Binary Star Habitable Zones

Part 2

Topics overview

1. Definition of “Habitable Zone”
2. Static HZ
3. Dynamical HZ
4. Application to real systems

1. Definition of Habitable Zone

- **Definition "Habitable Zone" (HZ):**
  region around a (main-sequence) star, where an **Earth-analogue** planet with "not too thick" **atmosphere** can maintain **liquid water** on the surface
- Questions:
  - Single star ?
  - Terrestrial planet (minimum mass) ?
  - Atmosphere, composition, … ?
  - Orbit dynamically stable orbit over long periods of time ?

Single Star HZ (SSHZ)

- **Classical HZ (Kasting+ 1993):**
  HZ limits for single star by runaway states …
  - **Runaway greenhouse** = total evaporation of surface water
  - **Maximum greenhouse** = freeze-out of CO_2
- Parameters:
  - Stellar luminosity → effective temperature $T_{\rm eff}$
  - Spectral energy distribution → effective insolation limits $S_{\rm in}$, $S_{\rm out}$
  - Solar constant $S_\odot$ = 1368 W/m²

$$r_{in} = \sqrt{\frac{(L/L_\odot)}{(S_{\rm in}/S_\odot)}} = \sqrt{\Lambda_{\rm in}} \qquad r_{out} = \sqrt{\frac{(L/L_\odot)}{(S_{\rm out}/S_\odot)}} = \sqrt{\Lambda_{\rm out}}$$

HZ insolation thresholds

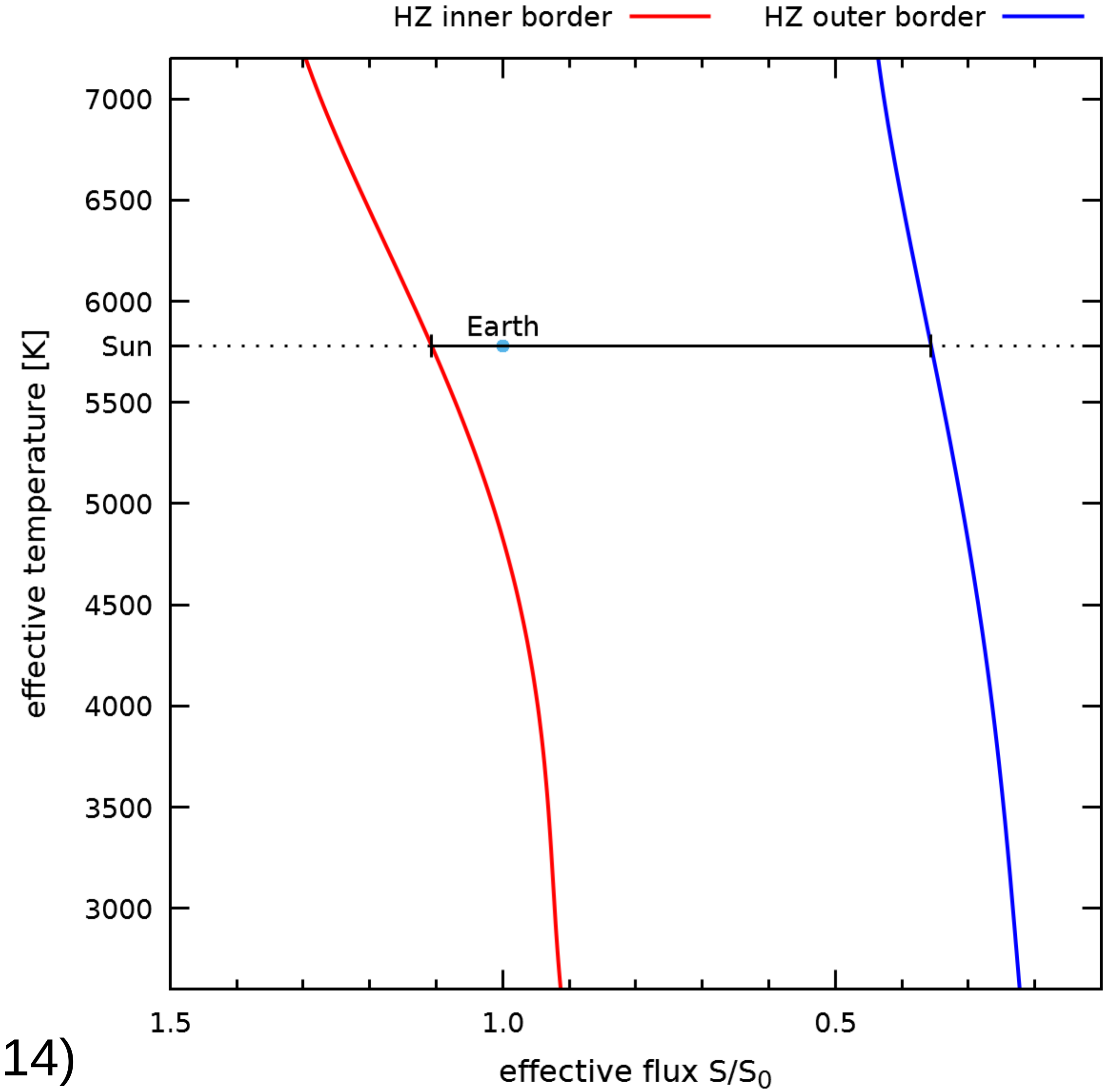
- Modify stellar luminosity *L* by spectral weights *S*: $\Lambda = L/S$
- Kopparapu+ (2014) → effective insolation thresholds as functions of effective temperature and planet mass
- Model dependent coefficients (*a*,*b*,*c*,*d*)

$$S_{\rm eff} = S_{\rm eff}(T_{\rm eff})$$

$$S_{\rm eff} = S_{{\rm eff},\odot} + a\tilde{T} + b\tilde{T}^2 + c\tilde{T}^3 + d\tilde{T}^4$$

$$\tilde{T} = T_{\rm eff} - 5780\ {\rm K}$$

HZ insolation thresholds



after: Kopparapu+ (2014)

2. Static HZ

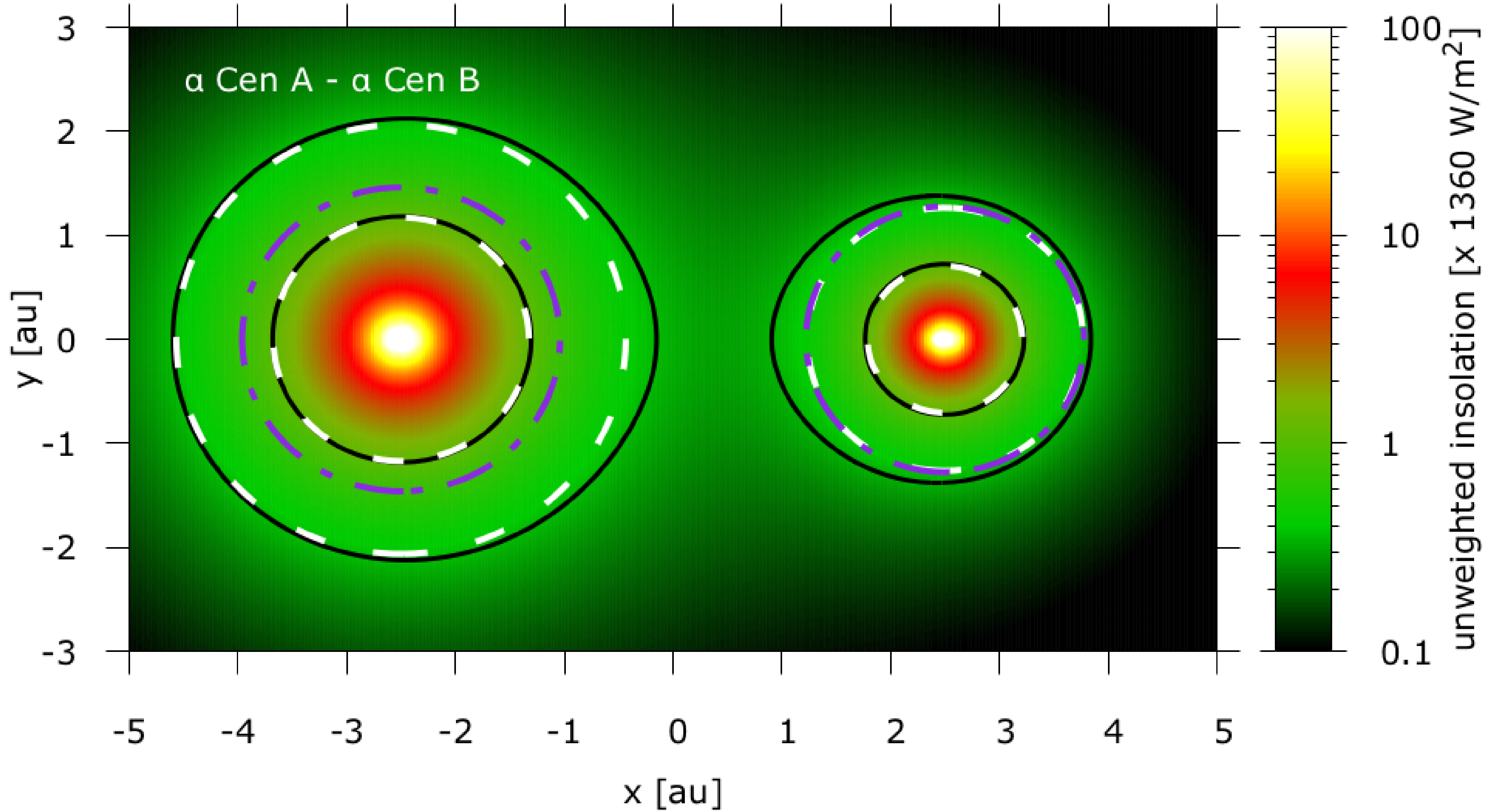
Radiative HZ (RHZ)

- Superposition of all radiation sources:

$$\sum_{i=1}^{N} \frac{\Lambda_i}{r_i^2} = 1$$

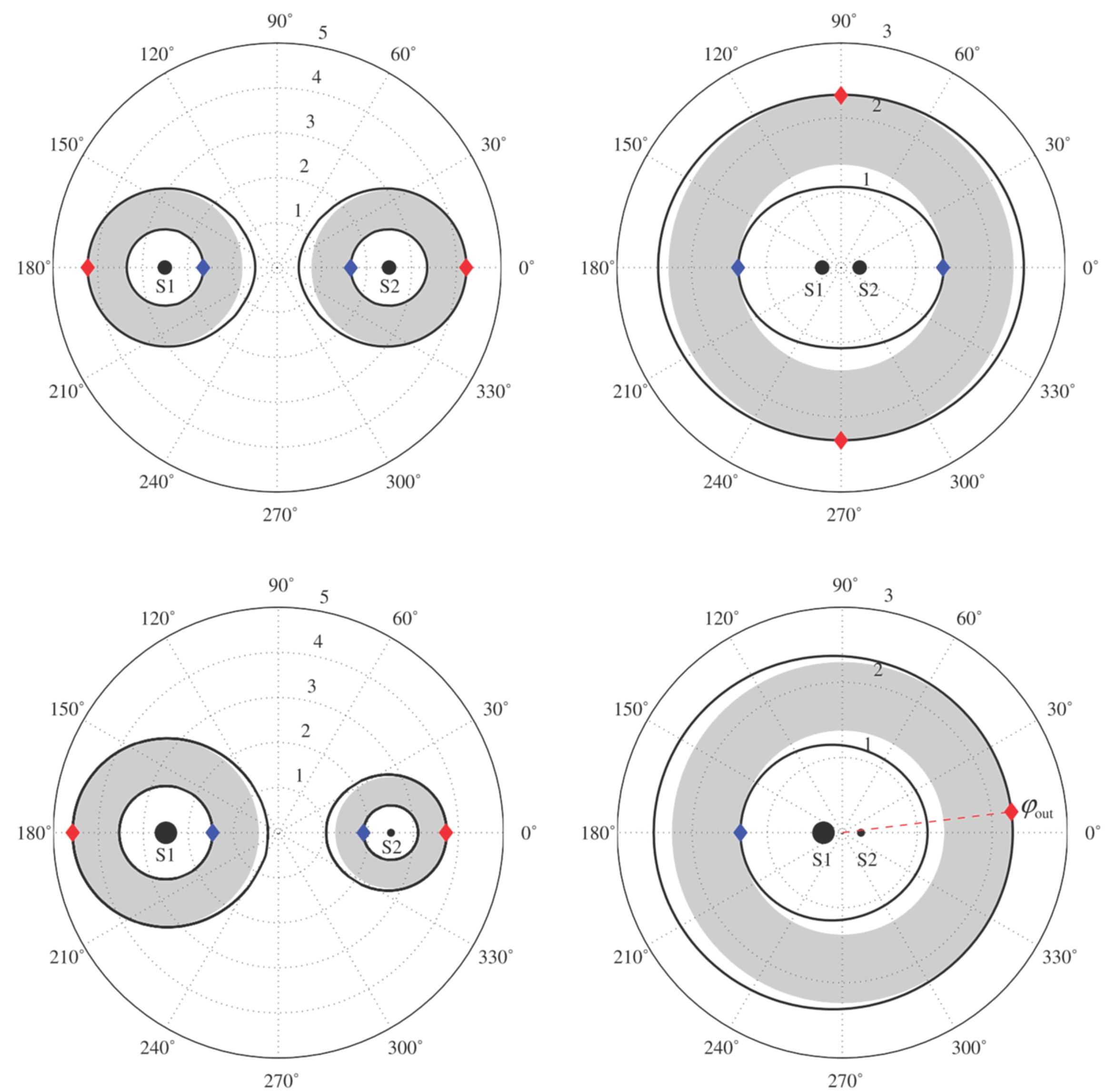
- Find locations (x,y,z) of constant insolation ("isophotes")
- In 2D: solve quartic equation in $r(\varphi)$
- **Definition of RHZ (Cuntz 2014, 2015):**
  largest circular region (ring) to fit inside borders [r_{in} : r_{out}]

RHZ example for α Centauri



RHZ – circular binary

S-type P-type



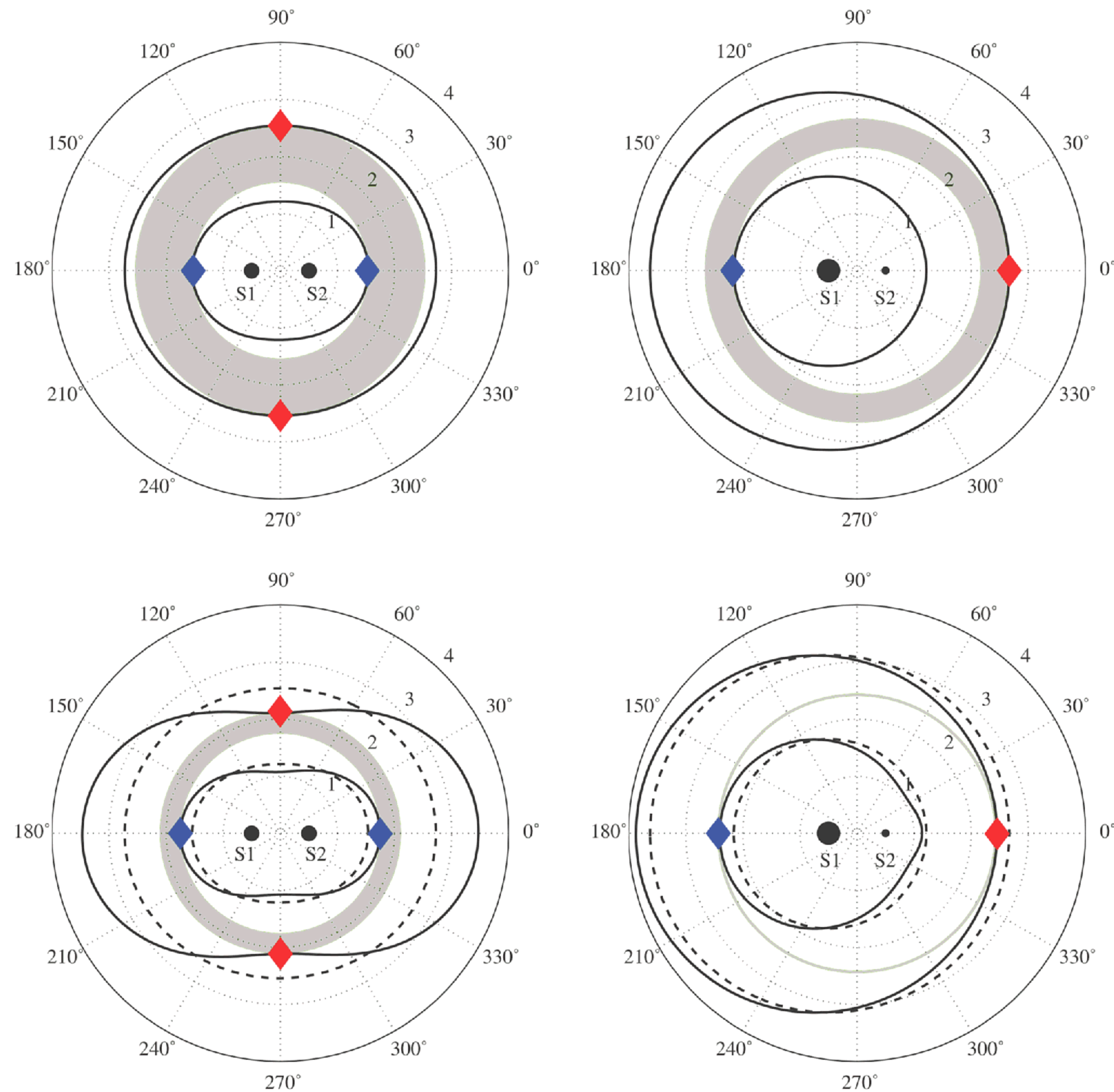
$M_A = M_B = 1$

$M_A = 1.5$, $M_B = 0.5$

Cuntz (2014)

RHZ – elliptic binary

$M_A = M_B = 1$ $M_A = 1.5, M_B = 0.5$



$e_B = 0.0$

$e_B = 0.5$

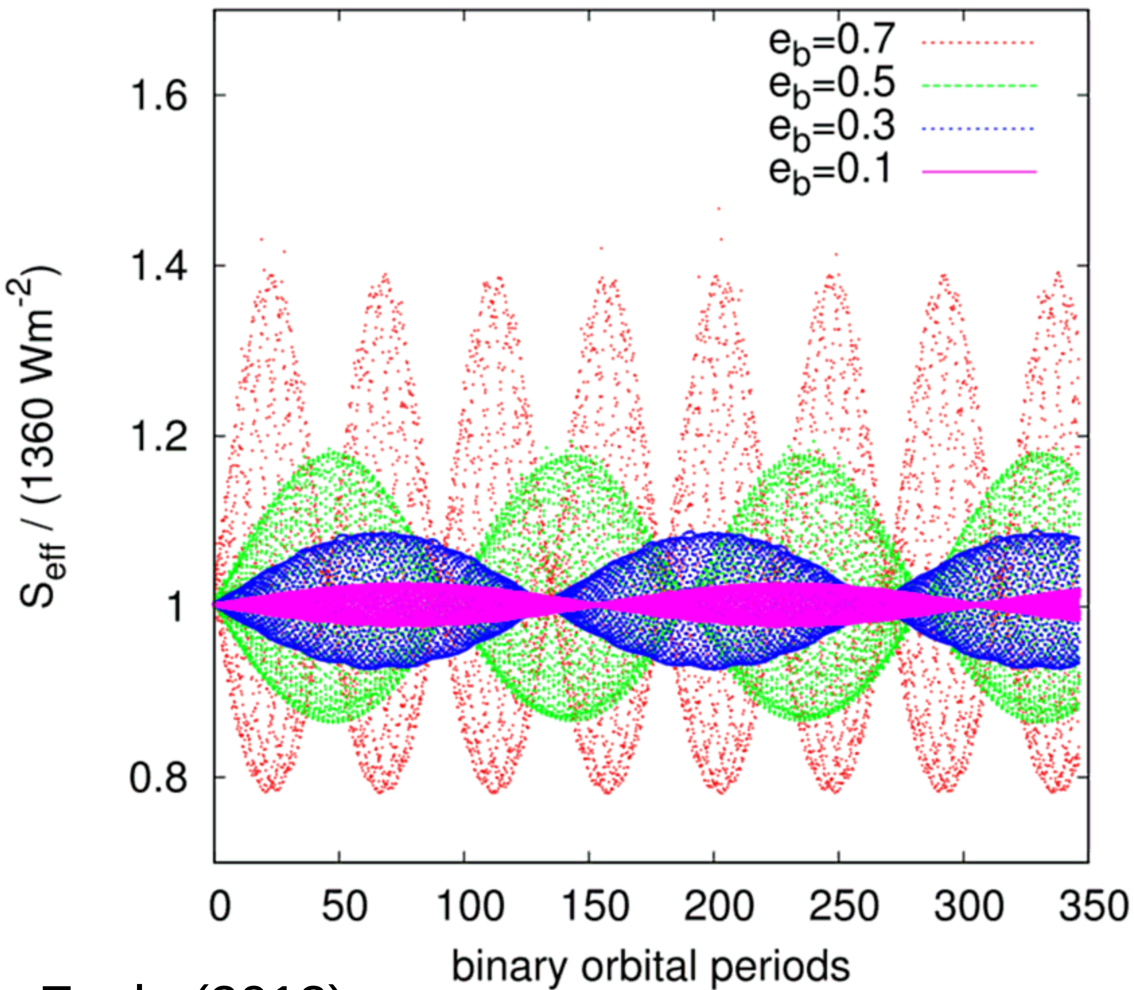
Cuntz (2015)

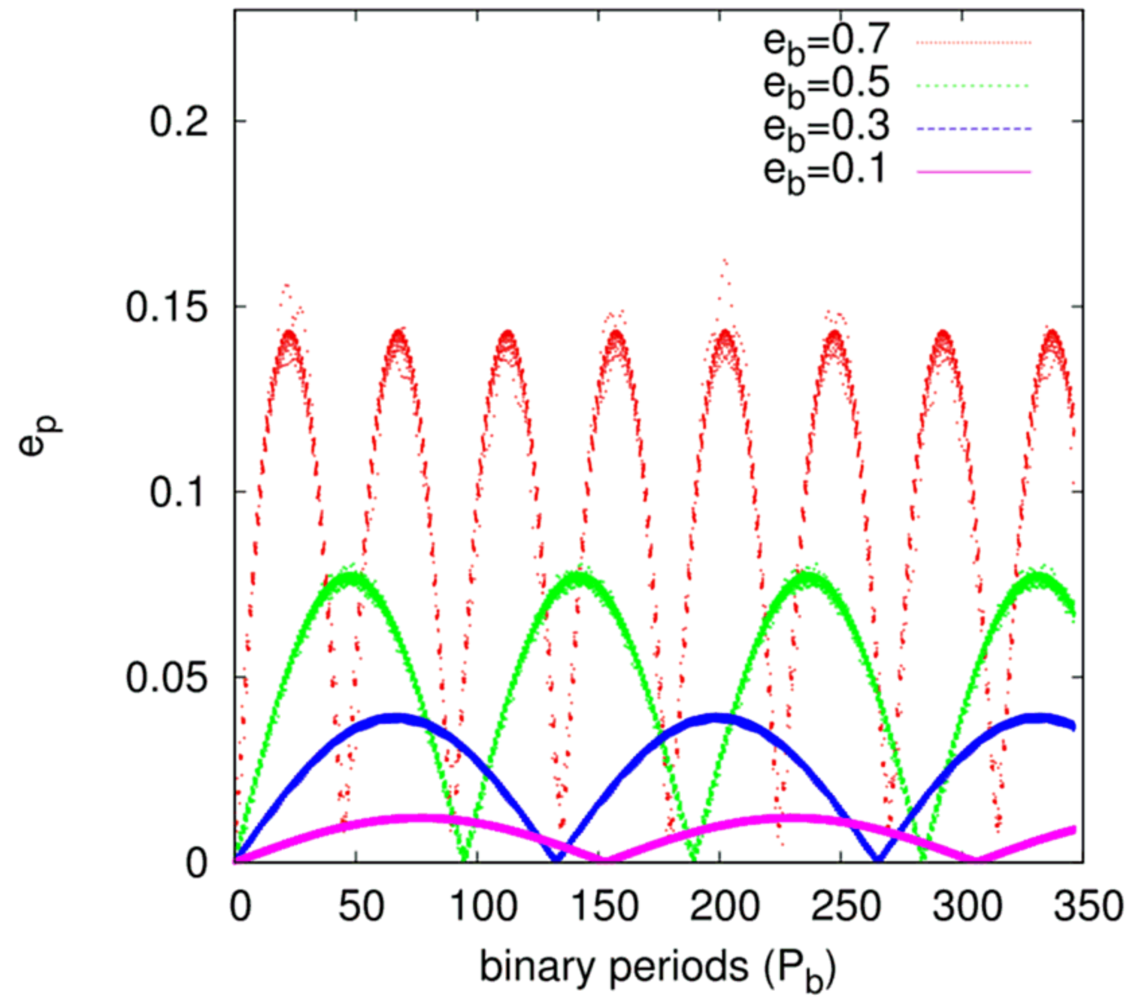
RHZ results

- **S-type RHZ**
  - RHZ $\longrightarrow$ SSHZ for stellar separation $d \longrightarrow \infty$
  - RHZ shrinks with increasing binary eccentricity
  - Strongest deformation along line connecting stars
- **P-type RHZ**
  - RHZ $\longrightarrow$ SSHZ for stellar separation $d \longrightarrow 0$
  - RHZ depends strongly on *d*
  - RHZ only exists for $\left(\frac{d}{2}\right)^2 \leqslant \Lambda_A + \Lambda_B$

3. Dynamical HZ

Insolation variation onto planet – S-type





Eggl+ (2012)

Insolation variation onto planet – P-type

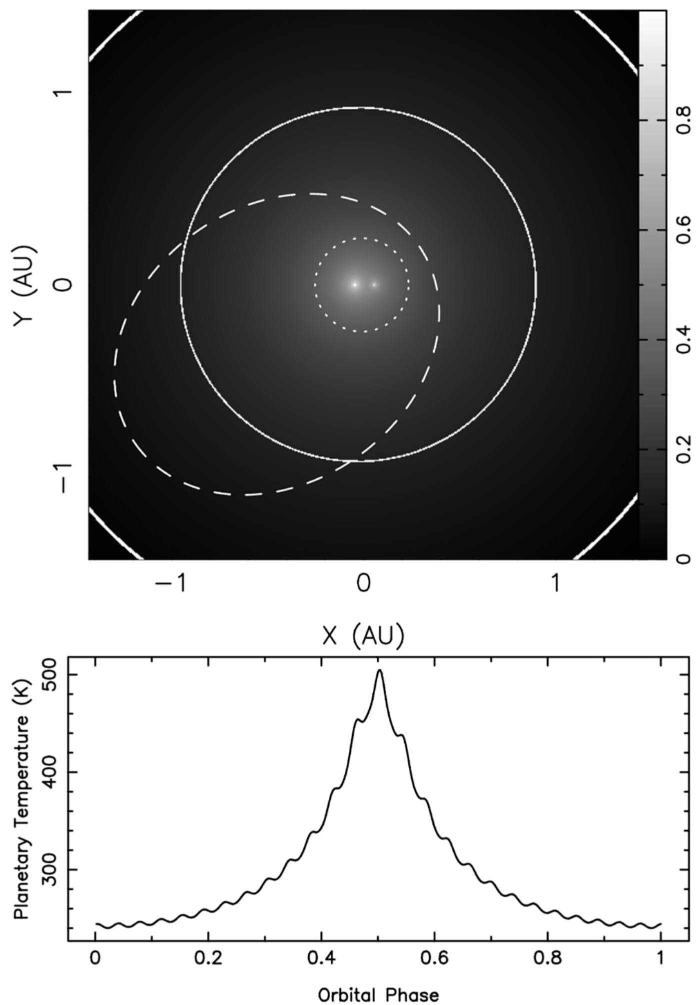


Figure 7. Top panel: the G2V–K5V binary system showing the HZ boundaries (solid lines), critical semimajor boundary (dotted line), and a planetary orbit (dashed line). The planetary orbit has a semimajor axis of $a = 0.9$ AU and an eccentricity of $e = 0.6$. Bottom panel: the equilibrium temperature of the planet as a function of planetary orbital phase. Phase 0.0 is at apastron and phase 0.5 is at periastron.

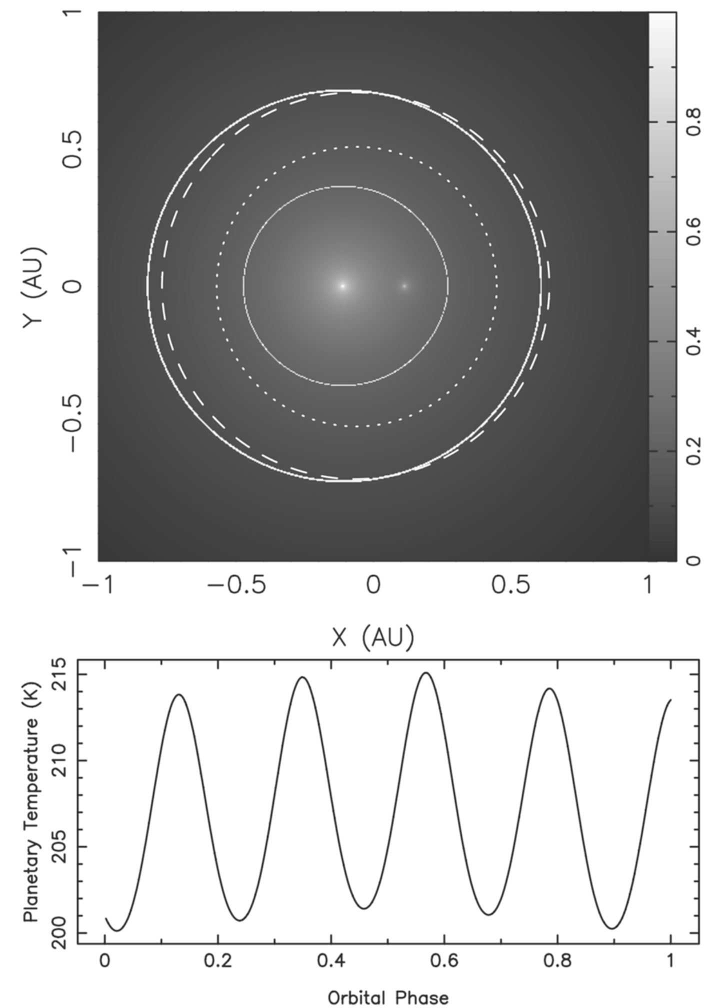


Figure 8. Top panel: the Kepler-16 system showing the HZ boundaries (solid lines), critical semimajor boundary (dotted line), and planetary orbit (dashed line). Bottom panel: the equilibrium temperature of the planet as a function of planetary orbital phase. Phase 0.0 is at apastron and phase 0.5 is at periastron.

Kane & Hinkel (2013)

HZ + dynamics

- Insolation $S_{\mathrm{eff}} = S_{\mathrm{eff}}(r)$ – but $r = r(t)$
- Planet distance $r(t)$ depends on eccentricity e
- Need to know time-evolution of $e(t)$
- **Definitions (Eggl+, 2012):**

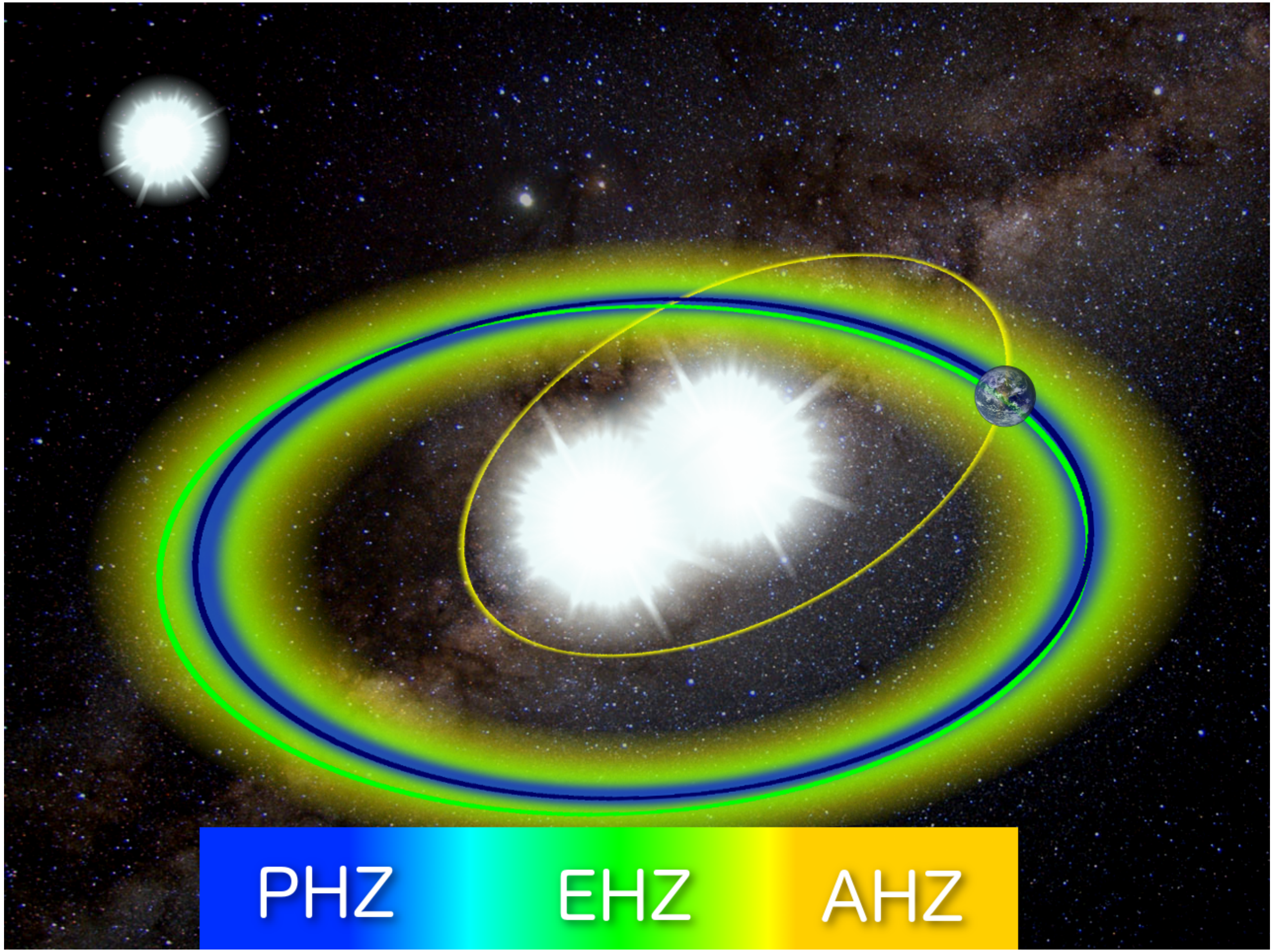
$$\mathrm{PHZ}: S_{\mathrm{in}} \geq S_{\mathrm{eff}} \geq S_{\mathrm{out}} \quad \forall t$$

$$\mathrm{EHZ}: S_{\mathrm{in}} \geq \langle S_{\mathrm{eff}} \rangle_t + \sigma \wedge \langle S_{\mathrm{eff}} \rangle_t - \sigma \geq S_{\mathrm{out}}$$

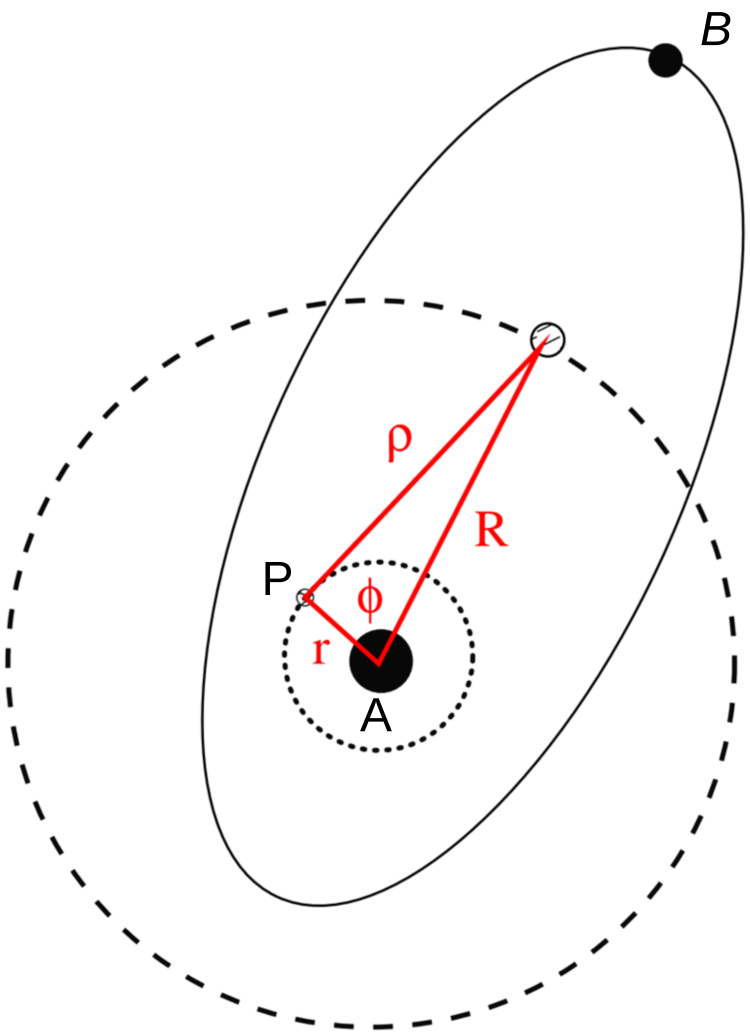
$$\mathrm{AHZ}: S_{\mathrm{in}} \geq \langle S_{\mathrm{eff}} \rangle_t \geq S_{\mathrm{out}}$$

$$\frac{\Lambda_A}{r_A^2(t)} + \frac{\Lambda_B}{r_B^2(t)} = 1$$

“Dynamically Informed HZ”



PHZ limits



$$\mathrm{PHZ_{in}}: \frac{\Lambda_{A,\mathrm{in}}}{q_p^2} + \frac{\Lambda_{B,\mathrm{in}}}{(q_p - q_B)^2} \leq 1 \quad \ldots \quad L_A > L_B$$

$$\mathrm{PHZ_{in}}: \frac{\Lambda_{A,\mathrm{in}}}{Q_p^2} + \frac{\Lambda_{B,\mathrm{in}}}{(Q_p - q_B)^2} \leq 1 \quad \ldots \quad L_A < L_B$$

$$\mathrm{PHZ_{out}}: \frac{\Lambda_{A,\mathrm{out}}}{Q_p^2} + \frac{\Lambda_{B,\mathrm{out}}}{(Q_p + Q_B)^2} \geq 1 \quad \ldots \quad L_A > L_B$$

$$q_p = a_p(1 - e_p^{max})$$

$$Q_p = a_p(1 + e_p^{max})$$

$$q_B = a_B(1 - e_B)$$

$$Q_p = a_p(1 + e_B)$$

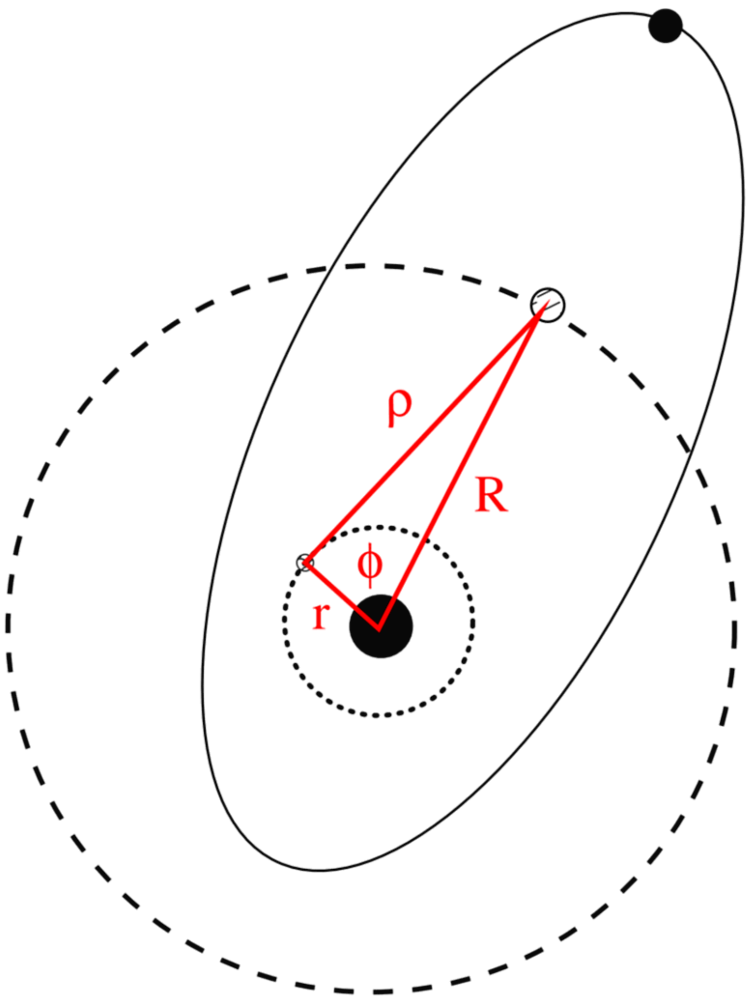
Maximum eccentricity

- Georgakarakos (2003): maximum eccentricity includes short period + secular contributions
- For planets with *e*(*t*=0) = 0

$$e_p^{max} = e_p^{sp} + e_p^{sec} = F(m_A, m_B, m_p, a_p, a_B, e_B)$$

$$e_p^{sec} \approx 2\epsilon = \frac{5}{2}\frac{a_p}{a_B}\frac{e_B}{1-e_B^2}$$

AHZ limits



$$\mathrm{AHZ_{in}} : \frac{\Lambda_{A,\mathrm{in}}}{r^2} + \frac{\Lambda_{B,\mathrm{in}}}{R^2 - r^2} \leq 1$$

$$\mathrm{AHZ_{out}} : \frac{\Lambda_{A,\mathrm{out}}}{r^2} + \frac{\Lambda_{B,\mathrm{out}}}{R^2 - r^2} \geq 1$$

$$r = a_p(1 - \langle e^2 \rangle)$$

$$R = a_B(1 - e_B^2)$$

Time-averaged squared eccentricity

Georgakarakos (2003, 2005)

$$\overline{e_{\rm in}^2} = \frac{m_3^2}{M^2}\frac{1}{X^4(1-e^2)^{9/2}}\left\{\frac{43}{8}+\frac{129}{8}e^2+\frac{129}{64}e^4+\frac{1}{(1-e^2)^{3/2}}\left(\frac{43}{8}+\frac{645}{16}e^2+\frac{1935}{64}e^4+\frac{215}{128}e^6\right)+\frac{1}{X^2(1-e^2)^3}\right.$$

$$\times\left[\frac{365}{18}+\frac{44327}{144}e^2+\frac{119435}{192}e^4+\frac{256105}{1152}e^6+\frac{68335}{9216}e^8\right.$$

$$\left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{365}{18}+\frac{7683}{16}e^2+\frac{28231}{16}e^4+\frac{295715}{192}e^6+\frac{2415}{8}e^8+\frac{12901}{2048}e^{10}\right)\right]$$

$$+\frac{1}{X(1-e^2)^{3/2}}\left[\frac{61}{3}+\frac{305}{2}e^2+\frac{915}{8}e^4+\frac{305}{48}e^6+\frac{1}{(1-e^2)^{3/2}}\left(\frac{61}{3}+\frac{854}{3}e^2+\frac{2135}{4}e^4+\frac{2135}{12}e^6+\frac{2135}{384}e^8\right)\right]$$

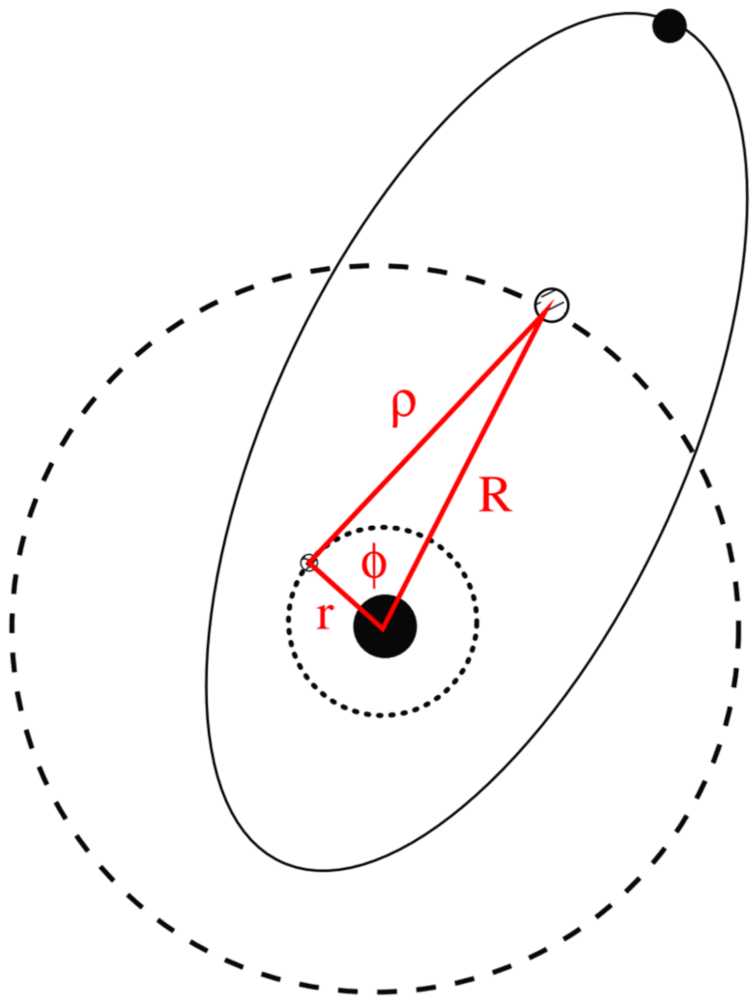
$$+m_*^2X^{2/3}(1-e^2)\left[\frac{225}{256}+\frac{3375}{1024}e^2+\frac{7625}{2048}e^4+\frac{29225}{8192}e^6+\frac{48425}{16384}e^8+\frac{825}{2048}e^{10}\right.$$

$$\left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{225}{256}+\frac{2925}{1024}e^2+\frac{775}{256}e^4+\frac{2225}{8192}e^6+\frac{25}{512}e^8\right)\right]$$

$$+m_*^2\frac{1}{X^{4/3}(1-e^2)^2}\left[\frac{8361}{4096}+\frac{125415}{8192}e^2+\frac{376245}{32768}e^4+\frac{41805}{65536}e^6\right.$$

$$\left.\left.+\frac{1}{(1-e^2)^{3/2}}\left(\frac{8361}{4096}+\frac{58527}{2048}e^2+\frac{877905}{16384}e^4+\frac{292635}{16384}e^6+\frac{292635}{524288}e^8\right)\right]\right\}+2\left(\frac{C}{B-A}\right)^2.$$

EHZ limits

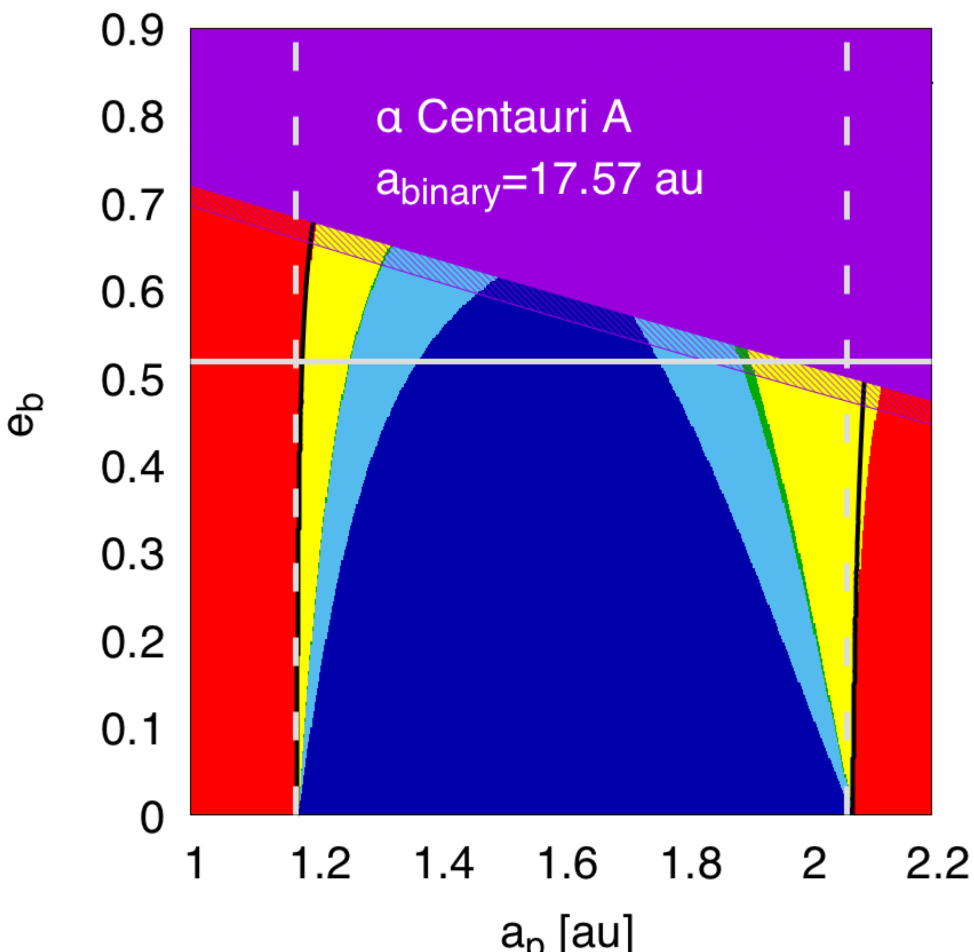


$$\mathrm{EHZ_{in}} : \frac{\Lambda_{A,\mathrm{in}}}{r^2} + \frac{\Lambda_{B,\mathrm{in}}}{R^2 - r^2} + \sigma_{\mathrm{in}} \leq 1$$

$$\mathrm{AHZ_{out}} : \frac{\Lambda_{A,\mathrm{out}}}{r^2} + \frac{\Lambda_{B,\mathrm{out}}}{R^2 - r^2} - \sigma_{\mathrm{out}} \geq 1$$

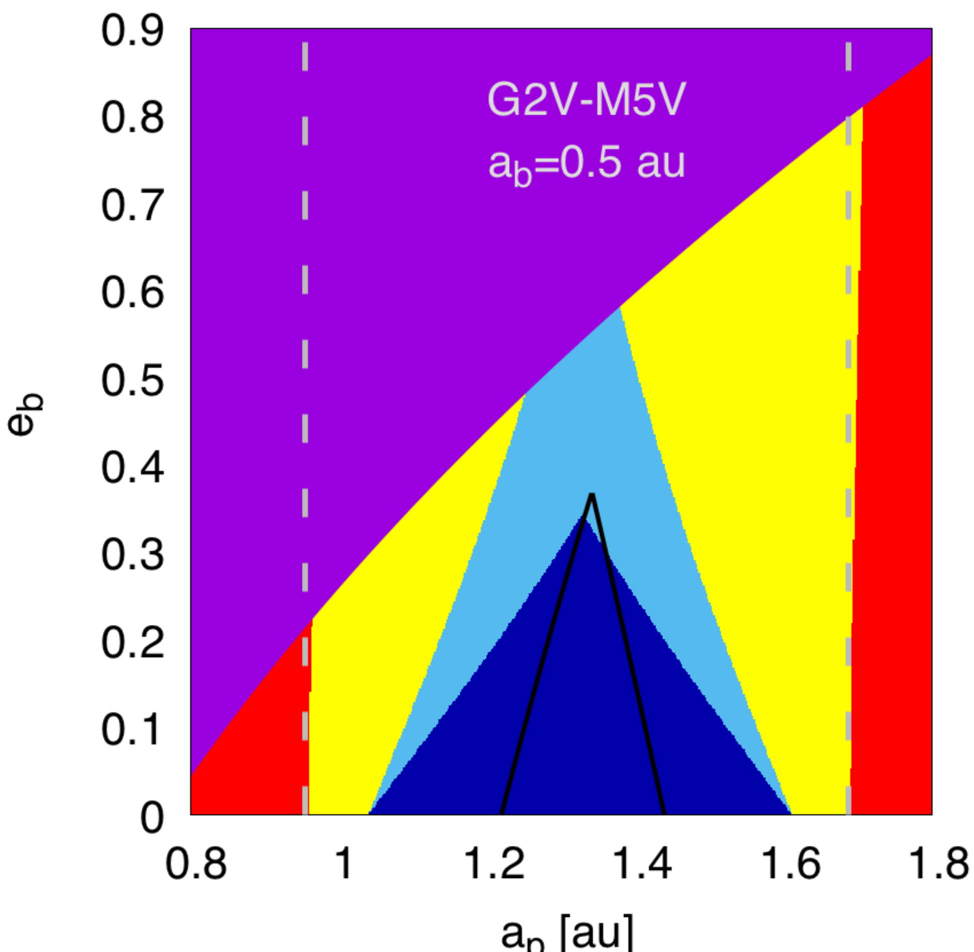
$$\sigma^2 = \langle S_{tot}^2 \rangle_t - \langle S_{tot} \rangle_t^2$$

Application – S-type HZs



- Unstable
- Non-HZ
- AHZ
- EHZ
- PHZ
- SSHZ
- RHZ

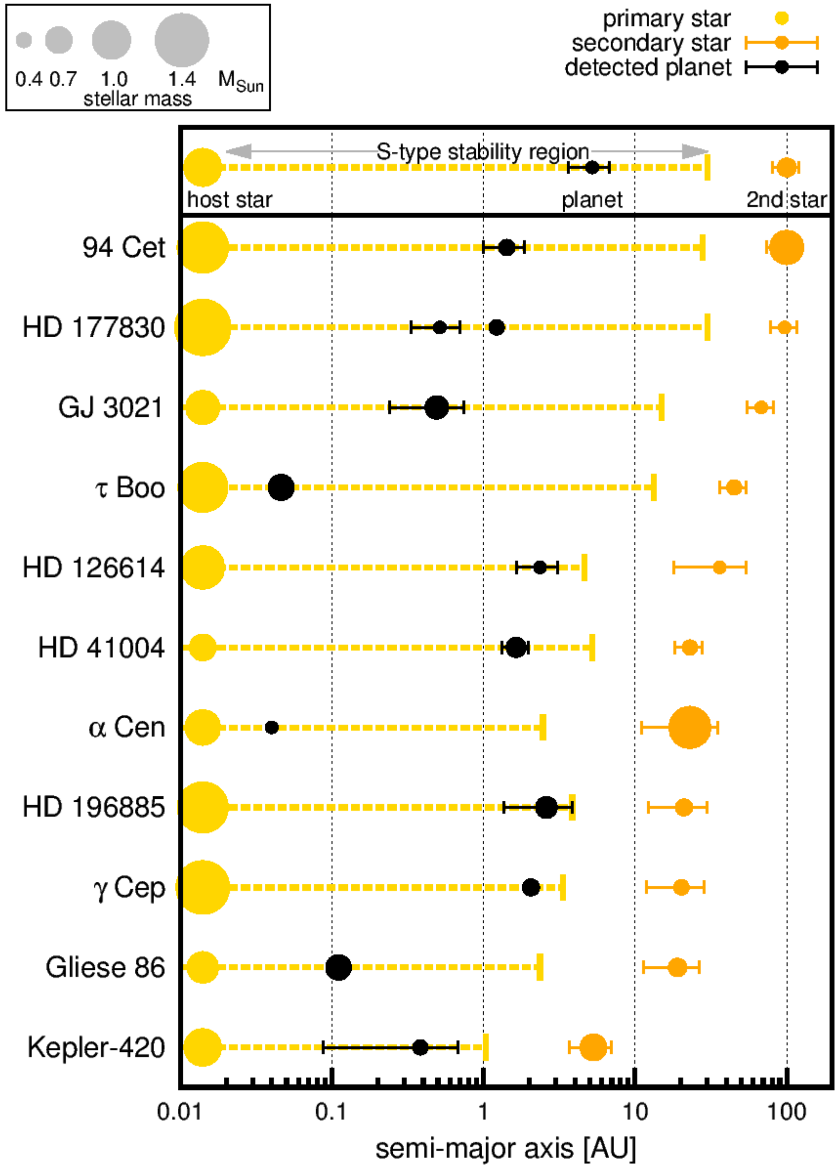
Application – P-type HZs



- Unstable
- Non-HZ
- AHZ
- EHZ
- PHZ
- SSHZ
- RHZ

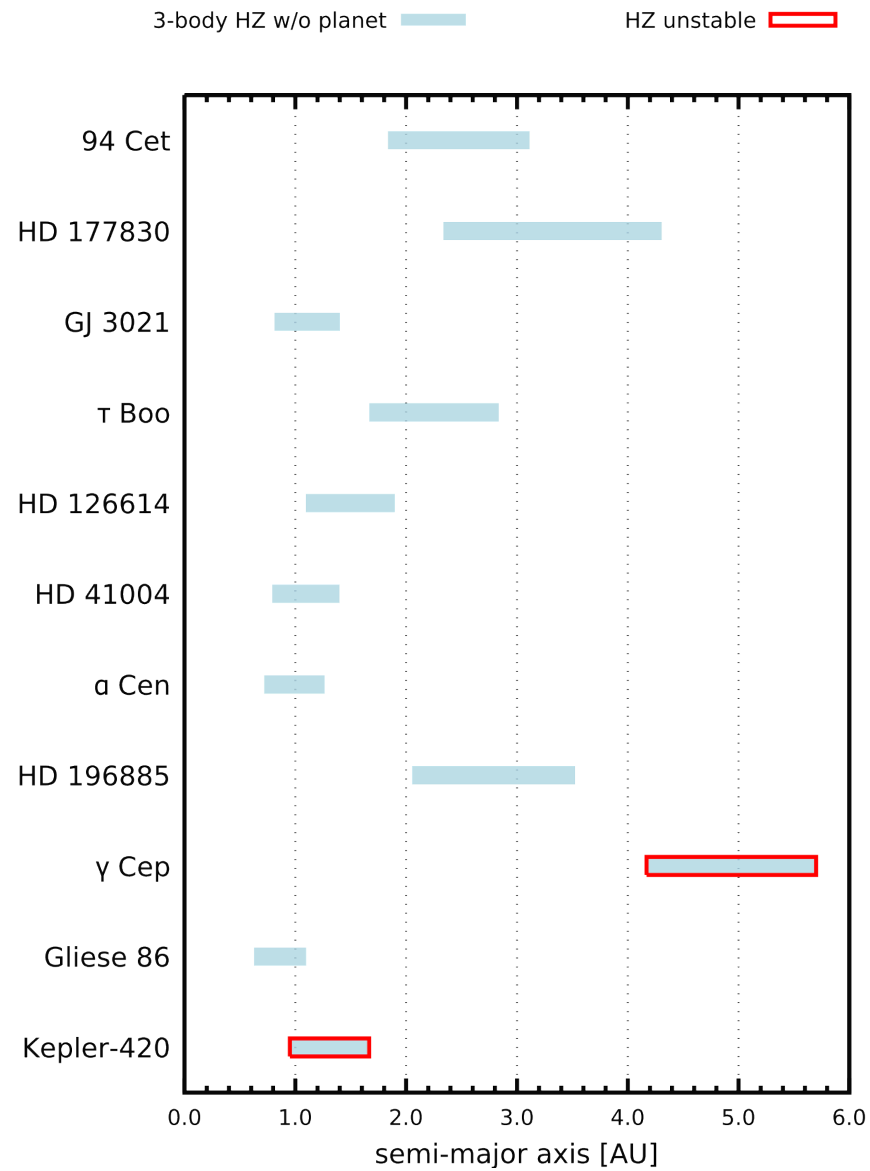
4. Application to real systems

Binary star exoplanet systems

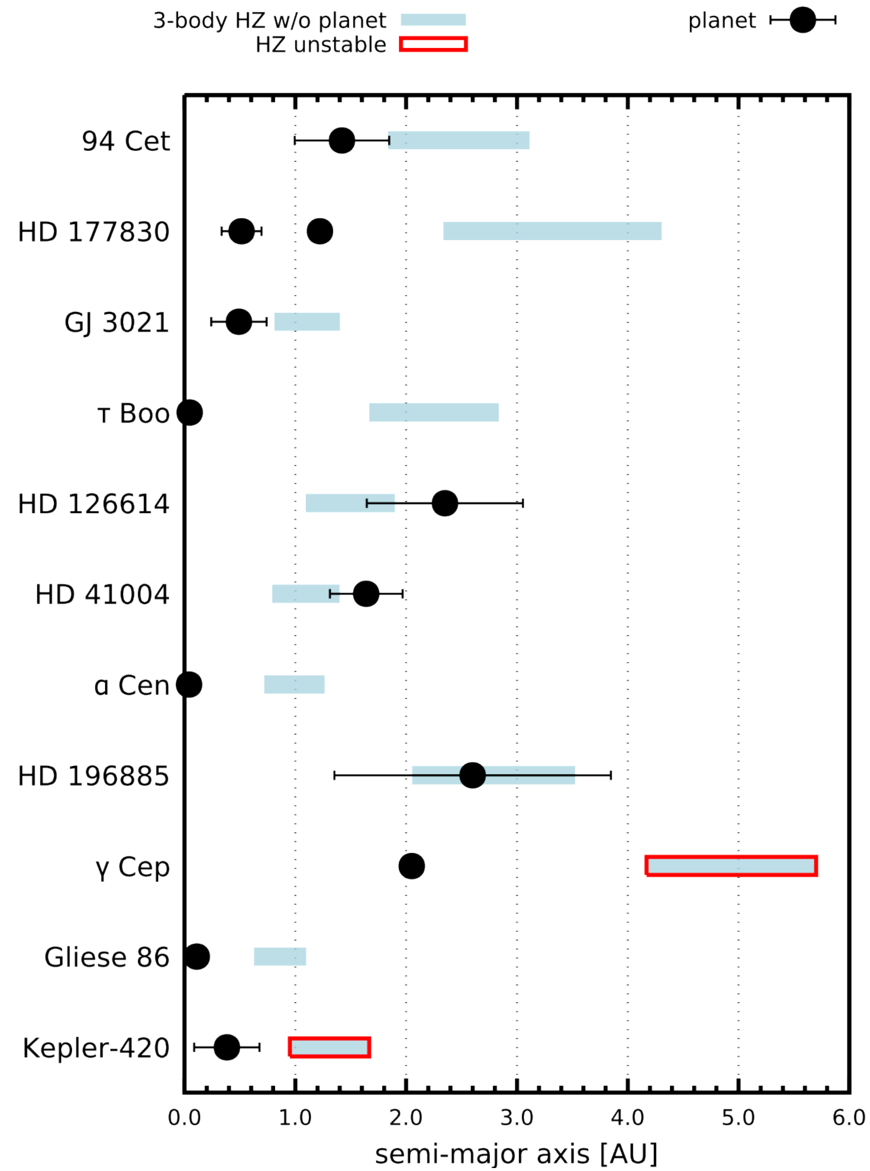


Bazsó+ (2017)

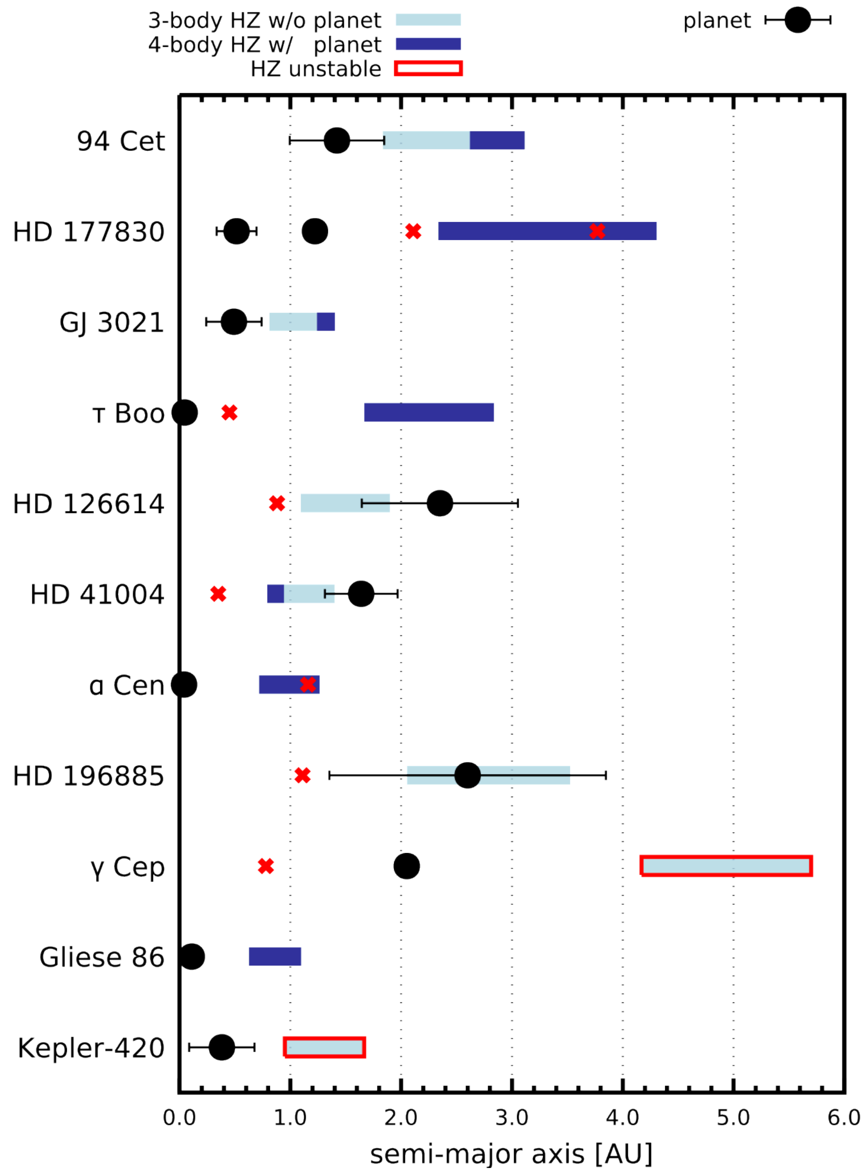
Application to exoplanet systems



Application to exoplanet systems



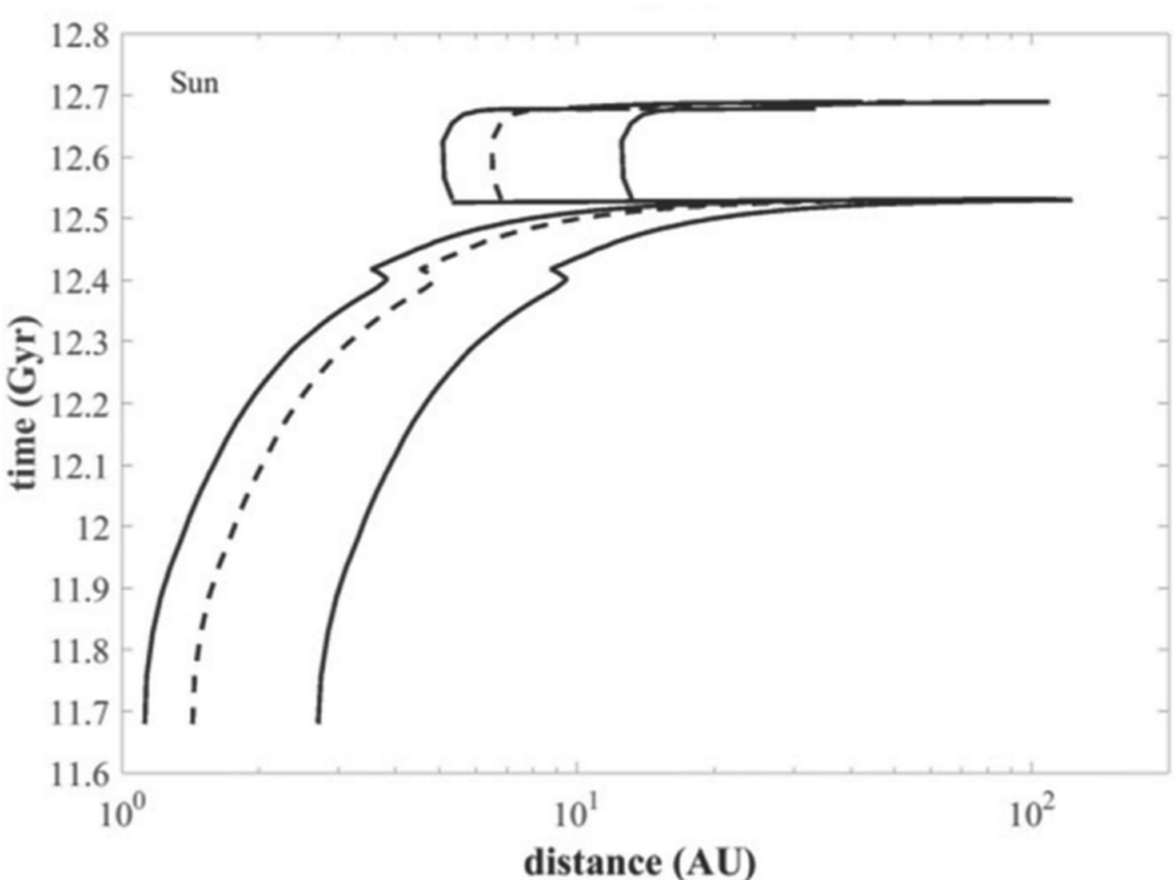
Application to exoplanet systems

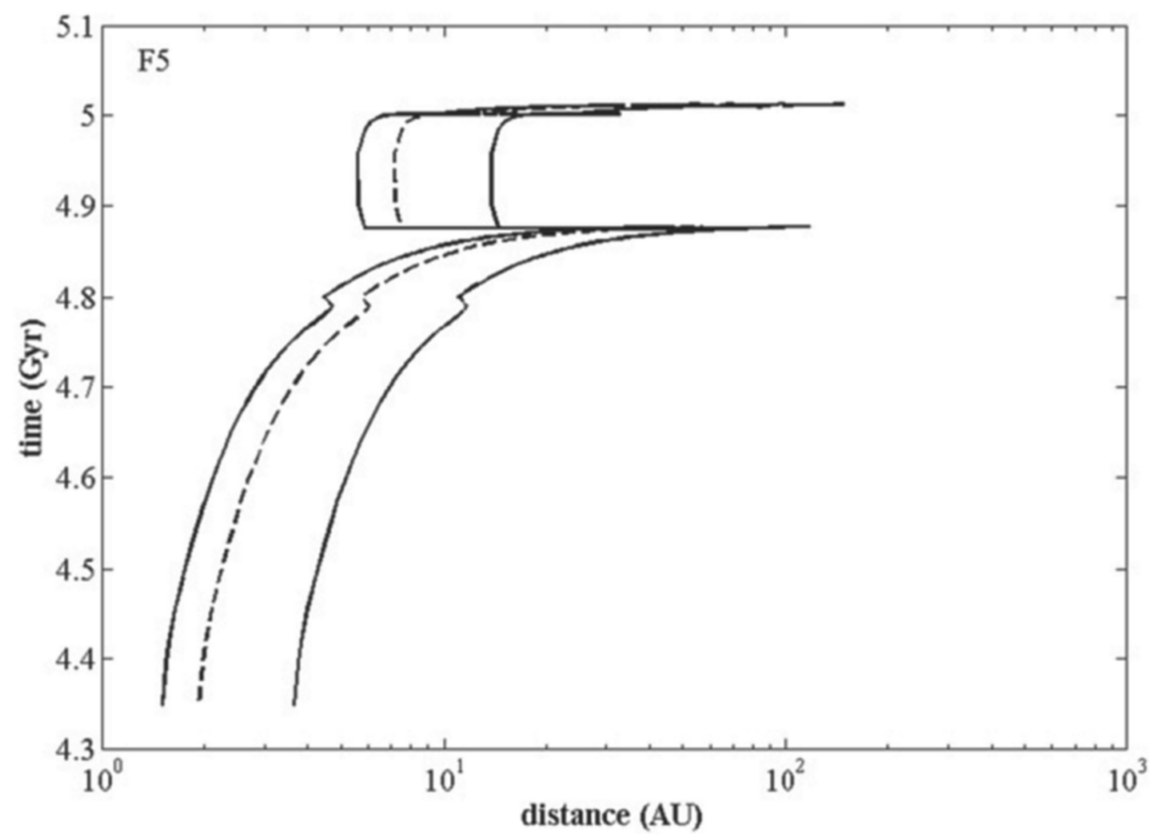


Post-main-sequence star HZ

- Stellar evolution on RGB and AGB
- Increase in luminosity and HZ distance

Ramirez & Kaltenegger (2016)





Summary

- **Concepts:**
  - Single star HZ
  - Radiative HZ
  - HZ involving dynamics (PHZ, EHZ, AHZ)
- **HZ types:**
  - Static vs Dynamical
  - P-type vs S-type
- **Other points:**
  - Eccentricities (planet & binary)
  - HZ evolution in time (stellar luminosities)

References

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