Exoplanets
Introduction

Planets and Astrobiology (2020-2021)

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Importance of the study of extrasolar planets

- Main scientific motivations
  - Setting our understanding of planetary physics in a Galatic context

    Planetary physics so far only based on the Solar System

    Testing models of formation and evolution of planetary systems

  - Understanding how general are the Solar System properties

    Architecture: dichotomy between rocky and giant planets

    Dynamical properties: nearly circular and aligned orbits

  - Setting terrestrial life in a universal context

    Quantifying the frequency of planets that have suitable conditions for hosting life ("habitable planets")

Importance of the study of extrasolar planets

- Technological and scientific spin-offs
  - Exoplanet observations are driving huge technological improvements to classical astronomical instrumentation

    Imaging, coronagraphy, high resolution spectroscopy, photometry, interferometry, etc.

  - Stellar physics strongly benefits from exoplanet observations

    A huge amount of high quality stellar measurements is becoming available

    Studies of asteroseismology, microvariability, …

    Exoplanet science is providing fresh motivation to improve our understanding of stellar physics and stellar chemical abundances

  - In turn, exoplanet studies will benefit from the higher level of understanding of stellar properties

Planet definition for extrasolar systems

- As in the Solar System, orbiting sub-stellar objects are referred as planets is their mass is less than ~13 M_J
- However, attempts to formulate a precise definition of planet in extrasolar systems face a number of difficulties
  - (Basri & Brown 2006, Ann. Rev. Earth Plan. Sci., 34, 193)
- The IAU definition of planet cannot be directly applied to extrasolar planets
  - We can test whether its mass is below the deuterium burning limit (M~13 M_J), but we cannot experimentally determine whether the exoplanet has cleared its orbit or its shape is exactly round
- A definition free of upper and lower mass limits is:
  - A planet is an end product of disk accretion around a primary star of substar

Planet definition for extrasolar systems

A simple metric has been proposed to determine whether a planet can clear its orbital zone during a characteristic time scale, $t_\star$,

such as the main-sequence life time of its central star (Margot 2015)

The <u>feeding zone</u> of the planet scales with the Hill radius

$$R_H = \left(\frac{M_p}{3M_\star} \right)^{1/3} a_p.$$

where M_p is the planet mass, a_p the radius of the(circular) orbit,

and M_* the mass of the central star

If we neglect gravitational effects of other bodies of the planetary system, the Hill radius is the distance within which the gravity of the planet dominates that of the host star

Planet definition for extrasolar systems

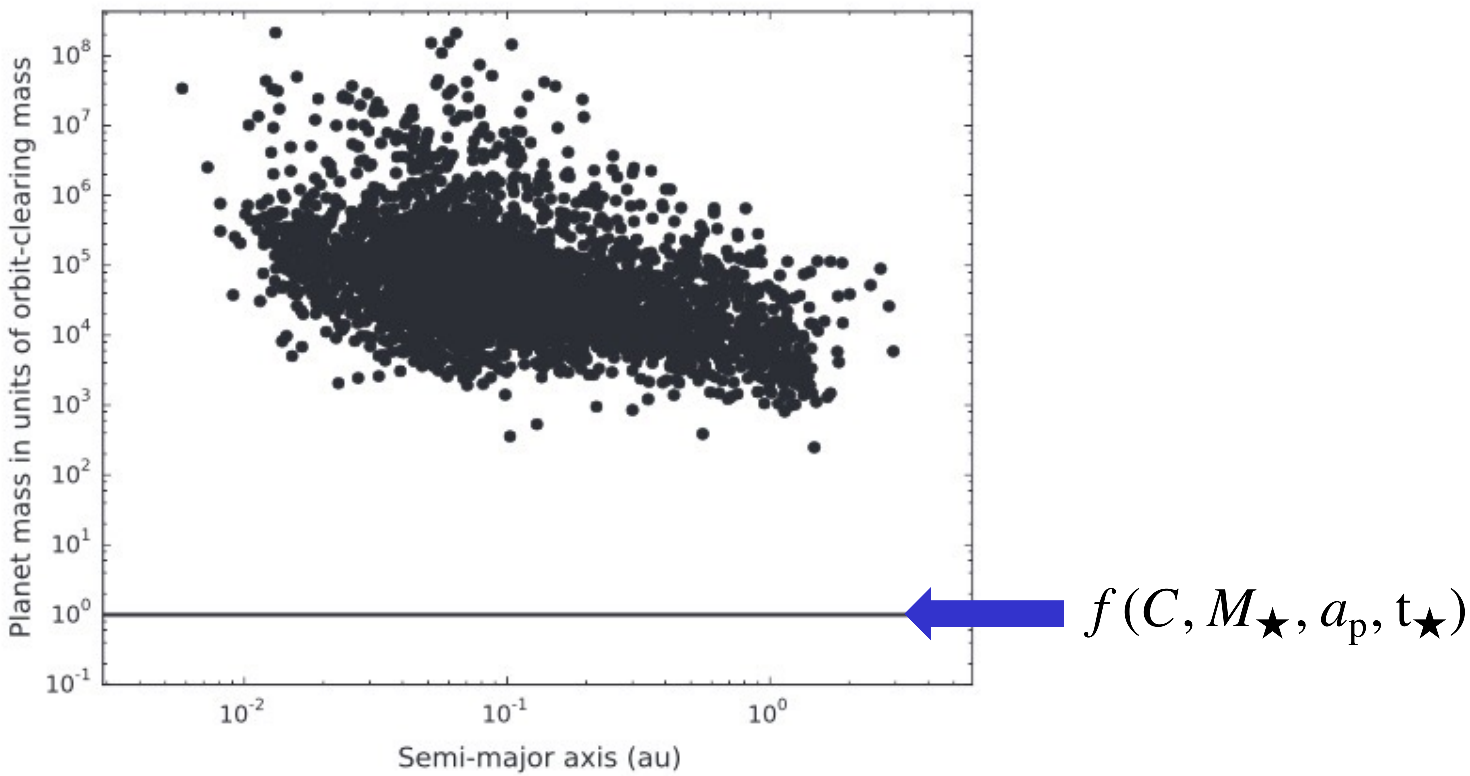
By requiring that the planet has cleared its orbit in a time scale less than the age of the planetary system, a lower limit can be derived

(Margot 2015)

$$M_p > f(C, M_\star, a_p, t_\star)$$

$$t_\star = t_\star(M_\star) \text{ stellar age}$$

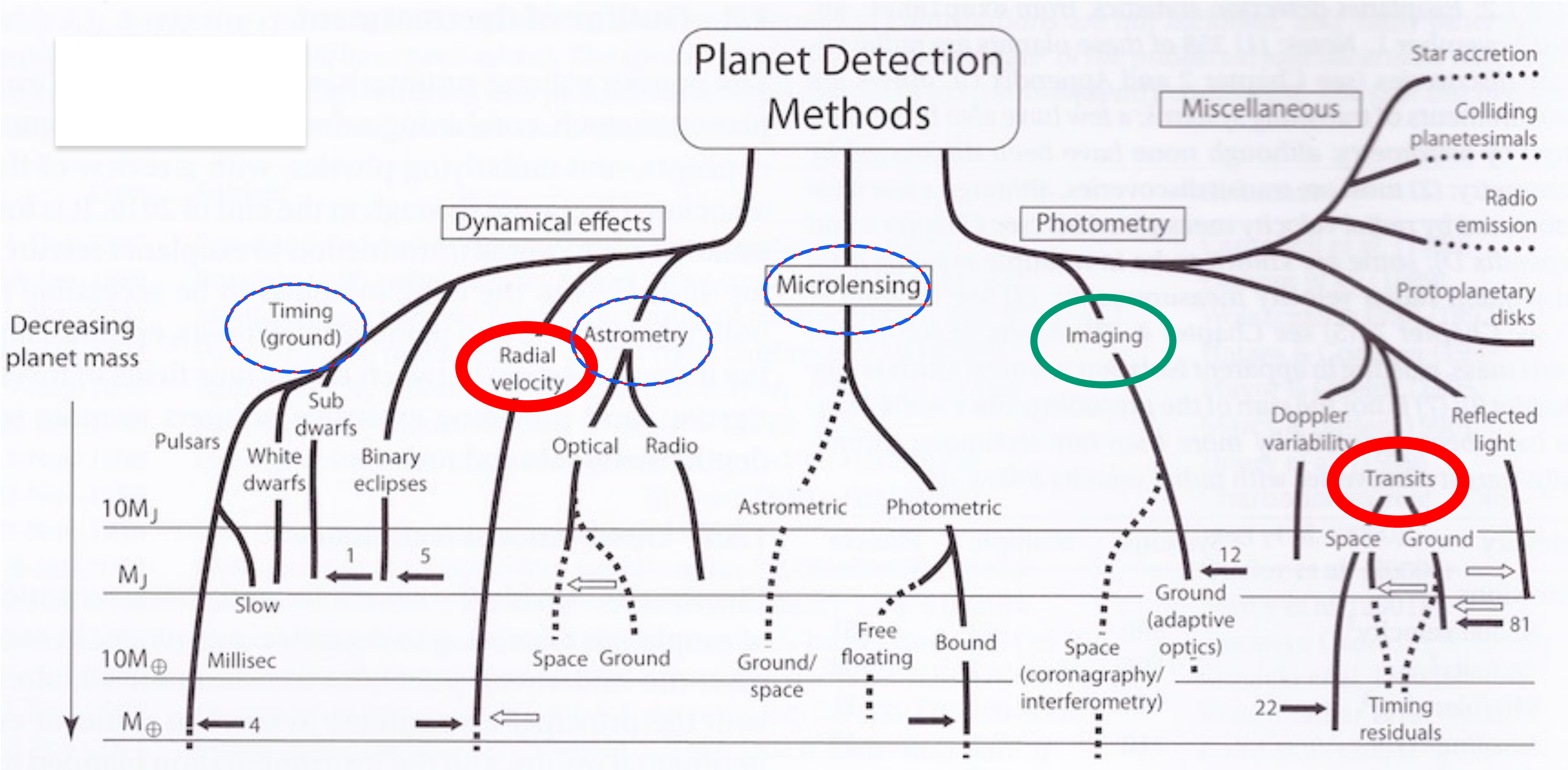
Example: application of the clearing mass algorithm to Kepler exoplanets



Detection methods of exoplanets

- Direct methods
  - Direct imaging of the planet
- Indirect methods
  - Mostly based on effects induced on the host star
    - Gravitational perturbation of the stellar motion
    - Variations of the stellar luminosity

Exoplanet detection methods



Exoplanet catalogs

- Exoplanets catalogs
  - www.exoplanet.eu

    Extrasolar planet encyclopedia

  - https://exoplanetarchive.ipac.caltech.edu

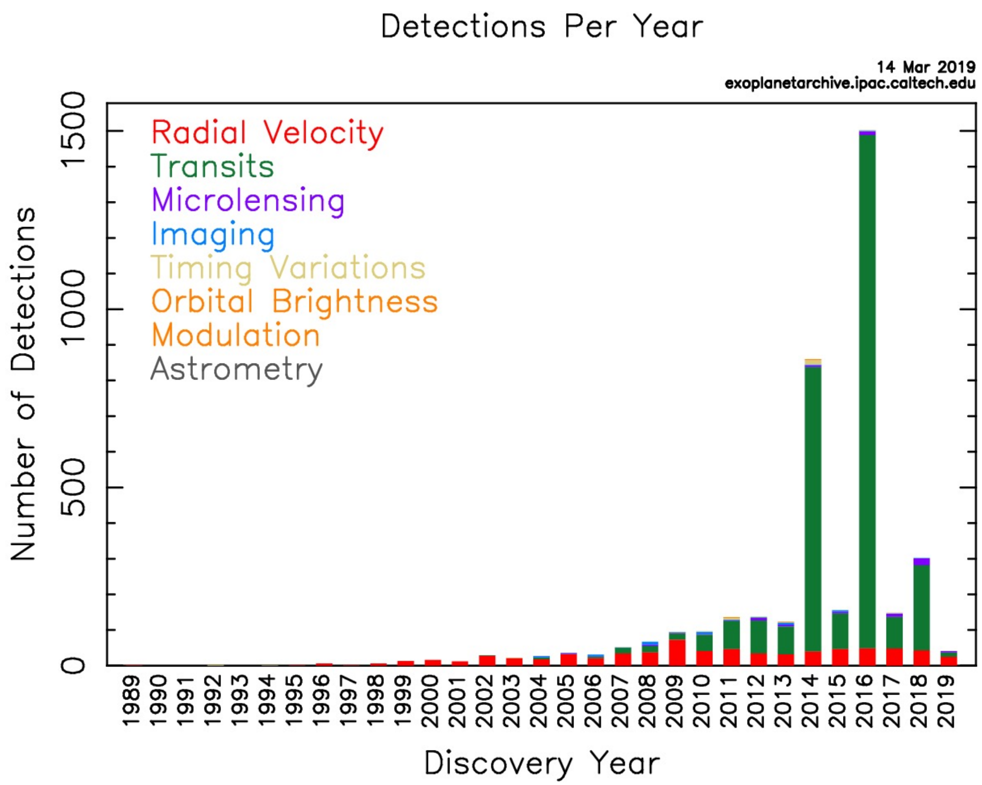
    NASA Exoplanet Archive

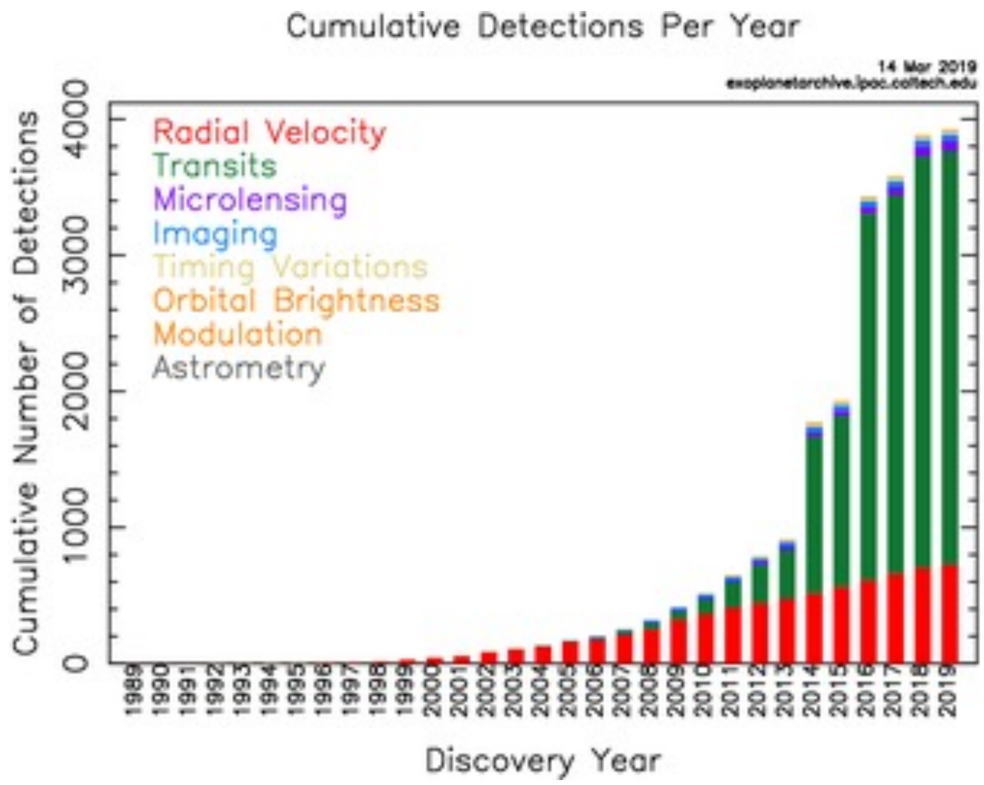
  - www.exoplanets.or

    Exoplanet Orbit Database (Jones et al. 2008)

- Planets around star X are denoted as X b, c, … in alphabetic order *according to the discovery sequence* (not according to the semi-major axis, which would demand constant revision as additional planets are discovered around the same star)

Histogram of number of exoplanet detections versus year of discovery/publication





Detection of exoplanets:

Geometric configuration of the observation

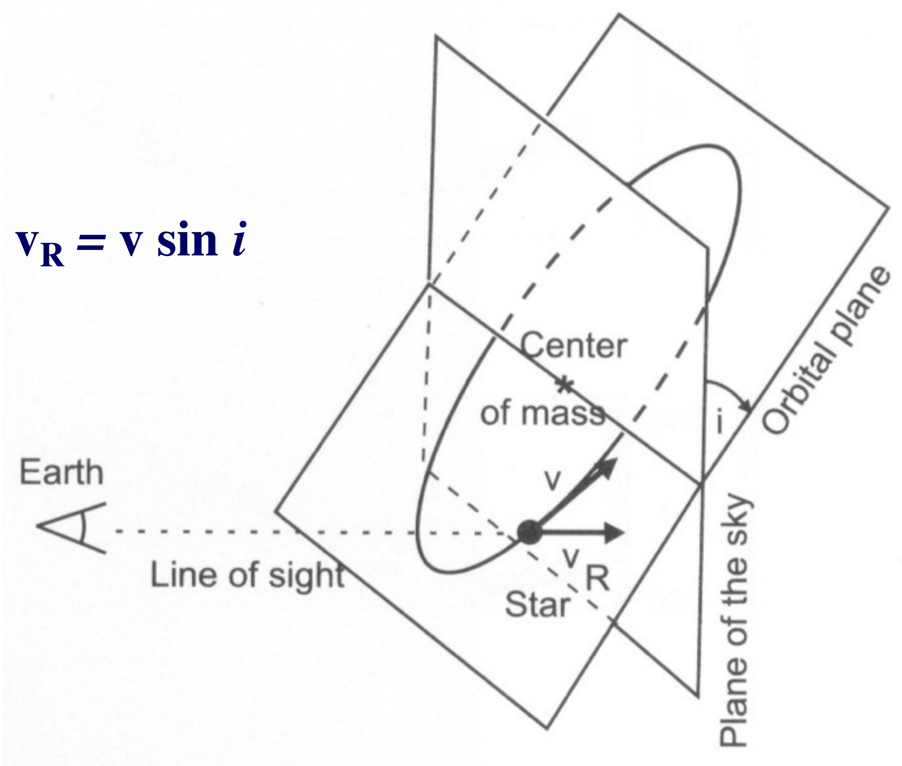
We call ***i*** the angle between the orbital spin and the line of sight (i.e., the angle between the orbital plane and the plane of the sky)

$i = 0^o \rightarrow$ face on

$i = 90^o \rightarrow$ edge on

With this convention, the velocity vector of the motion of the central star in the orbital plane is projected along the line of sight with a factor **sin *i***

$v_R = v \sin i$



Detection of exoplanets:
Derivation of the orbital period and semi-major axis

– We use the third Kepler's law

$$P^2 = \frac{4\pi^2 a^3}{G(M_\star + m_p)}$$

– We assume that the planet mass is negligible compared to the mass of the central star: $m_p << M_*$

– We estimate the mass of the central star, M_*, from a spectroscopic study of the star and models of stellar evolution

– In most detection methods we obtain a measurement of the orbital period, P using indirect methods. We then use the third Kepler's law to estimate the semimajor axis, a

– If the detection method provides a direct measurement of the semimajor axis, a, we use the third Kepler's law to estimate the orbital period, P

- Temporal baseline of the observations with indirect methods

  - The orbital period *P* is measured from the time variability of a stellar signal that bears signatures of the presence of a planet

    Different types of signal can be employed:

    stellar pulses, spectroscopy, photometry or angular position of the star

  - In order to measure *P* (and to derive *a* from the third Kepler's law), the star should be observed over a temporal baseline covering at least a few orbital periods

  - This leads to an observational selection bias: *planets with long orbital periods will require a long temporal baseline of observations*

Detection of exoplanets:
Indirect methods: temporal baseline of the observations

- The orbital periods of the Solar System planets show that a temporal baseline in the order of tens of years would be required to prove the existence of periodicity for planets with $a \gtrsim 5$ AU

- This observational bias affects all indirect methods of exoplanet detection and favours the discovery of planets with short orbital periods, very close to the host star
  - This is (one of the reasons) why most detected exoplanets have orbital period of a few days and $a \lesssim 0.1$ AU

Planet	a [AU]	P [years]
Mercury	0.387	0.24
Venus	0.723	0.62
Earth	1.000	1.00
Mars	1.523	1.88
Jupiter	5.203	11.86
Saturn	9.537	29.42
Uranus	19.191	83.75
Neptun	30.069	163.72

Generalization of planetary orbits to the case of binary stars

- Solar System planets orbit a single star
- Many stars occur in binary or multiple star systems
  - Nearby G-K dwarfs, for example, are known to occur more often in binary or multiple systems than they do in isolation

- Many young binaries are known to possess disks, either around one of the stars (circumstellar disk) or surrounding both stars (circumbinary disk) which, in analogy to single stars, may provide the accretion material necessary for planet formation
- The presence of one or more planets around a binary or multiple star system is limited by considerations of dynamical stability

Stable planetary orbits around binary stars

Several types of stable orbits around binary stars are possible in principle

S-type orbits

- The planet lies in a circumstellar orbit, i.e. orbiting either the primary or the secondary star

P-type orbits

- The planet lies in a circumbinary orbit, i.e. orbiting both stars

L-type orbits

- The planet lies in a 1:1 “Trojan” resonance around L4 or L5 Lagrange points

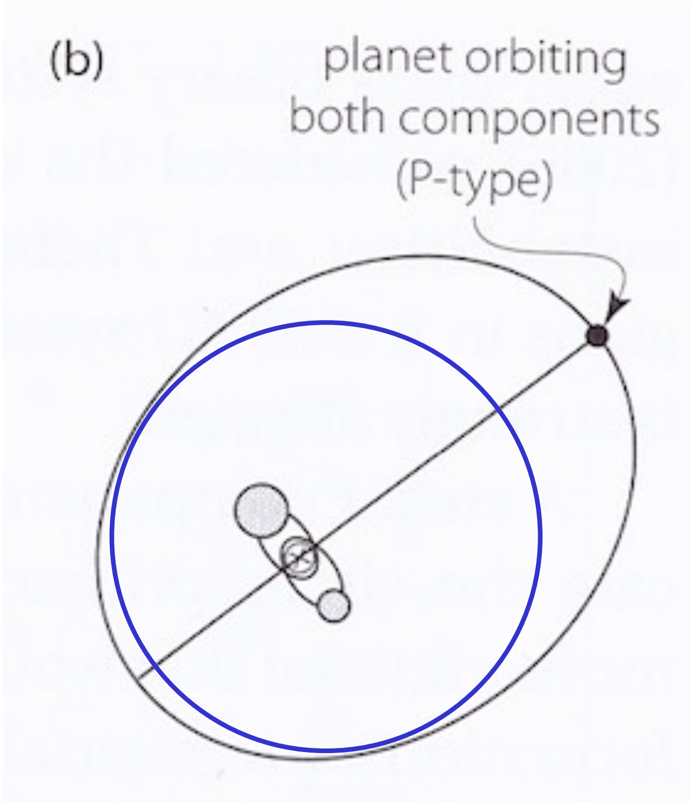
P-type orbits

- The planet lies in a circumbinary orbit, i.e. orbiting both stars
- Numerical simulations indicate that the P-type planetary orbit is stable for semimajor axes exceeding a critical value

Only P-type orbits with

$a > a_{\mathrm{crit}}$

are stable

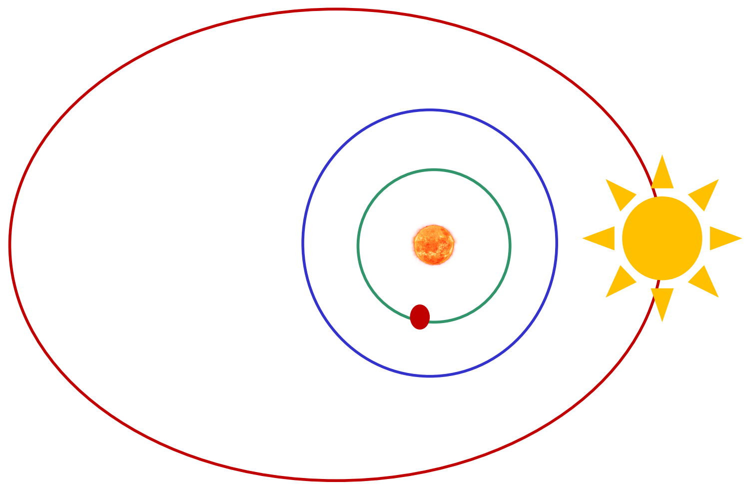


S-type orbits

– The planet orbits either the primary or the secondary star
– The gravitational force of the secondary induces orbital perturbations

The perturbative effect varies with the companion star mass and according to the eccentricity and semimajor axis of the binary which together determine the closest approach of the planet to the secondary

– Simulations indicate that the S-type planetary orbit is stable for semimajor axes below a critical value



Only S-type orbits with

$a < a_{\text{crit}}$

are stable