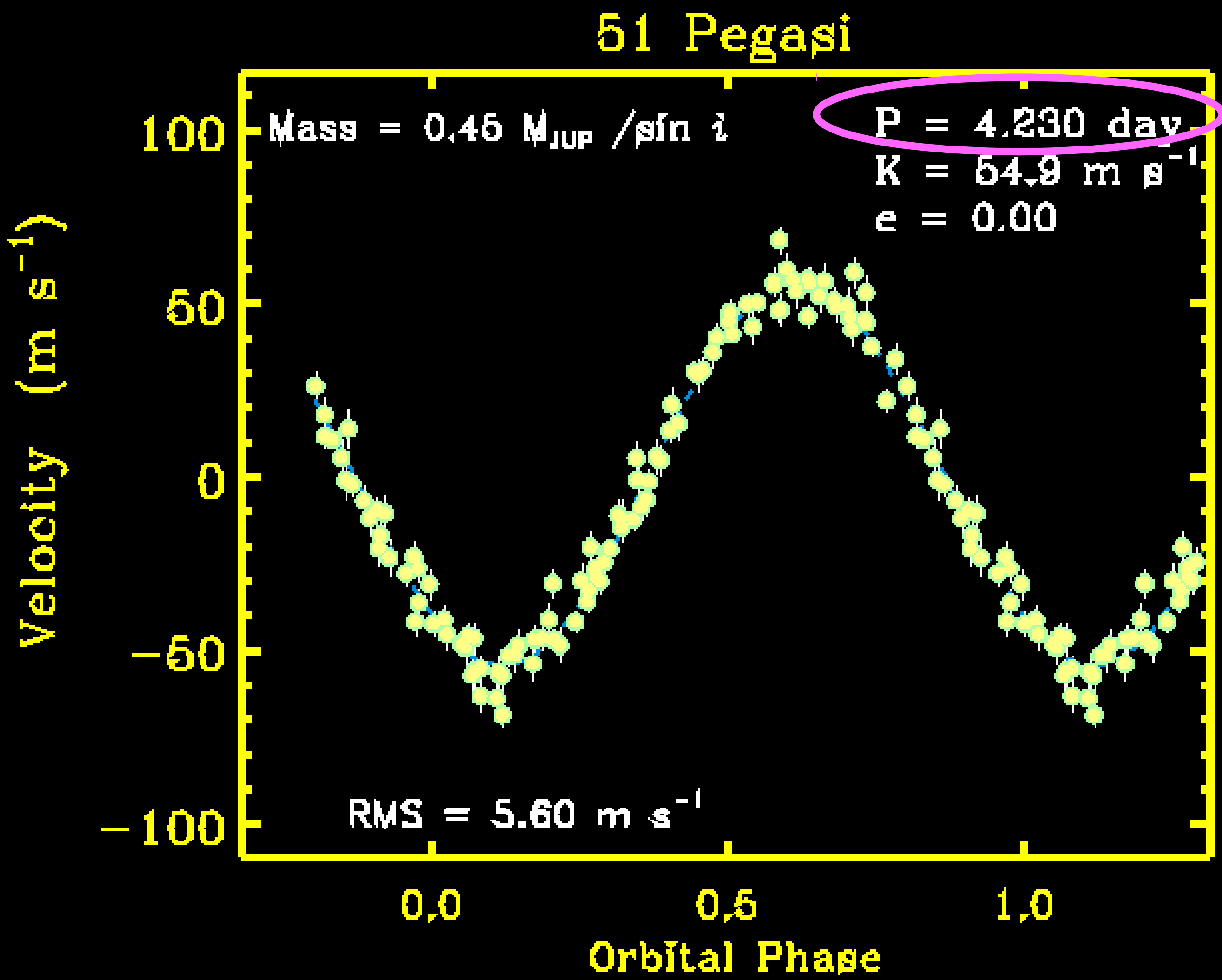
Exoplanets

METHODS AND PRINCIPLES

1) RADIAL VELOCITY	Gravity causes star to "wobble": Radial Velocity: Motion toward and away detected by Doppler shifts in **stellar spectra**
2) ASTROMETRY	Astrometry: Motion in plane of sky detected in **images of stars** compared to background
3) TRANSIT	Eclipses by planets (slightly!) dim the star light Detected by brightness decrease in **light curve**
4) MICROLENSING	Stars sometimes gravitationally lens background stars and the planet can contribute (very slightly) Detection by small blip in lens **light curve**
5) IMAGING	Image of starlight reflected by planet. Very Difficult: Requires **nulling** the star

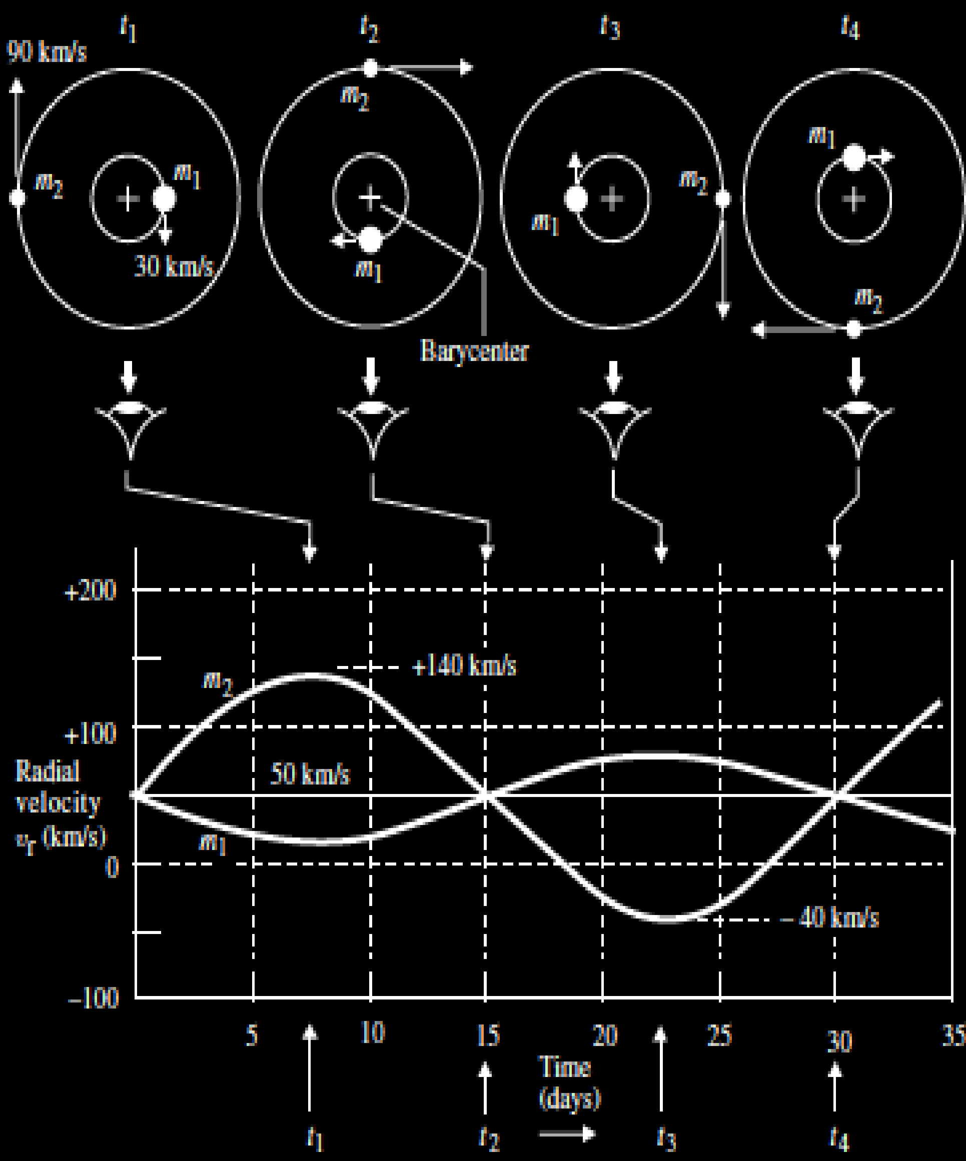
The first confirmed exoplanet orbiting a MS star



Mayor & Queloz (1995)

The mass function

$$a_* = a \frac{M_o}{M_* + M_o}$$

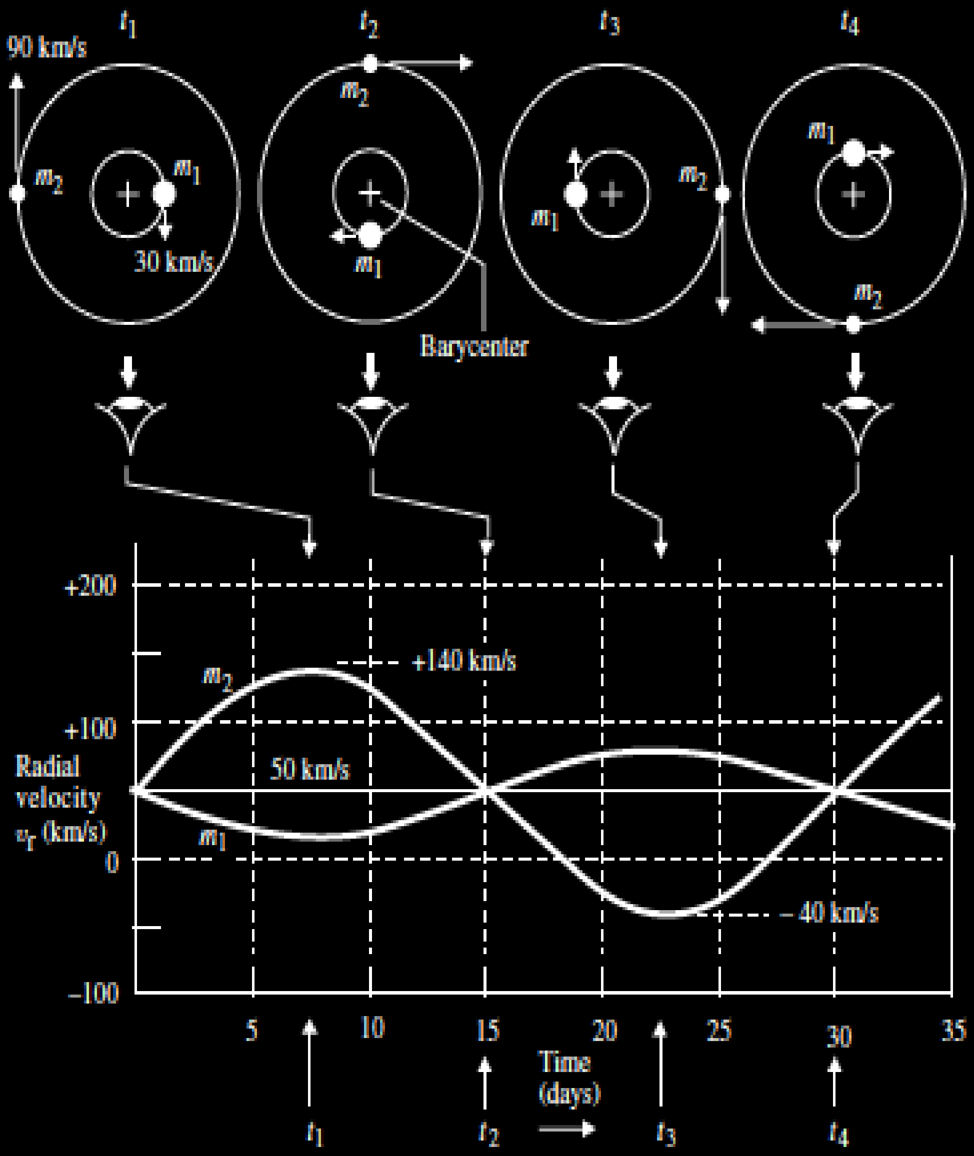


The mass function

$$a_* = a\frac{M_o}{M_* + M_o}$$

Kepler's 3rd law becomes:

$$\omega^2 = G\frac{M_* + M_o}{a^3}$$



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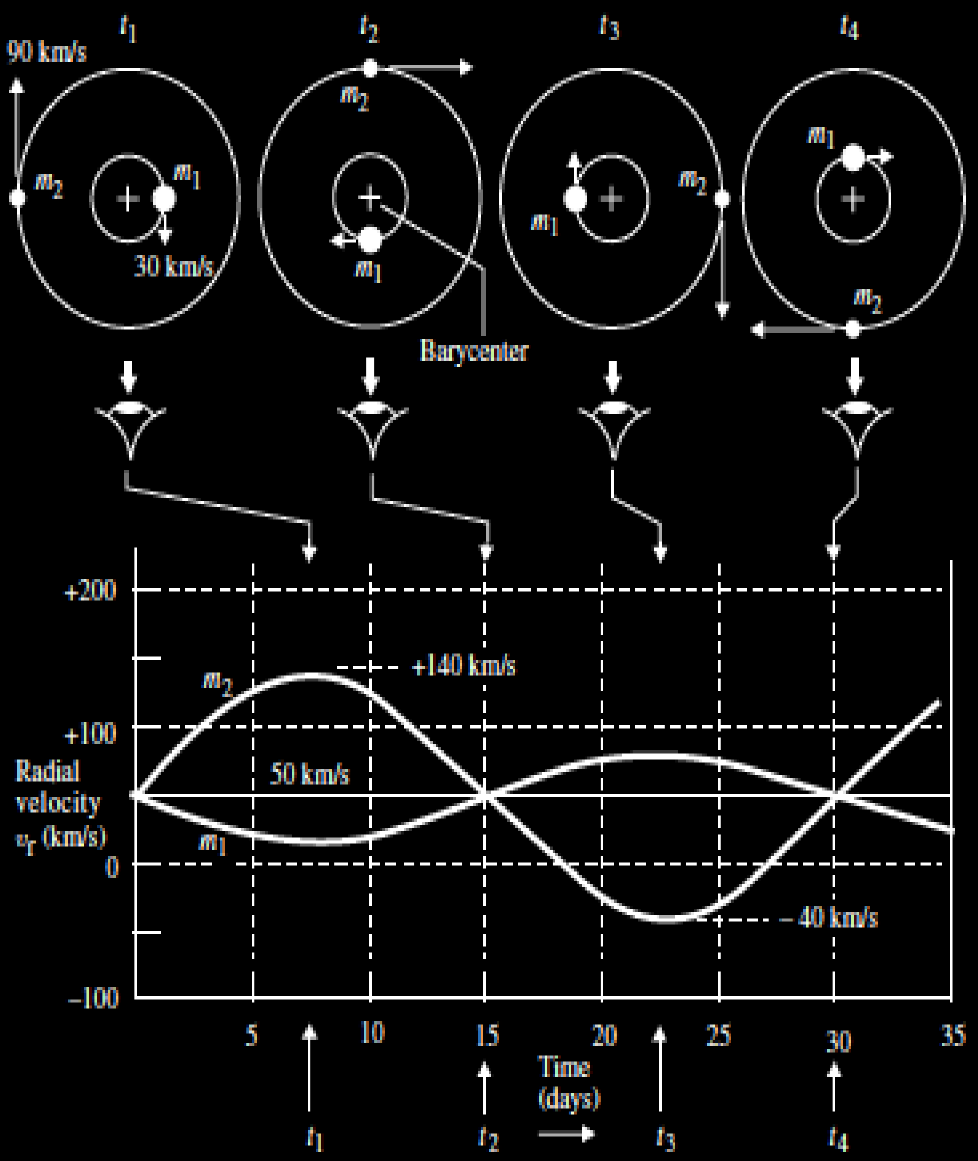
We can also measure :

$$v_{max} = \omega a_* sin(i)$$



The mass function

$$a_* = a\frac{M_o}{M_* + M_o}$$

Kepler's 3rd law becomes:

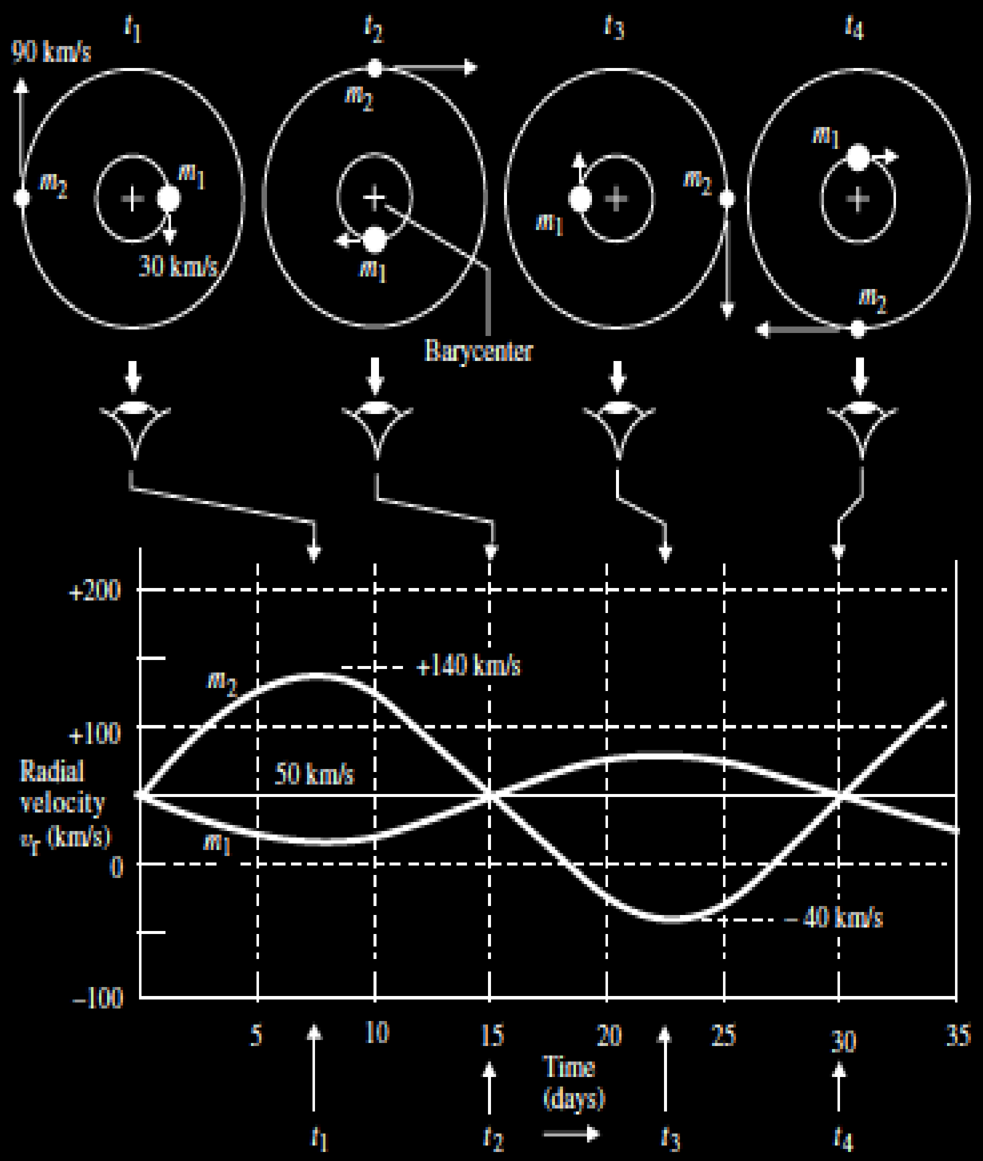
$$\omega^2 = G\frac{M_* + M_o}{a^3}$$

We can also measure :

$$v_{max} = \omega a_* sin(i)$$

We define ***mass function*** :

$$f = \frac{v_m^3}{\omega G} = \frac{M_o^3 sin^3 i}{(M_* + M_o)^2}$$



The mass function

$$f = \frac{v_m^3}{\omega G} = \frac{M_o^3 sin^3 i}{(M_* + M_o)^2}$$

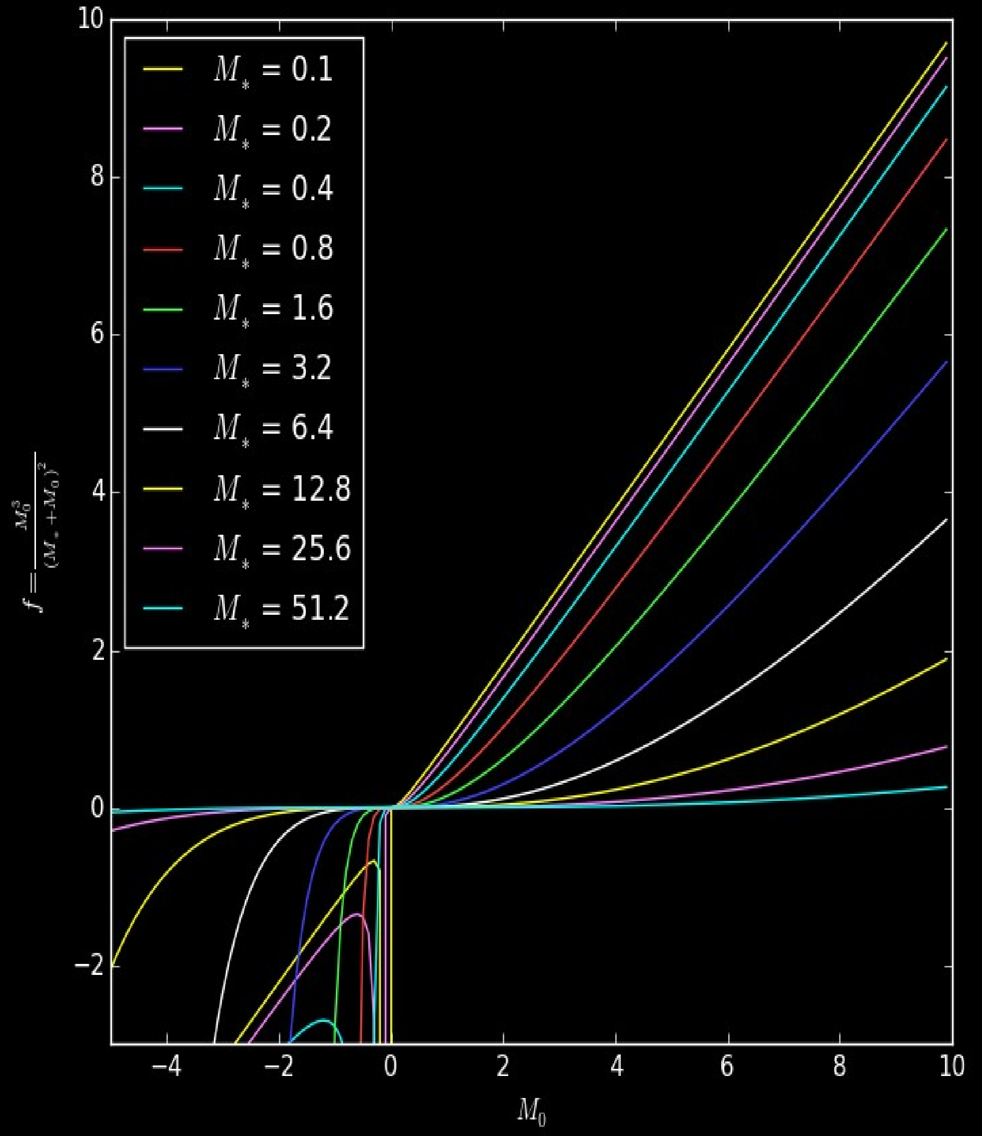
Mass function (*f*): contains all measurable quantities

if stellar mass is known,

f**$_*$* **provides** $\boldsymbol{m_o}$ **sin** ***i

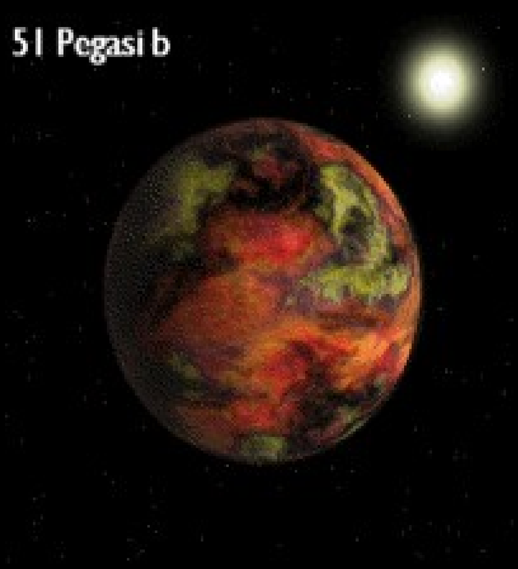
with sin *i* = 1

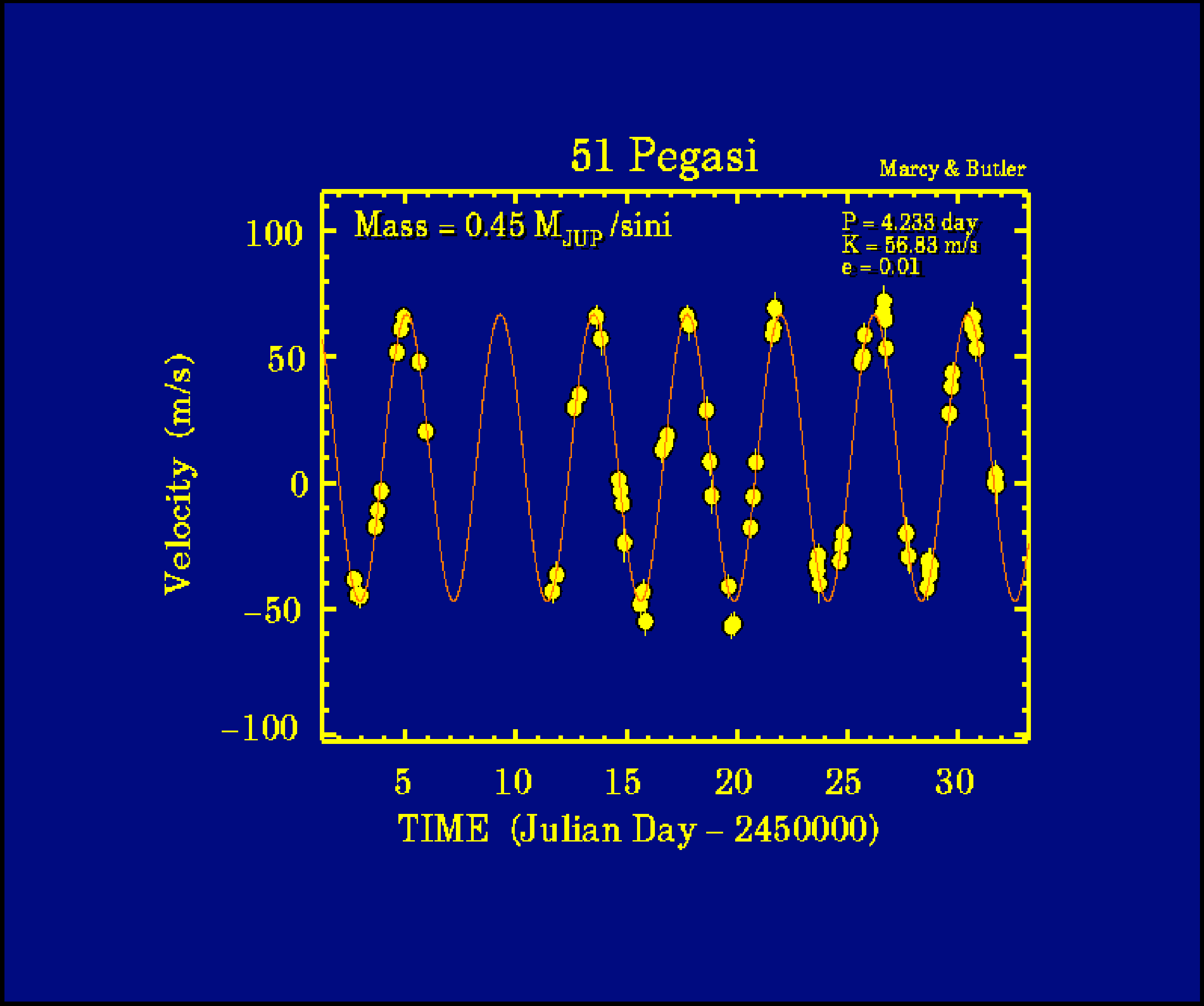
lower limit on $\boldsymbol{m_o}$



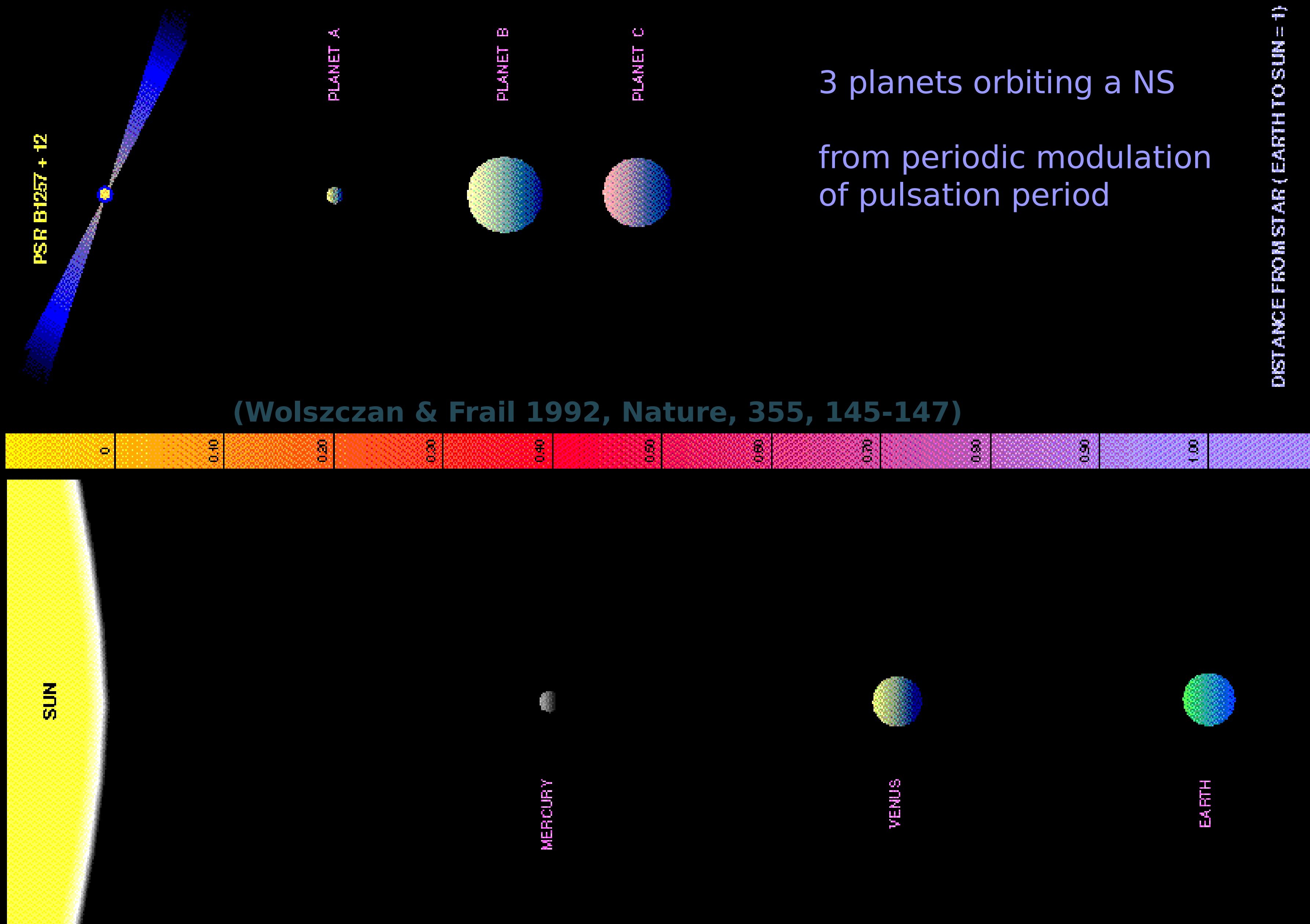
RADIAL VELOCITY METHOD

(Doppler Shifts Of Star Light)





Pulsar Planets



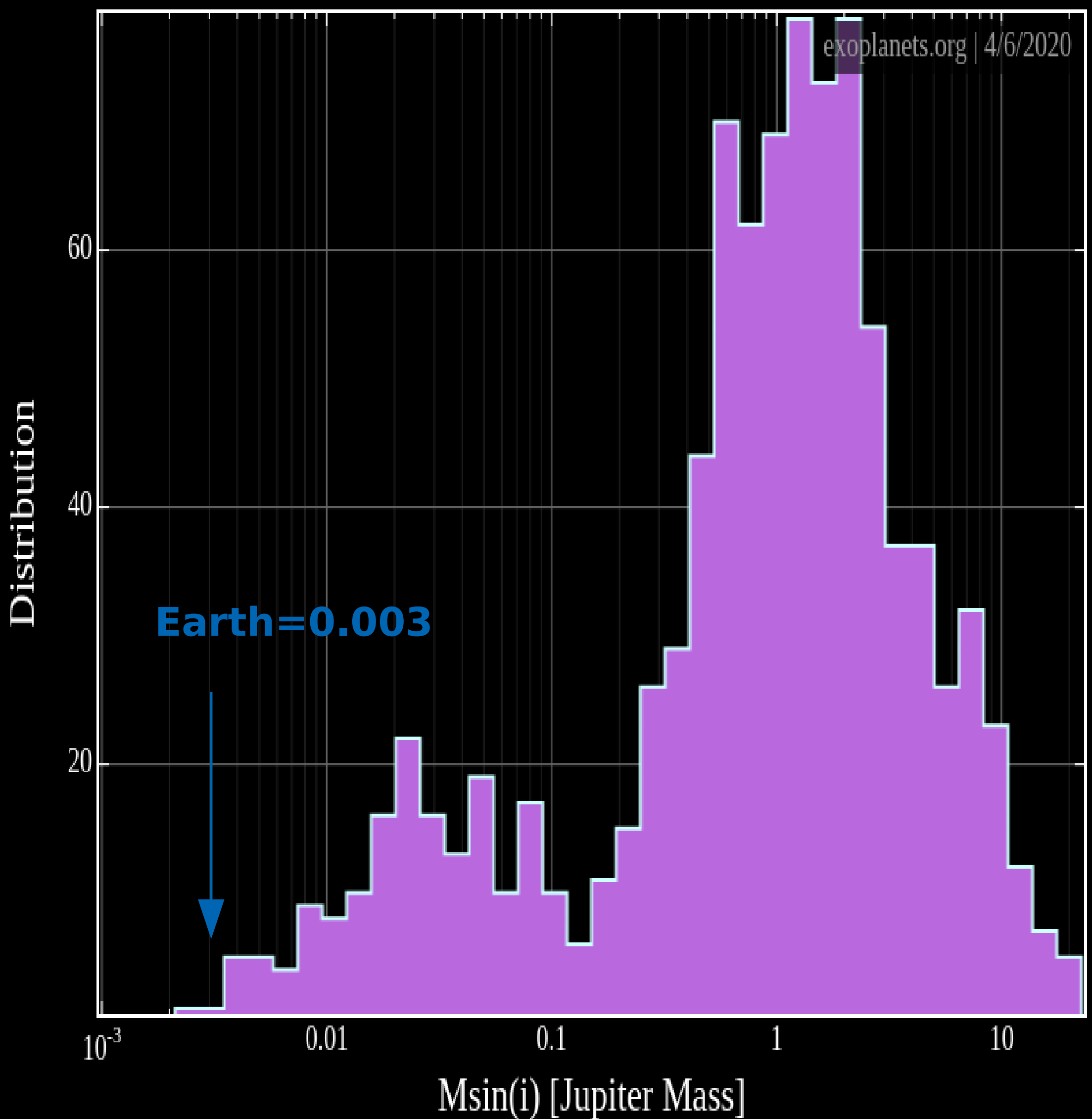
3 planets orbiting a NS

from periodic modulation of pulsation period

(Wolszczan & Frail 1992, Nature, 355, 145-147)

Radial Velocity Method

(Doppler Shifts Of Star Light)

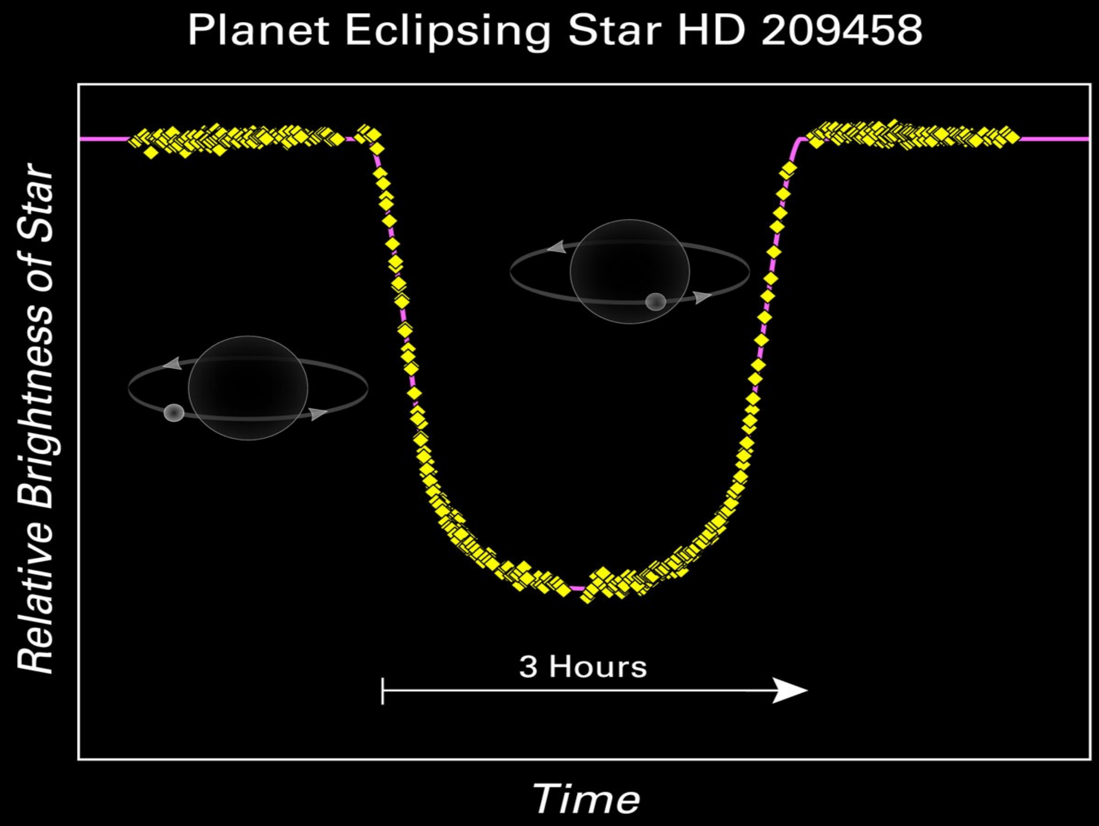


One cannot get the mass directly, if the **inclination** of the system is unknown

One determines combined quantity of planet mass and the inclination angle

Smaller “mass” planets are the hardest to find) ⇒ **small planets are very numerous**

Transit Method



- Planet **candidates** need to be confirmed by RV observations
- **Follow-up** observations are also needed to derive **planet mass** and to study **star properties**

Transit Method

CoRoT 7b

Rocky planet

Mass = 5 Earth

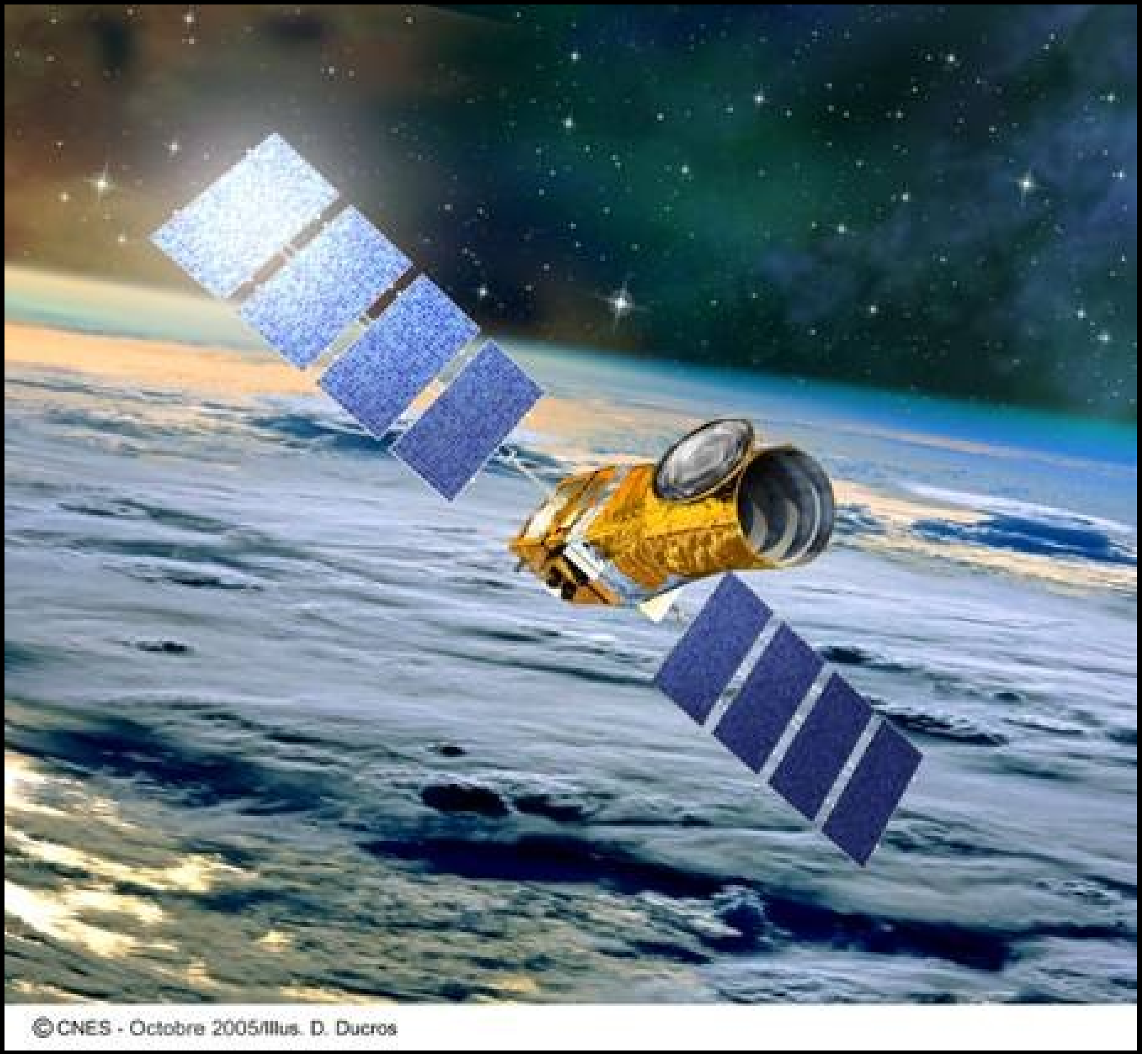
R= 2.5 10^6 km

(23 times closer than Mercury)

P = 20.4 h

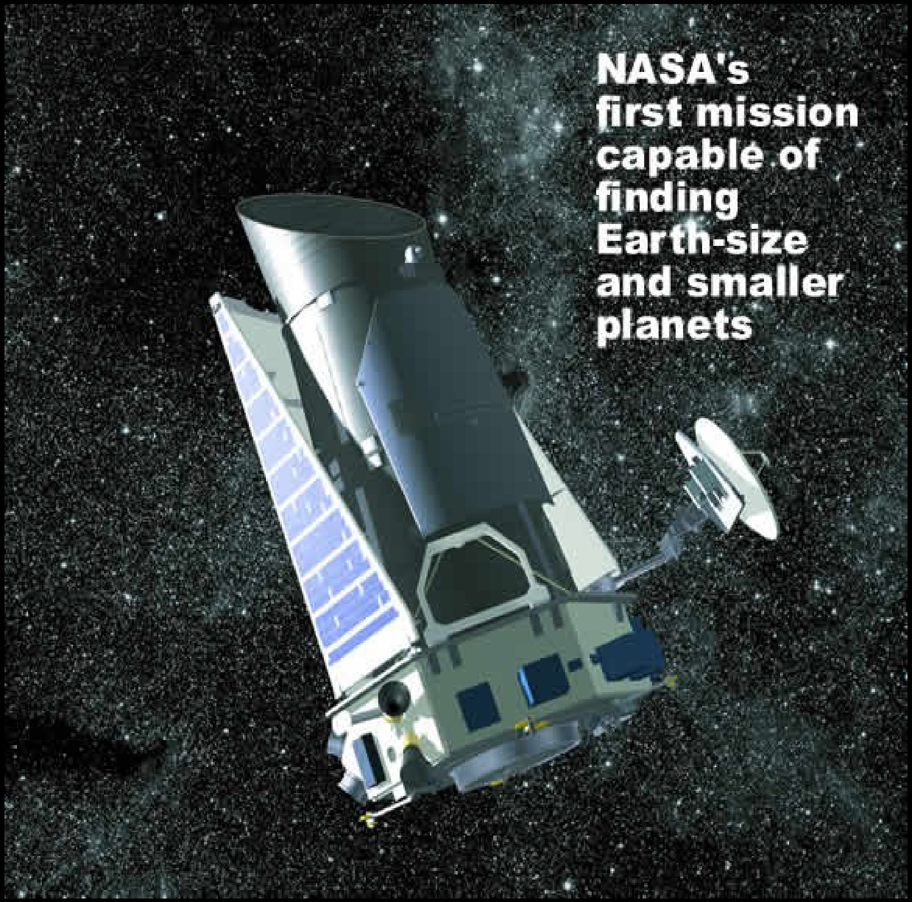
Star age= 1.5 Gy

- When discovered, Corot-7b was the closest known exoplanet to its host star, thus the fastest.
- *Day-face* temperature >2,000°, but –200° on *night face*. CoRoT 7b may have lava or boiling oceans on its surface.
- The sister planet, Corot-7c, is more distant.



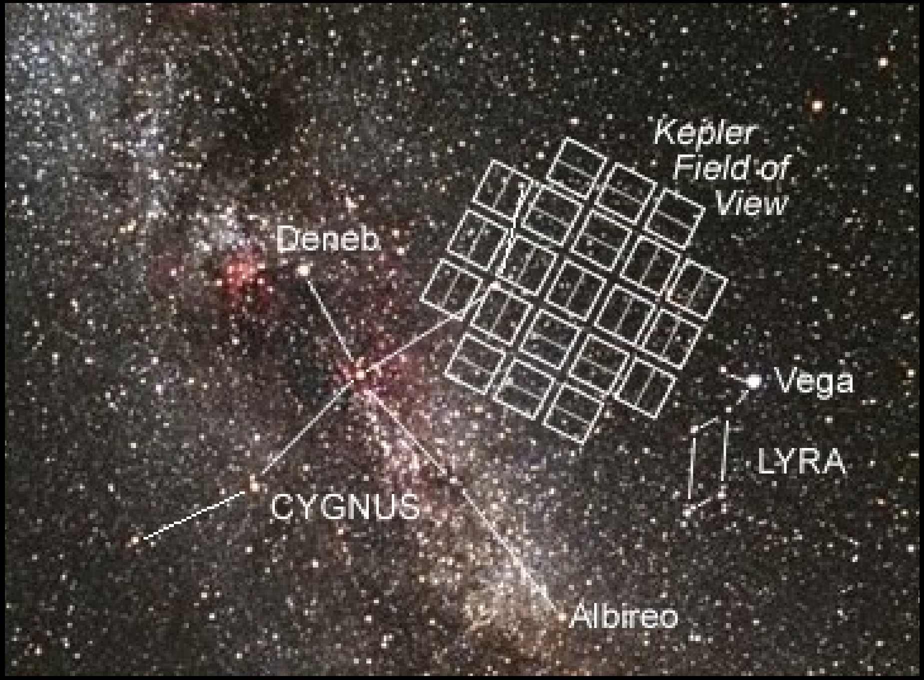
COROT (*COnvection ROtation et Transits planétaires*) operated from 2006 December 27 to 2012 November 2. The project was led by CNES, in cooperation with ESA

Kepler Space Telescope



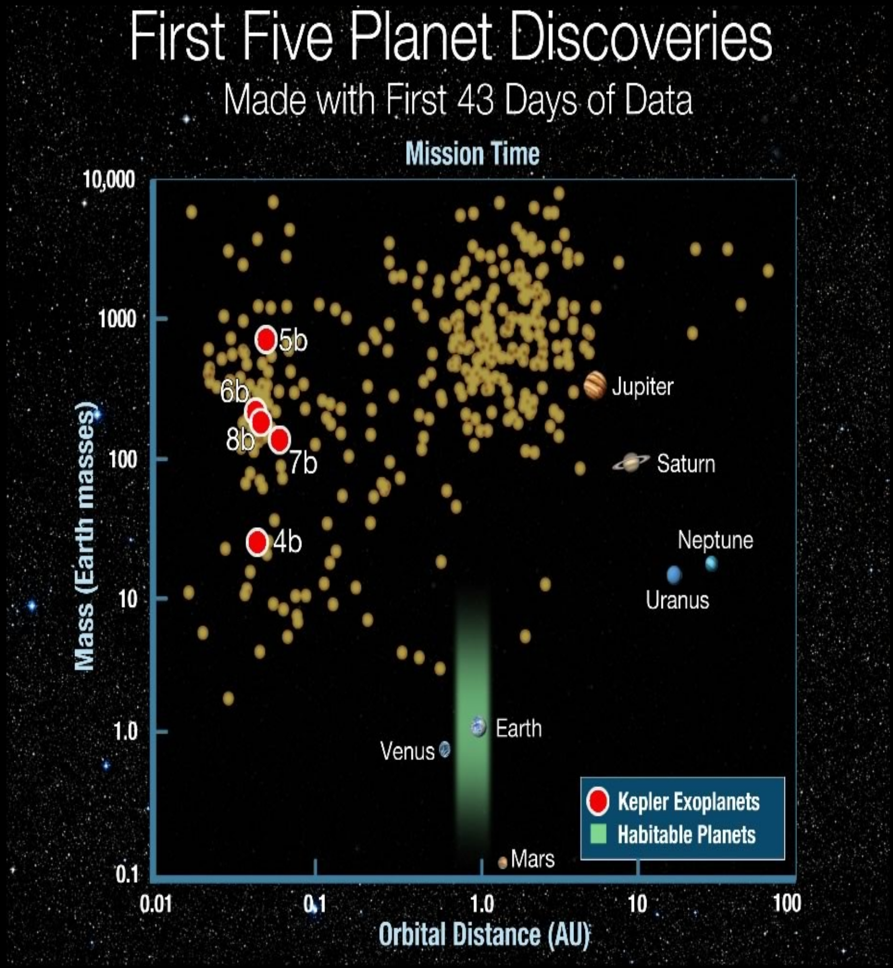
- **Launched in March 2009**

Kepler Space Telescope



- **Launched in March 2009**
- **Pointing sky region in Cygnus**

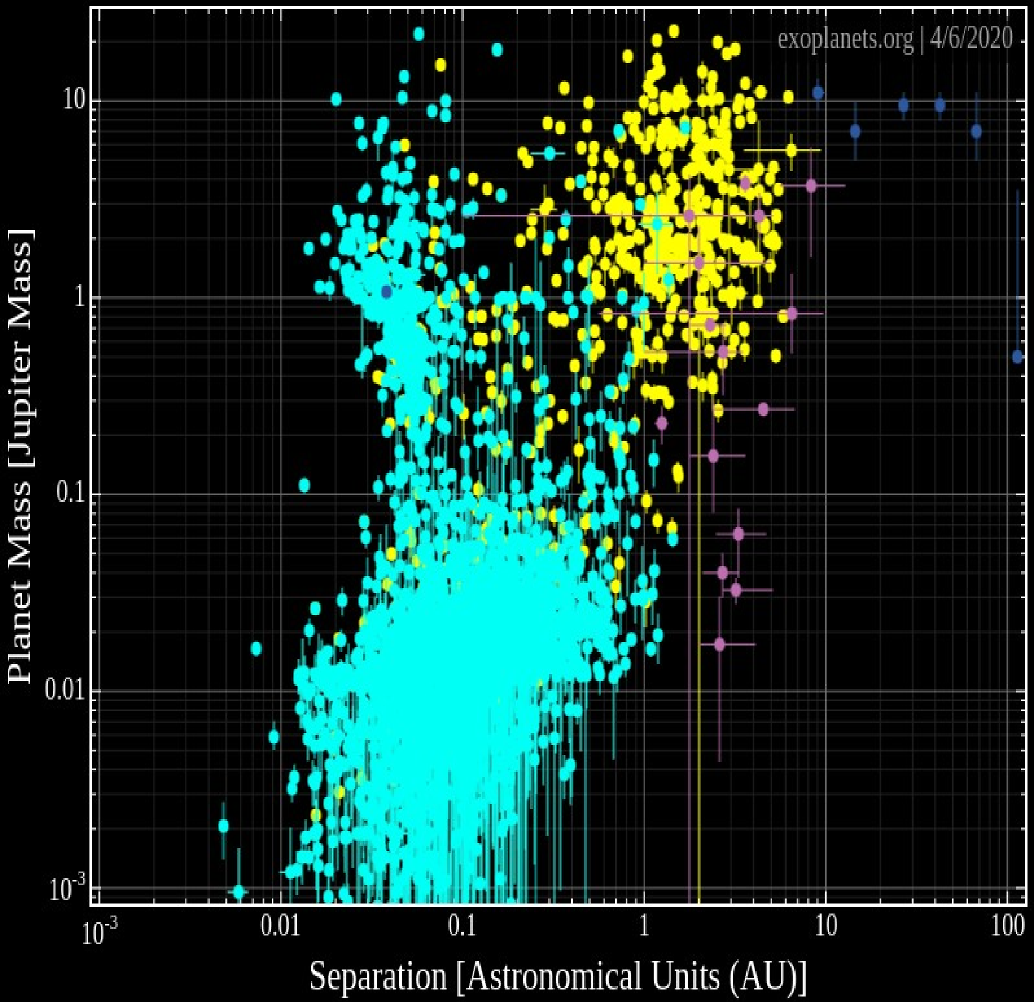
Kepler Space Telescope



- **Launched in March 2009**
- **Pointing sky region in Cygnus**
- **4570 planet candidates (961 confirmed)**
- **Multiple systems (!)**
- **Earth-sized planet candidates (!!)**

Transit vs Radial-Velocity Method

99% of all confirmed planets (~3300) have been discovered with one of these two methods



~18% discovered with **RV** method
~81% discovered with **Transits** method

RV method selects **high mass** planets with relatively small orbits

With **transits**, even **smaller orbits/mass** (less dependent on mass)

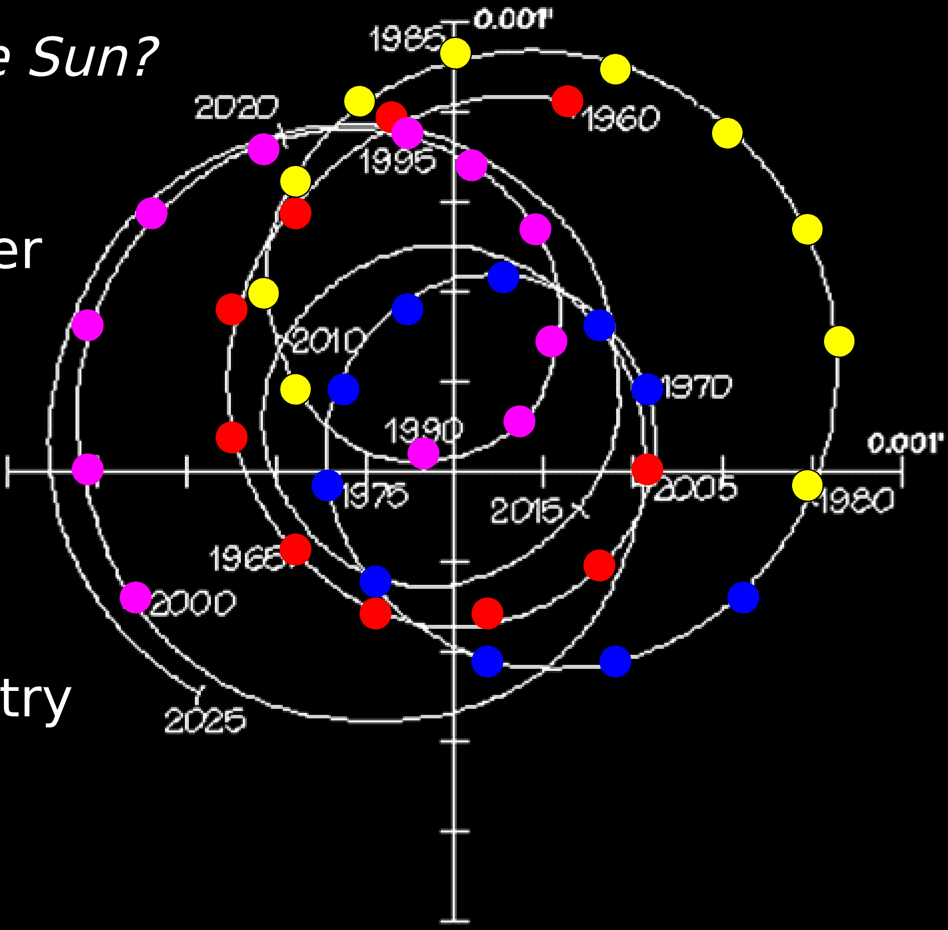
Astrometry

Motion in plane of sky detected in **images of stars** compared to background

Is Jupiter detectable looking at the Sun?

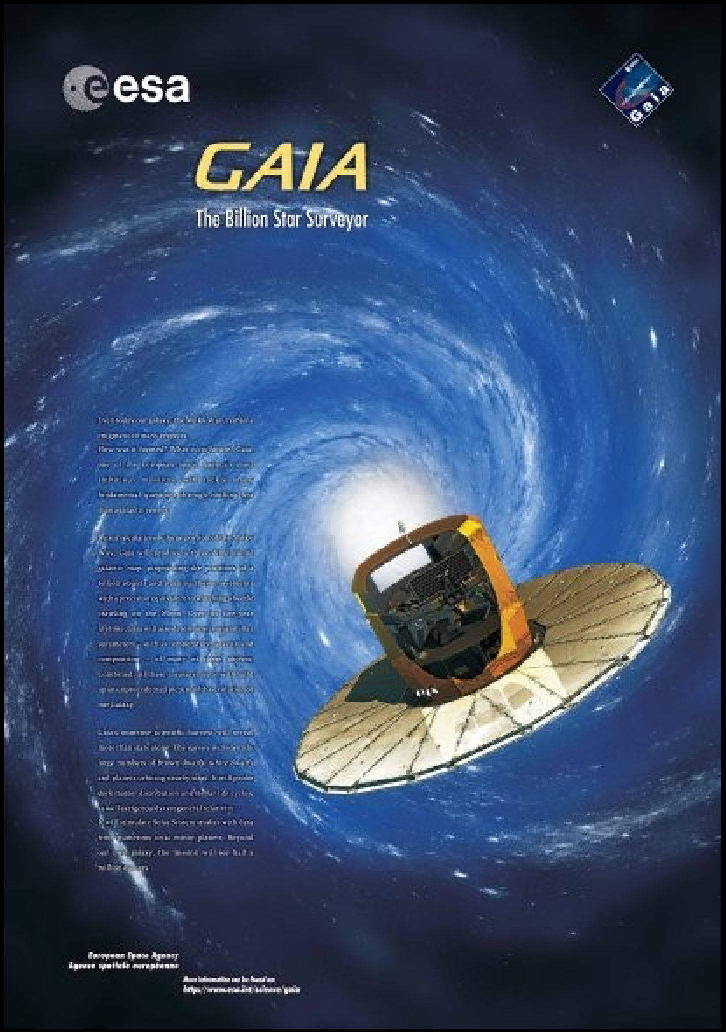
We would not have detected Jupiter around our star using the Radial Velocity Method

We could detect Jupiter if we had been watching using Astrometry



Astrometry

No confirmed planet discoveries yet, but will be soon possible with GAIA (ESA, μ−arcsec astrometry)



GAIA aims to construct by far the largest and most precise 3D space catalog ever made, totalling approximately 1 billion astronomical objects (1% of MW stars)

Combining Astrometry and Radial Velocity methods

⇒ orbit **inclination**

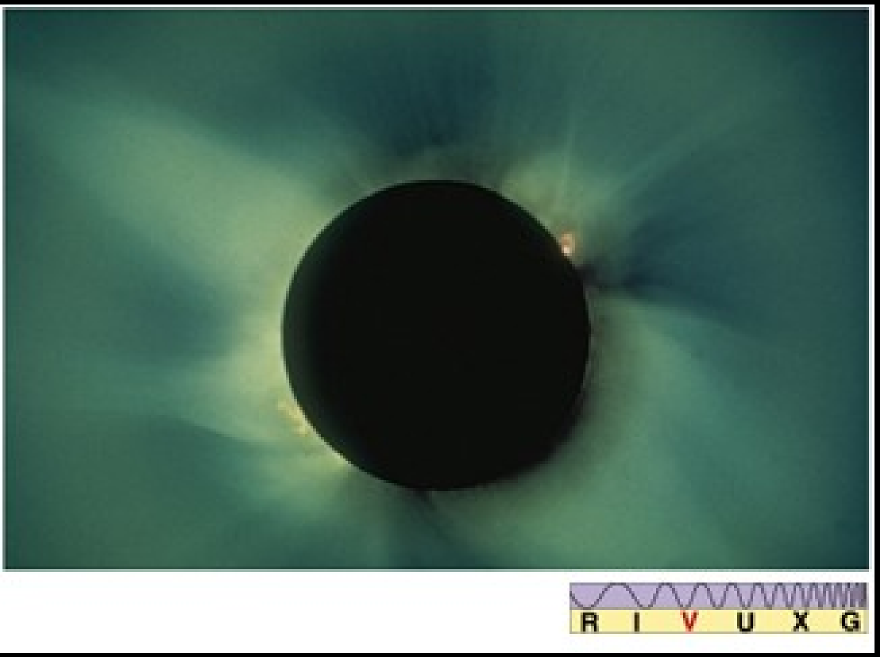
⇒ planet **mass**

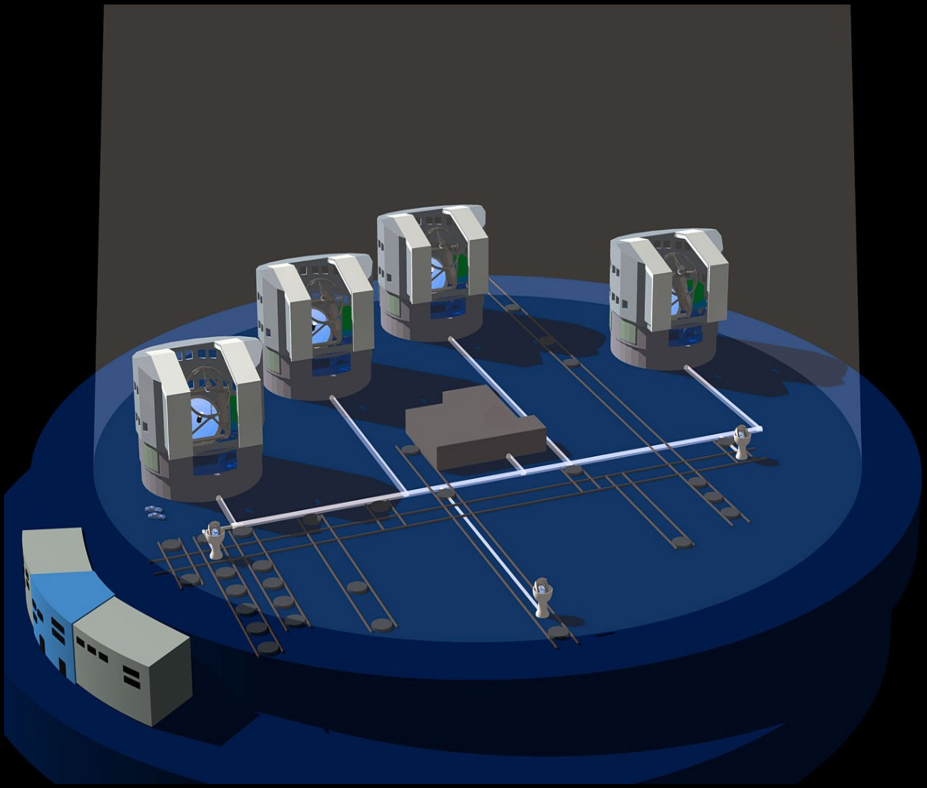
~8000 (massive) planets should be discovered by GAIA

Imaging Method

Interferometery and Adaptive Optics (AO) nulling the star light

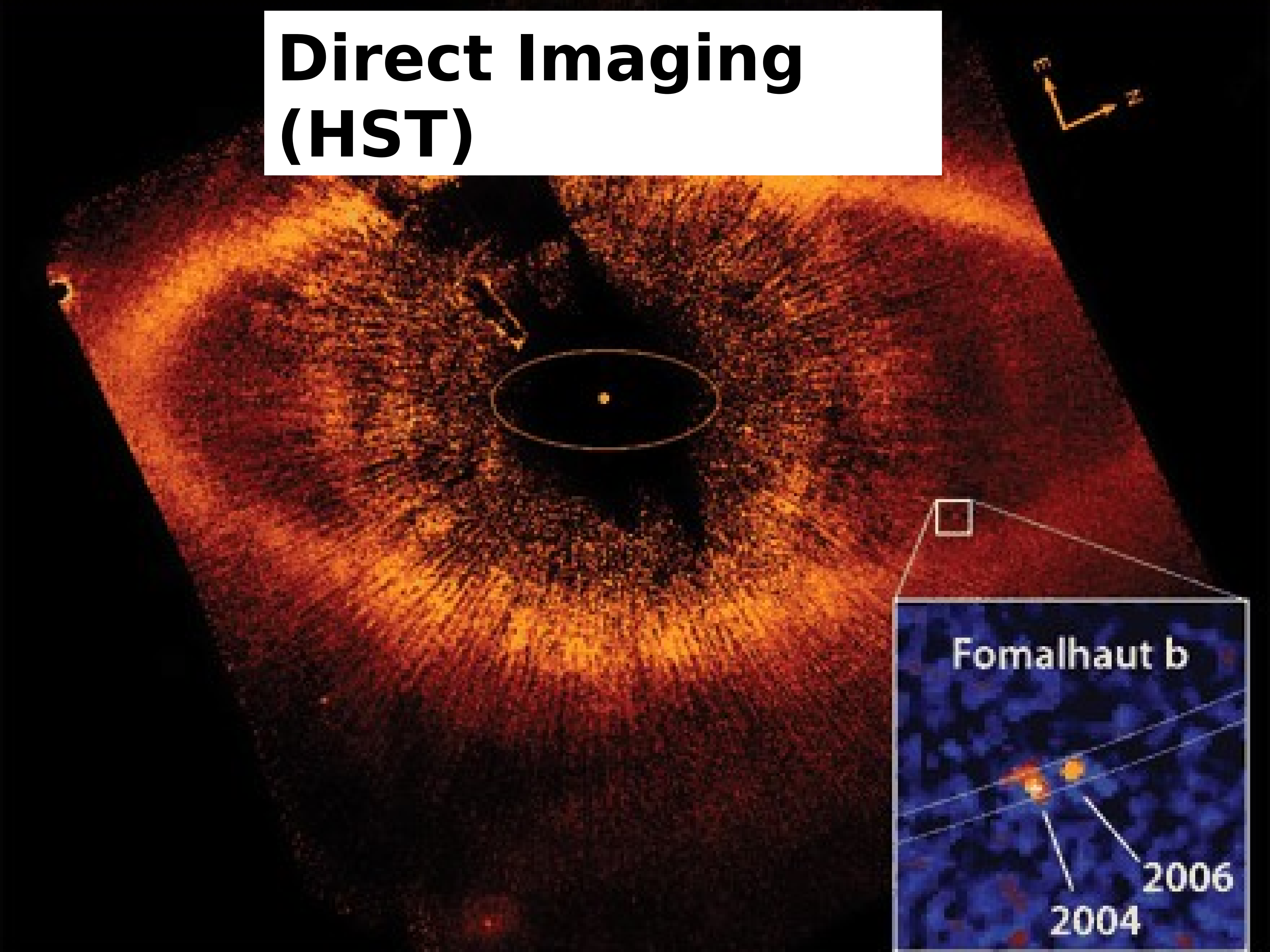
The star can be blocked out using a **coronagraph**





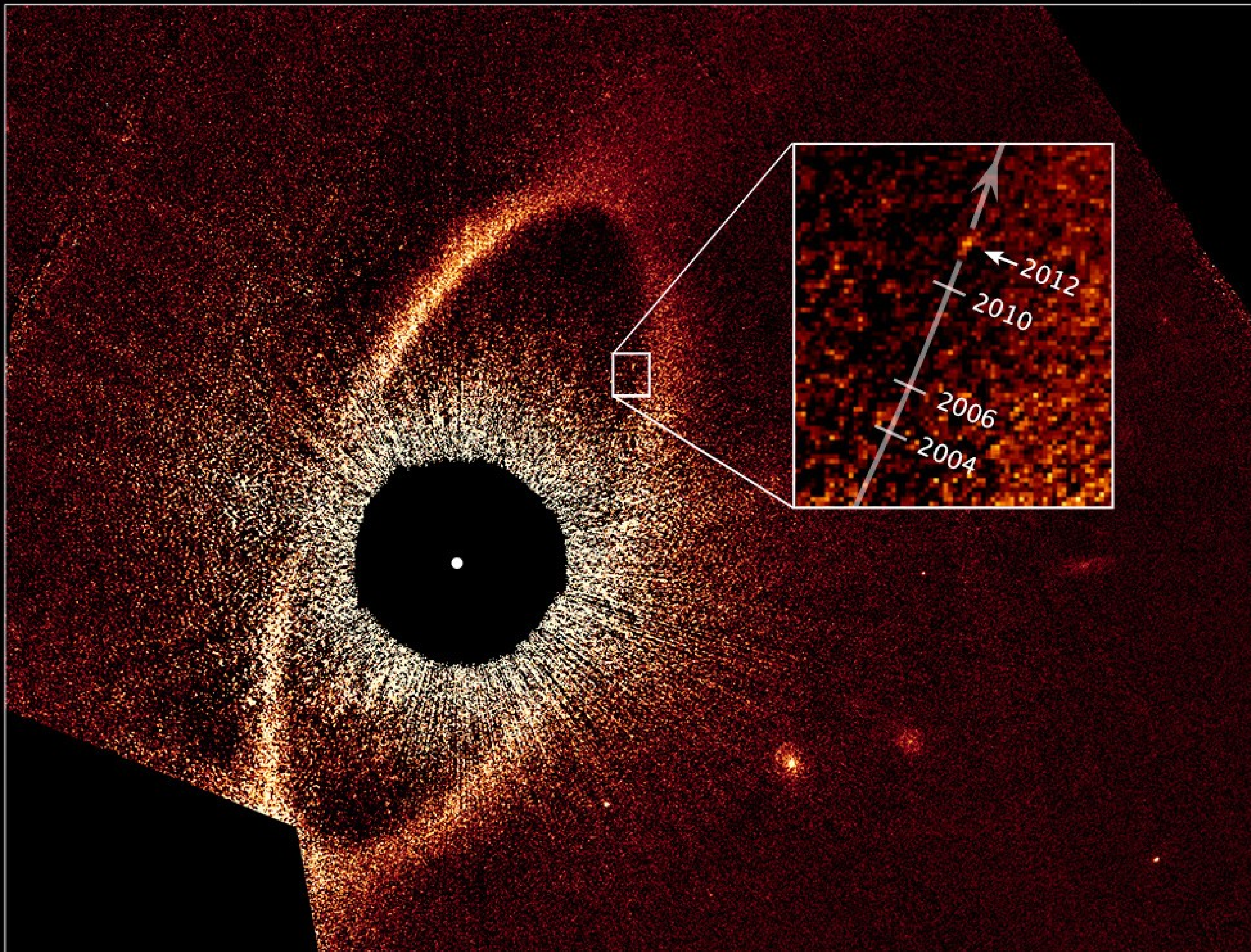
Now we can do it with **interferometers** (with excellent **spatial resolution** as a bonus!)

Direct Imaging (HST)



Fomalhaut System

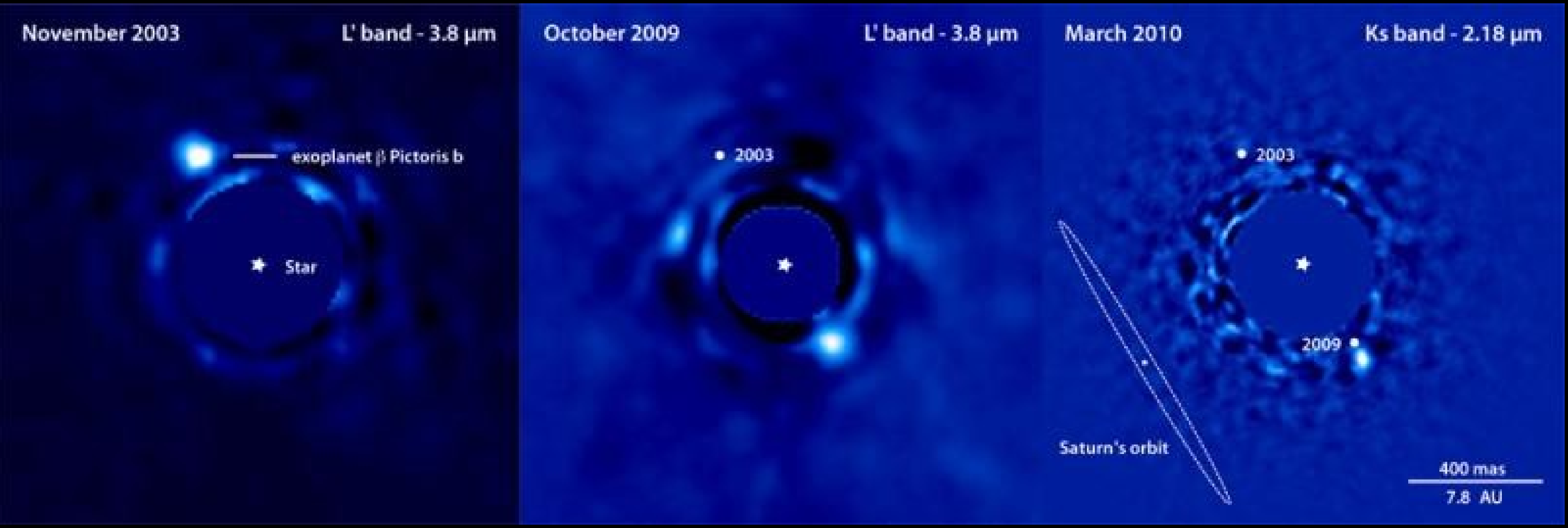
Hubble Space Telescope • STIS



NASA and ESA

STScI-PRC13-01a

Beta Pictoris b imaged with VLT, NaCo (infrared)

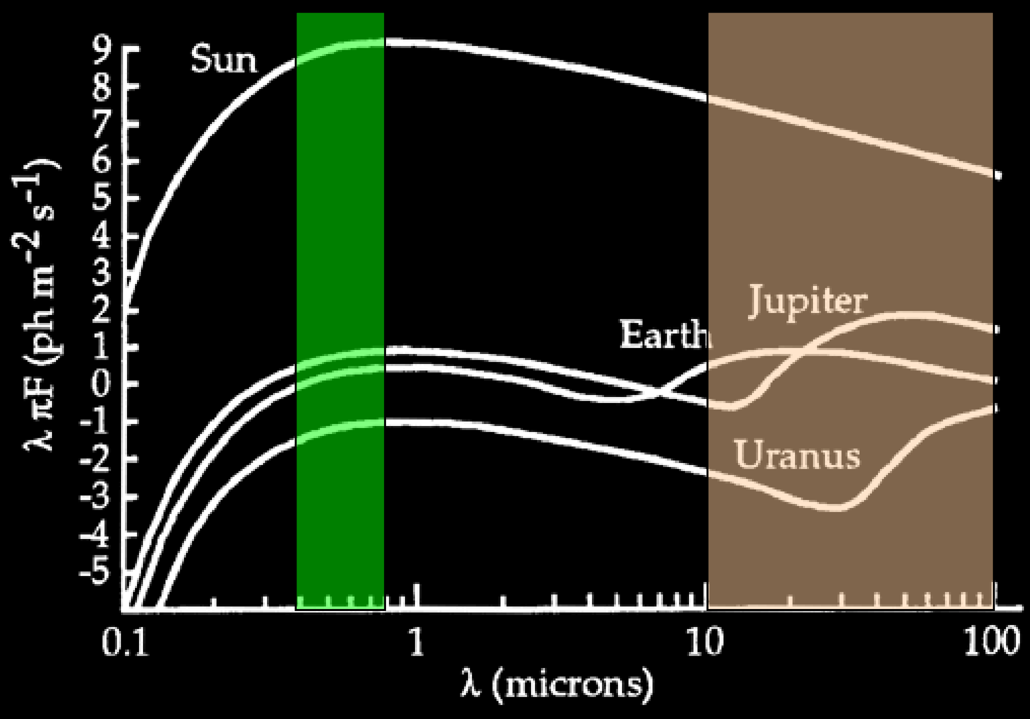


M ≈ 10 Jupiter masses; T ≈ 1500° C

Imaging Method

(Imaging of Reflected/Reprocessed Starlight)

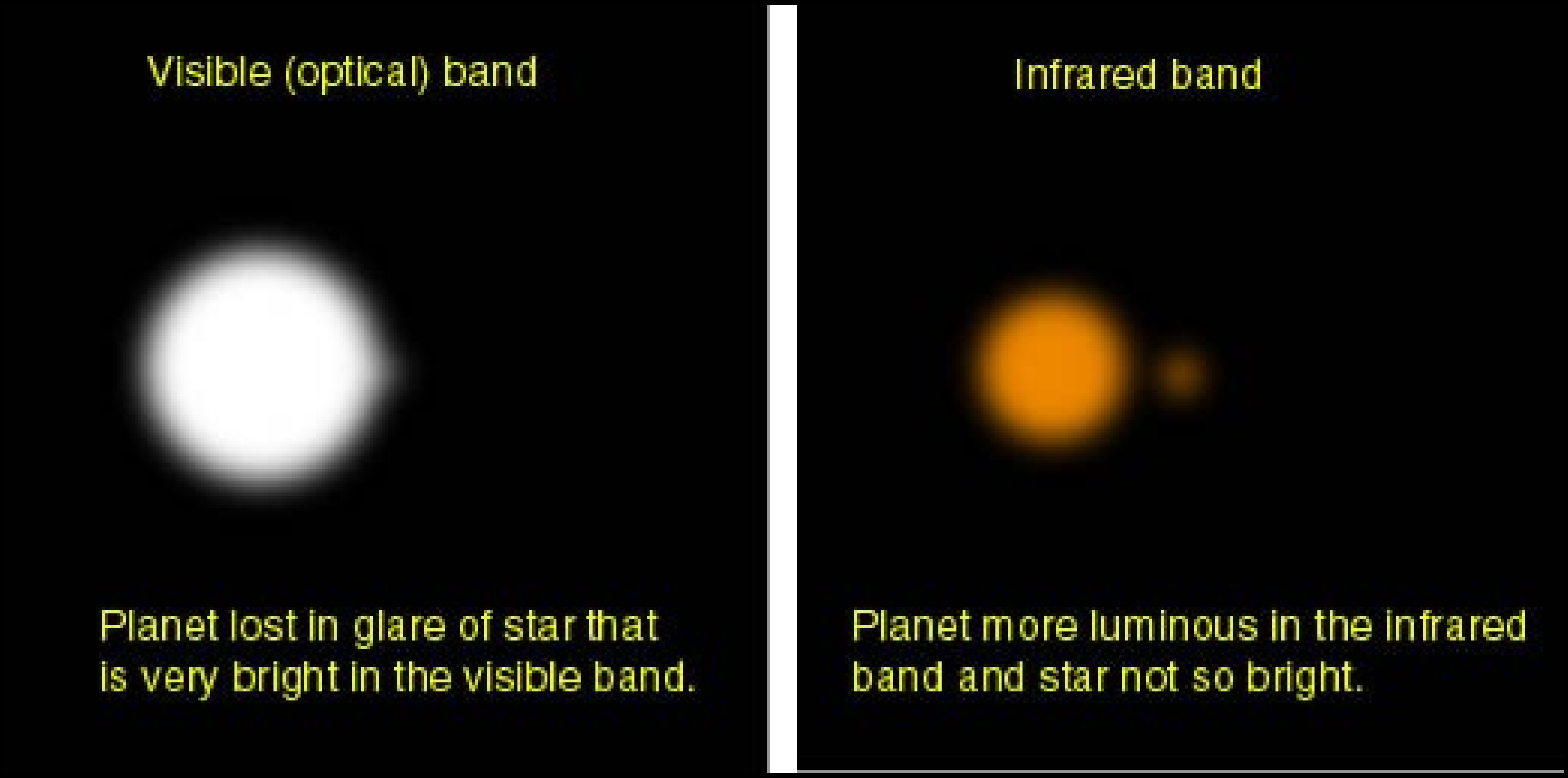
<u>Optical</u>: star/planet = 1 billion = 10^9 <u>Infrared</u>: star/planet = 1 million = 10^6



We need to search in the infrared and to lock out the star!

Imaging Method

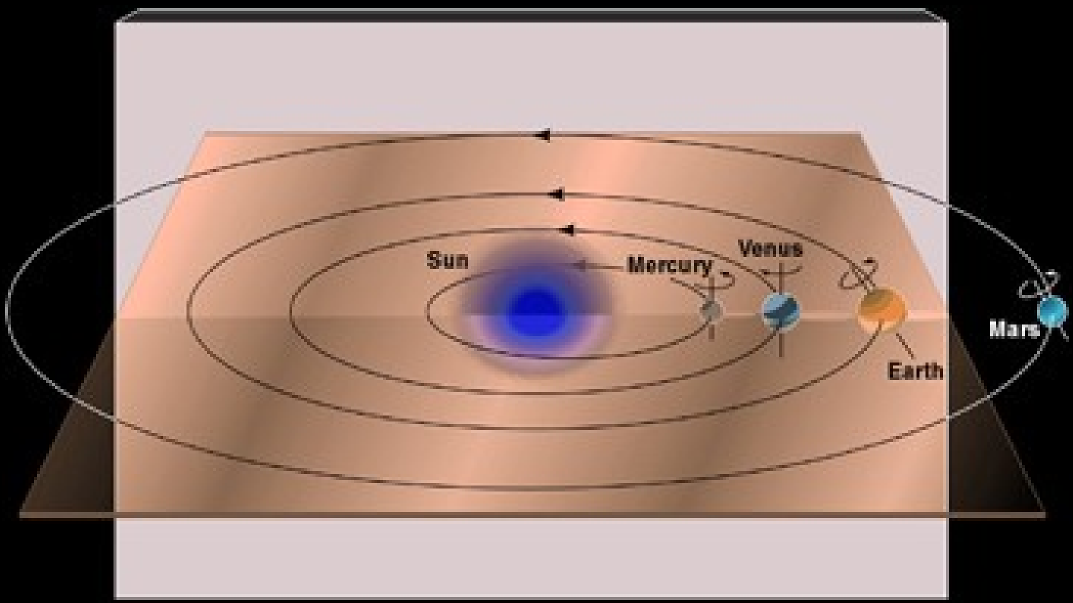
(Imaging of Reflected/Reprocessed Starlight)



PLANETARY SYSTEMS ALIGN IN A PLANE

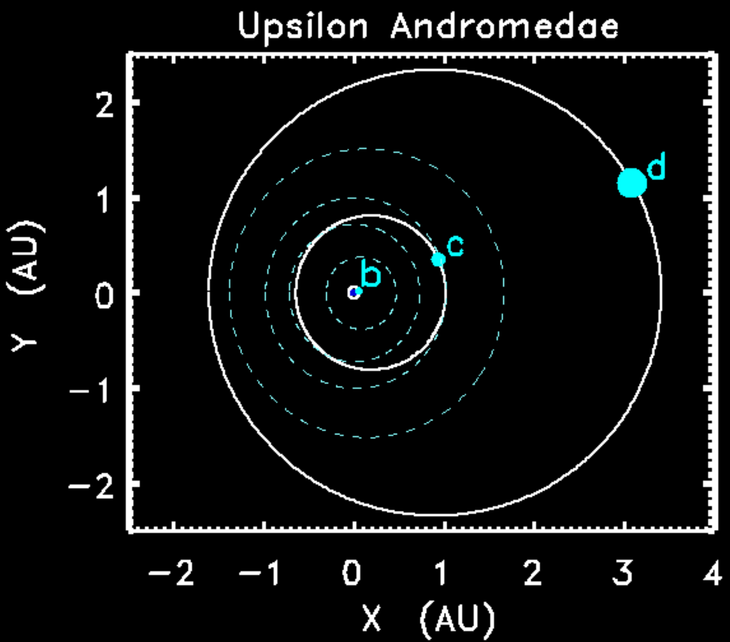
The inclination of a planetary system can range from **edge on** to **face on**

edge-on = high inclination



Radial Velocity and **Transit** methods

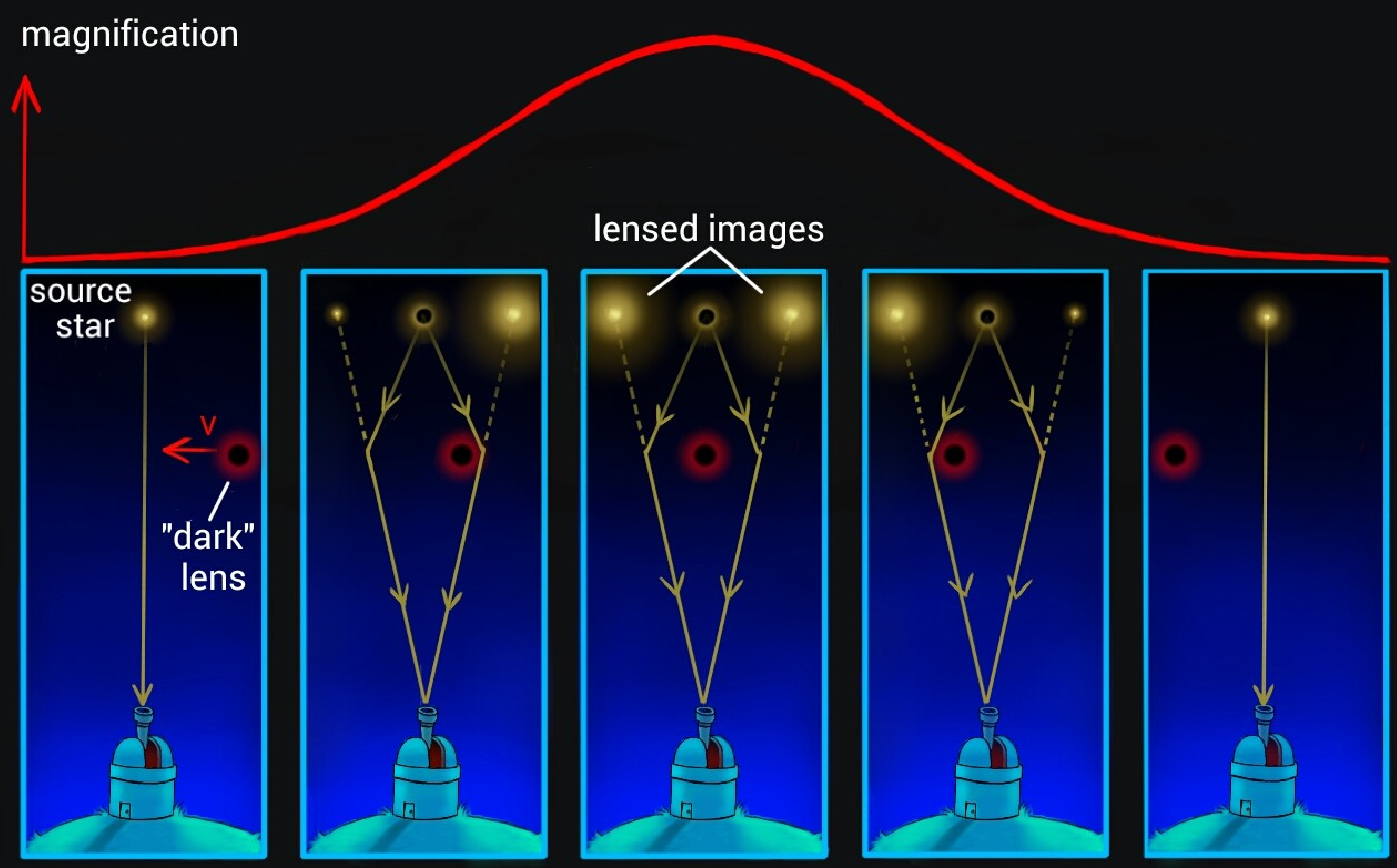
face-on = low inclination



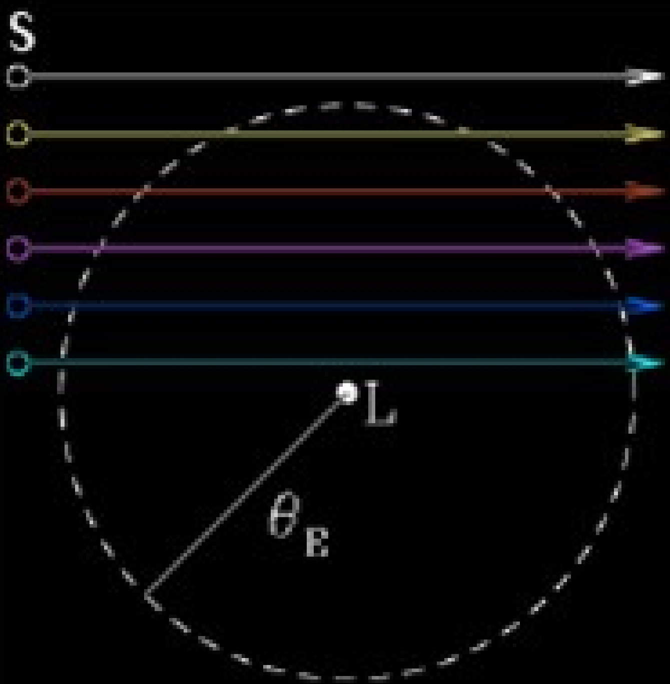
Astrometry and **imaging** methods

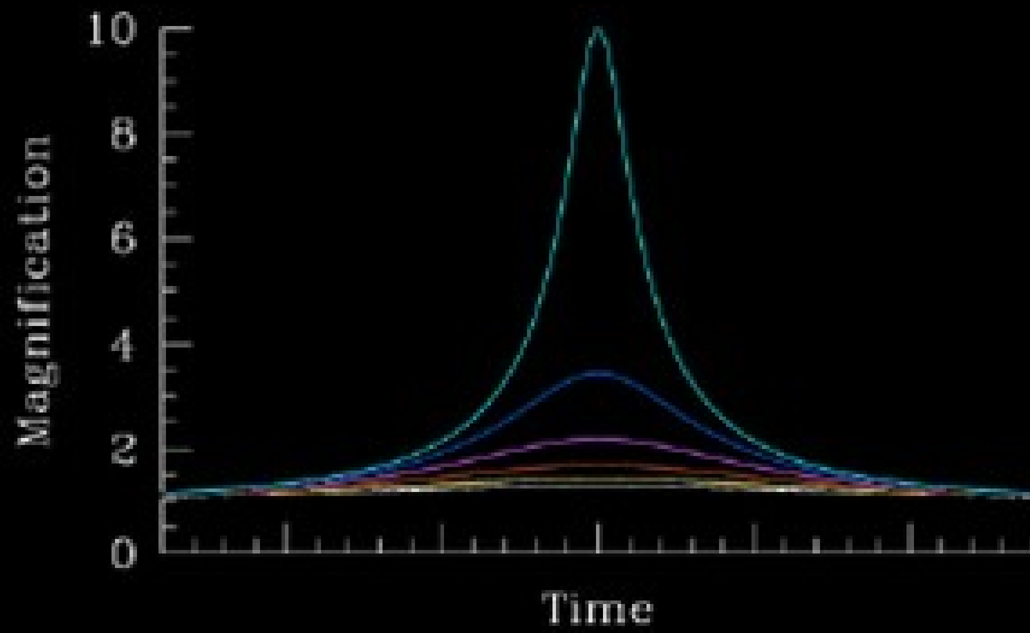
Microlensing method does not depend on orbital inclination

MICROLENSING METHOD



Microlensing





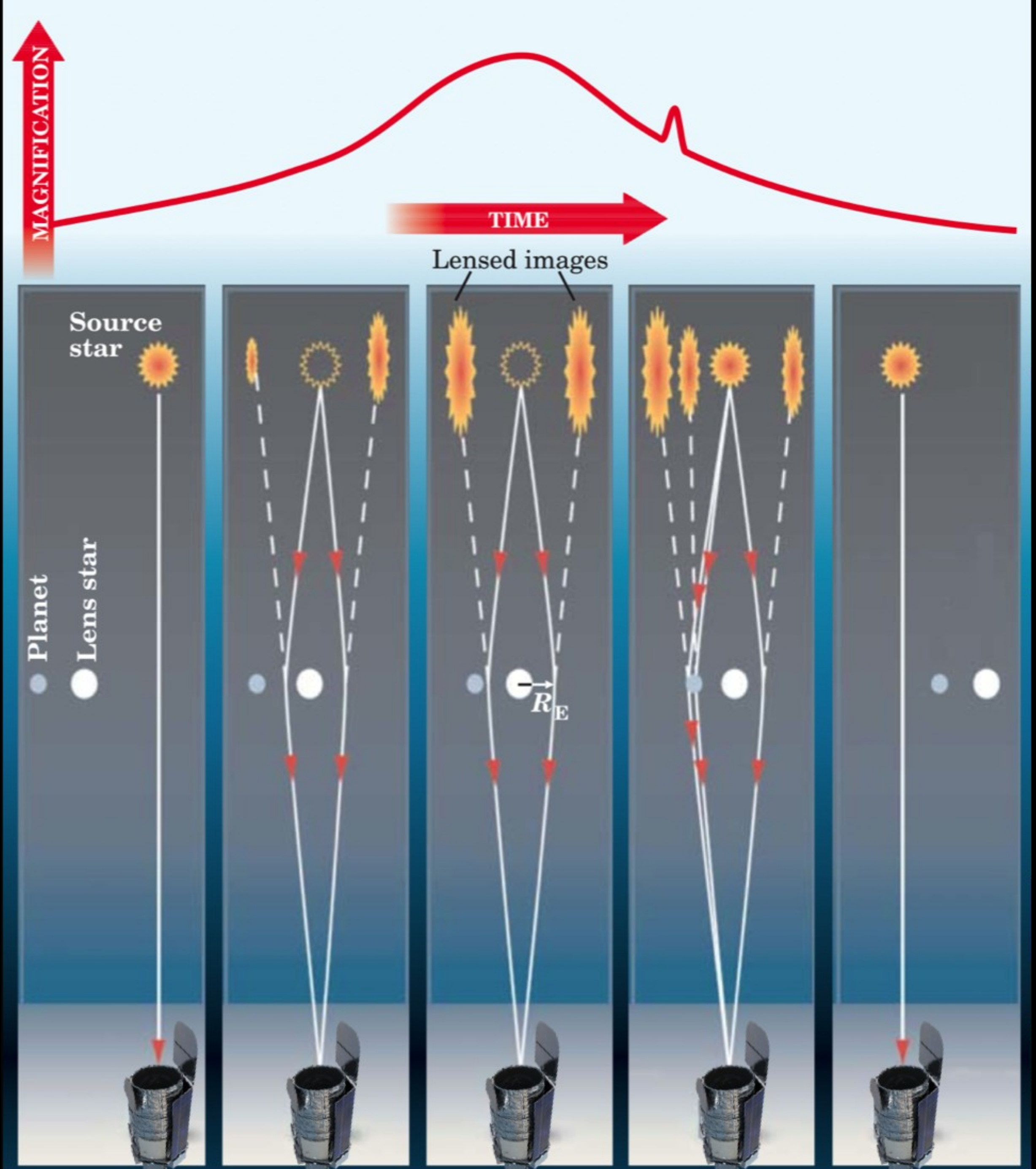
S … source object
L … lens object
θ_E … Einstein ring radius

$$\theta_E = \left(\frac{4GM}{c^2} \frac{d_{LS}}{d_L d_S} \right)^{1/2}$$

if source much further away than lens $(d_{LS} \approx d_S)$

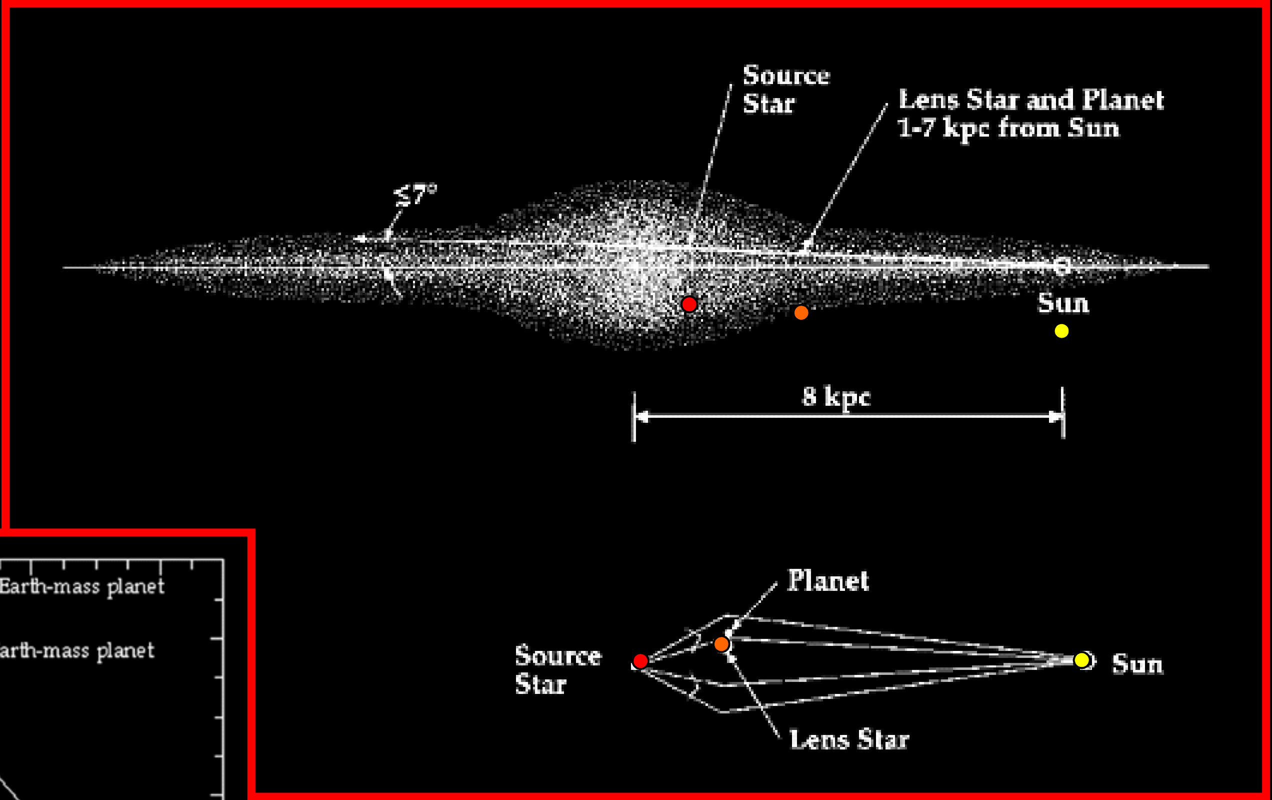
$$\theta_E \approx 0.1 \left(\frac{M \text{ in } M_\odot}{d_L \text{ in parsecs}} \right)^{1/2} \text{ arcsec}$$

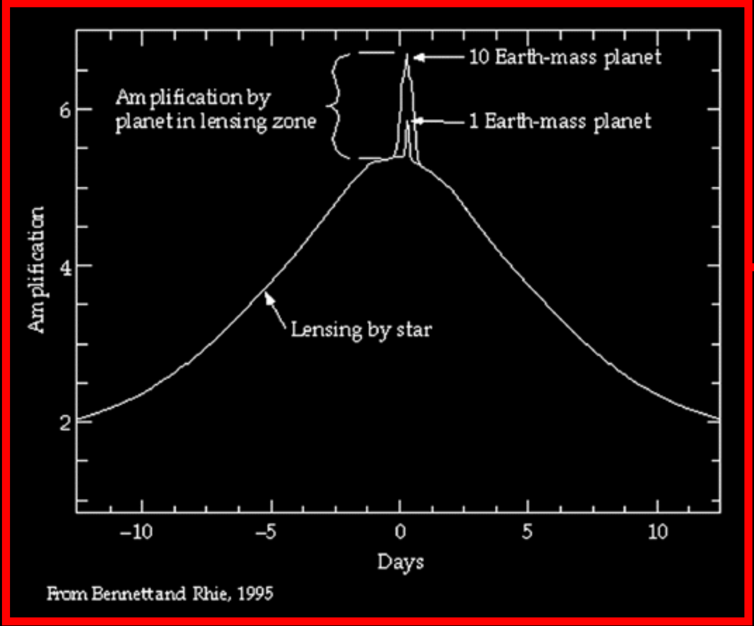
for galaxy with $10^{15} M_\odot$ at 1 Gpc, $\theta_E \approx 100$ arcsec,
for star with 1 $M_\odot$ at 1 kpc, $\theta_E \approx 3$ milliarcsec


MAGNIFICATION
TIME
Lensed images
Source star
Planet
Lens star
R_E

Microlensing

(Quick Brightness Spikes Due to Gravitational Lensing of Background Stars)

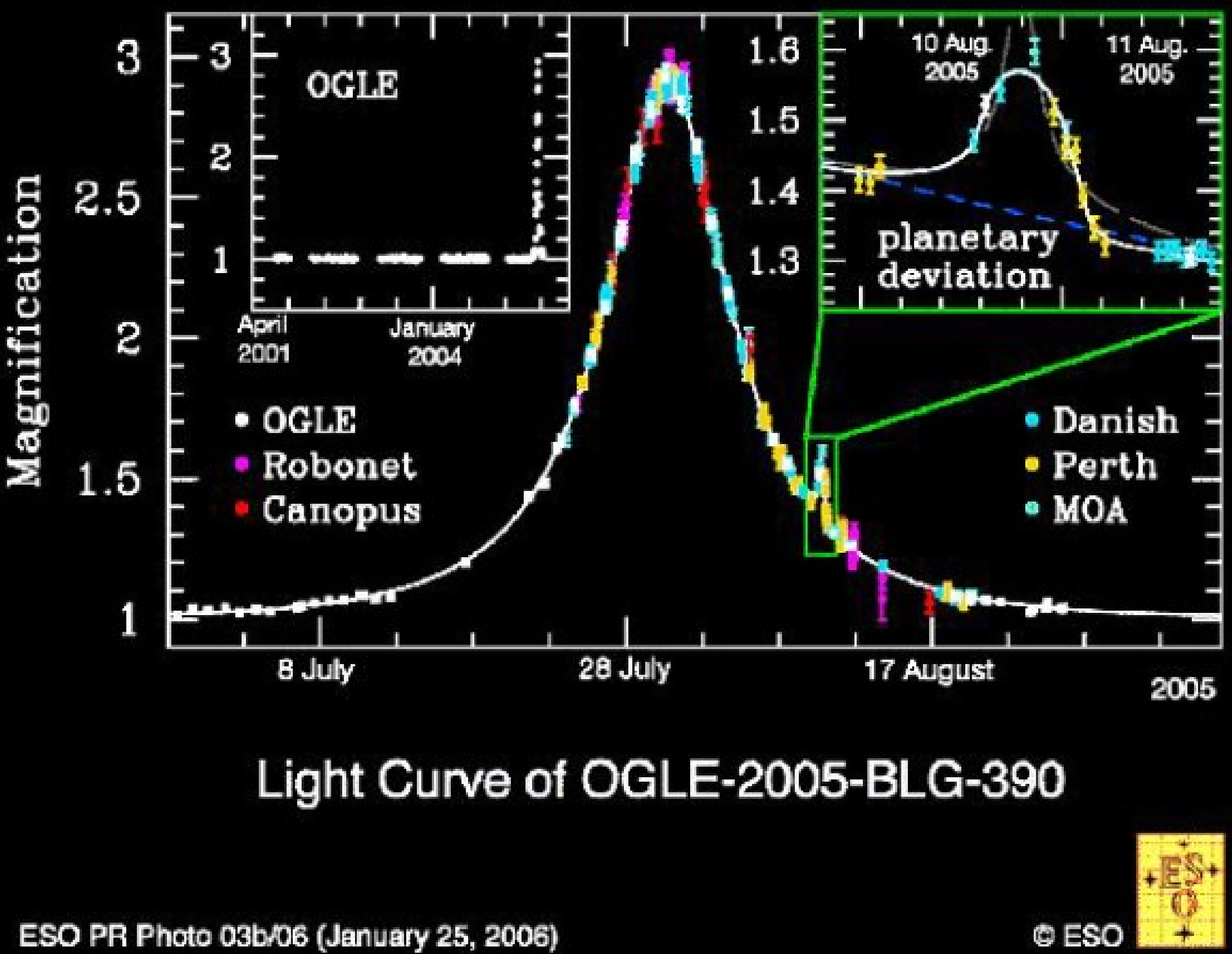




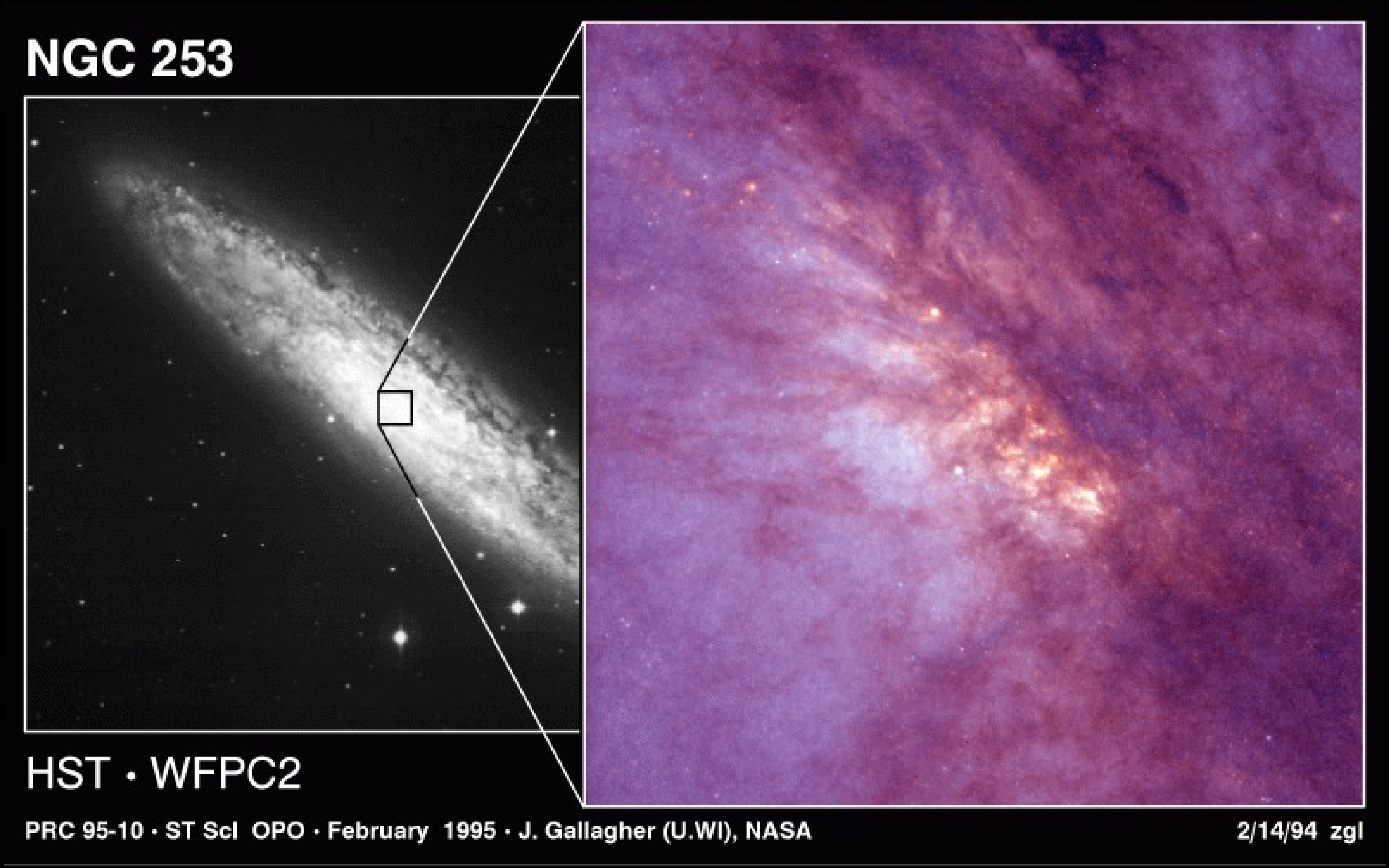
Pros: All masses and orbits and independent of star brightness

Cons: Distant planets and observation cannot be repeated

Earth mass planet detected with microlensing

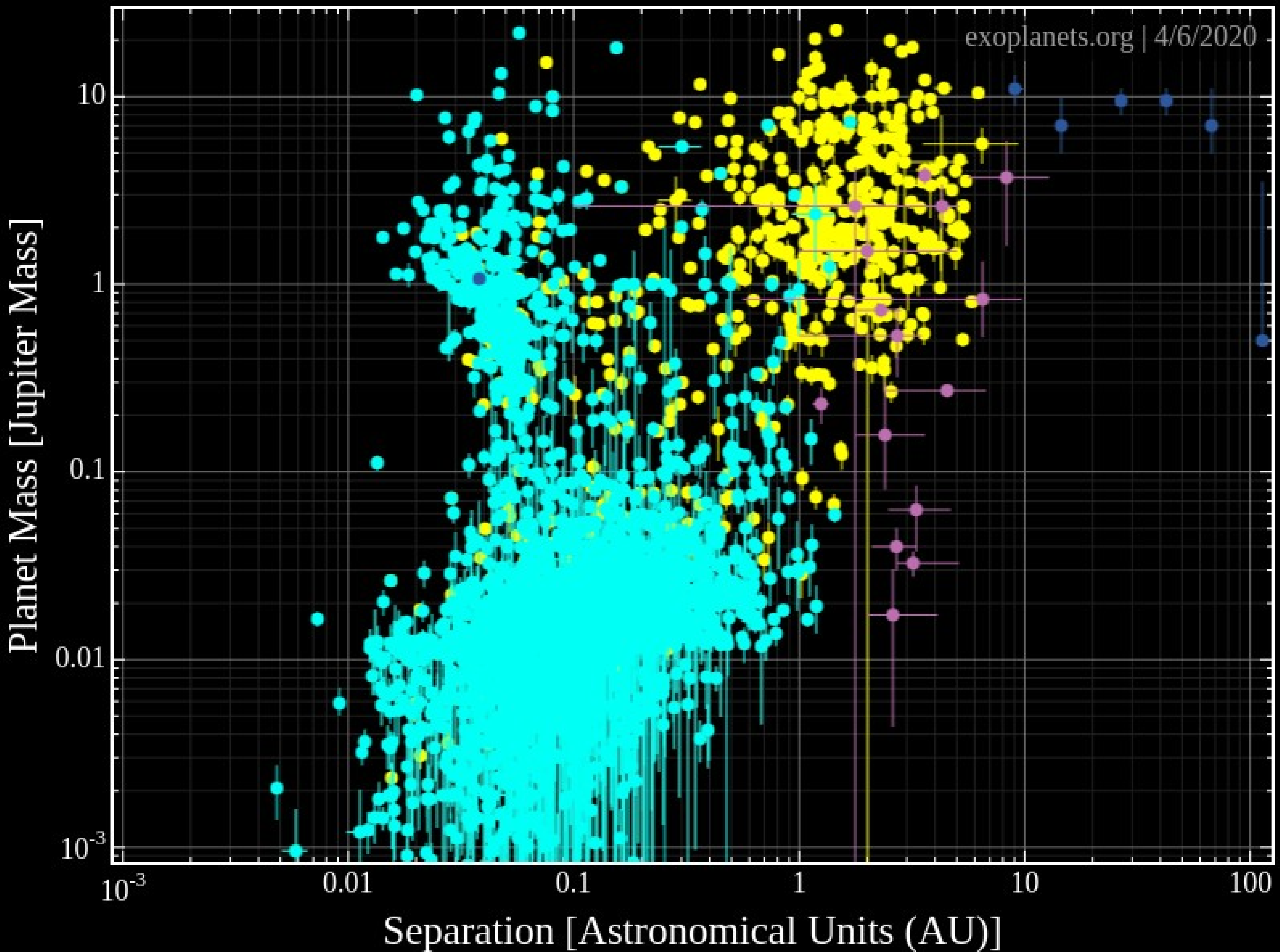


MICROLENSING METHOD

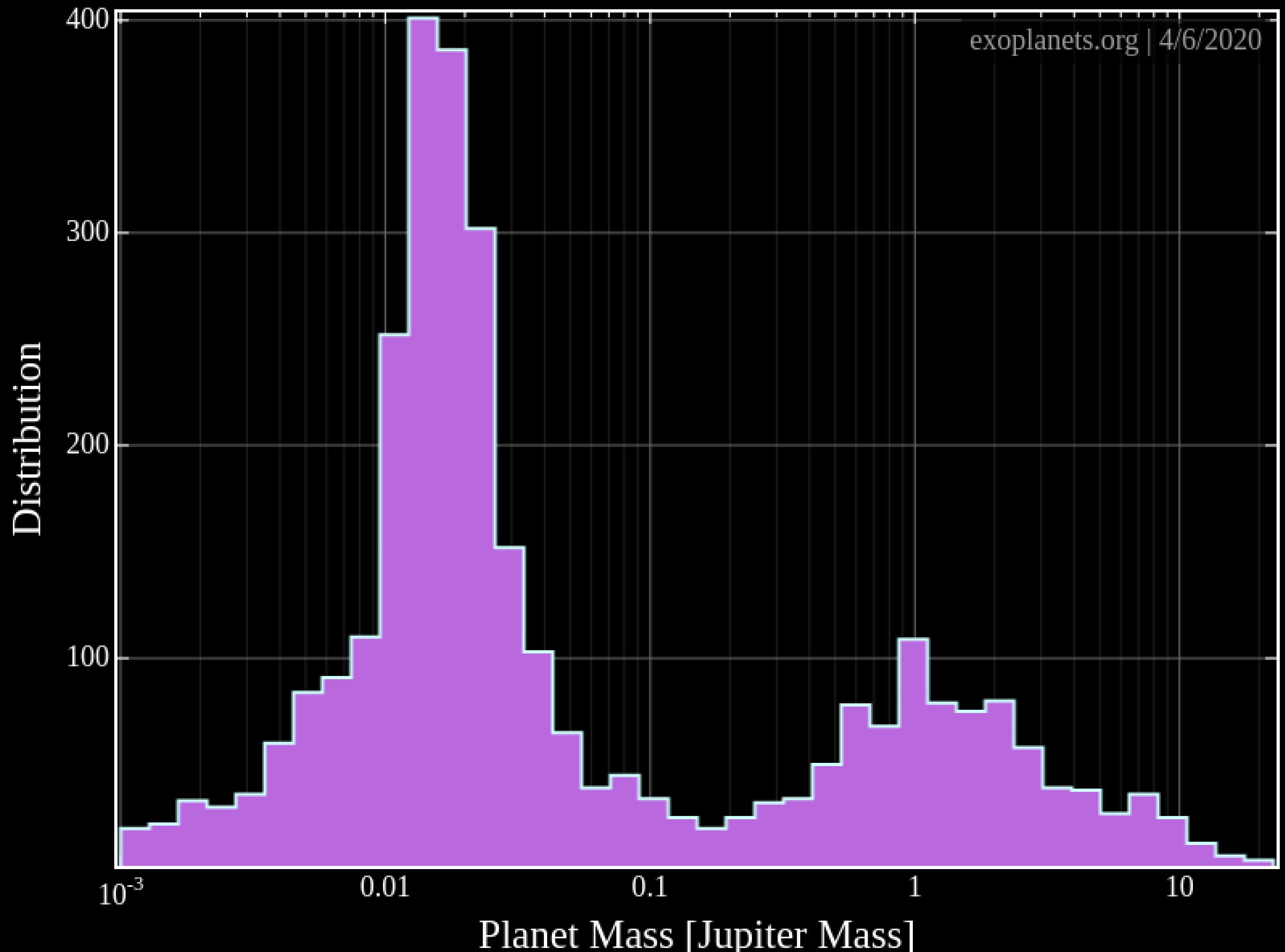


In the future, one can do this in external galaxies!

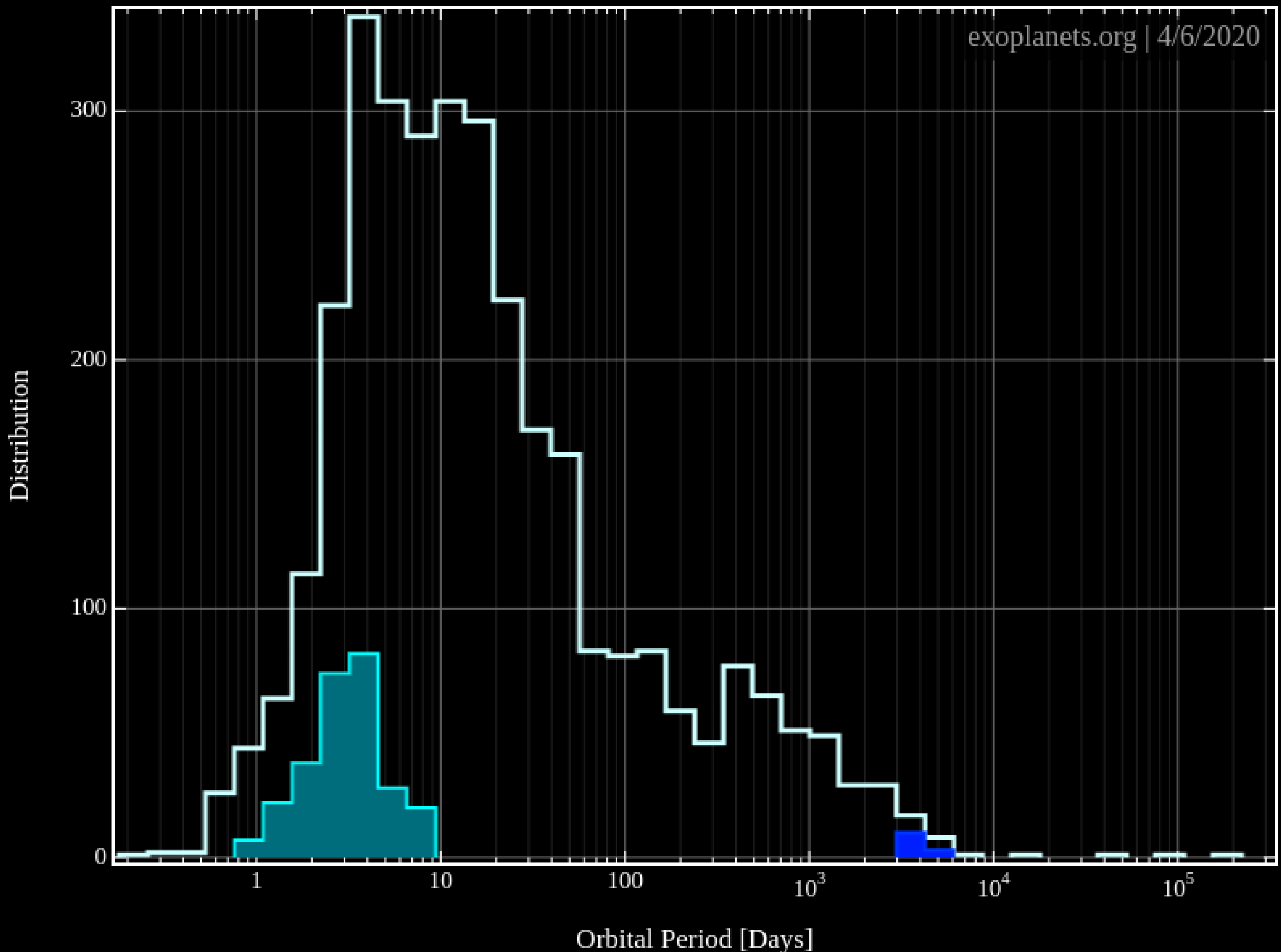
Mass vs Separation



Planetary Masses

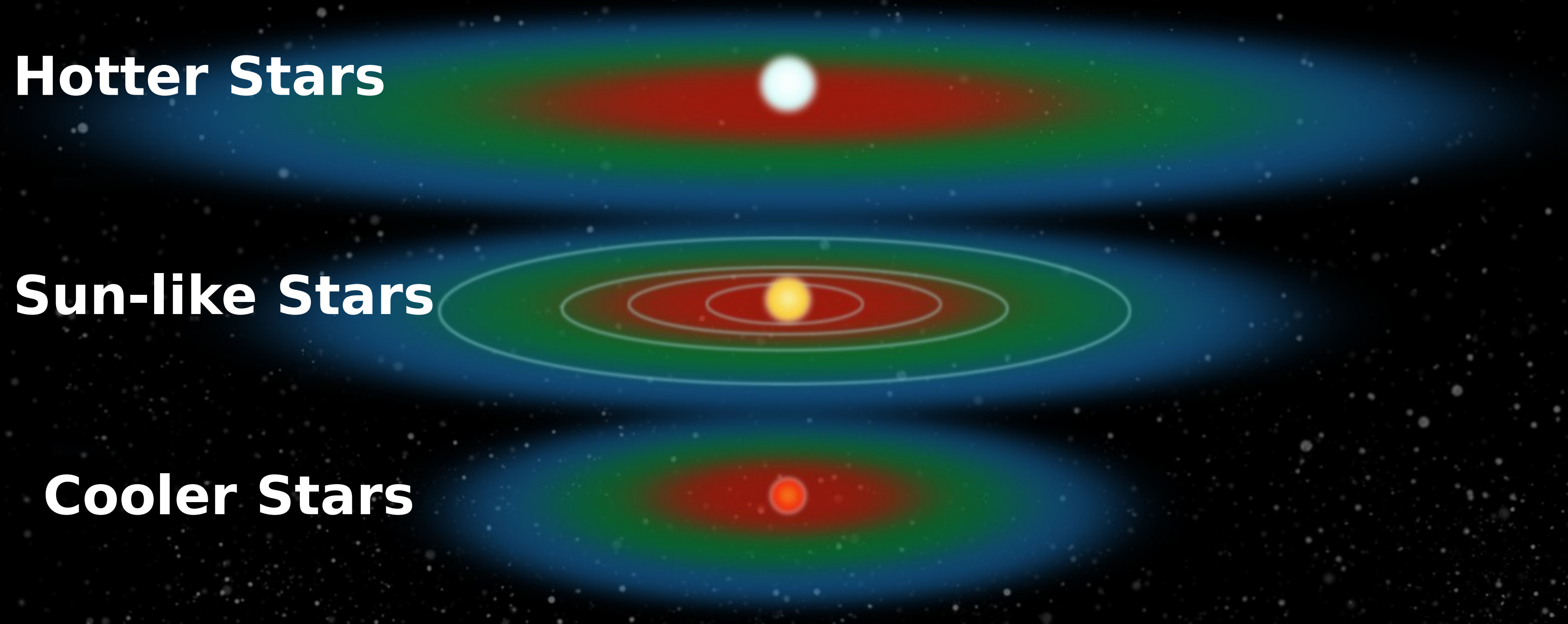


Jupiter-like planets and Hot Jupiters

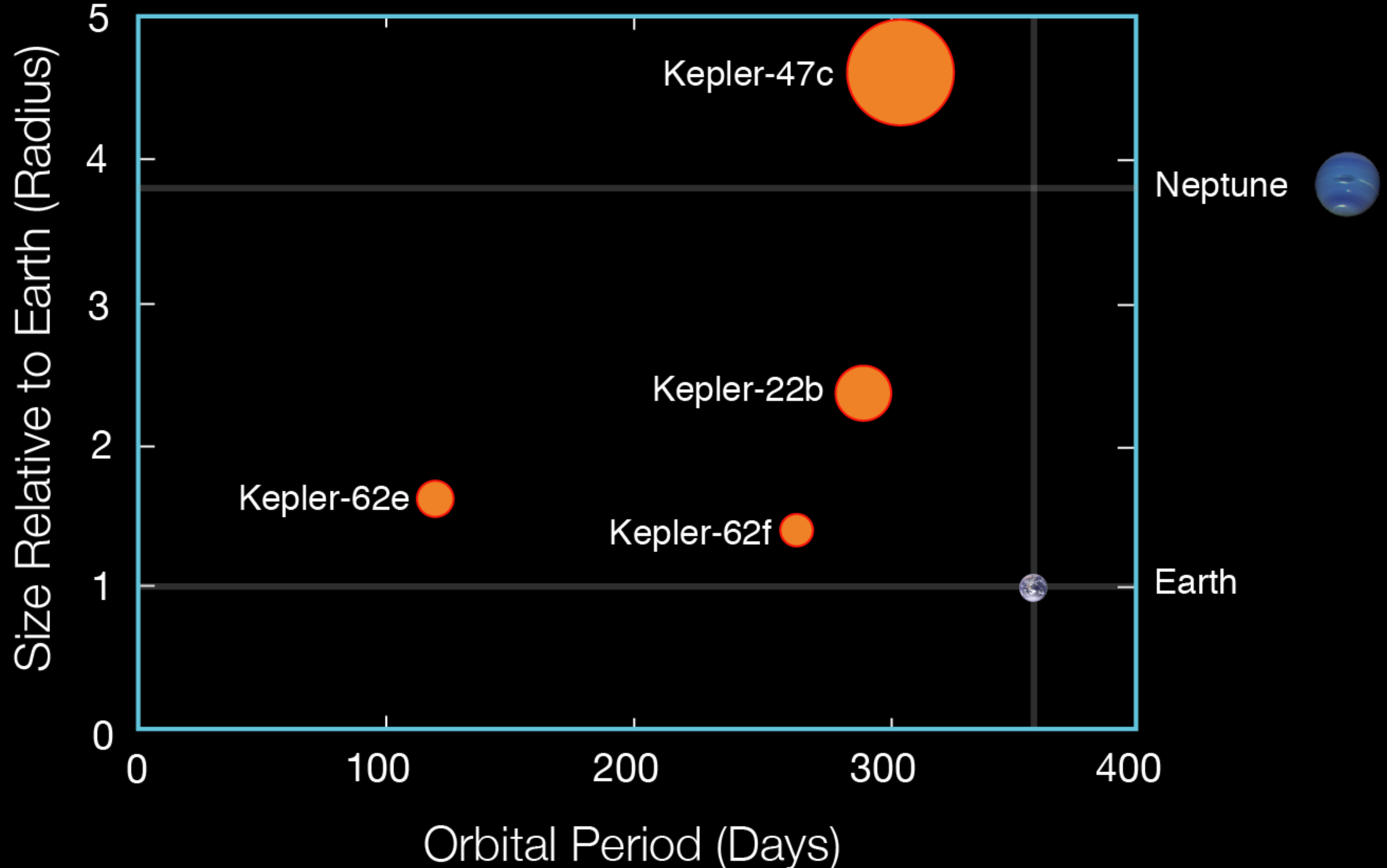


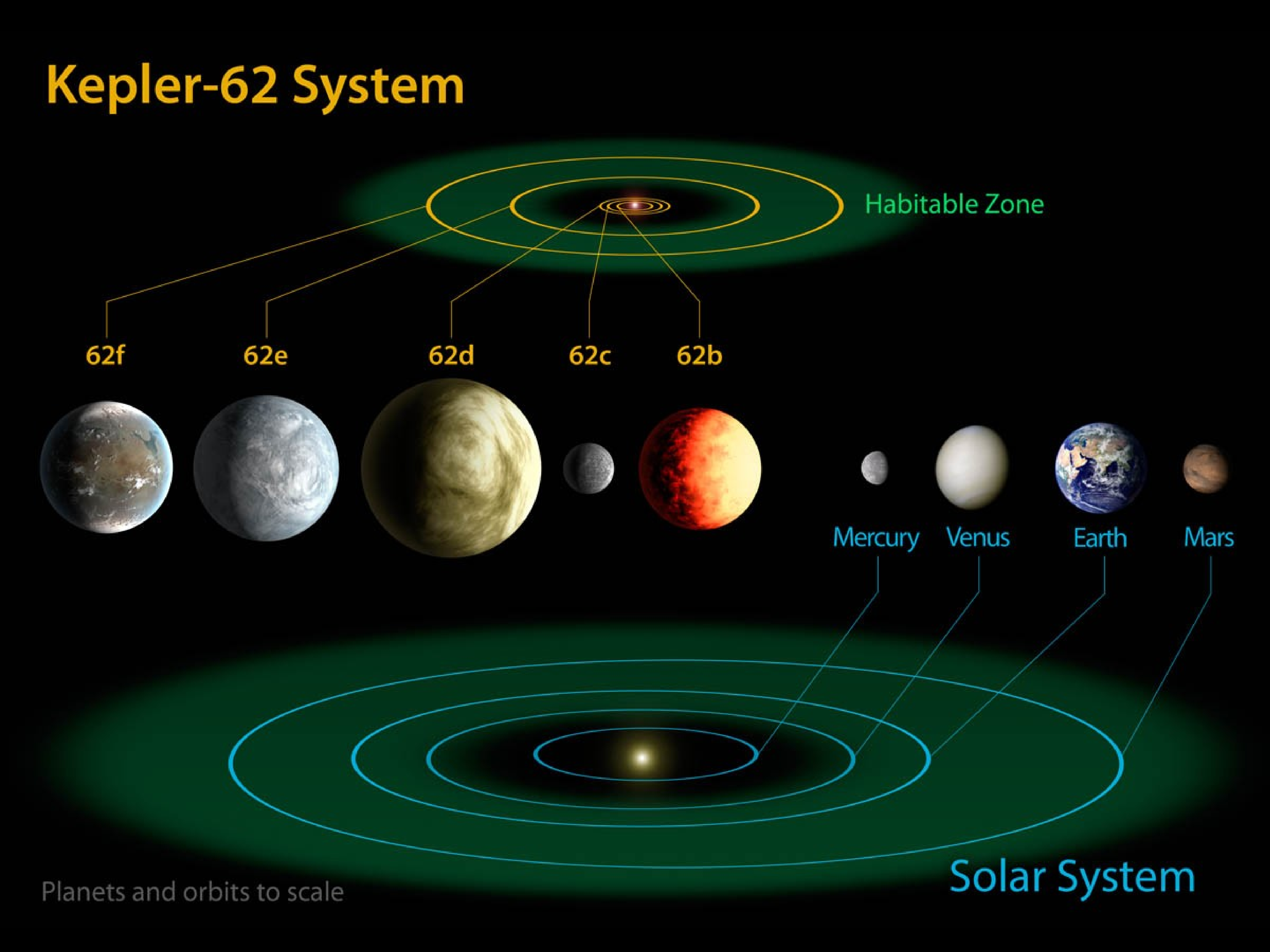
The Habitable Zone

(where water is liquid)



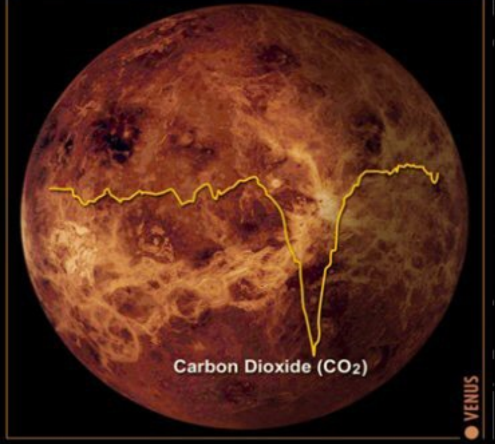
Kepler's Habitable Zone Planets

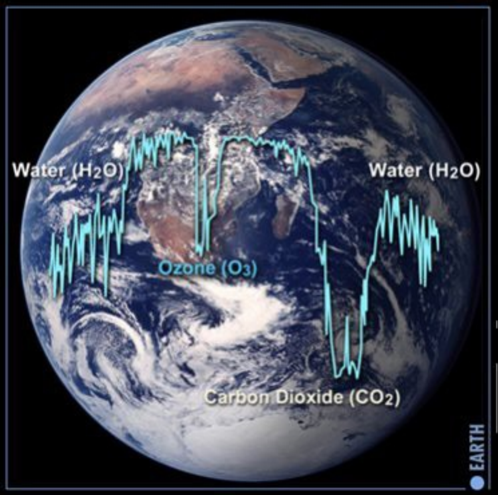


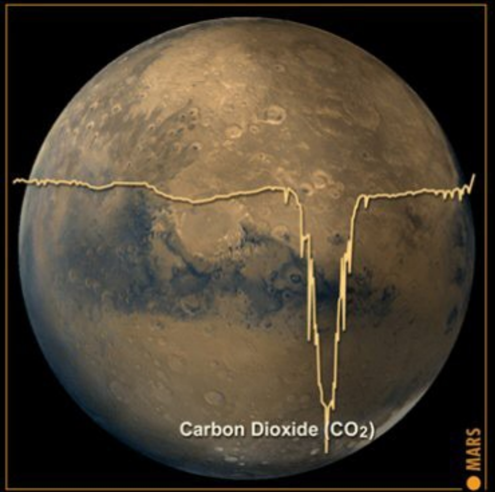

Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

Exoplanets Spectroscopy

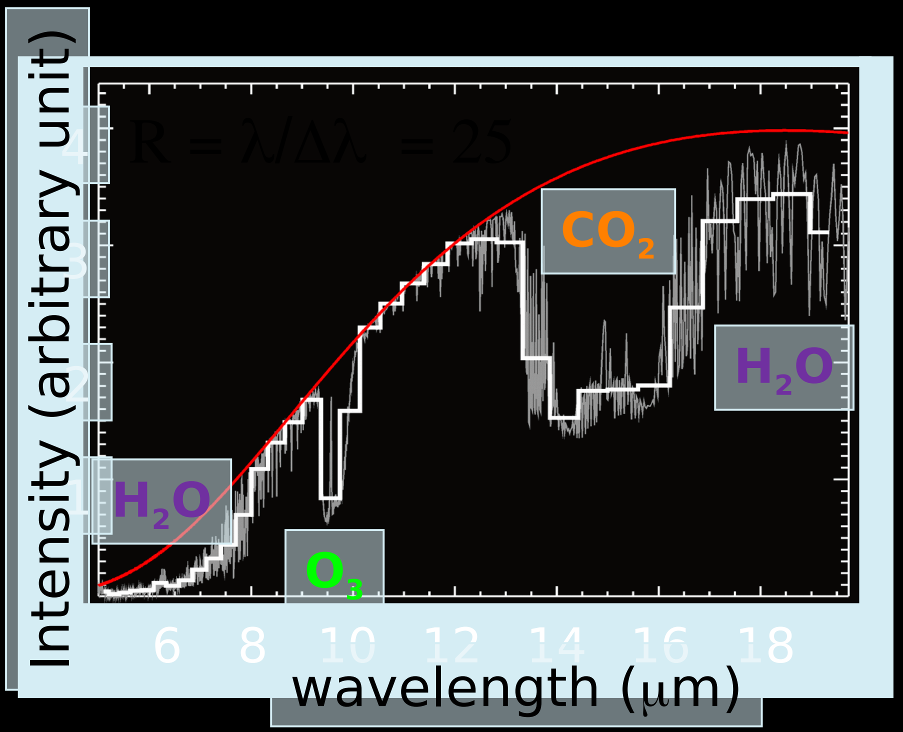
To look for key molecules







$\{CO_2 + H_2O + O_3\}$

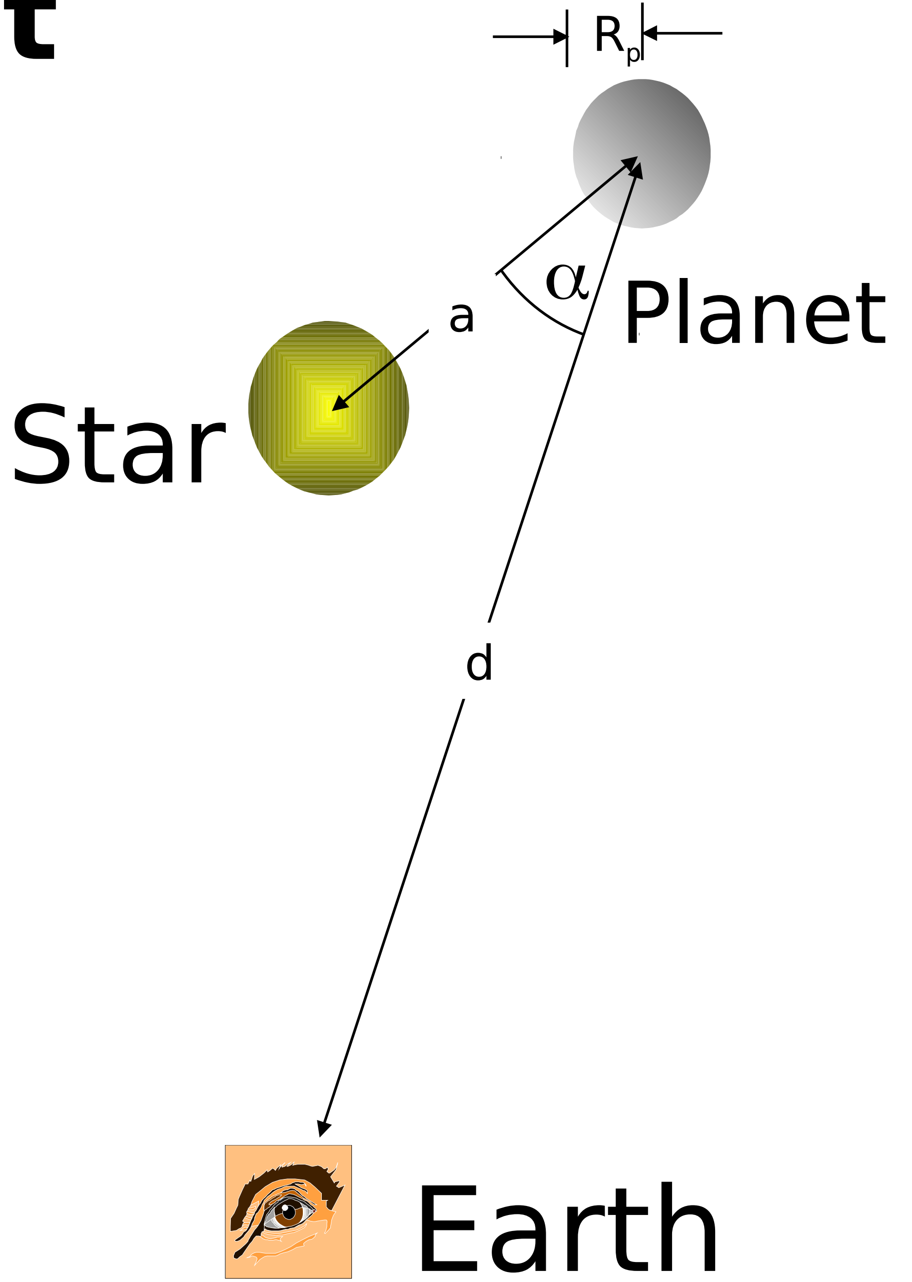


Reflected Light

planet/star flux ratio is:

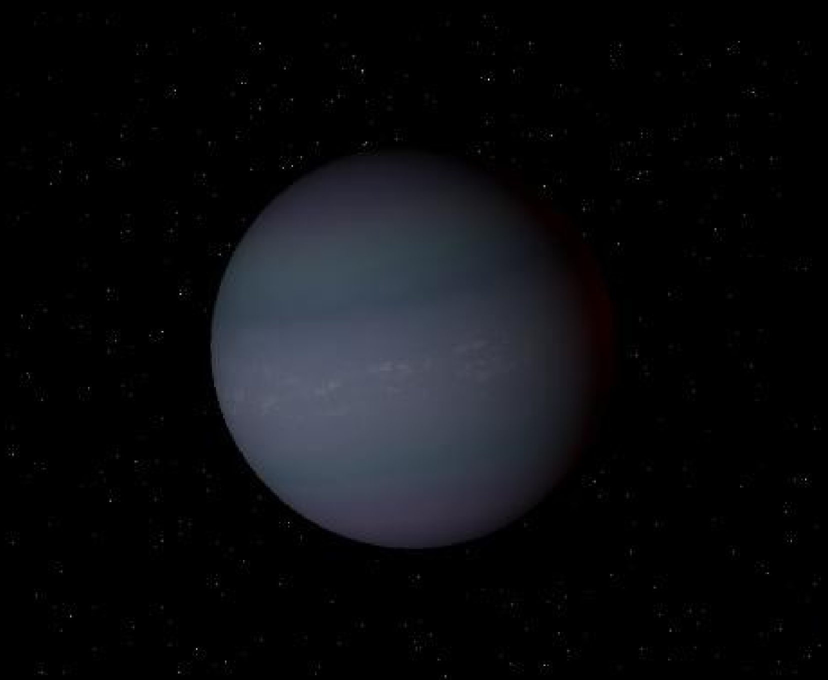
$$\varepsilon \equiv \frac{f_{\text{planet}}}{f_*} = p\,\frac{R_p^2}{a^2}$$

p is ***albedo***



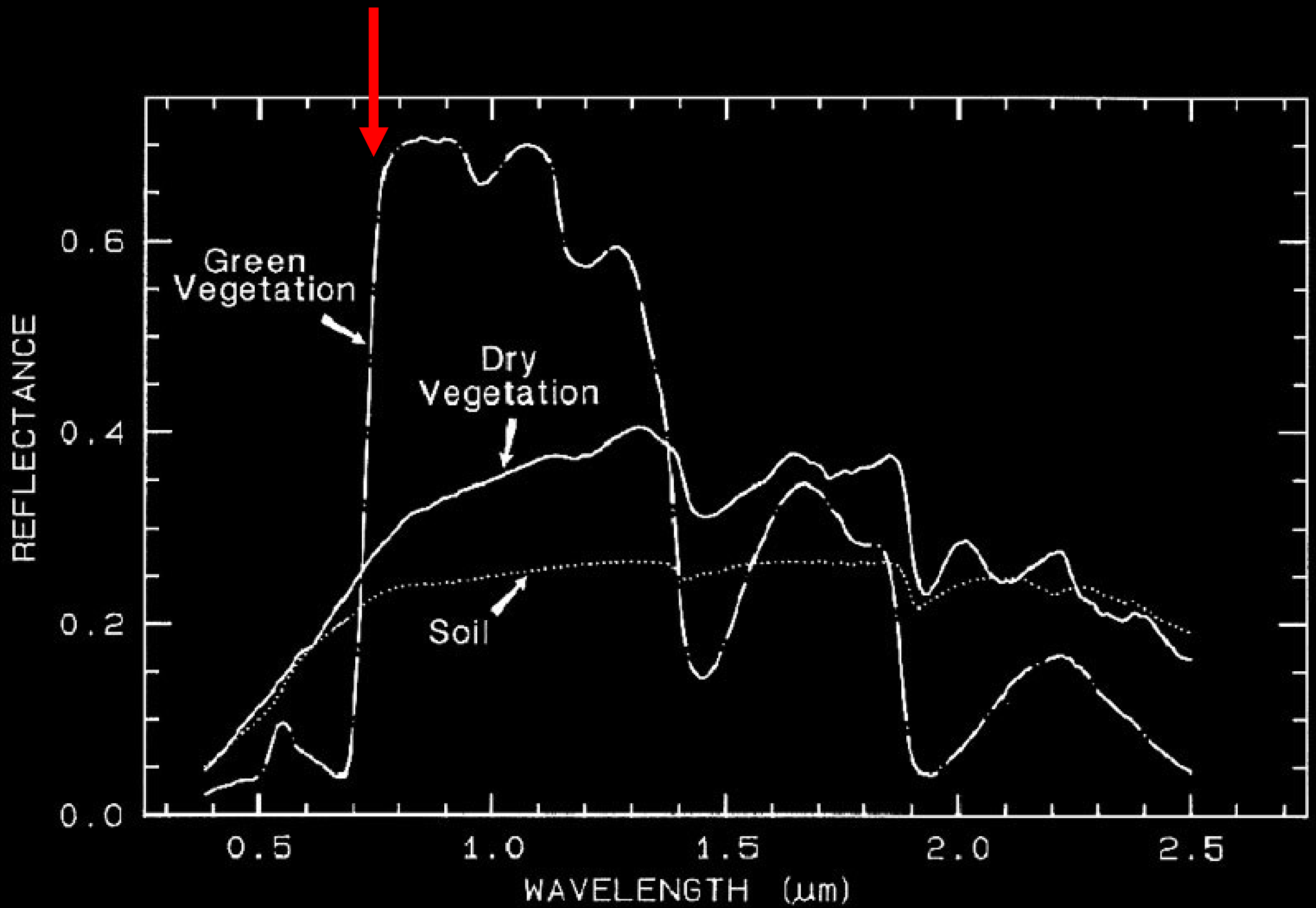
Atmospheric Probe

- Sudarsky Planet types
  - I : Ammonia Clouds
  - II : Water Clouds
  - III : Clear
  - IV : Alkali Metal
  - V : Silicate Clouds
- Predicted Albedos:
  - IV : 0.03
  - V : 0.50



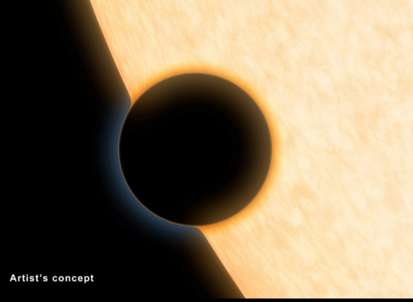
Picture of class IV planet generated using Celestia Software

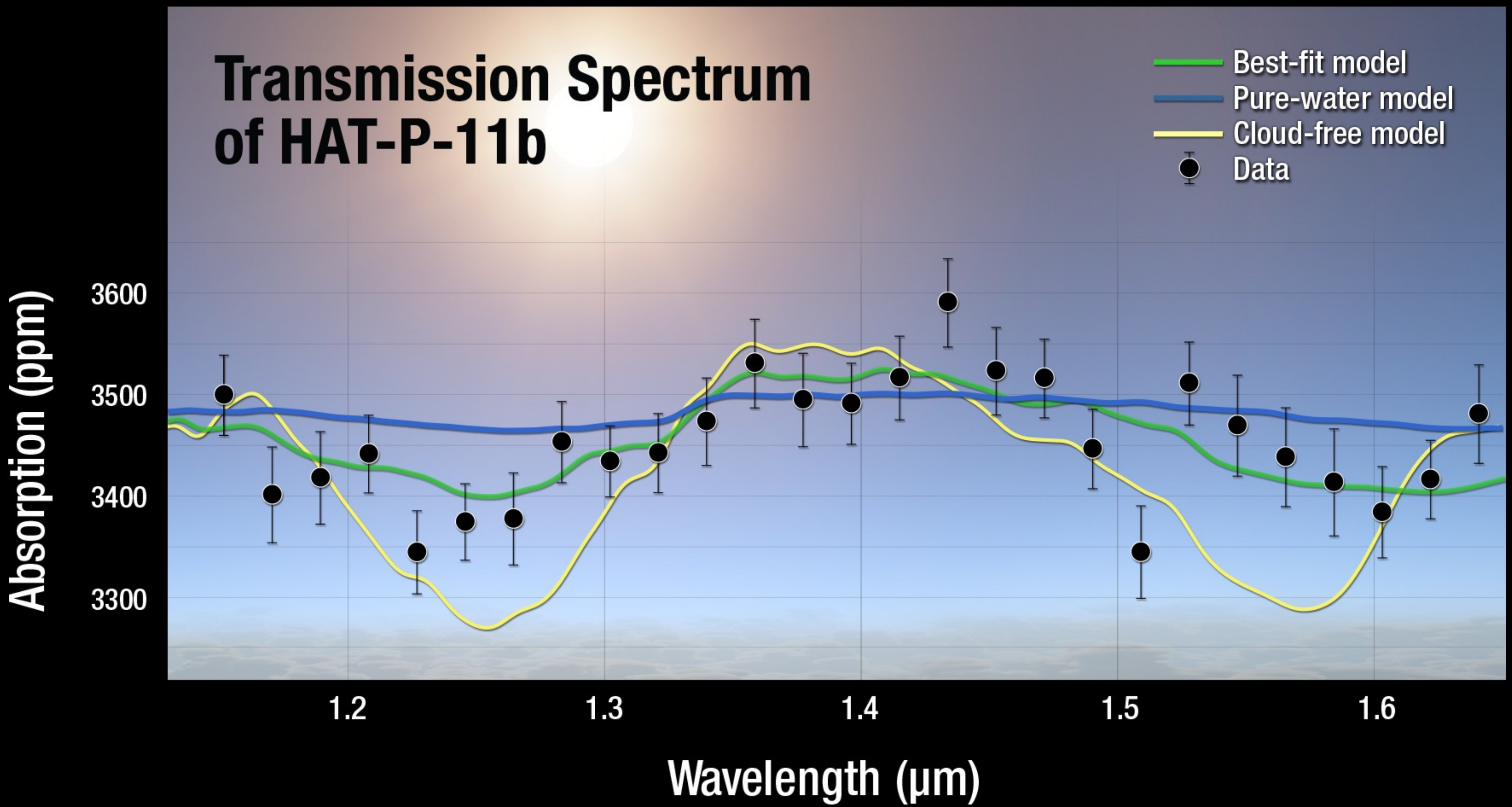
Sudarsky et al. 2000



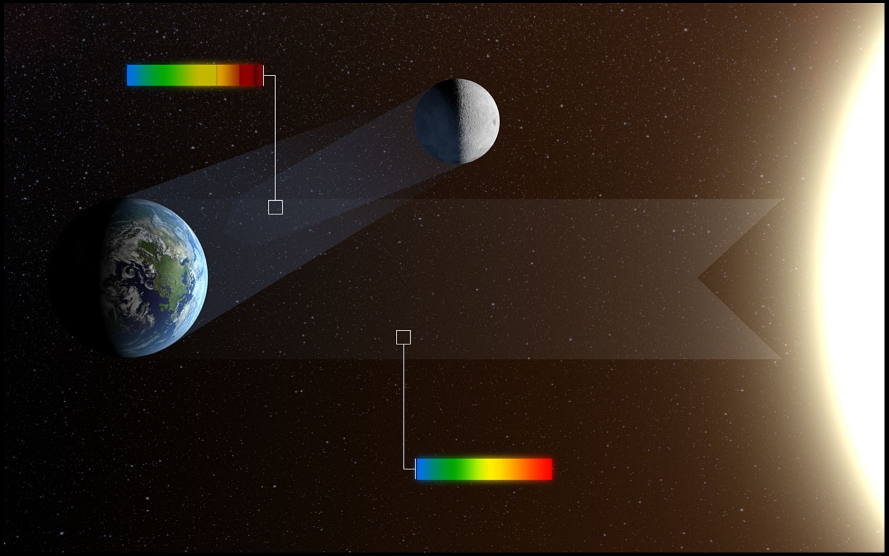
The “red edge” is a signature of vegetation on Earth.

Water vapor in exoplanet





The first astronomical detection of life
(Sterzik, Bagnulo & Palle, 2012, Nature 483, 64)



- Moon observations from VLT (Chile) have studied Earth light (coming from the Sun) reflected from the Moon.
- Biosignatures in spectra (O_2 and CH_4 abundances outside equilibrium and vegetation bump) and polarization

Drake equation

SOMEWHAT CERTAIN ⟵⟶ EXTREMELY UNCERTAIN

$$N = R^{*} \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

- N: Number of **technologically advanced civilizations** in the Milky Way galaxy
- R^{*}: Rate of formation of **stars** in the galaxy
- f_p: Fraction of those stars with **planetary systems**
- n_e: Number of planets, per solar system, with an **environment suitable for life**
- f_l: Fraction of suitable planets on which **life actually appears**
- f_i: Fraction of life-bearing planets on which **intelligent life** emerges
- f_c: Fraction of civilizations that develop a **technology that releases detectable signs** of their existence into space
- L: **Length of time** such civilizations release detectable signals into space

Life in the Vostok Lake !