Fine-tuning stellar models: steps towards calibrated calculations

Achim Weiss

Max-Planck-Institut für Astrophysik

(Garching, Germany)

What do you want?

- stellar models (global properties)
- all masses
- all compositions
- all evolutionary phases
- dense grids (for accurate interpolation)
- homogeneous physics
- accurate models
- reliable models
- models that give you “nice” results

What do you get?

- stellar models
- all masses
- all compositions
- all evolutionary phases
- dense grids
- homogeneous physics
- accurate models
- reliable models

- plenty from everywhere
- sometimes restricted
- standard compositions
- AGB? late phases?
- possibly
- today almost, but not really
- within code capabilities
- how should one know?

- you could also get interior structure and chemical yields

Basic requirements

- for any specified physical assumption
  - microphysics (opacities, equation of state, neutrino emission, diffusion coefficients, ...)
  - physical effect (overshooting, rotation, mass loss)

  models should be unique and not depend on the source

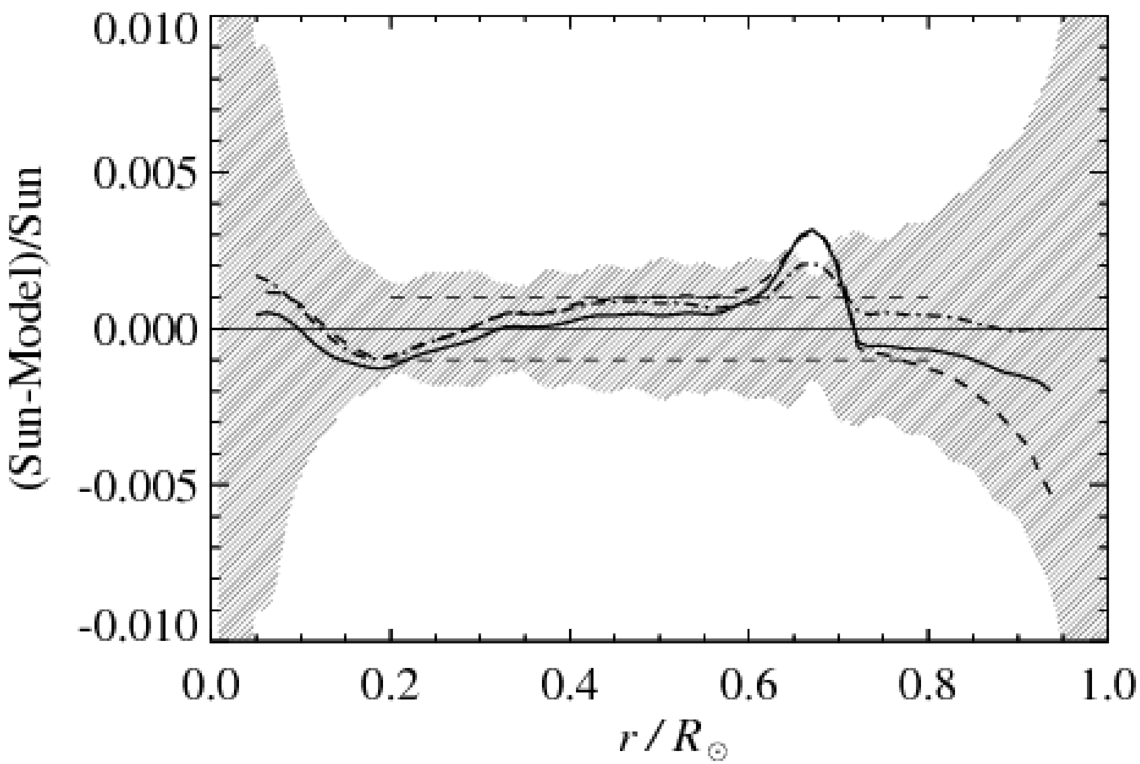
- differences in the models can be traced back to differences in these physical details, and not be due to code specifics
- technical code development should not alter the results

  present stellar evolution codes do not fulfill these requirements

- implication: the choice of the source for the models may determine your result, not the choice of the model physics

The Solar Model

- solar models suffered from the same problem
- but it was solved (GONG initiative)



sound speed of three solar models (Princeton, Århus, Garching) agrees within 0.001 over 80% of solar radius.
Others have followed (Padova, Yale, ...)

to achieve this, you may have to worry about details like table interpolation

Asteroseismology

- same problem:
  - predicted oscillation frequency should depend on physical assumption
  - want to learn about stellar physics (diffusion, rotation, convection) and determine stellar parameters (mass, age)
- much higher requirements
  - complete internal structure
  - high sensitivity of mode frequencies
  - depend on derivatives of physical quantities, not only on values
- restricted parameter range
- some stellar quantities known

COROT/ESTA

- COROT working group
- Evolution and Seismic Tools Activity (ESTA)
- regular meetings
- comparison of stellar evolution and oscillation frequency codes and models
- definition of set of standard cases with standard physical assumptions
- task 1: stellar models – mostly completed
- task 2: pulsation frequencies – 2006
- codes: Århus, CESAM, CLES, Franec (Pisa), TGEC, Starox, Garstec, ...

ESTA task 1 cases

case	mass	Y0	Z0	X_c	T_c	M_{Hecore}	overshoot	phase
1.1	0.9	0.28	0.02	0.35	–	–	–	MS
1.2	1.2	0.28	0.02	0.69	–	–	–	ZAMS
1.3	1.2	0.26	0.01	–	–	0.1	–	Post-MS
1.4	2.0	0.28	0.02	–	1.9×10^7	–	–	Pre-MS
1.5	2.0	0.26	0.02	0.01	–	–	0.15 Hp	TAMS
1.6	3.0	0.28	0.01	0.69	–	–	–	ZAMS
1.7	5.0	0.28	0.02	0.35	–	–	–	MS

(selected in view of possible COROT targets)

ESTA physics definitions

ITEM	Selection	References
EoS	OPAL	Rogers et al. (1996, 2001 Tables)
Opacities	OPAL	Iglesias & Rogers (1996) +
		Alexander & Fergusson (1994)
Reaction rates	NACRE	Angulo et al. (1999)
Convection	MLT (α = 1.6)	Böhm-Vitense (1958) + Henyey et al. (1965)
Overshoot	$\nabla = \nabla_{ad}$	Zahn (1991) + ...
Diffusion	– none –	
Mixture	solar	Grevesse & Noels (1993)
Atmosphere	gray	–

(additional details and clarifications in a separate ESTA-document)

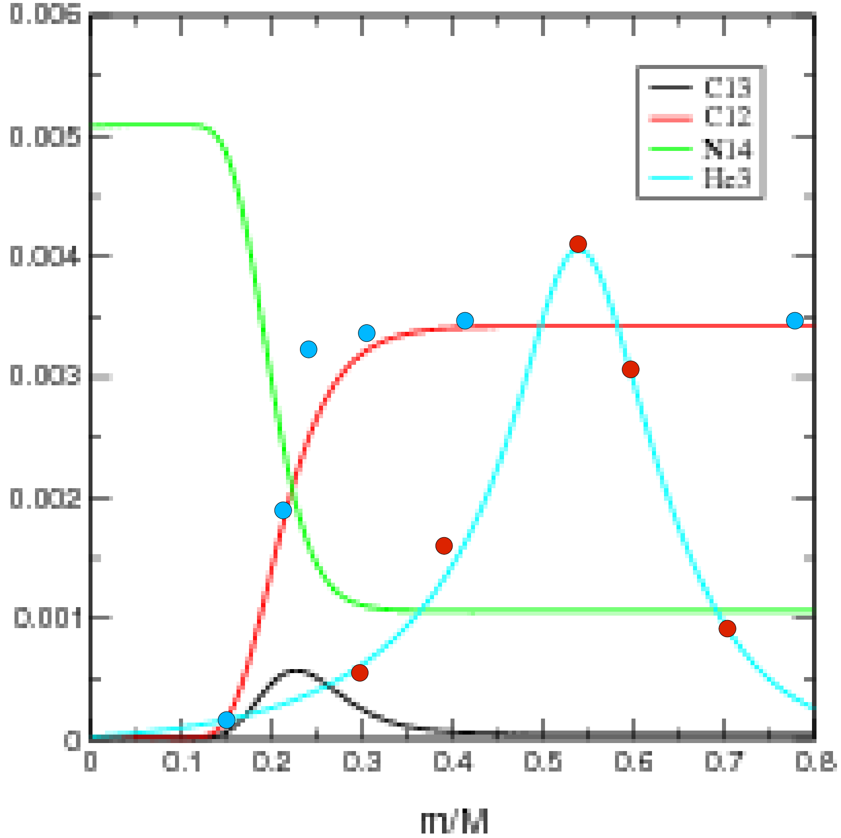
0.9 $M_\odot$ – evolved MS model (Z=0.02)

(taken from Lebreton & Monteiro, ESTA meeting Nice, Sept. 2005)

	Age	$\frac{R}{R_\odot}$	$\frac{L}{L_\odot}$	$T_{\rm eff}$	$\frac{T_c}{10^7}$	ρ_c	X_c	$\frac{M_{\rm cor}}{M}$	$\frac{R_{\rm env}}{R}$
Case 1.1:									
ASTEC	6 745	0.8927	0.6237	5 434	1.443	150.5	0.3500	-	0.6954
CESAM_0	6 782	0.8916	0.6262	5 443	1.448	150.9	0.3501	-	0.6958
CESAM_1	6 886	0.8933	0.6237	5 432	1.444	150.0	0.3500	-	0.6957
CLES	6 816	0.8954	0.6245	5 428	1.447	151.2	0.3496	-	0.6972
FRANEC	6 823	0.9038	0.6269	5 408	1.452	152.3	0.3500	-	0.7002
STAROX	6 674	0.8926	0.6259	5 439	1.446	151.8	0.3500	-	0.6964
TGEC	6 539	0.8942	0.6504	5 489	1.458	153.9	0.3499	-	0.7015
GARSTEC	6899	0.8853	0.6235	5449	1.445	145.0	0.3500	-	0.6960

task 1.1 – chemical profile

- relative deviations generally below 0.5–1% except for Pisa code in centre, and Århus code around ^{3}He bump



dots: Garstec model

3 $M_\odot$ – ZAMS model (Z=0.02)

	Age	$\frac{R}{R_\odot}$	$\frac{L}{L_\odot}$	$T_{\rm eff}$	$\frac{T_c}{10^7}$	ρ_c	X_c	$\frac{M_{\rm cor}}{M}$	$\frac{R_{\rm env}}{R}$
Case 1.6:									
ASTEC	13.71	1.864	101.5	13 432	2.479	42.68	0.6900	0.2129	0.9990
$CESAM_0$	14.47	1.854	101.4	13 466	2.486	43.04	0.6901	0.2114	0.9945
$CESAM_1$	14.04	1.854	101.4	13 470	2.486	43.05	0.6900	0.2114	0.9945
CLES	14.76	1.852	101.6	13 479	2.487	43.08	0.6900	0.2104	0.9938
FRANEC	14.95	1.853	101.4	13 469	2.481	42.94	0.6894	0.2151	0.9939
STAROX	14.46	1.855	101.6	13 468	2.487	43.17	0.6900	0.2118	0.9939
TGEC	21.00	1.981	78.5	12 223	2.401	40.50	0.6900	0.1976	0.9989

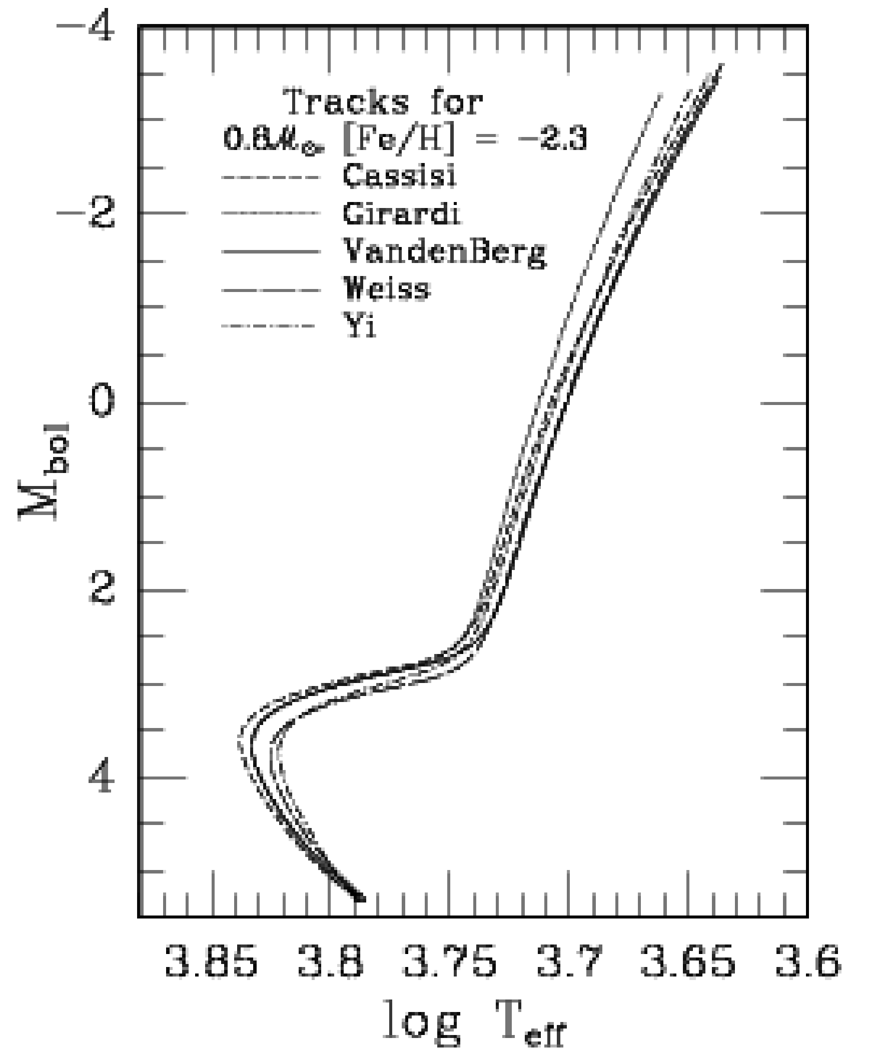
- definitely larger differences (age: 5% and more!)
- also in hydrogen profile (ZAMS-definition!) up to 10%
- problem: boundary of convective core

ESTA conclusions

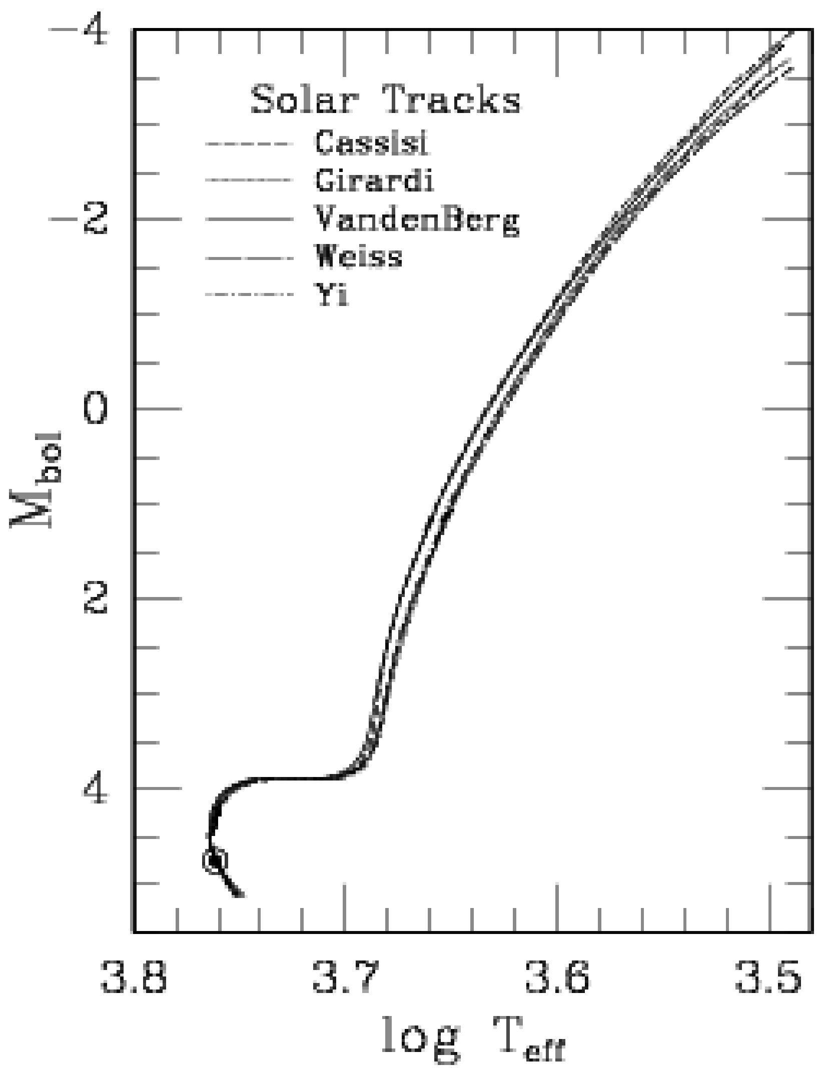
- global quantities differences 1–5%
- age up to 20%
- convective core problem
- partially due to deviations from physics specifications or hidden differences
- pre–MS and overshooting increase differences
- CLES/$CESAM_0$ codes:
  - same origin (numerics)
  - very similar physics implementation
  - differences < 0.5%

Comparisons at low Z

- D.A. VandenBerg ("Resolved Stellar Populations", 2005)
- comparison of tracks for low-mass, low-metallicity stars
- differences in Y_i: 0.230 (Girardi, Yi) - 0.235 (VdB, Weiss)
- TO ages from 12.58 Gyr (Cassisi) to 13.74 (Weiss)
- 4 of 5 ages > 13.22 Gyr

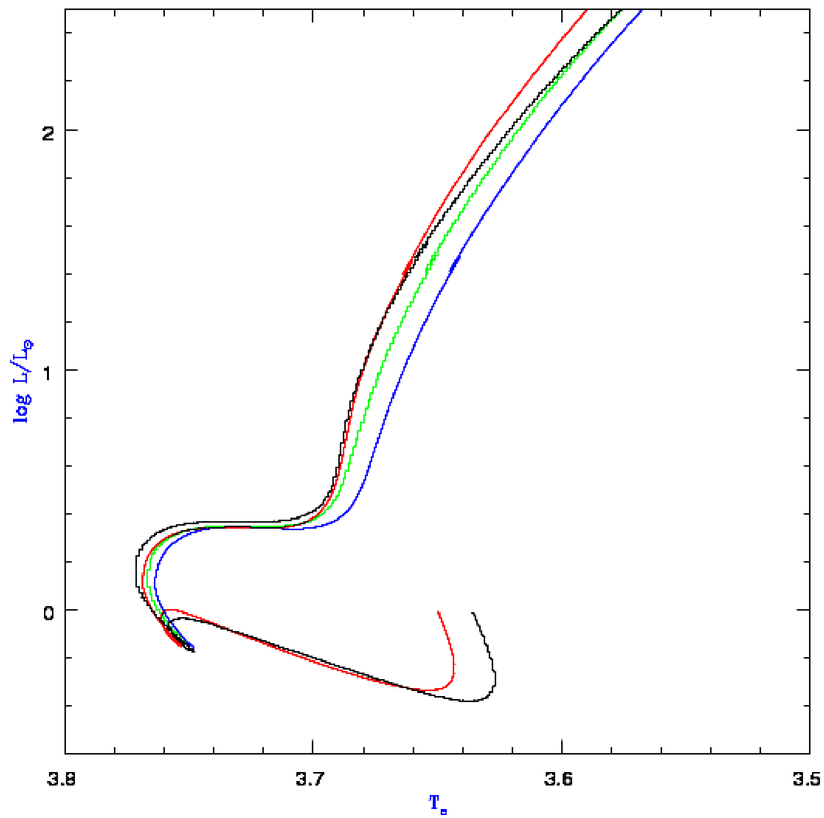


The solar case



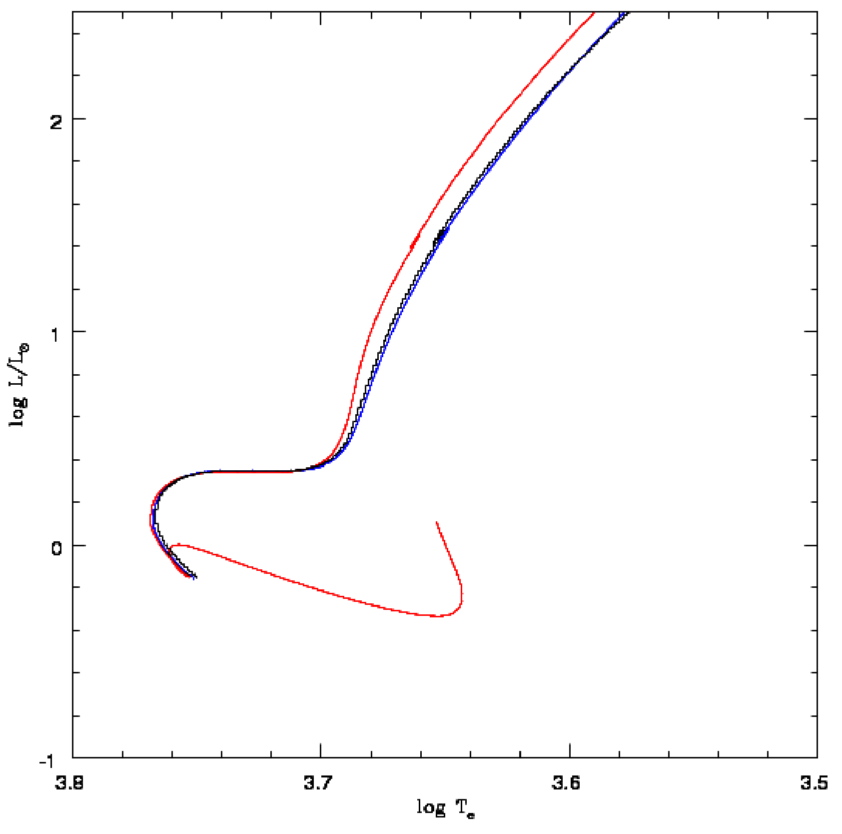
- same physics, but solar abundances
- all match solar constraints
- no diffusion in Girardi and VandenBerg
- Y_i from 0.2670 (Yi) to 0.2768 (VandenBerg)
- Z_i from 0.01810 (Yi) to 0.01998 (Weiss)
- α_{MLT} from 1.68 (Girardi) to 1.90 (VandenBerg)

standard 1 $M_\odot$ star (Z=0.02, X=0.70)



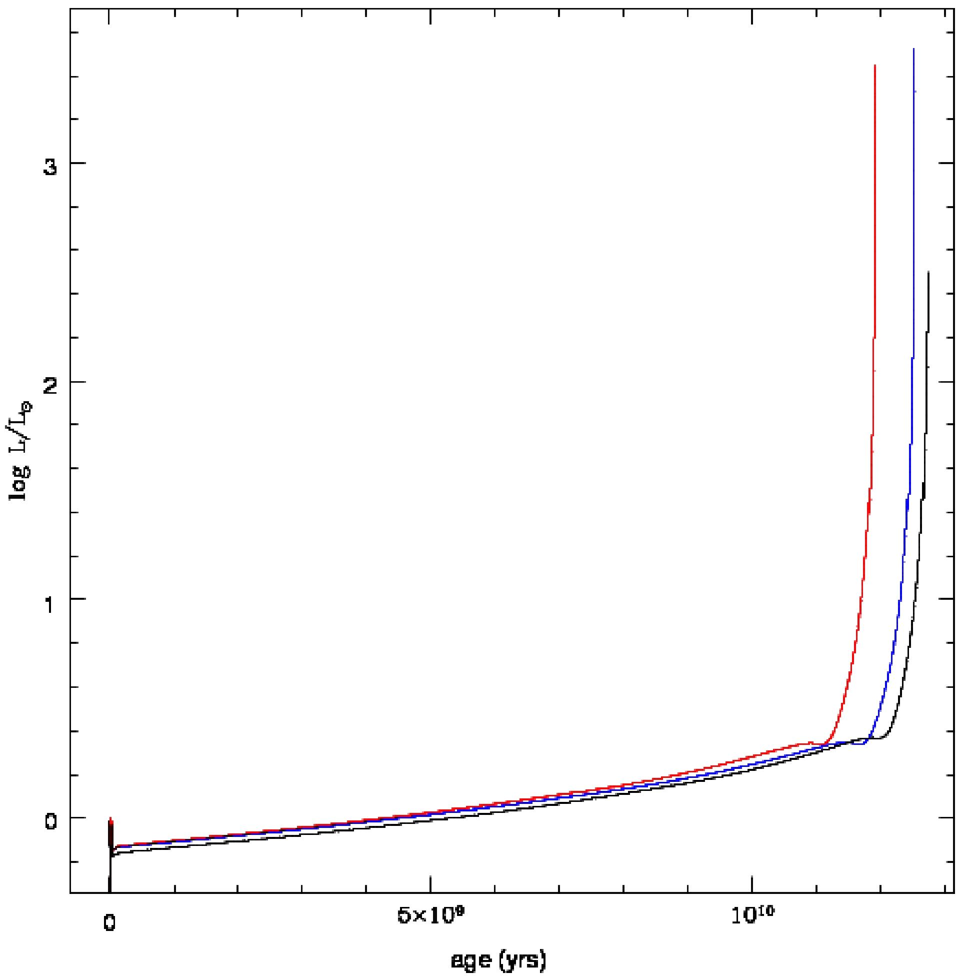
- blue: Weiss (Garstec)
- red: Salaris (FRANEC)
- green: Serenelli (LaPlata), analytical EoS
- black: Serenelli, Magni & Mazzitelli EoS
- Garstec: uncalibrated α_{MLT}
- reaction rates and opacities similar
- grey atmospheres
- T_{eff} differences on RGB up to 200 K!

standard 1 $M_\odot$ star (Z=0.02, X=0.70)



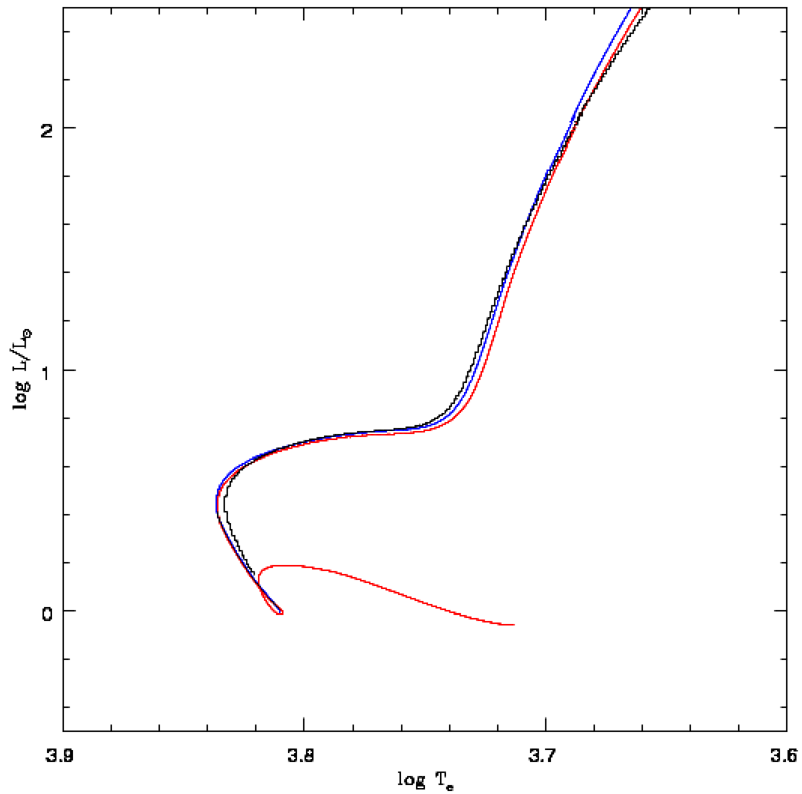
- blue: Weiss (Garstec)
- red: Salaris (FRANEC)
- black: Serenelli (LaPlata), analytical EoS
- Garstec: calibrated α_{MLT}
- reaction rates and opacities similar
- grey atmospheres
- T_{eff} differences on RGB below 100 K

... and L(t)

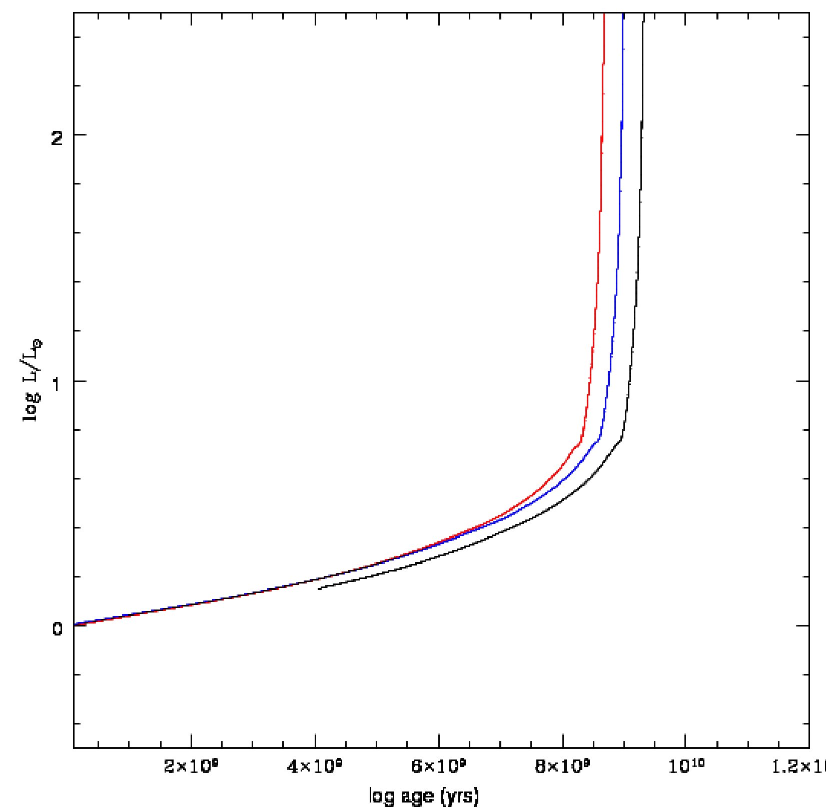


systematic age difference between FRANEC (red) and Garstec (blue) ages due to MS evolution

0.9 $M_\odot$ (Z=0.001, Y=0.250)



- same physics as in solar mixture case
- HRDs agree much better



but ages differ more
(Serenelli model lives
longer due to lower luminosity)

on-going comparisons

- RGB bump luminosity (from literature and calculations):

	Padova	Pisa	BASTI	Y^2	Garching
age (Gyr)	6.514	6.331	6.023	6.769	6.222
$\log L/L_\odot$	1.971	2.089	2.106	2.101	2.153
T_{eff}	3.698	3.689	3.694	3.689	3.693
metal mix.	solar	solar	α-enh.	α-enh.	α-enh.
diffusion	no	yes	no	yes	yes
overshooting	yes	no	no	no	no

- RGB tip luminosity $\log L/L_\odot$ ($1.0\ M_\odot$, Z=0.001):
  - for timesteps "standard" -> 0.01*standard
  - BASTI: 3.35 -> 3.29
  - Garstec: 3.41 -> 3.34 (saturation from 0.2*standard on)

calibration attempts

- define a set of simple problems
- and a standard set of input physics (ESTA is a good start)
- get stellar evolution modellers to present their solutions to these problems
- compare, learn, adjust ...
- independently, solve obvious discrepancies between 2 codes
  - bump brightness
  - RGB tip
  - RGB effective temperatures
  - MS lifetimes

suggested cases – to be discussed

- physics as defined by COROT/ESTA
- model exchange format: GONG
- ESTA cases, internal structure comparison
  - 1.1 (0.9 $M_\odot$, X_c=0.35, Z=0.02)
  - 1.3 (1.2 $M_\odot$, ZAMS, Z=0.01)
  - 1.6 (3.0 $M_\odot$, ZAMS, Z=0.02)
- ZAMS cases (definition?), global quantities L, T_e, ρ_c, T_c
  - X=0.70, Y=0.28, Z=0.02
  - X=0.749, Y=0.25, Z=0.001
  - masses from 0.7 to 20 $M_\odot$
- Evolution cases, global quantities L(t), T_e(t)
  - M=1 and 20 $M_\odot$(Z=0.02), from ZAMS to tip RGB resp. end He-burning