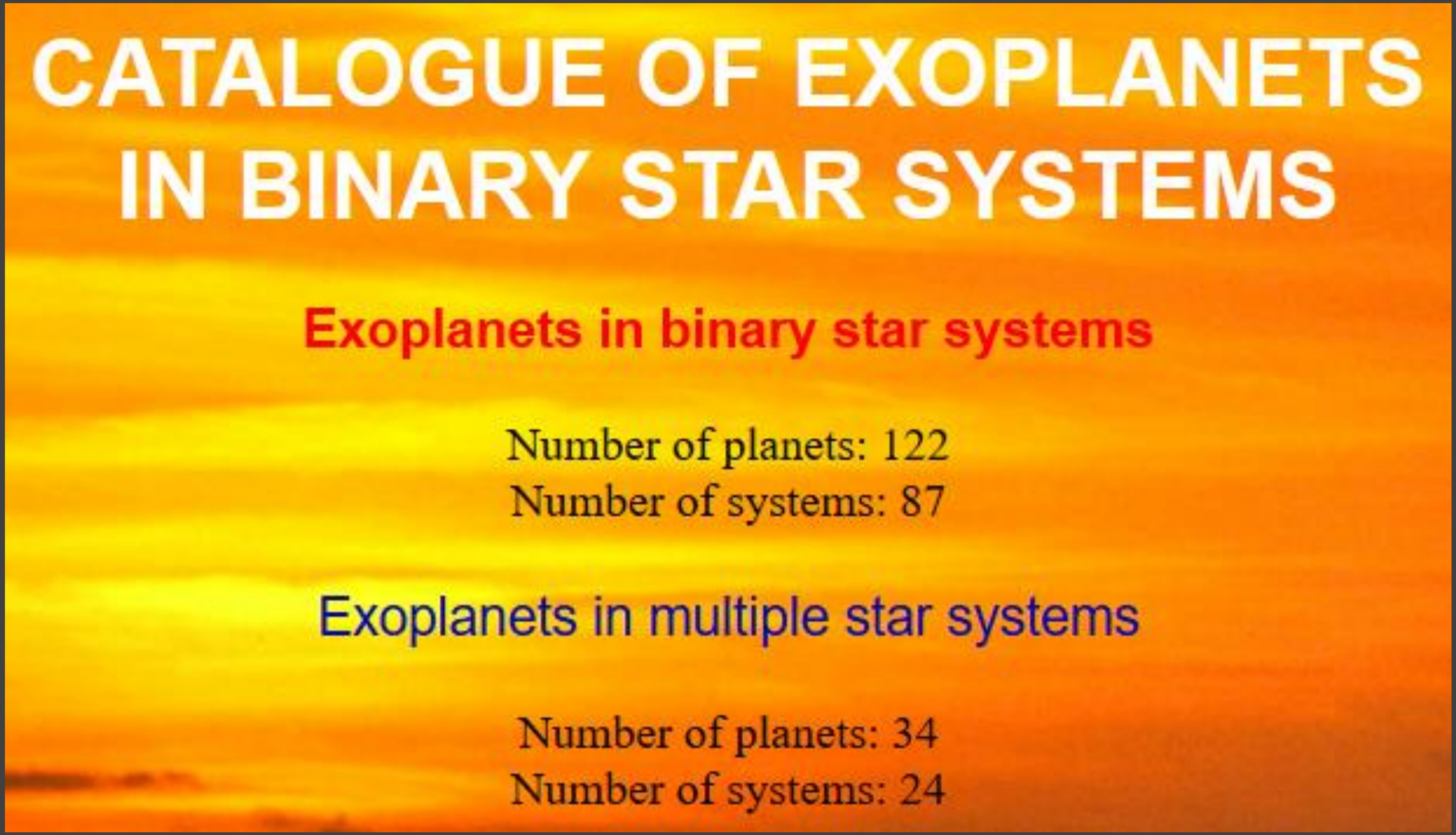
Planets in binaries

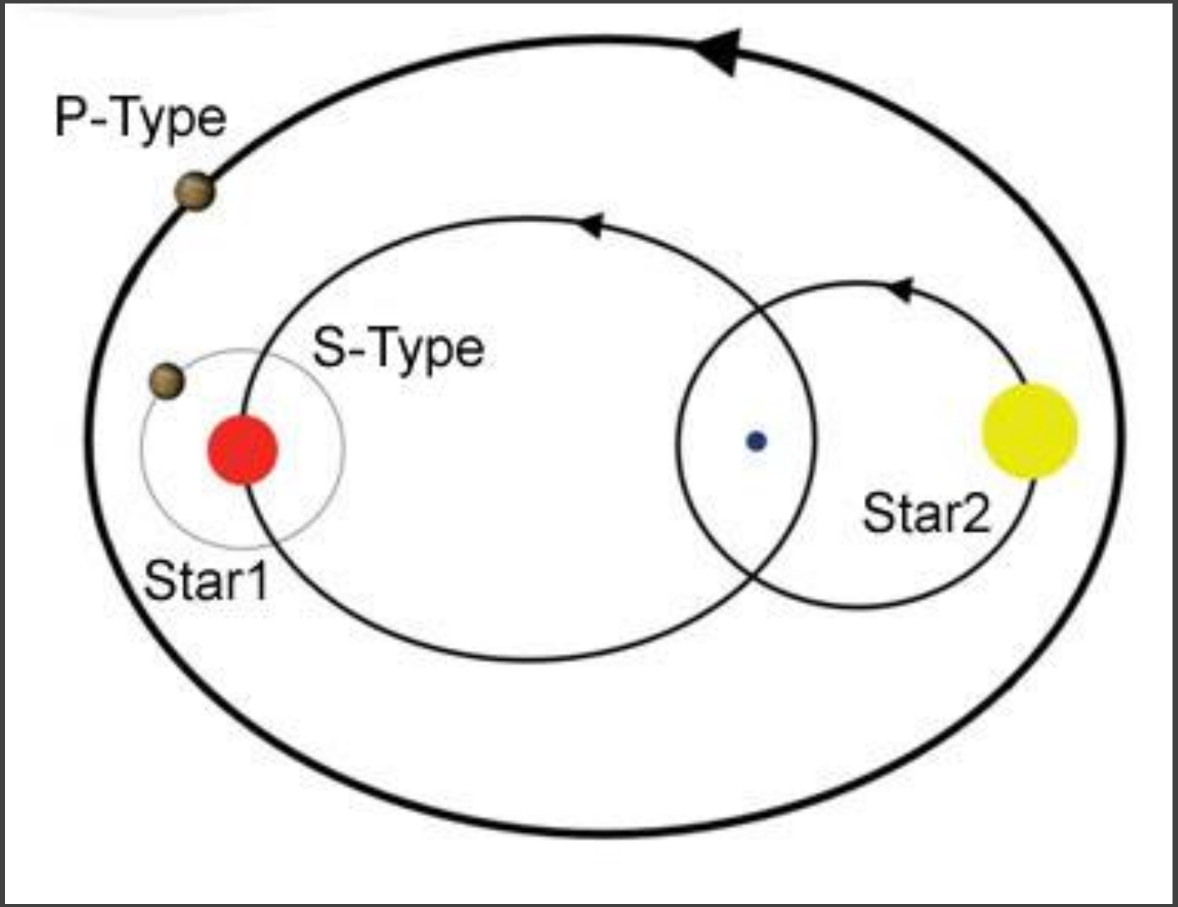
SERGEI POPOV

Catalogue of planets in binaries



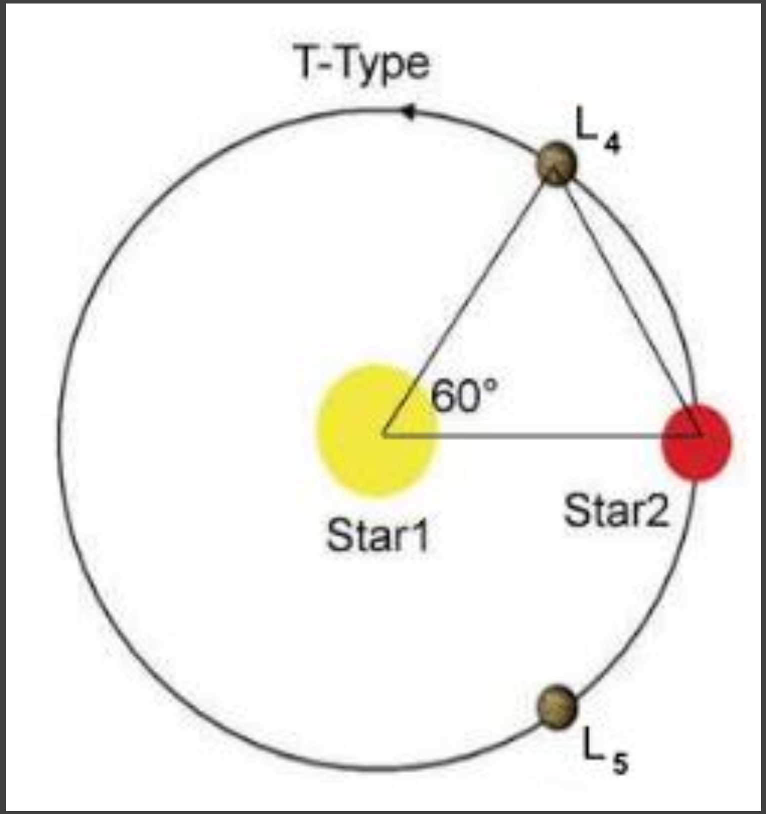
http://www.univie.ac.at/adg/schwarz/multiple.html

S-type and P-type. And T-type!



The central stars strongly perturb the region around them, clearing out orbits to distances of 2–5 times the binary separation.

In addition to known S-type and P-type planetary orbits, also so-call T-type planets, similar to Troyans, can exist.



Orbit stability

$$R_p = \left(0.464 - 0.38\frac{m_2}{m_1 + m_2}\right) a_*$$

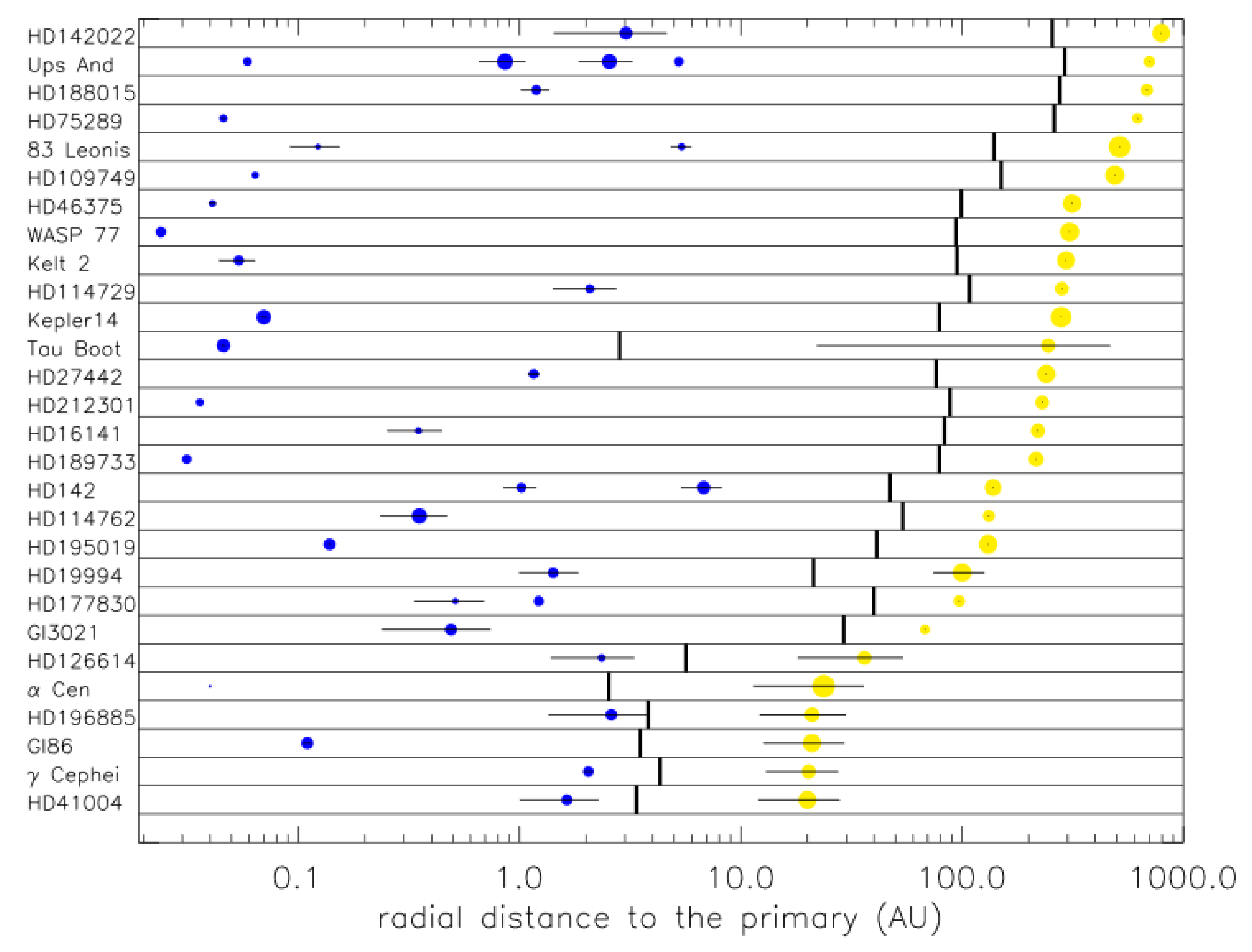
S-type

$$a_c = (1.60 + 4.12\mu - 5.09\mu^2)a_b$$

P-type

$$\mu = m_2/(m_1 + m_2)$$

Both estimates are given for e=0.



$$R_p = \left(0.464 - 0.38\frac{m_2}{m_1 + m_2}\right) a_*$$

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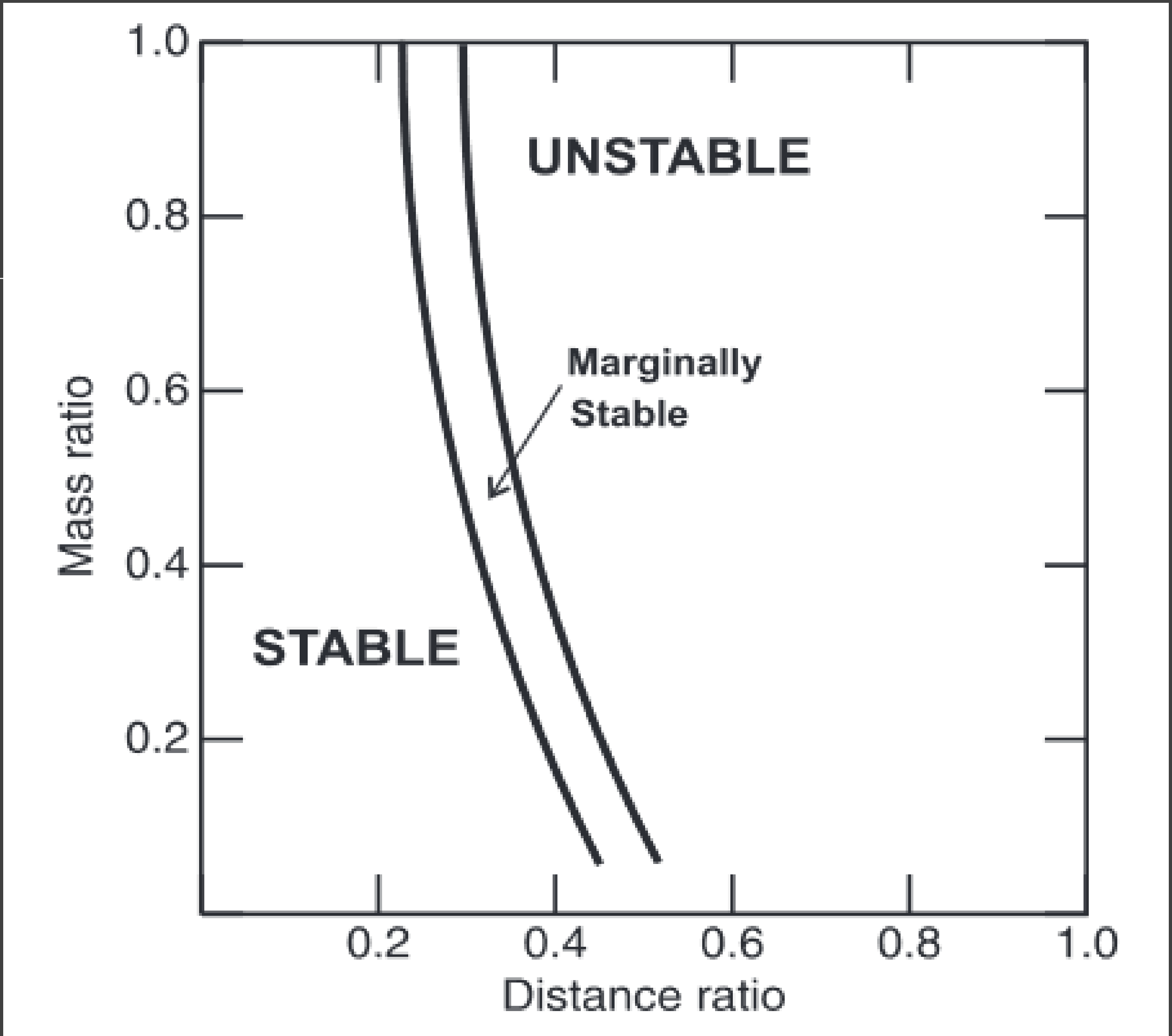
S-type

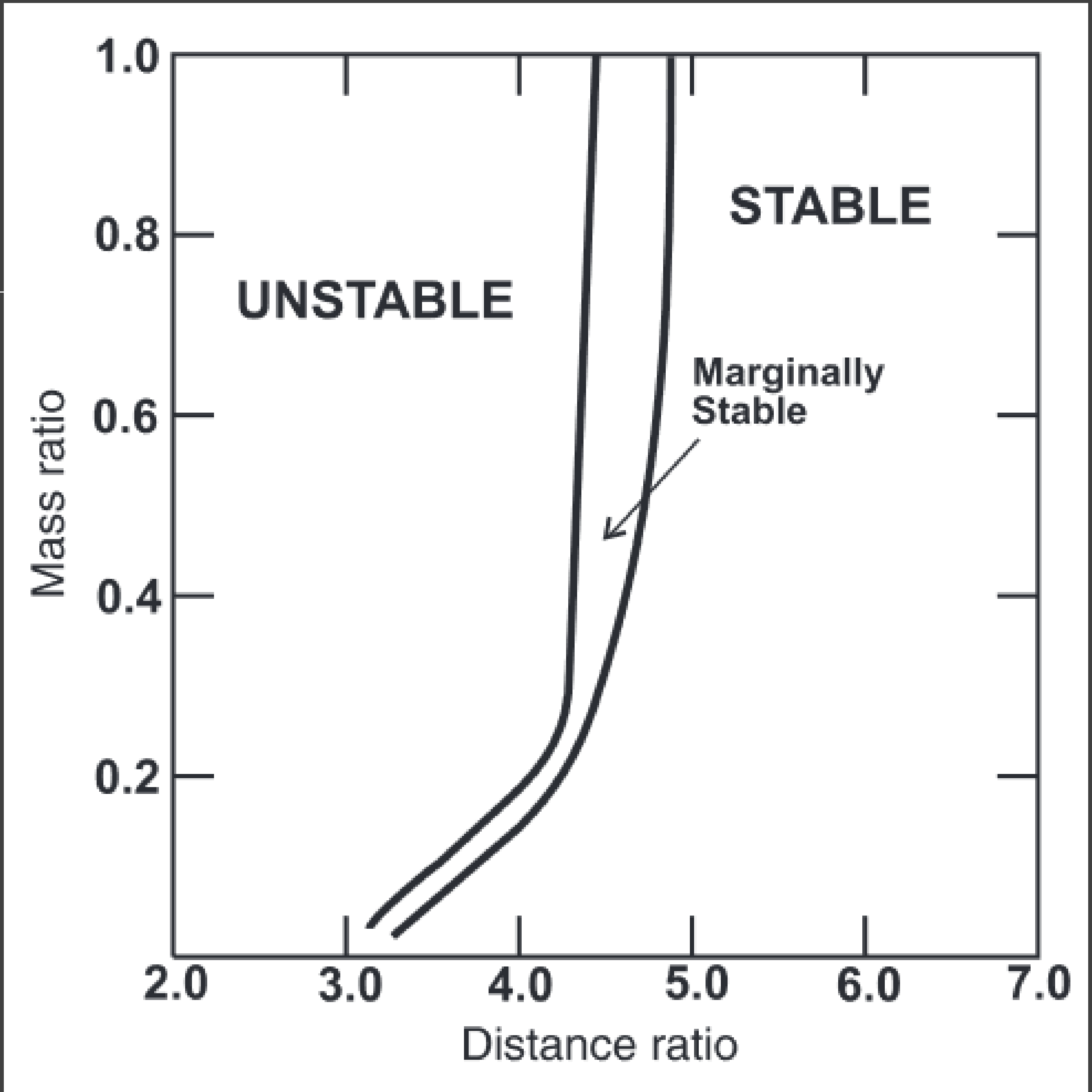
Distance ratio: $R_{planet-A}/R_{AB}$

Mass ratio: M_B/M_A



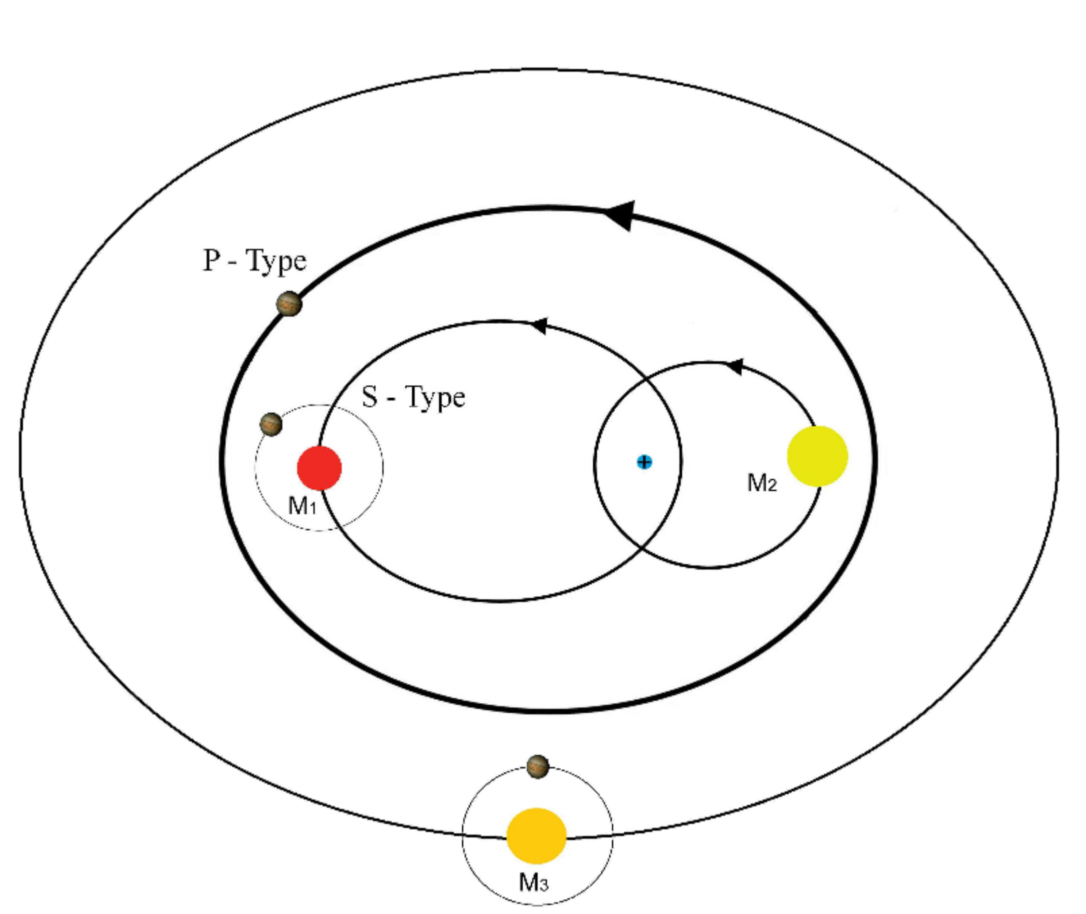
Musielak et al. (2005)

P-type



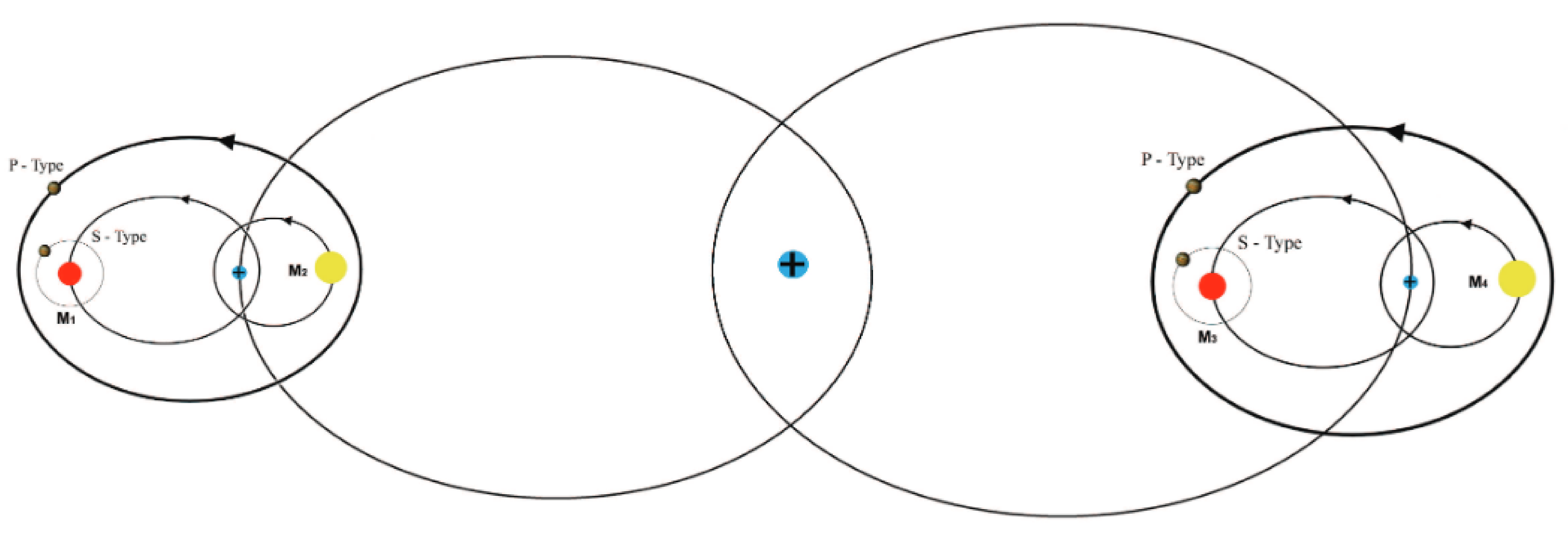
Musielak et al. (2008)

Planets in triple-star systems

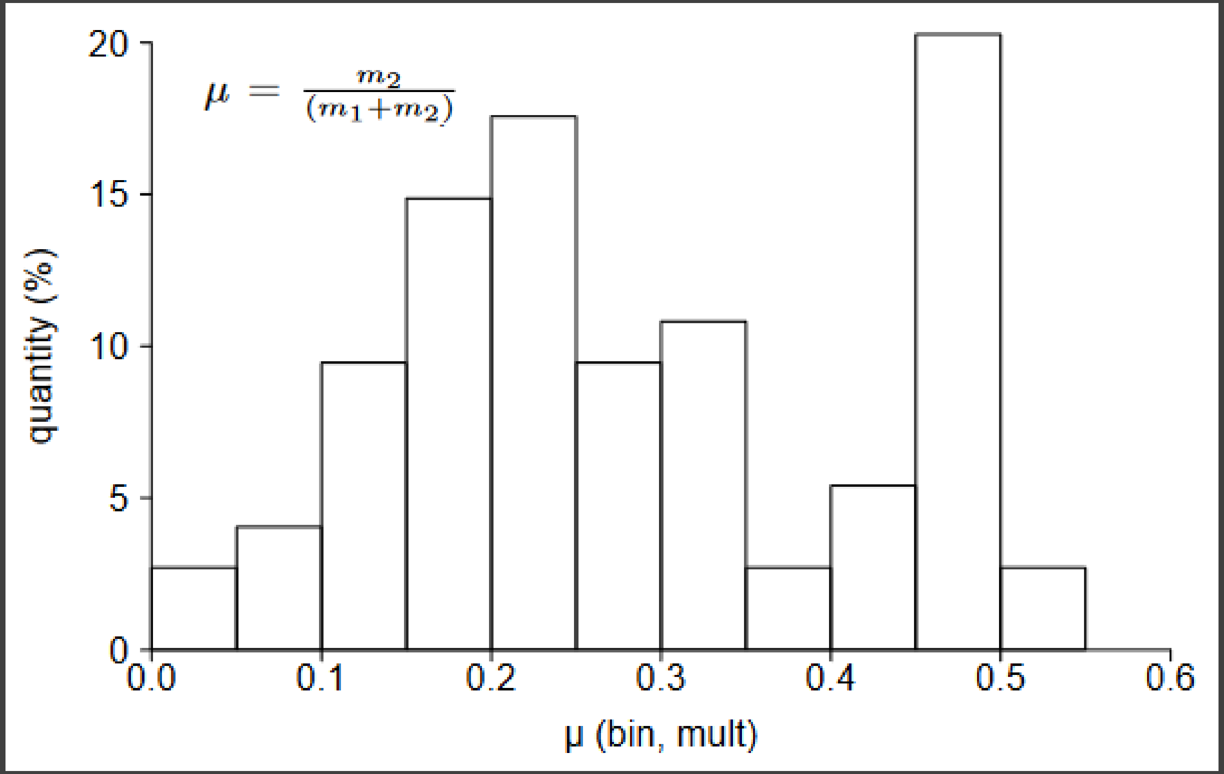


Stable orbits of S-, P-, and T-types
are possible in different kinds of multiple systems.

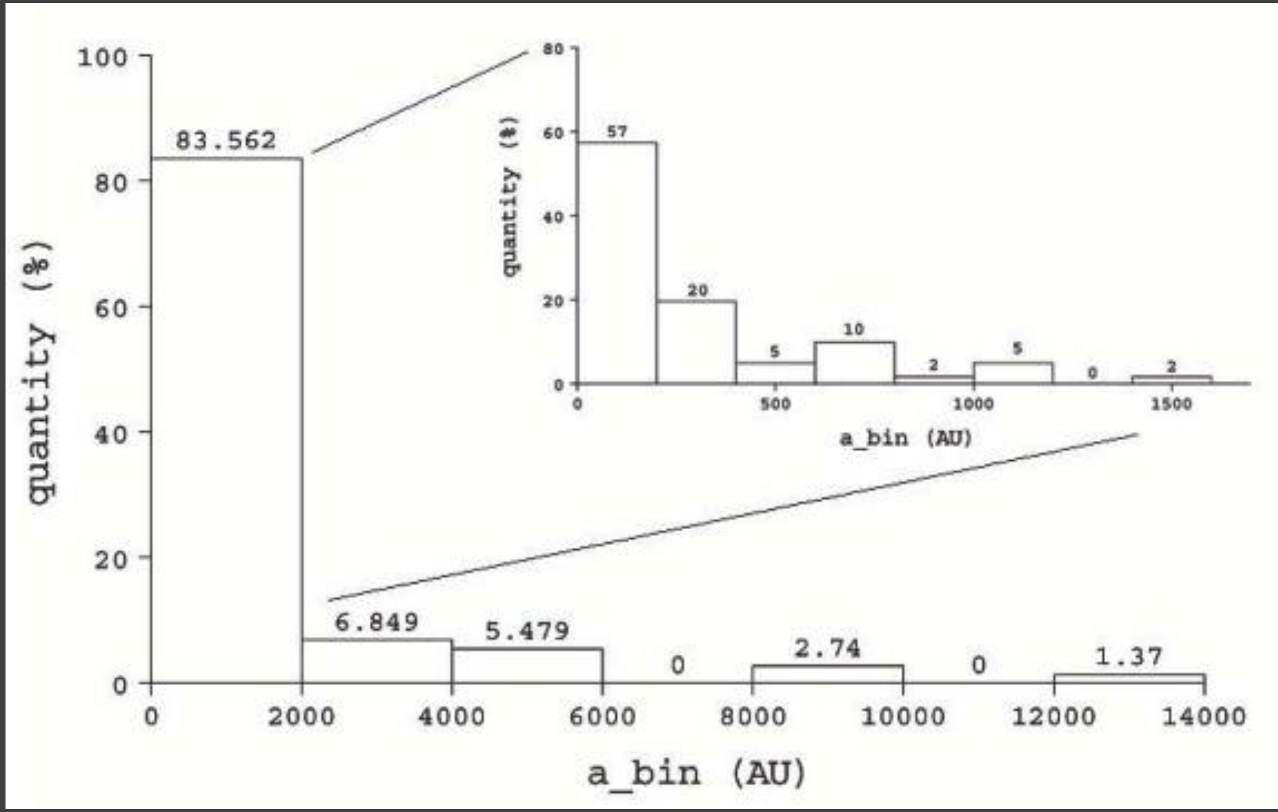
Quadruple star systems



Statistics



$\mu = \frac{m_2}{(m_1+m_2)}$
quantity (%)
μ (bin, mult)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20



quantity (%)
a_bin (AU)
83.562
6.849
5.479
0
2.74
0
1.37
0
2000
4000
6000
8000
10000
12000
14000
0
20
40
60
80
100
57
20
5
10
2
5
0
2
0
500
1000
1500

First circumbinary planet found by microlensing

Only triple lensing model (star+2 planets or planet+ 2stars) can fit the light curve.

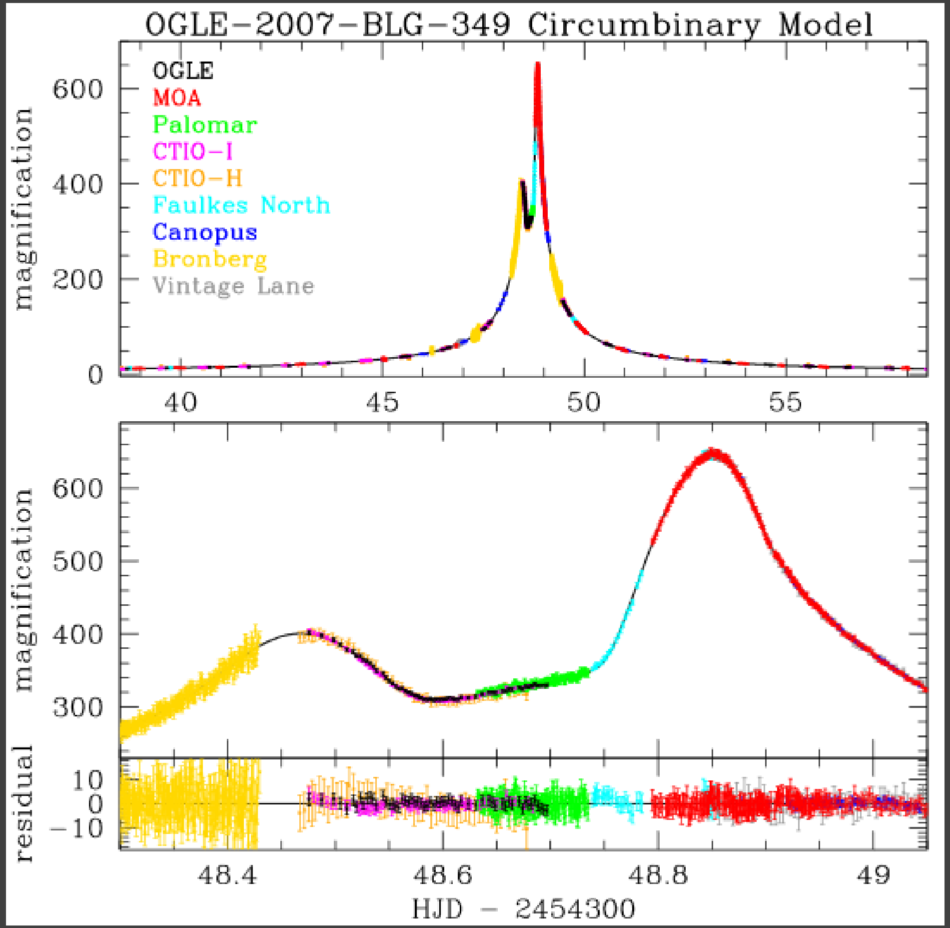
Subsequent HST observations favour the circumbinary model.

Parameter	units	average value	2-σ range
D_L	kpc	2.76 ± 0.38	2.06-3.56
$M_{\rm A+B}$	$M_\odot$	0.71 ± 0.12	0.50-0.95
$M_{\rm A}$	$M_\odot$	0.41 ± 0.07	0.28-0.54
$M_{\rm B}$	$M_\odot$	0.30 ± 0.07	0.15-0.45
m_c	$M_\oplus$	80 ± 13	56-107
$a_{\perp \rm AB}$	AU	0.061 ± 0.007	0.048-0.074
$a_{\rm AB}$	AU	$0.080^{+0.027}_{-0.015}$	0.054-0.162
$P_{\rm AB}$	days	$9.7^{+5.4}_{-2.5}$	5.7-28.1
$a_{\perp \rm CMc}$	AU	$2.59^{+0.43}_{-0.34}$	1.97-3.89

Planetary orbit ~3.2AU
Orbital period ~7 years

$80 \pm 13 M_\oplus$

Planetary orbit



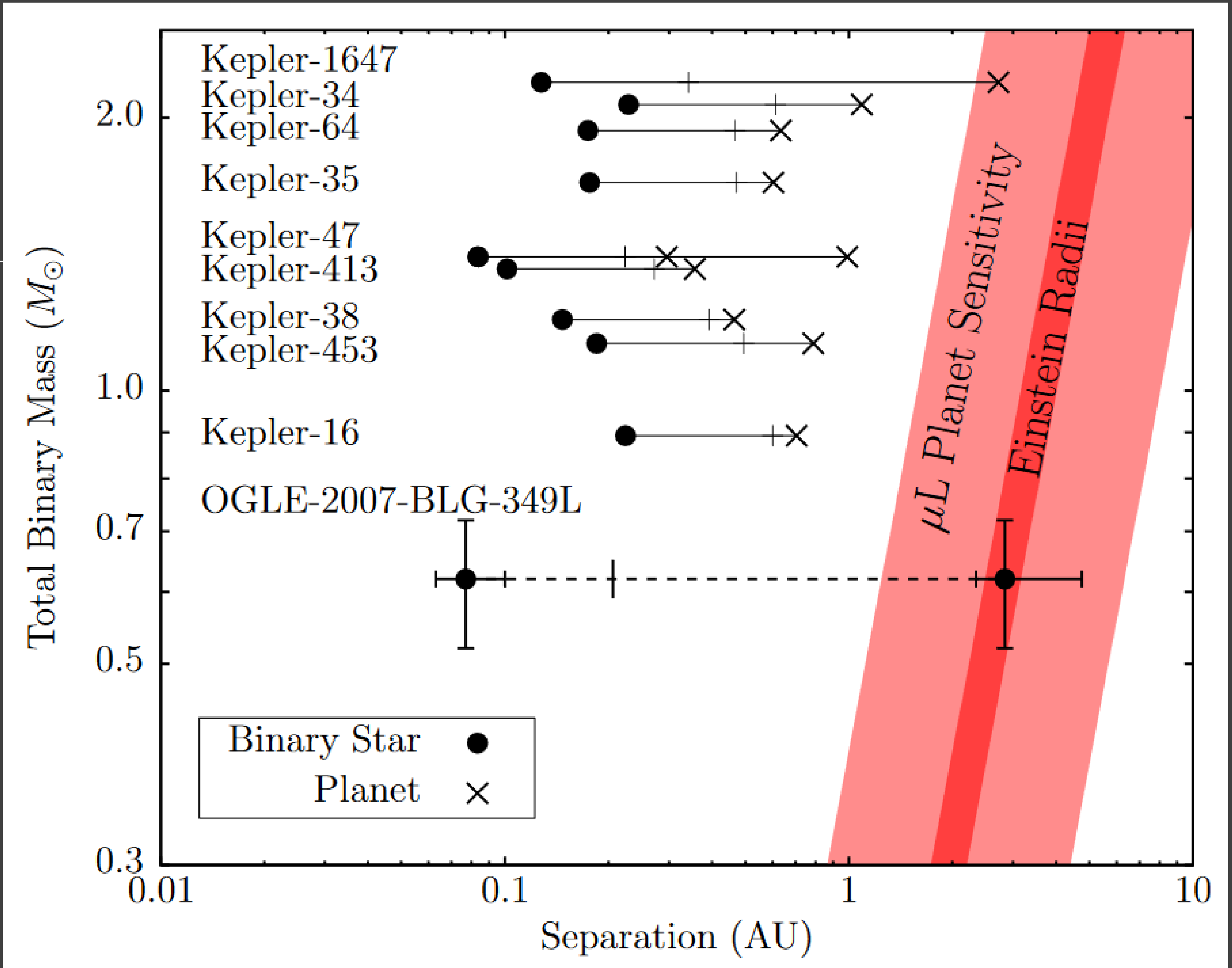
Comparison

Kepler planets have tight orbits, as if they moved close to their stars after formation.
They are close to the stability limit.

$$a_c \simeq (2.28 \pm 0.01) + (3.8 \pm 0.3)e + (1.7 \pm 0.1)e^2,$$

a_c is measured in binary semi-major axis

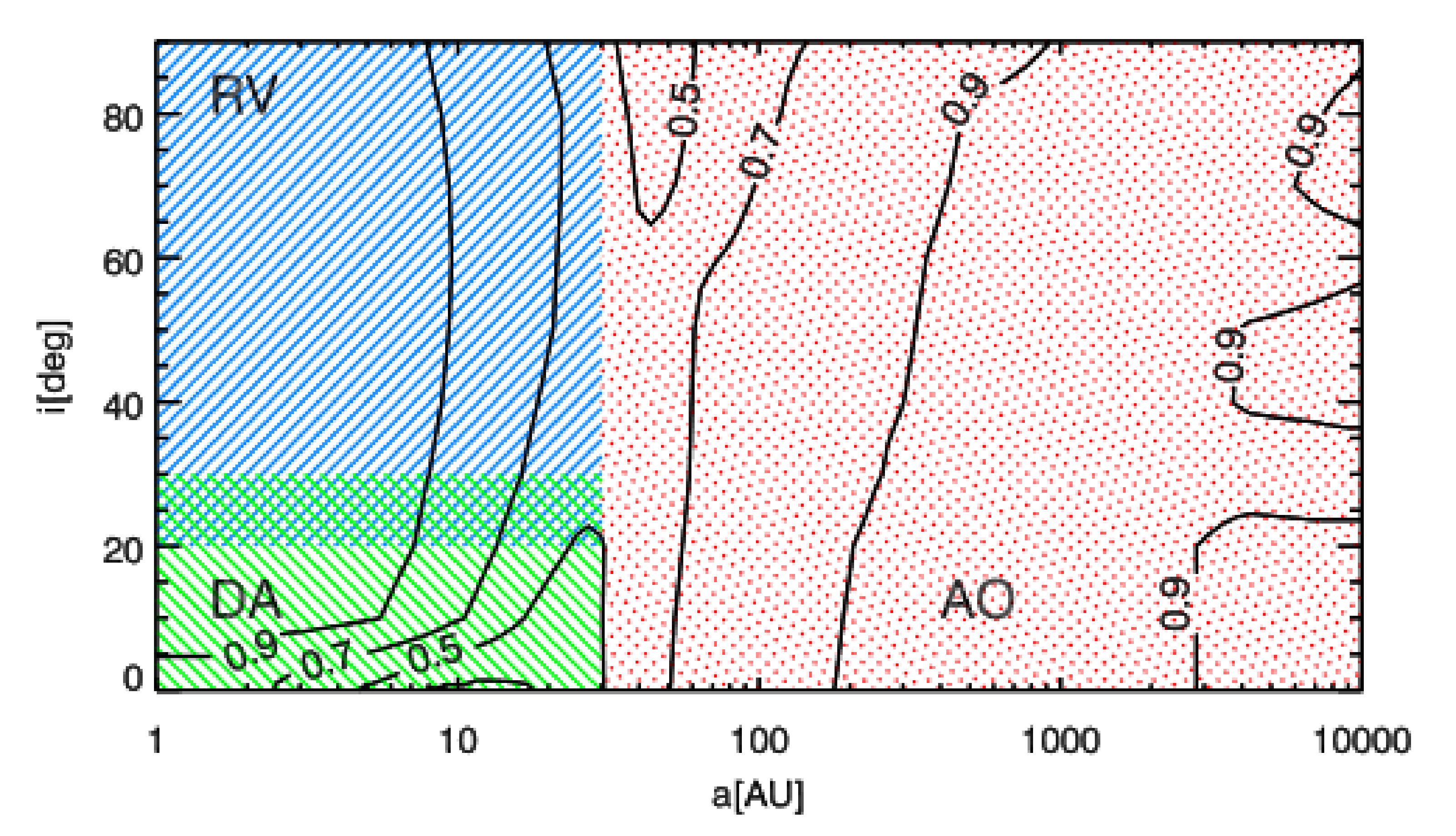
Circles show binary separation,
And crosses – planetary.
Vertical ticks mark the stability limit.



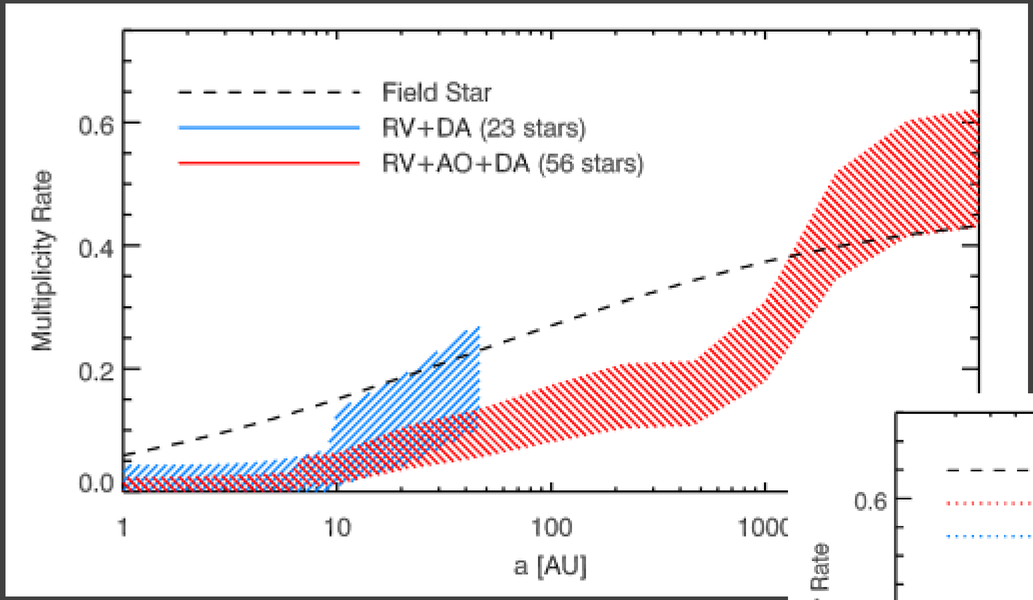
Search for binary component around planets hosts

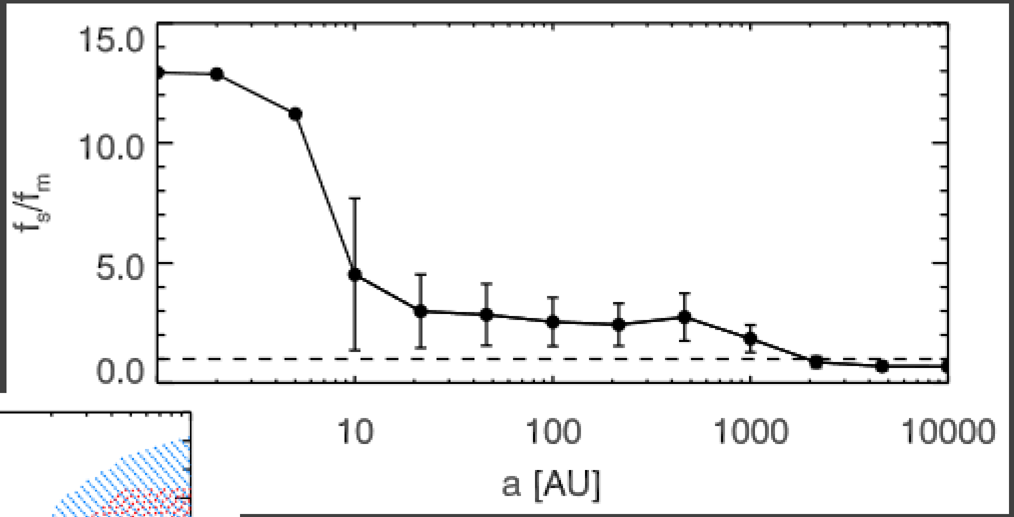
Three techniques:

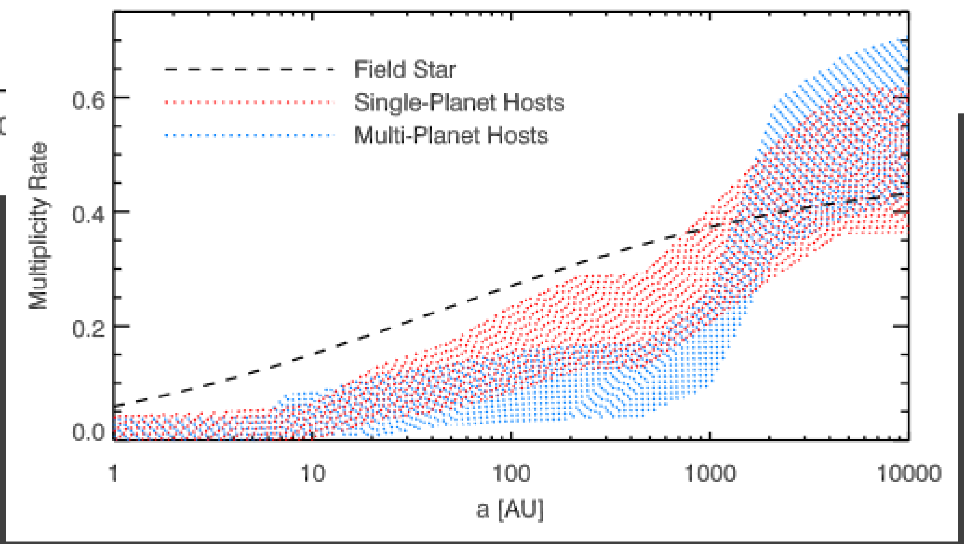
- RV
- AO
- DA



Statistics of planets in close binaries



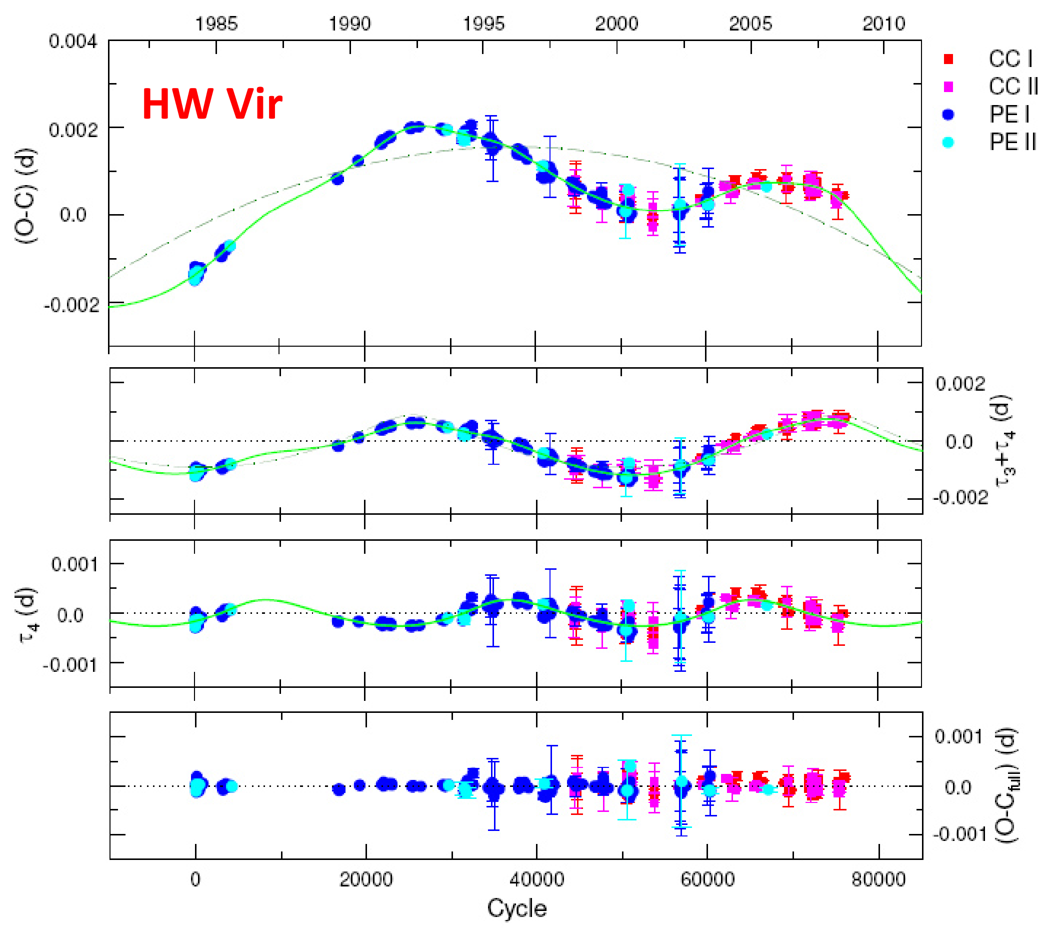




1407.3344

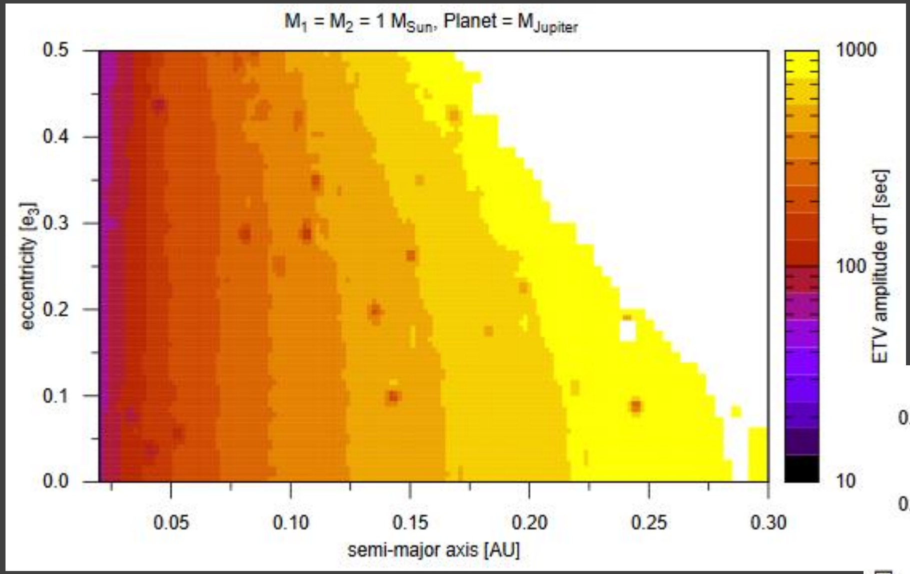
ETV: Eclipse timing variations

CoRoT: 4 sec – for bright stars (12),
and 16 sec – for dim stars (15.2 mag).
Kepler: 0.5 sec – for bright stars (9 mag),
and 4 sec – for dim stars (14.5 mag).



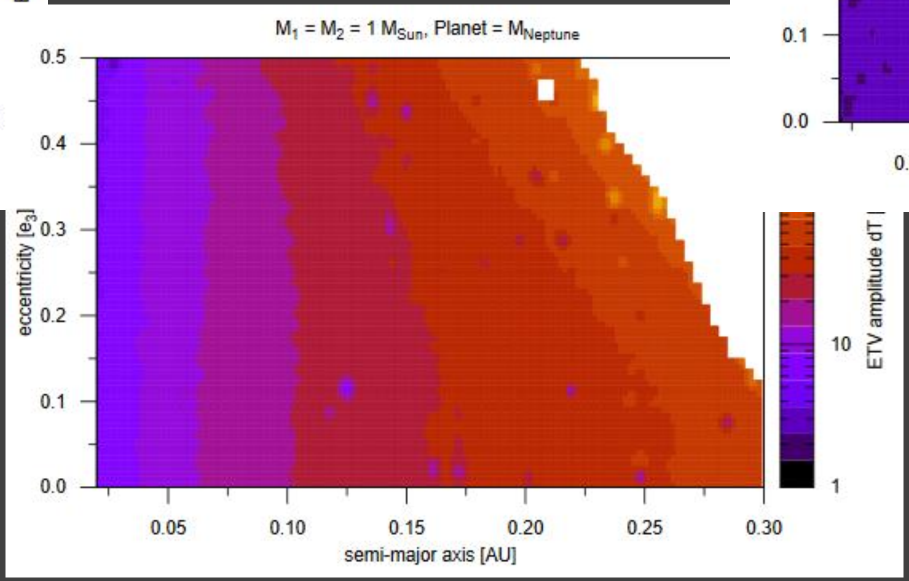
http://astronomy.science.upjs.sk/projectdwarf/scientific-background/

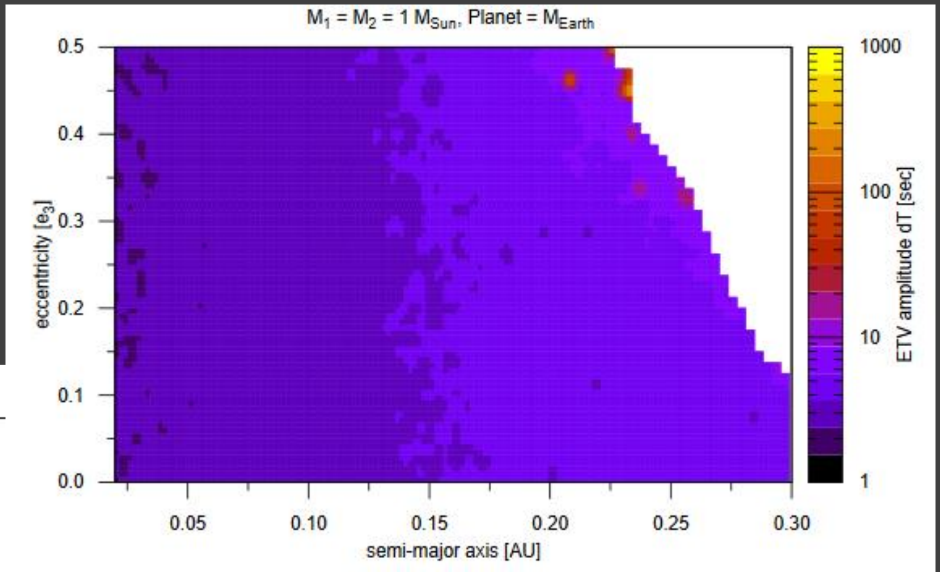
Modeling ETV. S-type systems



a_{bin}=1AU
i=0 (planar orbit)

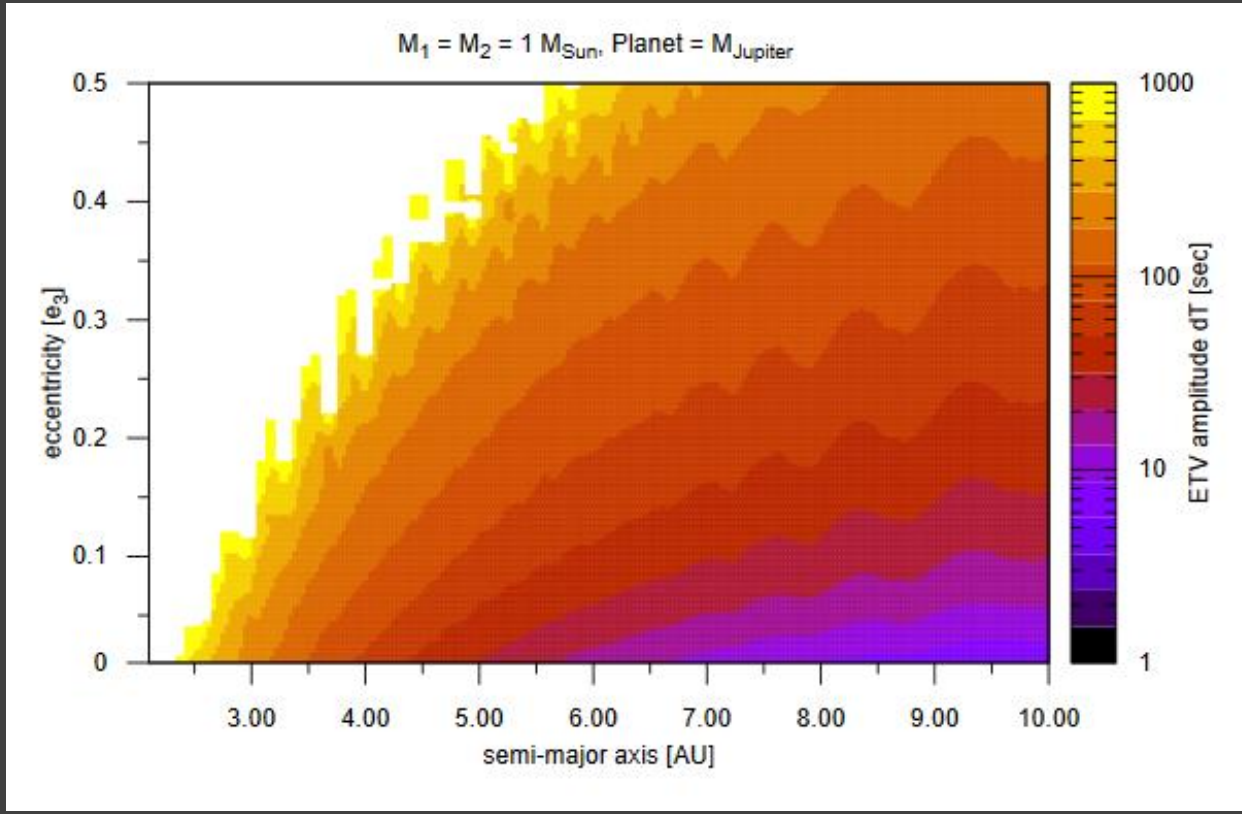
Jupiters are 100% detectable

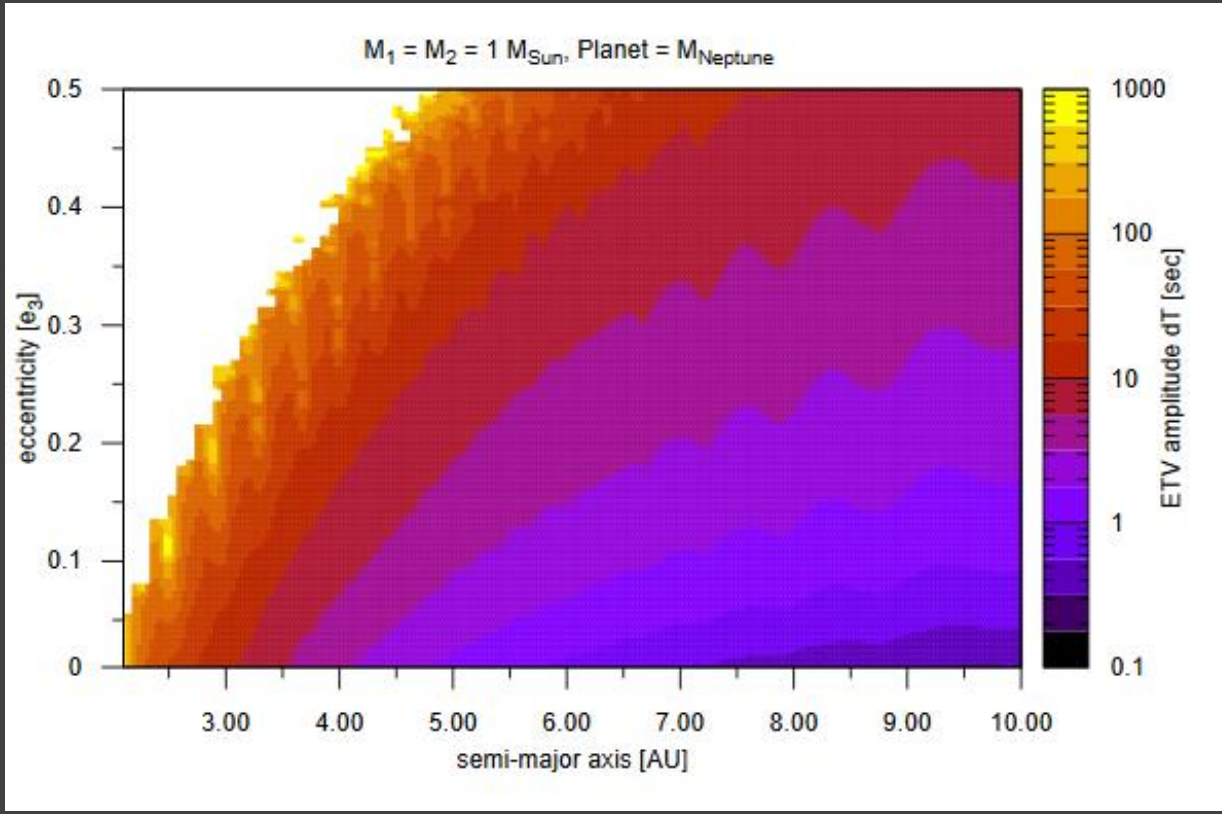




Earth-like planets are undetectable

Modeling ETV. P-type systems



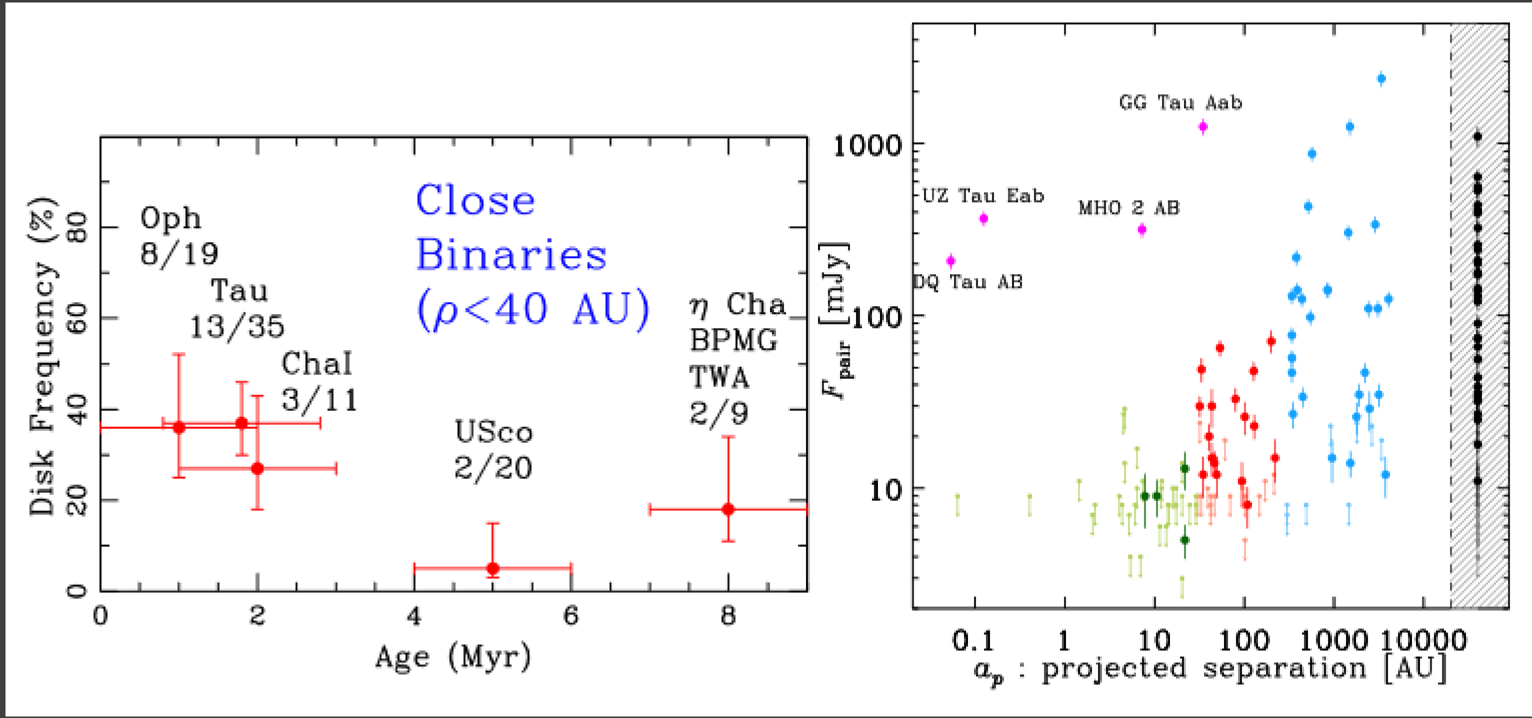


a_{bin}=1 AU; e_{bin}=0

1608.00764

Protoplanetary discs in binaries. S-type

Discs in binaries might be truncated (at 1/3 - 1/4 of the orbital separation).



Perturbations in the disc also modifies planet growth.

Disc frequency for wide binaries is similar to that in single stars, but for close binaries it is lower.

Dust mass is smaller for smaller binary separation.

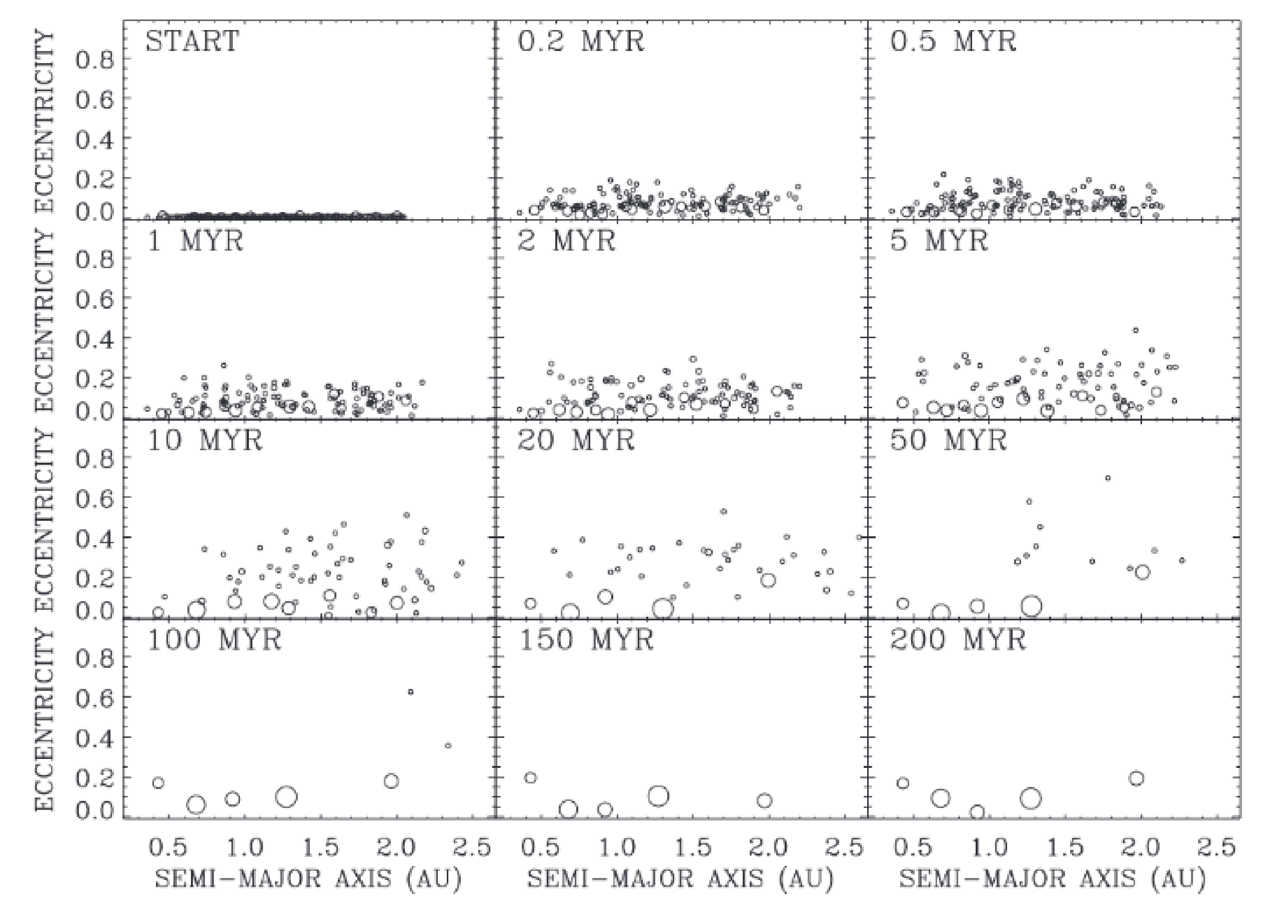
Truncated discs with lower dust mass can be a bad place to form planets, especially massive.

Discs in close binaries are also short lived.
Also bad for planet formation, especially for giants.
In 2/3 of close binaries discs live for <1 Myr.

Temperature is higher in such discs, so dust growth can be less efficient.

1406.1357

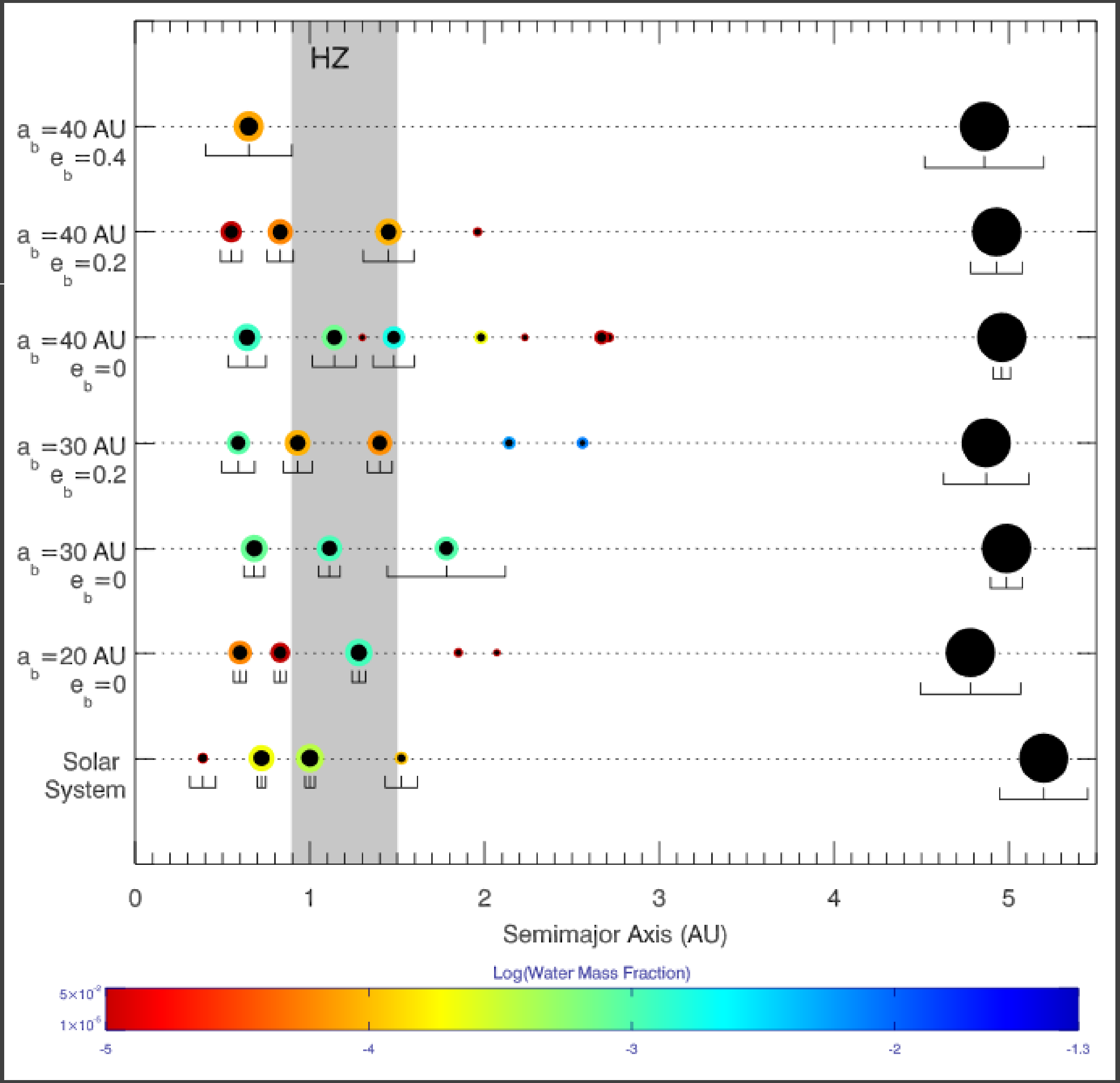
Alpha Centauri-like binary



In a compact binary system planet formation is possible only at small distances from the host star.

Water delivery

Earth-like planets can be formed
in a habitable zone in a compact binary.

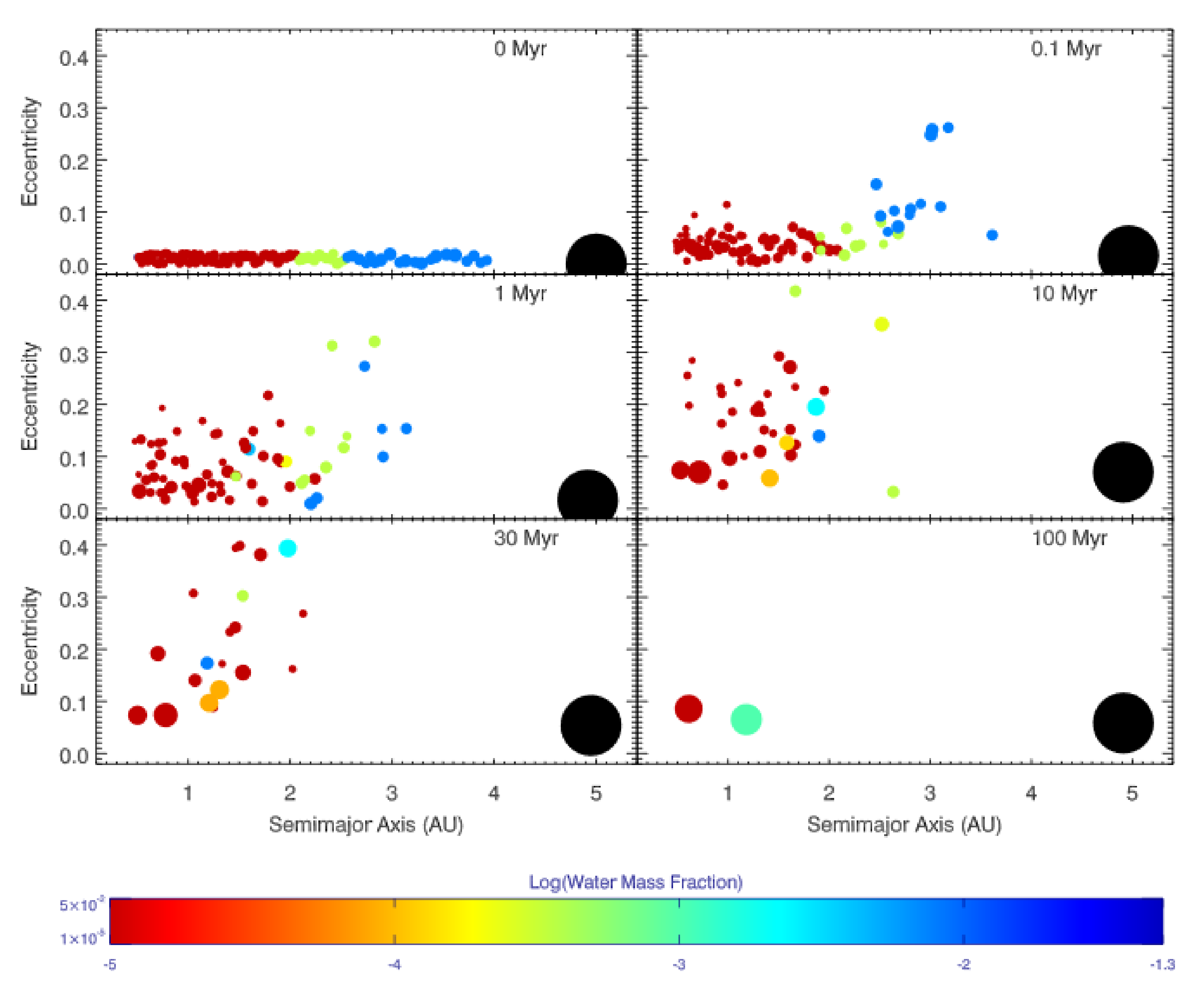


1406.1357

Earth-like

Snap shots of formation of Earth-like planets in a HZ.

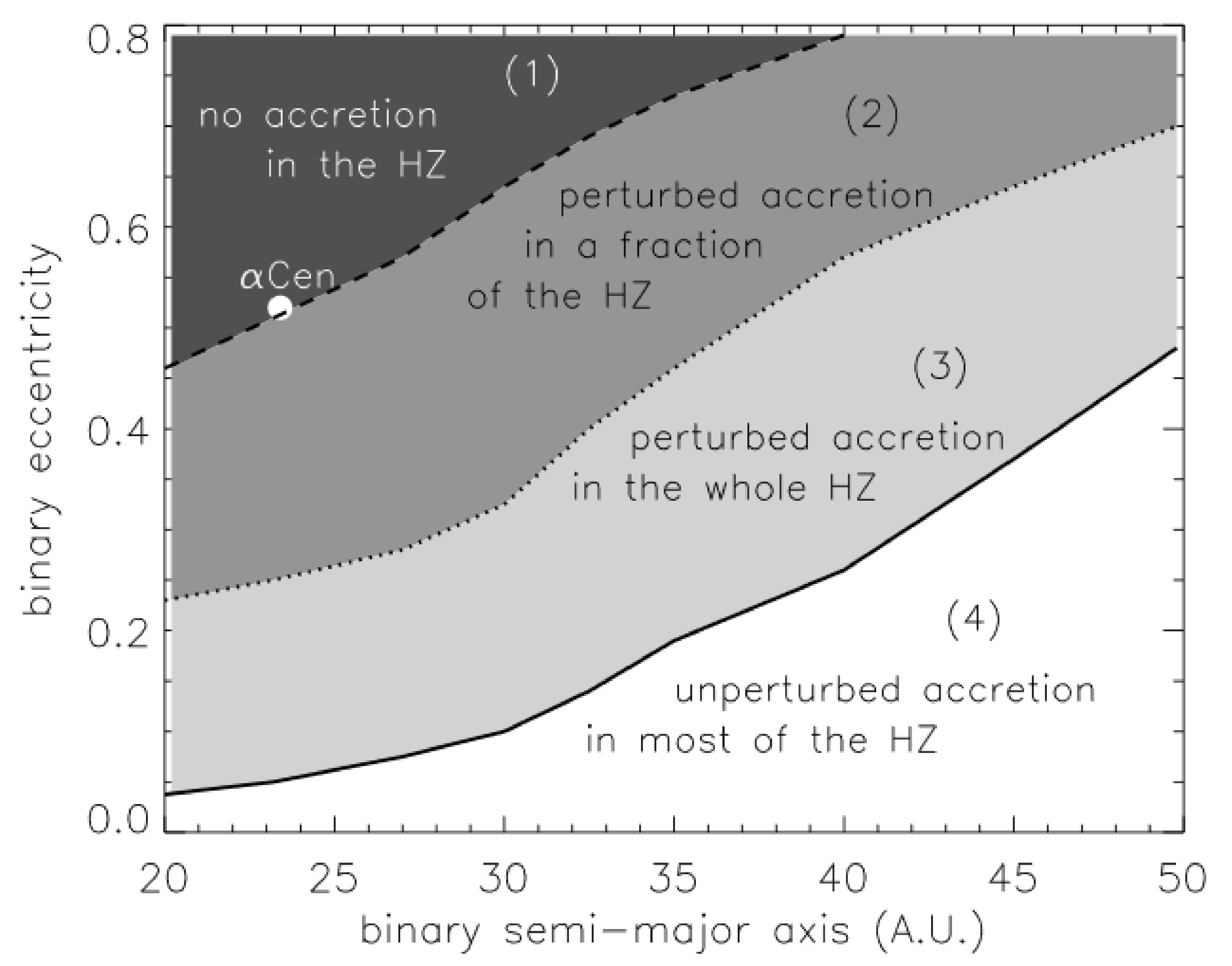
In this study it was assumed that the initial phases of planet formation have been successful.



Accretion

Accretion onto forming planets in a binary system is influenced dynamically by the companion.

High velocity collisions results in erosion, not in growth.



Other ideas for S-type

Several other ideas are discussed

- Planet migration
- Changing of the binary separation
- Gravitational instability

1. Planets could be formed at different orbits, and then migrate outwards. Seems problematic to increase the planetary orbit significantly.
2. It is possible that some compact binaries have been wider, but then their orbits shrink due to interaction with stars in a cluster.
3. Gravitational instability in a protoplanetary disc can help to form planets at larger distances avoiding problems with dust growth, accretion, etc.

Stability of orbits

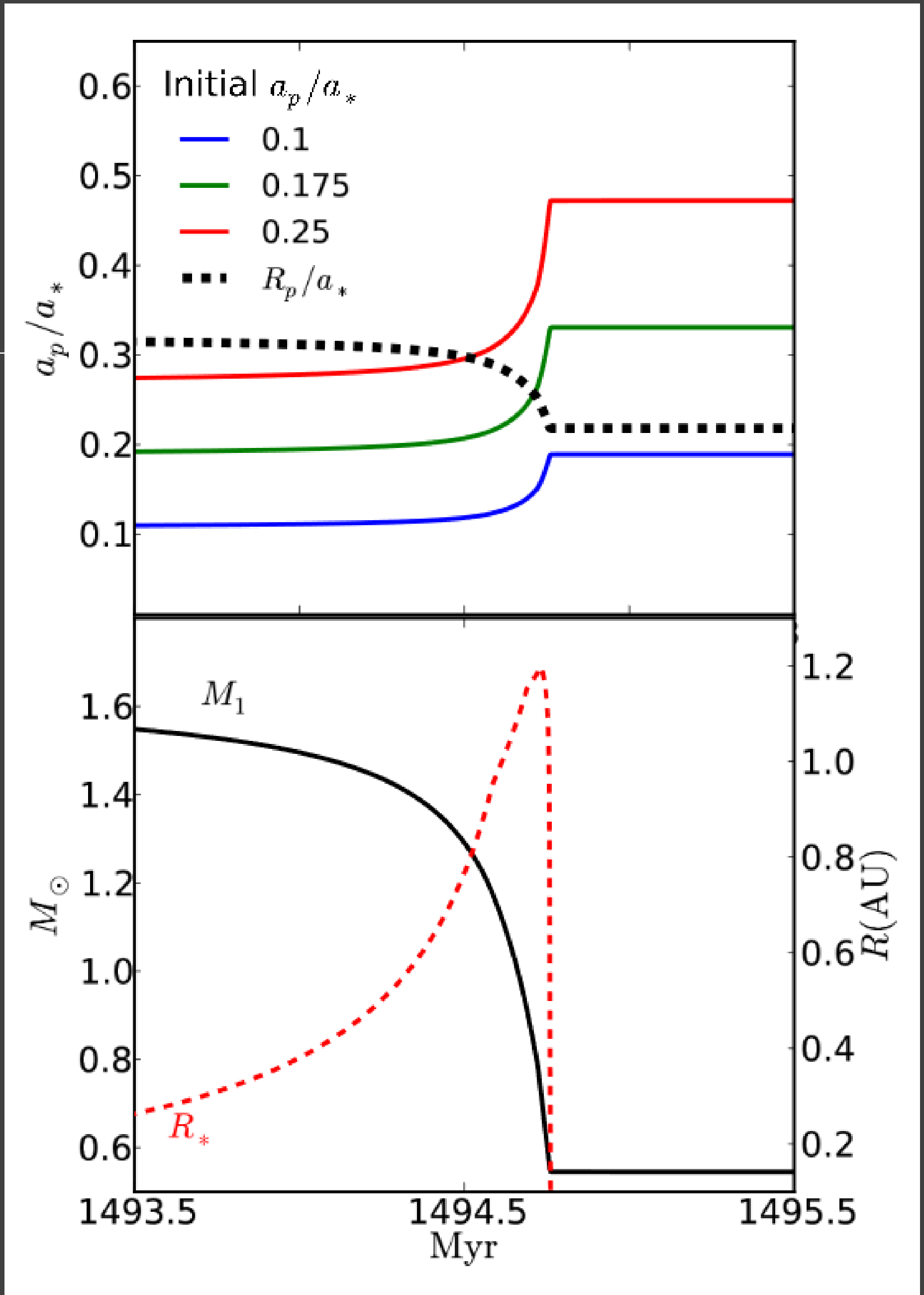
$$R_p = \left(0.464 - 0.38\frac{m_2}{m_1 + m_2}\right) a_*$$

For slow (adiabatic) mass loss the orbit expands as:

$$a_f = \frac{M_i}{M_f} a_i,$$

If we consider the planetary mass as a very small value:

$$\left(\frac{a_{p,f}}{a_{*,f}}\right) / \left(\frac{a_{p,i}}{a_{*,i}}\right) = \left(\frac{m_{1,i}}{m_{1,f}}\right)\left(\frac{m_{1,f} + m_2}{m_{1,i} + m_2}\right)$$

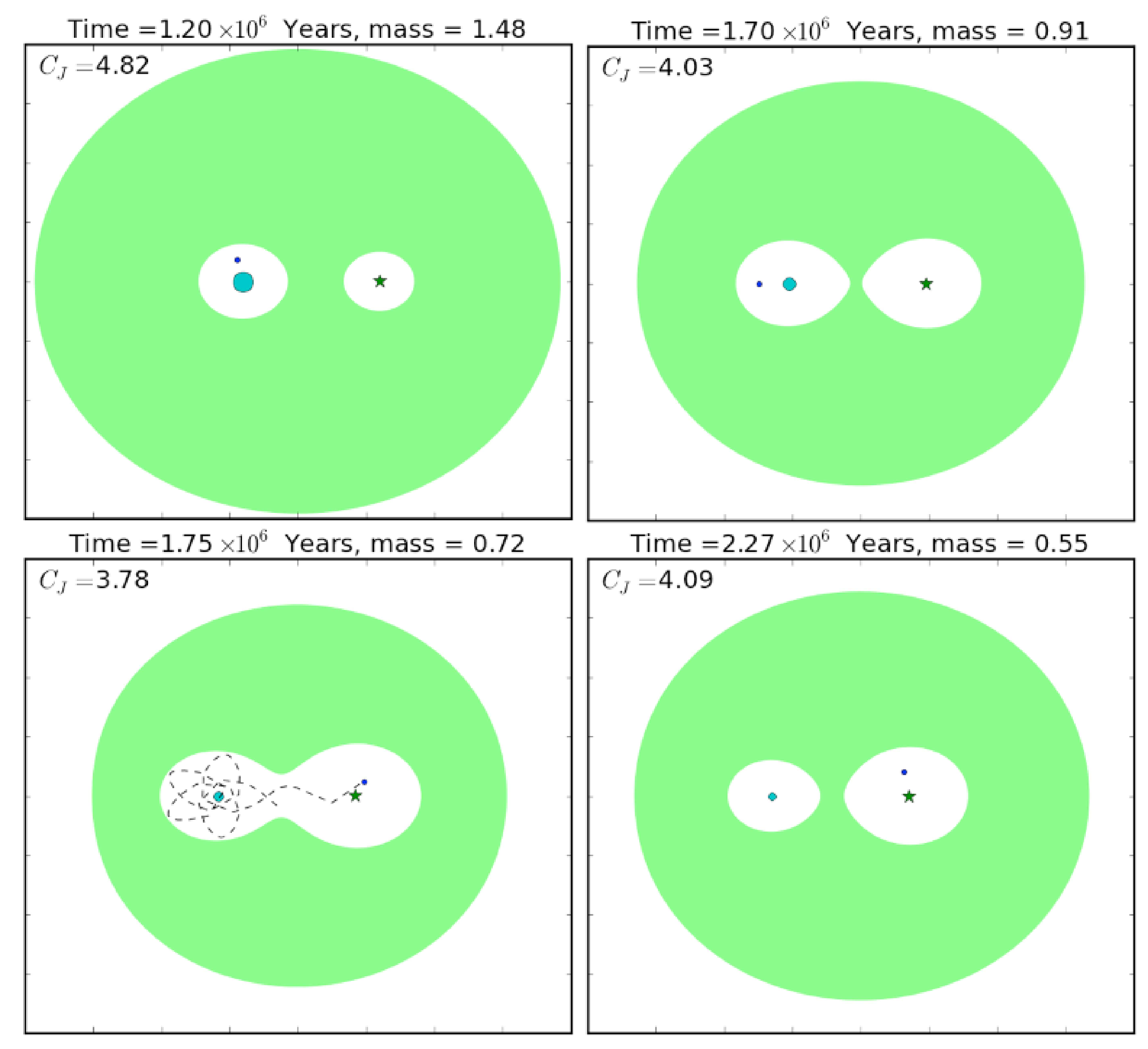


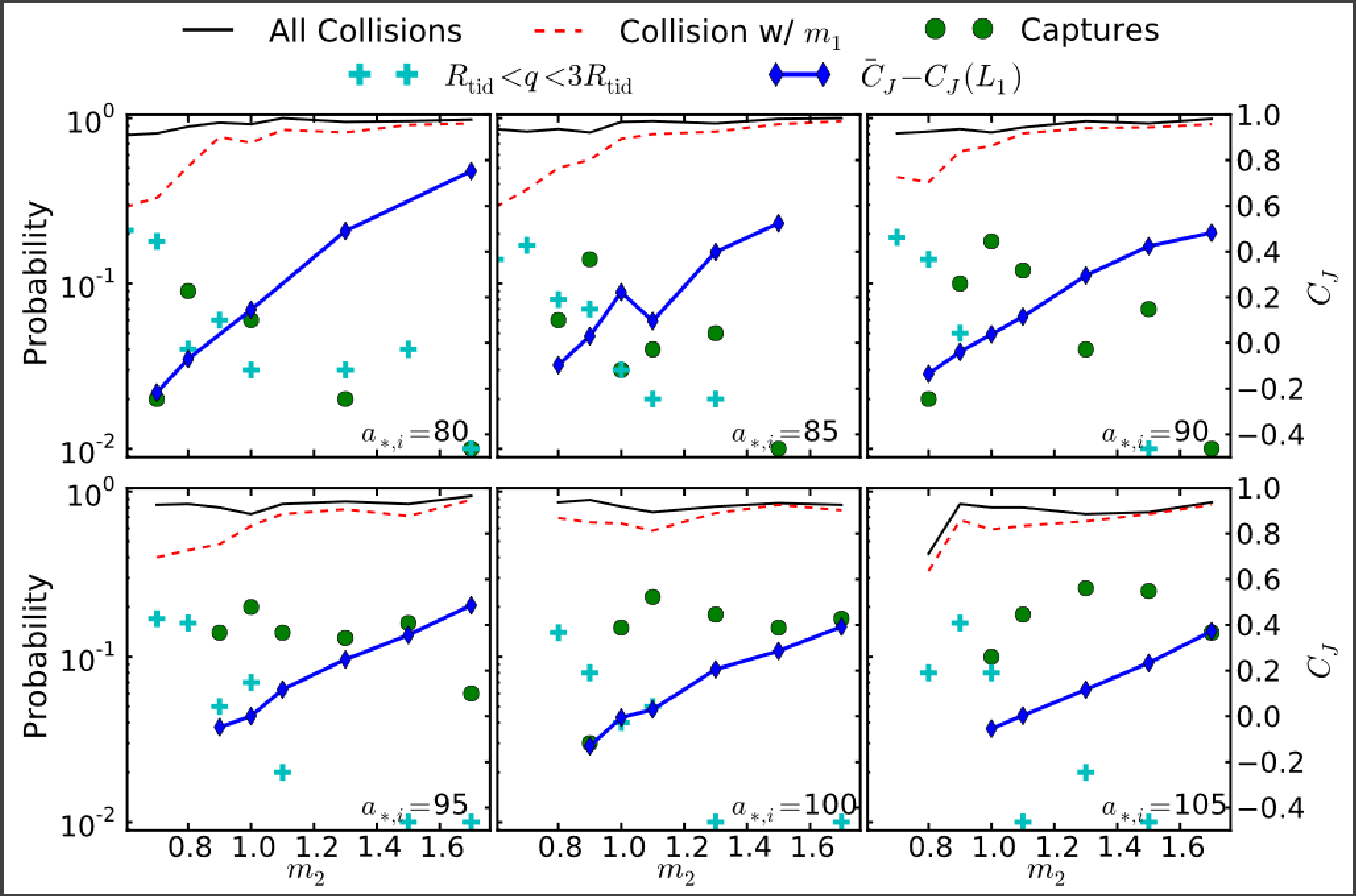
Star-hoppers

In a binary if the primary is loosing mass planets can change the host.

This is important to form some peculiar types of planets.

M_1=2 -> 0.55 M_{solar}
M_2=1 M_{solar}
a_{ini}=90 AU





All Collisions
Collision w/ m_1
Captures
$R_{\rm tid} < q < 3R_{\rm tid}$
$\bar{C}_J - C_J(L_1)$
Probability
C_J
m_2
$a_{*,i}=80$
$a_{*,i}=85$
$a_{*,i}=90$
$a_{*,i}=95$
$a_{*,i}=100$
$a_{*,i}=105$

Circumbinary (P-type) planets

$$a_{\mathrm{crit}} \approx 1.60 + 5.10\, e_{\mathrm{bin}} - 2.22\, e_{\mathrm{bin}}^2 + 4.12 \frac{M_s}{M_p + M_s} - 4.27\, e_{\mathrm{bin}} \frac{M_s}{M_p + M_s} - 5.09 \frac{M_s^2}{(M_p + M_s)^2} + 4.61\, e_{\mathrm{bin}}^2 \frac{M_s^2}{(M_p + M_s)^2},$$

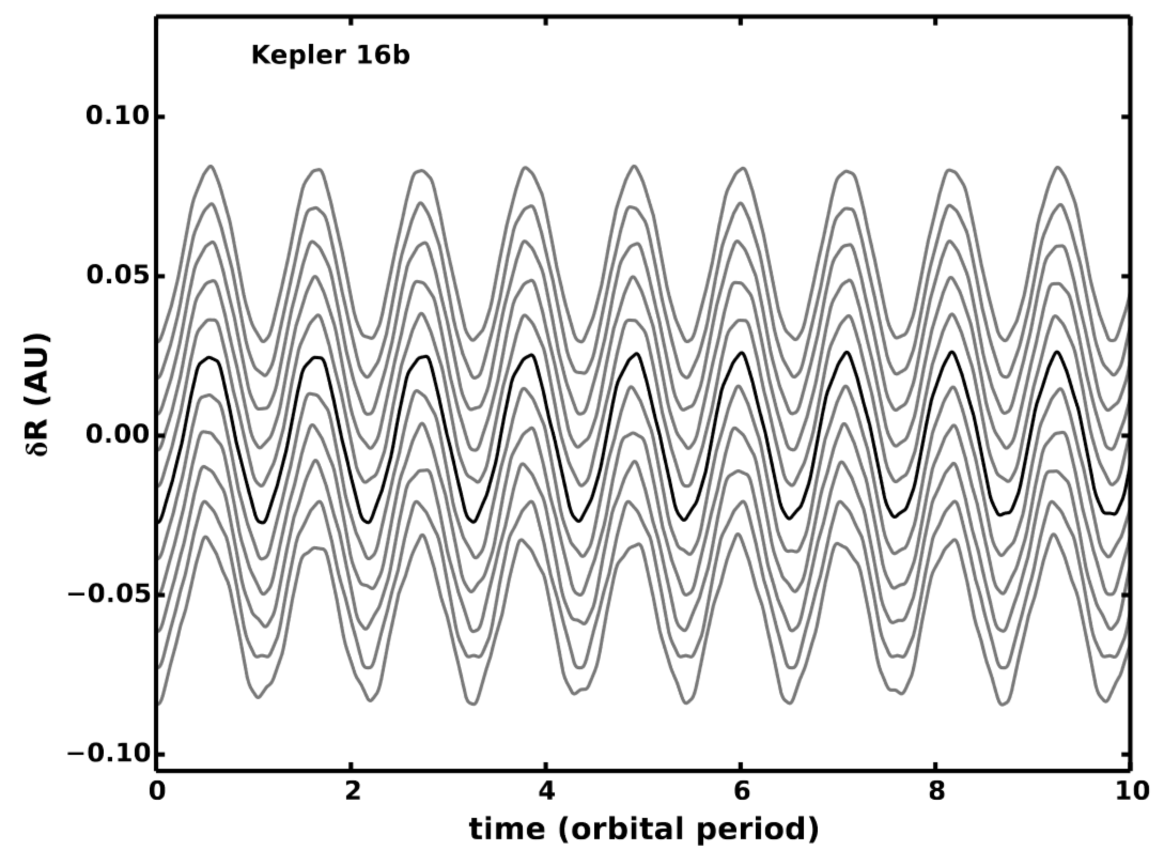
Inside the critical radius orbits of light satellites are unstable.

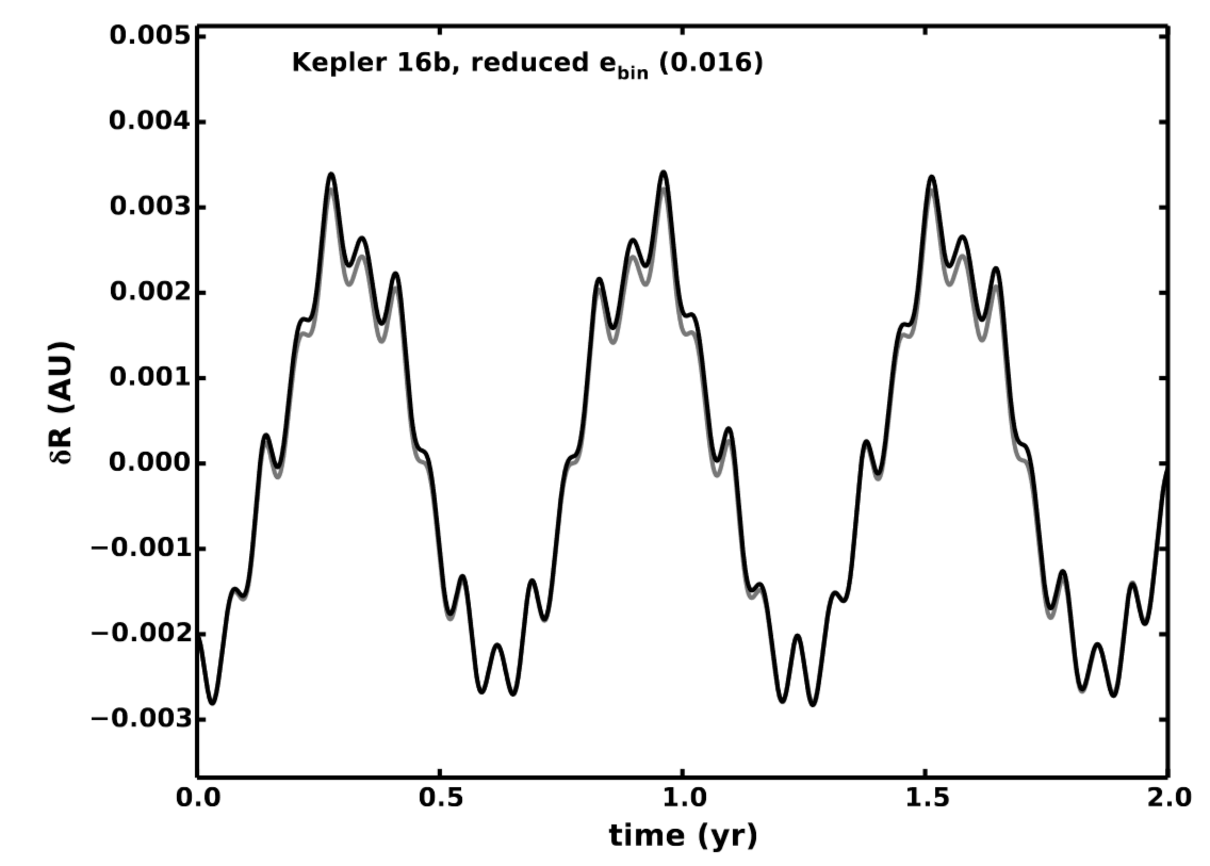
A binary cleans out orbits around it up to 2-5 binary separations.

Outside critical distance (except some resonances) there is a family of nested quasi circular (most circular) orbits, which behave quite similar to orbits around single stars.
Beyond 6:1 resonance orbits are stable for small binary eccentricity.
This allows to form planets around binary stars (in the circumbinary regime) in a usual way.

Most circular orbits

Particles having these orbits make minimal radial excursions and never collide.





Planetary formation in P-type binaries

Gas and small particles quickly settle to most circular orbits.

$$v_{\rm dest} \gtrsim 0.1 \text{ km/s} \qquad [\text{destructive collisions, } r = 1\,\text{km}]$$

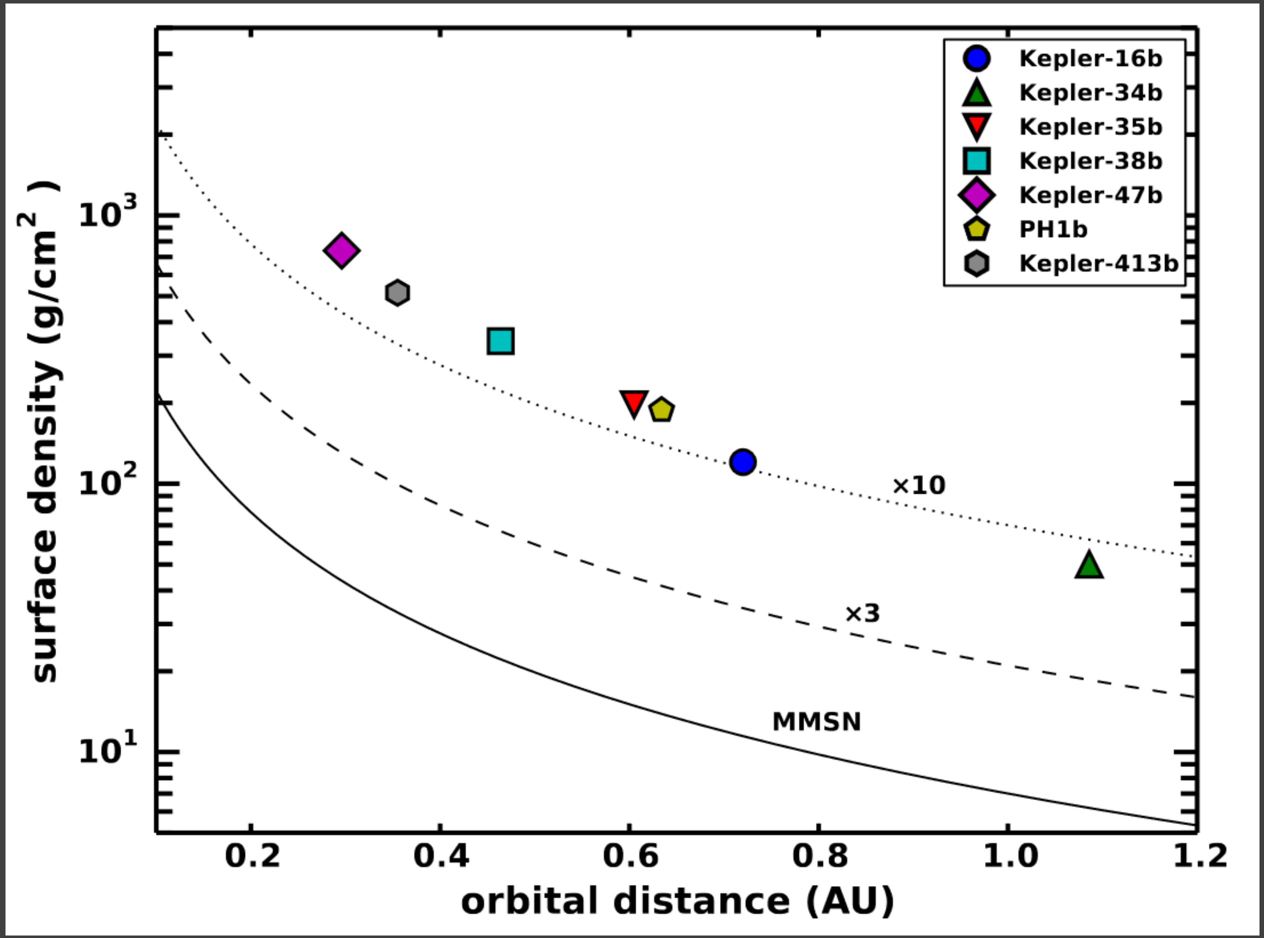
In most circular orbits particles have low relative velocity.
So, collisions are not destructive.
And a set of lunar-size objects for planets as around single stars.

Still, there are problems with some known planets, as they are situated close to their hosts.
It requires too massive discs (>10 times more massive than in the classical MMSN scenario).
Four scenarios are discussed:

- *In situ* formation
- Migration – then assemble
- Migration through a gas disk
- Planet scattering

Analysis of six known planets favours
“migration –then assemble” or “disc migration”,
and in few cases – scattering, but not *in situ* formation.

In situ formation in massive discs



Minimal surface density necessary to build known planets.

Lower curve – MMSN (Hayashi 1981)

Upper – multiplied.

Typical disc masses in the MMSN 0.01 Msolar.

It is difficult to explain massive planets by *in situ* formation.

Light planets can form at small distances without migration.

Another circumbinary disc model

$$\frac{\partial \Sigma}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\frac{dl}{dr}\right)^{-1}\frac{\partial}{\partial r}\left(r^3\nu\Sigma\frac{d\Omega}{dr}\right) + 2\frac{\Sigma\Lambda}{\Omega}\right].$$

$$\Lambda(r) = \mathrm{sgn}(r - a_b) f \frac{q^2 G M_c}{a_b}\left(\frac{a_b}{r - a_b}\right)^4,$$

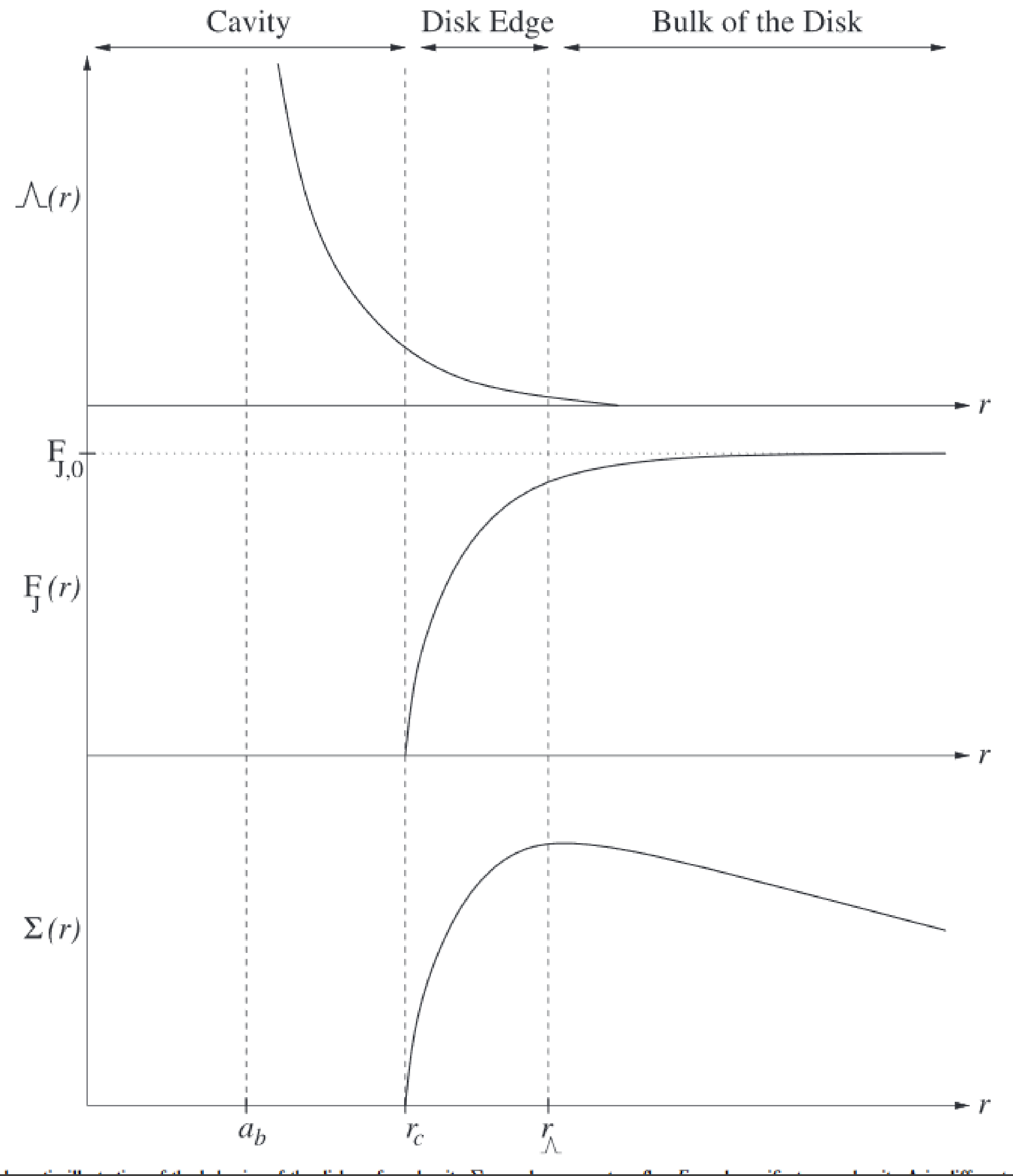
$$F_J \equiv -2\pi\nu\Sigma r^3 \frac{d\Omega}{dr} = 3\pi\nu\Sigma l,$$

Angular momentum in injected to the disc from the binary

$$\frac{\partial}{\partial t}\left(\frac{F_J}{D_J}\right) = \frac{\partial}{\partial l}\left[\frac{\partial F_J}{\partial l} - \frac{2F_J}{D_J}\frac{d\ln l}{d\ln r}\Lambda(l)\right],$$

$$\dot{M}(l, t) = \frac{\partial F_J}{\partial l} - \frac{2F_J}{D_J}\frac{d\ln l}{d\ln r}\Lambda(l).$$

Accretion to the binary from the disc can be small or even zero.



Energy in the disc

Disc has three sources of energy:

- Viscosity;
- Illumination;
- Dissipation of shock generated by the binary.

$$\mathcal{F}_v = \frac{1}{4\pi r}\frac{d\dot{E}_v}{dr} = \frac{3}{8\pi}\frac{F_J\Omega}{r^2},$$

$$\mathcal{F}_{\rm irr} = \frac{1}{2}\frac{L_c}{4\pi r^2}\zeta,$$

$$\mathcal{F}_{\rm tid} = \frac{1}{2}(\Omega_b - \Omega)\Lambda\Sigma,$$

$\tau \ll 1$: $$\tau\sigma T^4 \approx \mathcal{F}_v + \mathcal{F}_{\rm tid} + \tau\mathcal{F}_{\rm irr}.$$

$\tau \gg 1$: $$\sigma T^4 \approx \frac{3}{8}\tau\left(\mathcal{F}_v + \mathcal{F}_{\rm tid}\right) + \mathcal{F}_{\rm irr}.$$

$$\sigma T^4 = f(\tau)\left(\mathcal{F}_v + \mathcal{F}_{\rm tid}\right) + \mathcal{F}_{\rm irr},$$

$$f(\tau) \approx \frac{3}{8}\tau + \tau^{-1}.$$

Important issues for planet formation

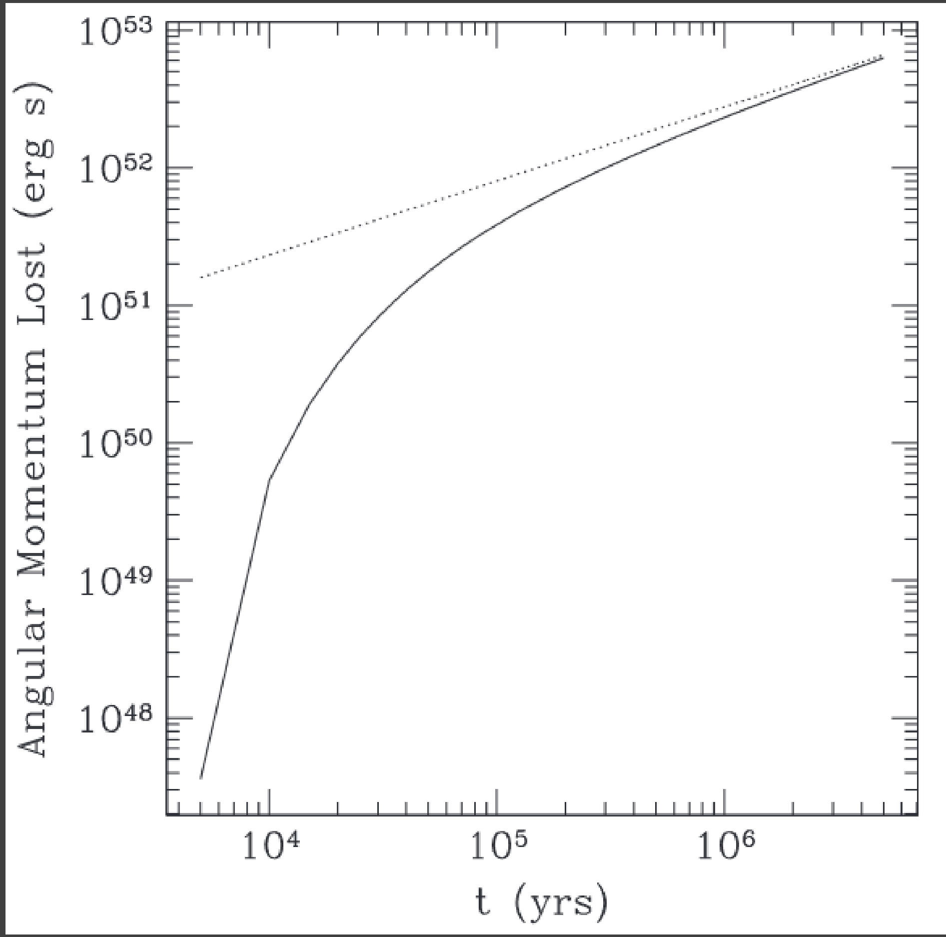
- Disc is more massive than around a single star
- Relative speeds at collisions are smaller
- Isolation masses are larger
- Ice line is shifted outwards
- Dissipation of the binary-driven density waves dominates heating of the inner disk, within 1–2AU

Circumbinary disks are in many ways more favorable sites of planet formation than their analogs around single stars

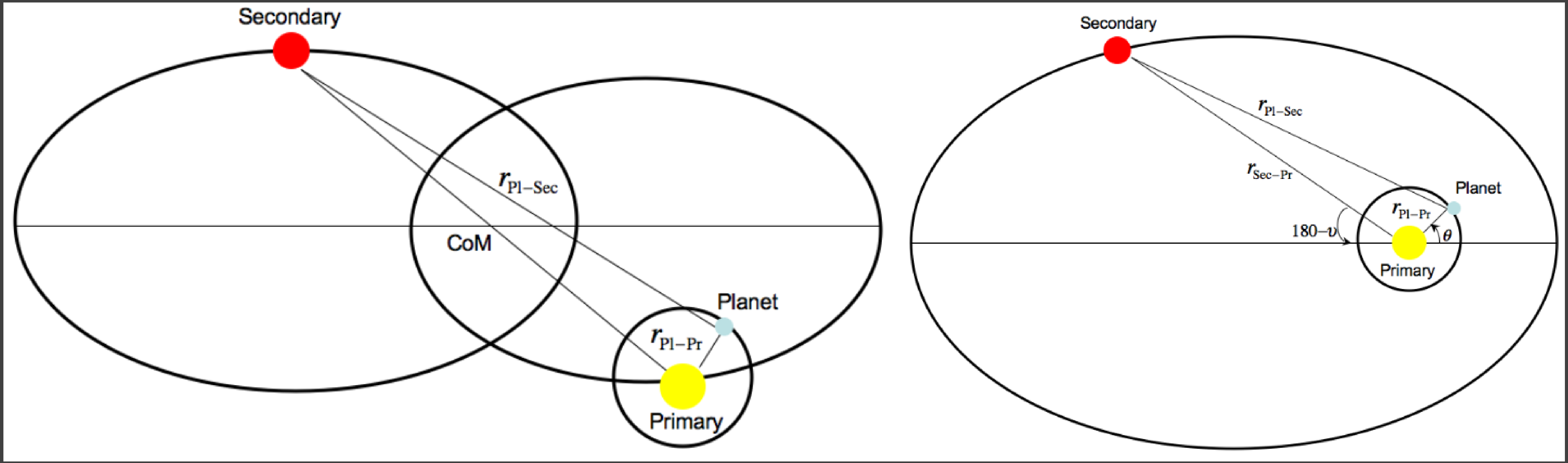
Binary evolution due to the disc

$$L_b = \frac{q}{(1+q)^2}\left(GM_c^3 a_b\right)^{1/2} \approx 4 \times 10^{52}\ \mathrm{g\,cm^2\,s^{-1}} \times \frac{q}{(1+q)^2} M_{c,1}^{3/2}\left(\frac{a_b}{0.2\ \mathrm{AU}}\right)^{1/2}.$$

The binary can coalesce due to tidal interaction with the disc.



Habitable zone calculations



Calculations

$$F_{Pl}(f, T_{Pr}, T_{Sec}) = W_{Pr}(f, T_{Pr}) \frac{L_{Pr}(T_{Pr})}{r^2_{Pl-Pr}} + W_{Sec}(f, T_{Sec}) \frac{L_{Sec}(T_{Sec})}{r^2_{Pl-Sec}} .$$

$$W_{Pr}(f, T_{Pr}) \frac{L_{Pr}(T_{Pr})}{l^2_{x-Bin}} + W_{Sec}(f, T_{Sec}) \frac{L_{Sec}(T_{Sec})}{r^2_{Pl-Sec}} = \frac{L_{Sun}}{l^2_{x-Sun}} .$$

$$l_{x-Star} = l_{x-Sun} \left[\frac{L/L_{Sun}}{1 + \alpha_x(T_i)\, l^2_{x-Sun}} \right]^{1/2}$$

, $l_x = (l_{in}, l_{out})$ is in AU, $T_i(K) = T_{Star}(K) - 5780$

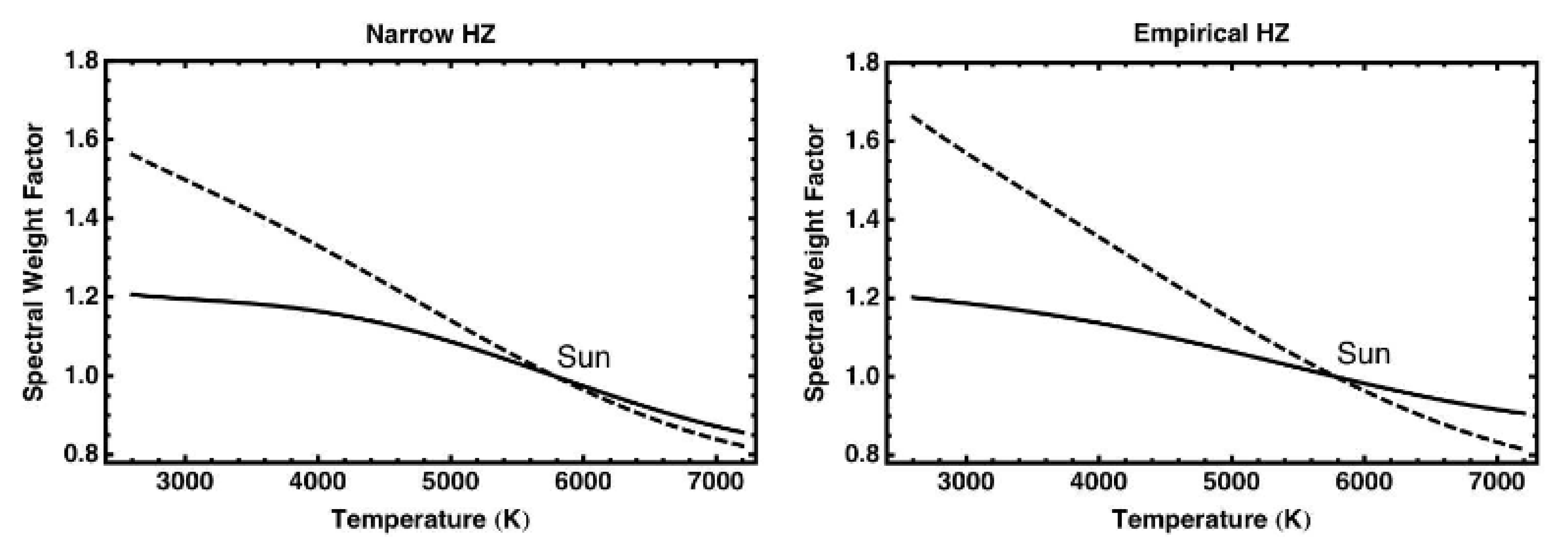
$$\alpha_x(T_i) = a_x T_i + b_x T_i^2 + c_x T_i^3 + d_x T_i^4 ,$$

	Narrow HZ		Empirical HZ	
	Runaway Greenhouse	Maximum Greenhouse	Recent Venus	Early Mars
l_{x-Sun} (AU)	0.97	1.67	0.75	1.77
Flux (Solar Flux @ Earth)	1.06	0.36	1.78	0.32
a	1.2456×10^{-4}	5.9578×10^{-5}	1.4335×10^{-4}	5.4471×10^{-5}
b	1.4612×10^{-8}	1.6707×10^{-9}	3.3954×10^{-9}	1.5275×10^{-9}
c	-7.6345×10^{-12}	-3.0058×10^{-12}	-7.6364×10^{-12}	-2.1709×10^{-12}
d	-1.7511×10^{-15}	-5.1925×10^{-16}	-1.1950×10^{-15}	-3.8282×10^{-16}

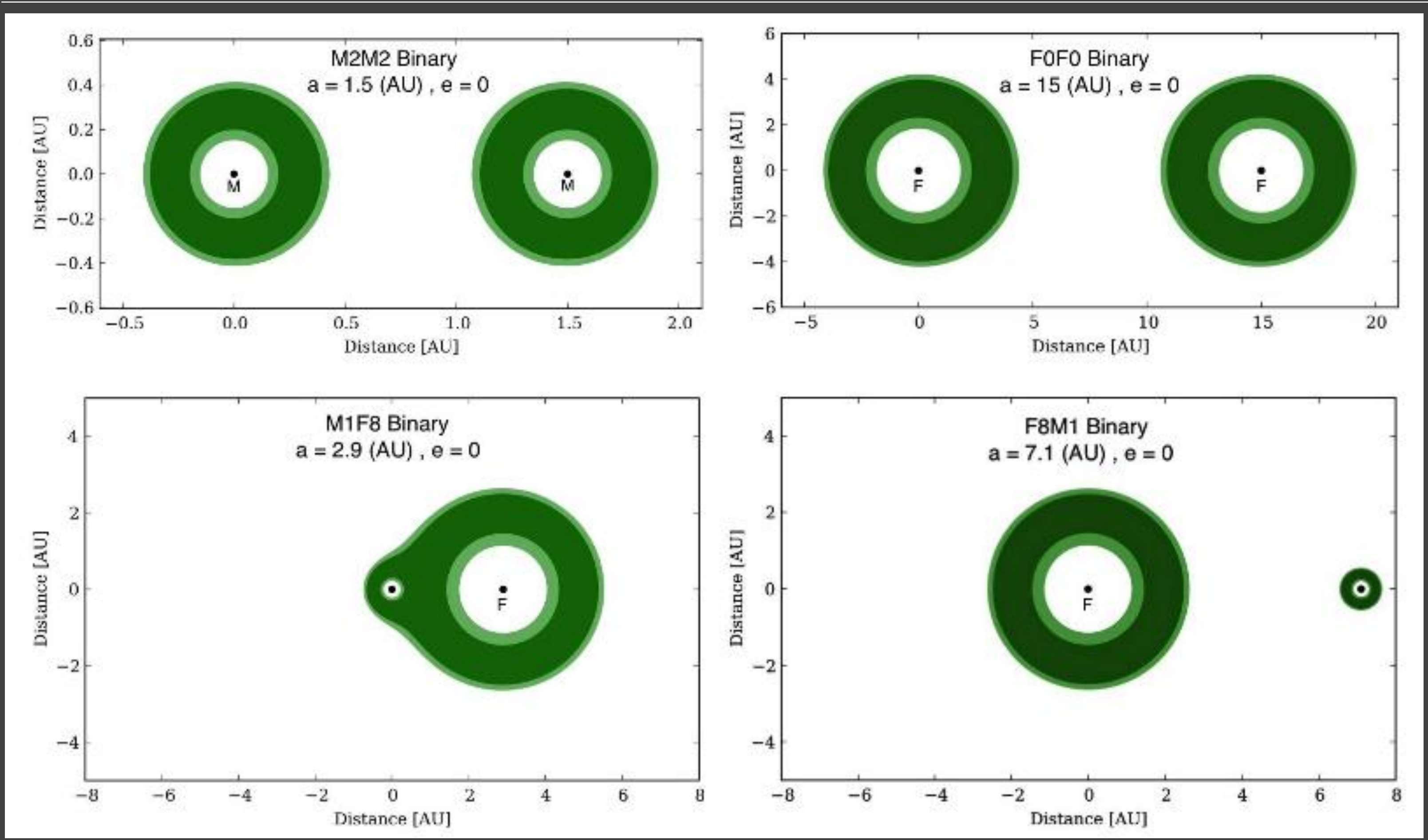
$$F_{x-Star}\left(f, T_{Star}\right) = F_{x-Sun}(f, T_{Star}) \left[1 + \alpha_x(T_i)\, l^2_{x-Sun} \right]$$

$$W_i(f, T_i) = \left[1 + \alpha_x(T_i)\, l^2_{x-Sun} \right]^{-1}$$

Weight coefficients



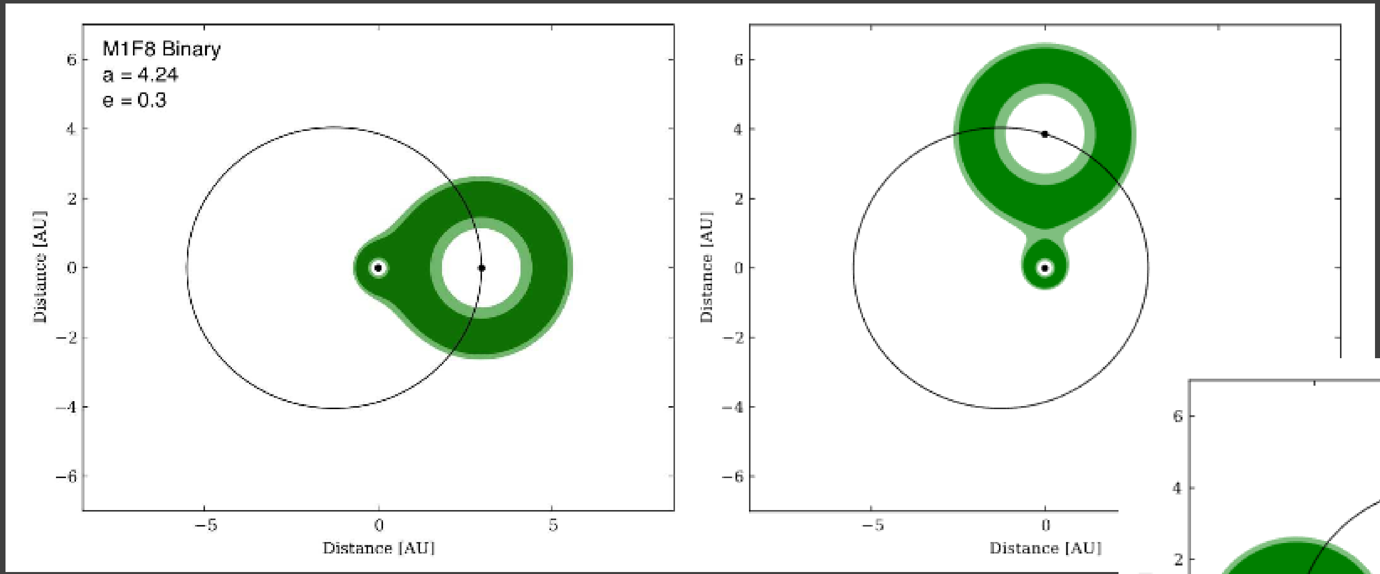
Examples

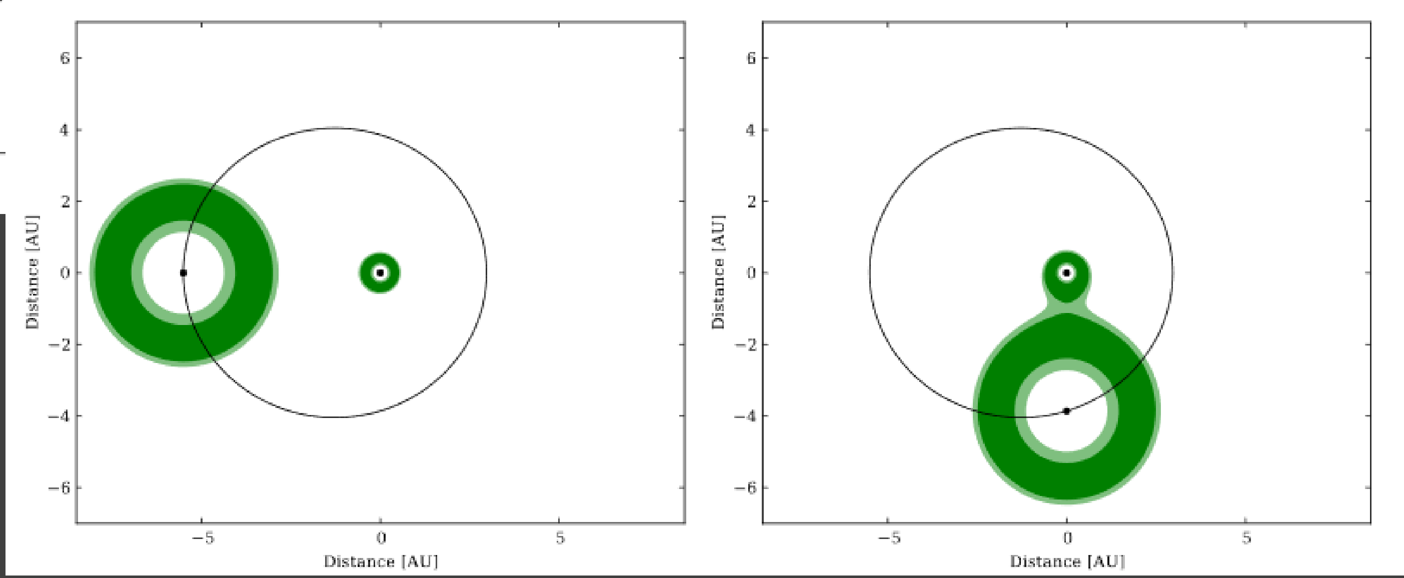


Dark green – narrow HZ.

Light green- empirical HZ.

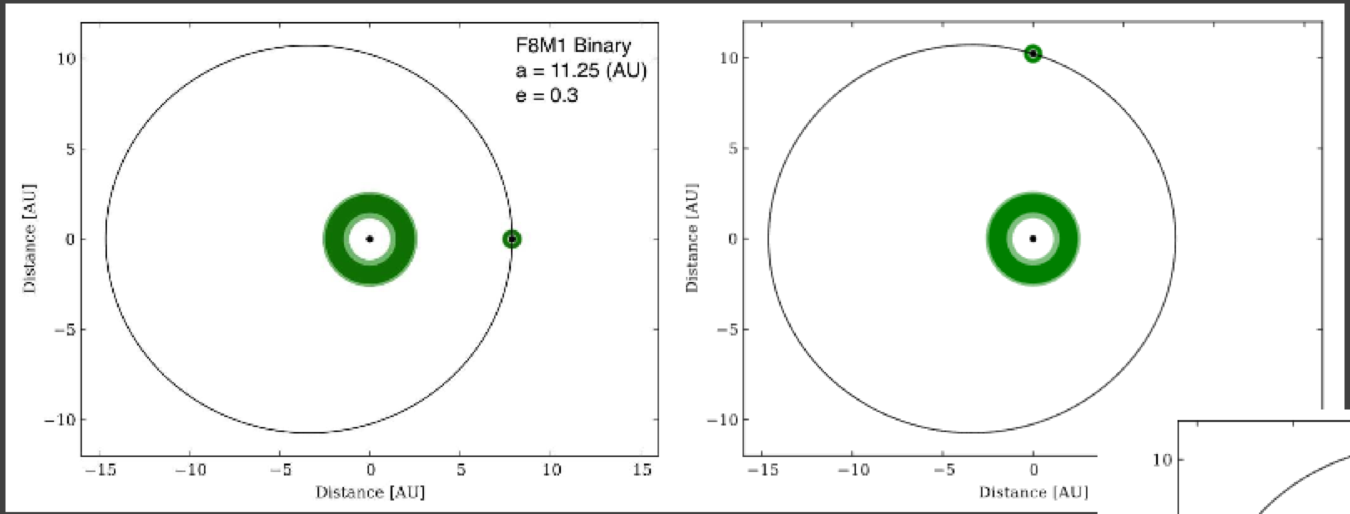
Examples: eccentricity=0.3

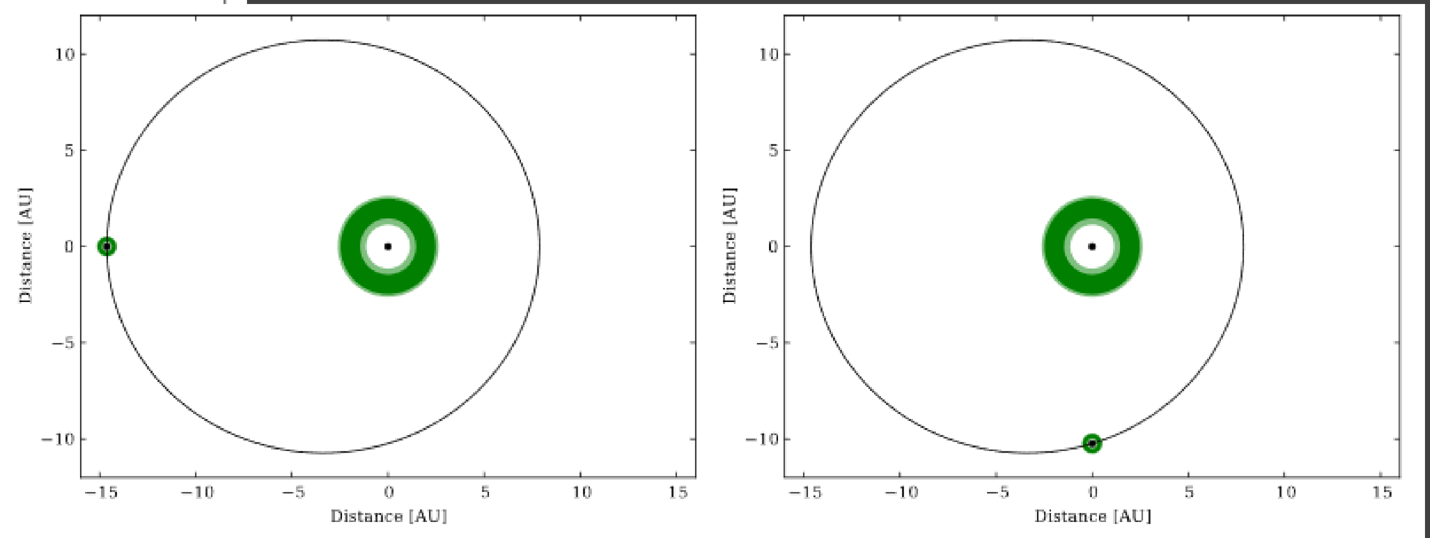




M-dwarf is the primary

Examples: eccentricity=0.3





F-star is the primary

Habitable zone calculation. II. Circumbinary

Let us start with single stars

$$L_\star = 4\pi R_\star^2 \sigma T_{\rm eff}^4$$

$$S_{\rm inner} = 4.190 \times 10^{-8} T_{\rm eff}^2 - 2.139 \times 10^{-4} T_{\rm eff} + 1.268$$

$$S_{\rm outer} = 6.190 \times 10^{-9} T_{\rm eff}^2 - 1.319 \times 10^{-5} T_{\rm eff} + 0.2341 \,.$$

$$r_{\rm inner} = \sqrt{L_\star / S_{\rm inner}}$$

$$r_{\rm outer} = \sqrt{L_\star / S_{\rm outer}}$$

Here luminosity and flux are in solar units, and distance – in AU.

1211.2812

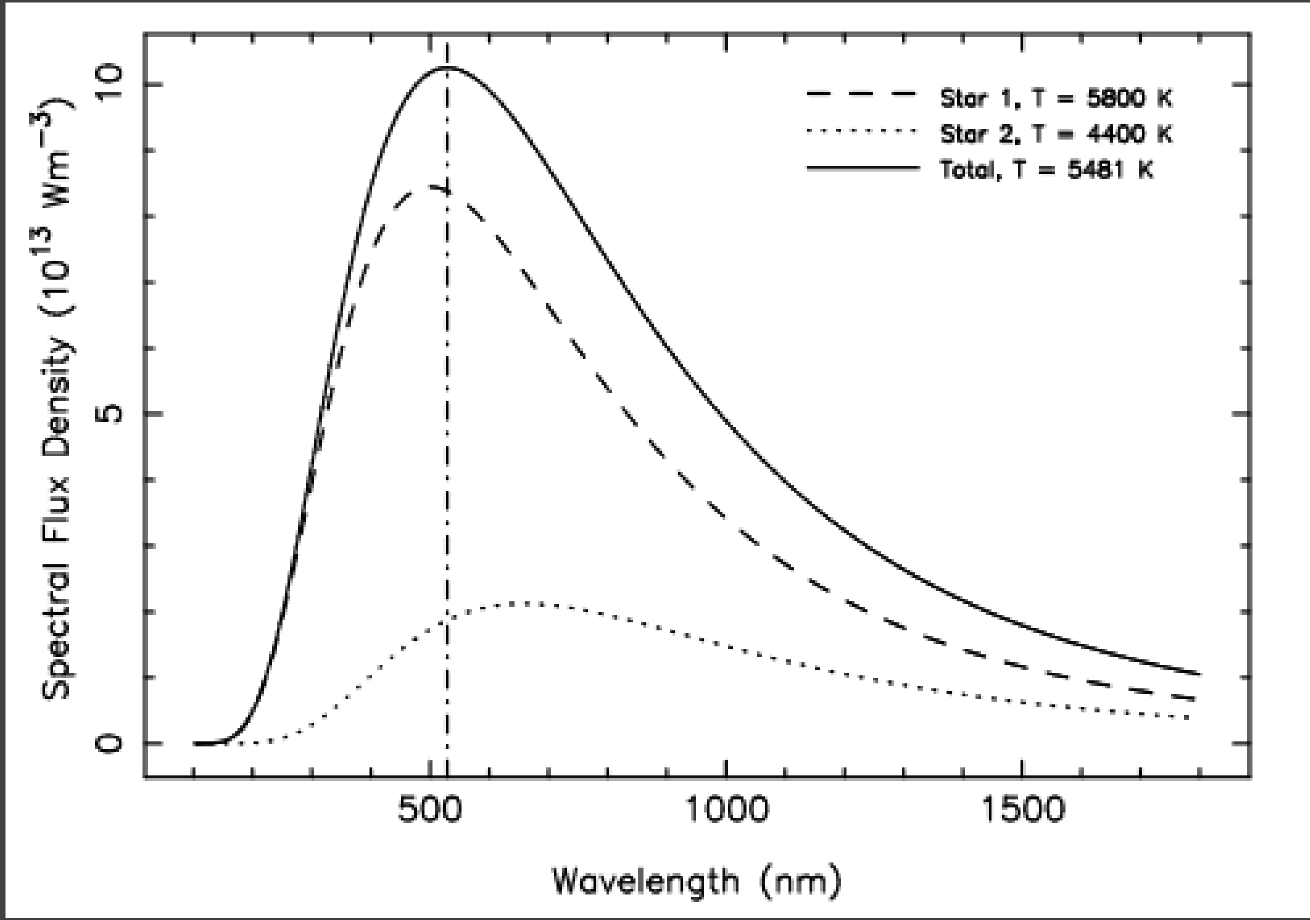
Binary stars

$$S_1 = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k T_{\mathrm{eff},1}} - 1} \left(\frac{R_{\star,1}}{r_1}\right)^2$$

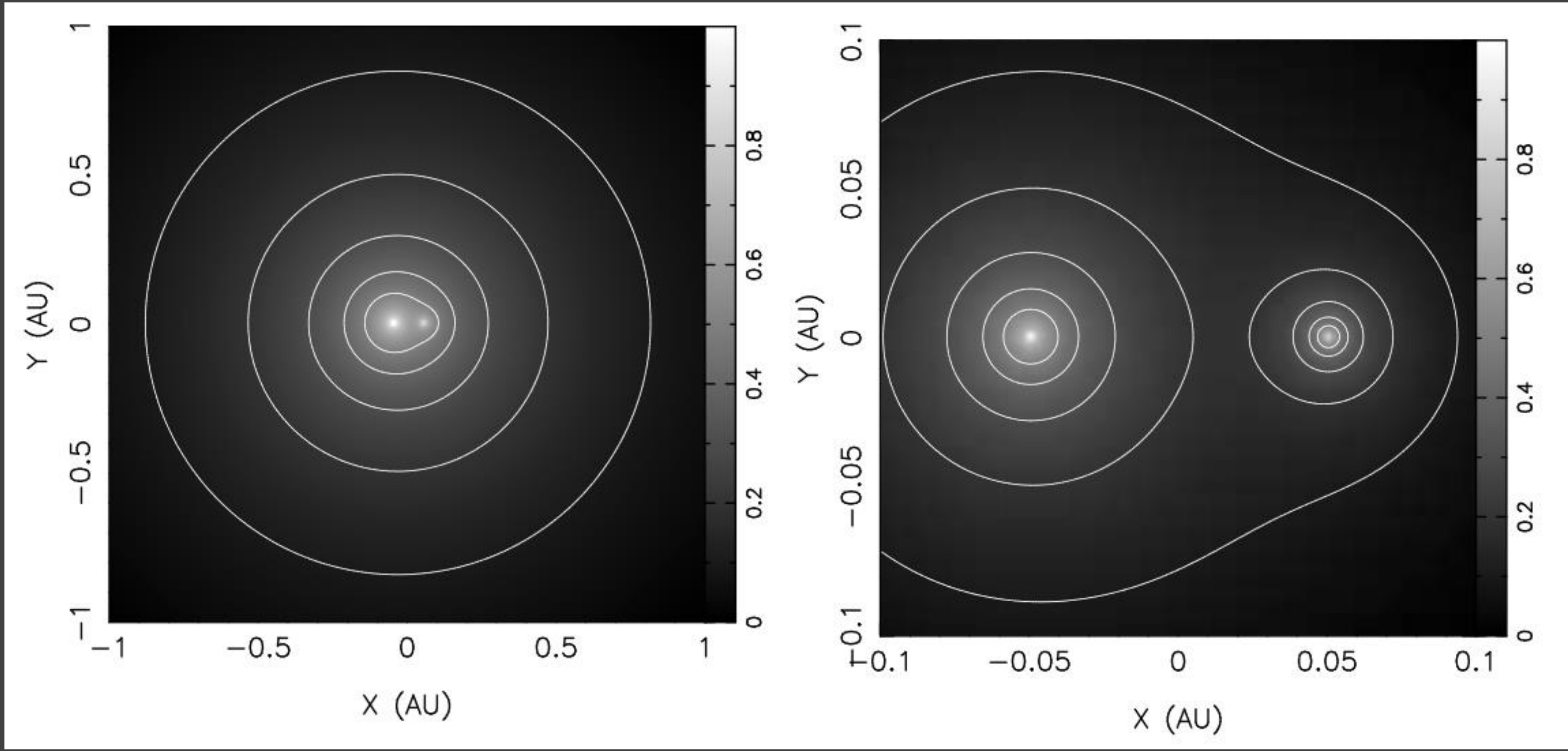
$$S_2 = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k T_{\mathrm{eff},2}} - 1} \left(\frac{R_{\star,2}}{r_2}\right)^2$$

$$S = S_1 + S_2.$$

G2V+K5V
0.1 AU



Stellar flux map

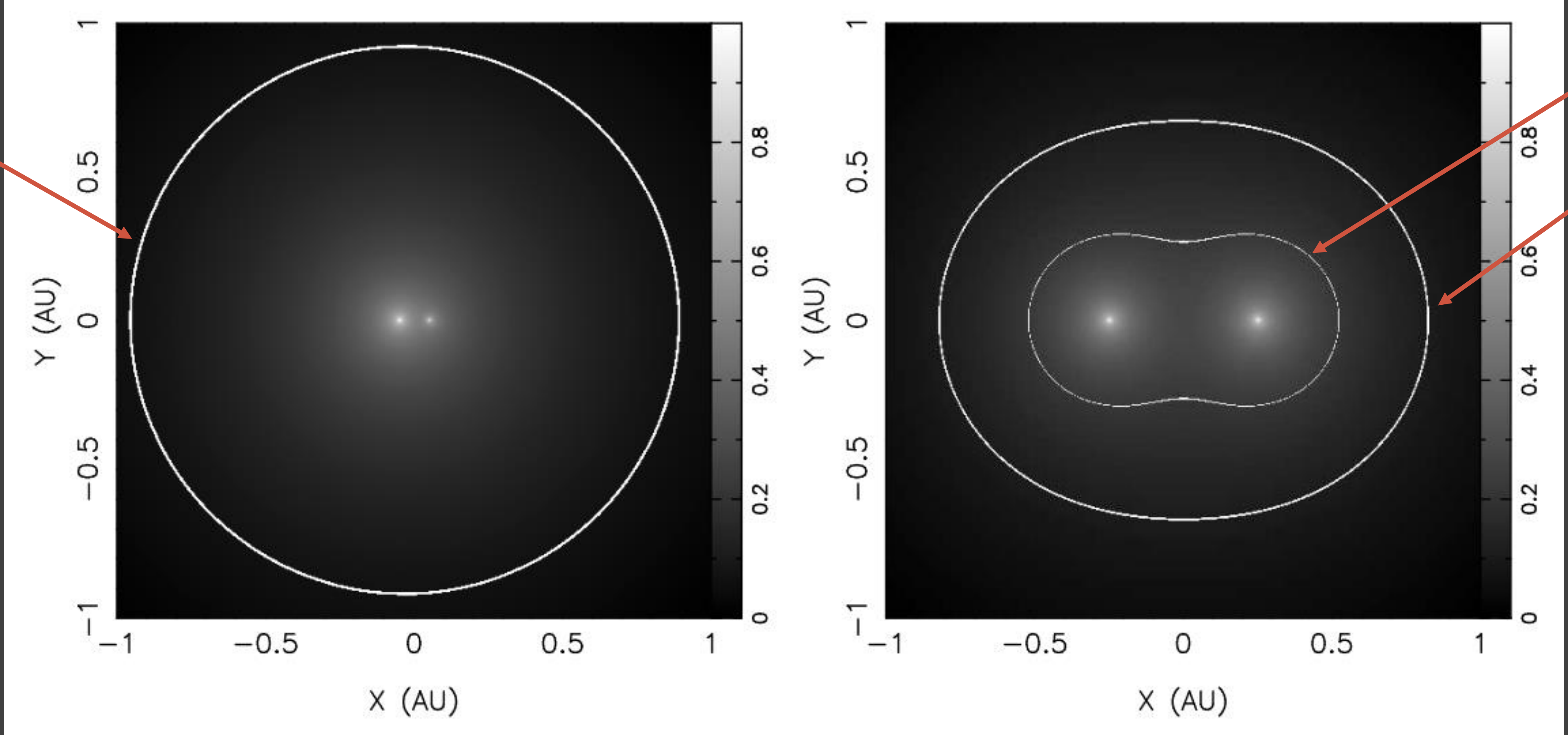


G2V+K5V
0.1 AU

HZ edges

Inner edge

G2V+K5V
0.1 AU

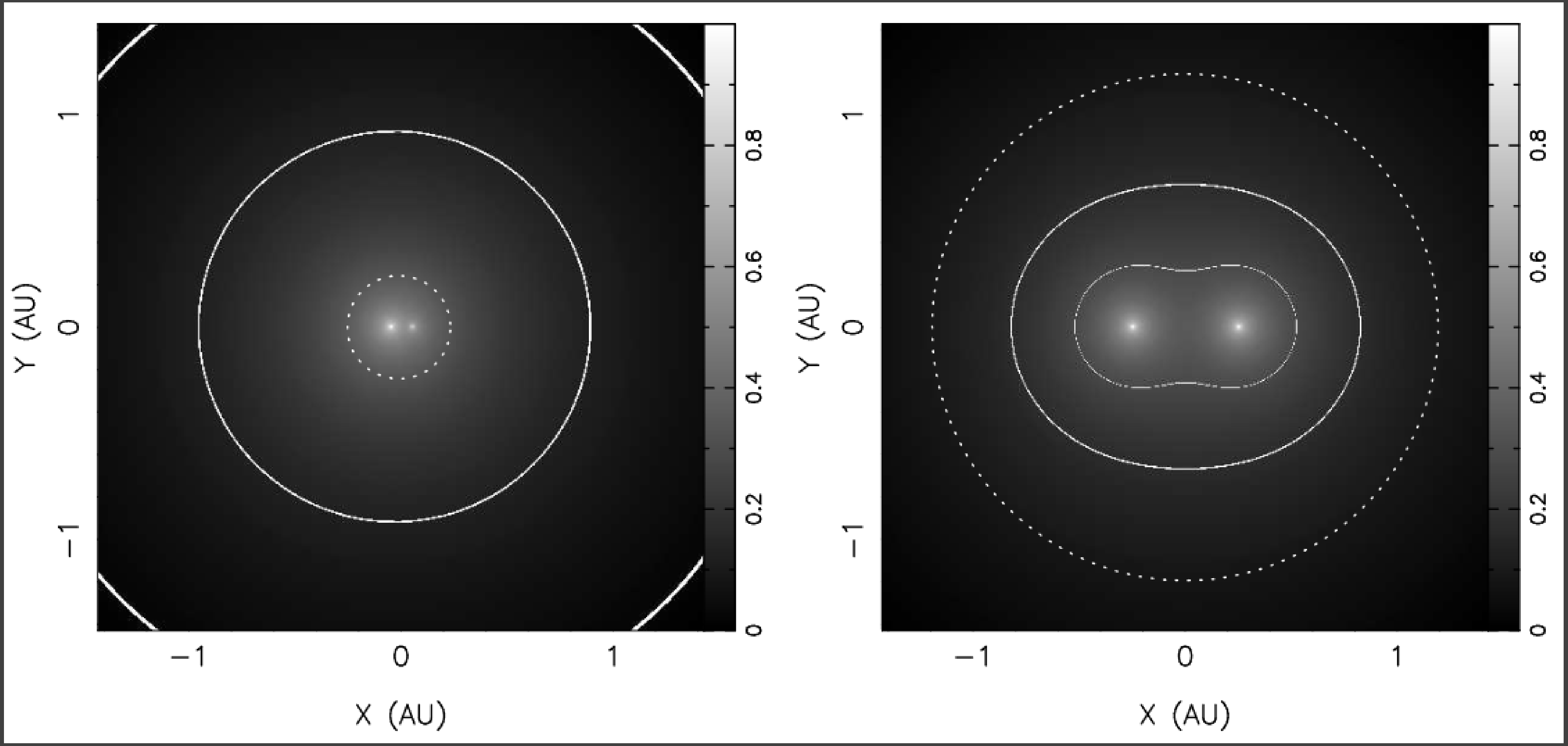


Inner edge

Outer edge

M0V+M0V
0.5 AU

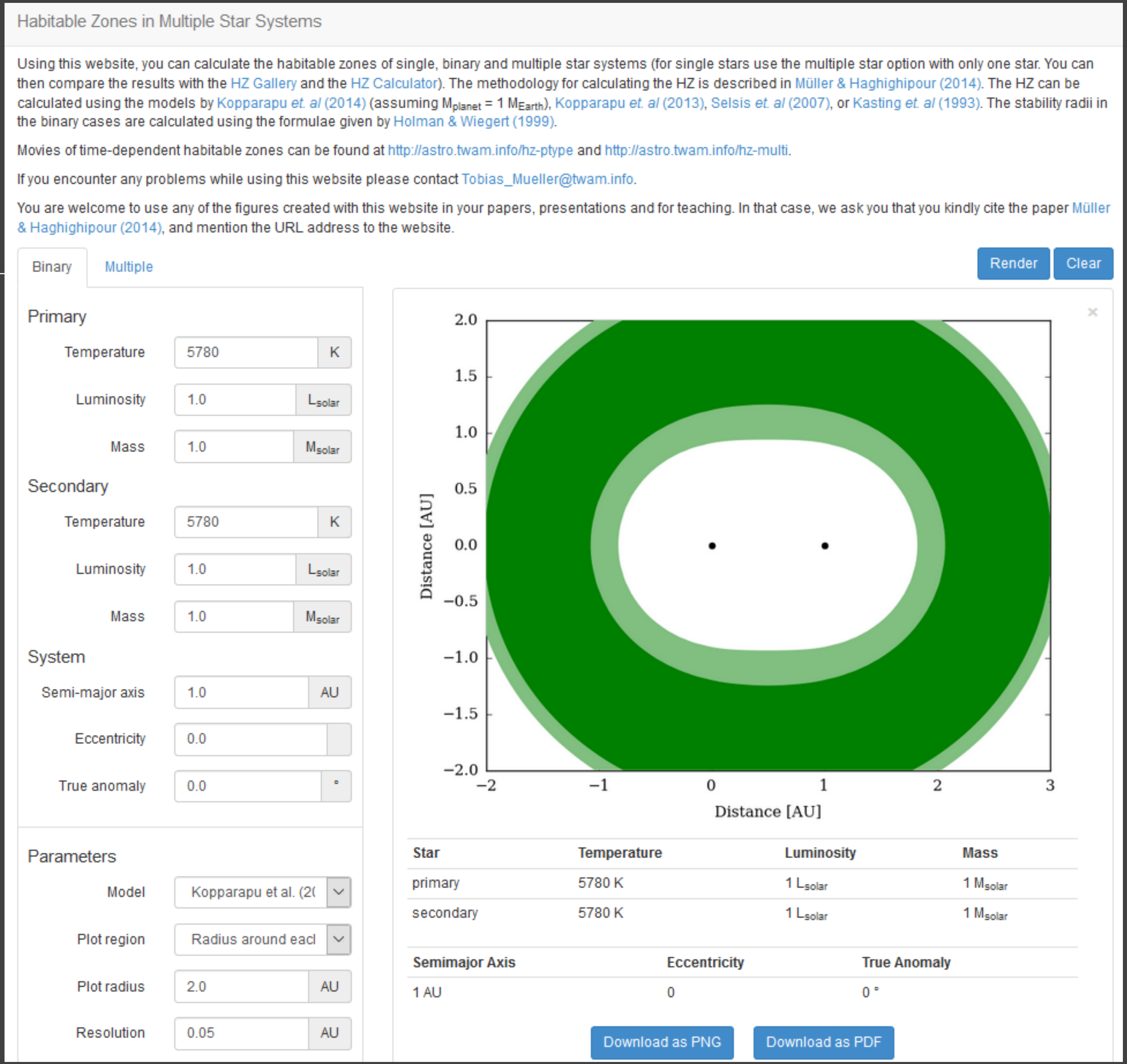
Stability of the planetary orbit



On-line calculator

Described in 1401.0601

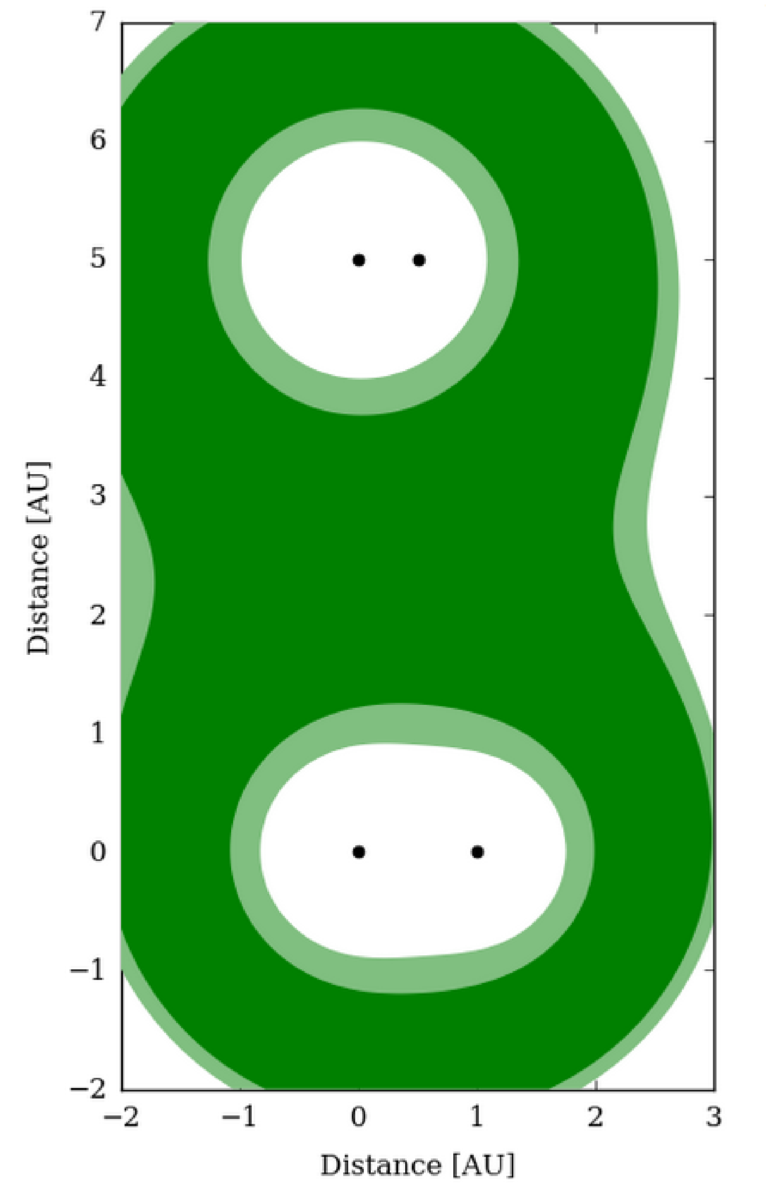
T, L, and M can be changed independently
(i.e., there is not fit for the MS, etc.)



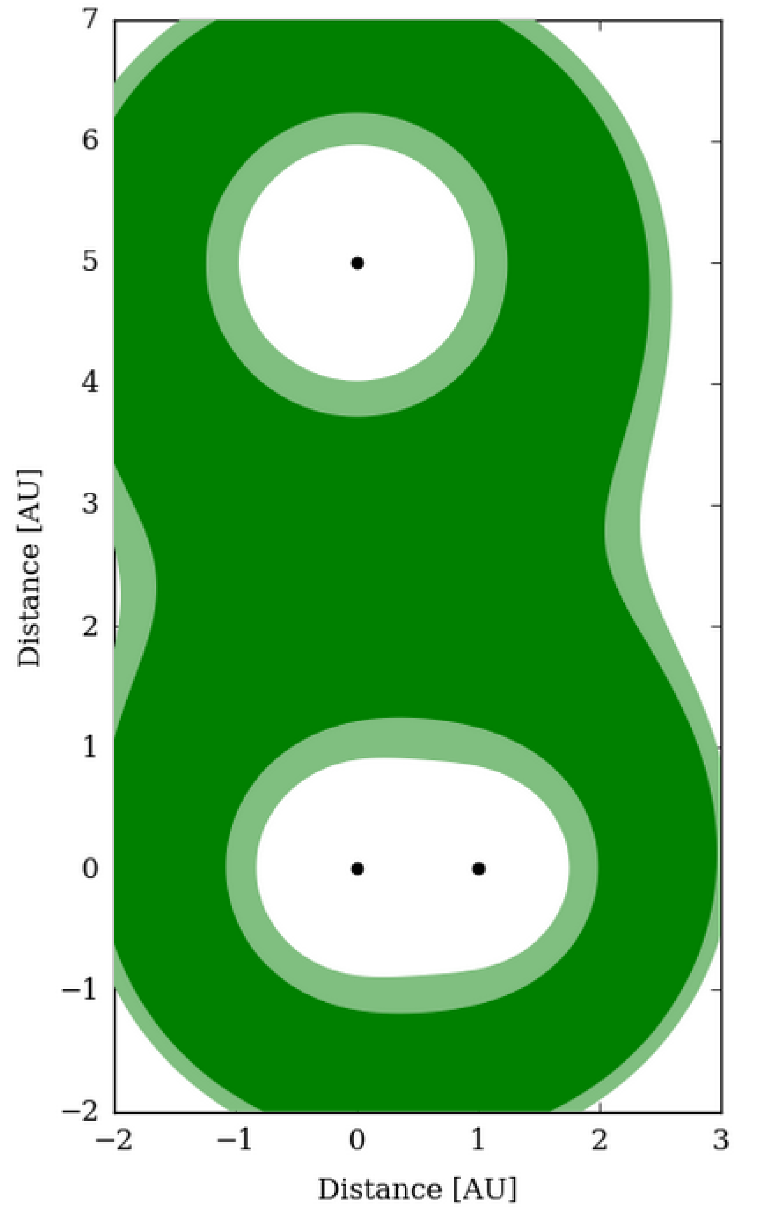
Multiple systems

The method allows to make plots for any number of stars.

However, consistency of all conditions (orbital stability, etc.) is not automatically controlled.



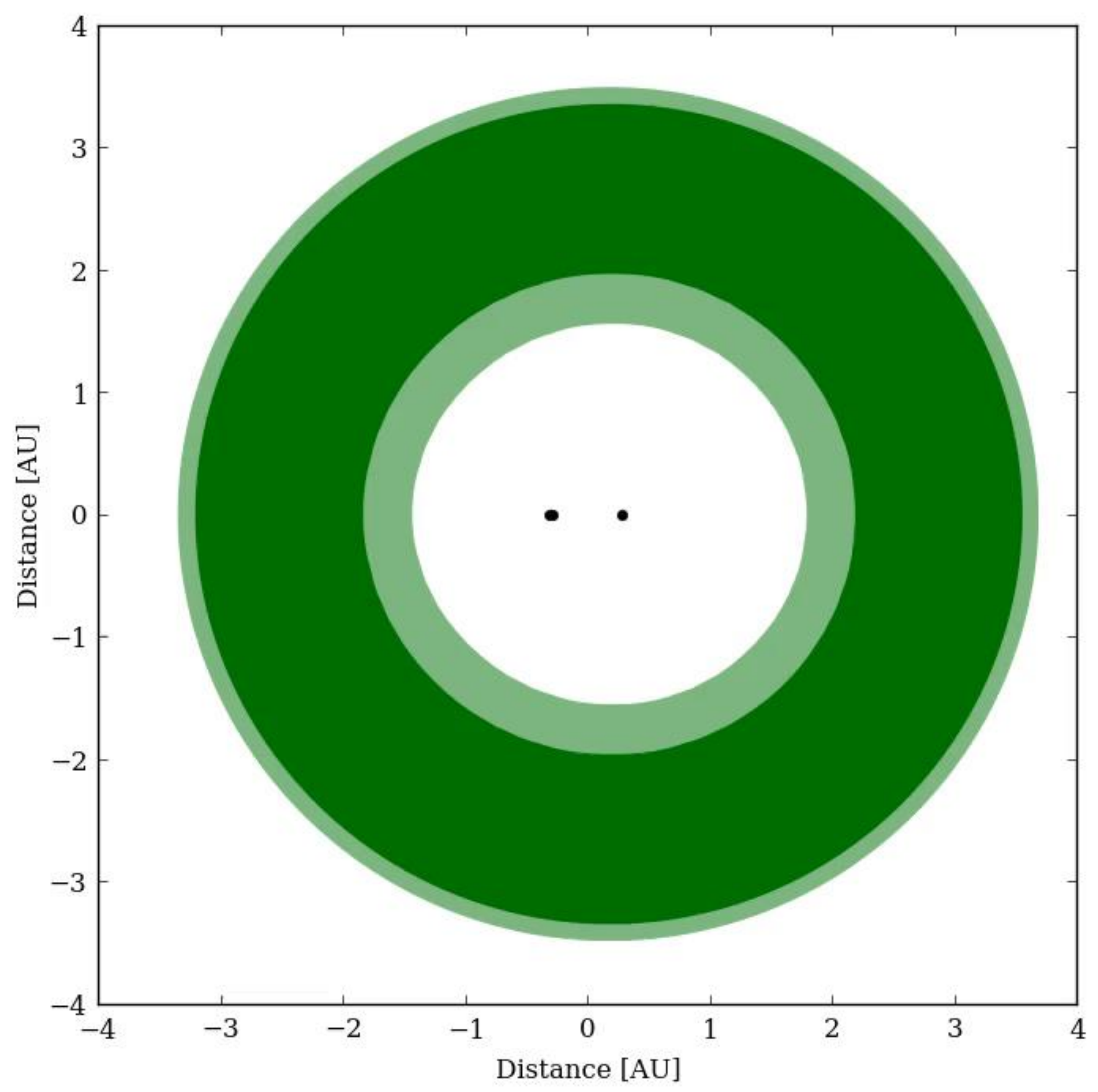
Star	Temperature	Luminosity	Mass	X	Y
A	5780 K	1 L_{solar}	1 M_{solar}	0 AU	0 AU
B	4780 K	0.7 L_{solar}	0.7 M_{solar}	1 AU	0 AU
C	6780 K	1.8 L_{solar}	1.4 M_{solar}	0 AU	5 AU
D	3780 K	0.1 L_{solar}	0.2 M_{solar}	0.5 AU	5 AU



Star	Temperature	Luminosity	Mass	X	Y
A	5780 K	1 L_{solar}	1 M_{solar}	0 AU	0 AU
B	4780 K	0.7 L_{solar}	0.7 M_{solar}	1 AU	0 AU
C	6780 K	1.8 L_{solar}	1.4 M_{solar}	0 AU	5 AU

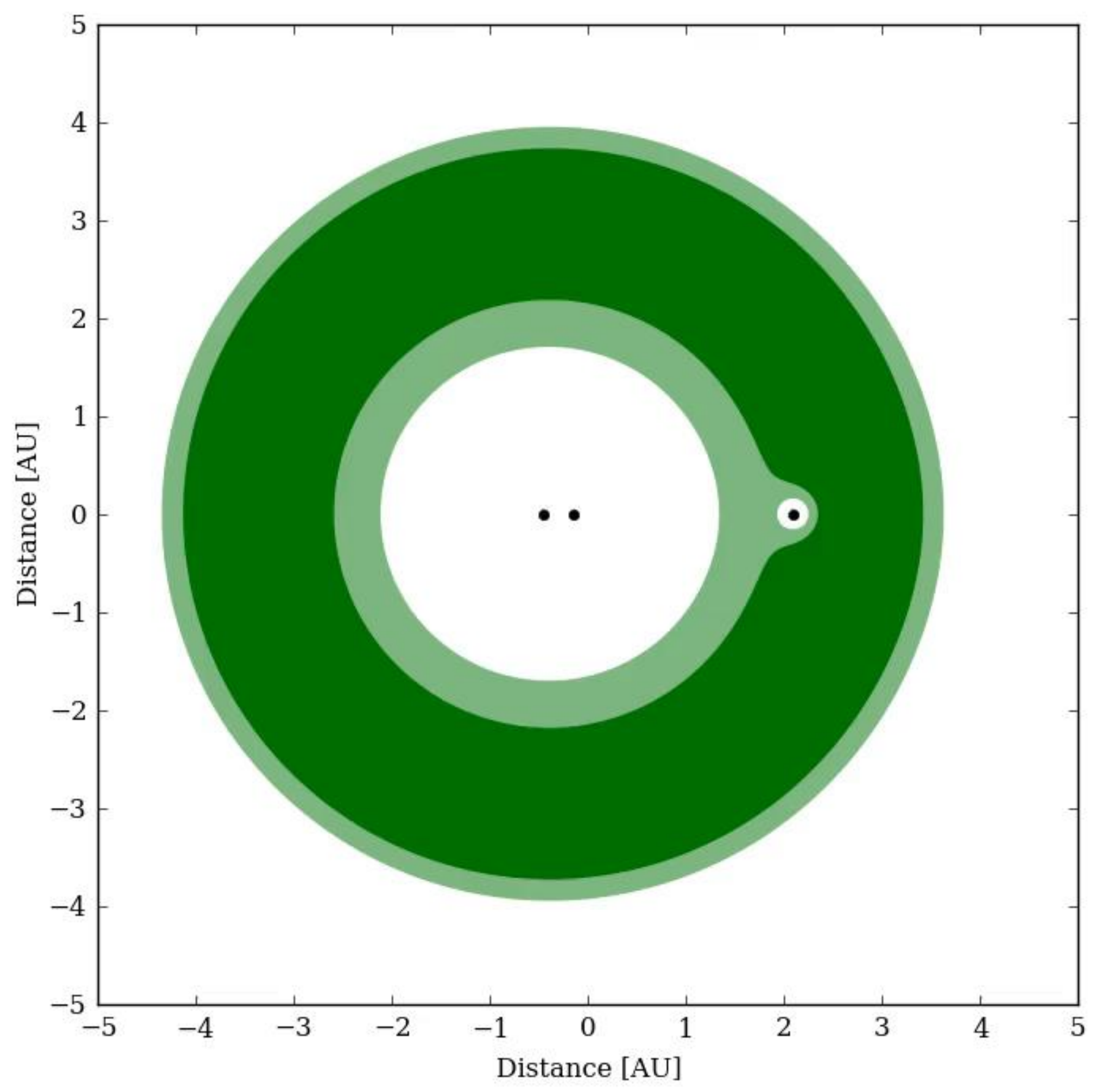
http://astro.twam.info/hz/

KIC 4150611

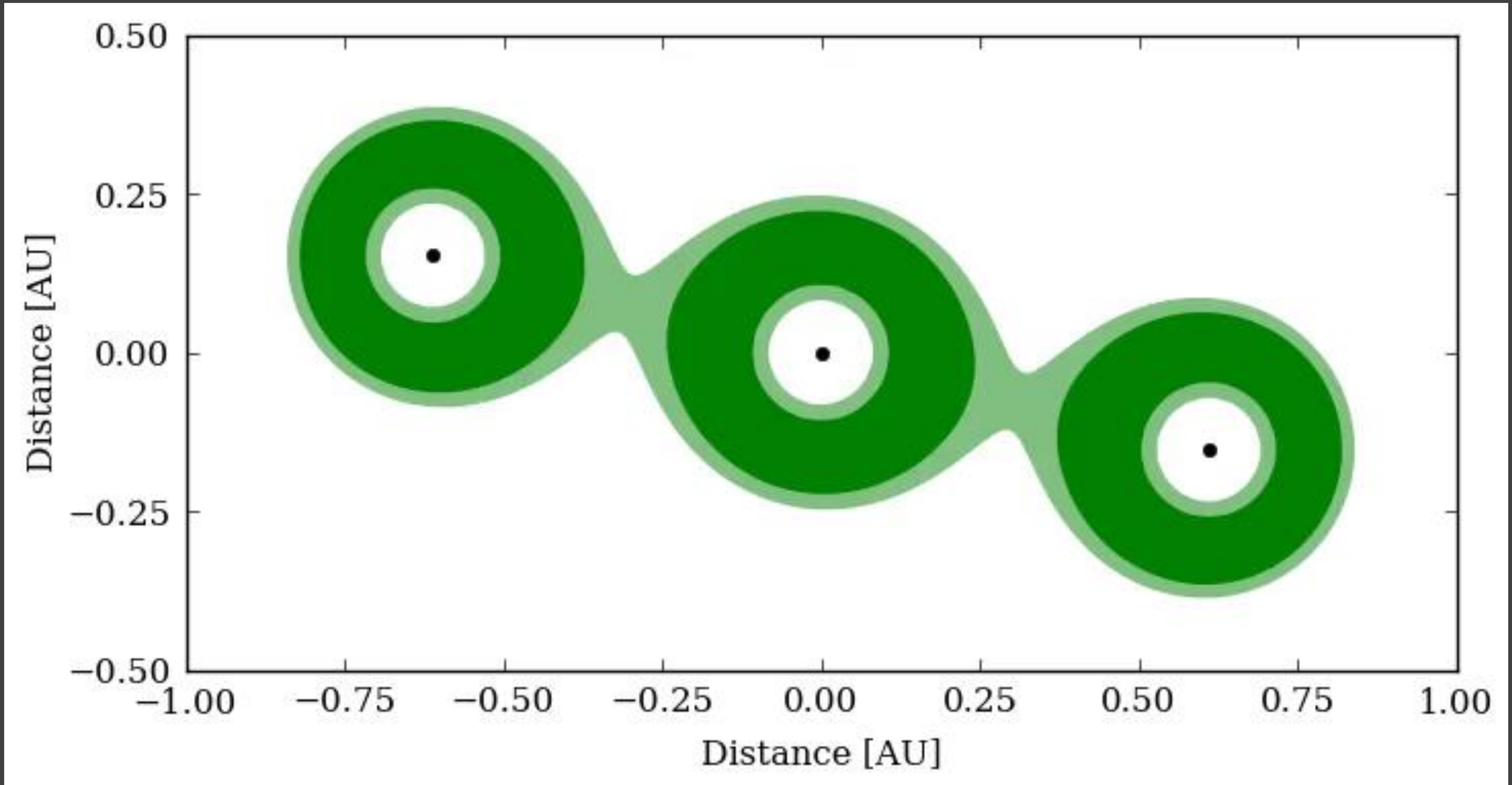


http://astro.twam.info/hz/

KID 5653126



http://astro.twam.info/hz/



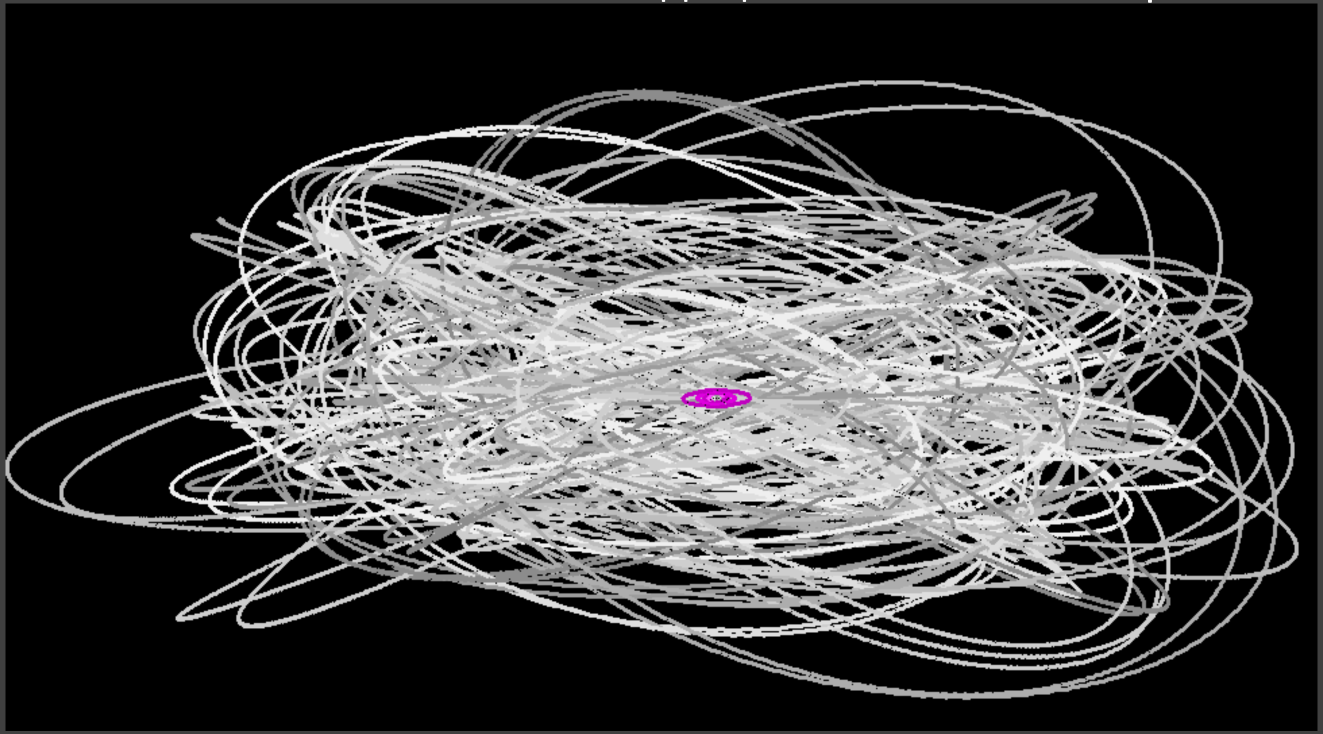
http://astro.twam.info/hz/

Эффект Лидова-Козаи

У орбиты могут одновременно меняться наклонение эксцентриситет.

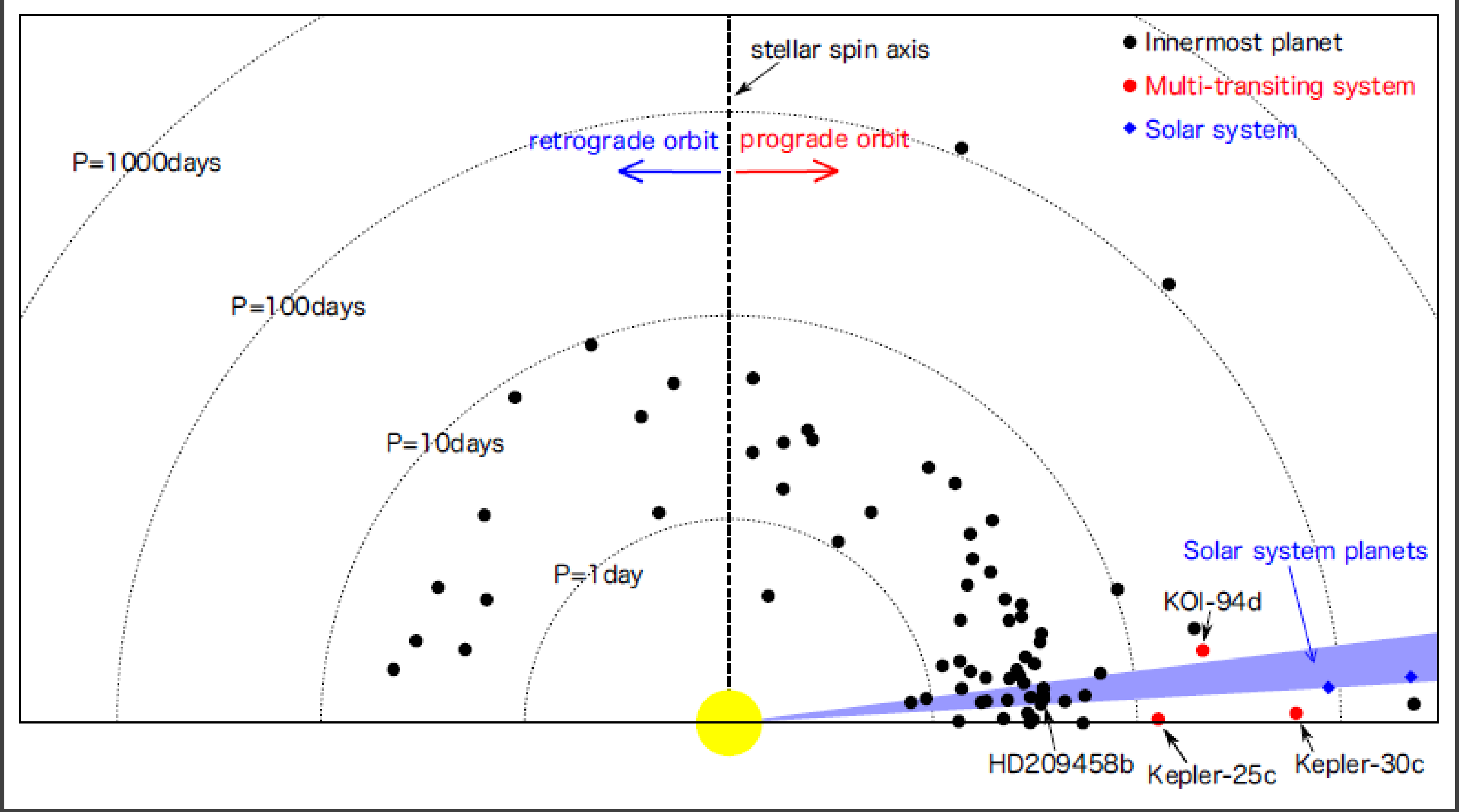
Эффект связан с воздействием тела, находящегося на внешней орбите.

$$e_{max} \simeq \sqrt{1-(5/3)\cos^2 i_0}$$



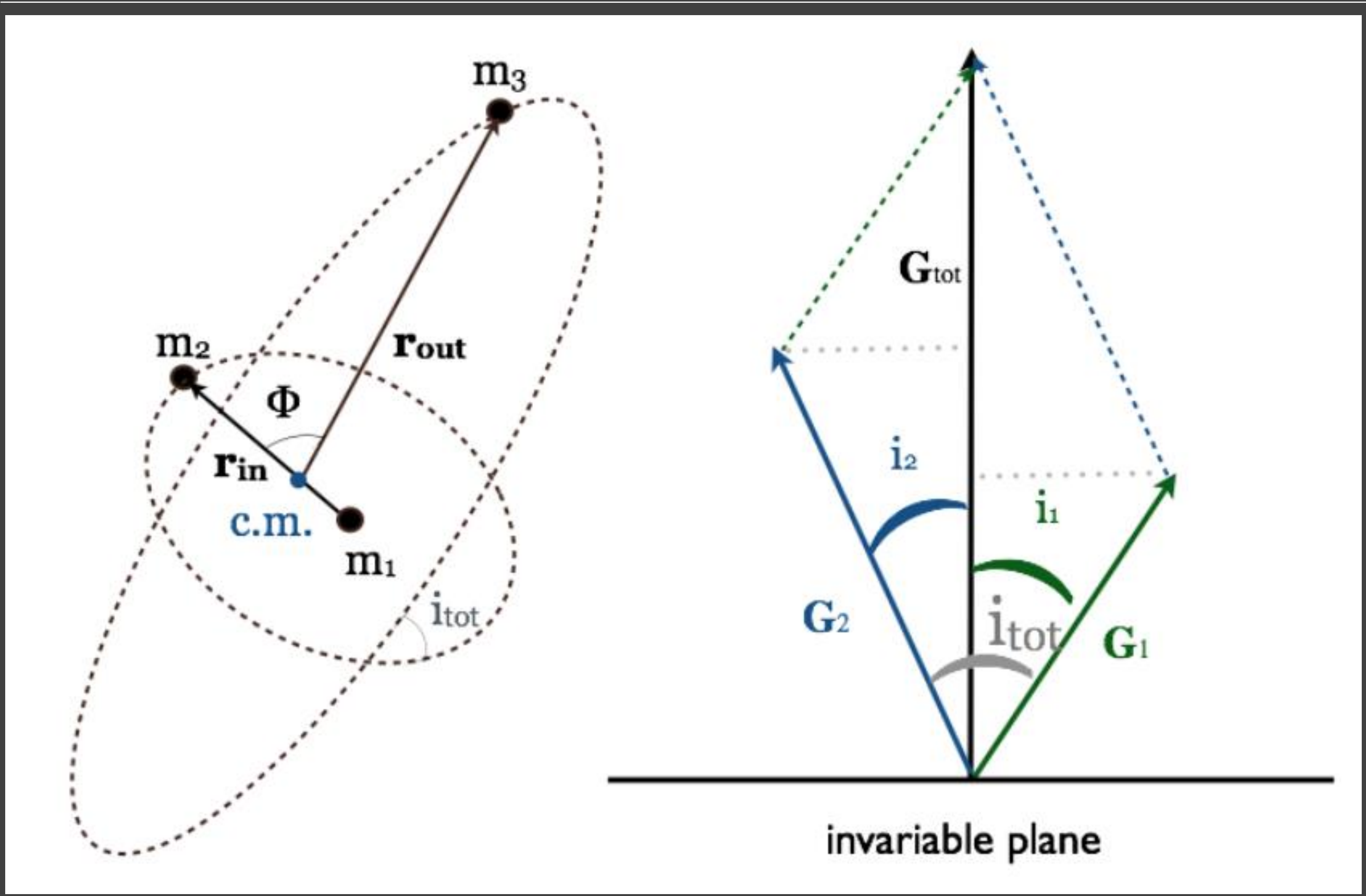
Эффект был впервые описан Михаилом Лидовым для спутников в 1961 г., а затем в 1962 г. был описан Козаи для астероидов.

Распределение планет по ориентации орбиты



Есть планеты с полярными и даже обратными орбитами.

Approximation



Wide outer body's orbit.
No resonances.

Two orbits exchange angular momentum, but not energy.
So, orbits can change shape and orientation, but not semi-major axes.

Conservation of projection of the angular momentum results in

$$j_z = \sqrt{1-e_1^2}\cos i_{tot} = \text{Const.}$$

Circular outer orbit

$$j_{z,1} = \sqrt{1 - e^2_{1,max/min}} \cos i_{1,min/max} = \sqrt{1 - e^2_{1,0}} \cos i_{1,0}$$

m_2 → 0 (test particle approximation)

$e_{1,0} = 0$ and $\omega_{1,0} = 0$

$$E_0 = 2e^2_{1,min} - 2 + (1 - e^2_{1,min}) \cos i^2_{max}$$

→

$$e_{max} = \sqrt{1 - \frac{5}{3} \cos^2 i_0}$$

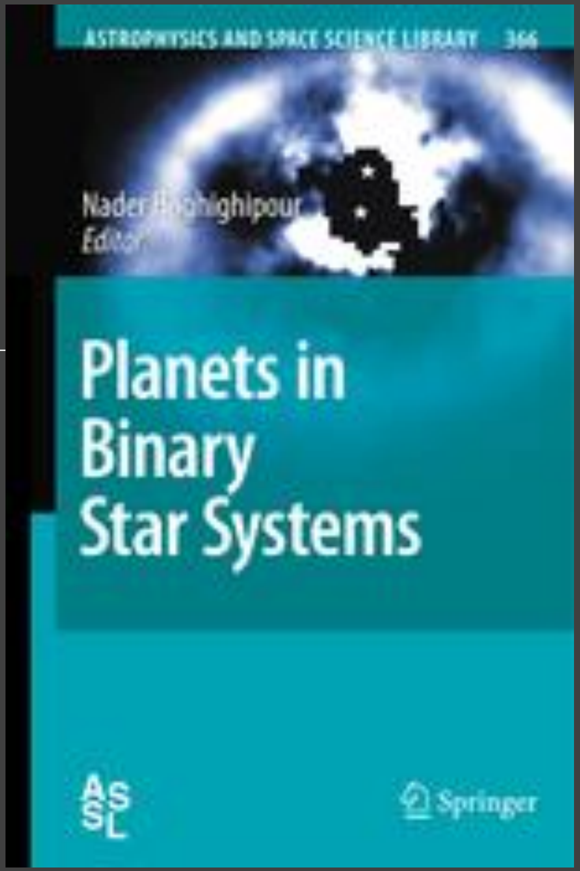
$$\cos i_{min} = \pm \sqrt{\frac{3}{5}}$$

~40 and 140 degrees
(Kozai angles)

The z-component of the angular momentum of the inner and outer orbits (i.e., the nominal $\sqrt{1 - e^2_{1,2}} \cos i_{1.2}$) are only conserved if one of the binary members is a test particle and the outer orbit is axisymmetric ($e_2 = 0$).

Literature

- 1608.00764 New prospects for observing and cataloguing exoplanets in well detached binaries R. Schwarz et al.
- 1401.0601 Calculating the Habitable Zone of Multiple Star Systems Tobias Mueller, Nader Haghighipour
- 1601.07175 The Eccentric Kozai-Lidov Effect and Its Applications Smadar Naoz
- 1406.1357 Planet formation in Binaries P. Thebault, N. Haghighipour



(2010)