How do stellar evolution and parameters influence the habitable zone ?

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Definition of the habitable zone

The Habitable Zone (HZ) is defined as the range of circumstellar distances from a star within which a planet could have liquid water on its surface, given a dense enough atmosphere.

(Kasting et al. 2993; Selsis et al. 2007, Kopparapu et al. 2013, 2014)

The key parameter to compute this distance is the effective stellar flux S_{eff}

It represents the value of the solar constant required to maintain a given temperature

→ ratio between the outgoing IR flux from the planet and the net incident stellar flux

Followin'g this definition, the HZ depends on 2 stellar parameters : L_* and T_{eff}

$$d = \left(\frac{L/L_\odot}{S_{eff}} \right)^{0.5} AU$$

Definition of the habitable zone

To compute the effective stellar flux, a model for the outgoing IR flux of the planet is needed

→ 1-D radiative-convective climate models

IHZ : Earth-mass planet with H_2O dominated atmosphere

OHZ : Earth-mass planet with CO_2 dominated atmosphere

(Kasting et al. 2993; Selsis et al. 2007, Kopparapu et al. 2013, 2014)

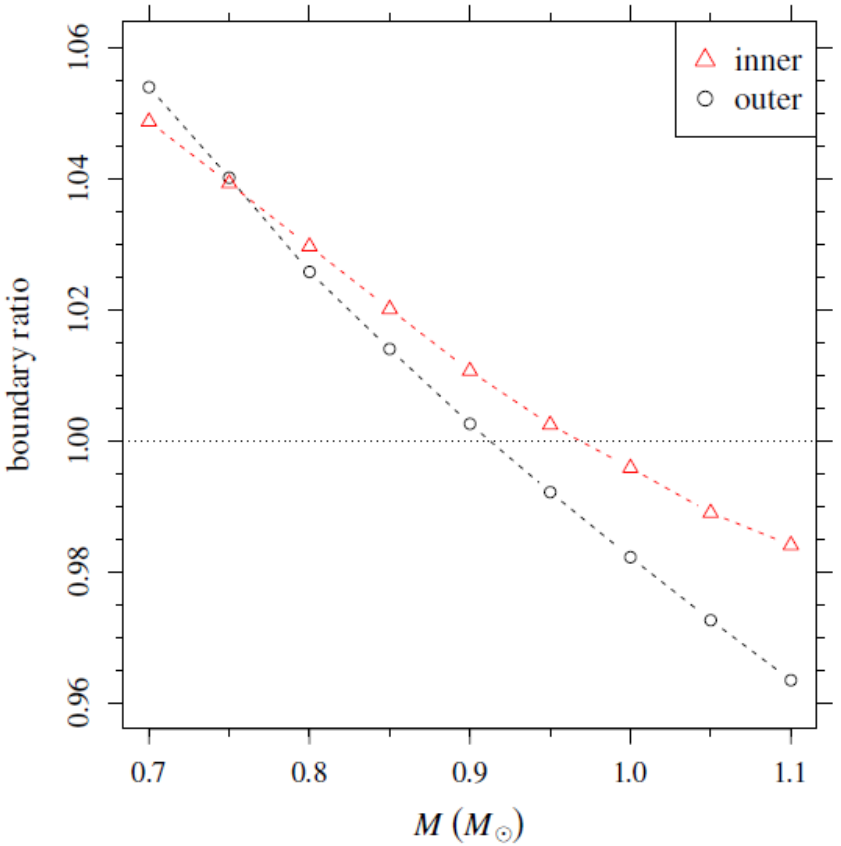
$$S_{eff} = S_{eff\odot} + aT_\star + bT_\star^2 + cT_\star^3 + dT_\star^4$$
$$\text{with } T_\star = T_{eff} - 5780K$$

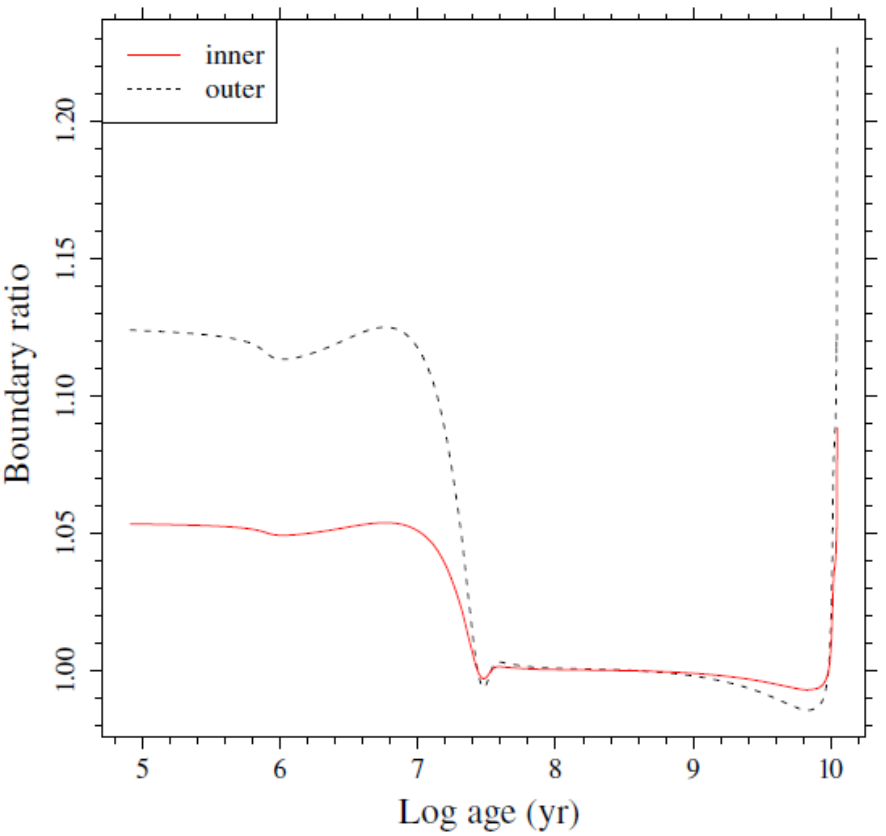
Table 3
Updated Coefficients to Calculate Habitable Stellar Fluxes, and Corresponding Habitable Zones, for Stars with $2600 \leqslant T_{\rm eff} \leqslant 7200$ K

Constant	Recent Venus	Runaway Greenhouse	Moist Greenhouse	Maximum Greenhouse	Early Mars
$S_{\rm eff\odot}$	1.7763	1.0385	1.0146	0.3507	0.3207
a	1.4335×10^{-4}	1.2456×10^{-4}	8.1884×10^{-5}	5.9578×10^{-5}	5.4471×10^{-5}
b	3.3954×10^{-9}	1.4612×10^{-8}	1.9394×10^{-9}	1.6707×10^{-9}	1.5275×10^{-9}
c	-7.6364×10^{-12}	-7.6345×10^{-12}	-4.3618×10^{-12}	-3.0058×10^{-12}	-2.1709×10^{-12}
d	-1.1950×10^{-15}	-1.7511×10^{-15}	-6.8260×10^{-16}	-5.1925×10^{-16}	-3.8282×10^{-16}

Modification of the HZ parameters

Effect of non-constant albedo (Kopparapu 2013 / Kasting 1993) on the HZ extent

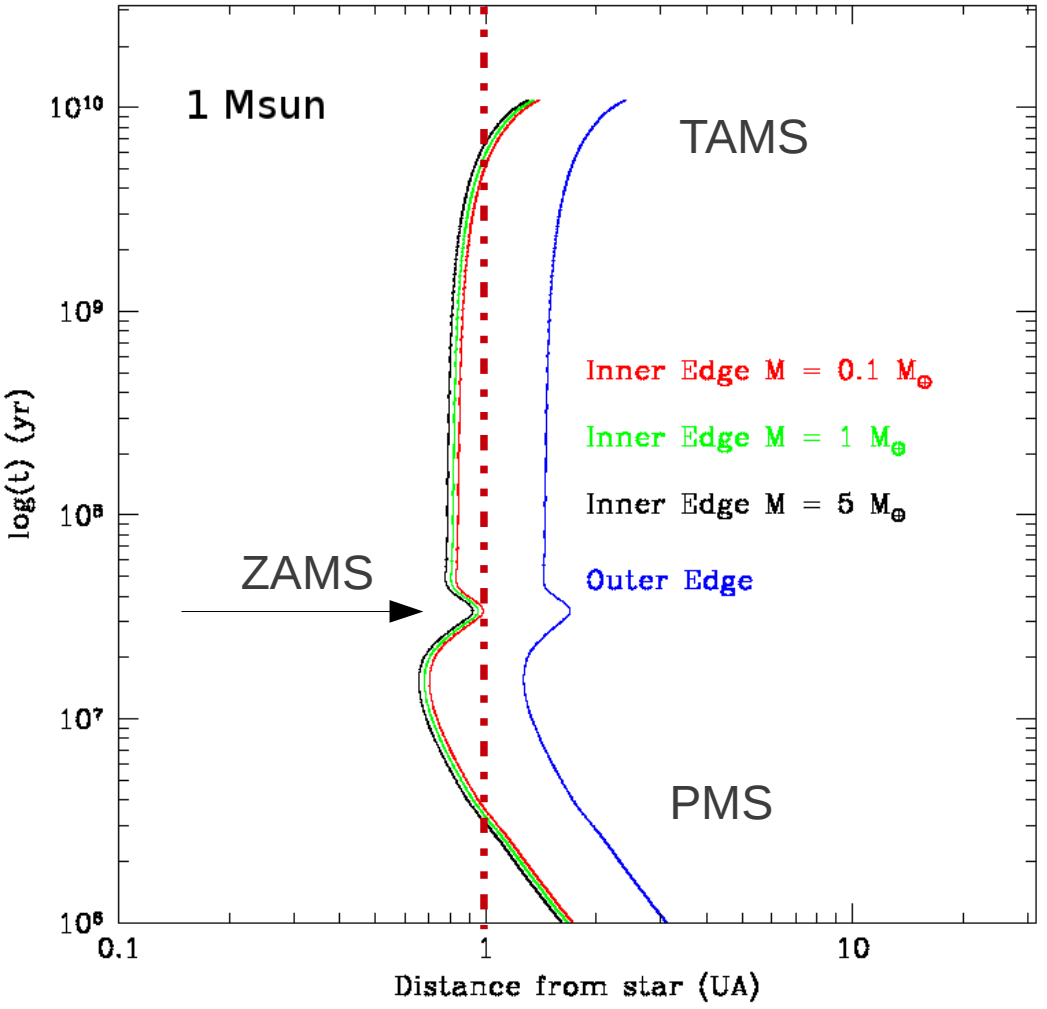




Valle et al. 2014

Parameters that affect T_{eff} and L_*

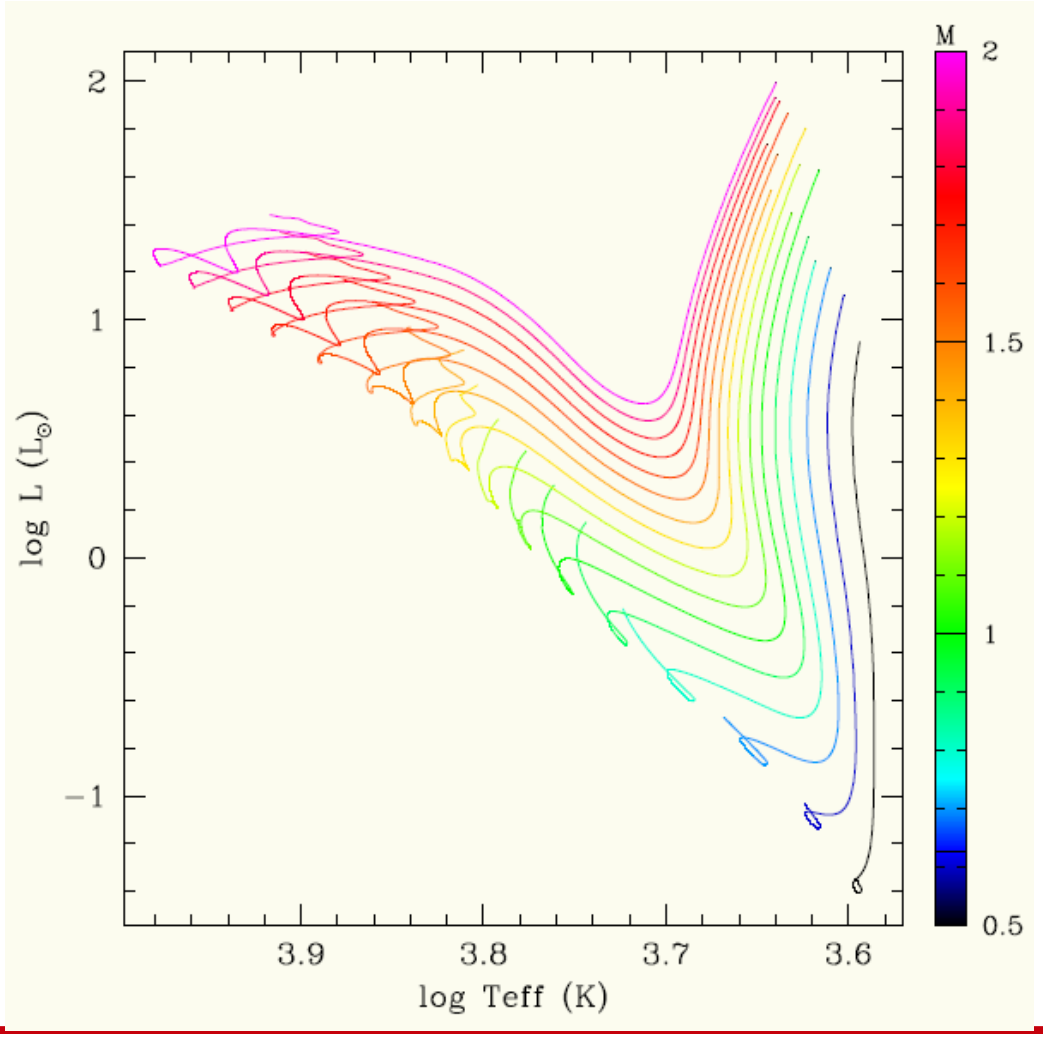
@ given M, temperature and luminosity will vary with time → modification of the HZ



Parameters that affect T_{eff} and L_*

@ given M, temperature and luminosity will vary with time → modification of the HZ

@ given age, temperature and luminosity will vary with mass → modification of the HZ



Effect of aging

HD40307

$M_* = 0.77 \pm 0.05\ M_\odot$

Teff = 4956 ± 50 K

[Fe/H] = -0.31 ± 0.03 dex

Tau Ceti

Teff = 5344 ± 50 K

[Fe/H] = -0.55 ± 0.05 dex

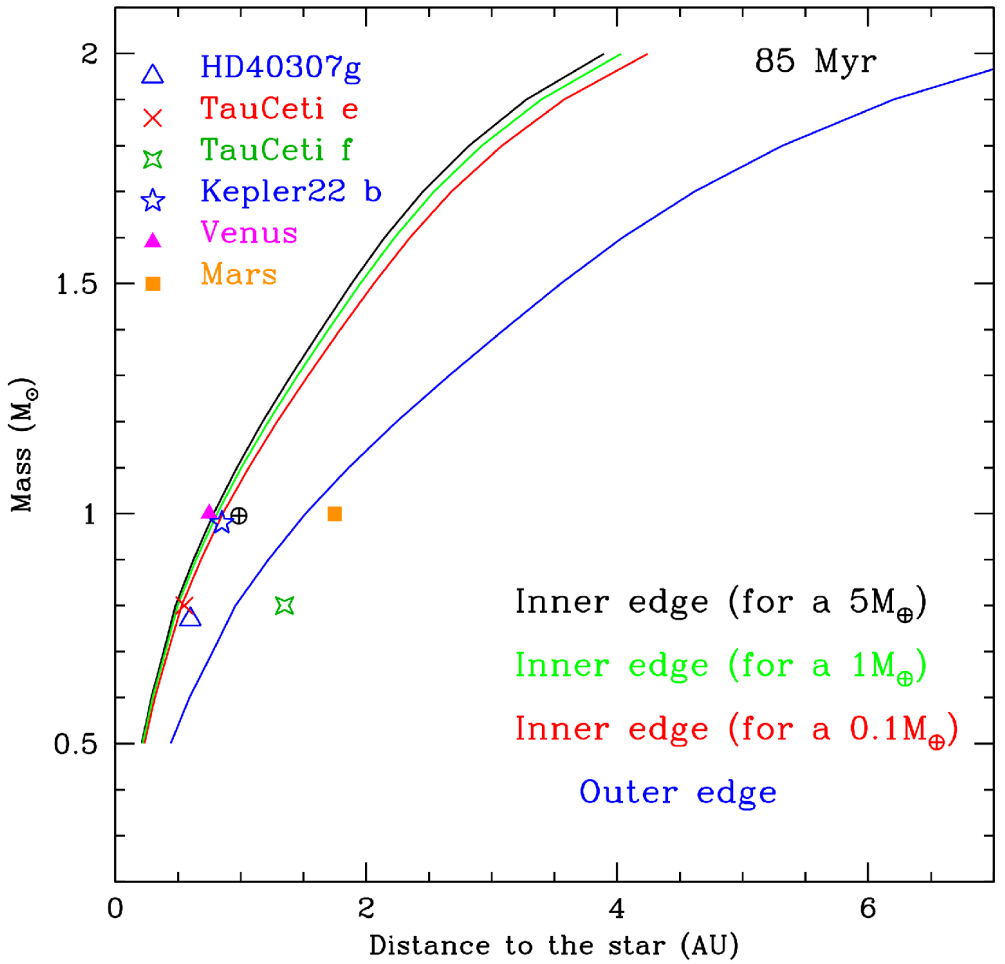
$M_* = 0.783 \pm 0.012\ M_\odot$

Kepler 22

$M_* = 0.97\ (\pm 0.06)\ M_\odot$

Teff = 5518.0 (± 44.0) K

[Fe/H] = -0.29 (± 0.06) dex



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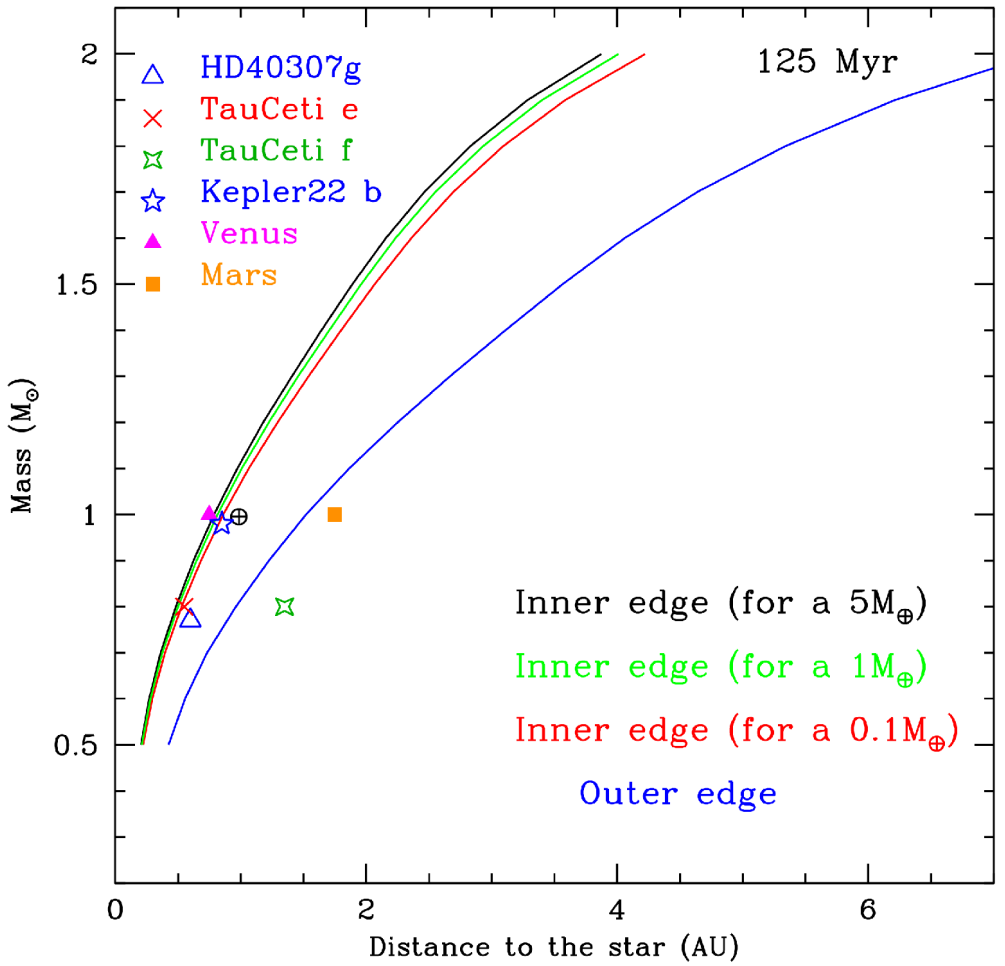

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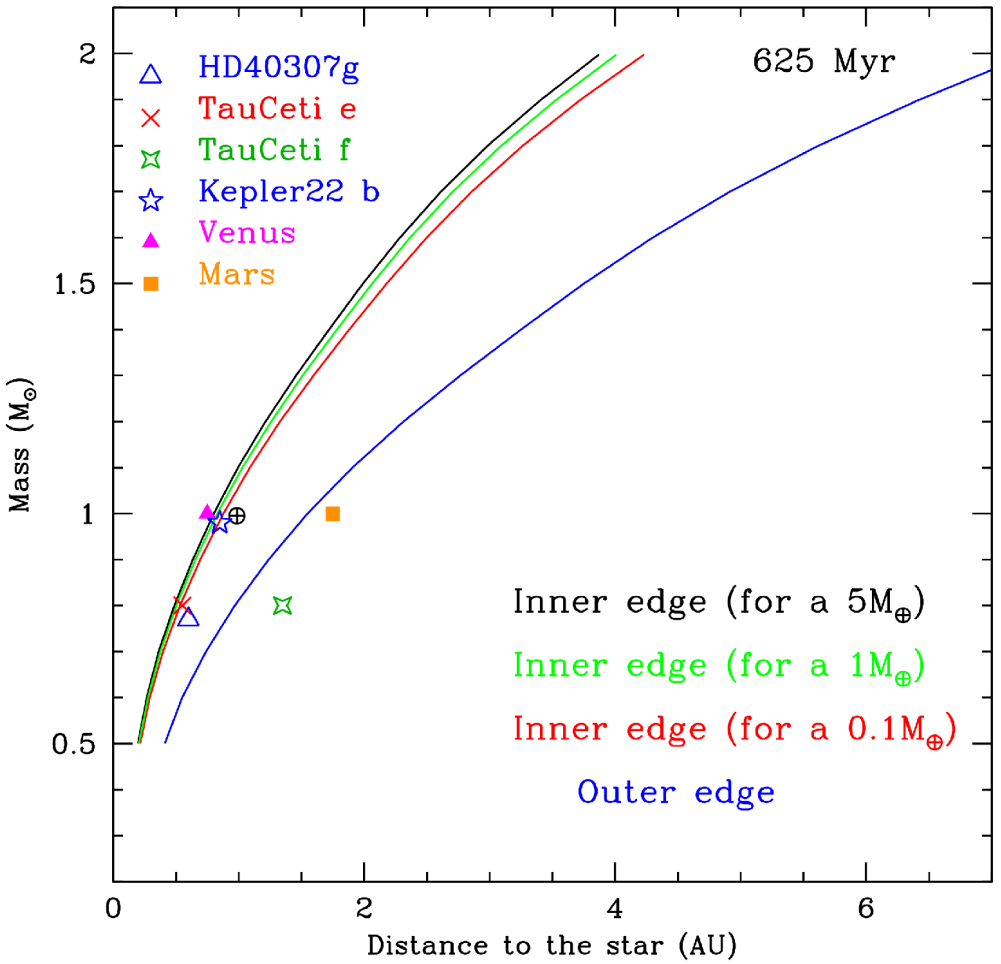

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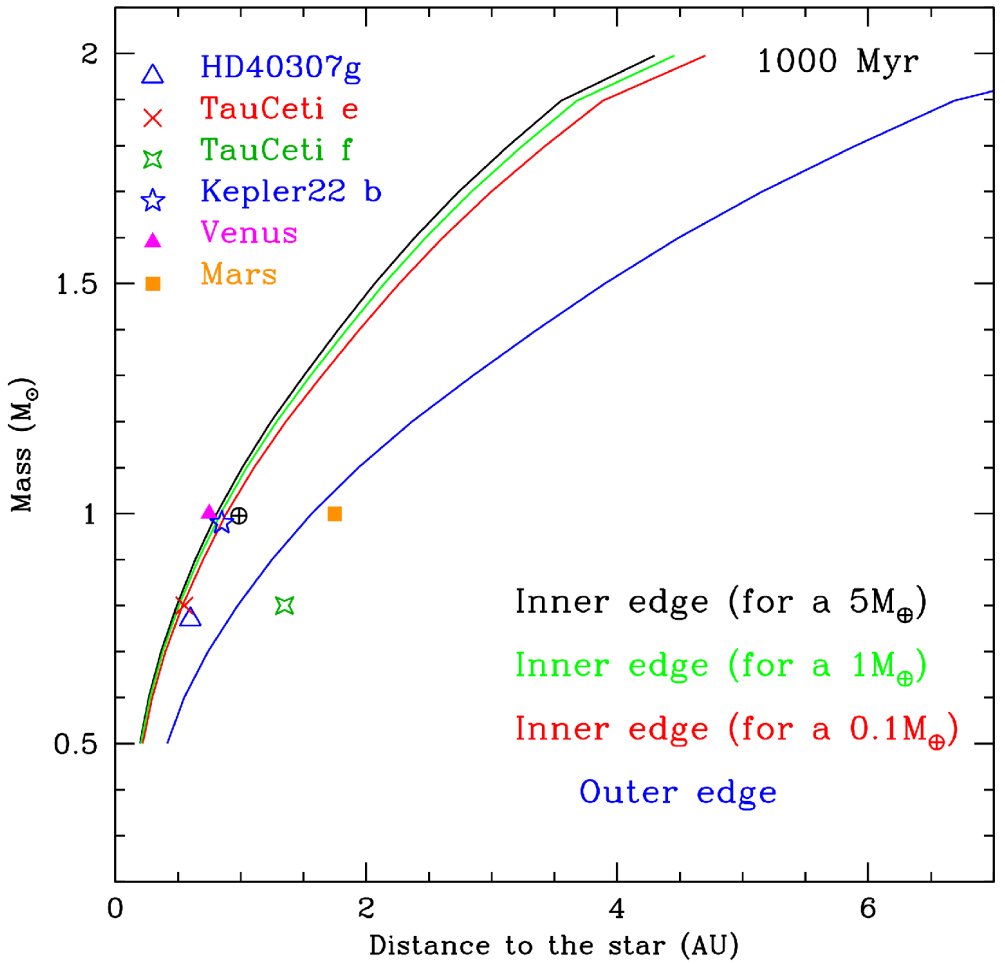

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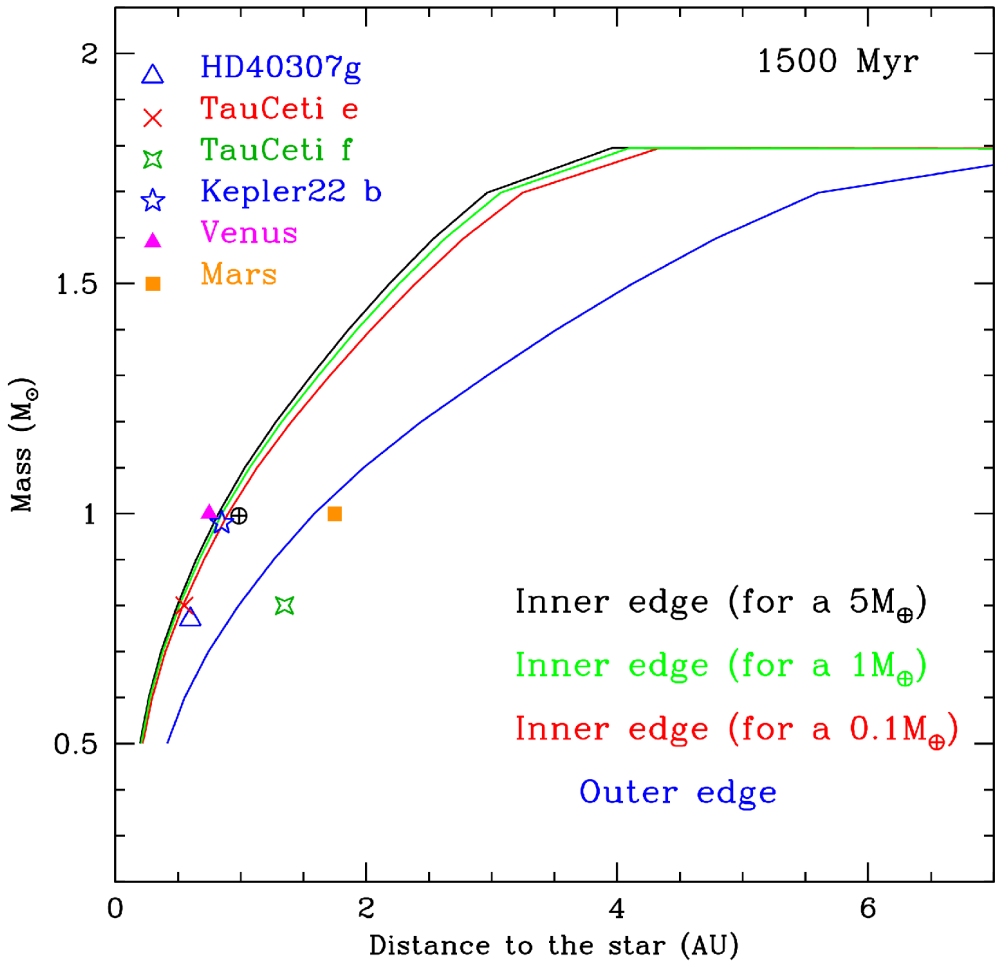

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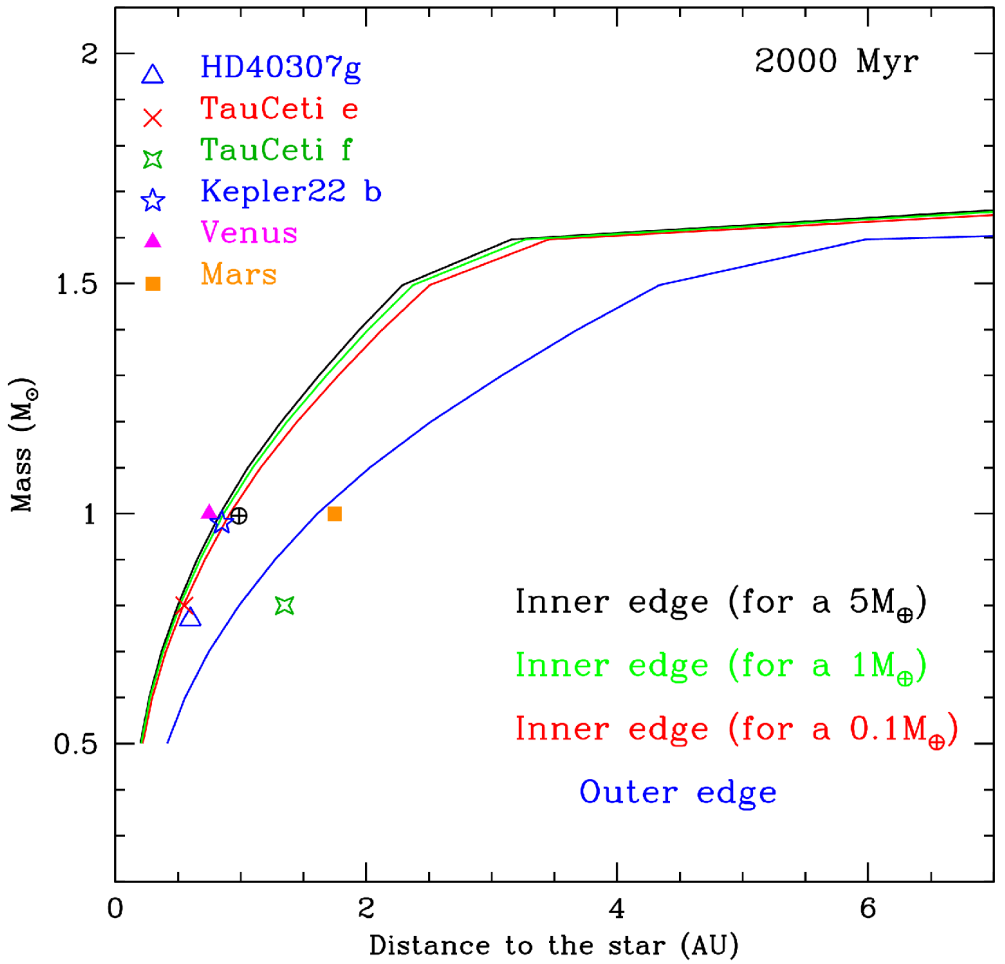

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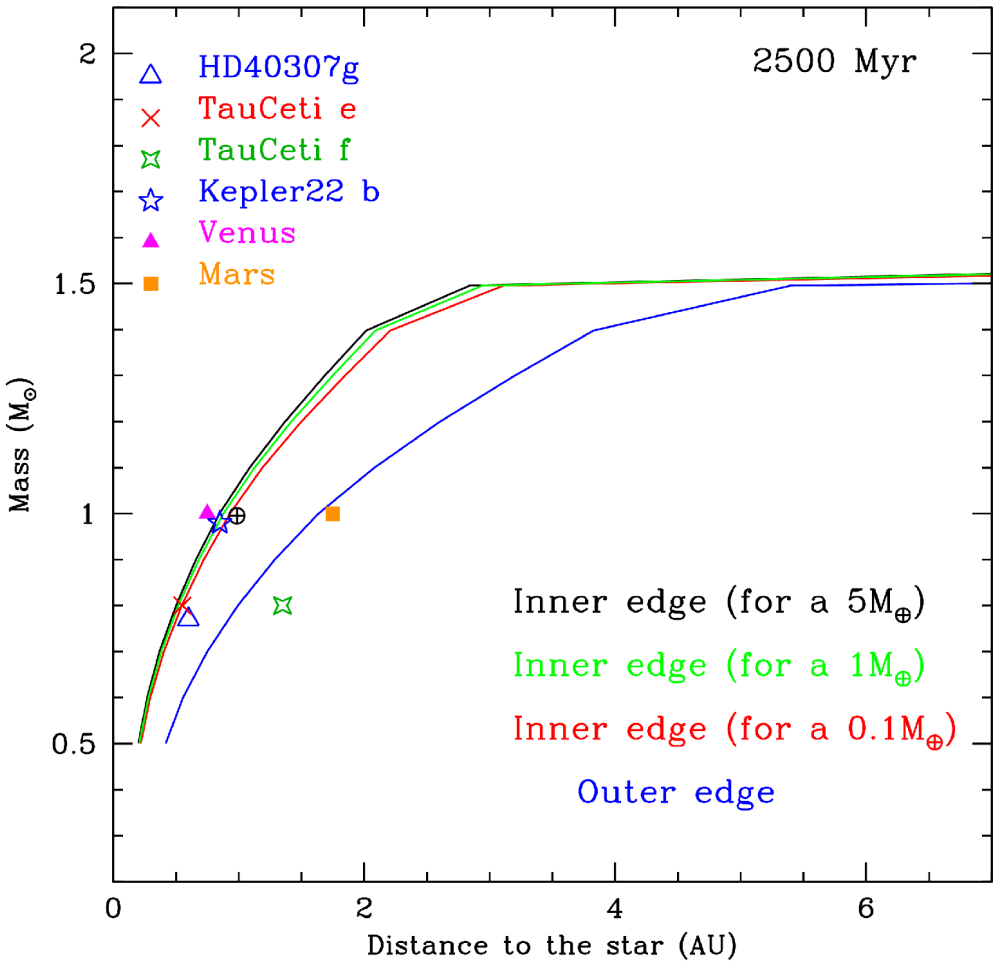

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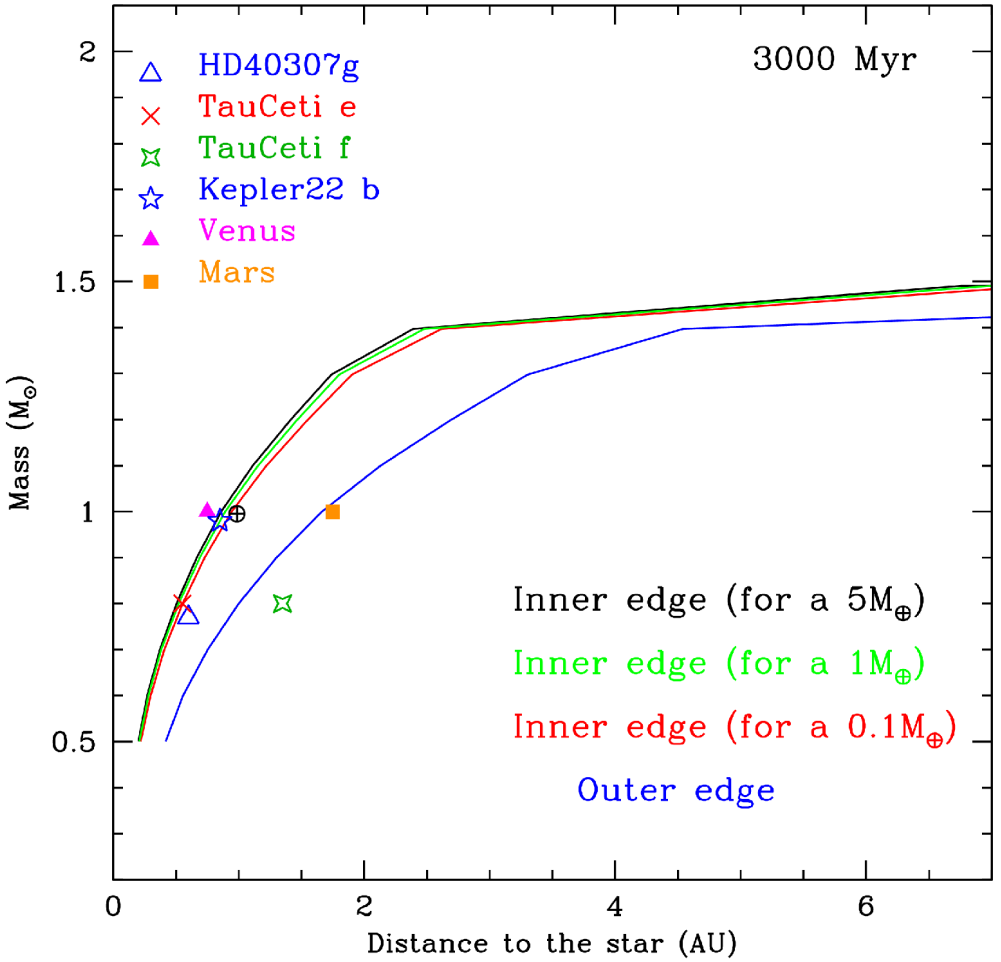

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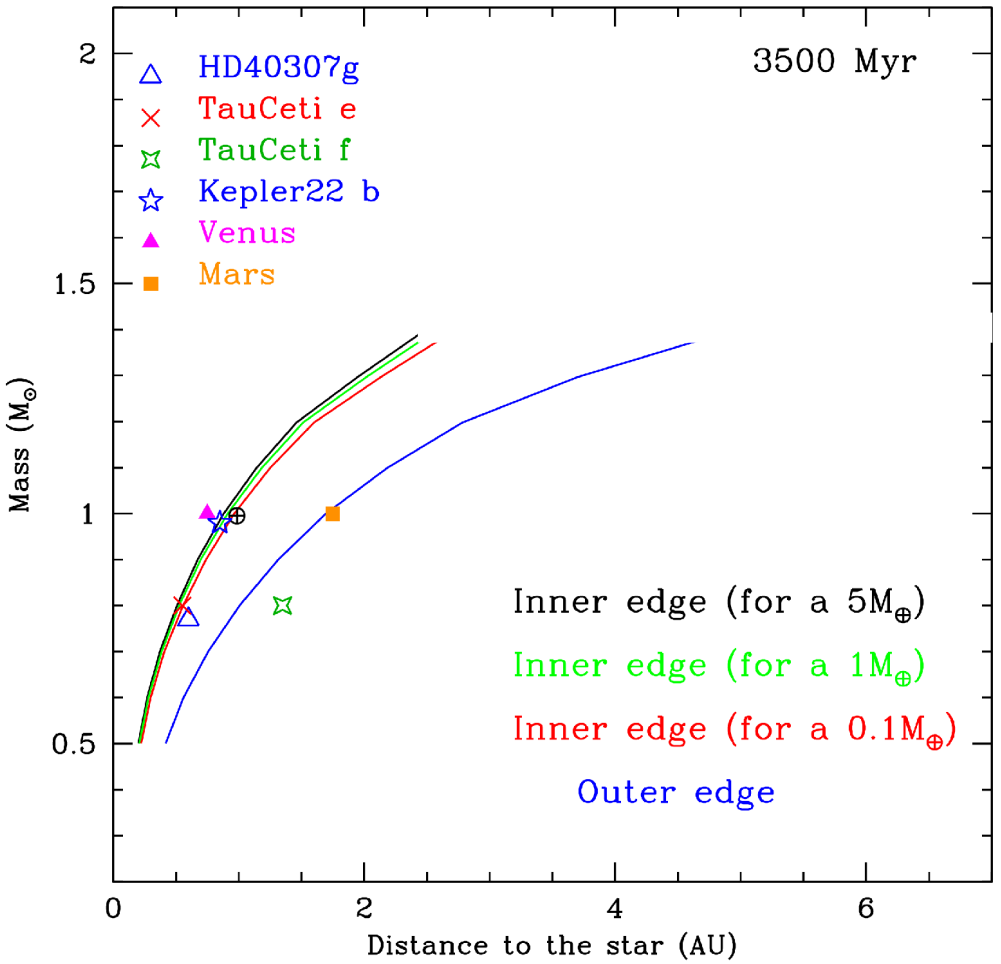

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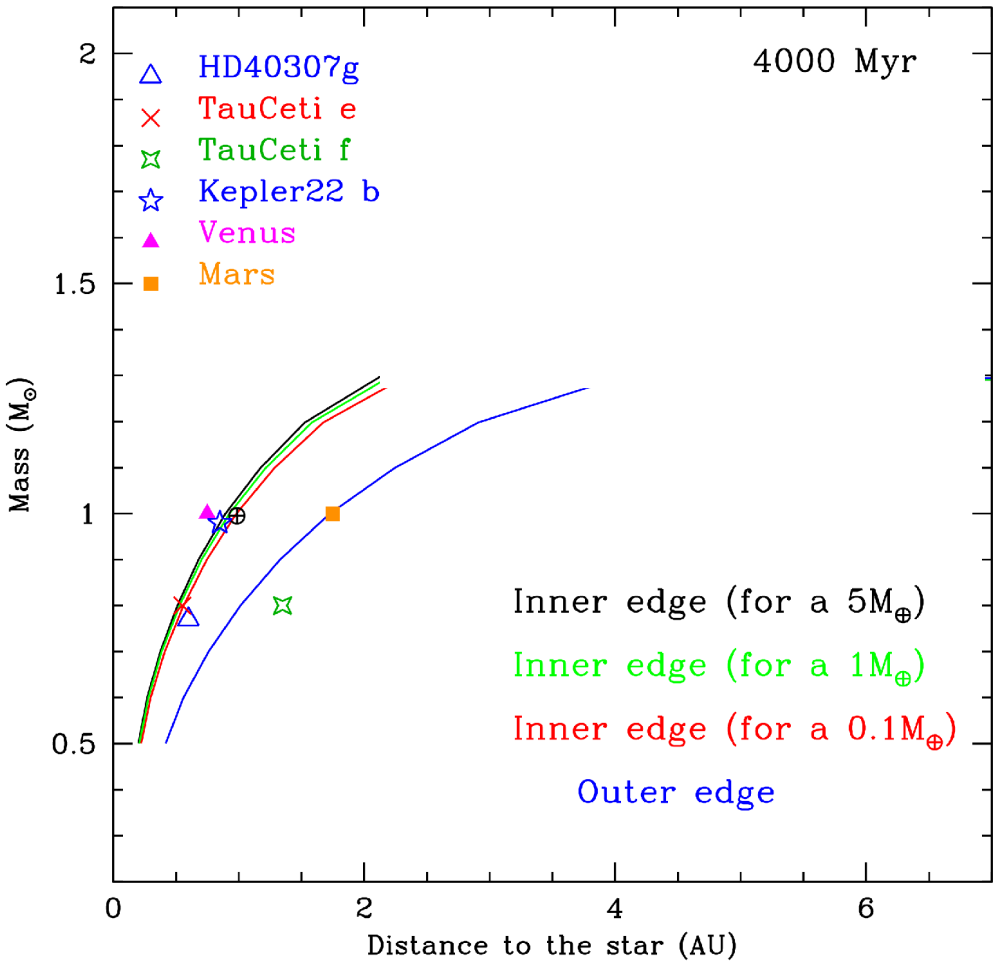

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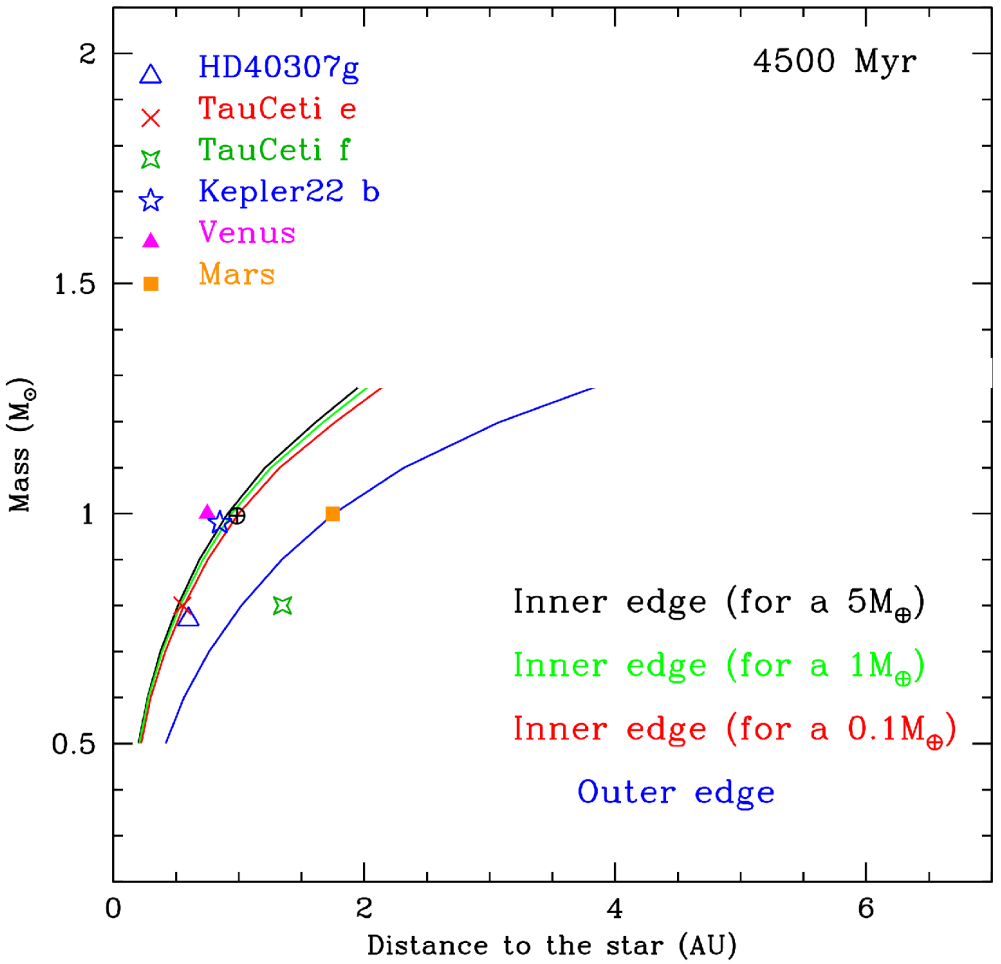

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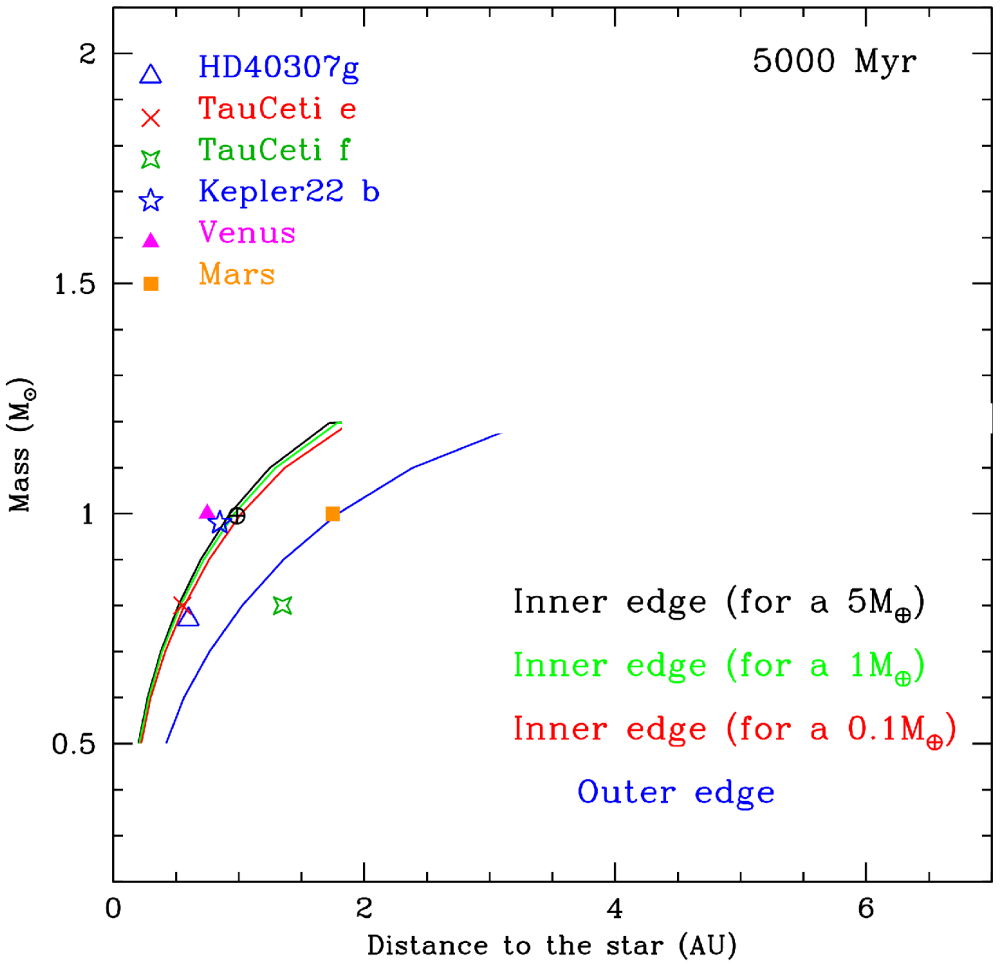

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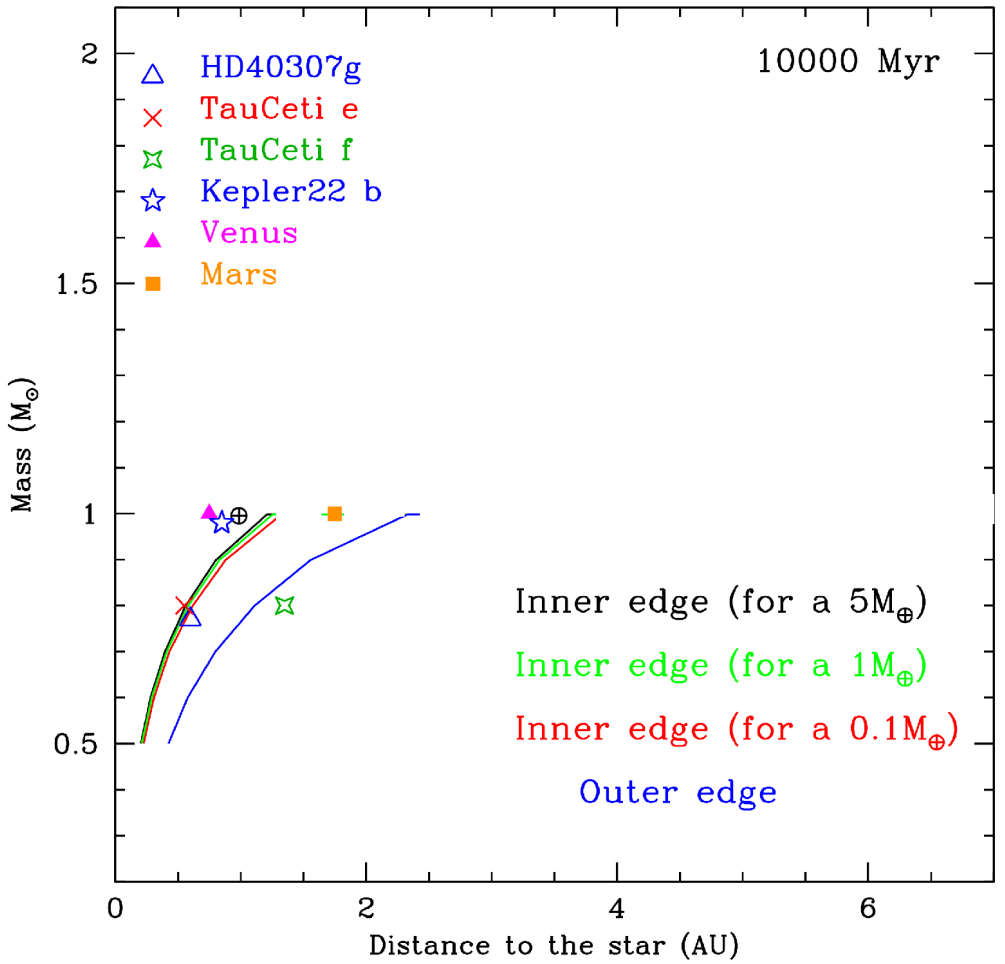

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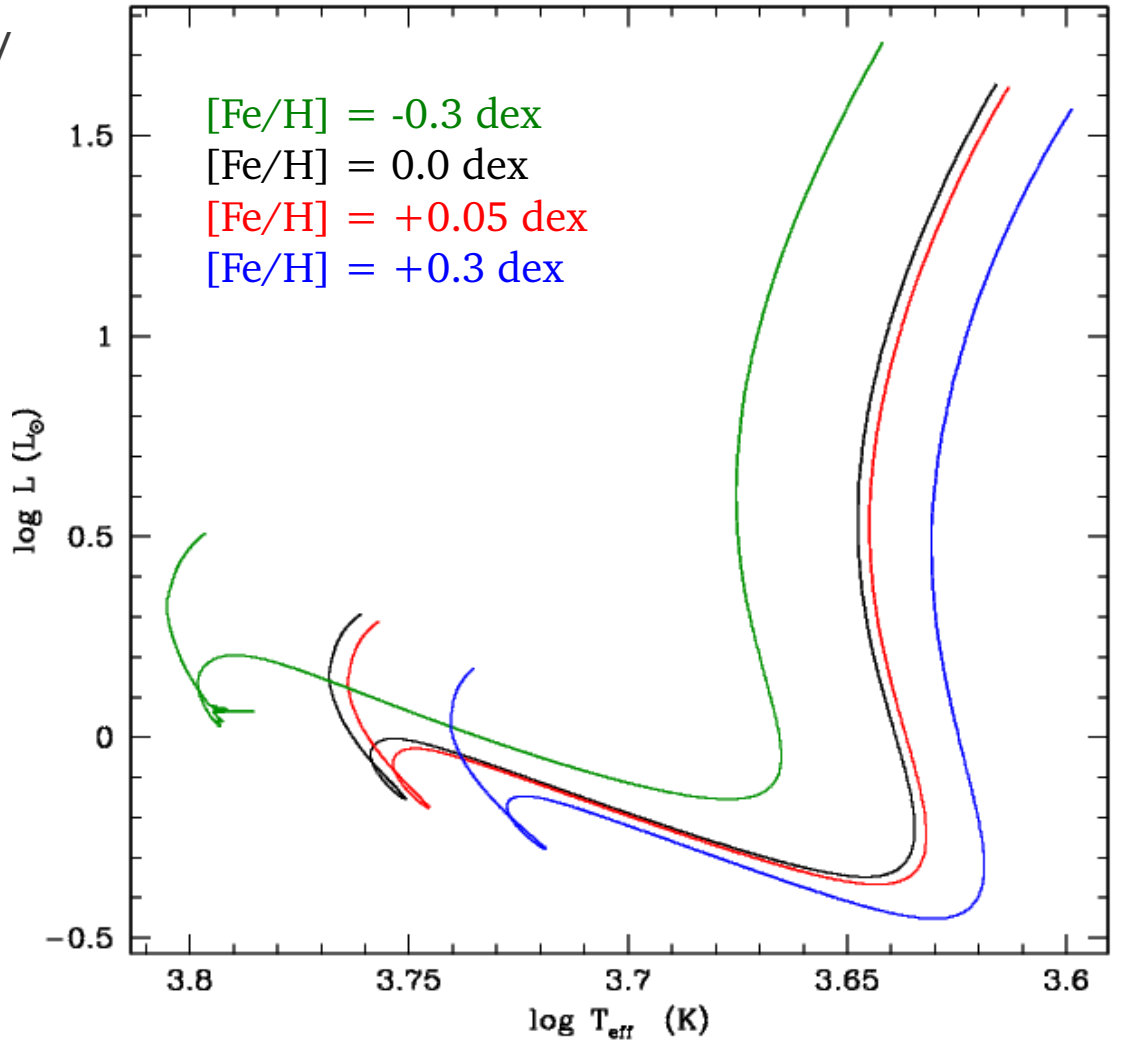
Effect of chemical composition

The amount of metals affects the opacity of the stellar plasma.

The less metals, the less opaque the envelope and the bluer and hotter the track.



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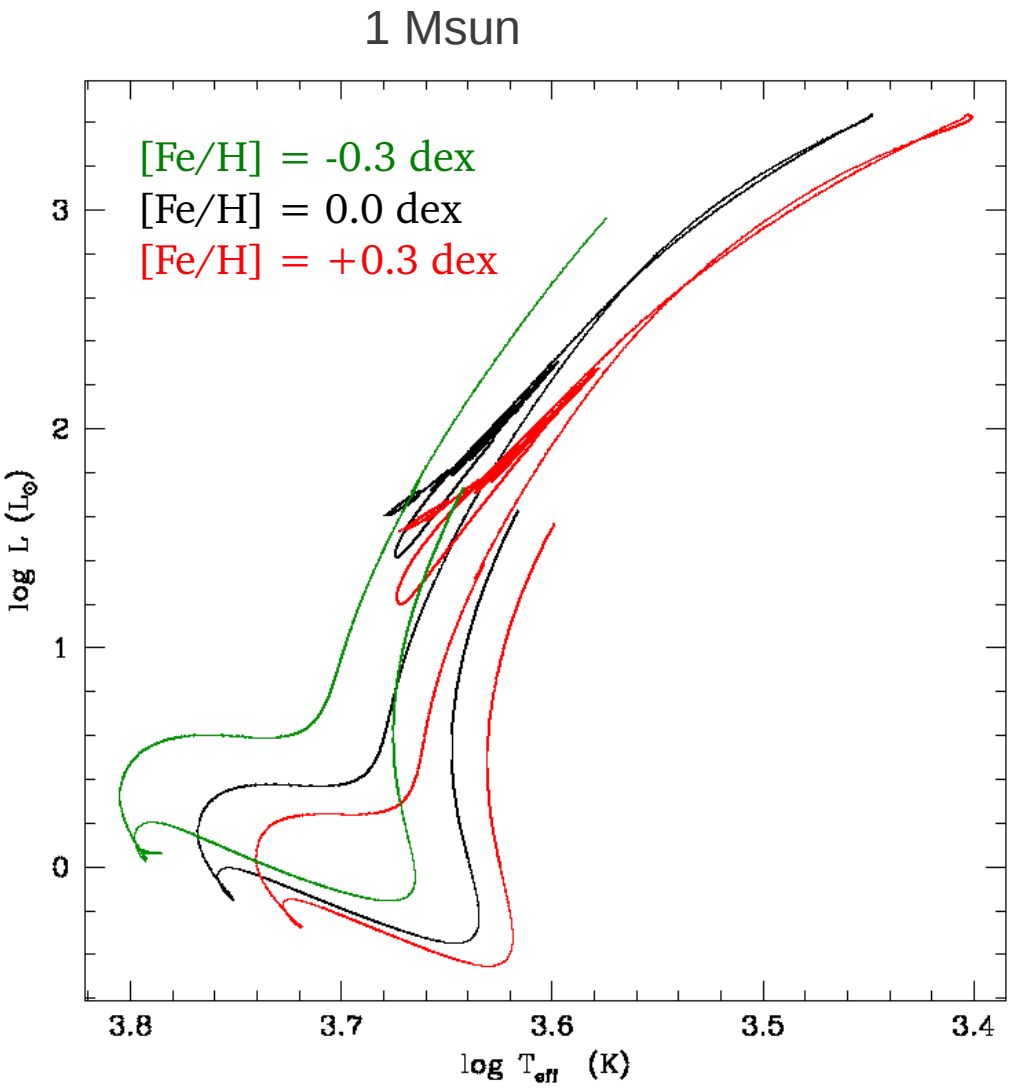
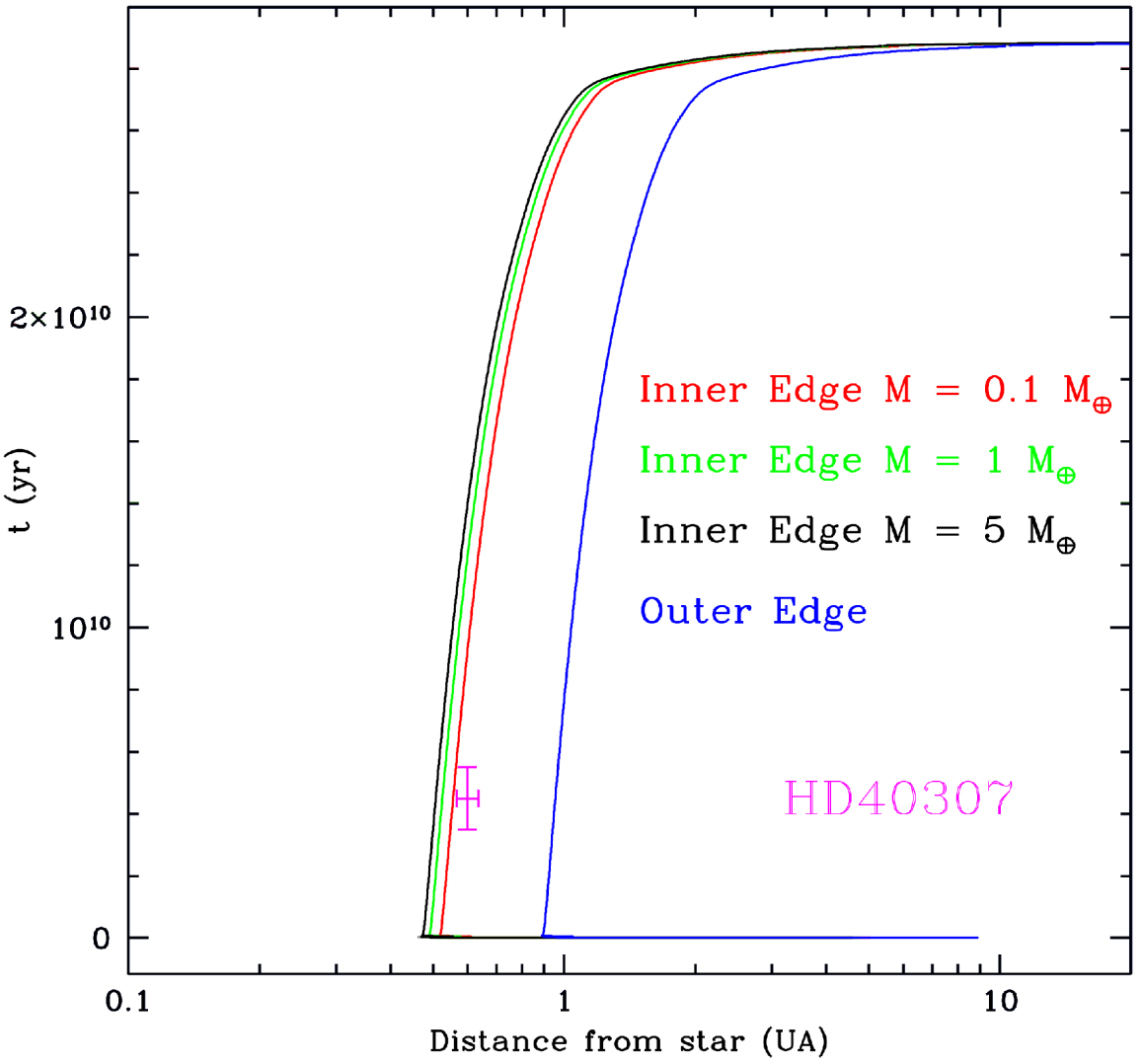


Case of HD40307 (Tuomi et al. 2012)

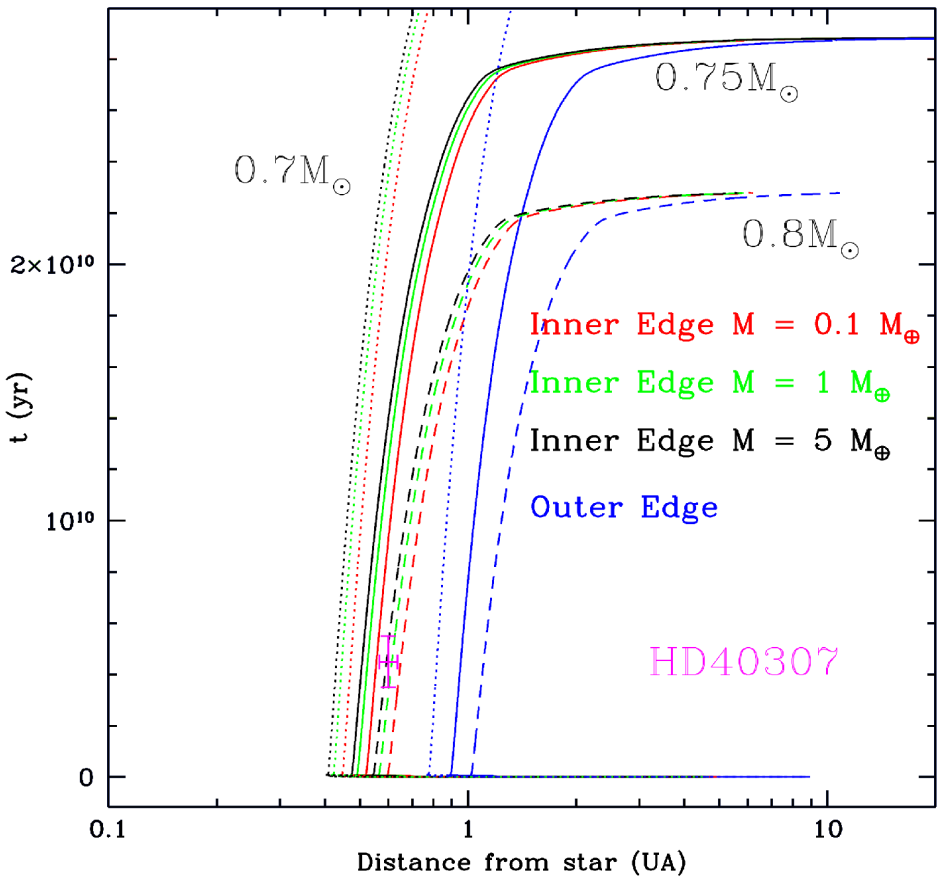
Stellar Properties	HD40307
L	$0.23 \pm 0.03 L_{\odot}$
T_{eff}	$4956 \pm 50 K$
$M_{\star}$	$0.77 \pm 0.05 M_{\odot}$
$[Fe/H]$	-0.31 ± 0.03
Age	$\simeq 4.5$ Gyr
Planet Properties	**HD40307g**
M_P	$\in [4.5; 9.7] M_{\oplus}$
d	$0.6 \pm 0.033 UA$
e	0.29

Case of HD40307 (Tuomi et al. 2012)

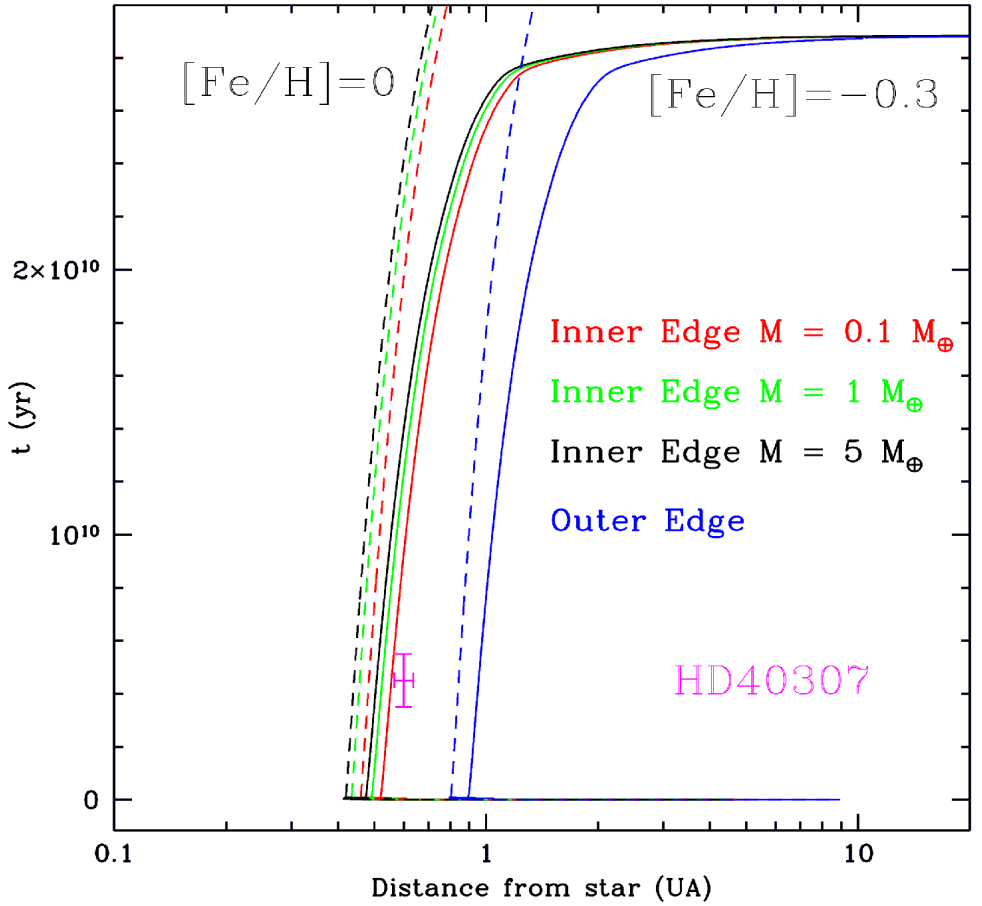


Case of HD40307 (Tuomi et al. 2012)

Varying M



Varying metallicity



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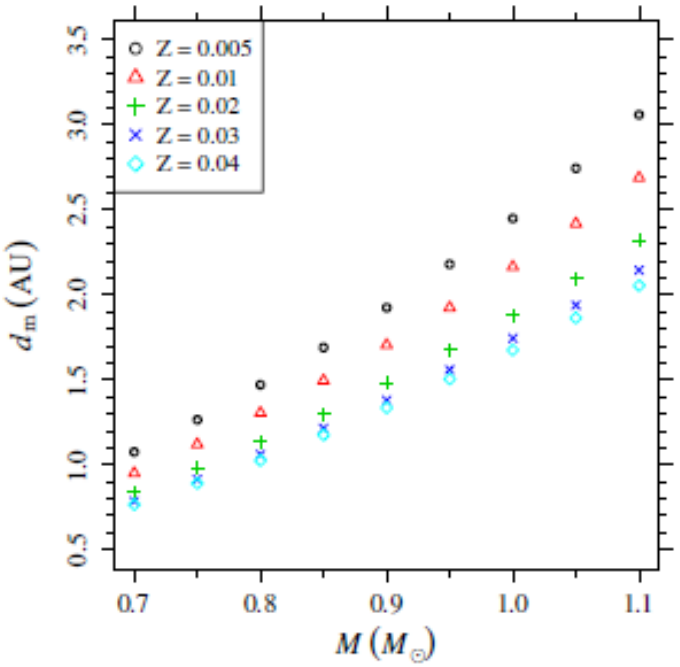
Effect of chemical composition

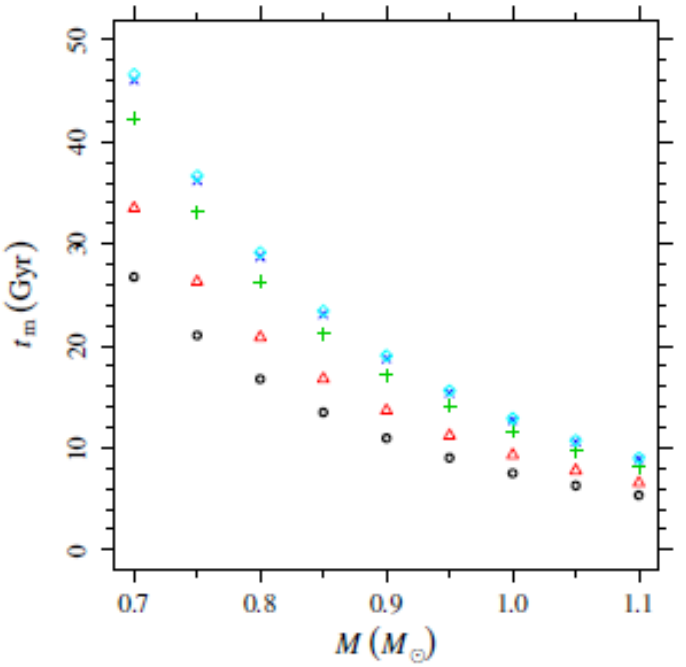
Valle et al. 2014 → explore the impact of stellar chemical composition and mass on the HZ

$\Delta Y/\Delta Z = 2$ fixed

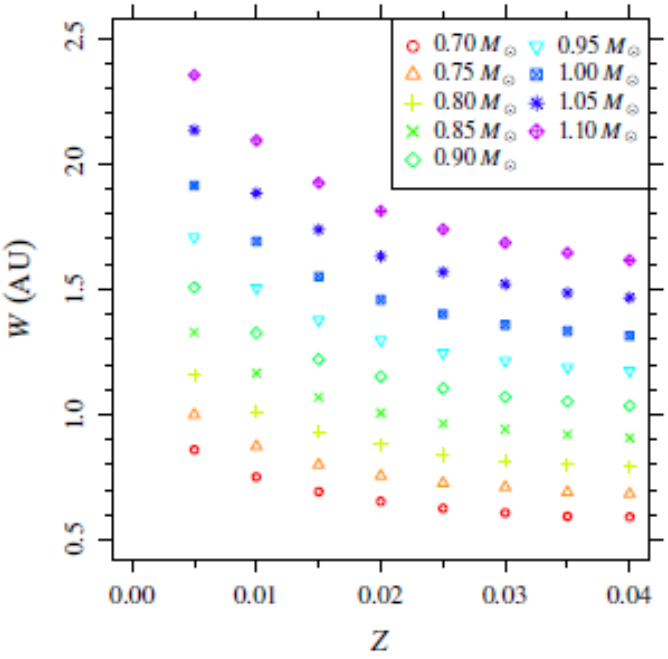
distance for which the duration of the habitability is the longest



Maximum duration of habitability



width of the zone for which habitabillity lasts $t_m/2$



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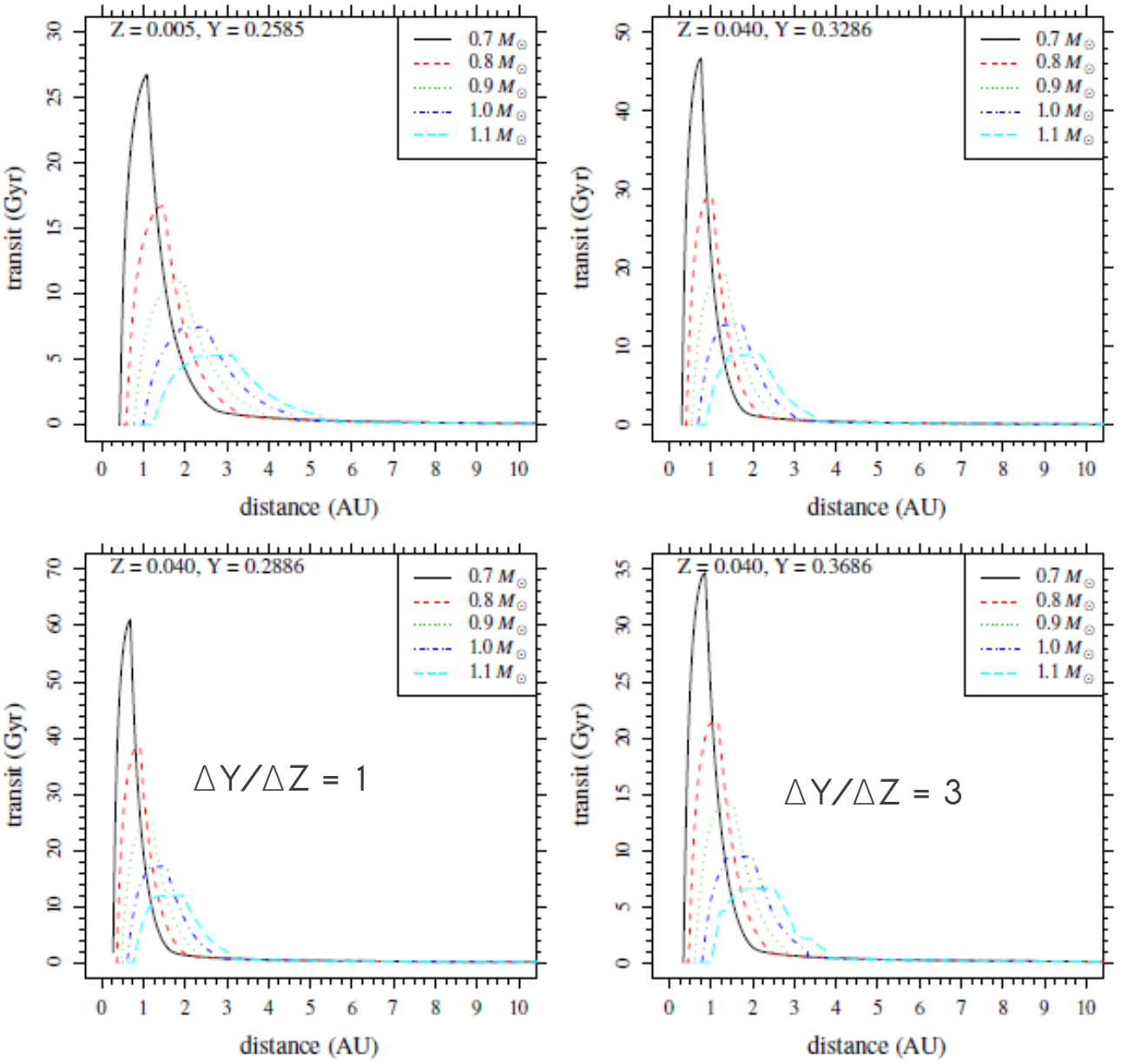
Effect of chemical composition

Fixed ΔY/ΔZ and varying Z

Fixed Z and varying ΔY/ΔZ



Valle et al. 2014

Effect of chemical composition

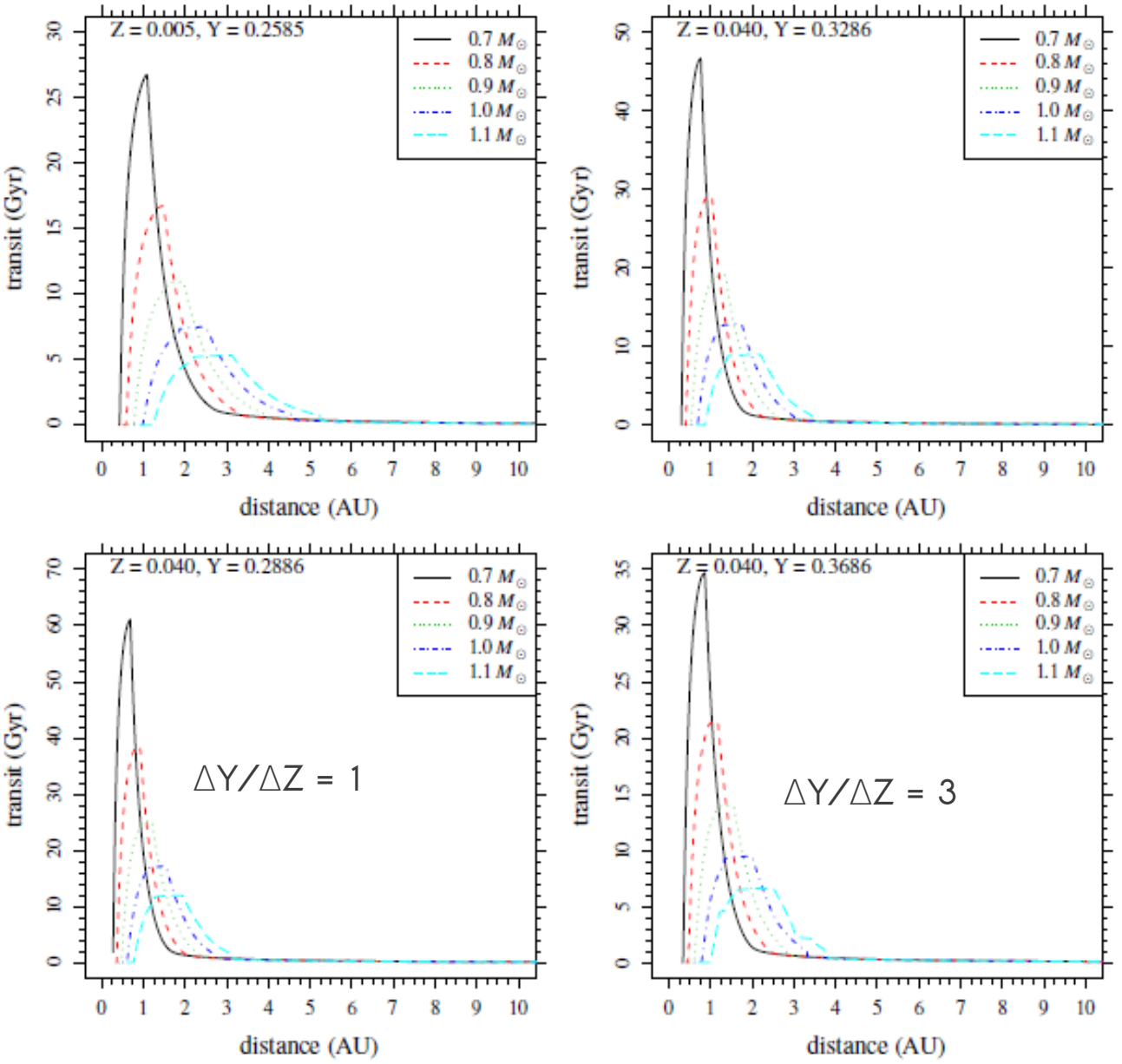
Duration of habitability @ given distance longer for metal-rich stars

Fixed ΔY/ΔZ and varying Z

Fixed Z and varying ΔY/ΔZ

Duration of habitability @ given distance shorter for helium-rich stars

Valle et al. 2014



Effect of rotation

Rotation → modification of the stellar structure (centrifugal forces, non-sphericity, gravity darkening)

→ transport of angular momentum and chemicals

(macroscopic movements and hydrodynamical instabilities)

In low-mass stars, the centrifugal forces dominate during the PMS

→ modification of the tracks

The transport of AM dominates on the MS

→ no memory of initial rotation

Zahn 1992, Maeder & Zahn 1998

$$\rho \frac{d}{dt}\left(r^2\Omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^4 \rho \nu_v \frac{\partial \Omega}{\partial r}\right) + \dot{\tau}_{wind}$$

advection diffusion wind torque

Kawaler 1988, Matt et al. 2012, Matt et al. priv. comm.

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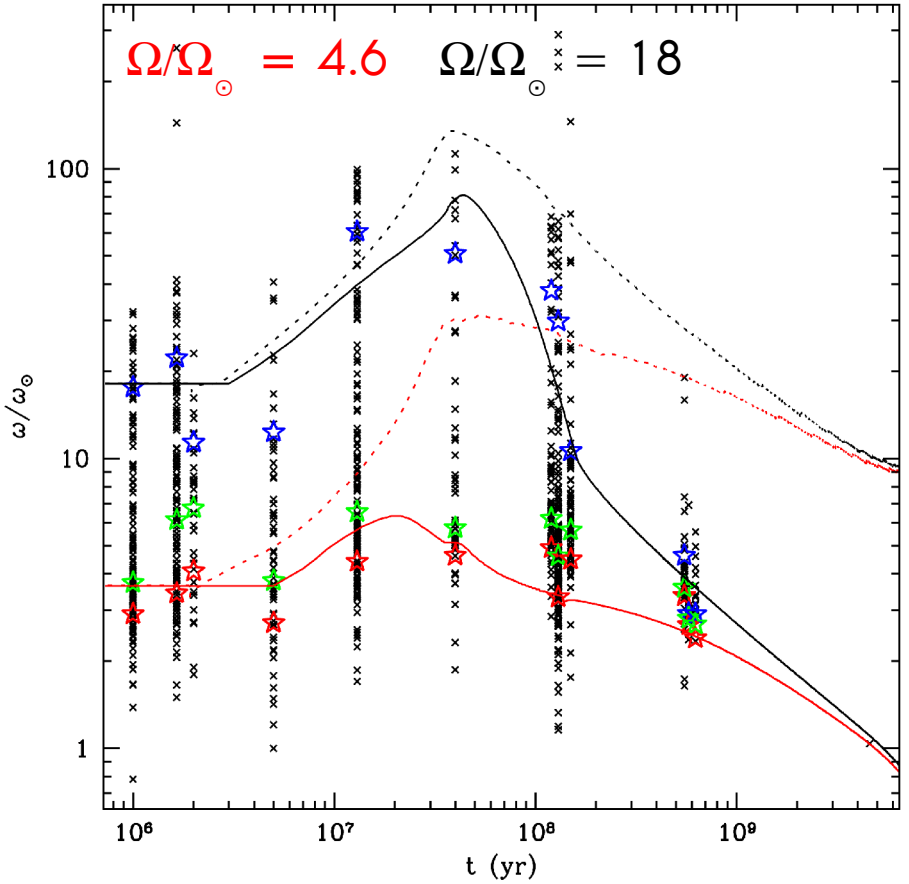

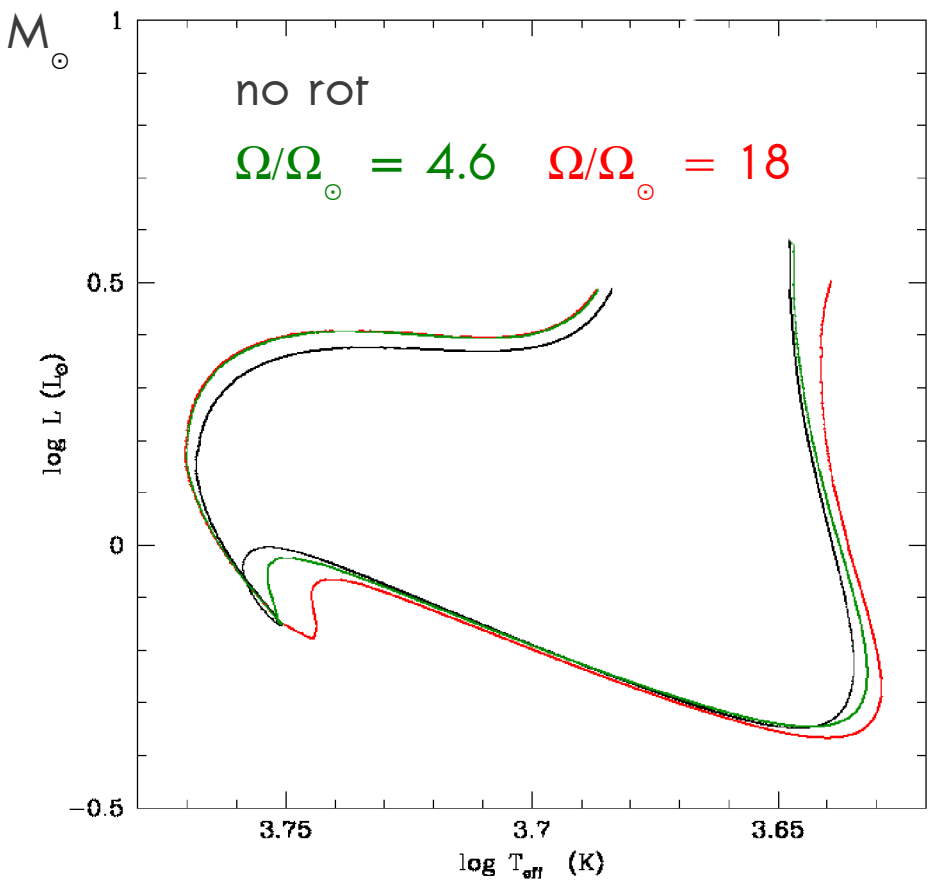

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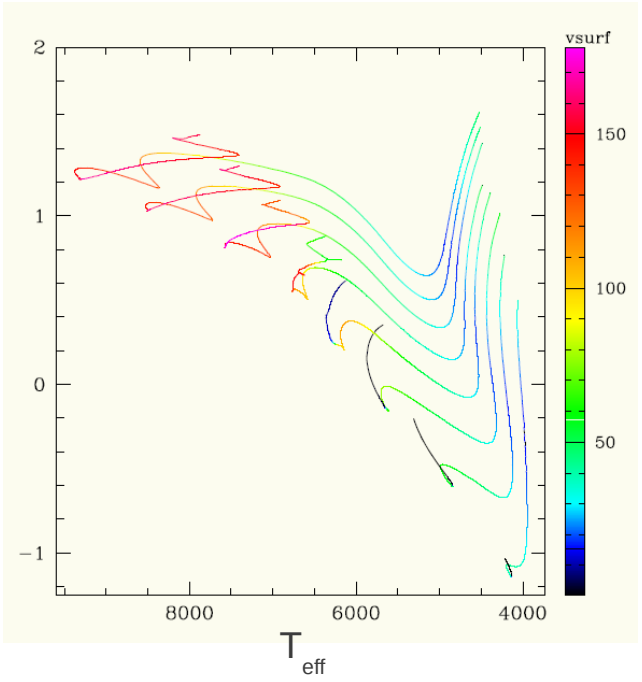
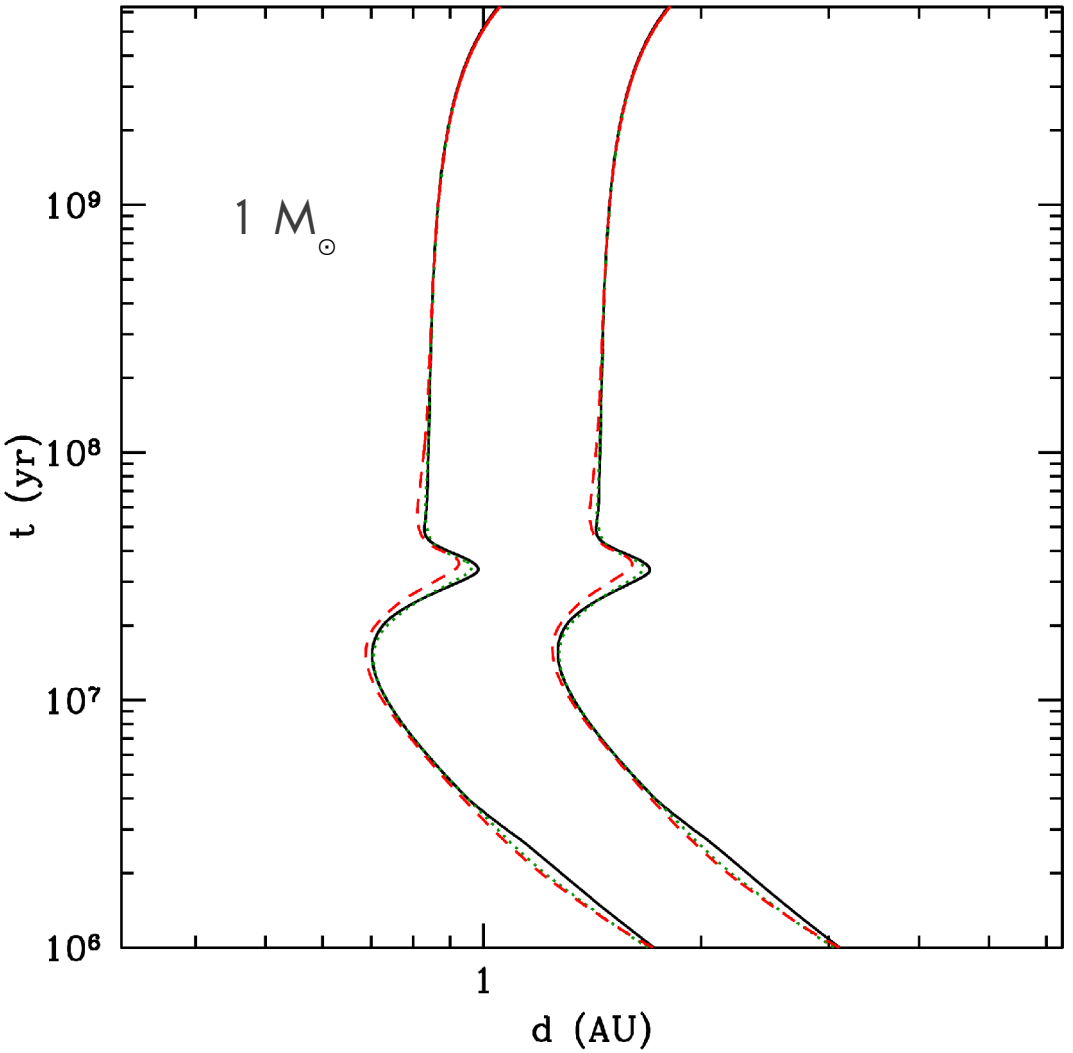
Effect of rotation

Small effect on the ZAMS due to centrifugal effects

no rot

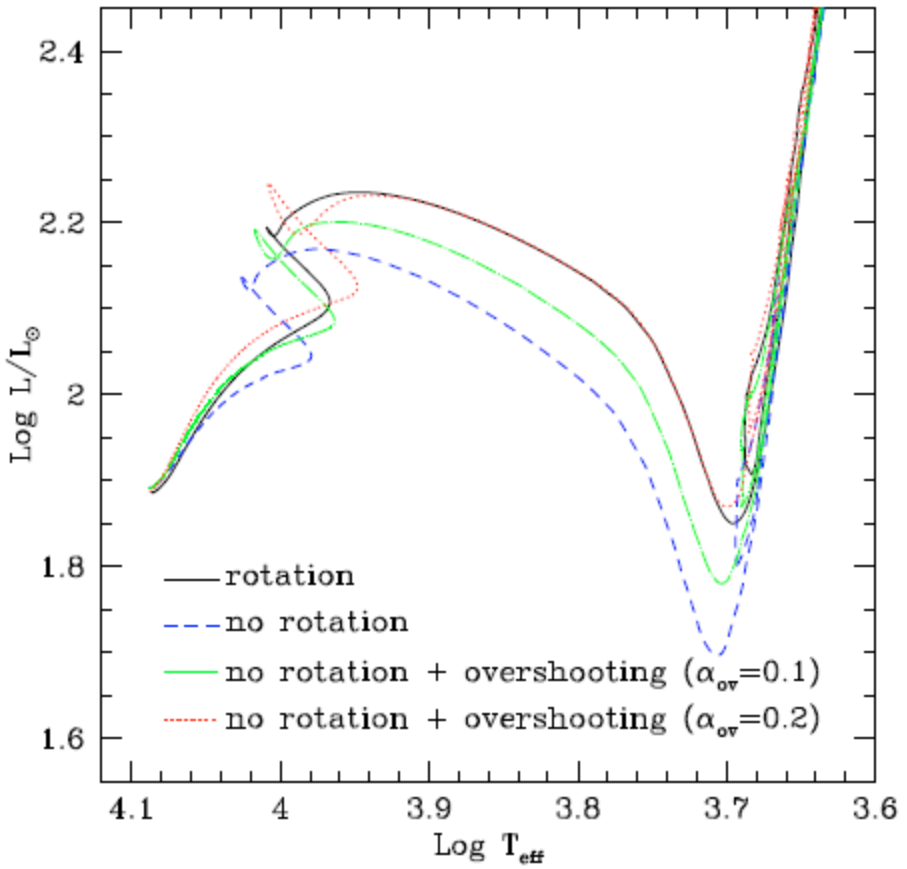
$\Omega/\Omega_\odot = 4.6$ $\Omega/\Omega_\odot = 18$



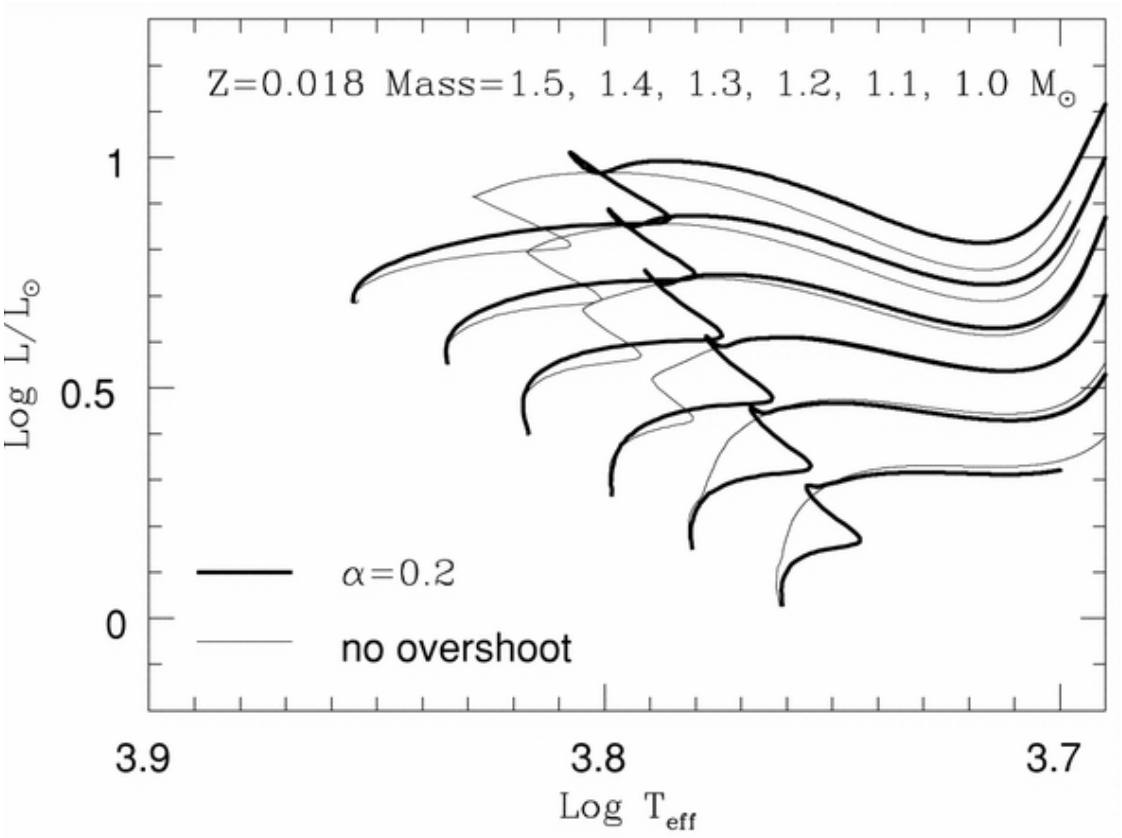


Other processes affecting evolutionary tracks

Core overshooting affects evolutionary tracks → expected effect on HZ position



Eggenberger et al. 2010



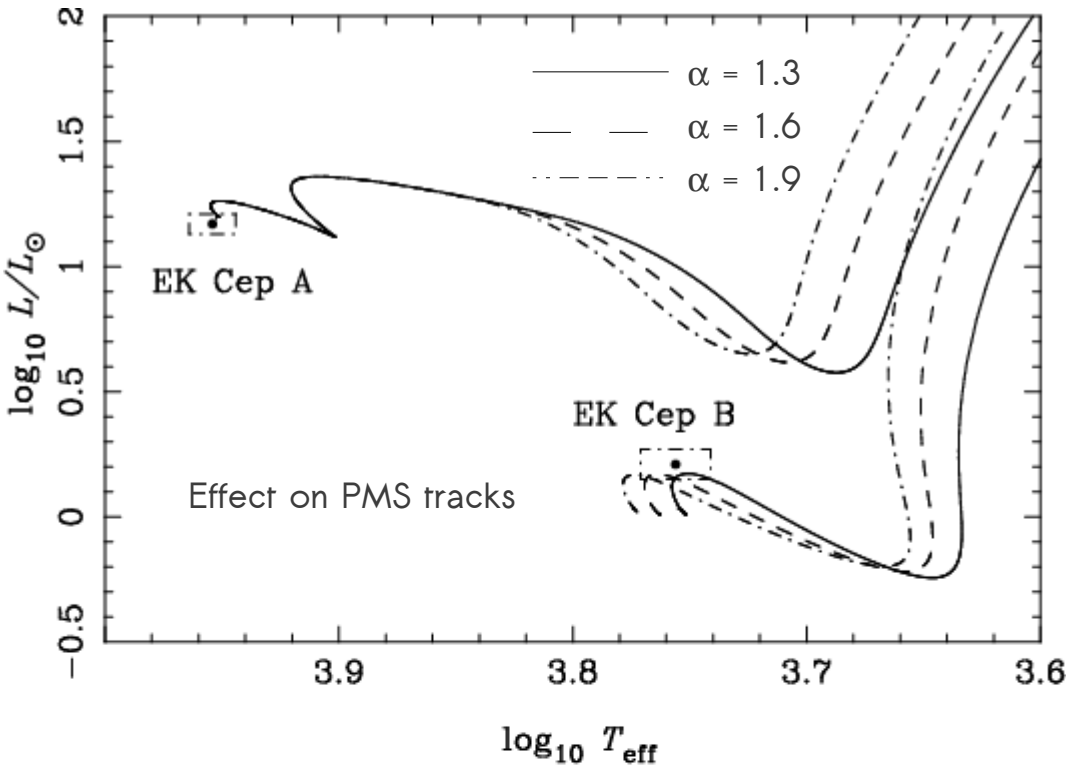
Woo & Demarque 2001

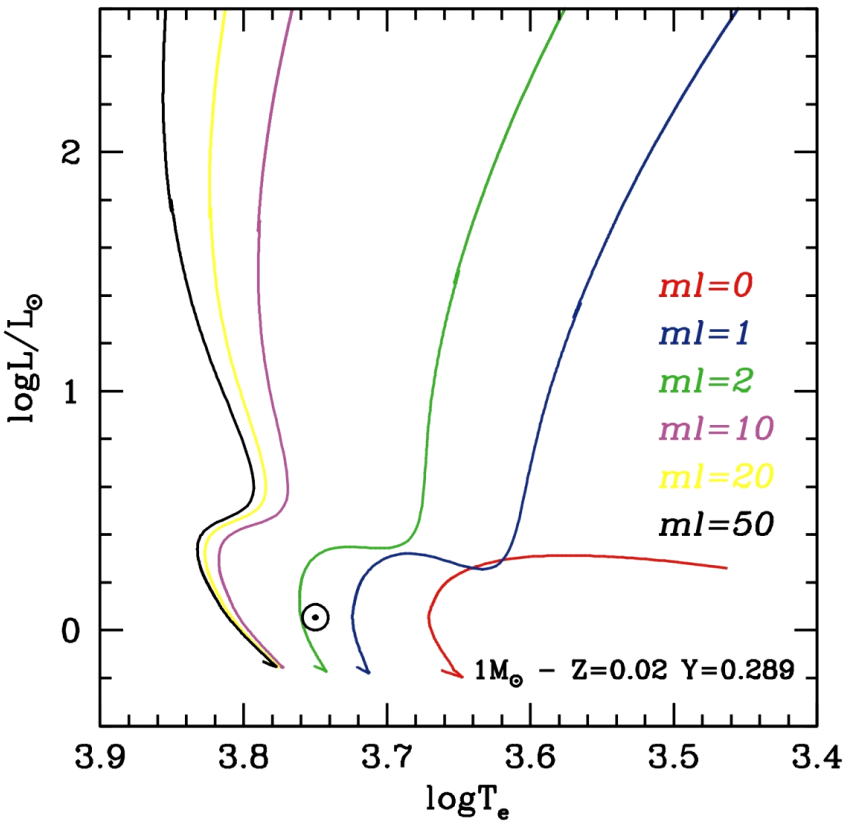
Other processes affecting evolutionary tracks

Mixing length parameter (= model for convection) affects the evolutionary track

→ expected to modify the HZ location

Effect on MS tracks





Marques et al. 2004

Take away message

Importance of ingredients used in stellar evolution codes on HZ definition

Z plays a crucial role (Valle et al. 2014, Danchi & Lopez 2013)

It is also the case for any physical process affecting the opacity / the distribution of the nuclides contributing to energy generation

Importance to do self-consistent analysis when using stellar evolution models
(Rushby et al 2013 !!!)

HZ calculator http://astro.df.unipi.it/stellar-models/HZ/

Stay tuned for TOUPIES rotating models!