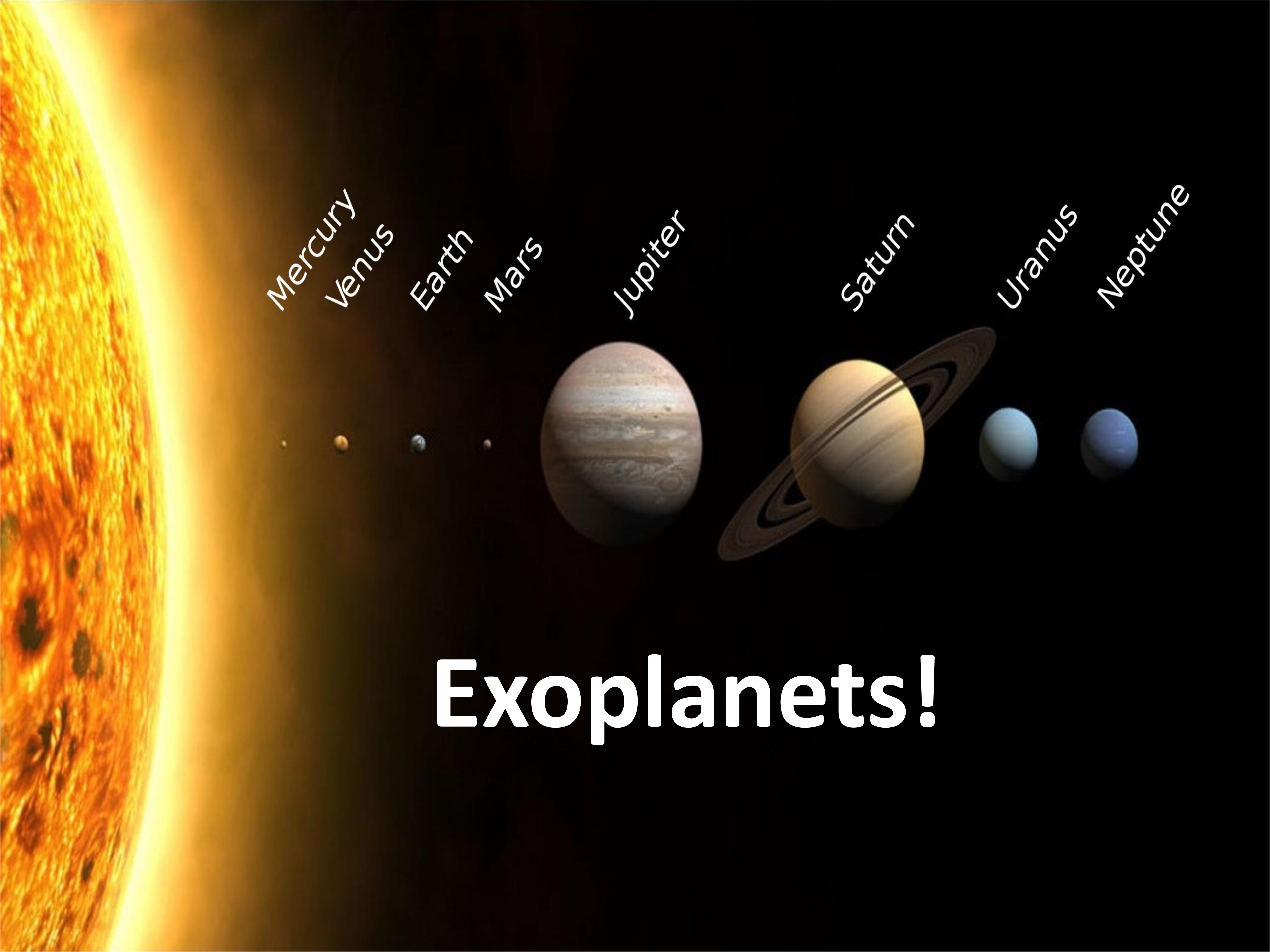


Exoplanets!

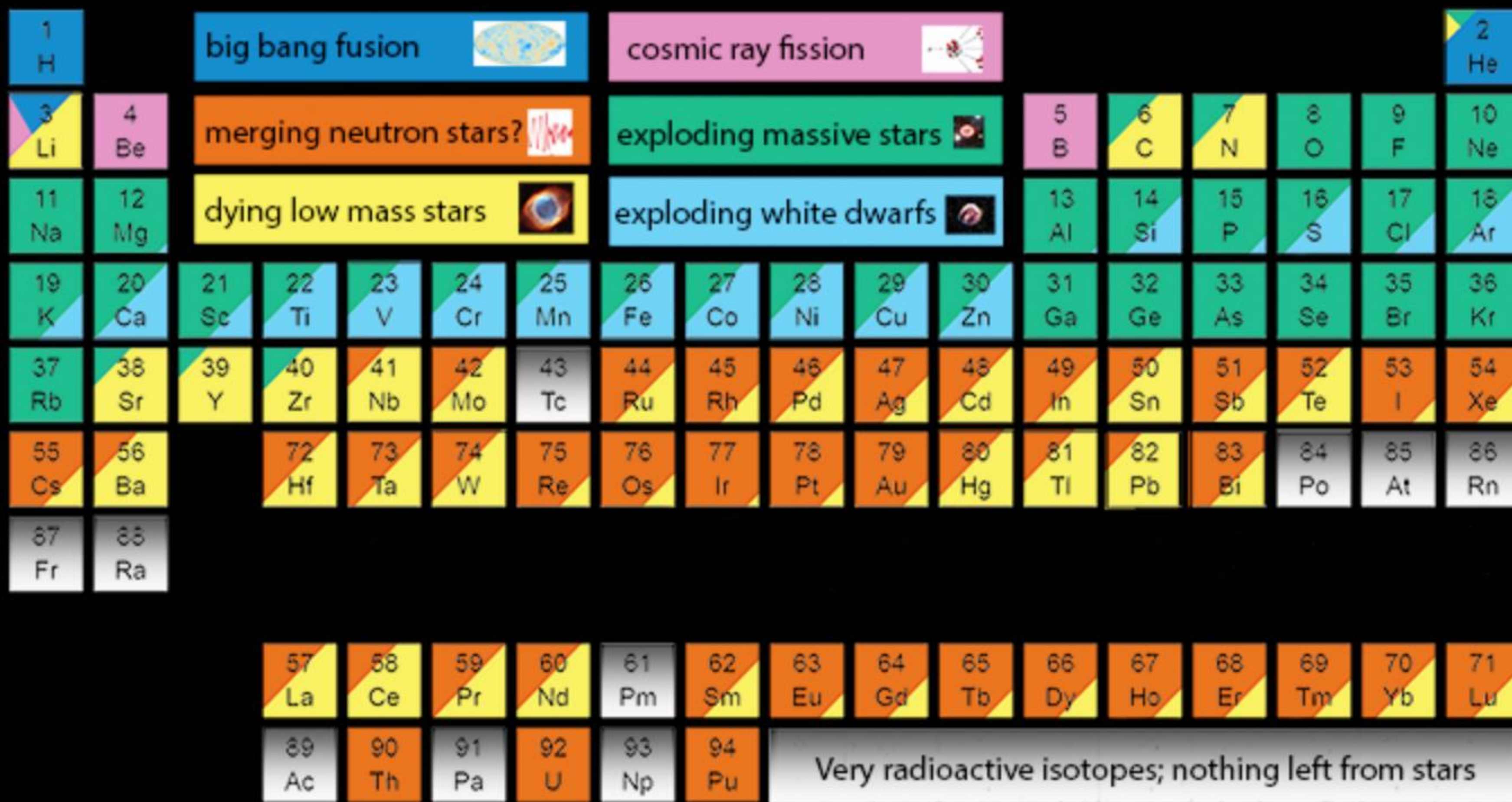
Homework: due now!

Probably a 2-week turnaround for grades

Project 1: due on 10.24

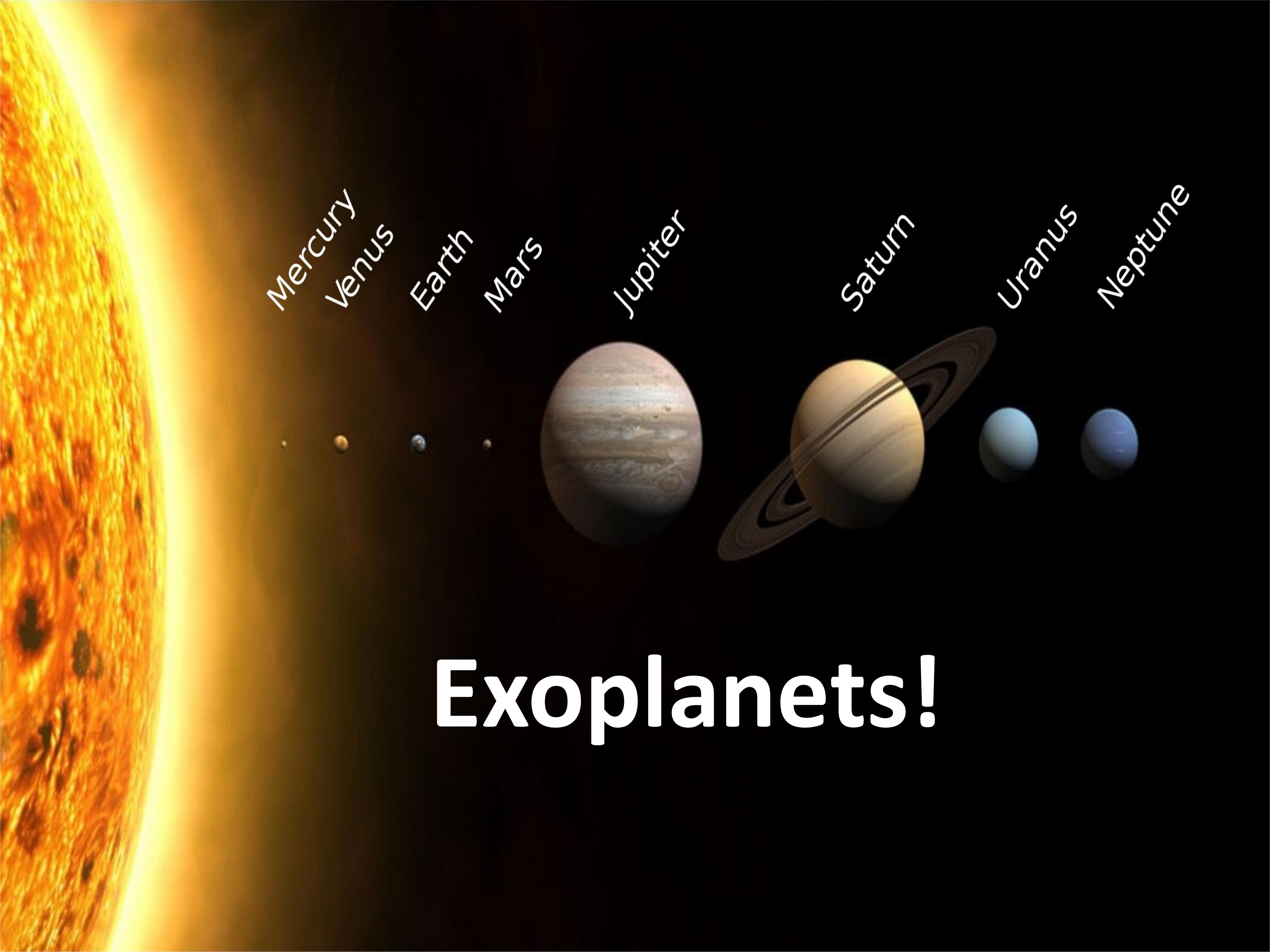
- Due before class on October 24
- Oral report
  - 5 min (don't go over)
  - Max 7 slides (including intro slide)
- Choose any astronomy-related topic
- Make it interesting!
- Upload video to PKU server

The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova



Exoplanets!

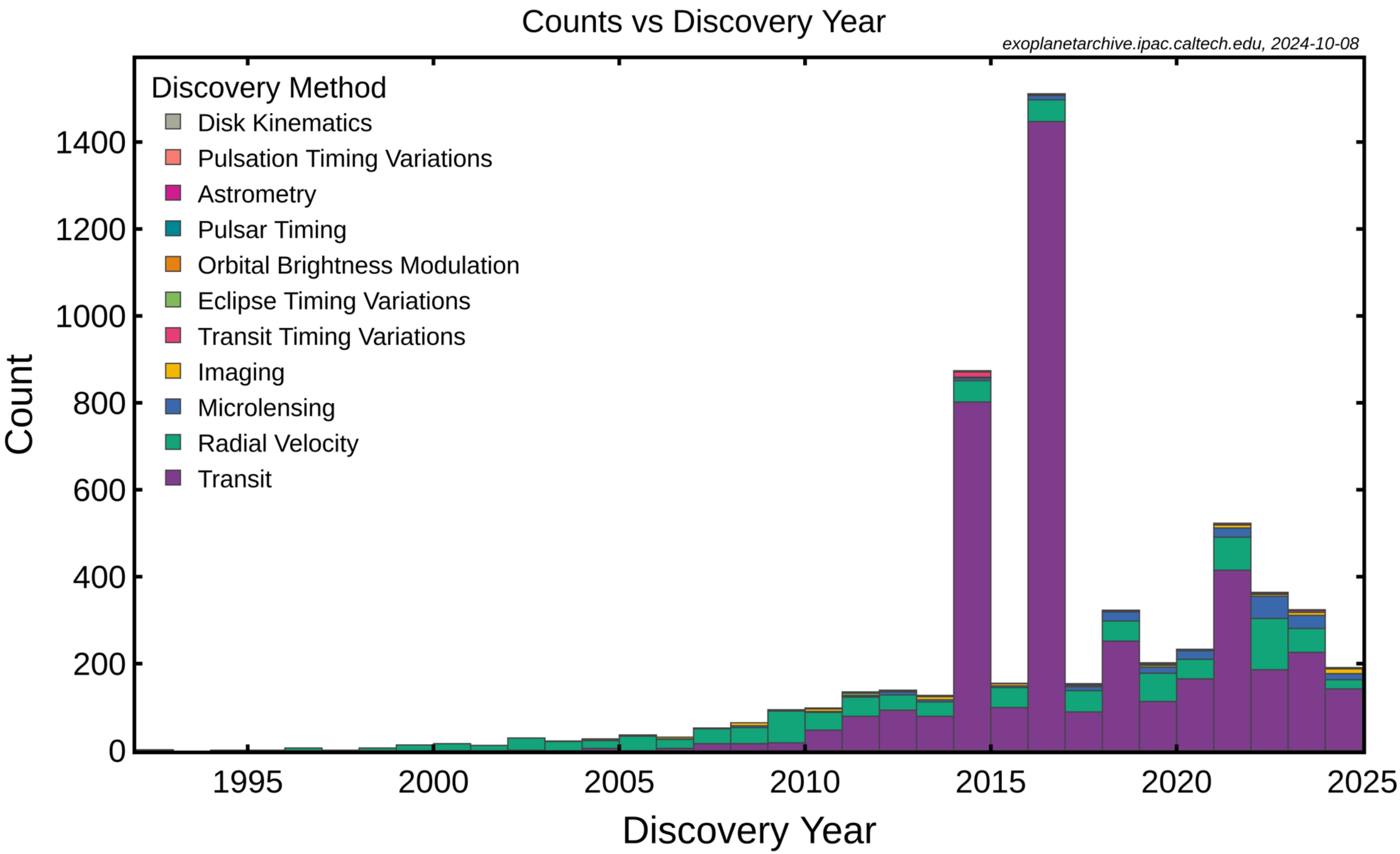
Exoplanets

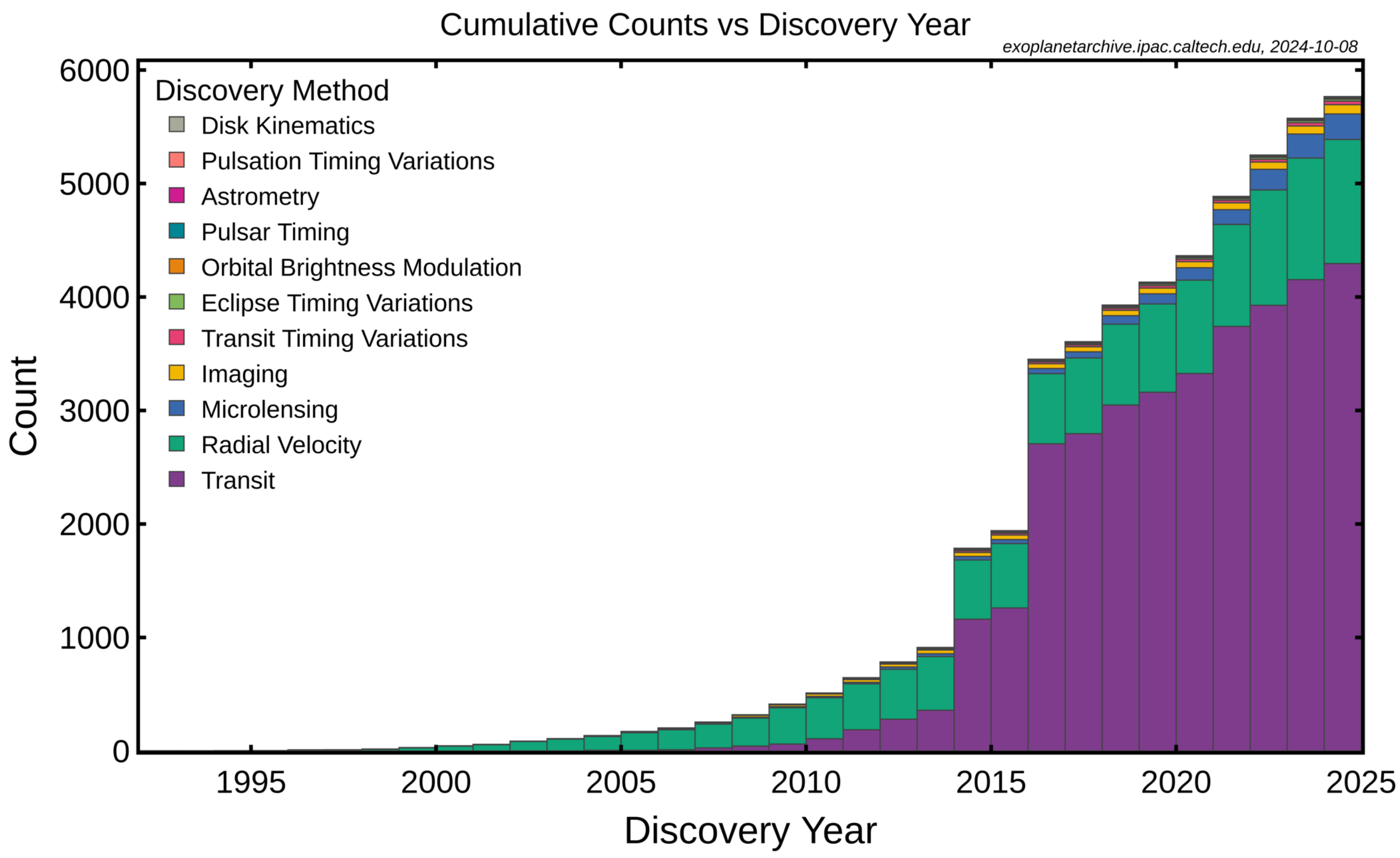
5,766 confirmed exoplanets!

first detection around normal star: 1995

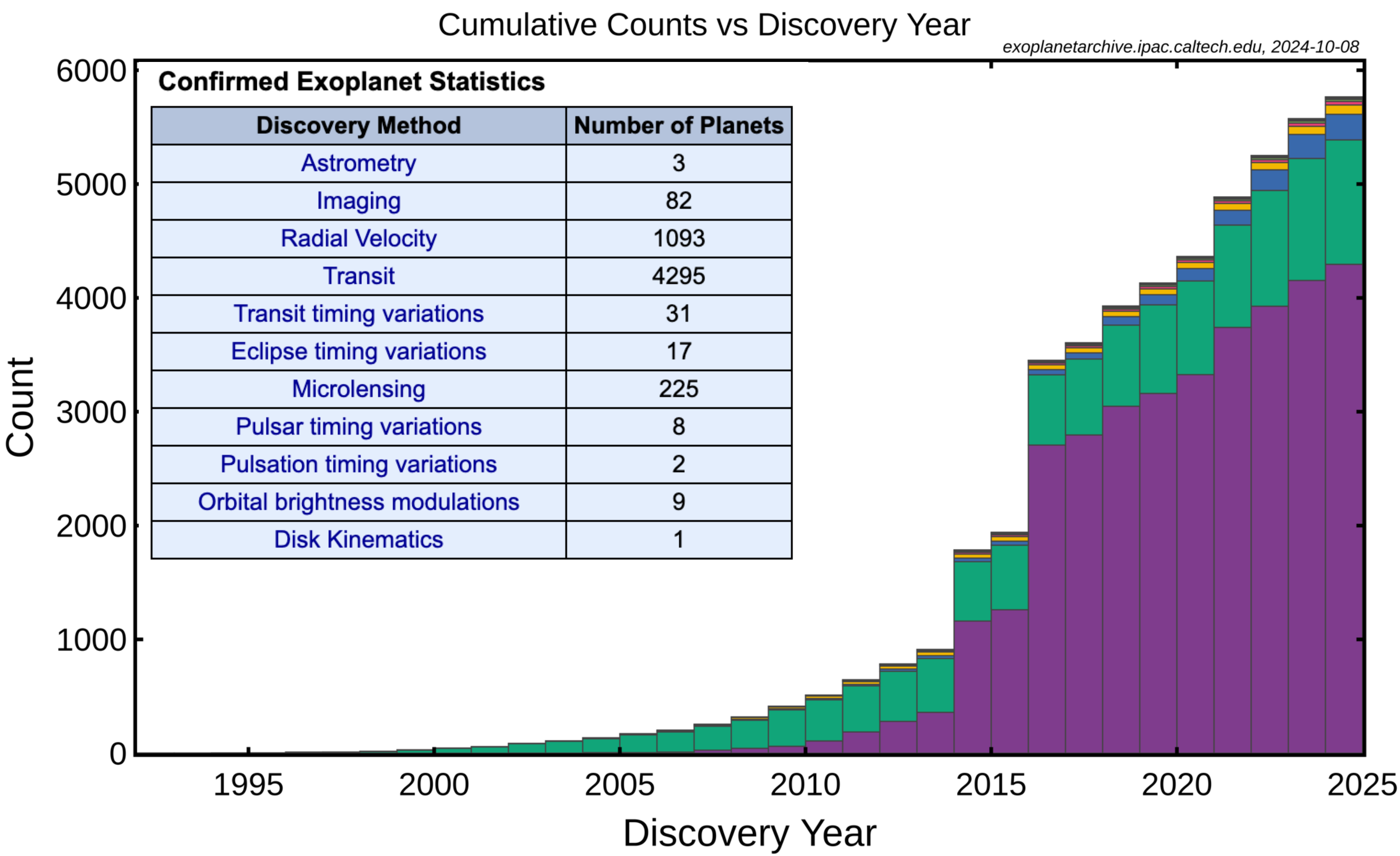
~8,000 more likely planets

This is amazing!


Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-10-08
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Count
0
200
400
600
800
1000
1200
1400
1995
2000
2005
2010
2015
2020
2025
Discovery Year

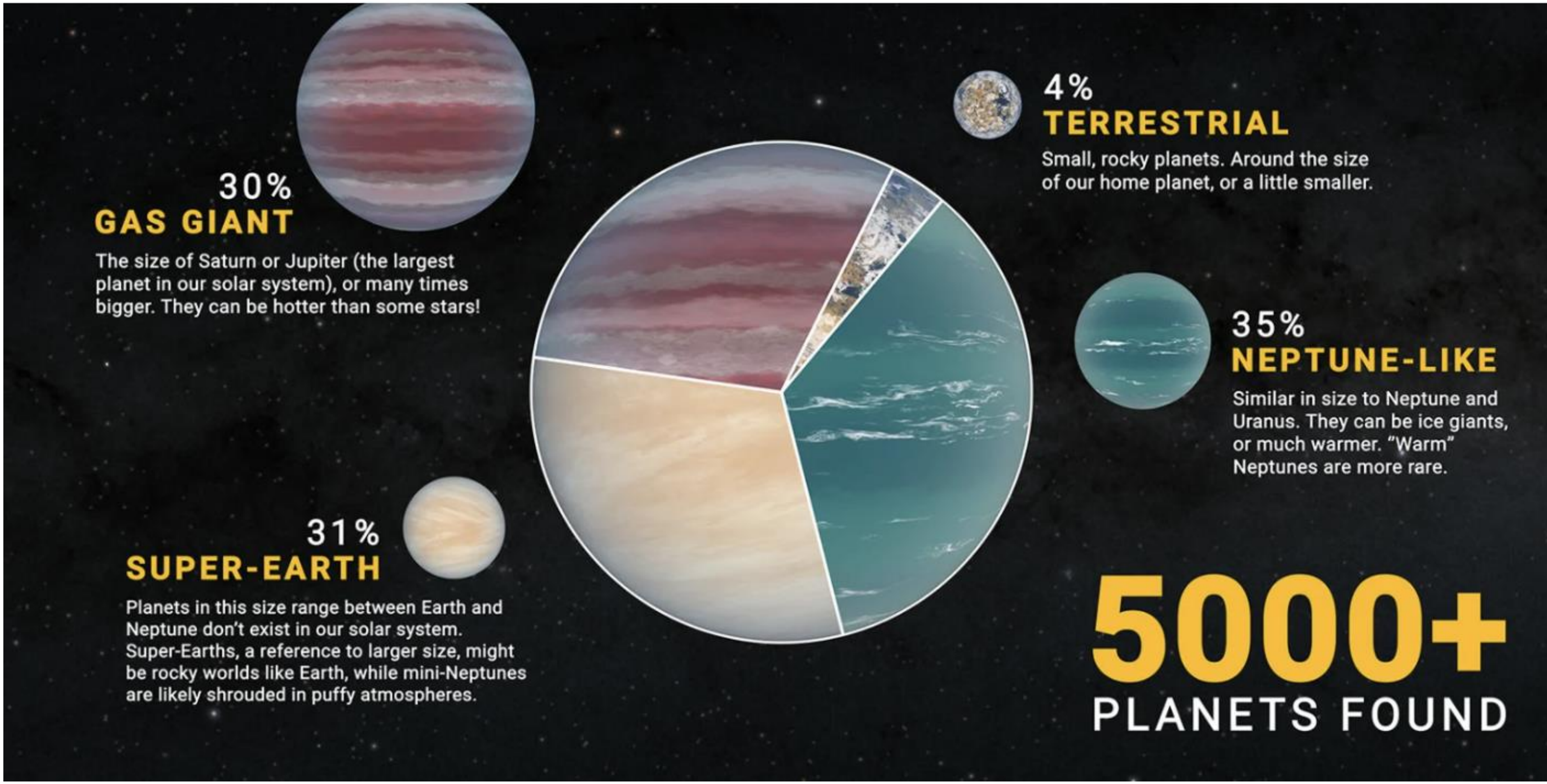


Cumulative Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-10-08
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Count
0
1000
2000
3000
4000
5000
6000
1995
2000
2005
2010
2015
2020
2025
Discovery Year



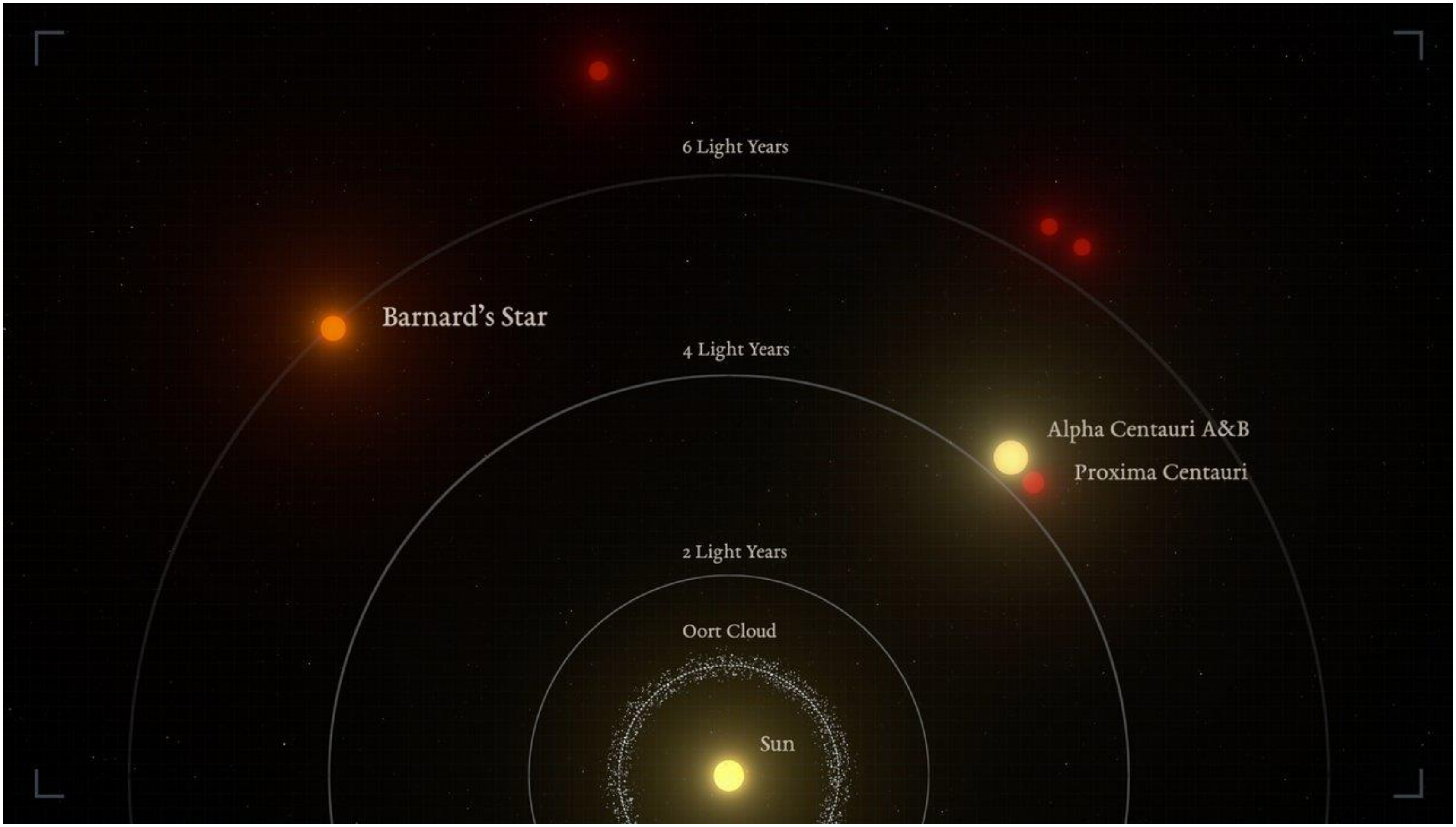
Confirmed Exoplanet Statistics

Discovery Method	Number of Planets
Astrometry	3
Imaging	82
Radial Velocity	1093
Transit	4295
Transit timing variations	31
Eclipse timing variations	17
Microlensing	225
Pulsar timing variations	8
Pulsation timing variations	2
Orbital brightness modulations	9
Disk Kinematics	1



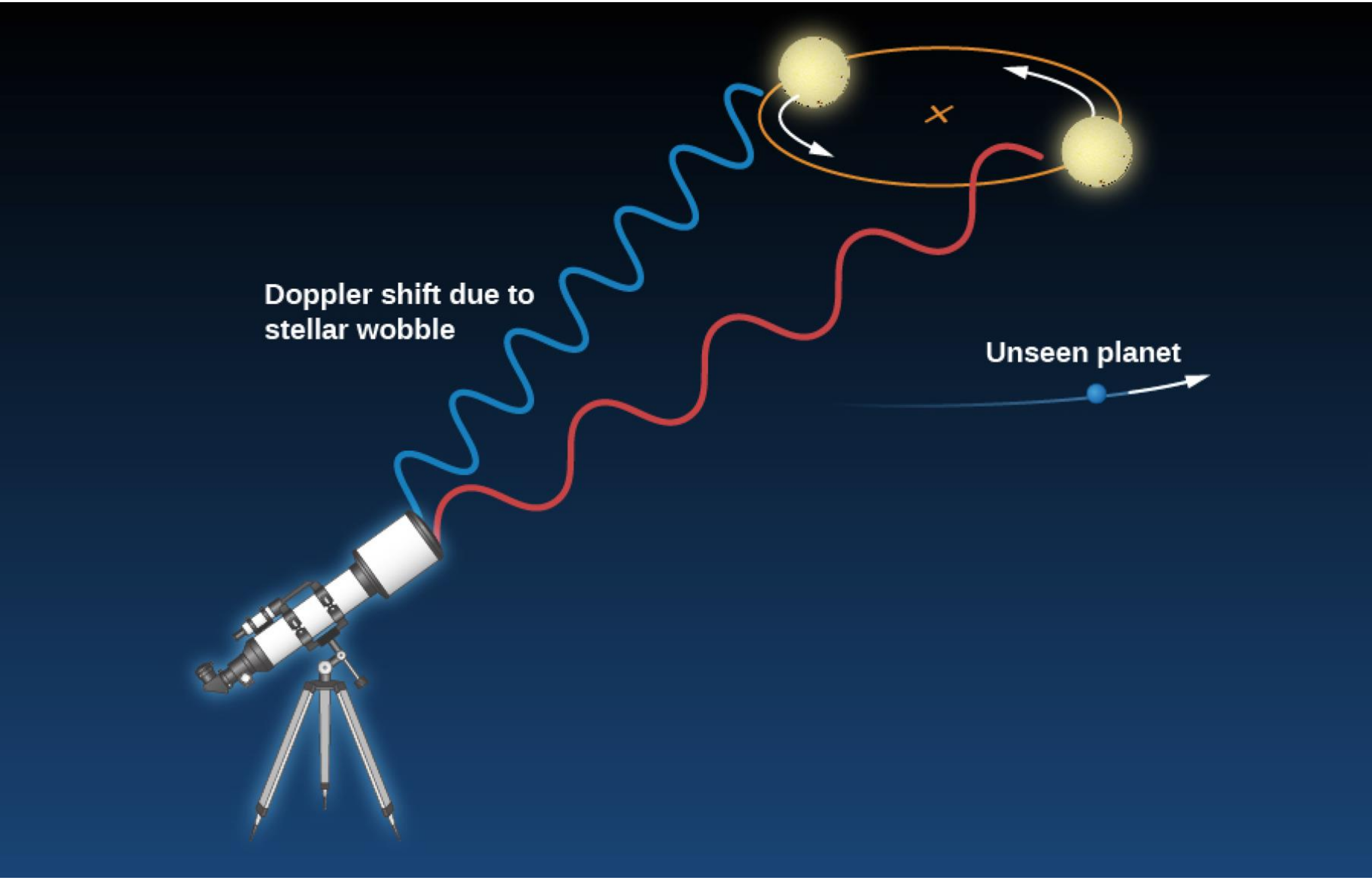
30%
GAS GIANT
The size of Saturn or Jupiter (the largest planet in our solar system), or many times bigger. They can be hotter than some stars!
4%
TERRESTRIAL
Small, rocky planets. Around the size of our home planet, or a little smaller.
35%
NEPTUNE-LIKE
Similar in size to Neptune and Uranus. They can be ice giants, or much warmer. "Warm" Neptunes are more rare.
31%
SUPER-EARTH
Planets in this size range between Earth and Neptune don't exist in our solar system. Super-Earths, a reference to larger size, might be rocky worlds like Earth, while mini-Neptunes are likely shrouded in puffy atmospheres.
5000+
PLANETS FOUND

Last week: 0.37 M_{earth} planet around Barnard's star (one of the closest systems to us)

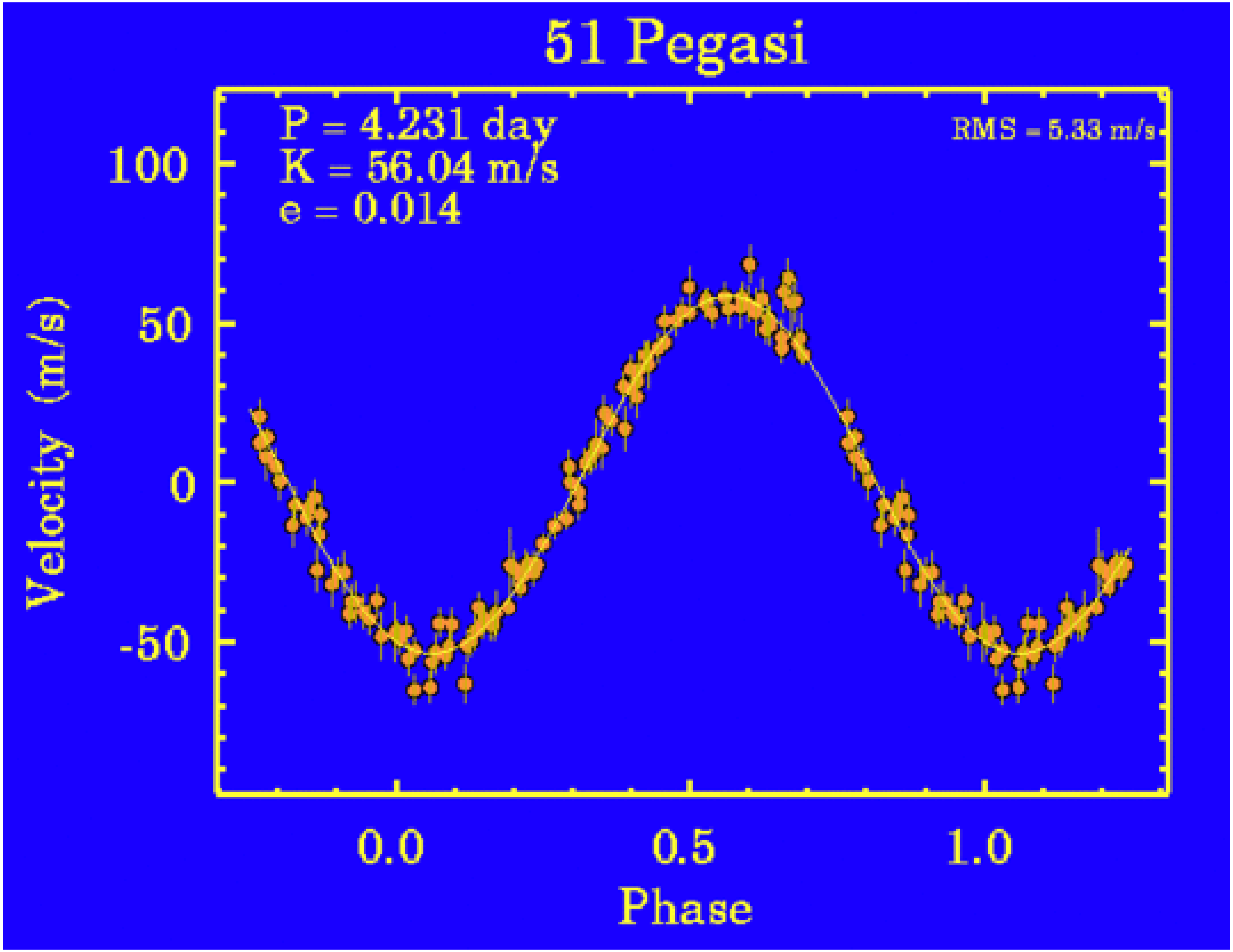


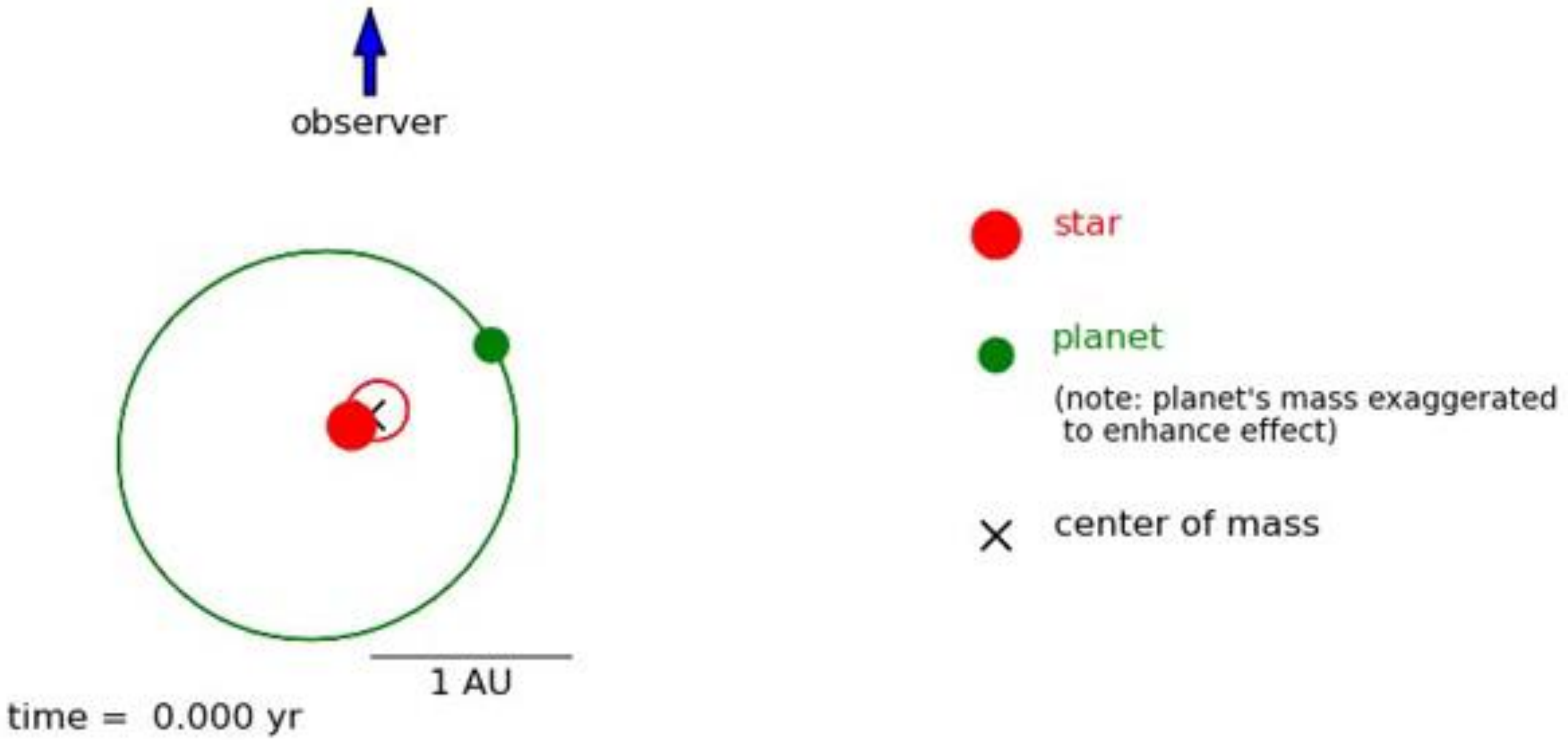
Keywords for Lecture 4

- Exoplanet: a planet around a different star
- Detection techniques: how exoplanets are detected?
  - Radial Velocity
  - Transits
  - Direct Imaging
- Atmospheres
- Protoplanetary disks
- Habitability
- Biases


Doppler shift due to
stellar wobble
Unseen planet

The first planet: a hot Jupiter




observer
star
planet
(note: planet's mass exaggerated
to enhance effect)
center of mass
1 AU
time = 0.000 yr

Bias of radial velocity

- What kinds of planets are easiest to detect?
  - Higher mass
  - Closer to the star
- Motion of star

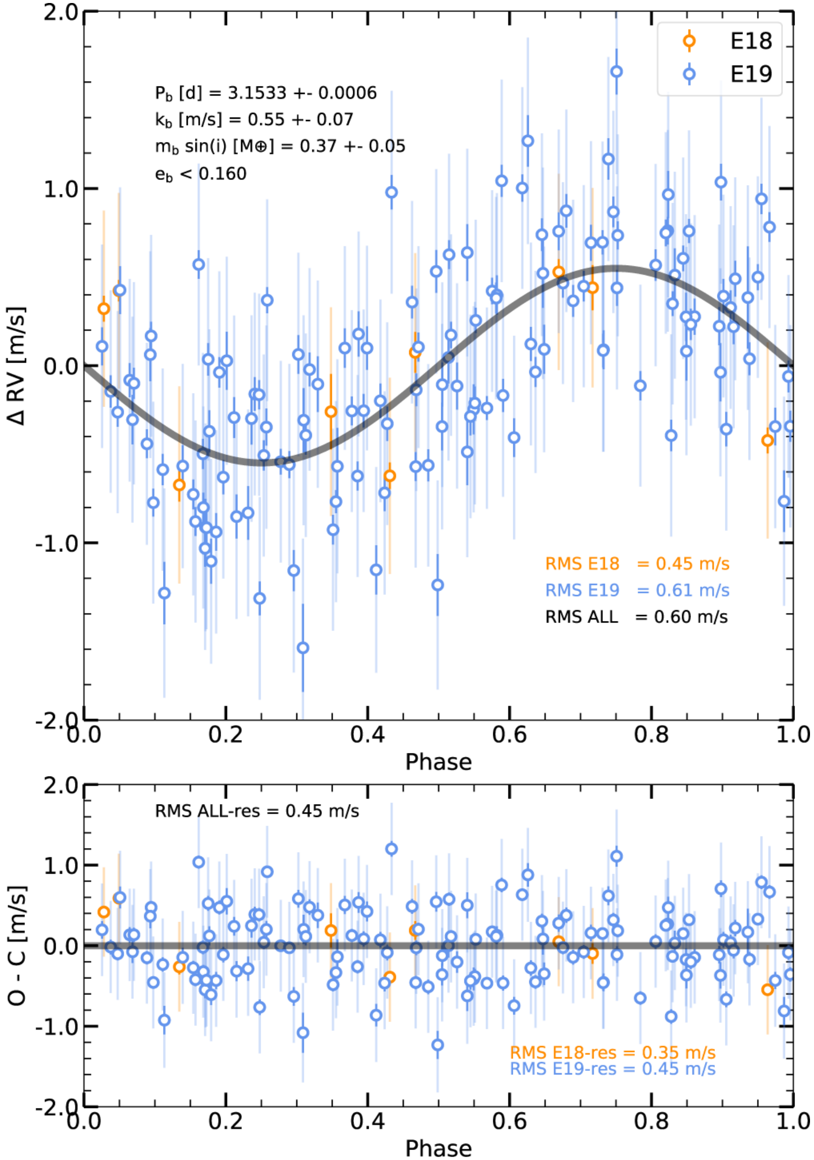
$$v_{\mathrm{obs}} = 28.4 \frac{M_P \sin i}{P_{\mathrm{orb}}^{1/3} M_*^{2/3}}$$

- M_P in Jupiter masses
- P_{orb} in years
- M_* in solar masses

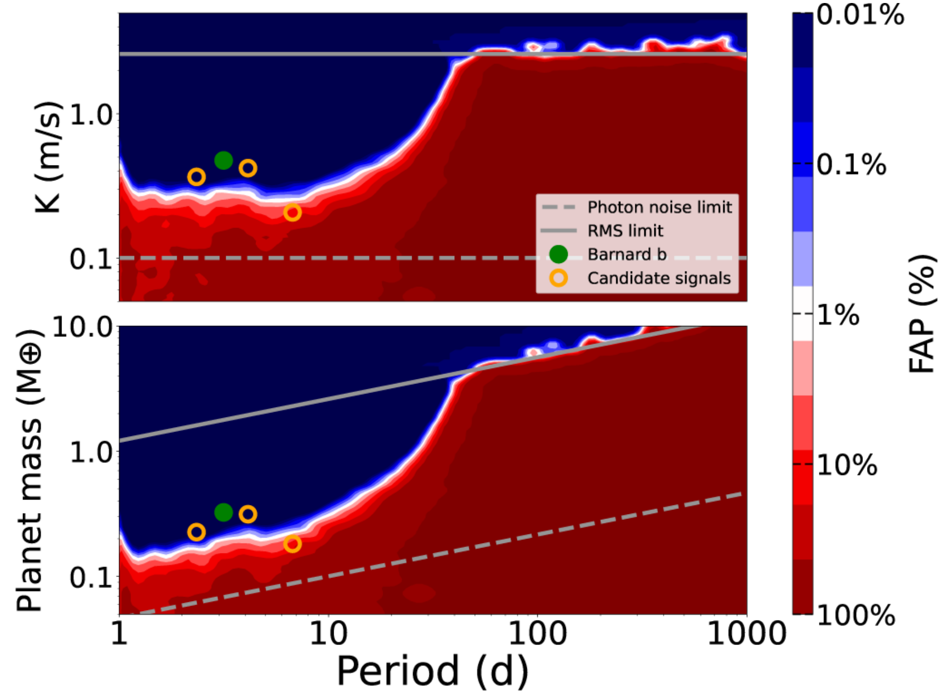
Barnard star planet:

-3-day period

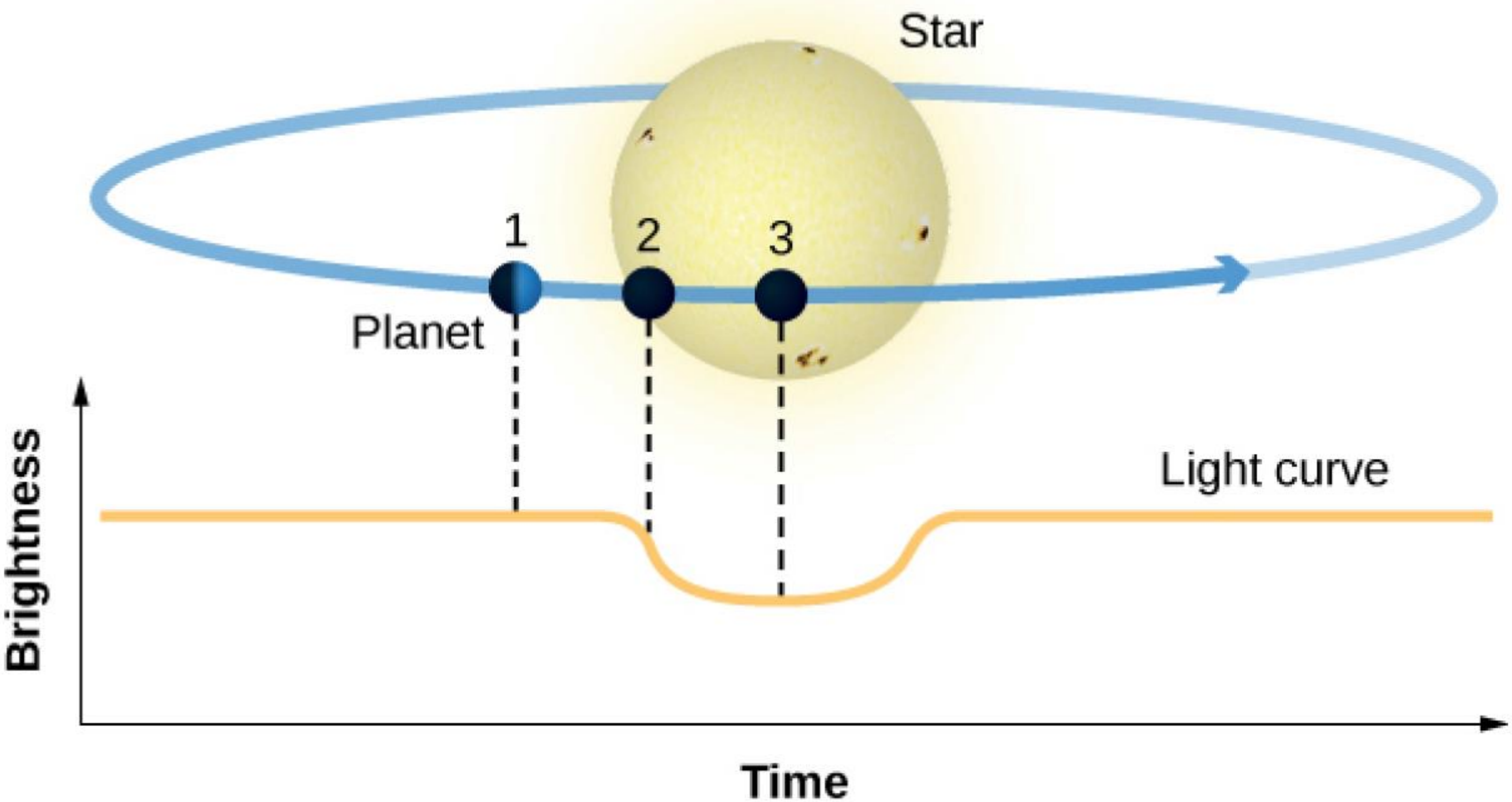
-0.37 M_{earth}



Radial velocity signal+residual



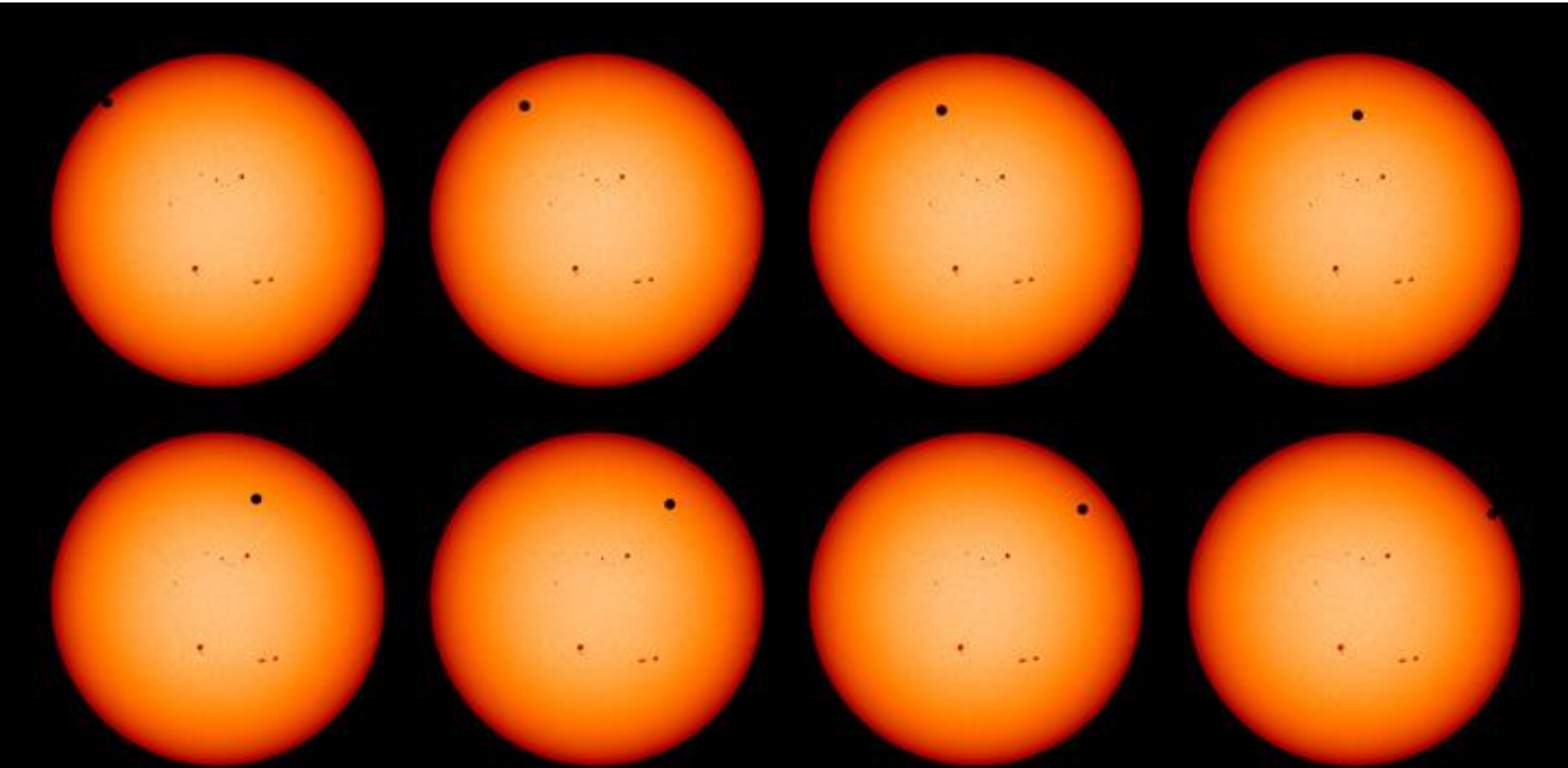
Bias: sensitivity to planet mass/radius


Star
1
2
3
Planet
Brightness
Light curve
Time

Venus transit

Every 112 years: (two times, separated by 8 years)

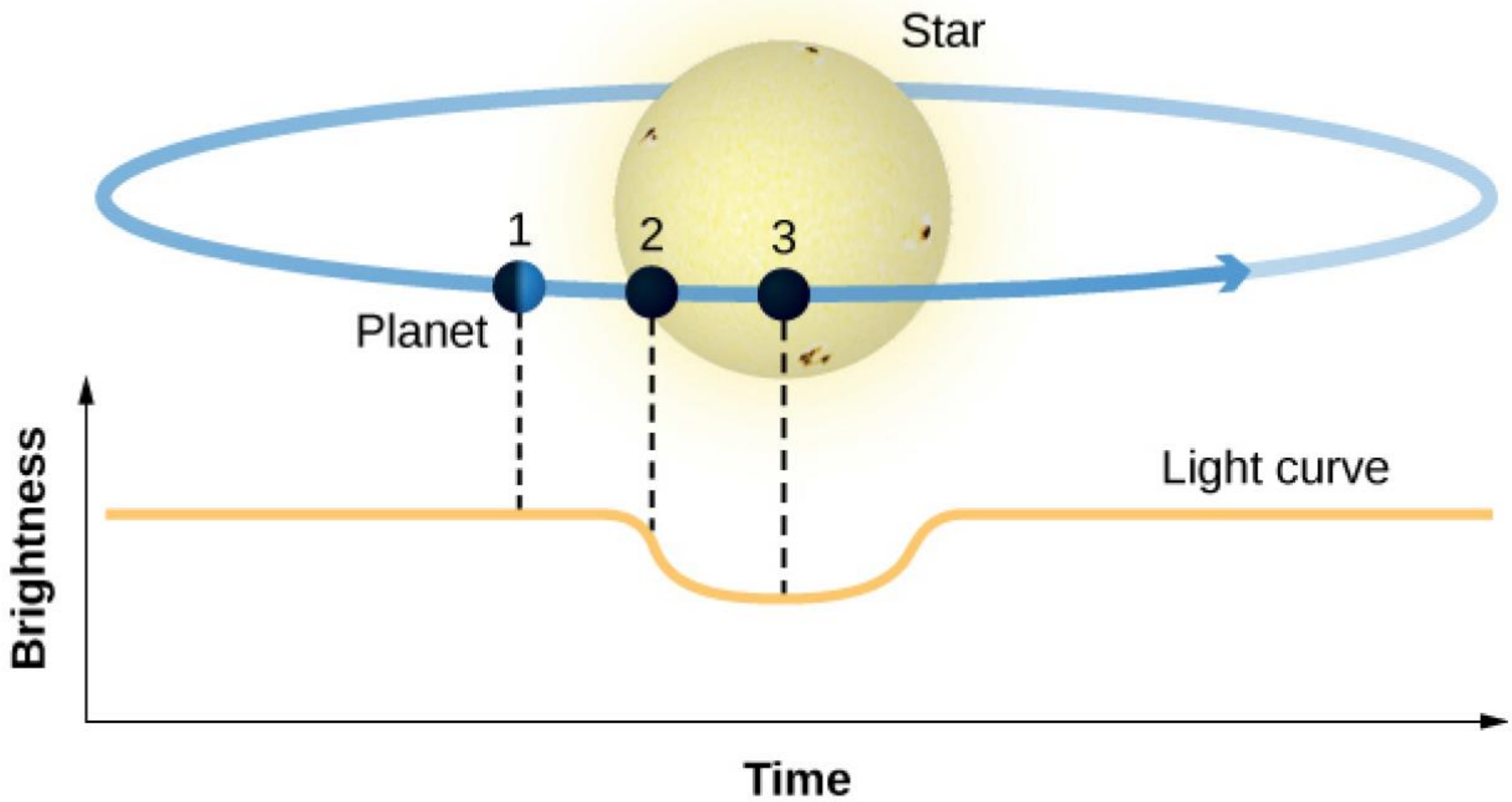
last time in 2004/2012

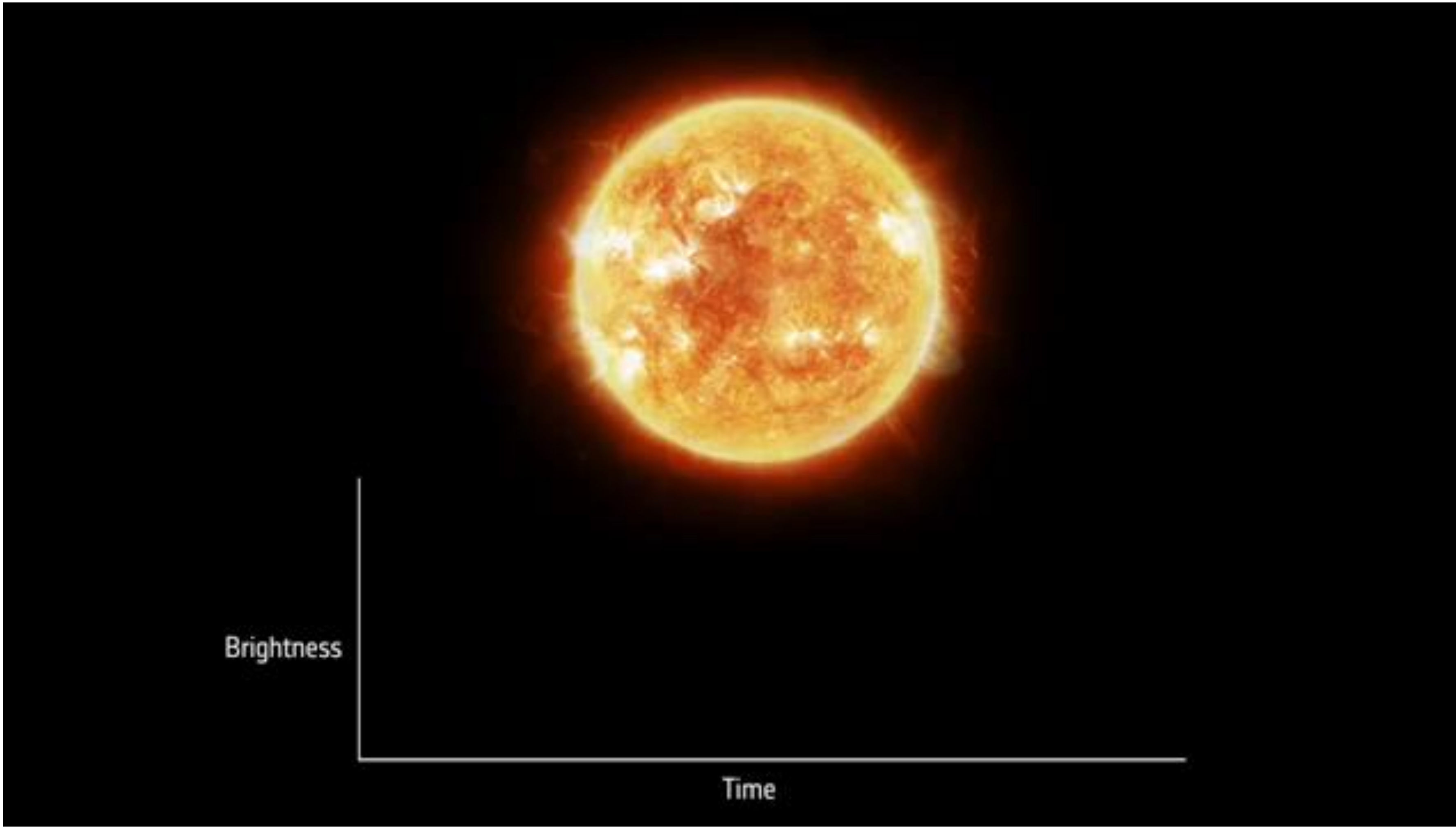


Venus transit

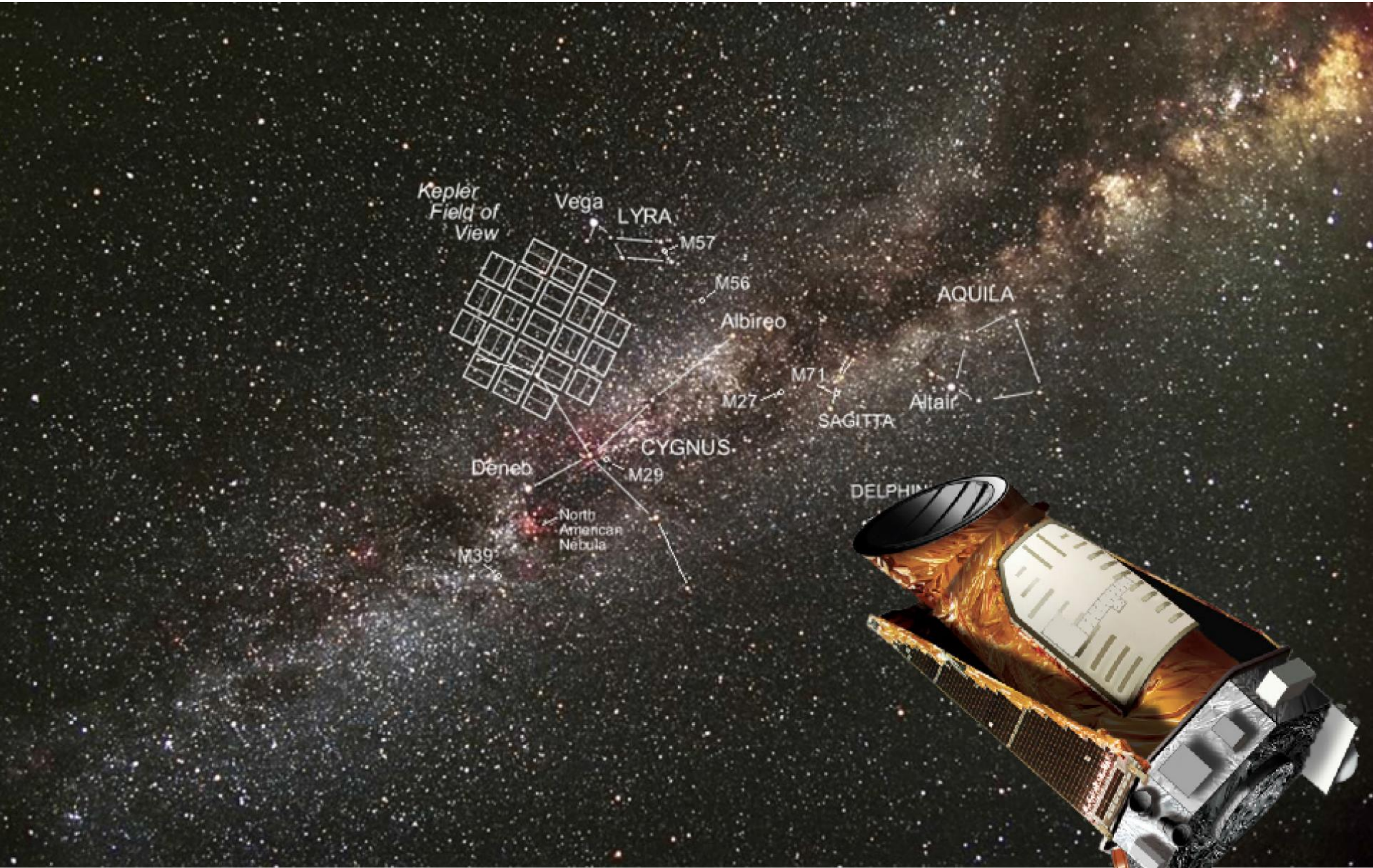
Guillaume Le Gentil: the unluckiest astronomer

1761/1769 transits from India?

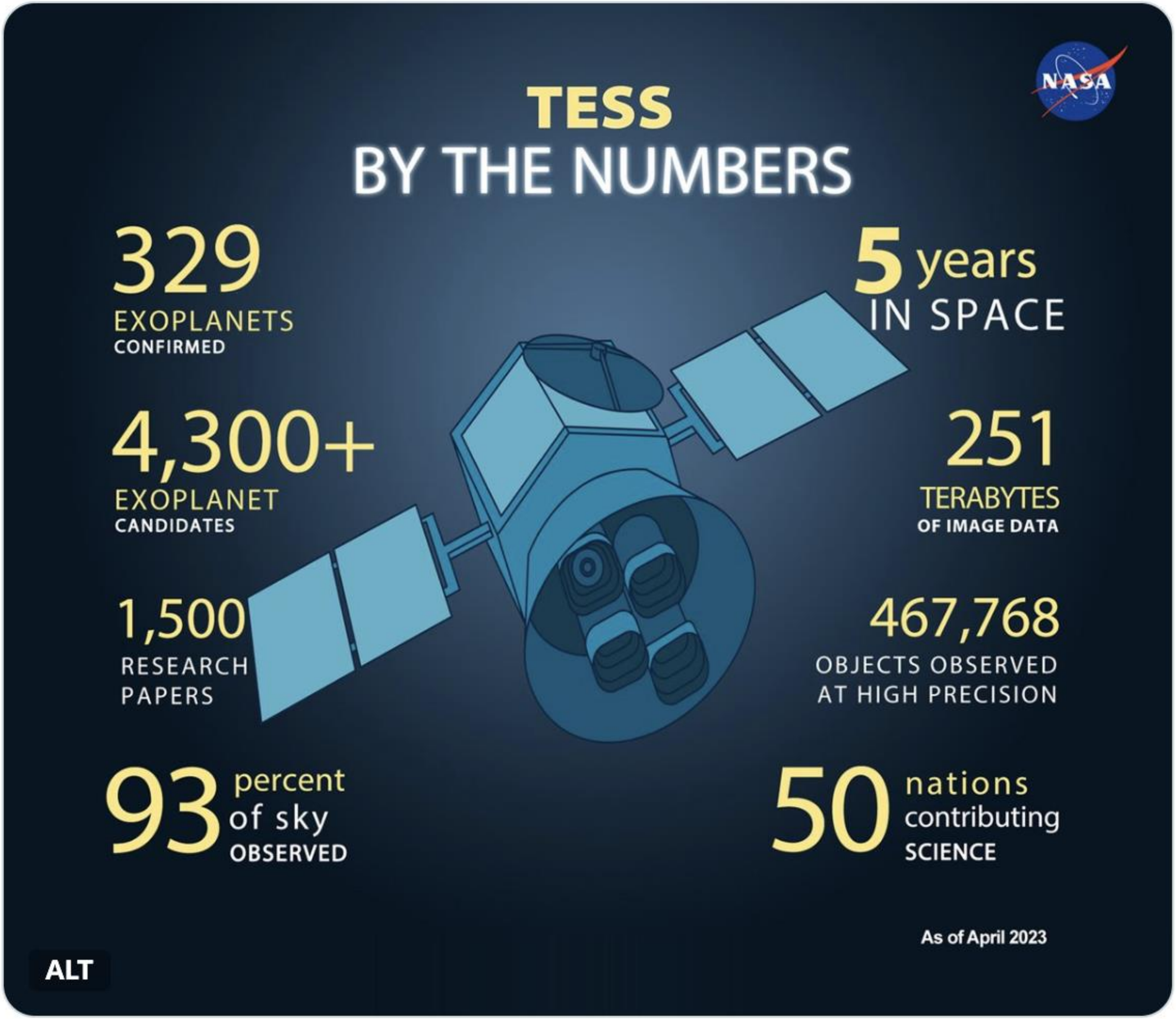

Star
1
2
3
Planet
Light curve
Brightness
Time

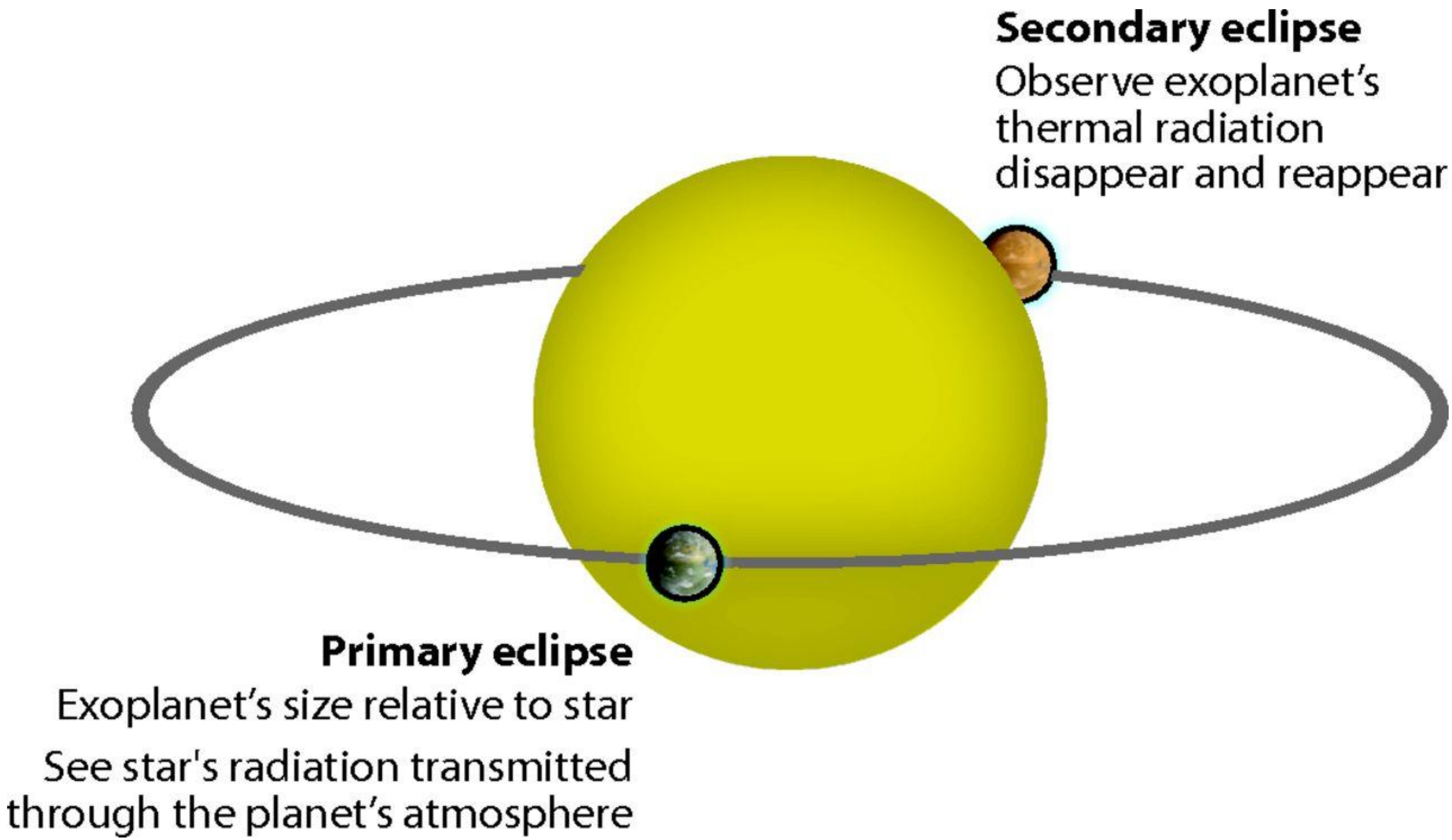

Brightness
Time

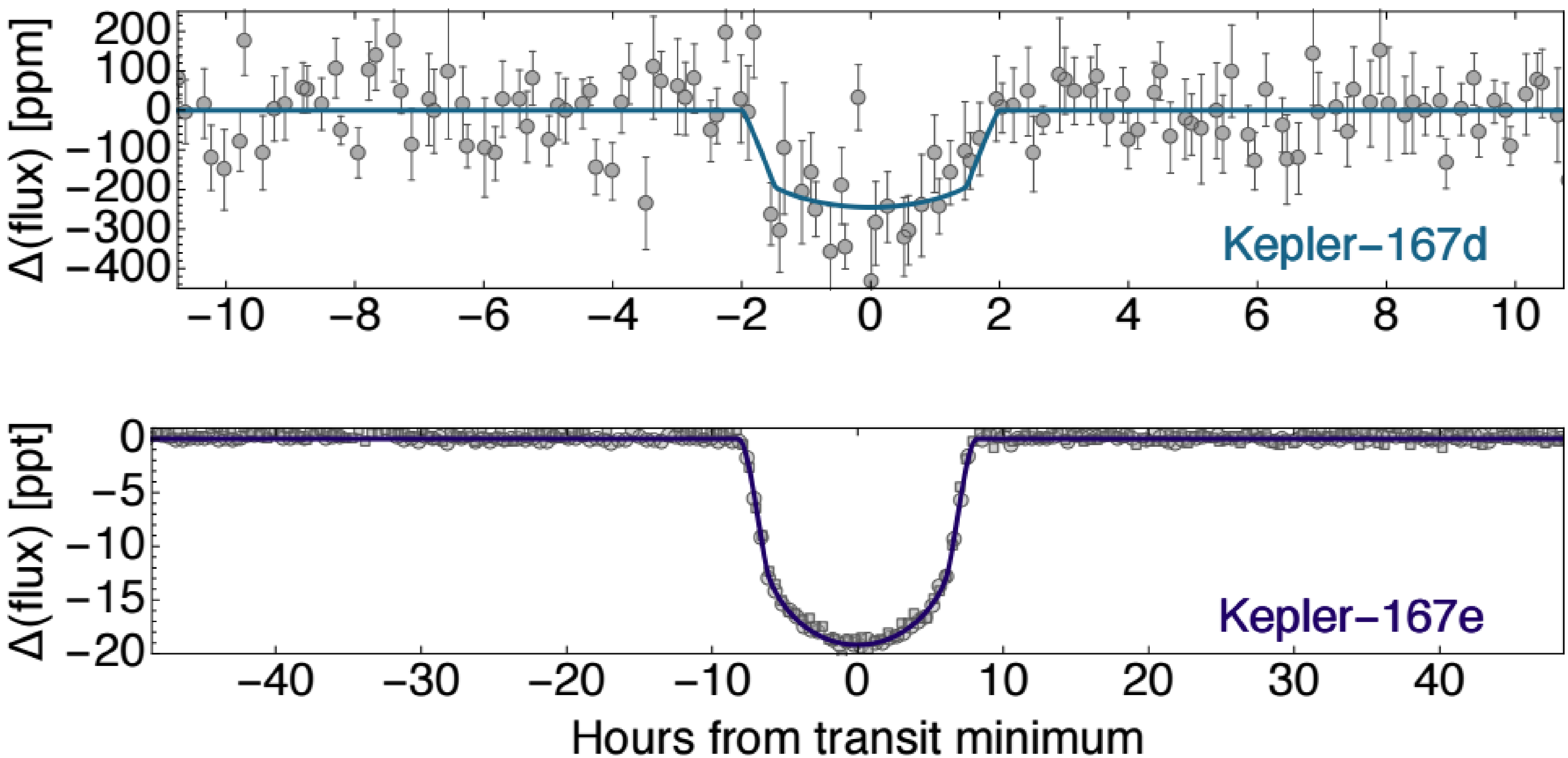
Kepler Observatory: thousands of planets



TESS Observatory: all-sky, bright stars




Secondary eclipse
Observe exoplanet's thermal radiation disappear and reappear
Primary eclipse
Exoplanet's size relative to star
See star's radiation transmitted through the planet's atmosphere



Δ(flux) [ppm]
200
100
0
−100
−200
−300
−400
Kepler−167d
−10
−8
−6
−4
−2
0
2
4
6
8
10
Δ(flux) [ppt]
0
−5
−10
−15
−20
Kepler−167e
−40
−30
−20
−10
0
10
20
30
40
Hours from transit minimum

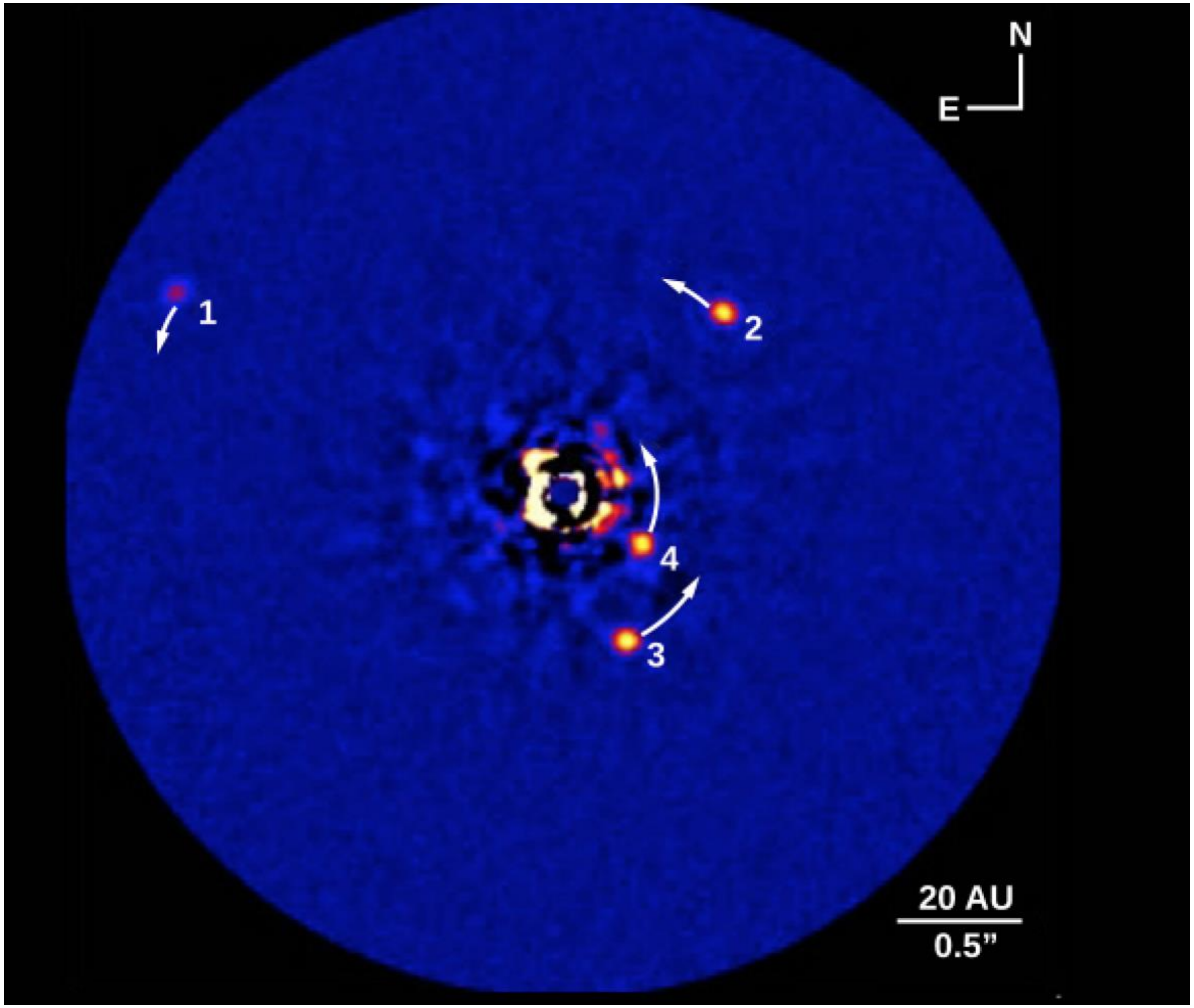
Bias of transits

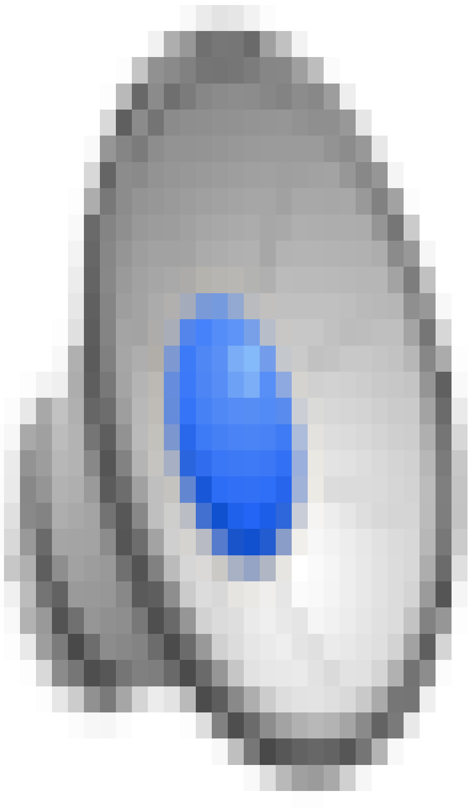
- What kinds of planets are easiest to detect?

- Close to star
- Large radius

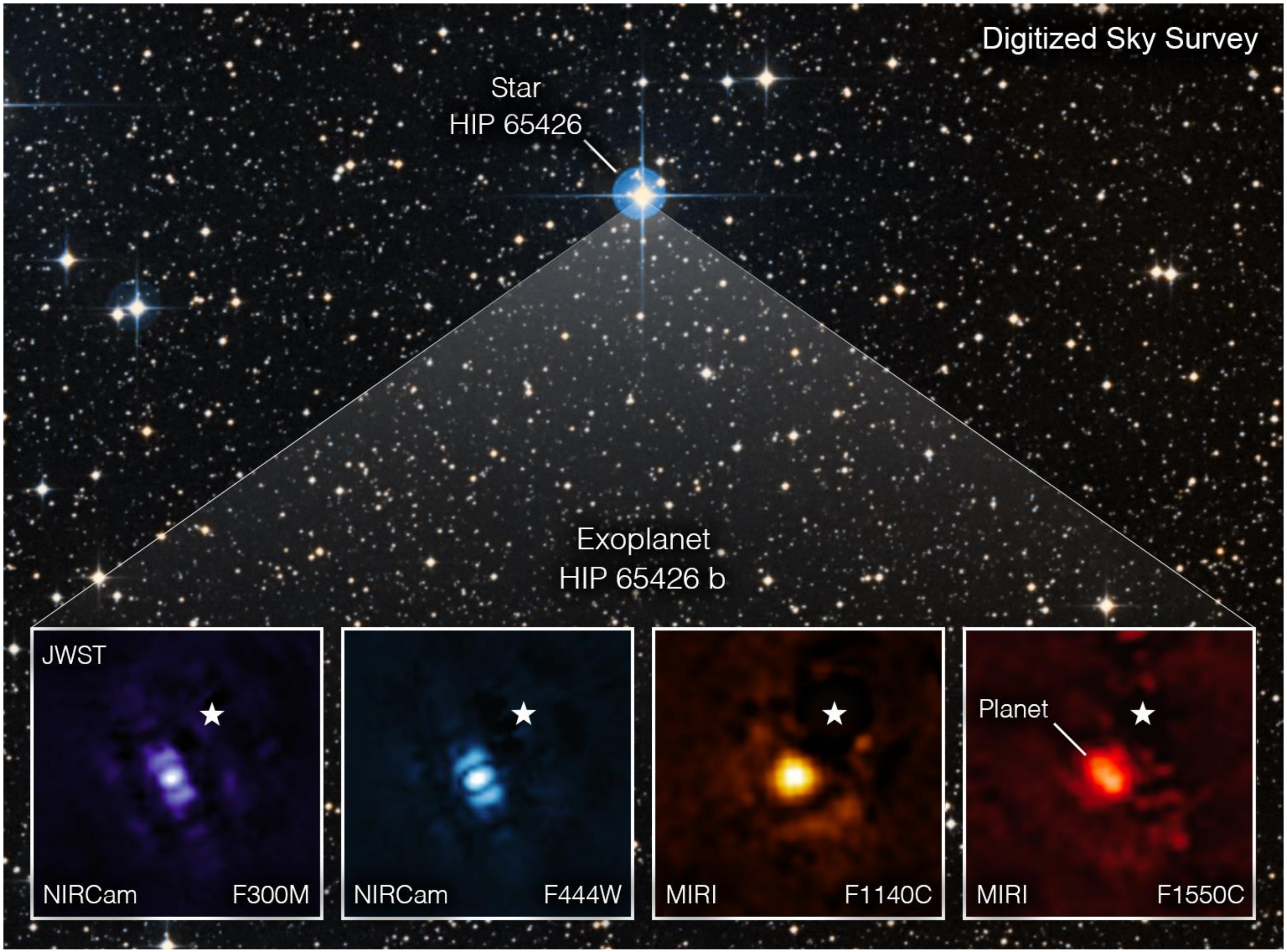
$$R_p = R_\star \sqrt{\text{Depth}}$$

Direct Imaging: requires coronagraph to block out the star (similar to eclipse)





First JWST image of a planet



JWST:
Powerful new infrared telescope

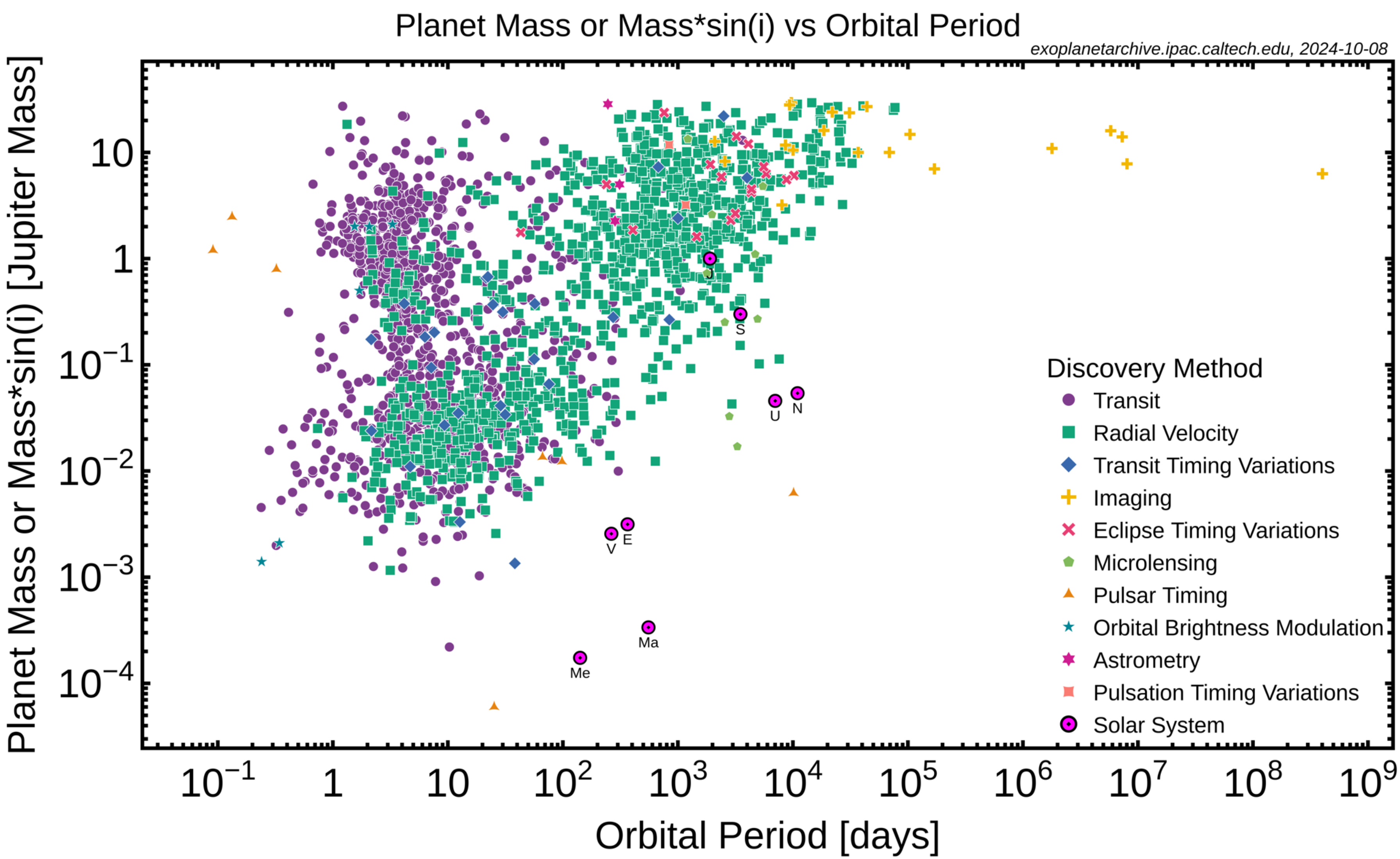
Bias of direct imaging

- What kinds of planets are easiest to detect?

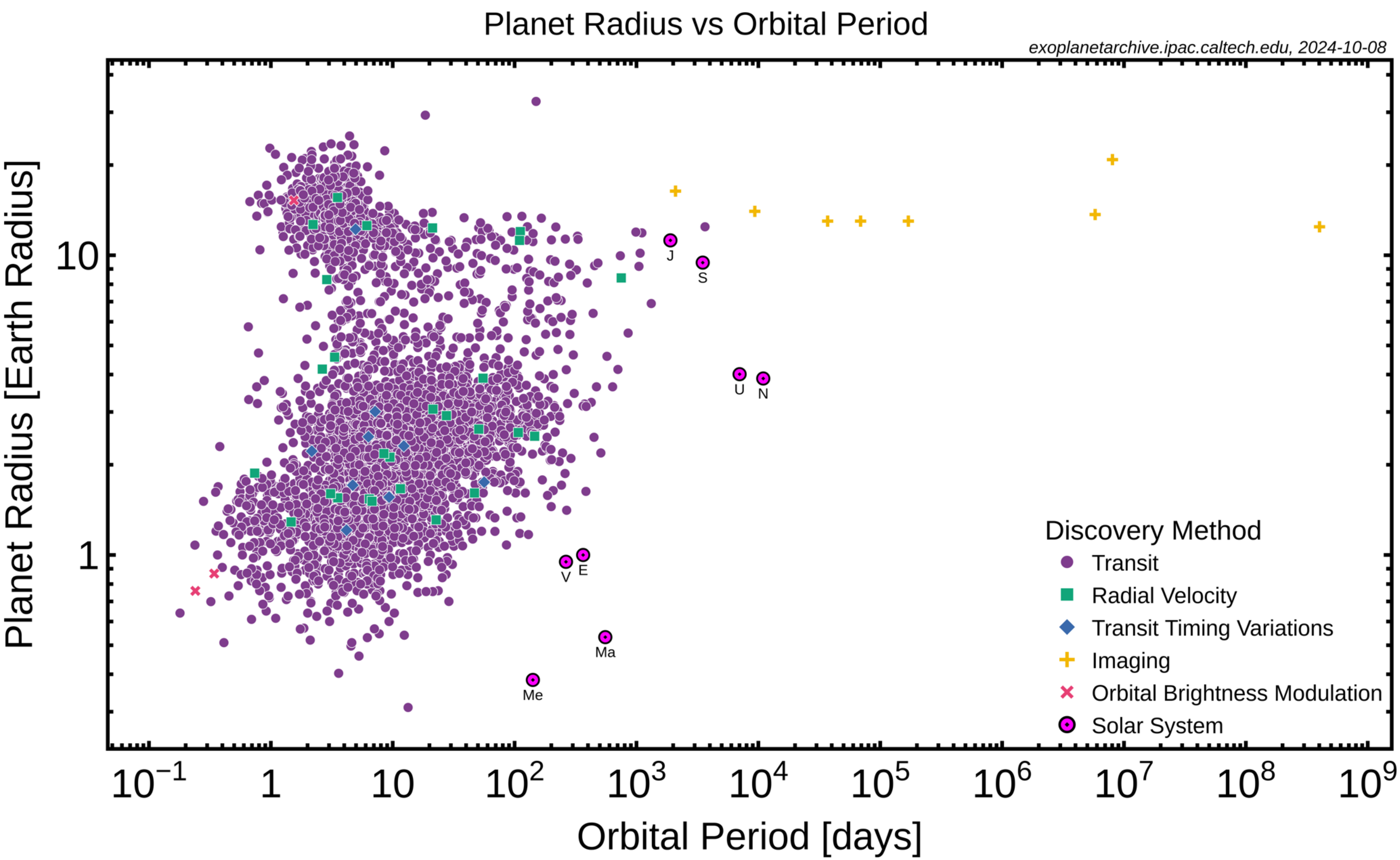
- Very bright (higher mass)
- Far from the star!

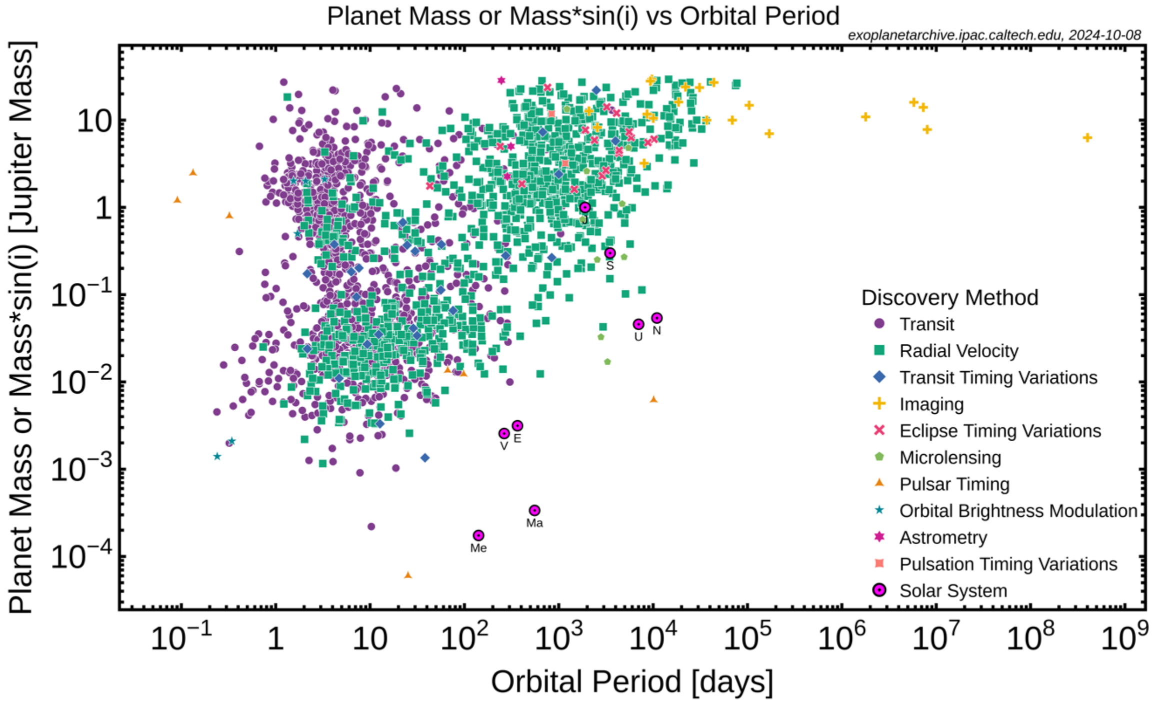
[also this is very hard]

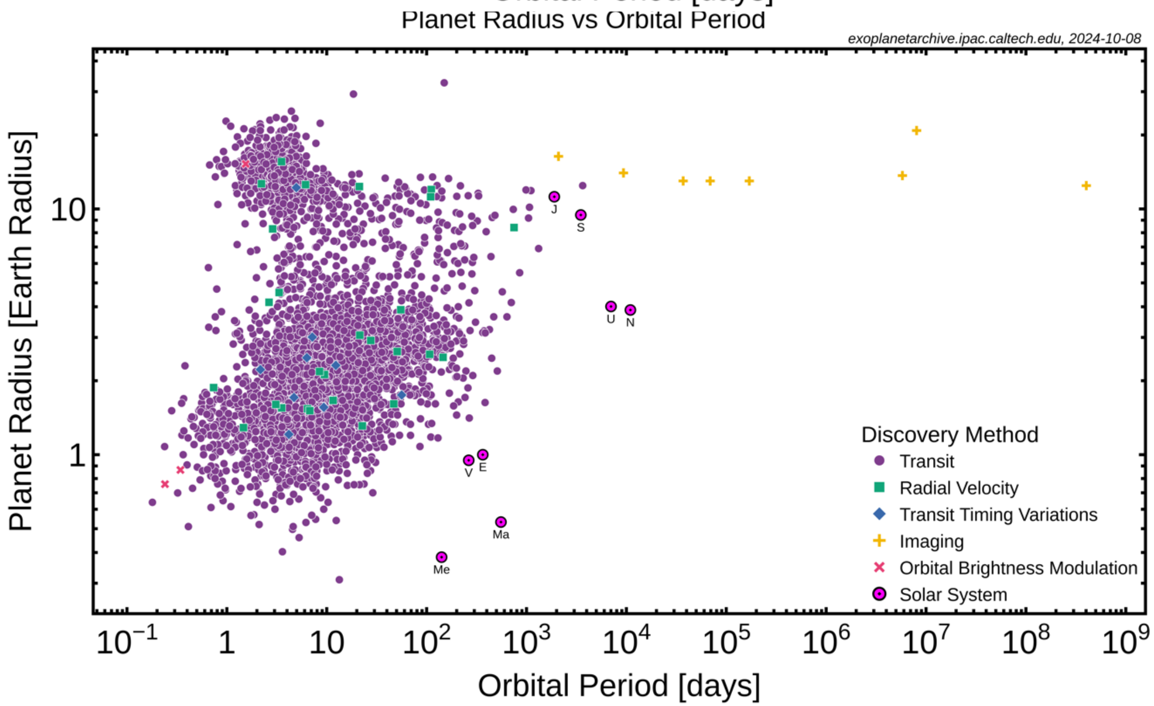
Exoplanets are common!



Exoplanets are common!





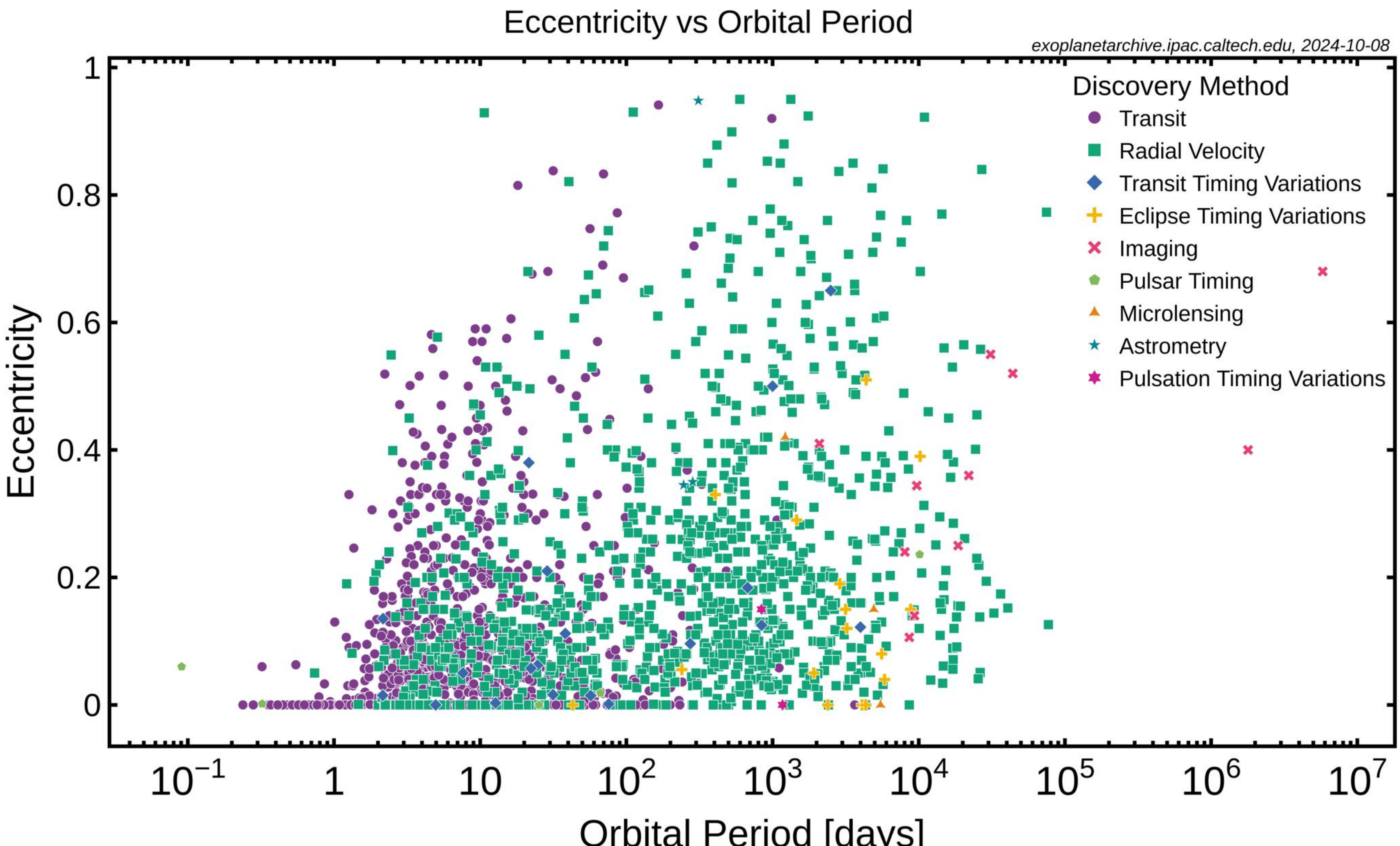


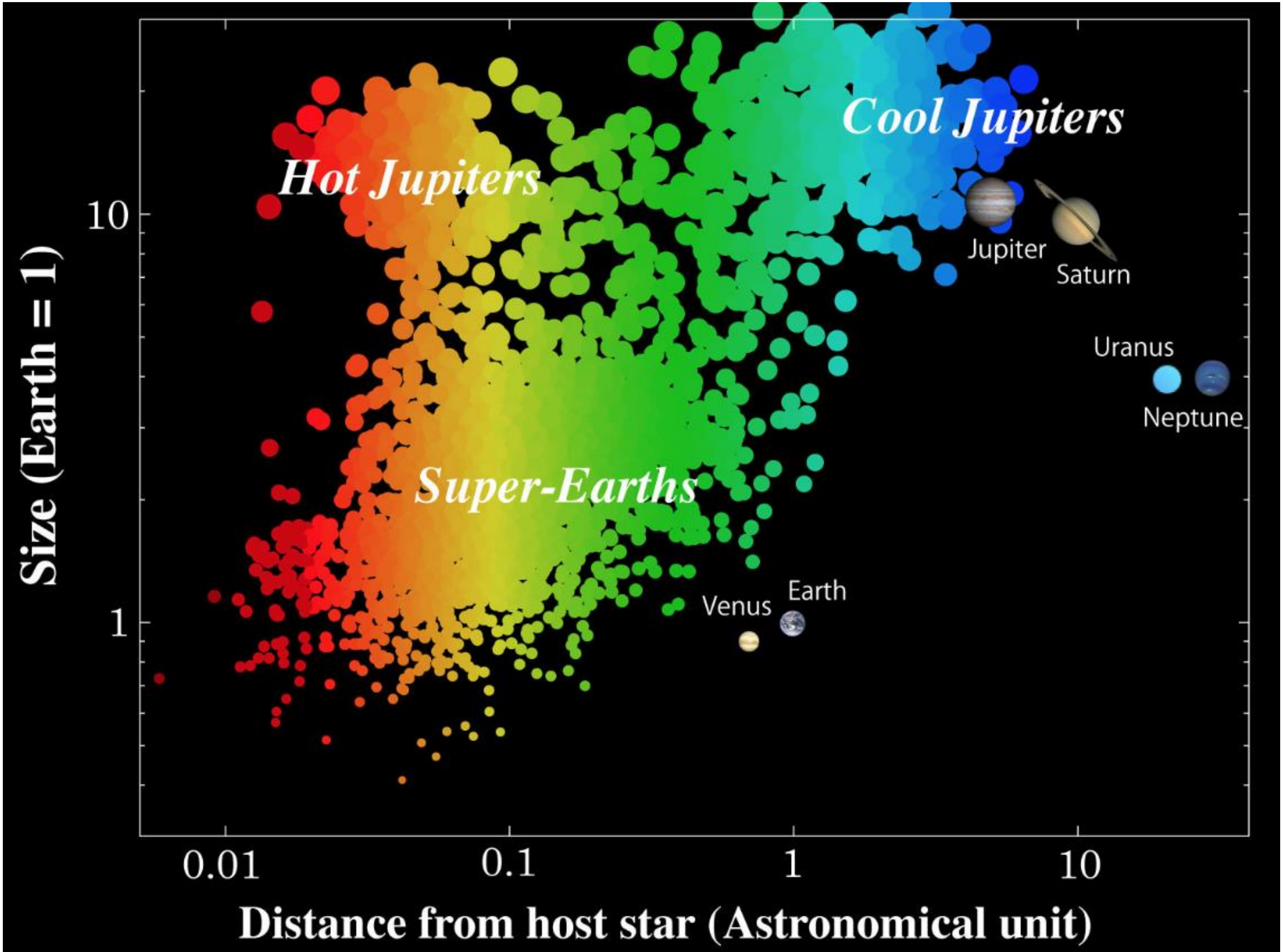
Differences in methods:

measuring mass or radius?

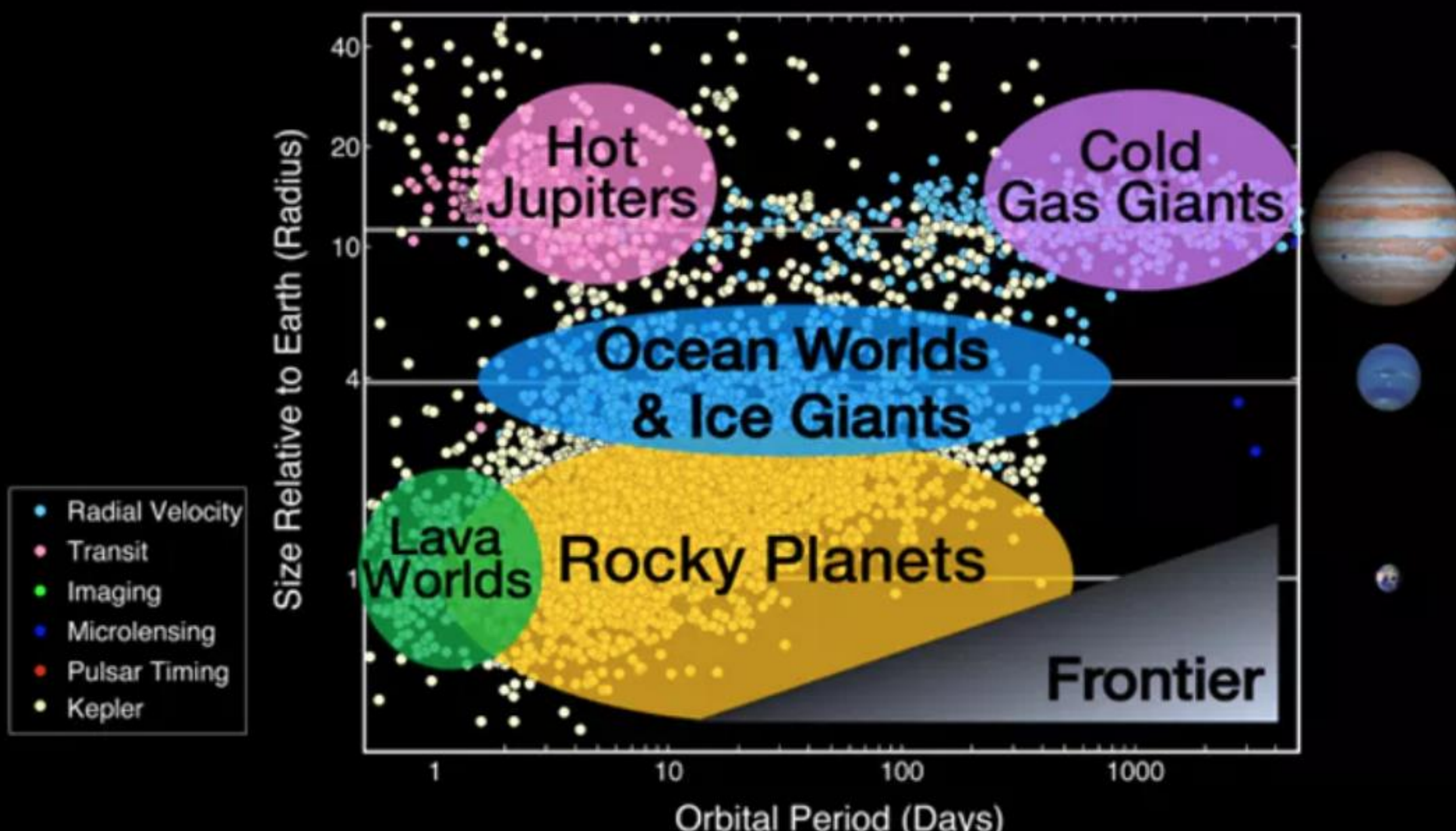
(ideally both)

Most orbits are circular (but some eccentric)

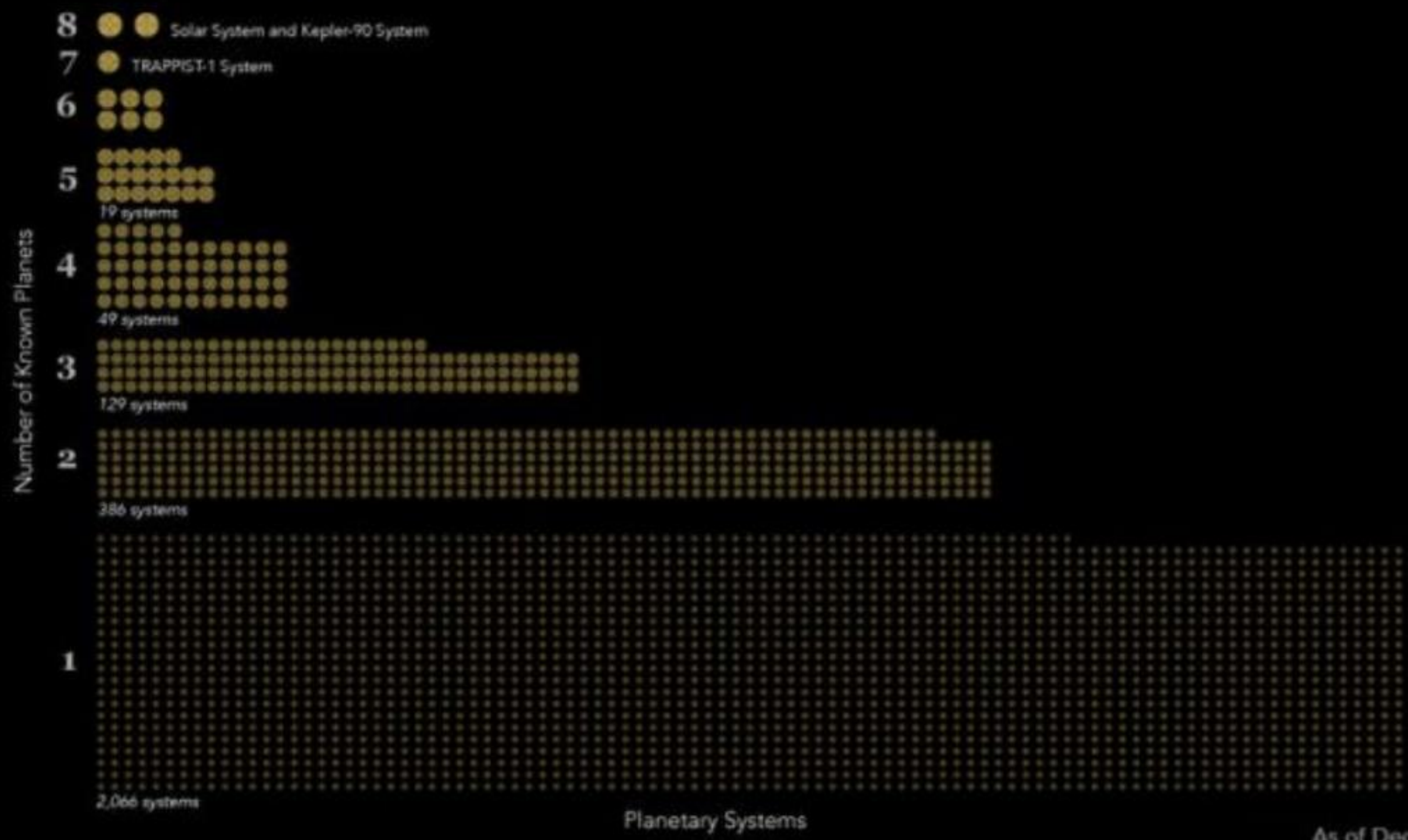



Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
10
1
0.01
0.1
1
10
Size (Earth = 1)
Distance from host star (Astronomical unit)

Exoplanet Populations



Planetary Systems by Number of Known Planets



As of December 14, 2017

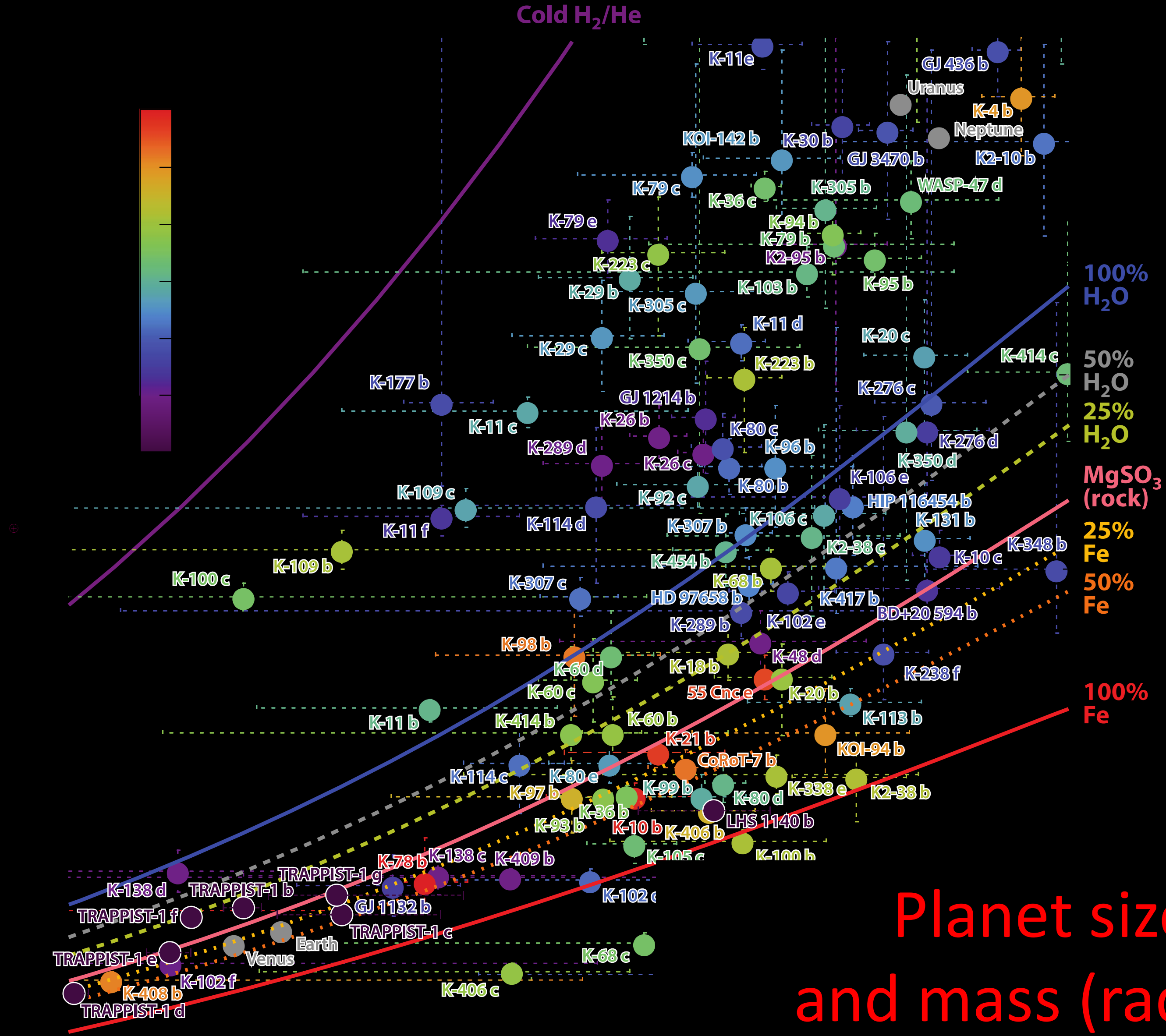
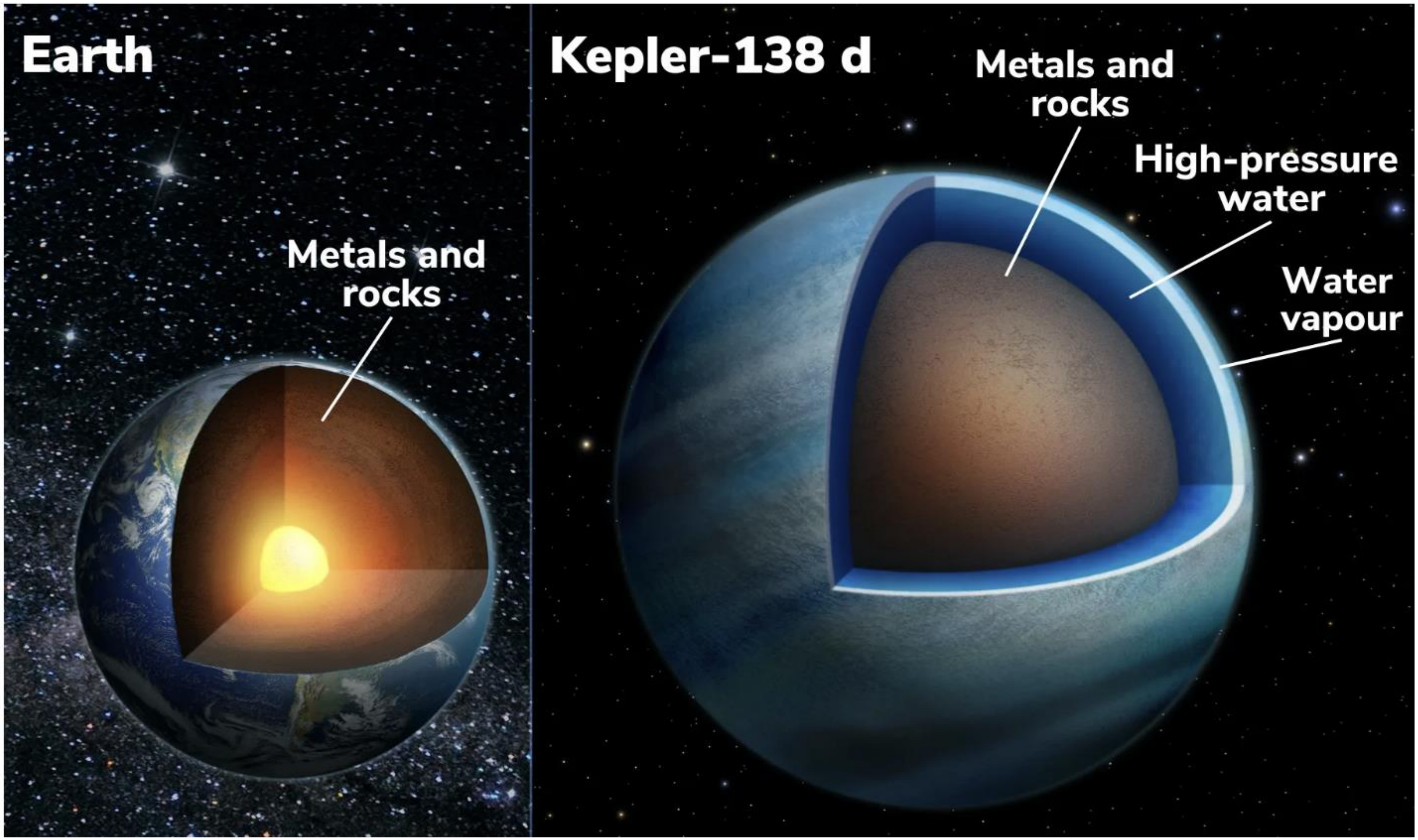


Figure 1

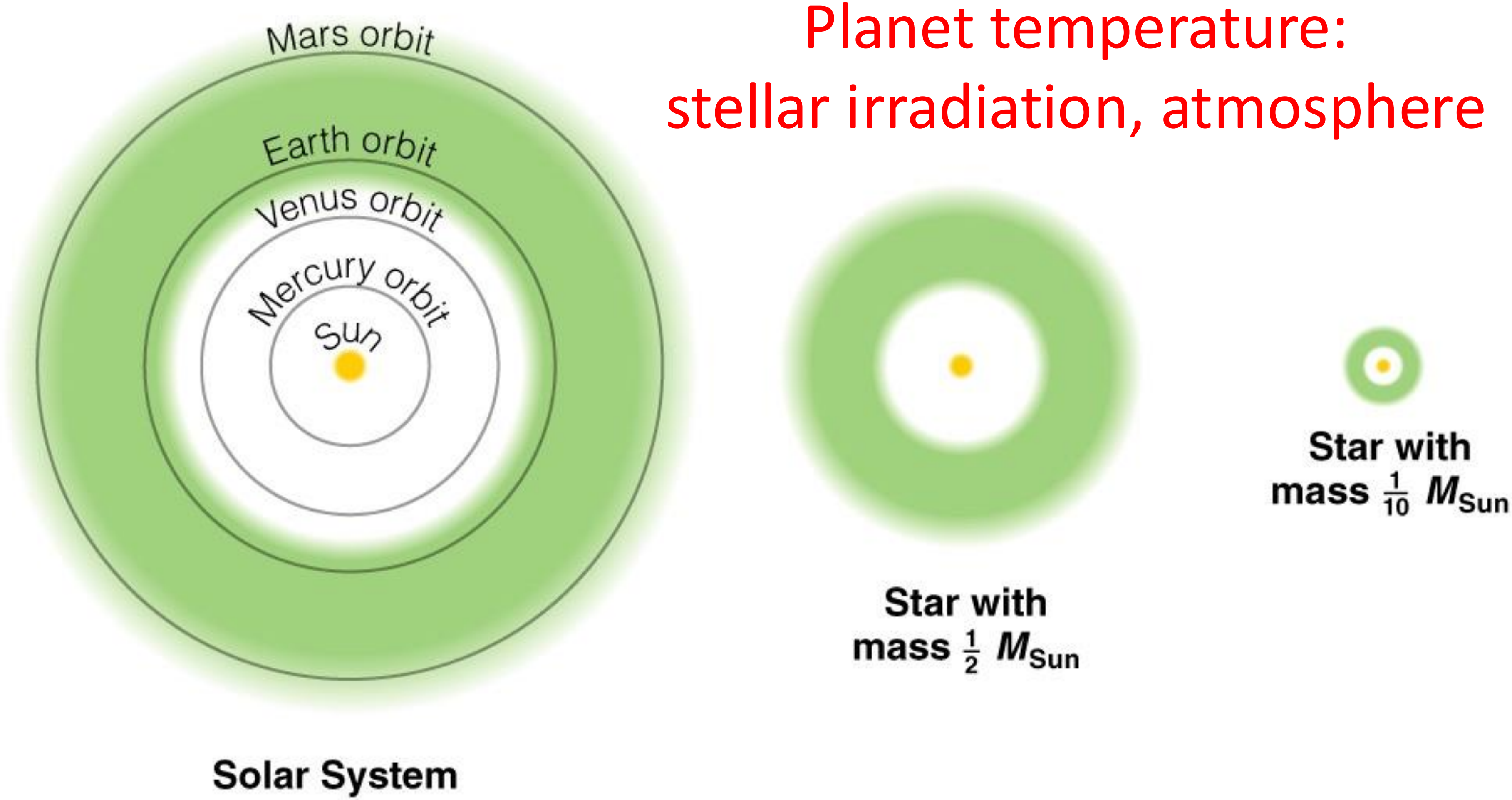
Planet size (transit)
and mass (radial velocity):
density/composition

Water worlds?
Perhaps common for "super-earths"

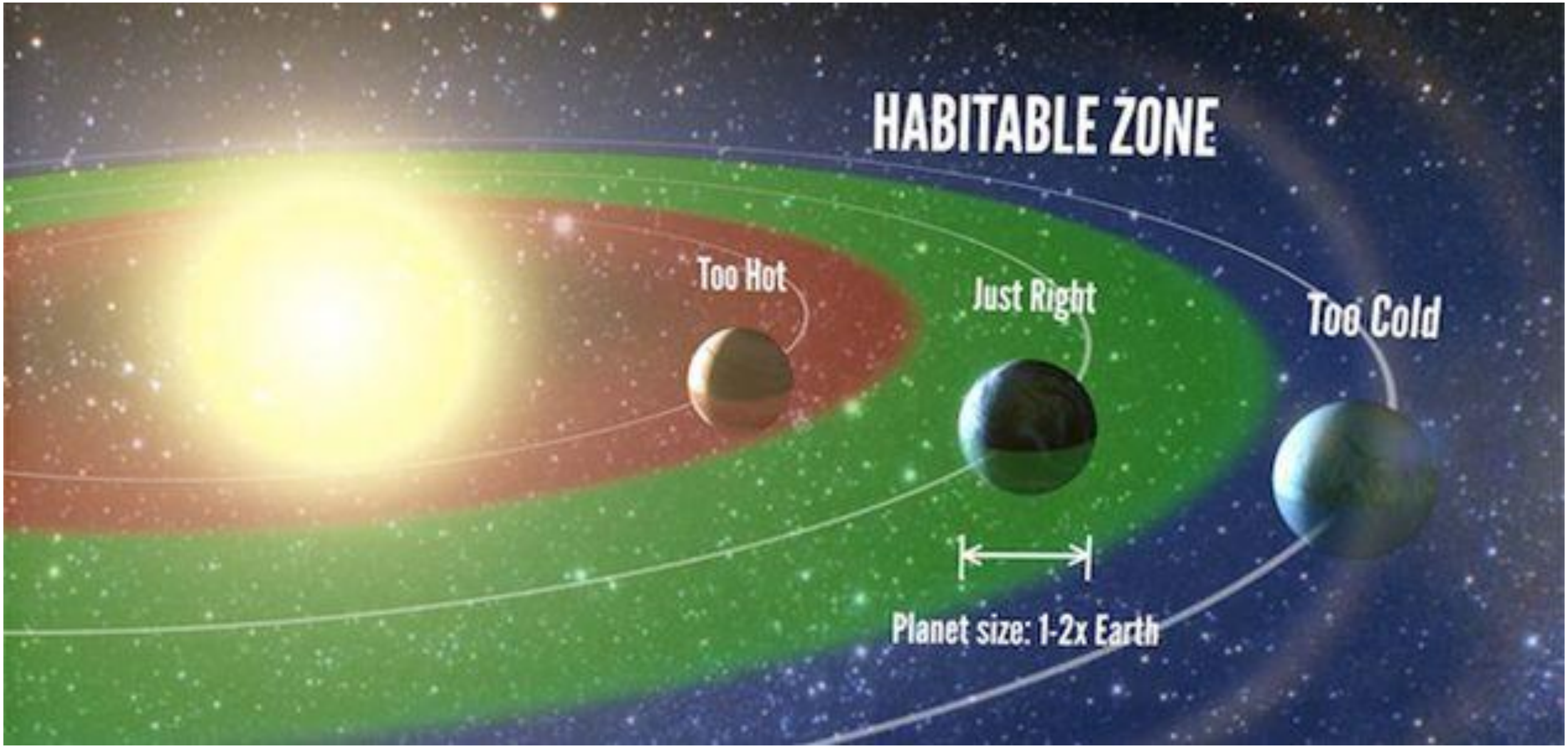


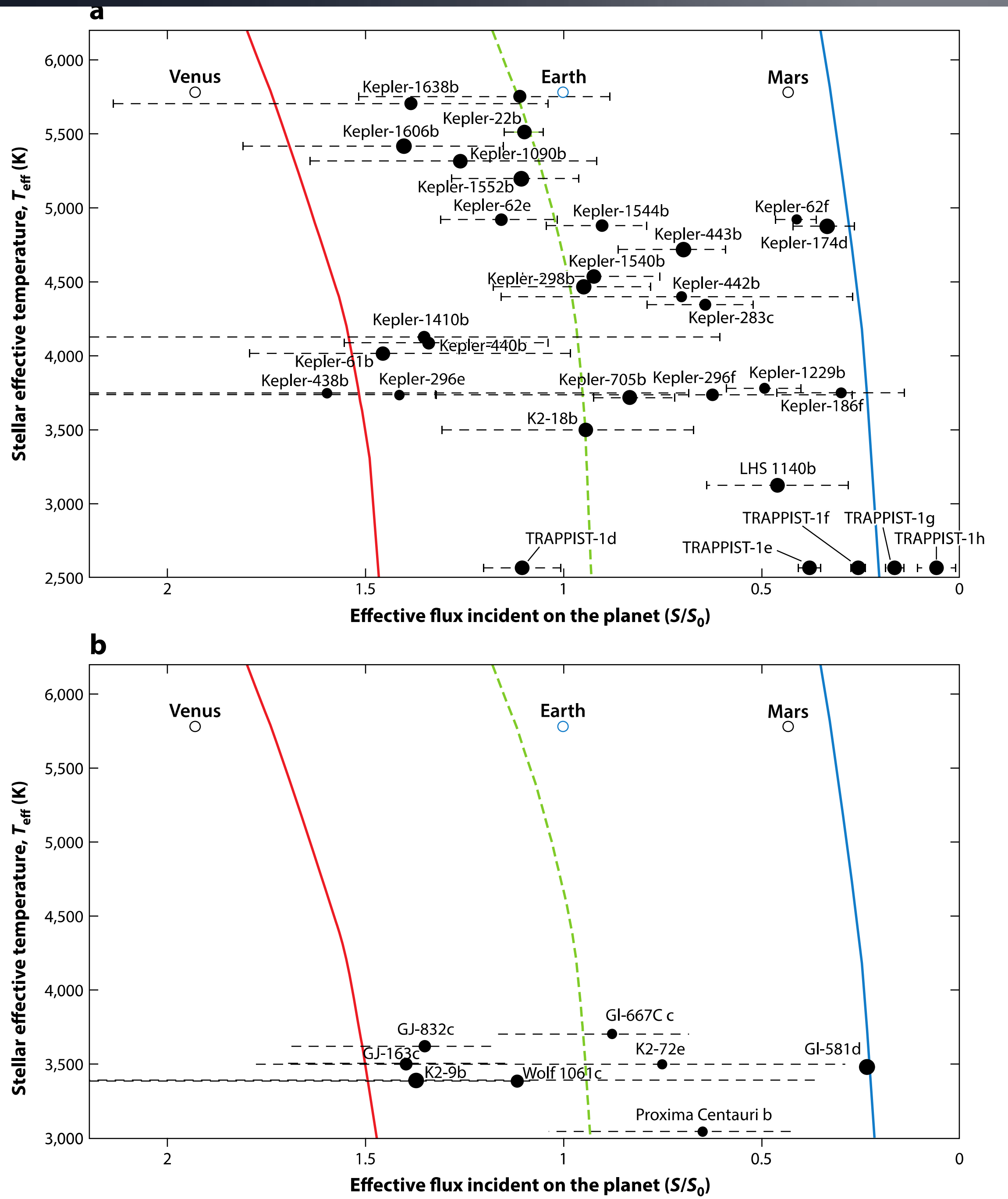
Are habitable planets likely?

Planet temperature:
stellar irradiation, atmosphere

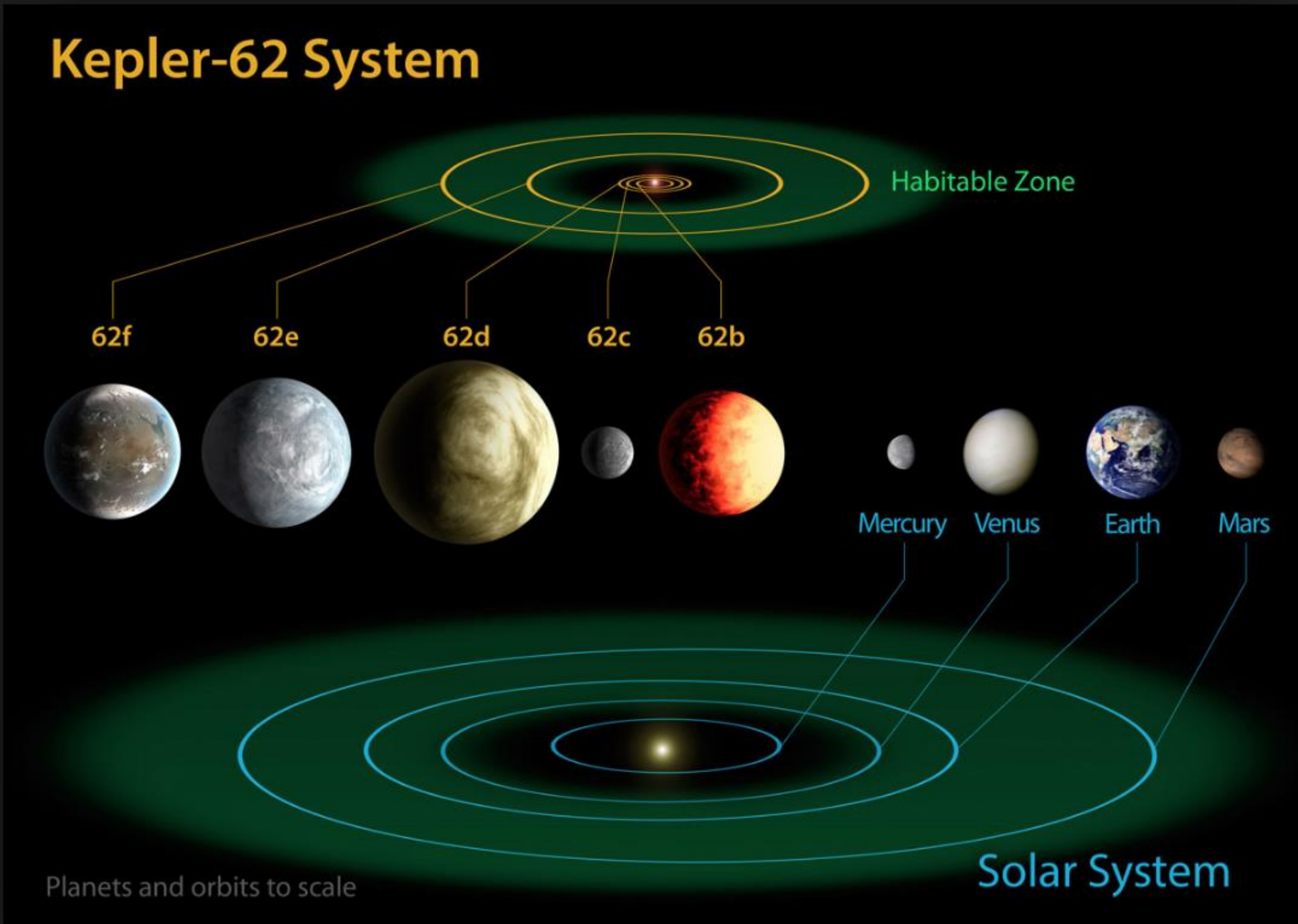


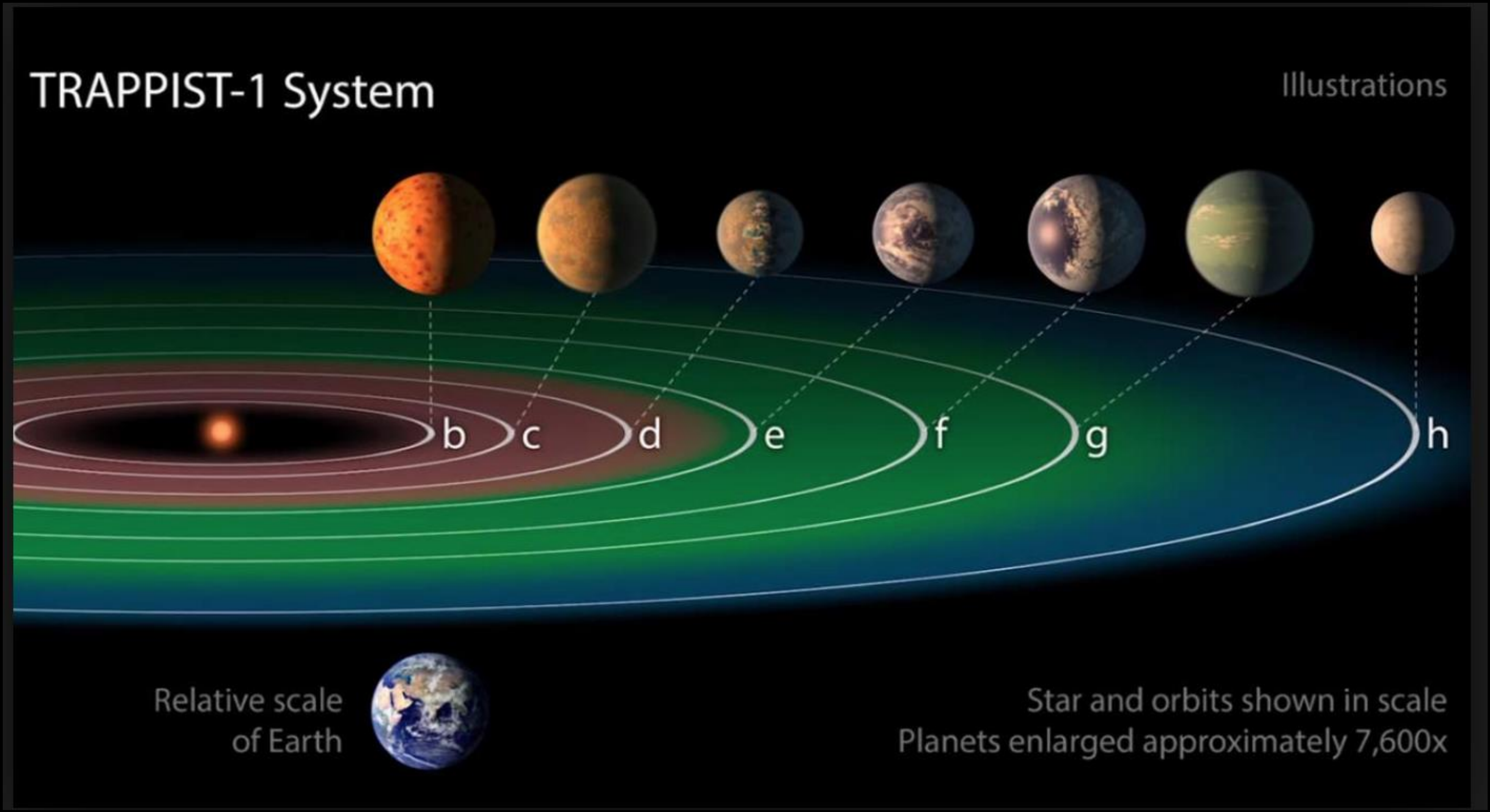
Habitable: liquid water

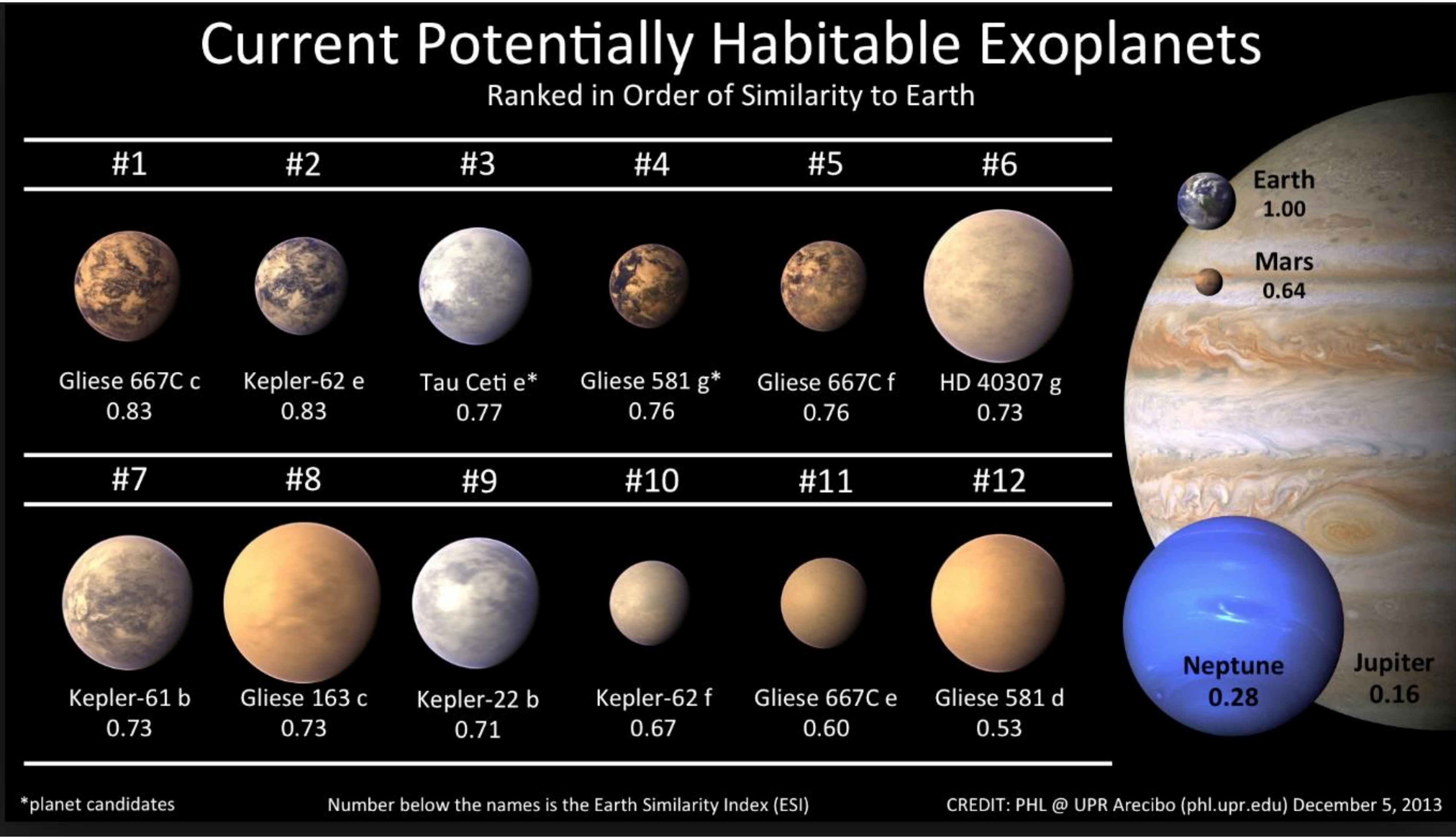

HABITABLE ZONE
Too Hot
Just Right
Too Cold
Planet size: 1-2x Earth



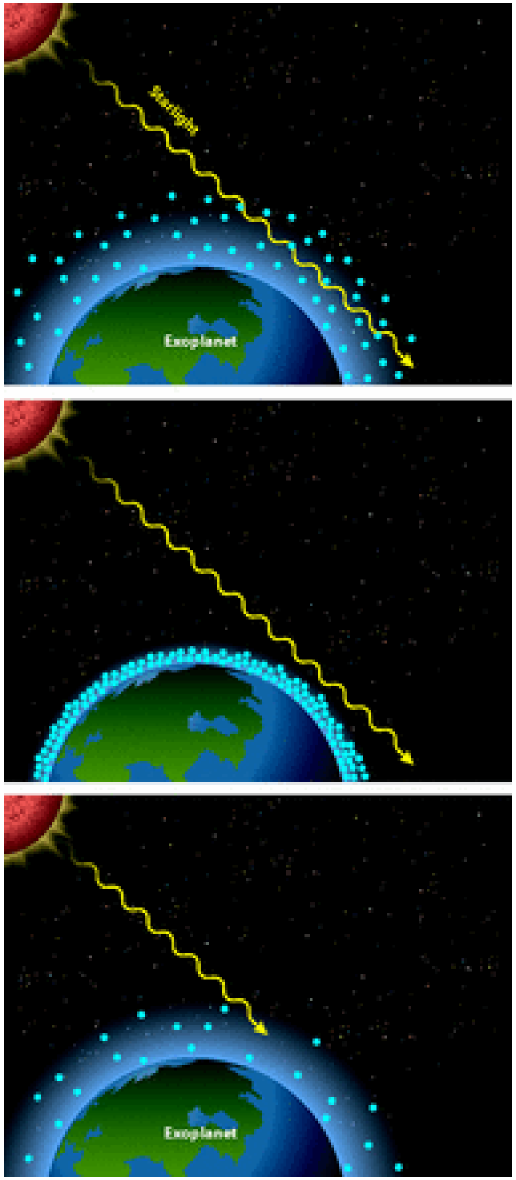
Exoplanets in habitable zone

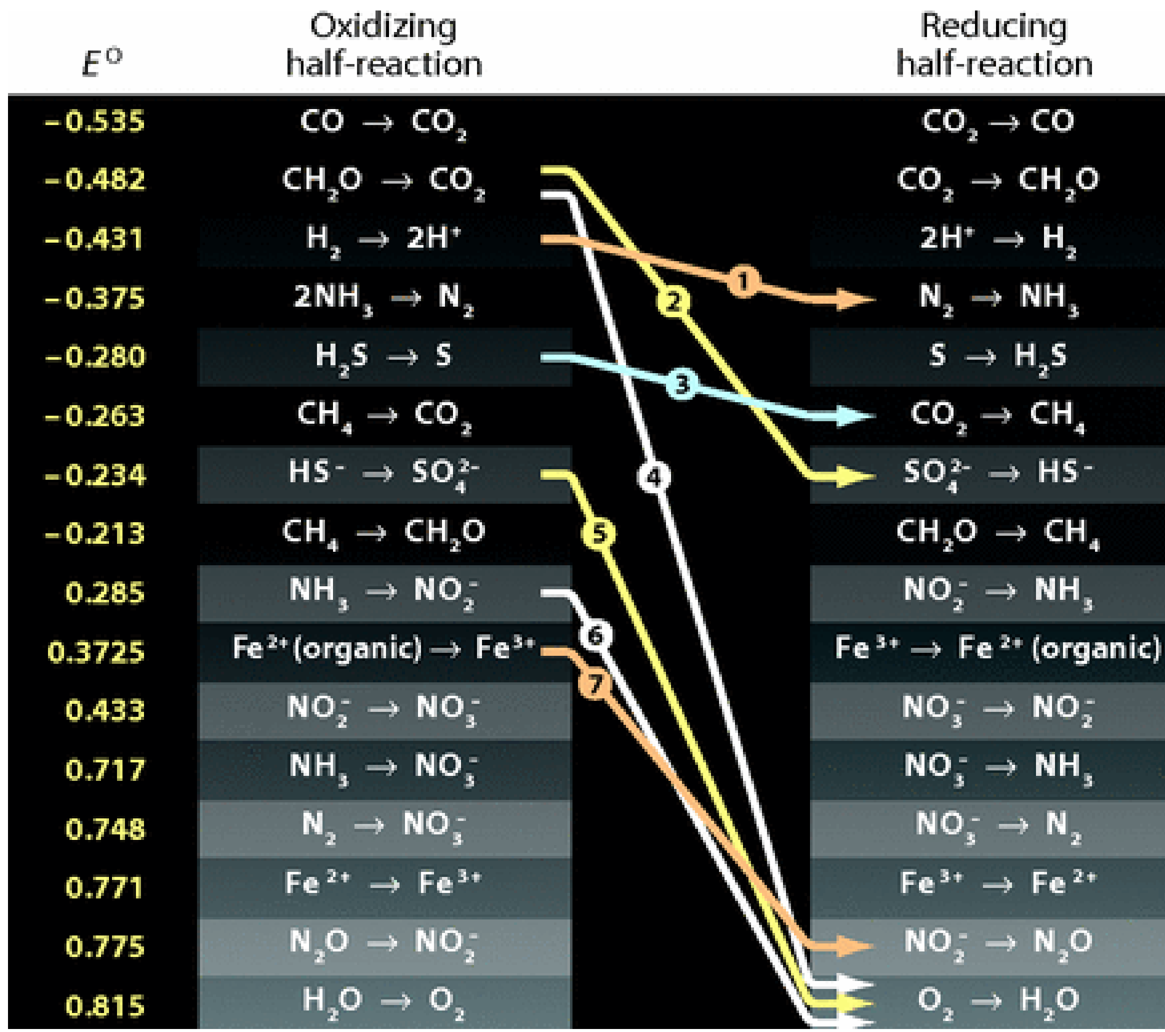

Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

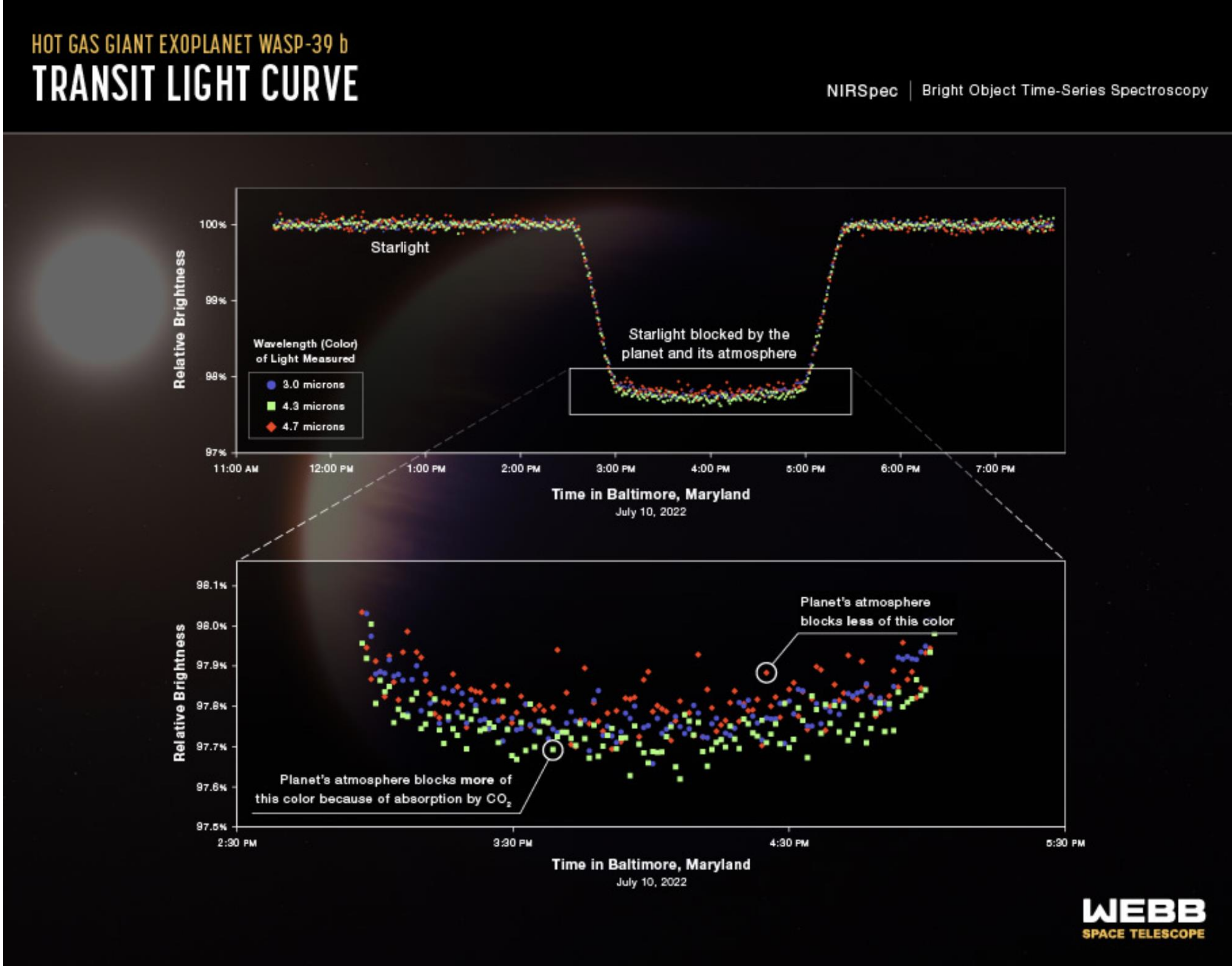

TRAPPIST-1 System
Illustrations
b
c
d
e
f
g
h
Relative scale
of Earth
Star and orbits shown in scale
Planets enlarged approximately 7,600x

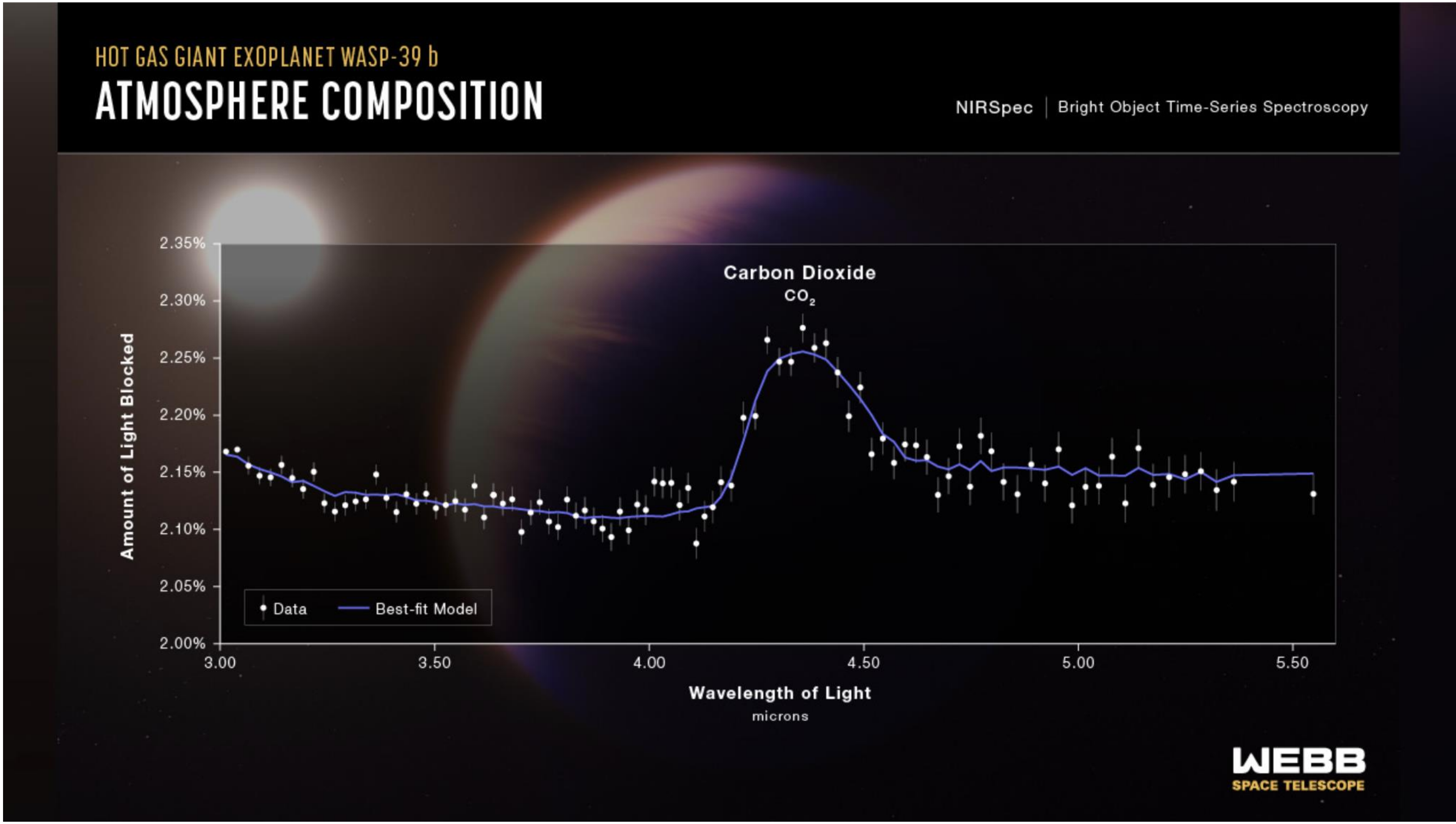

Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
#1
#2
#3
#4
#5
#6
Gliese 667C c
0.83
Kepler-62 e
0.83
Tau Ceti e*
0.77
Gliese 581 g*
0.76
Gliese 667C f
0.76
HD 40307 g
0.73
#7
#8
#9
#10
#11
#12
Kepler-61 b
0.73
Gliese 163 c
0.73
Kepler-22 b
0.71
Kepler-62 f
0.67
Gliese 667C e
0.60
Gliese 581 d
0.53
Earth
1.00
Mars
0.64
Neptune
0.28
Jupiter
0.16
*planet candidates
Number below the names is the Earth Similarity Index (ESI)
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) December 5, 2013

Exoplanet atmospheres!



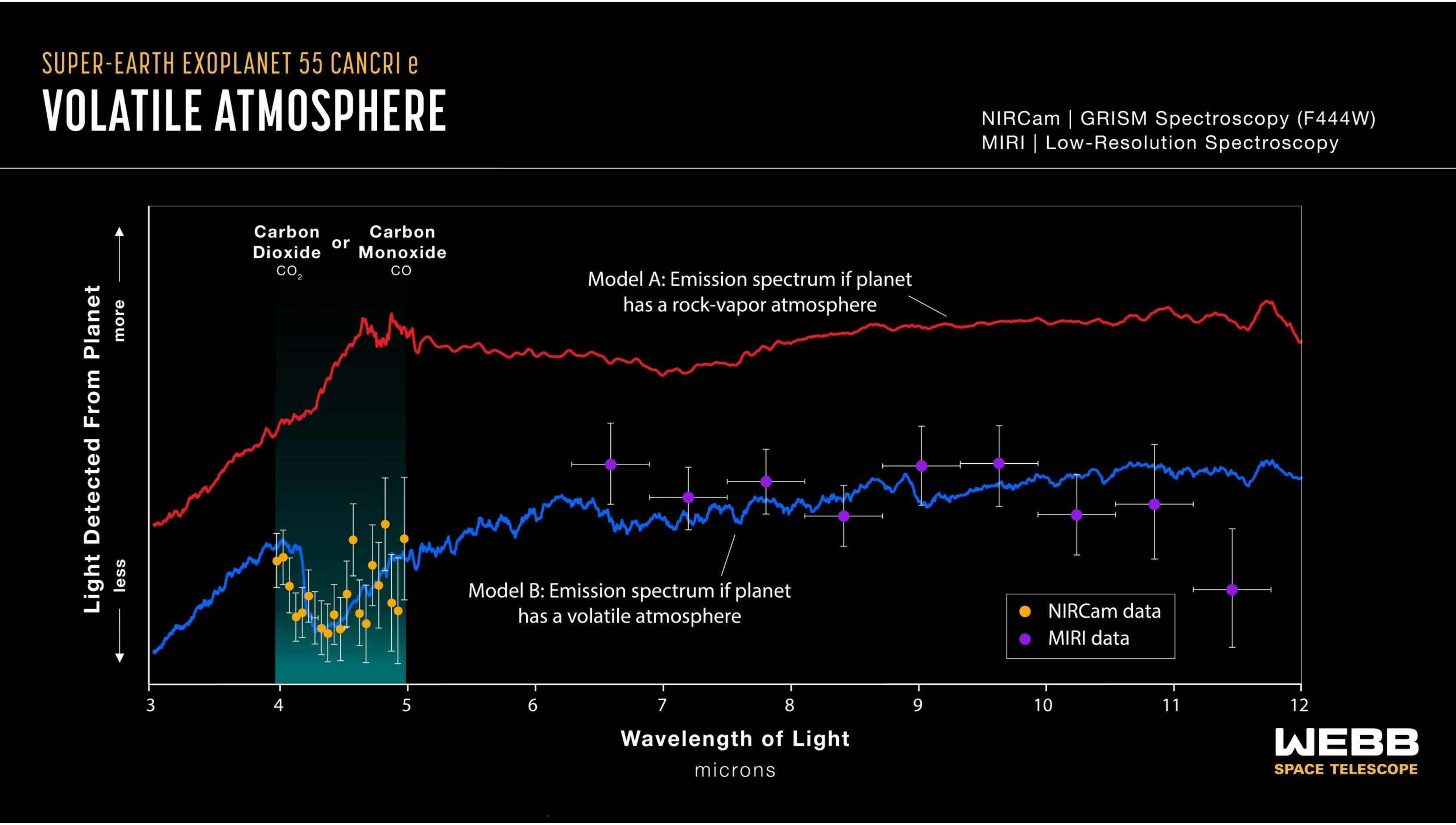


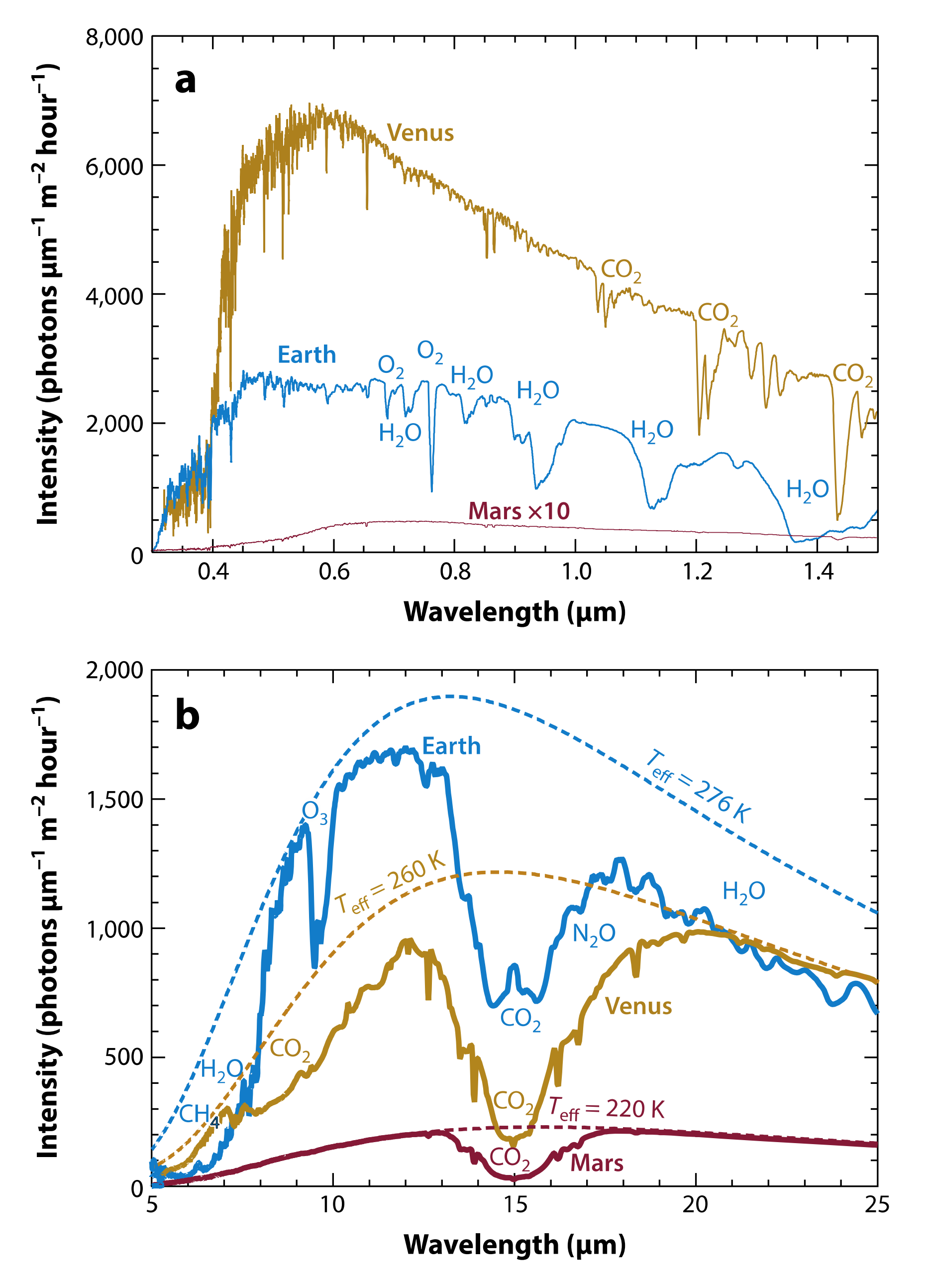

HOT GAS GIANT EXOPLANET WASP-39 b
TRANSIT LIGHT CURVE
NIRSpec | Bright Object Time-Series Spectroscopy
Relative Brightness
100%
99%
98%
97%
Starlight
Starlight blocked by the planet and its atmosphere
Wavelength (Color) of Light Measured
3.0 microns
4.3 microns
4.7 microns
11:00 AM
12:00 PM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
Time in Baltimore, Maryland
July 10, 2022
Relative Brightness
98.1%
98.0%
97.9%
97.8%
97.7%
97.6%
97.5%
Planet's atmosphere blocks less of this color
Planet's atmosphere blocks more of this color because of absorption by CO_2
2:30 PM
3:30 PM
4:30 PM
5:30 PM
Time in Baltimore, Maryland
July 10, 2022
WEBB
SPACE TELESCOPE



HOT GAS GIANT EXOPLANET WASP-39 b
ATMOSPHERE COMPOSITION
NIRSpec | Bright Object Time-Series Spectroscopy
Carbon Dioxide
CO2
Amount of Light Blocked
2.35%
2.30%
2.25%
2.20%
2.15%
2.10%
2.05%
2.00%
Data
Best-fit Model
3.00
3.50
4.00
4.50
5.00
5.50
Wavelength of Light
microns
WEBB
SPACE TELESCOPE

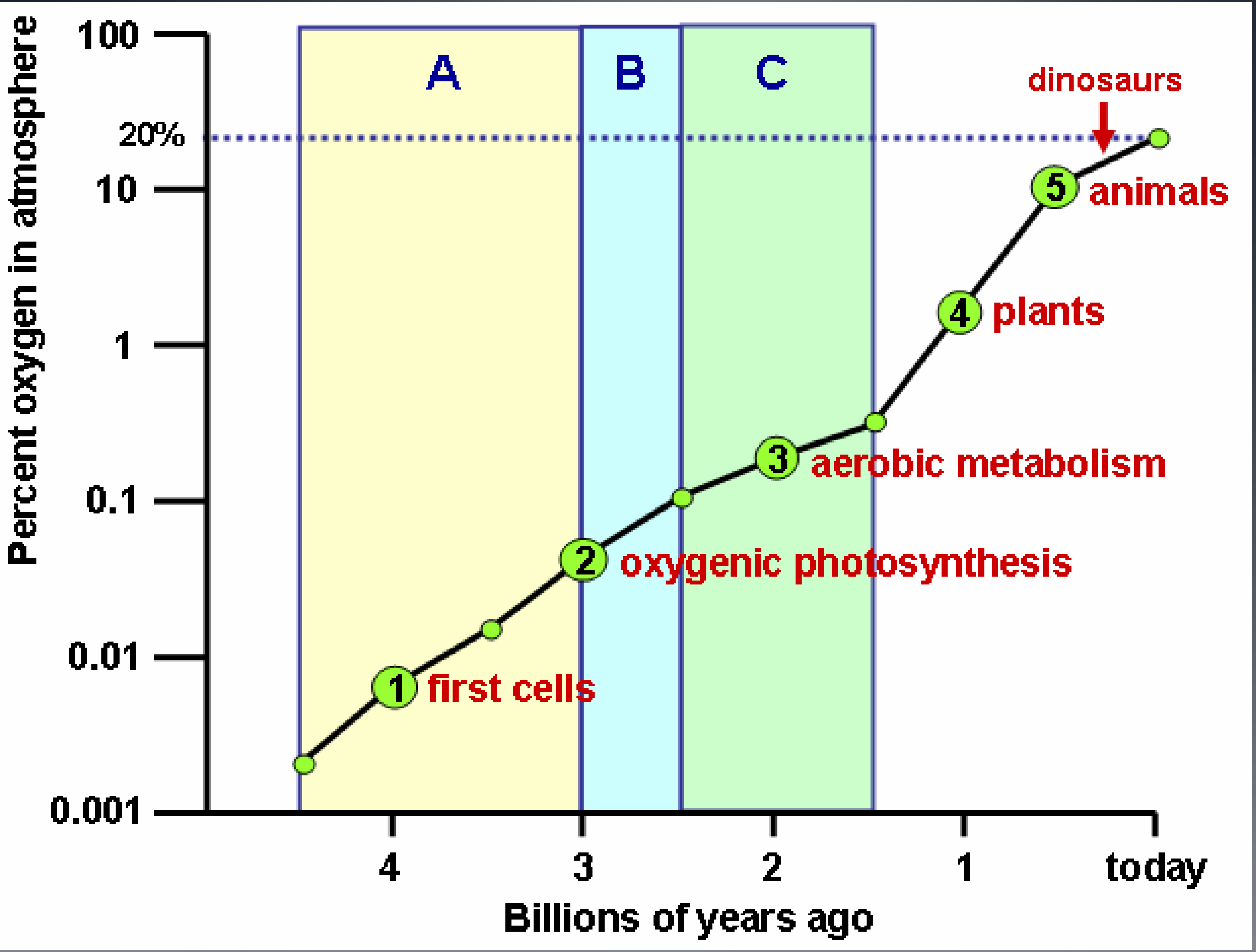
First atmosphere around a terrestrial exoplanet





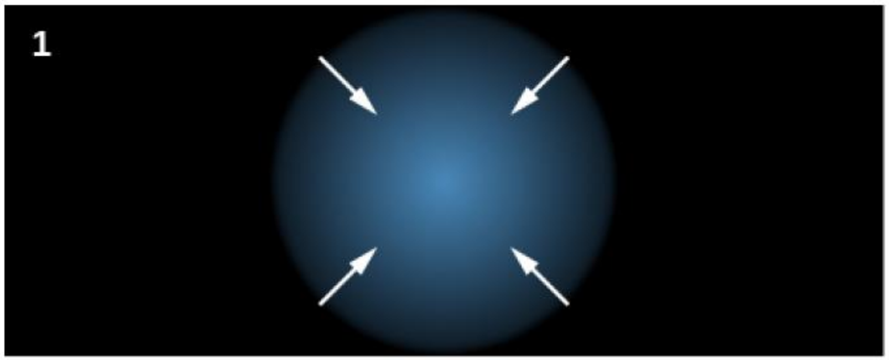
Life changes its environment

- Life needs a suitable environment to flourish.
- Feedback on environment and atmosphere
- Changes: biosignature, a sign of the presence of life
- Oxygen: a biosignature of life. Looking from afar, we cannot see plants and bacteria directly, but we can infer the presence of photosynthetic life if there is atmospheric oxygen.

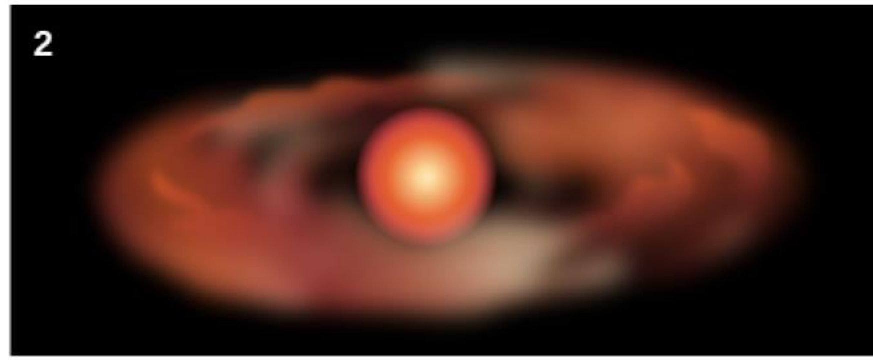


Percent oxygen in atmosphere
100
20%
10
1
0.1
0.01
0.001
A
B
C
dinosaurs
1 first cells
2 oxygenic photosynthesis
3 aerobic metabolism
4 plants
5 animals
4
3
2
1
today
Billions of years ago

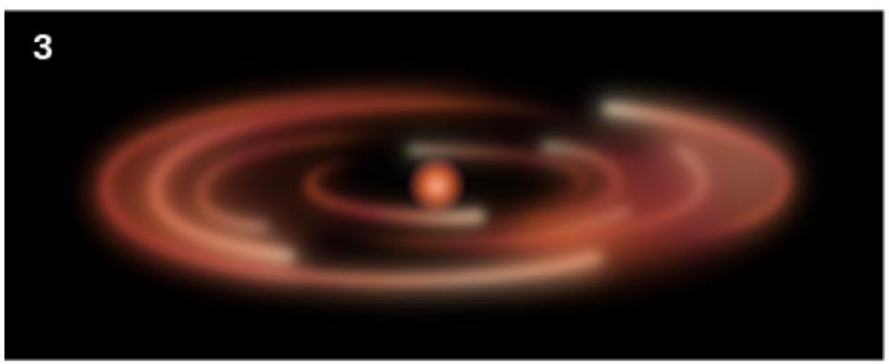
Planet Formation



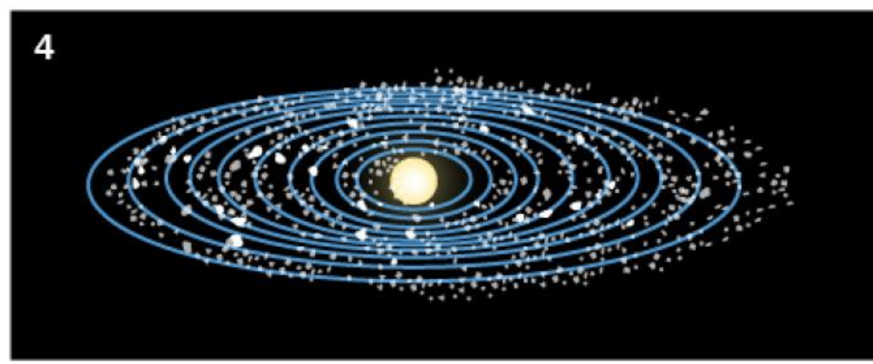
The solar nebula contracts.



As the nebula shrinks, its motion causes it to flatten.



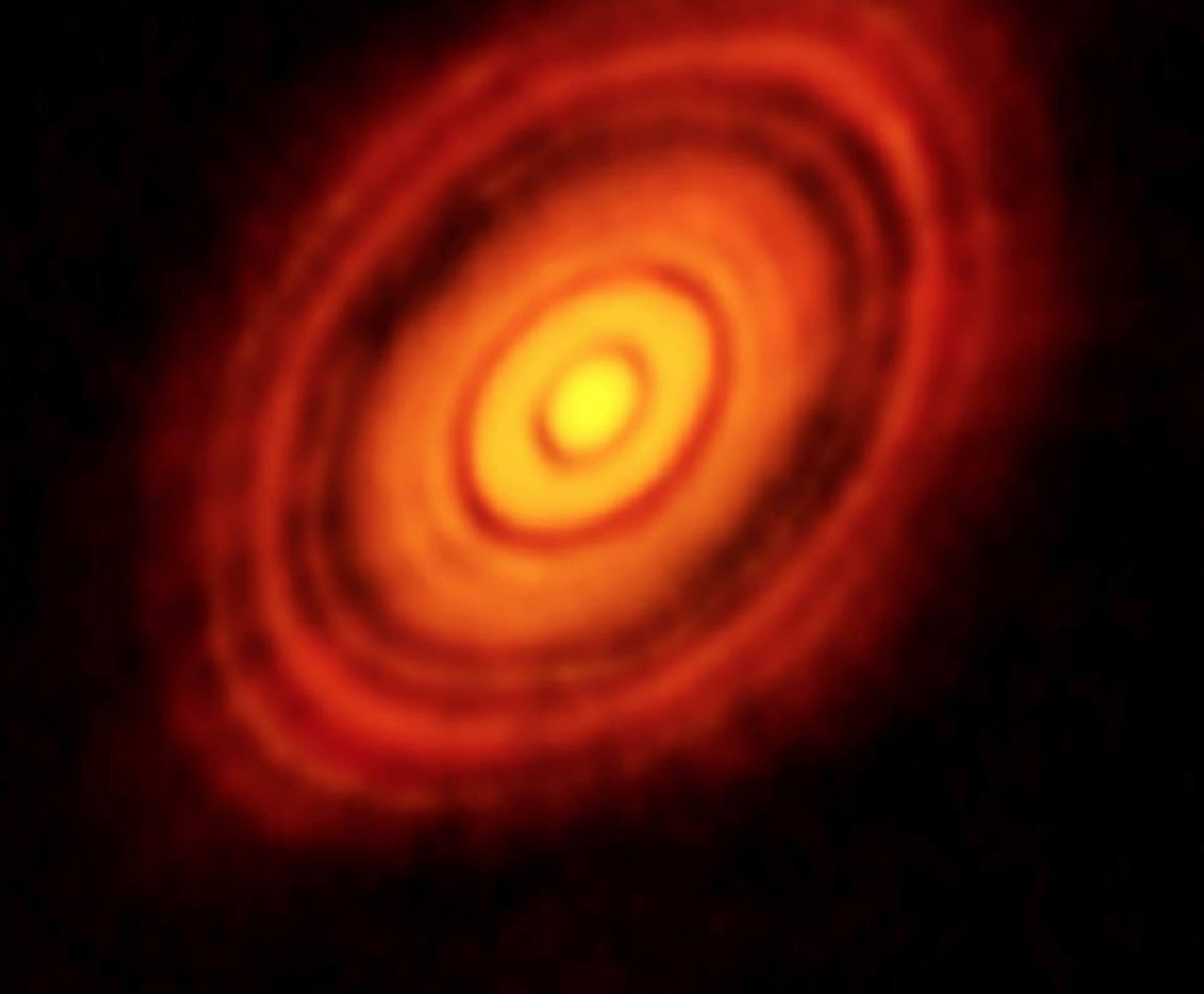
The nebula is a disk of matter with a concentration near the center.

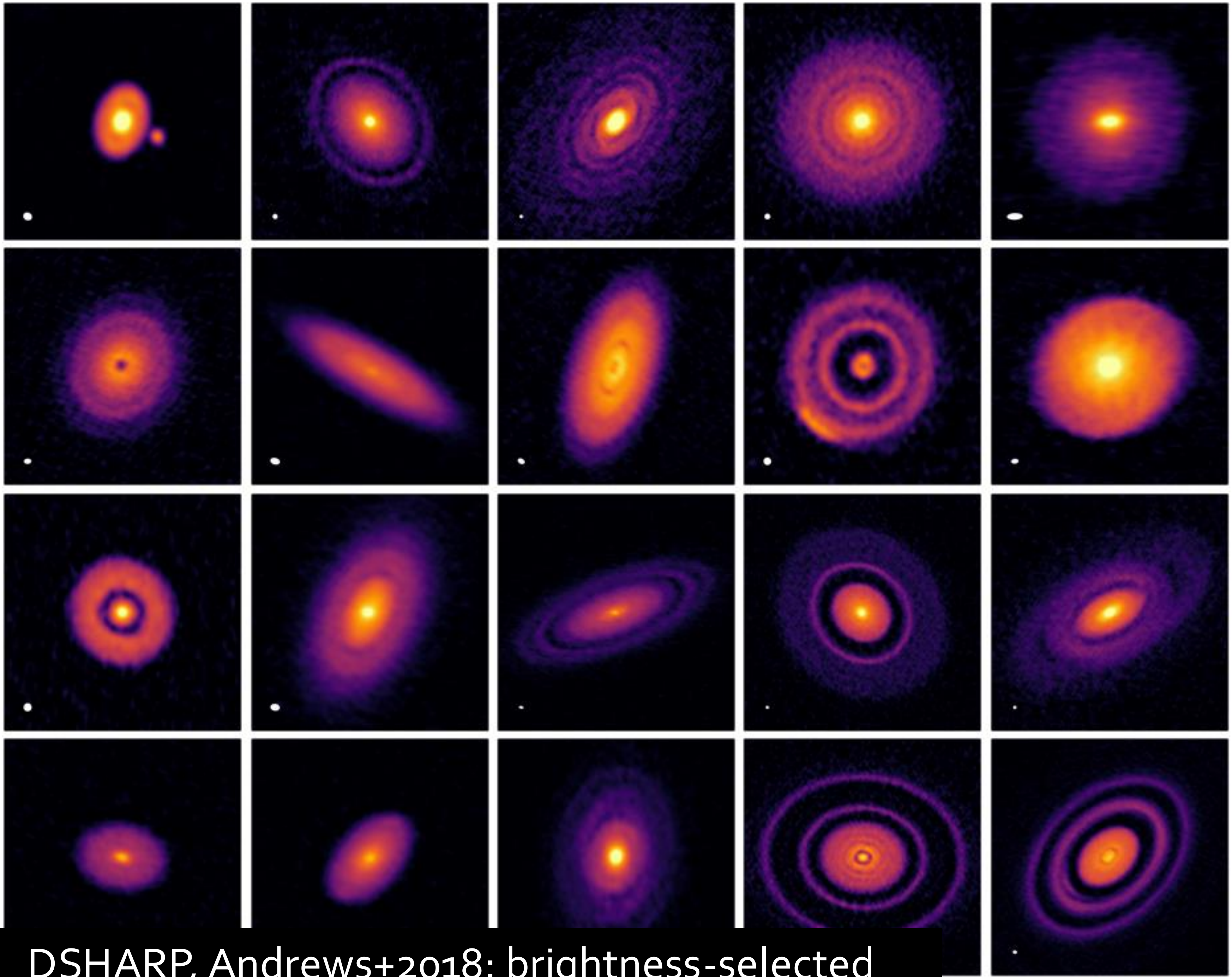


Formation of the protosun. Solid particles condense as the nebula cools, giving rise to the planetesimals, which are the building blocks of the planets.

Planets should form in disk and carve a gap

Image of a protoplanetary disk

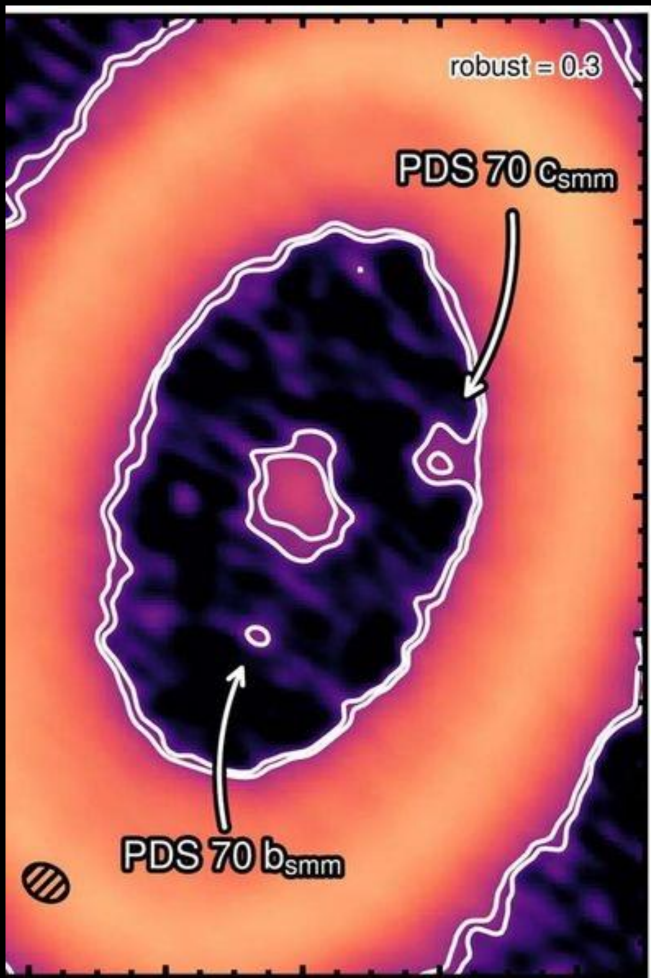




DSHARP, Andrews+2018: brightness-selected

Planet in a protoplanetary disk!

Proto-lunar disks around PDS 70bc?

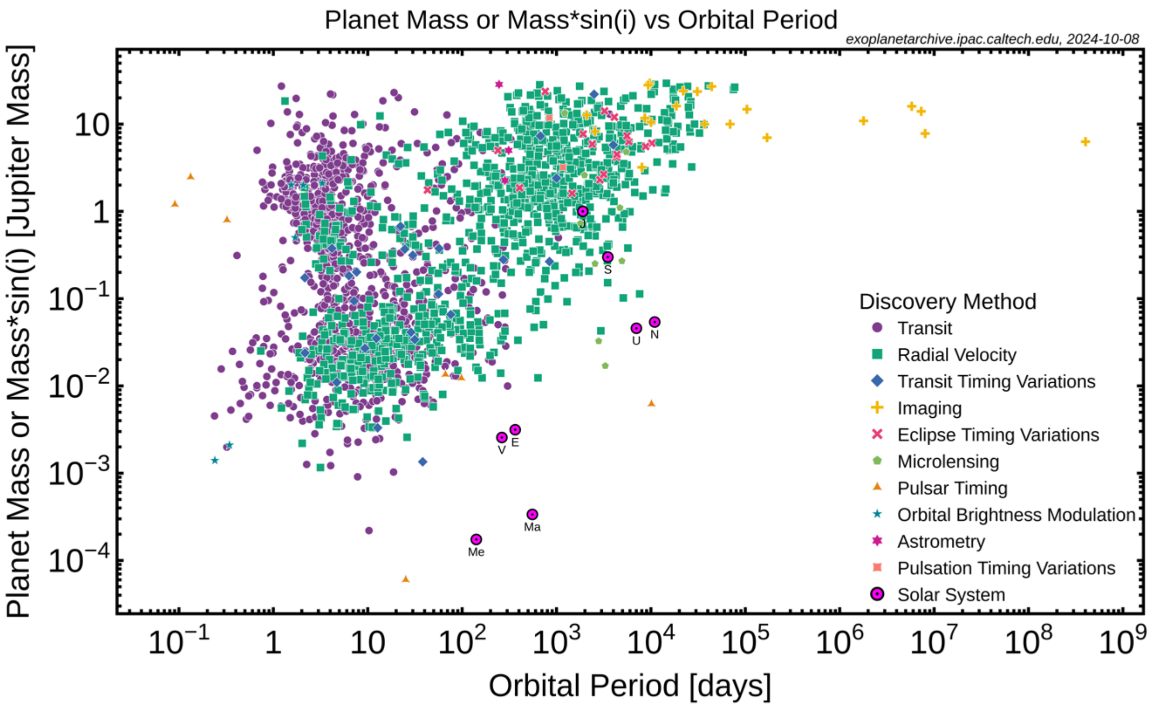


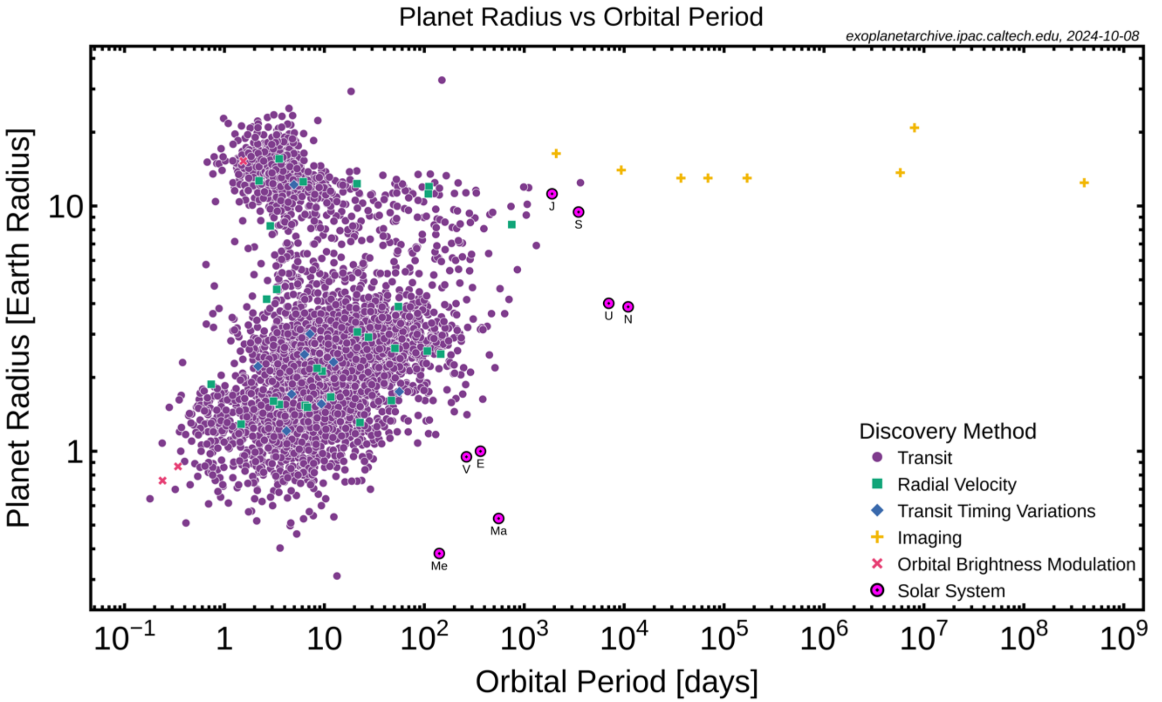
ALMA/dust, Isella+2019

Planets are everywhere!

- Many different detection techniques
  - Most common planet: "Super Earth"
  - Earths still challenging
  - Atmospheres very challenging
  - Many biases to larger planets, closer objects

- Planet Formation
  - Observational evidence for unseen planets
  - Challenge: Microscopic interactions on tiny scales lead to planets
  - Requires simulations+observations





Planets are everywhere!

Next lecture: the Milky Way!