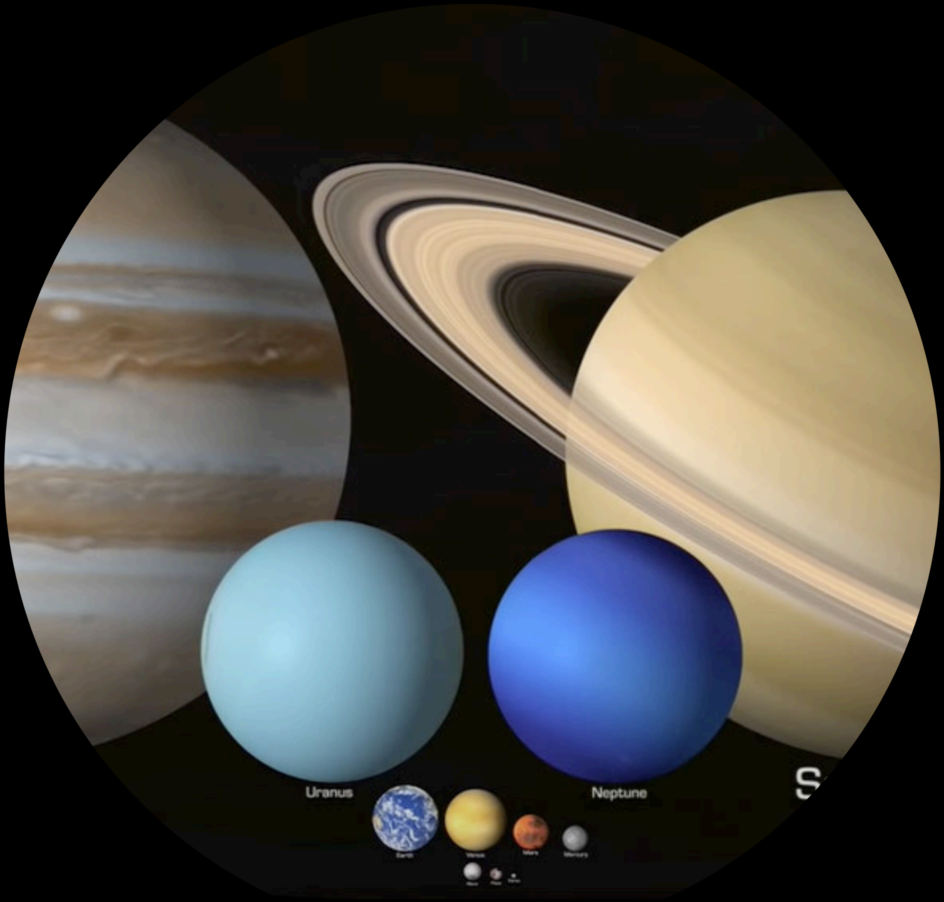
Lecture 1 - Our Solar System in the Context of Exoplanets



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

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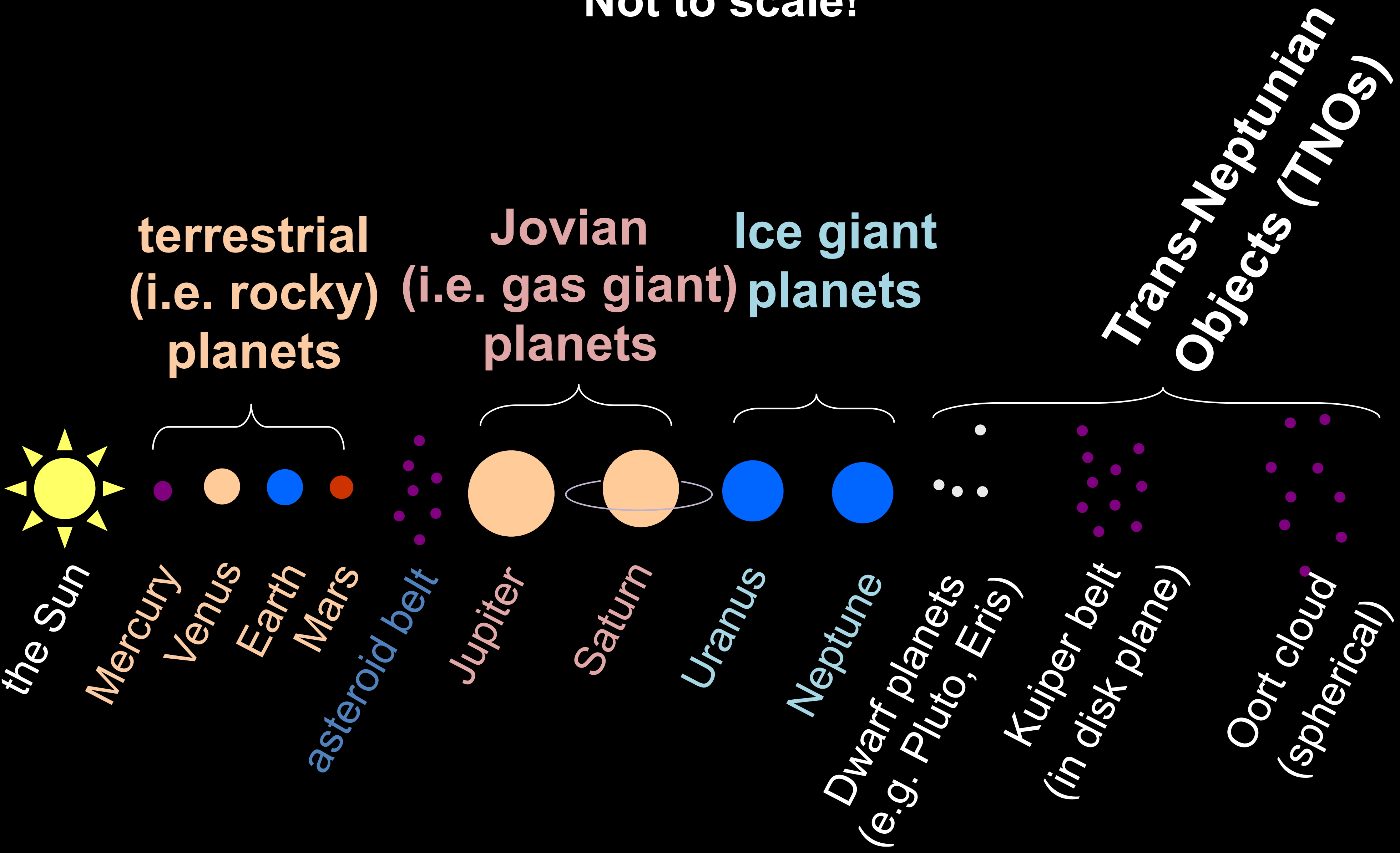
1) Describe the contents of the Solar System and what their orbital properties tell us about how they formed
2) Compare the properties of the Solar System to those of known exoplanetary systems
3) Describe the physics behind six techniques for exoplanet detection and the limitations of each technique

The Solar System

Not to scale!



terrestrial (i.e. rocky) planets

Jovian (i.e. gas giant) planets

Ice giant planets

Trans-Neptunian Objects (TNOs)

the Sun

Mercury

Venus

Earth

Mars

asteroid belt

Jupiter

Saturn

Uranus

Neptune

Dwarf planets (e.g. Pluto, Eris)

Kuiper belt (in disk plane)

Oort cloud (spherical)

The Solar System

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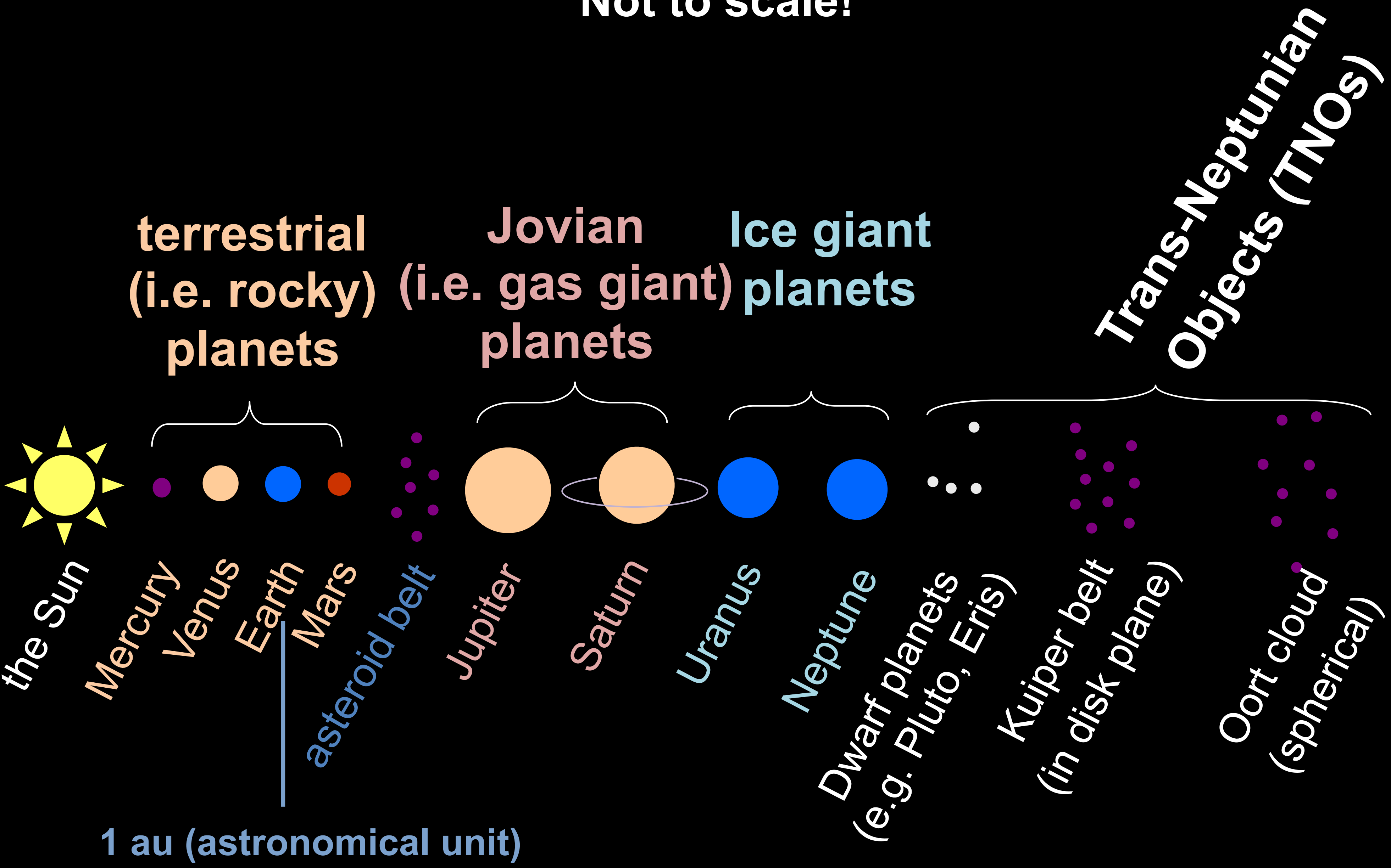

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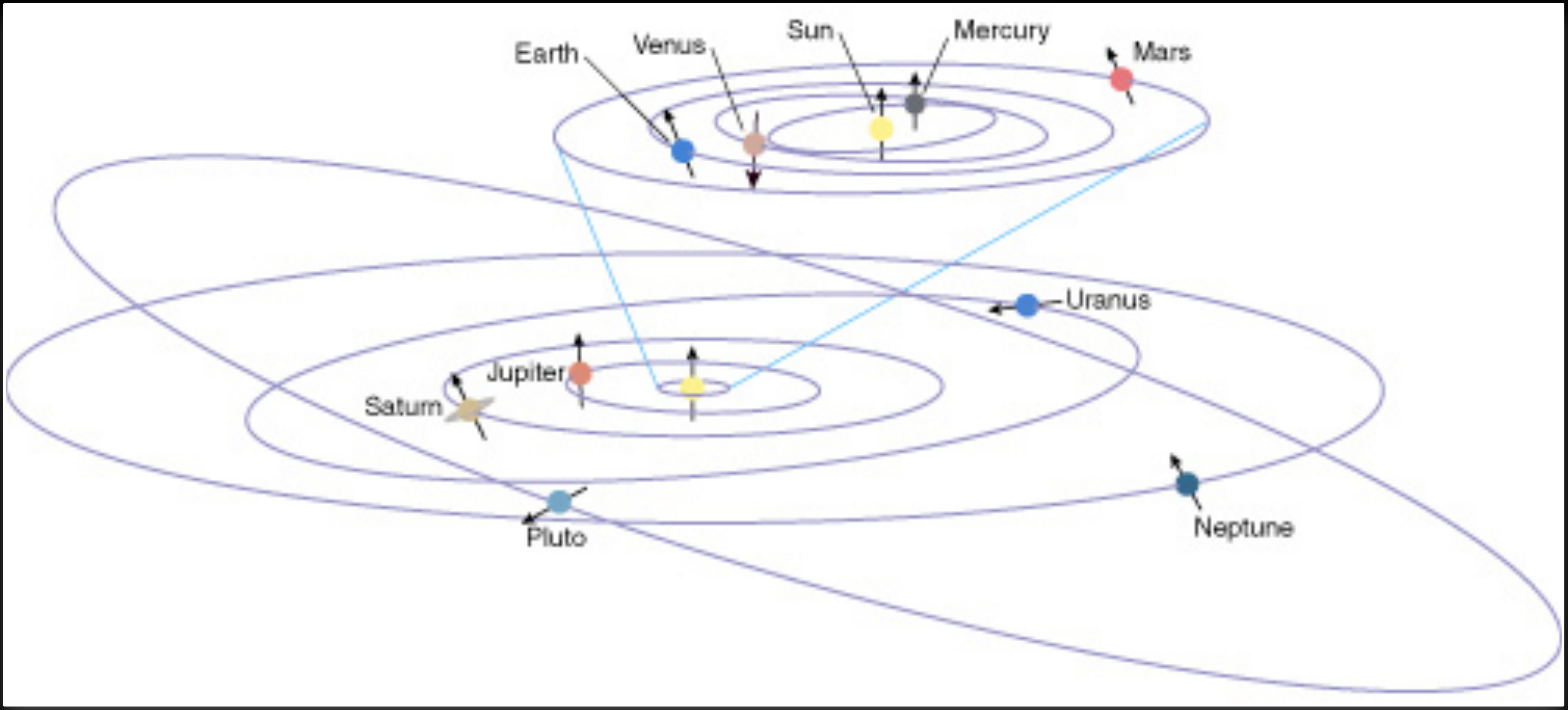
1 au (astronomical unit)

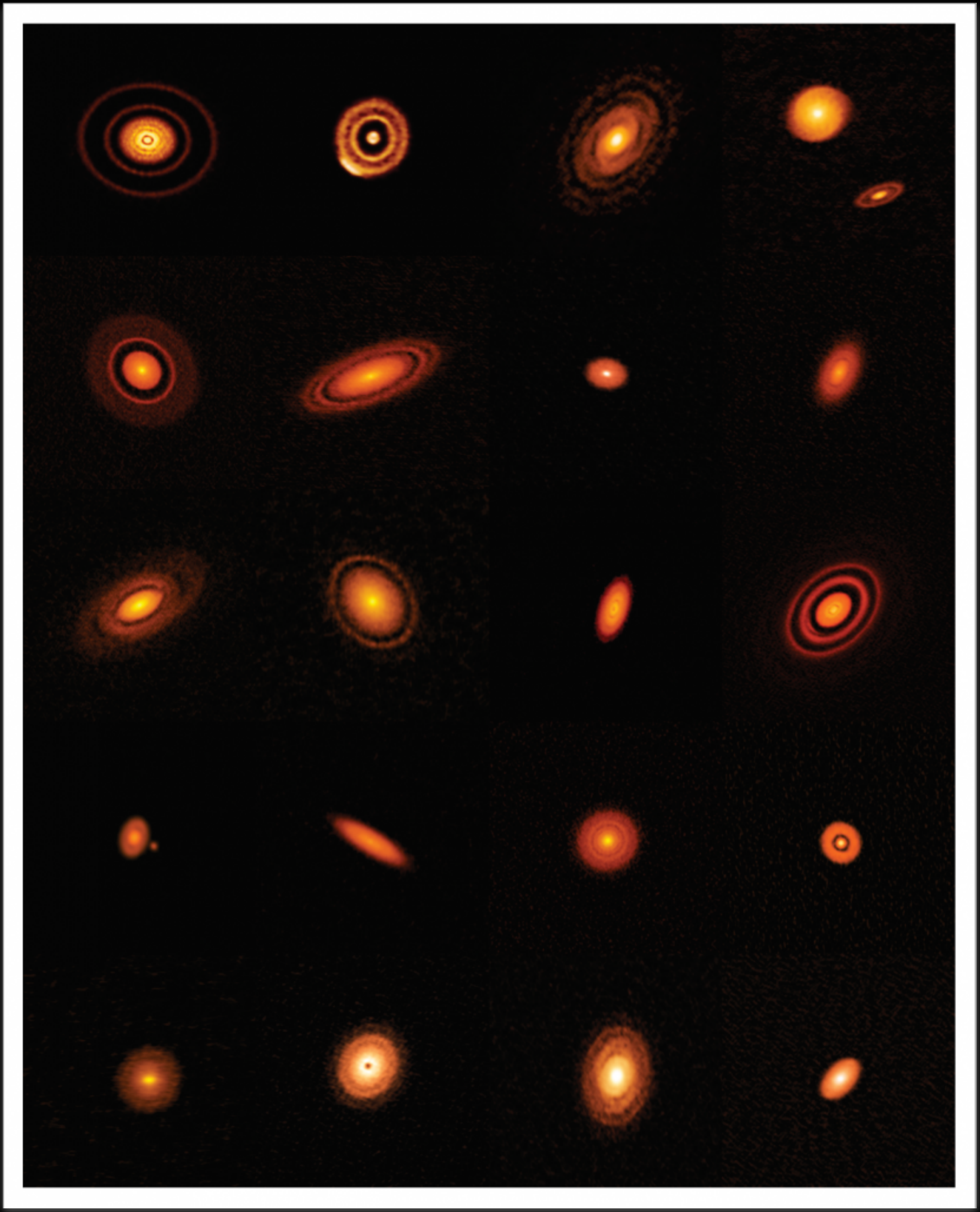
Planetary orbits are (nearly) co-planar



- 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

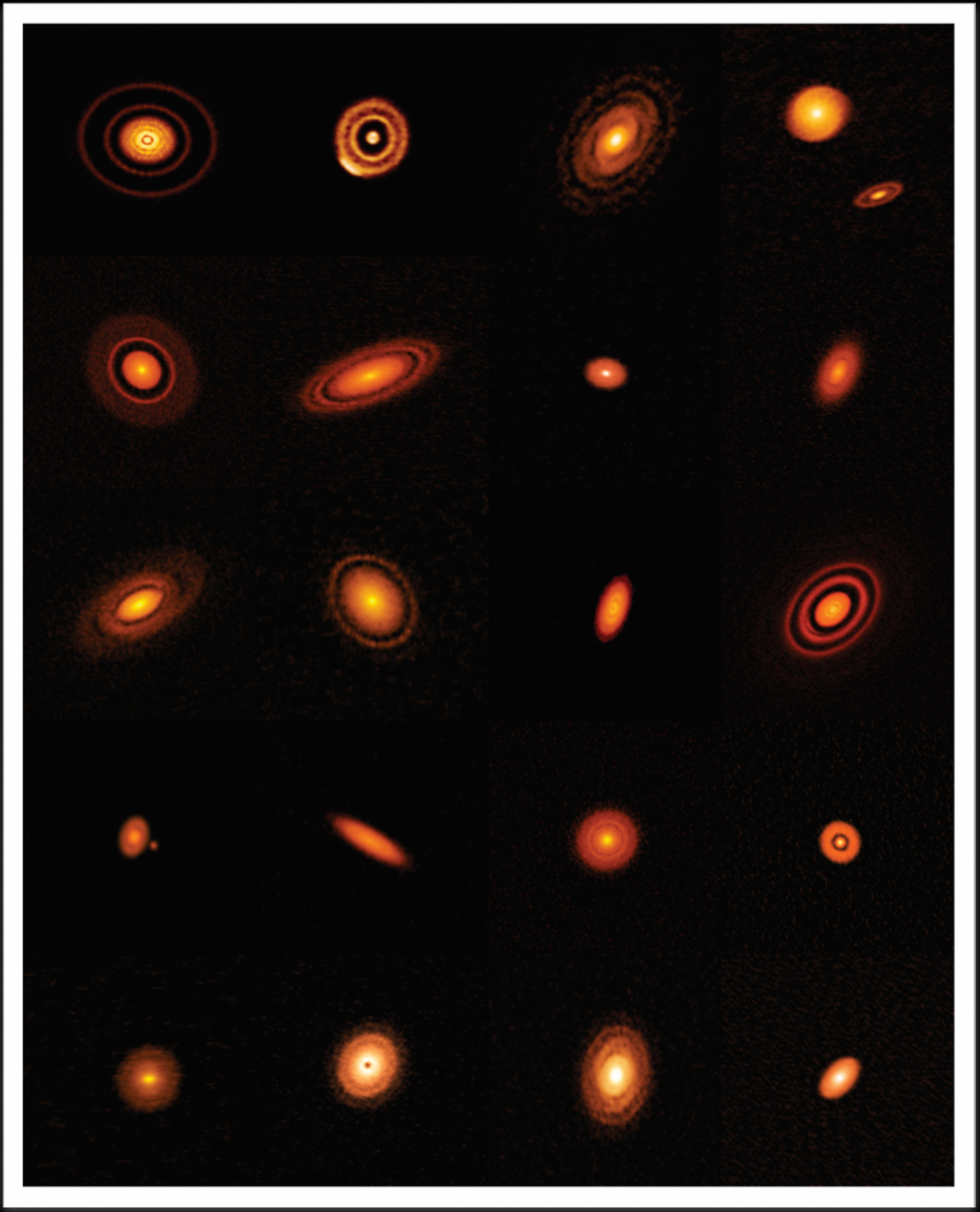
- Radio images of warm dust continuum around young stars (<~10 Myrs)
- Disk sizes ~ 100 au
  - cannot resolve the inner disk regions
- Variety of disk morphologies
- Concentric gaps opened by protoplanets?



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?



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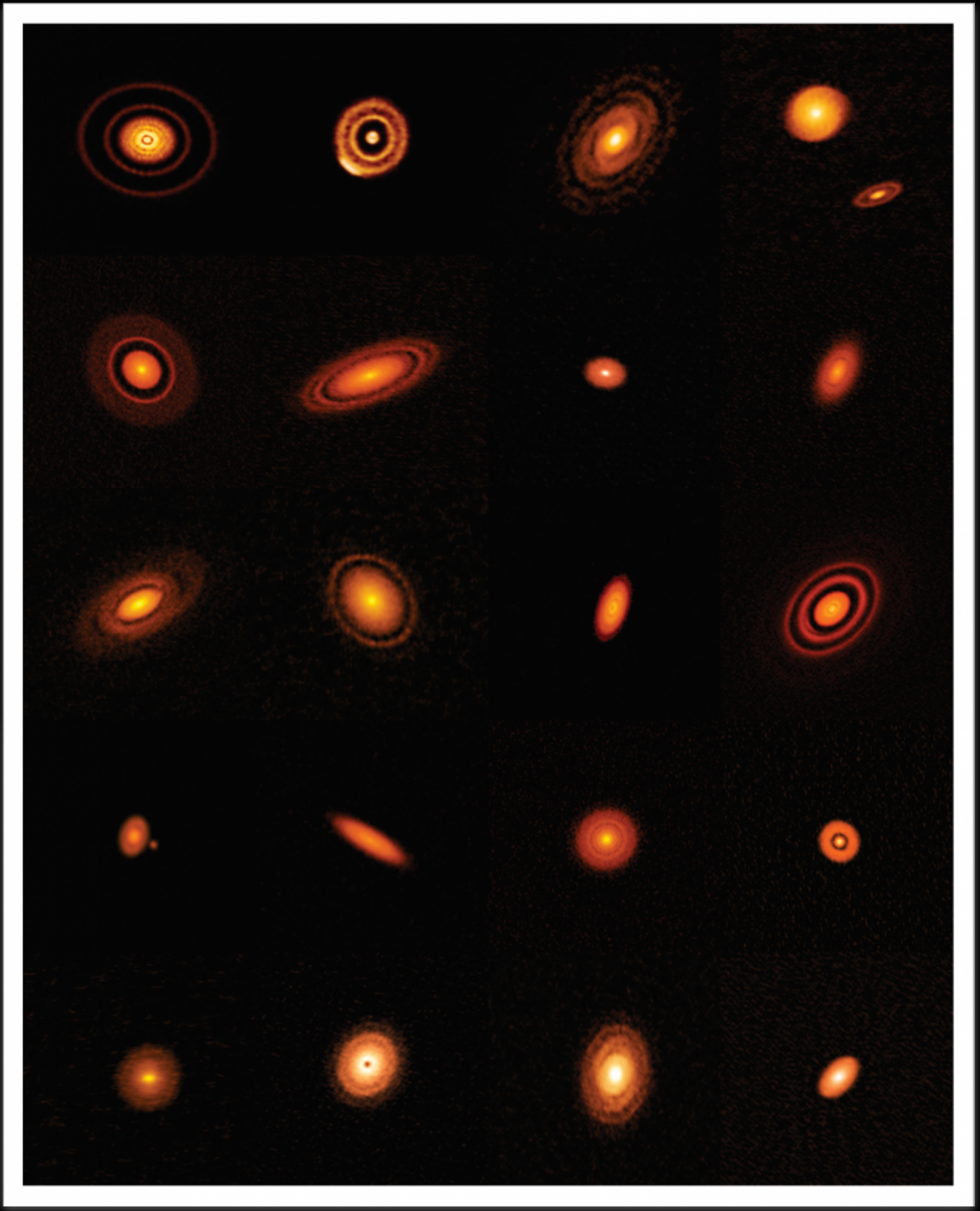
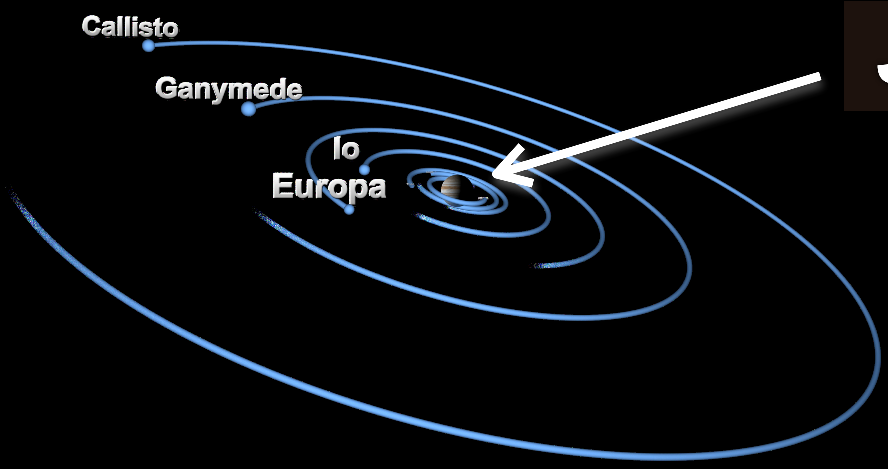


Regular vs Irregular Satellites (a.k.a. moons)

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



Jupiter

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

Regular satellites

- resemble mini planetary systems

- prograde, nearly circular orbits, low mutual inclinations

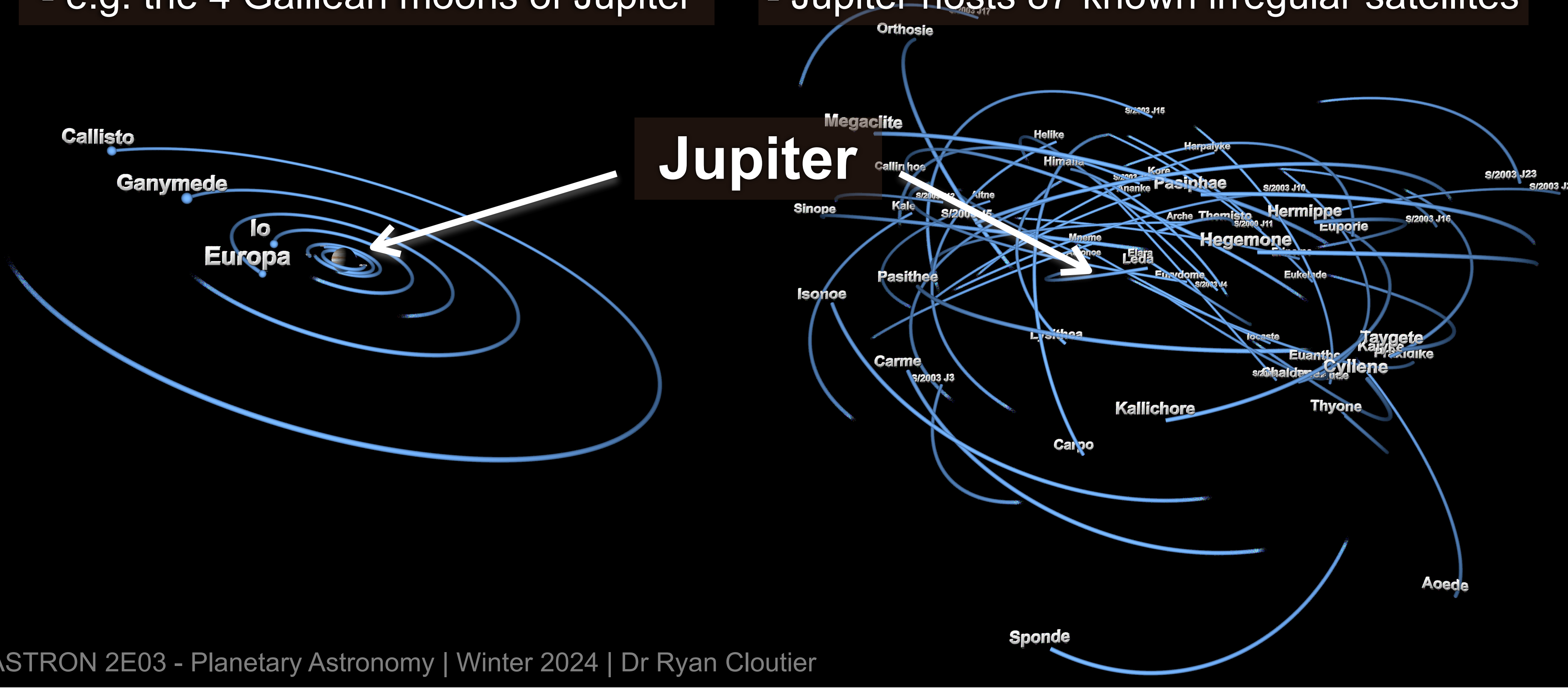
- e.g. the 4 Galilean moons of Jupiter

Irregular satellites

- irregular orbits

- prograde or retrograde orbits, highly elliptical and highly inclined

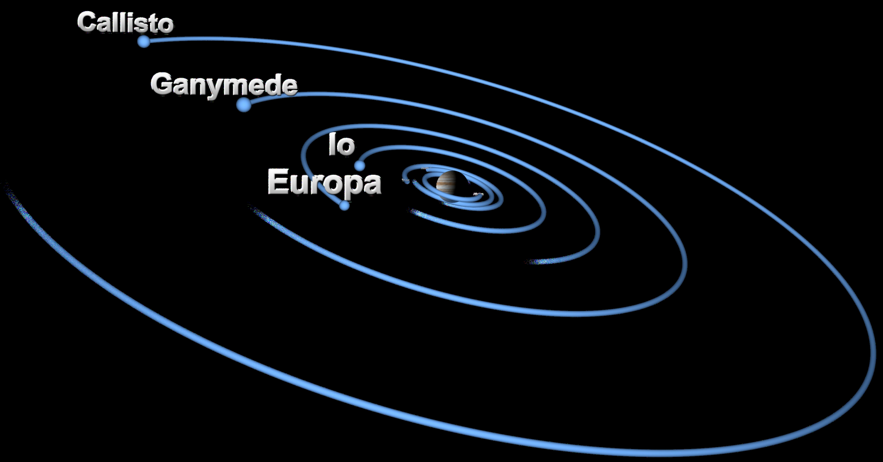
- Jupiter hosts 87 known irregular satellites

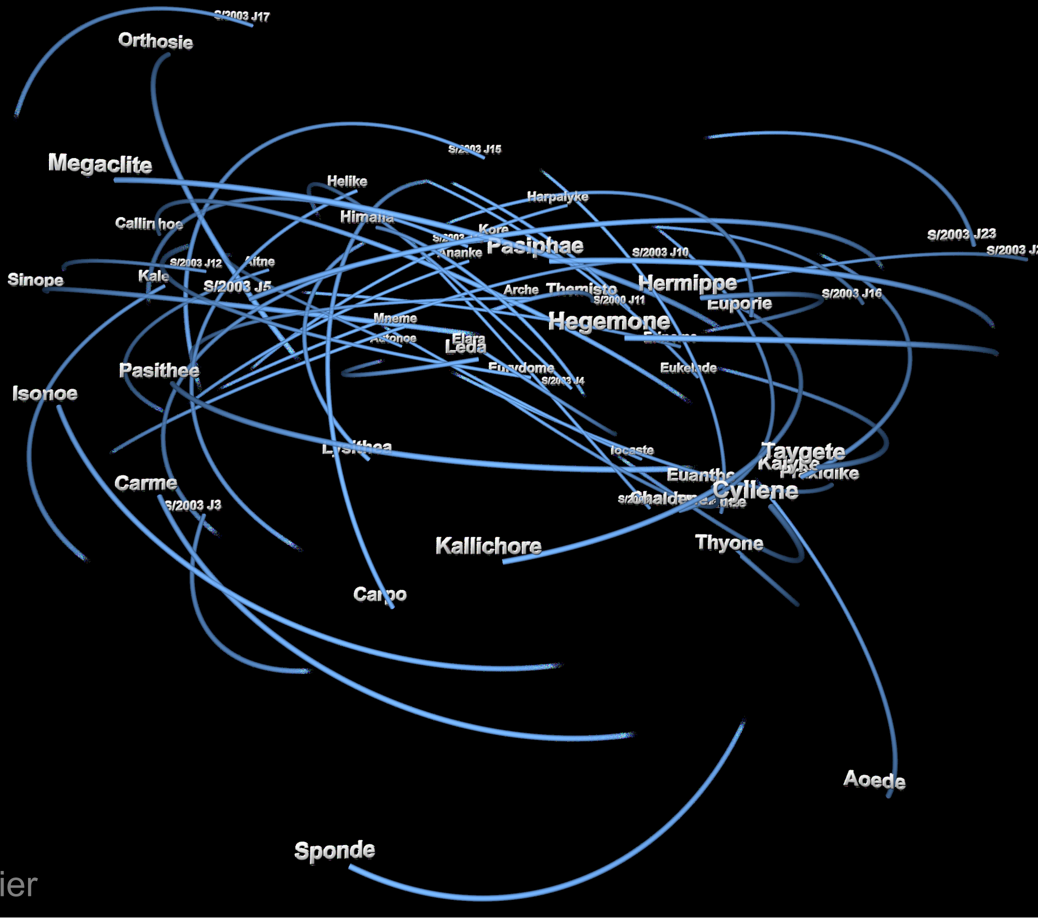


TPS Activity

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

(First consider: are they the same?)





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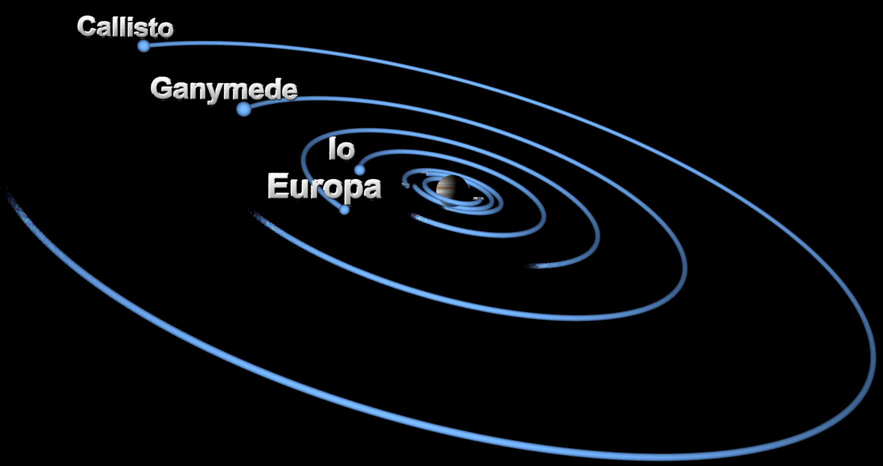

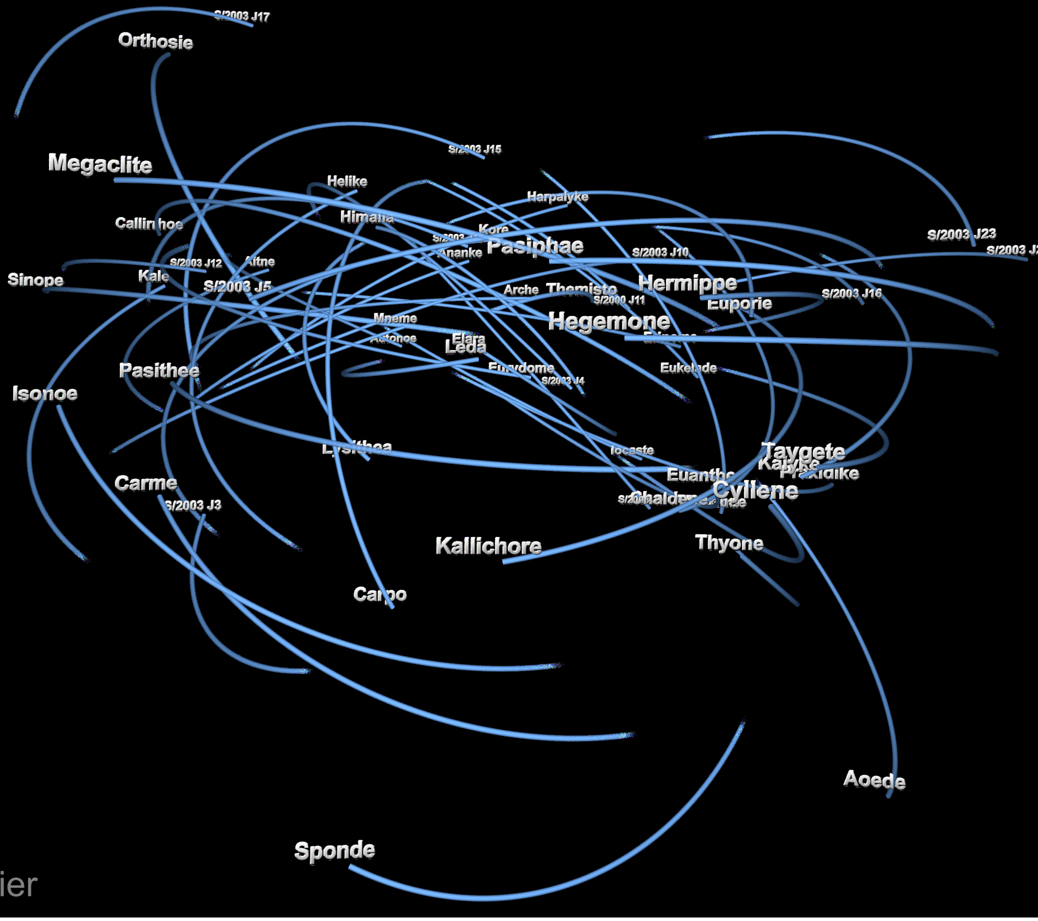

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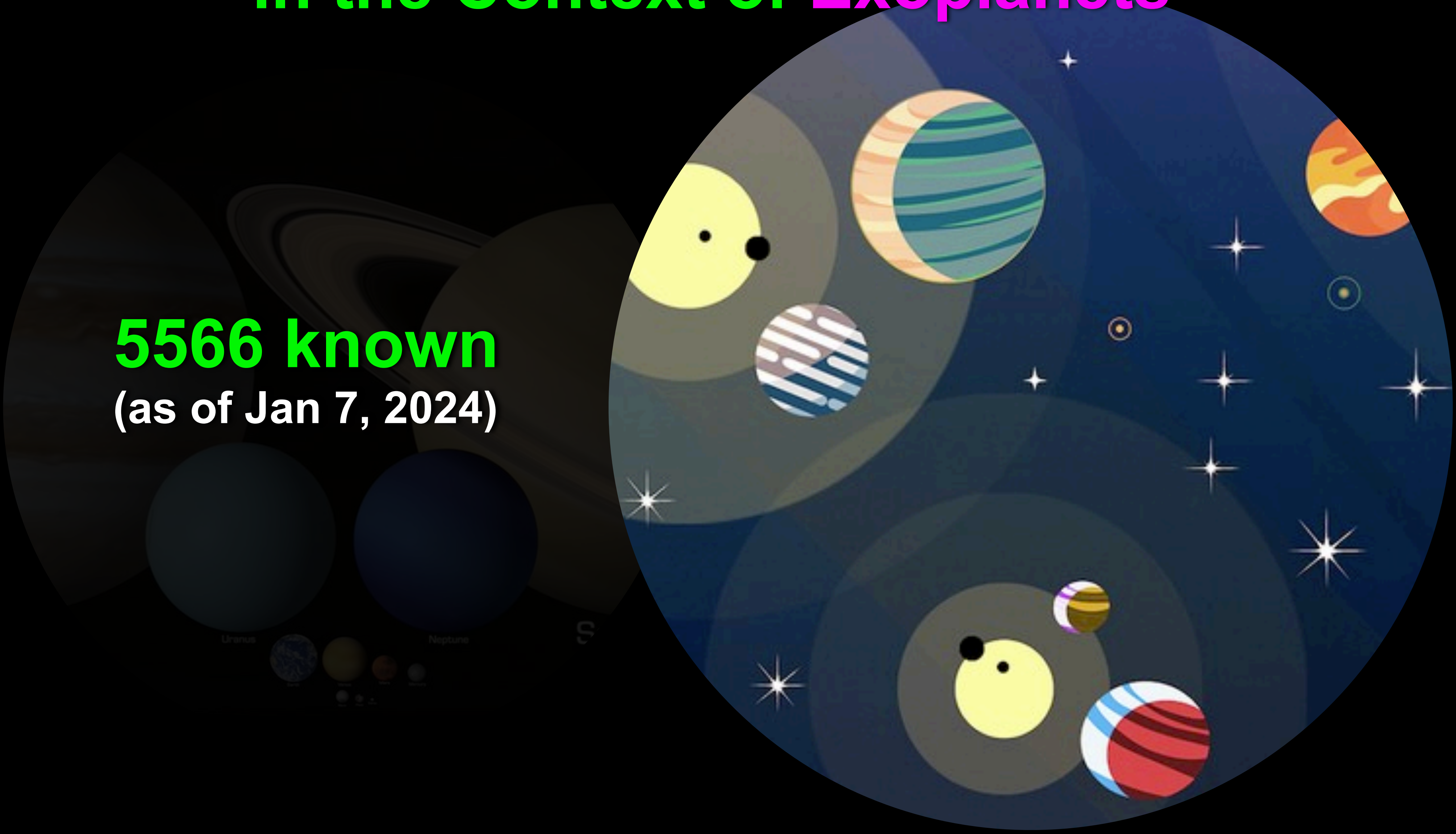
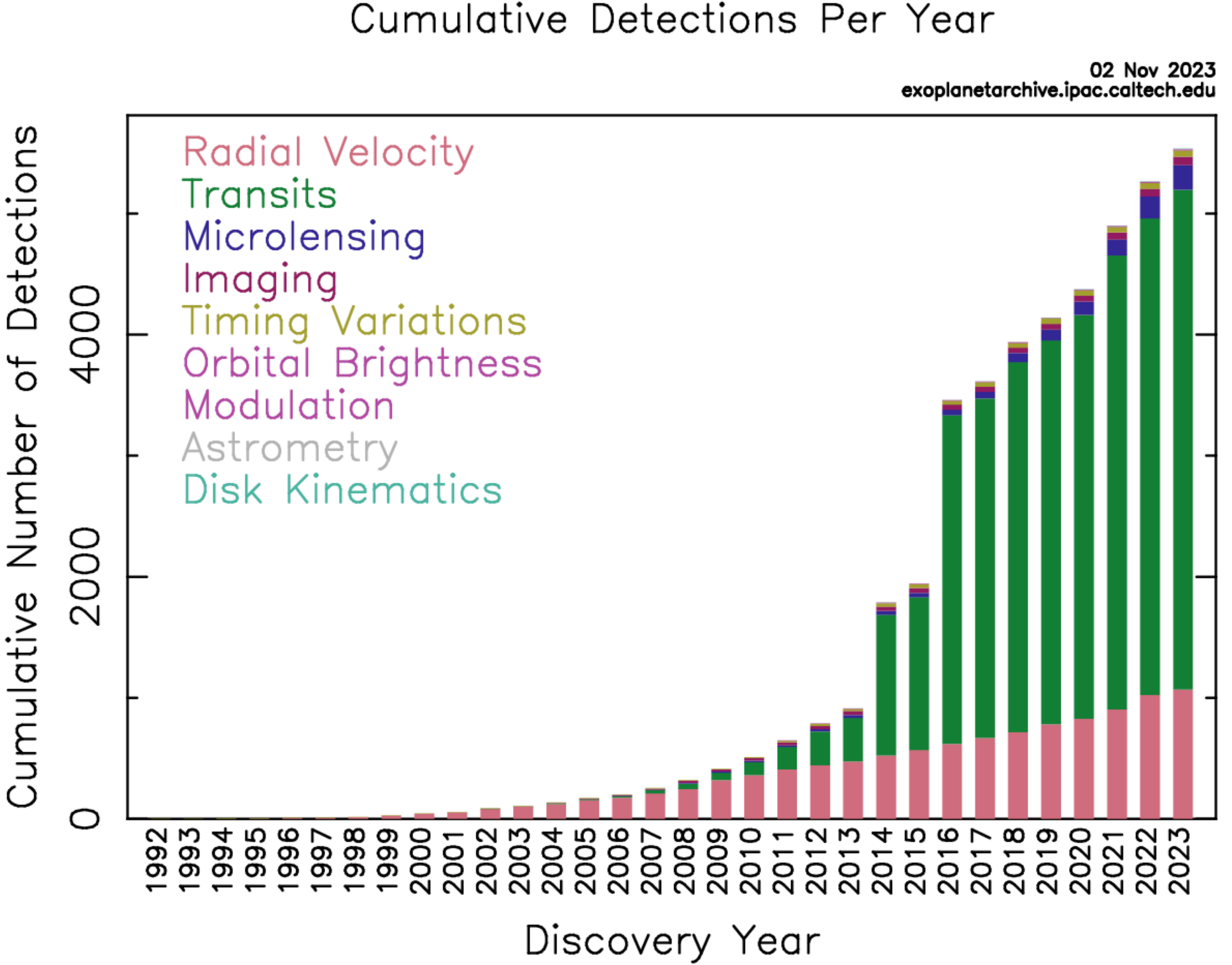


5566 known

(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
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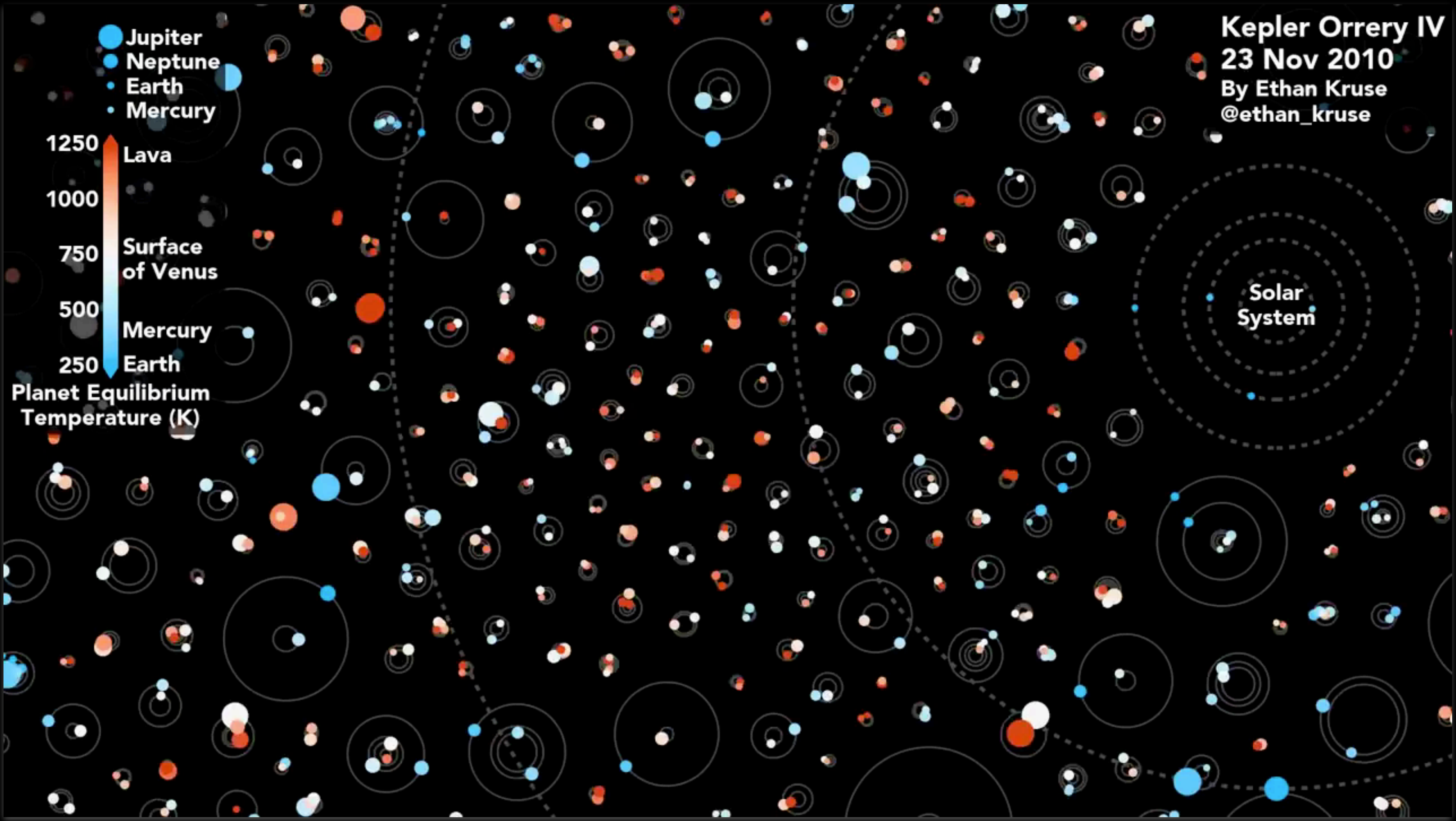
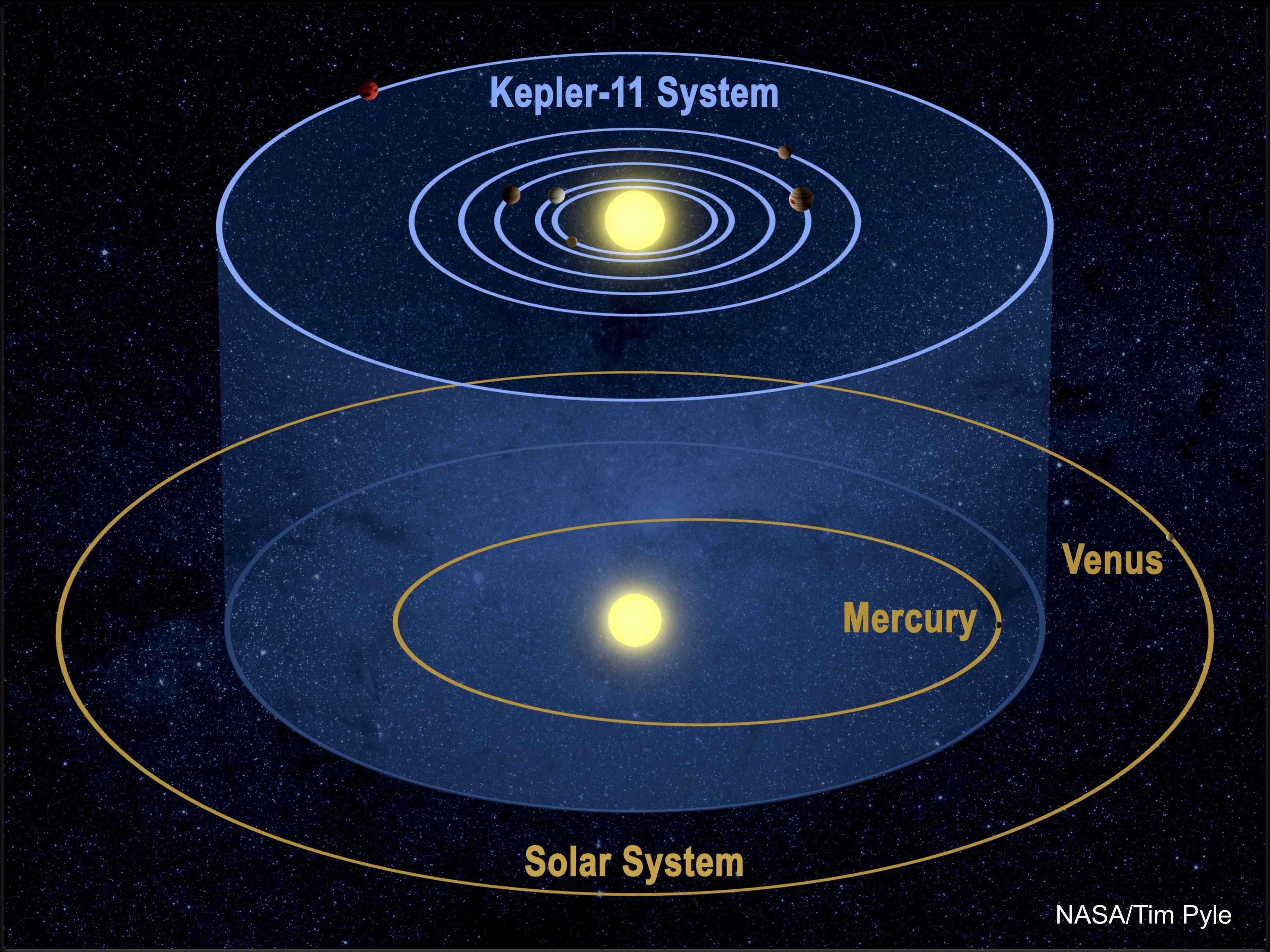
2022
2023
Discovery Year

Most exoplanetary systems are compact

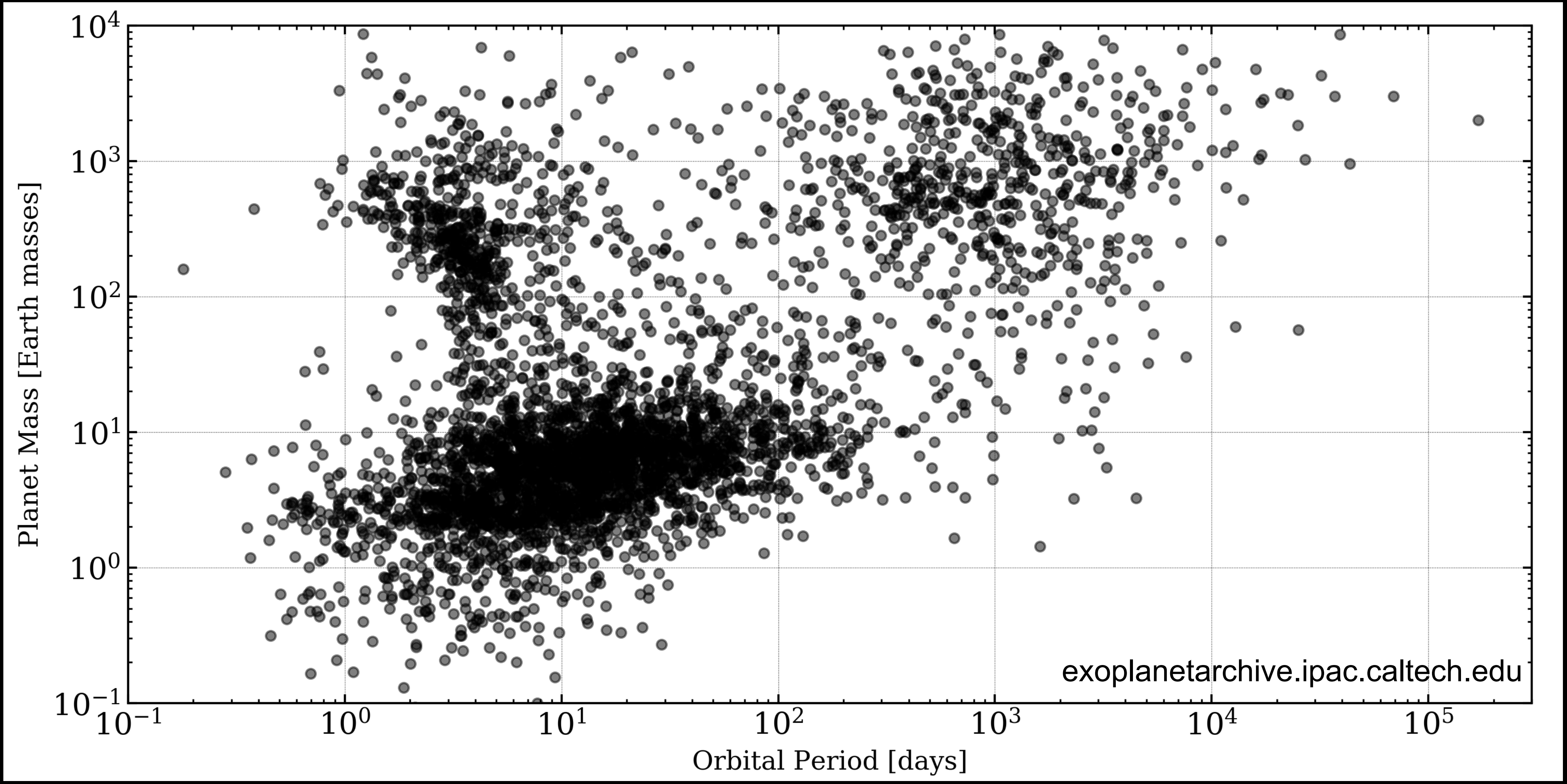


Most exoplanetary systems are **compact**



NASA/Tim Pyle

Mass-Period diagram



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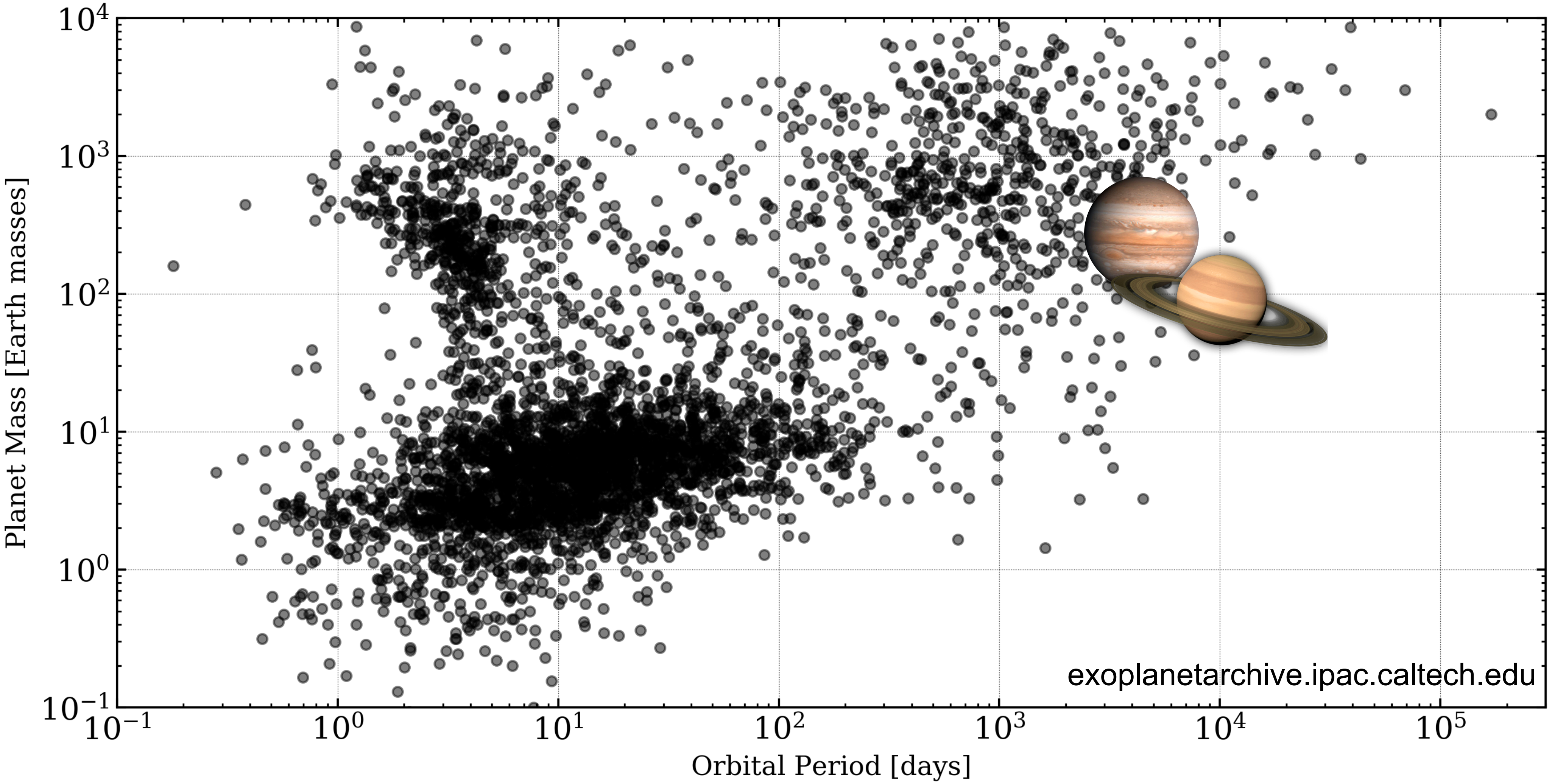

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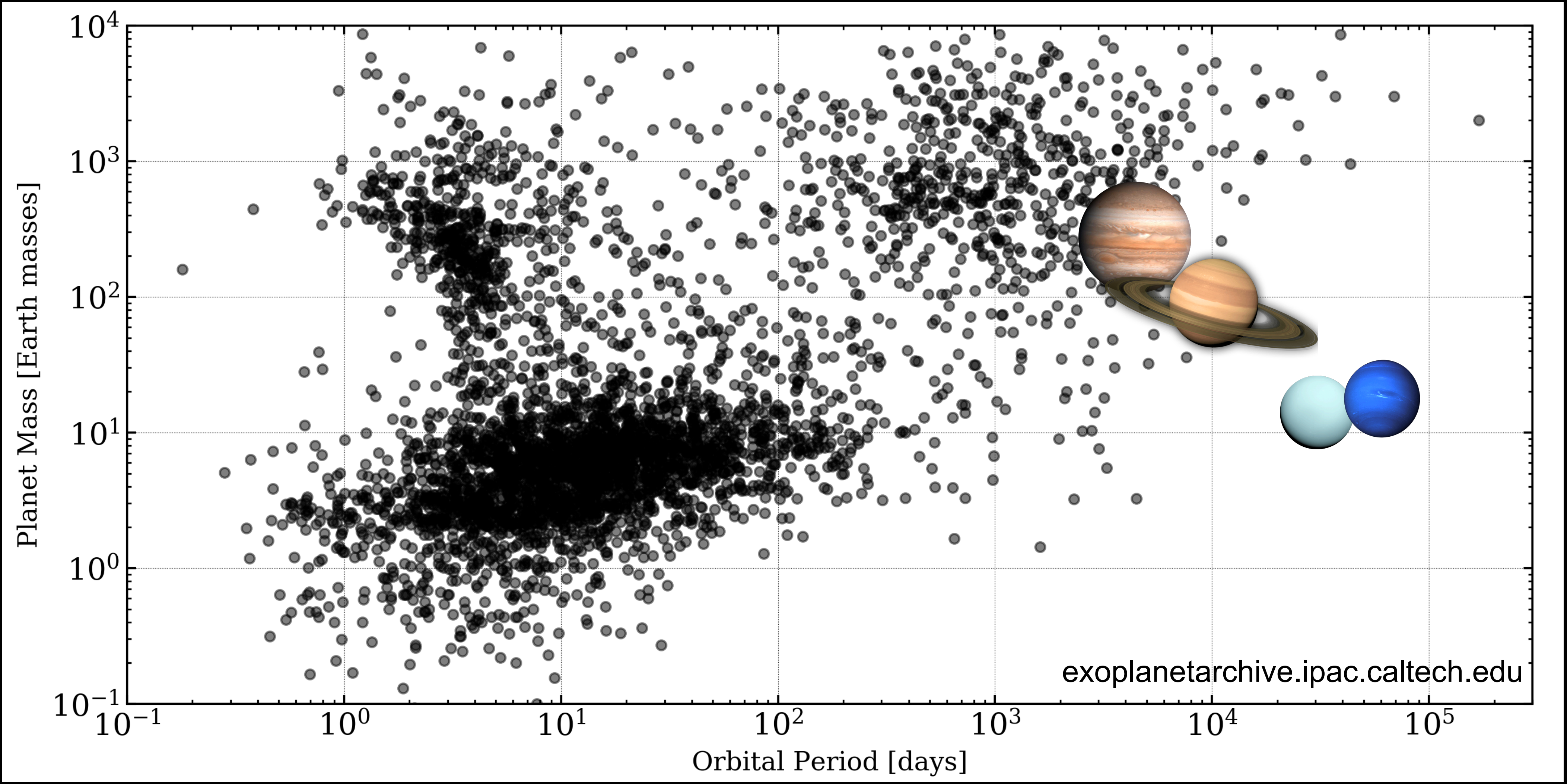

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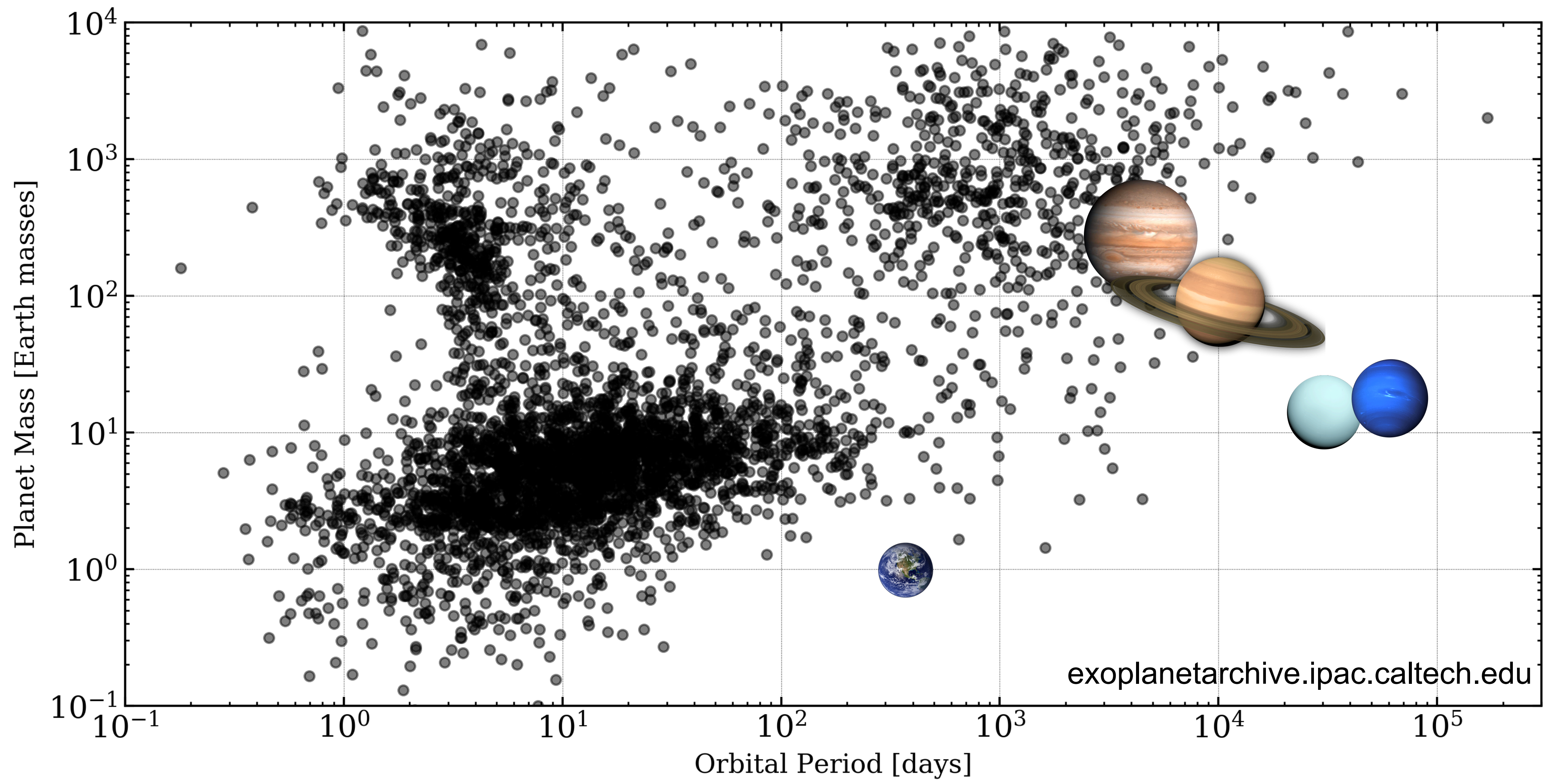

exoplanetarchive.ipac.caltech.edu

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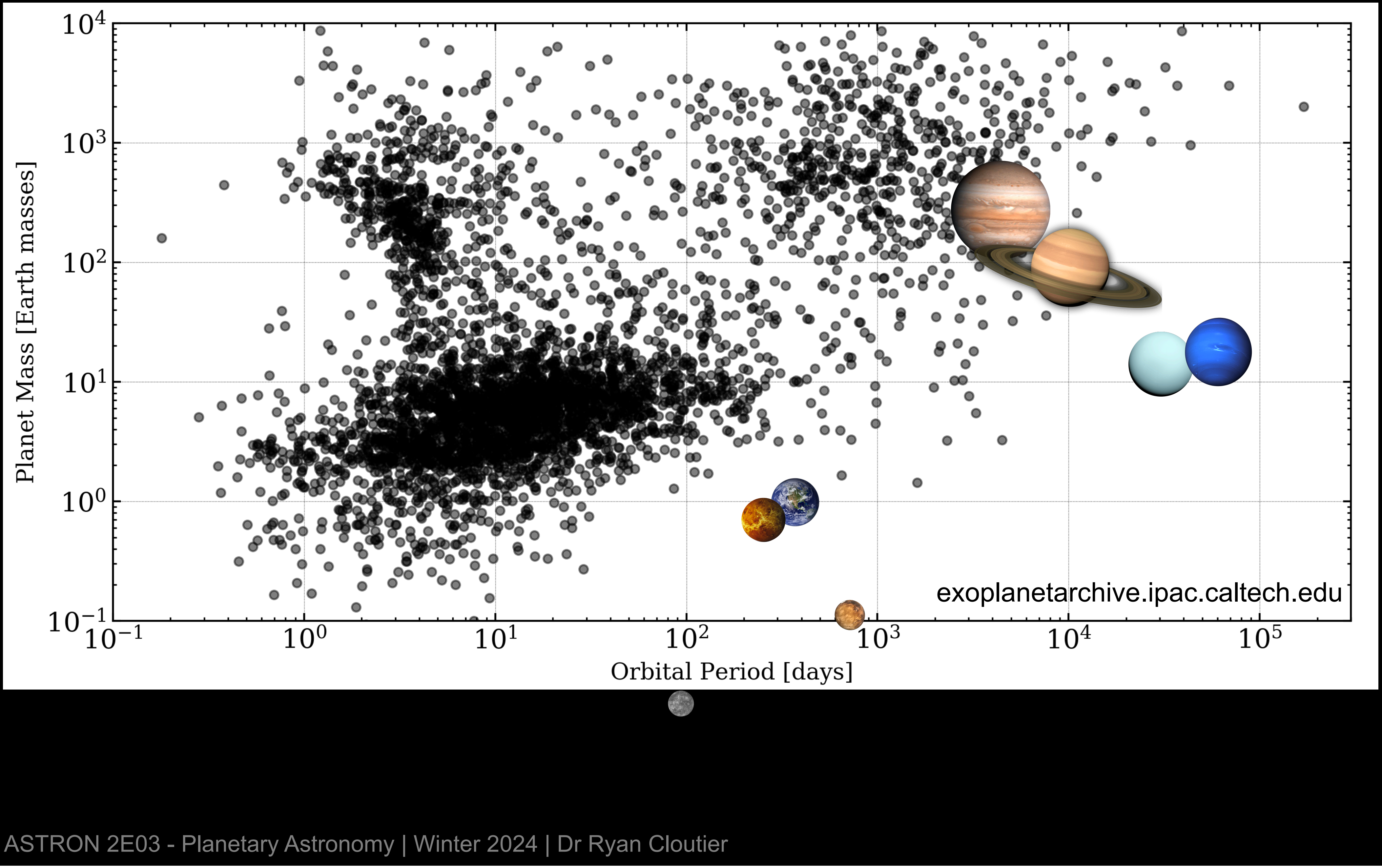
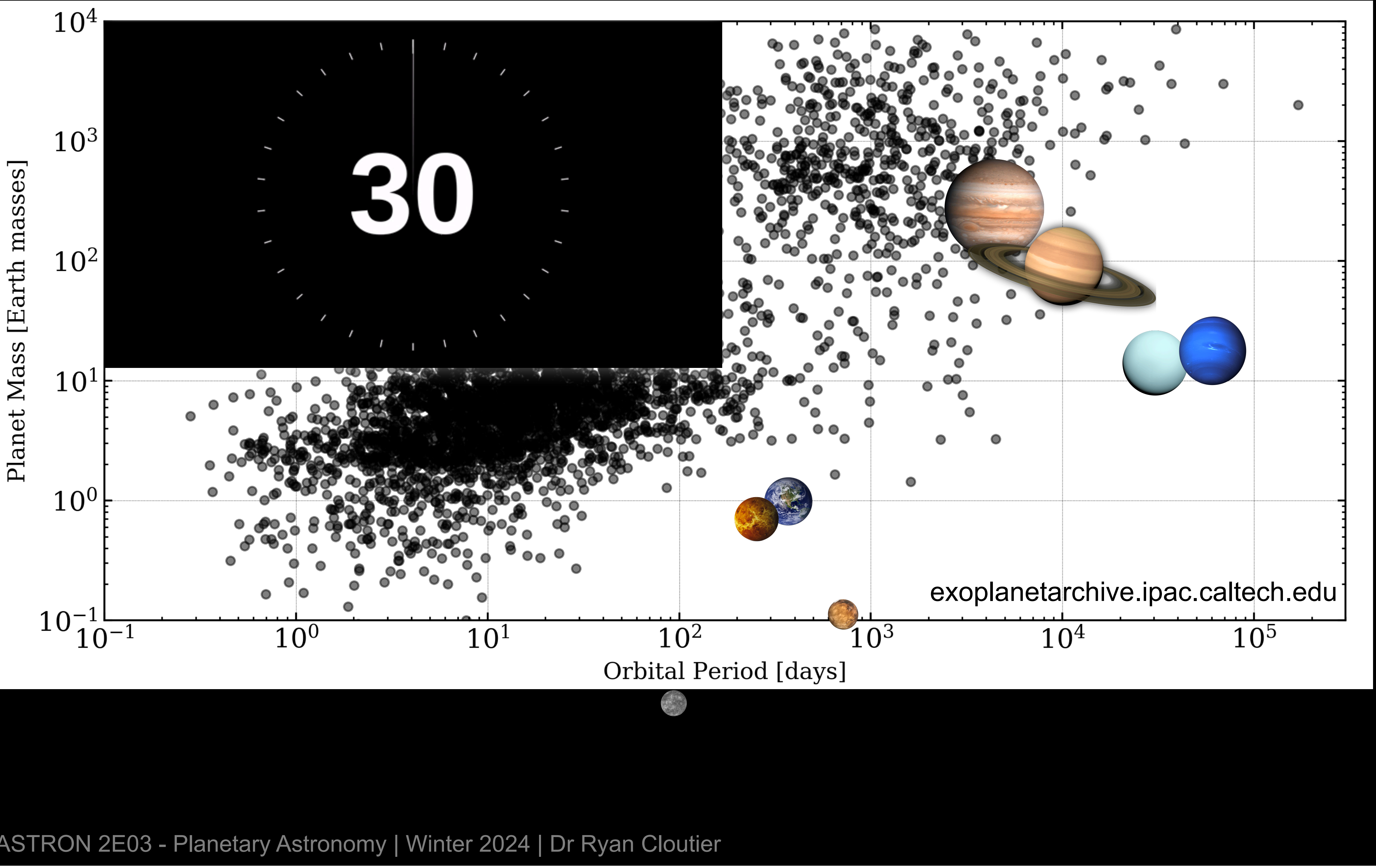


TPS activity - Why haven't we discovered an exo-Mars?



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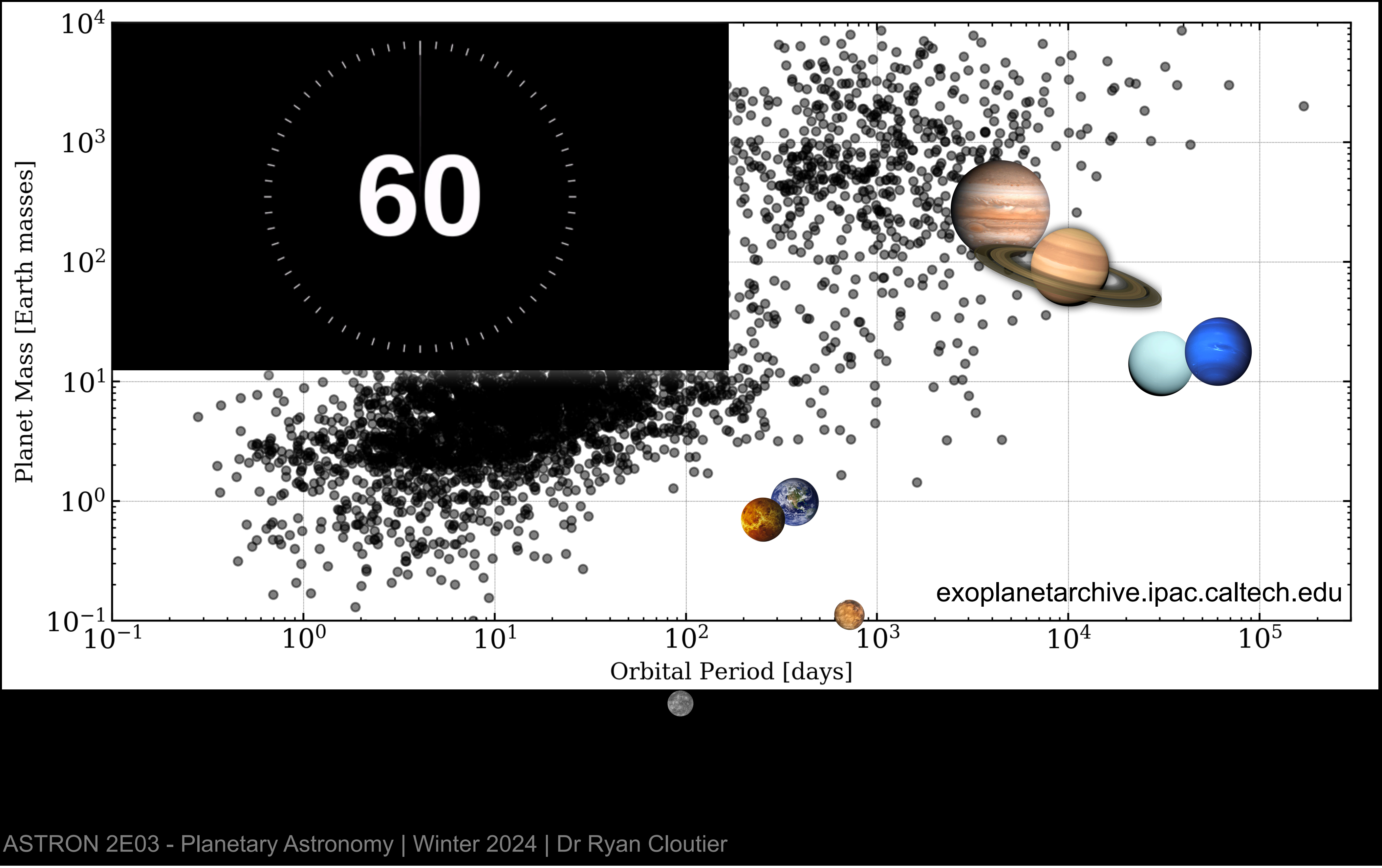

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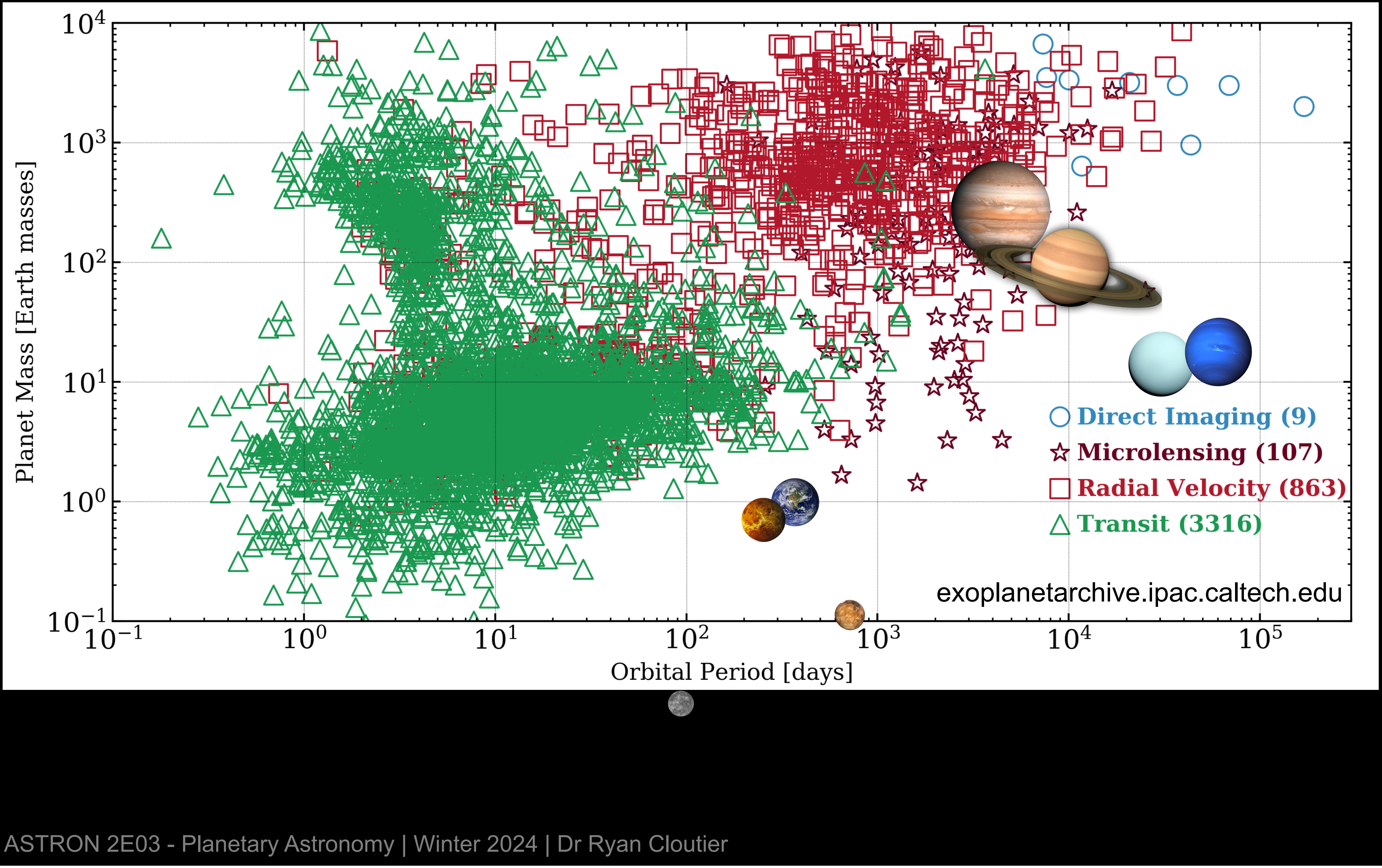
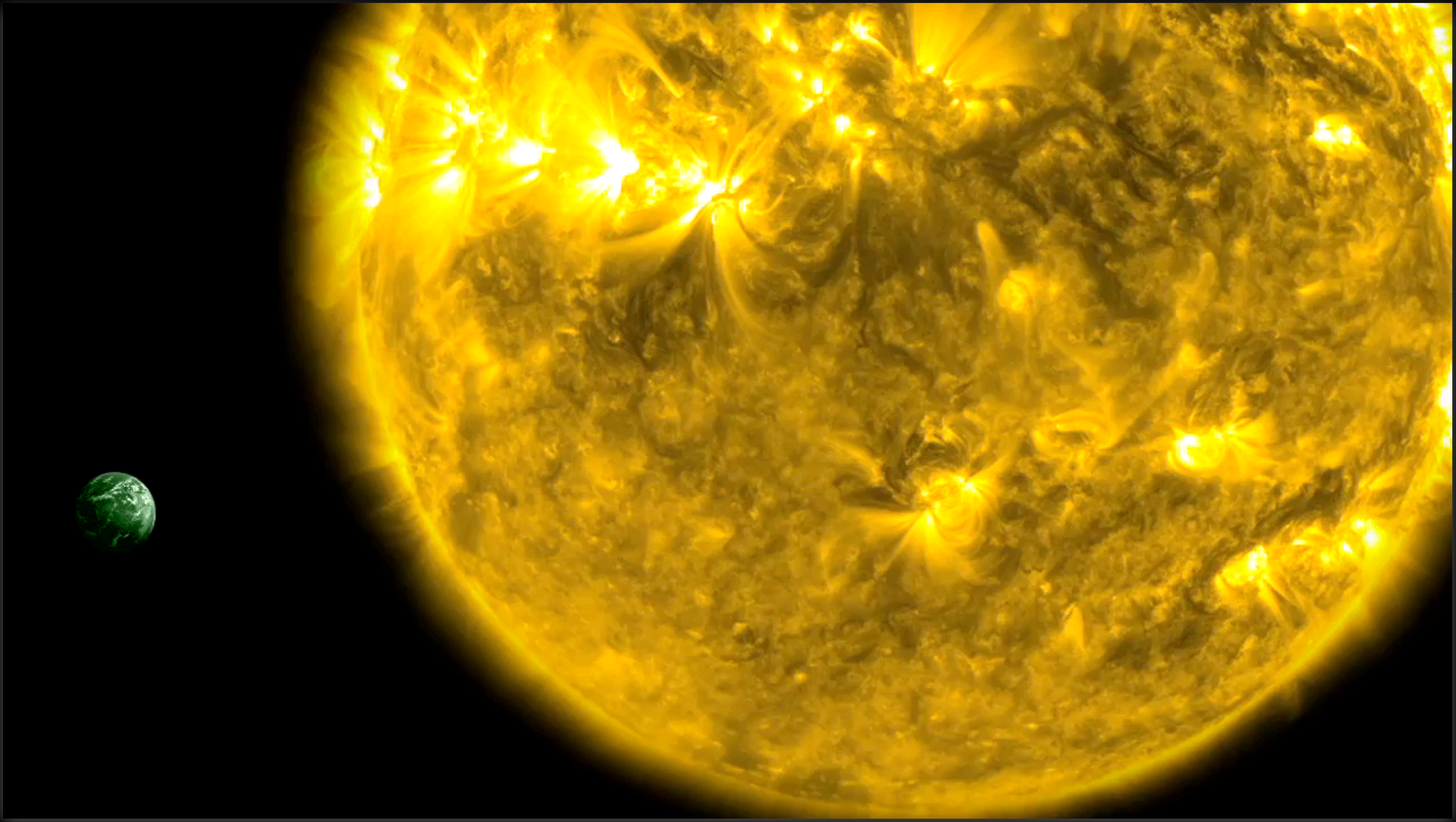


Method 1 - Transits



NASA/GSFC

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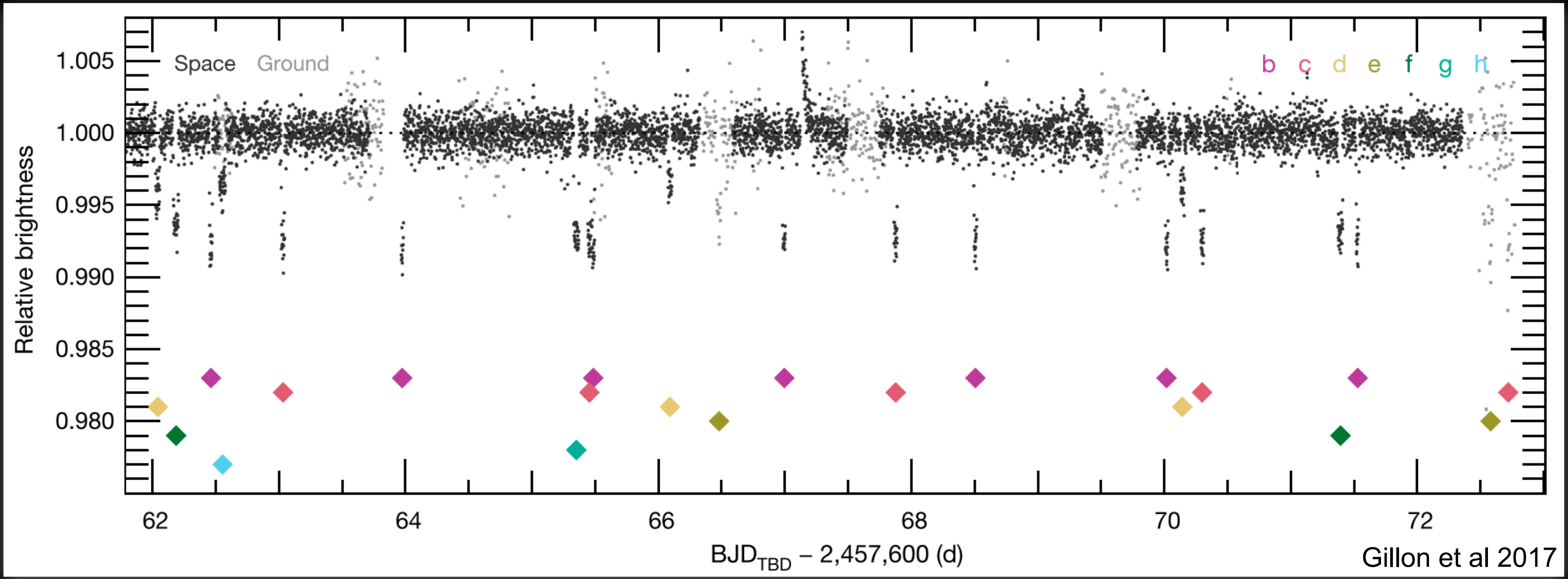


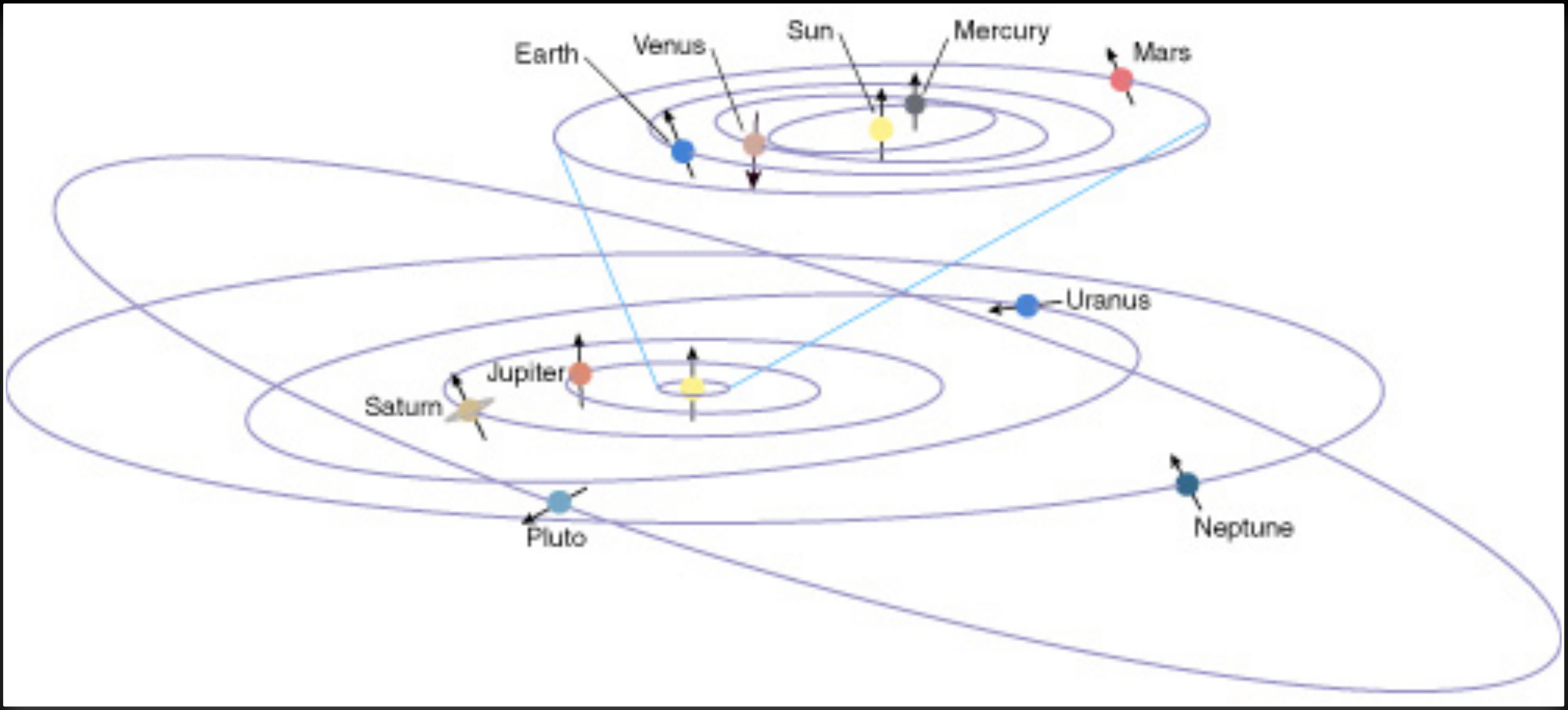
Gillon et al 2017

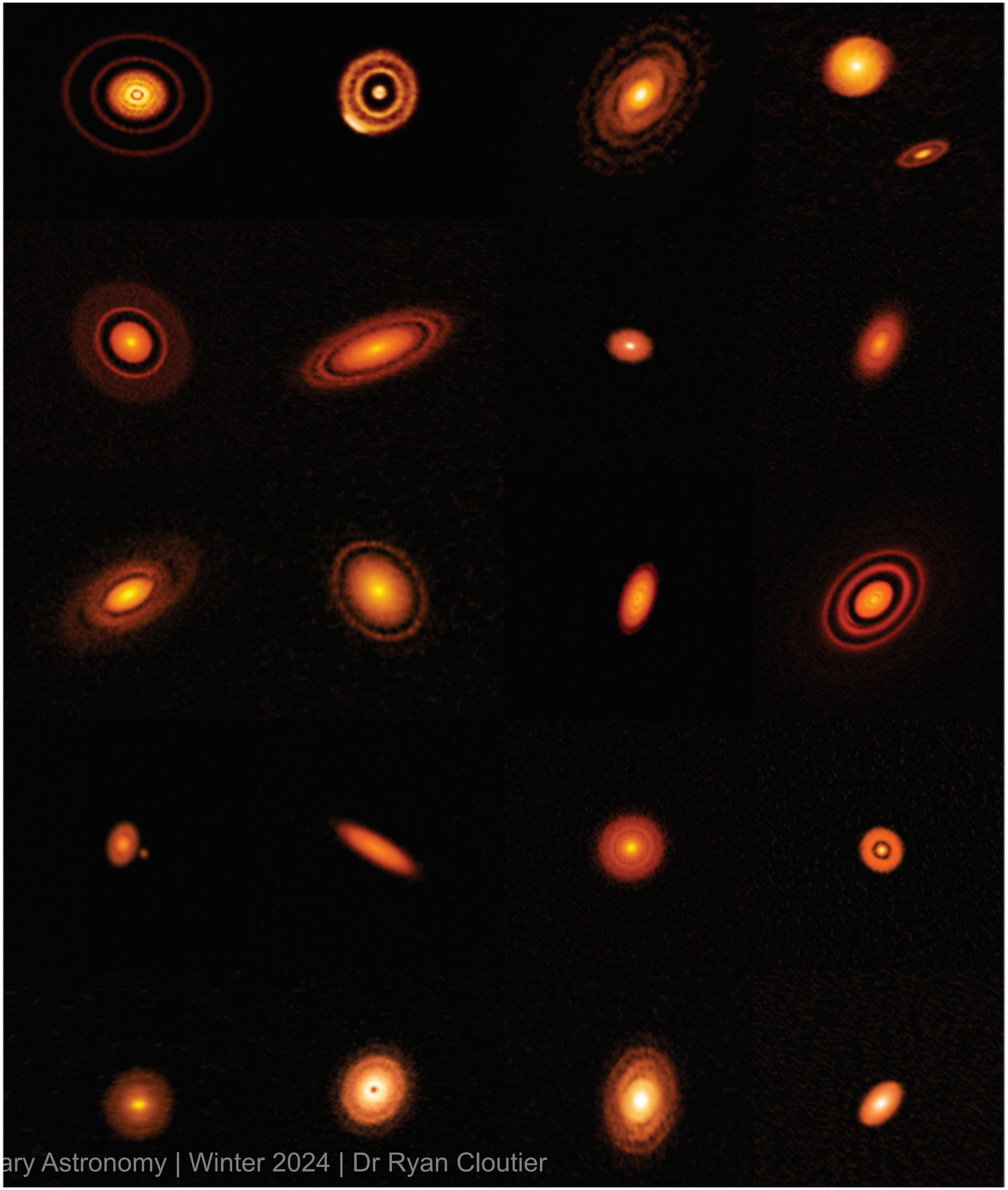
- Time-resolved photometry (i.e. stellar brightness) = **“light curve”**

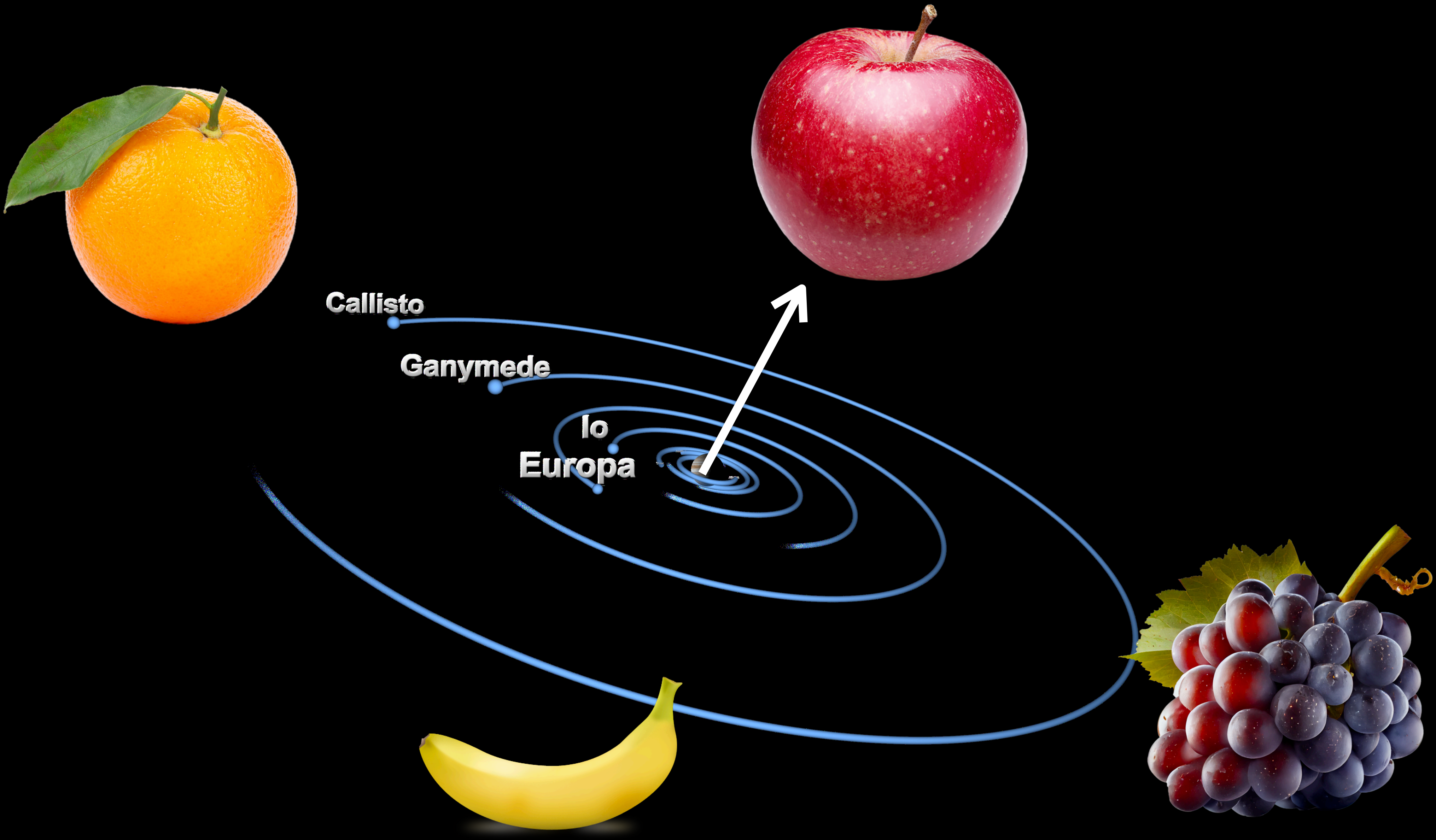
Can measure:

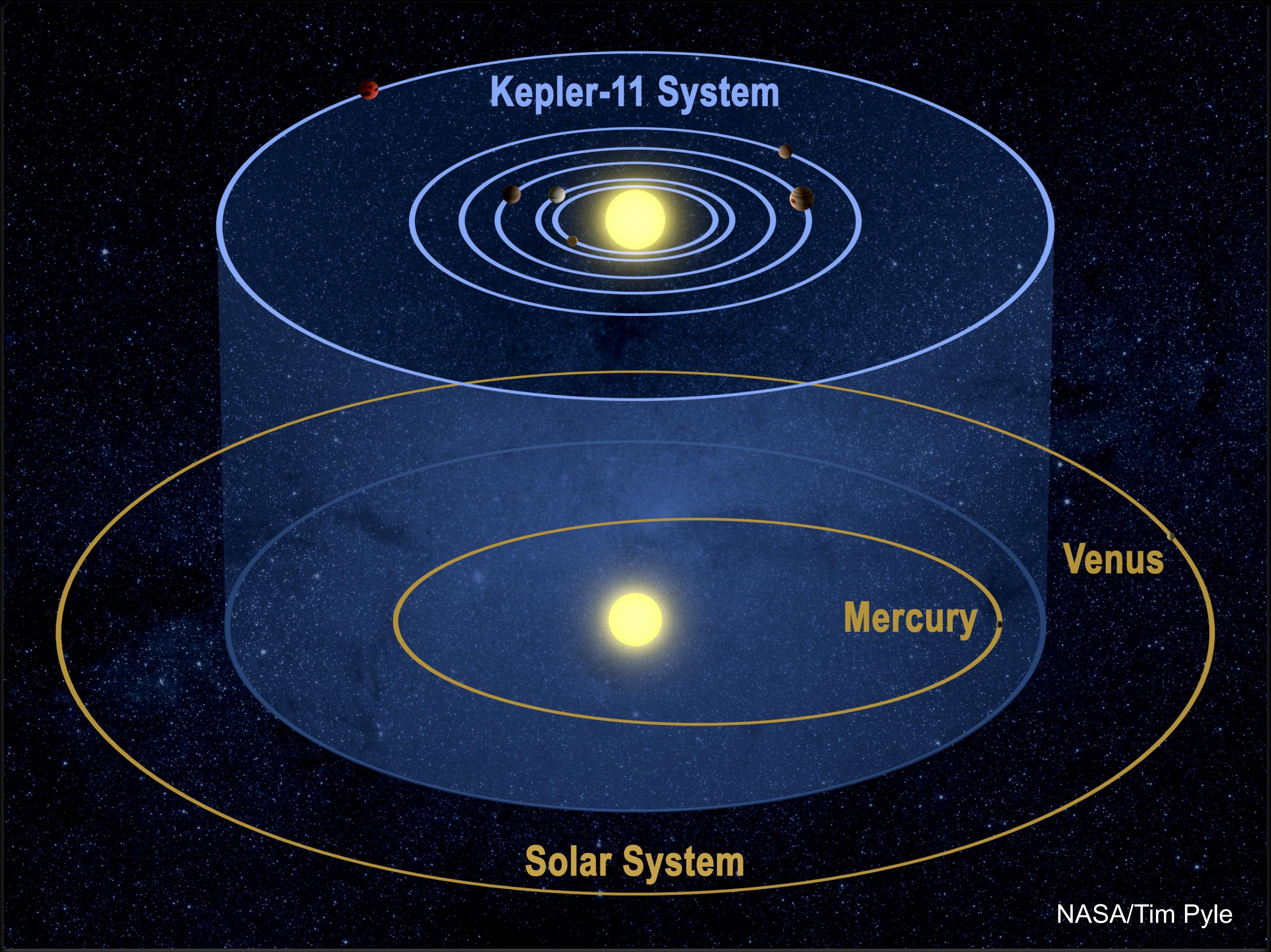
- Orbital period
- Orbital inclination
- Planet radius

Interactive Lecture

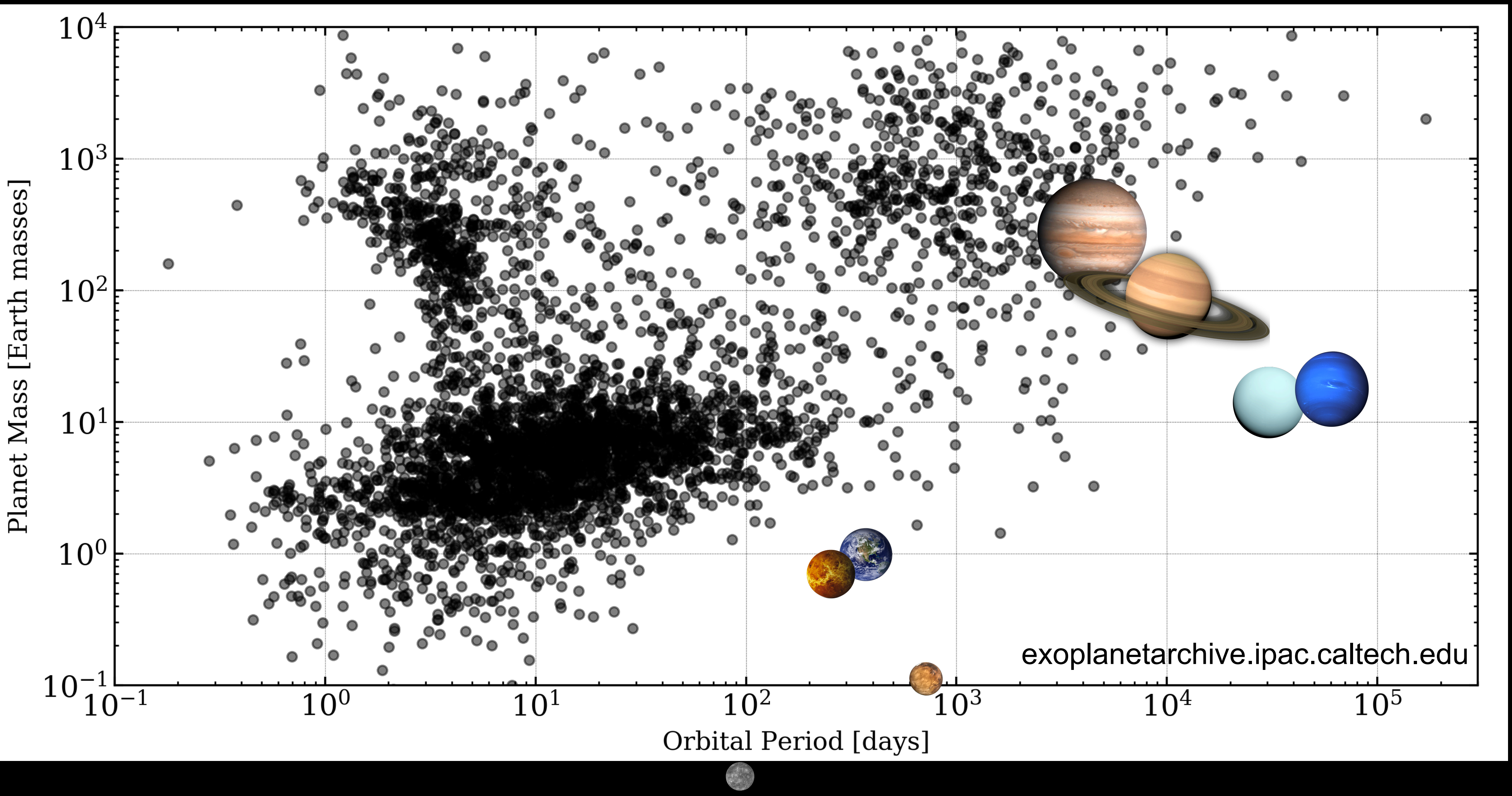




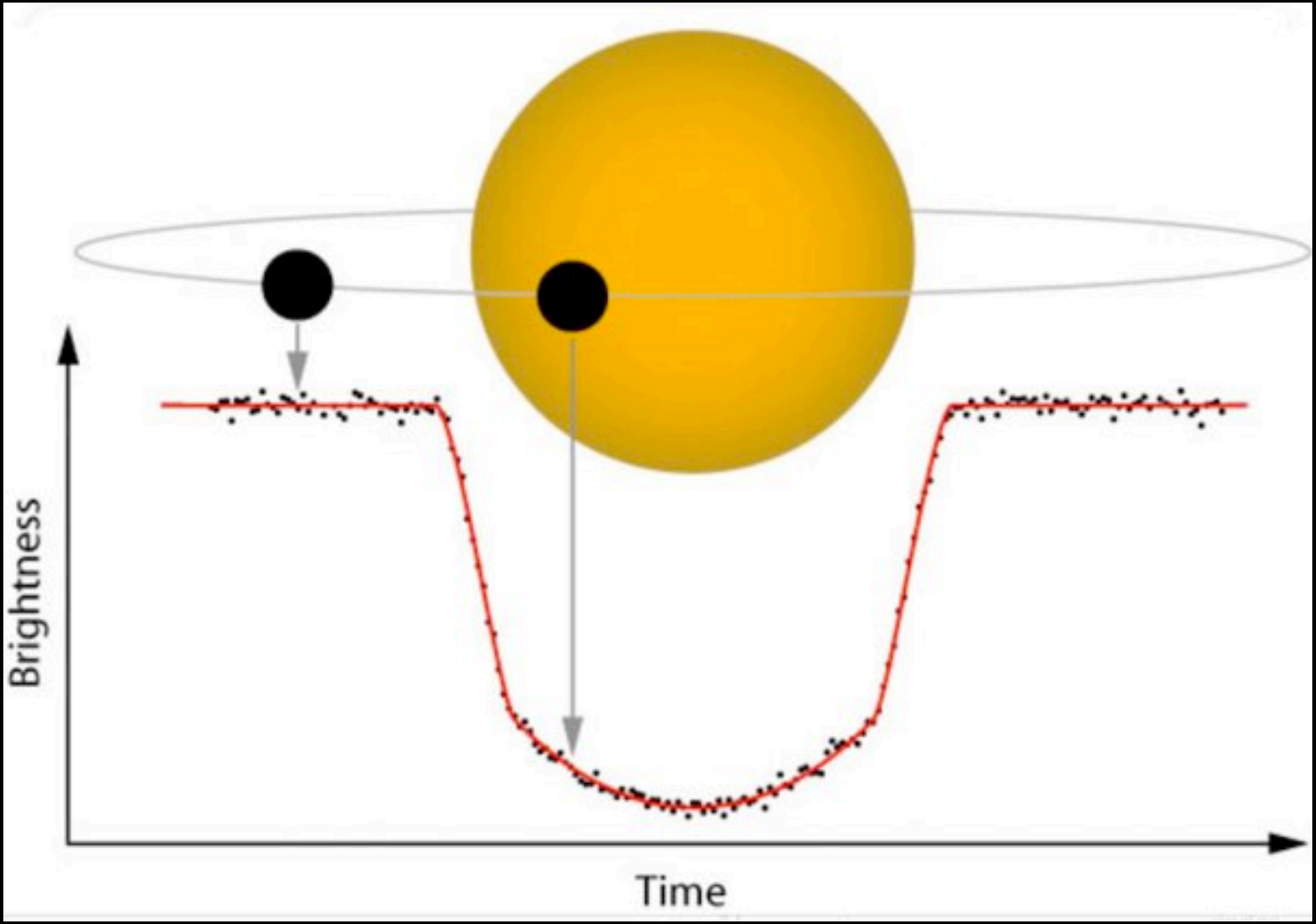

Callisto
Ganymede
Io
Europa



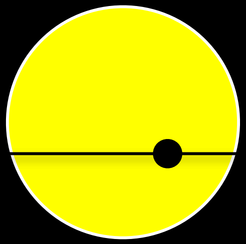
NASA/Tim Pyle



Planet Mass [Earth masses]
10^4
10^3
10^2
10^1
10^0
10^{-1}
Orbital Period [days]
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
exoplanetarchive.ipac.caltech.edu


Brightness
Time

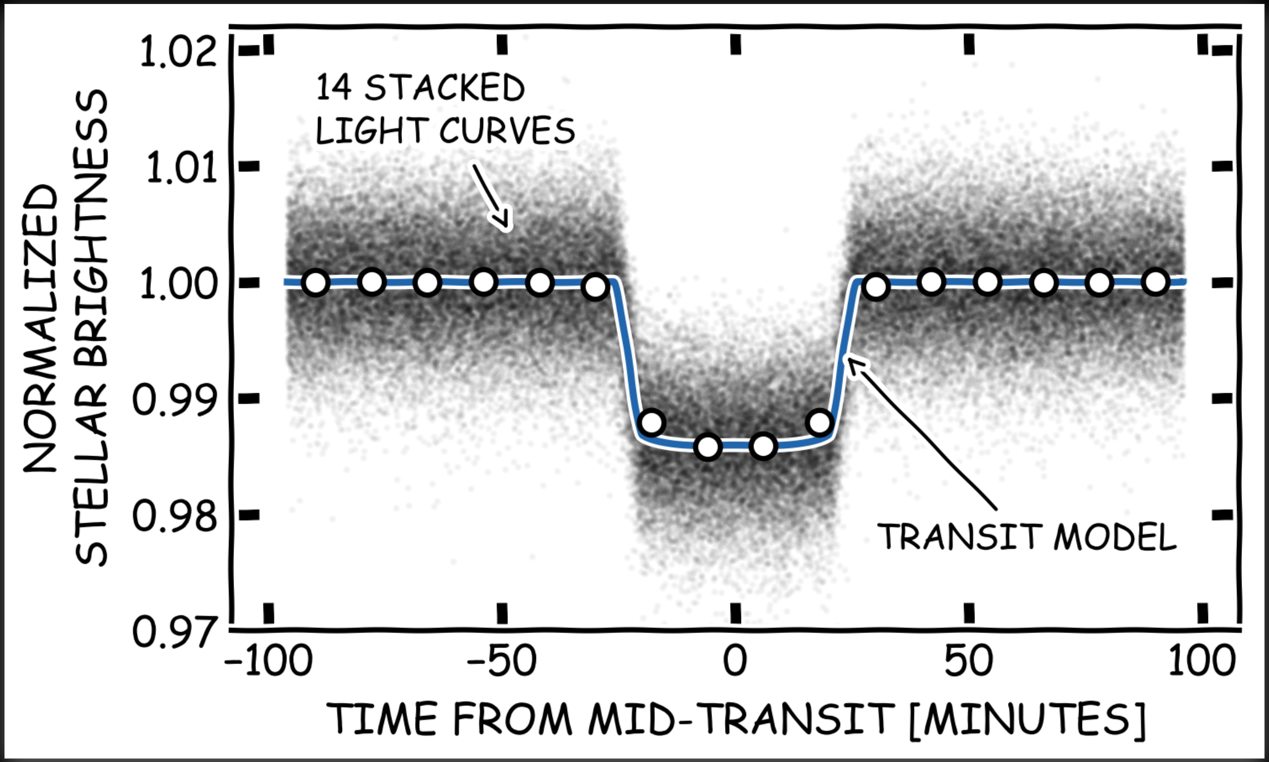
Transit Depth



$$Z = \frac{\mathrm{Area}_{\mathrm{pl}}}{\mathrm{Area}_\star}$$

$$= \left(\frac{R_{\mathrm{pl}}}{R_\star}\right)^2$$

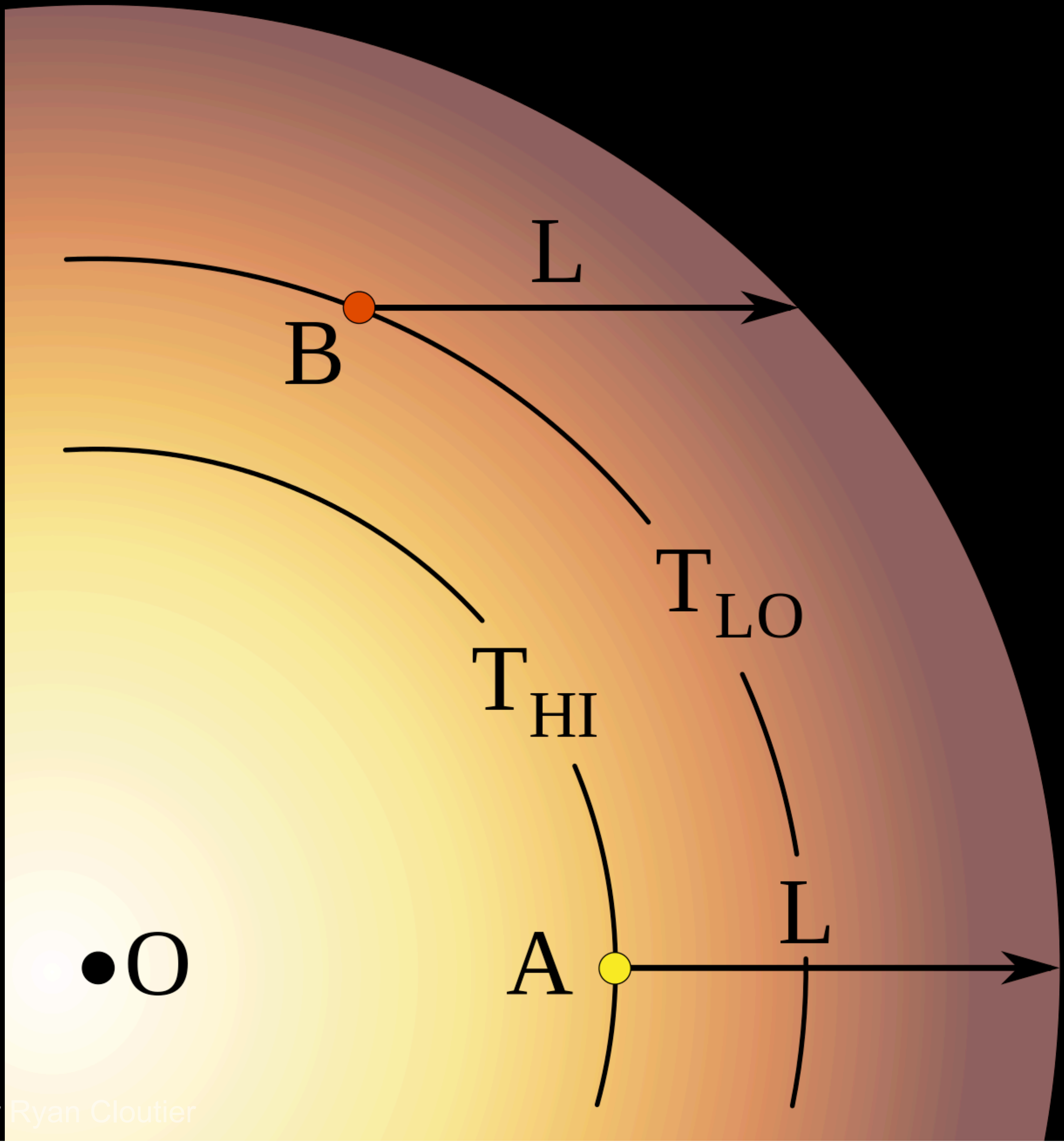
- Z: transit depth
- R_{pl}: planet radius
- $R_\star$: stellar radius



Cloutier et al 2021

Limb-darkening

- Stars appear fainter at their edges compared to their centers
- this limb-darkening depends on the star's temperature structure and the wavelength of the observations



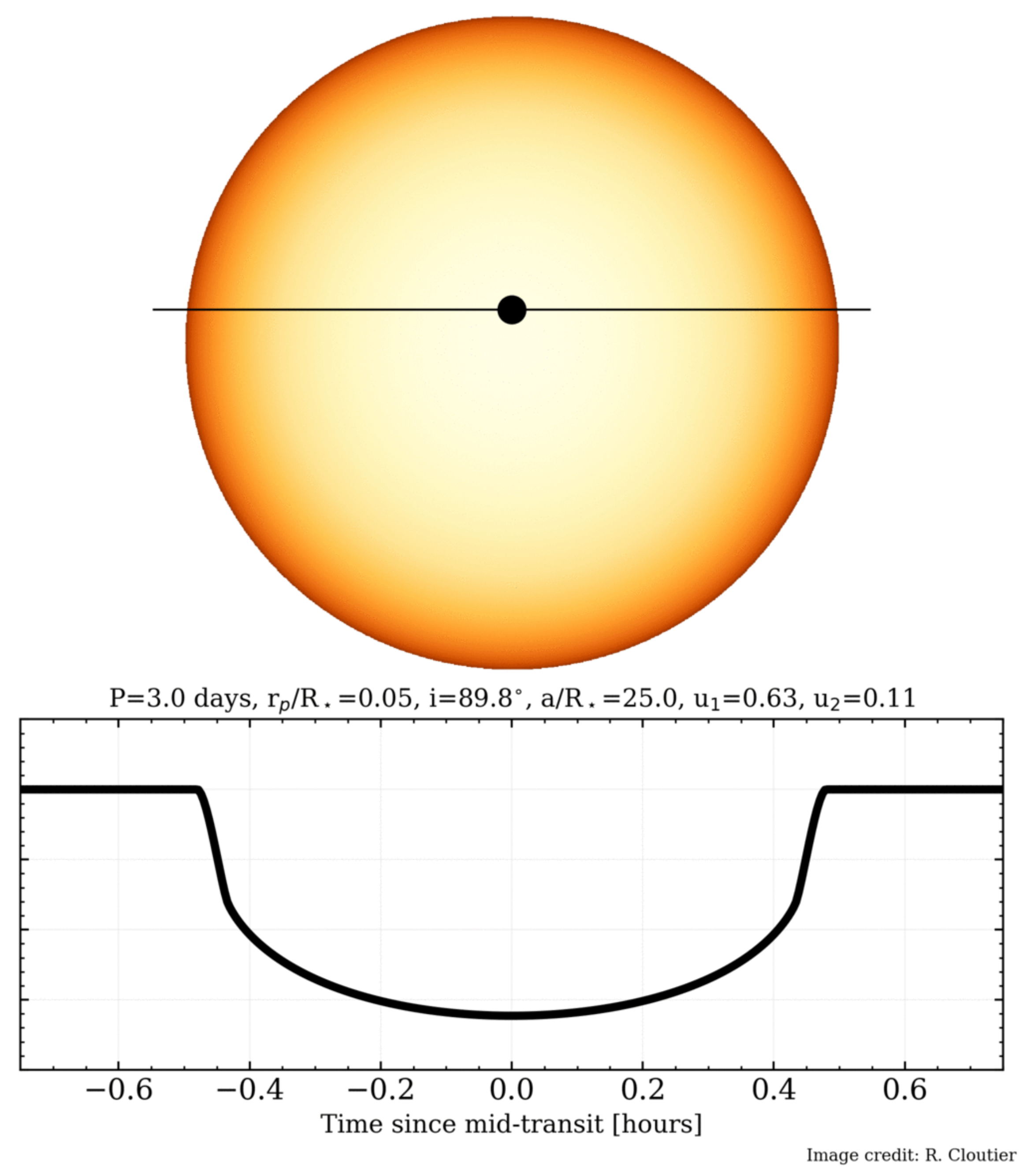


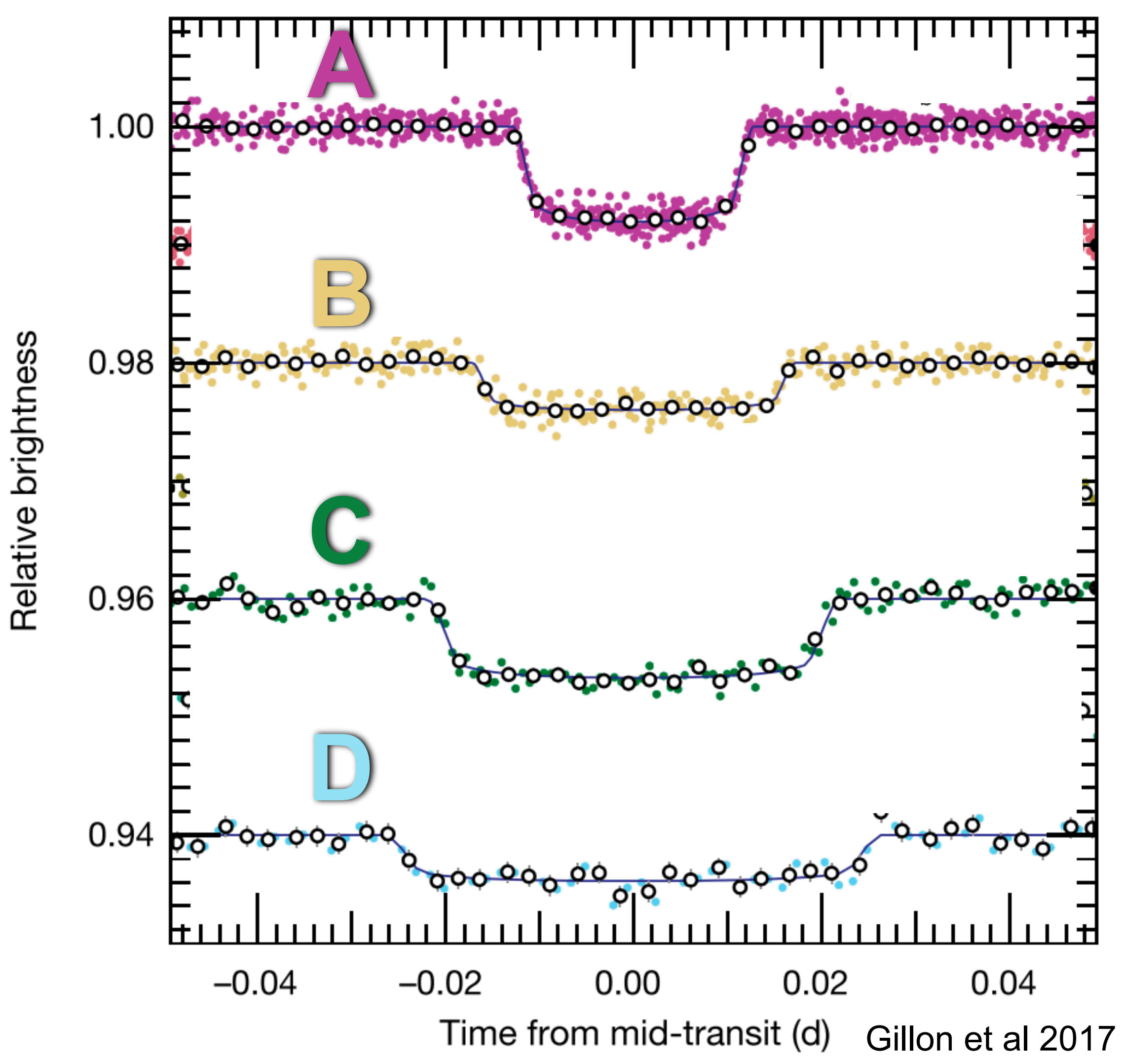
Image credit: R. Cloutier

A B

C D

All of these planets are in the same planetary system.

Which planet is the largest?

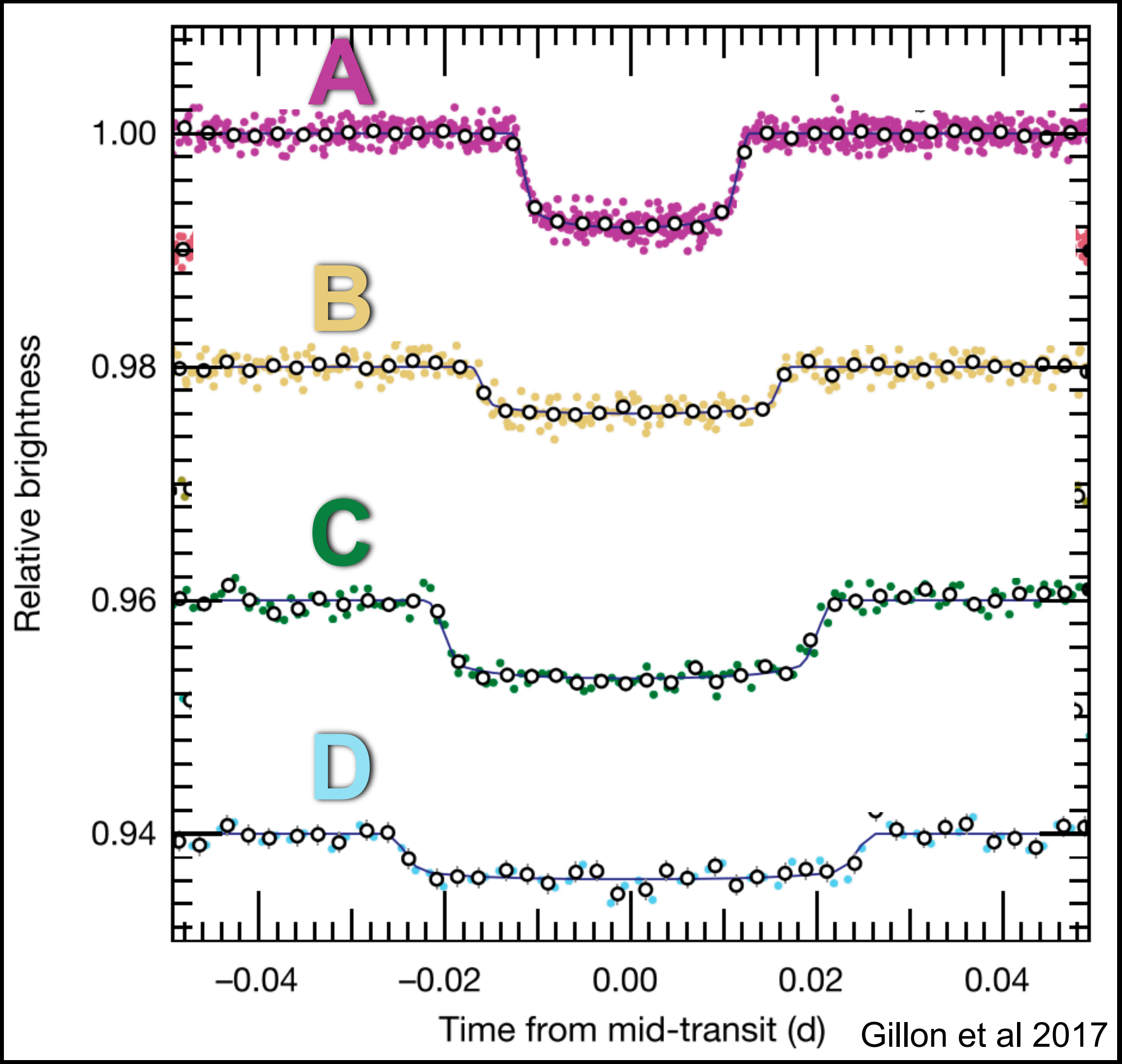


Gillon et al 2017

A	B
C	D

All of these planets are in the same planetary system.

Which planet exhibits the most severe limb-darkening effect?



Gillon et al 2017

A

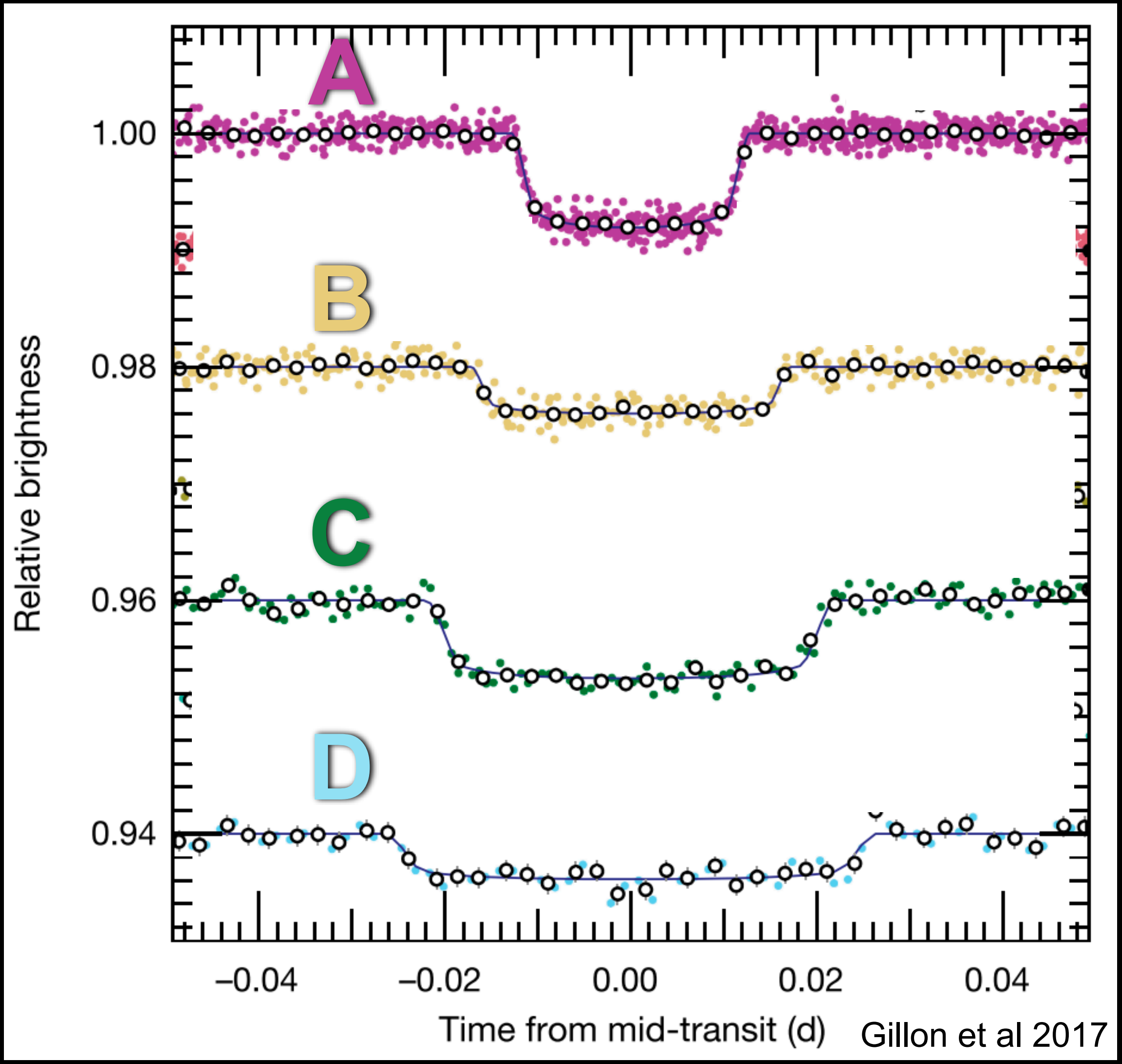
B

C

D

All of these planets are in the same planetary system.

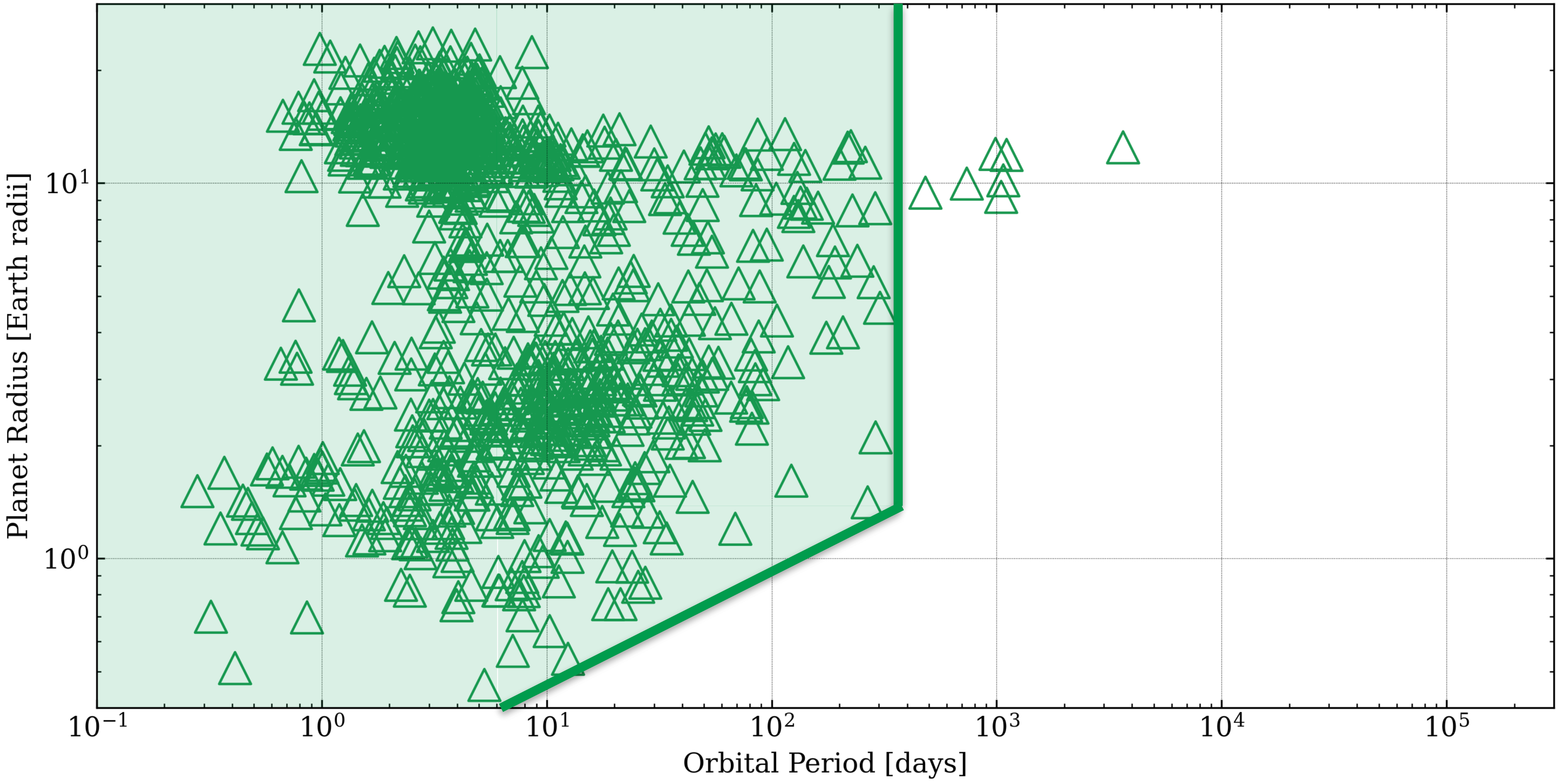
Which planet has the longest orbital period?



Gillon et al 2017

Known Transiting Exoplanets

Radius-Period diagram



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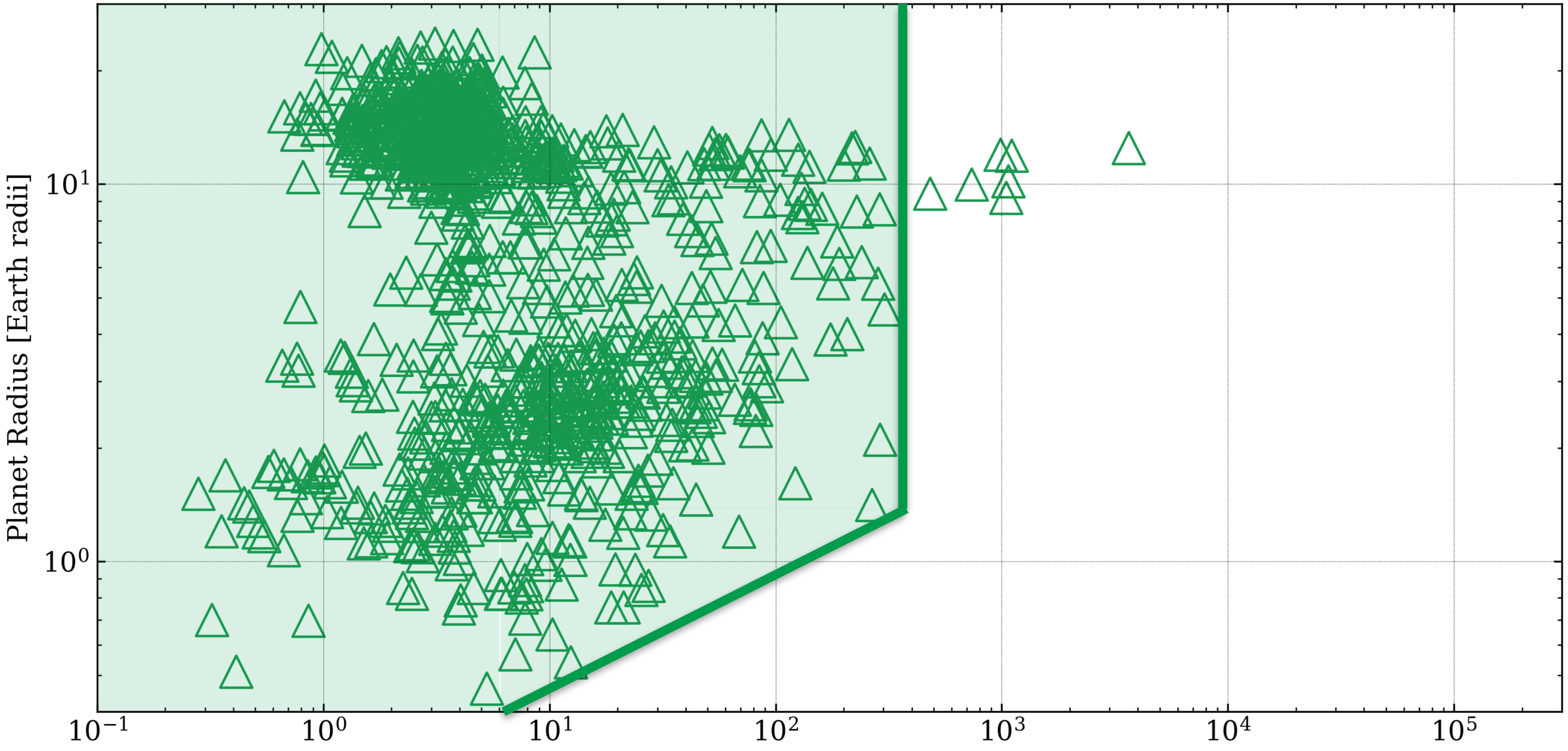
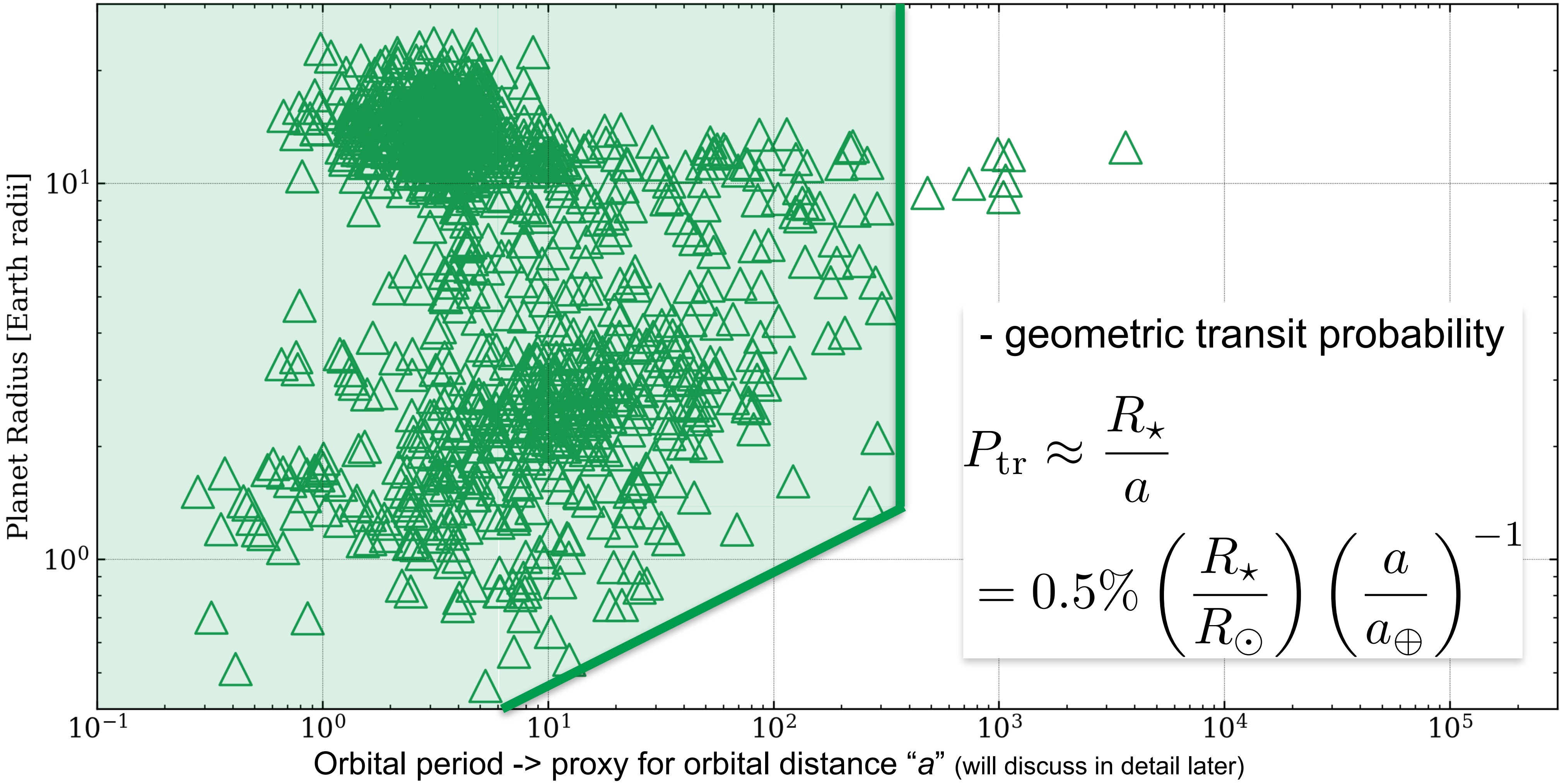


Orbital period -> proxy for orbital distance “*a*” (will discuss in detail later)

Known Transiting Exoplanets

Radius-Period diagram



- geometric transit probability

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

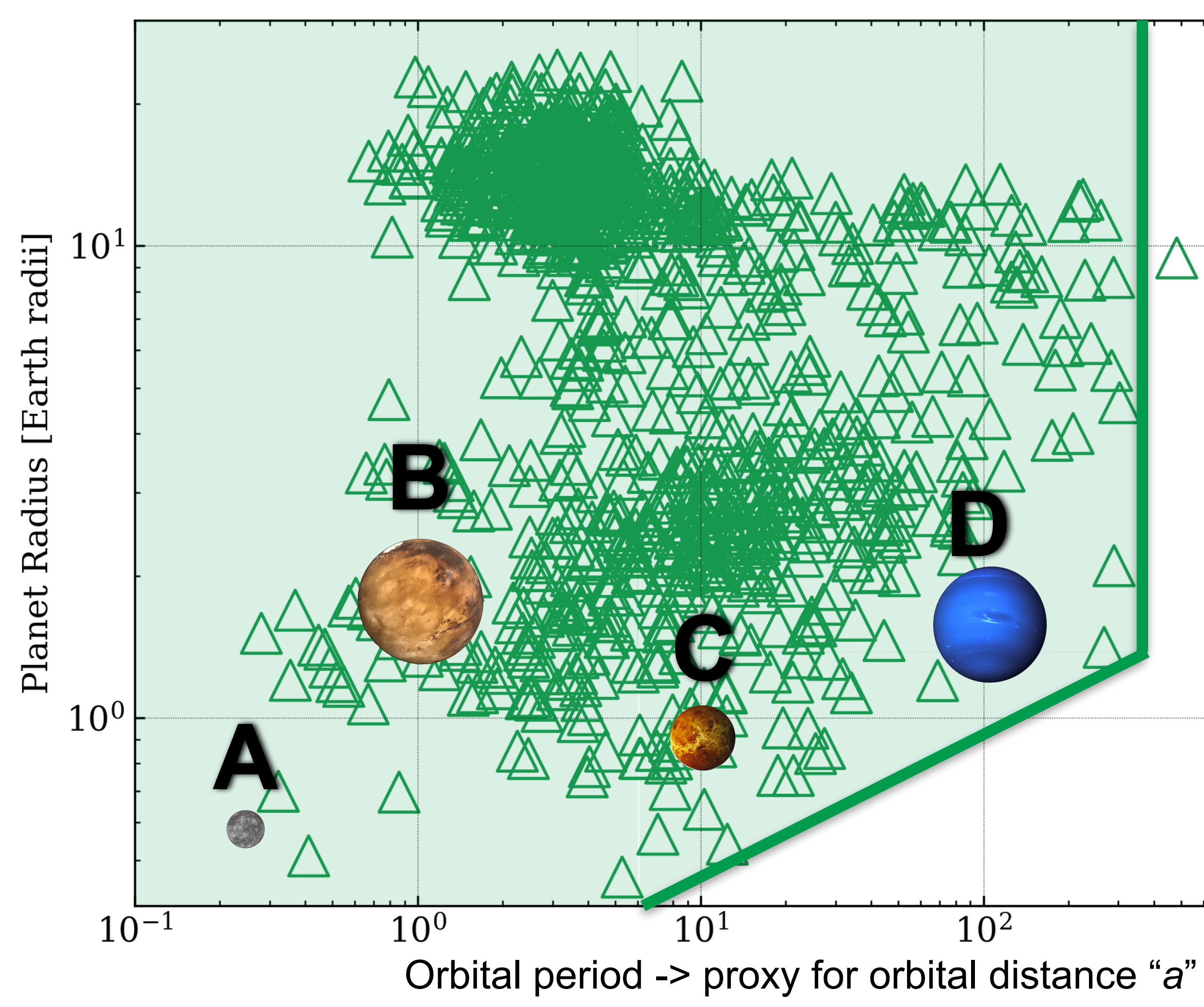
$$= 0.5\% \left(\frac{R_\star}{R_\odot}\right)\left(\frac{a}{a_\oplus}\right)^{-1}$$

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

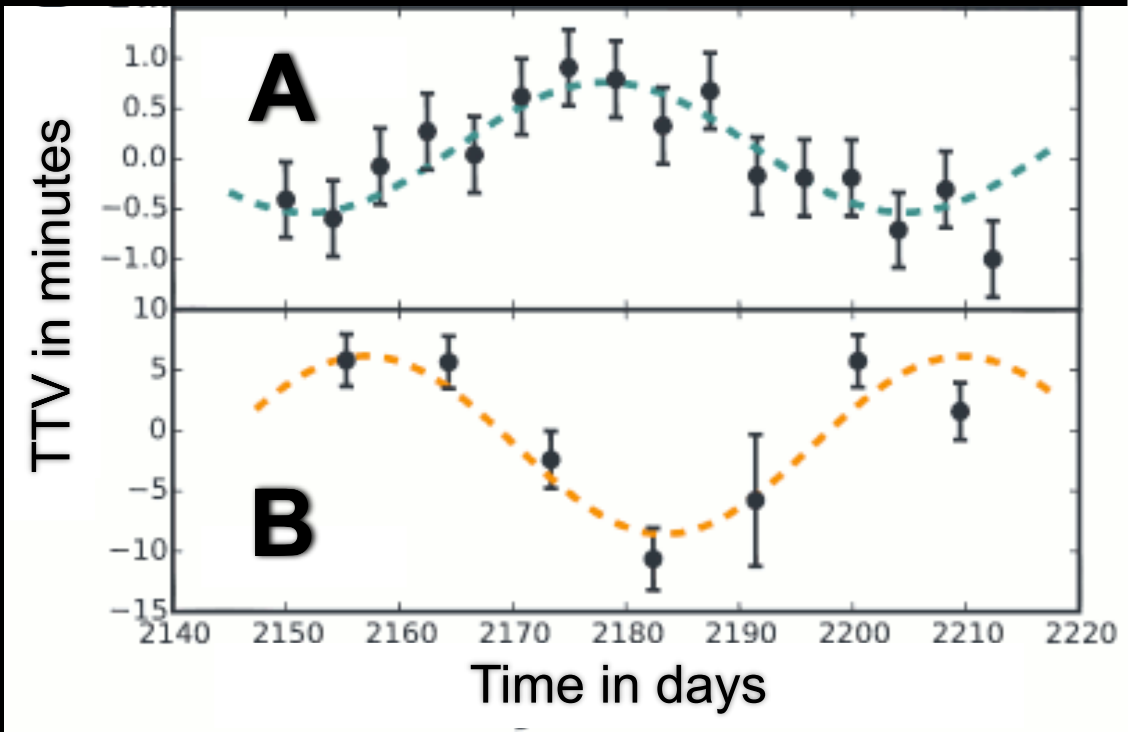
NASA Ames

A B

C D

Both planets in this planetary system exhibit transit timing variations.

Which planet exhibits the larger TTVs?



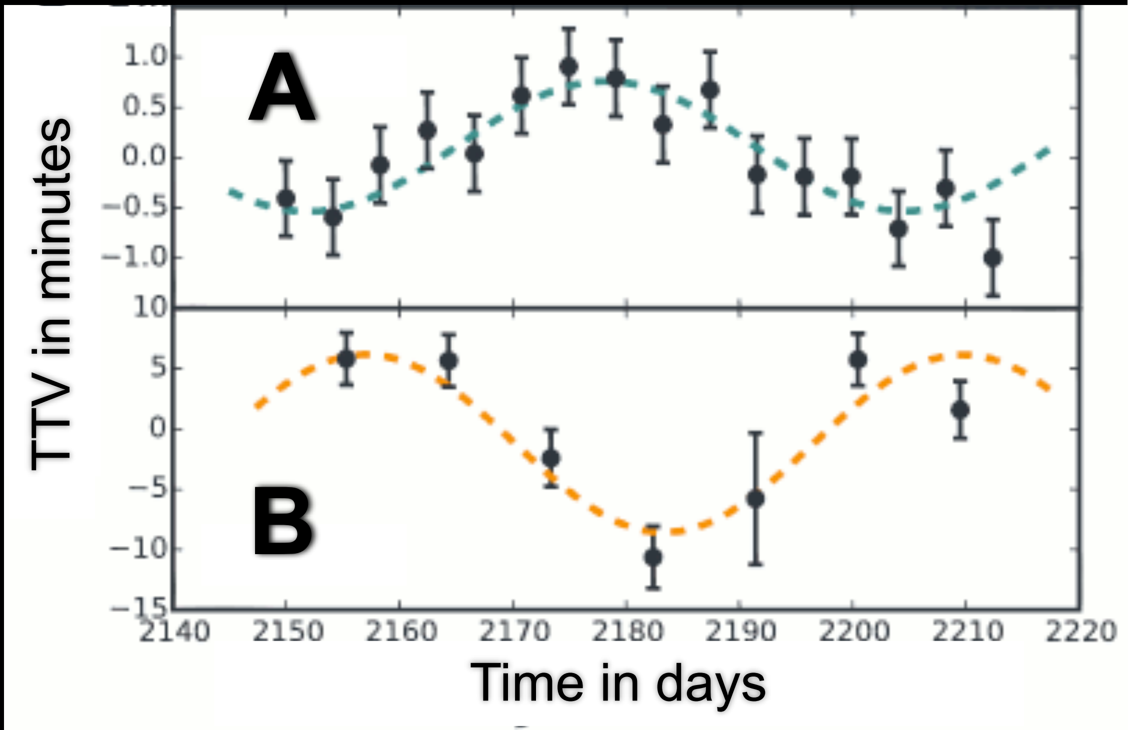
Becker et al 2015

A B

C D

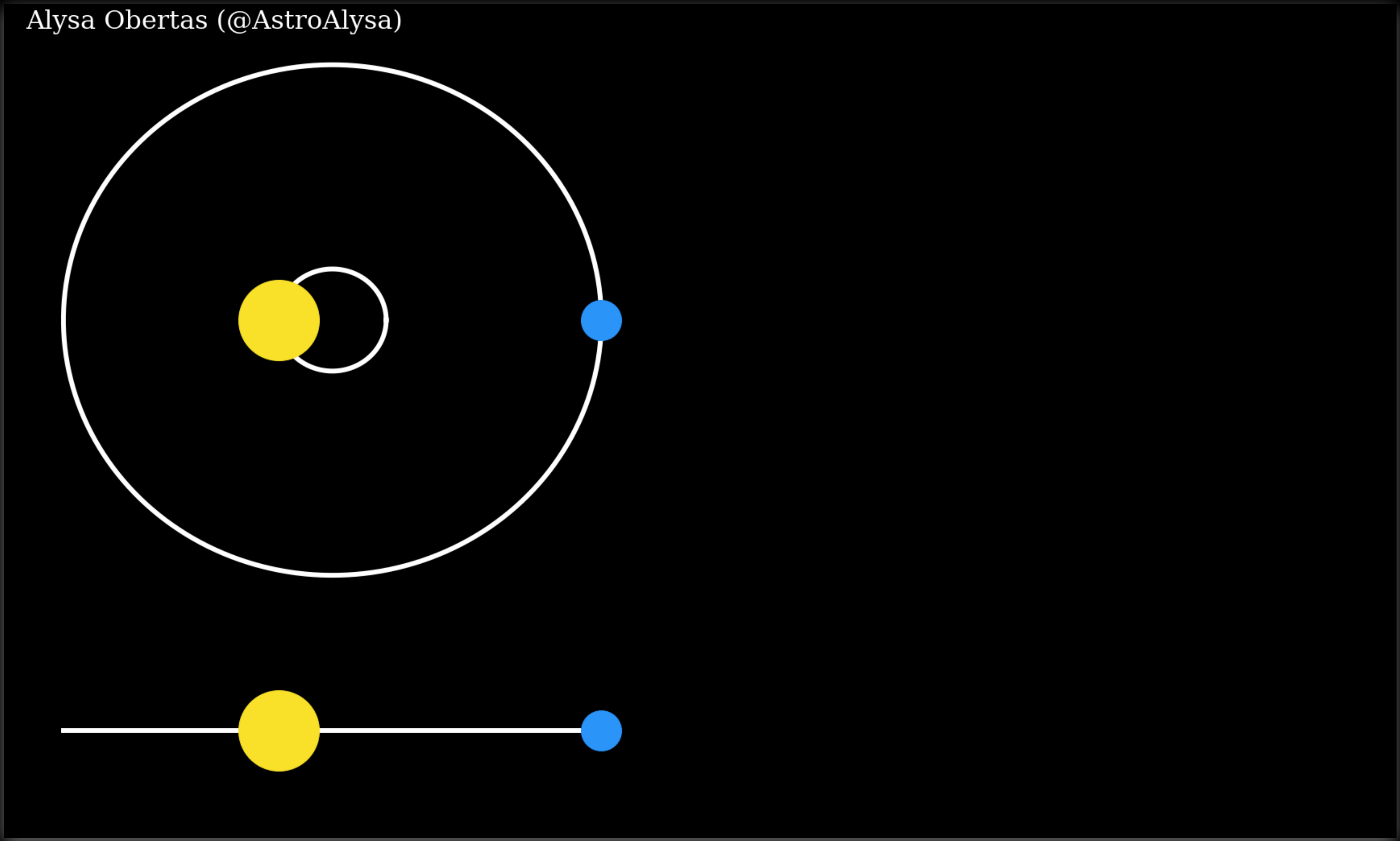
Both planets in this planetary system exhibit transit timing variations.

Which planet is more massive?



Becker et al 2015

Method 3 - Radial Velocity


Alysa Obertas (@AstroAlysa)

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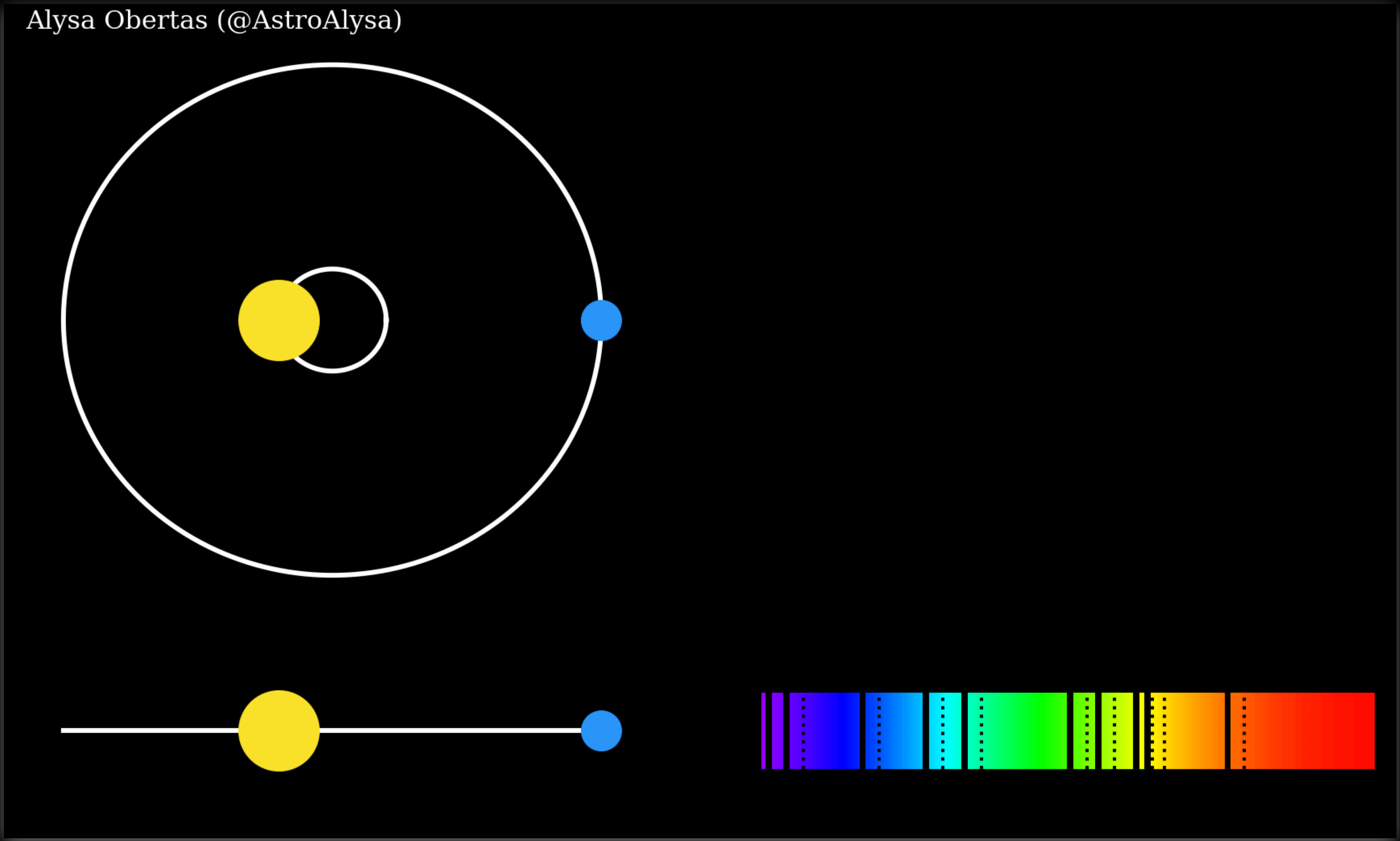
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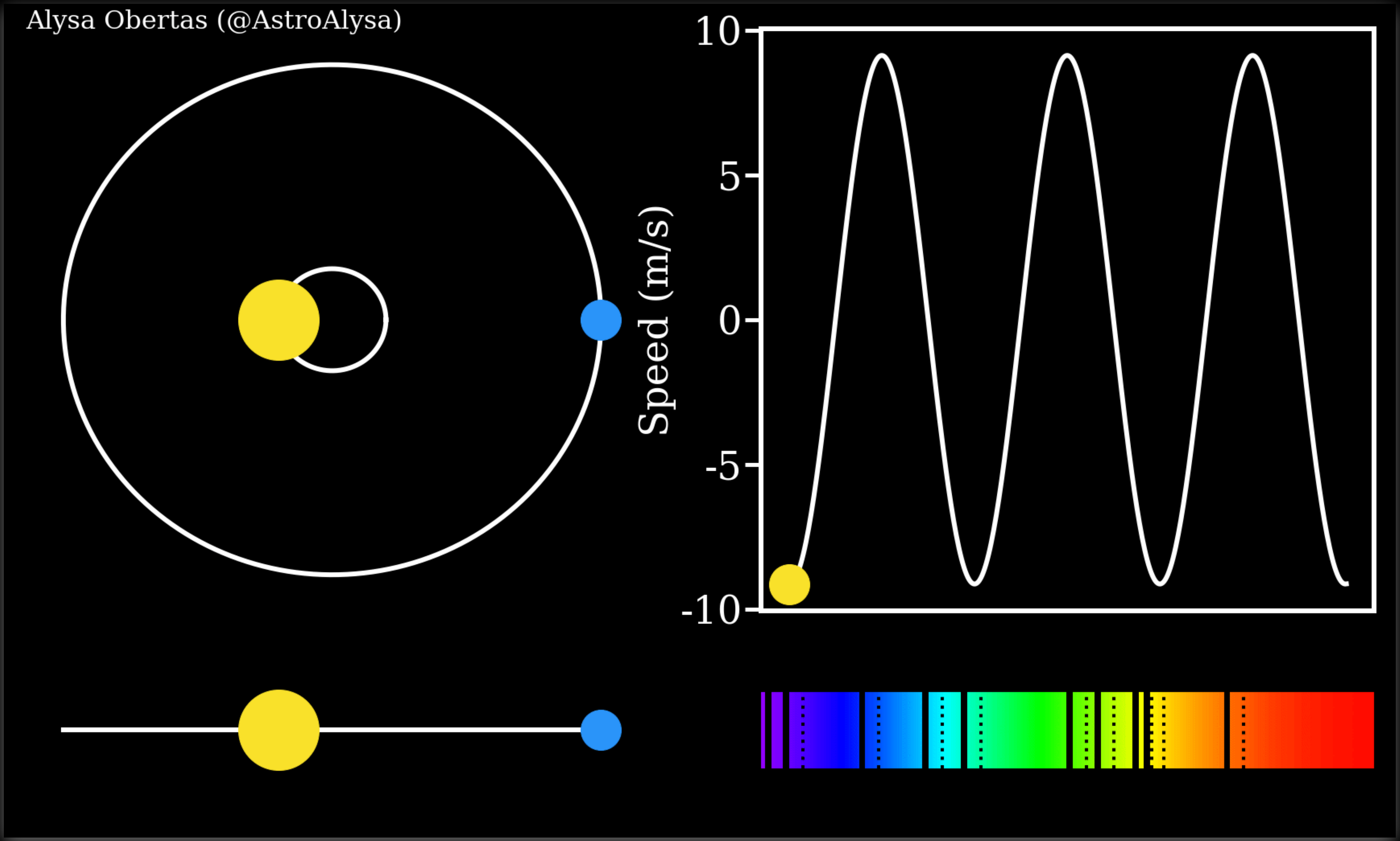
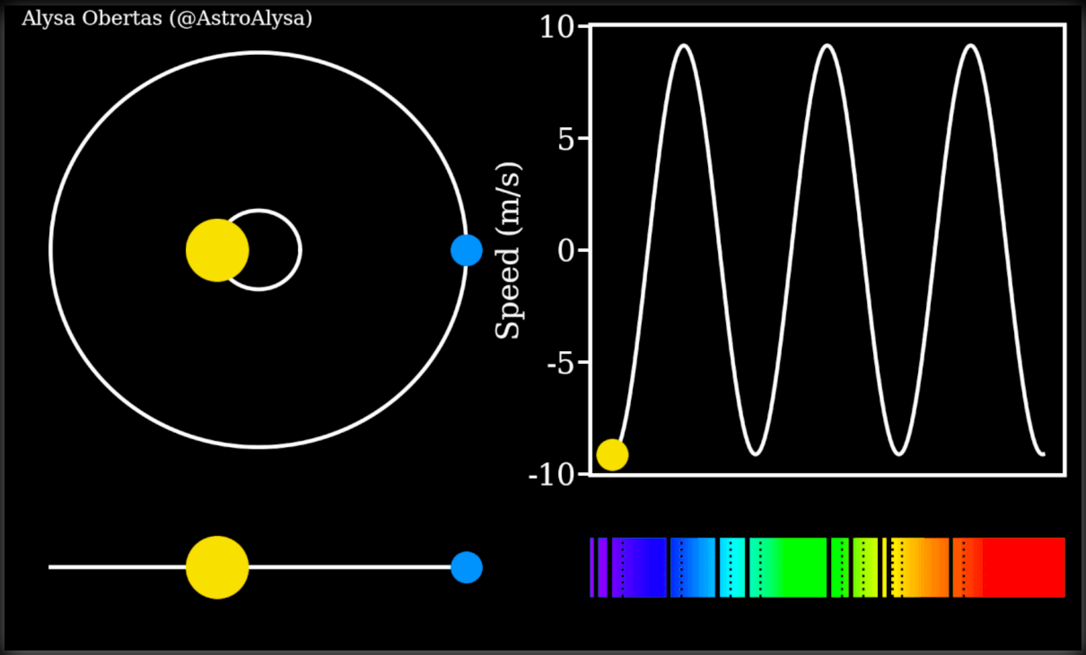


Method 3 - Radial Velocity

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

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



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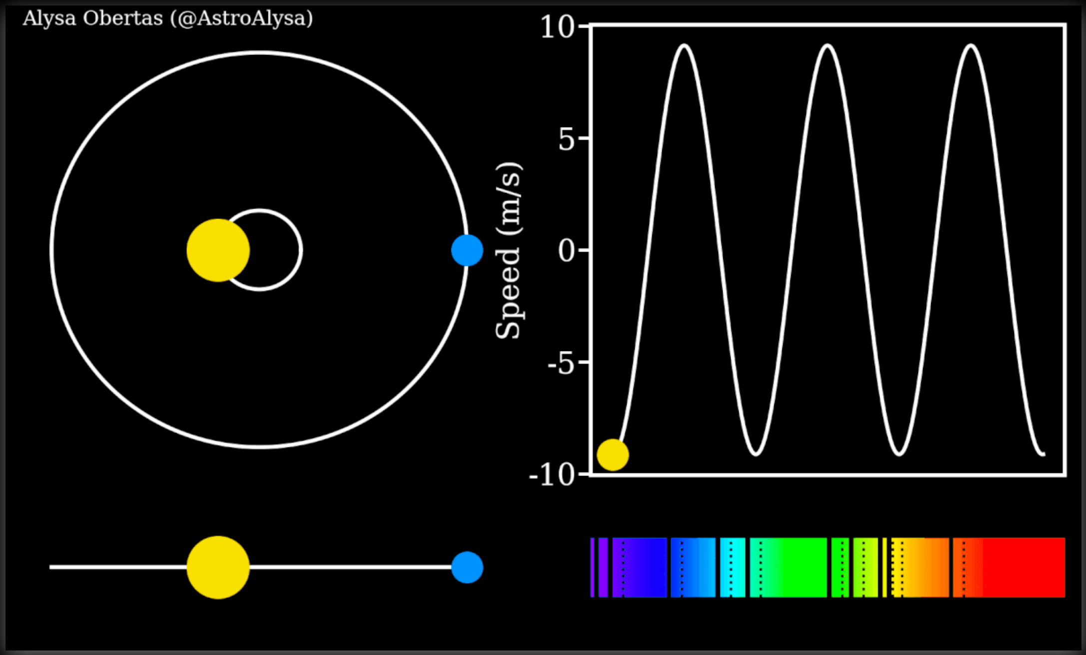
Can measure:

  - Orbital period



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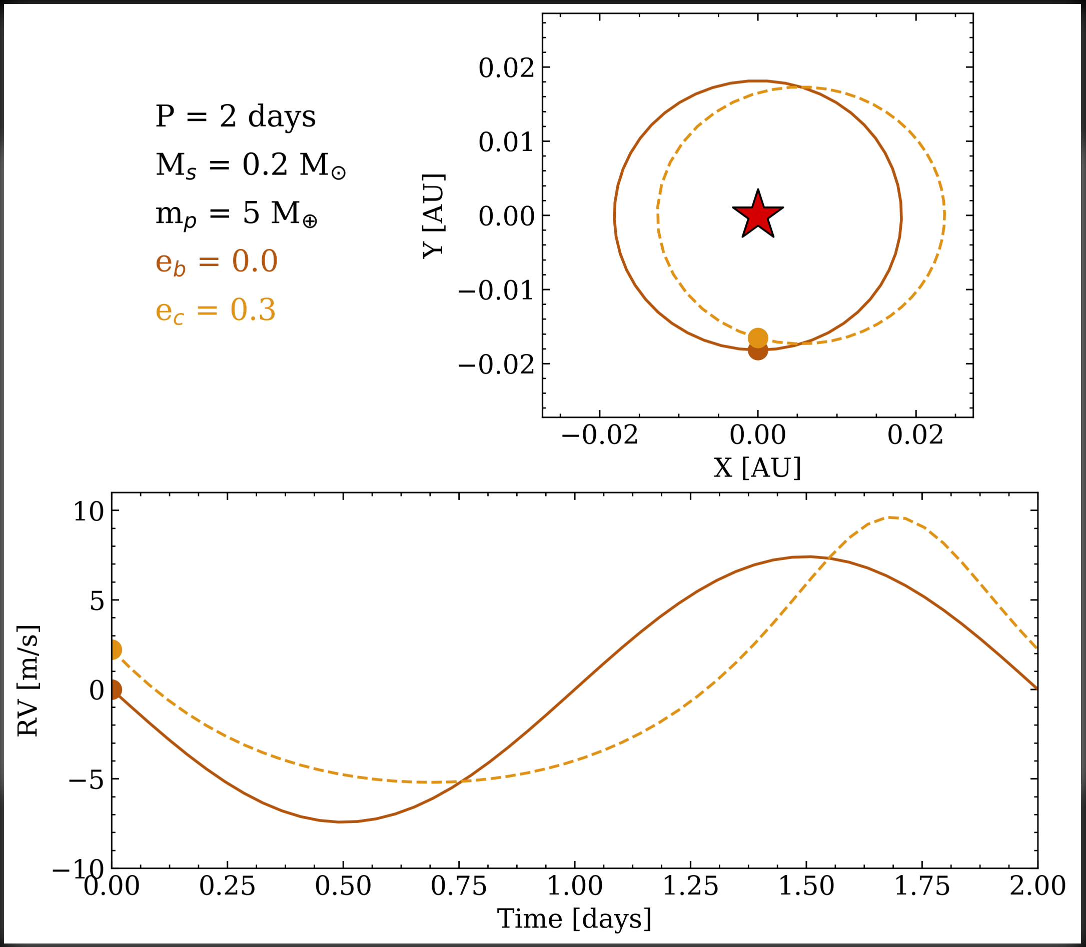
Can measure:

- Orbital period
- Orbital eccentricity



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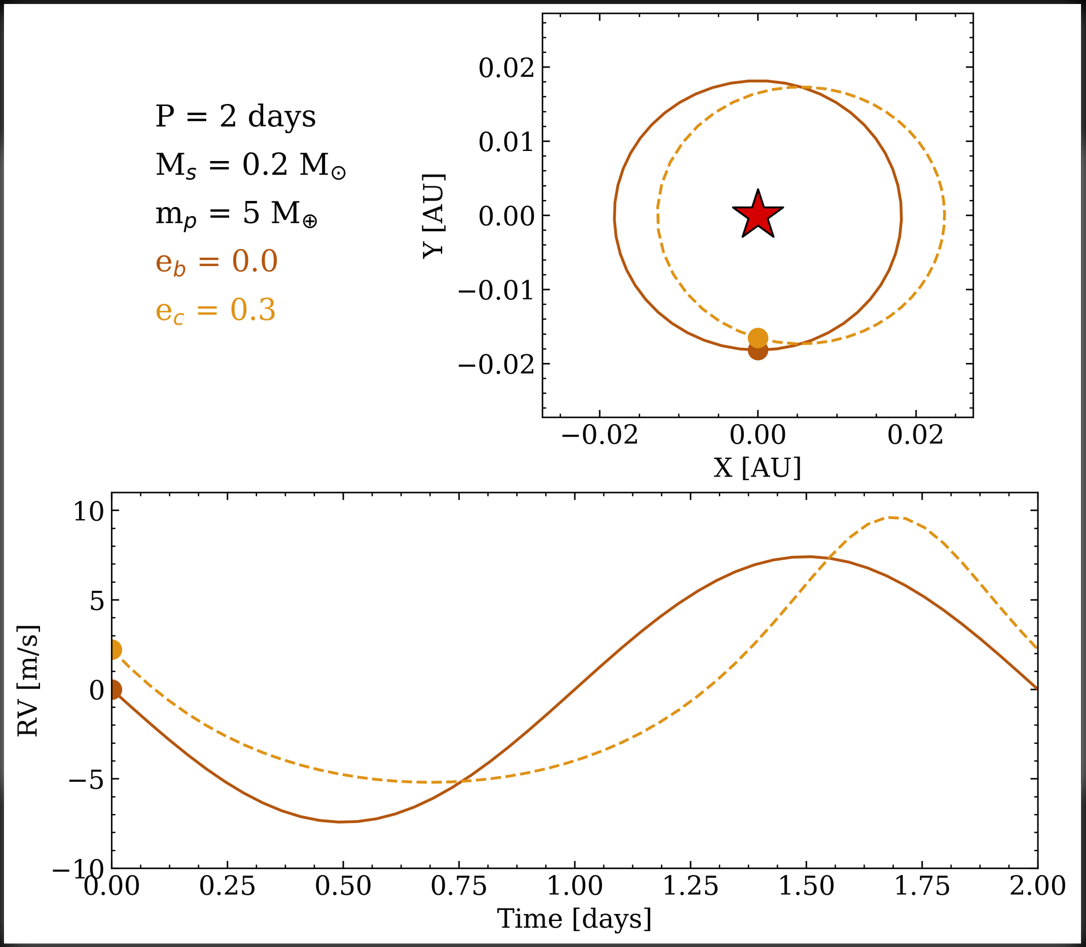
Can measure:

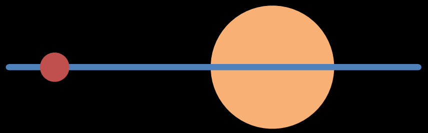
- Orbital period
- Orbital eccentricity
- Planet's *minimum mass



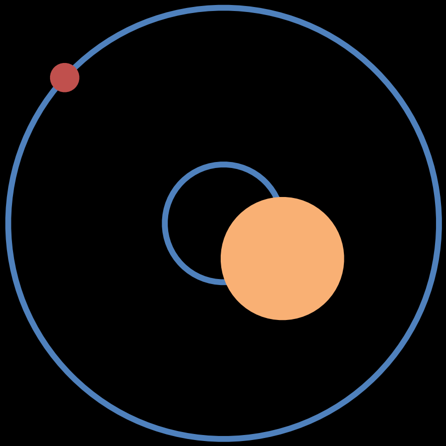
A B
C D

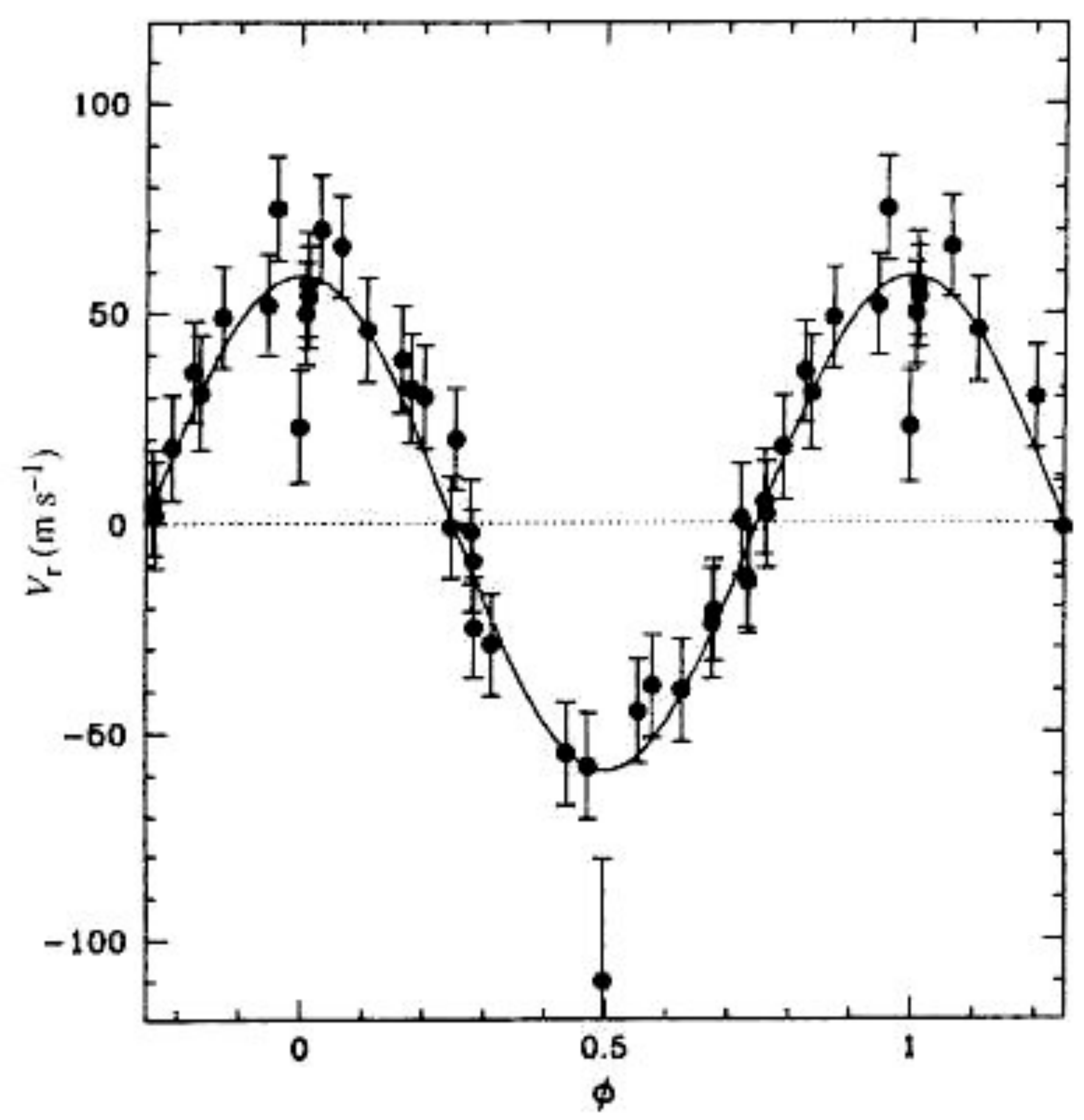
From your point of view, which orbital orientation below produced the RV variations shown in the figure?

A



B





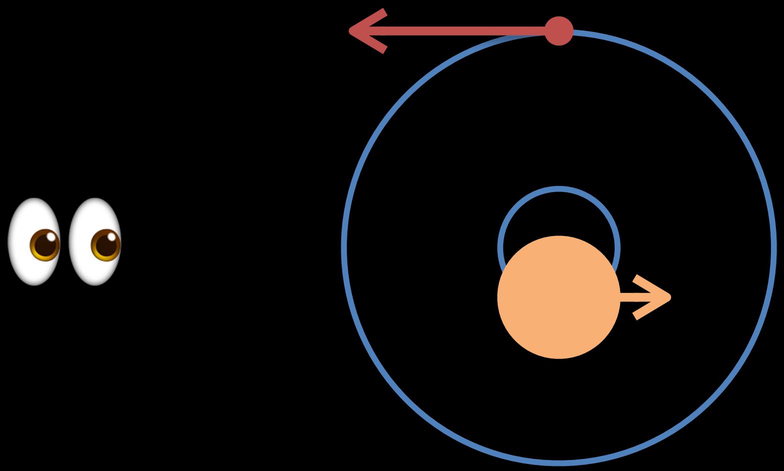
Mayor & Queloz 1995

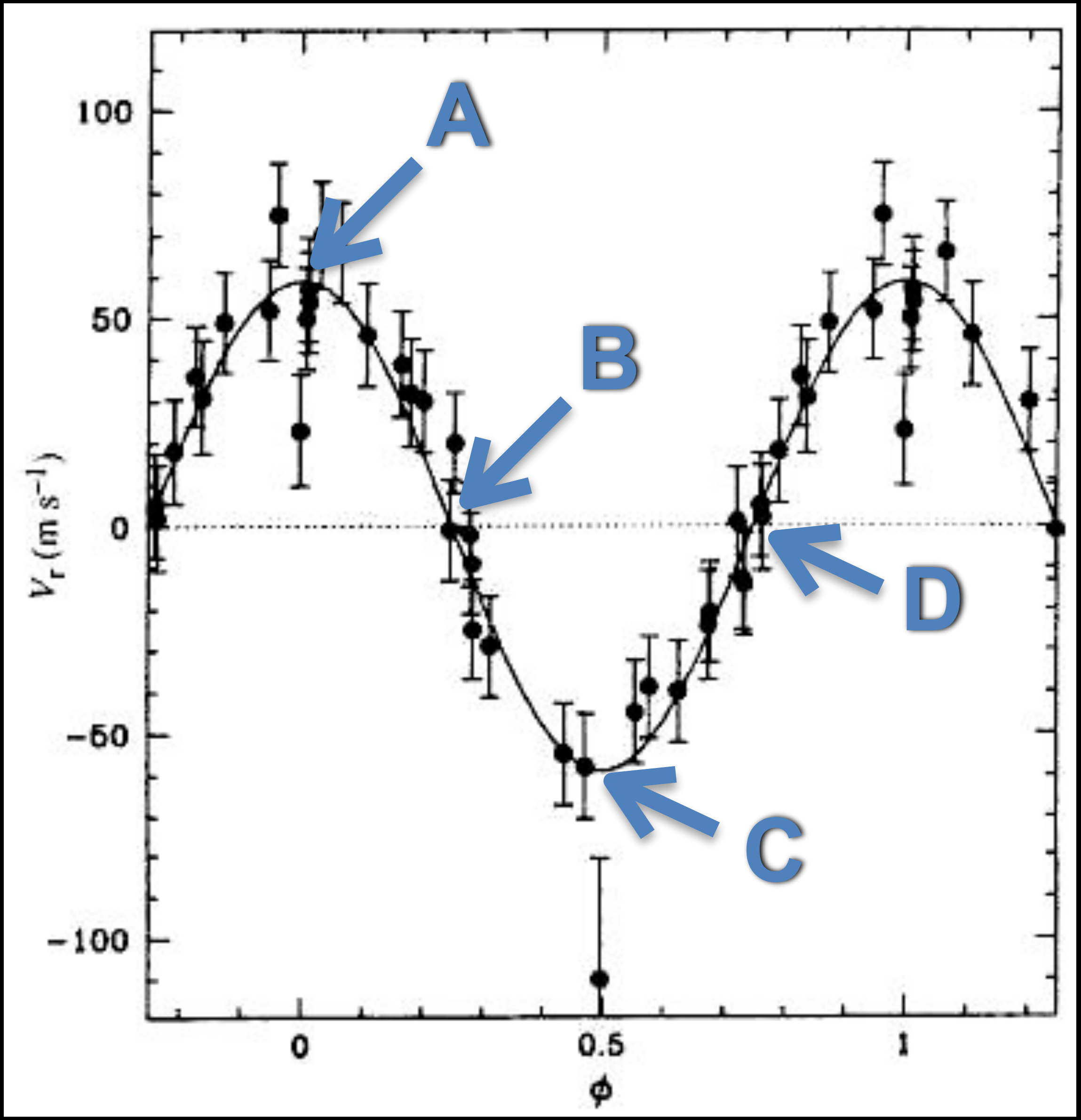
A B

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

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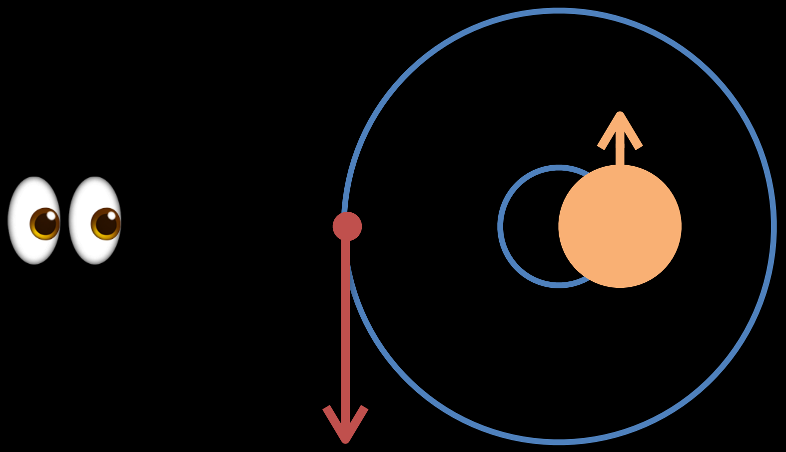

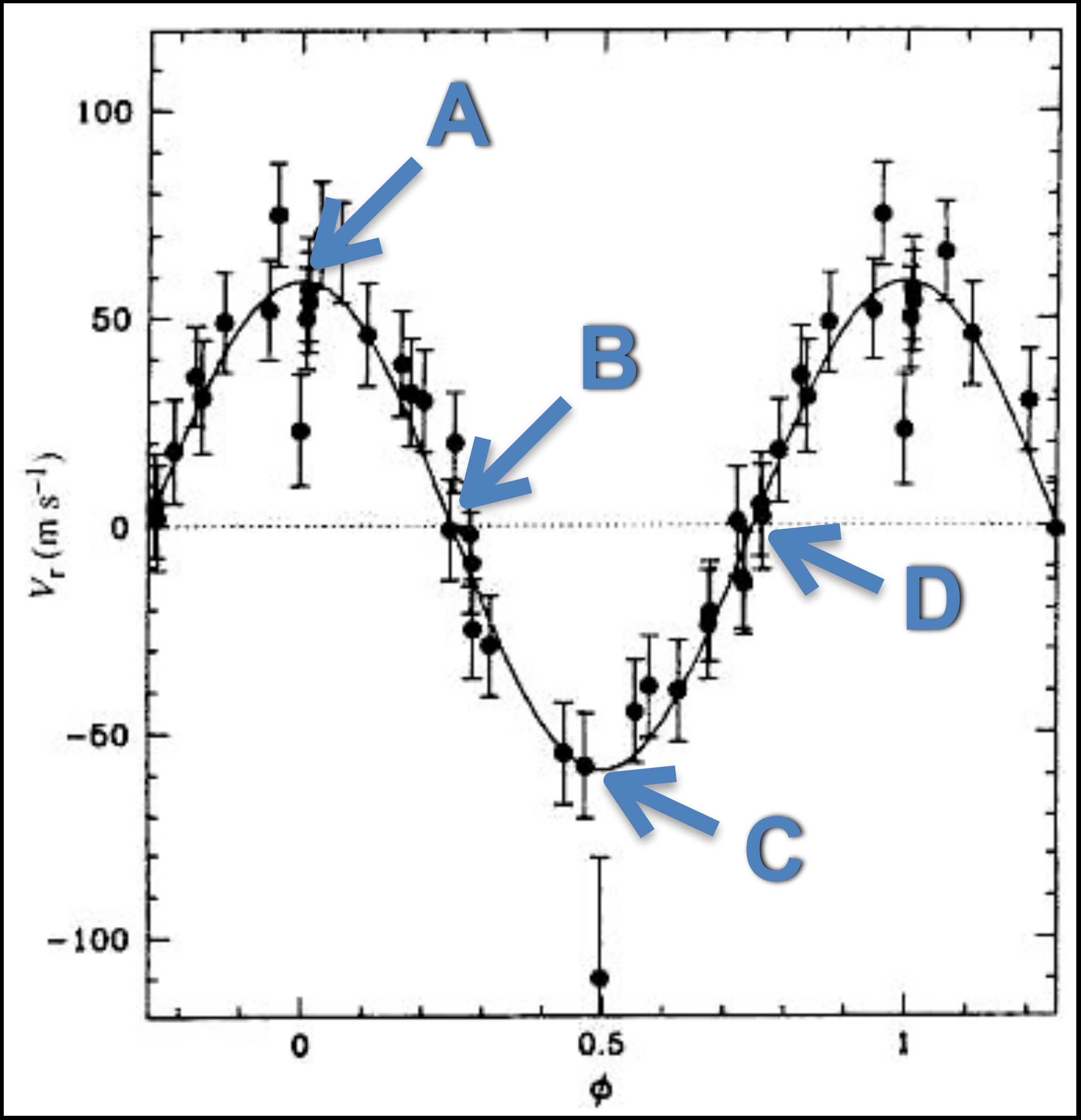

Mayor & Queloz 1995

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

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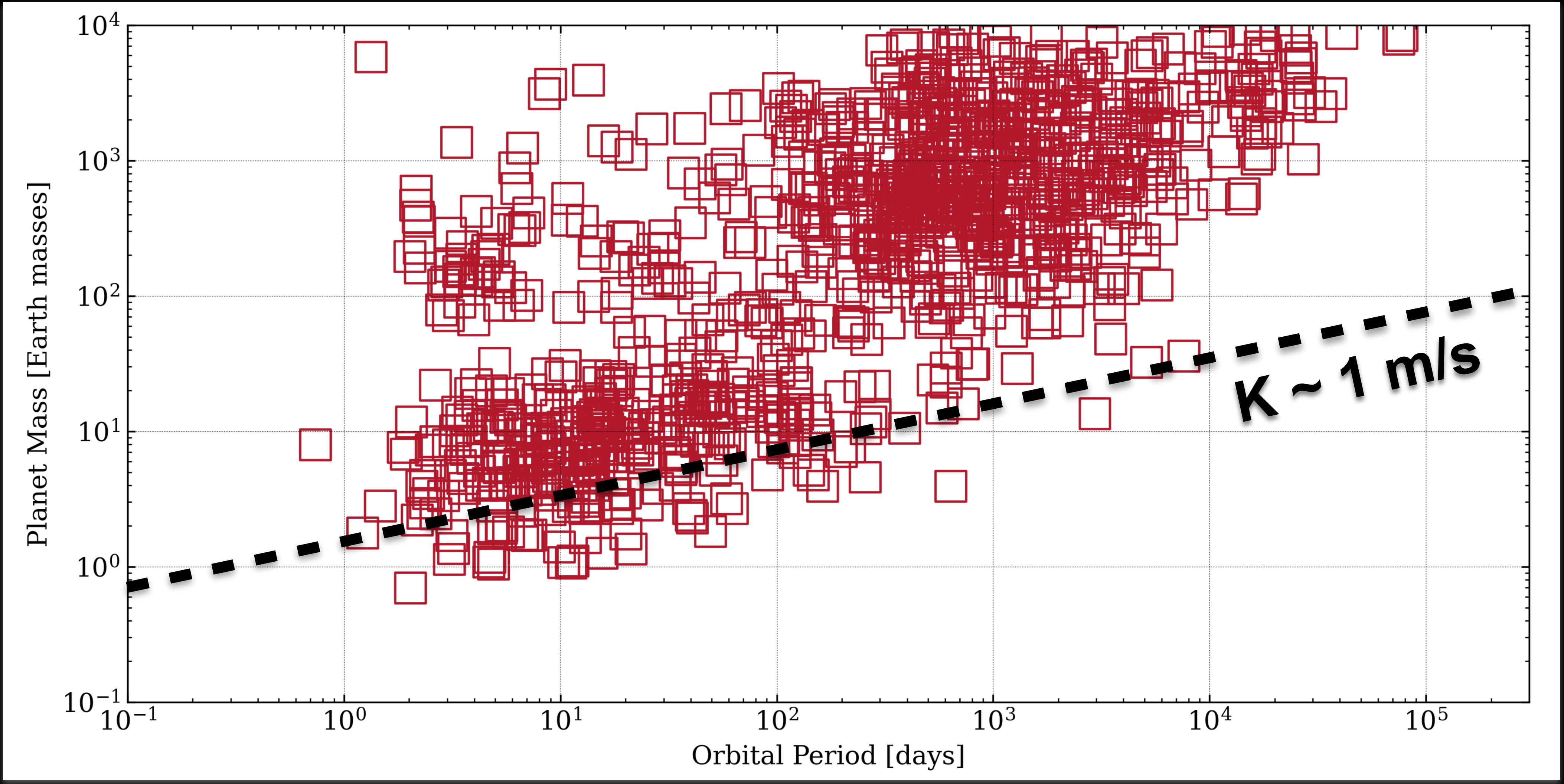
$$K = M_p \sin i \left(\frac{2\pi G}{P M_\star^2} \right)^{1/3}$$

Known **RV** Exoplanets

Mass-Period diagram



Transits + Radial Velocity

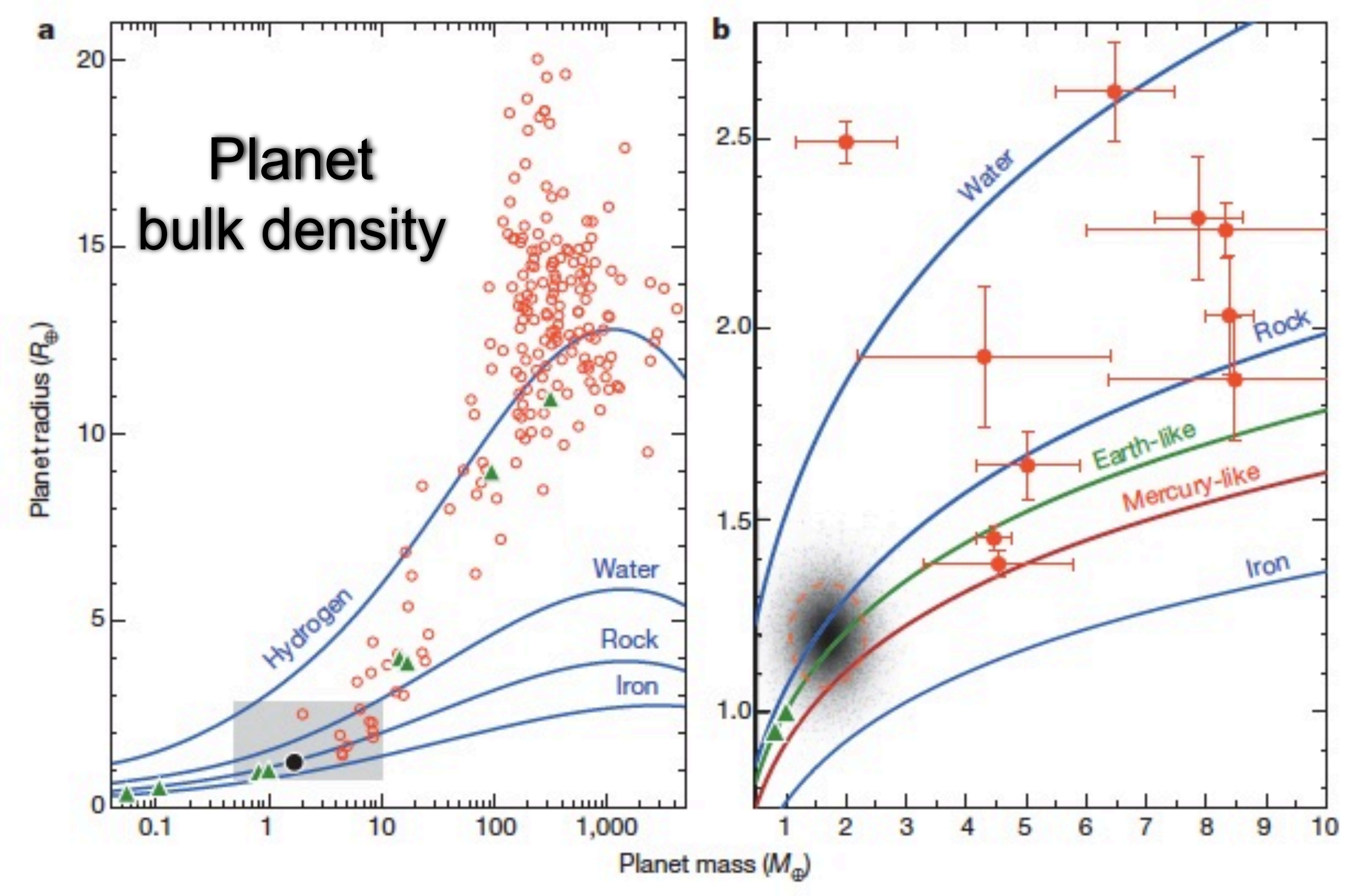
Planet Radius

Planet Mass
(*mass not minimum mass)

Transits + Radial Velocity

Planet Radius

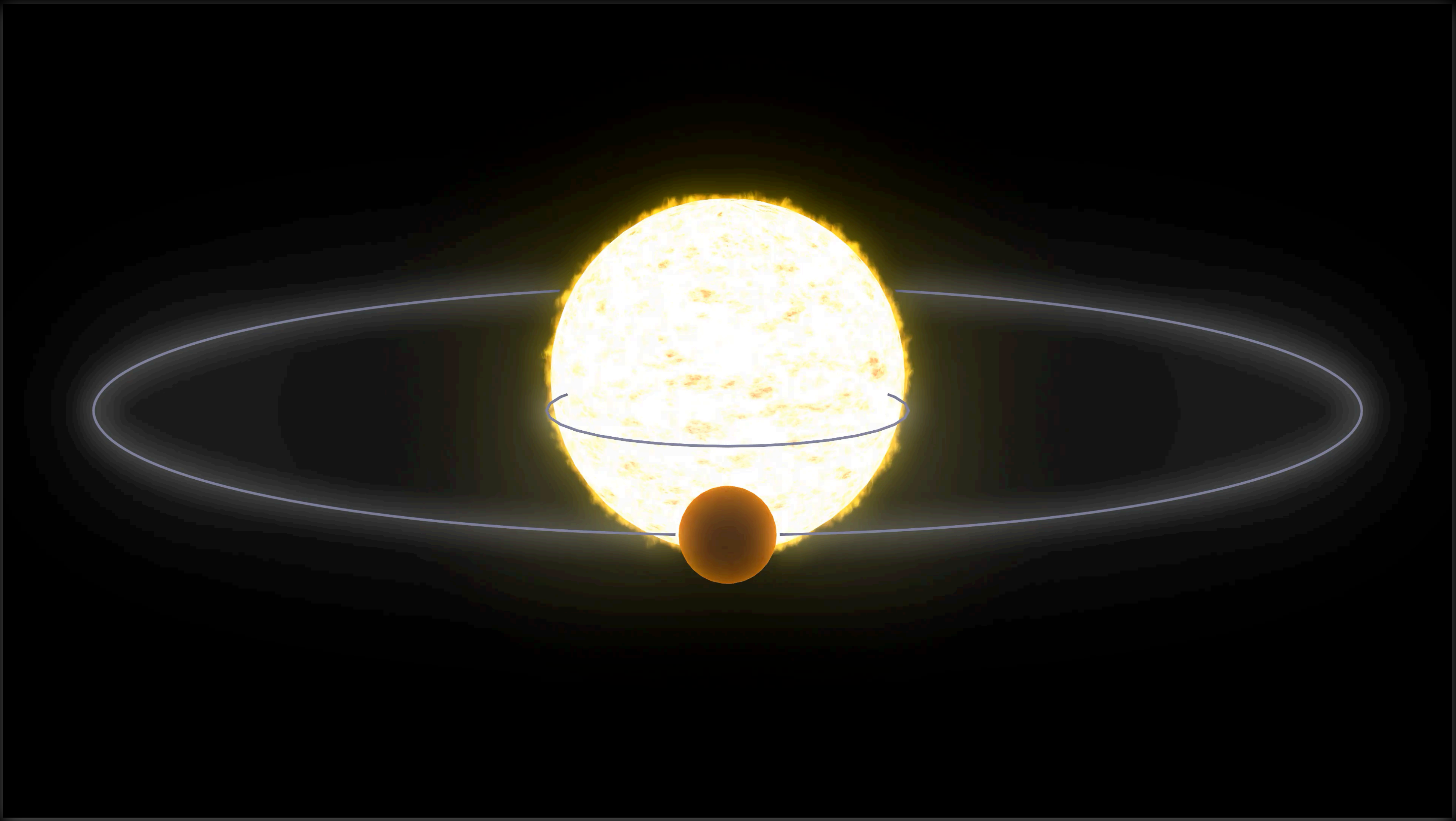
Planet Mass
(*mass not minimum mass)



Planet bulk density

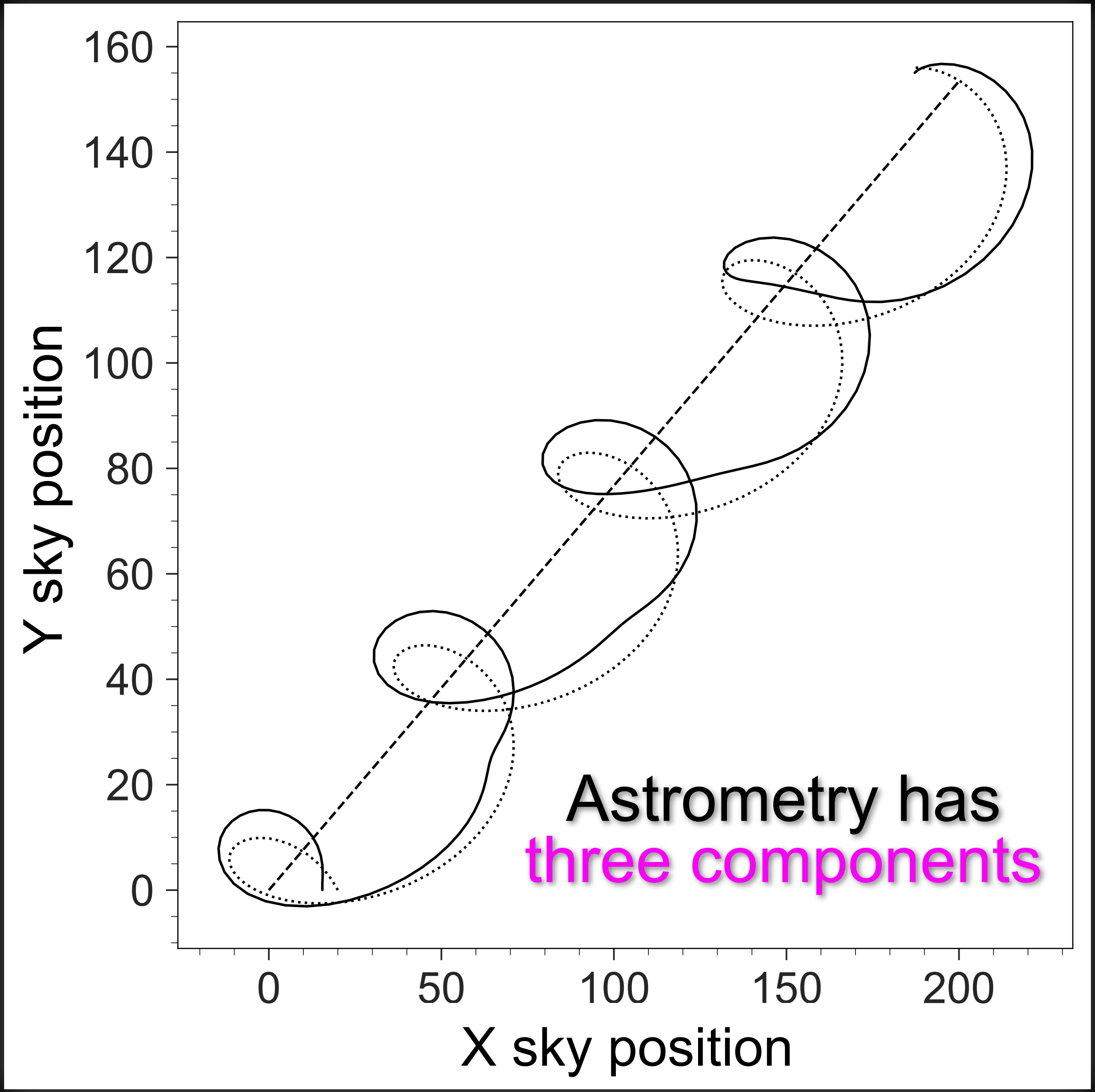
Howard et al 2013

Method 4 - Astrometry



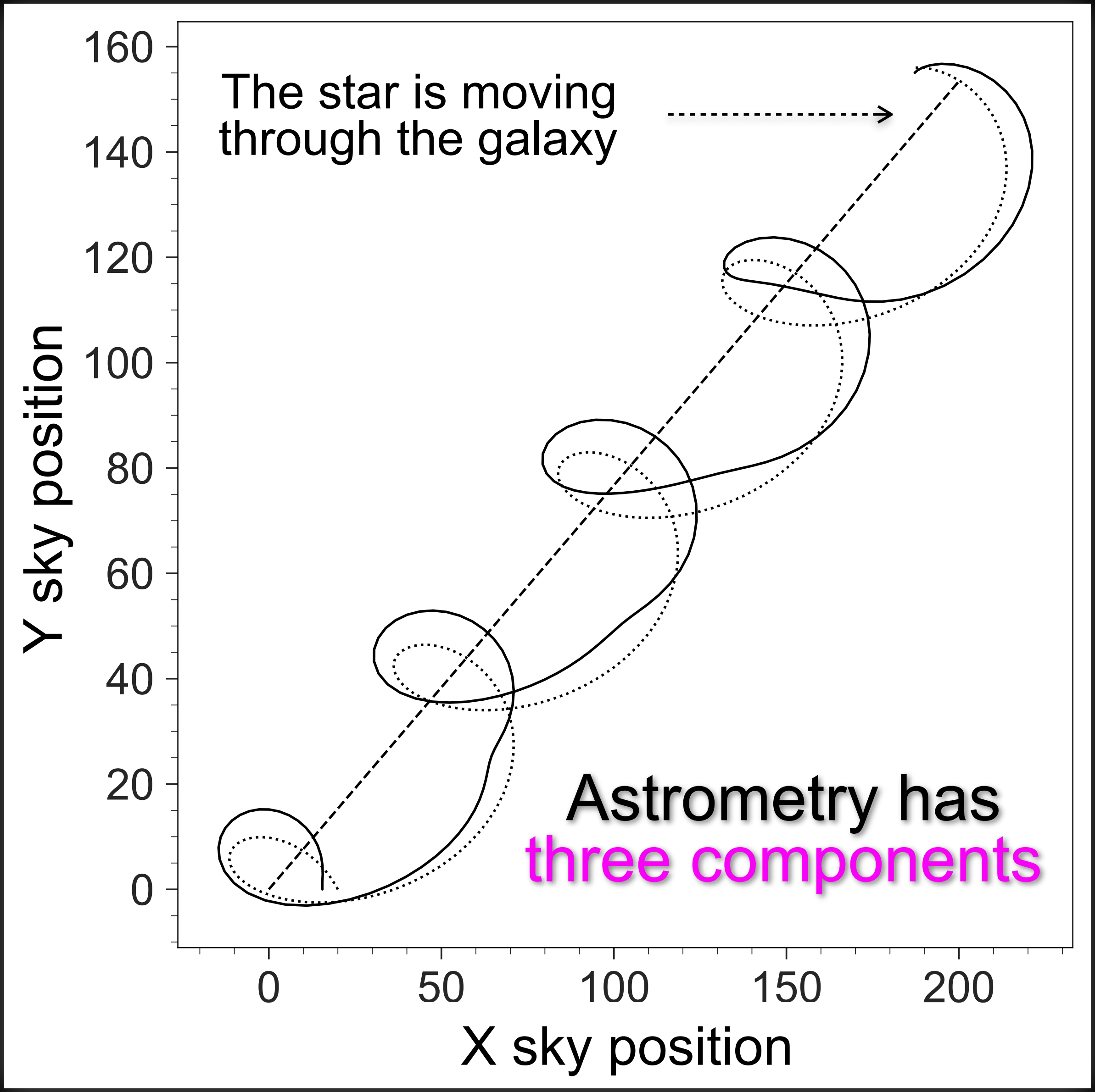
NASA/GSFC

Method 4 - Astrometry



Astrometry has three components

Method 4 - Astrometry



Astrometry has
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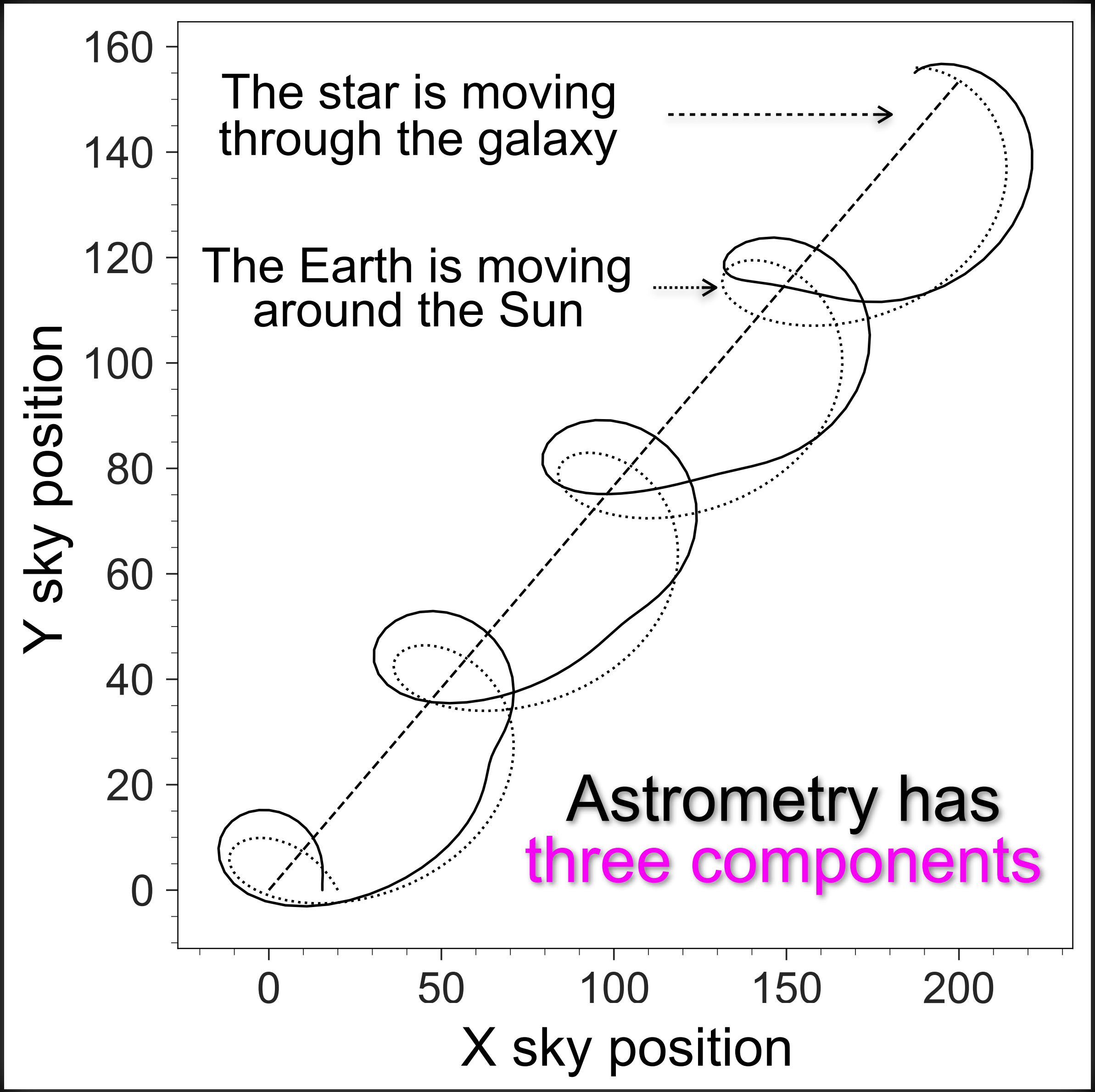
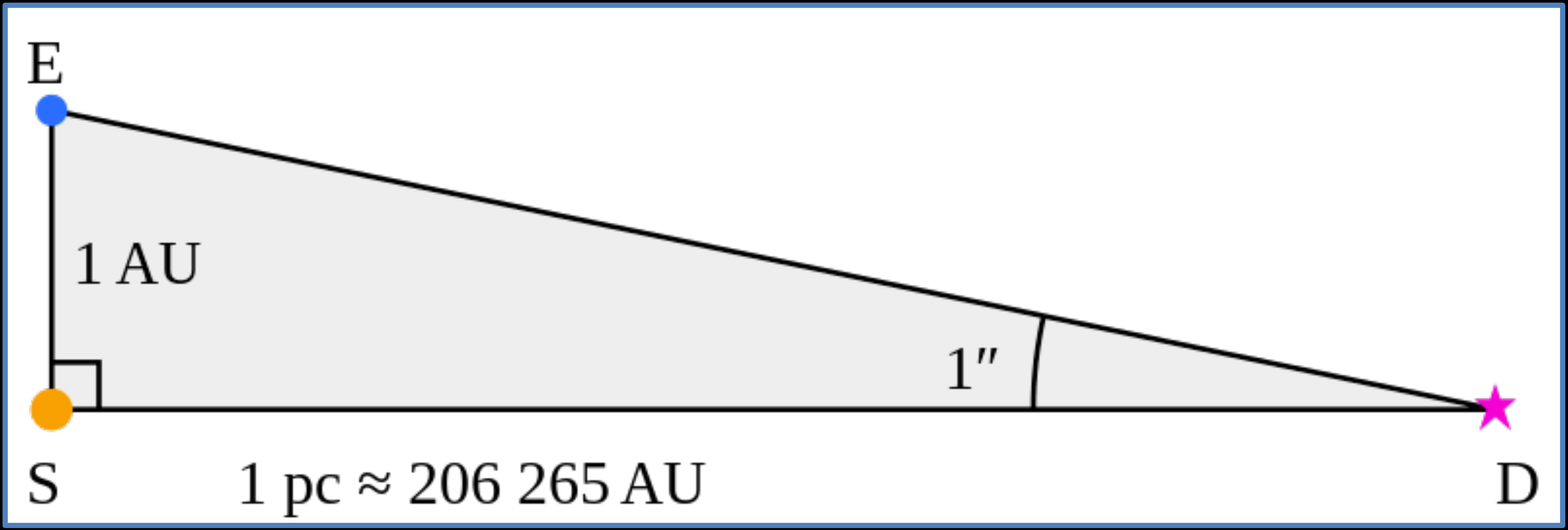
Method 4 - Astrometry



Astrometry has three components

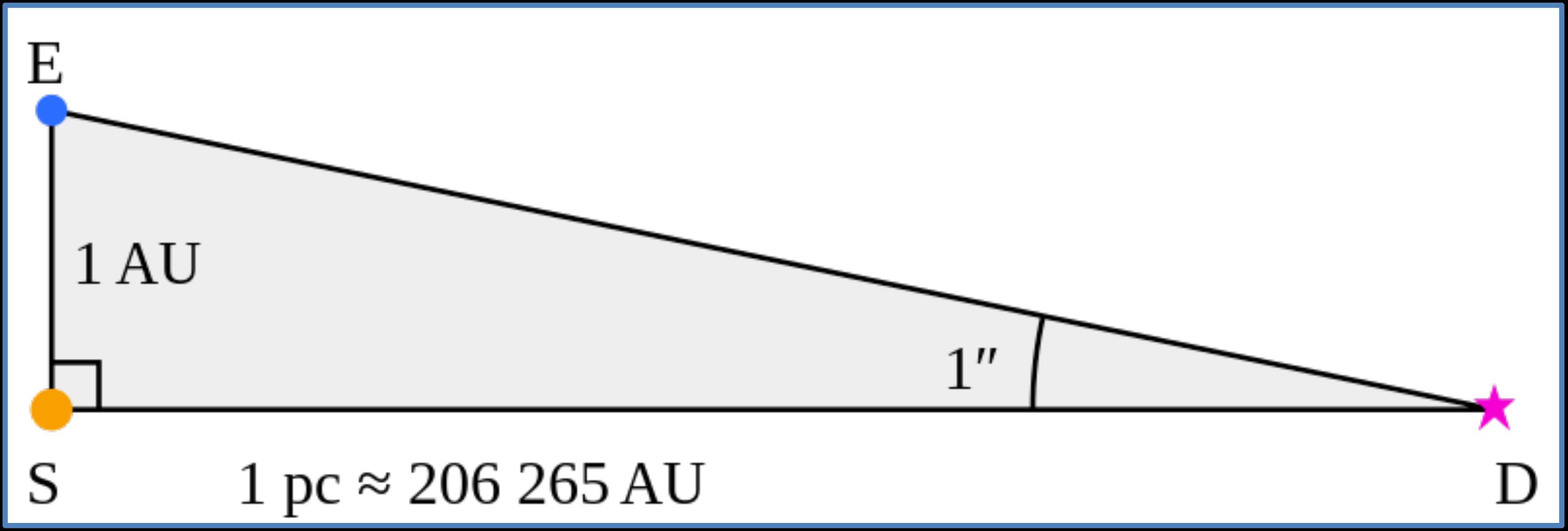
Aside - Parallax



Aside - Parallax

Astronomical Unit (AU)

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



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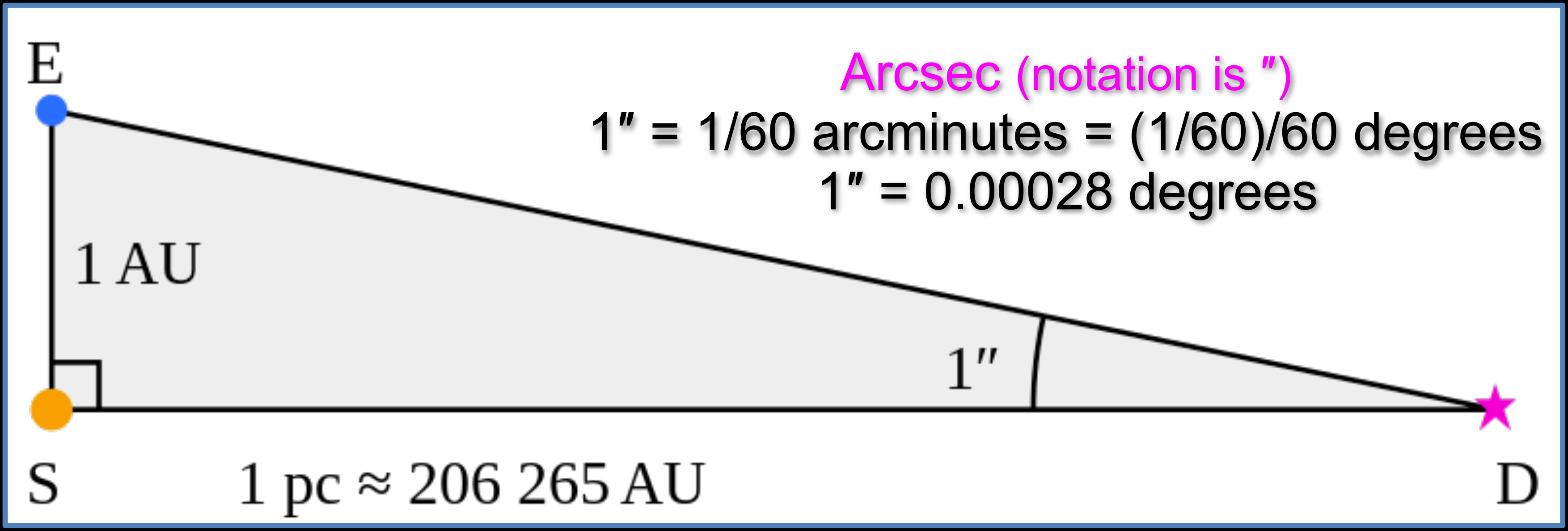


Arcsec (notation is ″)

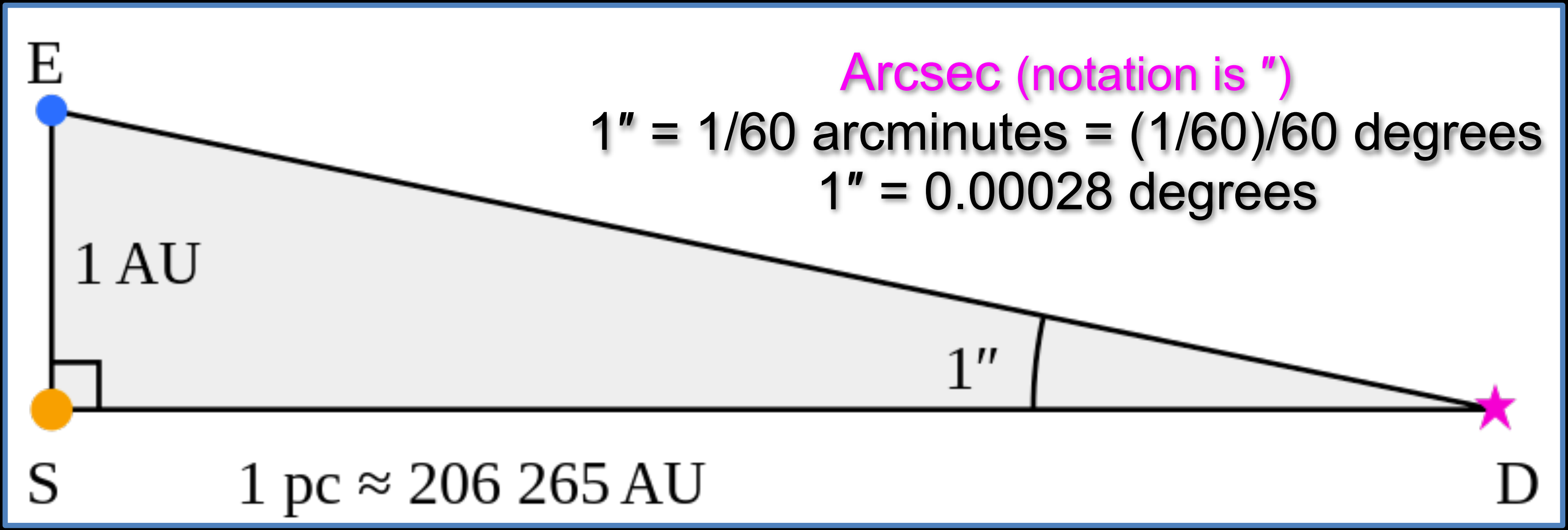
1″ = 1/60 arcminutes = (1/60)/60 degrees

1″ = 0.00028 degrees

Aside - Parallax

Astronomical Unit (AU)

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



Arcsec (notation is ″)

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

1″ = 0.00028 degrees

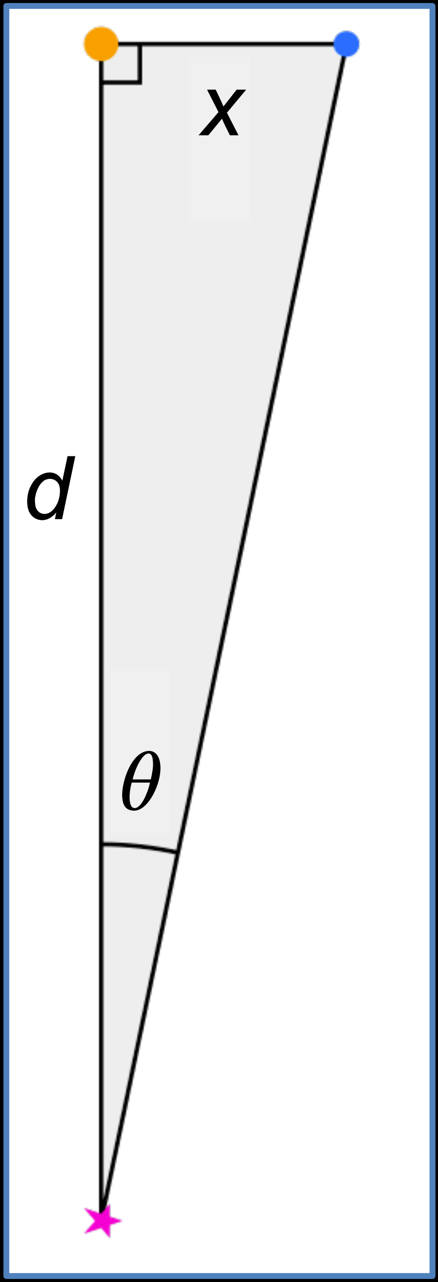
Parsec (pc)

1 pc = 1 AU / 1″

Aside - Parallax

General Expression:

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



Aside - Parallax

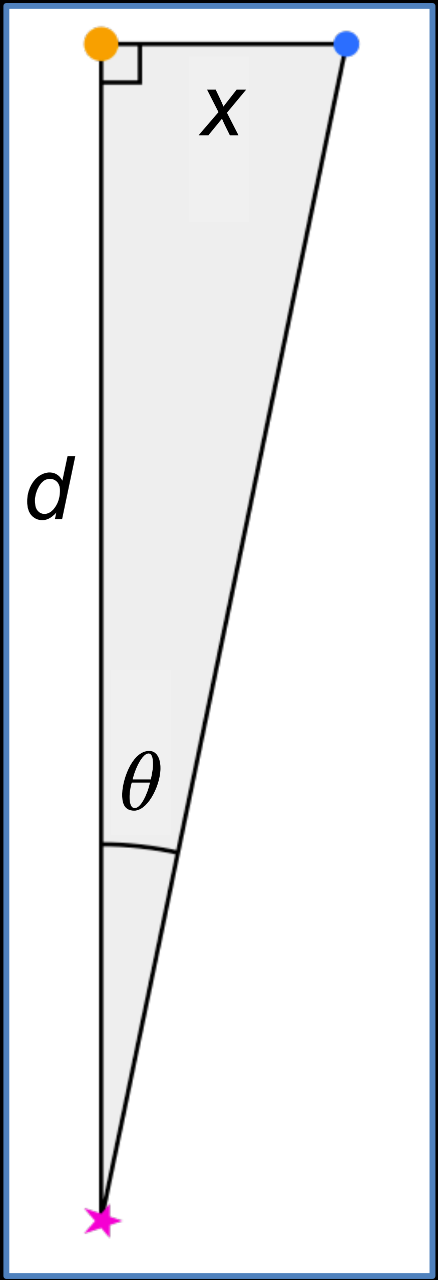
General Expression:

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

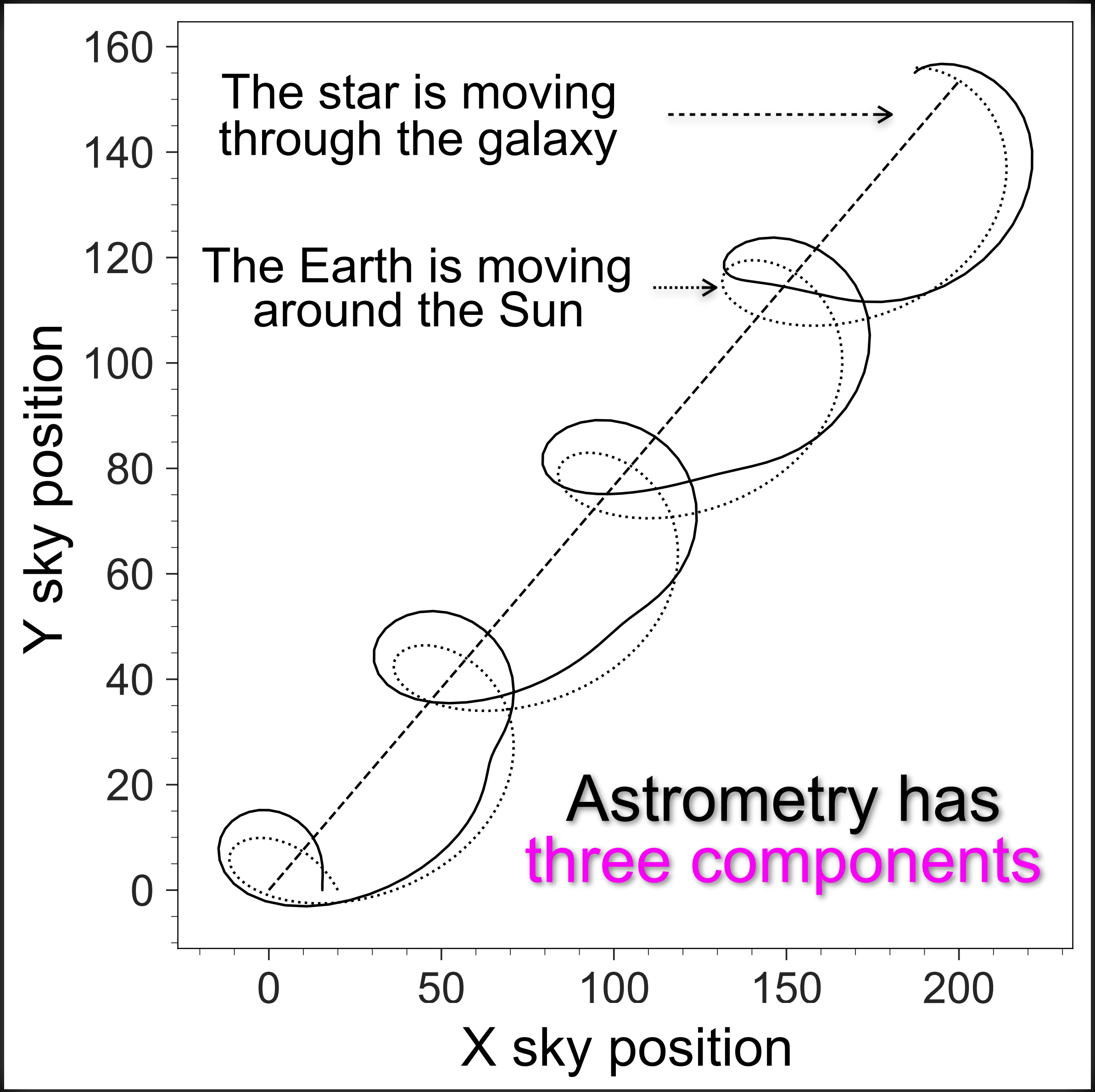
$$x = d\,\theta$$

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

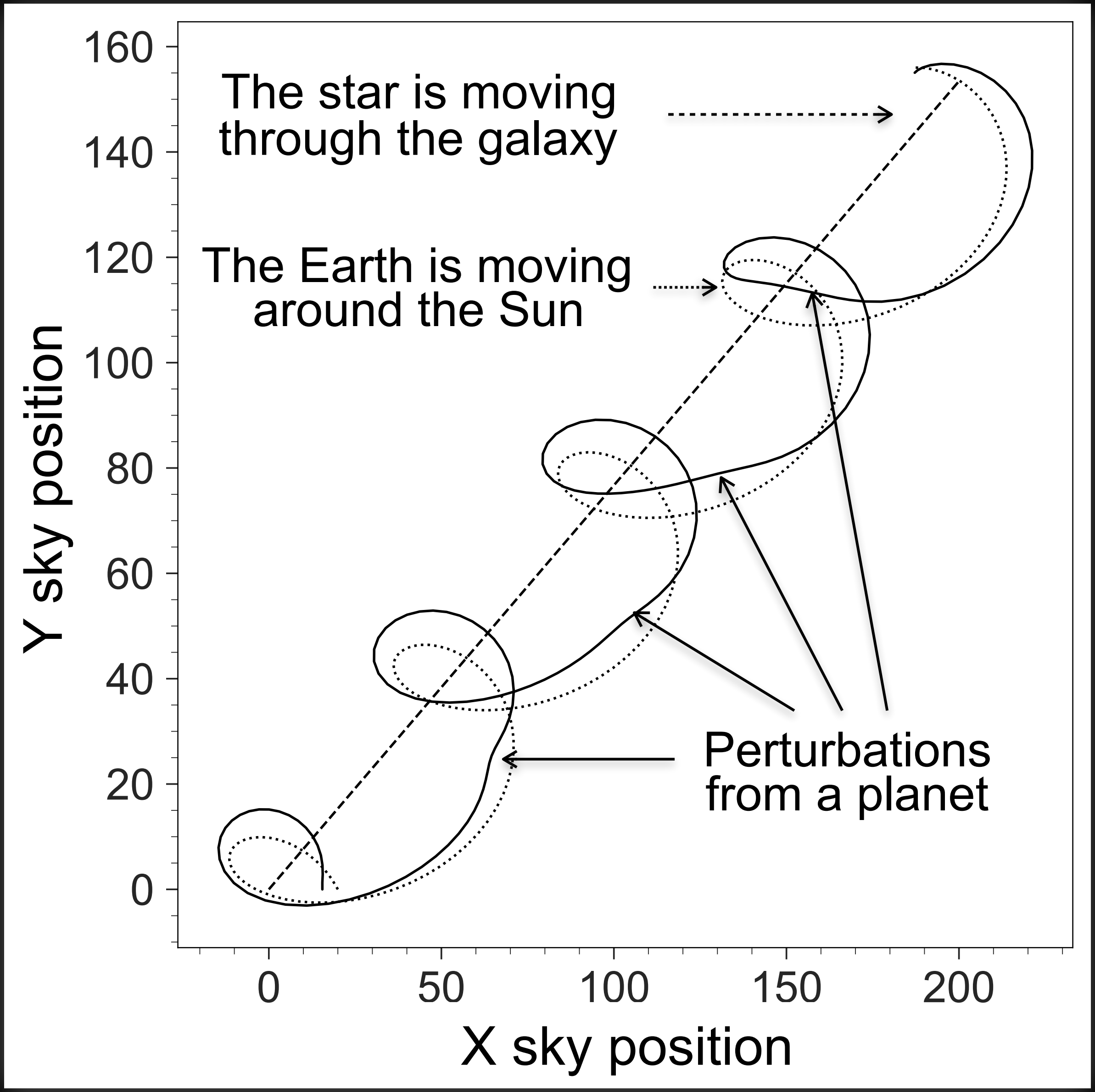
Note the units!



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

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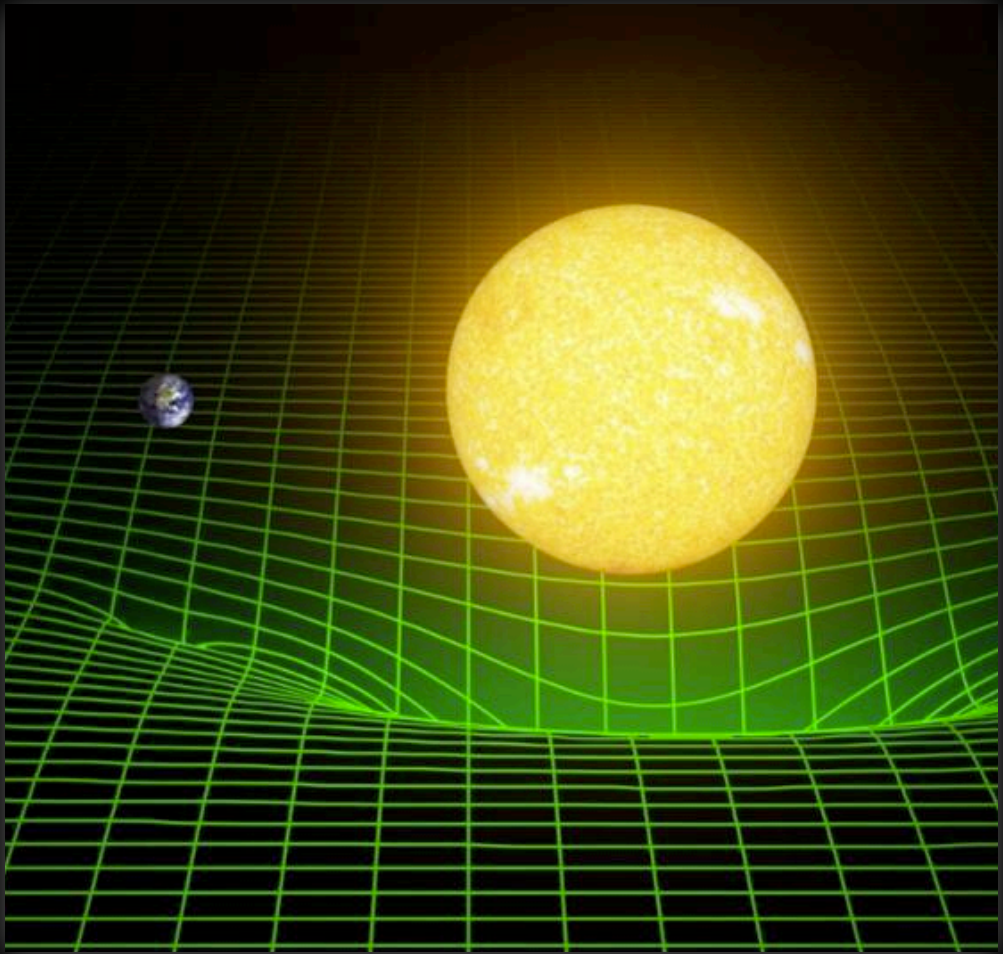
Method 5 - Gravitational Microlensing

Mass bends spacetime



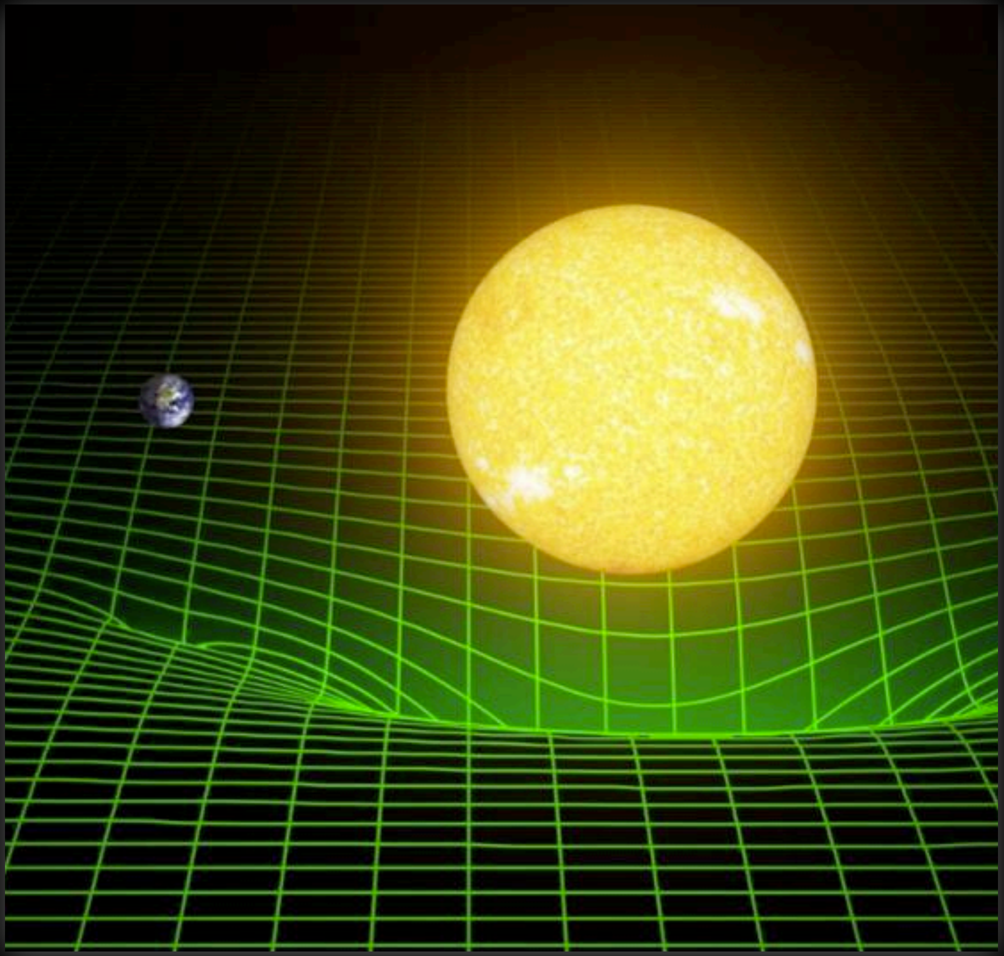
LIGO Lab

Method 5 - Gravitational Microlensing

Mass bends spacetime

↧

Light rays are bent by a curved spacetime



LIGO Lab

Method 5 - Gravitational Microlensing

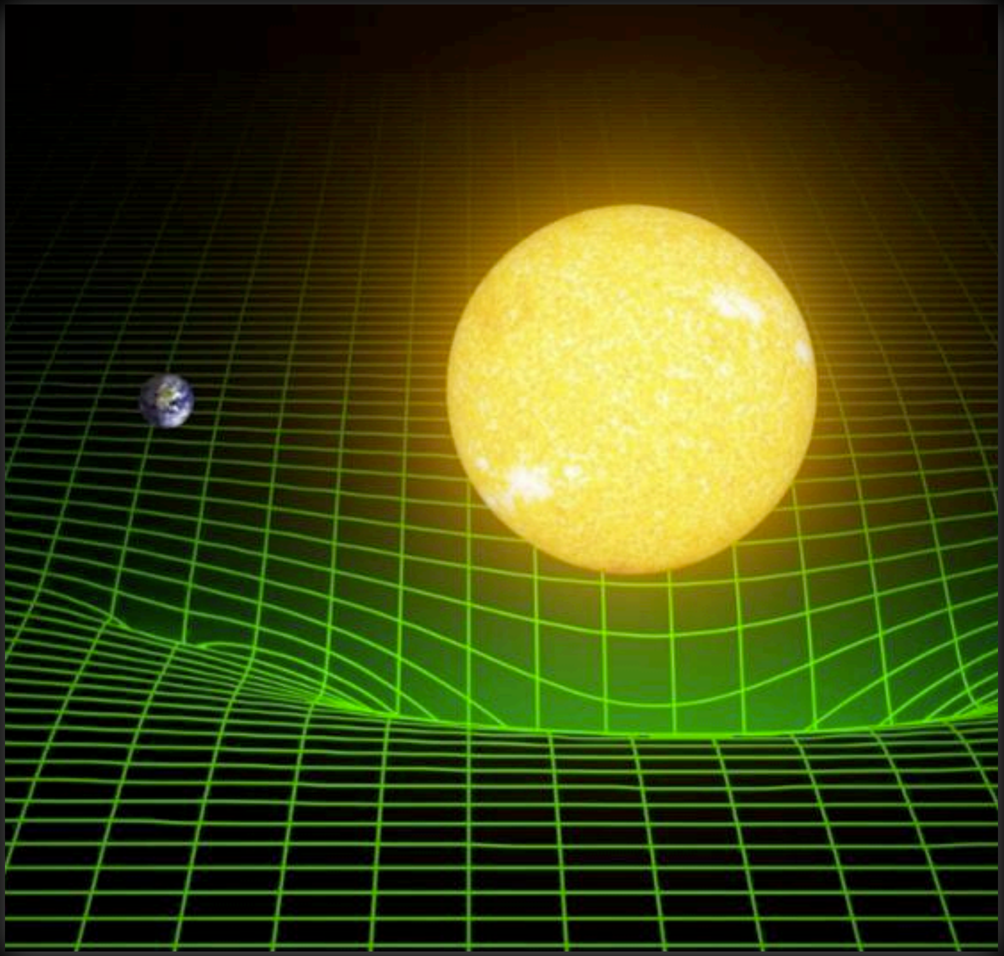
Mass bends spacetime

↧

Light rays are bent by a curved spacetime

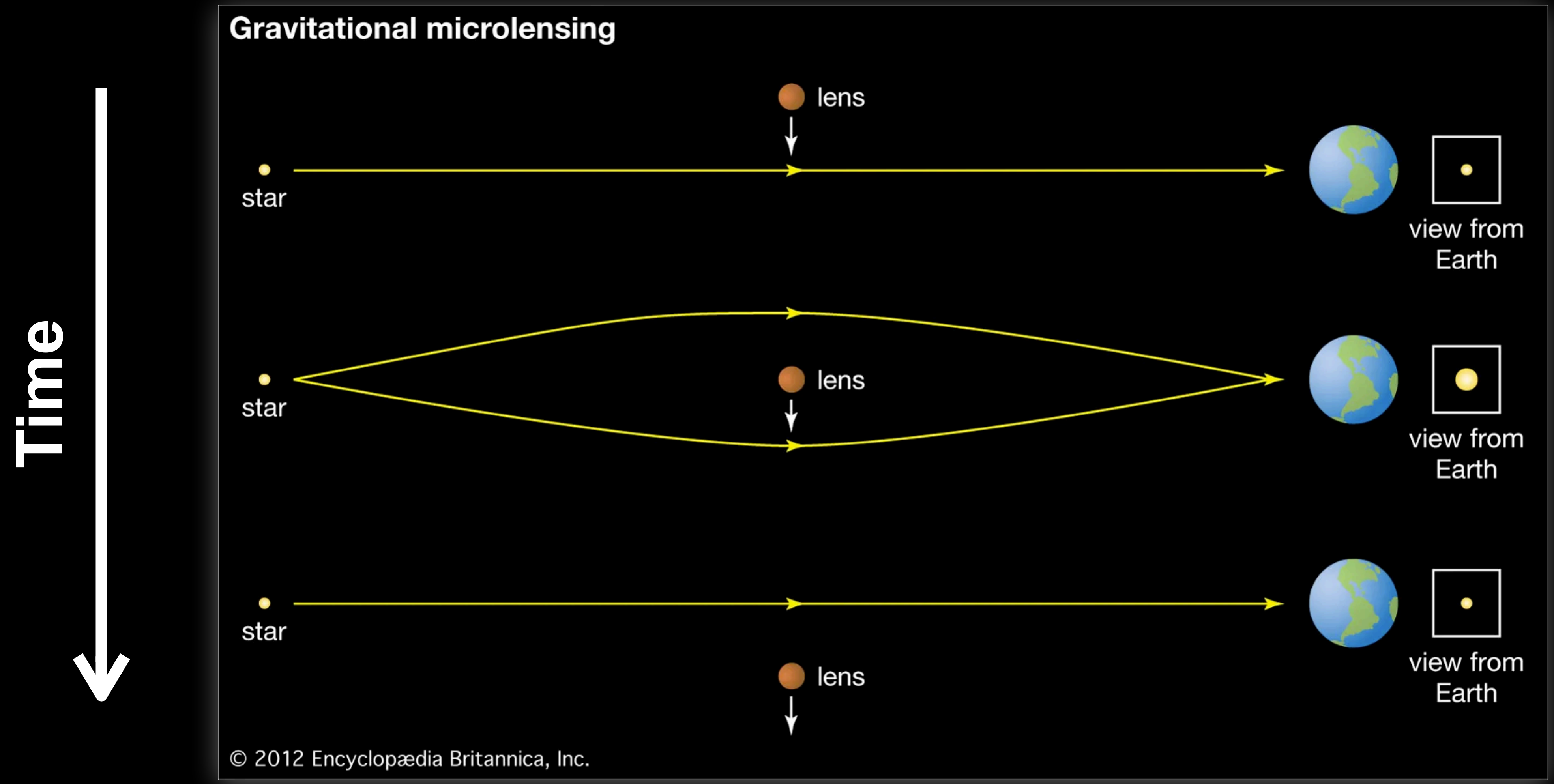
↧

Massive objects act as a gravitational lens



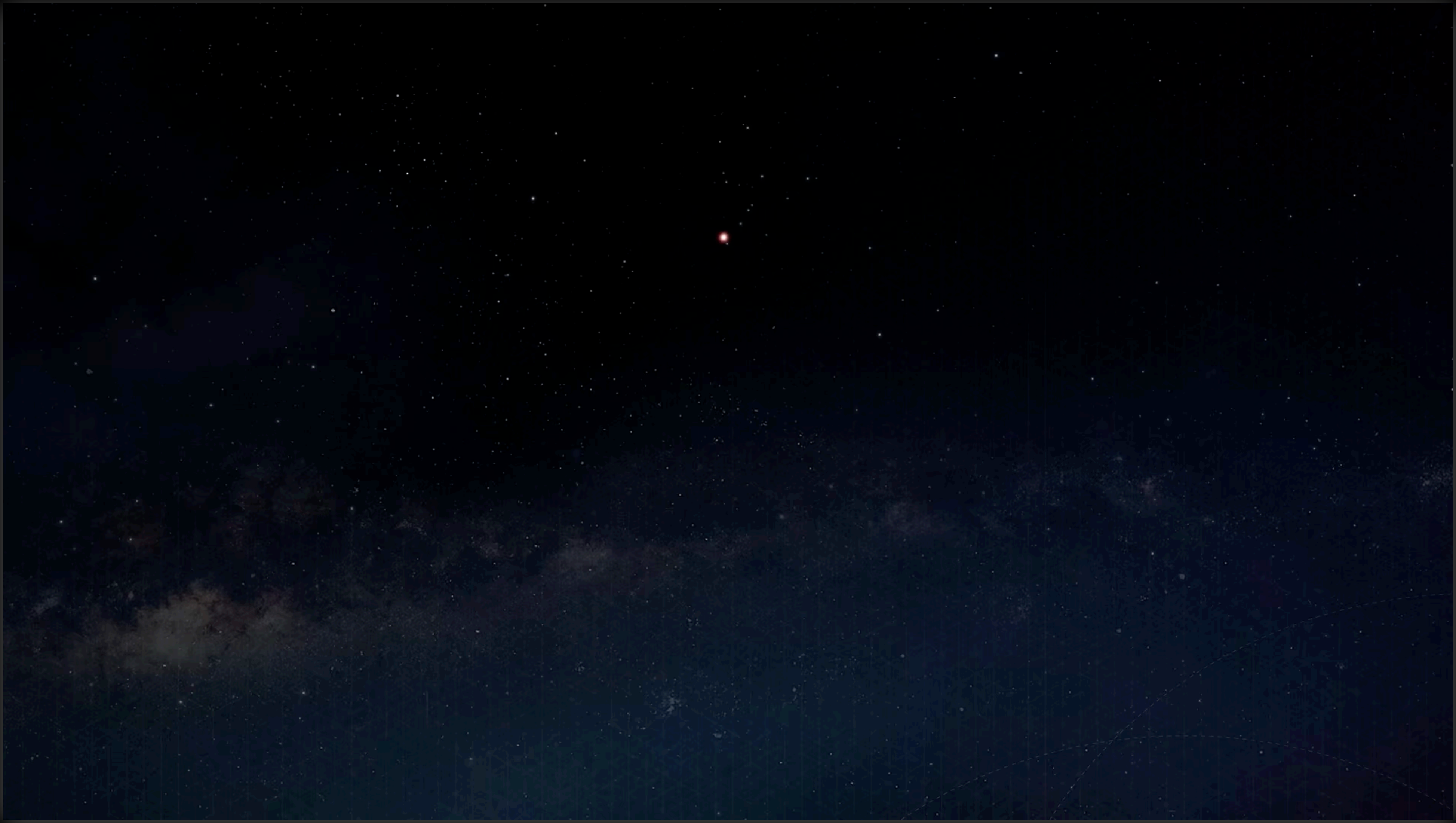
LIGO Lab

Method 5 - Gravitational Microlensing



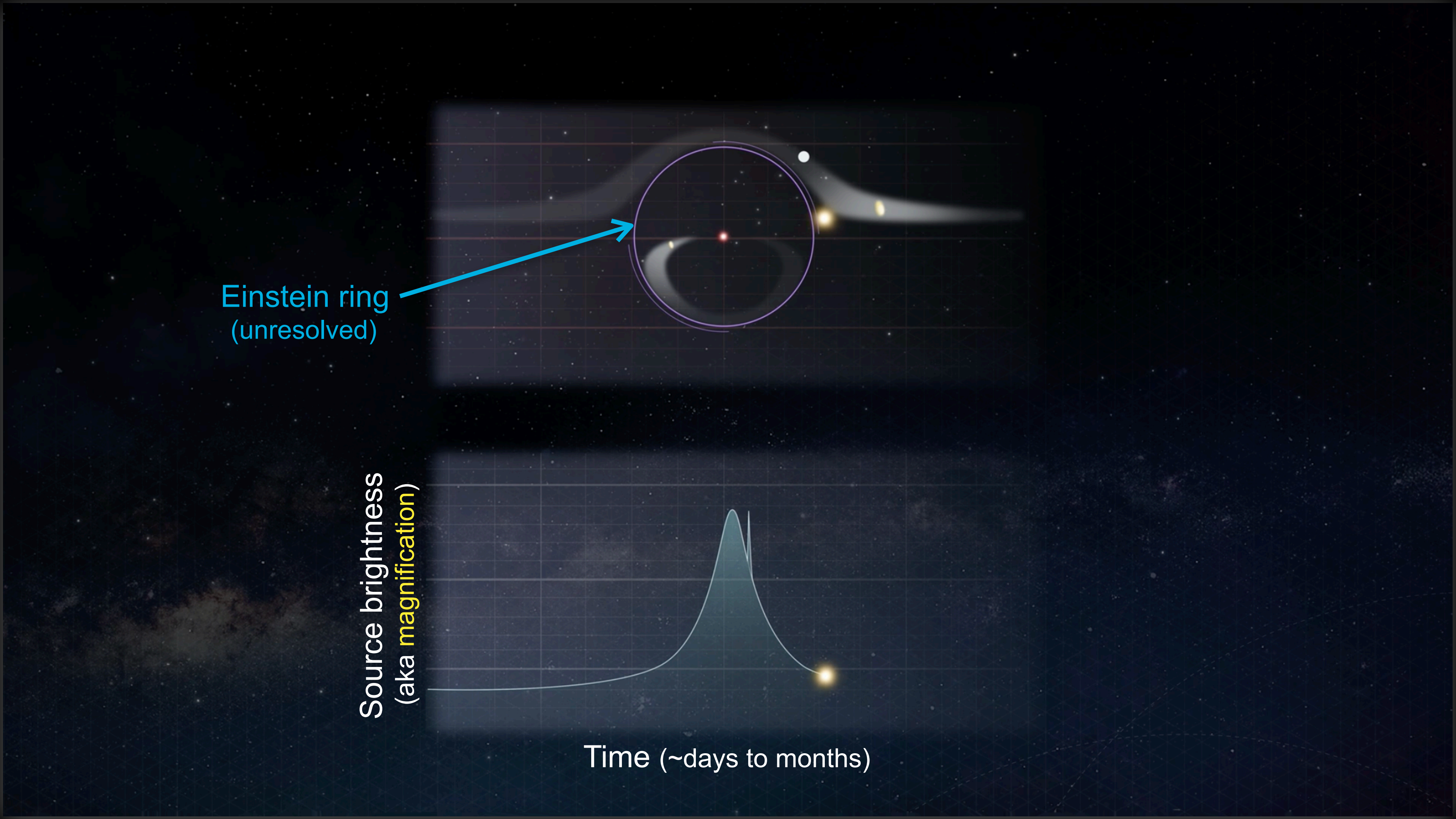
Encyclopedia Britannica

Method 5 - Gravitational Microlensing



NASA/CI Lab

Method 5 - Gravitational Microlensing



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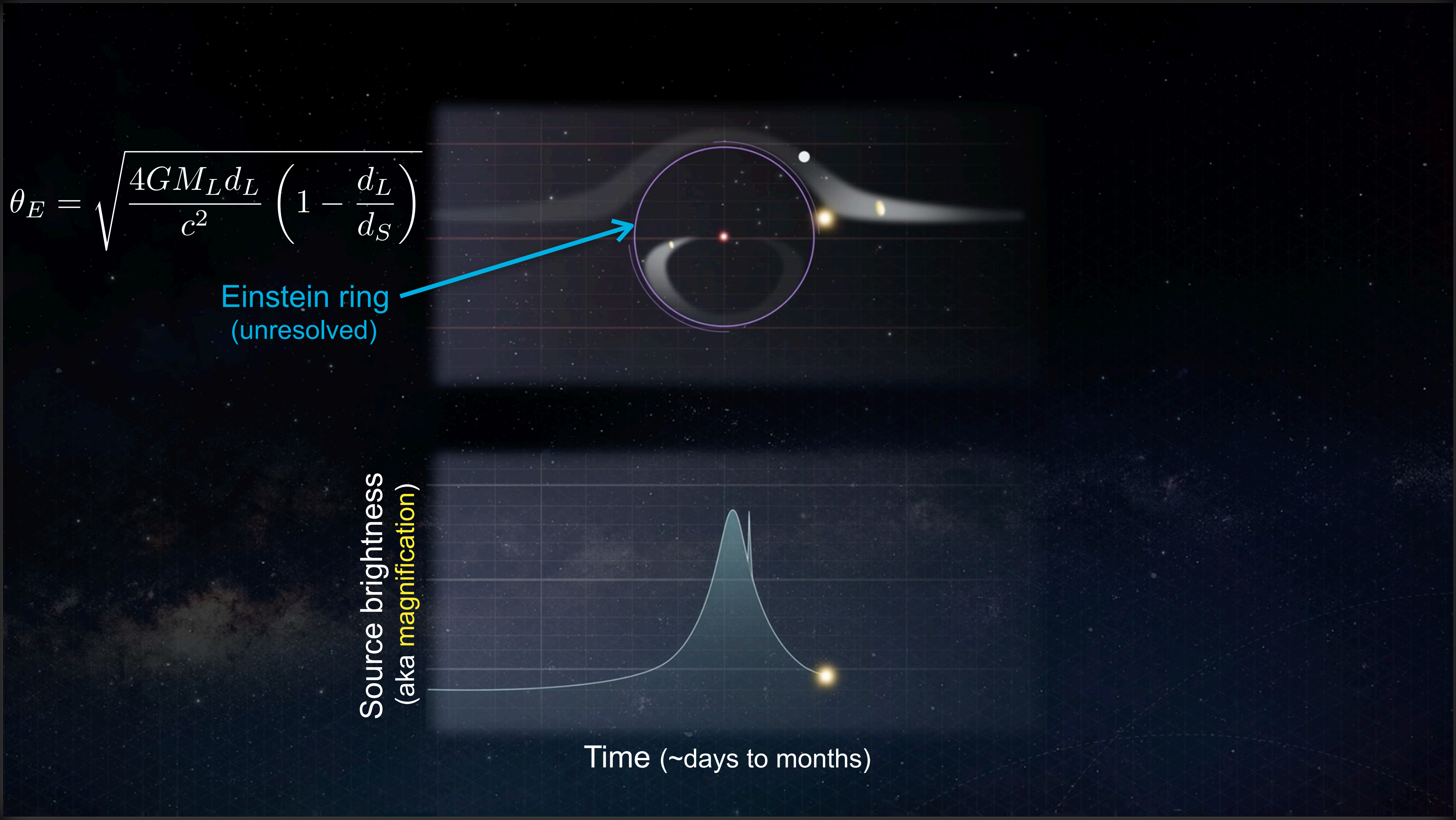
Method 5 - Gravitational Microlensing

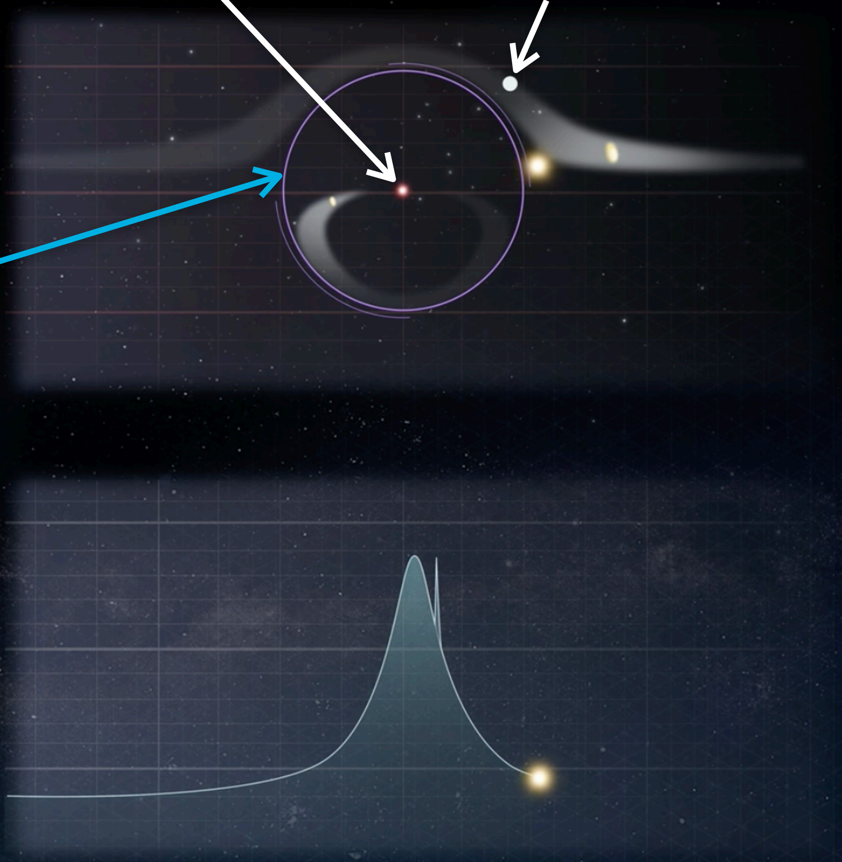


$$\theta_E = \sqrt{\frac{4GM_L d_L}{c^2}\left(1 - \frac{d_L}{d_S}\right)}$$

NASA/CI Lab

Method 5 - Gravitational Microlensing

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



Lens star

Lens planet (*orbits the lens star)

Einstein ring
(unresolved)

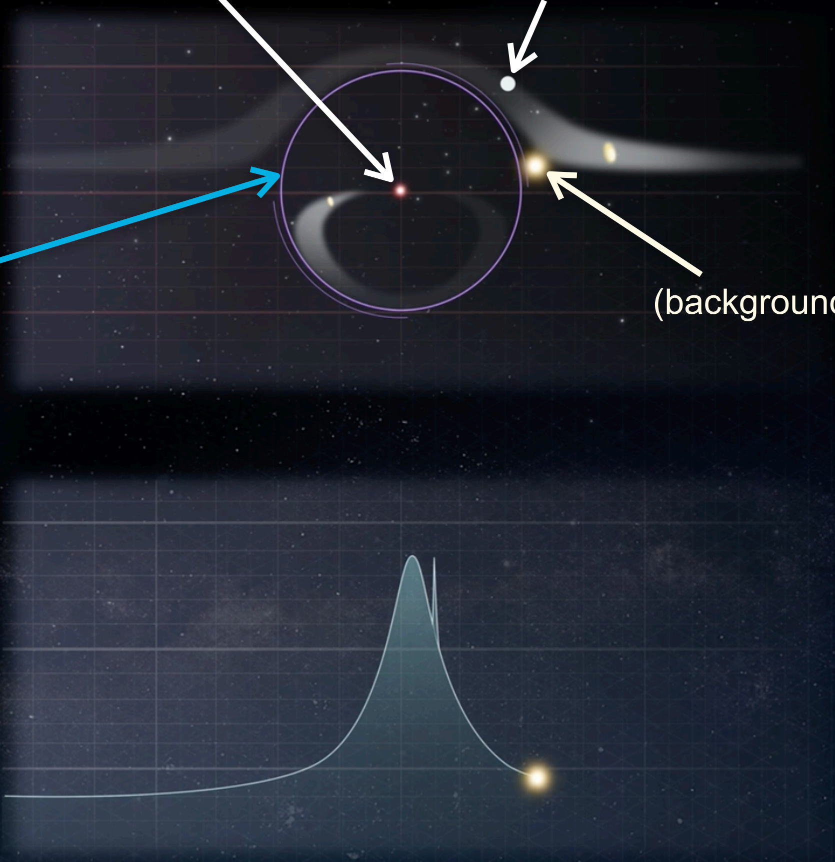
Source brightness
(aka magnification)

Time (~days to months)

NASA/CI Lab

Method 5 - Gravitational Microlensing

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



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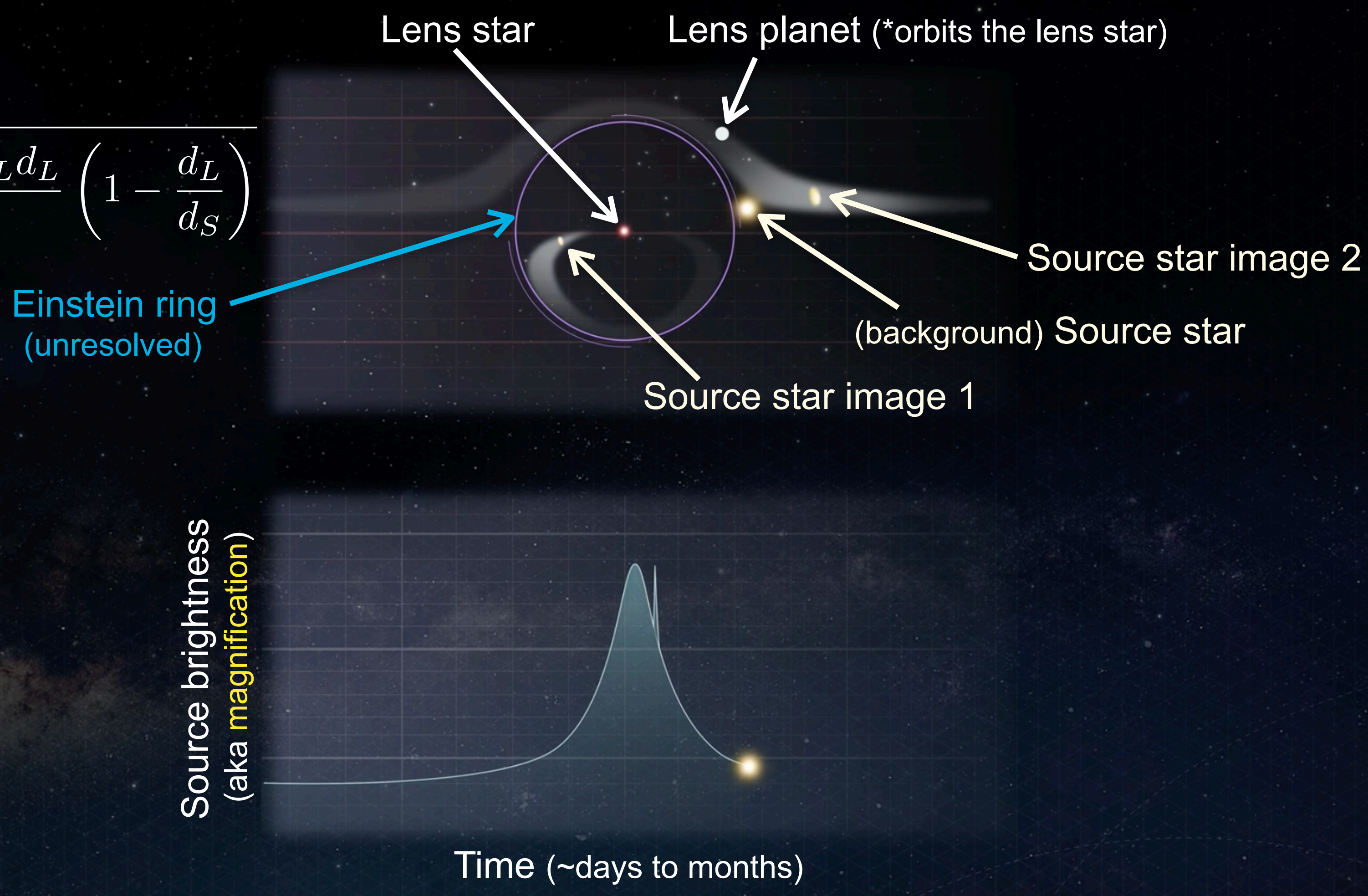
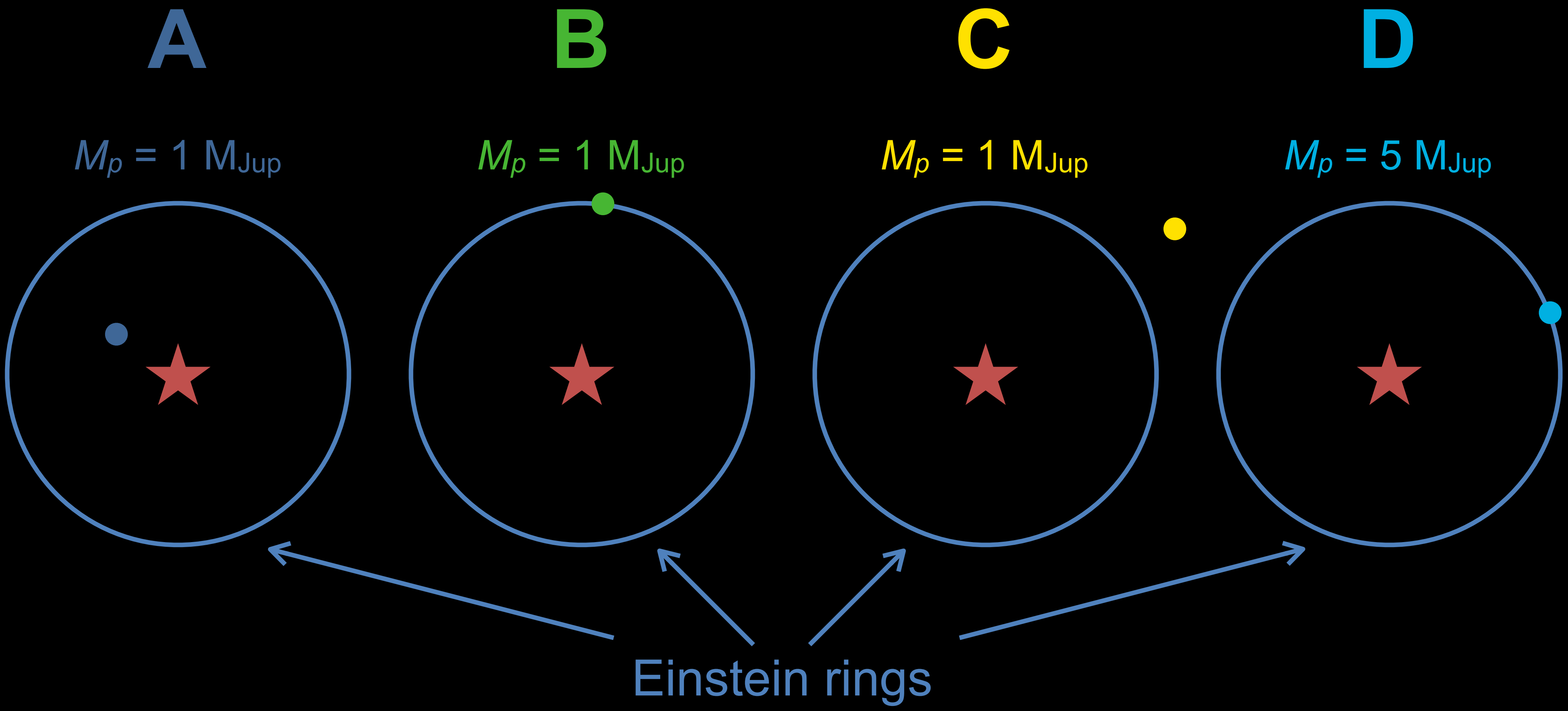


NASA/CI Lab

A B

C D

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



A

M_p = 1 MJup

B

M_p = 1 MJup

C

M_p = 1 MJup

D

M_p = 5 MJup

Einstein rings

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

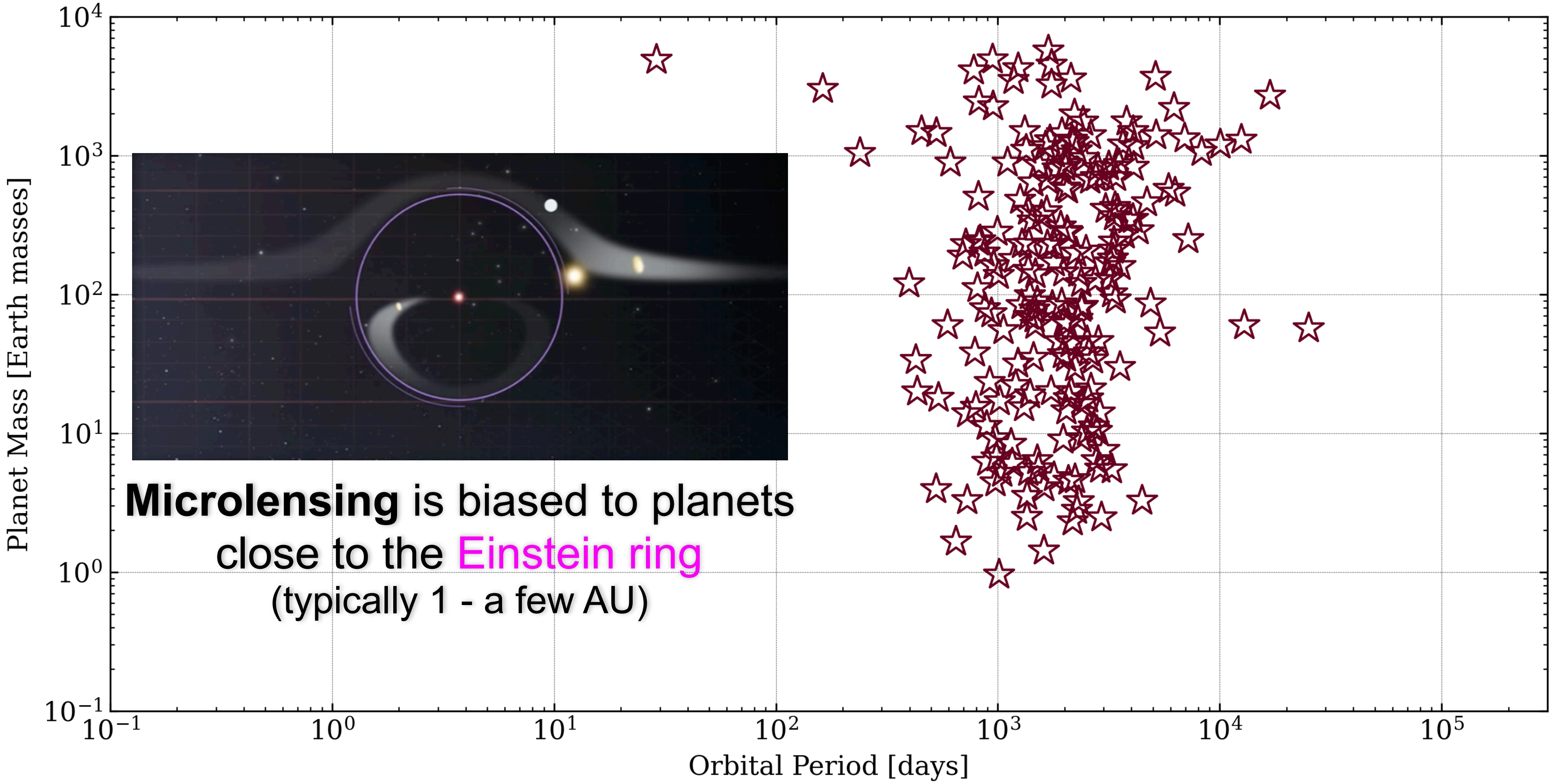
$\theta_E = 0.0005''$ (recall that ″ means arcseconds)

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

(now you can do the math)

Known **Microlensed** Exoplanets

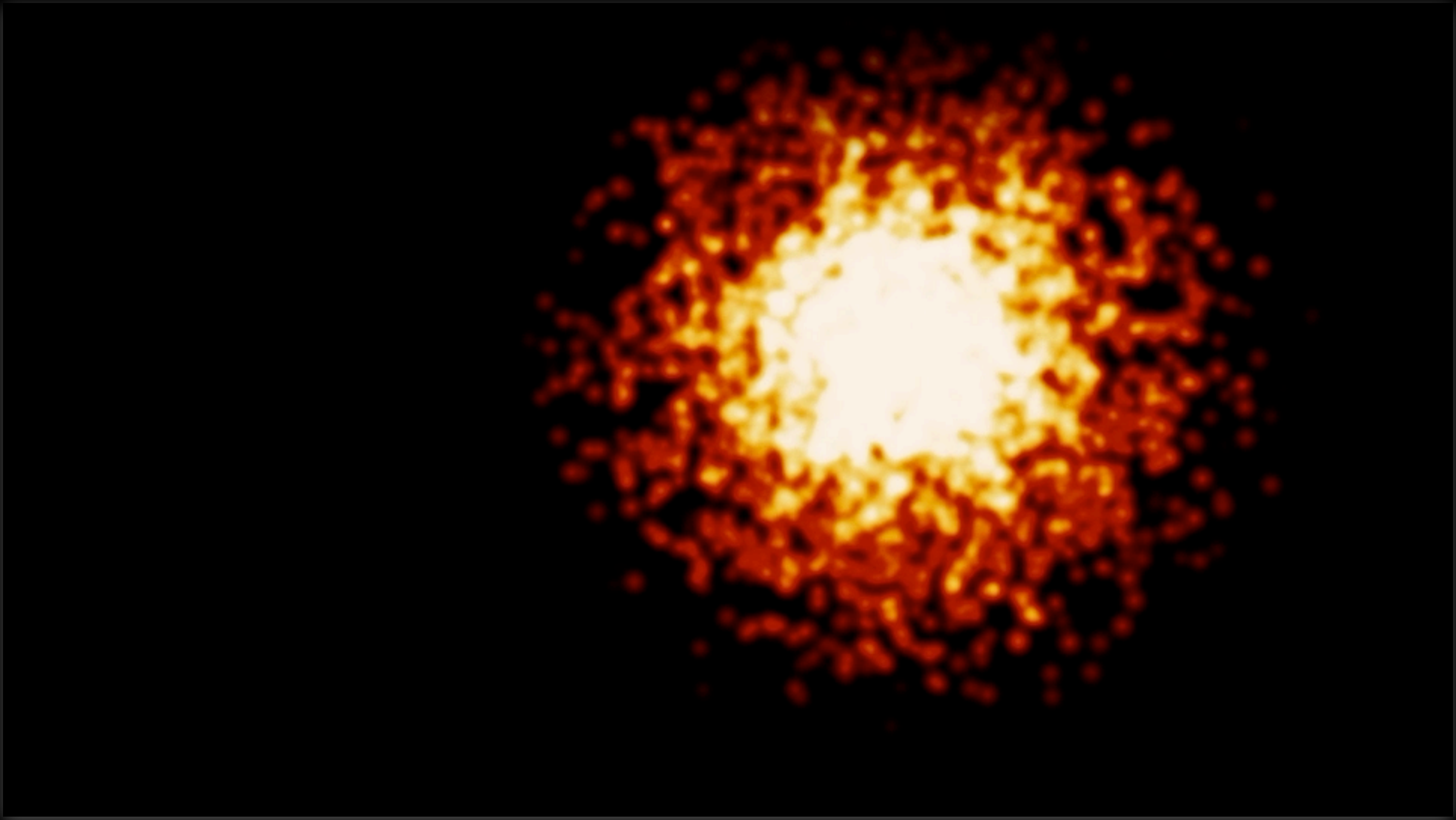
Mass-Period diagram



Microlensing is biased to planets close to the Einstein ring

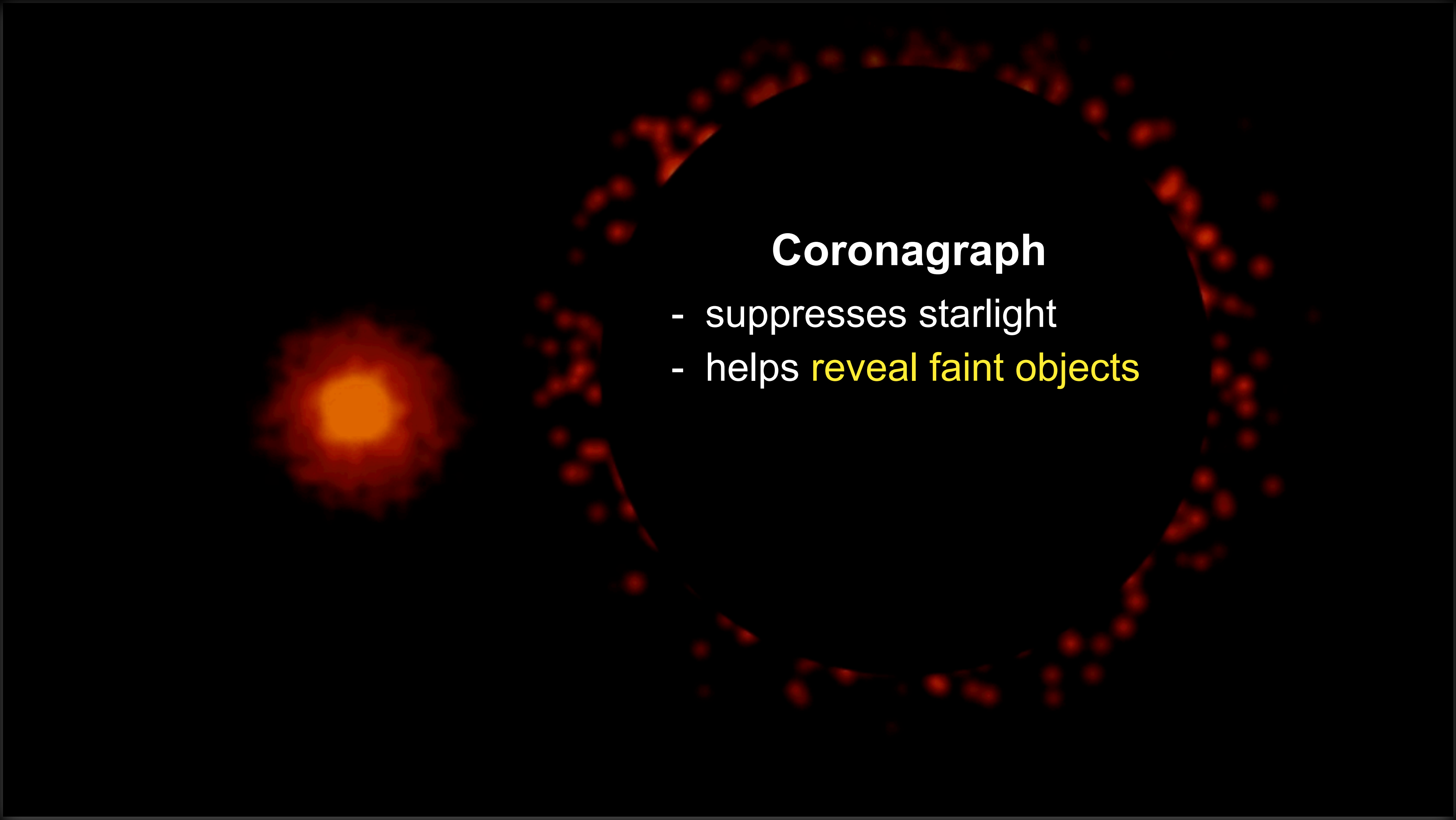
(typically 1 - a few AU)

Method 6 - Direct Imaging



NASA

Method 6 - Direct Imaging

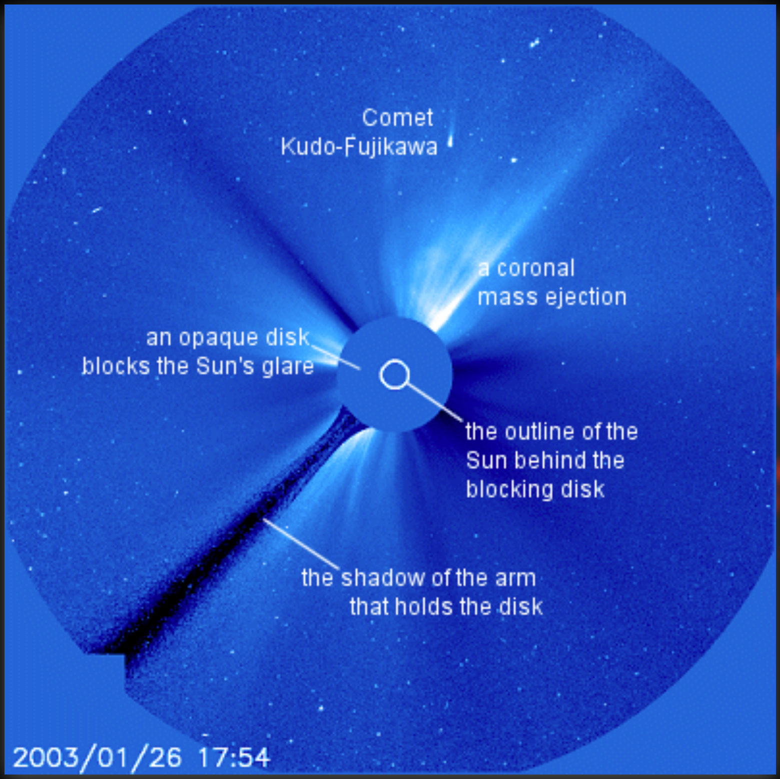


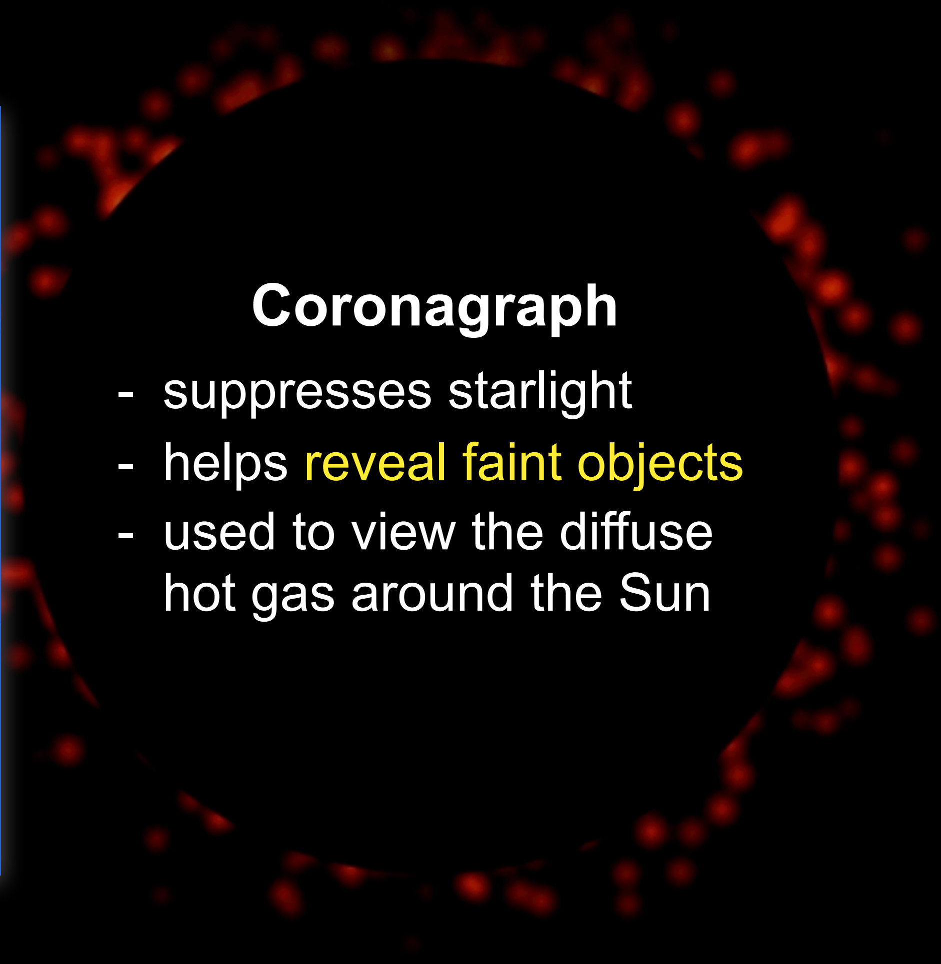
Coronagraph

- suppresses starlight
- helps reveal faint objects

NASA

Method 6 - Direct Imaging



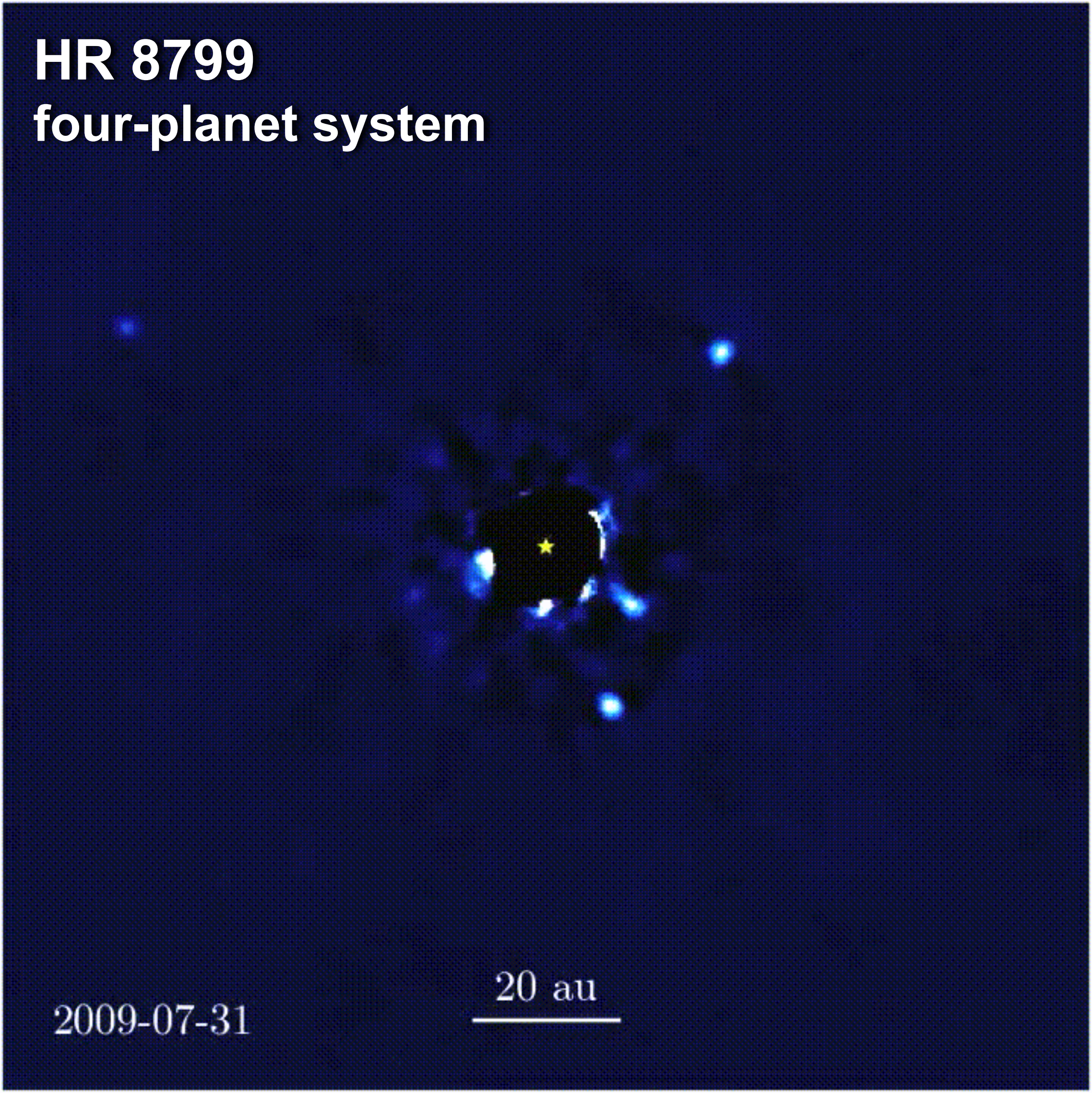


Coronagraph

- 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

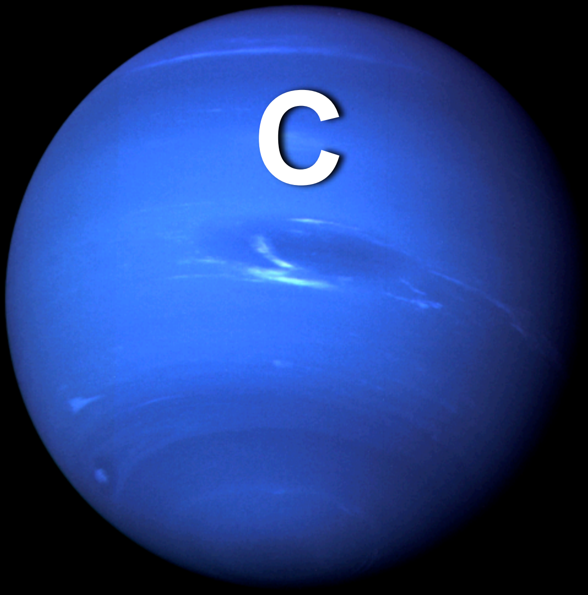
The coronagraph used to study the HR 8799 system was 20 au in diameter.

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



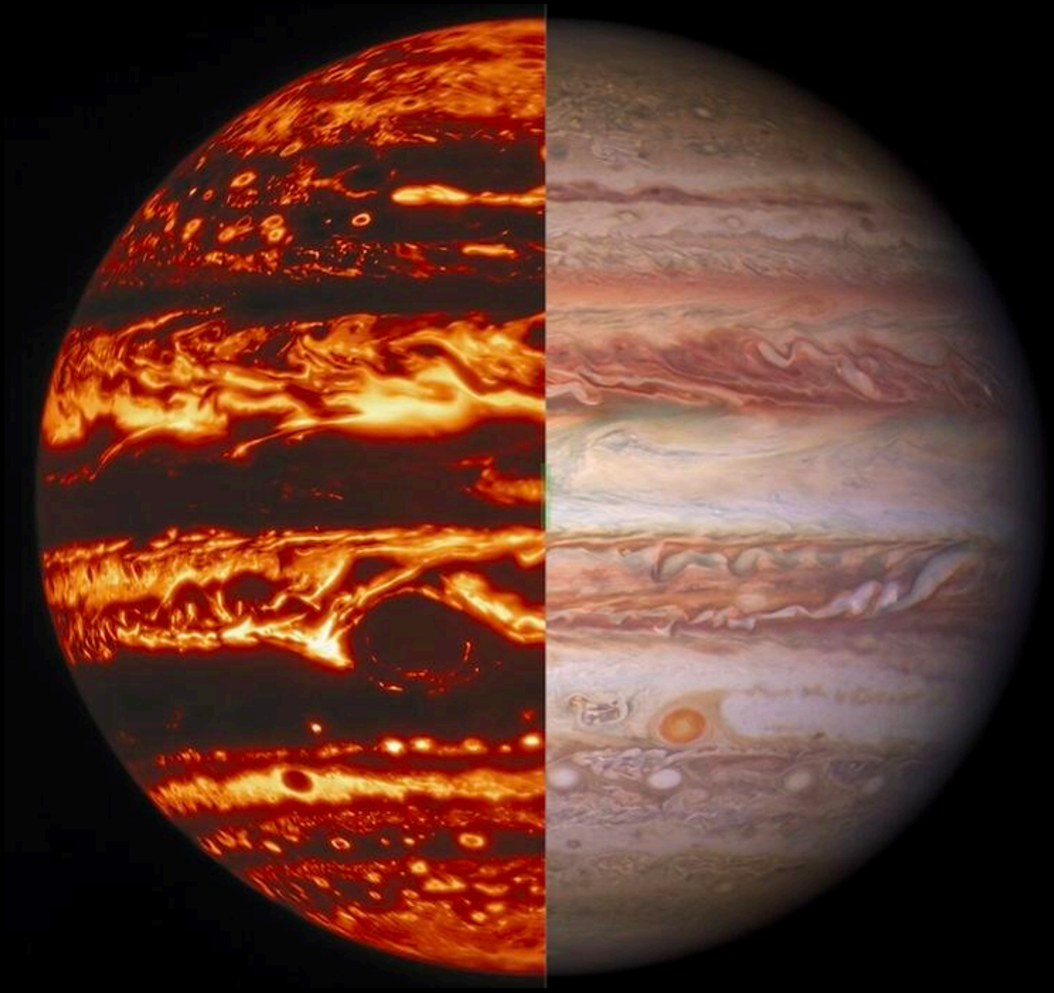
A B
C D

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?

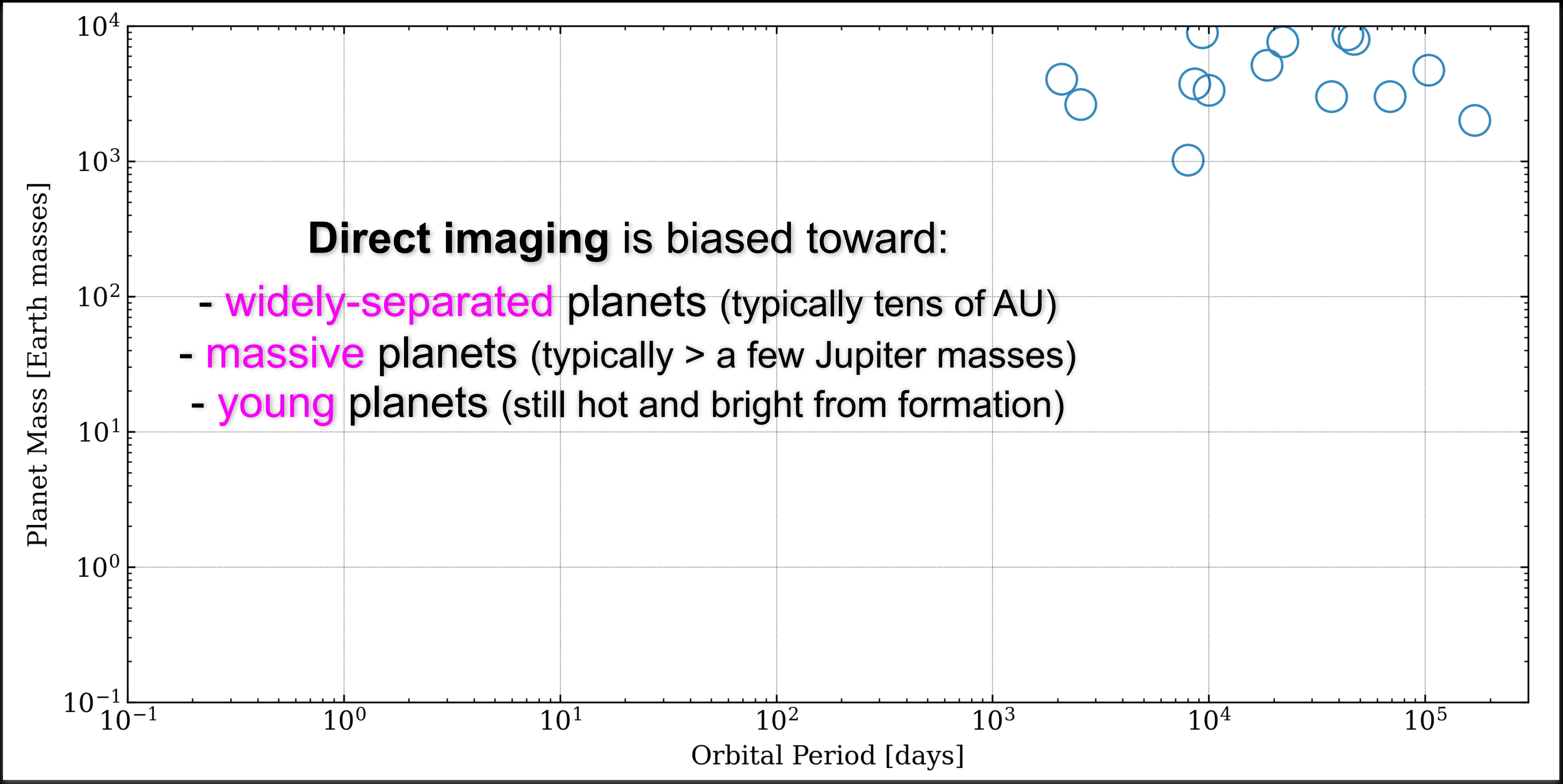
A: 50 million years

B: 5 billions years (~current age)



Known Directly Imaged Exoplanets

Mass-Period diagram



Direct imaging is biased toward:

- widely-separated planets (typically tens of AU)
- massive planets (typically > a few Jupiter masses)
- young planets (still hot and bright from formation)