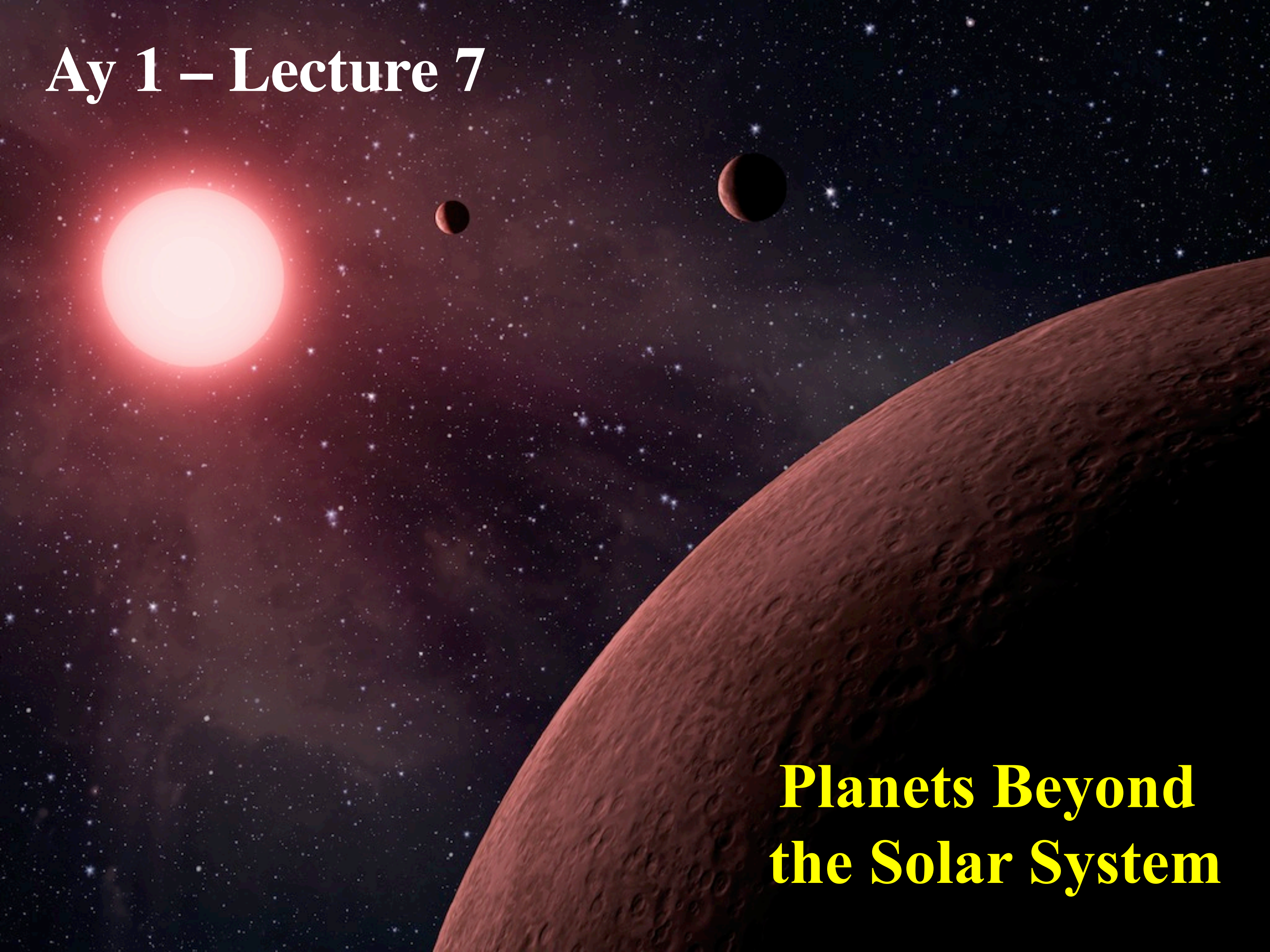
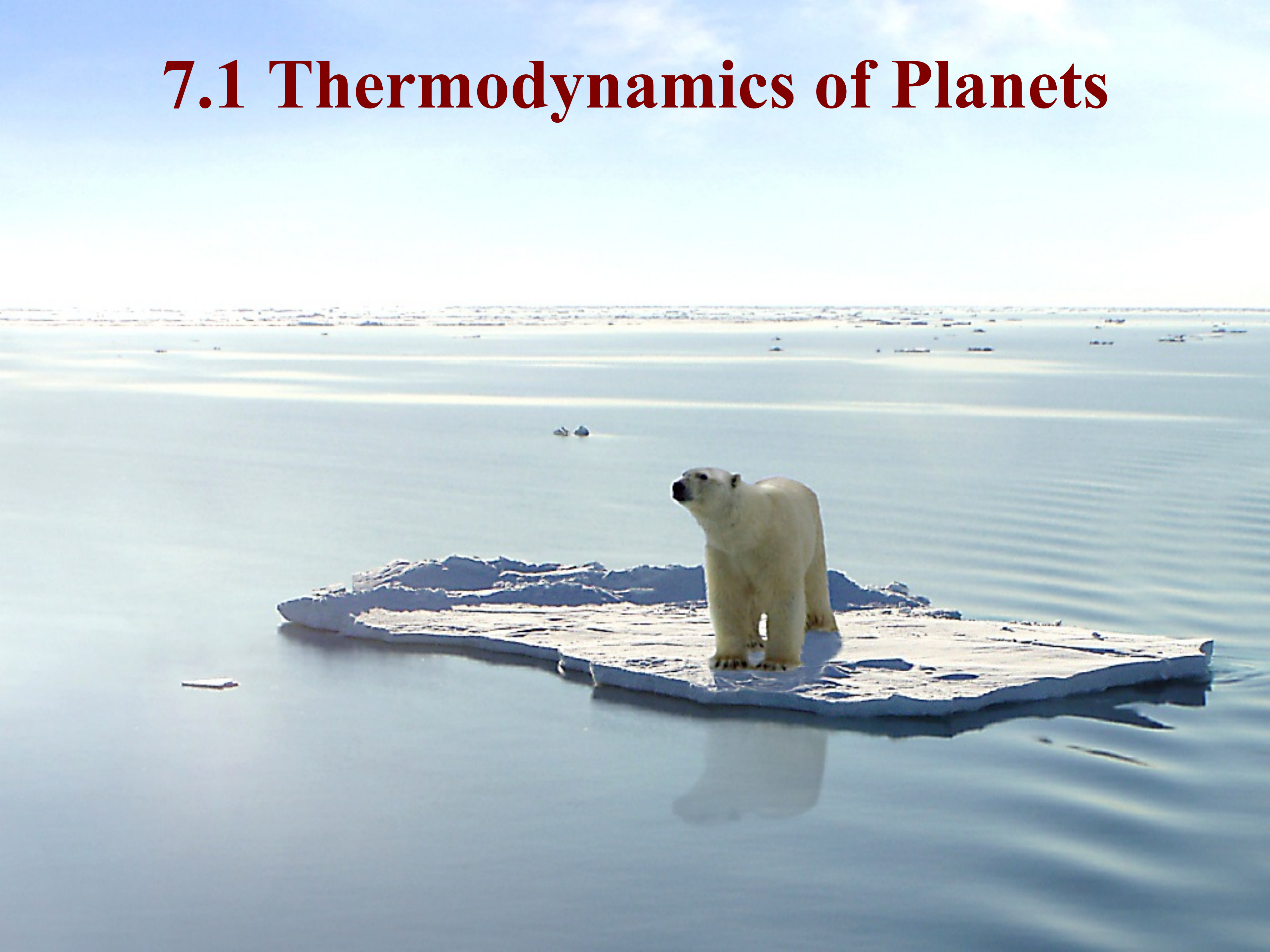


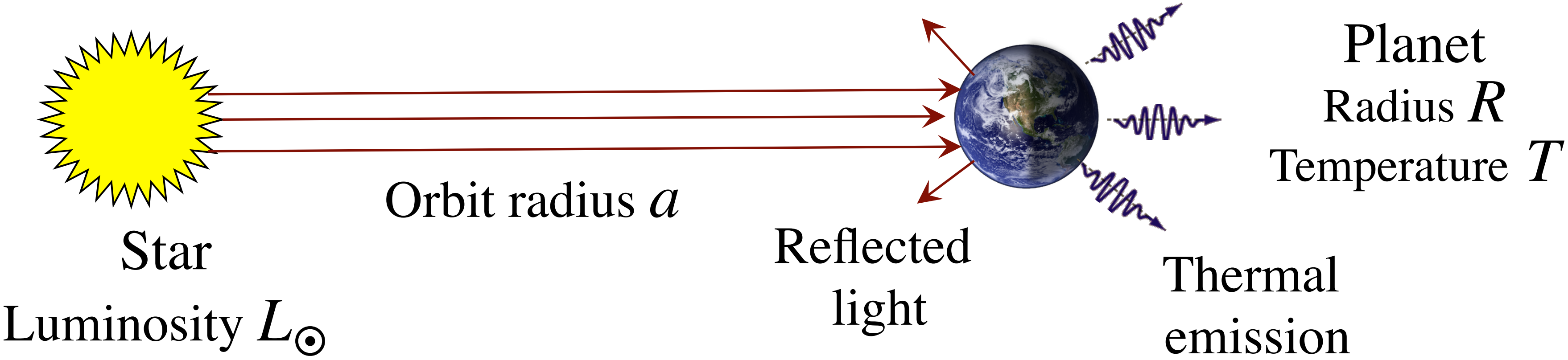
Ay 1 – Lecture 7

Planets Beyond the Solar System

7.1 Thermodynamics of Planets



Planets in a Thermal Balance



Planet
Radius R
Temperature T

Orbit radius a

Star
Luminosity $L_\odot$

Reflected light

Thermal emission

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

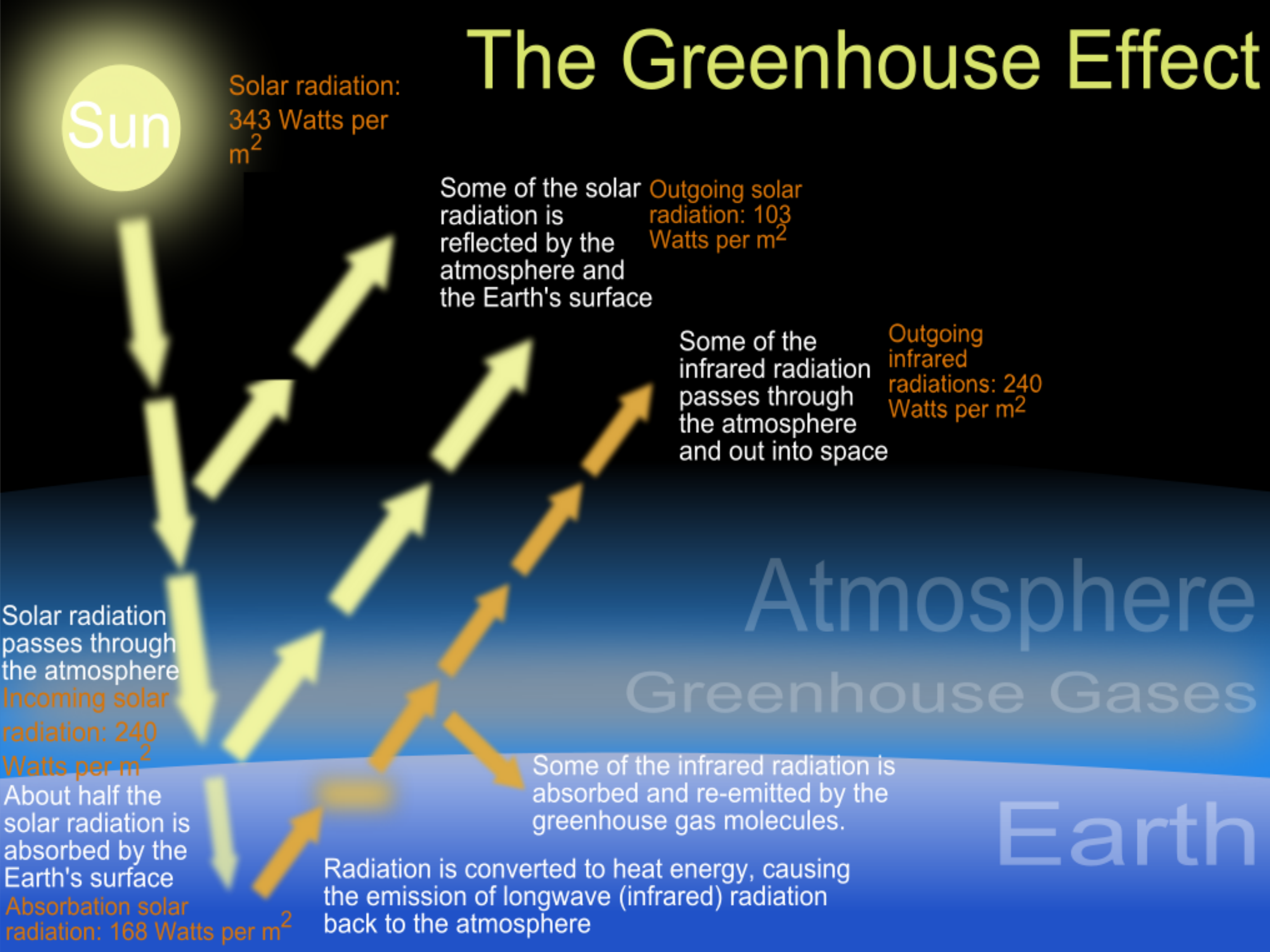
Yet, the actual value is more like $T \sim 287$ K. Why?

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



Solar radiation: 343 Watts per m^2

Some of the solar radiation is reflected by the atmosphere and the Earth's surface

Outgoing solar radiation: 103 Watts per m^2

Some of the infrared radiation passes through the atmosphere and out into space

Outgoing infrared radiations: 240 Watts per m^2

Solar radiation passes through the atmosphere

Incoming solar radiation: 240 Watts per m^2

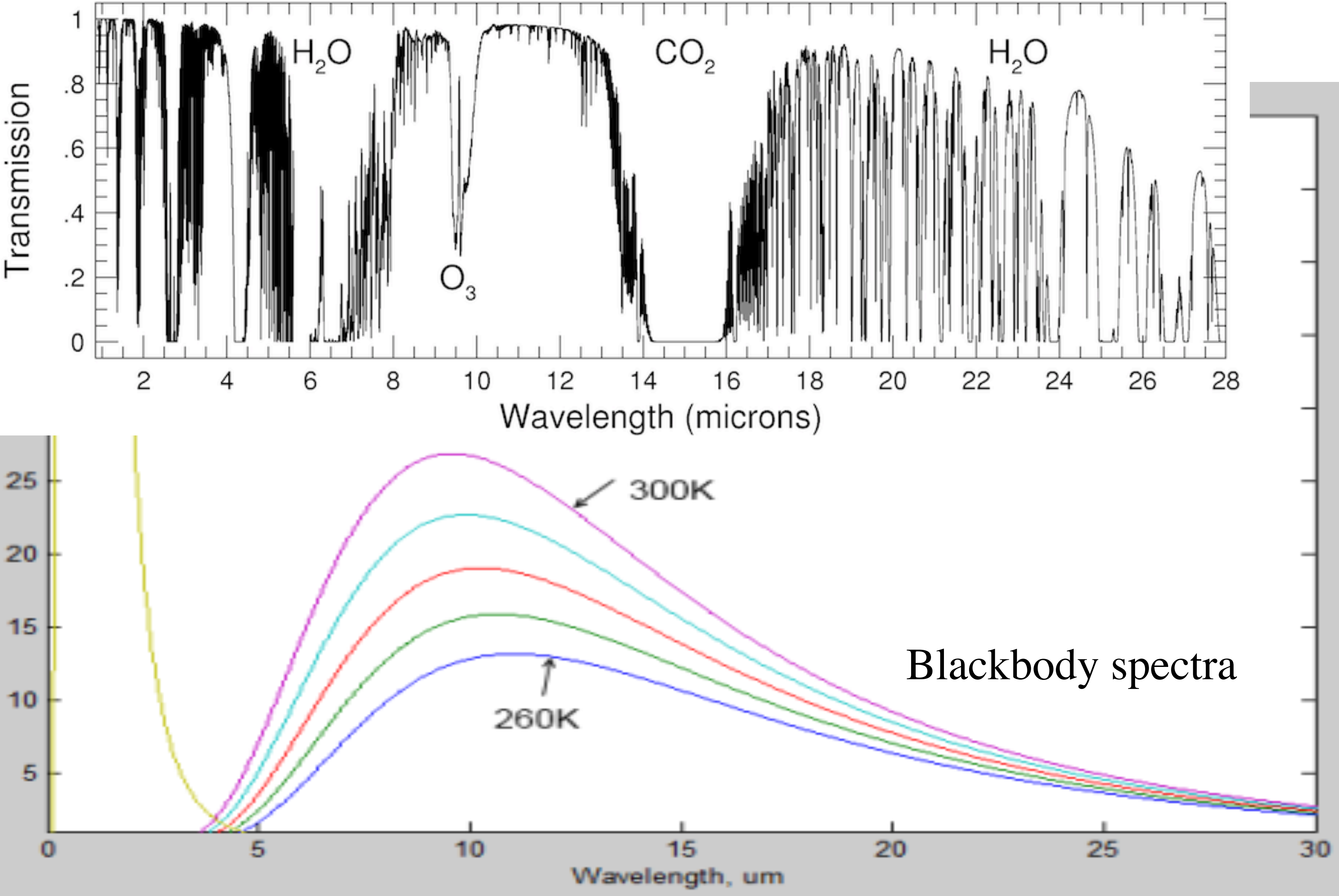
About half the solar radiation is absorbed by the Earth's surface

Absorbation solar radiation: 168 Watts per m^2

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

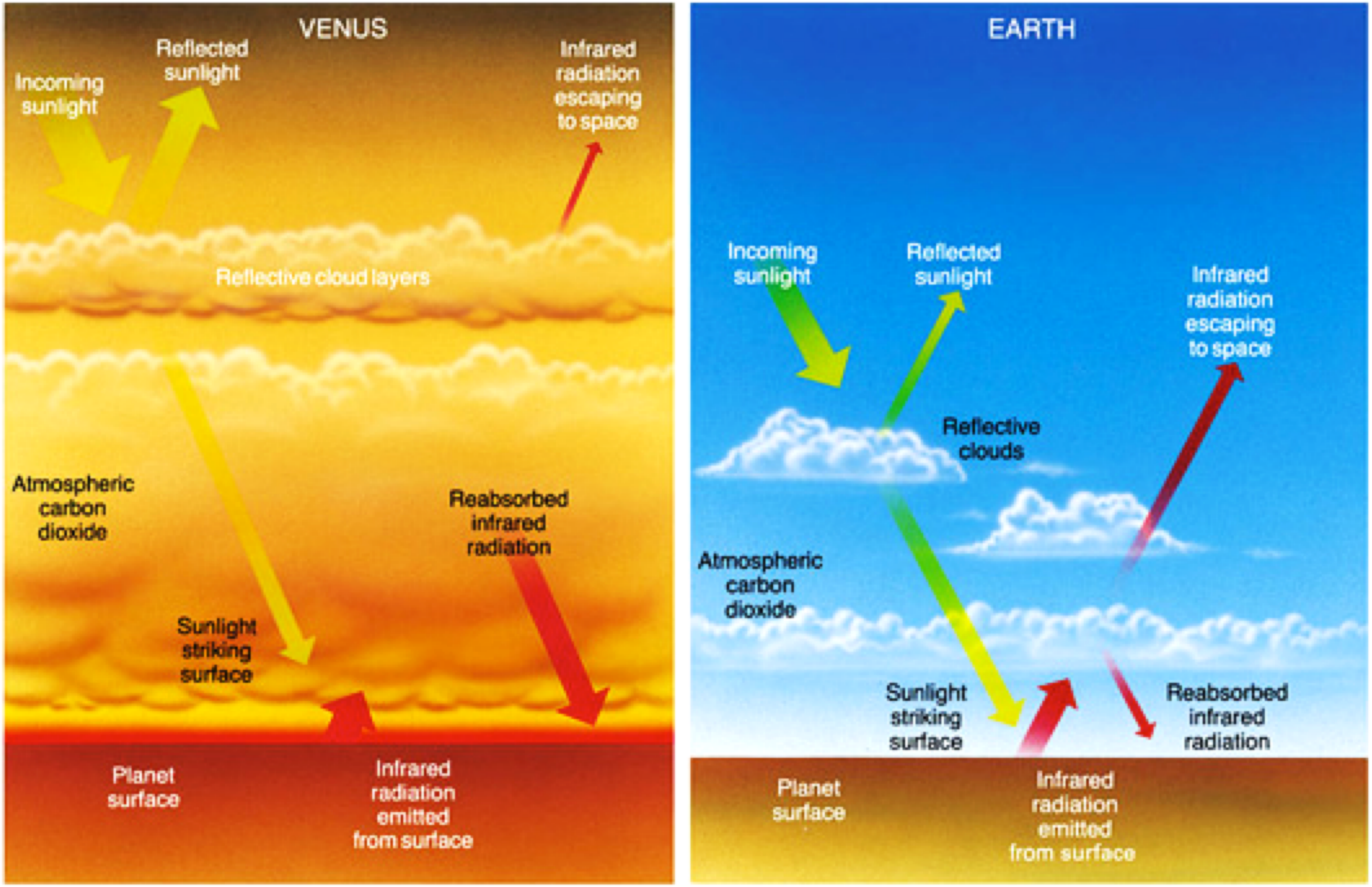
Earth’s Atmosphere Absorption Spectrum



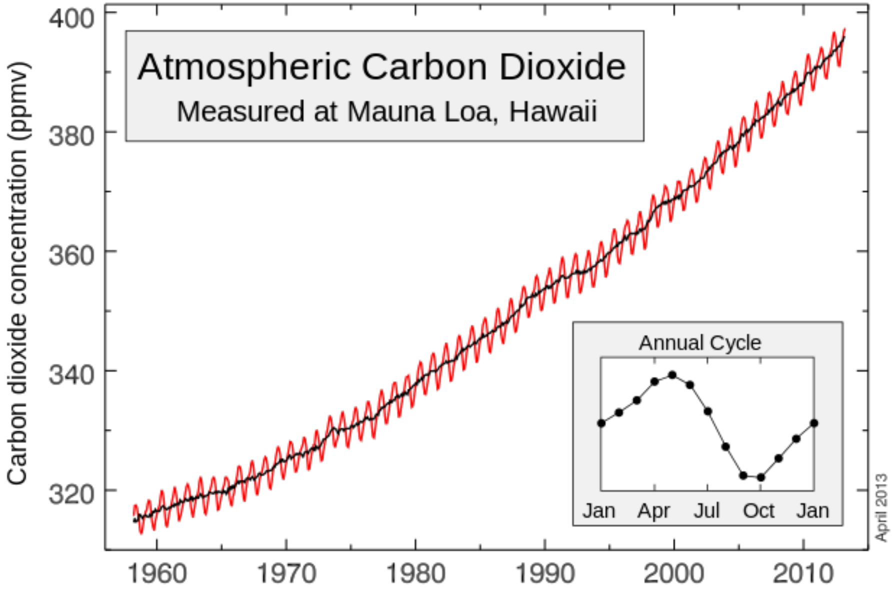
Blackbody spectra

Runaway Greenhouse Effect

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

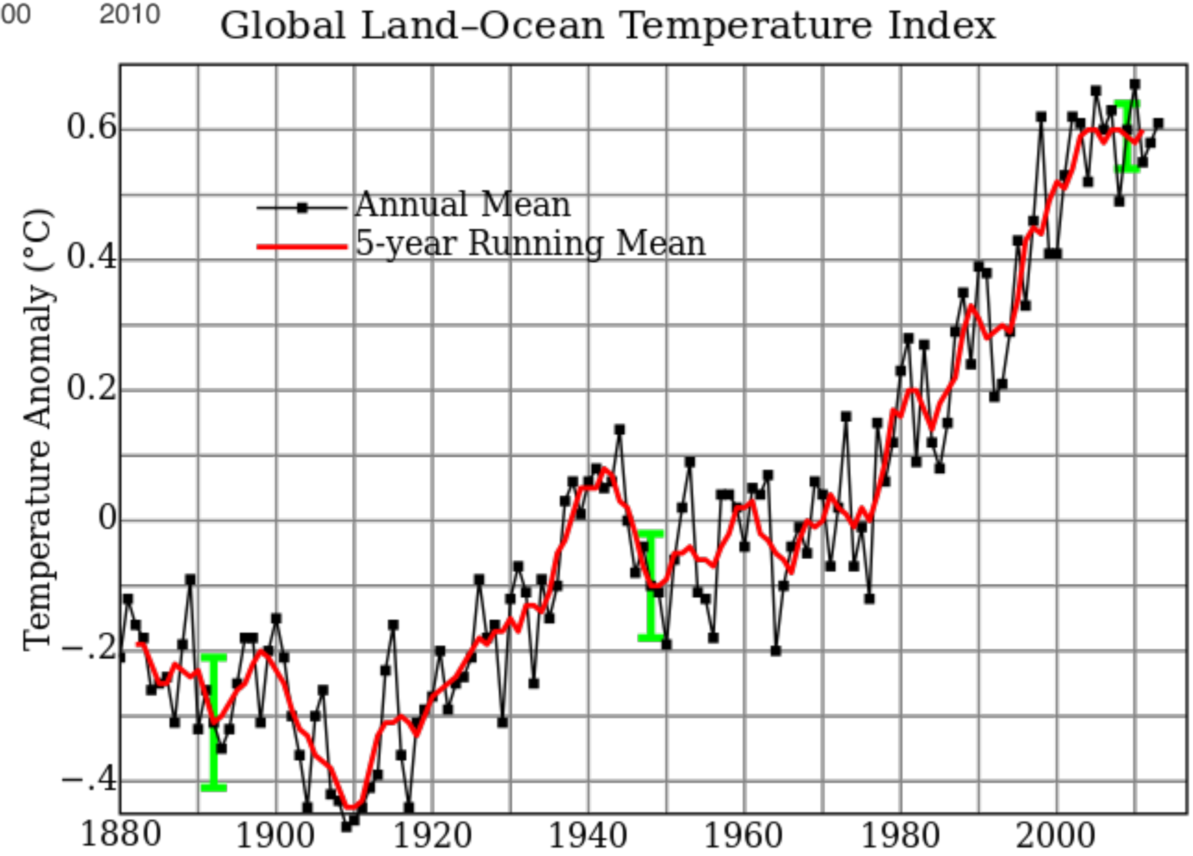


Global Warming



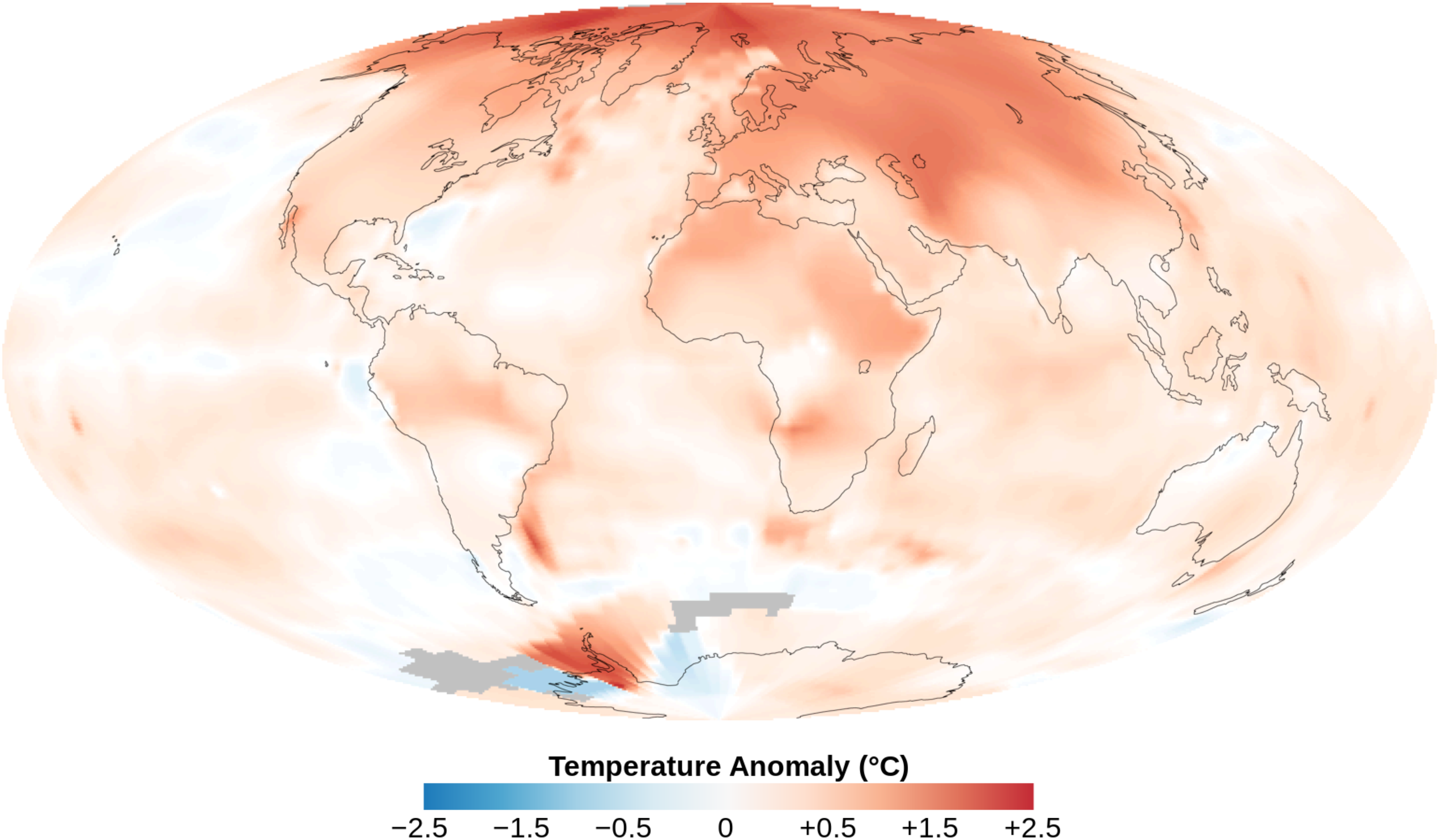
< The cause: increasing concentration of the greenhouse gases

The effect >
Increasing global temperatures



Global Warming

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

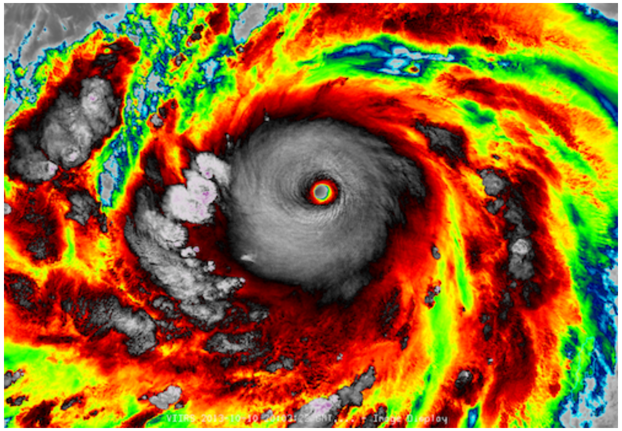


Consequences of the Global Warming

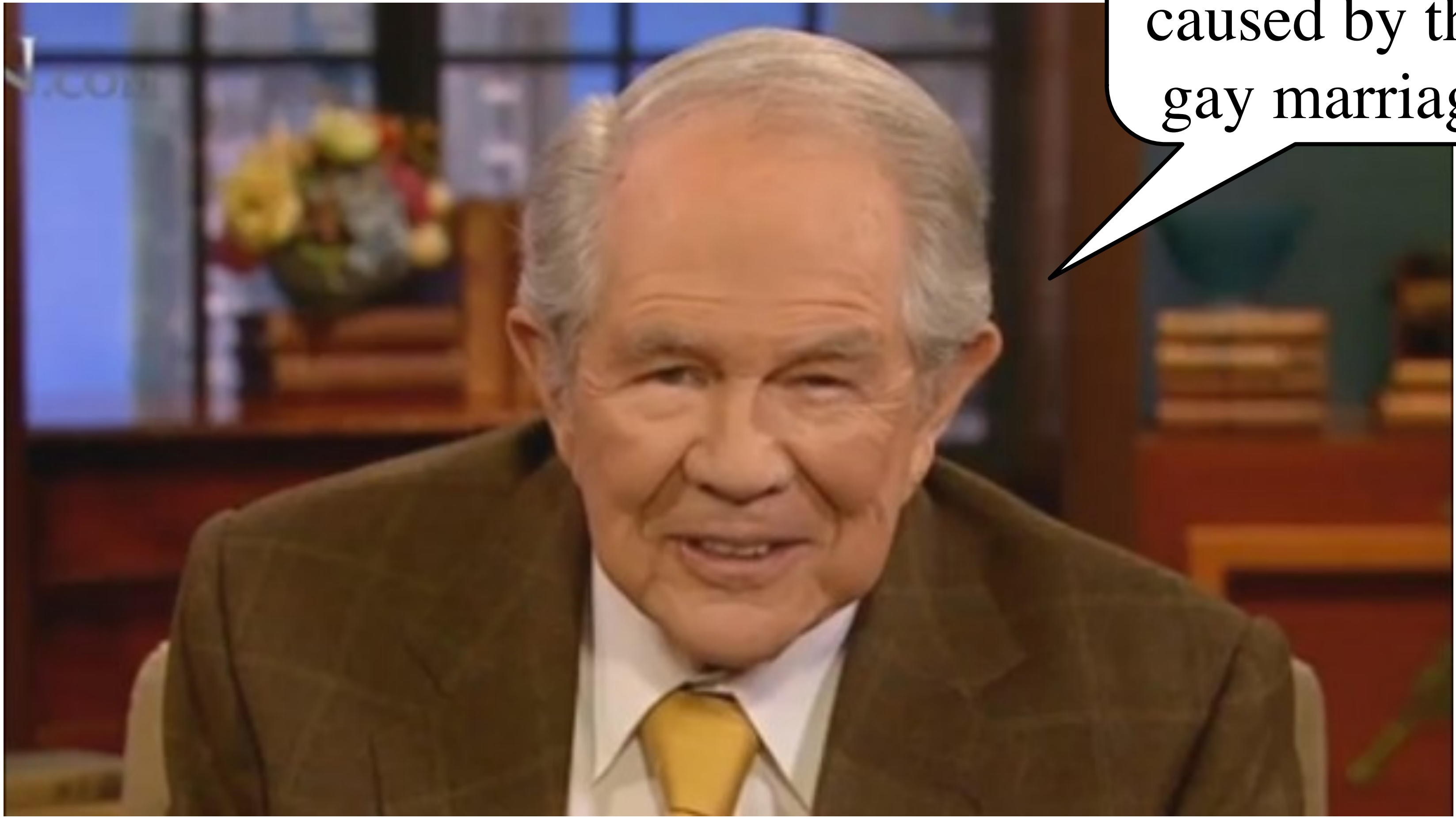
- Average temperature increases
  - ➢ Antarctic and Greenland ice melts and increases the global ocean level; many coastal areas get submerged

- 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…



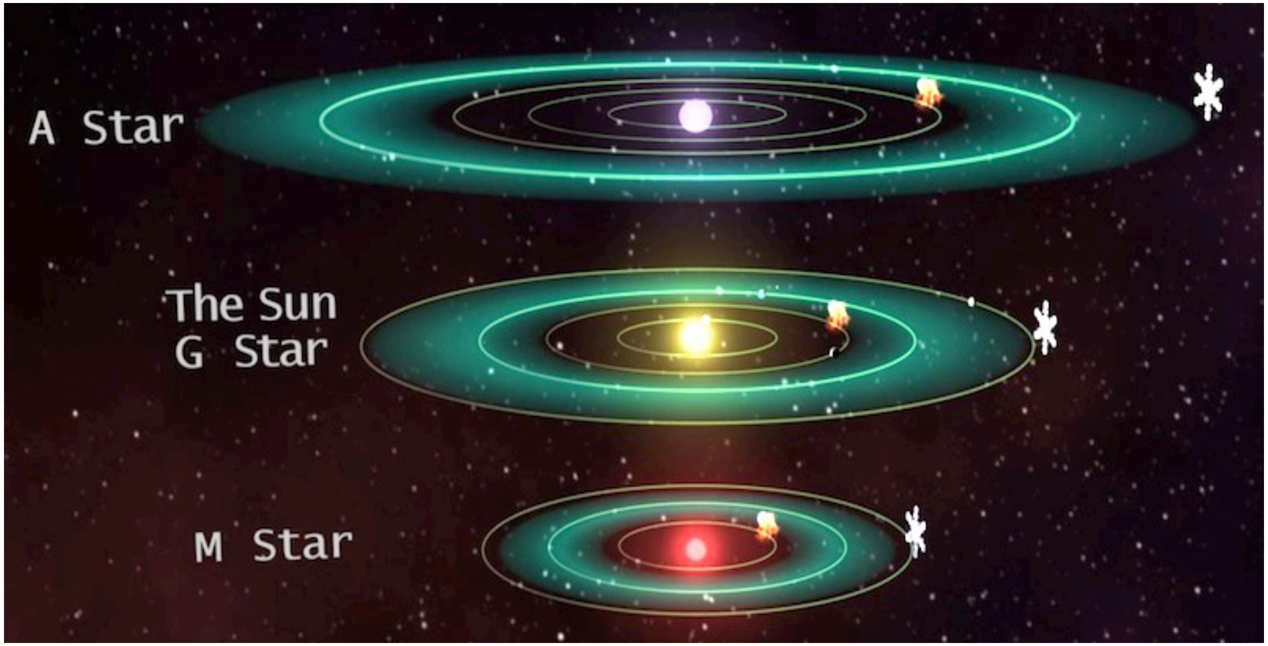
Extreme weather is caused by the gay marriage

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

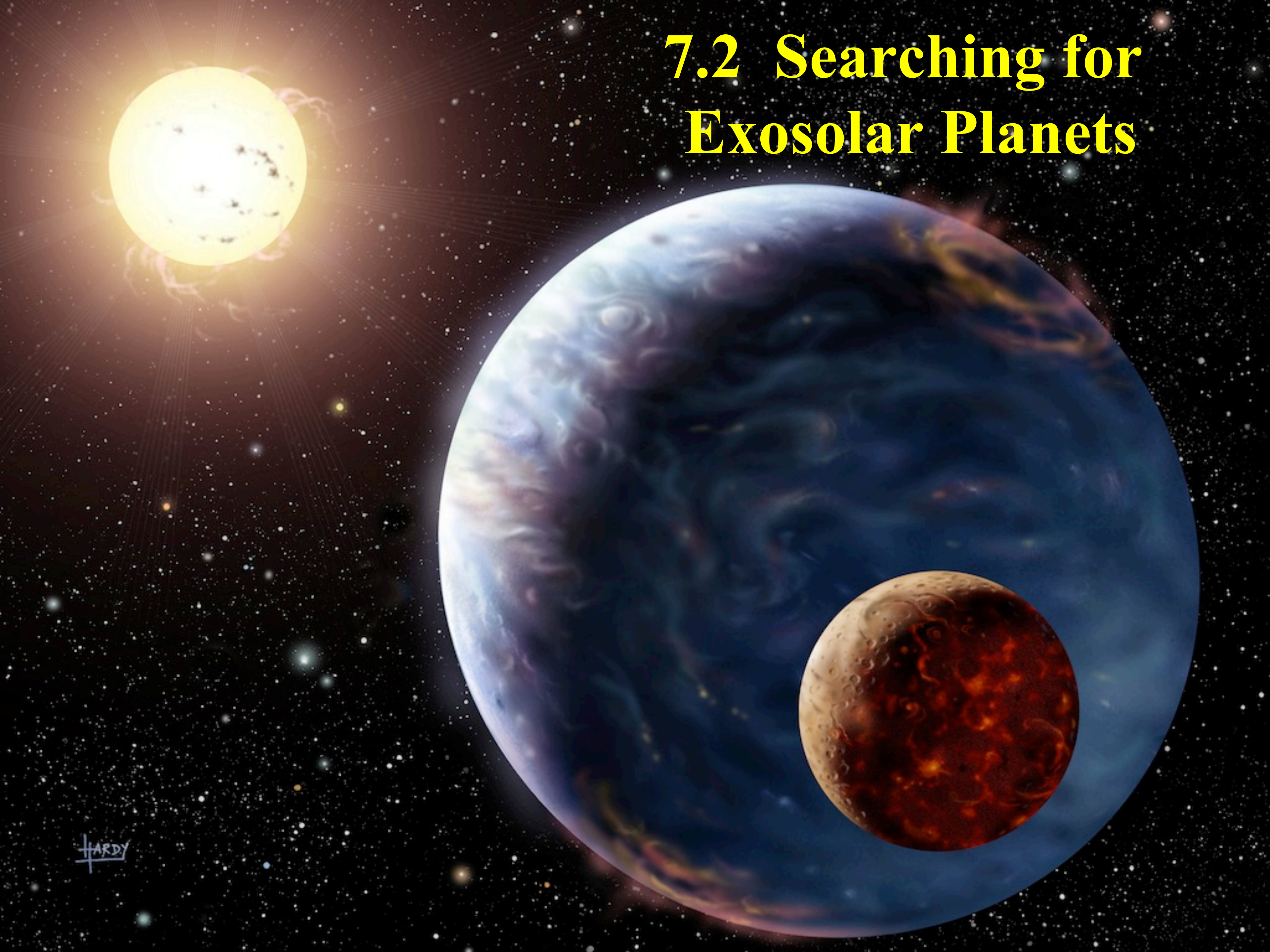


Frost line

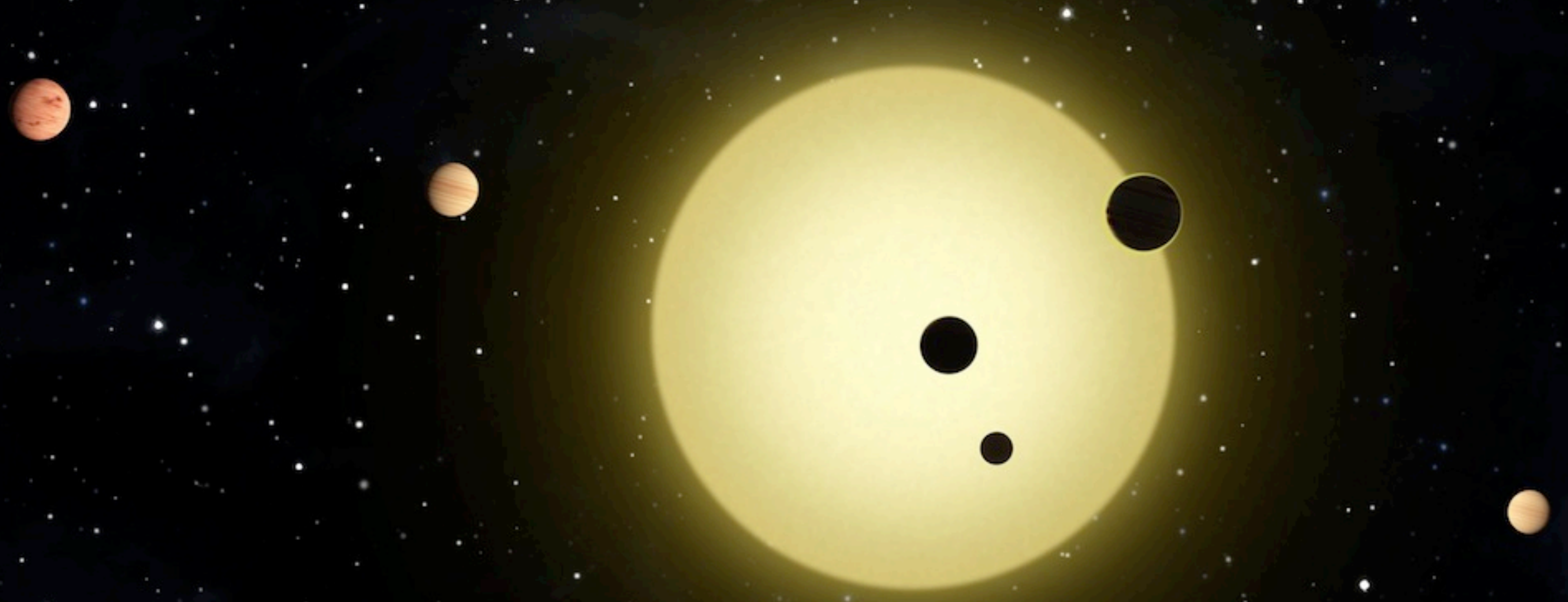
Steam line

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 2019, there are ~ 4000 confirmed exoplanets known, in ~ 2900 planetary systems, plus another ~ 3500 candidates

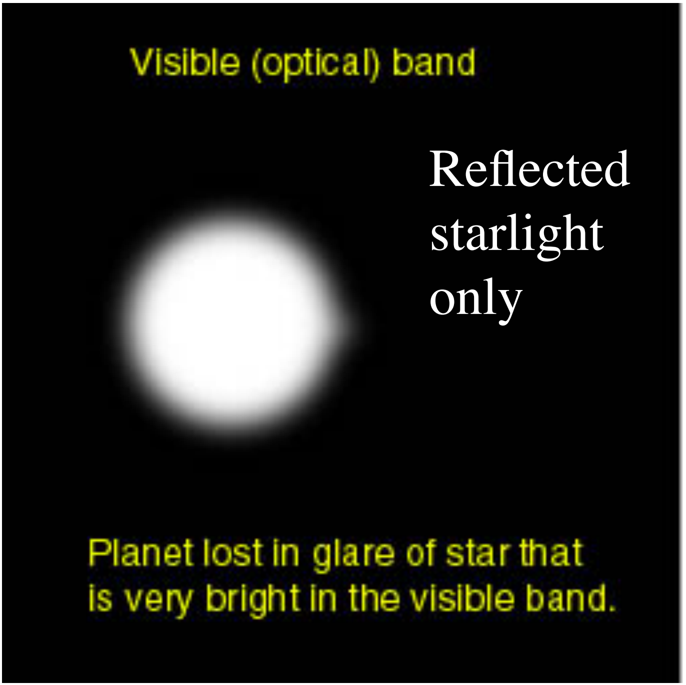


By studying other planetary systems we can learn more about our own. One goal is to look for Earth-like planets

Search Methods for Exosolar Planets

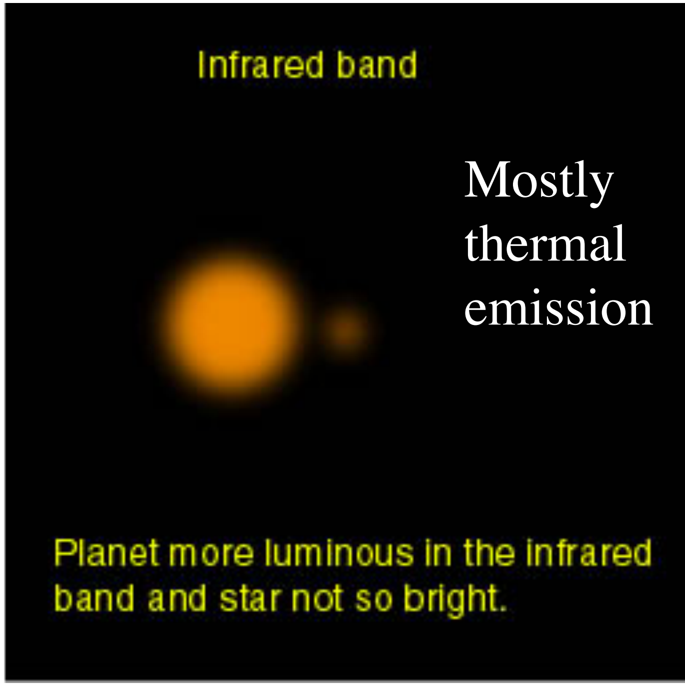
- **Direct imaging**: extremely difficult, since planets may be a billion times fainter than their parent stars
  - Use coronographs and AO to suppress the scattered light
  - Image in thermal IR: the brightness ratio is more favorable
- **Doppler shift:** periodic variation in a star's radial velocity, 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



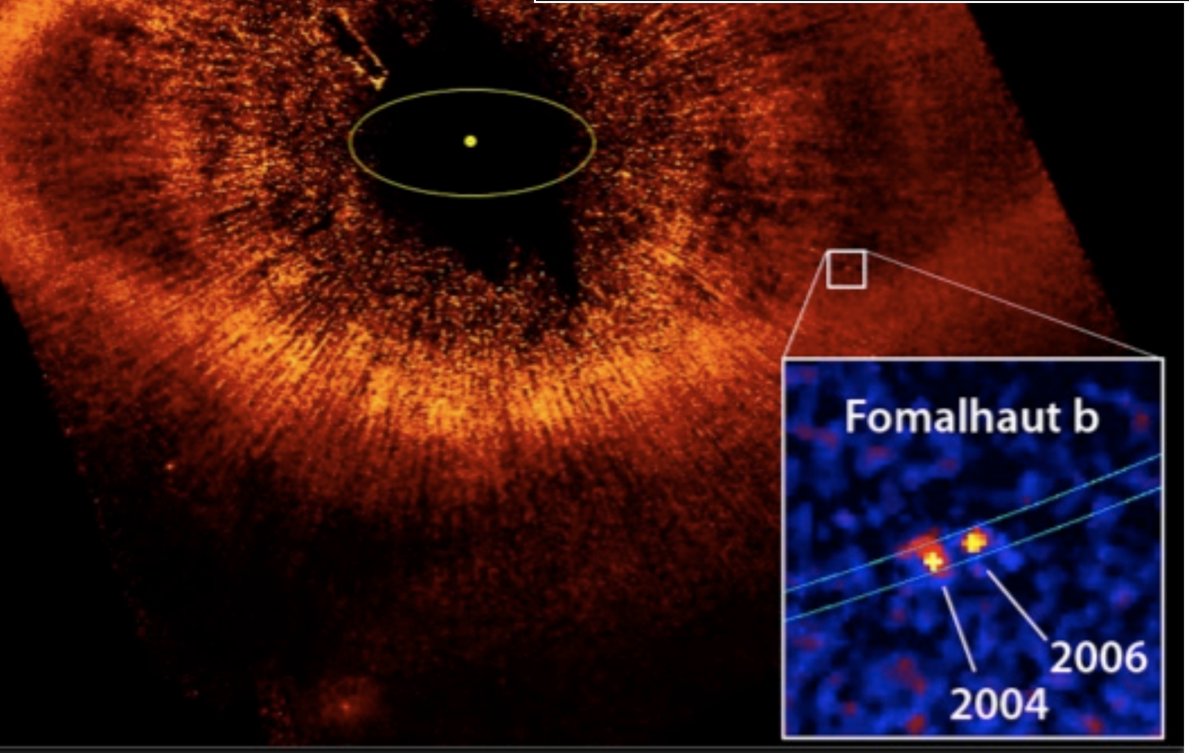
Reflected starlight only

Planet lost in glare of star that is very bright in the visible band.



Mostly thermal emission

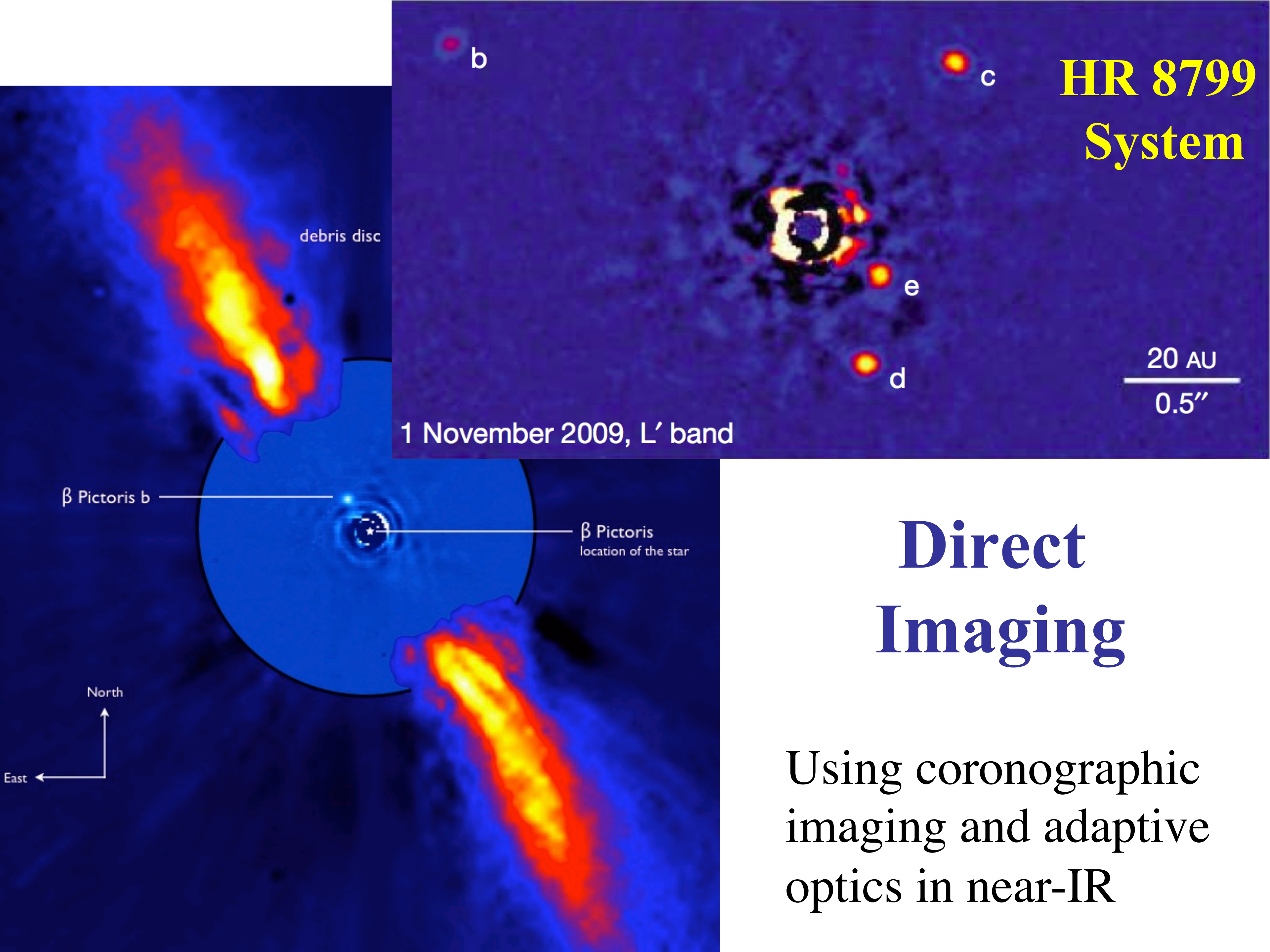
Planet more luminous in the infrared band and star not so bright.



< Coronographic image of Fomalhaut

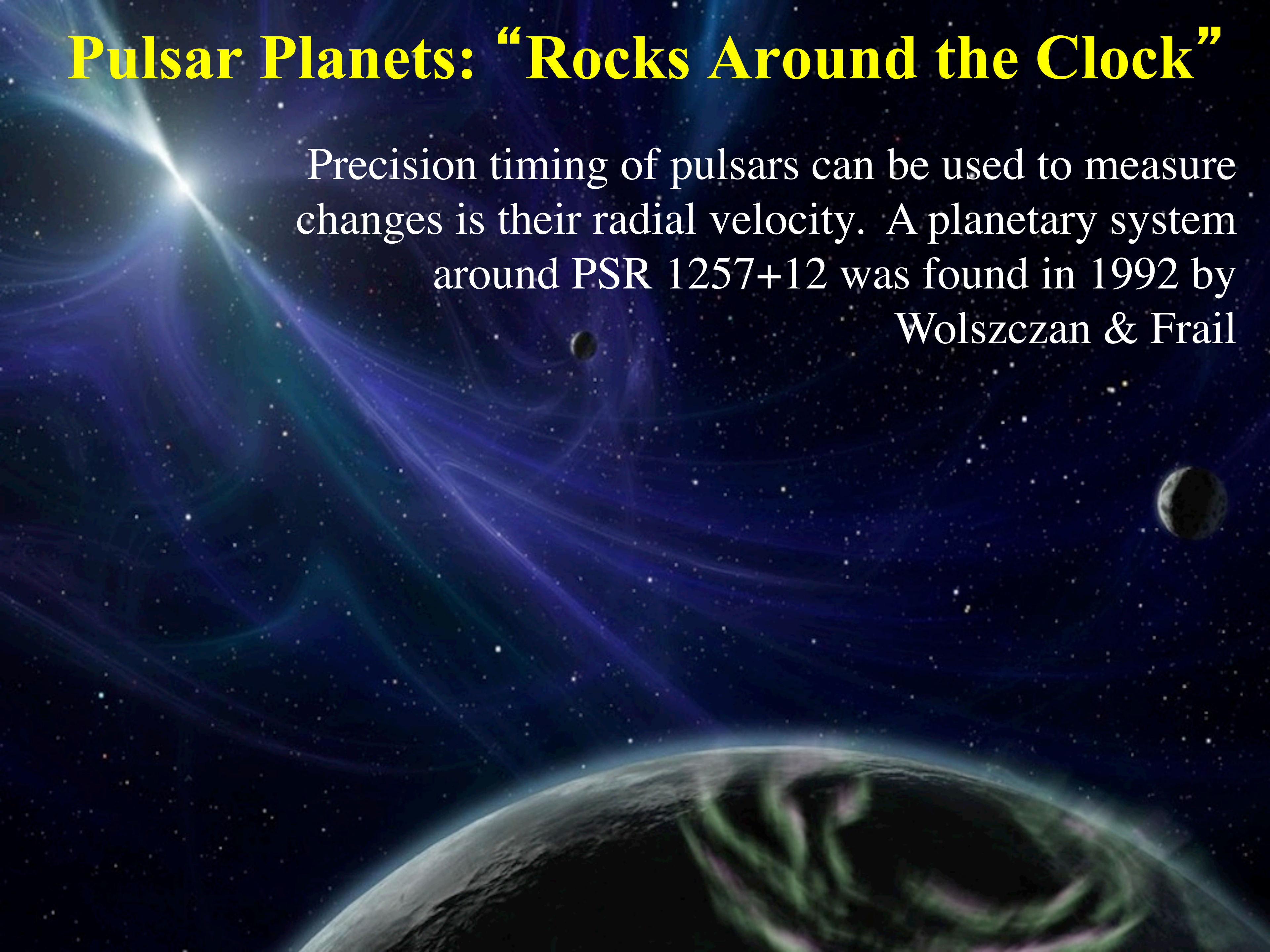
< Comparing images 2 years apart shows the planet moving

Direct Imaging



Using coronographic imaging and adaptive optics in near-IR

Pulsar Planets: "Rocks Around the Clock"



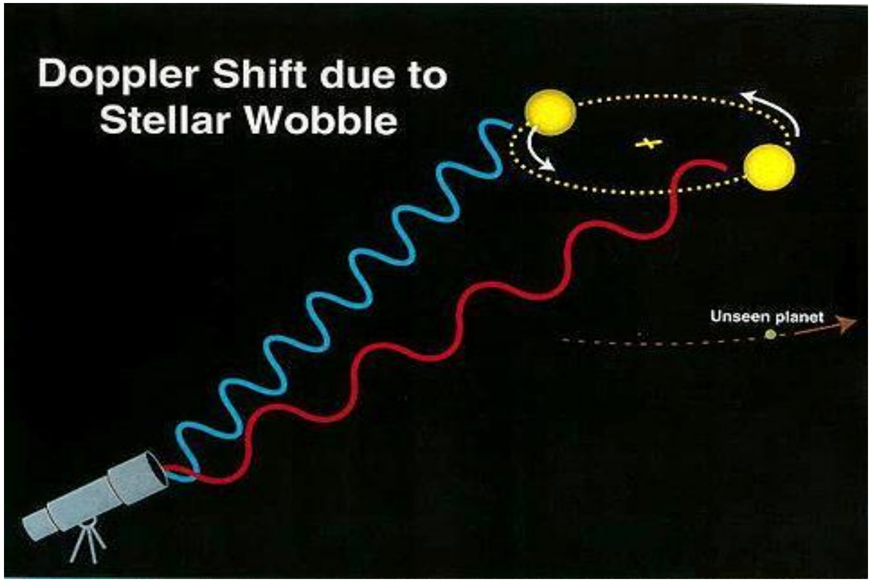
Precision timing of pulsars can be used to measure changes is their radial velocity. A planetary system around PSR 1257+12 was found in 1992 by Wolszczan & Frail

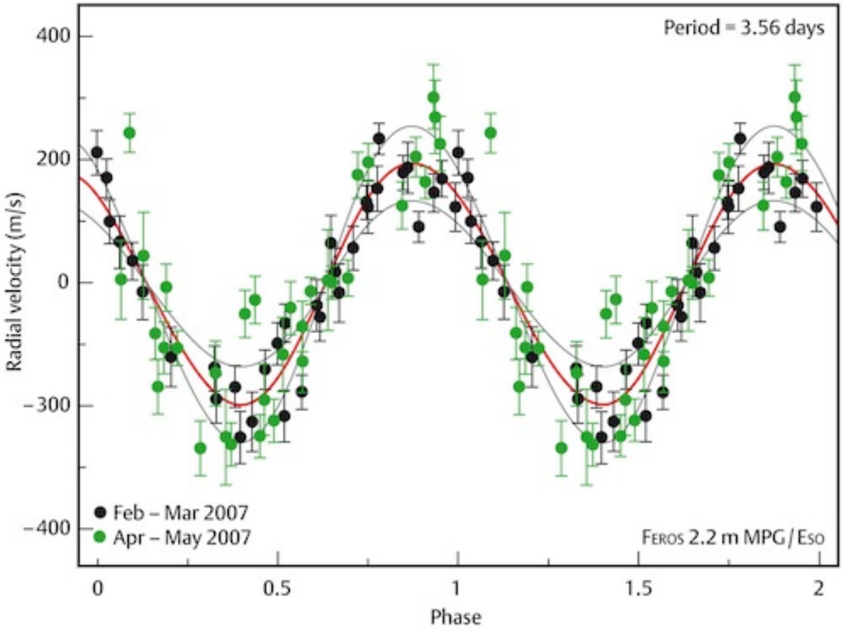
Radial Velocity Method

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

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

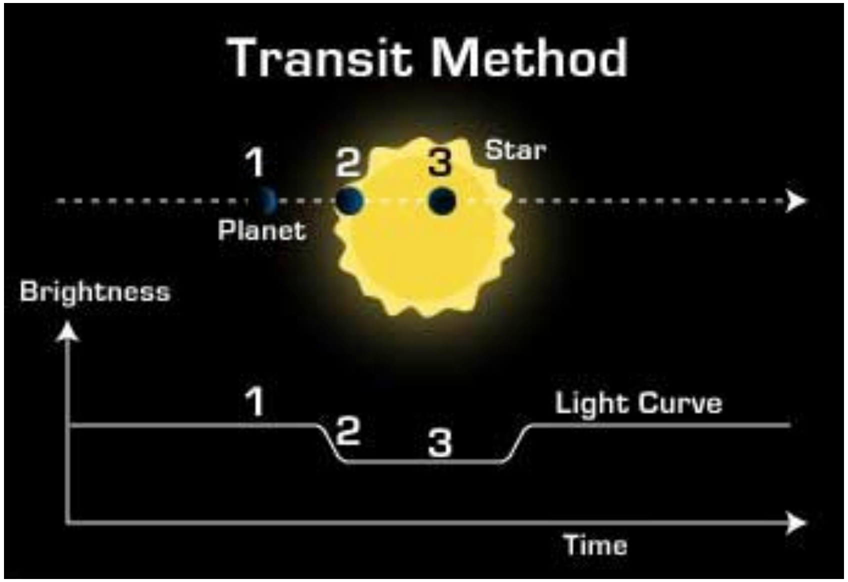
State of the art precision ~ 1 m/s

51 Pegasi b – the first confirmed exoplanet (1995)

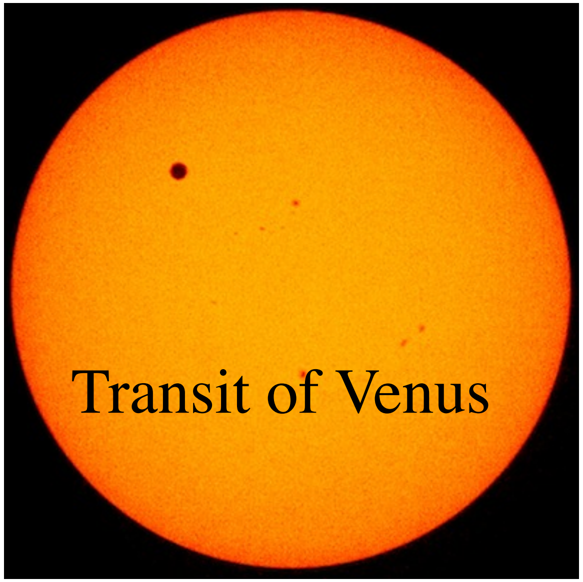
Discovered using the radial velocity technique

An example of a “Hot Jupiter”

Planetary Transits (Eclipses)

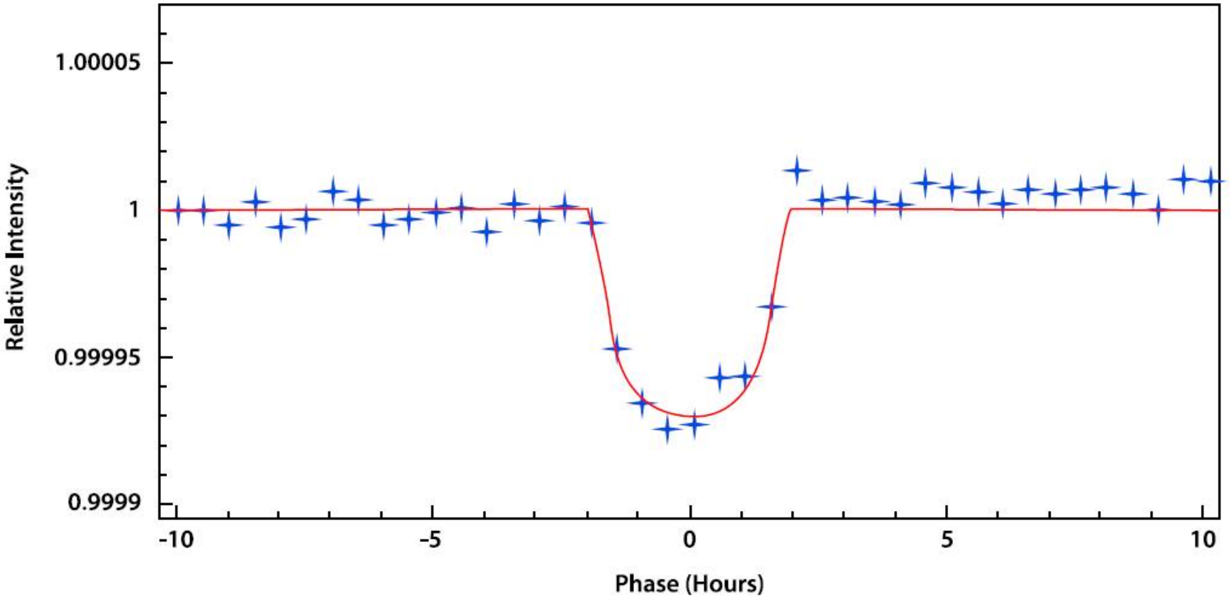


An Earth-sized planet crossing a Sun-like stellar disk would cause a 10^{-4} eclipse → need a very high precision photometry



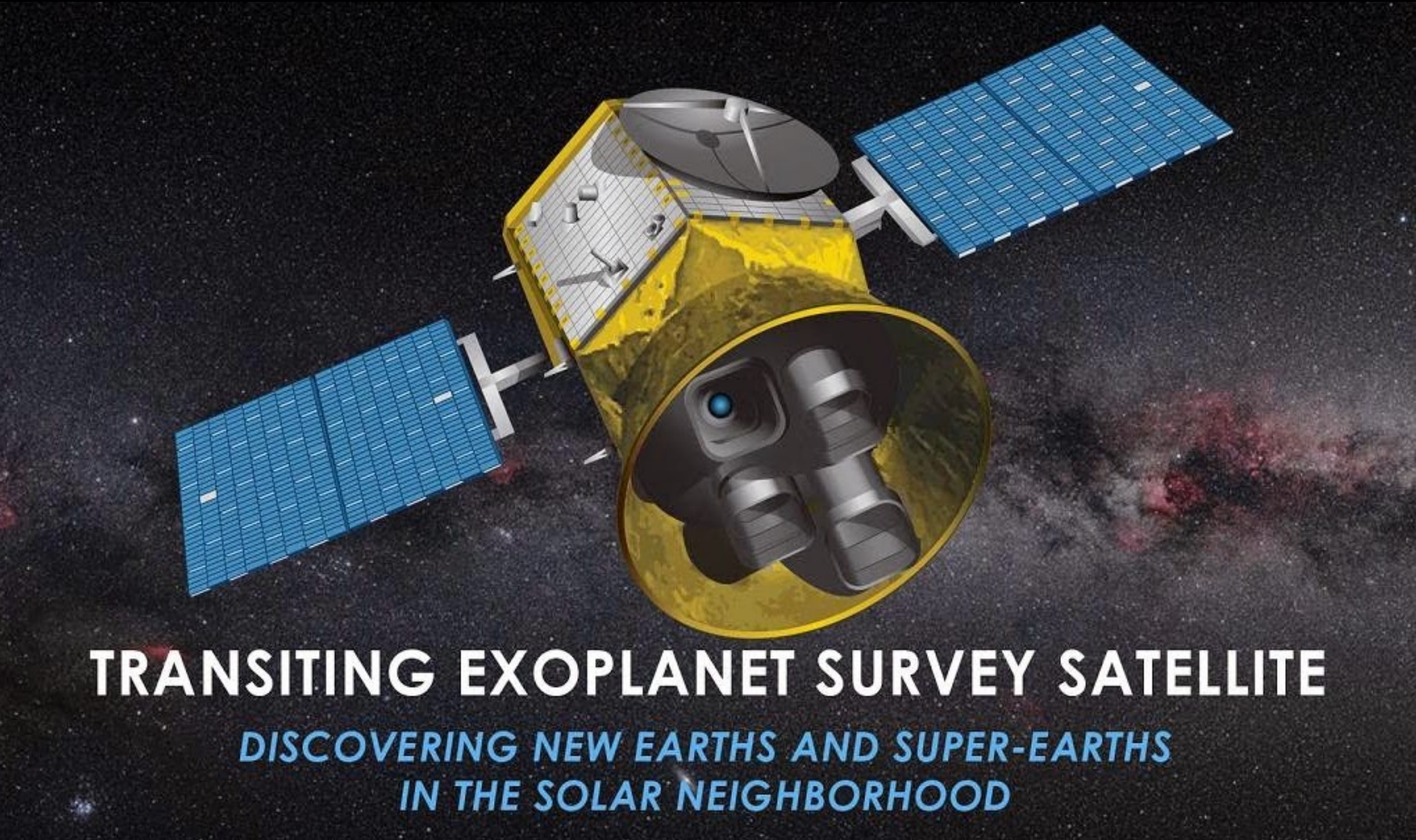
Transit of Venus

Kepler light curve of HD 179070

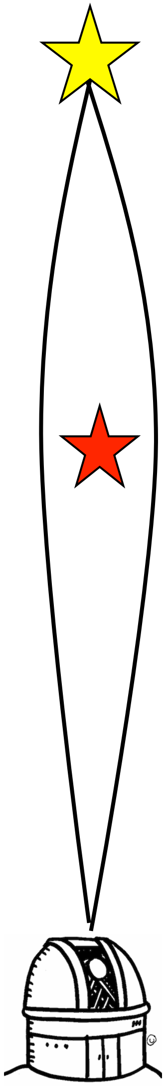


Kepler Mission

TESS


TRANSITING EXOPLANET SURVEY SATELLITE
DISCOVERING NEW EARTHS AND SUPER-EARTHS IN THE SOLAR NEIGHBORHOOD

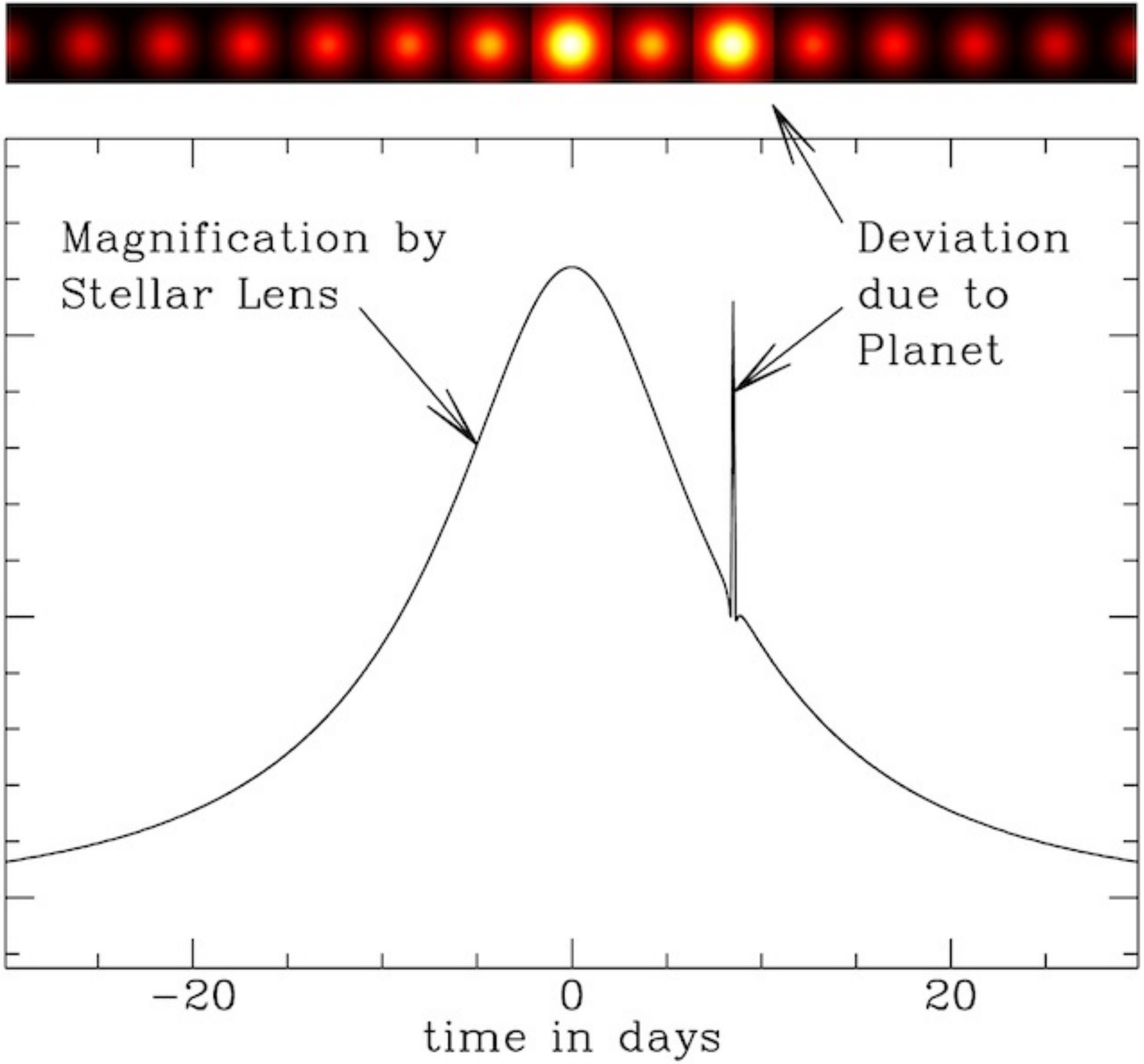
Gravitational Microlensing

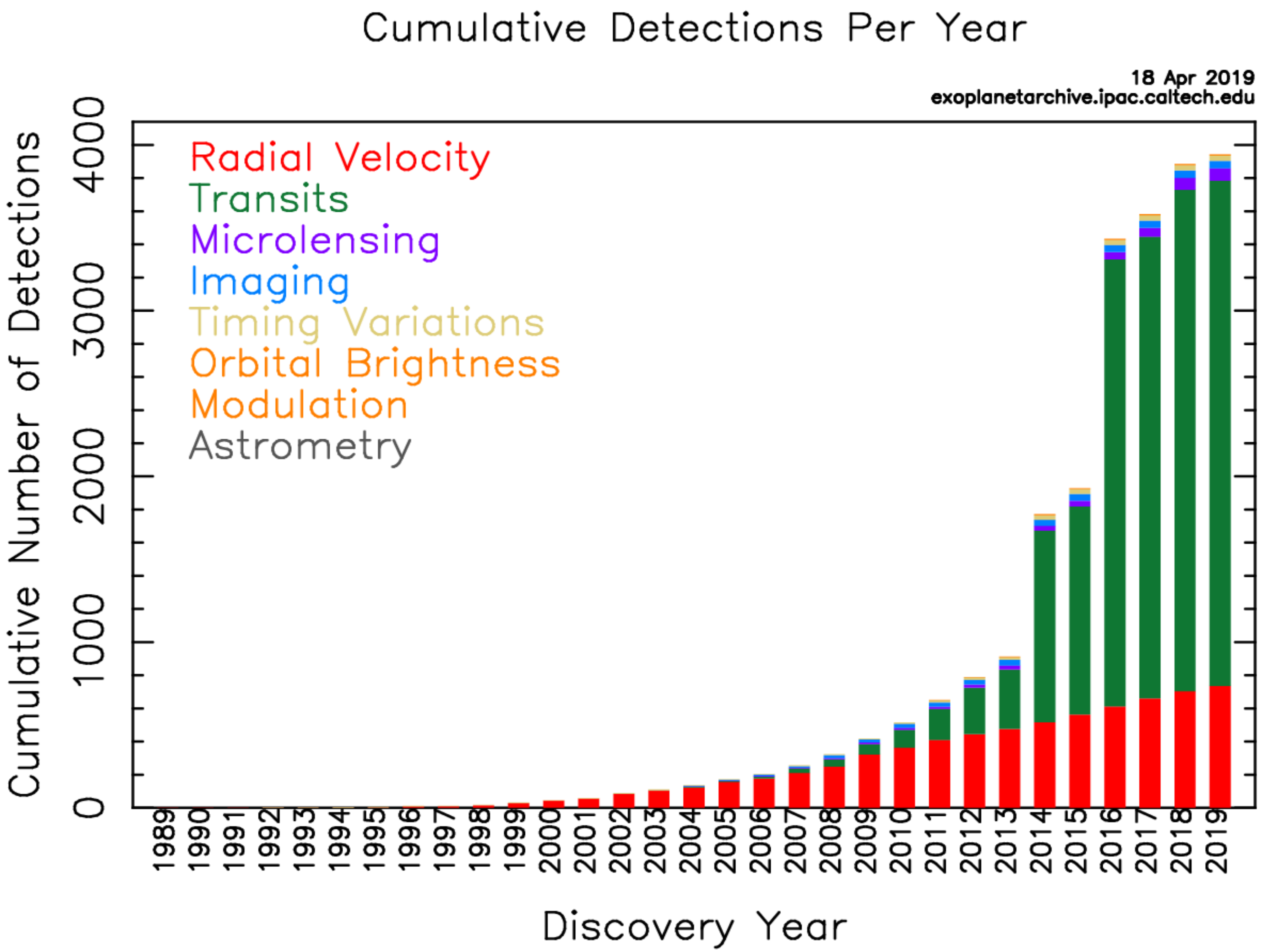


Background star

Foreground star bends light rays, magnifies the bgd star

Observer sees a light curve like this




Cumulative Detections Per Year
18 Apr 2019
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Cumulative Number of Detections
0
1000
2000
3000
4000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
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2007
2008
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2011
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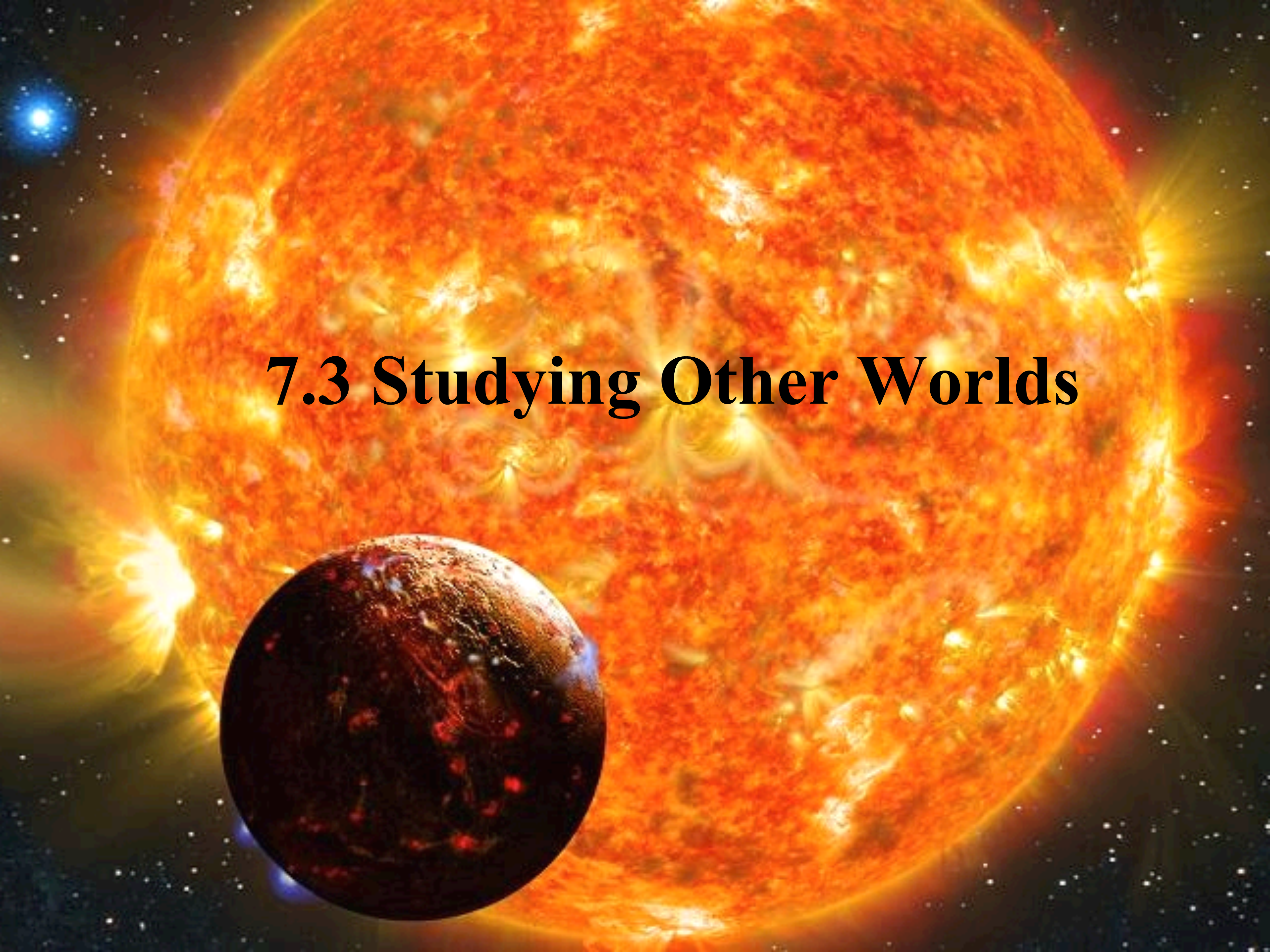
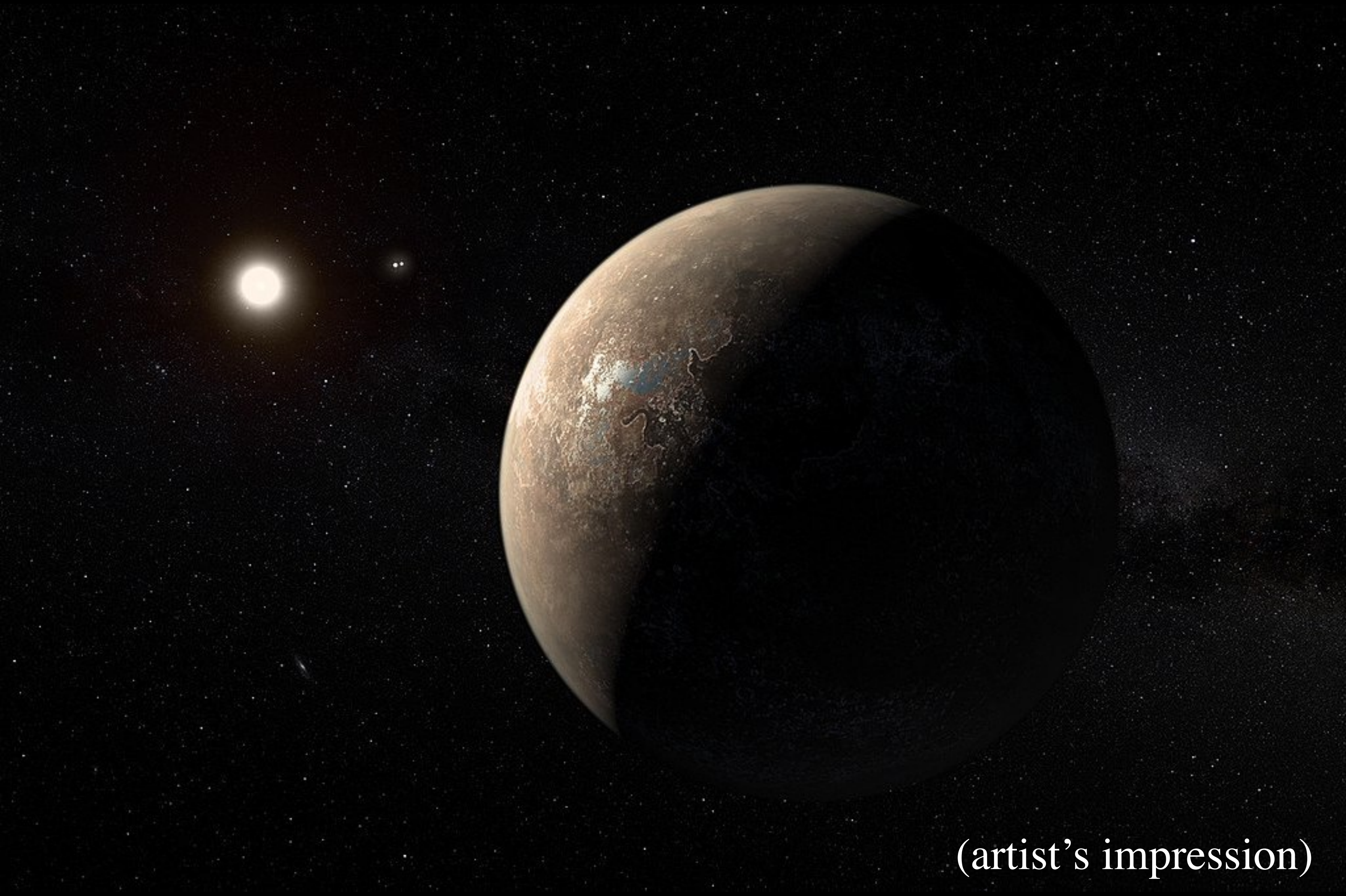
2013
2014
2015
2016
2017
2018
2019
Discovery Year



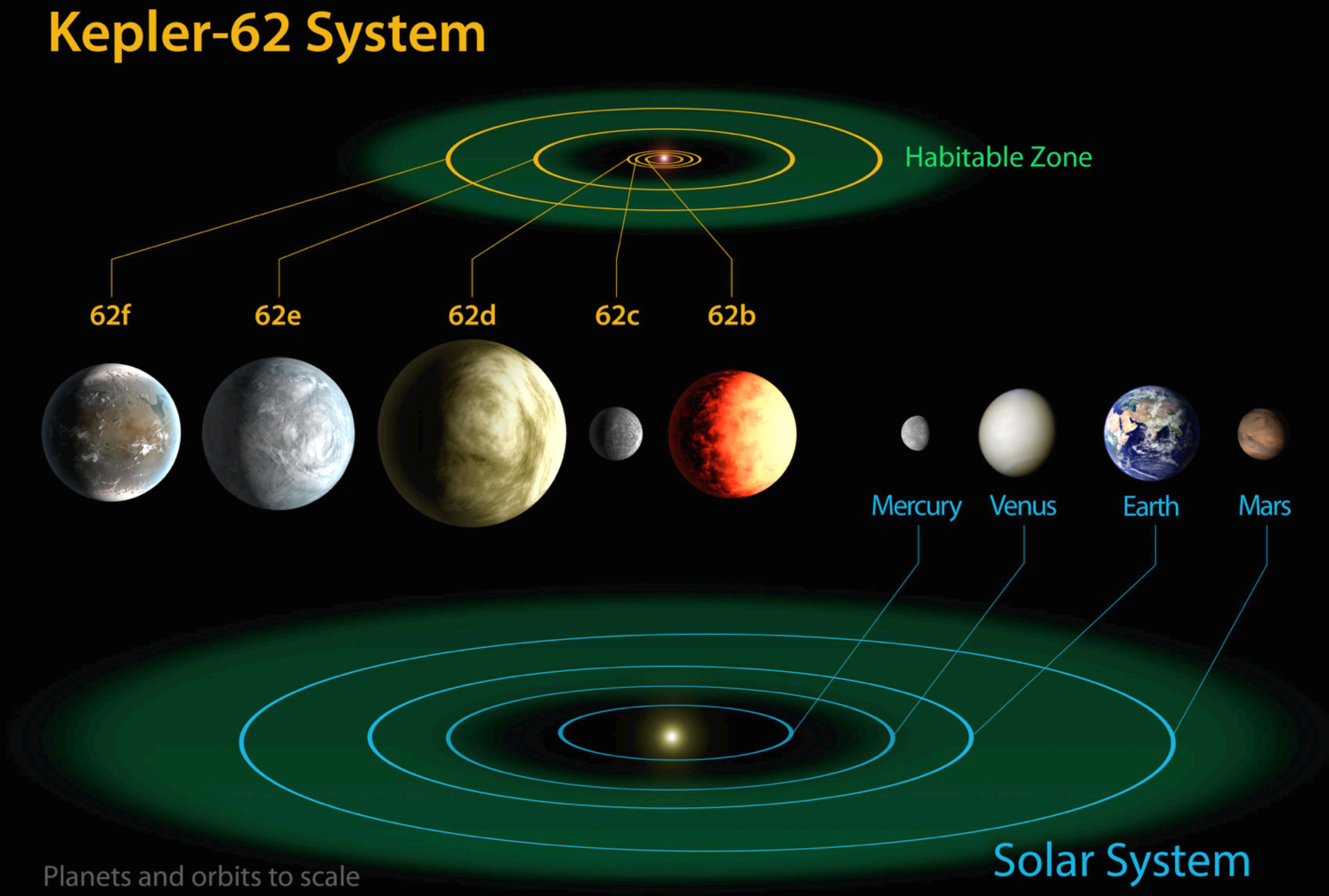
7.3 Studying Other Worlds

A Planet Orbiting Proxima Centauri b

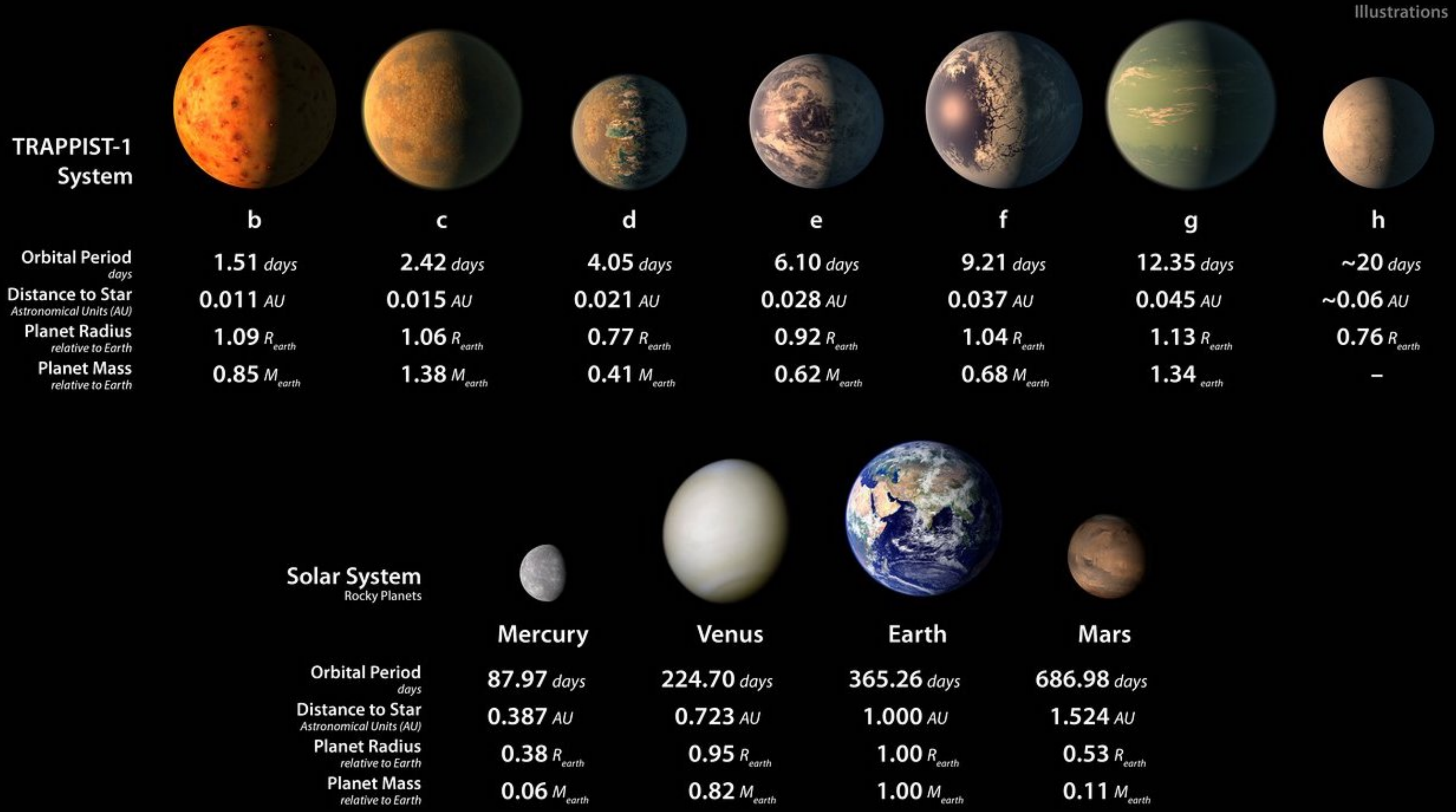


(artist's impression)

Comparing Planetary Systems



The Trappist-1 Planetary System



Illustrations

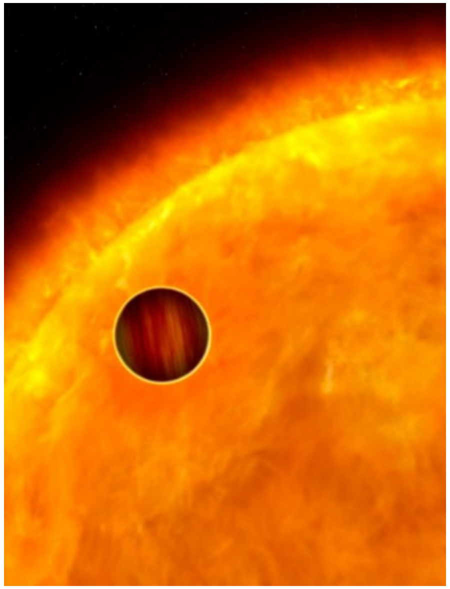
TRAPPIST-1 System

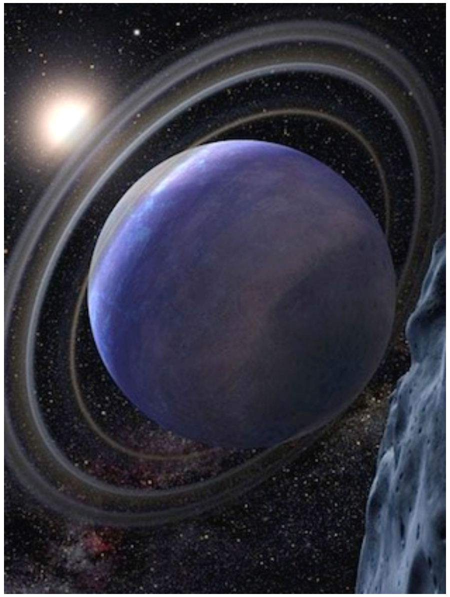
	b	c	d	e	f	g	h
Orbital Period *days*	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.35 *days*	~20 *days*
Distance to Star *Astronomical Units (AU)*	0.011 *AU*	0.015 *AU*	0.021 *AU*	0.028 *AU*	0.037 *AU*	0.045 *AU*	~0.06 *AU*
Planet Radius *relative to Earth*	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass *relative to Earth*	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–

Solar System
Rocky Planets

	Mercury	Venus	Earth	Mars
Orbital Period *days*	87.97 *days*	224.70 *days*	365.26 *days*	686.98 *days*
Distance to Star *Astronomical Units (AU)*	0.387 *AU*	0.723 *AU*	1.000 *AU*	1.524 *AU*
Planet Radius *relative to Earth*	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass *relative to Earth*	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}

Characterizing Exoplanets





From radial velocities:

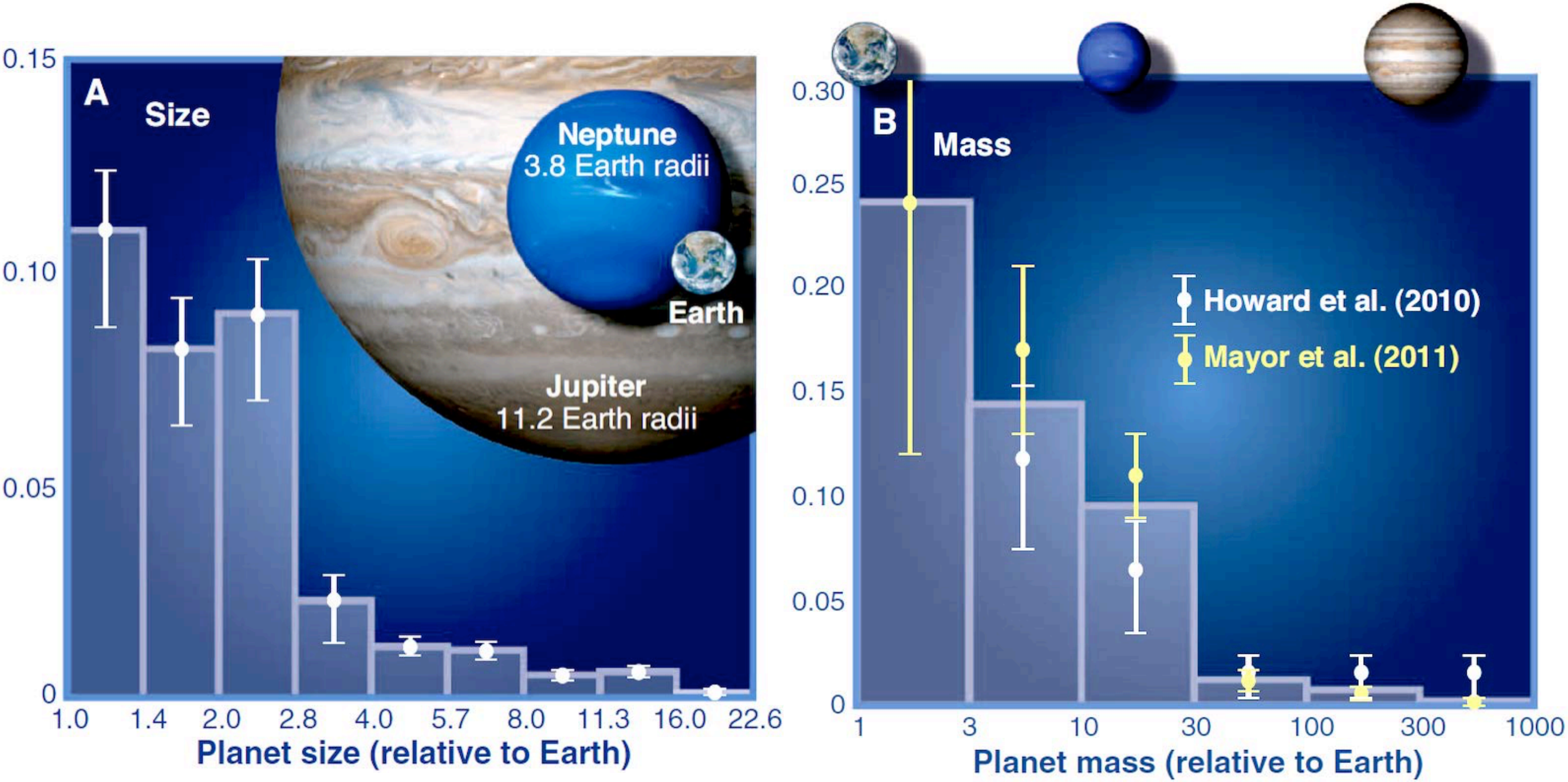
- Measure velocity, period, thus the size of the orbit, infer the mass using Kepler's laws
- Also infer orbital shape (eccentricity)

From transits:

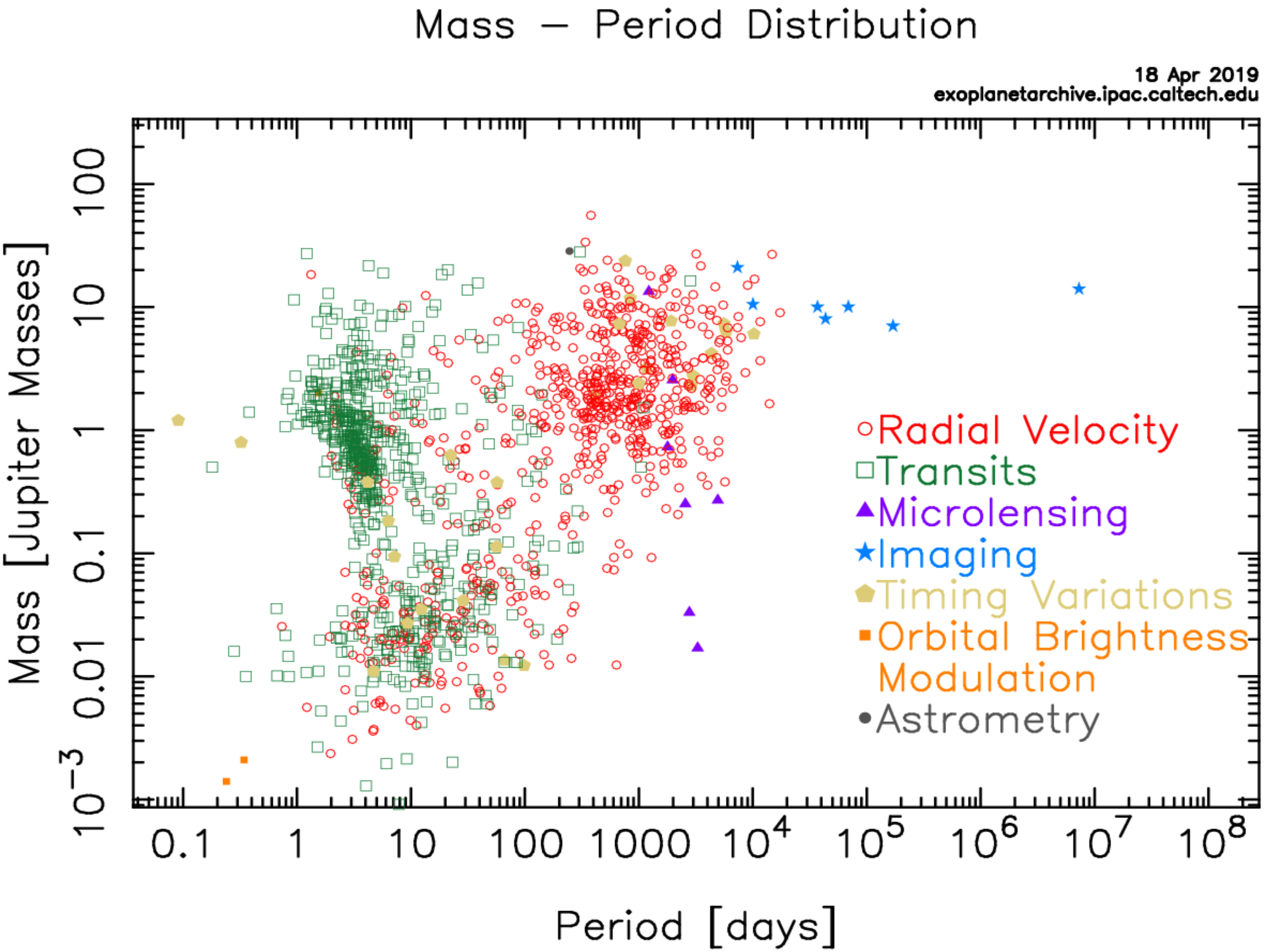
- Infer planetary radii, thus densities, possible composition
- From the proximity to the star, infer the temperature
- Measure the composition of the atmosphere

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)

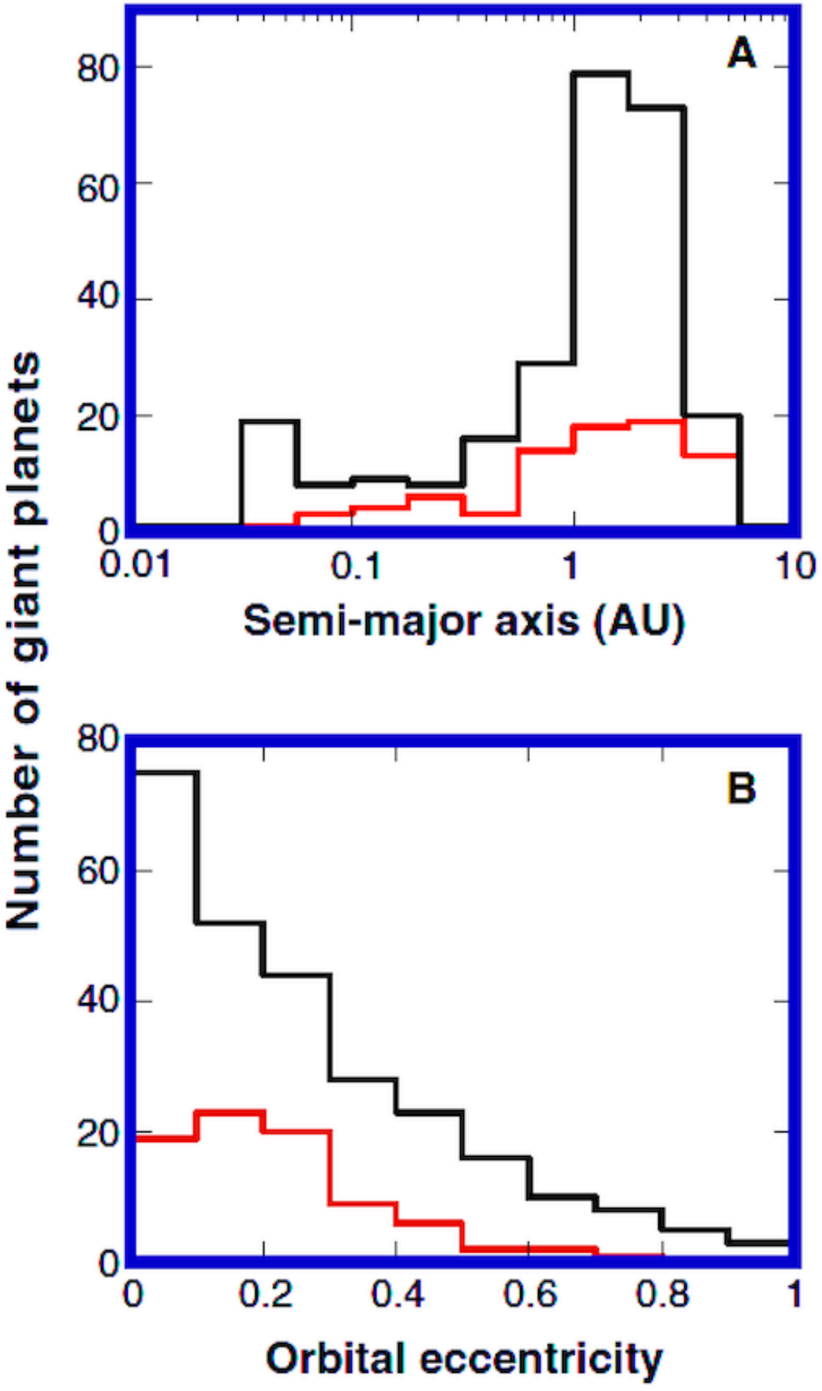

Mass — Period Distribution
18 Apr 2019
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
Period [days]
○ Radial Velocity
□ Transits
▲ Microlensing
★ Imaging
⬟ Timing Variations
■ Orbital Brightness Modulation
● Astrometry

Distribution of orbit semimajor axes

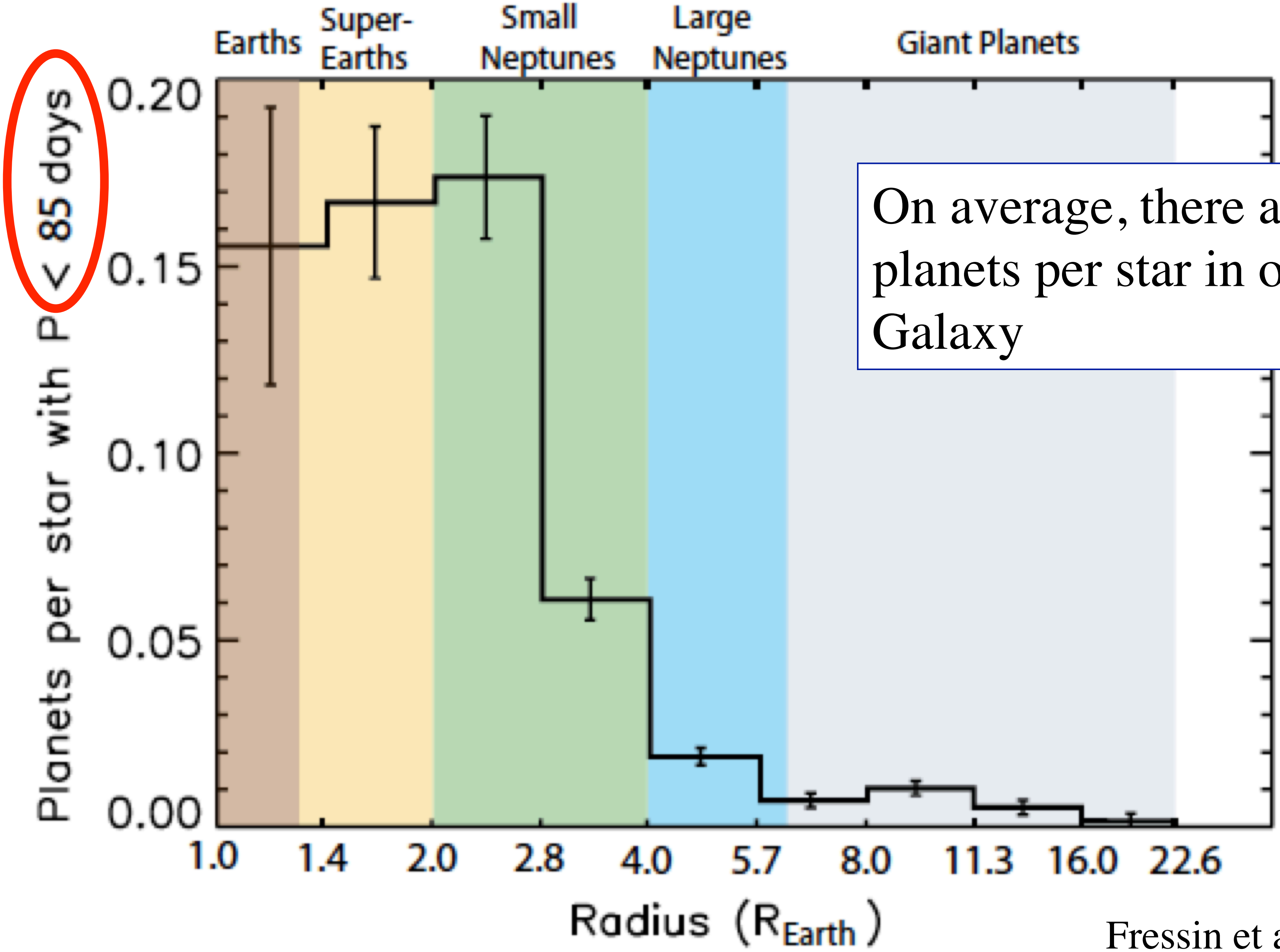
Planets closer in are easier to find, so there is a selection effect against the more distant tones

Distribution of orbit shapes

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



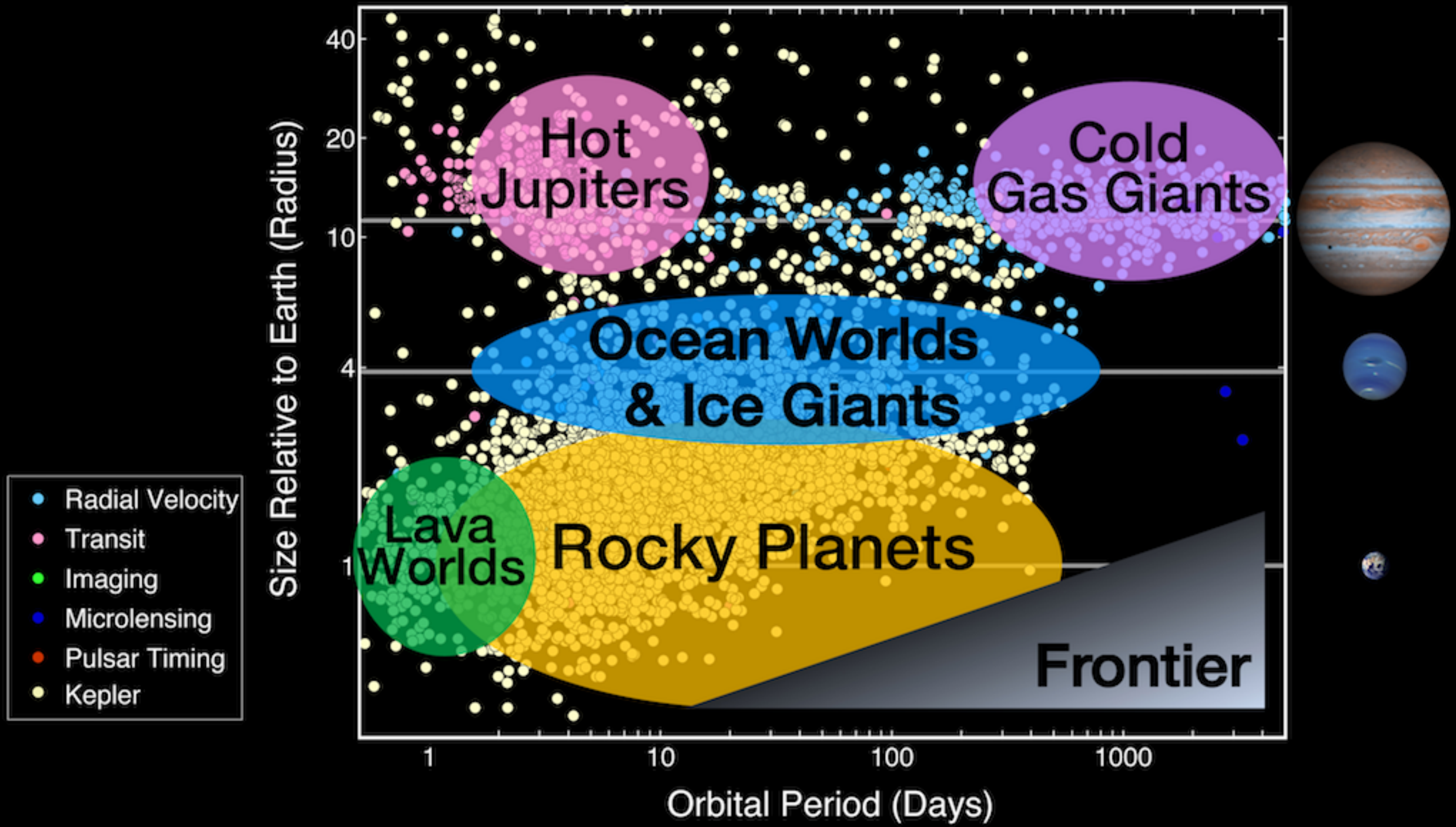
Kepler Survey: Planets are Common!



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

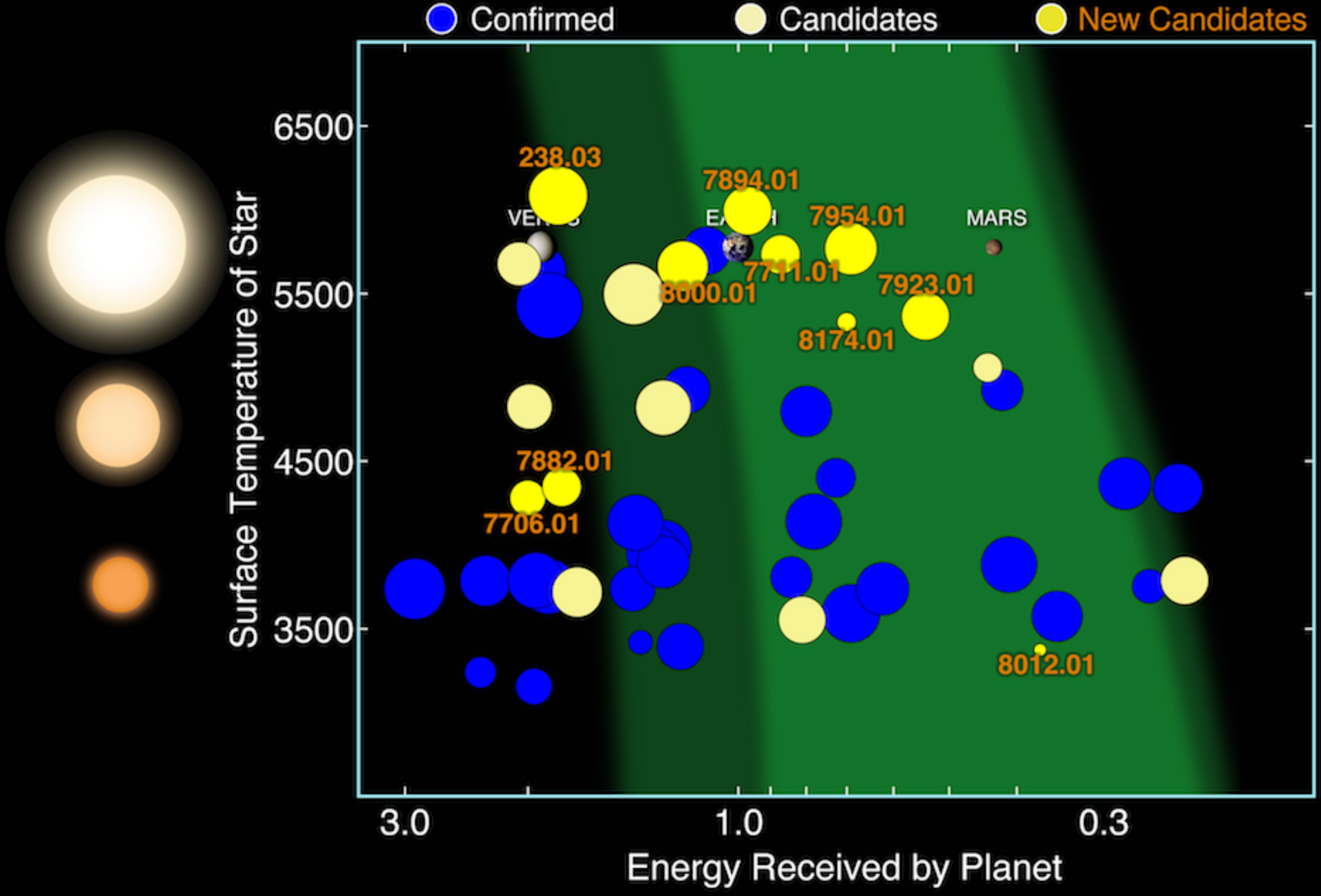
Fressin et al. (2013)

Exoplanet Populations

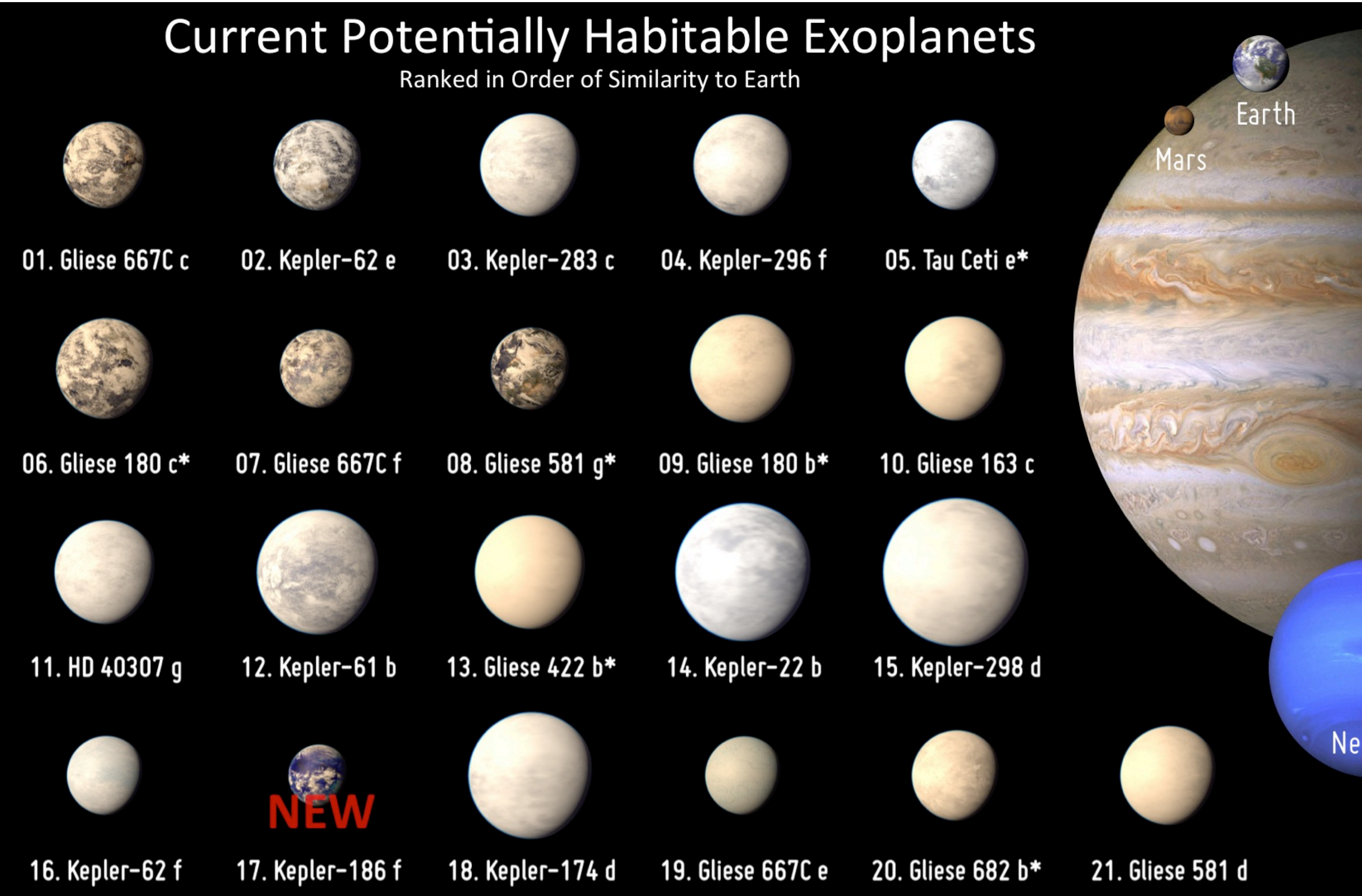


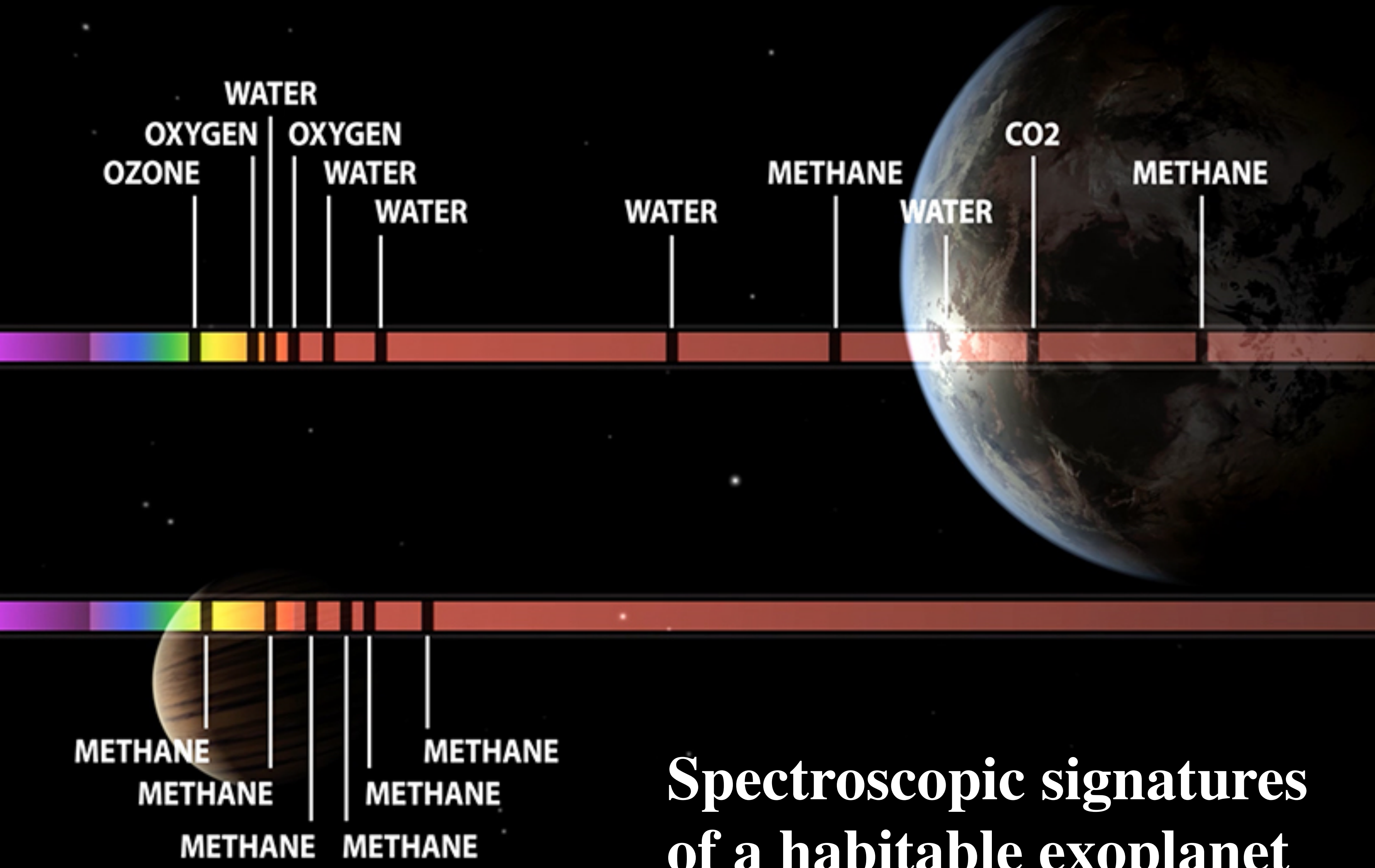
Kepler Habitable Zone Planets

As of June 2017



Planets in the Habitable Zones

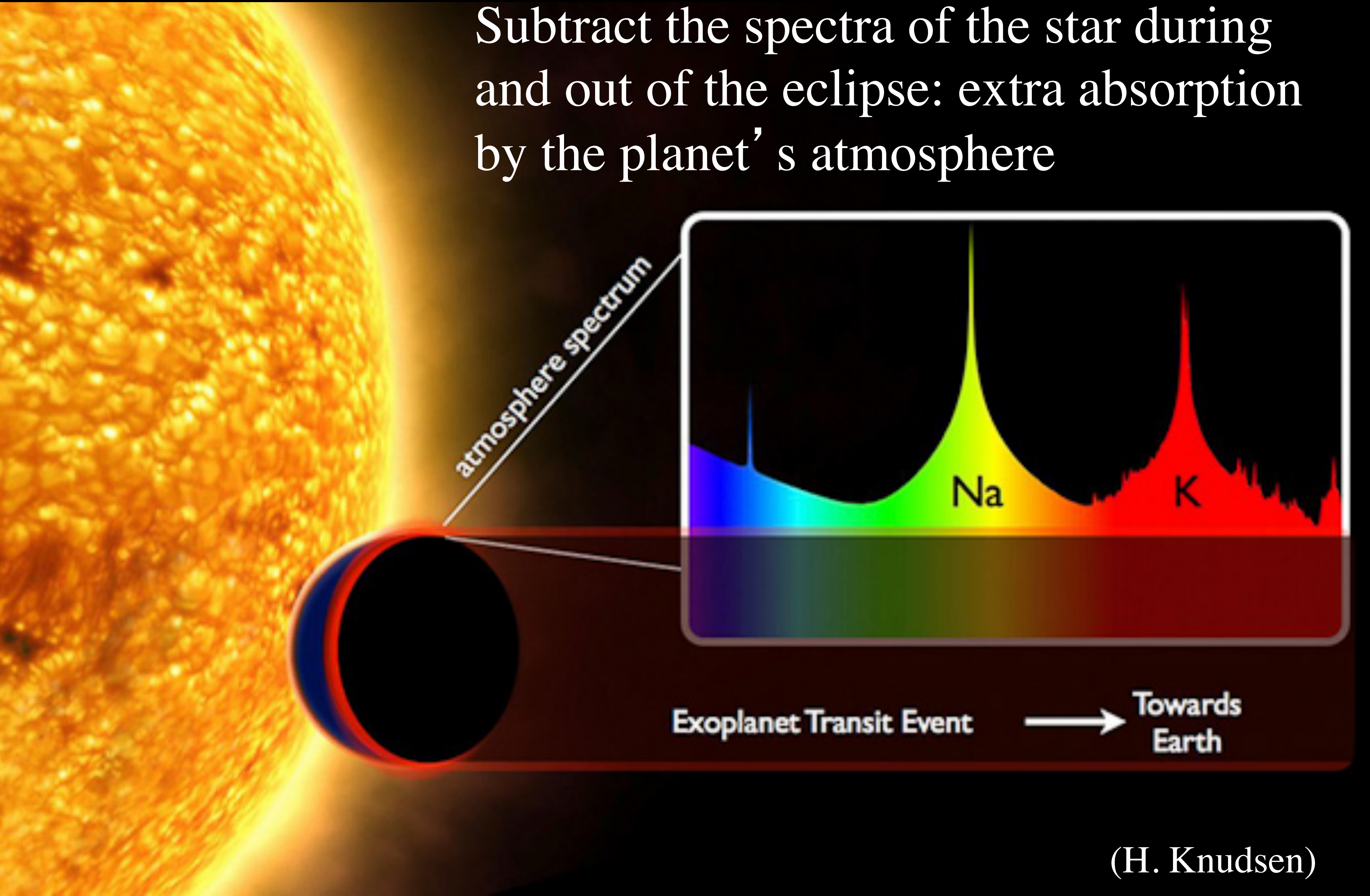




Spectroscopic signatures of a habitable exoplanet

Observing the Exoplanet Atmospheres

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



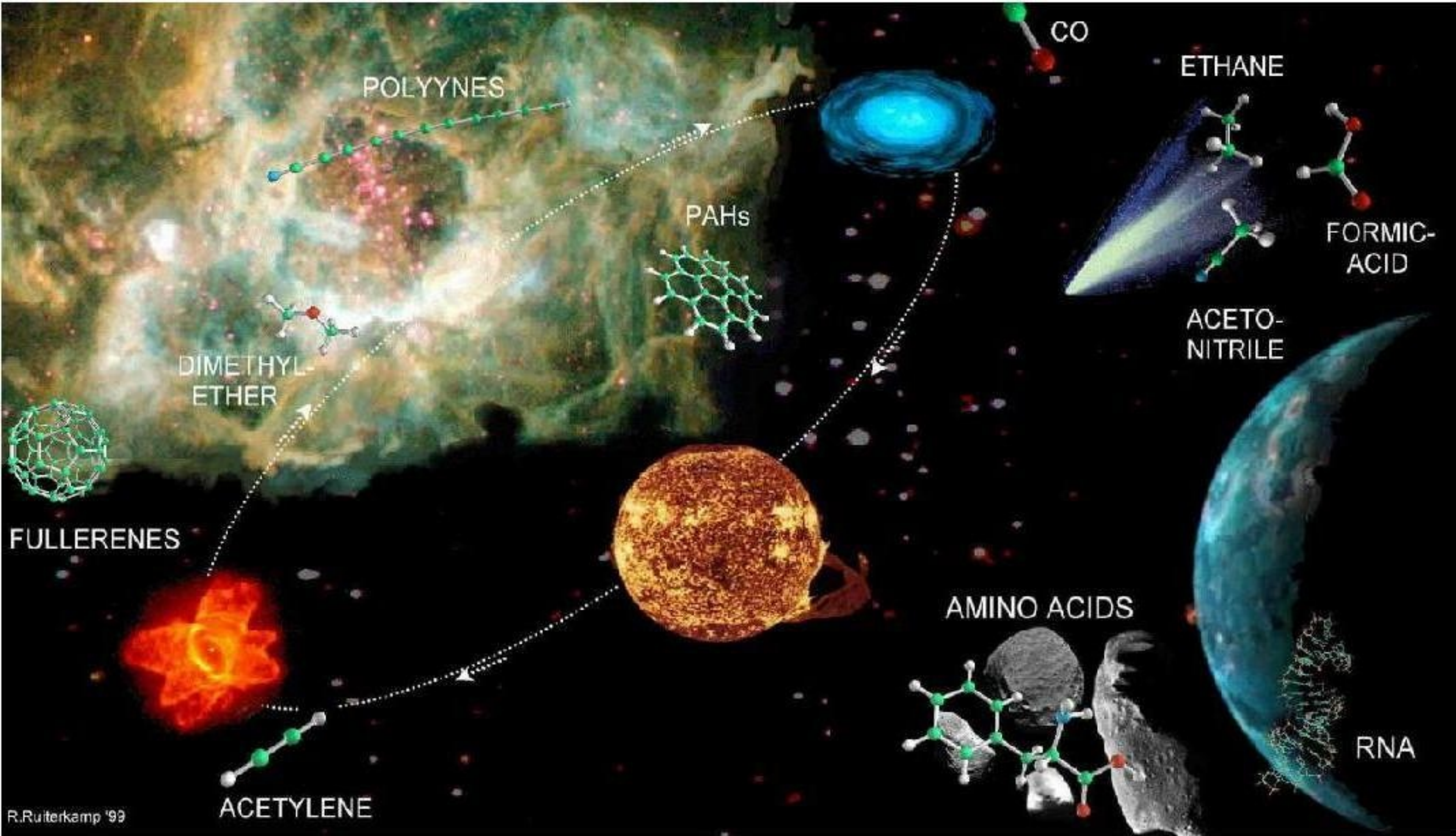
(H. Knudsen)

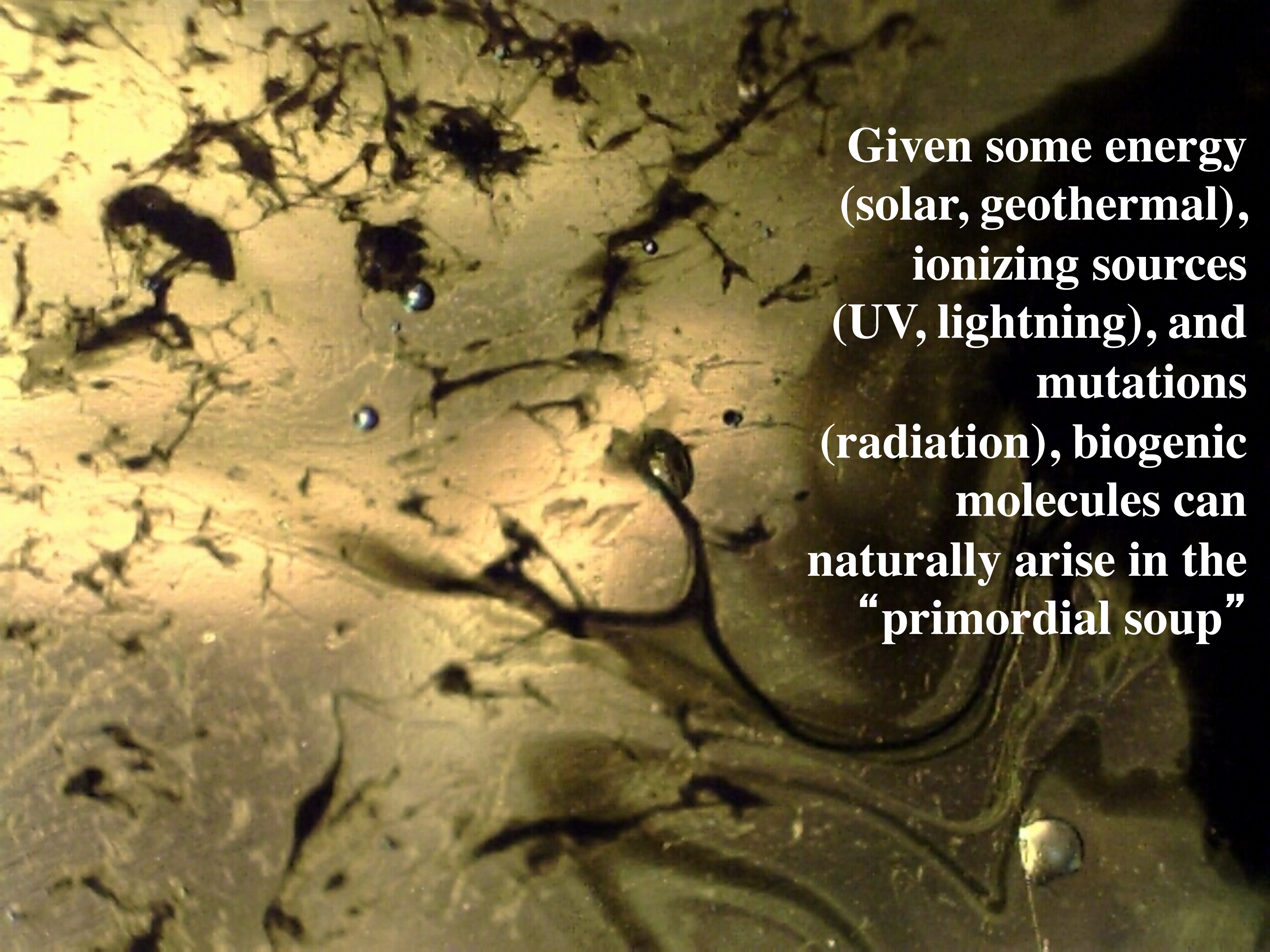
Rogue or Interstellar Planets

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

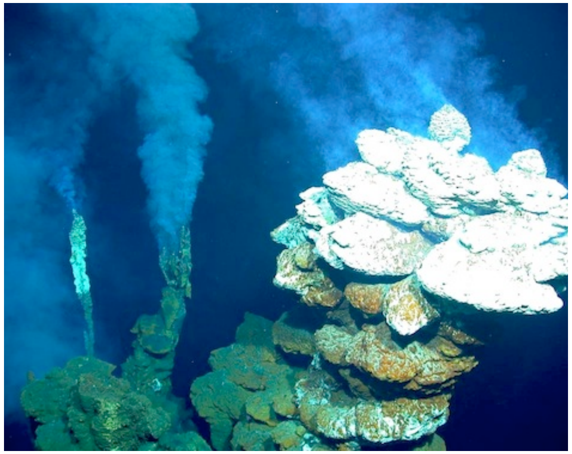




Given some energy (solar, geothermal), ionizing sources (UV, lightning), and mutations (radiation), biogenic molecules can naturally arise in the “primordial soup”

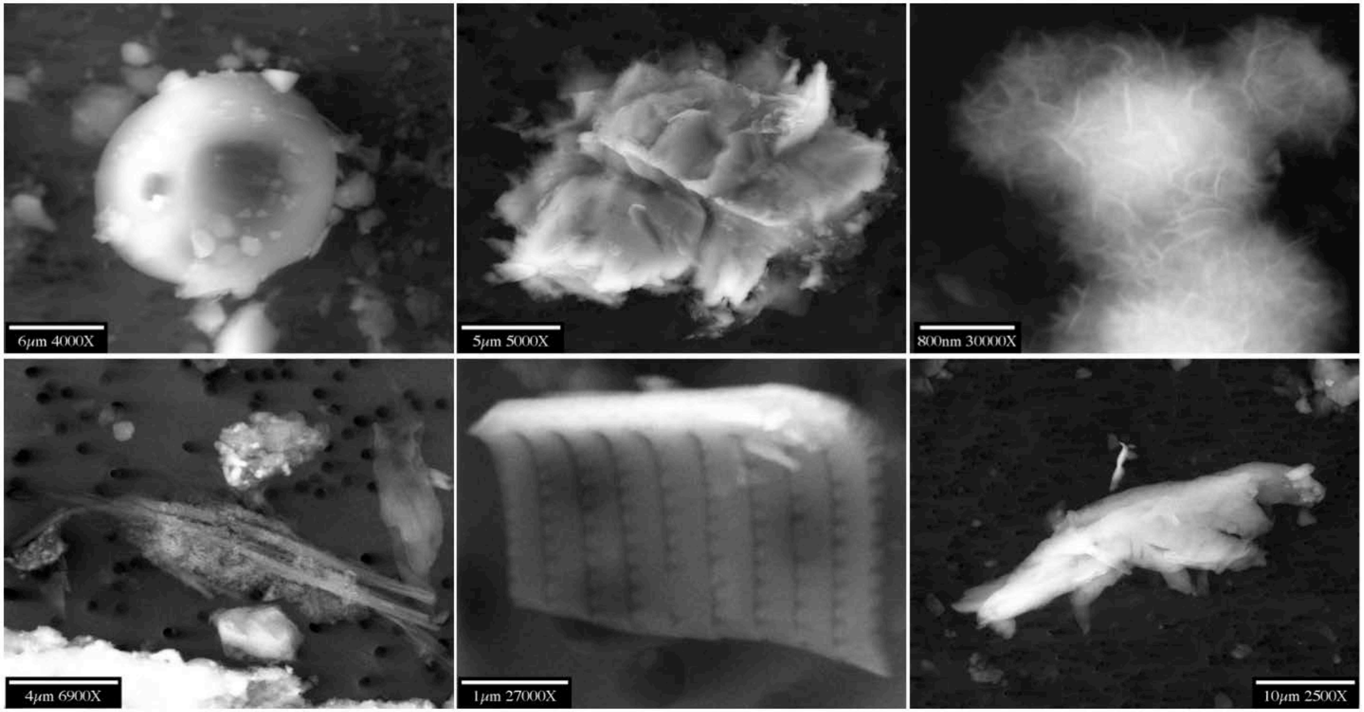
Astrobiology

- 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

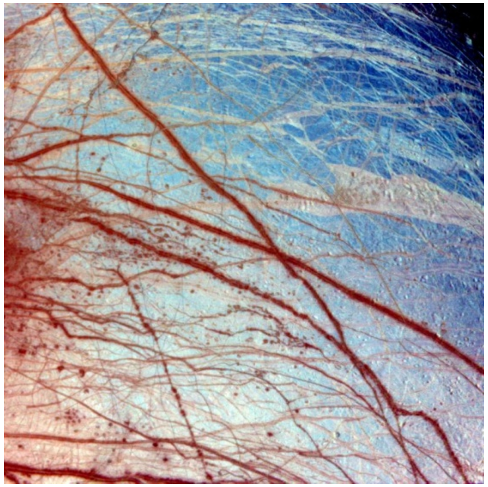
Grand Prismatic Spring, Yellowstone

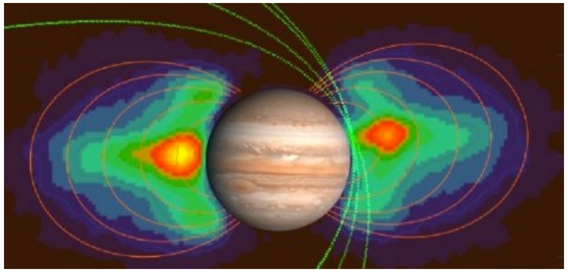


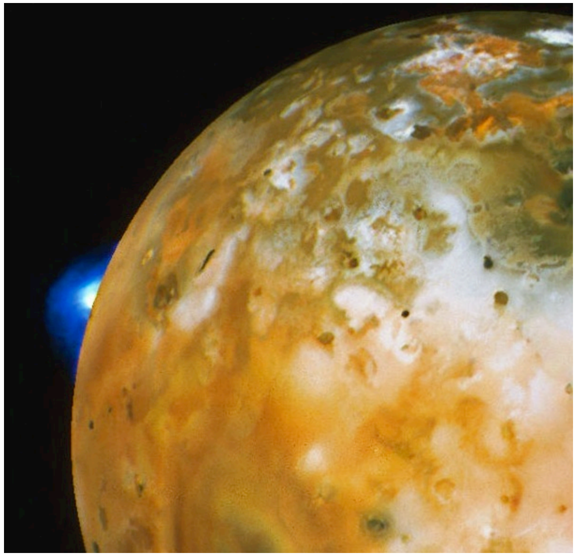
< Microorganisms found under the ice in lake Vostok, Antarctica

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

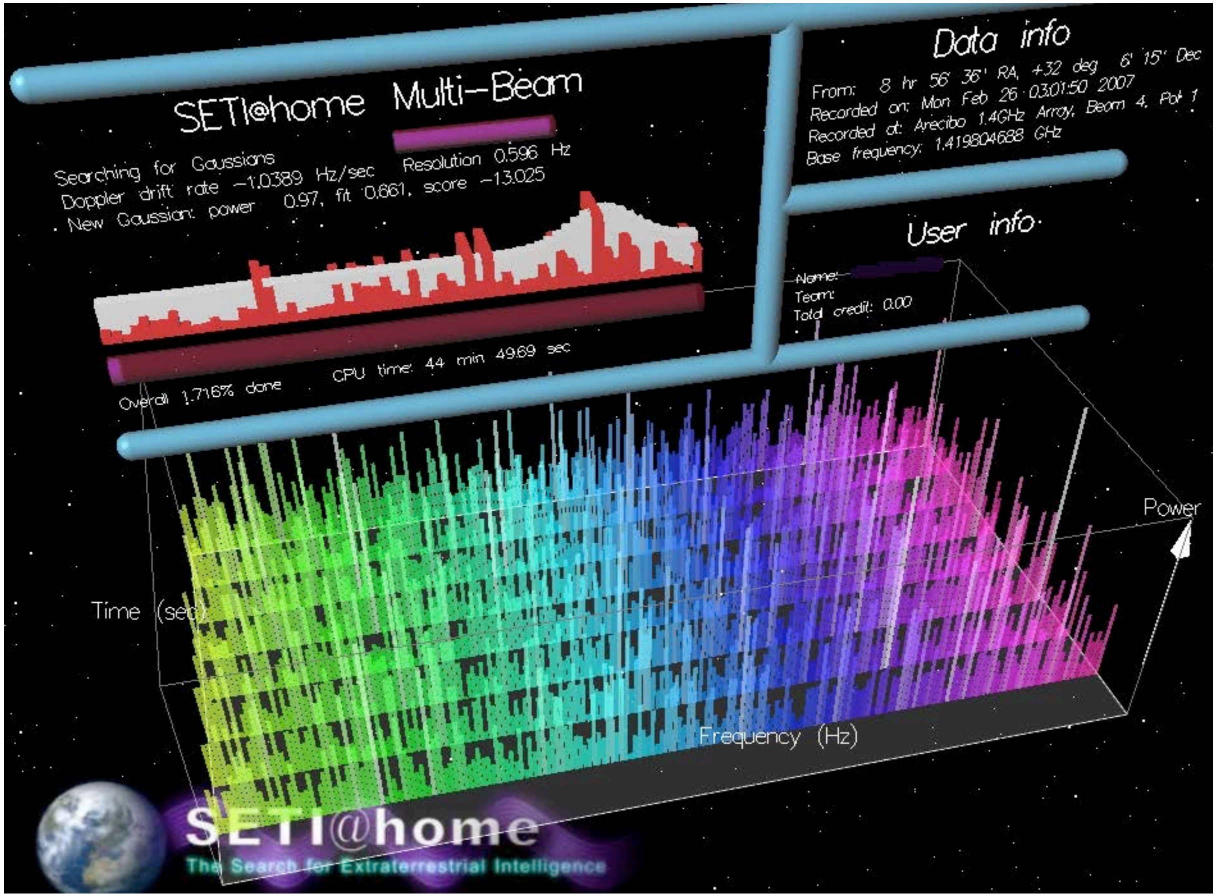






Search for ExtraTerrestrial Intelligence

- 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:



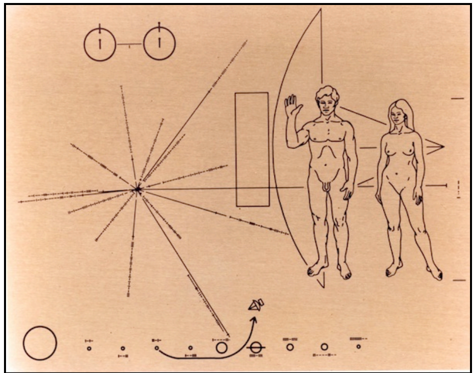
SETI@home Multi-Beam

Searching for Gaussians
Doppler drift rate −1.0389 Hz/sec Resolution 0.596 Hz
New Gaussian: power 0.97, fit 0.661, score −13.025

Overall 1.716% done CPU time: 44 min 49.69 sec

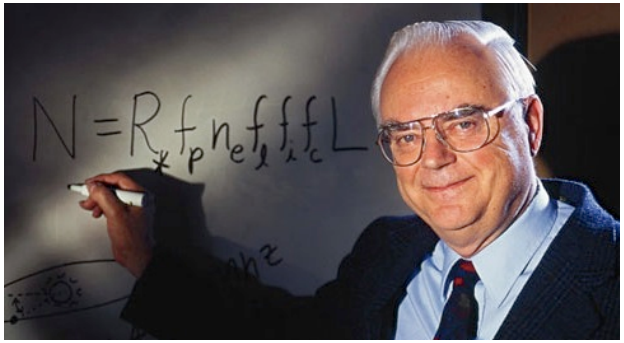
Data info
From: 8 hr 56' 36' RA, +32 deg 6' 15' Dec
Recorded on: Mon Feb 26 03:01:50 2007
Recorded at: Arecibo 1.4GHz Array, Beam 4, Pol 1
Base frequency: 1.419804688 GHz

User info
Name: [redacted]
Team:
Total credit: 0.00



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

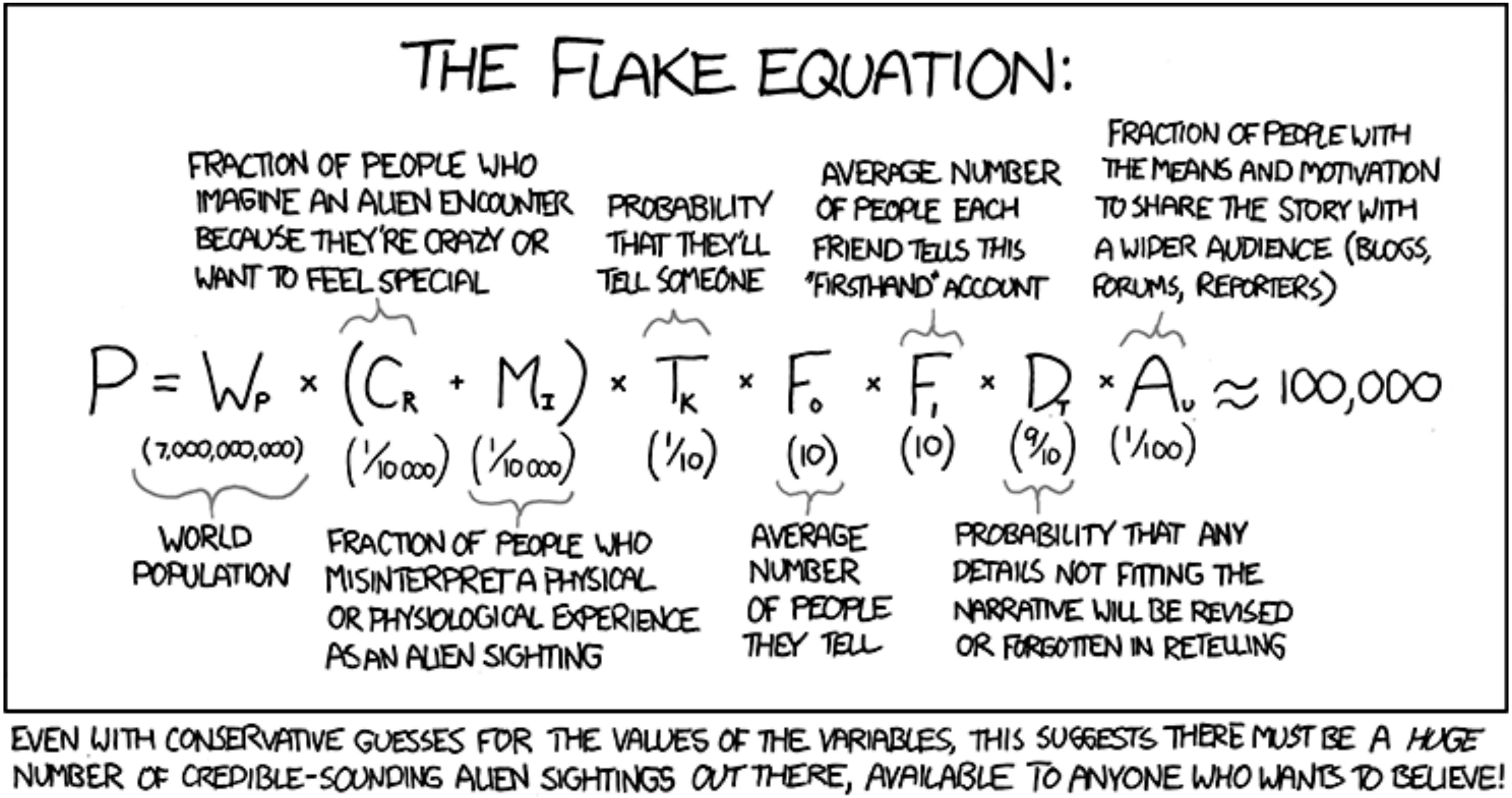
f_{l} = The fraction of suitable planets on which life actually appears

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 FLAKE EQUATION:

FRACTION OF PEOPLE WHO IMAGINE AN ALIEN ENCOUNTER BECAUSE THEY'RE CRAZY OR WANT TO FEEL SPECIAL

PROBABILITY THAT THEY'LL TELL SOMEONE

AVERAGE NUMBER OF PEOPLE EACH FRIEND TELLS THIS "FIRSTHAND" ACCOUNT

FRACTION OF PEOPLE WITH THE MEANS AND MOTIVATION TO SHARE THE STORY WITH A WIDER AUDIENCE (BLOGS, FORUMS, REPORTERS)

$$P = \underset{(7{,}000{,}000{,}000)}{W_P} \times \left(\underset{(1/10\,000)}{C_R} + \underset{(1/10\,000)}{M_I}\right) \times \underset{(1/10)}{T_K} \times \underset{(10)}{F_0} \times \underset{(10)}{F_1} \times \underset{(9/10)}{D_T} \times \underset{(1/100)}{A_U} \approx 100{,}000$$

WORLD POPULATION

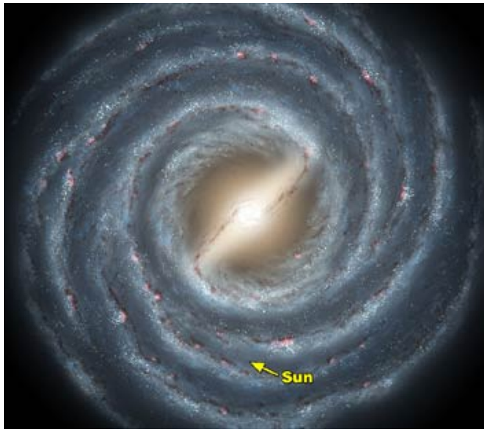
FRACTION OF PEOPLE WHO MISINTERPRET A PHYSICAL OR PHYSIOLOGICAL EXPERIENCE AS AN ALIEN SIGHTING

AVERAGE NUMBER OF PEOPLE THEY TELL

PROBABILITY THAT ANY DETAILS NOT FITTING THE NARRATIVE WILL BE REVISED OR FORGOTTEN IN RETELLING

EVEN WITH CONSERVATIVE GUESSES FOR THE VALUES OF THE VARIABLES, THIS SUGGESTS THERE MUST BE A *HUGE* NUMBER OF CREDIBLE-SOUNDING ALIEN SIGHTINGS OUT THERE, AVAILABLE TO ANYONE WHO WANTS TO BELIEVE!

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?**