently computed by Nanni et al. 2012



e.g. comparison with MIR observationsvs (LMC)

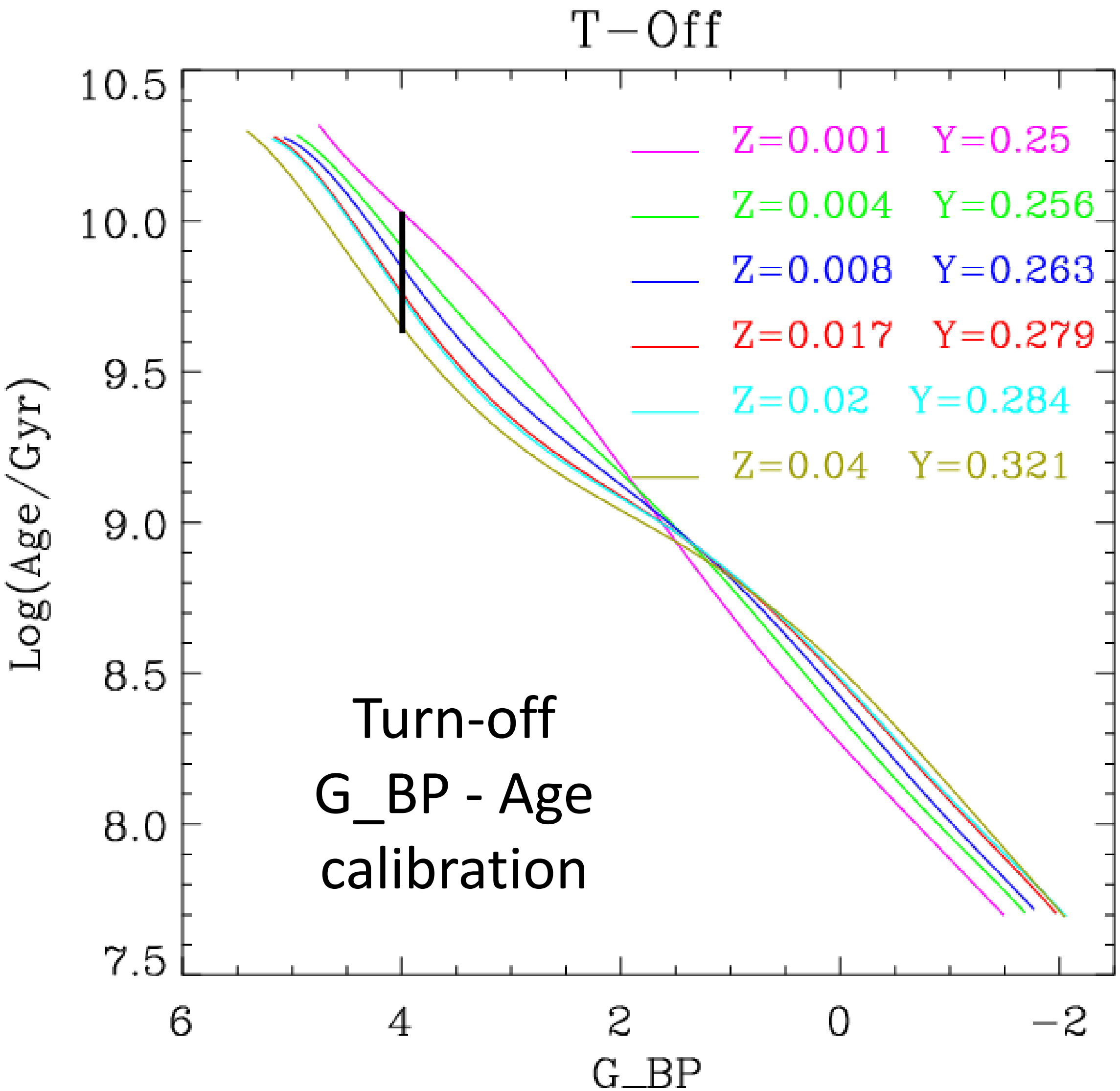


➢ Preliminary comparison with star clusters



➢ Age determination

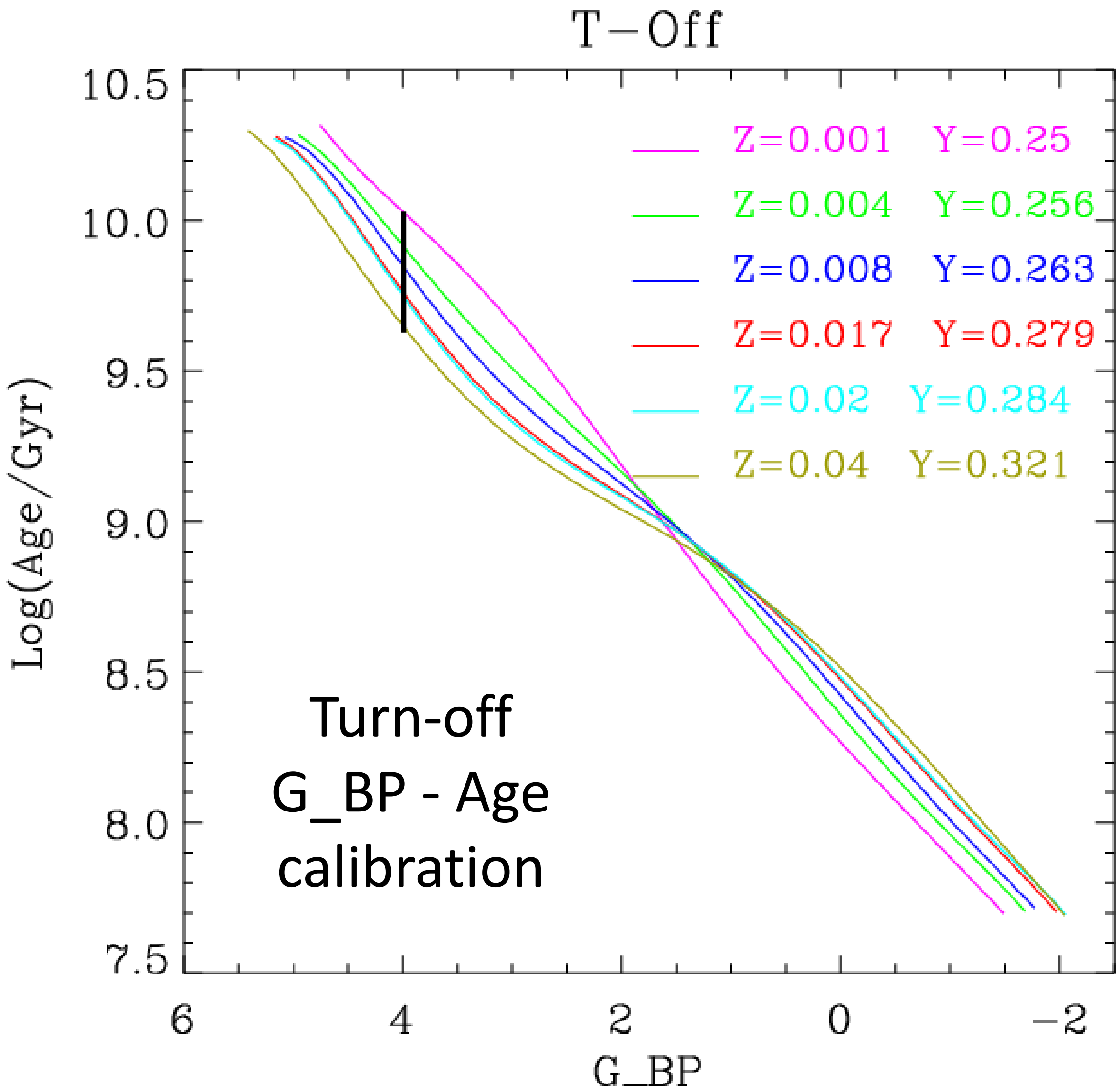
Metallicity effect
Z (+dY/dZ)



G_BP-G_RP	$\frac{\partial Log\, t}{\partial Z}$					δZ				
	Z= 0.002	0.006	0.012	0.018	0.028	0.002	0.006	0.012	0.018	0.028
-1.0	25.316	12.153	7.554	3.119	1.873	0.076	0.049	0.068	0.009	0.037
-0.5	25.812	15.120	7.105	2.788	2.121	0.077	0.060	0.064	0.008	0.042
0.0	30.341	16.021	5.910	2.788	1.524	0.091	0.064	0.053	0.008	0.030
0.5	33.601	13.461	3.968	2.460	0.442	0.101	0.054	0.036	0.007	0.009
1.0	29.554	7.485	1.454	1.491	-0.682	0.089	0.030	0.013	0.004	-0.014
1.5	15.217	-0.793	-1.371	-0.108	-1.535	0.046	-0.003	-0.012	-0.000	-0.031
2.0	-7.517	-9.600	-4.210	-2.051	-2.040	-0.023	-0.038	-0.038	-0.006	-0.041
2.5	-32.030	-16.940	-6.759	-3.871	-2.366	-0.096	-0.068	-0.061	-0.012	-0.047
3.0	-49.114	-21.057	-8.718	-5.060	-2.832	-0.147	-0.084	-0.078	-0.015	-0.057
3.5	-51.066	-20.942	-9.763	-5.239	-3.722	-0.153	-0.084	-0.088	-0.016	-0.074
4.0	-37.772	-16.853	-9.508	-4.379	-4.986	-0.113	-0.067	-0.086	-0.013	-0.100
4.5	-24.753	-10.885	-7.428	-3.046	-5.852	-0.074	-0.044	-0.067	-0.009	-0.117

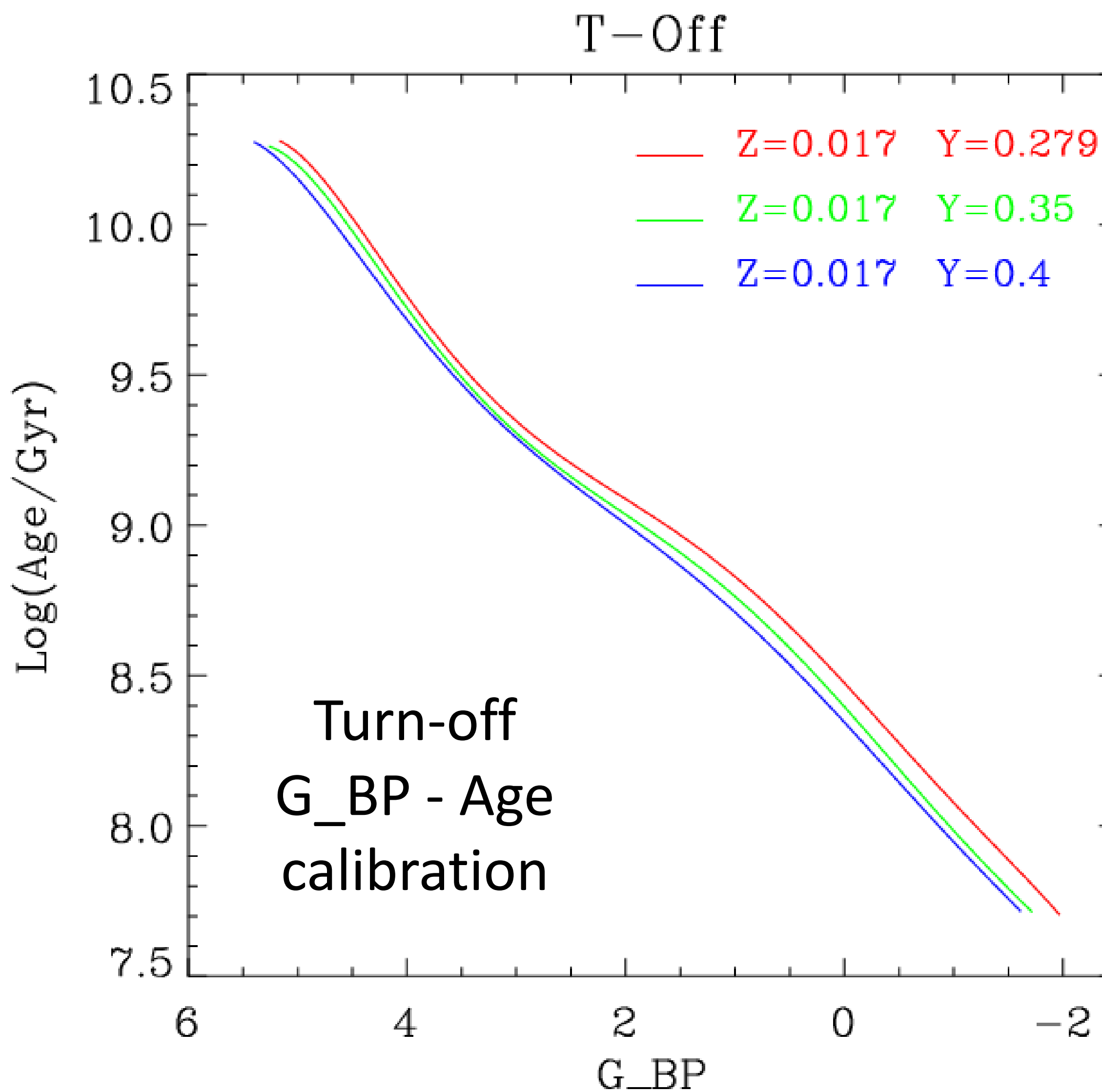
Age determination

Metallicity effect
Z (+dY/dZ)

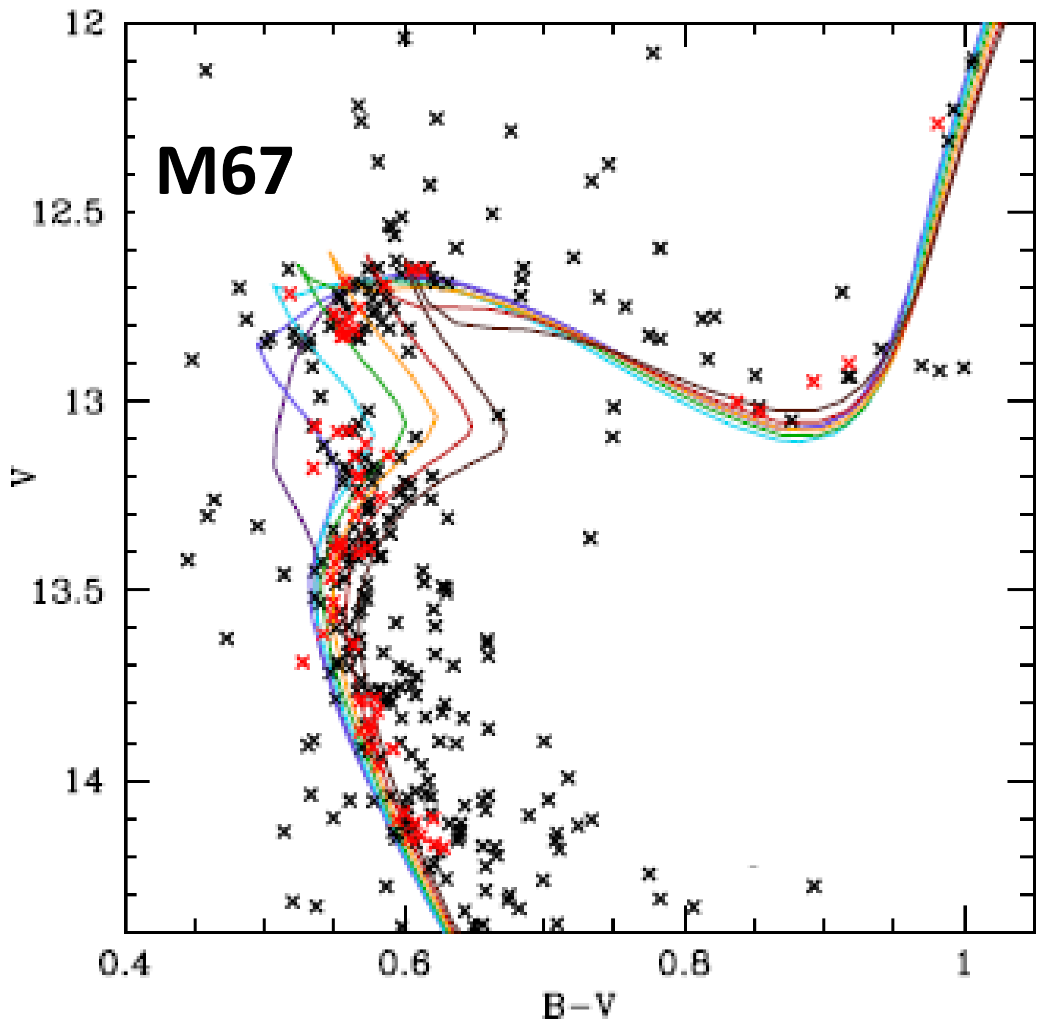


Age determination

He effect



➢ Effects of Core Overshoot



x Montgomery et al. 93

x high-probability single star members (Sandquist 04)

Λ_c=0.1, 4.17 Gyr

Λ_c=0.2, 4.07 Gyr

Λ_c=0.3, 4.26 Gyr

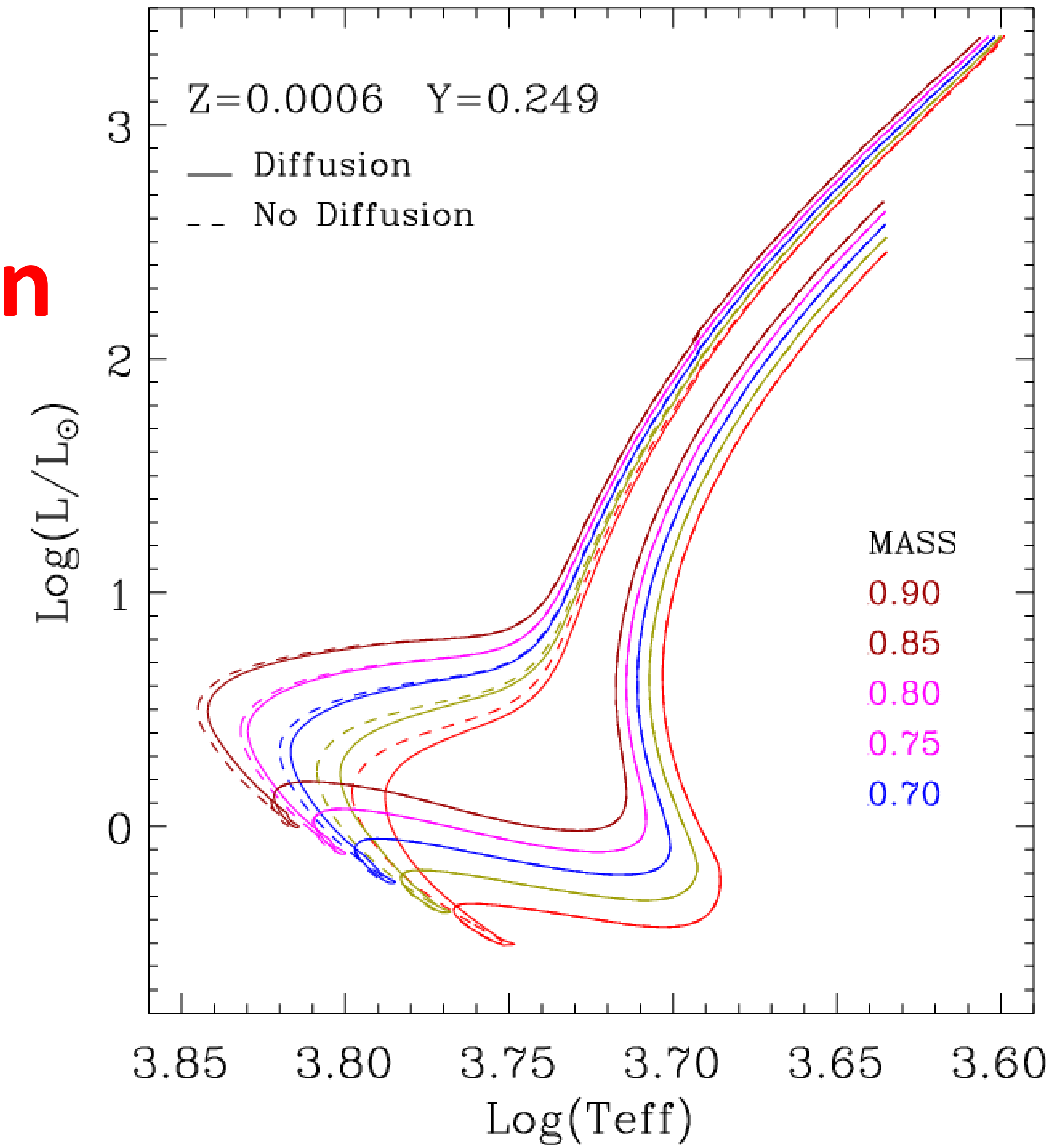
Λ_c=0.4, 4.57 Gyr

Λ_c=0.5, 4.90 Gyr

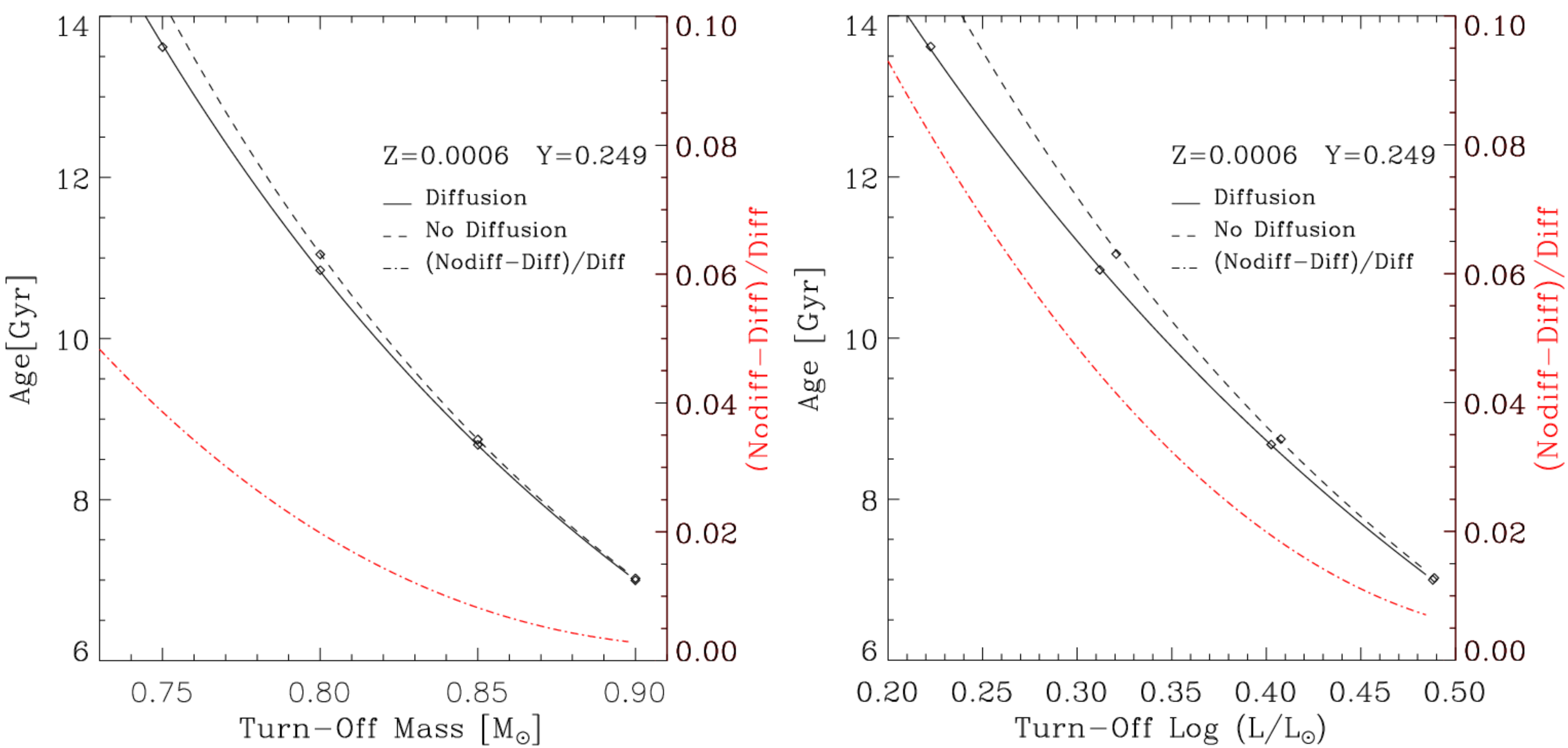
Λ_c=0.6, 5.37 Gyr

Λ_c=0.7, 5.89 Gyr

➢ Effects of Diffusion



Effects of Diffusion



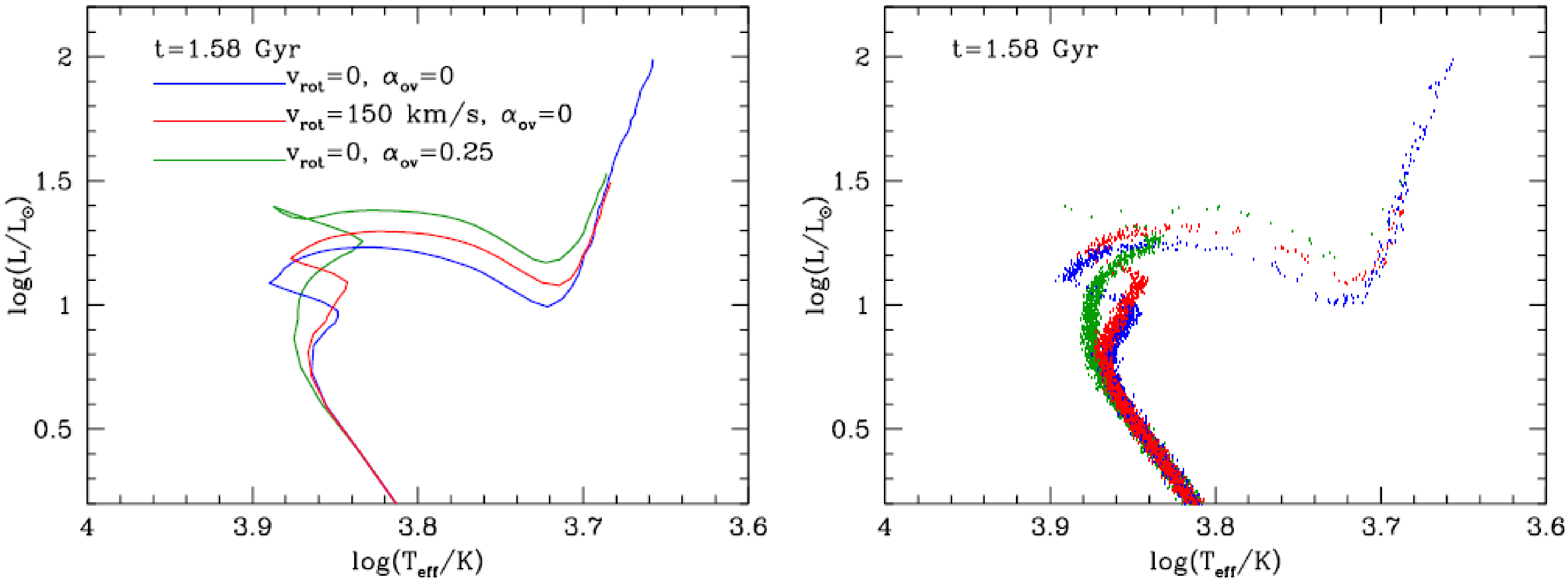
➢ EFFECTS OF ROTATION

For M=1.5 $M_\odot$ Bastian & de Mink 09 found cooler and less luminous TMS

$$T_{\rm eff}(\omega)/T_{\rm eff}(0) = 1 - a\omega^2$$ a = 0.17-0.19

$$L(\omega)/L(0) = 1 - b\omega^2$$ b = 0.11-0.03

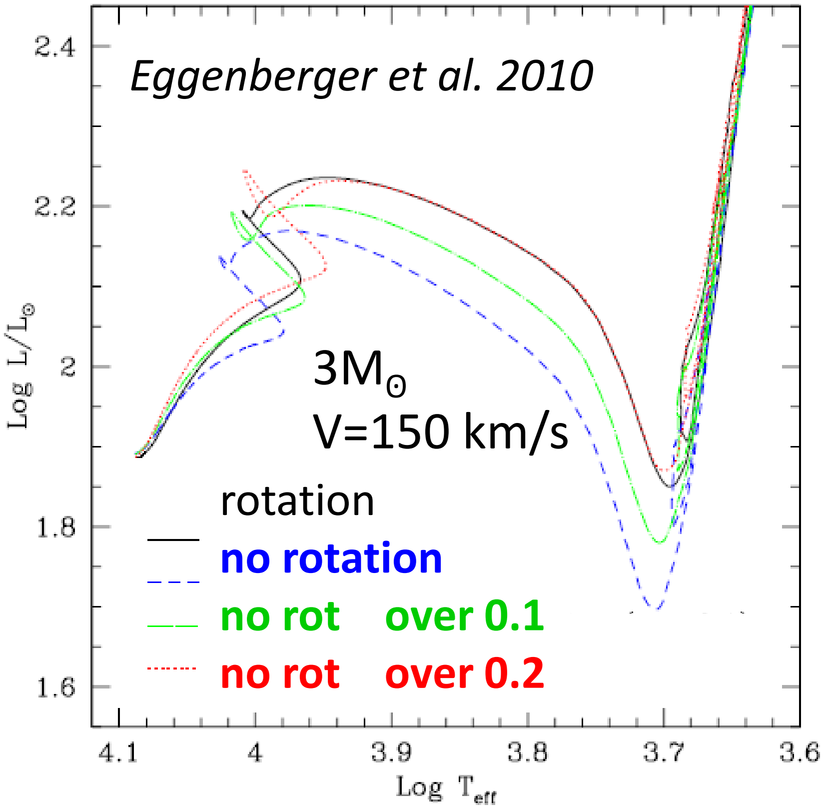
Not confirmed by Girardi, Eggenberger & Miglio 09



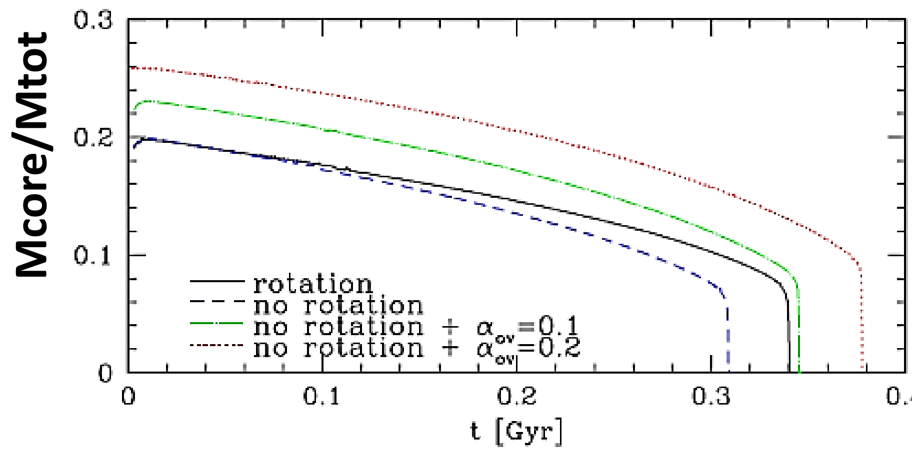
Girardi et al. result confirmed by similar colour distribution of upper MS stars of slow/fast rotators, v sin(i) > 90 km/s, in TRUMPLER 20 (Platais et al. 2012)

Rotation

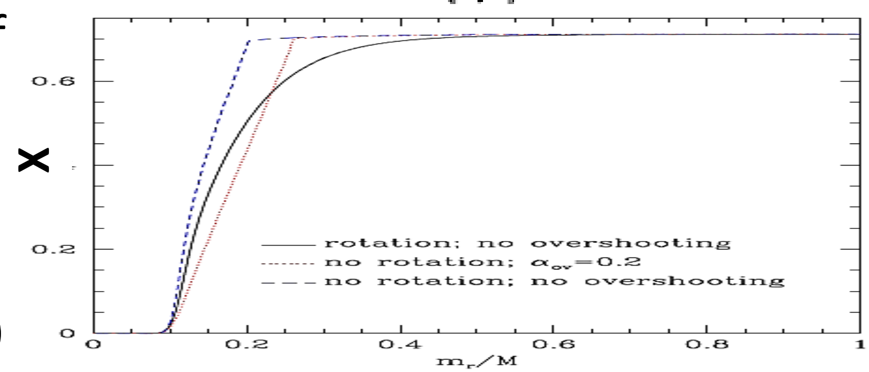
(Zahn 92, Maeder & Zahn 98, Maeder & Meynet 00)



- hydrostatic corrections (minor)
  3M$_\odot$ & V=150 km/s < 0.1%
- mixing in radiative zones (diffusive)
  - meridional circulation
  - shear mixing



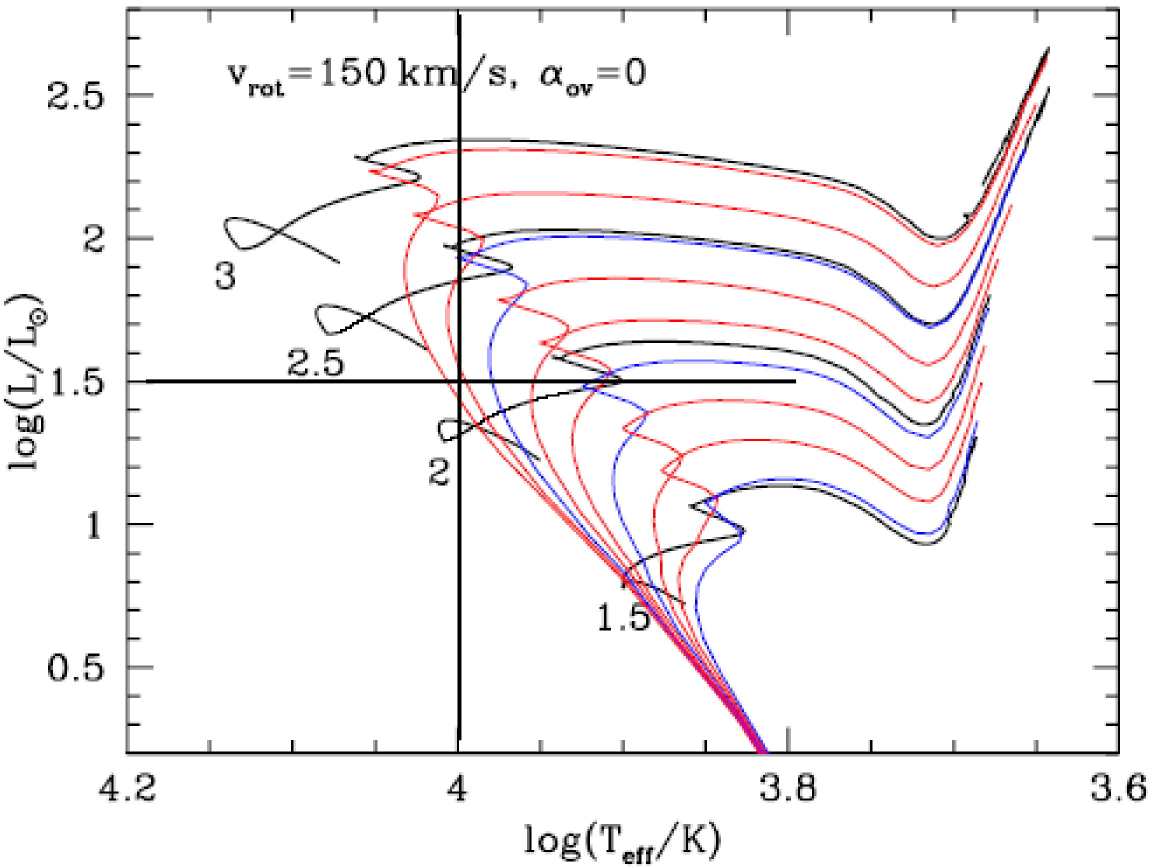
MS: Higher Luminosity & Lower Teff
Longer Duration (~ 10%)



- Age ~ ov 0.1
- Main Seq. ~ ov 0.1
- SGB and He ~ ov 0.2 (smoother X profile)

NO ROTATION vs ROTATION

Girardi, Eggenberger & Miglio 09

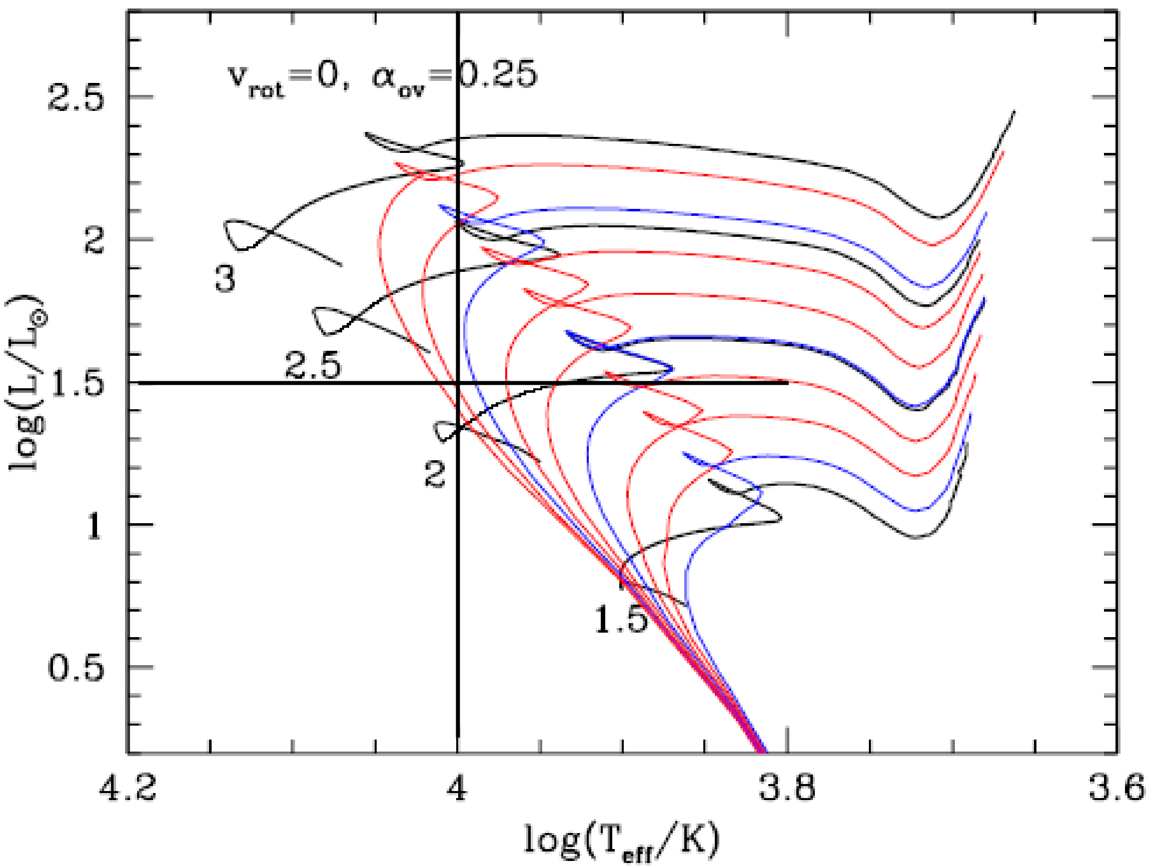


log t

8.5
8.6
8.7
8.8
8.9
9.0
9.1
9.2
9.3

NO-OVERSHOOT vs OVERSHOOT

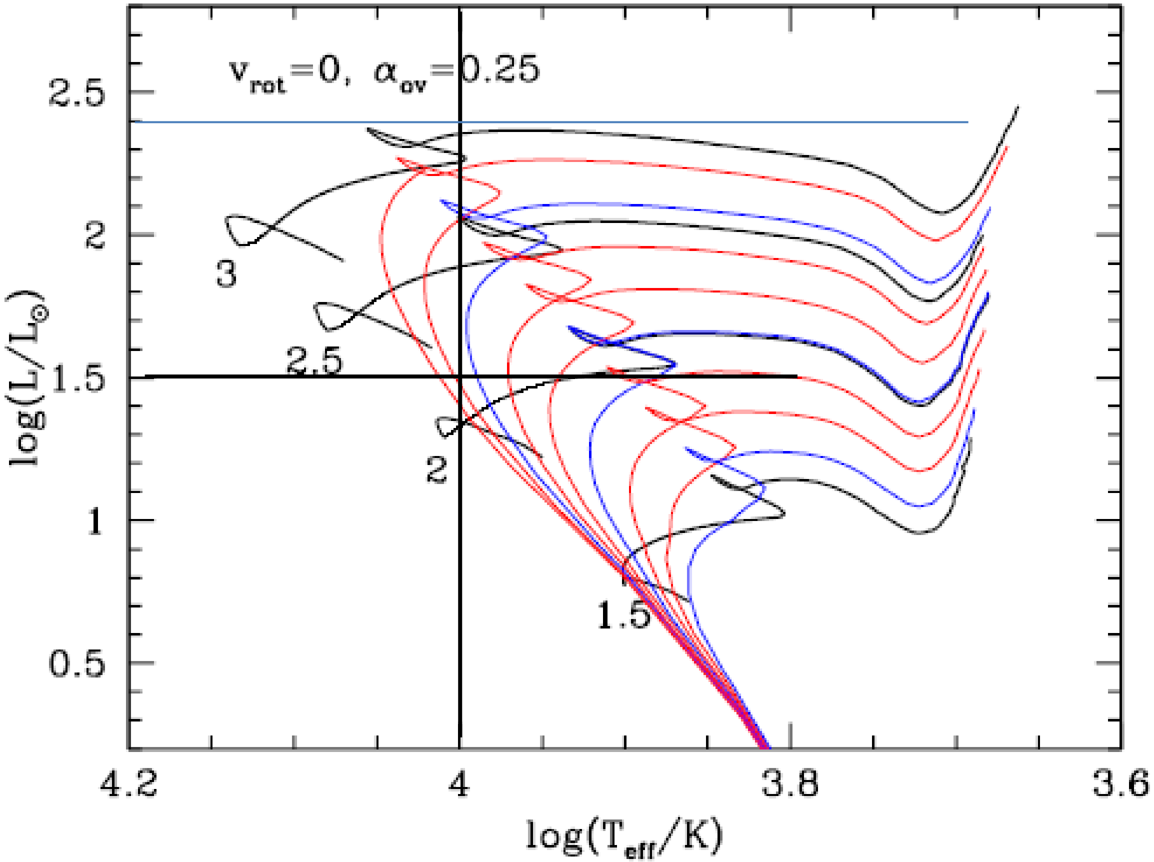
Girardi, Eggenberger & Miglio 09



log t
8.5
8.6
8.7
8.8
8.9
9.0
9.1
9.2
9.3

ROTATION vs. OVERSHOOT

Girardi, Eggenberger & Miglio 09



log t
8.5
8.6
8.7
8.8
8.9
9.0
9.1
9.2
9.3

New Tracks and Isochrones

will be available very soon

http://stev.oapd.inaf.it

Thanks!