Water transport to the habitable zone and impact probabilities in the early phases of planetary systems in binary star systems

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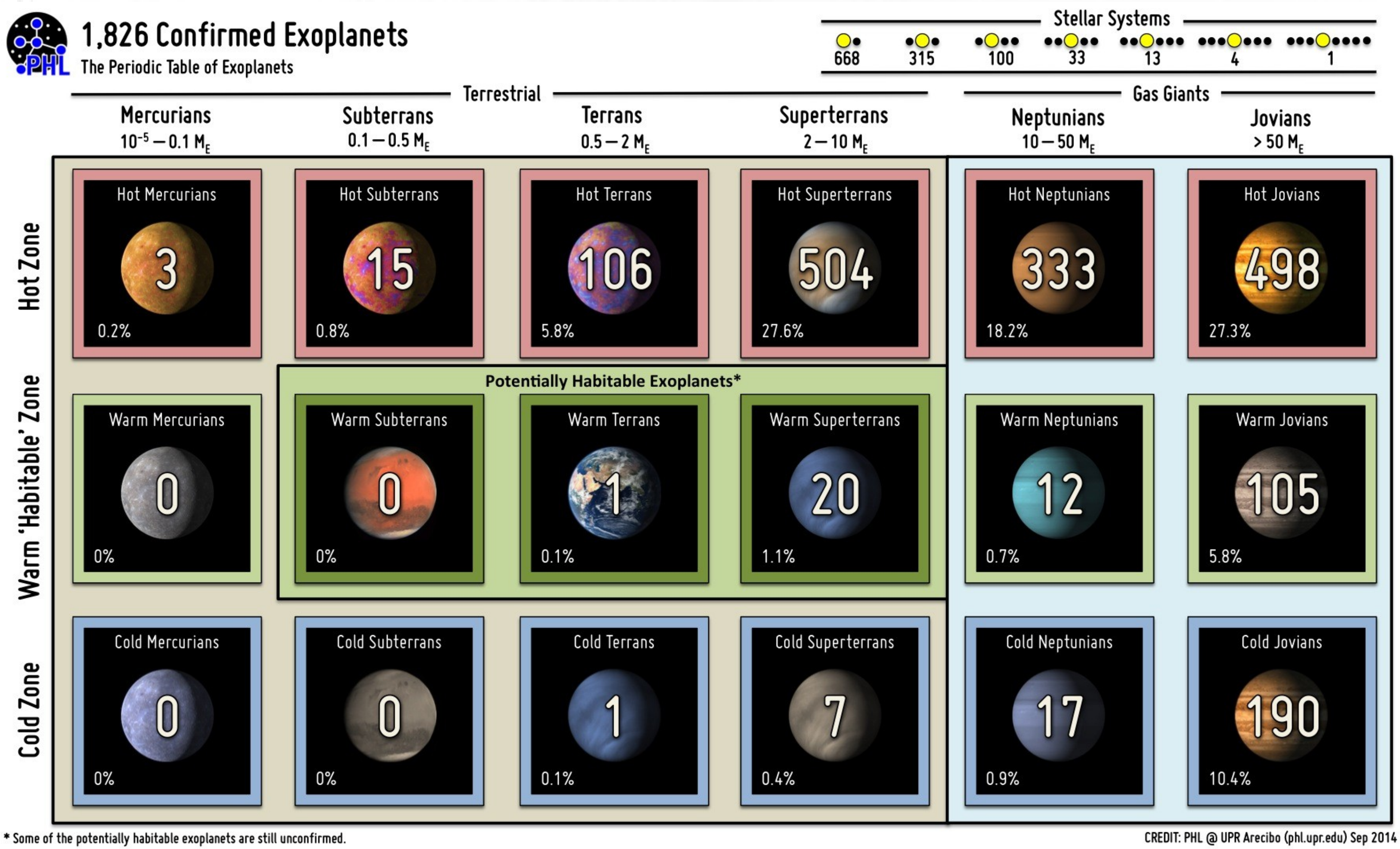
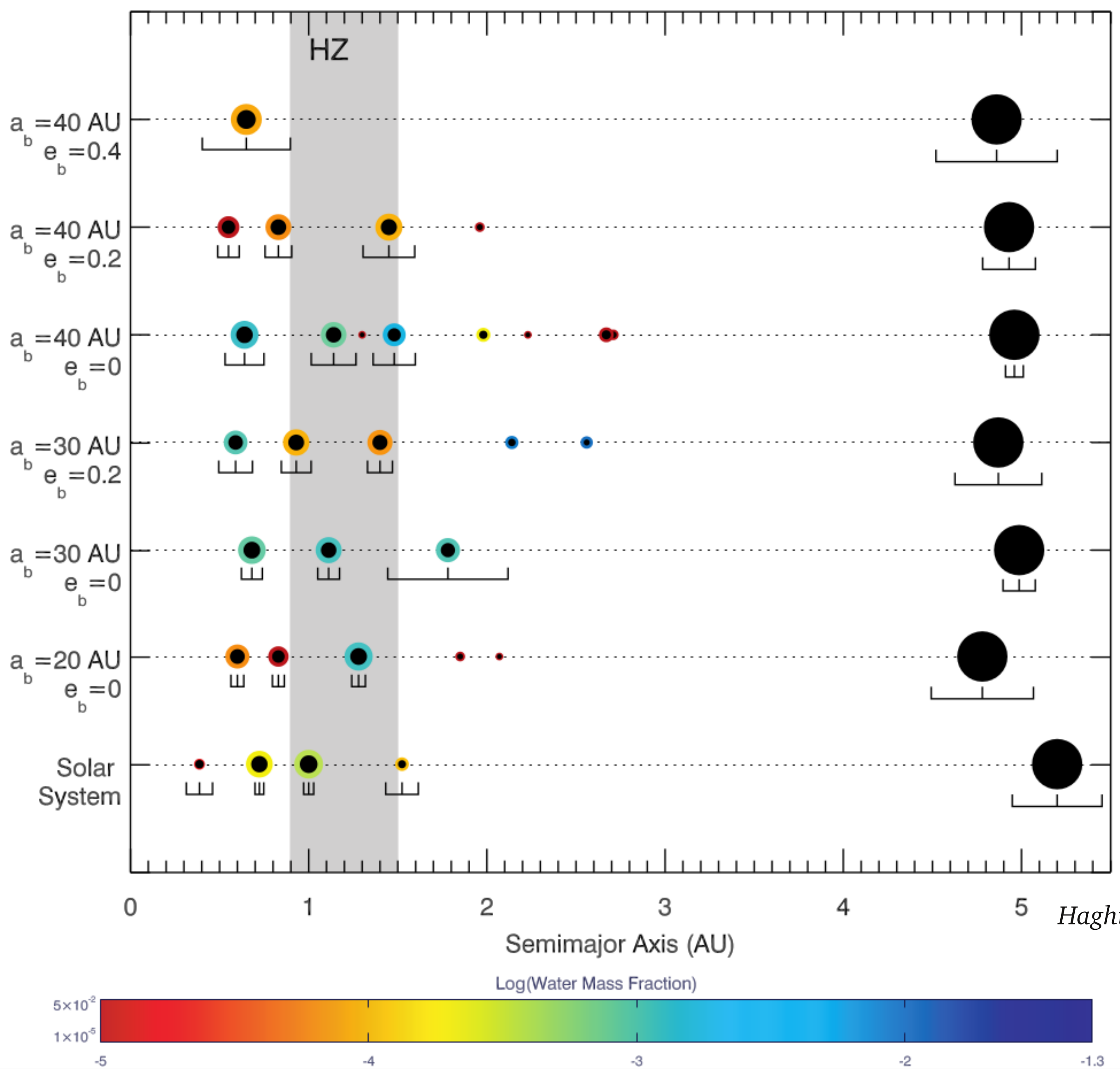
Outline :

❶ Introduction



❶ Introduction

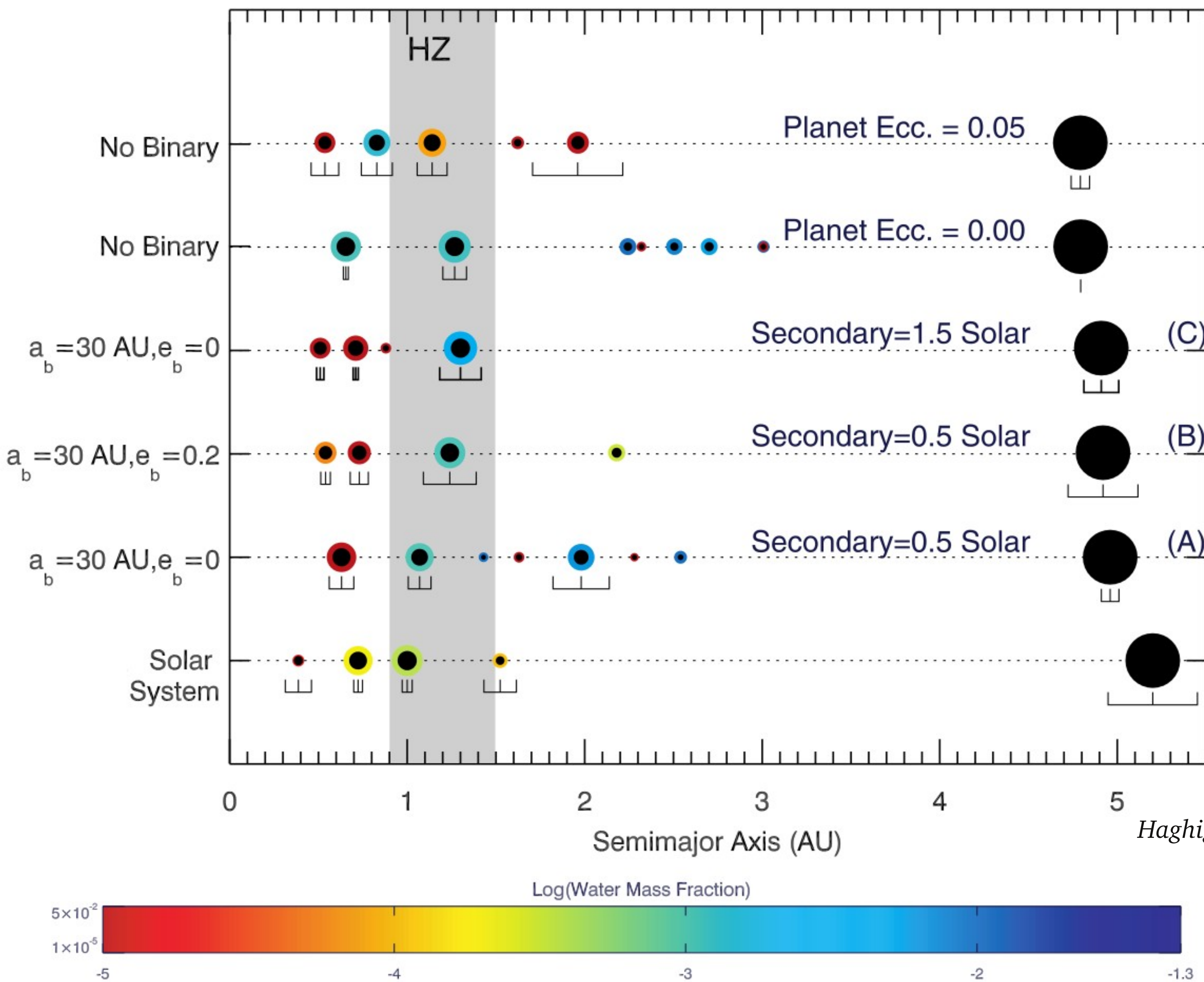
Influence of the secondary's eccentricity



Haghighipour & Raymond 2007

❶ Introduction

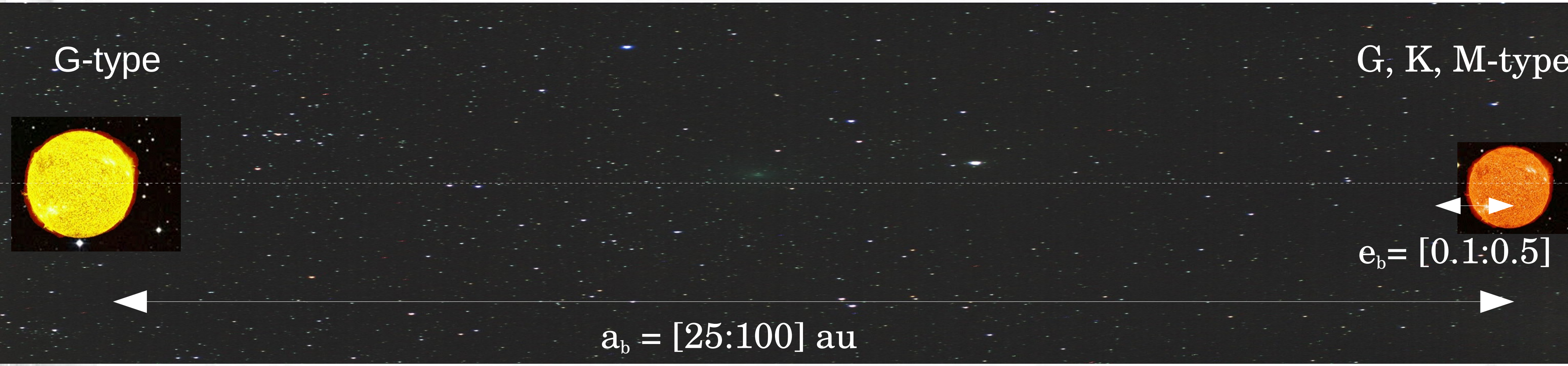
Influence of the secondary's mass – GG planet eccentricity



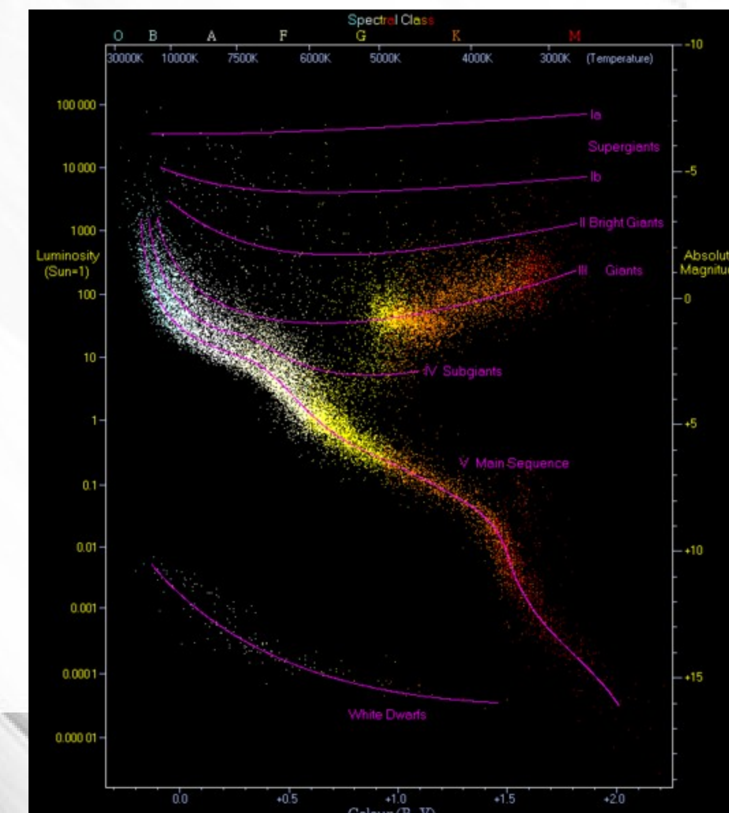
Haghighipour & Raymond 2007

❷ Initial conditions : The binary star systems

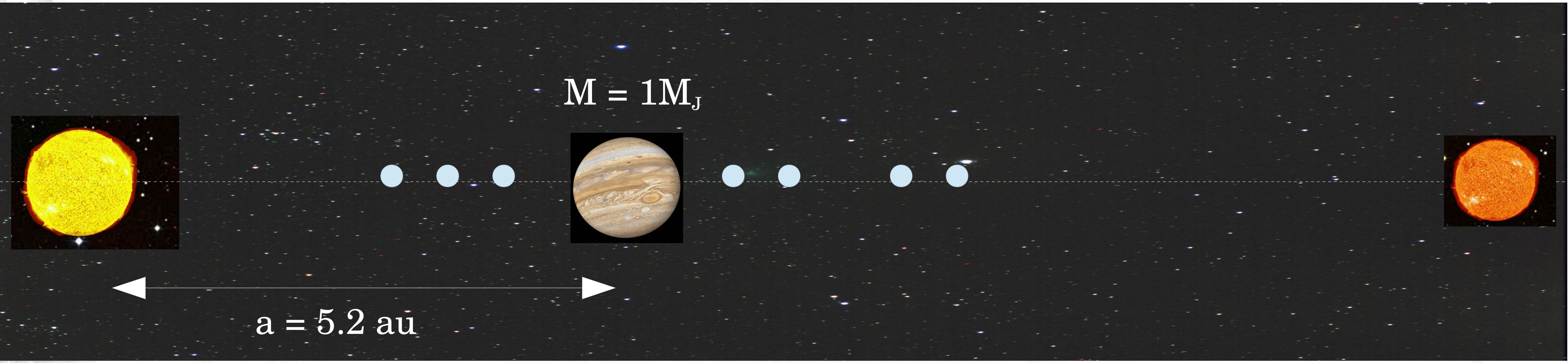
Primary : **Secondary** :



Stellar-type	$M_\star$ [$M_\odot$]	$L_\star$ [$L_\odot$]	$T_\star$ [K]
G	1.0	1.0	5780
K	0.7	0.38	5200
M	0.4	0.08	3800



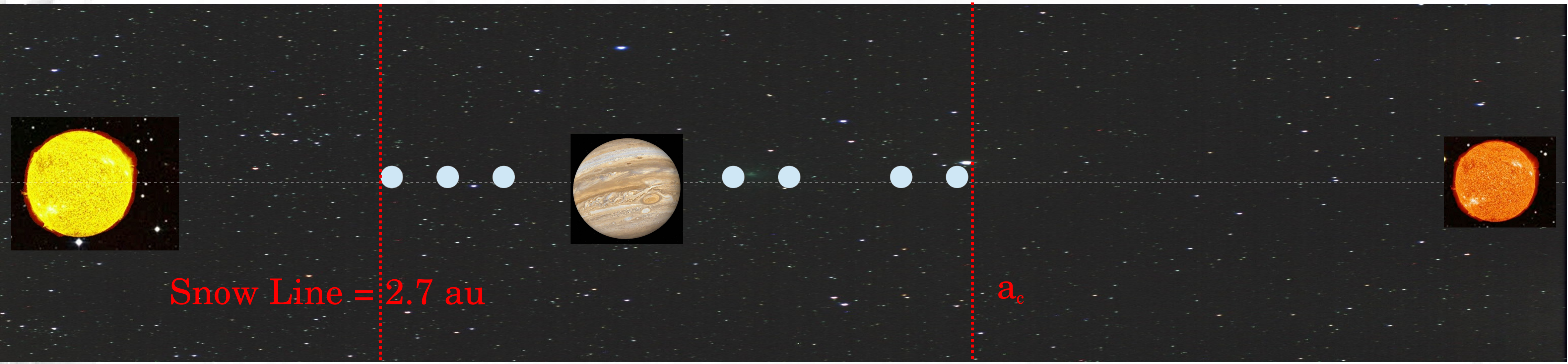
❷ Initial conditions : The asteroid ring

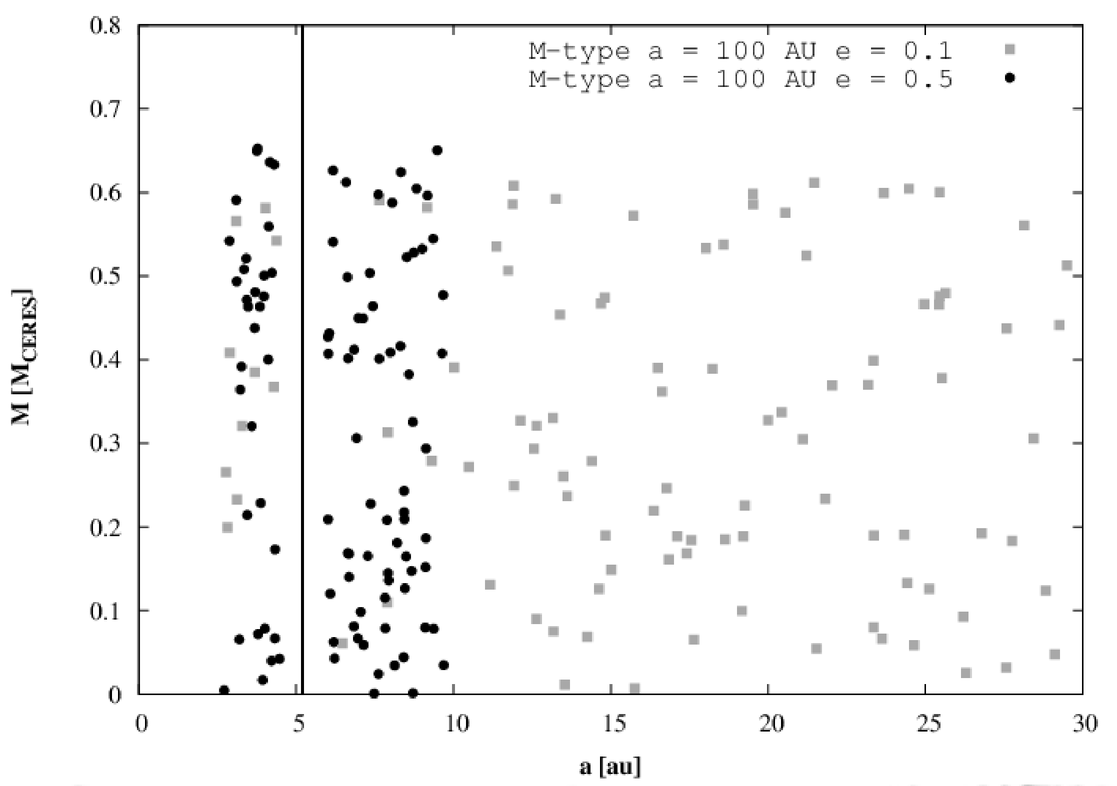


<u>Asteroids ring</u> :

- 100 asteroids with $M_{max} = 1\ M_{ceres}$
- Total mass = 0.005 M⊕
- e <0.01, i <1°
- Water mass fraction (wmf) = 10 % => 2 oceans in the ring

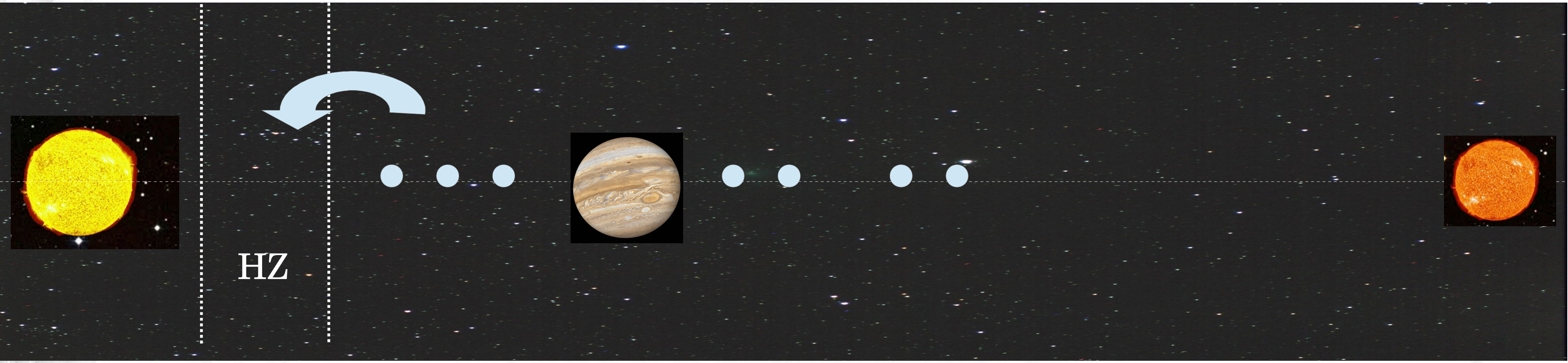
❷ Initial conditions : The asteroid ring





e_b \ a_b [AU]	25	50	75	100
0.1	K – M	G – K – M	G – K – M	G – K – M
0.3		G – K – M	G – K – M	G – K – M
0.5			M	K – M

❷ Initial conditions : Numerical method



- Lie integrator – gravitational perturbations
- 10 Myr integration
- 100 clones of each system [Primary + Giant + disk + Secondary]
- => statistics with 10000 asteroids (200 oceans)

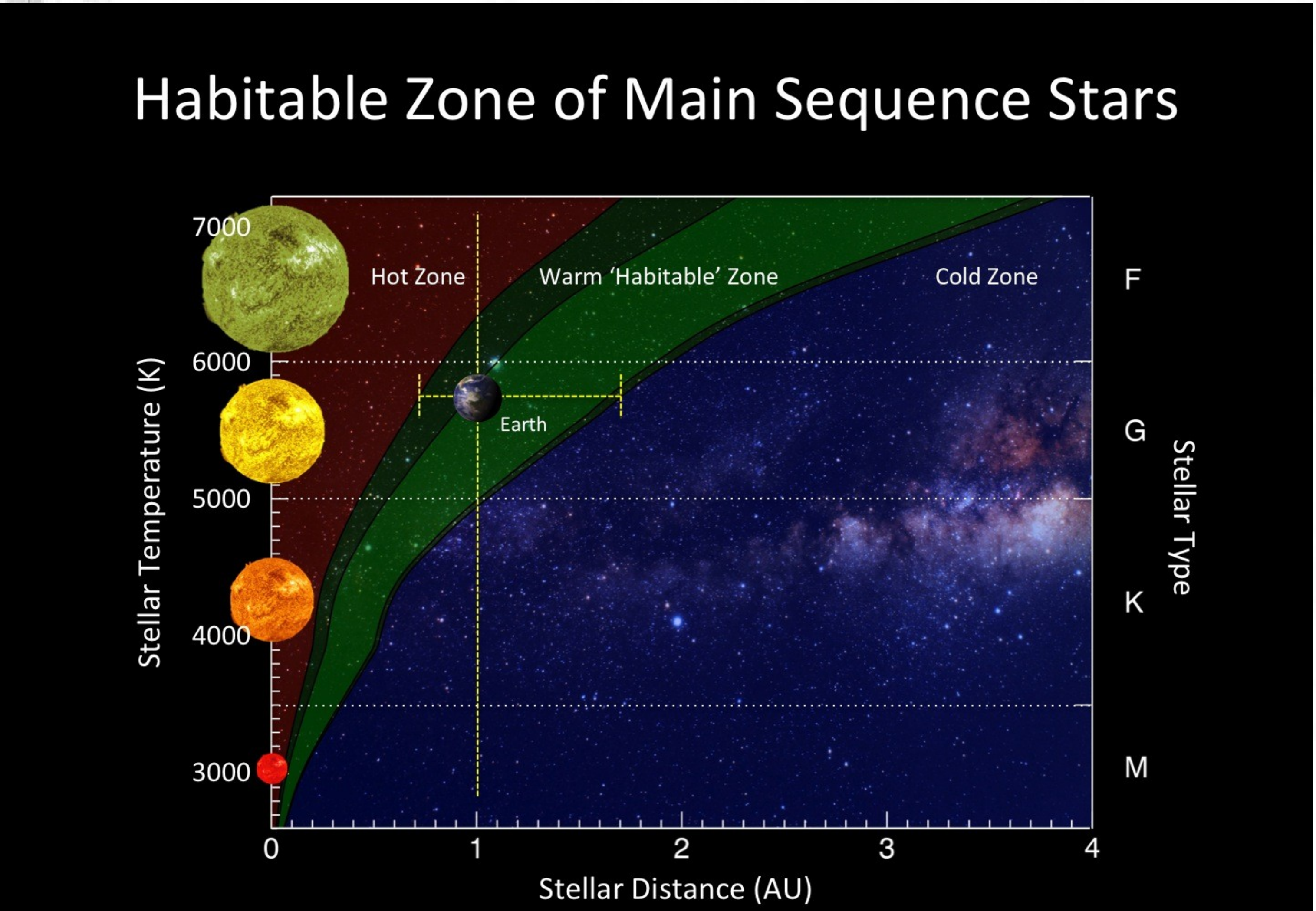
Questions :

- Dynamics of each asteroids ? [collision – ejection – Habitable Zone crossers (**HZc**)]
- Incoming amount of water in the **Habitable Zone (HZ)**?
- Water delivered to an Earth-like planet ?

❸ The habitable zone (HZ)

Definition : HZ = f (S_*,T_*), S_* = stellar flux, T_* = star temperature

Modelisation : Cloud-free climat model [*Kasting et al. 1993, Kopparapu et al, 2013]*

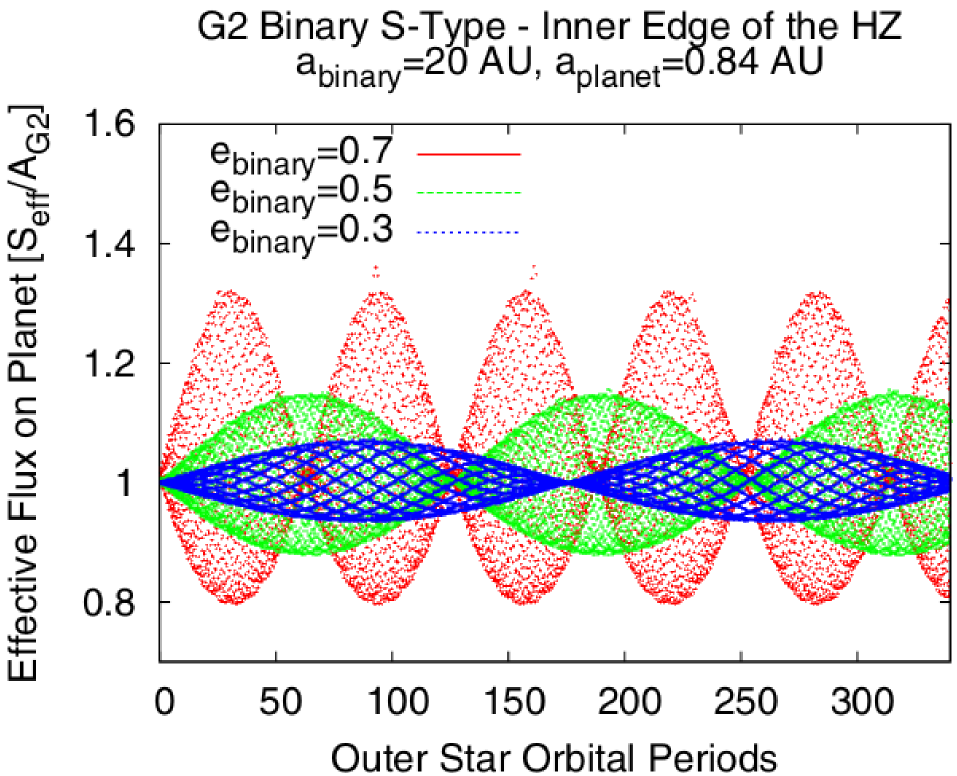


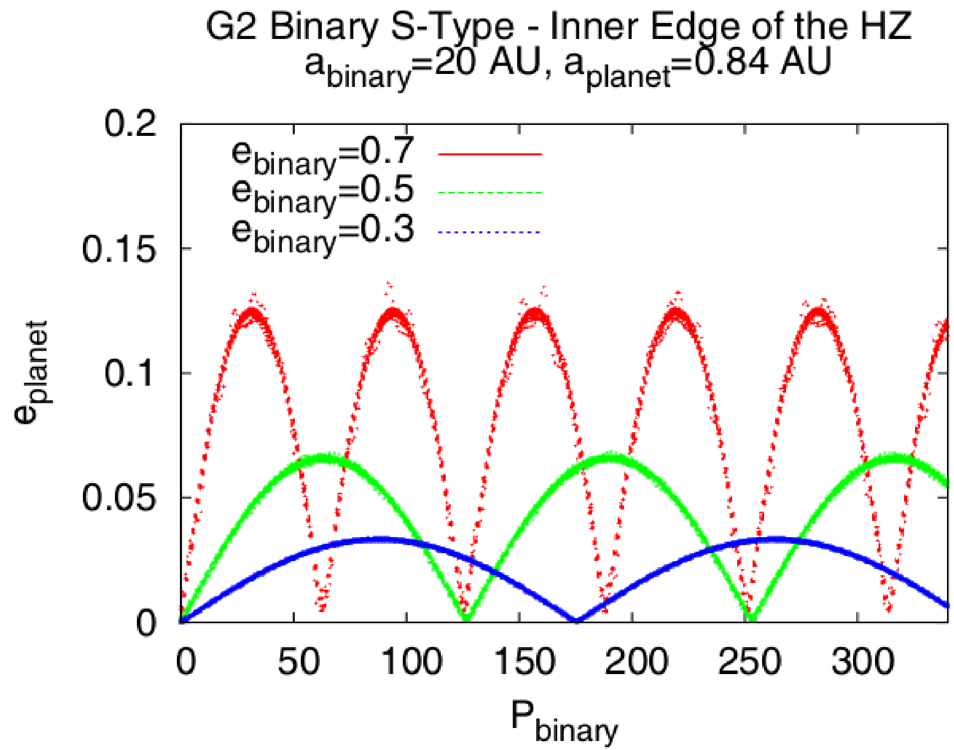
G-type : CHZ = [0.95 – 1.67] au

Recent Venus(**RV**)
Runaway Greenhouse(**RG**)
Maximum Greenhouse(**MG**
Early Mars(**EM**)

❸ The habitable zone (HZ) in binary star systems

additional radiation **+** **additional gravitational perturbation**





Eggl et al. 2012

❸ The habitable zone (HZ) in binary star systems

(A,B) = insolation limits of the corresponding CHZ

Permanently Habitable Zone (**PHZ**) : depends on e_{max} – planet must fulfil

$$A \geqslant S_{\text{eff}} \geqslant B$$

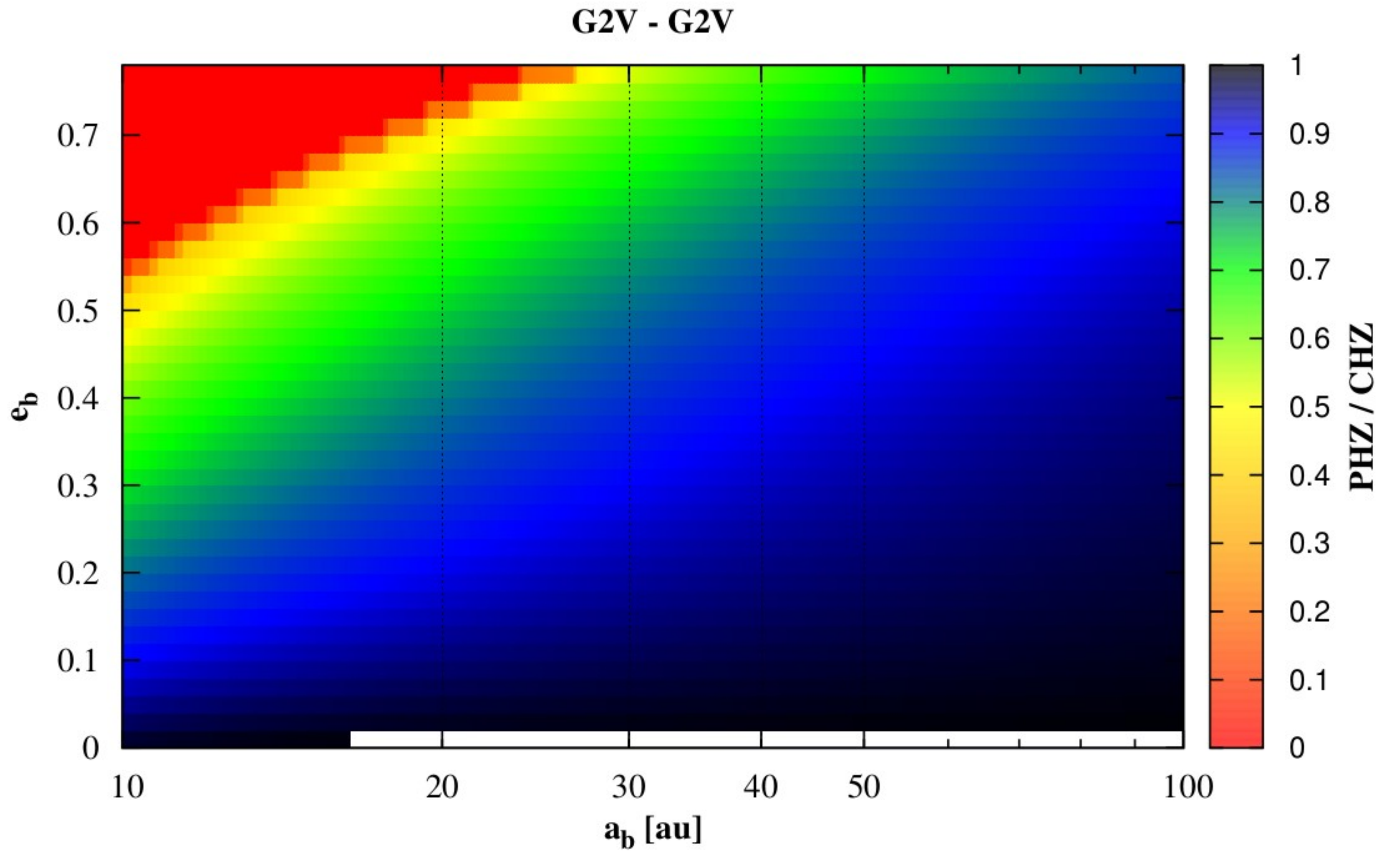
Extended Habitable Zone (**EHZ**) : depends on $<e_p>$ – planet must fulfil :

$$\langle S_{\text{eff}} \rangle_t + \sigma \leqslant A \wedge \langle S_{\text{eff}} \rangle_t - \sigma \geqslant B,$$

Average Habitable Zone (**AHZ**) : depends on $<e_p>$ – planet must fulfil :

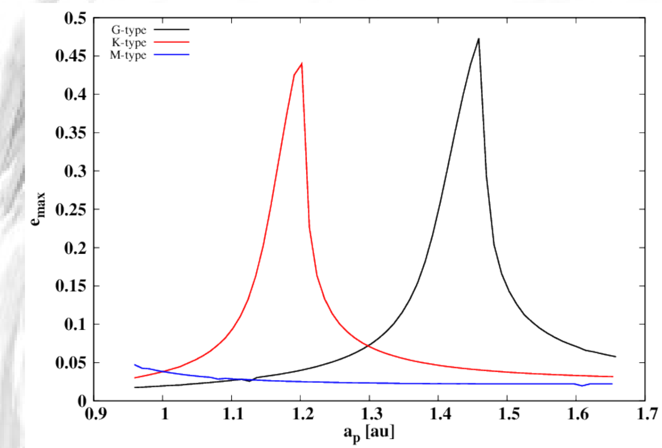
$$A \geqslant \langle S_{\text{eff}} \rangle_t \geqslant B.$$

❸ The habitable zone (HZ) in binary star systems



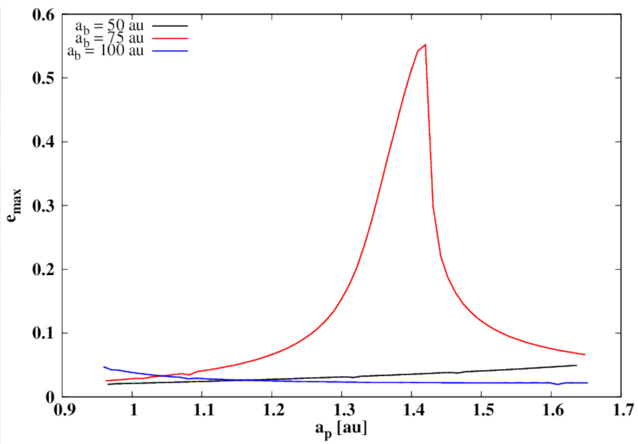
e_b \ a_b [AU]	25	50	75	100
0.1	[0.959:1.654] **[0.031]**	[0.955:1.664] **[0.017]**	[0.954:1.668] **[0.012]**	[0.953:1.670] **[0.009]**
0.3		[0.964:1.639] **[0.051]**	[0.959:1.651] **[0.034]**	[0.957:1.657] **[0.026]**
0.5			[0.968:1.627] **[0.067]**	[0.964:1.638] **[0.052]**

❸ The habitable zone (HZ) in binary star systems + giant planet

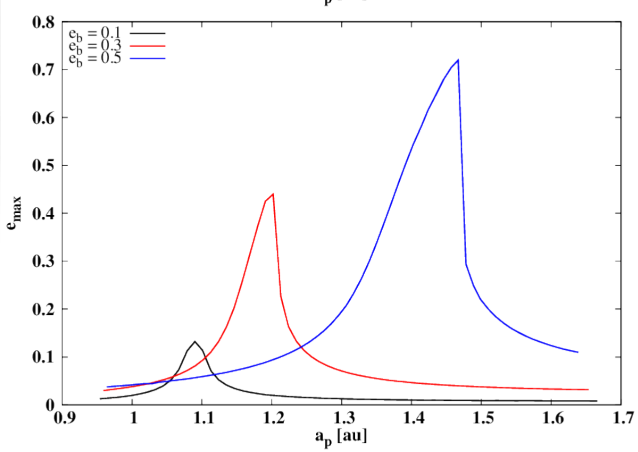


=> Secular perturbation … sometimes inside HZ

(a_b, e_b) fixed – M_* variable: secular perturbation shifts closer to primary for decreasing M_*



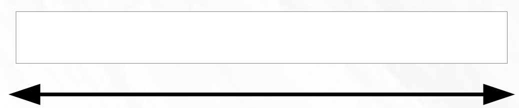
(e_b, M_*) fixed – a_b variable: secular perturbation shifts closer to primary for increasing a_b



(a_b, M_*) fixed – e_b variable: secular perturbation shifts closer to giant planet for increasing e_b

❸ The habitable zone (HZ) in binary star systems + giant planet

Consequence for the (**A**)(**E**)(**P**)**HZ** borders



CHZ [0.95 – 1.676 au]

❸ The habitable zone (HZ) in binary star systems + giant planet

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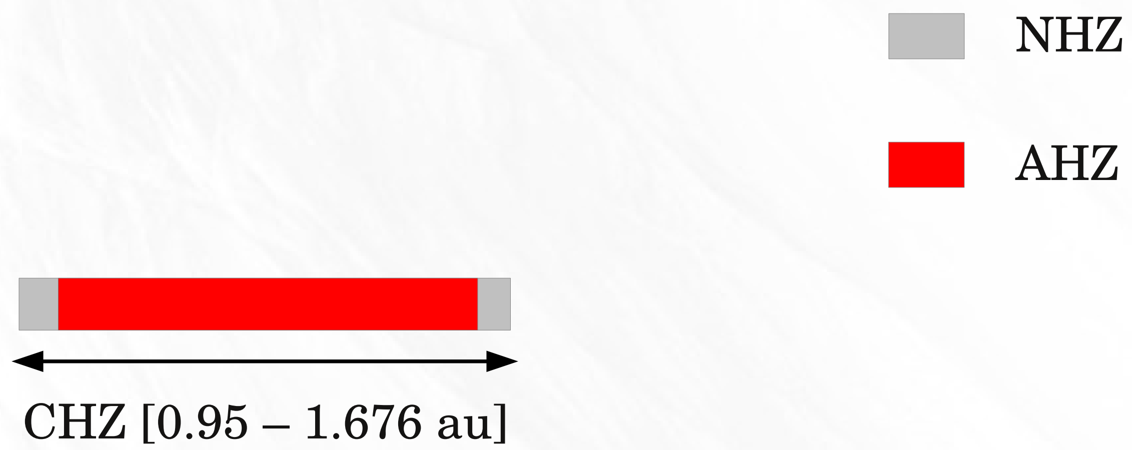

❸ The habitable zone (HZ) in binary star systems + giant planet

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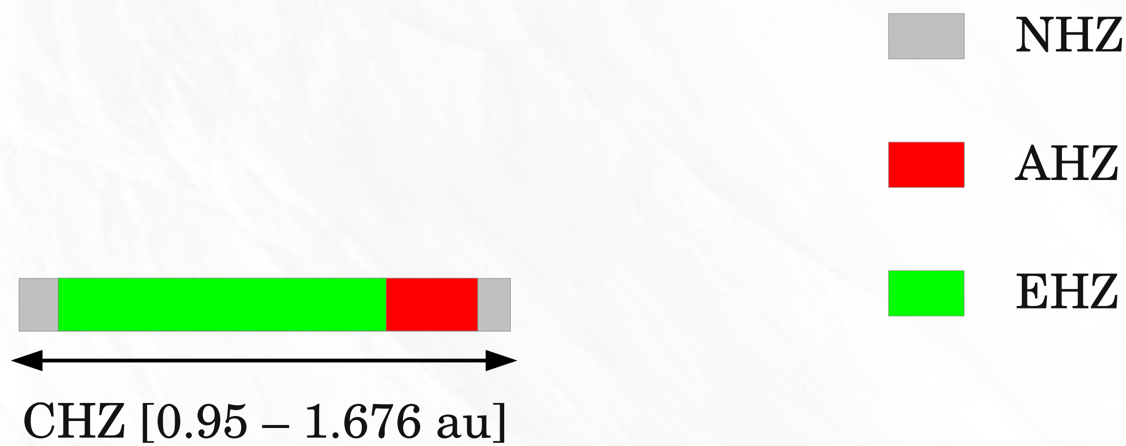

❸ The habitable zone (HZ) in binary star systems + giant planet

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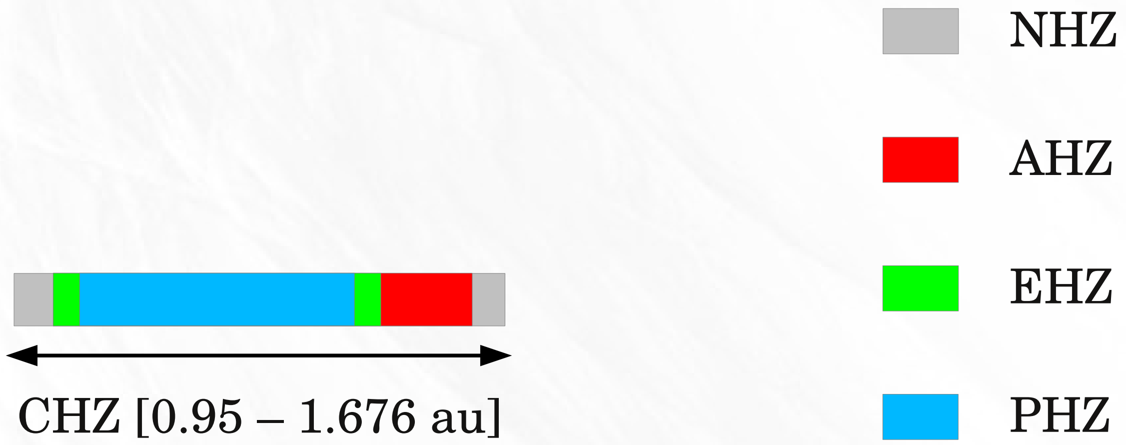

❸ The habitable zone (HZ) in binary star systems + giant planet

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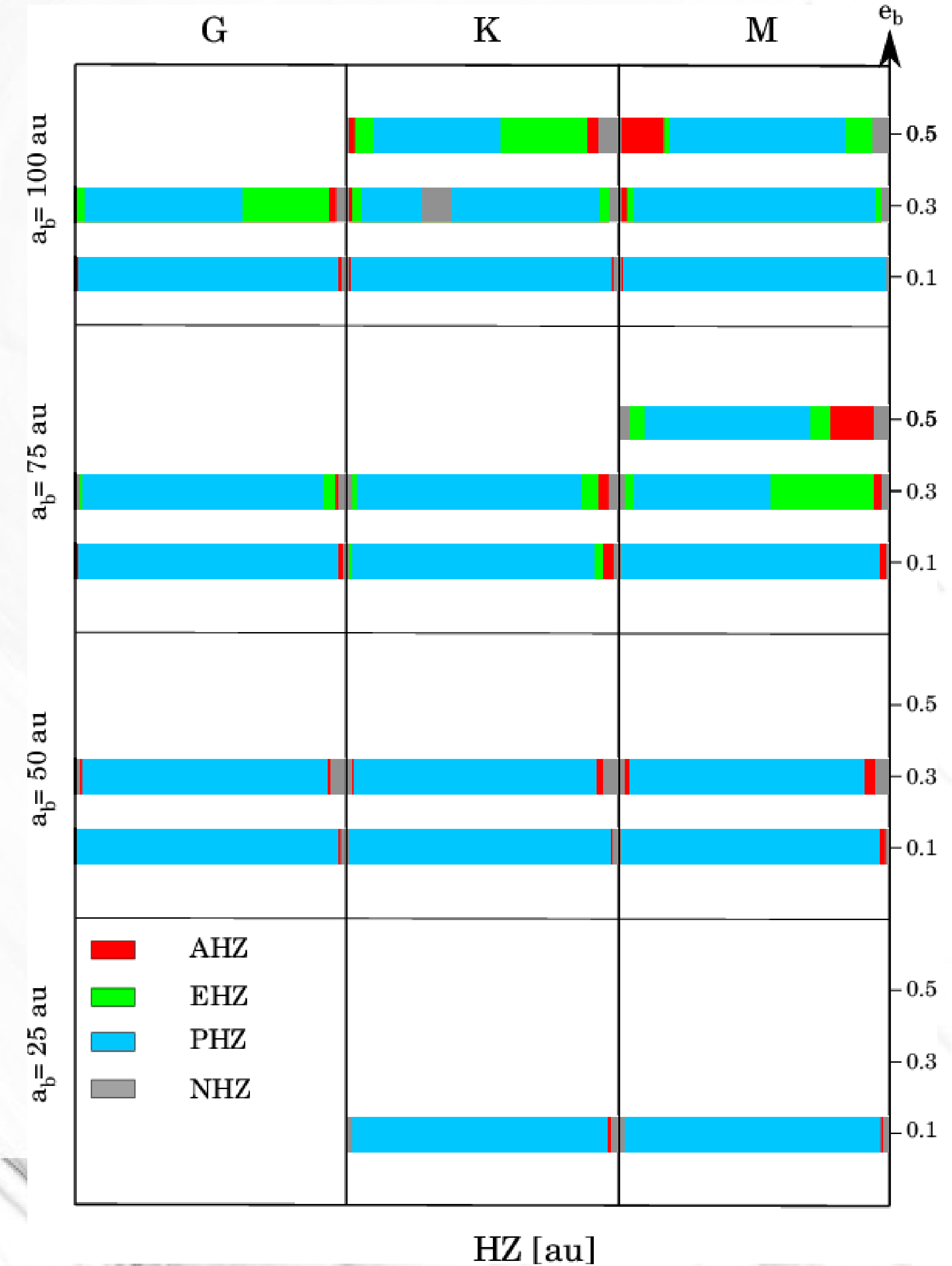
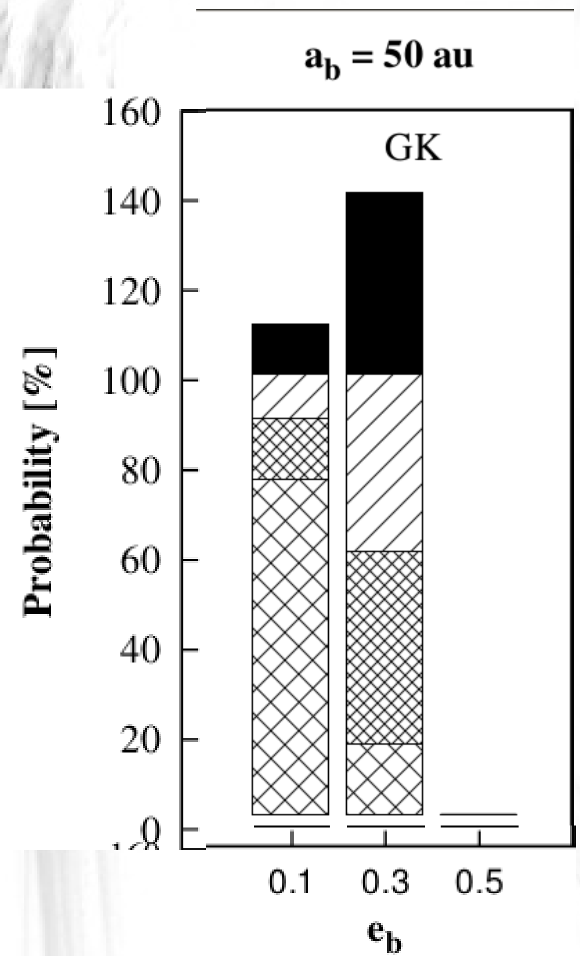
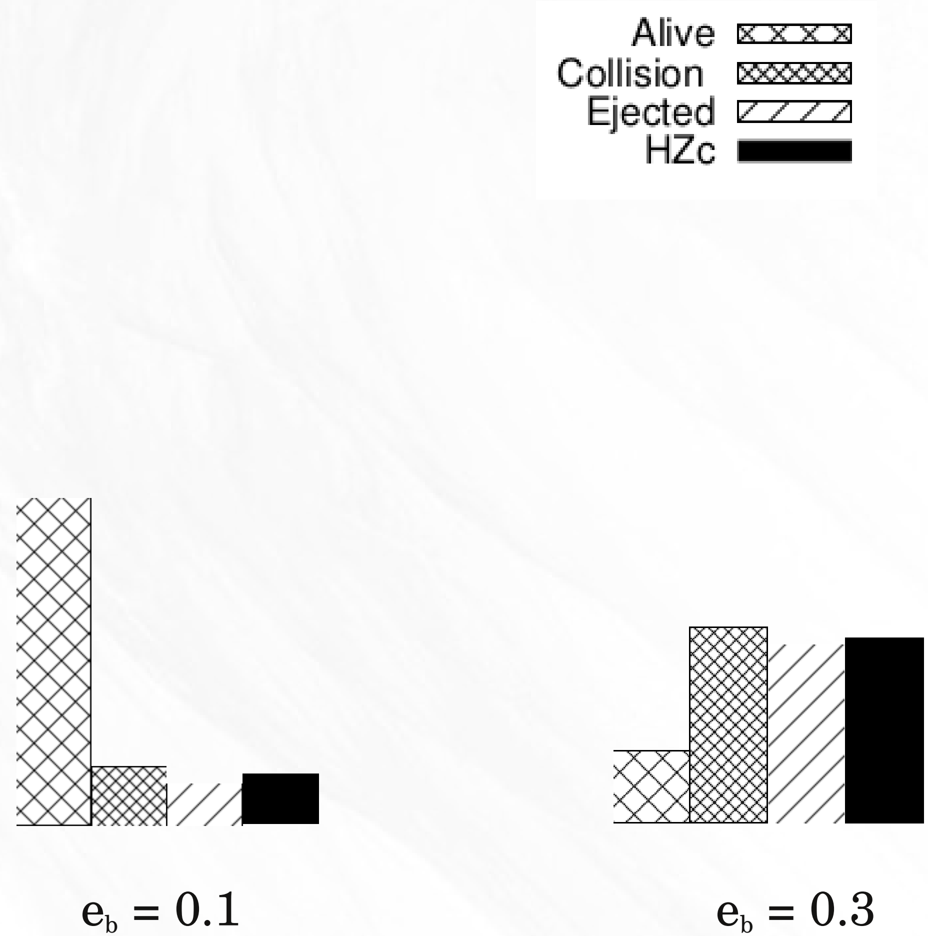


❹ Water transport (1) – asteroids dynamics





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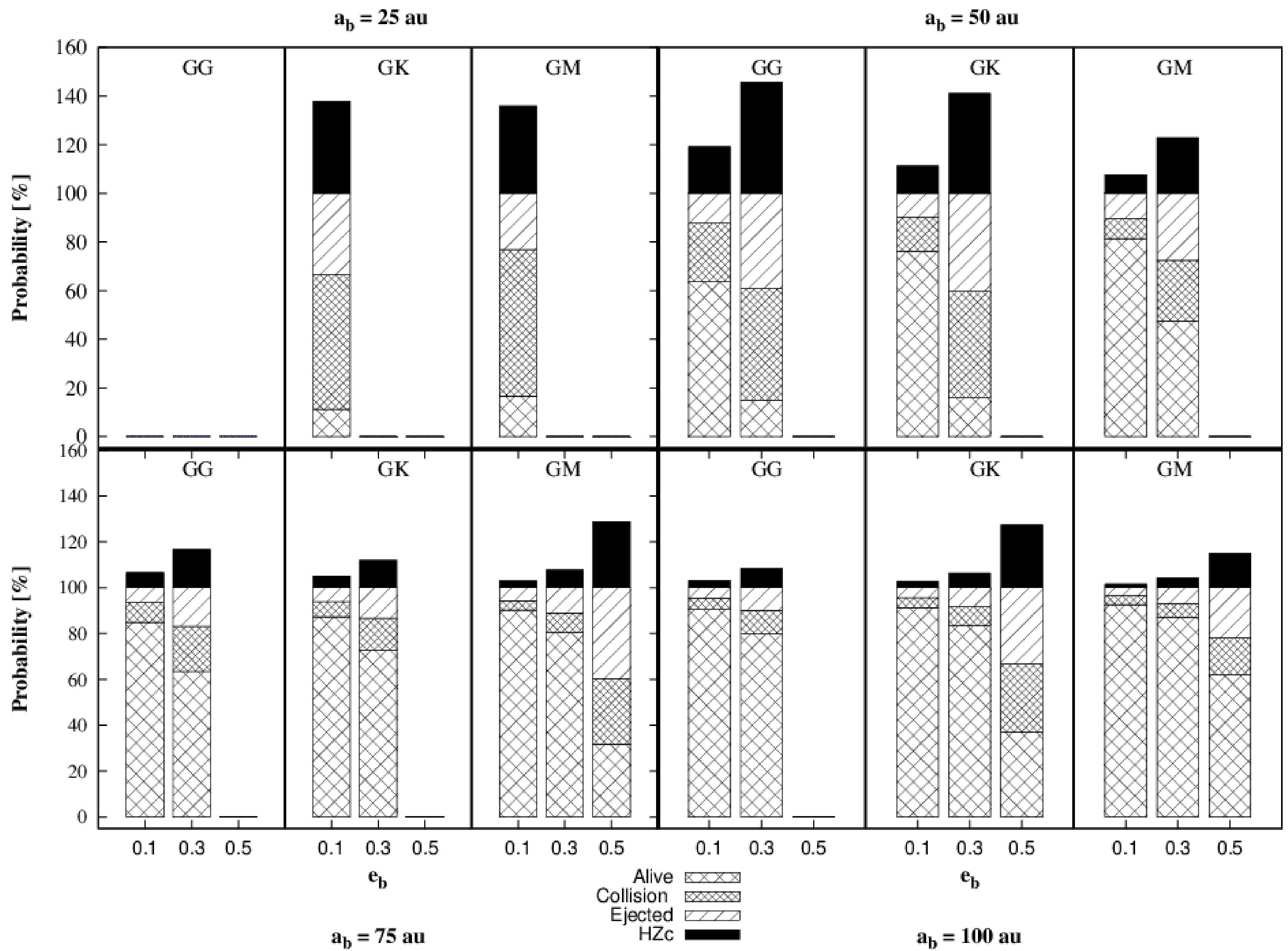
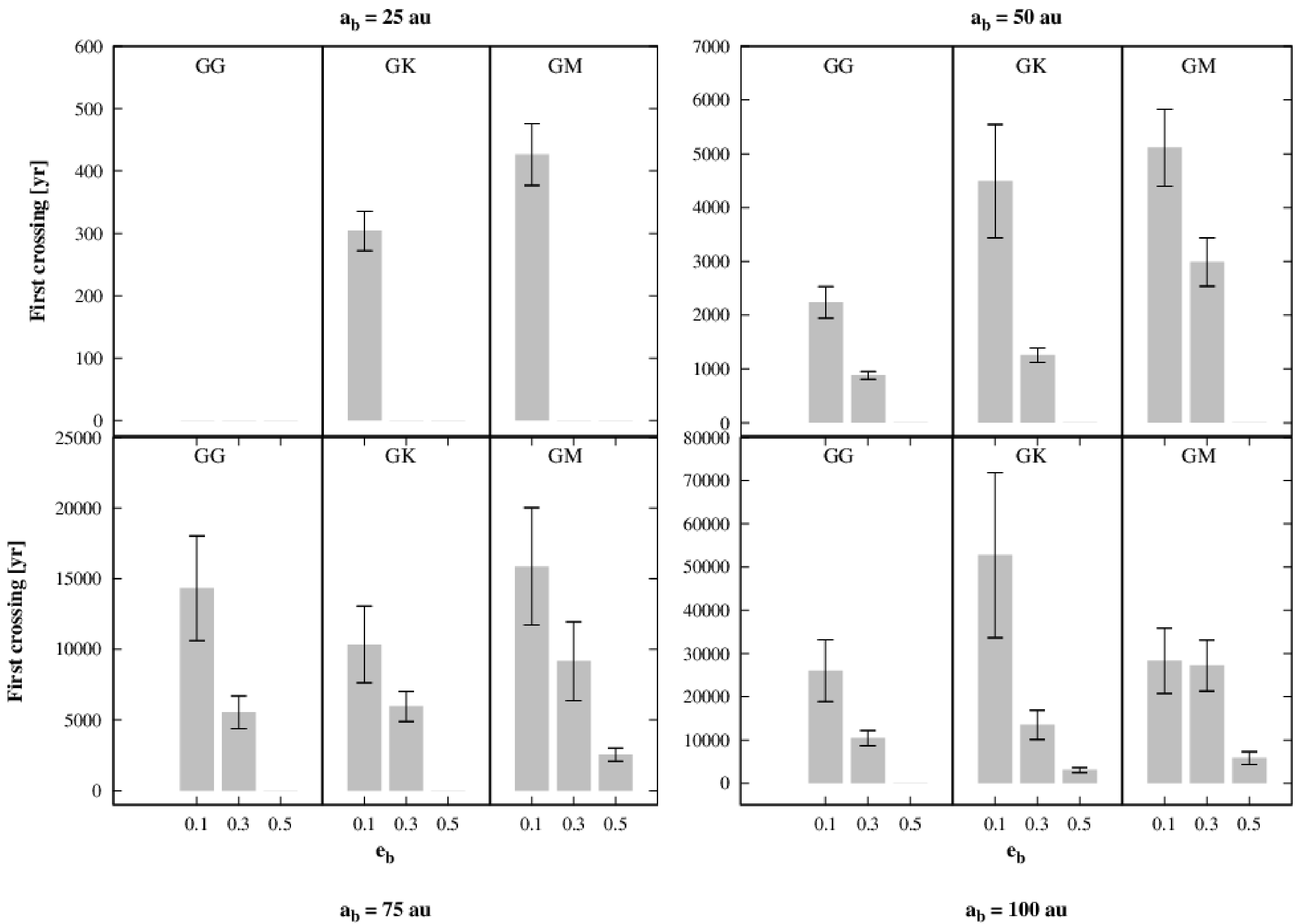


❹ Water transport (2) – Timescale statistics

Time to reach the HZ



❹ Water transport (3) – water content of incoming HZc

Mass loss due to ice sublimation

Sublimation mass flux [kg/m²/s]

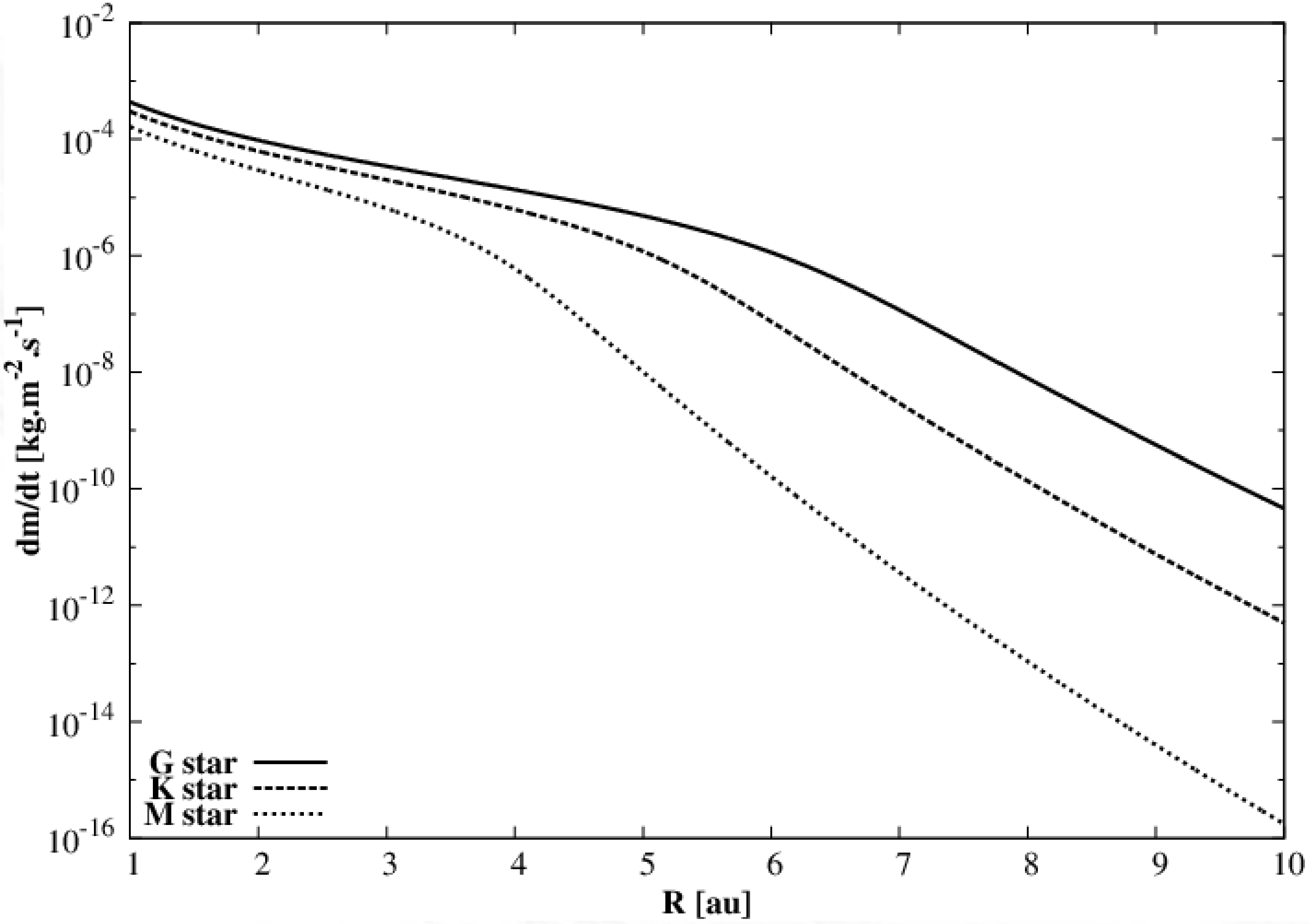
$$\sum_{i=1}^{2} \frac{F_{\star,i}(1-A_i)}{R_i^2[\mathrm{au}]} \cos\theta_i = \epsilon\sigma T^4 + L(T)\dot{m}(T)$$

Energie received at the surface

Thermal re-radiation

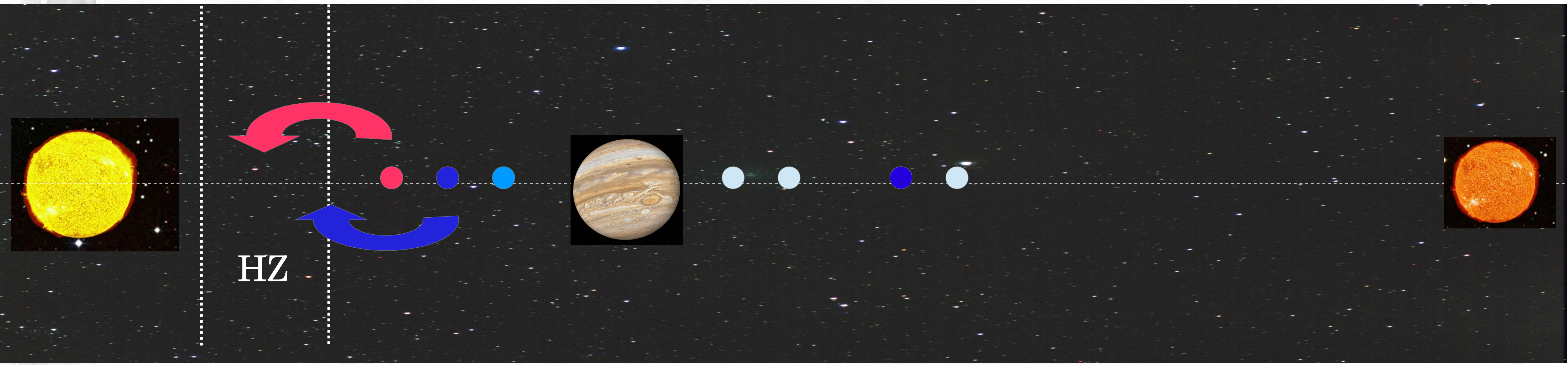
Ice sublimation

❹ Water transport (3) – water content of incoming HZc



❹ Water transport (3) – water content of incoming HZc

Check wmf of HZc when crossing the HZ for the 1st time



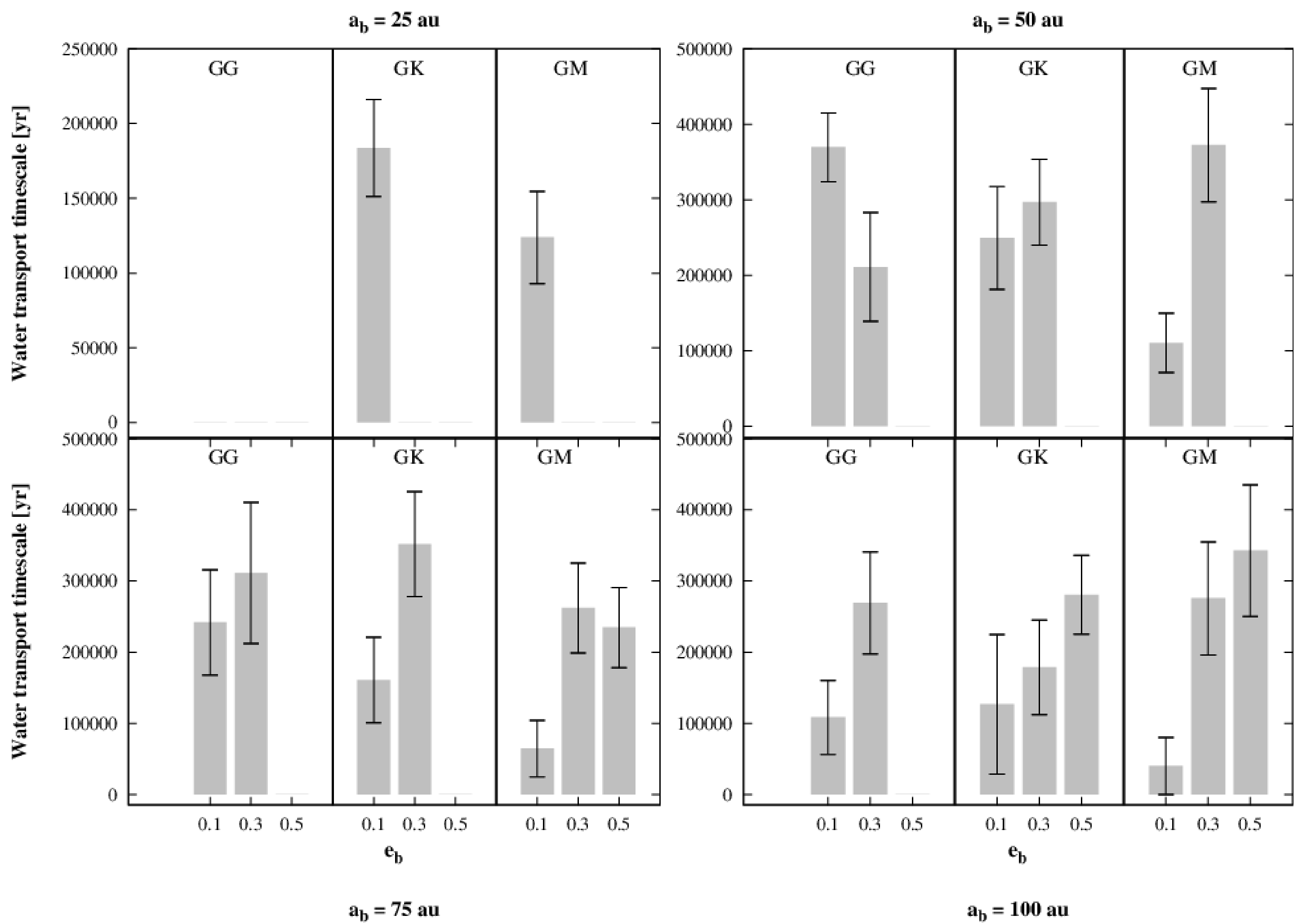
● = HZc n° 1 – wmf (t_1)

● = HZc n° 2 – wmf (t_2)

$$\text{Total water} = \sum_{i=1}^{n} \text{wmf}\,(i)$$

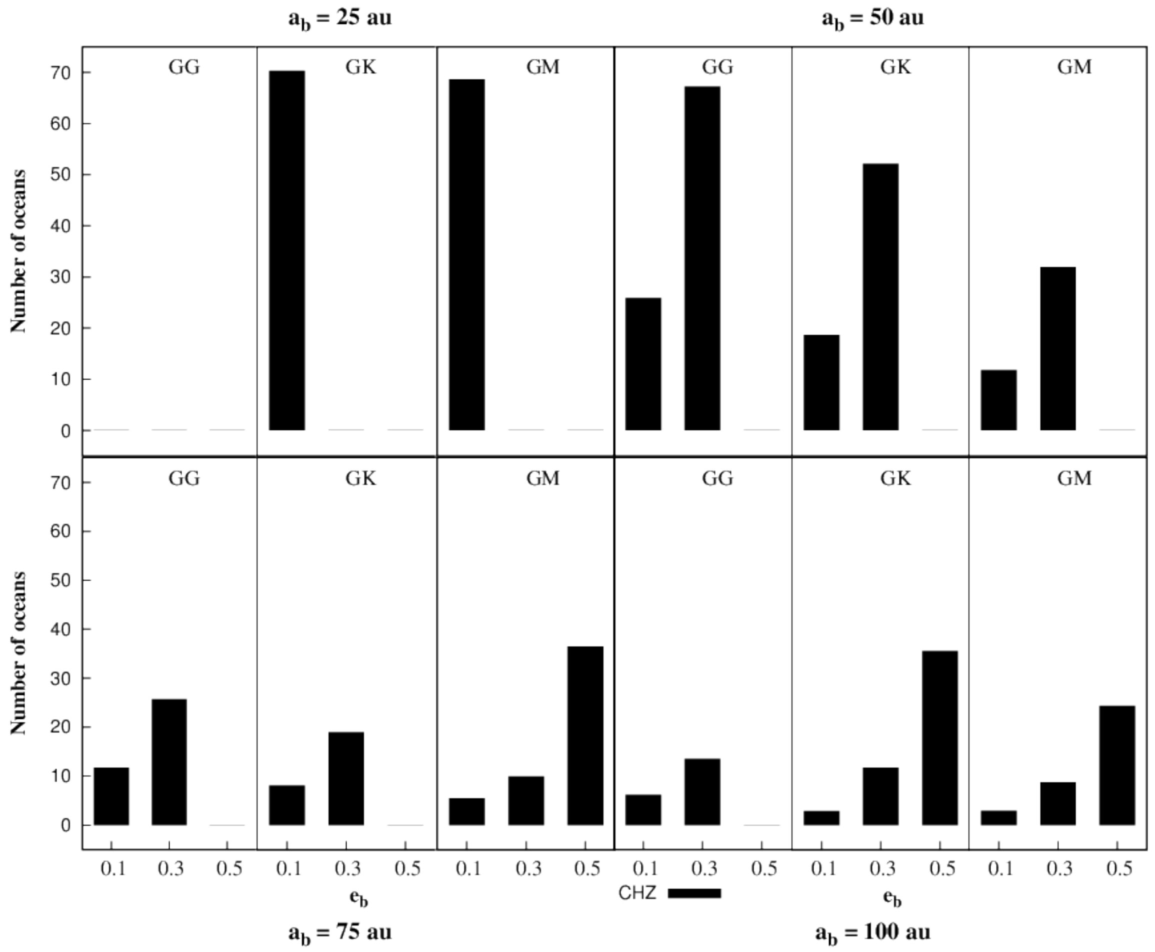
❹ Water transport (3) – water content of incoming HZc

Water delivery timescale



❹ Water transport (3) – water content of incoming HZc

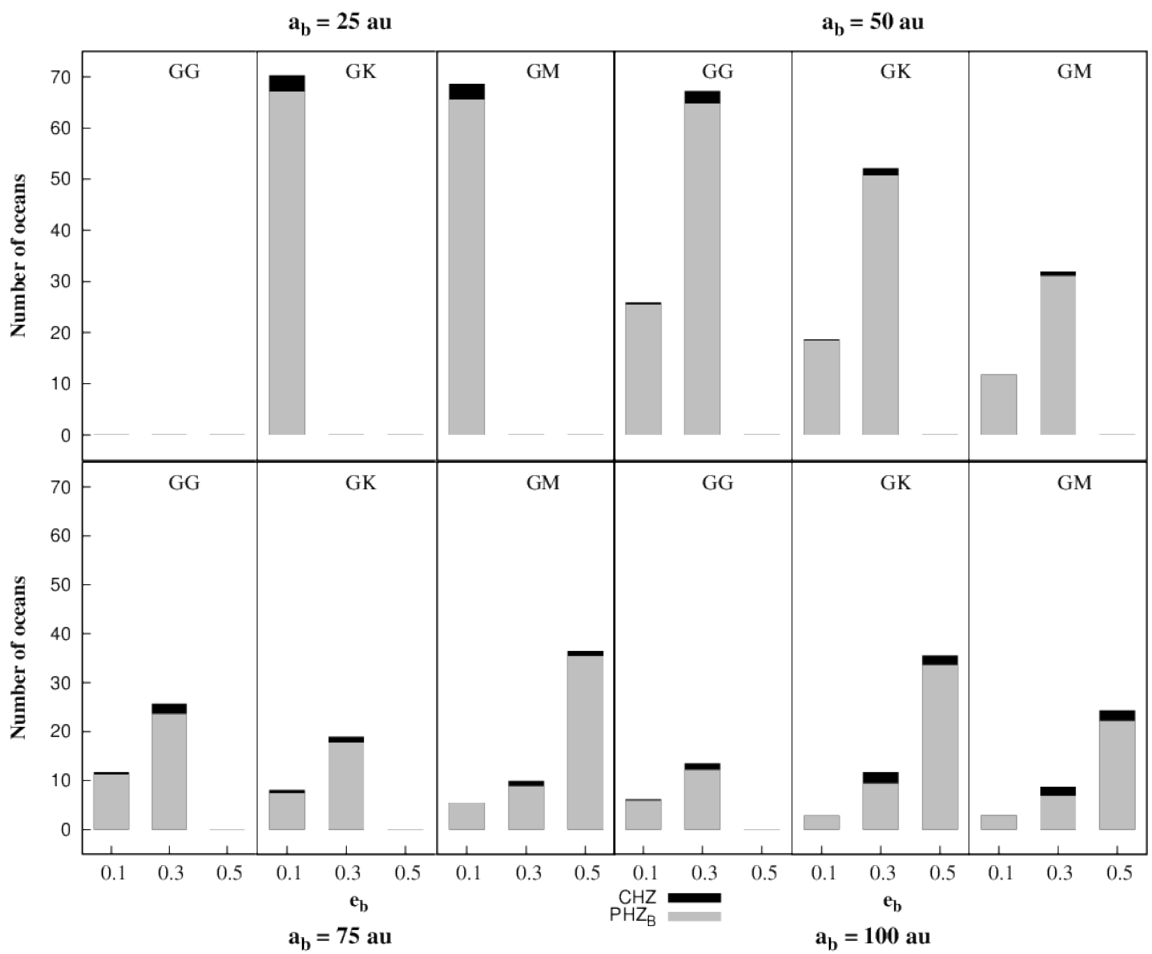
Using single star HZ definition : ■ CHZ



- 70 oceans transported to the HZ ~ 35% of the initial content
- Fast and efficient systems to make a planet habitable

❹ Water transport (3) – water content of incoming HZc

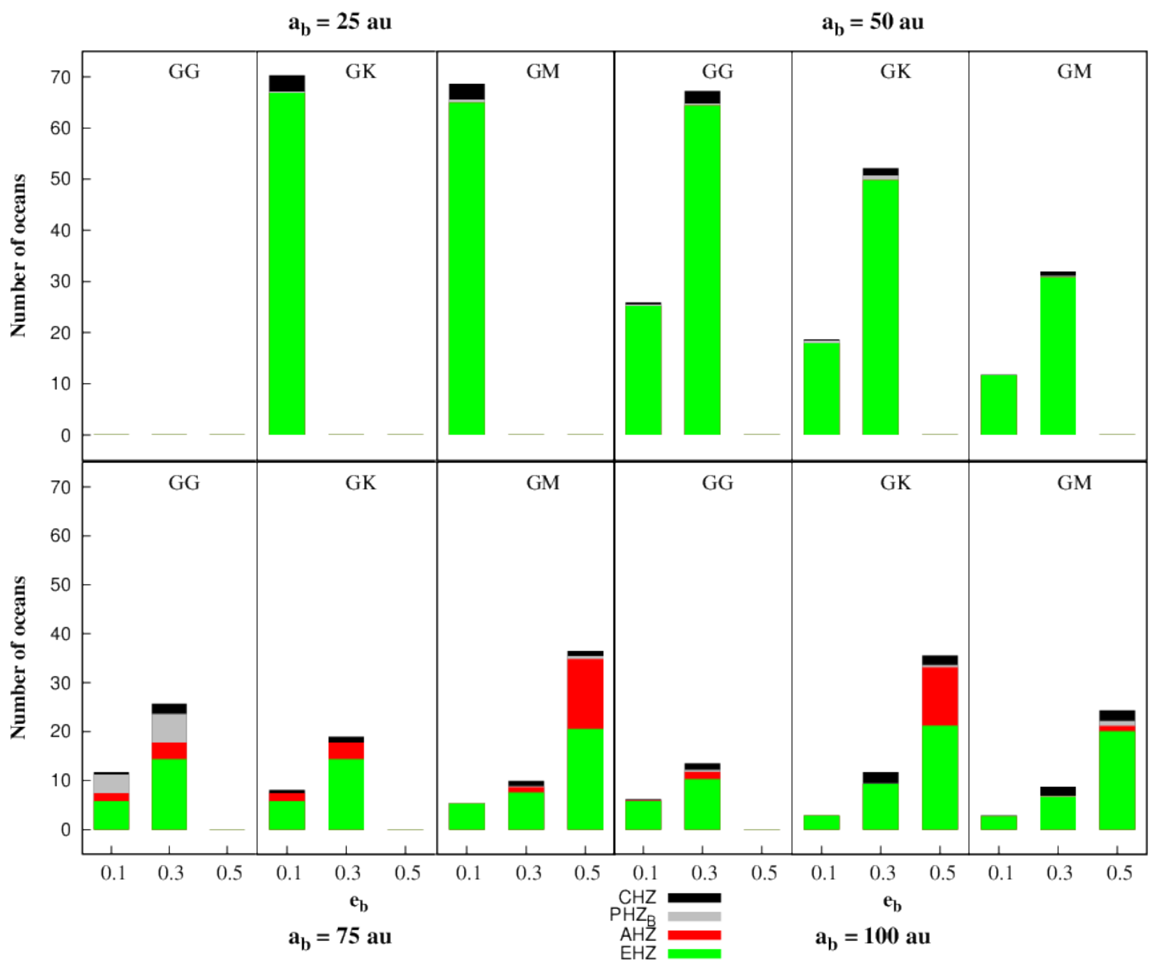
Using binary star HZ definition : ▢ PHZ_B



- Small estimation error with CHZ (single star) and PHZ_B (binary)

❹ Water transport (3) – water content of incoming HZc

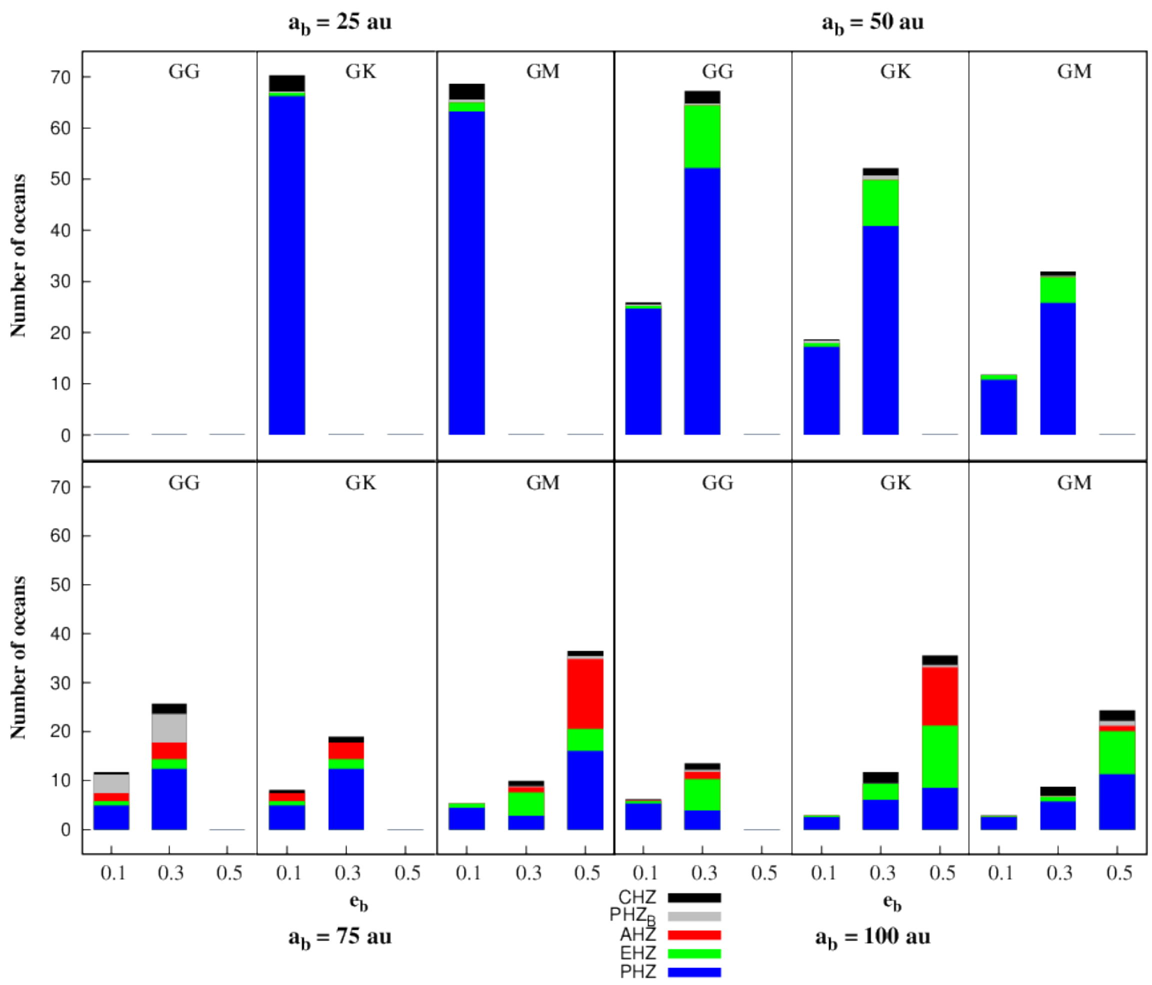
Using binary star + giant HZ definition : AHZ EHZ



- Planets in distant binary systems most affected by the secular perturbation

❹ Water transport (3) – water content of incoming HZc

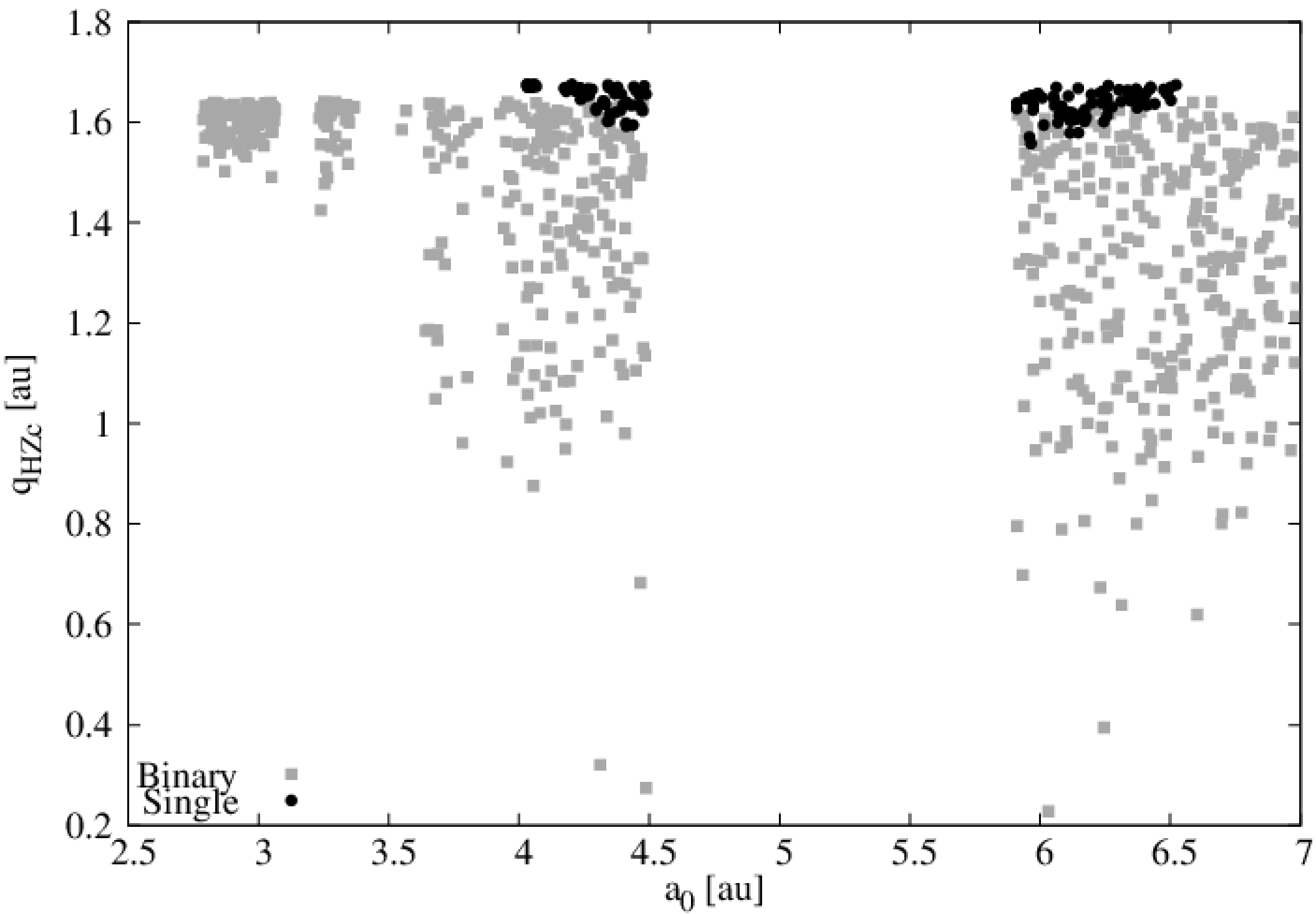
Using binary star + giant HZ definition : PHZ



- ~50 % less of water with the PHZ definition
- Terrestrial planets in tight binaries are more likely to be fed with water in tight binaries

❹ Water transport (4) – Comparison with single star syst.

(a) HZc dynamics



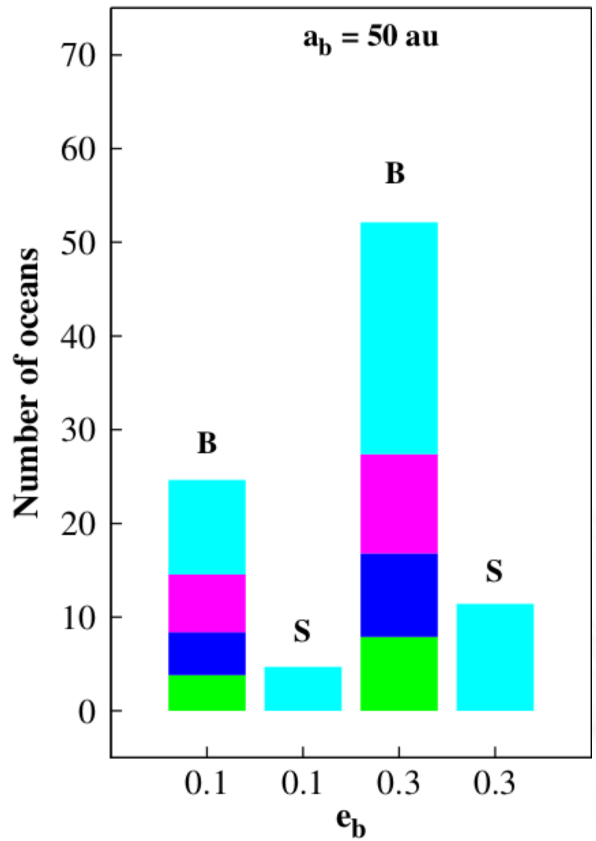
~4 – 6 less HZc in single star syst.

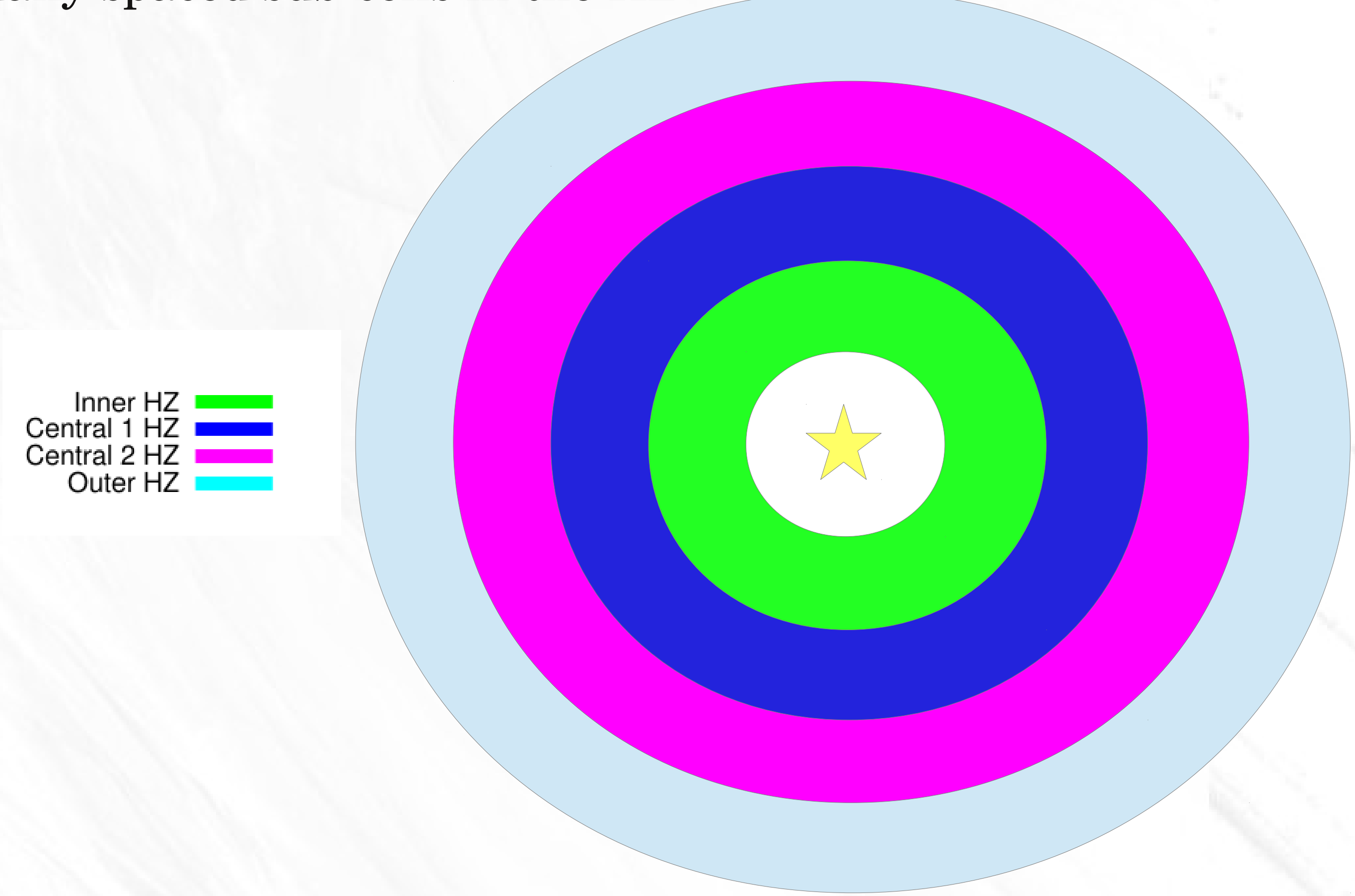
~2 – 20 times longer to reach the HZ in single star syst.

❹ Water transport (4) – Comparison with single star syst.

(b) Transport of water

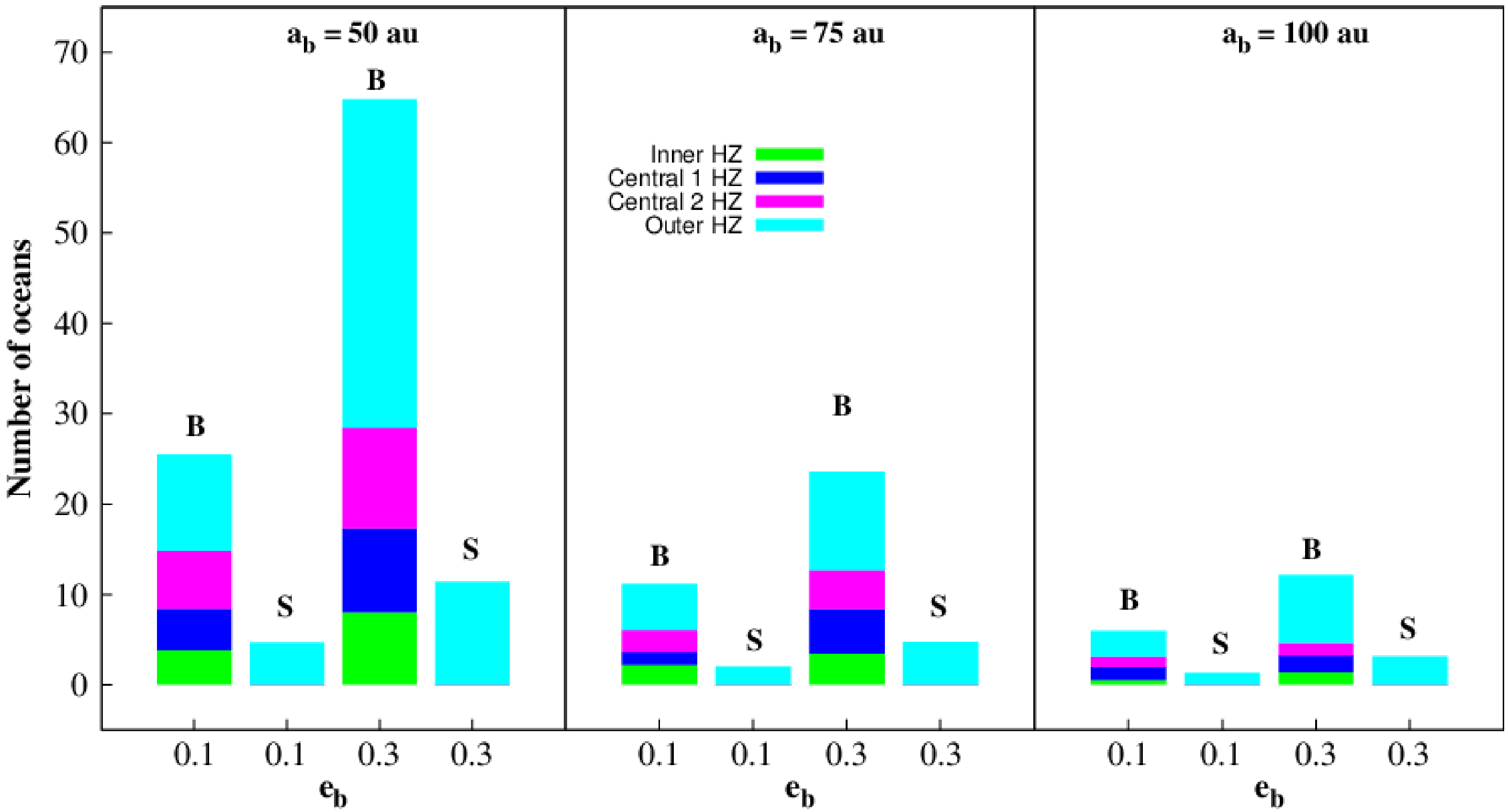
4 equally spaced sub-cells in the HZ





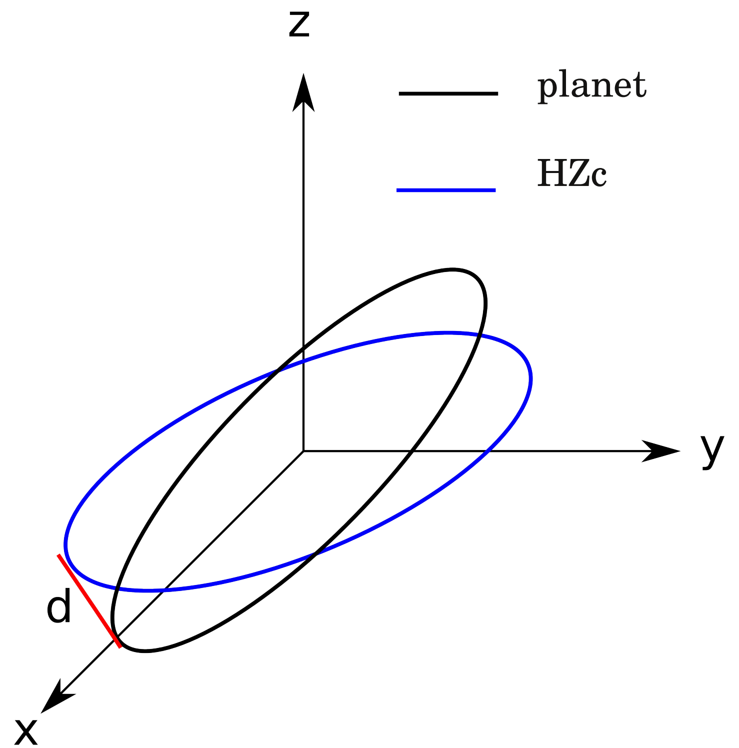
❹ Water transport (4) – Comparison with single star syst.

(b) Transport of water



❺ Water delivery to a TP (1) – Conditions for impact

(2) Check minimum orbital distance planet (MOID) – HZc



- **Computation of d = MOID** :
  - orbital elements of HZc (given by my outputs)
  - orbital elements of the planet : $(a_P, e_P, 0,0,0,0)$ but :
    - e_P randomly between $[0:e_{max}]$ = 100 test orbits
    - $a_P \in [a_i : a_{i+1}]$ randomly

- **Impact if** : $d \leq b_{TP}$ with $b_{TP} = R_P \sqrt{1+\left(\frac{v_e}{v_i}\right)^2}$

- **Oceans delivery to the planet at the position a_P**: $O_T(a_P) = \sum_{e_P=0}^{e_{max}} O_{a_P}(e_P)$

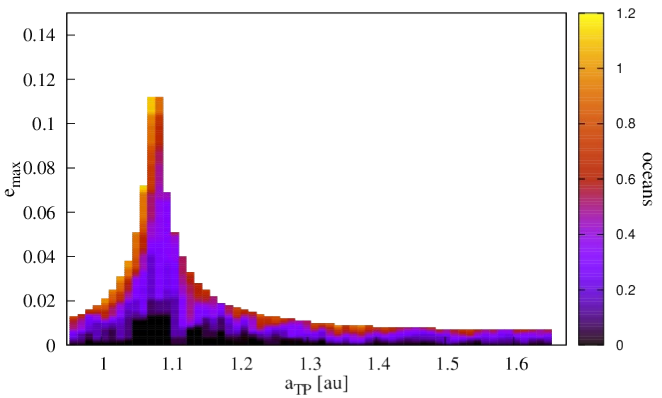
- **Probability of delivery at the position a_P**:

$$IP_T(a_P) = \frac{N_{crossing}[a_i ; a_{i+1}]}{N_{TOT}[crossing\ HZ]} \sum_{e_P=0}^{e_{max}} \frac{N_{orb}(d \leqslant b_{TP})}{N_{TOT}(test\ orbits)}$$

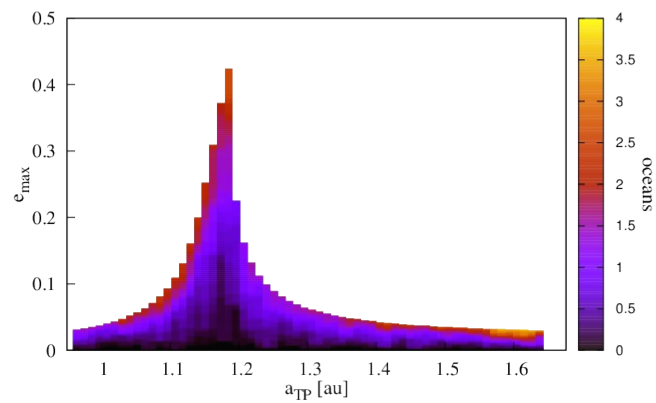
❺ Water delivery to a TP and IP (2) – Example results (GK a_b=100 au)

Number of oceans

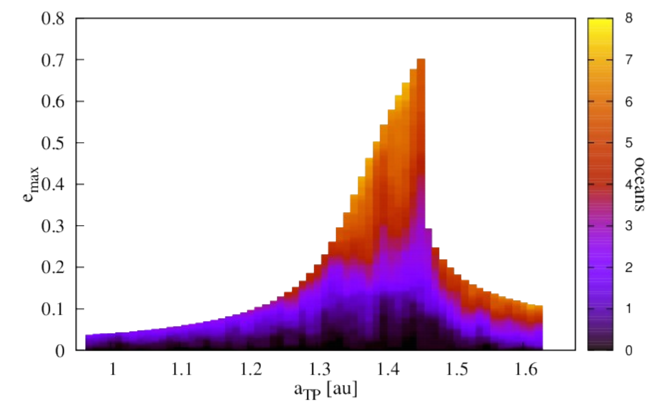
e_b = 0.1



e_b = 0.3

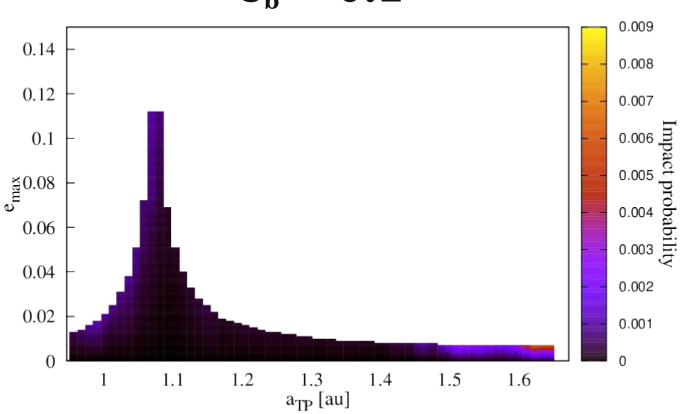


e_b = 0.5

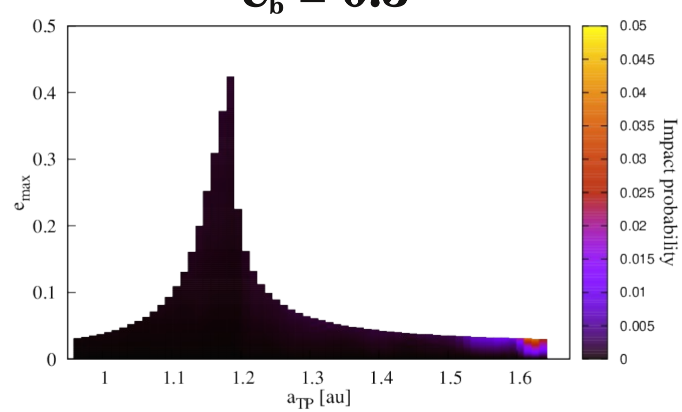


I.P

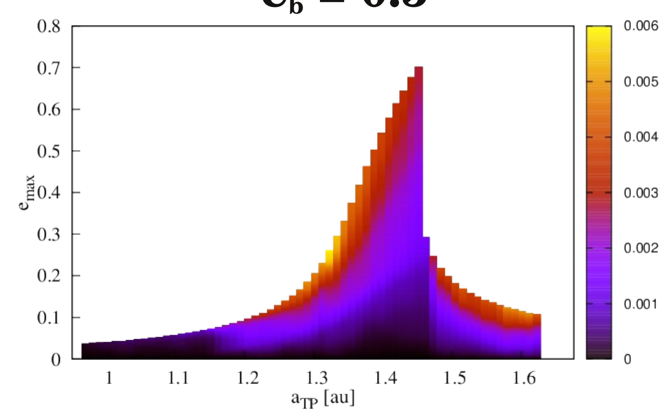
e_b = 0.1



e_b = 0.3



e_b = 0.5



❻ Conclusion

- Water can be transported in the HZ – compared to a single star syst :
  - Short timescale
  - Distributed in the whole HZ
  - More efficient

- Dynamics plays a key role in HZ borders computation
  - => consequence for habitability of planets
  - => consequence for water delivery to planets