Results from tests of stellar physics uncertainties

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ASTERO CHRONOMETRY

UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

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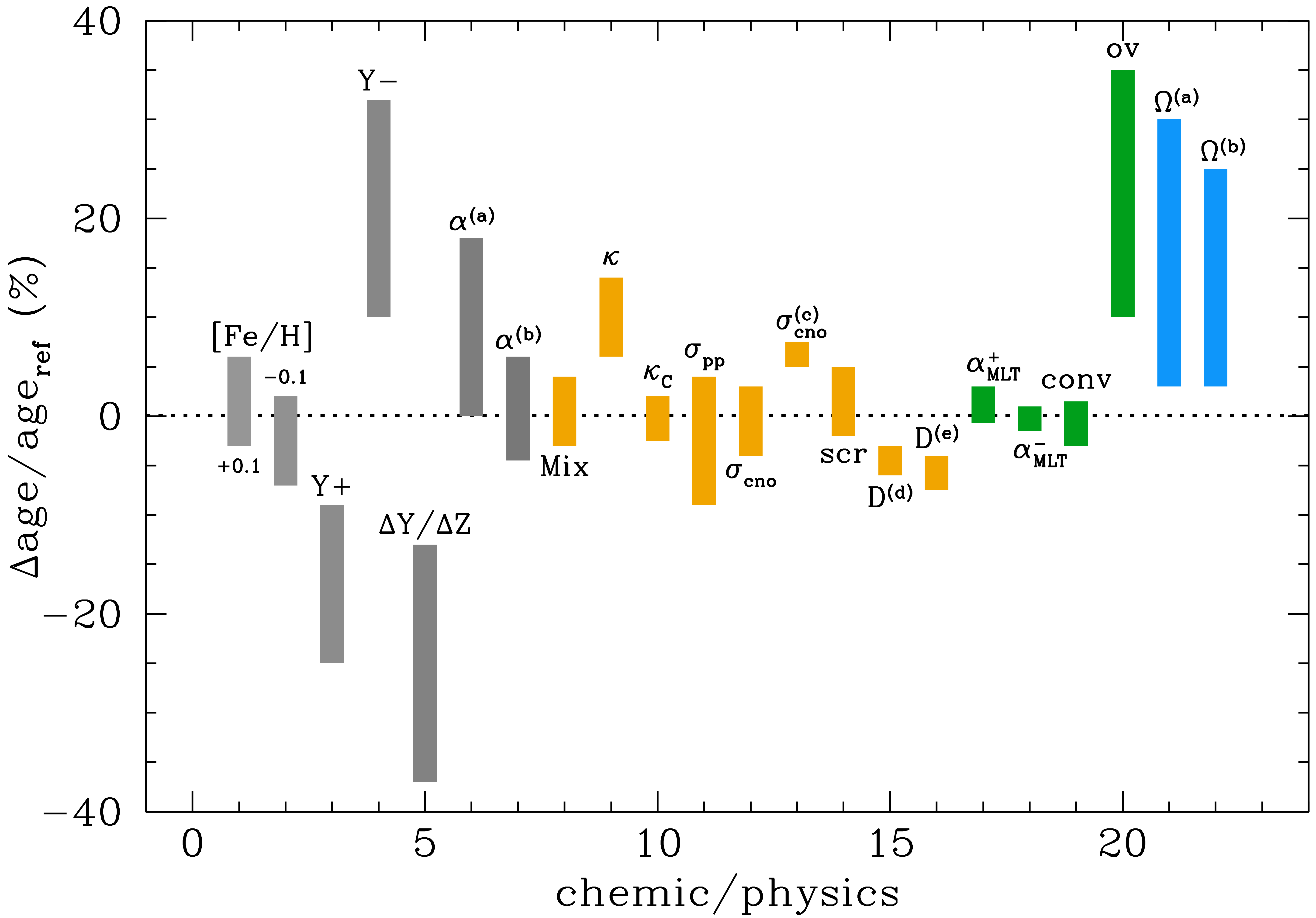
Ingredients for a stellar model

- Opacity tables (interior and low temperature) ….. .OPAL, OP, OPAS,OPLIB
- Chemical composition : [Fe/H], Y, and [X/H] ……AGSS09, GN93,GS98, CLSFB11…
- Equation of State ……OPAL, SAHA-S, freeEOS.
- Nuclear reaction rates ……NACRE, NACREII, Solar FusionII
- Surface boundary conditions: Atm. Models …… 1D , 3D, grey/non-grey, Eddington , KS, Val-C..
- Treatment of superadiabatic convection …….MLT/FST, 3D simulations
- Boundaries of convective regions …….Overshooting instantaneous, diffusive one…
- Microscopic diffusion and radiative acceleration ……Microscopic diffusion and radiative acceleration

- Transport of angular momentum and chemicals induced by stellar rotation.
- Magnetic fields.
- Tidal effects in binaries.

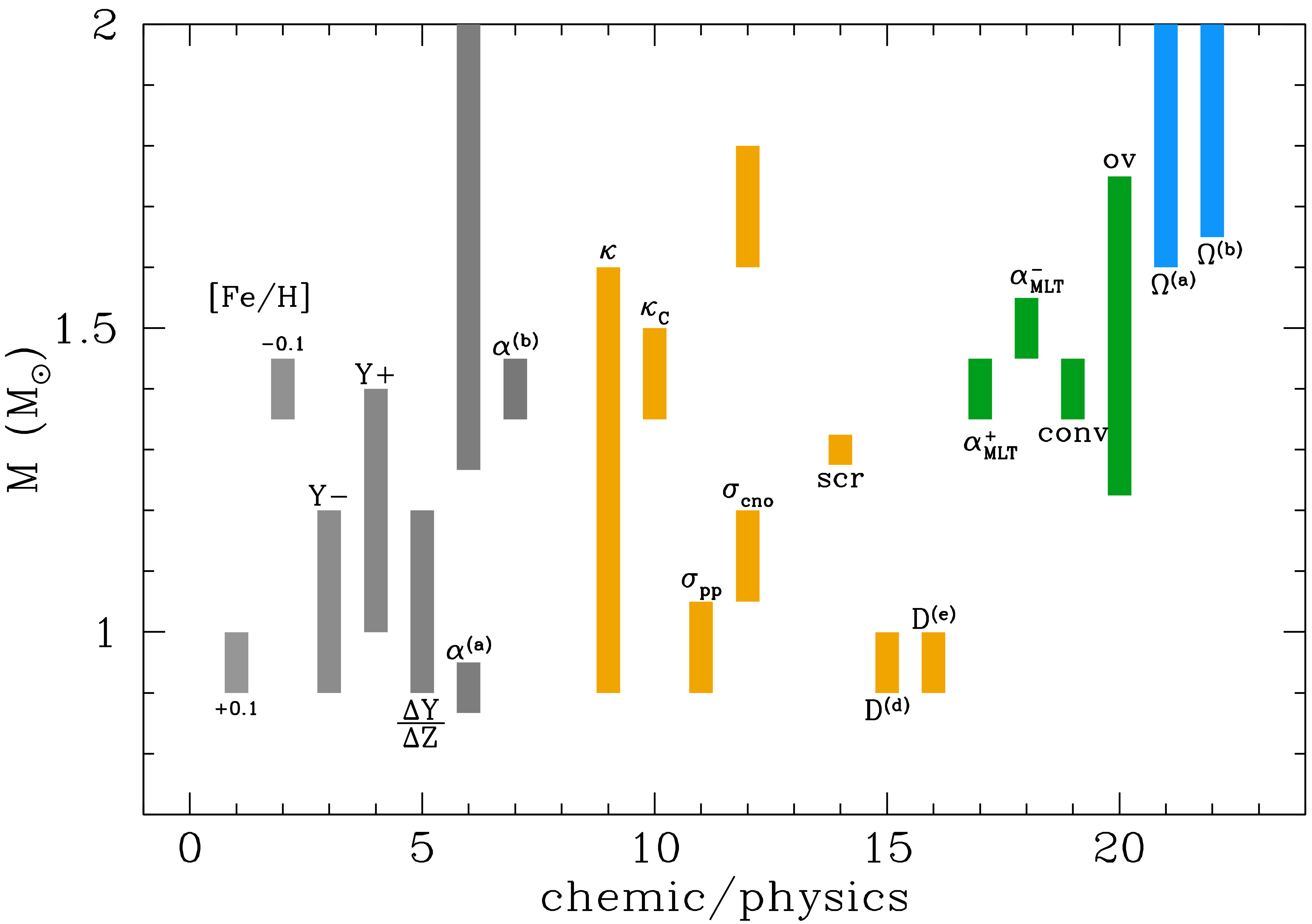
Effect on TO age of uncertainties in micro/macro physical inputs in stellar models



- Y : +/- 0.03 respect to solar
- ΔY/ΔZ: +3 respect to solar
- α-elements enhancement of +0.4 dex at [Fe/H]=0.0 (a) and −1.0 dex (b)
- κ: +10%
- κ_c: Iben 75 vs. Cassisi et al. 07
- OV: $\alpha_{ov:}$ 0 vs. 0.2
- Rotation: 50 km/s at [Fe/H]=0 (Ω_a); [Fe/H]=-1.0 (Ω_b)

Lebreton, Goupil & Montalban 2014

Mass domain affected by those uncertainties

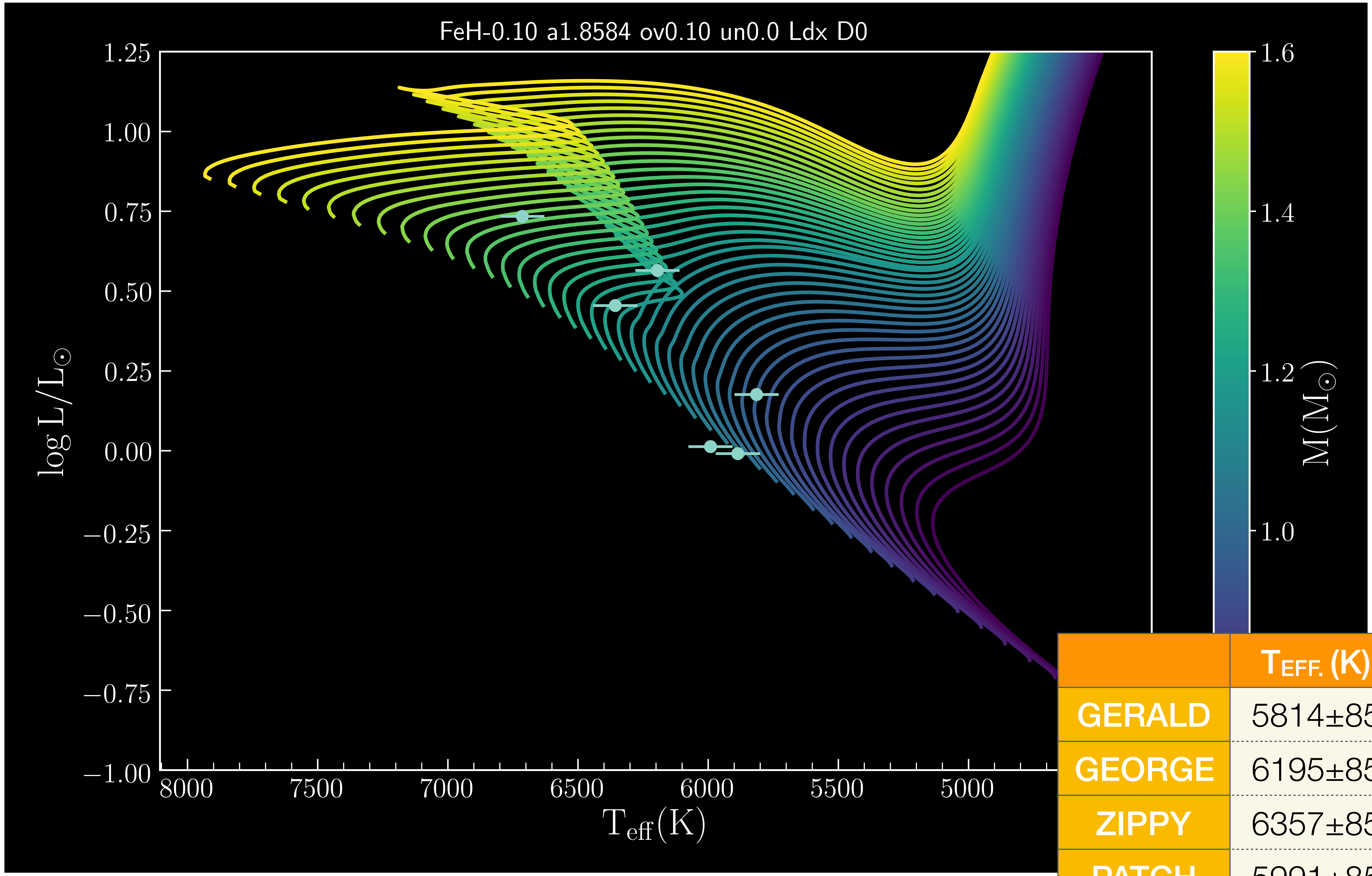


Lebreton, Goupil & Montalban 2014

INPUT PHYSICS TEST

● Opacity tables (interior and low temperature)	OPAL/OP
● Chemical composition : [Fe/H], Y, and [X/H]	AGSS09/GN93
● Equation of State	
● Nuclear reaction rates	14N,p and pp
● Surface boundary conditions: Atm. Models	
● Treatment of superadiabatic convection	
● Boundaries of convective regions	Overshooting & semiconvection
● Microscopic diffusion and radiative acceleration	MP93 / Burgers Eq.
● Transport of angular momentum and chemicals induced by stellar rotation.	
● Magnetic fields.	
● Tidal effects in binaries.	

TARGETS



6 Synthetic Main Sequence Stars used by WP124 in H&H and by WP121

- ν_{max} and $\Delta\nu$
- T_{eff} [Fe/H]
- Luminosity
- ~ 30 individual frequencies with angular degree : 0, 1 and 2

In each test L, Teff, [Fe/H} and individual frequencies are used as observational constraints, and the corresponding grid of stellar uses solar calibrated convection parameter for the corresponding physics

	$T_{EFF.}$ (K)	Lum/L⊙	[Fe/H]	ν_{max} (μHz)	$\Delta\nu$ (μHz)	N modes
GERALD	5814±85	1.50±0.05	0.03±0.09	2207±108	106.3±2.1	28
GEORGE	6195±85	3.67±0.11	0.35±0.09	1284±68	68.8±1.4	35
ZIPPY	6357±85	2.85±0.09	-0.17±0.09	1660±85	86.4±1.7	33
PATCH	5991±85	1.03±0.03	-0.28±0.09	2906±143	132.9±2.7	25
ZEBEDEE	5886±85	0.98±0.03	0.10±0.09	3254±167	136.5±2.8	23
FRED	6714±85	5.42±0.16	-0.04±0.09	1393±69	67.0±1.4	32

CHARACTERIZATION OF TARGETS

- Stellar evolution CODE : GARSTEC (Weiss & Schlattl, 2008)
- Nuclear reaction rates : Solar Fussion (Aldelberger et al 2011)
- FreeEOS (Cassisi et al 2003)
- Convection: MLT
- Solar mixture : GN93 (Z/H=0.0245), (Grevesse & Noels 1993)
- Undershooting (Formalism Vandenberg et al.2012)
- Diffusive Overshooting (f=0.02 ~ 0.25Hp)
- Microscopic diffusion (Thoul et al.1994) + attenuation between 1.25-1.35 Msun
- $T(\tau)$: Eddington relation

- Adiabatic oscillation code ADIPLS (Christensen-Dalsgaard 2008)
- Optimization/Inference : AIMS (Lund & Reese 2018, Rendle et al 2019) with Ball & Gizon (2014) for surface effects correction
- Constraints : L, Teff, [Fe/H] and individual frees

Grid of stellar models :

M in [0.7,1.6] Msun ΔM=0.01 Msun

[Fe/H] in [-0.95,+0.6], Δ([Fe/H])=0.05dex

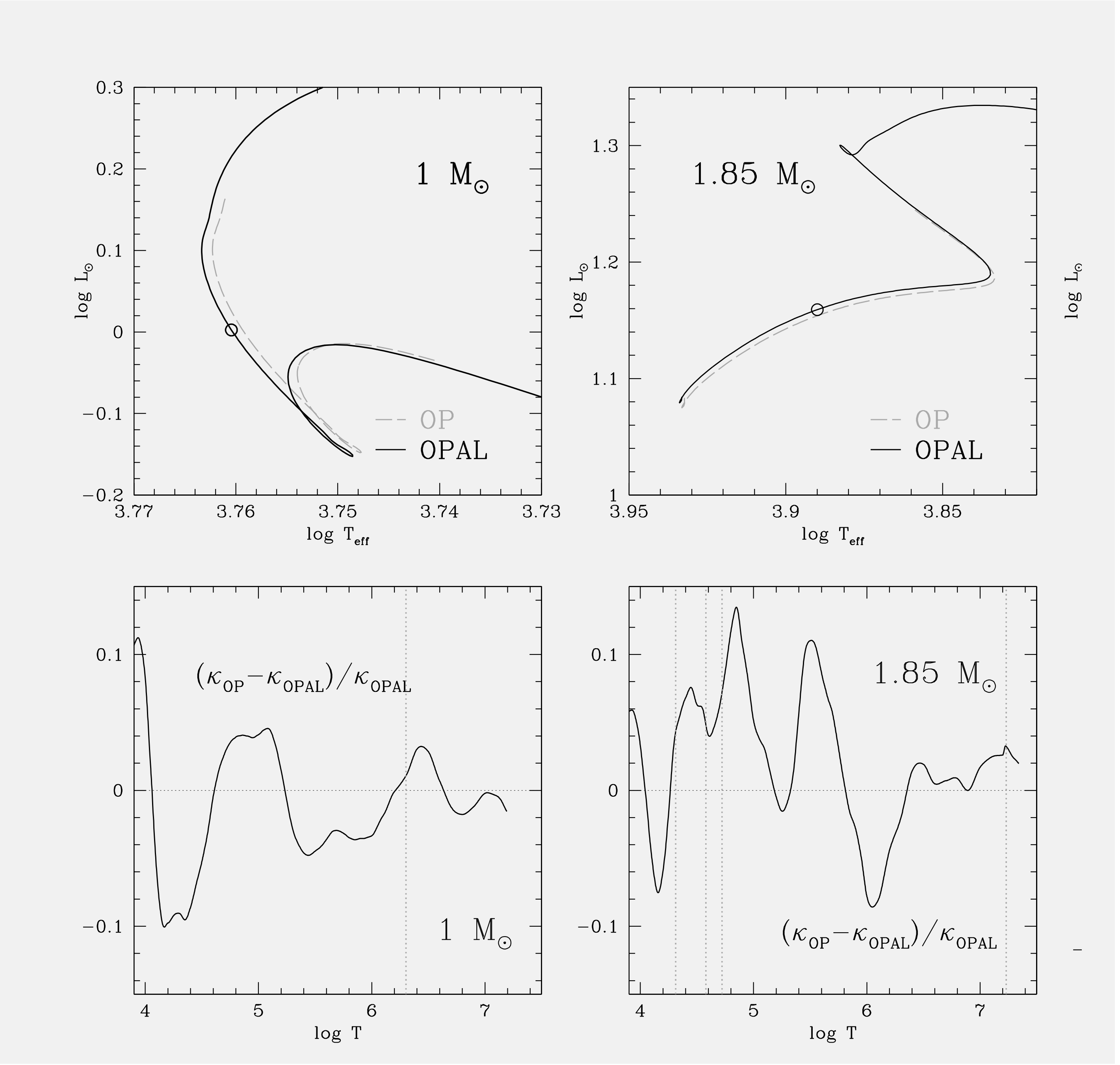
ID	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)	$\log g$	ρ (g.cm^{-3})	$Z_{\rm ini}$	[Fe/H]
Fred	1.41 ± 0.05	1.715 ± 0.027	1.85 ± 0.20	4.12 ± 0.01	0.396 ± 0.003	0.016 ± 0.005	-0.039 ± 0.12
Georges	1.38 ± 0.01	1.737 ± 0.001	3.11 ± 0.03	4.10 ± 0.01	0.307 ± 0.001	0.032 ± 0.001	0.28 ± 0.01
Gerald	1.00 ± 0.02	1.119 ± 0.005	8.41 ± 0.30	4.28 ± 0.01	0.828 ± 0.002	0.019 ± 0.002	-0.04 ± 0.05
Patch	0.89 ± 0.01	0.966 ± 0.002	7.54 ± 0.10	4.42 ± 0.01	1.397 ± 0.003	0.009 ± 0.003	-0.37 ± 0.01
Zebedee	1.02 ± 0.01	0.966 ± 0.002	2.34 ± 0.15	4.48 ± 0.01	1.596 ± 0.002	0.019 ± 0.001	0.02 ± 0.01
Zippy	1.16 ± 0.03	1.409 ± 0.015	3.76 ± 0.30	4.21 ± 0.01	0.589 ± 0.004	0.014 ± 0.003	-0.19 ± 0.08

OPACITY TABLES

- Stellar evolution CODE : CESTAM (Morel & Lebreton , 2008, Marques et al .2013)
- Nuclear reaction rates : NACRE (Angulo 1999)
- OPAL2005 EoS
- Convection: FST (Canuto et al 1996)
- Solar mixture : AGSS09 (Z/H=0.0181), + Serenelli (2010)
- Adiabatic oscillation code ADIPLS (Christensen-Dalsgaard 2008)
- Optimization/Inference : AIMS (Lund & Reese 2018, Rendle et al 2019) with Ball & Gizon (2014) for surface effects correction

OPAL versus OP

(Rogers & Nayfonov 2002) (Seaton 2005)



ID	Opacities	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)	$\log g$	ρ (g.cm^{-3})	$Z_{\rm ini}$	[Fe/H]
Gerald	OPAL	1.02 ± 0.01	1.202 ± 0.005	9.62 ± 0.45	4.29 ± 0.0	0.828 ± 0.003	0.0124 ± 0.0013	-0.044 ± 0.046
	OP	1.02 ± 0.01	1.201 ± 0.004	9.61 ± 0.42	4.29 ± 0.0	0.829 ± 0.002	0.0122 ± 0.0012	-0.052 ± 0.044
Patch	OPAL	0.82 ± 0.02	0.935 ± 0.007	9.67 ± 0.46	4.41 ± 0.0	1.404 ± 0.006	0.0055 ± 0.0008	-0.37 ± 0.062
	OP	0.82 ± 0.02	0.939 ± 0.006	9.81 ± 0.48	4.41 ± 0.0	1.4 ± 0.006	0.0056 ± 0.0009	-0.366 ± 0.067
Zebedee	OPAL	0.98 ± 0.01	0.951 ± 0.002	2.5 ± 0.17	4.47 ± 0.0	1.601 ± 0.006	0.0129 ± 0.0002	0.005 ± 0.007
	OP	0.98 ± 0.01	0.951 ± 0.002	2.53 ± 0.17	4.47 ± 0.0	1.601 ± 0.006	0.0129 ± 0.0002	0.005 ± 0.008
Zippy	OPAL	1.24 ± 0.0	1.425 ± 0.0	3.82 ± 0.0	4.22 ± 0.0	0.601 ± 0.0	0.0114 ± 0.0	-0.085 ± 0.001
	OP	1.24 ± 0.0	1.424 ± 0.0	3.83 ± 0.0	4.22 ± 0.0	0.603 ± 0.0	0.0114 ± 0.0	-0.085 ± 0.0
Fred	OPAL	1.38 ± 0.04	1.687 ± 0.023	1.74 ± 0.13	4.12 ± 0.01	0.405 ± 0.011	0.0129 ± 0.0011	0.005 ± 0.043
	OP	1.43 ± 0.06	1.71 ± 0.033	1.81 ± 0.16	4.13 ± 0.01	0.403 ± 0.01	0.013 ± 0.0023	-0.007 ± 0.085

$\Delta M=0.025M_\odot$,

From ZAMS to Xc=0.05 ,

ATOMIC DIFFUSION

- Stellar evolution CODE : CESTAM (Morel & Lebreton , 2008, Marques et al .2013)
- Nuclear reaction rates : NACRE (Angulo 1999)
- OPAL2005 EoS + OPAL opacities (Rogers & Nayfonov 2002)
- Convection: FST (Canuto et al 1996)
- Solar mixture : AGSS09 (Z/H=0.0181), + Serenelli (2010)
- Adiabatic oscillation code ADIPLS (Christensen-Dalsgaard 2008)
- Optimization/Inference : AIMS (Lund & Reese 2018, Rendle et al 2019) with Ball & Gizon (2014) for surface effects correction

MP93 versus Burgers eqs.

(Michaud & Proffitt 1993) (Burgers 1969)

Initial Helium:

Gerald: 0.222 Burgers, 0.223 MP3

Patch: 0.279 Burgers, 0.281 MP93

Zippy: 0.275 Burgers, 0.281 MP93

Zebedee: 0.281 Burgers, 0.282 MP93

ID	Opacities	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)	$\log g$	ρ (g.cm^{-3})	$Z_{\rm ini}$	[Fe/H]
Gerald	MP93	1.06 ± 0.01	1.22 ± 0.004	8.59 ± 0.4	4.29 ± 0.0	0.826 ± 0.002	0.0151 ± 0.0011	-0.078 ± 0.033
	Burgers	1.07 ± 0.01	1.222 ± 0.004	8.63 ± 0.44	4.29 ± 0.0	0.825 ± 0.002	0.0155 ± 0.001	-0.065 ± 0.029
Patch	MP93	0.85 ± 0.02	0.949 ± 0.008	7.96 ± 0.42	4.41 ± 0.0	1.399 ± 0.005	0.0072 ± 0.0009	-0.386 ± 0.057
	Burgers	0.85 ± 0.02	0.951 ± 0.008	7.99 ± 0.38	4.41 ± 0.0	1.397 ± 0.004	0.0071 ± 0.0008	-0.386 ± 0.05
Zebedee	MP93	0.98 ± 0.01	0.954 ± 0.005	2.75 ± 0.22	4.47 ± 0.0	1.599 ± 0.005	0.0142 ± 0.0005	-0.001 ± 0.017
	Burgers	0.99 ± 0.01	0.954 ± 0.004	2.72 ± 0.22	4.47 ± 0.0	1.6 ± 0.005	0.0142 ± 0.0005	0.002 ± 0.017
Zippy	MP93	1.15 ± 0.04	1.402 ± 0.019	3.6 ± 0.31	4.21 ± 0.01	0.588 ± 0.006	0.0122 ± 0.0025	-0.231 ± 0.135
	Burgers	1.19 ± 0.02	1.417 ± 0.01	3.52 ± 0.22	4.21 ± 0.0	0.586 ± 0.004	0.0141 ± 0.0014	-0.15 ± 0.077

SOLAR MIXTURE

- Stellar evolution CODE : MESA (Paxton et al, 2011,13,15,18,19)
- Nuclear reaction rates : NACRE (Angulo 1999)
- OPAL opacities (Rogers & Nayfonov 2002)
- Convection: MLT
- Core-convective overshoot (fH=0.01) and envelope unders. (fund=0.001)
- T(τ) : Eddington relation
- Adiabatic oscillation code: GYRE (Townsend & Tailer 2013)
- Optimization/Inference : AIMS (Lund & Reese 2018, Rendle et al 2019) with Ball & Gizon (2014) for surface effects correction

GN93

(Grevesse & Noels1993)

$Z/X_\odot=0.0245$

versus

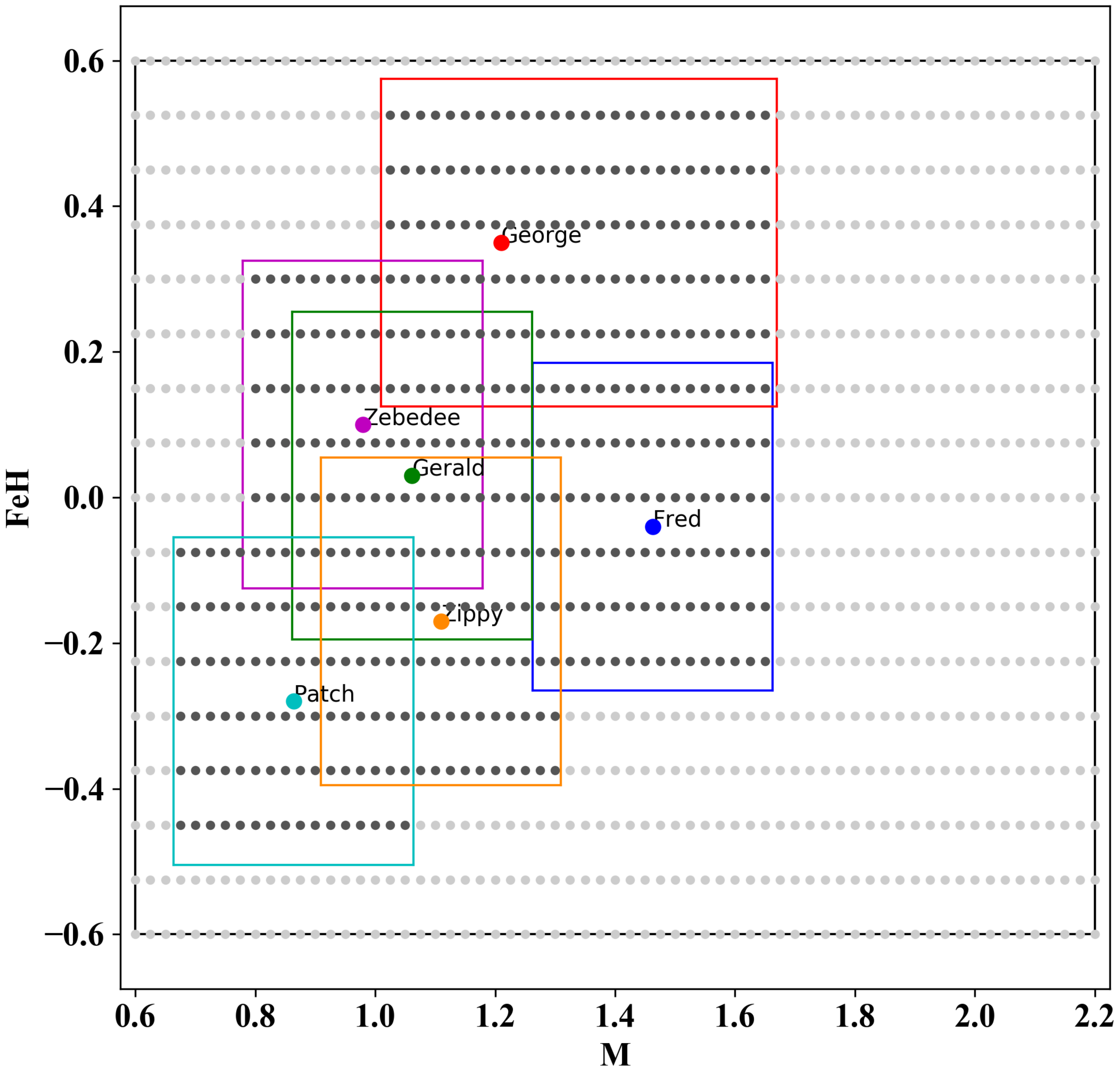
AS09

(Asplund et al. 2009)

$Z/X_\odot=0.0178$

From ZAMS to $\Delta\nu=50\mu$Hz ,

$\Delta M=0.025M_\odot$,



SOLAR MIXTURE

GN93

(Grevesse & Noels1993)

$Z/X_\odot$=0.0245

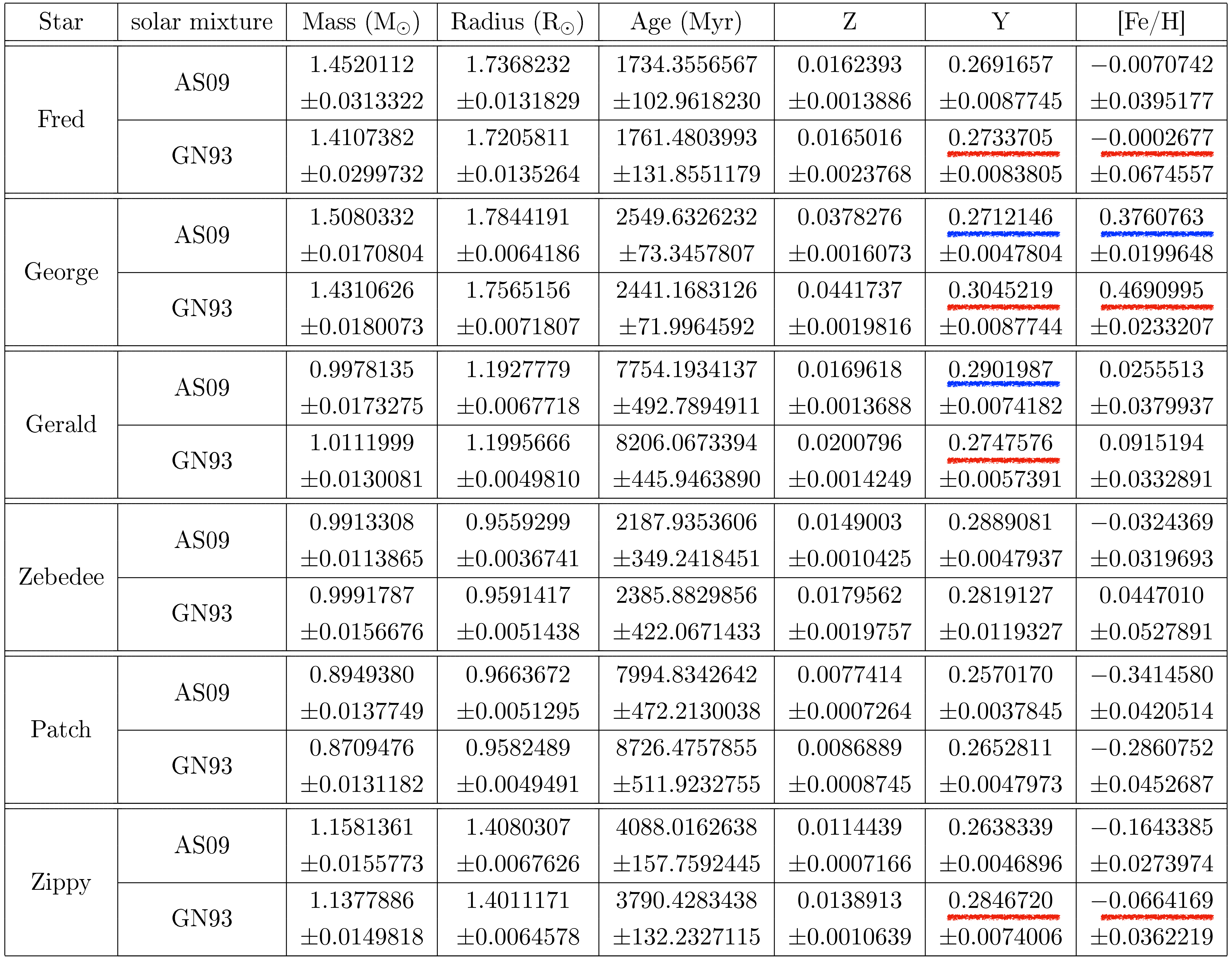
versus

AS09

(Asplund et al. 2009)

$Z/X_\odot$=0.0178

Effect on MASS ~ 2-3%



Star	solar mixture	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Myr)	Z	Y	[Fe/H]
Fred	AS09	1.4520112 ±0.0313322	1.7368232 ±0.0131829	1734.3556567 ±102.9618230	0.0162393 ±0.0013886	0.2691657 ±0.0087745	−0.0070742 ±0.0395177
	GN93	1.4107382 ±0.0299732	1.7205811 ±0.0135264	1761.4803993 ±131.8551179	0.0165016 ±0.0023768	0.2733705 ±0.0083805	−0.0002677 ±0.0674557
George	AS09	1.5080332 ±0.0170804	1.7844191 ±0.0064186	2549.6326232 ±73.3457807	0.0378276 ±0.0016073	0.2712146 ±0.0047804	0.3760763 ±0.0199648
	GN93	1.4310626 ±0.0180073	1.7565156 ±0.0071807	2441.1683126 ±71.9964592	0.0441737 ±0.0019816	0.3045219 ±0.0087744	0.4690995 ±0.0233207
Gerald	AS09	0.9978135 ±0.0173275	1.1927779 ±0.0067718	7754.1934137 ±492.7894911	0.0169618 ±0.0013688	0.2901987 ±0.0074182	0.0255513 ±0.0379937
	GN93	1.0111999 ±0.0130081	1.1995666 ±0.0049810	8206.0673394 ±445.9463890	0.0200796 ±0.0014249	0.2747576 ±0.0057391	0.0915194 ±0.0332891
Zebedee	AS09	0.9913308 ±0.0113865	0.9559299 ±0.0036741	2187.9353606 ±349.2418451	0.0149003 ±0.0010425	0.2889081 ±0.0047937	−0.0324369 ±0.0319693
	GN93	0.9991787 ±0.0156676	0.9591417 ±0.0051438	2385.8829856 ±422.0671433	0.0179562 ±0.0019757	0.2819127 ±0.0119327	0.0447010 ±0.0527891
Patch	AS09	0.8949380 ±0.0137749	0.9663672 ±0.0051295	7994.8342642 ±472.2130038	0.0077414 ±0.0007264	0.2570170 ±0.0037845	−0.3414580 ±0.0420514
	GN93	0.8709476 ±0.0131182	0.9582489 ±0.0049491	8726.4757855 ±511.9232755	0.0086889 ±0.0008745	0.2652811 ±0.0047973	−0.2860752 ±0.0452687
Zippy	AS09	1.1581361 ±0.0155773	1.4080307 ±0.0067626	4088.0162638 ±157.7592445	0.0114439 ±0.0007166	0.2638339 ±0.0046896	−0.1643385 ±0.0273974
	GN93	1.1377886 ±0.0149818	1.4011171 ±0.0064578	3790.4283438 ±132.2327115	0.0138913 ±0.0010639	0.2846720 ±0.0074006	−0.0664169 ±0.0362219

Effect on AGE

6%

9%

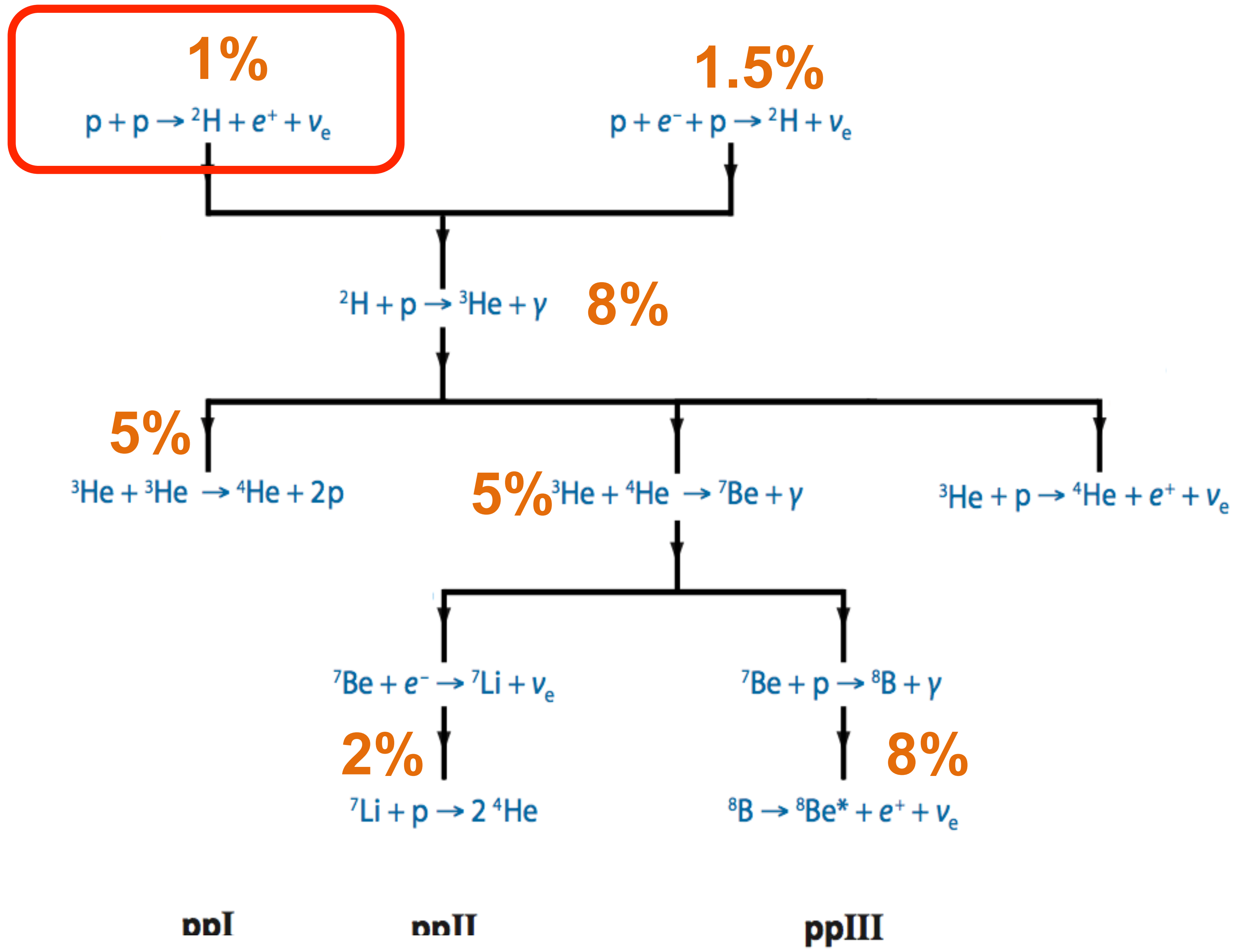
8%

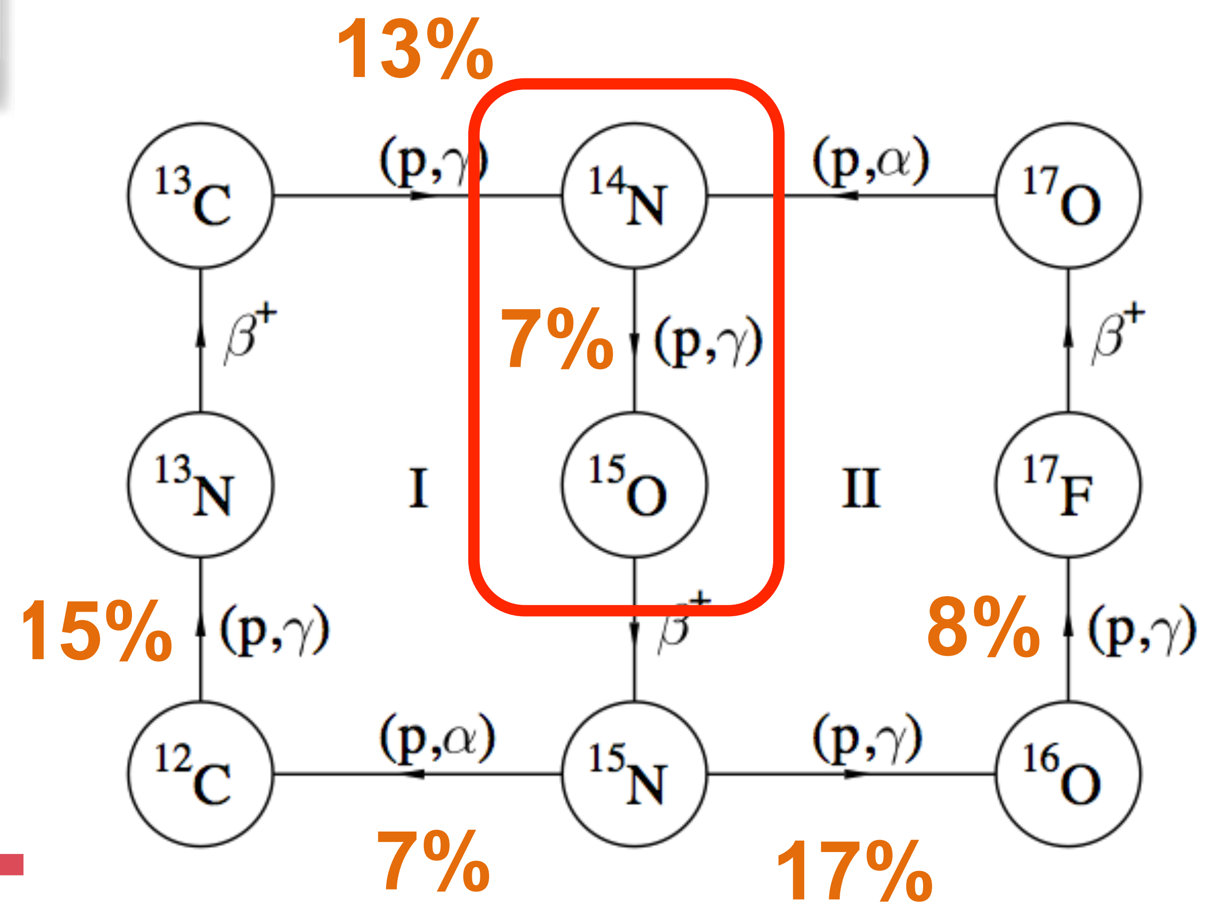
NUCLEAR REACTION RATES

- Stellar evolution CODE : STAREVOL (Siess et al.2000, Amard et al. 2019)
- Nuclear reaction rates : NACRE (Angulo 1999)
- OPAL opacities (Rogers & Nayfonov 2002) + Fergunson at low T.
- Convection: MLT, Schwarzschild criterium
- Core-convective classical overshoot (ov=0.10) T(τ) : Eddington relation
- Grey atmospheres
- Solar mixture : AGSS09
- Adiabatic oscillation code: ADIPLS (Christensen-Dalsgaard 2008)
- Optimization/Inference : Aldo Serenelli one, with Ball & Gizon (2014) for surface effects correction

^{14}N+p -> ^{15}O,γ : +/- 7%. and +/- 14%

p+p -> d+e^++ν_e : +/- 2% and +/- 5%





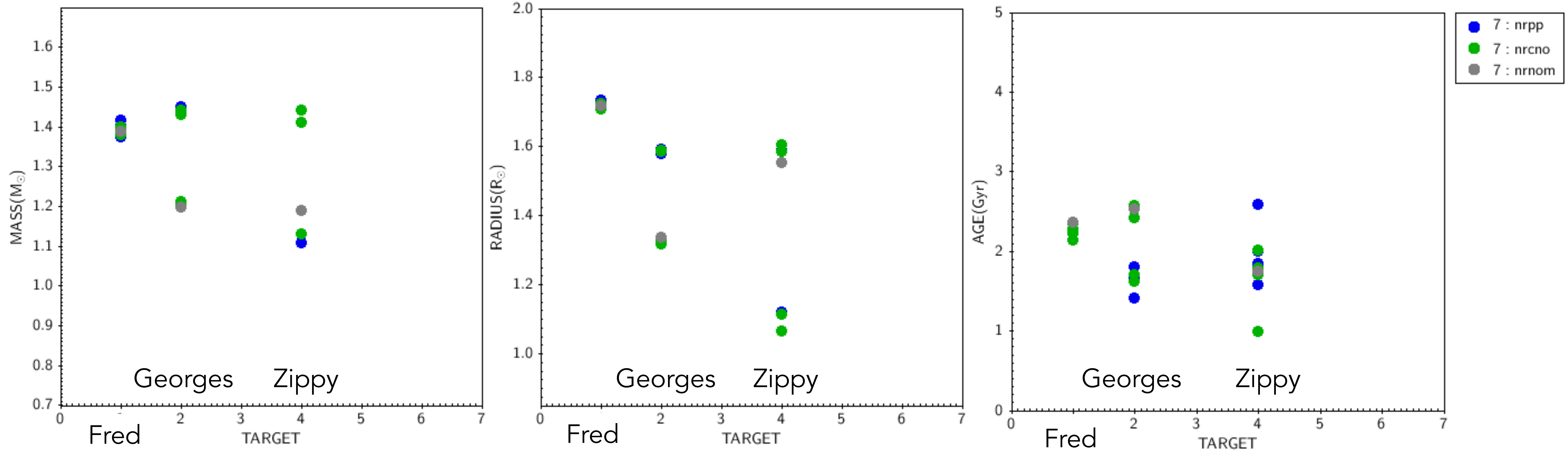
From compilation Solar Fusion II (Aldelberger et al. 2011)

NUCLEAR REACTION RATES

From compilation Aldelberger et al. 2011

$^{14}N+p \rightarrow {}^{15}O,\gamma$: +/- 7%. and +/- 14%

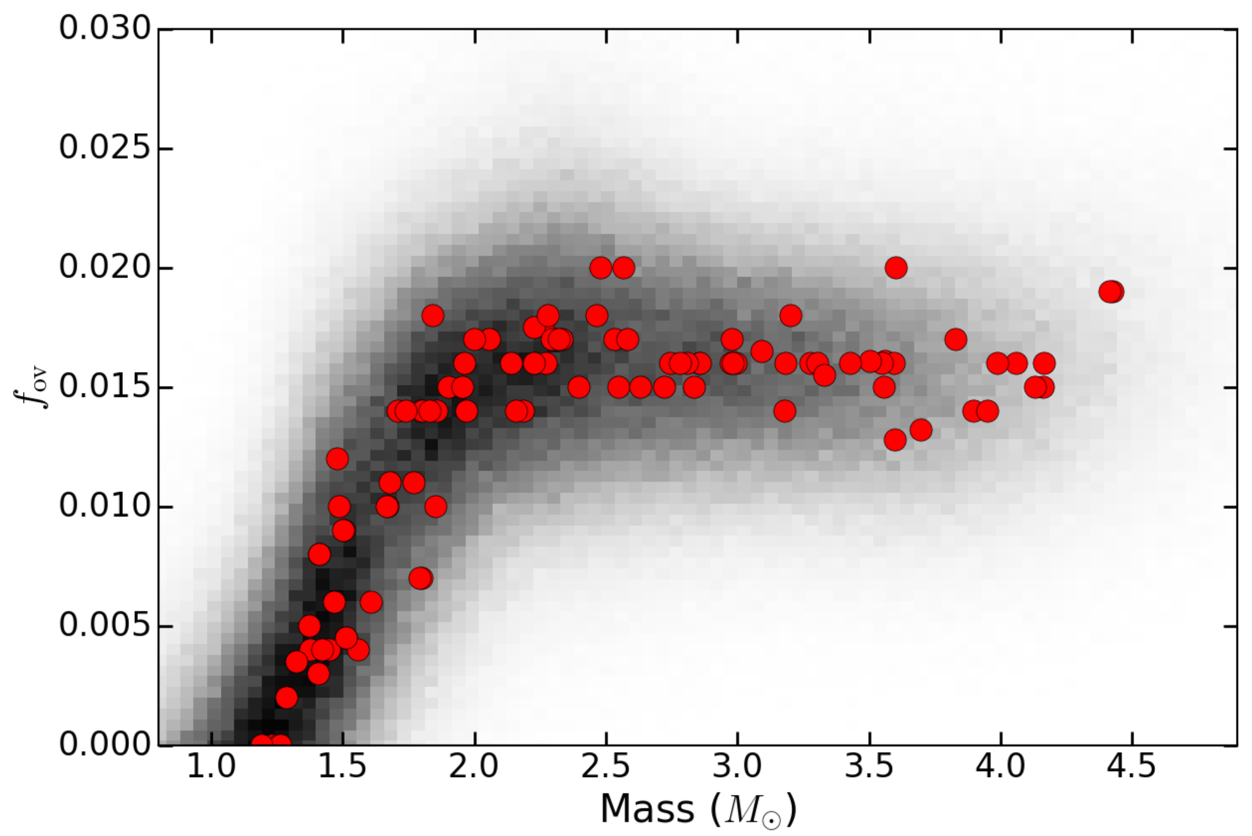
$p+p \rightarrow d+e^{+}+\nu_{e}$: +/- 2% and +/- 5%



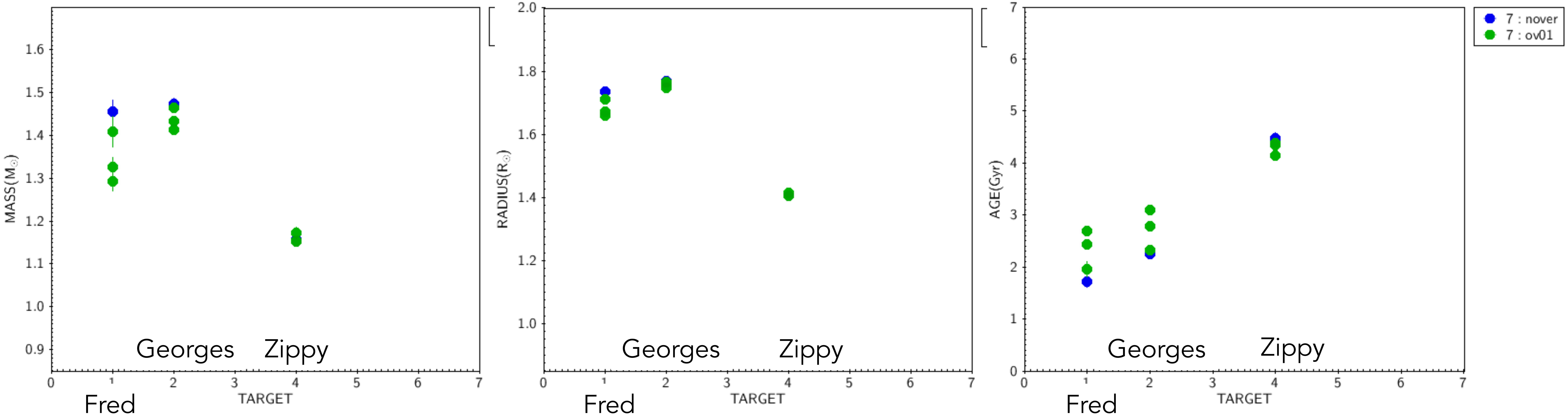
CONVECTIVE CORE OVERSHOOTING

- Diffusive overshoot, with a parameter fov=f(M) between 1.1 and 1.4Msun. No overshoot at M=1.1Msun and full value for M>1.4msun. Four different values: fov=0., 0.01, 0.02 and 0.03

GARSTEC models & Aldo's optimisation method

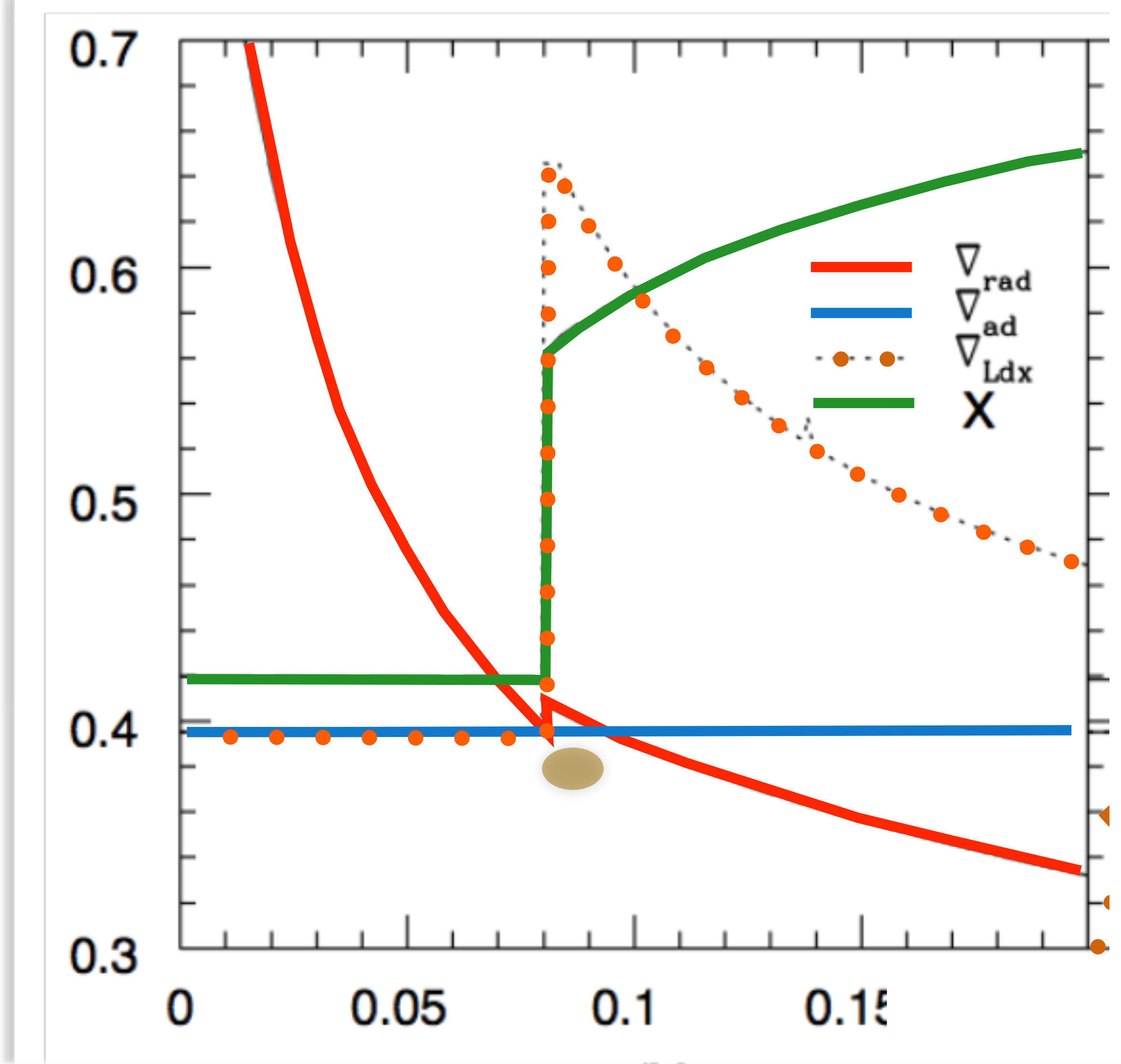


Claret & Torres 2019



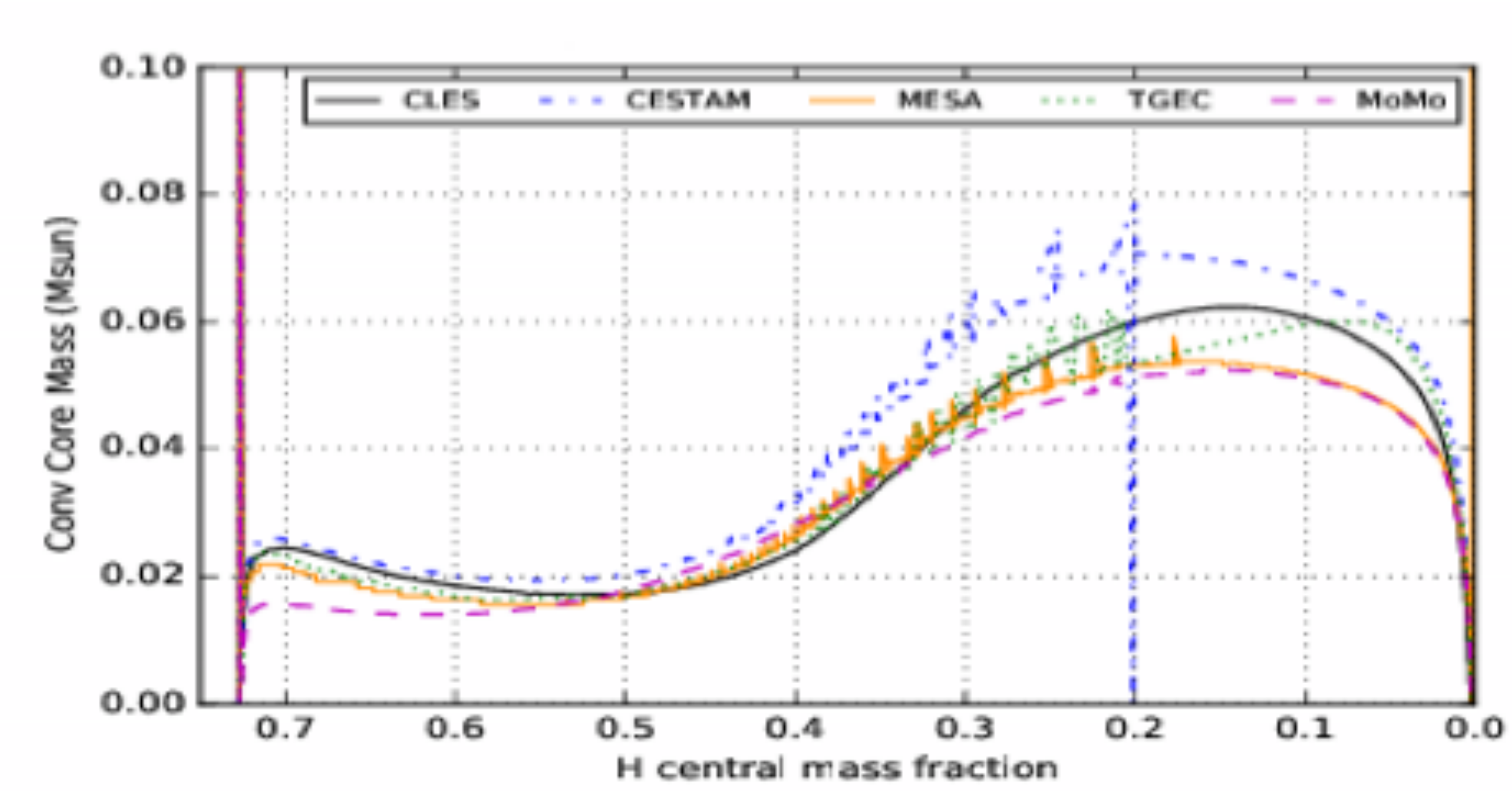
SEMICONVECTION AT THE BORDER OF CONVECTIVE CORES

- The strong gradient of chemical composition at the border of convective cores that grows => a region that is convectively unstable after Schwarzschild criterum, and only vibrational unstable by Ledoux's one.
- HOW SHOULD WE TREAT THAT REGION?



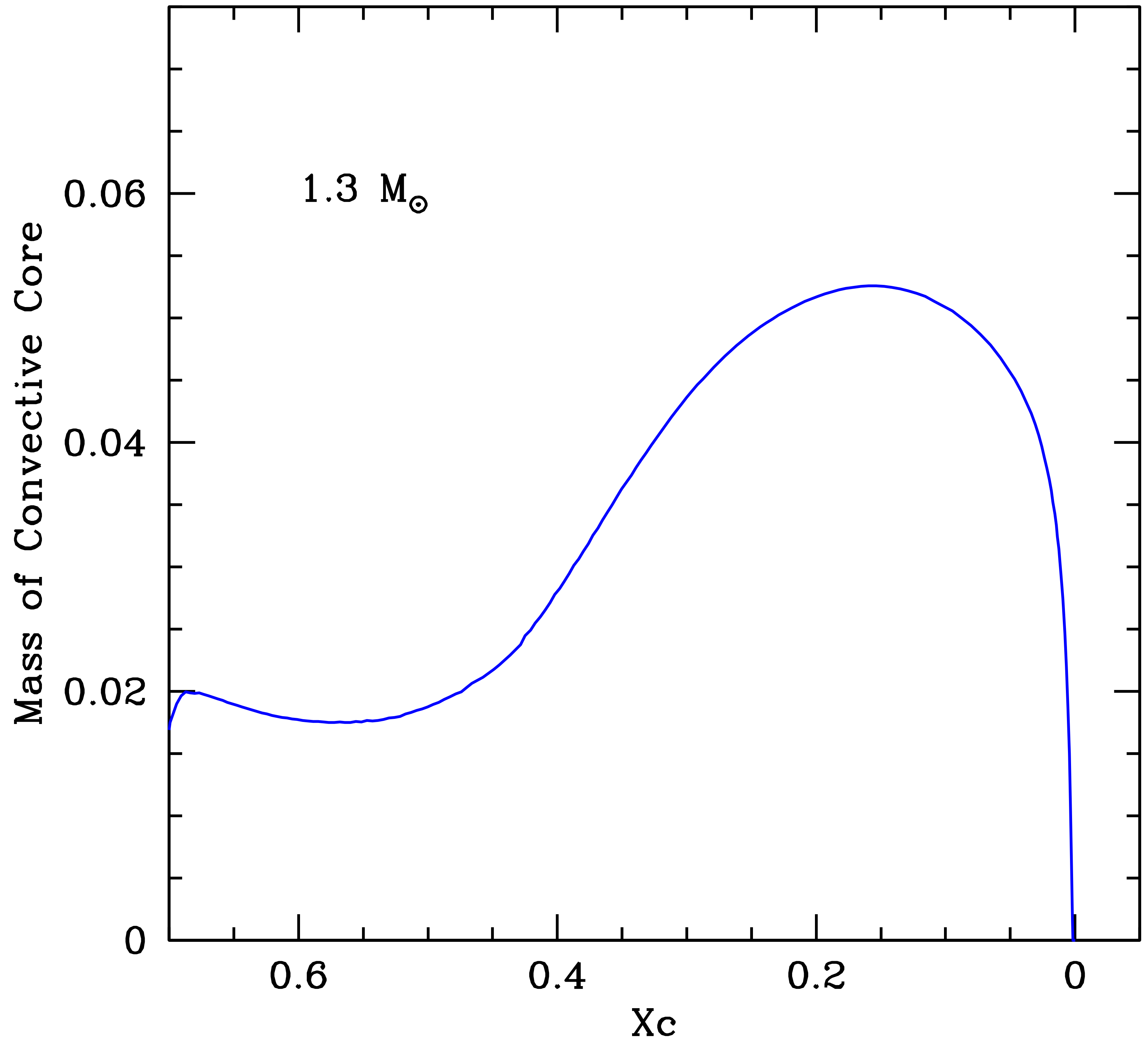
- Partial mixing until neutrality of gradients?
- Diffusion coefficient with free parameters?
- Do not mix but set an adiabatic temperature gradient?

CLES (Scuflaire et al 2008) here used Ldx criterium for convection; double mesh point at the boundary of a convective region; extrapolation from the core ; no mixing of the semiconvective region + adiabatic gradient there



SEMICONVECTION AT THE BORDER OF CONVECTIVE CORES

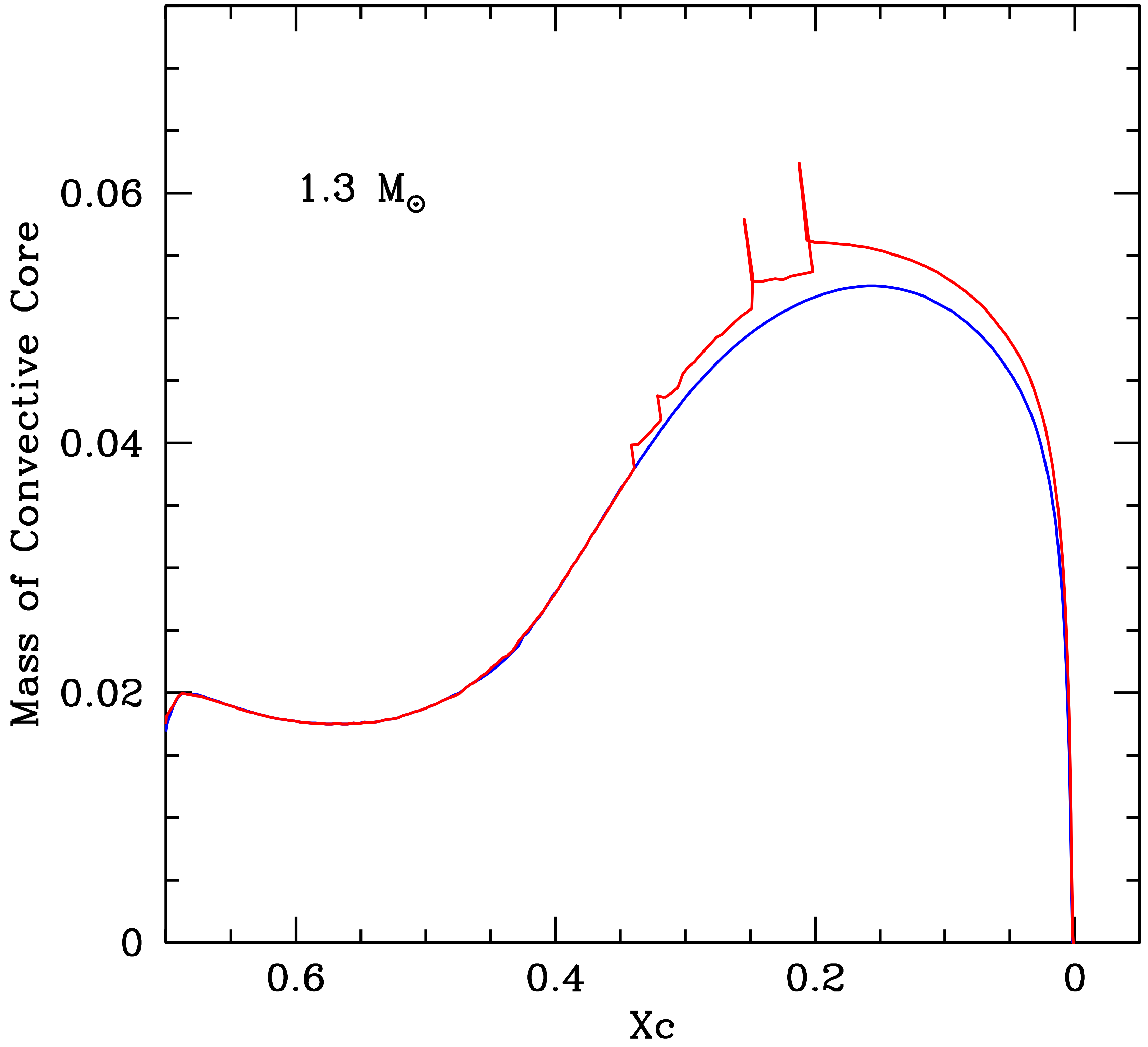
CLES here used Ldx criterium for convection; double mesh point at the boundary of a convective region; extrapolation from the core ; no mixing of the semiconvective region + adiabatic gradient there



SEMICONVECTION AT THE BORDER OF CONVECTIVE CORES

CLES here used Ldx criterium for convection; double mesh point at the boundary of a convective region; extrapolation from the core ; no mixing of the semiconvective region + adiabatic gradient there

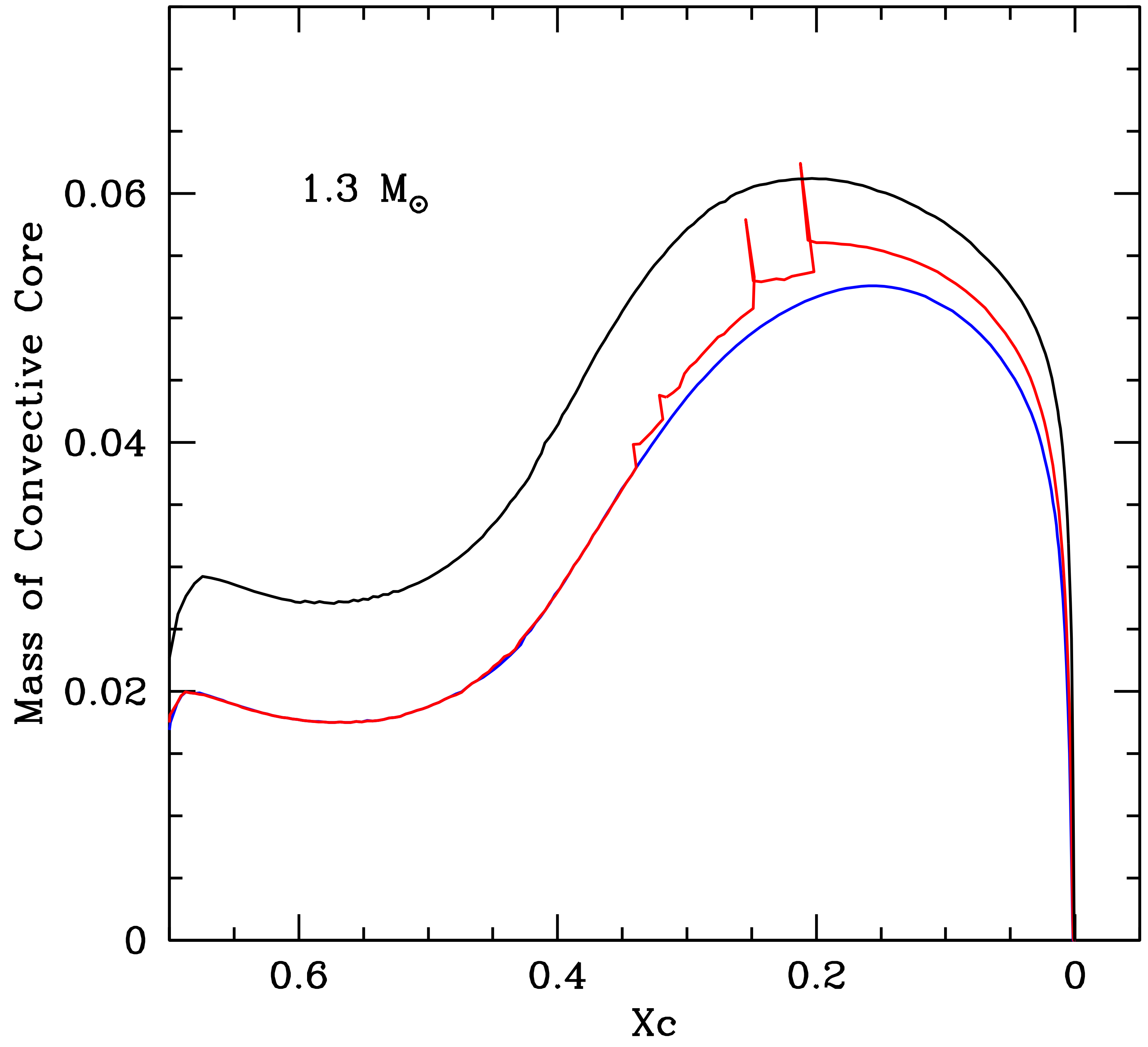
CLES with Sch criterium for convection;

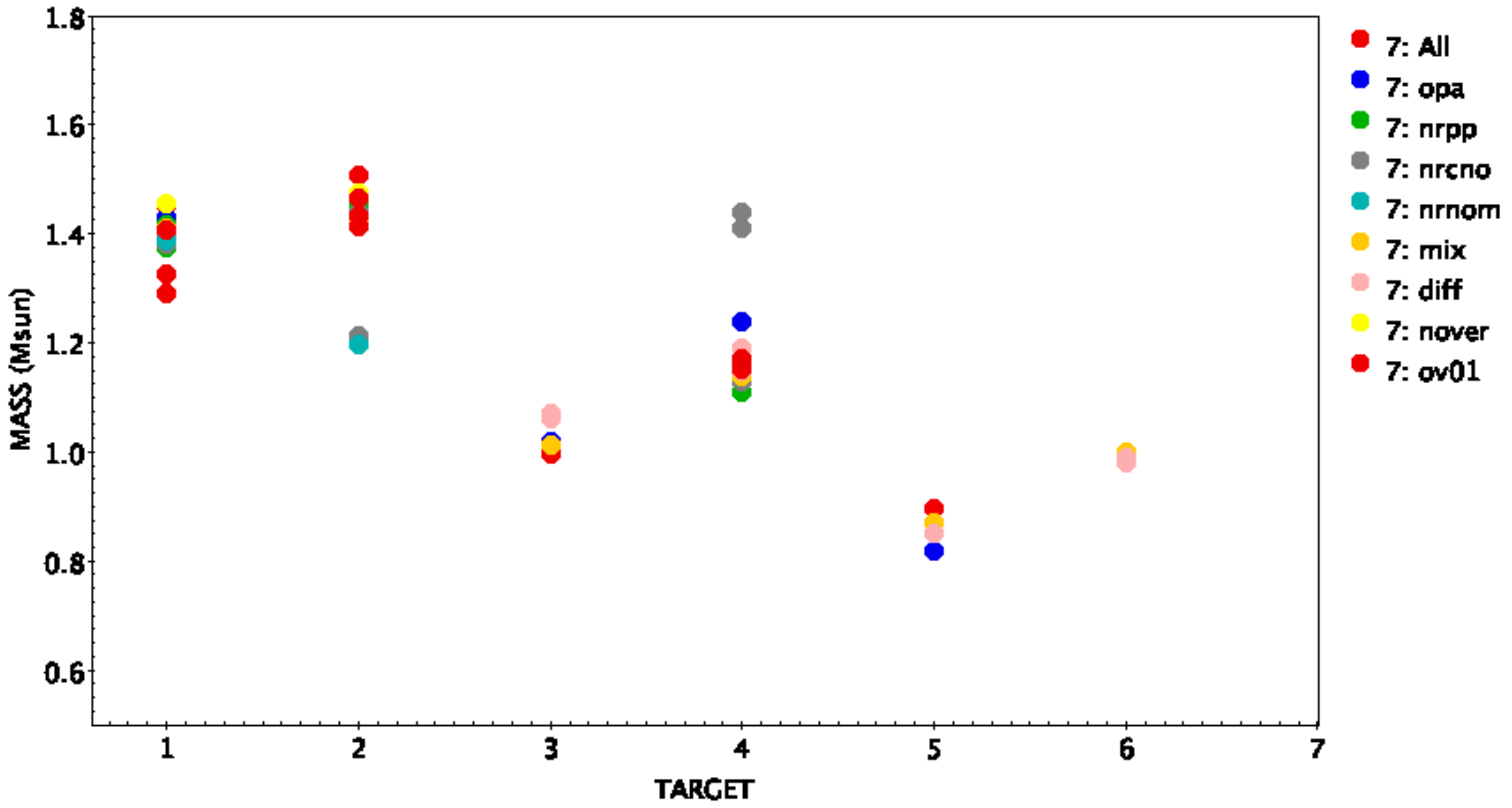


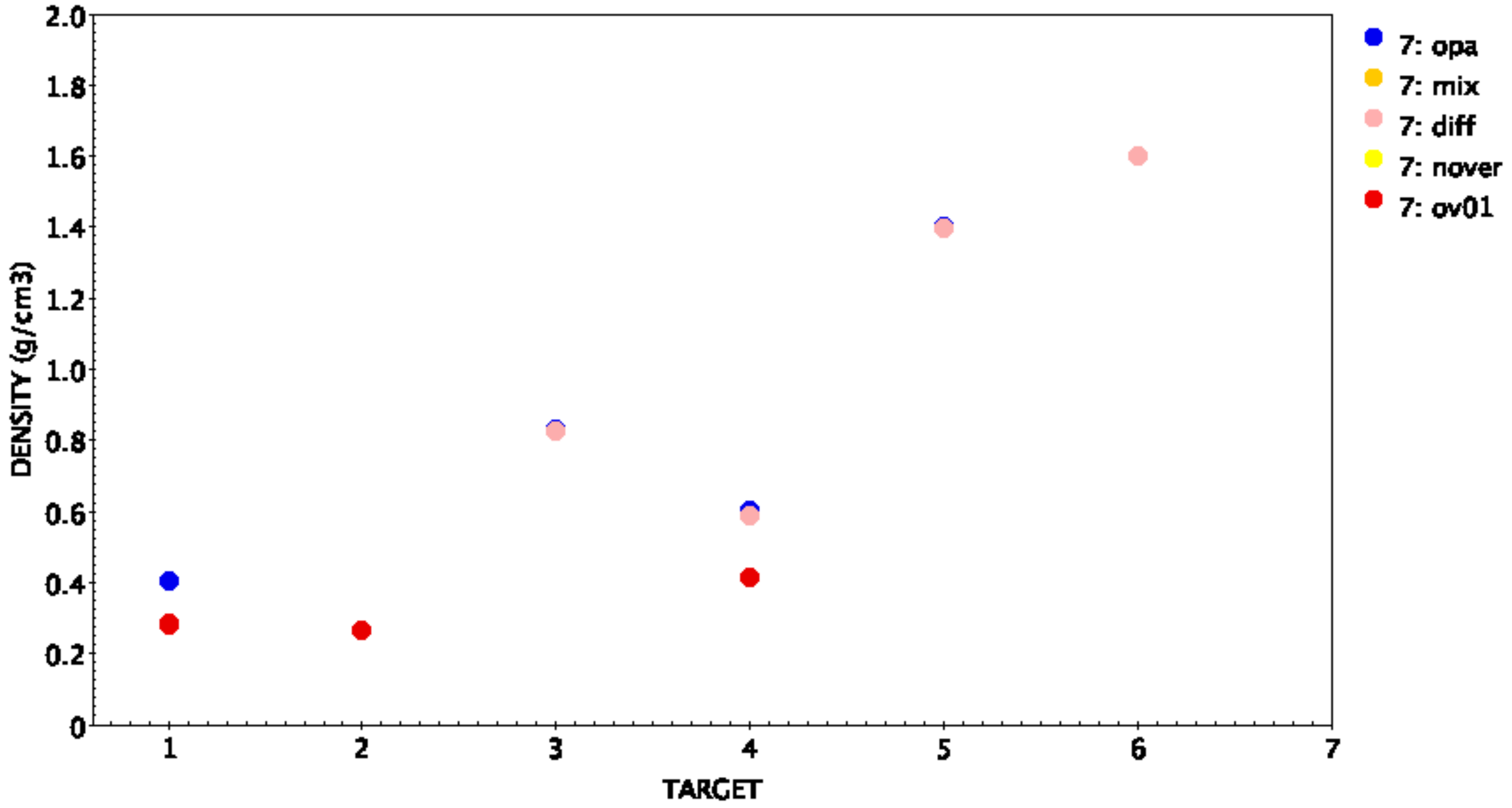
SEMICONVECTION AT THE BORDER OF CONVECTIVE CORES

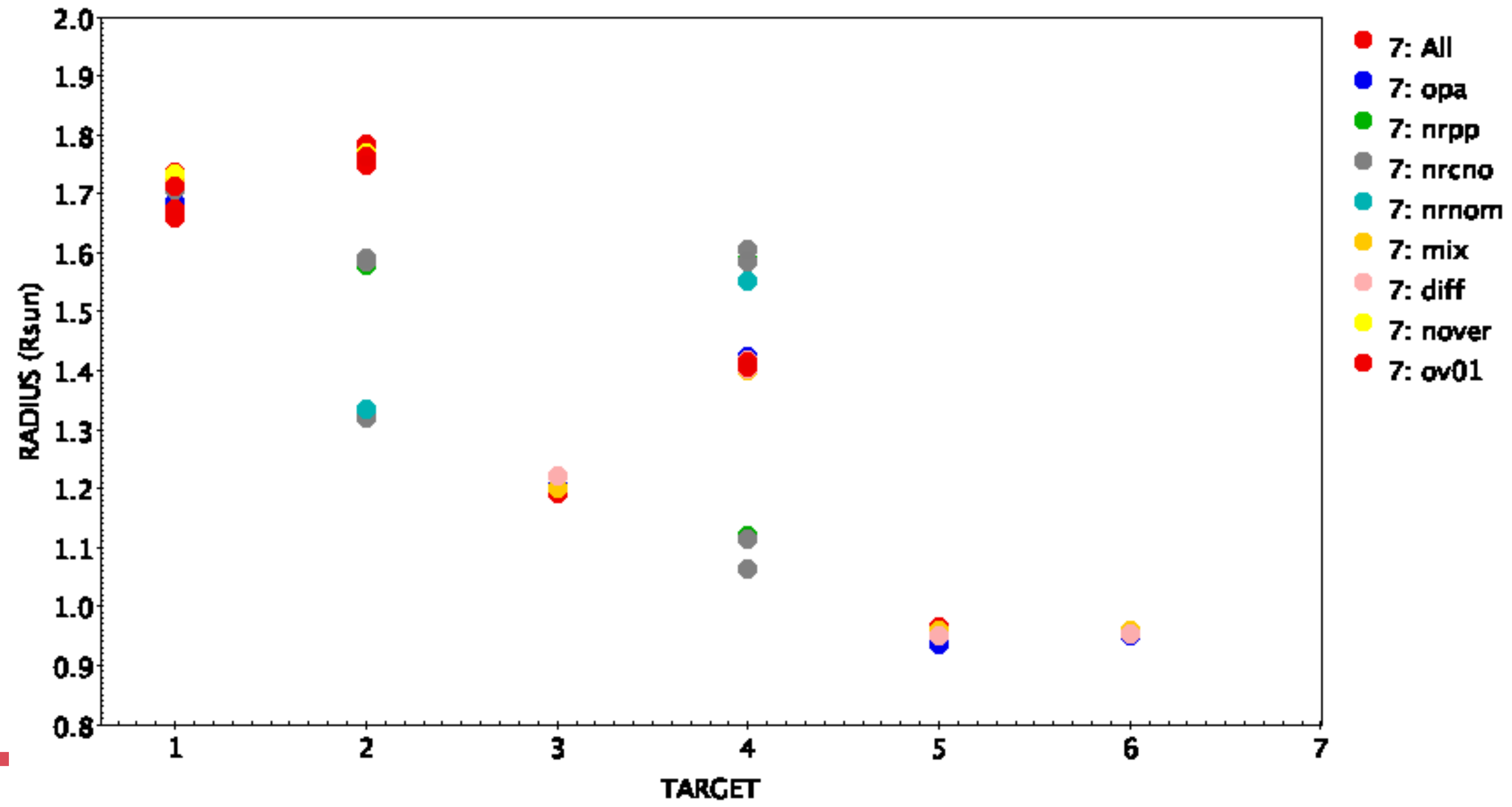
CLES here used Ldx criterium for convection; double mesh point at the boundary of a convective region; extrapolation from the core ; no mixing of the semiconvective region + adiabatic gradient there

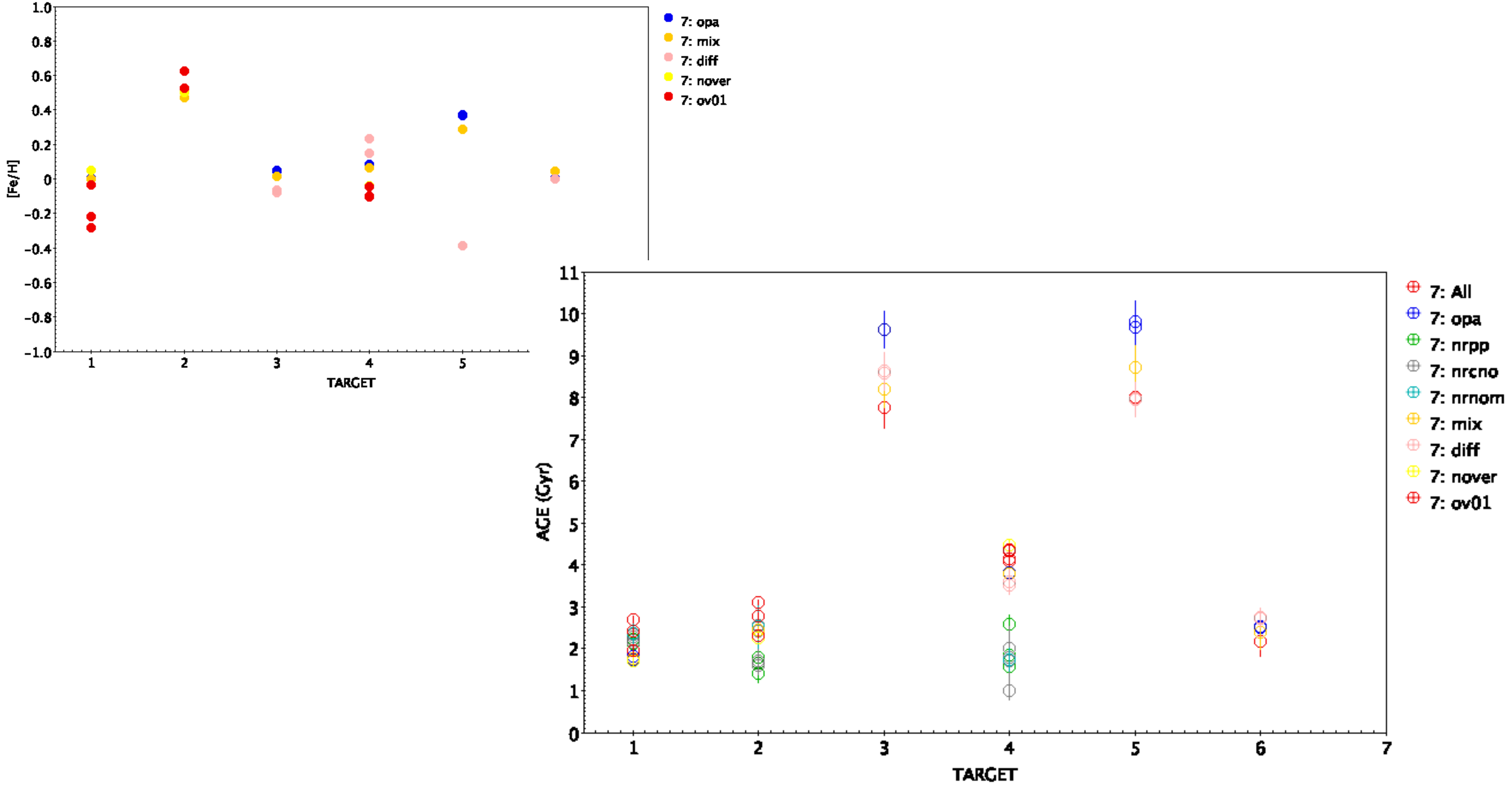
CLES with Sch criterium **+ 0.05 Hp** of instantaneous overshooting ;




MASS (Msun)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
TARGET
1
2
3
4
5
6
7
● 7: All
● 7: opa
● 7: nrpp
● 7: nrcno
● 7: nrnom
● 7: mix
● 7: diff
● 7: nover
● 7: ov01


DENSITY (g/cm3)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
TARGET
1
2
3
4
5
6
7
● 7: opa
● 7: mix
● 7: diff
● 7: nover
● 7: ov01


RADIUS (Rsun)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
TARGET
1
2
3
4
5
6
7
● 7: All
● 7: opa
● 7: nrpp
● 7: nrcno
● 7: nrnom
● 7: mix
● 7: diff
● 7: nover
● 7: ov01


[Fe/H]
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1.0
1
2
3
4
5
TARGET
7: opa
7: mix
7: diff
7: nover
7: ov01
AGE (Gyr)
0
1
2
3
4
5
6
7
8
9
10
11
1
2
3
4
5
6
7
TARGET
7: All
7: opa
7: nrpp
7: nrcno
7: nrnom
7: mix
7: diff
7: nover
7: ov01

Conclusions

- As expected, mixing processes are the main contributor to the uncertainties
- Opacity tables and diffusion implementation, at least for the domain considered have a low impact
- Solar mixture can affect by 3% the mass and 9% the age
- We proceed with optimisation also with models with semiconvection vs overshooting
- To improve our study of nuclear reaction rate effects