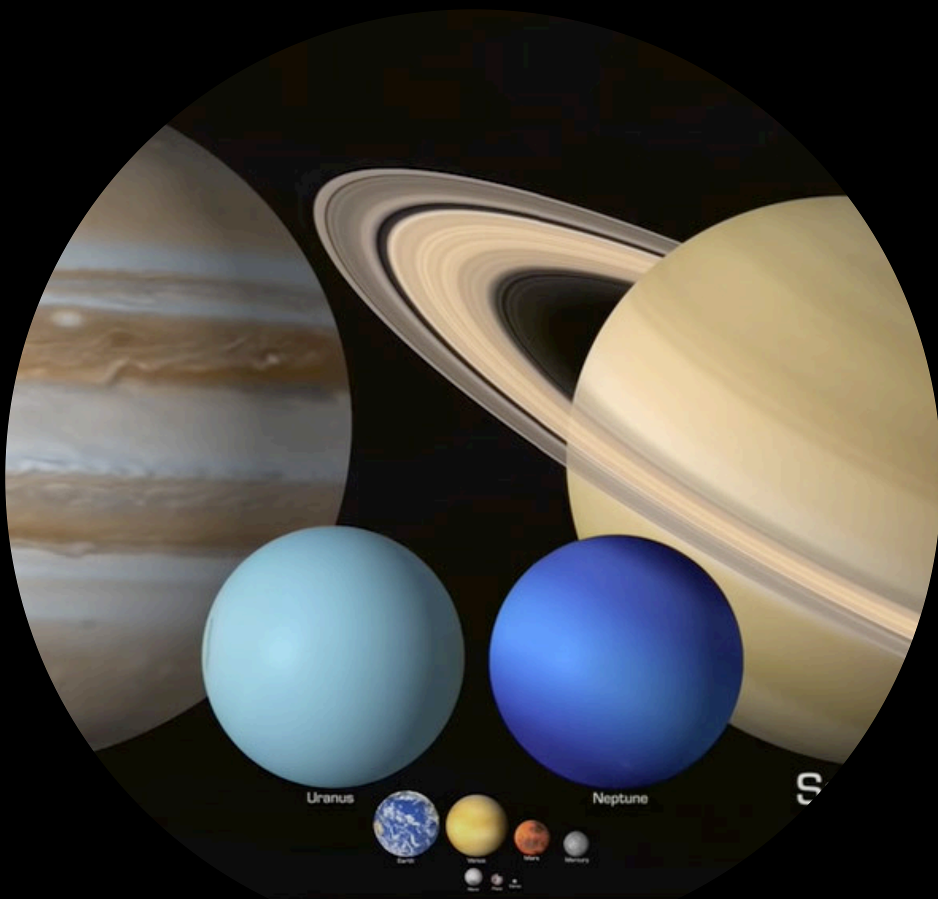
Lecture 1 - Our Solar System in the Context of Exoplanets



Learning Objectives - Our Solar System in the Context of Exoplanets

1) Describe the contents of the Solar System and what their orbital properties tell us about how they formed

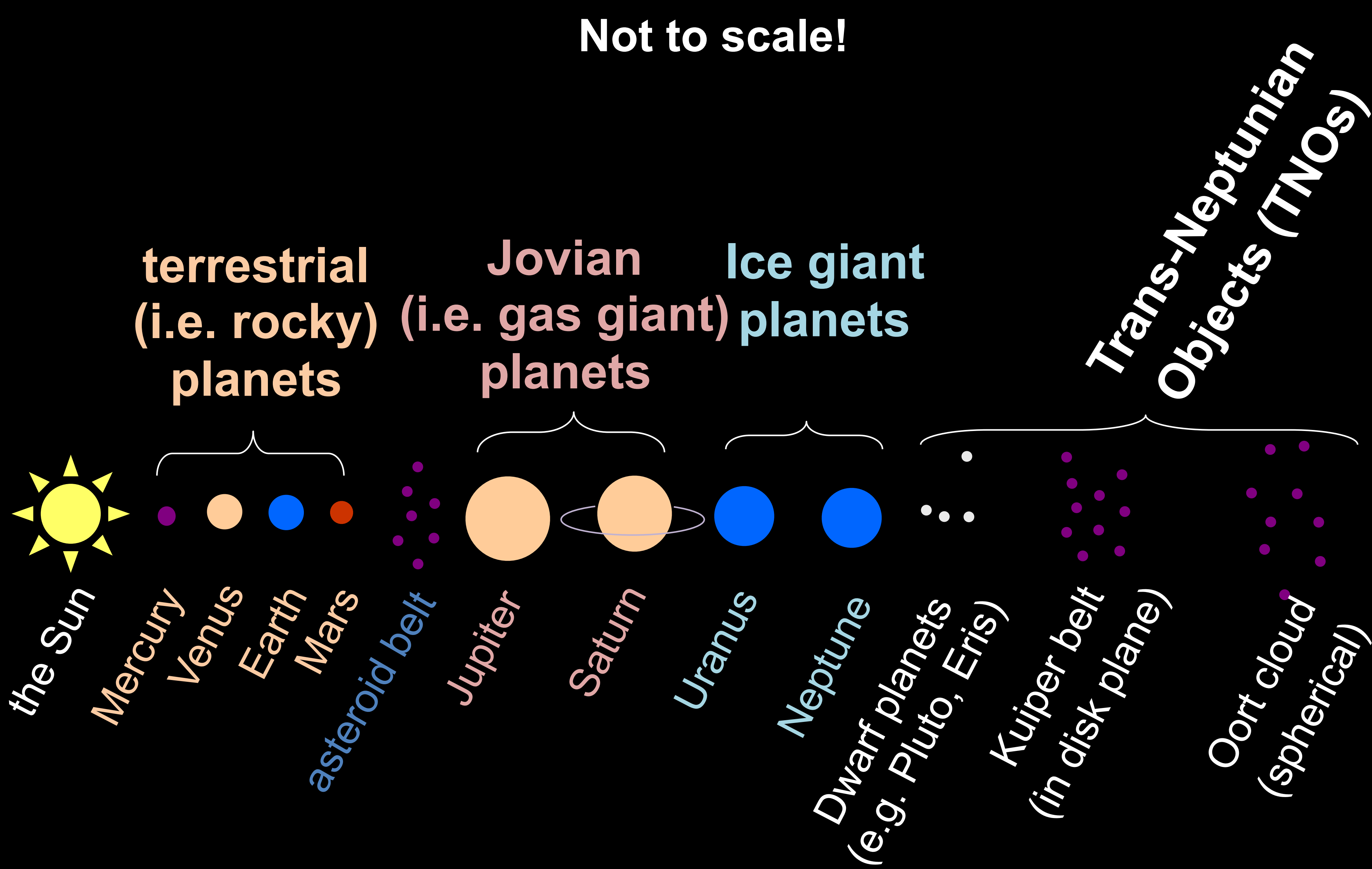
Learning Objectives - Our Solar System in the Context of Exoplanets

1) Describe the contents of the Solar System and what their orbital properties tell us about how they formed
2) Compare the properties of the Solar System to those of known exoplanetary systems

Learning Objectives - Our Solar System in the Context of Exoplanets

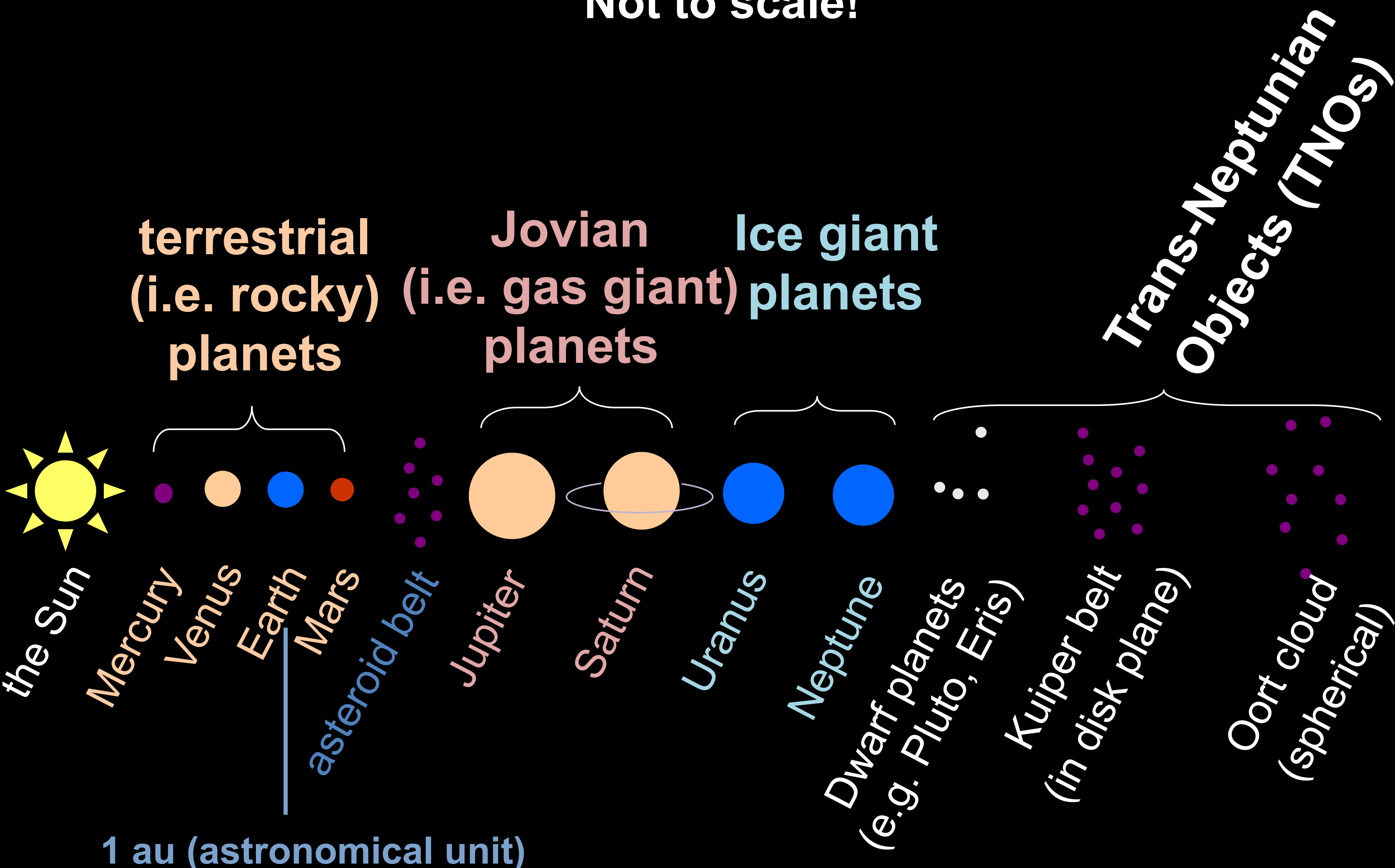
1) Describe the contents of the Solar System and what their orbital properties tell us about how they formed
2) Compare the properties of the Solar System to those of known exoplanetary systems
3) Describe the physics behind six techniques for exoplanet detection and the limitations of each technique

The Solar System

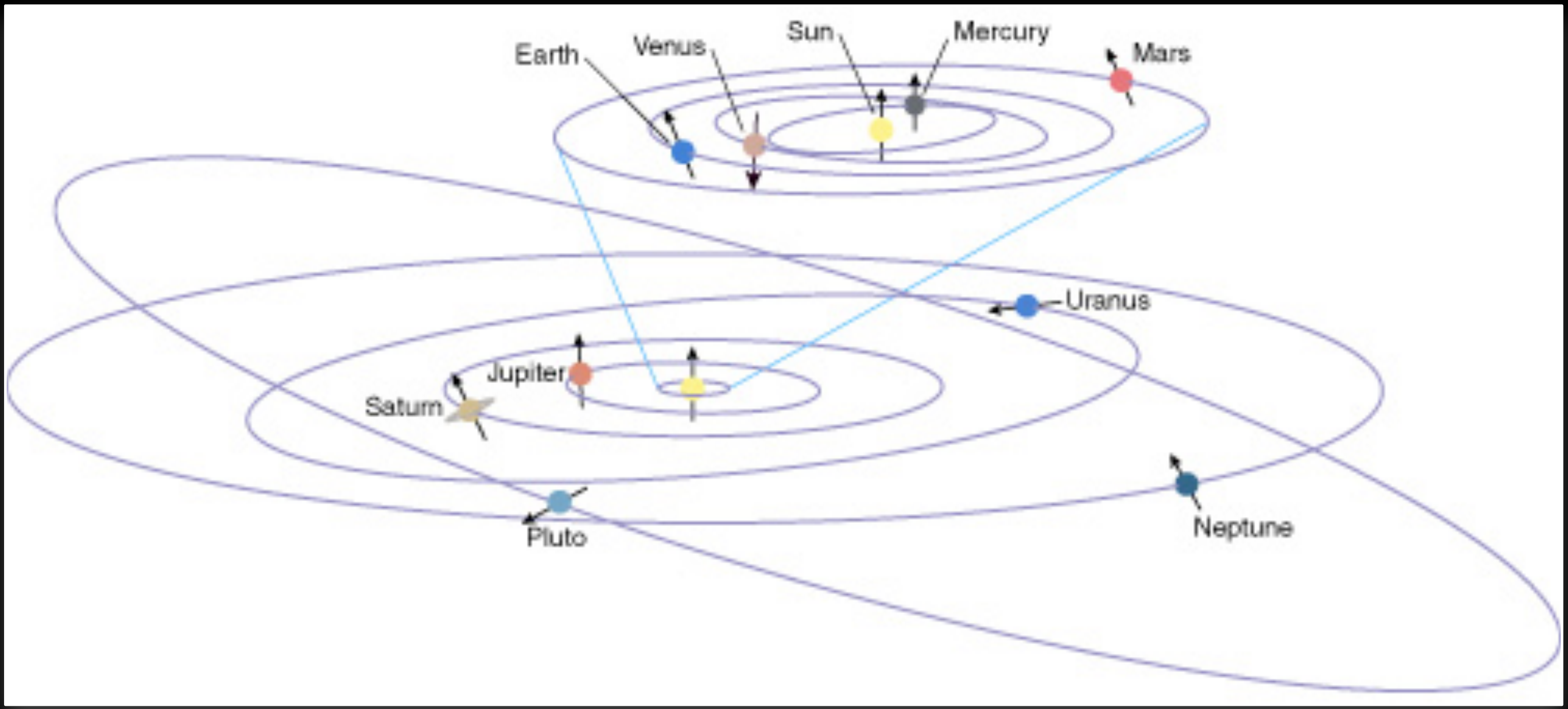


The Solar System

Not to scale!



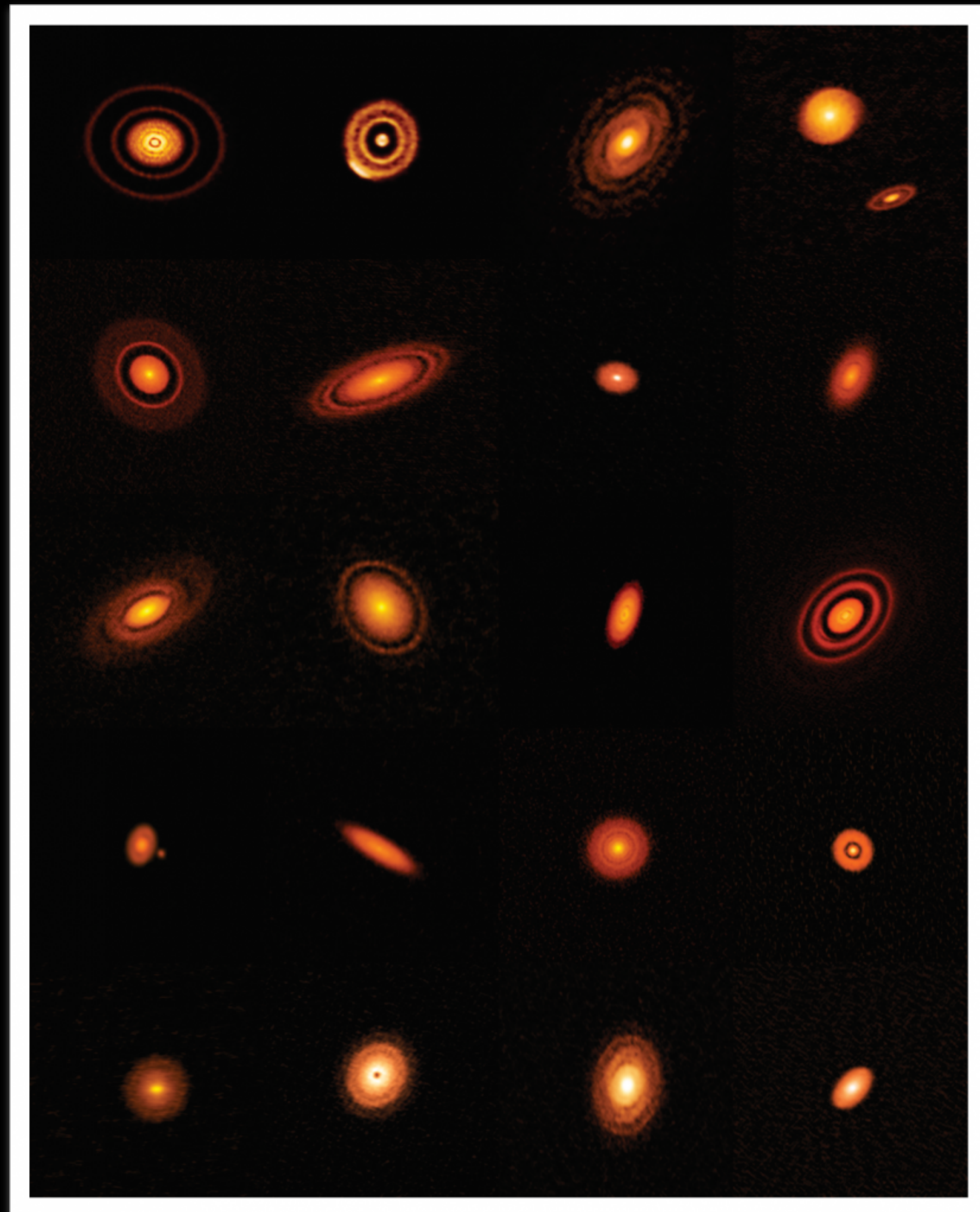
Planetary orbits are (nearly) co-planar



- Dispersion in mutual inclinations: $\Delta i \sim 2$ deg
- Pluto and many other TNOs are more highly inclined

A consequence of formation in a protoplanetary disk

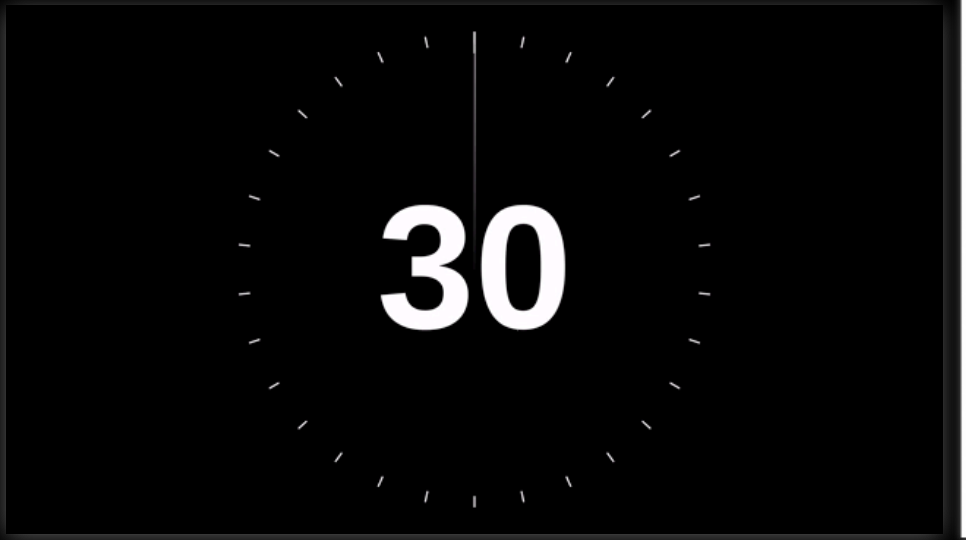
- Radio images of warm dust continuum around young stars (<~10 Myrs)
- Disk sizes ~ 100 au
  - cannot resolve the inner disk regions
- Variety of disk morphologies
- Concentric gaps opened by protoplanets?

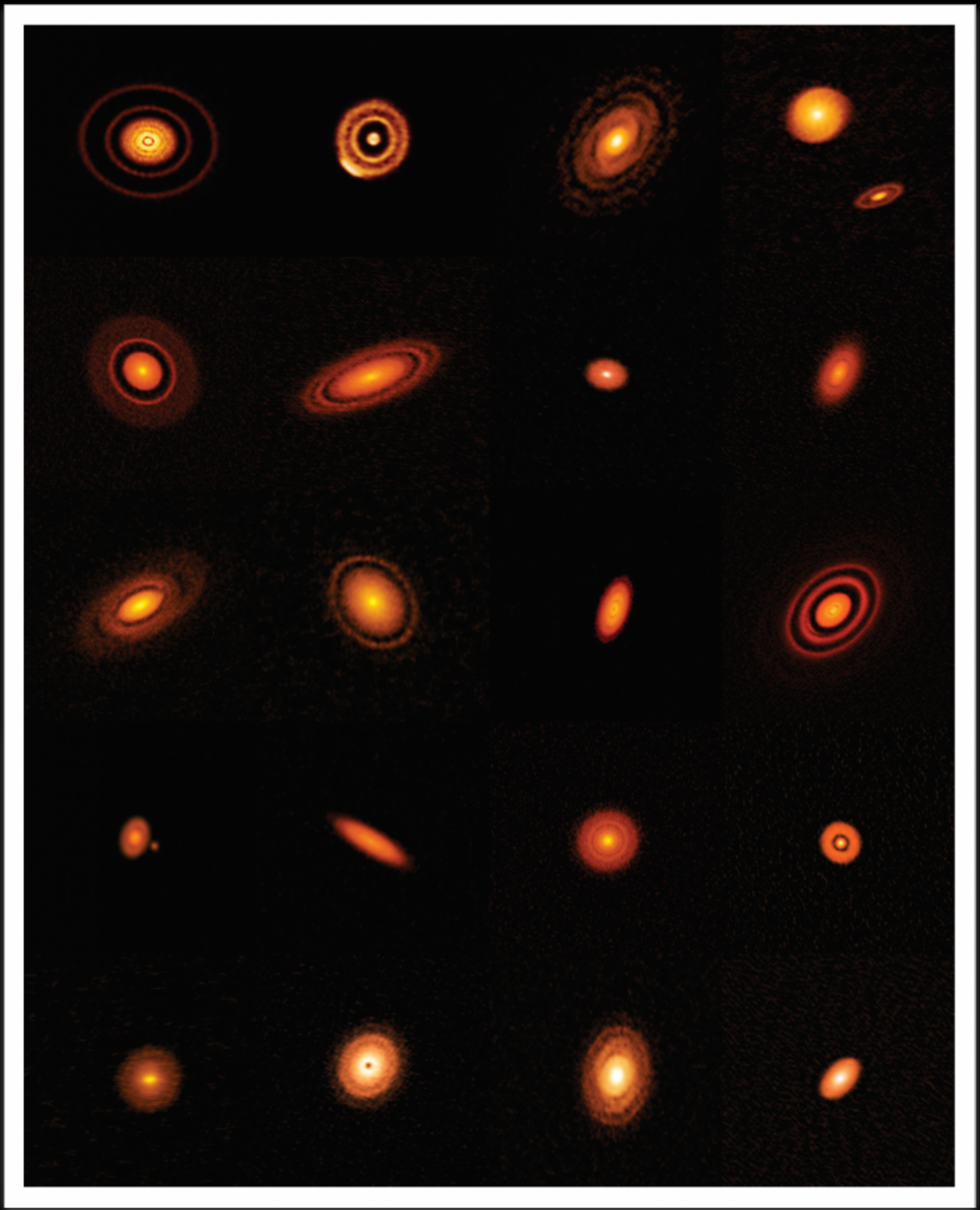


TPS Activity

The planets' orbital planes in the Solar System are co-planar,

what other dynamical properties do you expect for planets formed from a disk?

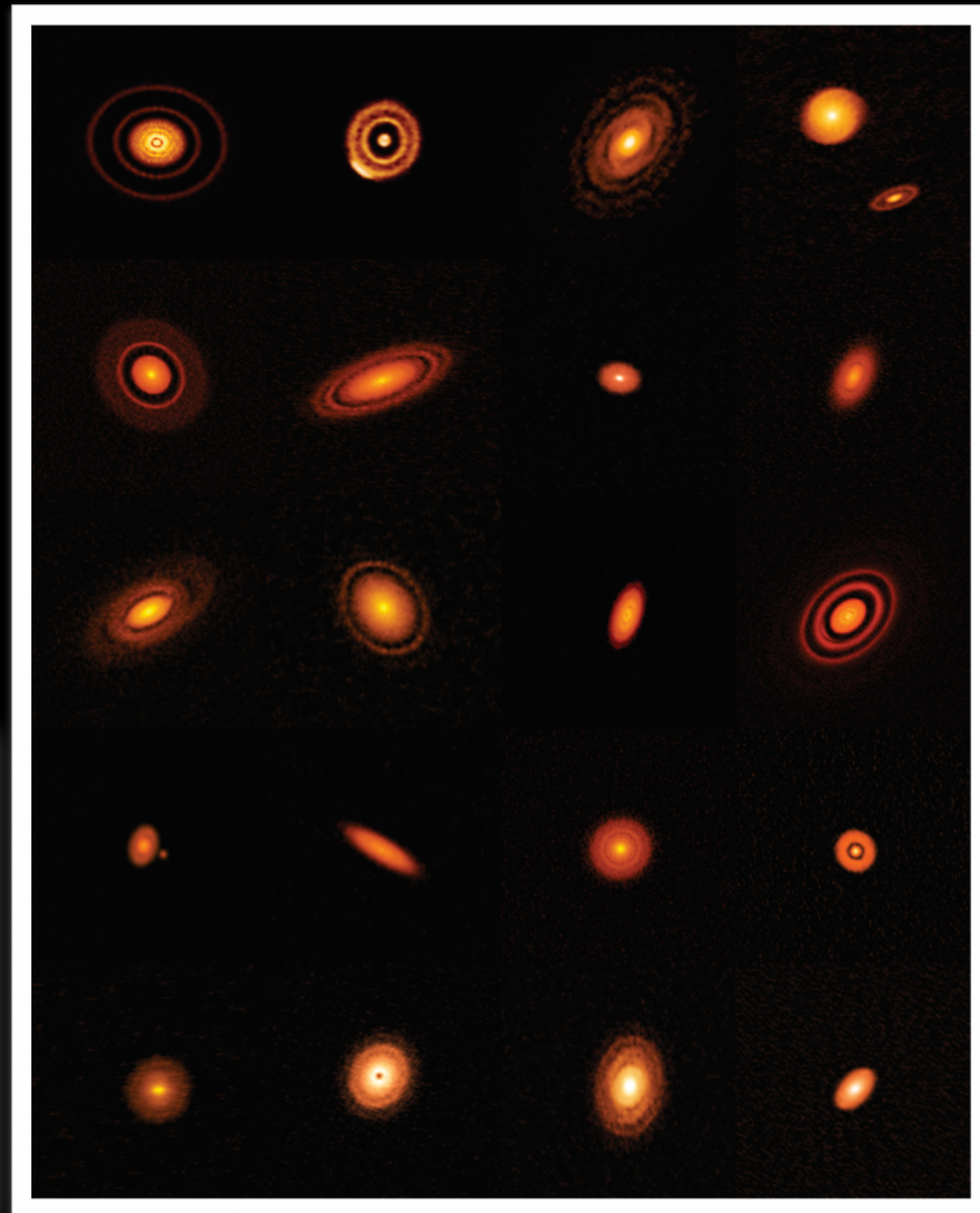




TPS Activity

The planets' orbital planes in the Solar System are co-planar,

what other dynamical properties do you expect for planets formed from a disk?

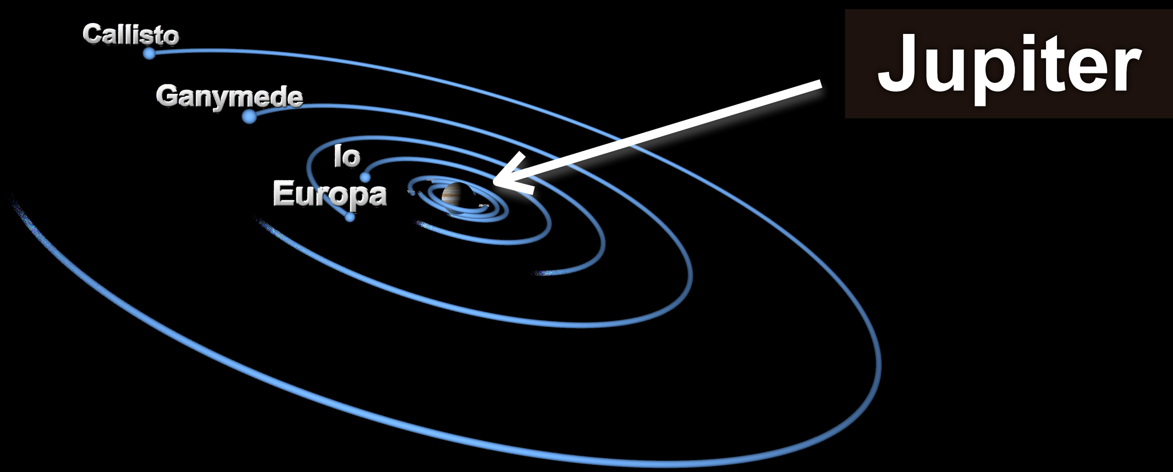


Regular vs Irregular Satellites (a.k.a. moons)

Regular vs Irregular Satellites (a.k.a. moons)

Regular satellites

- resemble mini planetary systems
- prograde, nearly circular orbits, low mutual inclinations
- e.g. the 4 Galilean moons of Jupiter



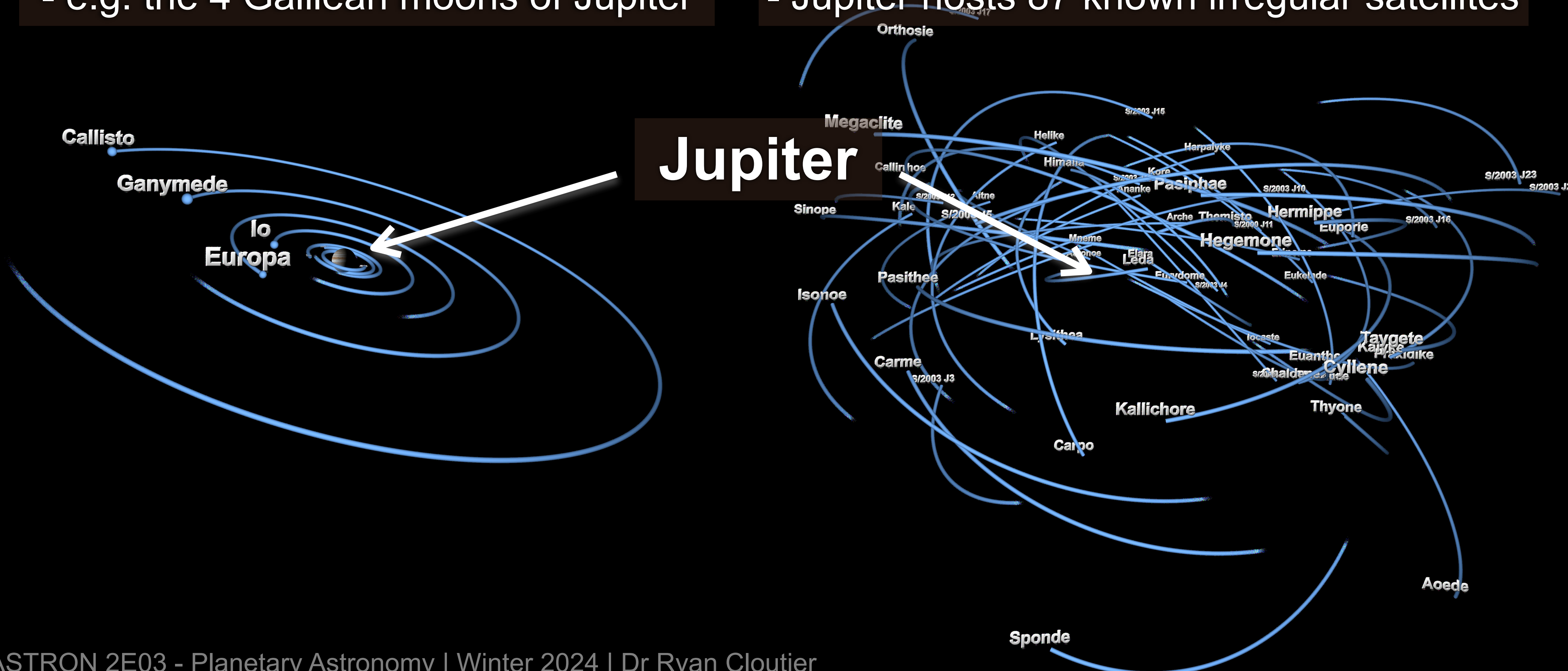
Regular vs Irregular Satellites (a.k.a. moons)

Regular satellites

- resemble mini planetary systems
- prograde, nearly circular orbits, low mutual inclinations
- e.g. the 4 Galilean moons of Jupiter

Irregular satellites

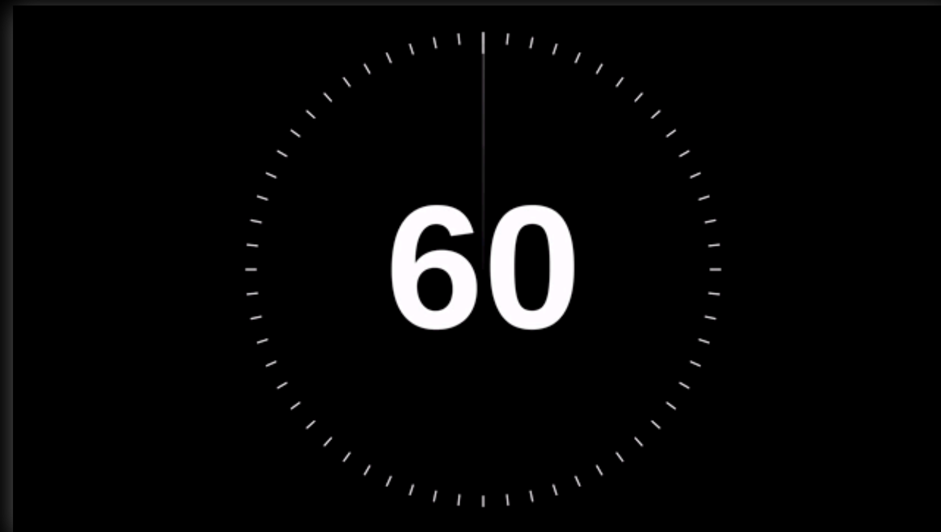
- irregular orbits
- prograde or retrograde orbits, highly elliptical and highly inclined
- Jupiter hosts 87 known irregular satellites

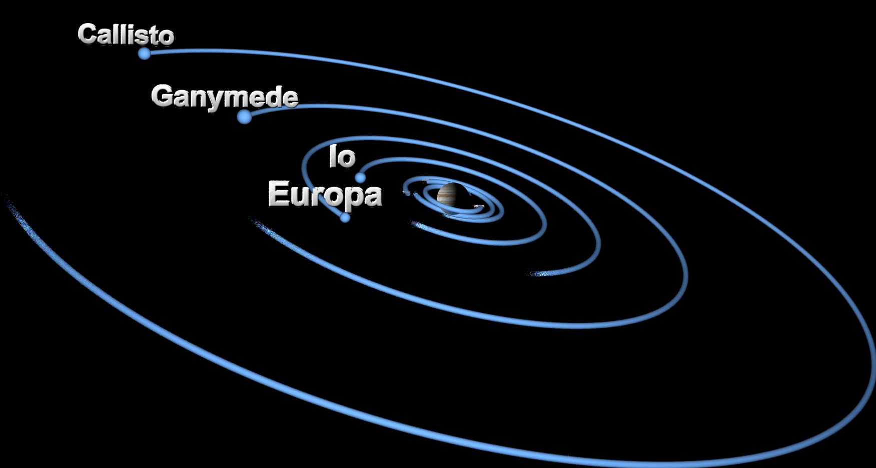


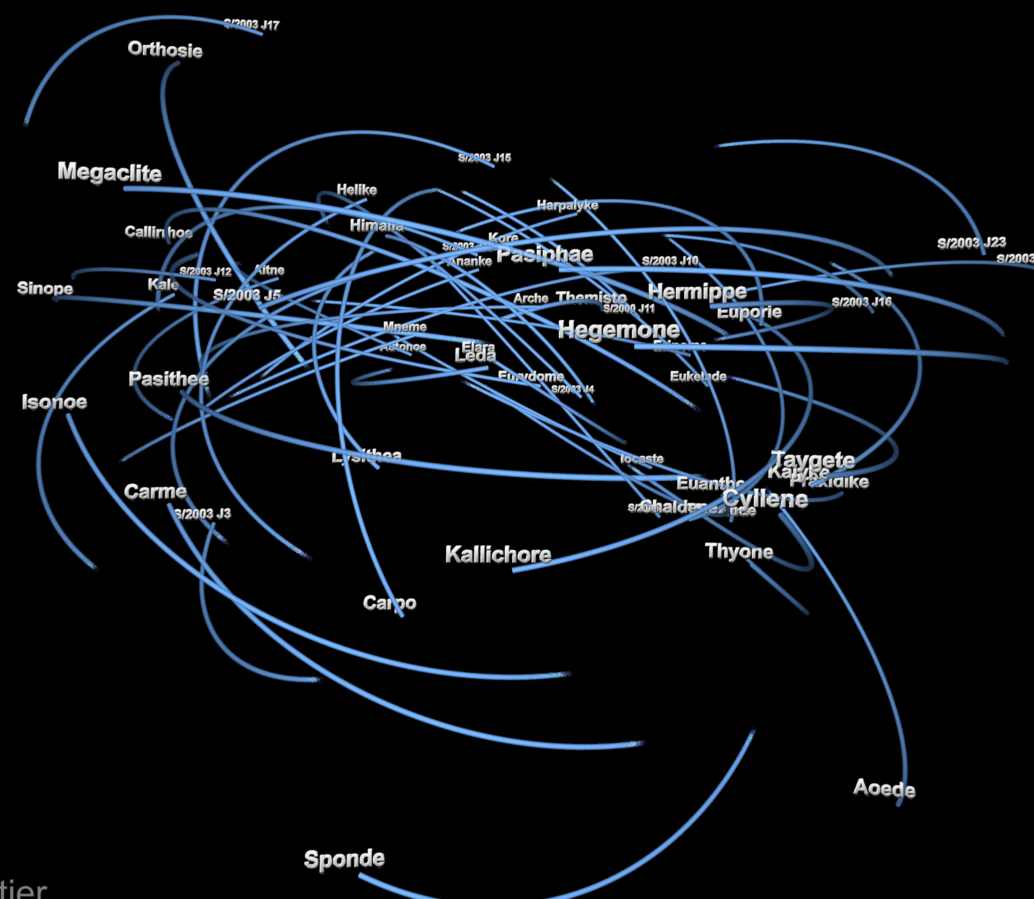
TPS Activity

Hypothesize and defend possible formation mechanisms for regular and irregular satellites?

(First consider: are they the same?)



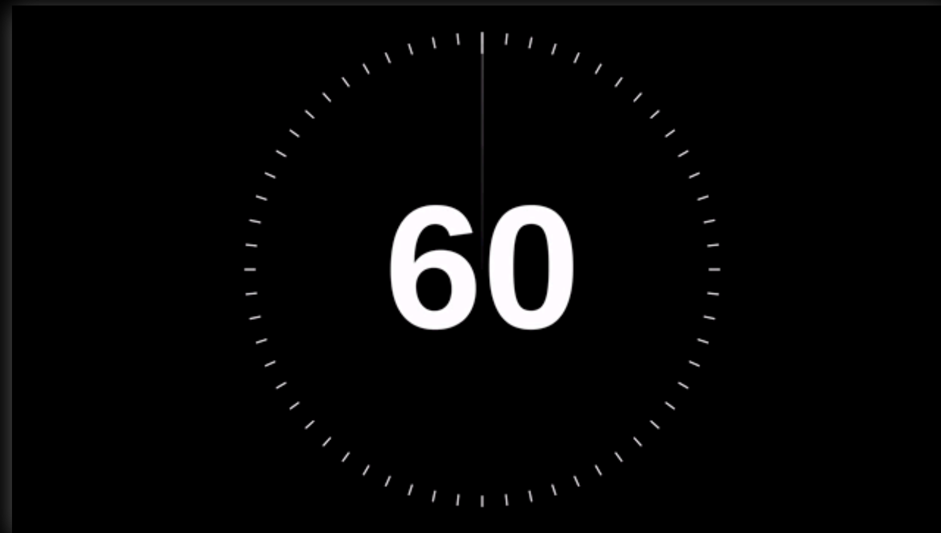


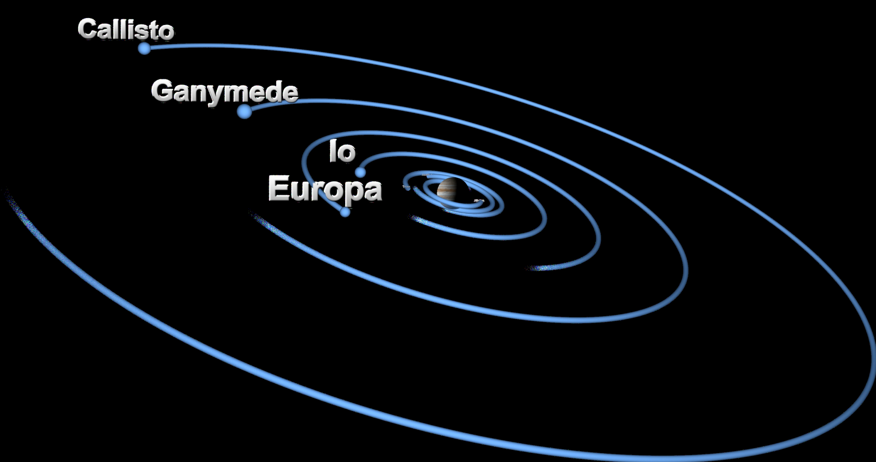


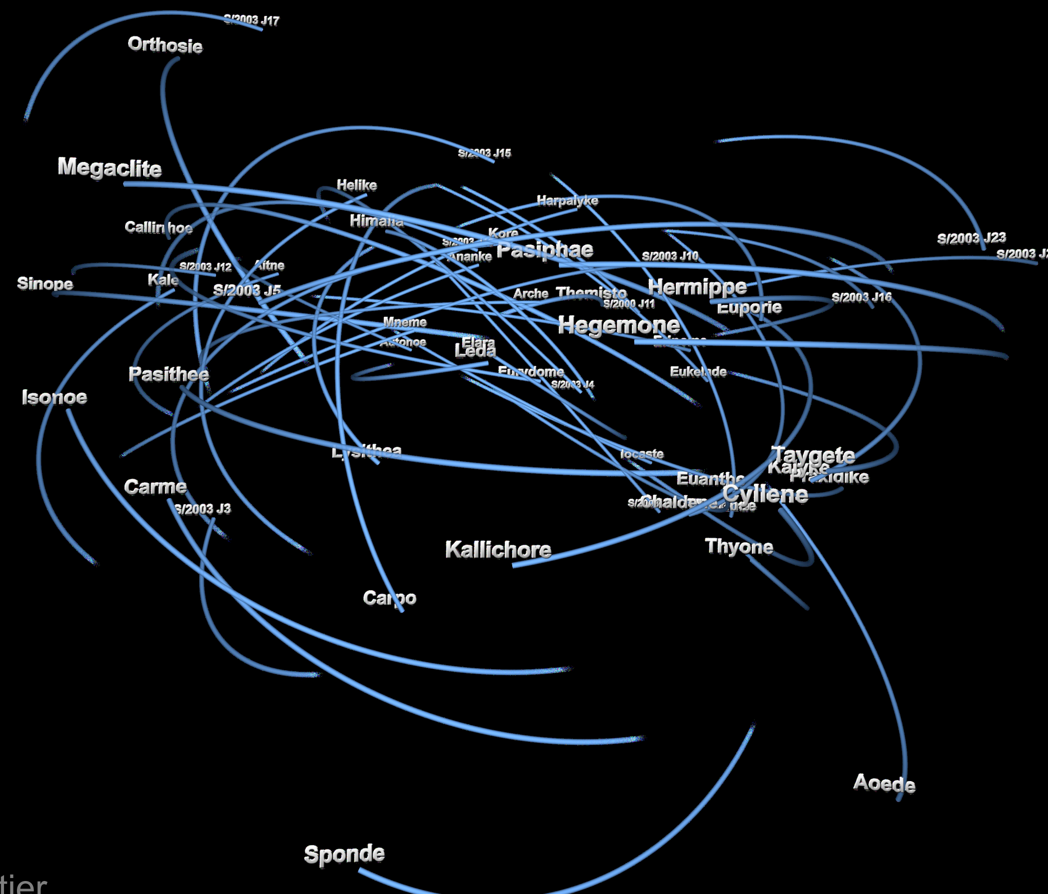
TPS Activity

Hypothesize and defend possible formation mechanisms for regular and irregular satellites?

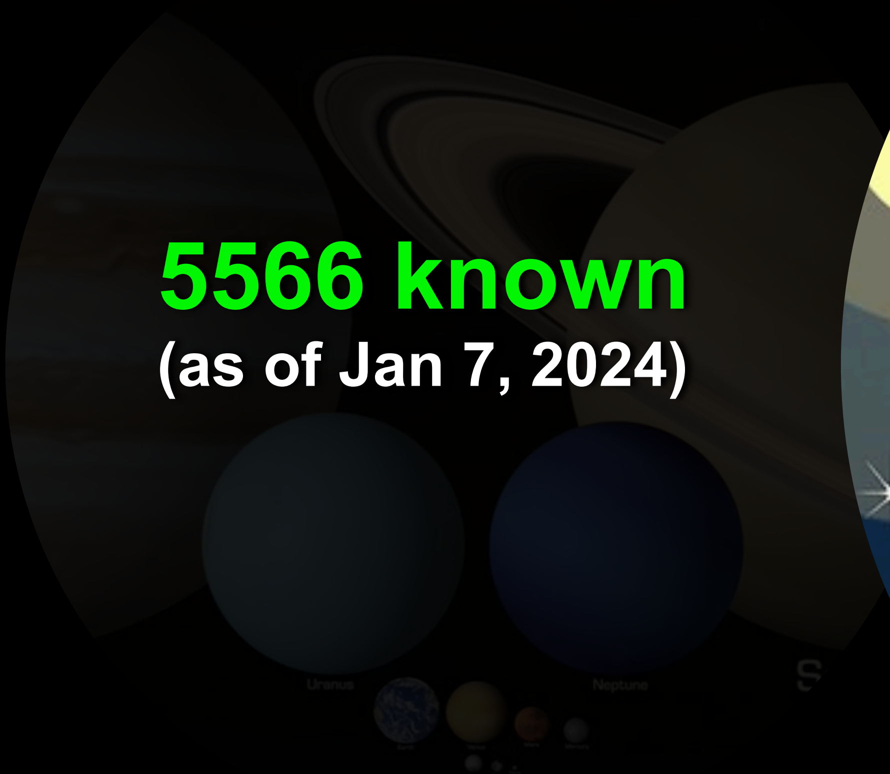
(First consider: are they the same?)





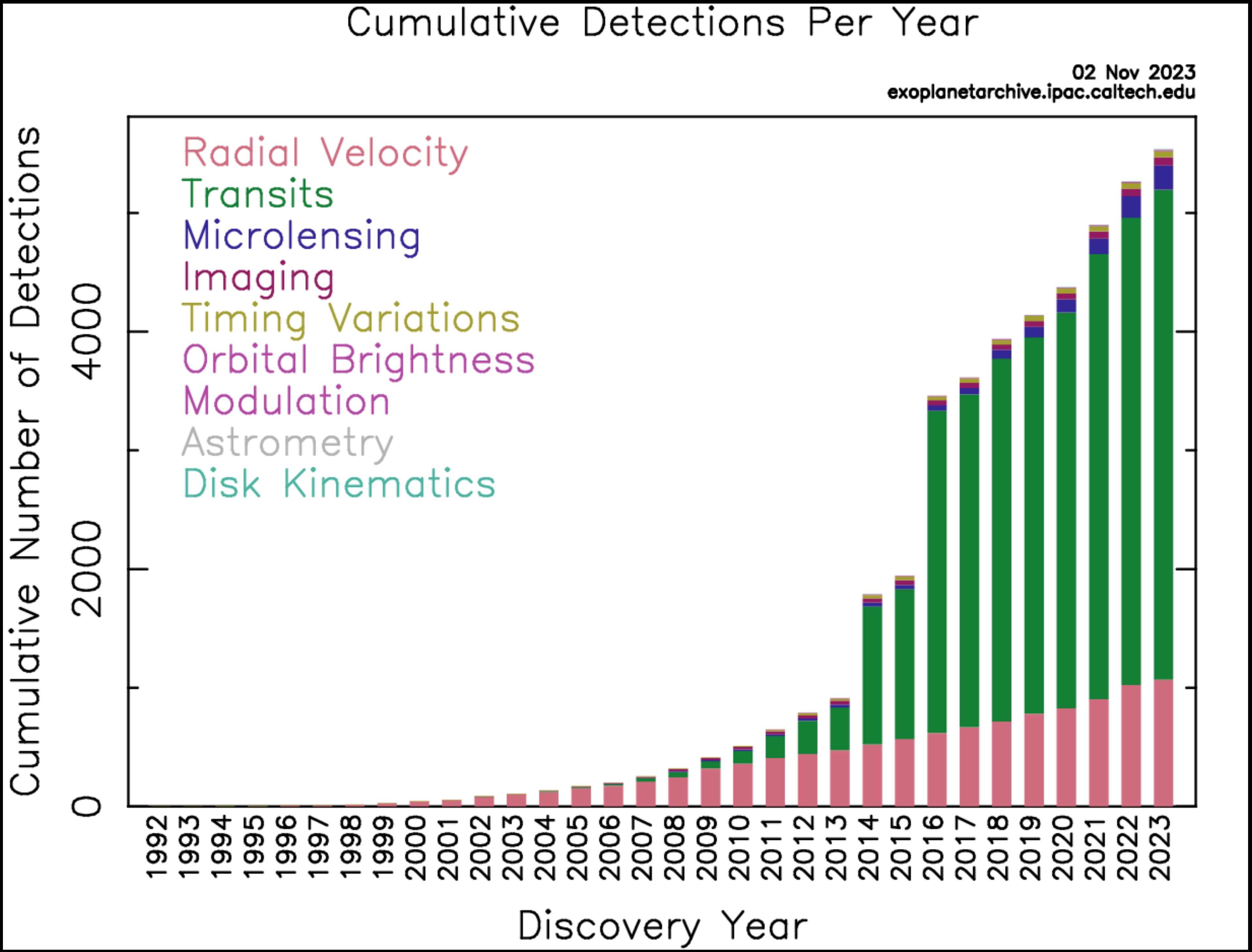


Lecture 1 - Our Solar System in the Context of Exoplanets



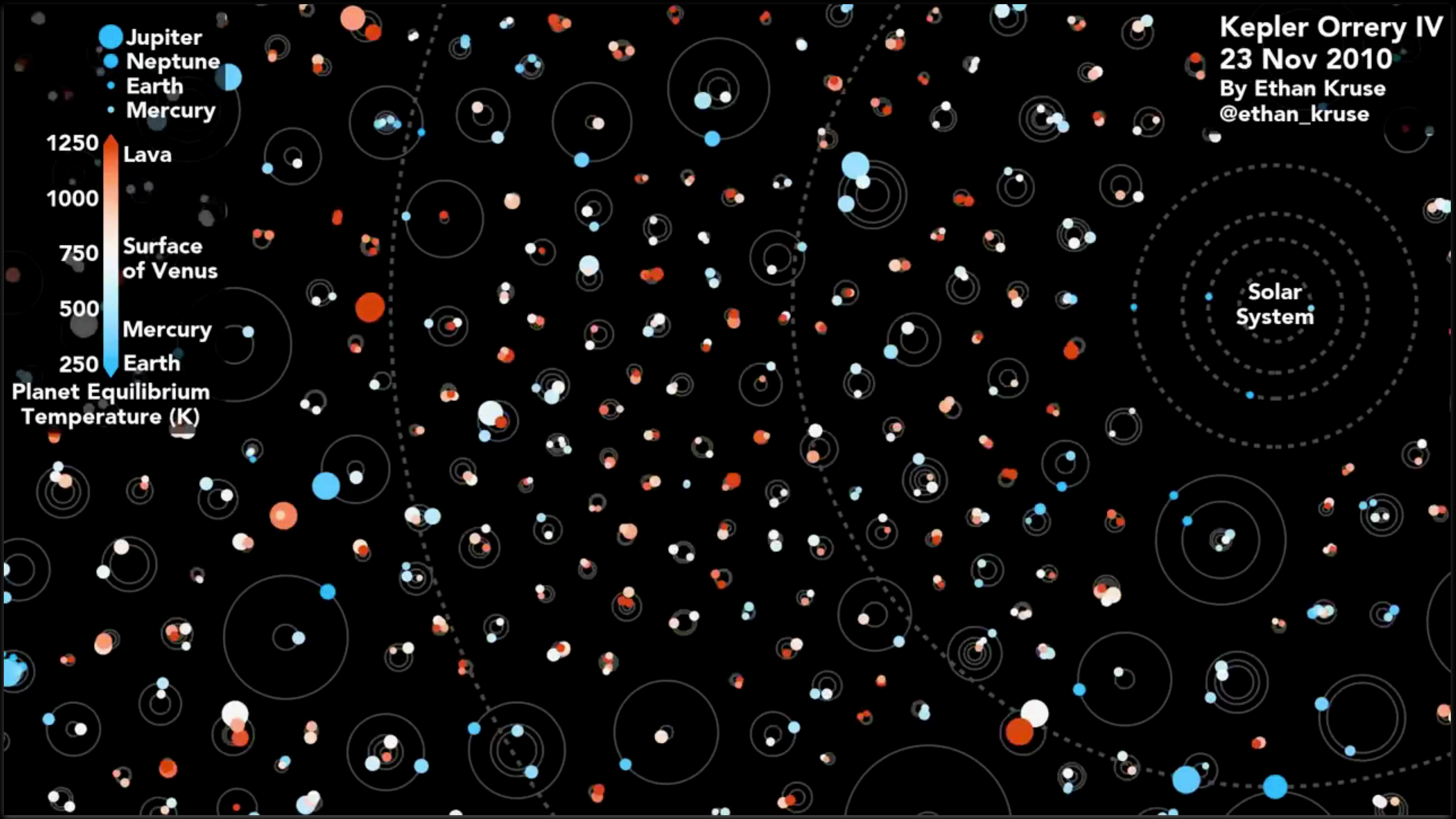
5566 known

(as of Jan 7, 2024)

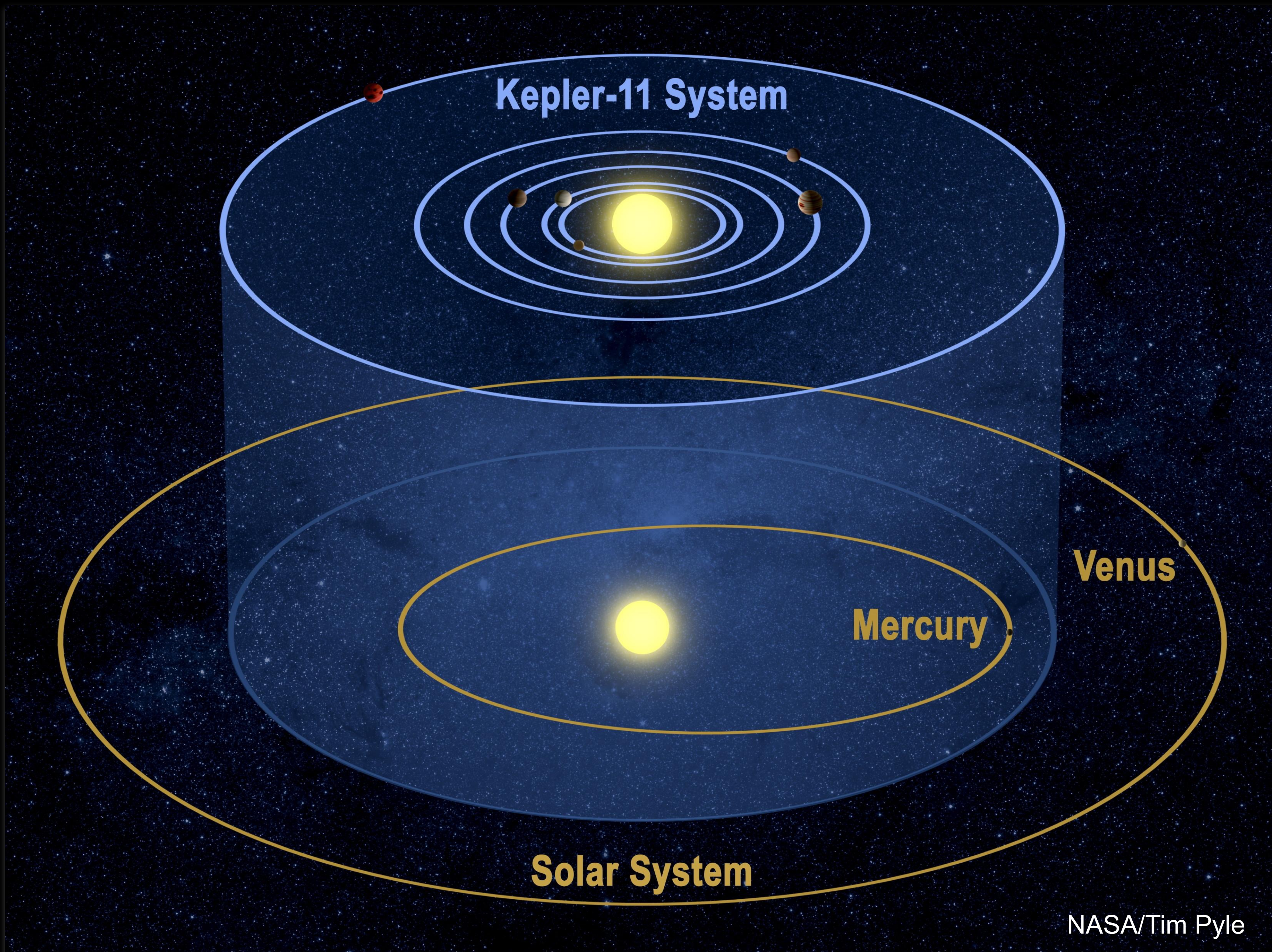


Cumulative Detections Per Year
02 Nov 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year

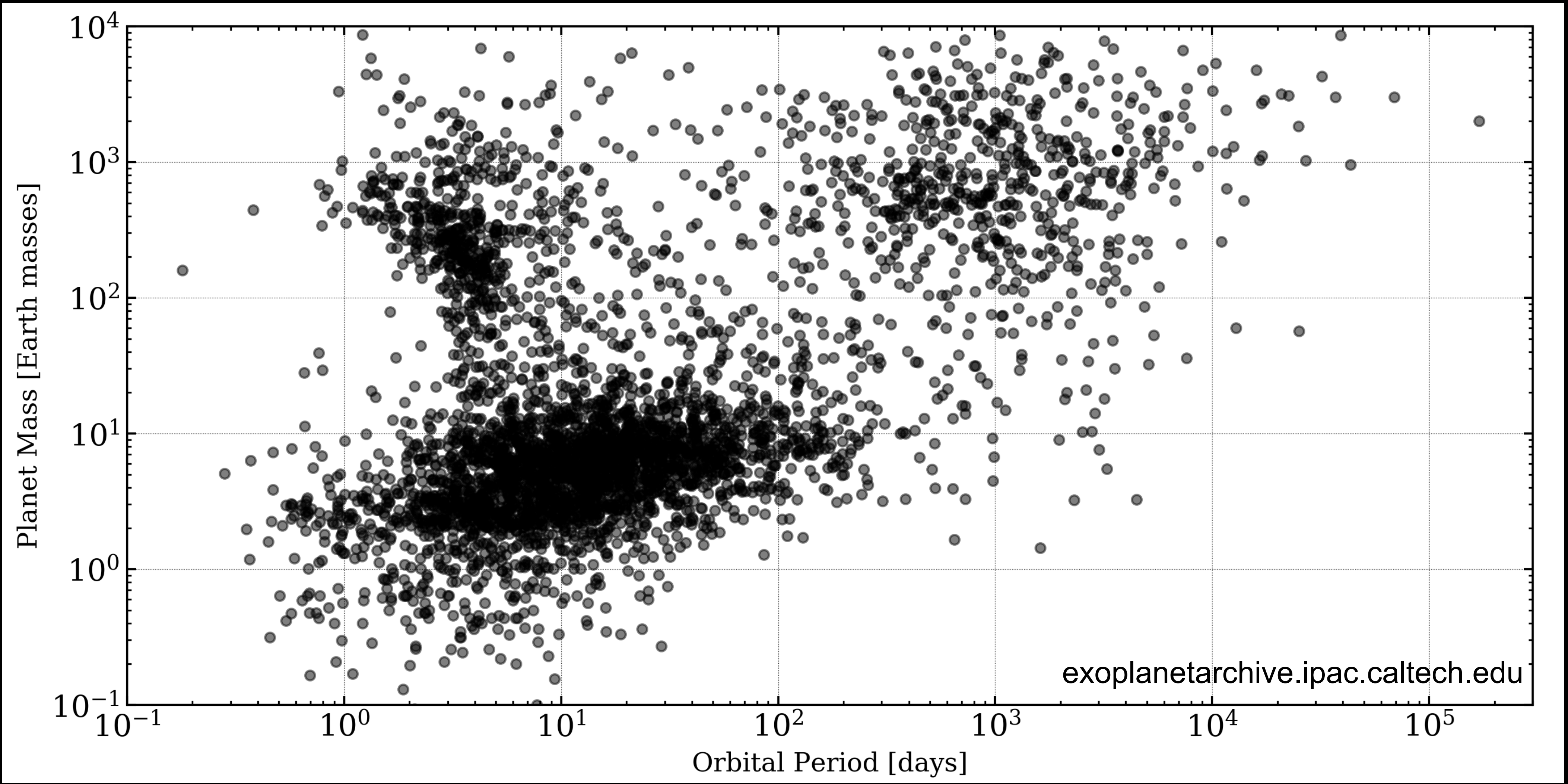
Most exoplanetary systems are compact



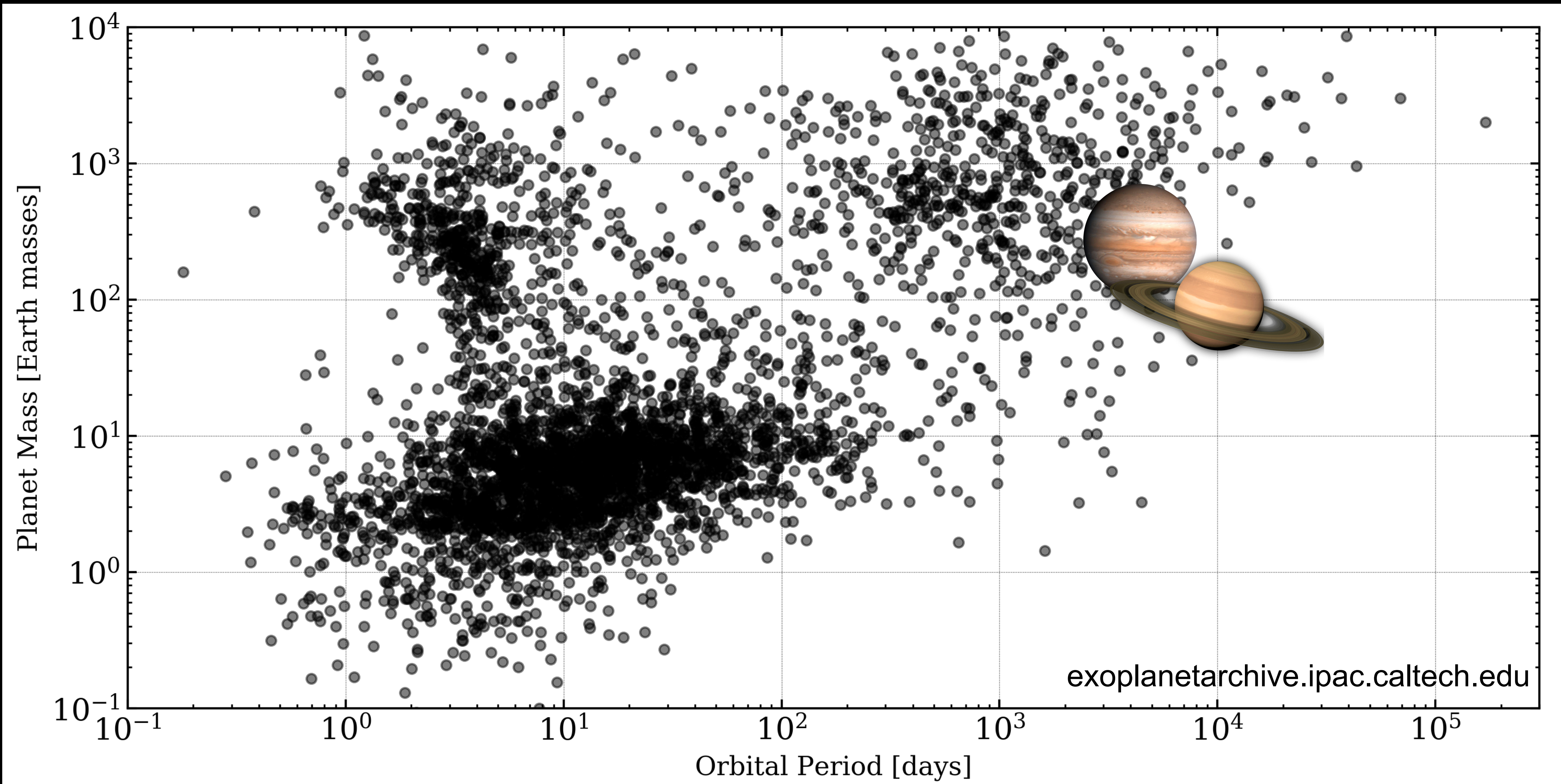
Most exoplanetary systems are compact



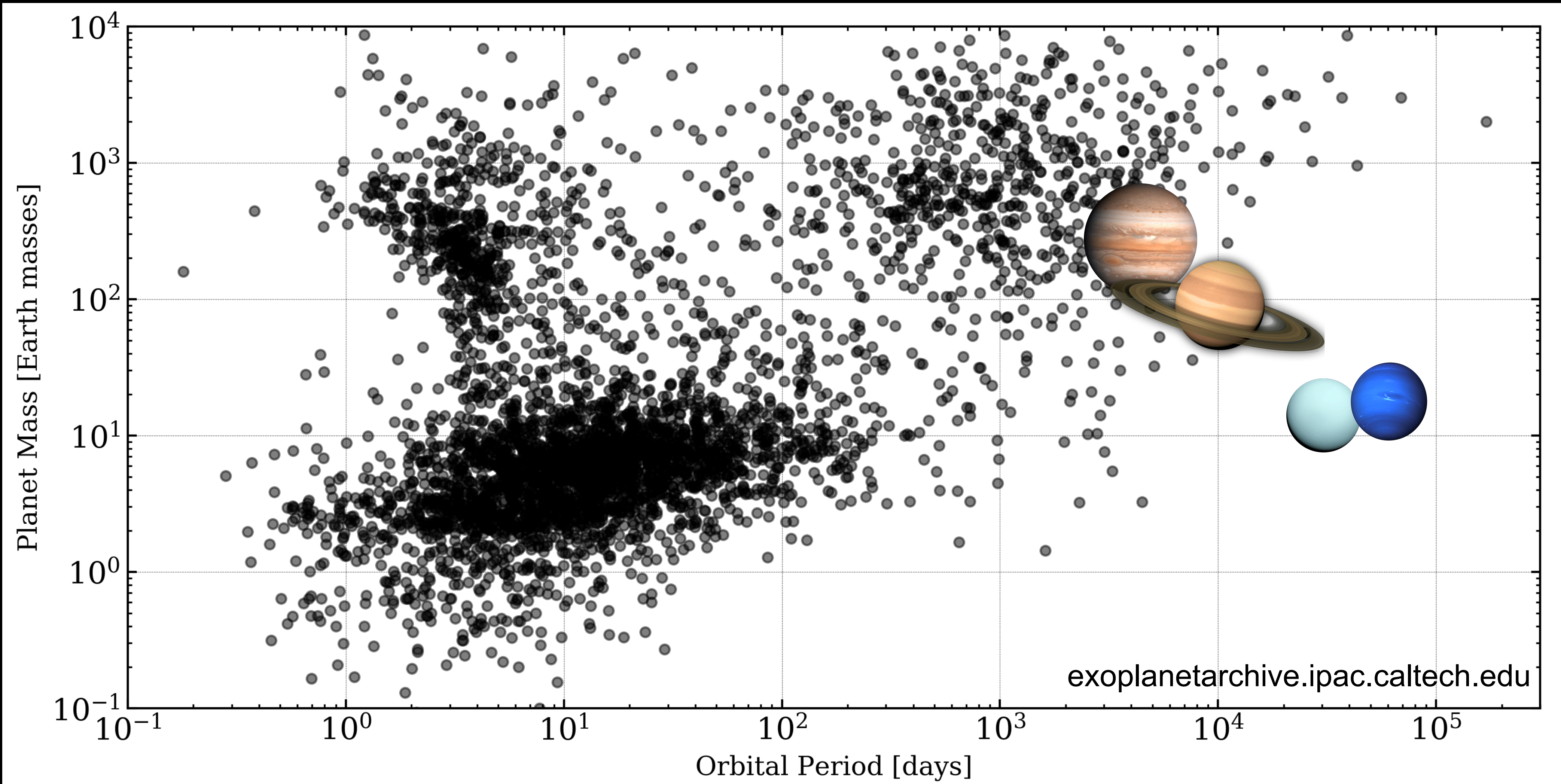
Mass-Period diagram



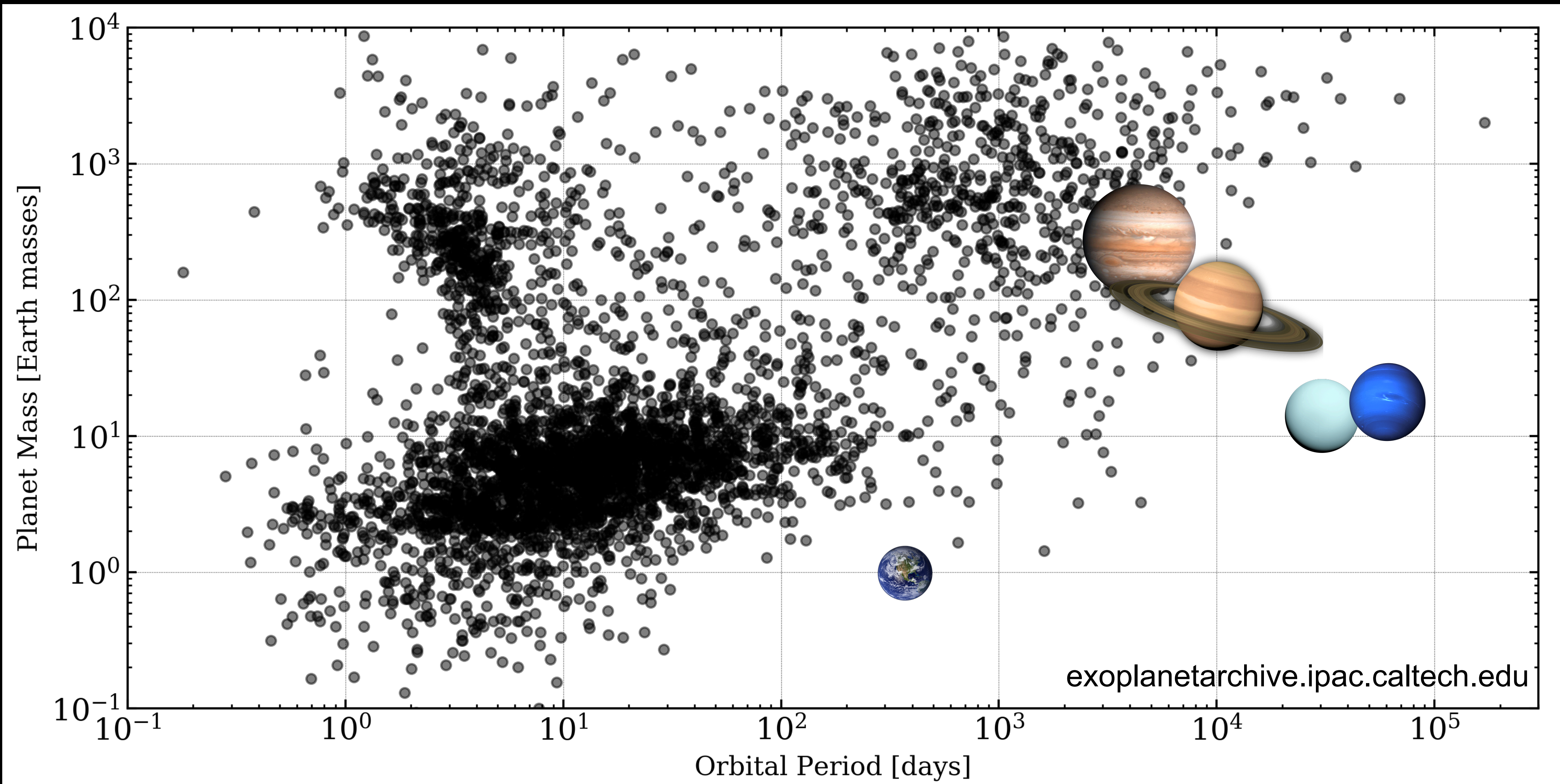
Mass-Period diagram



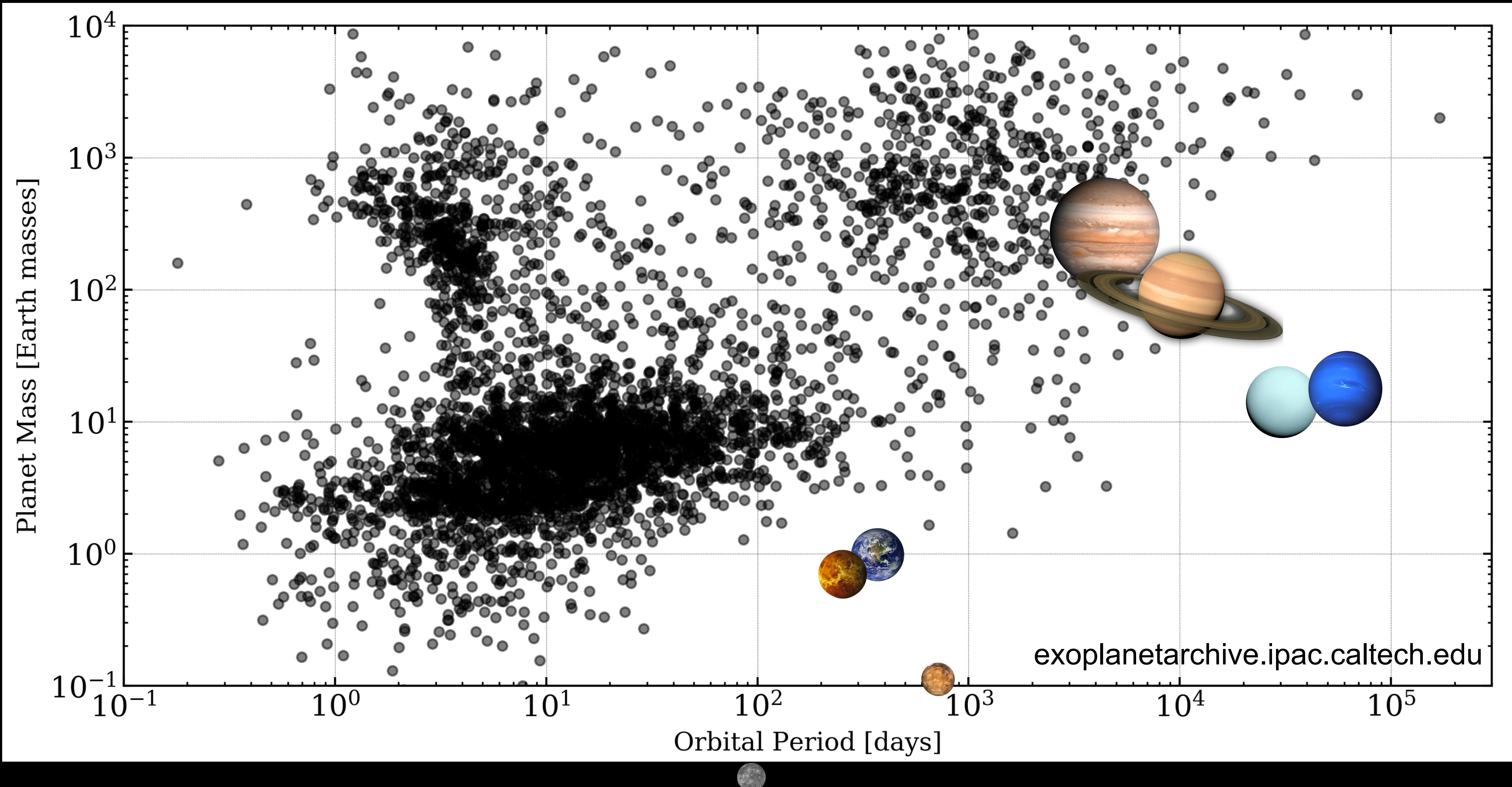
Mass-Period diagram



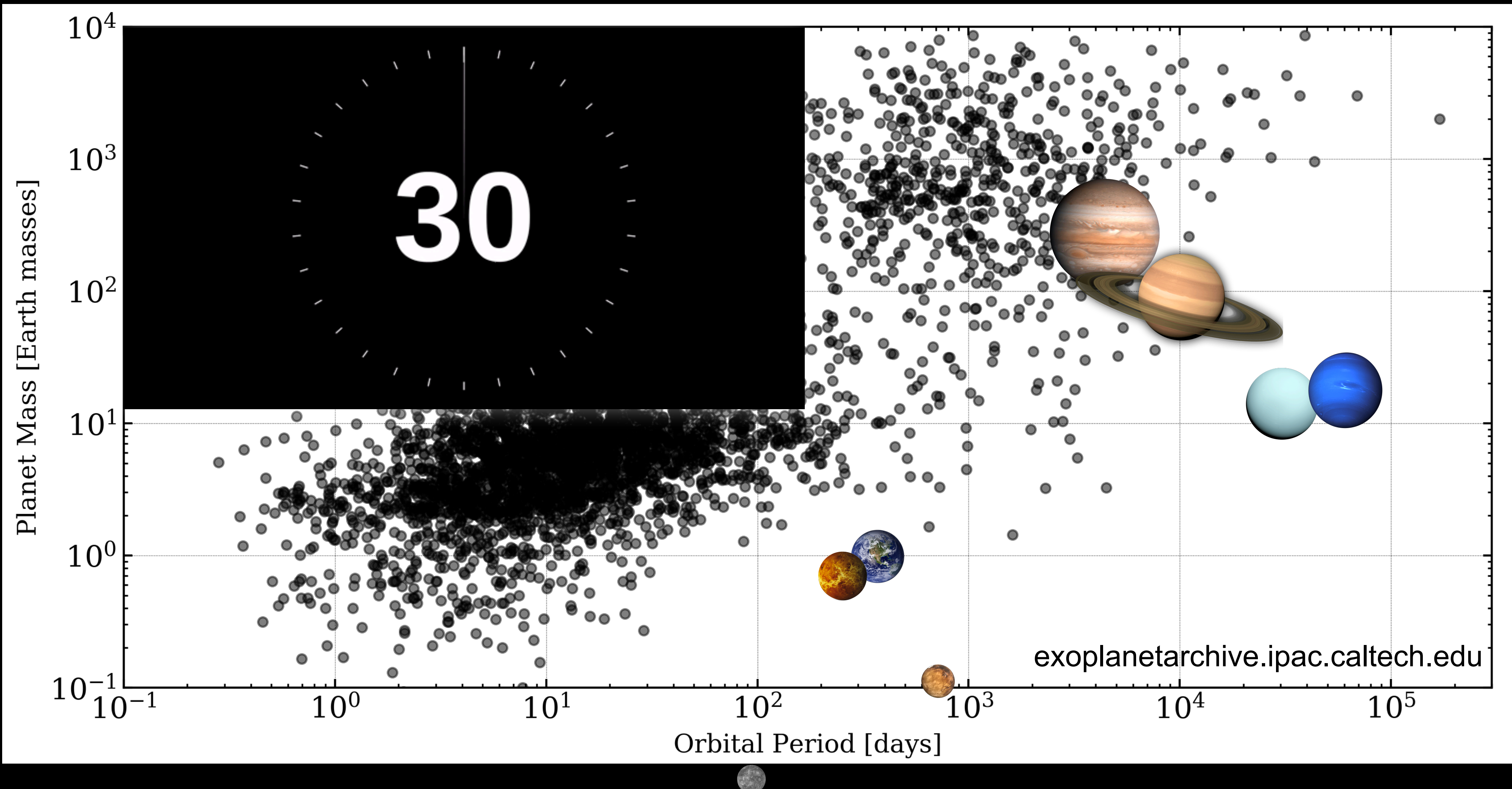
Mass-Period diagram



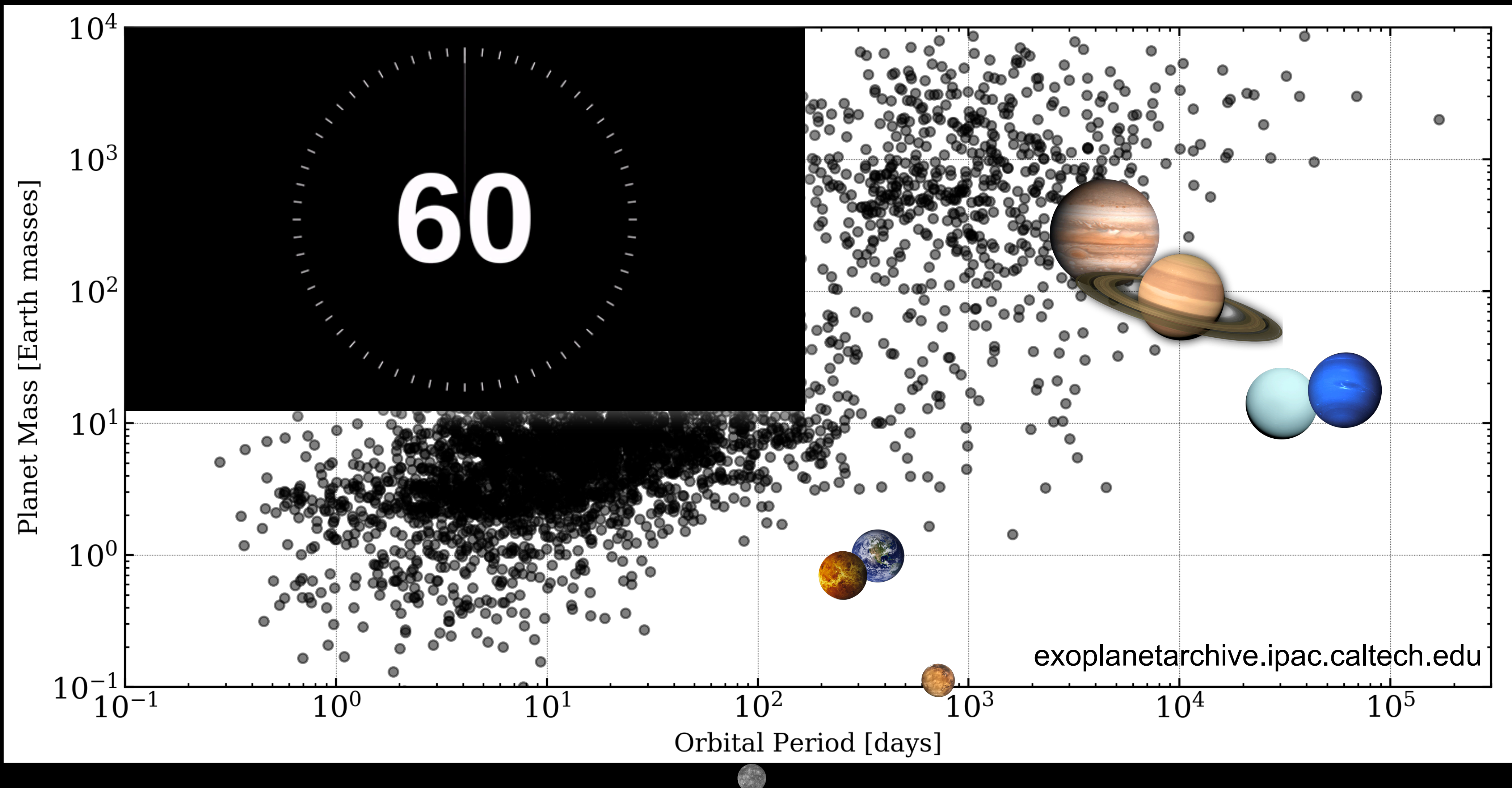
Mass-Period diagram



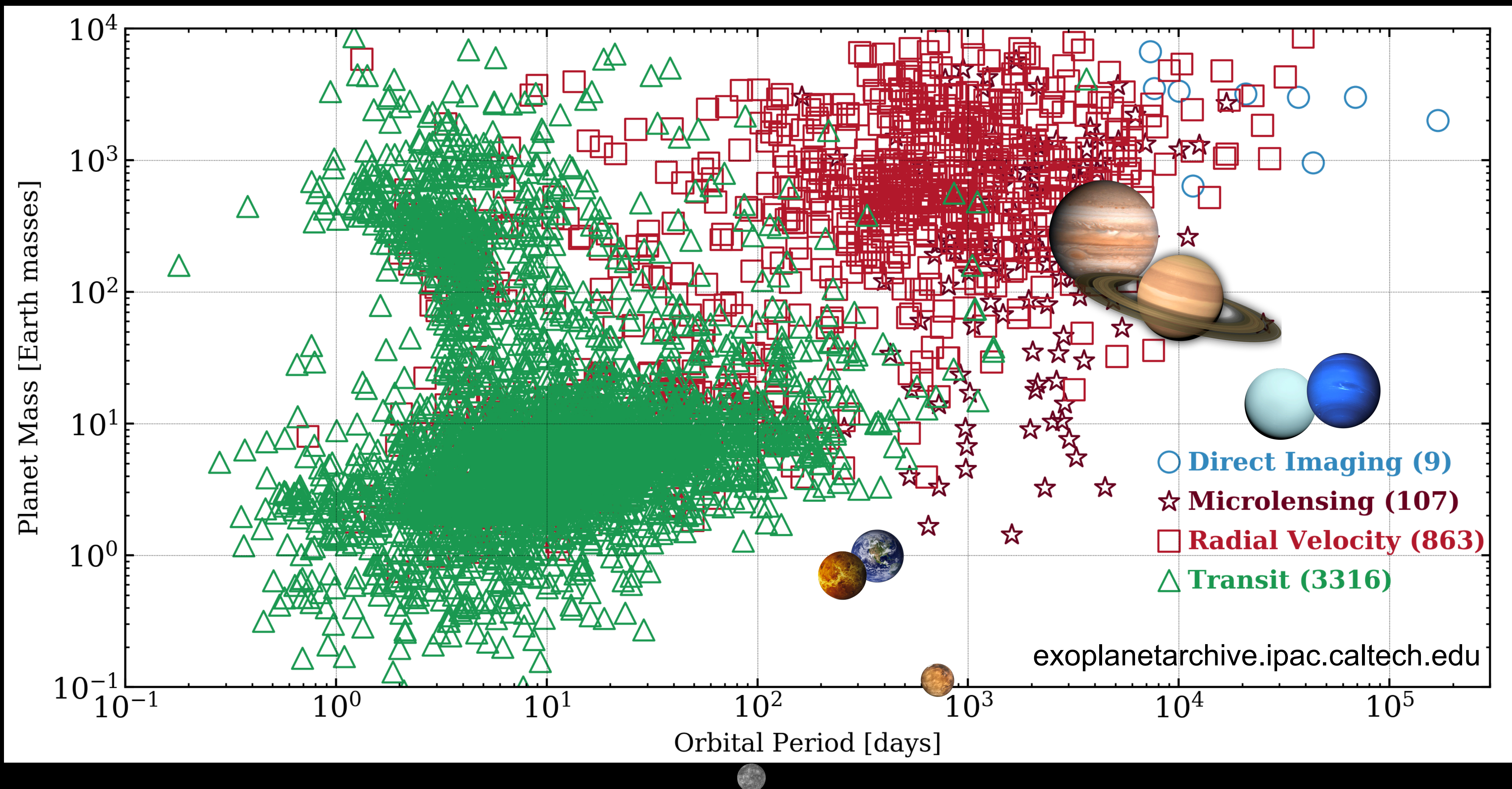
TPS activity - Why haven't we discovered an exo-Mars?



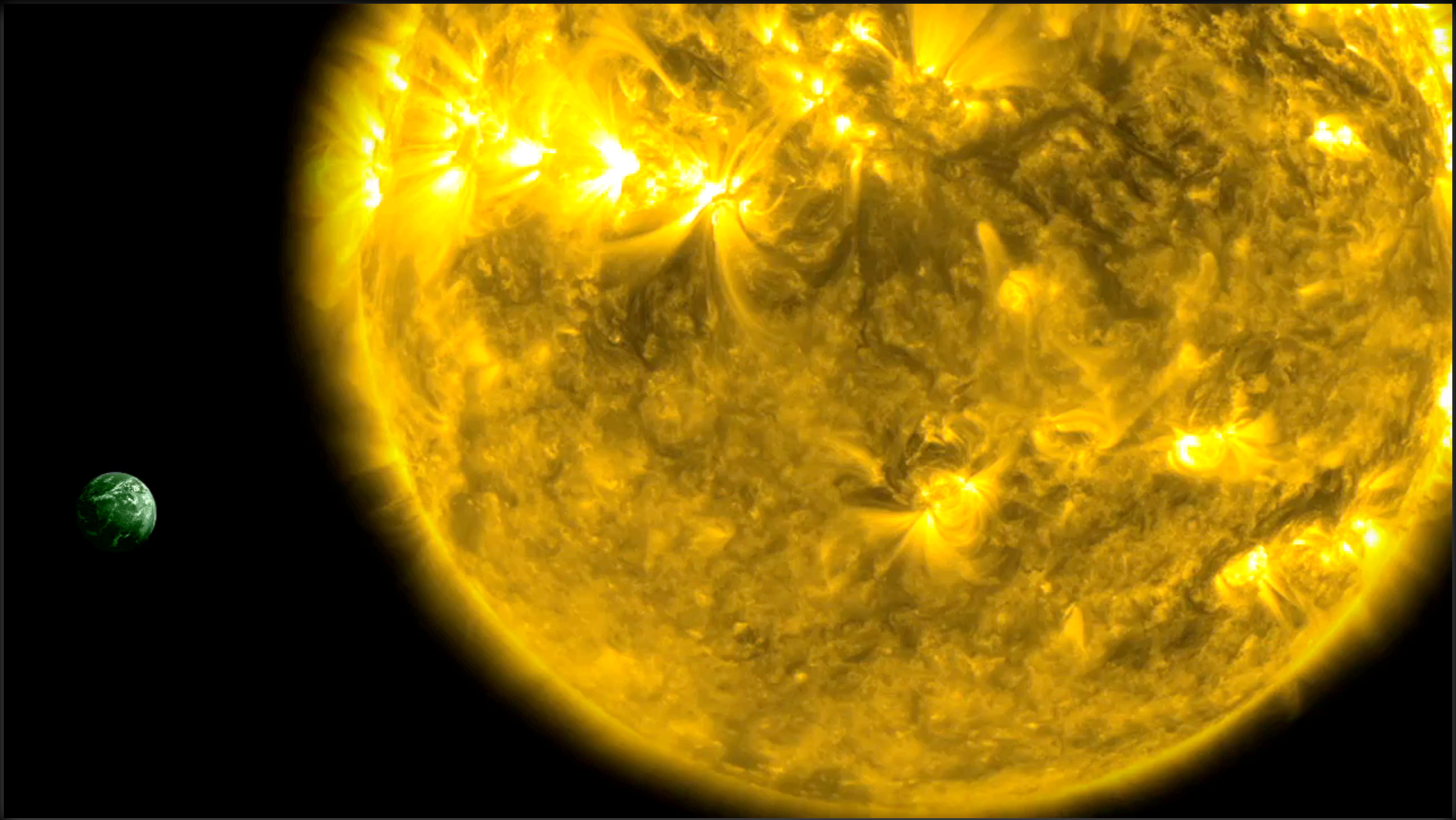
TPS activity - Why haven't we discovered an exo-Mars?



Mass-Period diagram

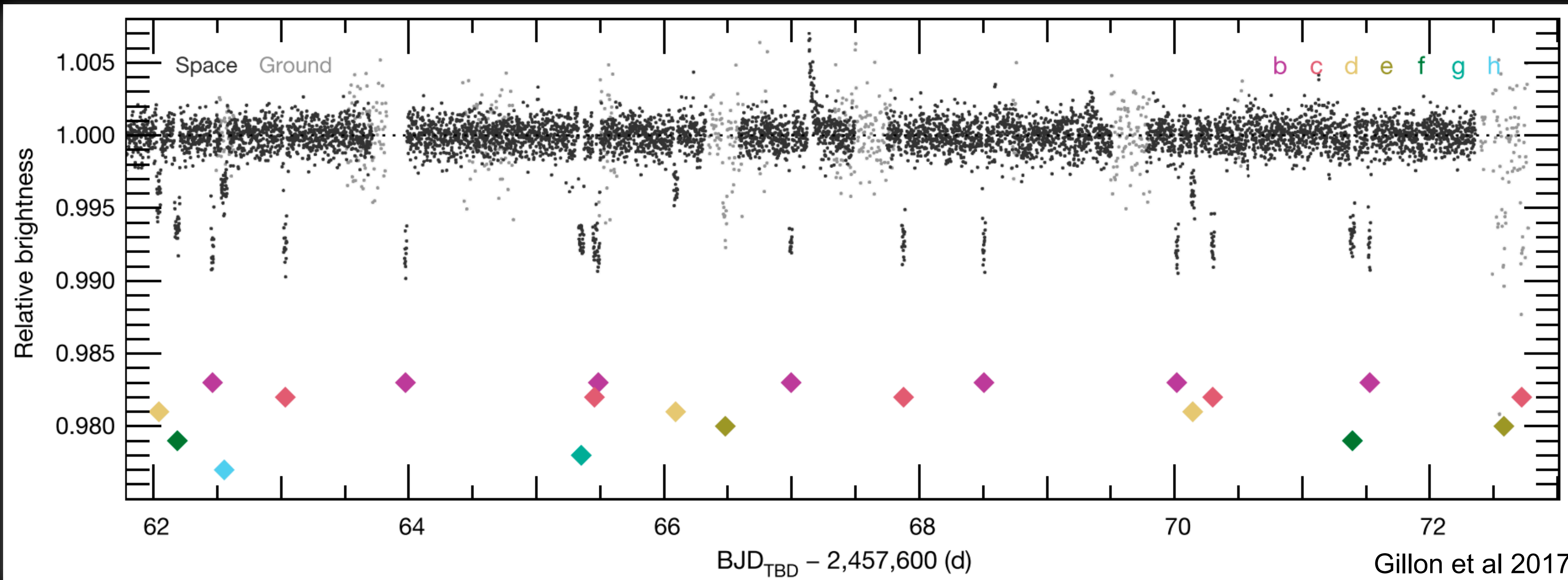


Method 1 - Transits



NASA/GSFC

Method 1 - Transits

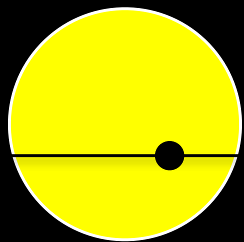


- Time-resolved photometry (i.e. stellar brightness) = **"light curve"**

Can measure:

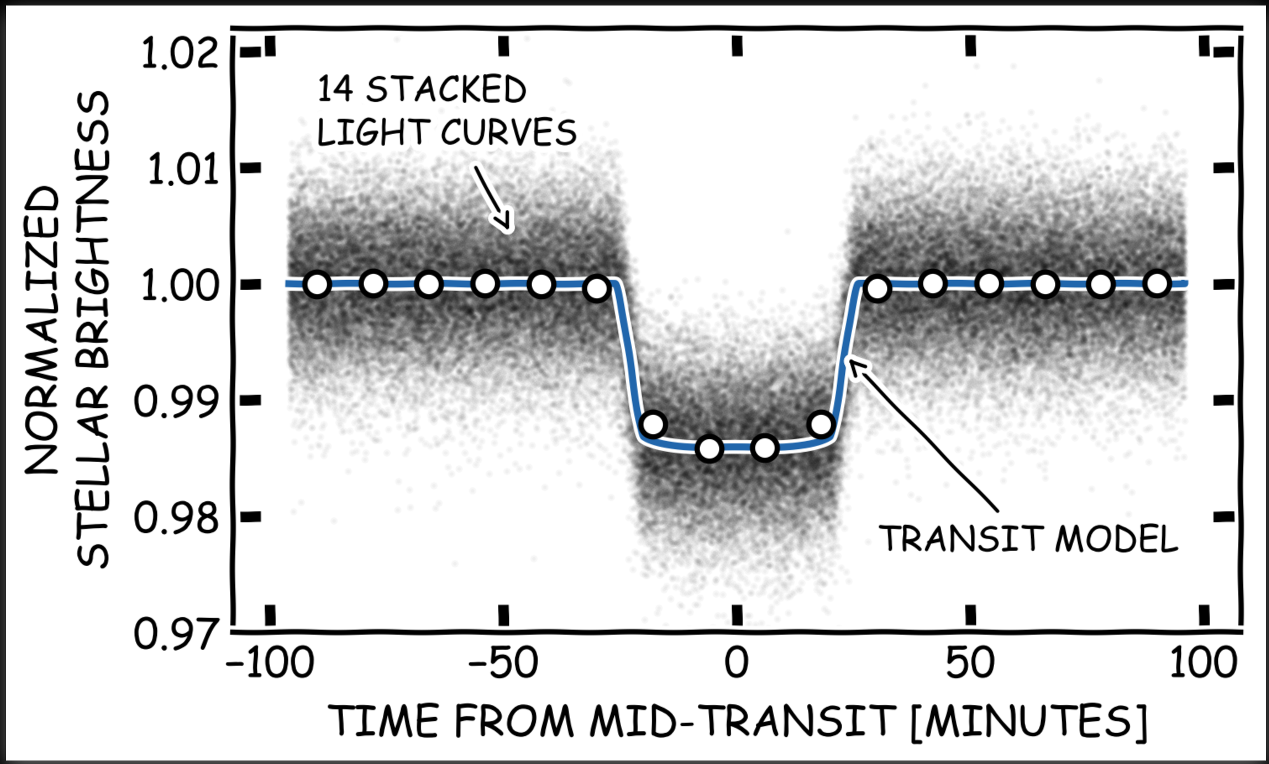
- Orbital period
- Orbital inclination
- Planet radius

Method 1 - Transits



$$Z = \frac{\text{Area}_{\text{pl}}}{\text{Area}_\star} = \left(\frac{R_{\text{pl}}}{R_\star}\right)^2$$

- Z: transit depth
- R_{pl}: planet radius
- $R_\star$: stellar radius

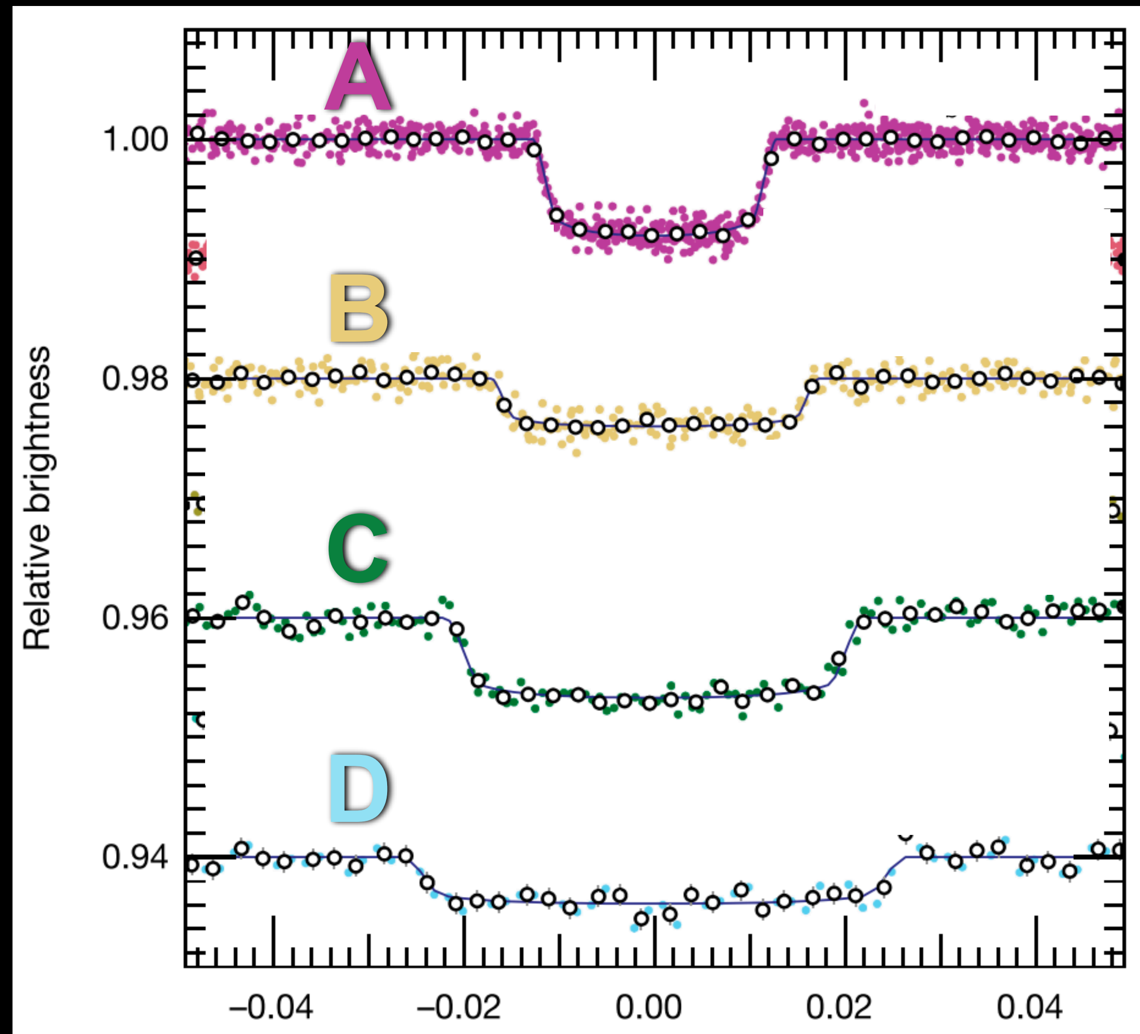


Cloutier et al 2021

A B
C D

All of these planets are in the same planetary system.

Which planet is the largest?



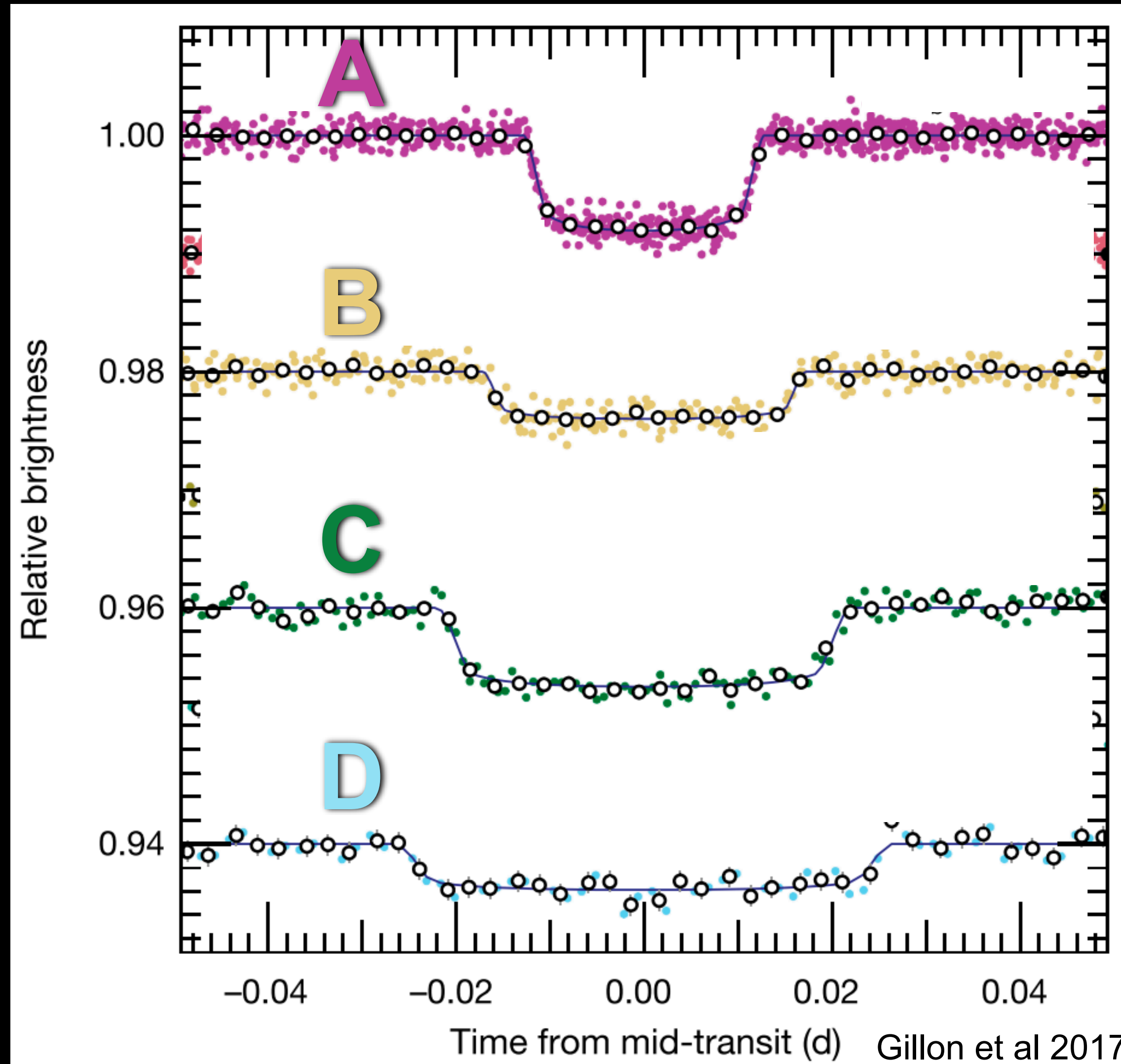
Gillon et al 2017

A B

C D

All of these planets are in the same planetary system.

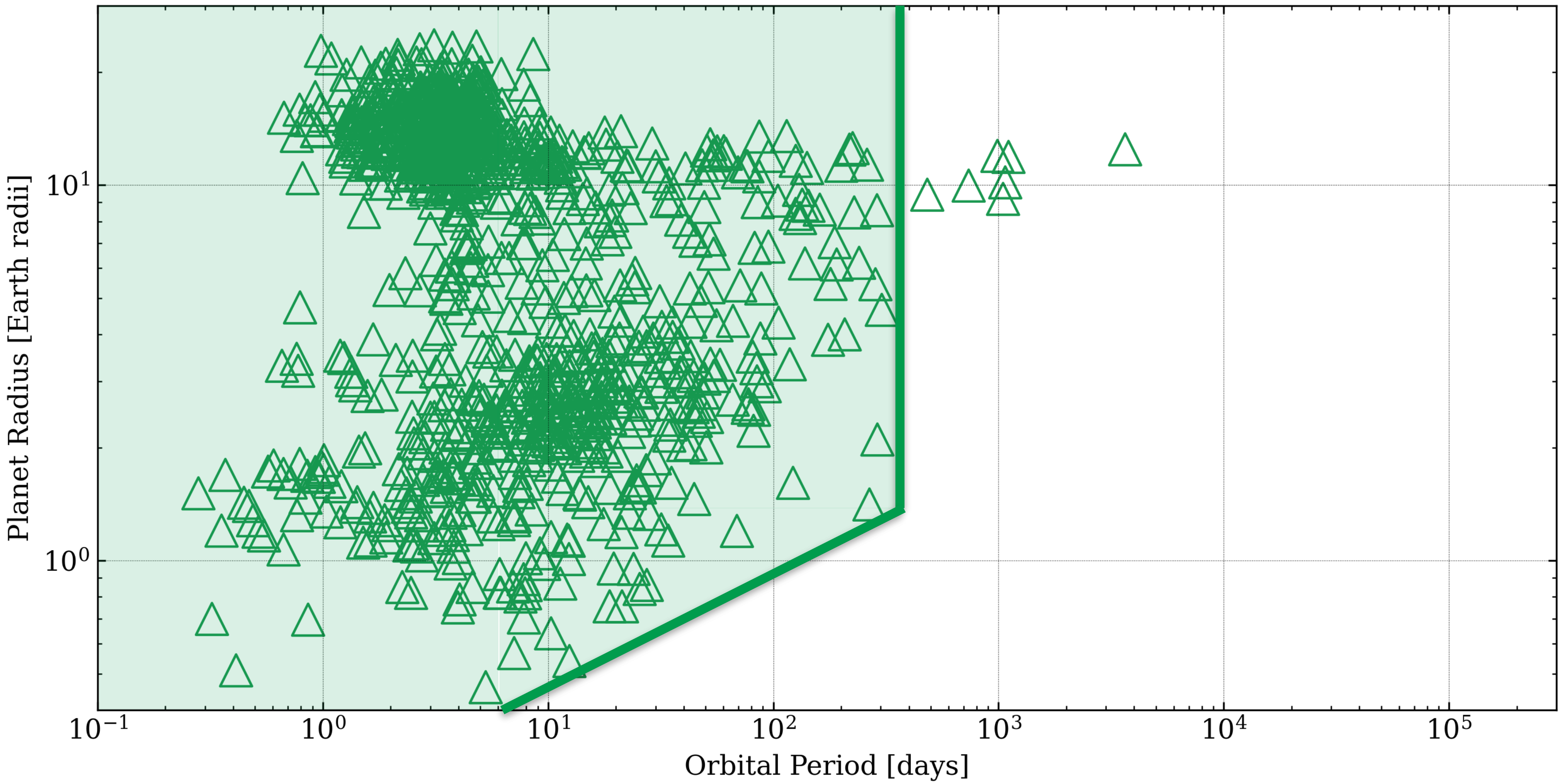
Which planet has the longest orbital period?



Gillon et al 2017

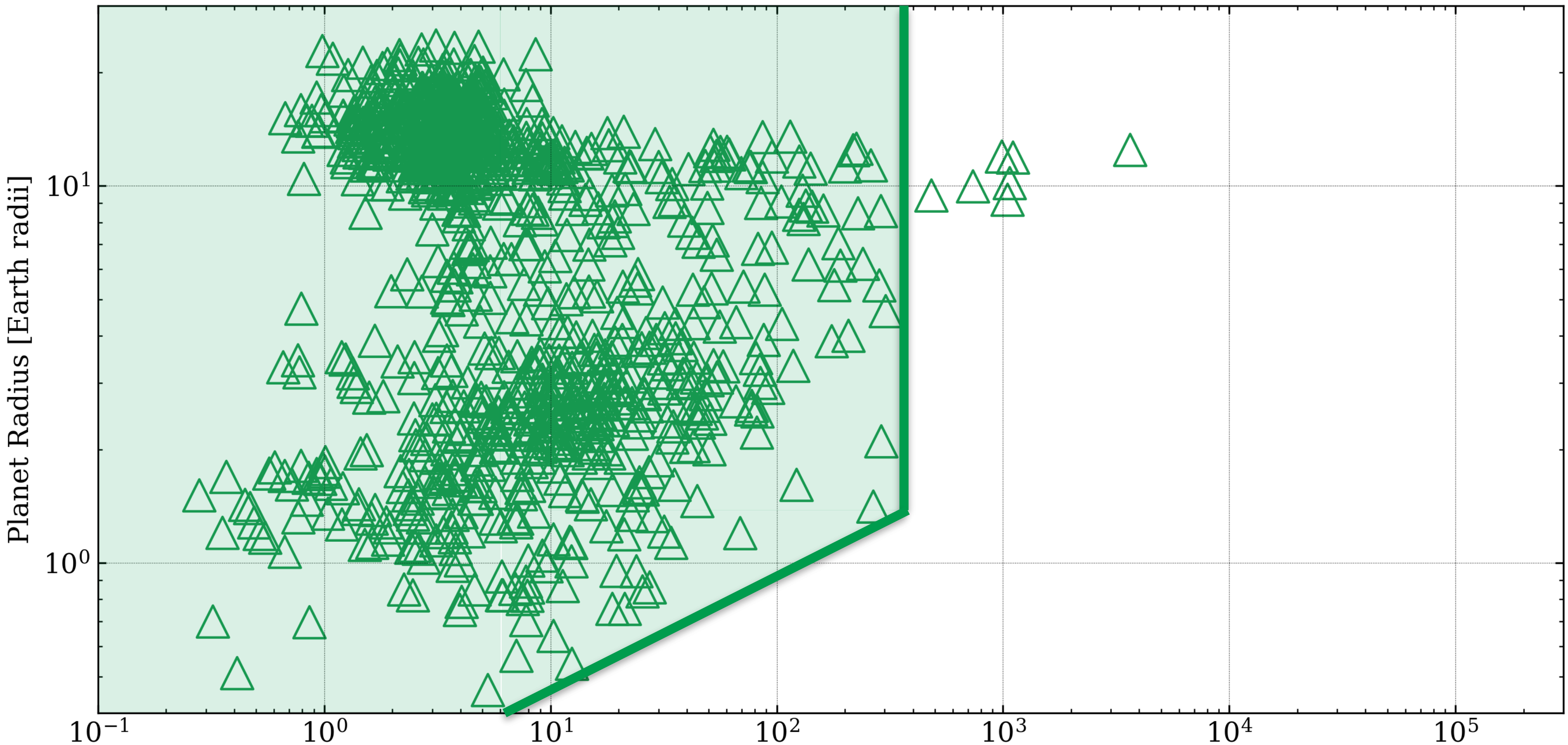
Known Transiting Exoplanets

Radius-Period diagram



Known Transiting Exoplanets

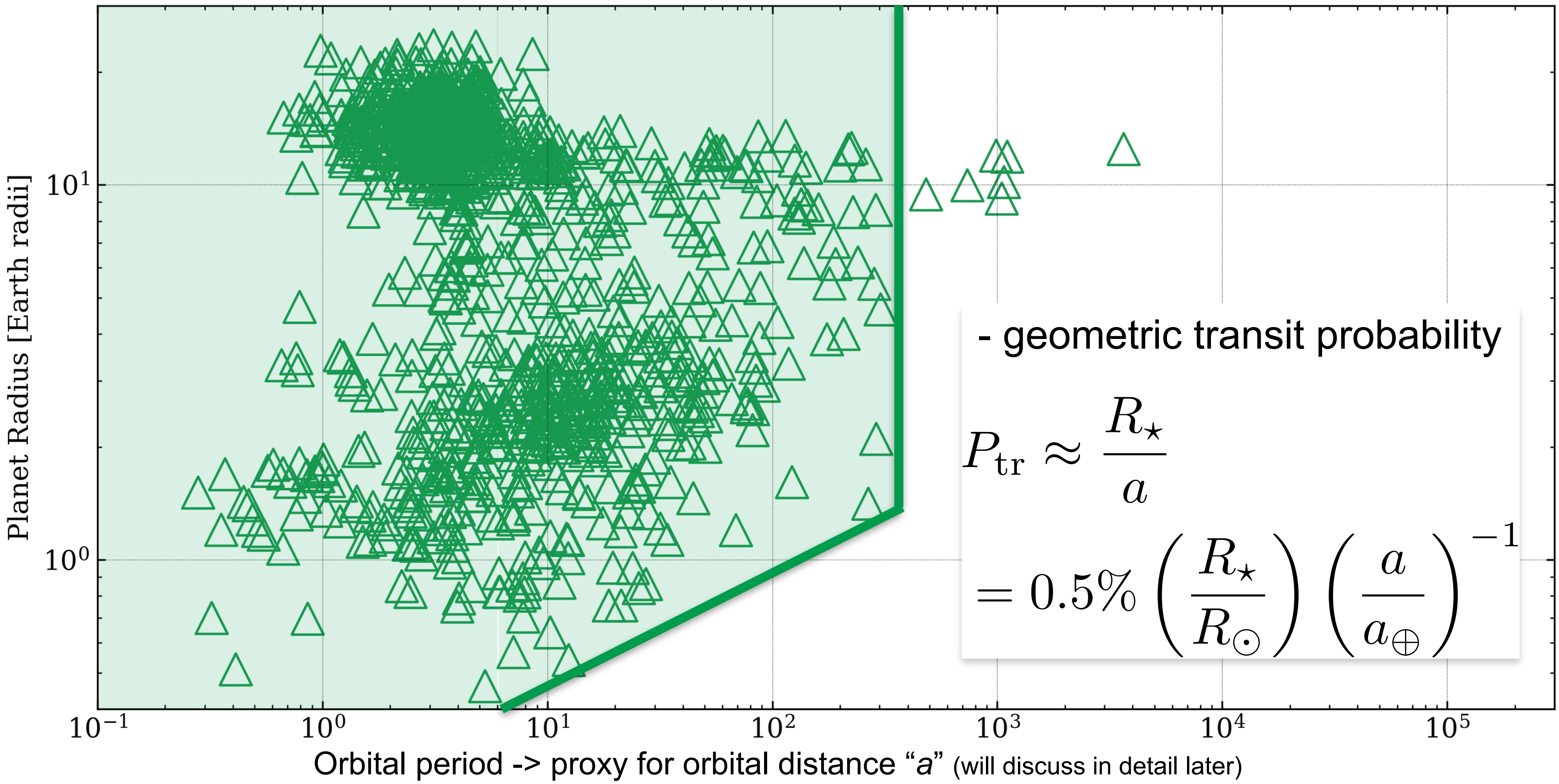
Radius-Period diagram



Orbital period -> proxy for orbital distance "*a*" (will discuss in detail later)

Known Transiting Exoplanets

Radius-Period diagram



- geometric transit probability

$$P_{\rm tr} \approx \frac{R_\star}{a}$$

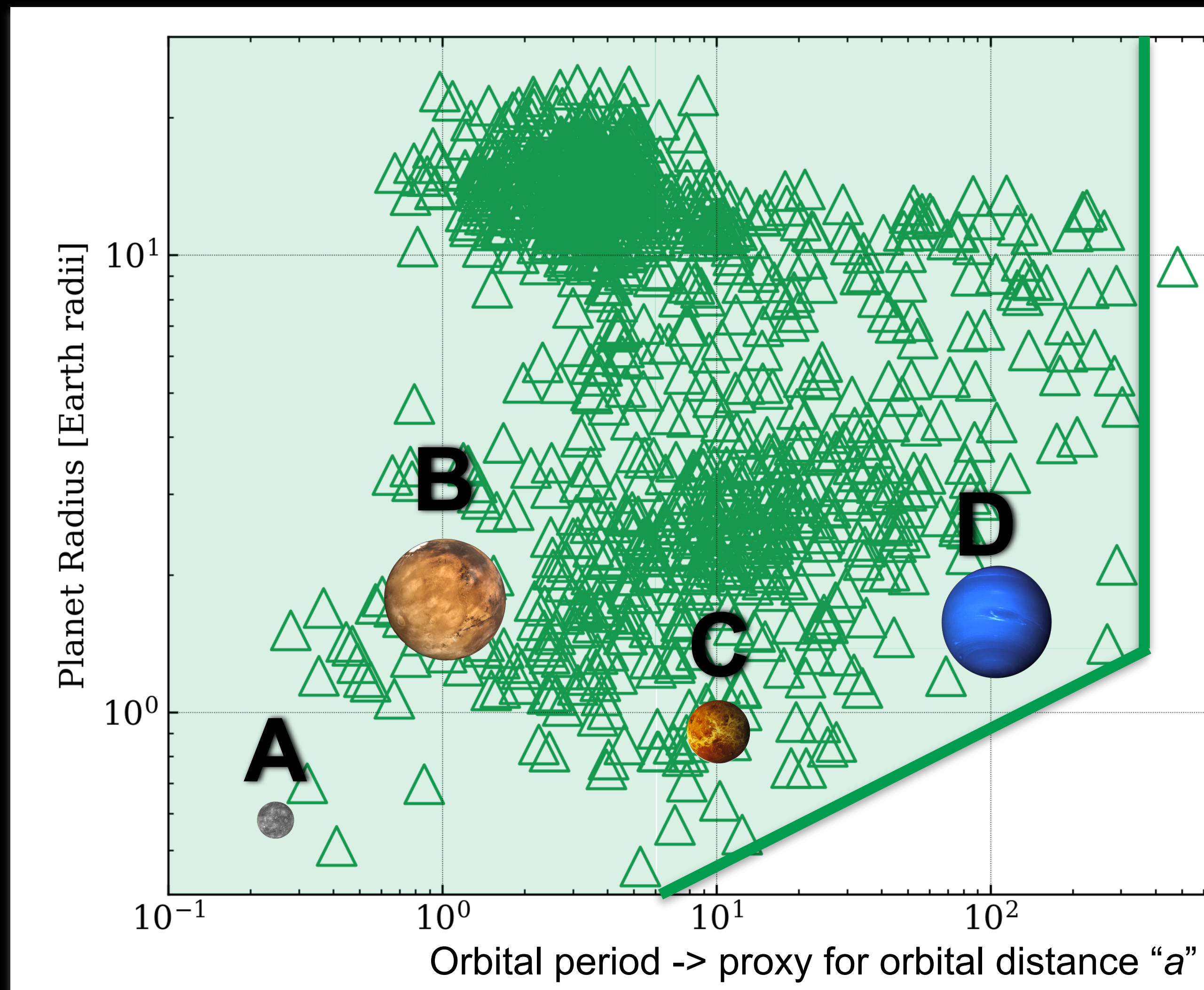
$$= 0.5\% \left(\frac{R_\star}{R_\odot}\right)\left(\frac{a}{a_\oplus}\right)^{-1}$$

A B

C D

The four hypothetical planets in this figure all orbit a solar twin (i.e. a star that is identical to our Sun)

Which planet is the least likely to transit?



Method 2 - Transit Timing Variations

NASA Ames

A

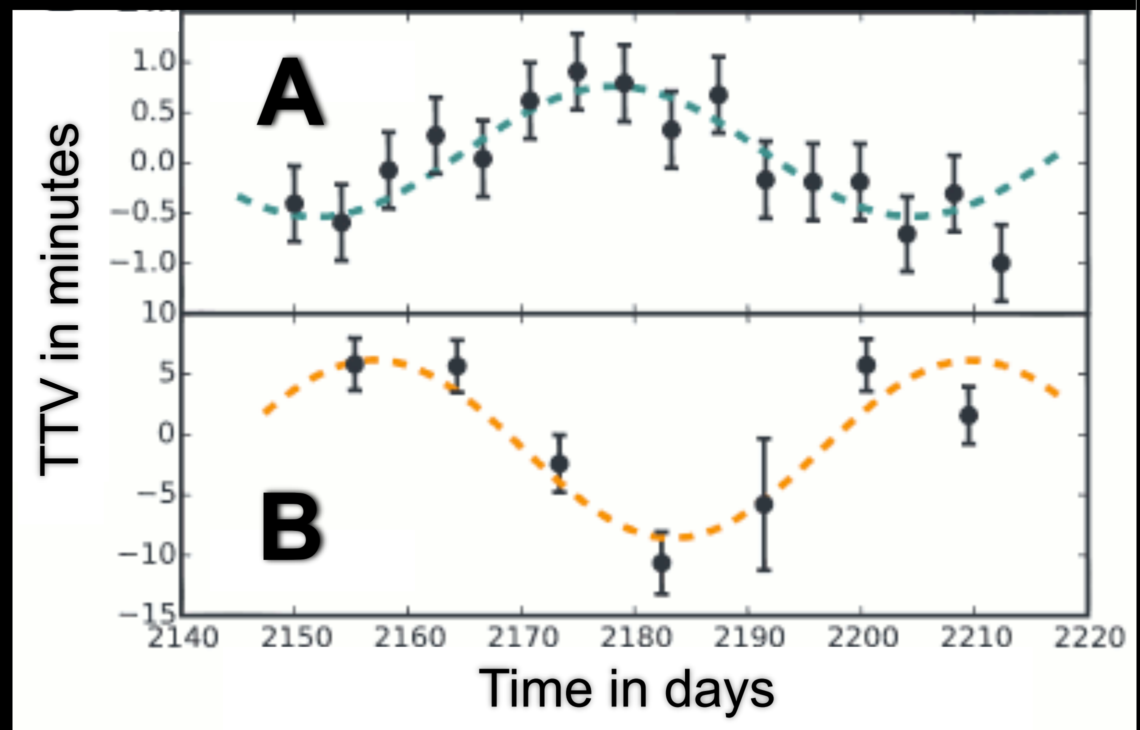
B

C

D

Both planets in this planetary system exhibit transit timing variations.

Which planet exhibits the larger TTVs?

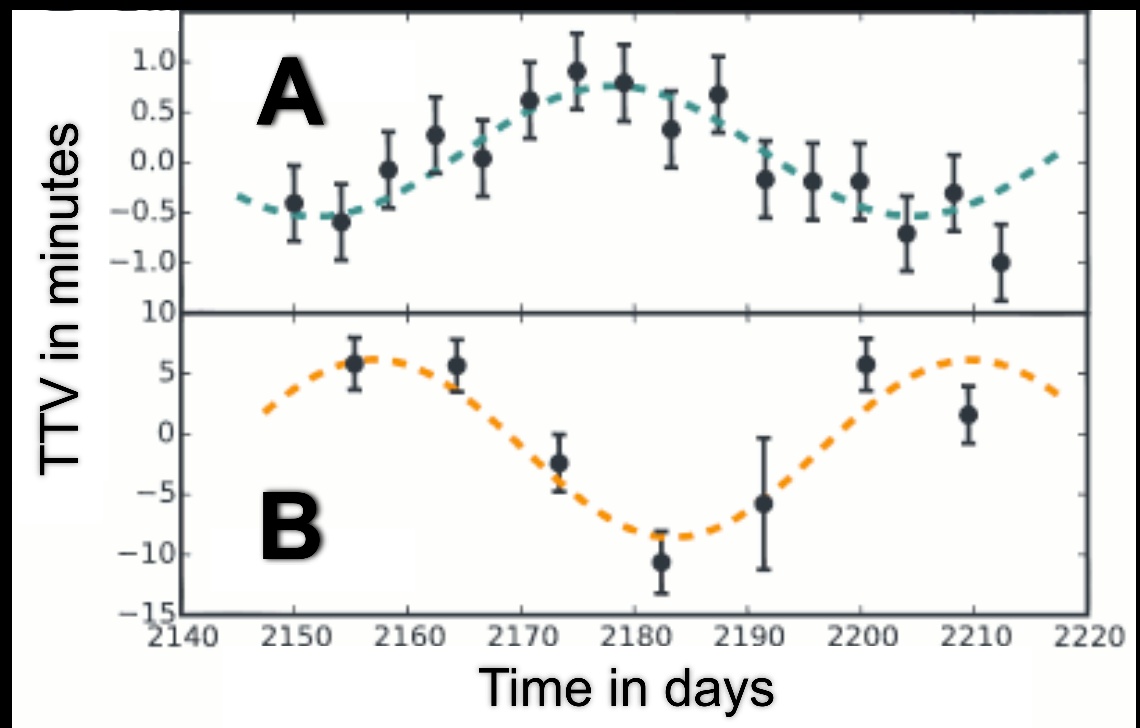


Becker et al 2015

A B
C D

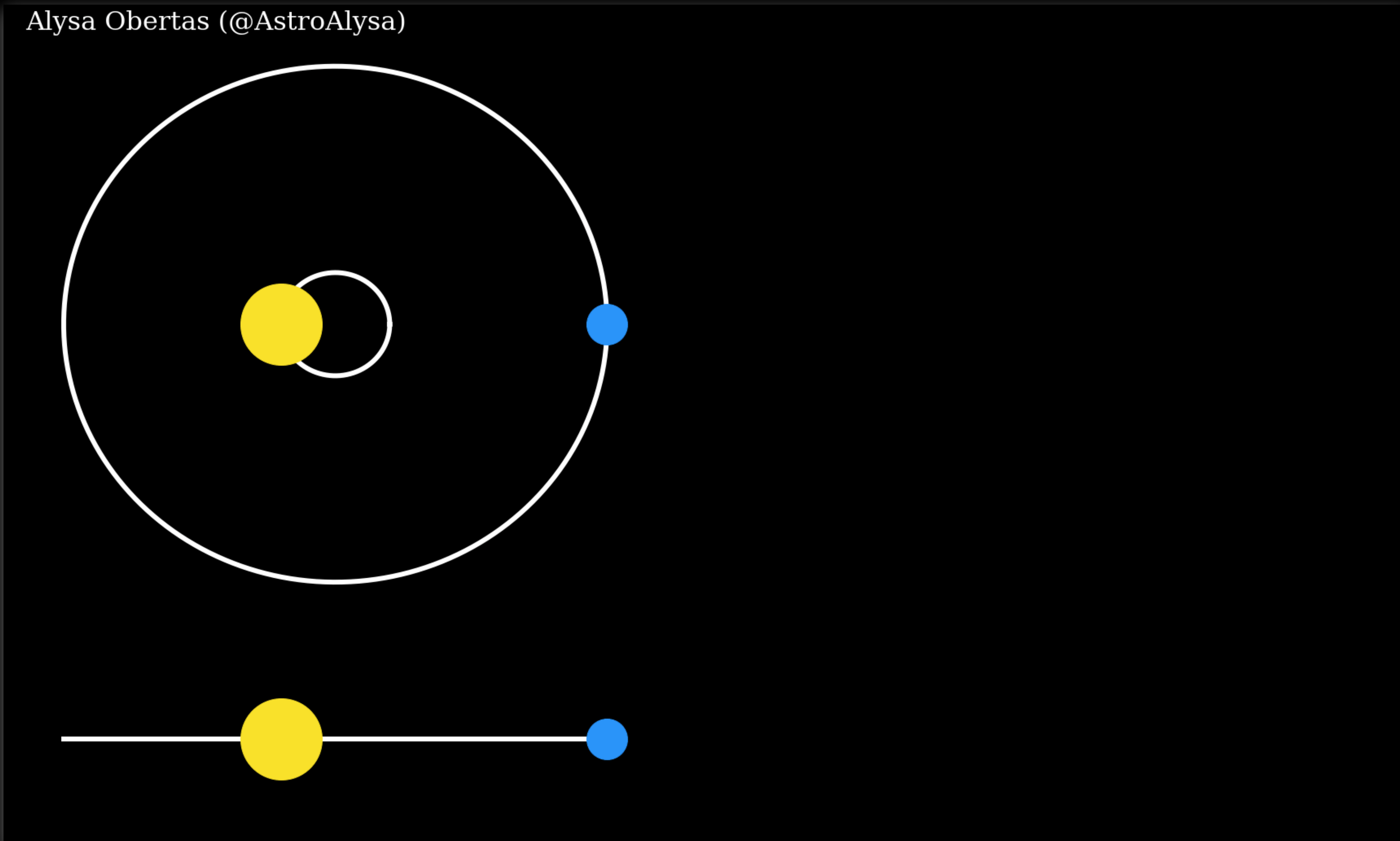
Both planets in this planetary system exhibit transit timing variations.

Which planet is more massive?

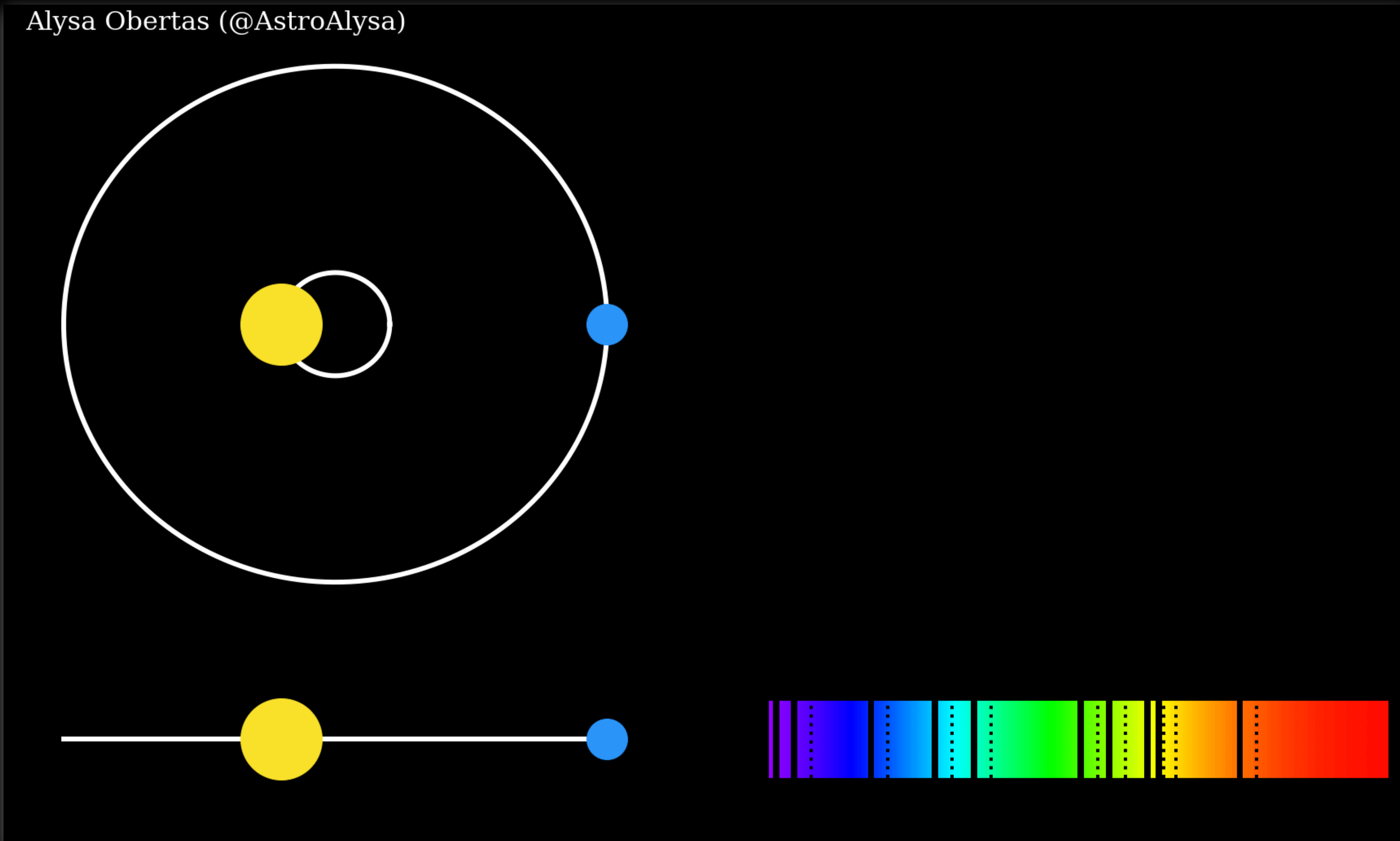


Becker et al 2015

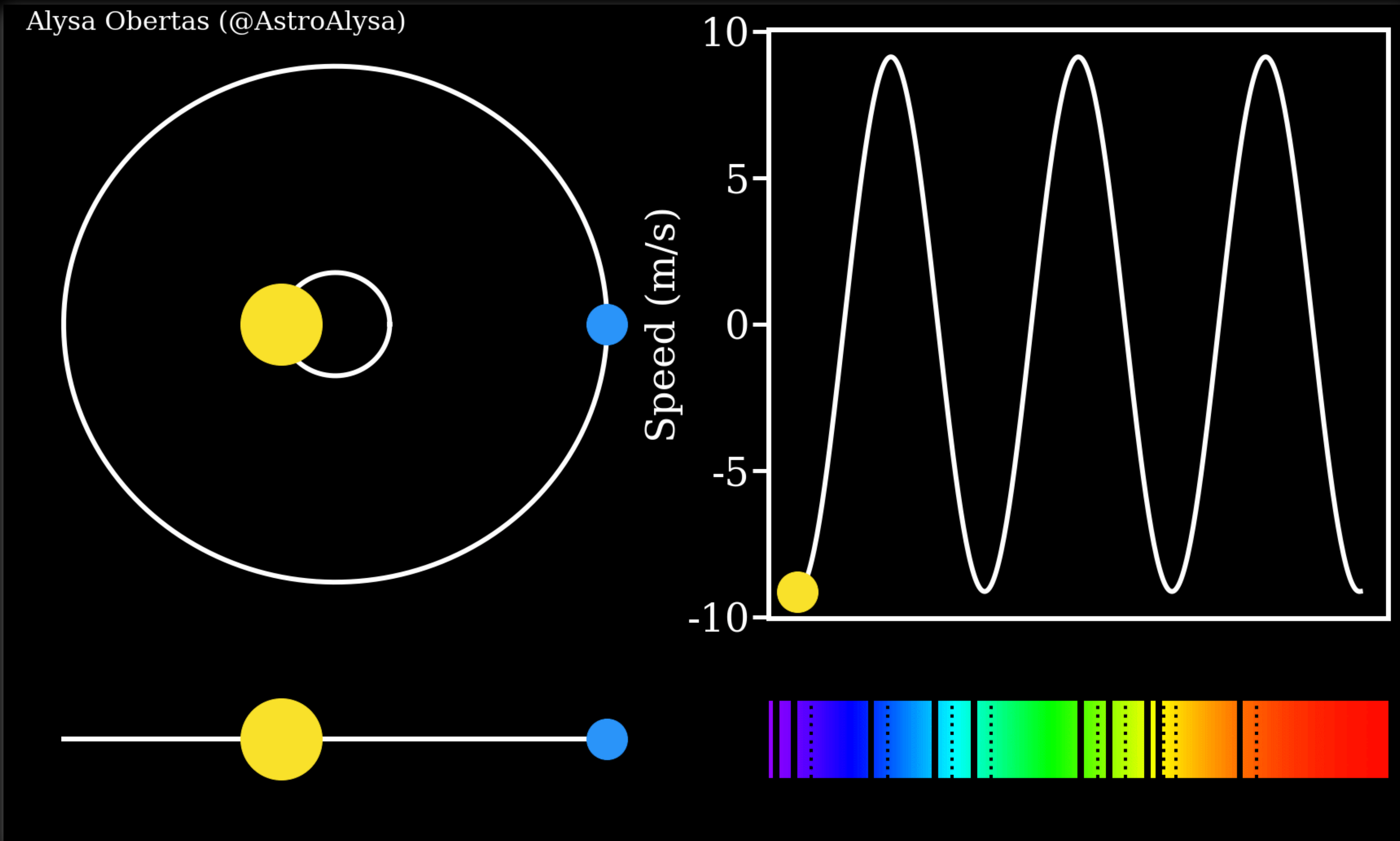
Method 3 - Radial Velocity



Method 3 - Radial Velocity



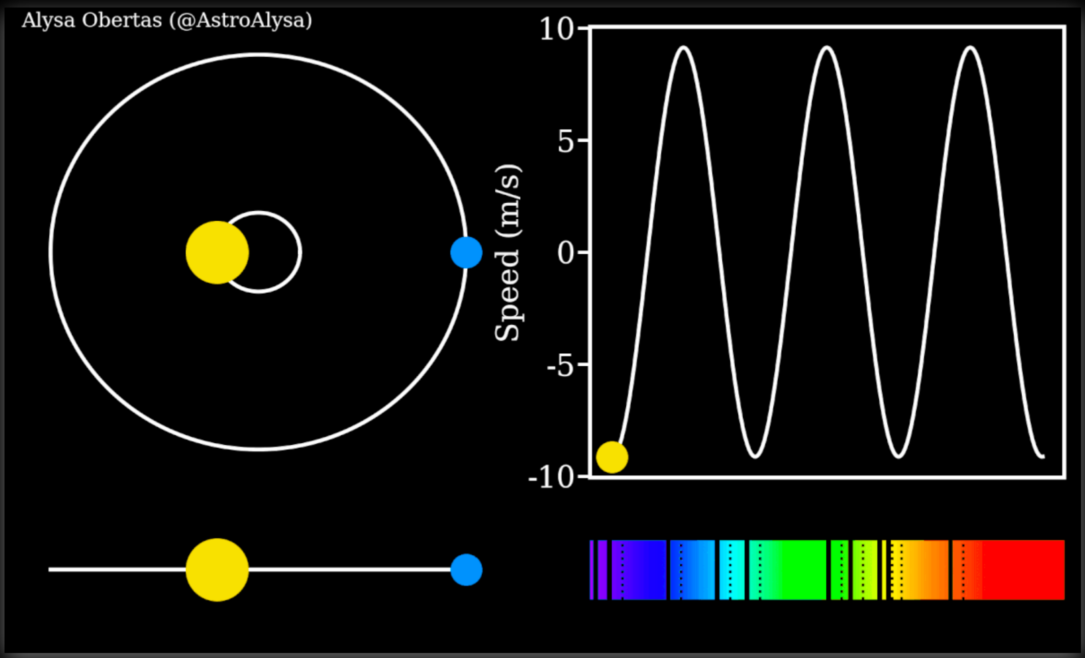
Method 3 - Radial Velocity



Method 3 - Radial Velocity

- Time-resolved spectroscopy to measure Doppler-shifted spectral features
- Radial velocity shift translates into a wavelength shift

$$\frac{\lambda_{\mathrm{obs}}}{\lambda_{\mathrm{ref}}} = \sqrt{\frac{1 + v_{\mathrm{rad}}/c}{1 - v_{\mathrm{rad}}/c}}$$

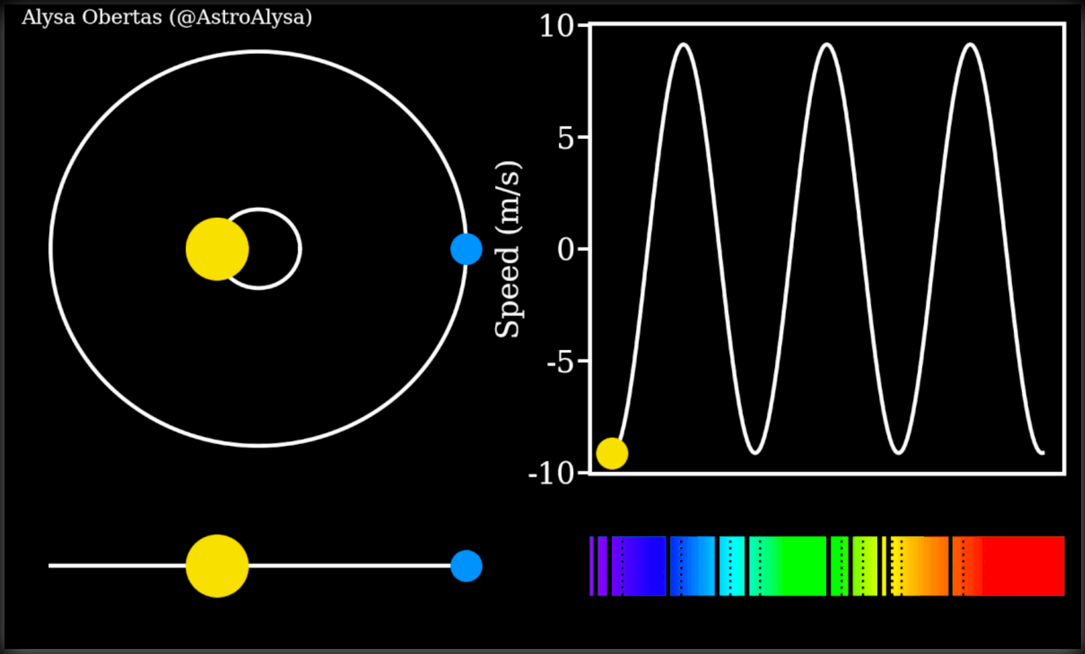


Method 3 - Radial Velocity

- Time-resolved spectroscopy to measure Doppler-shifted spectral features
- Radial velocity shift translates into a wavelength shift

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{ref}}} = \sqrt{\frac{1 + v_{\text{rad}}/c}{1 - v_{\text{rad}}/c}}$$

Can measure:
- Orbital period



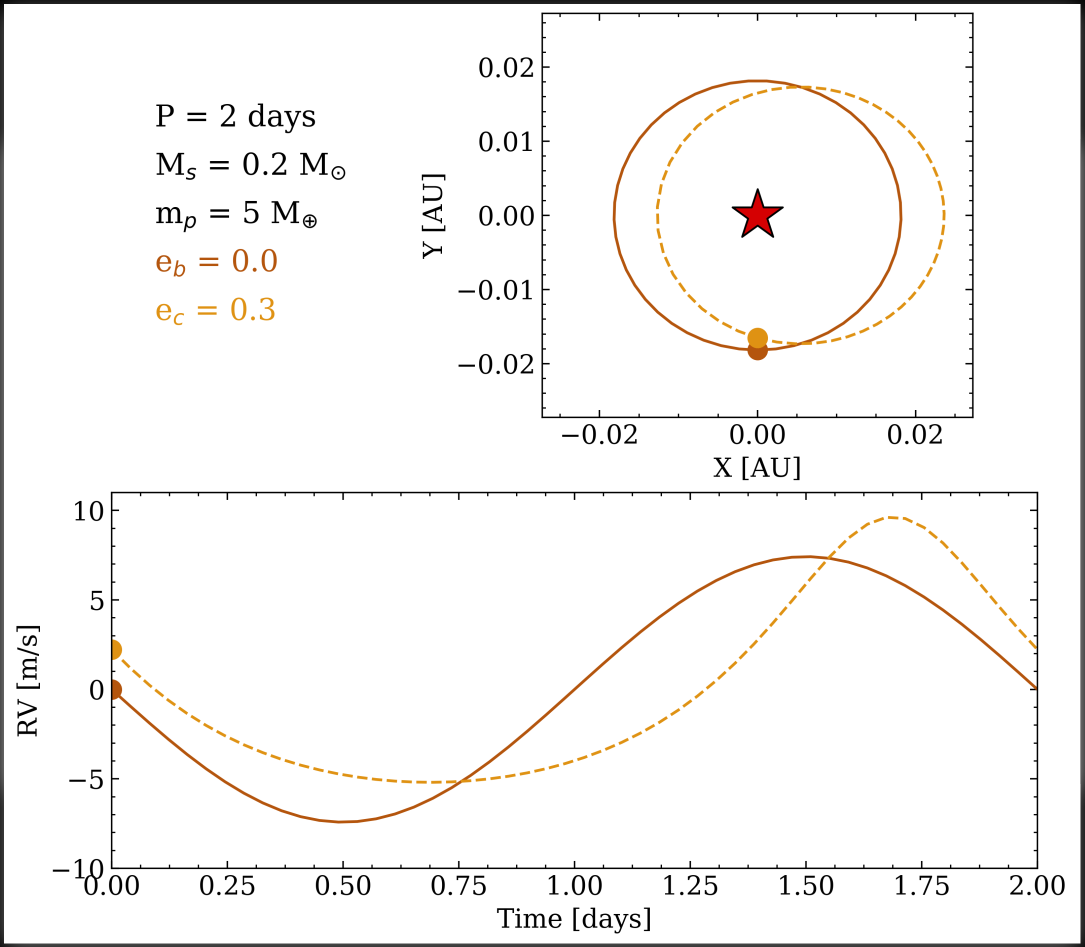
Method 3 - Radial Velocity

- Time-resolved spectroscopy to measure Doppler-shifted spectral features
- Radial velocity shift translates into a wavelength shift

$$\frac{\lambda_{\rm obs}}{\lambda_{\rm ref}} = \sqrt{\frac{1 + v_{\rm rad}/c}{1 - v_{\rm rad}/c}}$$

Can measure:

- Orbital period
- Orbital eccentricity



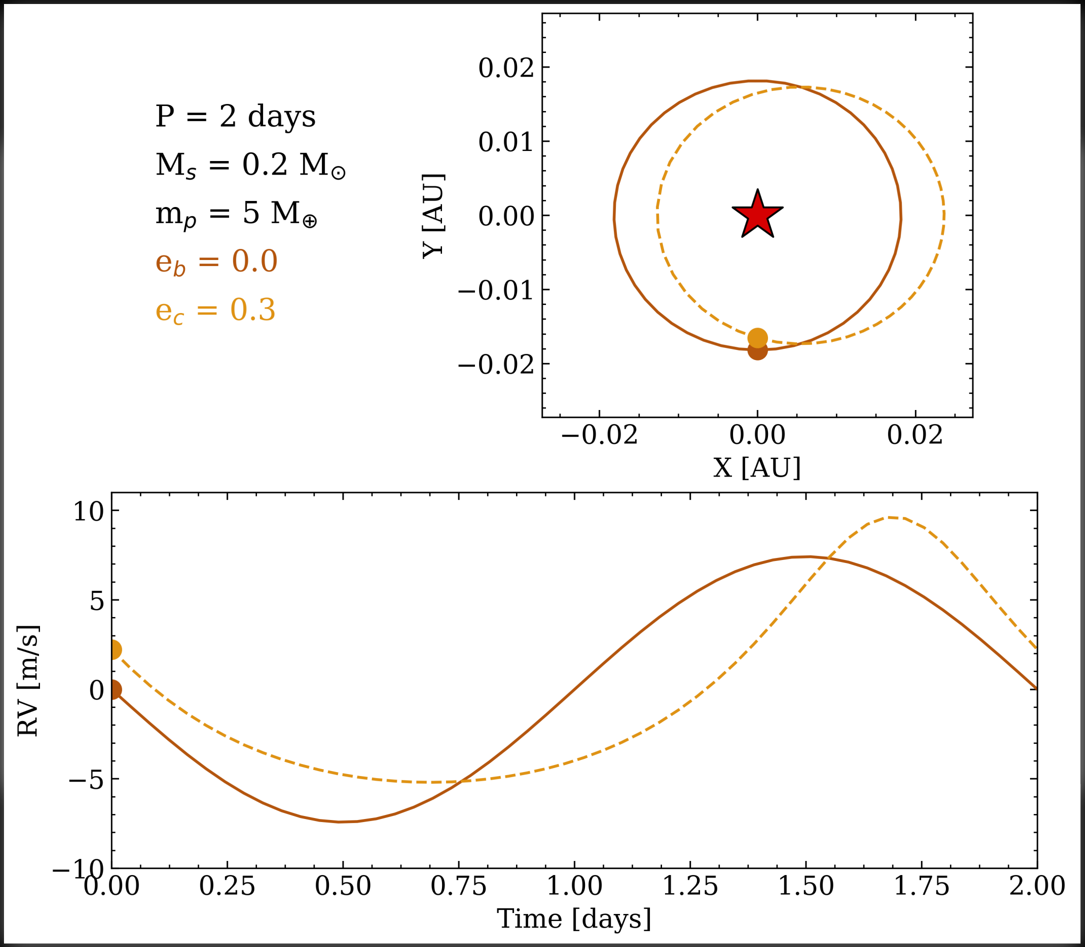
Method 3 - Radial Velocity

- Time-resolved spectroscopy to measure Doppler-shifted spectral features
- Radial velocity shift translates into a wavelength shift

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{ref}}} = \sqrt{\frac{1 + v_{\text{rad}}/c}{1 - v_{\text{rad}}/c}}$$

Can measure:

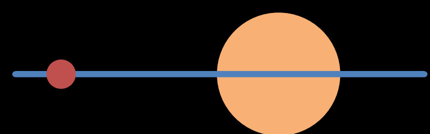
- Orbital period
- Orbital eccentricity
- Planet's *minimum mass



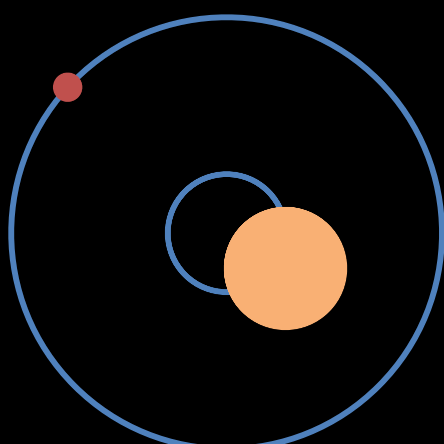
A B
C D

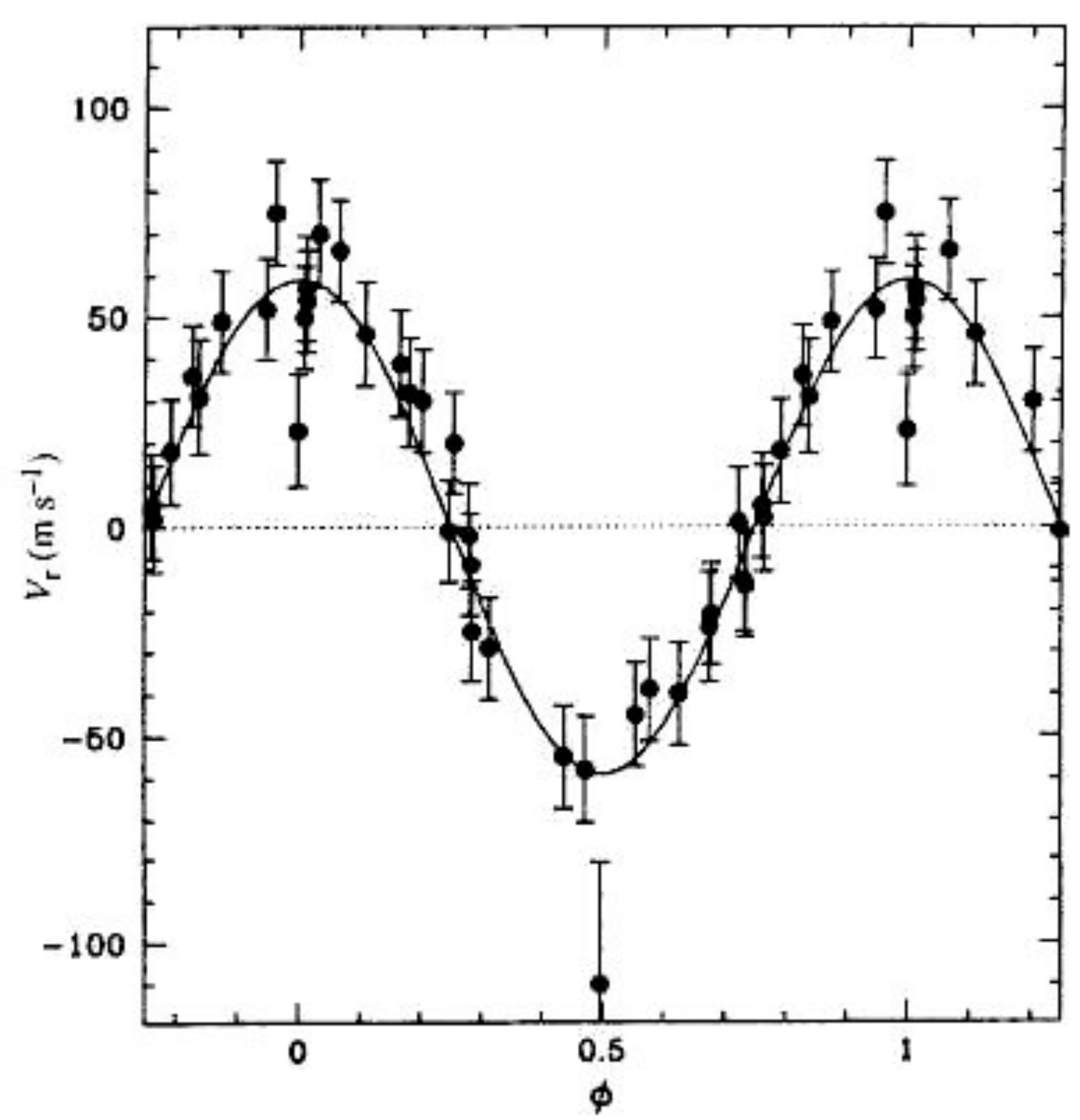
From your point of view, which orbital orientation below produced the RV variations shown in the figure?

A



B





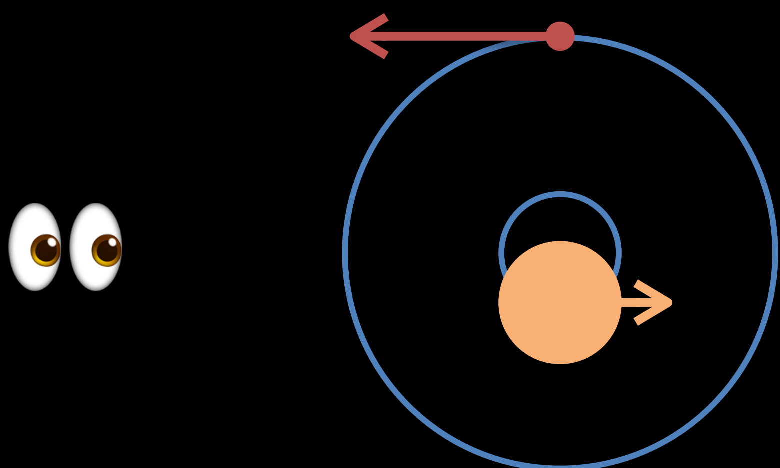
Mayor & Queloz 1995

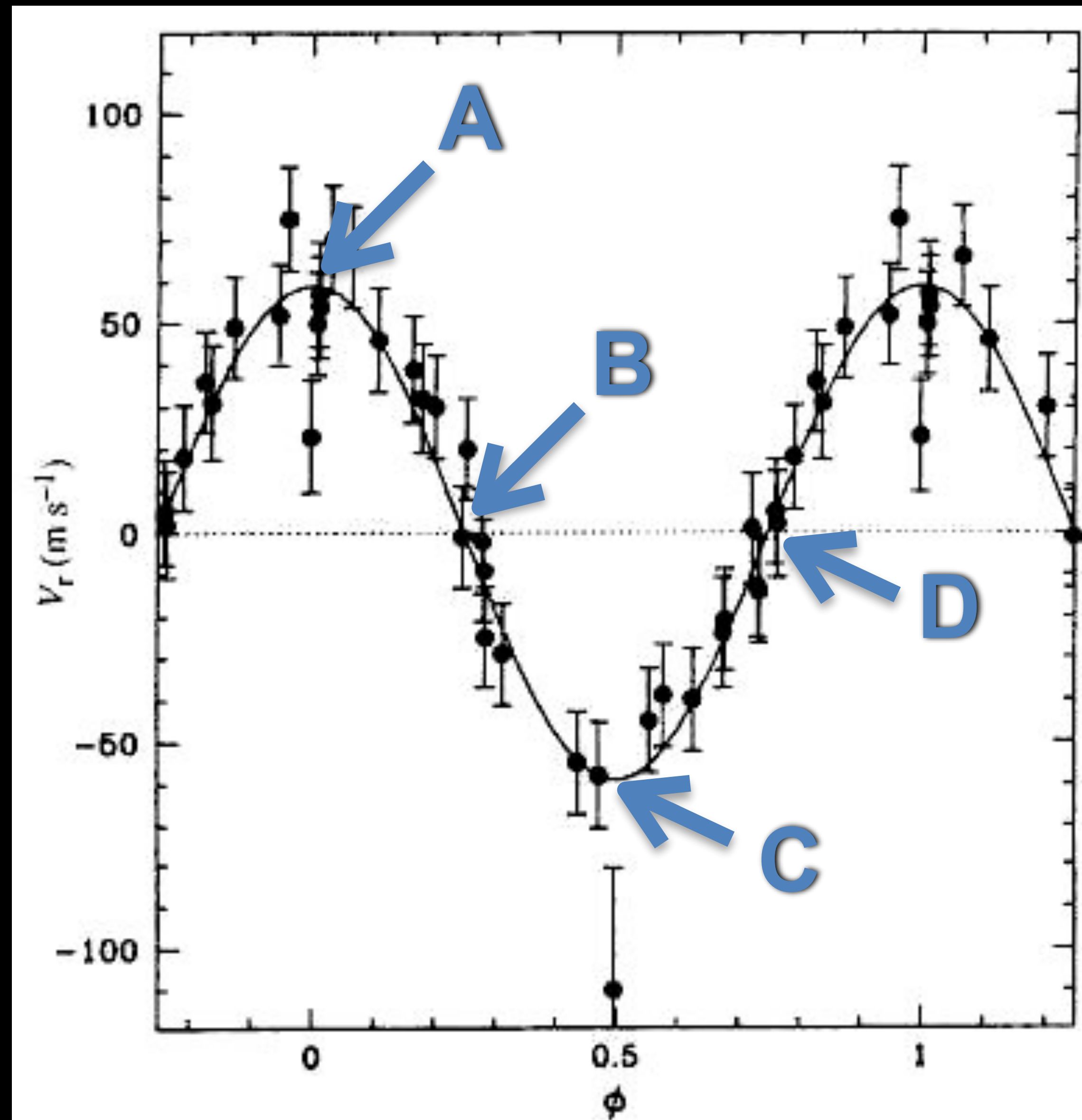
A B

C D

Where does the orbital orientation below lie on the RV curve?

(*positive v_r is defined as away from the observer)

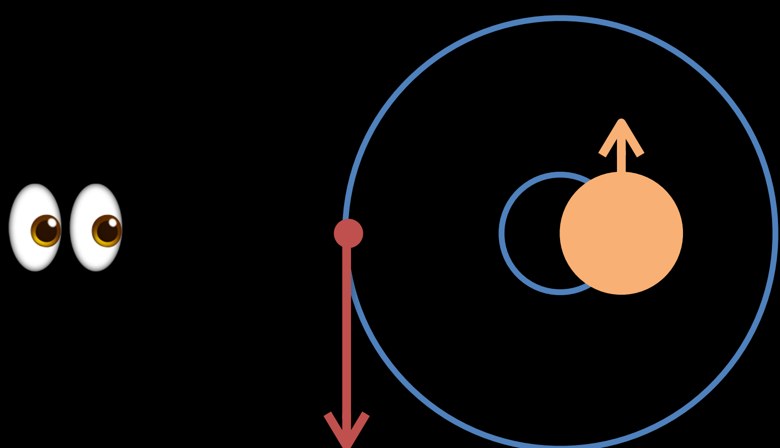


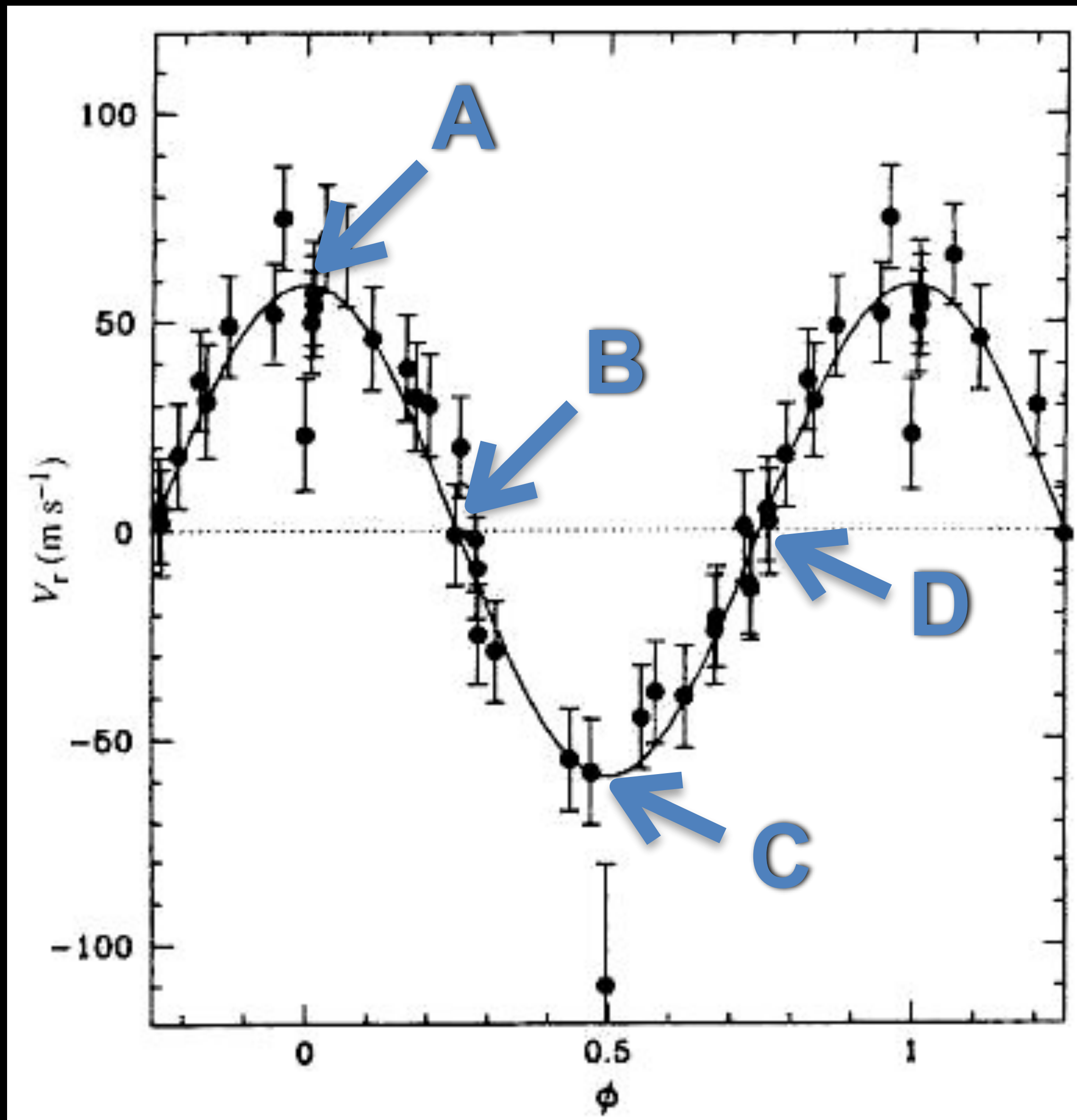


Mayor & Queloz 1995

A B
C D

Where does the orbital orientation below lie on the RV curve?
(*positive v_r is defined as away from the observer)





Mayor & Queloz 1995

Method 3 - Radial Velocity

- In class we'll derive the semi-amplitude of a RV signal *K*

$$K = M_p \left(\frac{2\pi G}{P M_\star^2} \right)^{1/3}$$

- More generally, we'll see how *K* depends on the orbital inclination *i,* such that the RV method is only sensitive an upper limit on planetary mass

$$K = M_p \sin i \left(\frac{2\pi G}{P M_\star^2} \right)^{1/3}$$

TPS Activity

Given the dependence of the RV semi-amplitude on

M_p: planet mass
i: orbital inclination
P: orbital period
$M_\star$: stellar mass

Describe the types of planets that the RV method is biased toward.

$$K = M_p \sin i \left(\frac{2\pi G}{P M_\star^2} \right)^{1/3}$$

TPS Activity

Given the dependence of the RV semi-amplitude on

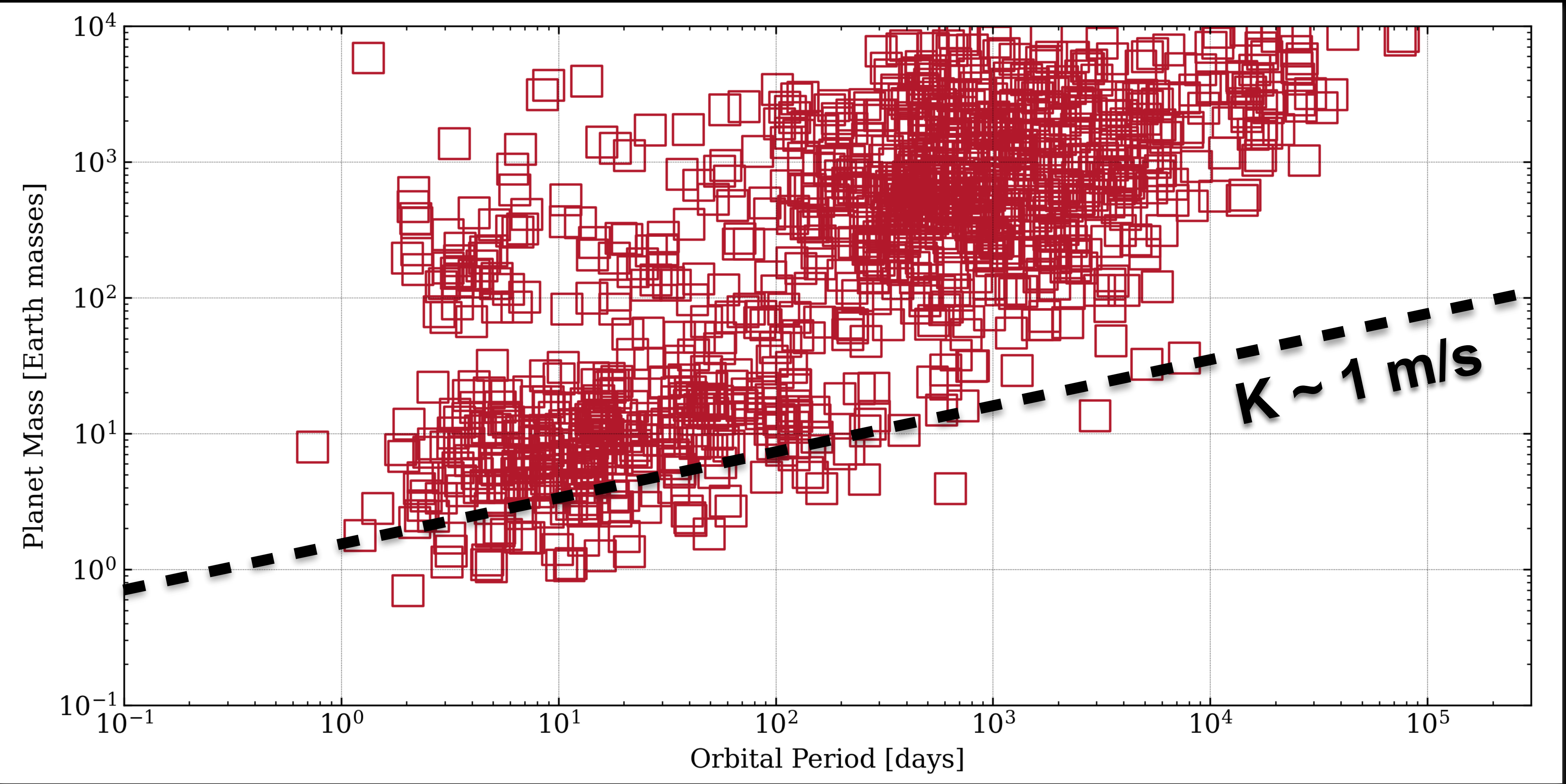
M_p: planet mass
i: orbital inclination
P: orbital period
$M_\star$: stellar mass

Describe the types of planets that the RV method is biased toward.

$$K = M_p \sin i \left(\frac{2\pi G}{P M_\star^2} \right)^{1/3}$$

Known RV Exoplanets

Mass-Period diagram



Transits + Radial Velocity

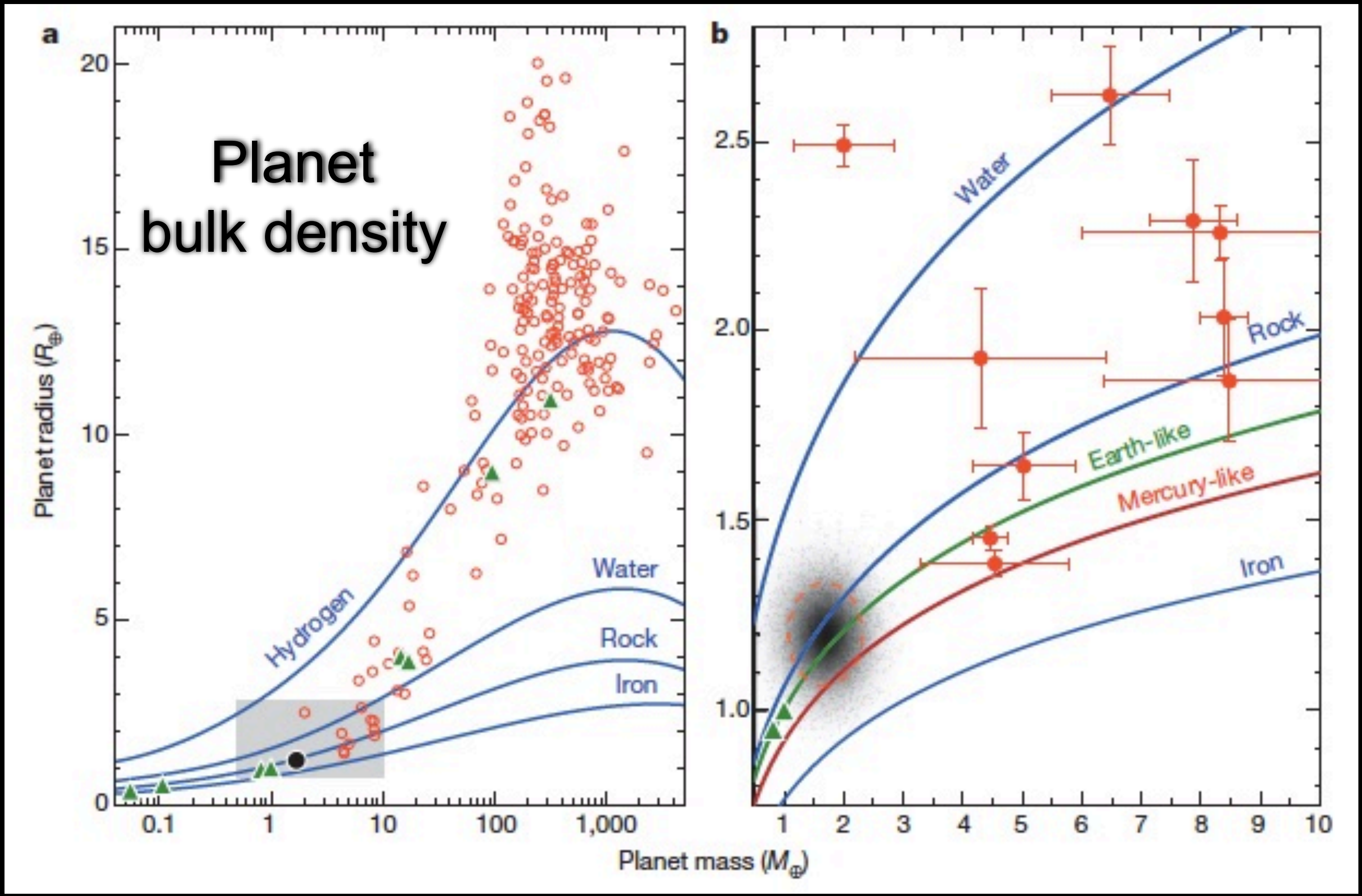
Planet Radius

Planet Mass
(*mass not minimum mass)

Transits + Radial Velocity

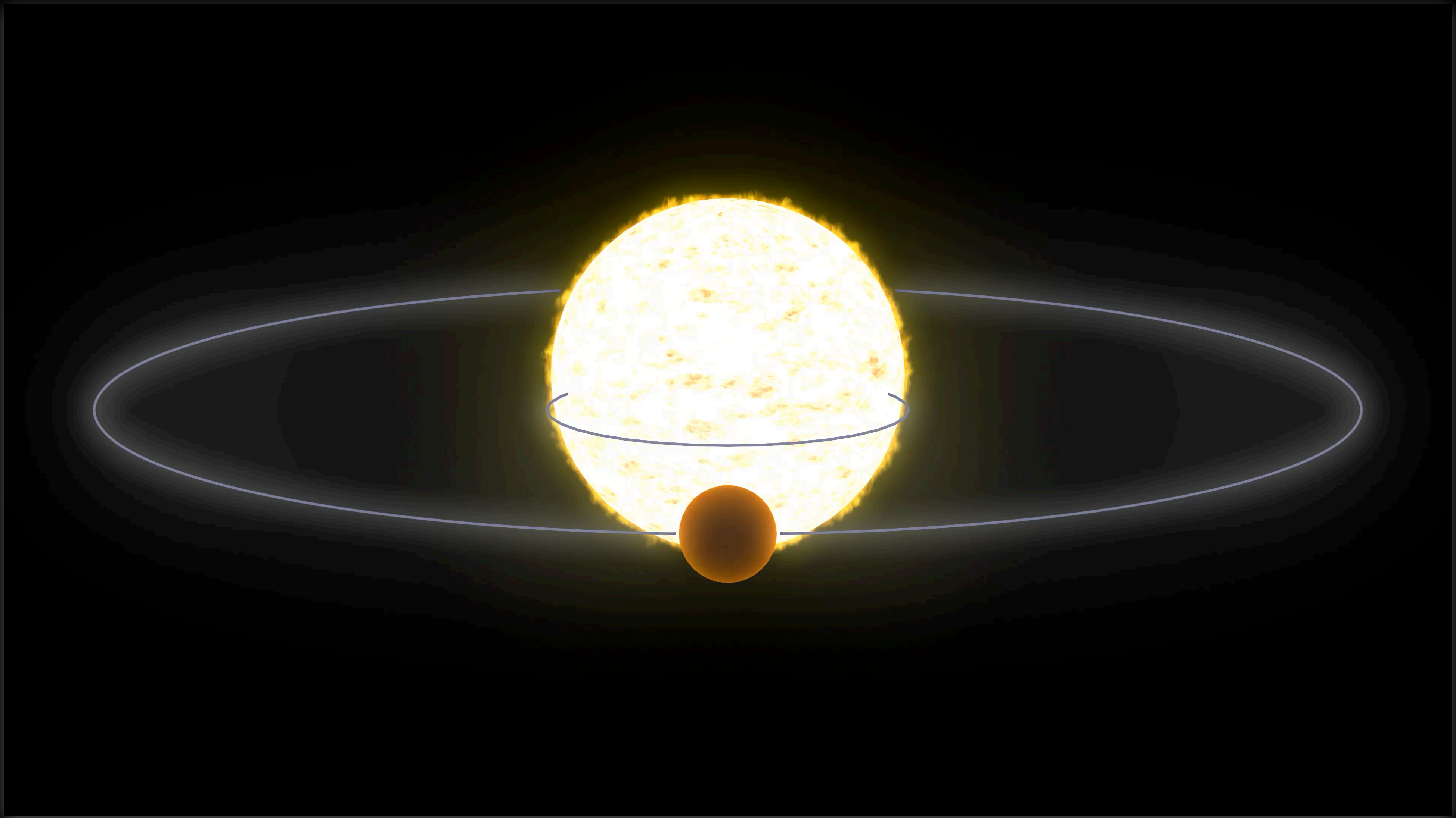
Planet Radius

Planet Mass
(*mass not minimum mass)



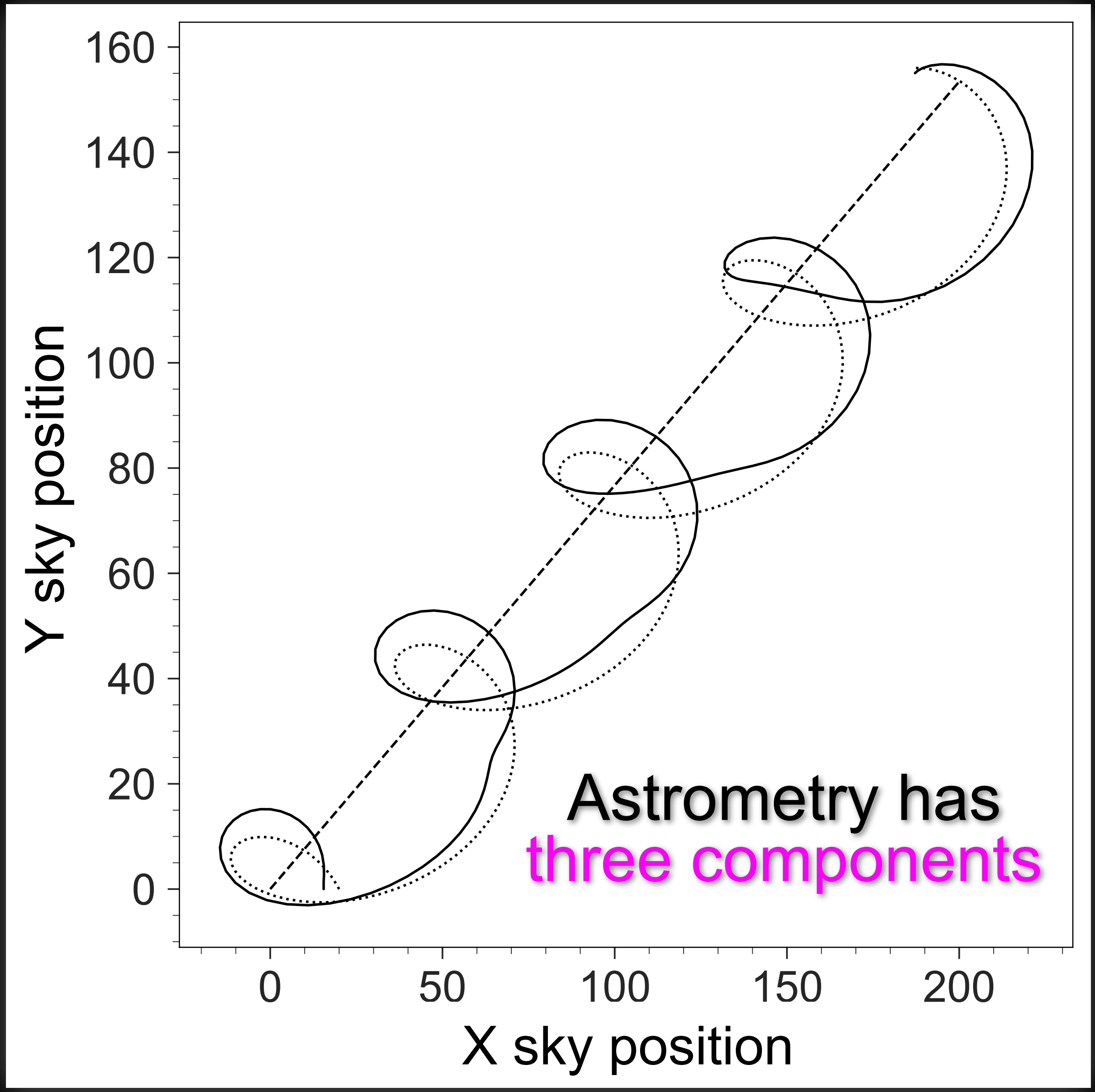
Howard et al 2013

Method 4 - Astrometry

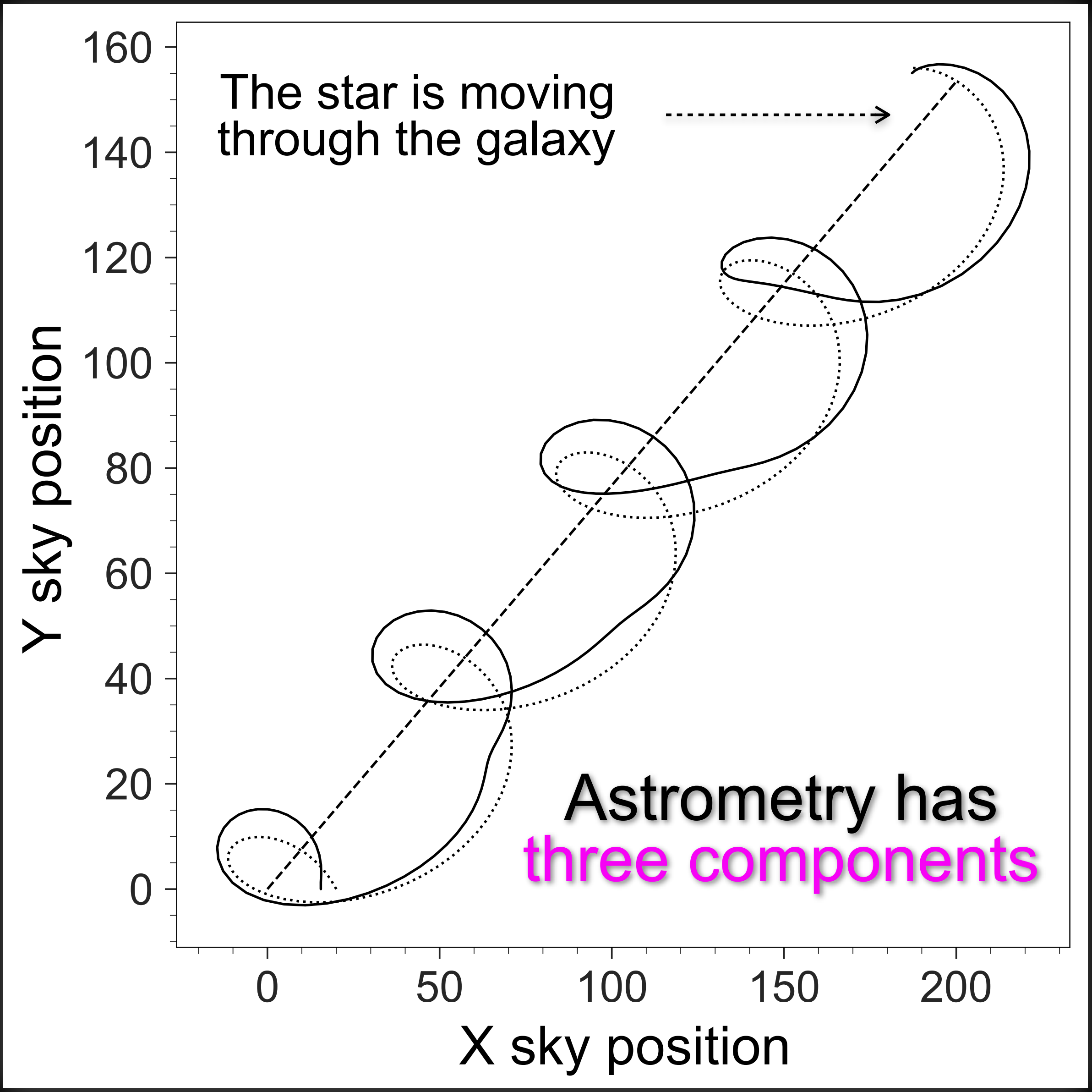


NASA/GSFC

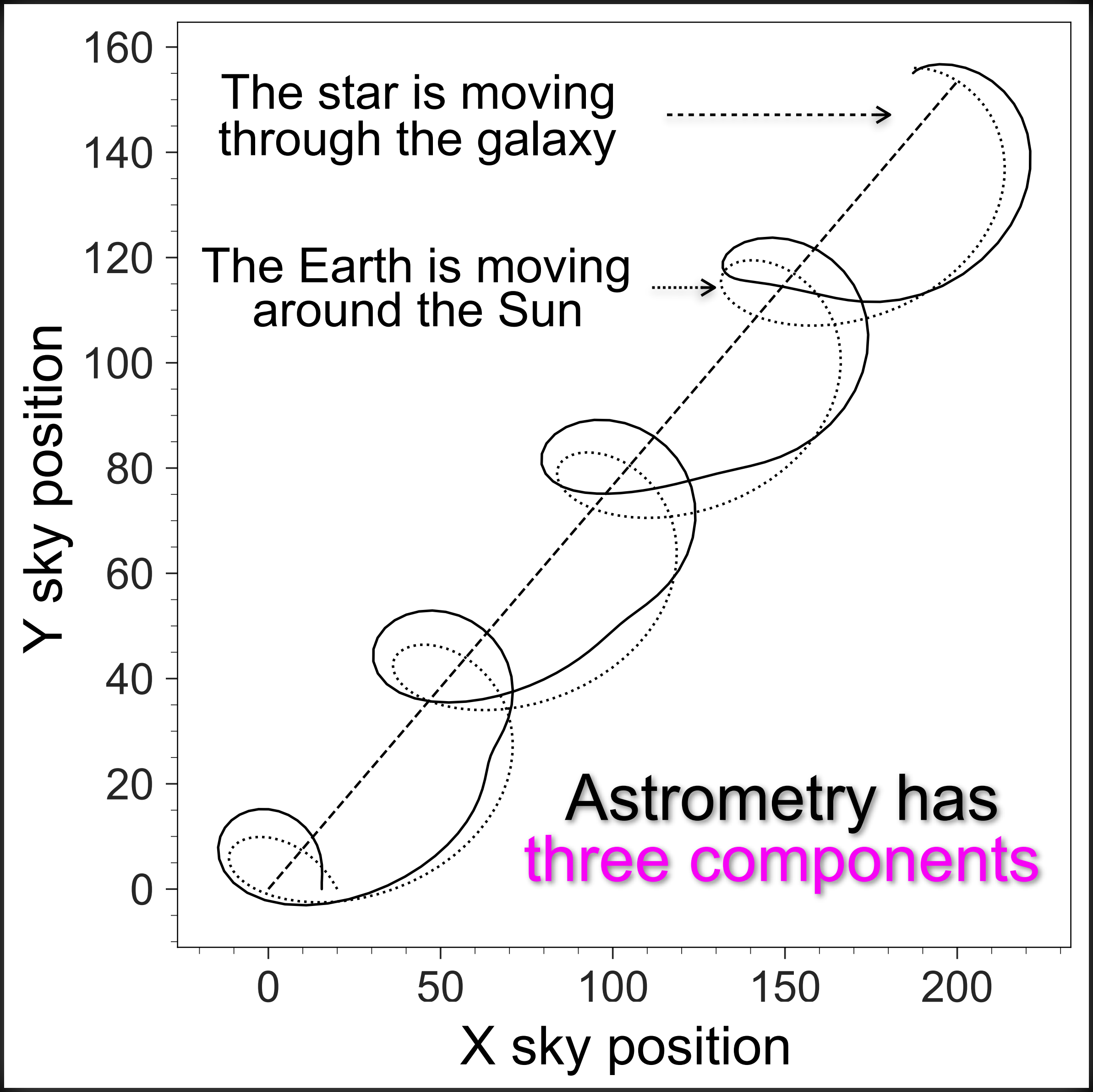
Method 4 - Astrometry



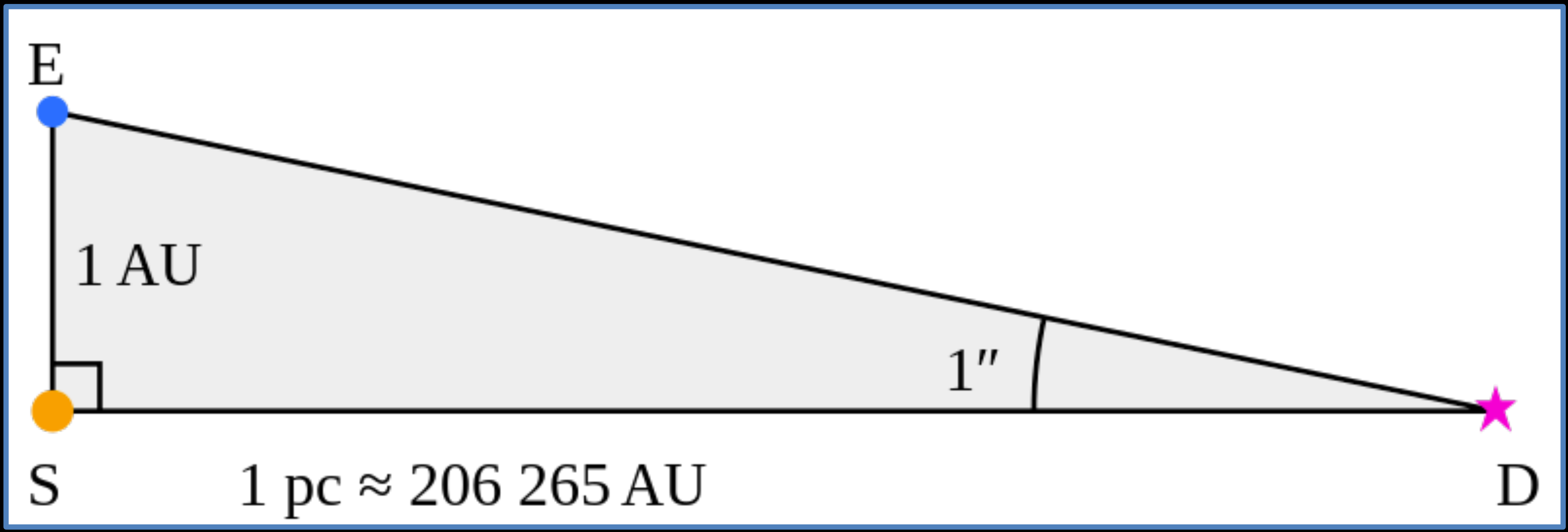
Method 4 - Astrometry



Method 4 - Astrometry



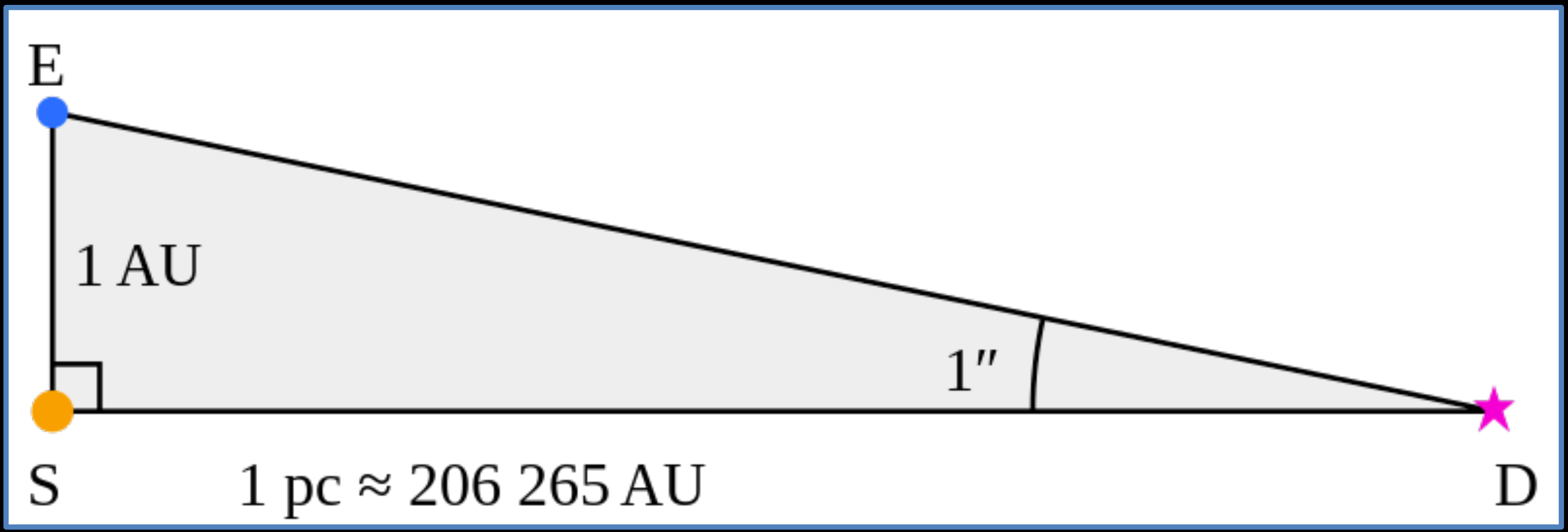
Aside - Parallax



Aside - Parallax

Astronomical Unit (AU)

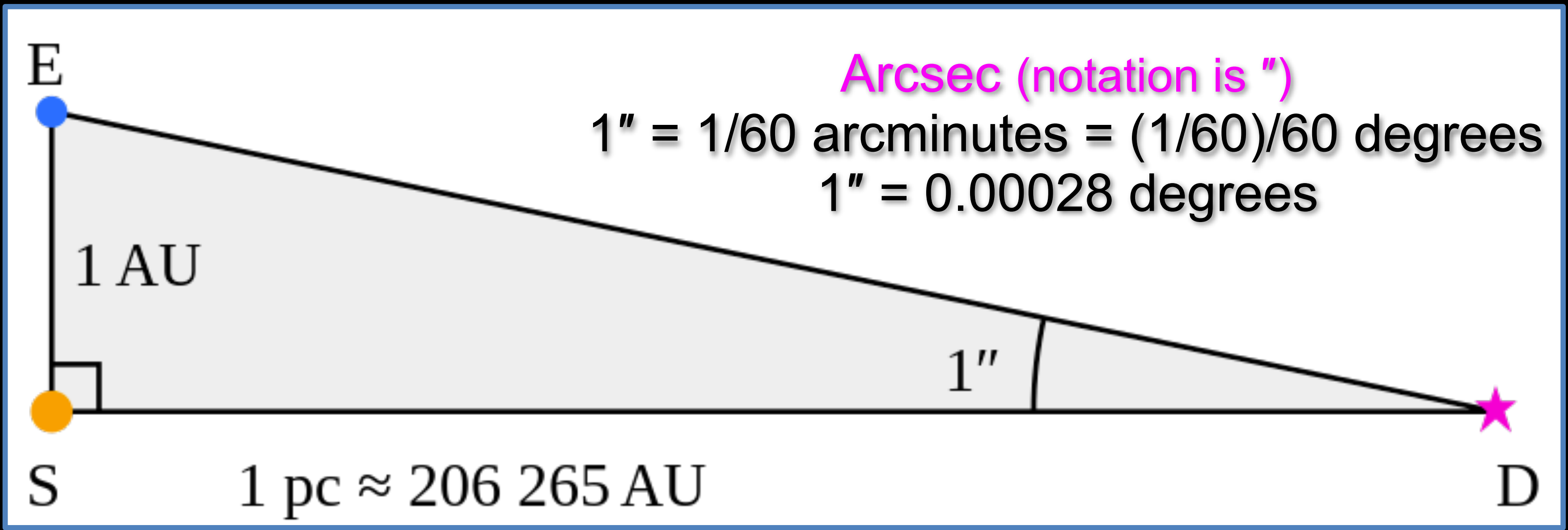
1 AU = 150 million km = average Earth-Sun distance



Aside - Parallax

Astronomical Unit (AU)

1 AU = 150 million km = average Earth-Sun distance



Arcsec (notation is ″)

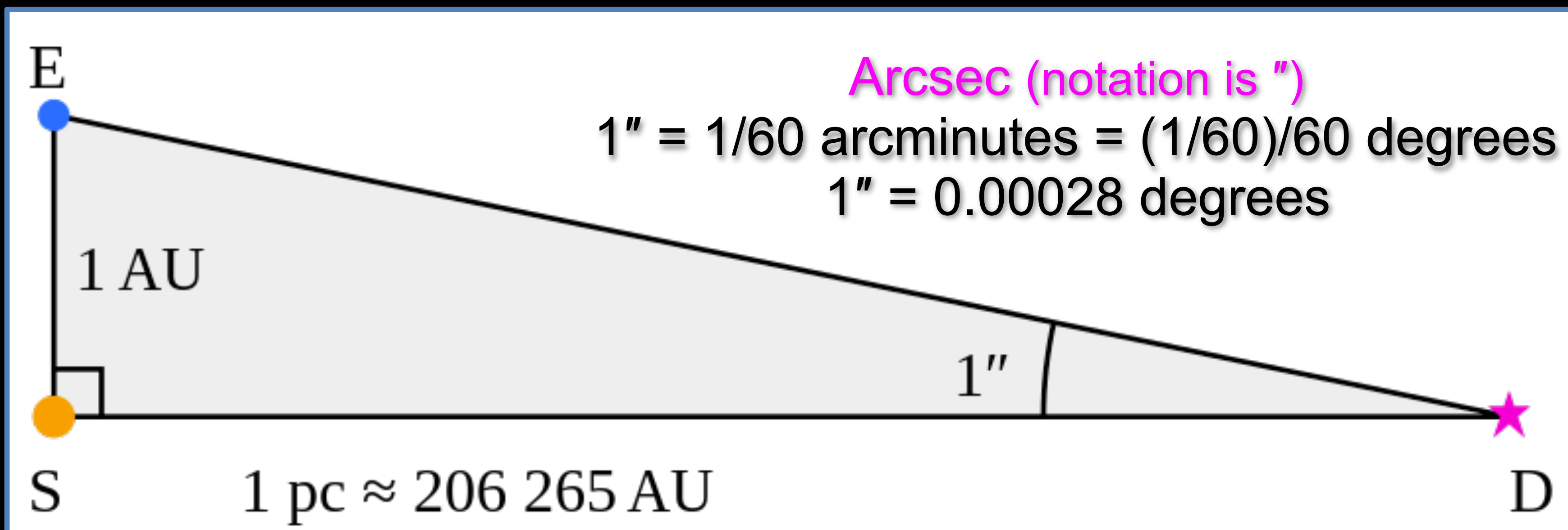
1″ = 1/60 arcminutes = (1/60)/60 degrees

1″ = 0.00028 degrees

Aside - Parallax

Astronomical Unit (AU)

1 AU = 150 million km = average Earth-Sun distance



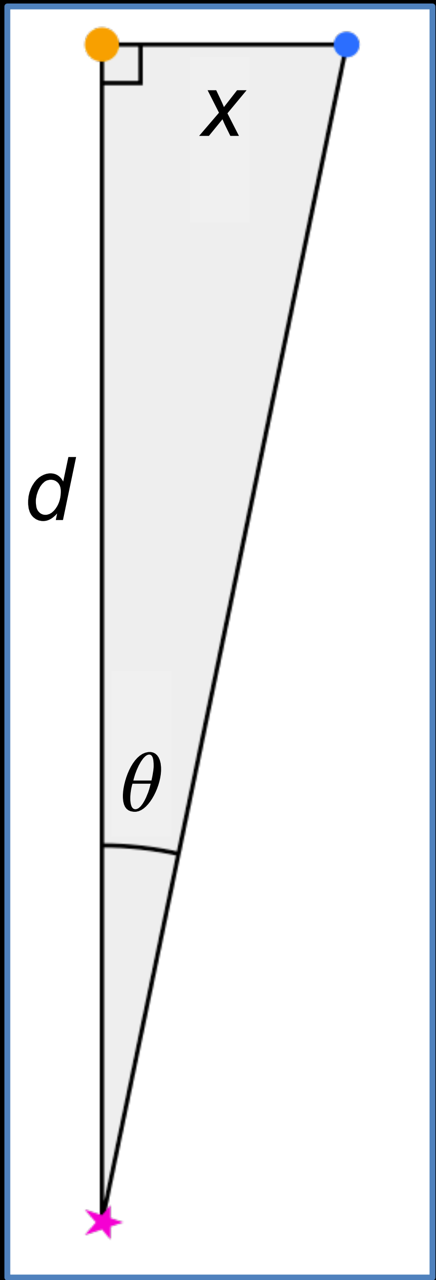
Parsec (pc)

1 pc = 1 AU / 1″

Aside - Parallax

General Expression:

- Consider a star-planet system located at a distance d from us



Aside - Parallax

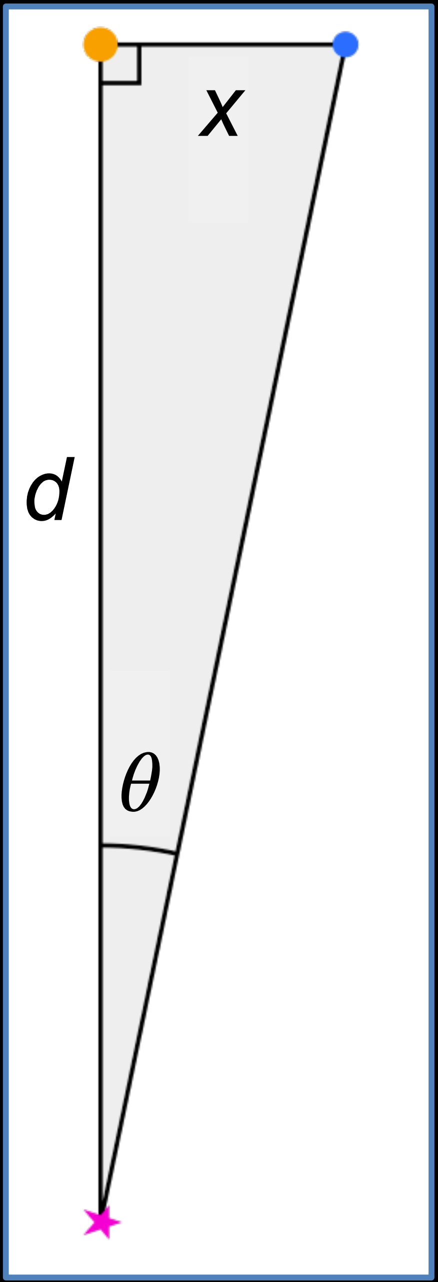
General Expression:

- Consider a star-planet system located at a distance d from us
- Measuring an angular separation θ gives the star-planet separation x

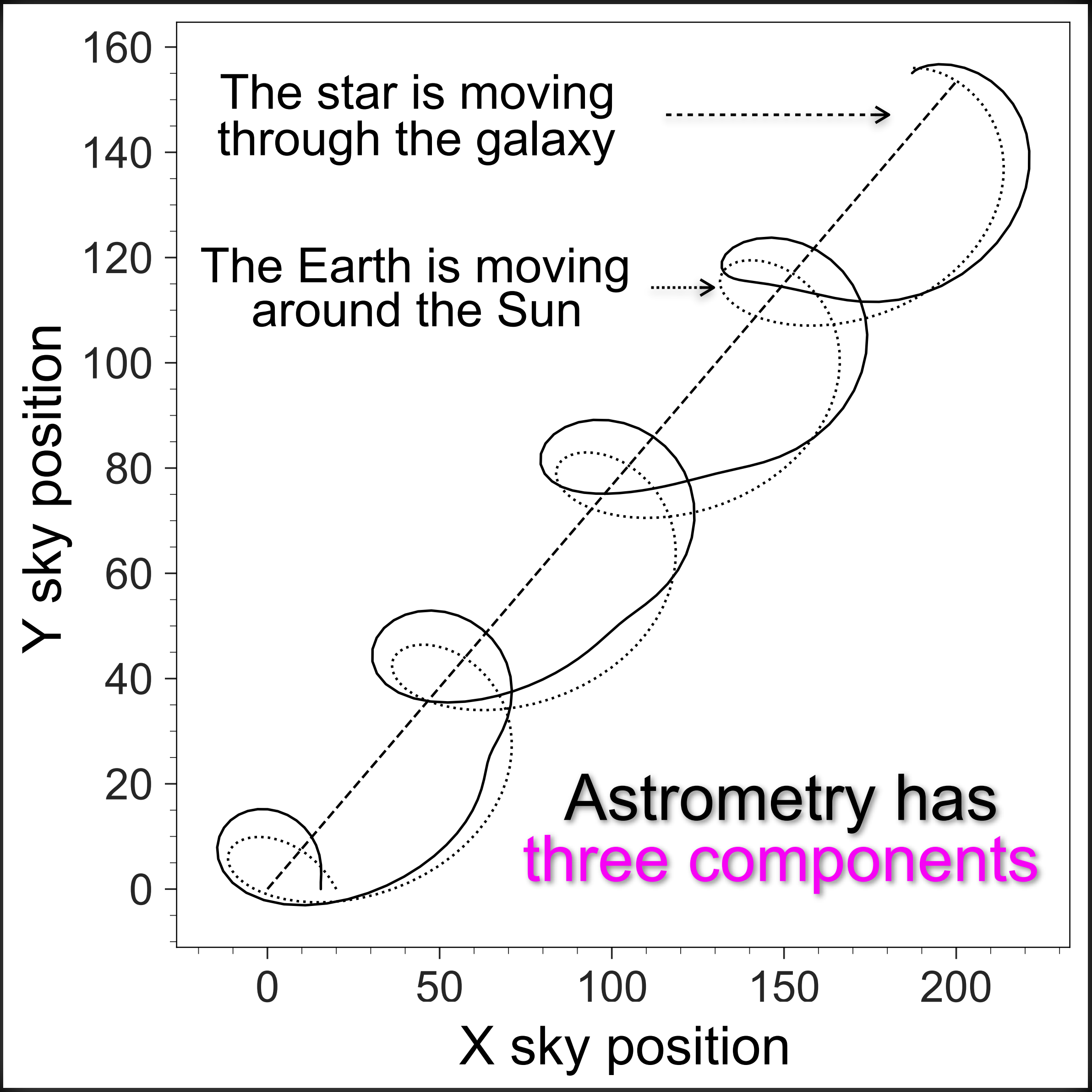
$$x = d\,\theta$$

$$= 1\,\mathrm{AU}\left(\frac{d}{1\,\mathrm{pc}}\right)\left(\frac{\theta}{1''}\right)$$

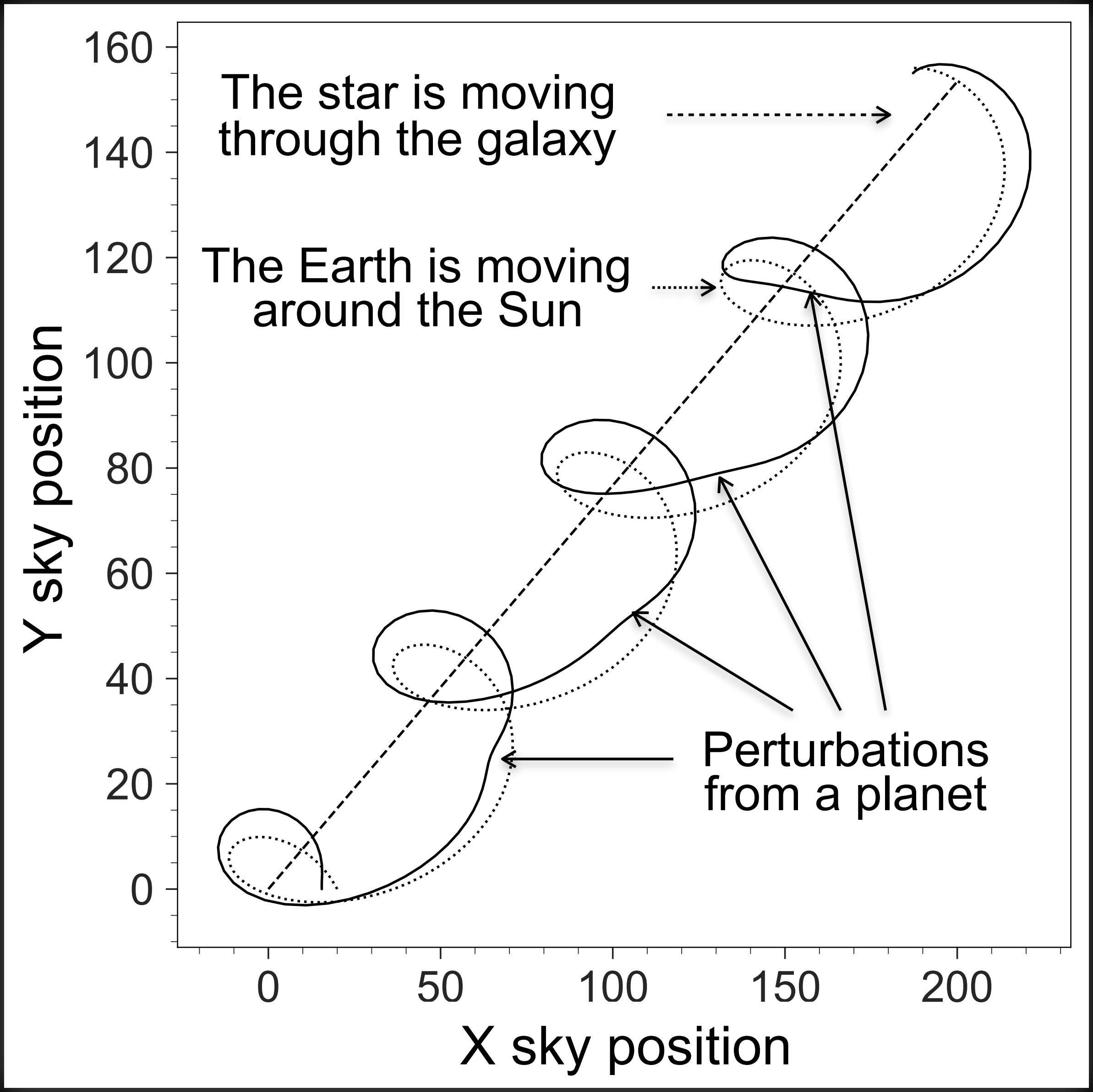
Note the units!



Method 4 - Astrometry



Method 4 - Astrometry

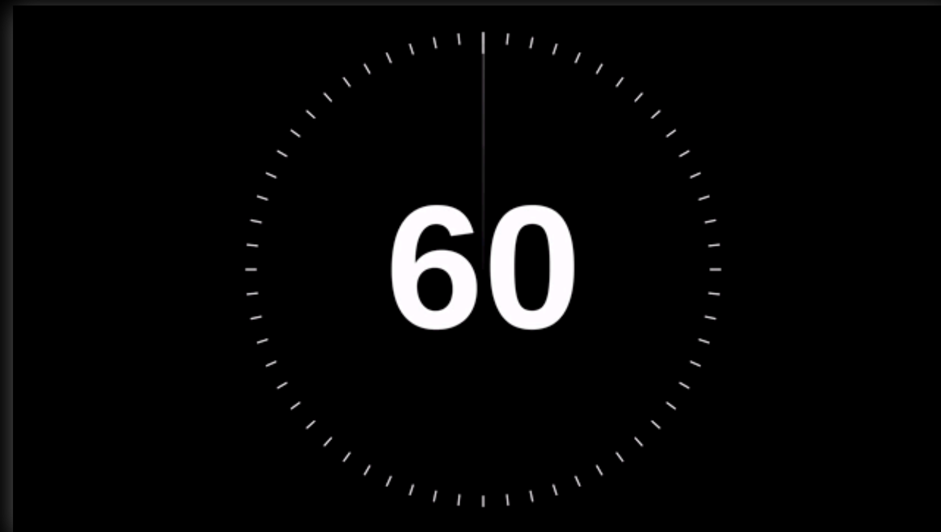


Method 4 - Astrometry

- In class we'll derive the astrometric signal amplitude $\Delta\theta$

$$\Delta\theta = \frac{M_p}{d}\left(\frac{GP^2}{4\pi^2 M_\star^2}\right)^{1/3}$$

TPS Activity



Given the dependence of the astrometric signal amplitude on

M_p: planet mass
d: distance
P: orbital period
$M_\star$: stellar mass

Describe the types of planets that the astrometry method is biased toward.

$$\Delta\theta = \frac{M_p}{d}\left(\frac{GP^2}{4\pi^2 M_\star^2}\right)^{1/3}$$

TPS Activity

Given the dependence of the **astrometric signal amplitude** on

M_p: planet mass

d: distance

P: orbital period

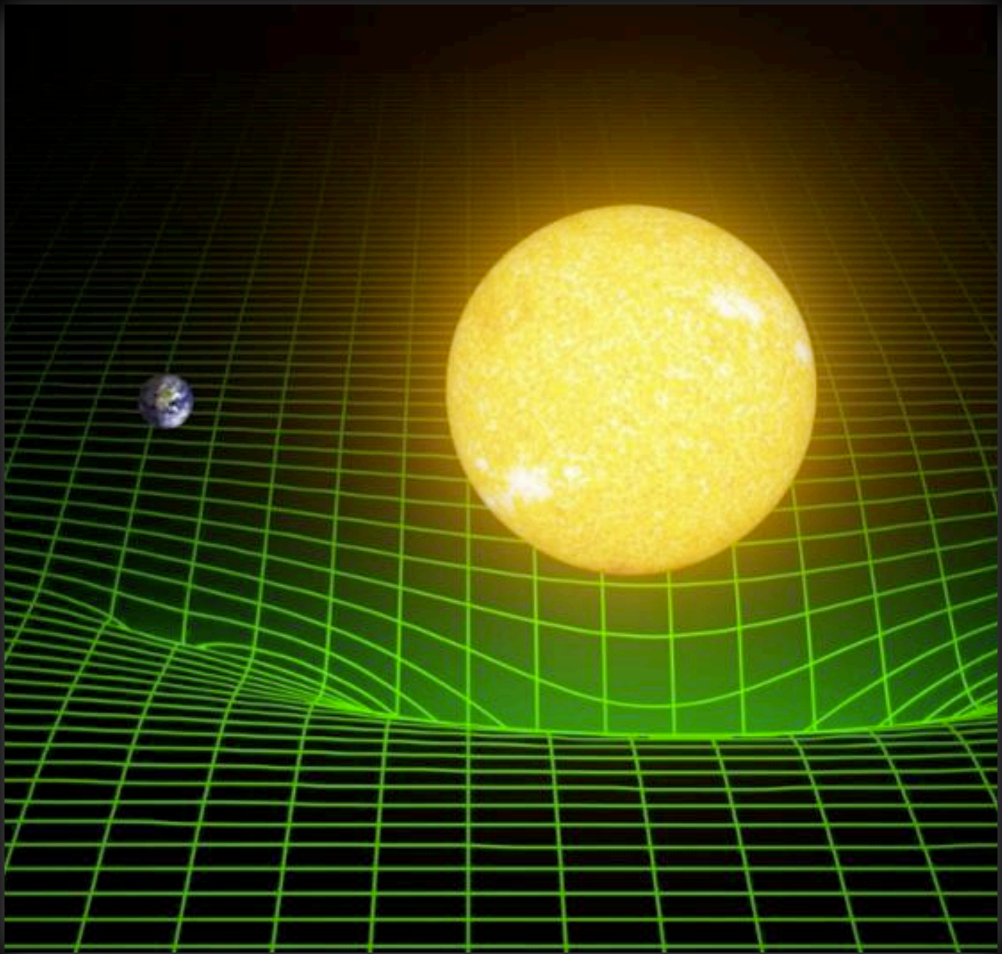
$M_\star$: stellar mass

Describe the types of planets that the astrometry method is biased toward.

$$\Delta\theta = \frac{M_p}{d}\left(\frac{GP^2}{4\pi^2 M_\star^2}\right)^{1/3}$$

Method 5 - Gravitational Microlensing

Mass bends spacetime



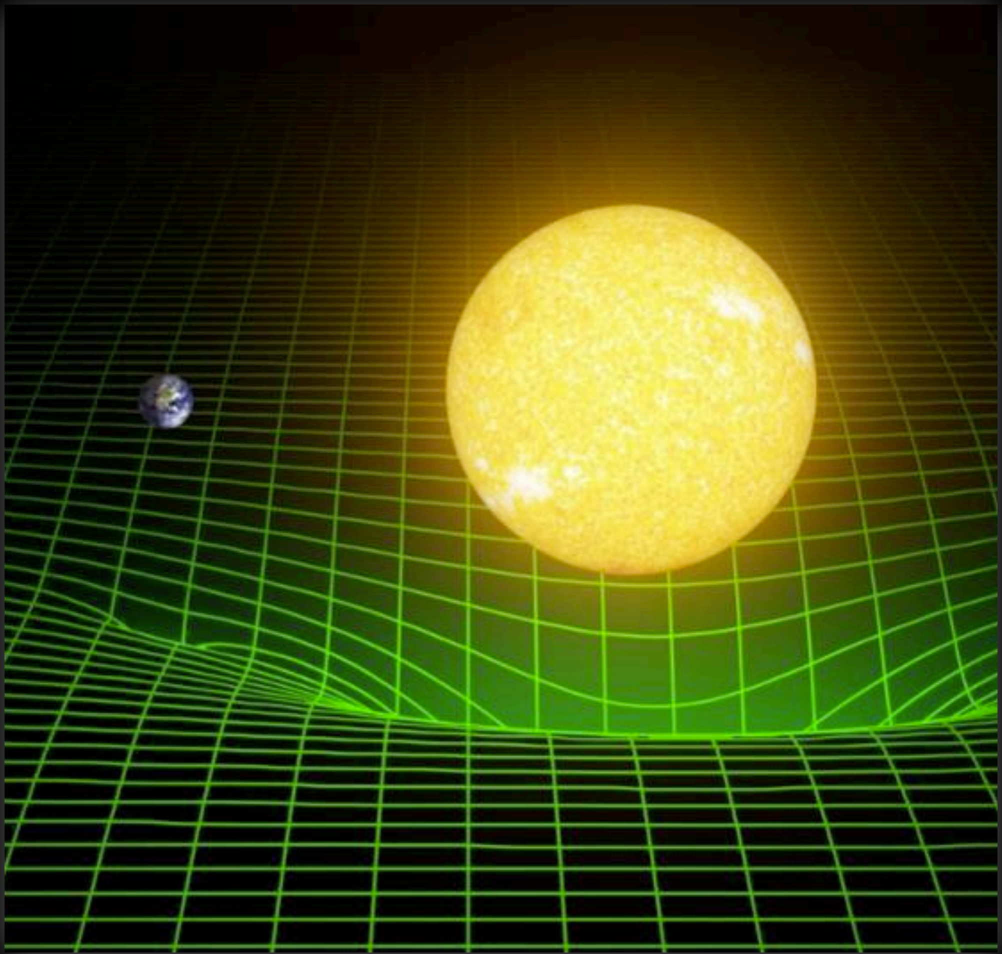
LIGO Lab

Method 5 - Gravitational Microlensing

Mass bends spacetime

↧

Light rays are bent by a curved spacetime



LIGO Lab

Method 5 - Gravitational Microlensing

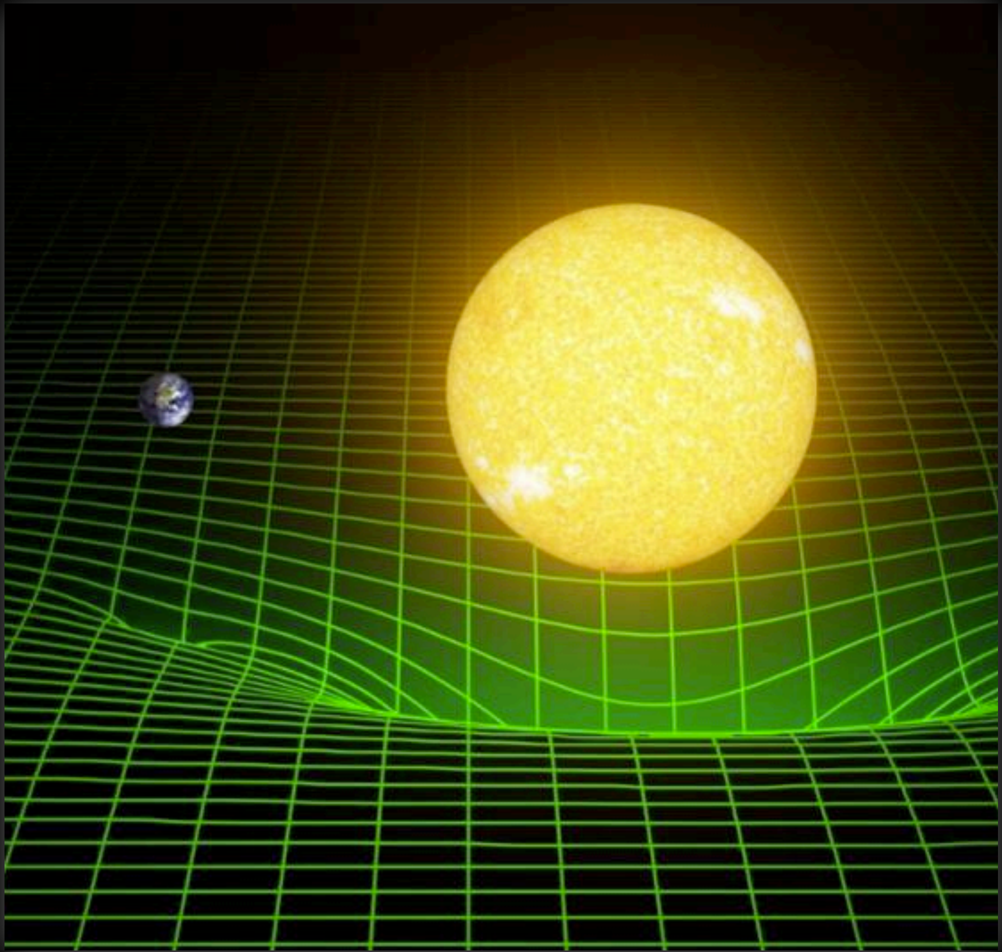
Mass bends spacetime

↧

Light rays are bent by a curved spacetime

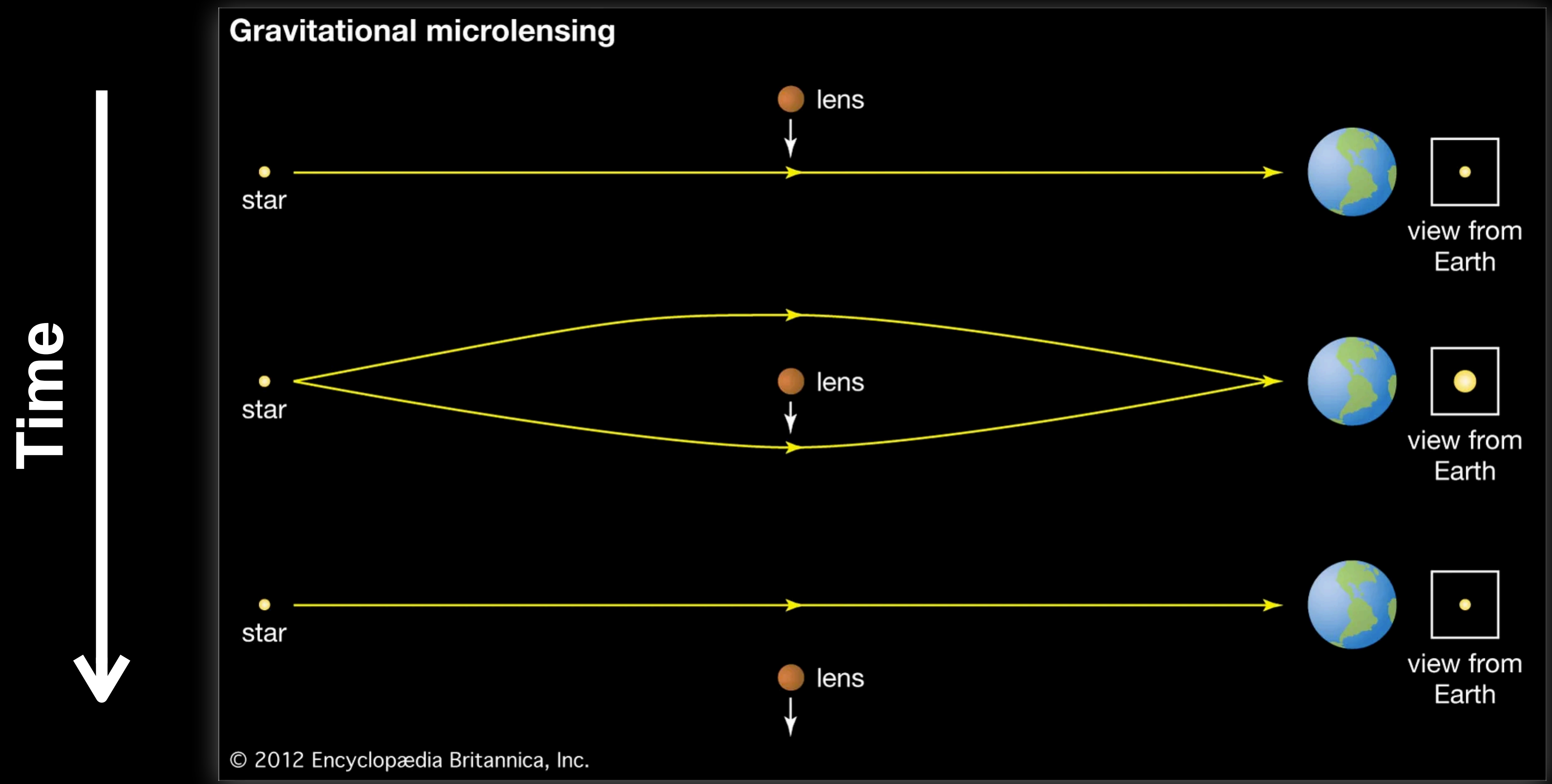
↧

Massive objects act as a gravitational lens



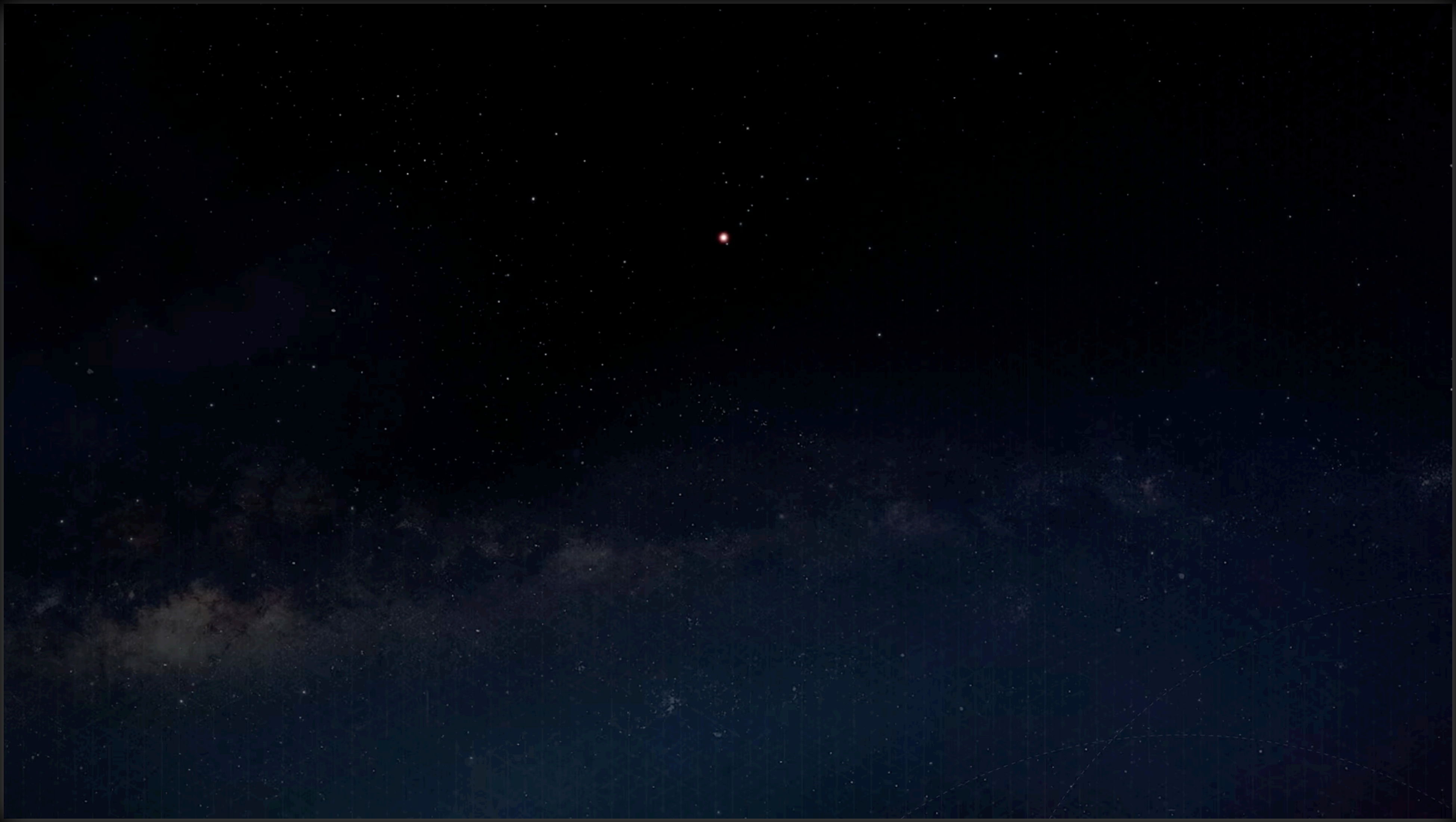
LIGO Lab

Method 5 - Gravitational Microlensing



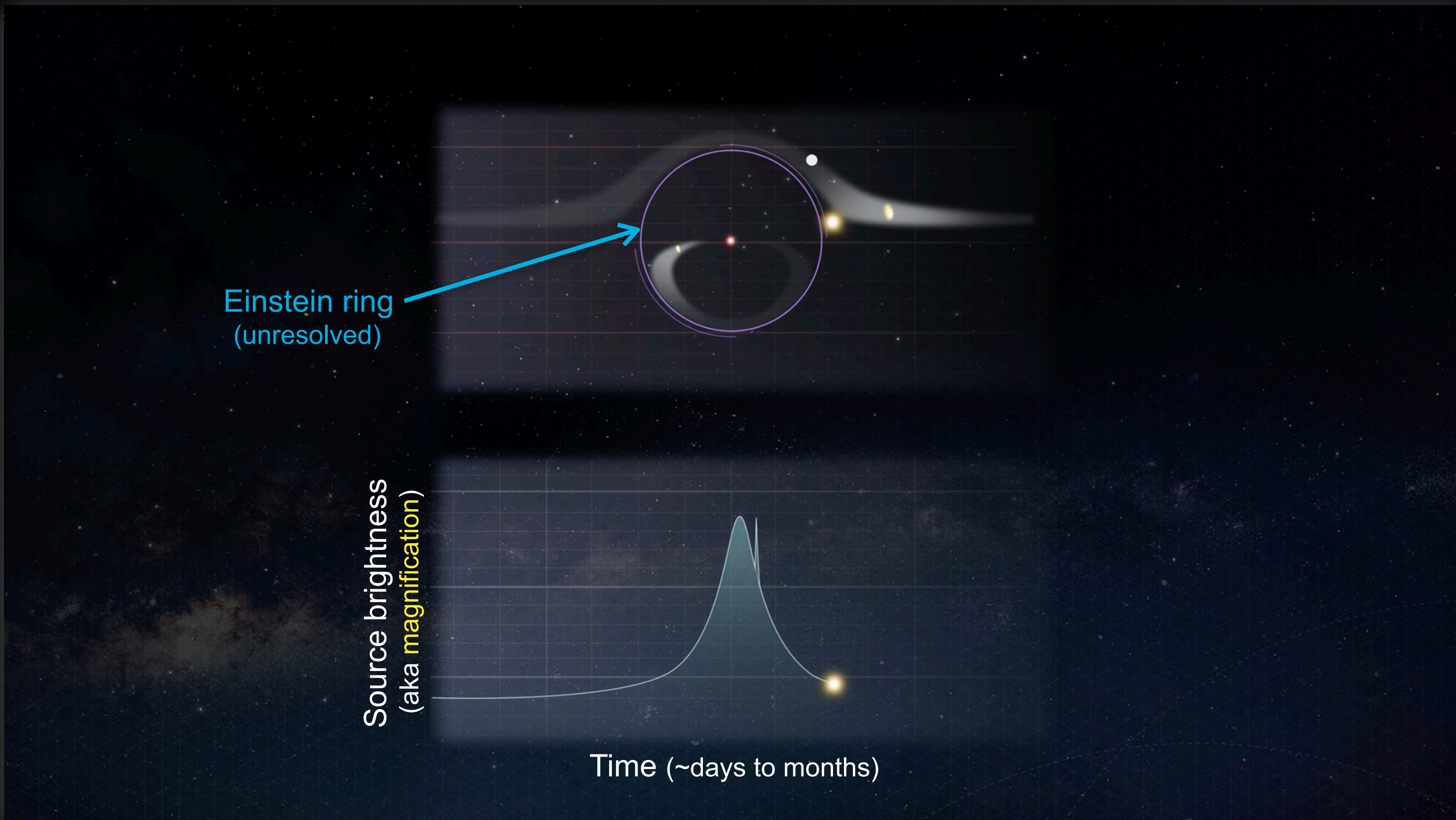
Encyclopedia Britannica

Method 5 - Gravitational Microlensing



NASA/CI Lab

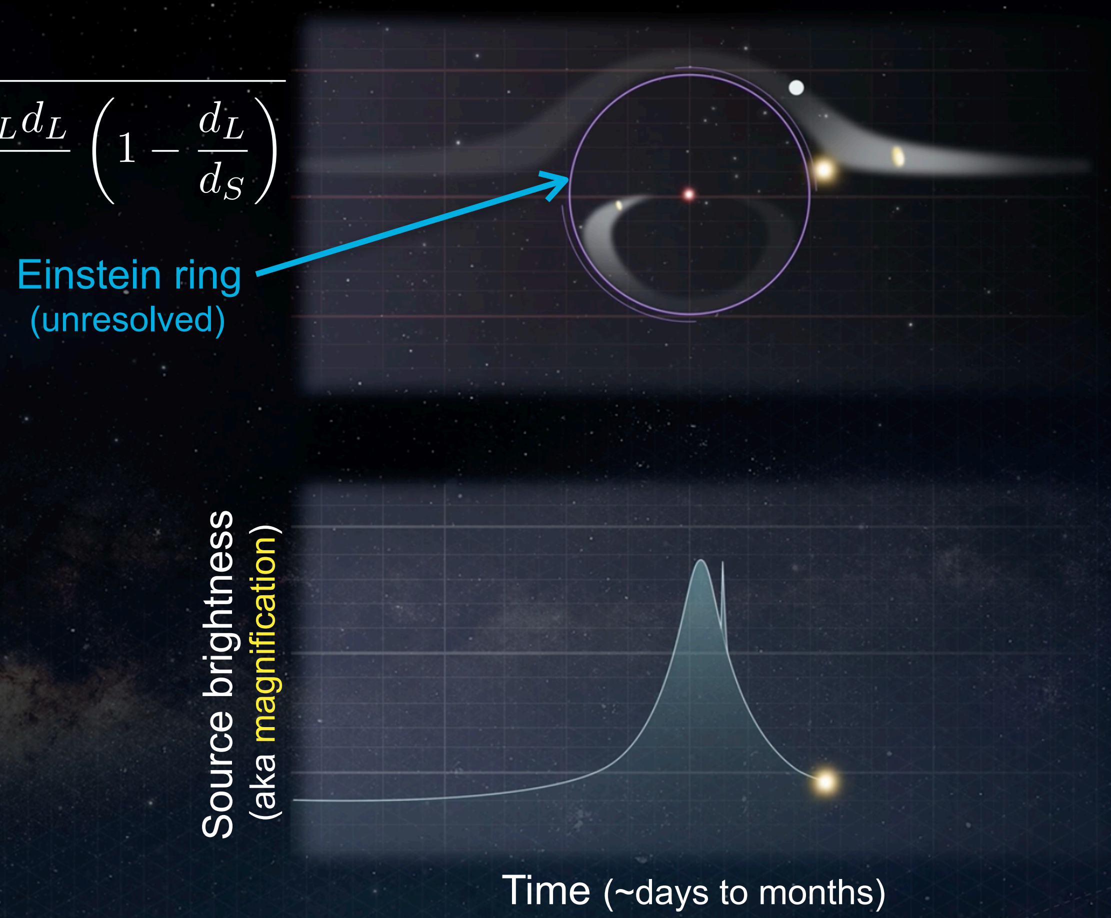
Method 5 - Gravitational Microlensing



NASA/CI Lab

Method 5 - Gravitational Microlensing

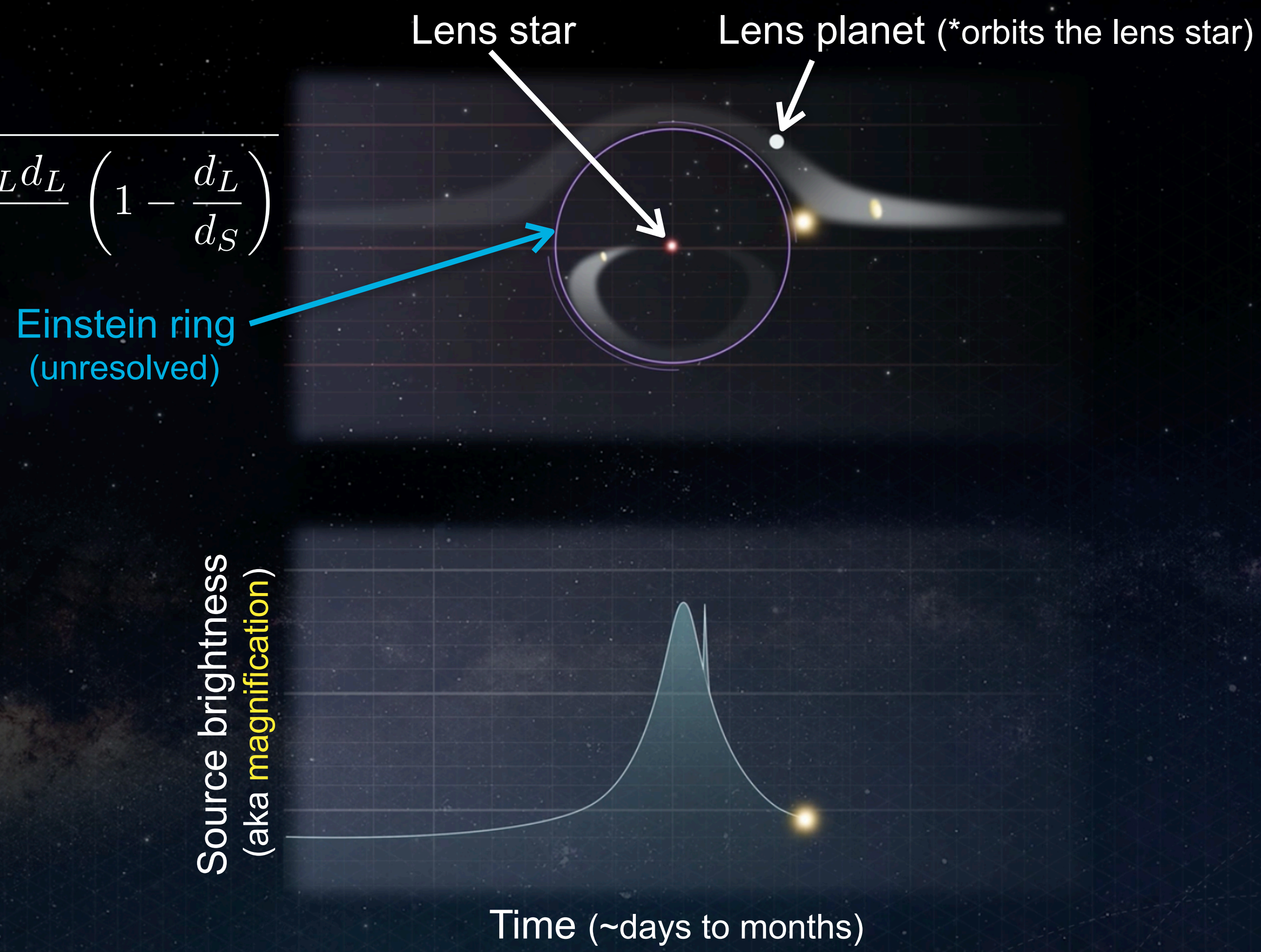
$$\theta_E = \sqrt{\frac{4GM_L d_L}{c^2}\left(1 - \frac{d_L}{d_S}\right)}$$



NASA/CI Lab

Method 5 - Gravitational Microlensing

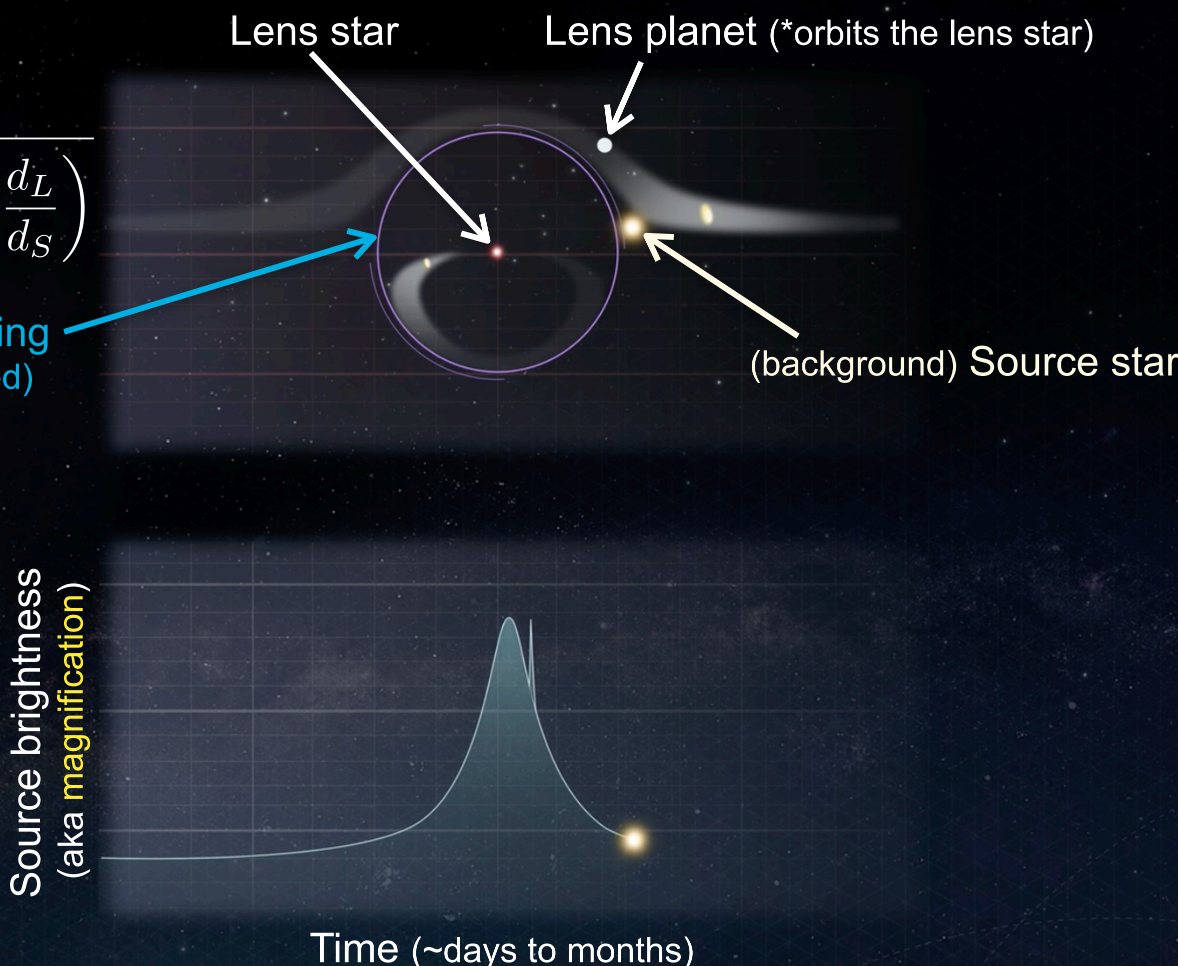
$$\theta_E = \sqrt{\frac{4GM_L d_L}{c^2}\left(1 - \frac{d_L}{d_S}\right)}$$



NASA/CI Lab

Method 5 - Gravitational Microlensing

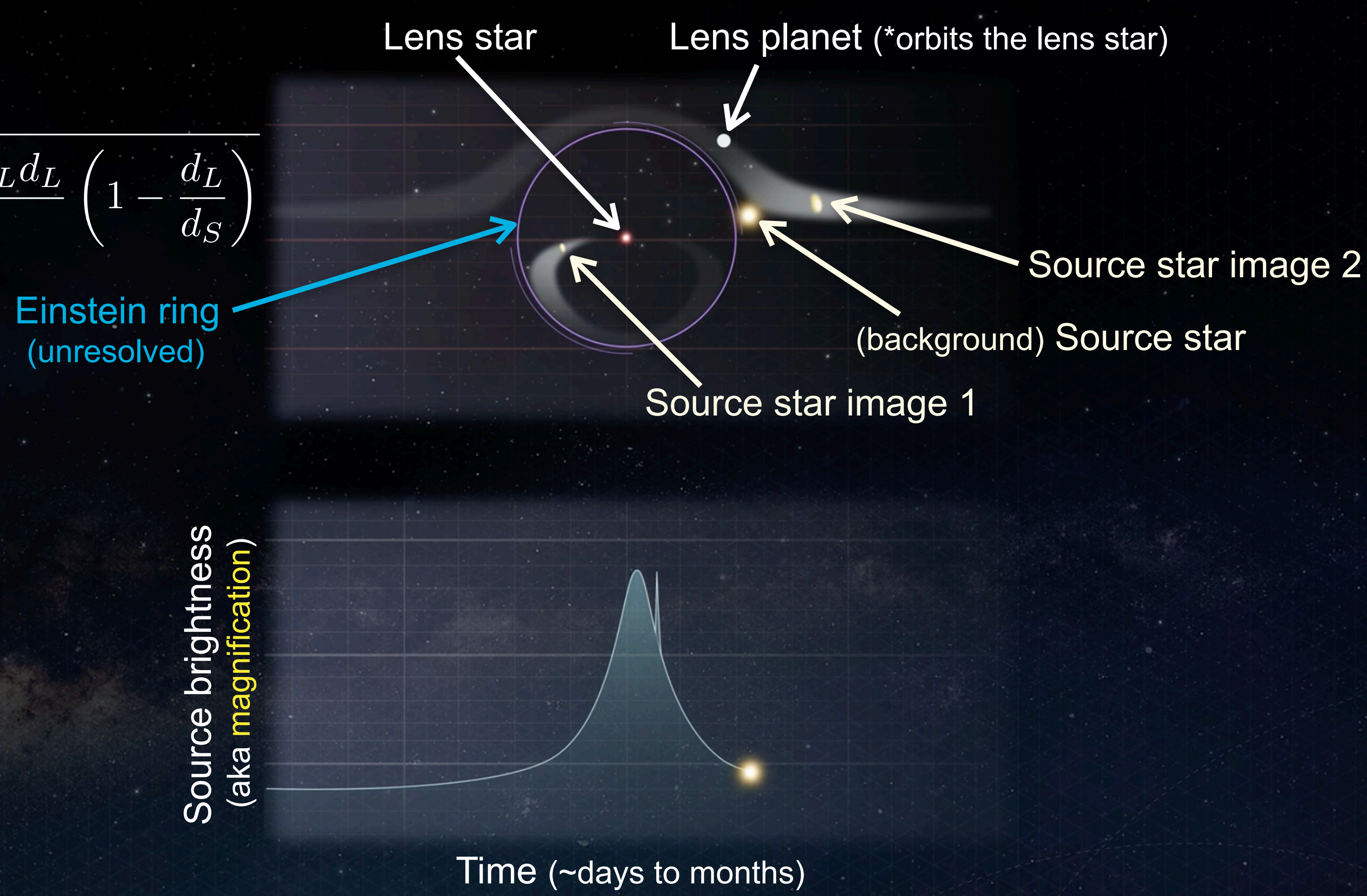
$$\theta_E = \sqrt{\frac{4GM_L d_L}{c^2}\left(1 - \frac{d_L}{d_S}\right)}$$



NASA/CI Lab

Method 5 - Gravitational Microlensing

$$\theta_E = \sqrt{\frac{4GM_L d_L}{c^2}\left(1 - \frac{d_L}{d_S}\right)}$$

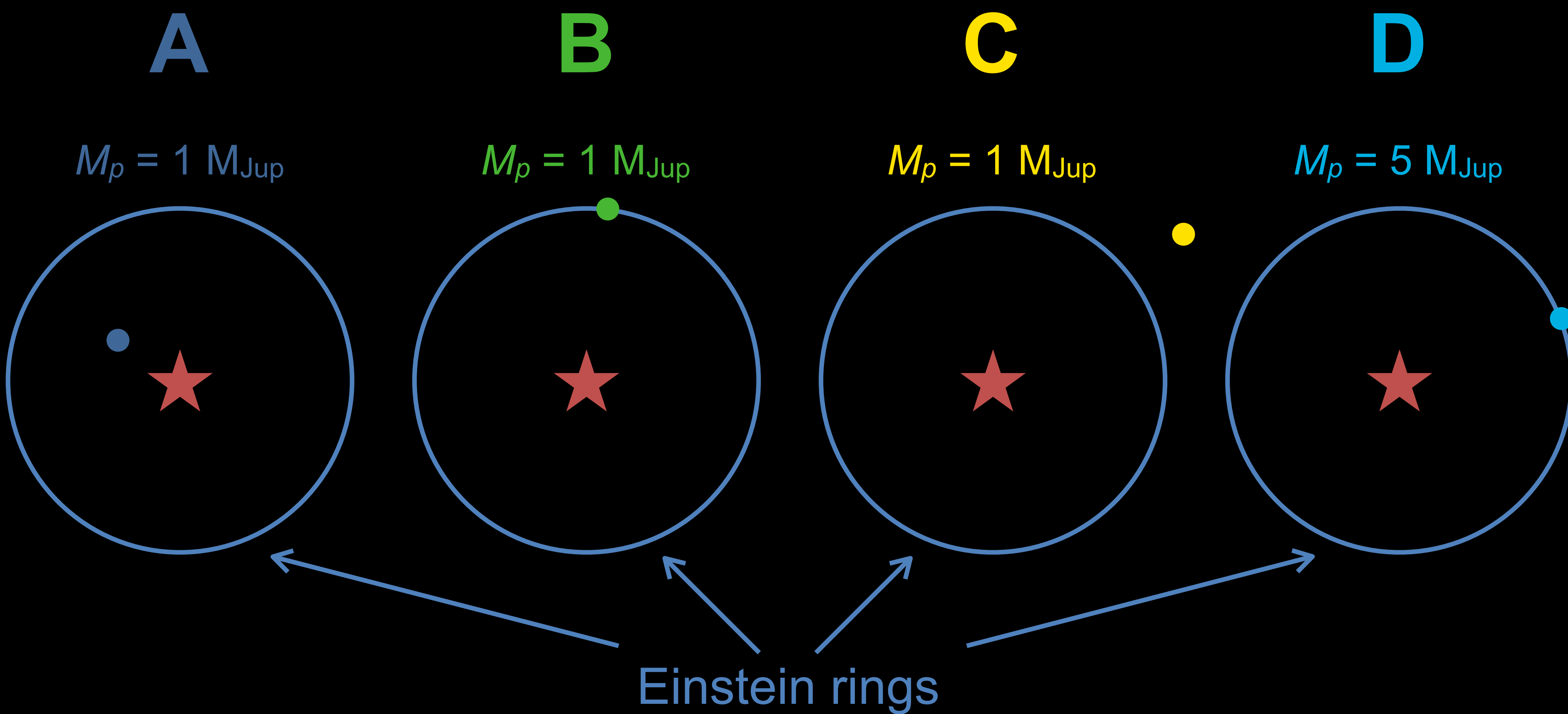


NASA/CI Lab

A B

C D

Rank the four planets below in order of detectability with gravitational microlensing.



TPS Activity
(with some math!)

Consider a microlensed planetary system located at a distance of

$d = 6000$ pc

and whose Einstein ring radius is

$\theta_E = 0.0005''$ (recall that $''$ means arcseconds)

TPS Activity
(with some math!)

Consider a microlensed planetary system located at a distance of

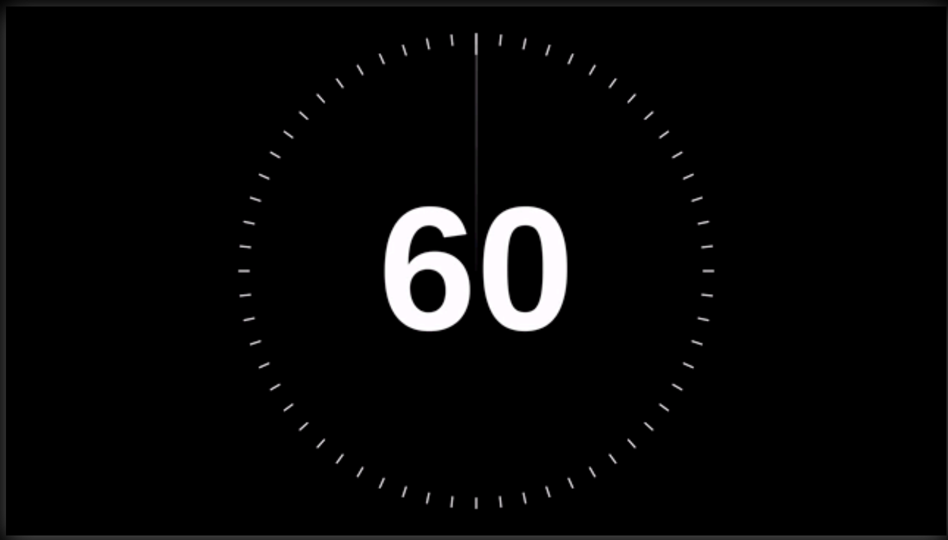
$d = 6000$ pc

and whose Einstein ring radius is

$\theta_E = 0.0005''$ (recall that ″ means arcseconds)

What is the planet's orbital distance around its host star?

(just consider what expression to use for now, no numbers yet!)



TPS Activity
(with some math!)

Consider a microlensed planetary system located at a distance of

$d = 6000$ pc

and whose Einstein ring radius is

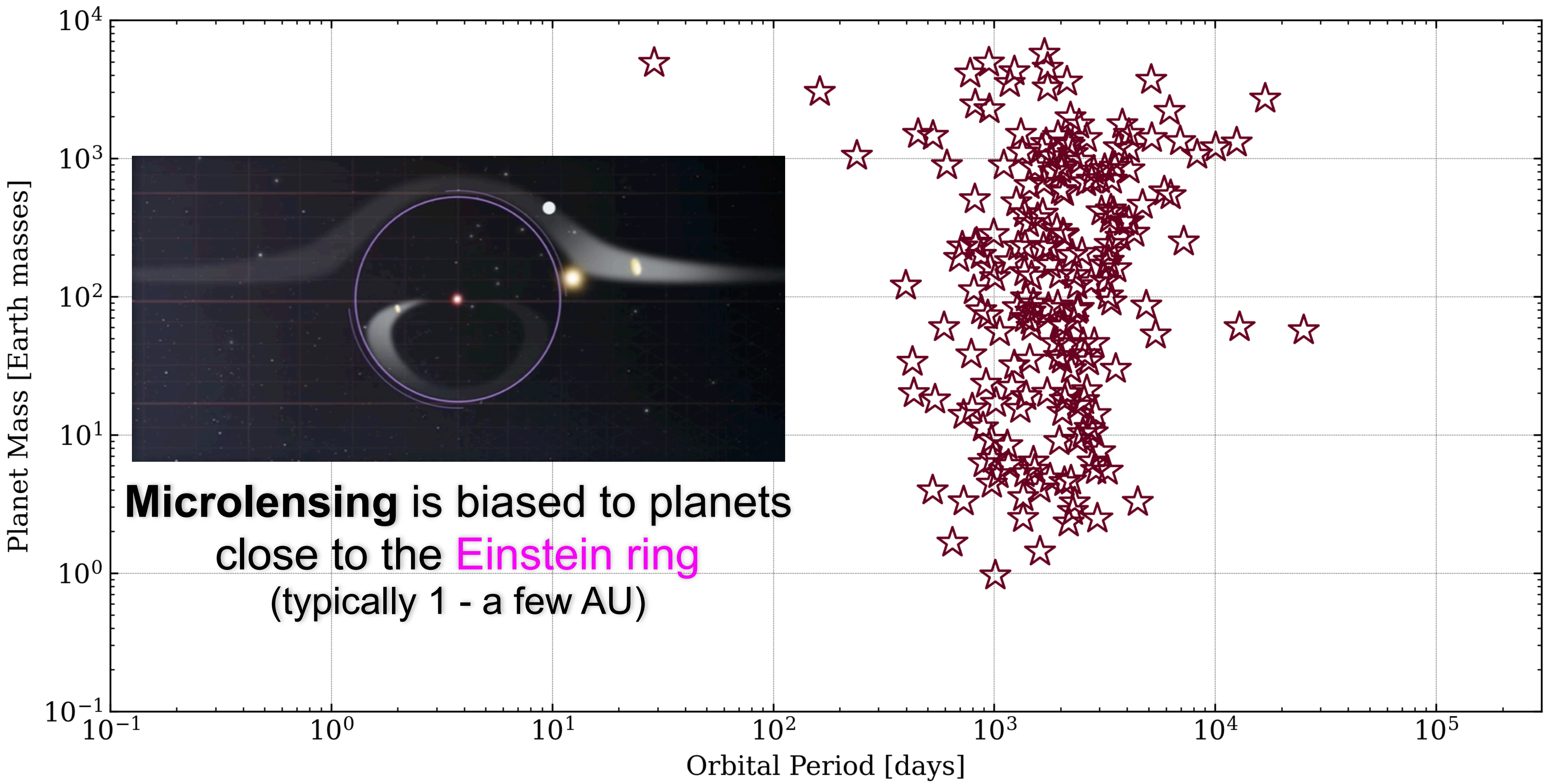
$\theta_E = 0.0005''$ (recall that $''$ means arcseconds)

What is the planet's orbital distance around its host star?

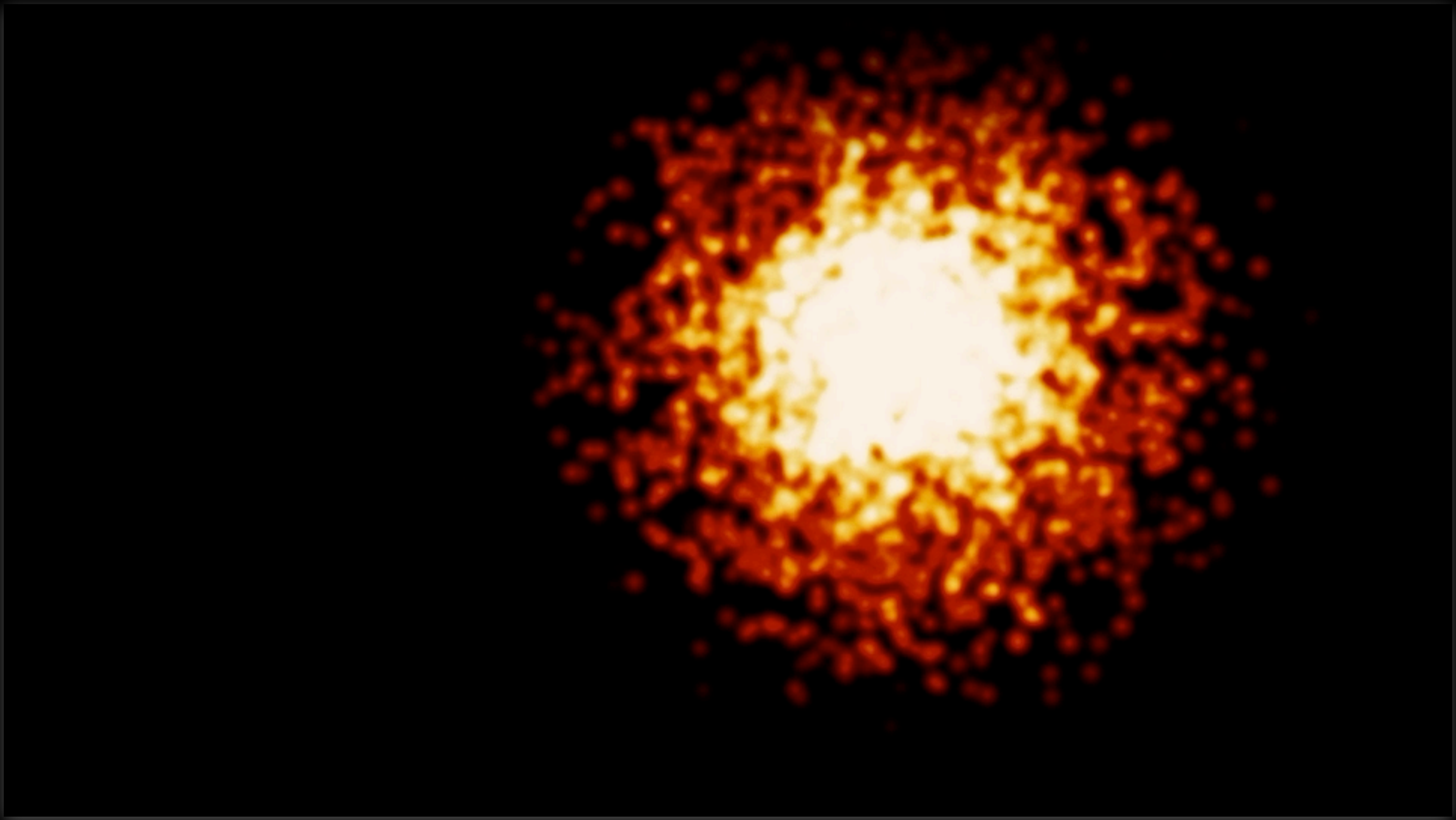
(now you can do the math)

Known Microlensed Exoplanets

Mass-Period diagram

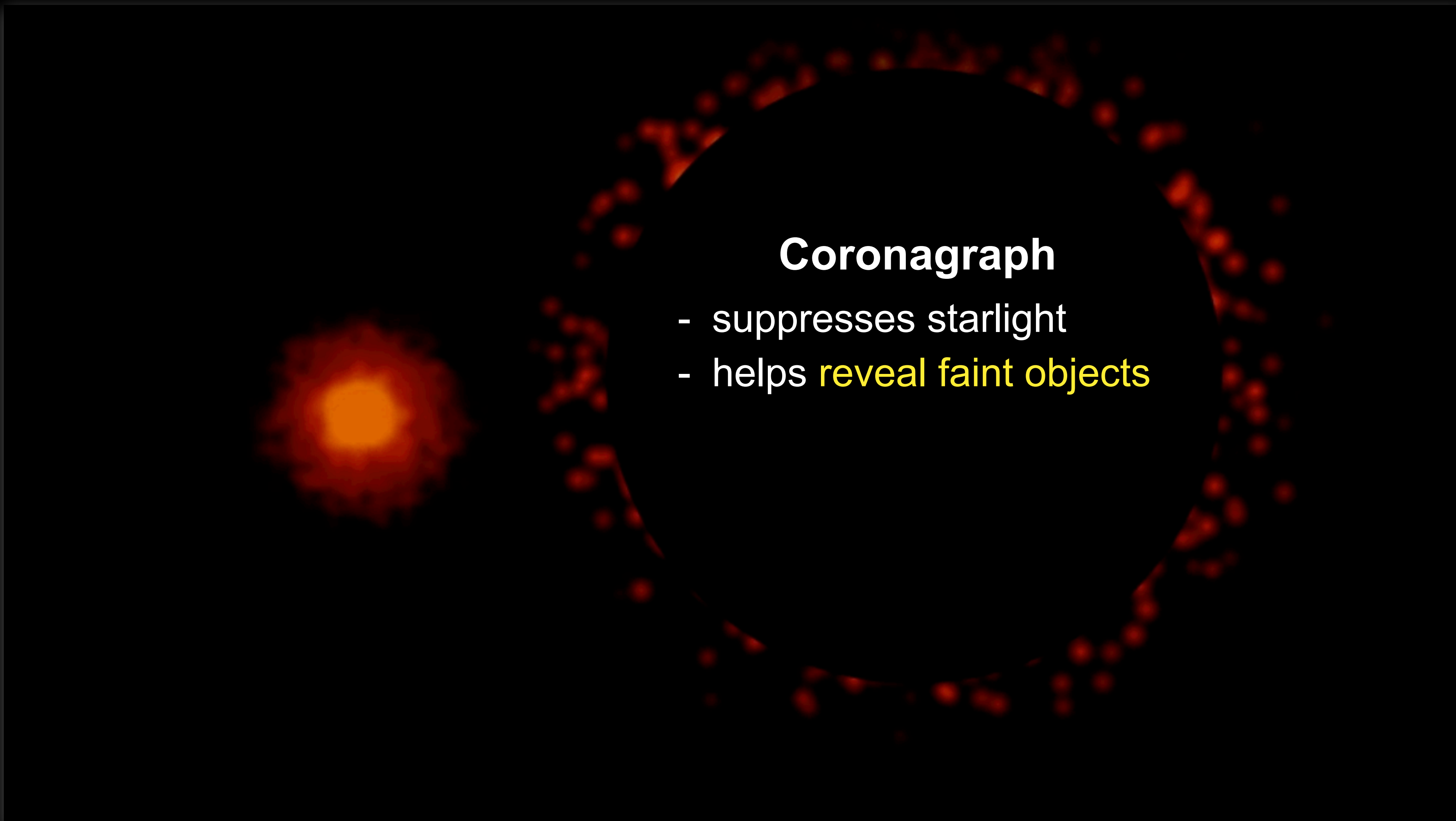


Method 6 - Direct Imaging



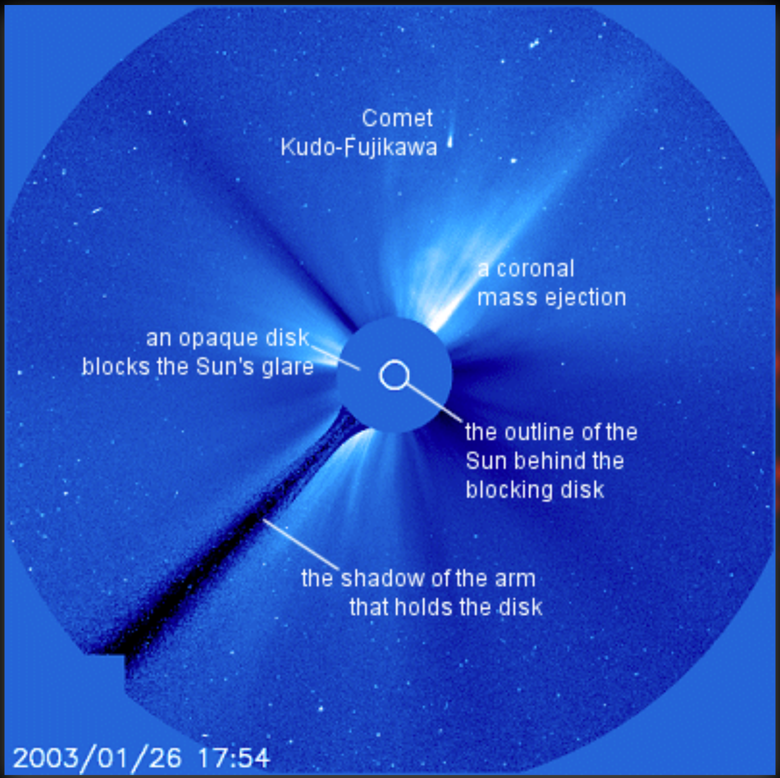
NASA

Method 6 - Direct Imaging



NASA

Method 6 - Direct Imaging

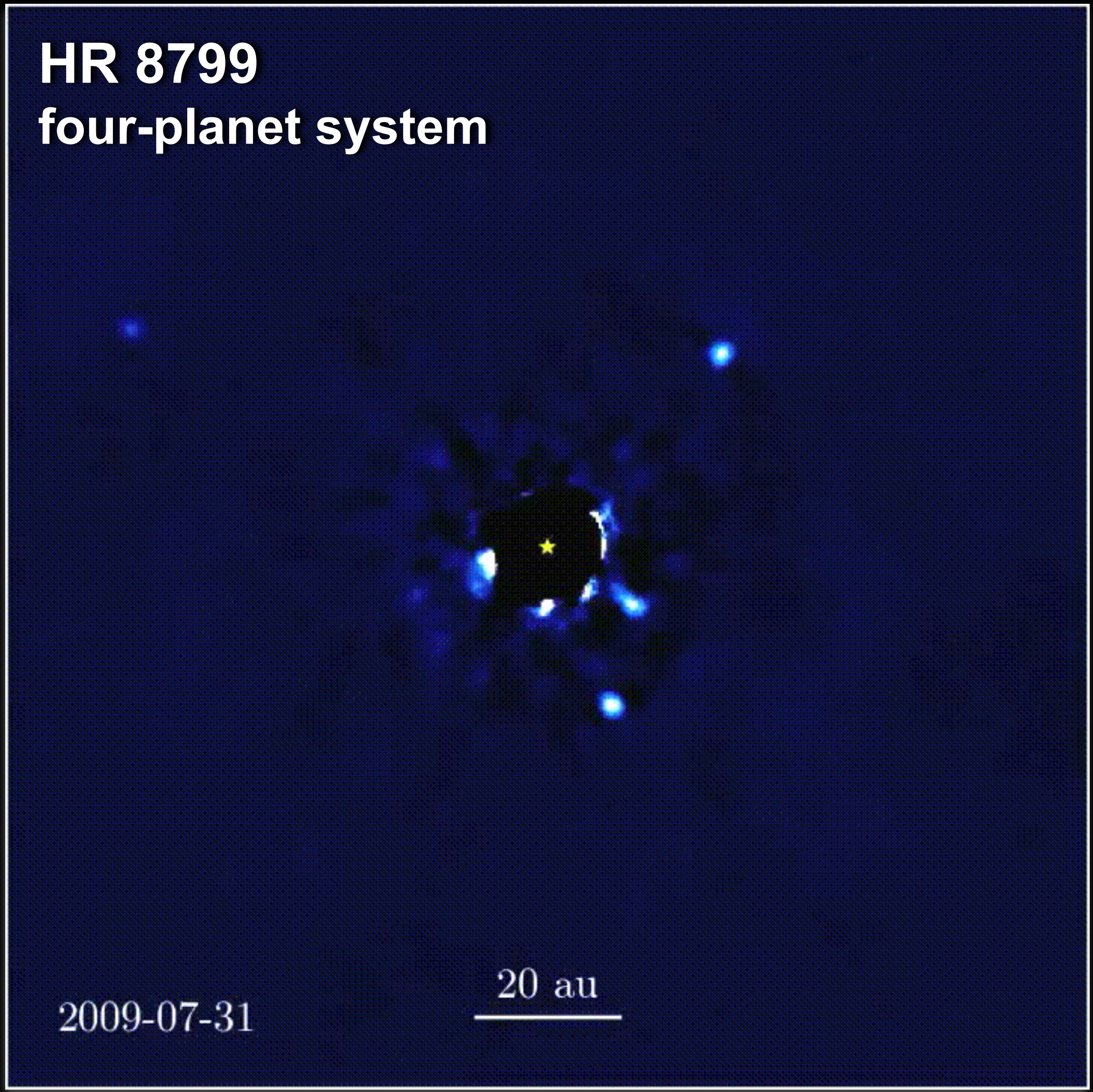


Coronagraph

- suppresses starlight
- helps reveal faint objects
- used to view the diffuse hot gas around the Sun

NASA

Method 6 - Direct Imaging



Jason Wang &
Christian Marois

A	B
C	D

The coronagraph used to study the HR 8799 system was 20 au in diameter.

If HR 8799 hosted an Earth-twin, would it be detectable?

A: Yes

B: No

A

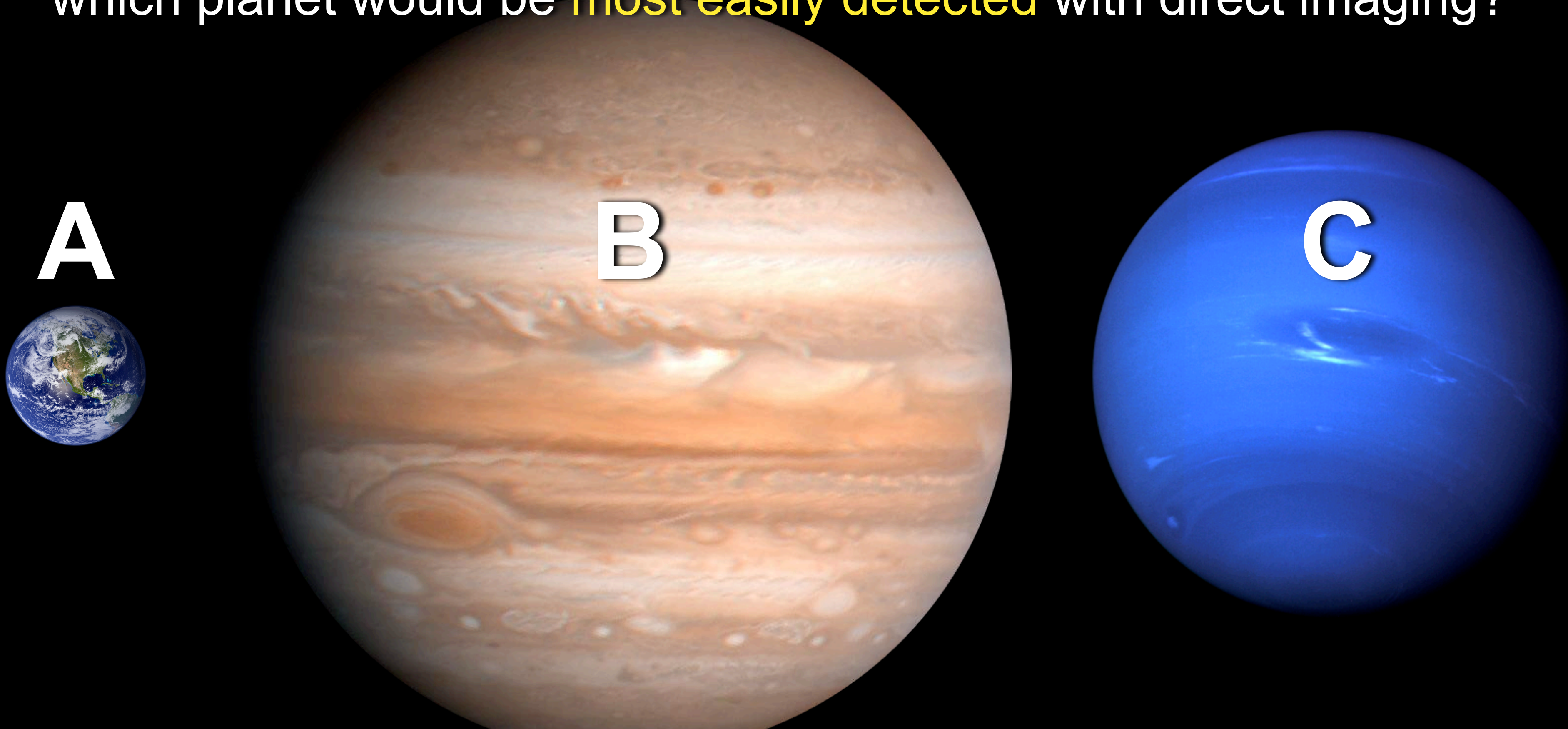
B

C

D

The coronagraph used to study the HR 8799 system was 20 au in diameter.

If HR 8799 hosted an Earth-mass planet, a Jupiter-mass planet, and a Neptune-mass planet, all orbiting beyond 30 au, which planet would be most easily detected with direct imaging?



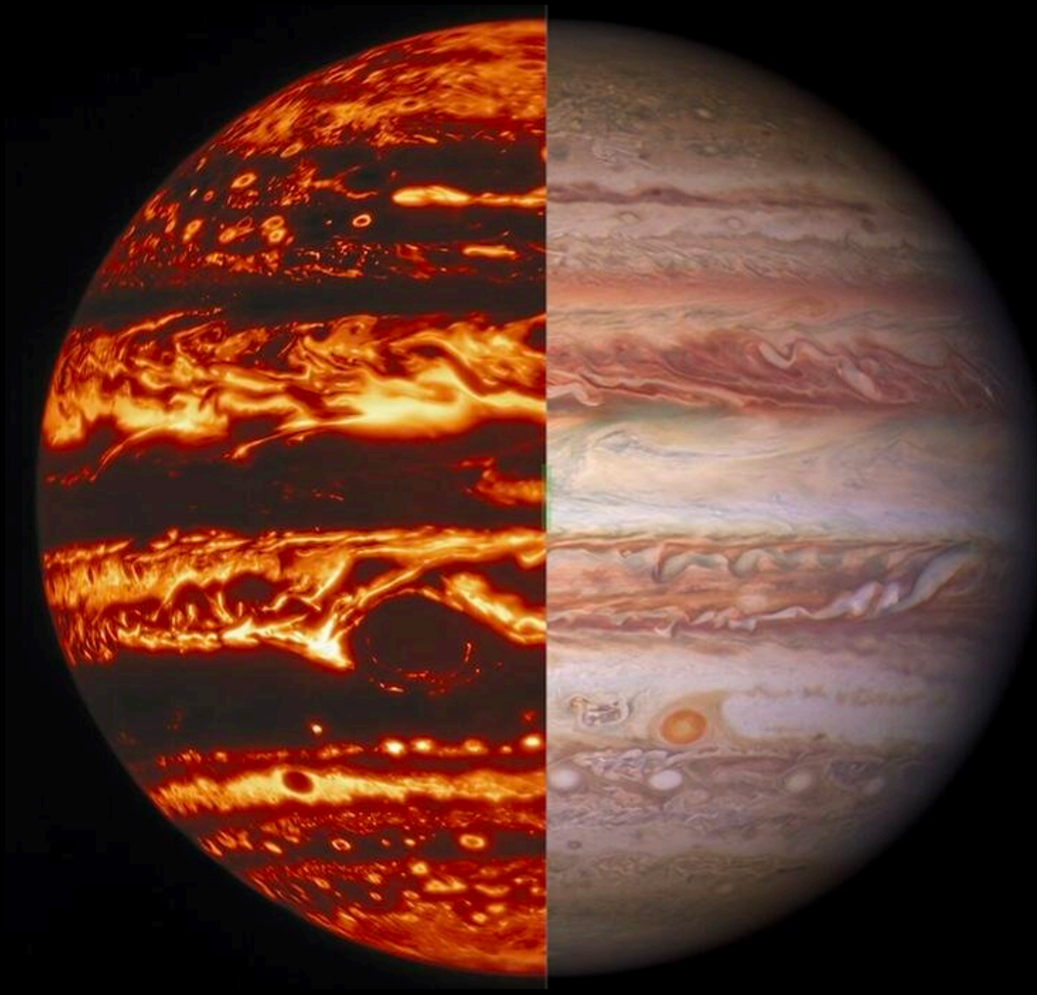
A B
C D

The coronagraph used to study the HR 8799 system was 20 au in diameter.

If HR 8799 hosted a Jupiter-mass planet at 100 AU, at what age would it be easier to detect?

A: 50 million years

B: 5 billions years (~current age)



Known Directly Imaged Exoplanets

Mass-Period diagram