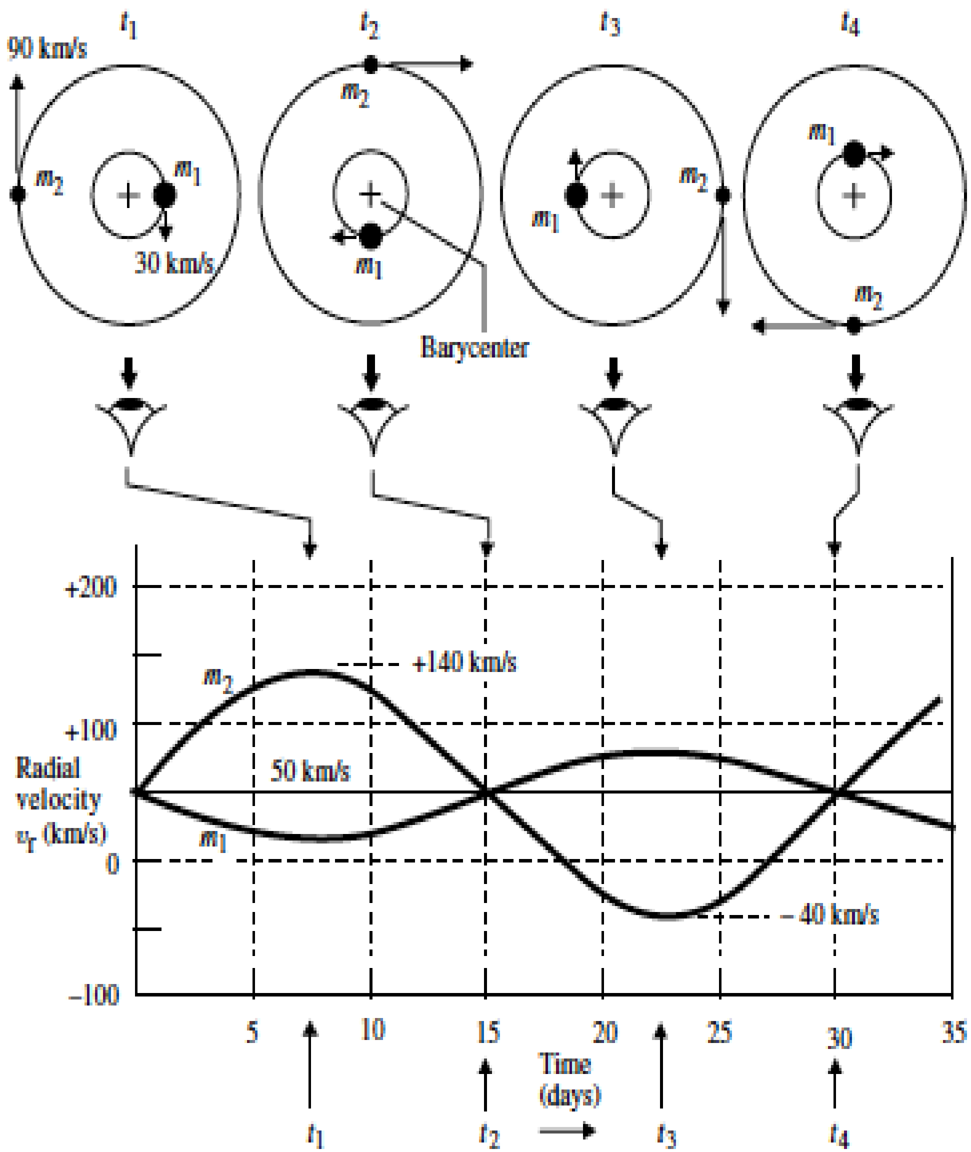
The mass function

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

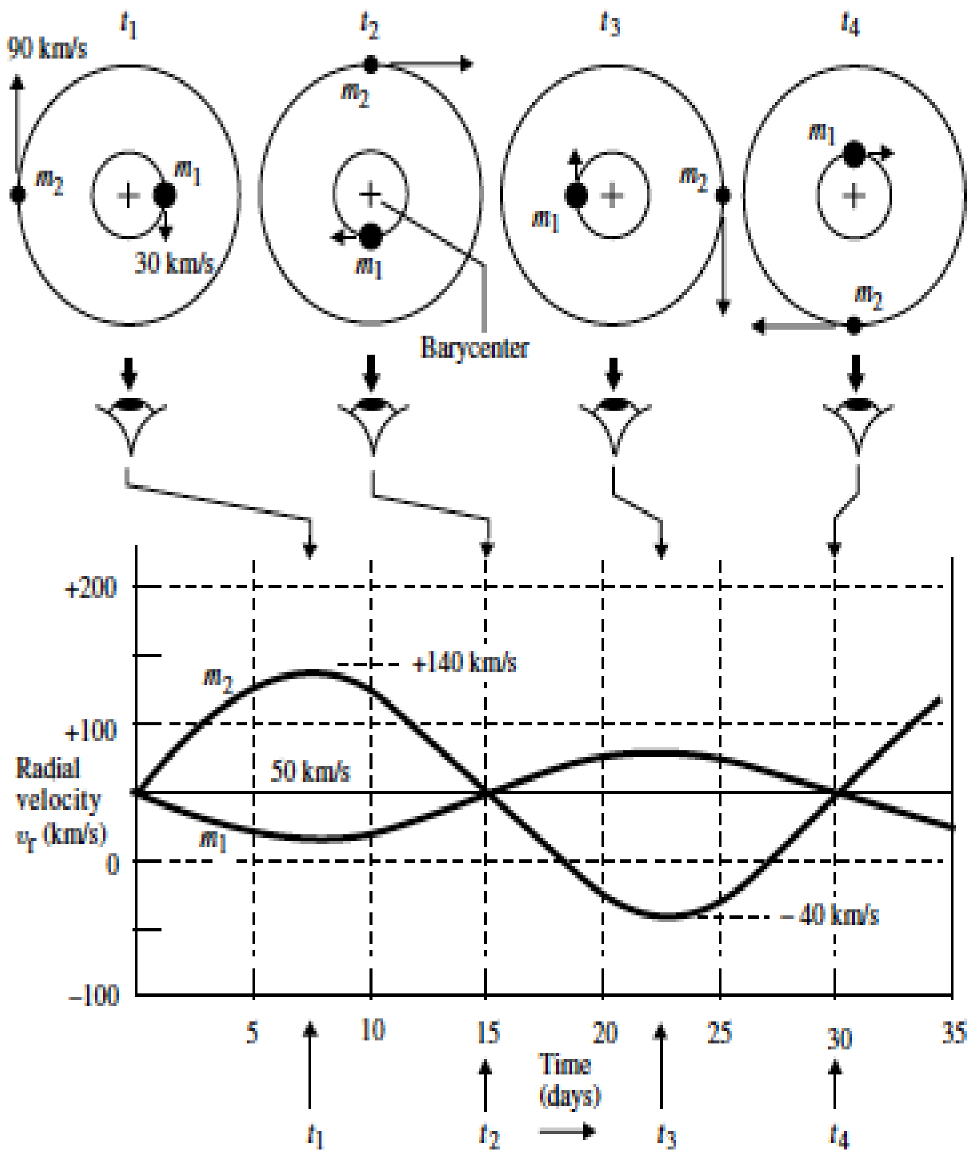


The mass function

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

Kepler's 3rd law becomes:

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



The mass function

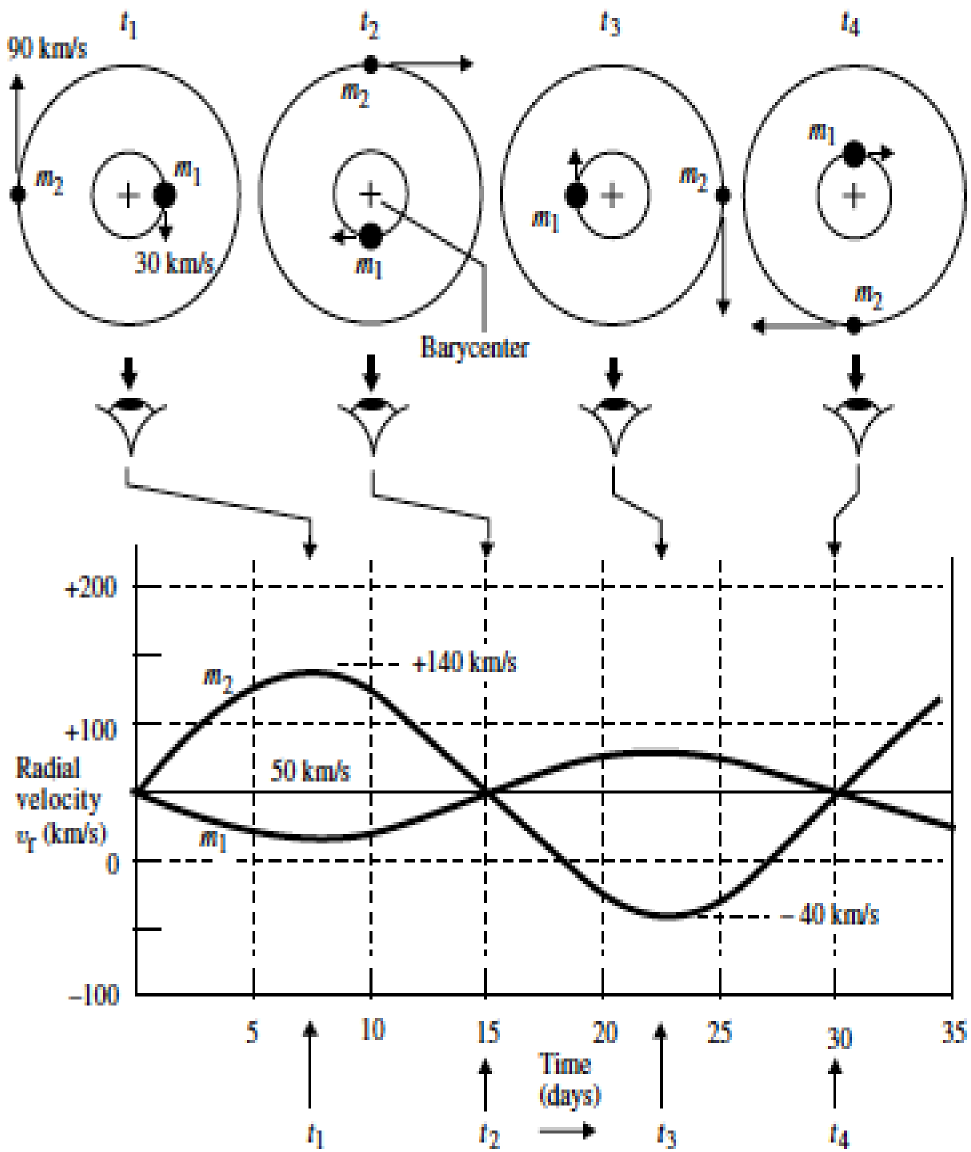
$$a_* = a\frac{M_o}{M_* + M_o}$$

Kepler's 3rd law becomes:

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

We can also measure :

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



The mass function

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

Kepler's 3rd law becomes:

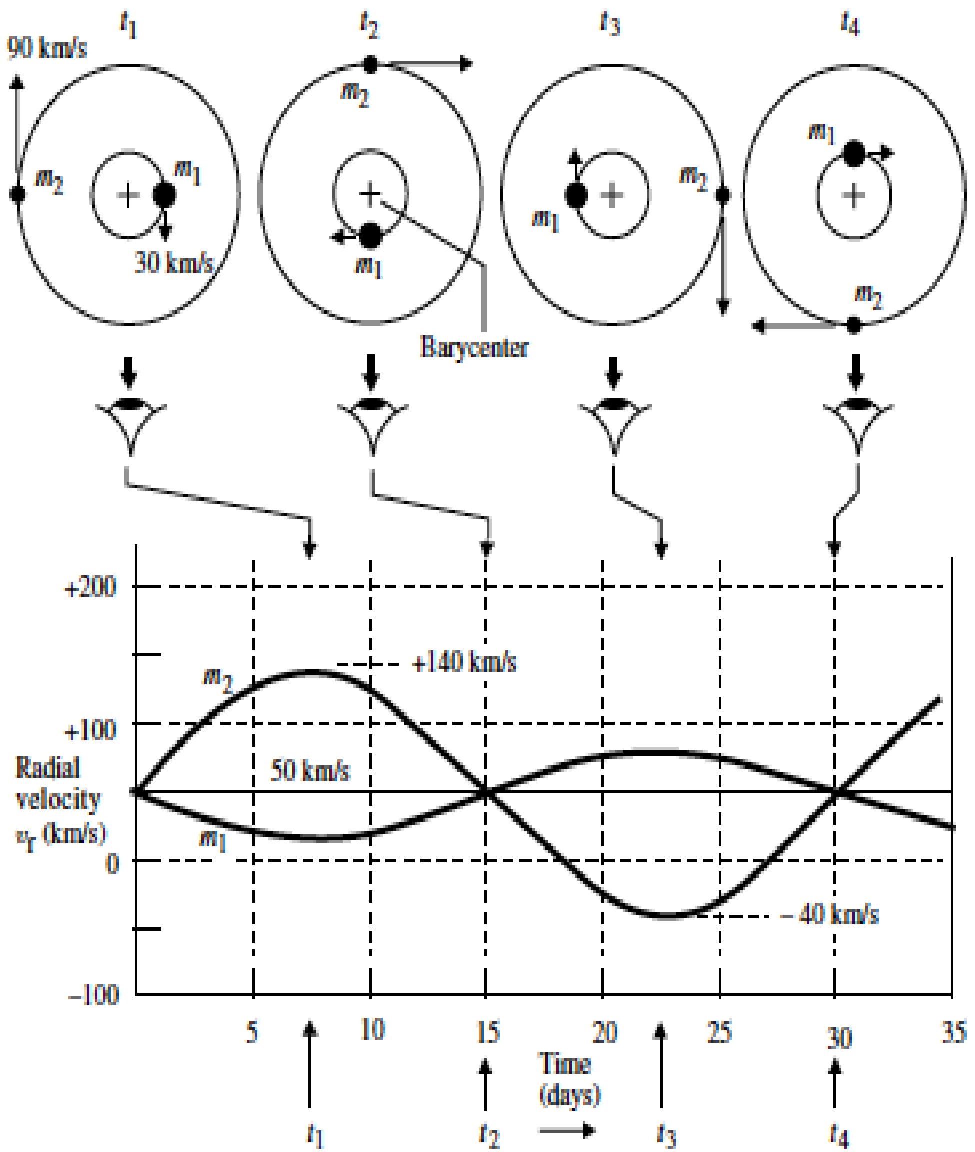
$$\omega^2 = G\frac{M_* + M_o}{a^3}$$

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

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

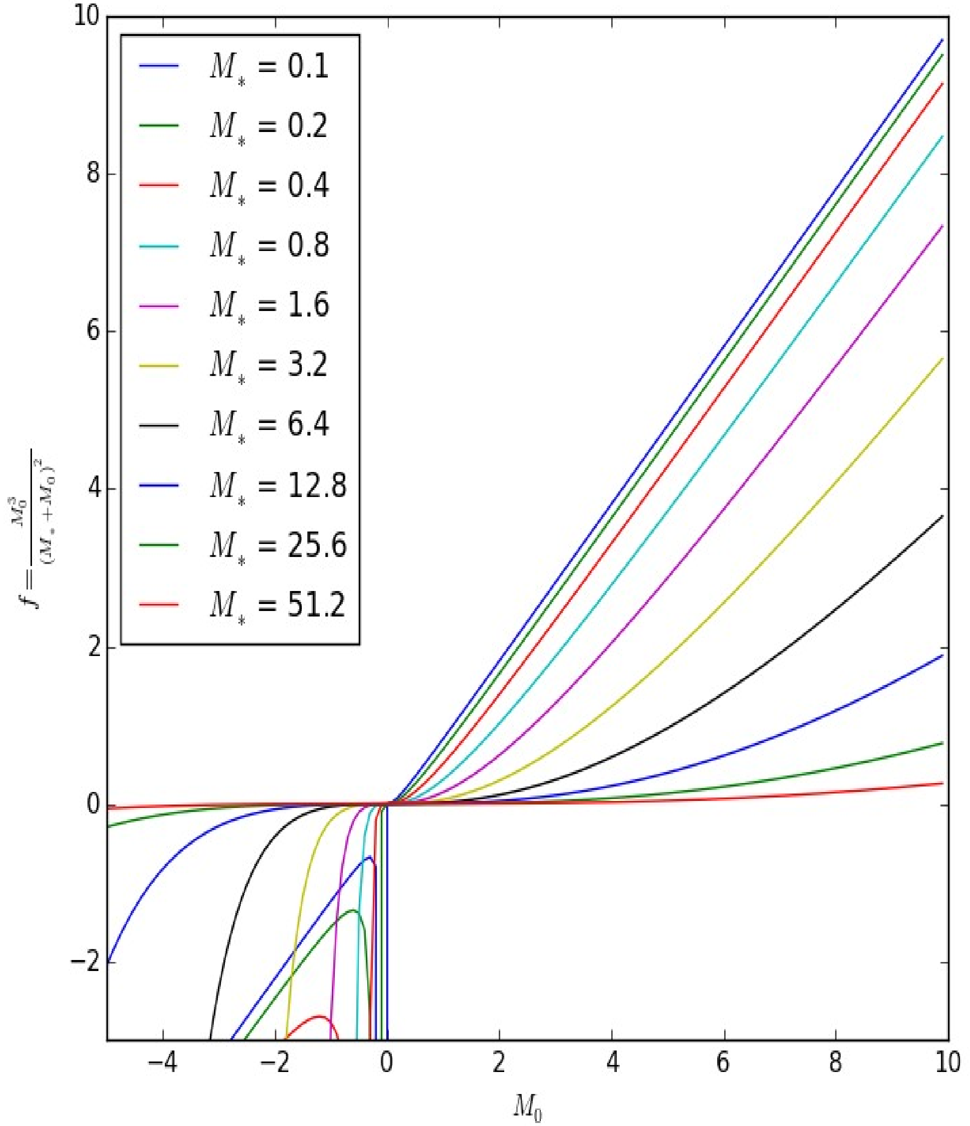
Mass function (f): contains all measurable quantities

if stellar mass is known,

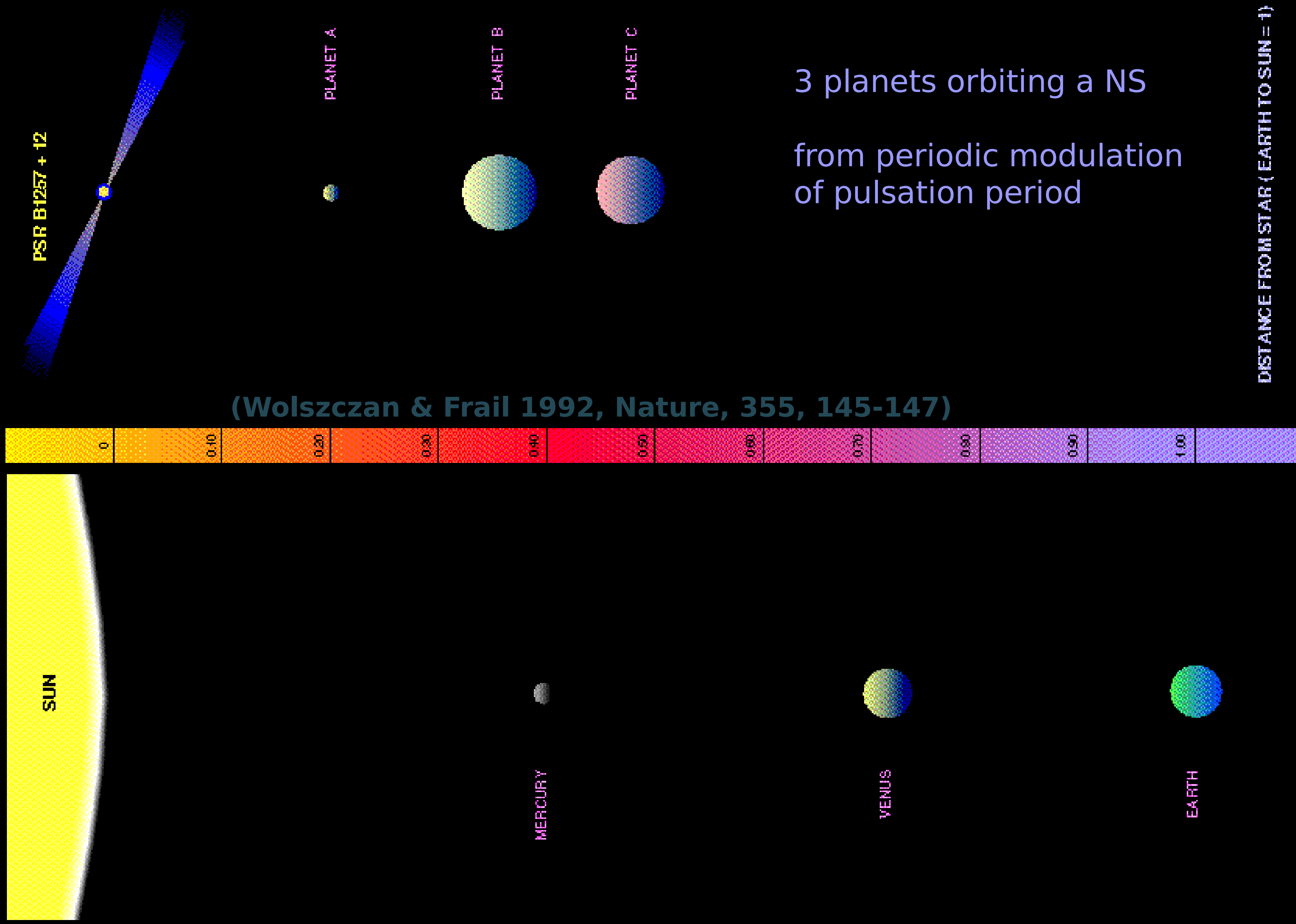
f_* provides m_o sin i

with sin i = 1

lower limit on m_o



Pulsar Planets



3 planets orbiting a NS

from periodic modulation
of pulsation period

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

Exoplanets

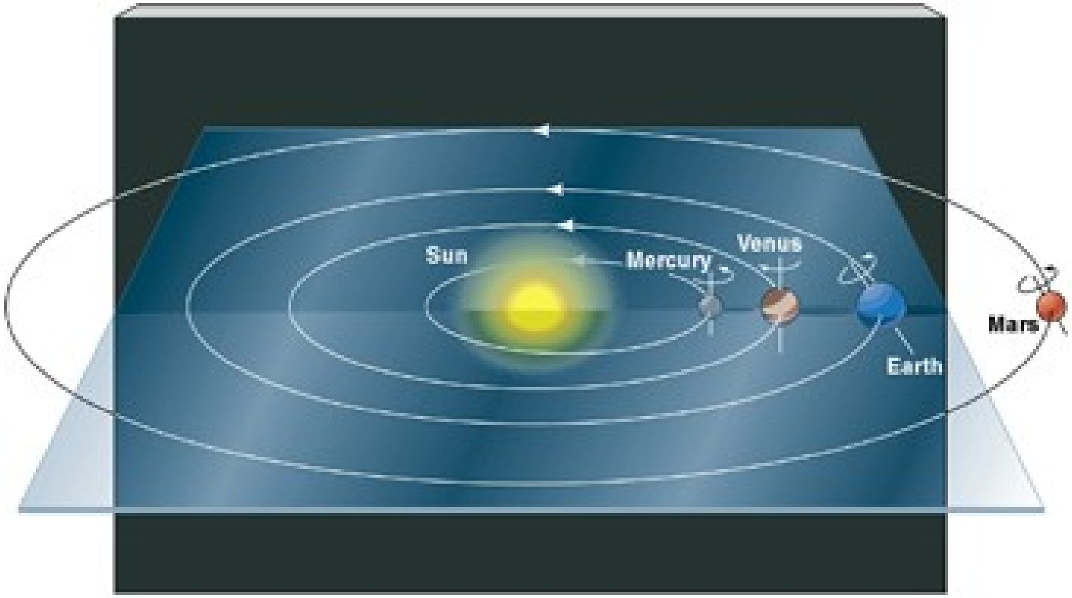
METHODS AND PRINCIPLES

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

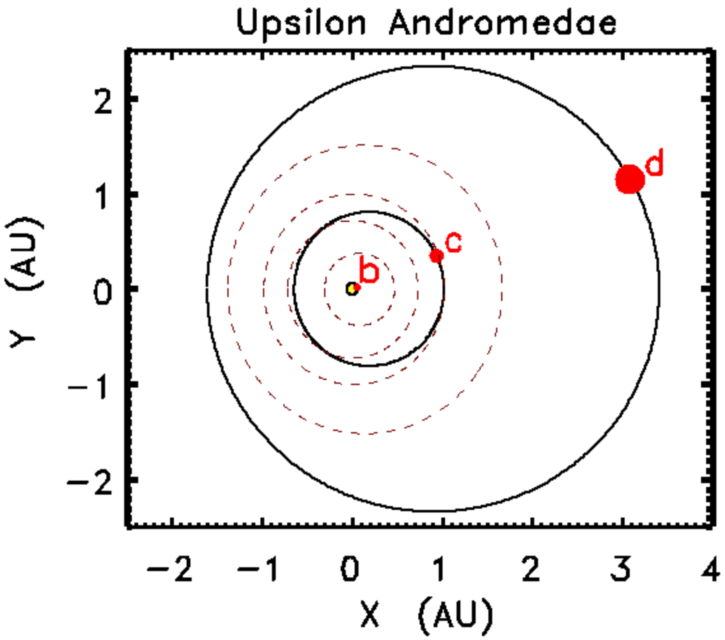
PLANETARY SYSTEMS ALIGN IN A PLANE

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

edge-on = high inclination



face-on = low inclination

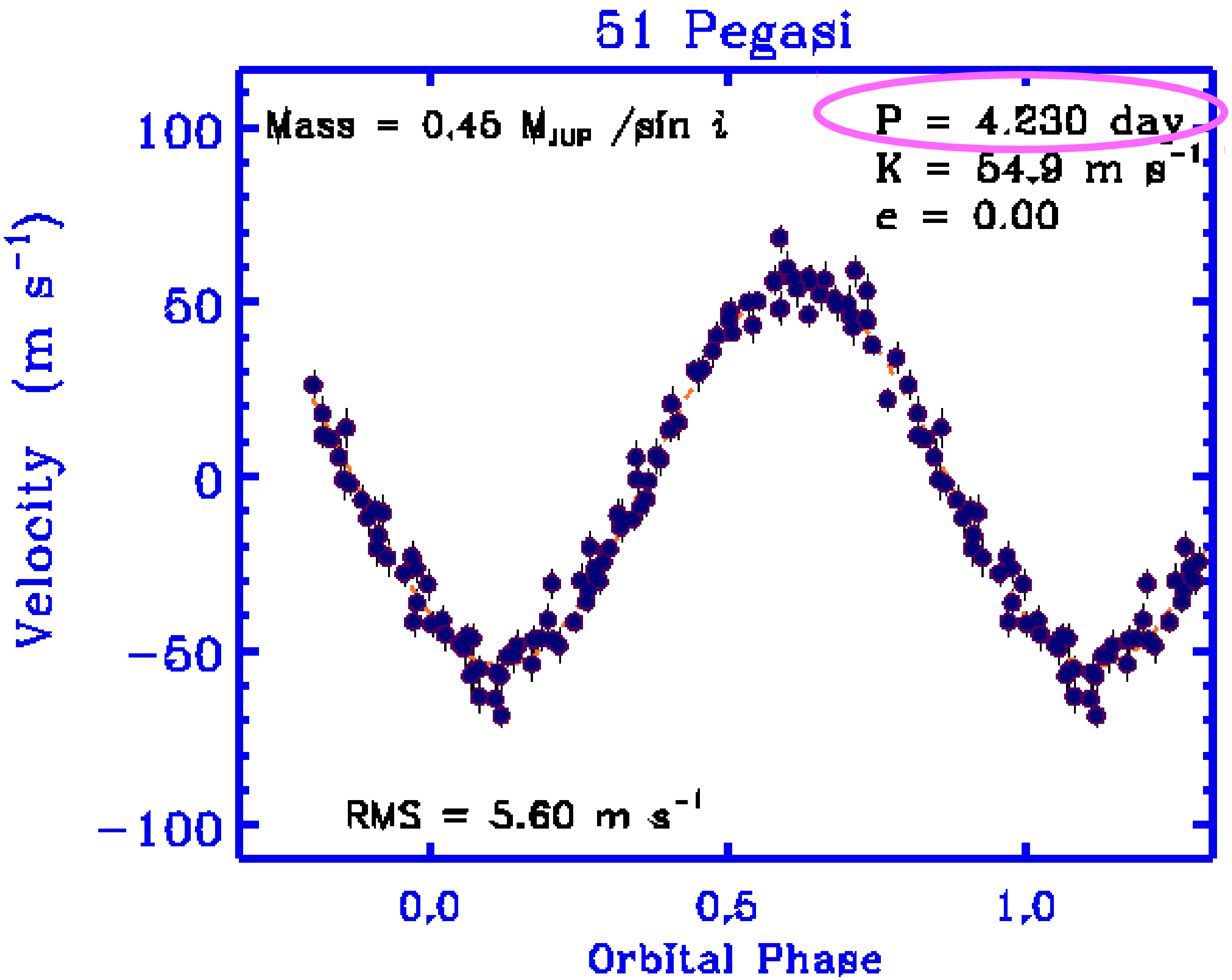


Radial Velocity and **Transit** methods

Astrometry and **imaging** methods

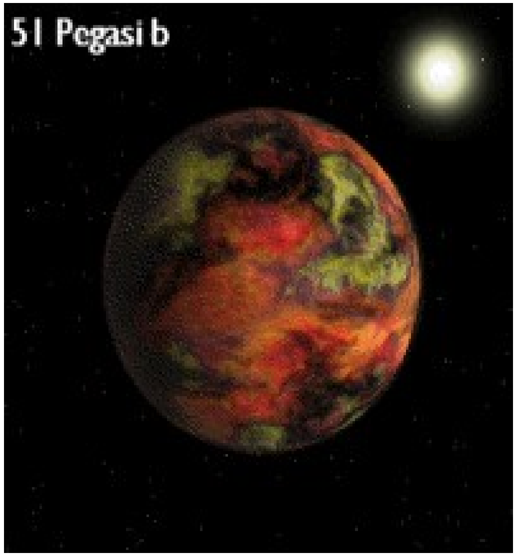
Microlensing method does not depend on orbital inclination

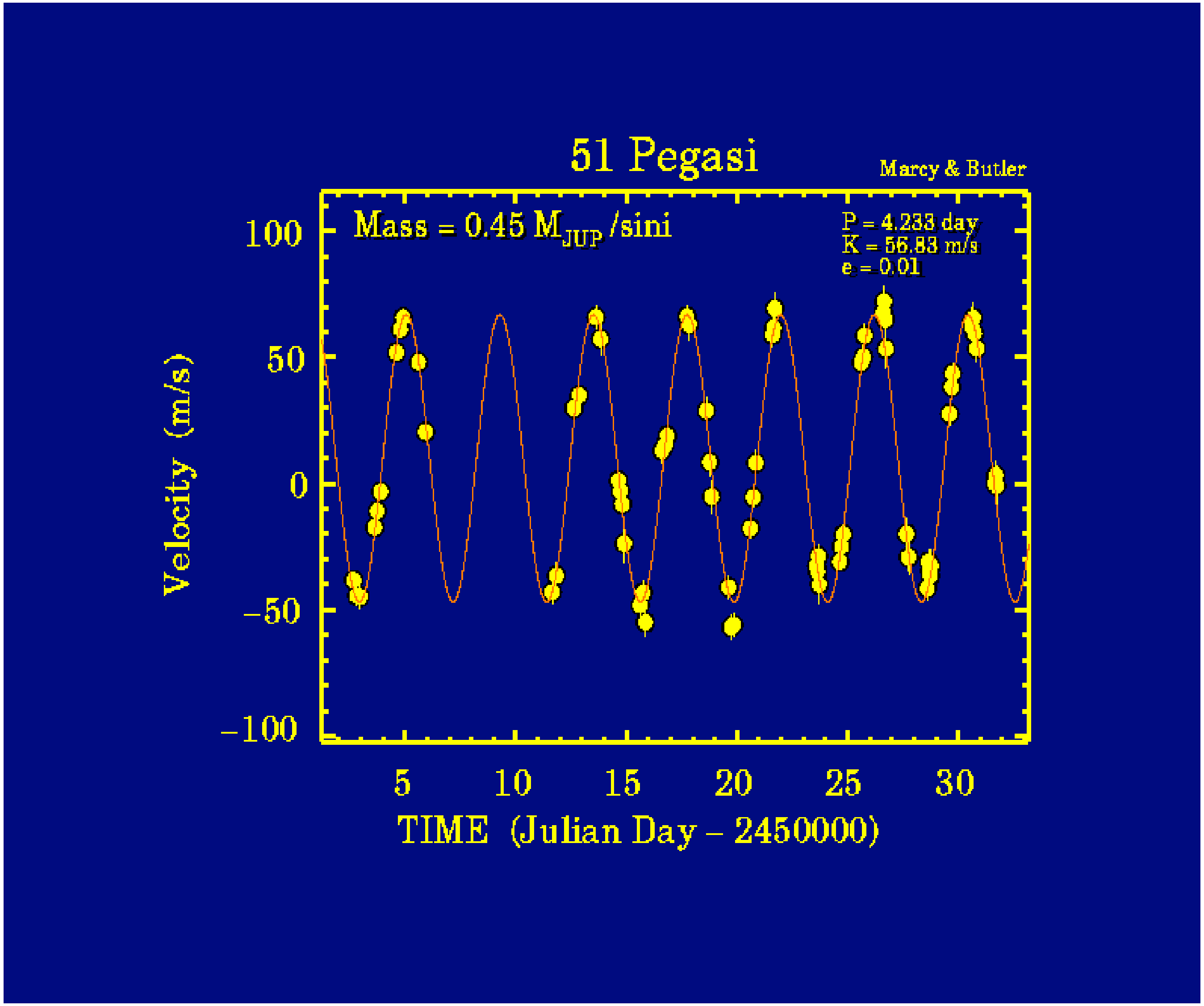
The first confirmed exoplanet orbiting a MS star

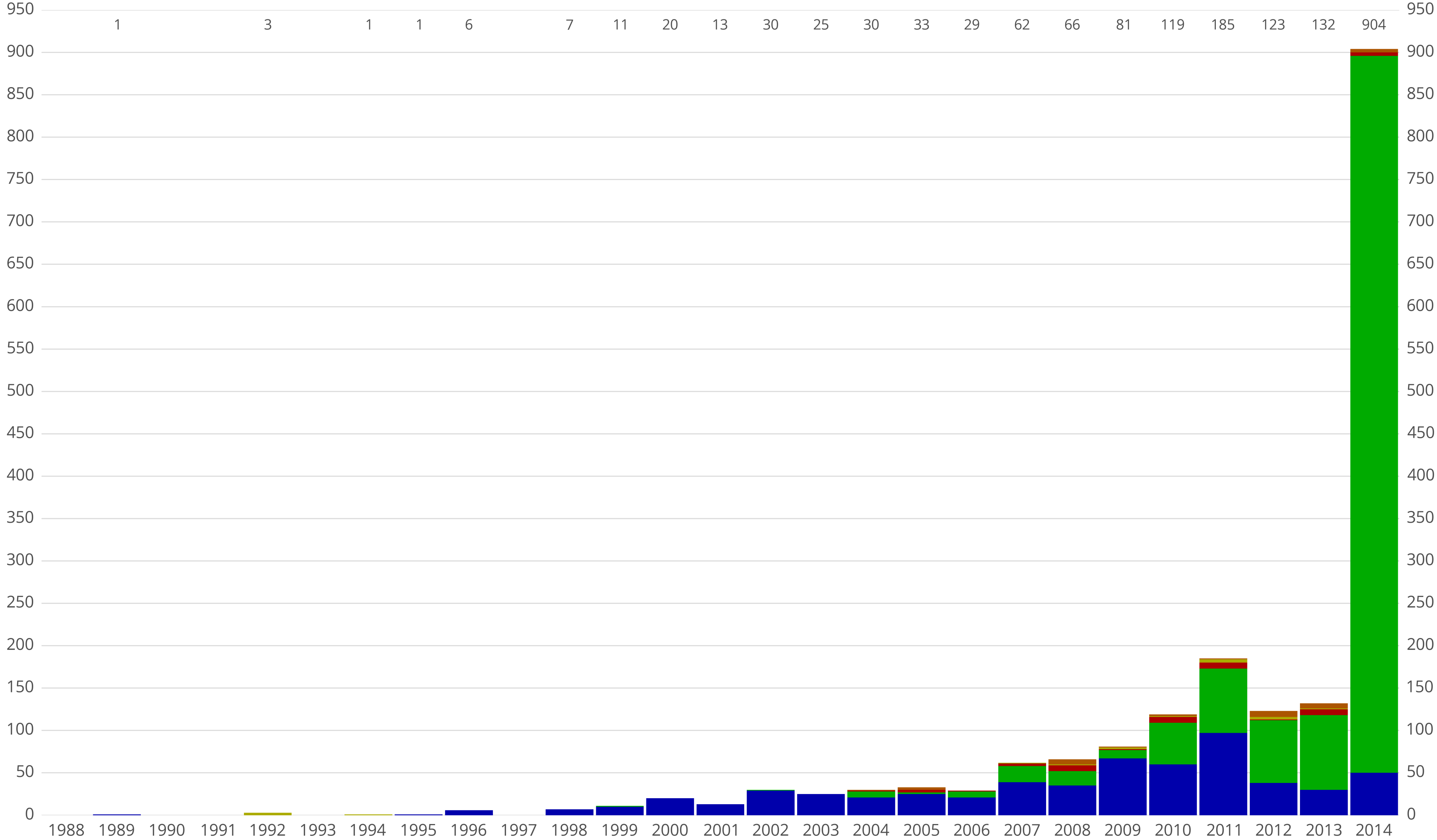


Mayor & Queloz (1995)

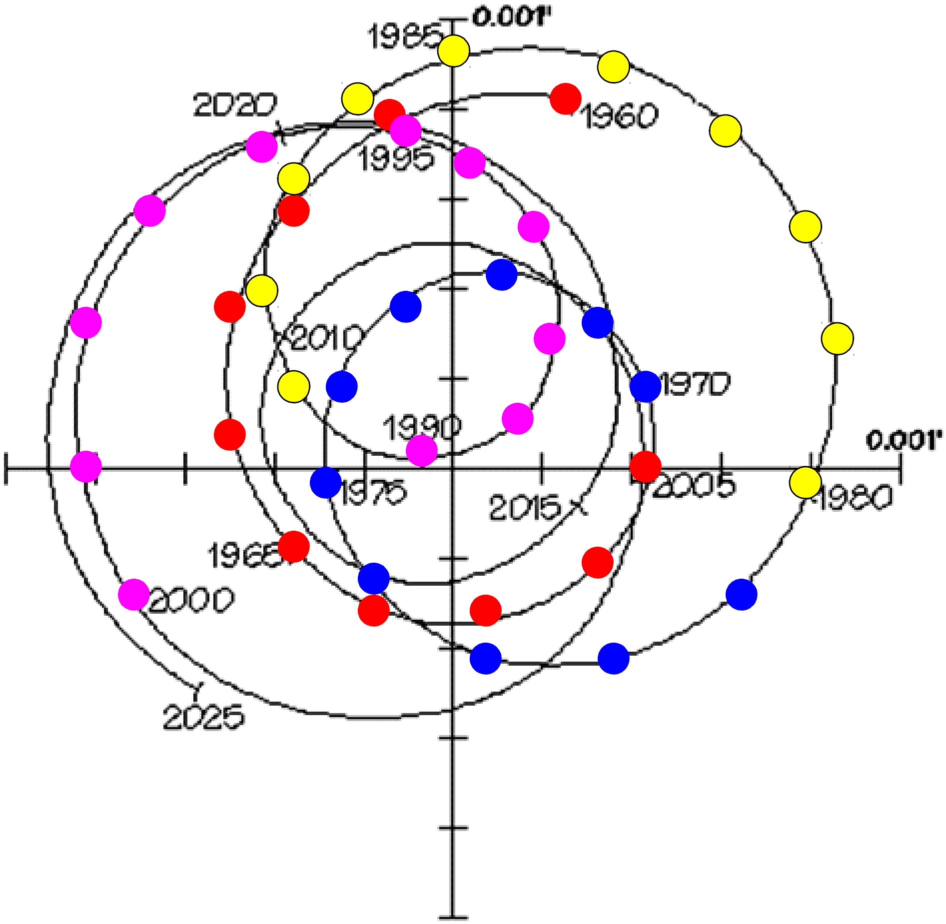
RADIAL VELOCITY METHOD






950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
1 3 1 1 6 7 11 20 13 30 25 30 33 29 62 66 81 119 185 123 132 904
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

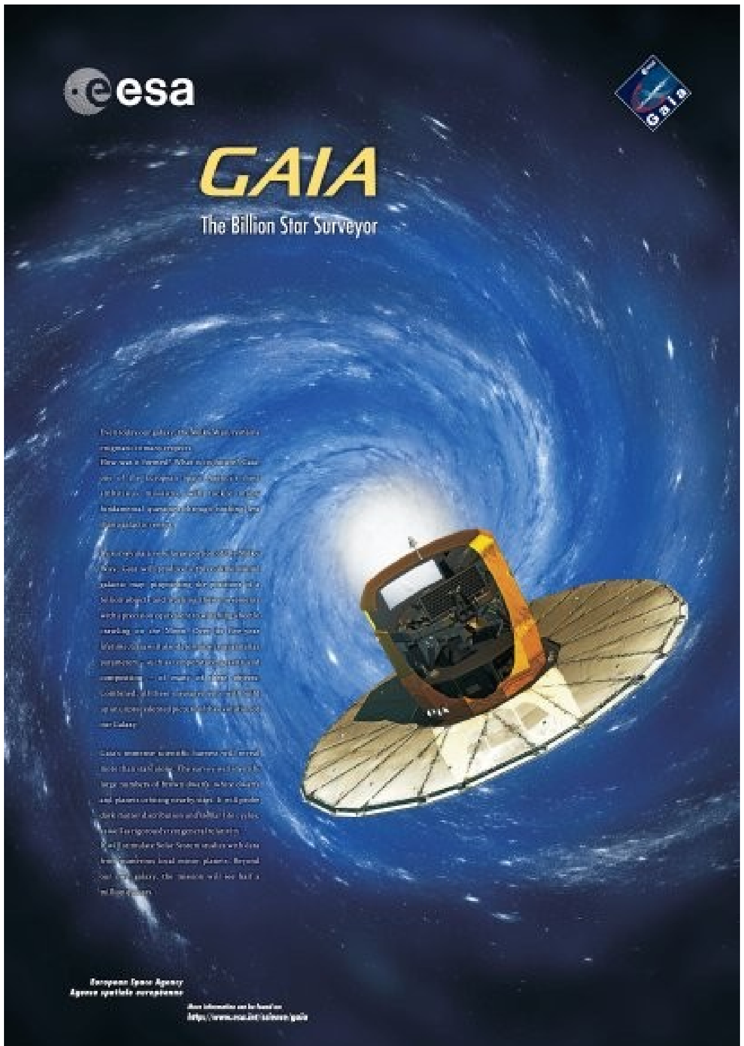
STELLAR WOBBLE: THE SUN



We would not have detected Jupiter around our star using Radial Velocity
We could detect Jupiter if we had been watching using Astrometry

ASTROMETRY METHOD

No confirmed planet discoveries yet, but will be soon possible with GAIA (ESA, **2013 December 19**; μ−arcsec astrometry)



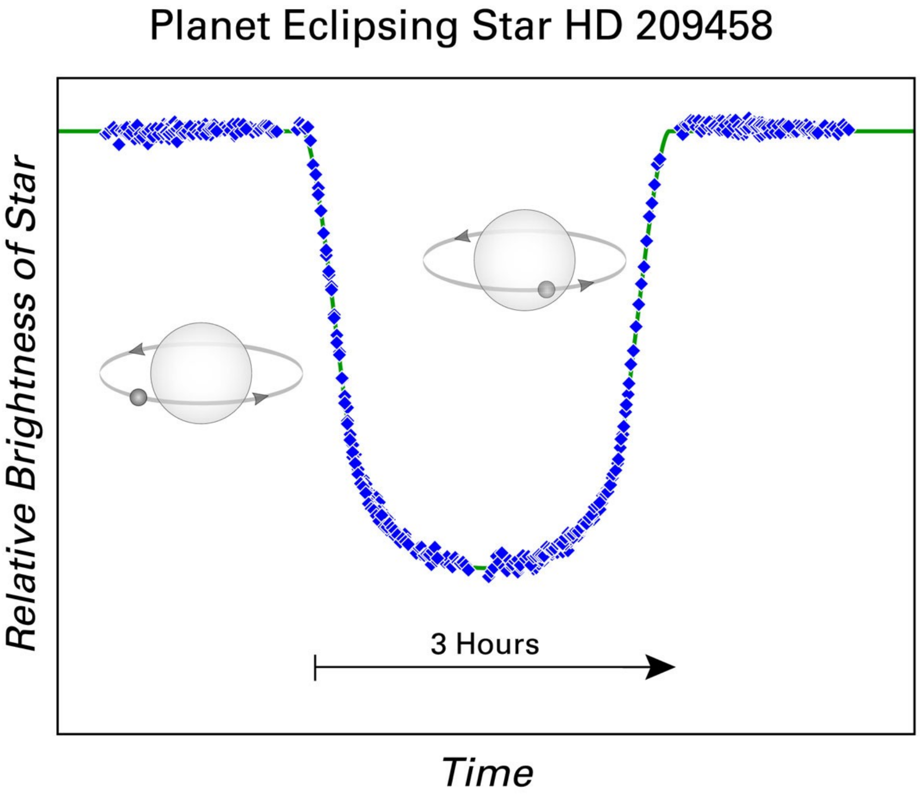
Combining Astrometry and Radial Velocity methods

⇒ orbit **inclination**

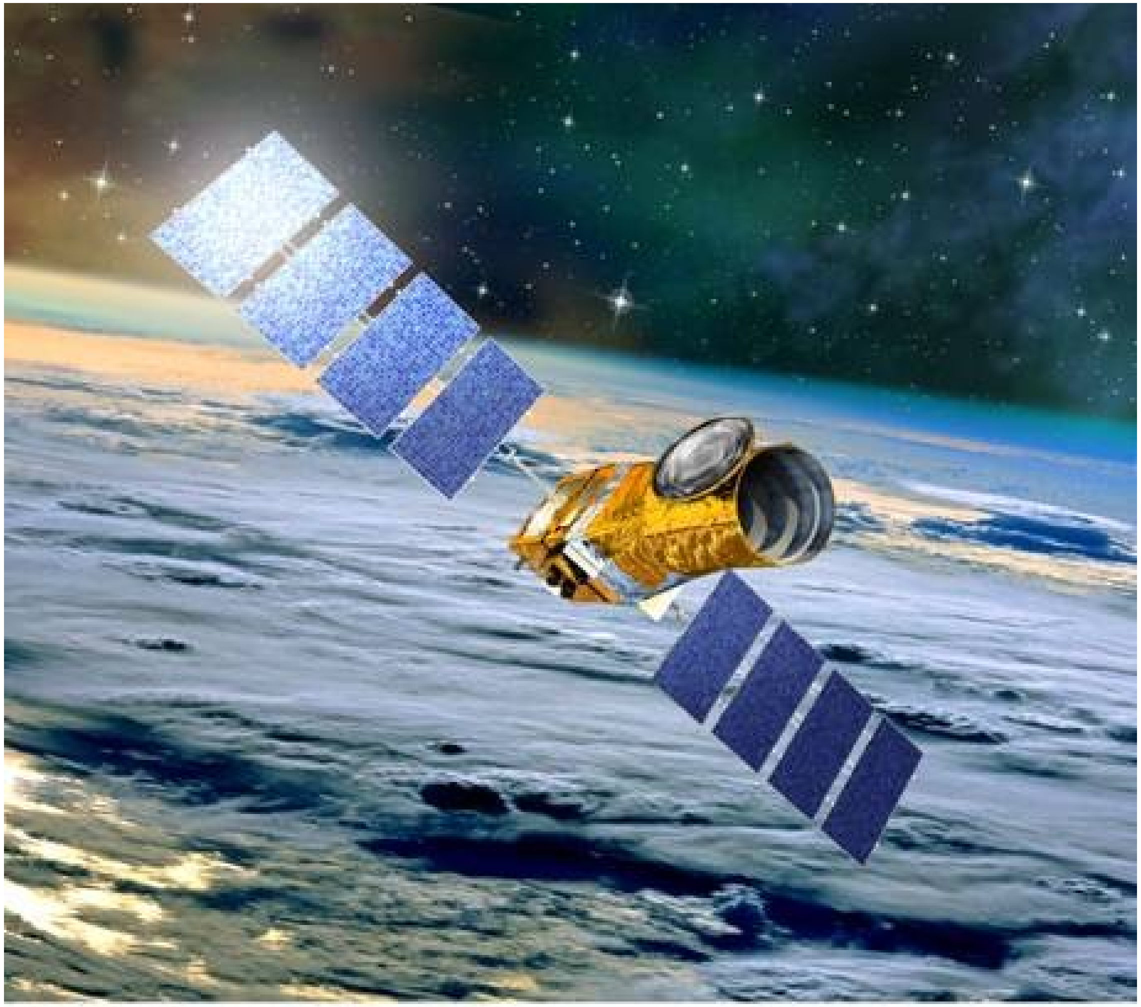
⇒ planet **mass**

~8000 (massive) planets should be discovered by GAIA (until 2020)

Eclipse = transit



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



©CNES - Octobre 2005/Illus. D. Ducros

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

CoRoT 7b

Rocky planet

Mass = 5 Earth

R= 2.5 10^6 km

(23 times closer than Mercury)

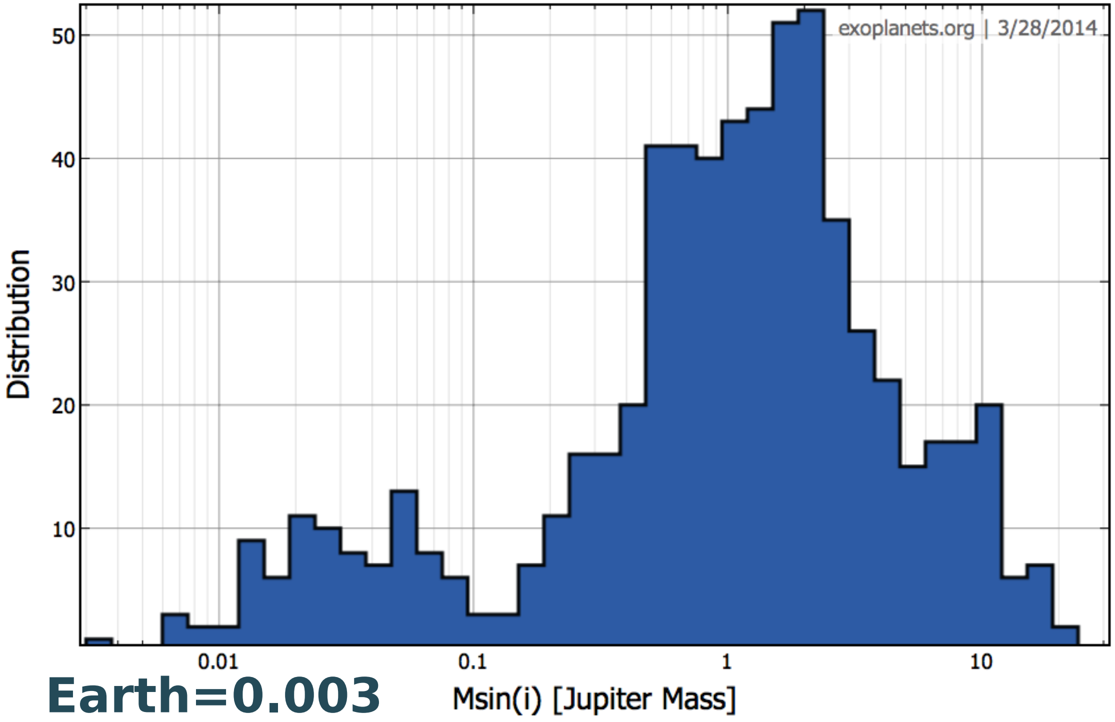
P = 20.4 h

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.

RADIAL VELOCITY METHOD

Number of planets with a given "mass"



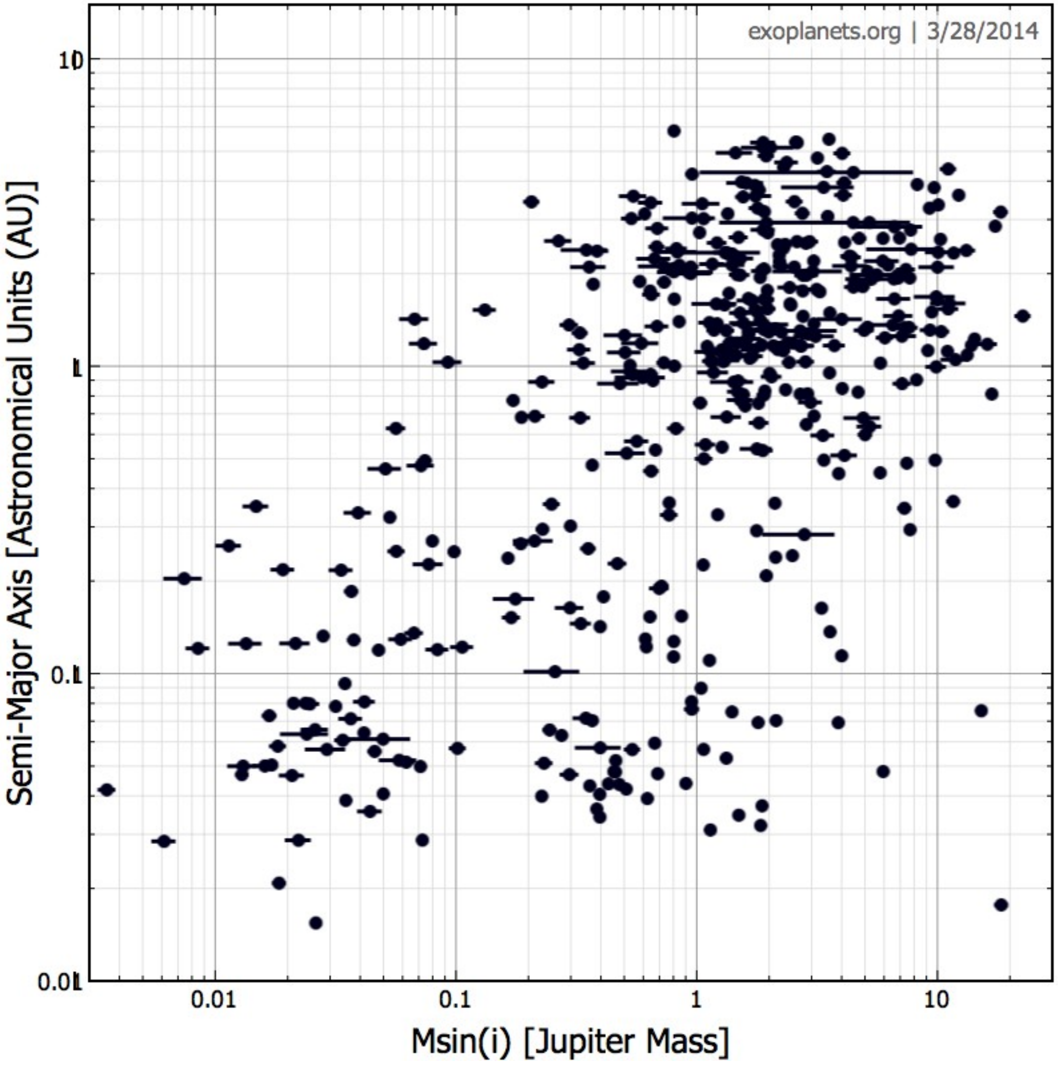
Earth=0.003

1. One cannot get the mass directly, if the **inclination** of the system is unknown
2. One determines combined quantity of planet mass and the inclination angle
3. Smaller "mass" planets are the hardest to find) ⇒ **small planets are very numerous**

exoplanets.org

RADIAL VELOCITY METHOD

Planets discovered with RV method

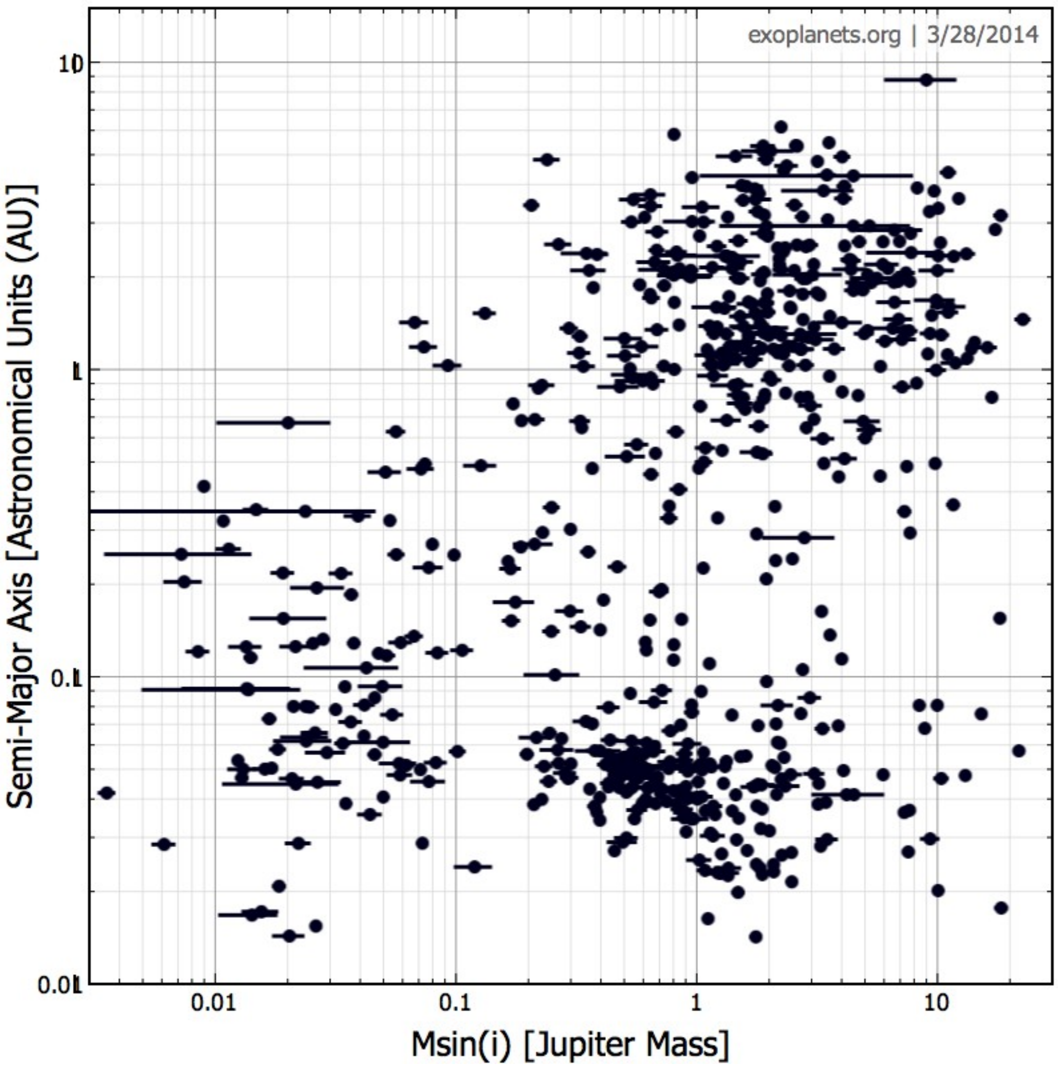


1) 440 planets (**~30%**) discovered since 1995 with **RV** method

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

RADIAL VELOCITY METHOD

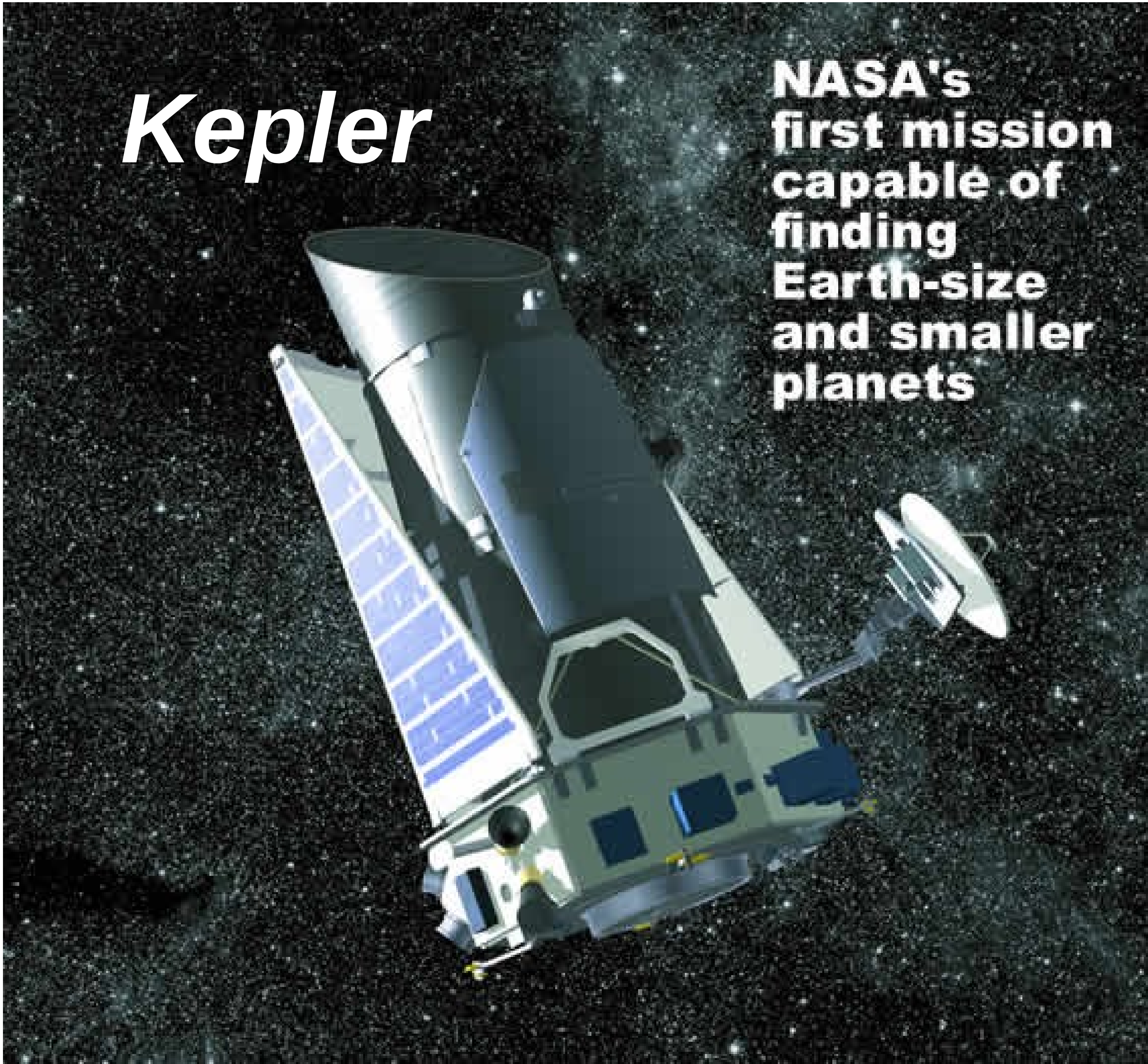
All confirmed planets



1) 440 planets (**~30%**) discovered since 1995 with **RV** method

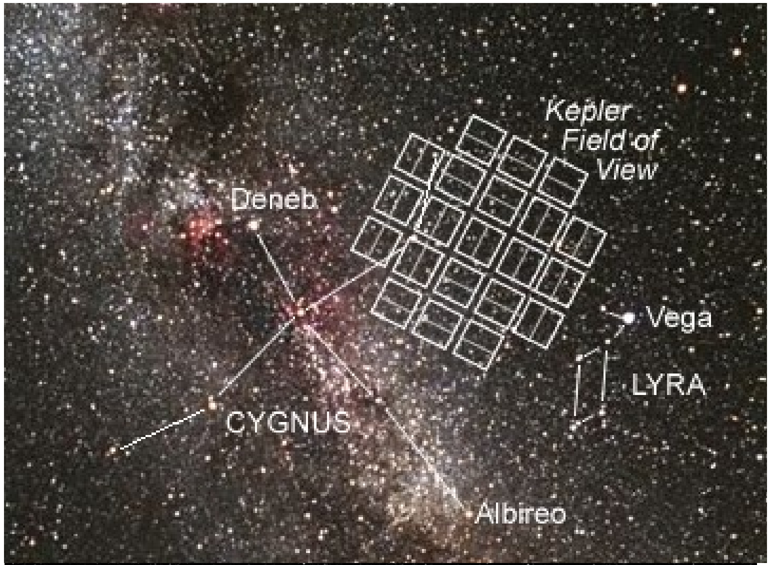
2) **RV** method selects **high mass** planets with relatively small orbits

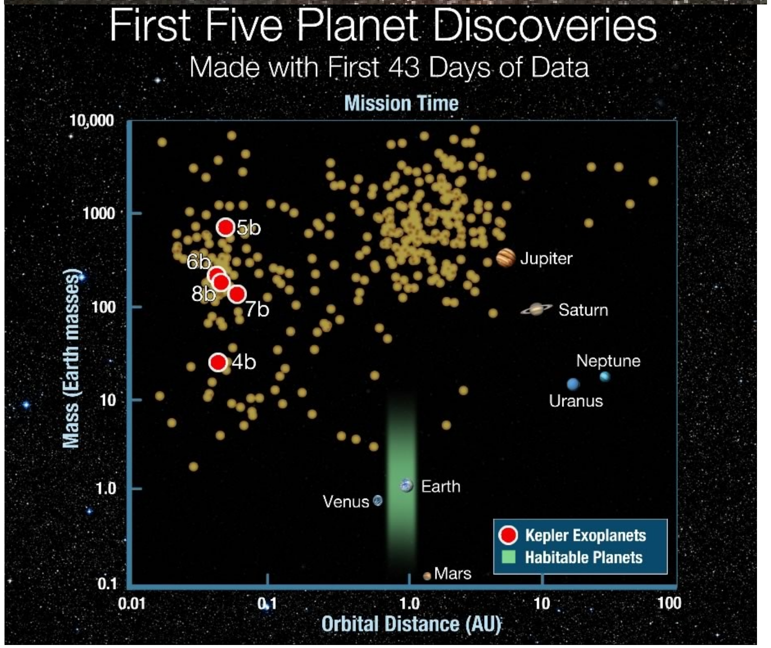
3) With **transits**, even **smaller orbits** (less dependent on mass)


Kepler
NASA's first mission capable of finding Earth-size and smaller planets

Kepler

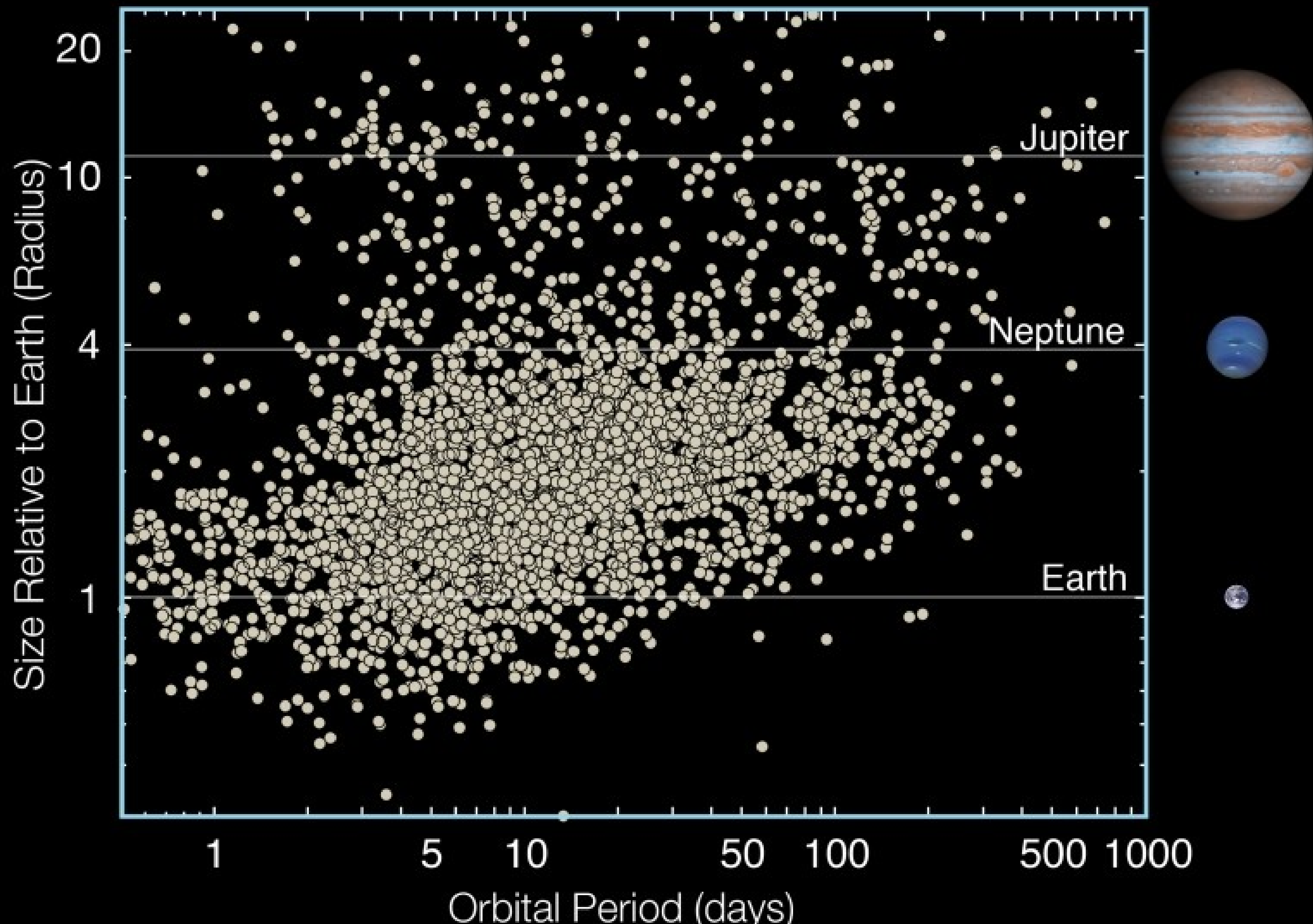
- Launched in March 2009
- Pointing sky region in Cygnus
- 4570 planet candidates
- 961 confirmed planets
- Multiple systems
- Earth-sized planet candidates

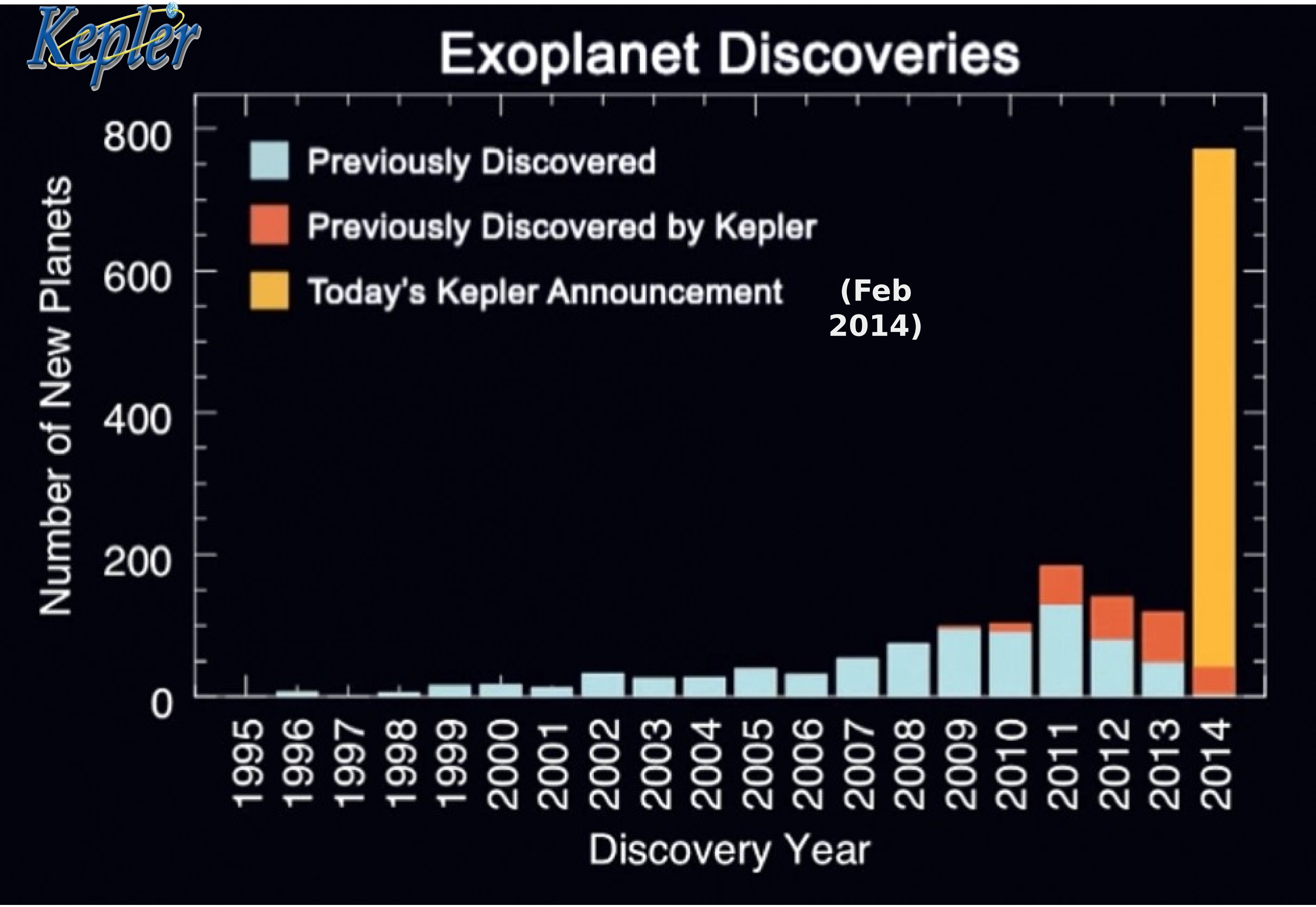


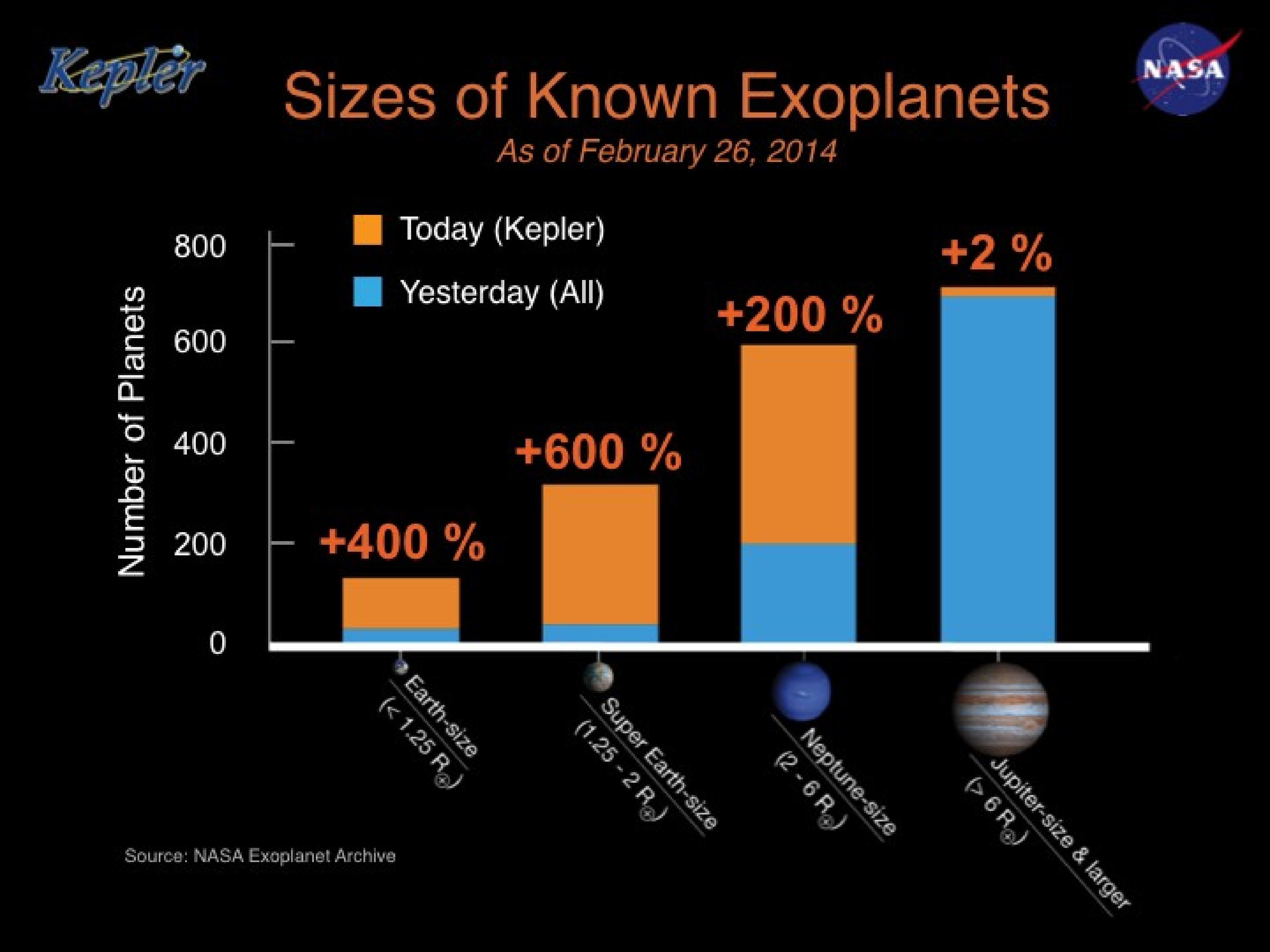


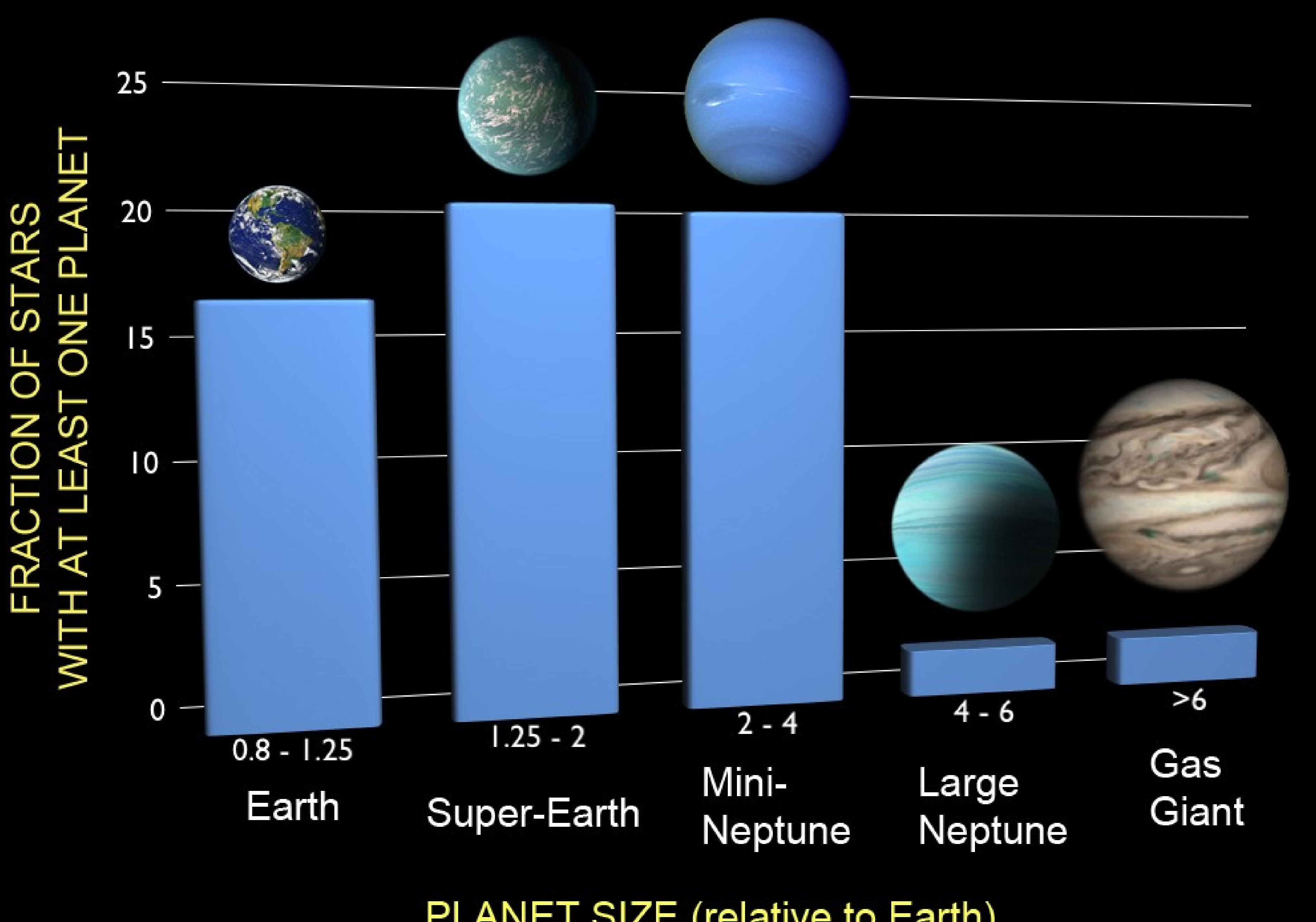
Planet Candidates

As of November 4, 2013



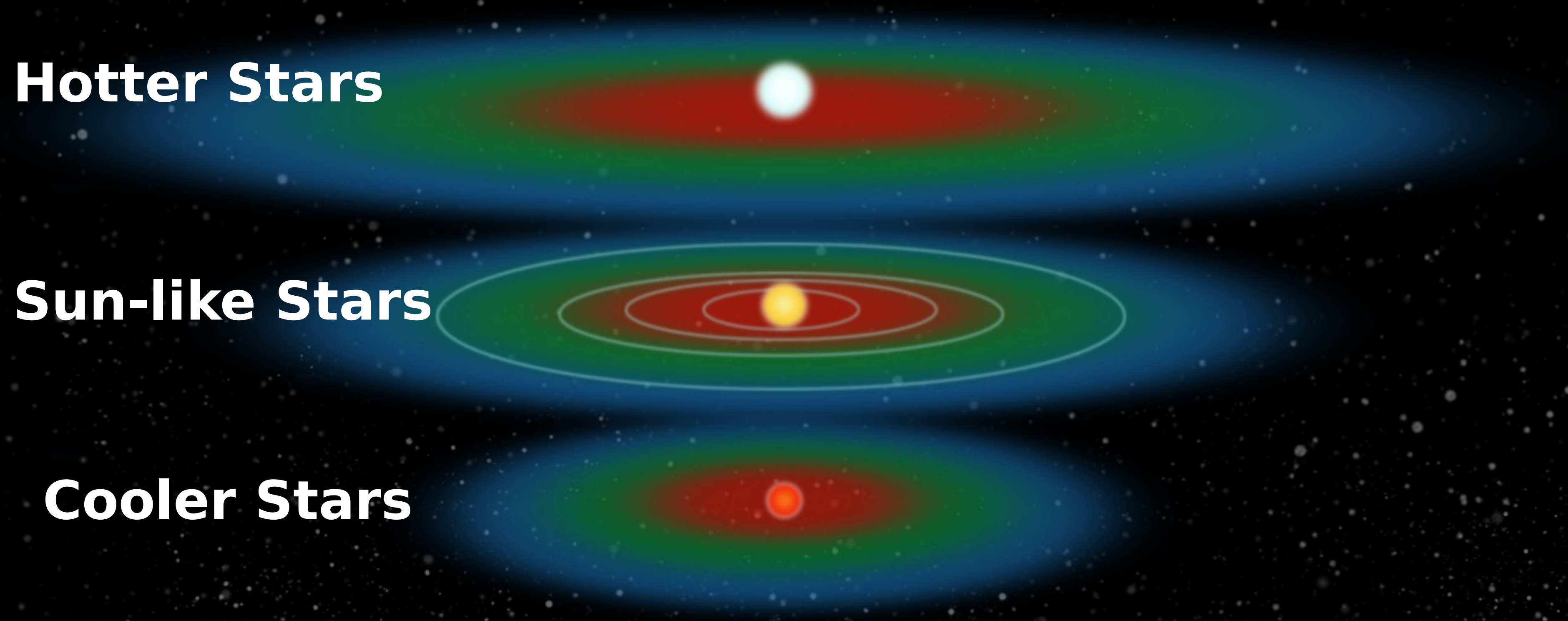

Kepler
Exoplanet Discoveries
Previously Discovered
Previously Discovered by Kepler
Today's Kepler Announcement
(Feb 2014)
Number of New Planets
800
600
400
200
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year


Kepler
NASA
Sizes of Known Exoplanets
As of February 26, 2014
Today (Kepler)
Yesterday (All)
Number of Planets
800
600
400
200
0
+400 %
+600 %
+200 %
+2 %
Earth-size
(< 1.25 R⊕)
Super Earth-size
(1.25 - 2 R⊕)
Neptune-size
(2 - 6 R⊕)
Jupiter-size & larger
(> 6 R⊕)
Source: NASA Exoplanet Archive

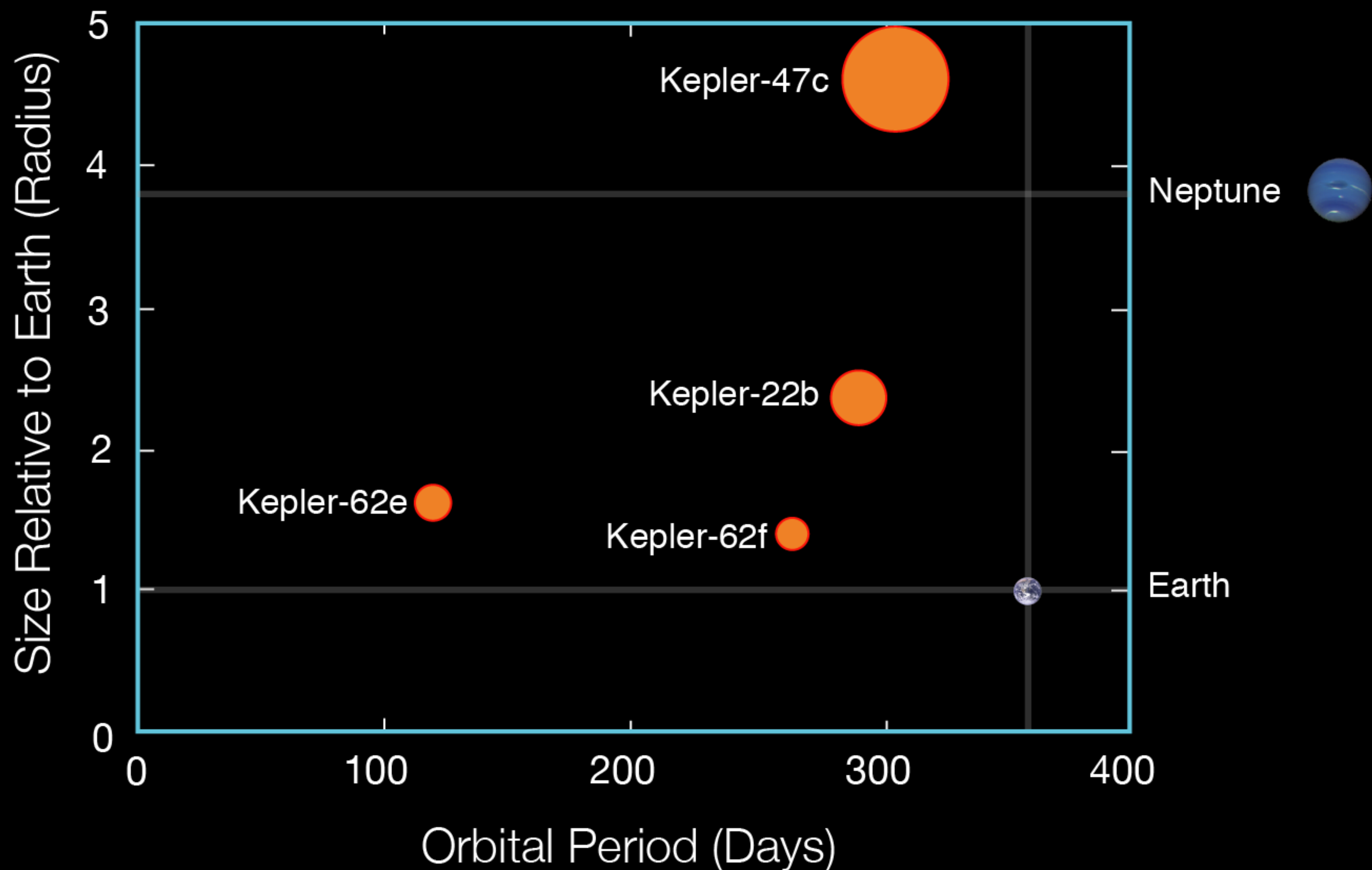

FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-
Neptune
4 - 6
Large
Neptune
>6
Gas
Giant
PLANET SIZE (relative to Earth)

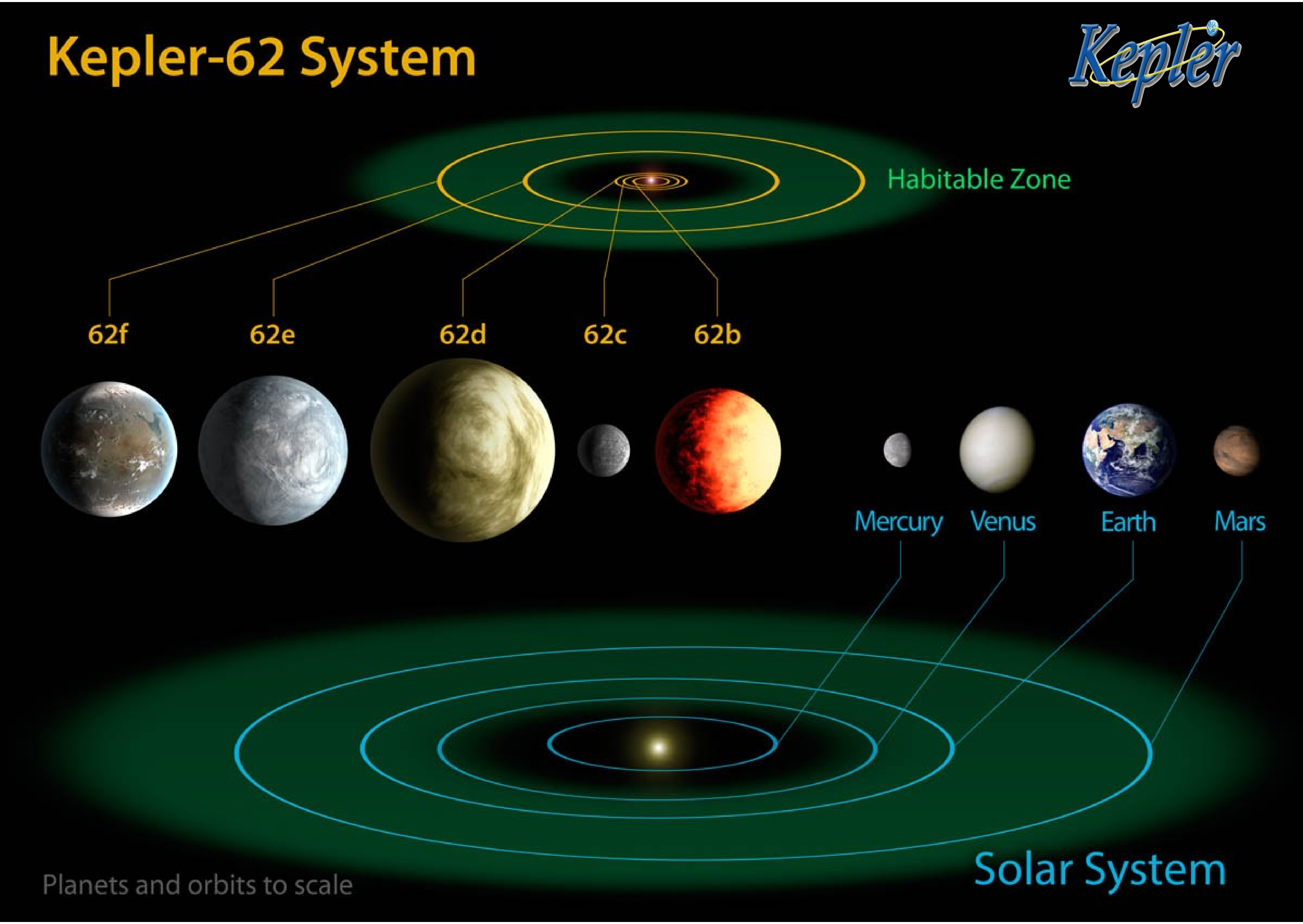
The Habitable Zone

(where water is liquid)

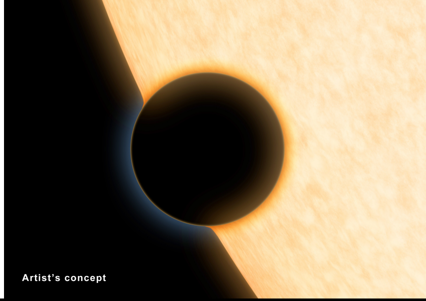


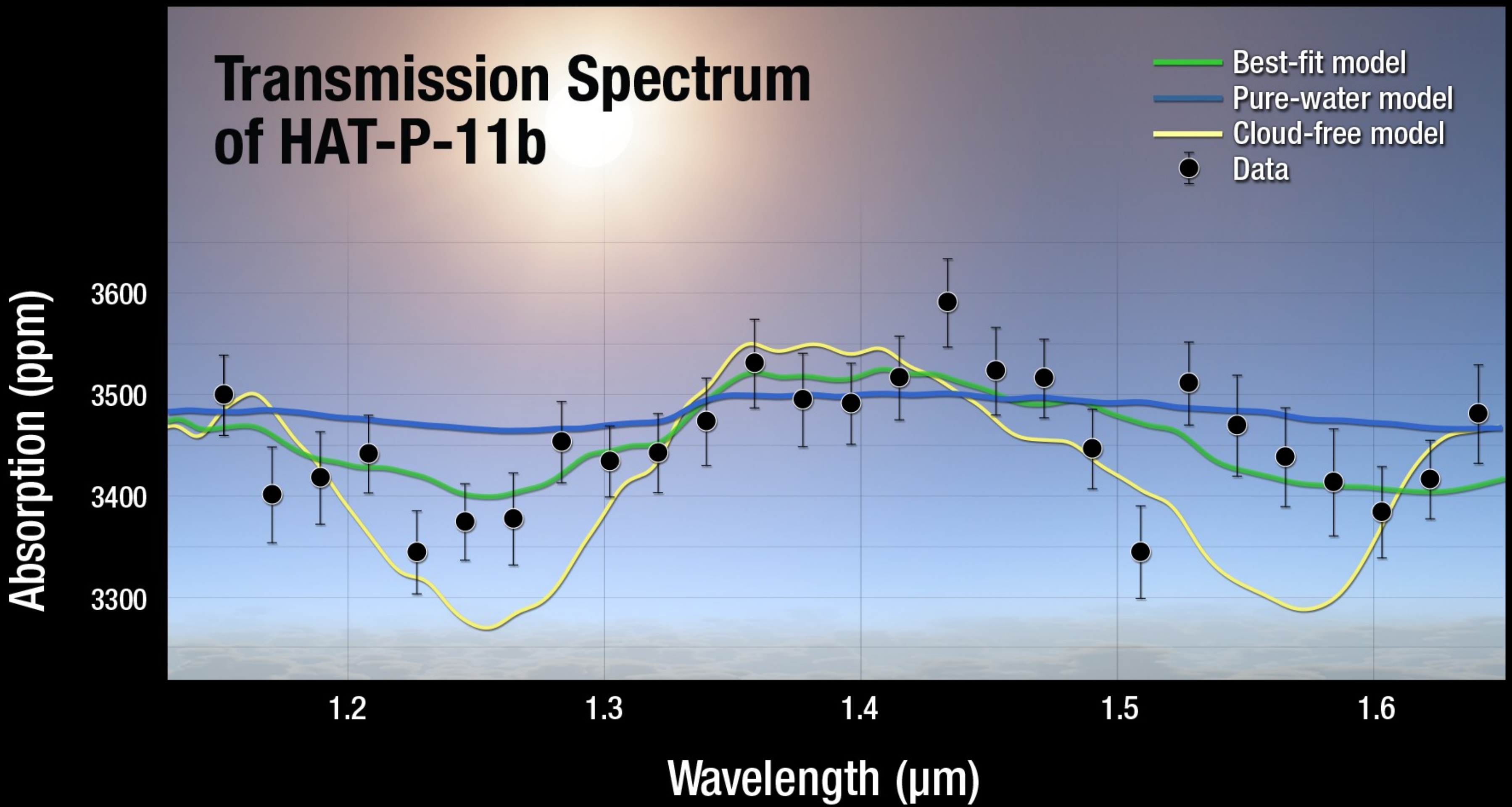
Kepler's Habitable Zone Planets

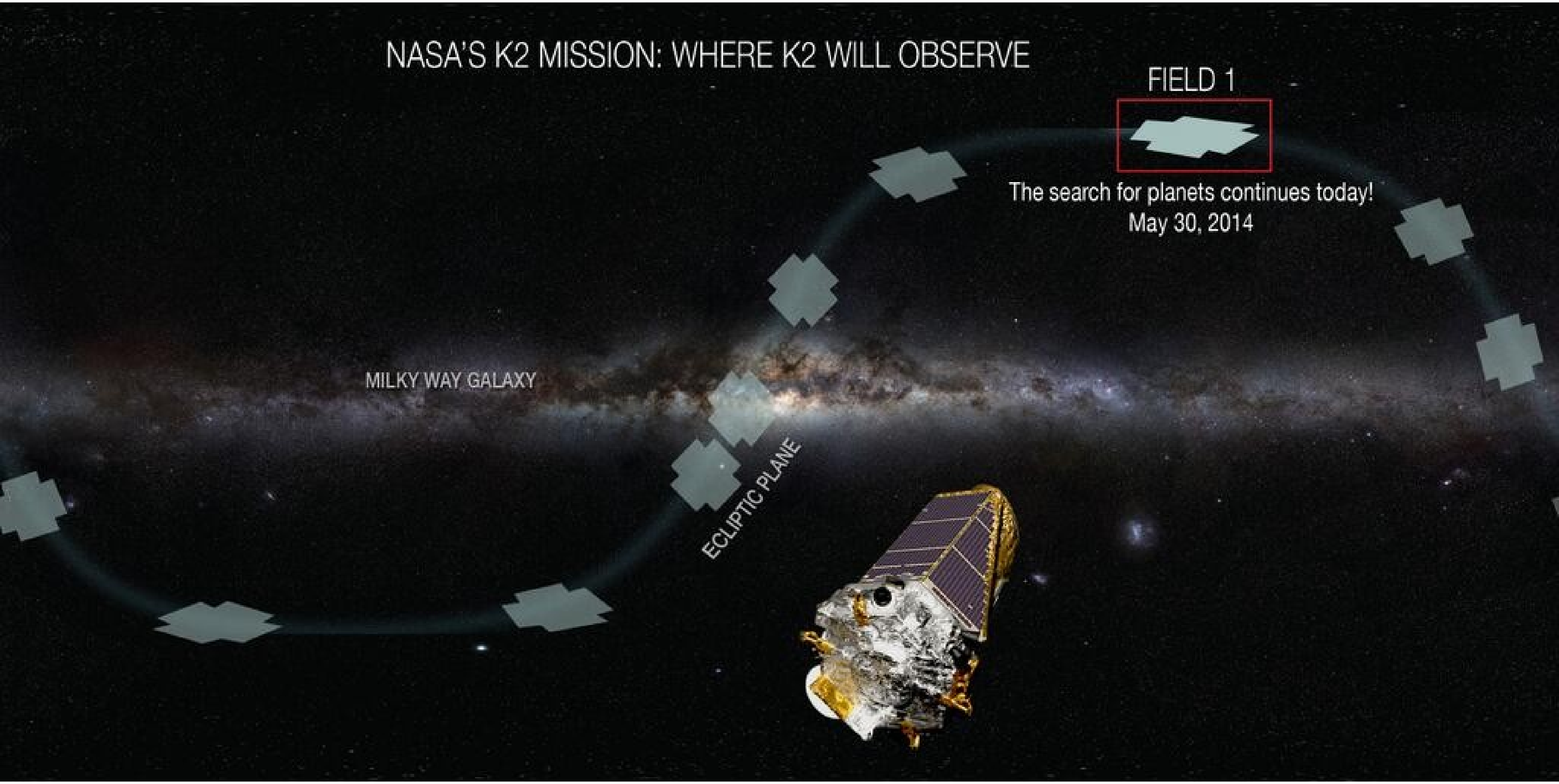




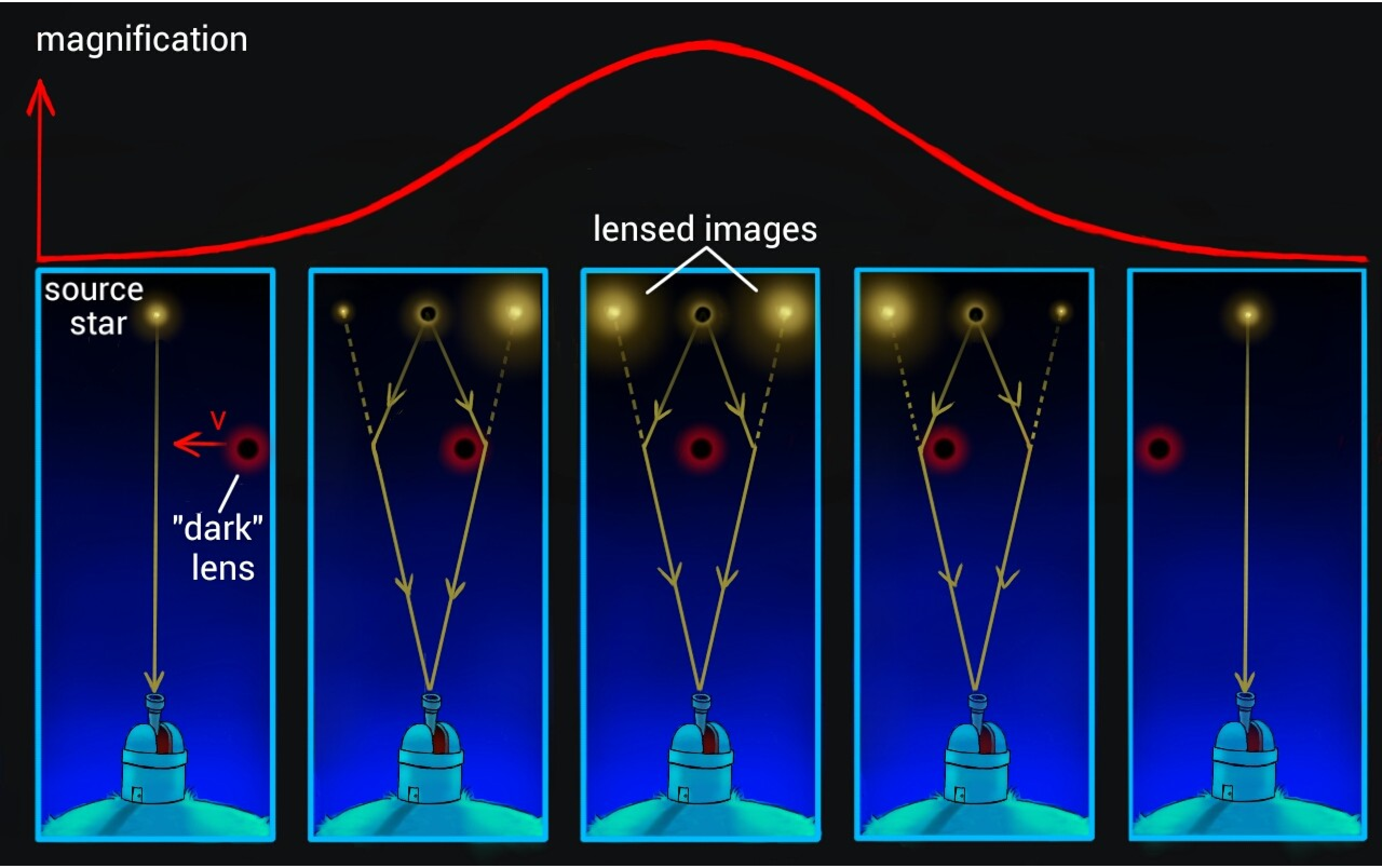
Kepler-62 System
Kepler
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

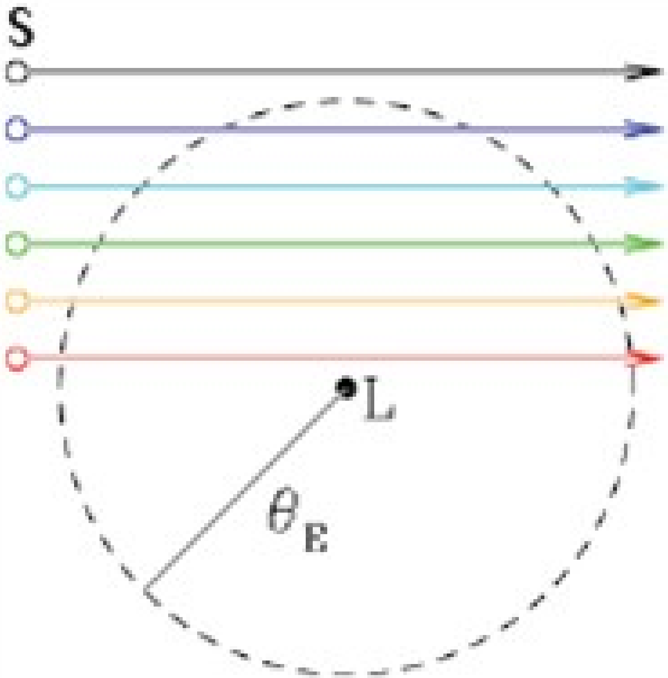

Artist's concept

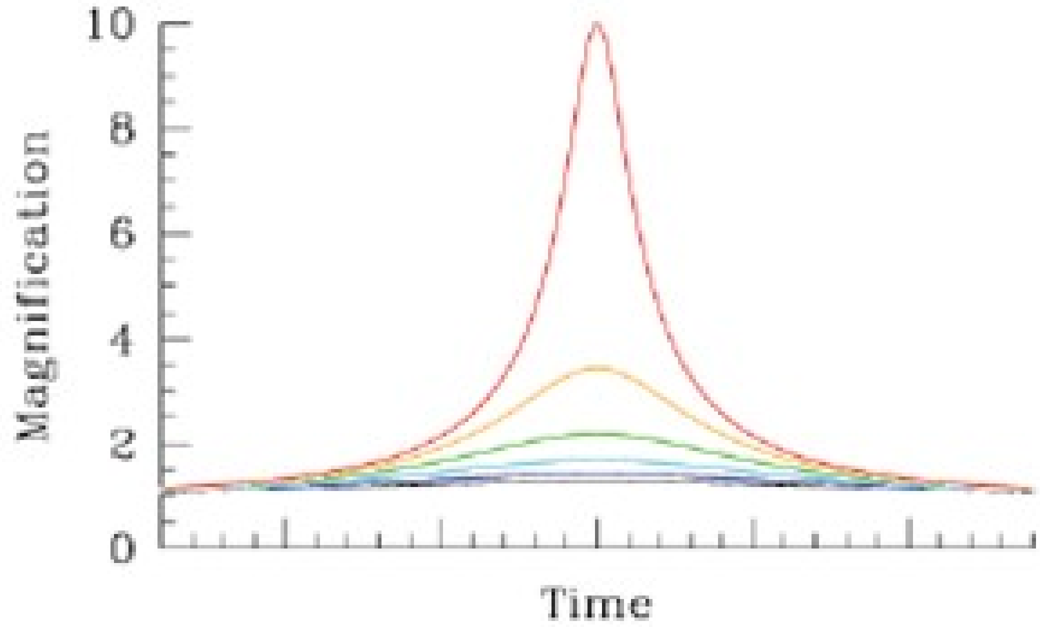

Transmission Spectrum
of HAT-P-11b
Best-fit model
Pure-water model
Cloud-free model
Data
Absorption (ppm)
3600
3500
3400
3300
1.2
1.3
1.4
1.5
1.6
Wavelength (μm)


NASA'S K2 MISSION: WHERE K2 WILL OBSERVE
FIELD 1
The search for planets continues today!
May 30, 2014
MILKY WAY GALAXY
ECLIPTIC PLANE

MICROLENSING METHOD







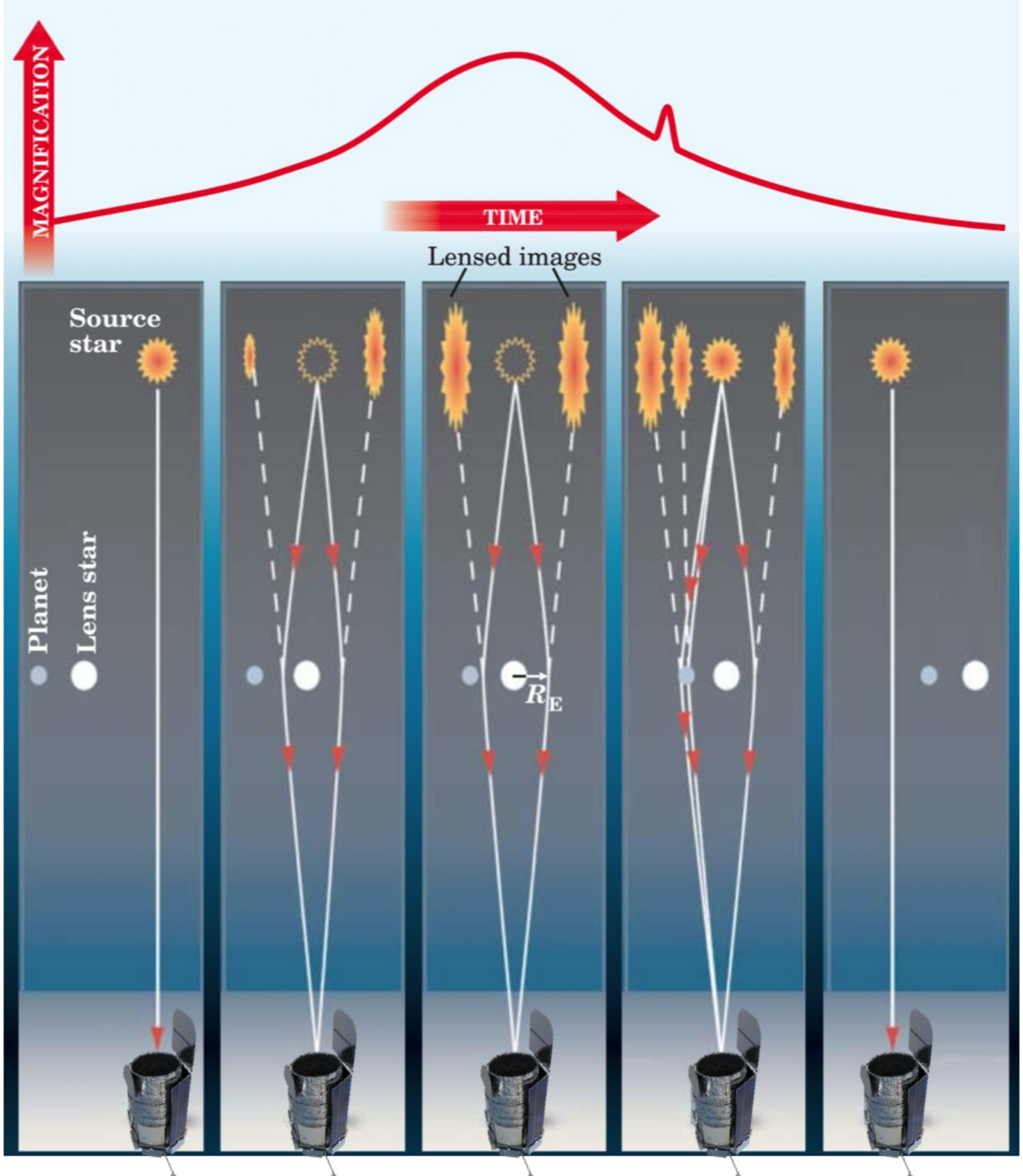
S … source object
L … lens object
θ_E … Einstein ring radius

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

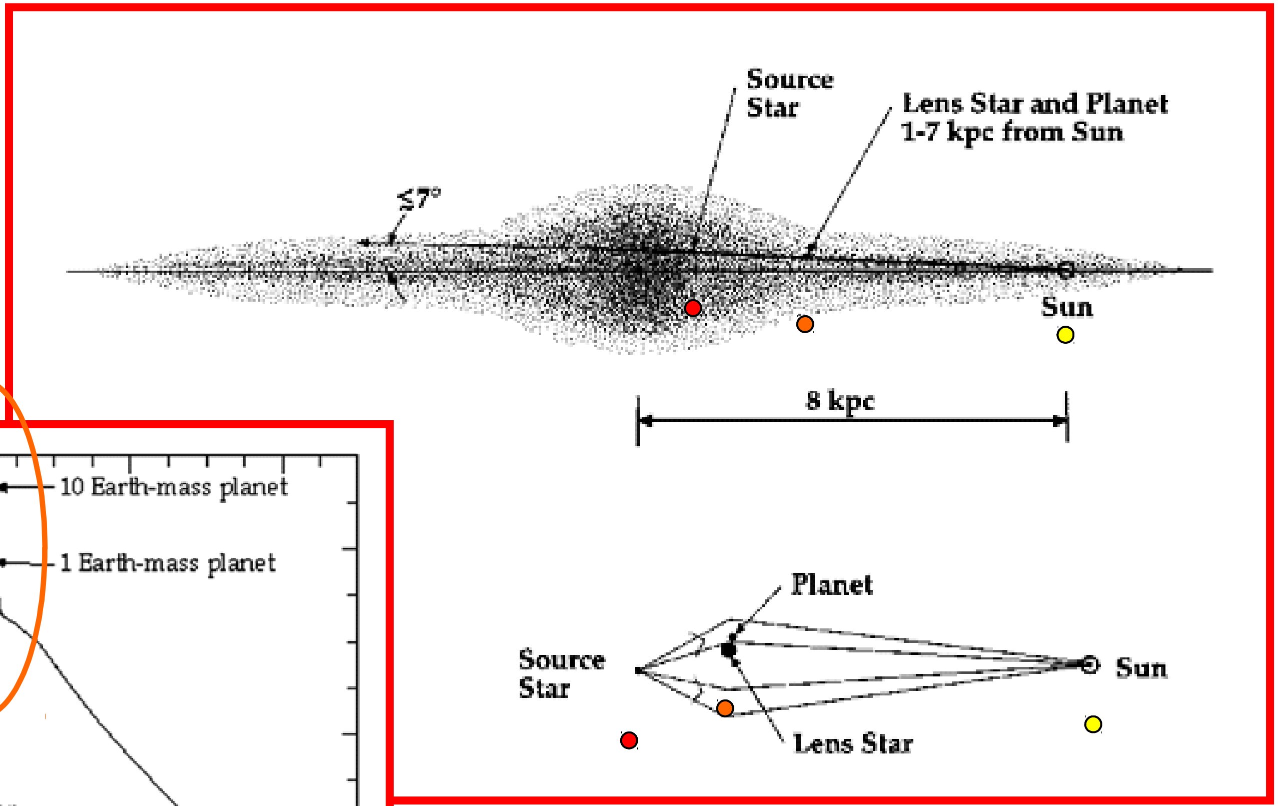
$$\theta_E \approx 0.1 \left(\frac{M \text{ in } M_\odot}{d_L \text{ in parsecs}} \right)^{1/2} \text{arcsec}$$

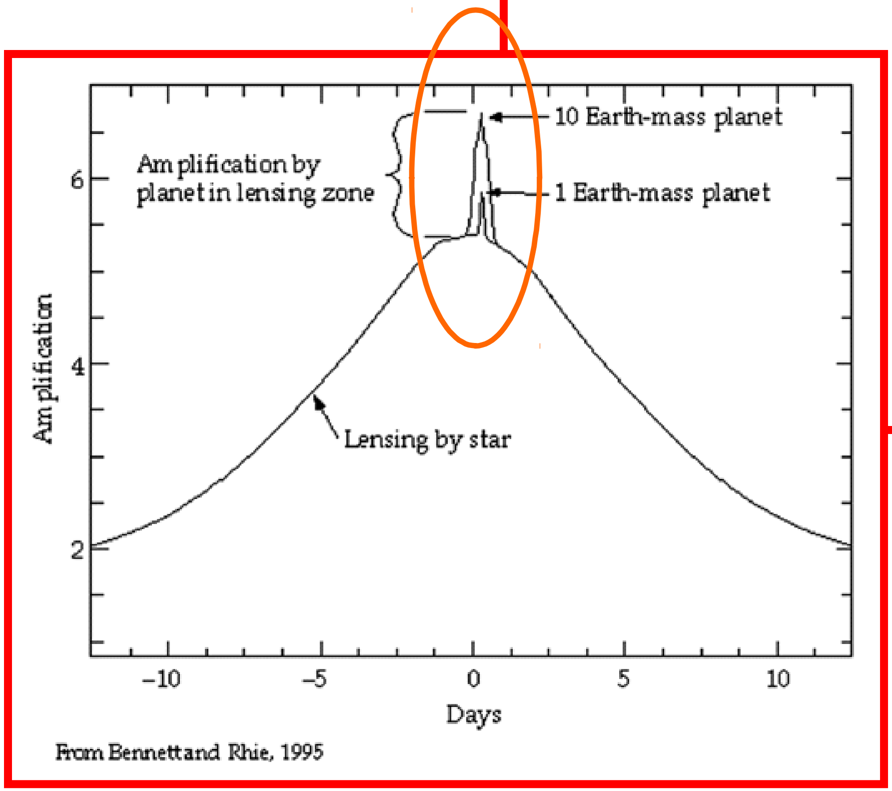
$$\theta_E = \left(\frac{4GM}{c^2} \; \frac{d_{LS}}{d_L d_S} \right)^{1/2}$$

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 METHOD

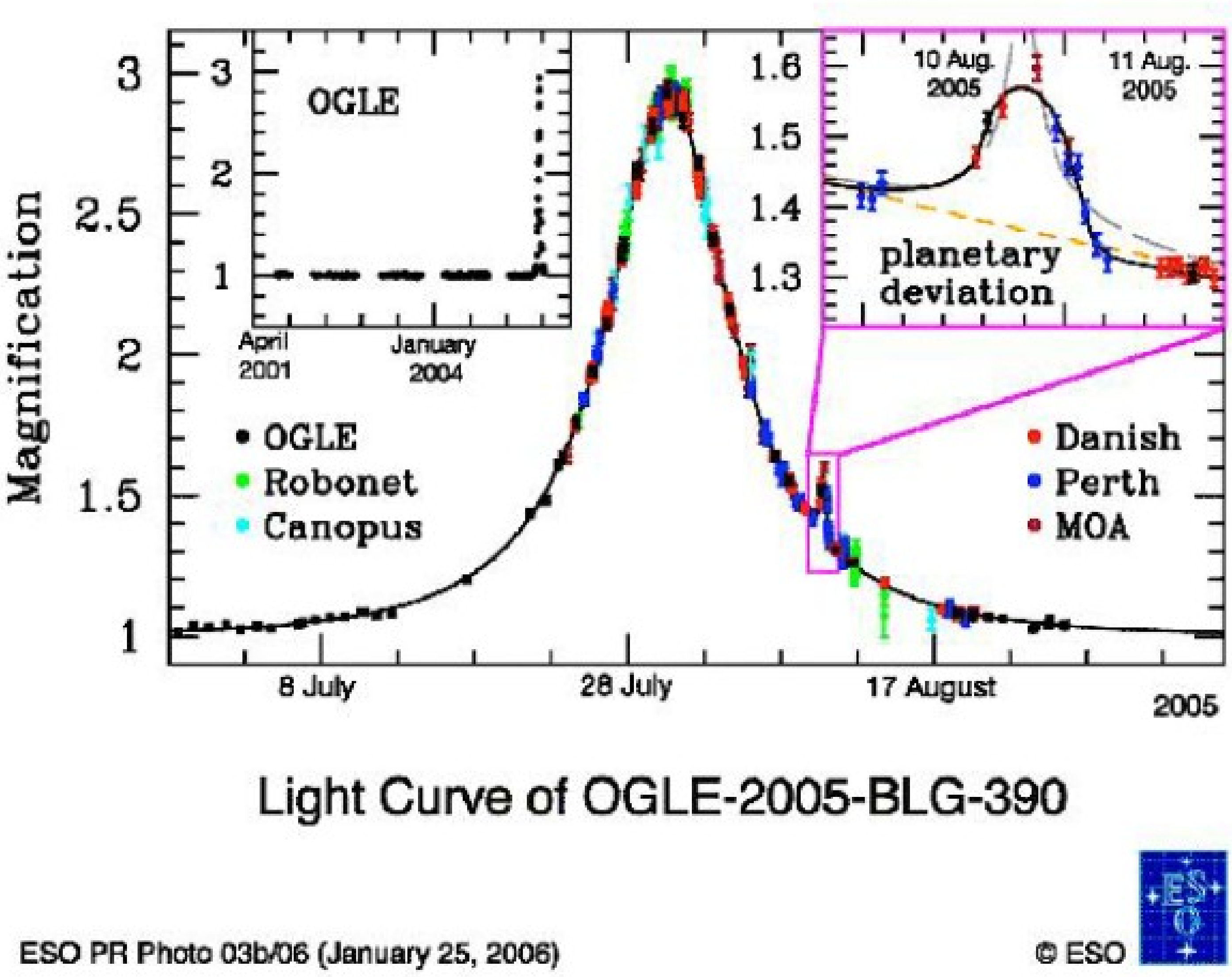




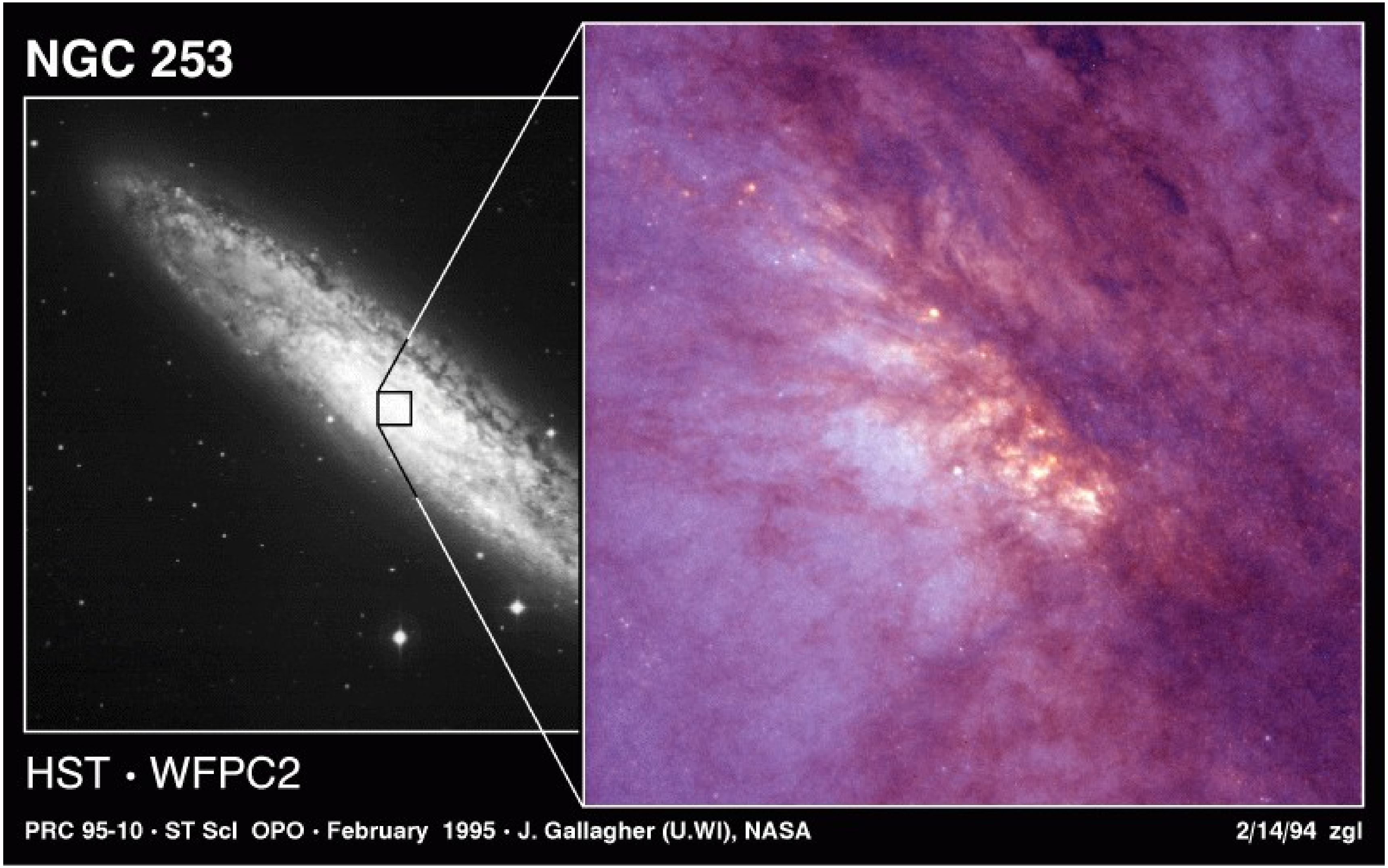
<u>Pros</u>: All masses and orbits and independent of star brightness

<u>Cons</u>: Distant planets and observation cannot be repeated

Earth mass planet detected with microlensing

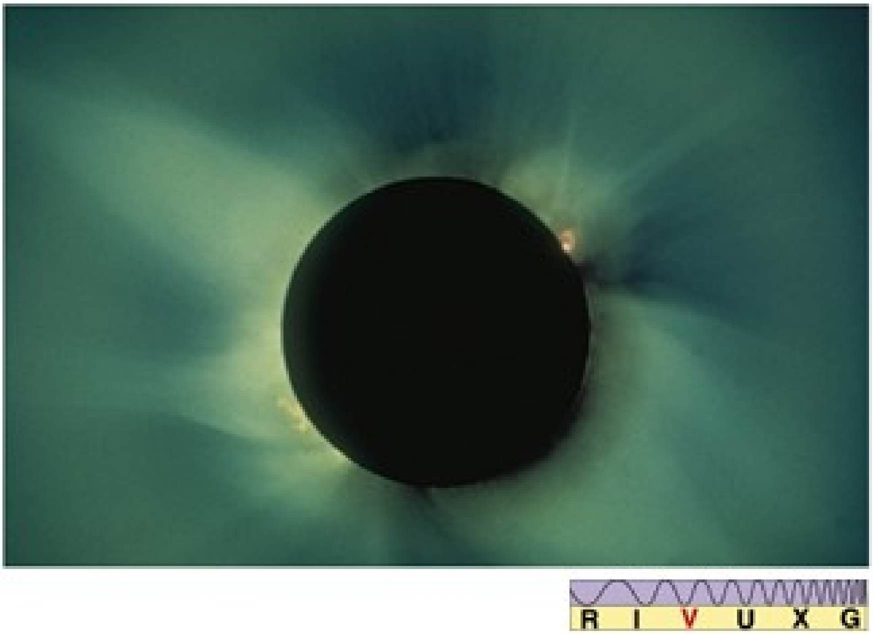


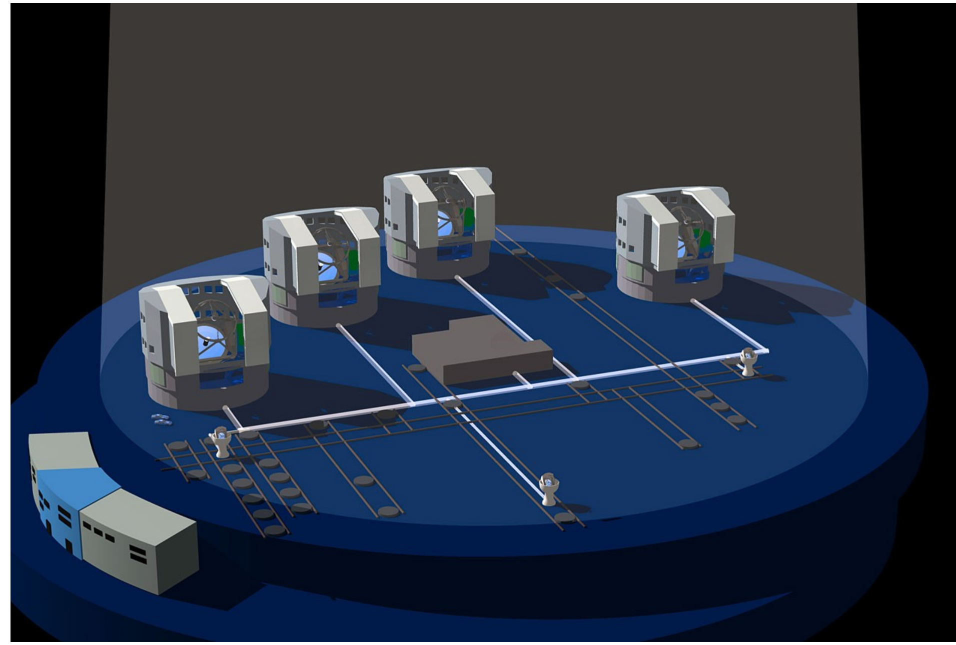
MICROLENSING METHOD



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

IMAGING METHOD

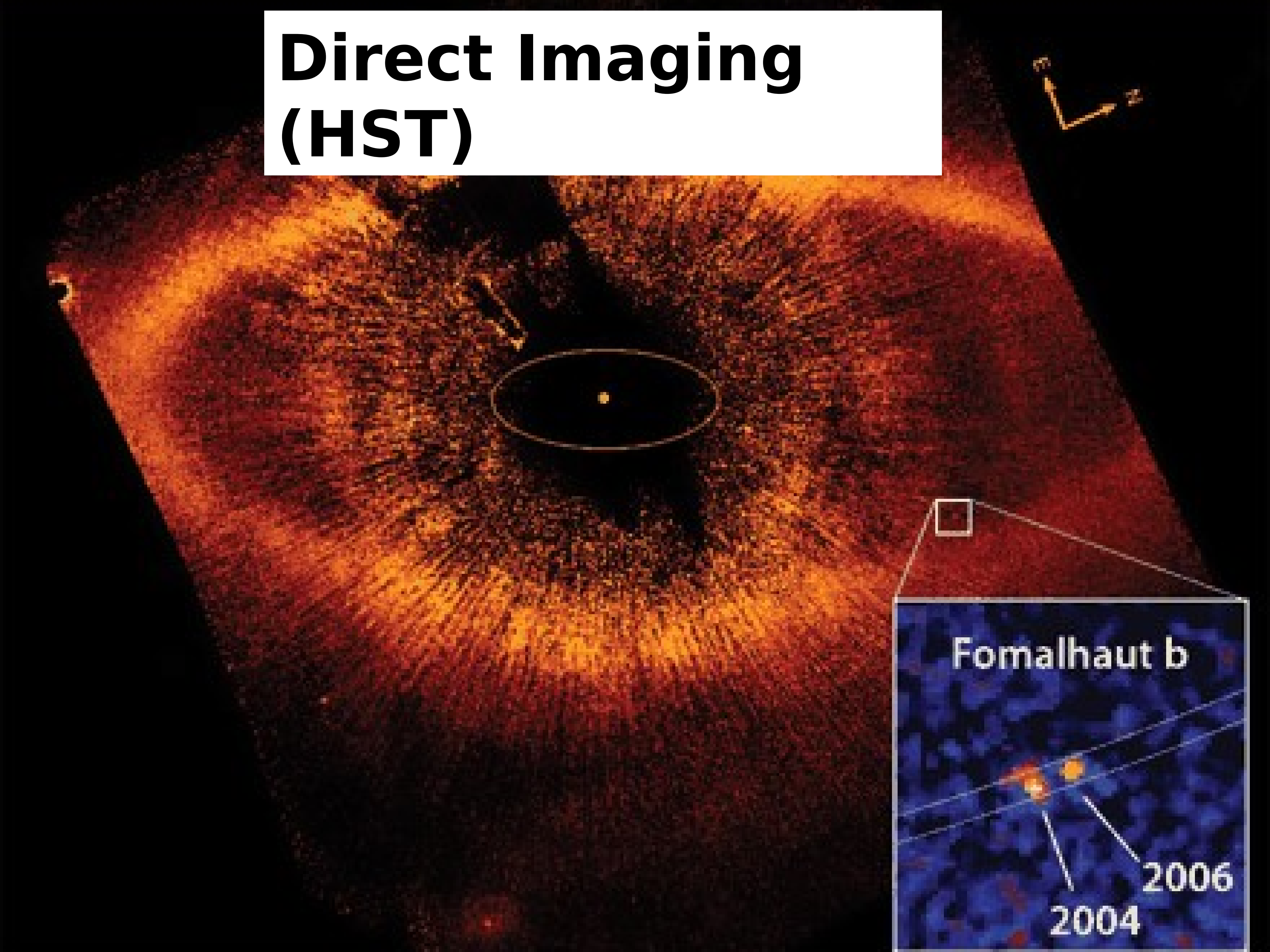


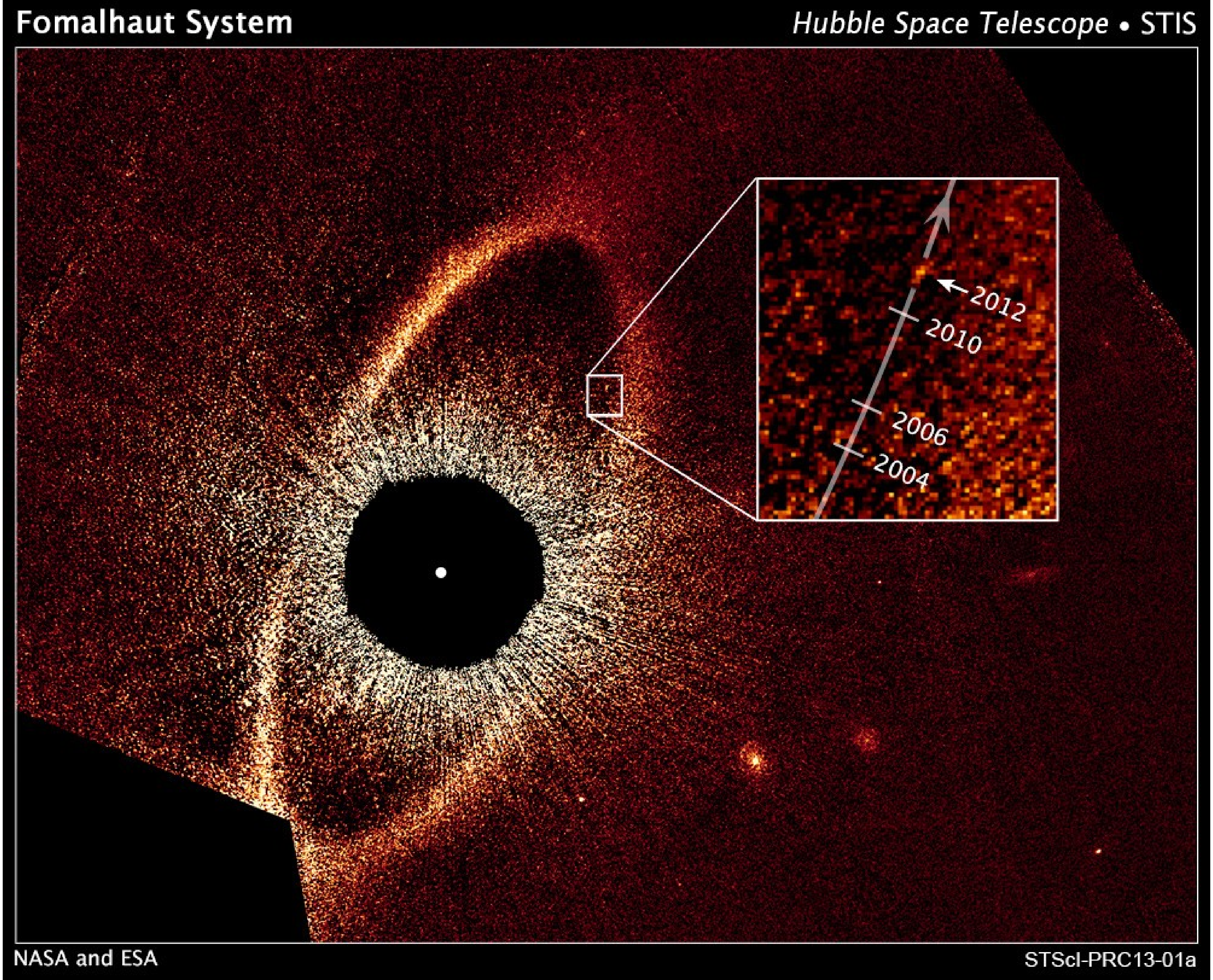


The star can be blocked out using a **coronagraph**

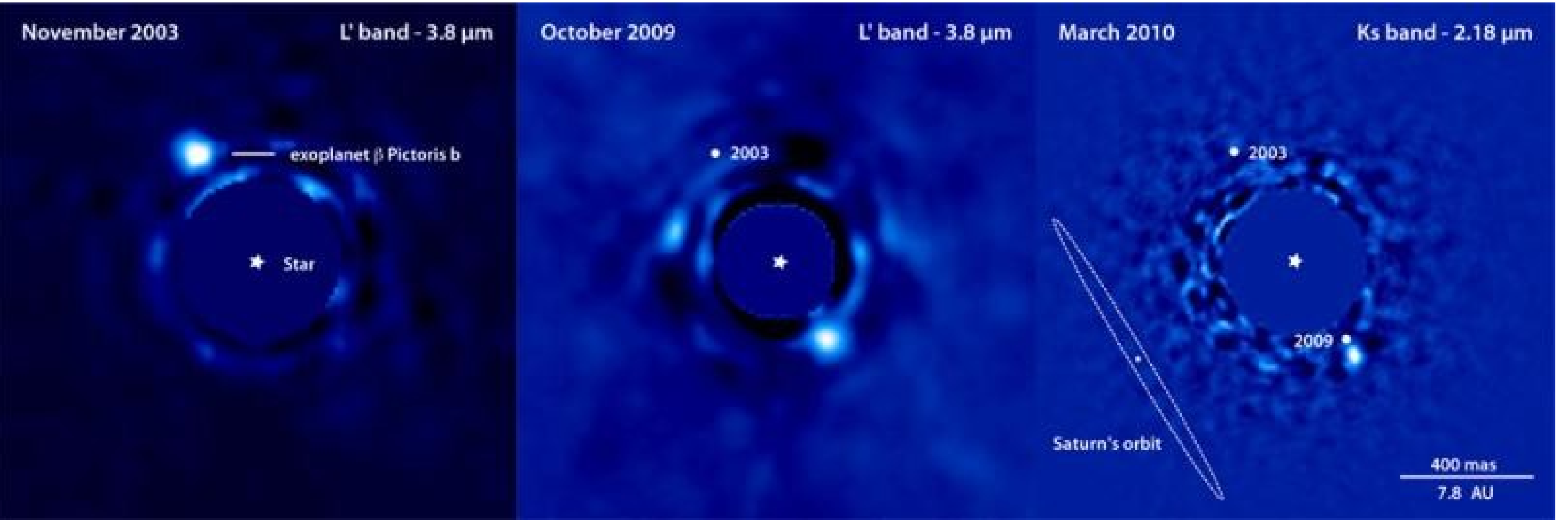
Now we can do it with **interferometers** (with excellent **spatial resolution** as a bonus!)

Direct Imaging (HST)




Fomalhaut System
Hubble Space Telescope • STIS
2012
2010
2006
2004
NASA and ESA
STScI-PRC13-01a

Beta Pictoris b imaged with VLT, NaCo (infrared)



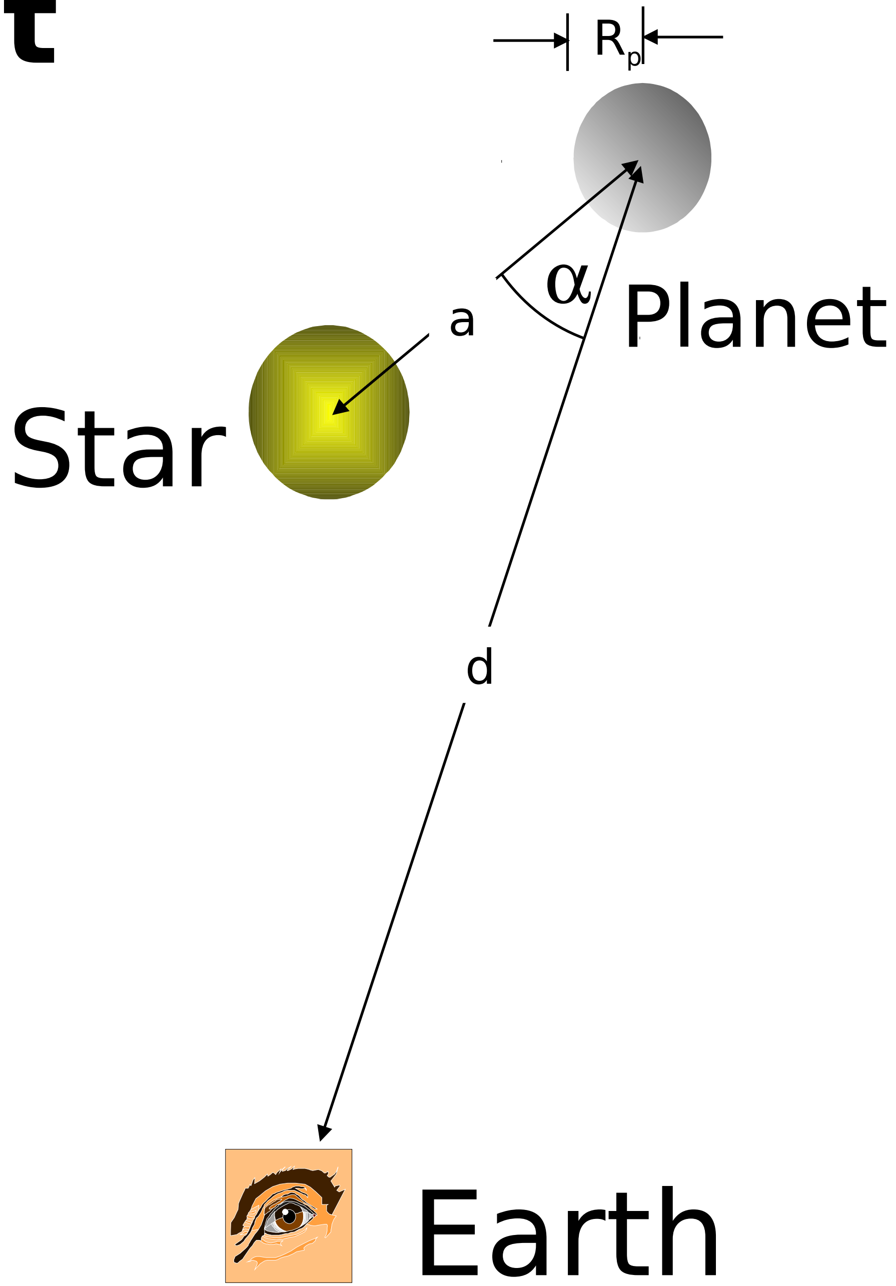
M ≈ 10 Jupiter masses; T ≈ 1500° C

Reflected Light

planet/star flux ratio is:

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

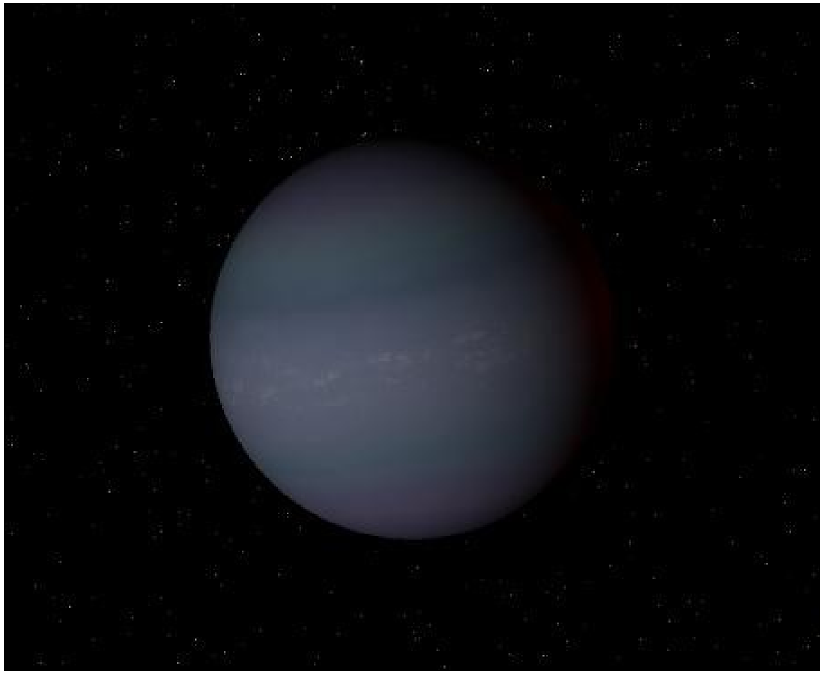
p is albedo



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

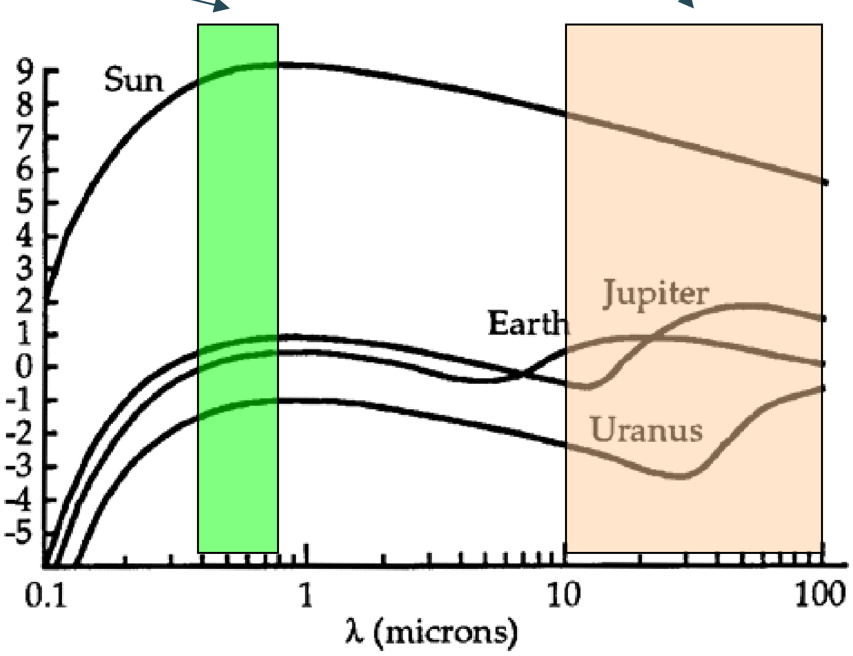
Sudarsky et al. 2000



Picture of class IV planet generated using Celestia Software

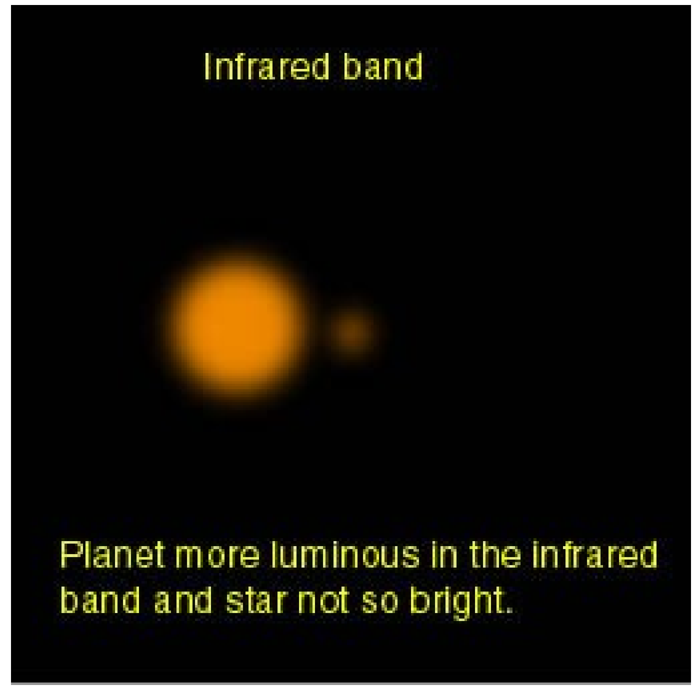
IMAGING METHOD

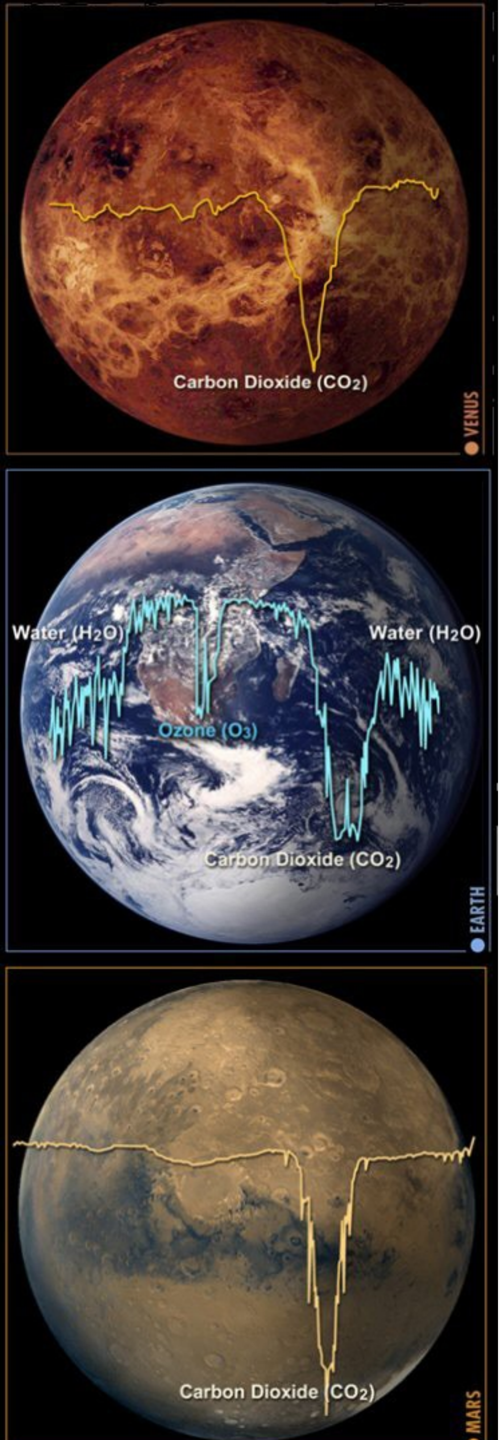
Optical: star/planet = 1 billion = 10^9 Infrared: star/planet = 1 million = 10^6



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

IMAGING METHOD

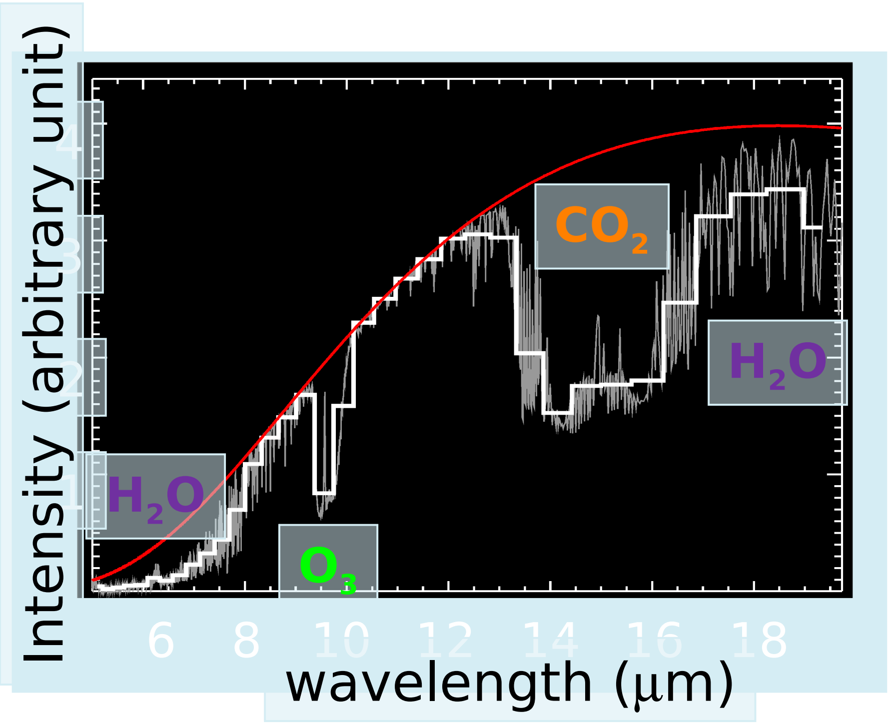


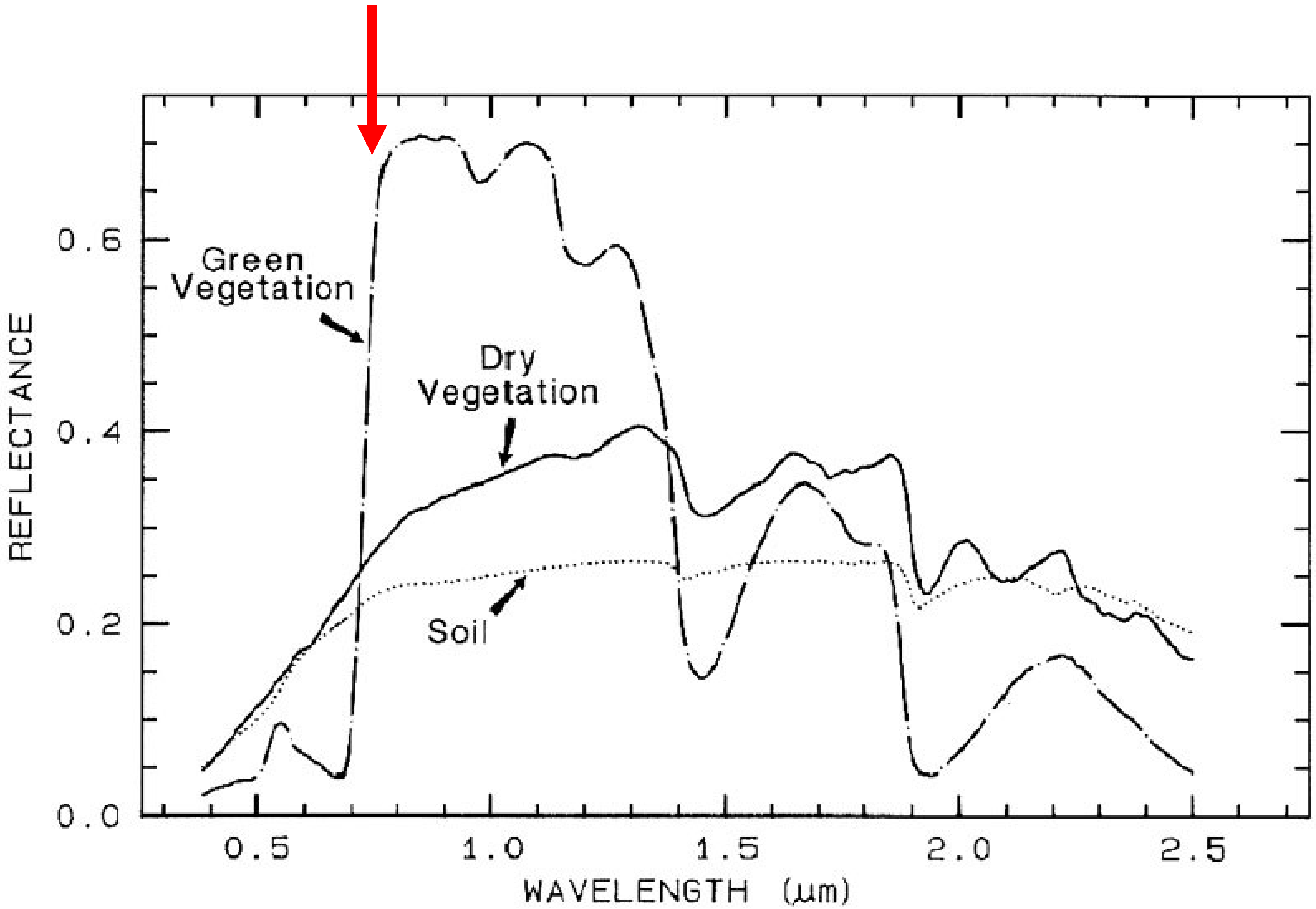


Exoplanets Spectroscopy

To look for key molecules

$$\{CO_2 + H_2O + O_3\}$$

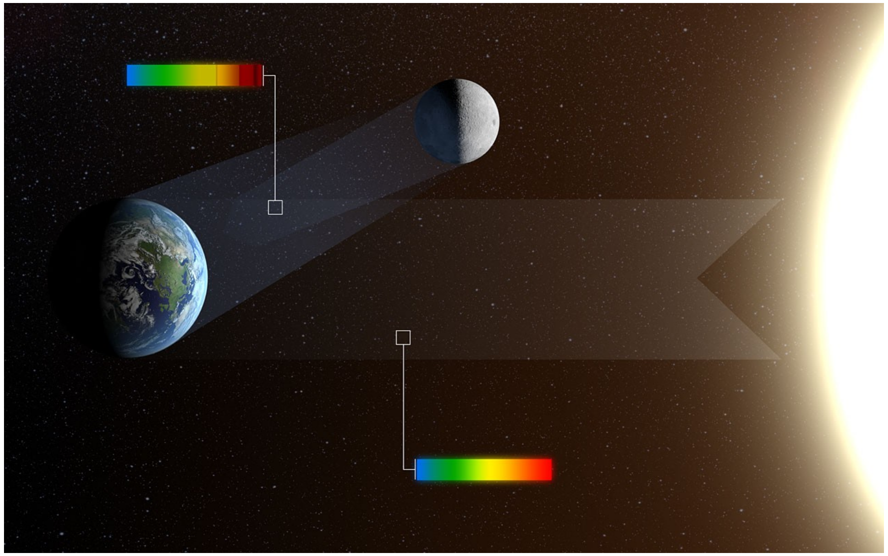




The “red edge” is a signature of vegetation on Earth.

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