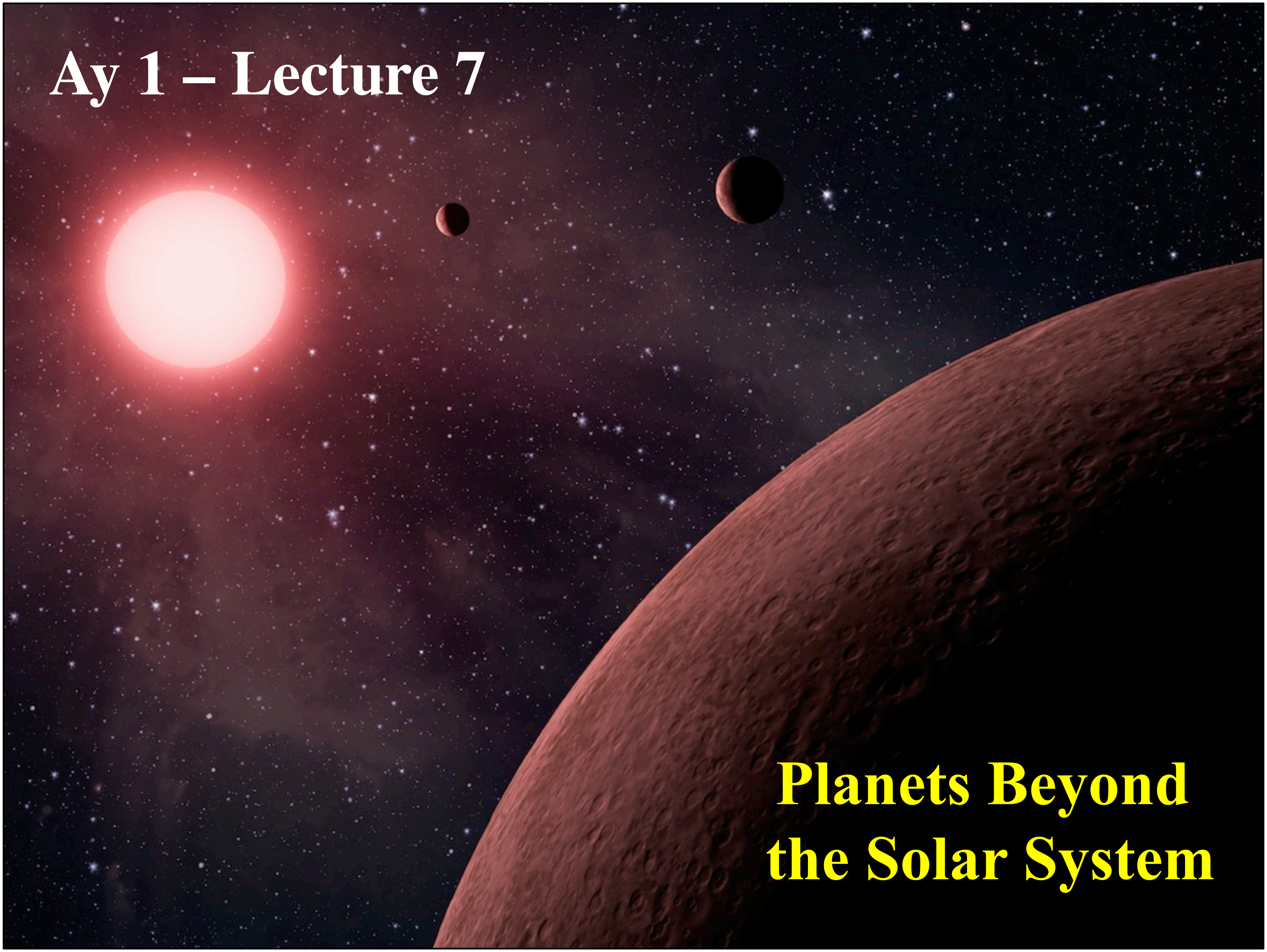
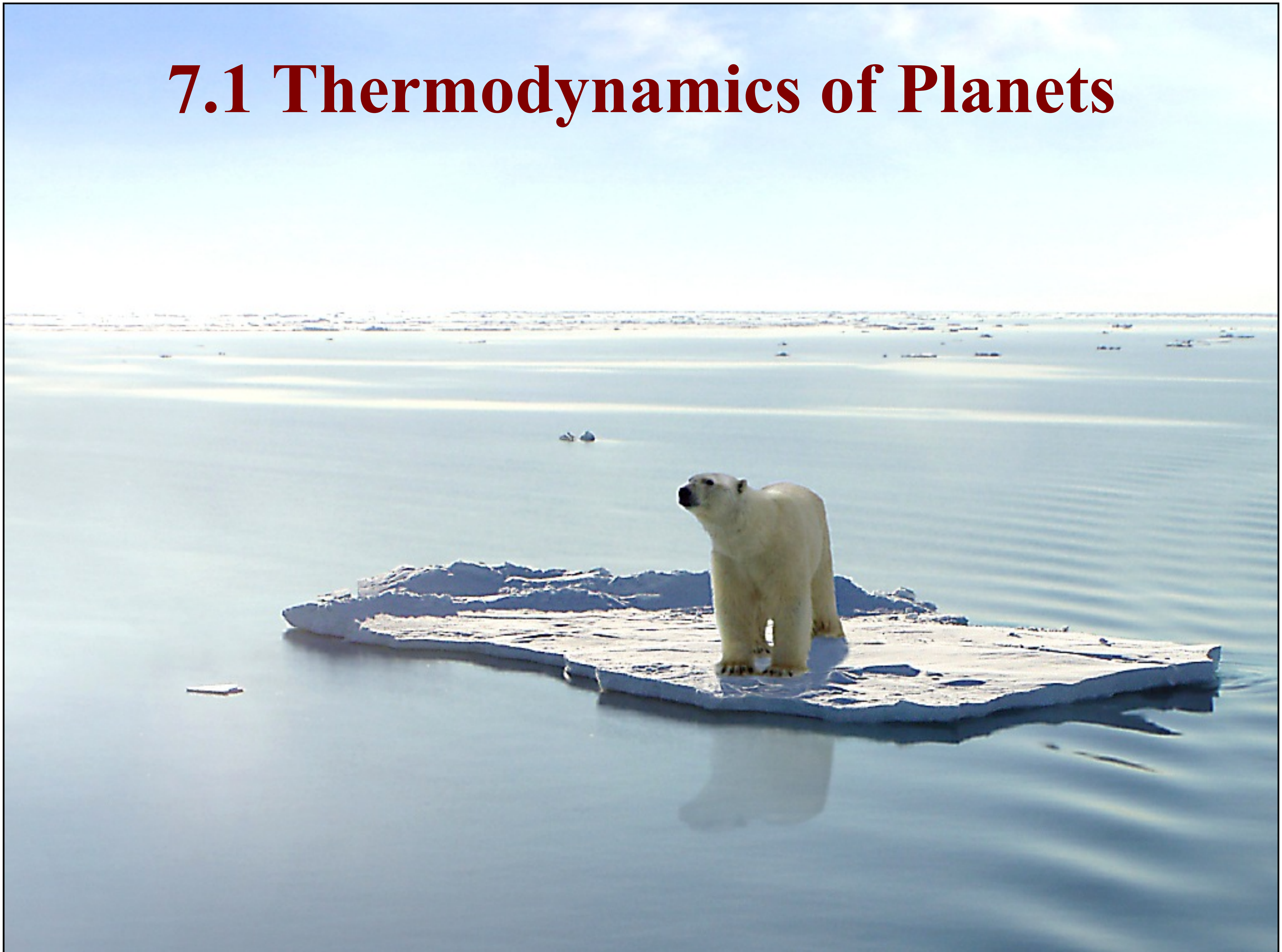
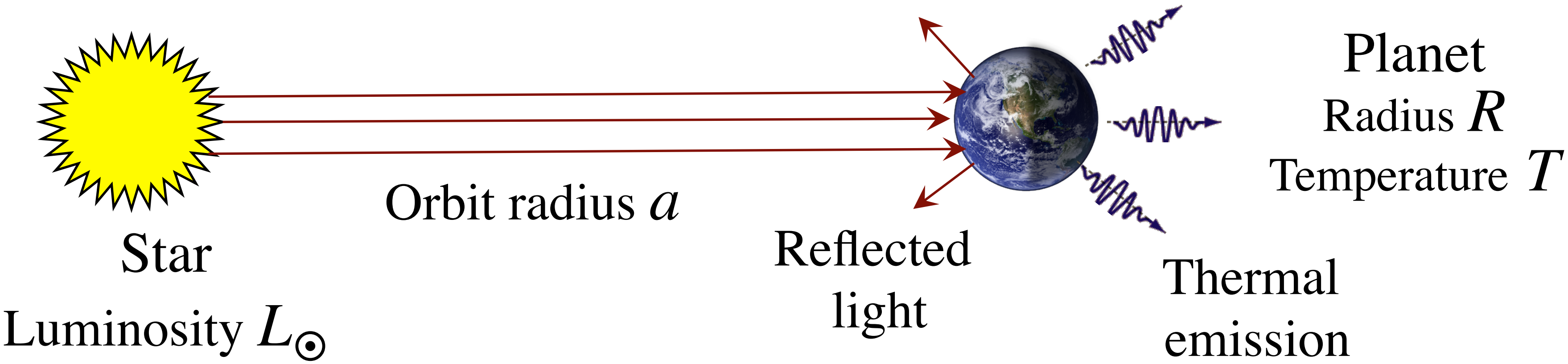

Ay 1 – Lecture 7
Planets Beyond
the Solar System

7.1 Thermodynamics of Planets



Planets in a Thermal Balance



α = albedo, fraction of the reflected light (for the Earth, $\alpha \sim 0.3 - 0.35$)

Fraction of the intercepted luminosity: $\dfrac{\pi R^2}{4 \pi a^2}$

Absorbed luminosity: $\dfrac{R^2}{4 a^2} (1 - \alpha) L_\odot = 4 \pi R^2 \sigma T^4$ = Emitted luminosity

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

Planet's effective blackbody temperature: $T^4 = L_\odot \dfrac{(1 - \alpha)}{16 \pi \sigma a^2}$

Planet's Temperature

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

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

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

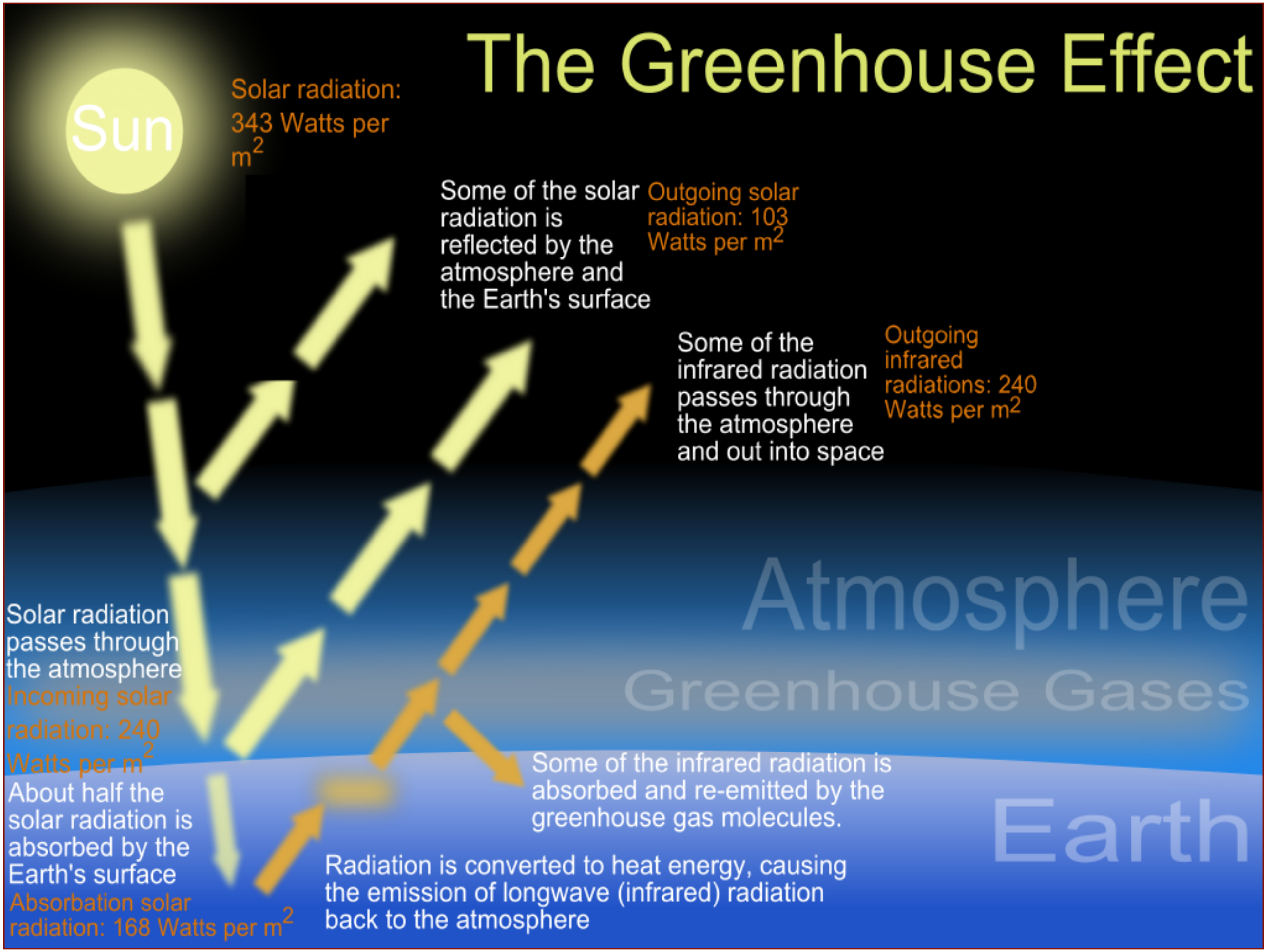
Estimate $T \sim 253$ K

Yet, the actual value is more like $T \sim 287$ K. Why?

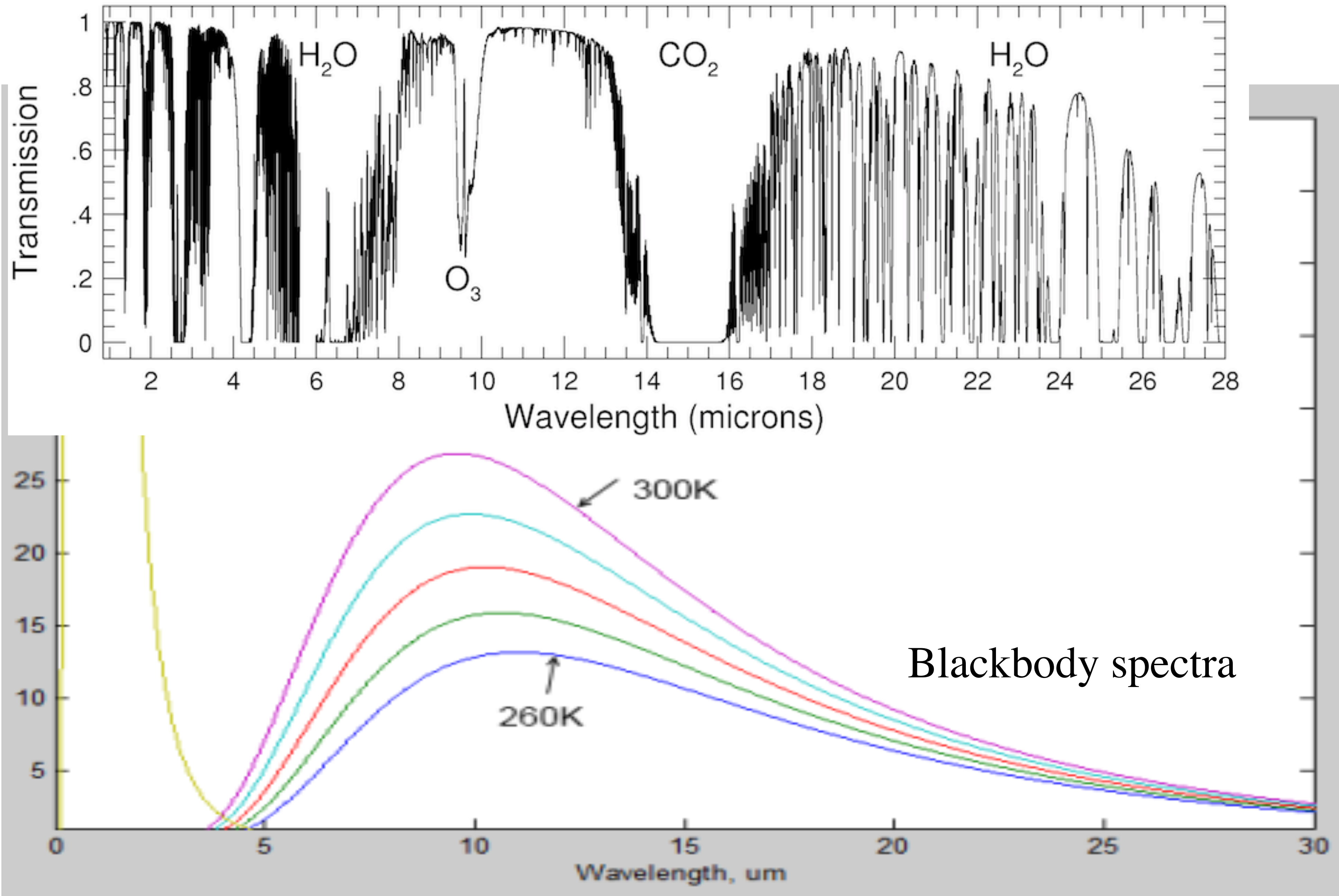
The answer: **the Greenhouse Effect**

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.

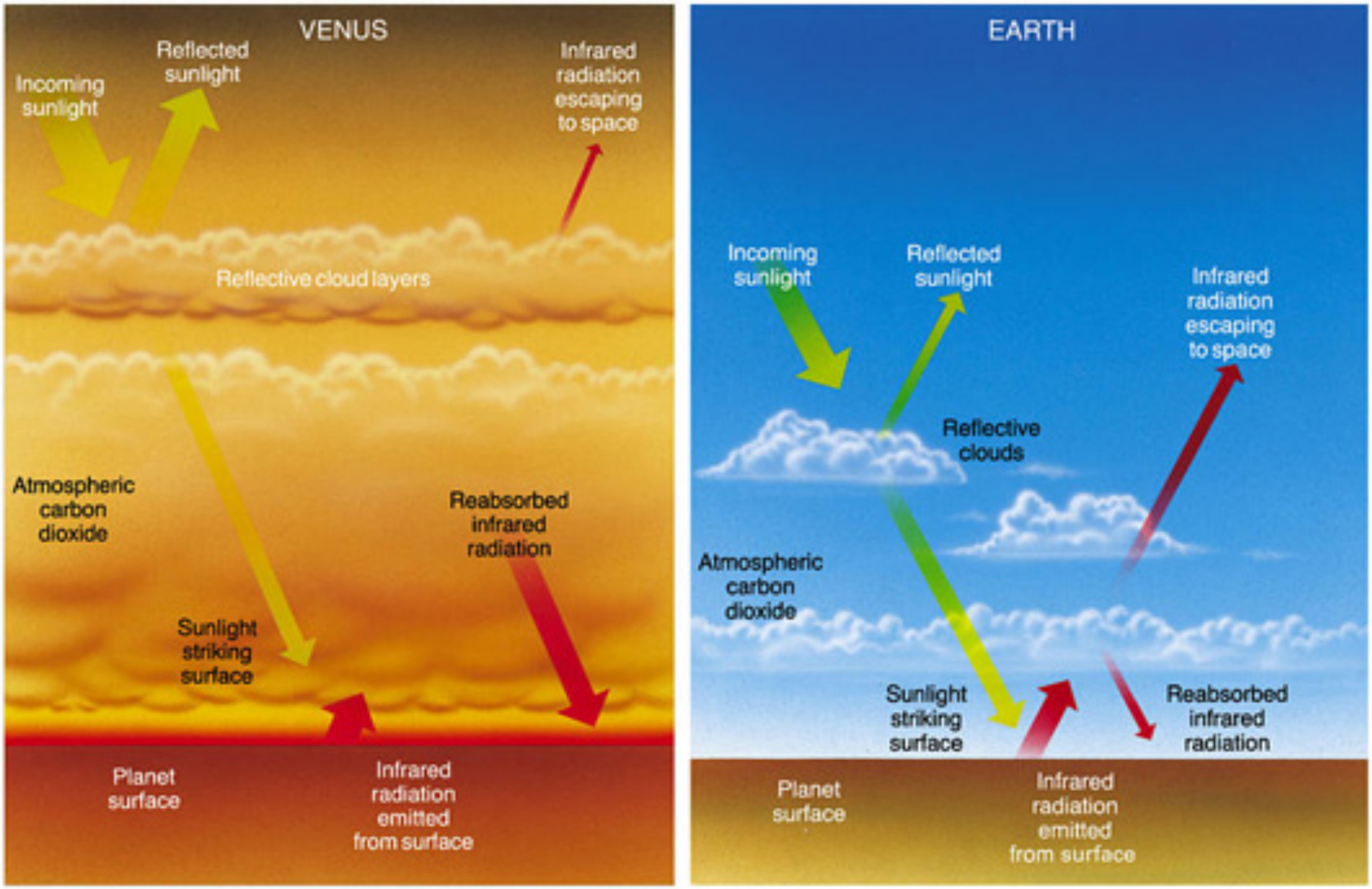

The Greenhouse Effect
Sun
Solar radiation: 343 Watts per m2
Some of the solar radiation is reflected by the atmosphere and the Earth's surface
Outgoing solar radiation: 103 Watts per m2
Some of the infrared radiation passes through the atmosphere and out into space
Outgoing infrared radiations: 240 Watts per m2
Atmosphere
Greenhouse Gases
Solar radiation passes through the atmosphere
Incoming solar radiation: 240 Watts per m2
About half the solar radiation is absorbed by the Earth's surface
Absorbation solar radiation: 168 Watts per m2
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules.
Radiation is converted to heat energy, causing the emission of longwave (infrared) radiation back to the atmosphere
Earth

Earth's Atmosphere Absorption Spectrum

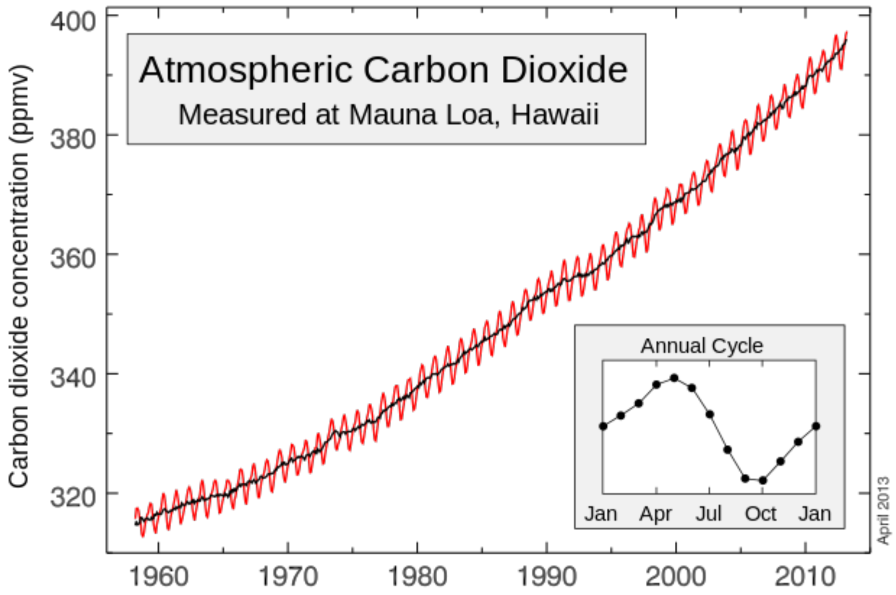


Runaway Greenhouse Effect

If a planet absorbs more heat than it radiates away, the temperature will keep rising until the cooling becomes effective again

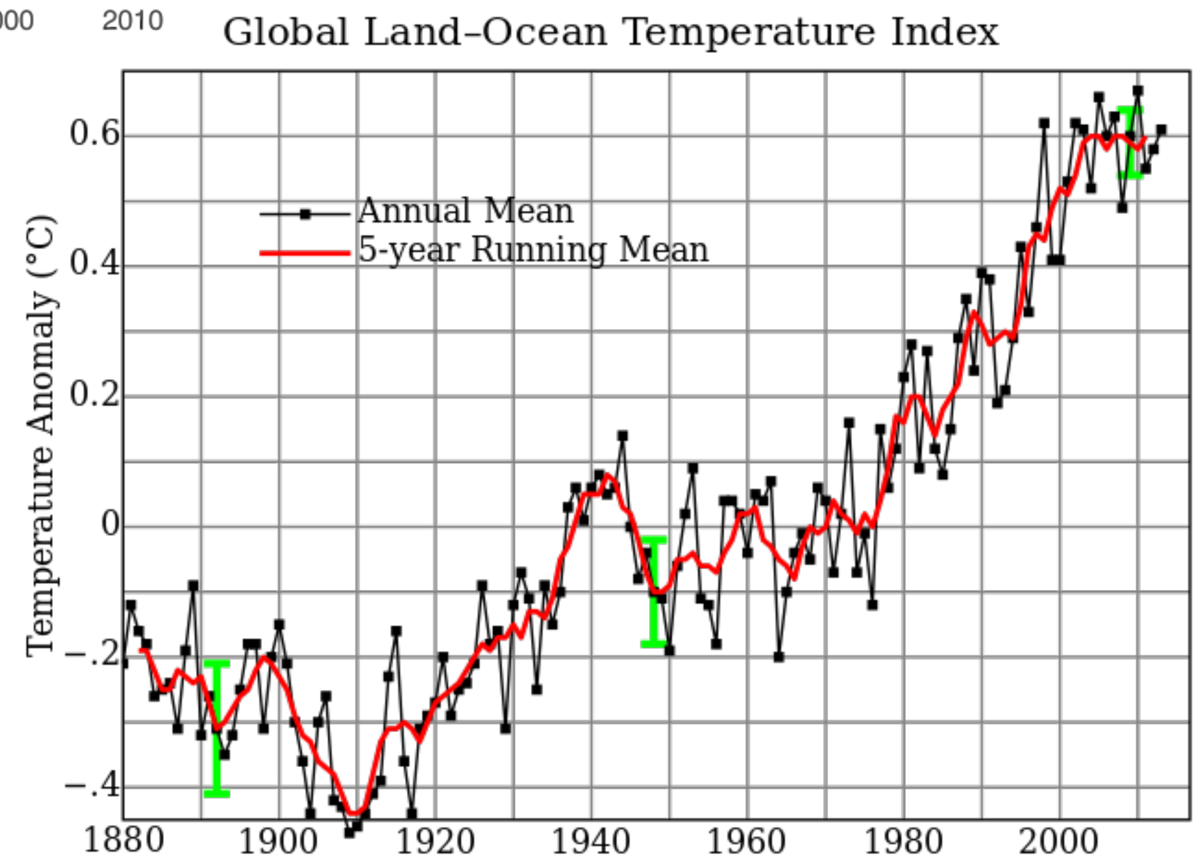


Global Warming



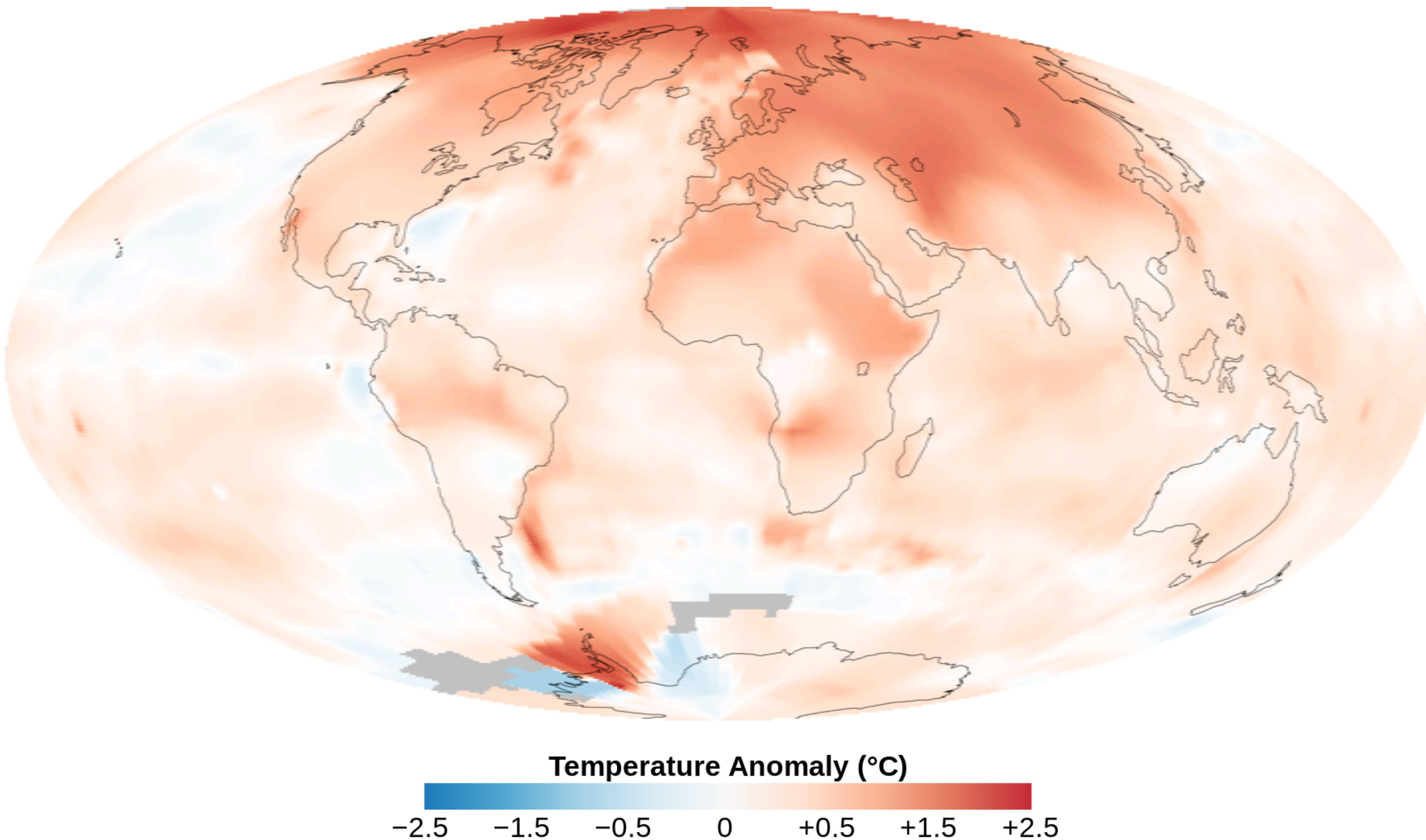
< The cause: increasing concentration of the greenhouse gases

The effect >
Increasing global temperatures



Global Warming

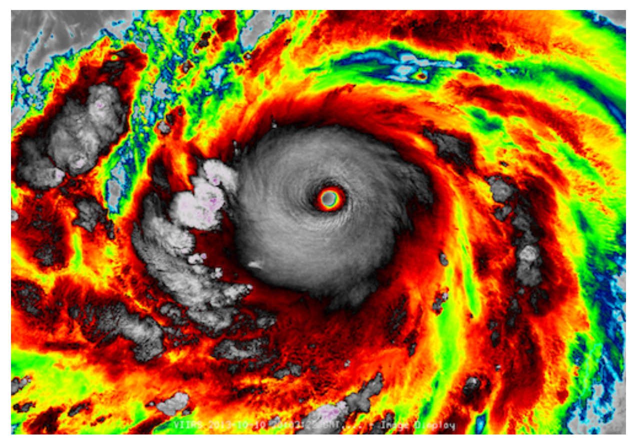
The10-year average (2000–2009) global mean temperature anomaly relative to the 1951–1980 mean



Consequences of the Global Warming

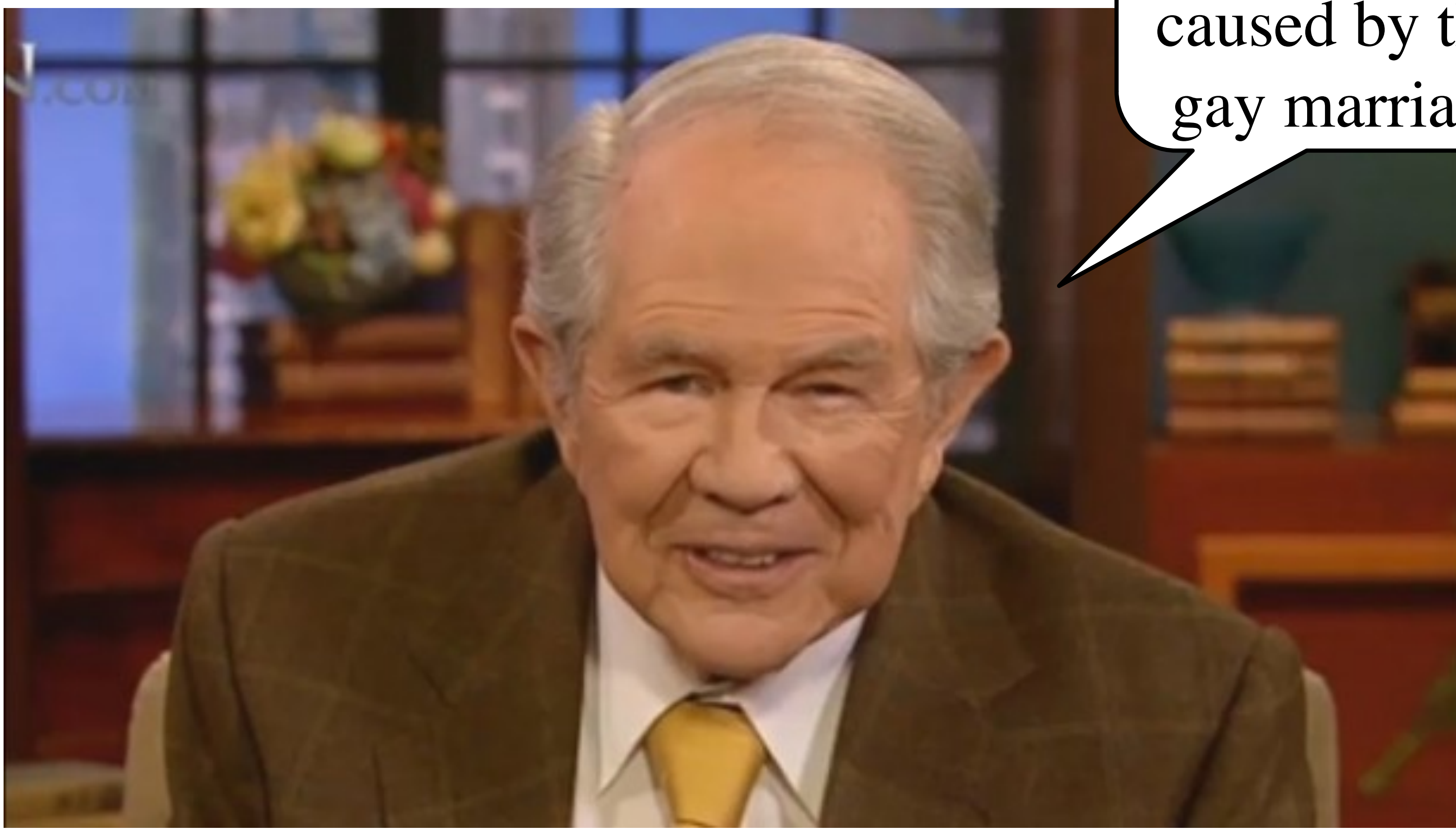
- Average temperature increases
  - ➢ Antarctic and Greenland ice melts and increases the global ocean level; many coastal areas get submerged

- Climate zones expand from the Equator towards the poles
  - ➢ Disruption of agriculture, water supply



- Amplitude and frequency of extreme weather events increase
  - ➢ Major damage, loss of life

There is an Alternative Theory…

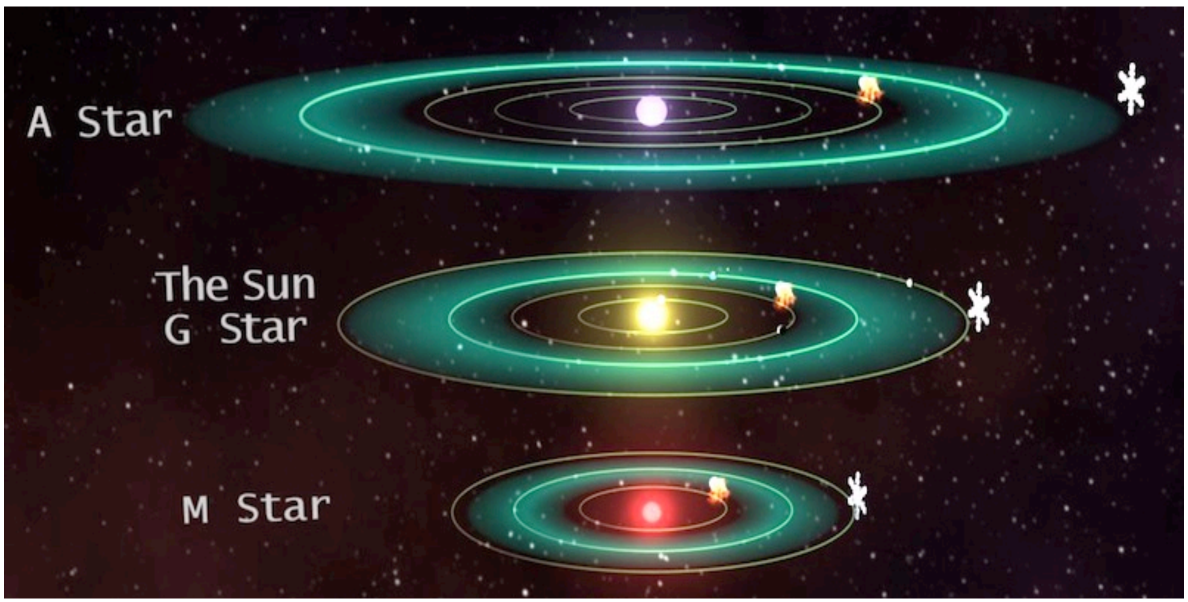


Habitable Zones and Goldilock Planets

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

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

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

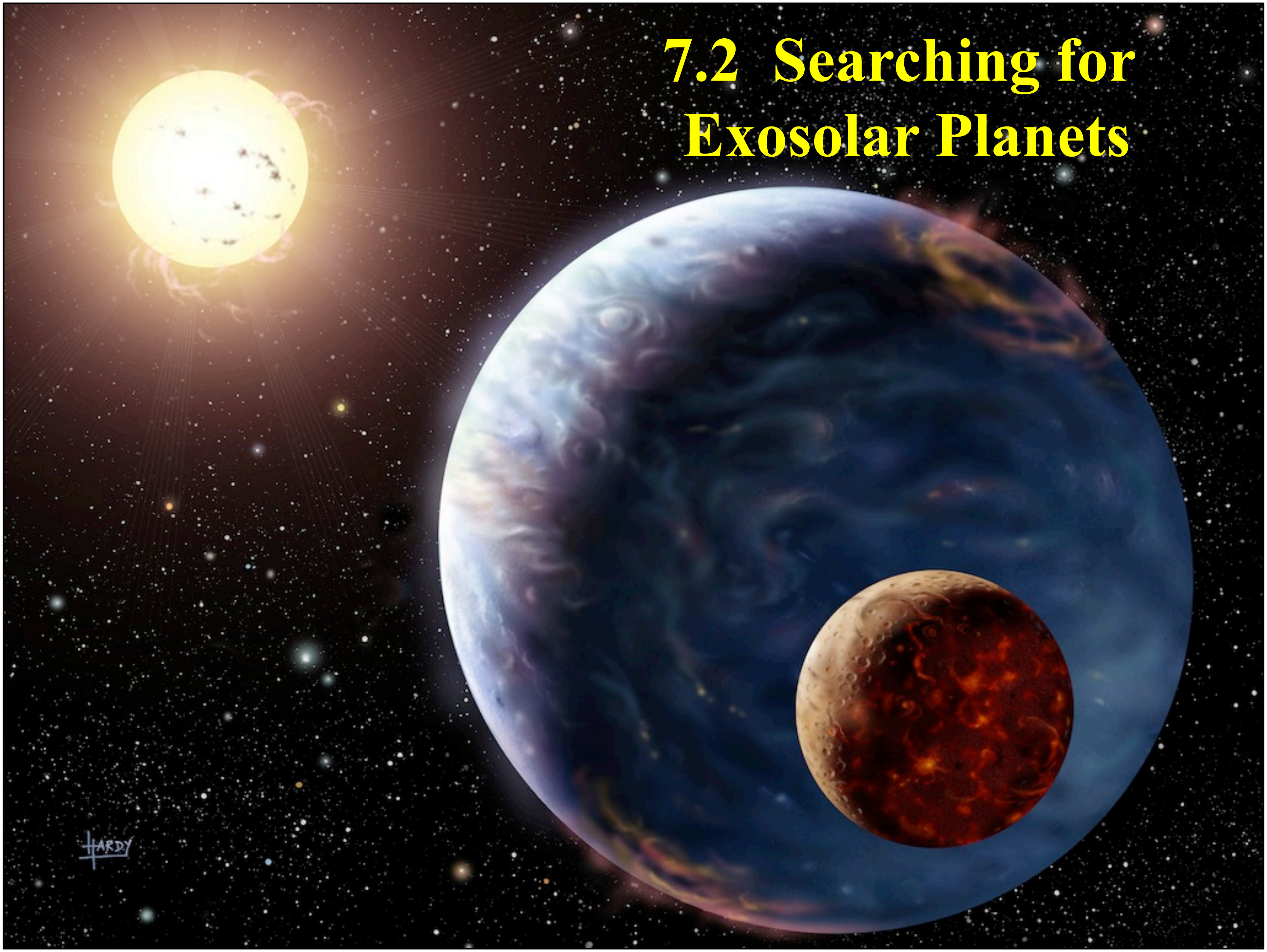


Frost line

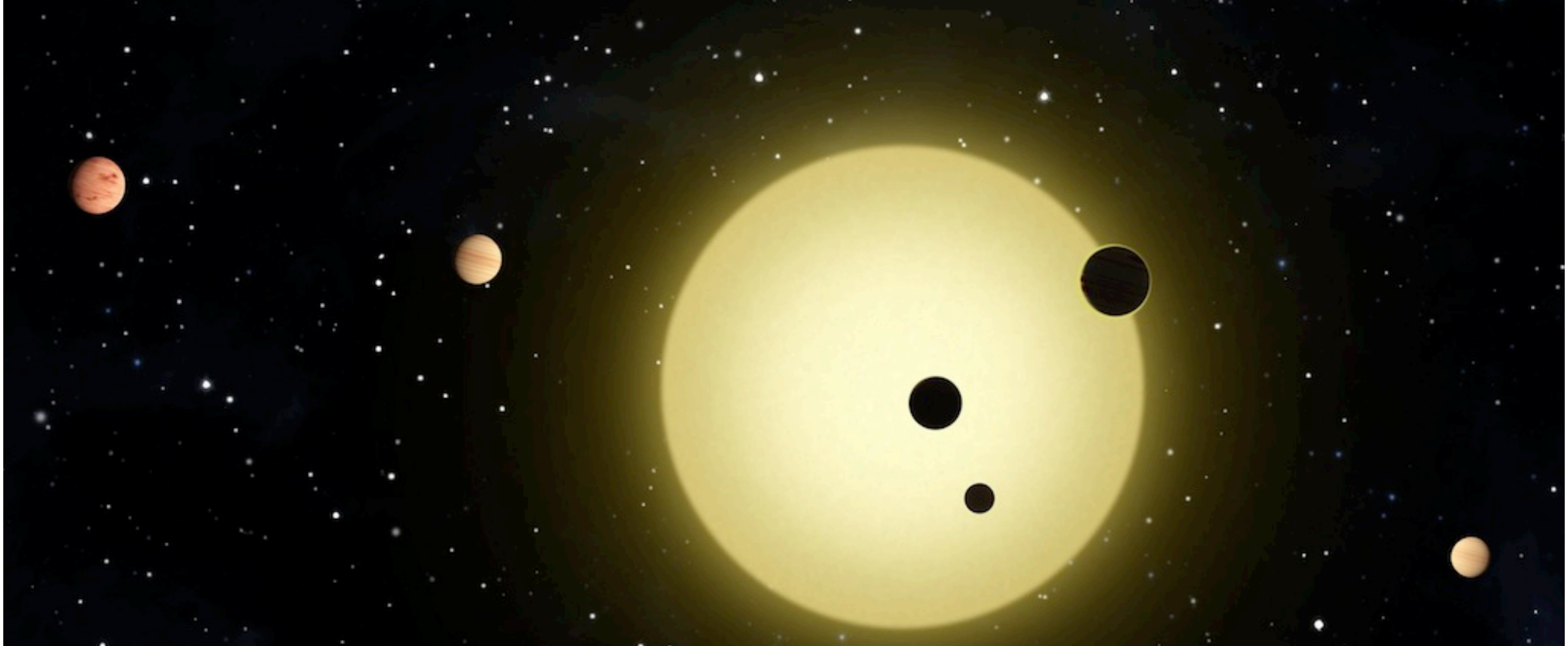
Steam line

Since the albedo dependence is relatively weak, this defines a range of planetary orbit radii where liquid water (and thus life?) can exist on the surface

7.2 Searching for Exosolar Planets



As of April 2014, there are ~ 1800 confirmed exoplanets known, in ~ 1100 planetary systems, plus another ~ 3000 candidates

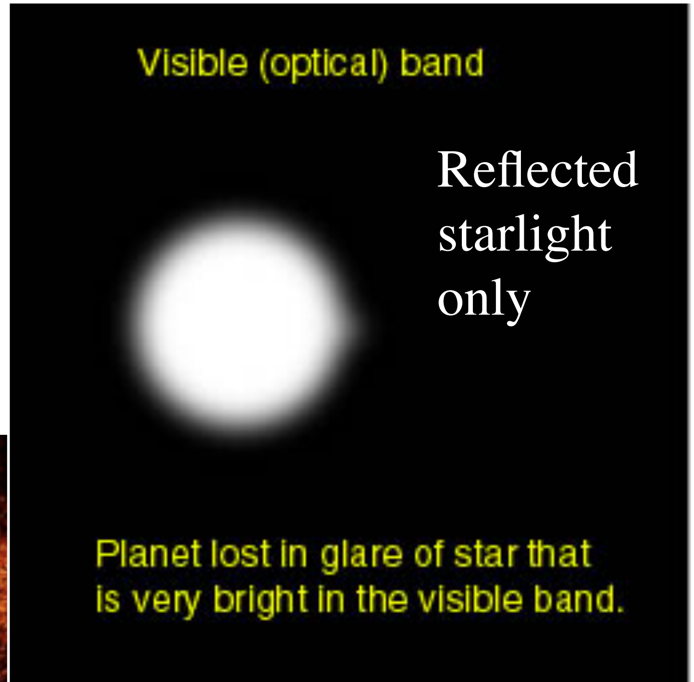


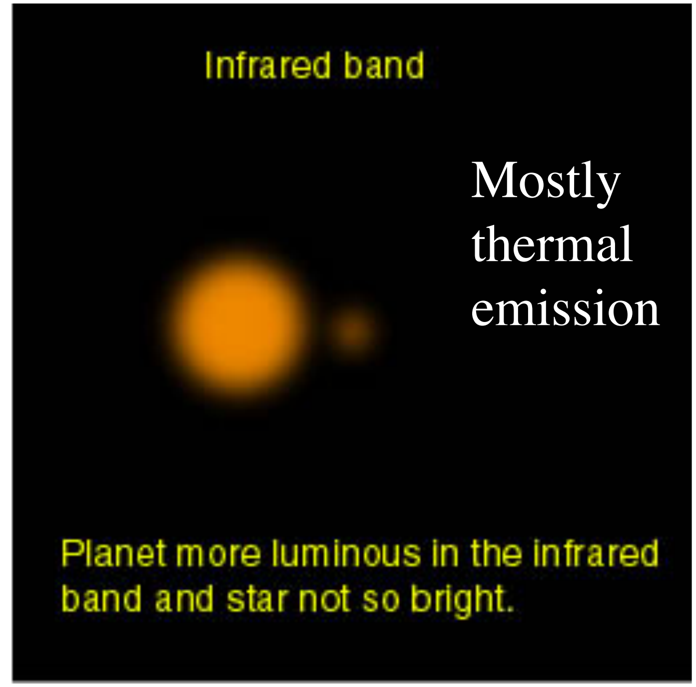
By studying other planetary systems we can learn more about our own. One goal is to look for Earth-like planets

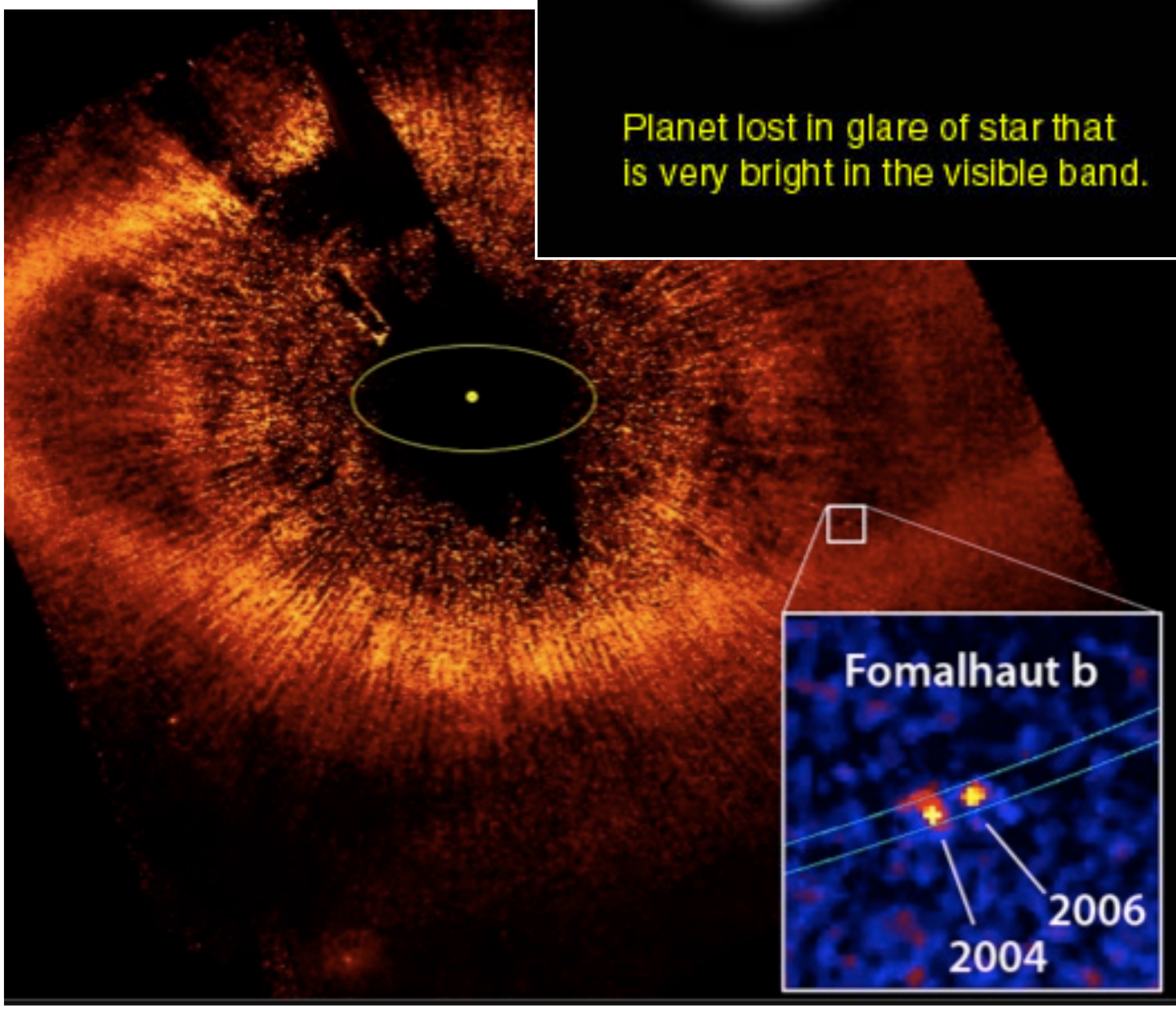
Search Methods for Exosolar Planets

- **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:** a planet changes the light curve of a microlensing event
  - Rare, requires monitoring of vast numbers of stars

Direct Imaging

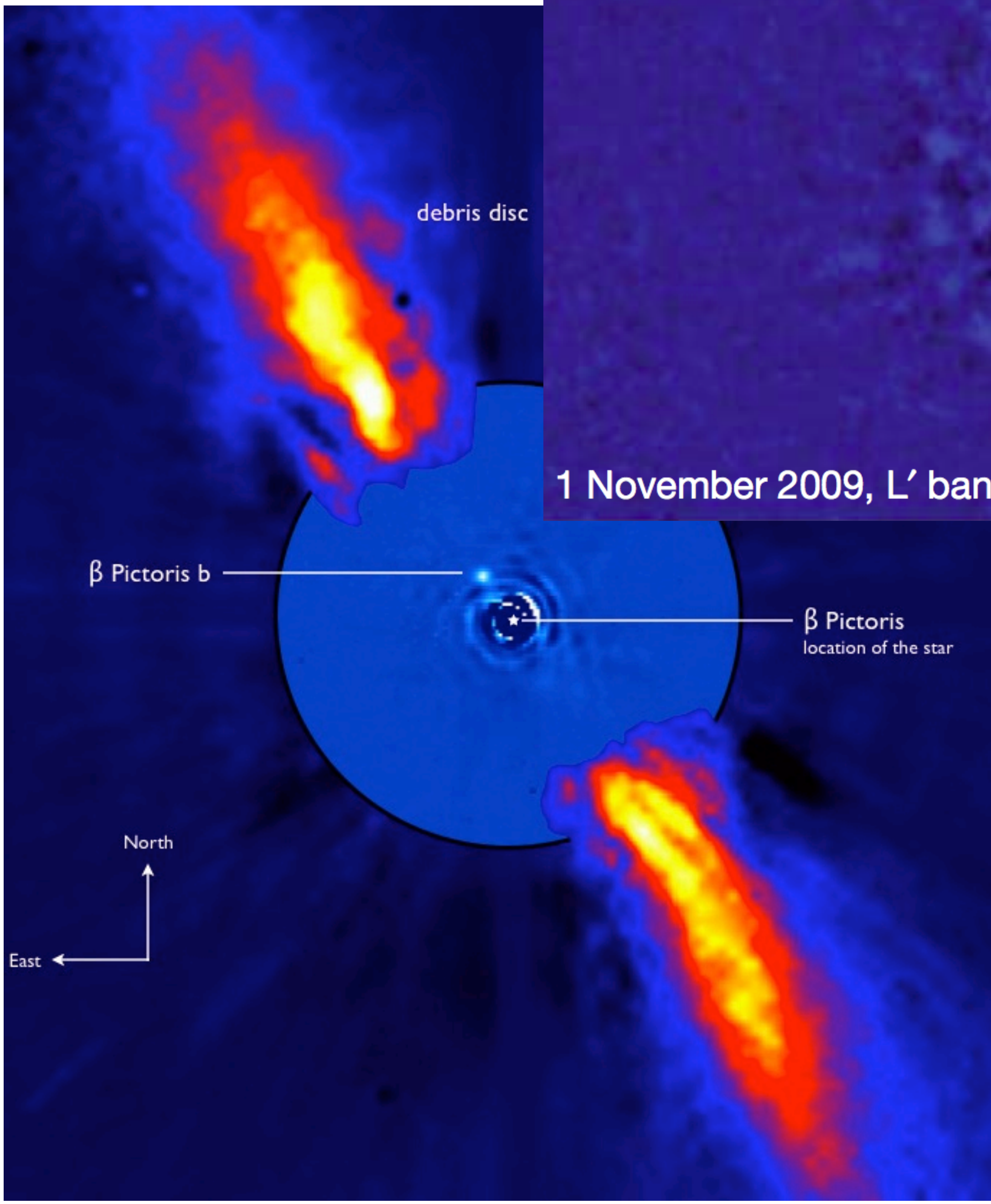


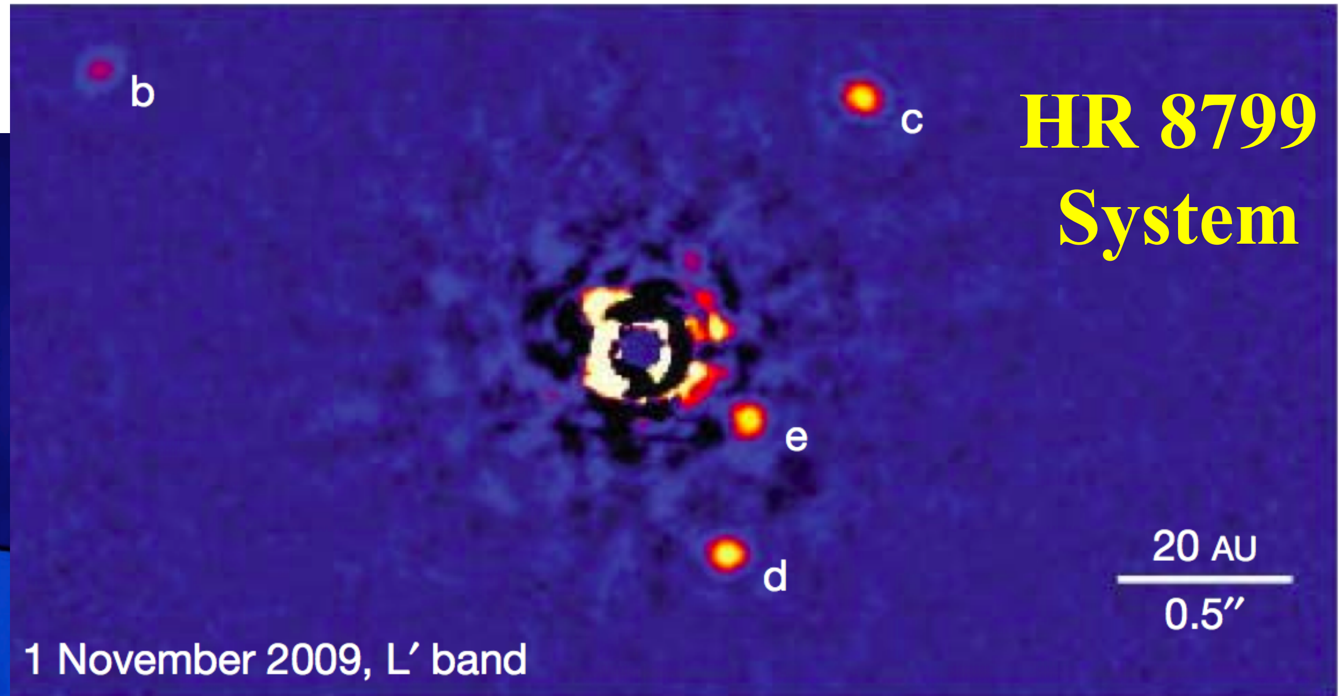




< Coronographic image of Fomalhaut

< Comparing images 2 years apart shows the planet moving





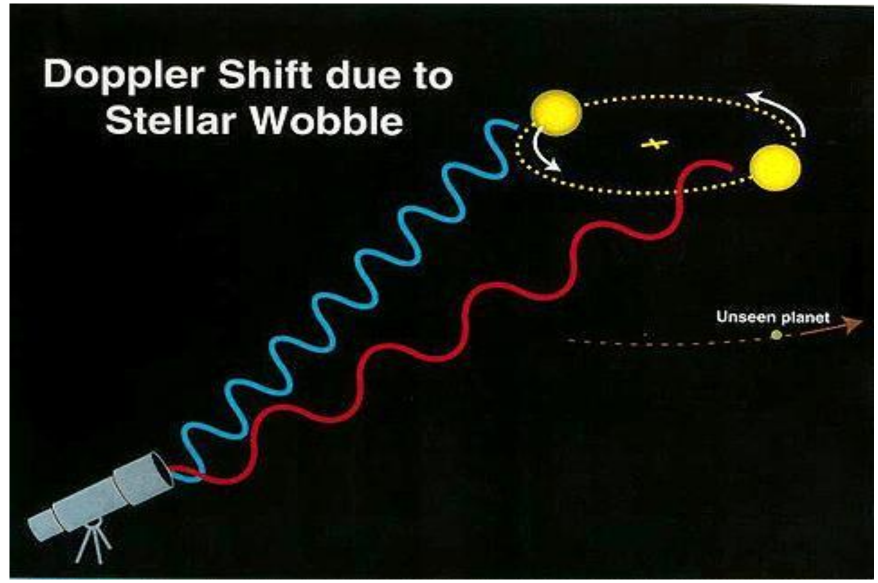
Direct Imaging

Using coronographic imaging and adaptive optics in near-IR

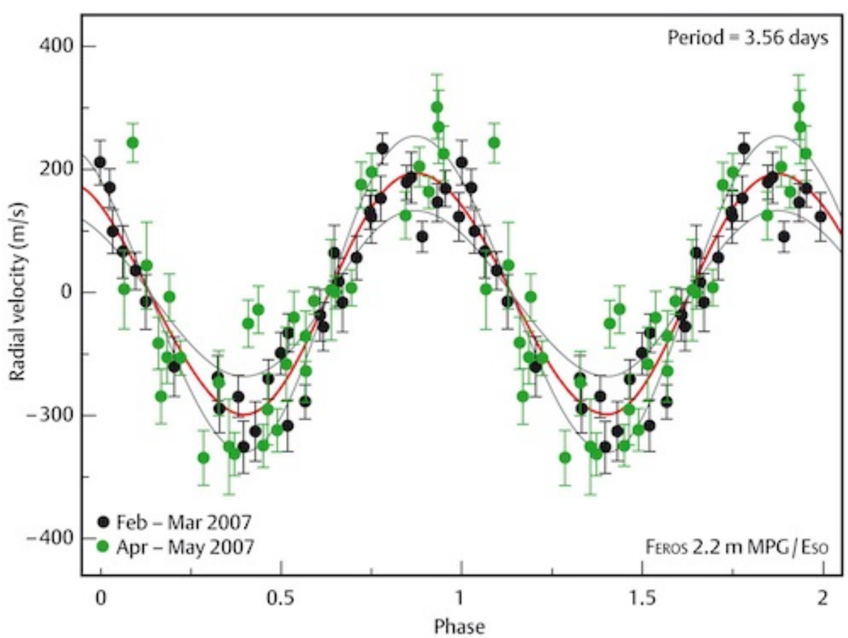
Radial Velocity Method

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 $V_{\odot} \approx 9$ cm/s

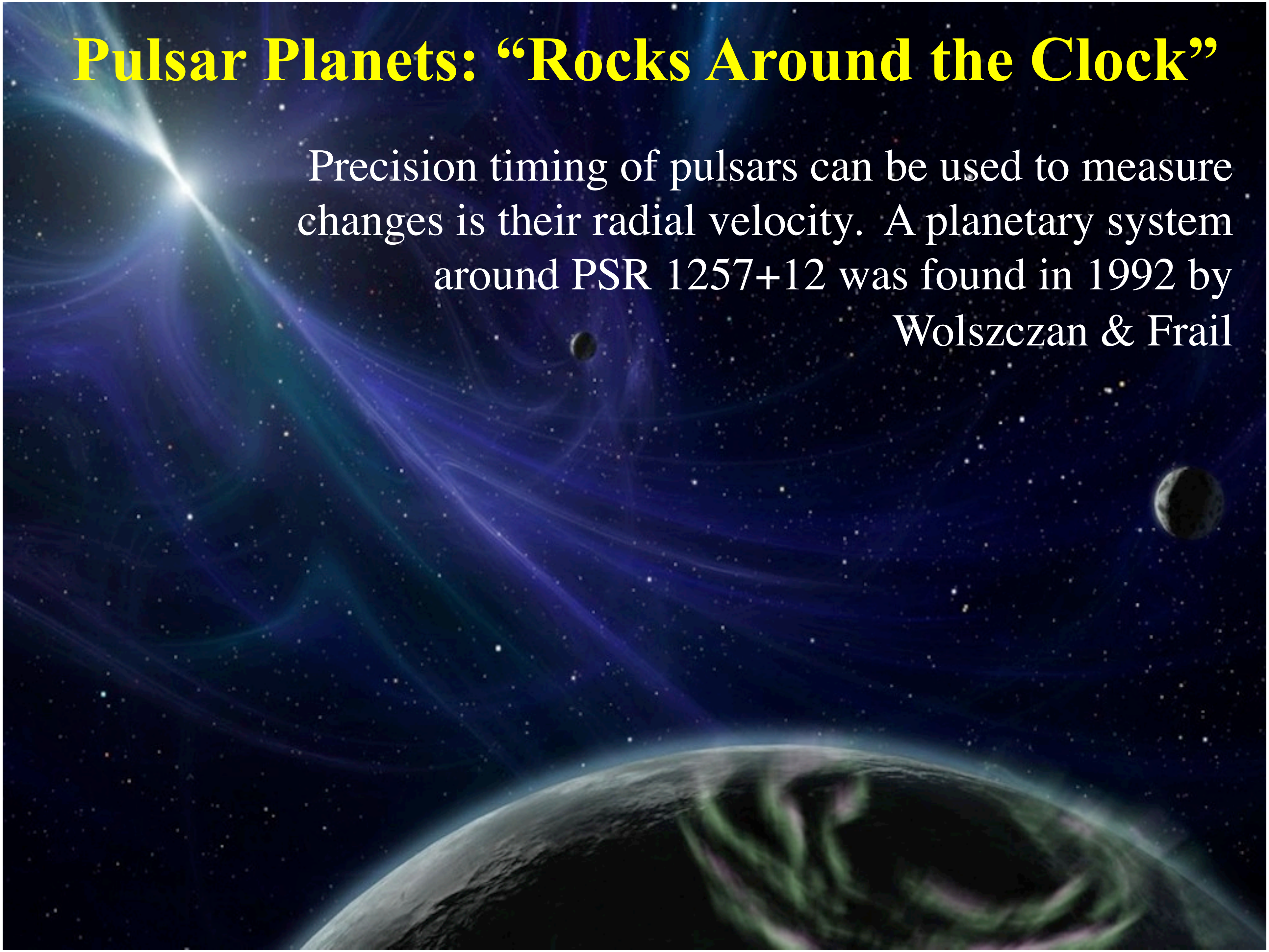
But consider a planet with

$M_{planet} = 10\, M_{jupiter}$ in a Mercury's orbit. Then $V_{star} \approx 460$ m/s

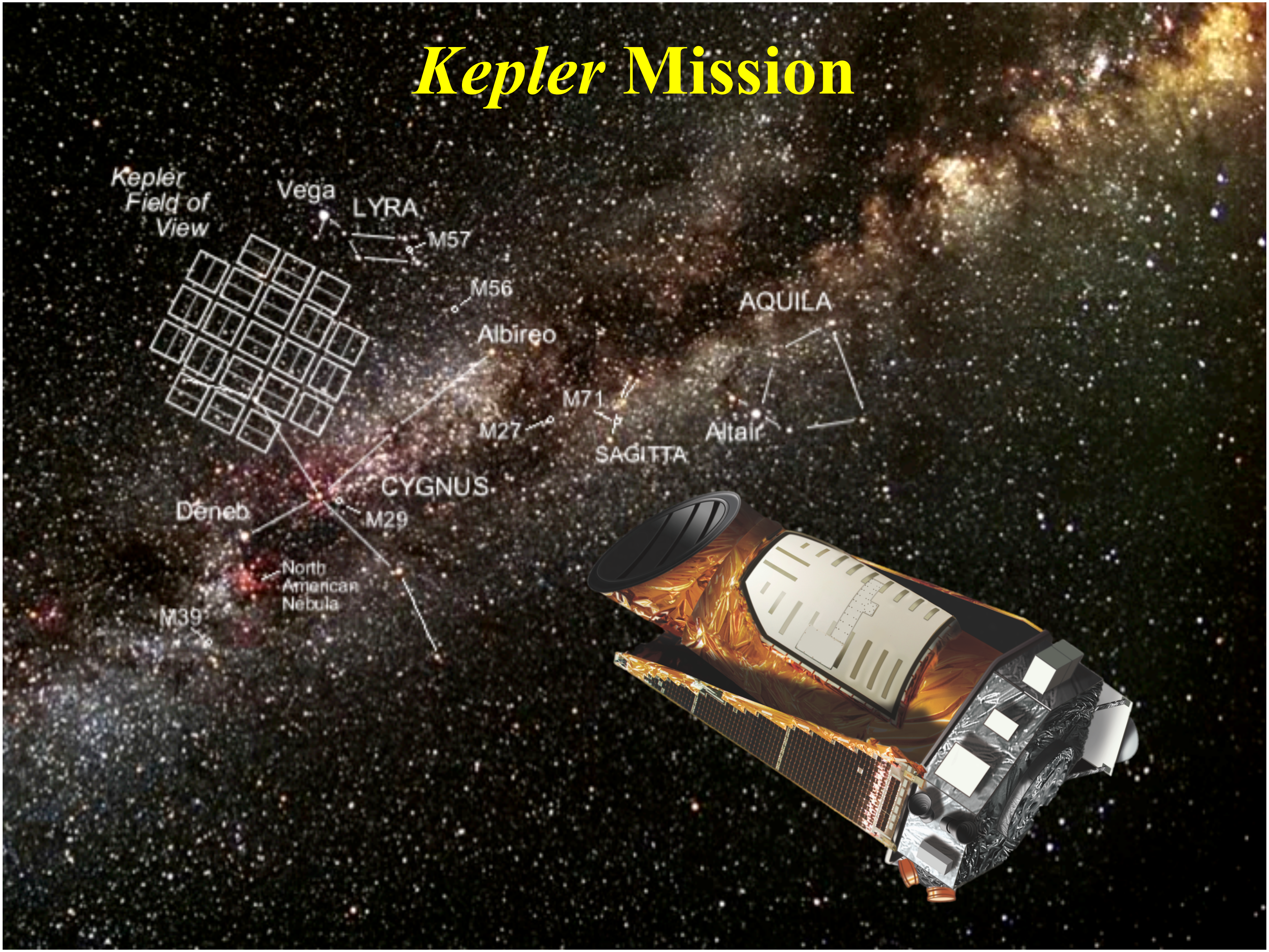
State of the art precision ~ 1 m/s

Pulsar Planets: "Rocks Around the Clock"

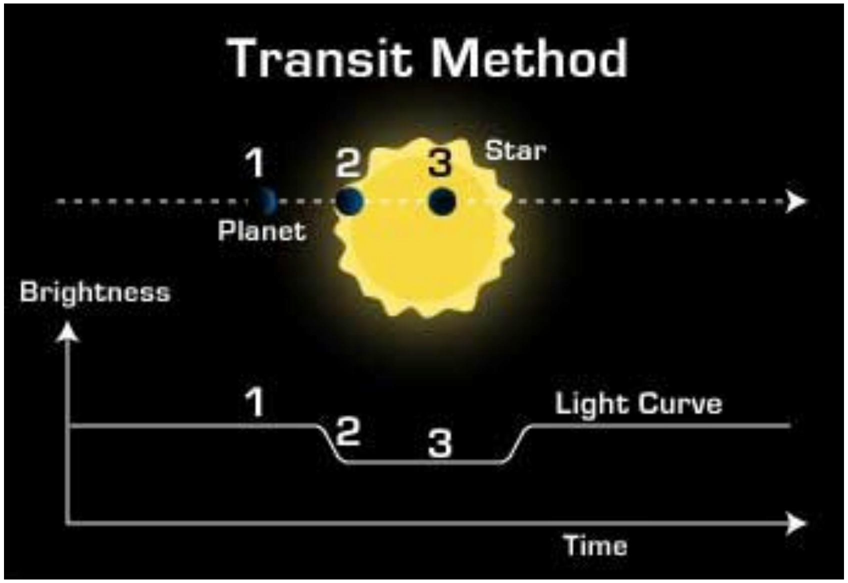
Precision timing of pulsars can be used to measure changes is their radial velocity. A planetary system around PSR 1257+12 was found in 1992 by Wolszczan & Frail



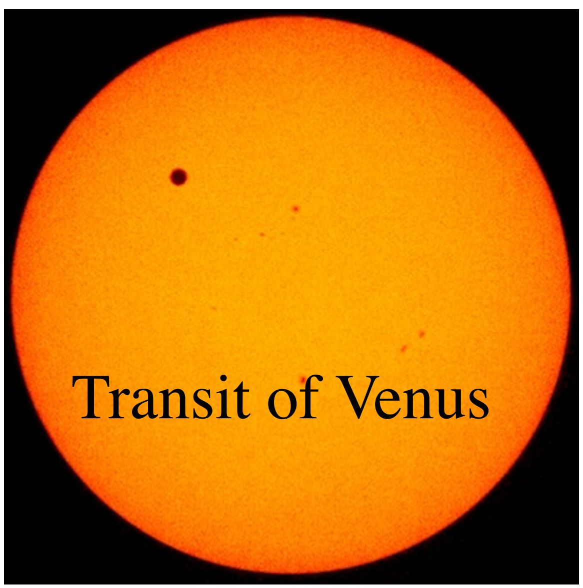
Kepler Mission



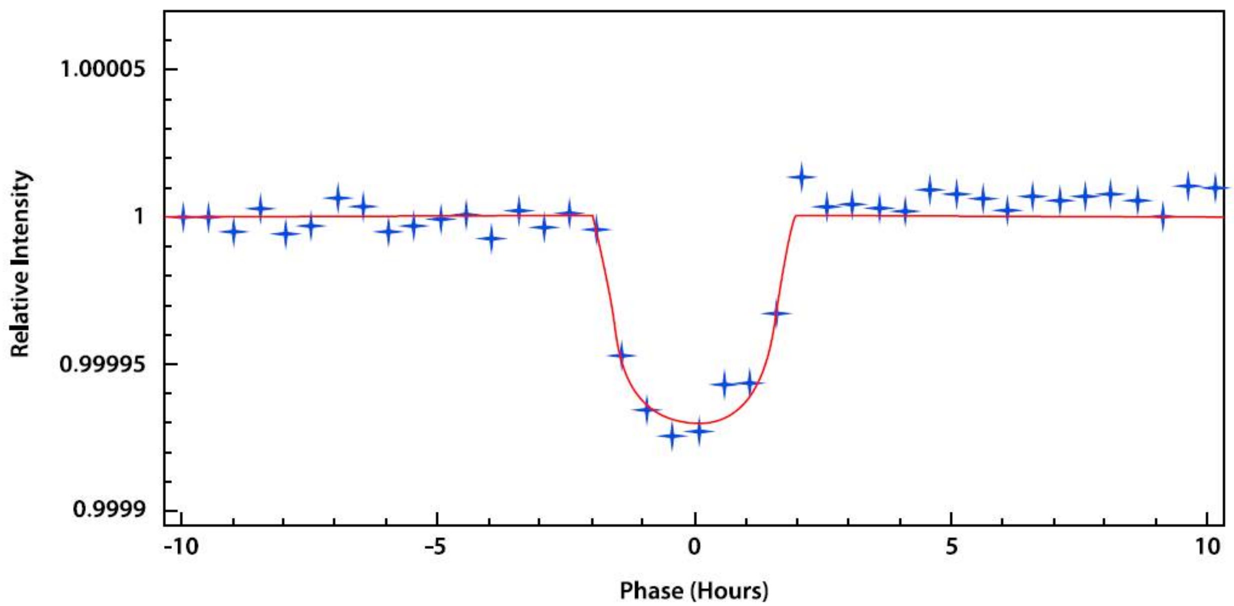
Planetary Transits (Eclipses)



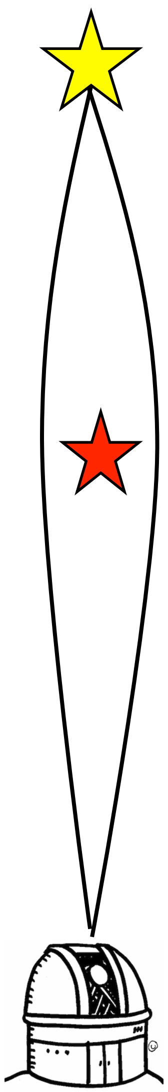
An Earth-sized planet crossing a Sun-like stellar disk would cause a 10^{-4} eclipse → need a very high precision photometry


Transit of Venus

Kepler light curve of HD 179070



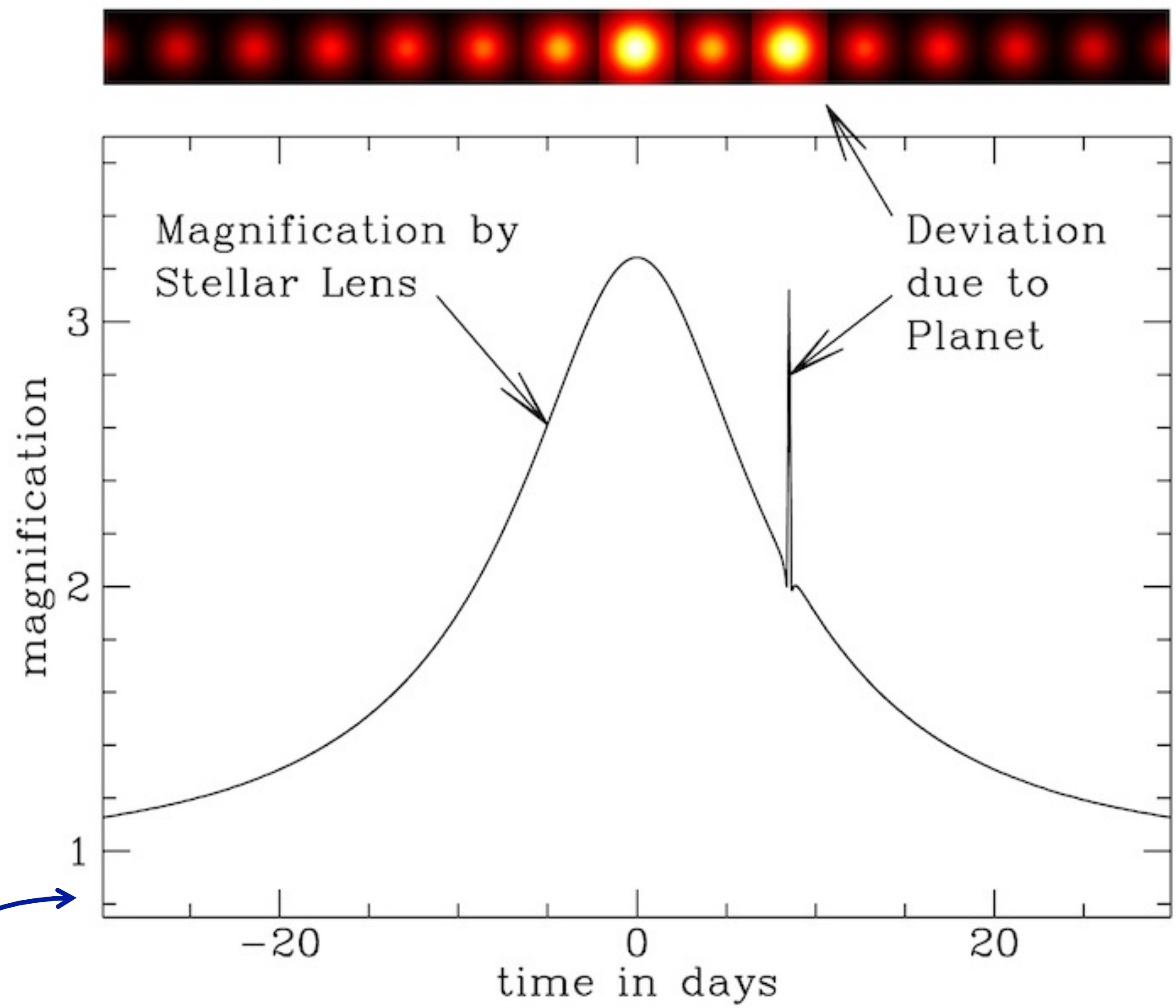
Gravitational Microlensing



Background star

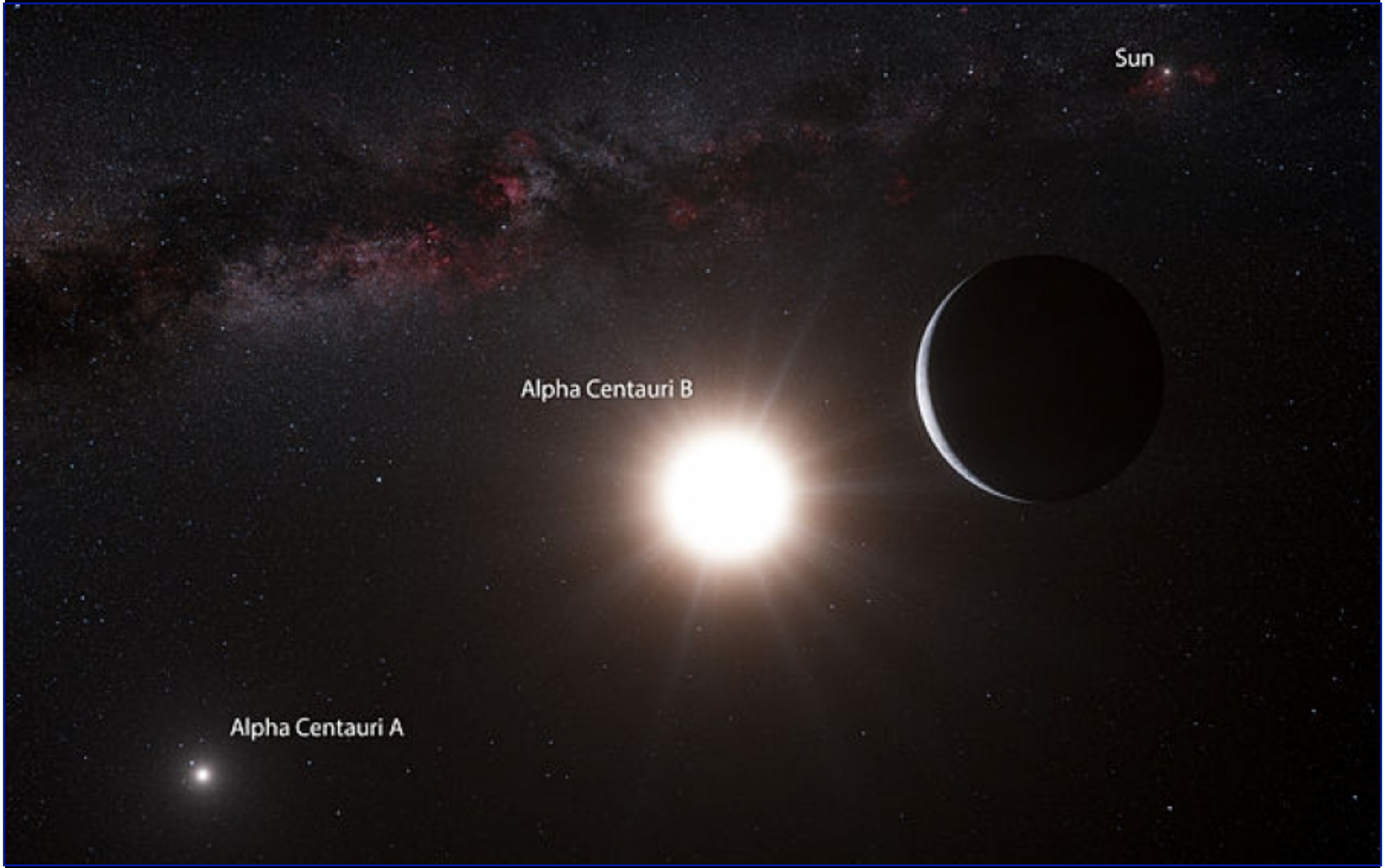
Foreground star bends light rays, magnifies the bgd star

Observer sees a light curve like this

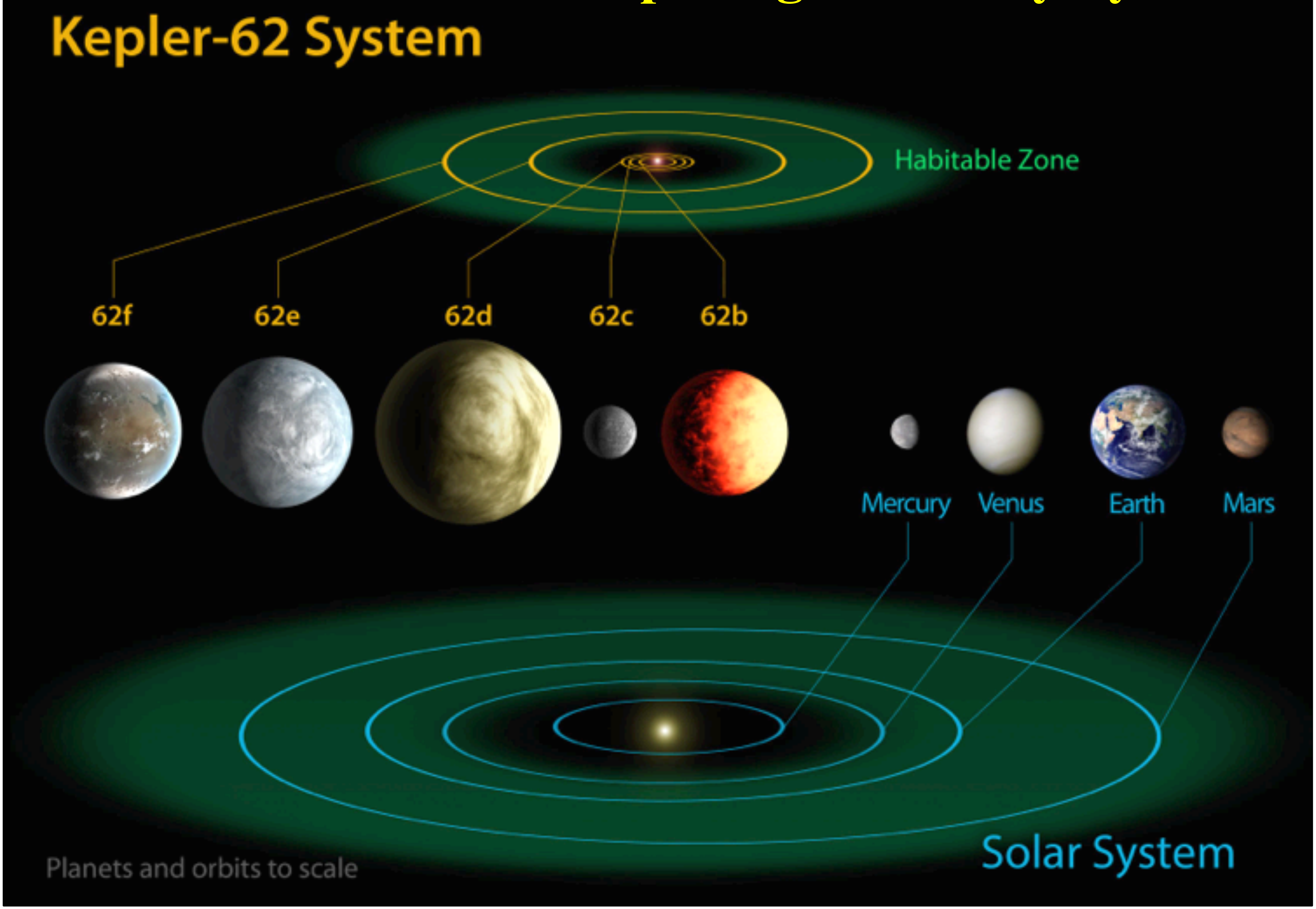


7.3 Studying Other Worlds

A Planet Orbiting One of Our Nearest Neighbors



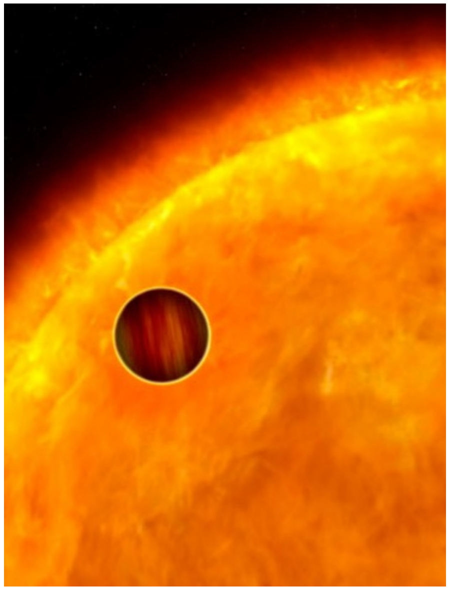
Comparing Planetary Systems



Characterizing Exoplanets

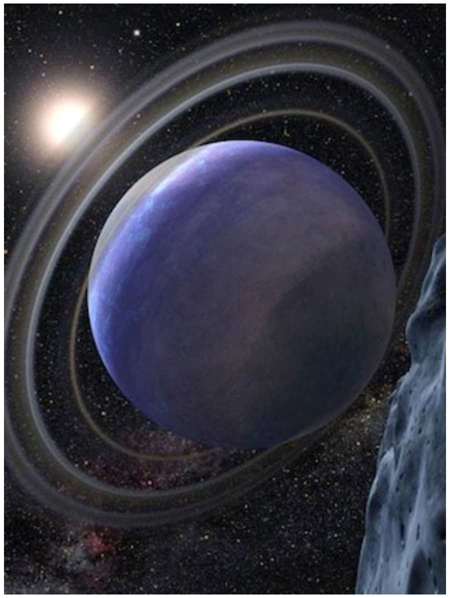
From radial velocities:

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



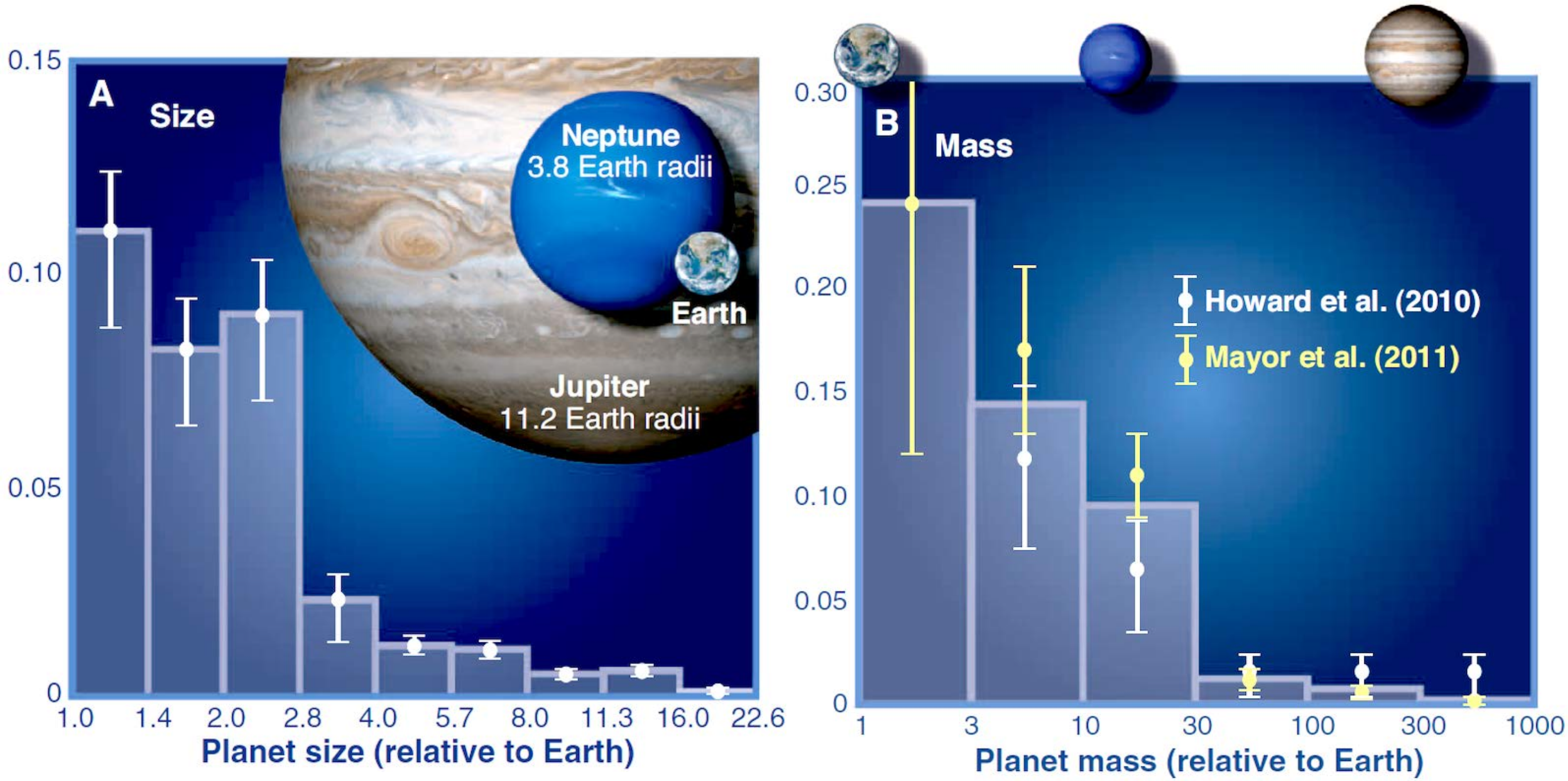
From transits:

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



Census of Exoplanet Properties

Larger and more massive planets are easier to find,
so there is a selection effect against the smaller ones



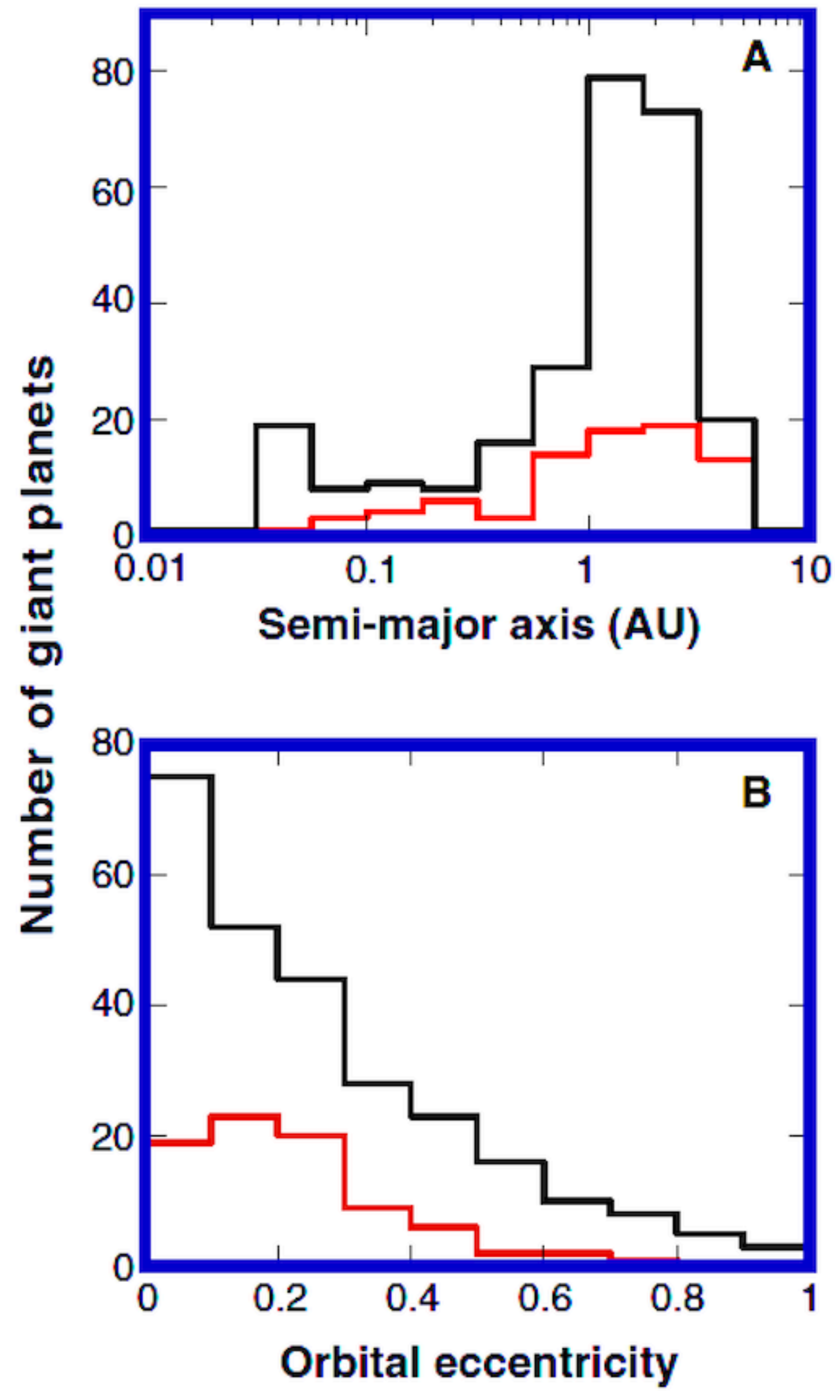
(Howard 2013)

Distribution of orbit semimajor axes

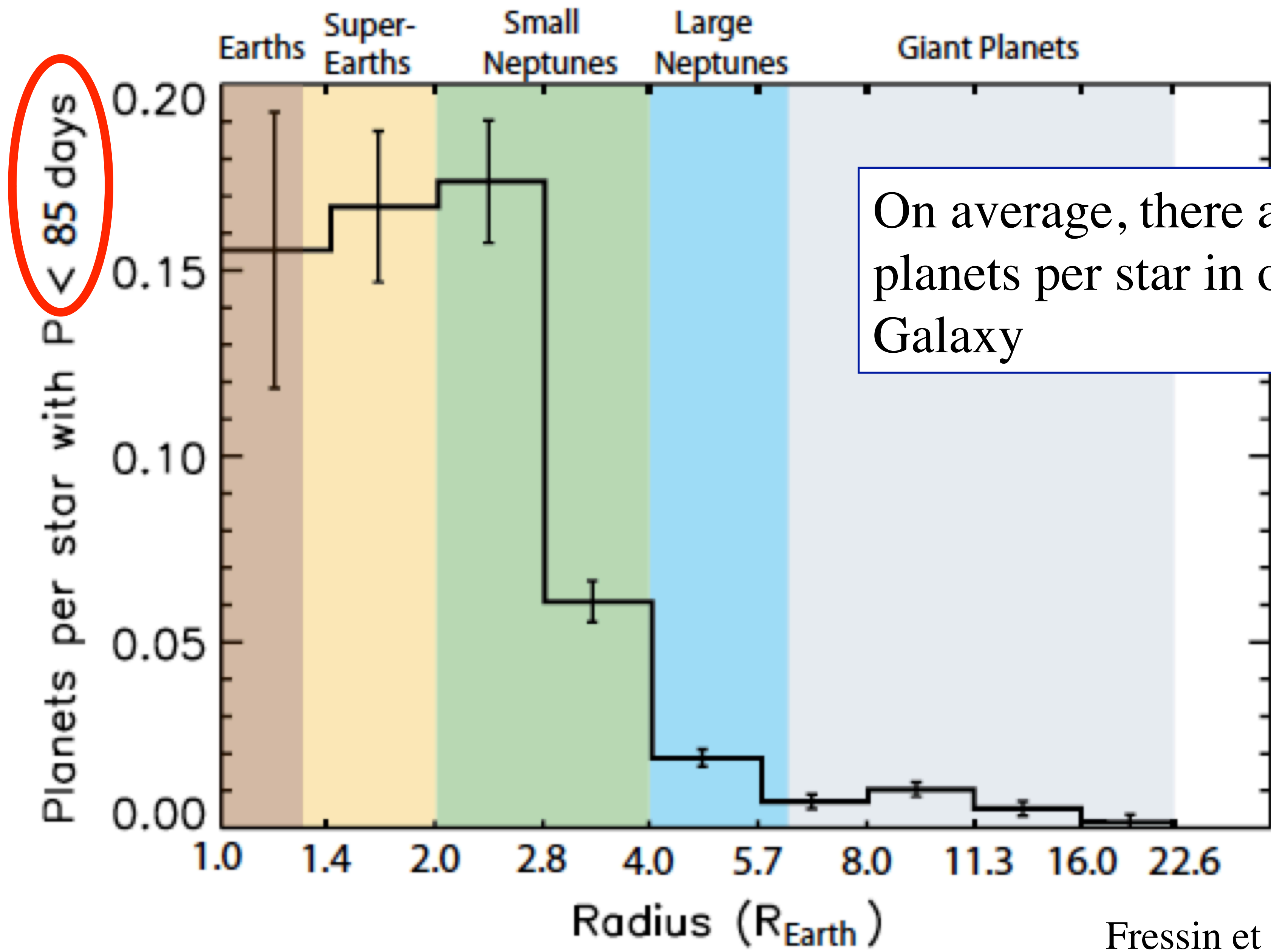
Planets closer in are easier to find, so there is a selection effect against the more distant tones

Distribution of orbit shapes

There are many more on highly elliptical orbits, compared to our Solar system



Kepler Survey: Planets are Common!

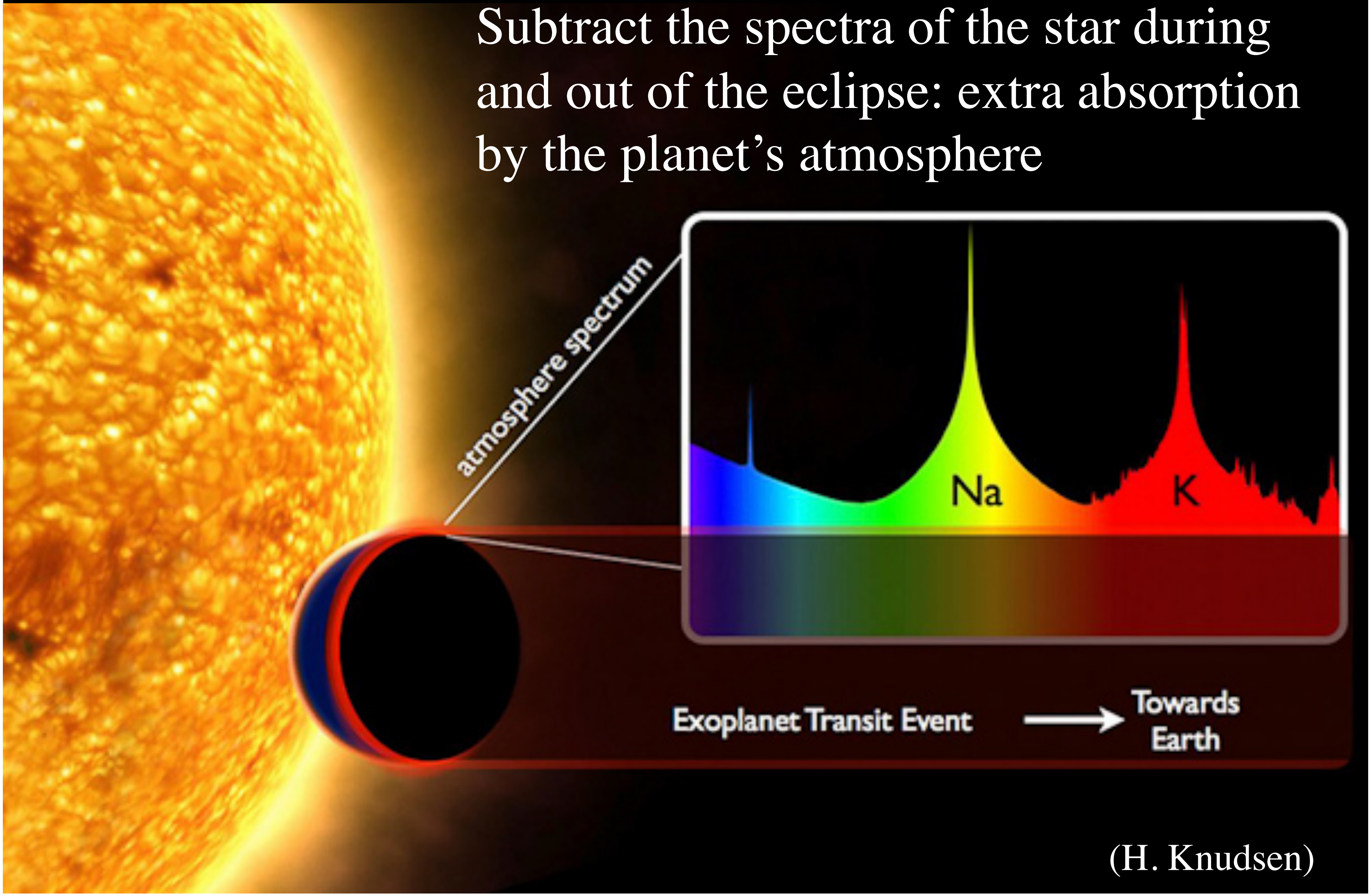


On average, there are ~ 2 planets per star in our Galaxy

Fressin et al. (2013)

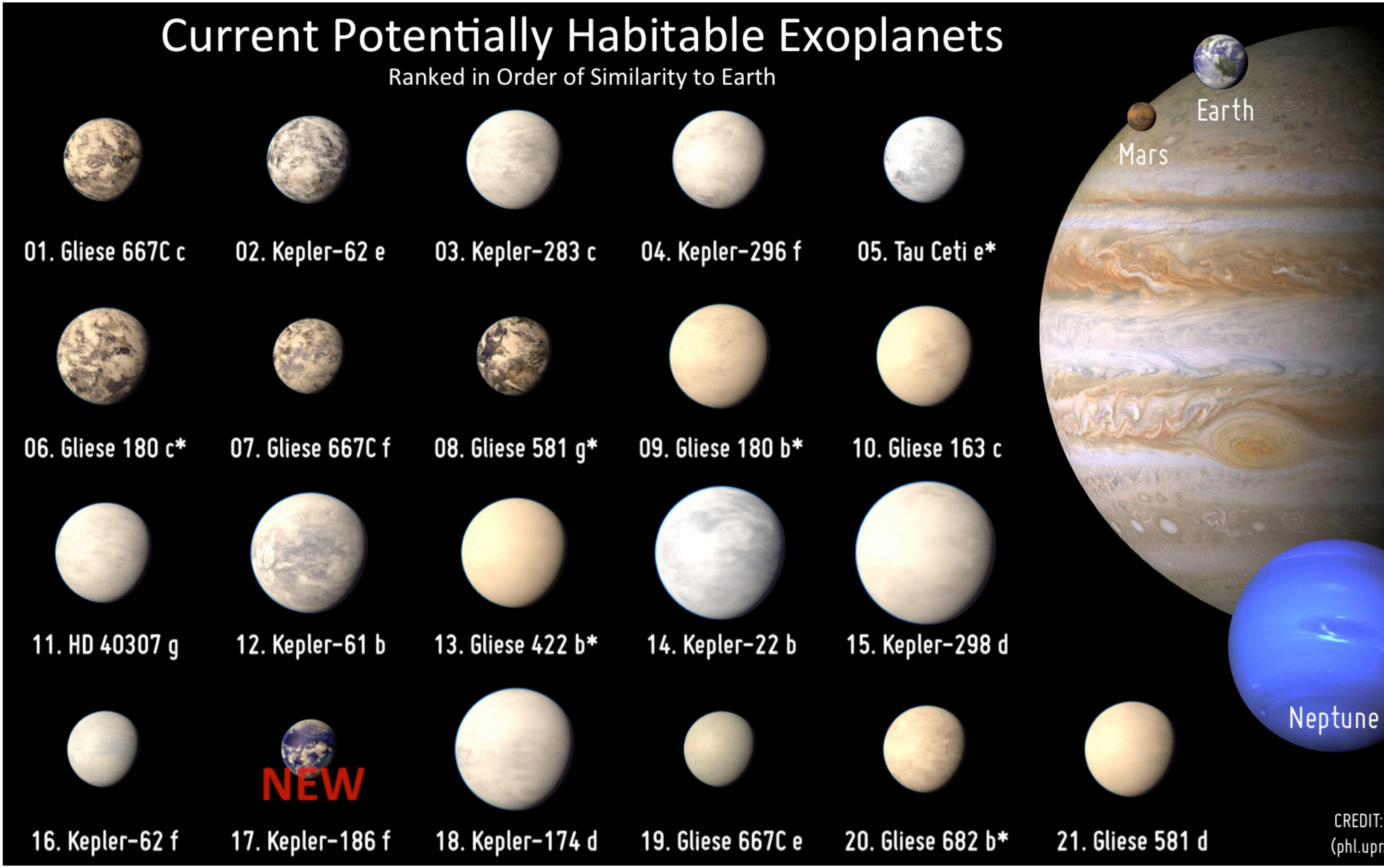
Observing the Exoplanet Atmospheres

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

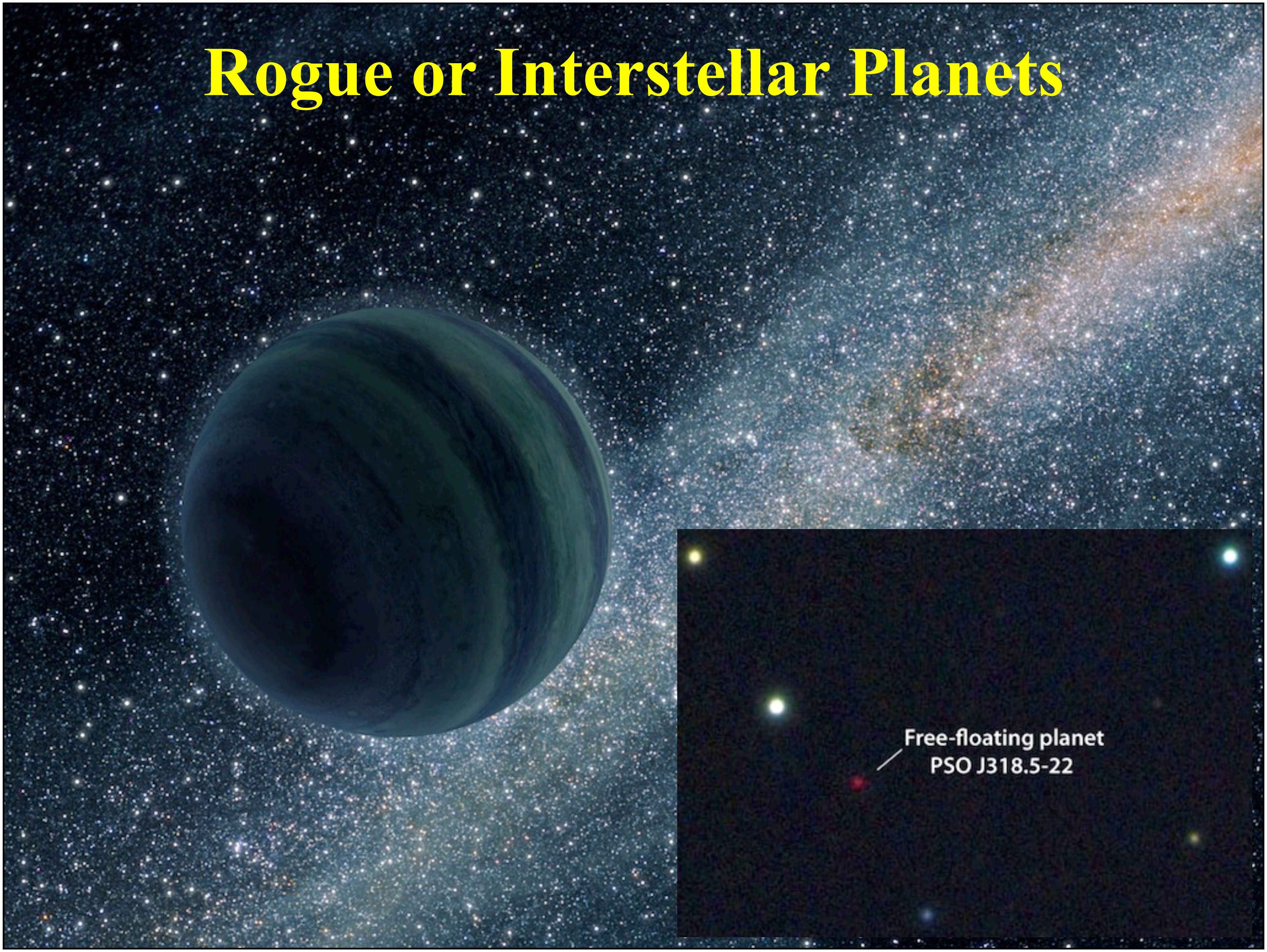


(H. Knudsen)

Planets in the Habitable Zones



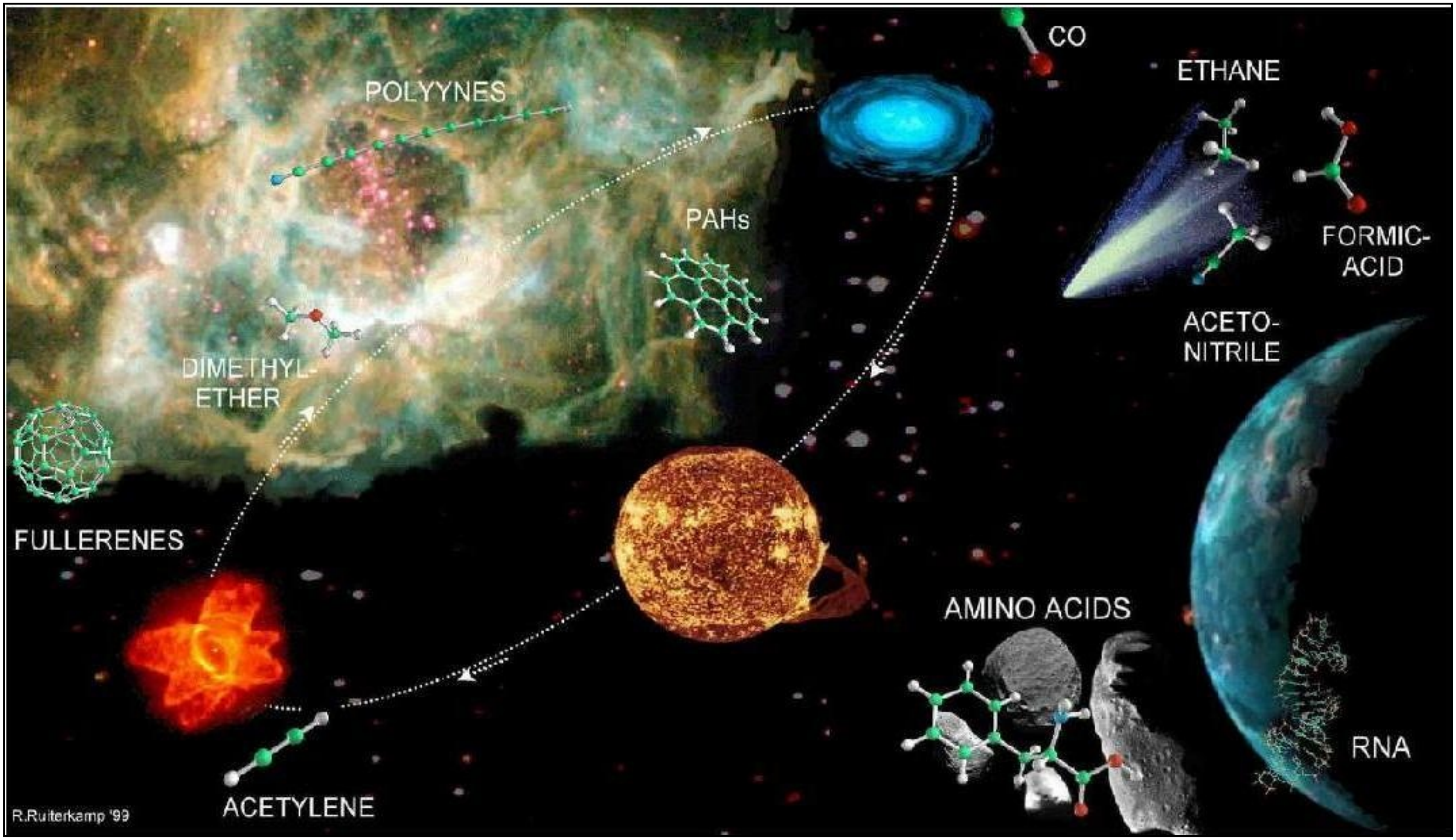
Rogue or Interstellar Planets

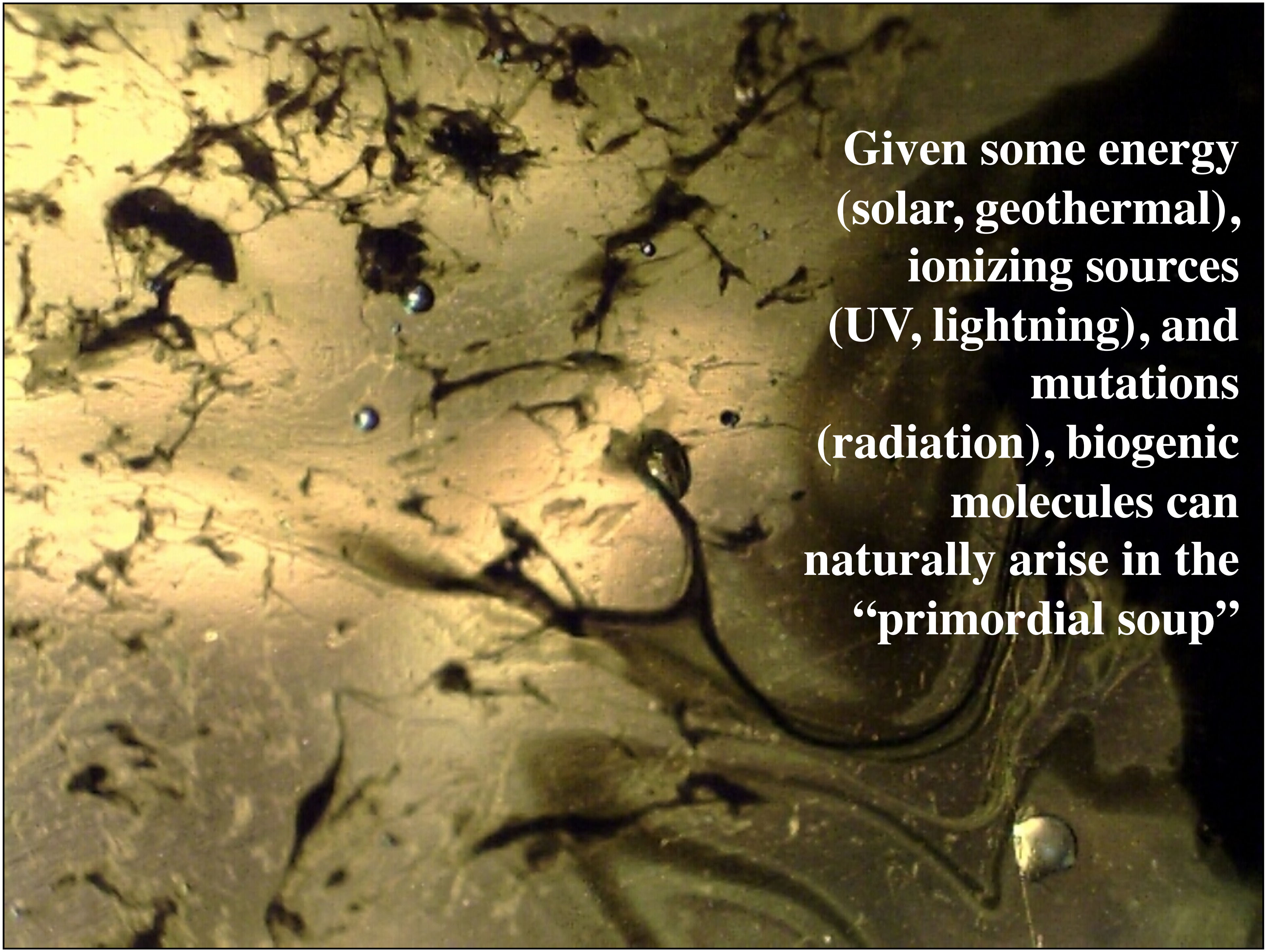


7.4 Life in the Universe

Life in the Universe: the Building Blocks

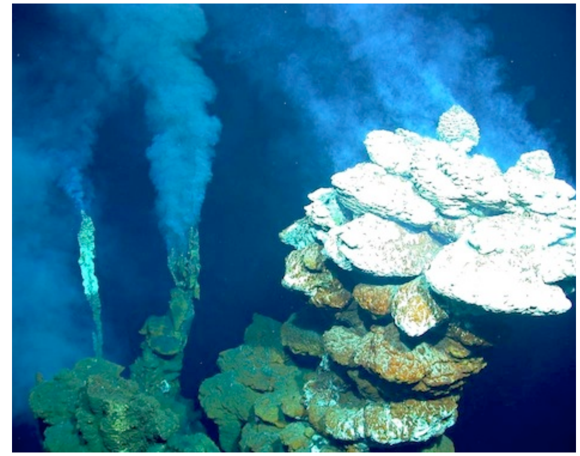
Water and organic compounds (sometimes very complex) are common in the ISM, the material from which planets form




Given some energy (solar, geothermal), ionizing sources (UV, lightning), and mutations (radiation), biogenic molecules can naturally arise in the "primordial soup"

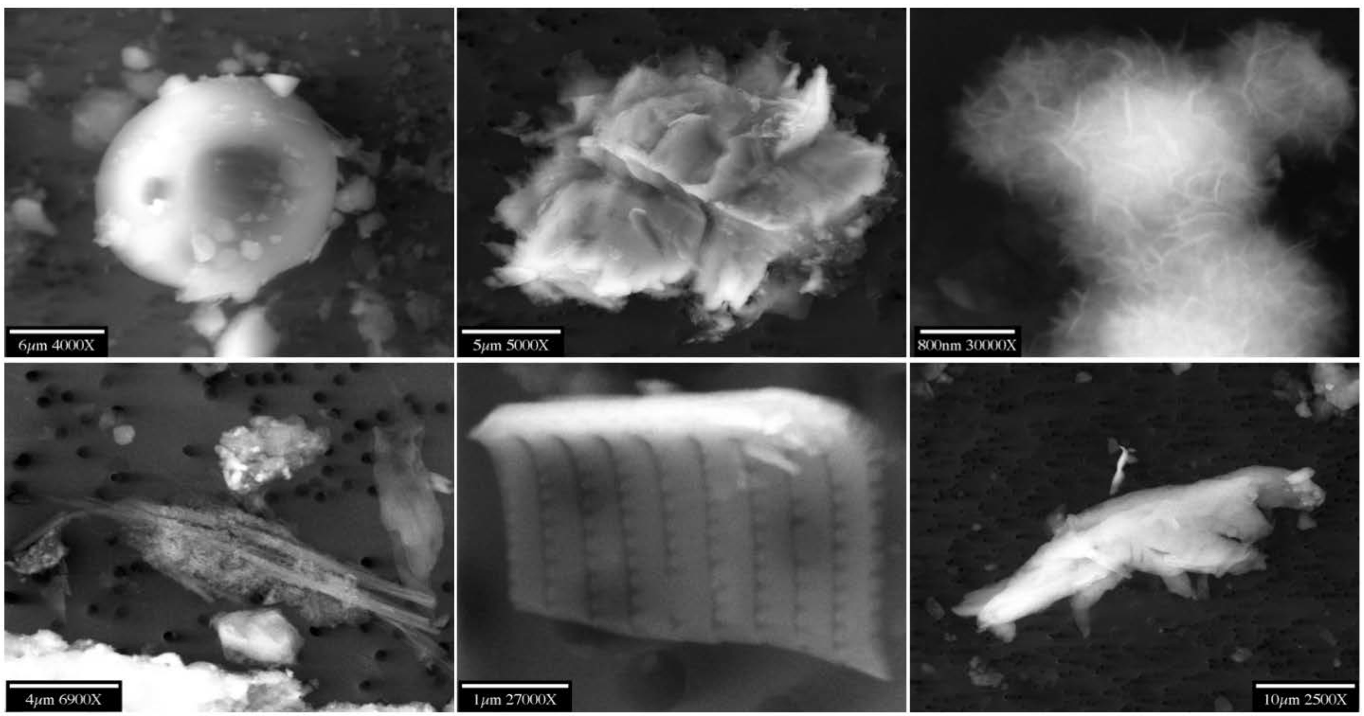
Astrobiology

- Life in extreme environments on the Earth
  - 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



Deep undersea vents

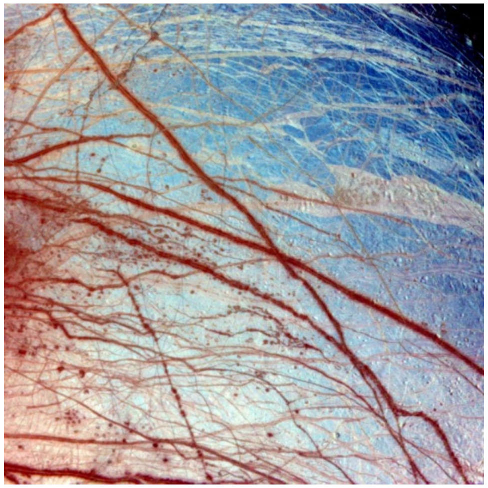
Grand Prismatic Spring, Yellowstone

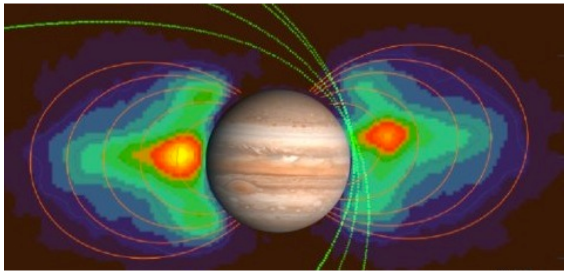
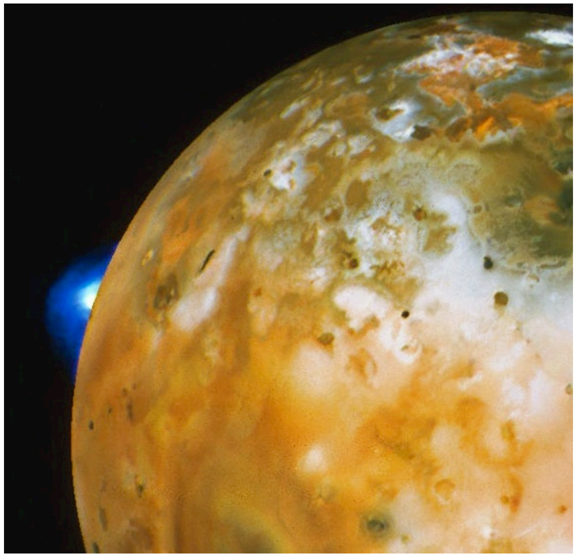


< Microorganisms found under the ice in lake Vostok, Antarctica

Life Elsewhere in the Solar System?

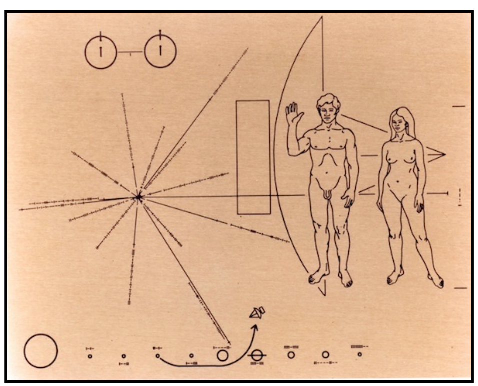
- Mars once had an ocean and the atmosphere
- Oceans on Europa, Enceladus, and maybe other moons of Jupiter and Saturn
- Volcanoes on Io, Jupiter’s radiation belts

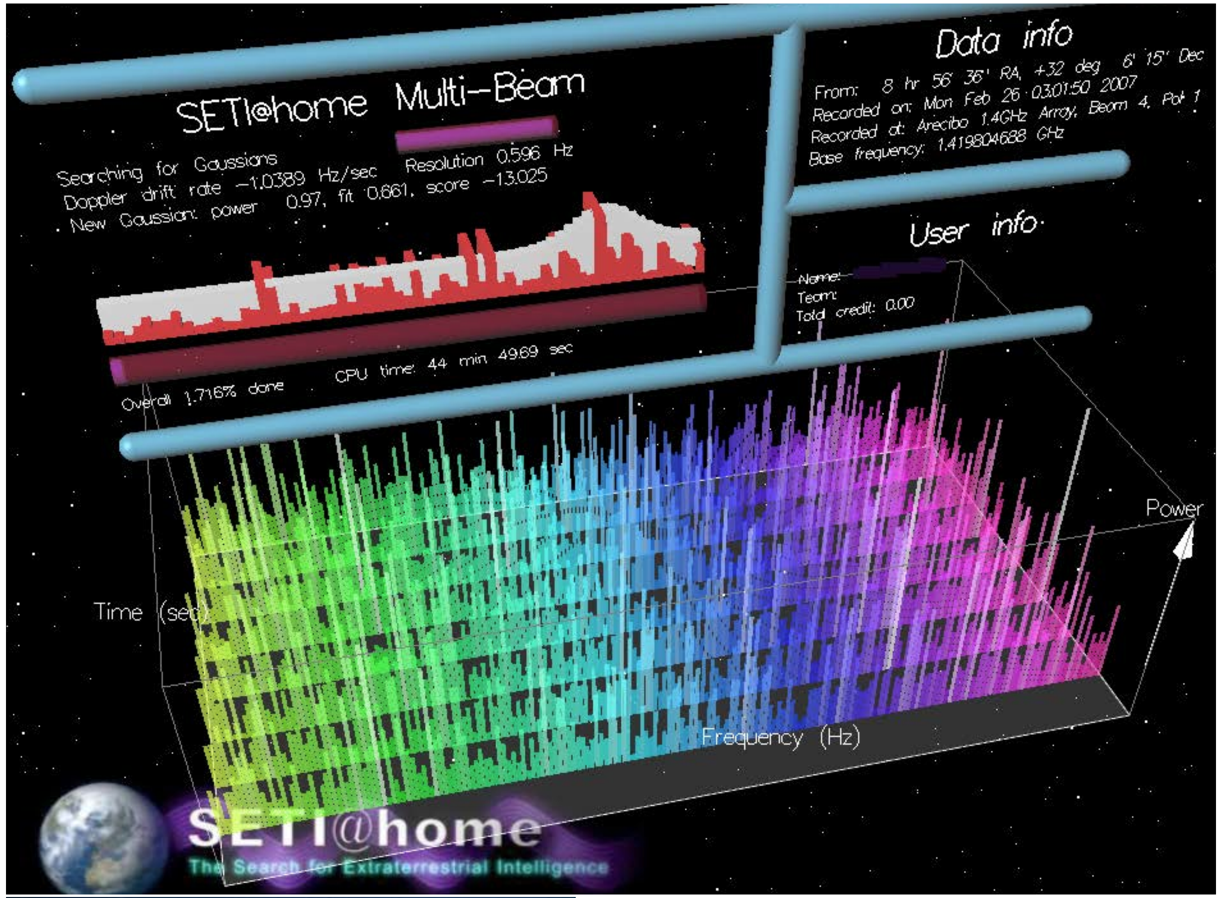



Search for ExtraTerrestrial Intelligence

- Assumes that advanced civilizations would communicate by radio…
- SETI@home: a piggyback search using observations from Arecibo, VLA, ATA, etc.
- Or we can send them a postcard:





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

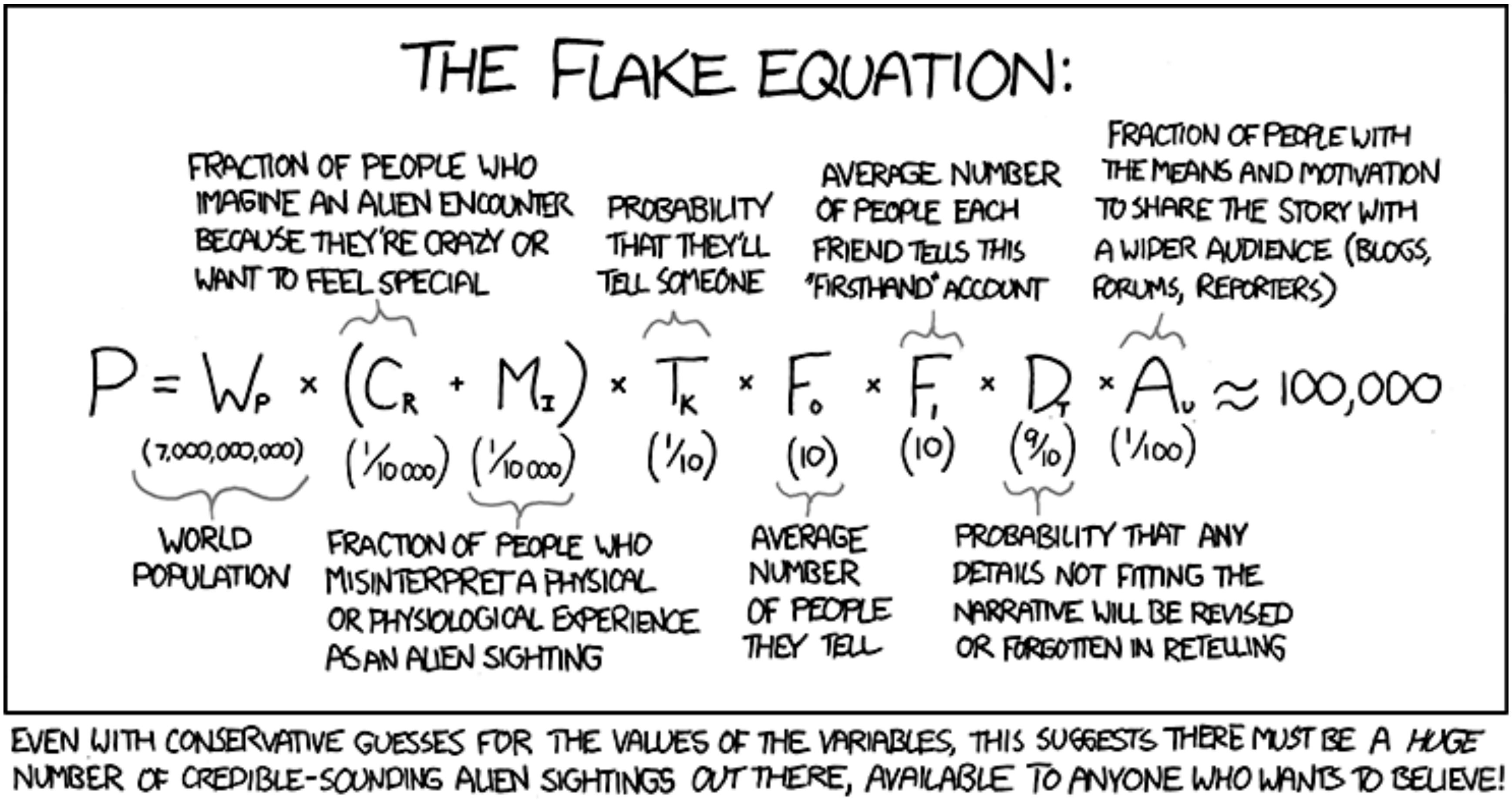
f_l = The fraction of suitable planets on which life actually appears

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 Flake Equation (from XKCD)



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 ~ 12 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?
- **What do you think?**