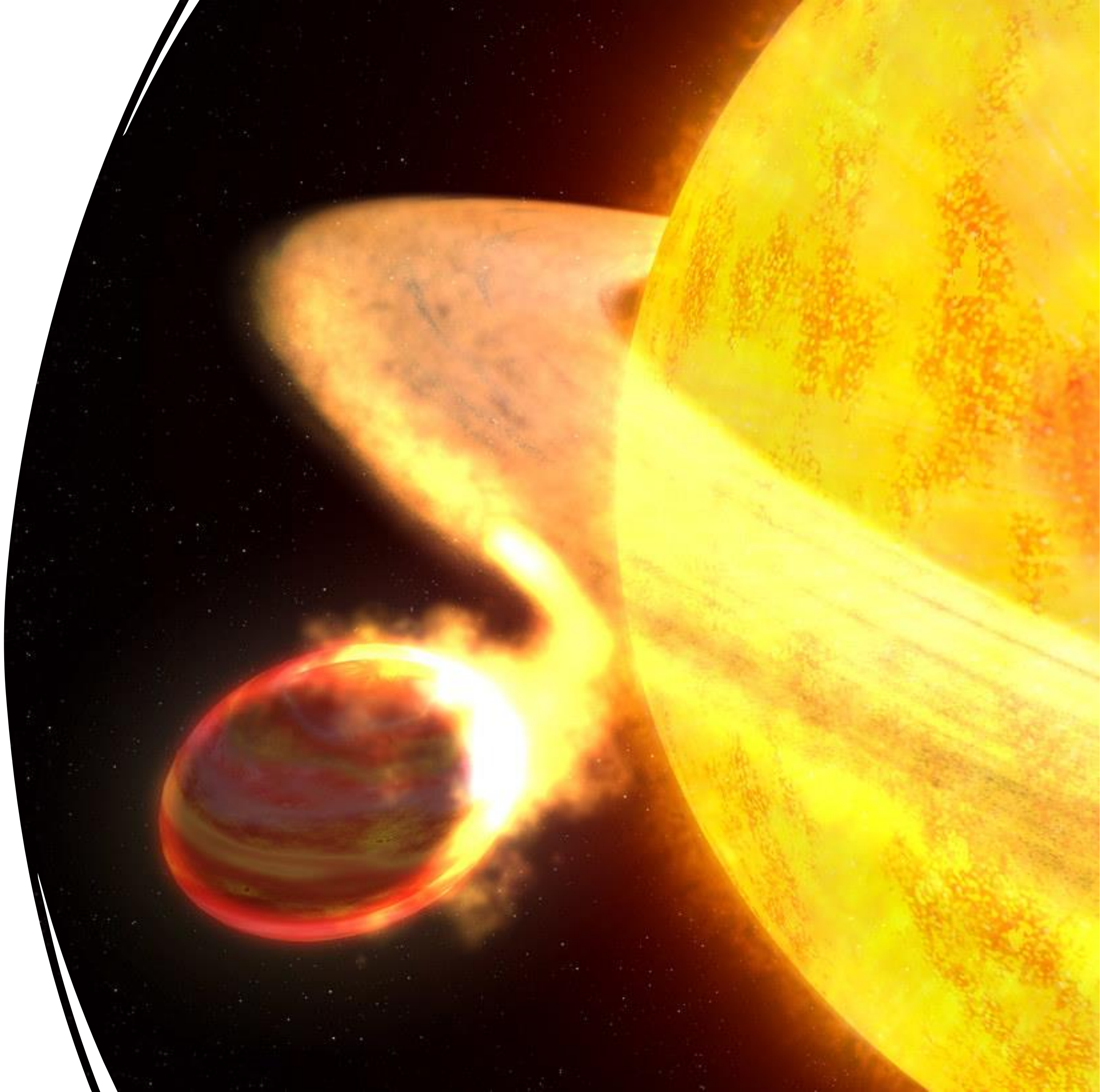
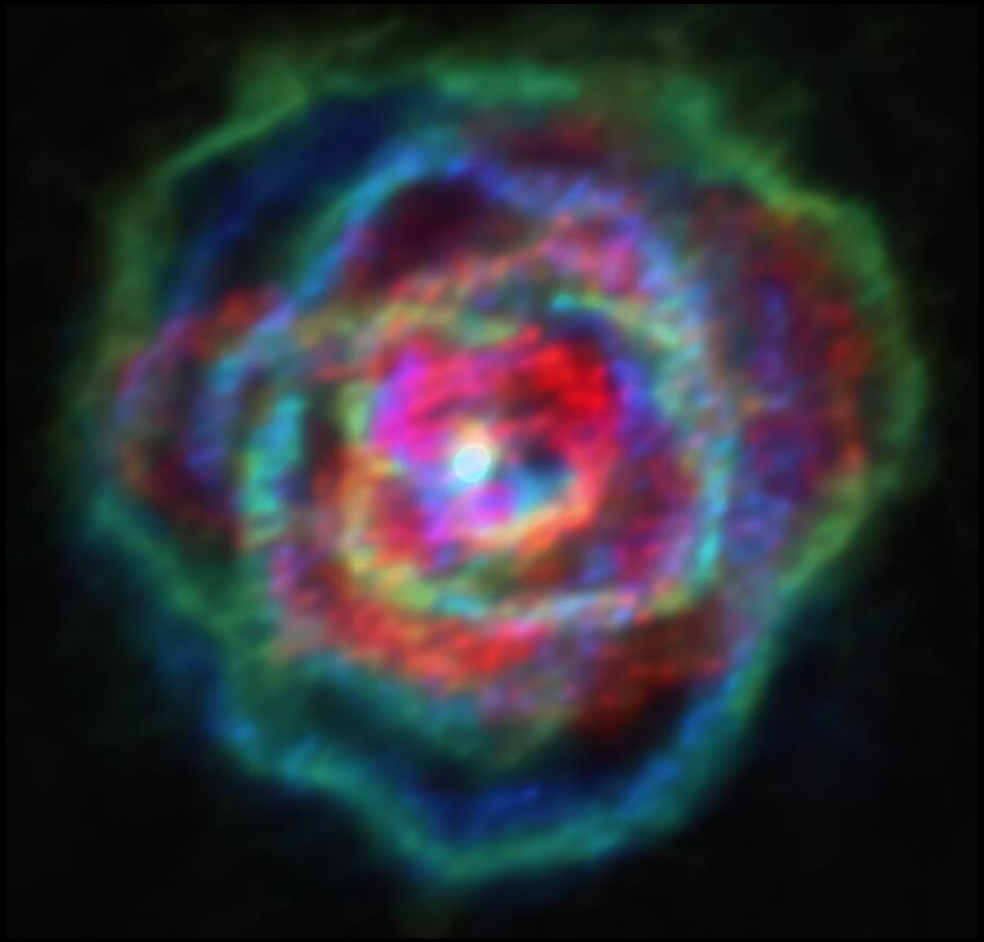
Tidal Dissipation in Cool Evolved Stars

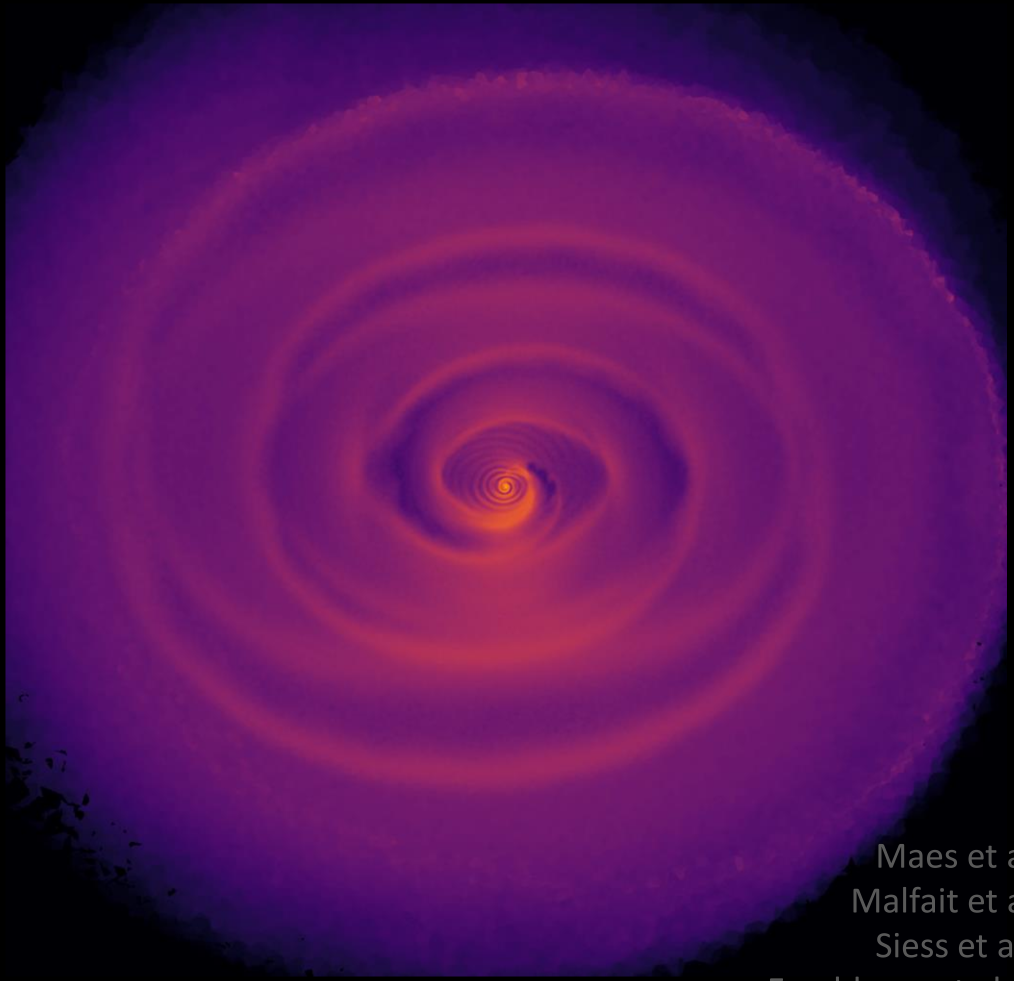
Mats Esseldeurs
Stéphane Mathis
Leen Decin



Observations and Simulations

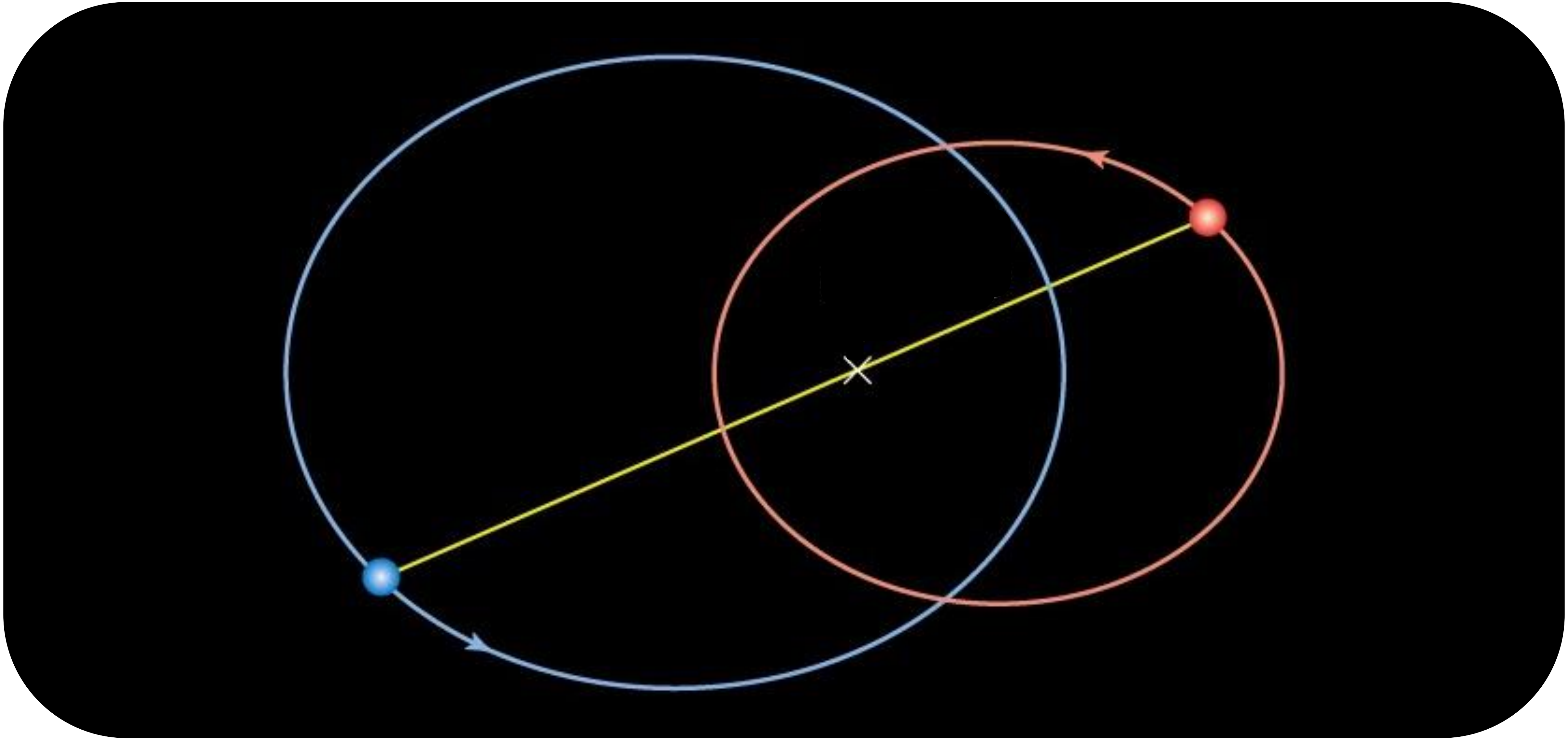


Decin et al. 2020

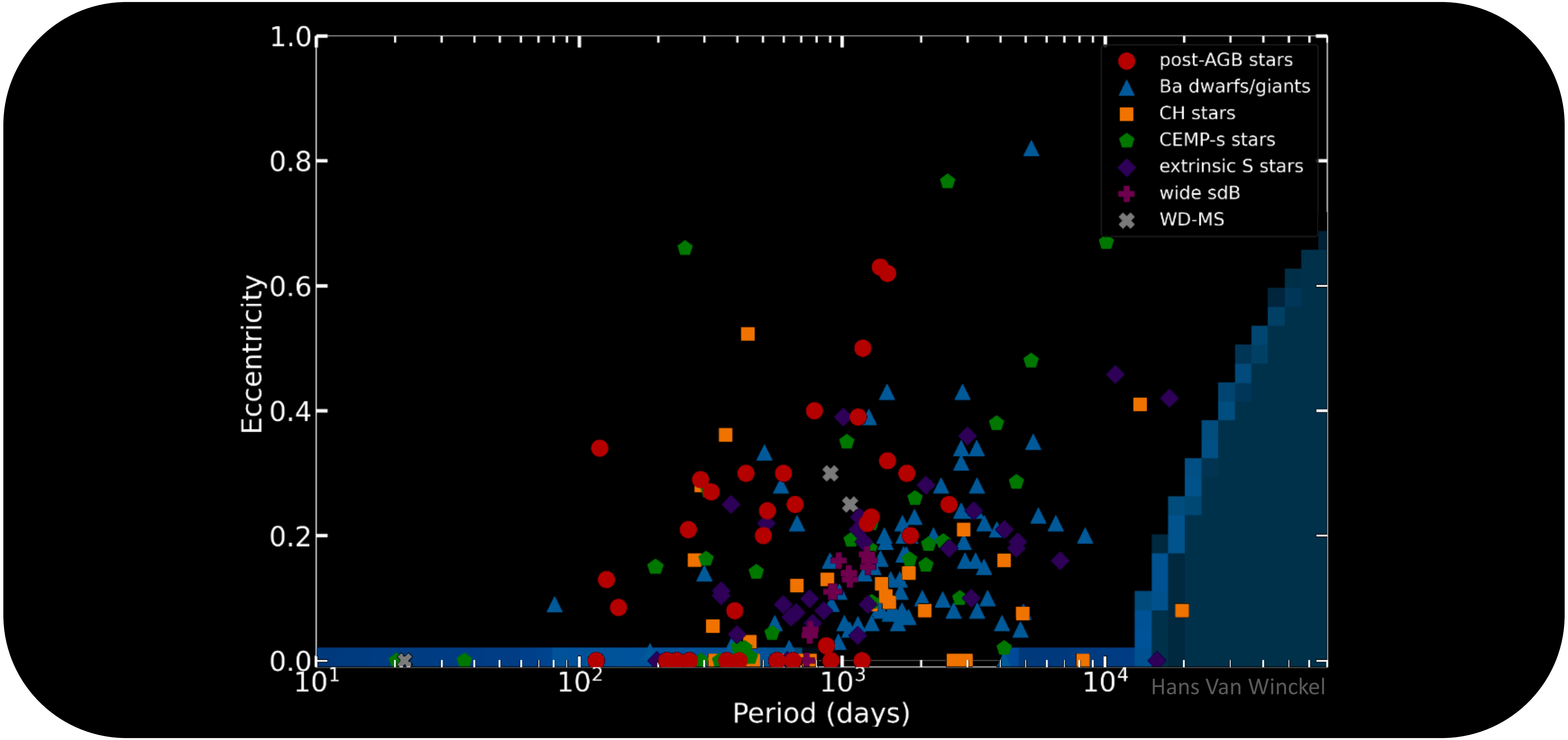


Maes et al. 2021
Malfait et al. 2021
Siess et al. 2022
Esseldeurs et al. 2023
Malfait et al. 2024a,b (in prep)

Orbital properties of binary systems

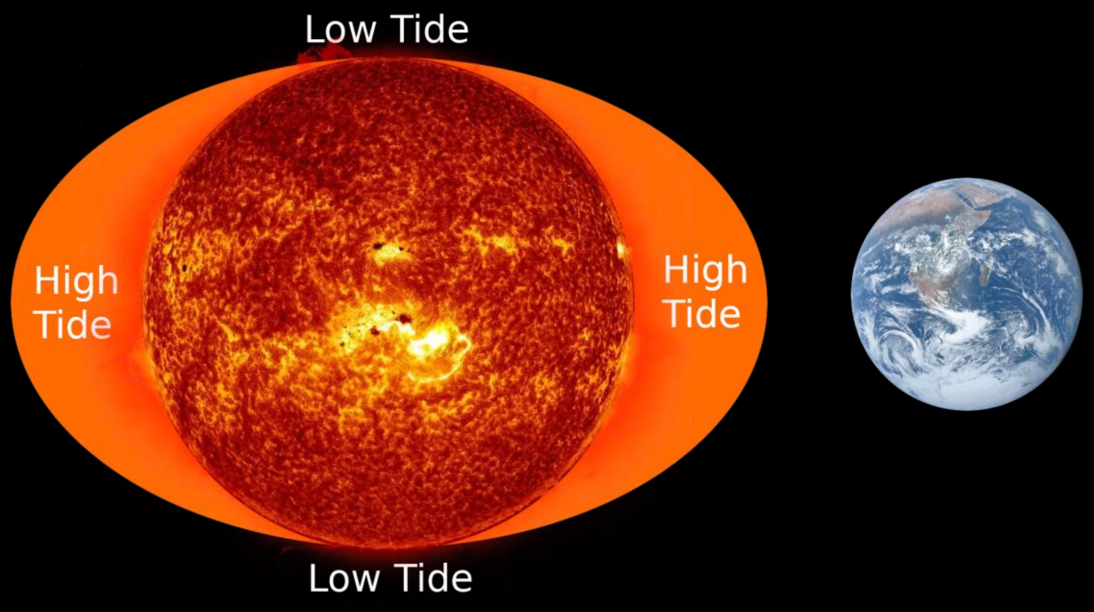


Statistics of orbital properties



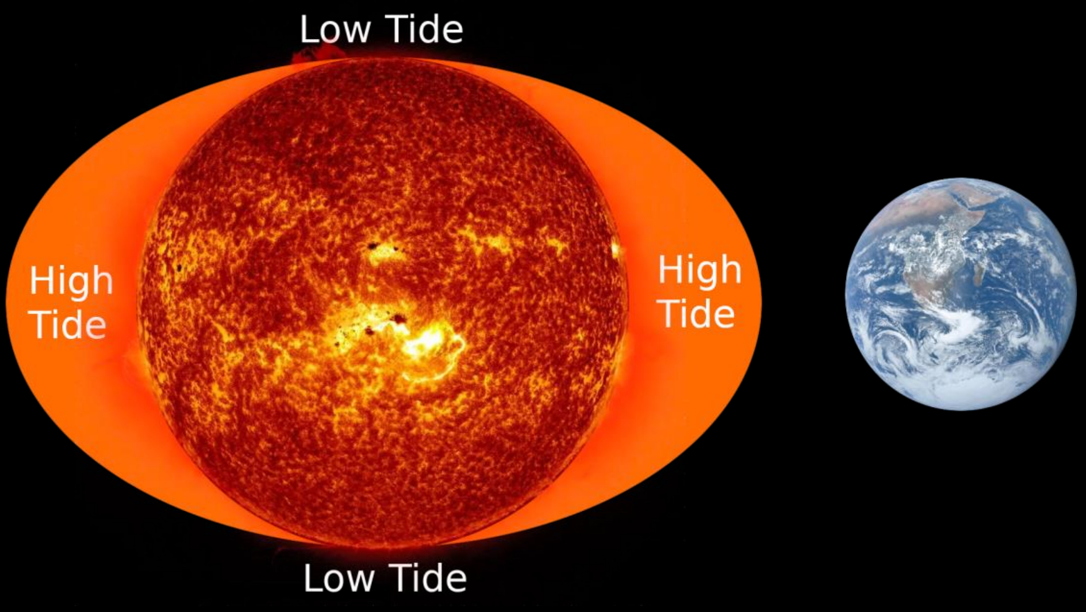
Tidal Dissipation mechanisms

Equilibrium Tides

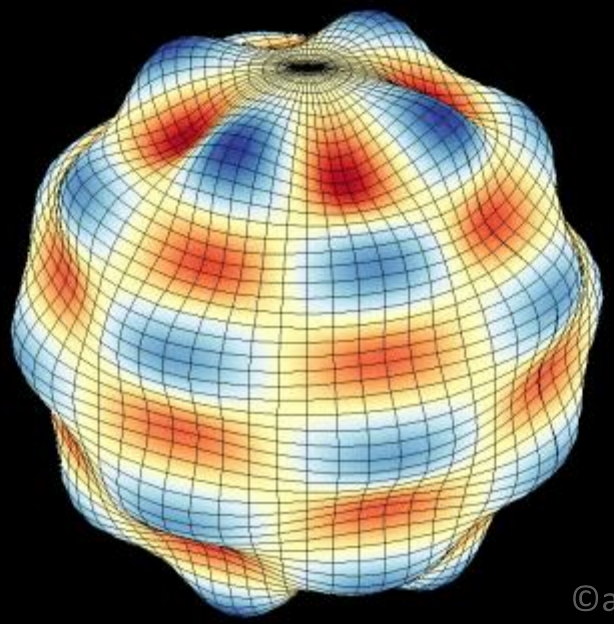


Tidal Dissipation mechanisms

Equilibrium Tides



Dynamical Tides



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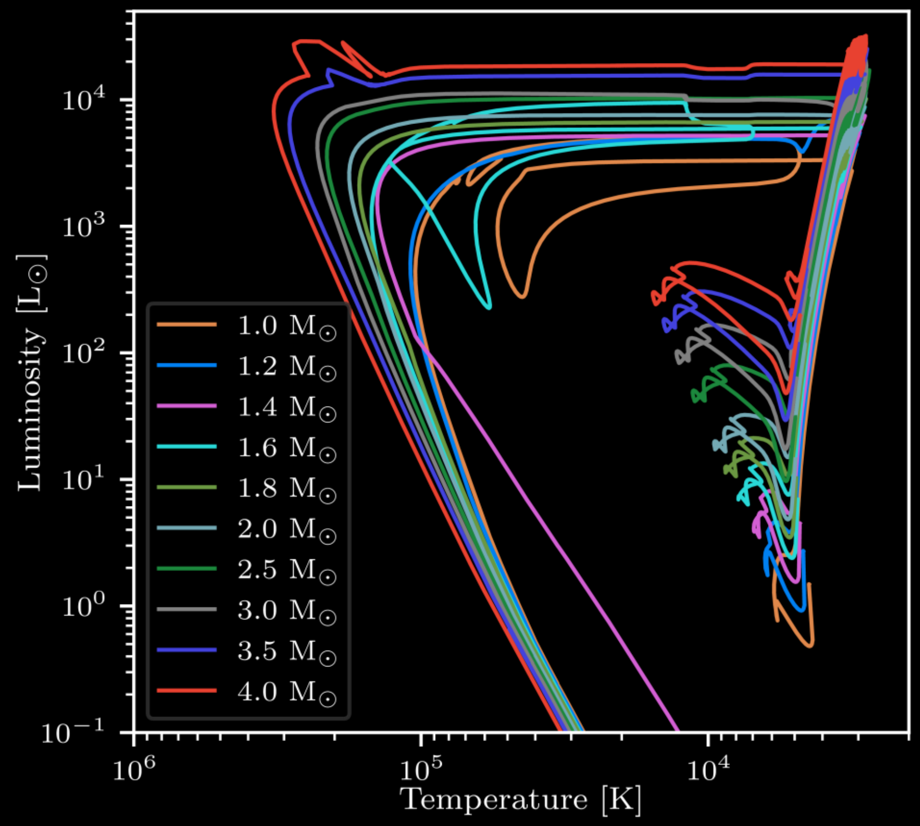
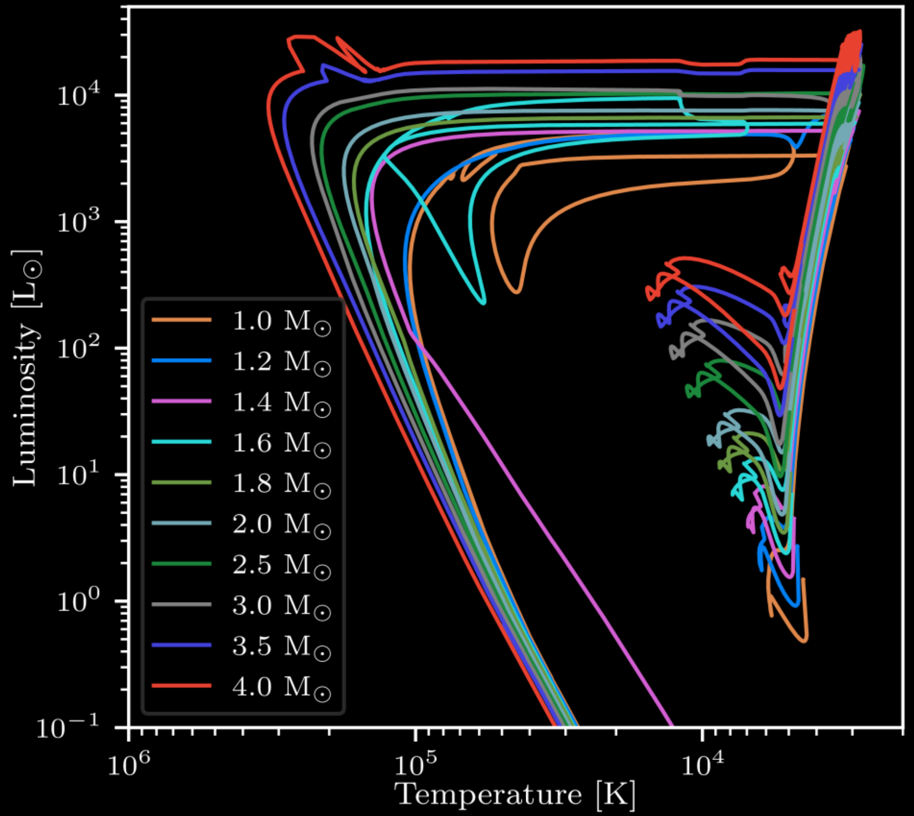
Stellar Structure and Evolution

Stellar evolution

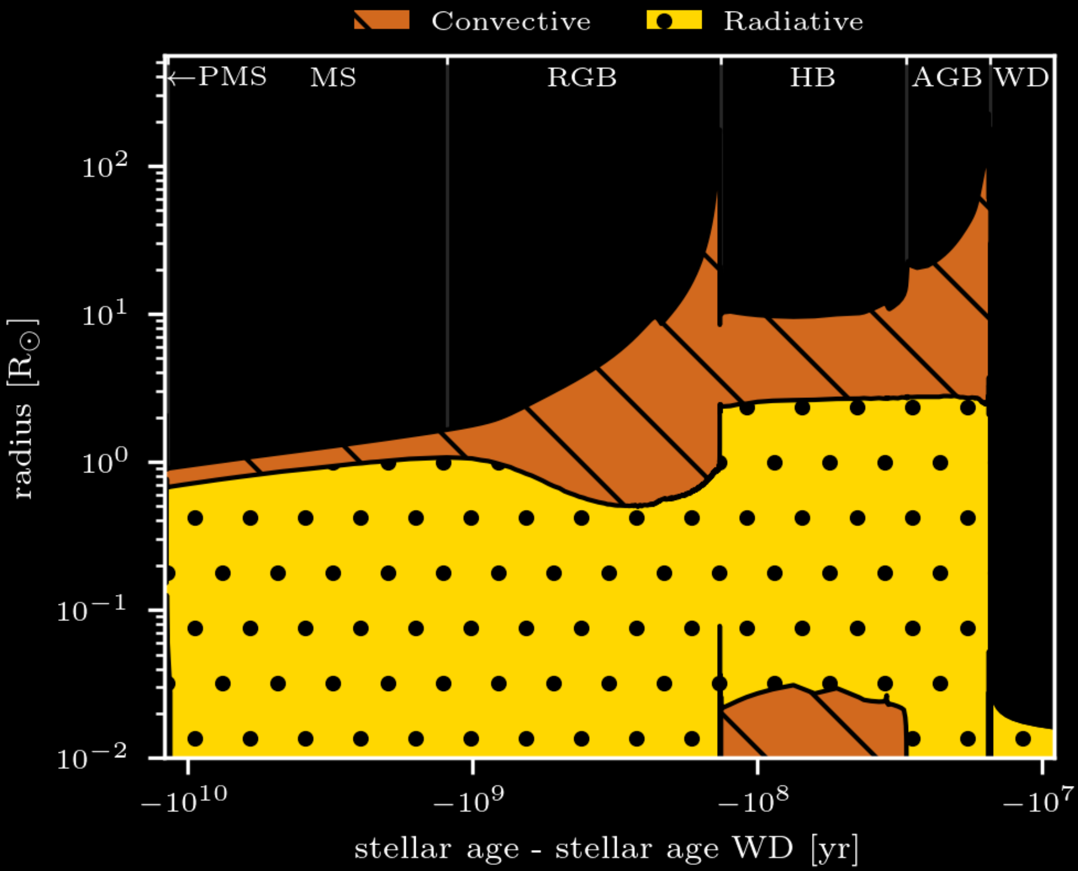


Stellar Structure and Evolution

Stellar evolution



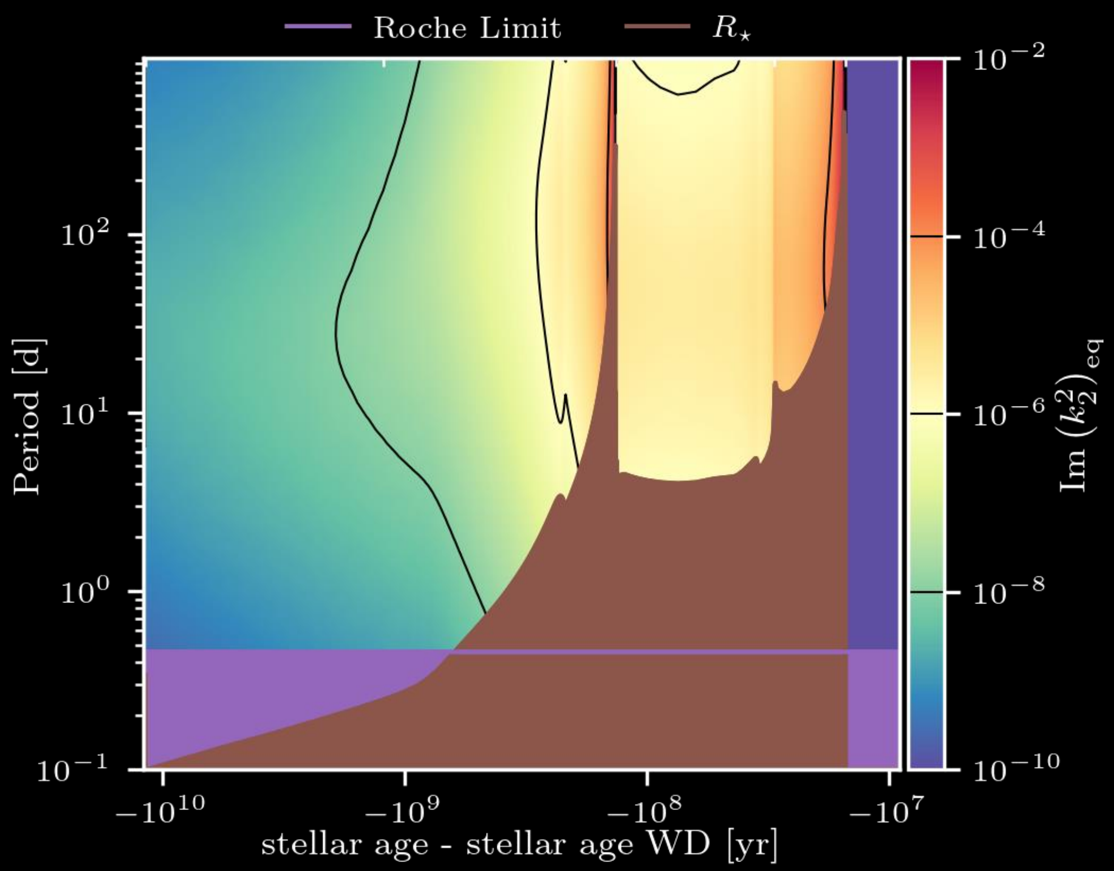
Internal structure



1 M⊙ Model

Tidal Dissipation in Cool Evolved Stars

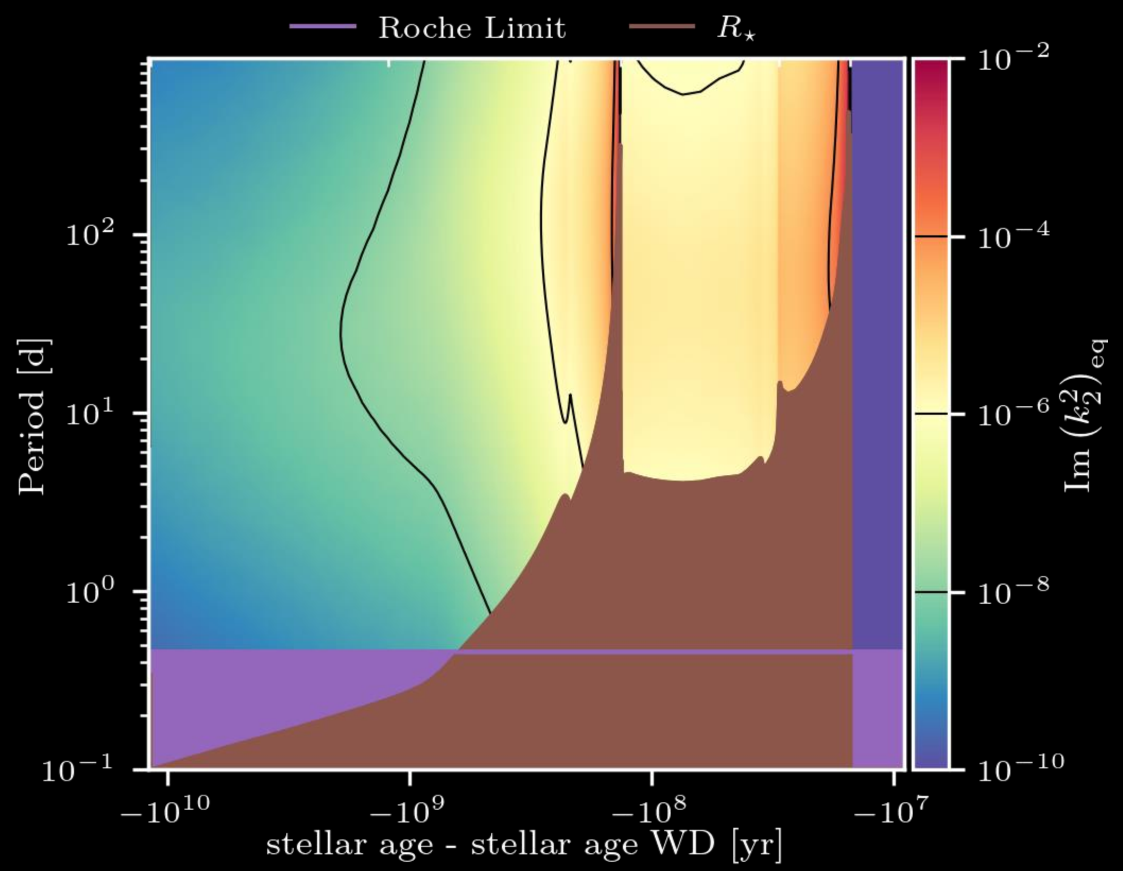
Equilibrium Tides



1 $M_\odot$ Model

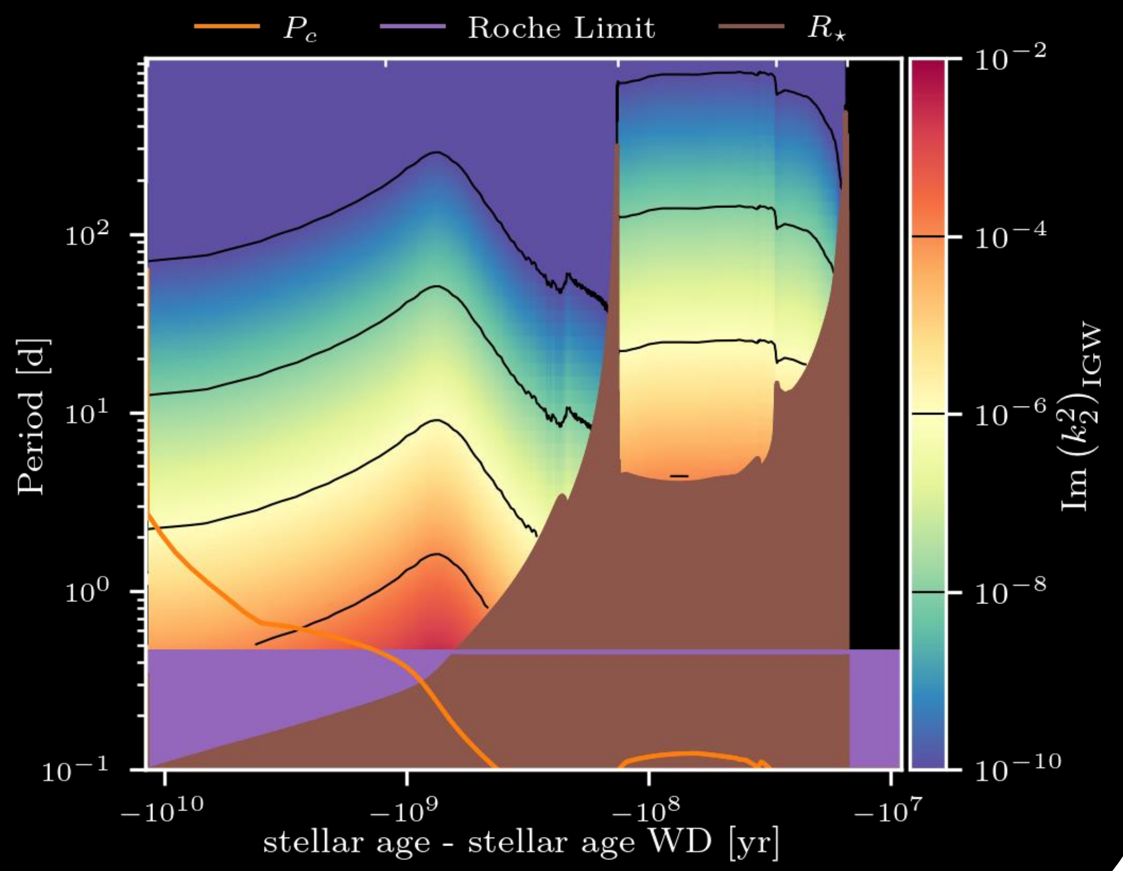
Tidal Dissipation in Cool Evolved Stars

Equilibrium Tides



1 $M_\odot$ Model

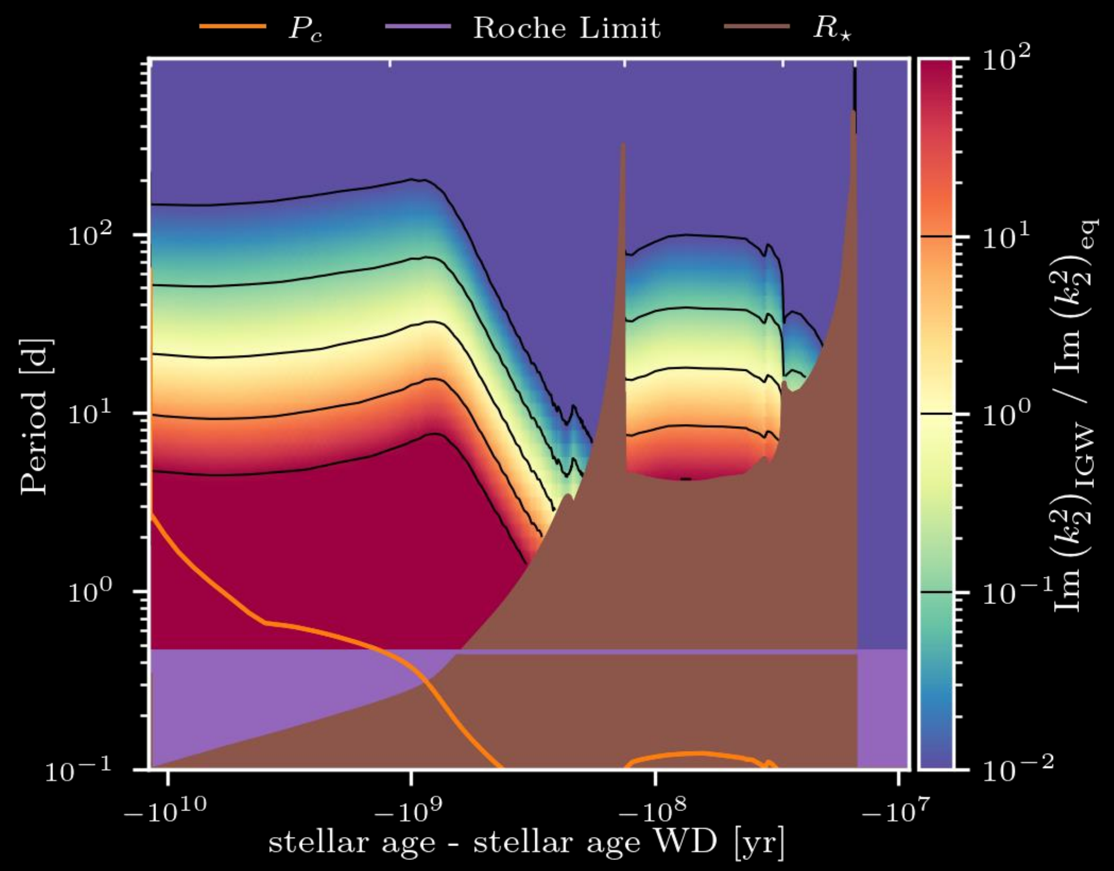
Dynamical Tides



1 $M_\odot$ Model

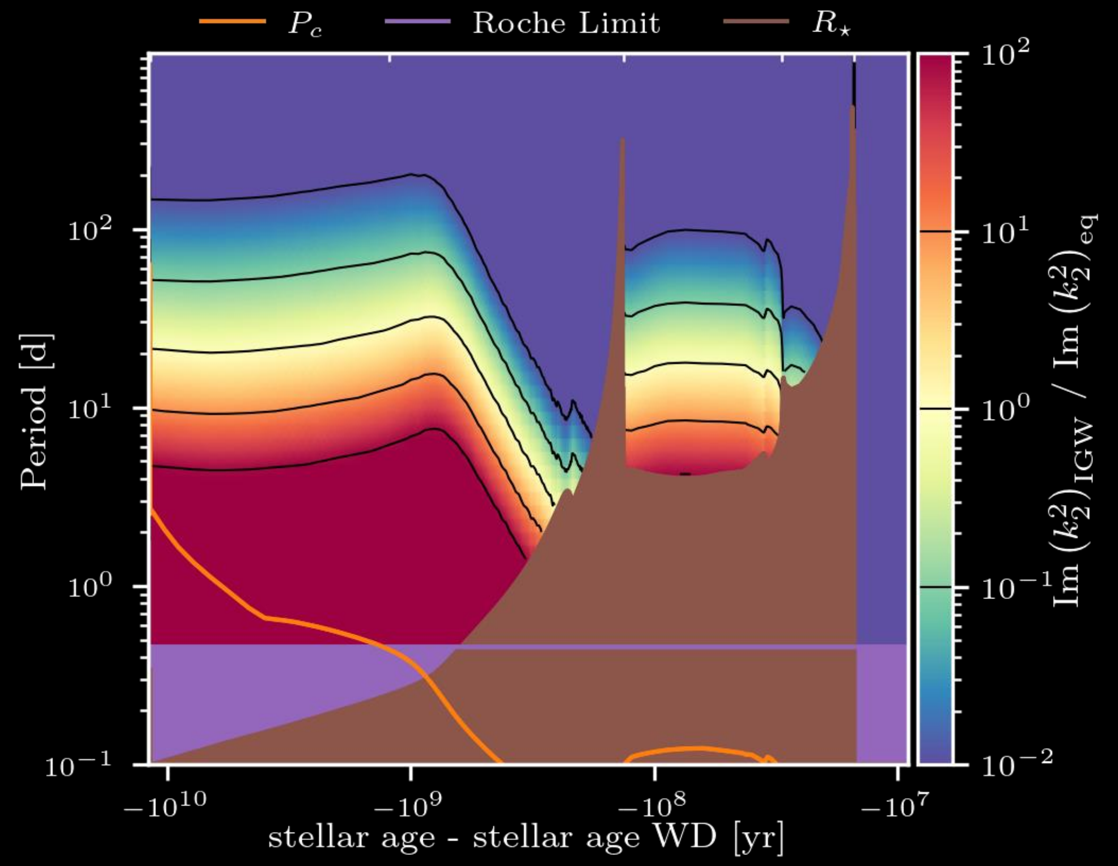
Relative strengths of tidal dissipation

1 $M_\odot$ Model

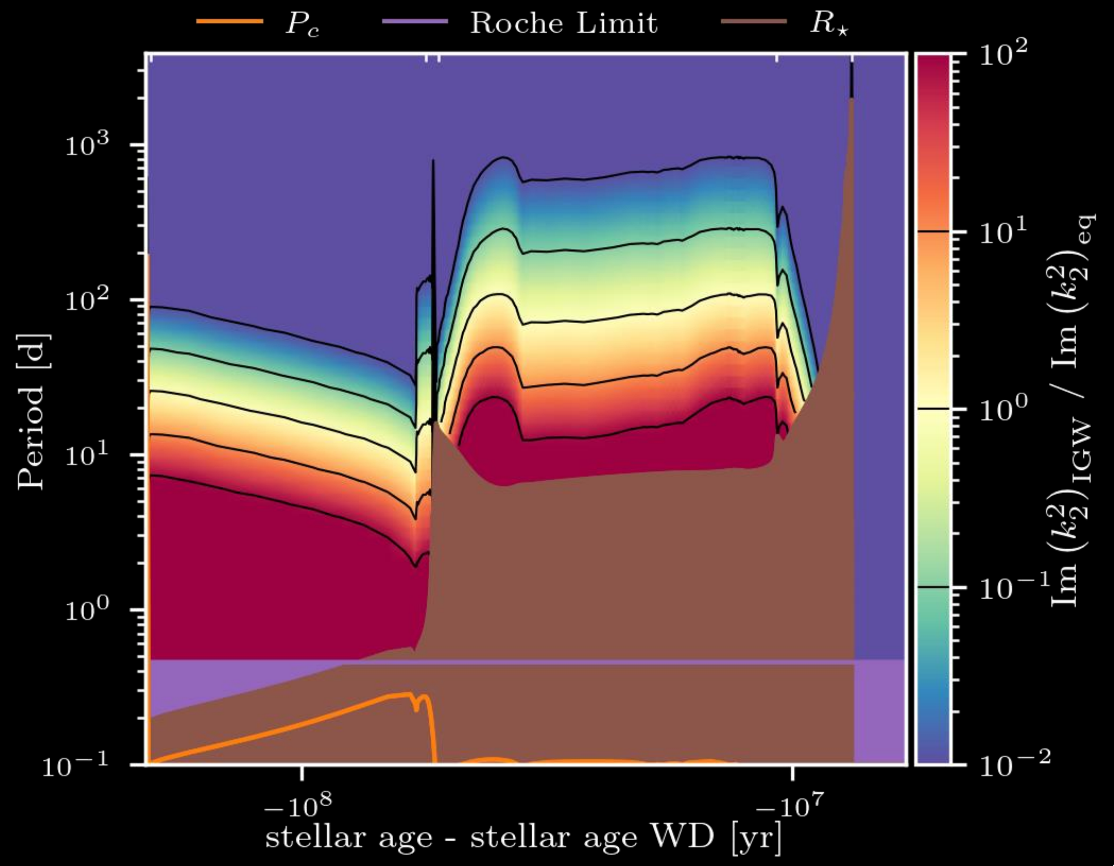


Relative strengths of tidal dissipation

1 $M_\odot$ Model

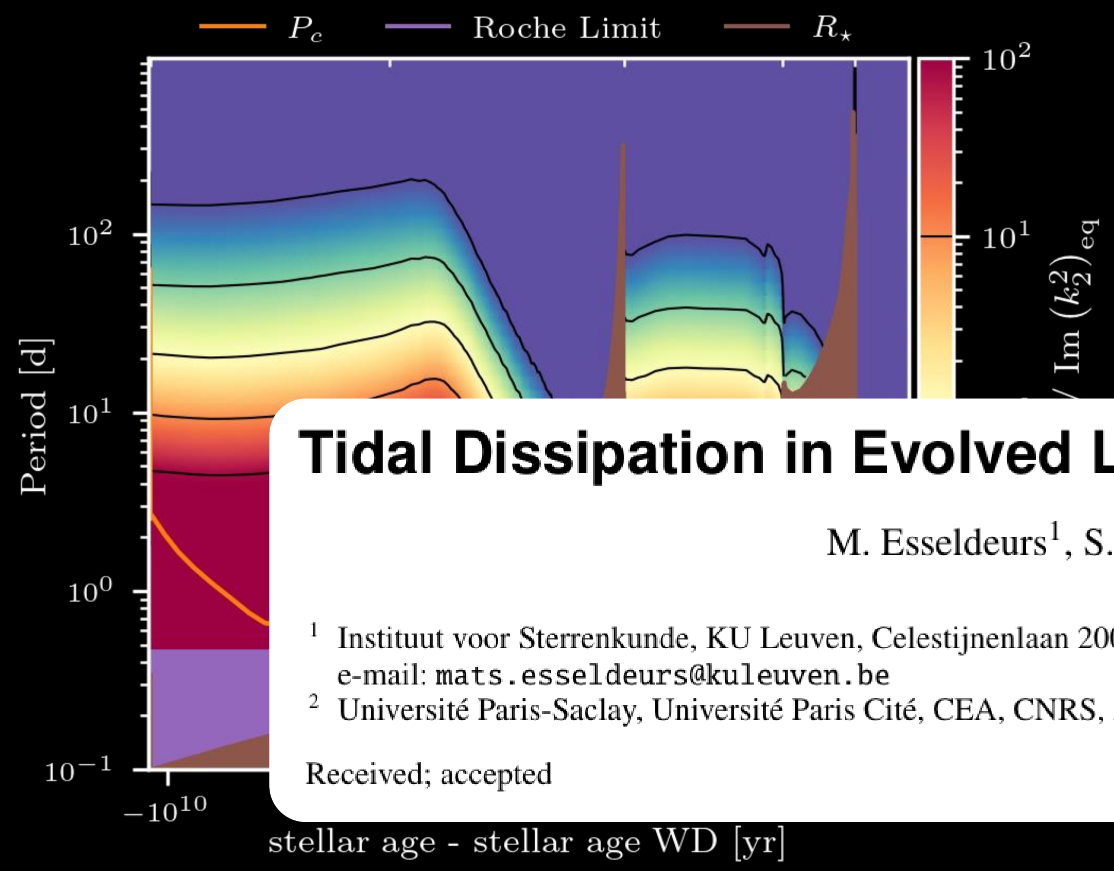


4 $M_\odot$ Model

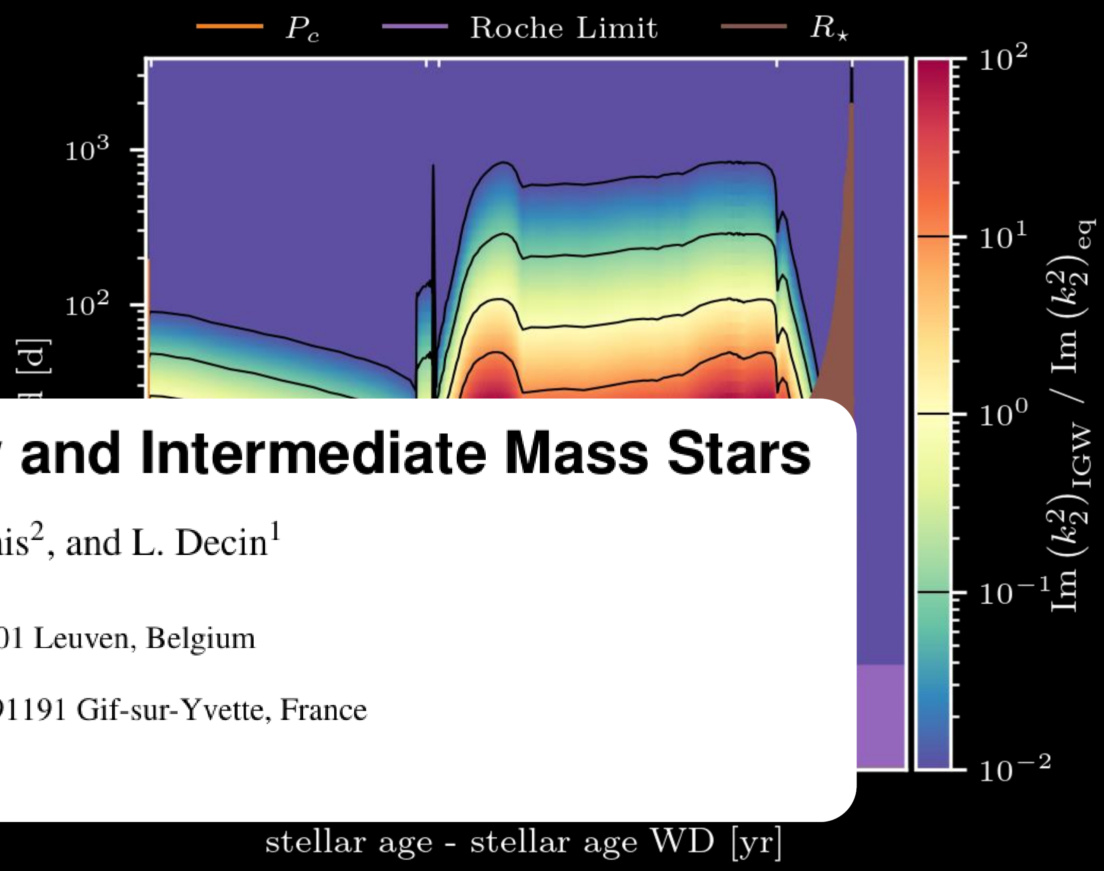


Relative strengths of tidal dissipation

1 $M_\odot$ Model



4 $M_\odot$ Model



Tidal Dissipation in Evolved Low and Intermediate Mass Stars

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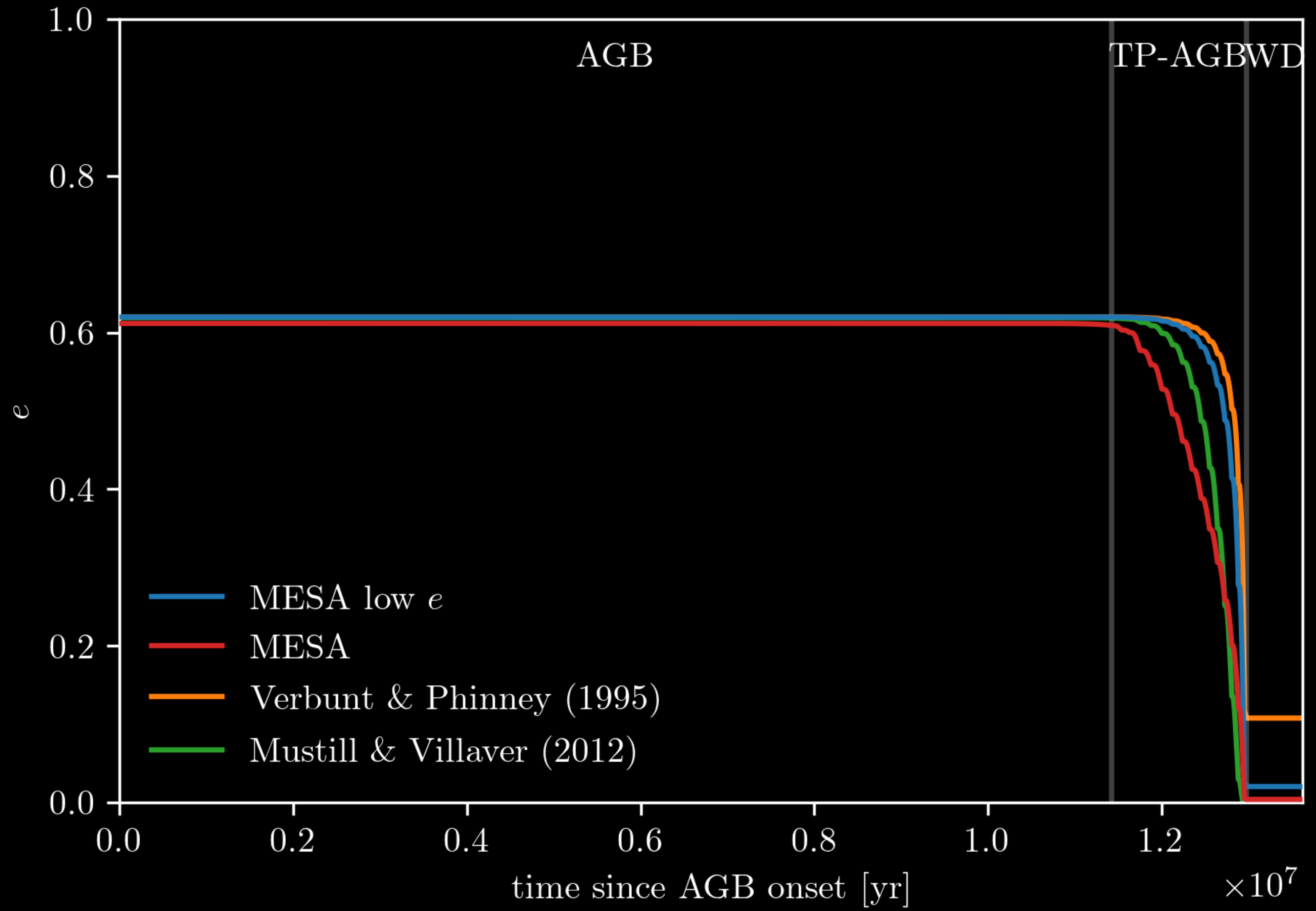
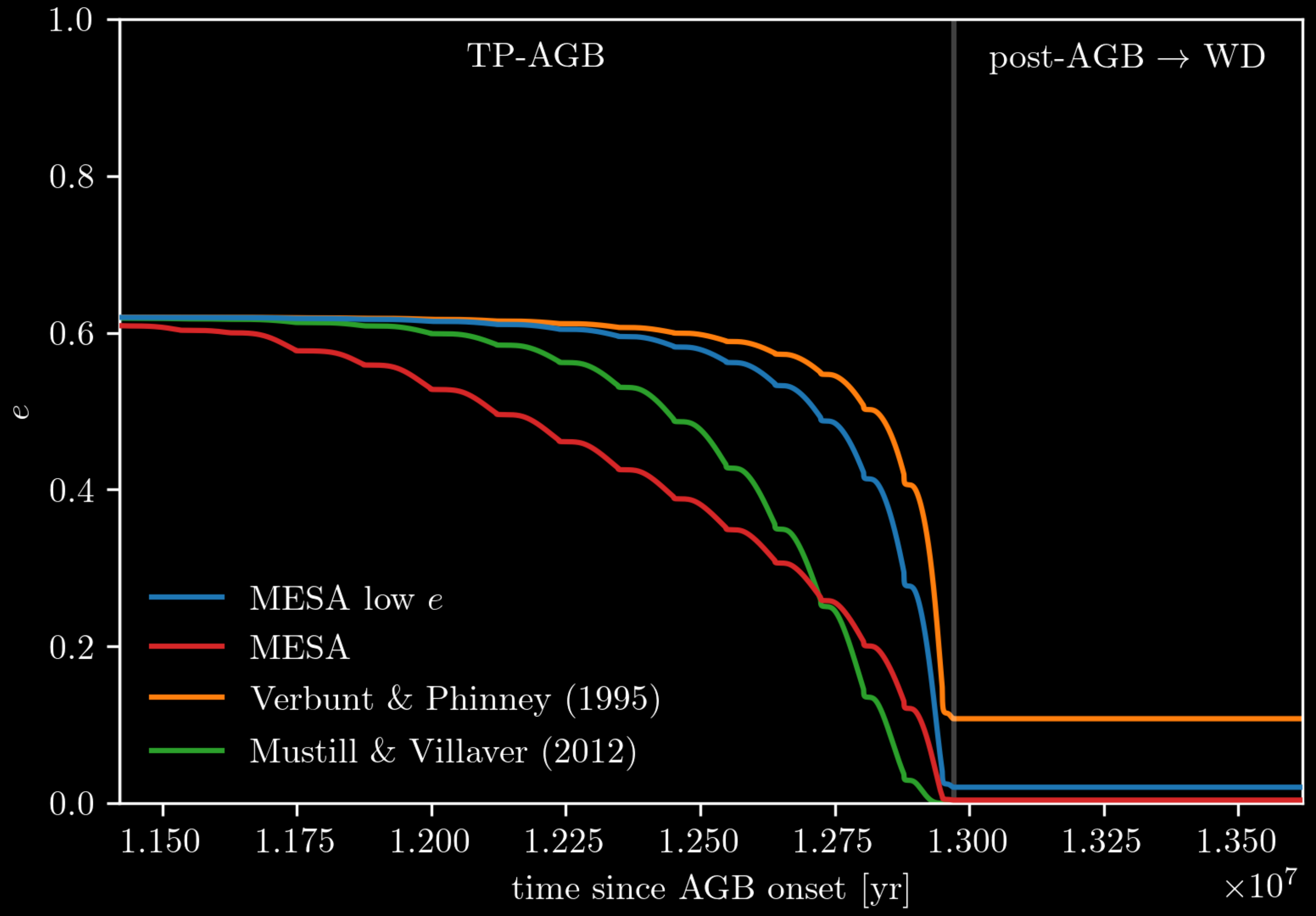
Received; accepted

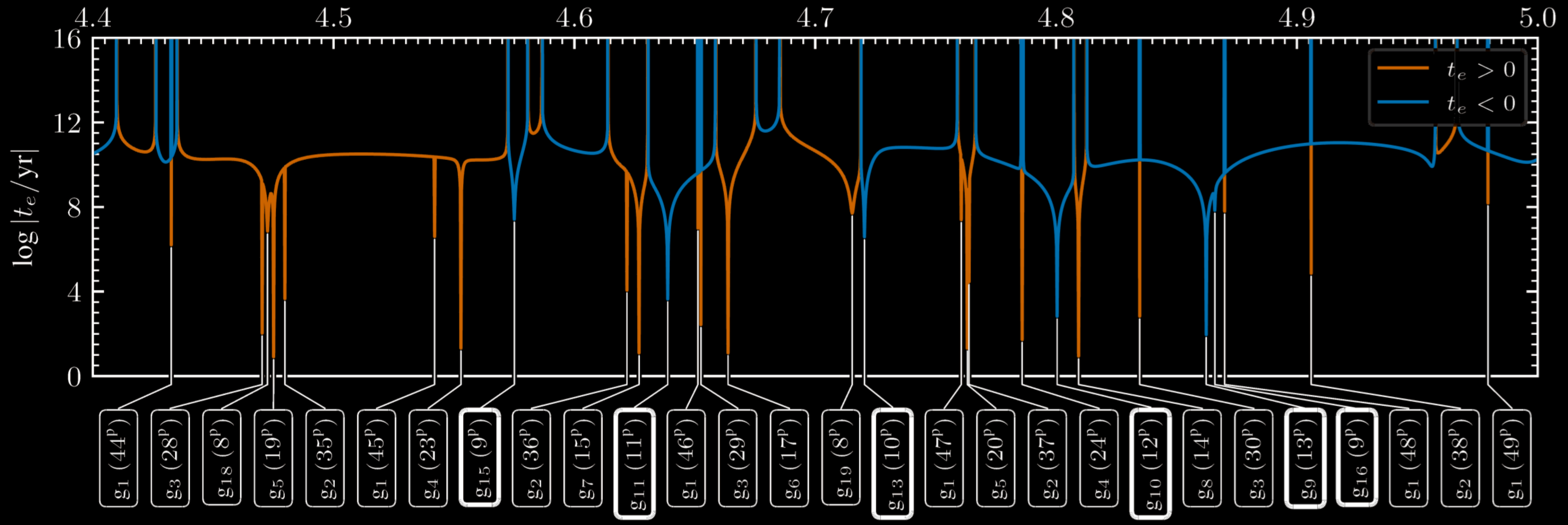
Eccentricity change during the AGB phase



Eccentricity change during the AGB phase



Tidal eccentricity pumping through resonances

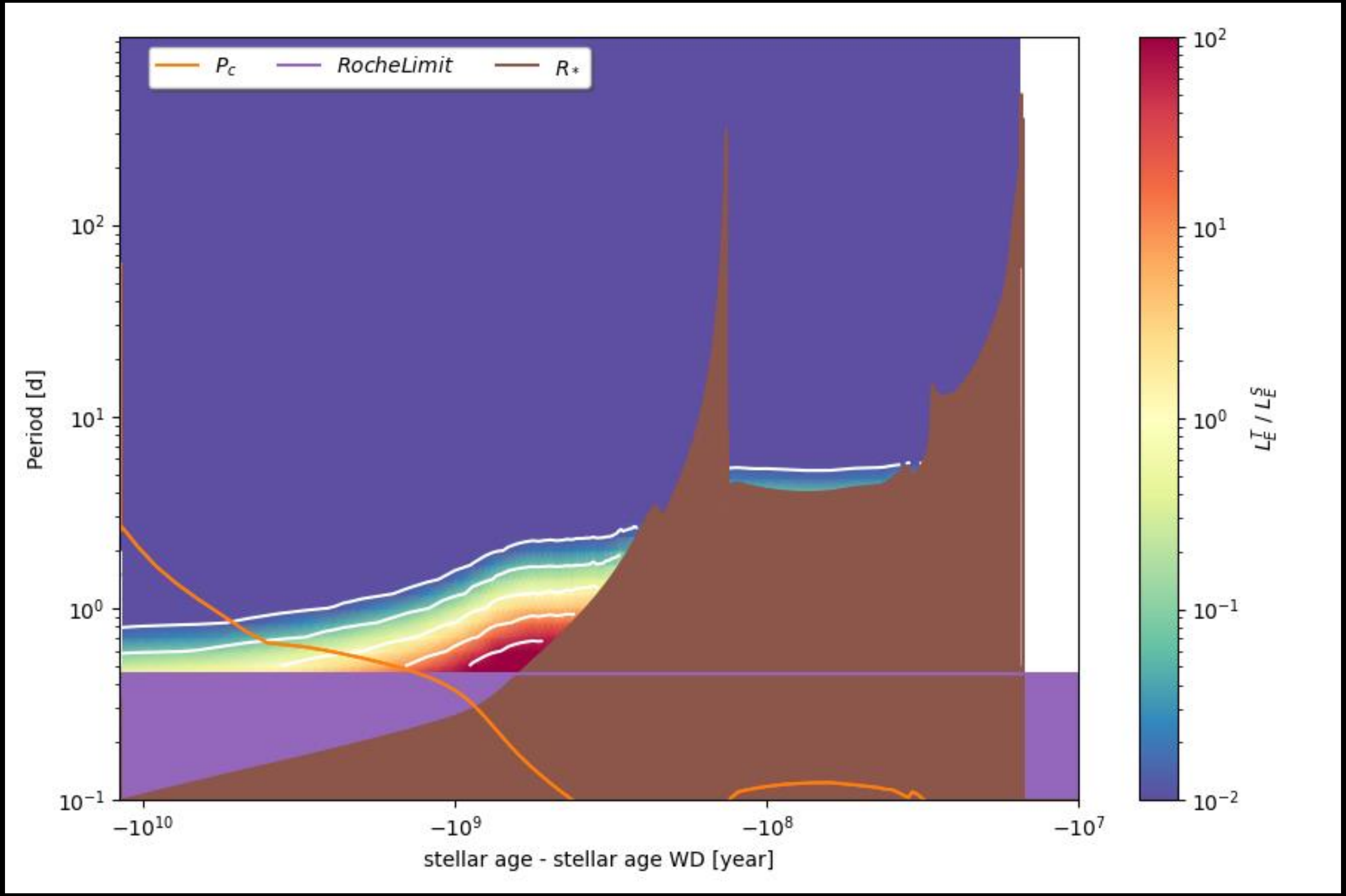


Sun et al. (2023)

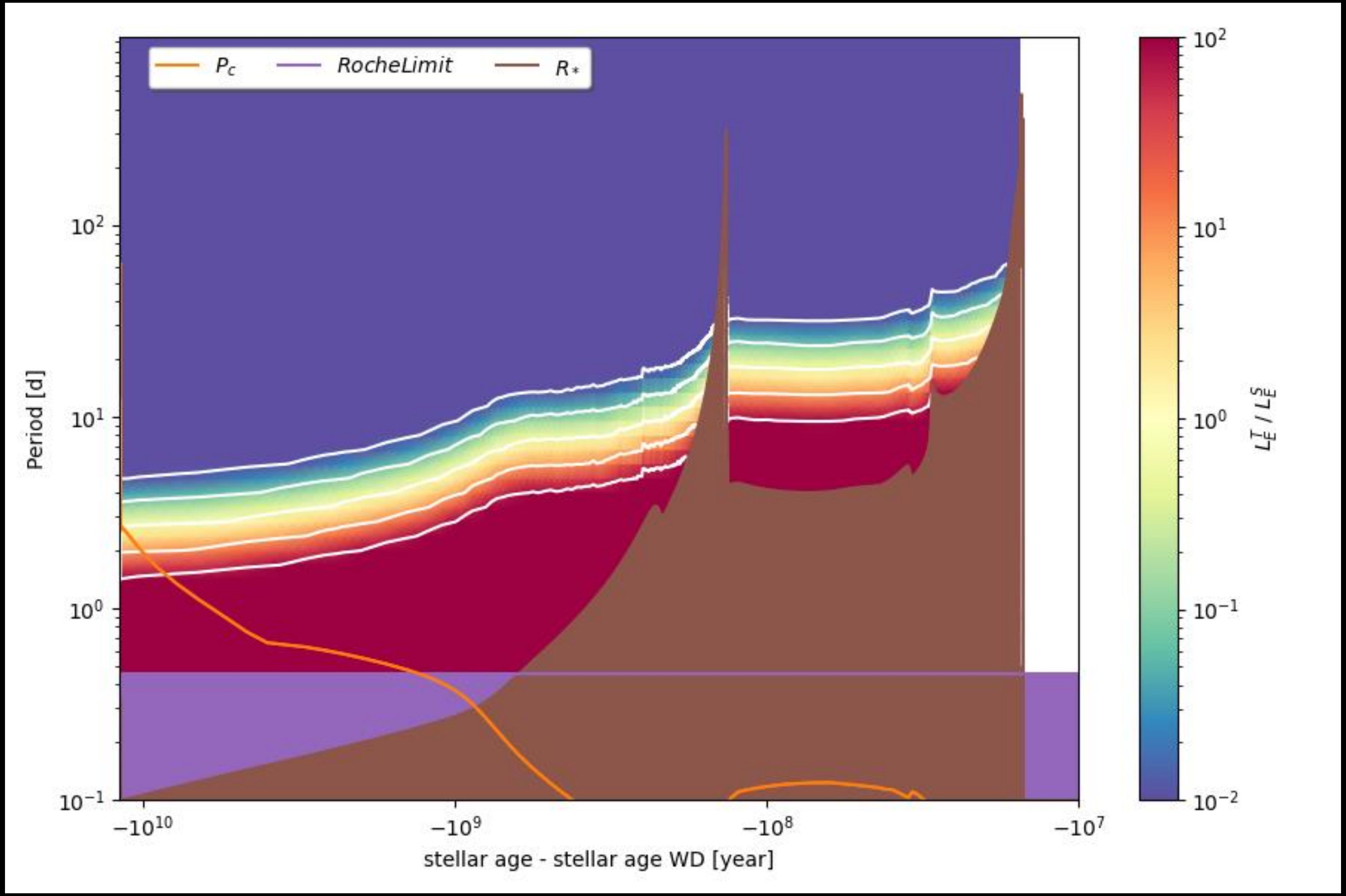
Conclusions

- Tidal dissipation can be calculated ab-initio throughout the entire lifetime of a star
- The dynamical tide of gravity waves remains moderate during the giant phases
- The eccentricity problem is not yet solved
- The dynamical tide connecting with pressure modes remains to be studied

Mixing due to tidal waves



Mixing due to tidal waves



Tidal Dissipation in Cool Evolved Stars

Equilibrium Tides

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}\Phi_l^{\mathrm{nw}}}{\mathrm{d}r}\right)-\frac{l(l+1)}{r^2}\Phi_l^{\mathrm{nw}}-4\pi G\frac{\mathrm{d}\rho_0}{\mathrm{d}r}\frac{1}{g_0}\left(\Phi_l^{\mathrm{nw}}+\Psi_l\right)=0$$

$$\begin{cases}\dfrac{\mathrm{d}\ln\Phi_l^{\mathrm{nw}}}{\mathrm{d}\ln r}=l & \text{at } r=\eta R_\star \text{ for } \eta\to 0\\ \dfrac{\mathrm{d}\ln\Phi_l^{\mathrm{nw}}}{\mathrm{d}\ln r}=-(l+1) & \text{at } r=R_\star\end{cases}.$$

$$\xi_{r,l}^{\mathrm{nw}}=-\frac{\Phi_l^{\mathrm{nw}}+\Psi_l}{g_0}\,,\quad \xi_{h,l}=\frac{1}{l(l+1)}\left(2\xi_{r,l}^{\mathrm{nw}}+r\frac{\mathrm{d}\xi_{r,l}^{\mathrm{nw}}}{\mathrm{d}r}\right).$$

$$\begin{aligned}D_l(r)=\frac{1}{3}&\left(3\frac{\mathrm{d}\xi_{r,l}^{\mathrm{nw}}}{\mathrm{d}r}-\frac{1}{r^2}\frac{\mathrm{d}\left(r^2\xi_{r,l}^{\mathrm{nw}}\right)}{\mathrm{d}r}+l(l+1)\frac{\xi_{h,l}^{\mathrm{nw}}}{r}\right)^2\\ &+l(l+1)\left(\frac{\xi_{r,l}^{\mathrm{nw}}}{r}+r\frac{\mathrm{d}\left(\xi_{h,l}^{\mathrm{nw}}/r\right)}{\mathrm{d}r}\right)^2\\ &+(l-1)l(l+1)(l+2)\left(\frac{\xi_{h,l}^{\mathrm{nw}}}{r}\right)^2,\end{aligned}$$

$$\mathrm{Im}\left(k_2^2\right)_{\mathrm{eq}}=\frac{16\pi G\omega_t}{4(2l+1)R_\star|\varphi_T(R_\star)|^2}\int_0^{R_\star}r^2\rho\nu_t D_l(r)\mathrm{d}r\,,$$

Dynamical Tides

$$\mathcal{F}_{\mathrm{in}}=\int_0^{r_{\mathrm{in}}}\left[\left(\frac{r^2\varphi_T}{g_0}\right)''-\frac{l(l+1)}{r^2}\left(\frac{r^2\varphi_T}{g_0}\right)\right]\frac{X_{1,\mathrm{in}}}{X_{1,\mathrm{in}}(r_{\mathrm{in}})}\mathrm{d}r$$

$$\mathcal{F}_{\mathrm{out}}=\int_{r_{\mathrm{out}}}^{R_\star}\left[\left(\frac{r^2\varphi_T}{g_0}\right)''-\frac{l(l+1)}{r^2}\left(\frac{r^2\varphi_T}{g_0}\right)\right]\frac{X_{1,\mathrm{out}}}{X_{1,\mathrm{out}}(r_{\mathrm{out}})}\mathrm{d}r\,,$$

$$\begin{cases}X''_{1,\mathrm{out}}-\dfrac{\partial_r\rho_0}{\rho_0}X'_{1,\mathrm{out}}-\dfrac{l(l+1)}{r^2}X_{1,\mathrm{out}}=0\\ X_{1,\mathrm{out}}(r)_{r\to 0}\propto r^{1/2+\sqrt{1/4+l(l+1)}}\\ X'_{1,\mathrm{out}}(r)_{r\to 0}\propto\left(1/2+\sqrt{1/4+l(l+1)}\right)r^{-1/2+\sqrt{1/4+l(l+1)}}\end{cases}$$

$$\begin{cases}X''_{1,\mathrm{in}}-\dfrac{\partial_r\rho_0}{\rho_0}X'_{1,\mathrm{in}}-\dfrac{l(l+1)}{r^2}X_{1,\mathrm{in}}=0\\ X_{1,\mathrm{out}}(r)_{r\to R_\star}\propto\rho_0\left(r-R_\star-\dfrac{\varphi_T(R_\star)}{g_0(R_\star)}\right)\\ X'_{1,\mathrm{out}}(r)_{r\to R_\star}\propto\rho_0(R_\star)\end{cases}$$

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$$\mathrm{Im}\left(k_2^2\right)_{\mathrm{eq}}=\frac{16\pi G\omega_t}{4(2l+1)R_\star|\varphi_T(R_\star)|^2}\int_0^{R_\star}r^2\rho\nu_t D_l(r)\mathrm{d}r\,,$$

Dynamical Tides

$$\begin{aligned}\mathcal{F}_{\mathrm{in}}&=\int_0^{r_{\mathrm{in}}}\left[\left(\frac{r^2\varphi_T}{g_0}\right)''-\frac{l(l+1)}{r^2}\left(\frac{r^2\varphi_T}{g_0}\right)\right]\frac{X_{1,\mathrm{in}}}{X_{1,\mathrm{in}}(r_{\mathrm{in}})}\mathrm{d}r\\ \mathcal{F}_{\mathrm{out}}&=\int_{r_{\mathrm{out}}}^{R_\star}\left[\left(\frac{r^2\varphi_T}{g_0}\right)''-\frac{l(l+1)}{r^2}\left(\frac{r^2\varphi_T}{g_0}\right)\right]\frac{X_{1,\mathrm{out}}}{X_{1,\mathrm{out}}(r_{\mathrm{out}})}\mathrm{d}r\end{aligned},$$

$$\begin{aligned}\mathrm{Im}\left(k_2^2\right)_{\mathrm{IGW}}=&\frac{3^{-\frac{1}{3}}\Gamma^2\left(\frac{1}{3}\right)}{2\pi}[l(l+1)]^{-\frac{4}{3}}\omega_t^{\frac{8}{3}}\frac{a^6}{GM_2^2R_\star^5}\\ &\times\left(\rho_0(r_{\mathrm{in}})r_{\mathrm{in}}\left|\frac{\mathrm{d}N^2}{\mathrm{d}\ln r}\right|_{r_{\mathrm{in}}}^{-\frac{1}{3}}\mathcal{F}_{\mathrm{in}}^2\right.\\ &\left.+\rho_0(r_{\mathrm{out}})r_{\mathrm{out}}\left|\frac{\mathrm{d}N^2}{\mathrm{d}\ln r}\right|_{r_{\mathrm{out}}}^{-\frac{1}{3}}\mathcal{F}_{\mathrm{out}}^2\right)\end{aligned}$$