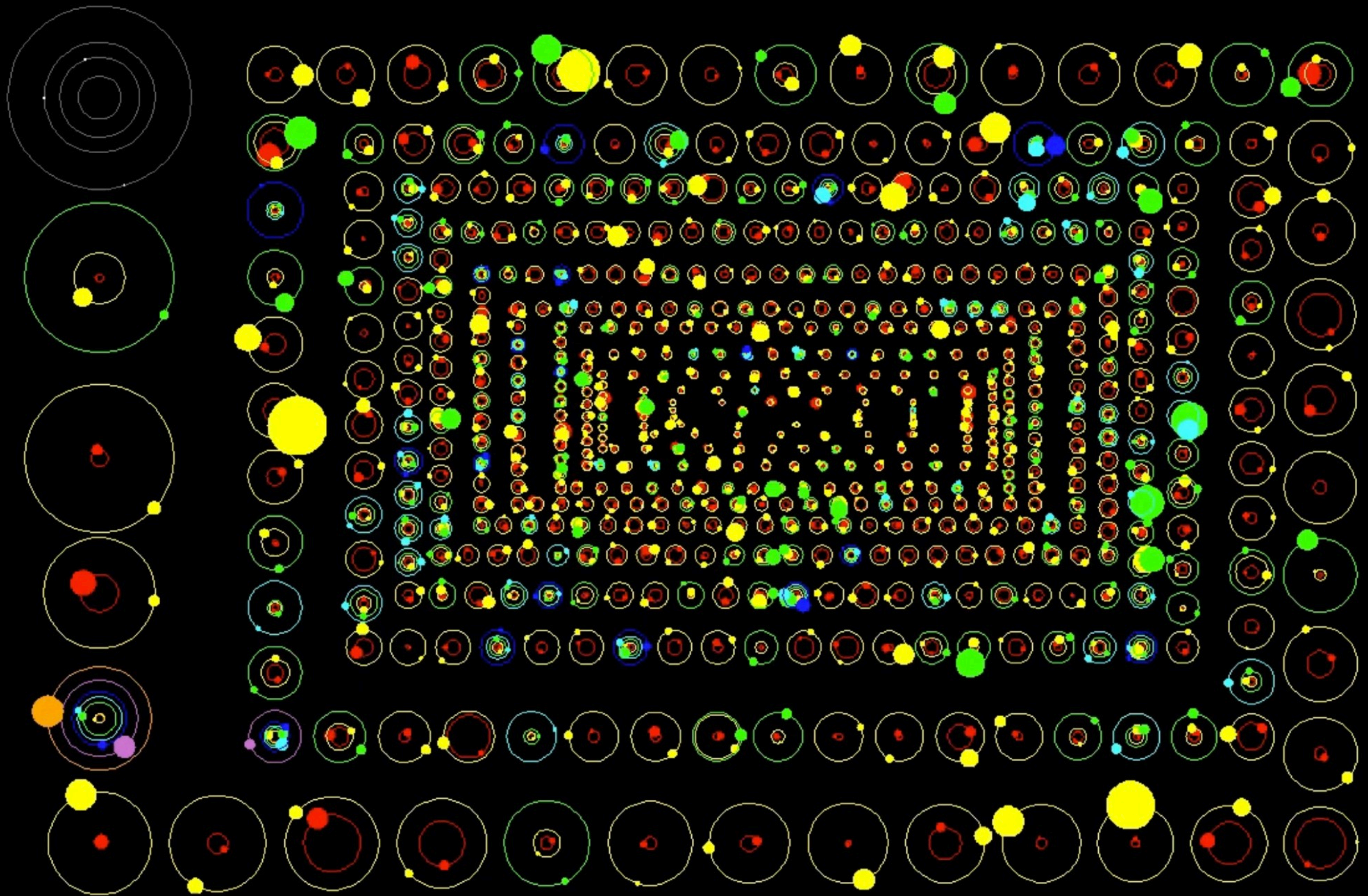
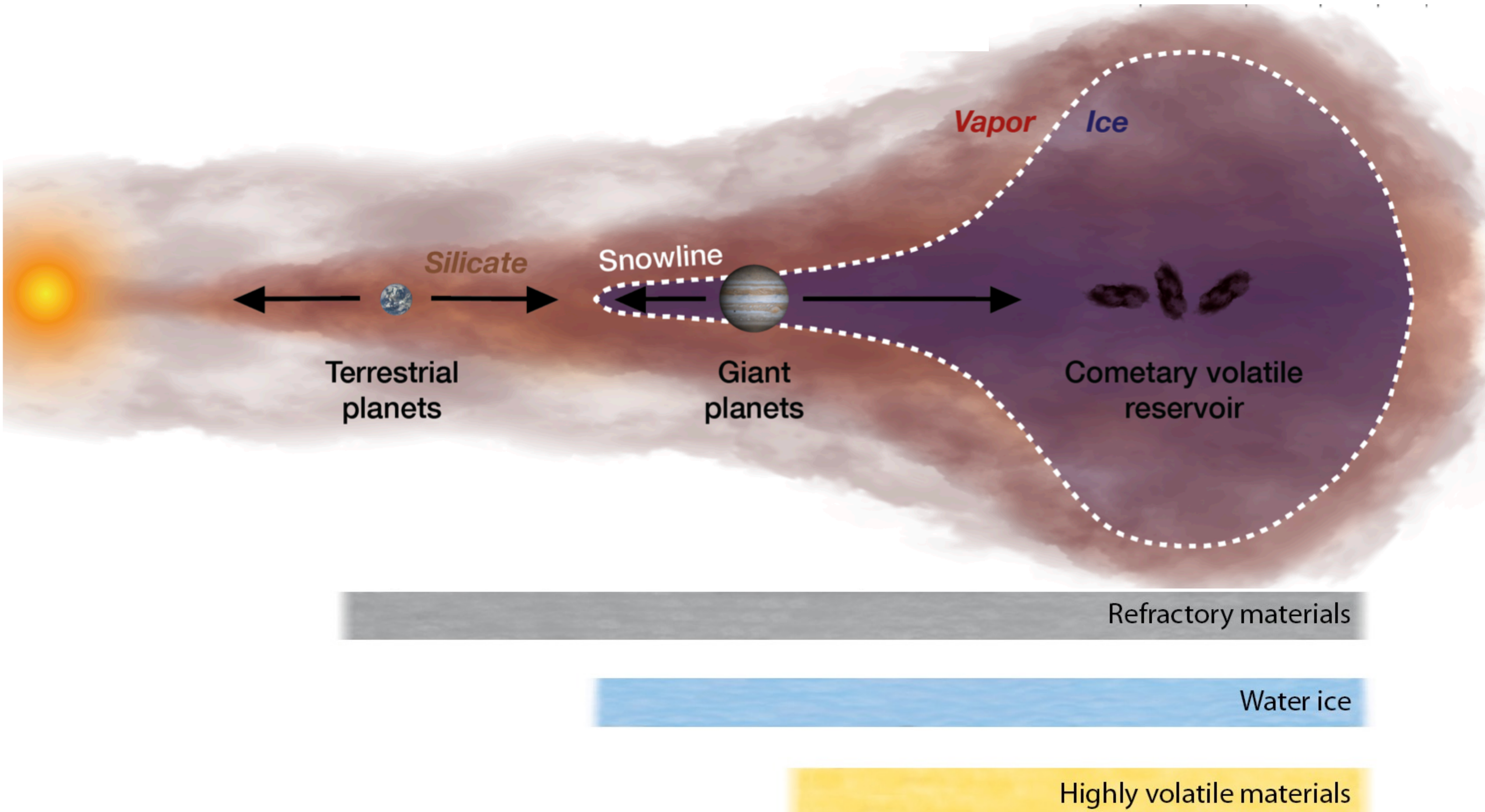
# Chap 8: Exoplanetary Systems

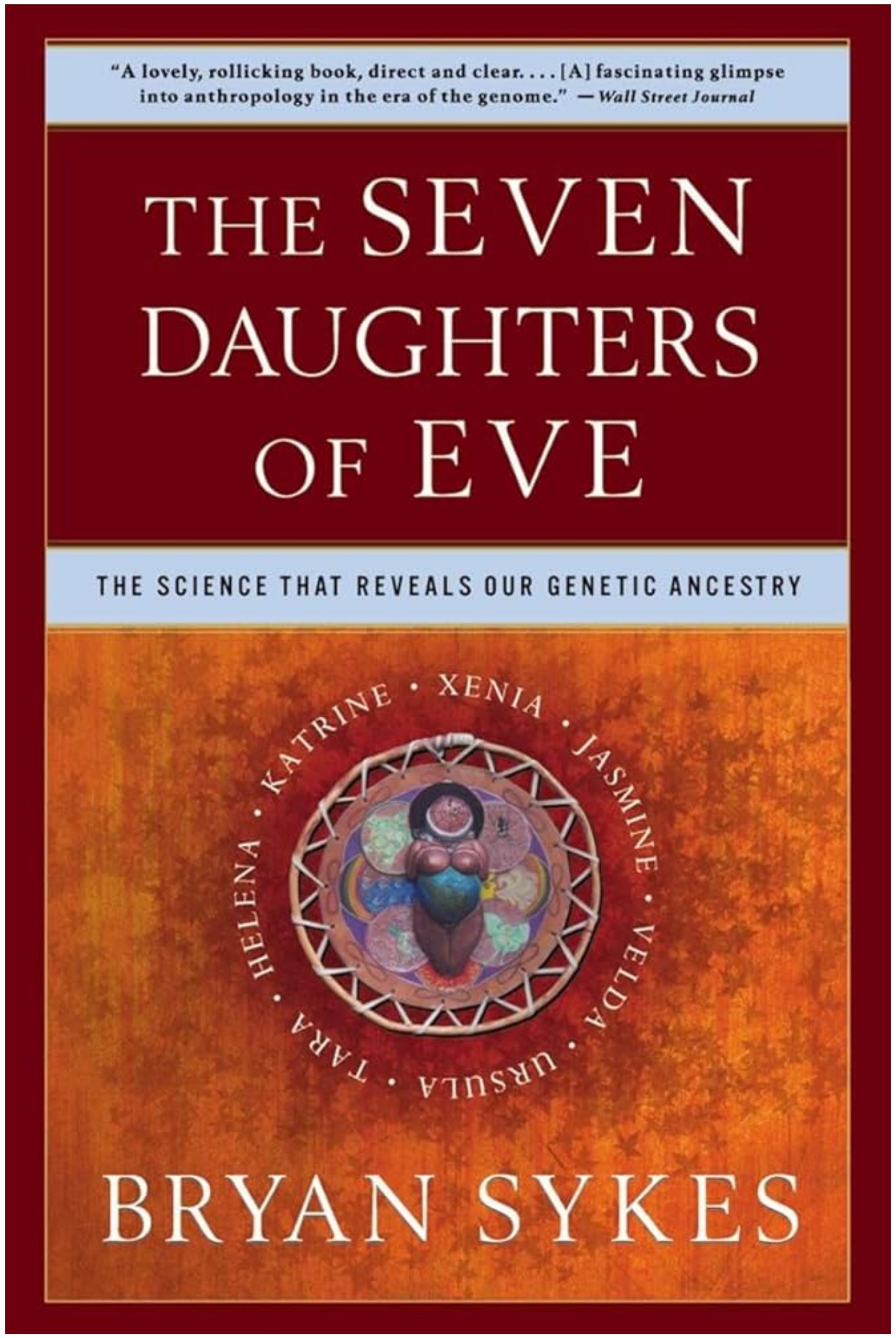


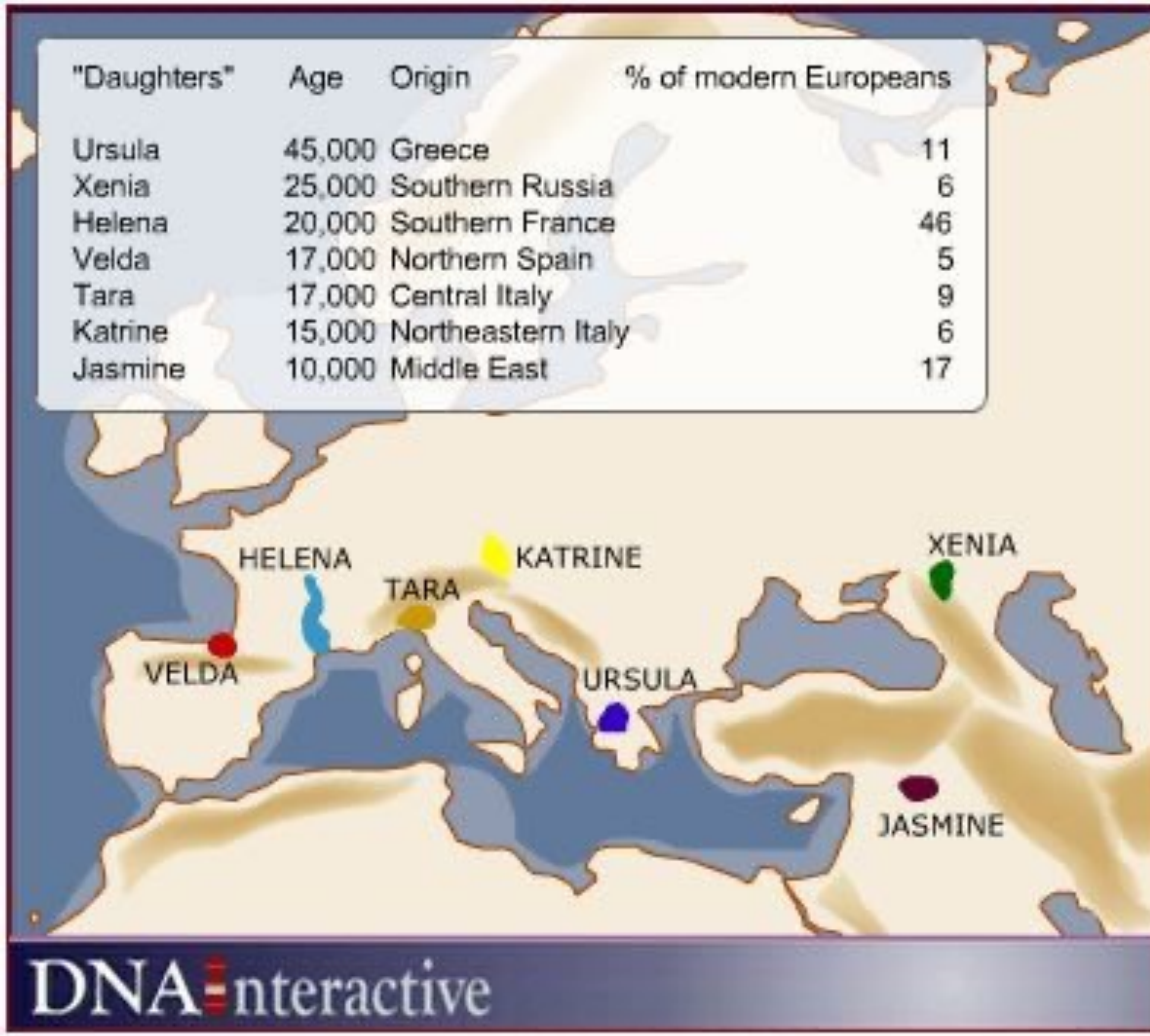
## Stellar wind from the proto-Sun removed most of the gas from the disk when $T_{disk}$ ~ 650 K at 1 AU, which explains the absence of gas giants in the inner system

Pontoppidan, et al. 2019



# Should we only be interested in the origin of the Solar system?



# Chap 8: Exoplanetary Systems

- The Search for Exoplanets
  - **Indirect methods**: Timing Variations, Radial Velocity, Transit
  - **Direct method**: Coronagraphic imaging
- Characterizing Exoplanetary Systems
  - **Period** v. **Radius**, Period v. **Mass**
  - Hot/cold Jupiters, Super-Neptunes, Super-Earths
- The Drake Equation (***N = L in years***)
  - How many advanced civilizations are in the Milky Way?
  - This type of estimation is called “Fermi Estimation”

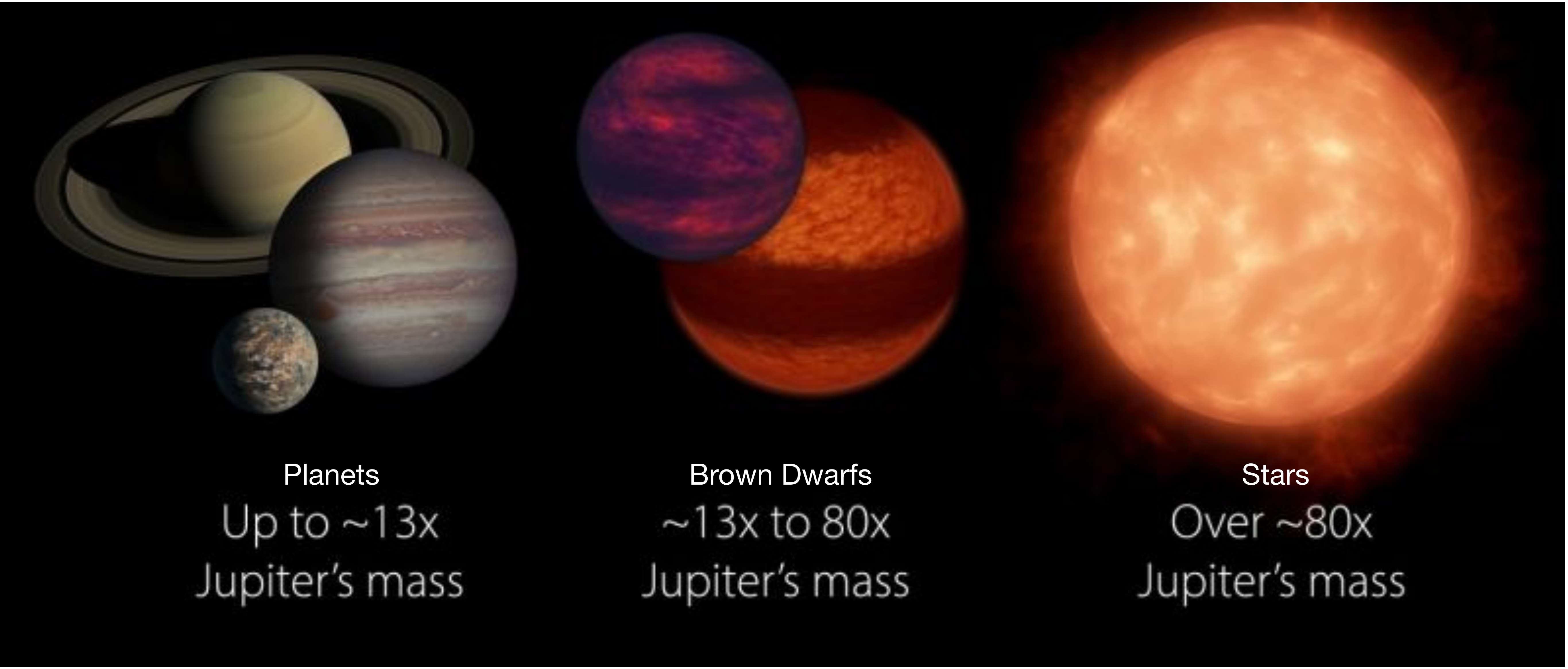
# The Search for Exoplanets

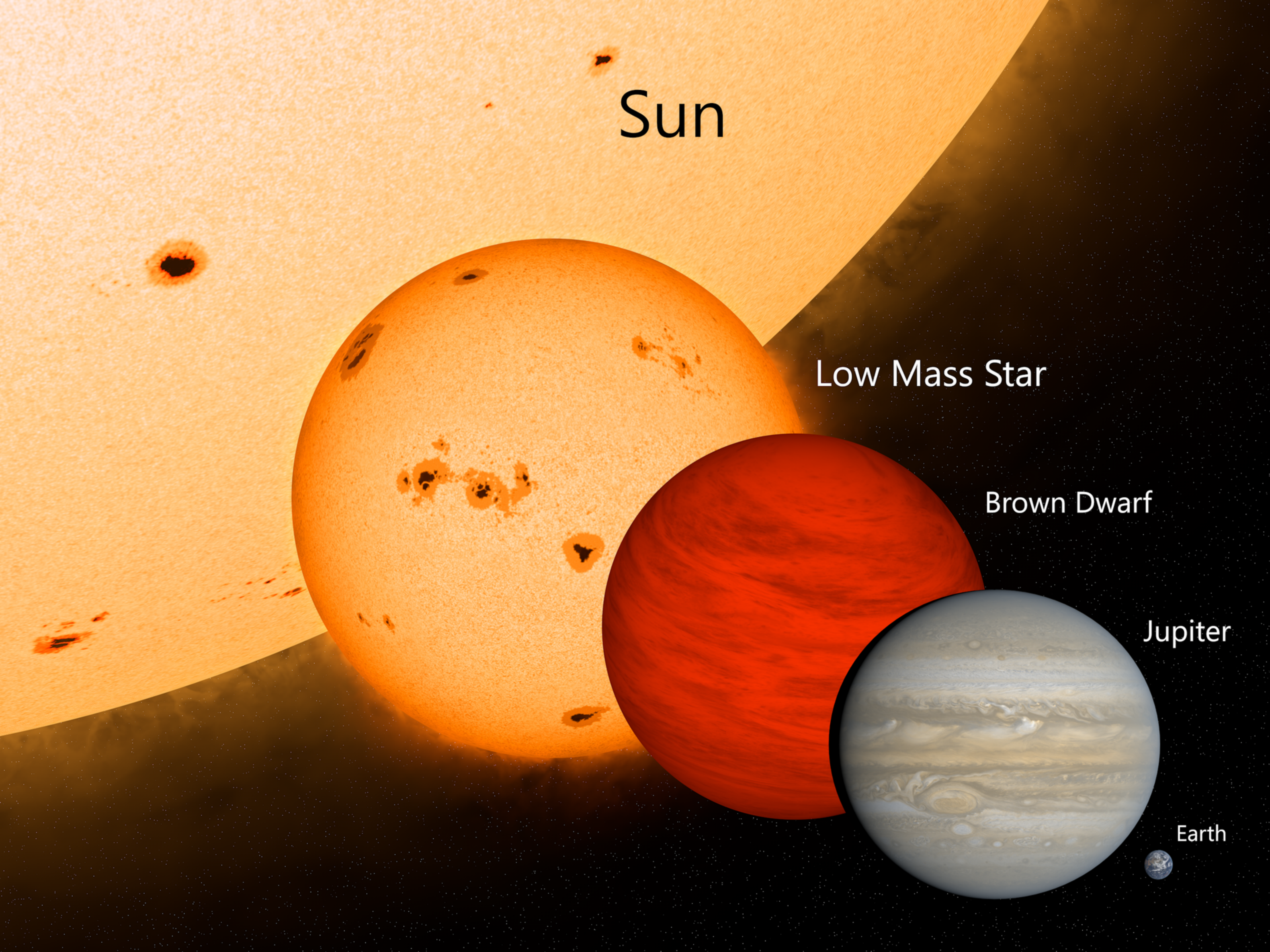
*introduction*

# Is it a planet or a star? How do we define a planet?

# Planets, Brown Dwarfs, and Stars

- **1 Jupiter mass = 318 Earth masses = 0.001 Solar mass**
- **Planets** are objects with mass less than **13 $M_{Jupiter}$**
- **Stars** are objects with masses greater than **80 $M_{Jupiter}$**, massive enough to sustain nuclear fusion of hydrogen.
- **Brown Dwarfs** are substellar objects with mass between 13 and 80 $M_{Jupiter}$; They fuse **deuterium** and **lithium** instead of hydrogen.




Sun
Low Mass Star
Brown Dwarf
Jupiter
Earth

## Historical Timeline of Exoplanet Discoveries

- 1984 - first protoplanetary debris disk discovered around $\beta$ **Pictoris**
- 1992 - first exoplanets (rocky) discovered around a pulsar: **PSR B1257+12**
- 1995 - first exoplanet (hot Jupiter) discovered around a main-sequence star: **51 Pegasi**
- 1999 - first transiting exoplanets discovered around **HD 209458**

- 2009 - Kepler planet-finding mission launched.
- 2018 - Transiting Exoplanet Survey Satellite (TESS) launched
- 2023 Nov: 5,539 exoplanets in 4,123 systems, with 937 multi-planet systems.

β Pictoris is a 4th magnitude A-type main-sequence star
It is surrounded by a thin disk of dust, comets, and asteroids
reaching 400 AU from the star, discovered in 1984 by Smith & Terrile

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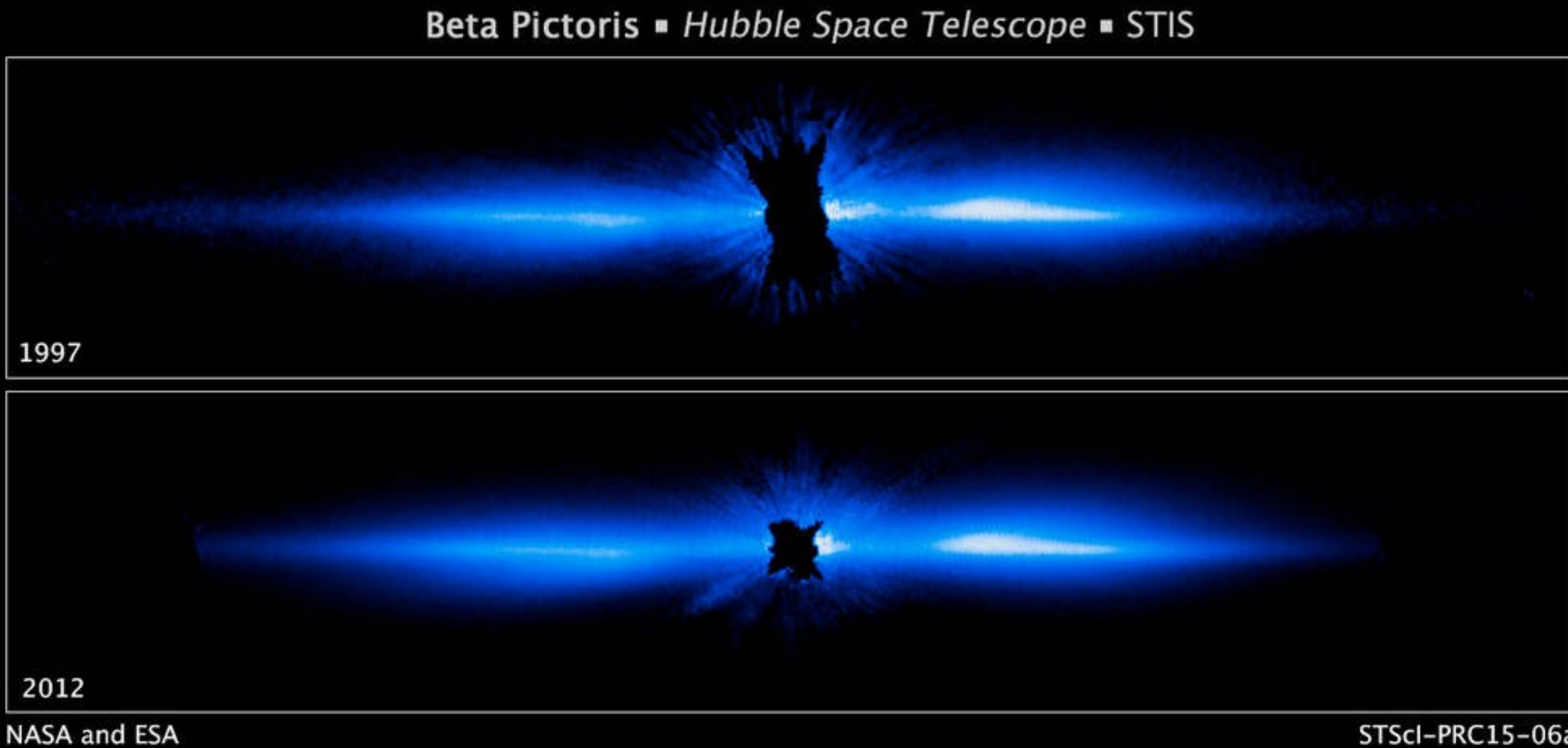
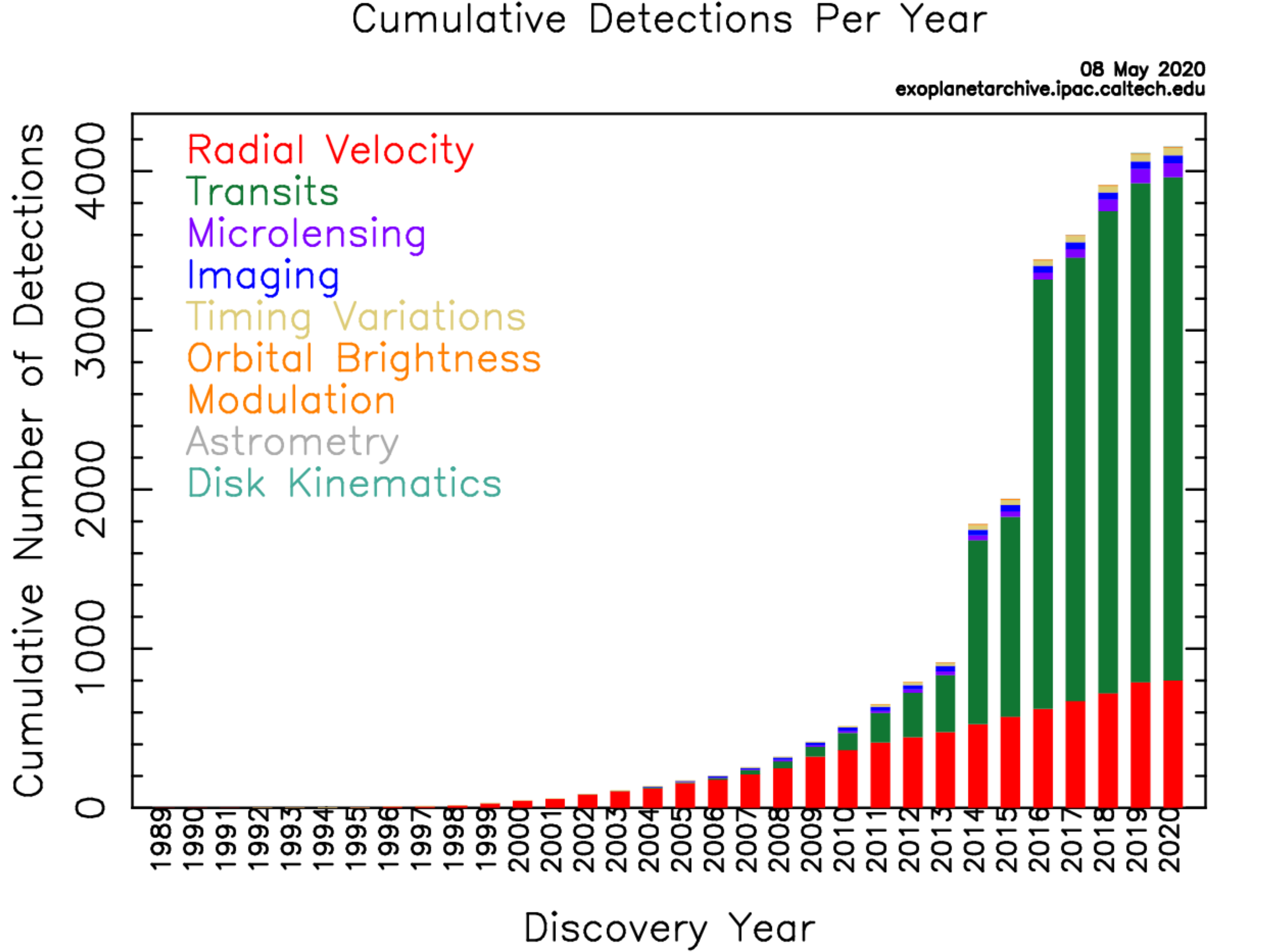


# Exoplanet Census

For planets with both measured or estimated orbital period and mass


Cumulative Detections Per Year
08 May 2020
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
1000
2000
3000
4000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
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2004
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2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Discovery Year

# The Search for Exoplanets

*indirect and direct techniques*

“Absence of evidence is NOT evidence of absence”
- Carl Sagan (1934-1996)

## Indirect methods for searching exoplanets and their biases

- *Clever methods to **infer** the existence of invisible bodies*

- Timing technique: **periodic anomalies**
  - biased towards uninhabitable worlds :)

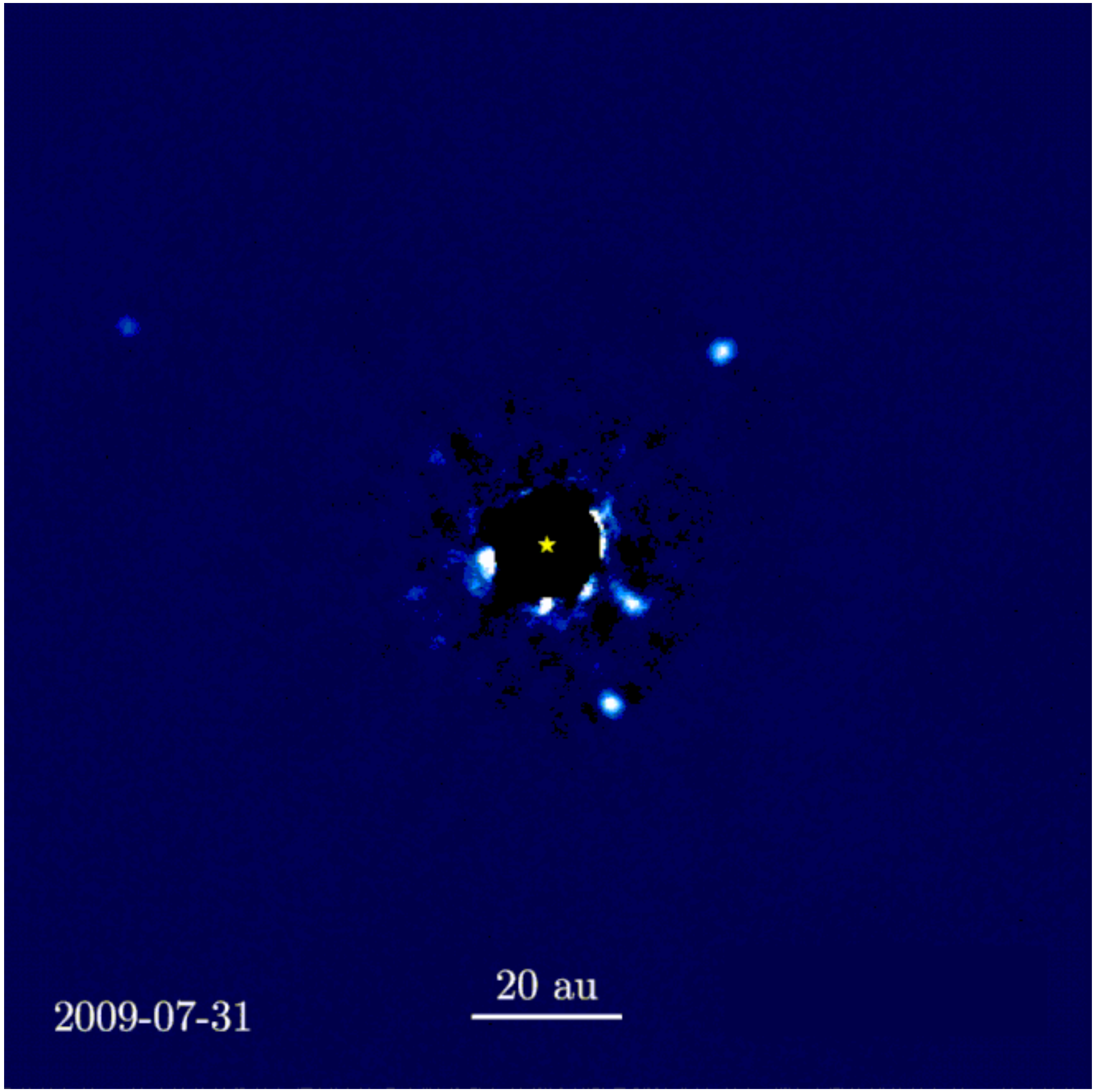
- Spectroscopic technique: **radial velocity**
  - biased towards large, close companions

- Occultation technique: **transit**
  - biased towards planetary systems viewed edge-on

- Astrometric technique: **periodic positional shift**
  - biased towards large companions of nearby stars

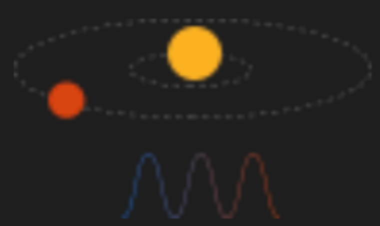
# Direct method for searching exoplanets and its bias

- ***Brute-force*** imaging with **coronographs**
  - biased towards large, distant companions of nearby stars

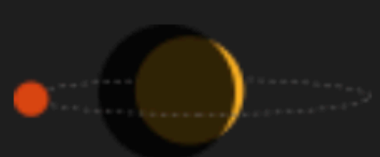


## By Method

75.3% Transit



19.6% Radial Velocity



1.2% Imaging

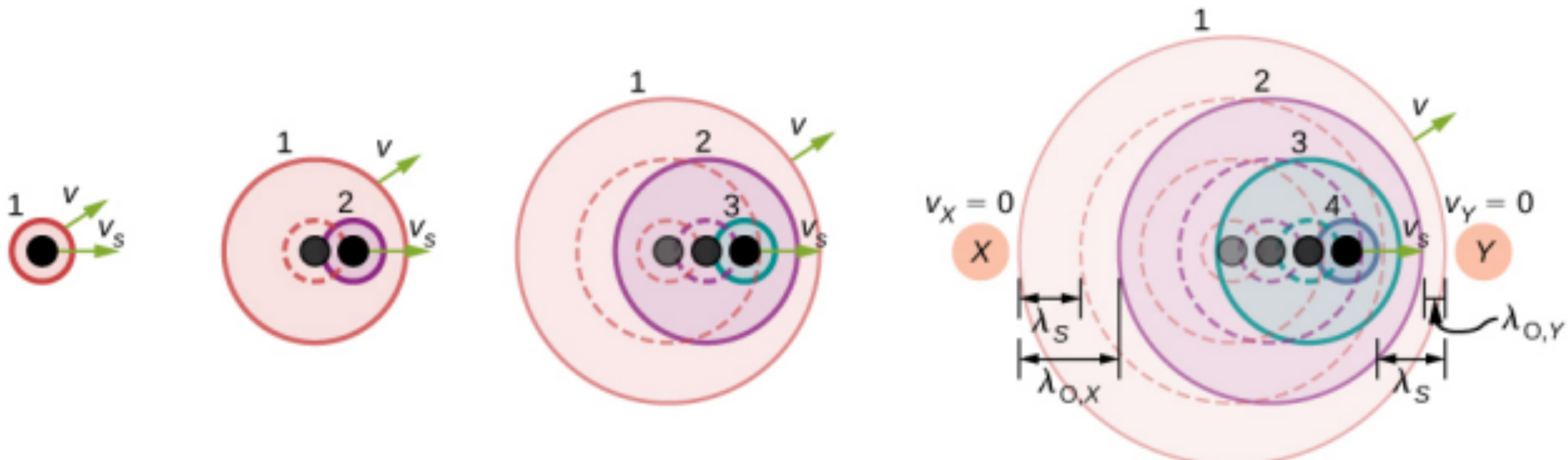
# Indirect Method I

*timing variations*
*(Timing Doppler)*

# Spectroscopic and Timing Doppler Shifts

$$\frac{V_r}{c} = \frac{\lambda_{\rm obs} - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{\Delta\lambda/c}{\lambda_0/c} = \frac{\Delta P}{P_0}$$

$V_r$ - **radial velocity (along line-of-sight)**, $c$ - speed of light,
$\lambda_{\rm obs}$- observed wavelength, $\lambda_0$ - rest-frame wavelength

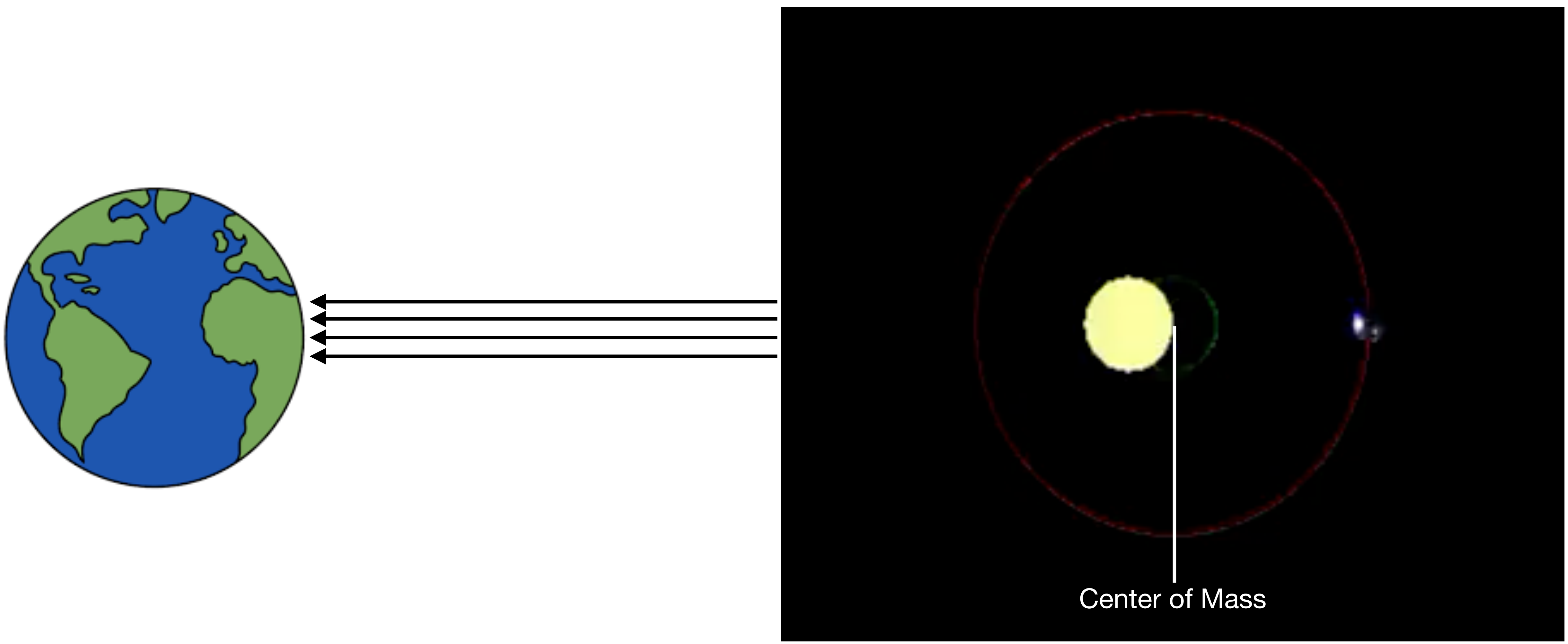



$$\lambda_{\rm obs} = \lambda_0 + v_r\delta t = \lambda_0 + v_r/\nu_0 = \lambda_0 + v_r(\lambda_0/c)$$

only the **radial v component** matters,
the ***transverse v component*** has no Doppler effect

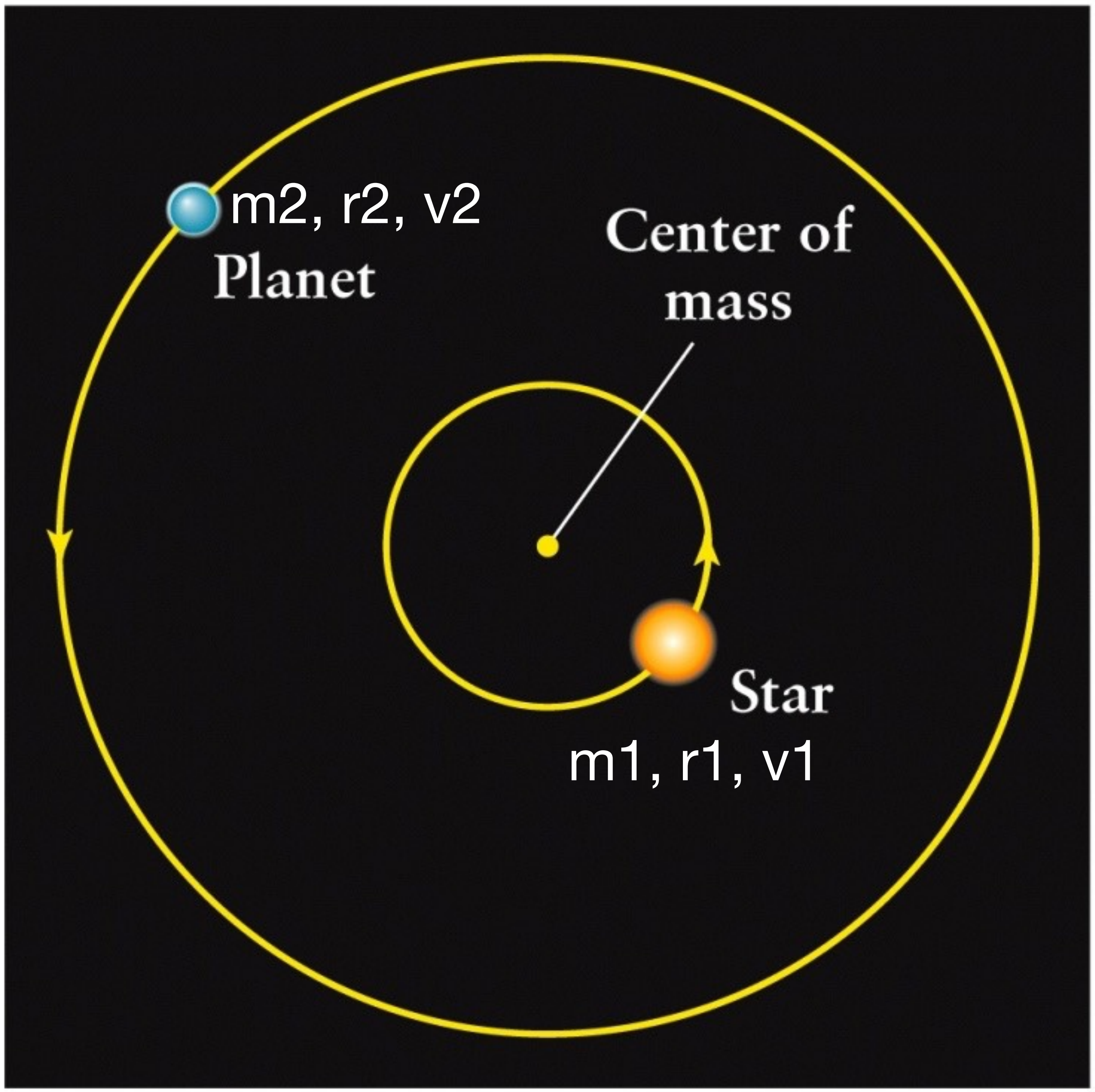
# Doppler effect of the star due to the gravity from the planet

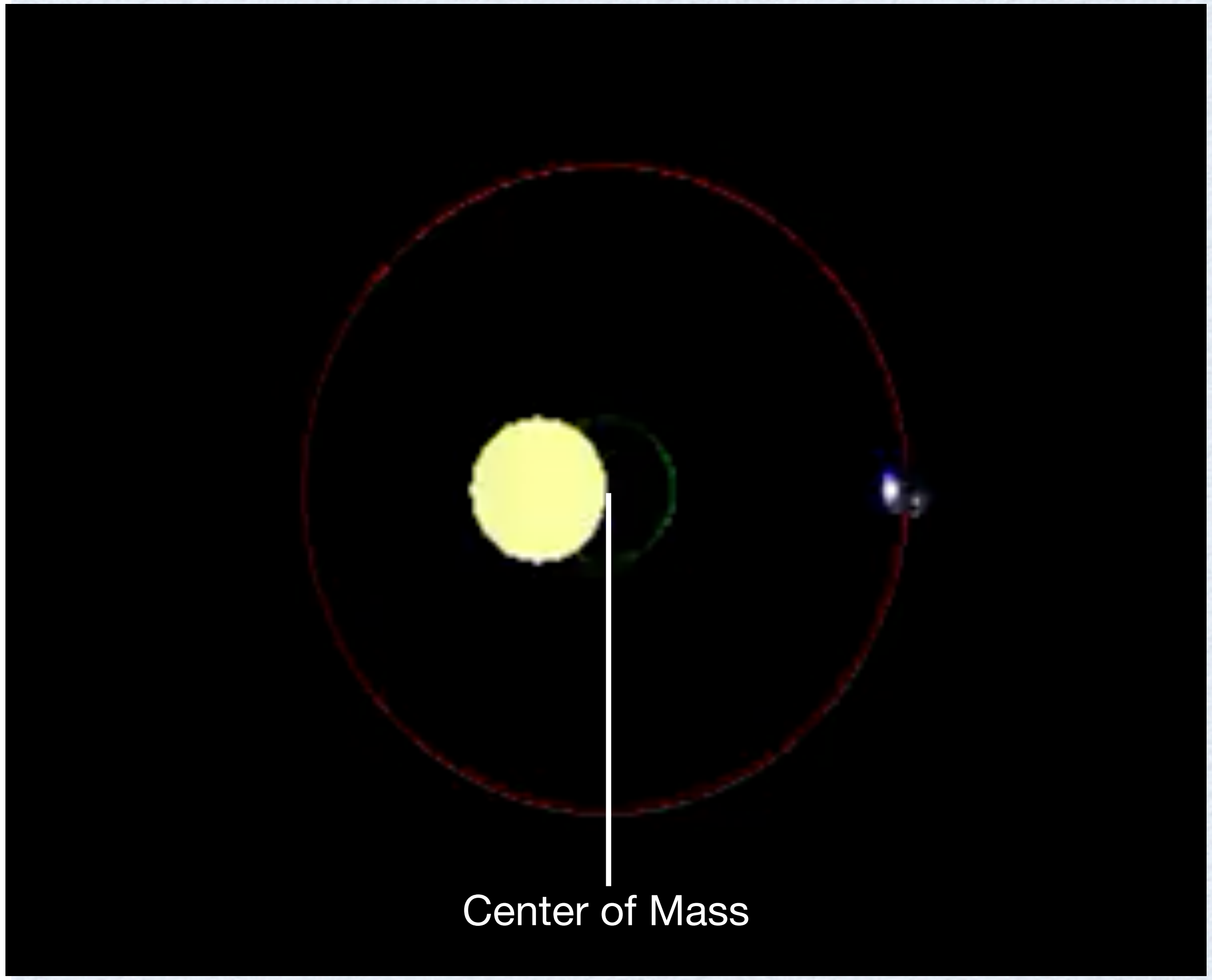
$$\frac{\Delta P}{P} = \frac{\Delta \lambda}{\lambda} = \frac{V_r}{c} = \frac{V_{\rm circ}}{c} \sin\left(\frac{t - t_0}{\rm Orbital\ \ Period}\right)$$



# Center of mass equation of a binary system
# "Seesaw Equation"

$$m_1 r_1 = m_2 r_2 \text{ \& because } P_1 = P_2 \text{ we have } m_1 v_1 = m_2 v_2$$

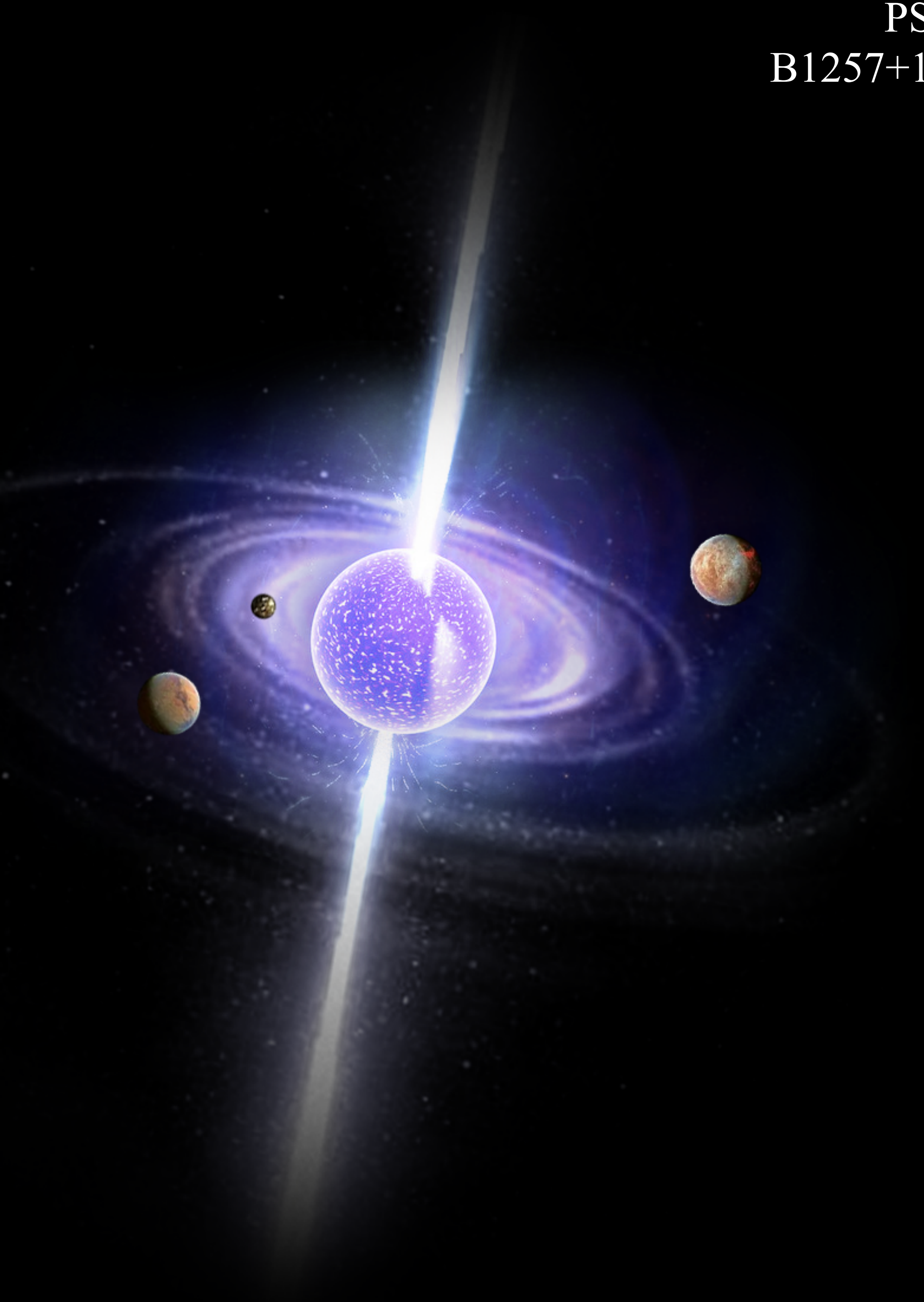


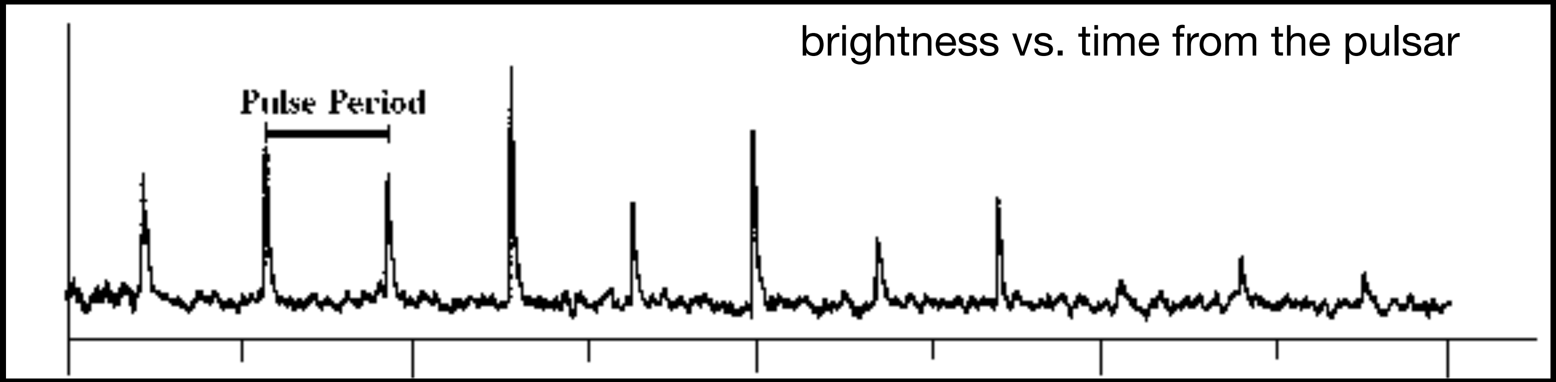



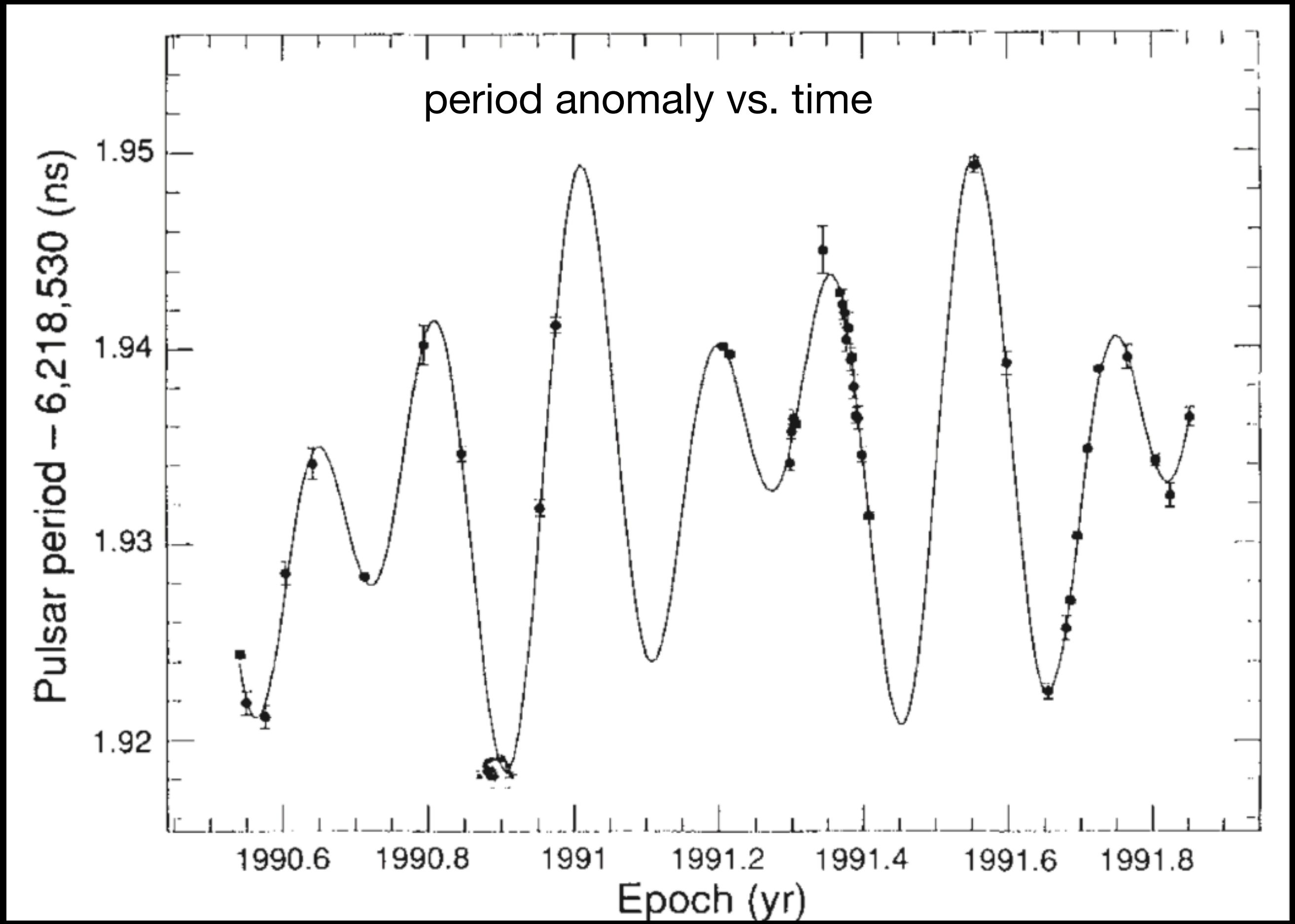

***For the Earth-Sun binary, what's the velocity of the Sun?***
***$V_{circ}$ of Earth = 30 km/s,***
***$M_{sun}/M_{Earth}$ = 333,000***

# PSR B1257+12 - a millisecond pulsar about 1.4 solar mass

PSR - Pulsating Source of Radio
B1257+12 - RA and Dec at the epoch of 1950






Wolszczan & Frail 1992

Published: 09 January 1992

# A planetary system around the millisecond pulsar PSR1257 + 12

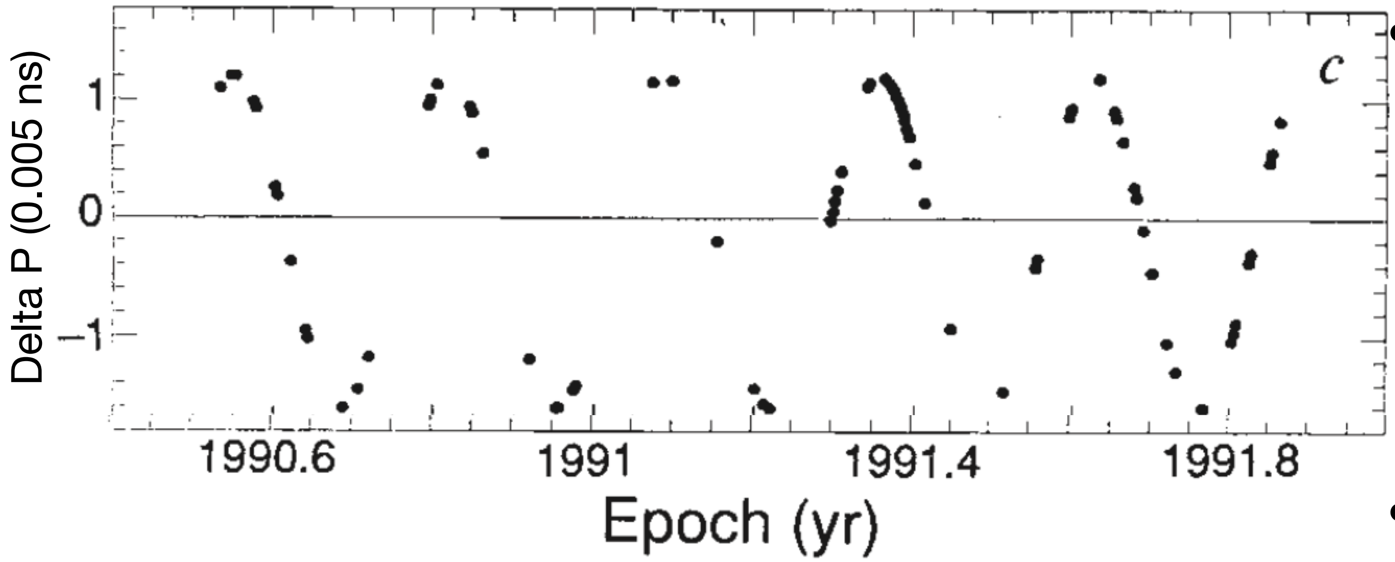
A. Wolszczan & D. A. Frail

*Nature* **355**, 145–147 (1992) | Cite this article



MILLISECOND radio pulsars, which are old (~$10^9$yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257 +12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_{\oplus}$ and 3.4 $M_{\oplus}$ where $M_{\oplus}$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829−10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

# Practice: measure planet mass based on period anomaly



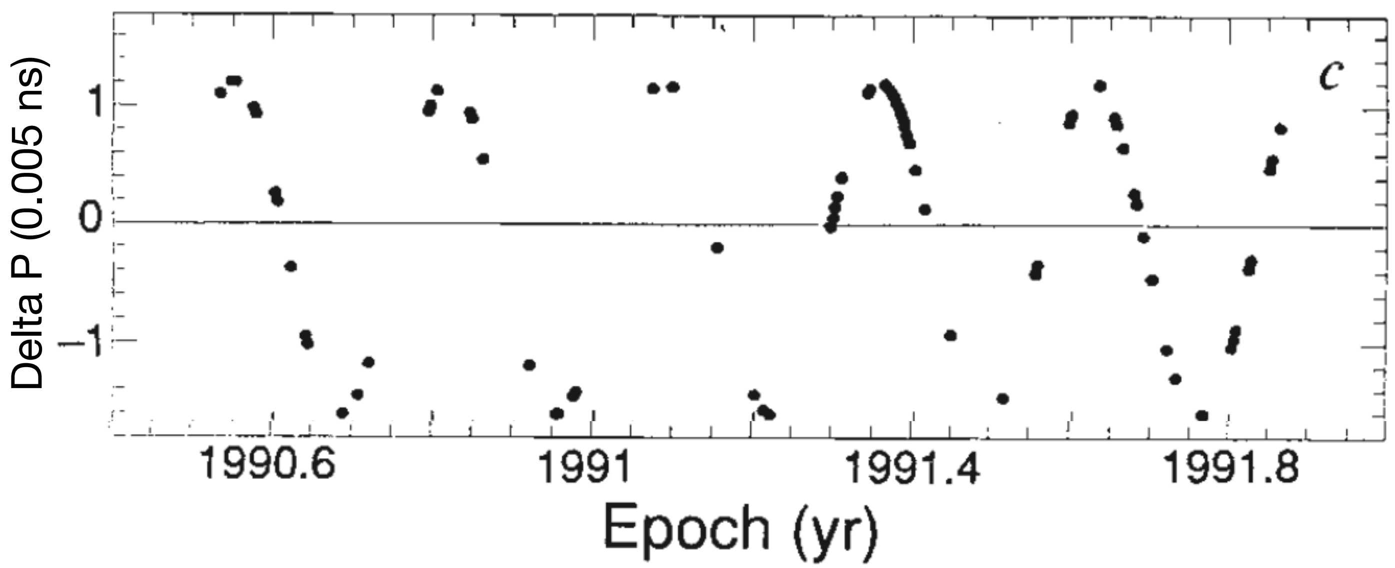

- What we know from this plot:
  - Orbital Period = 98.2 days
  - Average Pulsation Period P = 6.2 ms
  - Amplitude of Period Anomaly: ΔP = 0.006 ns
- What we know about the pulsar:
  - Mass = 1.4 Solar Mass

**Step 1: Use the Doppler shift equation to calculate the circular velocity of the Pulsar**

$$\frac{\Delta P}{P} = \frac{V_r}{c} = \frac{V_{\text{circ}}}{c} \sin\left(\frac{t - t_0}{\text{Orbital Period}}\right) \Rightarrow V_{\text{circ}} = c\frac{\max \Delta P}{P}$$

For PSR B1257+12, we have the pulsation period of P = 6.2 ms and a maximum ΔP = 0.006 ns. We can calculate that the circular velocity of the pulsar is $V_{circ}$ = 0.3 m/s

# Practice: measure planet mass based on period anomaly




- What we know from this plot:
  - Orbital period = 98.2 days
  - Amplitude of Delta P = 0.006 ns
- What we know from timing pulses:
  - Pulsation Period P = 6.2 ms
- What we know about the pulsar:
  - Mass = 1.4 Solar Mass

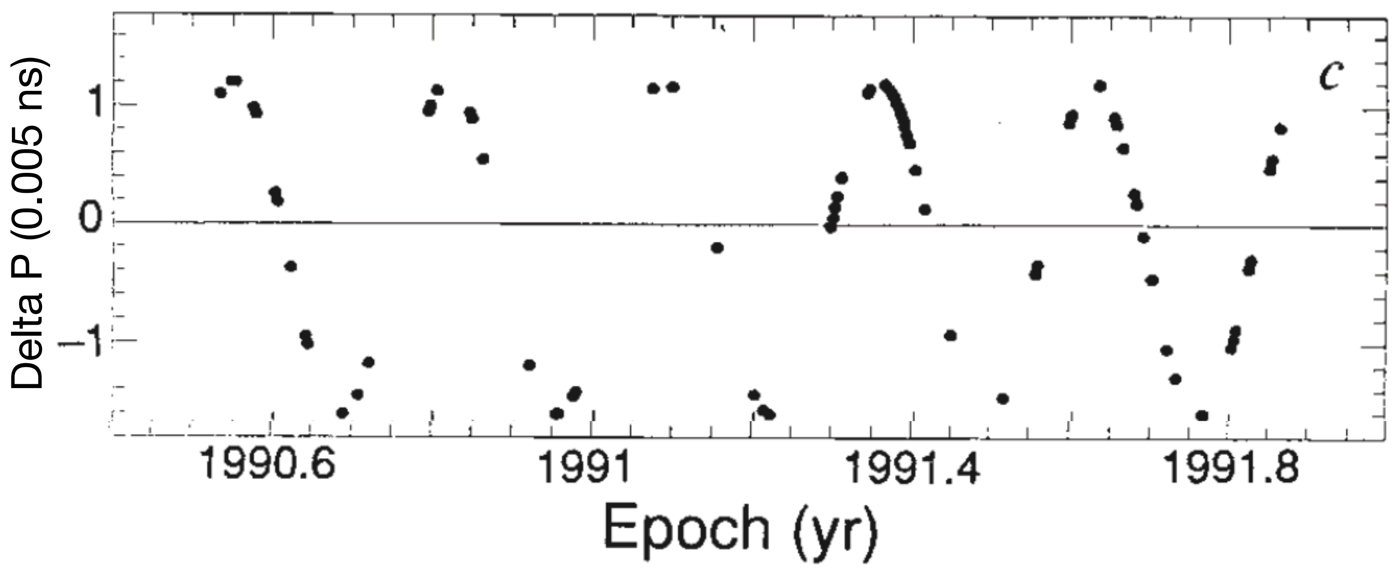
**Step 2: Use the Kepler's 3rd Law to calculate the <u>circular velocity of the invisible planet</u>**

$$a_{AU} = (M_{\mathrm{solar-mass}} P_{\mathrm{year}}^2)^{1/3}$$

$$v_{\mathrm{circ}} = \frac{2\pi a}{P_{\mathrm{orbit}}}$$

$$a_{AU} = (M_{\mathrm{solar-mass}} P_{\mathrm{year}}^2)^{1/3} = 0.466$$
$$v_{\mathrm{circ}} = 2\pi a / P = 51.6\ \mathrm{km/s}$$

# Practice: measure planet mass based on period anomaly




- What we know from this plot:
  - Orbital period = 98.2 days
  - Amplitude of Delta P = 0.006 ns
- What we know from timing pulses:
  - Pulsation Period P = 6.2 ms
- What we know about the pulsar:
  - Mass = 1.4 Solar Mass
  - 1 Solar Mass = 3.3e5 Earth Mass

**Step 3: Use the center of mass equation to calculate the mass ratio from velocity ratio**

$$\frac{m}{M} = \frac{V_{\text{circ}}}{v_{\text{circ}}}$$

mass ratio between the planet and the pulsar:

$$\frac{m}{M} = \frac{V_{\text{circ}}}{v_{\text{circ}}} = \frac{0.3 \text{ m/s}}{51.6 \text{ km/s}} = 6 \times 10^{-6}$$

**Step 4: Use the mass ratio and the mass of the Pulsar to calculate the mass of the planet**

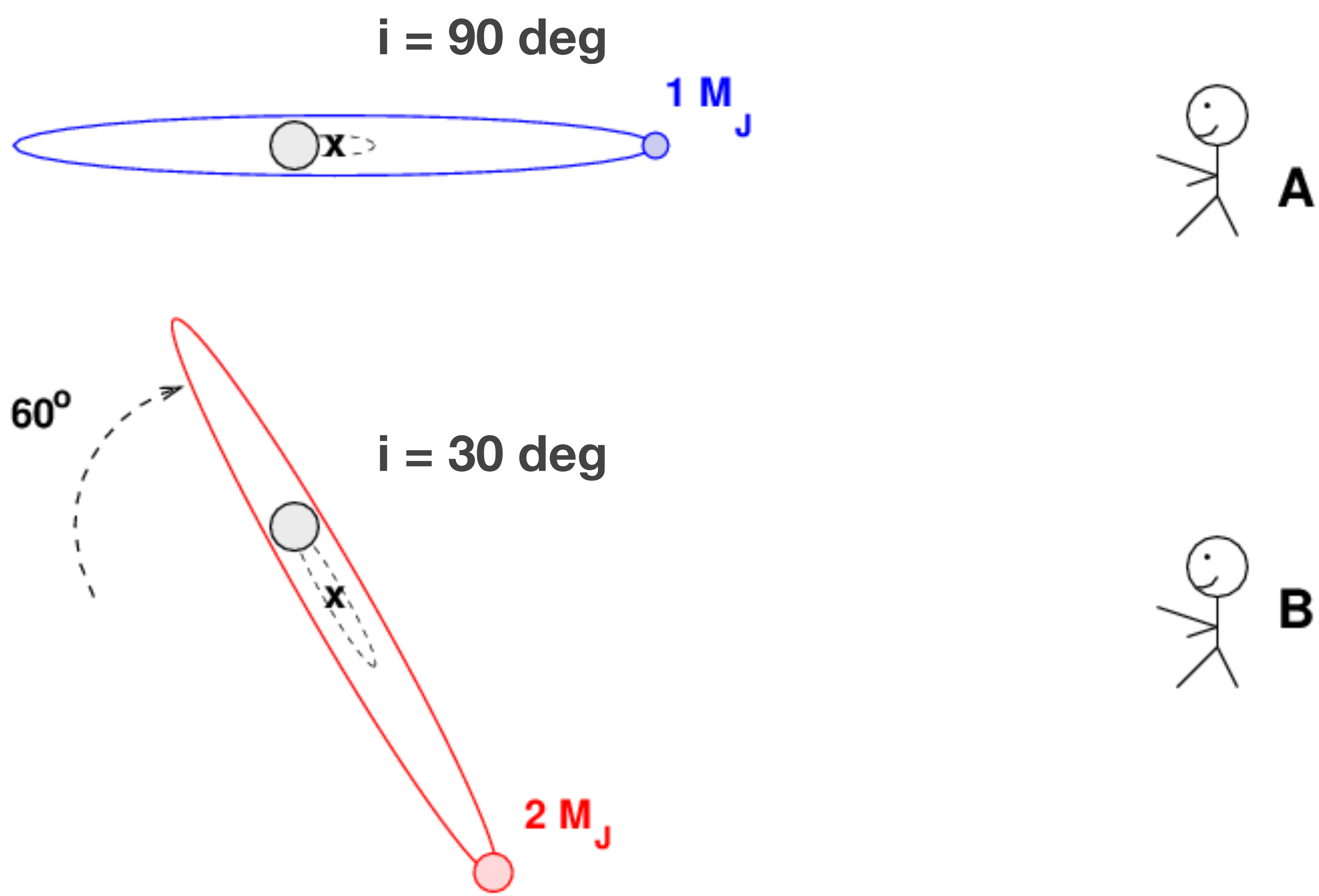
planet mass = 6e-6 x (1.4 solar mass)
given that 1 solar mass = 3.3e5 earth mass
we have planet mass = 2.8 Earth Mass

# The Importance of Geometry:

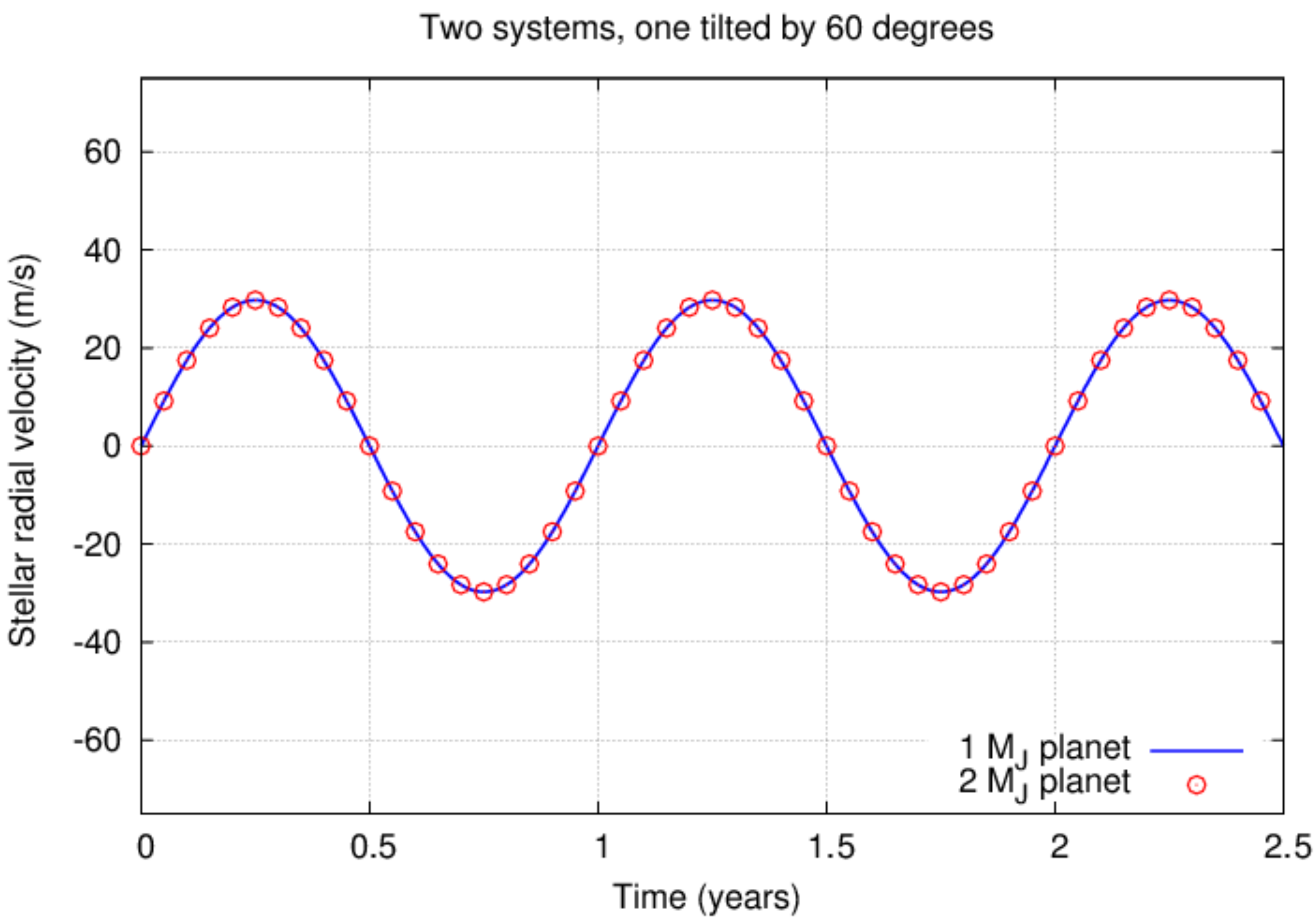
*ambiguities caused by*
*orbital inclination angle*

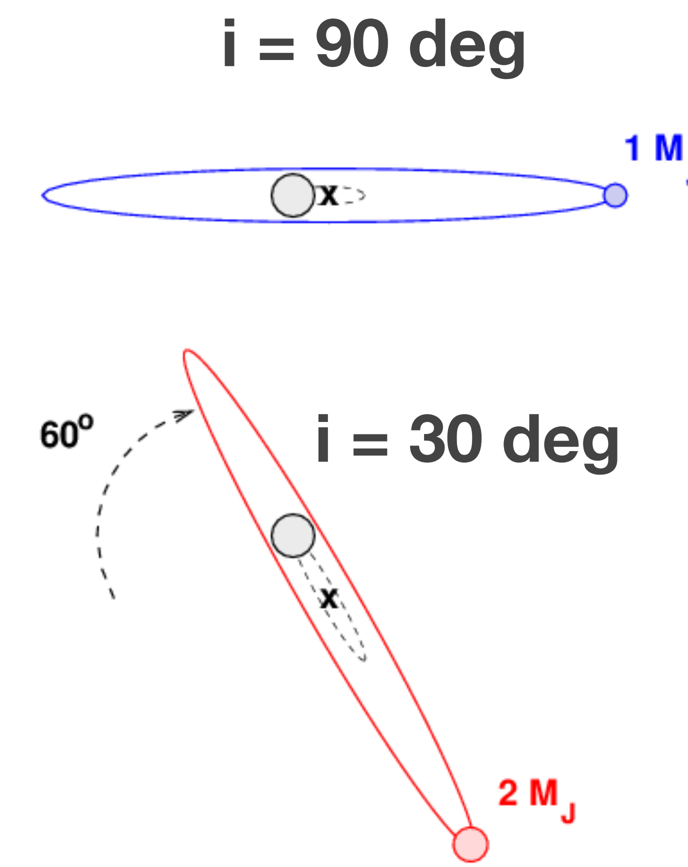
# Ambiguity Caused by the Unknown Inclination Angle

$$\frac{\Delta P}{P} = \frac{\Delta \lambda}{\lambda} = \frac{V_r}{c} = \frac{V_{\text{circ}}}{c} \sin\left(\frac{t - t_0}{\text{Orbital Period}}\right) \times \sin i$$



# Unknown Inclination Angle => Planetary masses are lower limits



# The Importance of Earth's Motion:

*false positive detections*

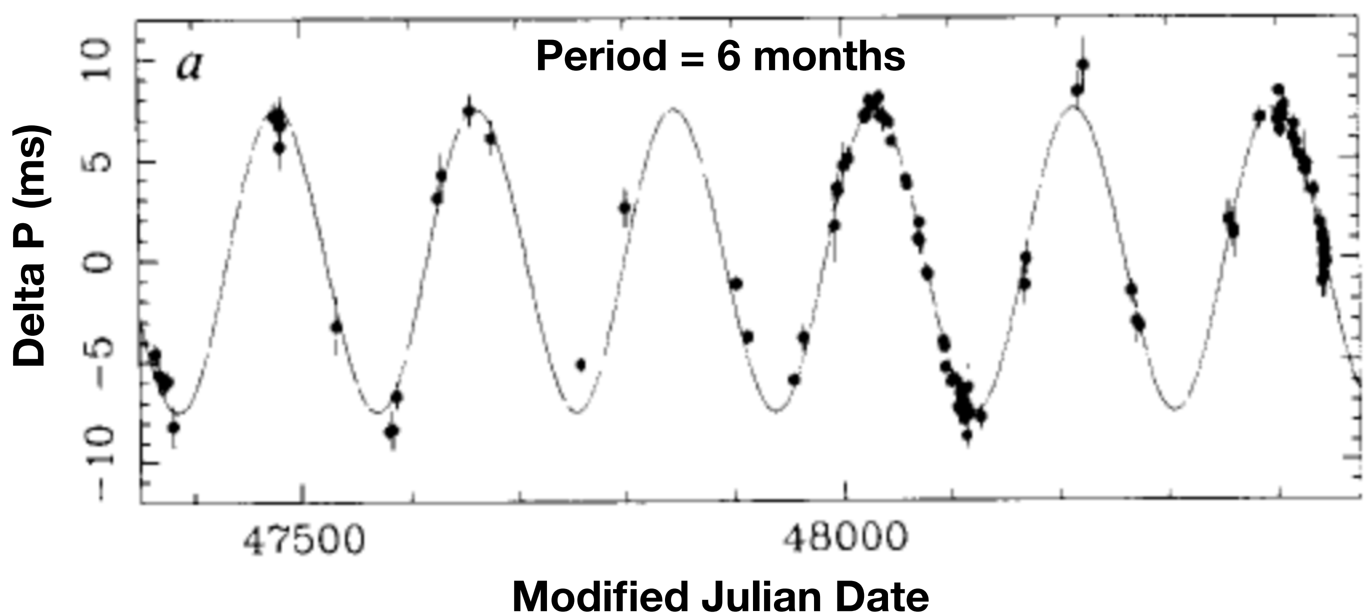
# The Importance of Earth's Motion

NATURE · VOL 352 · 25 JULY 1991

## A planet orbiting the neutron star PSR1829−10

**M. Bailes, A. G. Lyne & S. L. Shemar**

University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK




**Pulsation Period = 226.5 ms**

## No planet orbiting PSR1829−10

SIR — In an earlier paper[1], we reported a cyclic variation in the arrival times of the pulses from the neutron star PSR1829−10 with a period close to 6 months, and presented this as evidence for a 10-Earth-mass planet. As we noted in that paper, we were concerned that the 6-month periodicity might be an artefact concerned with the Earth's orbit around the Sun, but were encouraged by the fact that no such periodicity appeared in observational data for the 300 other pulsars currently under observation. We have nevertheless re-examined the algorithm used in compensating for the Earth's orbital motion and now find that we can account for the observed radiation without the presence of a planet.

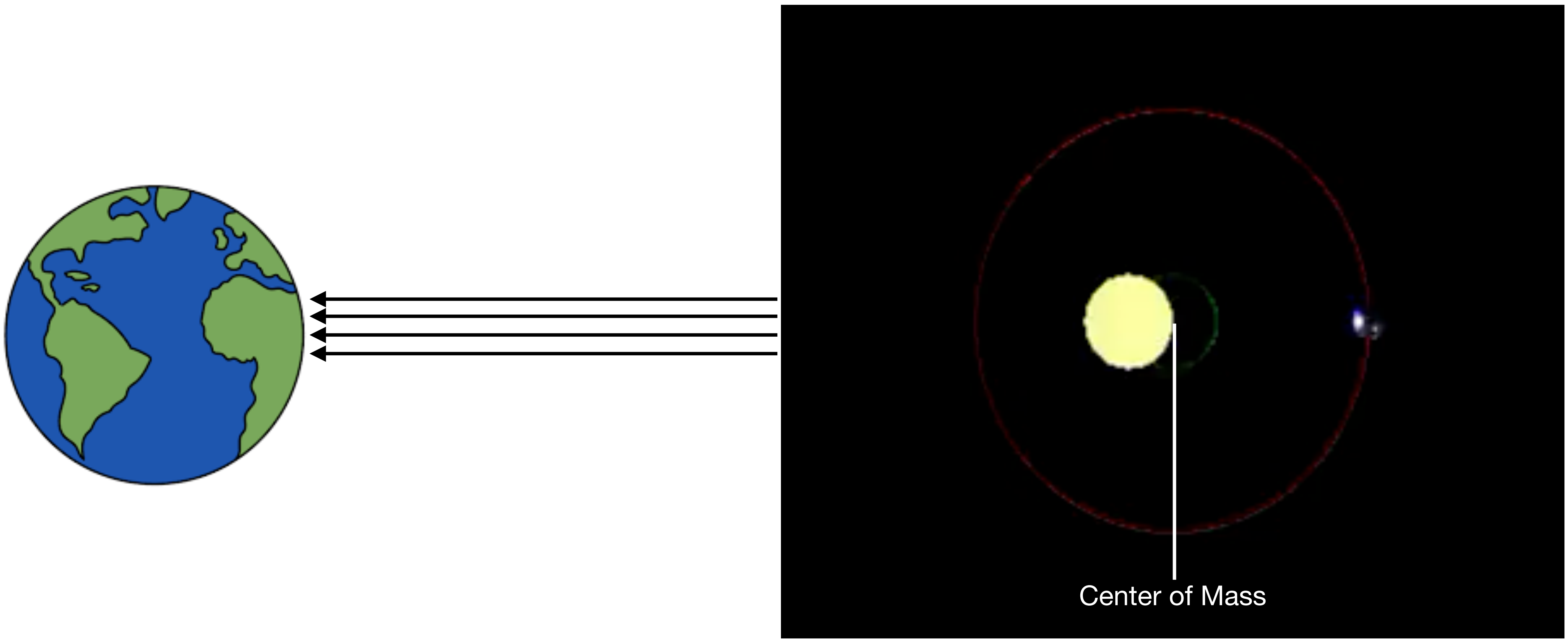
The standard analysis (p. 105 of ref. 2) involves correcting the observed arrival times to the barycentre of the Solar System using a precise ephemeris for the position of the Earth. An analytical model for the pulsar rotation and position is then adjusted to minimize a set of residuals, the differences between the observed barycentric arrival times and model times. Because this is a differential process, the approximation is made that the orbit of the Earth is circular. Provided that the difference between the

# Recap: Indirect Method I

*timing variations*
*(Timing Doppler)*

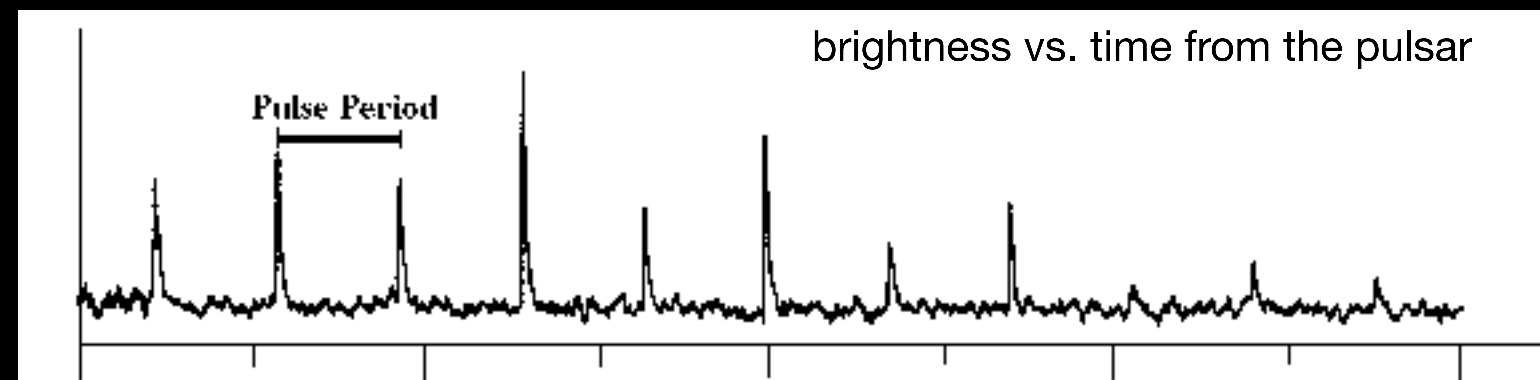
# Doppler effect of the star due to the gravity from the planet

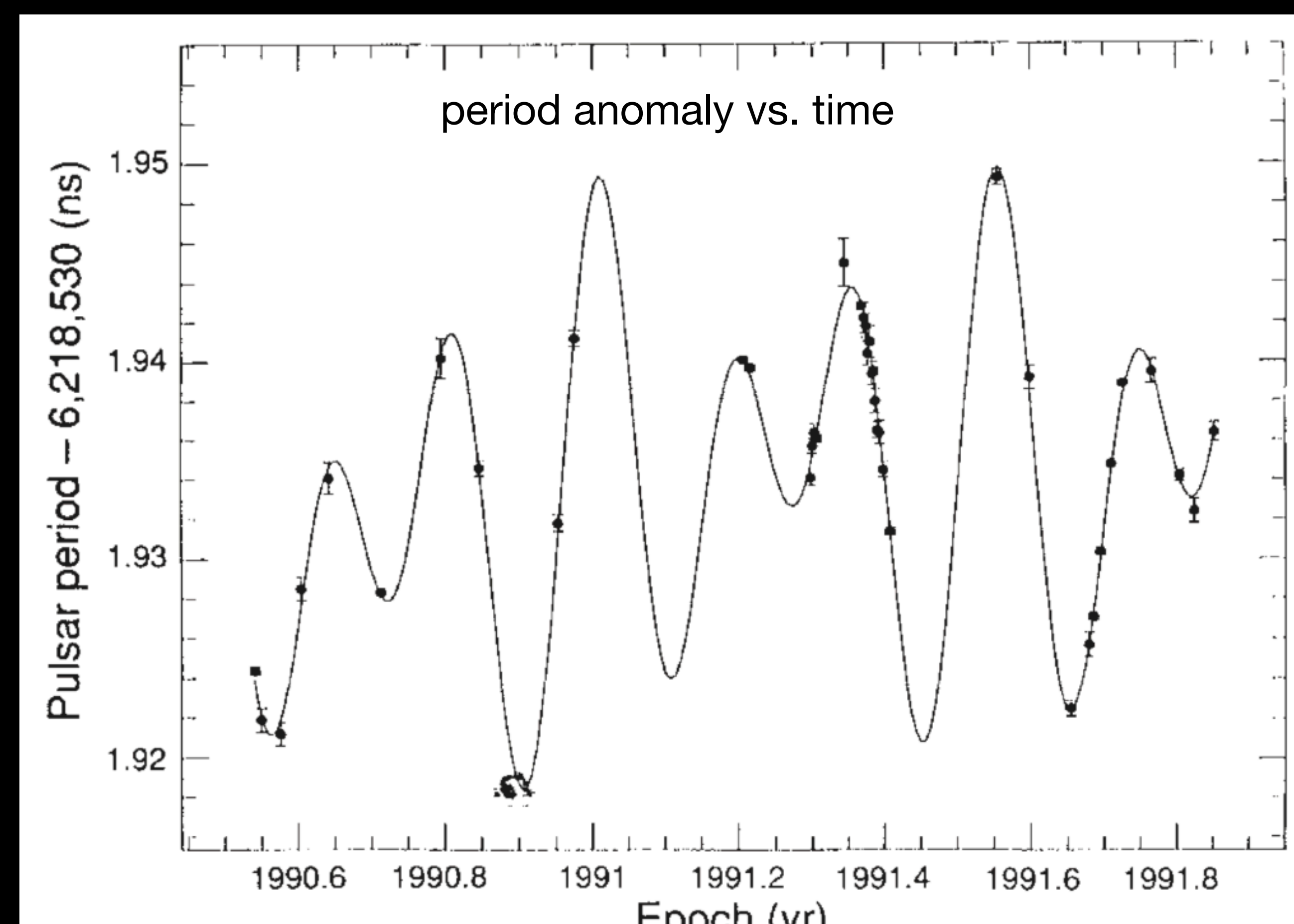
$$\frac{\Delta P}{P} = \frac{\Delta \lambda}{\lambda} = \frac{V_r}{c} = \frac{V_{\mathrm{circ}}}{c} \sin\left(\frac{t - t_0}{\mathrm{Orbital\ Period}}\right)$$



# Planets around PSR B1257+12 - a millisecond pulsar about 1.4 solar mass

*How did they achieve an accuracy of* ***0.001 ns*** *when the data were taken every* ***0.1 ms****?*




Wolszczan & Frail 1992

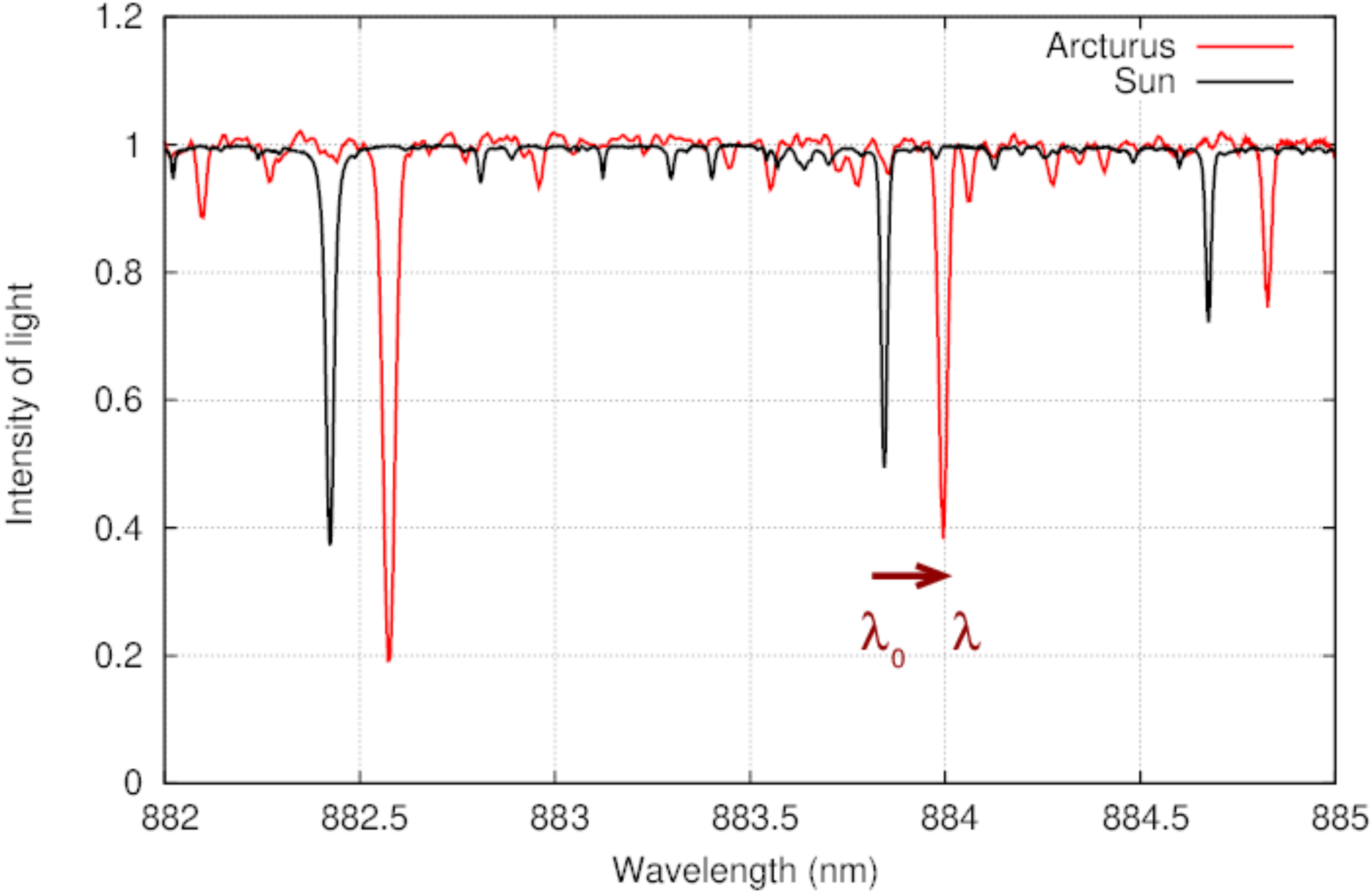
$$\frac{\Delta P}{P} = \frac{\Delta \lambda}{\lambda} = \frac{V_r}{c} = \frac{V_{\mathrm{circ}}}{c} \sin\left(\frac{t - t_0}{\mathrm{Orbital\ Period}}\right)$$

# Indirect Method II

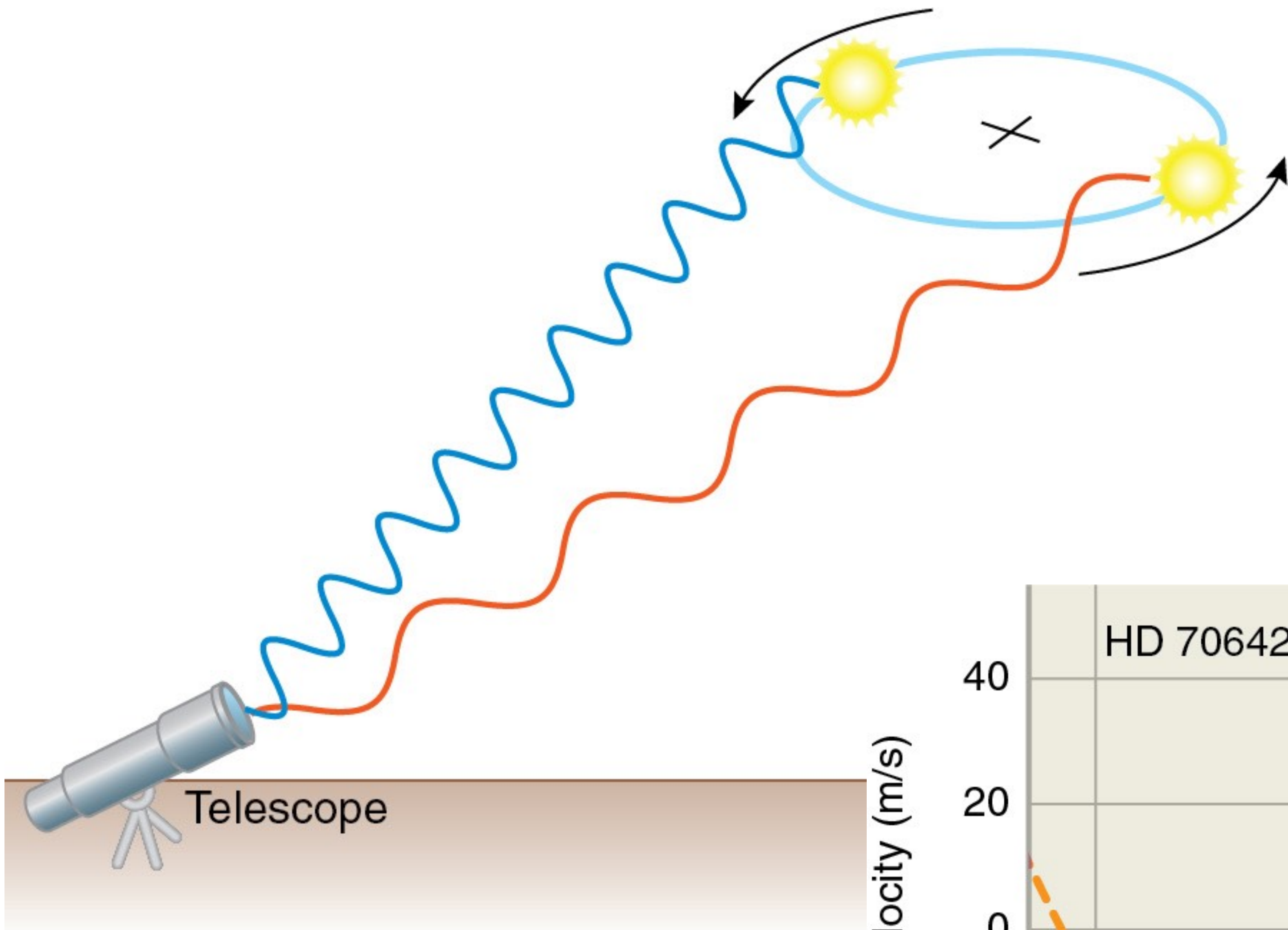
*the radial velocity method*
*(Spectroscopic Doppler)*

# Spectroscopic Doppler Shift

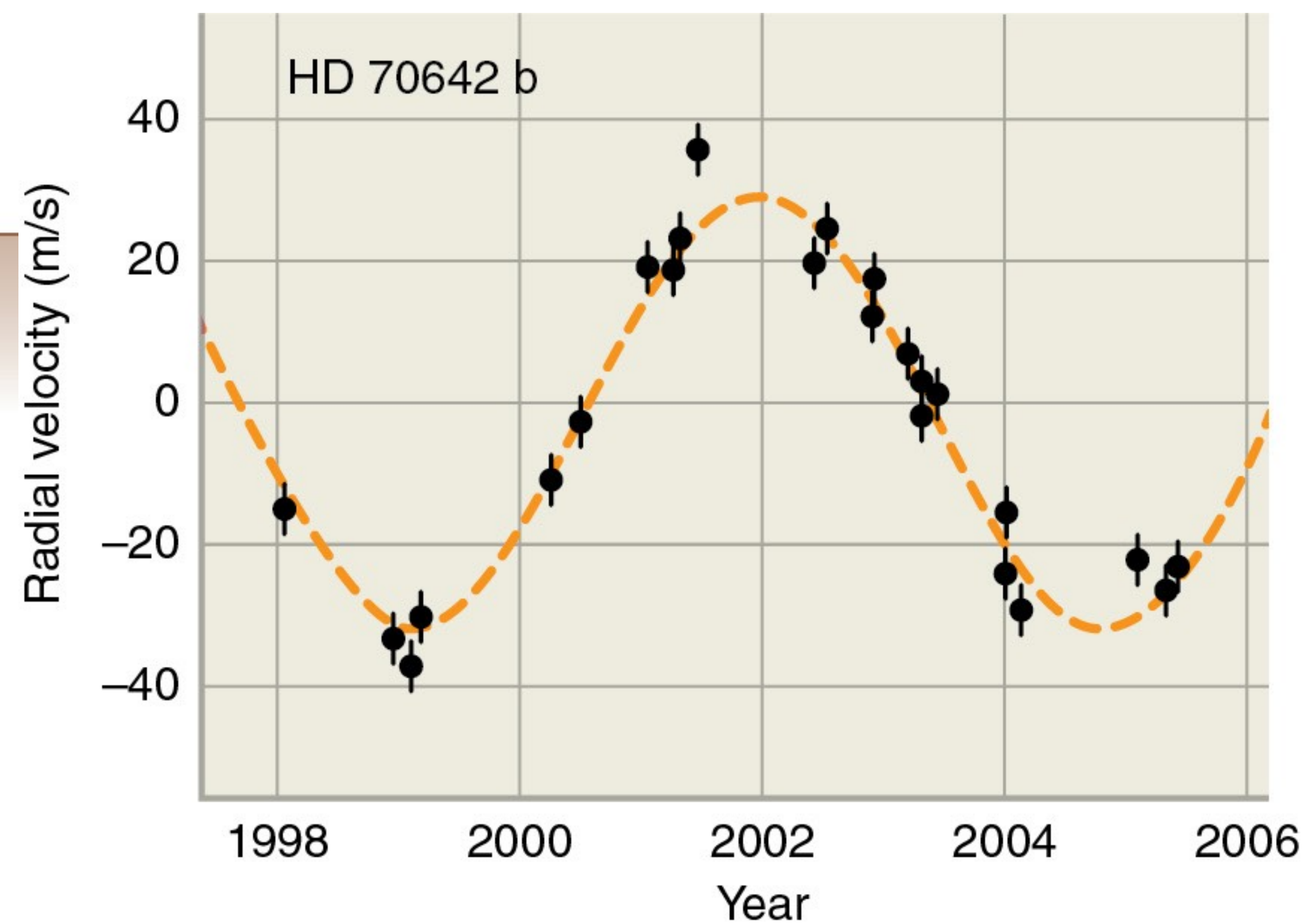
$$\frac{V_r}{c} = \frac{\Delta\lambda}{\lambda}$$



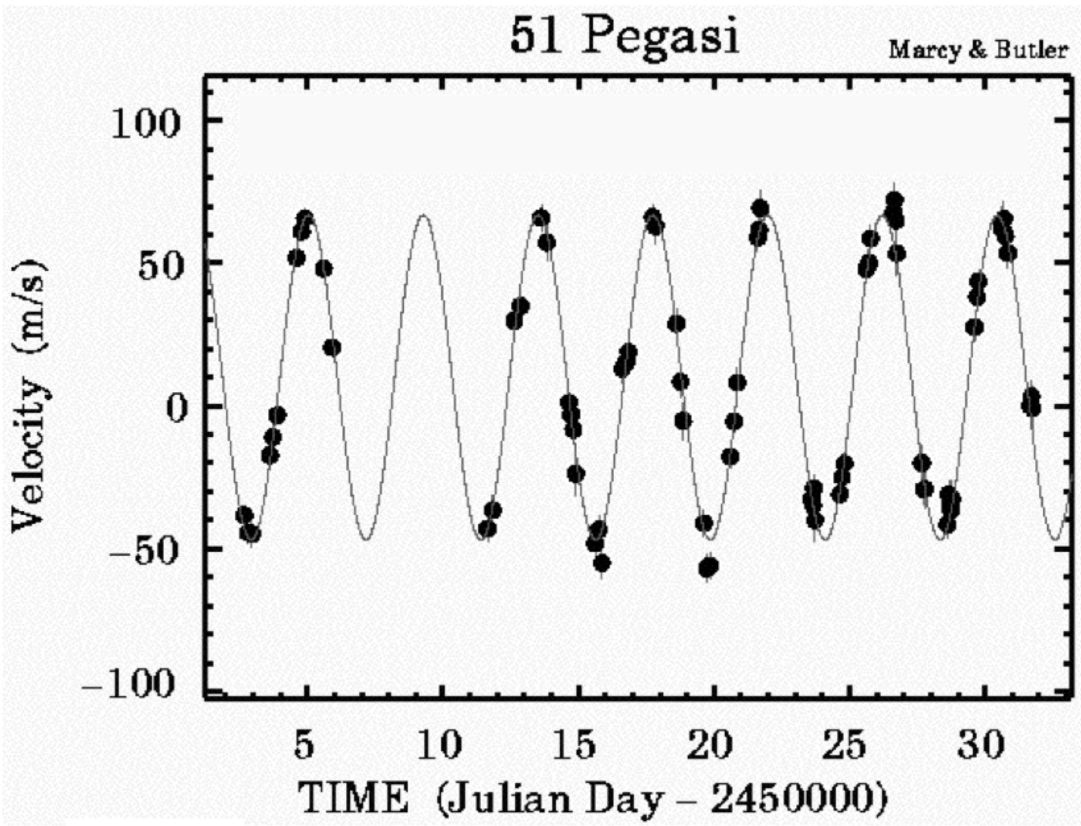
## Radial Velocity Method




$$\frac{V_r}{c} = \frac{\Delta\lambda}{\lambda}$$



# How to measure planet mass based on periodic radial velocity




- What we know from this plot:
  - Orbital period (4.2 days)
  - Amplitude of radial velocity of the star (55 m/s)
- What we know about the star:
  - Mass (1.1 solar mass)

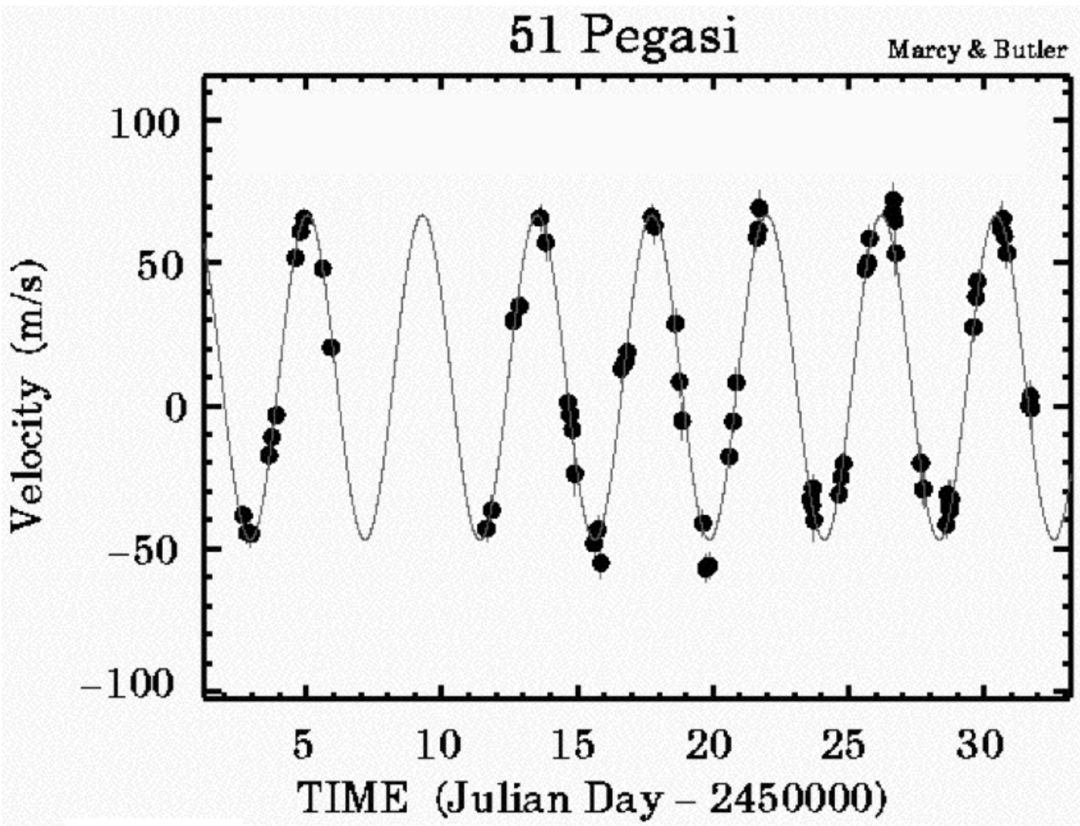
**Step 1: Get a lower limit on the circular velocity of the host star:**

$$V_r = V_{\rm circ} \sin i \cdot \sin\left(\frac{t - t_0}{\text{Orbital Period}}\right)$$

$$\Rightarrow V_{\rm circ} = \max(V_r)/\sin i$$

**where i is the inclination angle of the orbital plane from face-on**

# How to measure planet mass based on periodic radial velocity



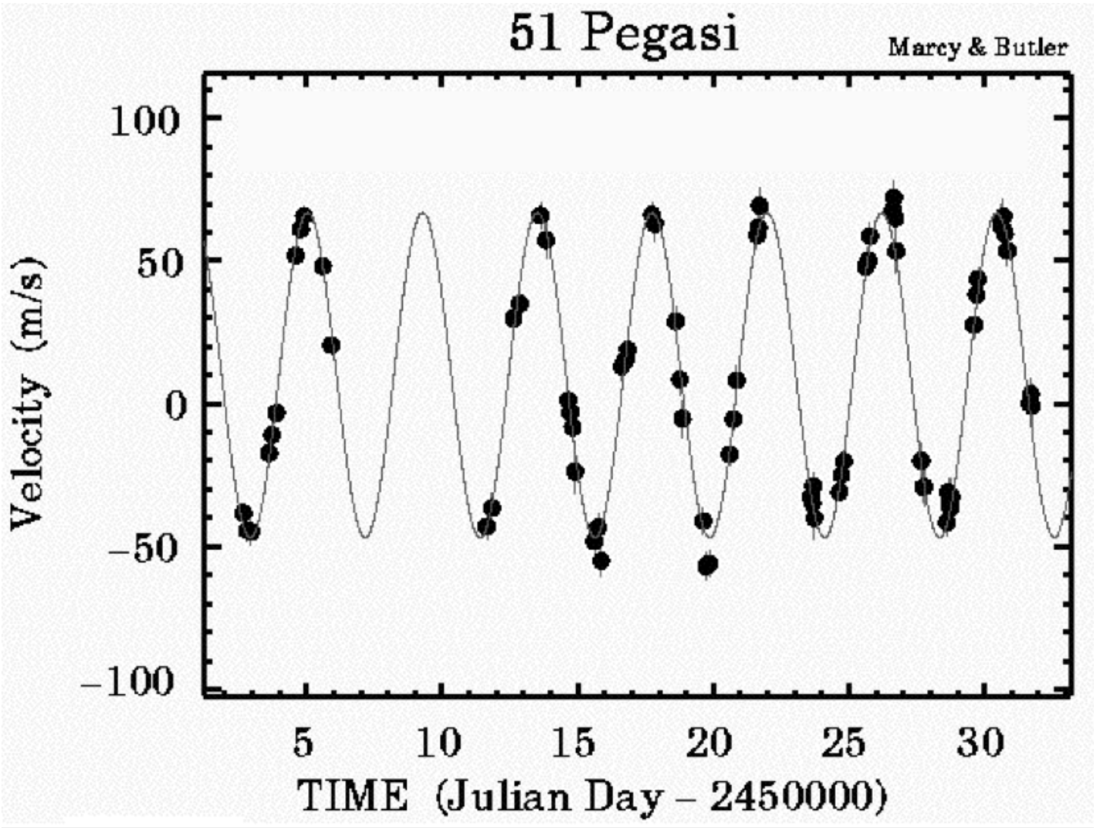

- What we know from this plot:
  - Orbital period (4.2 days)
  - Amplitude of radial velocity of the star (55 m/s)
- What we know about the star:
  - Mass (1.1 solar mass)

**Step 2: Use the Kepler's 3rd Law to calculate the circular velocity of the invisible planet**

$$a_{AU} = (M_{\text{solar-mass}} P_{\text{year}}^2)^{1/3}$$

$$v_{\text{circ}} = \frac{2\pi a}{P_{\text{orbit}}}$$

# How to measure planet mass based on periodic radial velocity




- What we know from this plot:
  - Orbital period (4.2 days)
  - Amplitude of radial velocity of the star (55 m/s)
- What we know about the star:
  - Mass (1.1 solar mass)

**Step 3: Use the center of mass equation to calculate the mass ratio from velocity ratio:**

$$\frac{m}{M} = \frac{V_{\text{circ}}}{v_{\text{circ}}} = \frac{\max(V_r)/\sin(i)}{v_{\text{circ}}}$$

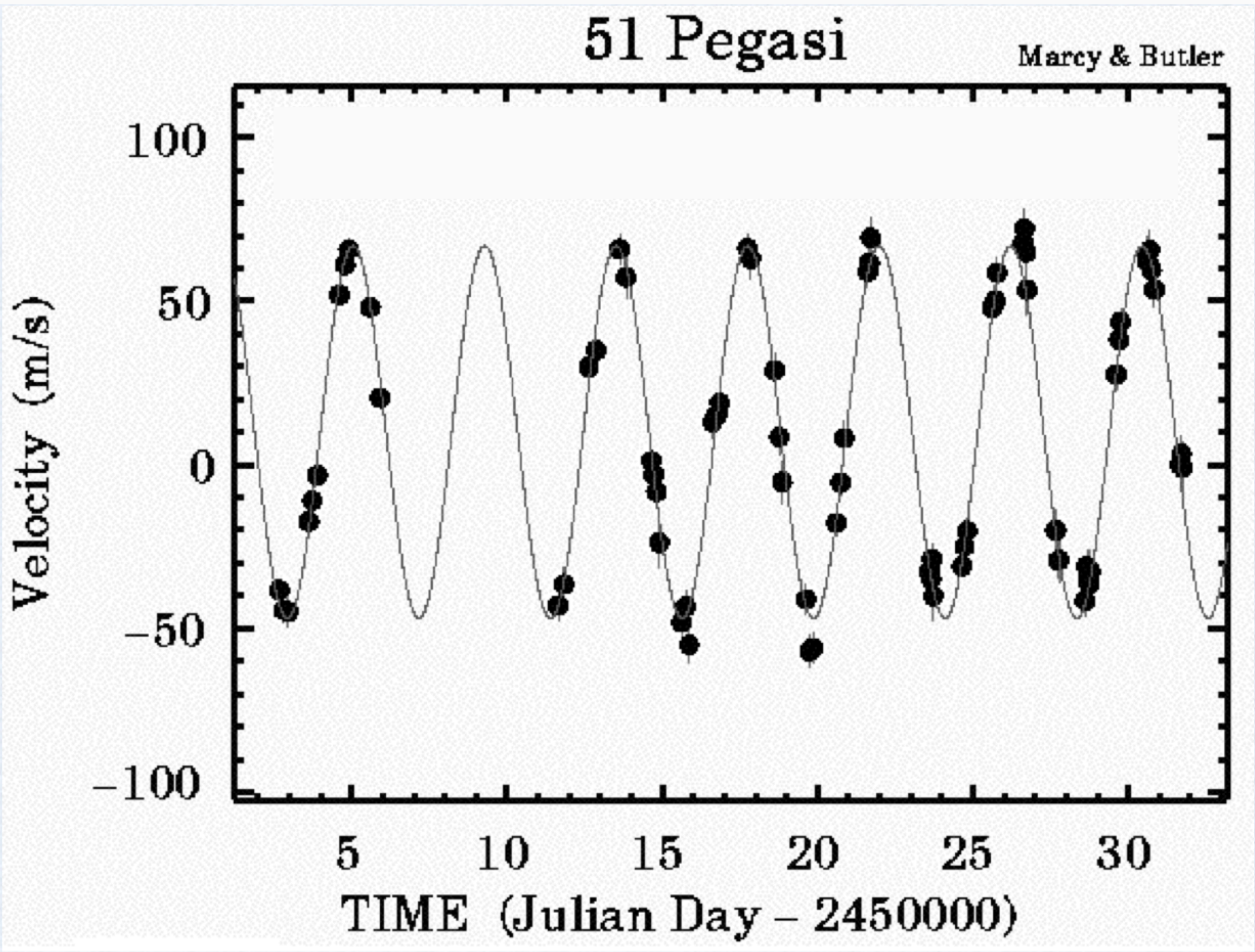
**Step 4: Use the mass ratio and the mass of the star to calculate the mass of the planet, because there is a sin i term on the denominator, the result is a lower mass limit.**

# A Jupiter-mass companion to a solar-type star

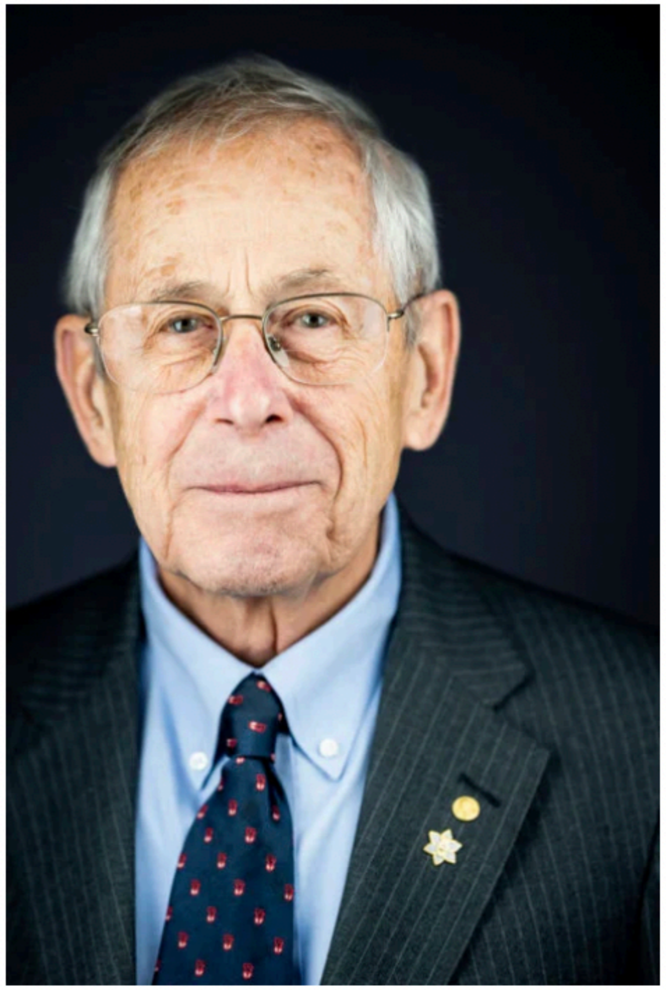
**Michel Mayor & Didier Queloz**

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

**The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.**



# The Nobel Prize in Physics 2019



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James Peebles

Prize share: 1/2

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Michel Mayor

Prize share: 1/4

© Nobel Media. Photo: A. Mahmoud

Didier Queloz

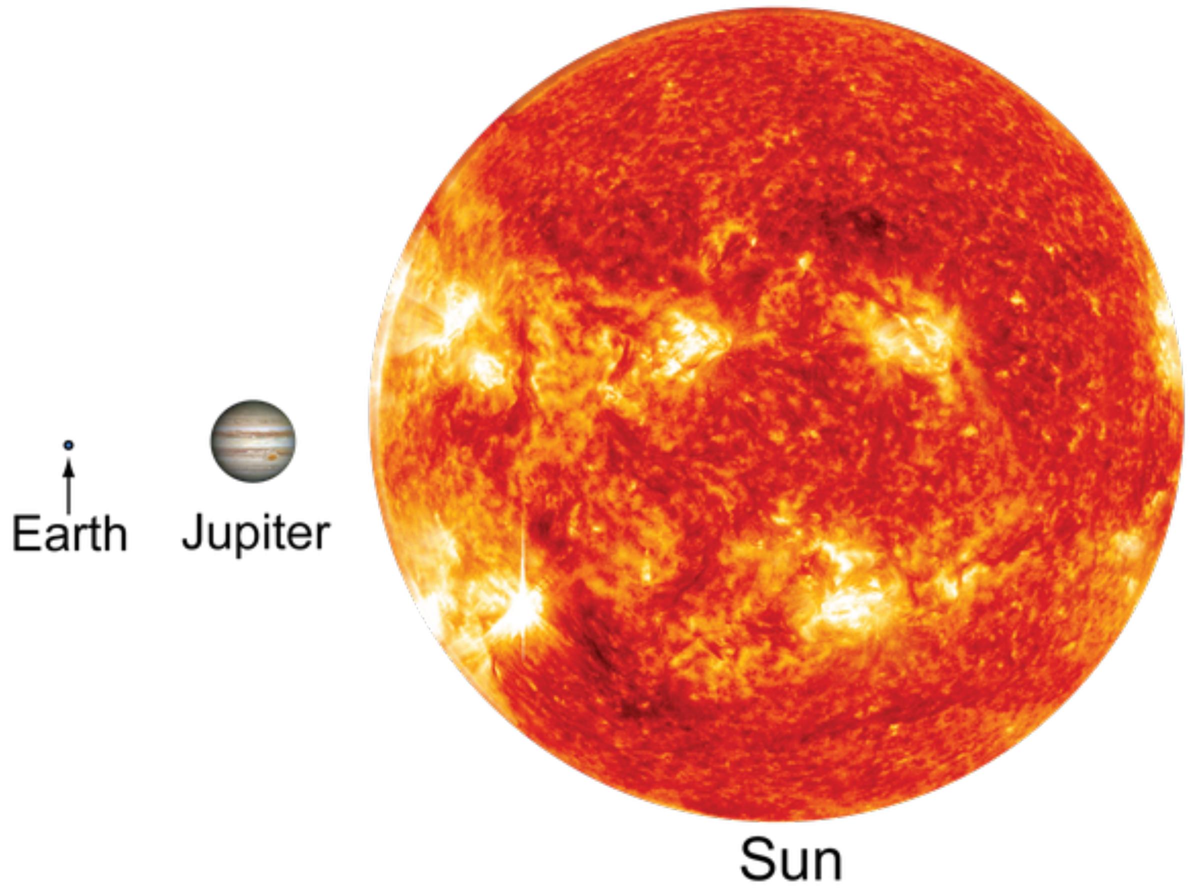
Prize share: 1/4

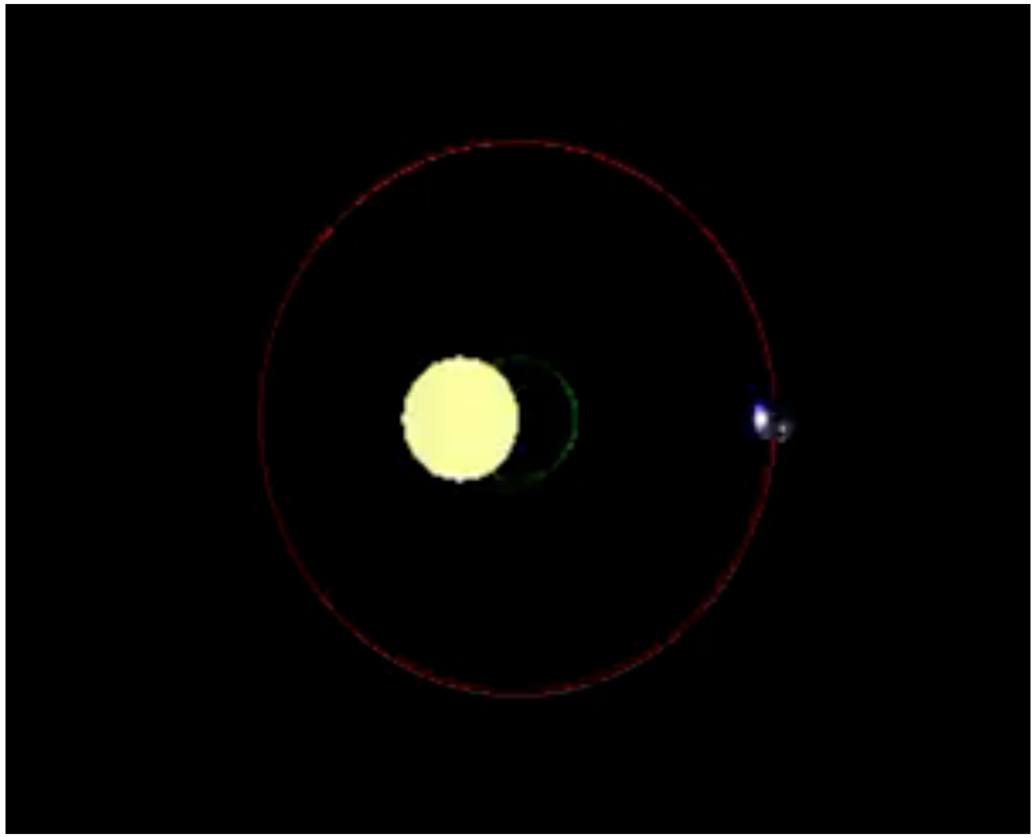
*Half of the award is* "for the discovery of an exoplanet orbiting a solar-type star." The other half for cosmology.

# Practice: Jupiter-Sun as an exoplanet system (Reversed Problem Solving)

- Jupiter distance: 5.2 AU
- Jupiter mass: 0.001 solar mass
- Jupiter period: 12 years
- What is the circular velocity of Jupiter? $v_{\text{circ}} = \sqrt{GM/a} \propto 1/\sqrt{a}$
- What is the amplitude of the radial velocity of the Sun caused by Jupiter?

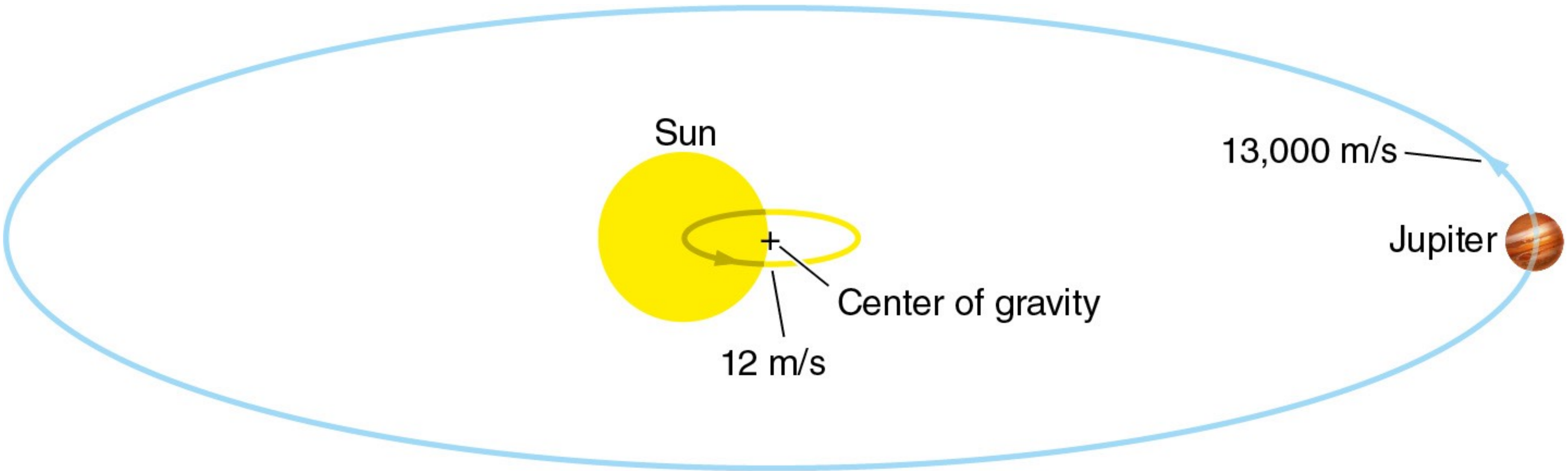
  recall the center of mass equation: $\dfrac{m}{M} = \dfrac{V_{\text{circ}}}{v_{\text{circ}}}$



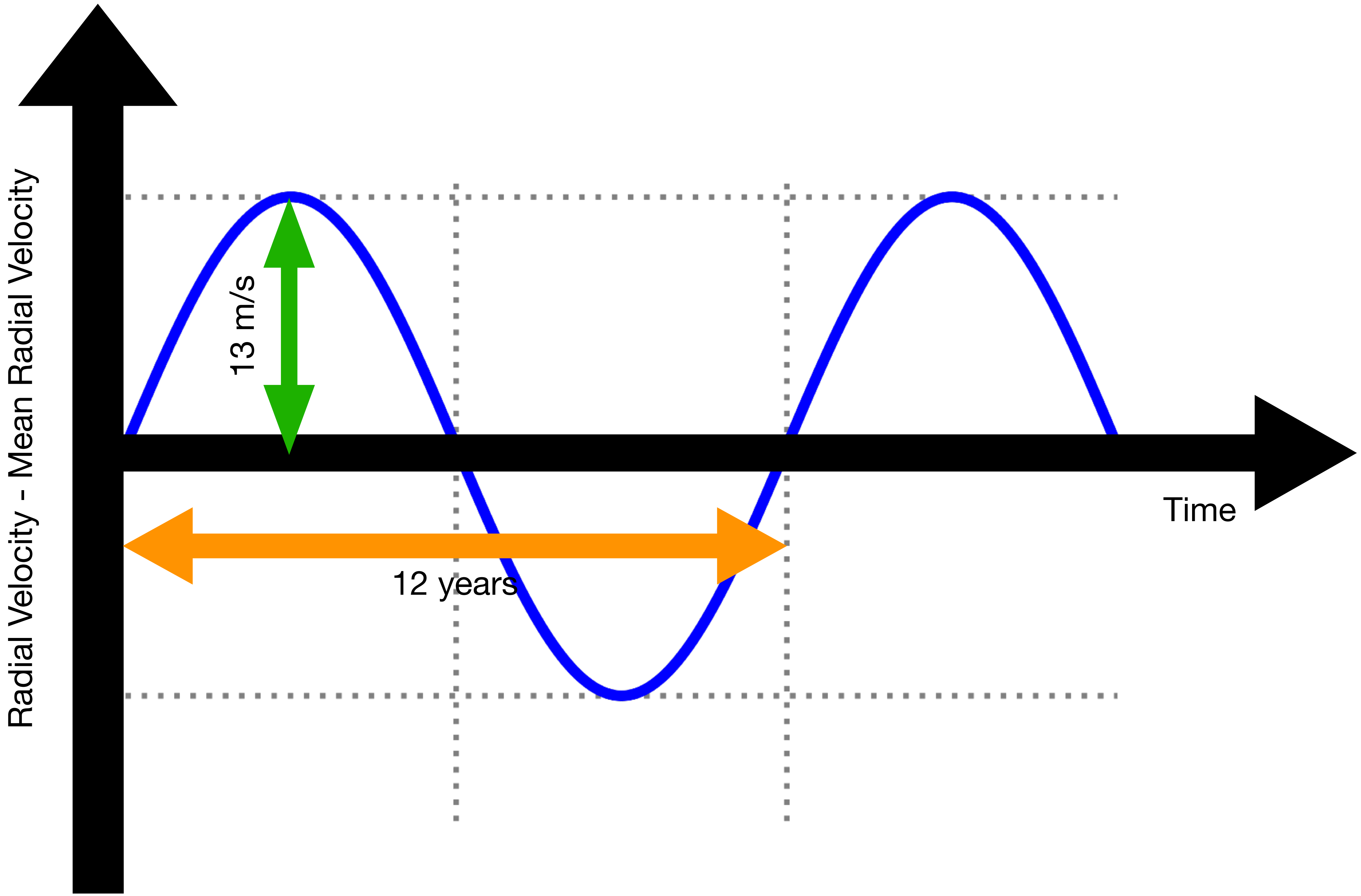
# Practice: Jupiter-Sun as an exoplanet system: Center of Mass

The radius of the outer blue circle is 5.2 AU, what is the radius of the inner yellow circle?




Answer: R = 5.2e-3 AU
given 1 AU = 215 $R_{sun}$, we have R = 1.1 $R_{sun}$

# Jupiter-Sun as an exoplanet system: radial velocity vs. time

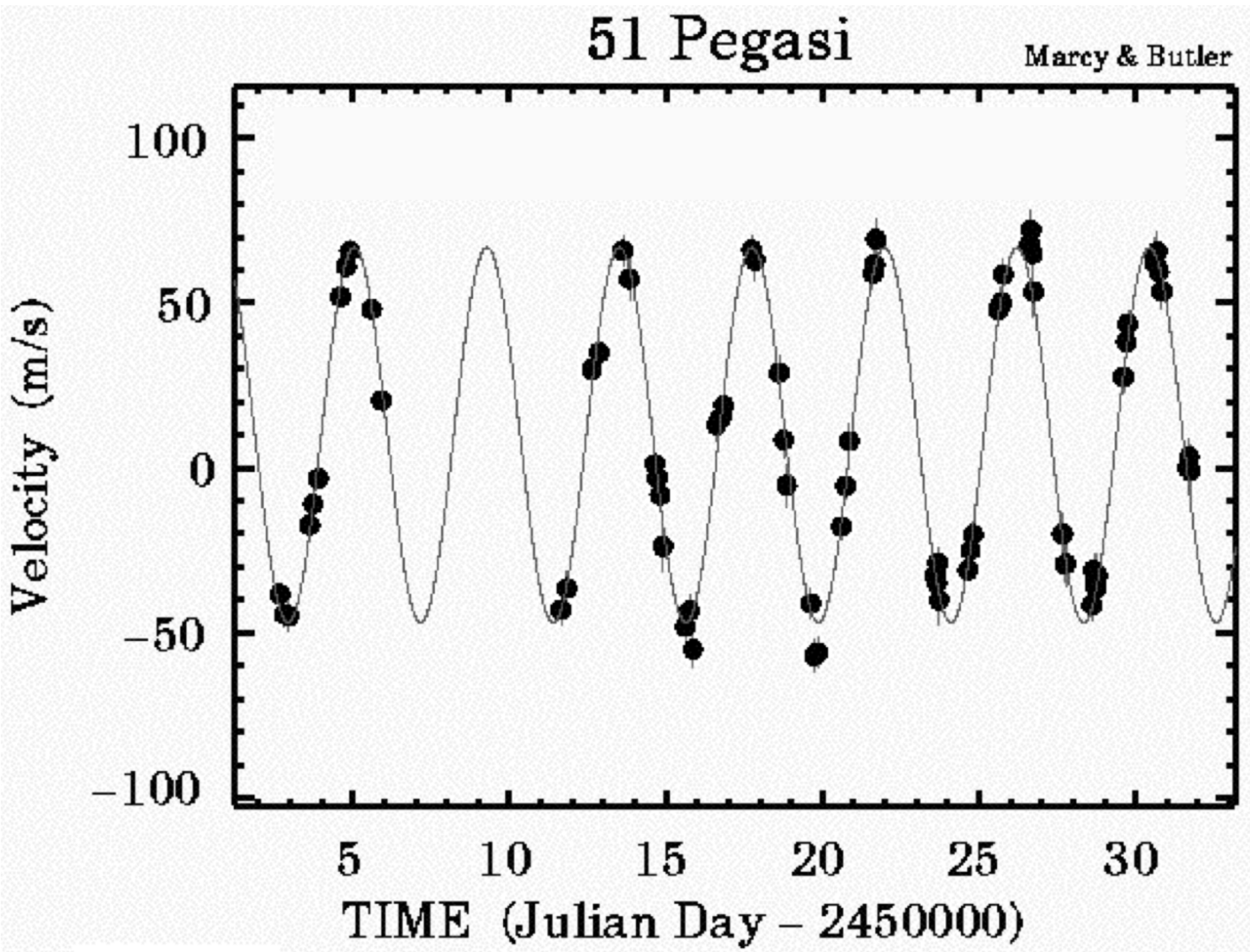


## By assuming exoplanet systems are similar to the Jupiter-Sun system, most astronomers missed the opportunity to discover 51 Pegasi b

# A Jupiter-mass companion to a solar-type star

**Michel Mayor & Didier Queloz**

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland




- Orbital period: 4.2 days, far from 12 years
- Amplitude of radial velocity of the star: 55 m/s, much greater than 13 m/s

# Indirect Method III

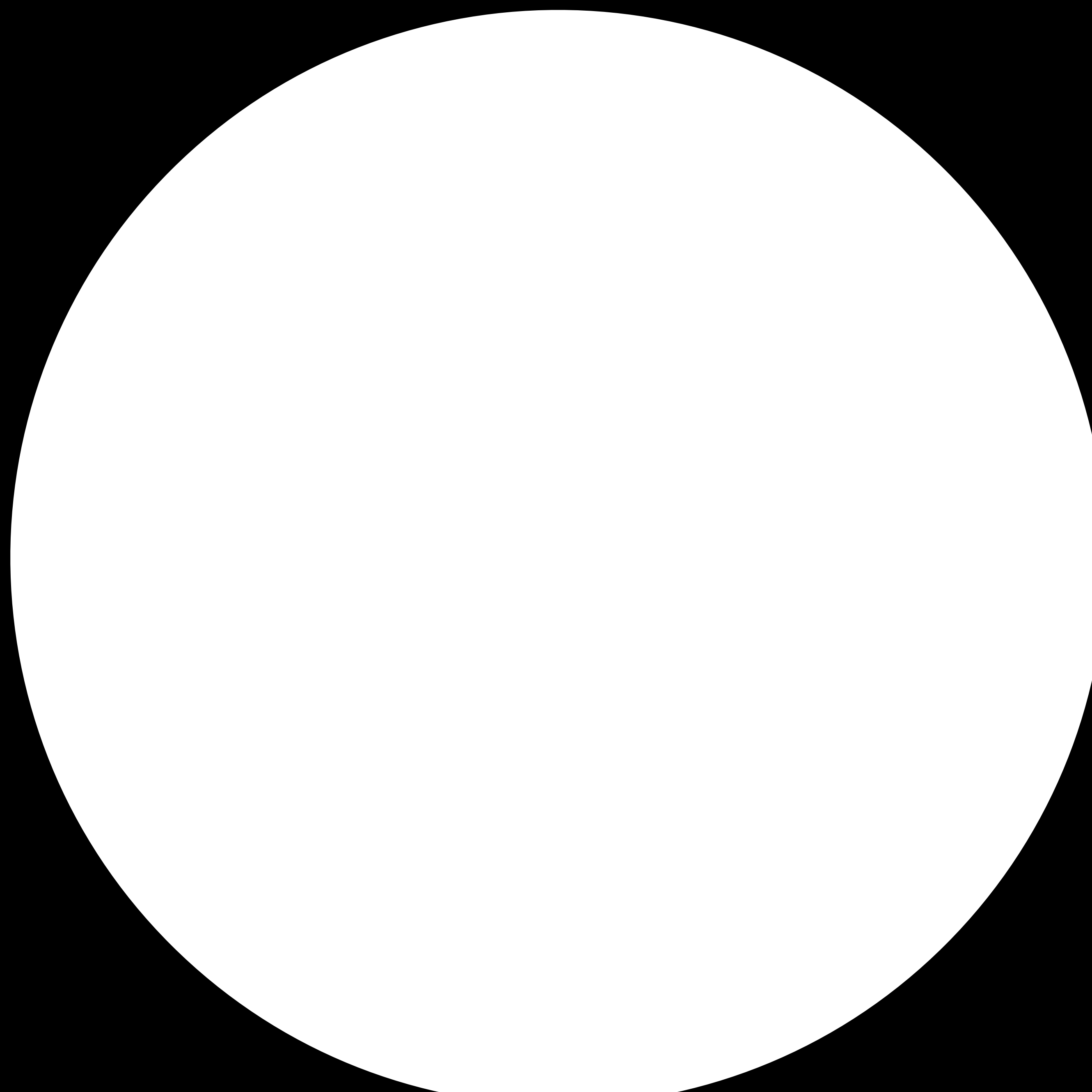
*the transit method*

# Received Flux = (Surface Flux/$\pi$) x Angular Area

$$F = \frac{L}{4\pi d^2} = \frac{4\pi R^2 F_S}{4\pi d^2} = \frac{F_S}{\pi}\frac{\pi R^2}{d^2}$$

F: received flux
$F_S$: surface flux ($\sigma_{SB}T^4$)
L: luminosity
d: distance
R: radius of star

Received Flux is in units of Joule/m$^2$/s, if the size of the emitting area changes, the received flux will change

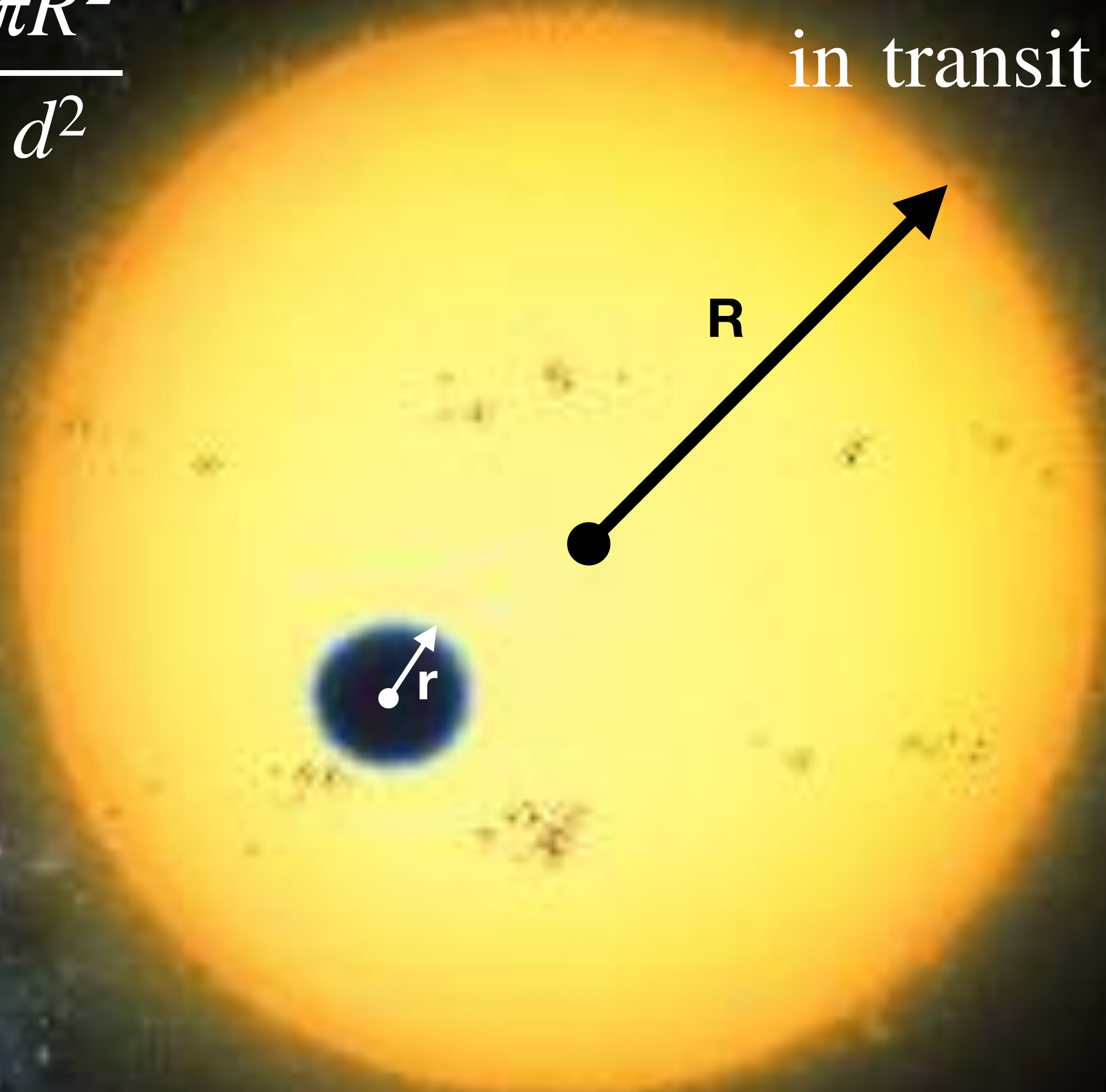


# Sketch of an Exoplanet Transit

*What would be the expression for the received flux during the transit?*
*What would be the fractional change in flux?*

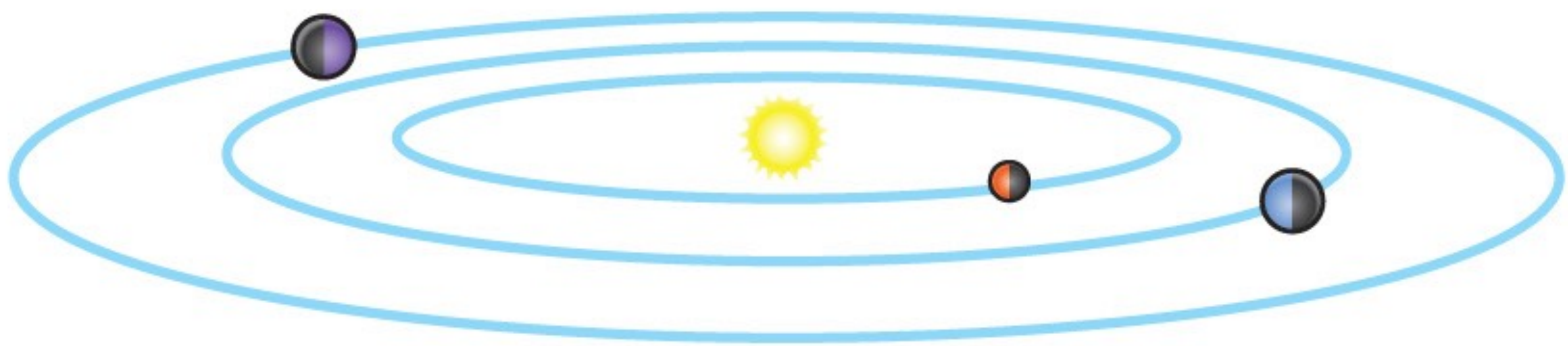
no transit : $F_0 = \frac{F_S}{\pi}\frac{\pi R^2}{d^2}$

in transit : $F_t = \frac{F_S}{\pi}\frac{\pi(R^2 - r^2)}{d^2}$

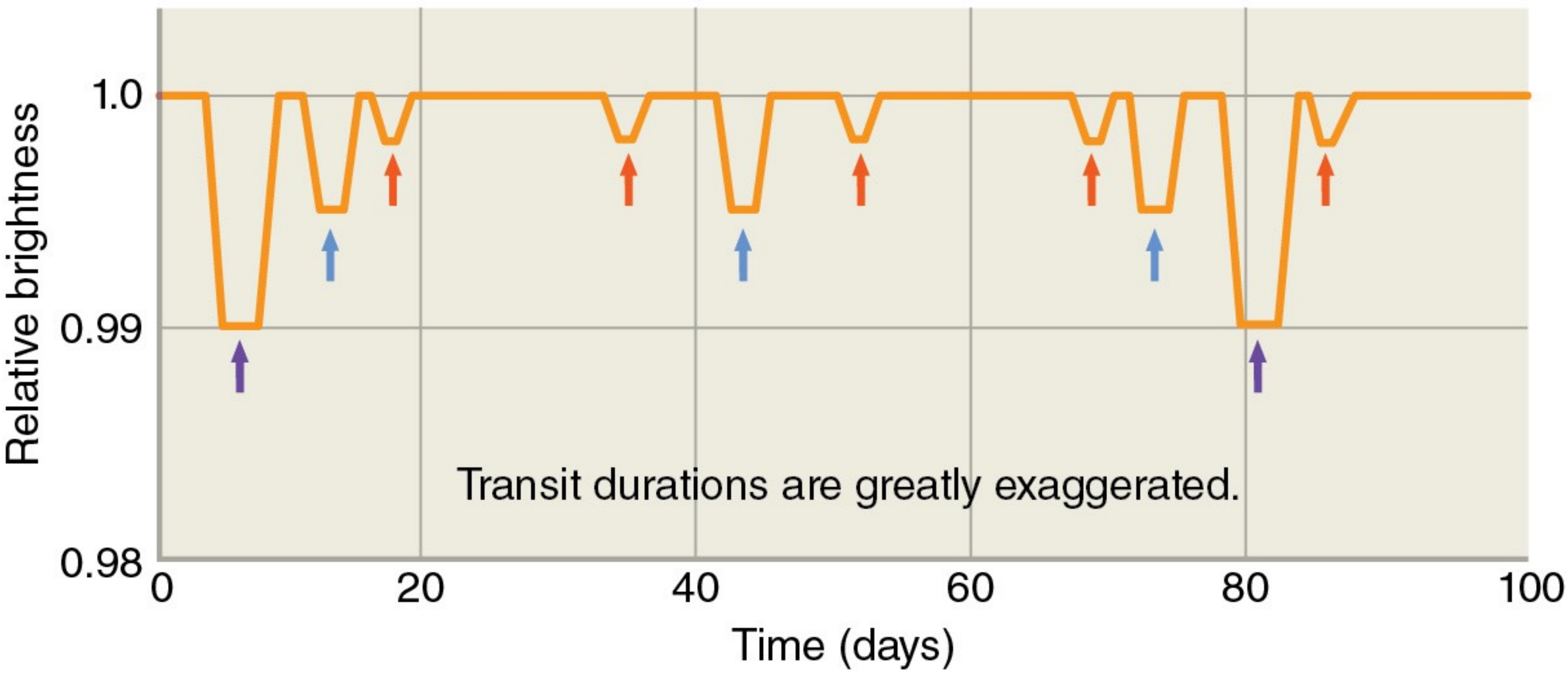



fractional difference : $\frac{F_0 - F_t}{F_0} = \frac{r^2}{R^2}$

# Transiting Signals from Multiple Planets

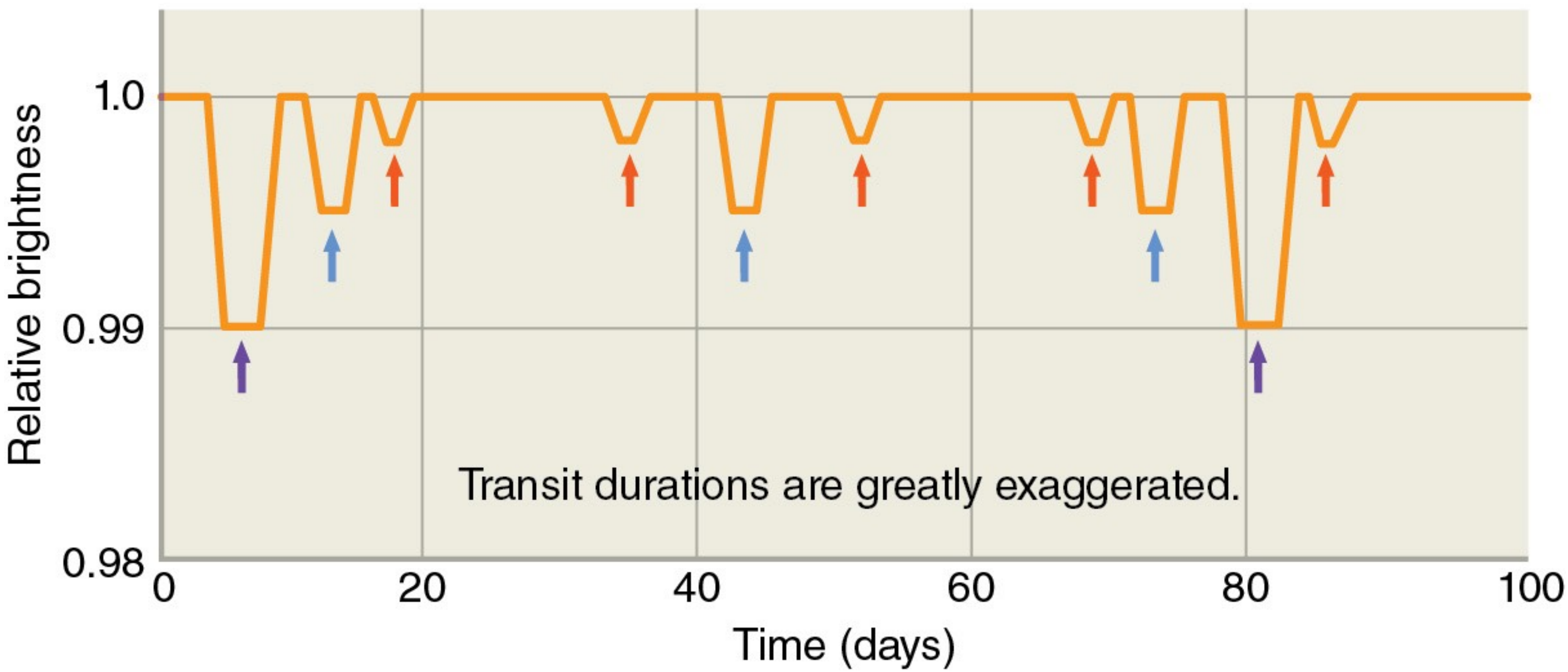


Planets can be distinguished by:
- different periods
- different depths
- different durations



# Planet Size from the Depth of the Transit and Radius of the Star

- By measuring the amount by which a star's light is dimmed during a planet's transit as well as the length of time the planet is in front of the star, you can estimate the size of the planet.



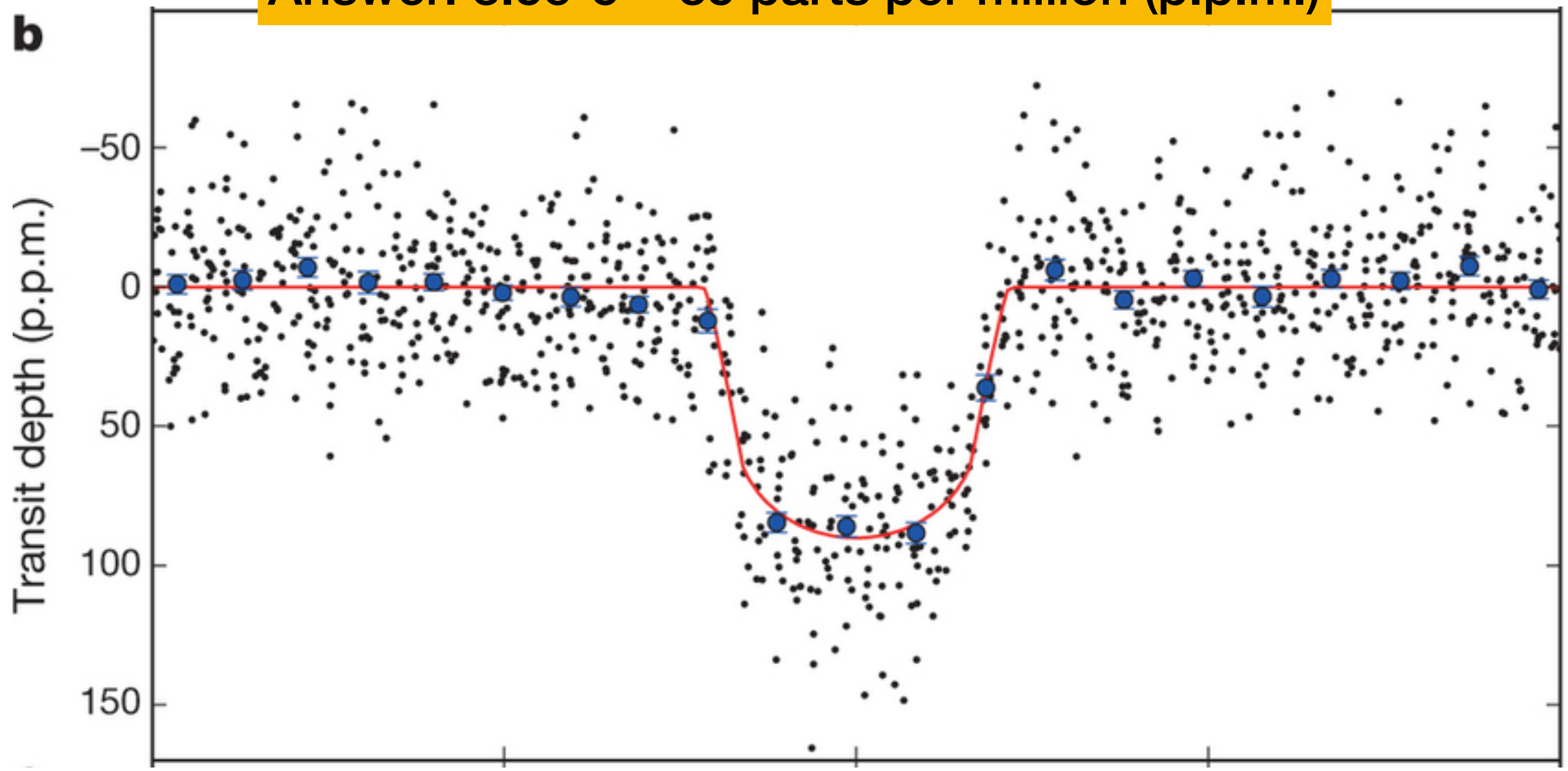

$$\text{Percentage reduction in light} = \frac{\text{Area of disk of planet}}{\text{Area of disk of star}} = \frac{\pi R^2_{\text{planet}}}{\pi R^2_{\text{star}}} = \frac{R^2_{\text{planet}}}{R^2_{\text{star}}}$$

# Practice: The Depth of Earth's Transit (Kepler's design requirement)

- Earth radius = 6,400 km, Solar radius = 695,700 km
- What would be the percentage reduction in the brightness of the Sun when the Earth transits in front of it?

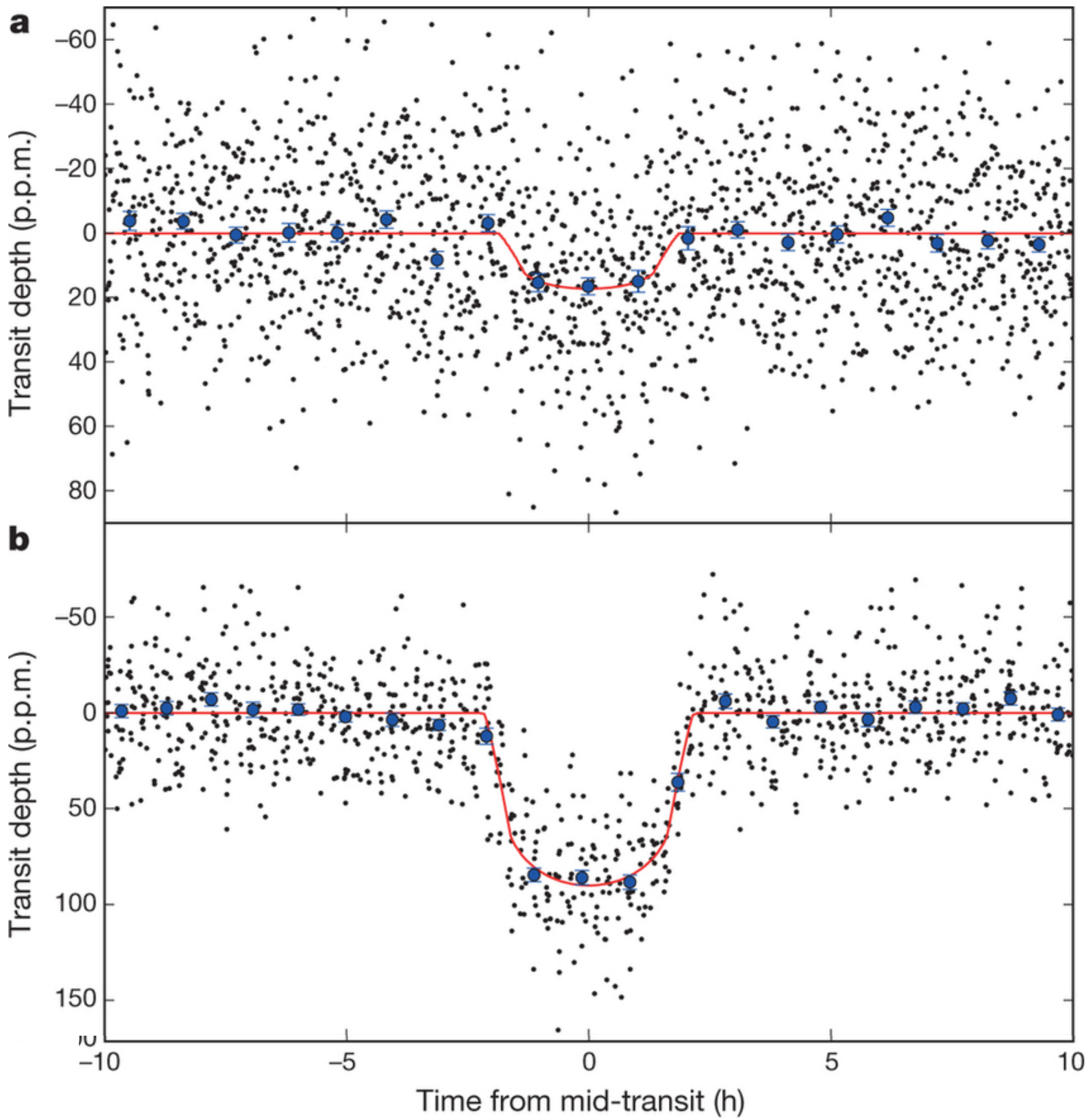
$$\frac{\text{Percentage}}{\text{reduction in light}} = \frac{\text{Area of disk of planet}}{\text{Area of disk of star}} = \frac{\pi R^2_{\text{planet}}}{\pi R^2_{\text{star}}} = \frac{R^2_{\text{planet}}}{R^2_{\text{star}}}$$

**Answer: 8.5e-5 = 85 parts per million (p.p.m.)**




Barclay et al. 2013

# What’s the size of the smallest planets that Kepler can detect?




**Transit depth: 12 p.p.m.**

**R = 0.3 $R_{Earth}$**
**A sub-Mercury**

**Transit depth: 81 p.p.m.**

**R = 0.7 $R_{Earth}$**

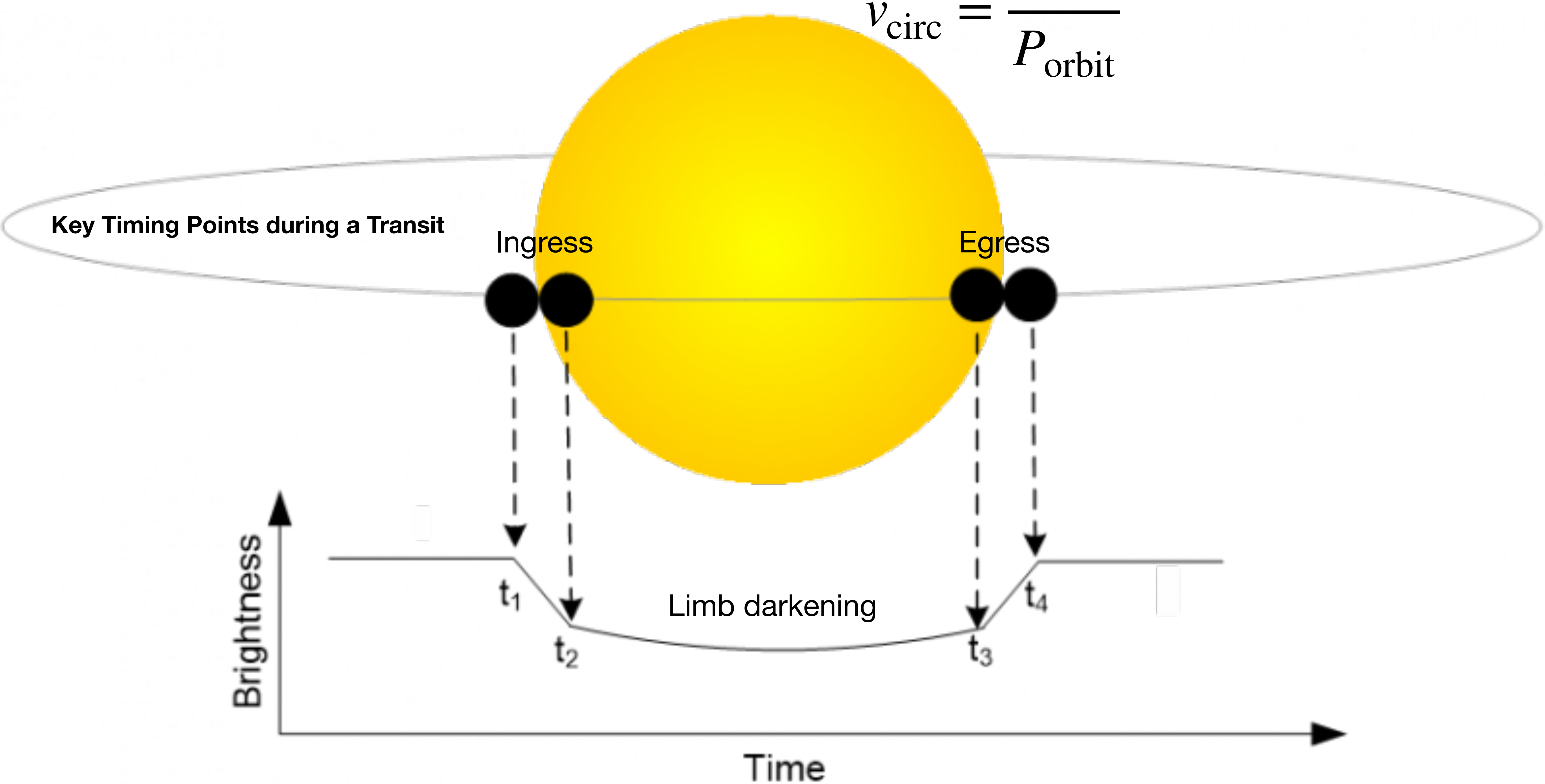
Barclay et al. 2013

# Planet Size from Ingress & Egress Duration and Mass of the Star

$$r = v_{\mathrm{circ}}(t_2 - t_1)/2$$

$$a_{AU} = (M_{\mathrm{solar-mass}} P^2_{\mathrm{year}})^{1/3}$$

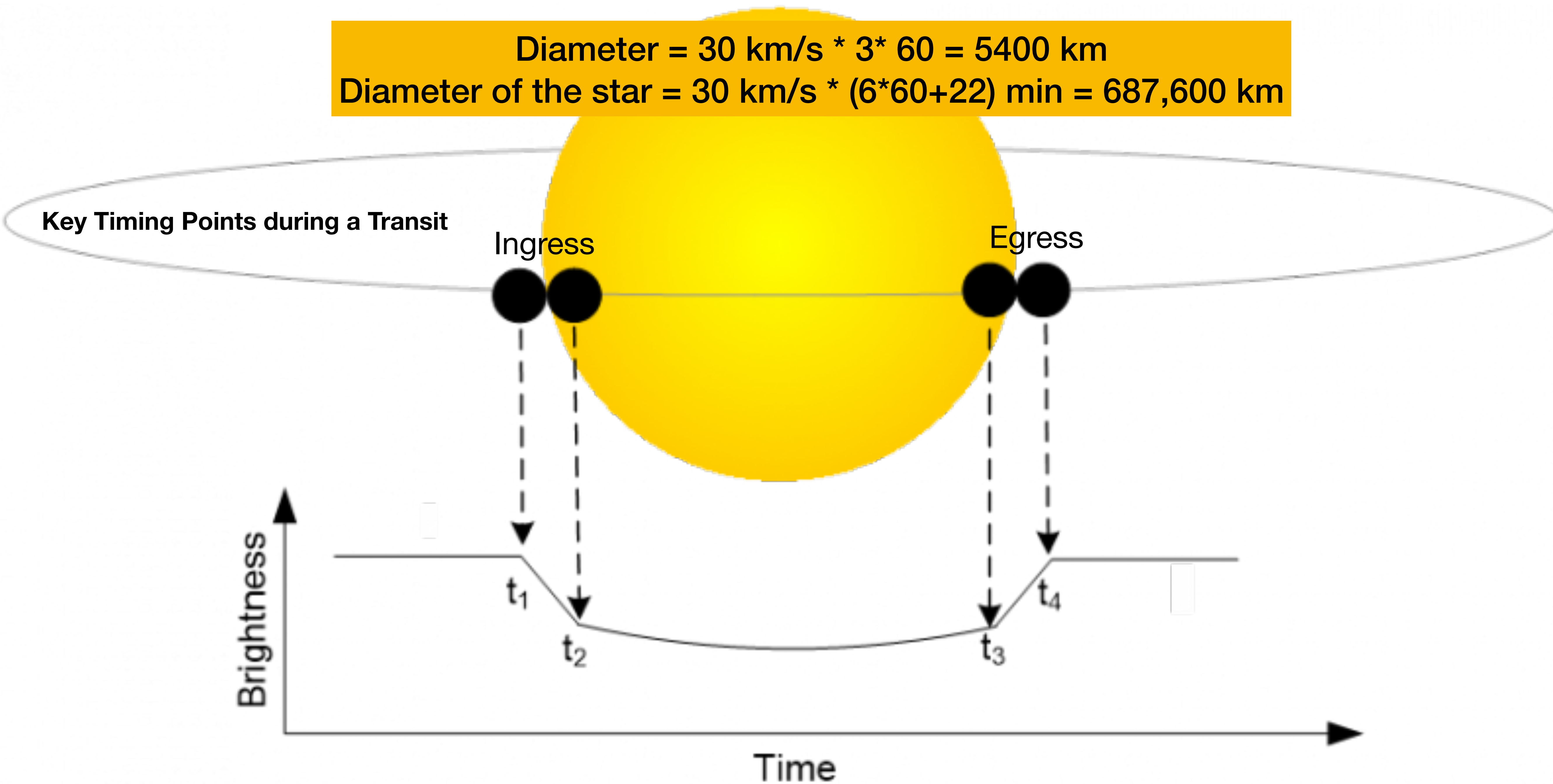
$$v_{\mathrm{circ}} = \frac{2\pi a}{P_{\mathrm{orbit}}}$$



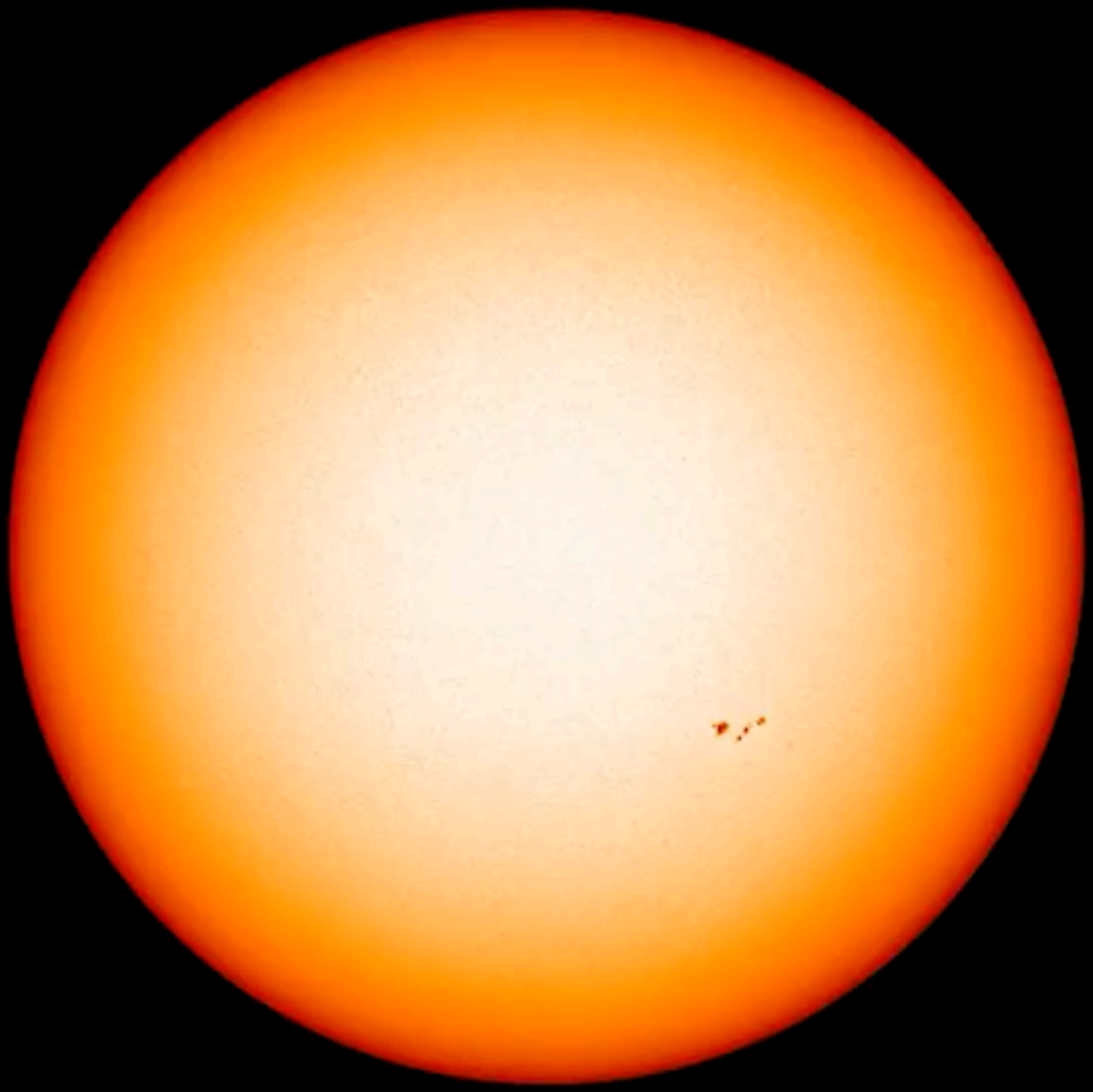
# Practice: Planet Size from Ingress & Egress Duration

- A transiting exoplanet around a Sun-like star (1 $M_{sun}$) has a transiting period of 1 year. From the transit light curve, you measure t1, t2, t3, t4 at 5:15, 5:18, 11:40, 11:43 (UTC), respectively.
- Estimate the **radius** of the planet and the **radius** of the star.

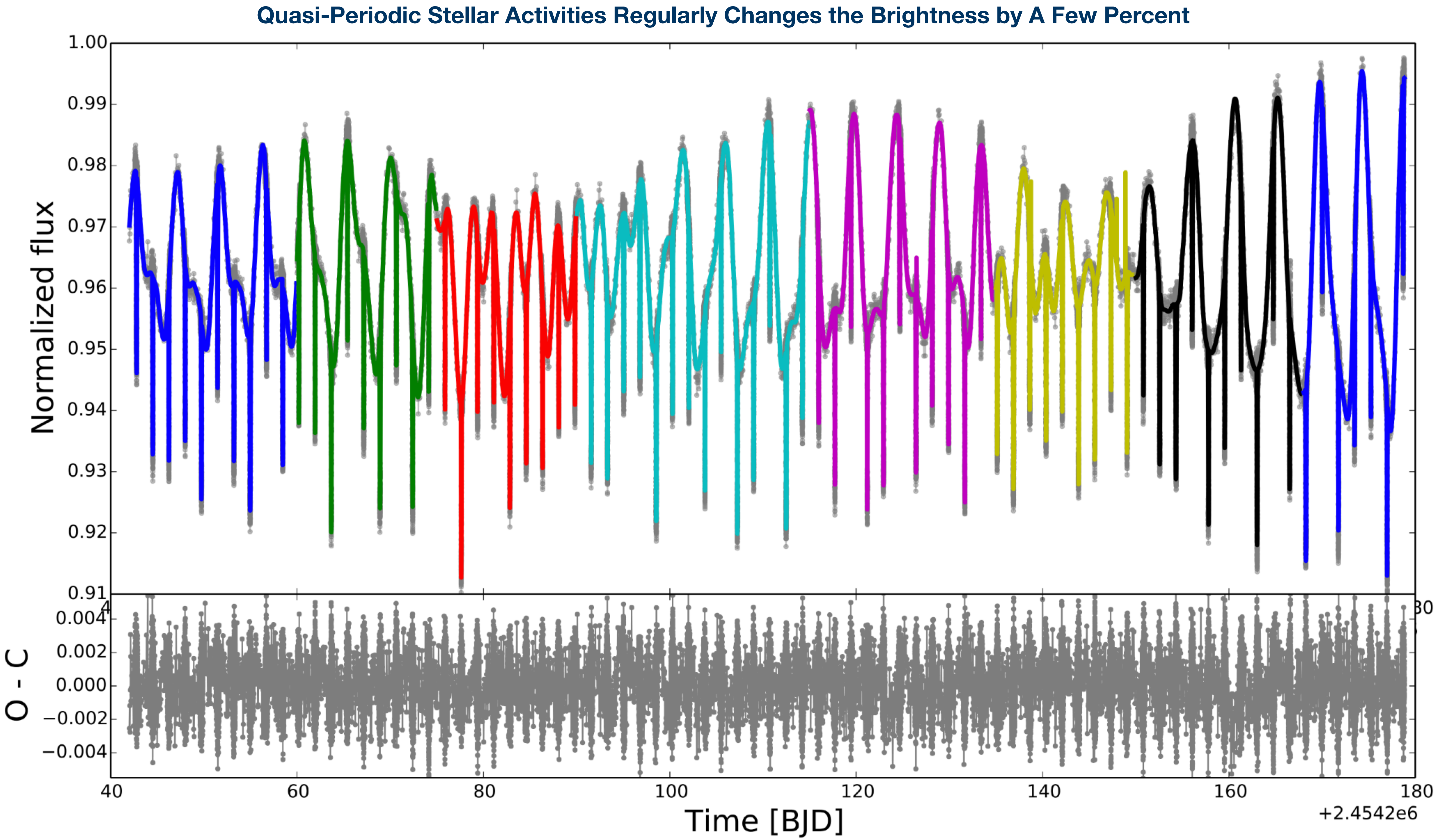
Diameter = 30 km/s * 3* 60 = 5400 km
Diameter of the star = 30 km/s * (6*60+22) min = 687,600 km



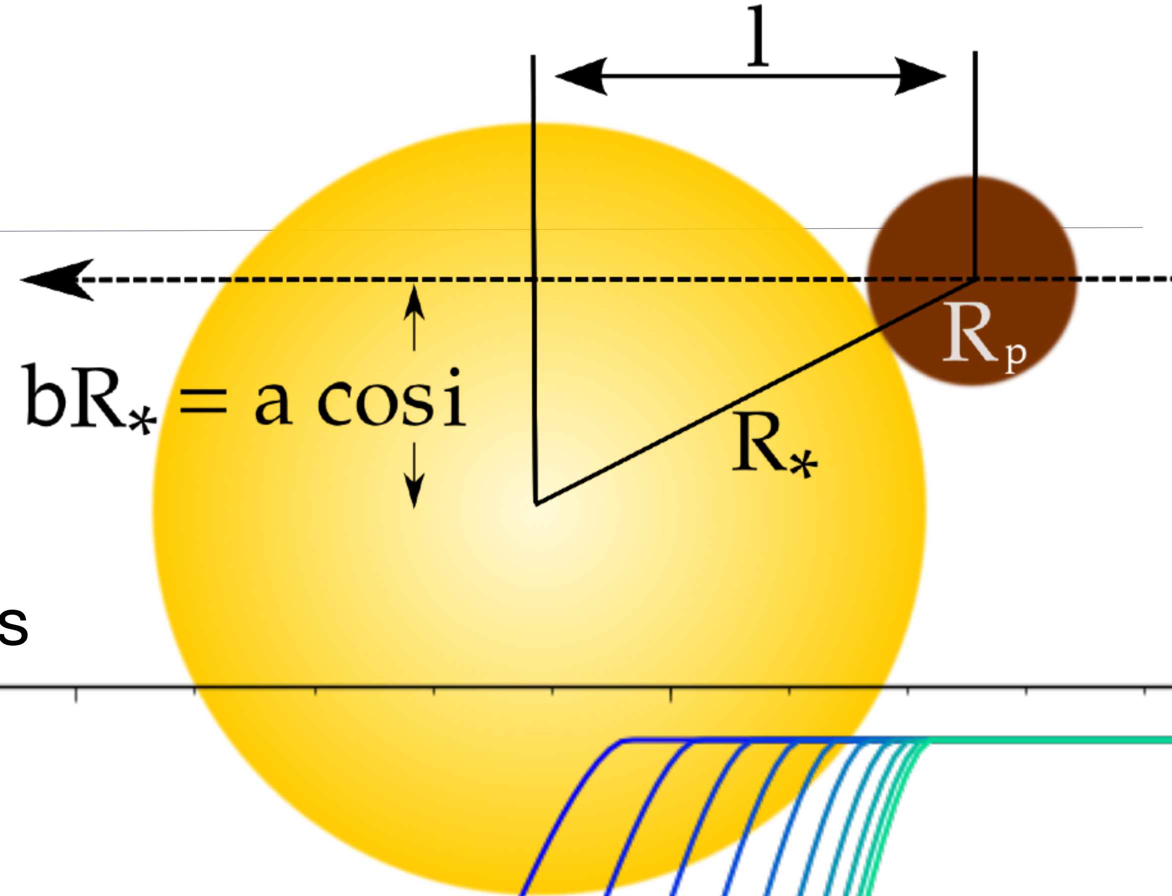
## Nothing is as simple as it appears:
## Stellar Activities, Stellar Rotation, & Limb Darkening



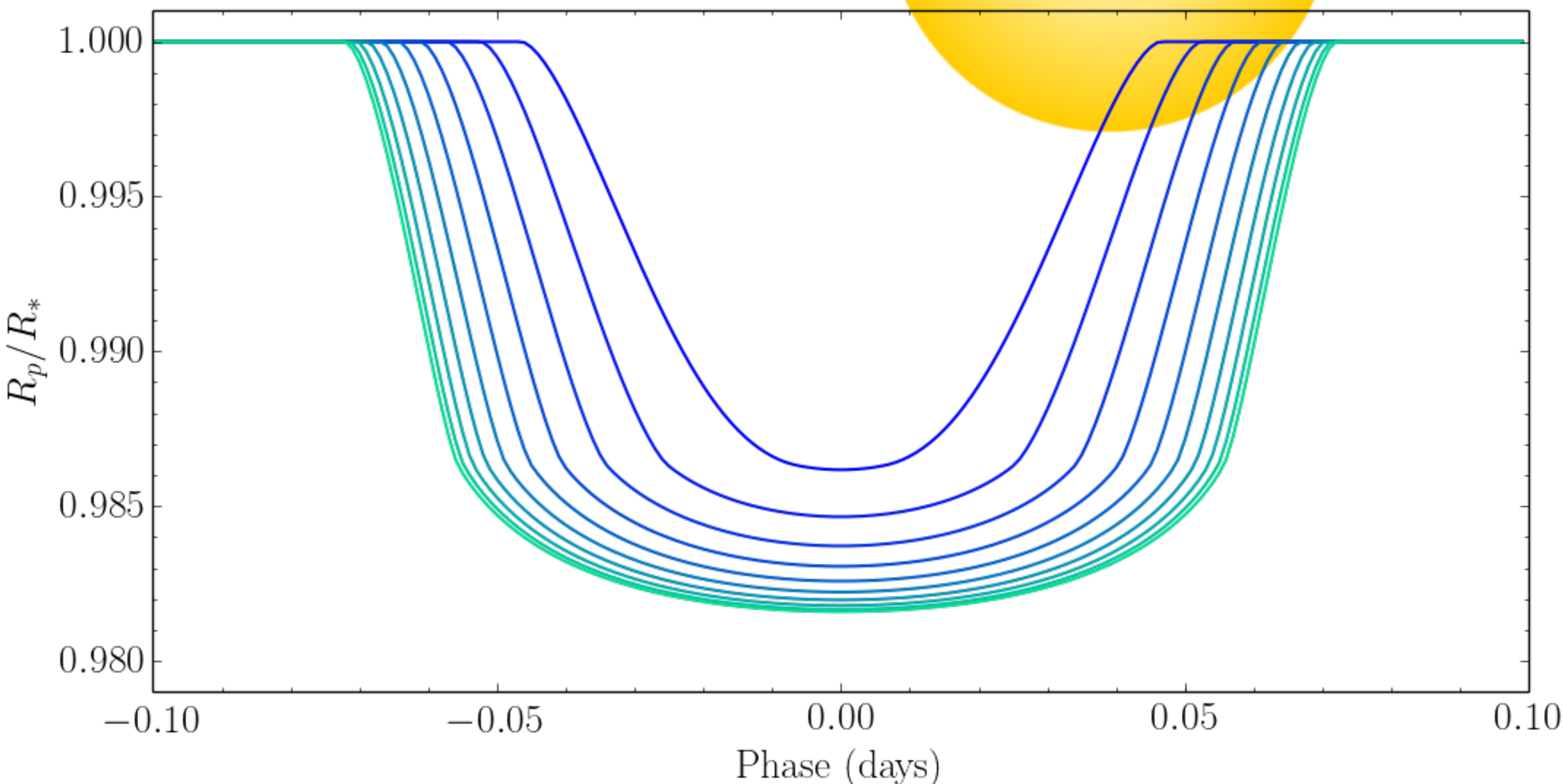
# Nothing is as simple as it appears: Stellar Activities & Rotation



## Orbital Inclination Effect




i = 80 to 90 deg simulated light curves

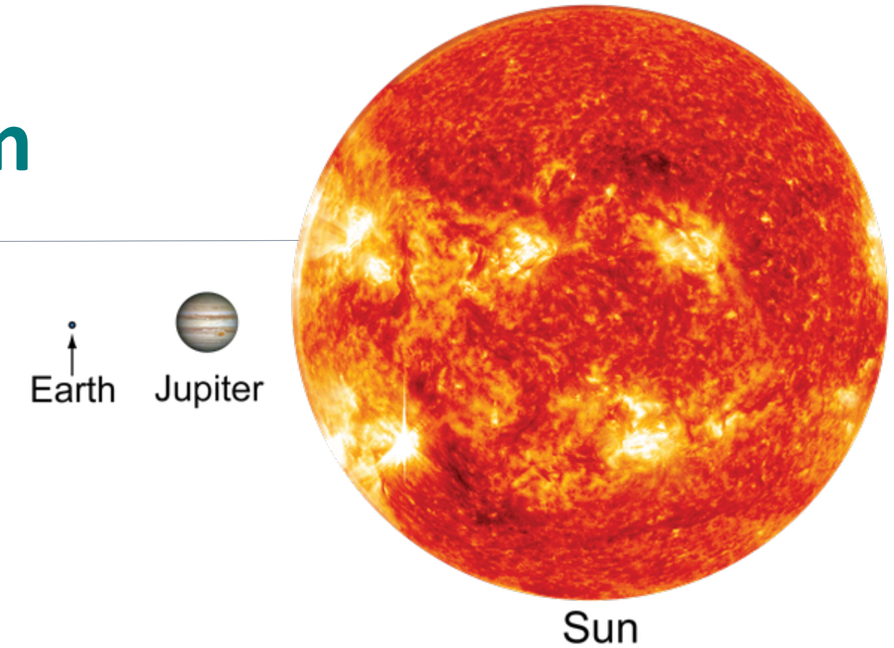


# Direct Method

*coronagraph imaging*

Directly imaging exoplanets around other stars is difficult because the planets are much much fainter compared to the star, and they appear very close to the star on the sky because of their great distances to Earth

# Practice: Earth-Sun as an exoplanet system




- Earth-Sun **distance**: 1 AU = 1.5e8 km
- Earth **radius**: 6400 km
- Earth **Albedo**: 0.3
- Assume **quarter phase** (i.e., Earth appears half illuminated)
- How many times brighter the Sun appears compared to the Earth to an observer on an alien planet far away?

**$L_{sun}/L_{earth}$ = 1.5e10, 15 billion brighter**

- How to estimate this ratio?
  - Can you express the luminosity of the Sun in terms of the Solar flux at Earth's orbit?
  - Can you express the luminosity of the Earth in terms of the Solar flux at Earth's orbit?

$$L_{\rm star} = F_{\rm @planet} \cdot 4\pi d^2_{\rm planet}$$

$$L_{\rm planet} = F_{\rm @planet} \cdot A \cdot \pi r^2_{\rm planet}/2$$

$$\Rightarrow$$

$$\frac{L_{\rm star}}{L_{\rm planet}} = \frac{8}{A}\frac{d^2_{\rm planet}}{r^2_{\rm planet}}$$

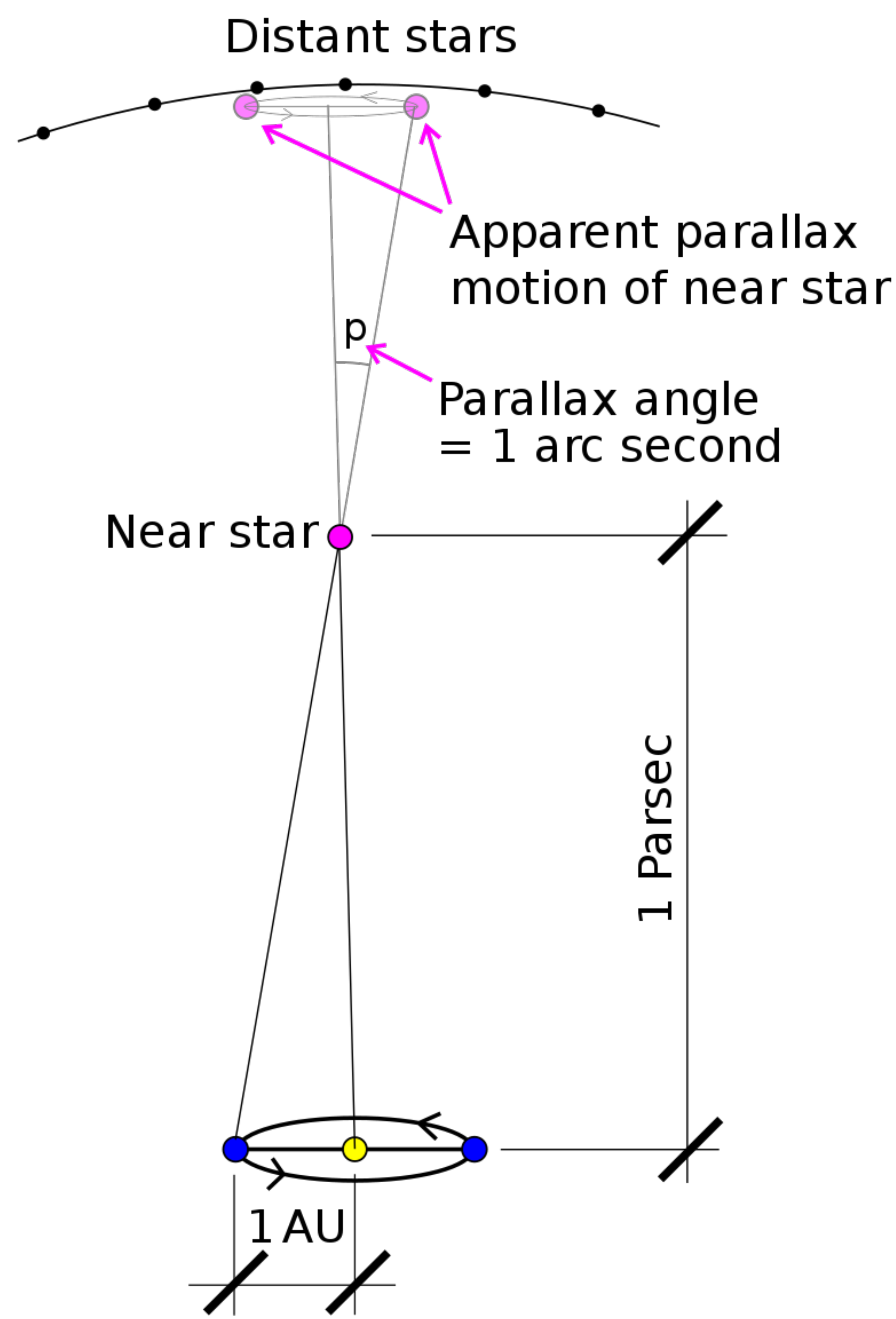
# Practice: Earth-Sun as an exoplanet system

- What is the ***maximum* angular separation** between Earth and the Sun seen by an alien observer located at a distance of **1 parsec (= 206265 AU)**?

- What if their distance is at 10 parsec?

**1AU @ 1 parsec => 1 arcsec**
**1AU @ 10 parsec => 0.1 arcsec**

$$\theta''_{\max} = \frac{a_{\text{AU}}}{d_{\text{parsec}}} = \frac{a}{1\ \text{AU}} \cdot \frac{1\ \text{parsec}}{d}$$

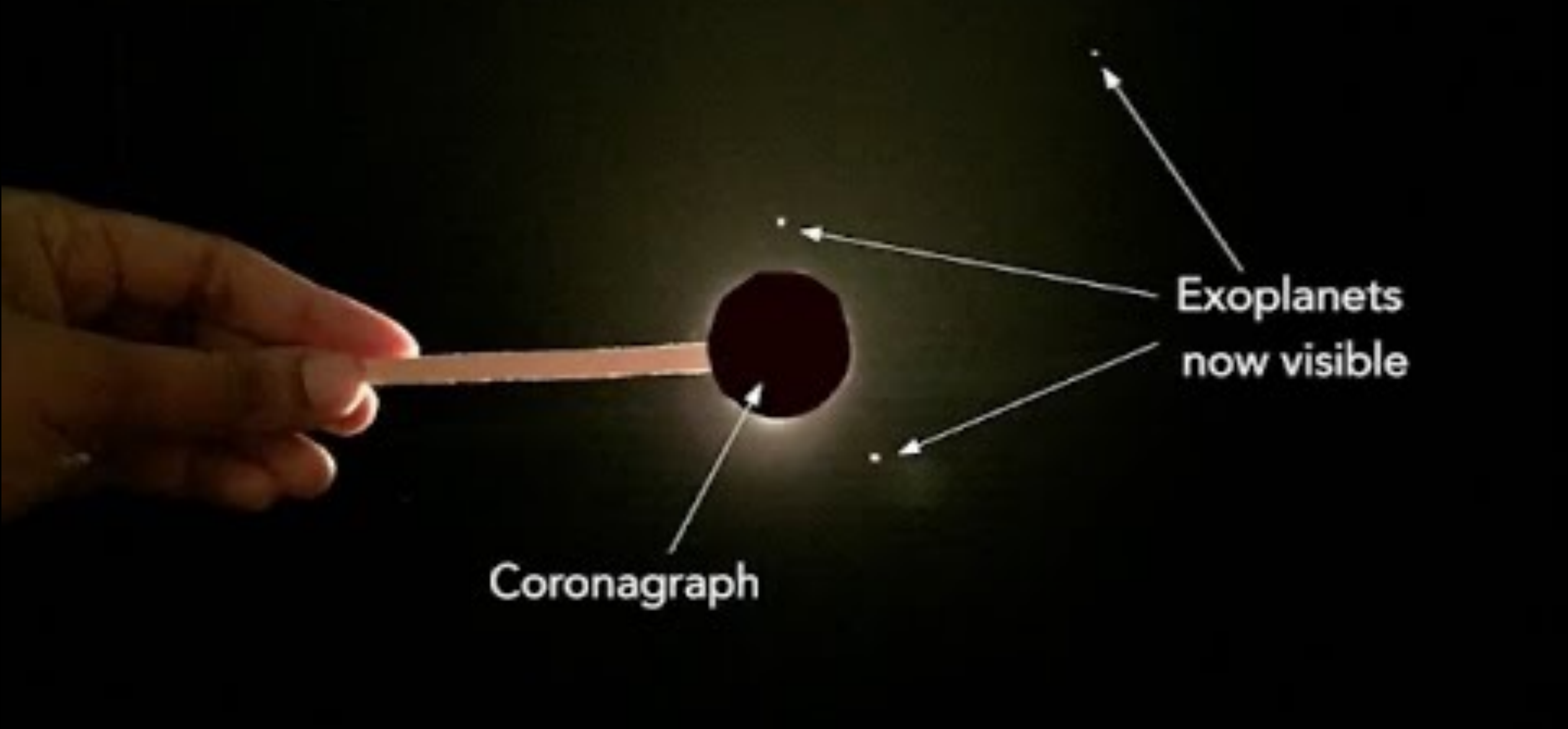



**The definition of 1 parsec**

**Inspired by the solar eclipse example, can we simply put an occulting mask in front of a telescope to block the starlight?**

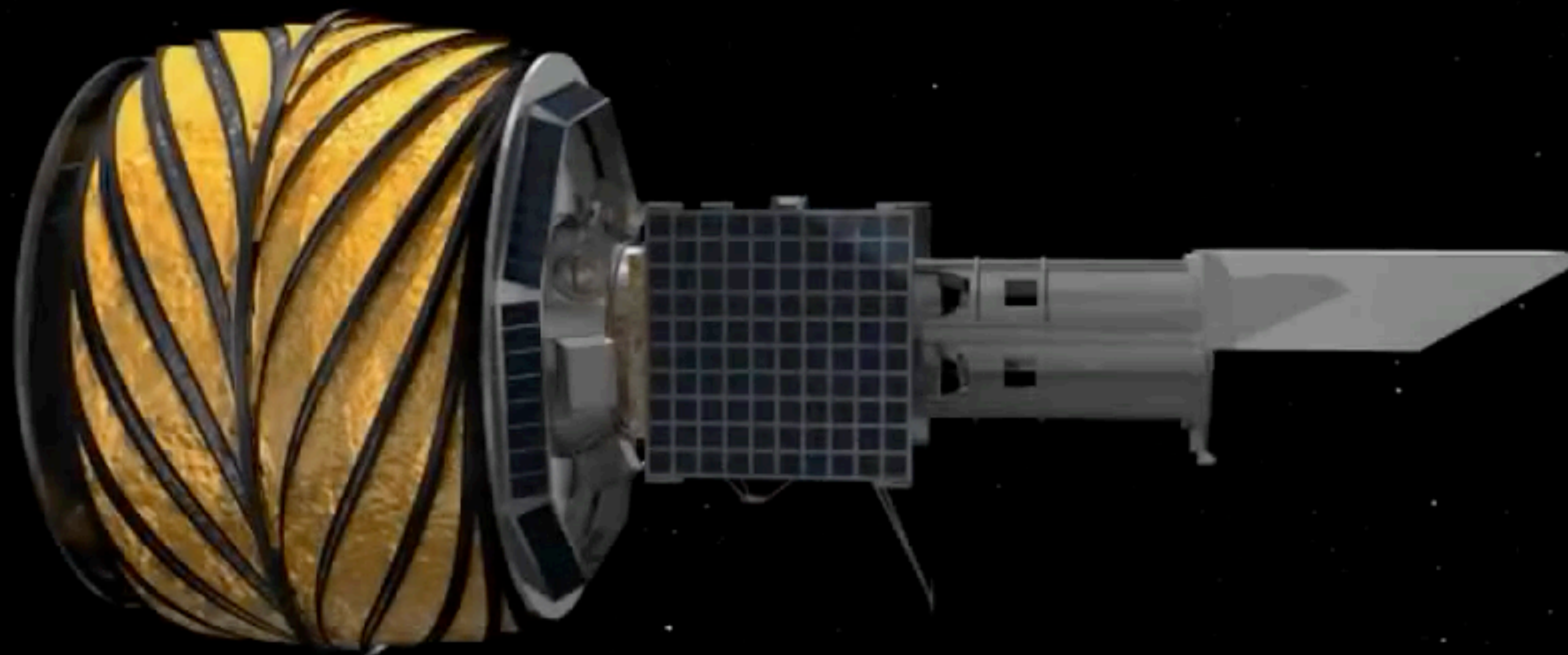
To be effective, the occulting mask must be larger than the size of the telescope pupil (e.g., > 10 m for Keck), and placed distant enough so that its angular size is comparable to that of the Sun (0.5 degree across).

*Distance = Mask Diameter / 0.5 deg in radian = 115 x Mask Diameter*

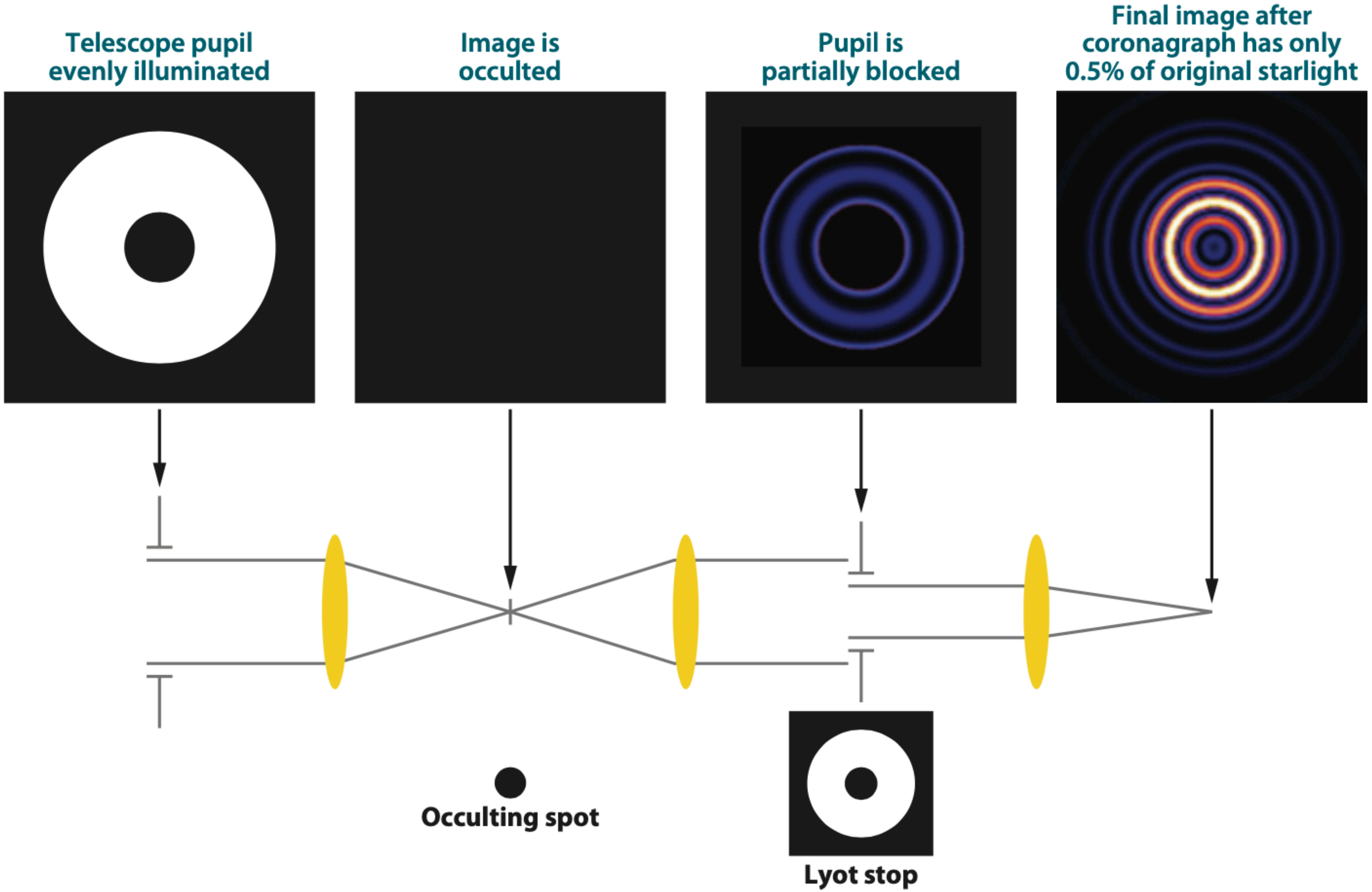


# The Ultimate Coronagraph - Starshade placed 72,000 km away from the space telescope

*Distance = Starshade Diameter / Angular Size of Exoplanet Orbit*



# A Typical Coronagraph (invented by Bernard Lyot in 1931) the occulting mask is placed inside the camera

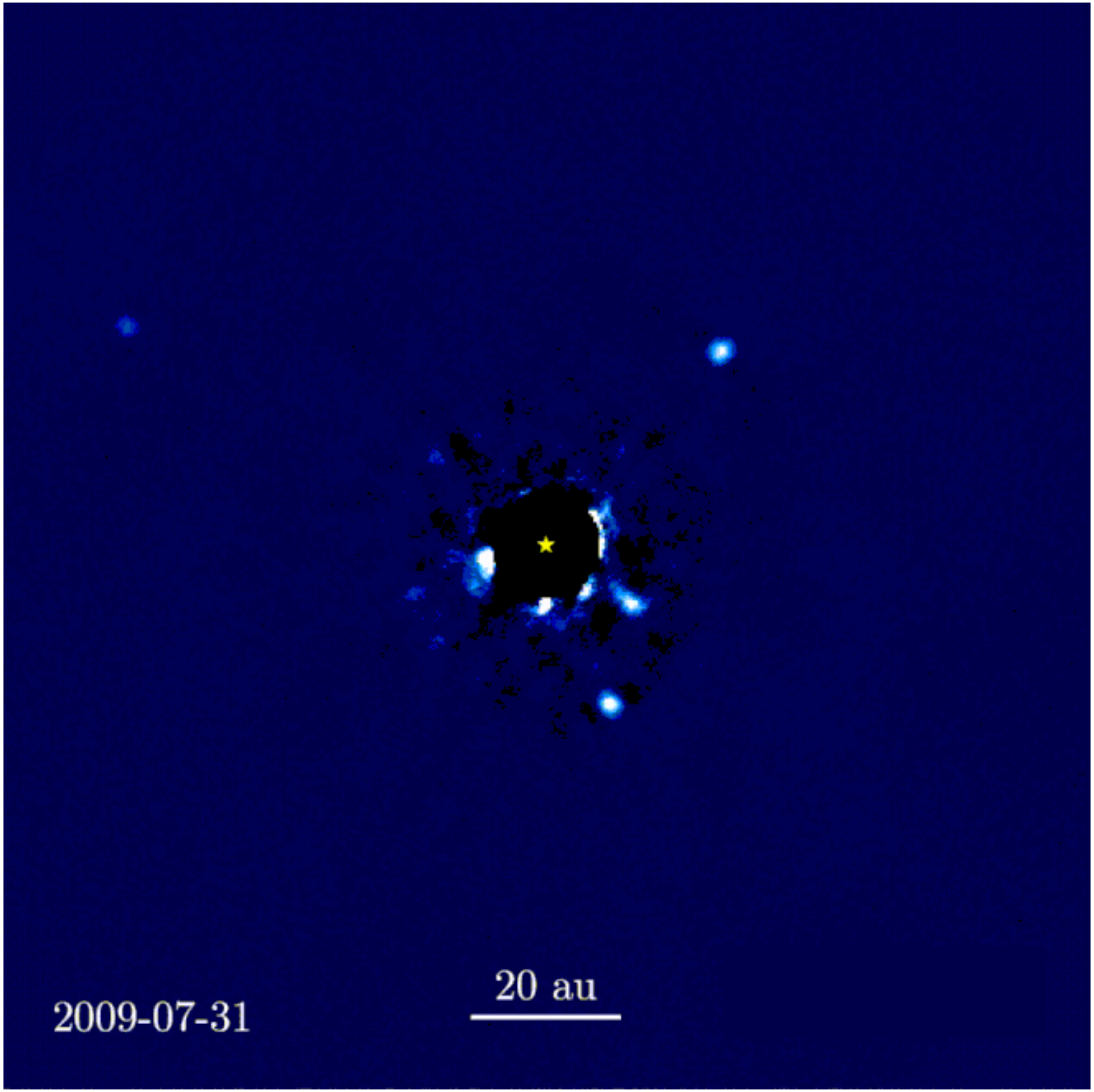


Direct imaging of exoplanets requires
(1) high dynamical range
(2) high spatial resolution

For high dynamical range, we use coronagraph.

For high spatial resolution, we use
(a) space-based telescopes,
(b) ground-based adaptive optics, or
(c) radio interferometers

**Four sub-stellar objects orbiting around HR 8799. Current mass estimates favor planet-size objects (< 13 Jupiter Mass), but we don’t know if these are correct.**

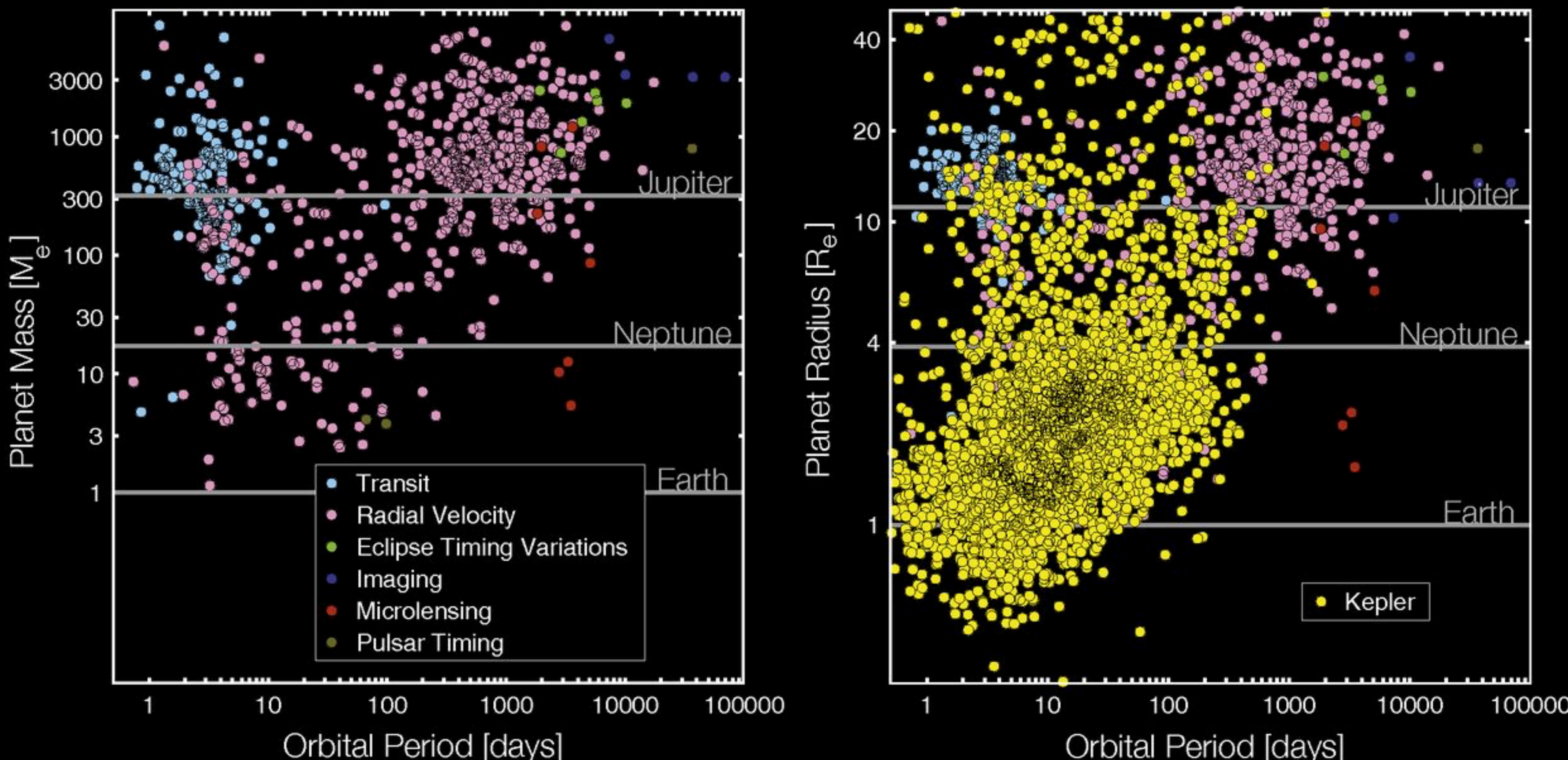


# Exoplanet Populations

*hot Jupiters and super-Earths*

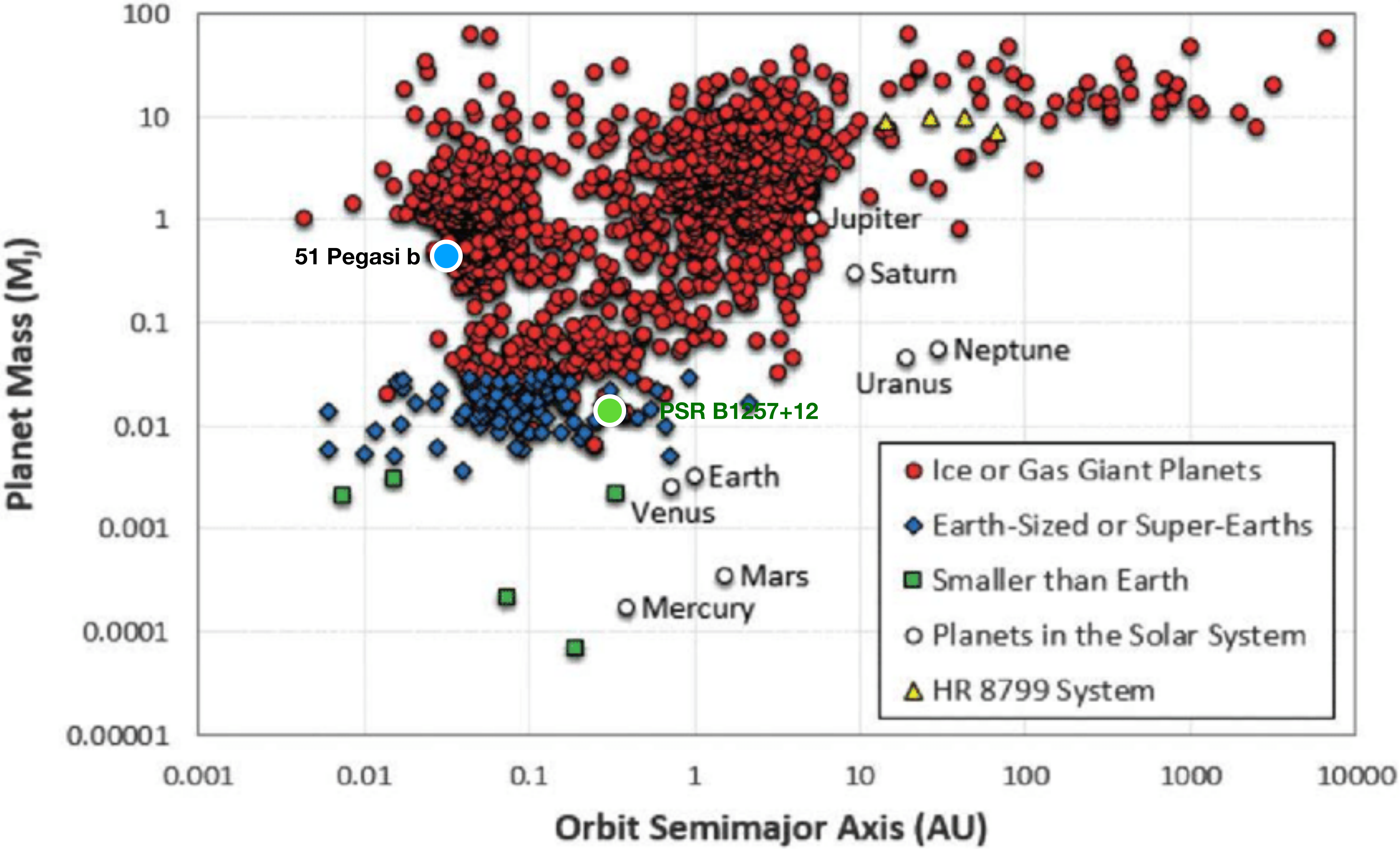
# What can we measure?

## Planet Mass [RV], Planet Size [Transit], & Orbital Period/Size [Both]



# Classification of the Exoplanets based on Orbital Size and Mass

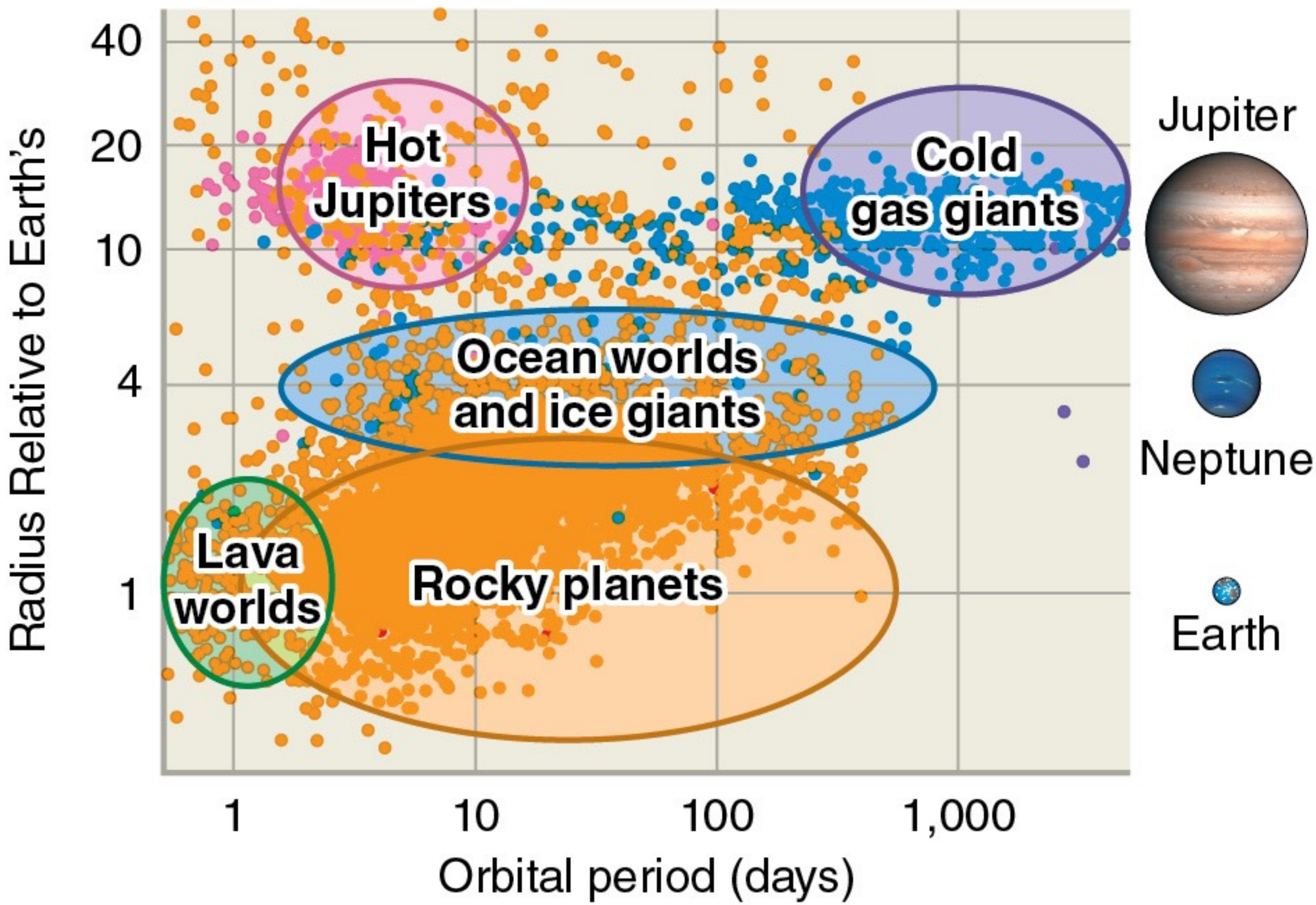
Below are planets discovered by the **RV method.**



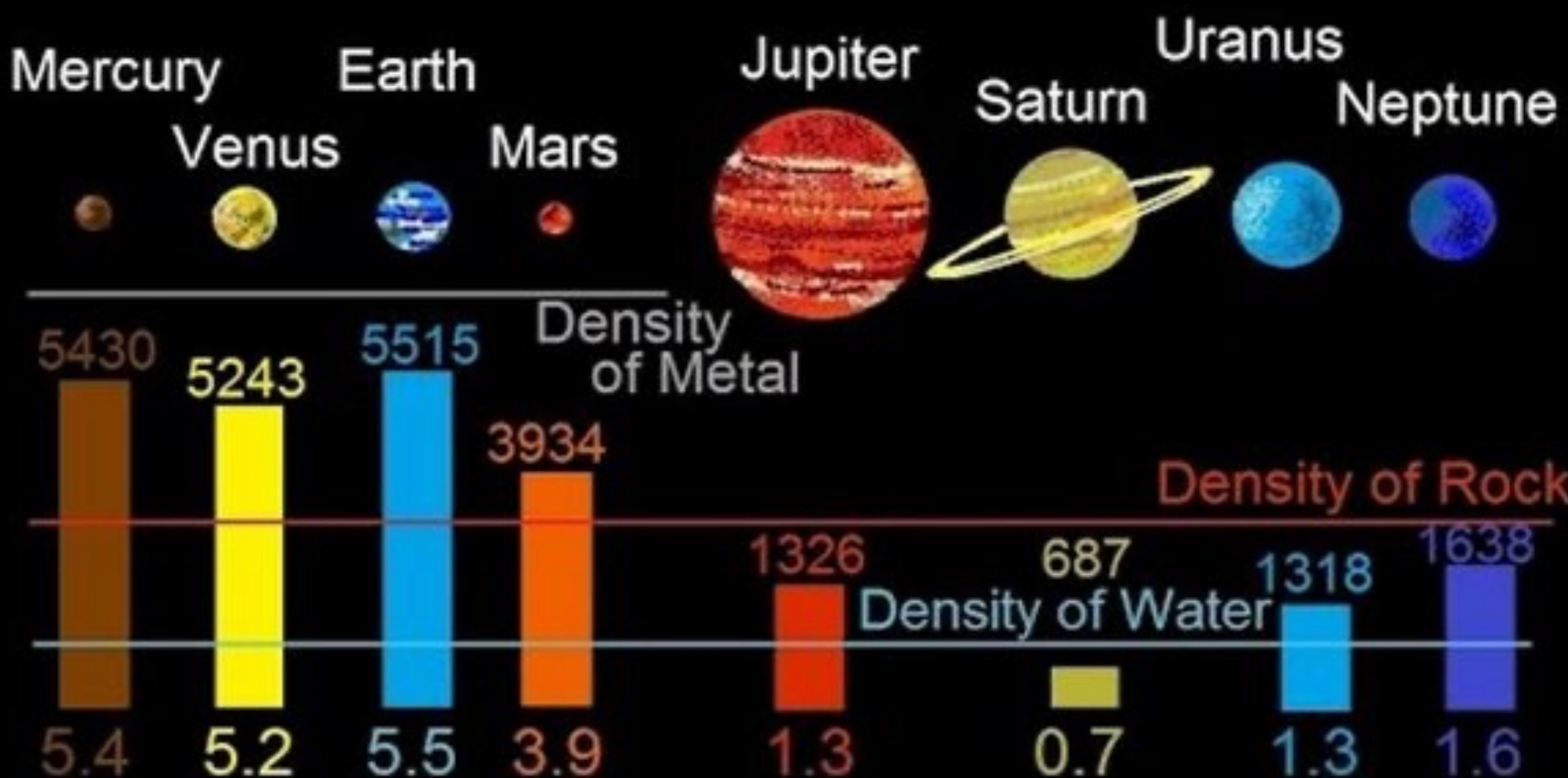

Ref: The Astrobiology Primer v2.0

# Classification of the Exoplanets based on Orbital Period and Size

Below are planets discovered by the **transit method**, because **planet size** needs to be measured from transit depth or ingress/ egress interval, the RV method cannot measure planet size.



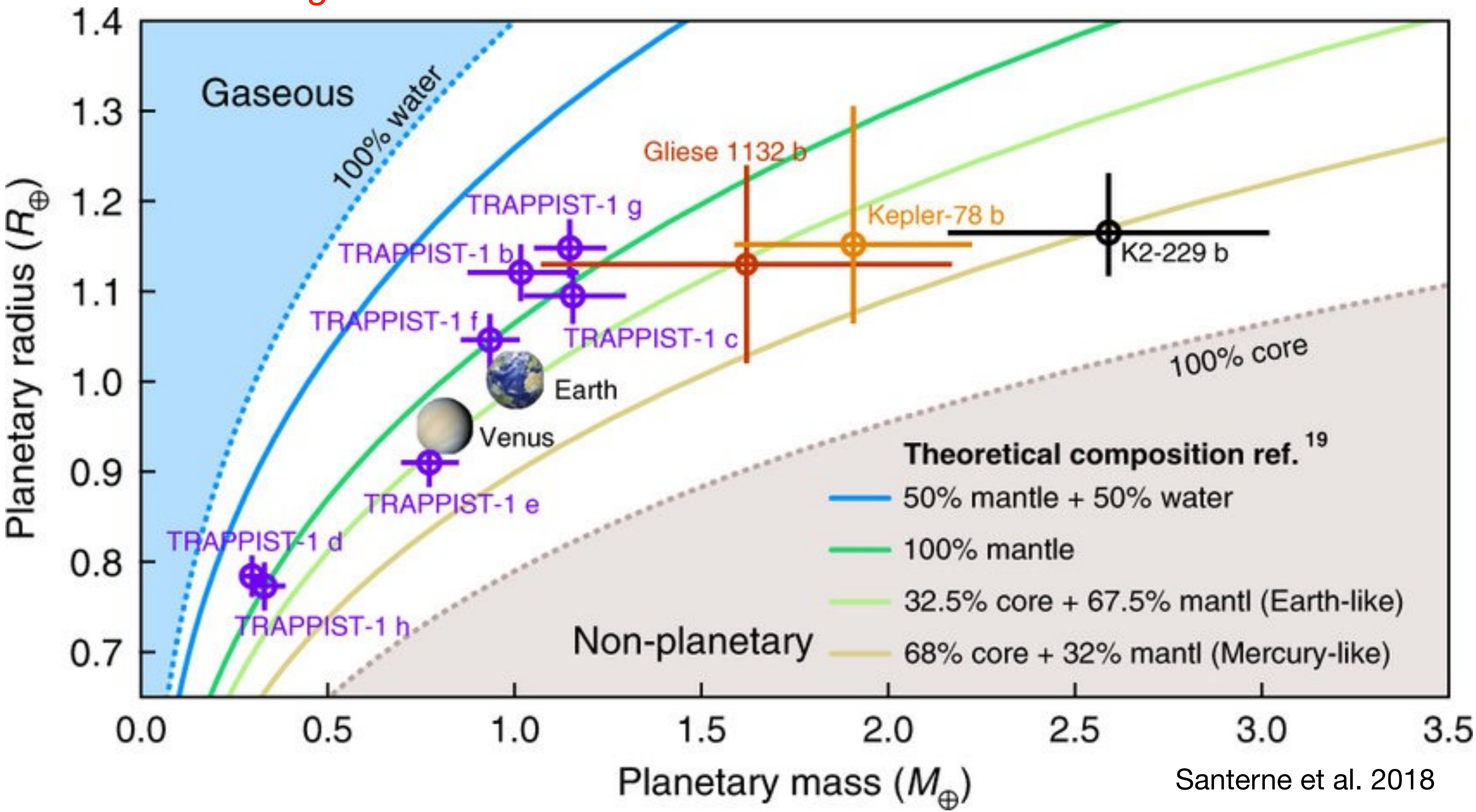
# The Mean Density of Planets in the Solar System




Densities at the bottom are in units of g/cm$^3$

## Densities of Exoplanets Require both RV and Transit Measurements

- To measure density, $\rho = 3m/(4\pi r^3)$, we need
  - **planet mass (m)** from RV method (m/M = V/v = D/d) and
  - **planet size (r)** from transit method (transit depth or ingress interval)
- Note the large error bars of the measurements




Santerne et al. 2018

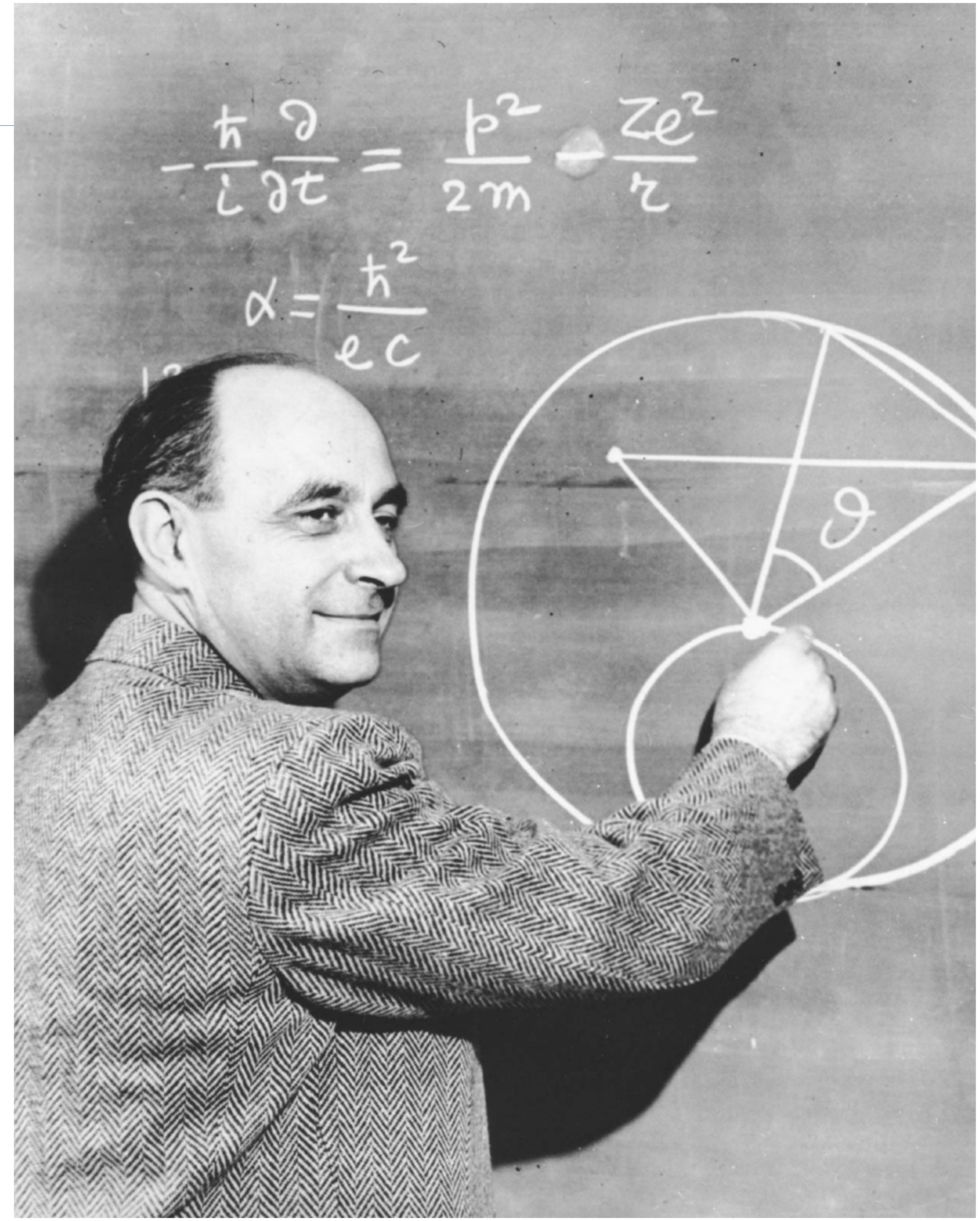
# How many planets hosting ET are out there?

Drake Equation

$$N \sim L_{yr}$$

# Fermi Estimation

- The goal is to get an **order-of-magnitude estimate**
- This is **not** a method to obtain accurate answers
- To reach the goal, Fermi needs to take advantage of various conversion factors



# How many piano tuners are there in Chicago?

- we assume # required = # actually exist (supply meets demand)

# How many piano tuners are there in Chicago?

- What is the unit of the answer?
  - the number of piano tuners

- What are some starting piece of information?
  - Population of Chicago - 3 million

- What are some conversion factors we might use?
  - what percentage of families have pianos? - about 1/10
  - how many people per family? - about 3
  - frequency of tuning - once per 3 years
  - number of tunings a tuner can do in a year - 300

# How many piano tuners are there in Chicago?

- What is the number of pianos?
  - 3 million / 3 people per family * 10% piano ownership
    = 100,000 pianos
- What is the number of tunings required per year?
  - 100,000 pianos * 1/3 tunings per year
    = 30,000 tunings per year
- What is the number of tuners required to complete the job?
  - 30,000 tunings per year / 300 tunings per year per tuner
    = 100 tuners

## Q1: How many advanced civilizations ever existed in the Milky Way?

- **Potential trap: we'll assume they live on planets similar to the Earth**

***Recall that by assuming exoplanet systems are similar to the Jupiter-Sun system, most astronomers missed the opportunity to discover 51 Pegasi b***

## Q1: How many advanced civilizations ever existed in the Milky Way?

- What is the unit of the answer?
  - the number of planets hosting advanced civilization ever existed

- What are some starting piece of information?
  - The Population of Stars in the Milky Way - 100 billion

- What are some conversion factors we might use?
  - percentage of stars have planets
  - average number of Earth-like planets per system
  - fraction of life-supporting planets
  - fraction of such planets that develop advanced civilization

# Q1: How Many Advanced Civilizations Ever Existed?

$$N_{\text{total}} = N_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c$$

$N_{\text{total}}$ = the cumulative number of advanced civilizations in the Galaxy
$N_*$ = the total number of stars in the Galaxy, i.e., the integral of the star formation history of the Galaxy

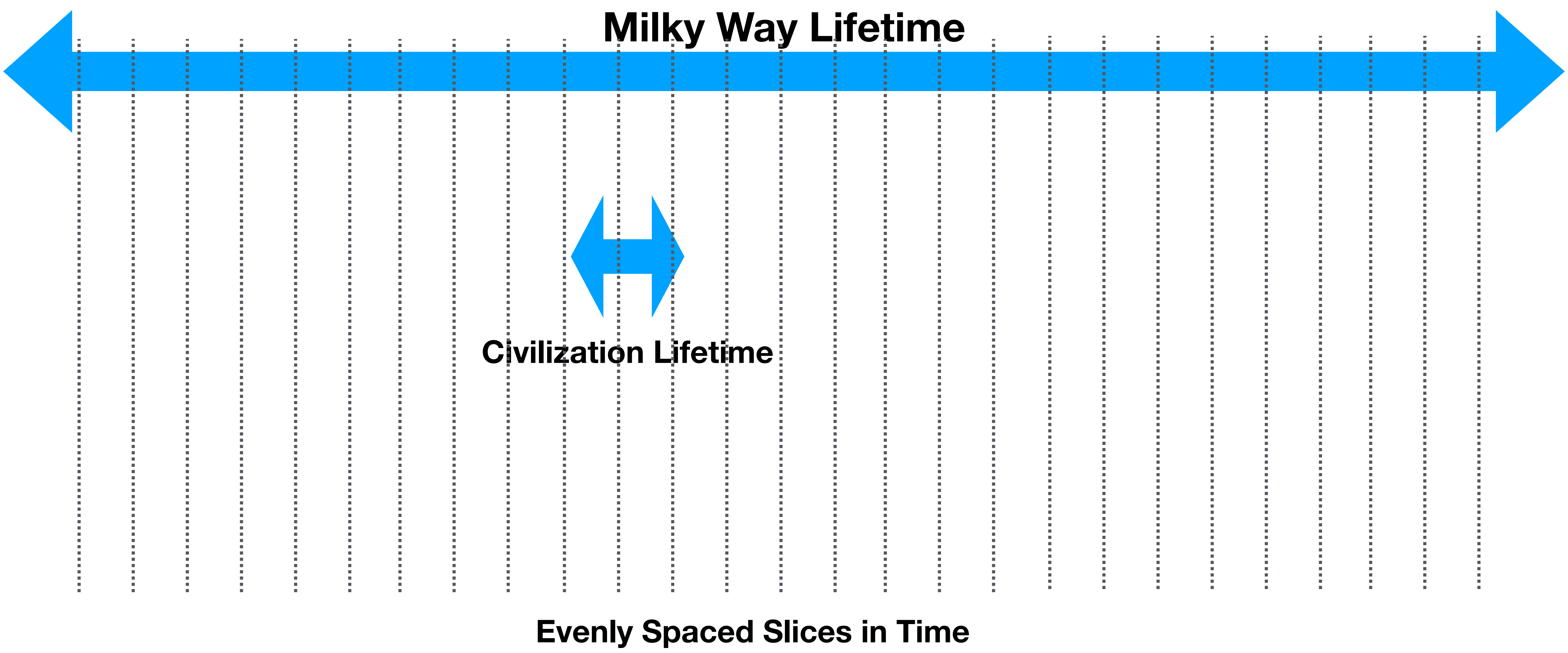
$f_{\text{p}}$ = the average fraction of stars that host planets
$n_{\text{e}}$ = the number of planets, per system, that can potentially support life
$f_{\text{l}}$ = the fraction of life-supporting planets that actually develop life
$f_{\text{i}}$ = the fraction of planets with life that actually develop intelligent life
$f_{\text{c}}$ = the fraction of planets with intelligent life that develop advanced civilizations that release potentially detectable signs of their existence

# Q2: How many advanced civilizations are present at a random time?

- Imagine life-supporting planets are fireflies, and advanced civilizations are like their brief flashes of light - At any moment, only a fraction of fireflies are visible.
- What's the probability of a photographer catching a photo of the flash from a certain firefly throughout a night? This photographer can only take one photo in one night.
- The probability depends on the duration of the flash and the duration of the night

# Q2: How many advanced civilizations are present at a random time?

- Imagine one of these civilizations, e.g., **Terra**, that lasted **1e4 years**
- What's the **probability** of an observer catching its existence at **a random time** t throughout the long (**~1e10 yrs**) history of our Galaxy?



# Q2: How many advanced civilizations are present at any given time?

$$N = N_{\text{total}} \cdot (L/L_{\text{G}})$$

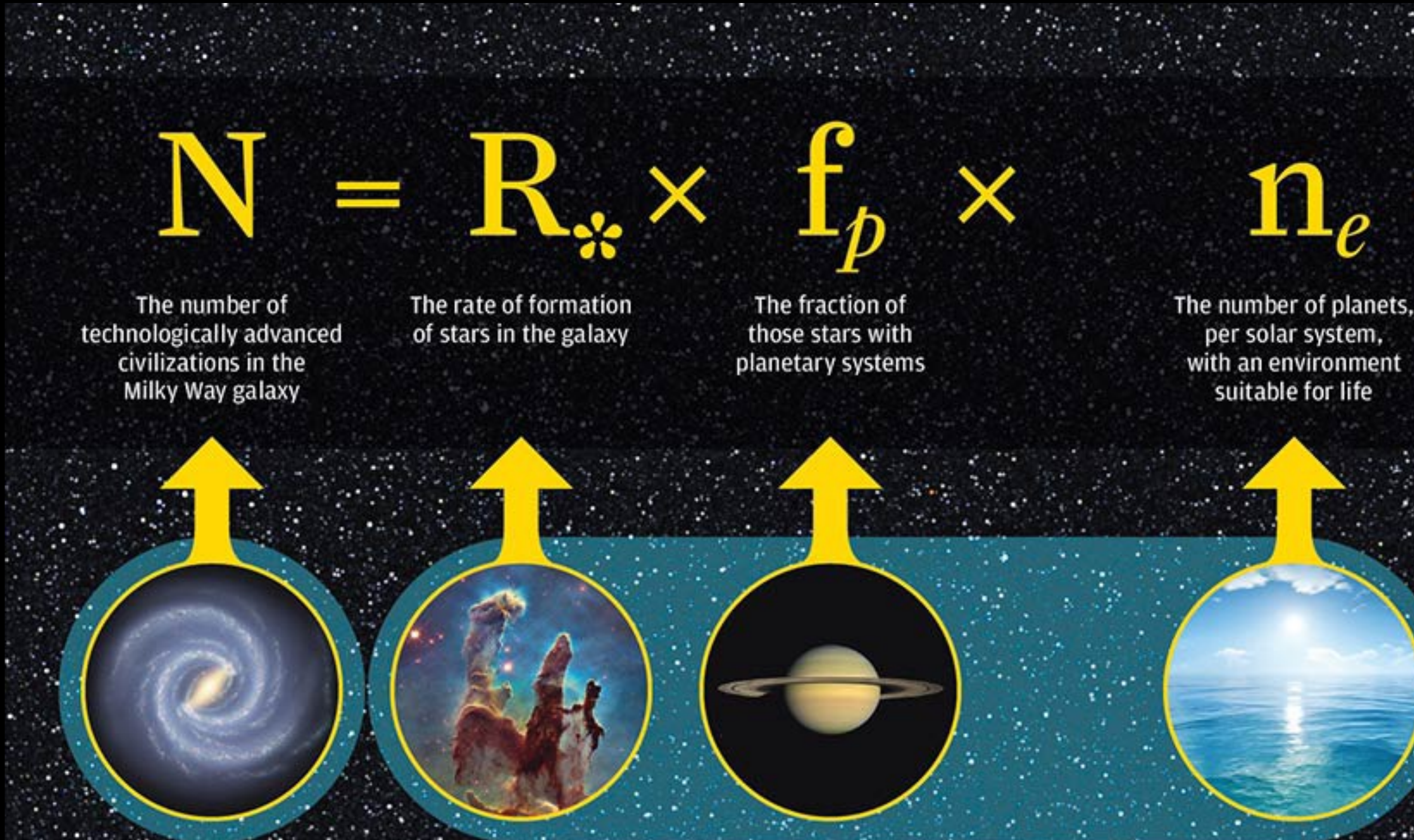
$$= N_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot (L/L_{\text{G}})$$

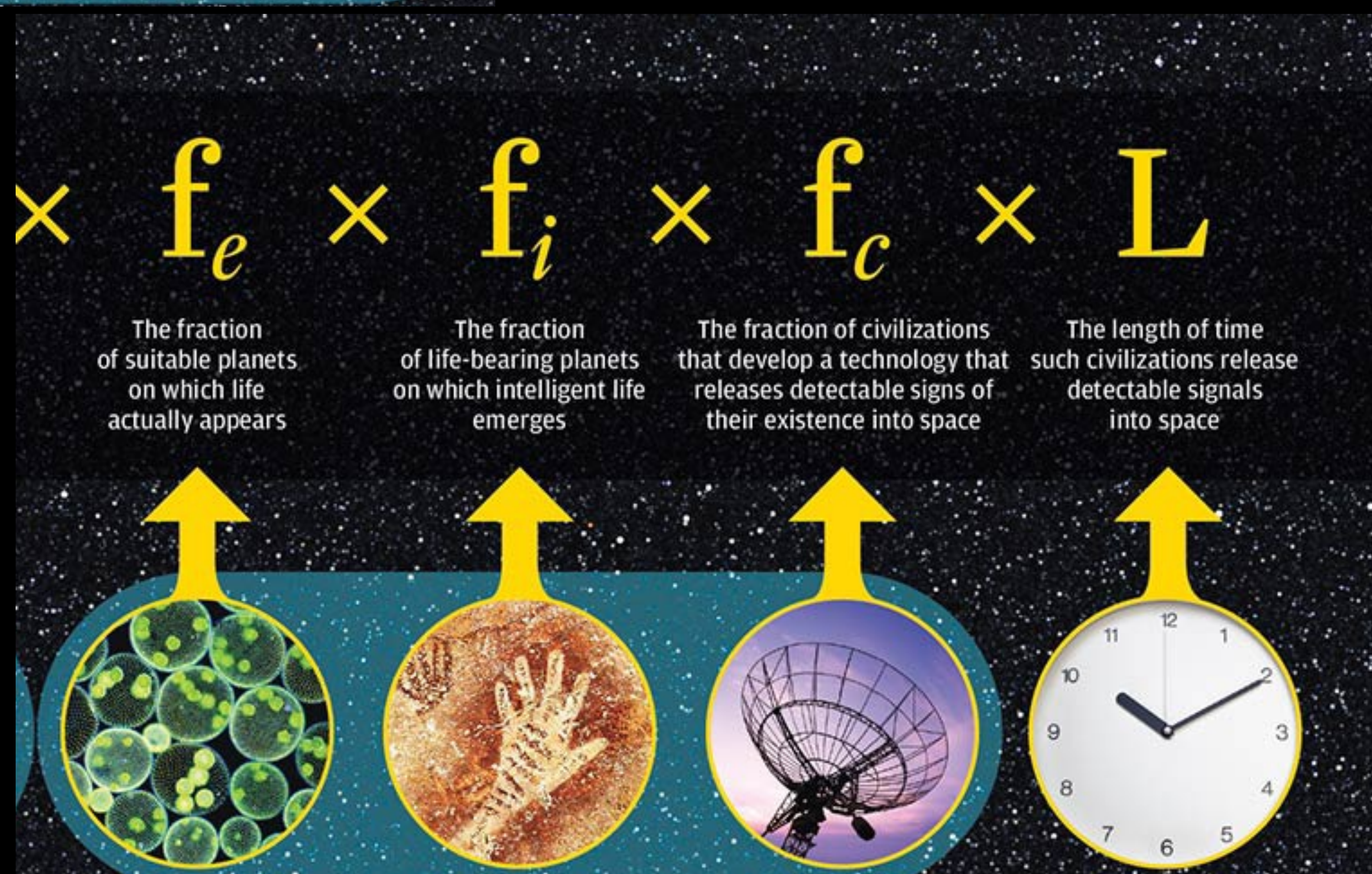
$$= (N_*/L_{\text{G}}) \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

$$= R_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

$N$ = the number of advanced civilizations that are alive today
$L$ = the mean lifetime of advanced civilizations
$L_G$ = the age of the Galaxy (i.e., the time it took to accumulate the number of stars we have today)
$R_*=N_*/L_G$ = the mean star formation rate of the Galaxy

# The Drake Equation (1961)



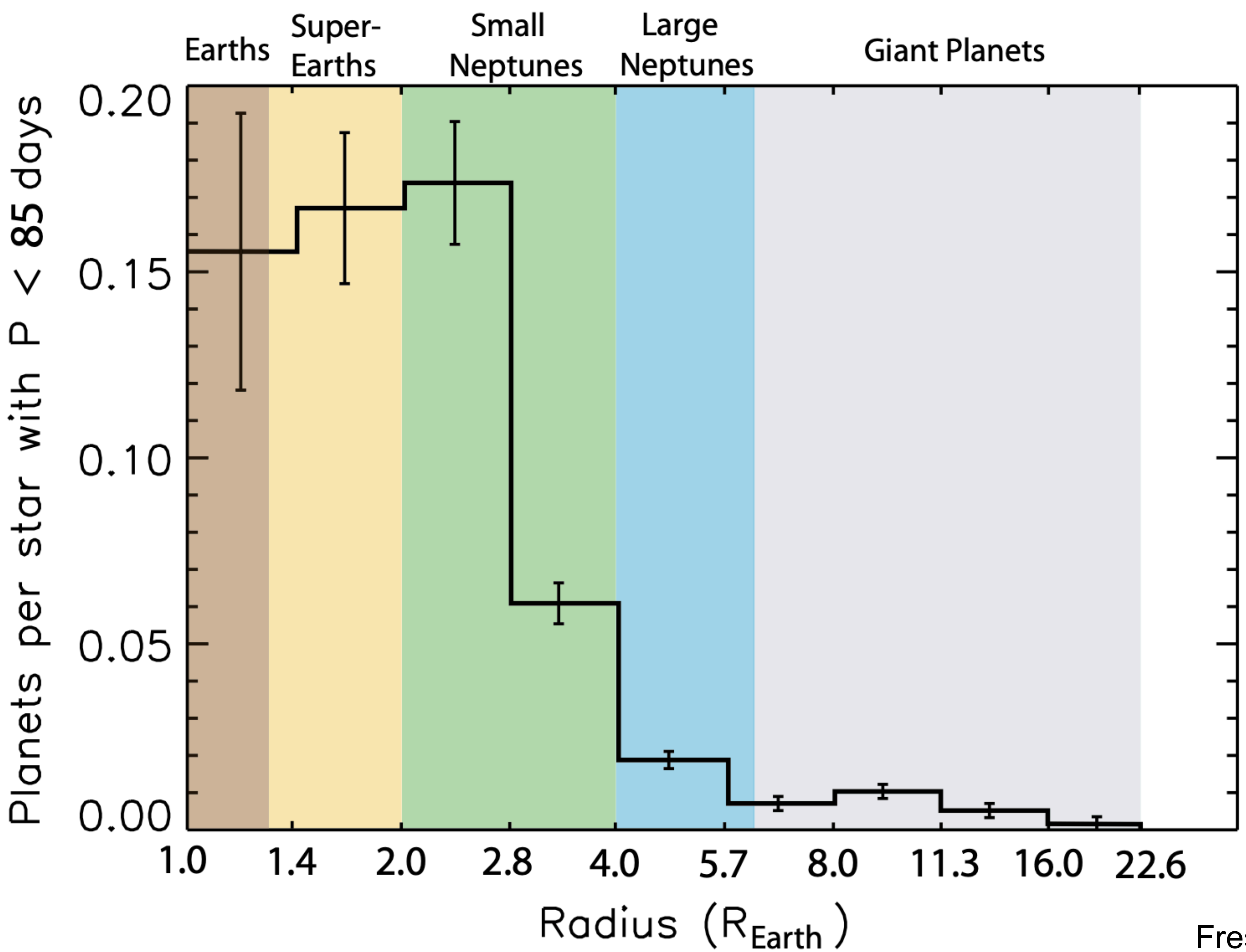
## What is the average fraction of stars that host planets?

- 2023 Nov: 5,539 exoplanets in 4,123 systems, with 937 multi-planet systems.
- NASA's *Kepler* mission observed 530,506 stars and discovered 2,662 exoplanets over its lifetime.
- How frequently do stars have planets?

- *"The absence of evidence is not the evidence of absence." We cannot simply get the answer from 2662/530506 = 0.5%*
- The RV technique is biased towards large, close companions, viewed edge-on
- The transit technique is biased towards planetary systems viewed edge-on

# Planet-hosting probabilities after de-biasing the Kepler transit data

## About 50% of normal stars have planet of Earth-size or larger!




Fressin et al. (2013)

# Here is a very optimistic answer to Q2:

$$N = R_* * f_p * n_e * f_l * f_i * f_c * L$$

- $R_* = 10\ \mathrm{yr}^{-1}$ (100 billion star formed over 10 billion years)
- $f_p = 0.5$ (one half of all stars formed will have planets)
- $n_e = 0.2$ (20% chance of hosting life-supporting planets)
- $f_l = 1$ (100% of the above will develop life)
- $f_i = 1$ (100% of the above will develop intelligent life)
- $f_c = 1$ (100% of the above will develop advanced civilizations)

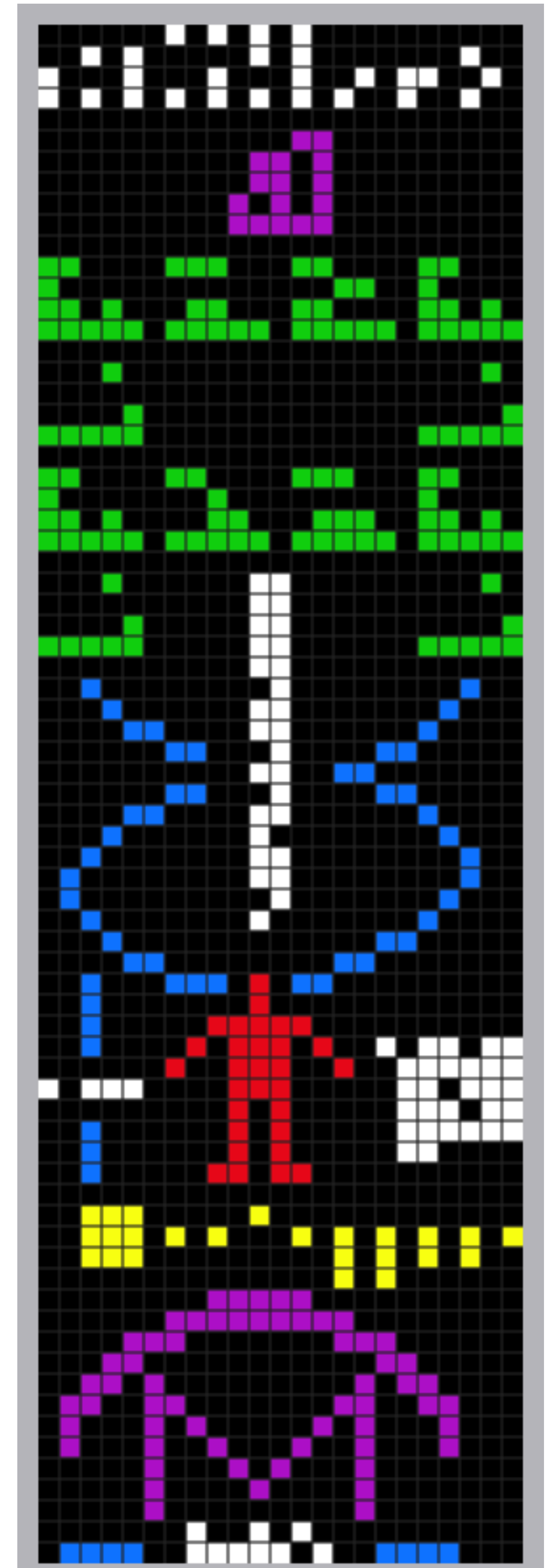
$$N \approx L_{\mathrm{year}}$$

# Contacting ET

# Contact (1997): Jodie Foster - Detecting the signal at the VLA

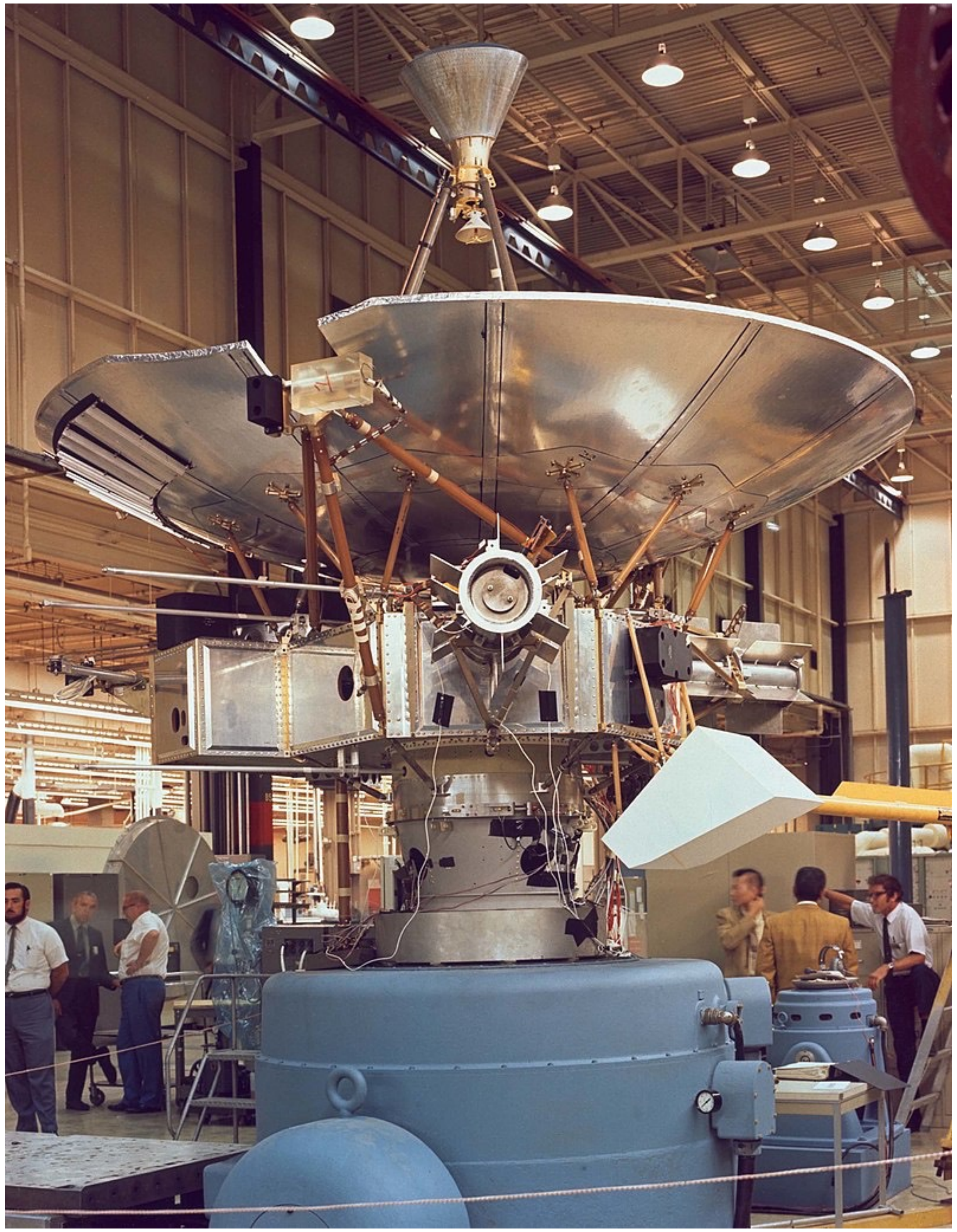
## The Arecibo Message (1974) to the Globular Cluster M13

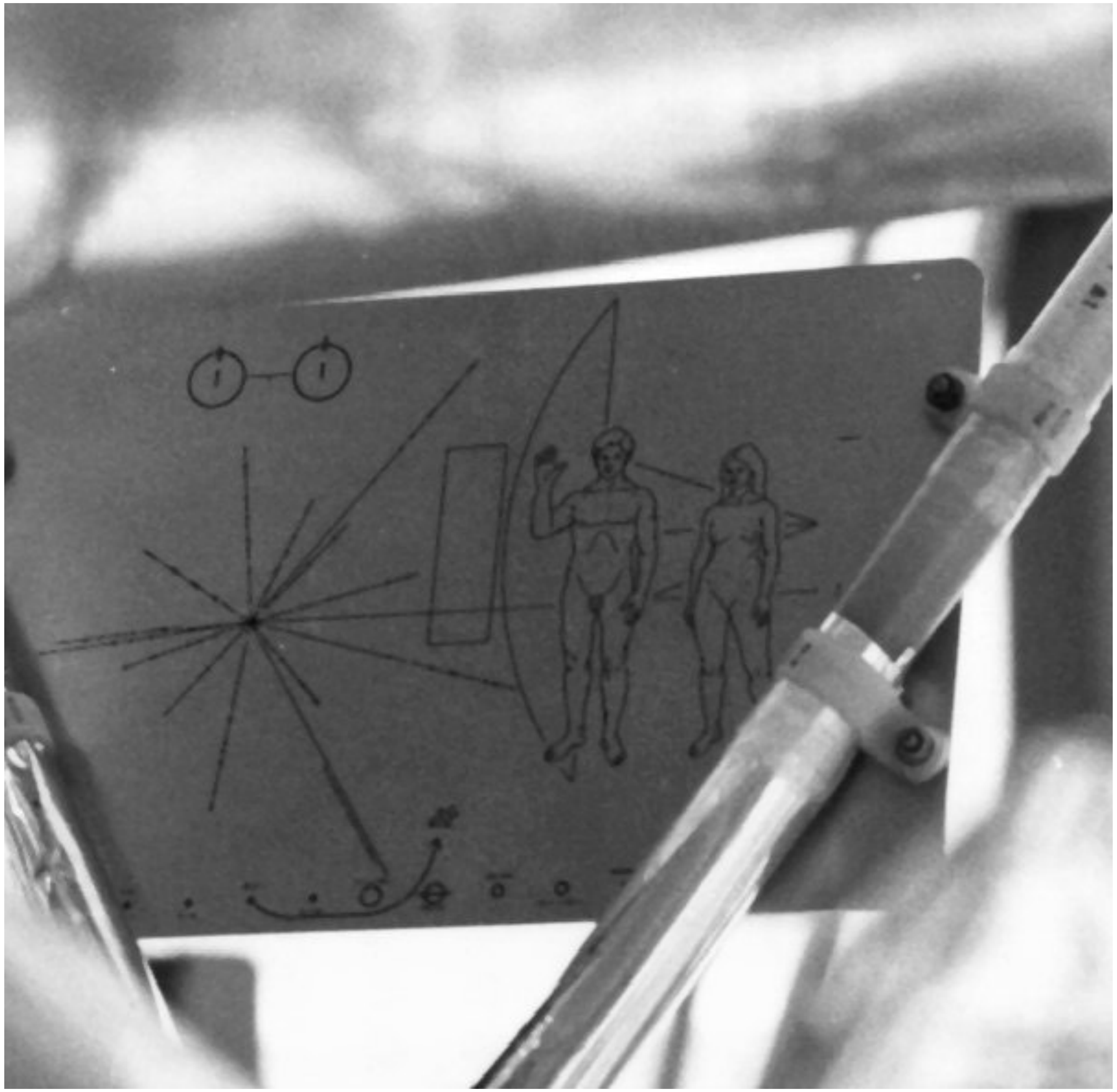
- Frank Drake, Carl Sagan, et al.
- Will take 25,000 years to arrive at M13
- Contains information of the DNA, the Solar system, and the radio telescope Arecibo



# Pioneer 10 and Pioneer 11 Spacecraft (Launched in 1972 & 1973)

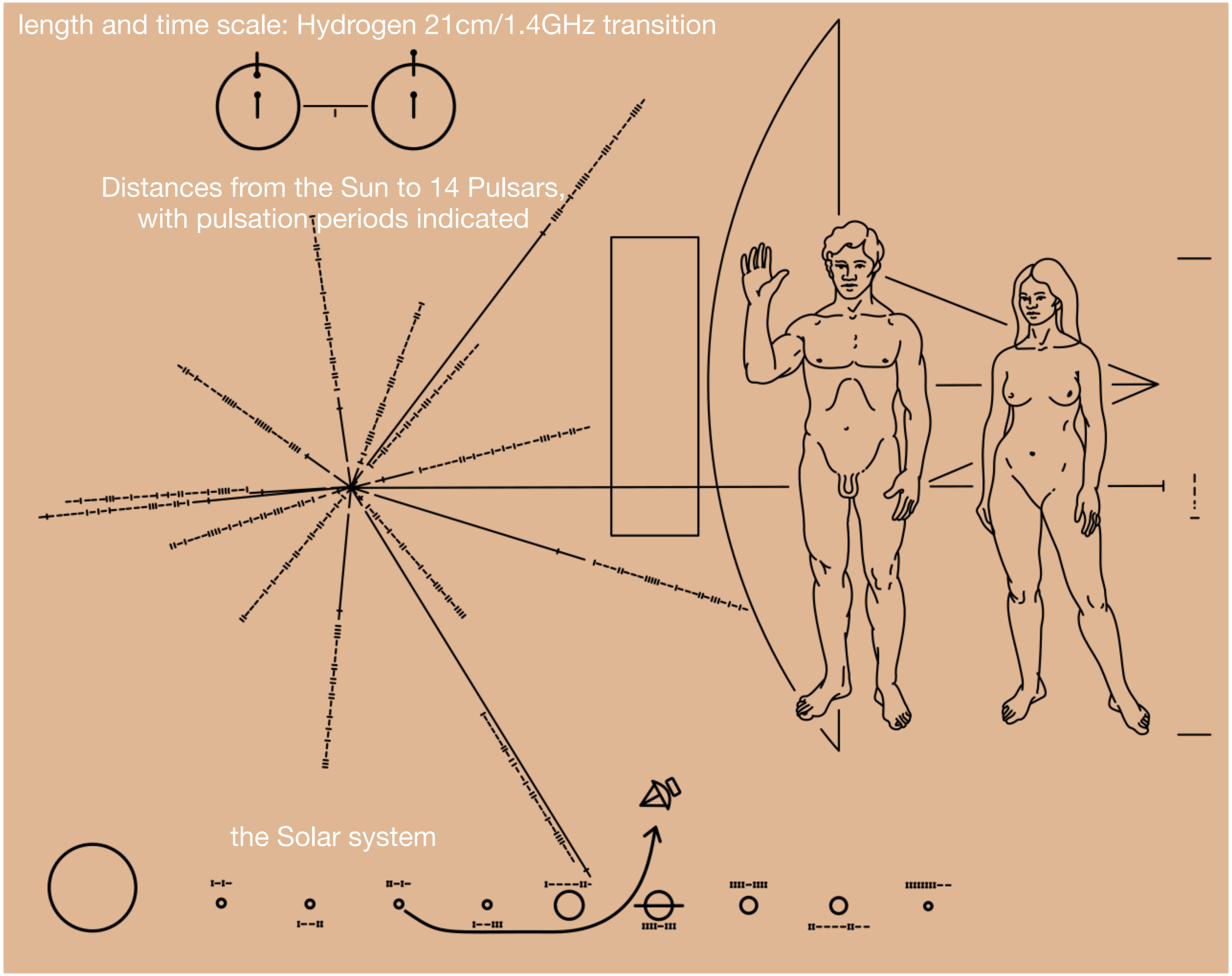
The *Pioneer 10* and *11* spacecraft were the first human-built objects to achieve escape velocity from the Solar System. The plaques were attached to the spacecraft's antenna support struts in a position that would shield them from erosion by interstellar dust.





# The Pioneer plaques - gold-anodized aluminum plaques (9x6in)

*Hopefully, the aliens can read this and find us …*



# Chap 8: Planet mass from timing / radial velocity method

Step 0: Use Doppler shift equation to get radial velocity:

$$\frac{V_r}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta P}{P}$$

Step 1: Get a lower limit on the circular velocity of the host star:

$$V_r = V_{\mathrm{circ}} \sin i \cdot \sin\left(\frac{t - t_0}{\mathrm{Orbital\ Period}}\right)$$

$$\Rightarrow V_{\mathrm{circ}} = \max(V_r)/\sin i$$

where i is the inclination angle of the orbital plane from face-on

Step 2: Use the Kepler's 3rd Law to calculate the circular velocity of the invisible planet

$$a_{AU} = (M_{\mathrm{solar-mass}} P_{\mathrm{year}}^2)^{1/3}, \quad v_{\mathrm{circ}} = \frac{2\pi a}{P_{\mathrm{orbit}}}$$

Step 3: Use the center of mass equation to calculate the mass ratio from velocity ratio:

$$\frac{m}{M} = \frac{V_{\mathrm{circ}}}{v_{\mathrm{circ}}} = \frac{\max(V_r)/\sin(i)}{v_{\mathrm{circ}}}$$

# Chap 8: Planet radius from transit method

**Relative Size Estimate from Transit Depth:**

$$\text{Percentage reduction in light} = \frac{\text{Area of disk of planet}}{\text{Area of disk of star}} = \frac{\pi R^2{}_{\text{planet}}}{\pi R^2{}_{\text{star}}}$$

**Absolute Size Estimate from Transit Ingress Interval:**

Step 1: Use the Kepler's 3rd Law to calculate the circular velocity of the invisible planet

$$a_{AU} = (M_{\text{solar-mass}} P^2_{\text{year}})^{1/3}$$

$$v_{\text{circ}} = \frac{2\pi a}{P_{\text{orbit}}}$$

Step 2: Use the ingress interval and the velocity to infer the size of the planet

$$r = v_{\text{circ}}(t_2 - t_1)/2$$

## Chap 8: Planet-Star Contrast and Angular Separation for Direct Imaging

$$L_{\text{star}} = F_{\text{@planet}} \cdot 4\pi d^2_{\text{planet}}$$

$$L_{\text{planet}} = F_{\text{@planet}} \cdot A \cdot \pi r^2_{\text{planet}}/2$$

$$\Rightarrow$$

$$\frac{L_{\text{star}}}{L_{\text{planet}}} = \frac{8}{A}\frac{d^2_{\text{planet}}}{r^2_{\text{planet}}}$$

$$\theta''_{\max} = \frac{a_{\text{AU}}}{d_{\text{parsec}}} = \frac{a}{1\ \text{AU}} \cdot \frac{1\ \text{parsec}}{d}$$