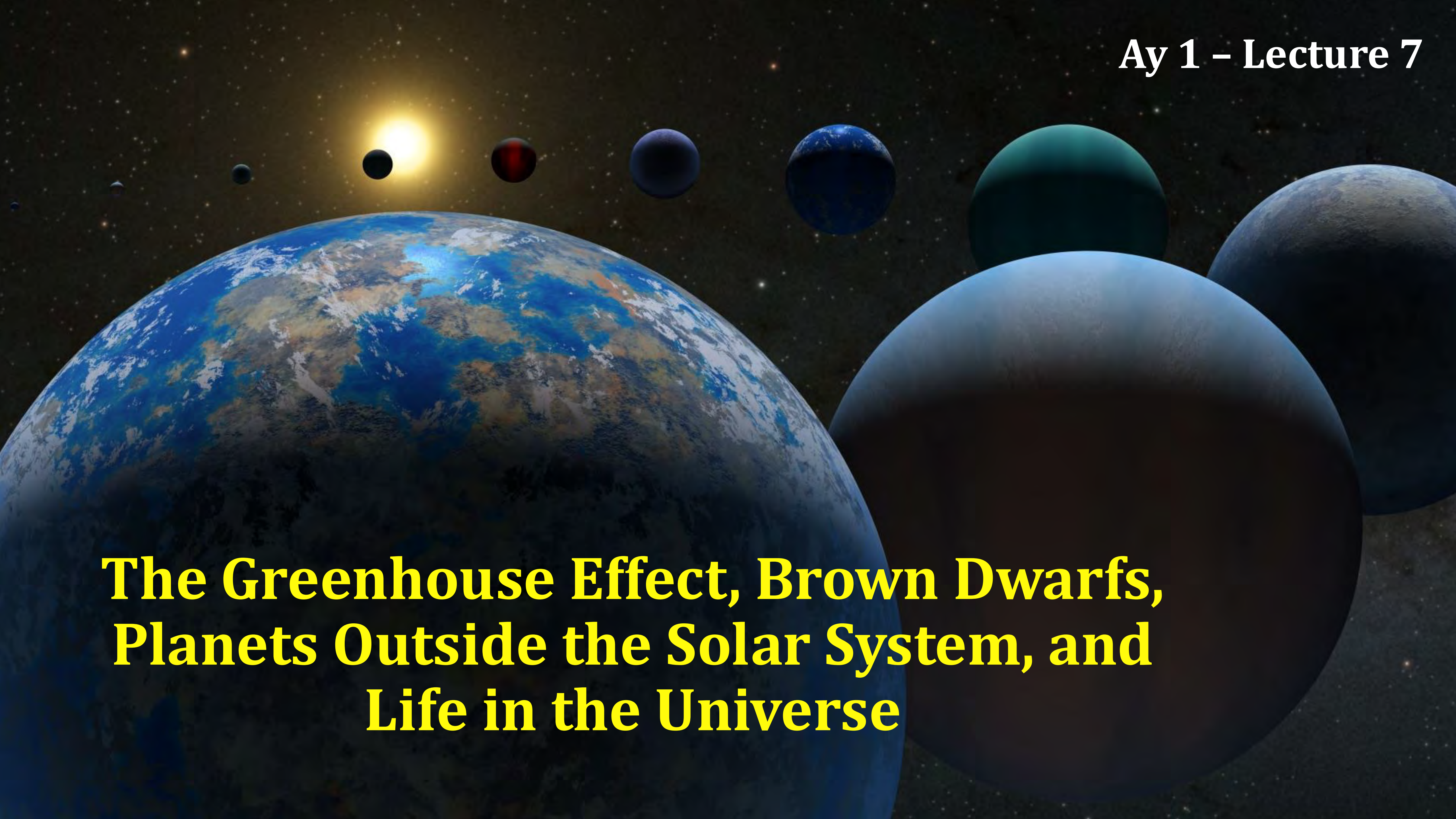


Ay 1 – Lecture 7

The Greenhouse Effect, Brown Dwarfs, Planets Outside the Solar System, and Life in the Universe

Planet's Temperature

For a given stellar luminosity, it depends *only* on the orbit radius and the albedo:

$$T^4 = L_\odot \frac{(1-\alpha)}{16\,\pi\,\sigma\,a^2}$$

This works well for the planets with no atmosphere

For the Earth: $\alpha \sim 0.33$, $a \sim 1.5 \times 10^{13}$ cm

$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} s^{-1} K^{-4}

$L_\odot = 3.85 \times 10^{33}$ erg/s

Estimate *T* ~ 253 K

Yet, the actual value is more like *T* ~ 287 K. Why?

The answer: **the Greenhouse Effect**

Various gases in the Earth's atmosphere (mainly CO_2) trap some of the thermal infrared emission. That effectively acts as an additional incoming luminosity

Temperature increases until a new equilibrium is reached

Venus is an extreme case of this

Planet Temperatures and Habitable Zones

Recall that for a given stellar luminosity, planet's temperature depends *only* on the orbit radius (a) and the albedo (α):
($L_\star$ = parent star's luminosity, σ = Stefan-Boltzmann constant)

$$T^4 = L_\star \frac{(1-\alpha)}{16\,\pi\,\sigma\,a^2}$$

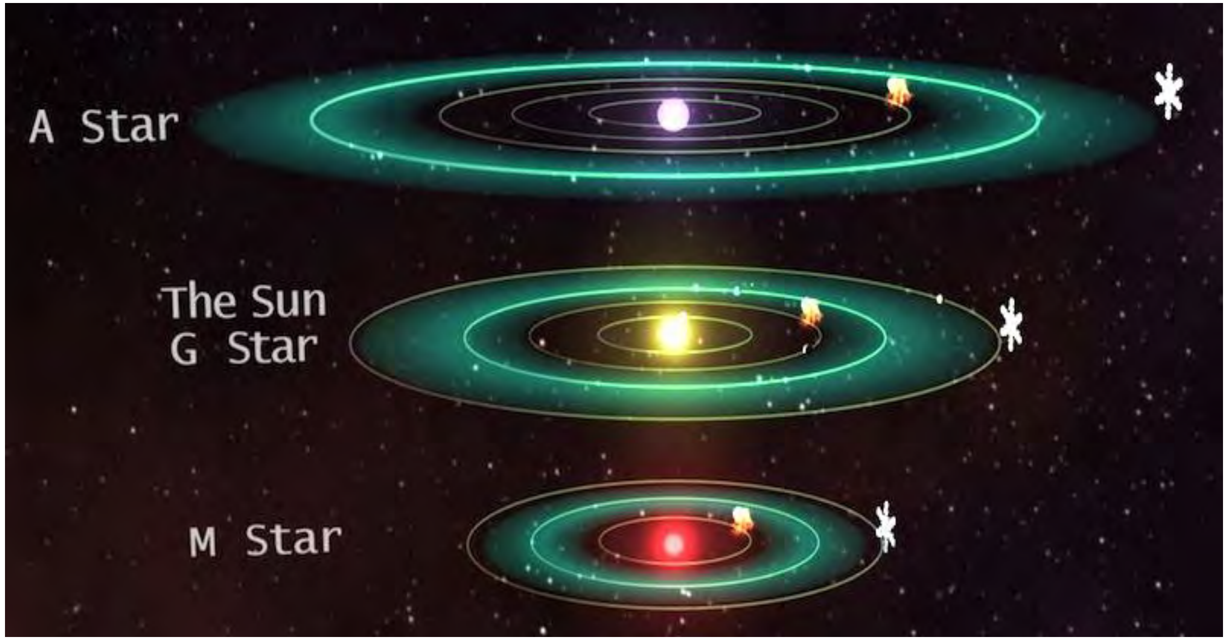
Liquid water can exist if 273 K < T < 373 K

Frost line   Steam line

This defines a range of planetary orbit radii where liquid water (and thus life?) can exist *on the planet's surface*

In the Solar system, this corresponds to the radii 0.84 AU < a < 1.7 AU

However, we know that subsurface oceans exist in the moons of Jupiter (5.2 AU) and Saturn (9.6 AU), due to the tidal heating



The Greenhouse Effect

Input Energy = Output Energy

↑

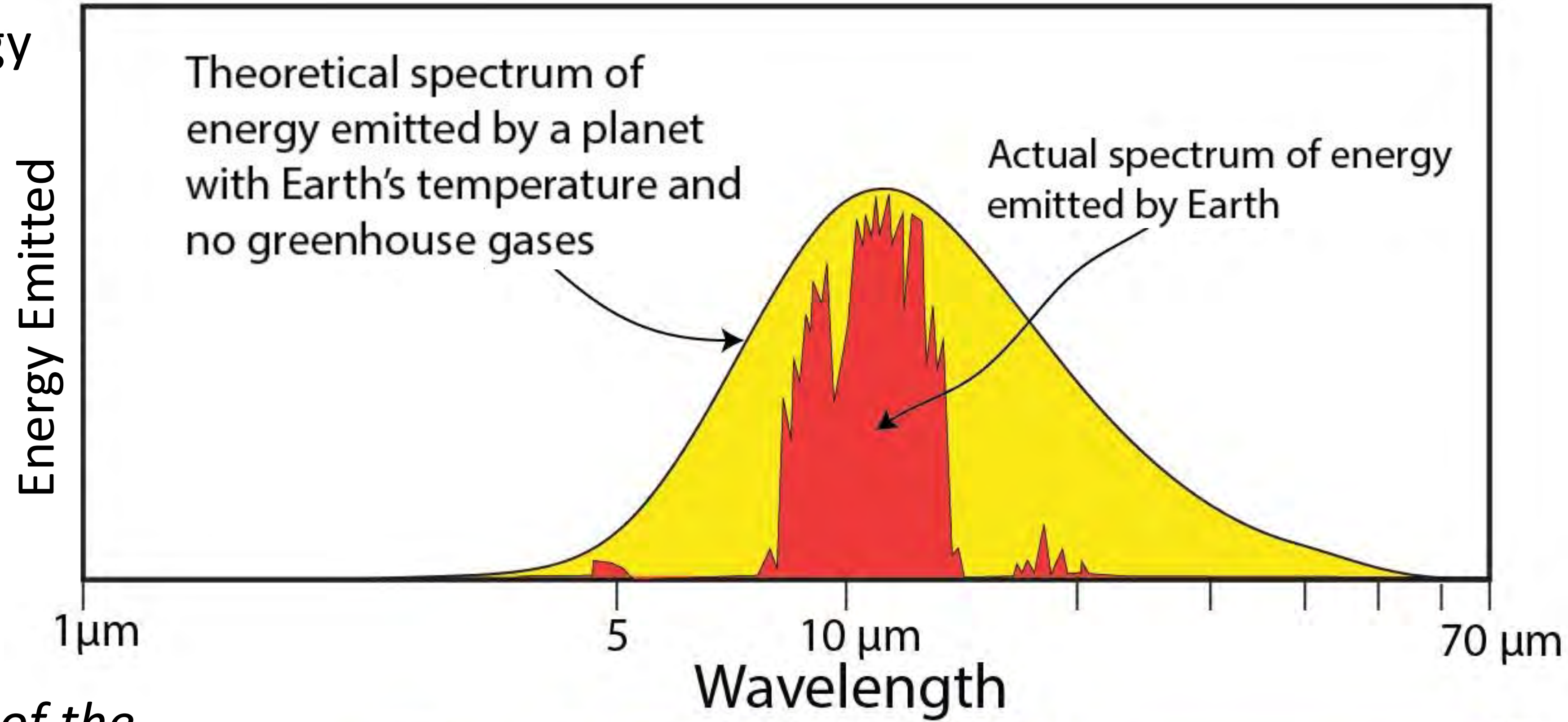
Fixed by $L_\star$, a, and α

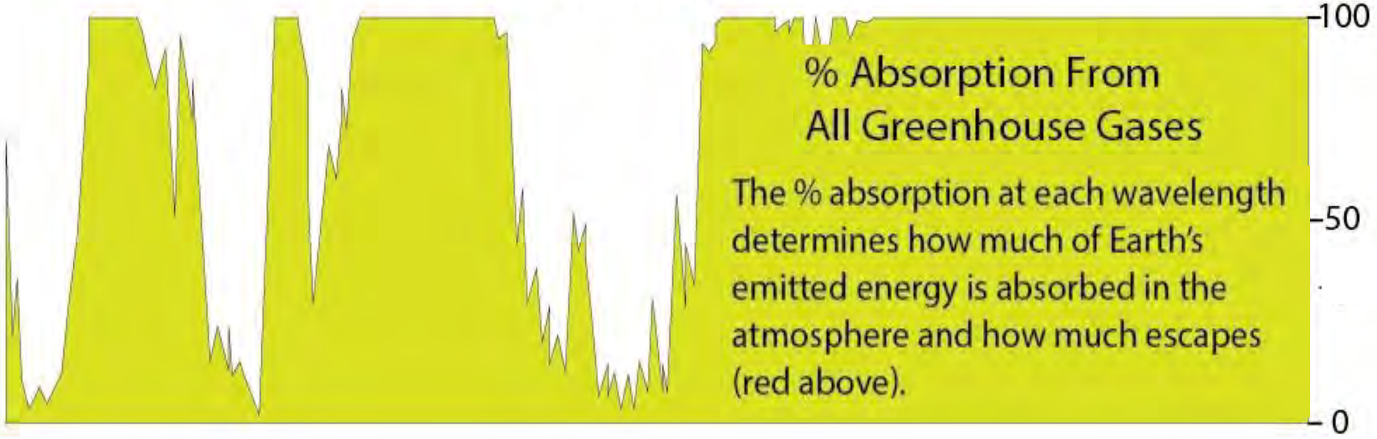
Output Luminosity:

$$L_{\mathrm{em}} = 4\,\pi\,\sigma\,R^2\,T^4_{\mathrm{planet}} \times \tau$$

where τ is the *transparency of the atmosphere* (1 = fully transparent)

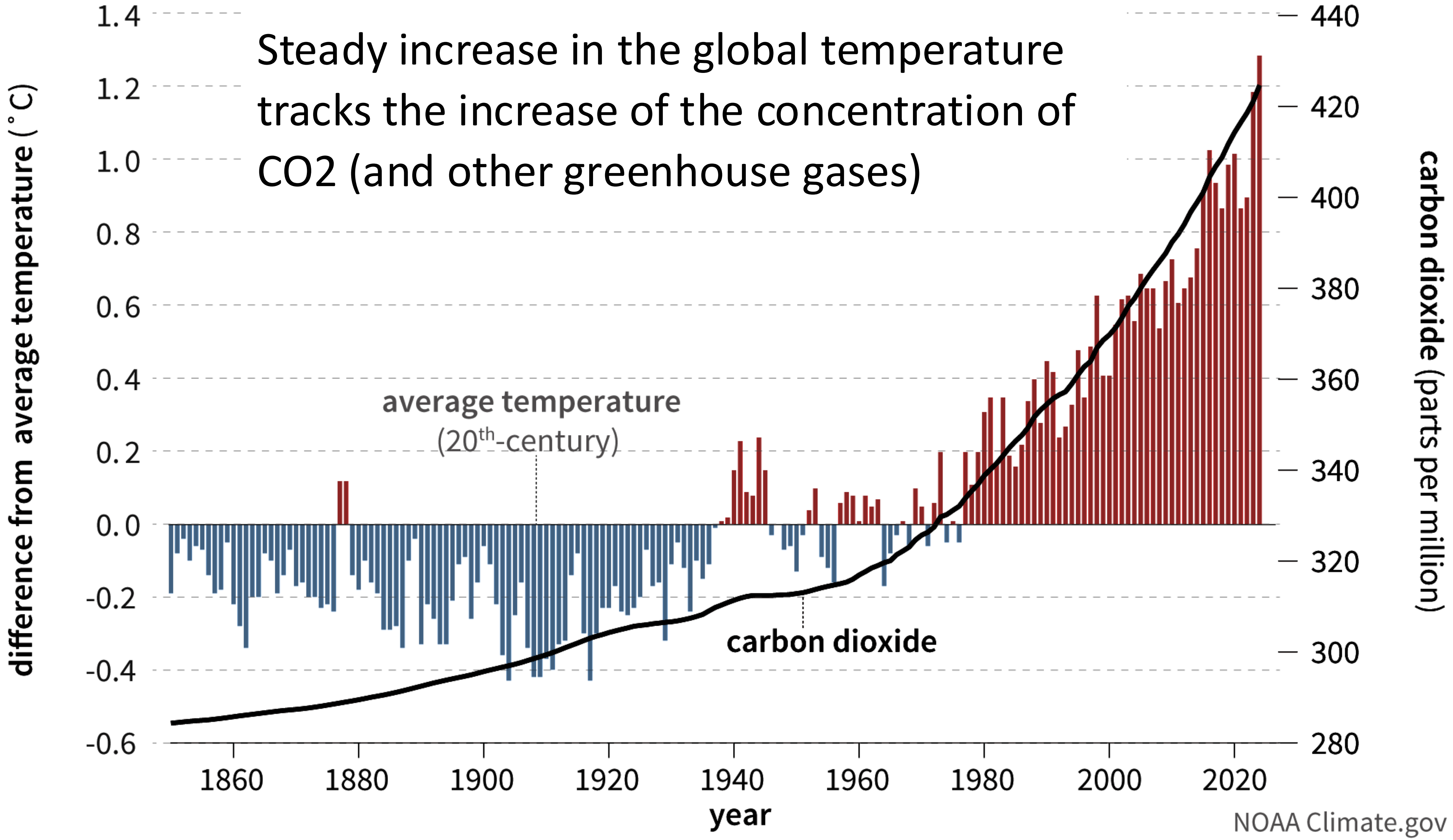
If $\tau < 1$ due to absorption, and R cannot be changed, **T_{planet} must increase to compensate**





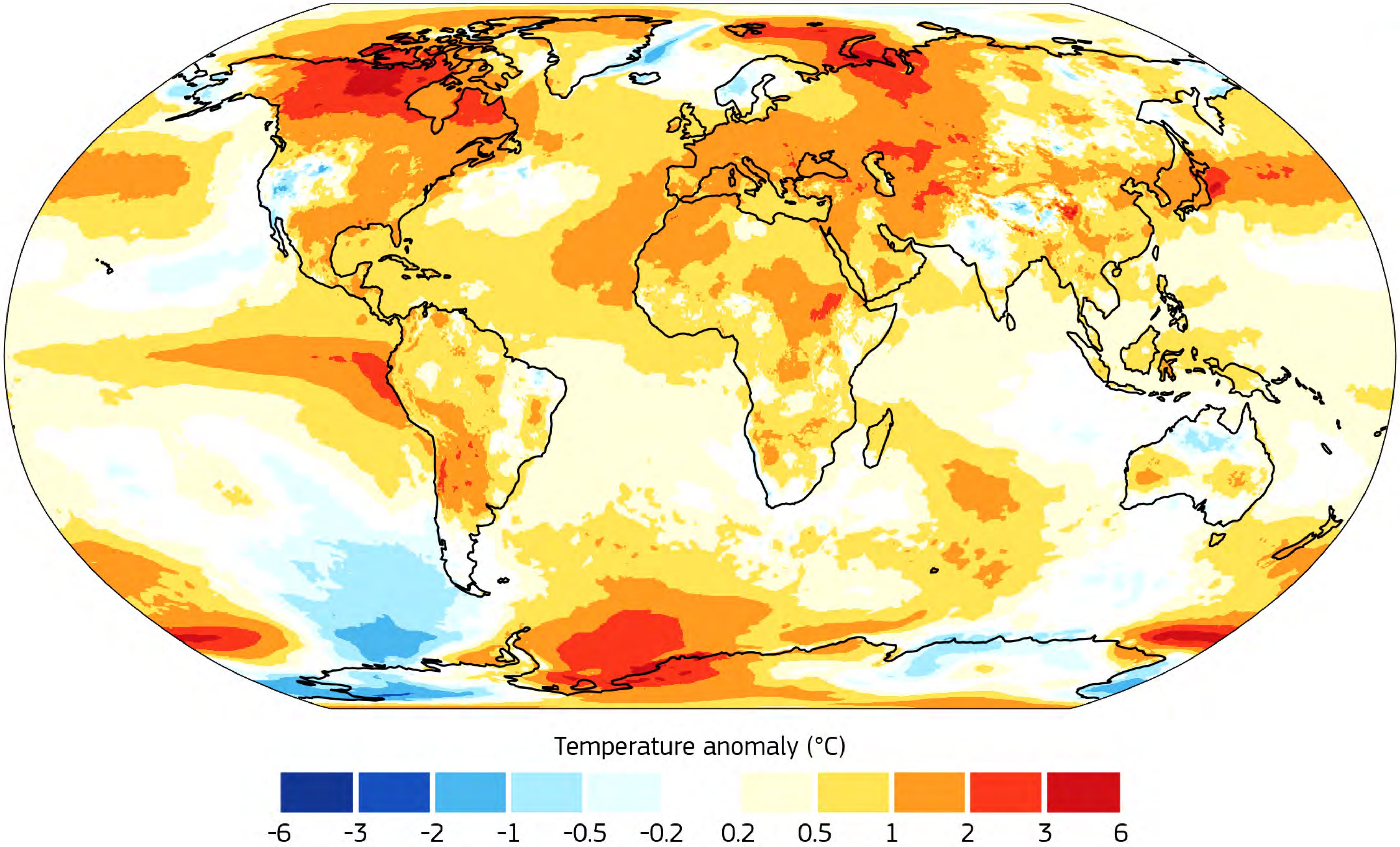
Increases in atmospheric carbon dioxide and global temperature (1850-2024)

Steady increase in the global temperature tracks the increase of the concentration of CO_2 (and other greenhouse gases)



SURFACE AIR TEMPERATURE ANOMALY • 2023

Reference period: 1991–2020 • Data: ERA5 • Credit: C3S/ECMWF



Consequences of the Global Warming

(It is not politics, it is thermodynamics)

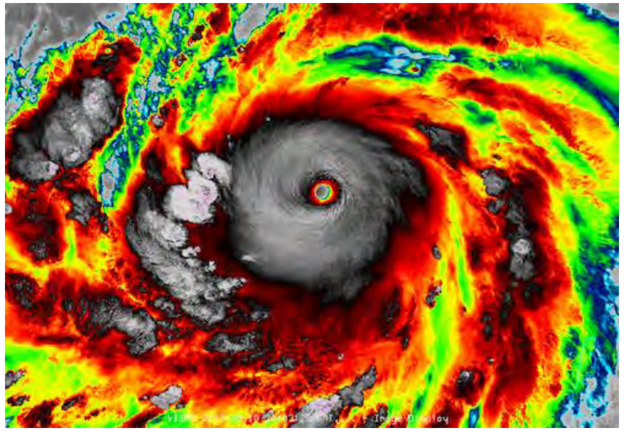
Climate modeling makes ***three robust predictions***:

1. **Average temperature increases**

   ➞ Antarctic and Greenland ice melts and increases the global ocean level; many coastal areas get submerged

2. **Climate zones expand from the Equator towards the poles**

   ➞ Disruption of agriculture, water supply



3. **Amplitude and frequency of extreme weather events increase**

   ➞ Major damage, loss of life

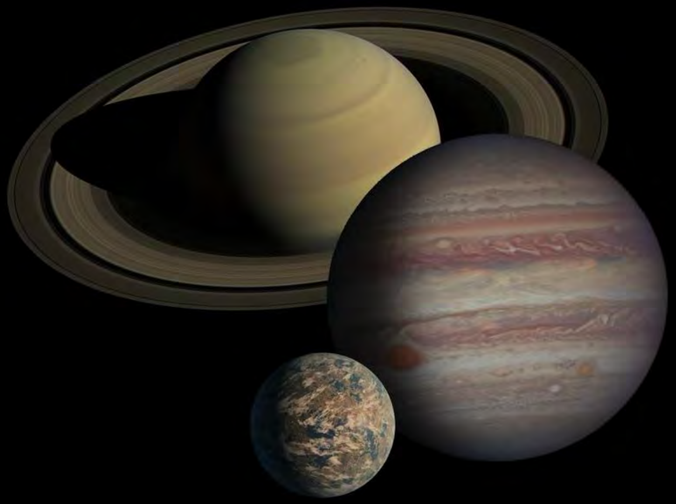
This will cause global social and political changes: mass migration (climate refugees), famines, water wars …

Global Warming is …

A. Conspiracy by the world's scientists to defraud the fossil fuel companies of their profits
B. An observed fact
C. Based on a simple thermodynamics of planets
D. "Just, like, your opinion, man!" – Dude Lebofsky
E. An unfolding global catastrophe
F. God's punishment for the gay marriage (according to Pat Robertson, the televangelist)

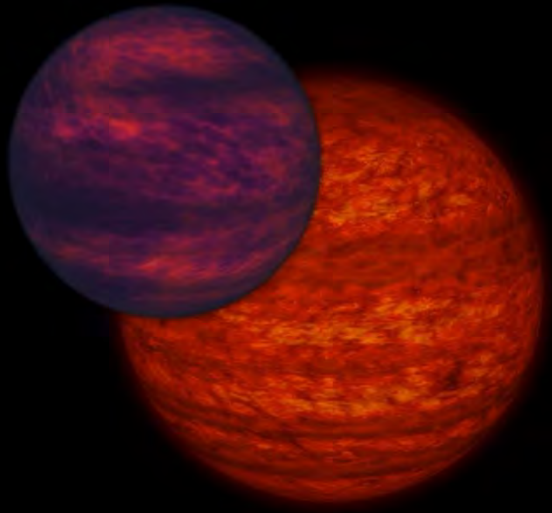
The Differences Between ...

Planets & Exoplanets



Up to ~13x Jupiter's mass

Brown Dwarfs



~13x to 80x Jupiter's mass

(Energy from shrinking, some fusion, D → He)

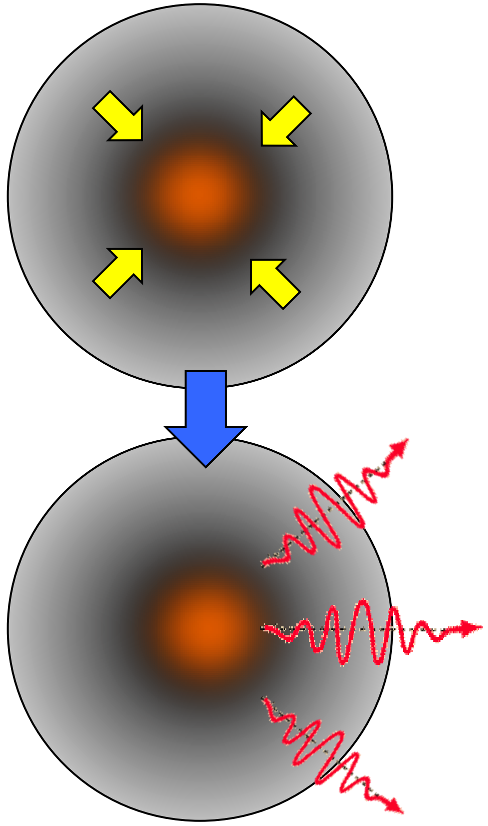
Stars

(Fueled by nuclear fusion, H → He)

Over ~80x Jupiter's mass

($\gtrsim$ 8% Solar mass)

The Kelvin-Helmholtz Mechanism



As a gravitationally bound object cools, it shrinks; e.g., protostellar clouds. The release of the binding energy produces heat that radiates away

This is called the ***Kelvin-Helmholtz mechanism***, and it was assumed to be the source of stellar energy before the nuclear fusion was known

Total binding energy available divided by the luminosity is the *Kelvin-Helmholtz time scale.* For Sun, that is ~ 18 million years

The same mechanism applies to Brown Dwarfs, and even planets (in addition to the release of the latent heat from their formation. For example, Jupiter emits about 1.67 to 2 times more energy than it receives from the Sun

Speculating About Other Worlds

The existence and possible inhabitants of other worlds was subject of much speculation since the antiquity

Giordano Bruno: *De l'infinito universo et mondi* (1584) →

"This space we declare to be infinite... In it are an infinity of worlds of the same kind as our own" [The Church took a different view 🔥]

← Bernard Le Bovier de Fontenelle: *Entretiens sur la pluralité des mondes* (Conversations on the Plurality of Worlds) (1686)

Christiaan Huygens: *Cosmotheoros: or, Conjectures Concerning the Inhabitants, Plants and Productions of the Planetary Worlds* (1698) →

… and many, many others

Exoplanets = Planets Around Other Stars

- Planets are ***an expected byproduct of star formation***, from the leftover material in the protostellar/protoplanetary disk, and are now known to be common
- As of April 2026, there are ~ 6,200 *confirmed* exoplanets in ~ 4,600 planetary systems, plus another ~ 7,000 planet candidates
- There are estimated to be between **100 billion** and over **3 trillion** planets in the Milky Way galaxy alone. *There are more planets than stars* (200 billion) in our Galaxy
- One major goal is to find *Earth-like planets* that can support life (as we know it), in the habitable zone. There are at least **11 billion** potentially habitable Earth-sized planets around stars like our Sun, and many more if we include other stellar types
- Many planetary systems have very different architectures from the Solar system, and there are types of planets that do not exist in our Solar system

Search Methods for Exosolar Planets

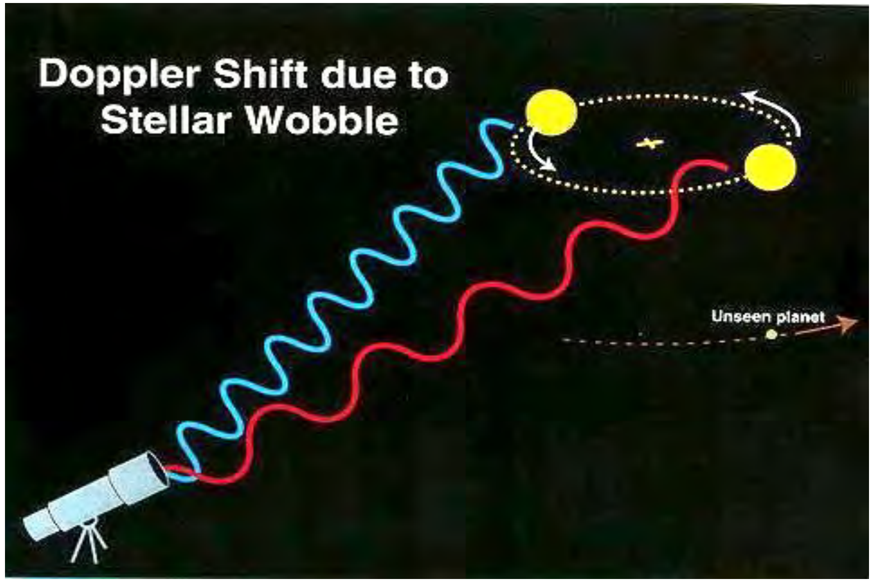
- **Direct imaging**: extremely difficult, since planets may be a billion times fainter than their parent stars
  - Use coronographs and AO to suppress the scattered light
  - Image in thermal IR: the brightness ratio is more favorable
- **Doppler shift:** periodic variation in a star's radial velocity, as the star and the planet orbit a common center of the mass
  - Requires extremely precise spectroscopy
  - More sensitive to more massive and closer planets
- **Eclipses (Transits)** as a planet crosses the stellar disk
  - Requires an extremely precise photometry
- **Gravitational microlensing:** spikes in the light curve of a microlensing event
  - Rare, requires monitoring of vast numbers of stars

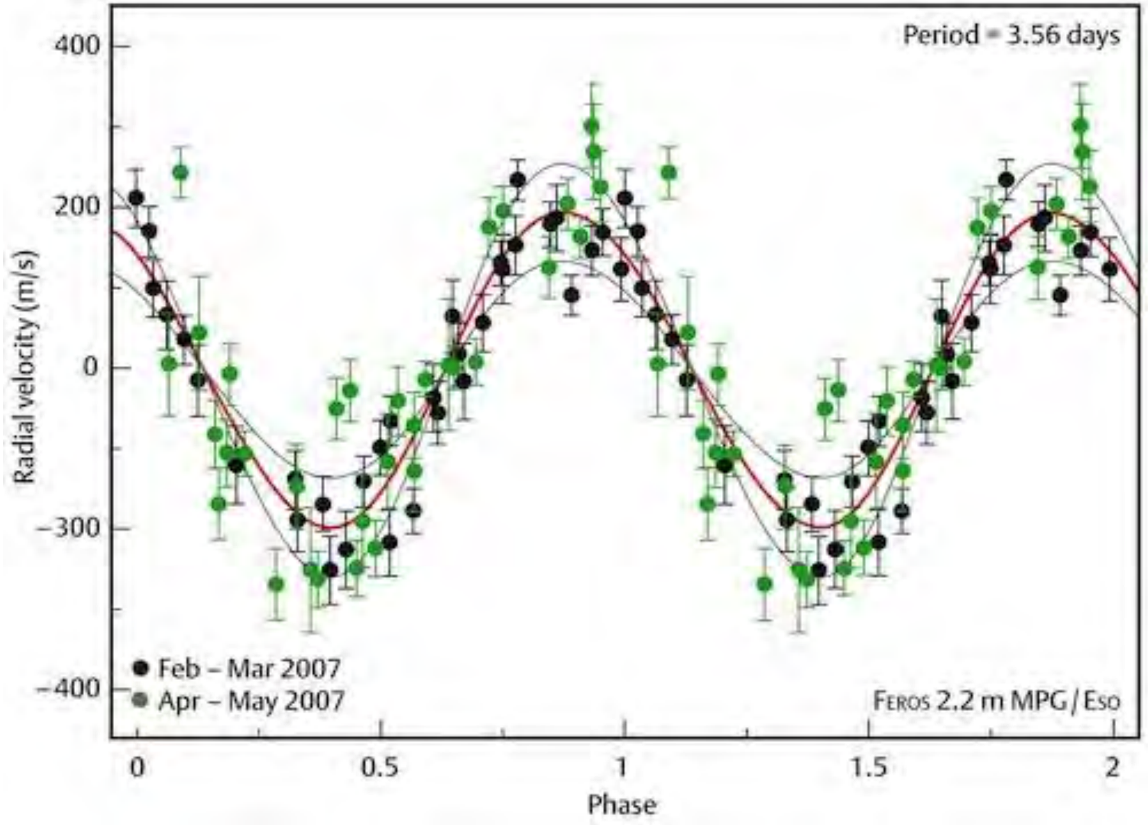
Every method has its **advantages** and **selection biases**

Radial Velocity Method

Both the star and the planet orbit the common center of mass: $M_{planet}\ V_{planet} = M_{star}\ V_{star}$

Observe *variations in the star's radial velocity* as the whole system moves in space:



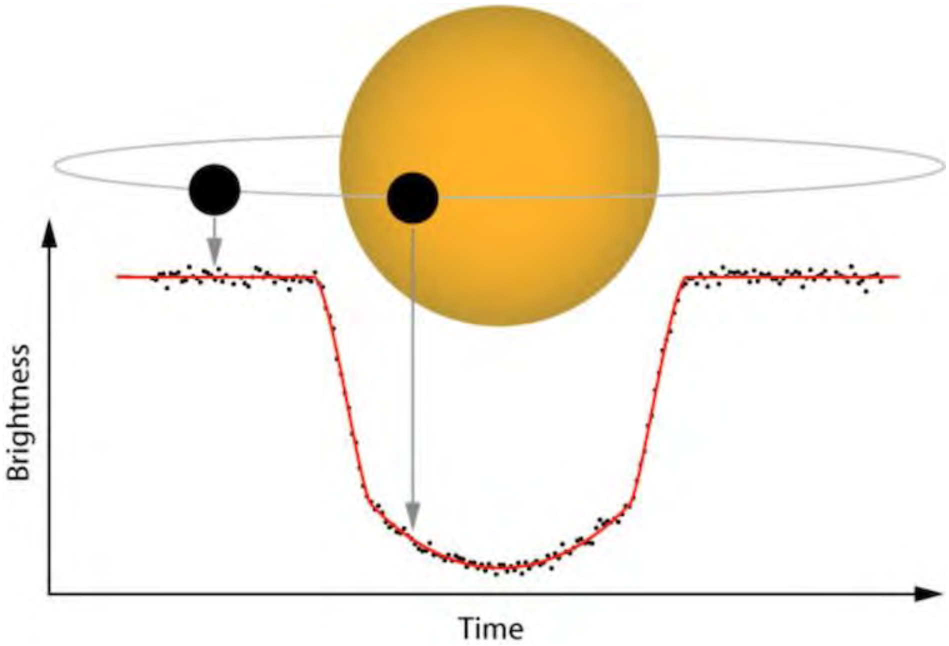


For example:
$M_{Earth} / M_{\odot} \approx 3 \times 10^{-6}$
$V_{Earth} = 30$ km/s $\quad V_{\odot} \approx 9$ cm/s

This method favors more massive planets in the orbits close to the parent star

State of the art precision ~ 30 cm/s

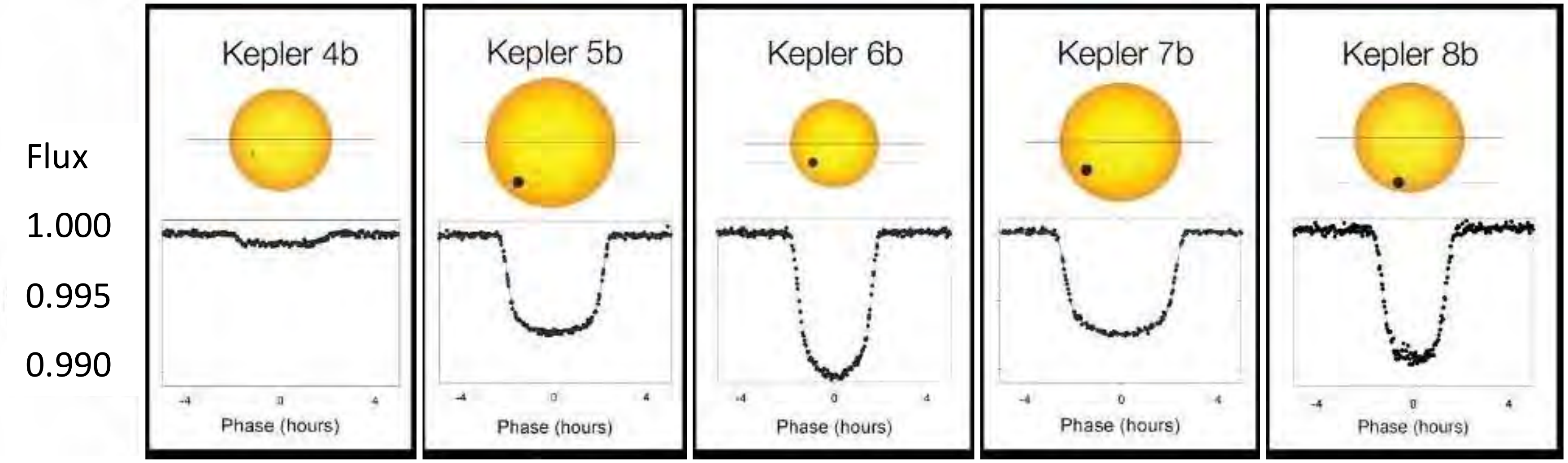
Planetary Transits (Eclipses)



An Earth-sized planet crossing a Sun-like stellar disk would cause a 10^{-4} eclipse ⟶ **need a very high precision photometry**, typically from space

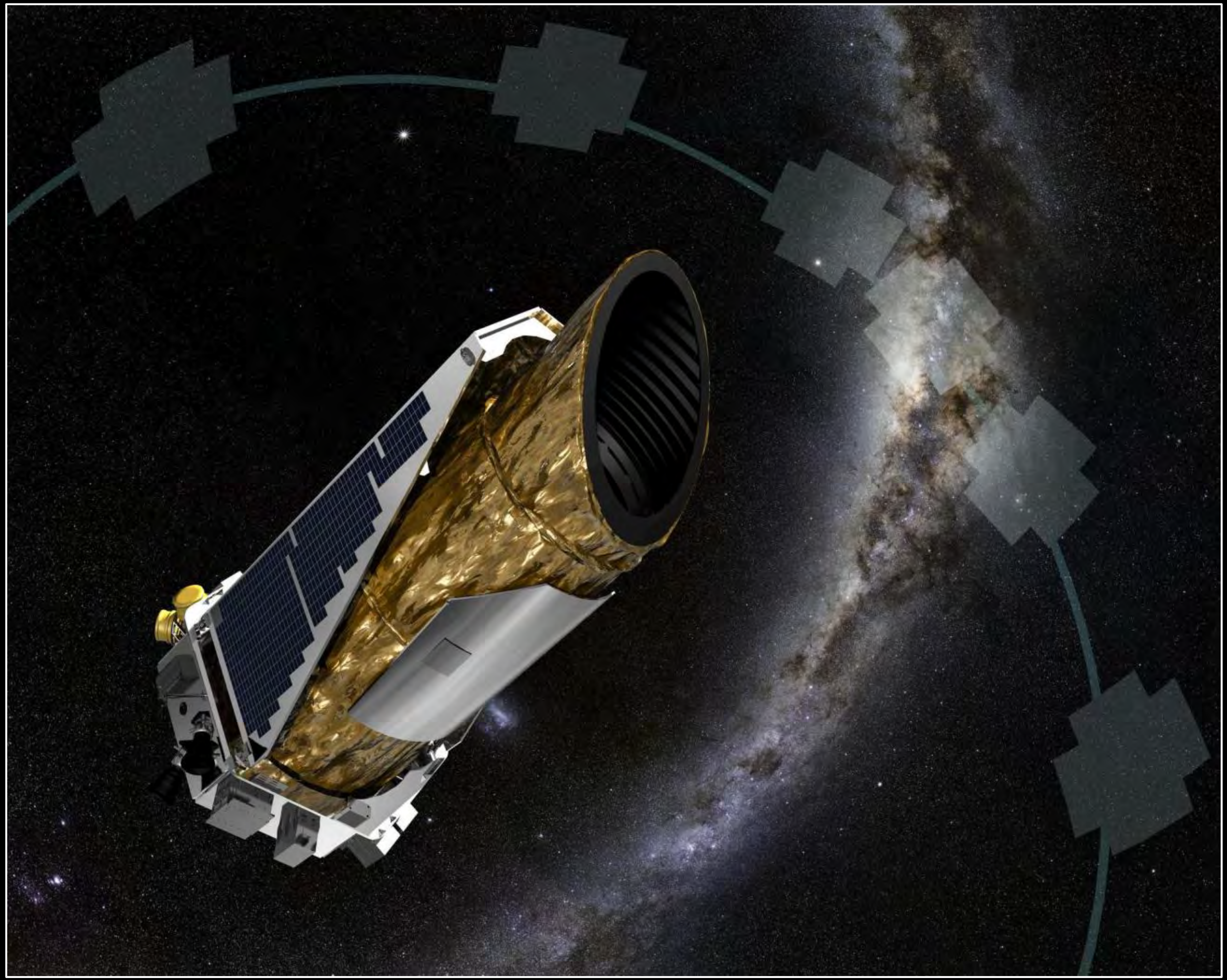
The depth of the eclipse depends on the ratio of the planet and star diameters, the duration depends on the orbital velocity, and the frequency of eclipses on the orbital period

A substantial majority of the known exoplanets have been found using this method

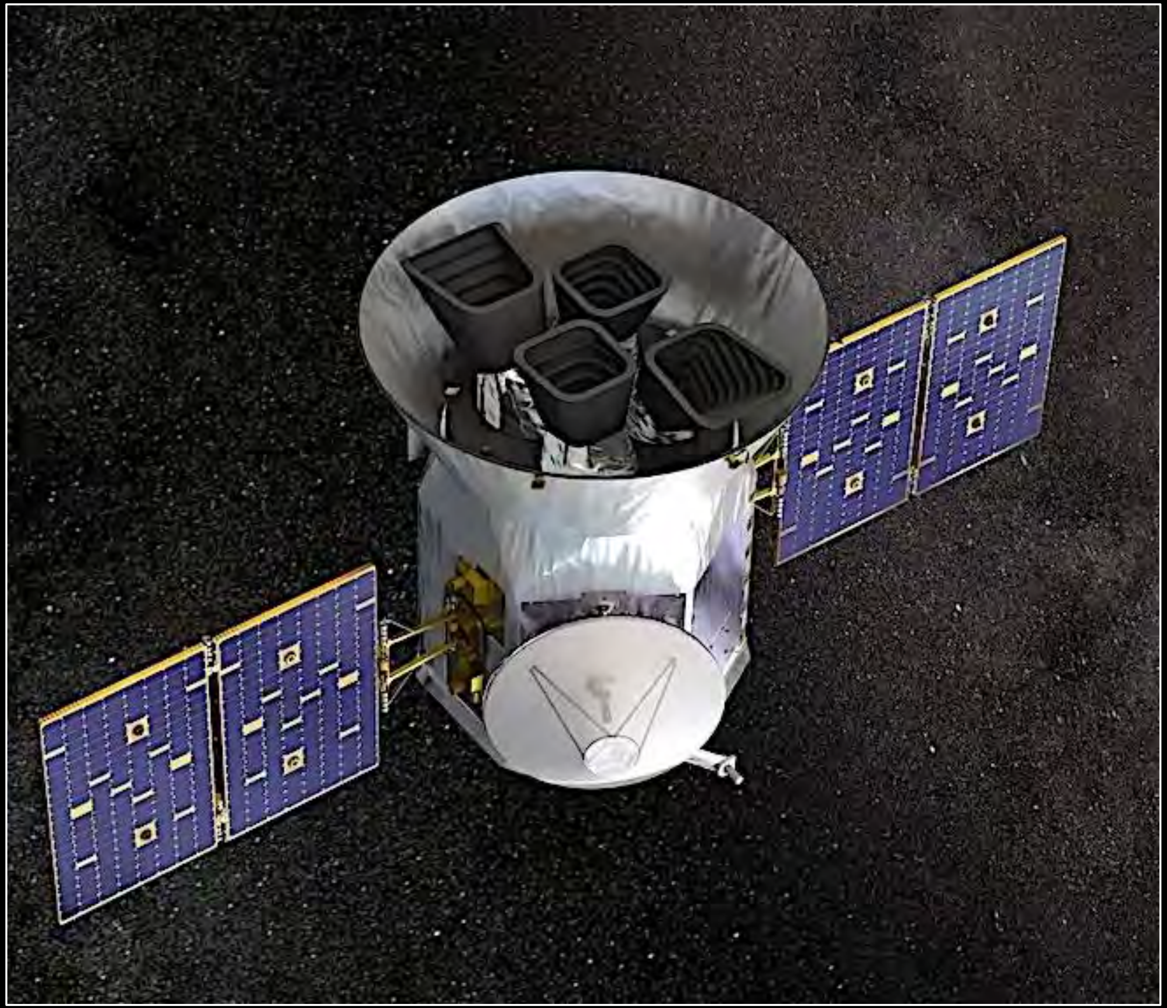


Orbital period	3.2 days	3.5 days	3.2 days	4.9 days	3.5 days

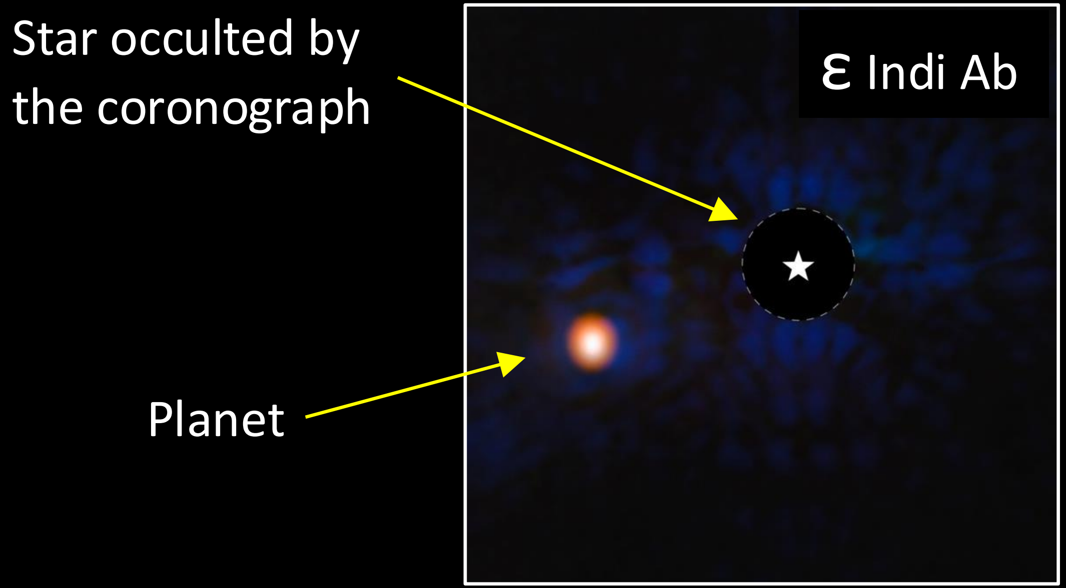
Kepler mission (2009 – 2018) found > 2,600 confirmed planets and > 2,500 additional candidates

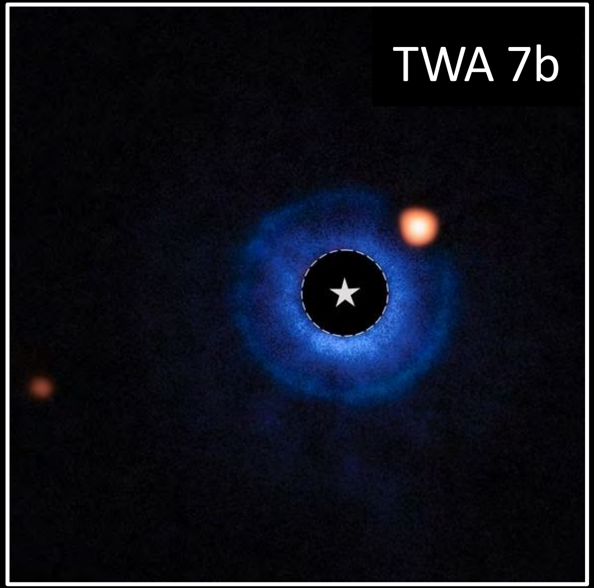


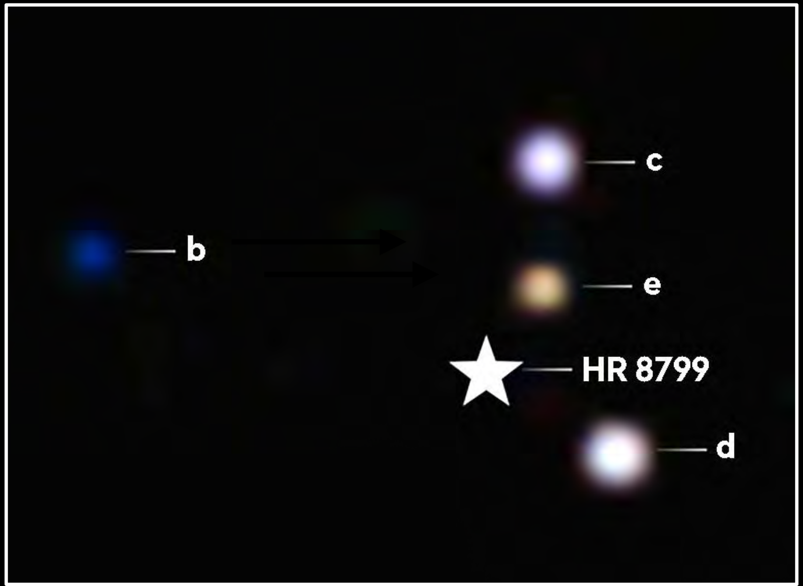
TESS (Transiting Exoplanet Survey Satellite) 2018 - 2022, found 7,821 candidate exoplanets)

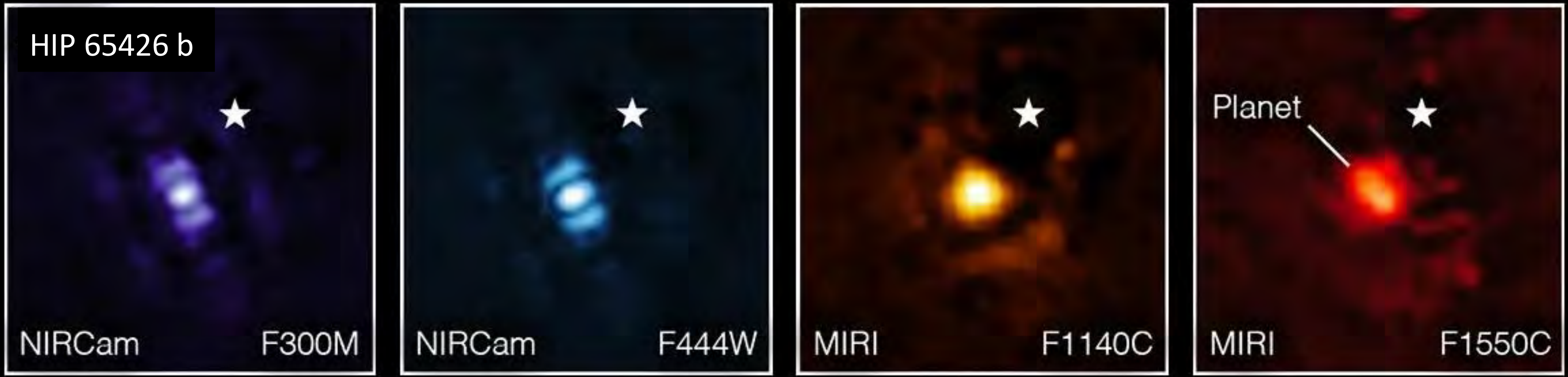


JWST Coronographic Images of Exoplanets







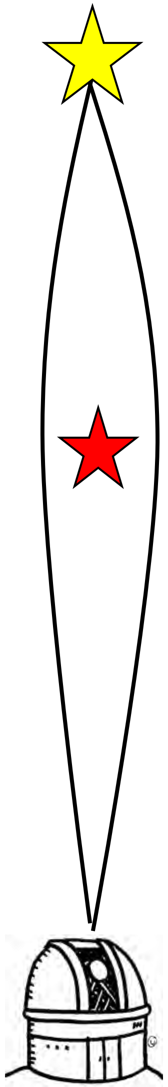


Gravitational Microlensing

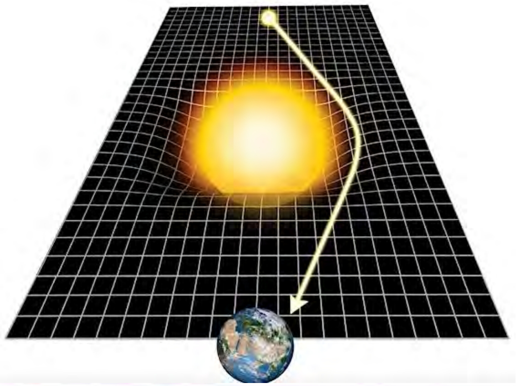
Based on the prediction of the ***General Theory of Relativity***, that the presence of a large mass bends the light rays, just like a lens

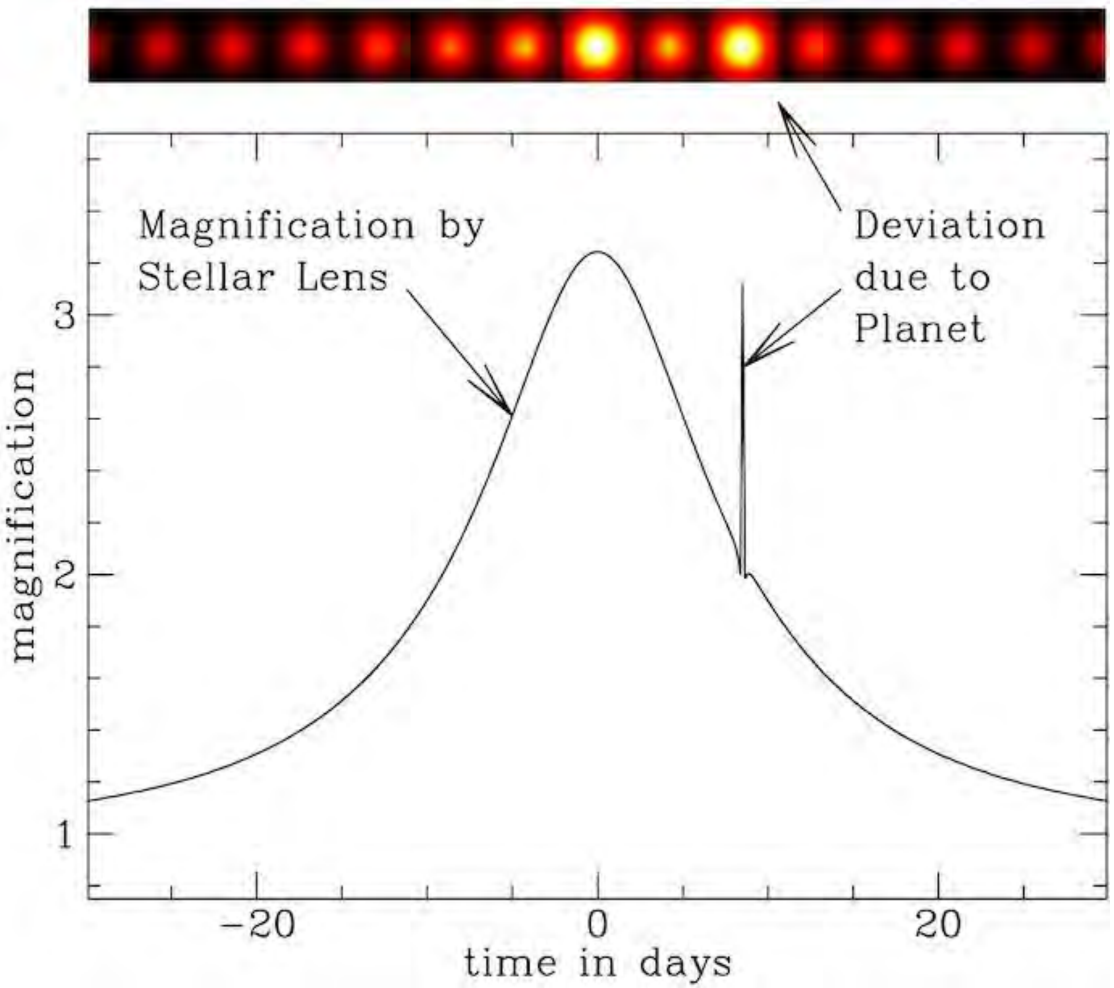
If a foreground star passes in the front of a background star, it bends light rays and *magnifies it*, making it appear **brighter**. Magnification rises and falls as the star moves across the line of sight

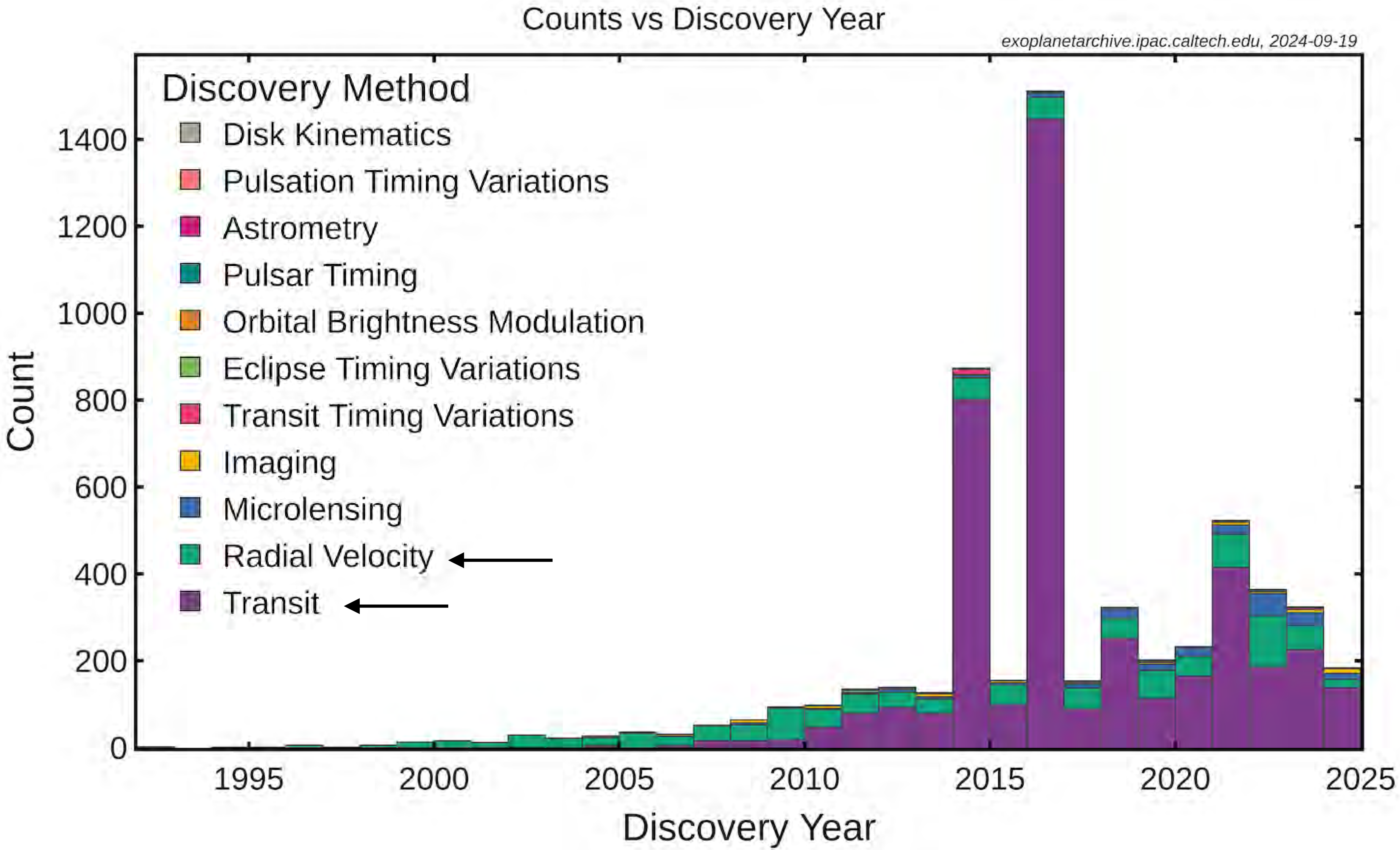
If there is also a planet present, it can cause an extra magnification flare



That is how the theory was proven in 1919 →





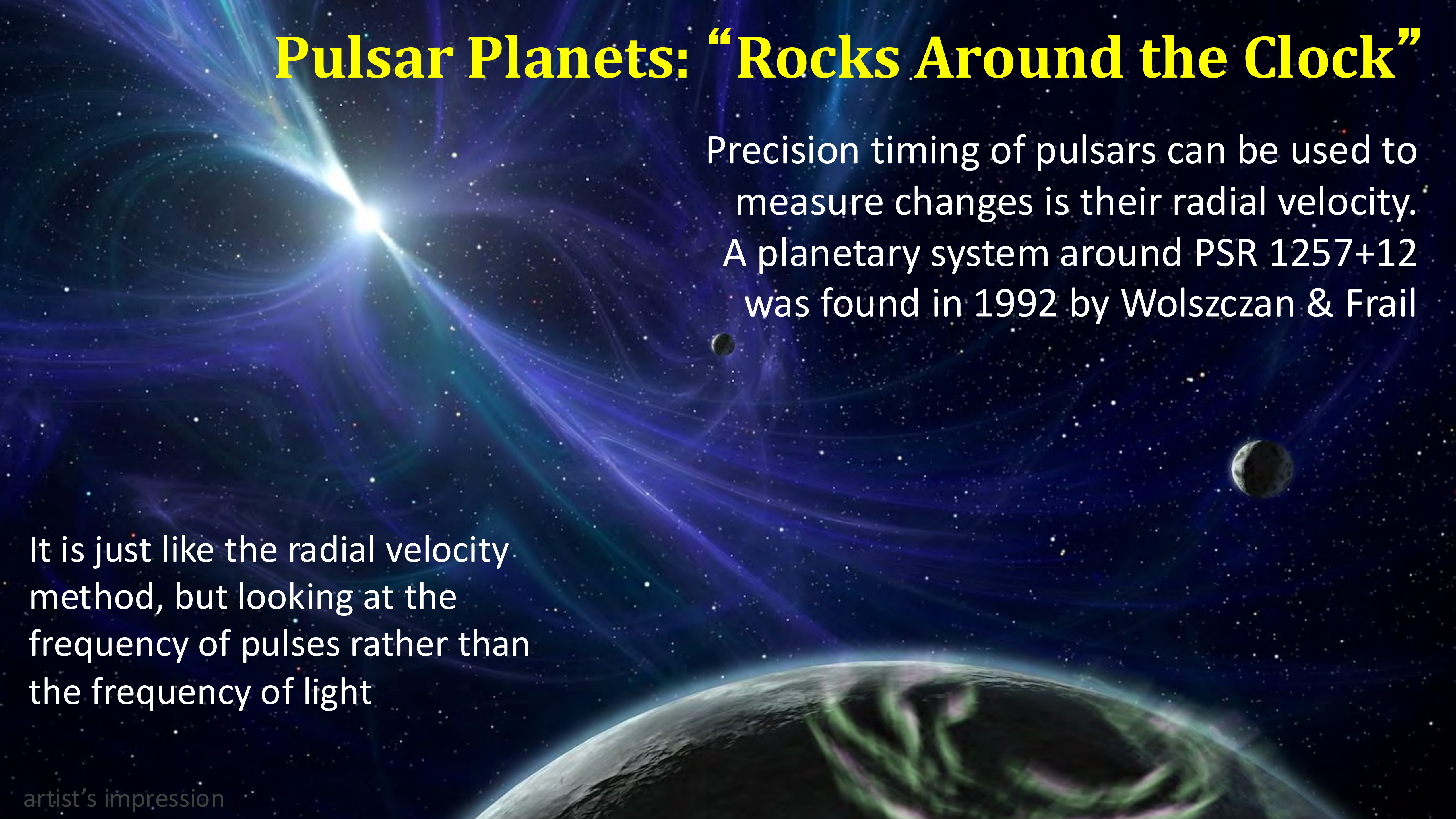


Counts vs Discovery Year
exoplanetarchive.ipac.caltech.edu, 2024-09-19
Discovery Method
Disk Kinematics
Pulsation Timing Variations
Astrometry
Pulsar Timing
Orbital Brightness Modulation
Eclipse Timing Variations
Transit Timing Variations
Imaging
Microlensing
Radial Velocity
Transit
Count
0
200
400
600
800
1000
1200
1400
1995
2000
2005
2010
2015
2020
2025
Discovery Year

Pulsar Planets: “Rocks Around the Clock”

Precision timing of pulsars can be used to measure changes is their radial velocity. A planetary system around PSR 1257+12 was found in 1992 by Wolszczan & Frail

It is just like the radial velocity method, but looking at the frequency of pulses rather than the frequency of light

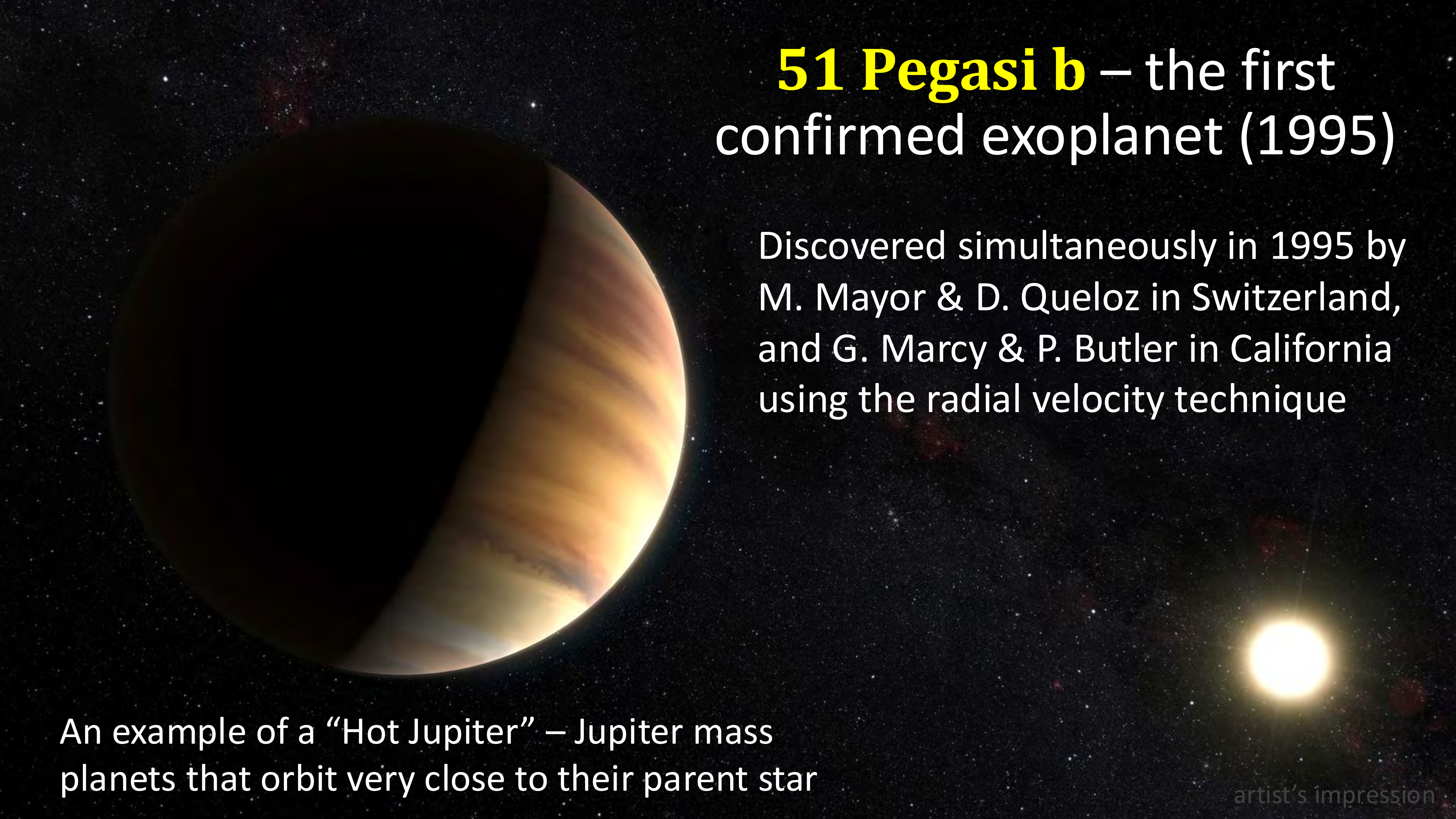


artist’s impression

51 Pegasi b – the first confirmed exoplanet (1995)

Discovered simultaneously in 1995 by M. Mayor & D. Queloz in Switzerland, and G. Marcy & P. Butler in California using the radial velocity technique

An example of a “Hot Jupiter” – Jupiter mass planets that orbit very close to their parent star



artist’s impression

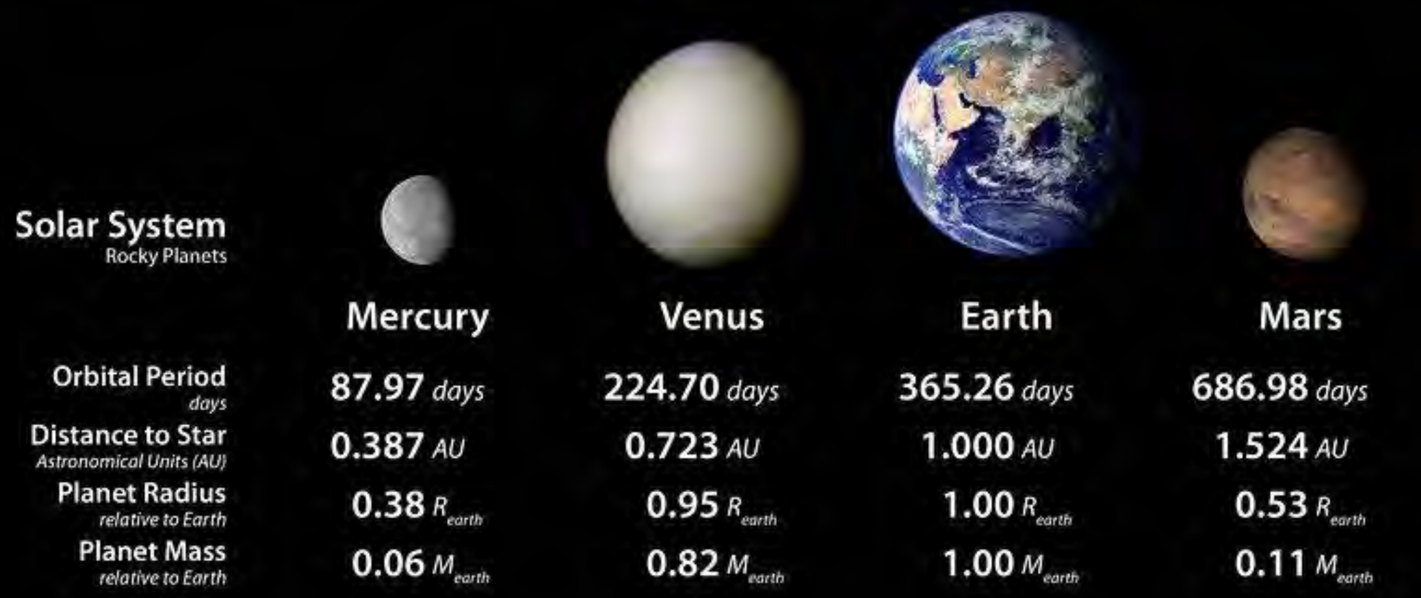
A Planet Orbiting Proxima Centauri b

The nearest exoplanet to us,
4.25 light-years = 1.3 pc away

artist's impression

The Trappist-1 Planetary System

A system of 7 planets orbiting a red dwarf star



artist's impression

Roughly how many exoplanets are now known?

A. 9
B. 1000
C. 7000
D. 10 billion
E. 3 trillion or so
F. Who knows …

Characterizing Exoplanets

From radial velocities and/or imaging:

- Measure velocity, period, thus the size of the orbit, infer the mass using Kepler's laws
- Also infer the orbital shape (eccentricity)

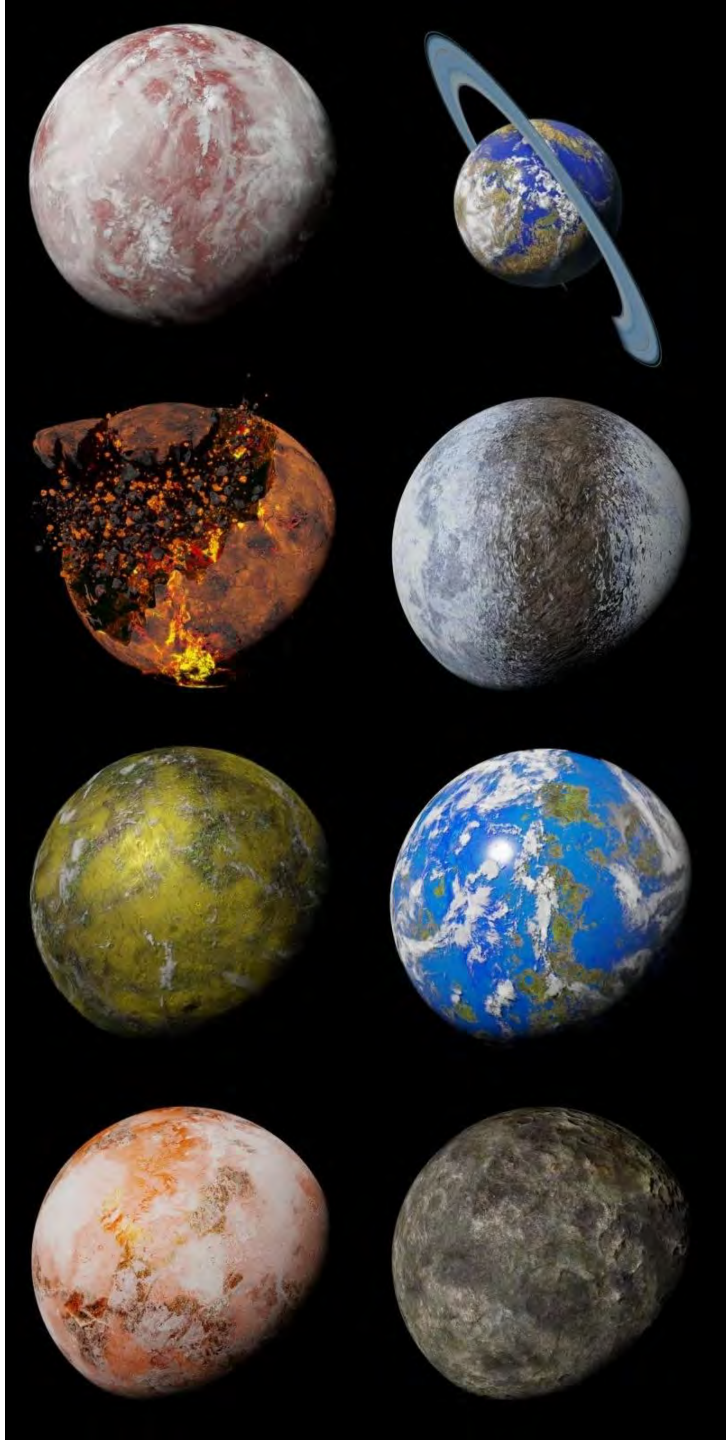
From transits:

- Infer planetary radii, thus densities, possible composition
- From the proximity to the star, infer the temperature

From spectroscopy:

- Measure the composition of the atmosphere

artist's impression →



Types of Exoplanets

Gas Giants: Massive gaseous planets, often in close orbits to their stars ("Hot Jupiters")

Mini-Neptunes: Smaller than Neptune but larger than Earth, these are often composed of thick hydrogen/helium atmospheres with cores of rock or ice

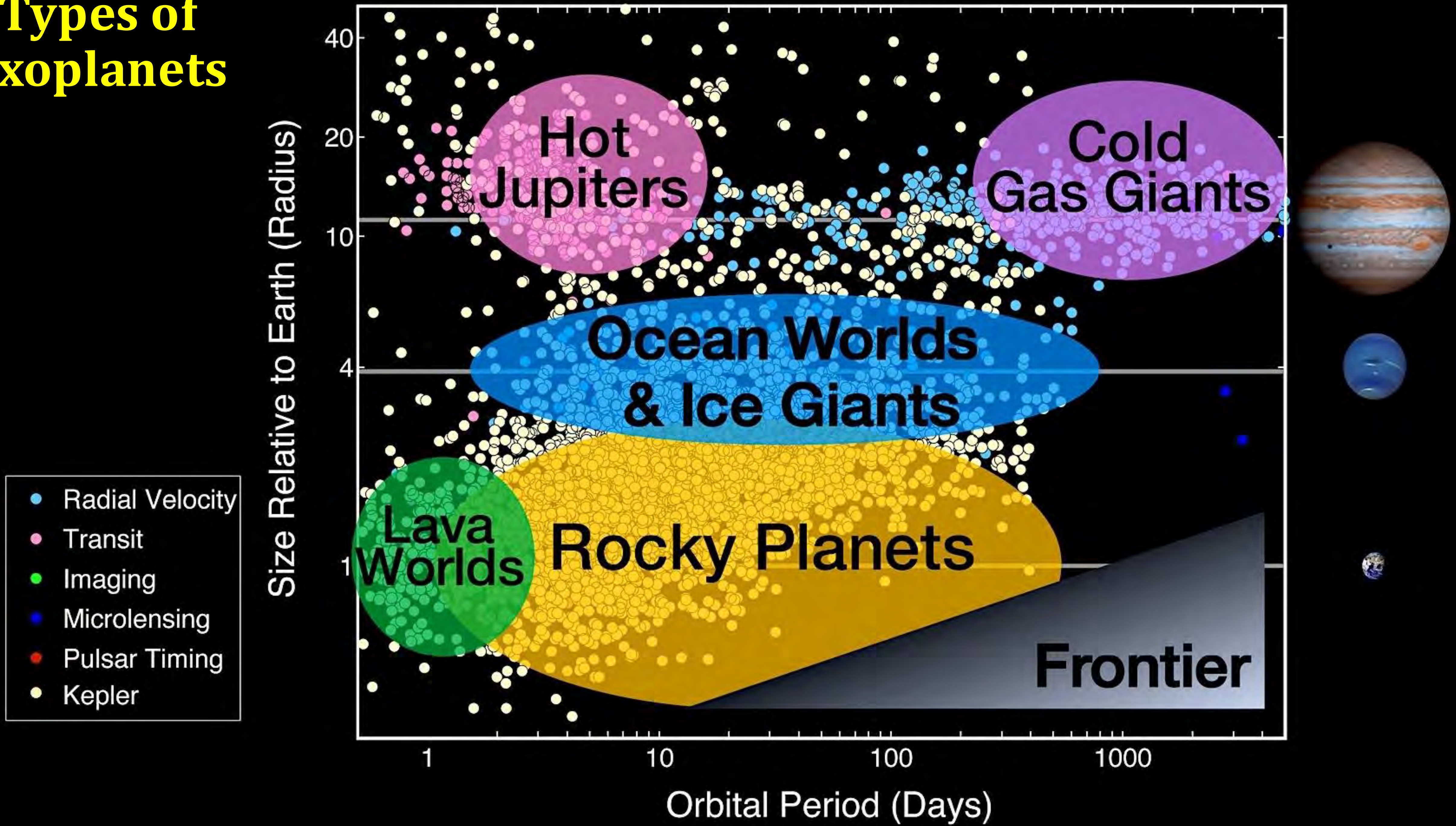
Super-Earths: Rocky or gaseous planets more massive than Earth, but lighter than ice giants. They are the most common type found in the Galaxy

Terrestrial (Rocky) Planets: Rocky, Earth-sized or smaller planets that may possess oceans or atmospheres

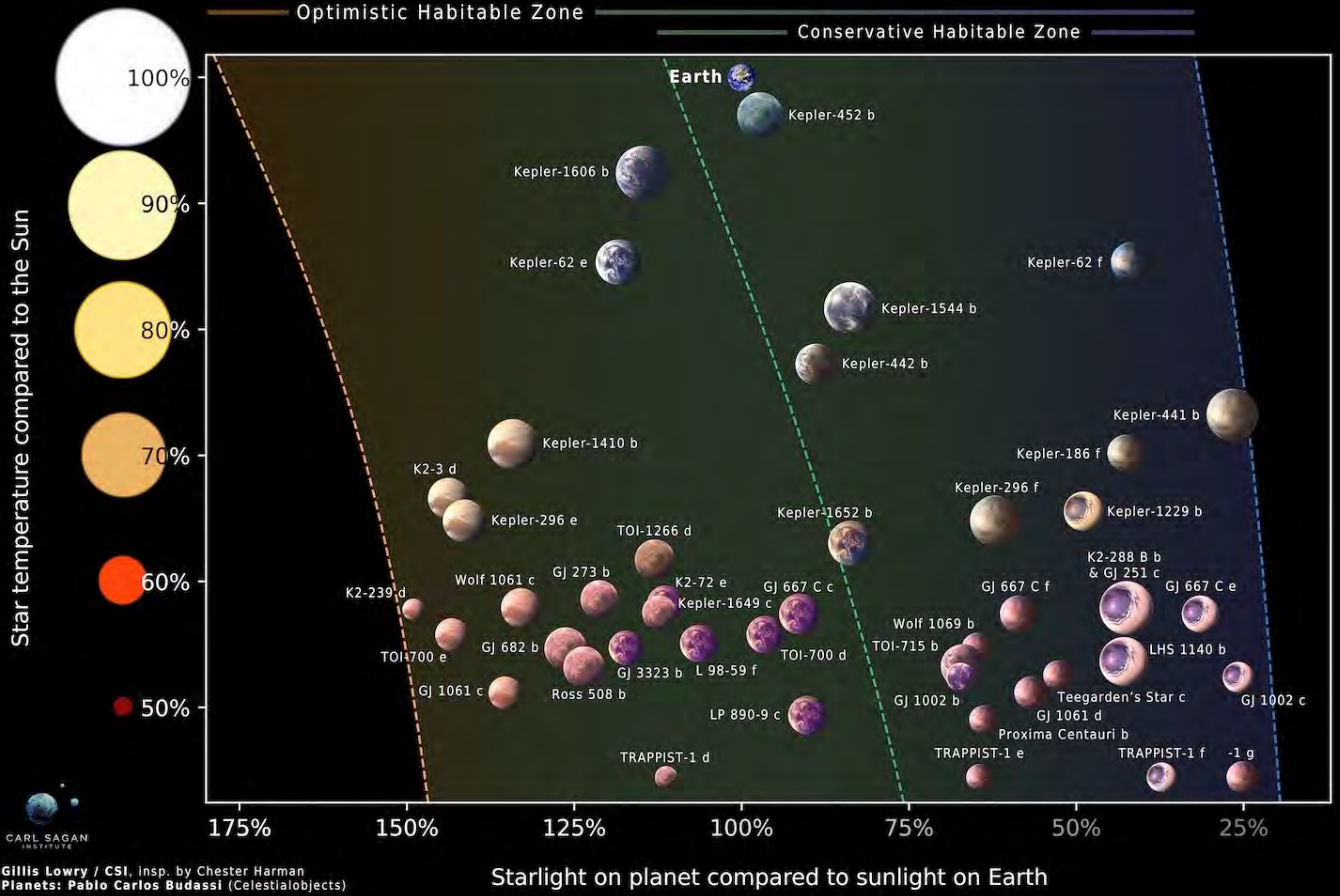
Some Unique Types:

- **Lava Worlds:** Rocky planets with surfaces covered in molten lava due to extreme heat
- **Ocean Worlds:** Planets covered in deep, liquid-water oceans
- **Carbon Planets:** Composed mainly of carbon compounds
- **Iron Planets:** Dominated by an iron core
- **Frozen/Roaster Worlds:** Extreme cold or hot temperature conditions

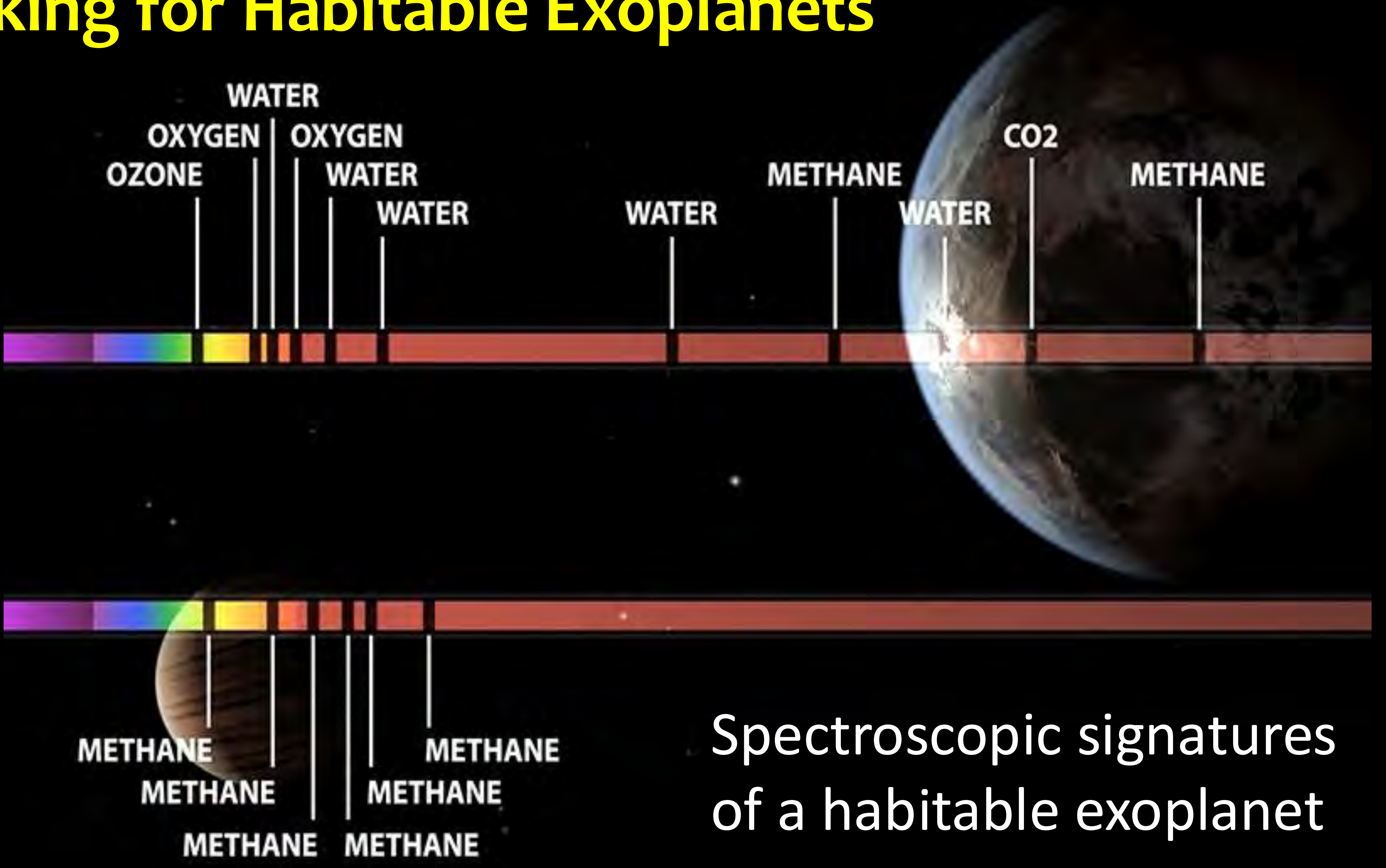
Types of Exoplanets



Planets in the Habitable Zone



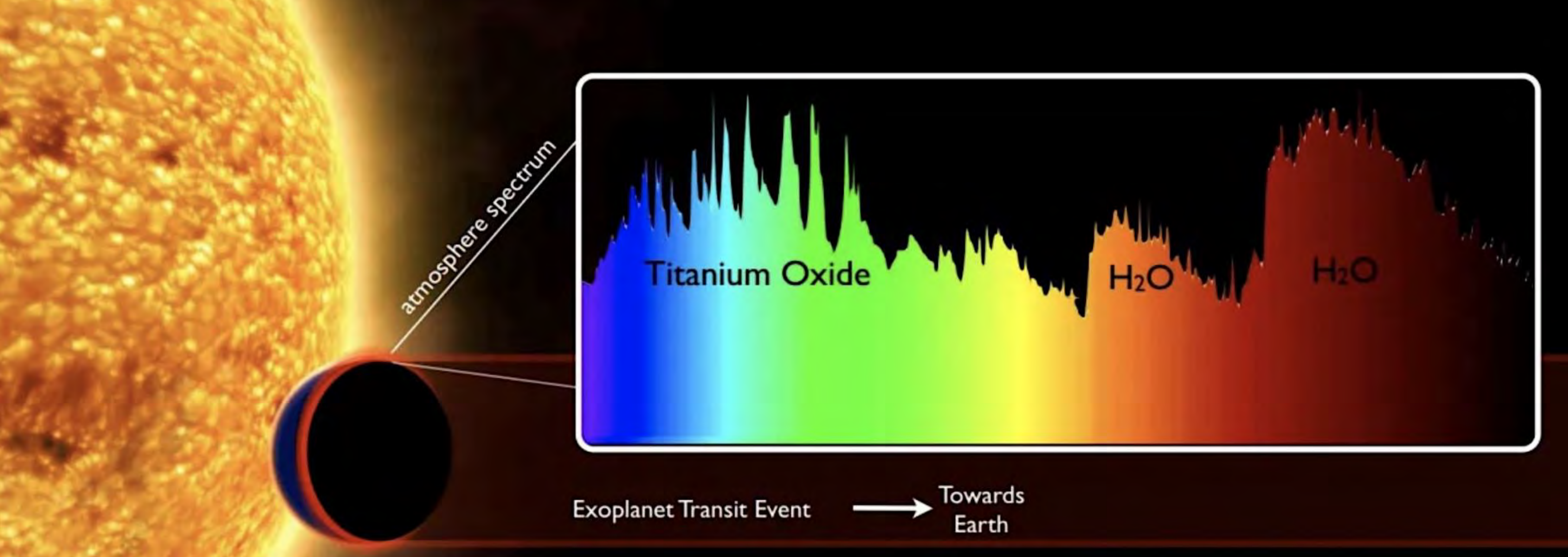
Looking for Habitable Exoplanets



Spectroscopic signatures of a habitable exoplanet

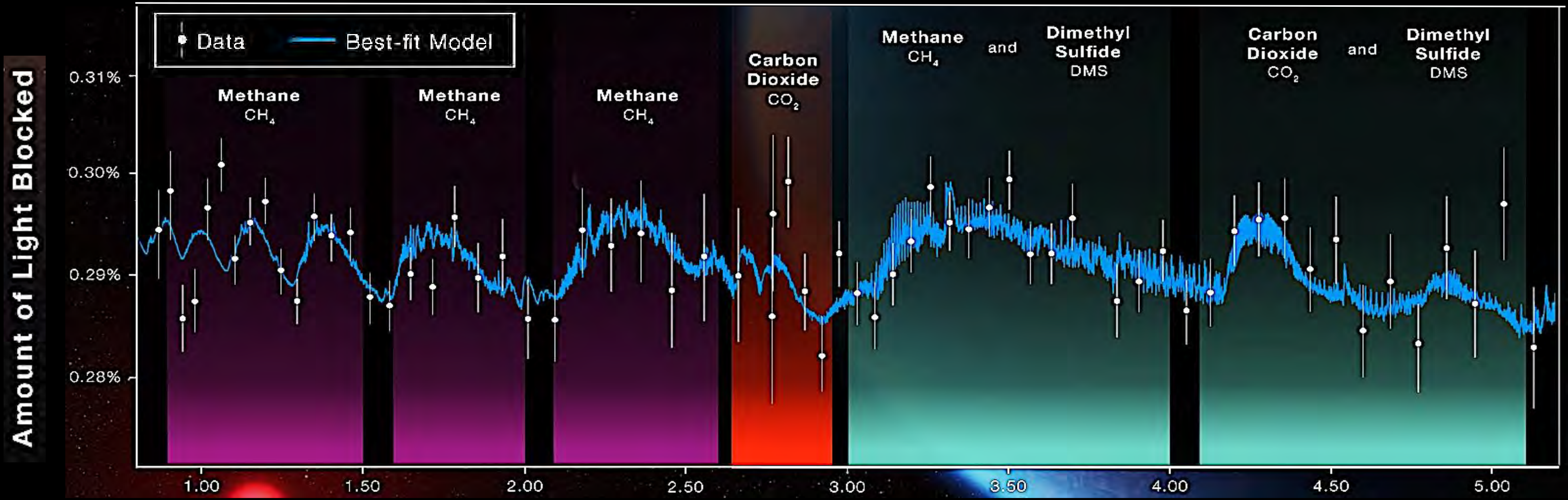
Observing the Exoplanet Atmospheres

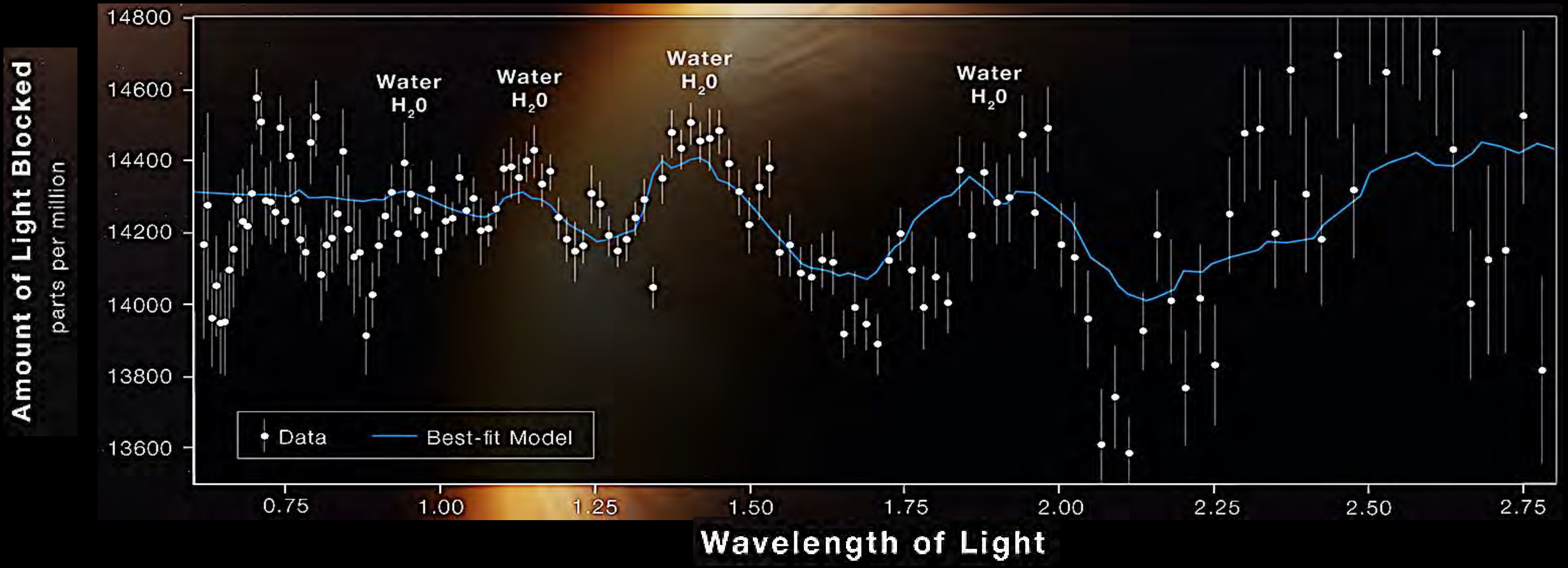
Subtract the spectra of the star during and out of the eclipse: extra absorption by the planet’s atmosphere



Look for biosignatures for Earth-like planets

First JWST Spectra of Exoplanets



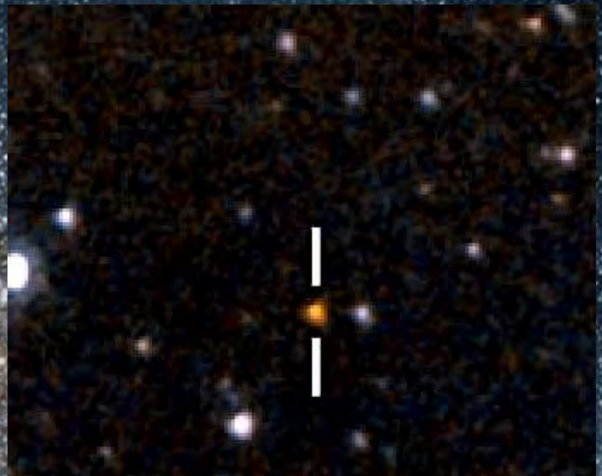


Rogue or Interstellar Planets

A rogue planet, or a free-floating planet, or an isolated planetary-mass object, is an interstellar object of planetary mass which is not gravitationally bound to any star or brown dwarf.   There may be billions to trillions of them in the Milky Way

They can form through a regular star formation process, but not reach a brown dwarf mass, or may have formed in a planetary system, but got ejected from it

artist's impression



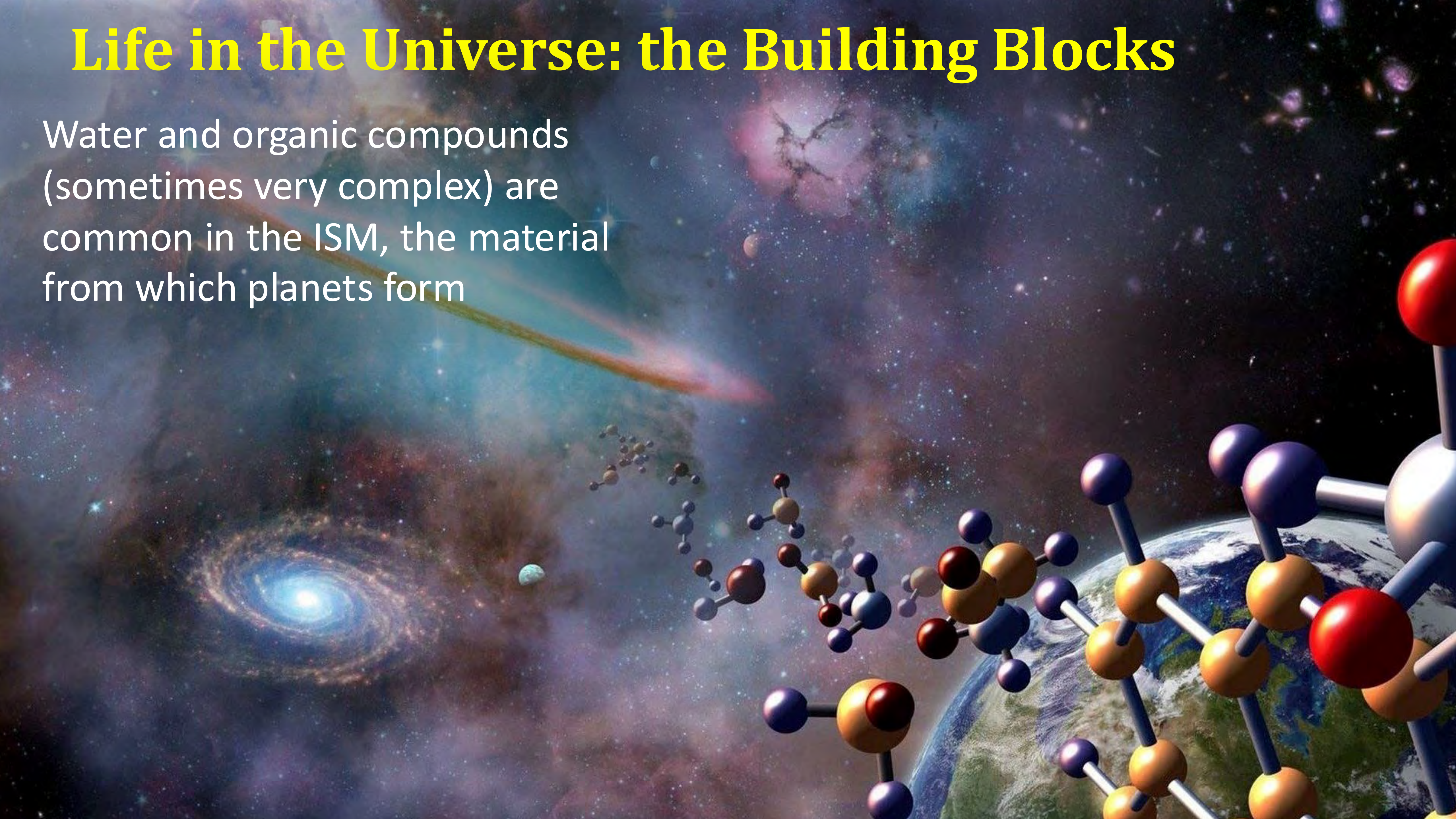
Interstellar planet
WISE J0830+2837

Planetary transits…

A. Tell us about the planet’s mass
B. Tell us about the planet’s radius
C. Tell us about the planet’s temperature
D. Tell us about the planet’s rotation period
E. Can be studied from the ground
F. Can be studied only from space
G. Can be used to improve horoscopes

Life in the Universe: the Building Blocks

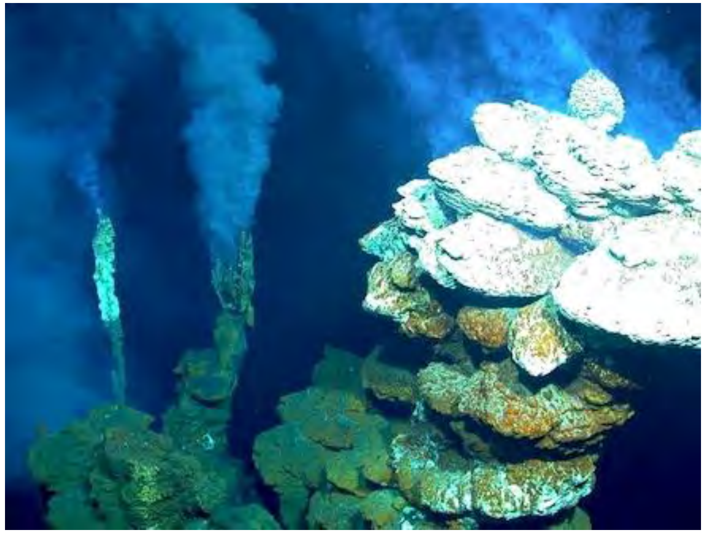
Water and organic compounds (sometimes very complex) are common in the ISM, the material from which planets form



Given energy (solar, geothermal), ionizing sources (UV, lightning), and mutations (radiation), biogenic molecules can naturally arise in the “primordial soup” of planetary oceans

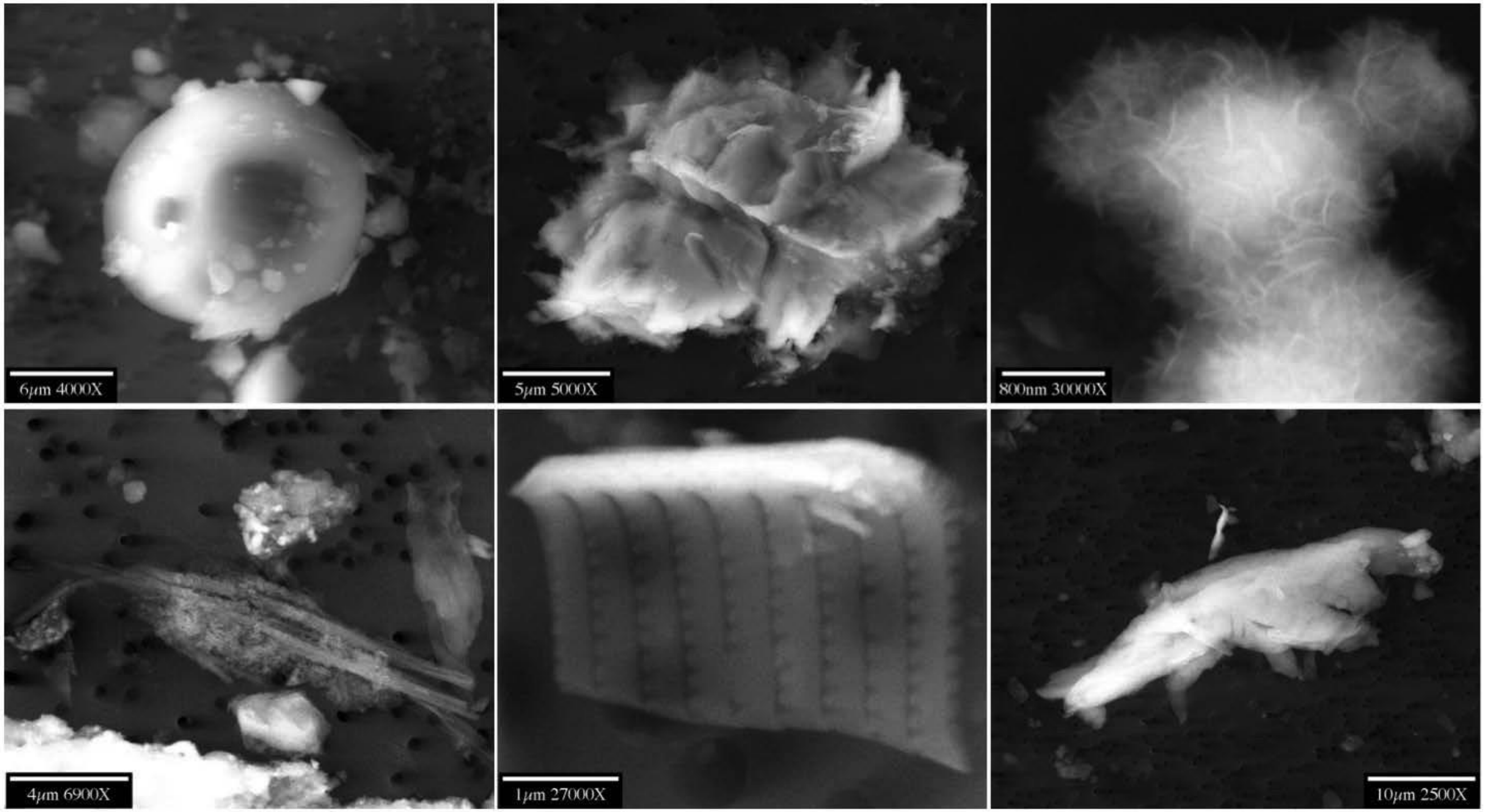
Life in Extreme Environments

- E.g., sulphur-based metabolism in the bacteria found near deep undersea vents; inside rocks; deep under ice (lake Vostok), in volcanic lakes, etc.
- Possibilities for life on other planets or moons



Deep undersea vents

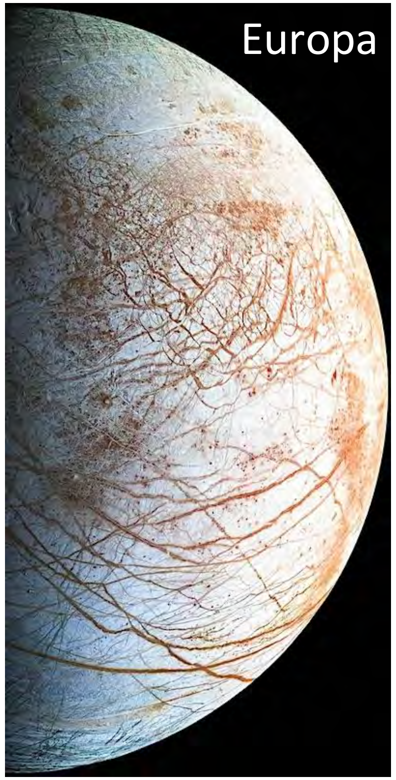
Yellowstone Grand Prismatic Spring

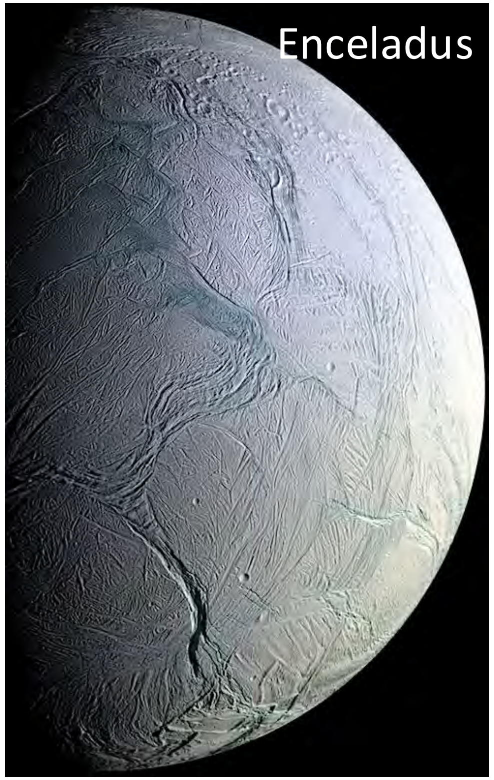


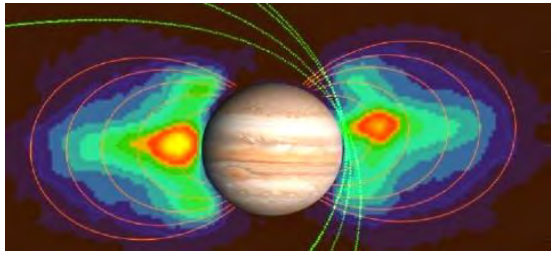
< Microorganisms found under the ice in lake Vostok, Antarctica

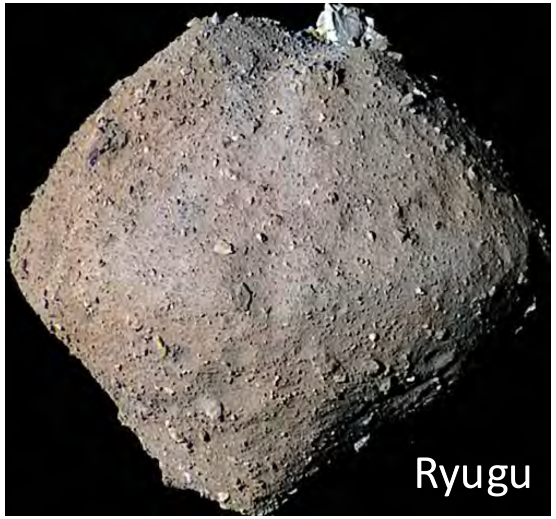
Life Elsewhere in the Solar System?

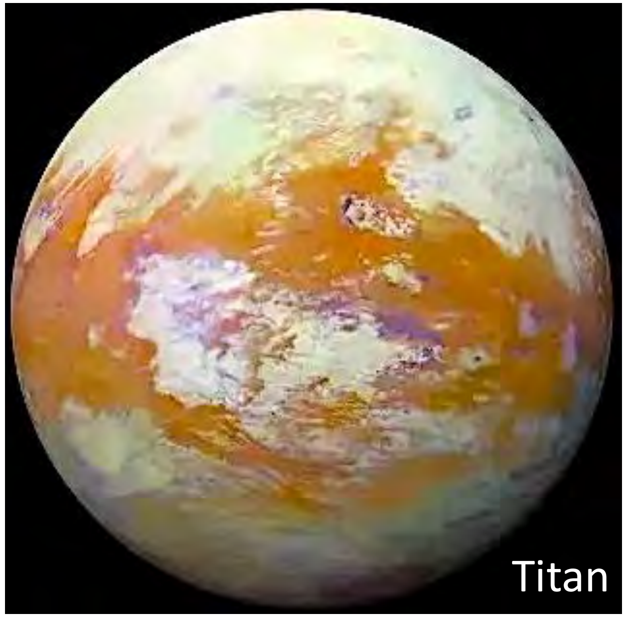
- Mars once had an ocean and the atmosphere
- Oceans on Europa, Enceladus, and likely other moons of Jupiter and Saturn
- Volcanoes on Io, Jupiter’s radiation belts
- Organic molecules on Titan, in comets and asteroids





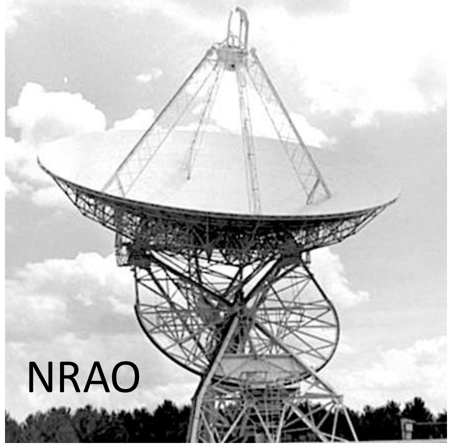






Search for ExtraTerrestrial Intelligence (SETI)

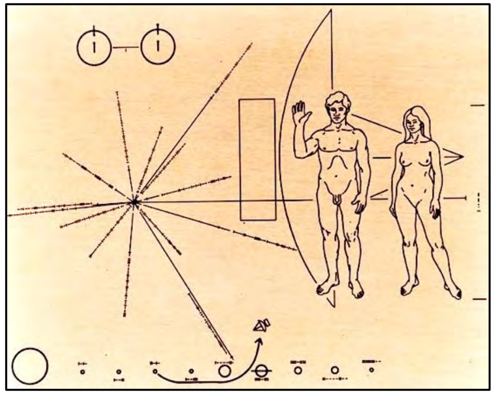
- Started with a paper by G. Cocconi & P. Morrison, "Searching for Interstellar Communications" in 1959
- The first search ("Project Ozma") by Frank Drake in 1960 at NRAO
- Many others followed, at Arecibo, VLA, etc. Now: Allen Telescope Array (ATA) in California, operated by the SETI Institute



- Typically using the 21 cm line of hydrogen as the "magic frequency"

Or we can send them a postcard:

Pioneer 10 plaque →



Voyager Golden record →

All this assumes that an advanced civilization would choose to communicate with a mid-20th century planet Earth technology…

The Drake Equation

$$N = R^{*} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

N = The number of civilizations in The Milky Way Galaxy whose electromagnetic emissions are detectable

R^{*} = The rate of formation of stars suitable for the development of intelligent life

f_p = The fraction of those stars with planetary systems

n_e = The number of planets, per solar system, with an environment suitable for life

f_l = The fraction of suitable planets on which life actually appears

f_i = The fraction of life bearing planets on which intelligent life emerges

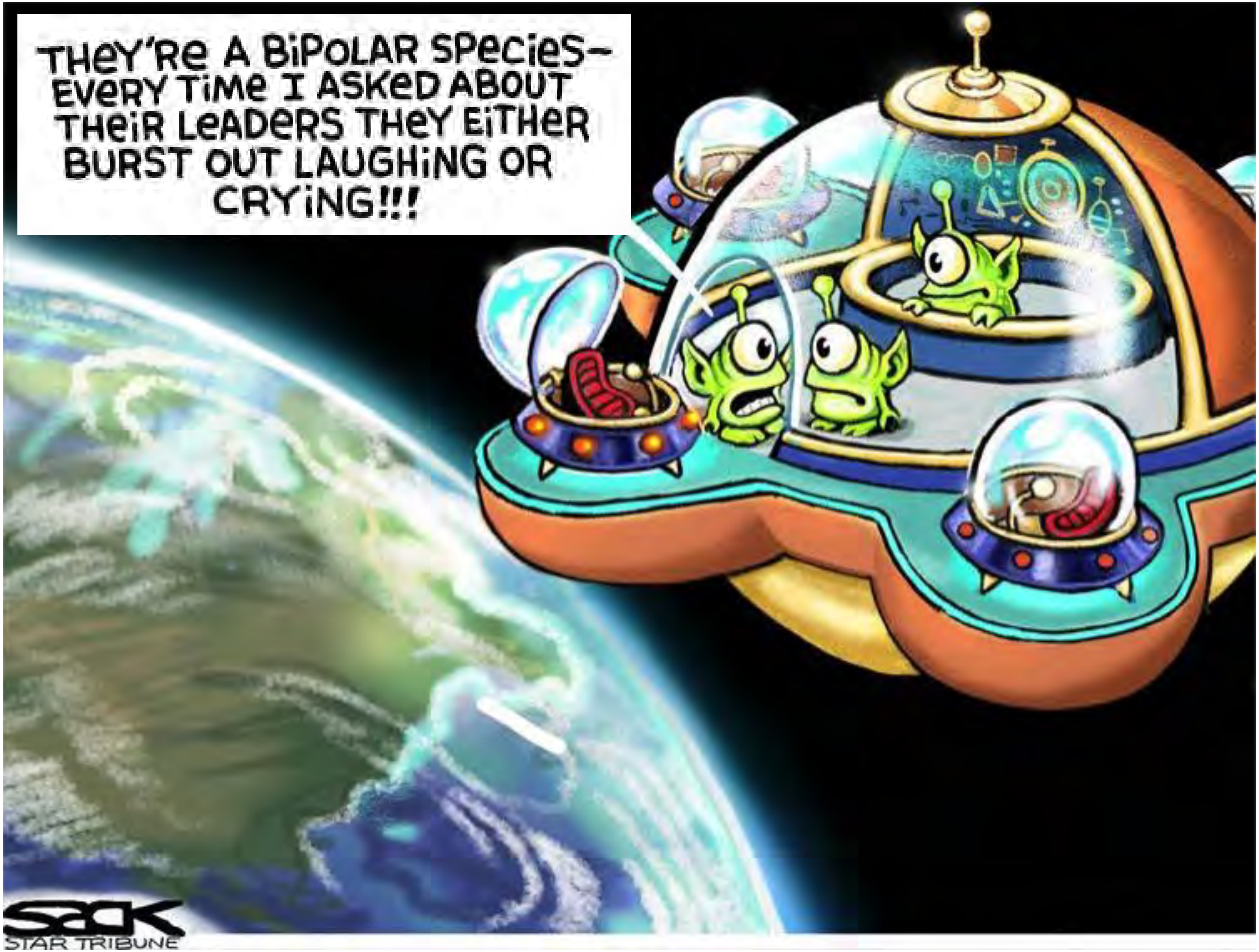
f_c = The fraction of civilizations that develop a technology that releases detectable signs of their existence into space

L = The length of time such civilizations release detectable signals

The Fermi Paradox

- Or: ***Where are they?***
- A civilization that can do interstellar travel at velocities ~ 1% of the speed of light would still conquer the Galaxy in ~ 10 million years
- Galaxy is ~ 13 billion years old
- So why don't we see them?
- Or do we?
- Or is something wrong with our implicit beliefs as to what advanced civilizations might do?
- More than a hundred of possible explanations have been proposed
- **What do you think?**

Or are they already here?



Key Concepts in This Lecture (1)

- Planet's temperature is determined only by its albedo and the distance to its parent star, but if there is any opacity in its atmosphere, some heat is retained, leading to a **greenhouse effect**. In our Solar system, Venus is an extreme case of this
- **Habitable zone** is the range of planet orbits radii where liquid water can exist on the surface. In the Solar system, this is 0.84 AU $< a < 1.7$ AU
- **Brown dwarfs** are objects that are larger than planets, but insufficiently massive to ignite thermonuclear reactions, $M < 0.085\ M_\odot$
- Brown dwarfs and large planets can generate energy through the **Kelvin-Helmholtz mechanism**, conversion of the binding energy into heat as the object shrinks. Jupiter emits twice the amount of energy than it receives from the Sun
- ***Planets are an expected byproduct of star formation***, from the leftover material in the protostellar/protoplanetary disk, and are now known to be common
- There are estimated to be between **100 billion** and over **3 trillion** planets in the Milky Way galaxy alone

Key Concepts in This Lecture (2)

- **Search methods for exosolar planets** include: **direct imaging**, **Doppler shift** as the planet and its star orbit the common center of mass, **eclipses (transits)** as a planet crosses the stellar disk, and **gravitational microlensing**
- **Types of exoplanets** include: **gas giants, mini-Neptunes, super-Earths, and Terrestrial (rocky)** planets. There are also **rare types** that do not exist in the Solar system. There are also **rogue** or **interstellar planets** that do not belong to any planetary system
- Architectures of exoplanetary systems can be very different from out own
- Water, oxygen, and various organic molecules have been detected in exoplanet spectra, and are also common in the interstellar medium, so **life could be relatively common** elsewhere in the Galaxy. In our Solar system, the most likely place for **extraterrestrial life** may be the larger moons of Jupiter and Saturn
- **Searches for Extraterrestrial Intelligence** (SETI) using radio have not yielded any results so far, but they have **anthropocentric biases**

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