SF2A Lyon 14-06-2016

From stellar evolution to tidal interaction

impact on planetary habitability

Florian Gallet

Corinne Charbonnel(Geneva), Louis Amard (LUPM/Geneva), Stephane Mathis (AIM Paris-Saclay), Emeline Bolmont (Namur), Ana Palacios (LUPM), Sacha Brun (AIM Paris-Saclay),

This work results within the collaboration of the COST Action TD 1308

SF2A Lyon 14-06-2016

From stellar evolution to tidal interaction

impact on planetary habitability

Florian Gallet

Corinne Charbonnel(Geneva), Louis Amard (LUPM/Geneva), Stephane Mathis (AIM Paris-Saclay), Emeline Bolmont (Namur), Ana Palacios (LUPM), Sacha Brun (AIM Paris-Saclay),

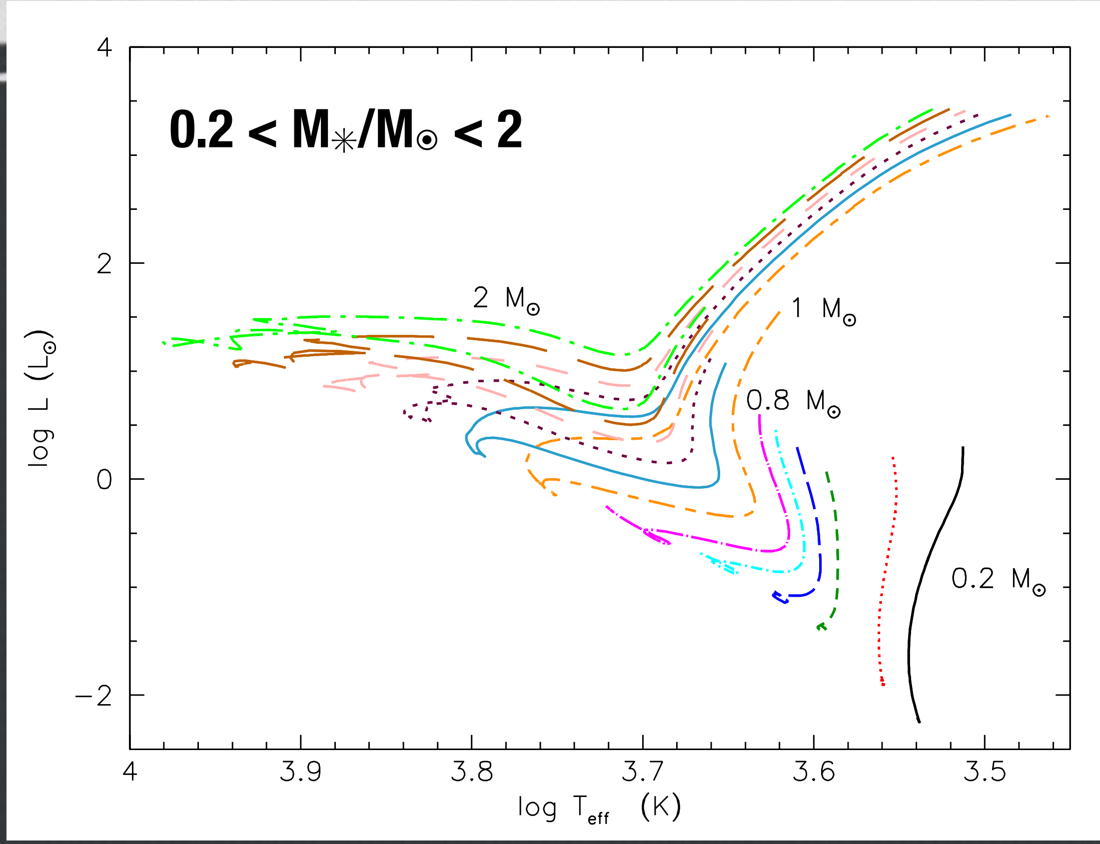
This work results within the collaboration of the COST Action TD 1308

STAREVOL

Follow evolution of main stellar quantities:

- Radius
- Mass
- T_{eff}
- L_{*}
- Ω_{*}
- internal structure
- …

Include a **full** and **self consistent** treatment of rotation



See Lagarde et al. (2012) and Amard et al. (2016) for more details

---

$S_{eff\odot}$, a, b, c = *f* (planet atmosphere)

Kopparapu et al. (2013)

$$S_{eff} = S_{eff\odot} + aT_{*} + bT_{*}^{2} + cT_{*}^{3} + \ldots$$

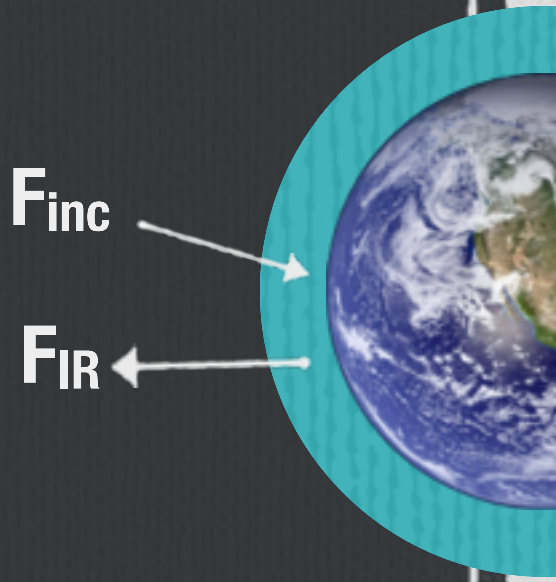
$2600\ K \leq T_{eff} \leq 7200\ K$

$$S_{eff} = \frac{F_{IR}}{F_{inc}}$$

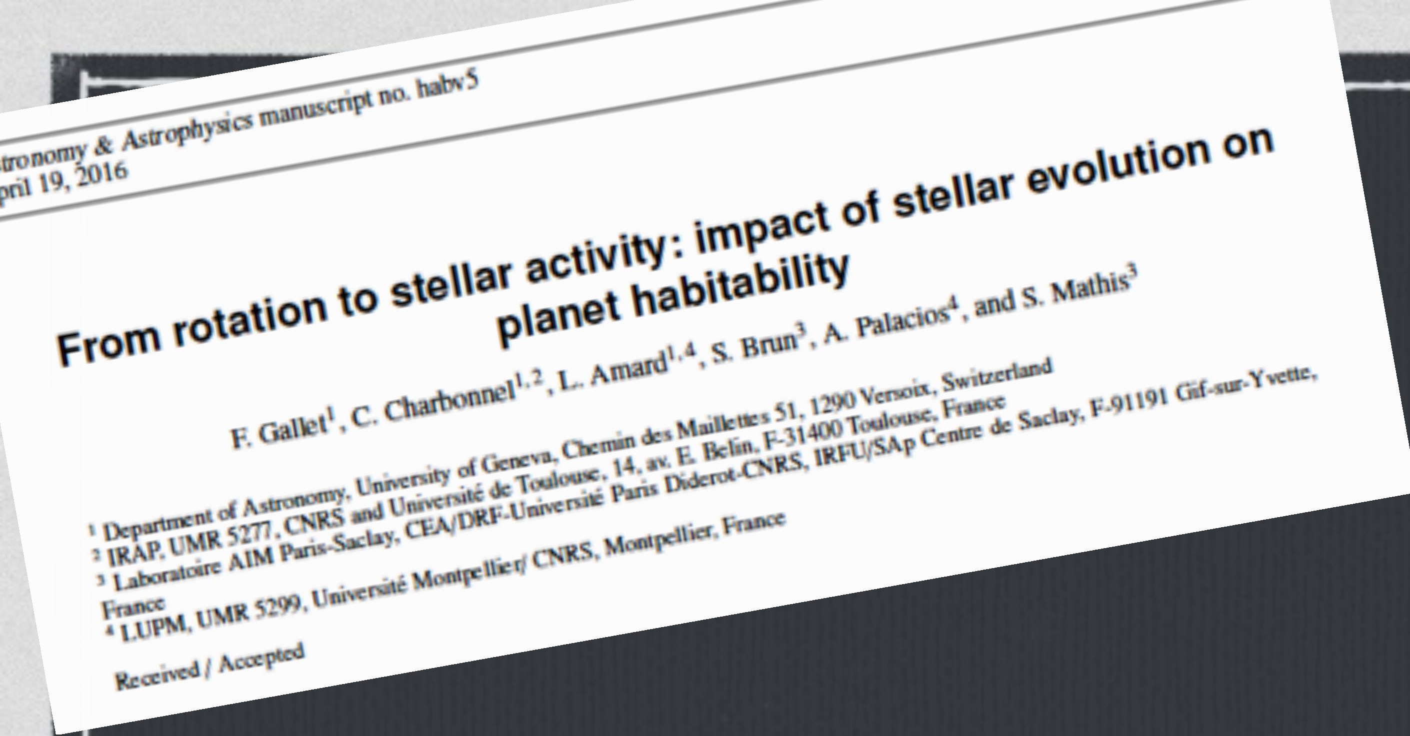
climate model

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

Kasting et al. (1993)



- ☐ R_{in} = Runaway greenhouse : net positif feedback of GH effect (T_{surf} > 647 K), ocean evaporate entirely
- ☐ R_{out} = Maximum greenhouse : Rayleigh scattering by CO_2 reduce GH (T_{surf} = 273 K)



tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

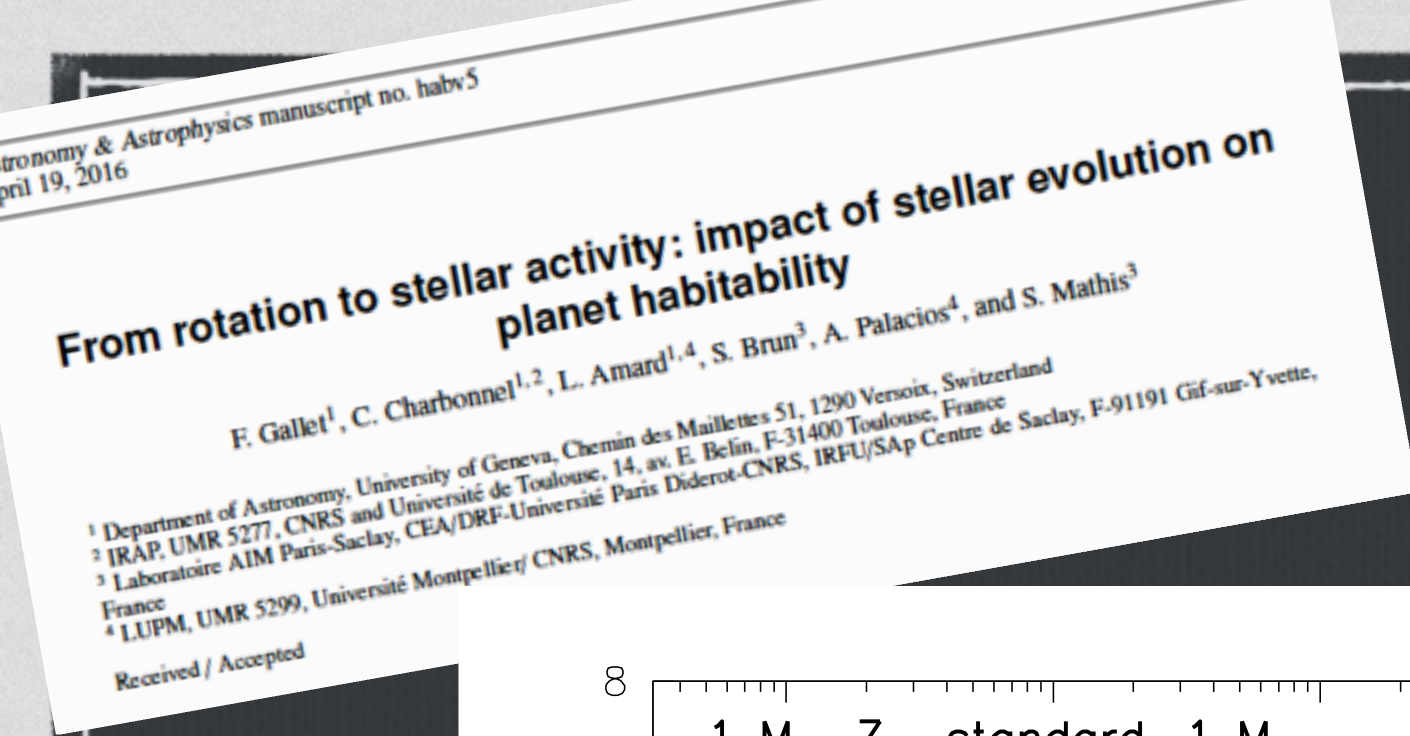
Received / Accepted

Habitable Zone

Impact of:

1) HZ prescriptions => small
2) Stellar models (i.e. input micro-physics) => small
3) Stellar mass => dramatic effect on HZ
4) Metallicity => dramatic effect on HZ
5) Stellar rotation => marginal effect
6) Stellar activity => depends on the mass

Habitable Zone



tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

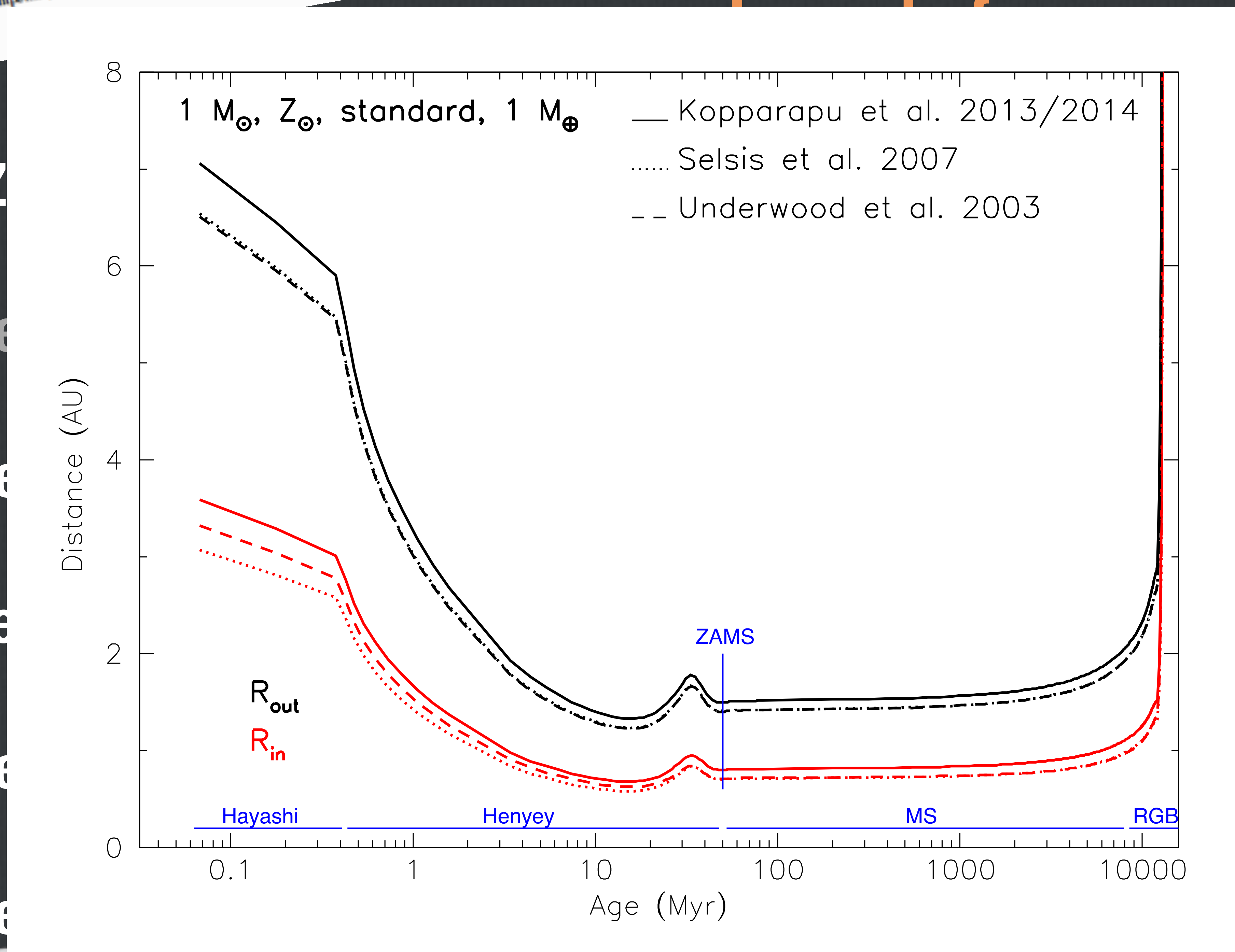
From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

1) HZ
2) Ste
3) Ste
4) Me
5) Ste
6) Ste



tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

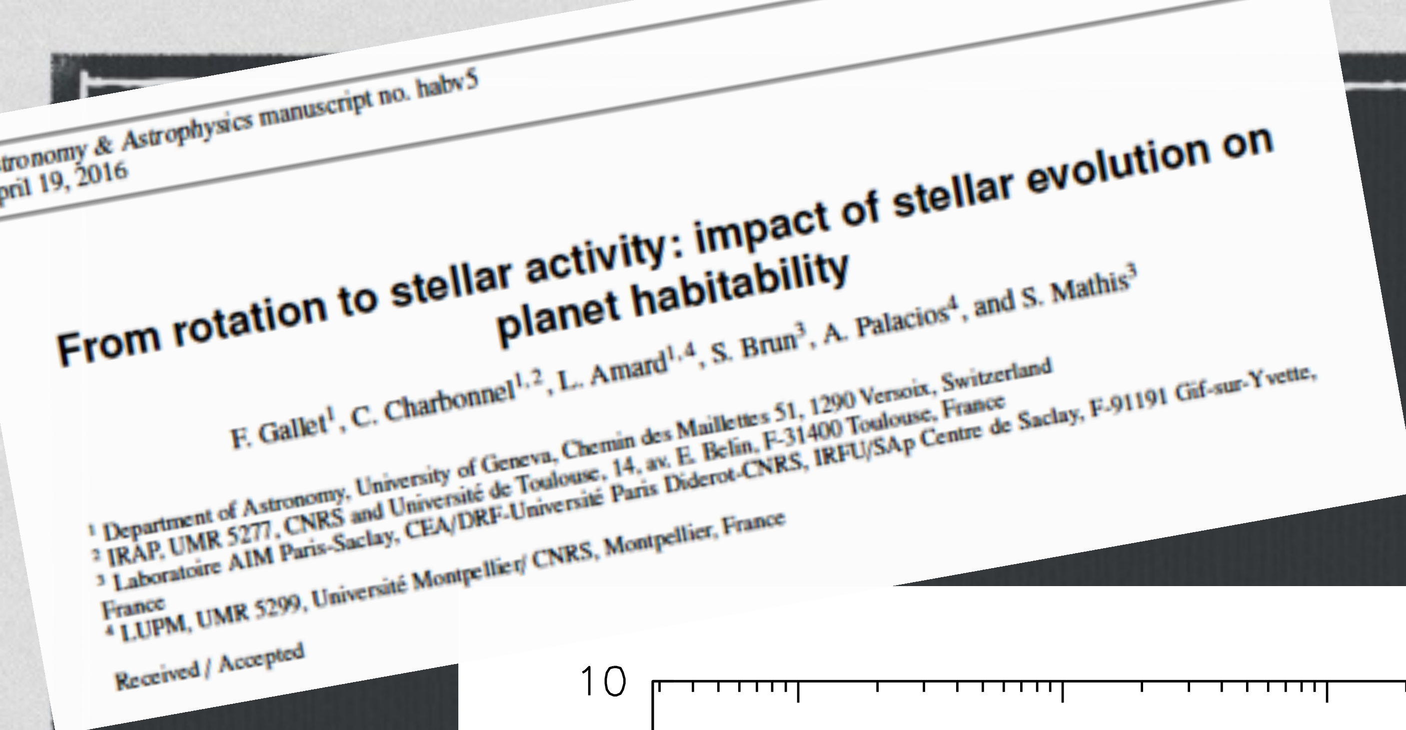
Received / Accepted

Habitable Zone

Impact of:

1) HZ prescriptions => small
2) Stellar models (i.e. input micro-physics) => small
3) Stellar mass => dramatic effect on HZ
4) Metallicity => dramatic effect on HZ
5) Stellar rotation => marginal effect
6) Stellar activity => depends on the mass

Habitable Zone


Astronomy & Astrophysics manuscript no. habv5
April 19, 2016

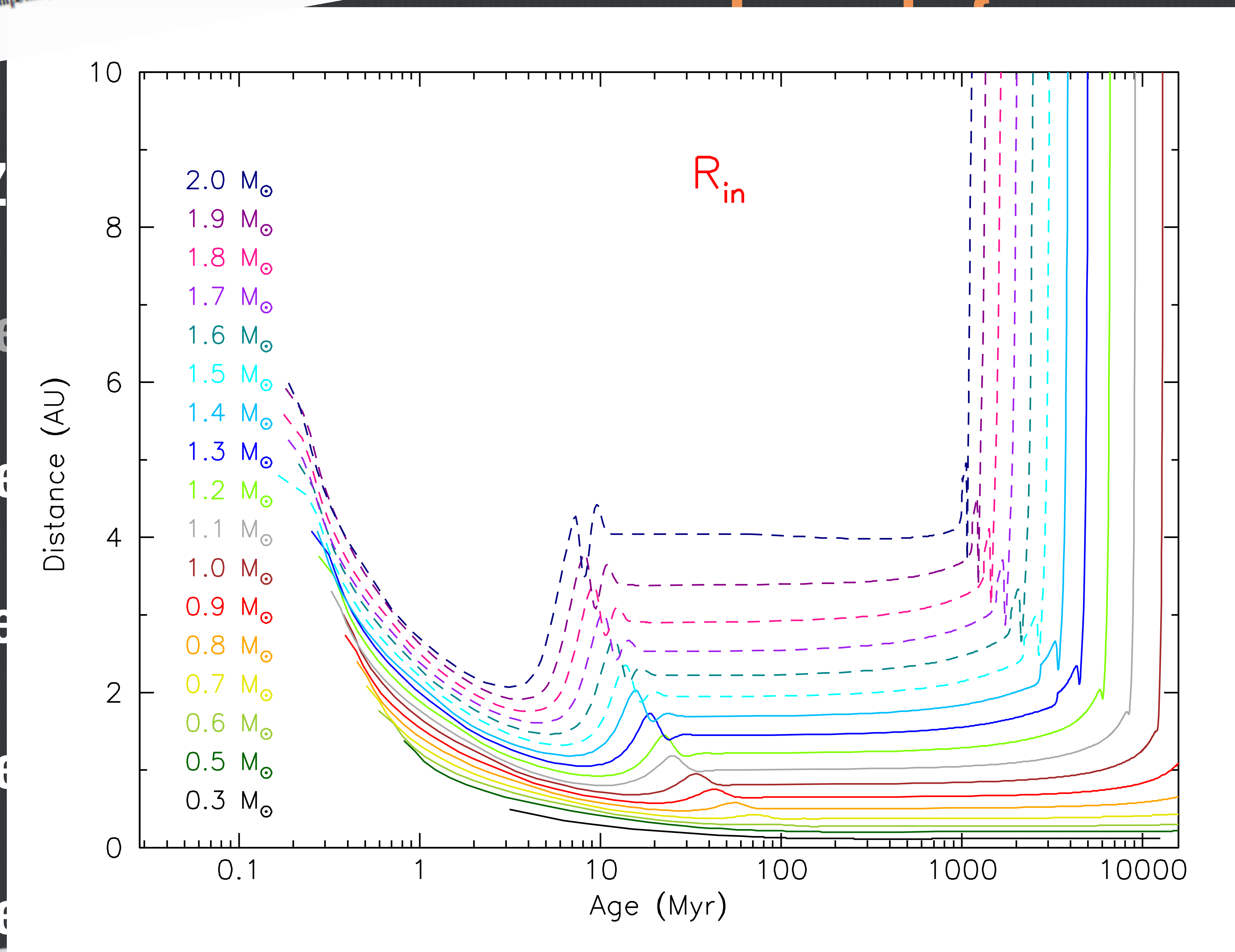
From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

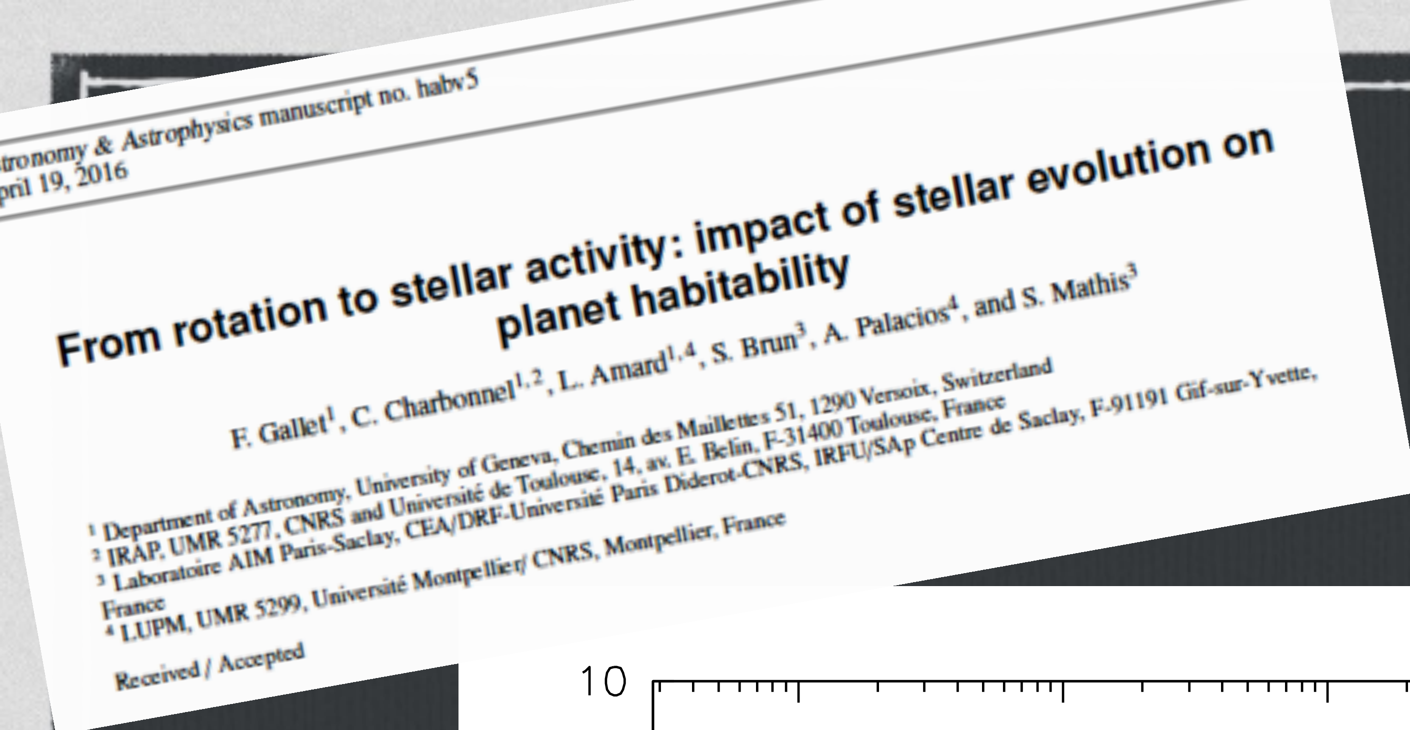
[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

1) HZ
2) Ste
3) Ste
4) Me
5) Ste
6) Ste



Habitable Zone


tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

1) HZ

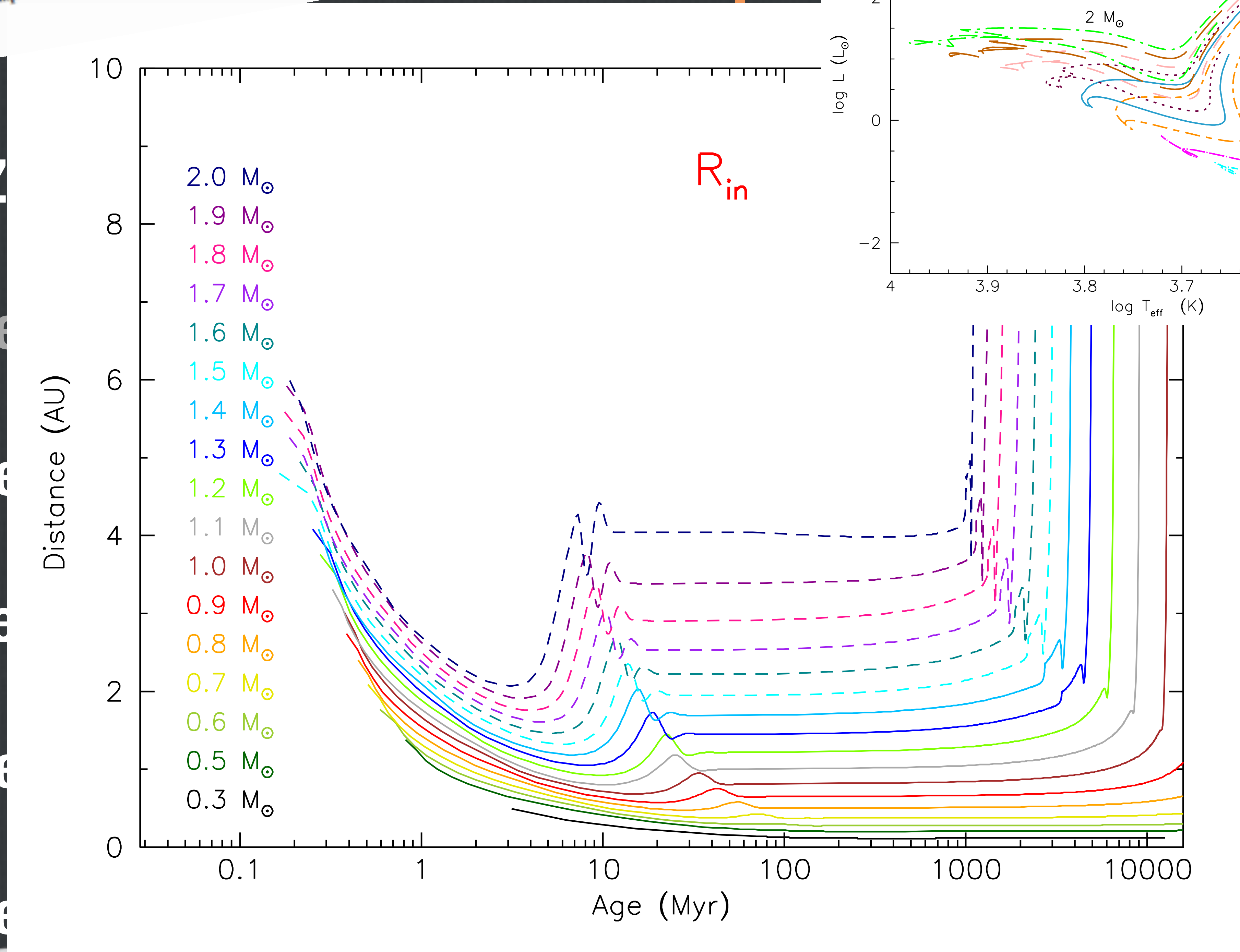
2) St

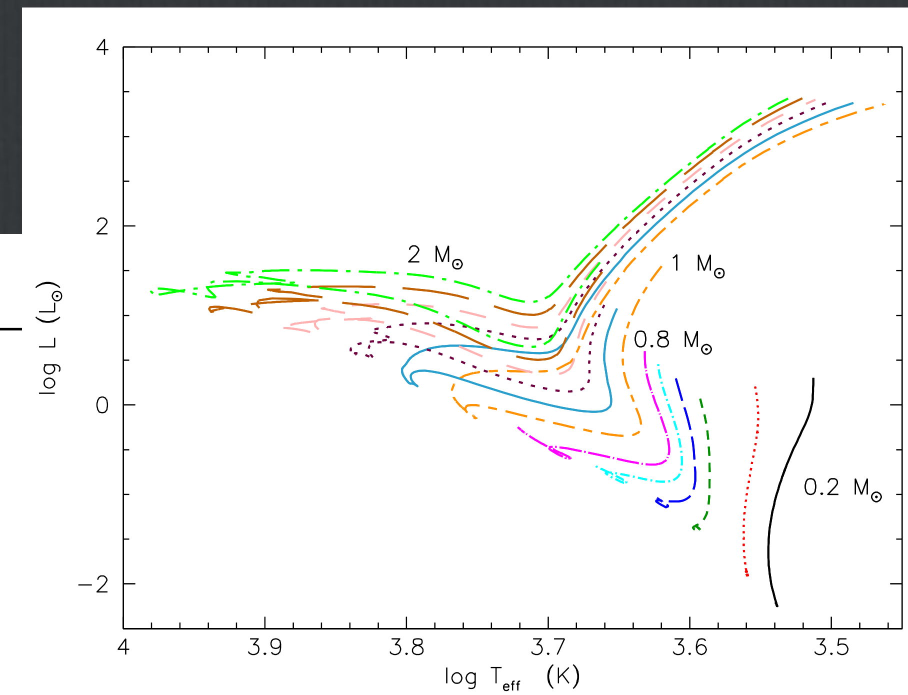
3) St

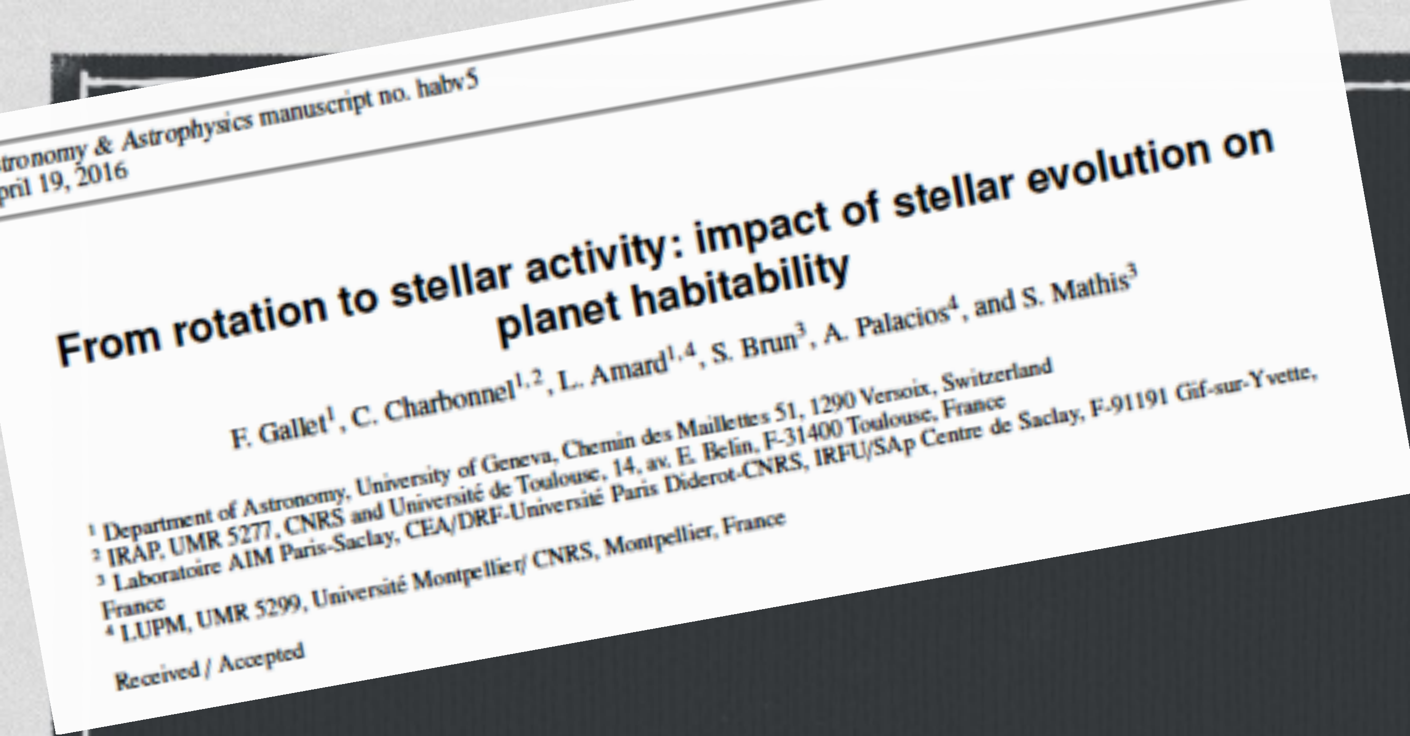
4) Me

5) St

6) St






tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

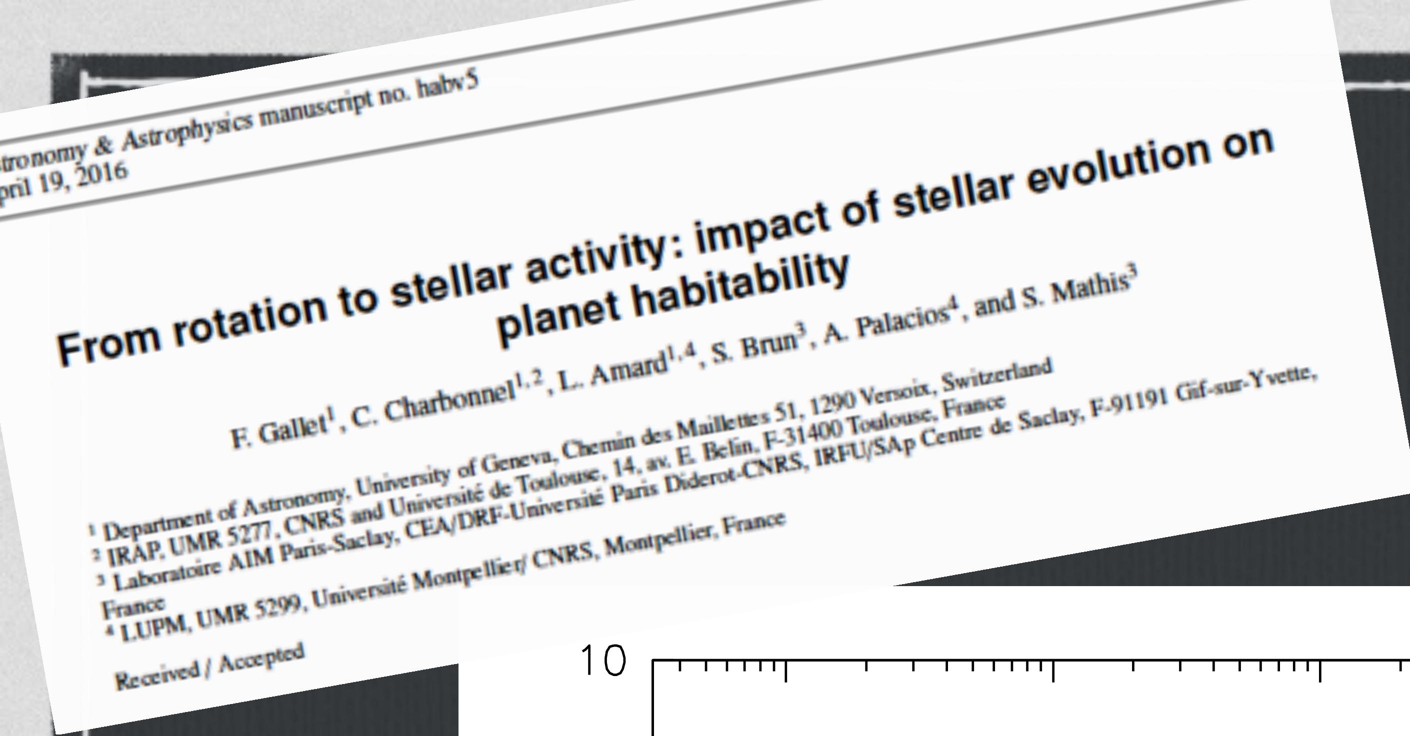
Received / Accepted

Habitable Zone

Impact of:

1) HZ prescriptions => small
2) Stellar models (i.e. input micro-physics) => small
3) Stellar mass => dramatic effect on HZ
4) Metallicity => dramatic effect on HZ
5) Stellar rotation => marginal effect
6) Stellar activity => depends on the mass

Habitable Zone


Astronomy & Astrophysics manuscript no. habv5
April 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

1) HZ

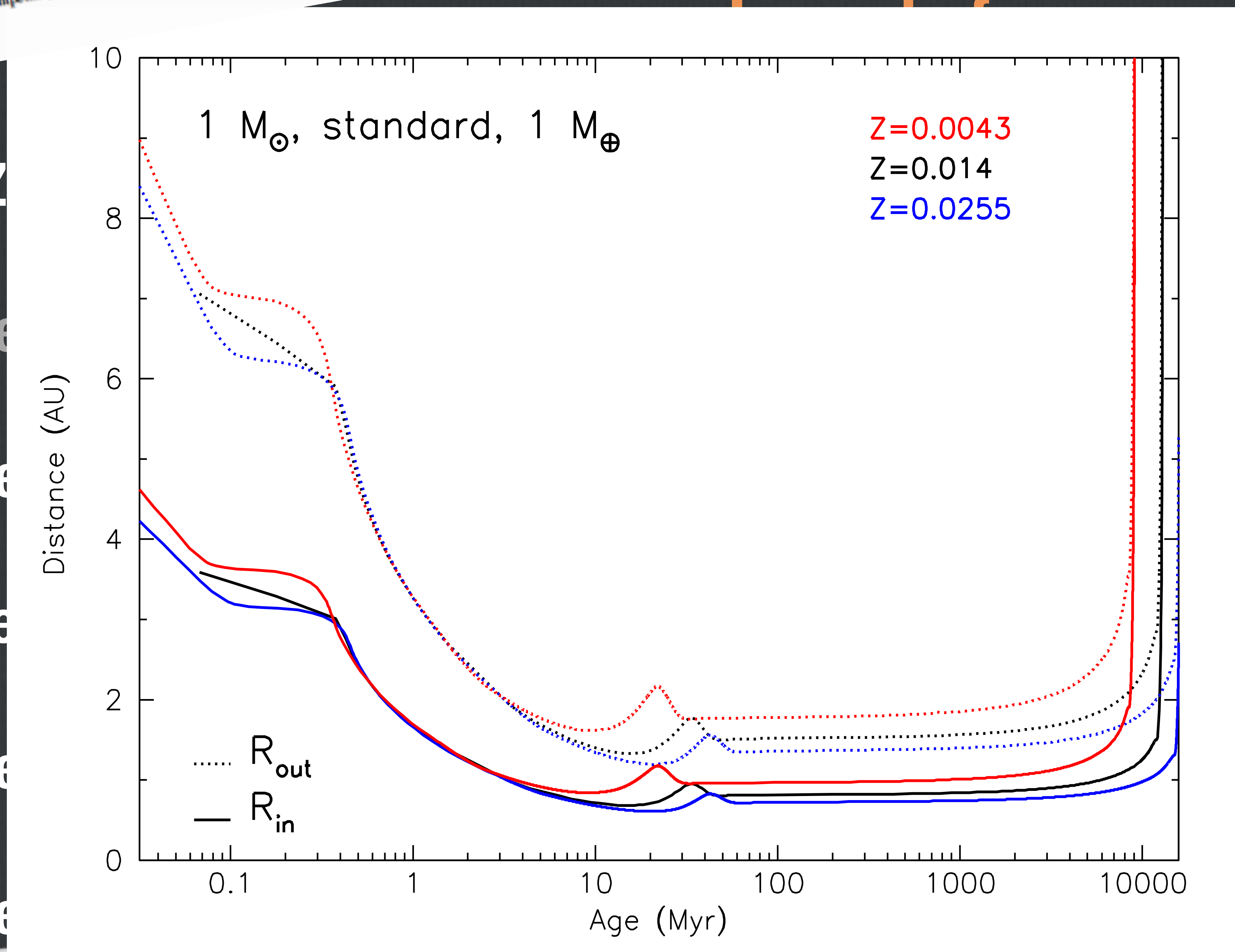
2) Ste

3) Ste

4) Me

5) Ste

6) Ste



tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

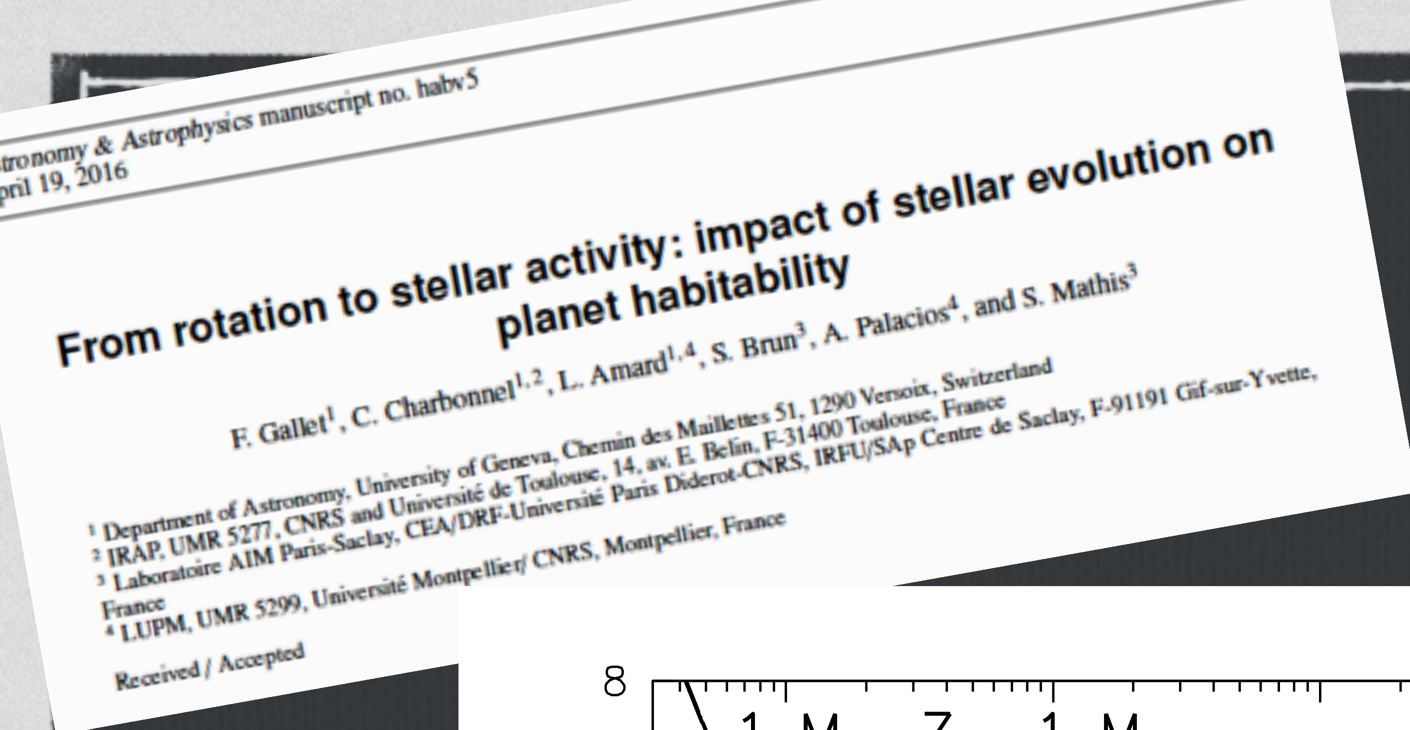
[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

Habitable Zone

Impact of:

1) HZ prescriptions => small
2) Stellar models (i.e. input micro-physics) => small
3) Stellar mass => dramatic effect on HZ
4) Metallicity => dramatic effect on HZ
5) Stellar rotation => marginal effect
6) Stellar activity => depends on the mass


Astronomy & Astrophysics manuscript no. habv5
April 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

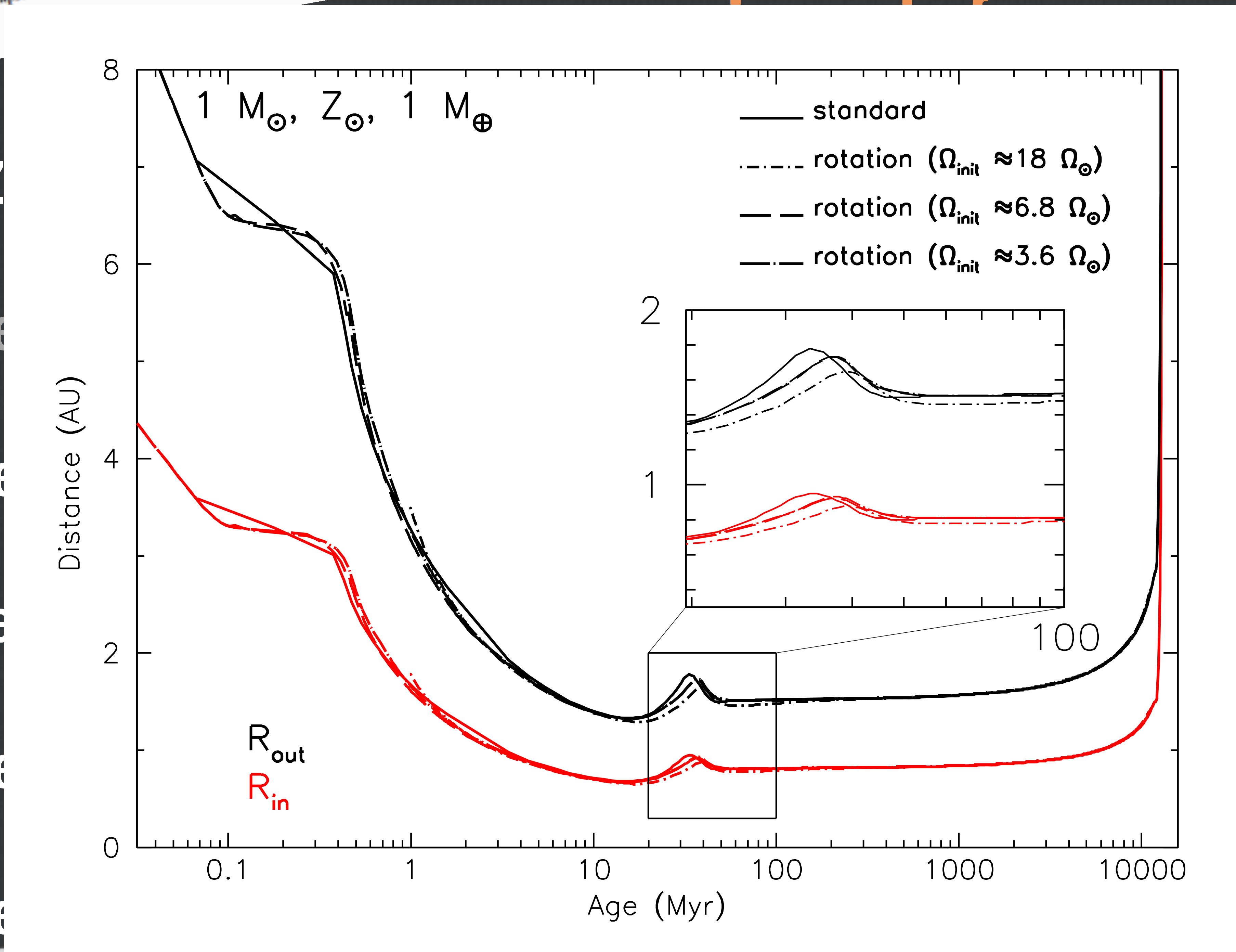
F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

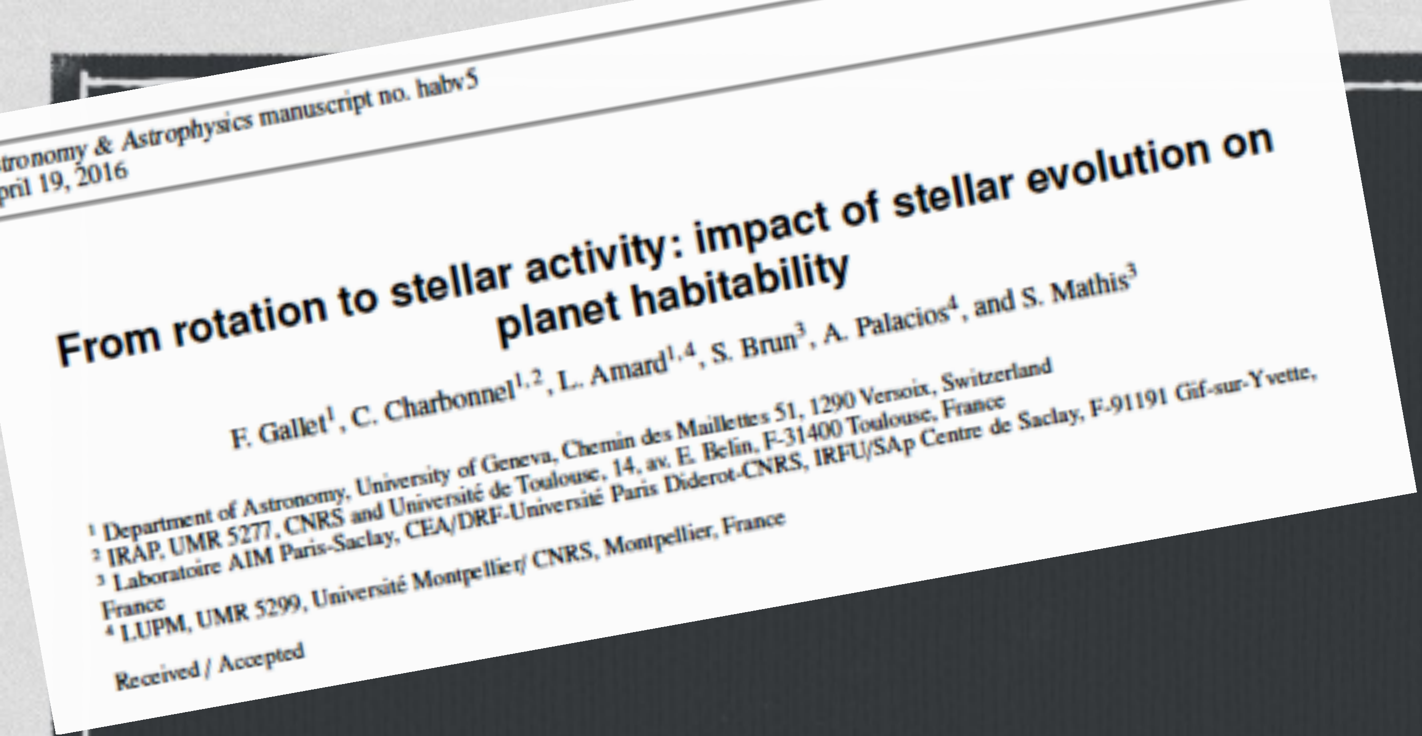
[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

Habitable Zone

1) HZ
2) Ste
3) Ste
4) Me
5) Ste
6) Ste





tronomy & Astrophysics manuscript no. habv5
pril 19, 2016

From rotation to stellar activity: impact of stellar evolution on planet habitability

F. Gallet[1], C. Charbonnel[1,2], L. Amard[1,4], S. Brun[3], A. Palacios[4], and S. Mathis[3]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E. Belin, F-31400 Toulouse, France
[3] Laboratoire AIM Paris-Saclay, CEA/DRF-Université Paris Diderot-CNRS, IRFU/SAp Centre de Saclay, F-91191 Gif-sur-Yvette, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received / Accepted

Habitable Zone

Impact of:

1) HZ prescriptions => small

2) Stellar models (i.e. input micro-physics) => small

3) Stellar mass => dramatic effect on HZ

4) Metallicity => dramatic effect on HZ

5) Stellar rotation => marginal effect

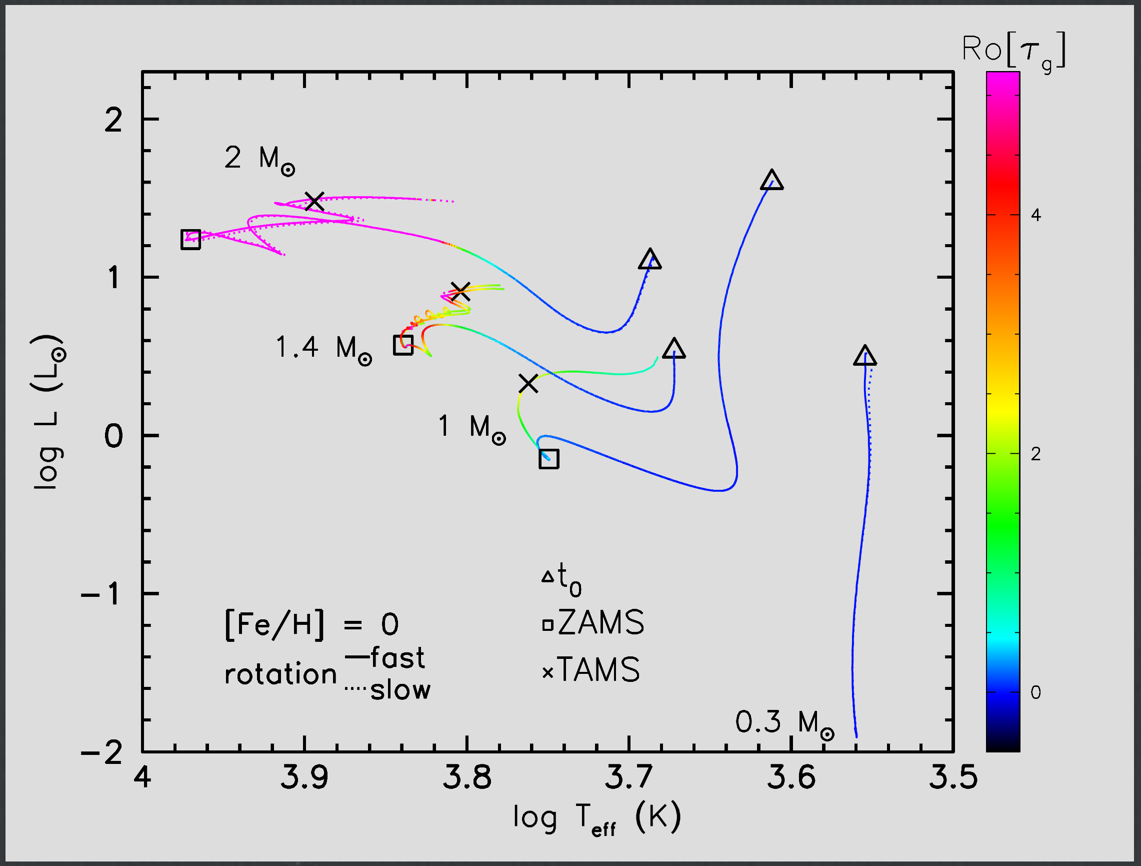
6) Stellar activity => depends on the mass

Stellar activity

$$\tau_g = \int_{R_b}^{R_*} \frac{dr}{Vc(r)}$$

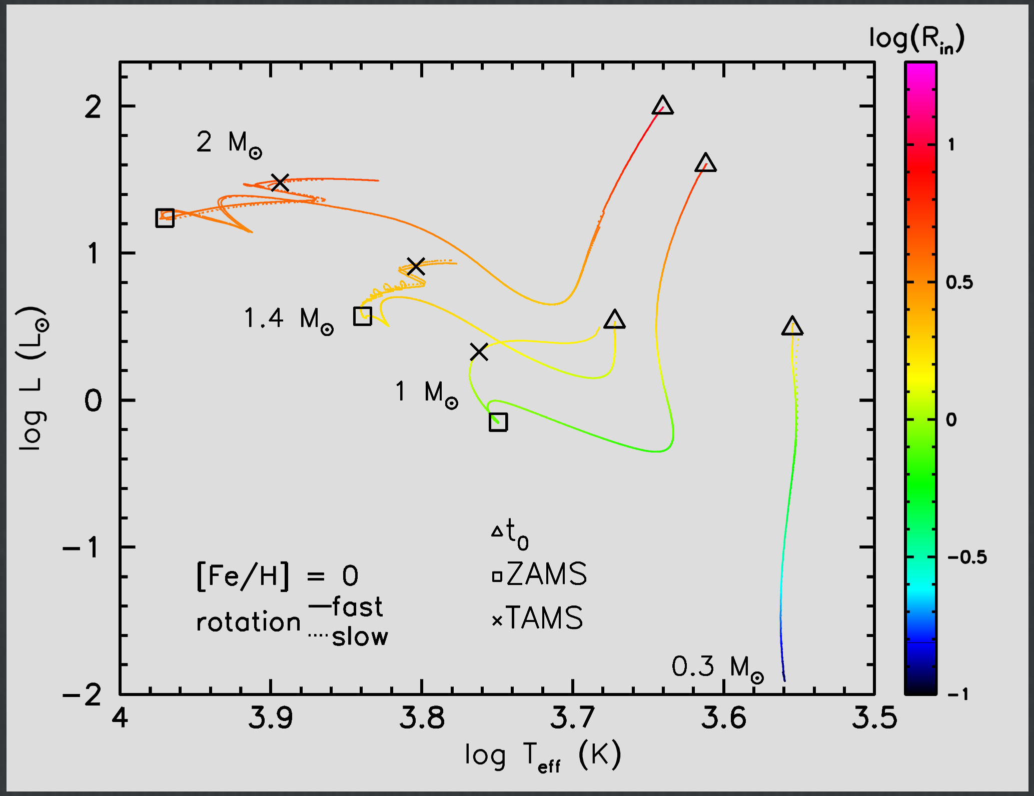
$$Ro_g = \frac{P_{rot}}{\tau_g}$$

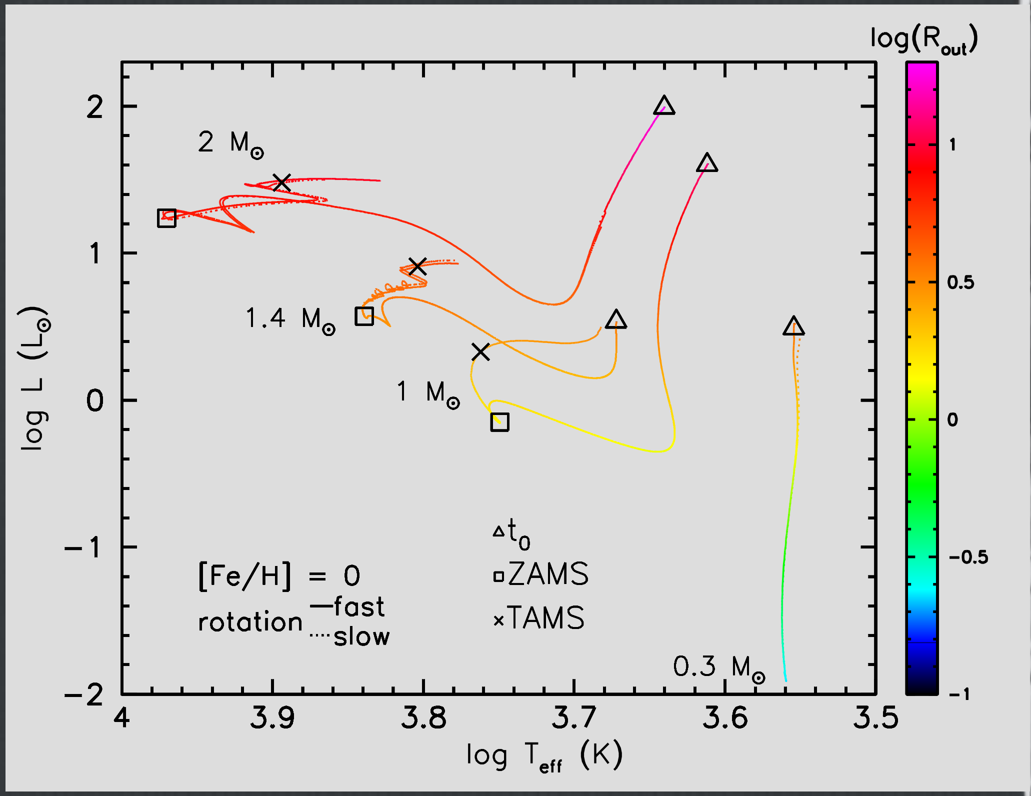
< 1 = stellar activity



High stellar activity during the early PMS when HZL closest for from the star

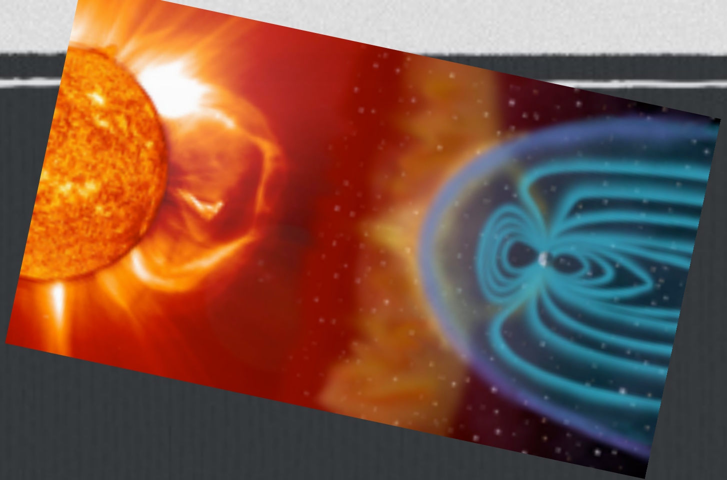
Magnetic protection?





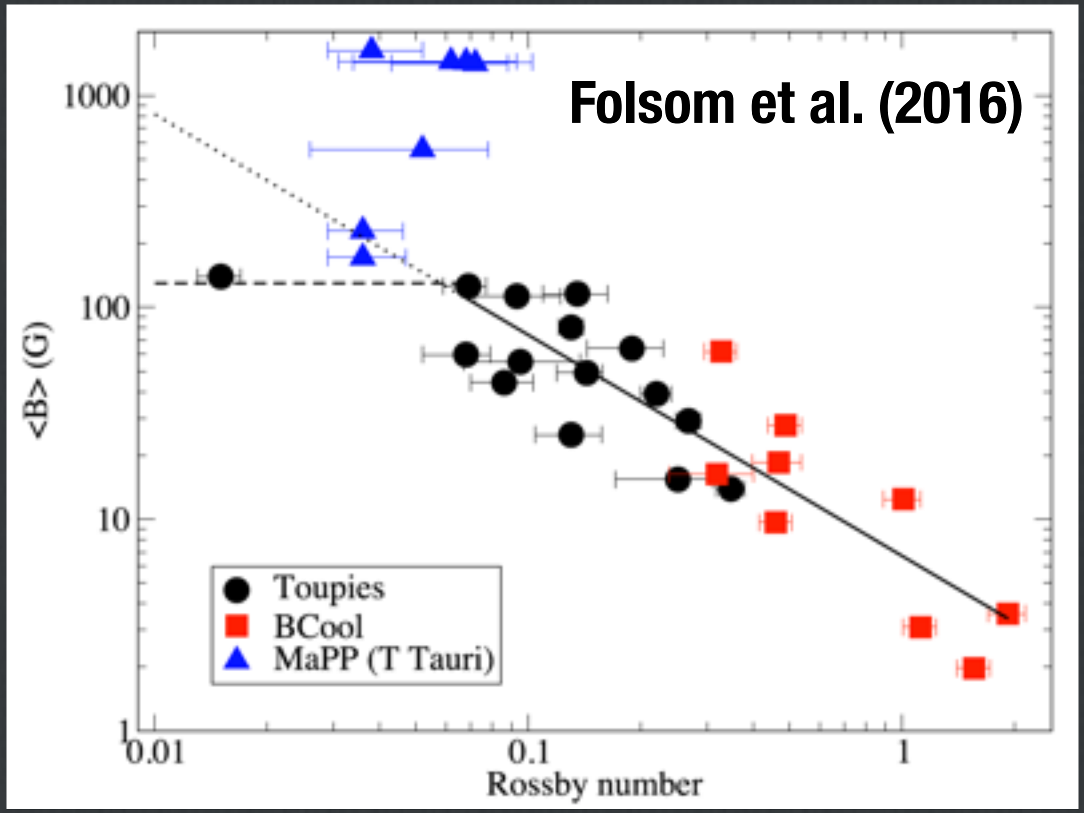
Gallet et al. (submitted)

Magnetic protection

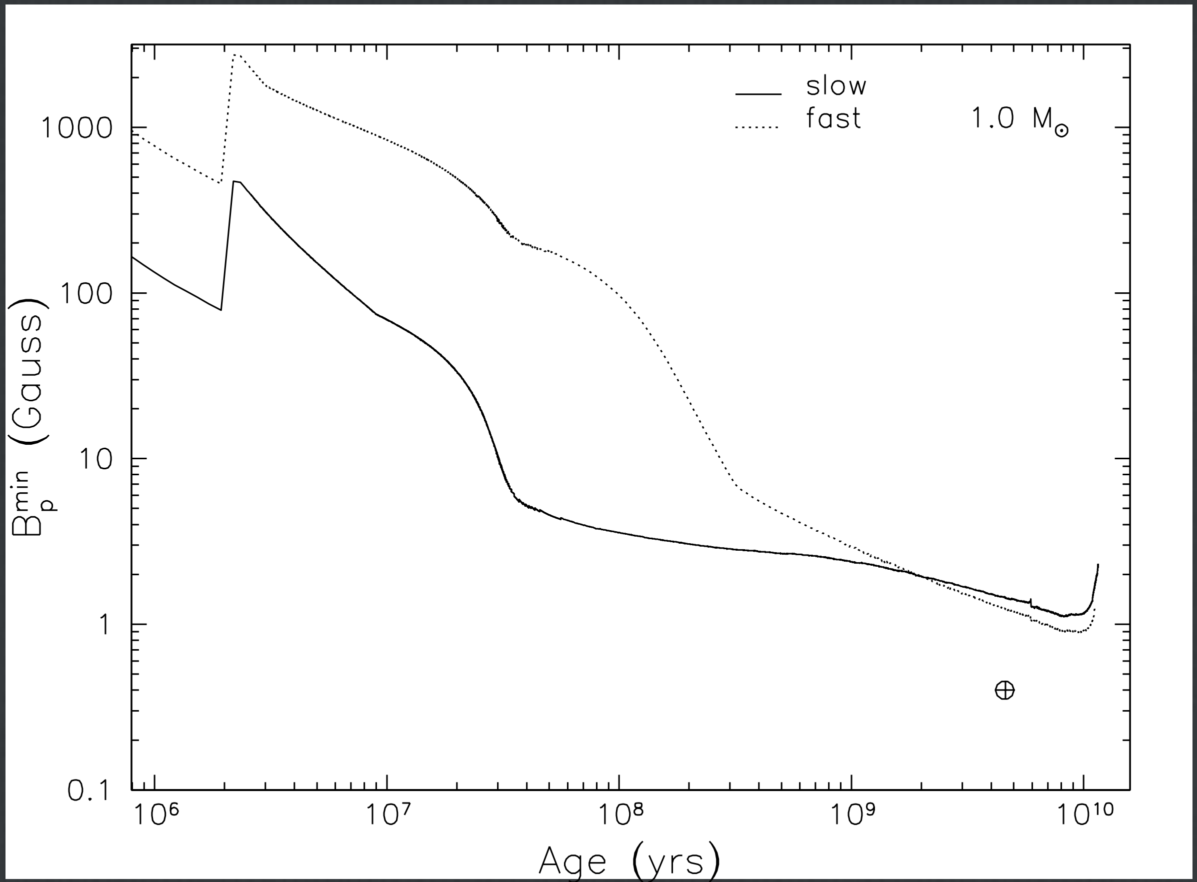


Minimum magnetic field required for magnetic protection

$$B_p^{\min} \propto B_* R_*^2$$ Vidotto et al. (2013)



$$B_* \approx Ro^{-1}$$



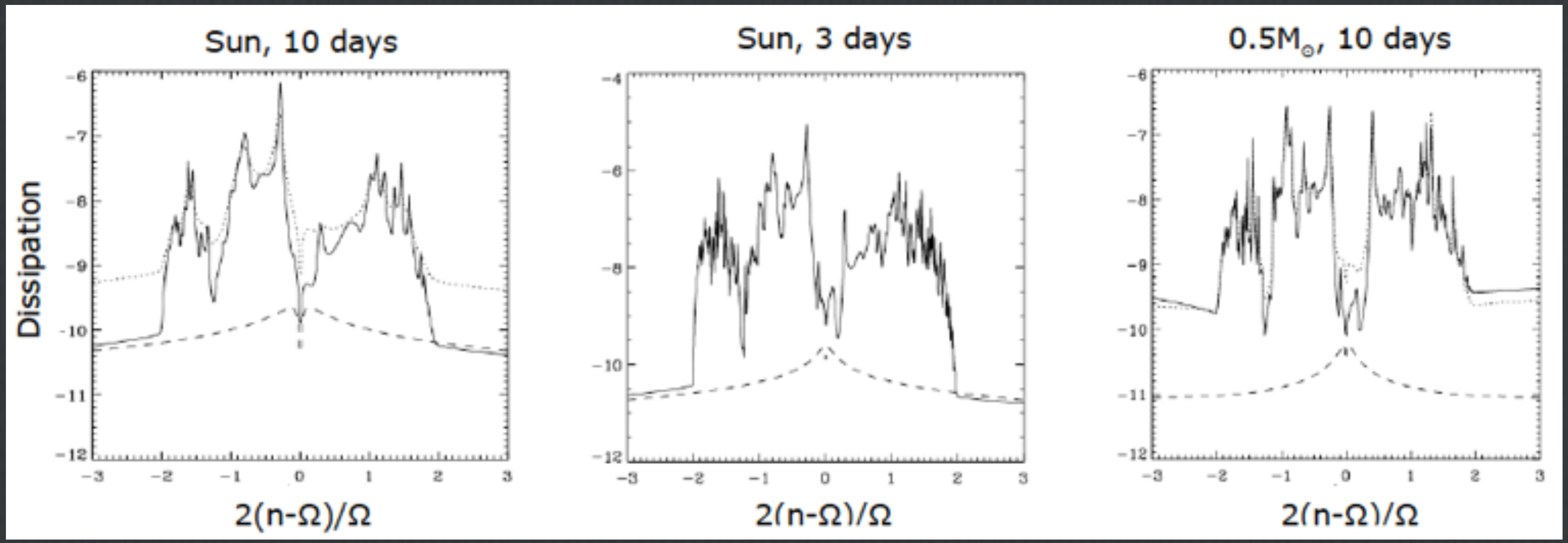
But planet fixed at 1 AU! => orbital evolution?? Tides??

Tidal dissipation

With the courtesy of Dr Bolmont and Dr Mathis

Tidal formalism currently too heavy to be implemented inside secular code!

Dissipation spectra



Excitation frequency

Order of magnitude of tidal dissipation along stellar evolution

=> **frequency-averaged dissipation** and equivalent tidal quality factor

The **tidal quality factor Q** is an estimation of the respond of a given object to tidal distortion

$$\frac{3}{2\overline{Q'}} = \frac{\overline{k_2}}{\overline{Q}} = \textbf{Dissipation} = \frac{100\pi}{63}\epsilon^2\left(\frac{\alpha^5}{1-\alpha^5}\right)(1-\gamma)^2$$

$$\times(1-\alpha)^4\left(1+2\alpha+3\alpha^2+\frac{3}{2}\alpha^3\right)^2\left[1+\left(\frac{1-\gamma}{\gamma}\right)\alpha^3\right]\left[1+\frac{3}{2}\gamma+\frac{5}{2\gamma}\left(1+\frac{1}{2}\gamma-\frac{3}{2}\gamma^2\right)\alpha^3-\frac{9}{4}(1-\gamma)\alpha^5\right]^{-2}$$

with

$$\alpha = \frac{R_c}{R_s},\quad \beta = \frac{M_c}{M_s}\quad \text{and}\quad \gamma = \frac{\rho_e}{\rho_c} = \frac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1. \qquad \text{structure}$$

$$\epsilon^2 \equiv \left(\Omega/\sqrt{GM_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1 \qquad \text{rotation}$$

Ogilvie 2013; Mathis 2015

Grid of tidal quality factor

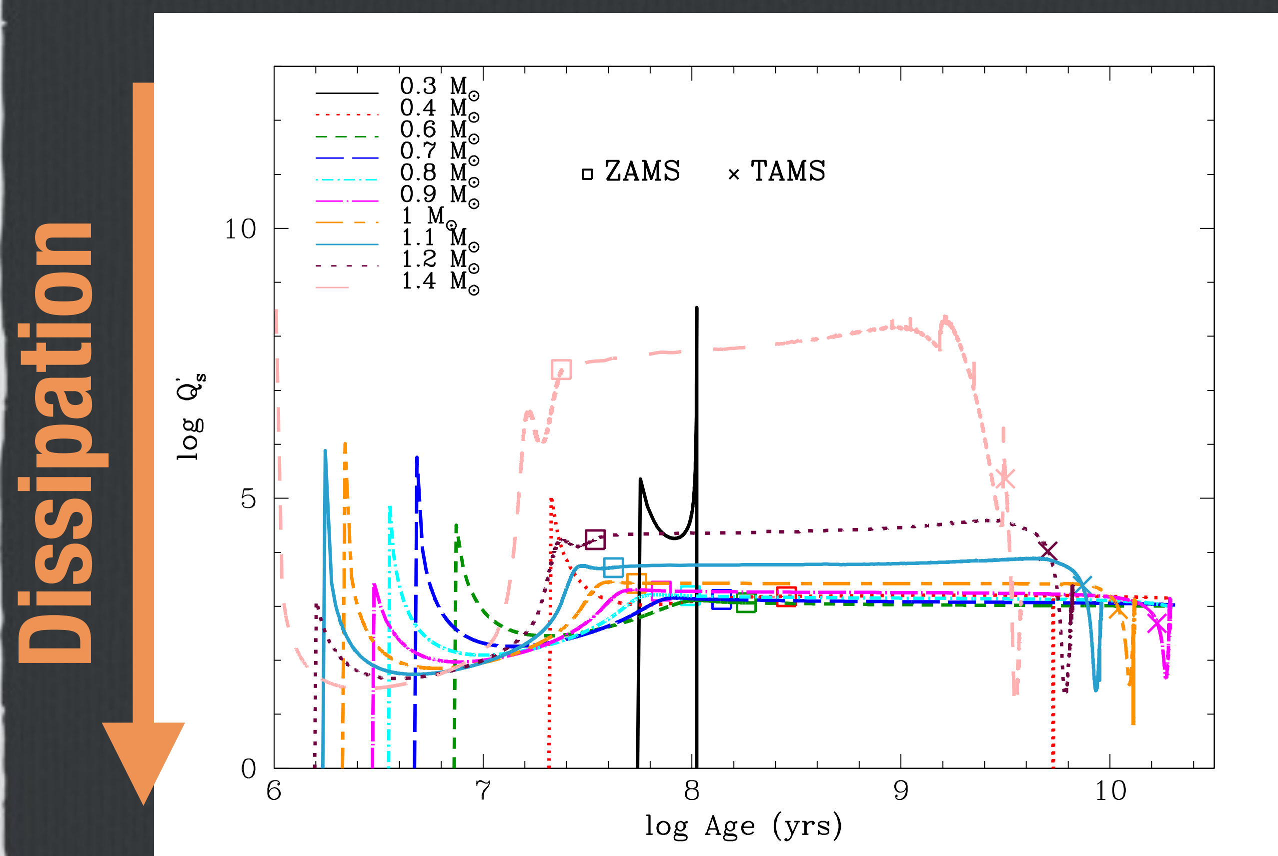
Tidal quality factor Q' in the convective envelope of rotating low-mass stars: from their formation to advanced stage of evolution

F. Gallet[1], S. Mathis[2], C. Charbonnel[1,3], and L. Amard[1,4]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] Laboratoire AIM Paris-Saclay, CEA/Irfu Université Paris-Diderot CNRS/INSU, 91191 Gif-sur-Yvette, France
[3] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E.Belin, F-31400 Toulouse, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received –; accepted –

- Variation over <u>several order of magnitude</u>:
  - amplitude on MS increases with mass (thickness of the CE)
  - importance of coupling structural and rotational evolution



$$\frac{3}{2\overline{Q'}} = \frac{k_2}{\overline{Q}} = \int_{-\infty}^{+\infty} \mathrm{Im}\left[k_2^2(\omega)\right]\frac{d\omega}{\omega} = \left\langle \mathrm{Im}\left[k_2^2(\omega)\right]\right\rangle_\omega = \frac{100\pi}{63}\epsilon^2\left(\frac{\alpha^5}{1-\alpha^5}\right)(1-\gamma)^2$$
$$\times(1-\alpha)^4\left(1+2\alpha+3\alpha^2+\frac{3}{2}\alpha^3\right)^2\left[1+\left(\frac{1-\gamma}{\gamma}\right)\alpha^3\right]\left[1+\frac{3}{2}\gamma+\frac{5}{2\gamma}\left(1+\frac{1}{2}\gamma-\frac{3}{2}\gamma^2\right)\alpha^3-\frac{9}{4}(1-\gamma)\alpha^5\right]^{-2}$$

with

$$\alpha = \frac{R_c}{R_s},\quad \beta = \frac{M_c}{M_s} \quad\text{and}\quad \gamma = \frac{\rho_e}{\rho_c} = \frac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1. \qquad \text{structure}$$

$$\epsilon^2 \equiv \left(\Omega/\sqrt{\mathcal{G}M_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1 \qquad \text{rotation}$$

Mathis (2015) & Gallet, Mathis, Charbonnel, Amard (in prep.)

Grid of tidal quality factor

☐ Variation over several order of magnitude:

- amplitude on MS increases with mass (thickness of the CE)
- importance of coupling structural and rotational evolution

...script no. aanda

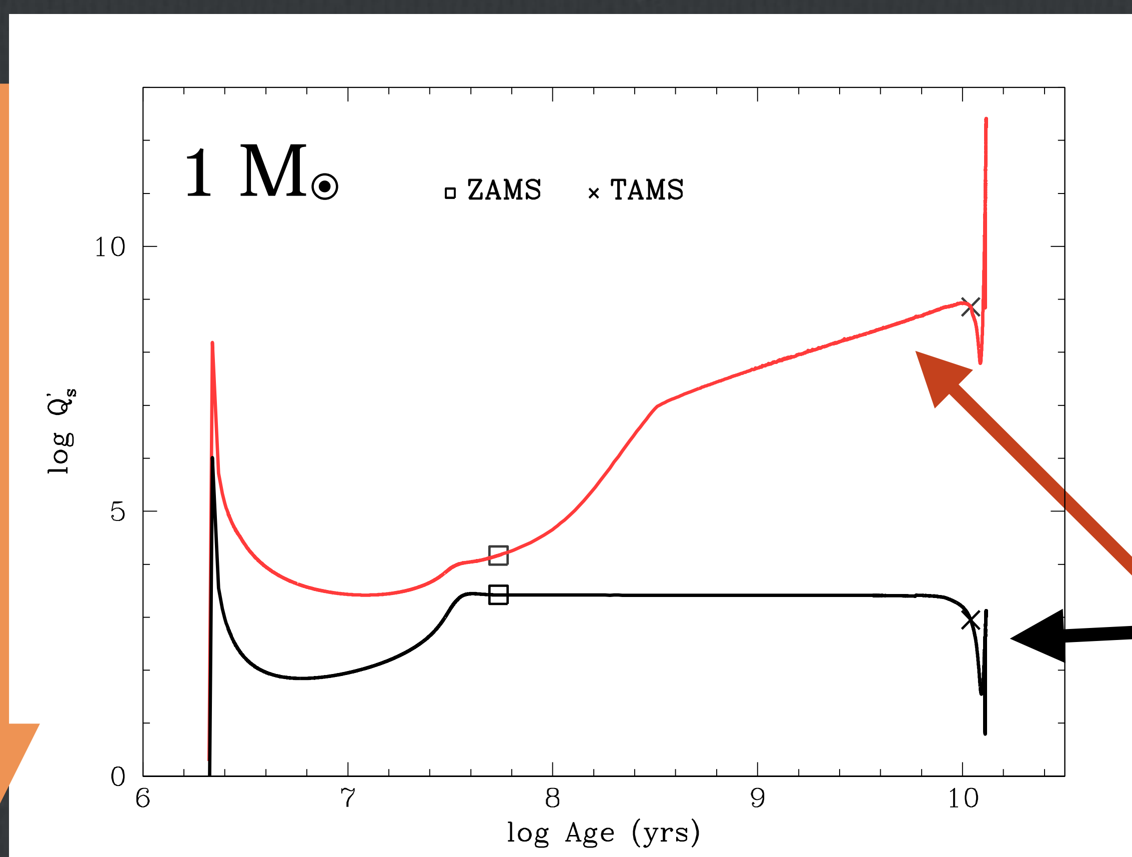
Tidal quality factor Q' in the convective envelope of rotating low-mass stars: from their formation to advanced stage of evolution

F. Gallet[1], S. Mathis[2], C. Charbonnel[1,3], and L. Amard[1,4]

[1] Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
[2] Laboratoire AIM Paris-Saclay, CEA/Irfu Université Paris-Diderot CNRS/INSU, 91191 Gif-sur-Yvette, France
[3] IRAP, UMR 5277, CNRS and Université de Toulouse, 14, av. E.Belin, F-31400 Toulouse, France
[4] LUPM, UMR 5299, Université Montpellier/ CNRS, Montpellier, France

Received –; accepted –

Dissipation



$$\frac{3}{2\overline{Q'}} = \frac{\overline{k_2}}{\overline{Q}} = \int_{-\infty}^{+\infty} \mathrm{Im}\left[k_2^2(\omega)\right] \frac{d\omega}{\omega} = \left\langle \mathrm{Im}\left[k_2^2(\omega)\right]\right\rangle_\omega = \frac{100\pi}{63}\epsilon^2\left(\frac{\alpha^5}{1-\alpha^5}\right)(1-\gamma)^2$$

$$\times(1-\alpha)^4\left(1+2\alpha+3\alpha^2+\frac{3}{2}\alpha^3\right)^2\left[1+\left(\frac{1-\gamma}{\gamma}\right)\alpha^3\right]\left[1+\frac{3}{2}\gamma+\frac{5}{2\gamma}\left(1+\frac{1}{2}\gamma-\frac{3}{2}\gamma^2\right)\alpha^3-\frac{9}{4}(1-\gamma)\alpha^5\right]^{-2}$$

with

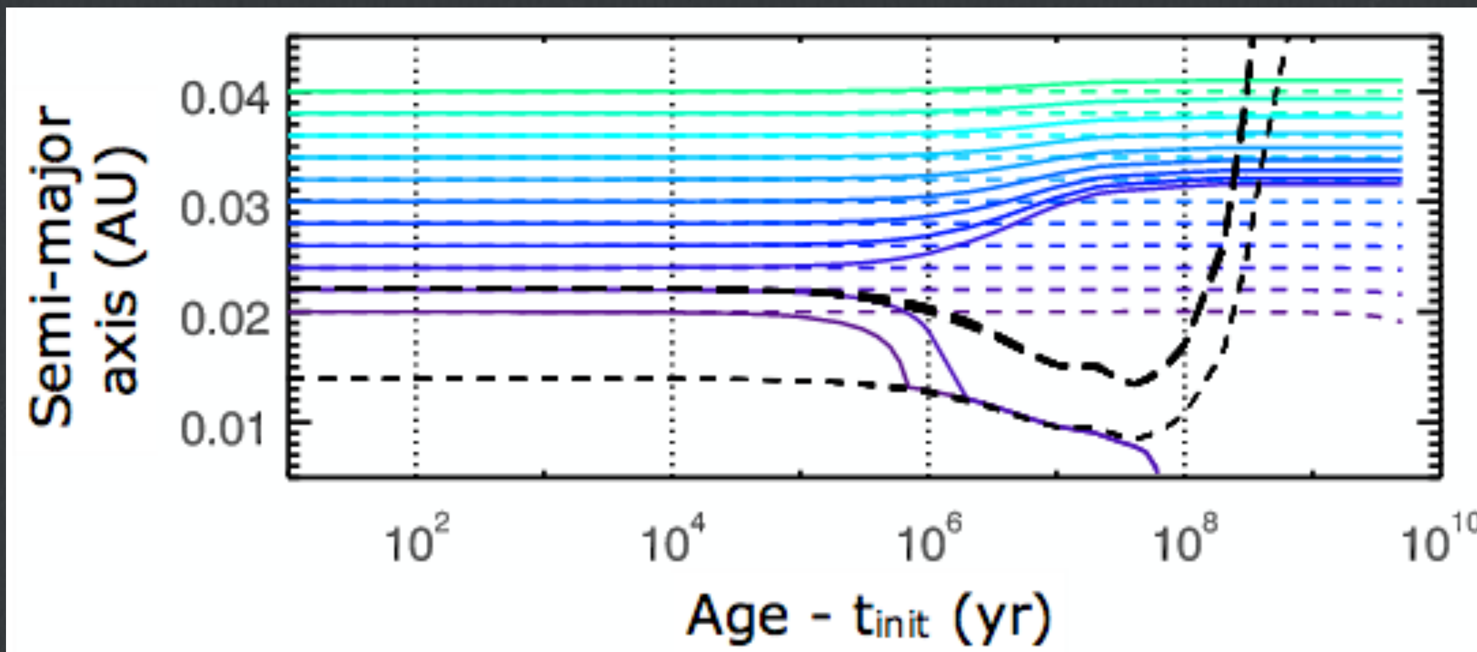
$$\begin{cases} \alpha = \frac{R_c}{R_s}, \quad \beta = \frac{M_c}{M_s} \quad \text{and} \quad \gamma = \frac{\rho_e}{\rho_c} = \frac{\alpha^3(1-\beta)}{\beta(1-\alpha^3)} < 1. & \text{structure} \\ \epsilon^2 \equiv \left(\Omega/\sqrt{GM_s/R_s^3}\right)^2 = (\Omega/\Omega_c)^2 \ll 1 & \text{rotation} \end{cases}$$

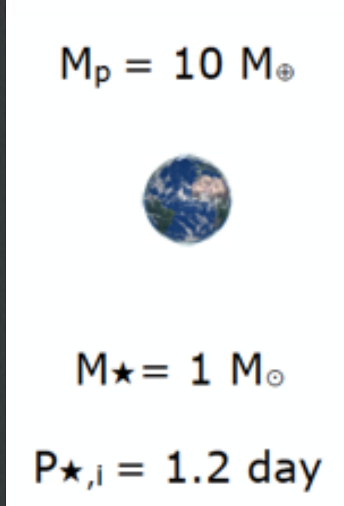
Structural evolution

Structure + rotational evolution

Mathis (2015) & Gallet, Mathis, Charbonnel, Amard (in prep.)

Tidal interaction modeling





with Q’ = cst

Standard tides model

Model Bolmont & Mathis with averaged dissipation

⚠ **non-rotating stellar model**

Bolmont & Mathis (2016)

Ad-hoc stellar rotation!

Tides will both affect rotation and internal structure
=> need to include a real retroaction of the rotation on the internal structure due to tides!

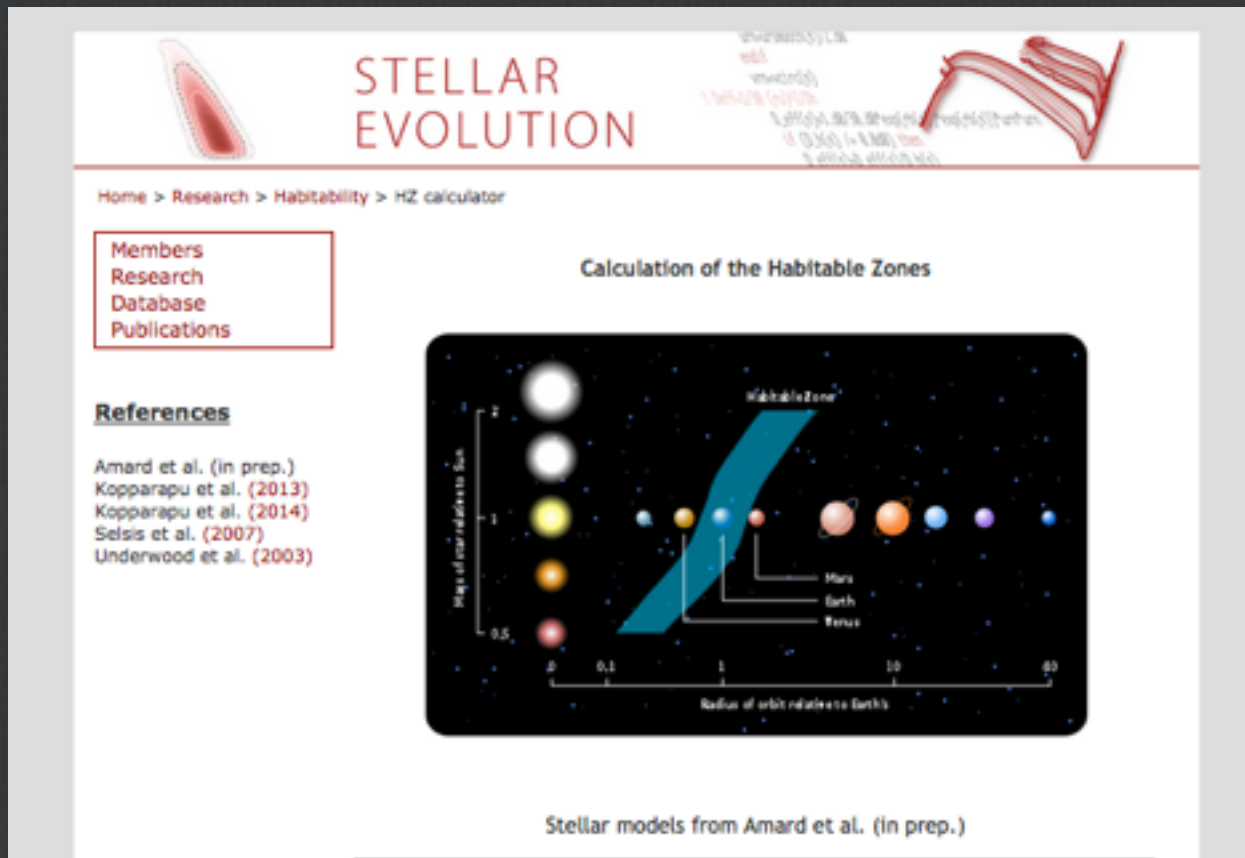
Conclusion/Perspective

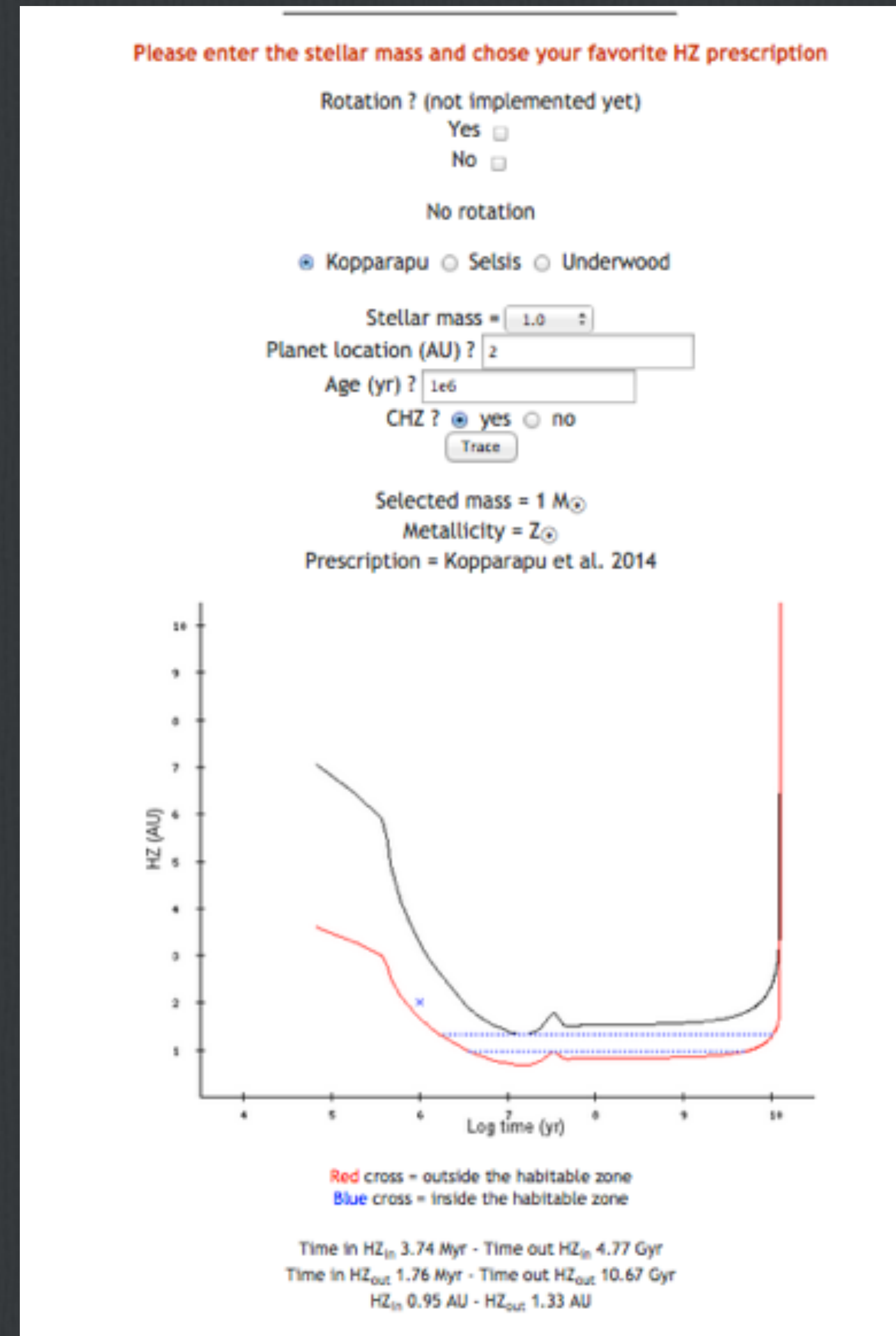
- Couple STAREVOL to secular orbital evolution code to get the impact of tides on rotation and structure as well as planetary migration => collaboration with E. Bolmont and S. Mathis
- Provide the community with stellar grids for HZ and tidal dissipation

---

- Mass and metallicity control HZ evolution
  - => require precise estimation of M_* and Fe/H
- Stellar models should be used to get HZ evolution
  - estimation of CHZ / duration of planet inside HZ?
  - tidal evolution?

obswww.unige.ch/Recherche/evol/starevol/HZcalculator.php

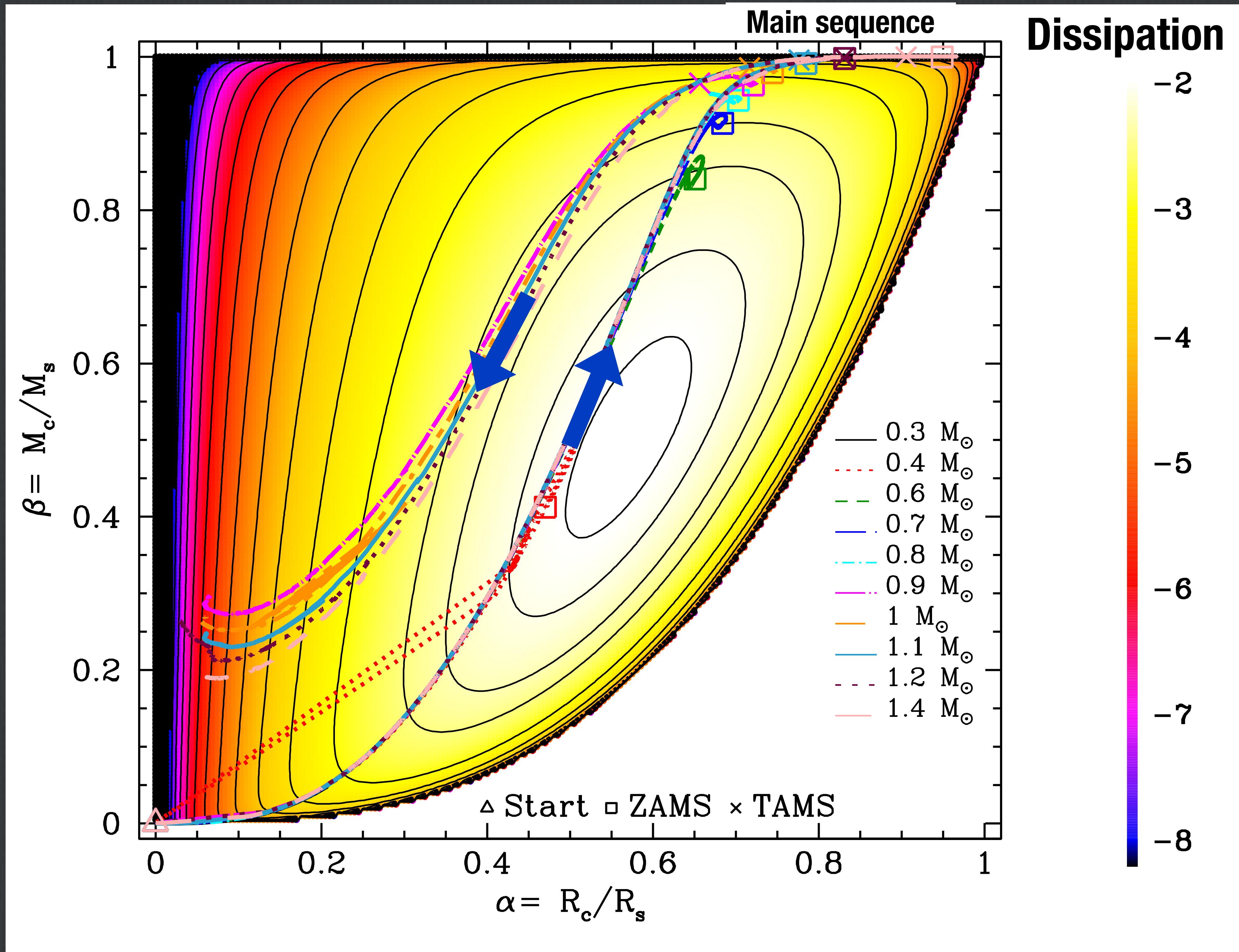




Beta HZ online tool available

we will provide stellar grids
and other
visualisation tools

Tidal H-R diagram



Mathis (2015) & Gallet, Mathis, Charbonnel, & Amard (2016)