Artist's impression of HD189733b, showing the planet's atmosphere being stripped by the radiation from its parent star. Credit: Ron Miller

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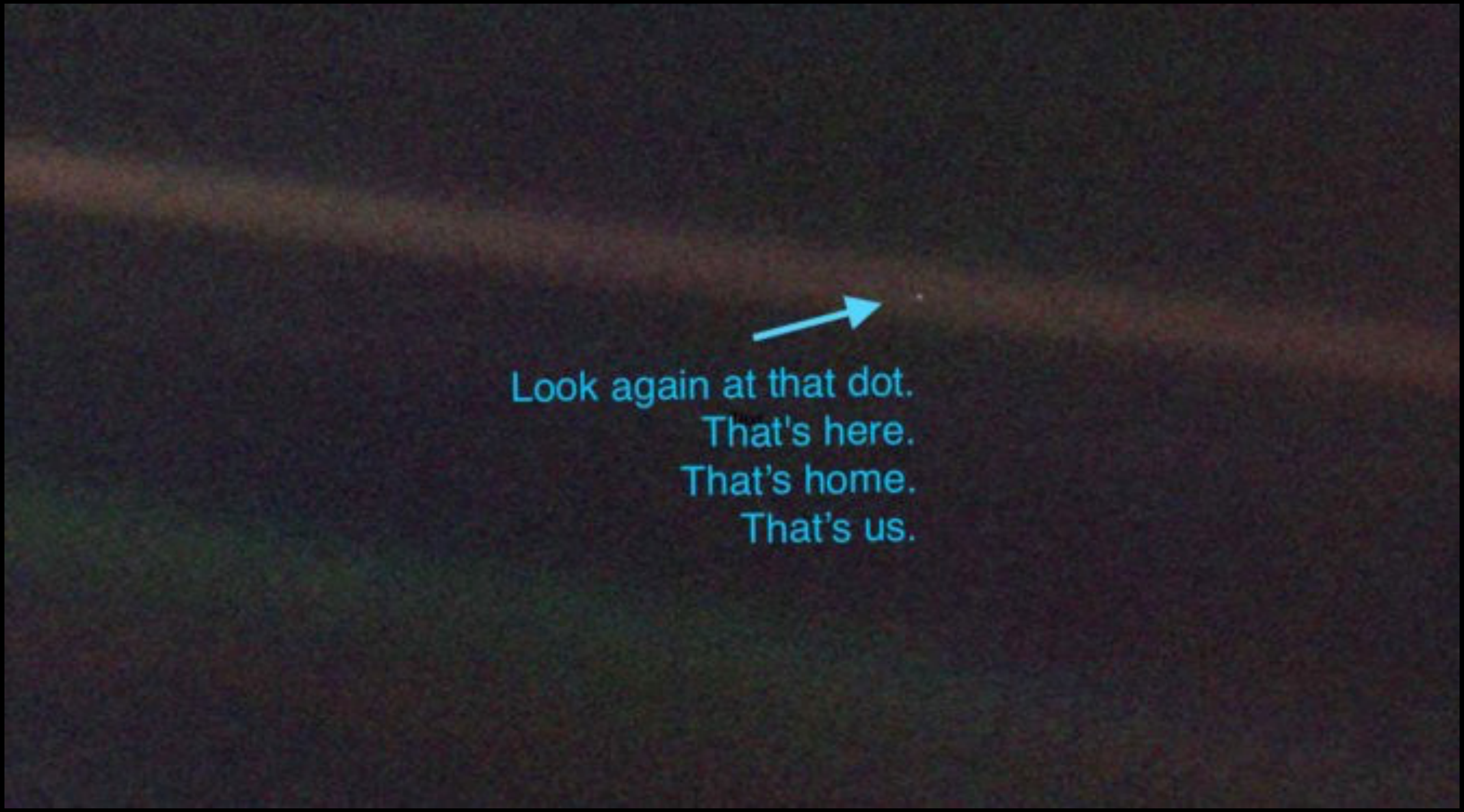
25 Anni di Esopianeti: Mondi Alieni e il futuro della ricerca in questo campo

Dr. Francesca Faedi
Universita' di Urbino, WIA-EU Rome, Fondazione Occhialini
Cavaliere Ordine al Merito della Repubblica Italiana

FONDAZIONE GIUSEPPE OCCHIALINI

THE PALE BLUE DOT



from 3.7 billion miles (circa 6 miliardi di km)
taken by Voyager on Valentine's Day 1990

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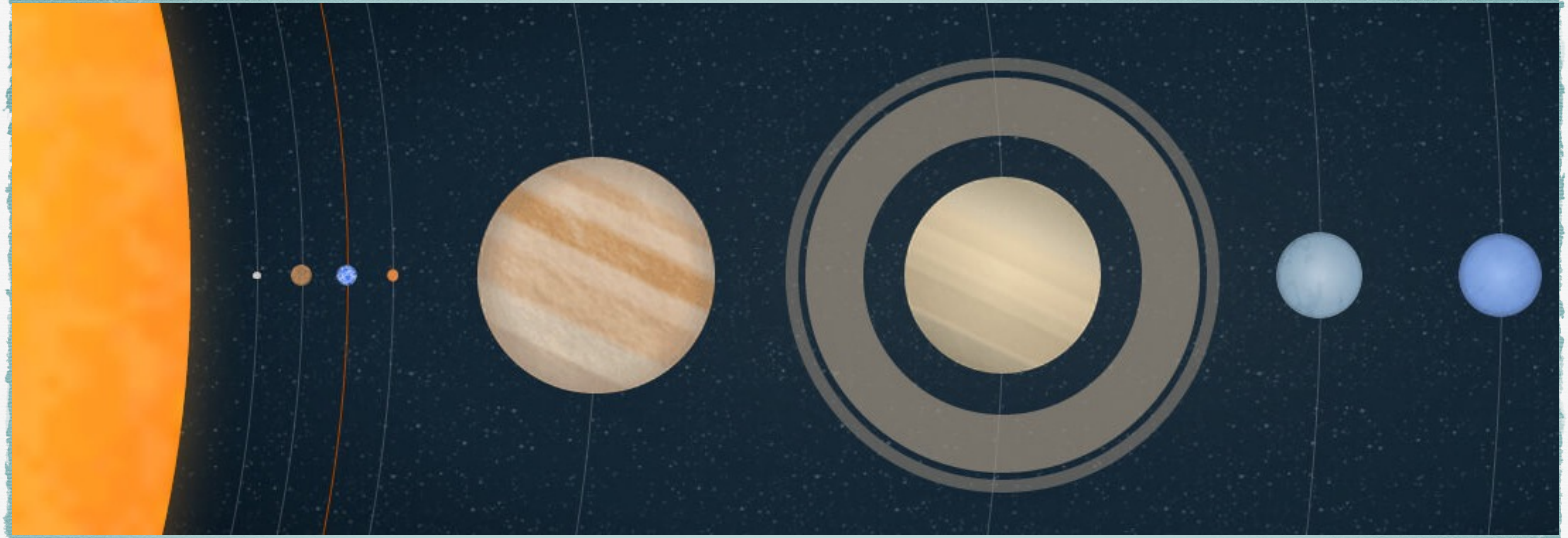
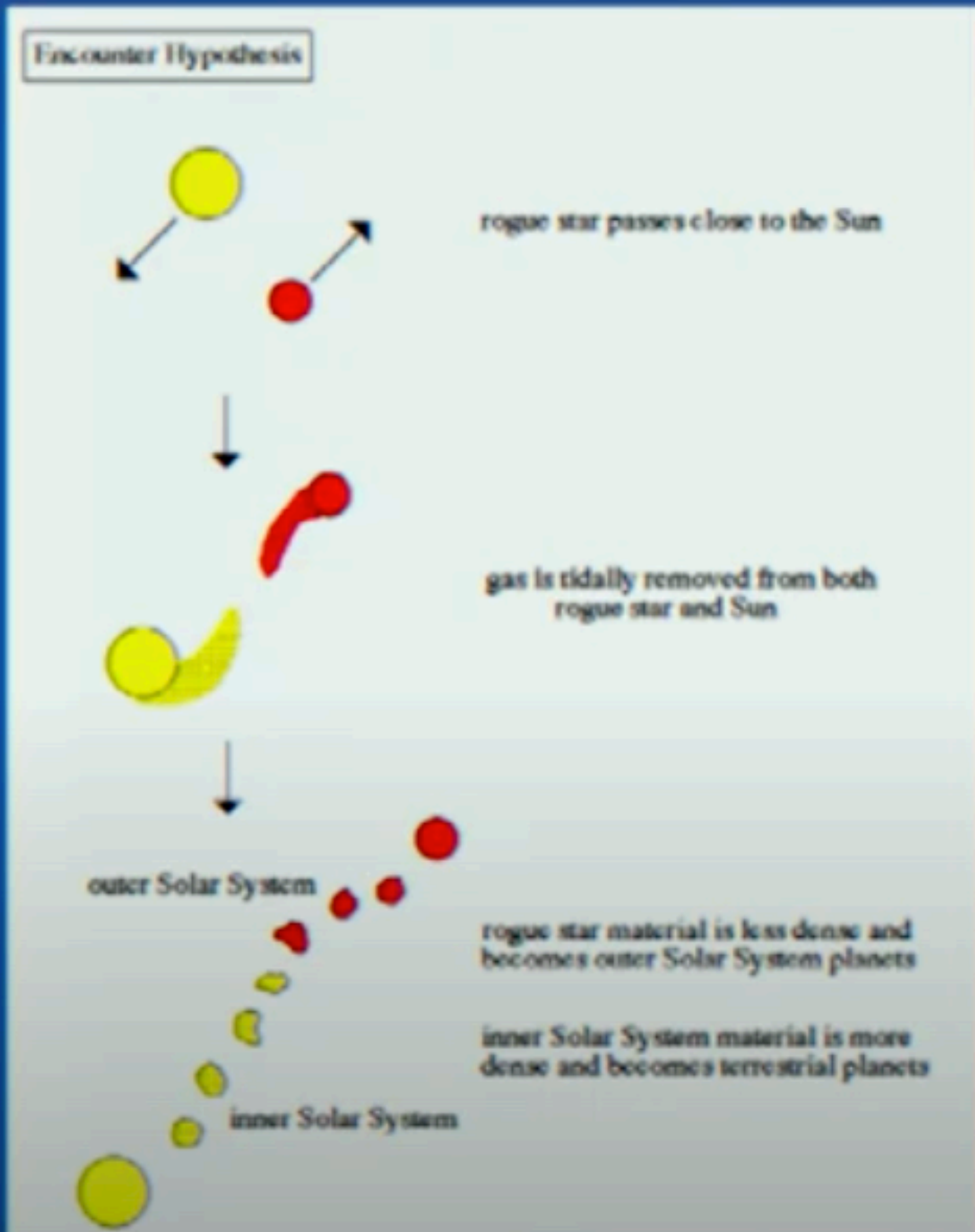
before 1995



SOLAR SYSTEM

before 1995

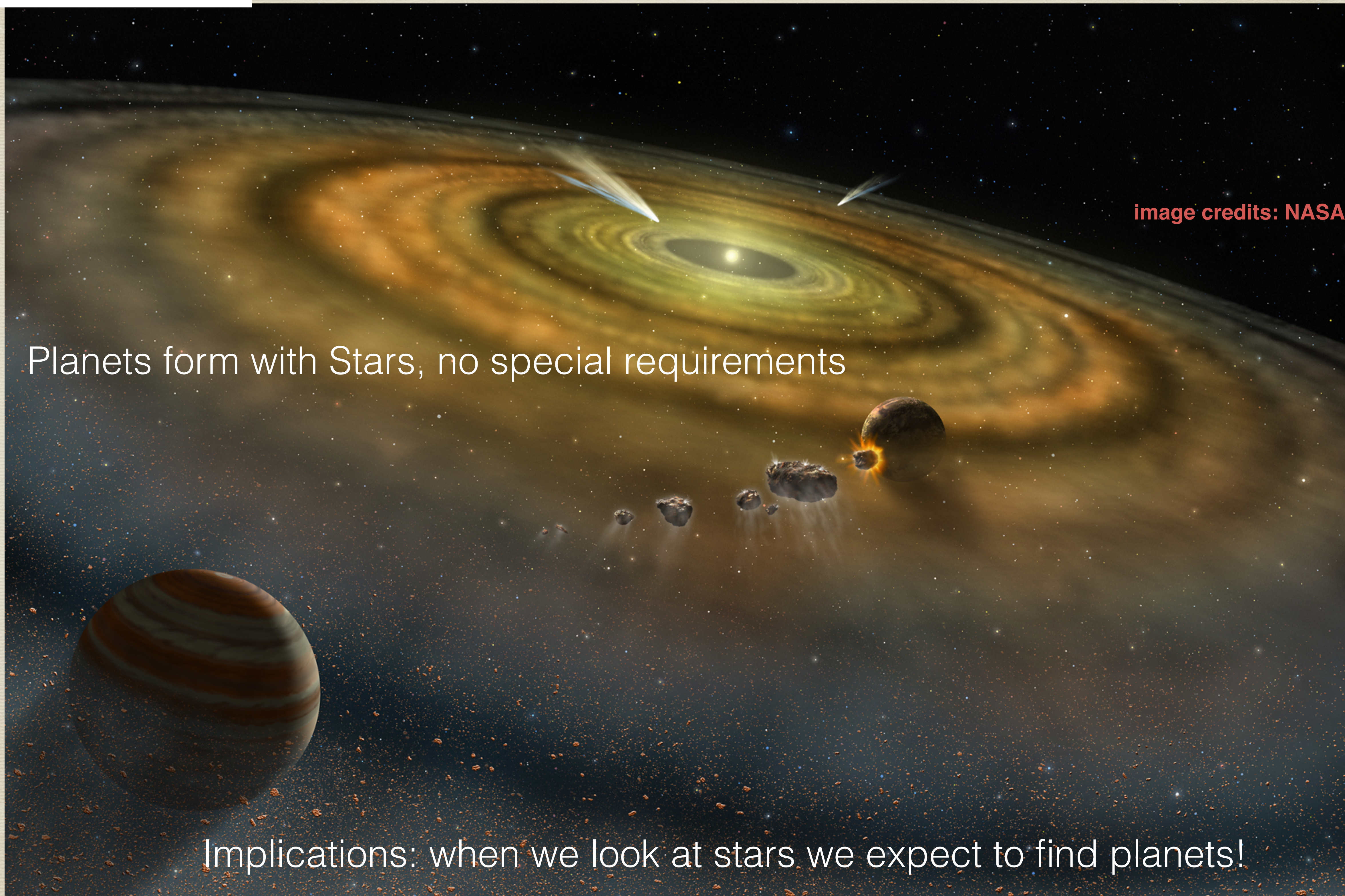


Until recently (1990s), we didn’t know if ANY other stars had planets.

Planet formation might have needed a rare event, like two stars almost crashing

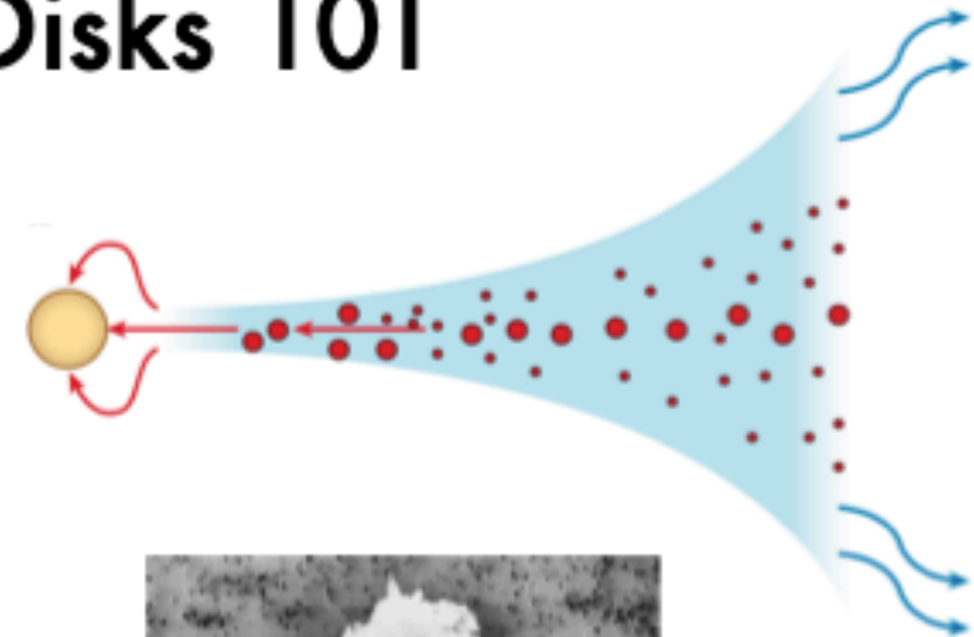
Our Sun might have been the only star with planets.

What we know now



But how?

Protoplanetary Disks 101



- Disks are made of gas + dust
  - G/D = 100:1 in ISM
  - ratio must decrease in disks?

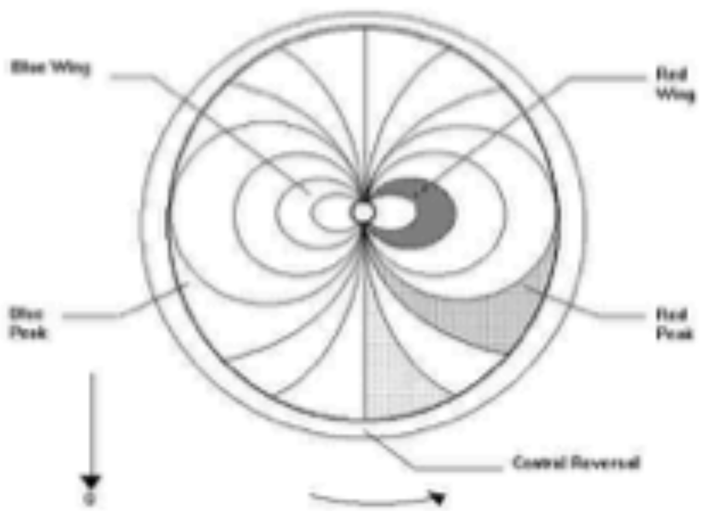
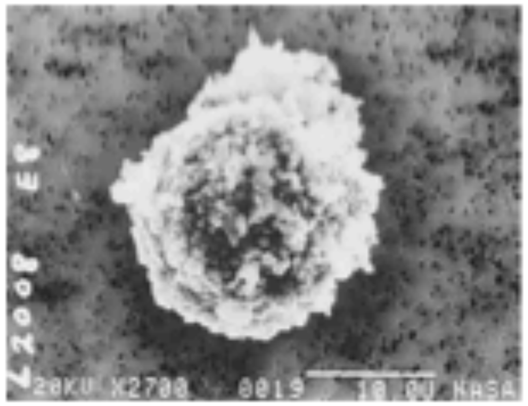
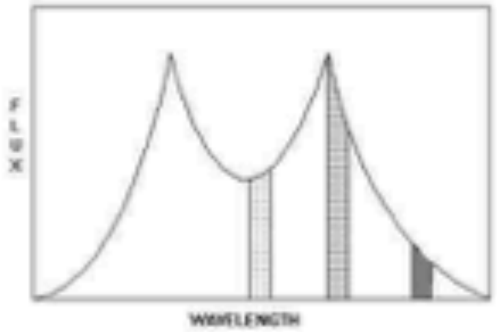


Figure 4a The characteristic 'dipole field' pattern created on the surface of a Keplerian disc by loci of points of constant radial velocity. The shaded areas correspond to emission in these parts of the line profile which are shown in Figure 4b



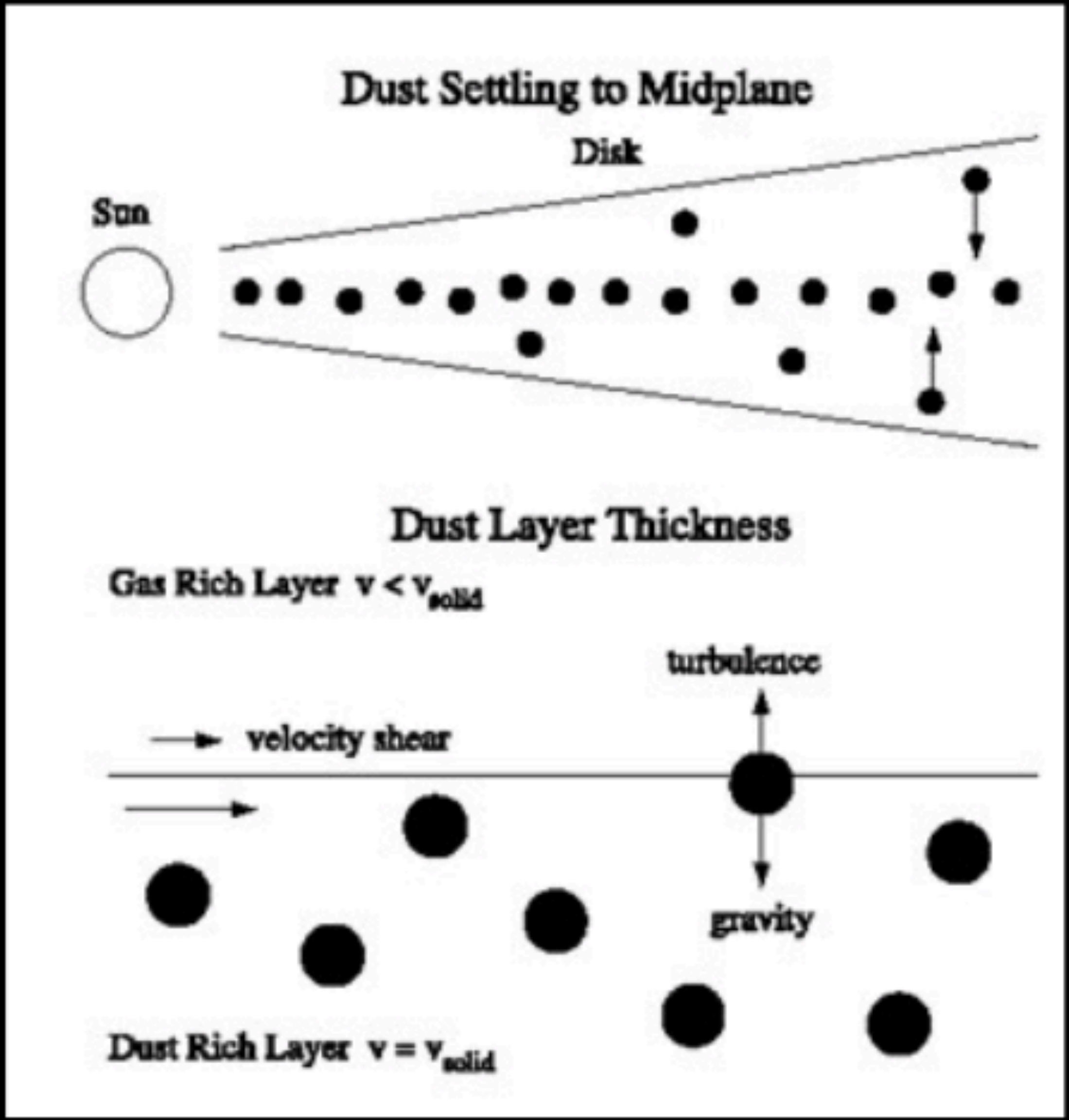
- Dust component:
  - sizes range from sub-μm to planets (?)
  - compositions likely vary (silicates, ices, graphite)
  - detection by continuum (thermal) emission



- Gas component:
  - vast majority of gas in H_2 (but also CO)
  - detected by line emission from molecules in disk

Protoplanetary Disc

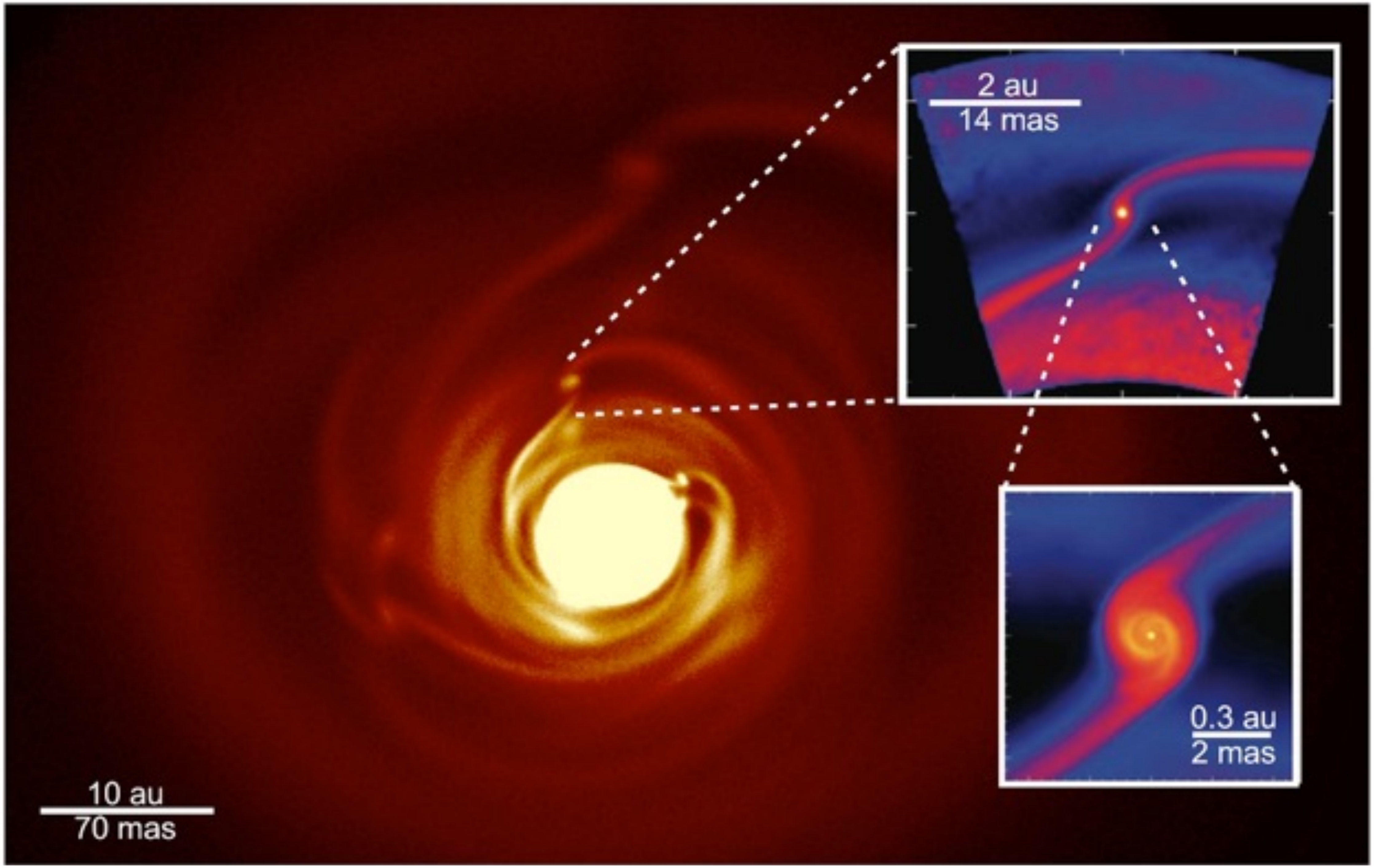
Early stages of planet formation



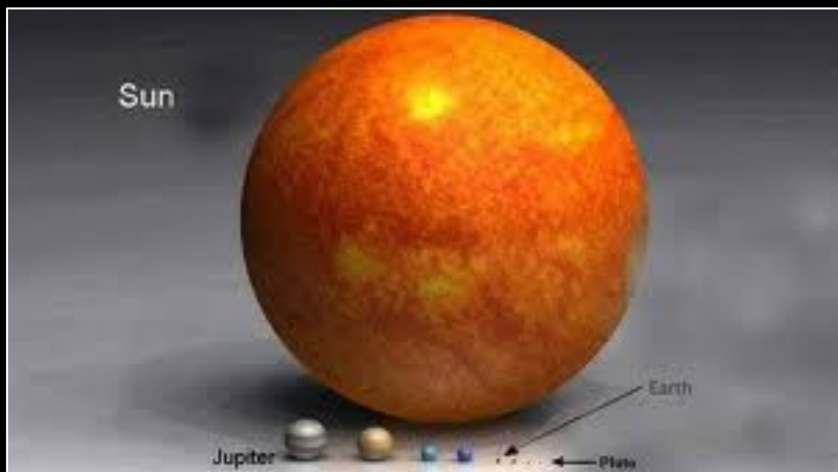
Chambers, *EPSL* (2004), Fig. 1

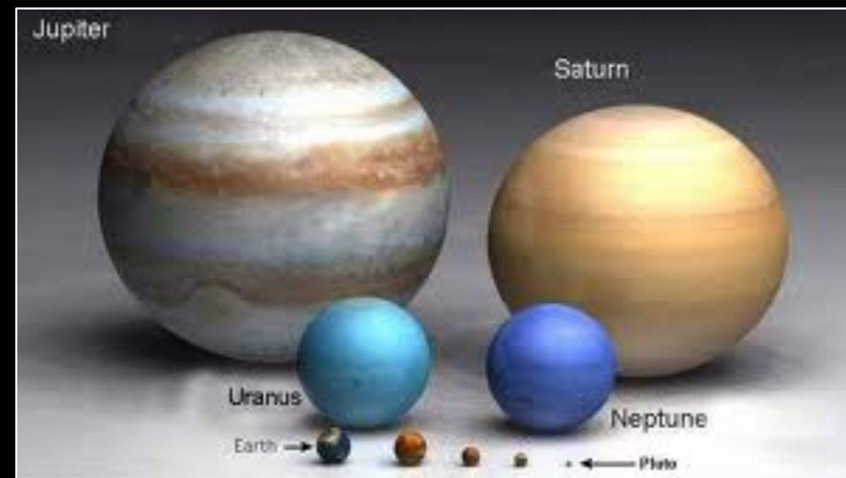
- Dust settles to the midplane of the solar nebula
- The dust orbits slightly faster than the gas because it doesn't feel the effects of pressure
- Gas drag causes some of the dust to spiral inwards
- *Turbulence* is generated, lifting some of the dust out of the midplane
- *If* the dust density is great enough, then gravitational instability sets in, forming km-size planetesimals

Protoplanetary Disc



Radiation hydrodynamics simulation of a protoplanetary disk with four embedded Jupiter-mass planets, computed for a wavelength of 10 micrometer (background image). The insets show the gap that is opened by one of the planets (top-right) and the circumplanetary accretion disk (bottom-right). Image credits: Kraus et al. 2014, simulations from Ayliffe, Bate, Dong, Whitney & Zhu



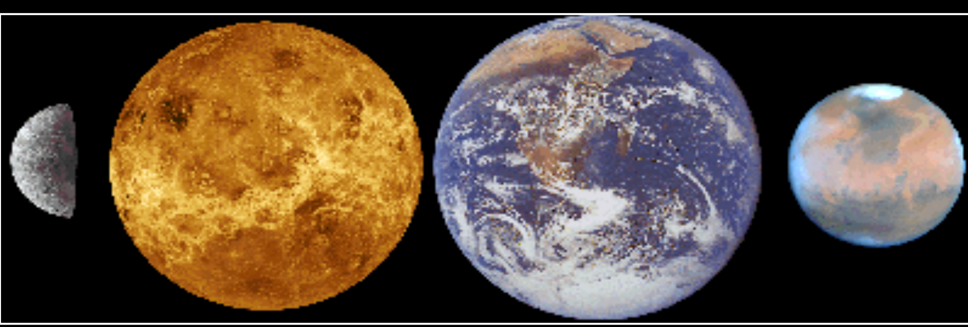


Disk of dust and gas

Challenge for the theorists:

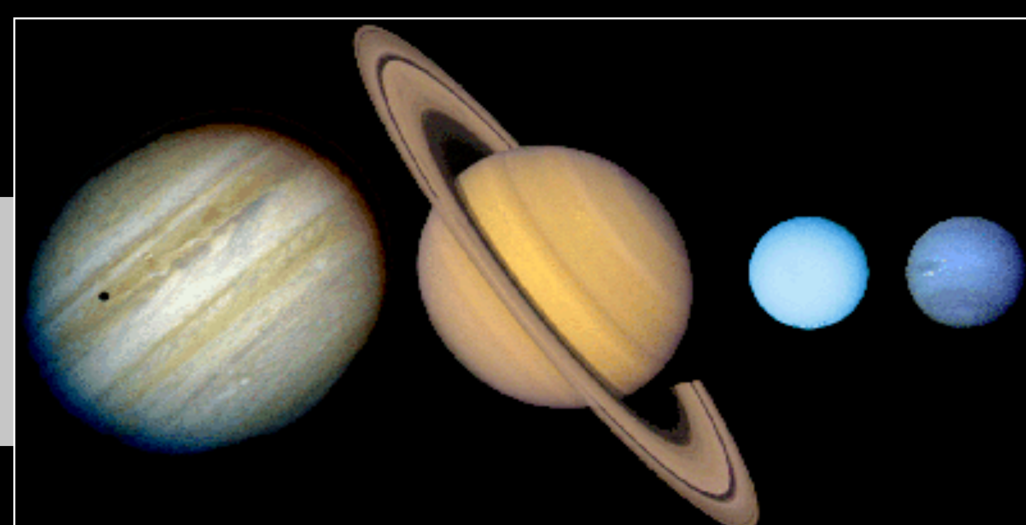
Explaining how to go from this to a planetary system in 100 Millions years

Bonne chance …!



Terrestrial planets (rocks, density ~4-5 g/cm3)

Beyond 466 Million Miles From the Sun

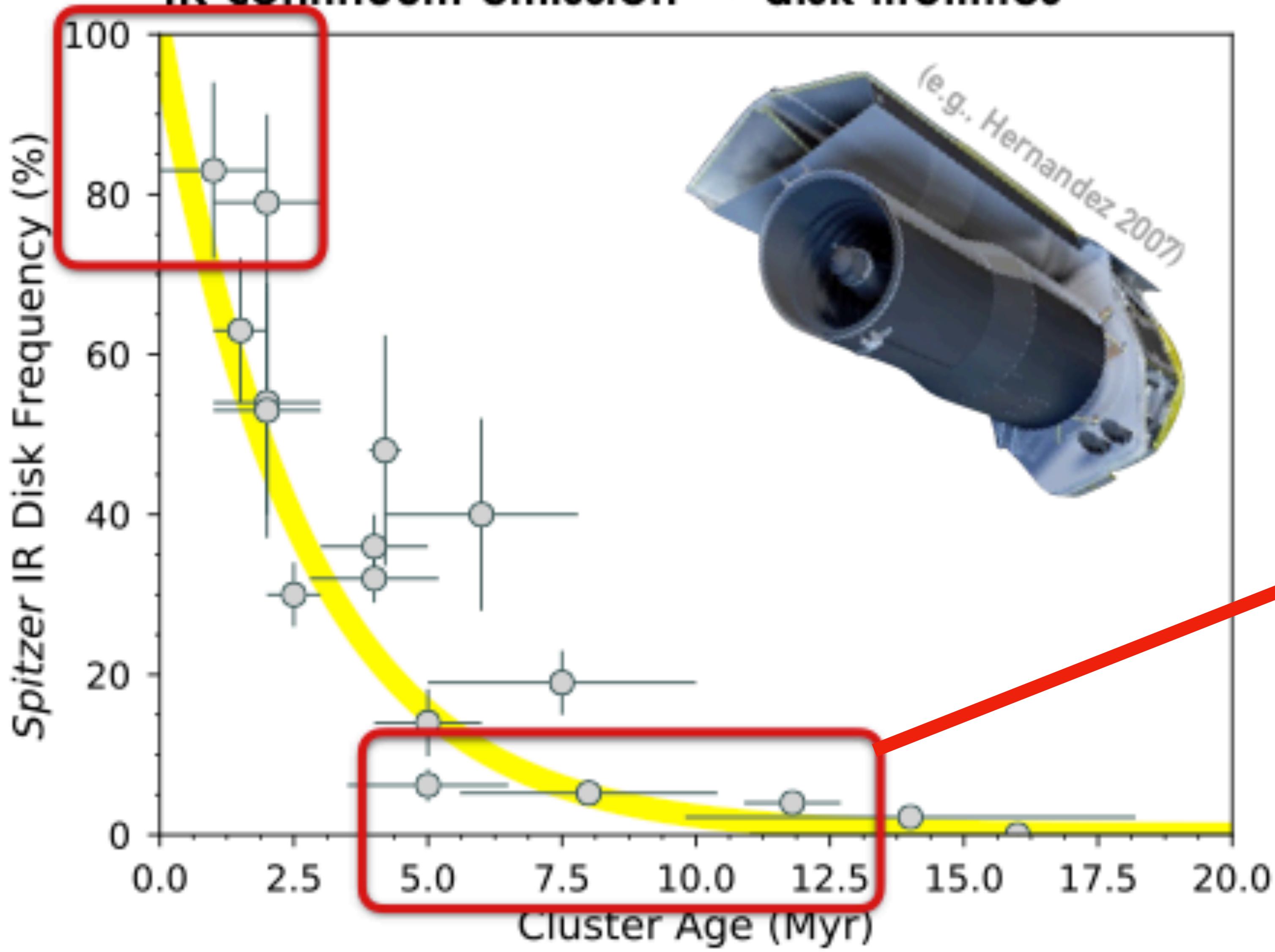


Giant planets (light, gaseous, H, He, density 0.7-2 g/cm3)

Images: Lunar and Planetary Laboratory: http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=178

Protoplanetary Disks 101

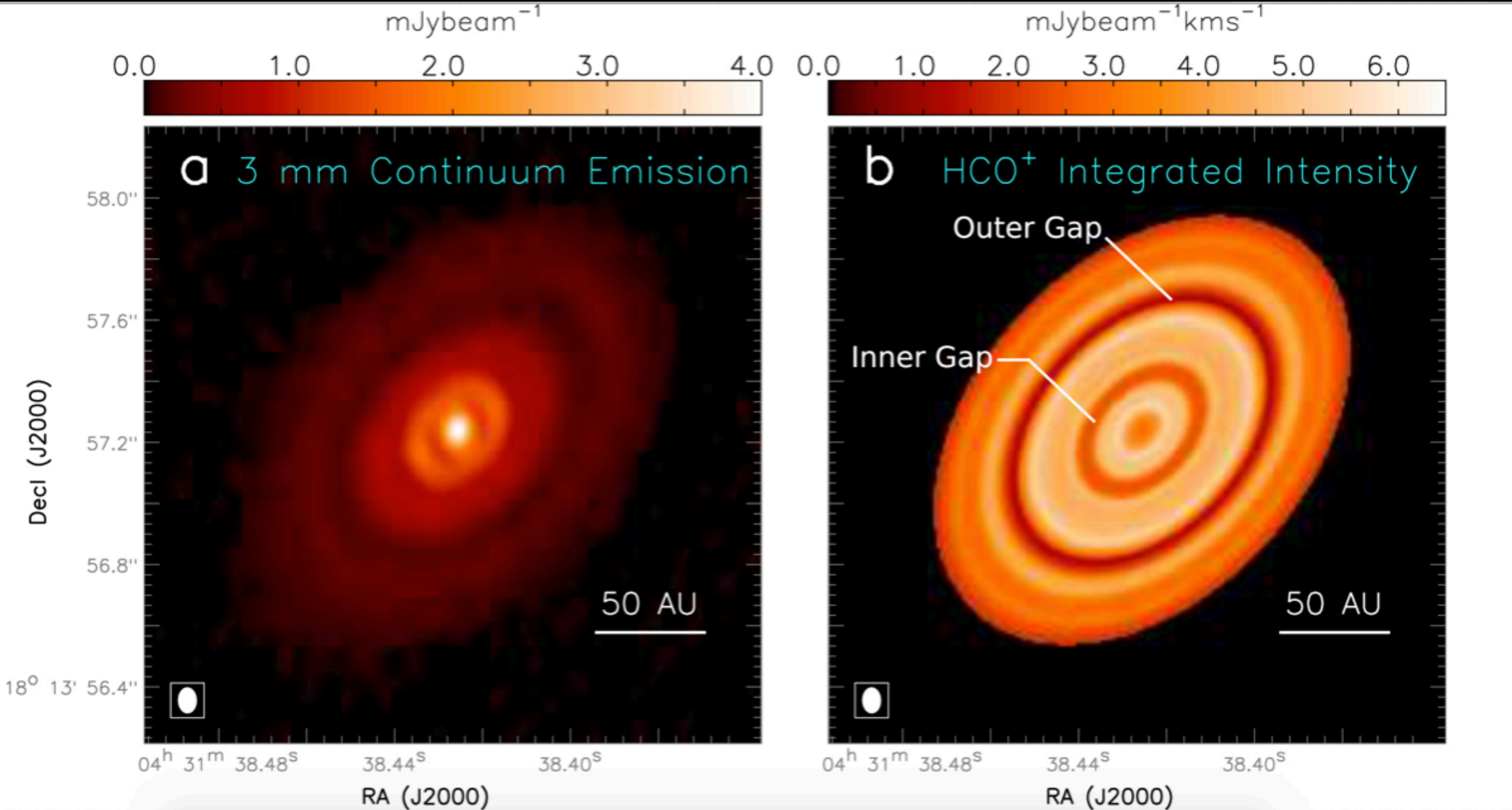
IR continuum emission → disk lifetimes



- Disks are ubiquitous around young stars at ~1 Myr
- Disks lifetimes ~5-10 Myr

IR disk emission optically thick → good for identifying disks, but poor tracer of disk mass

HL Tau Observations with ALMA



The dust (left) and gas (right) emission from HL Tau show that the gaps in its disk match up. [Yen et al. 2016]

Video disk

Then the First ExoPlanet!!

51 Peg b - The first known exoplanet to orbit a star similar to the Sun

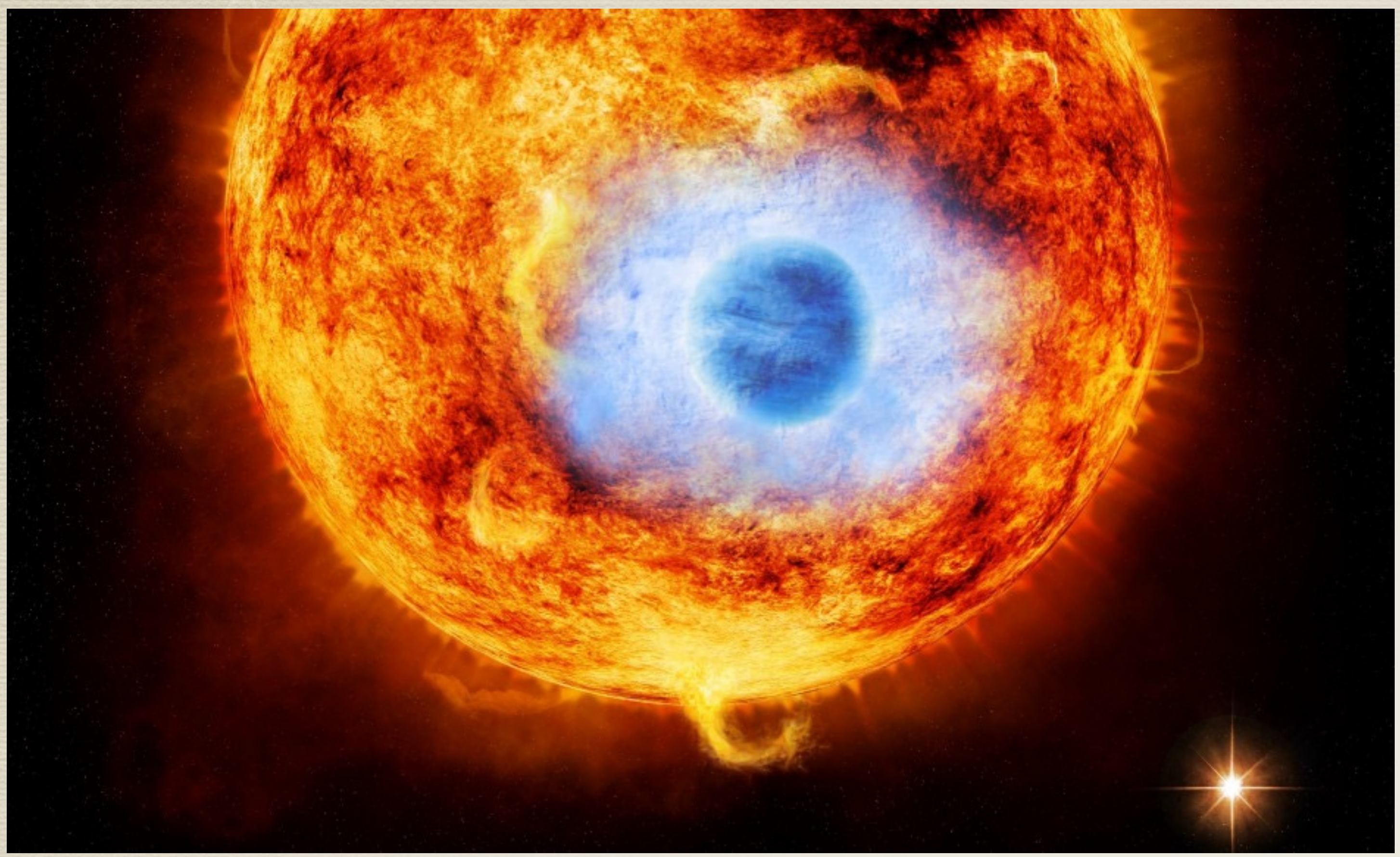
Hot Jupiter!!!

Mayor & Queloz 1995, Nature 378, 355!

Nobel Prize for Physics 2019

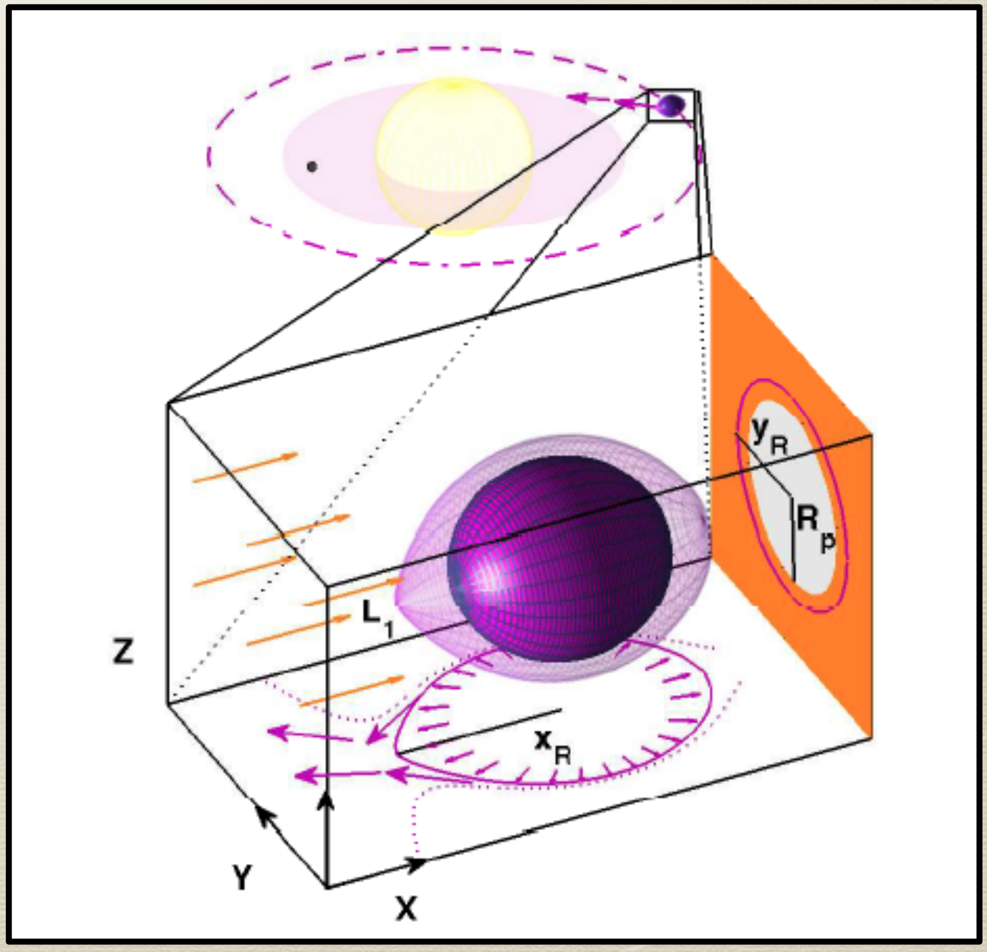
at todays date (May 19, 2021) we know 4728 exoplanets in 3497 planetary systems of which 774 are multiple planet systems

HOT JUPITERS

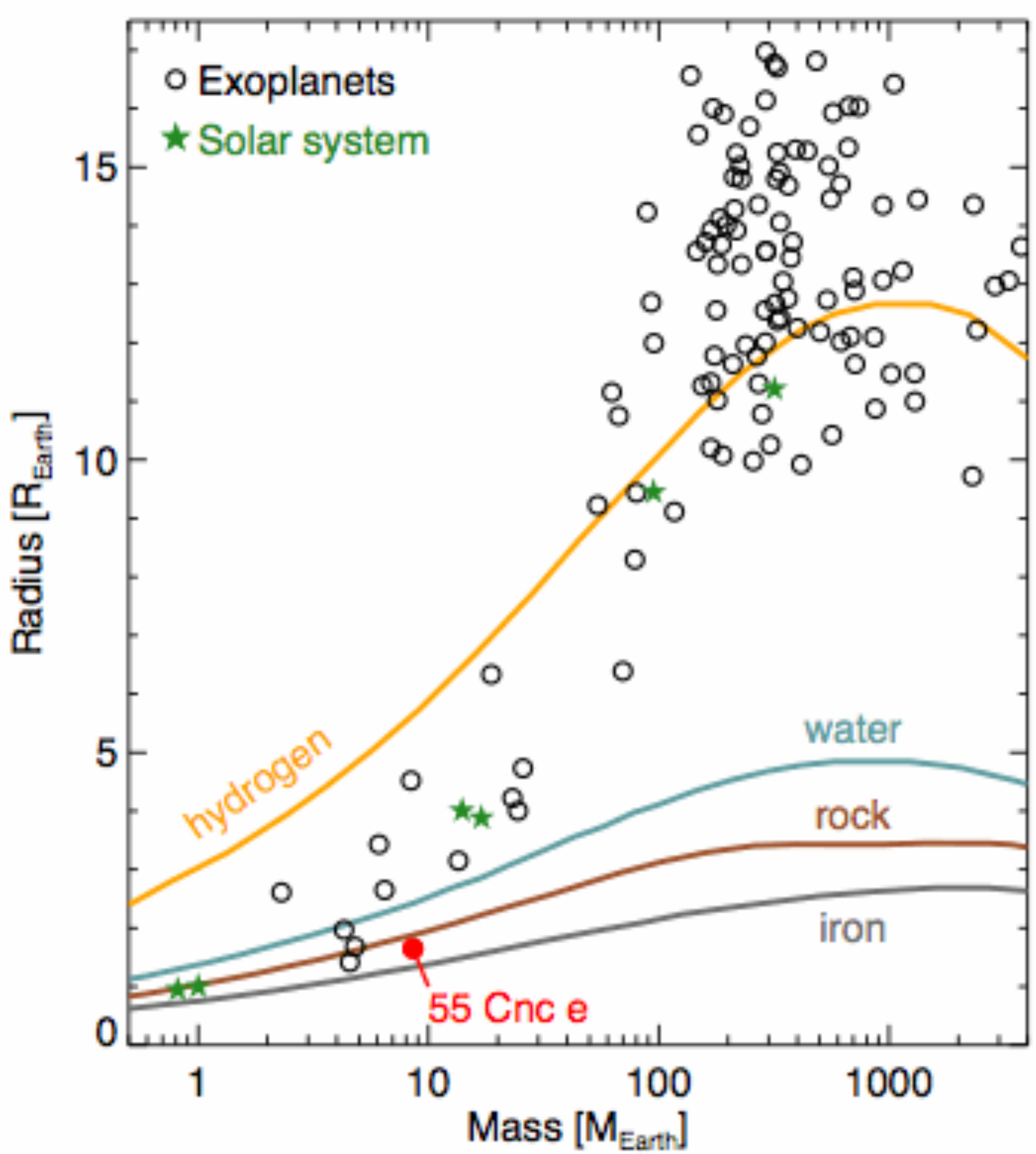


- Orbital Period < 10d
- Planet Mass ~ Jupiter/ Saturn
- Planet size up to 2x R_{Jup}
- T_{eq} > 1000 K

WASP-12b



Bottleneck of theory



Challenges:
Models developed for the Solar System clearly fail to explain the observed diversity

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Exoplanets are challenging

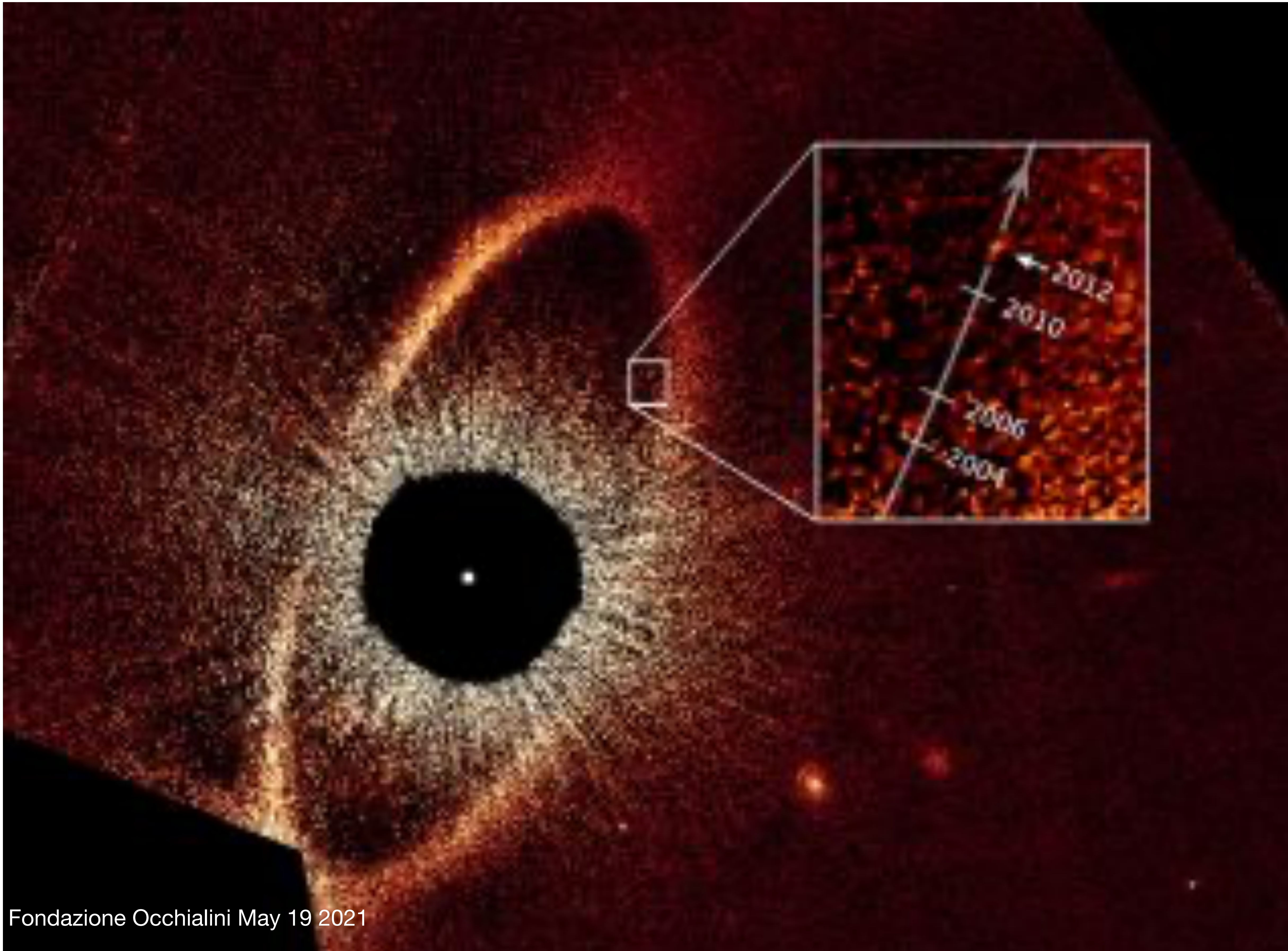
Stars are 10 billion times brighter than planets at visible light!!

We can not see planets directly (unless they are far away from their star) because they are outshone by their hosts stars

We use *indirect inferences* to detect planets

So the first ever exoplanets detected were giant Jupiter like planets

The EYE of SAURON



How Do we discover planets?

- *Radial velocity*
- *Transit photometry*

97% of planets

- Gravitational microlensing
- Direct imaging
- Astrometry (GAIA)
- Timing variations
  - Pulsar timing
  - Transit timing variation method
  - Transit duration variation method
- Polarimetry

.... etc

mass and radius

density

↓

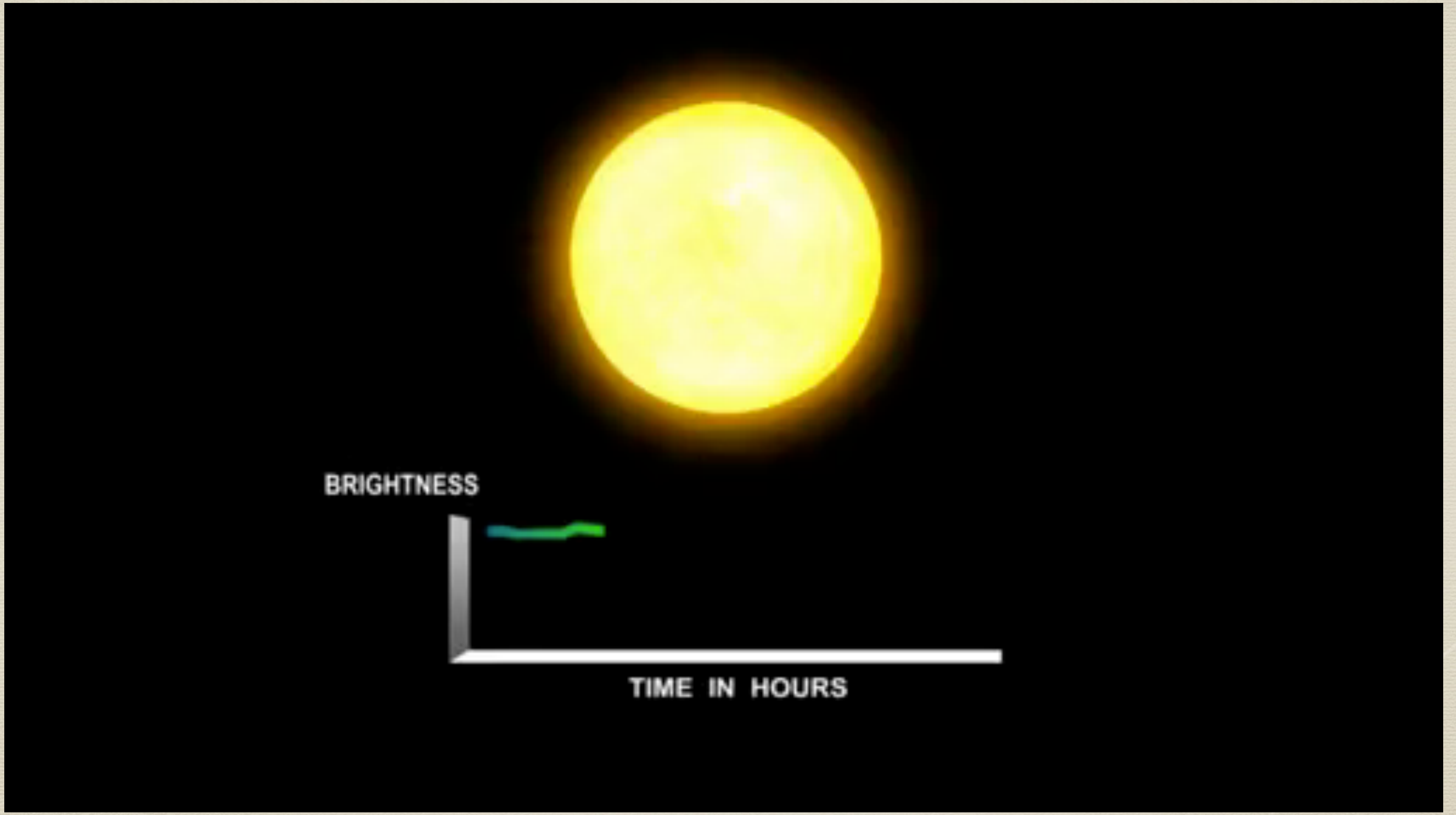
bulk composition

+

atmosphere

- Different sensitivity to planets of different mass regimes and orbital separation
- A complete census of the planet population requires the use of several different techniques

Planetary Transit



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Planetary Transit

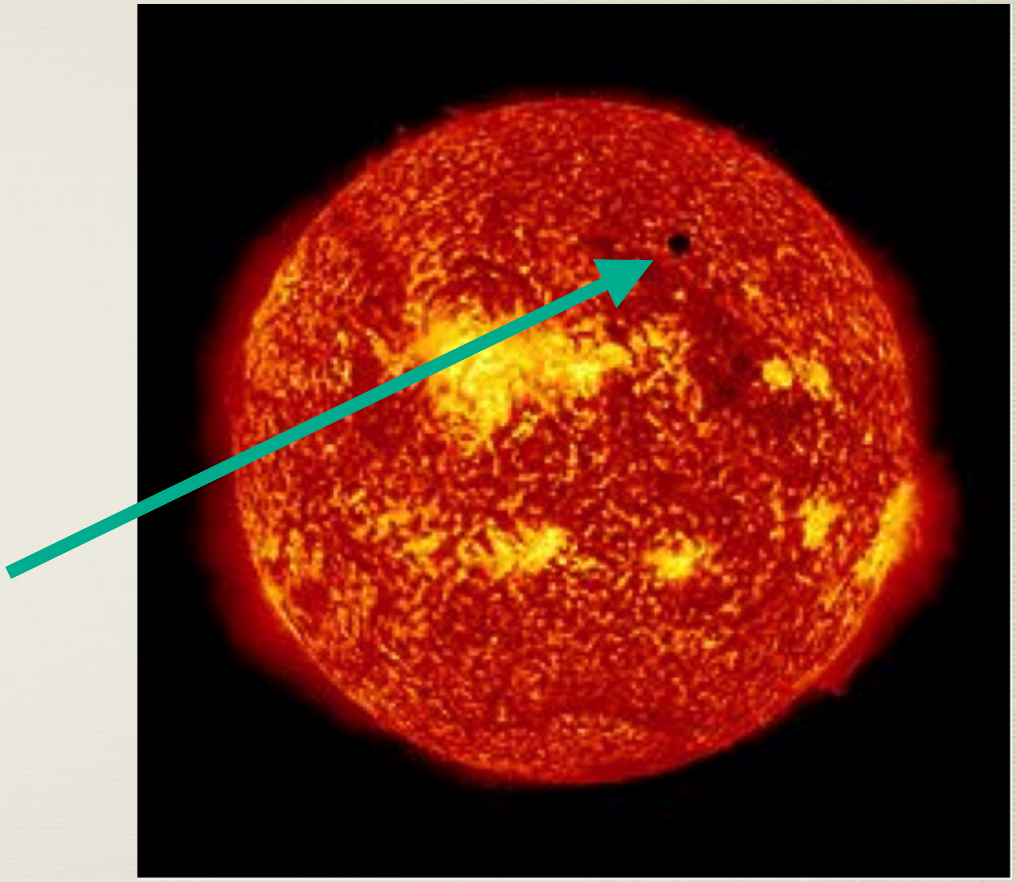
Reminder mostly geometry - get: radius of planet/star, inclination of orbit. Advantage of little physics needed.

$$r_{Jup} \sim 0.1 R_{Sun}$$

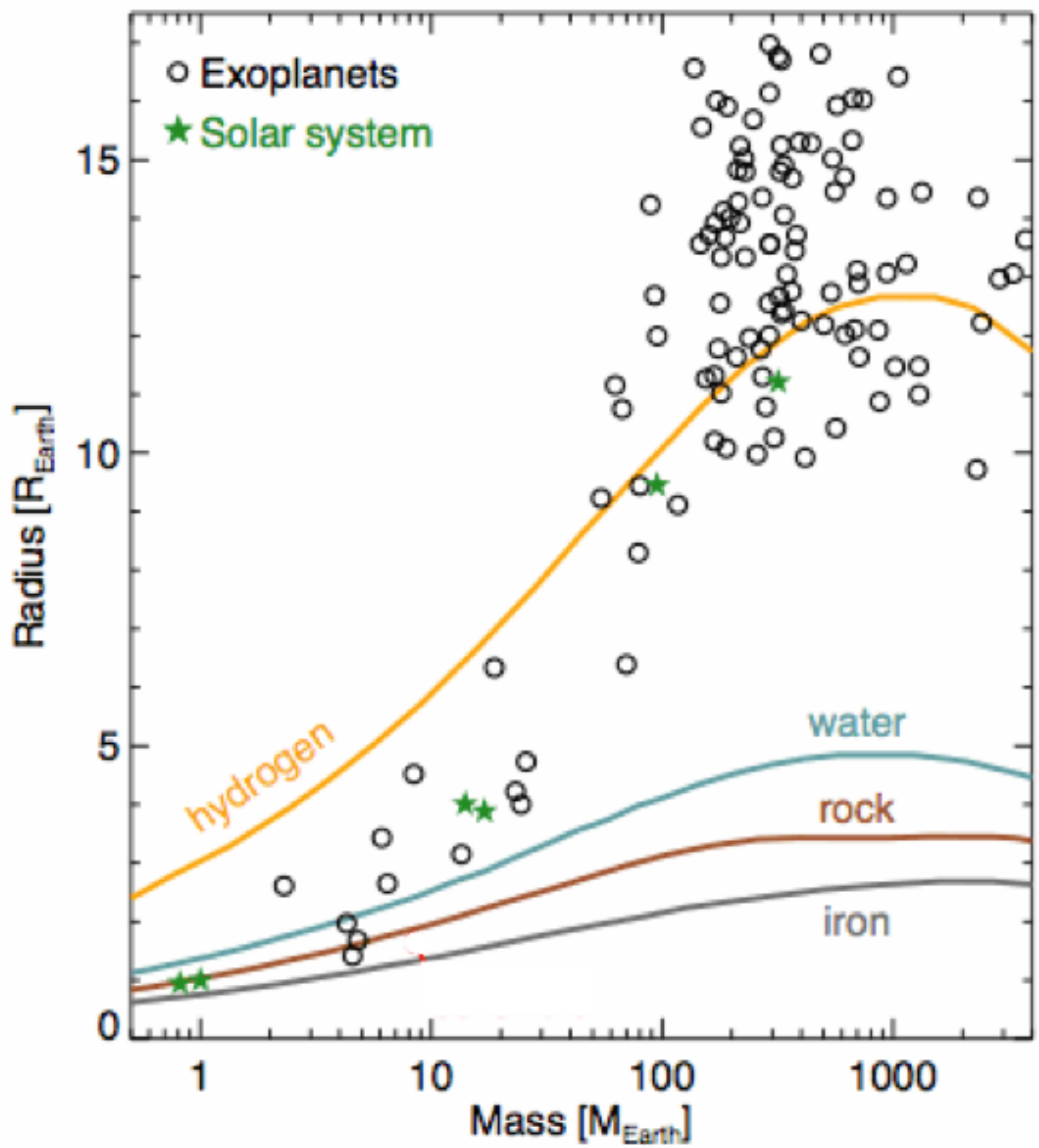
$$Depth: \frac{\Delta f}{f} \sim 1\,\% \left(\frac{r_{Pl}}{r_{Jup}}\right)^2 \left(\frac{R_{star}}{R_\odot}\right)$$

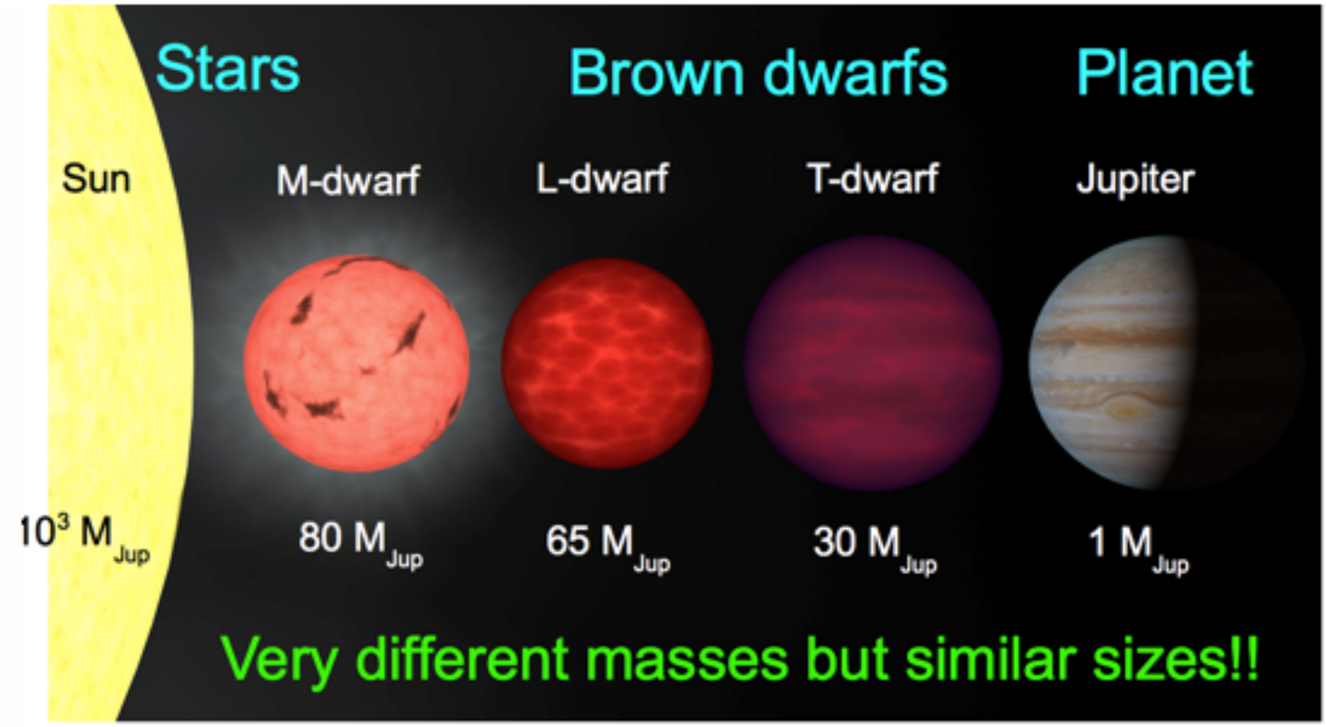
$$Duration: \Delta t \sim 3h \left(\frac{M_{star}}{M_\odot}\right)^{2/3} \left(\frac{P}{4d}\right)$$

$$Probability: P_{tr} \sim 10\,\% \left(\frac{R_{star}}{R_\odot}\right) \left(\frac{M_{star}}{M_\odot}\right)^{1/3} \left(\frac{P}{4d}\right)^{-2/3}$$

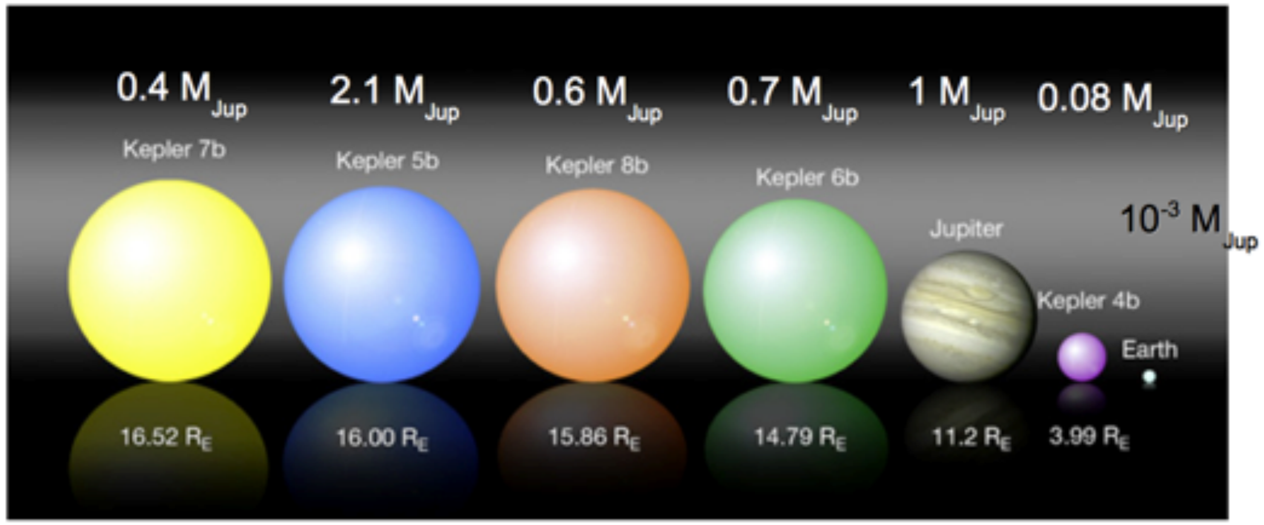


Why not just size!

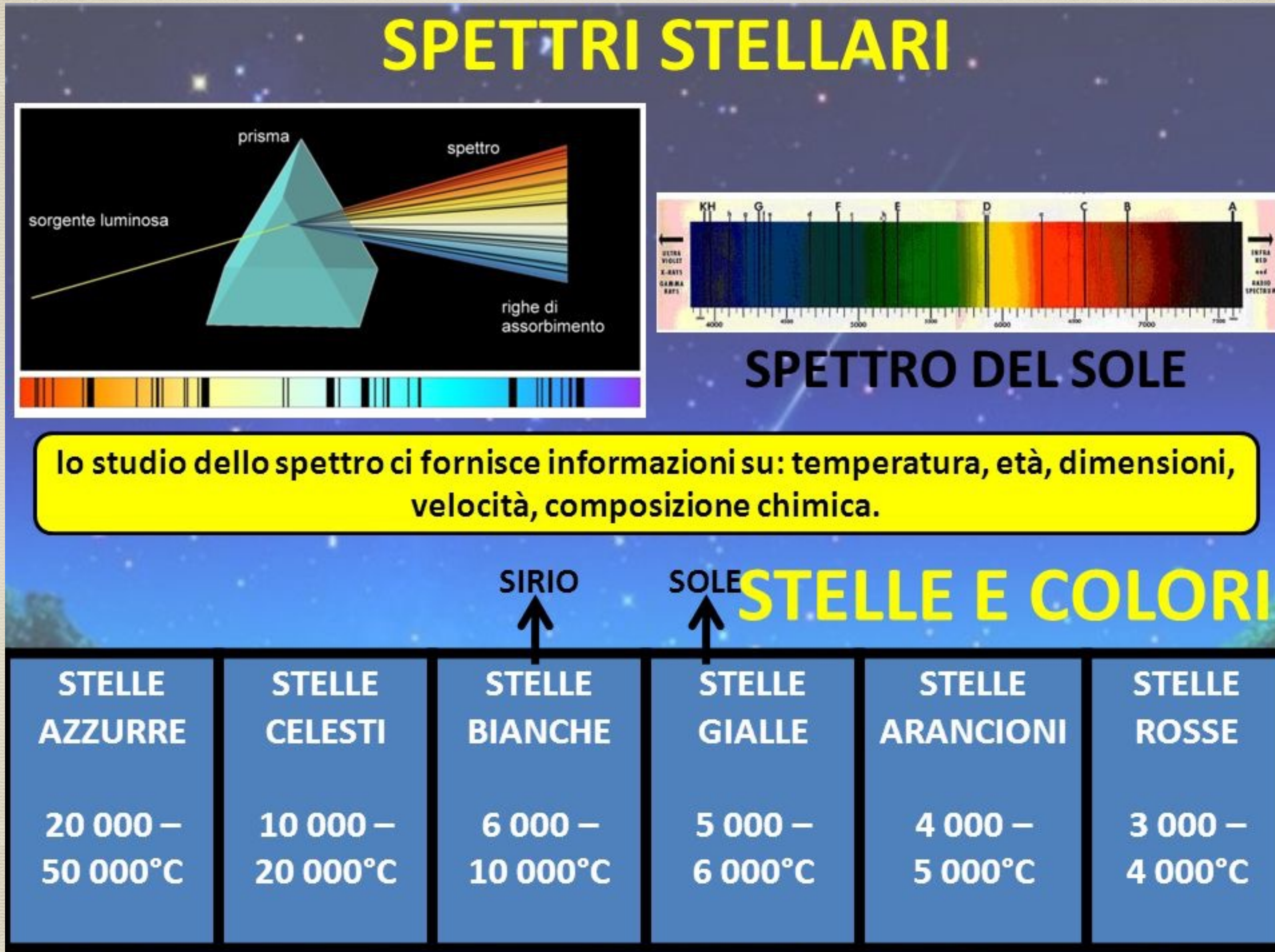




NASA/IPAC/R. Hurt



NASA/Kepler


SPETTRI STELLARI
prisma
spettro
sorgente luminosa
righe di assorbimento
SPETTRO DEL SOLE
lo studio dello spettro ci fornisce informazioni su: temperatura, età, dimensioni, velocità, composizione chimica.
SIRIO
SOLE
STELLE E COLORI
STELLE AZZURRE 20 000 – 50 000°C
STELLE CELESTI 10 000 – 20 000°C
STELLE BIANCHE 6 000 – 10 000°C
STELLE GIALLE 5 000 – 6 000°C
STELLE ARANCIONI 4 000 – 5 000°C
STELLE ROSSE 3 000 – 4 000°C

Radial Velocity: Doppler shift

Planet minimum mass

Hot Jupiters

$$K = 203.255 ms^{-1} \left(\frac{1d}{P}\right)^{1/3} \left(\frac{M_{pl}\ sini}{M_{Jup}}\right)^{2/3} \left(\frac{1}{\sqrt{1-e^2}}\right)$$

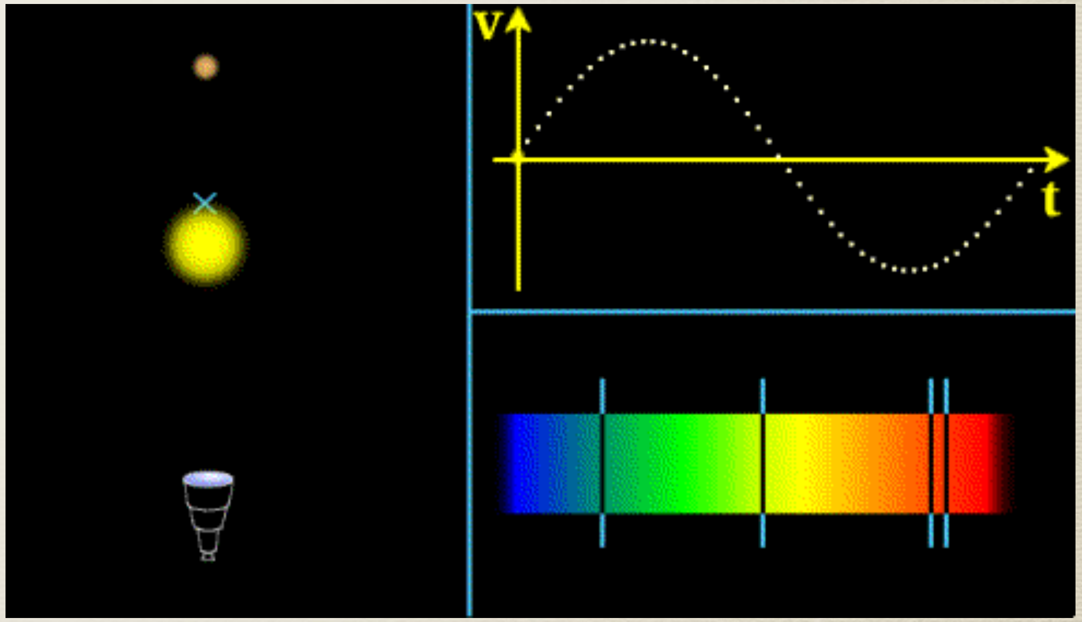
$$K = 28.435 ms^{-1} \left(\frac{1yr}{P}\right)^{1/3} \left(\frac{M_{pl}\ sini}{M_{Jup}}\right)^{2/3} \left(\frac{1}{\sqrt{1-e^2}}\right)$$

Earth-like

$$K = 0.639 ms^{-1} \left(\frac{1d}{P}\right)^{1/3} \left(\frac{M_{pl}\ sini}{M_{Earth}}\right)^{2/3} \left(\frac{1}{\sqrt{1-e^2}}\right)$$

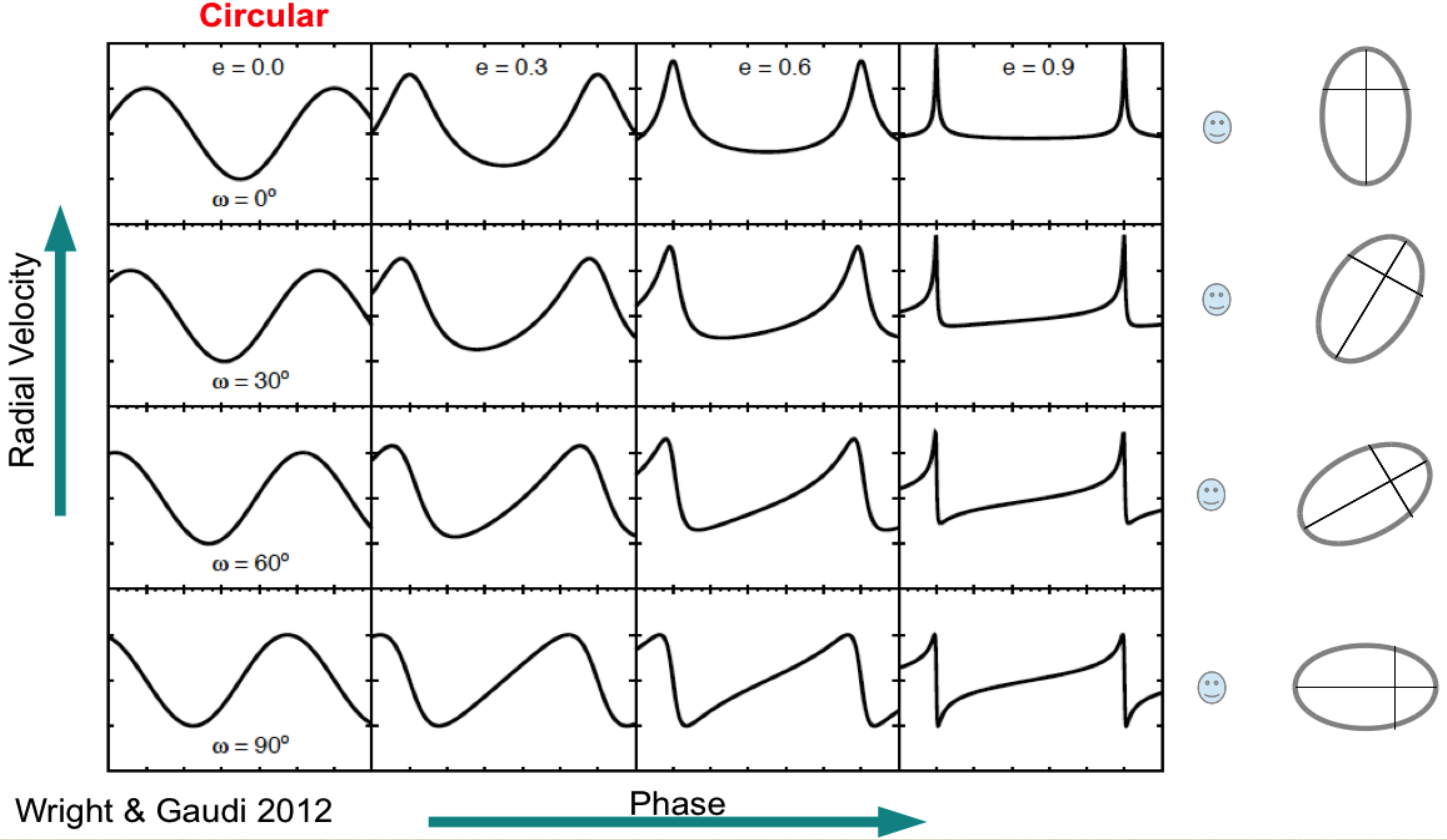
$$K = 0.089 ms^{-1} \left(\frac{1yr}{P}\right)^{1/3} \left(\frac{M_{pl}\ sini}{M_{Earth}}\right)^{2/3} \left(\frac{1}{\sqrt{1-e^2}}\right)$$

< 10cm!!



Radial Velocity: Doppler shift

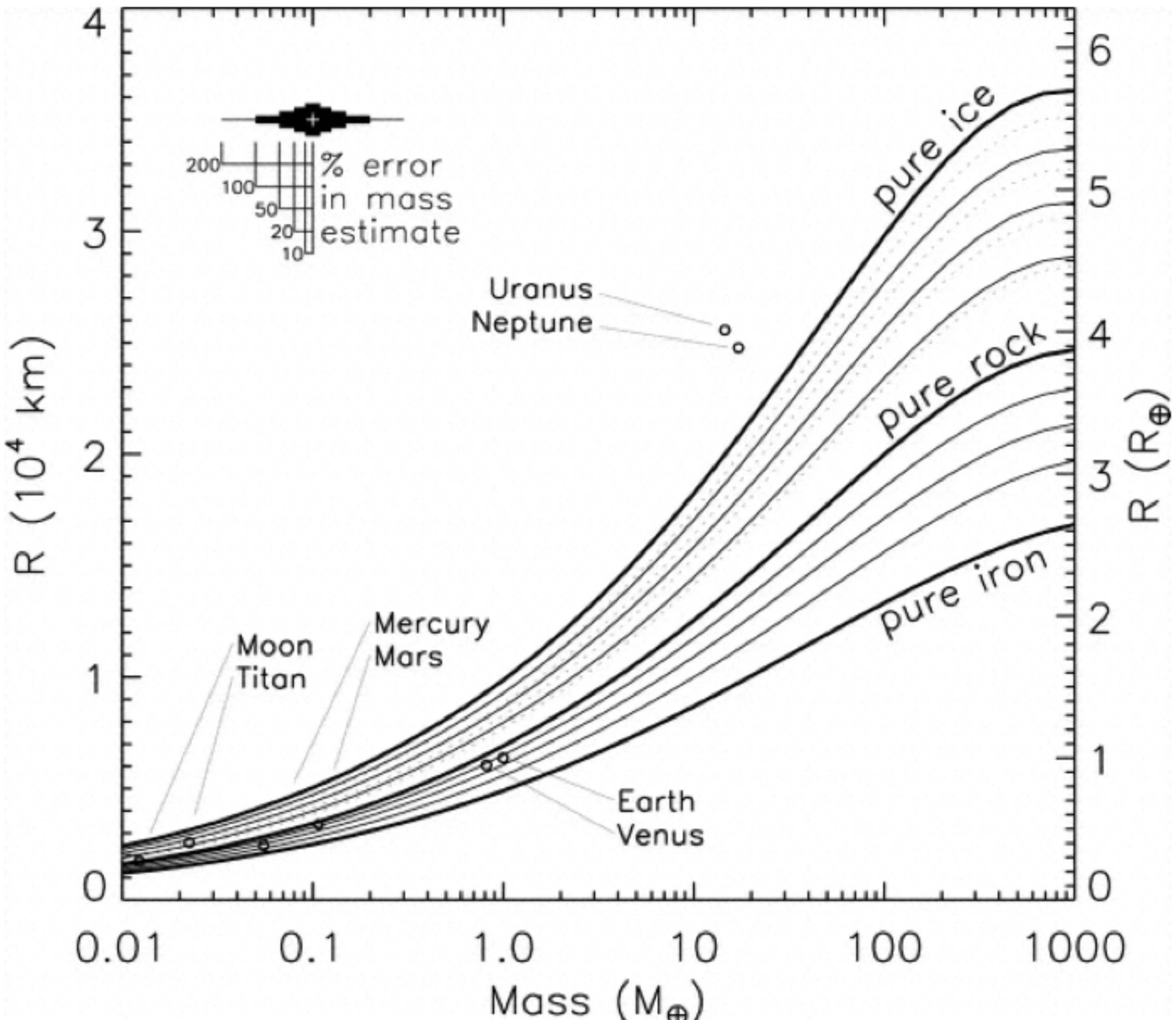
Eccentricity and Orientation



Wright & Gaudi 2012

Mass-Radius Diagram

We can infer the planet's bulk composition from its mass and radius.

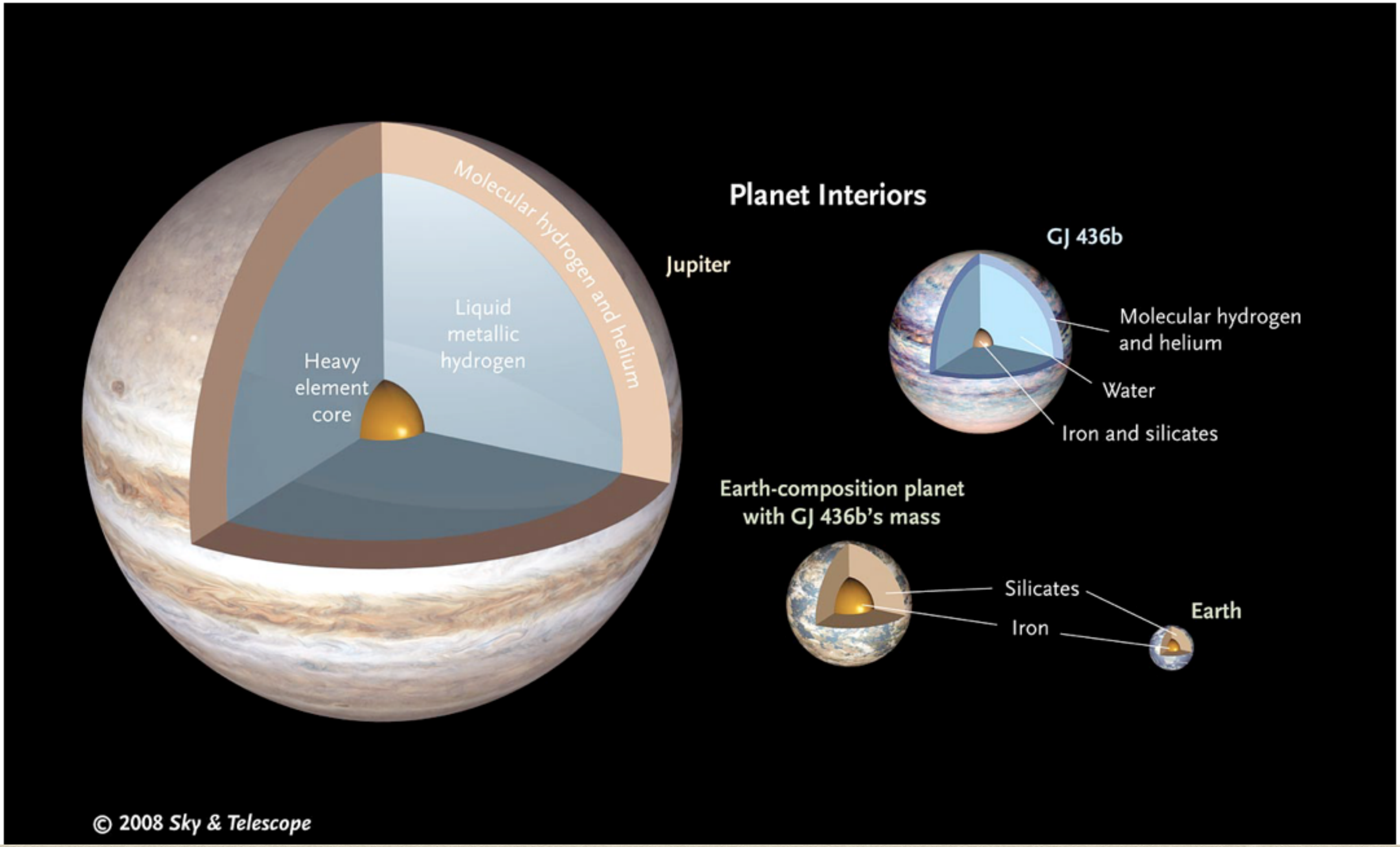


Fortney et al 2007

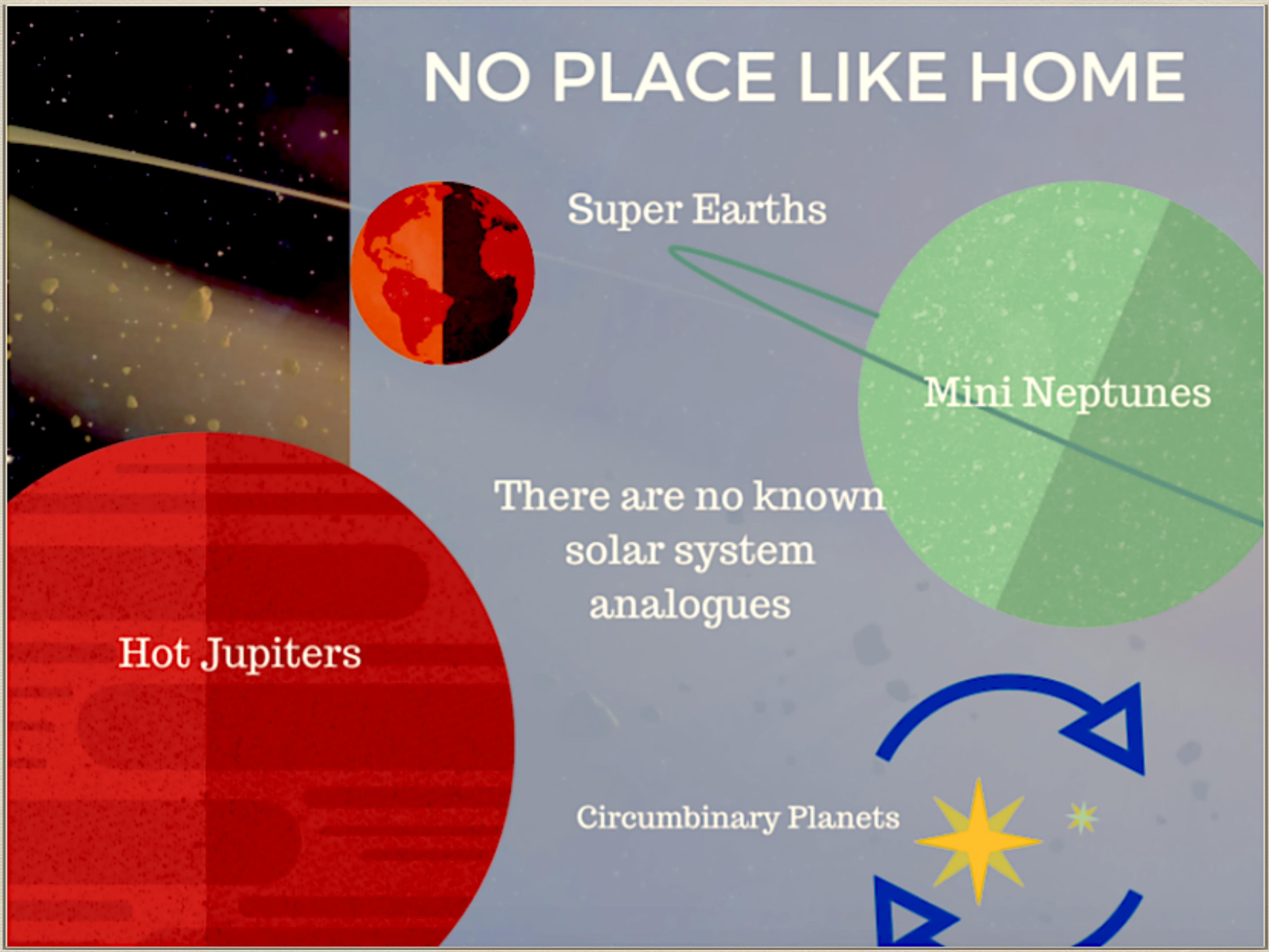
Transits + RVs

Mass-Radius Diagram

We can infer the planet's bulk composition from its mass and radius.

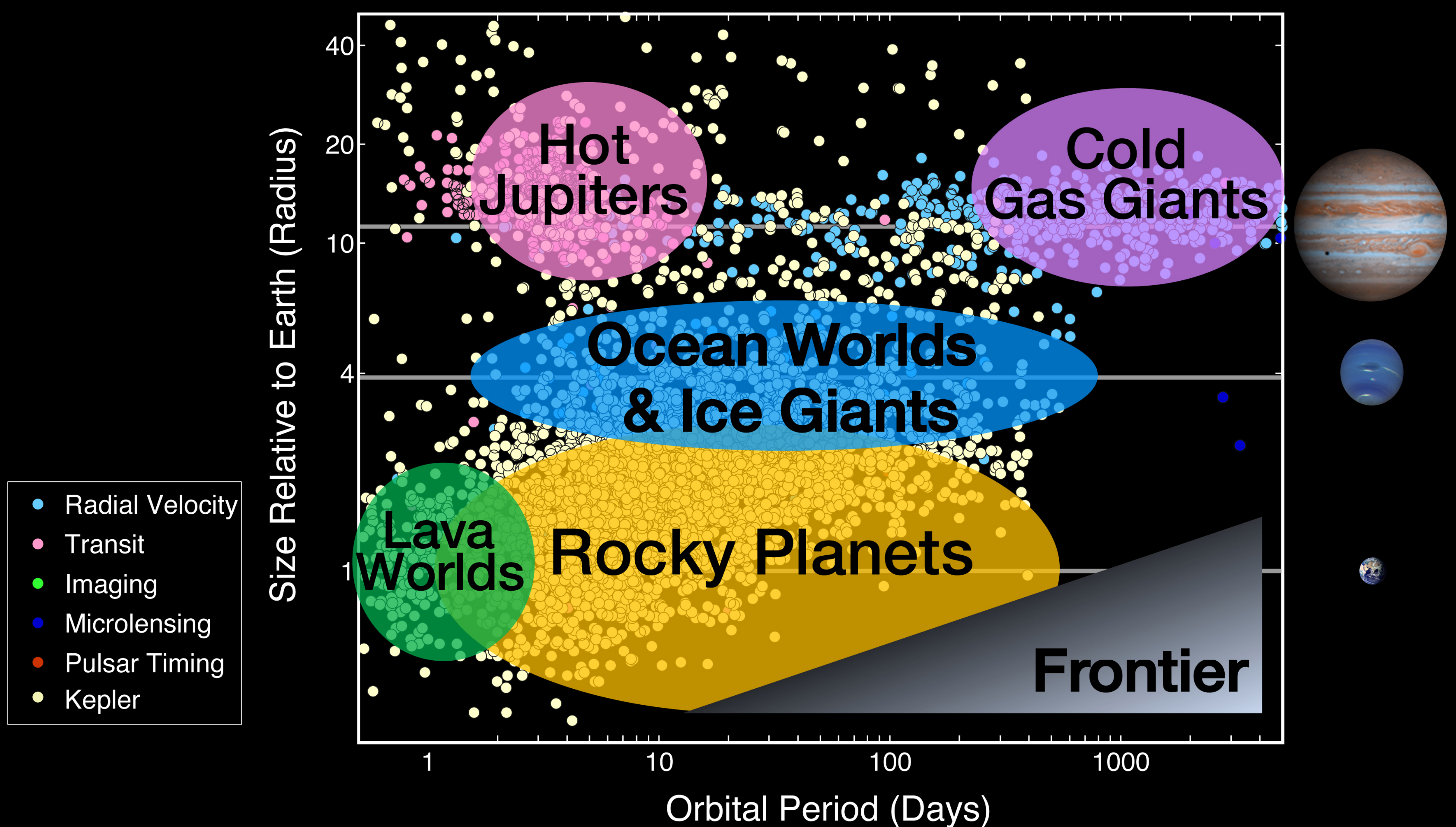


What have we learned …

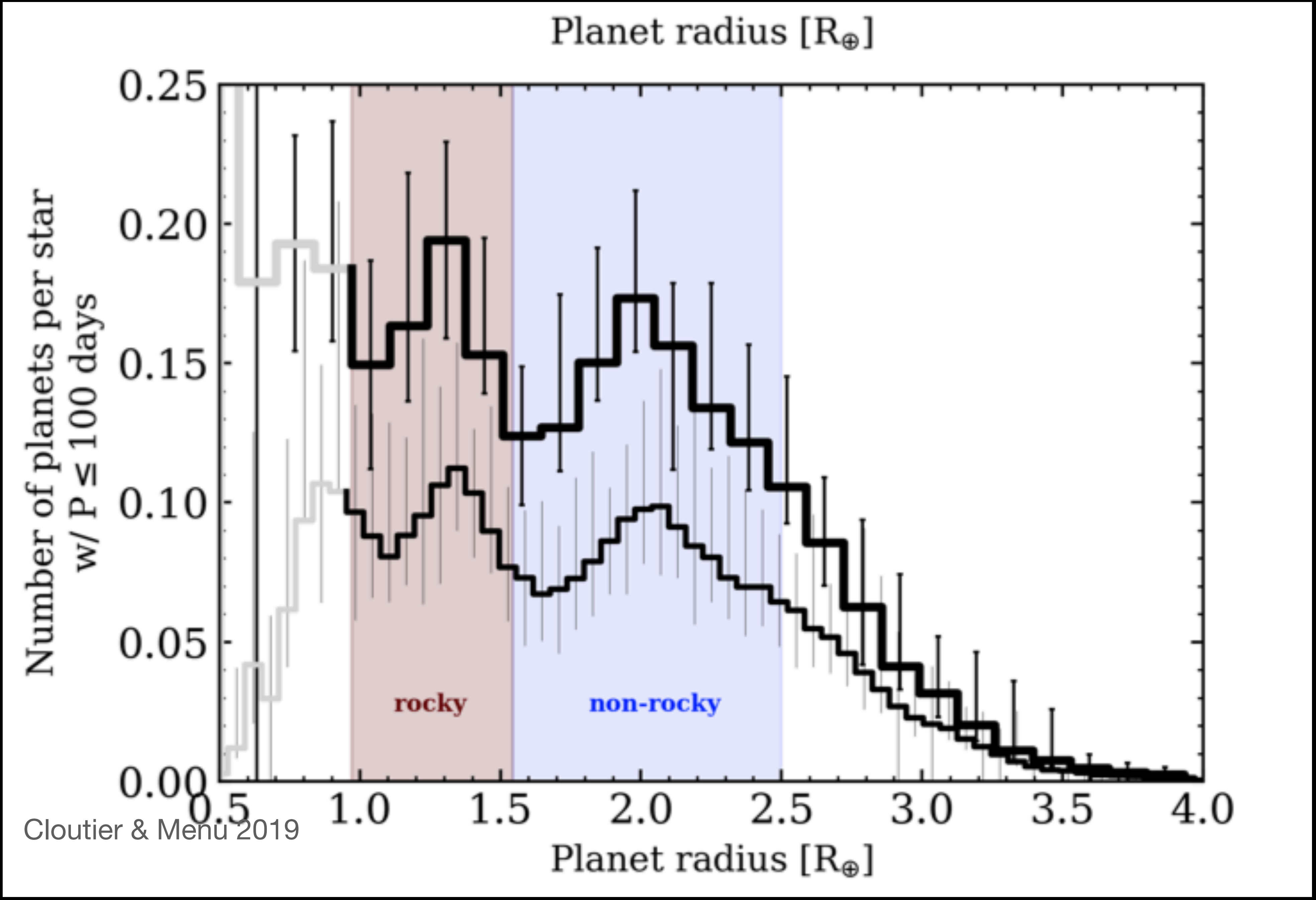


What have we learned …

Exoplanet Populations

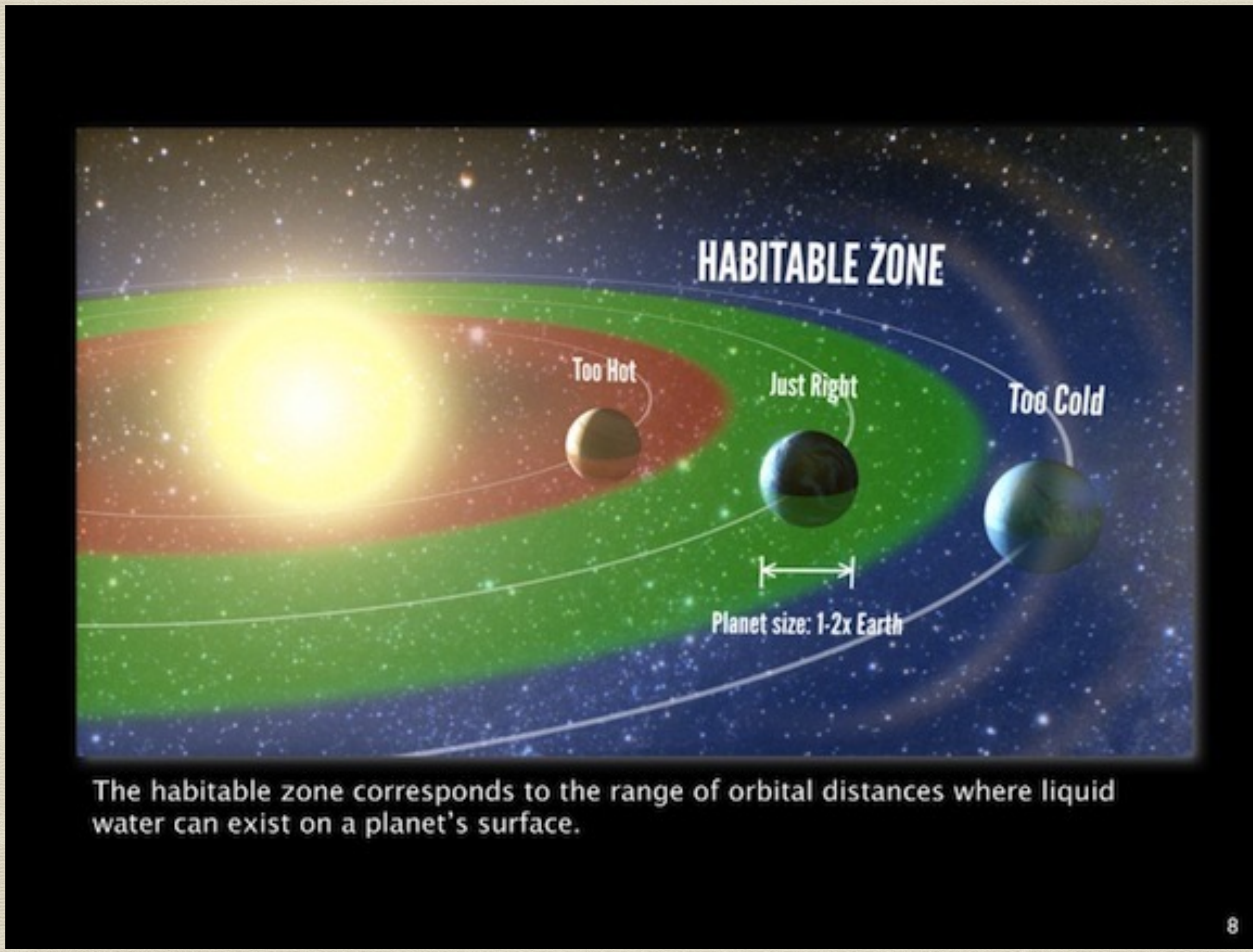


A striking result: Kepler Planet distribution

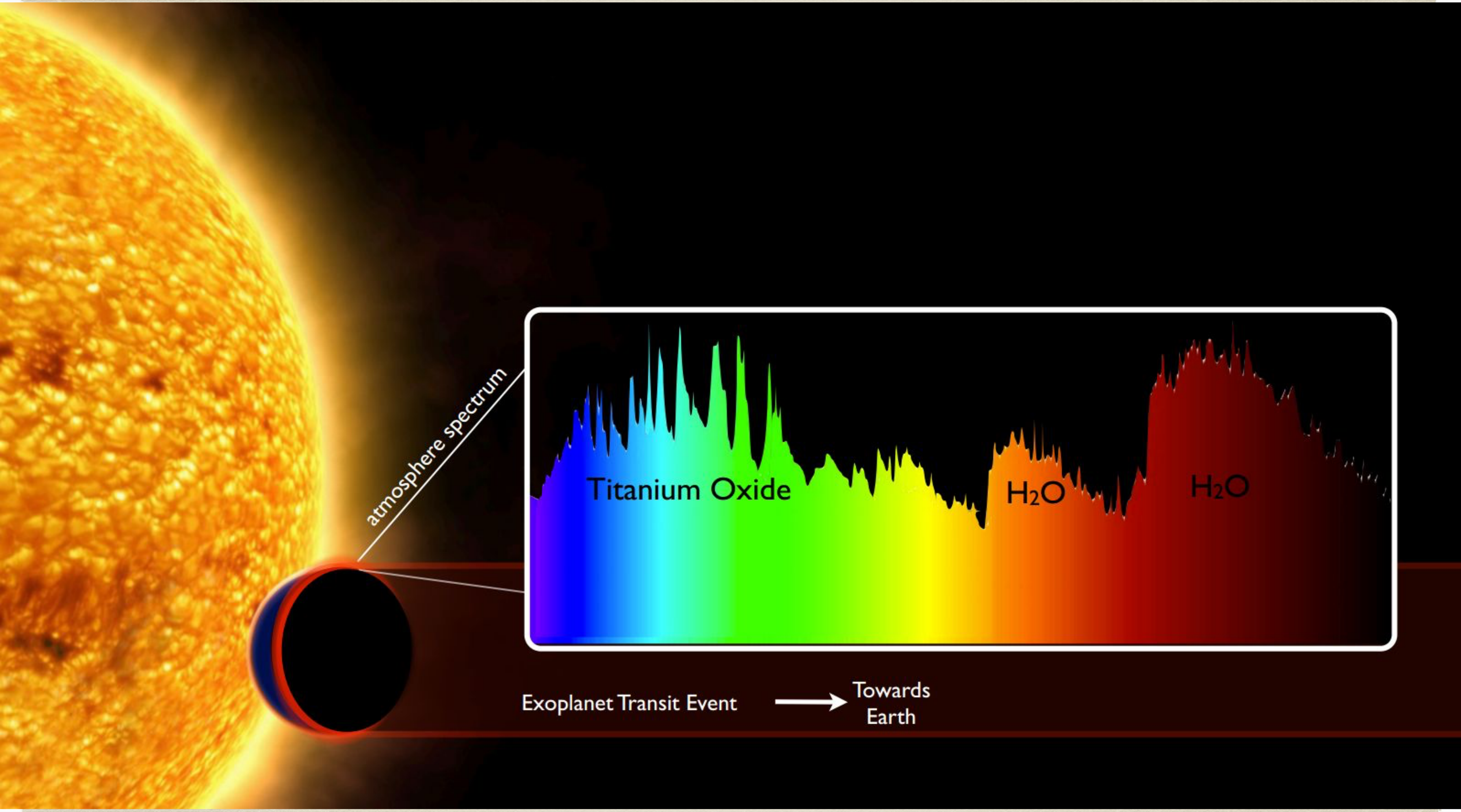


Cloutier & Menù 2019

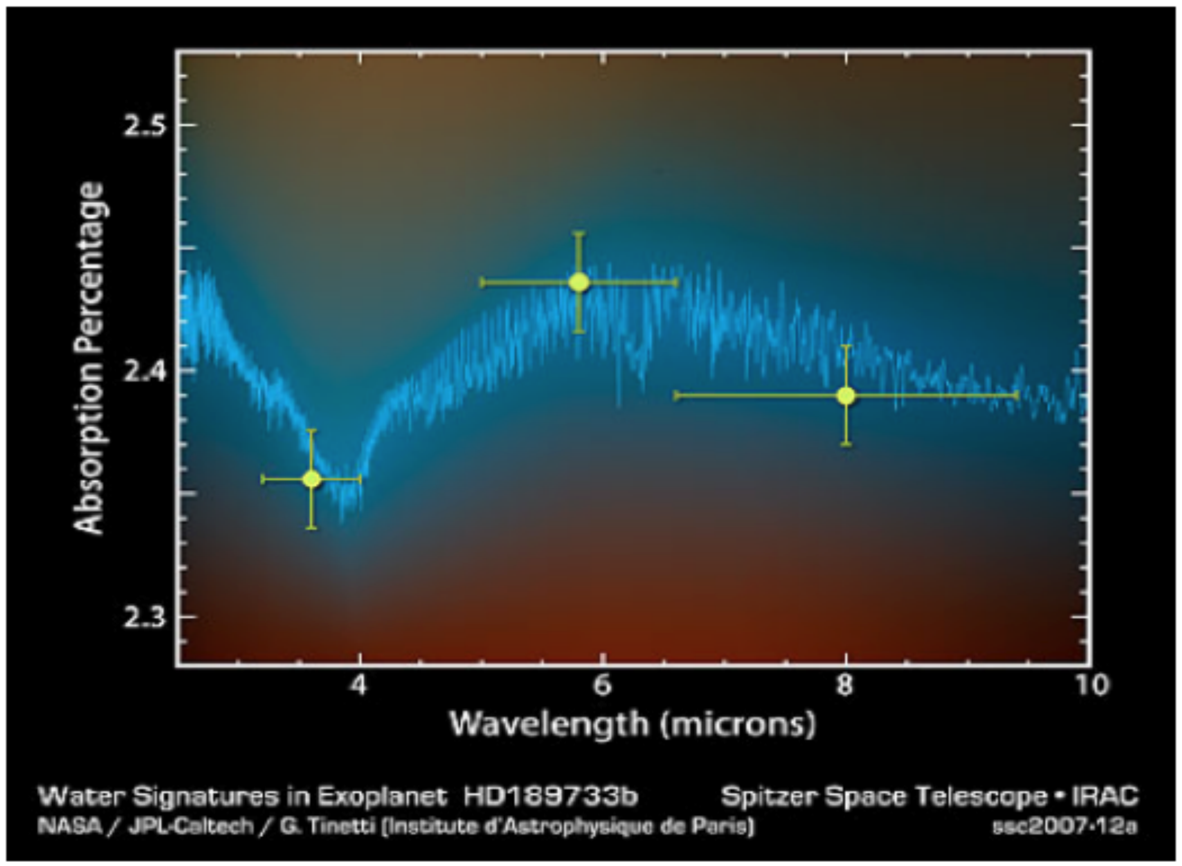
Habitable Zone



Exoplanet Atmospheres

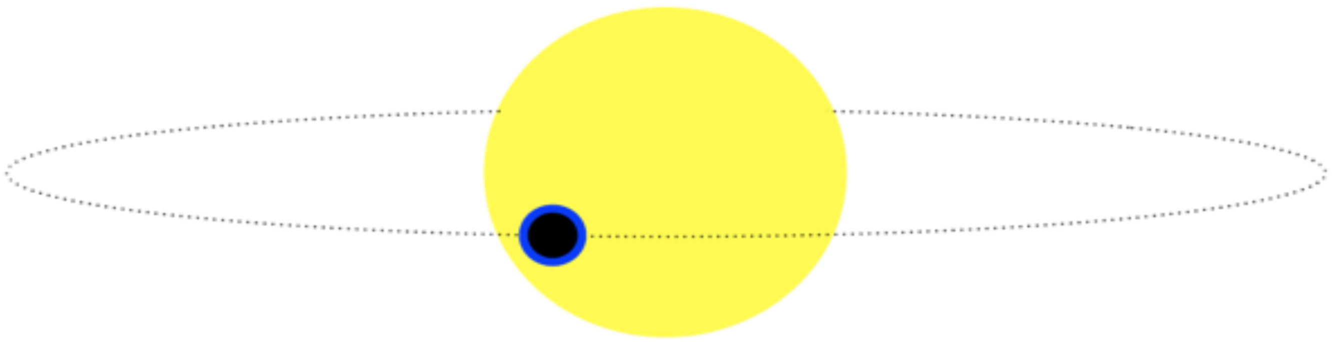


Transmission Spectroscopy

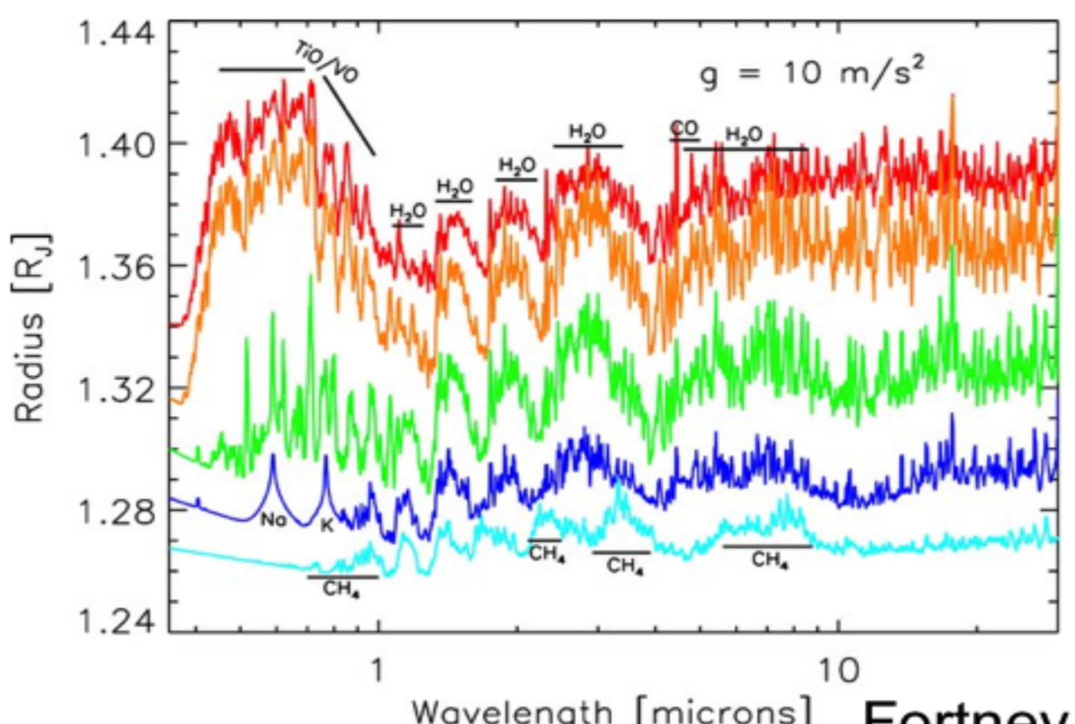


Observations of the host star during the primary eclipse in the mid-IR bands at 3.6, 4.5 and 8 microns. The absorption by water in the atmosphere of the planet creates a drop in flux in the 3.6 band.

The planet partially eclipses the star;
Transmission spectroscopy through the limb

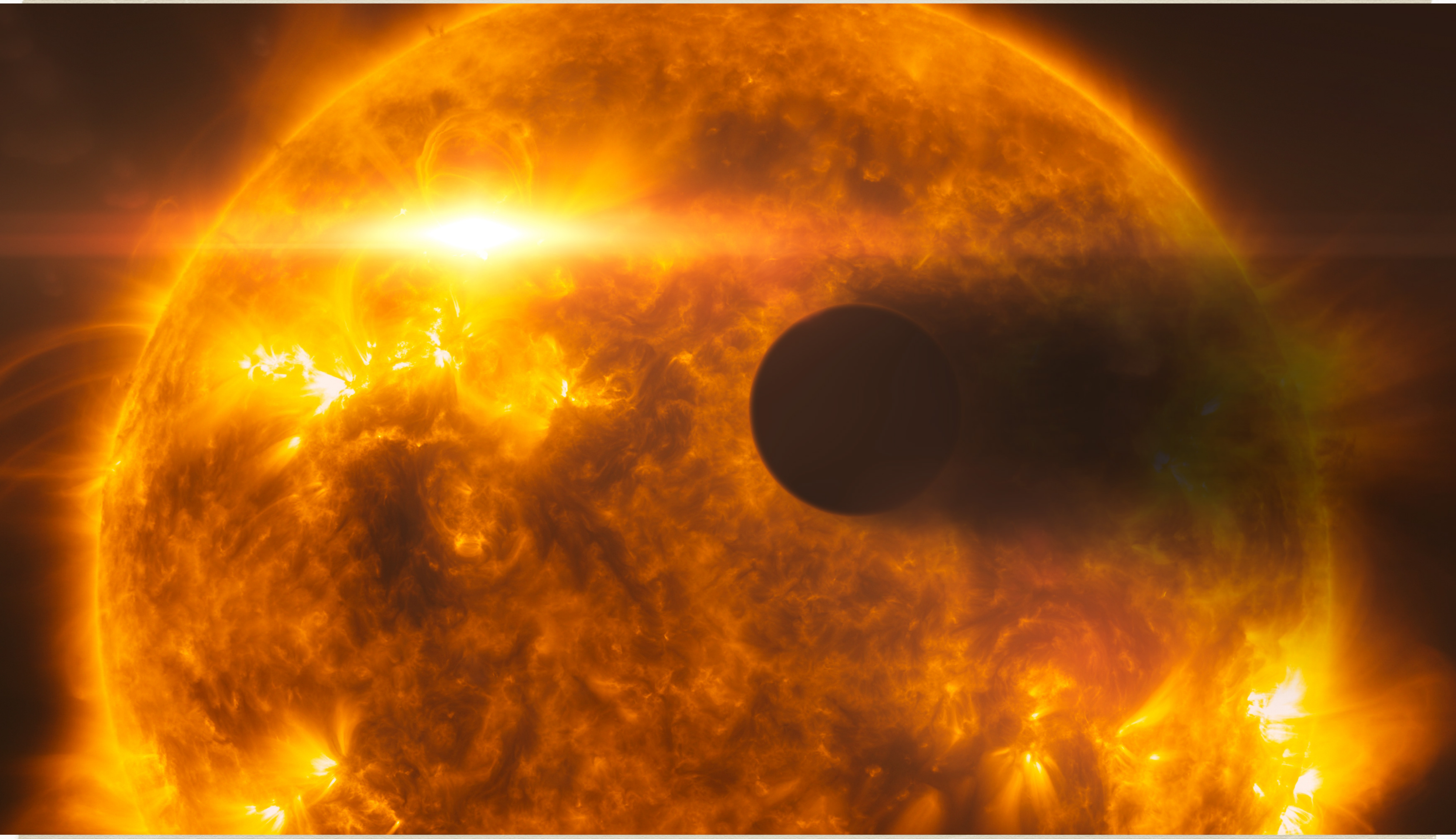


Planet blocks ~1% of star light;
~0.01% effect of planet atmosphere absorption

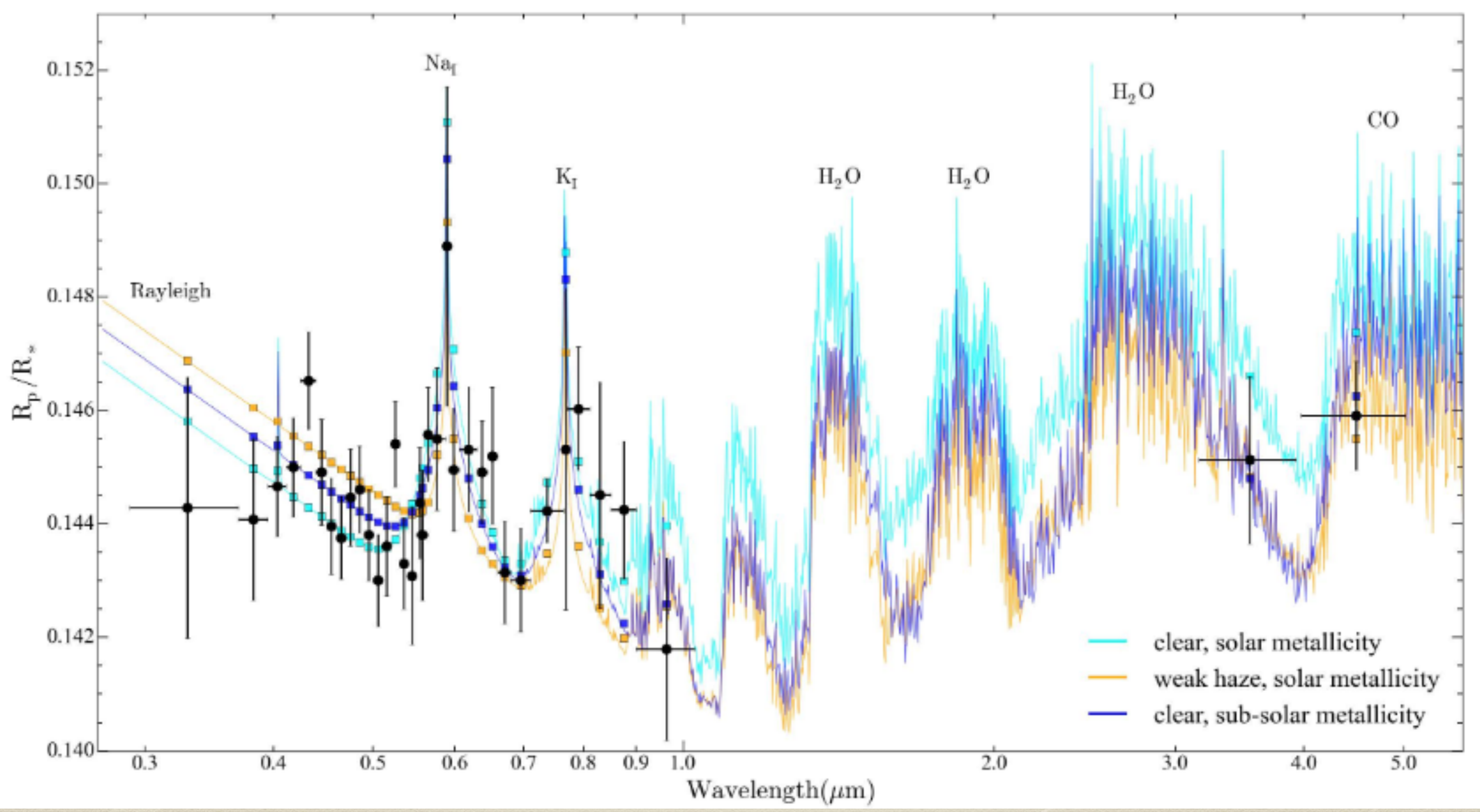


Fortney et al 2010

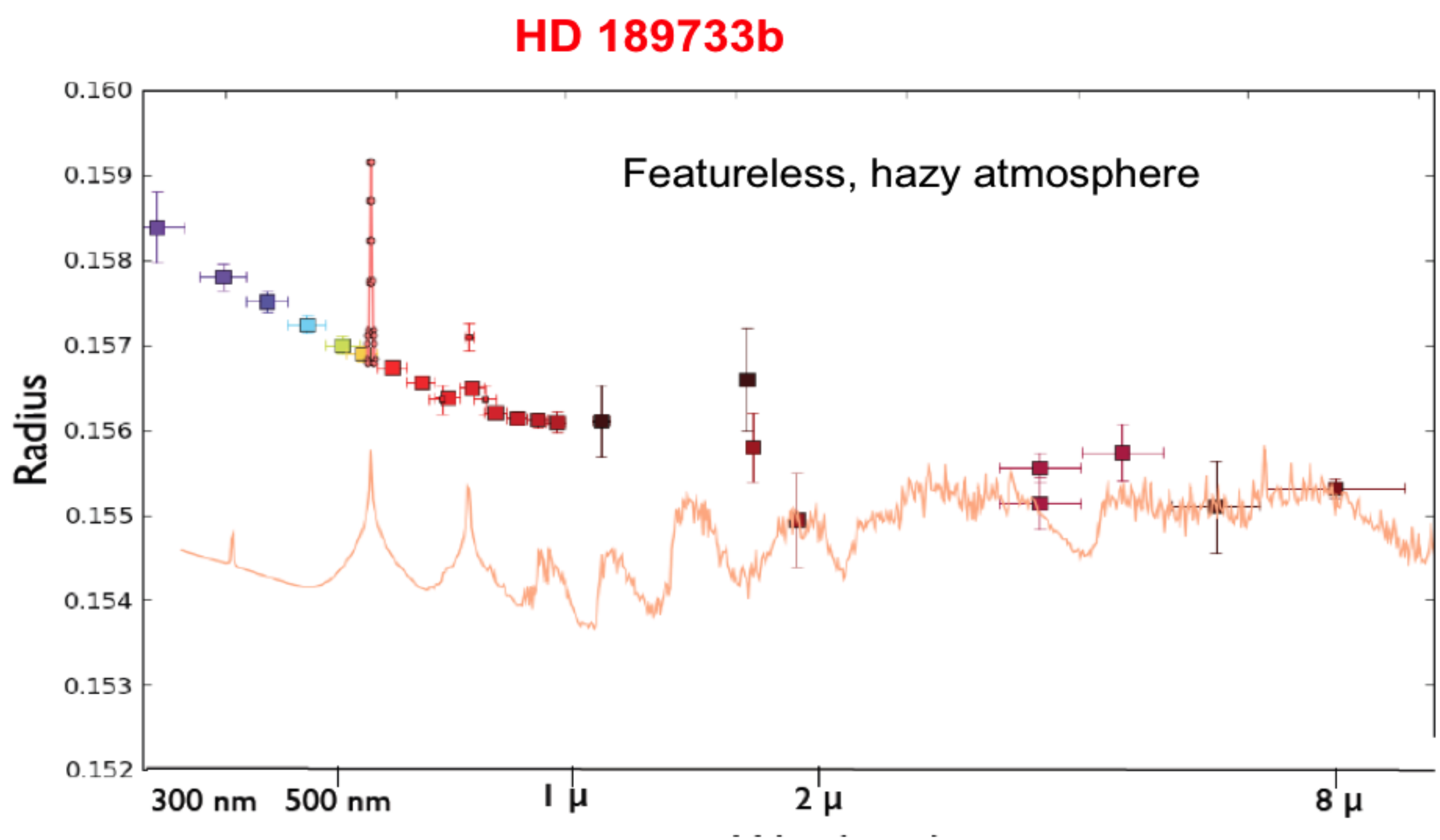
WASP-39b … one of my discoveries



WASP-39b
Transmission Spectroscopy —> Composition of planetary atmospheres



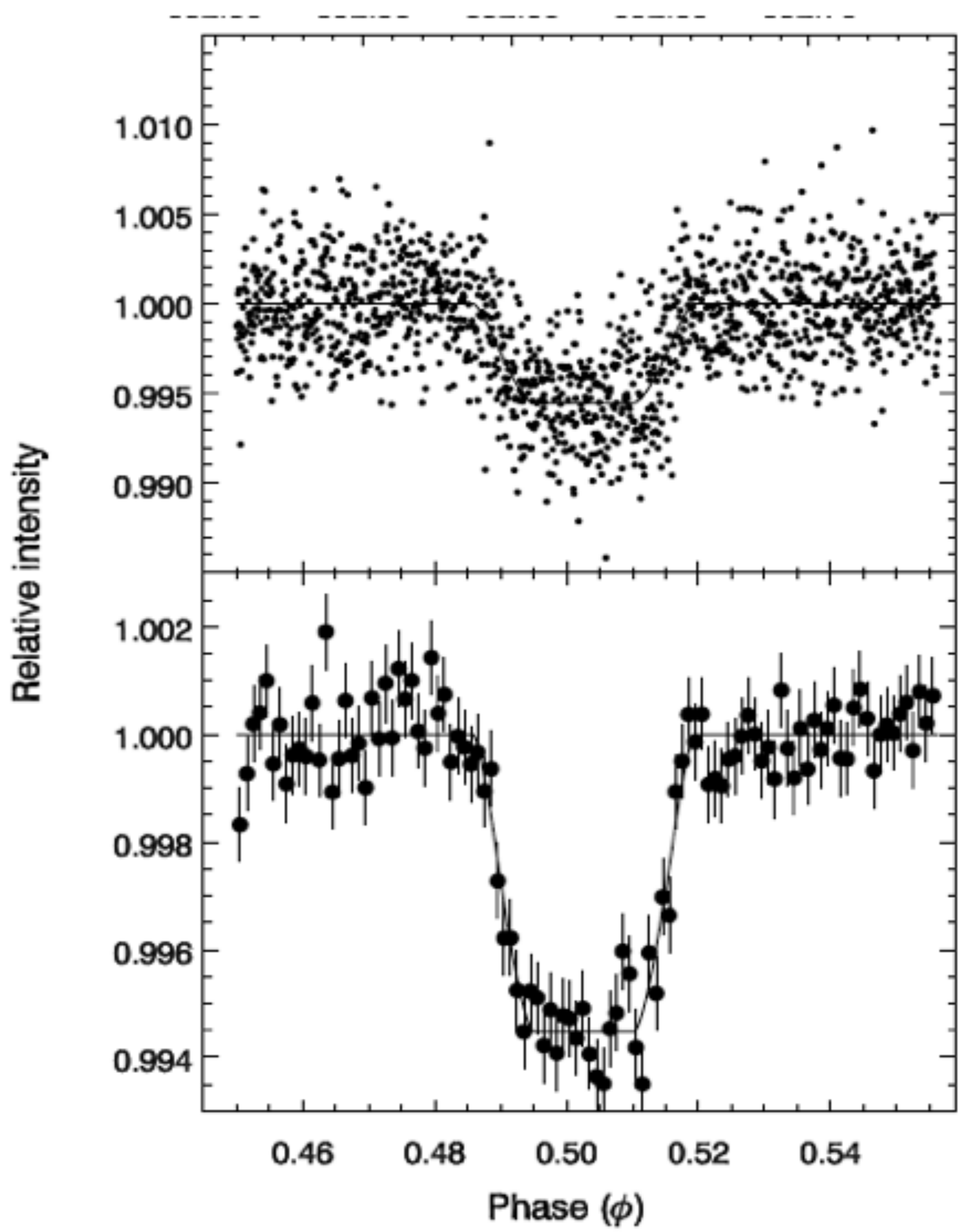
Transmission Spectroscopy

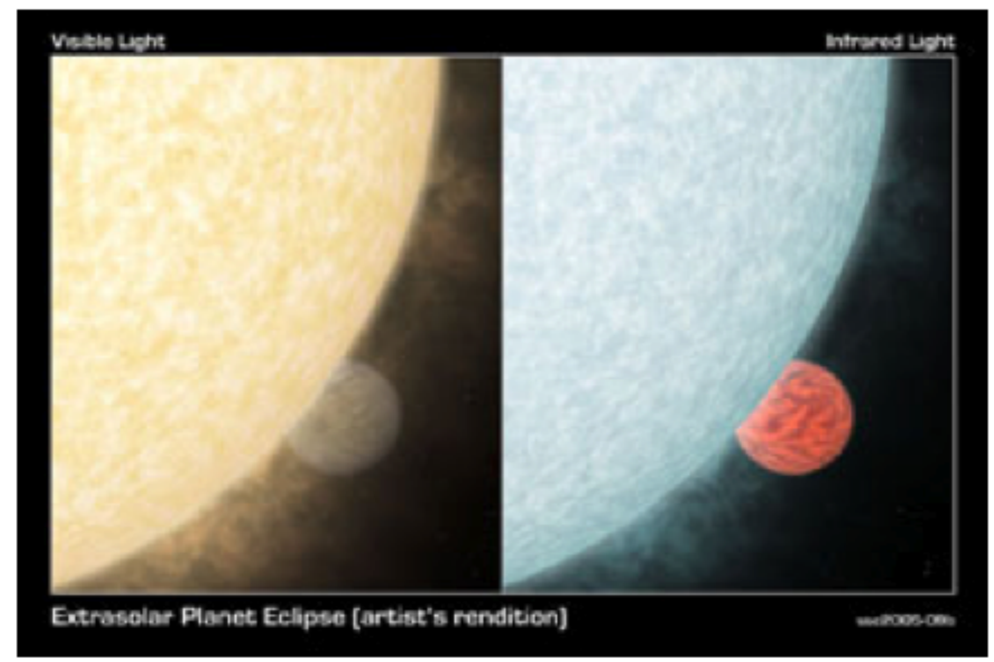


Pont et al 2008; Sing et al 2011; Huitson et al 2011; Gibson et al 2011; Sing et al 2009; Desert et al 2008, 2009; Agol et al 2010

Infrared emission of planet

HD189733





Observations of the secondary eclipse of this planet show the drop in flux as the planet moves behind the star. From this, the planet flux at 16 microns is 660 μJy and the brightness temperature of the planet is measured to be T_b=1117 K

(Deming et al 2006)

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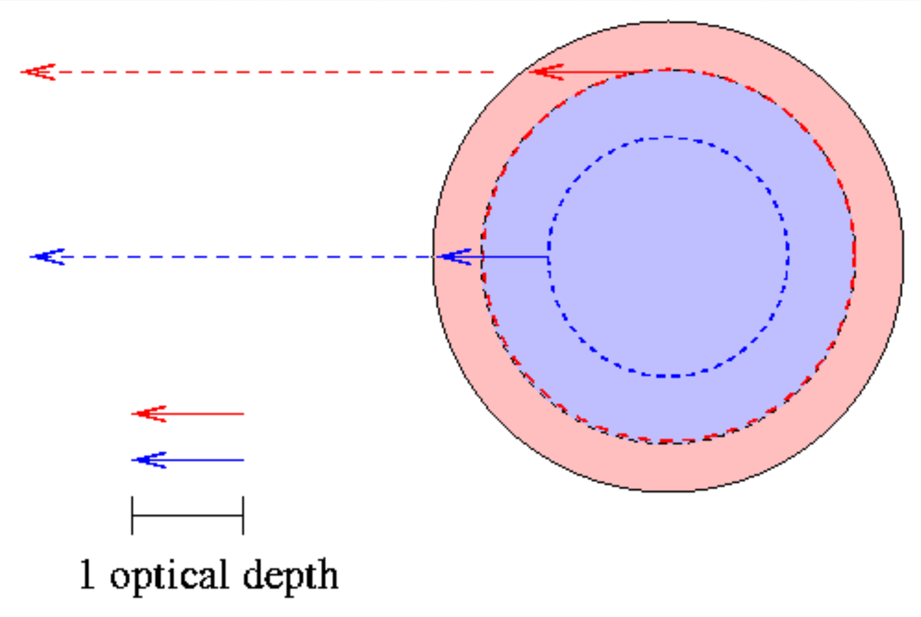
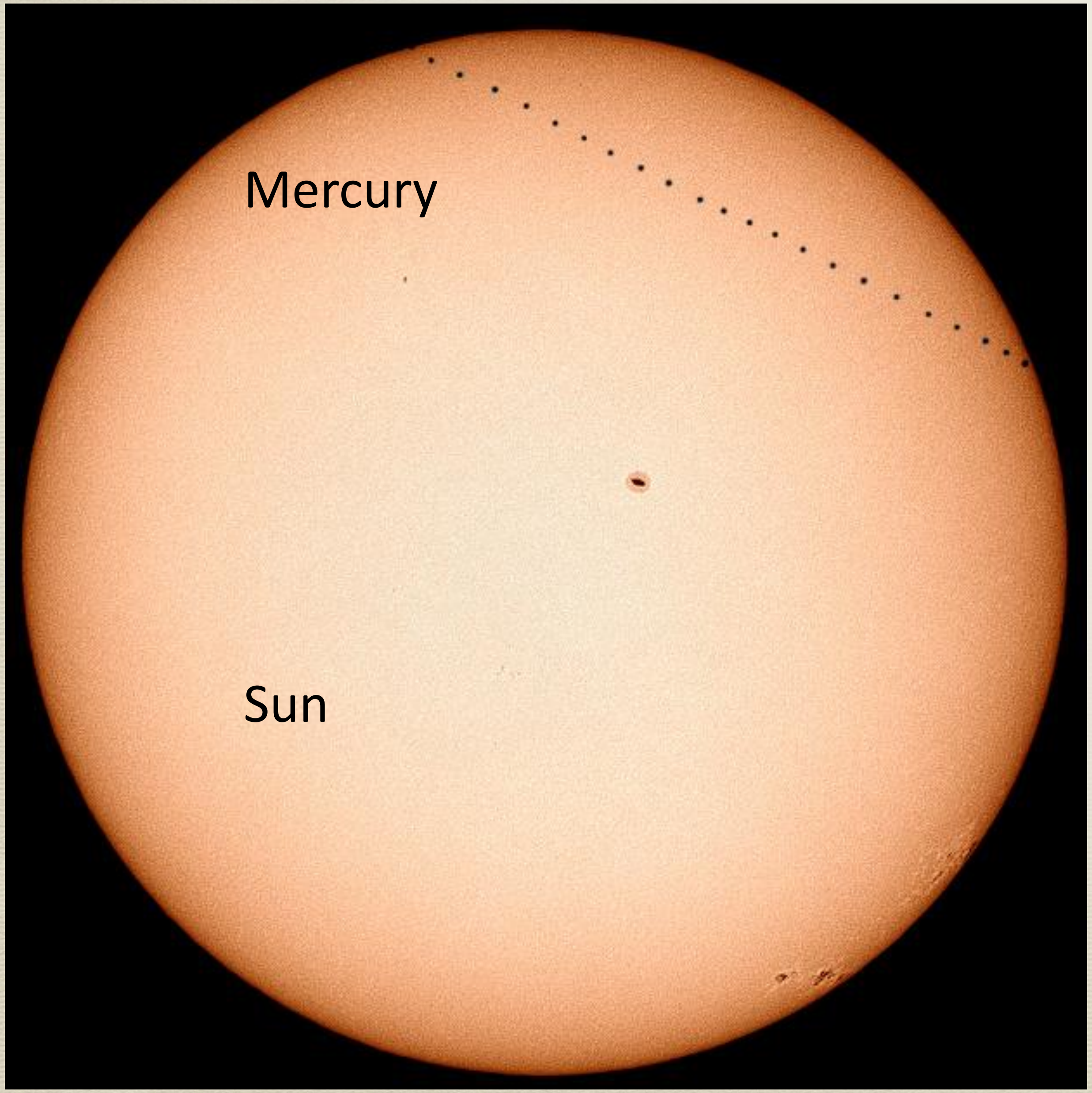
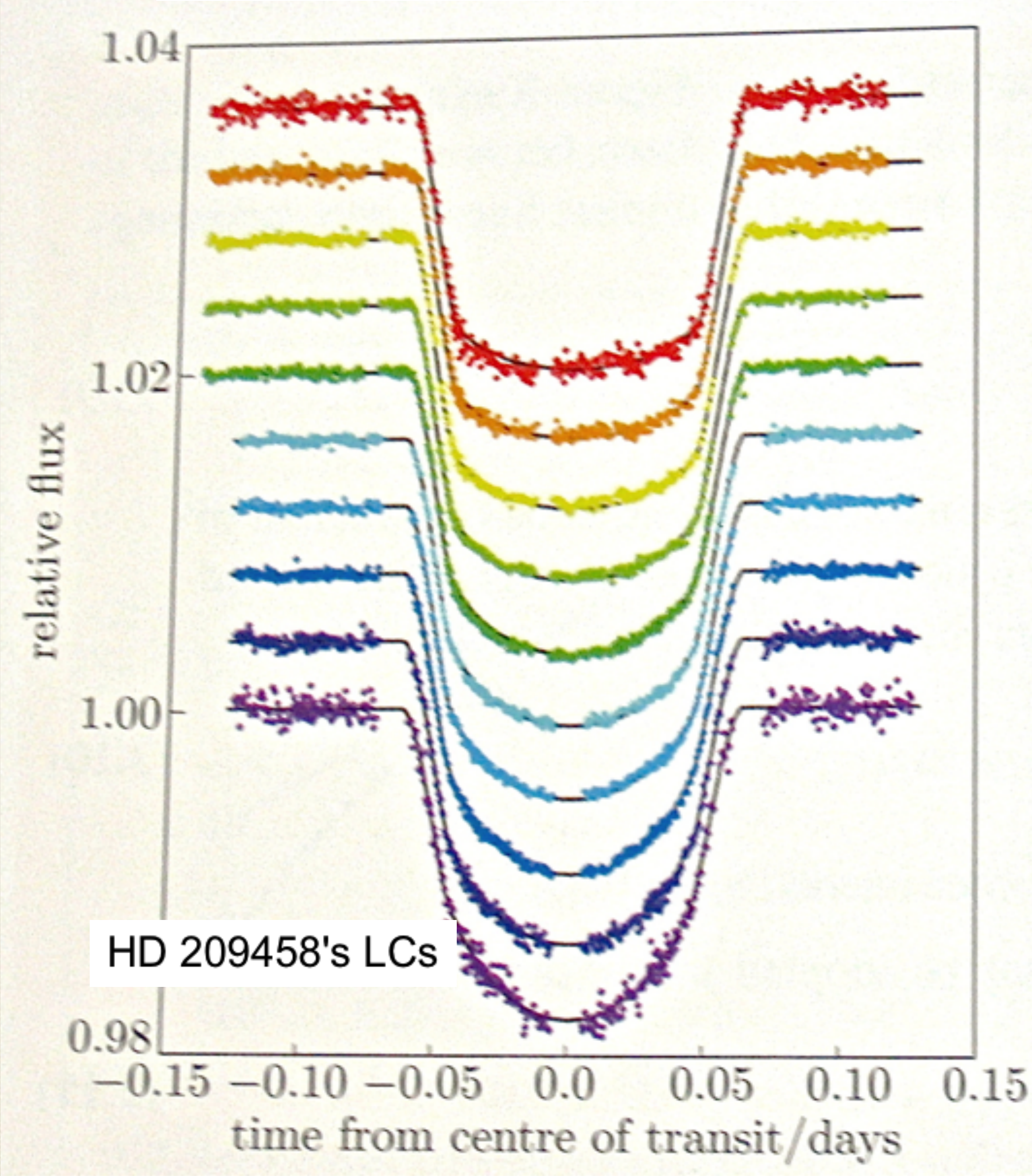
Limb-Darkening



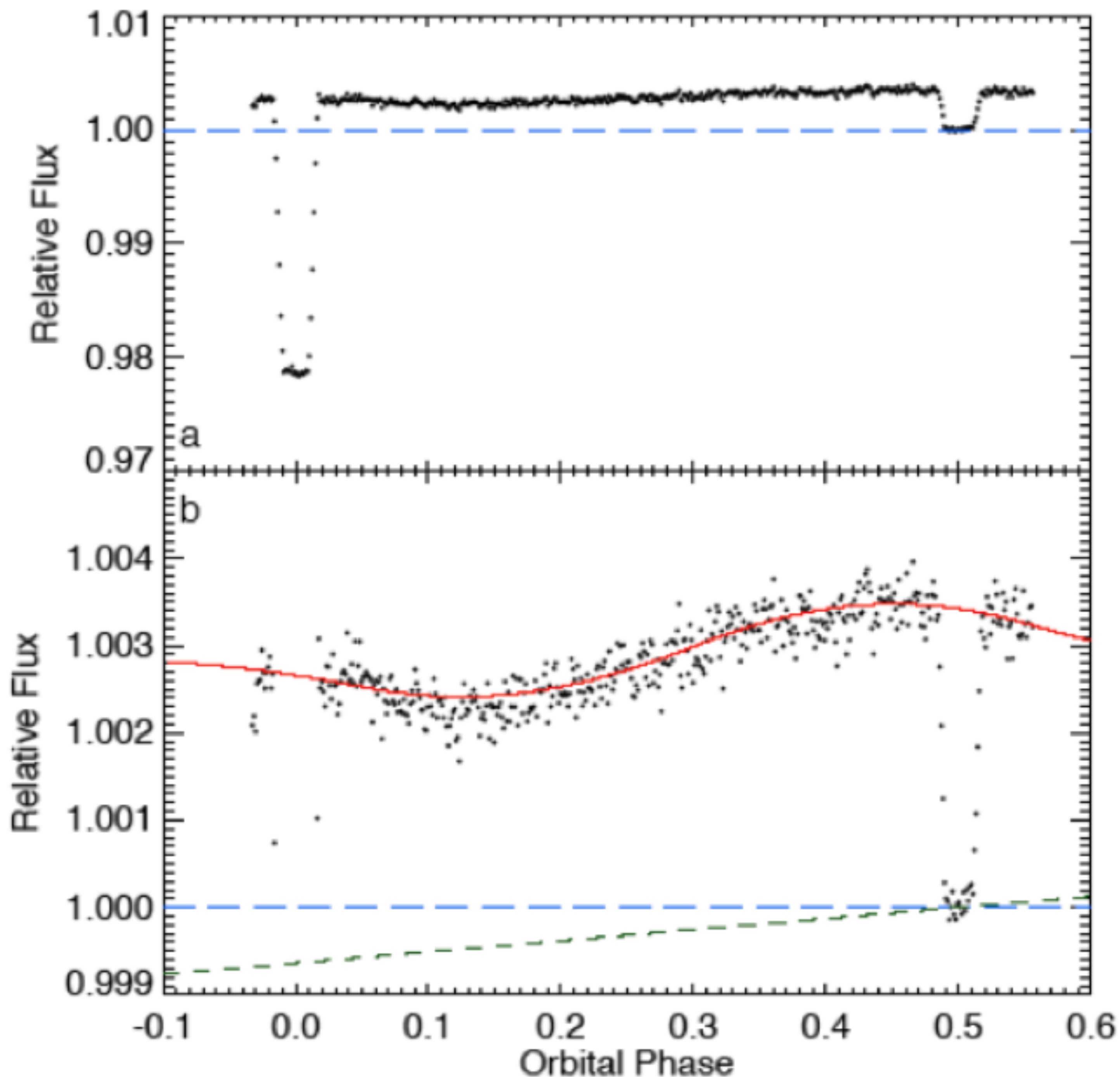
The shape of the transit tells us about stellar limb-darkening





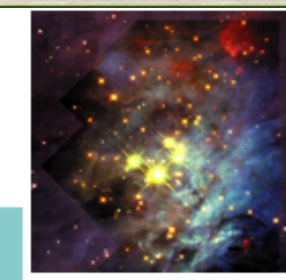
Phase curves in the Mid-IR

Spitzer 8–micron band observation of HD 189733. Showing brightness variations due to light from the host star reflecting off the planet during its orbit. The transit and secondary eclipse are also visible

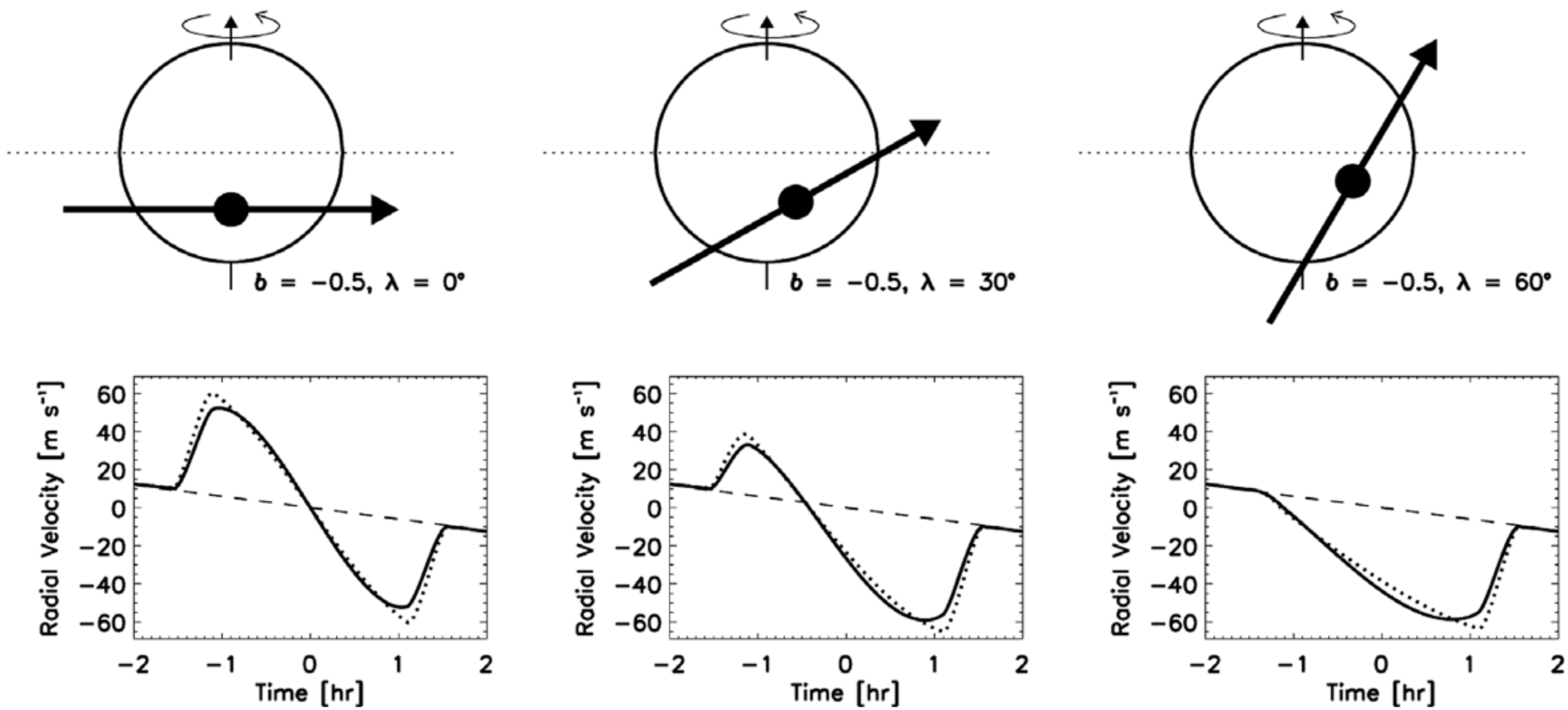


Knutson et al 2009

Obliquity: Rossiter-McLaughlin Effect

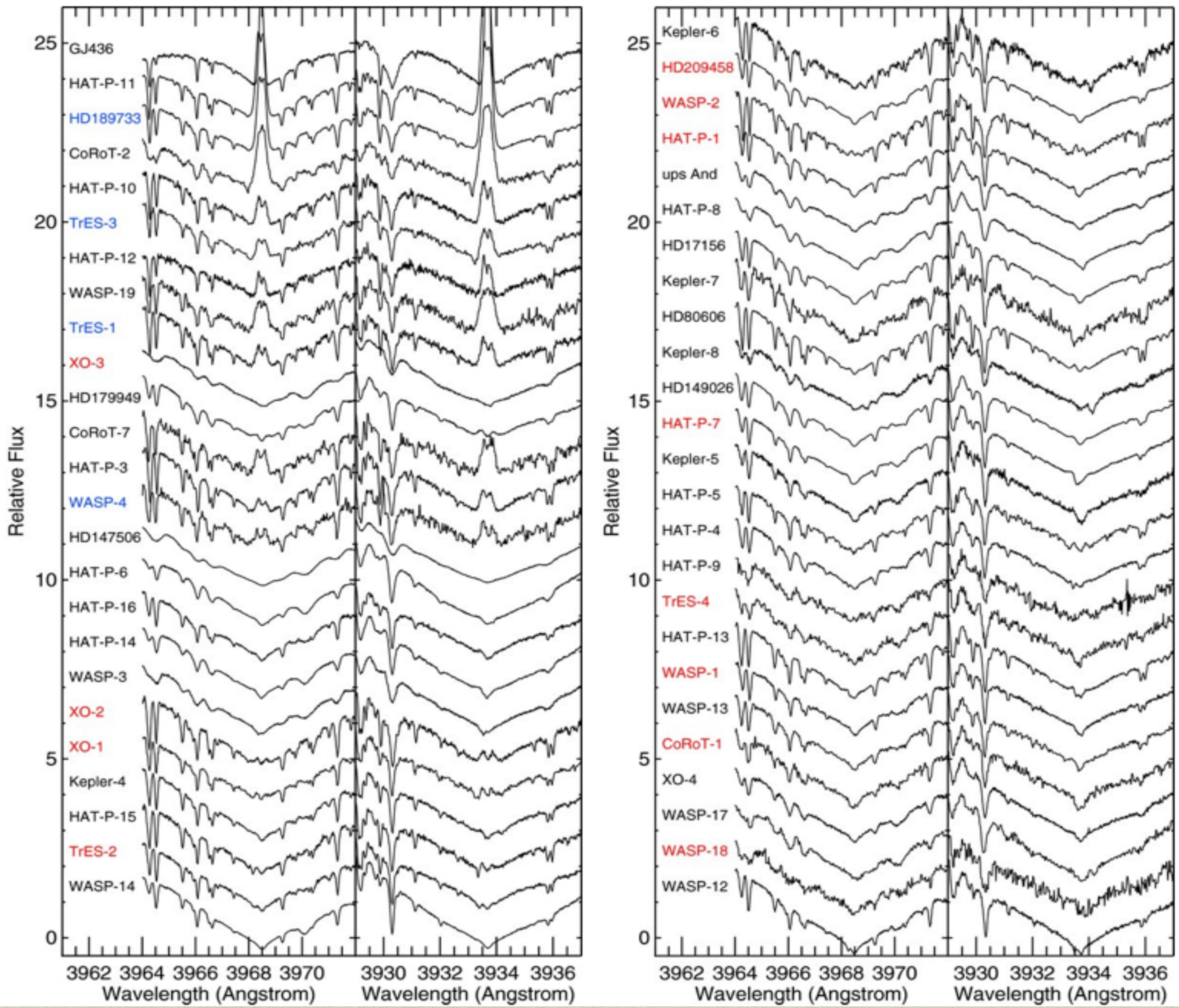


The Rossiter-McLaughlin effect measures the projection in the plane of the sky of the inclination of the planetary orbit with respect to the stellar rotation axis.



Gaudi & Winn 2007

Chromospheric Activity



Is activity due to planet? Correlations have not been found (e.g., Shkolnik et al. 2003; Canto Martins et al 2011)

Planet hosts selected to be inactive for RV and LC precision

Knutson et al 2010

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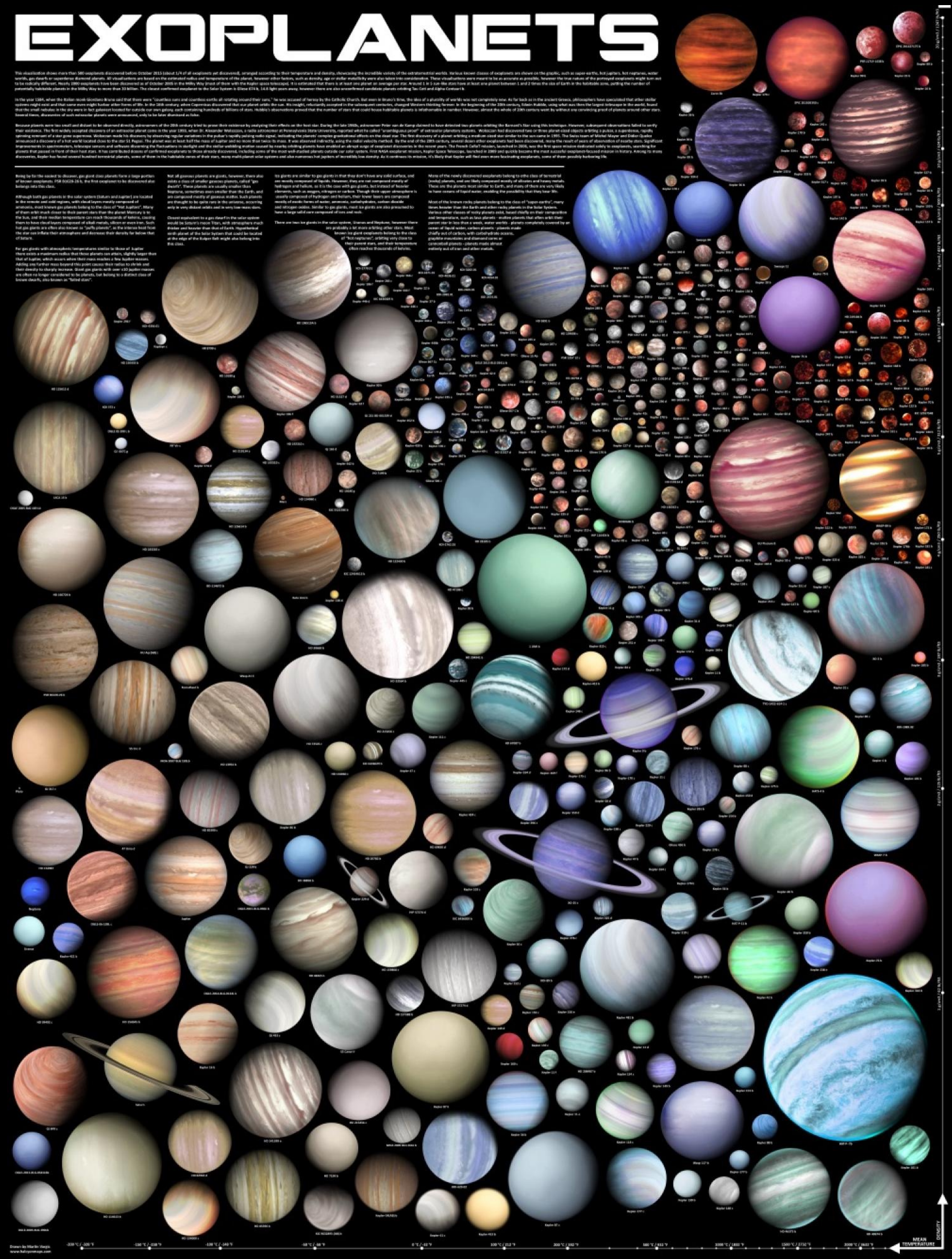
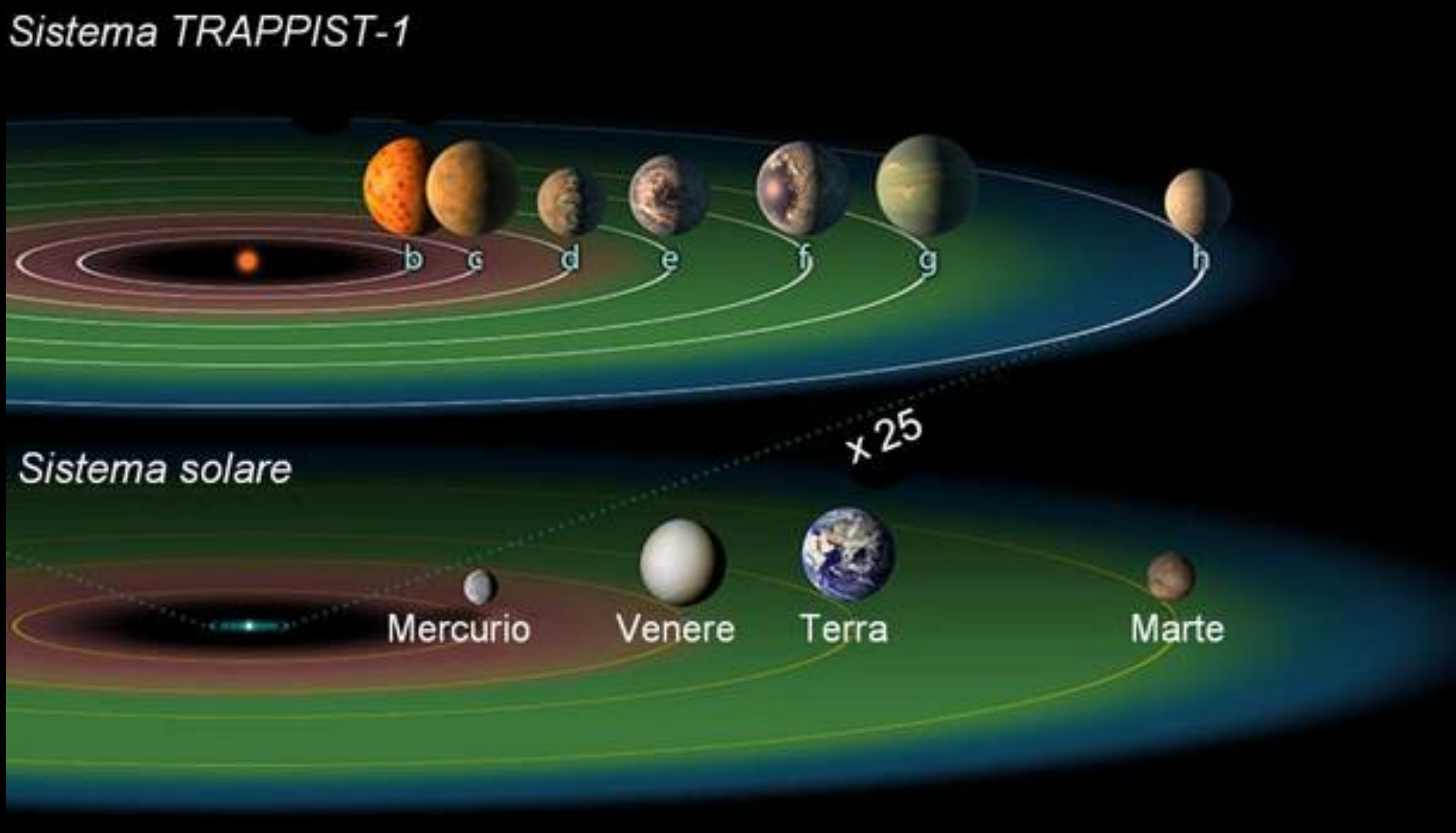
FONDAZIONE GIUSEPPE OCCHIALINI





Confronto tra le fasce 'abitabili' (in verde) del Sole e di TRAPPIST-1

evaporating Planets

Disperse Matter Planet Project

22h orbit!!

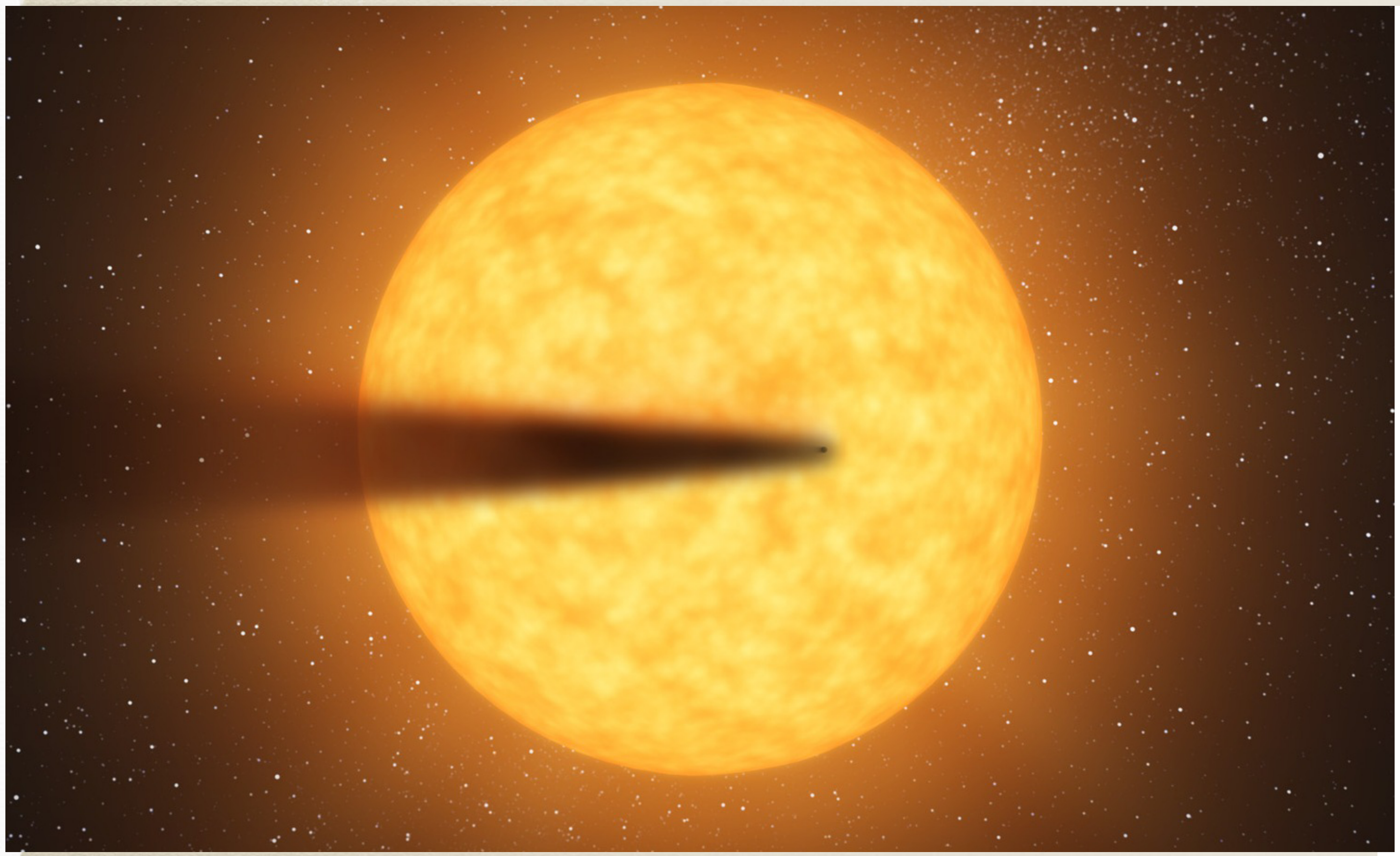
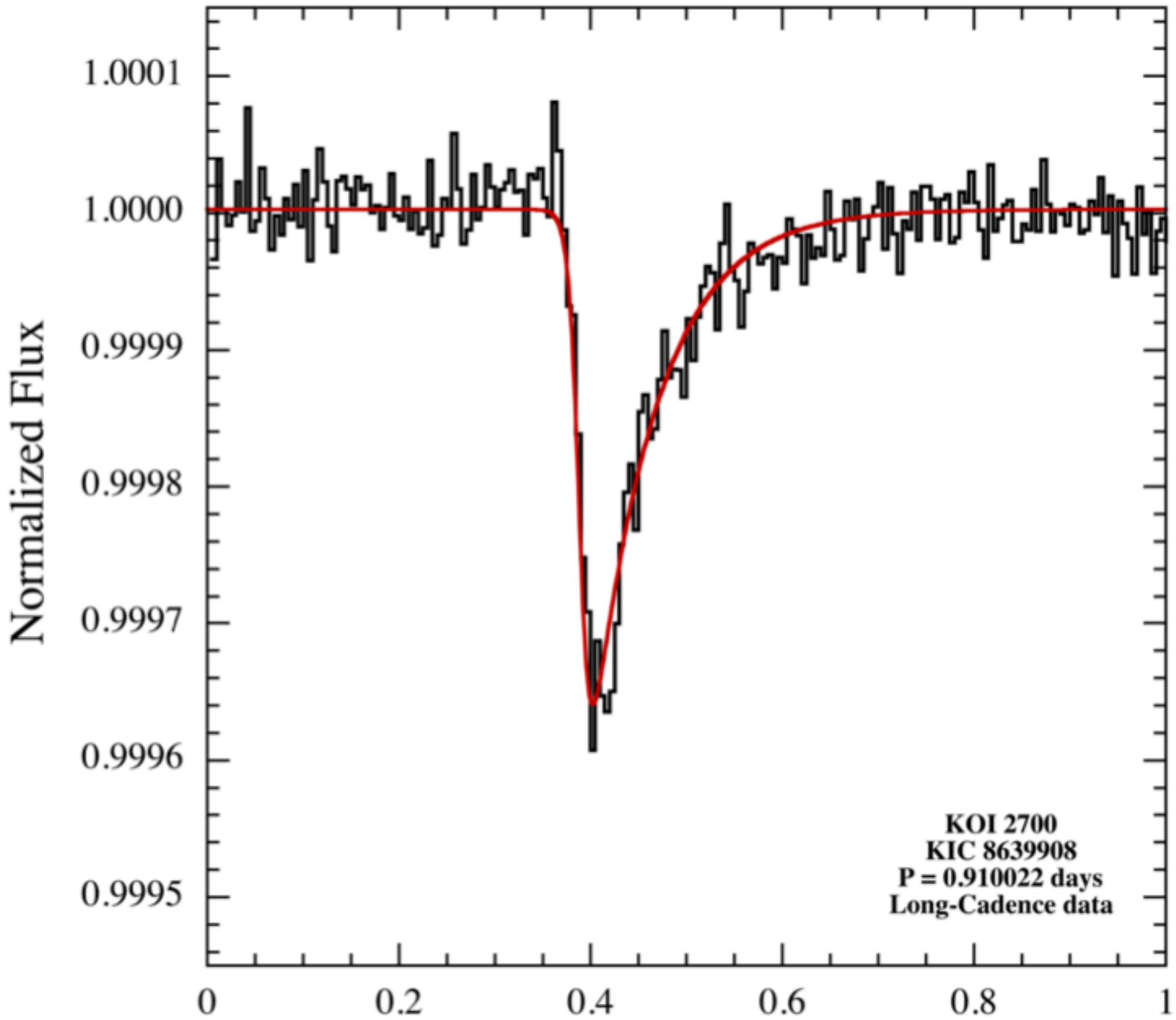


Image credits: NASA



Rappaport et al., 2014

Disperse Matter Planet Project

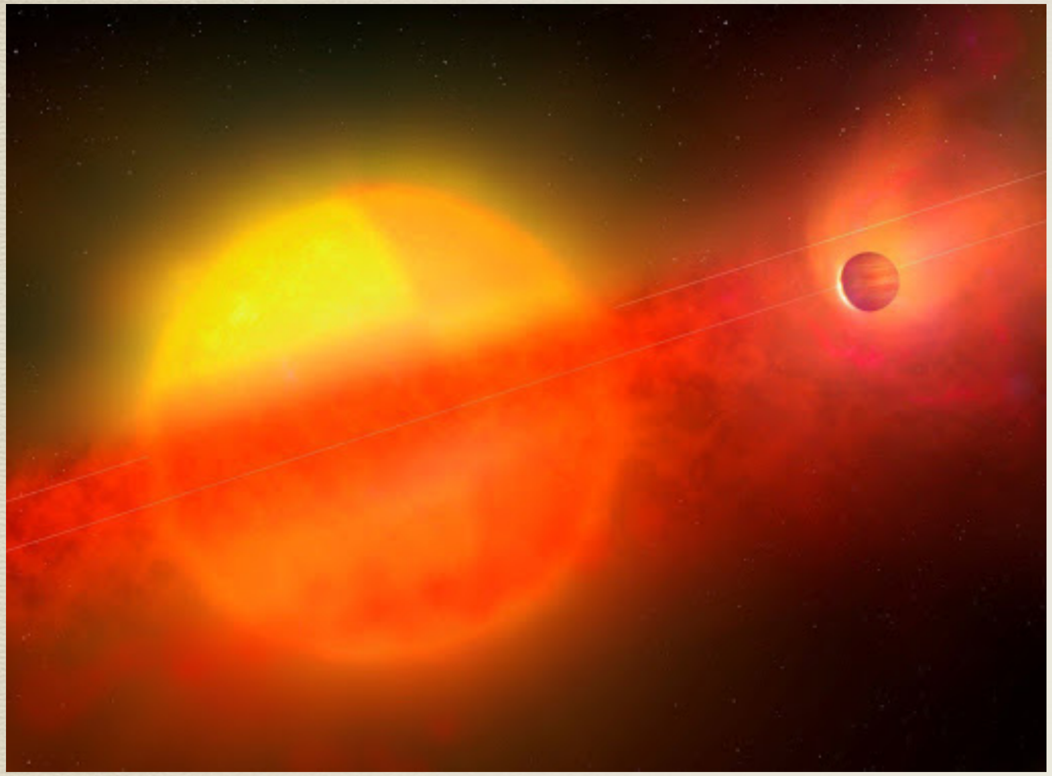
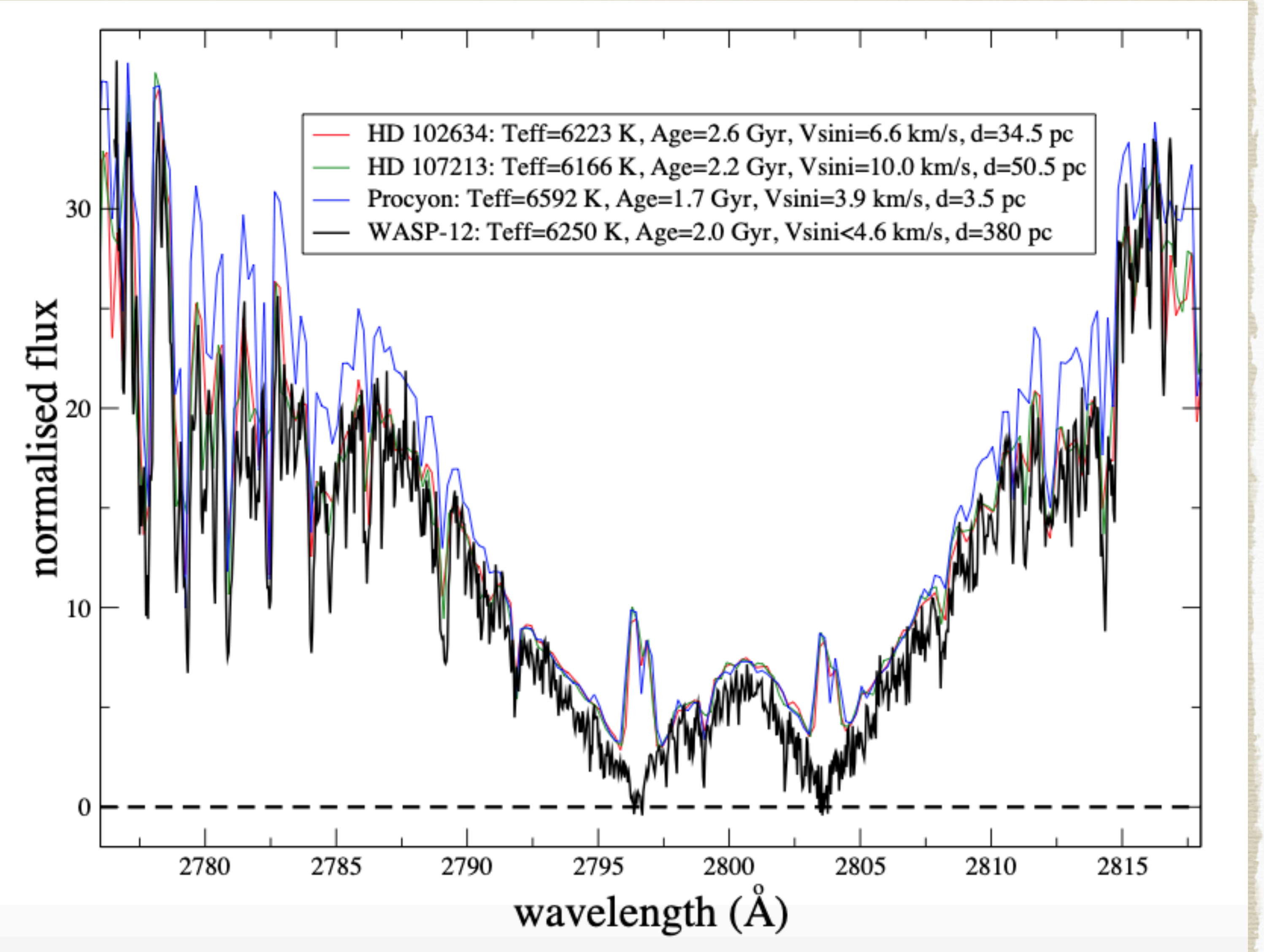
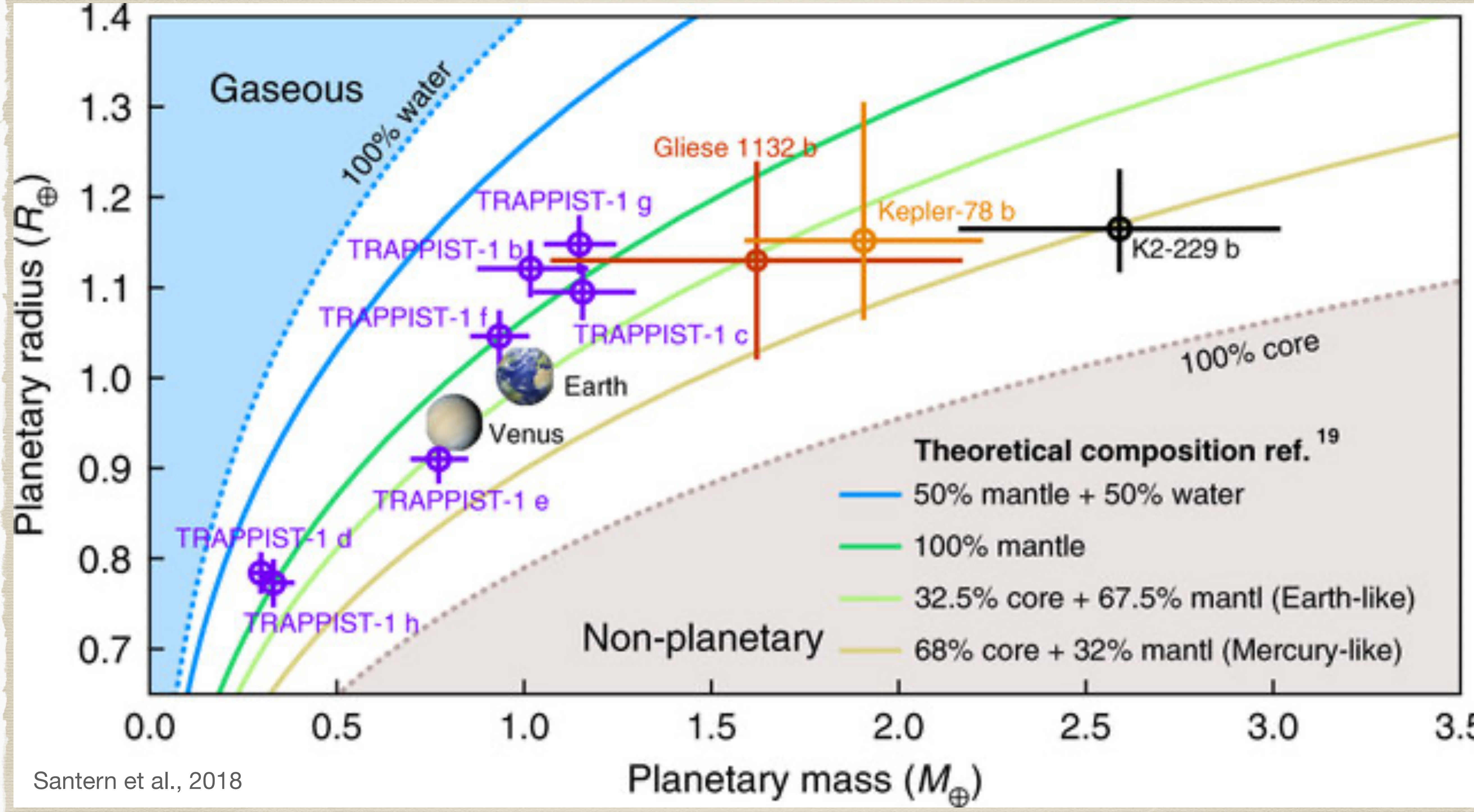


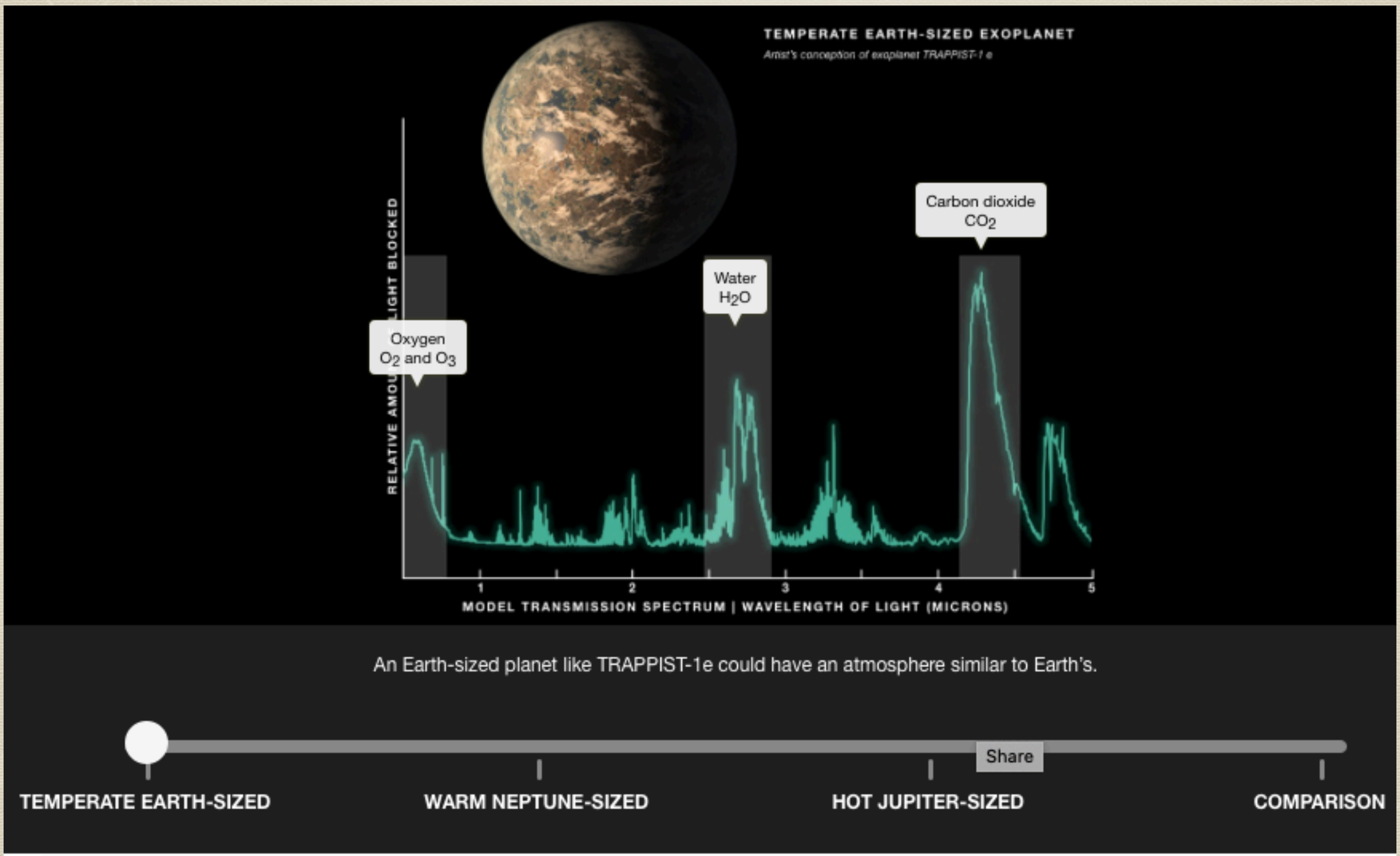
Image credits: Mark Garlick

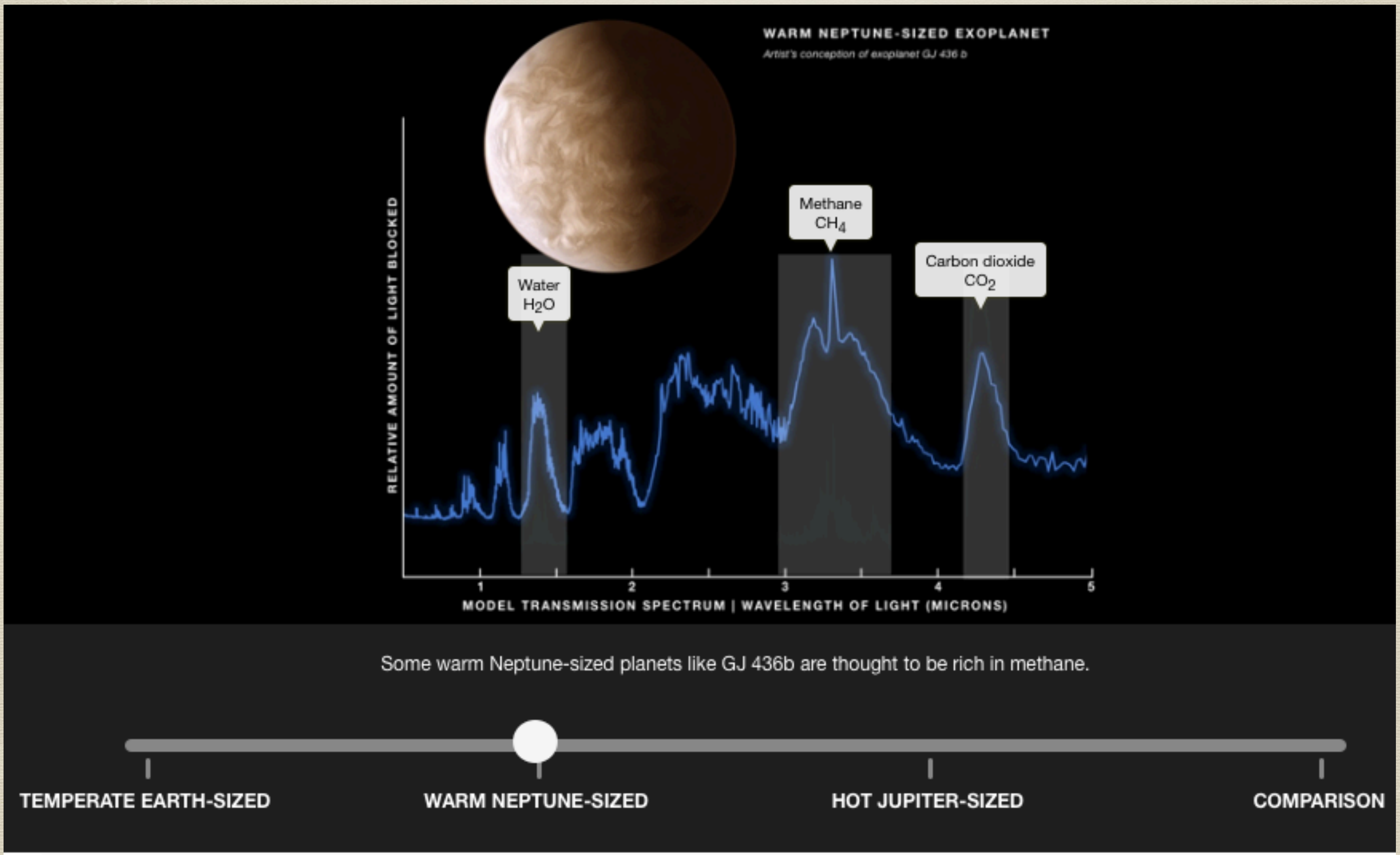


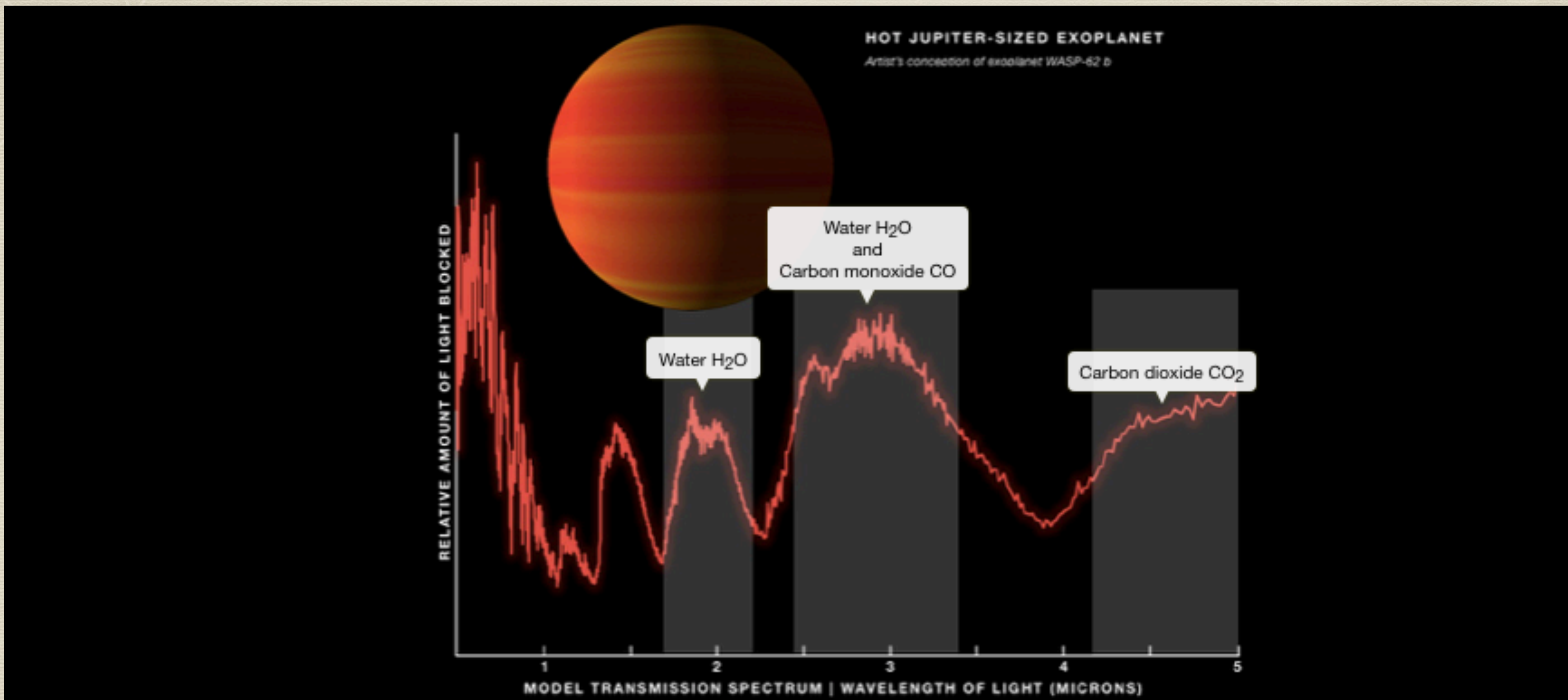
Mass-Radius Plot and Planetary composition



Santern et al., 2018


TEMPERATE EARTH-SIZED EXOPLANET
Artist's conception of exoplanet TRAPPIST-1 e
RELATIVE AMOUNT OF LIGHT BLOCKED
Oxygen
O_2 and O_3
Water
H_2O
Carbon dioxide
CO_2
1
2
3
4
5
MODEL TRANSMISSION SPECTRUM | WAVELENGTH OF LIGHT (MICRONS)
An Earth-sized planet like TRAPPIST-1e could have an atmosphere similar to Earth's.
Share
TEMPERATE EARTH-SIZED
WARM NEPTUNE-SIZED
HOT JUPITER-SIZED
COMPARISON


WARM NEPTUNE-SIZED EXOPLANET
Artist's conception of exoplanet GJ 436 b
RELATIVE AMOUNT OF LIGHT BLOCKED
Water
H_2O
Methane
CH_4
Carbon dioxide
CO_2
1
2
3
4
5
MODEL TRANSMISSION SPECTRUM | WAVELENGTH OF LIGHT (MICRONS)
Some warm Neptune-sized planets like GJ 436b are thought to be rich in methane.
TEMPERATE EARTH-SIZED
WARM NEPTUNE-SIZED
HOT JUPITER-SIZED
COMPARISON



Water can even exist on hot gas giants like WASP-62b, which are inhospitable to life as we know it.

TEMPERATE EARTH-SIZED | WARM NEPTUNE-SIZED | HOT JUPITER-SIZED | COMPARISON

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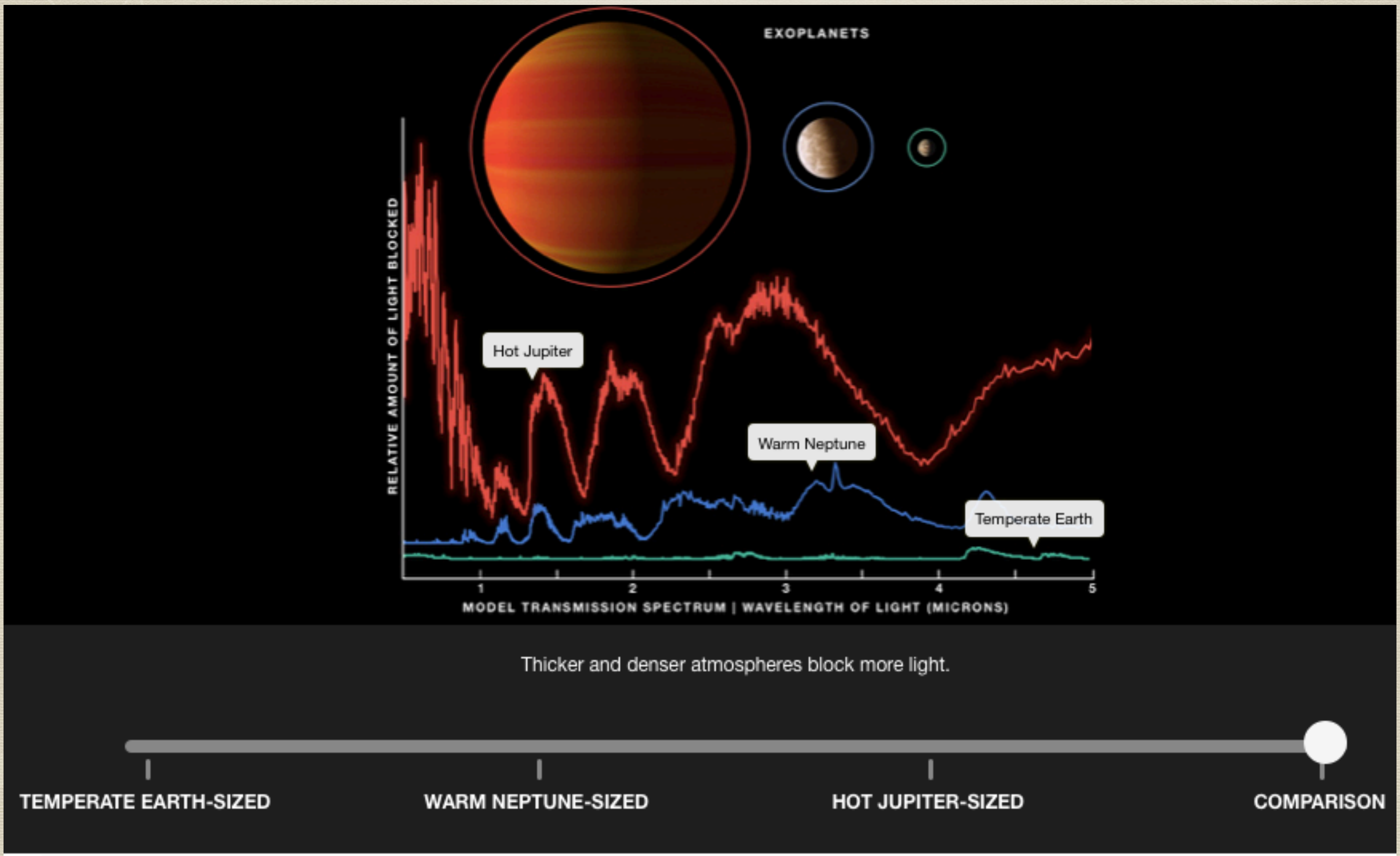
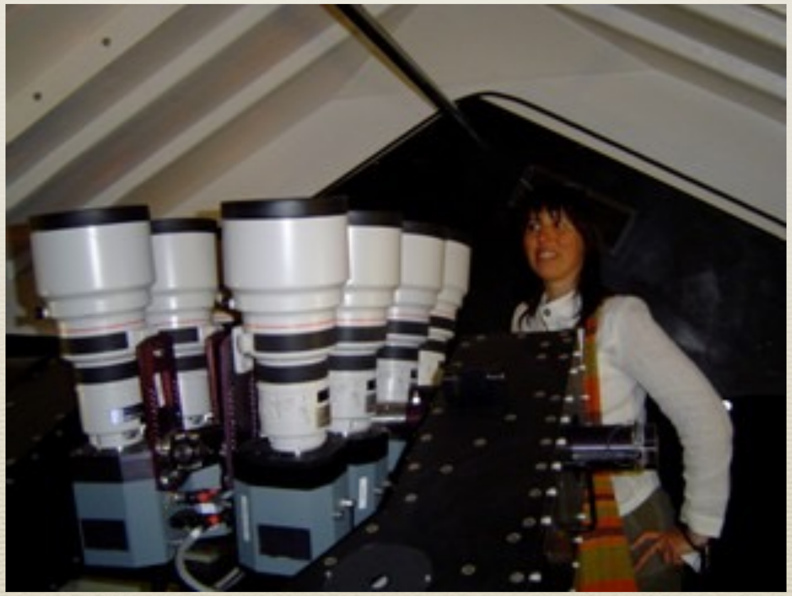


My contribution

círca 60

SuperWASP



NGTS

The NGTS 20cm telescopes on their mounts in the enclosure at ESO Paranal (Credit:ESO/R. West)

Observing Sites

Observing Sites

Telescopio
Nazionale
Galileo

La Silla - Chile

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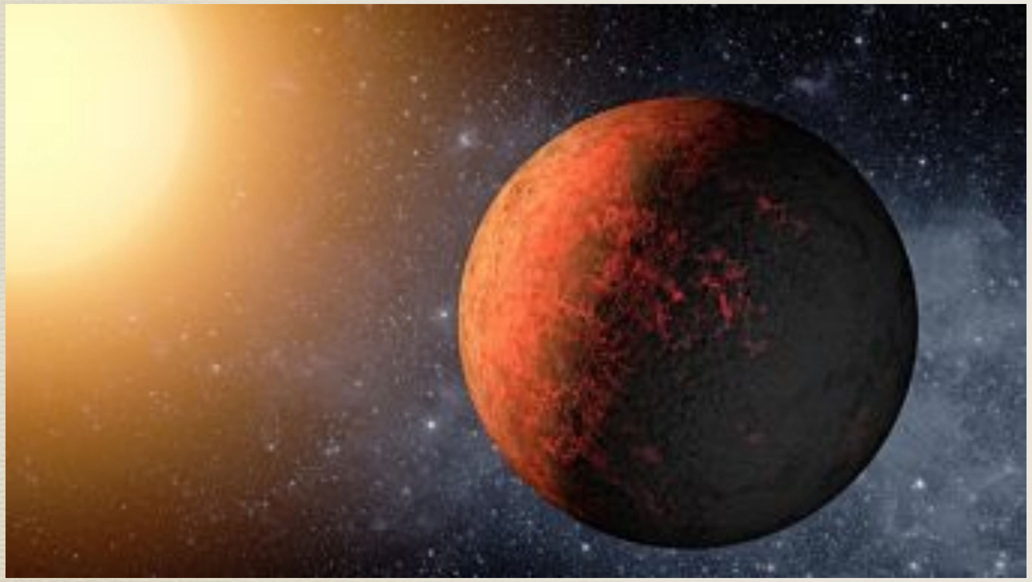
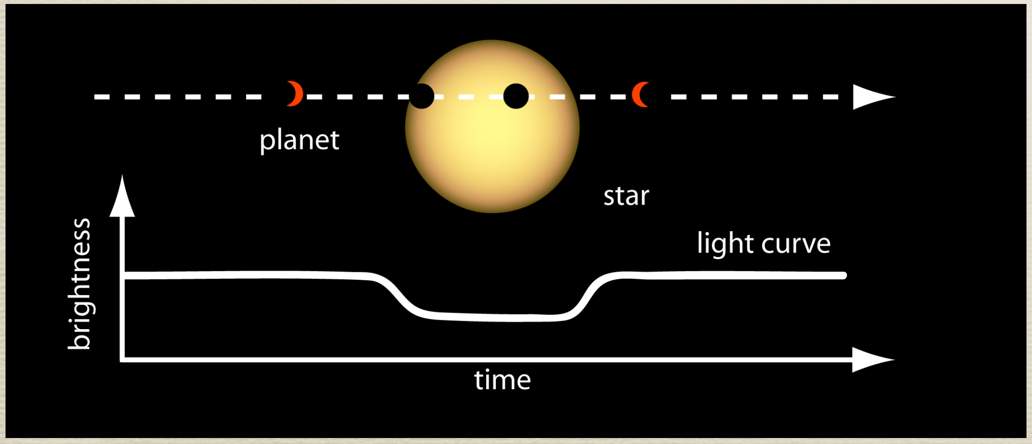
K2-229b un cugino stretto di Mercurio





Transit method

+

Radial velocity

mass and radius

↓

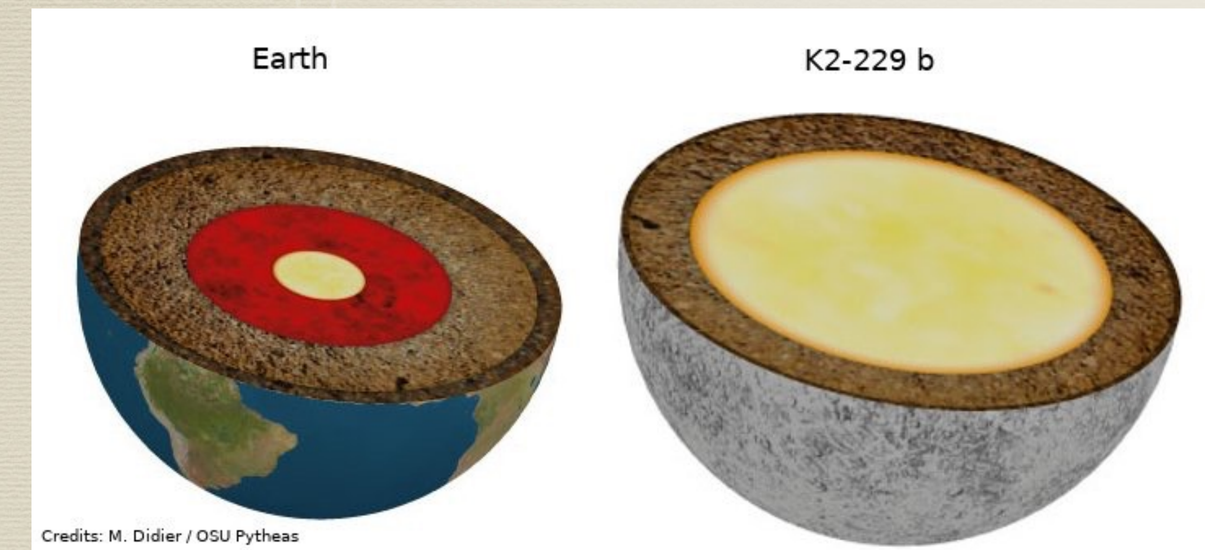
density

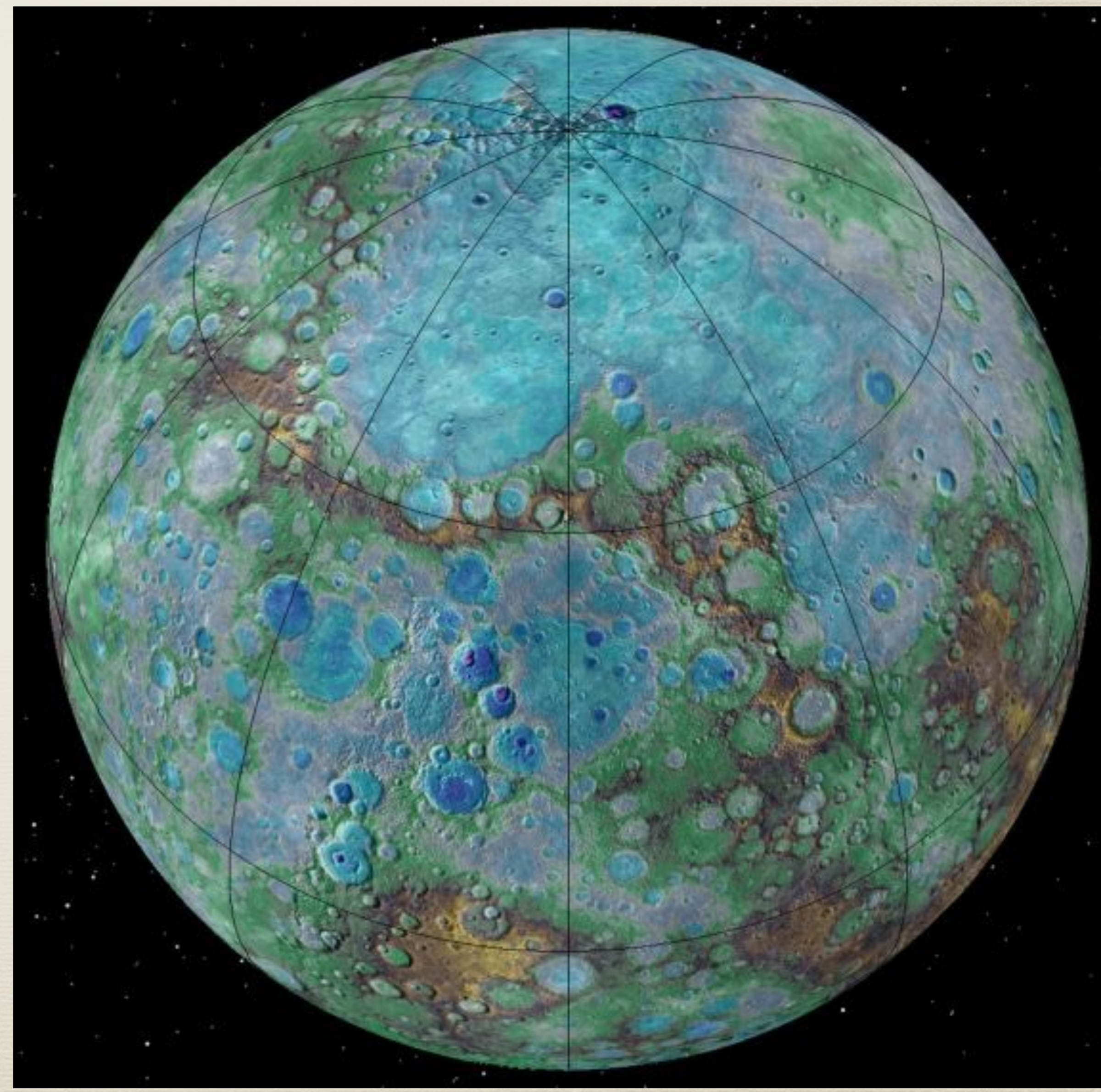
↓

bulk composition + atmosphere

K2-229b Super Mercury

Origin of our Solar System





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Il Futuro e' LO SPAZIO

The Earth!!

Fondazione Occhialini May 19 2021

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