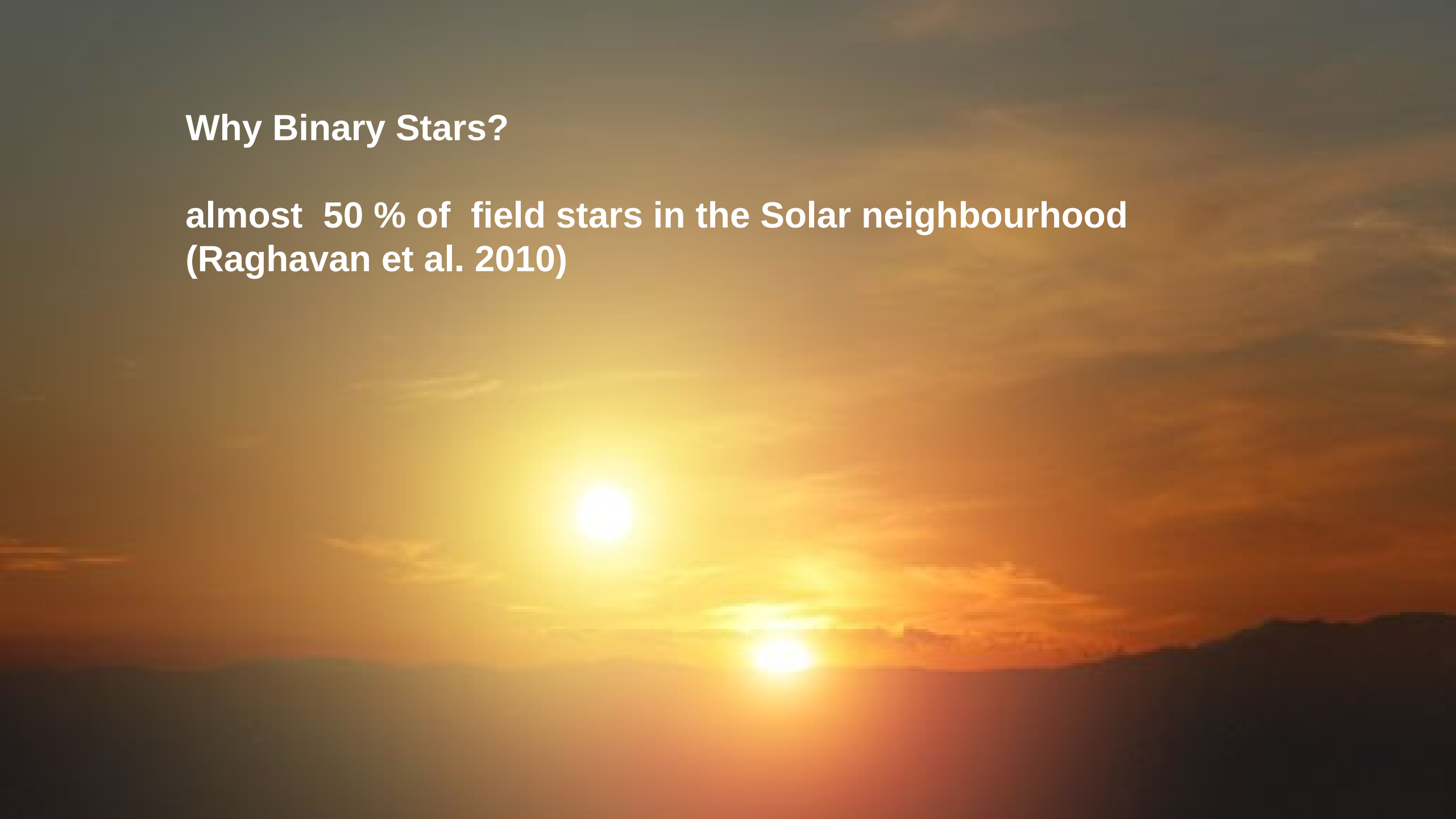
The effects of Binary Stars on Planets in the Habitable Zone

E. Pilat-Lohinger

Department of Astrophysics, University of Vienna (Austria)

Institute of Theoretical and Computational Physics, TU Graz (Austria)

CELMEC IX – Sept. 17th 2026



Why Binary Stars?

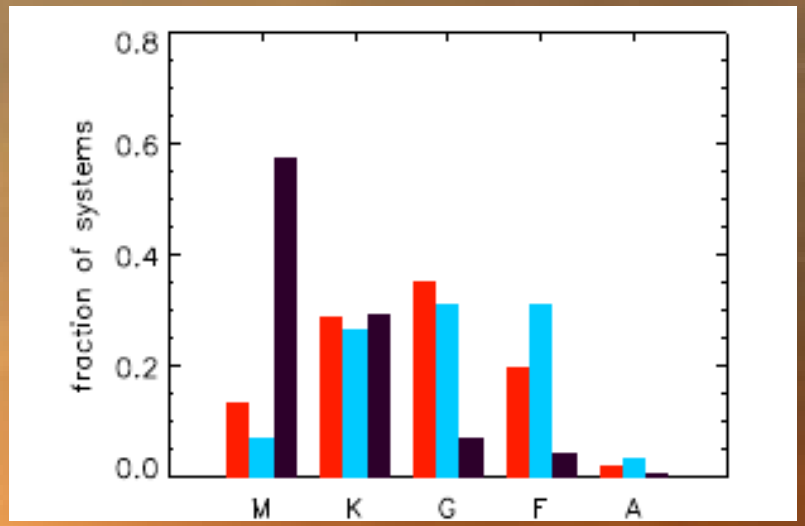
almost 50 % of field stars in the Solar neighbourhood (Raghavan et al. 2010)

Why Binary Stars?

almost 50 % of field stars in the solar neighbourhood (Raghavan et al. 2010)

	All distances	≤500 pc	Field stars
Full sample	16.1%	22.5%	46%
M primaries	9.2%	11.8%	35%
K primaries	15.2%	19.1%	41%
G primaries	14.6%	24.0%	45%
F primaries	22.9%	33.7%	51%

Thebault & Bonanni, 2025



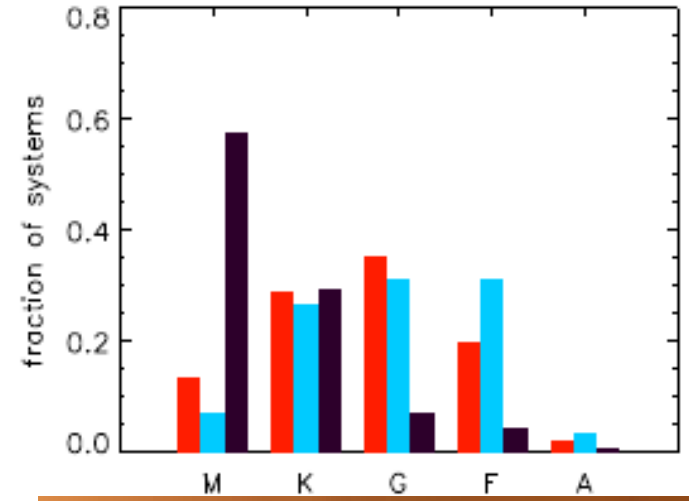
Raghavan et al. 2010

Stellar types as host-stars:
Red – Binary star
Blue – Single star
Black – Secondary star

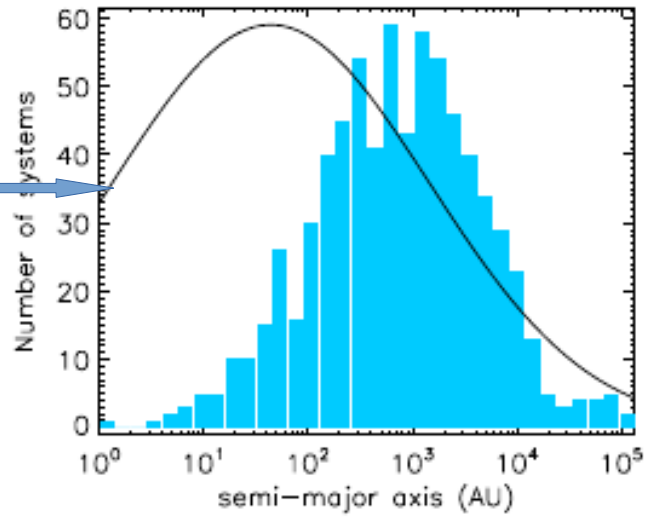
Why Binary Stars?

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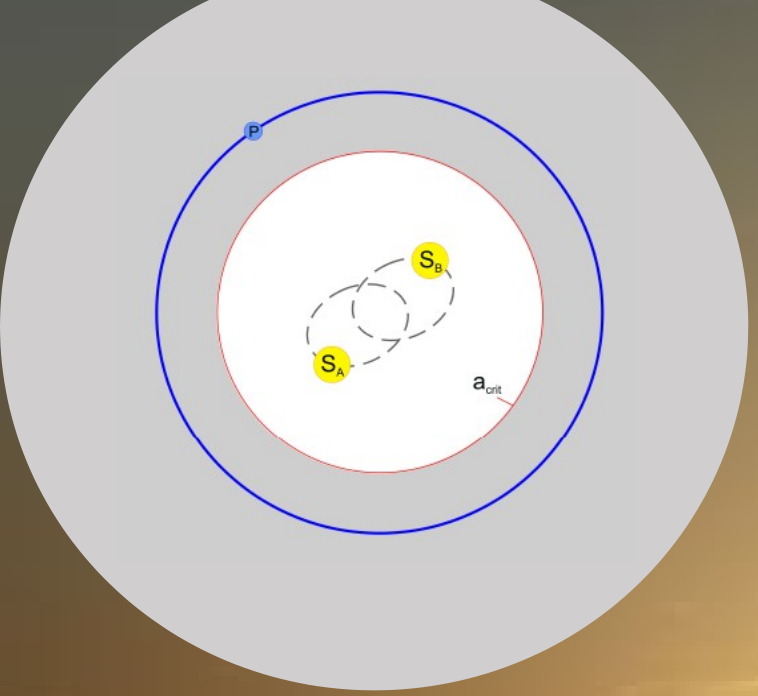
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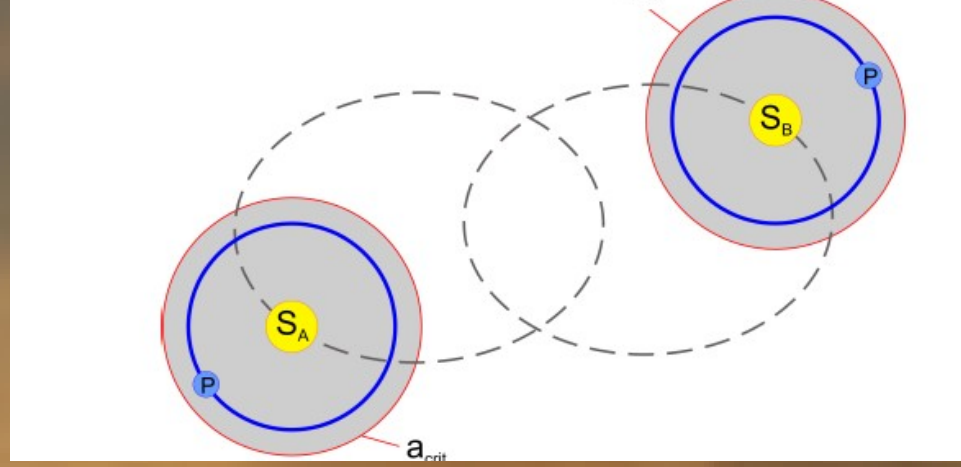


Normalized distribution for field stars derived by Raghavan et al. 2010



Stellar types as host-stars:
Red – Binary star
Blue – Single star
Black – Secondary star



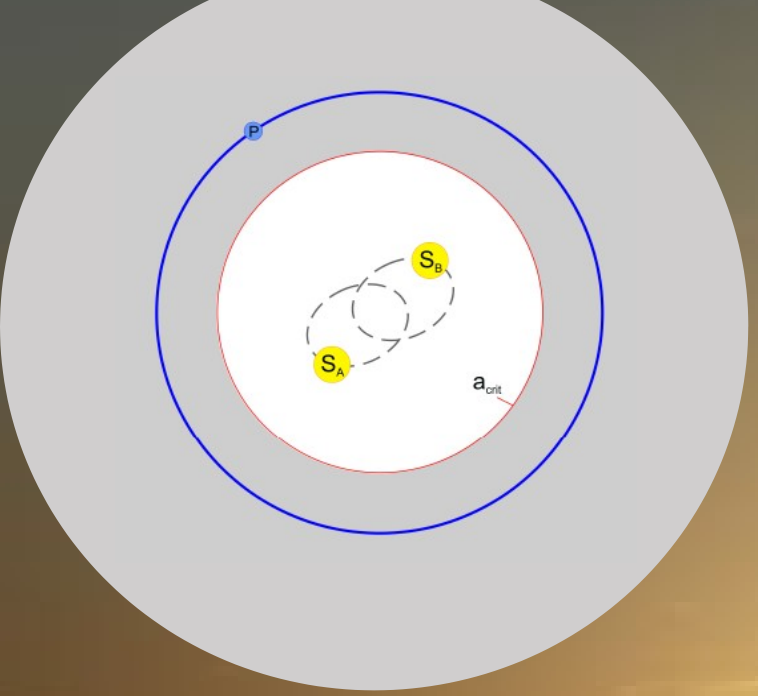


Planetary motion

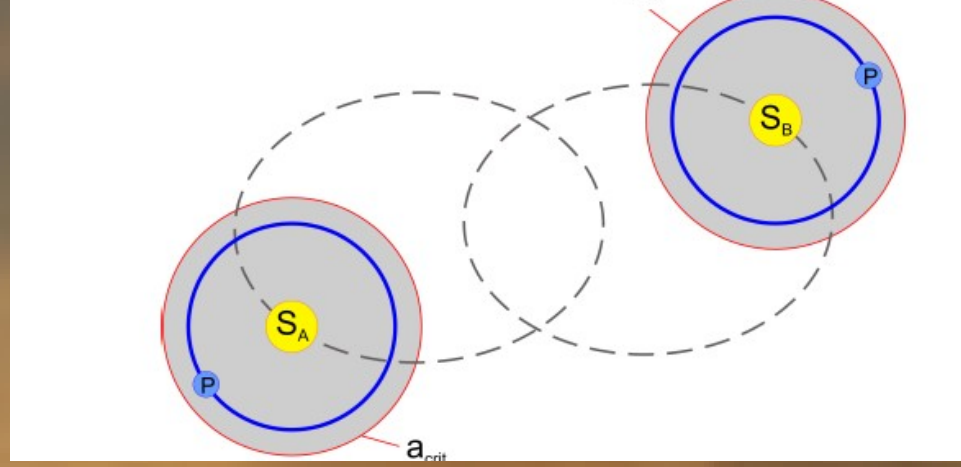
39
P-type Planets

853
S-type Planets

according to **„Planets in Binary Systems“**
https://exoplanet.eu/planets_binary/

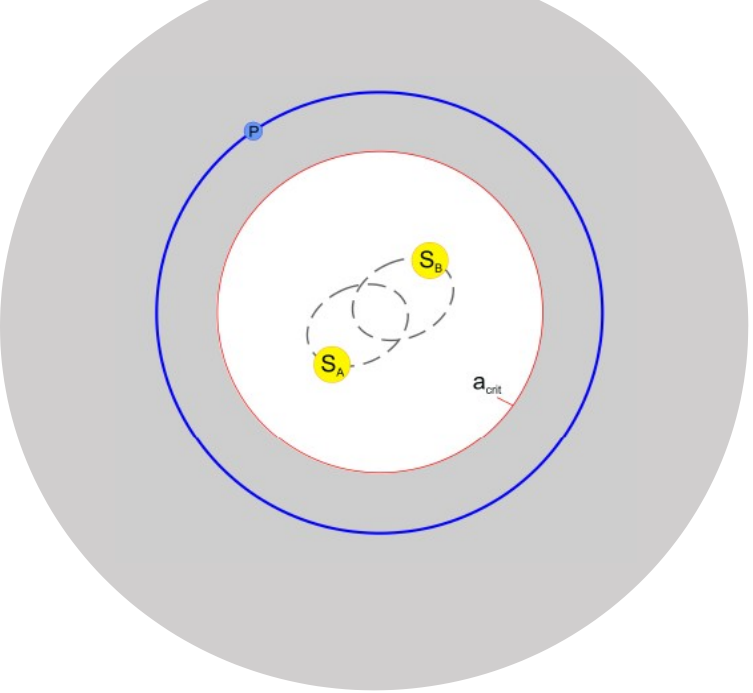


Stability of Planetary motion

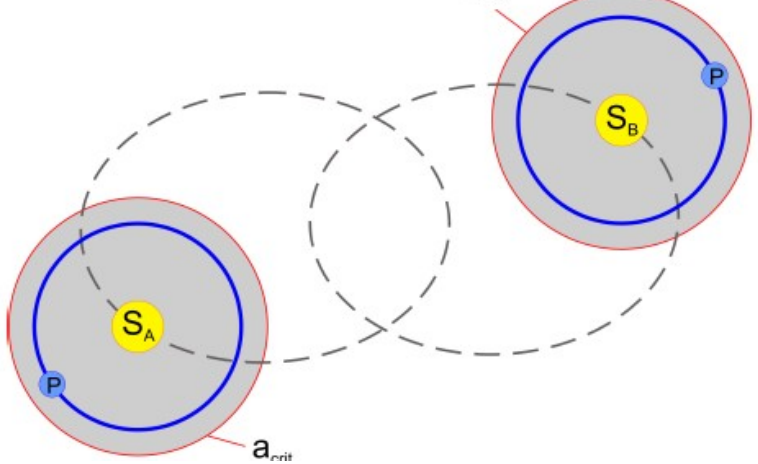


Harrington (1977)
Graziani & Black (1981)
Black (1982)
Pendleton & Black (1983)
Dvorak (1984, 1986)
Rabl & Dvorak (1988)
Dvorak , Froeschlé (1989)

Holman & Wiegert (1999)
Pilat-Lohinger & Dvorak (2002)
……



Stability of Planetary motion

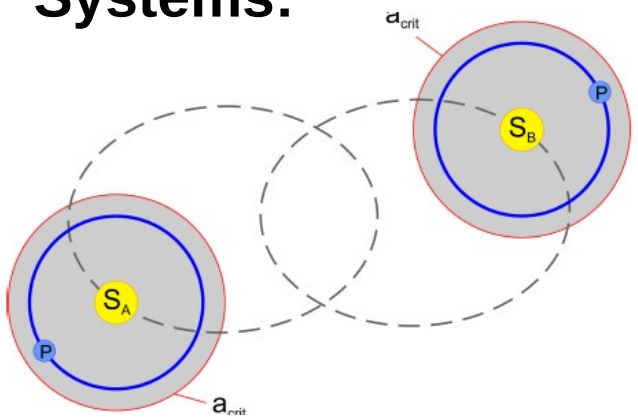


Holman & Wiegert (1999)

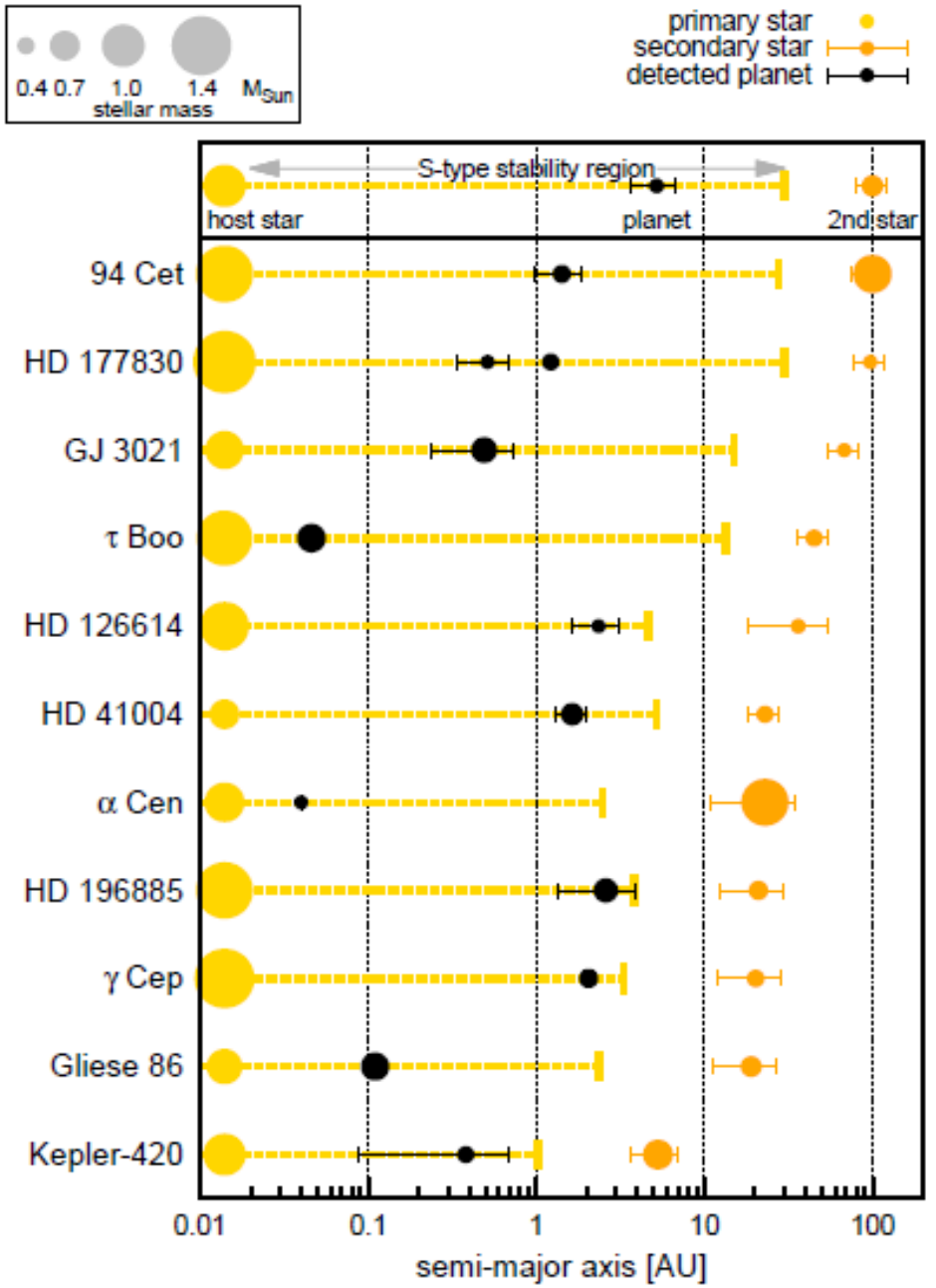
$$a_{\rm crit} = \big[(1.60 \pm 0.04) + (5.10 \pm 0.05)e + (-2.22 \pm 0.11)e^2 + (4.12 \pm 0.09)\mu + (-4.27 \pm 0.17)e\mu + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e^2\mu^2\big] a_B.$$

$$a_{\rm crit} = \big[(0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e + (0.586 \pm 0.061)\mu e + (0.150 \pm 0.041)e^2 + (-0.198 \pm 0.074)\mu e^2\big] a_B.$$

Application to real Systems:

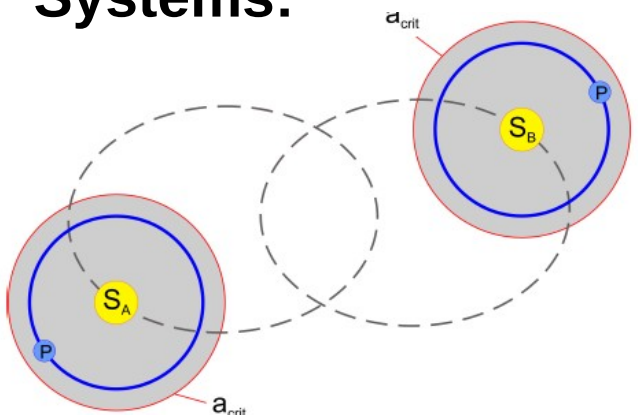


Secondary star restricts the region for stable planetary motion

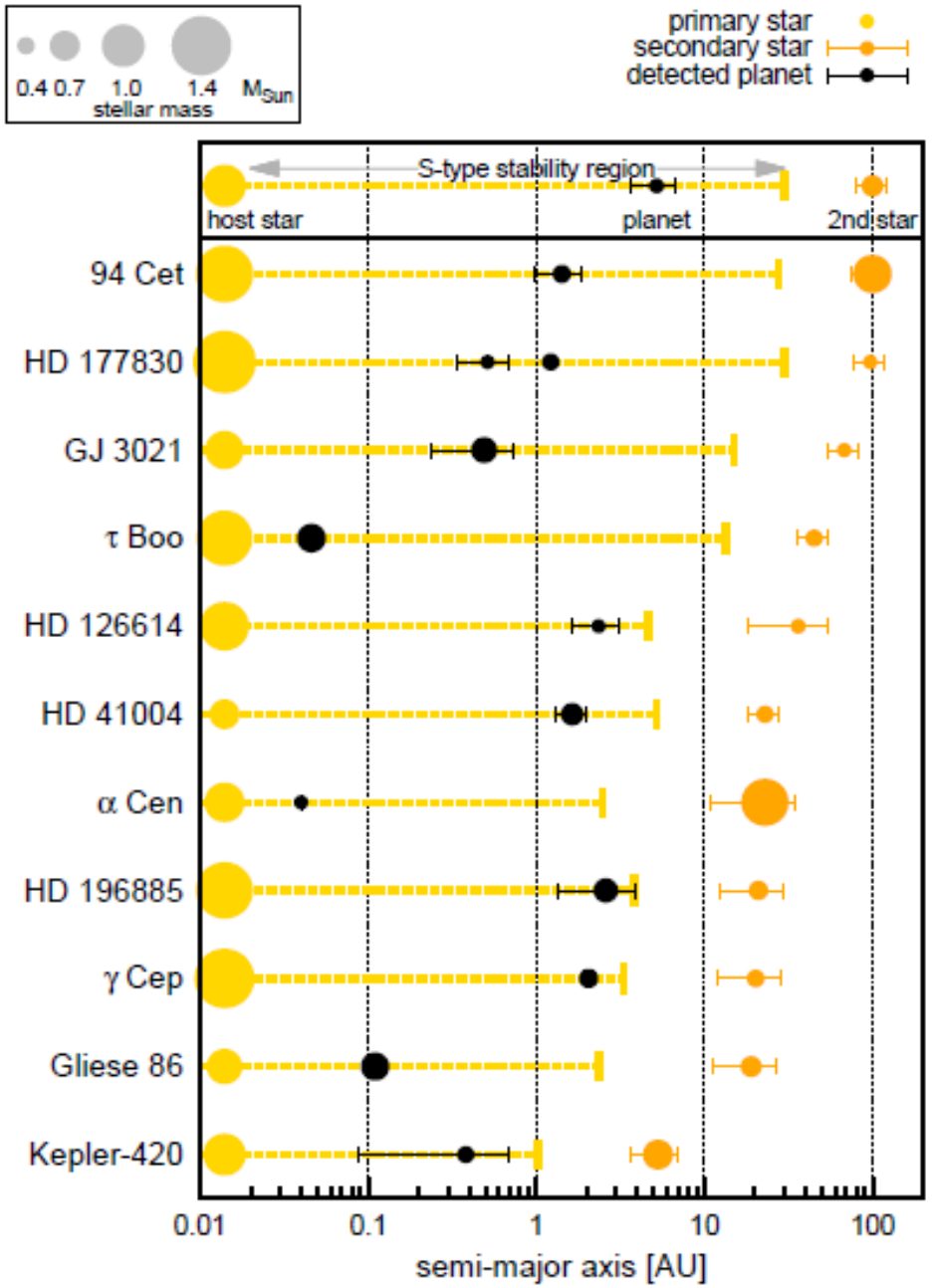


Bazsó, Pilat-Lohinger et al., MNRS, 2017

Application to real Systems:



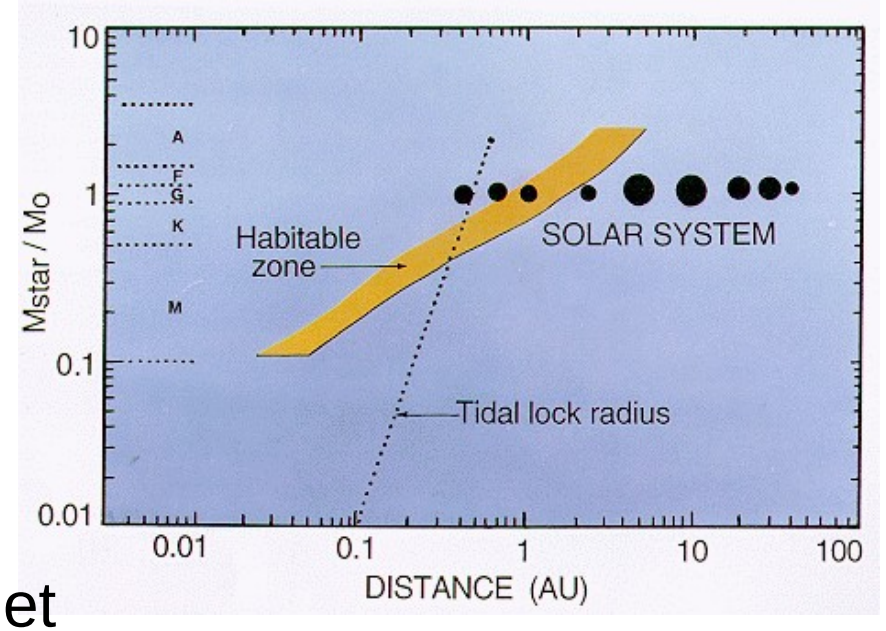
Secondary star restricts the region for stable planetary motion



Truncated Disk !

Bazsó, Pilat-Lohinger et al., MNRS, 2017

Habitable Zone (HZ)



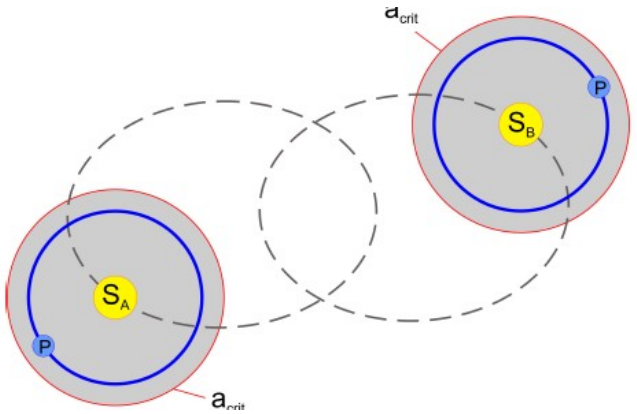
Kasting et al. 1993

- Zone around a star where liquid water can exist on the surface of a terrestial-like planet

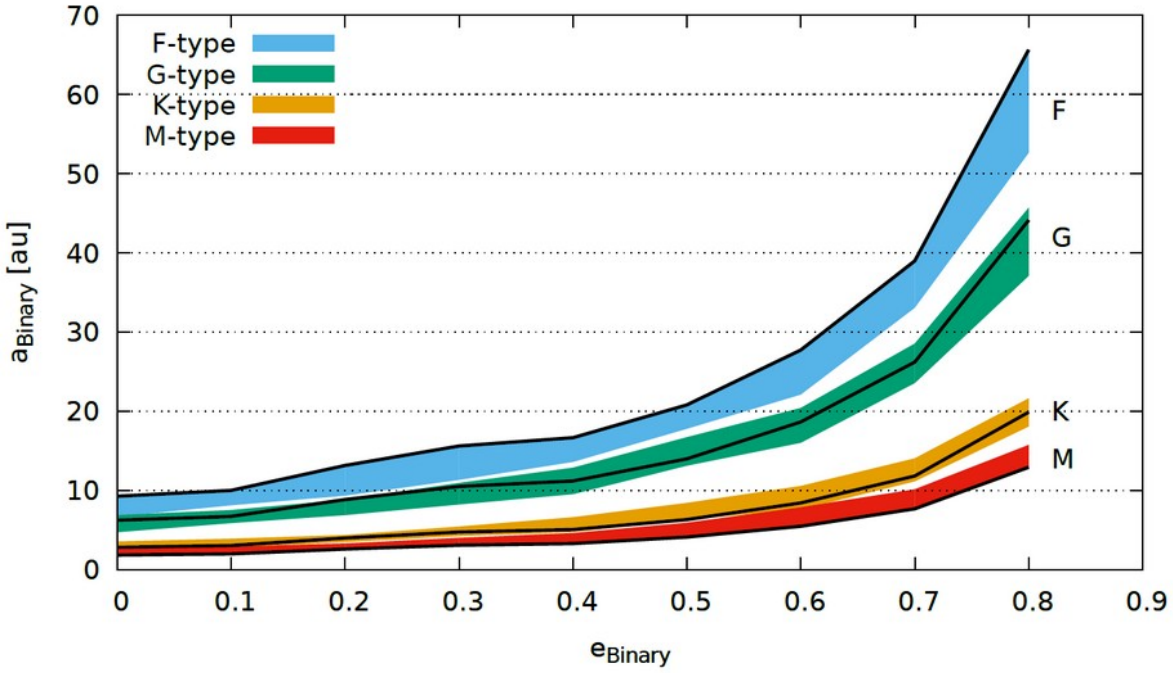
HZ depends on:

– Host-star: Spectral type, mass, age, …. of the star
– Planet in the HZ: Orbit, mass, composition, atmosphere
– Orbits of other planets in the system

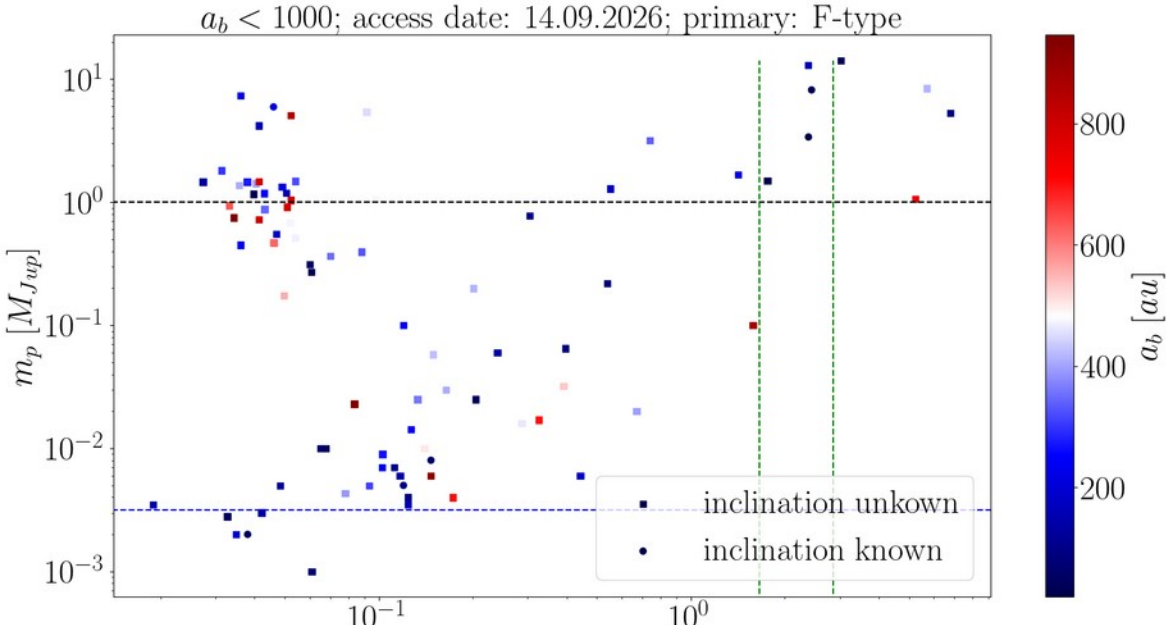
HZ must be in the stable zone

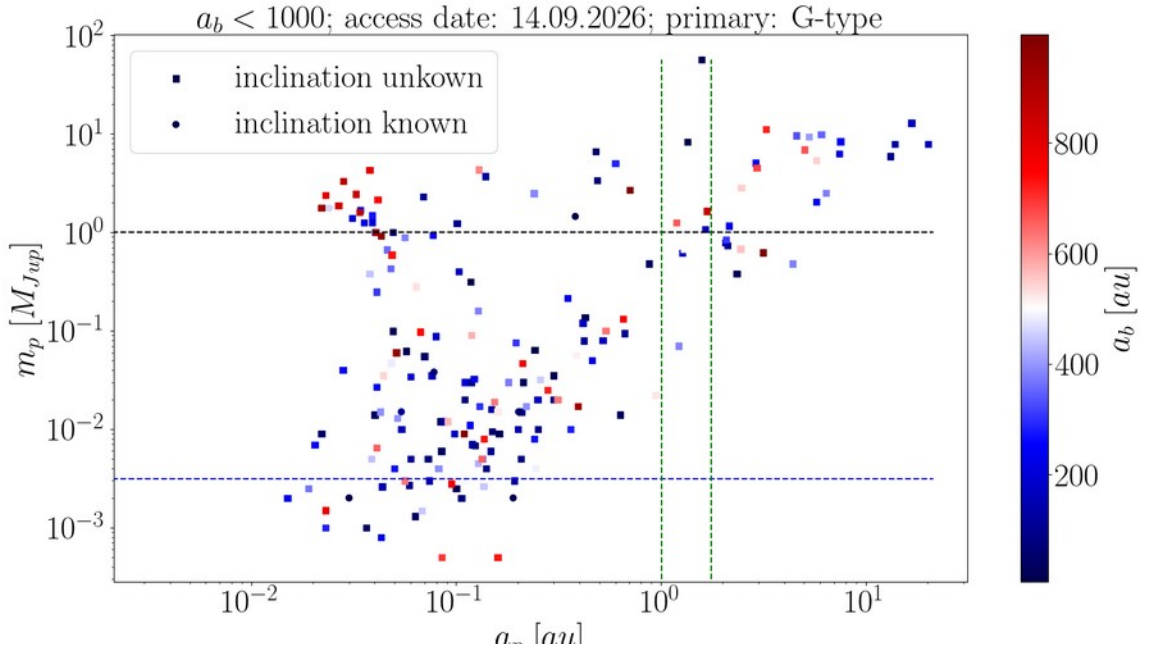


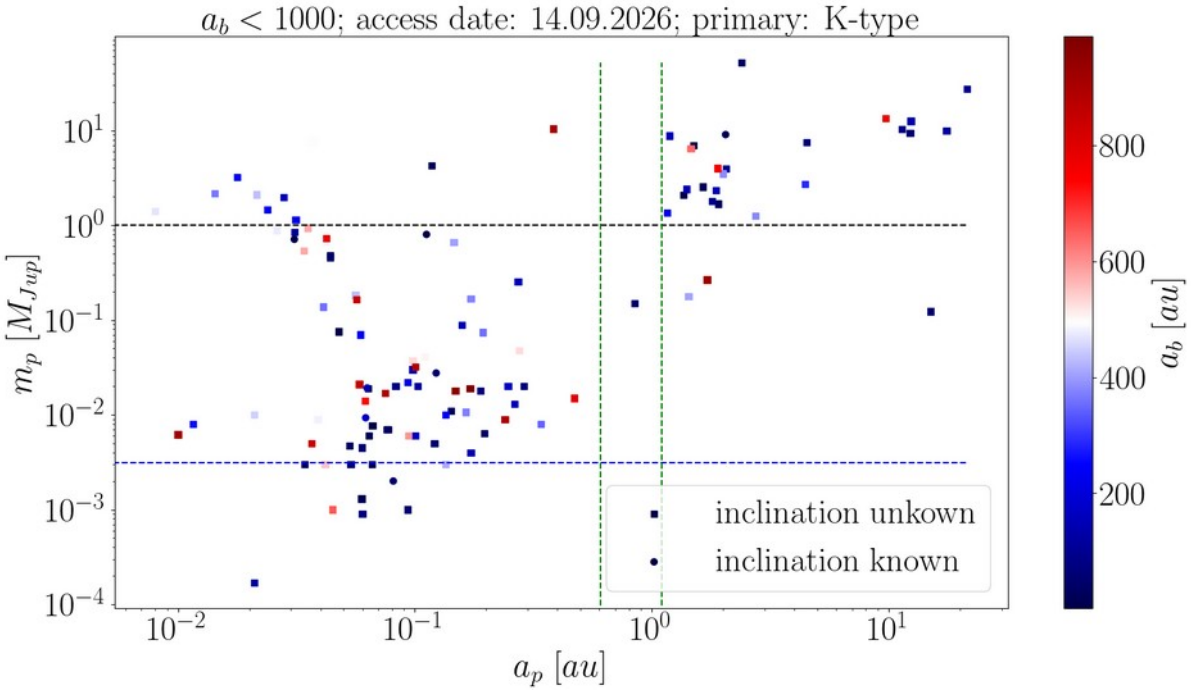
Secondary star restricts the region for stable planetary motion

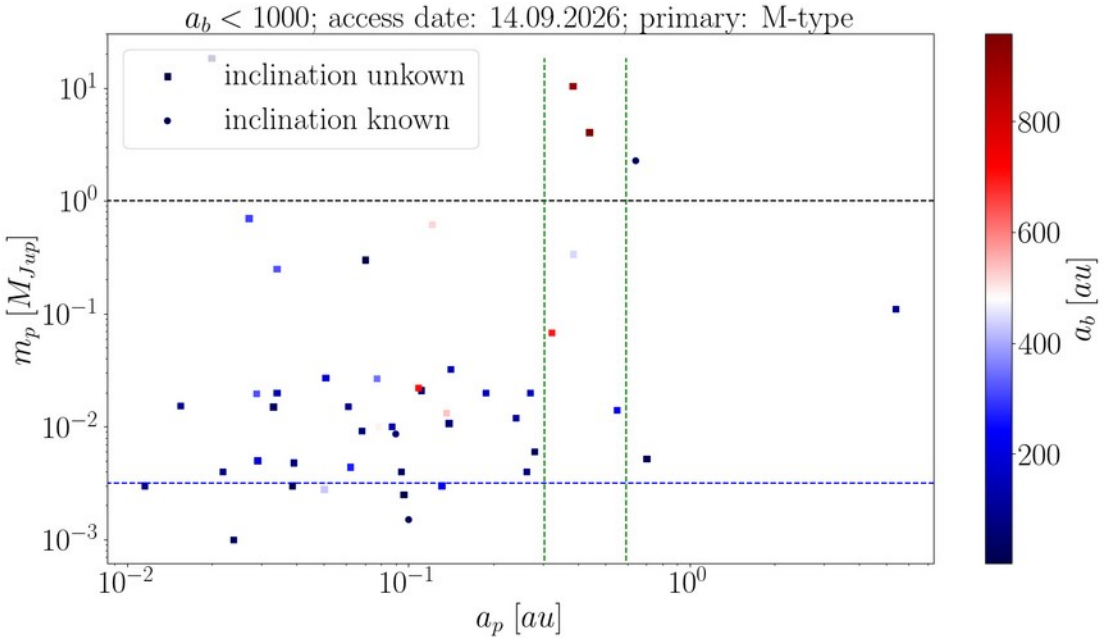


Pilat-Lohinger+, 2019


$a_b < 1000$; access date: 14.09.2026; primary: F-type
$m_p\ [M_{Jup}]$
$a_b\ [au]$
inclination unkown
inclination known


$a_b < 1000$; access date: 14.09.2026; primary: G-type
$m_p\ [M_{Jup}]$
$a_b\ [au]$
inclination unkown
inclination known


$a_b < 1000$; access date: 14.09.2026; primary: K-type
$m_p\ [M_{Jup}]$
$a_p\ [au]$
$a_b\ [au]$
inclination unkown
inclination known


$a_b < 1000$; access date: 14.09.2026; primary: M-type
$m_p\ [M_{Jup}]$
$a_p\ [au]$
$a_b\ [au]$
inclination unkown
inclination known

Can we apply HZ limits of Kasting, ….?

since 2011: numerous studies on HZs in Binary Star Systems

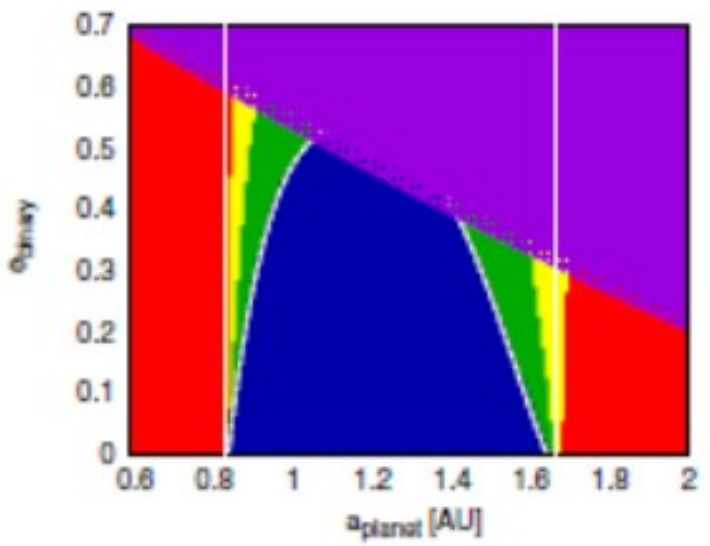
Cuntz M., Eggl S., Funk B., Georgakarakos N.,Haghighipour N., Jaime L., Kaltenegger L., Mason P., Müller T., Pilat-Lohinger E., Quarles B., Schwarz R.
….

THE ASTROPHYSICAL JOURNAL, 752:74 (11pp), 2012 June 10 doi:10.1088/0004-637X/752/1/74
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AN ANALYTIC METHOD TO DETERMINE HABITABLE ZONES FOR S-TYPE PLANETARY ORBITS IN BINARY STAR SYSTEMS

SIEGFRIED EGGL[1], ELKE PILAT-LOHINGER[1], NIKOLAOS GEORGAKARAKOS[2], MARKUS GYERGYOVITS[1], AND BARBARA FUNK[1]
[1] Institute for Astronomy, University of Vienna, Türkenschanzstr. 17, A-1180 Vienna, Austria; siegfried.eggl@univie.ac.at, elke.pilat-lohinger@univie.ac.at
[2] 128 V. Olgas str., Thessaloniki 546 45, Greece
Received 2012 January 31; accepted 2012 April 10; published 2012 May 25

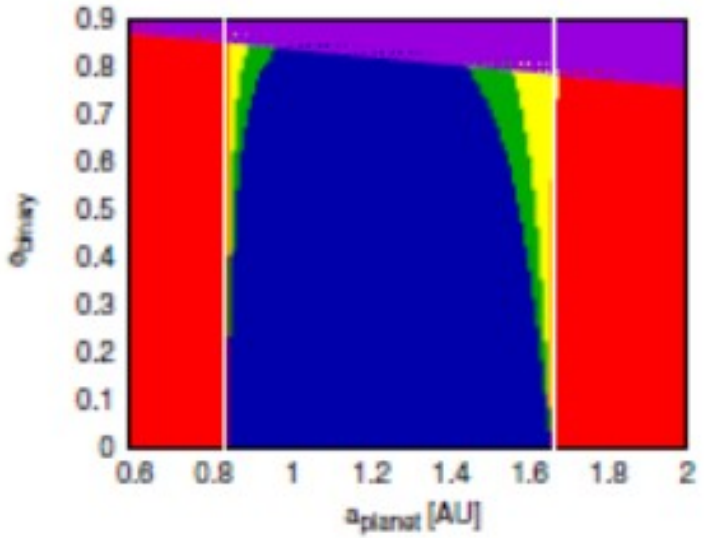
G2V - G2V



a_B = 10 au

a_B = 50 au

G2V - G2V

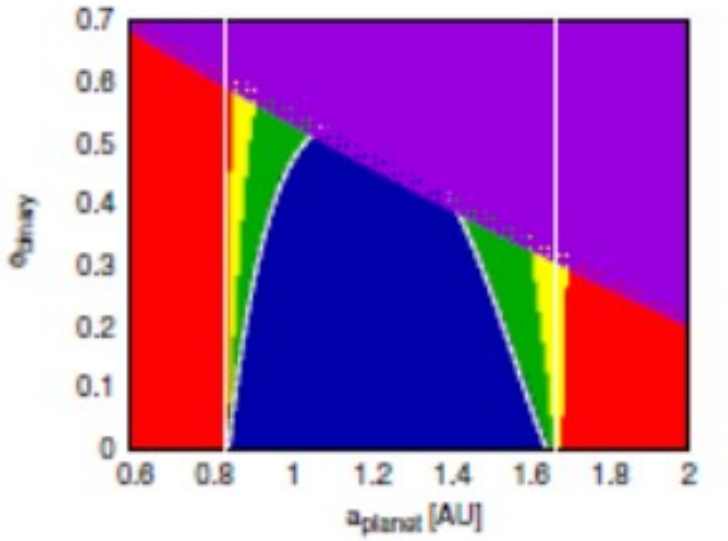


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[2] 128 V. Olgas str., Thessaloniki 546 45, Greece
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G2V - G2V



Permanent HZ

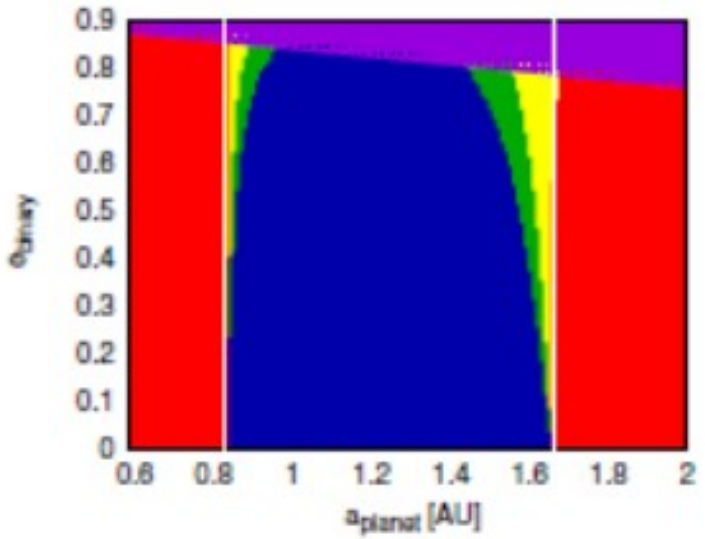
Extended HZ

Averaged HZ

a_B = 10 au

a_B = 50 au

G2V - G2V

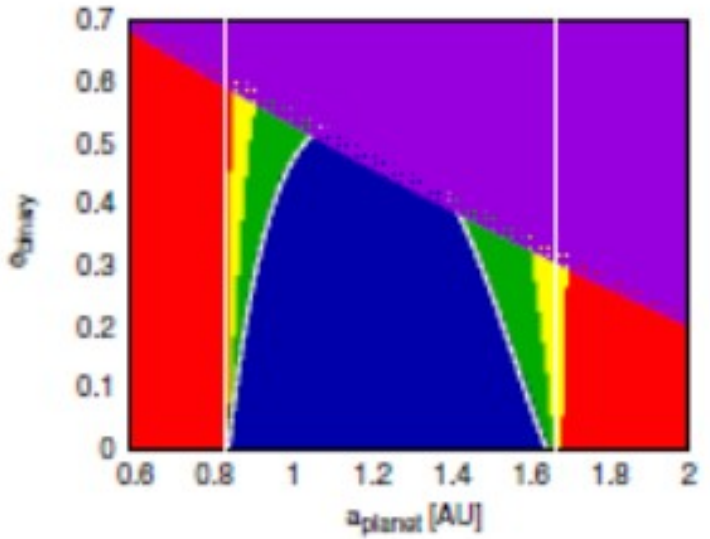


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Received 2012 January 31; accepted 2012 April 10; published 2012 May 25

G2V - G2V

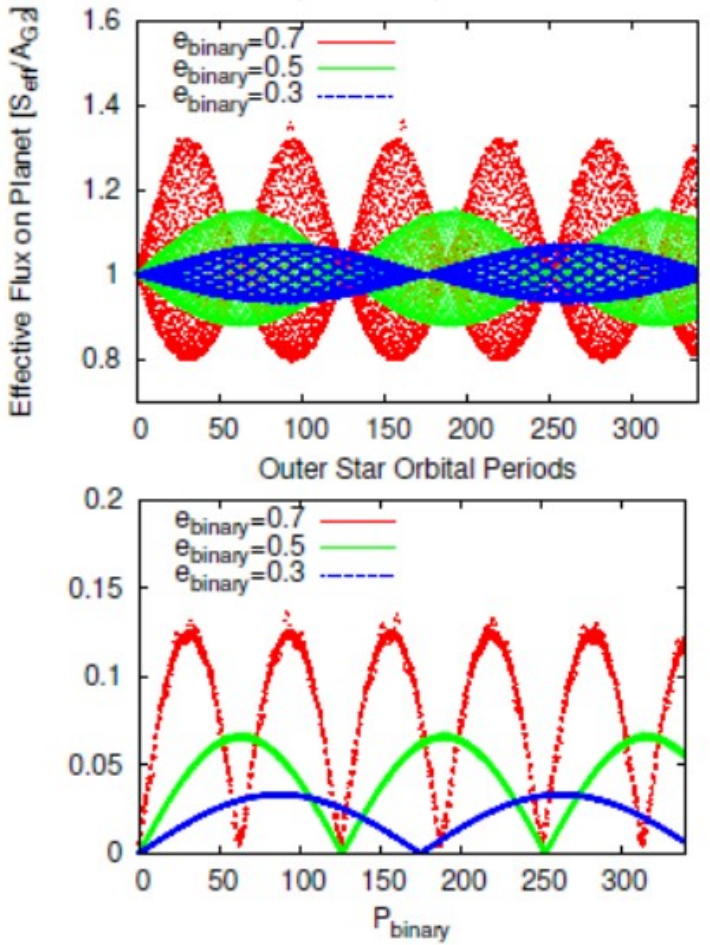


Permanent HZ

Extended HZ

Averaged HZ

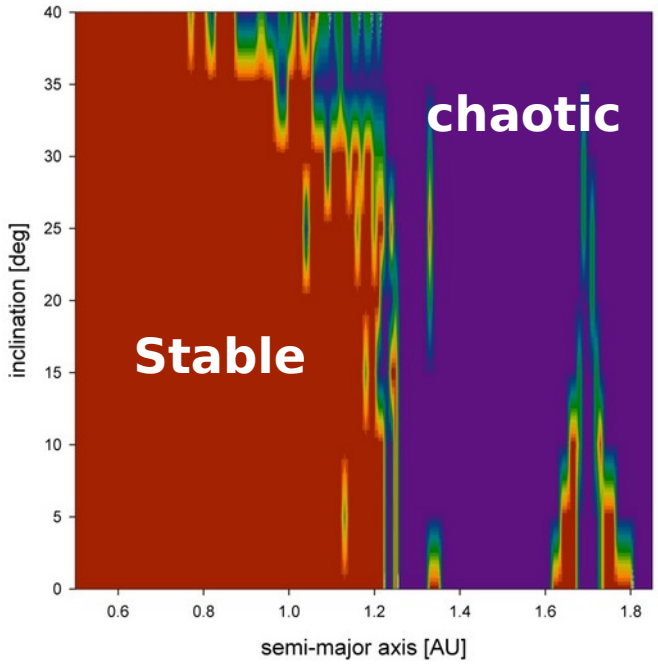
a_B = 10 au



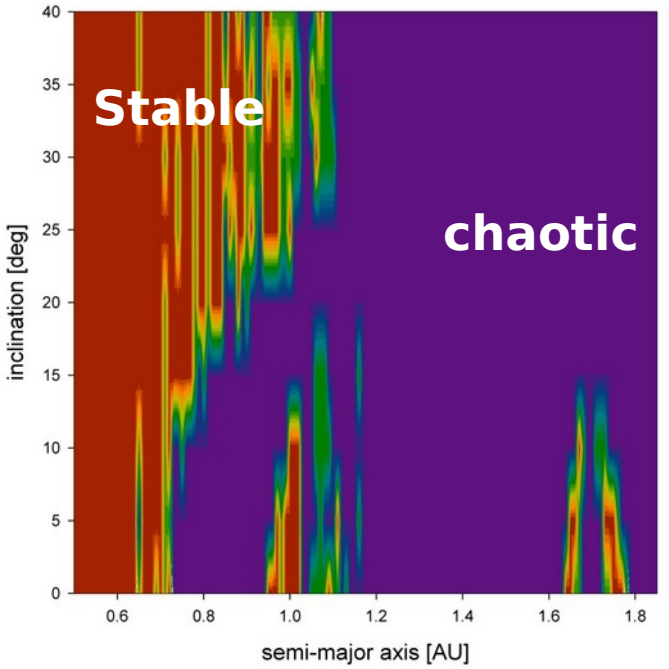
Perturbations: Single vs Binary Star

γ **Cephei**: giant planet (a=2 au) + test-planet in circumstellar motion

without secondary

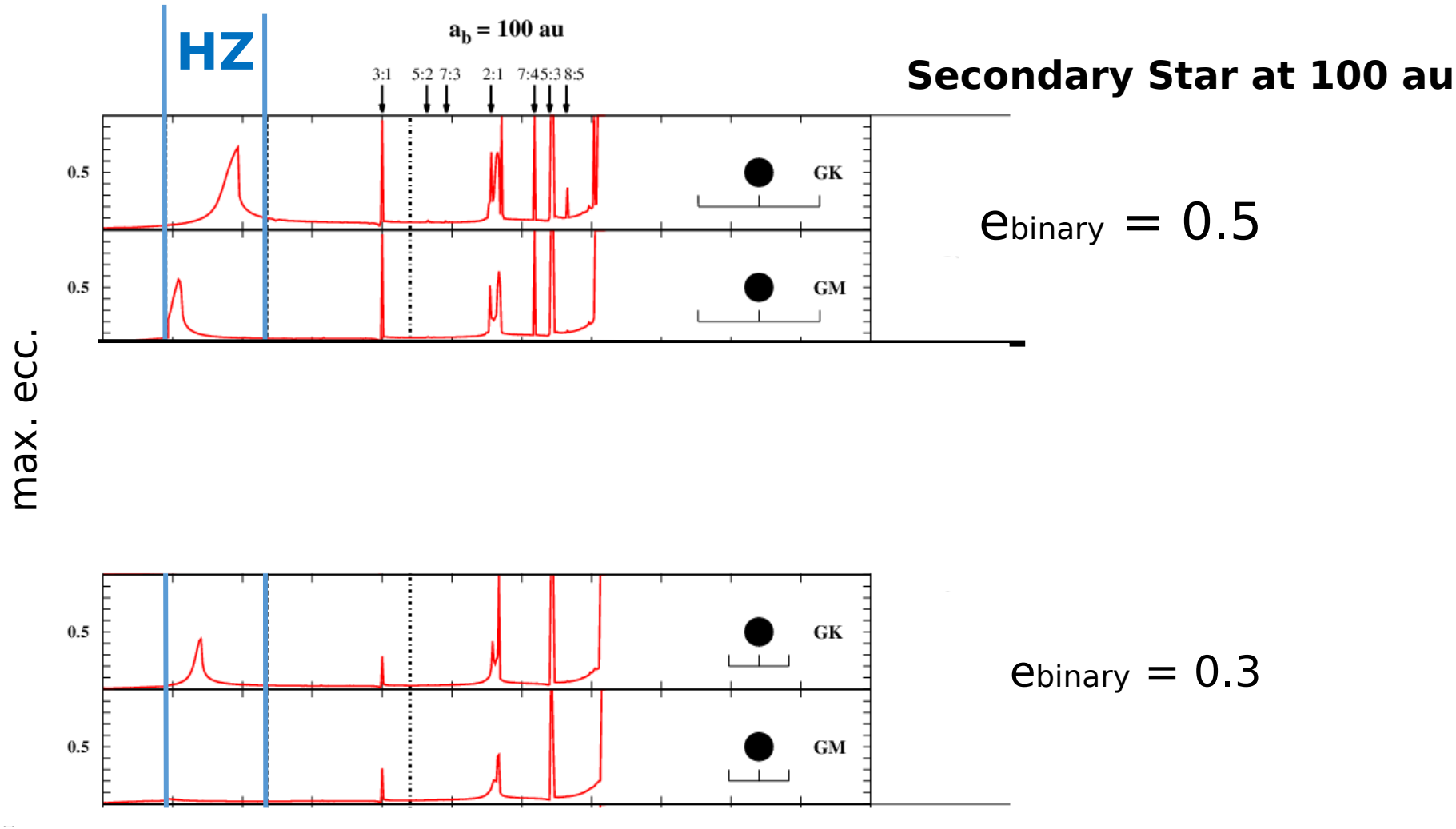


secondary at ~ 20 AU



FLI (Fast Lyapunov Indicator) maps

(Pilat-Lohinger, 2004, IAU Coll. Belgrade)



Secondary Star at 100 au

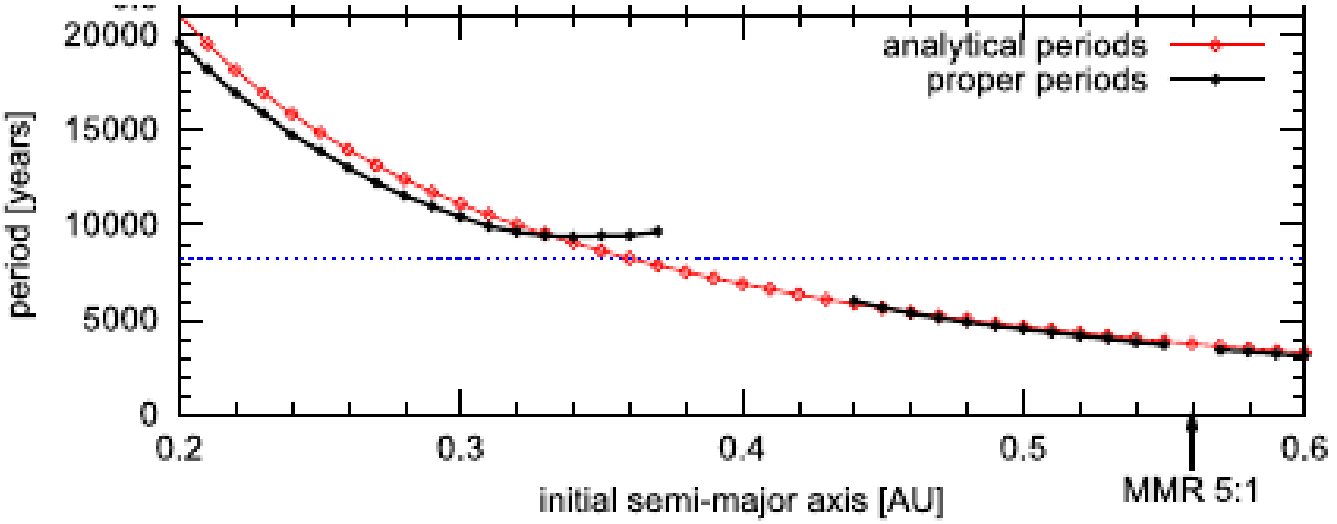
$e_{binary} = 0.5$

$e_{binary} = 0.3$

Bancelin, Pilat-Lohinger+, 2016

Semi-analytical Method to detect Secular Resonance in HZ in Binary Stars

Pilat-Lohinger E, Baszó A., Funk B., 2016, AJ 152



the proper periods of the test planets: black dots are the numerically determined values using a fast Fourier transform method and red dots represent the analytical solution. The horizontal blue line indicates the proper period of the giant planet.

Laplace – Lagrange Perturbation Theory

$$g = \frac{n}{4}\sum_{i=1}^{2}\frac{m_i}{m_0}\alpha_i^2 b_{3/2}^{(1)}(\alpha_i)$$

where $\alpha_i = a/a_i$ for $i = 1, 2$ and a_1, a_2, a are the semimajor axes of the giant planet, the secondary and the test planet, respectively. m_1 and m_2 are the masses of the giant planet and the secondary and m_0 is the mass of the primary star. $b_{3/2}^{(1)}$ is a Laplace coefficient.

Which Binary configurations could host a habitable planet?

5-dimensional parameter space

- Masses of Star B & GP
- Semi-major axis of Star B & GP
- Eccentricity of Star B

S H a D o S (online tool)

= Secular perturbations in Habitable Zones of Double Stars

https://adg.univie.ac.at/shados/

- Steps 1–4 provide input for different objects
- Step 5 visualizes results

THE ASTRONOMICAL JOURNAL, 160:2 (19pp), 2020 July https://doi.org/10.3847/1538-3881/ab910
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CrossMark

Fear the Shadows of the Giants: On Secular Perturbations in Circumstellar Habitable Zones of Double Stars

Ákos Bazsó and Elke Pilat-Lohinger
Department of Astrophysics University of Vienna Türkenschanzstrasse 17 A-1180 Vienna, Austria; akos.bazso@univie.ac.at
Received 2019 November 16; revised 2020 May 4; accepted 2020 May 5; published 2020 June 4

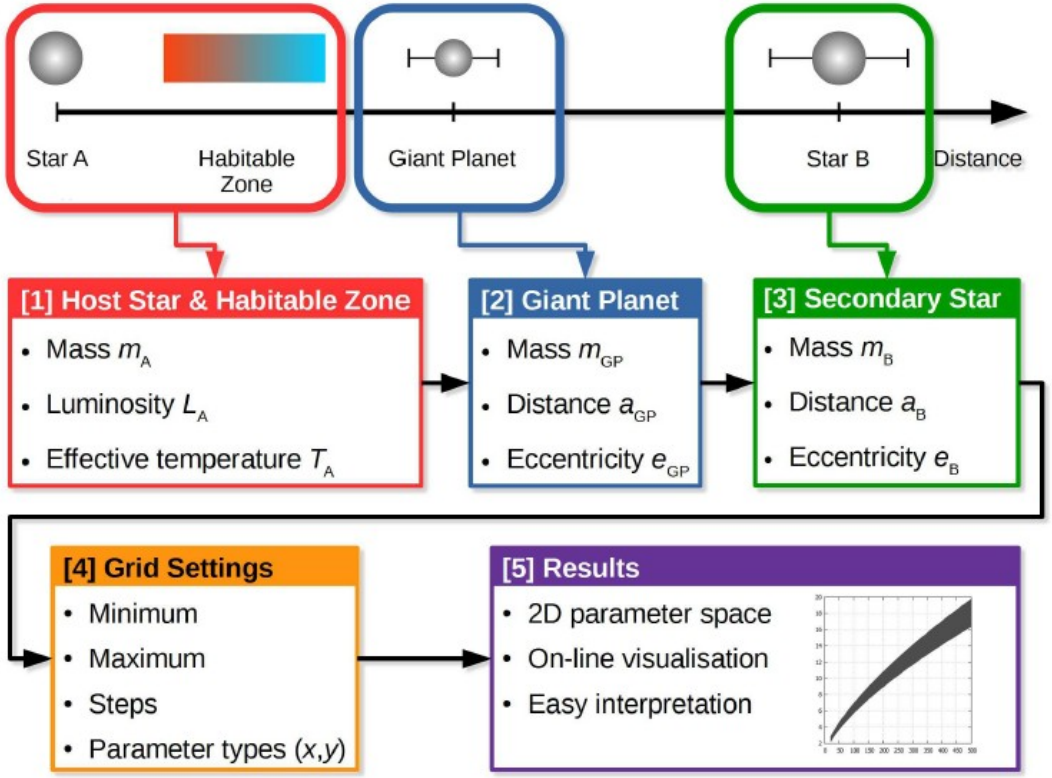
Baszó A. & P-L E.

S H a D o S (online tool)

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https://adg.univie.ac.at/shados/

- Steps 1–4 provide input for different objects
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Combined Analytical Model -- CAM

= a combination of two analytical models

1. Laplace Lagrange Theory for g_TP
2. Andradea-Ines & Eggl model (2017) for g_GP

$$g_{And} = g_{Hep}\left(1 - \delta_g\right)$$

$$g_{Hep} = \frac{3}{4}\mu\alpha^3 n\left(1 - e_B^2\right)^{-3/2}$$

$$\mu = m_B/m_A$$

$$\alpha = a_P/a_B$$

$$n^2 = Gm_A/a_P^3$$

S H a D o S (online tool)

= **S**ecular perturbations in **Ha**bitable Zones of **Do**uble **S**tars

https://adg.univie.ac.at/shados/

- Steps 1–4 provide input for different objects
- Step 5 visualizes results

$$\begin{aligned}\delta_g = \alpha^{3/2}[&-4.6274\mu^{1/2} - 4.0190\mu + 0.25041\mu^2 \\ &- 3.41e_2^2\mu^{1/2} + 11.09e_2^2\mu - 0.9823e_2^2\mu^2 \\ &- 20.13e_2^4\mu^{1/2} - 85.49e_2^4\mu + 4.996e_2^4\mu^2] \\ &+ \alpha^{9/2}[123.67\mu^{1/2} - 799.20\mu - 201.49\mu^2 \\ &+ 180e_2^2\mu^{1/2} - 5555e_2^2\mu - 617.7e_2^2\mu^2 \\ &+ 2.671 \times 10^4 e_2^4\mu^{1/2} - 1.0229 \times 10^5 e_2^4\mu \\ &- 23076e_2^4\mu^2],\end{aligned}$$

Combined Analytical Model -- CAM

= a combination of two analytical models

1. Laplace Lagrange Theory for g_{TP}
2. Andradea-Ines & Eggl model (2017) for g_{GP}

$$g_{And} = g_{Hep}\,(1 - \delta_g)$$

$$g_{Hep} = \frac{3}{4}\mu\alpha^3 n\,(1 - e_B^2)^{-3/2}$$

$$\mu = m_B/m_A$$

$$\alpha = a_P/a_B$$

$$n^2 = Gm_A/a_P^3$$

Secular perturbations in Habitable zones of Double Stars

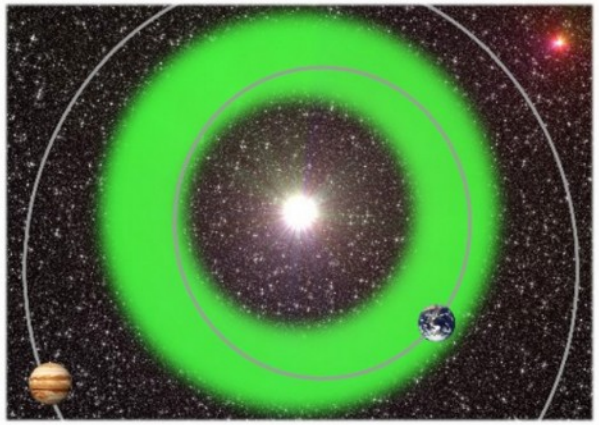
SHaDoS

SHaDoS is an online tool with the purpose to visualise secular perturbations in the circumstellar habitable zone of a star that is part of a binary star system. Currently this tool is in a beta-test phase.

Binary stars, or double stars, are pairs of stellar objects that are tied together by their mutual gravitational attraction.

The habitable zone is the region around a star where the temperature is just right - neither too hot nor too cold - to allow liquid water on the surface of a planet.

A circumstellar planet is a celestial body that orbits only one star in a double or multiple star system.



In the figure above two planets orbit the host star (in the center). An Earth-like planet is located in the habitable zone (green annular region), while a more massive Jupiter-like planet orbits the star at a greater distance. The companion star moves at a still larger distance, it is indicated in red in the upper right corner.

To learn more about the scientific background and to read a short introduction on how to use the SHaDoS tool, go to the Introduction page.

If you wish to start directly using the tool, go to the Start page.

Here you can find the contact information and disclaimer.

Figure: A circumstellar multi-planet system in a double star system.

SHaDoS - Input Form

univie.ac.at/adg/shados/input.php

Apps Dell Englisch - Deutsch...

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SHaDoS – Input Form

Host Star and Habitable Zone Settings

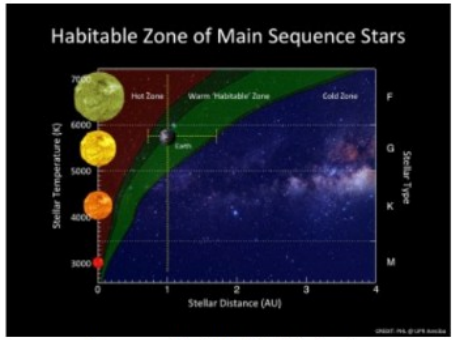


Image credit: PHL @ UPR Arecibo

Please cho

There are

Optionally

Stellar luminosity in solar units:

1.0

Stellar effective temperature in K (in the range 2600 – 7200):

5780

Mass of primary star in solar masses:

1,0

SHaDoS - Input Form

univie.ac.at/adg/shados/inpu

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SHaDoS – Input Form

Giant Planet Settings



Image credit: NASA/JPL-Caltech/SwRI/MSSS/ Kevin M. Gill © CC BY

Please enter the **mass**, **distance** fr

The planet's mass is given in units

The distance relative to the host st

Note that the eccentricity must be

Mass of giant planet in Jupiter masses:

1

Distance of giant planet in AU:

5,2

Eccentricity of giant planet:

0,05

SHaDoS - Input Form

univie.ac.at/adg/shados/input.php

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SHaDoS – Input Form

Secondary Star Settings

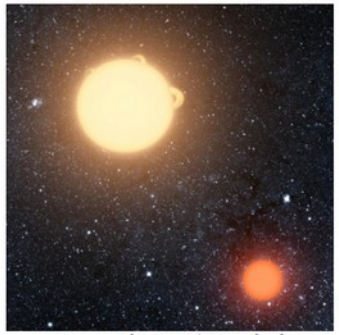


Image credit: NASA/JPL-Caltech

Please enter the **mass**, **distance** from the host star, and orbital **eccentricit**

The star's mass is given in units of the solar mass.

The distance relative to the host star is given in astronomical units.

Note that the distance of the planet has to be smaller than the distance to t

Note that the eccentricity must be in the range $0 \leq e < 0.6$.

Mass of secondary star in solar masses:

1,0

Distance of secondary star:

20,0

Eccentricity of secondary star:

0,4

SHaDoS – Input Form

Grid-type and Grid-dimension Settings

Here you can specify the two parameters of the parameter space.

Select a **first type** of variable from the drop-down list to assign it to the **x-dimension** of the grid (independent variable). Then, define the **minimum** and **maximum** values of the corresponding parameter, and choose the number of

Note that a large number of samples will slow down the computation.

Finally, select the **second type** of variable from the drop-down list to assign it to the **y-dimension** of the grid (dependent variable).

Type of variable for x-axis: ---

Minimum value for variable

0

Maximum value for variable

0

Number of steps in variable:

100

Type of variable for y-axis:

Planet mass

Secondary star mass

Planet distance

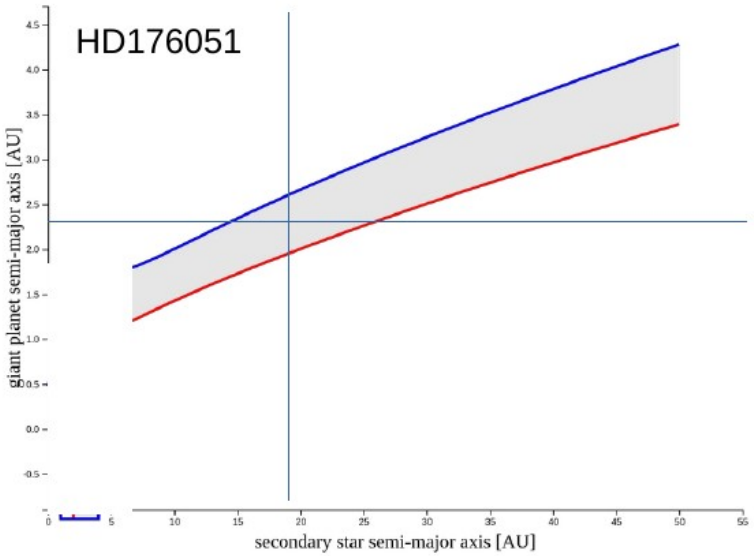
Secondary star distance

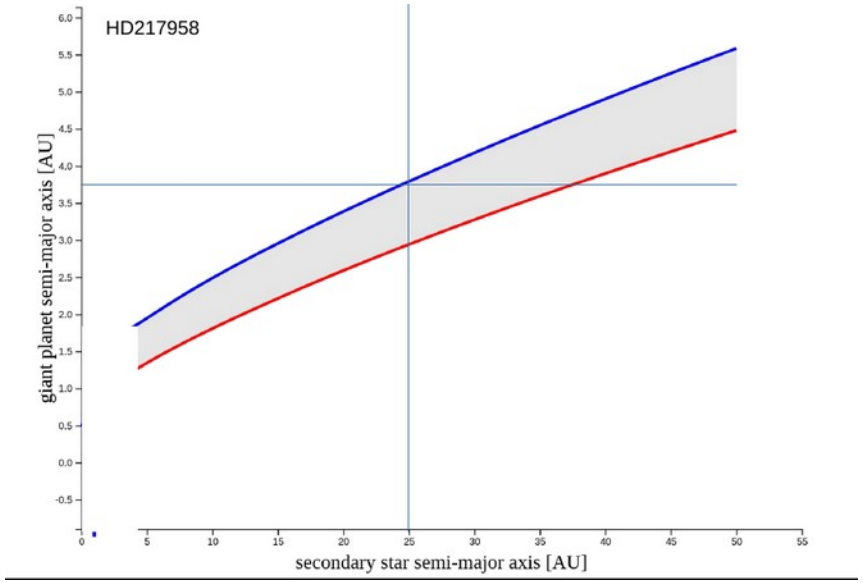
Secondary star eccentricity

Reset to default values

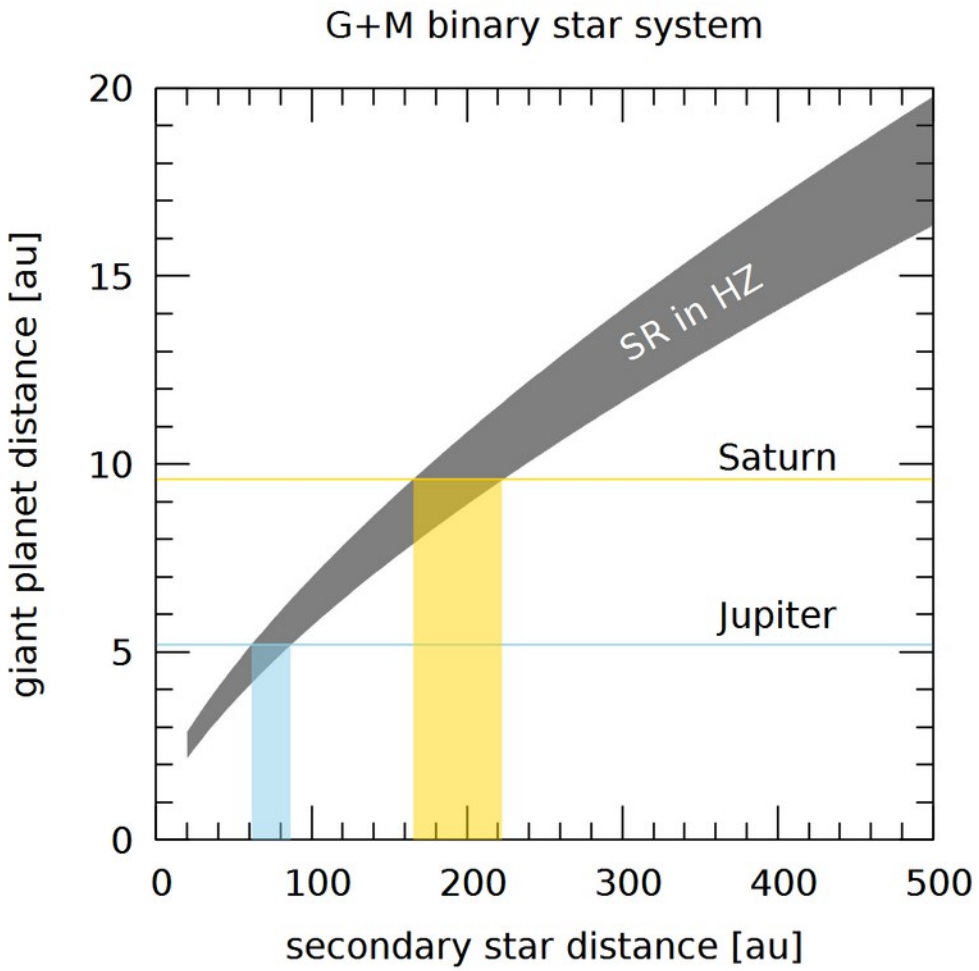
Secular resonance in HZ

HIP90988
HD176051
HD196885
HD41004A
HD217958
HD5608
HD7449
HD126614

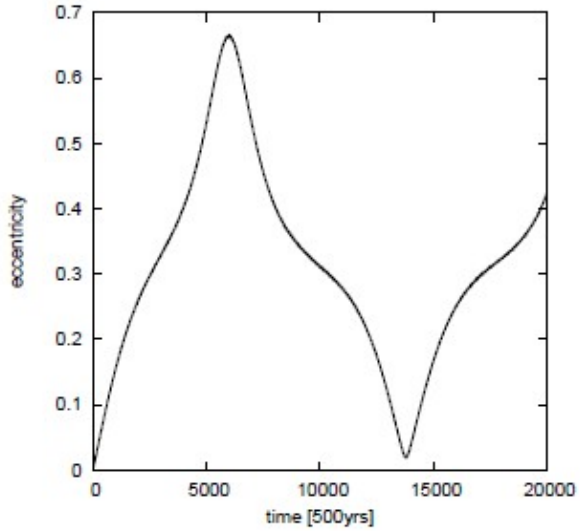




Far away secondary stars may perturb planets in habitable zones



Bazsó & Pilat-Lohinger (2020)



Orbit varies from circular to highly eccentric

→ **affects the habitability**

Summary I

Proto-planetary Disks (S-types) are truncated

The size of stable region depends on the Binary star configuration

HZ must be in the stable area and for the HZ borders the secondary star must be considered

Secular perturbations in HZ can occur even in wide binary star configuration

Which binary star system could harbour

Earth-like planets in the HZ ?

N-body simulation using our GPU-N-body code ‘GANBISS’
(Zimmermann M. & PL E, 2023, CeMDA 135)

Study Terrestrial planet formation via Collisions

Apply Collision Analysis of Leinhardt & Stewart (2012)

Study Terrestrial planet formation applying the

Collision model of Leinhardt & Stewart (2012)

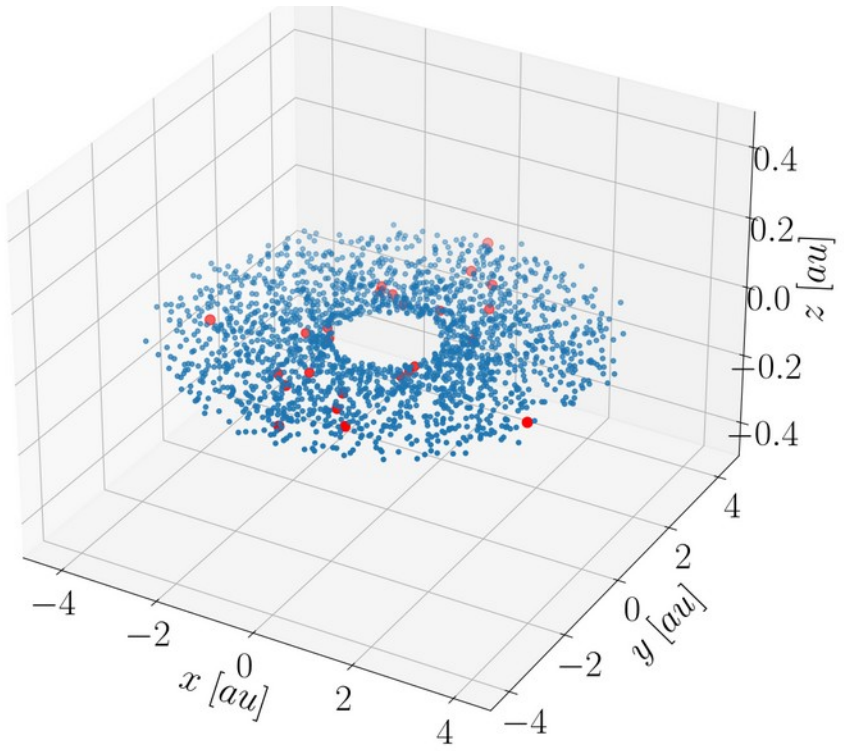
Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **545,** 1–15 (2026) https://doi.org/10.1093/mnras/staf2230
Advance Access publication 2025 December 18

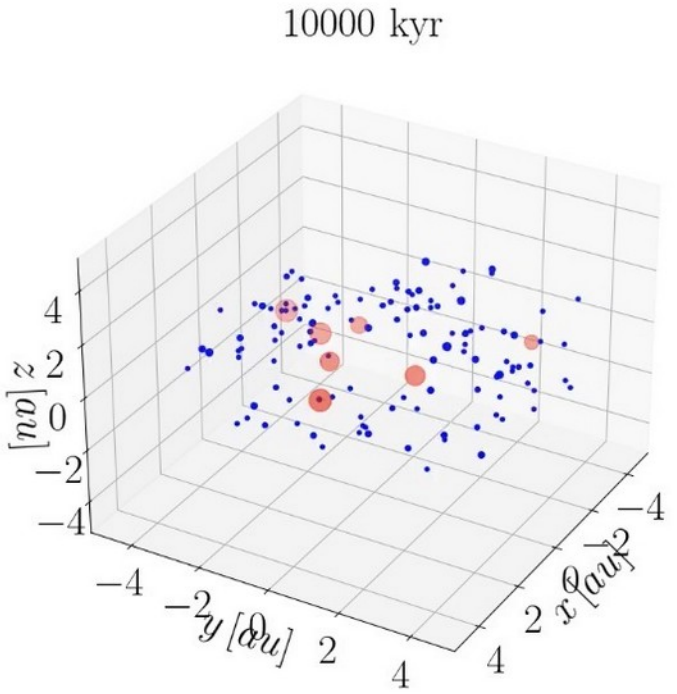
N-body interactions and collisions in circumstellar discs for planar and inclined binary star configurations

M. Zimmermann [1,2]★ and E. Pilat-Lohinger[1,2,3]

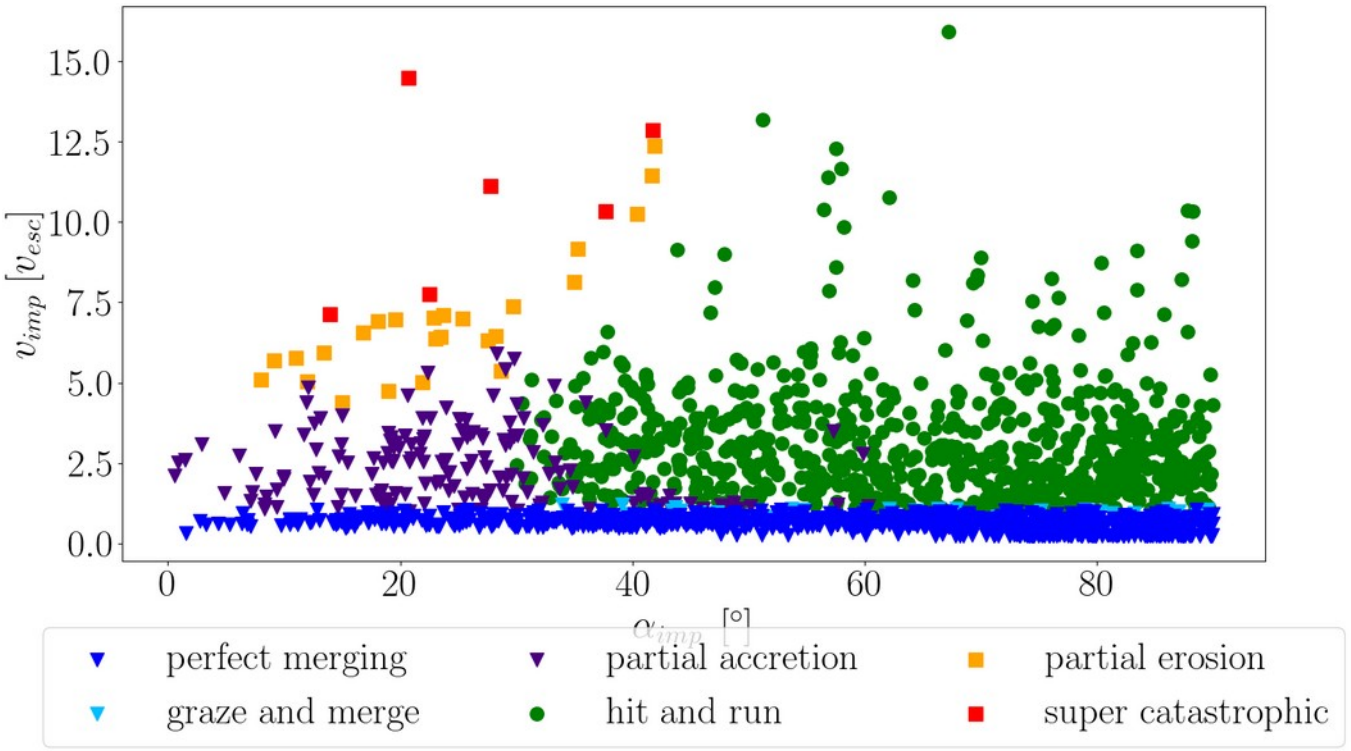
[1]*Department of Astrophysics, University of Vienna, Türkenschanzstraße 17, A-1180 Vienna, Austria*
[2]*Institute for Theoretical and Computational Physics , Graz University of Technology, Petersgasse 16/II, A-8010 Graz, Austria*
[3]*Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria*



N-body computations
GANBISS
10 Myrs



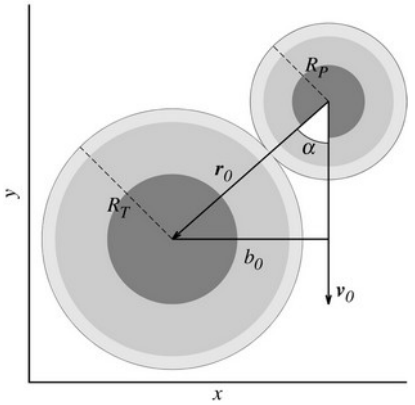
Collisions during the N-body simulation (M. Zimmermann)



Different collision outcomes

Impact velocity [v_{esc}]

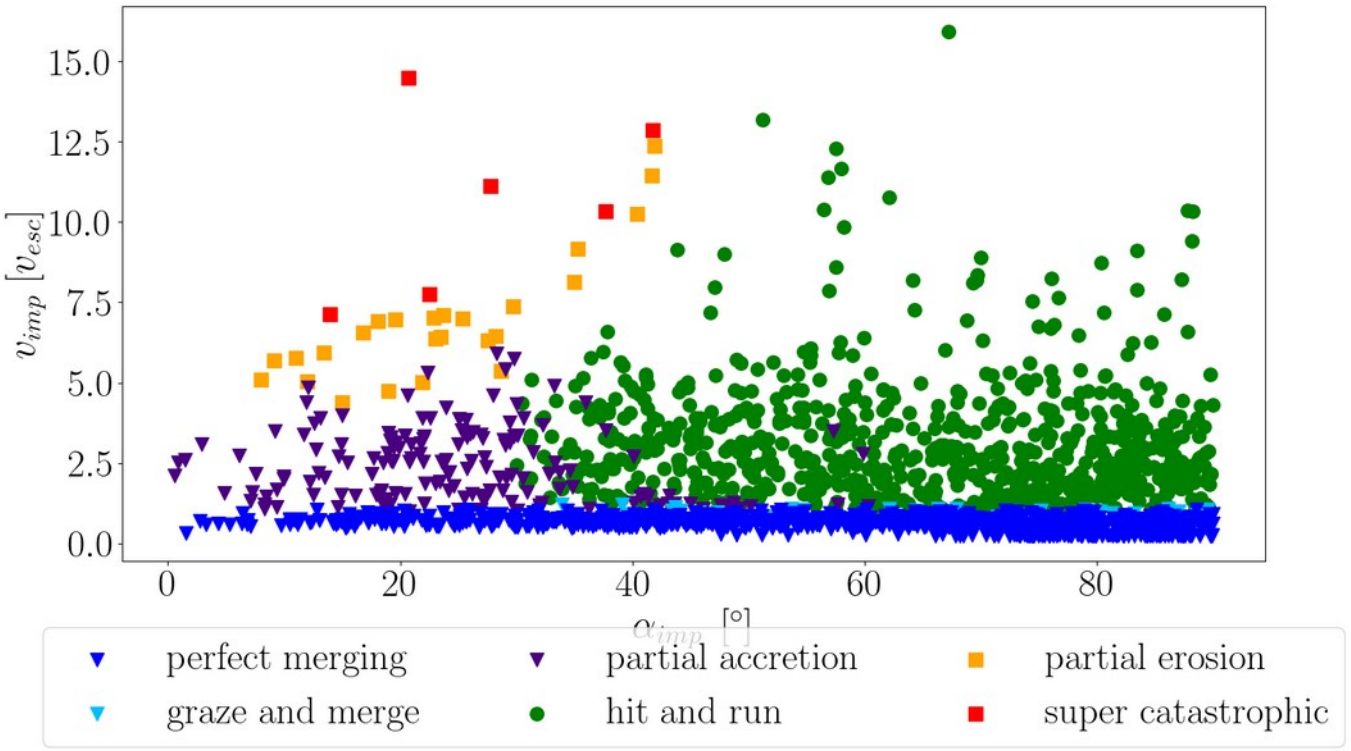
& Impact angle

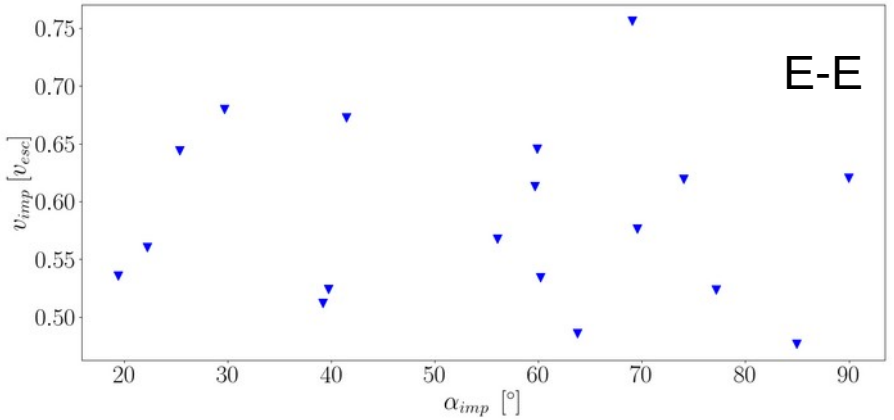


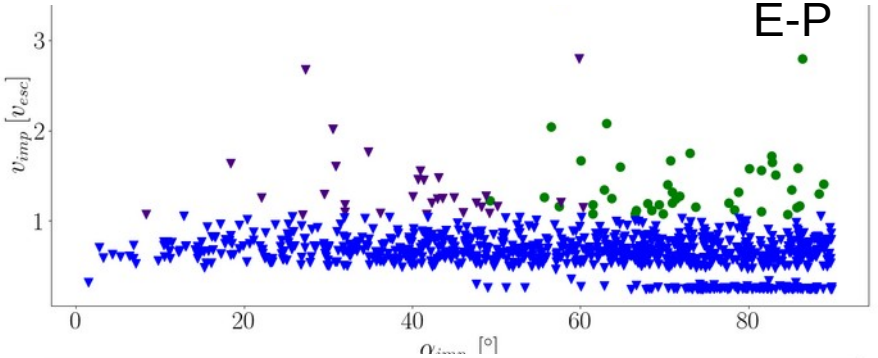
Based on the study by
Leinhardt & Stewart, 2012, ApJ 745

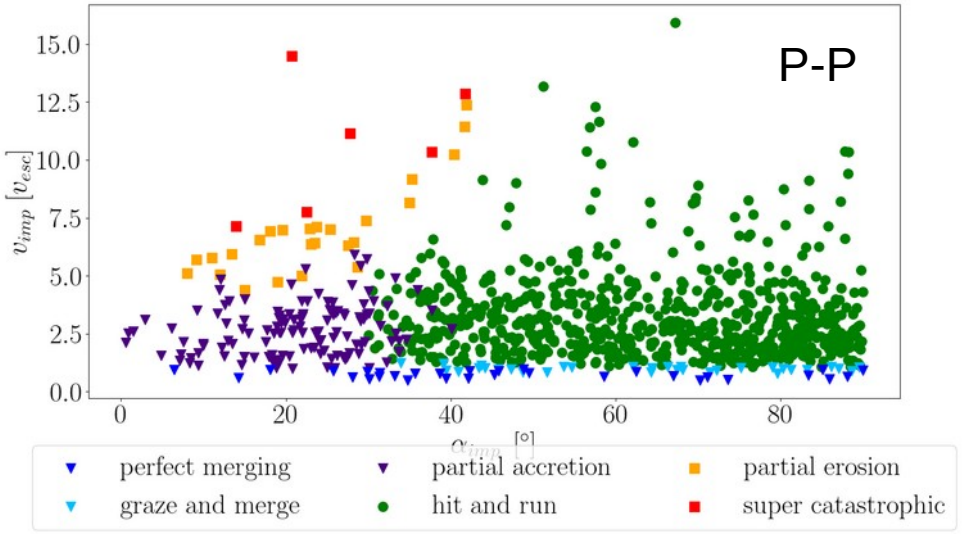
$V_{esc} = \sqrt{2GM_{tot}/(R_p + R_t)}$, with M_{tot} the total mass of the colliding objects, and R_p and R_t the spherical radius of the impactor and target, respectively.

Collisions during the N-body simulatic









Based on the study by
Leinhardt & Stewart, 2012, ApJ 745

Summary II

Application of the collision analysis by Leinhardt & Stewart (2012) esp. in case of Planetesimal Collisions seems to be promising

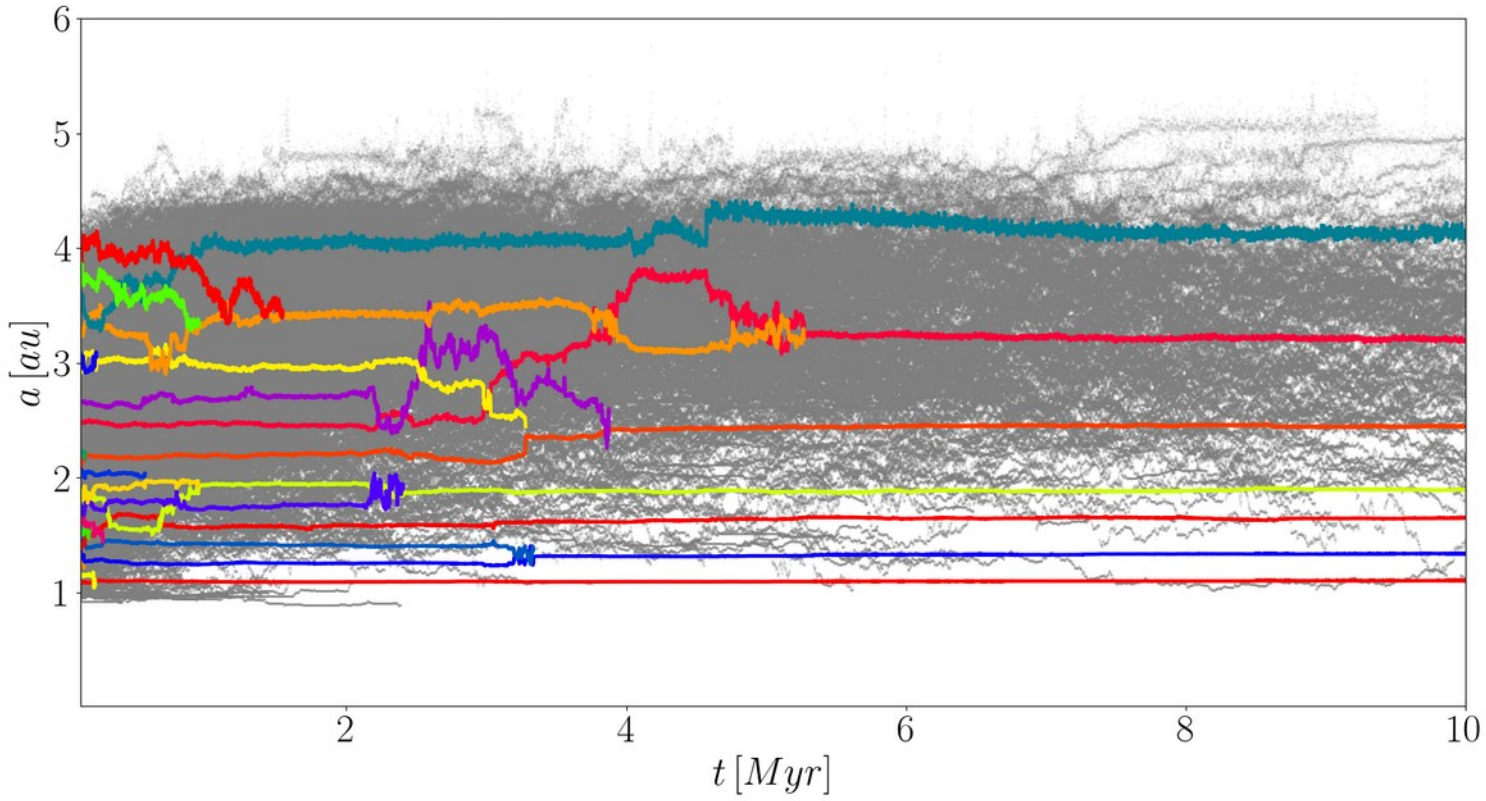
Application to larger masses has to be tested

As the number of remaining Protoplanets and larger Embryos in the HZ is quite small after 10 million years, the collisions can be investigated in the REBOUND calculations using SPH simulations (Burger et al. 2020, A&A 634)

Evolution in semi-major axis

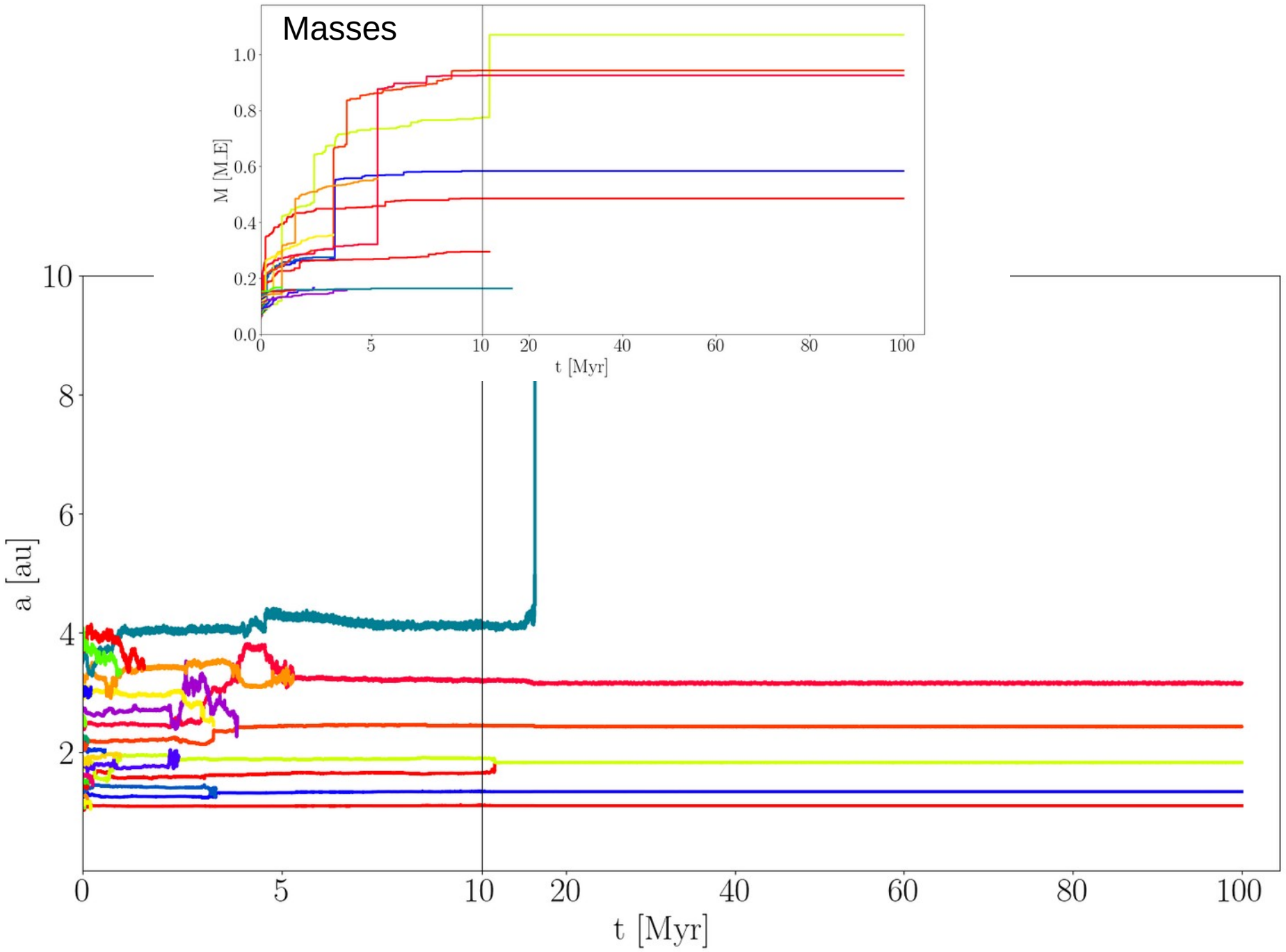
25 Embryos

2000 Planetesimals



7 Protoplanets/Embryos

120 Planetesimals


Masses
M [M_E]
t [Myr]
a [au]
t [Myr]