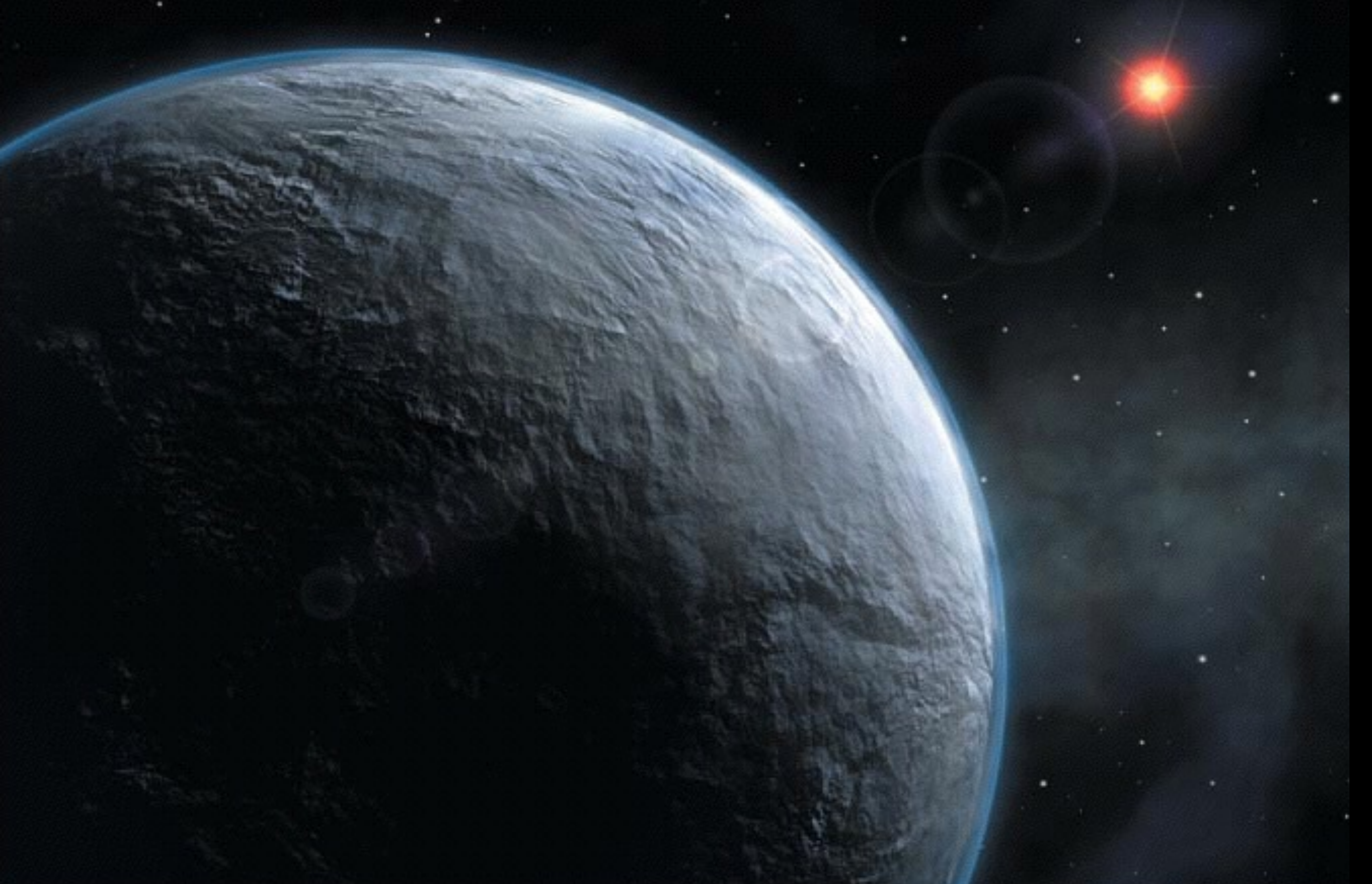
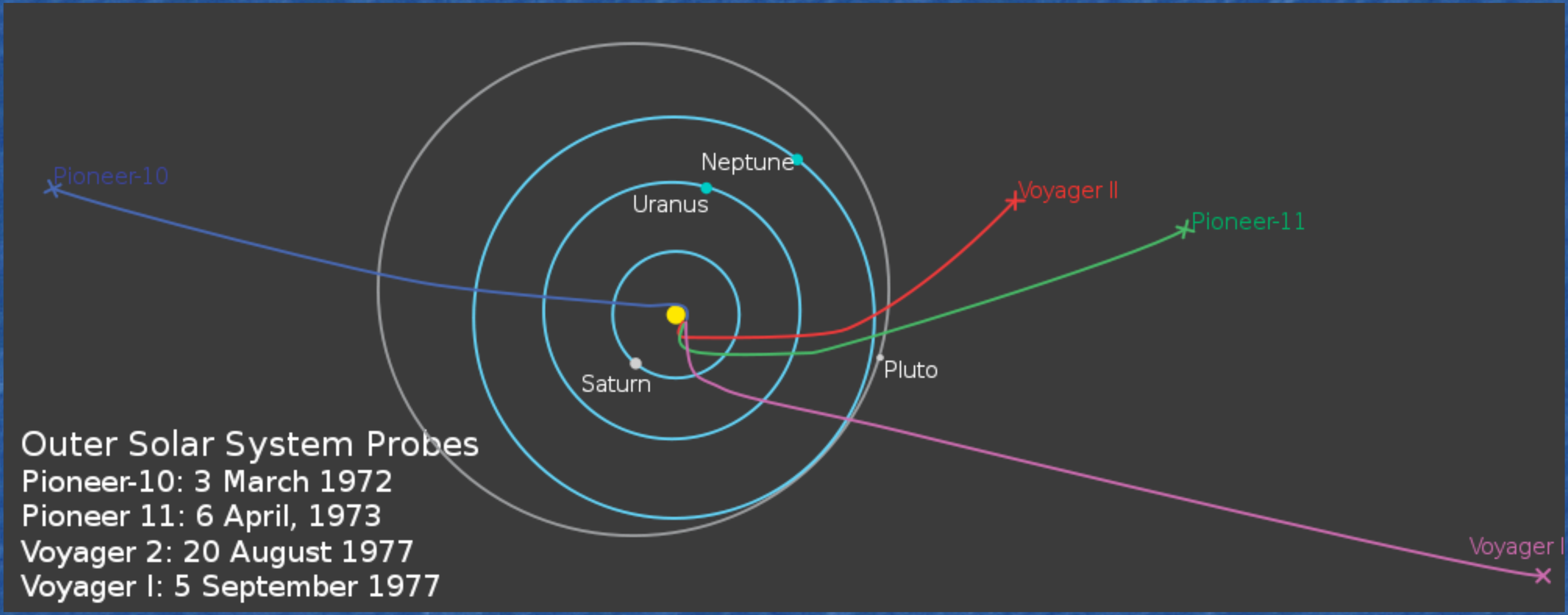
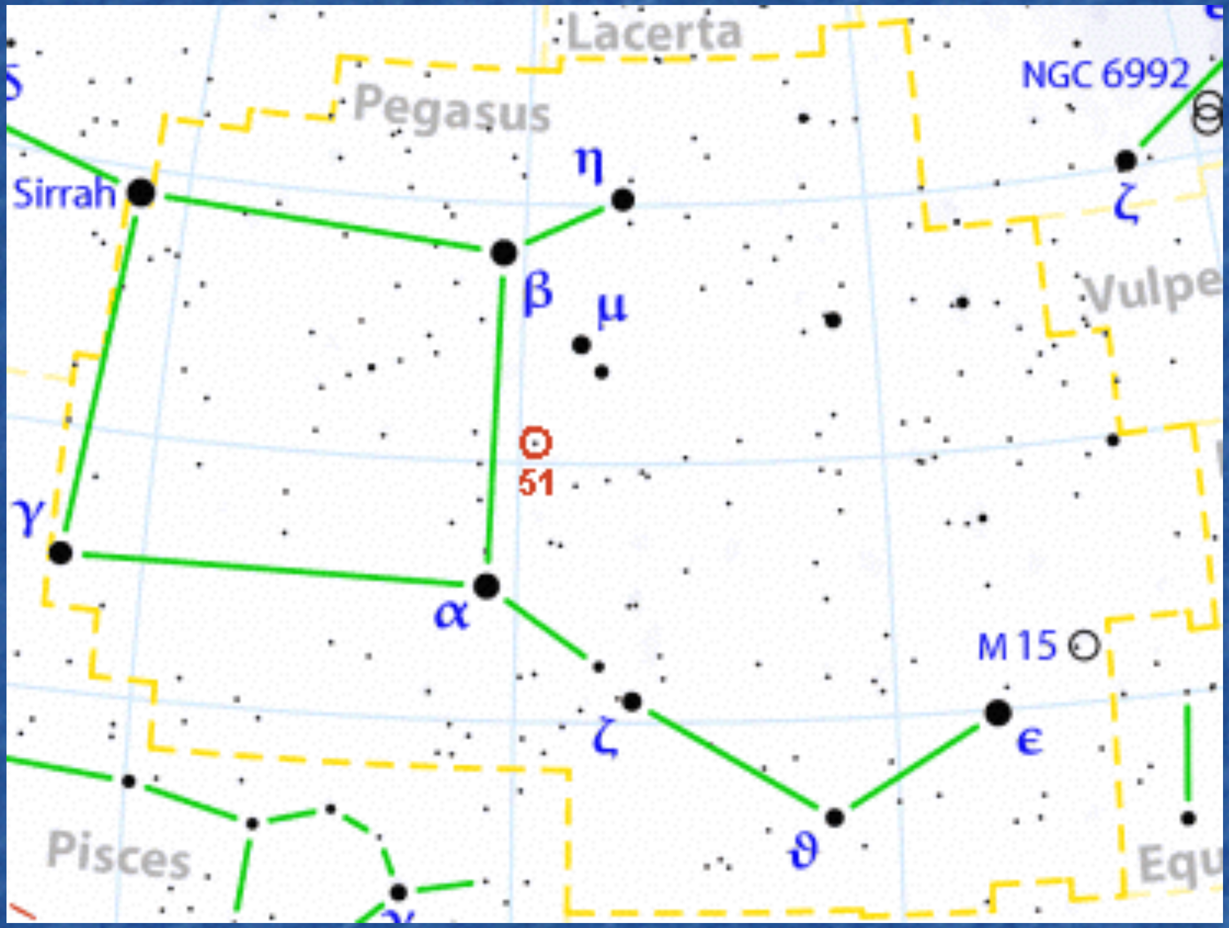
Life on extra-solar planets



Leaving the solar system

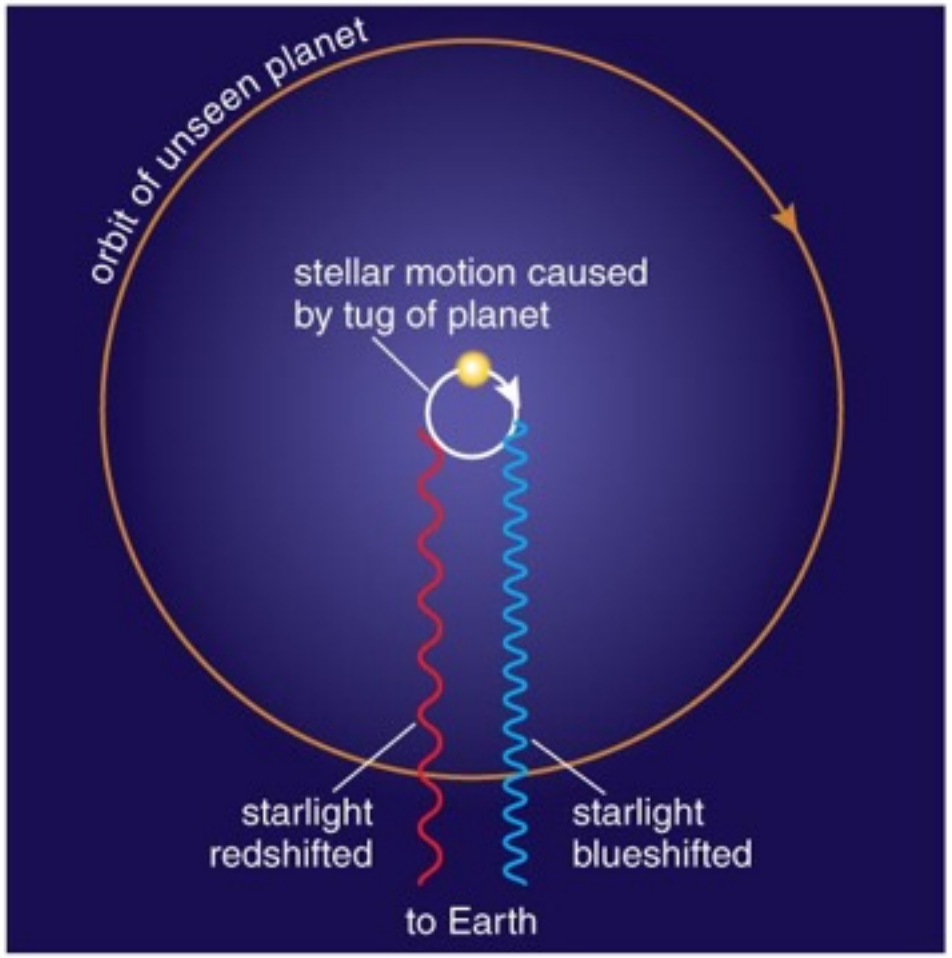


1995: 51 Pegasi

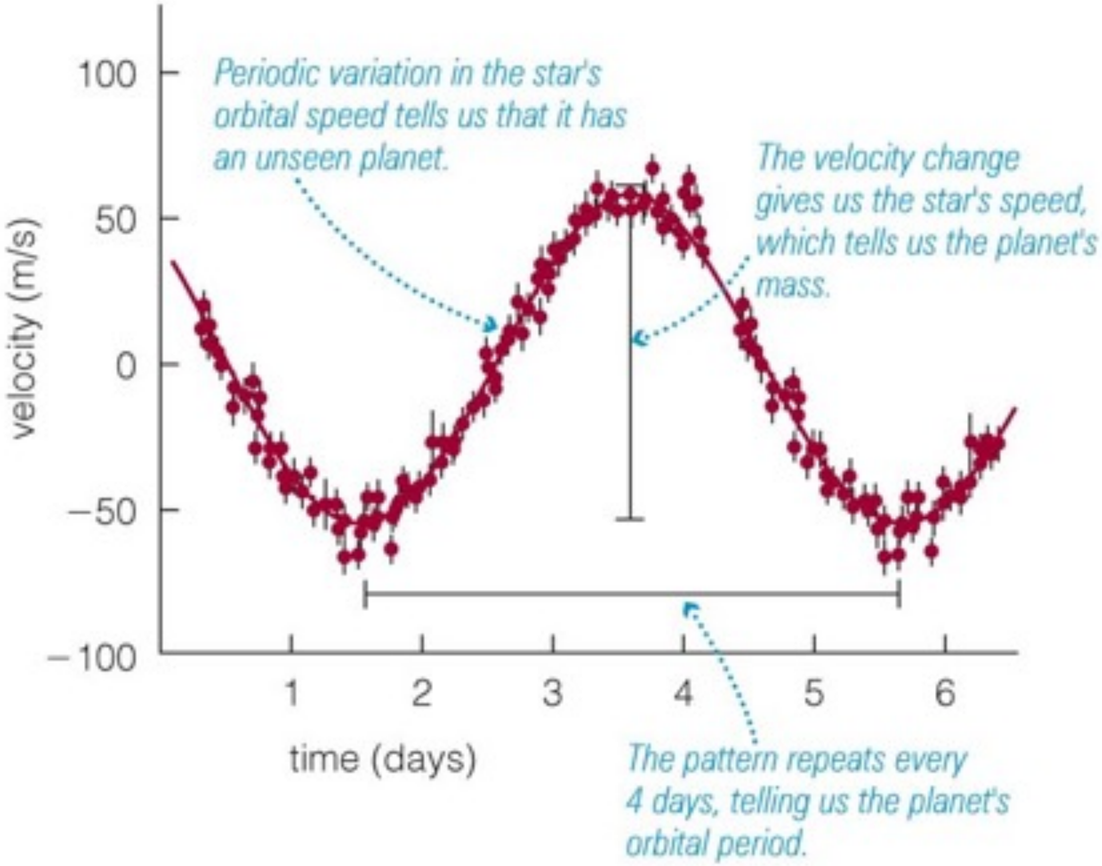


- 50 Ly from Earth
- V = 5.5
- Spectral class G2
- Sun-like star

1995: 51 Pegasi



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

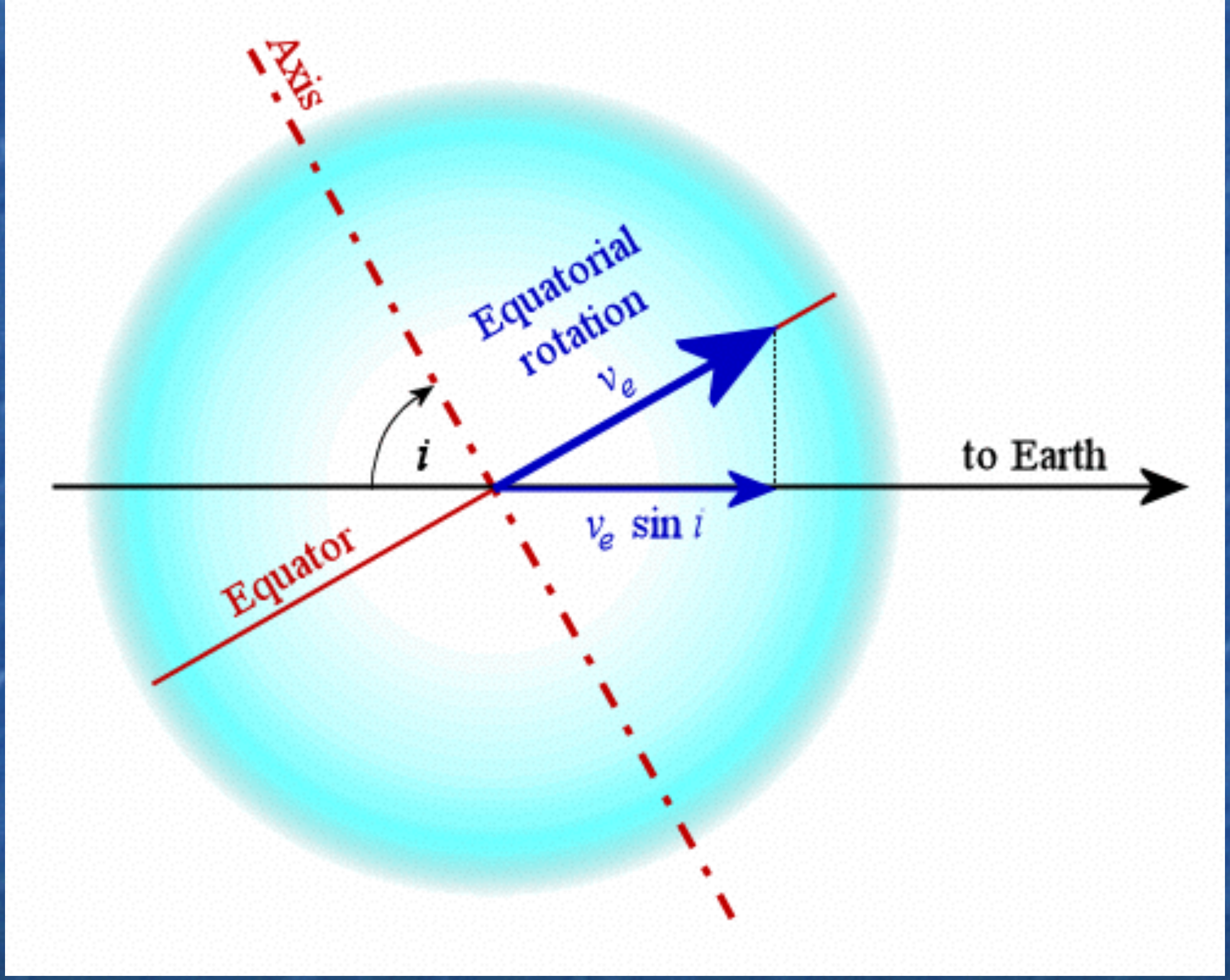
Unseen planets around stars

- cause a Doppler wobble in the stars motion which
- results in a periodic variation in the parent star's line of sight velocity.
- This causes the characteristic spectral absorption lines present in the star to shift their position in time with the velocity variation.
- Careful analysis of the star's spectrum then reveals the velocity shift.
- Which reveals the unseen planet.

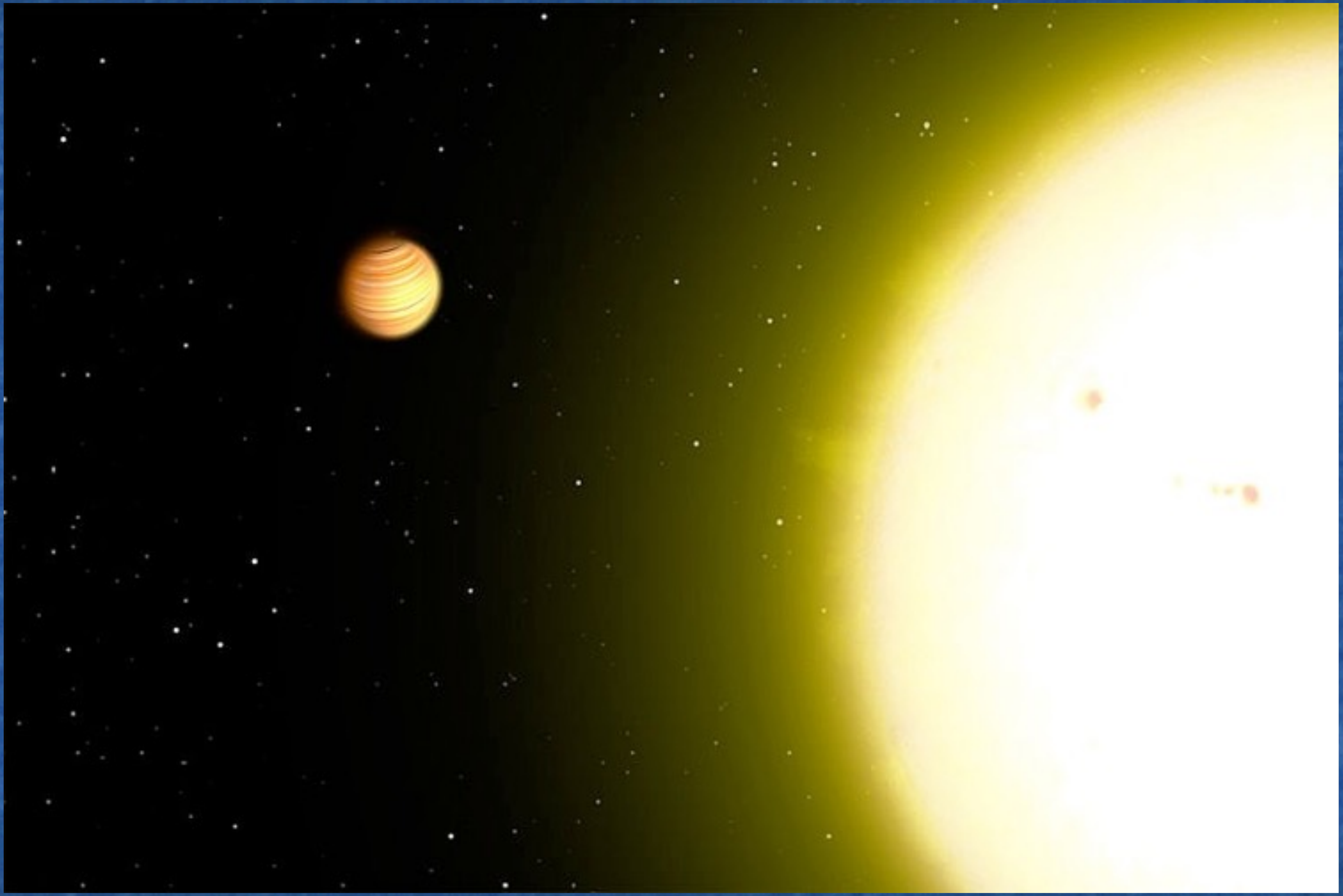
51 Pegasi b: a "hot Jupiter"

- 51 Peg b is a Jupiter sized planet orbiting some 0.05 AU from its parent, Sun-like star every 4 days.
- How do we know this information?
- The period of the velocity curve is the same as the orbital period.
- The amplitude of the velocity curve is equal to the max/min velocity "wobble" of the star.
- We can compute an accurate mass for the parent star from its spectral type (colour + spectrum): G2-G4.
- Given the star mass and velocity and the orbital period of the planet, we can calculate the planet mass.

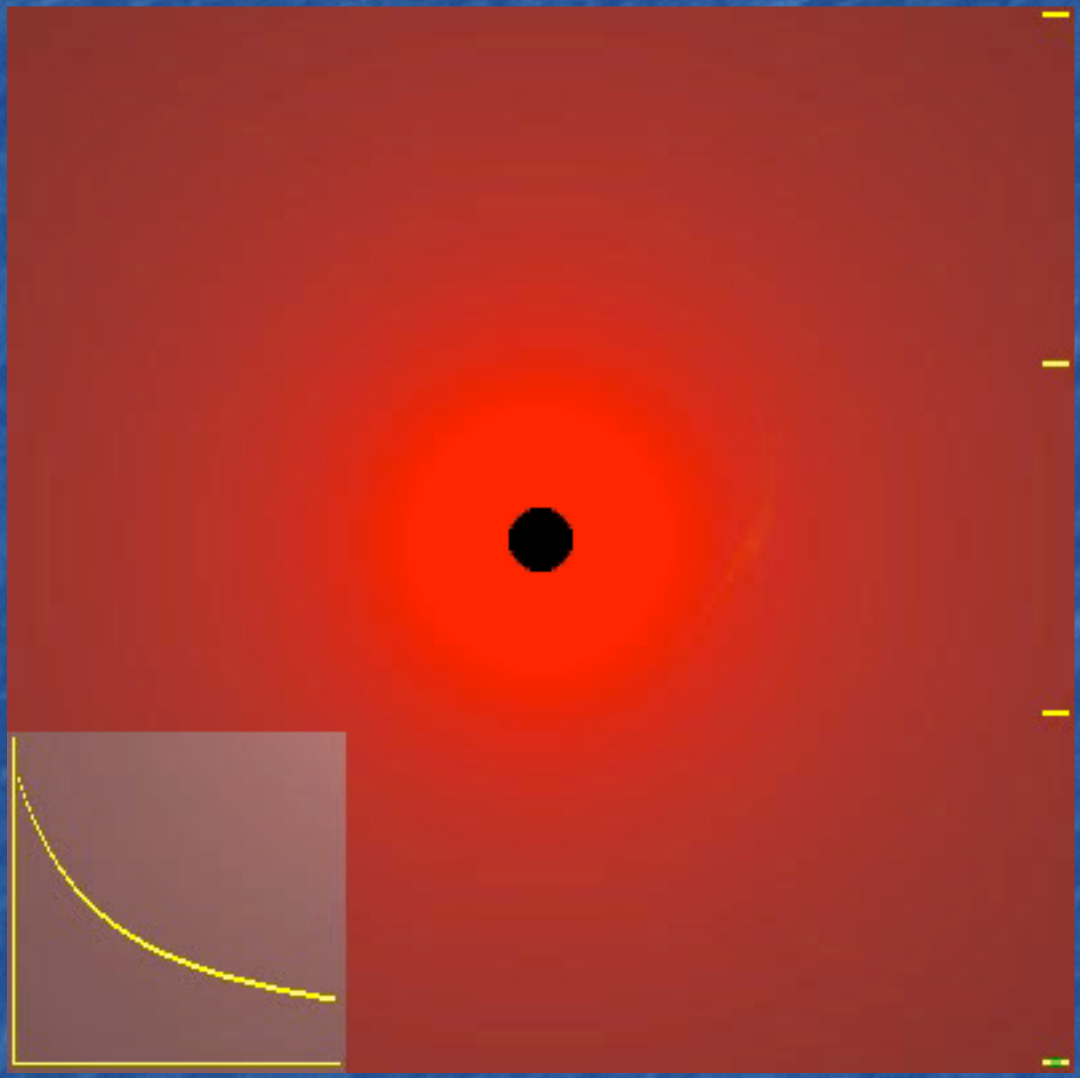
Masses from the Doppler technique are lower limits

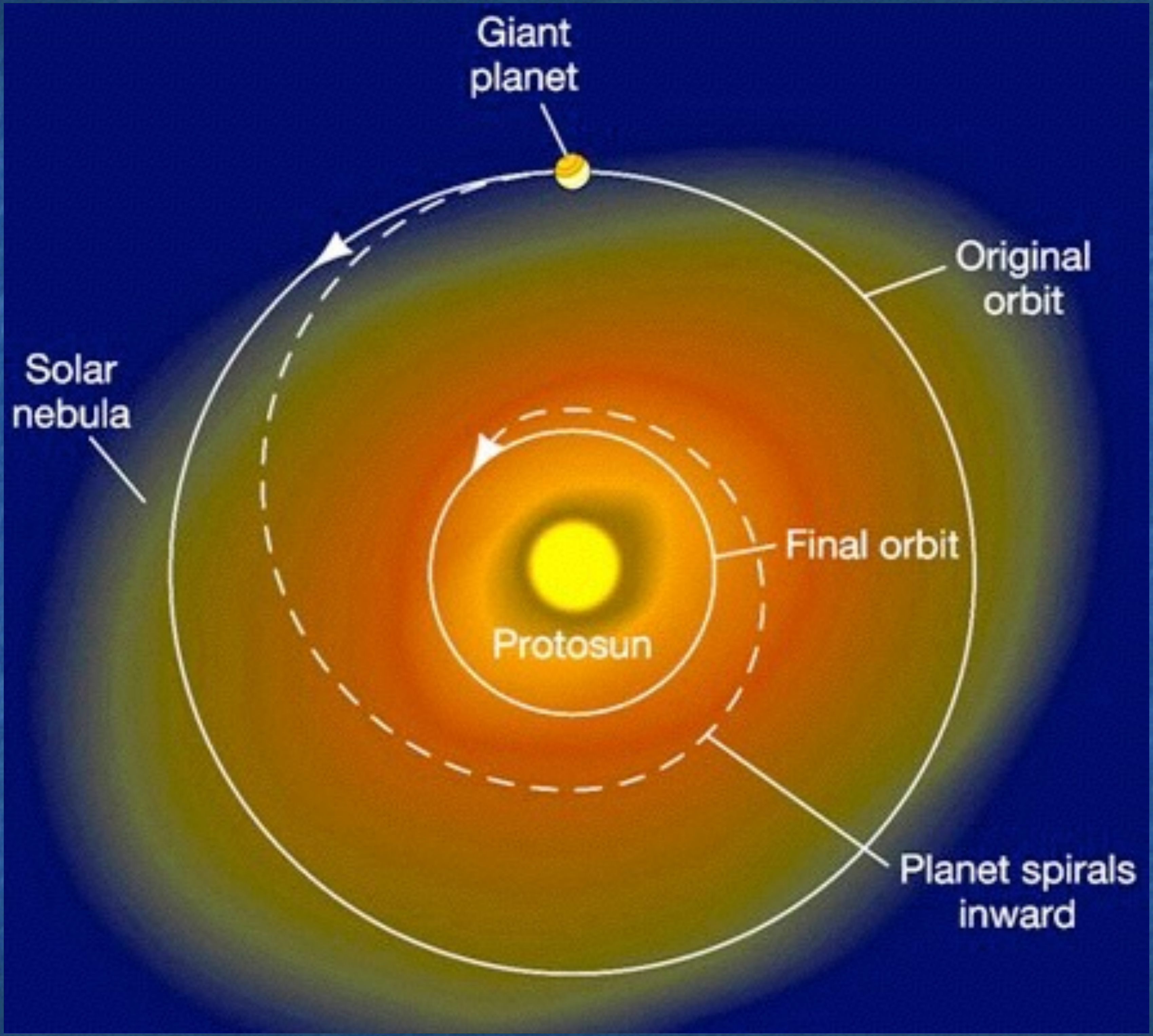


Hot Jupiters: a new class of planet

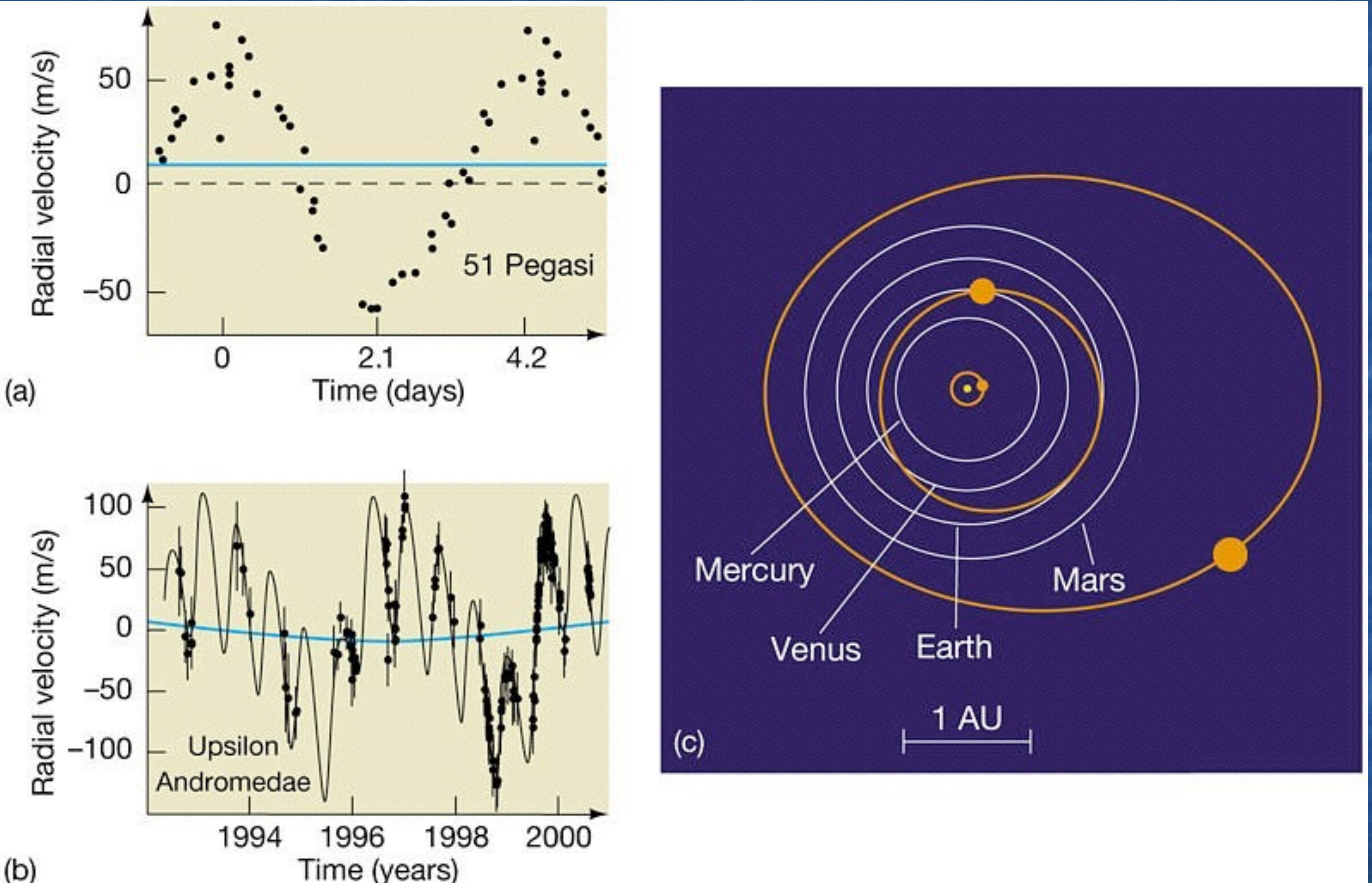


Planetary migration

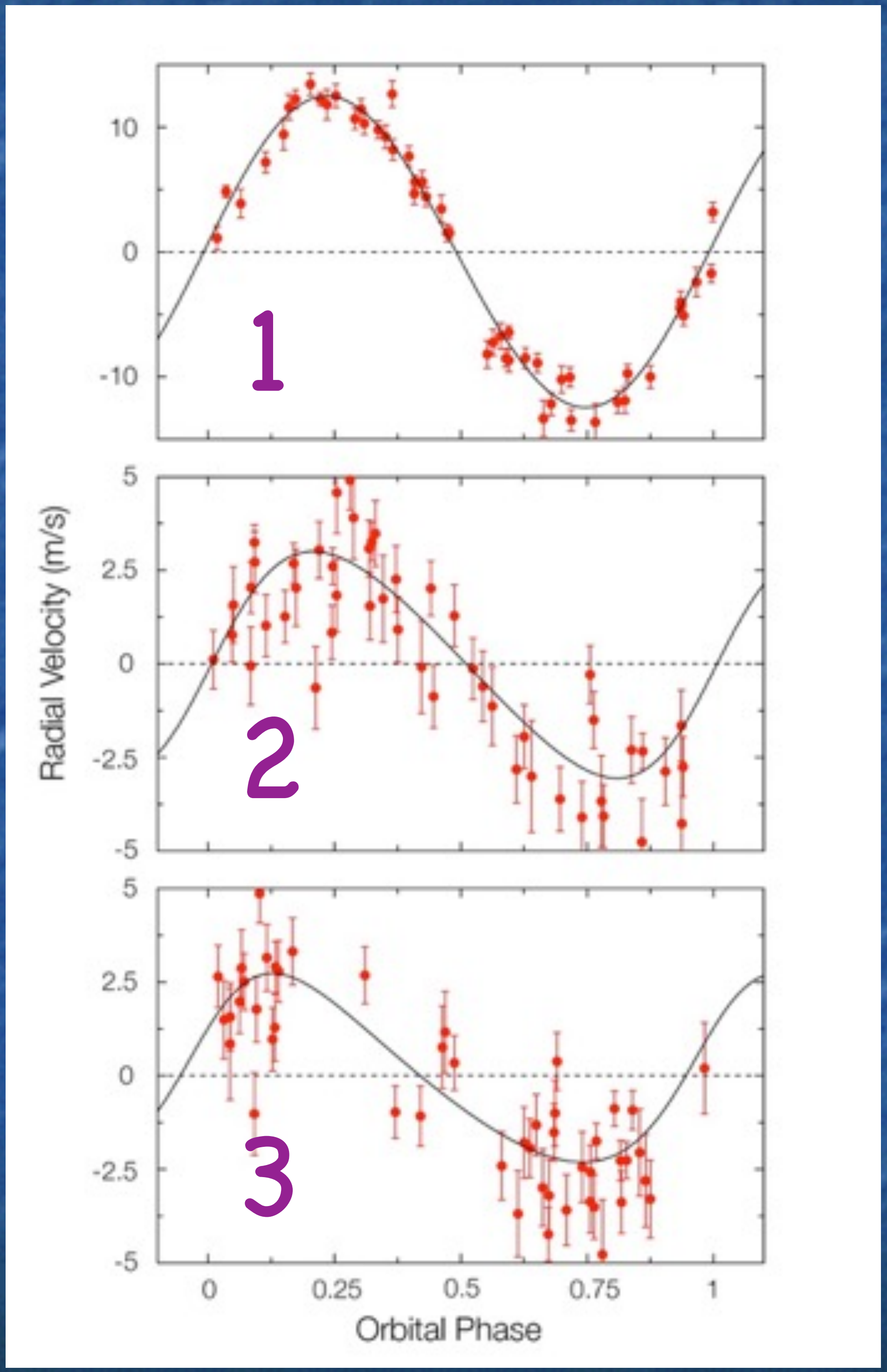



Giant
planet
Original
orbit
Solar
nebula
Final orbit
Protosun
Planet spirals
inward

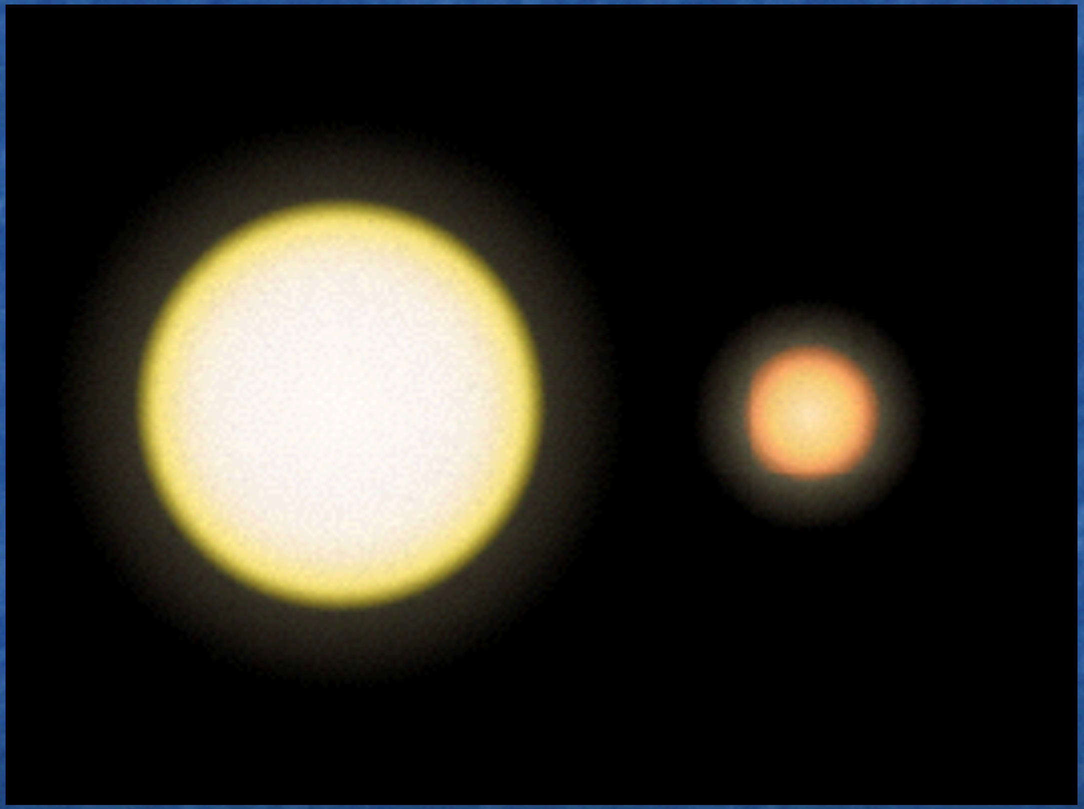
Upsilon Andromedae b, c, d!



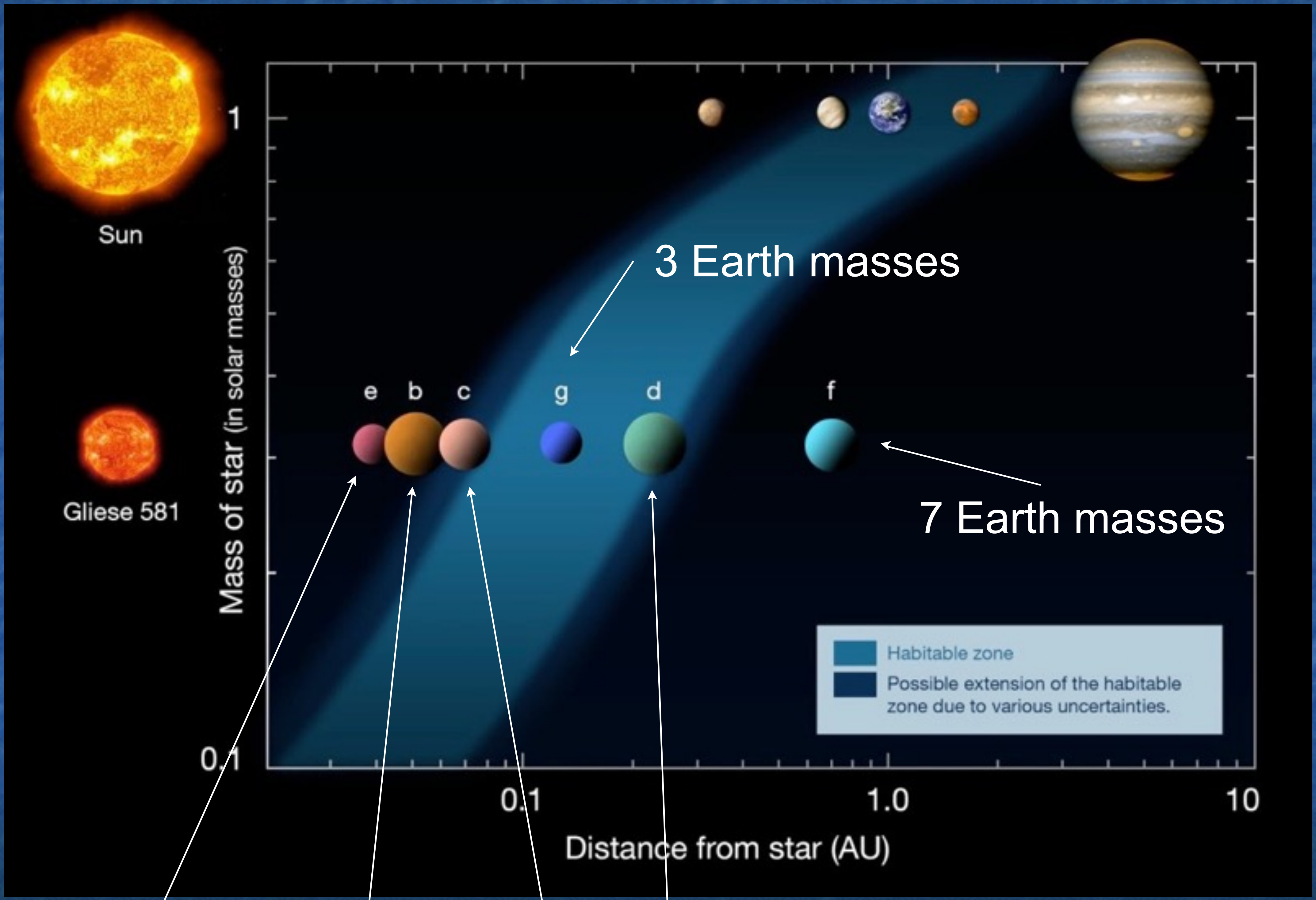
Gliese 581



- Gliese 581 is a cool, M-type star
- 30% the mass of the Sun
- 20 Ly away.

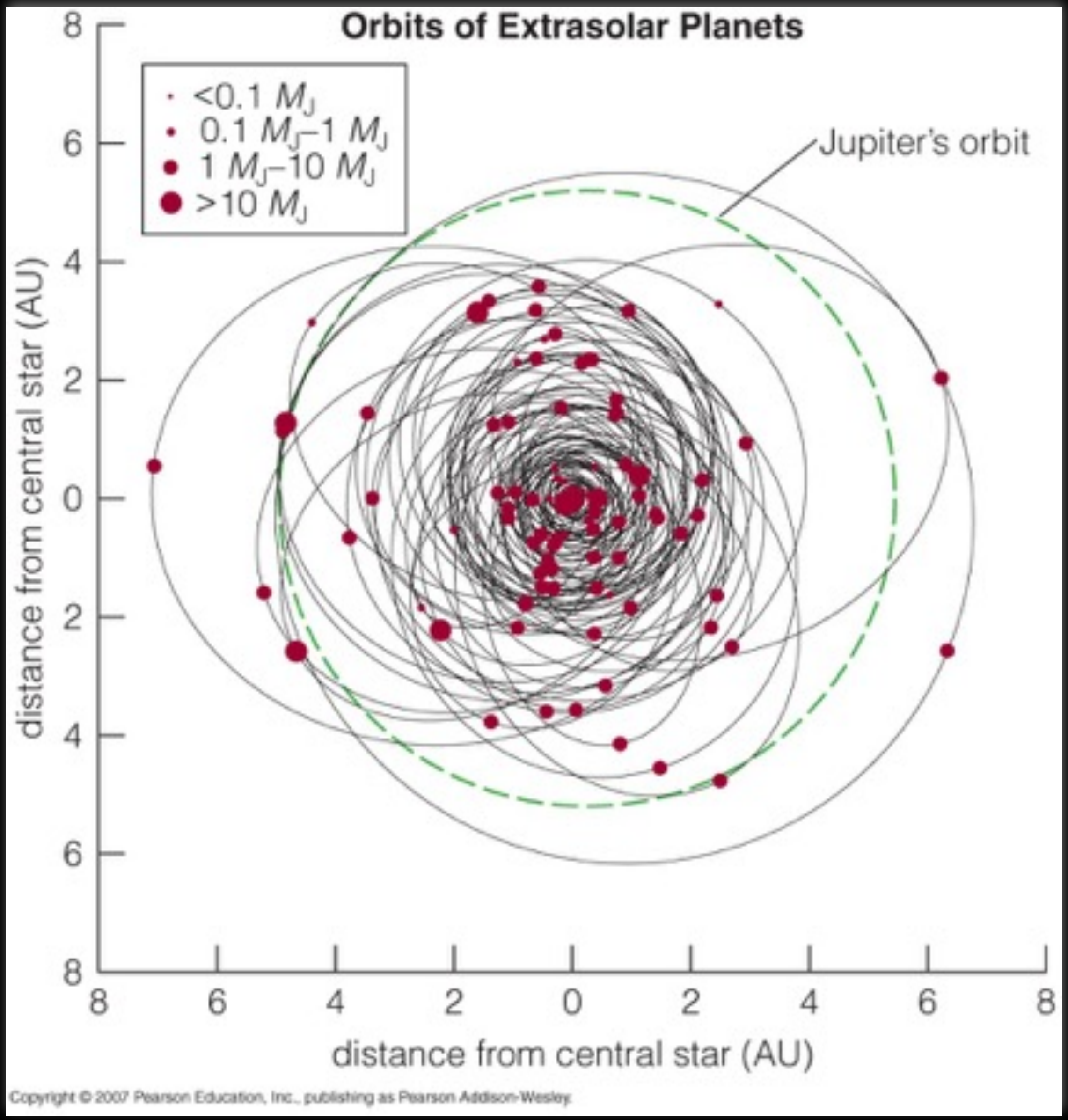


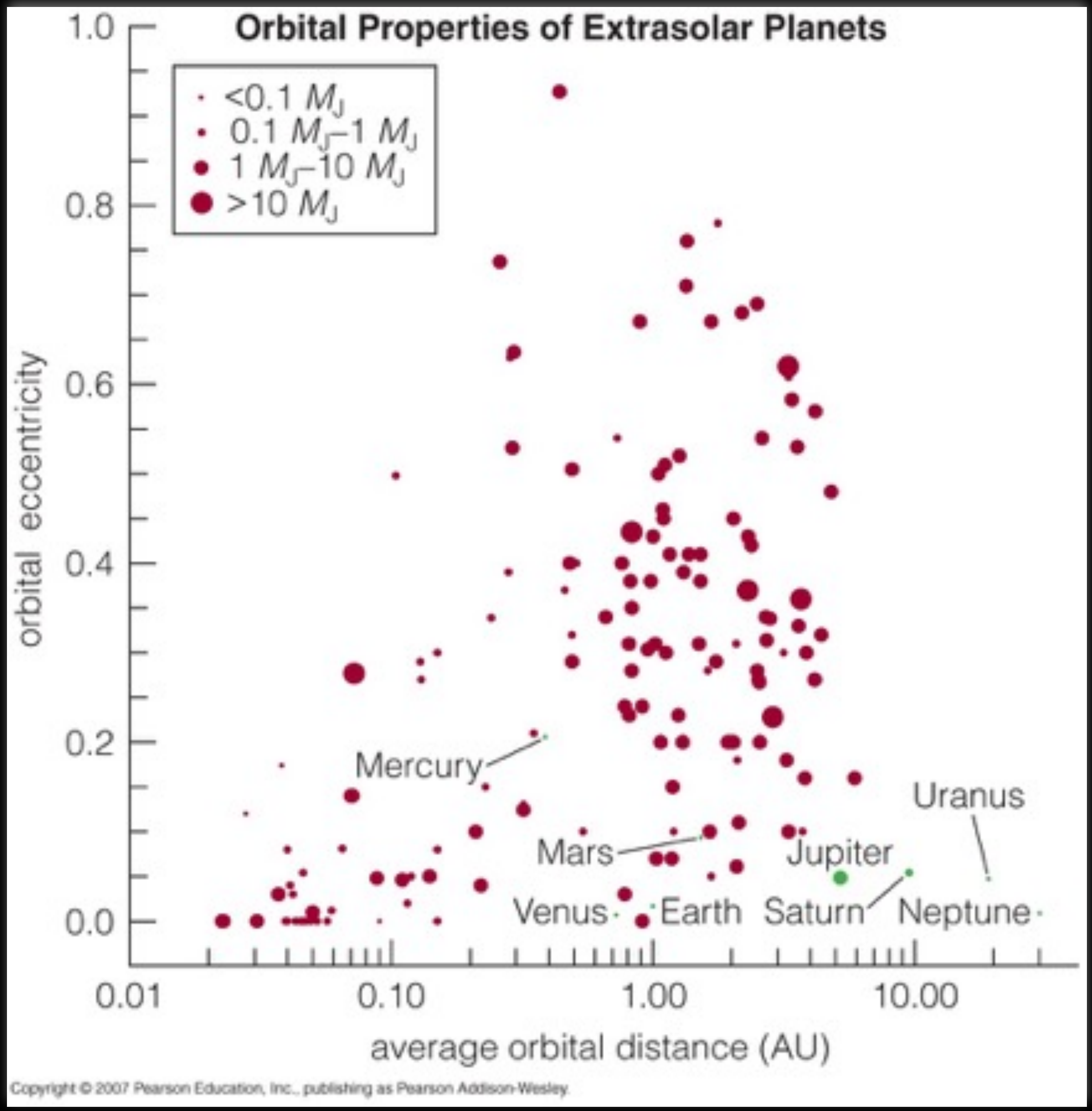
Gliese 581: first planet in habitable zone



2 16 5 7 Earth masses

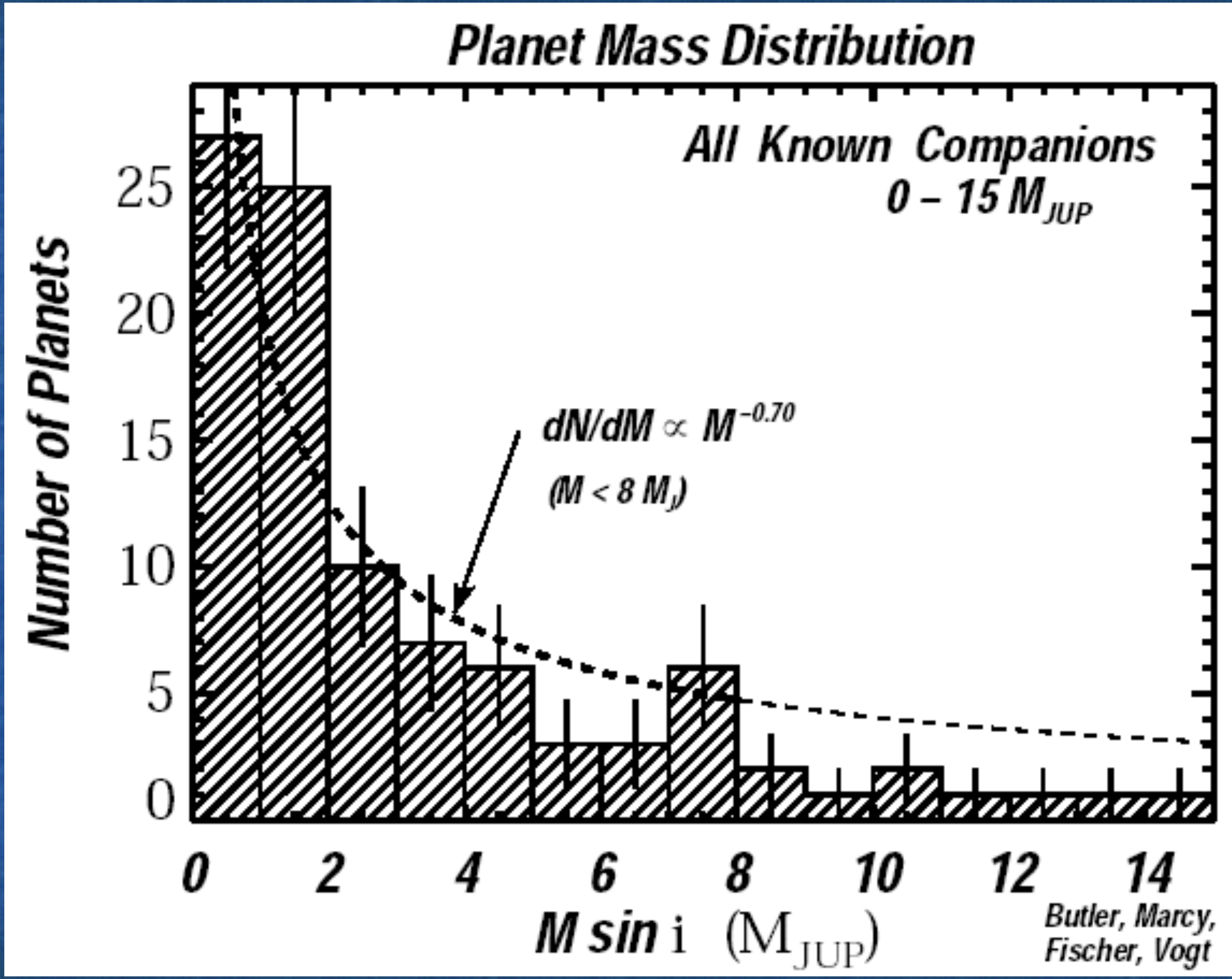
The properties of the known exoplanets





Limitations of the Doppler technique for finding planets

- The amplitude of the velocity curve is proportional to the planet mass - harder to discover small planets.
- The period of the velocity curve is equal to the orbital period.
- Orbital period $p^2 = a^3$ orbital radius.
- Harder to discover planets at large radius.
- Despite these difficulties we can guess at the presence of a large number of Earth mass planets.

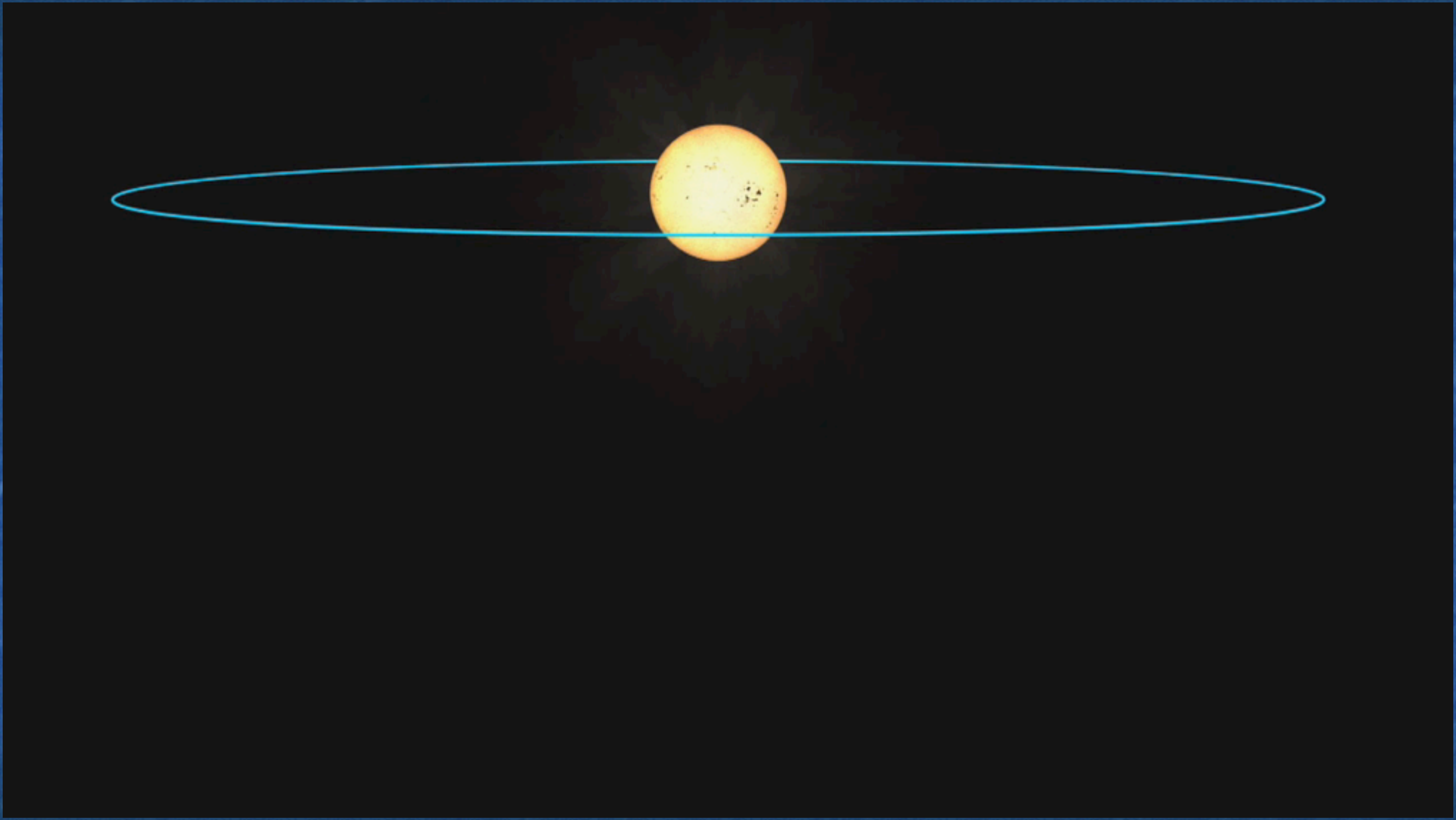


Planet Mass Distribution
All Known Companions
0 – 15 M_{JUP}
$dN/dM \propto M^{-0.70}$
($M < 8\ M_J$)
Number of Planets
0
5
10
15
20
25
0
2
4
6
8
10
12
14
M sin i (M_{JUP})
Butler, Marcy, Fischer, Vogt

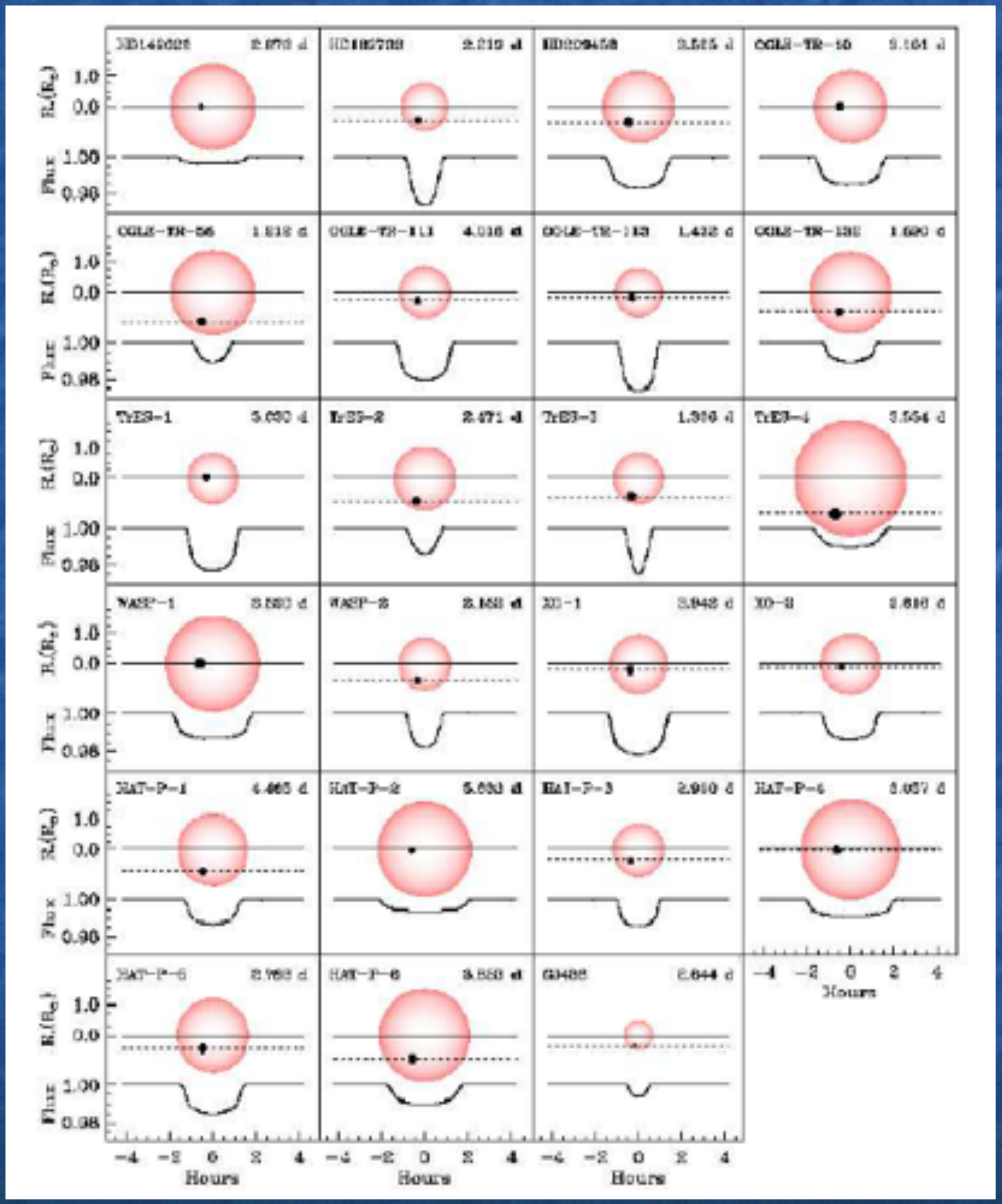
Planetary Transits

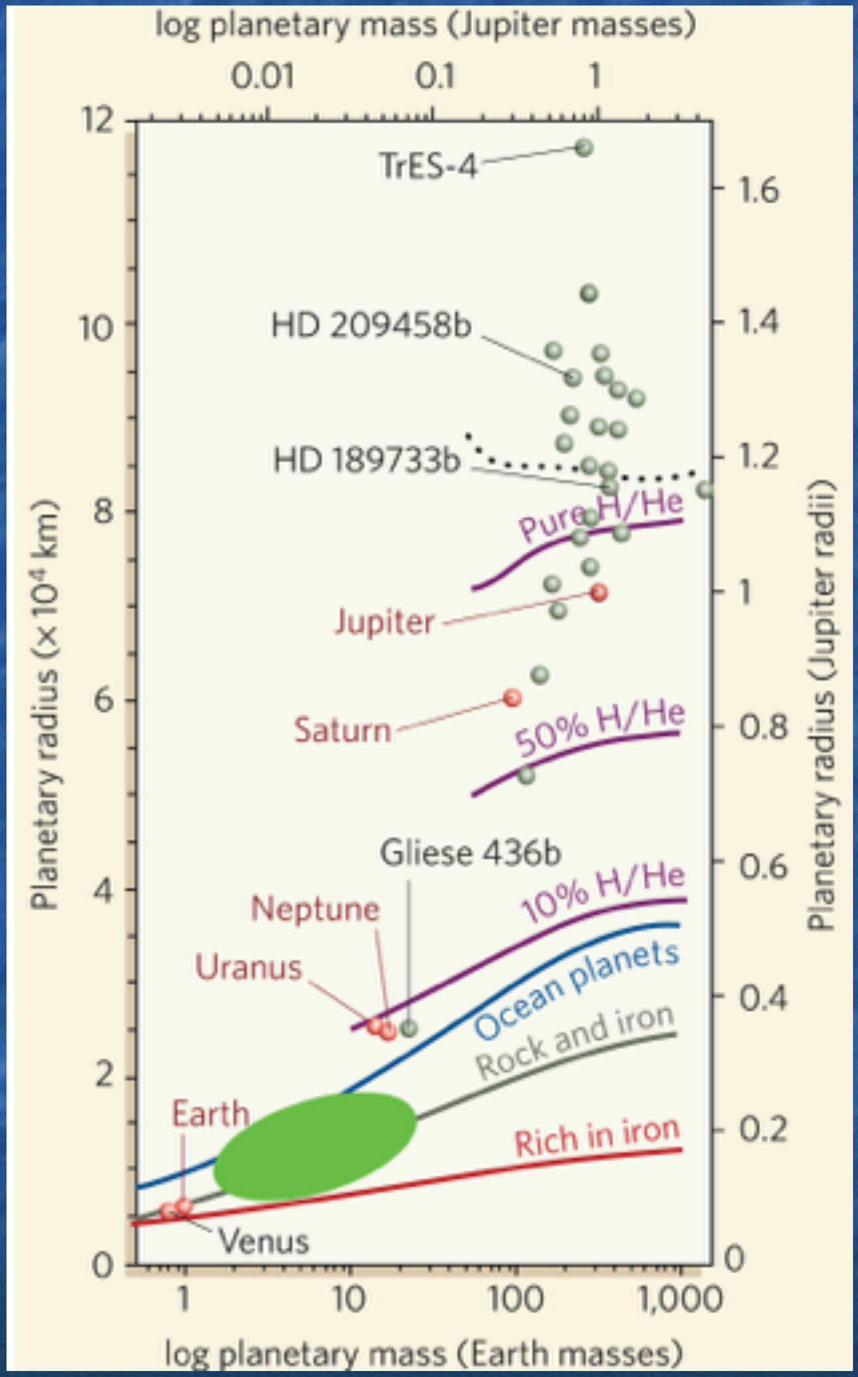
Transit of Venus: June 8, 2004

- During a transit the planet passes in front of the star as viewed from Earth.
- Careful monitoring of the star's brightness can reveal a characteristic dip in the "light curve".
- The size of the dip reveals the planet size.
- Subsequent Doppler observations reveal the mass.
- Mass/volume = density
- Density = composition!

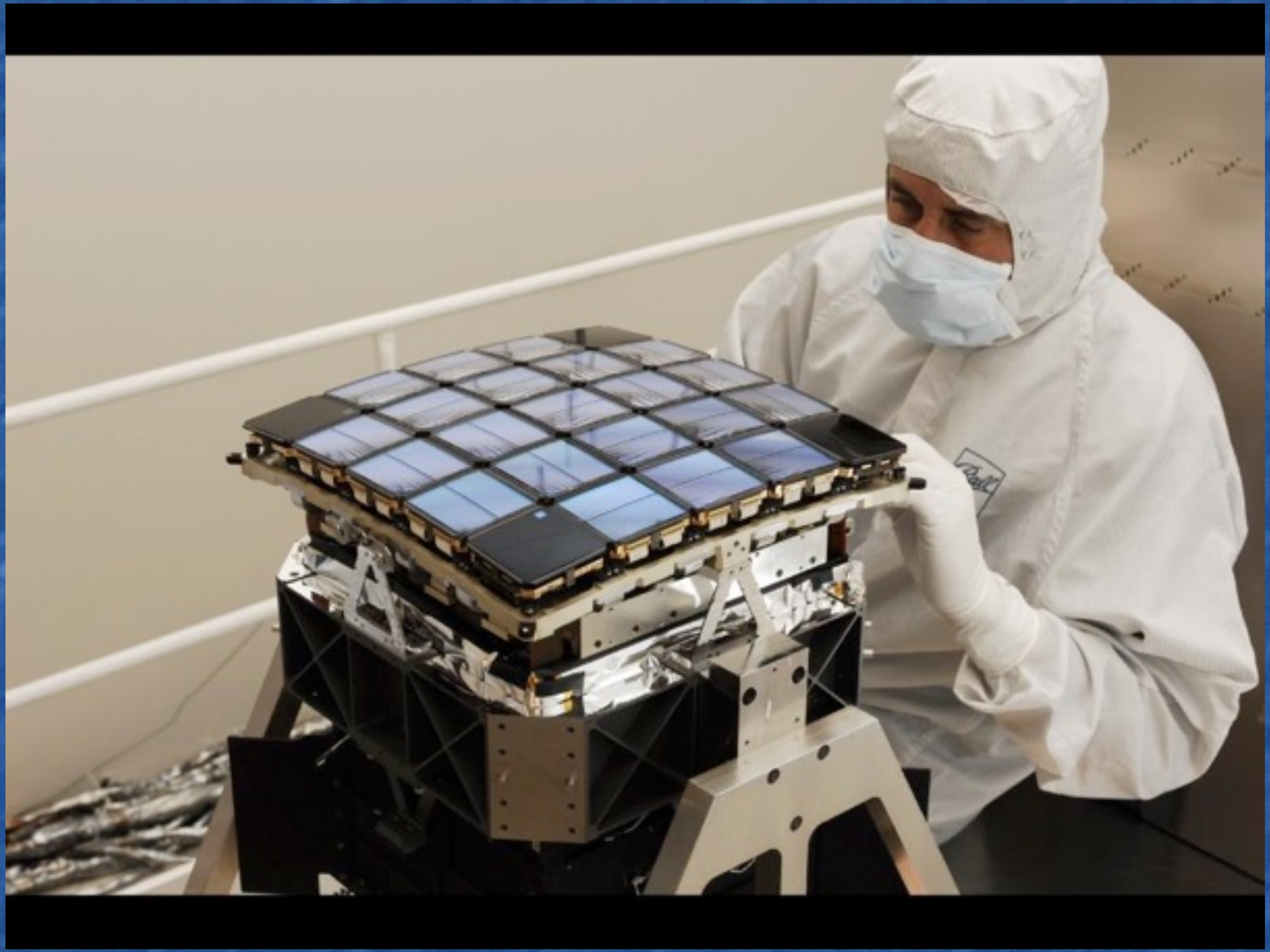


Transits as a fast-track to Earth 2.0?





The Kepler space mission

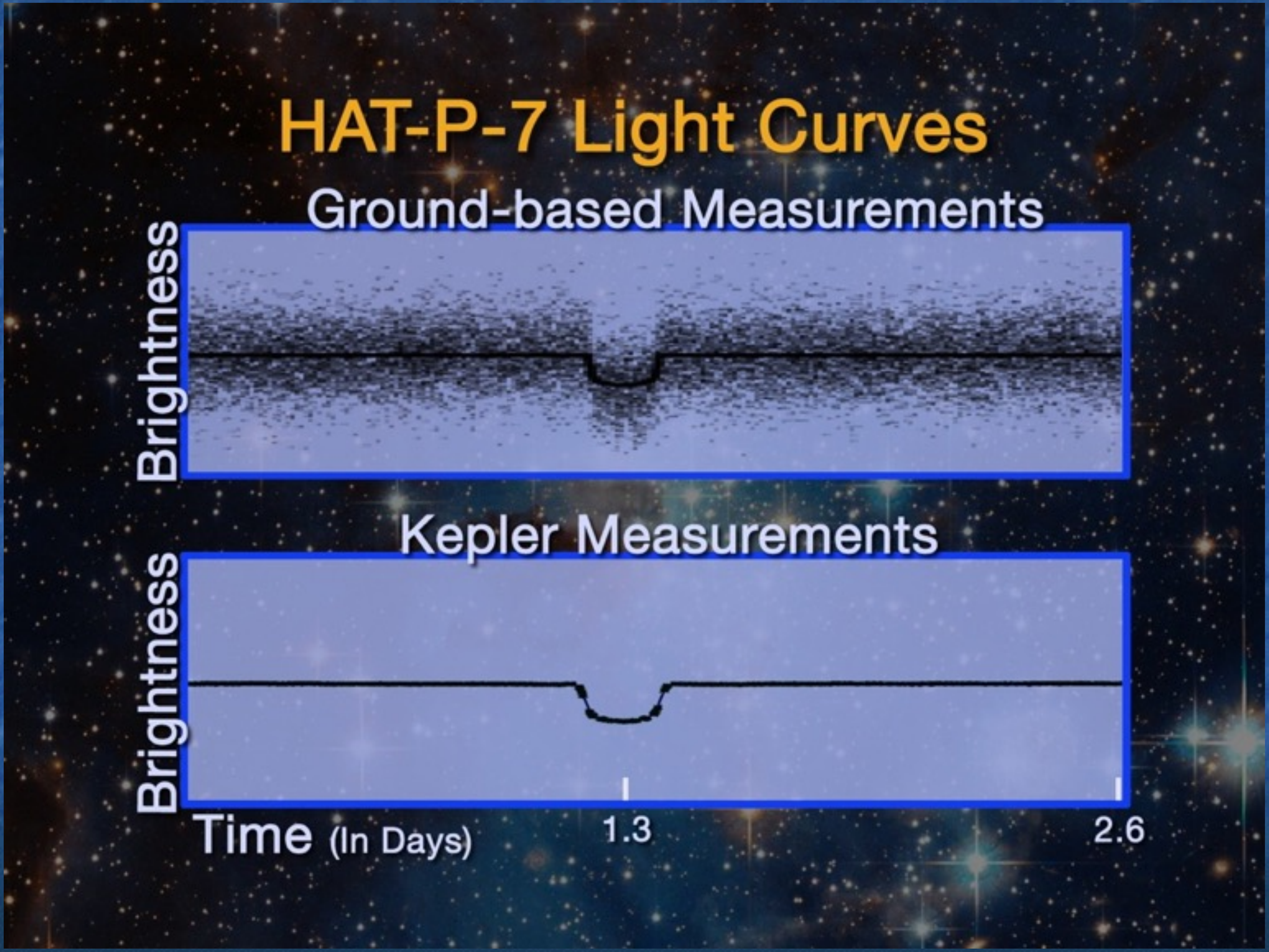



Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

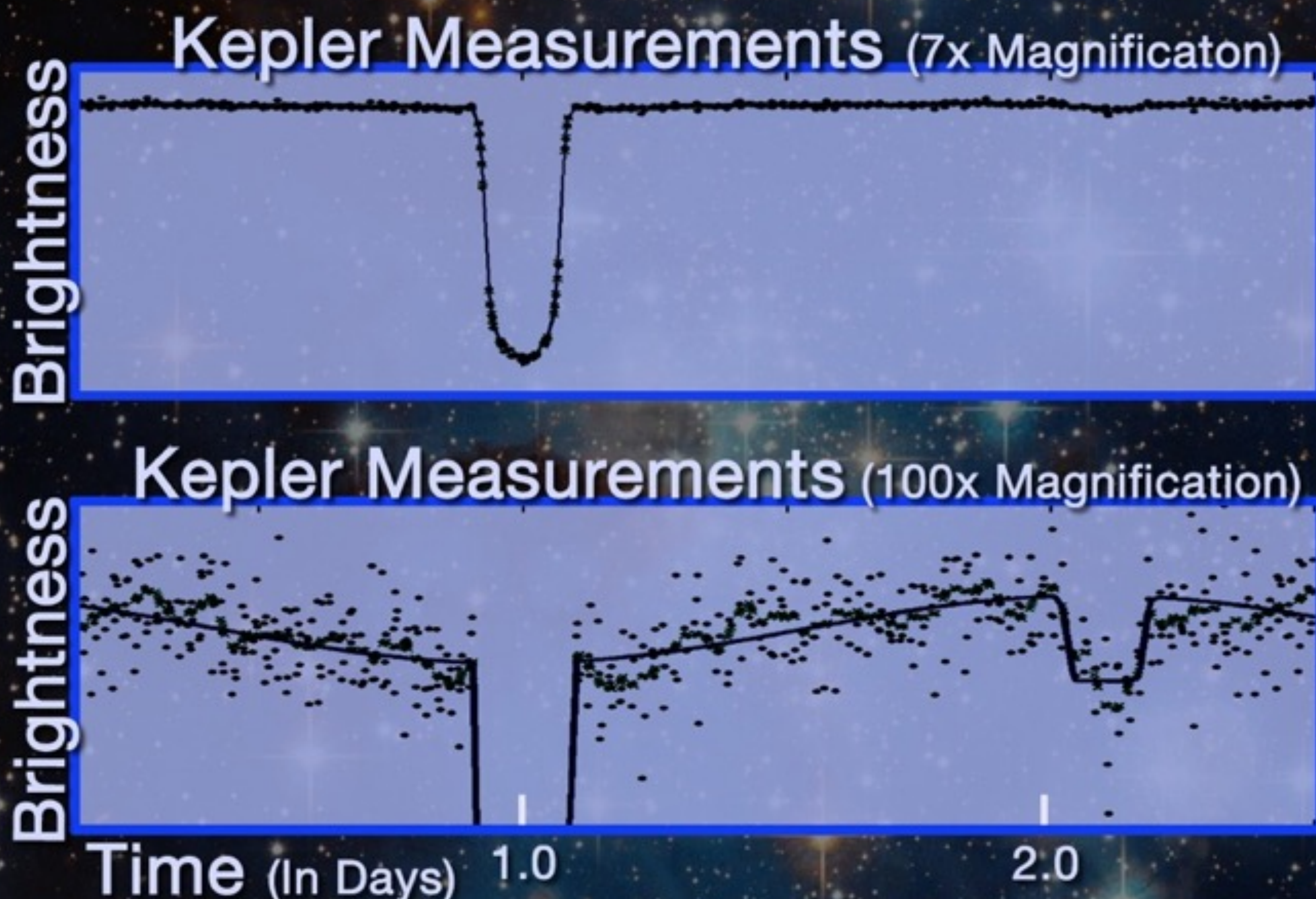
Kepler will measure

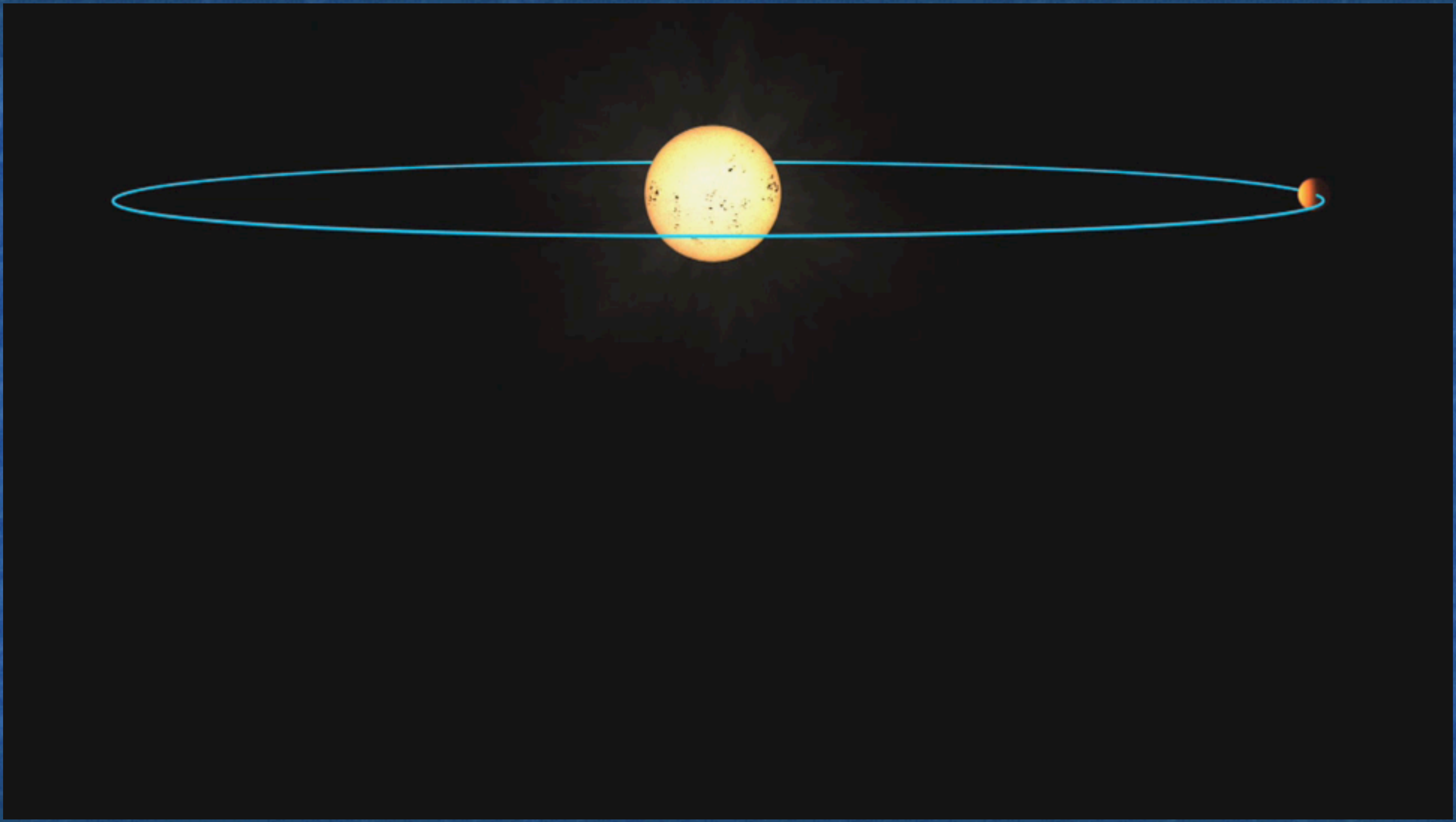
- 150,000 main sequence stars.
- Over a 105 square degree area.
- The mission lasted just under 4 years.
- Between 0.5 and 10% of stars will show transits (if they have planets).
- The exact numbers depends upon the orbital properties and planet size.

It is just a question of accuracy…

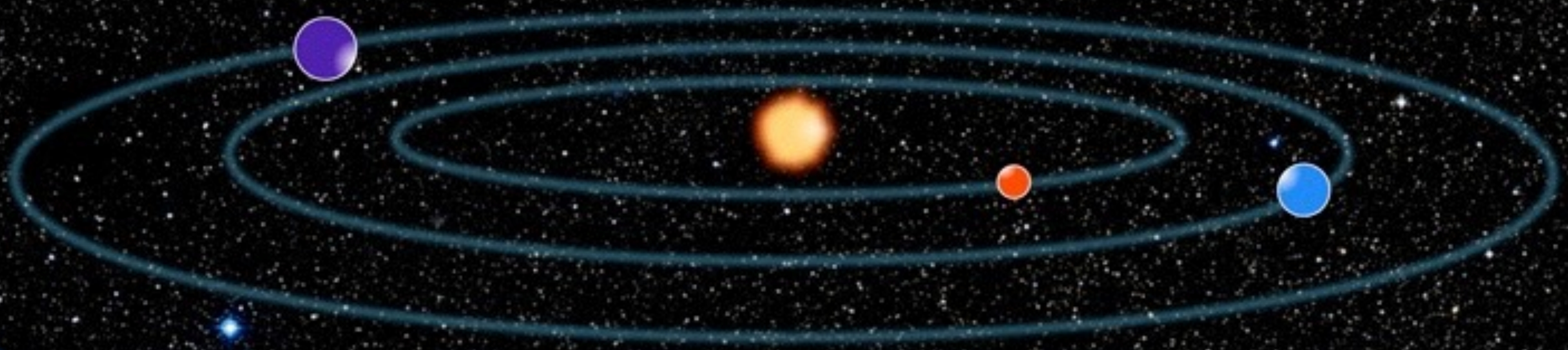


HAT-P-7 Light Curves

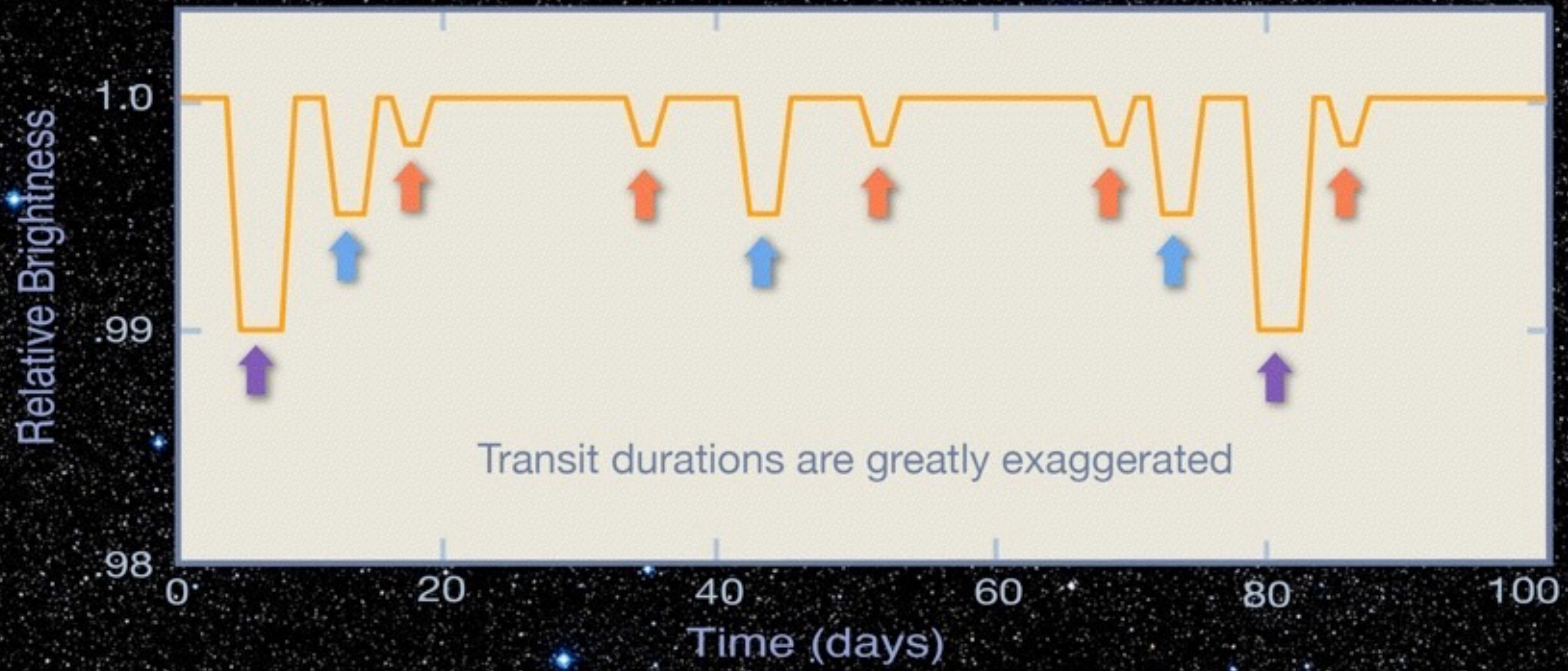




Transit Signature of a Multiple-Planet System

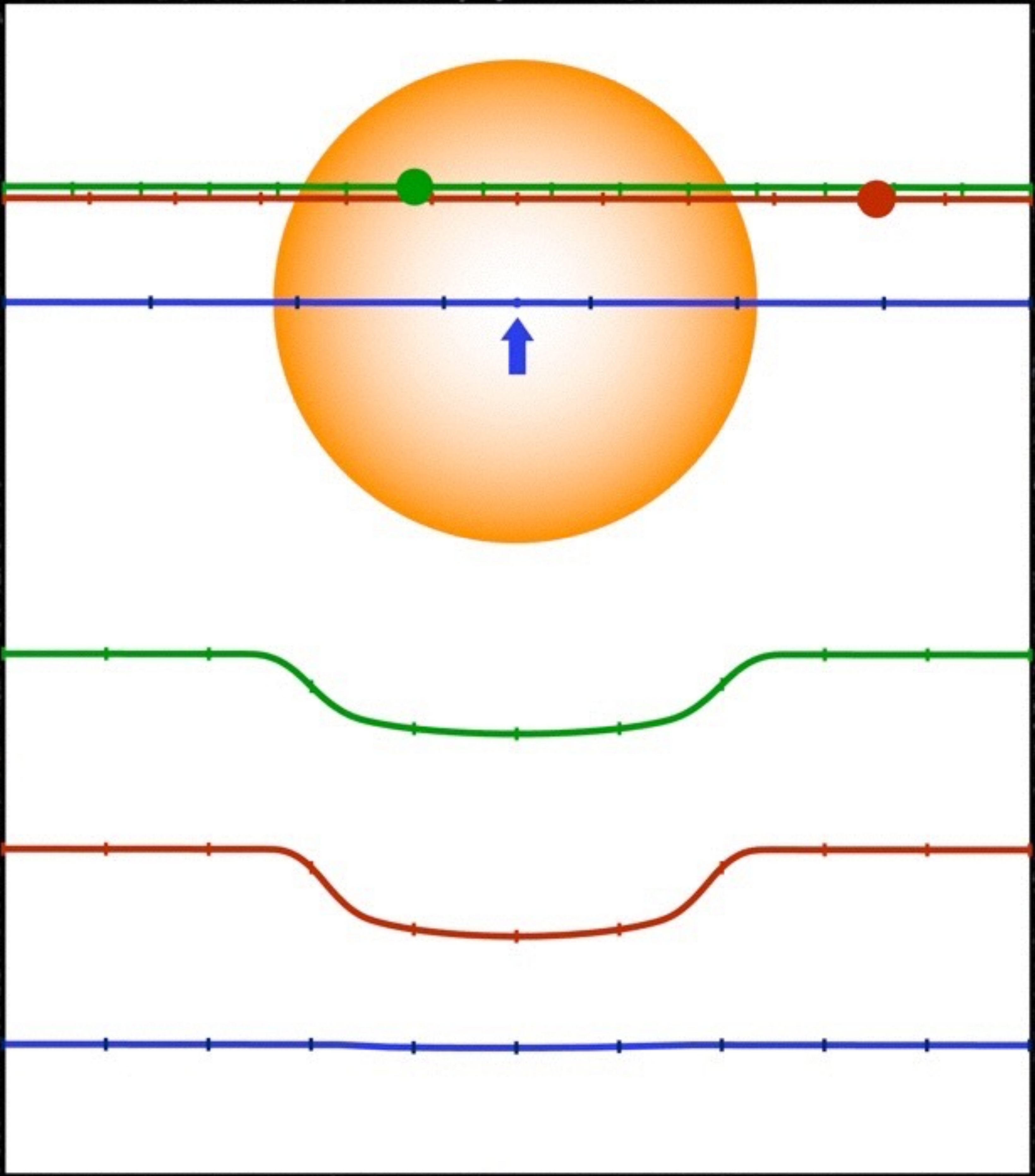


Planets can be distinguished by:
- Different periods
- Different depths
- Different durations



Kepler—9

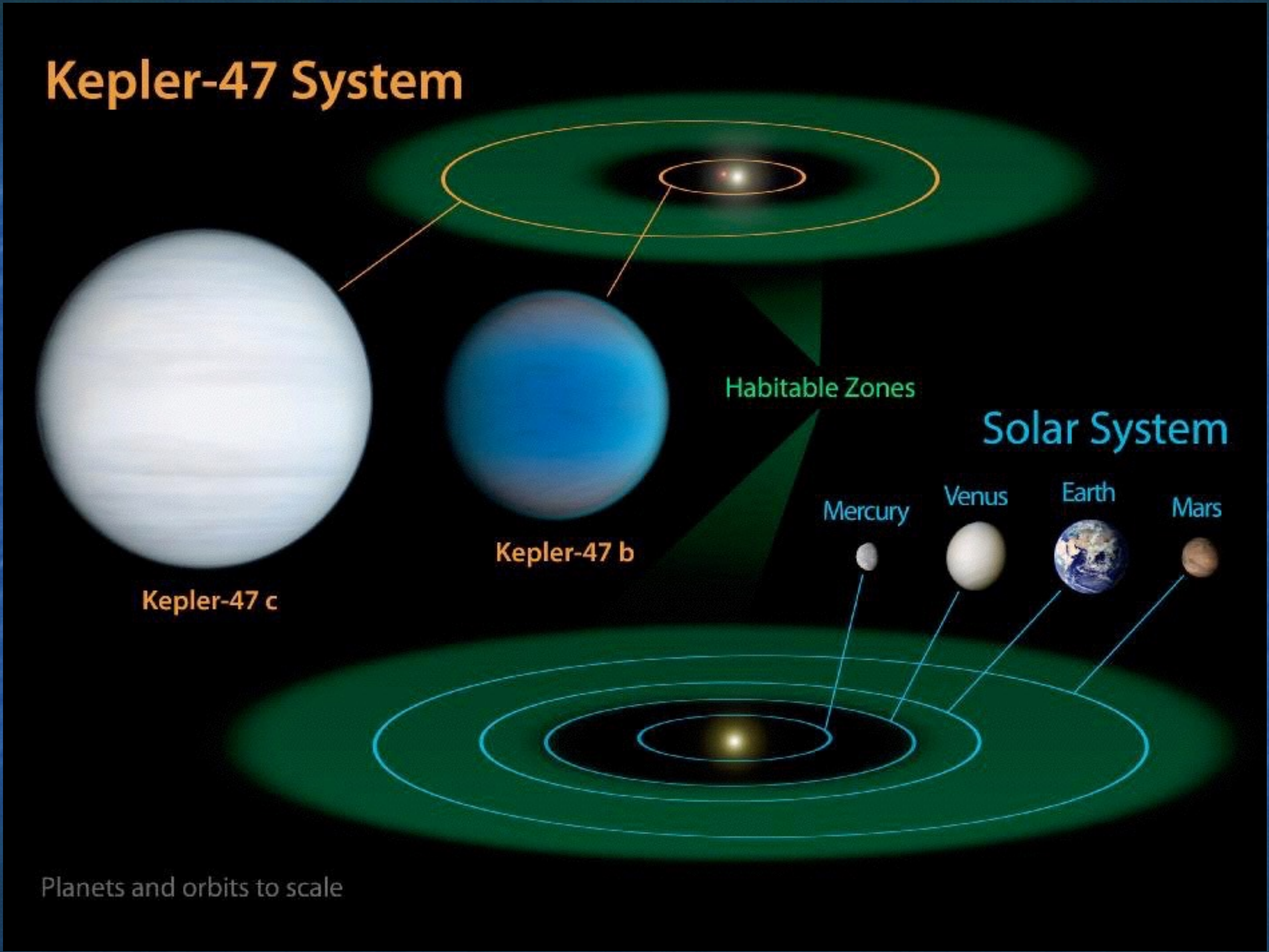
The First System of Multiple Transiting Planets, Confirmed by Timing Variations

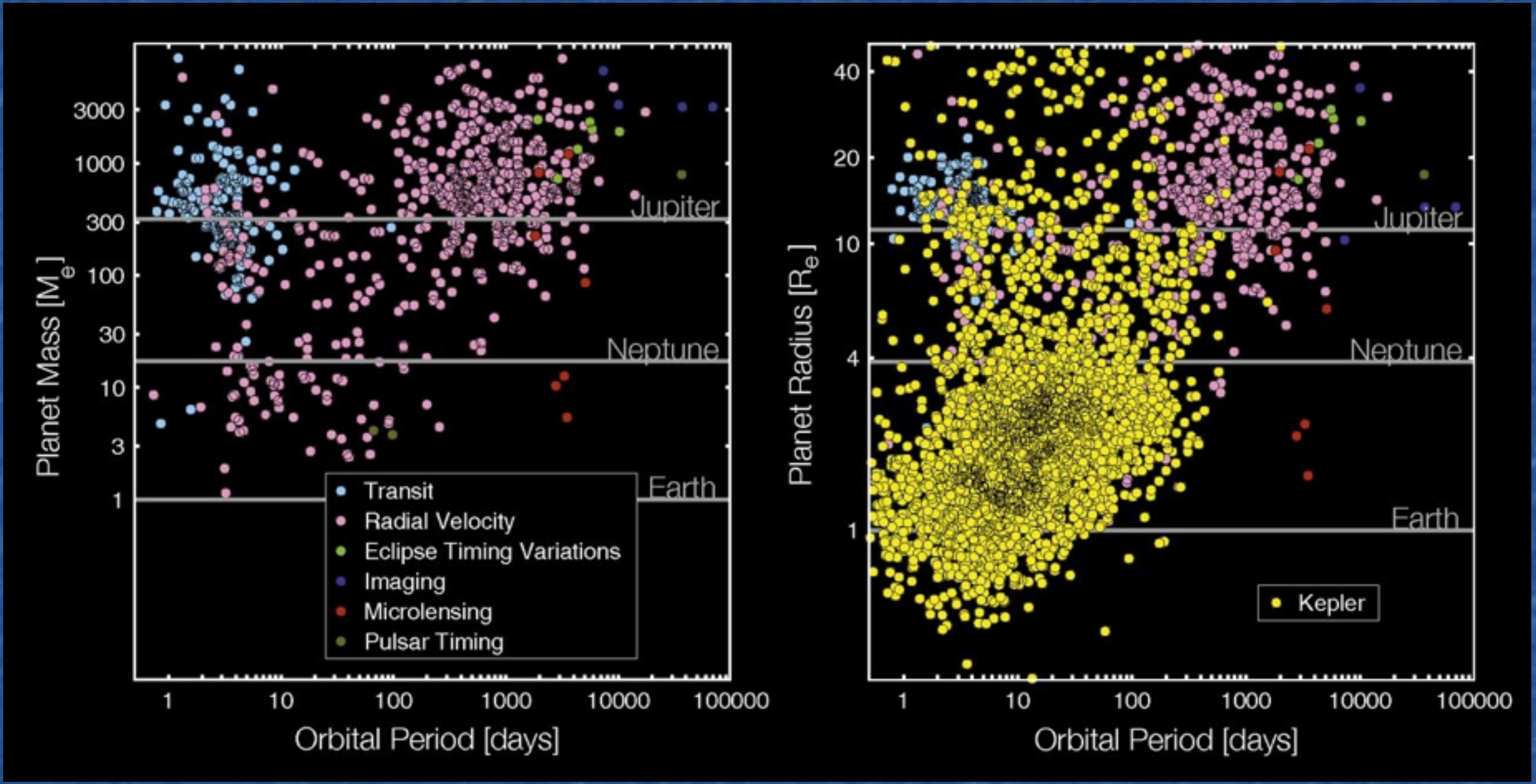


Kepler—9c
● 38.9–day period

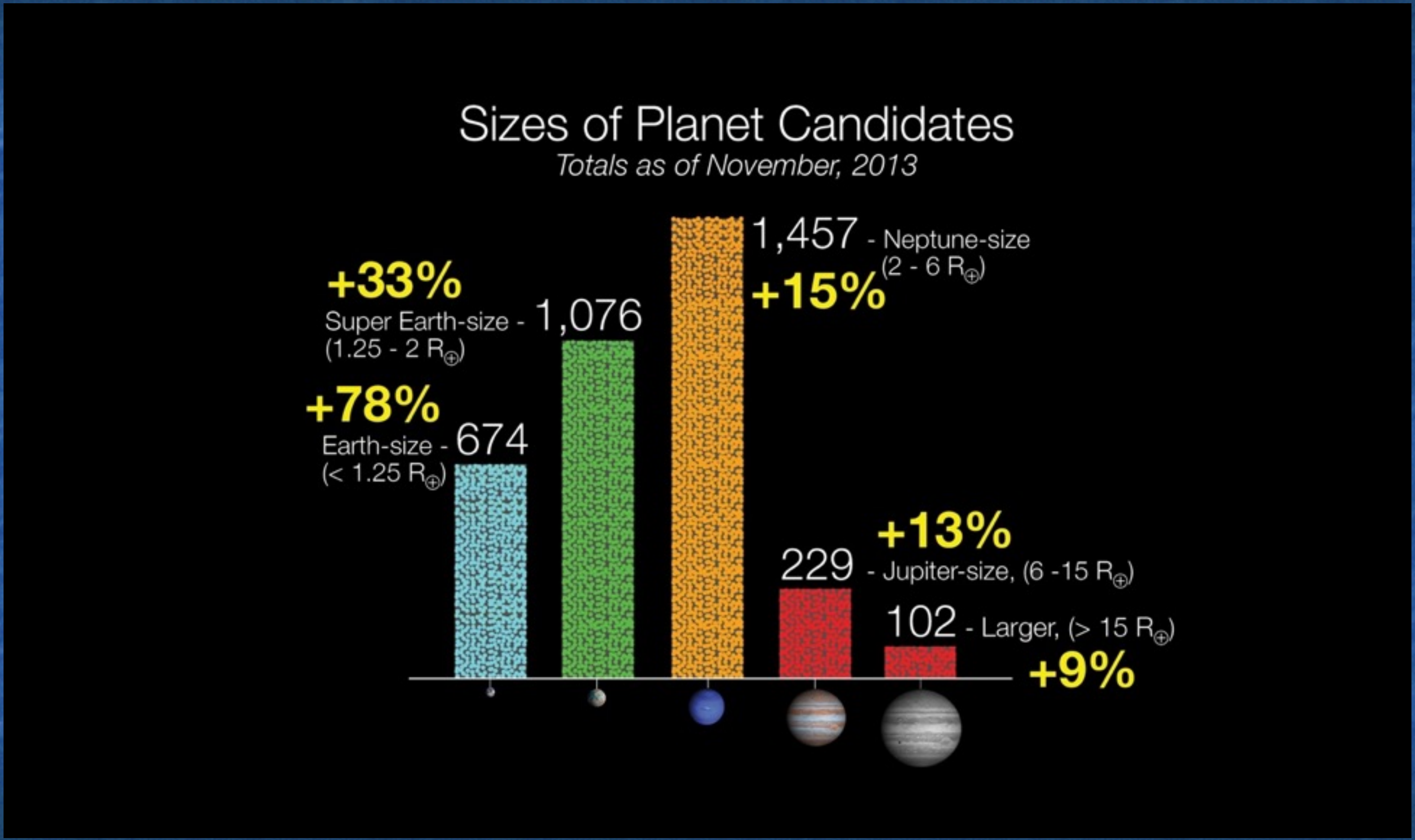
Kepler—9b
● 19.2–day period

Super-Earth Candidate
• 1.6–day period


Kepler-47 System
Habitable Zones
Solar System
Kepler-47 c
Kepler-47 b
Mercury
Venus
Earth
Mars
Planets and orbits to scale



Planet Mass [M_e]
3000
1000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial Velocity
Eclipse Timing Variations
Imaging
Microlensing
Pulsar Timing
1
10
100
1000
10000
100000
Orbital Period [days]
Planet Radius [R_e]
40
20
10
4
1
Kepler

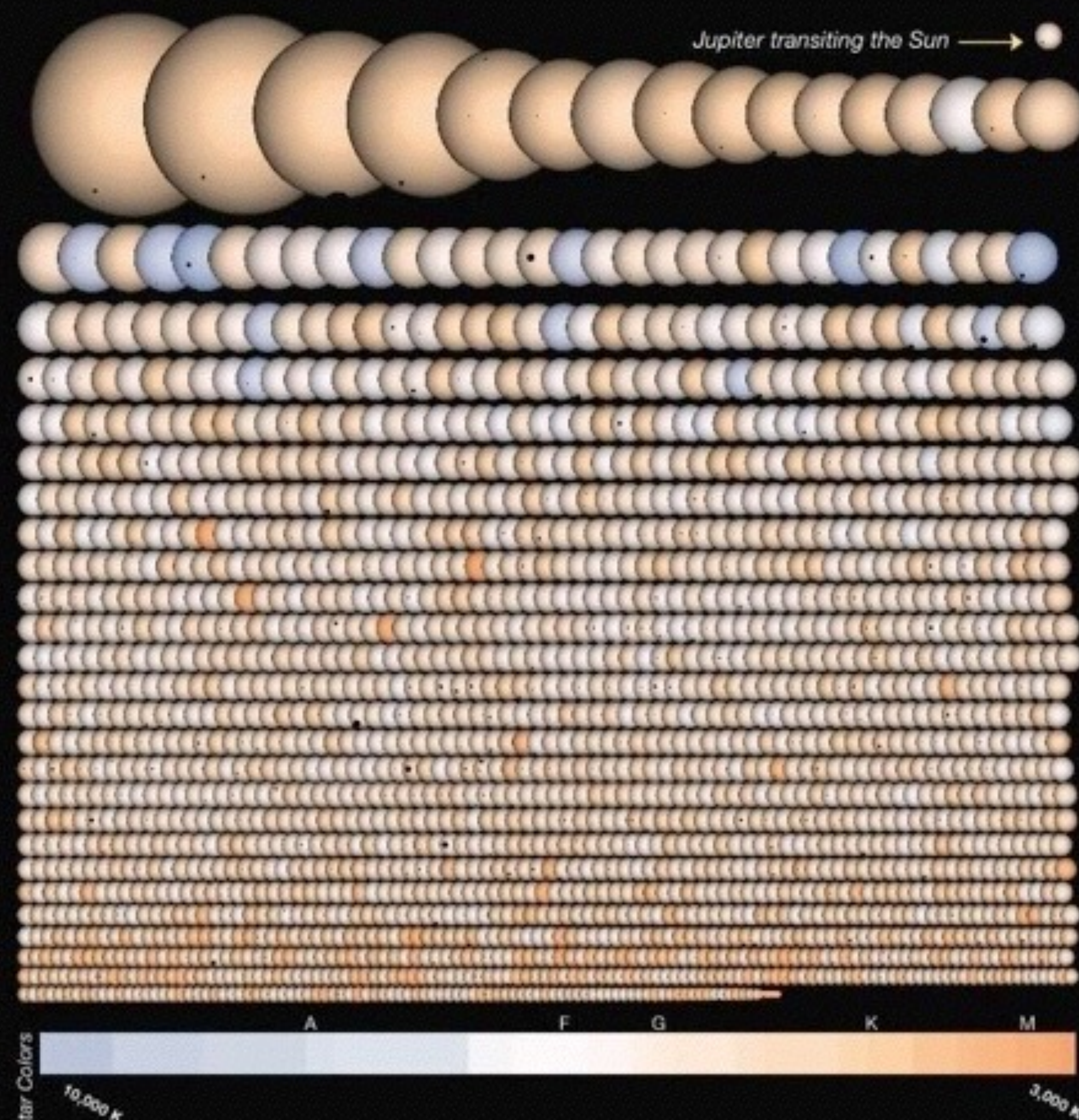


Sizes of Planet Candidates
Totals as of November, 2013
+33%
Super Earth-size - 1,076
(1.25 - 2 R⊕)
+78%
Earth-size - 674
(< 1.25 R⊕)
1,457 - Neptune-size
(2 - 6 R⊕)
+15%
+13%
229 - Jupiter-size, (6 -15 R⊕)
102 - Larger, (> 15 R⊕)
+9%

National Aeronautics and Space Administration

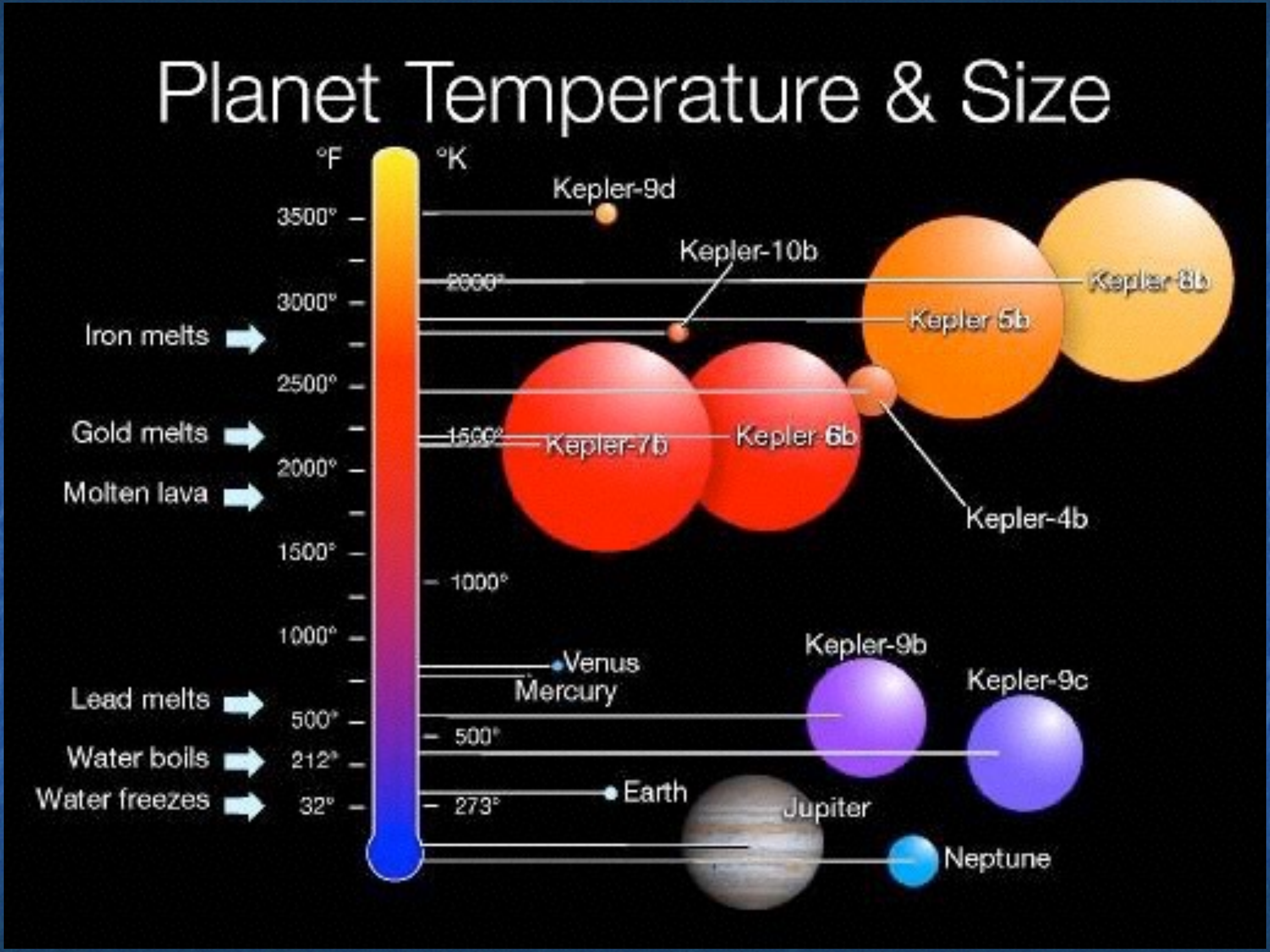
KEPLER'S PLANET CANDIDATES

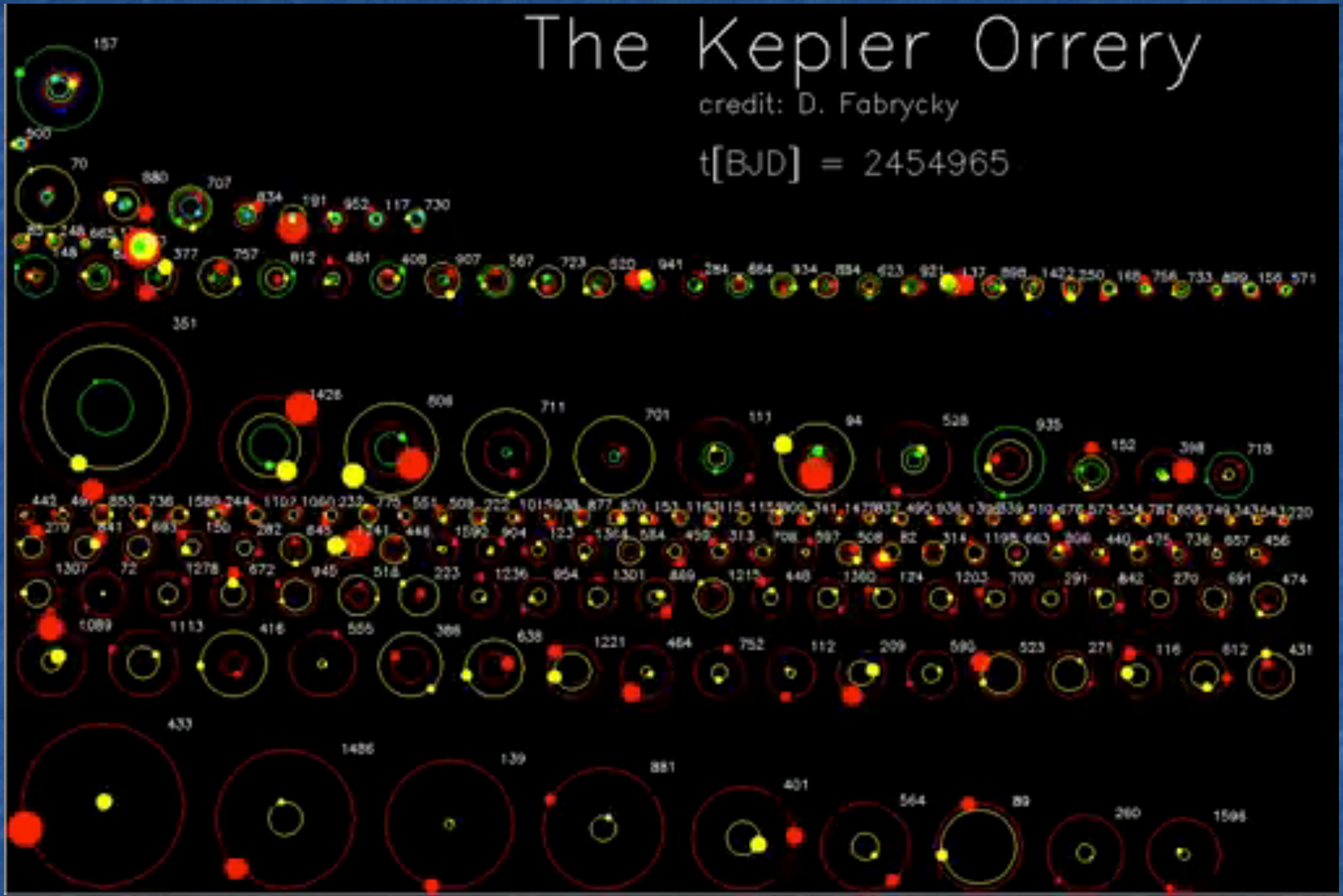
2,326 AS OF DECEMBER 5, 2011



Using NASA's planet-hunting *Kepler* spacecraft, astronomers have discovered 2,326 candidate planets orbiting other suns in a search for Earth-size worlds that began in 2009. *Kepler* monitors a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) are how astronomers classify star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Look carefully: some systems have multiple planets. For reference, Jupiter is shown transiting the Sun. Higher resolutions of this graphic are available at http://Kepler.NASA.gov/images/graphics

www.nasa.gov

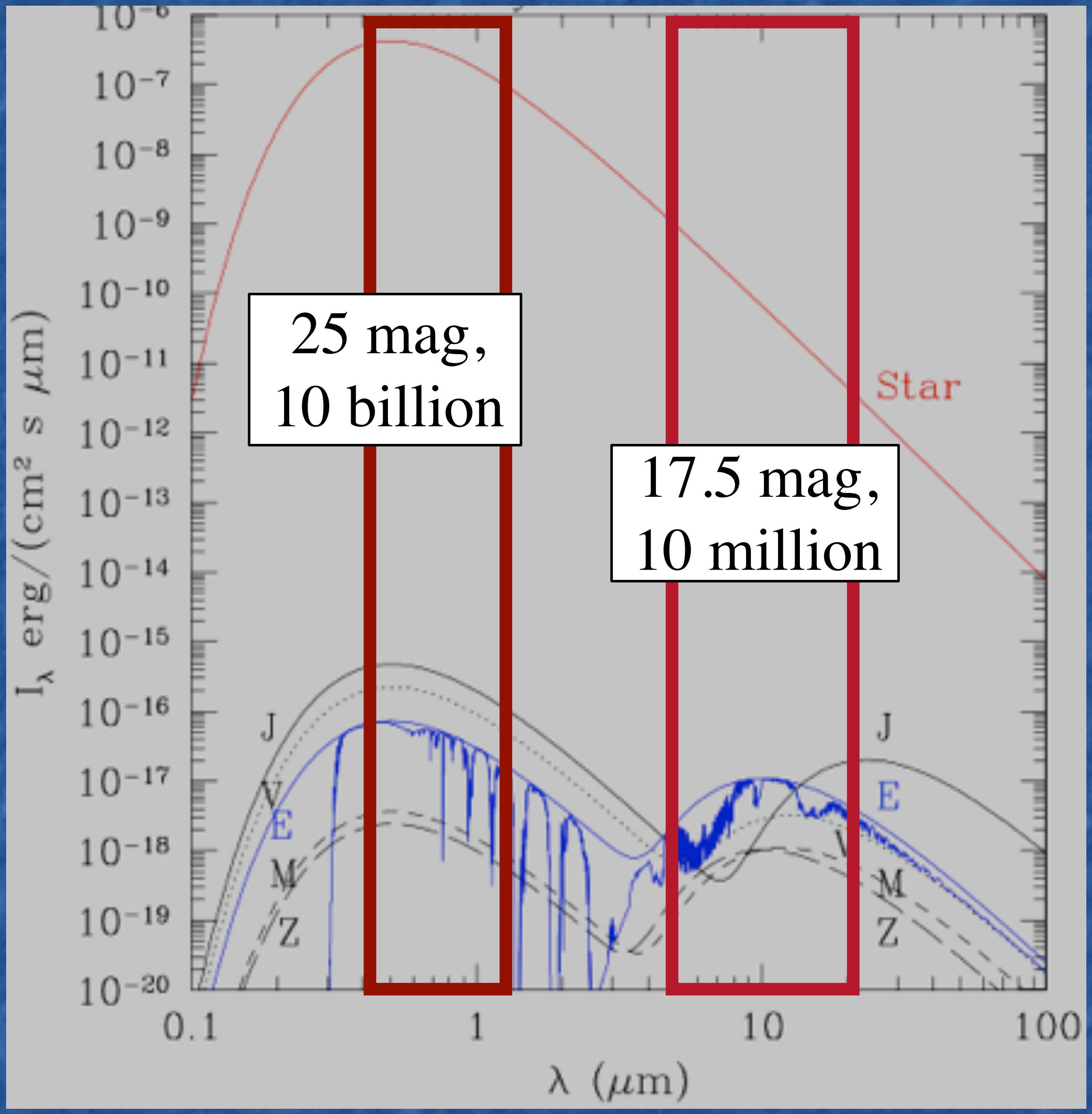

Planet Temperature & Size
°F
°K
3500°
3000°
2500°
2000°
1500°
1000°
500°
212°
32°
2000°
1500°
1000°
500°
273°
Iron melts
Gold melts
Molten lava
Lead melts
Water boils
Water freezes
Kepler-9d
Kepler-10b
Kepler-8b
Kepler 5b
Kepler-7b
Kepler 6b
Kepler-4b
Venus
Mercury
Kepler-9b
Kepler-9c
Earth
Jupiter
Neptune

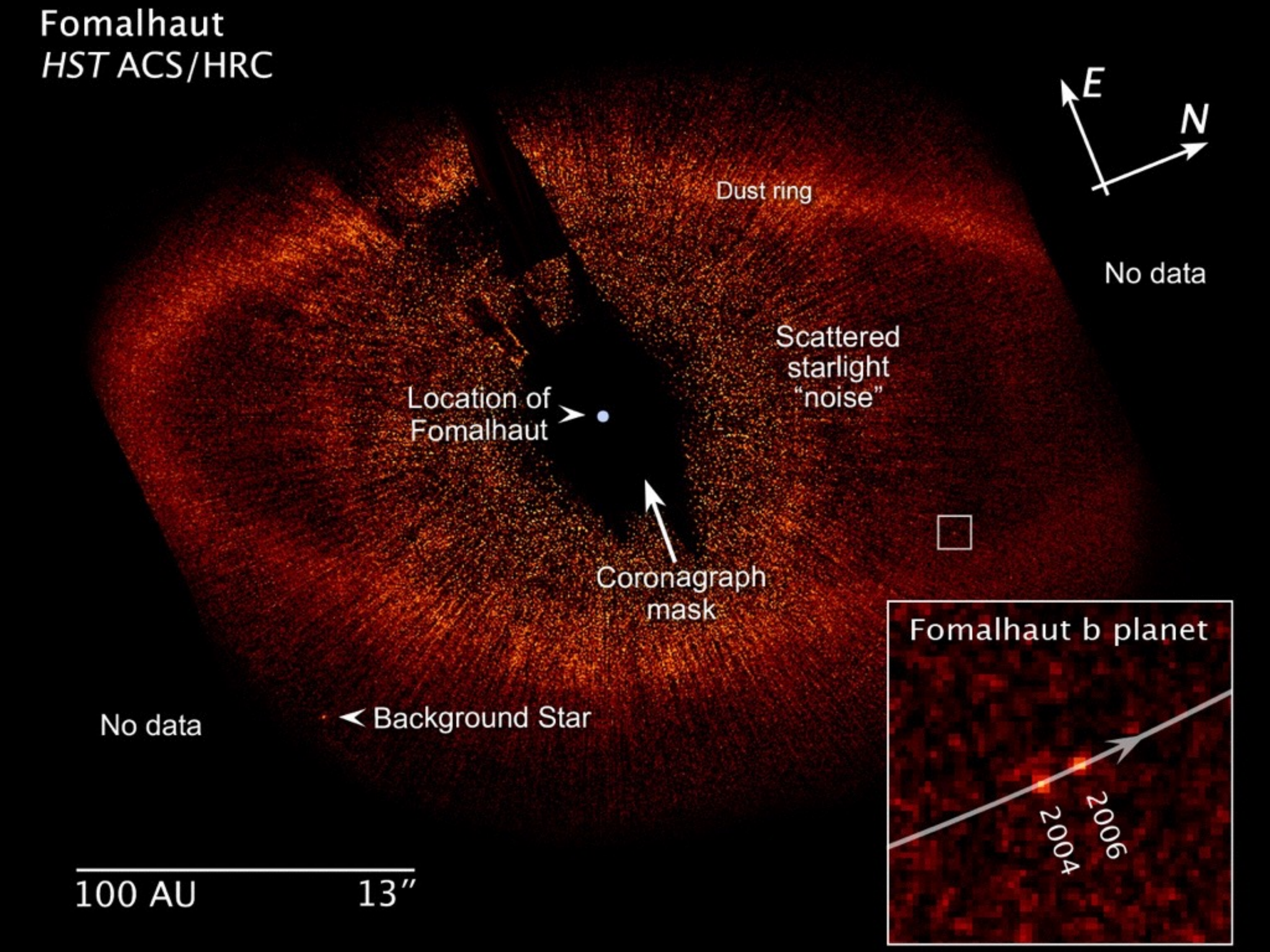

The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965

Direct imaging of exoplanets

- The most obvious way to find an exoplanet is by direct imaging
- However, this approach is extremely challenging
  - stars are typically ten billion times brighter than their planets
  - planets are also very close to their stars
    - much less than 1 arcsec
- Only a few planets have been found this way

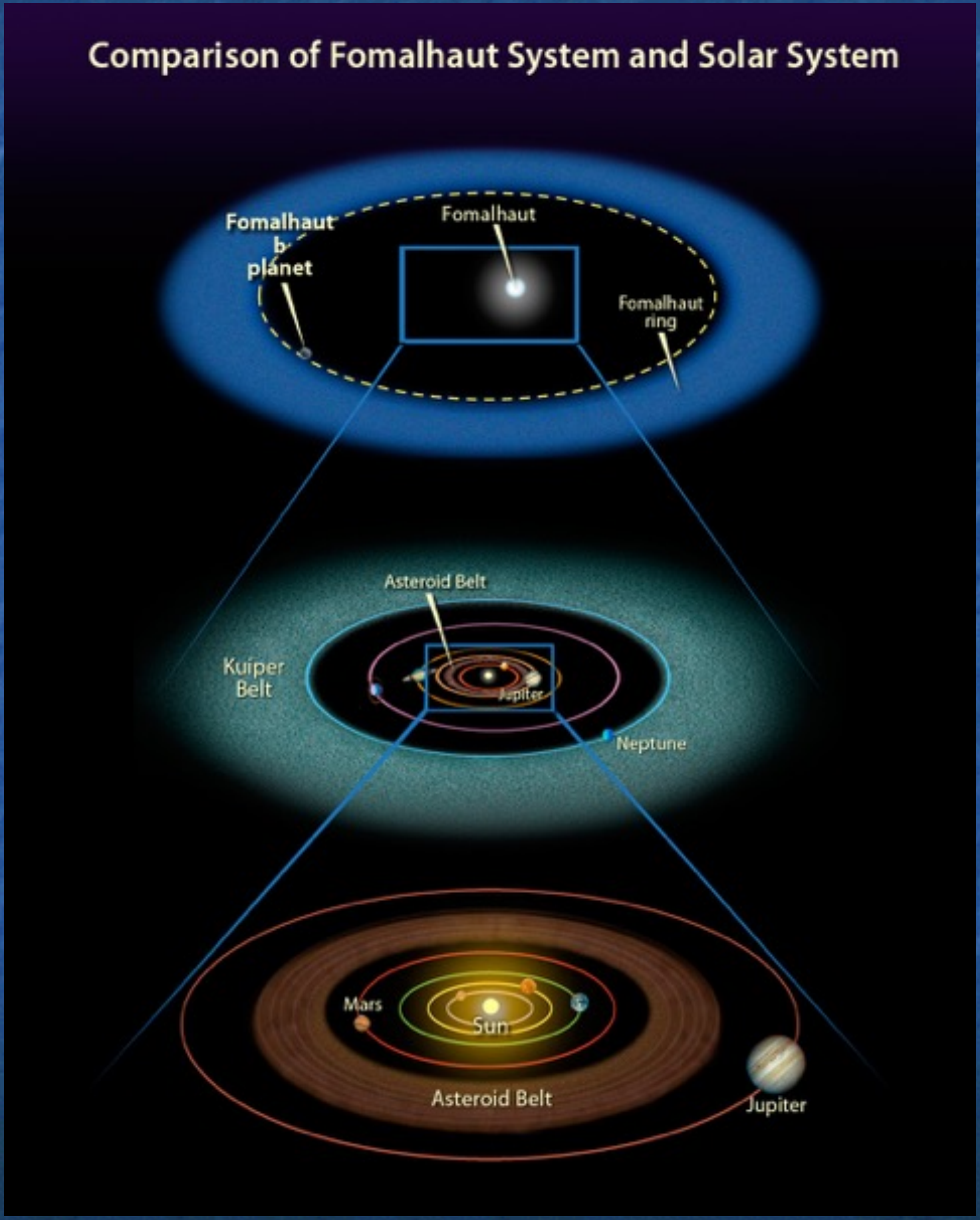
Exoplanet around brown dwarf 2M1207


25 mag,
10 billion
17.5 mag,
10 million
Star
J
V
E
M
Z
I_λ erg/(cm² s μm)
λ (μm)
0.1
1
10
100
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}



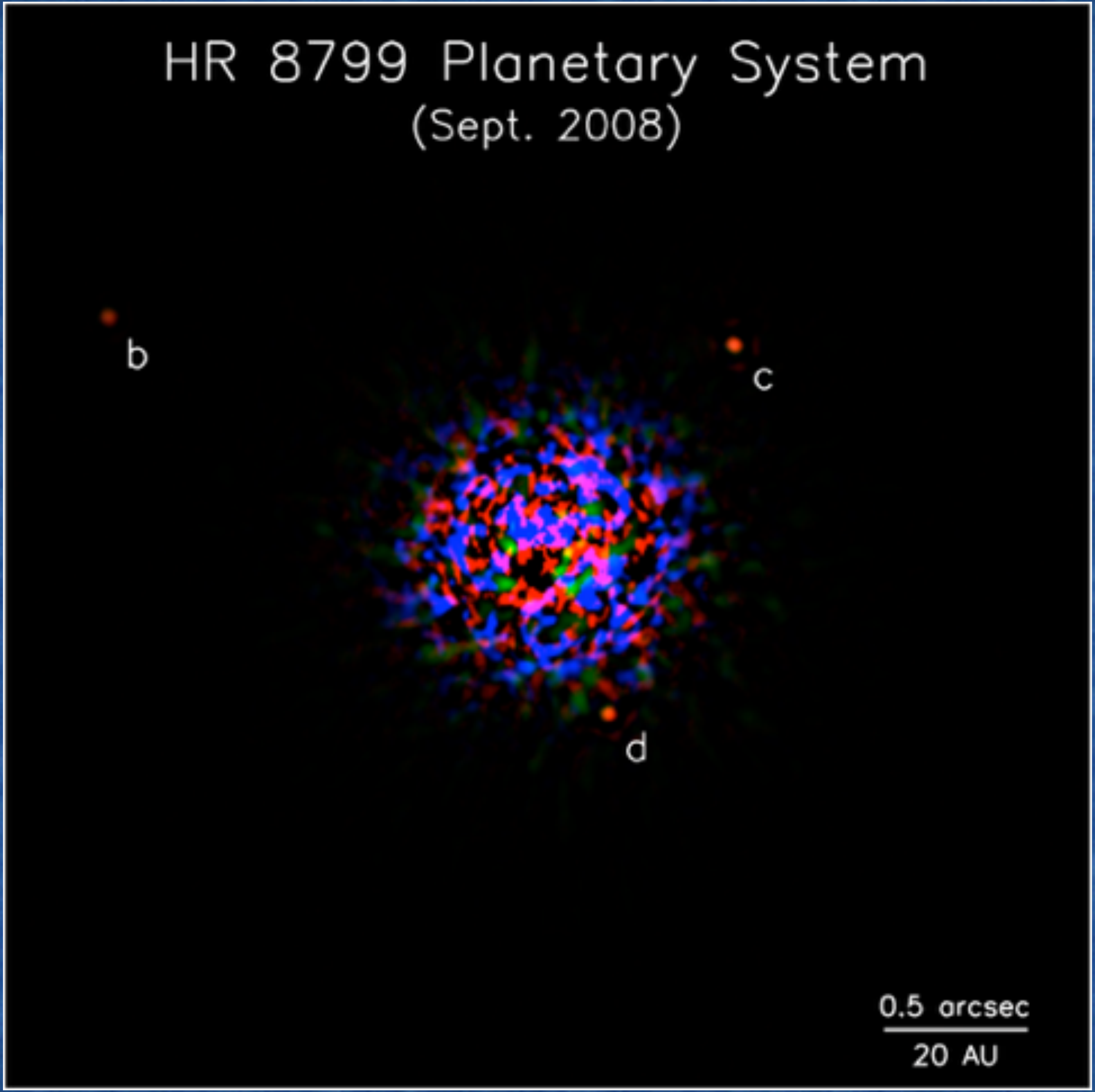
Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered
starlight
"noise"
Location of
Fomalhaut
Coronagraph
mask
Fomalhaut b planet
2004
2006
Background Star
No data
100 AU
13"

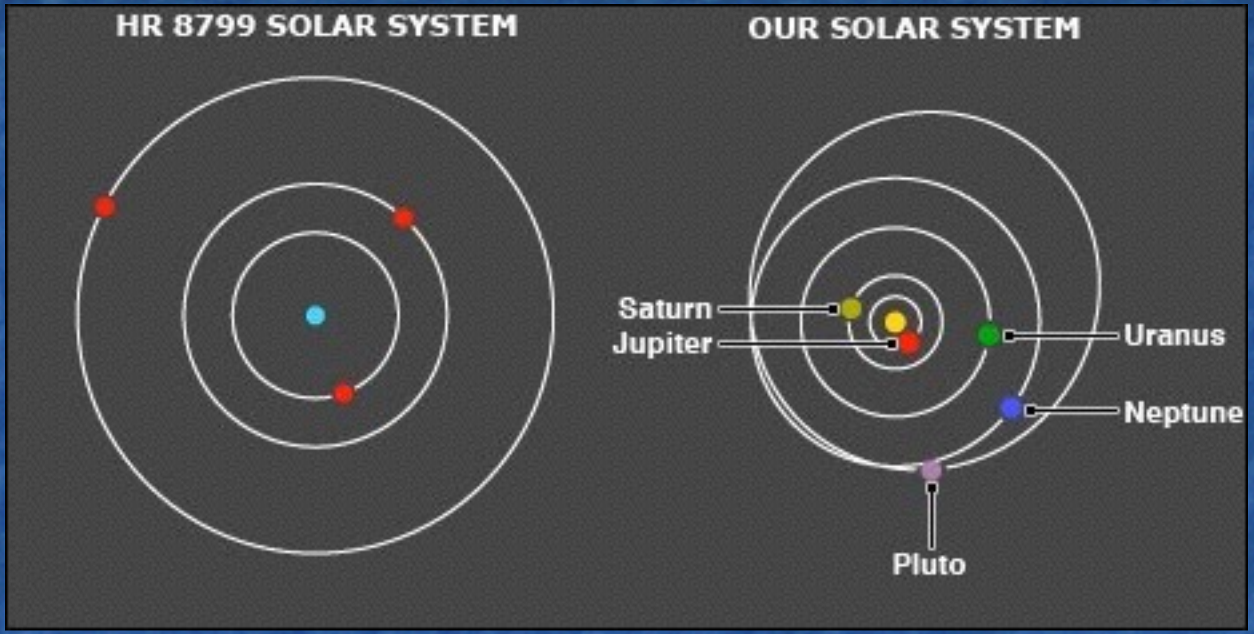
Fomolhaut b



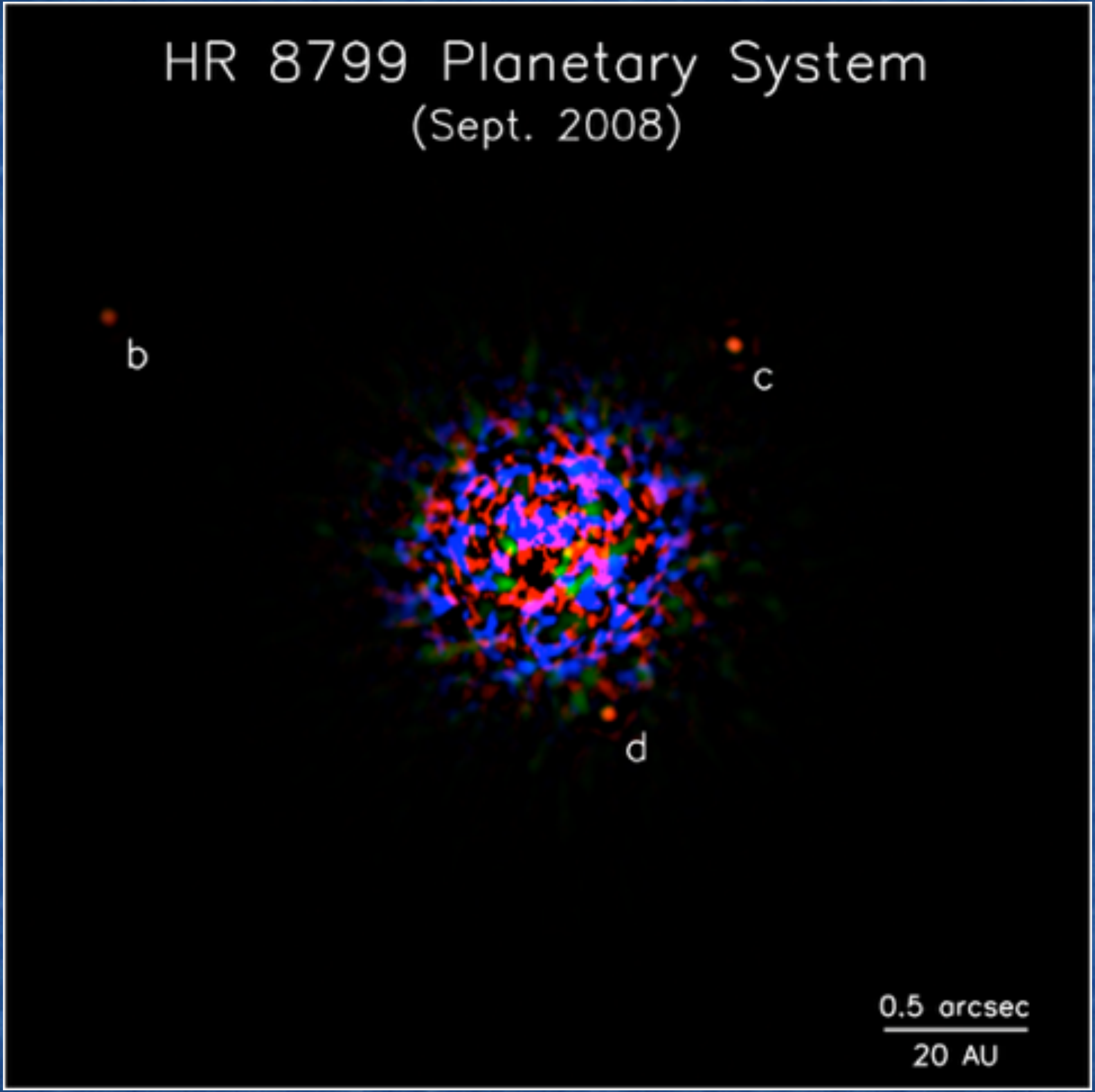
- 25 Ly from Earth
- A3 parent star (hot)
- Jupiter sized planet
- 115 AU, 872 year orbit

HR 8799

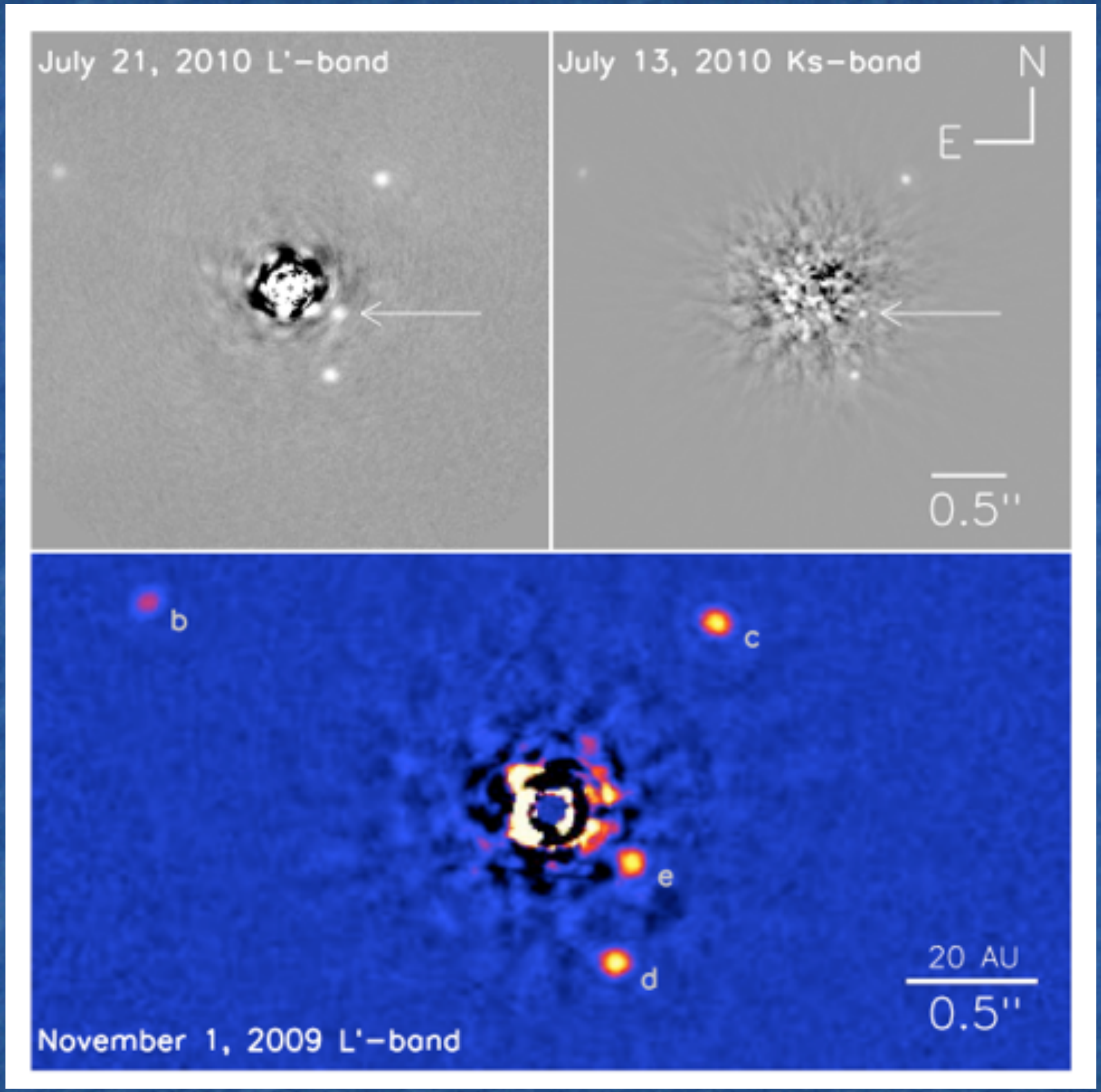




- 130 Ly from Earth
- A5 parent star
- 3 super-Jupiter sized planets
- Room for inner planets

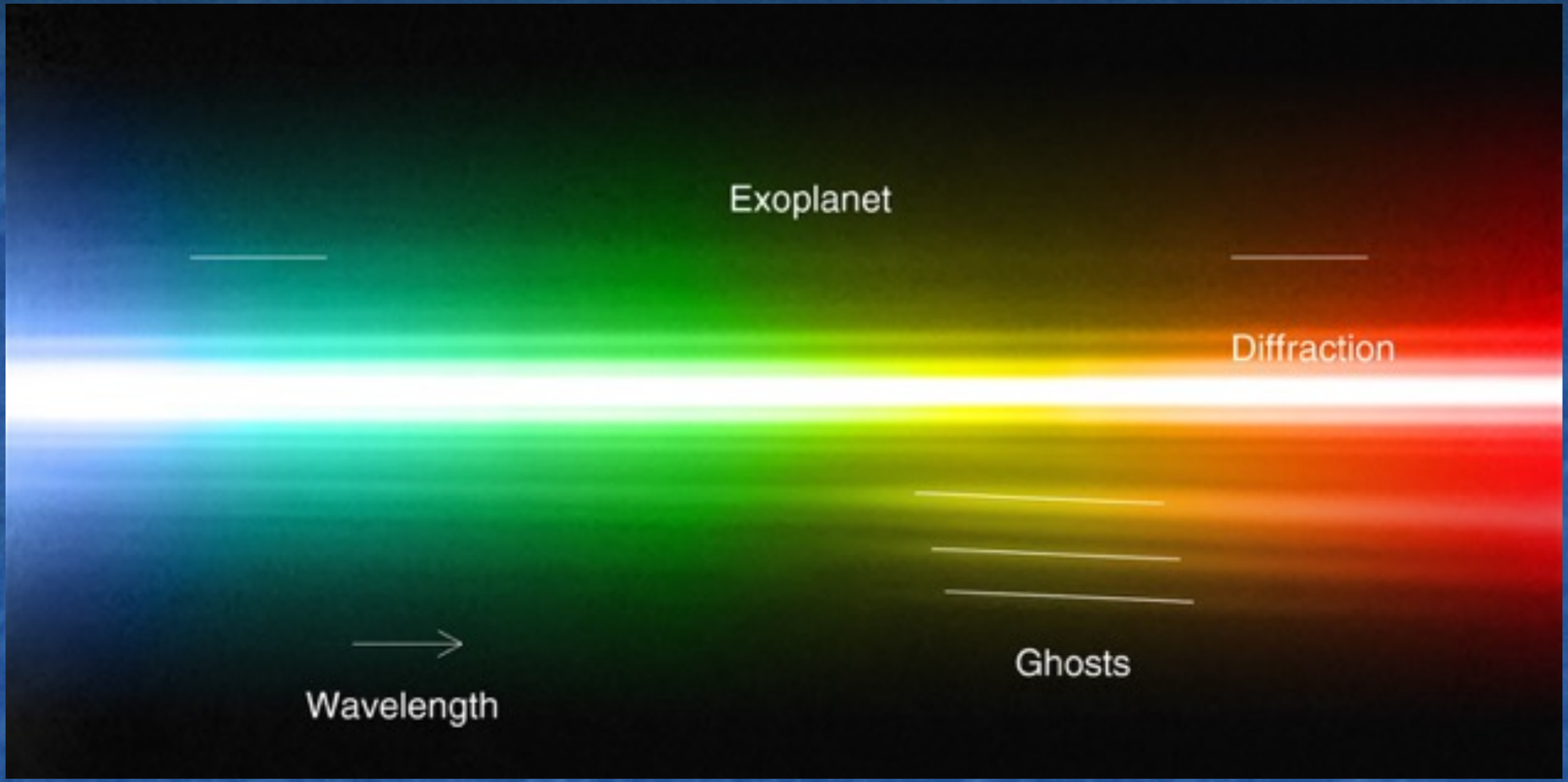


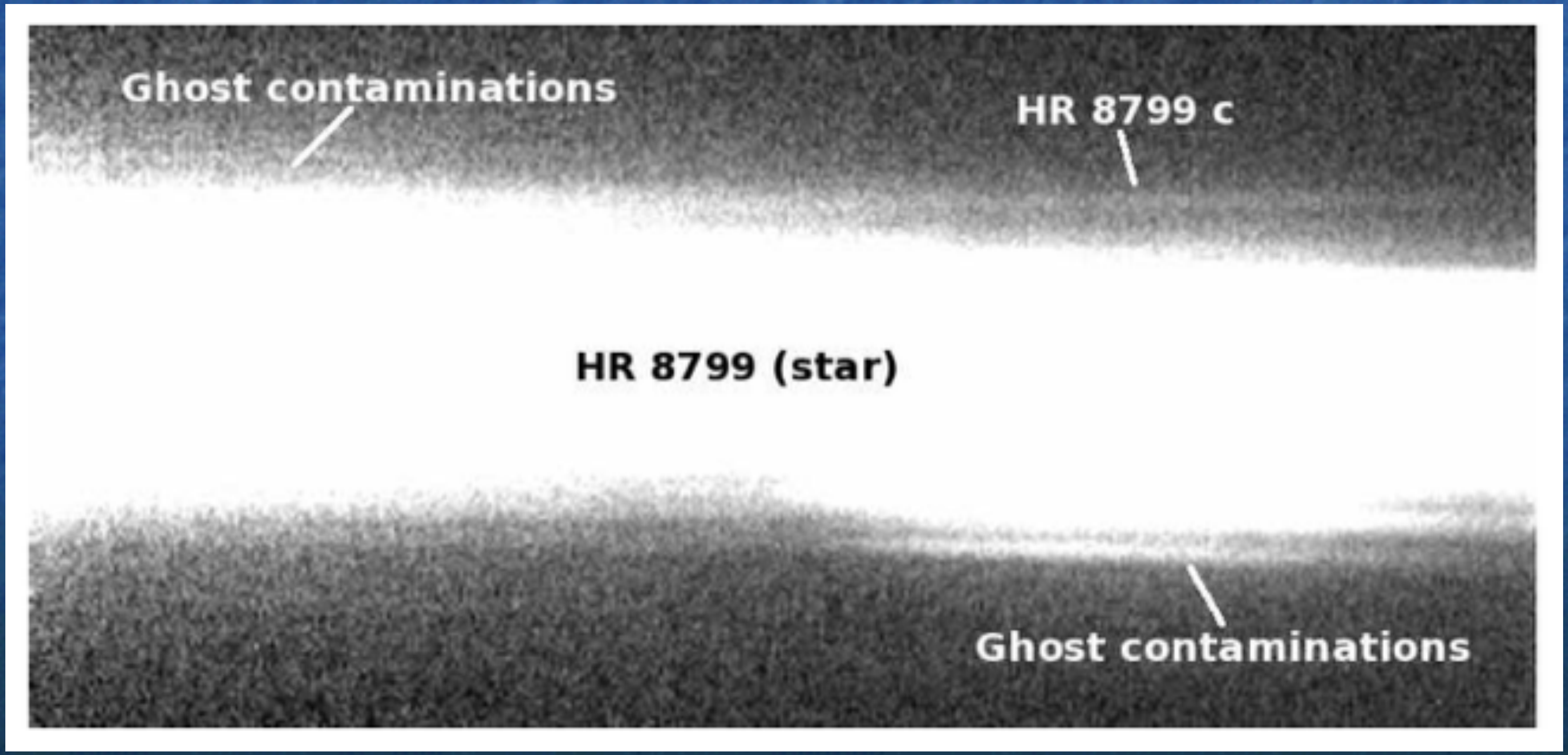
HR 8799 Planetary System
(Sept. 2008)
b
c
d
0.5 arcsec
20 AU



July 21, 2010 L'-band
July 13, 2010 Ks-band
N
E
0.5''
b
c
e
d
20 AU
0.5''
November 1, 2009 L'-band

Direct spectroscopy of HR 8799c





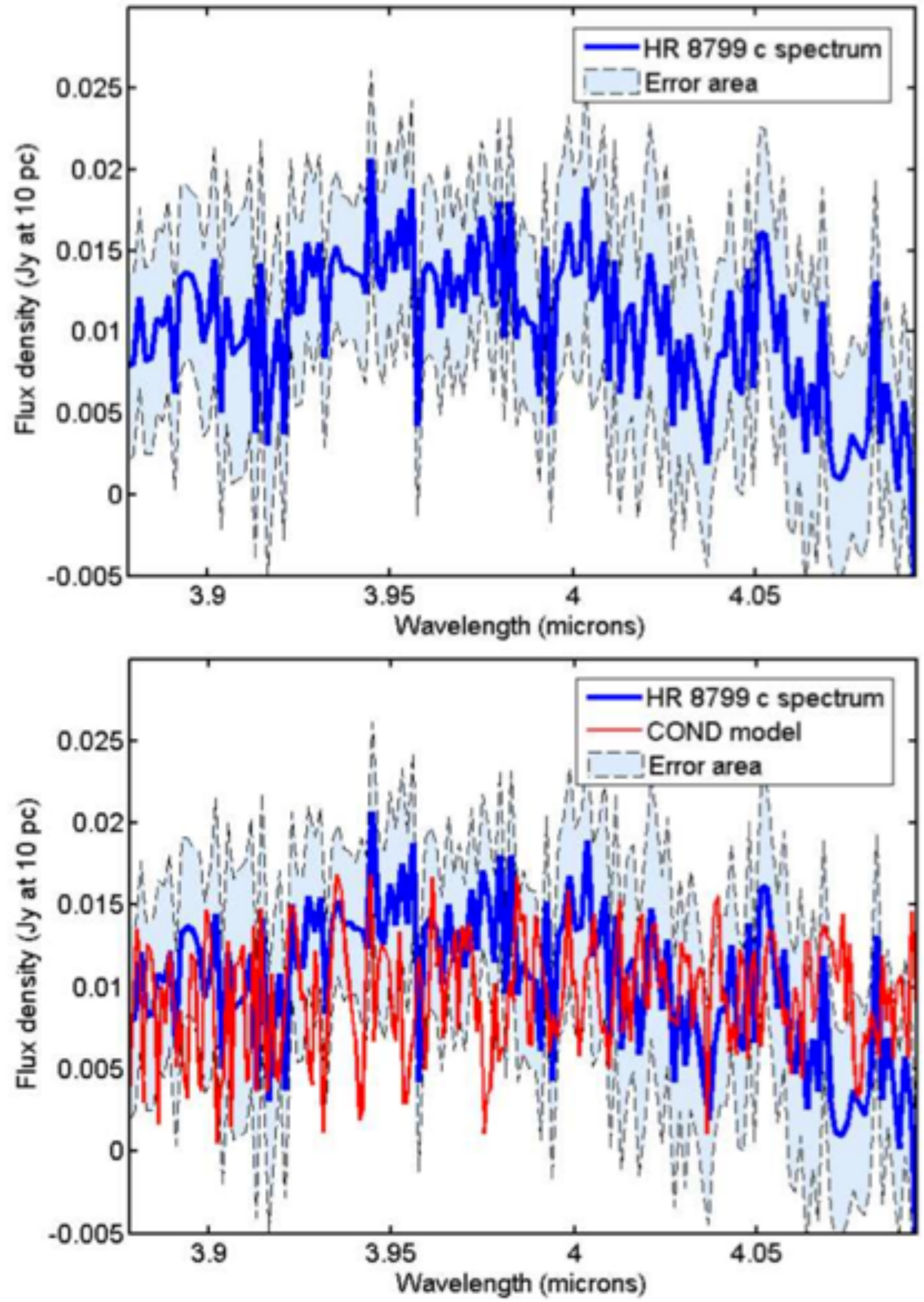
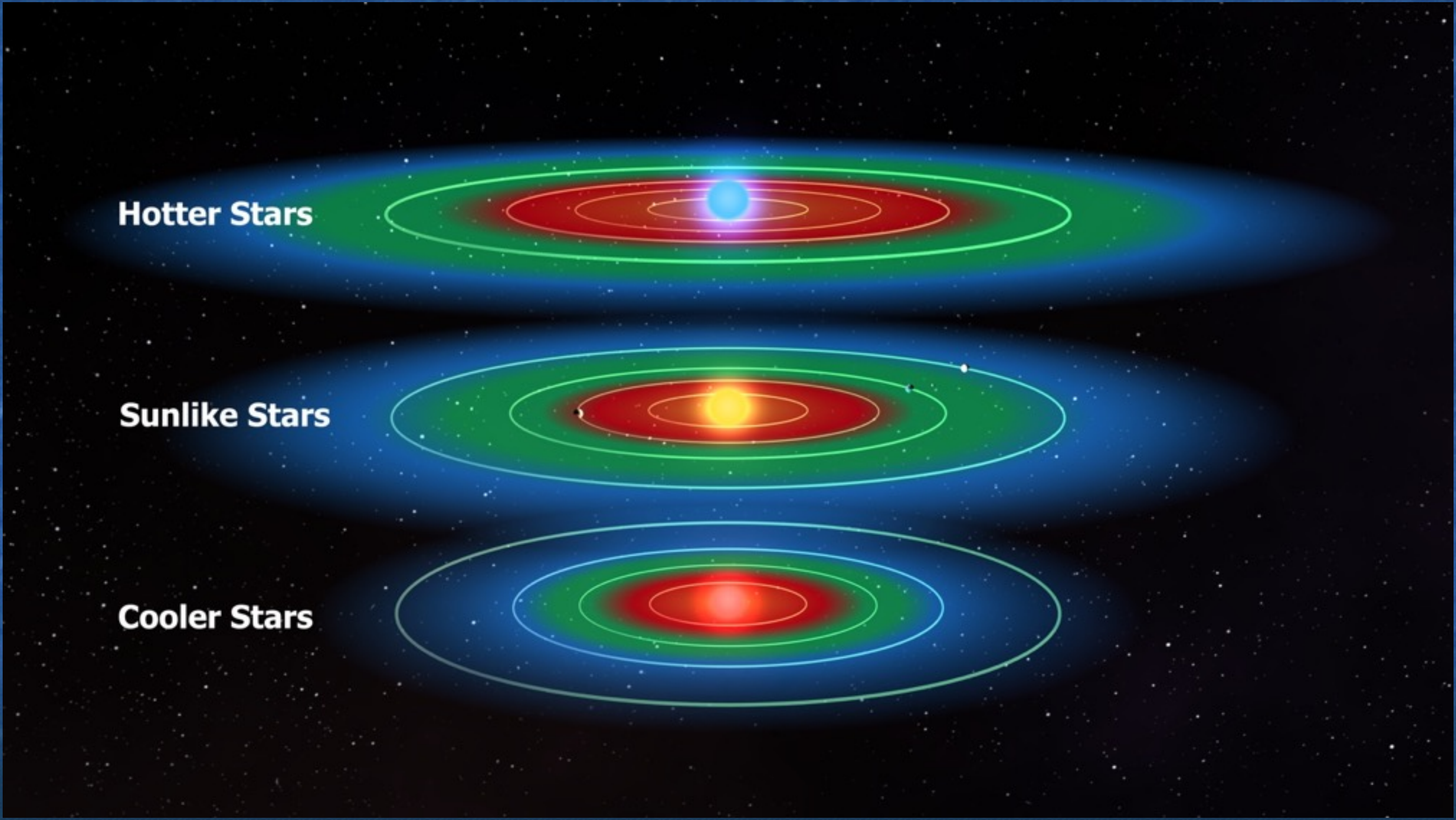


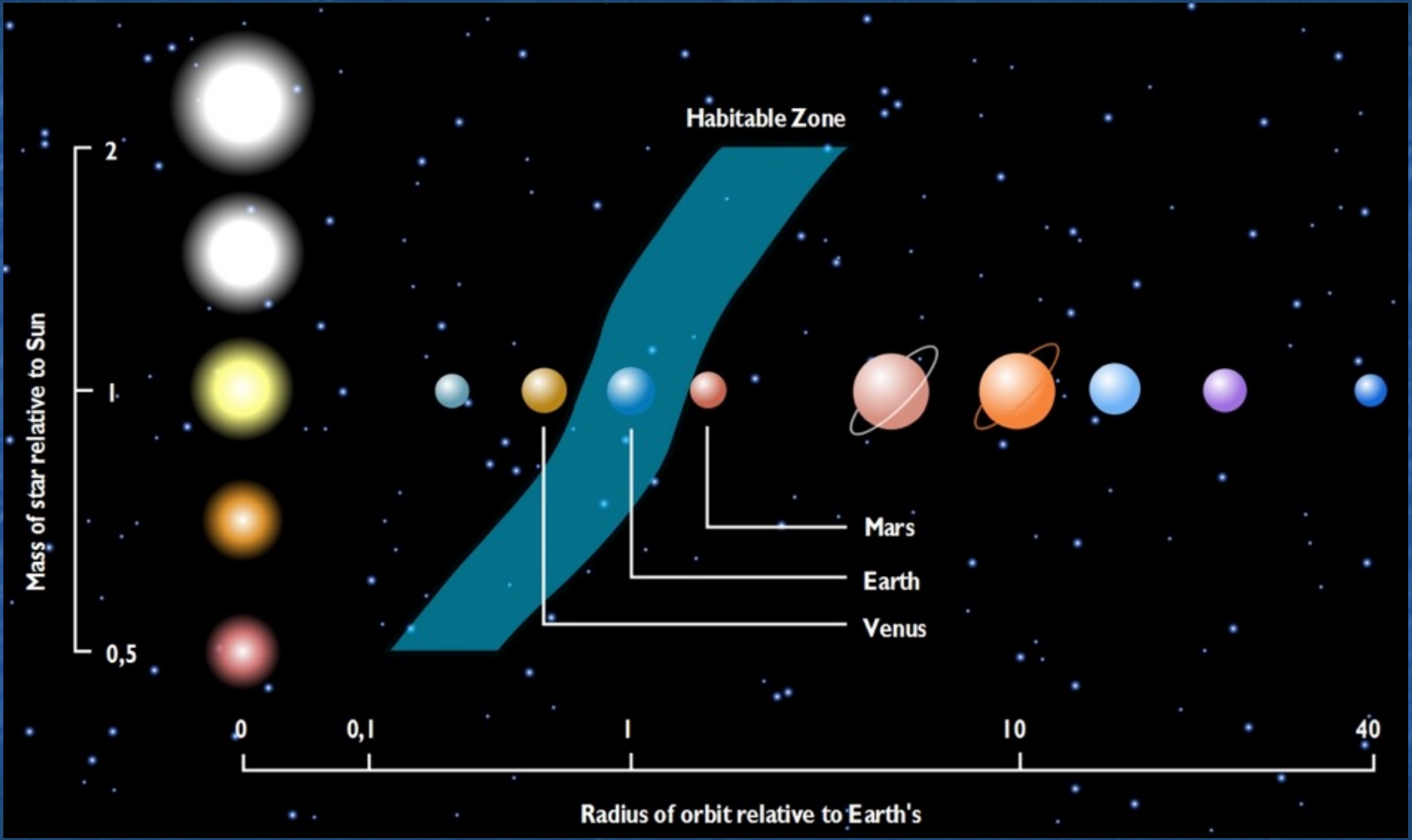
Fig. 3.— Upper: Spectrum of HR 8799 c. The dashed lines and faintly shaded area (light blue in the online version) denote the errors. Lower: Same figure but with a COND model spectrum overplotted as a thinner line (red in the online version).

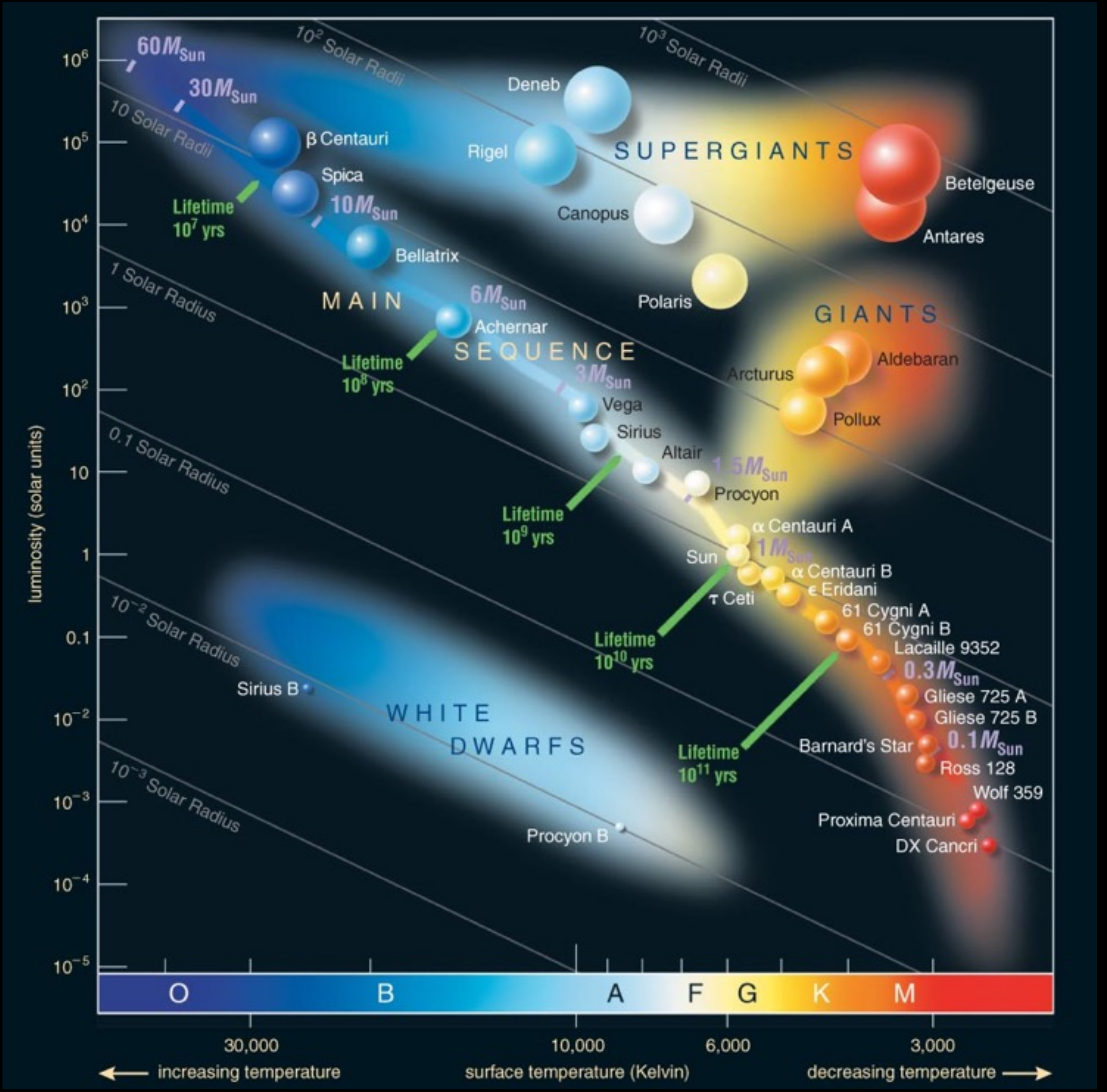
Which stars provide the best habitats?

- Stellar lifetimes and luminosities are the most relevant factors. The "metal" content is a further factor.
- Young supergiant stars (OB-type) are very luminous and have large habitable zones far from the planet.
- However, their lifetimes are measured in millions rather than billions of years.
- Old dwarf stars (KM-type) are under luminous and have small habitable zones - within the tidal locking radius.
- However, they can live for over 10 billion years.
- As far as we are concerned, the Sun, a G-type dwarf, is "just right".

The habitable zones of stars of different temperatures




Habitable Zone
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's



60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Canopus
Polaris
Betelgeuse
Antares
SUPERGIANTS
GIANTS
Aldebaran
Arcturus
Pollux
MAIN
SEQUENCE
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
WHITE
DWARFS
Sirius B
Procyon B
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

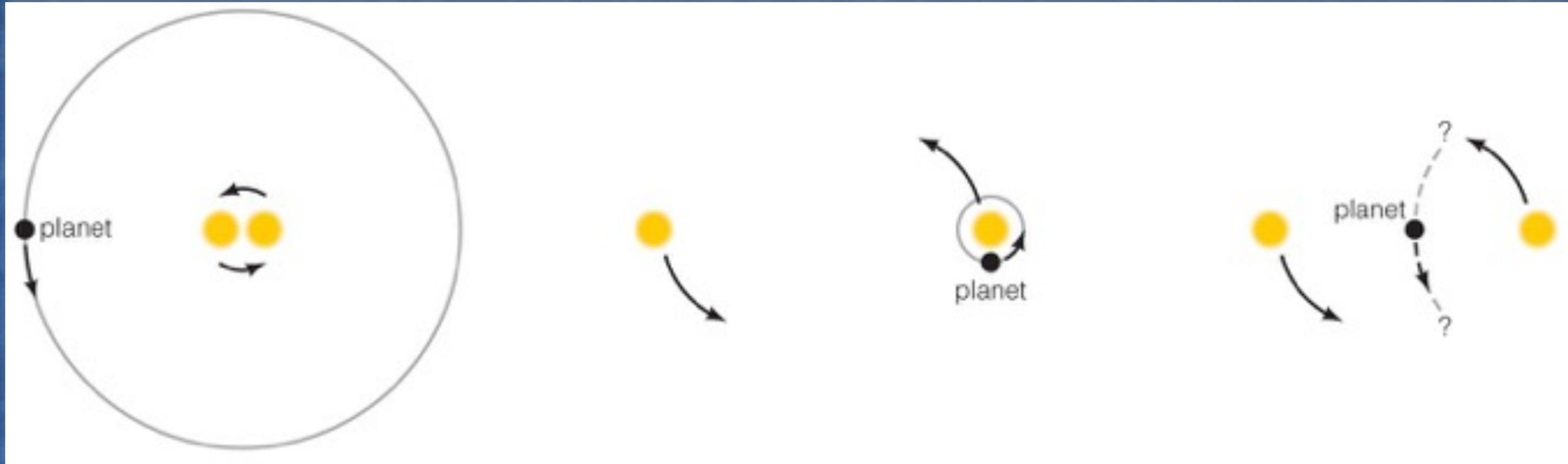
Lifetimes and Numbers of Stars of Different Spectral Types

TABLE 11.1 *Typical Properties for Hydrogen-Burning Stars of the Seven Major Spectral Types*

Numbers given in solar units are values in comparison to the Sun; for example, a mass of 60 solar units means 60 times the mass of the Sun. Note that the Sun is a G star. (More specifically, the Sun's spectral type is G2.)

Spectral Type	*Approximate Percentage of Stars in This Class*	*Surface Temperature (°C)*	*Luminosity (solar units)*	*Mass (solar units)*	*Lifetime (years)*
O	0.001%	50,000	1,000,000	60	500 thousand
B	0.1%	15,000	1,000	6	50 million
A	1%	8,000	20	2	1 billion
F	2%	6,500	7	1.5	2 billion
G	7%	5,500	1	1	10 billion
K	15%	4,000	0.3	0.7	20 billion
M	75%	3,000	0.003	0.2	600 billion

Planets in Binary Systems

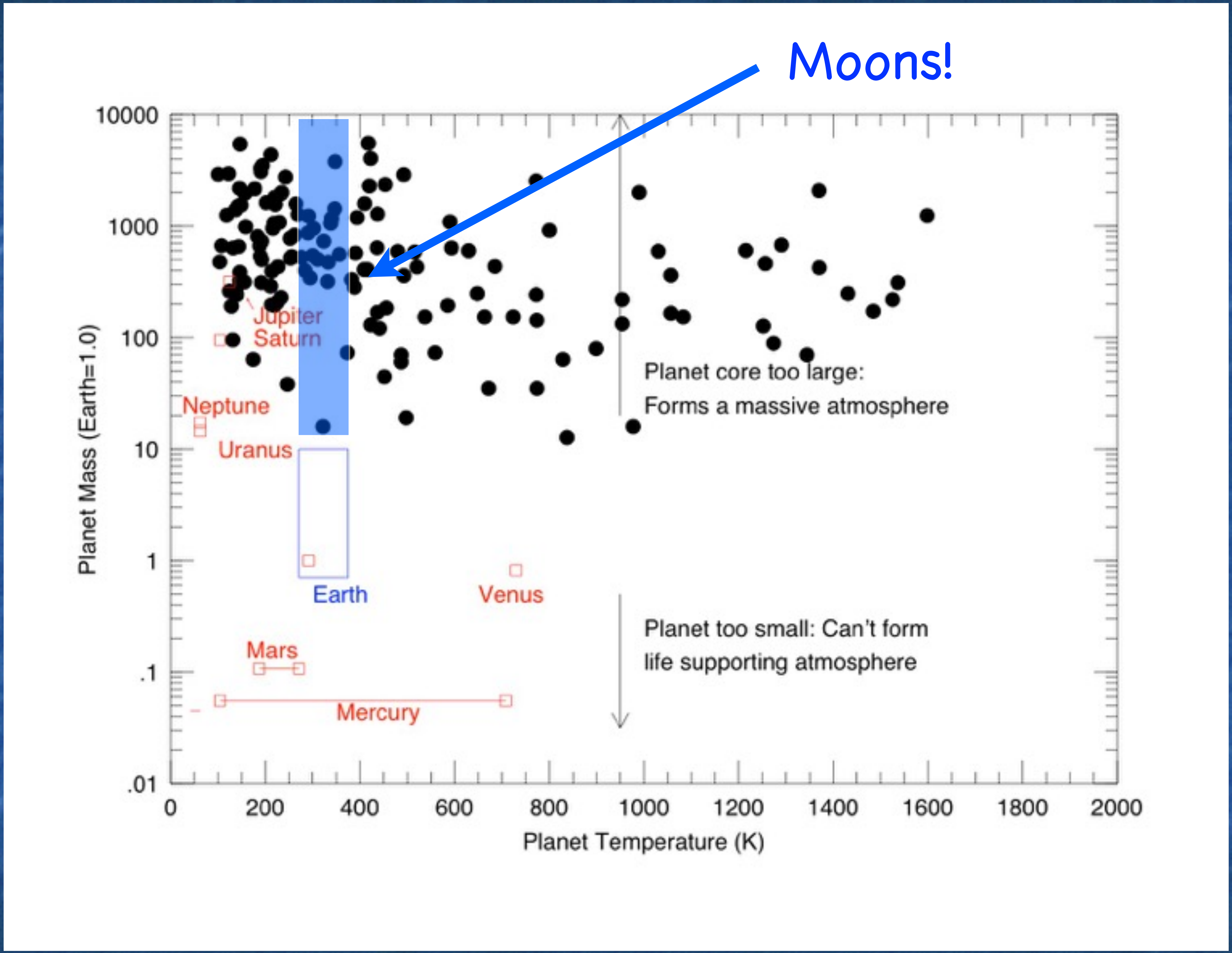


a *Potentially stable:* The planet orbits both stars; the radius of the planet's orbit is much larger than the separation between the stars.

b *Potentially stable:* The planet orbits one star; the radius of the planet's orbit is much smaller than the separation between the stars.

c *Not stable:* The orbit of the planet is neither much larger nor much smaller than the separation between the stars

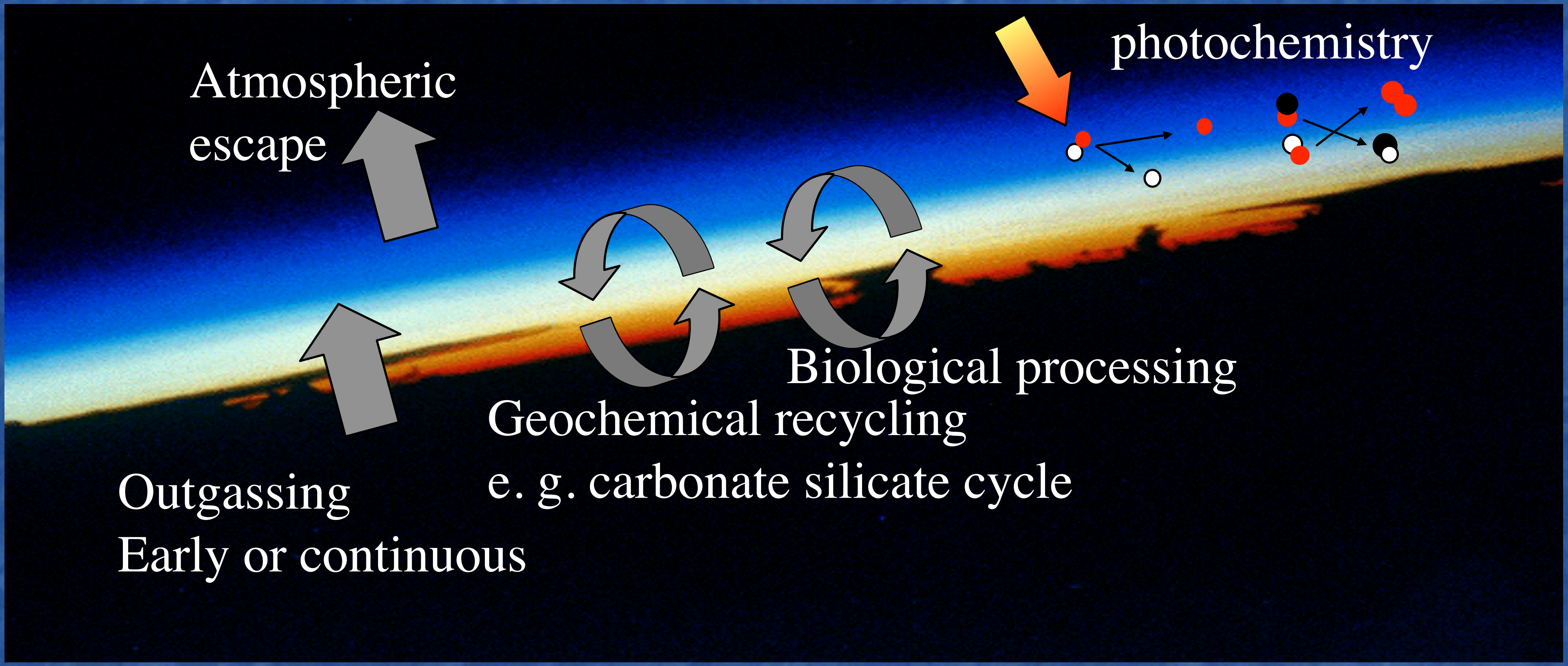
- Stable planetary orbits are possible if the stars are either quite close together or well separated
  - a) planet's orbital distance is more than 5 times the separation between the stars
  - b) planet's orbital distance is less than 1/5 the separation between the stars


Moons!
10000
1000
100
10
1
.1
.01
Planet Mass (Earth=1.0)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Planet Temperature (K)
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
Mars
Mercury
Planet core too large:
Forms a massive atmosphere
Planet too small: Can't form
life supporting atmosphere

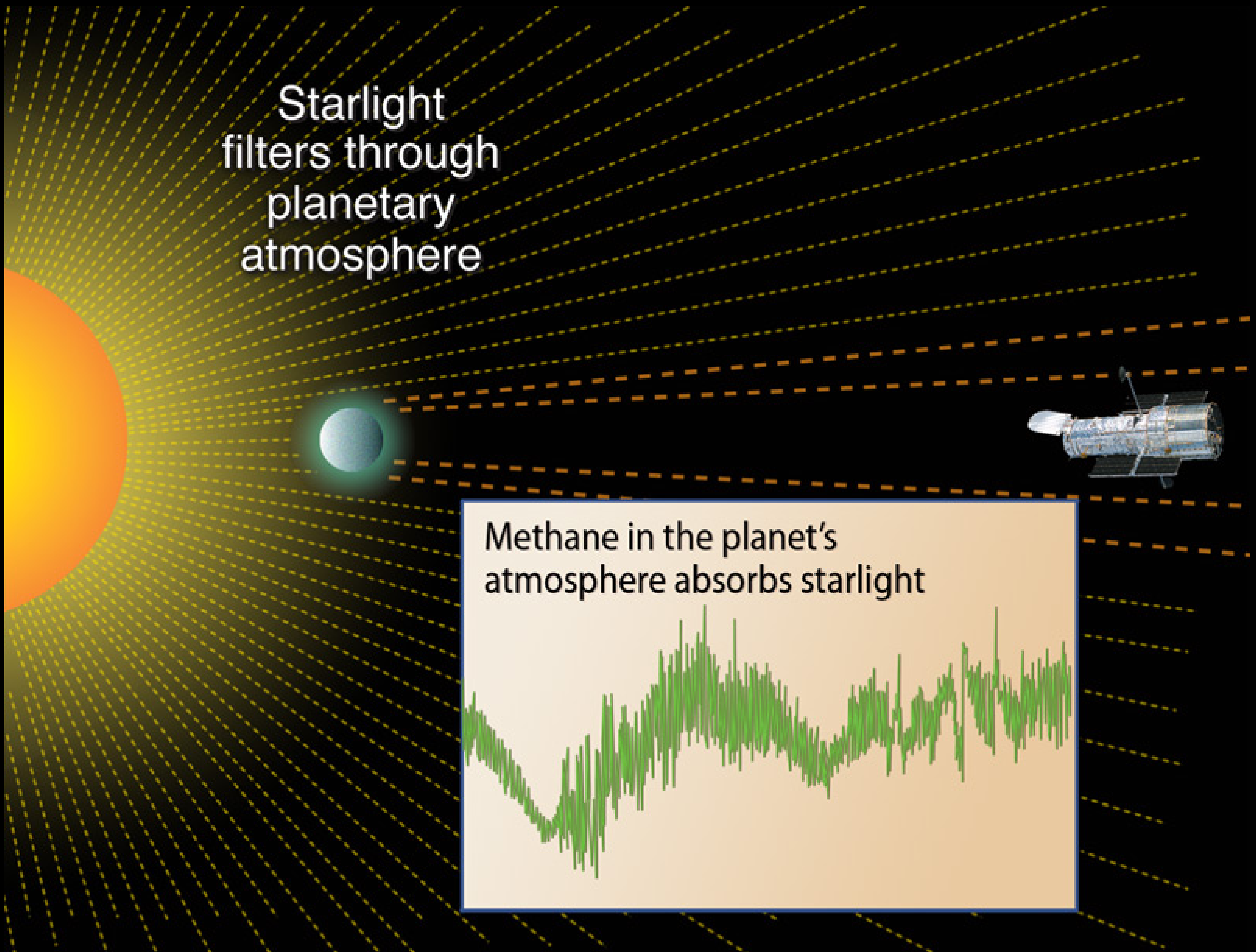
Can we detect atmospheres?

- Yes!
- The first planetary atmospheres have been detected.
- The method is indirect: as the planet transits in front of the star some of the starlight is absorbed at wavelengths characteristic of atmospheric constituents, e.g. methane.
- A tiny fraction of planets can current be imaged directly. We are viewing starlight reflected from their surfaces.
- However, the future will see direct spectroscopy of planet atmospheres.
- What will we look for? Signatures of biologically driven chemical disequilibrium.

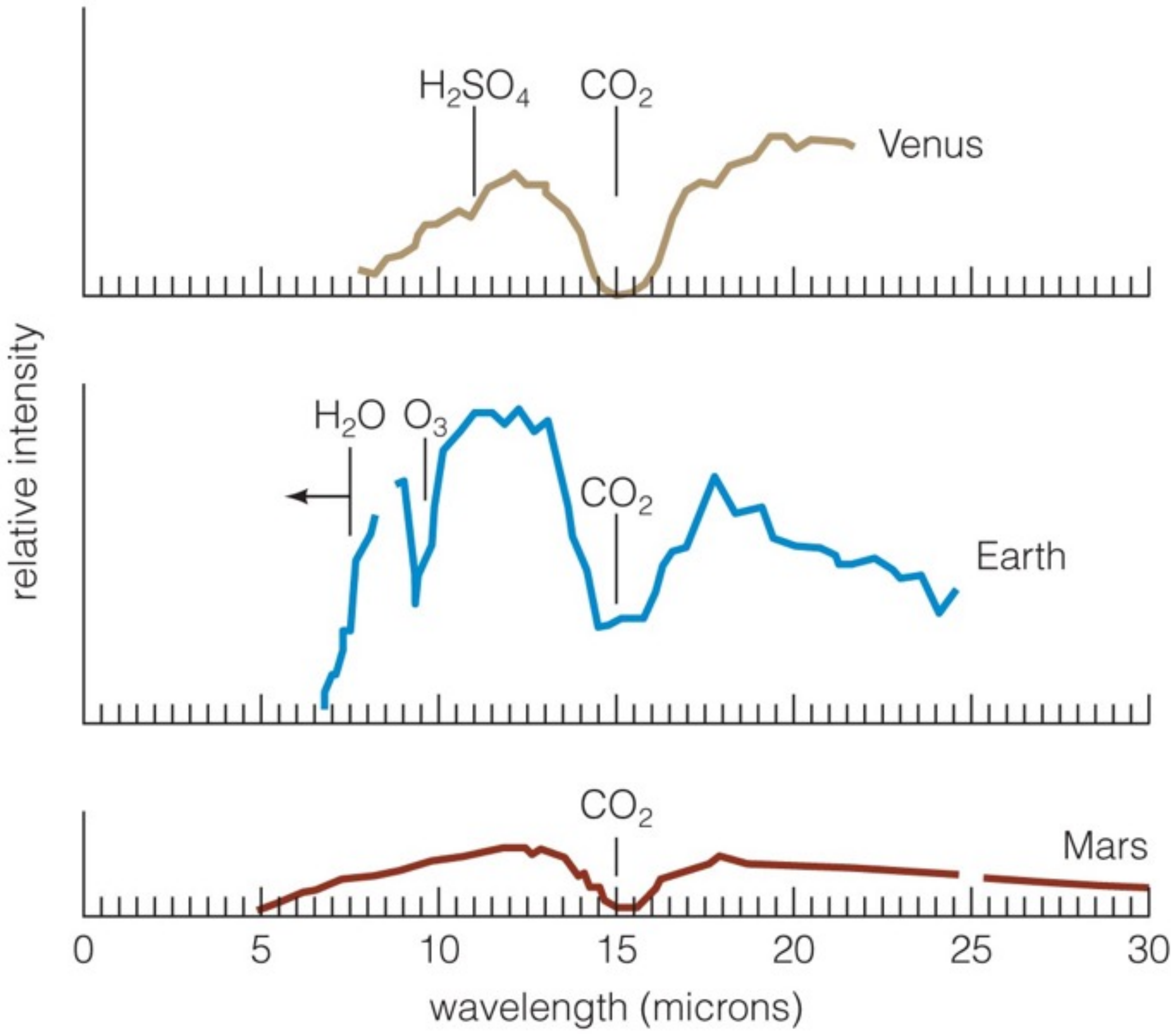
Atmospheric processing

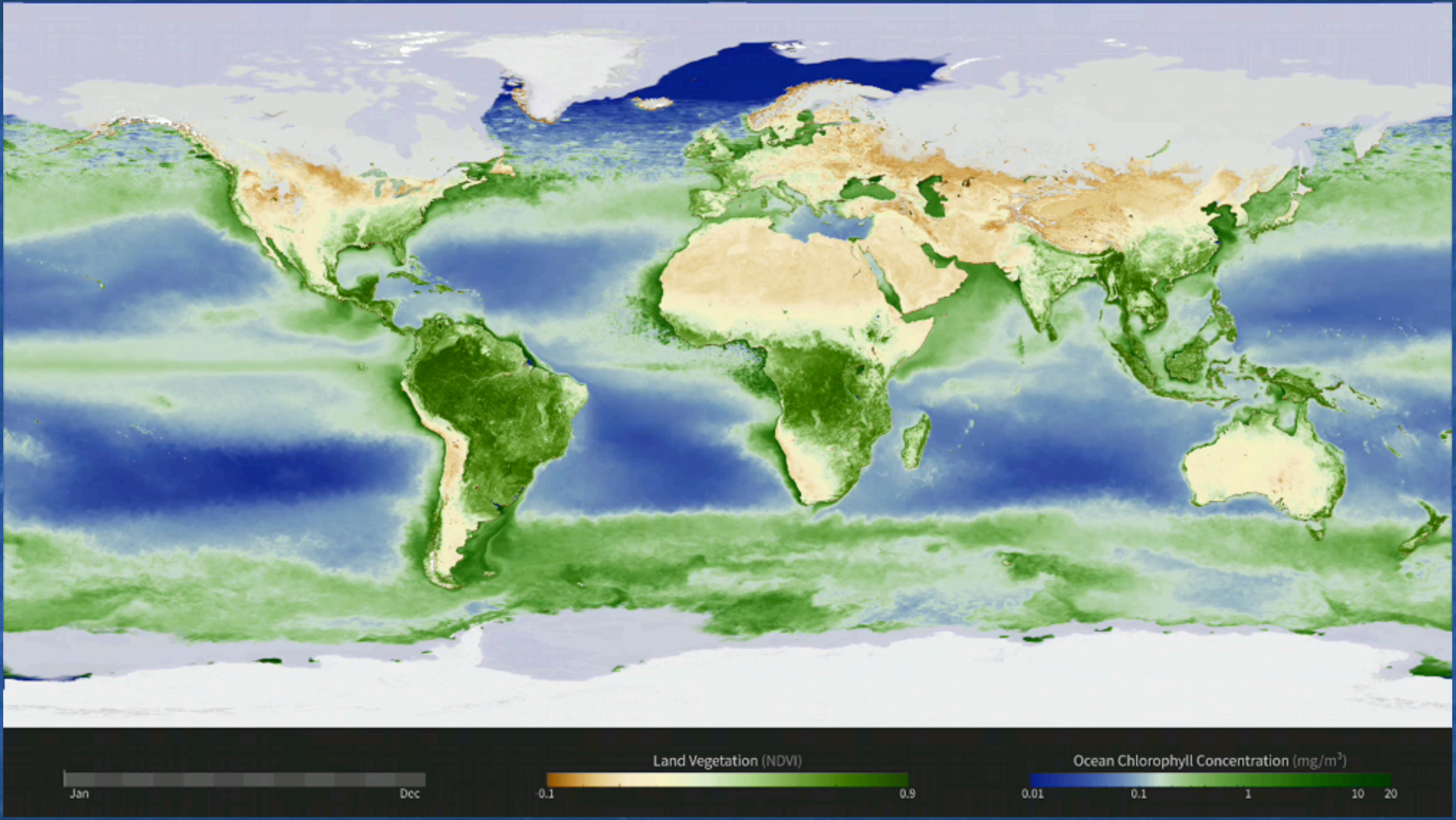


Hubble Detects Methane in the Atmosphere of an Exoplanet



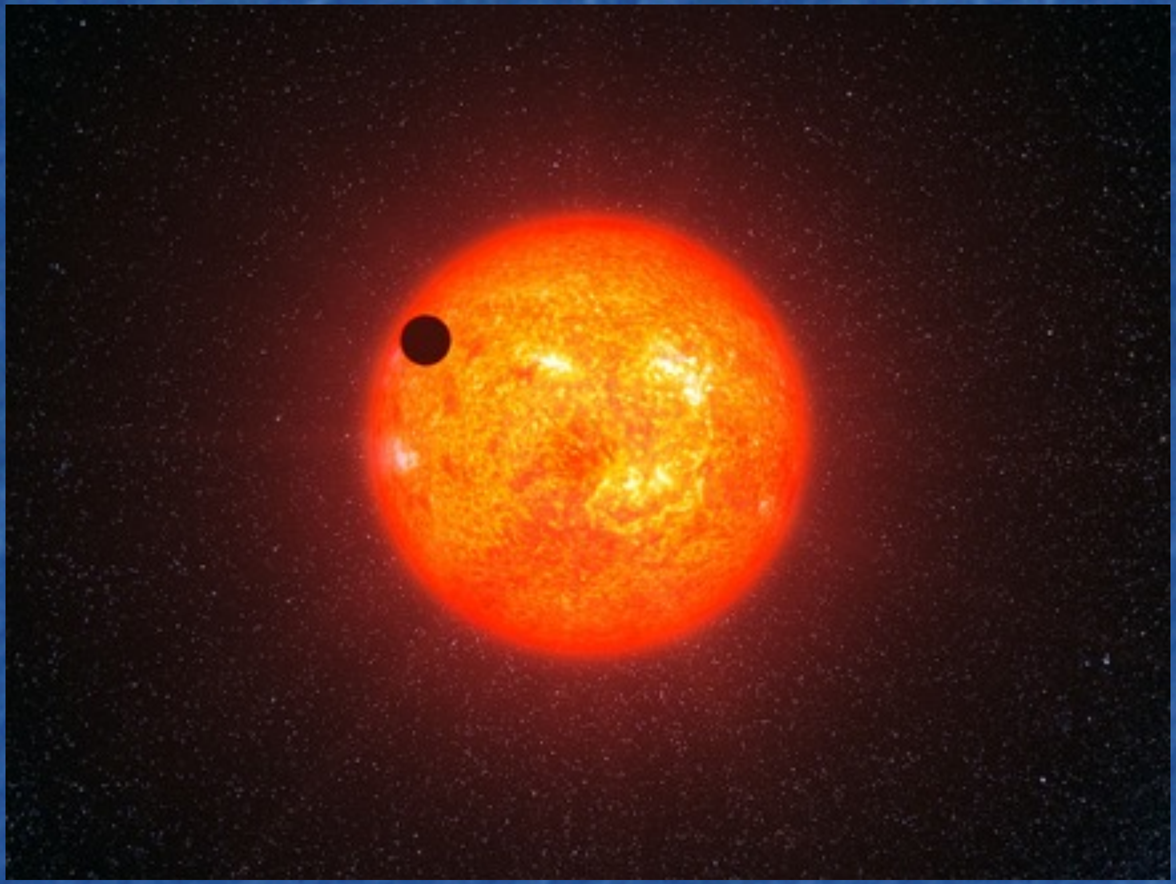
The Remote Detection of Life





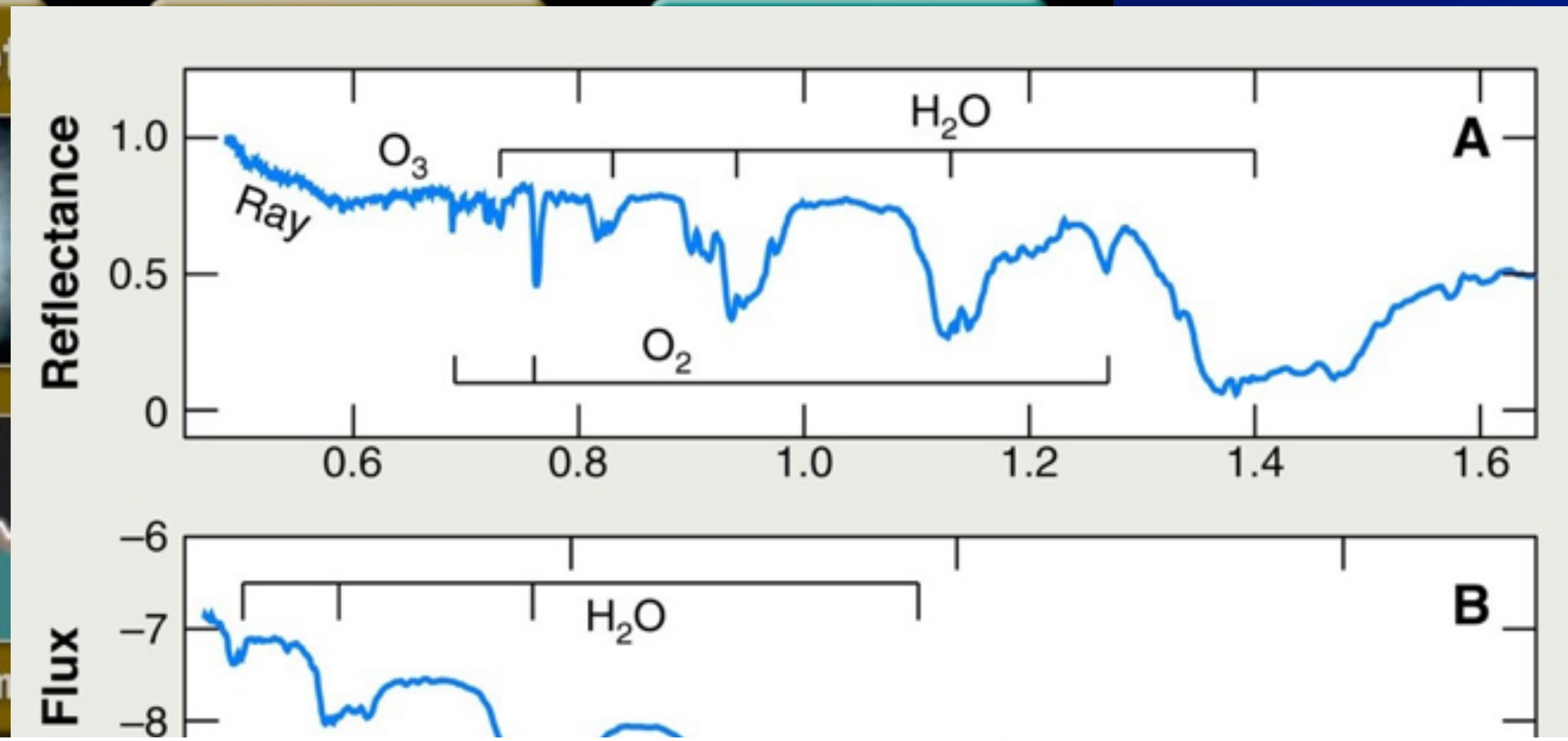
Jan
Dec
Land Vegetation (NDVI)
-0.1
0.9
Ocean Chlorophyll Concentration (mg/m³)
0.01
0.1
1
10
20

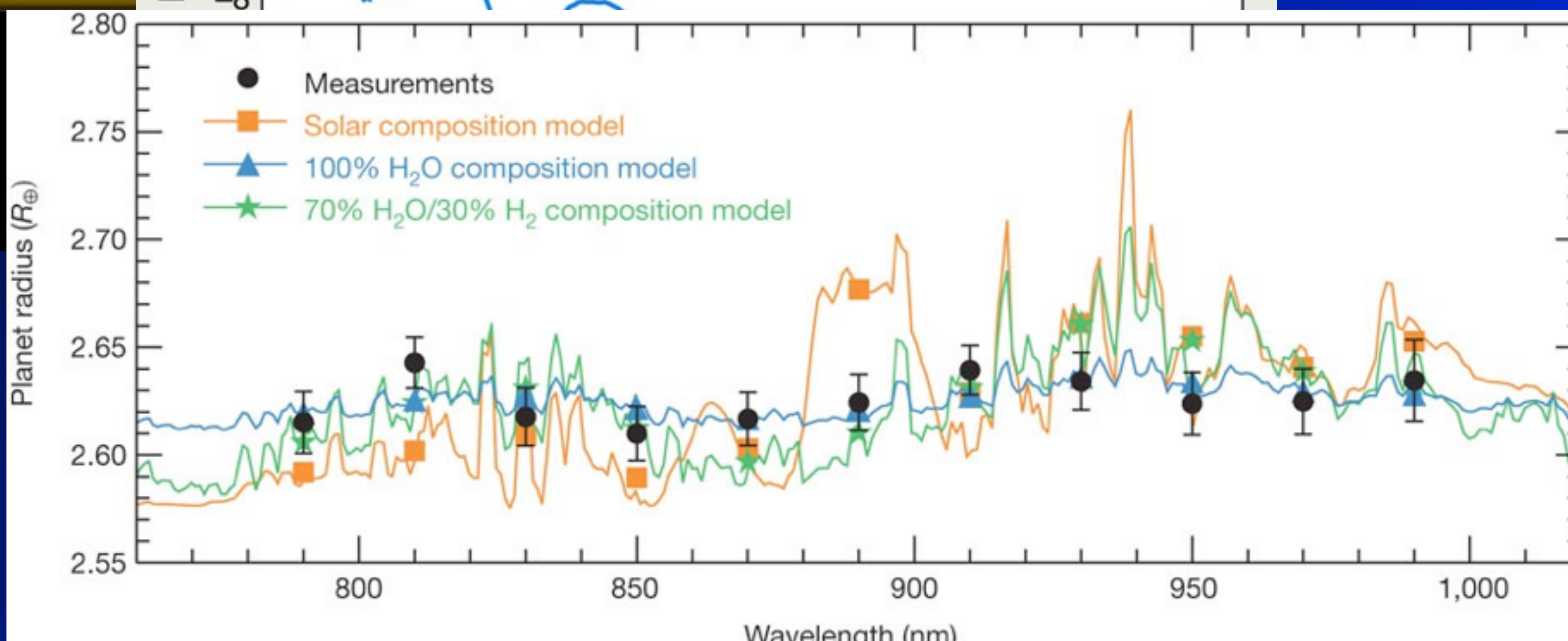
GJ1214b

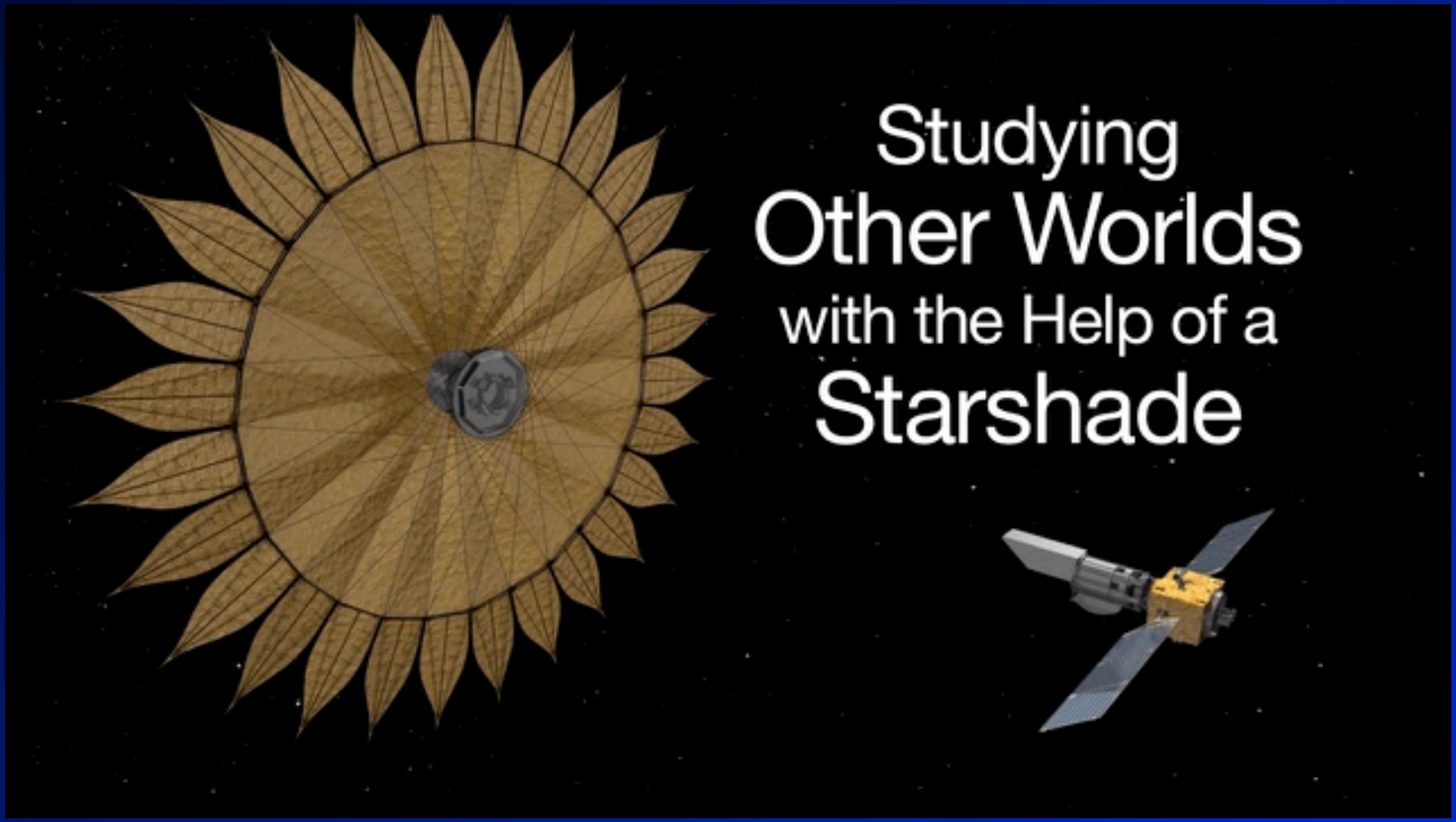


- Super-Earth orbiting a red dwarf star (M4).
- 42 Ly from Earth.
- 6 Earth masses, 2.6 Earth radii
- Density of 1800 kg m^{-3}.
- Receives 16 times the stellar radiation of Earth.

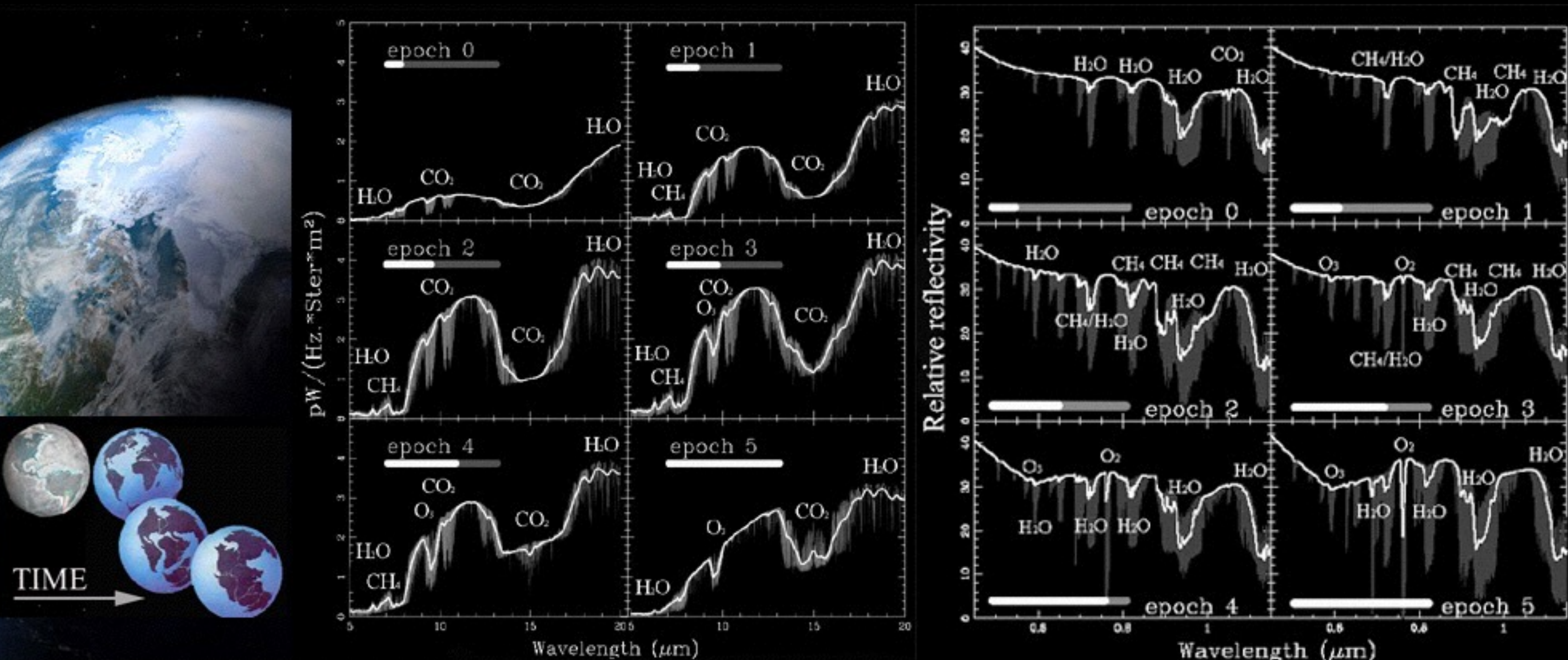

Star + Planet
Combined Spectrum


Reflectance
1.0
0.5
0
0.6
0.8
1.0
1.2
1.4
1.6
H_2O
O_3
Ray
O_2
A
Flux
−6
−7
−8
H_2O
B


Measurements
Solar composition model
100% H_2O composition model
70% H_2O/30% H_2 composition model
Planet radius ($R_\oplus$)
2.80
2.75
2.70
2.65
2.60
2.55
800
850
900
950
1,000
Wavelength (nm)


Studying
Other Worlds
with the Help of a
Starshade

Earth Evolution over geological time

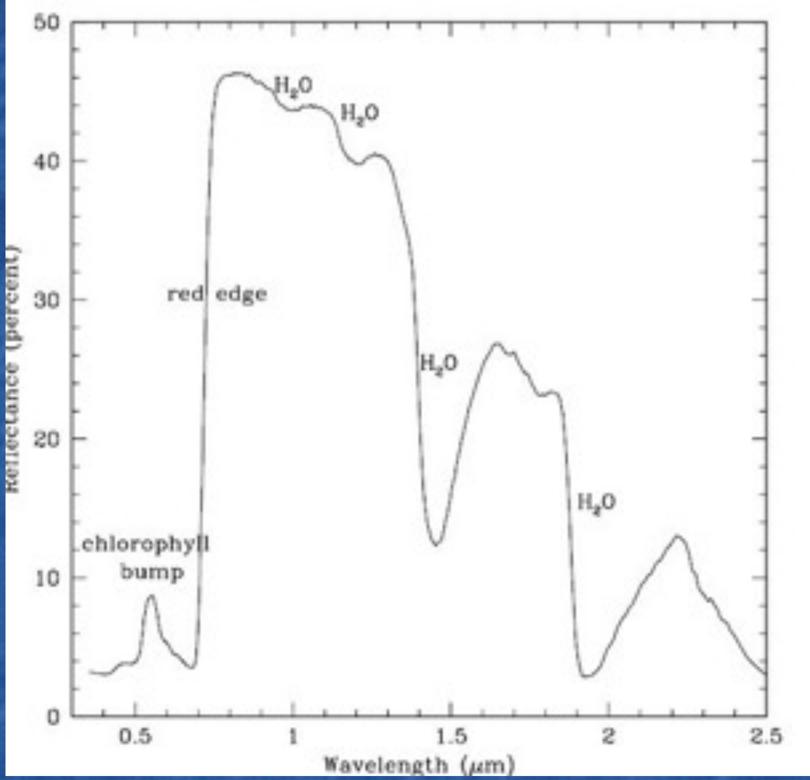


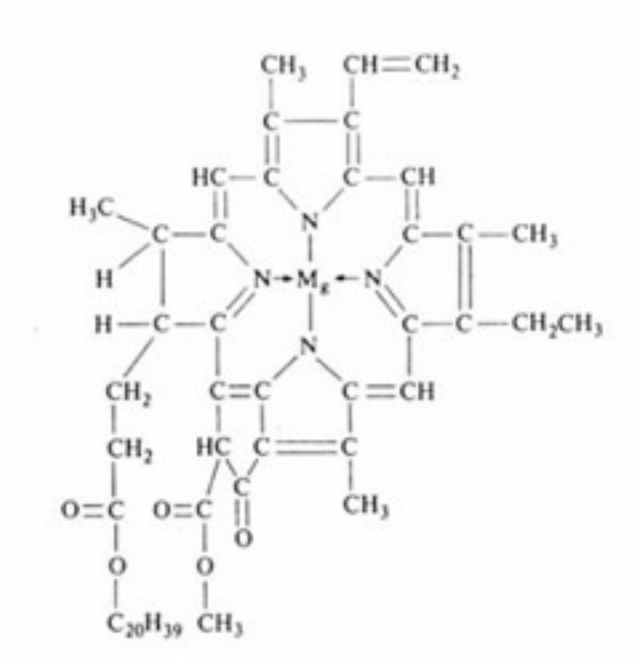
Kaltenegger et al 2007 ApJ

Can we detect life on Earth?

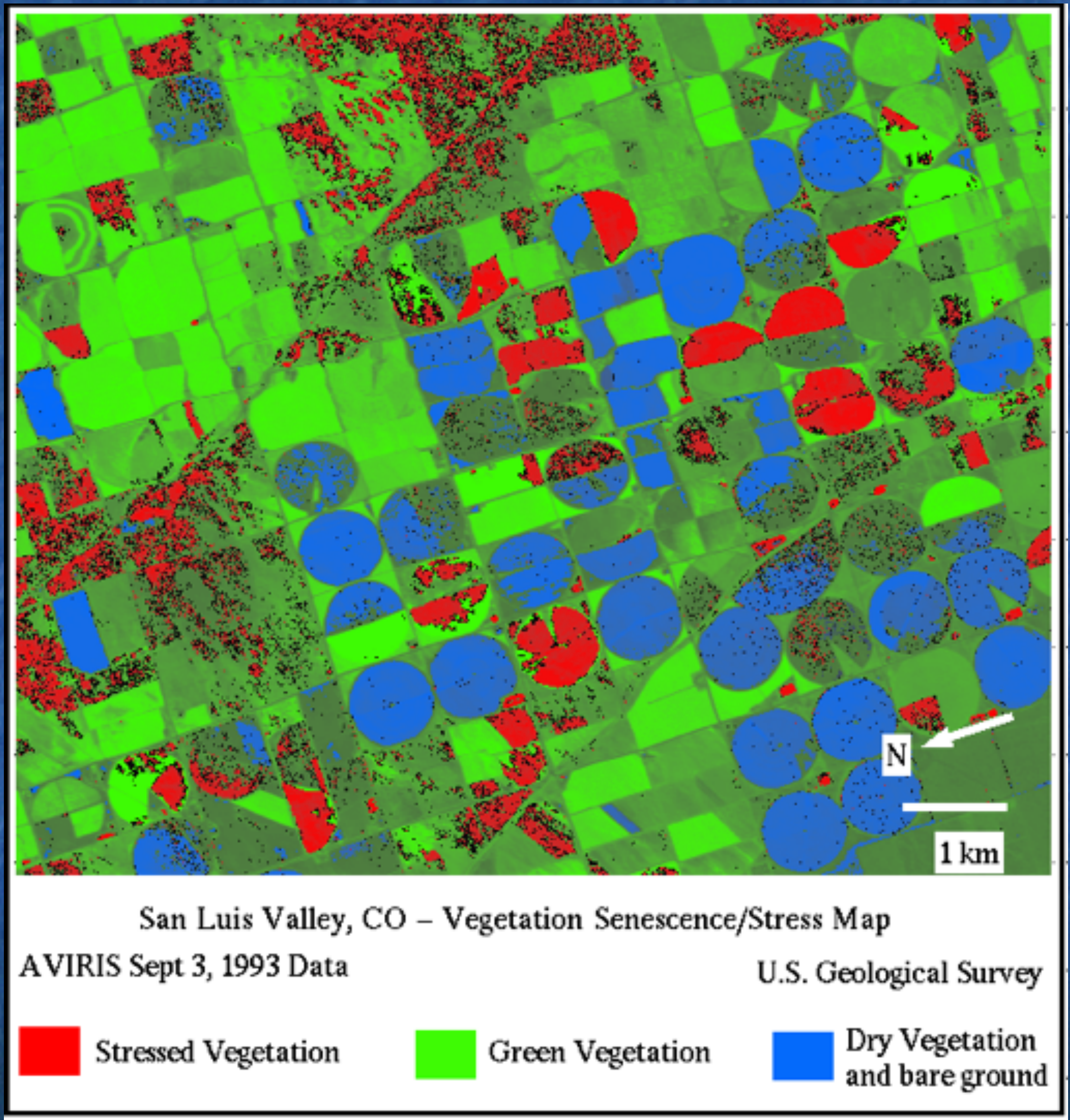
- In 1990 the Galileo spacecraft flew by Earth to gain orbital energy en route to Jupiter.
- Carl Sagan suggested using Galileo's instruments to detect life on Earth.
- Test run for detecting planetary bio-signatures in a flyby mission.
- Abundant atmospheric oxygen and methane (in extreme thermodynamic disequilibrium).
- Strong absorption red-edge inconsistent with known rock and soil types.
- Anomalous narrow-band, pulsed radio emission.
- No evidence of surface engineering associated with advanced civilisations.

The vegetation red edge



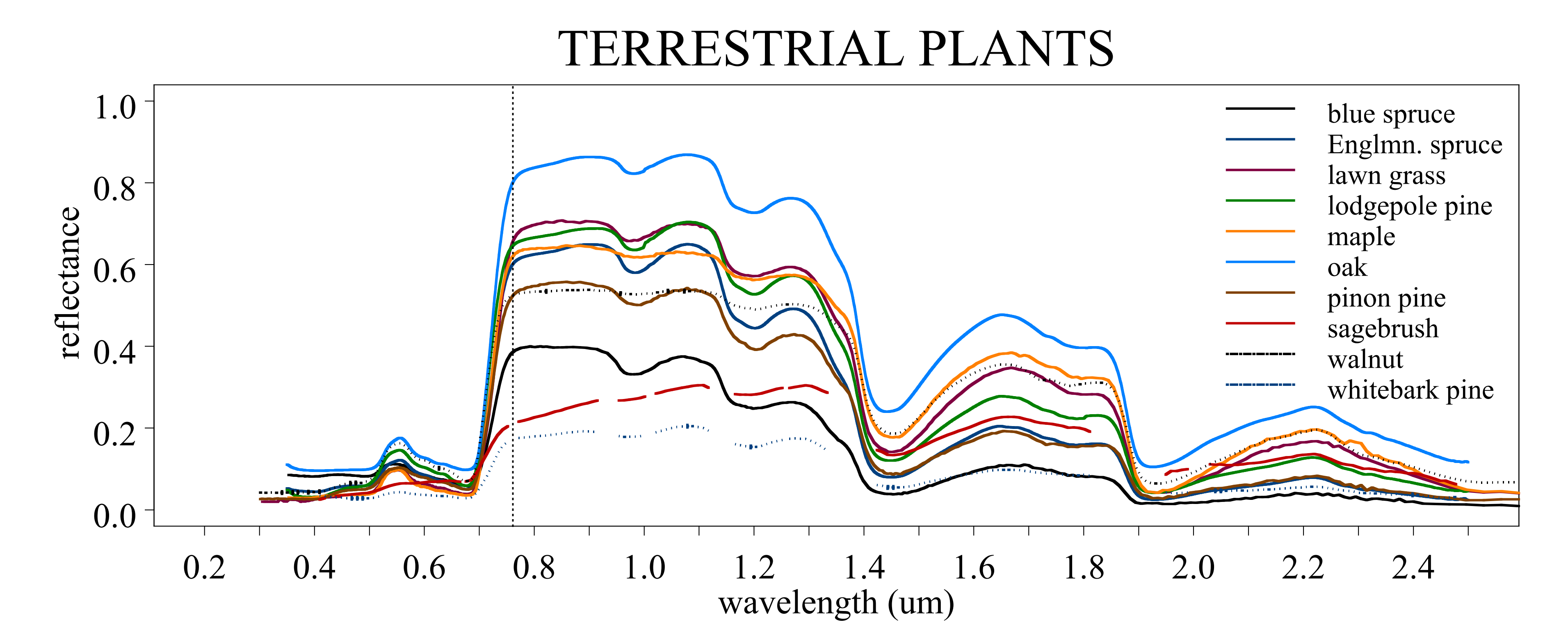


Chlorophyll



Should we expect to see the red-edge on a vegetated planet?

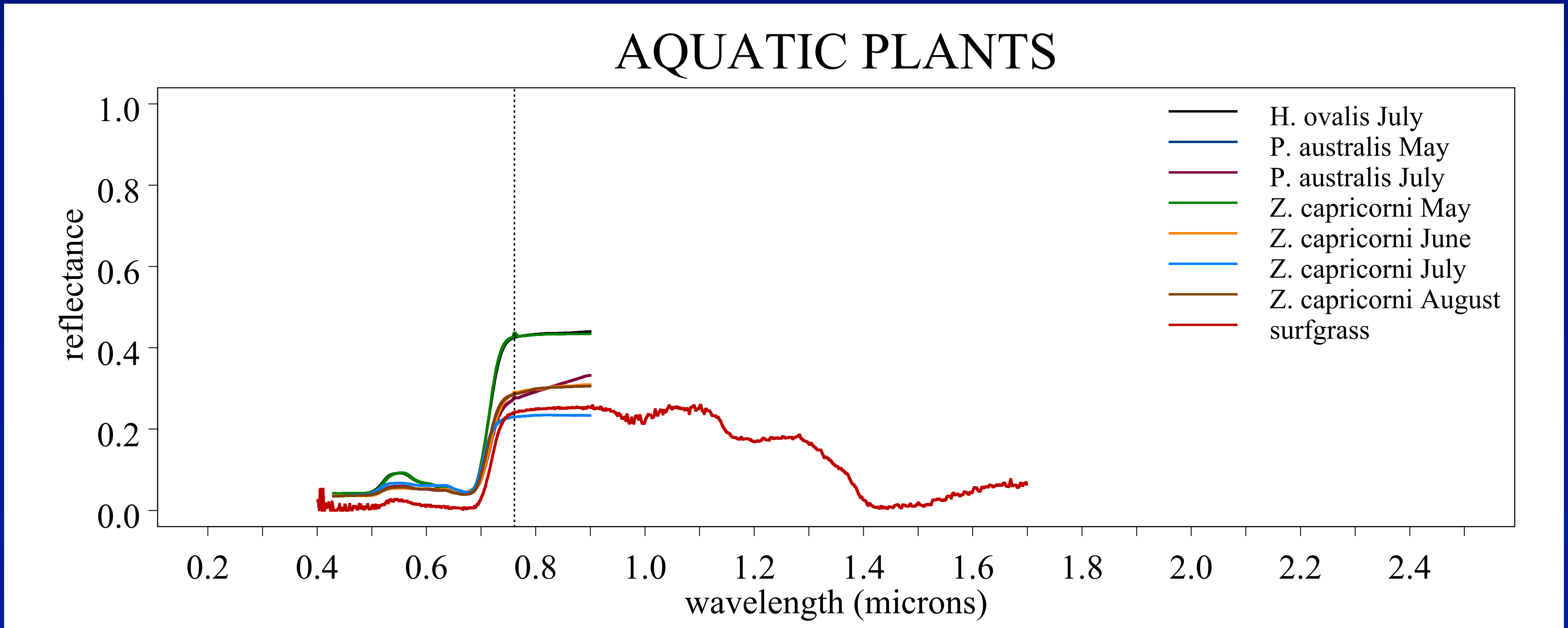
- Stellar photons represent an abundant energy source - at least for planets in the habitable zone.
- Utilising this energy source may well confer an evolutionary advantage.
- The location of the red edge may depend upon stellar type.
- The solar spectrum peaks at around 500nm.
- The atmosphere strongly absorbs photons at less than 350nm.
- Photons of longer wavelength (IR) carry less energy so there is less advantage to be obtained by collecting red photons.
- Therefore 350-800nm represents a sweet-spot for exploiting solar photons.
- This optimum photon collecting zone may vary with stellar-type: hot, blue stars peak at bluer wavelengths yet pump out more photons overall. Cool, red stars peak at redder wavelengths - 3 photon process required?



Lacey oak, Arlington, TX Parks&Recr.

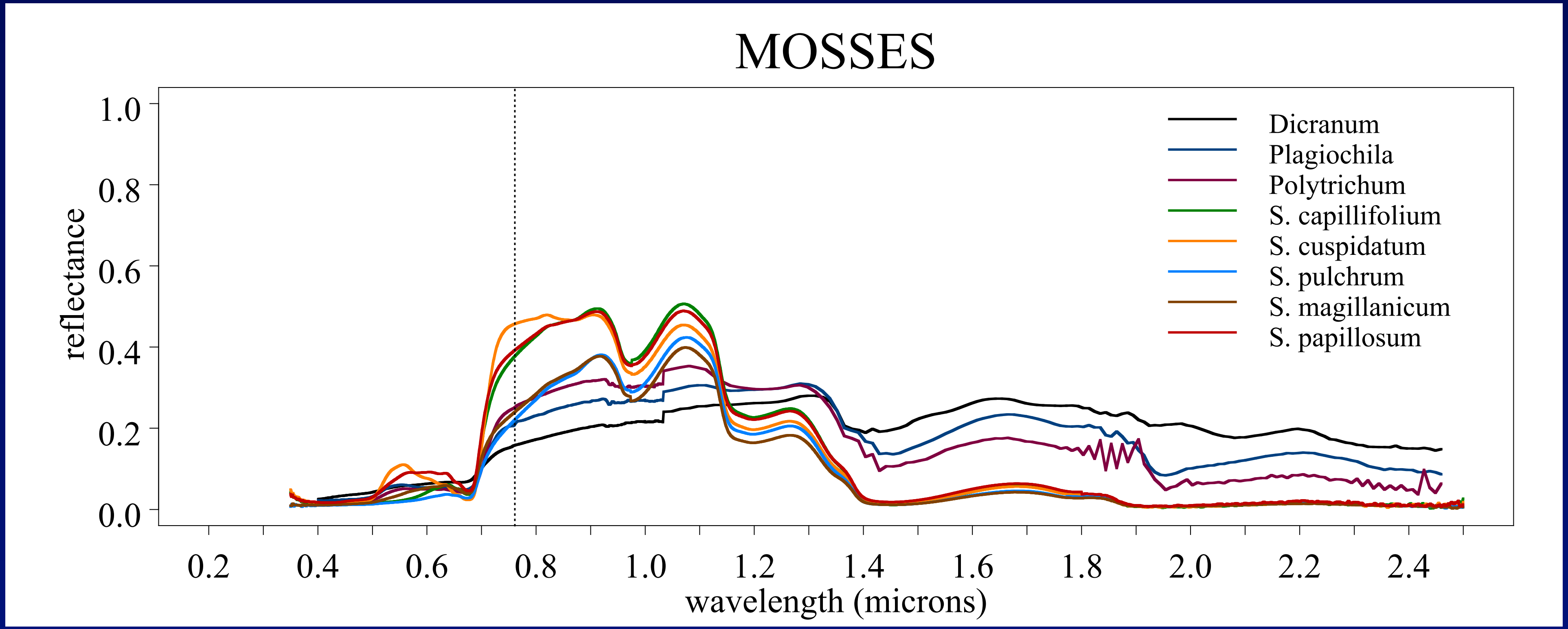
Sitka spruce, Offwell Woodland & Wildlife Trust

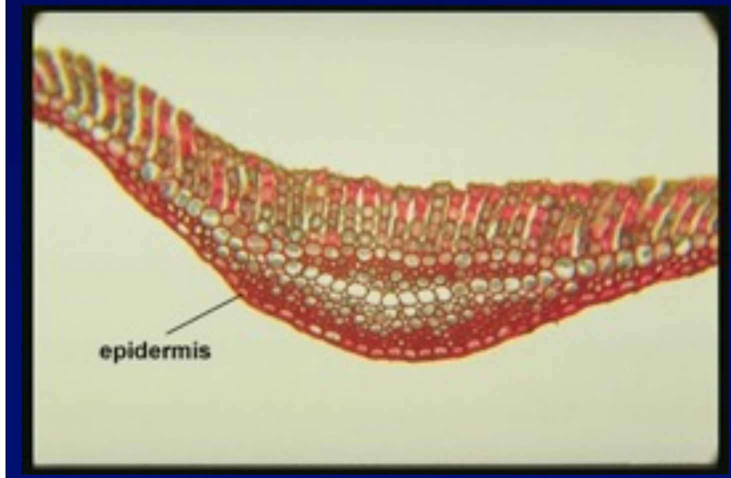
Land plants: Clark, et al. (2003).



Posidonia oceanica, MareNostrum.org

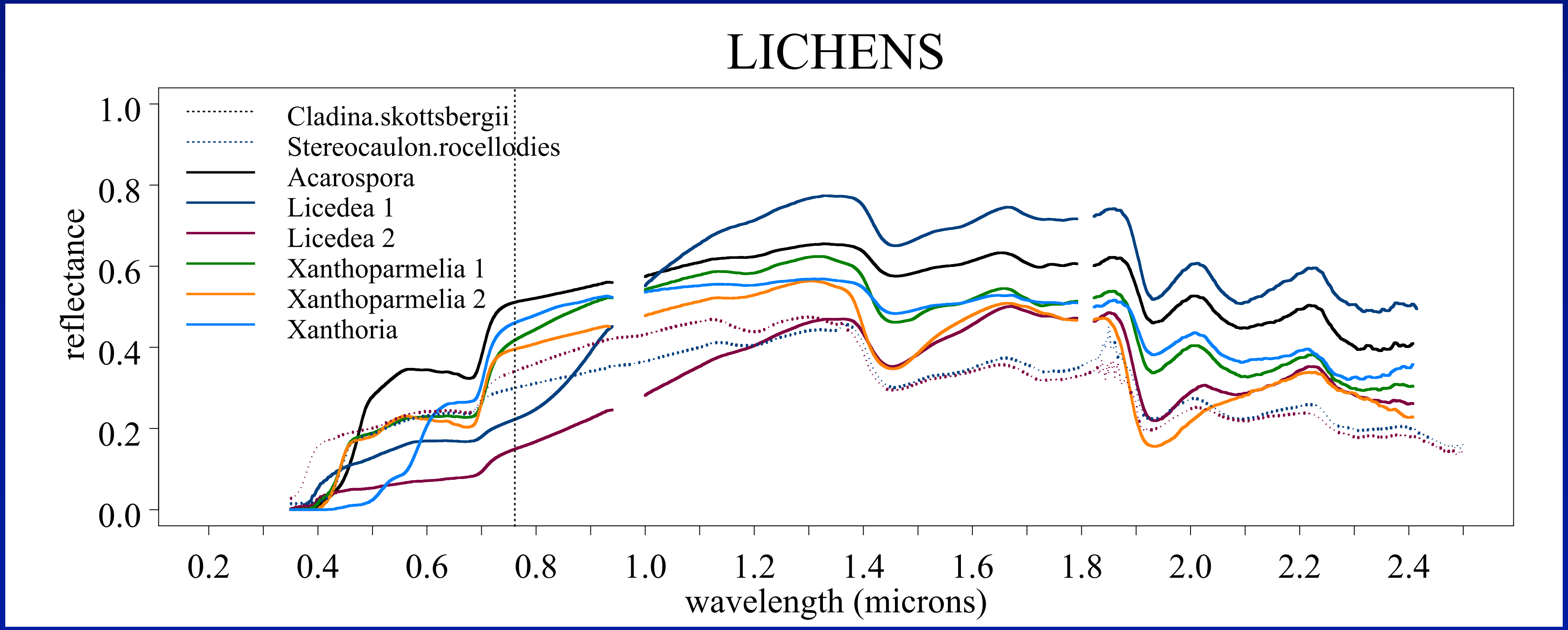
Aquatic plants: Fyfe, et al. (2003); surfgrass: N.Y. Kiang

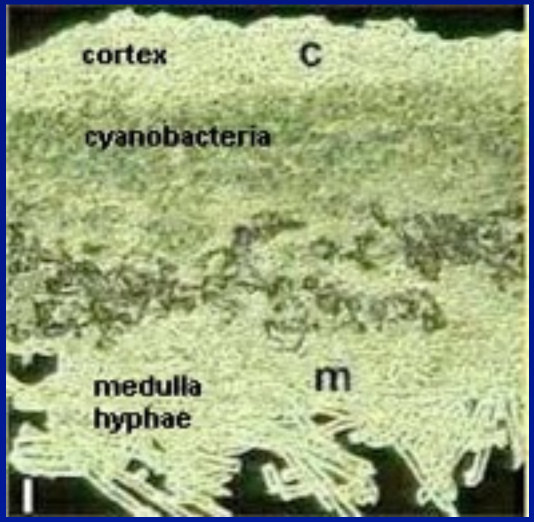




Moss leaf cross section: G. Muth

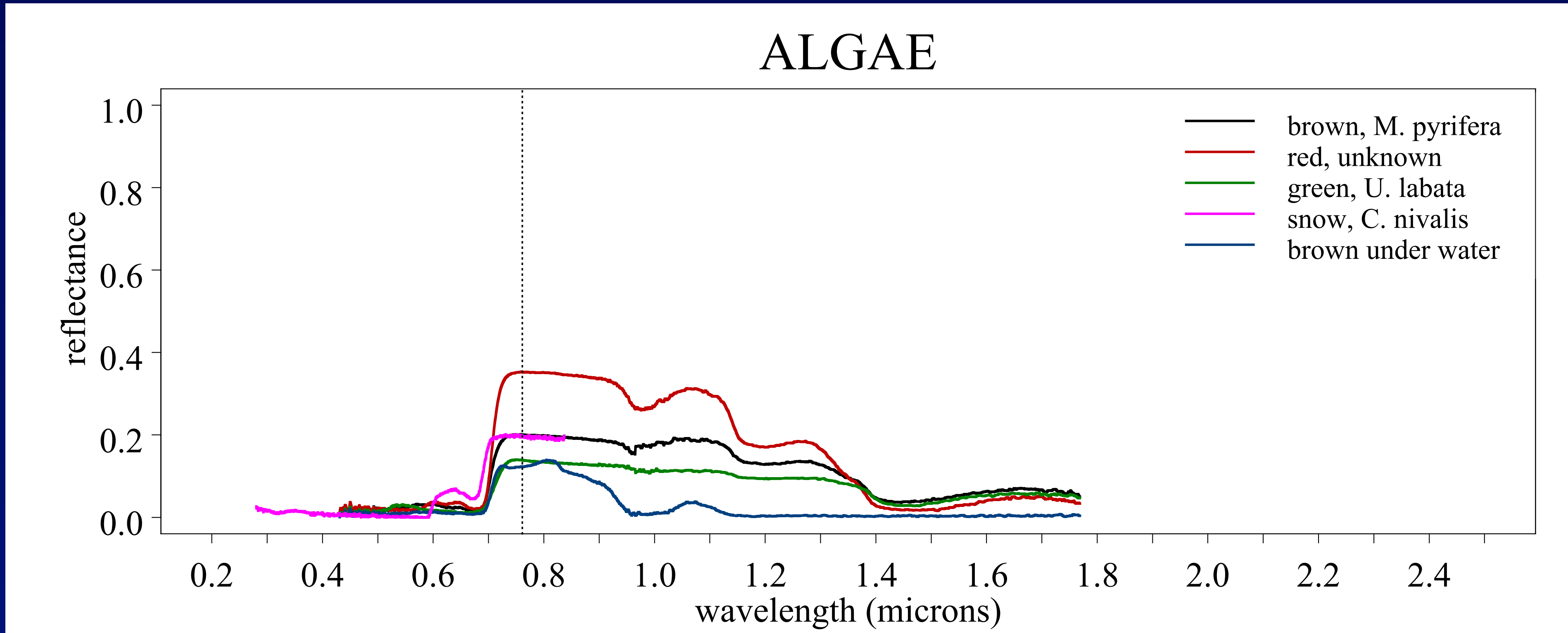
Moss spectra: Lang, M., Kuusk, A., Nilson, T., Lükk, T., Pehk, M., and Alm, G. Reflectance spectra of ground vegetation in sub-boreal forests. Tartu Observatory, Estonia. 2002. Greg Asner, Carnegie Institutution of Washington, Stanford University





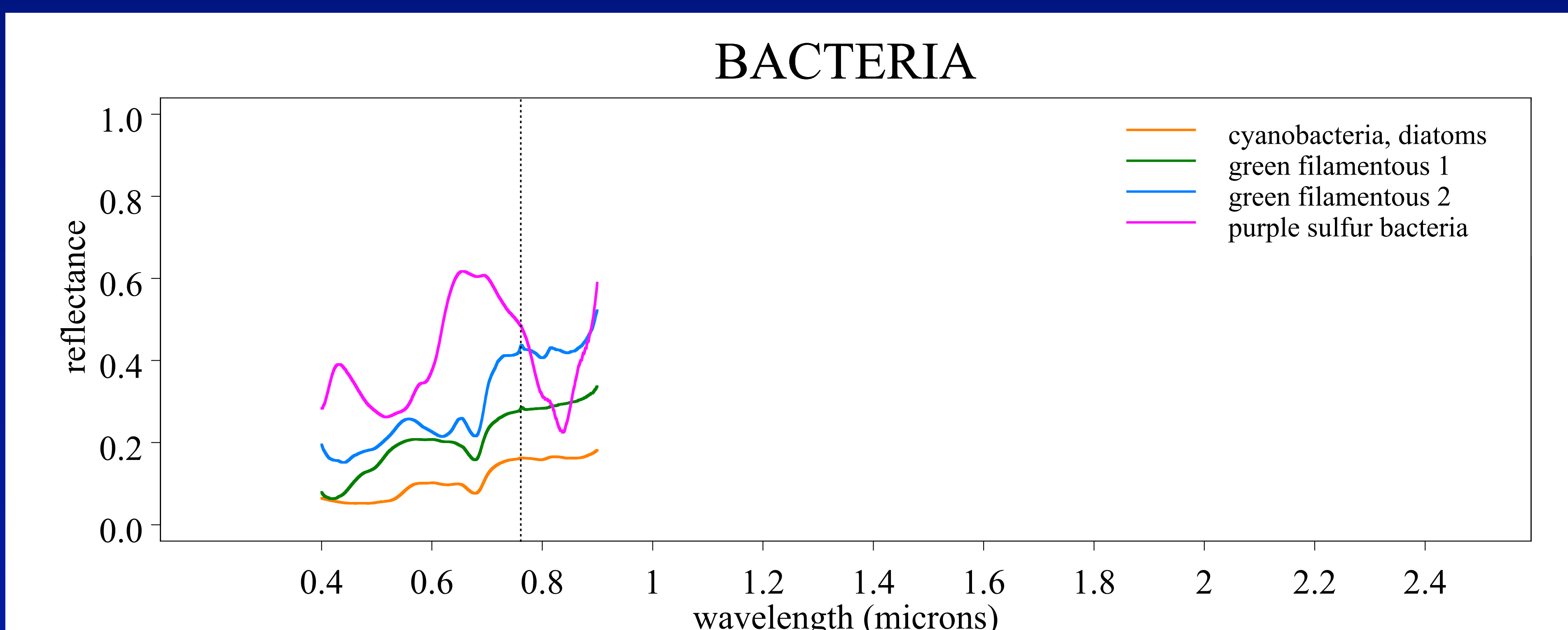
Lichen cross section: J. Deacon, University of Edinburgh

Lichen spectra: R. N. Clark, G. A. Swayze, R. Wise, K. E. Livo, T. M. Hoefen, R. F. Kokaly, and S. J. Sutley, 2003, USGS Digital Spectral Library splib05a, U.S. Geological Survey, Open File Report 03-395.



Red algae, UC Berkeley Museum of Paleontology

Snow algae: Gorton, et al. (2001). Other algae: N. Kiang.



Microbial mat layers

Bacteria in a microbial mat: from Reinhard Bachofen in Wiggli, et al. (1999)

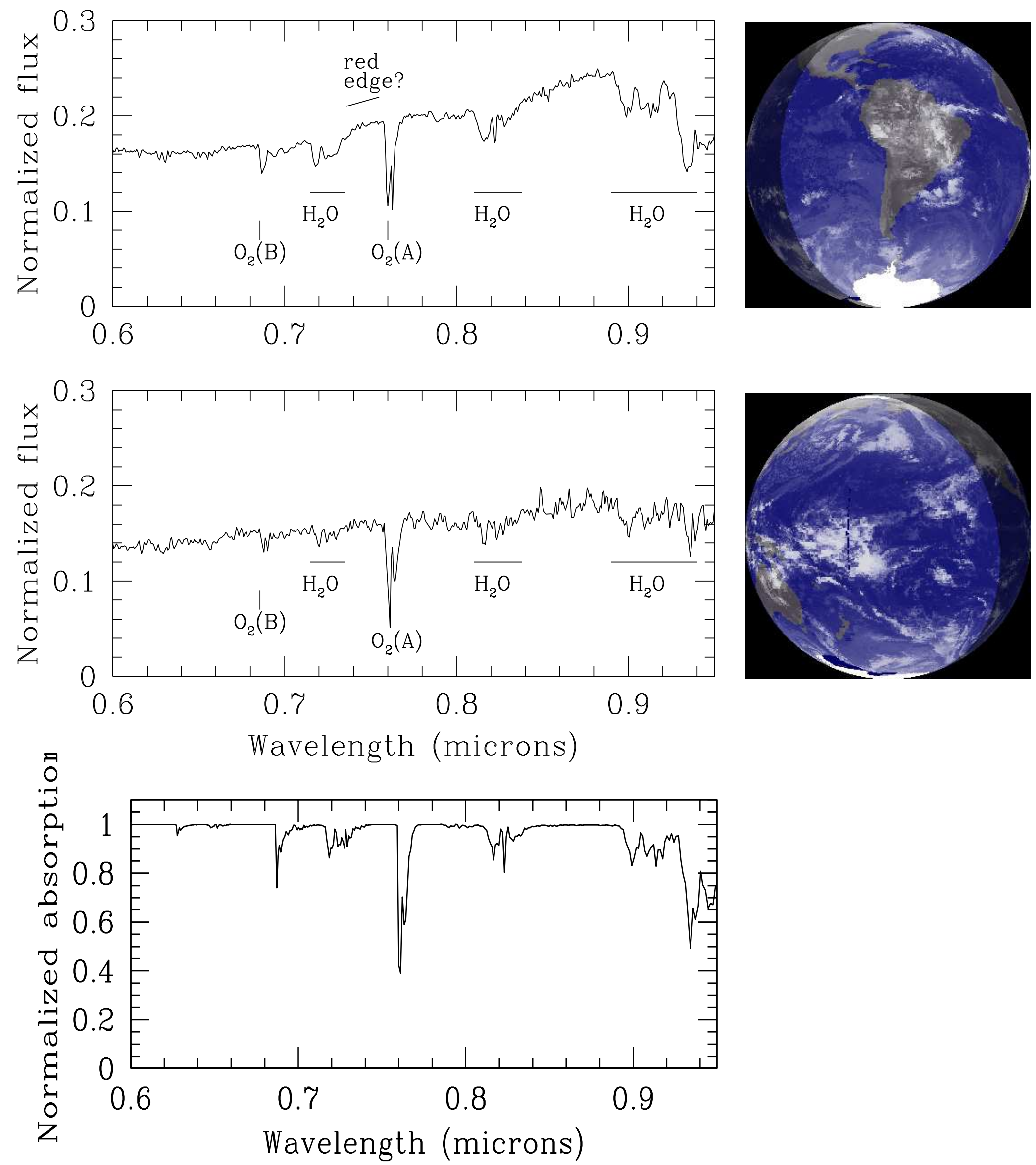


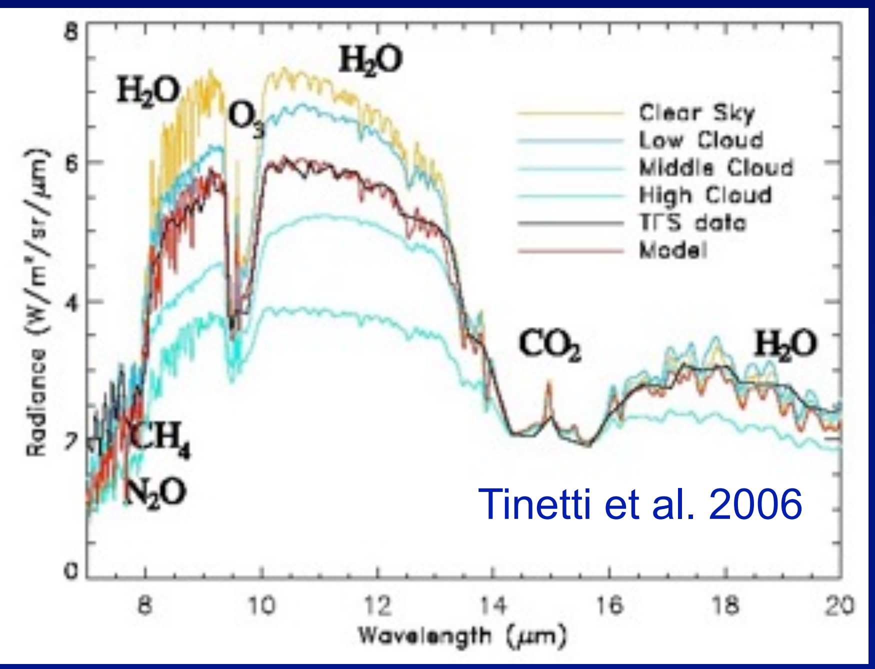
Fig. 4.— Earthshine observations from Apache Point Observatory. Top panel: Earthshine observations on 8 February 2002. The viewing geometry (including cloud coverage at the time of observations) of Earth from the moon is shown in the right image (http://www.fourmilab.ch/earthview/vplanet.html). Middle panel: same as upper panel for 16 February 2002. The viewing geometry of Earth includes much more vegetation in the top panel than in the middle panel. Bottom panel: an absorption spectrum through Earth's atmosphere from Kitt Peak National Observatory (ftp://ftp.noao.edu/catalogs/atmospheric_transmission/) smoothed to approximately the same resolution as the Apache Point Observatory Earthshine data. Note the different y axis on the absorption spectrum; the spectral features are much deeper than in the Earthshine spectra and there is no red edge feature.

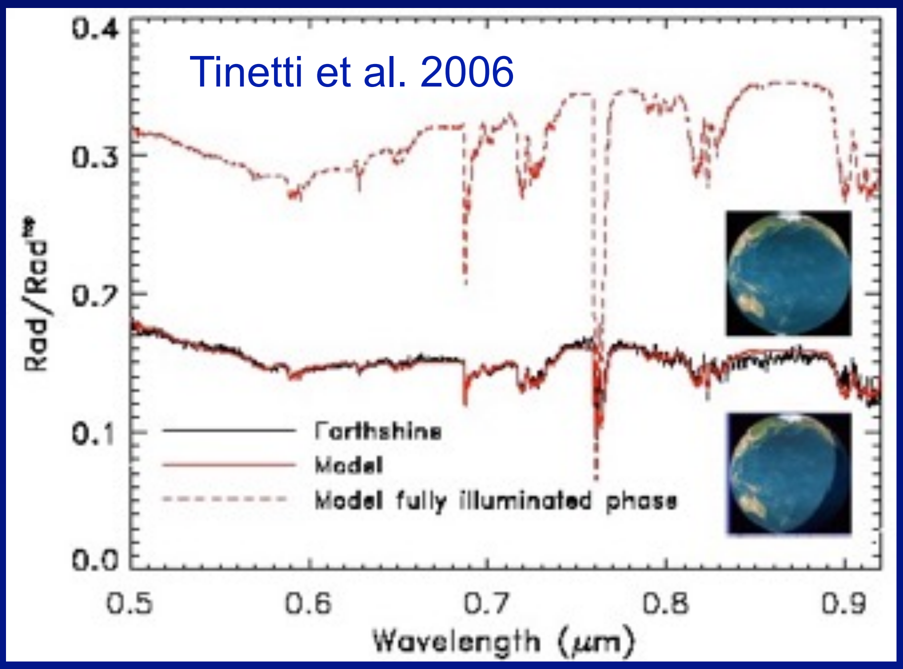
Biosignatures

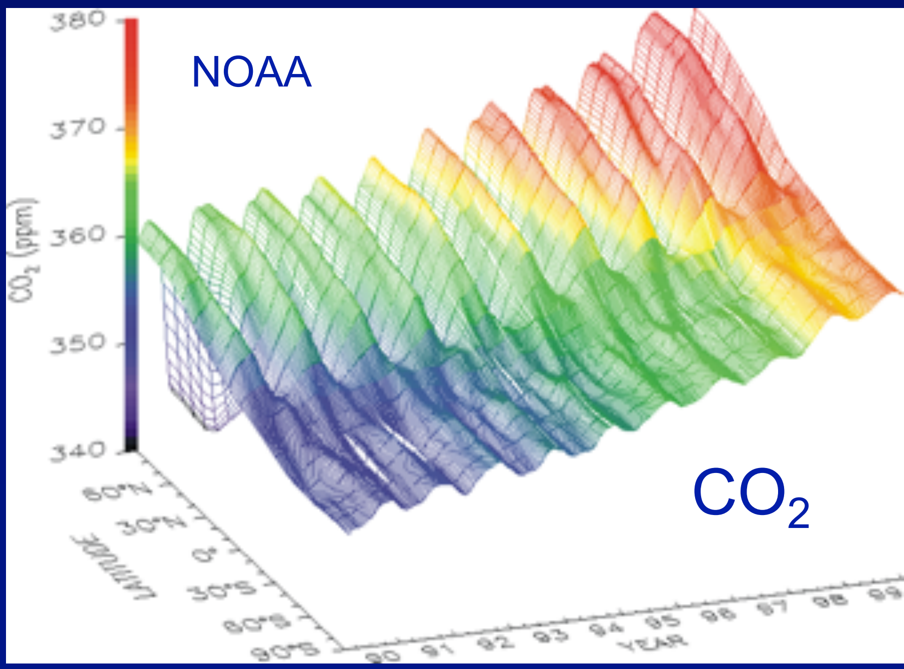
Biogenic gases & chemical disequilibrium

Surface biological pigments

Seasonal cycle







CH_4, CH_3Cl, N_2O

O_2, O_3

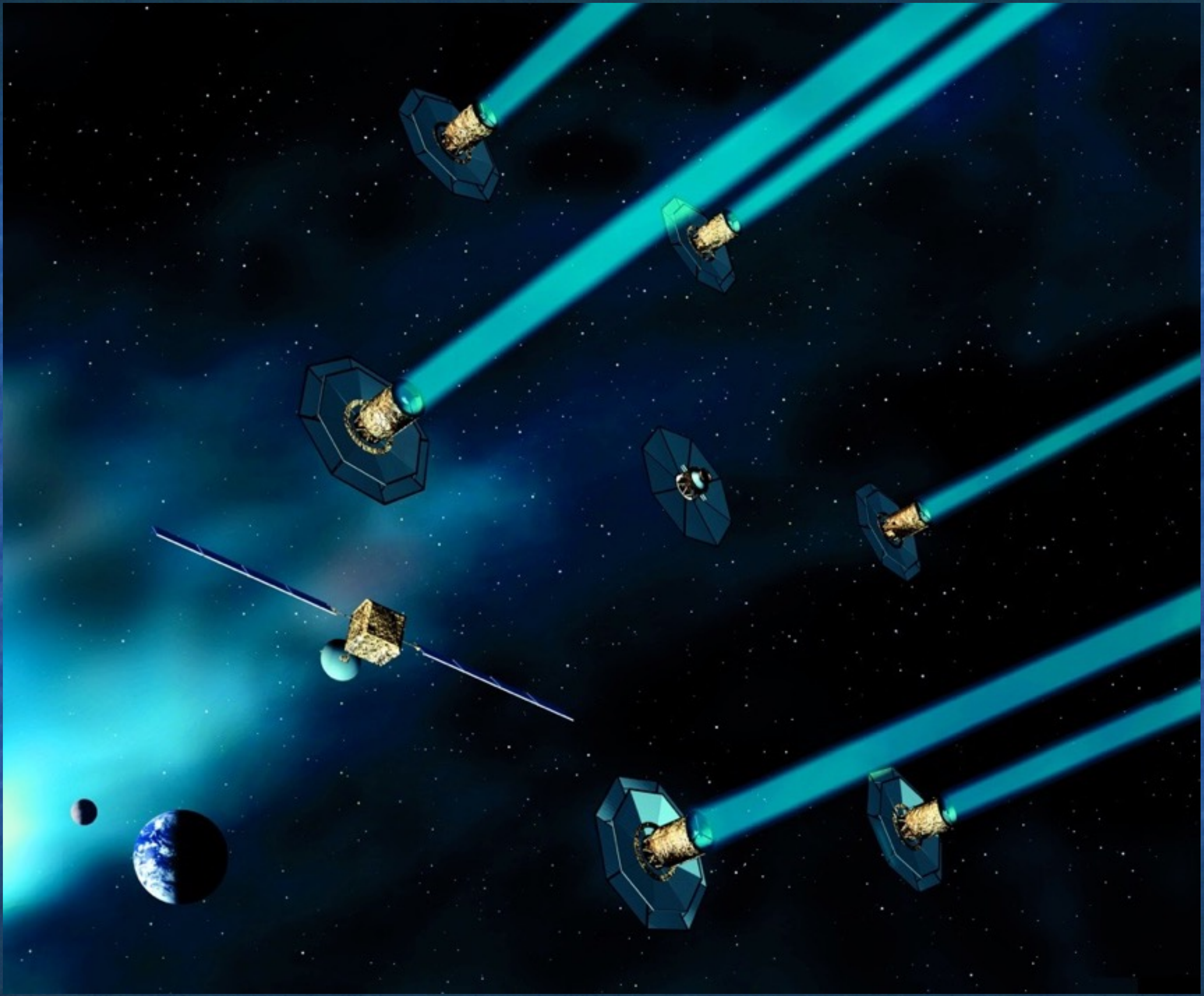
in presence of liquid H_2O

Vegetation red edge

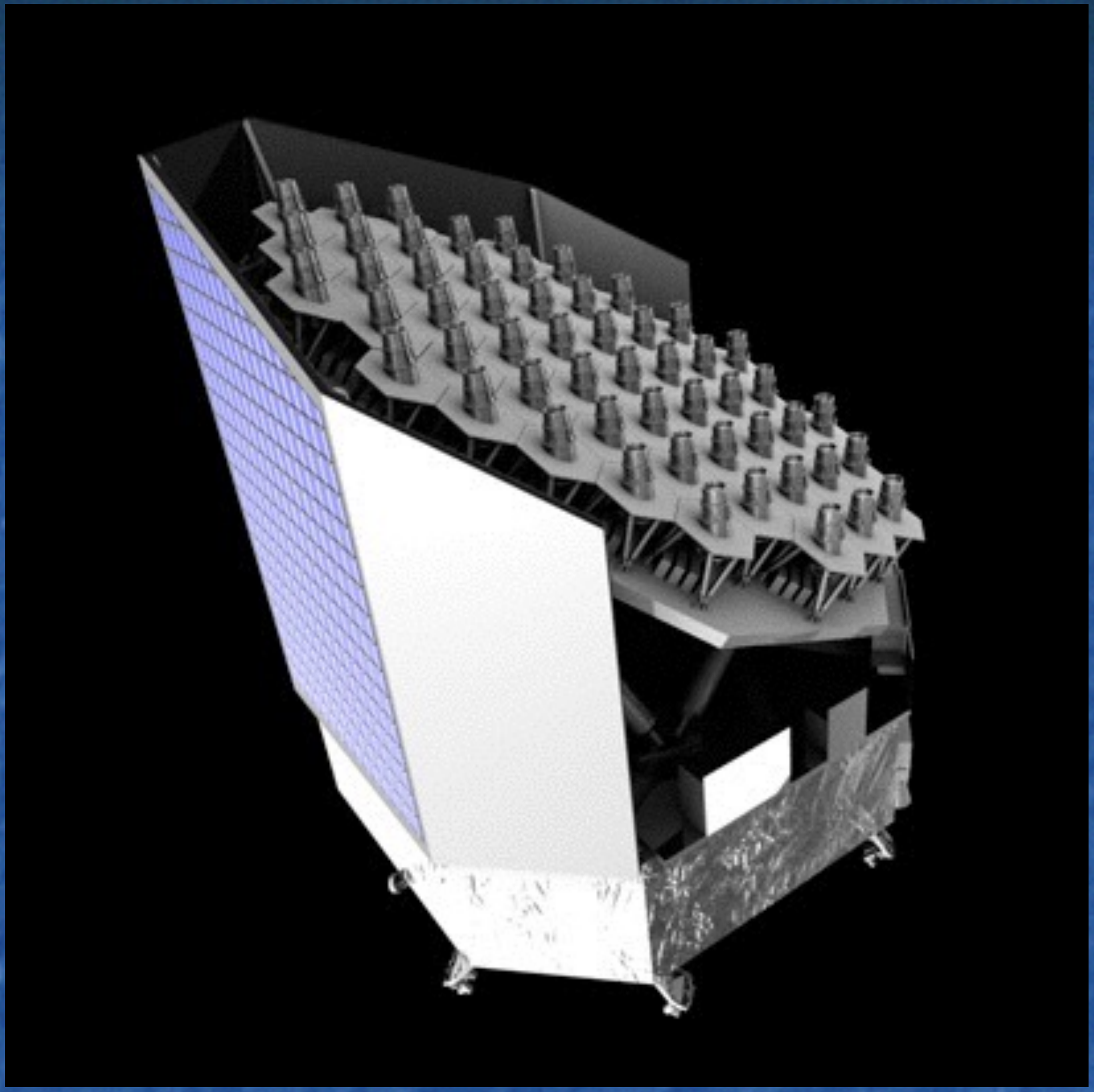
Seasonal cycles of oxidized and reduced gases

CO_2, CH_4

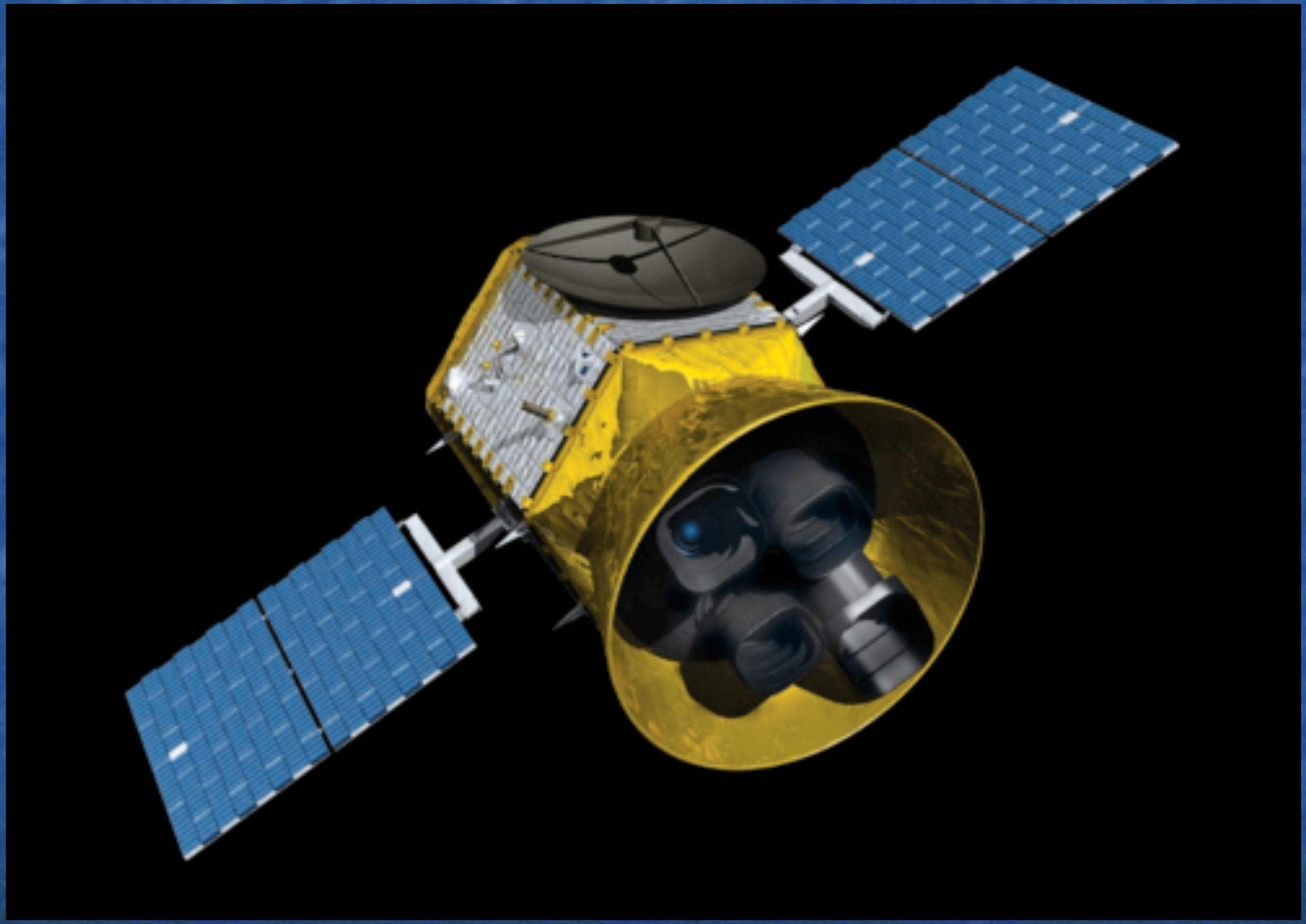
Primary source: photosynthesis



Plato



TESS



Summary

- Many hundreds of exo-planets are now known.
- With dedicated space missions many more are expected within the next decade.
- Awaiting the detection of Earth-like planets.
- Strong habitability arguments for other planets.
- Approaching the era of direct planetary spectroscopy.
- Direct moon spectroscopy?
- We can anticipate a range of atmospheric biosignatures - but certainly not the full range.