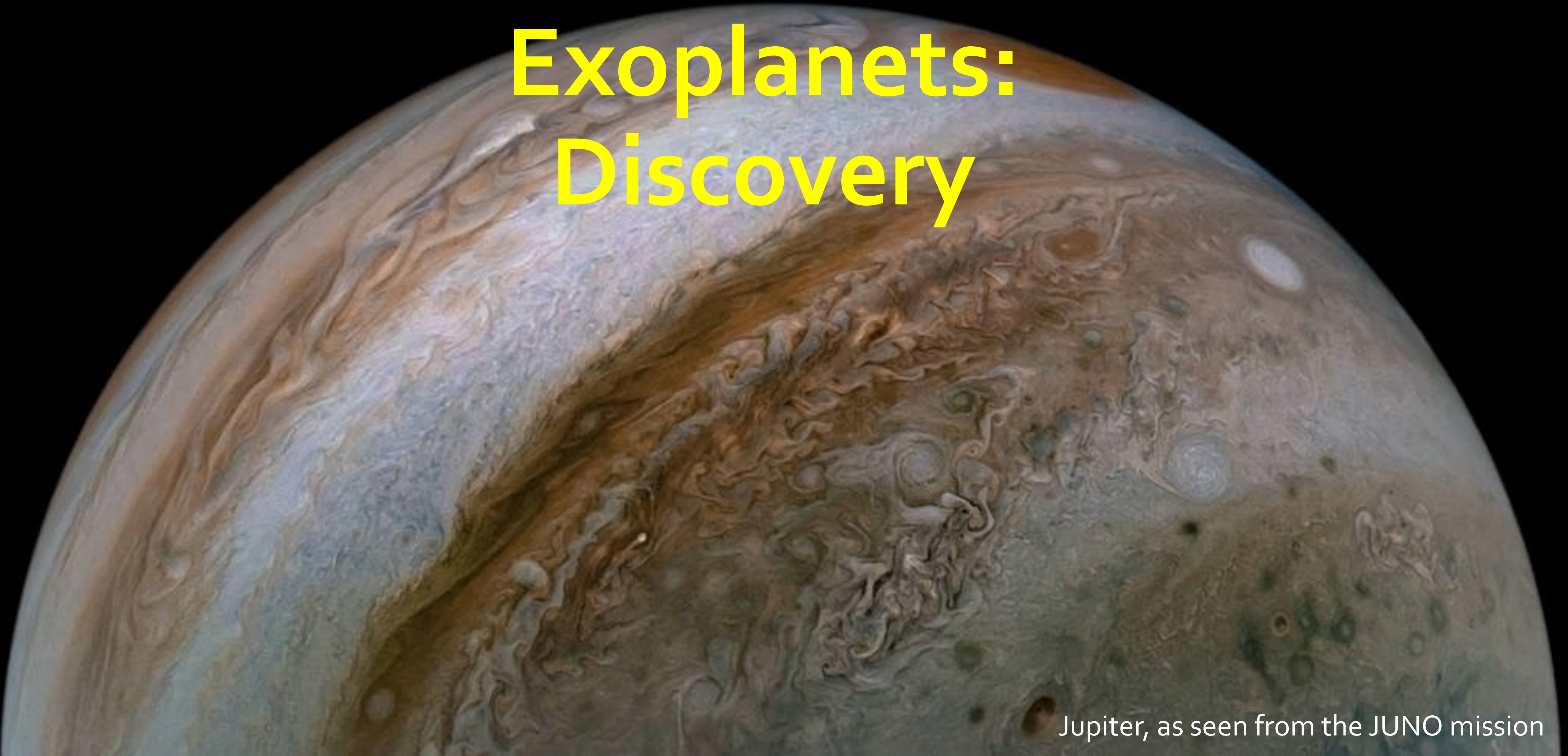
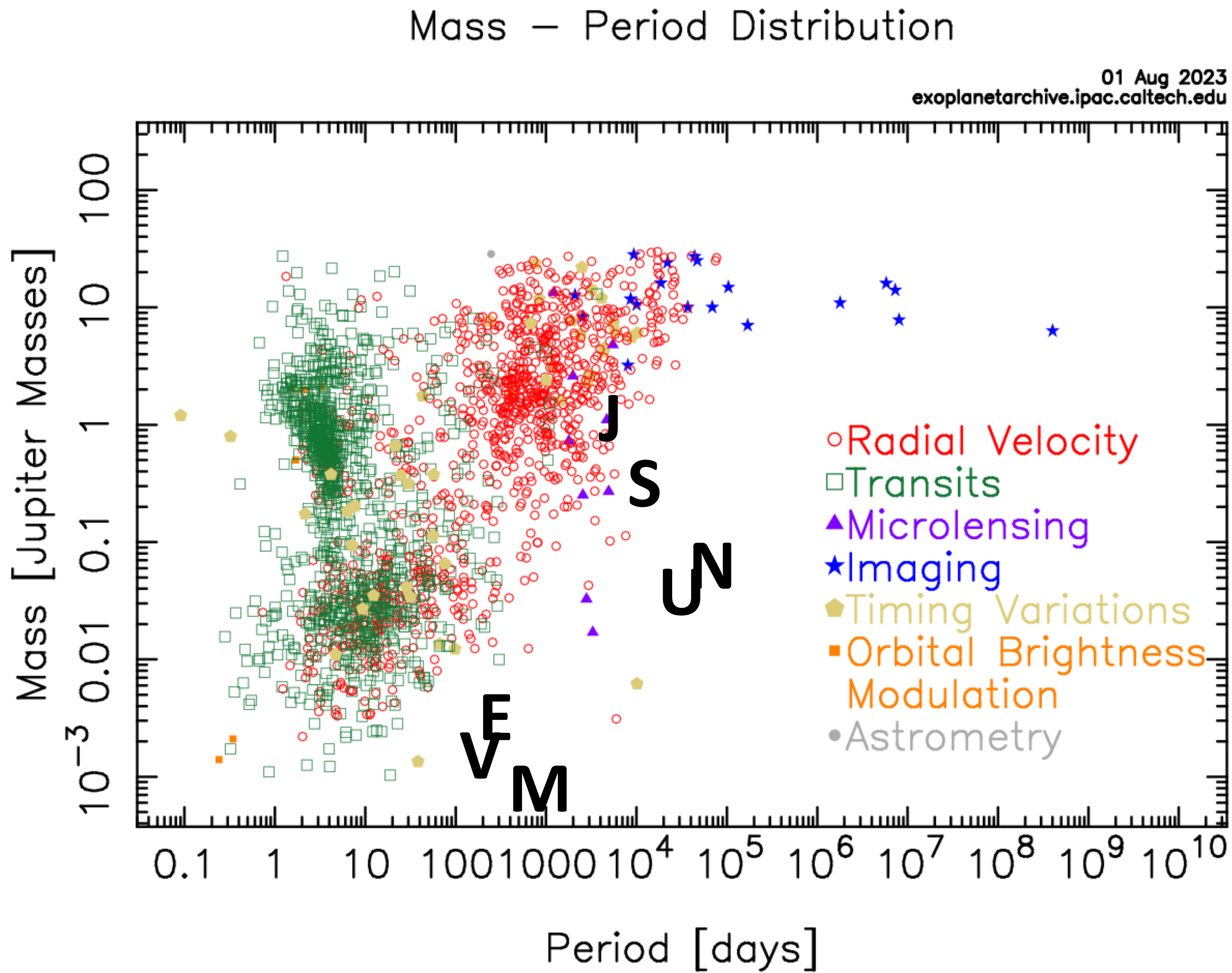
Exoplanets: Discovery



Jupiter, as seen from the JUNO mission

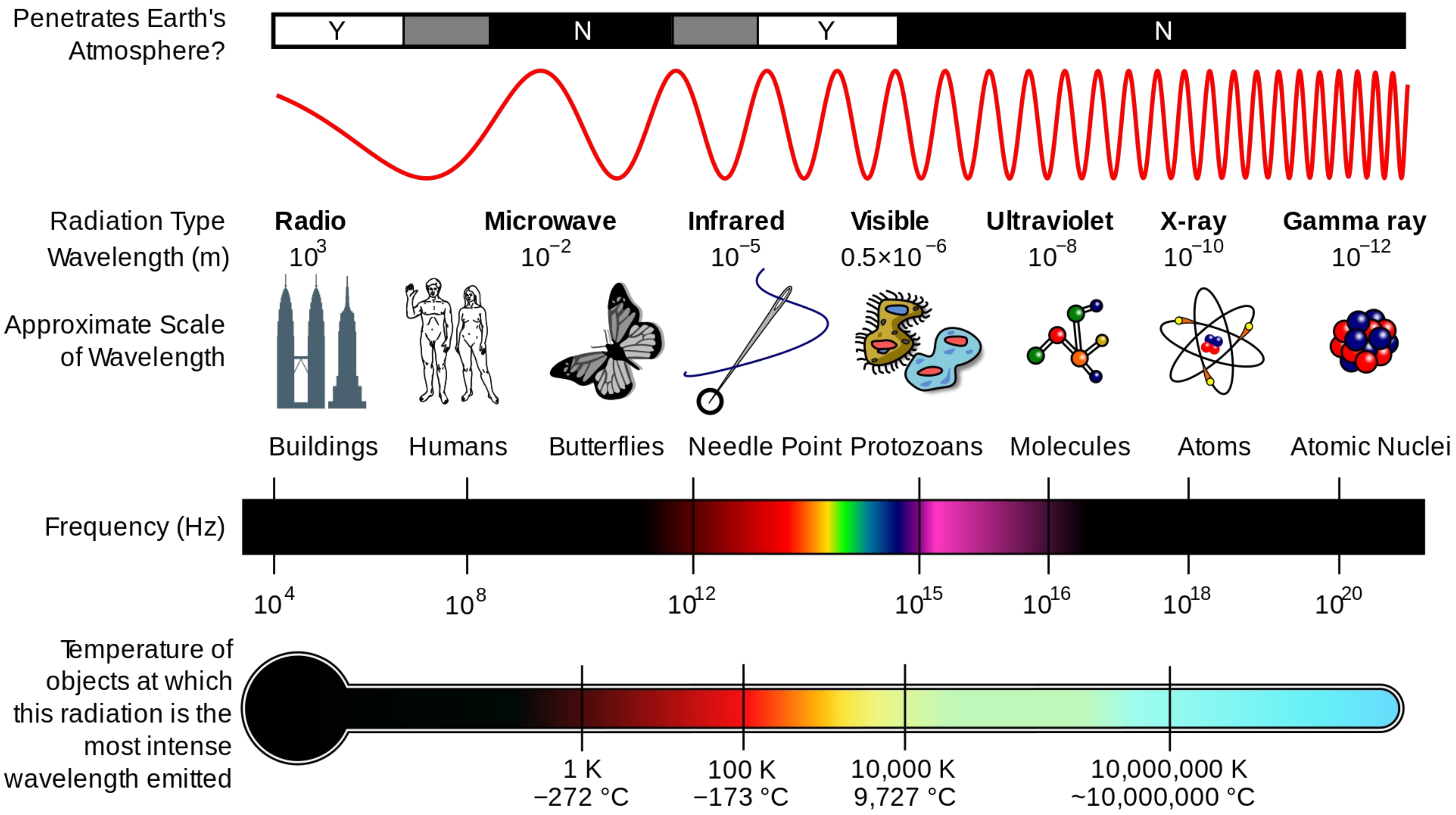


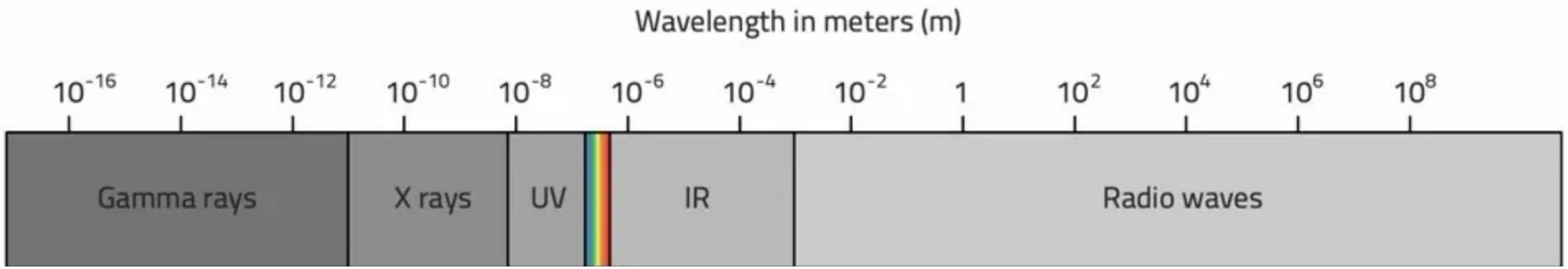
Mass – Period Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]
J
S
U
N
E
V
M
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

Observational astronomy: imaging and spectroscopy

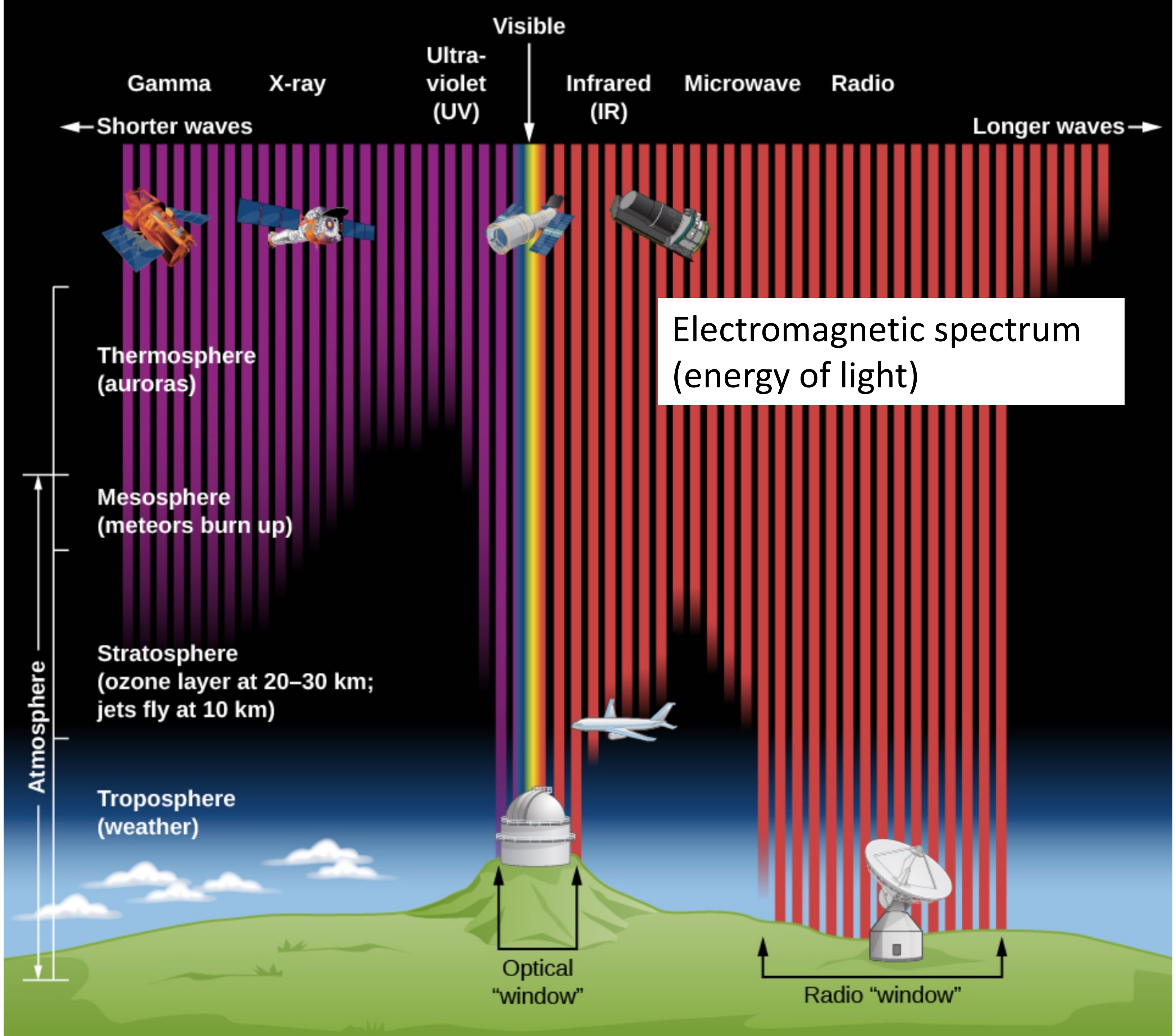
- Imaging (usually with filters): is an object red or blue?
- Spectroscopy: what elements/molecules are present
  - (and ionization/energy levels)

Electromagnetic spectrum (energy of light)



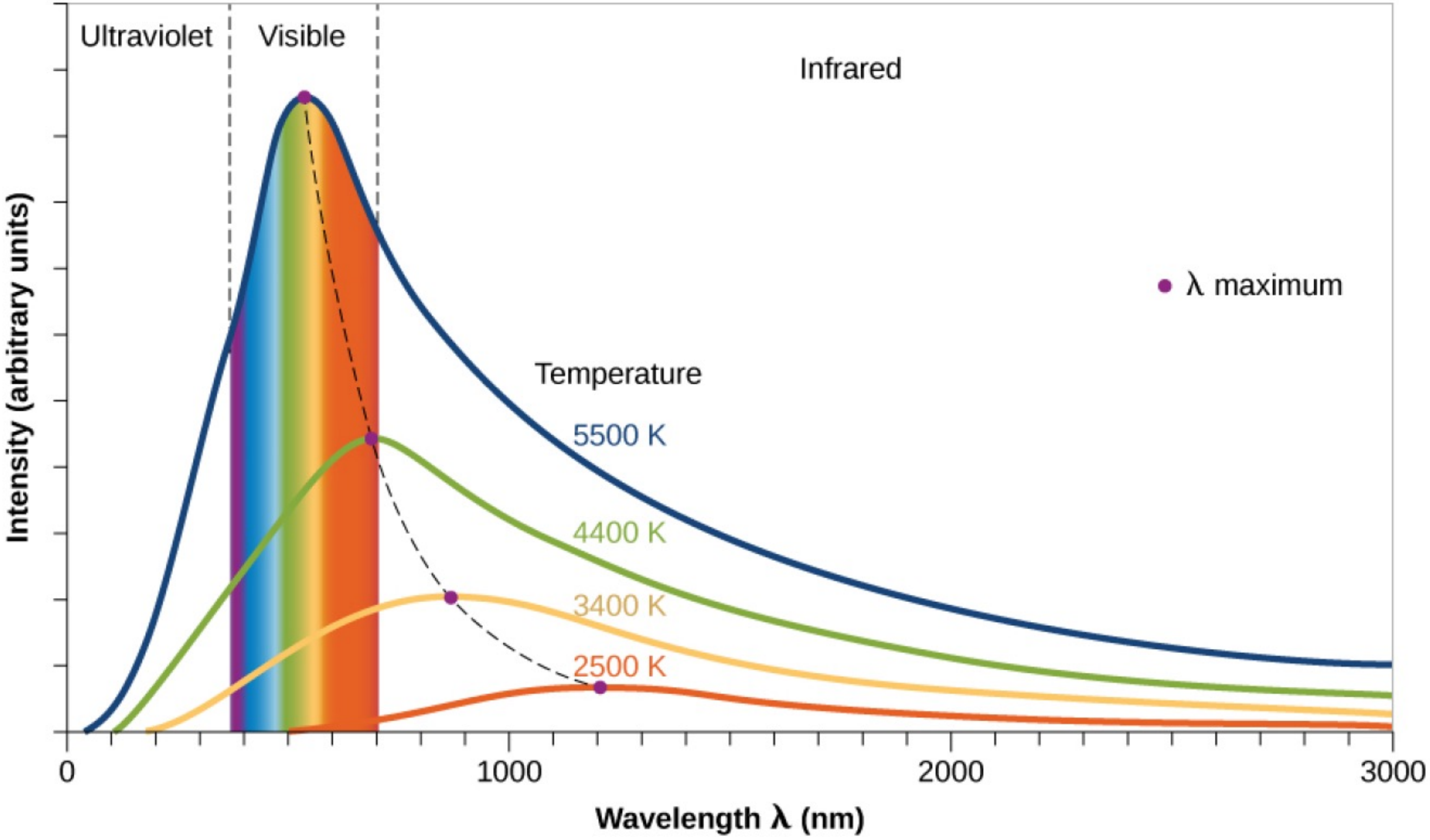


Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10^6–10^8 K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10^4–10^6 K	Supernova remnants, very hot stars
Visible	400–700	10^3–10^4 K	Stars
Infrared	10^3–10^6	10–10^3 K	Cool clouds of dust and gas, planets, moons
Microwave	10^6–10^9	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10^9	Less than 10 K	Supernova remnants, pulsars, cold gas

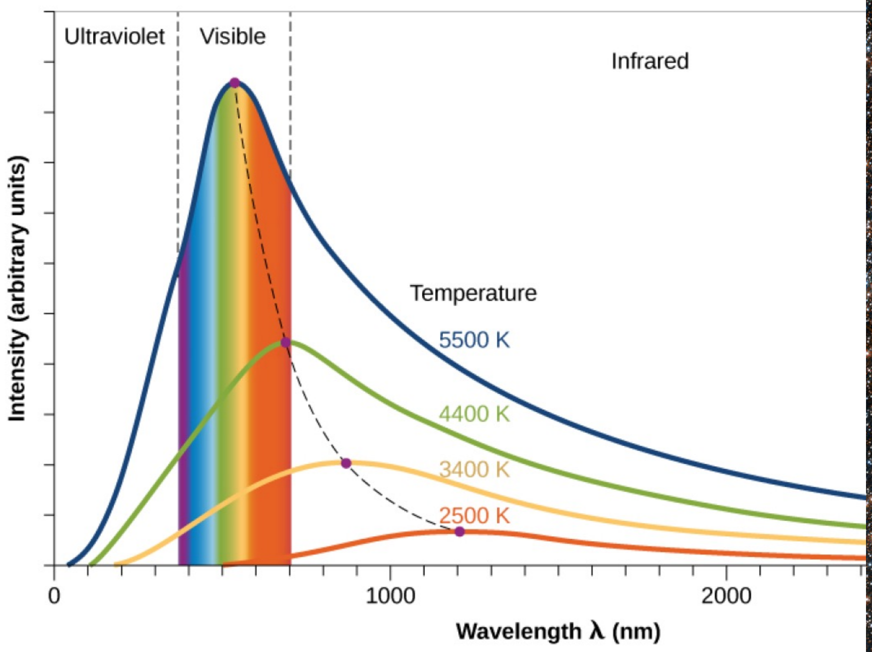

Visible
Gamma
X-ray
Ultra-violet (UV)
Infrared (IR)
Microwave
Radio
Shorter waves
Longer waves
Electromagnetic spectrum
(energy of light)
Thermosphere (auroras)
Mesosphere (meteors burn up)
Stratosphere (ozone layer at 20–30 km; jets fly at 10 km)
Troposphere (weather)
Atmosphere
Optical “window”
Radio “window”

Blackbody emission: hotter things emit at higher energies (=shorter wavelengths)

Peak of blackbody: $$\lambda_{\text{max}} \cdot T = 0.288 \text{ cm} \cdot \text{K}$$

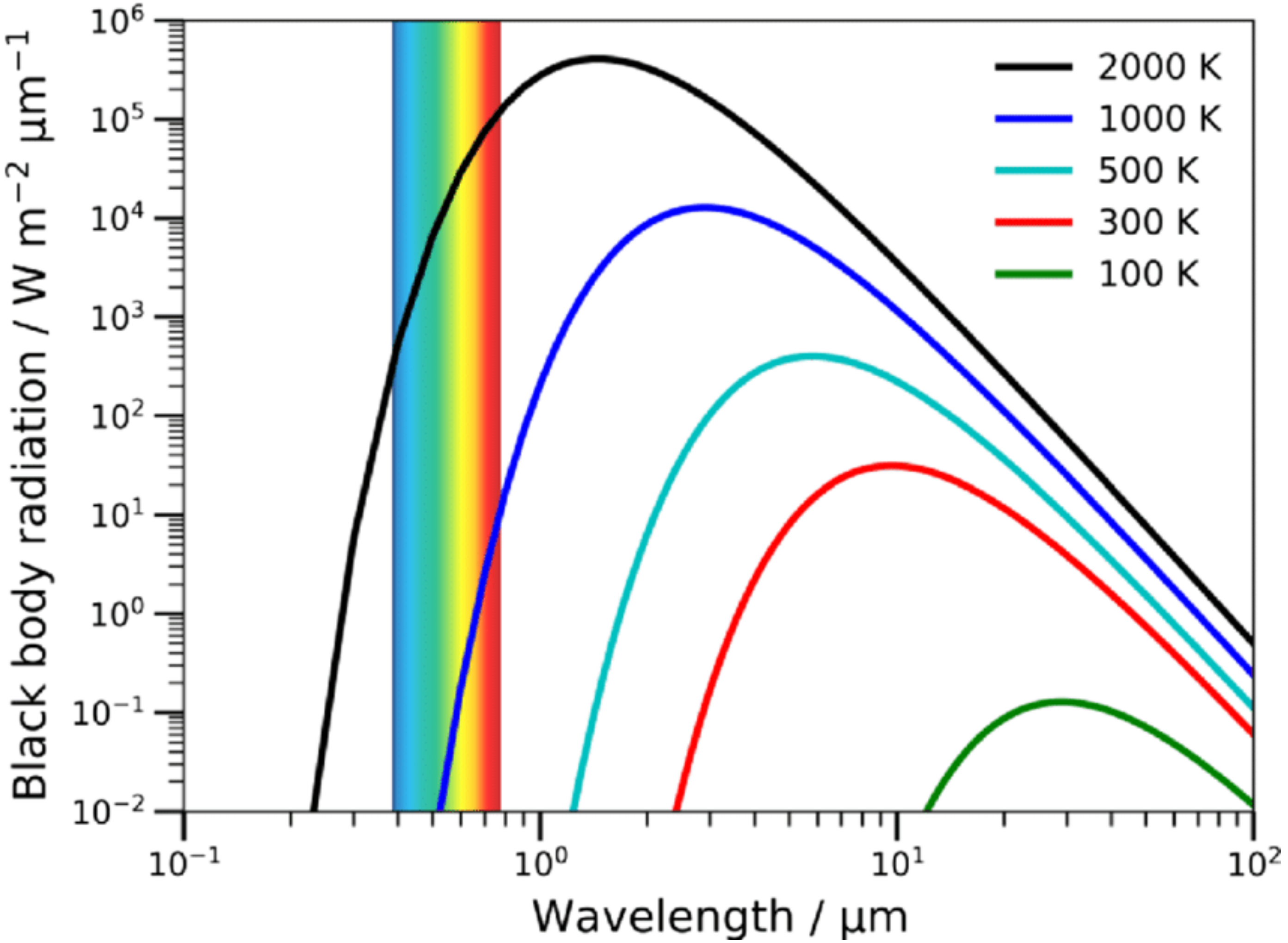


Star Color	Approximate Temperature	Example
Blue	25,000 K Blue	Spica
White	10,000 K	Vega
Yellow	6000 K	Sun
Orange	4000 K Red	Aldebaran

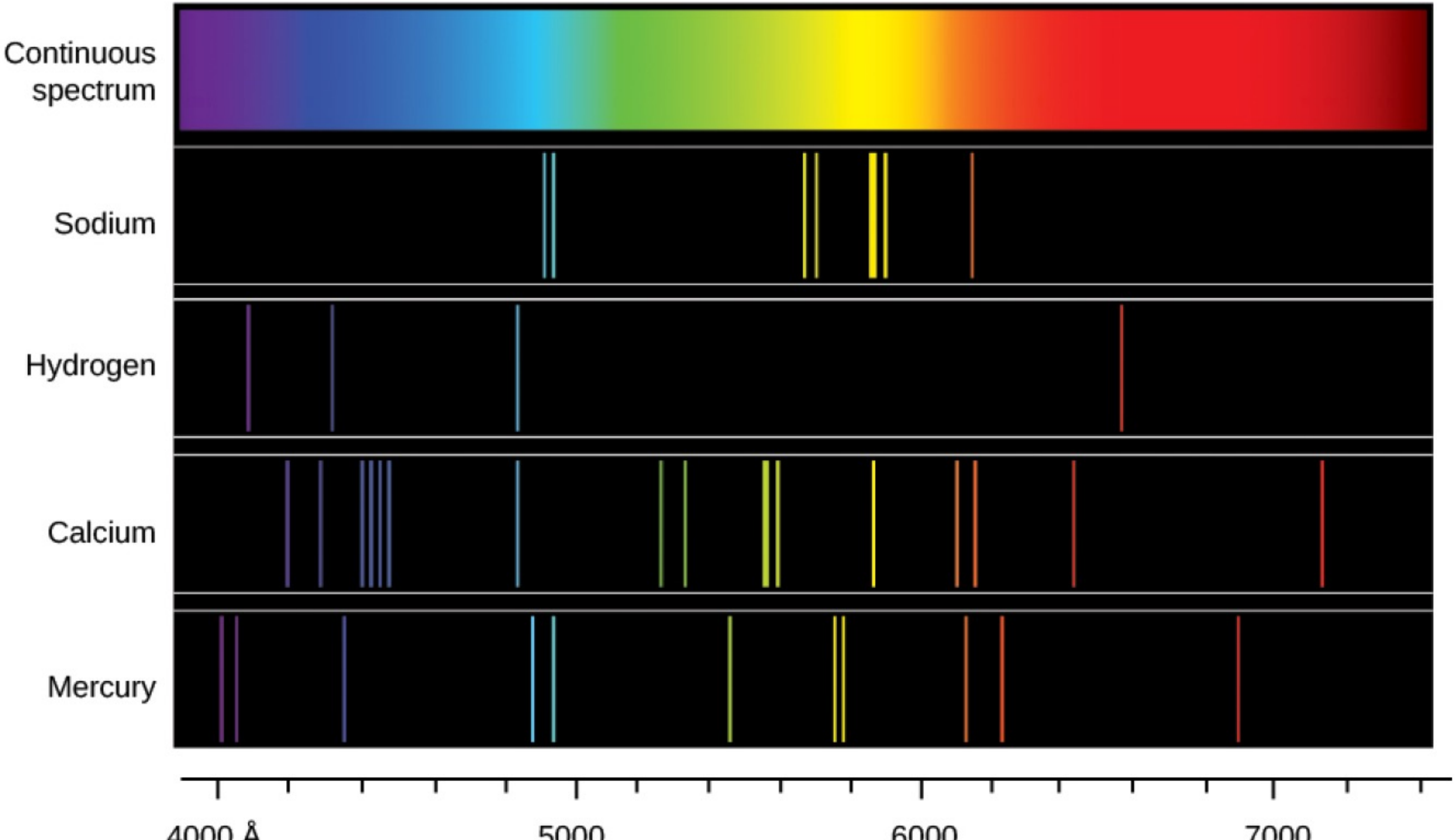


Blackbody emission: hotter objects emit at higher energies (=shorter wavelengths)

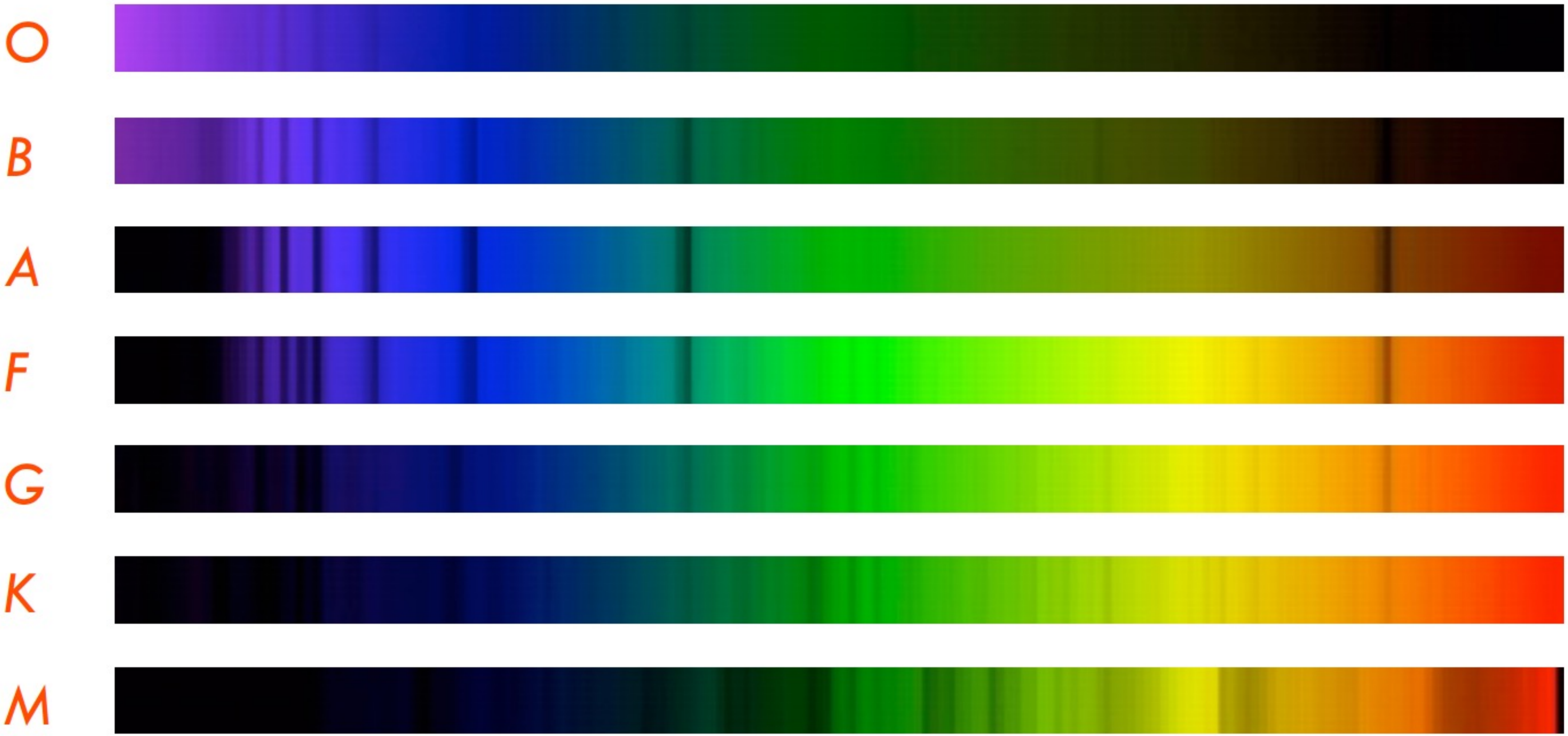
Peak of blackbody: $\lambda_{\text{max}} \cdot T = 0.288 \text{ cm} \cdot \text{K}$



Elements and molecules have transitions between different electron energy levels



Spectral Type (temperature) from dark absorption lines



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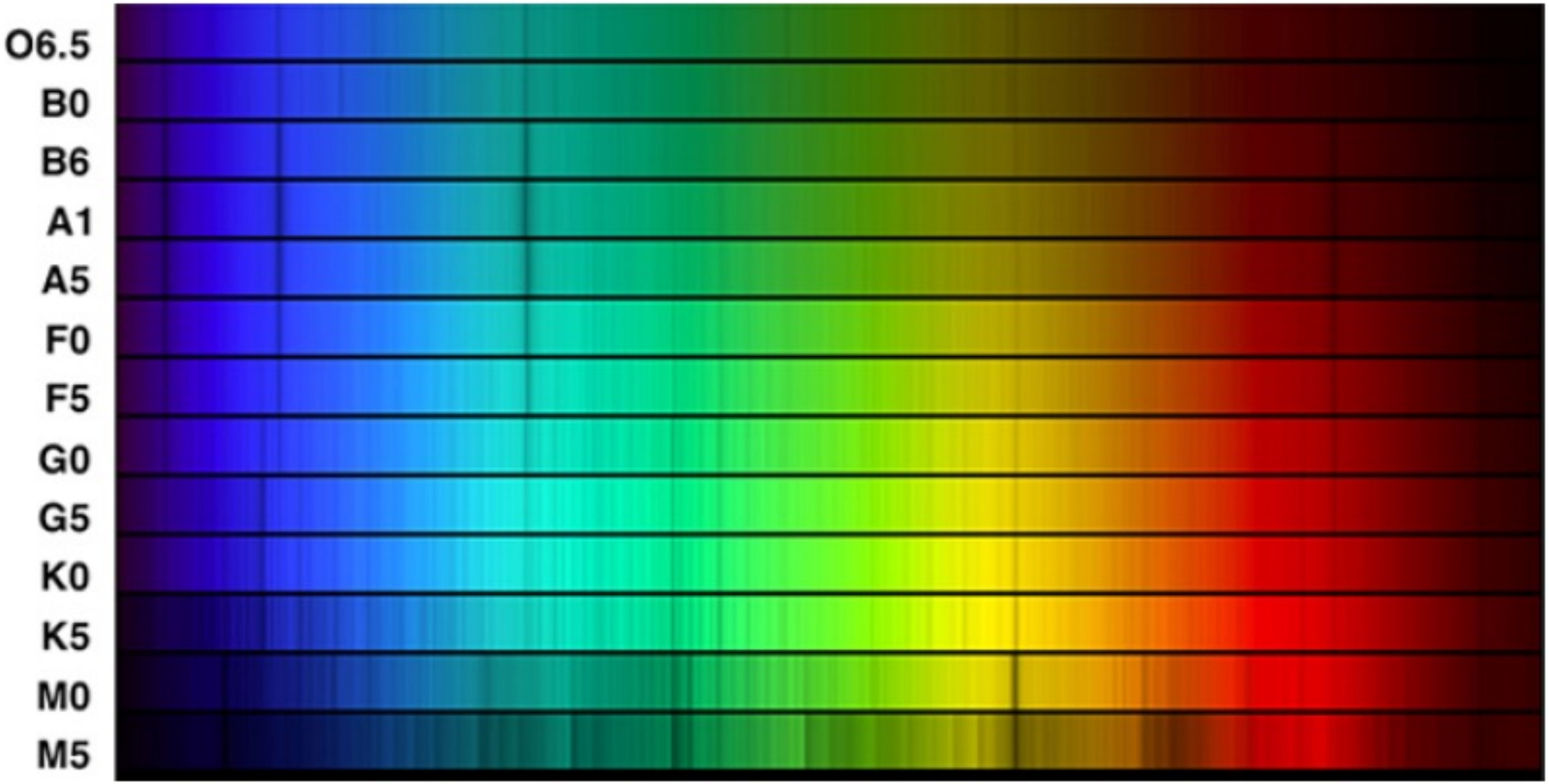
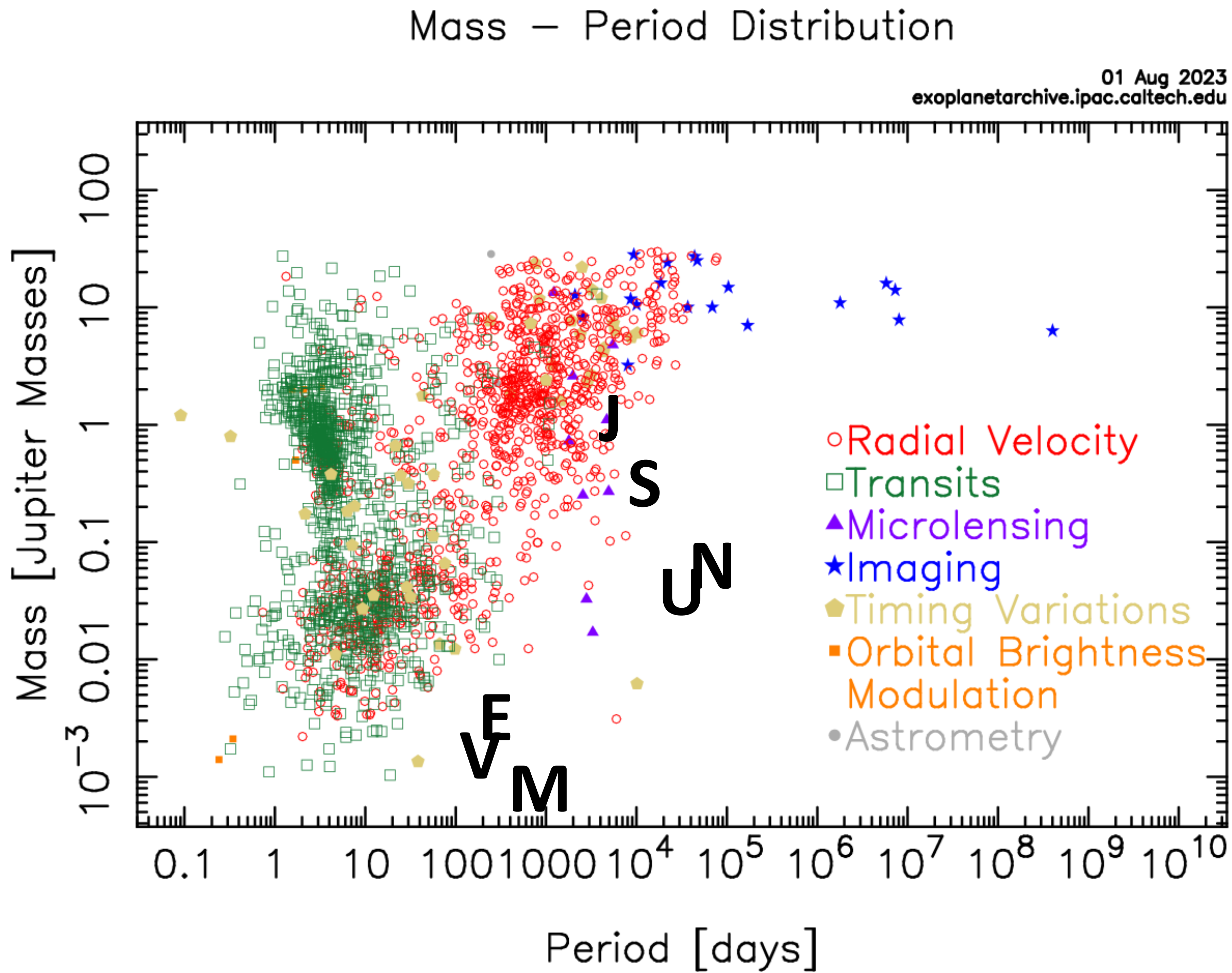


Techniques for discovering exoplanets

- **Radial velocity:** spectroscopy
- **Transits:** imaging (single-band)
- **Direct imaging:** imaging at high contrast
    - Coronagraph; ground+adaptive optics or space
- **Astrometry:** imaging with high precision
- **Microlensing:** imaging

Can combine methods: mass+radius

Characterization: multi-band photometry or spectroscopy



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Period [days]
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Radial Velocity
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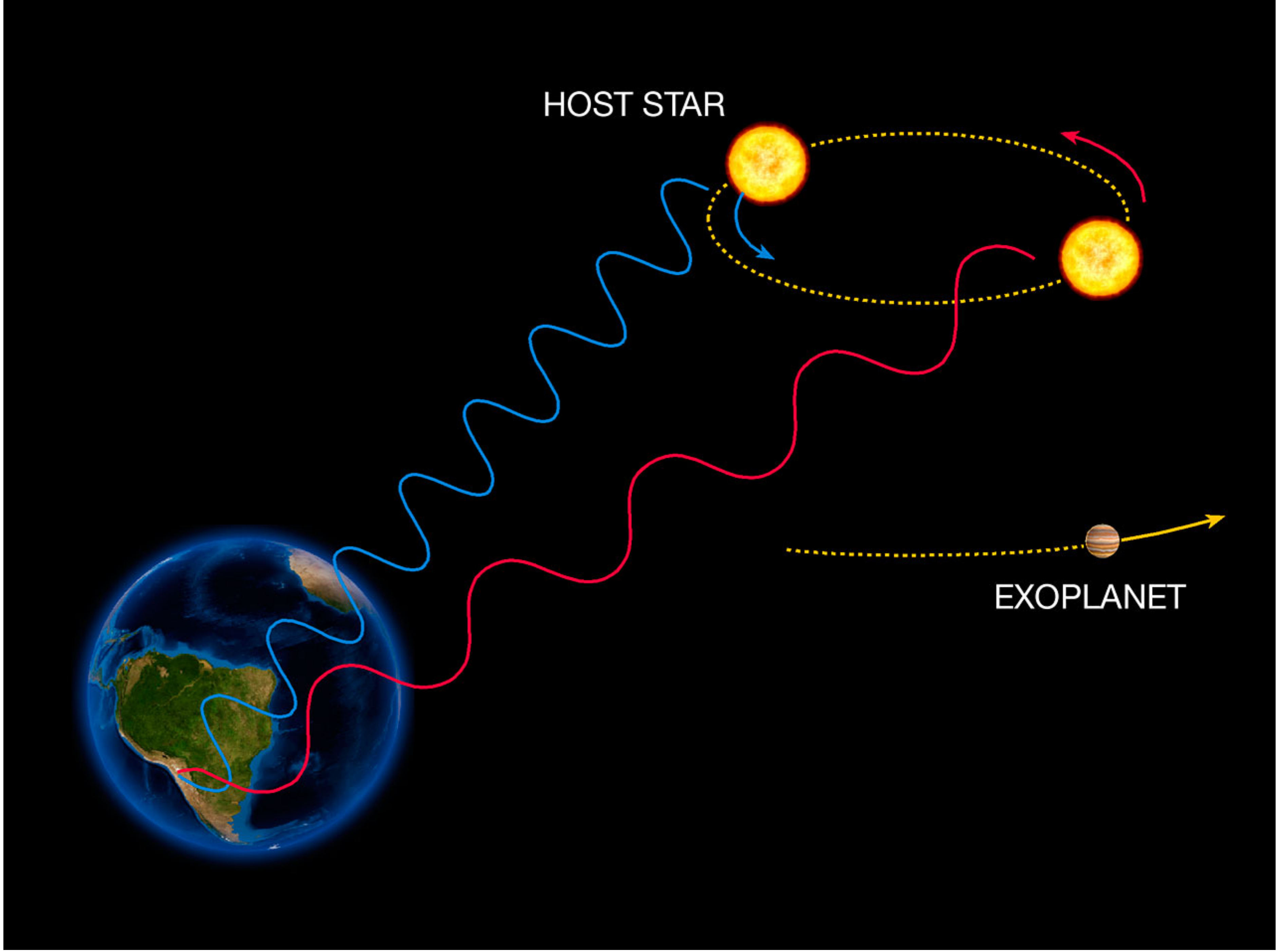
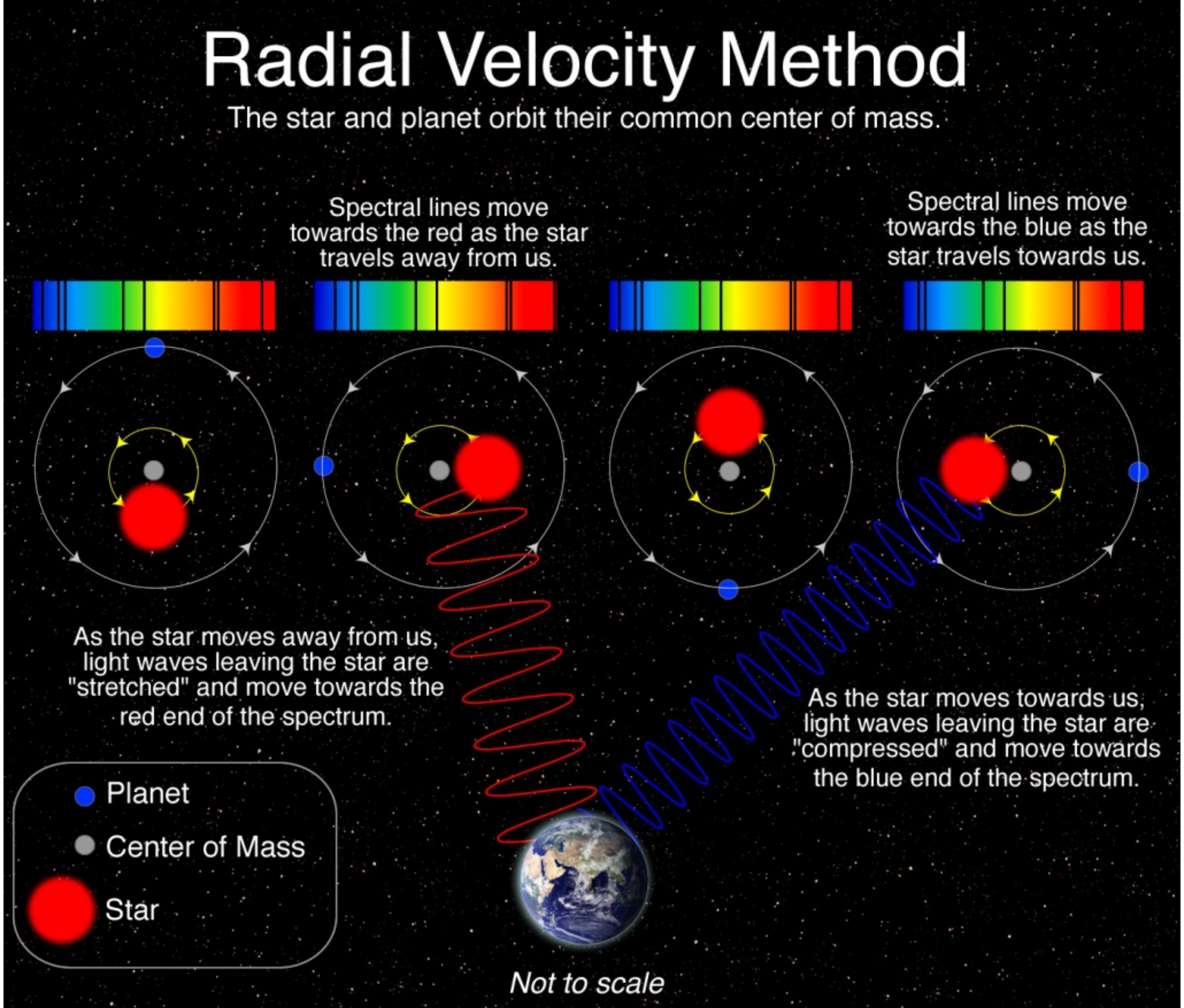
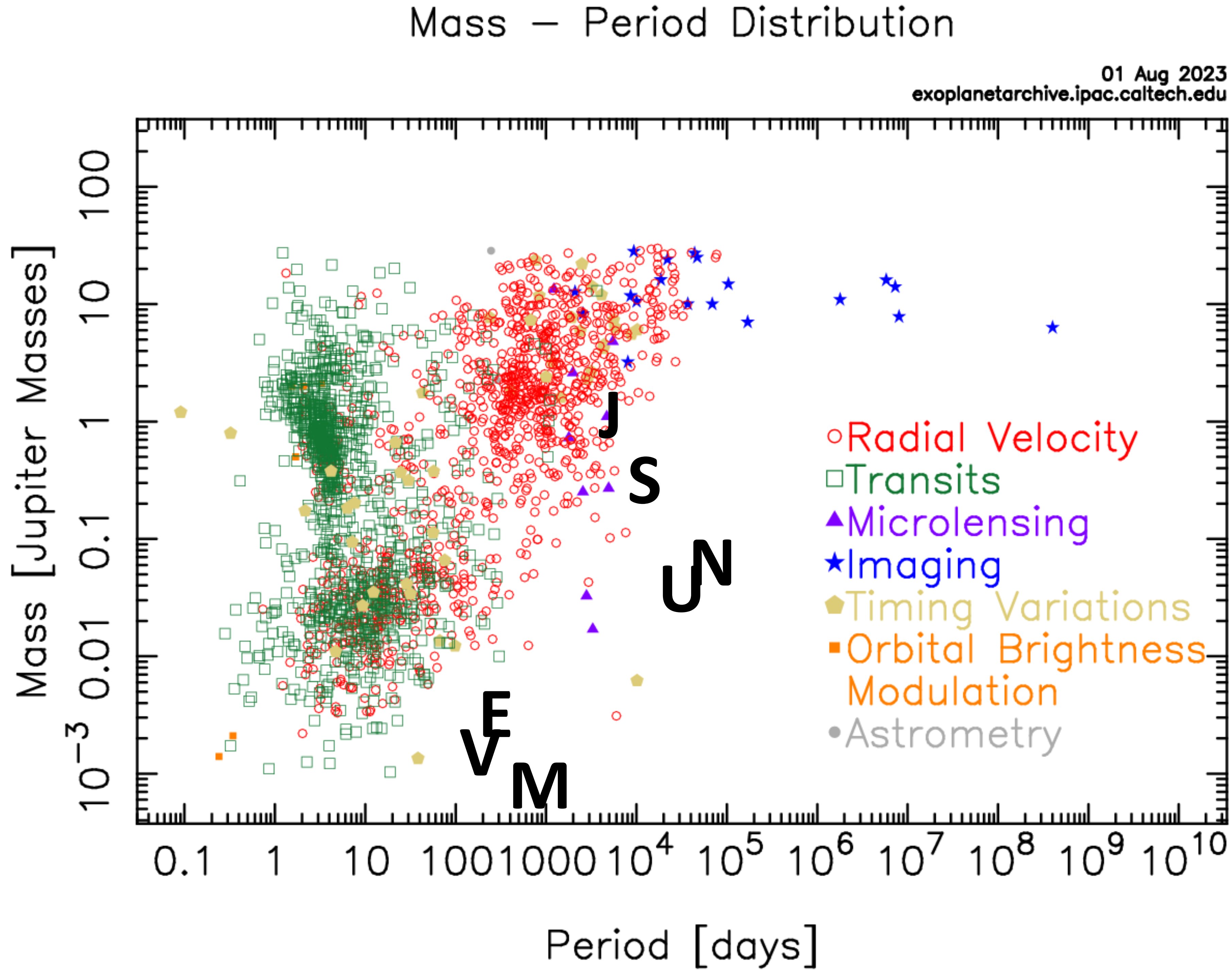

HOST STAR
EXOPLANET


Radial Velocity Method
The star and planet orbit their common center of mass.
Spectral lines move towards the red as the star travels away from us.
Spectral lines move towards the blue as the star travels towards us.
As the star moves away from us, light waves leaving the star are "stretched" and move towards the red end of the spectrum.
As the star moves towards us, light waves leaving the star are "compressed" and move towards the blue end of the spectrum.
Planet
Center of Mass
Star
Not to scale



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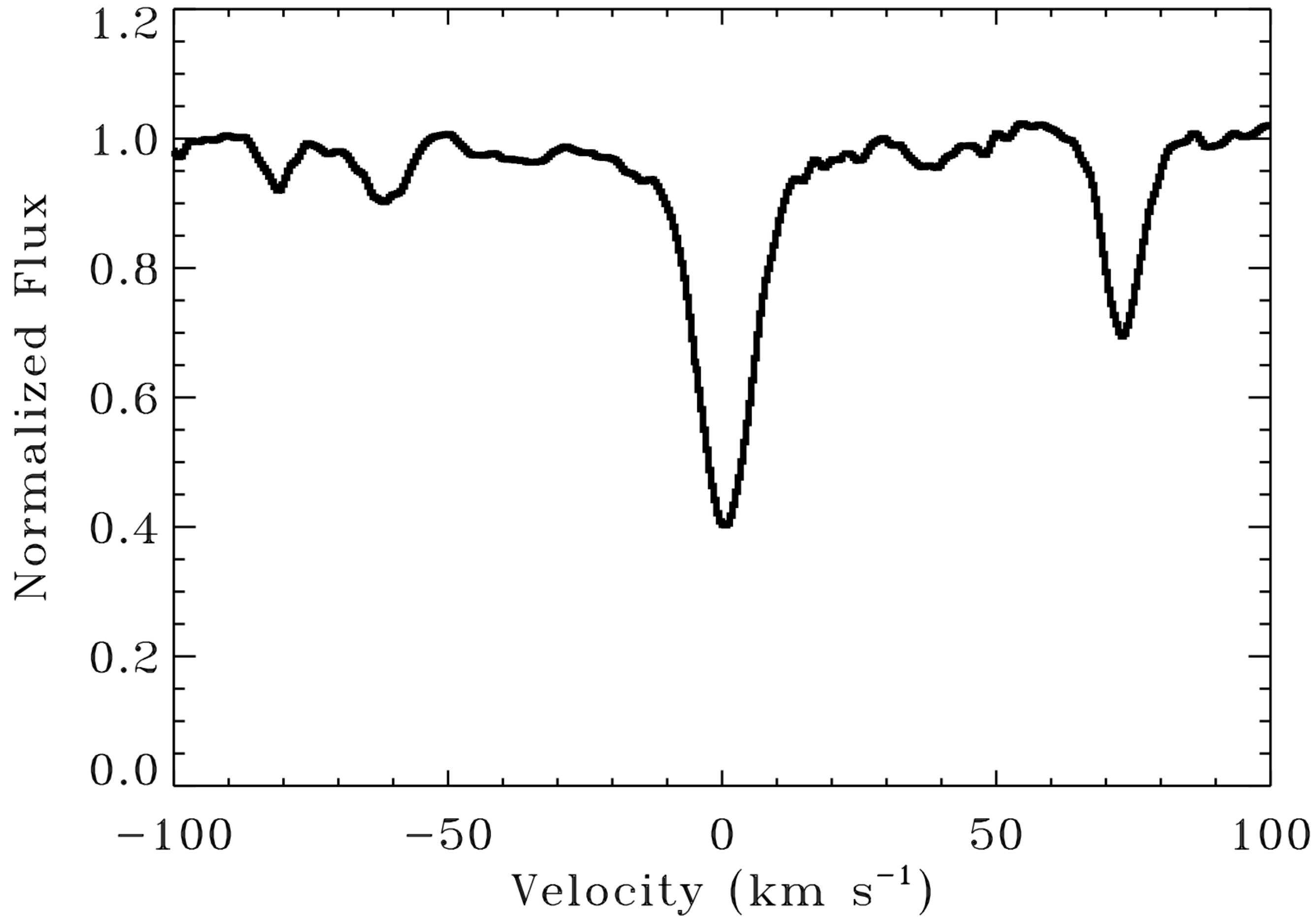
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry
J
S
U
N
E
V
M

Radial Velocity

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

- M_P in Jupiter masses
- P_{orb} in years
- M_* in solar masses
- V_{obs} in m/s

Radial velocity: centroid absorption lines



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

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

Centroid an absorption line

- Solar radius: 6.96e10 cm
- Solar rotation period: 27 days
- Velocity: ~2 km/s

- Jupiter at 0.1 AU: 90 m/s
- Jupiter at 1 AU: 28.4 m/s
- Jupiter at 5 AU: 13 m/s
- Earth at 0.1 AU: 0.3 m/s
- Earth at 1 AU: 0.09 m/s

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

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

To detect Earth: 0.09/2000: centroid to 1 part in 10^5 (hard – at current limits!)

- Jupiters: need time to build up signal

Centroid an absorption line

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

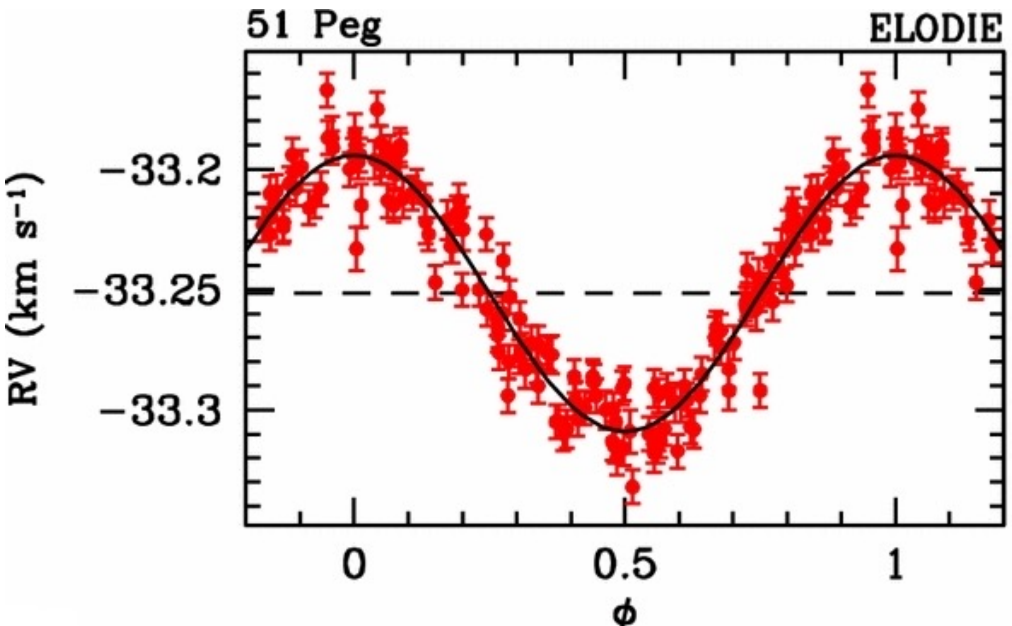
- M_P in Jupiter masses
- $P_{\rm orb}$ in years
- M_* in solar masses

To detect Earth: 9 cm/s

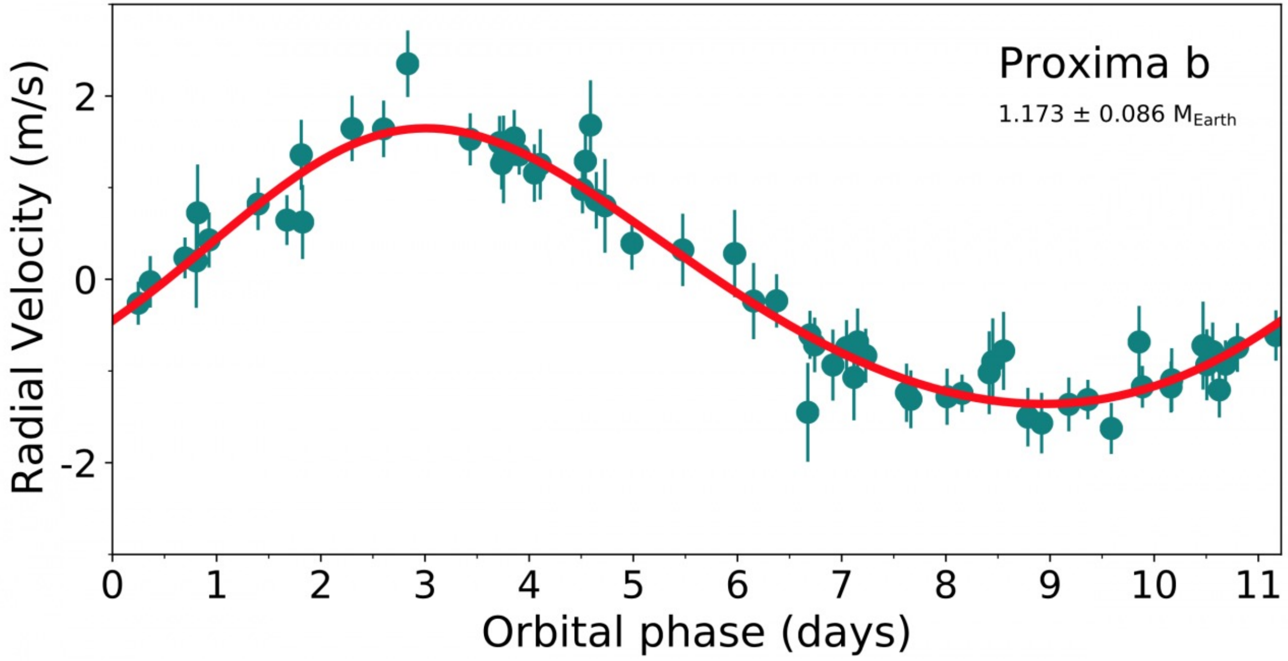
RV observations from first detections: 10 m/s

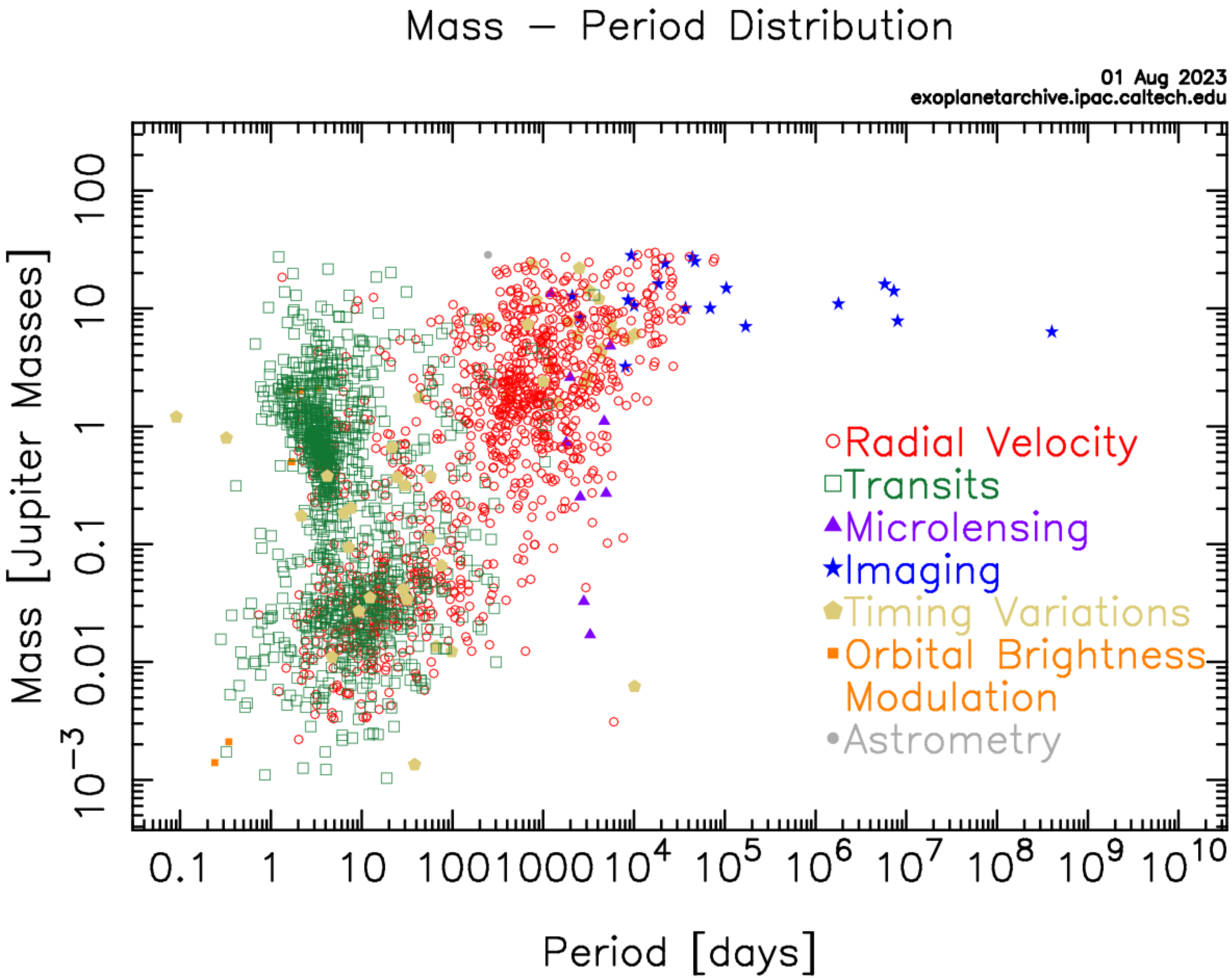
Best current instrument (VLT/ESPRESSO): 3 cm/s

First detection of 51 Peg (Nobel Prize)



ESPRESSO confirmation of Prox Cen b (nearest exoplanet)





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10^7
10^8
10^9
10^{10}
Period [days]
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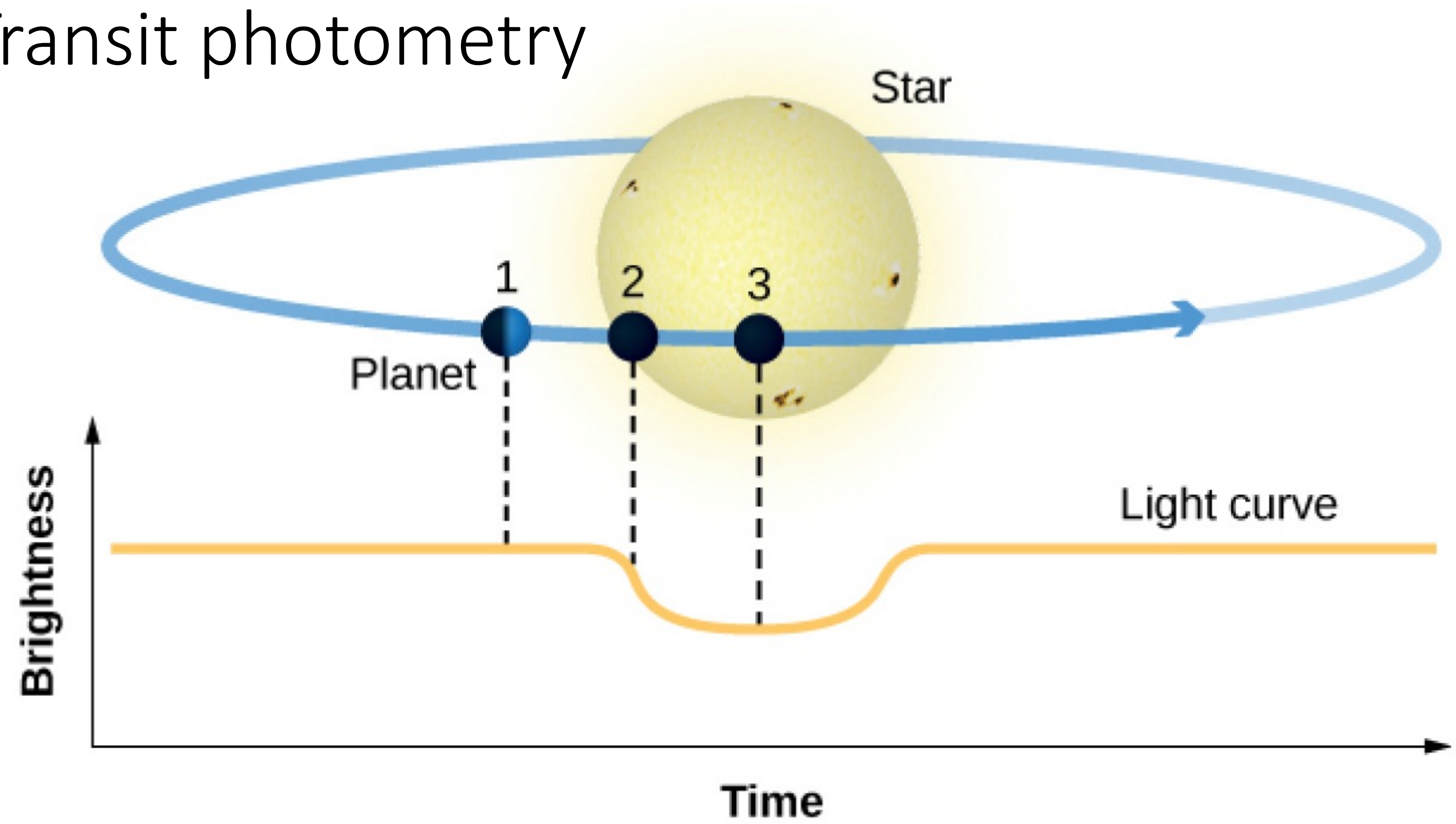
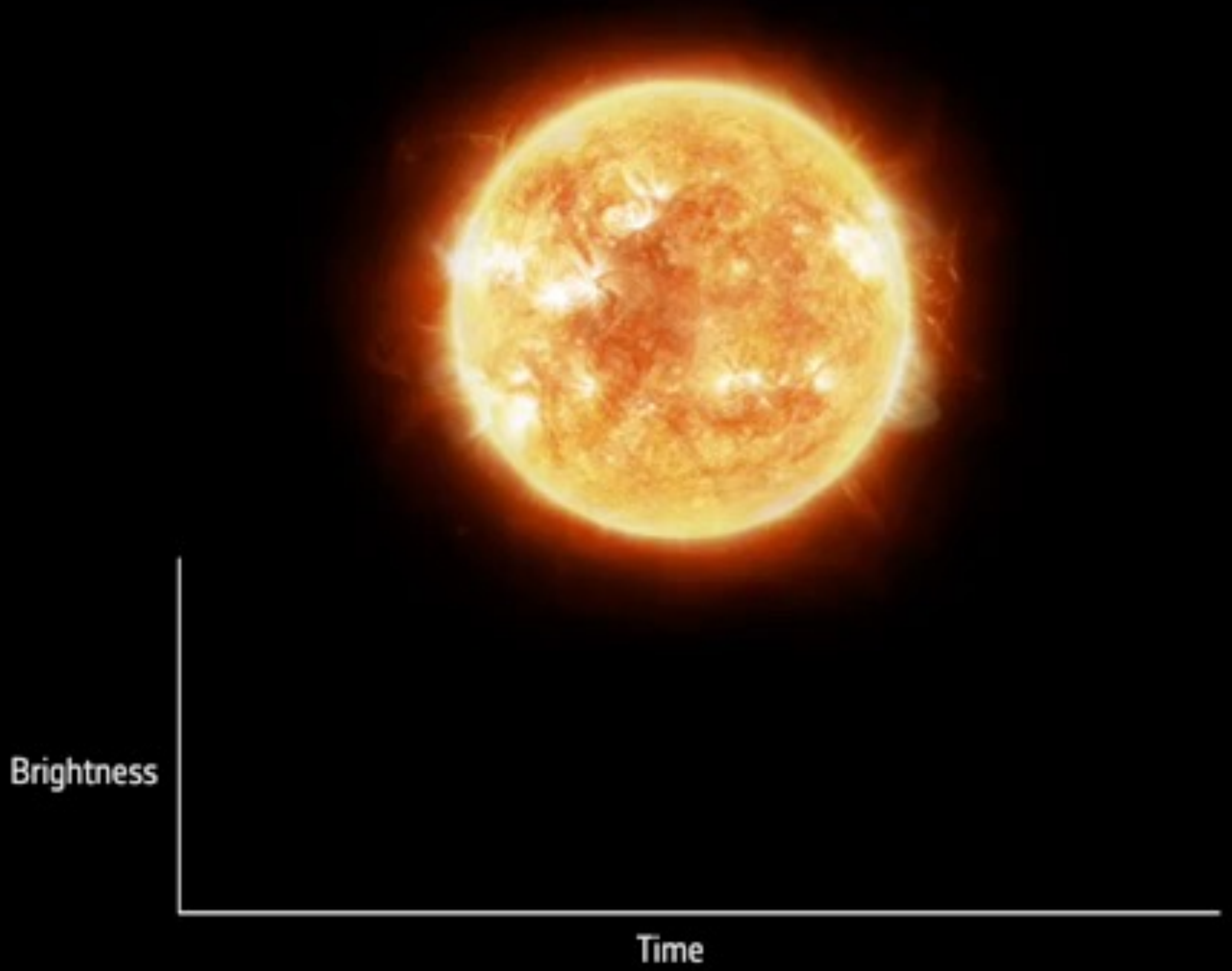
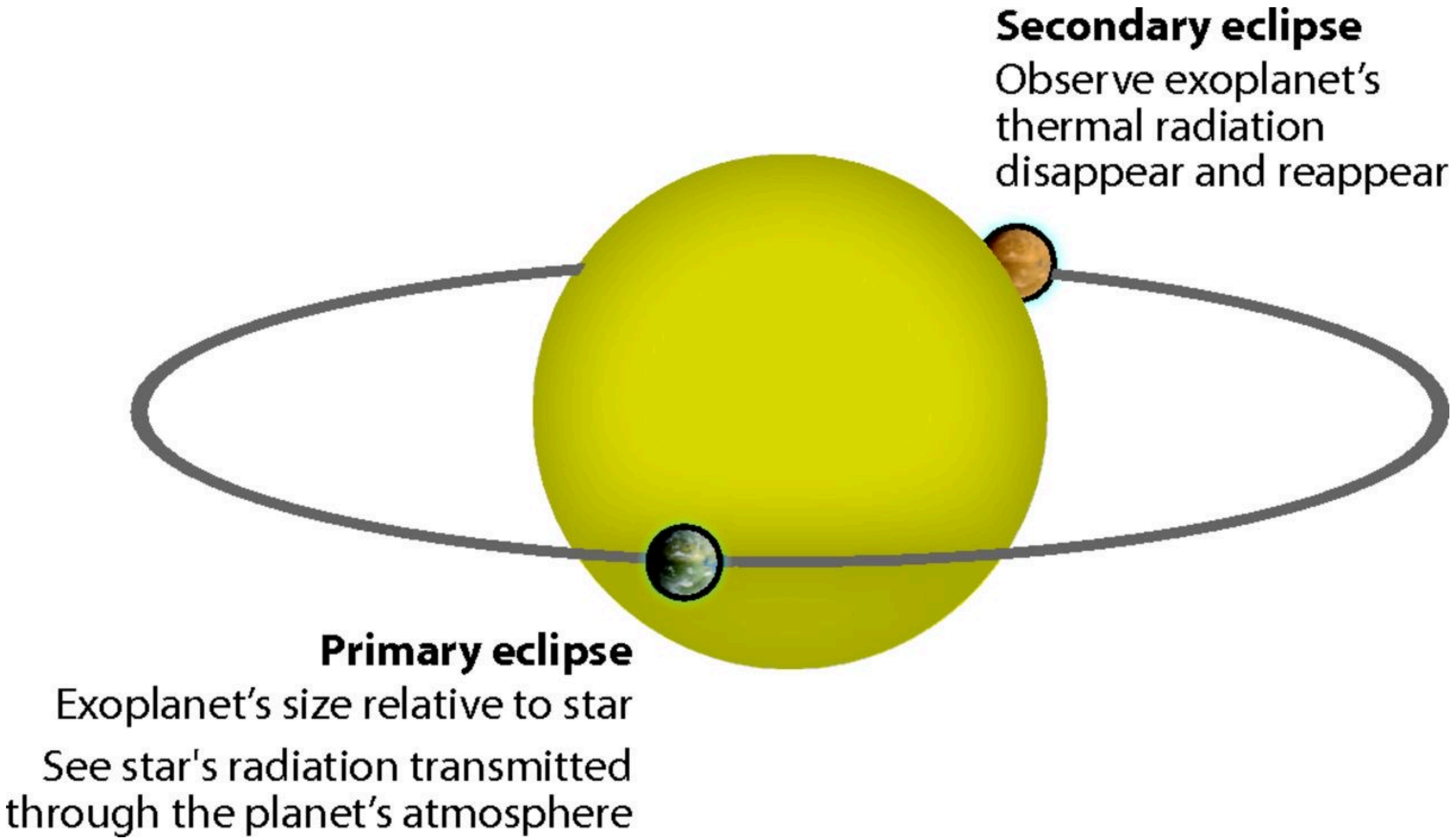
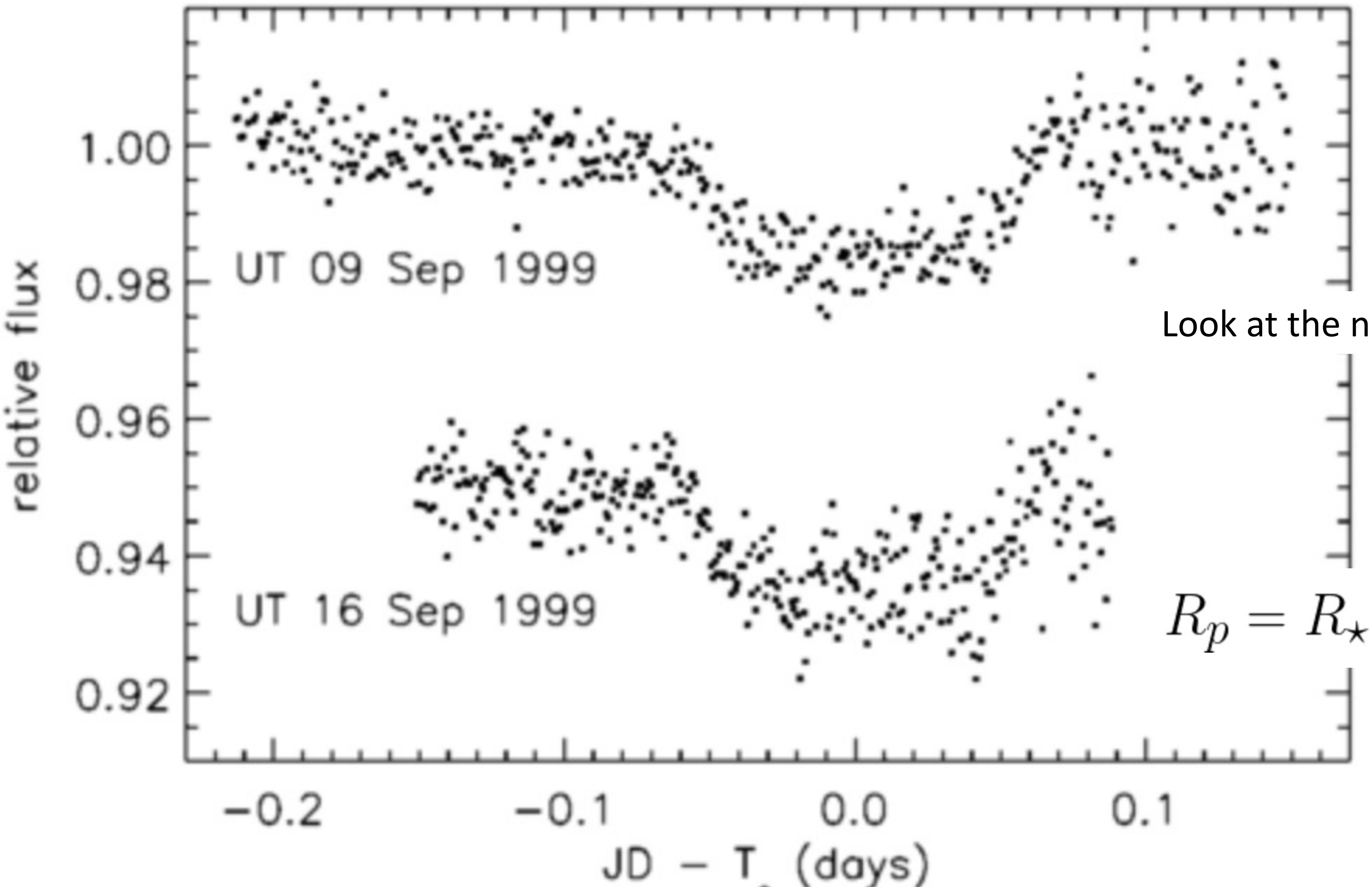
Transit photometry




Brightness
Time


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

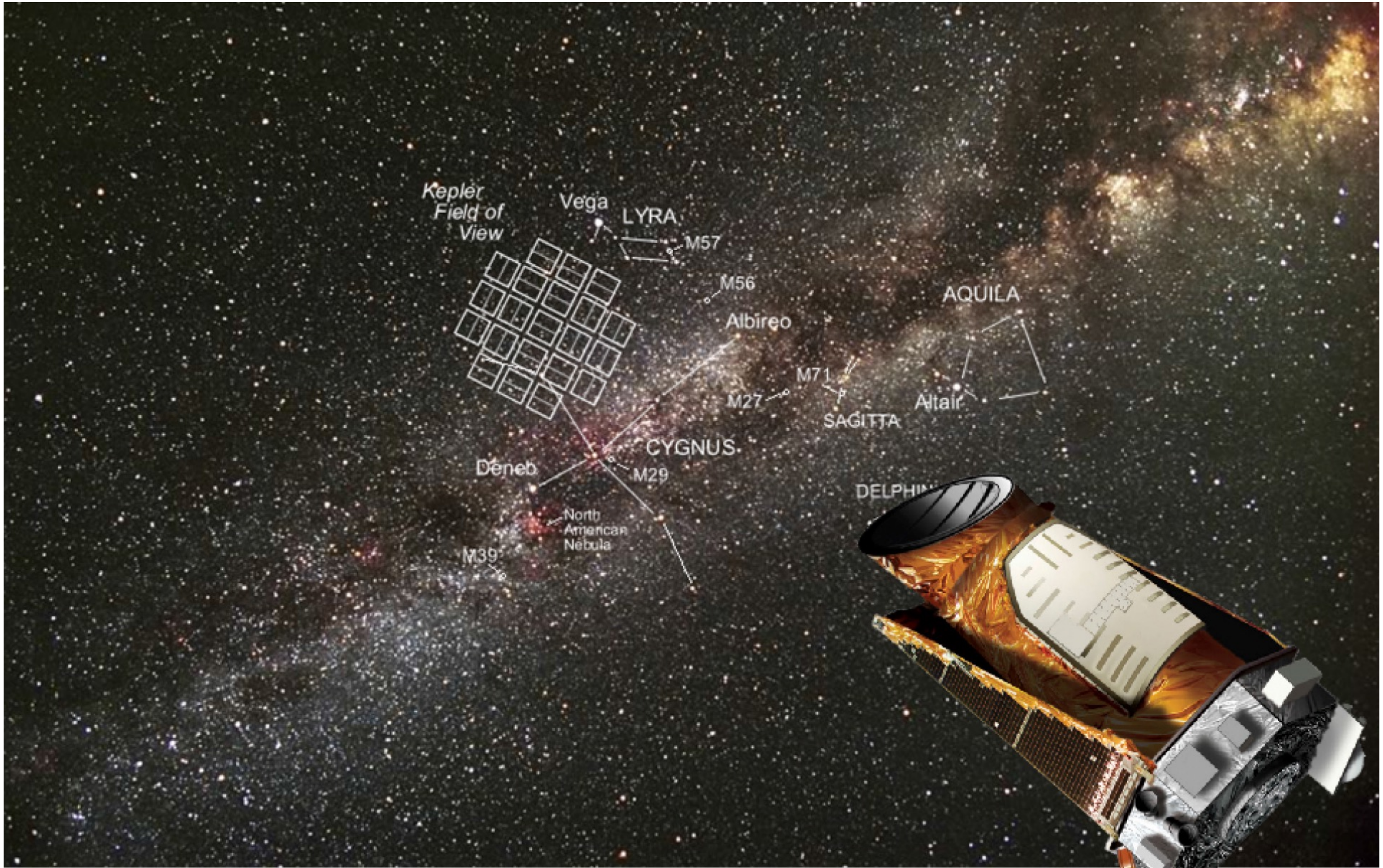
First transiting planet around the star HD209458



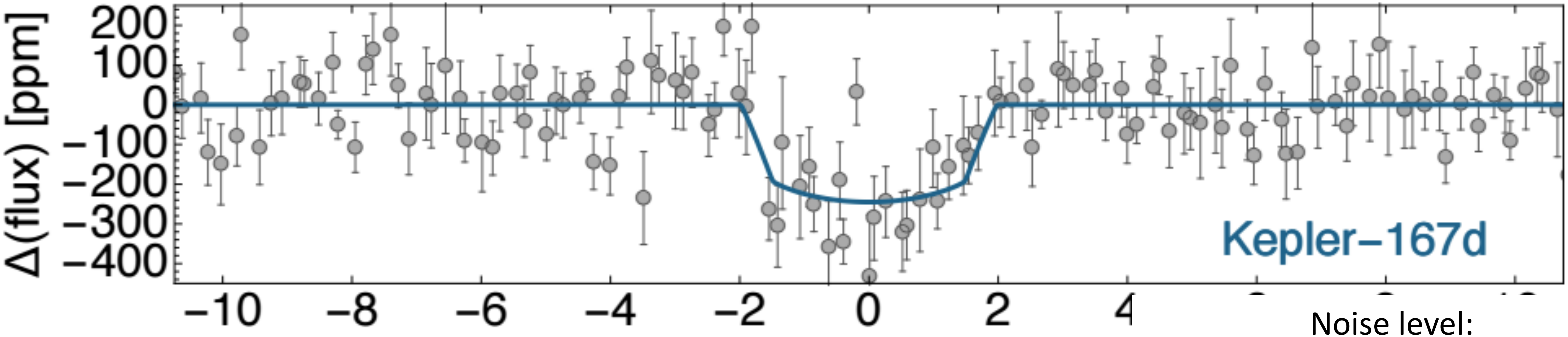
Look at the noise level: ~1%!

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

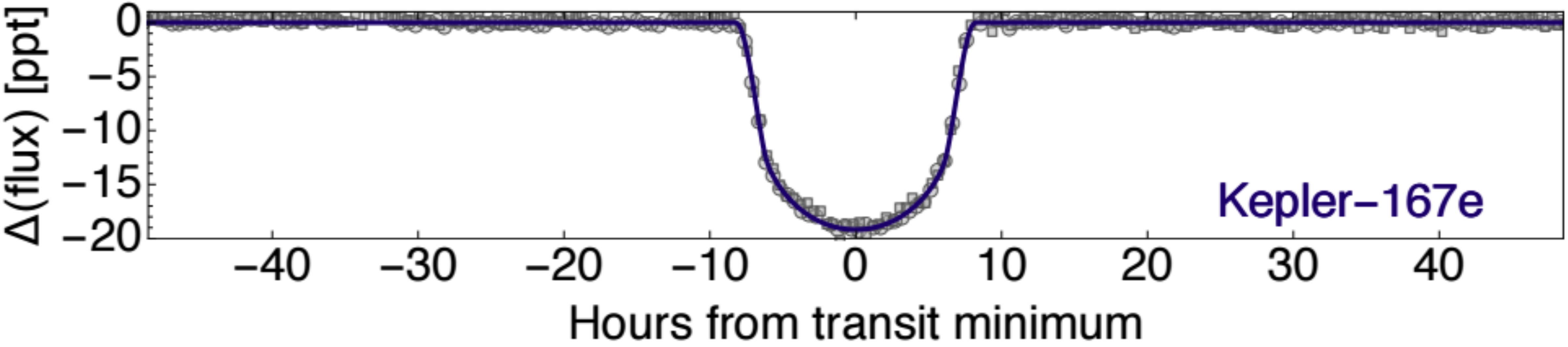
Kepler Observatory: thousands of planets



Example of a four (or more) planet system (two shown here)



Noise level:
50 parts per million (5e-5)



TESS and PLATO transit missions

TESS (NASA)

- Launched in 2018
- All-sky survey of brightest stars
  - 30 days at each position
  - Close-in planets, not 1 AU planets
- 1367 possible planets
  - 329 confirmed

PLATO (ESA)

- 2026 launch date
- Stare at one larger region
  - Discover terrestrial planets in habitable zones

Earth 2.0 (China): Uncertain

Bias of transits

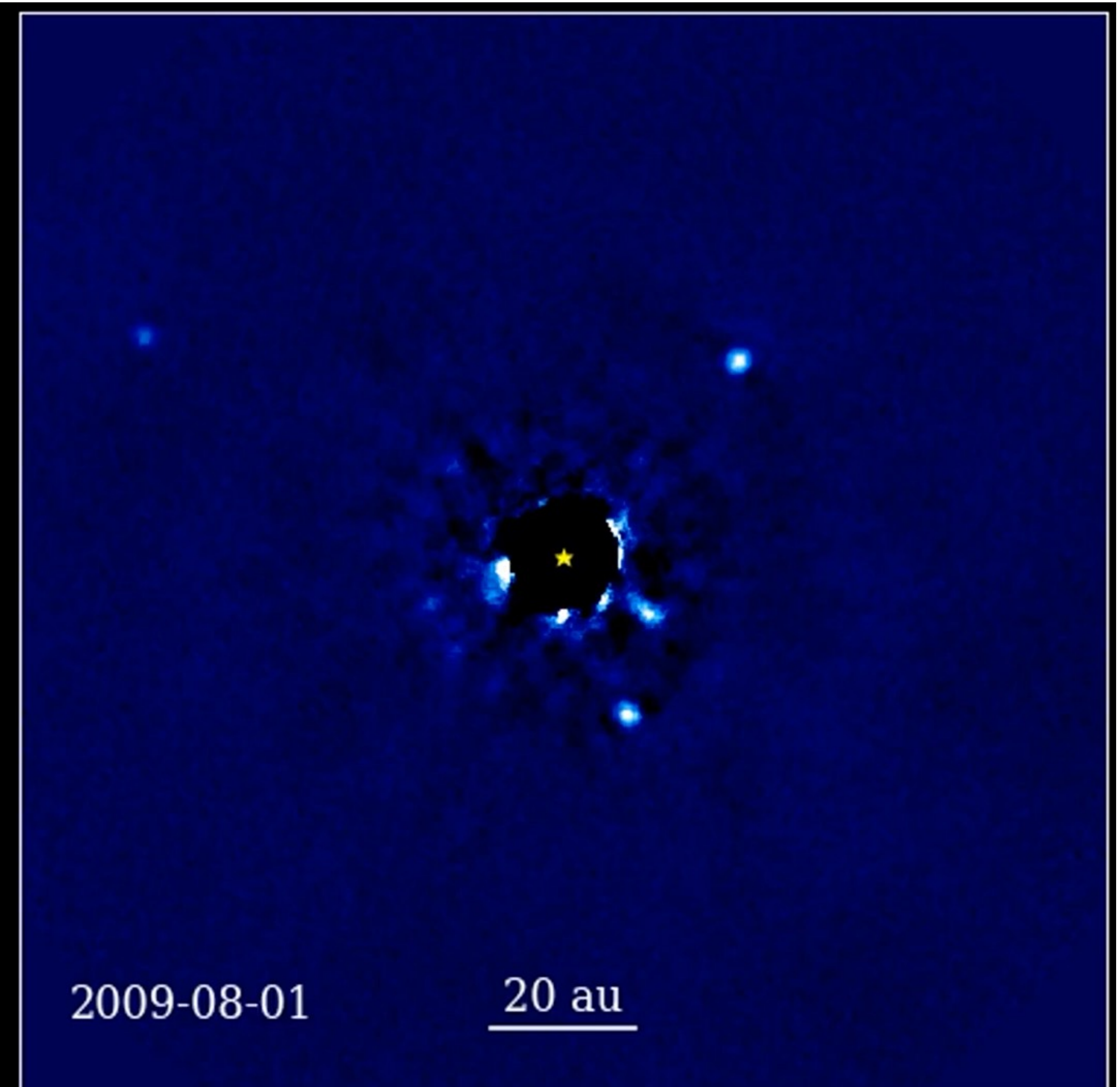
What kinds of planets are easiest to detect?

- Close to star

Probability of transit:
R_{star}/star-planet distance

- Large radius

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

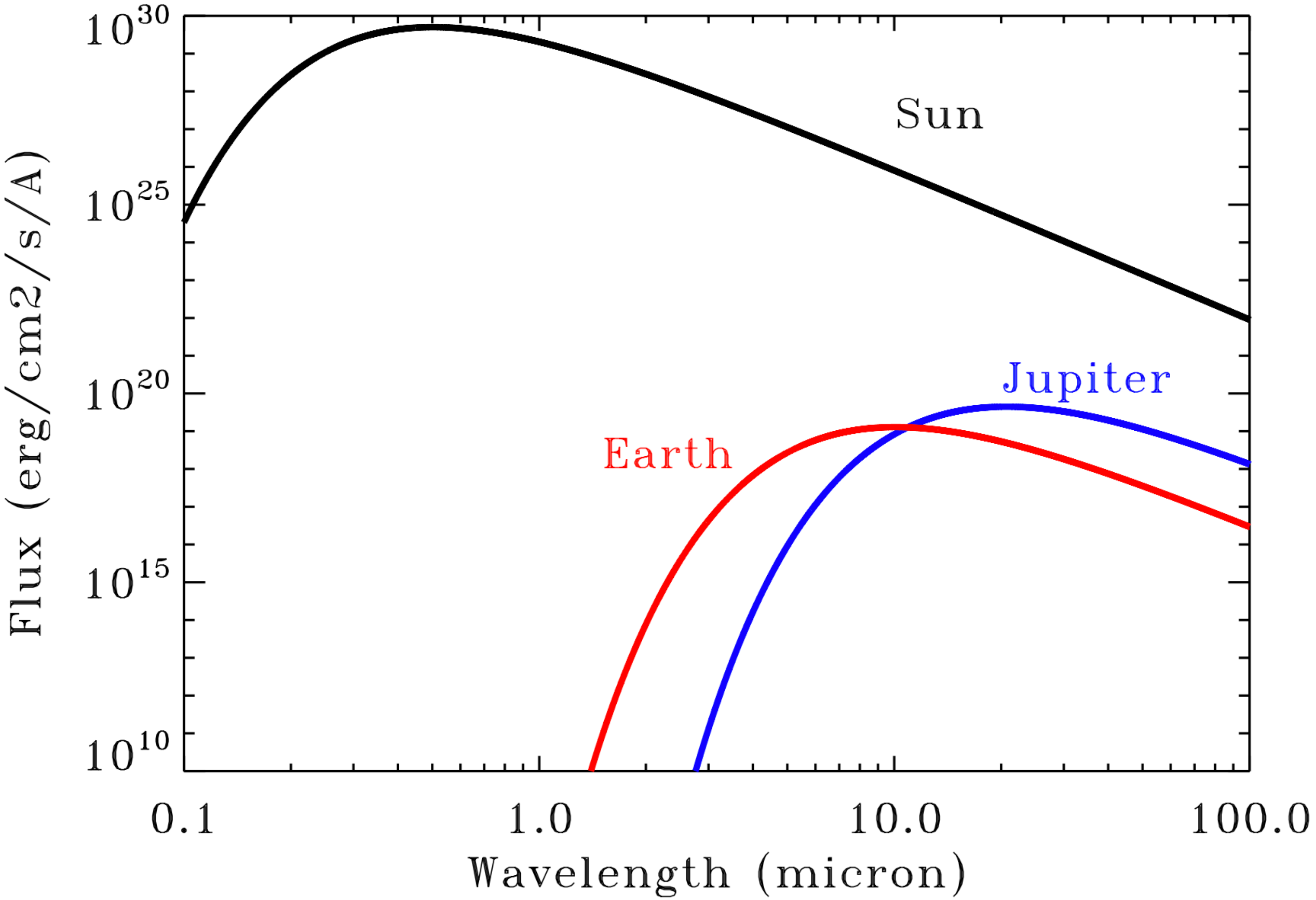


Direct Imaging:

requires coronagraph to block out a very bright star

- (similar to an eclipse)
- blocking bright starlight is not perfect

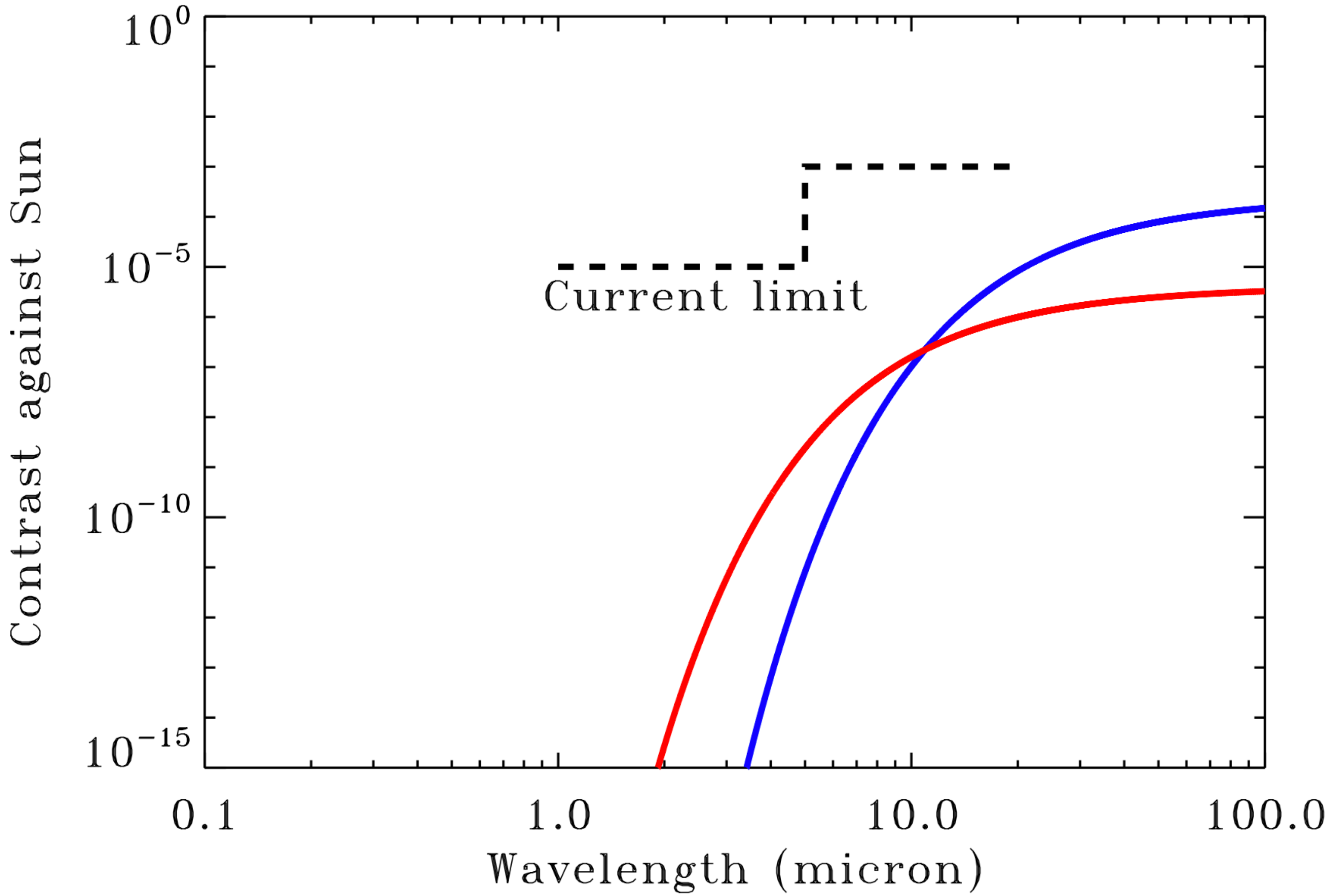
Prospects for direct imaging of the solar system



Flux = T^4 x R^2

Assume blackbody emission

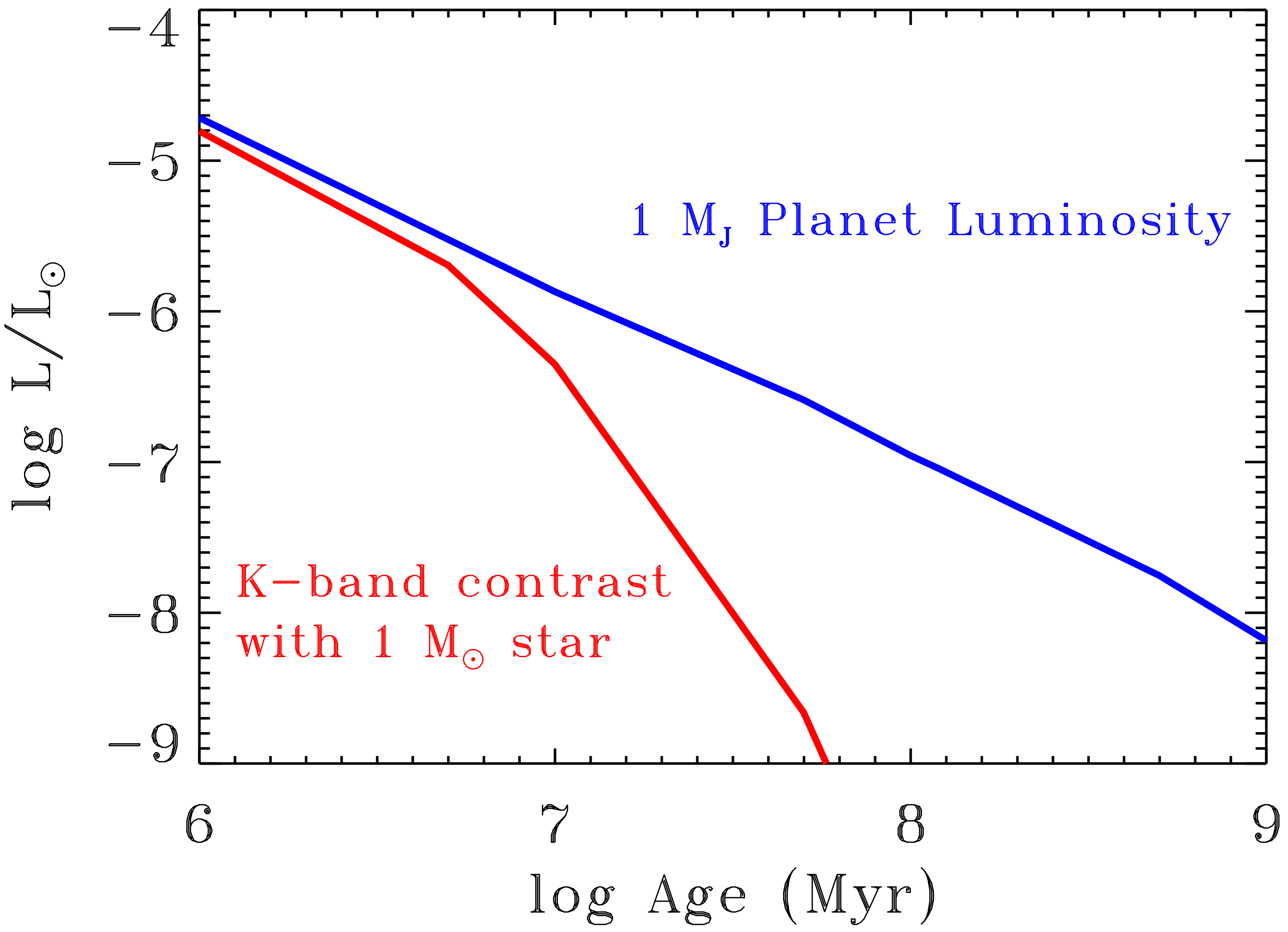
Prospects for direct imaging of the solar system



= T^4 x R^2

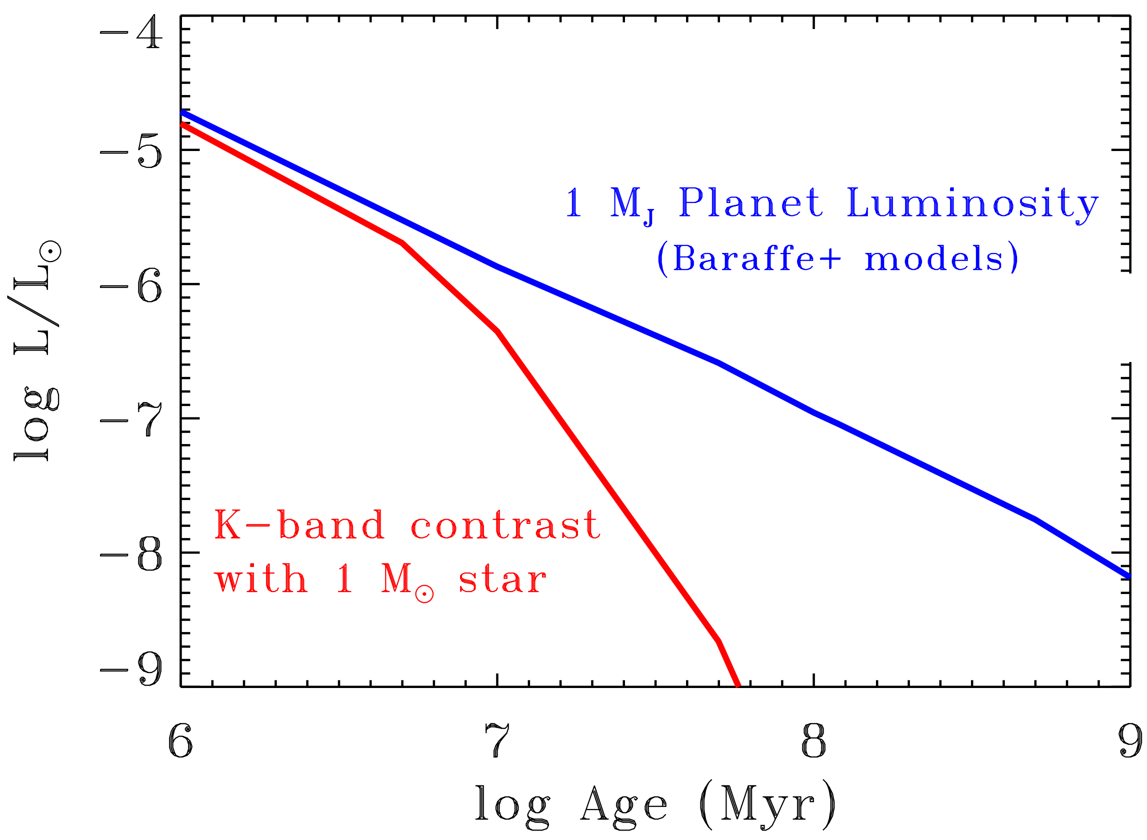
me blackbody emission

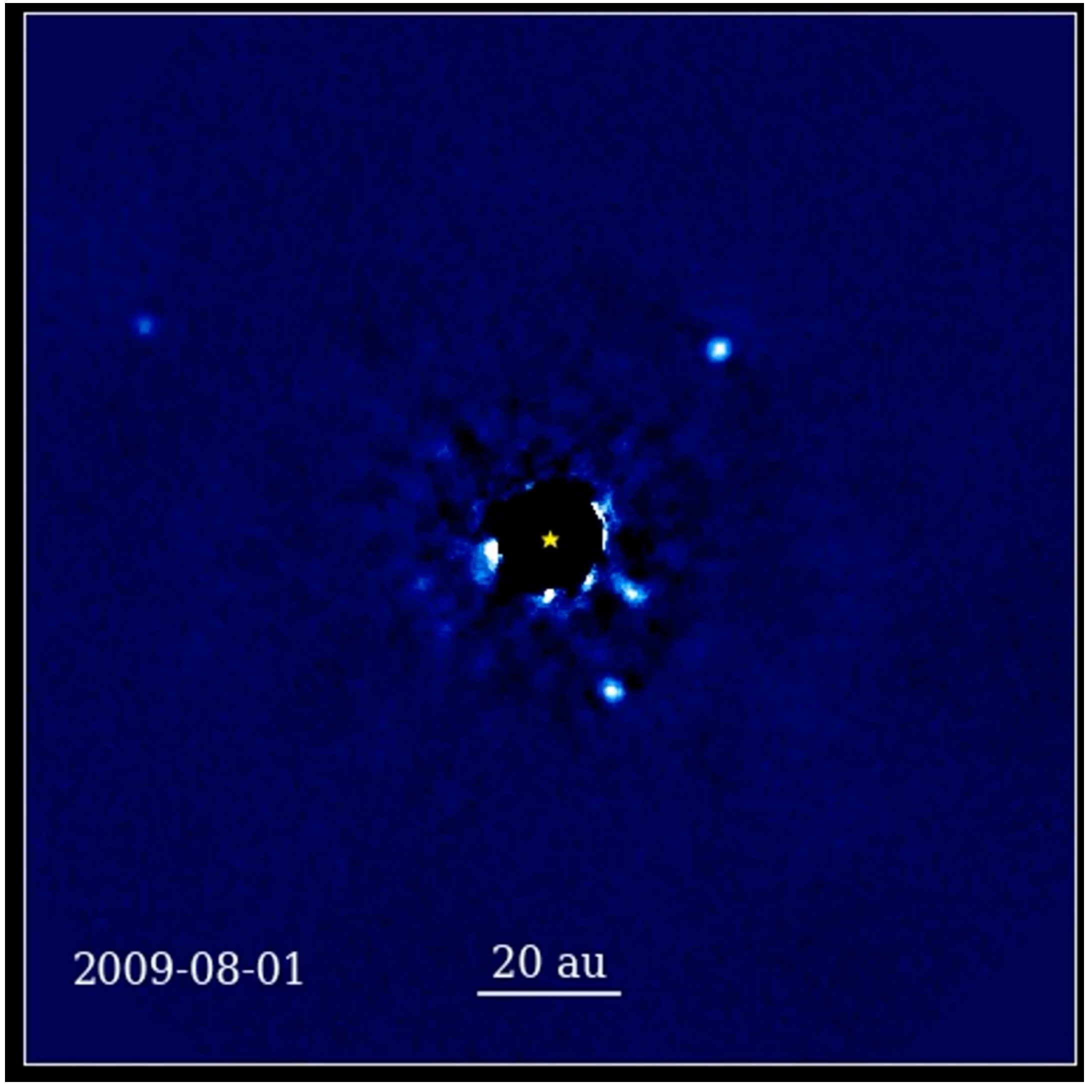
Prospects for direct imaging young solar systems!



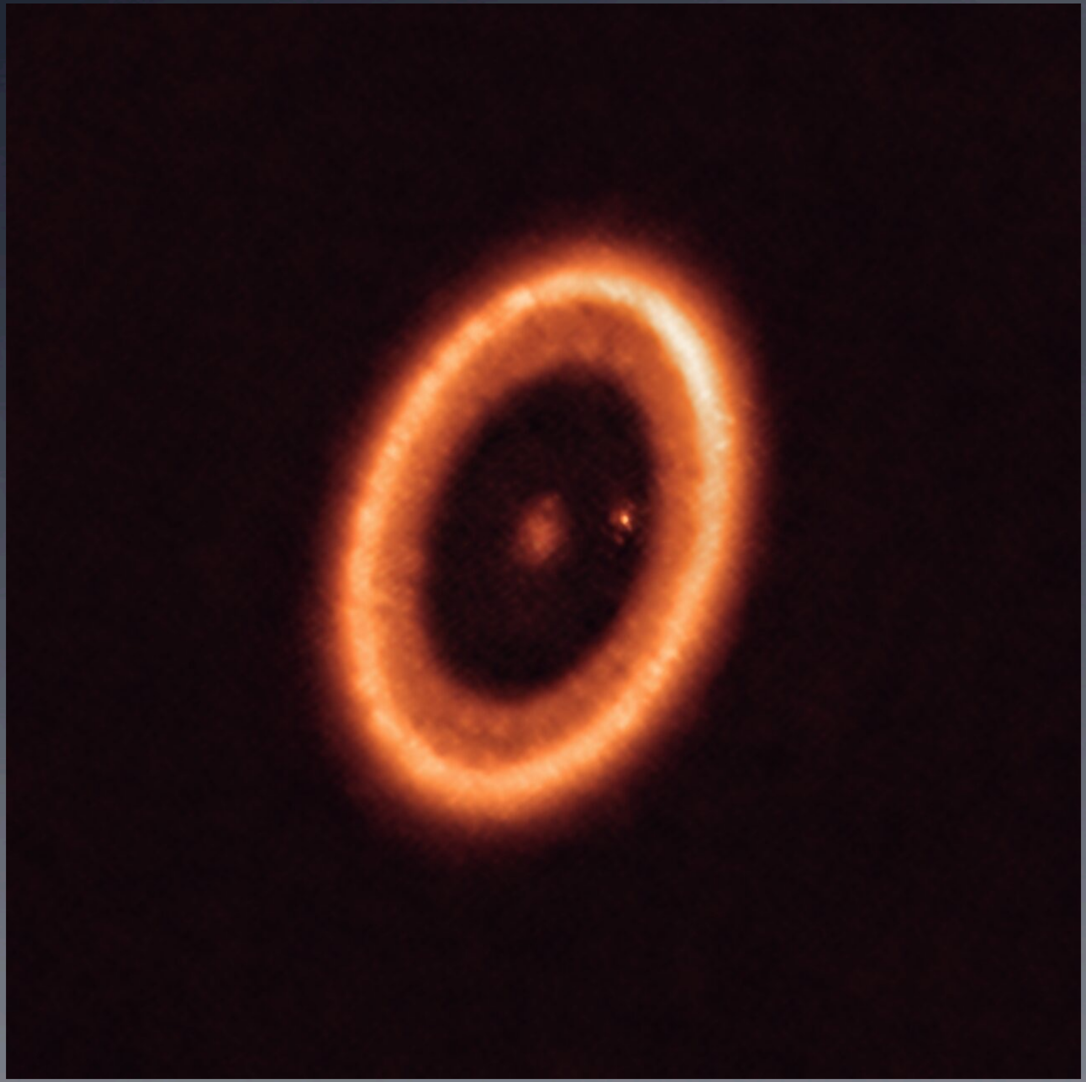
Direct imaging can detect light from young solar systems

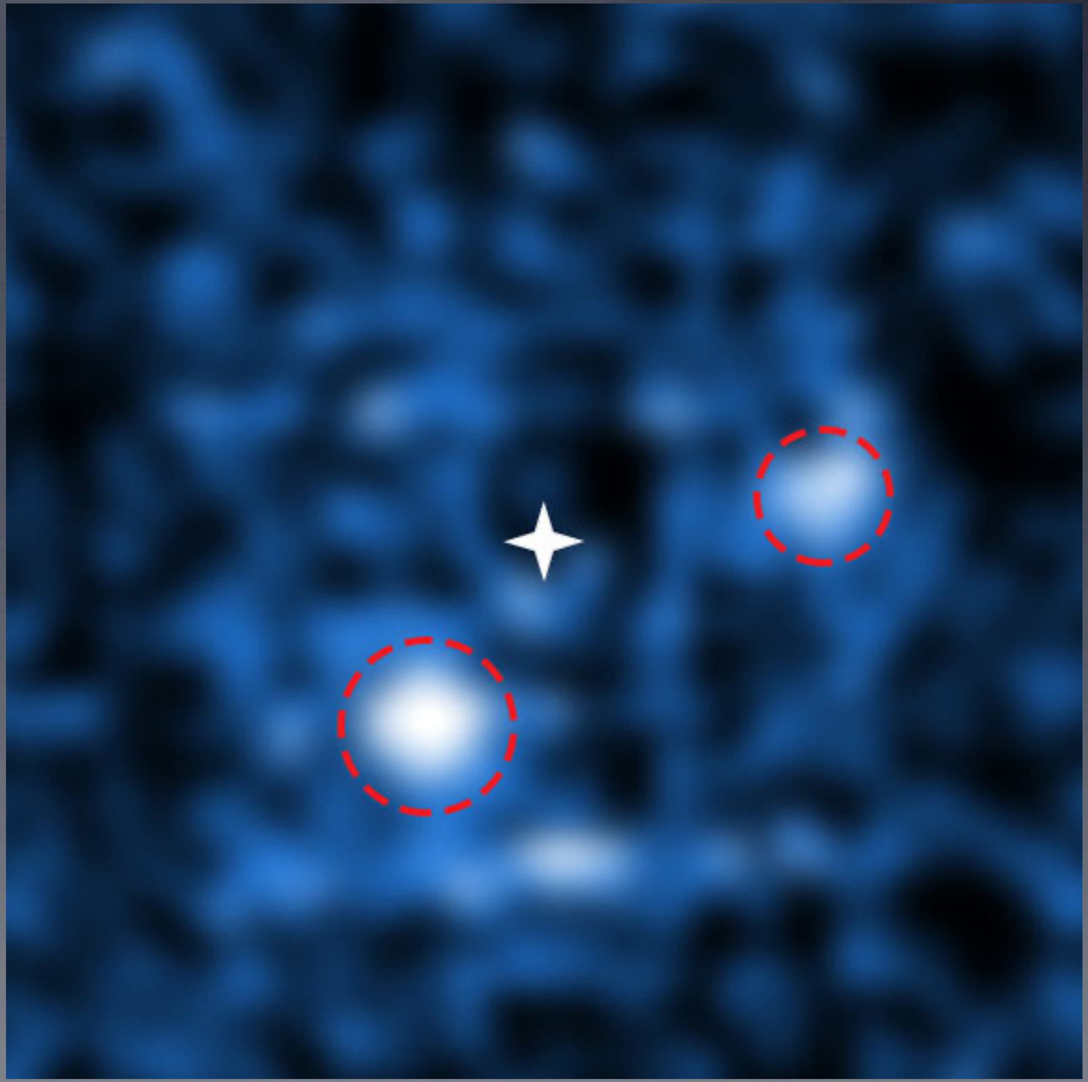
Prospects for direct imaging young solar systems!



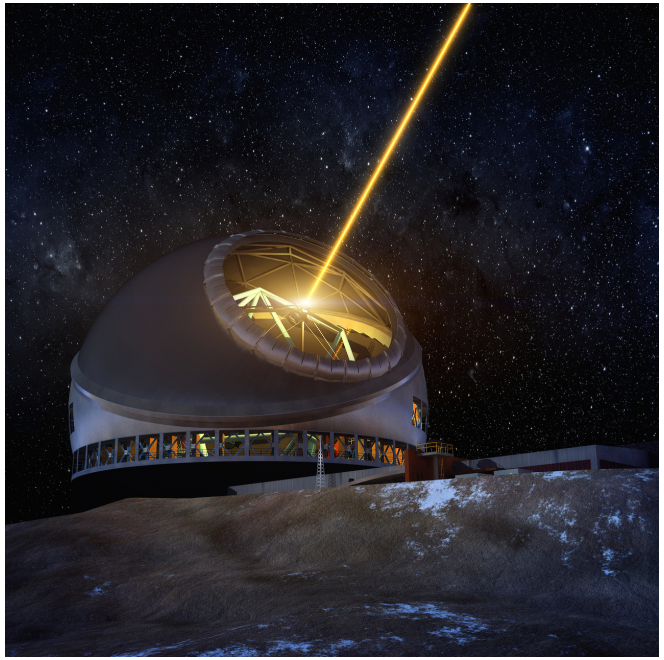


Proto-lunar disks in a planet-forming disk





What about in reflection?



Albedo (reflectivity): 0.3

Earth radius: 6.4e8 cm

Sun-Earth distance: 1.5e13 cm

Fraction of Sunlight reflected by Earth: about 2e-9

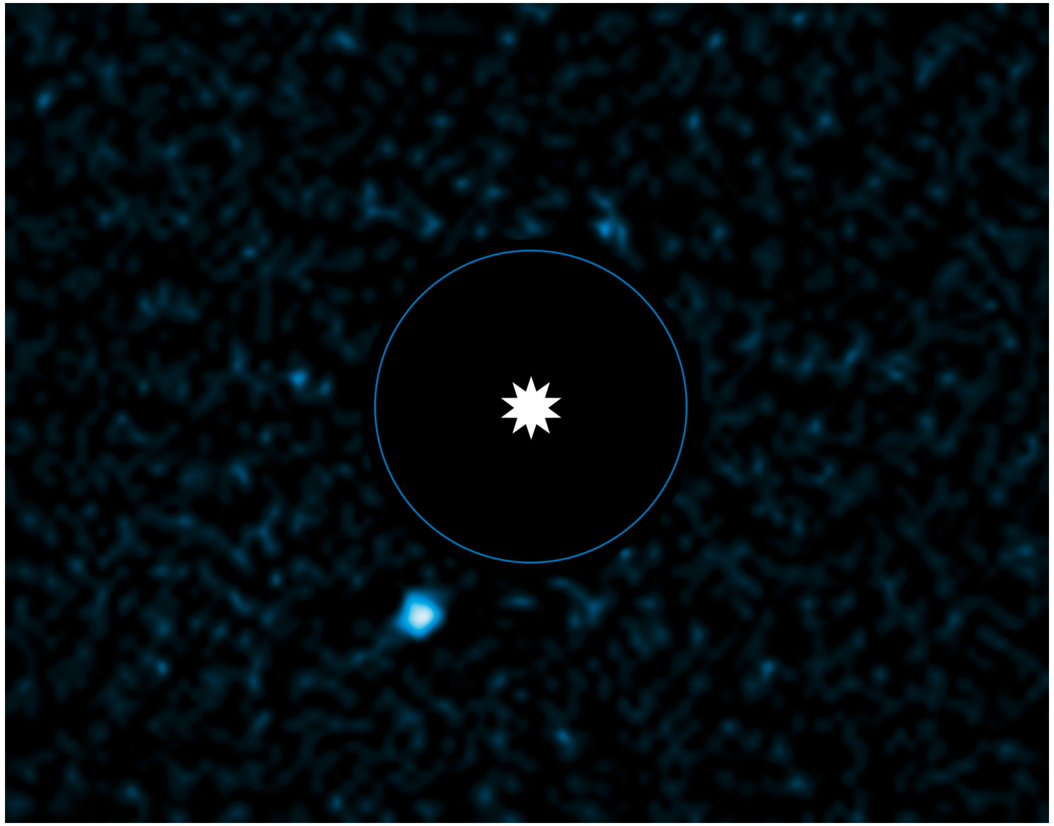
Best contrast at 0.7 arcsec (1 AU for nearest star): 5e-6

For next generation of telescopes

Biases of direct imaging

- Massive planets
- Large distance from their host star
- Young

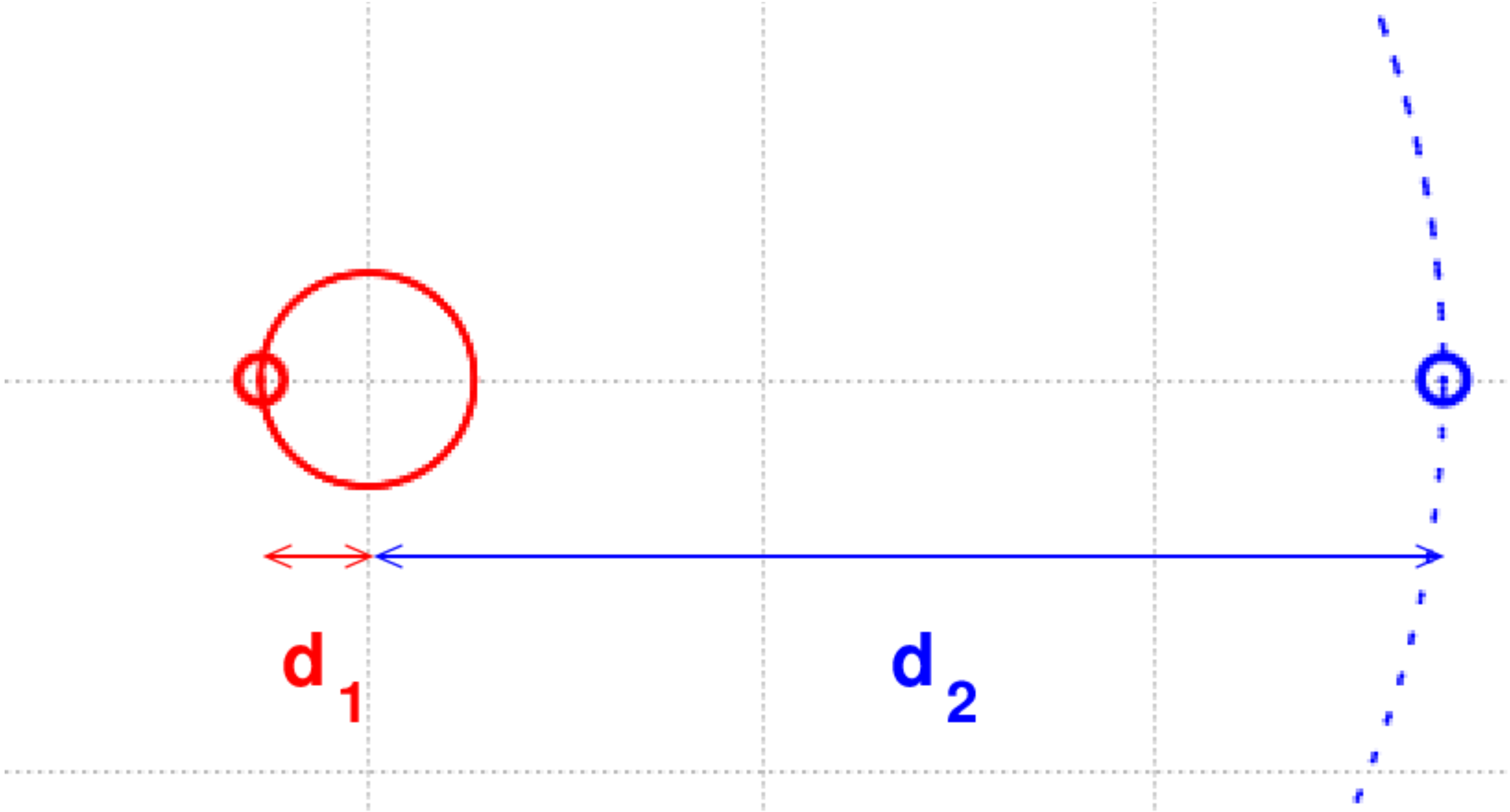
[this is very hard]



Astrometry

- Motion of star on plane of the sky
- d1/d2=m/M

Claim in 1963!



Astrometric Study of Barnard's Star. PETER VAN DE KAMP, *Sproul Observatory.*—A total of 2413 plates, taken with the Sproul 24-inch refractor, anging in epoch from 1916 to 1962 are available or analysis. About three-fourths of the material vas measured twice.

An intercomparison of the 12 measurers and their imes of measurements revealed a reasonable contancy of the Gaertner measuring machine over two lecades and a generally satisfactory small degree of personal equation.

All measurements were corrected for the latest values of parallax, proper motion, acceleration, and known color and magnitude effects. The yearly nean residuals, of average weight 64 (96 plates) learly exhibit a long-period systematic run, mainly n right ascension, but also in declination, which admits of no simpler explanation than that of a perturbation, caused by an unseen companion of Barnard's star.

Astrometry

Earth detection

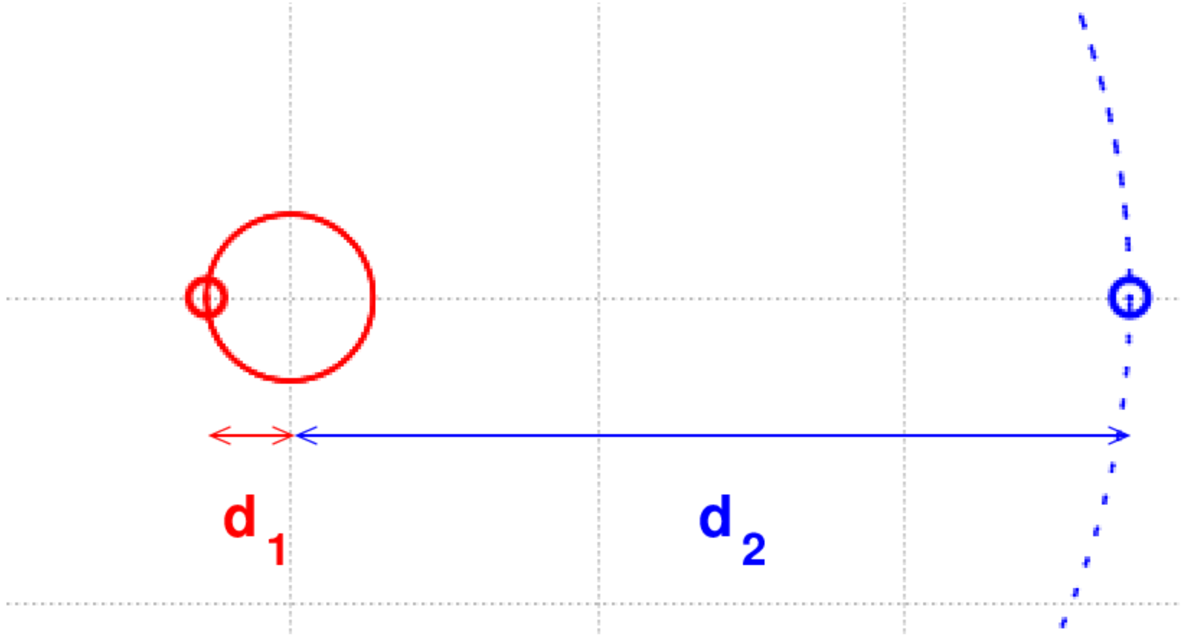
- d1/d2=m/M
- d2=1.5e13 cm = 1 AU
- m/M=d1=3e-6 AU

at 10 parsecs: 0.3 microarcseconds

Jupiter detection

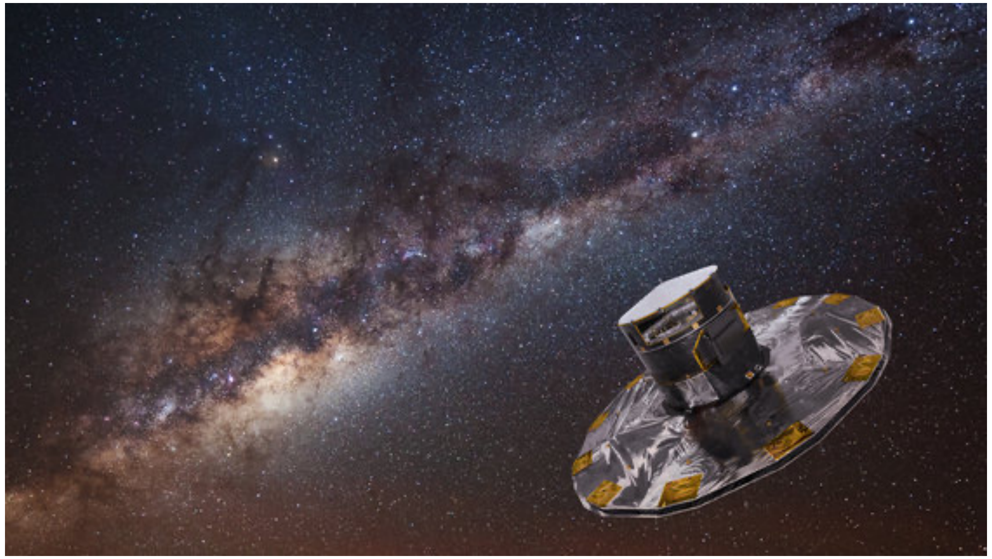
- d1/d2=m/M
- d2 = 5 AU
- m/M=1e-3 => 5e-3 AU

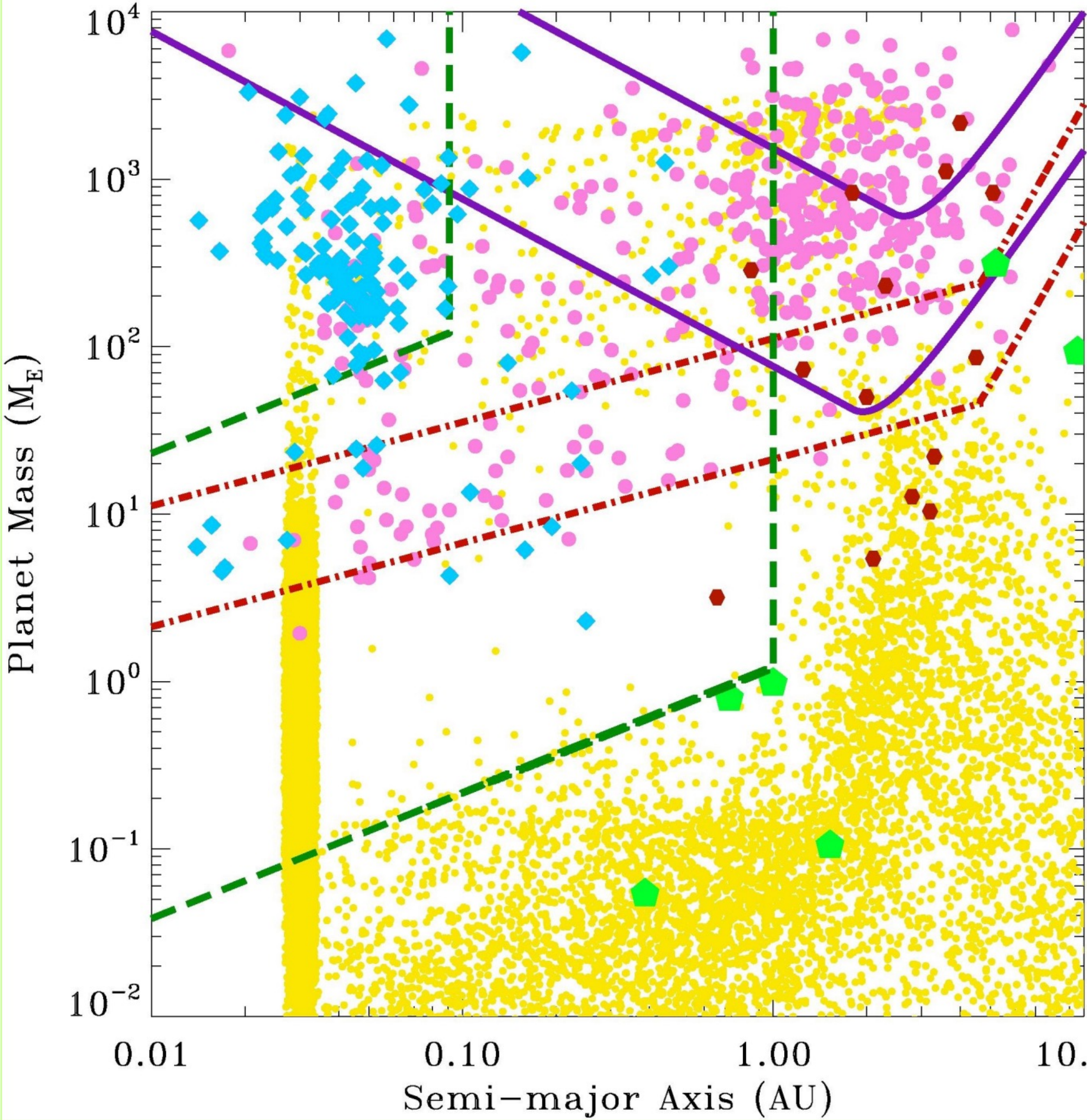
at 10 parsecs: 500 microarcseconds

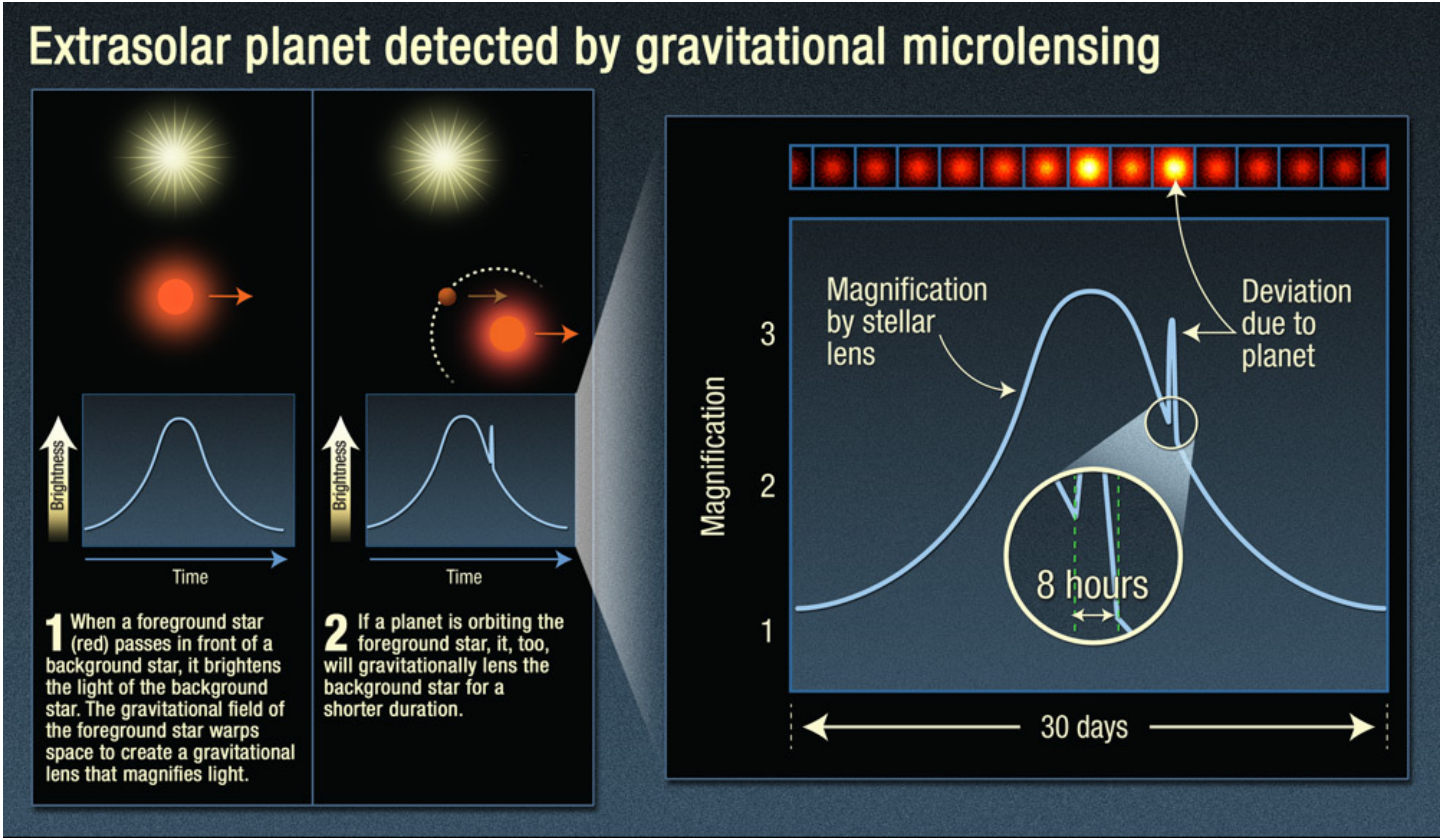


Gaia: an astrometry space mission

- Measure star centroids to 24 microarcseconds
  - Sun-Jupiter at 10 AU: 500 microarcseconds
  - Size of human hair at 1000 km!
  - Expect results in ~2-3 years

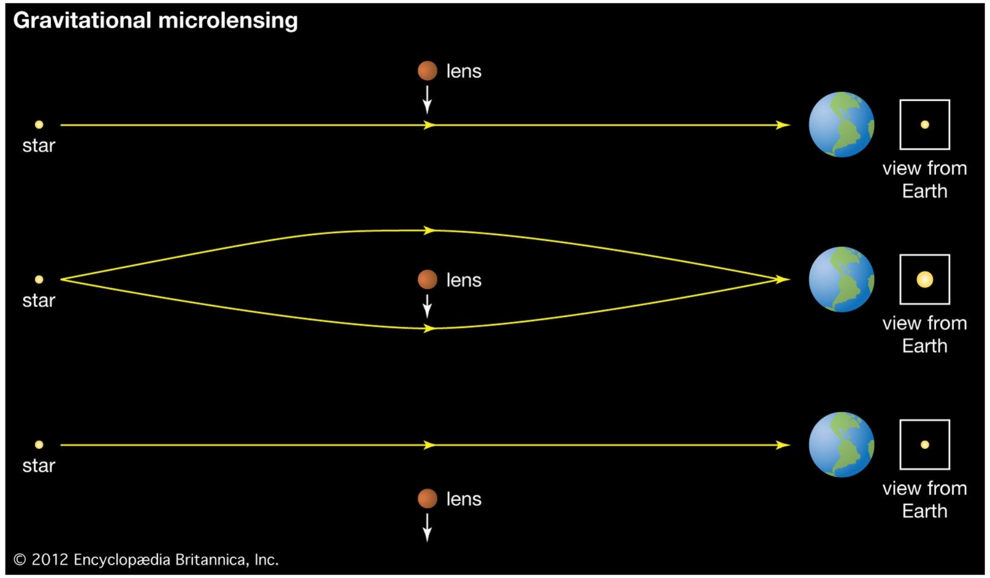


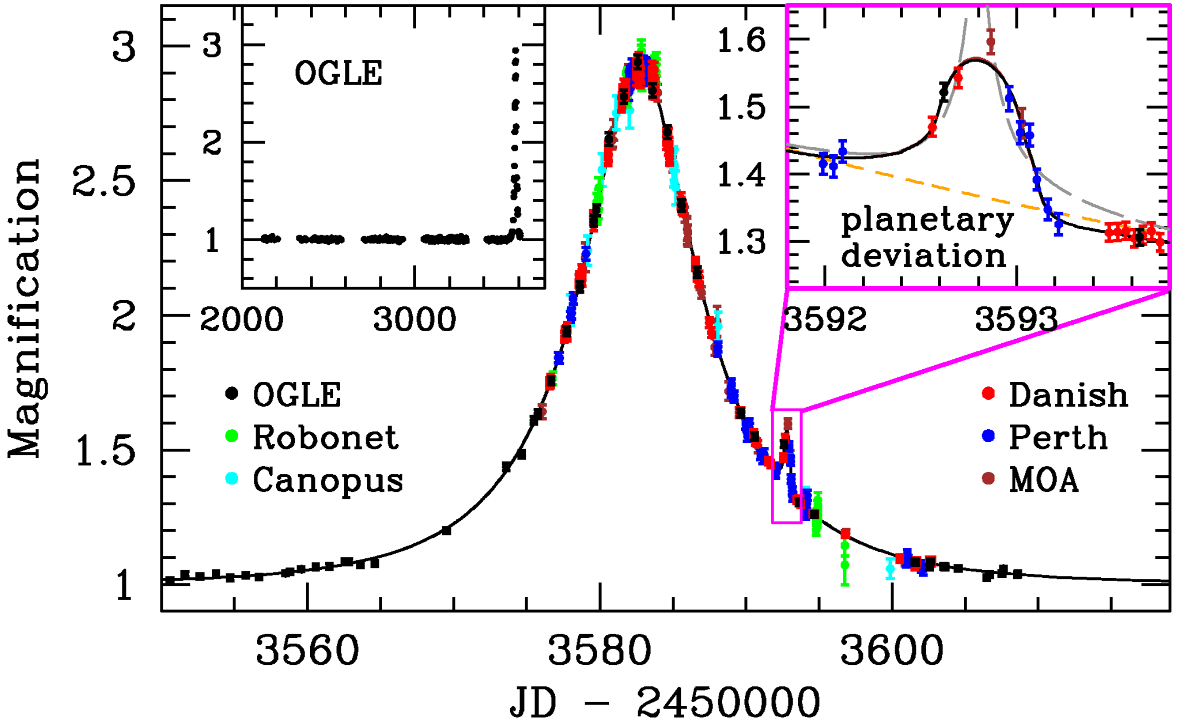




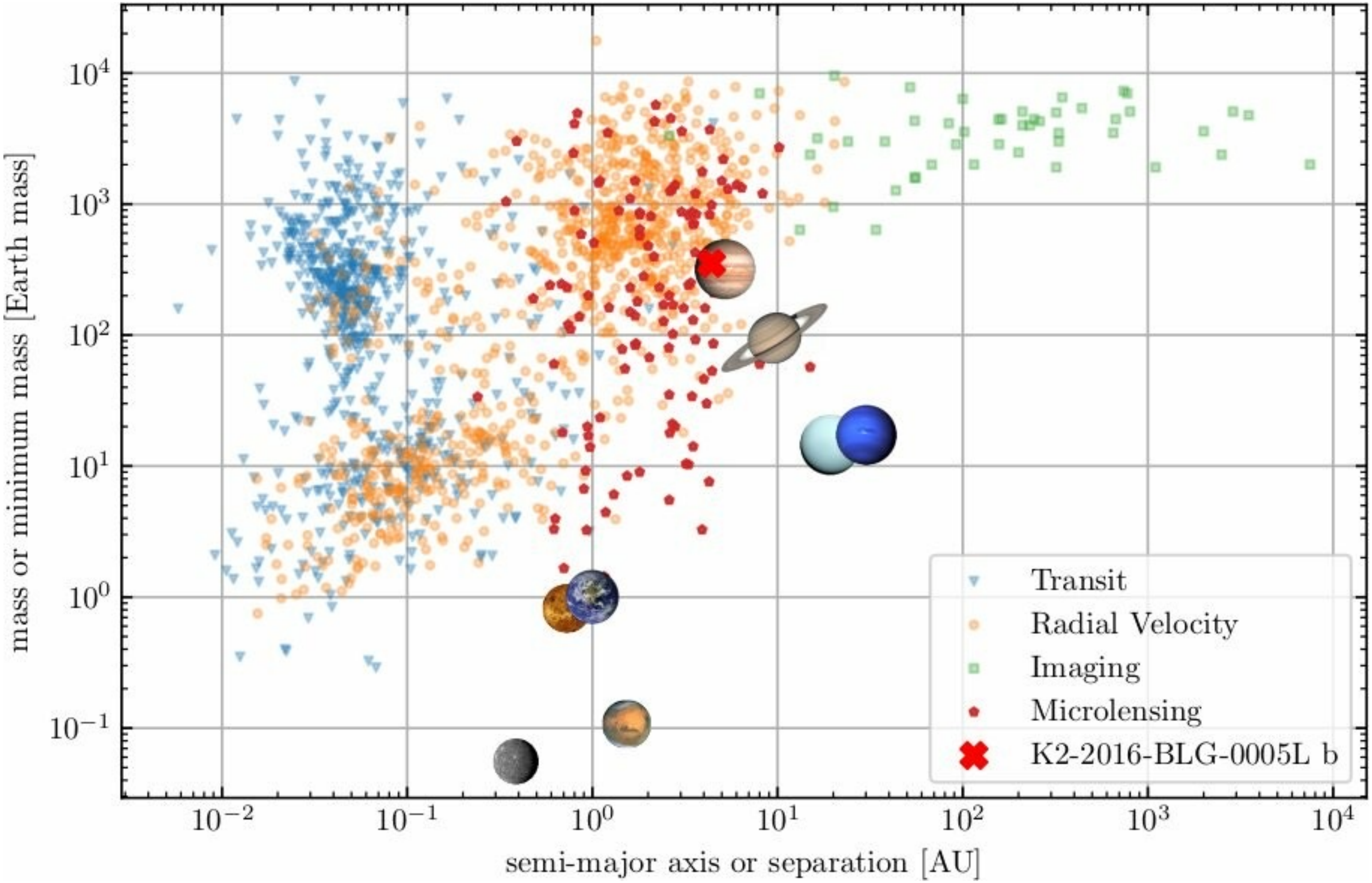
Extrasolar planet detected by gravitational microlensing
Brightness
Time
1 When a foreground star (red) passes in front of a background star, it brightens the light of the background star. The gravitational field of the foreground star warps space to create a gravitational lens that magnifies light.
Brightness
Time
2 If a planet is orbiting the foreground star, it, too, will gravitationally lens the background star for a shorter duration.
Magnification
3
2
1
Magnification by stellar lens
Deviation due to planet
8 hours
30 days

Microlensing discoveries of exoplanets

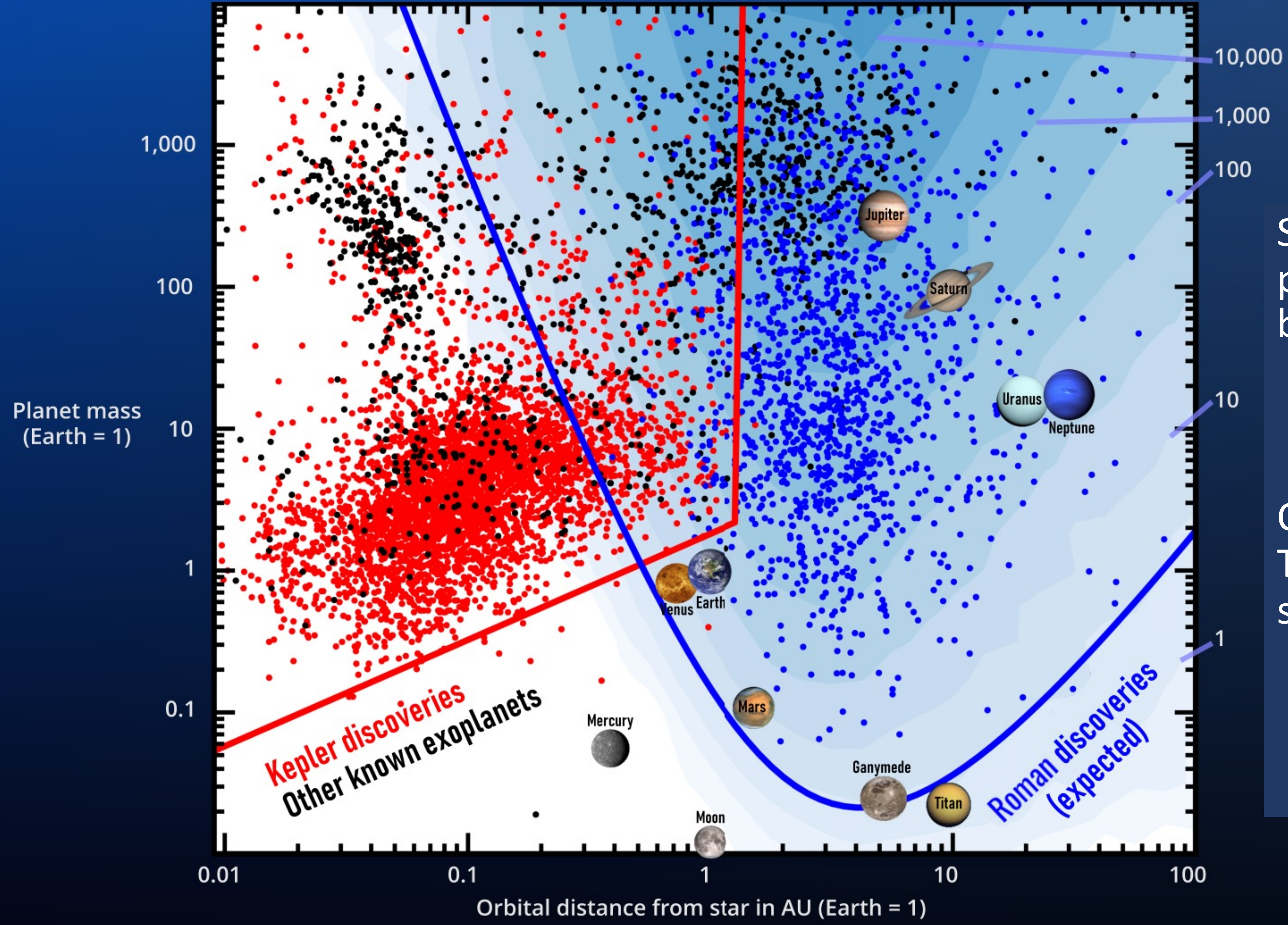




- Unusual geometry – need a lot of stars (stare at galactic center)
- Planet mass: equivalent to duration of deviation
- Limited follow-up
- Only current technique to measure frequency of true Earth analogs



mass or minimum mass [Earth mass]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
semi-major axis or separation [AU]
Transit
Radial Velocity
Imaging
Microlensing
K2-2016-BLG-0005L b



Shown: expected planets to be detected by NASA/Roman

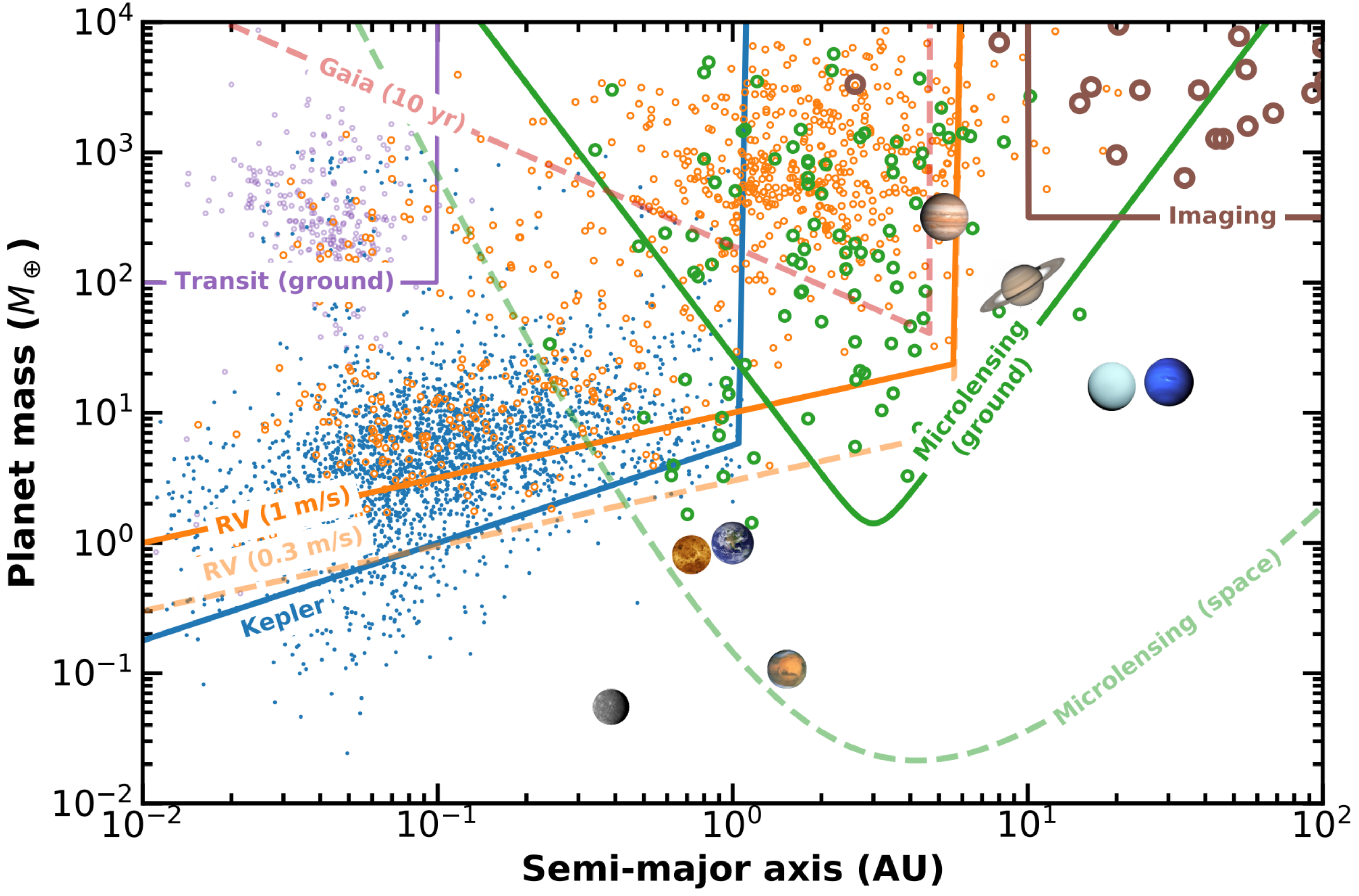
launch in ~5 yr

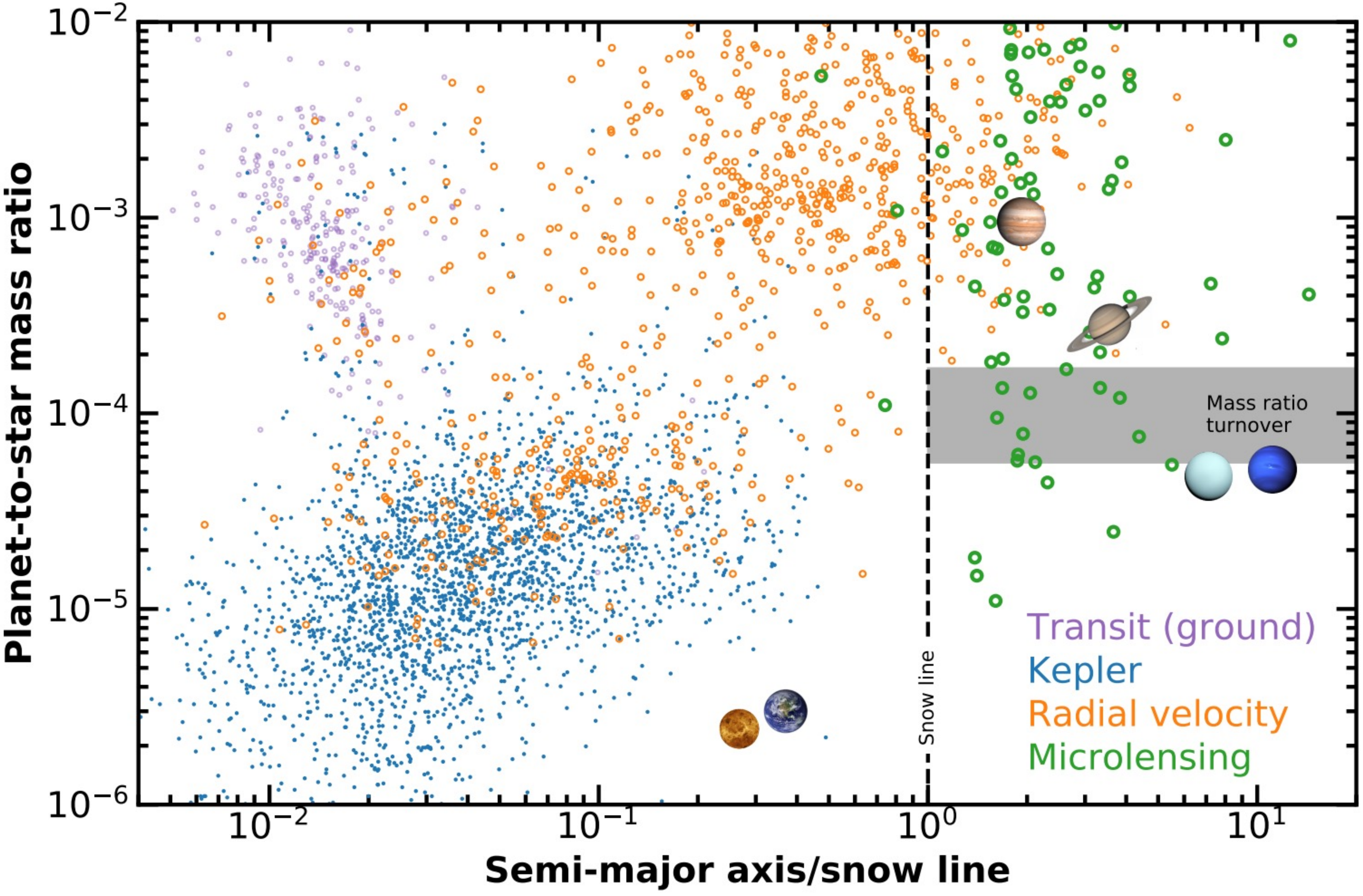
Chinese Space Station Telescope may yield similar results

Primary detection methods

- Radial Velocity
- Transit spectroscopy
- Direct Imaging
- (astrometry: 2-3 years away)
- Microlensing (statistics only)

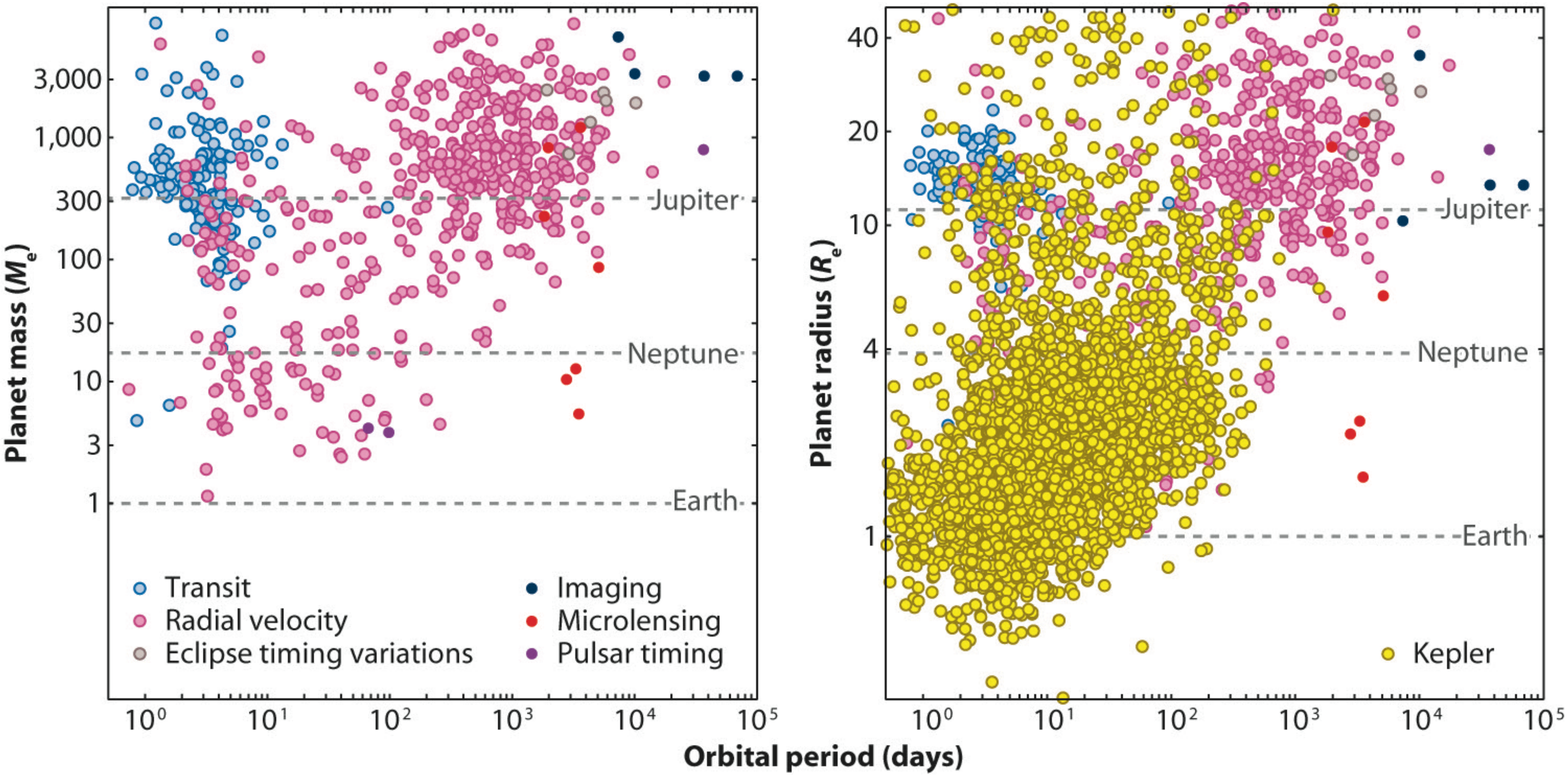
Can combine methods to make them even more powerful!

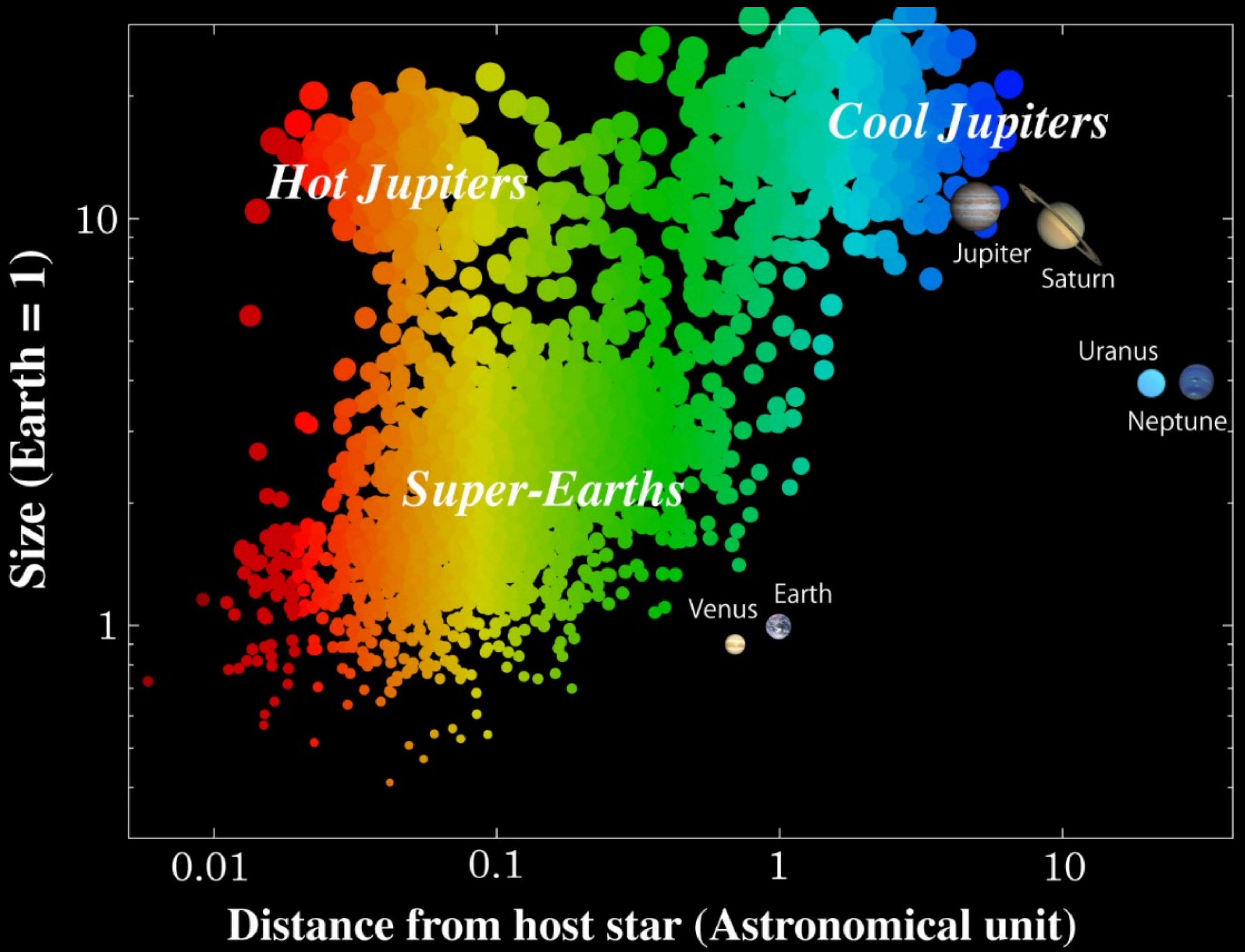

Gaia (10 yr)
Transit (ground)
Imaging
RV (1 m/s)
RV (0.3 m/s)
Kepler
Microlensing (ground)
Microlensing (space)
Planet mass ($M_\oplus$)
Semi-major axis (AU)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^0
10^1
10^2

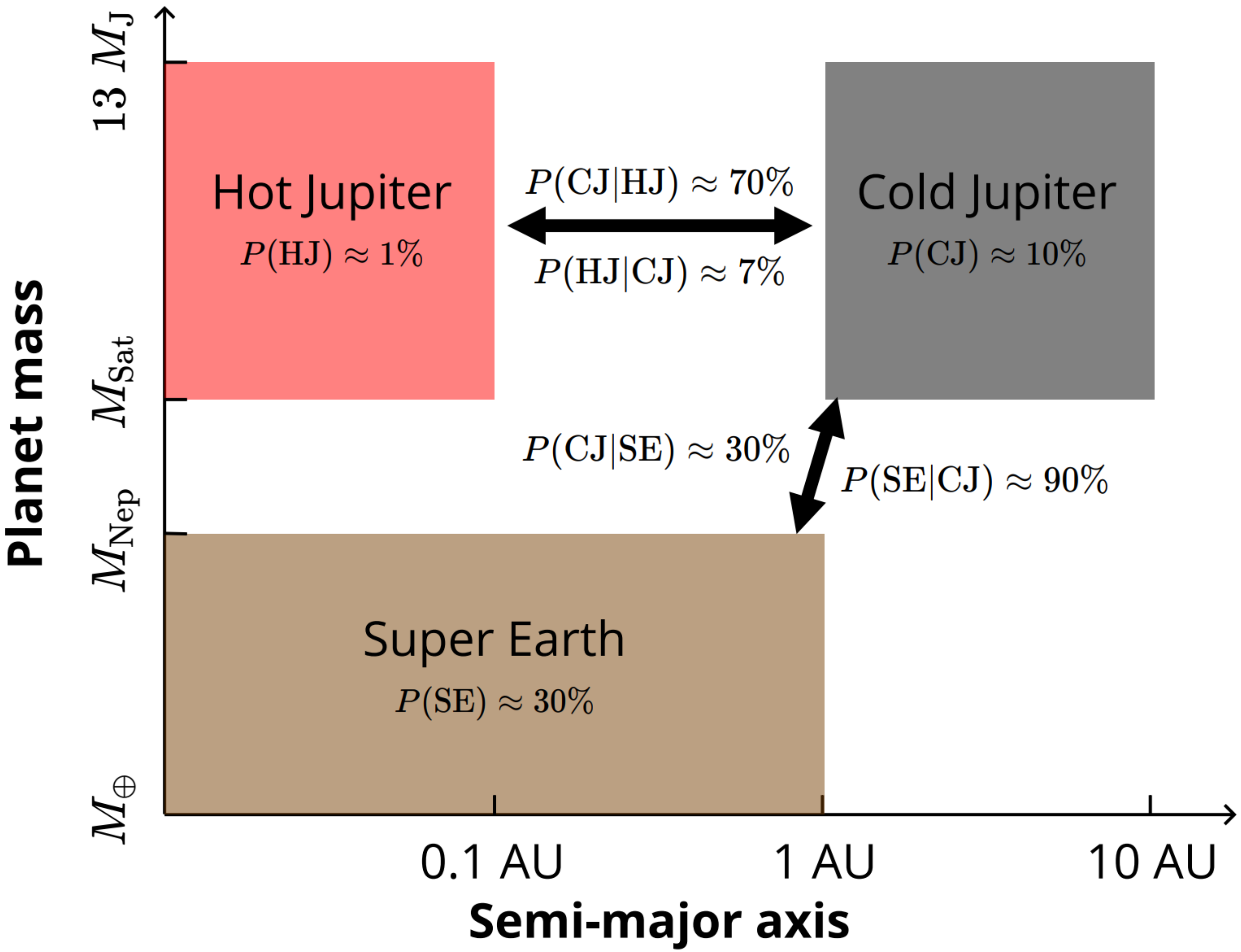


Planet-to-star mass ratio
Semi-major axis/snow line
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
Snow line
Mass ratio turnover
Transit (ground)
Kepler
Radial velocity
Microlensing

Exoplanets are common!

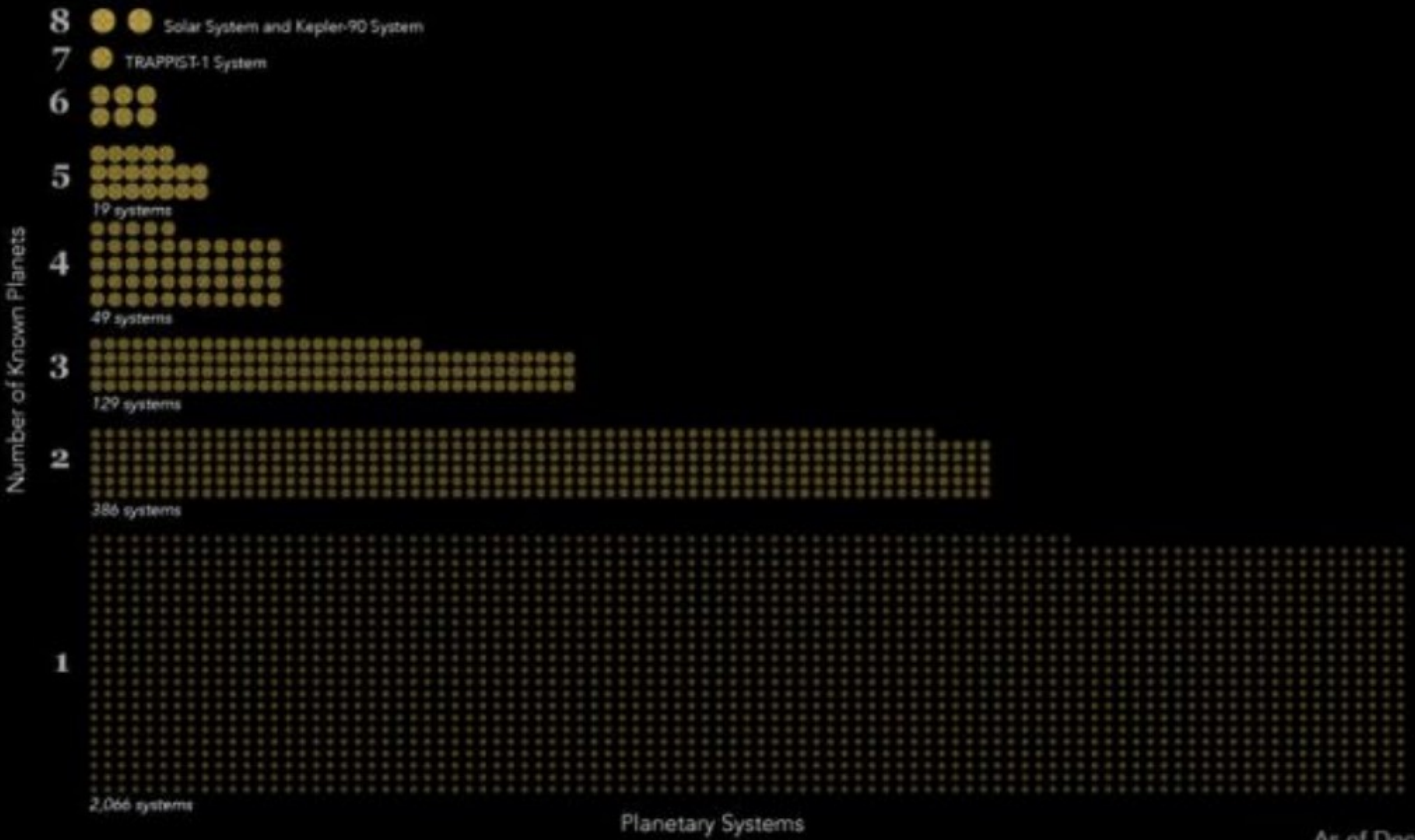



Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
Size (Earth = 1)
10
1
0.01
0.1
1
10
Distance from host star (Astronomical unit)

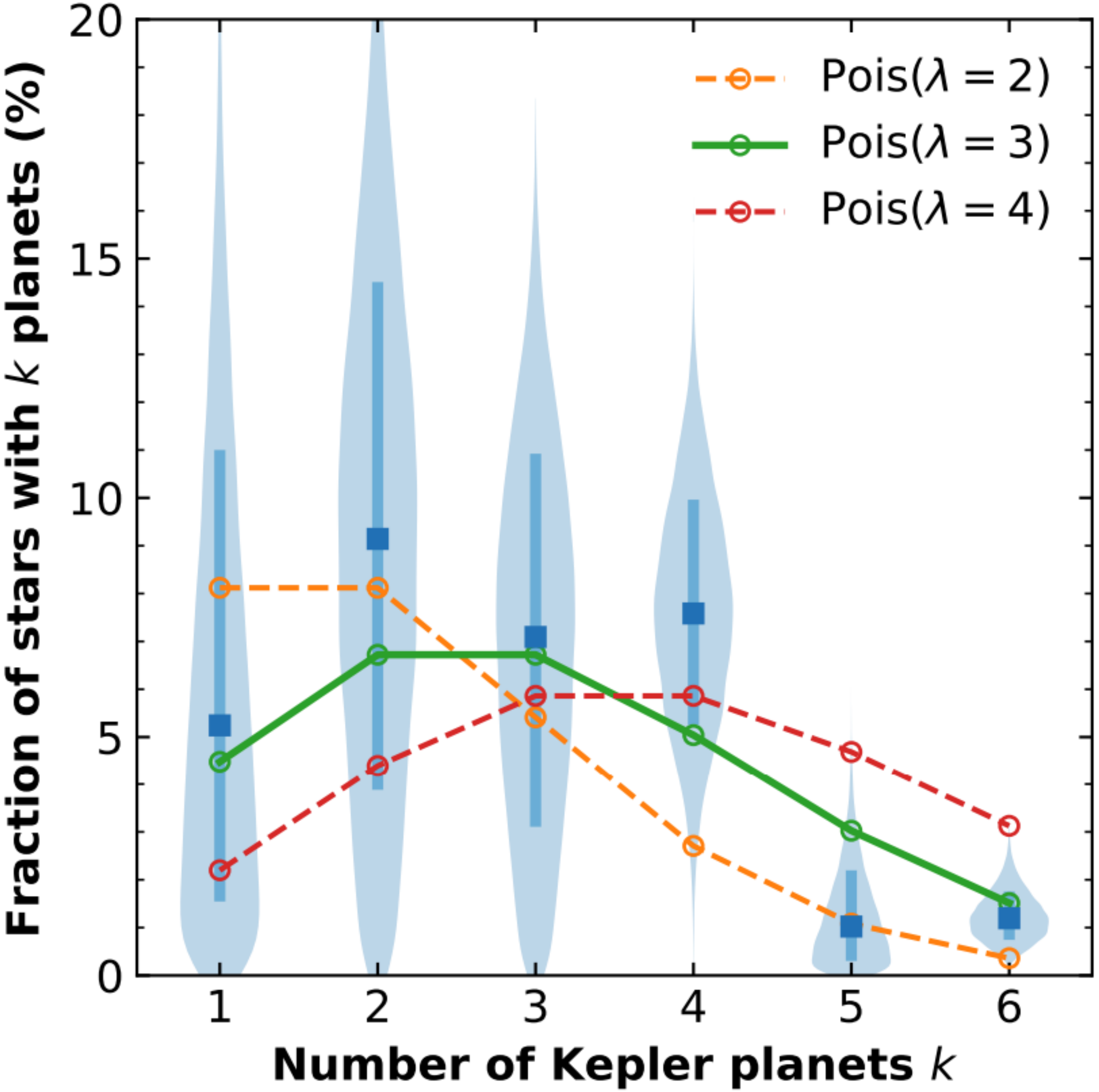


- Most common systems have Super-Earths
- Cold Jupiters (like solar system): not too unusual
- Hot Jupiters: rare but easy to detect

Planetary Systems by Number of Known Planets

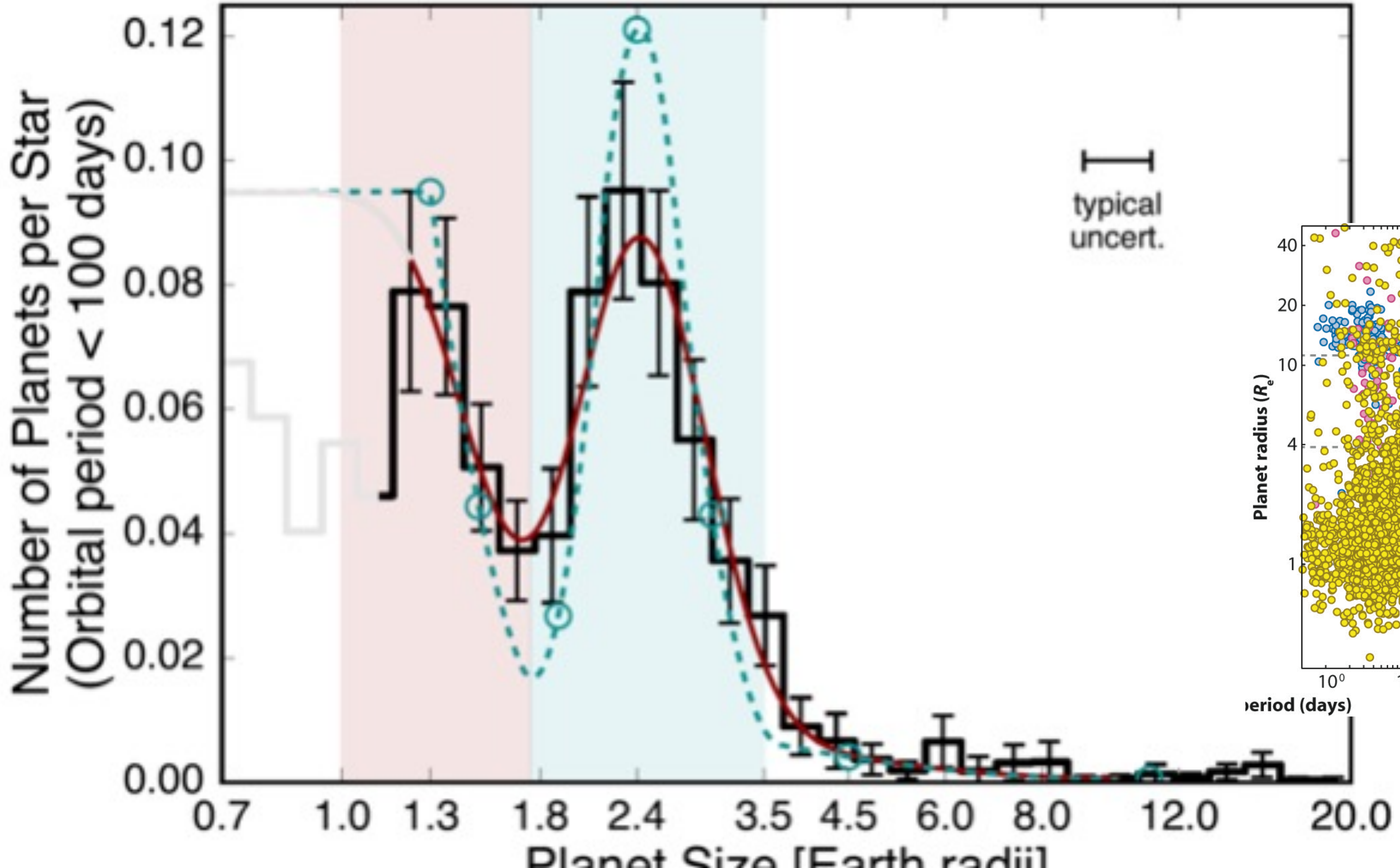


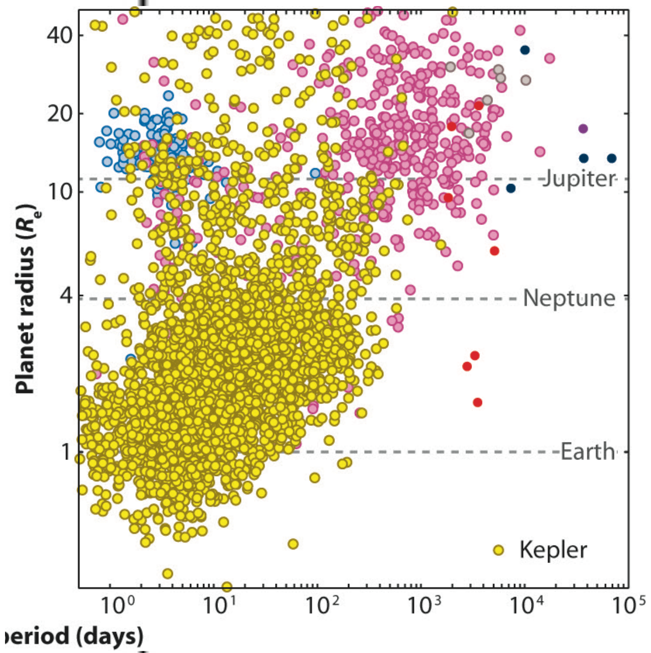
As of December 14, 2017



Fraction of stars with k planets (%)
Number of Kepler planets k
Pois(λ = 2)
Pois(λ = 3)
Pois(λ = 4)
0
5
10
15
20
1
2
3
4
5
6

Gap in planet distribution (Fulton Gap)

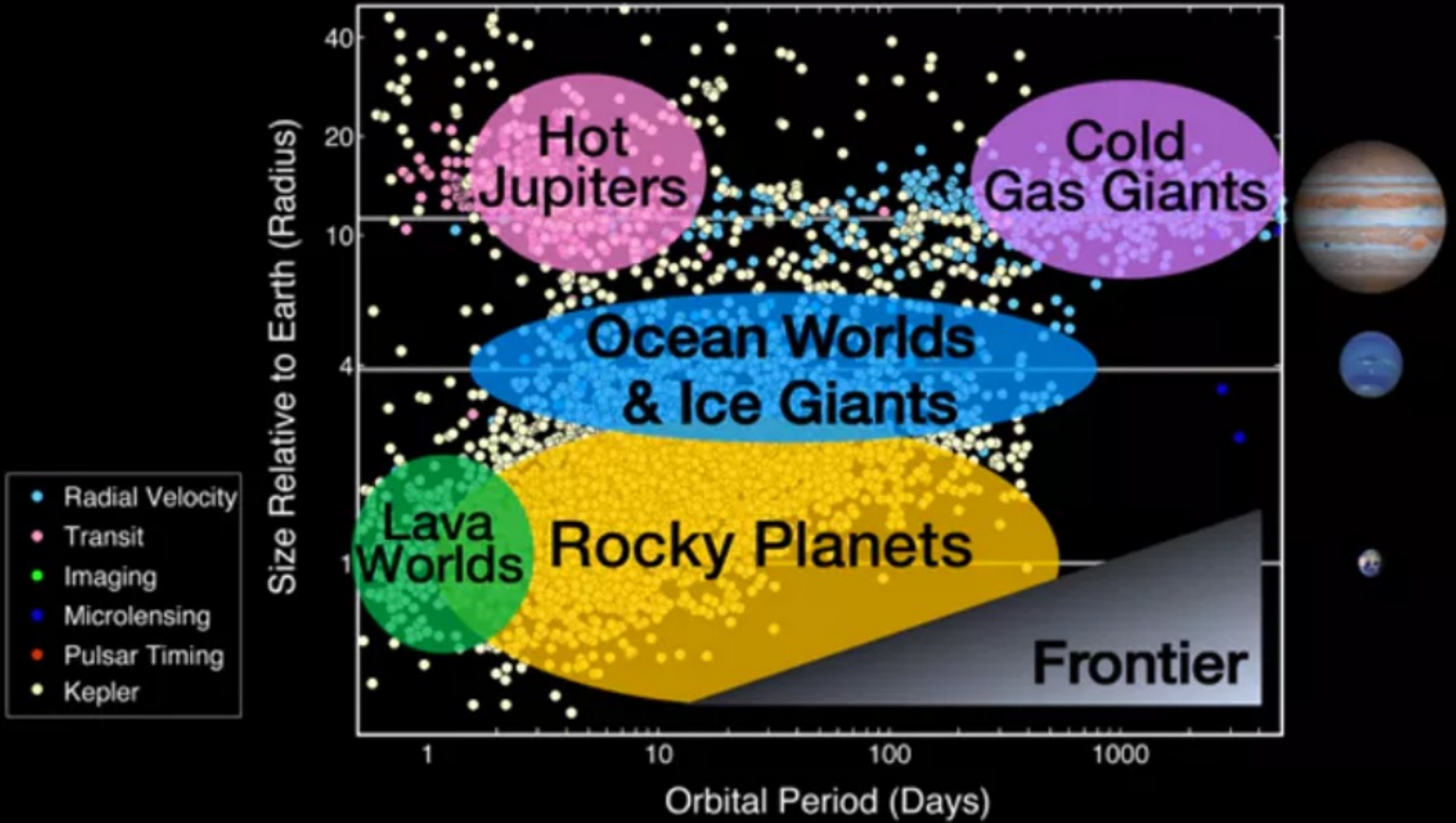




Some exoplanet extremes

- Closest: Prox Cen b (closest star!)
- Least massive: PSR B1257+12b (0.00067 M_earth)
- Hottest: KELT 9b, 4050 K
- Shortest period: SWIFT J1756.9-2508, 49 minutes!
- Smallest orbit: WD 1202-014, 0.0021 AU
- Most eccentric: HD 20782, 0.956
- Kepler 47AB and Kepler 16AB: examples of around binariespplaners
- Lowest metallicity: K2-344b, 10 times less than solar system

Exoplanet Populations



Exoplanet Populations

Next class: exoplanet characterization and atmospheres