Astrobiology
An Overview

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IMPRS Graduate School 🙂

November 20-24, 2023

Daily: 10:00-12:00 & 13:00-14:00

Astrobiology
An Overview

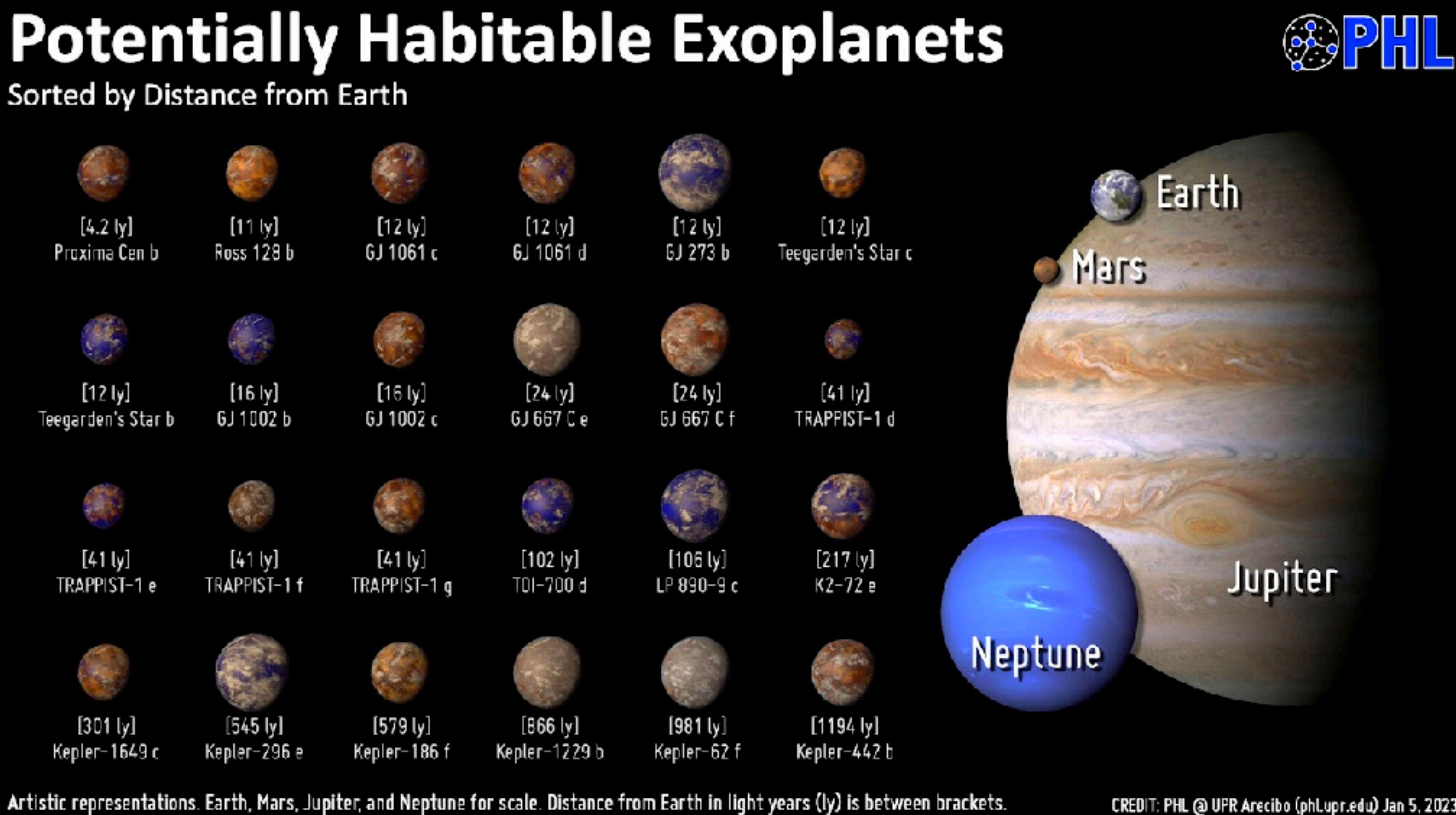
Day 4

Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures

https://www.cosmos.esa.int/web/astrobio/imprs-2023

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

How did we get there in the last 25 years?

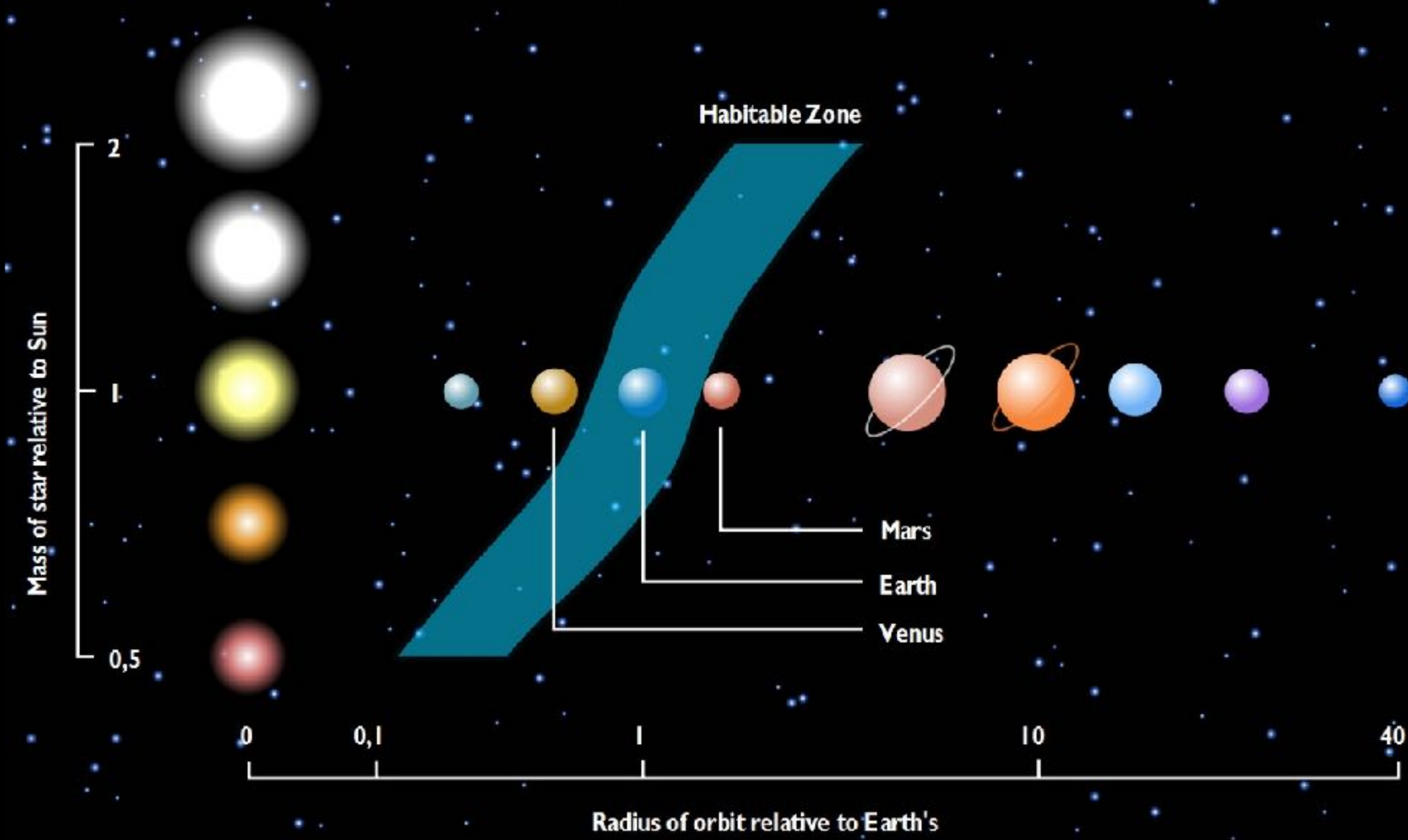


2023 version - Earth, Mars, Jupiter, Neptune are only shown for scale

Explore for a few minutes the 'Planetary Habitability Laboratory'

(http://phl.upr.edu/projects/habitable-exoplanets-catalog) ?

The Habitable Zone around Stars


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

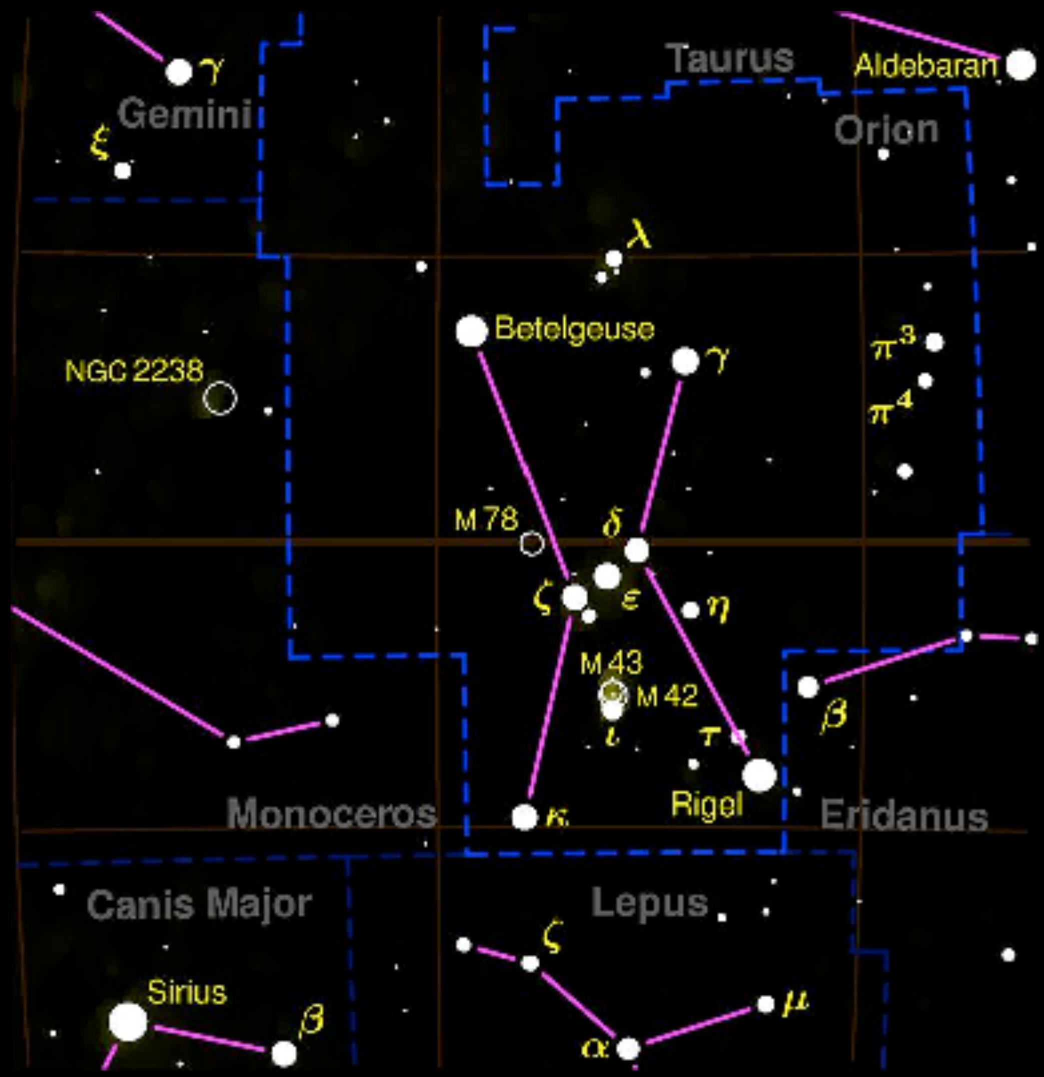
Planets around massive stars

What are the lifetimes of O,B,A,F stars?

The two key problems around massive stars

- ★ The short lifetime
  O (20-120 M_o): <10 Myr,
  B (3-20 M_o): ~50Myr,
  A (1.5-3 M_o): <500Myr)

- ★ The strong UV flux



O, B, A stars are too hot

F stars (<1.4 M_{sun})

- ★ lifetime: 2-3 Gyr
- ★ UV 4x Sun (but shielded by atm, or sub-surface)

Planets around low-mass stars

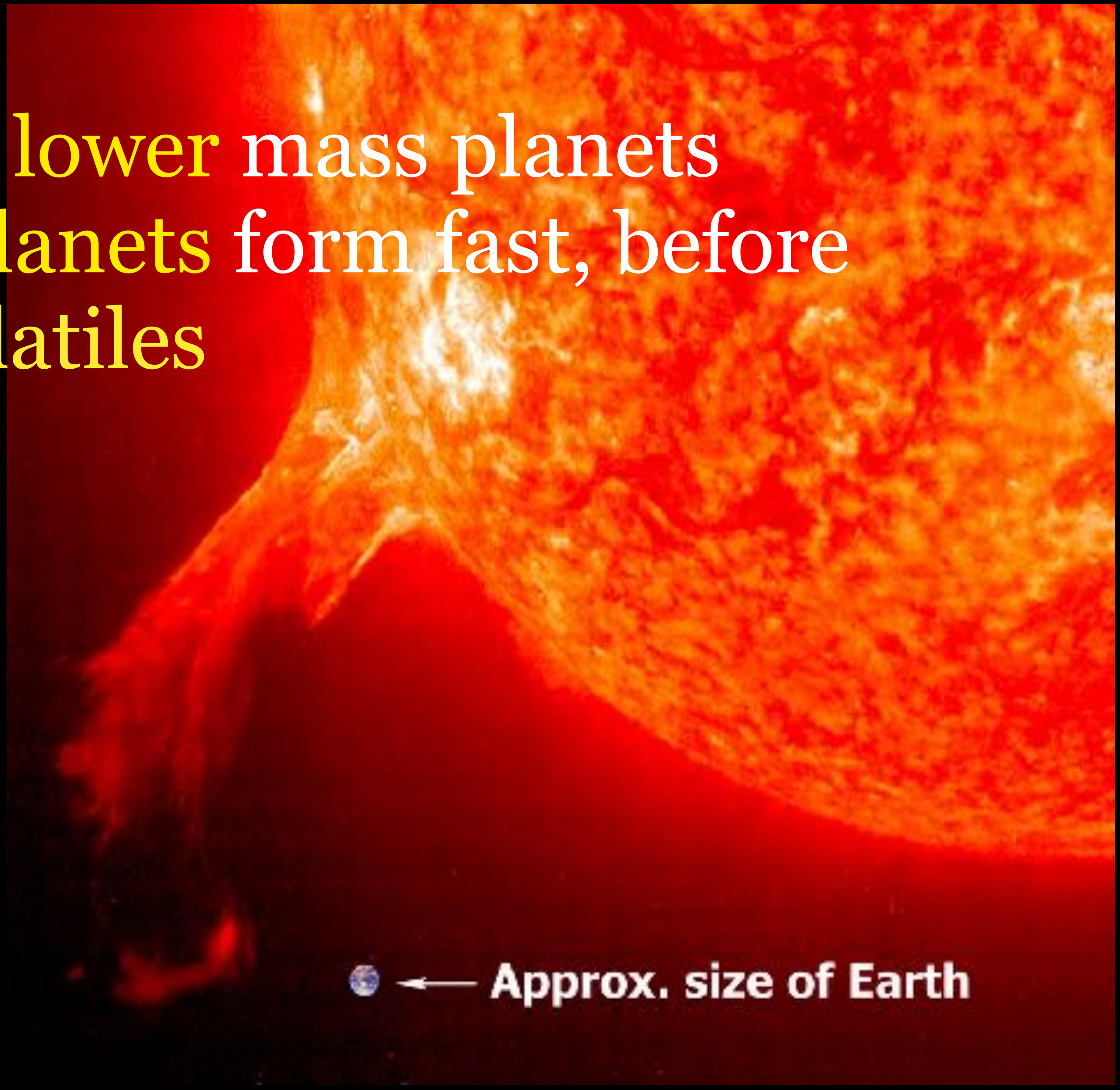
The key problems around low-mass stars
(K stars: 0.45-0.8 M_{sun}, M stars: <0.45 M_{sun})

★ The tidal locking radius

★ Ability to retain an atmosphere vs. flare activity

★ The planet formation process:
not much material available = lower mass planets
and orbital period is short = planets form fast, before
the nebula has time to cool volatiles

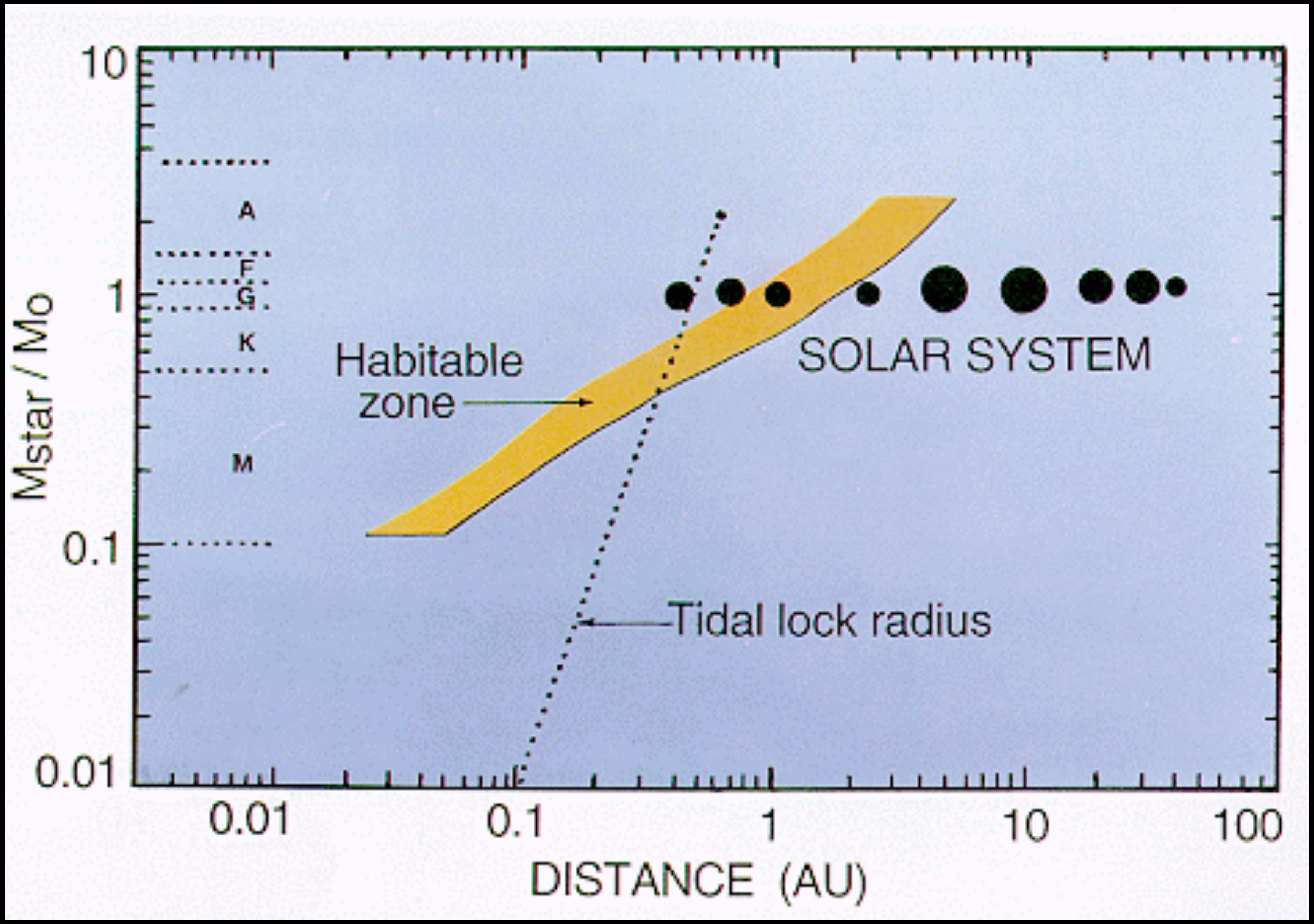
None of the above is a
show stopper

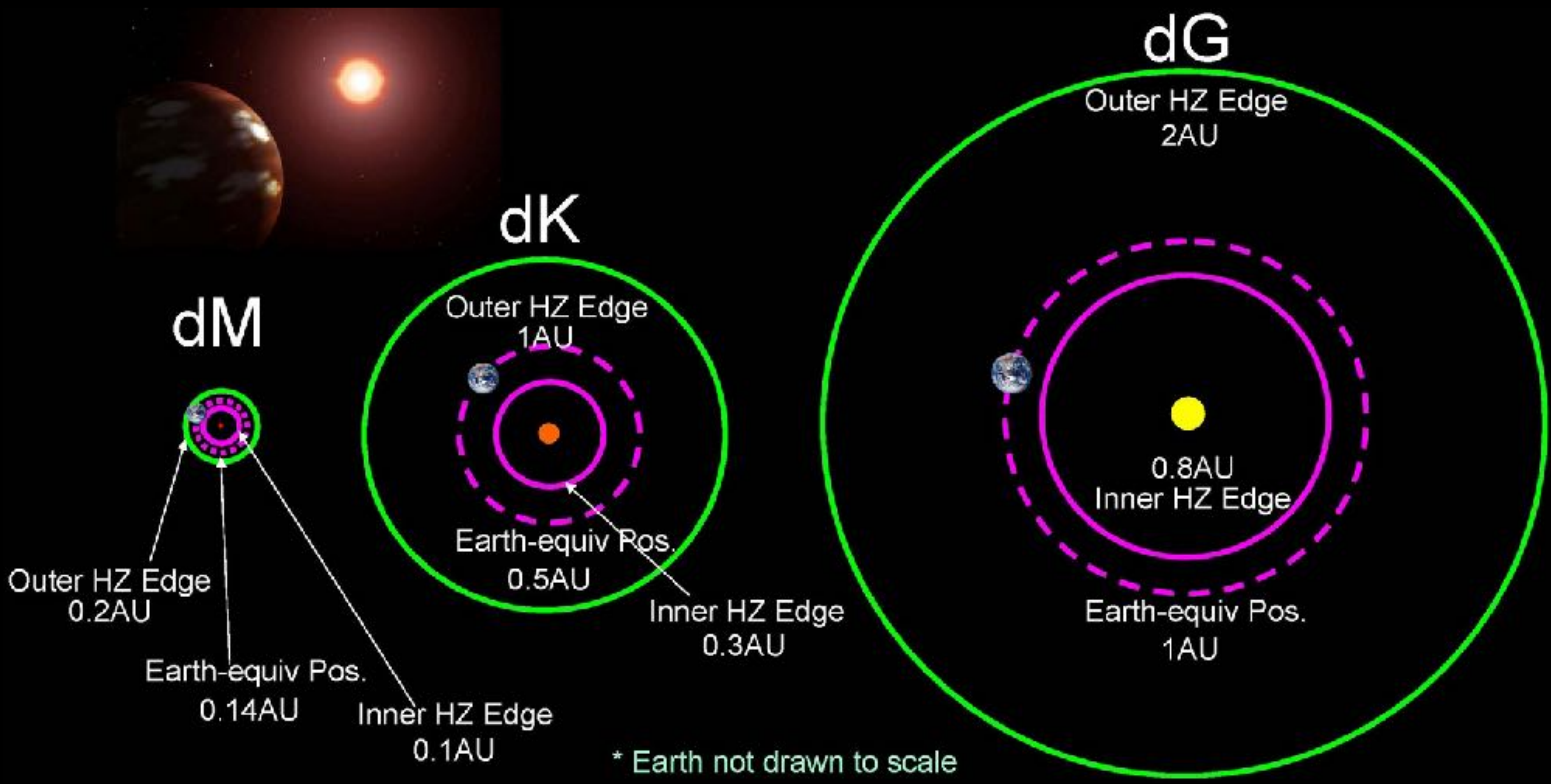


Tidal locking radius: at Earth dissipation rate, in 4.5 Gyr

Solutions:

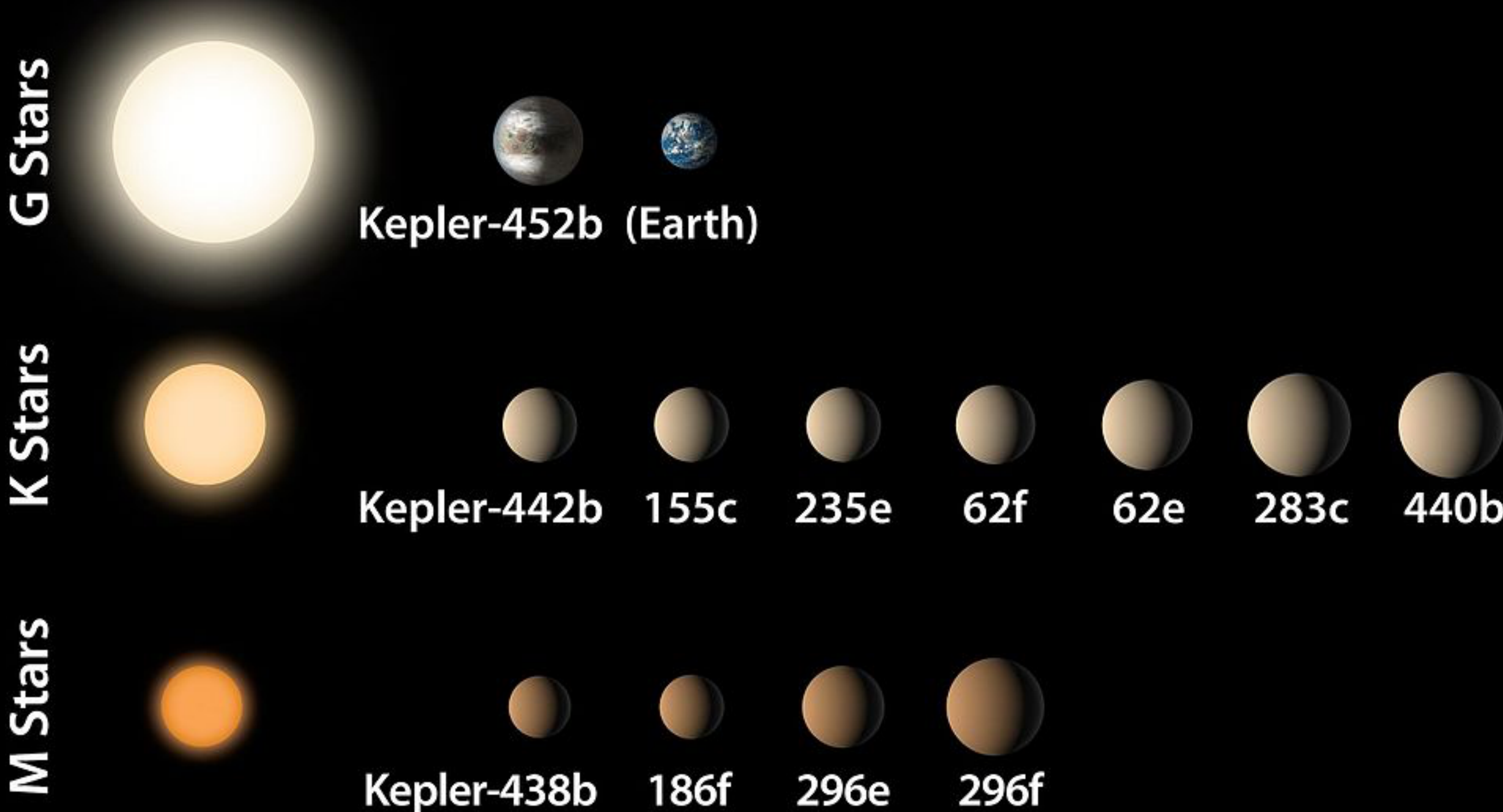
- Spin-Orbit resonance (like 3:2 Mercury)
- Efficient heat transfer (100 x Earth's CO_2 , and/or oceans)




dG
Outer HZ Edge
2AU
0.8AU
Inner HZ Edge
Earth-equiv Pos.
1AU
dK
Outer HZ Edge
1AU
Earth-equiv Pos.
0.5AU
Inner HZ Edge
0.3AU
dM
Outer HZ Edge
0.2AU
Earth-equiv Pos.
0.14AU
Inner HZ Edge
0.1AU
* Earth not drawn to scale

Kepler's Small Habitable Zone Planets

Planets enlarged 25x compared to stars



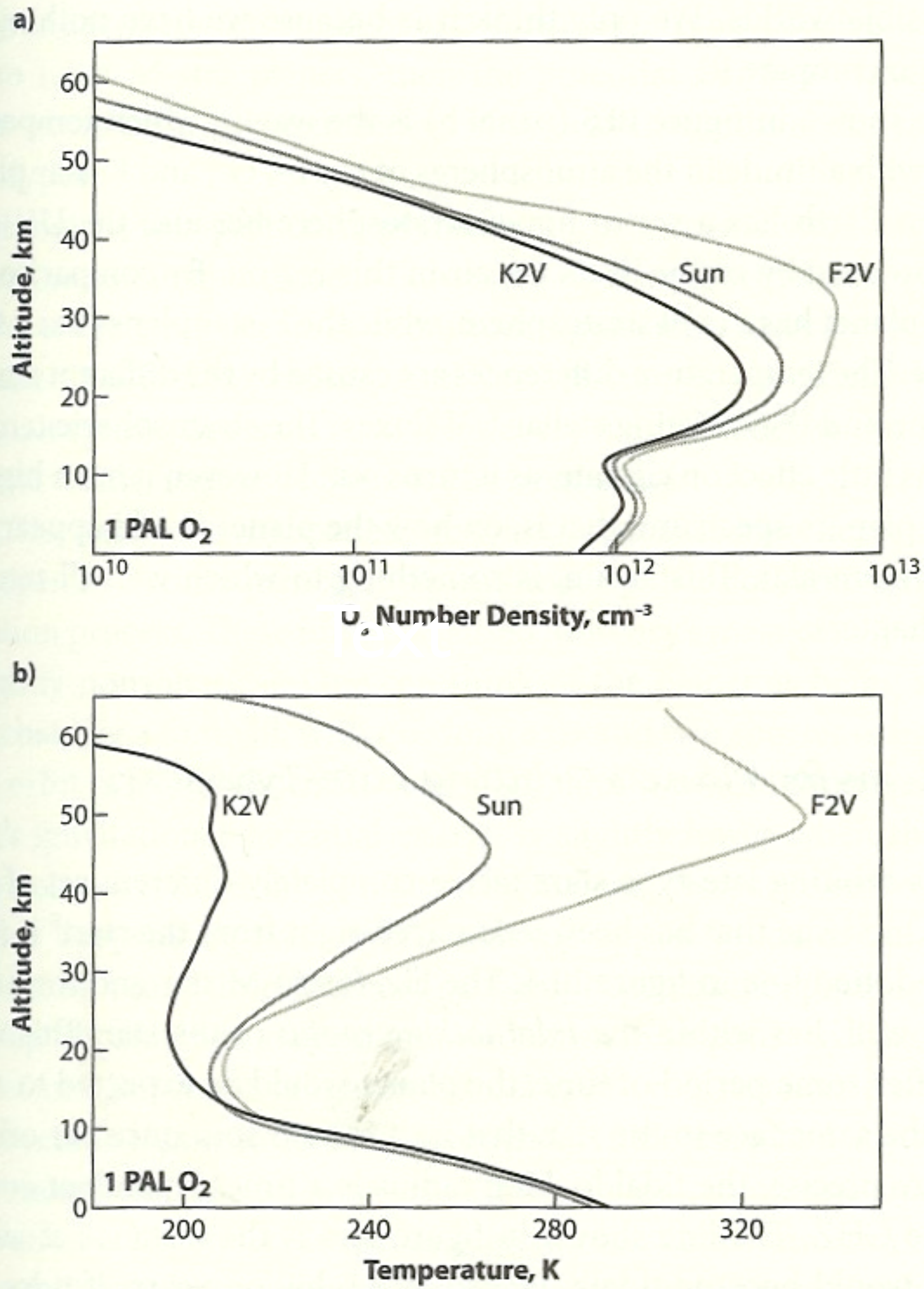
Why are M-dwarf so popular for finding exoplanets?

How many M-dwarfs are there within 10pc?

Best candidates for life as we know it:
F, G, K stars

Ozone

Temperature profile

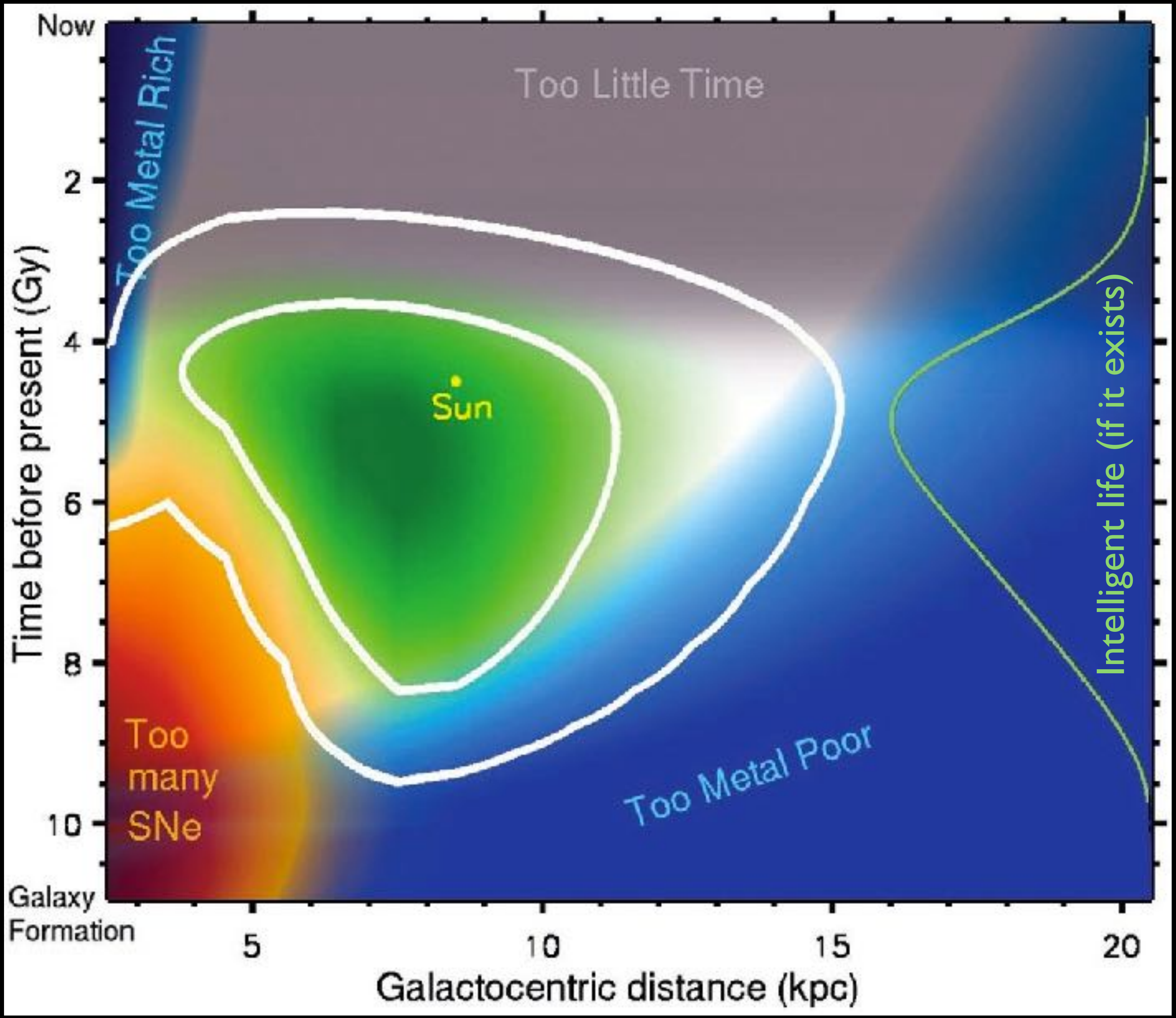


Current estimate: ~40% of all M-dwarfs have rocky planets in their habitable zone…

Expanding the Habitable Zone concept


~100 billion stars....

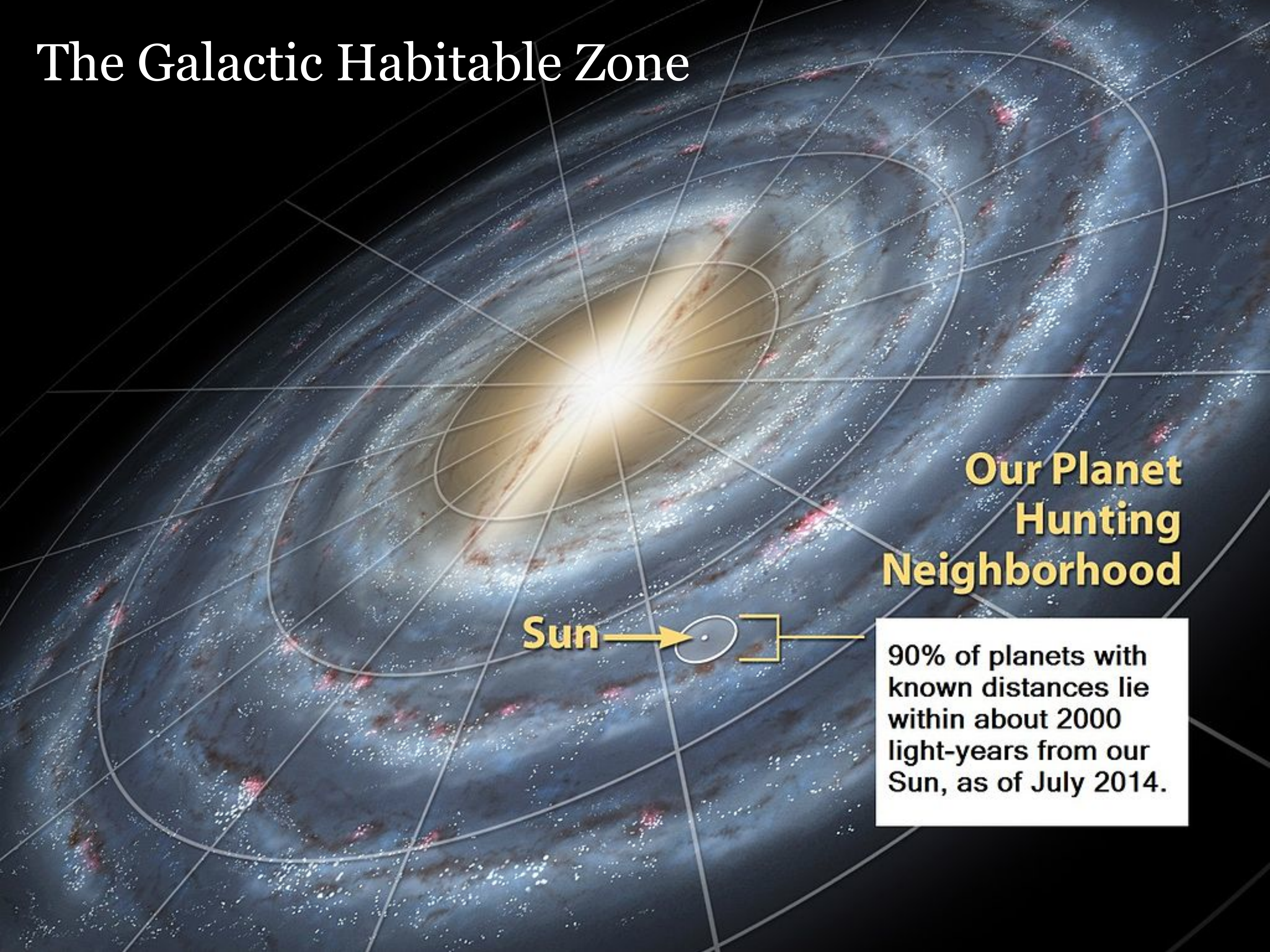
The Galactic Habitable Zone for *complex* Life



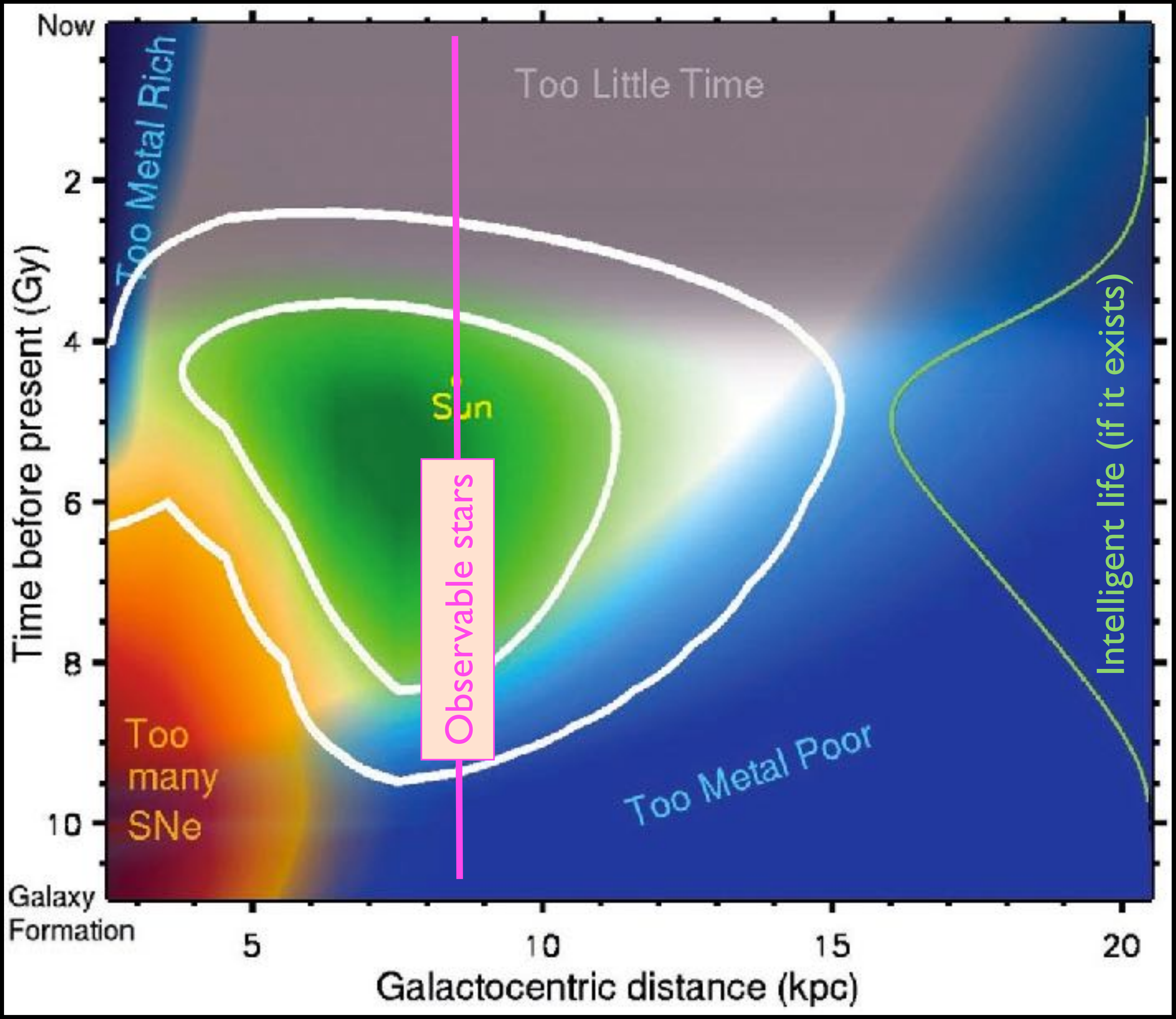
How far can we detect planets?

Where does it put these in the Galactic Habitable Zone?

The Galactic Habitable Zone



The Galactic Habitable Zone for *complex* Life



Exoplanet detection

https://www.youtube.com/watch?v=gai8dMA19Sw

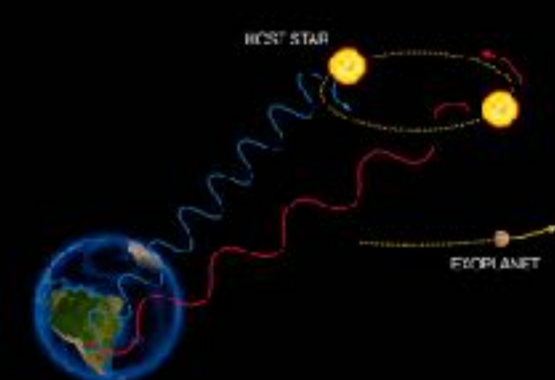
[18 min]

Ever since other Stars were identified as Suns (~400 years ago), people have considered the hypothesis of planets around them.

Detecting exoplanets is difficult…

Exoplanets can:

- reflect radiation
- emit radiation
- absorb or occult radiation
- refract radiation
- affect the motion of nearby matter

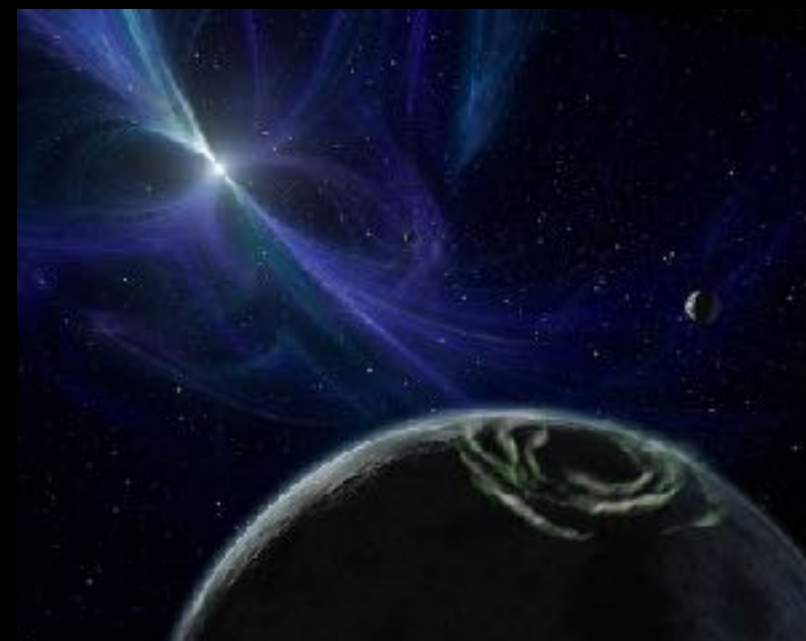


When were exoplanets first discovered?

How old were you?

1937: Peter van der Kamp claims to have found the first exoplanet around Barnard’s star via astrometry (false detection)

1992: Wolszczan & Frail find two planets around a pulsar



1995: Mayor & Queloz find the first planet around a sun-like star

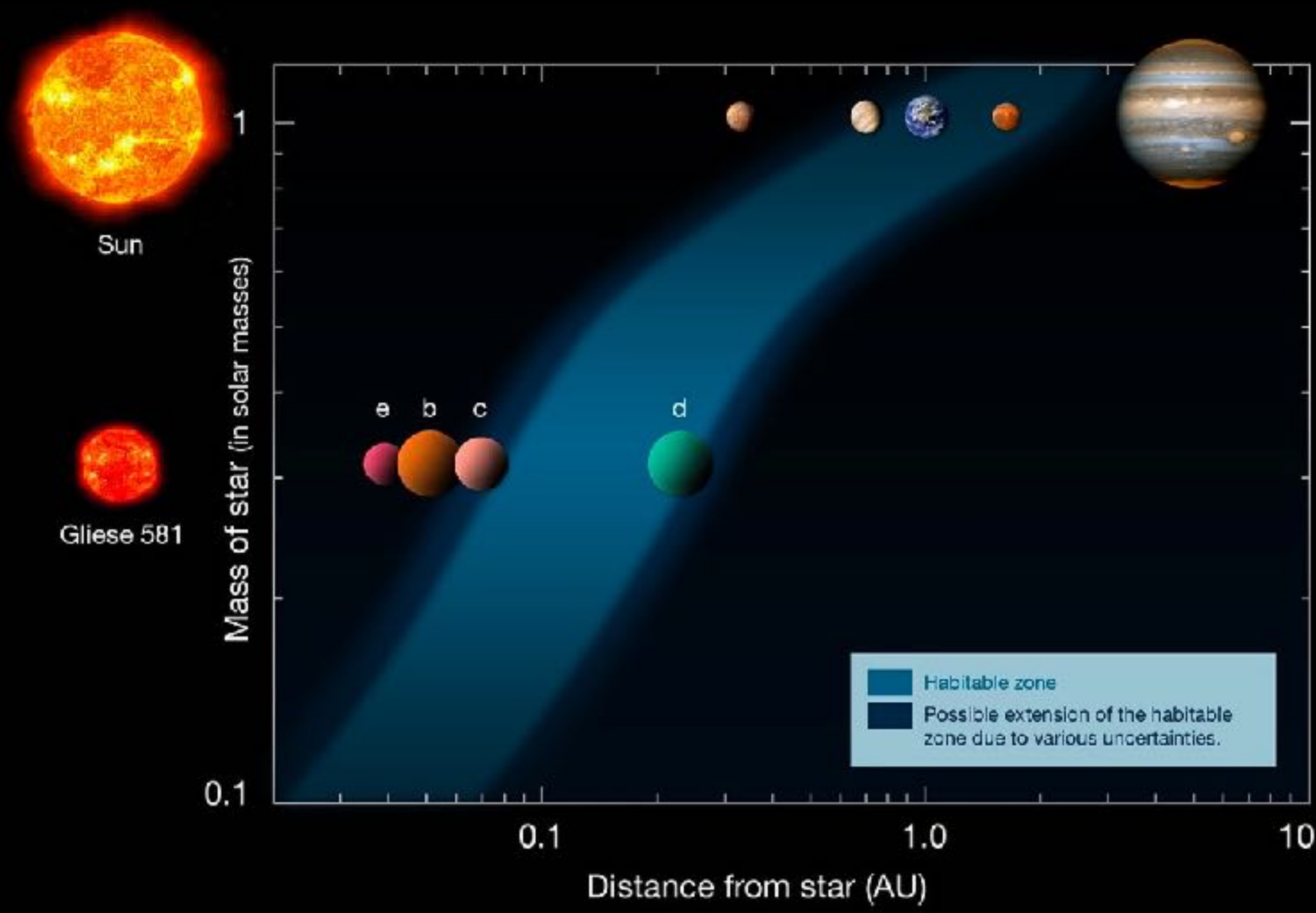
2003: The hundredth exoplanet is discovered

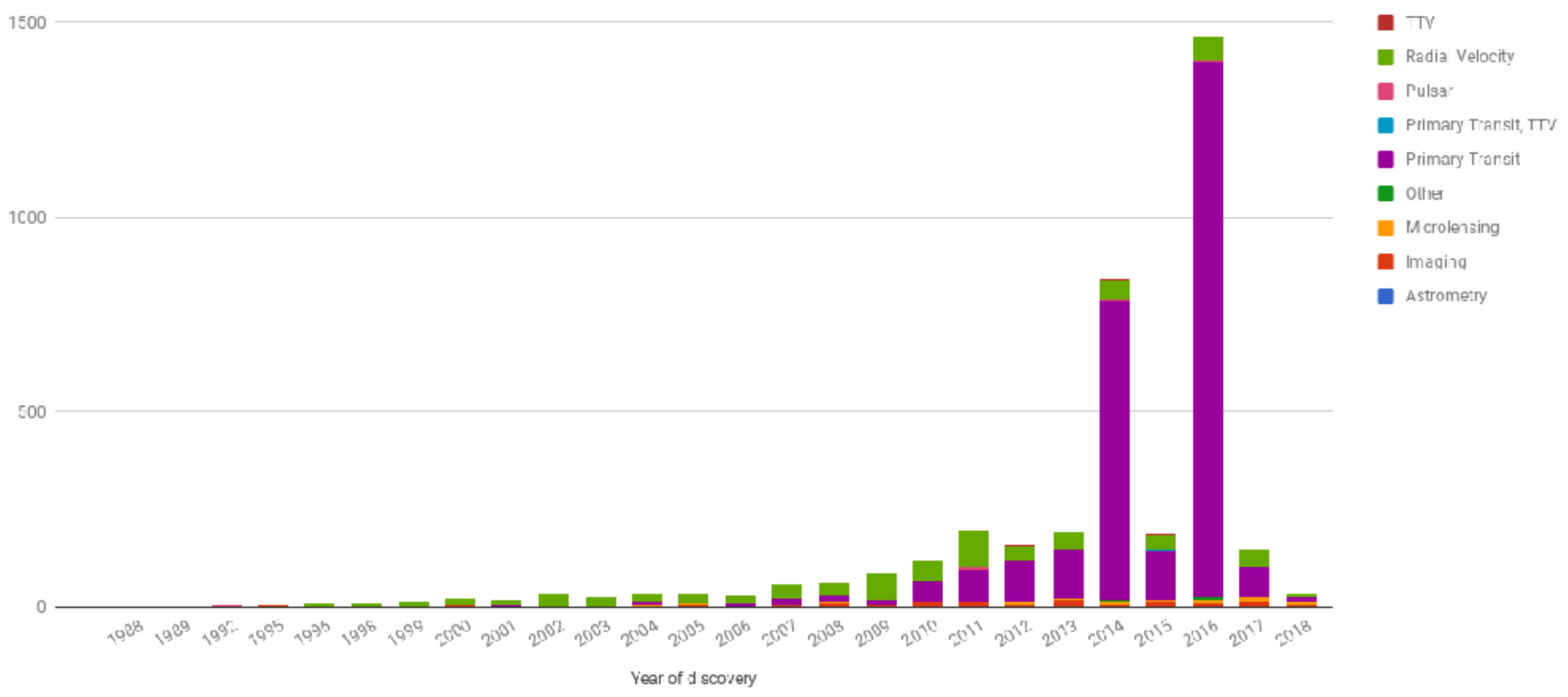
2005: First image of an exoplanet

2005: Water vapor observed in the atmosphere of a transiting exoplanet

2007: First exoplanet discovered in a habitable zone

2009: First telluric exoplanet discovered in a habitable zone



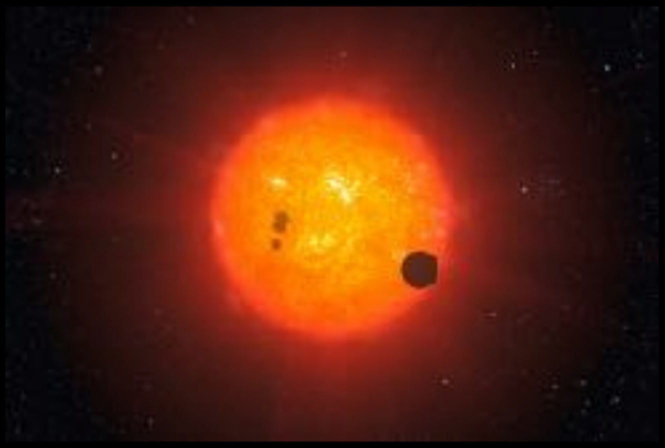

1500
1000
500
0
1988
1989
1992
1995
1996
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year of discovery
TTV
Radial Velocity
Pulsar
Primary Transit, TTV
Primary Transit
Other
Microlensing
Imaging
Astrometry

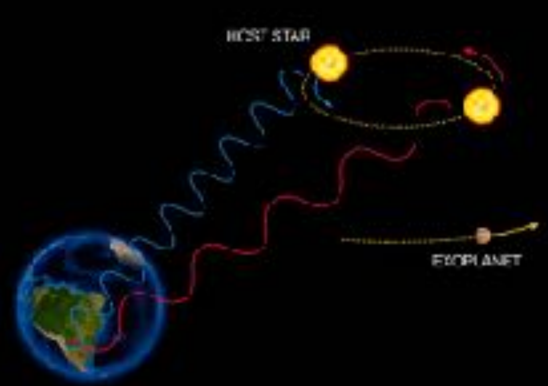
What do you think happened in 2014 and 2016?

Detection Methods

Detecting exoplanets is difficult… but as of August 2, 2016:
4168 exoplanets were discovered: (www.exoplanet.edu)
cf. July 30, 2014: 1811

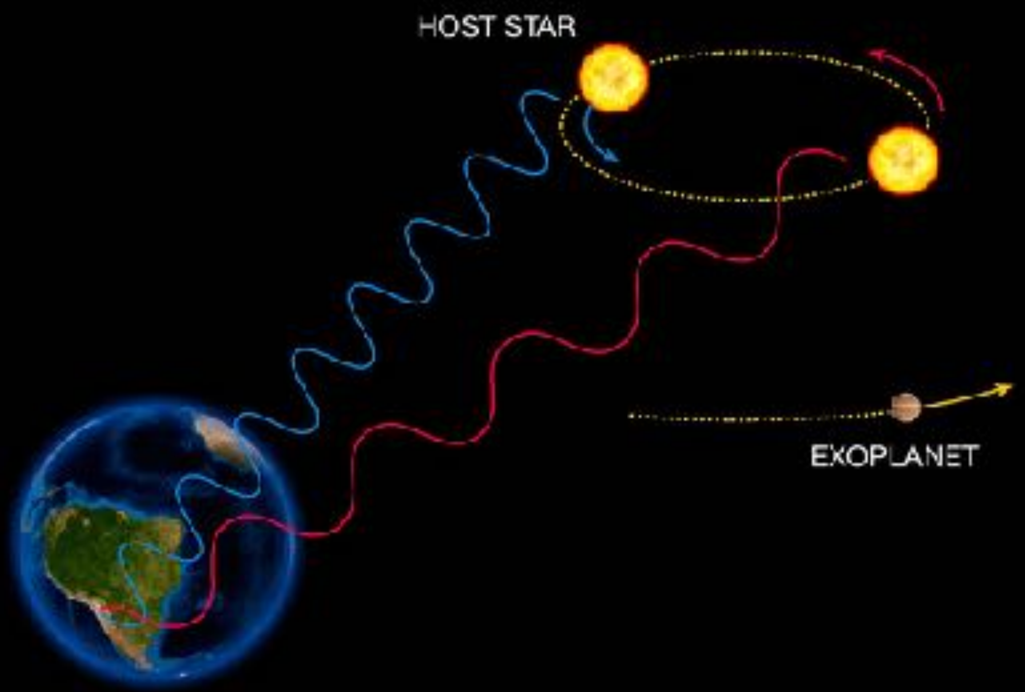
- reflected radiation — Direct imaging: unfavorable contrast (134)
- emitted radiation
- absorb or occult radiation — Transits: 'lucky' alignment (2991)
- refract radiation — Lensing: Rare events (105)
- affect the motion of nearby matter — Radial velocities (880)

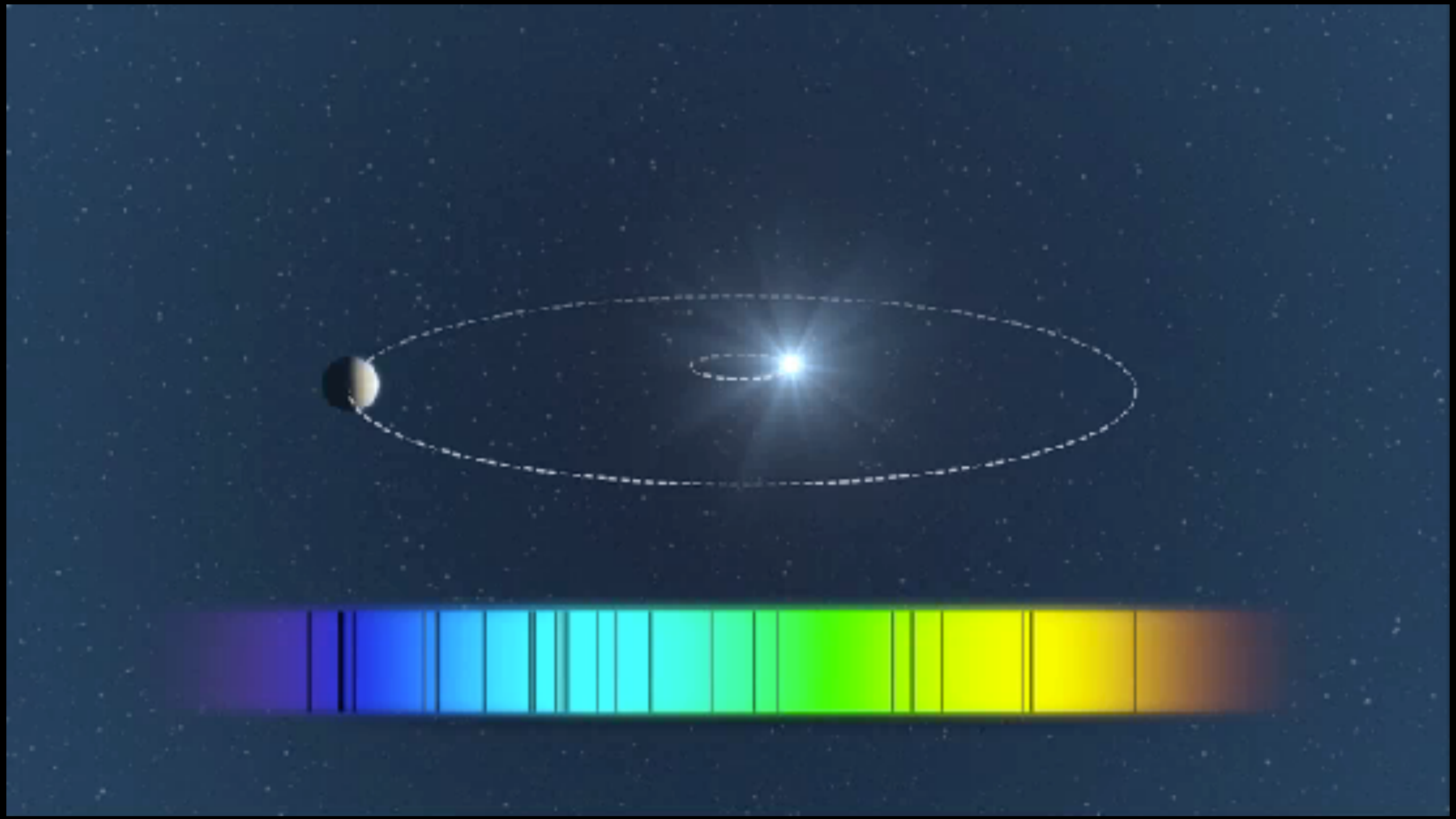




Radial Velocity Method

Radial velocity method





Required precision: ~m/s (Earth ~10 cm/s)

Required patience: Earth n x 1 year, Jupiter n x 10 years

Limits: precision of the spectrographs, photon noise, stellar noise

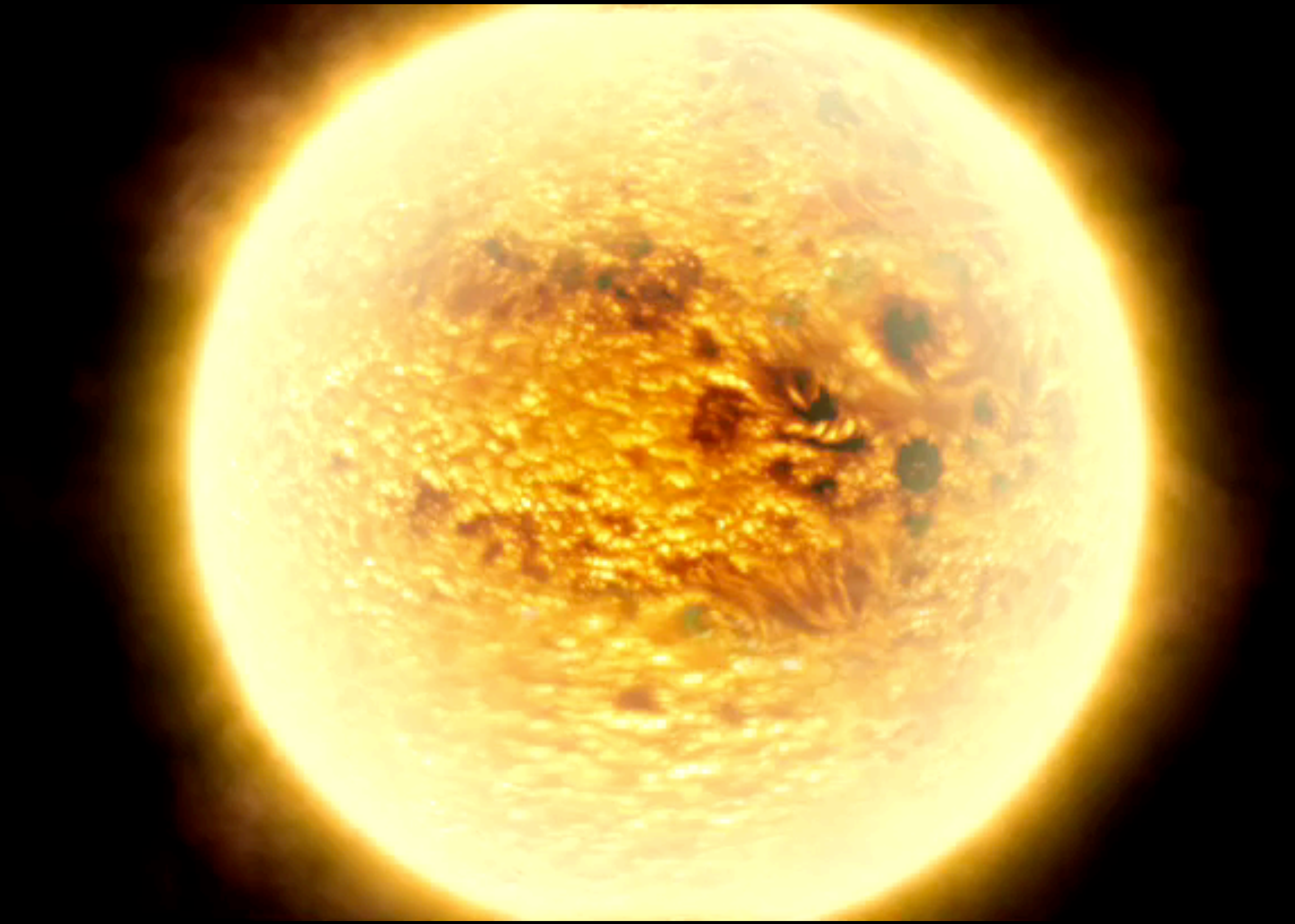
Go to www.exoplanet.eu
plot the year of discovery
against the planet mass.

What becomes apparent?

Take a break...

Planet transit Method

Planet transit method



Required precision: 1.0 - 0.01 % photometry

Required patience: Earth n x 1 year, Jupiter n x 10 years

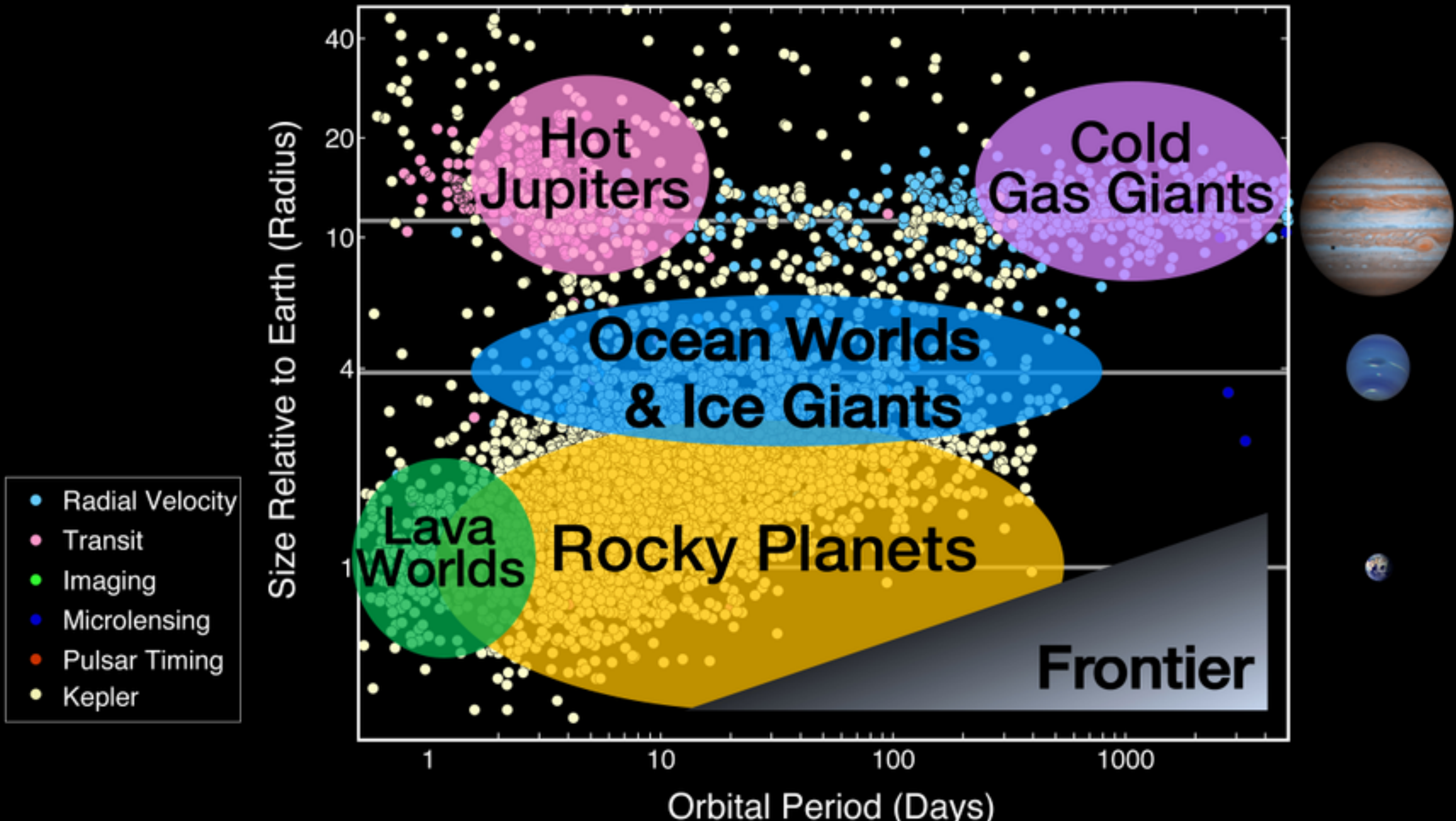
Limits: precision of the photometer, photon noise

Planet transit method

Transit Properties of Solar System Objects

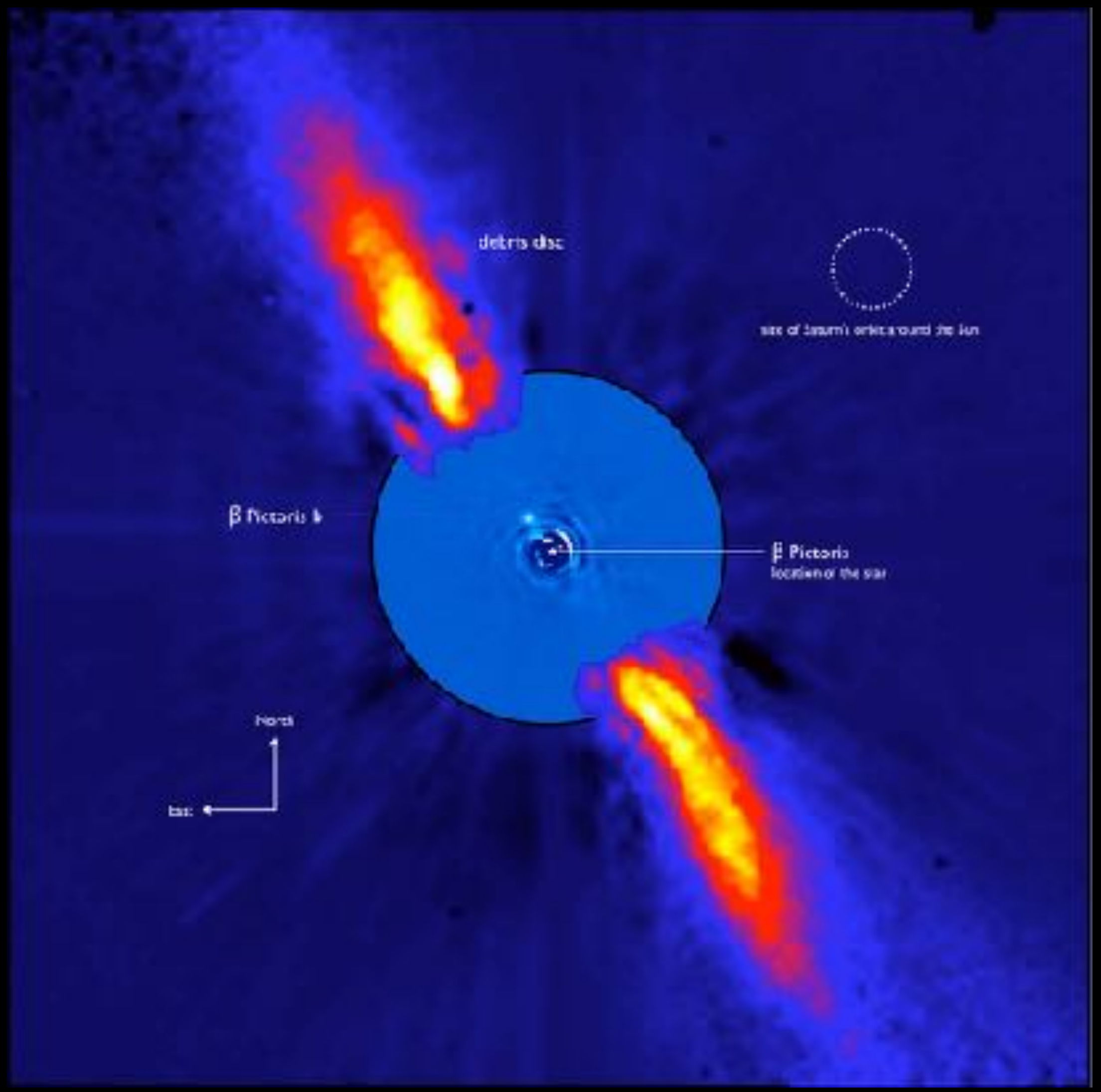
Planet	Orbital Period P (years)	Semi-Major Axis a (A.U.)	**Transit** Duration (hours)	**Transit** Depth (%)	Geometric **Probability** (%)	Inclination Invariant Plane (deg)
Mercury	0.241	0.39	8.1	0.0012	1.19	6.33
Venus	0.615	0.72	11.0	0.0076	0.65	2.16
Earth	1.000	1.00	13.0	0.0084	0.47	1.65
Mars	1.880	1.52	16.0	0.0024	0.31	1.71
Jupiter	11.86	5.20	29.6	1.01	0.089	0.39
Saturn	29.5	9.5	40.1	0.75	0.049	0.87
Uranus	84.0	19.2	57.0	0.135	0.024	1.09
Neptune	164.8	30.1	71.3	0.127	0.015	0.72
	$P^2 M^* = a^3$		13sqrt(a)	$\% = (d_p/d^*)^2$	d^*/D	*phi*

Planet transit method



Direct Imaging

Direct imaging



Required precision: contrast of 10^5 - 10^{10}

Required patience: none (almost)

Limits: image quality, coronography & high-contrast technology

Direct imaging

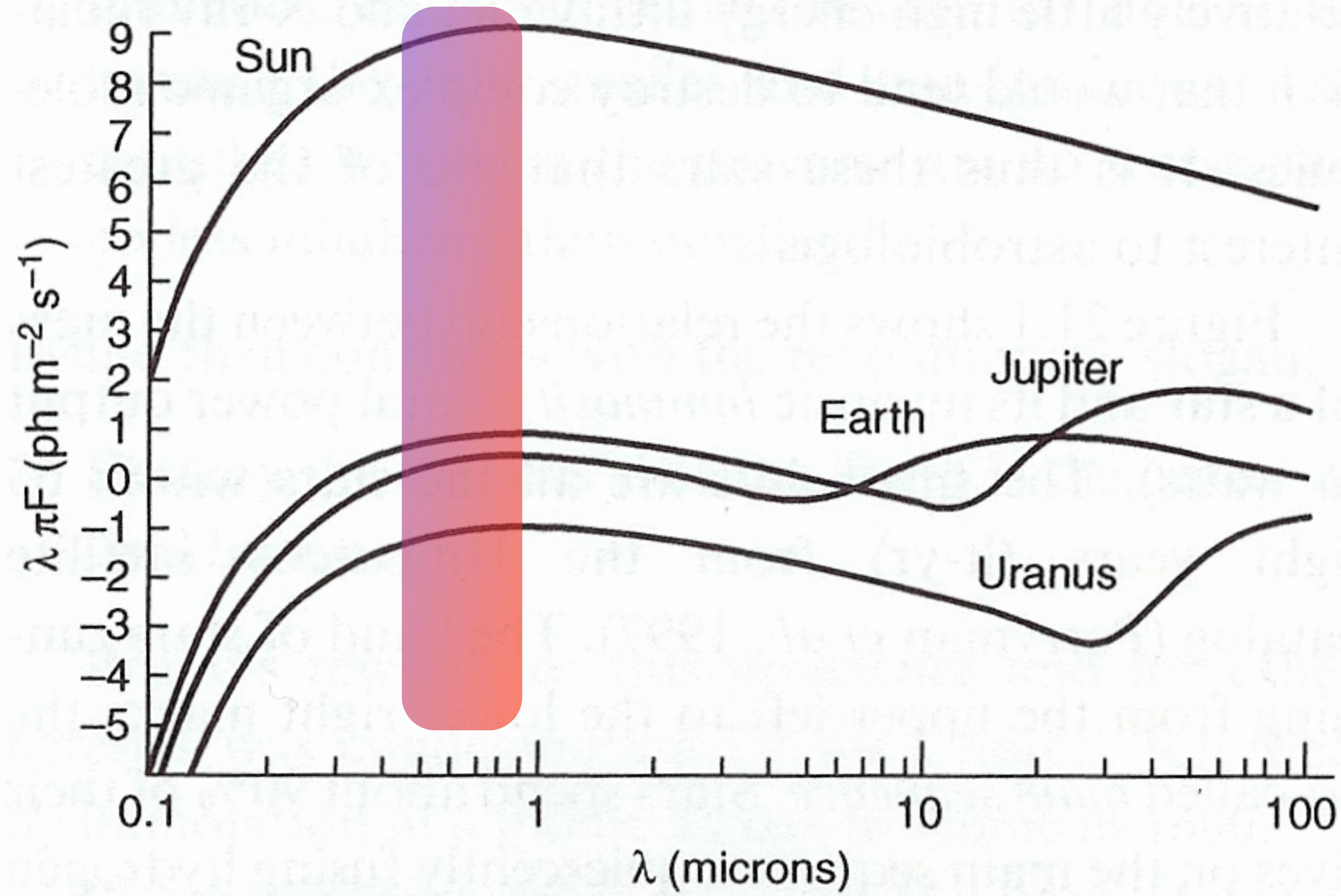


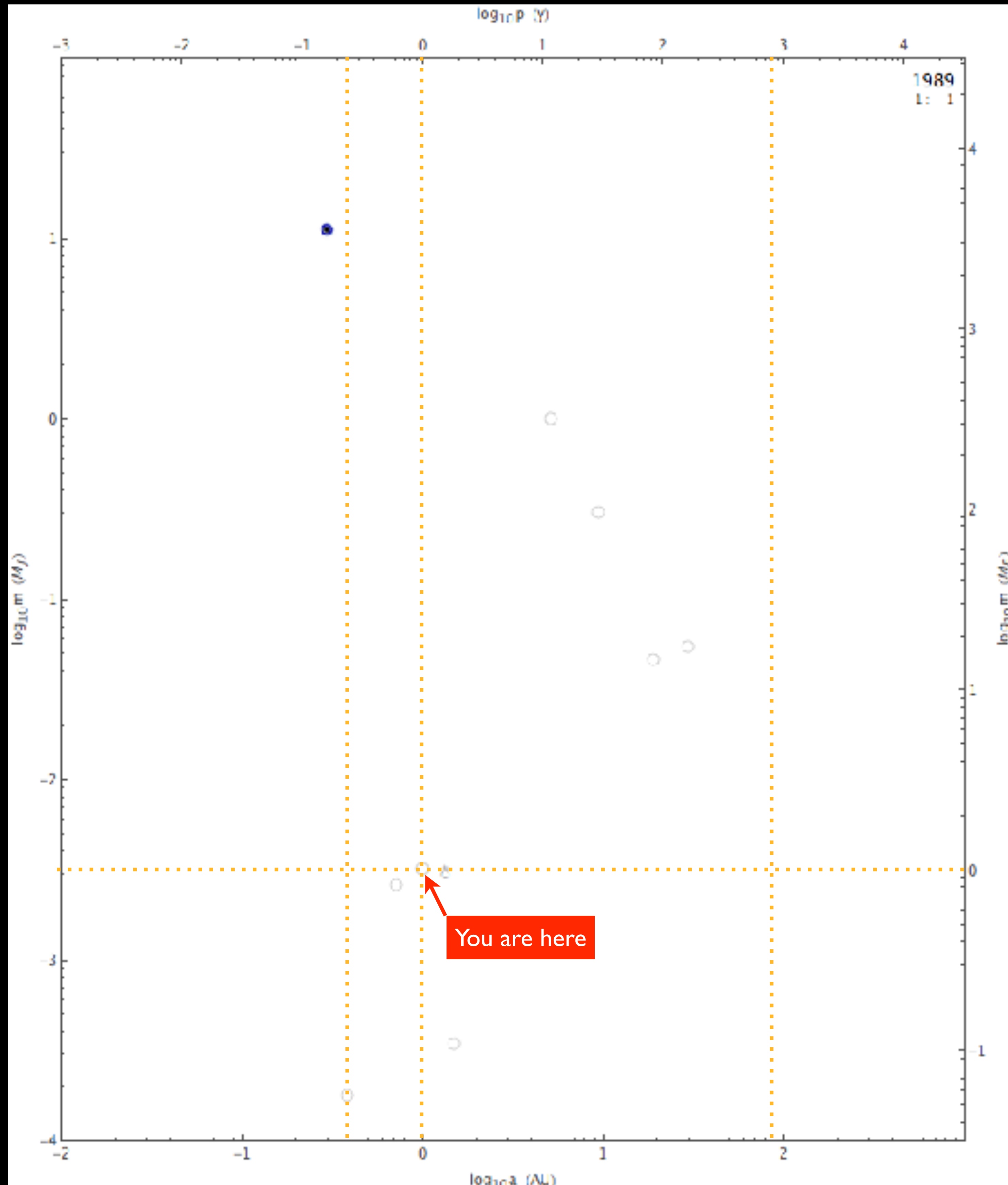
FIGURE 21.2 Spectra of the Sun and Solar System planets; ordinate is log (photons m^{-2} s^{-1}) as observed from a common distance. In the visual region (~0.6 microns) the Sun is $\sim 10^9$ brighter than Jupiter. This contrast improves to $\sim 10^5$ in the mid-infrared, while the Earth is $\sim 10^6$ times fainter than the Sun in the mid-infrared. (NASA/JPL/Caltech.)

At what angular separation from its star would Earth appear at 10 pc?

What contrast would be need to see it?

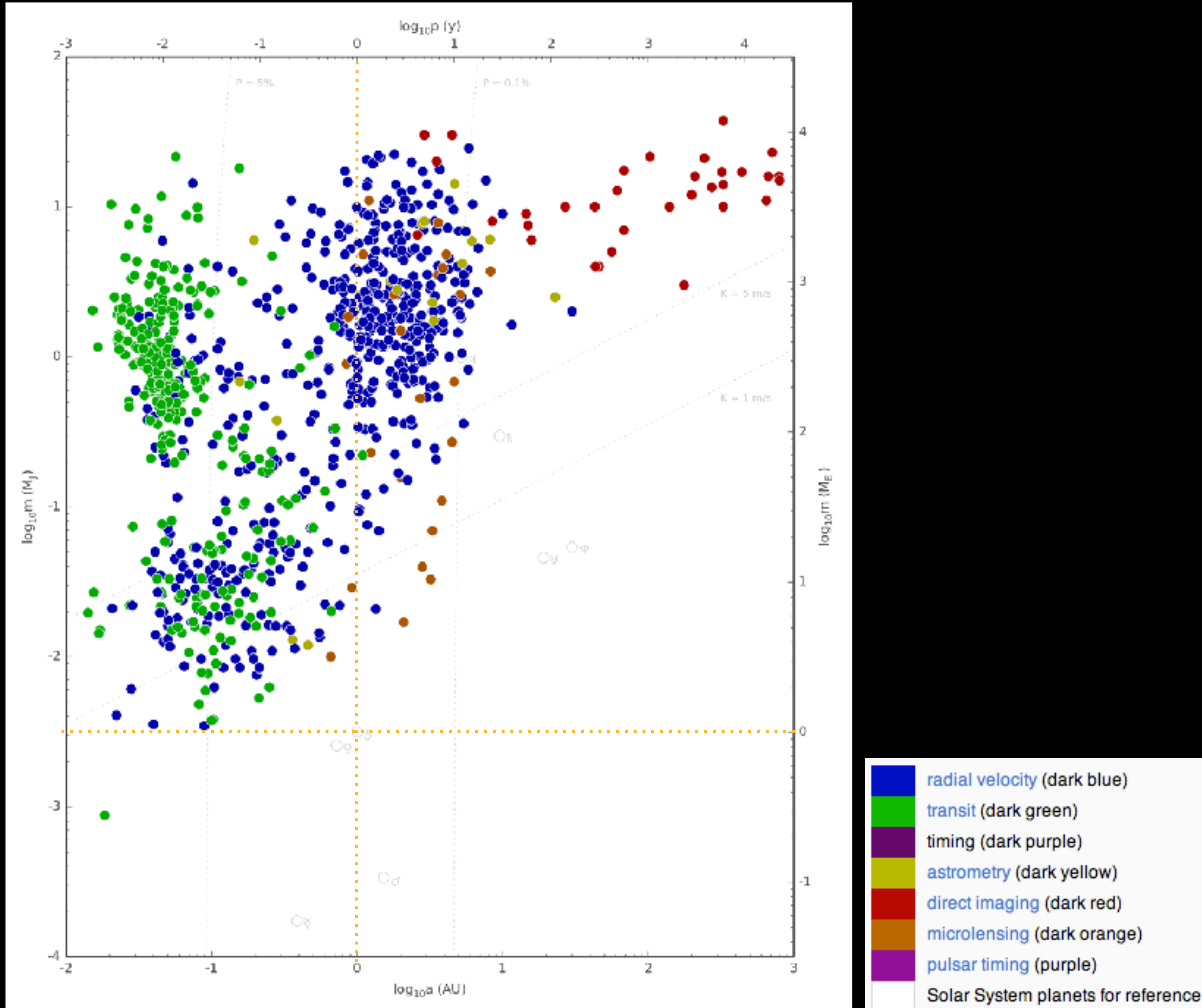
Strength and weaknesses of each method

Mass (in Jupiter masses)



Radius (in Earth-Sun units: AU)

Mass (in Jupiter masses)



Radius (in Earth-Sun units: AU)

By 2025 we will have discovered a few thousand *nearby* planets

The next step is to characterize them

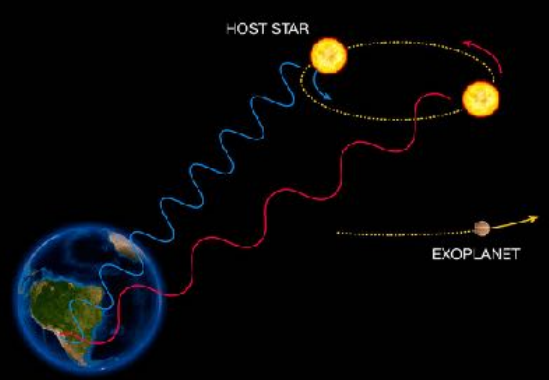
Measuring
Exoplanet properties

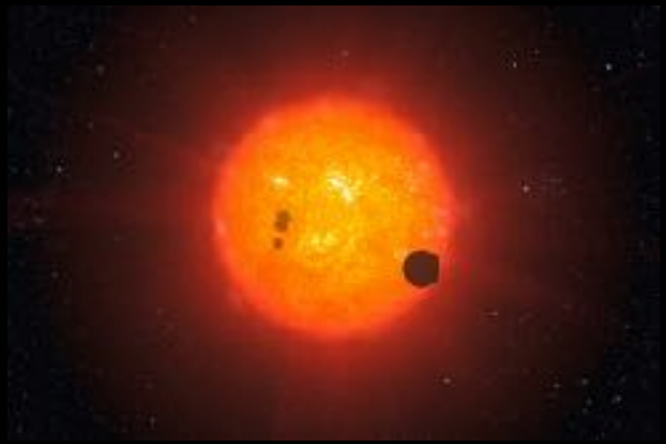
Warning: the research field is evolving extremely quickly. Knowledge will change on a timescale of a few years...

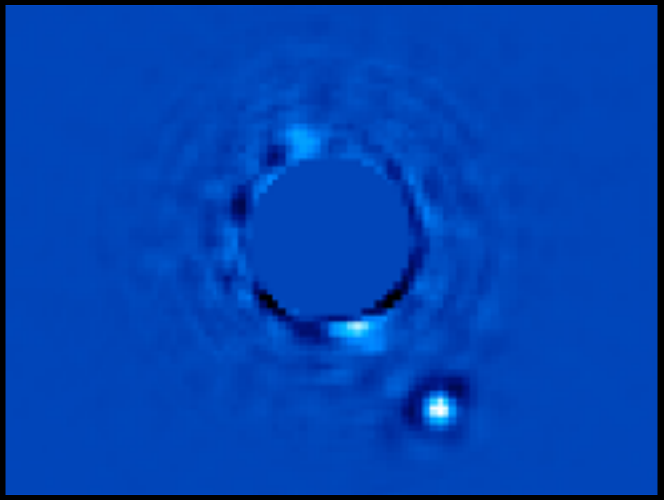
2020: Dominating methods

★ Transit photometry (~3000 planets)
★ Radial velocity method (~900 planets)

For many transiting planets, radial velocity measurements are feasible

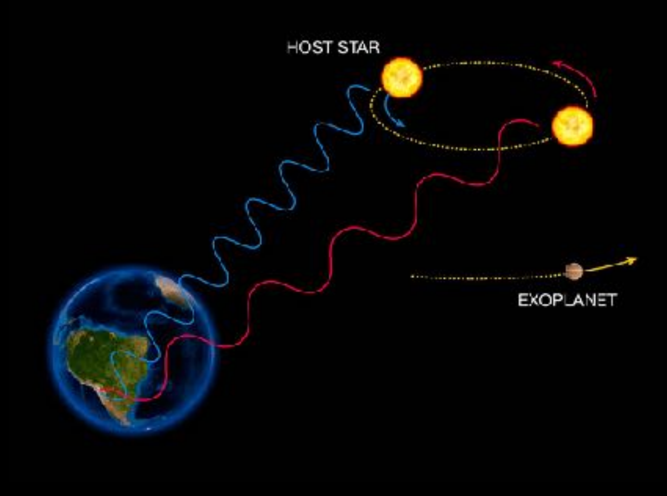




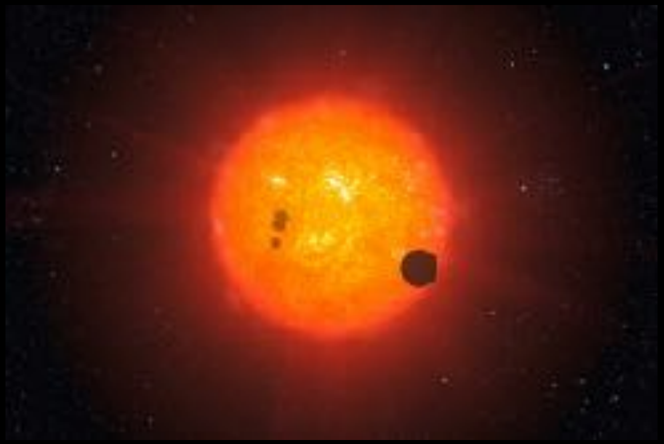


Coming soon, and probably dominating the next decade (2025-2035):
Direct imaging method
Spectroscopy of transits (ground and space)

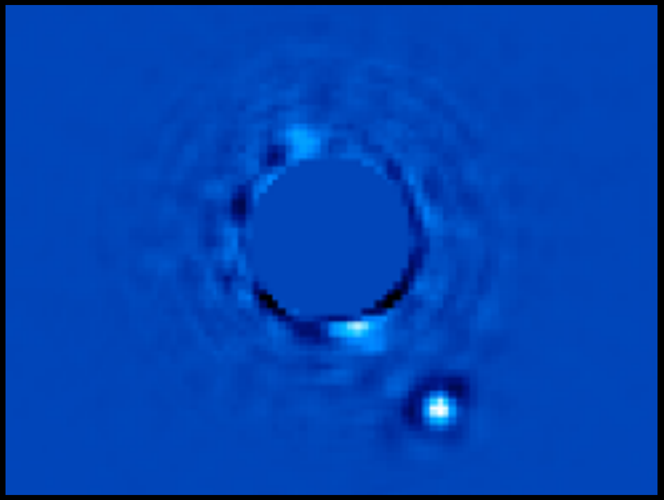
Which detection method provides which type of information?



Radial velocity method:
- Mass (lower limit)
- Orbit / period



Transit method:
- Radius (relative to stellar radius)
- Orbit / period
- [spectroscopic follow-up] Composition of atmosphere & surface



Direct imaging method:
- Orbit / period
- Emissivity / Albedo
- [spectroscopic follow-up] Composition of atmosphere & surface

Follow-up observations on transiting planets

Transiting planets can be observed:

- during the primary eclipse (transmission spectroscopy)
- before/after the secondary eclipse (emission line spectroscopy)

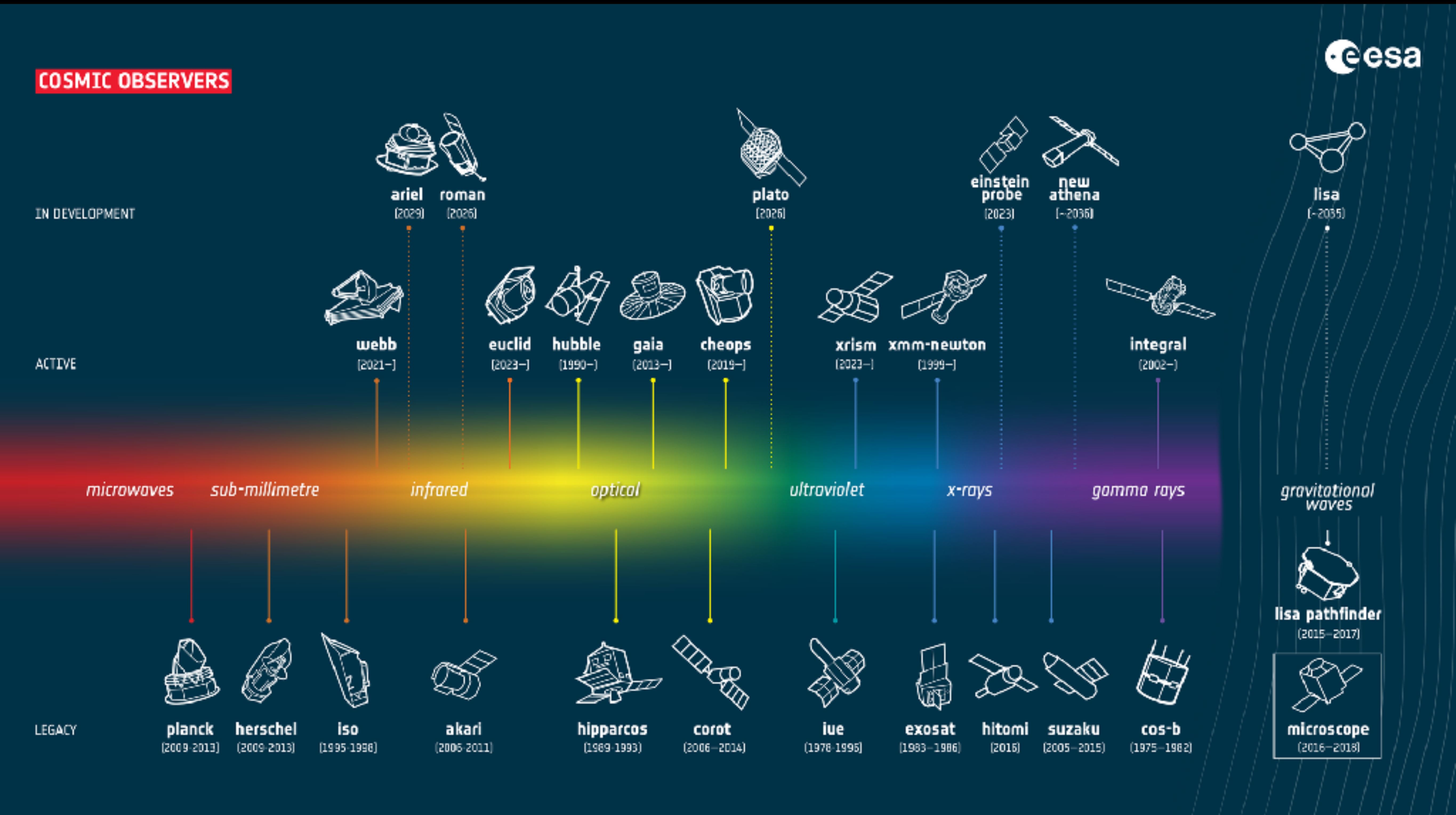
In both cases, a differential measurement is necessary

What are the typical periods of transiting planets ?

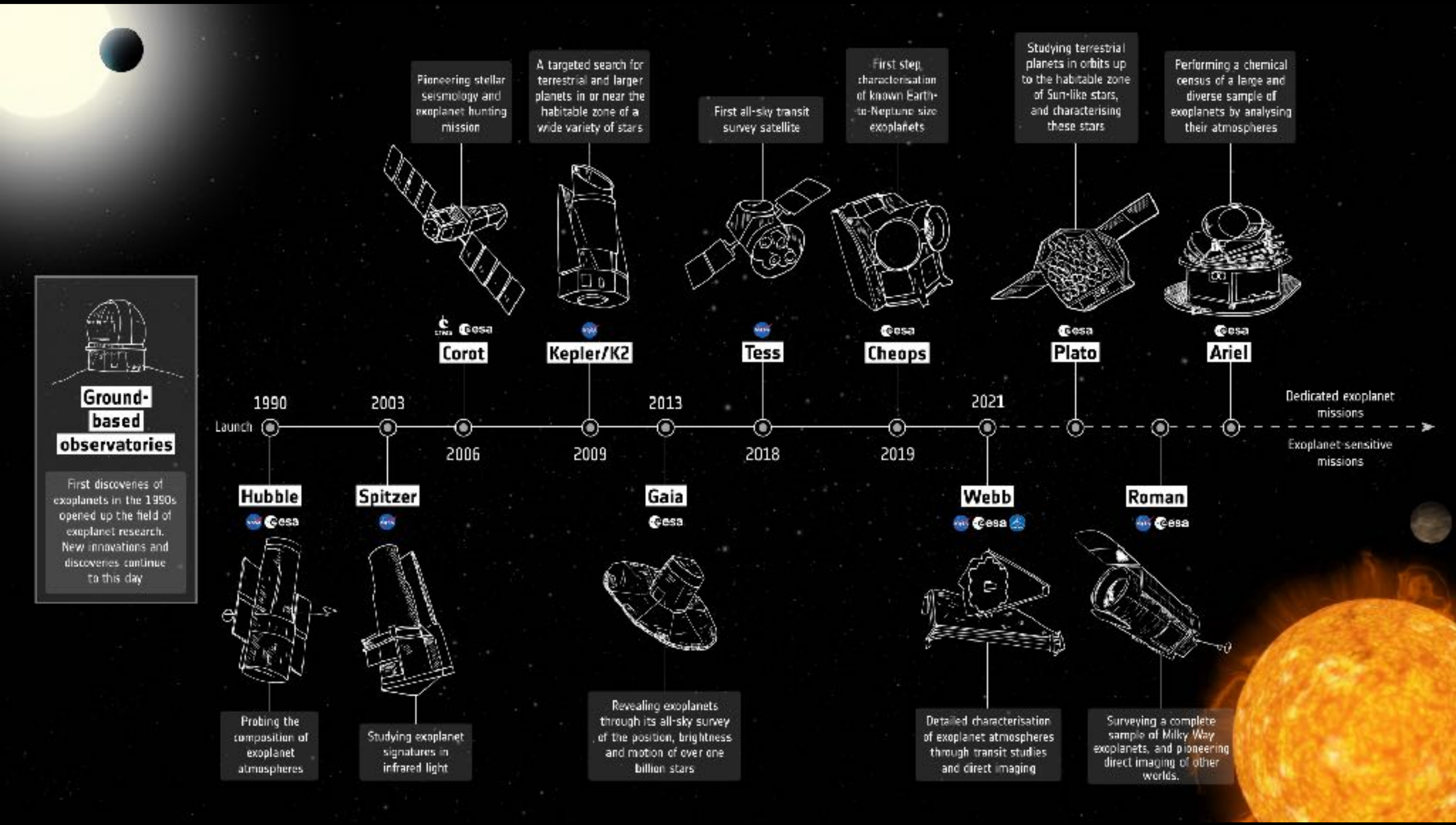
What are typical transit times?

How long would it take to acquire 100h of integration time?

Next Space Missions



COSMIC OBSERVERS
esa
IN DEVELOPMENT
ACTIVE
LEGACY
ariel
(2029)
roman
(2026)
plato
(2026)
einstein probe
(2023)
new athena
(~2036)
lisa
(~2035)
webb
(2021–)
euclid
(2023–)
hubble
(1990–)
gaia
(2013–)
cheops
(2019–)
xrism
(2023–)
xmm-newton
(1999–)
integral
(2002–)
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
gravitational waves
planck
(2009-2013)
herschel
(2009-2013)
iso
(1995-1998)
akari
(2006-2011)
hipparcos
(1989-1993)
corot
(2006–2014)
iue
(1978-1996)
exosat
(1983–1986)
hitomi
(2016)
suzaku
(2005–2015)
cos-b
(1975–1982)
lisa pathfinder
(2015–2017)
microscope
(2016–2018)


Ground-based observatories
First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day
Launch
1990
2003
2006
2009
2013
2018
2019
2021
Dedicated exoplanet missions
Exoplanet sensitive missions
Corot
Pioneering stellar seismology and exoplanet hunting mission
Kepler/K2
A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars
Tess
First all-sky transit survey satellite
Cheops
First step characterisation of known Earth-to-Neptune size exoplanets
Plato
Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars
Ariel
Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres
Hubble
Probing the composition of exoplanet atmospheres
Spitzer
Studying exoplanet signatures in infrared light
Gaia
Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars
Webb
Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging
Roman
Surveying a complete sample of Milky Way exoplanets, and pioneering direct imaging of other worlds.

Current and next dedicated Exoplanet missions…

TESS (NASA - 2018) - The Transiting Exoplanet Survey Satellite: discover thousands of exoplanets in orbit around the 200,000 brightest stars in the sky

CHEOPS (ESA - 2019) - CHaracterising ExOPlanet Satellite: ultra-high precision photometry on bright stars already known to host planets to measure the bulk density of super-Earths and Neptunes orbiting bright stars and provide suitable targets for future in-depth characterisation studies of exoplanets in these mass and size ranges

ARIEL (ESA - 2029) - Atmospheric Remote-sensing Infrared Exoplanet Large-survey: ~1000 extrasolar planets, simultaneously in visible and infrared wavelengths, measuring the chemical composition and thermal structures

PLATO (ESA - 2026) - PLAnetary Transits and Oscillations of stars: find and study a large number of extrasolar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone around solar-like stars

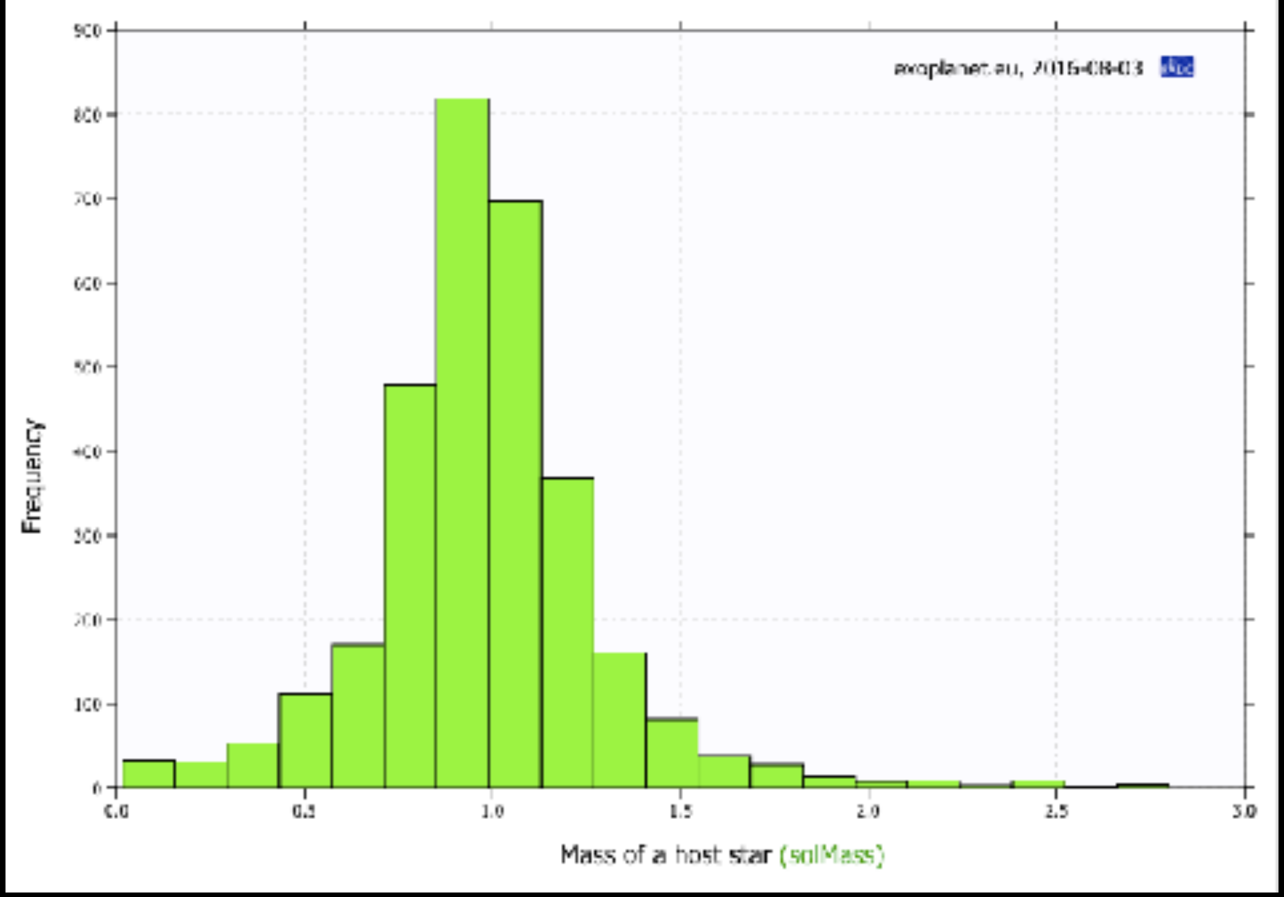
Exoplanet properties as known today

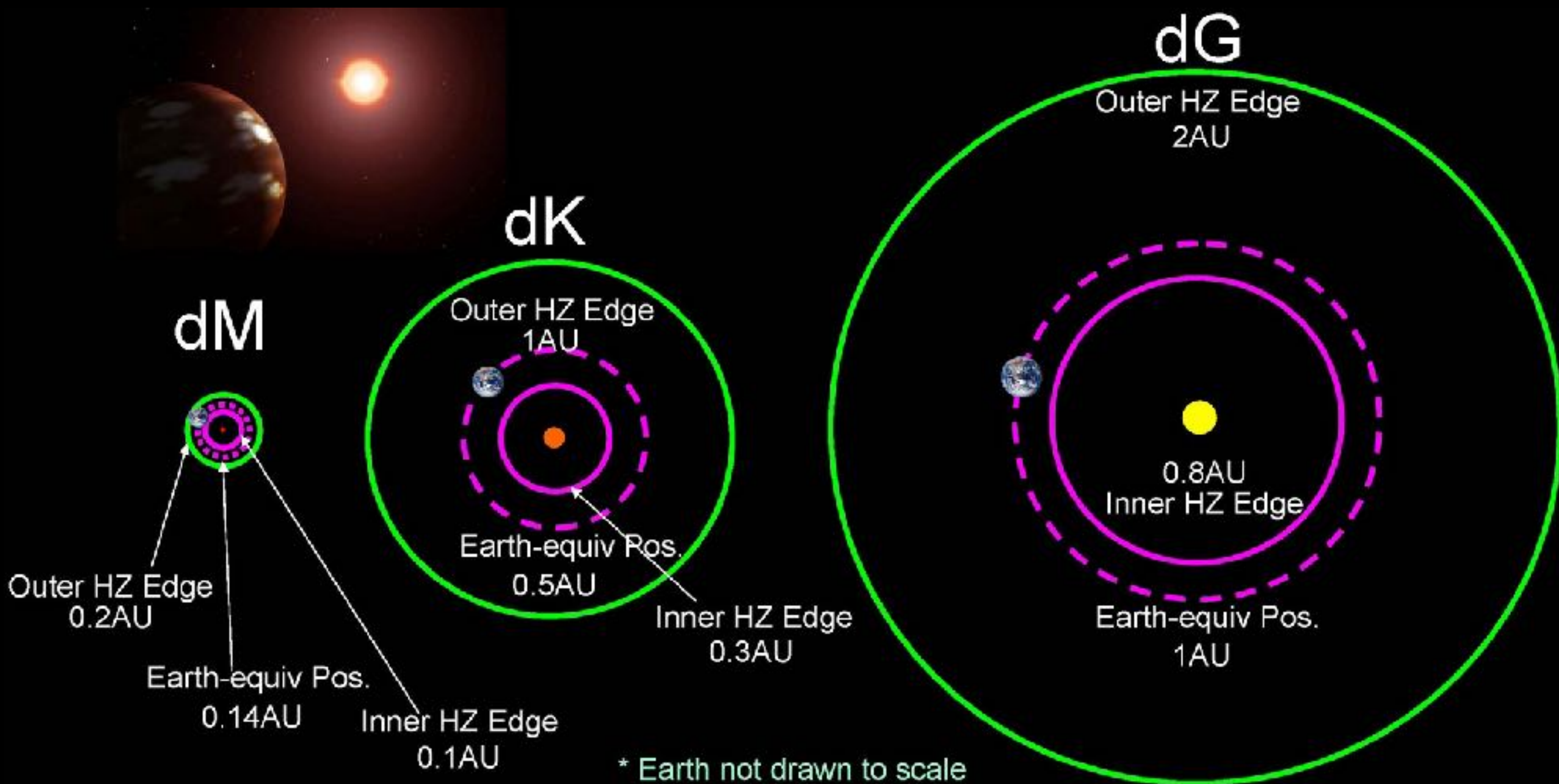
The **Host Stars** properties

Around which stars have we looked for/found exoplanets?

Ideally, we would select them by physical criteria:

- Massive stars (>2M_{sun}) are short lived and bright in X-rays and UV
- Degenerated stars mostly radiate X-rays
- Brown dwarf have unknown planet formation
- Stars of interest have masse between 0.2 and 1.5 M_{sun}



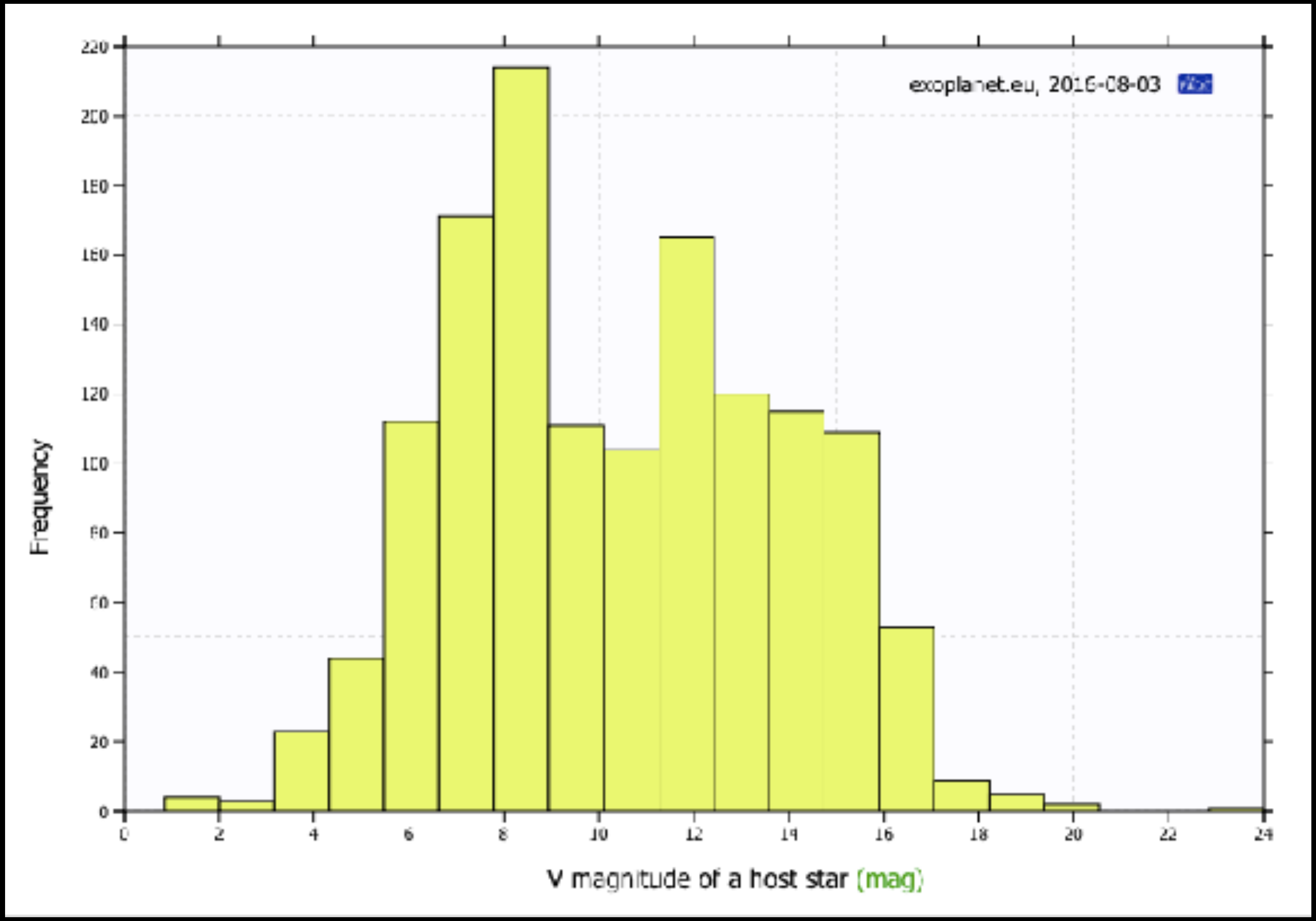


dM
Outer HZ Edge
0.2AU
Earth-equiv Pos.
0.14AU
Inner HZ Edge
0.1AU
dK
Outer HZ Edge
1AU
Earth-equiv Pos.
0.5AU
Inner HZ Edge
0.3AU
dG
Outer HZ Edge
2AU
0.8AU
Inner HZ Edge
Earth-equiv Pos.
1AU
* Earth not drawn to scale

Around which stars have we looked for/found exoplanets?

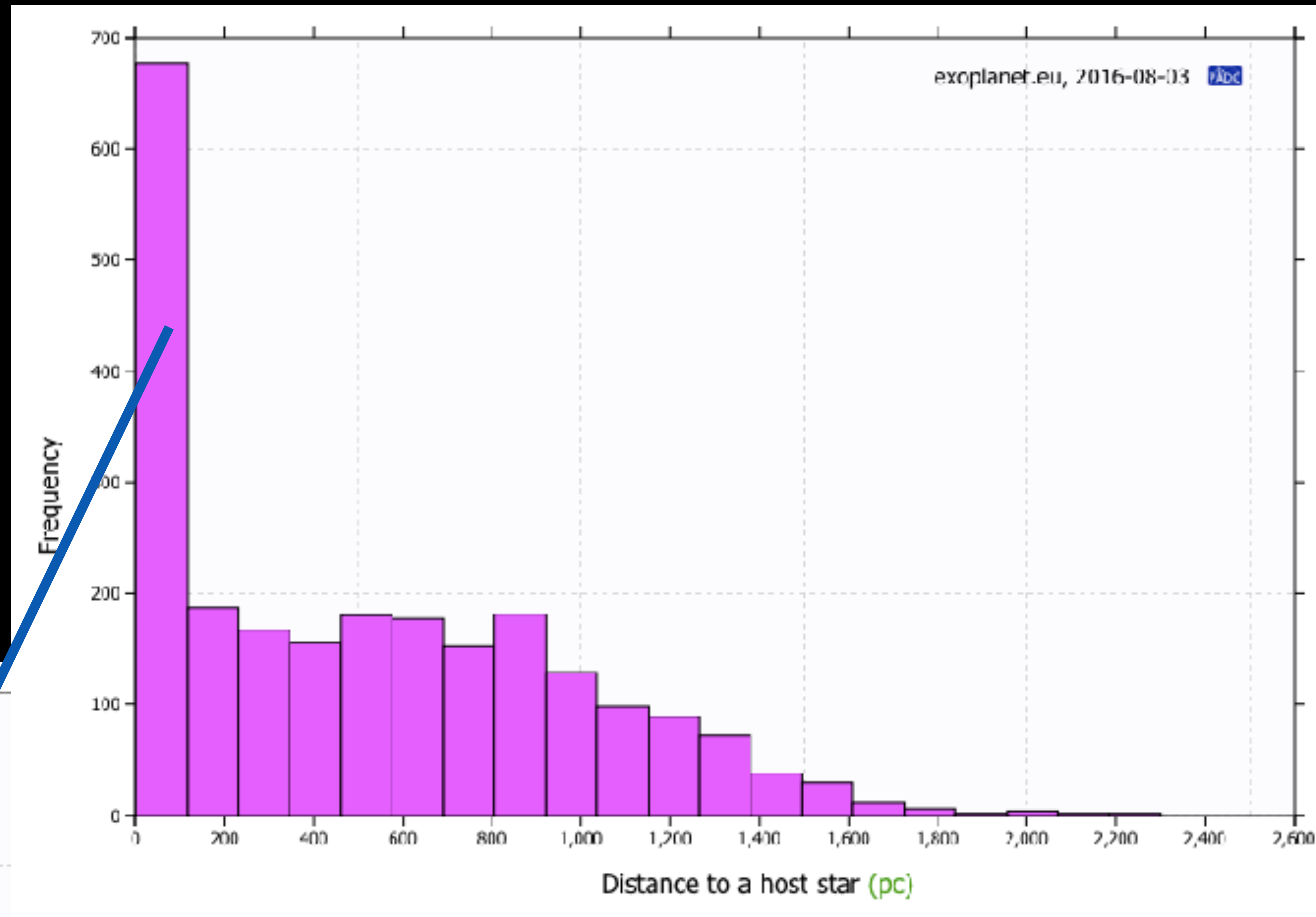
In practice, we are often driven by what we can observe…

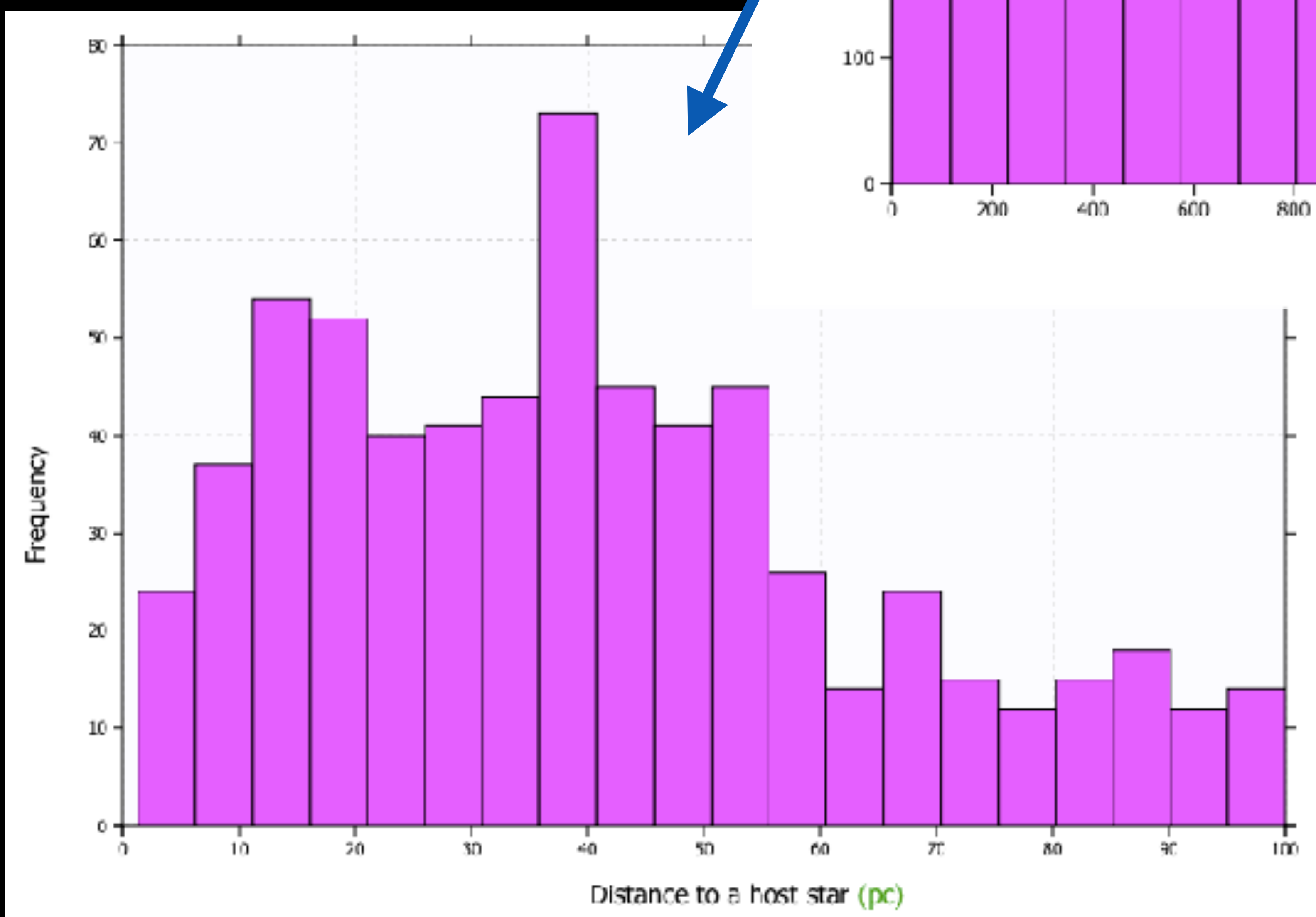
- Stars that are bright enough to be measured ($5<V_{mag}<15$)
- Stars that are close enough to be measured (<100 pc)



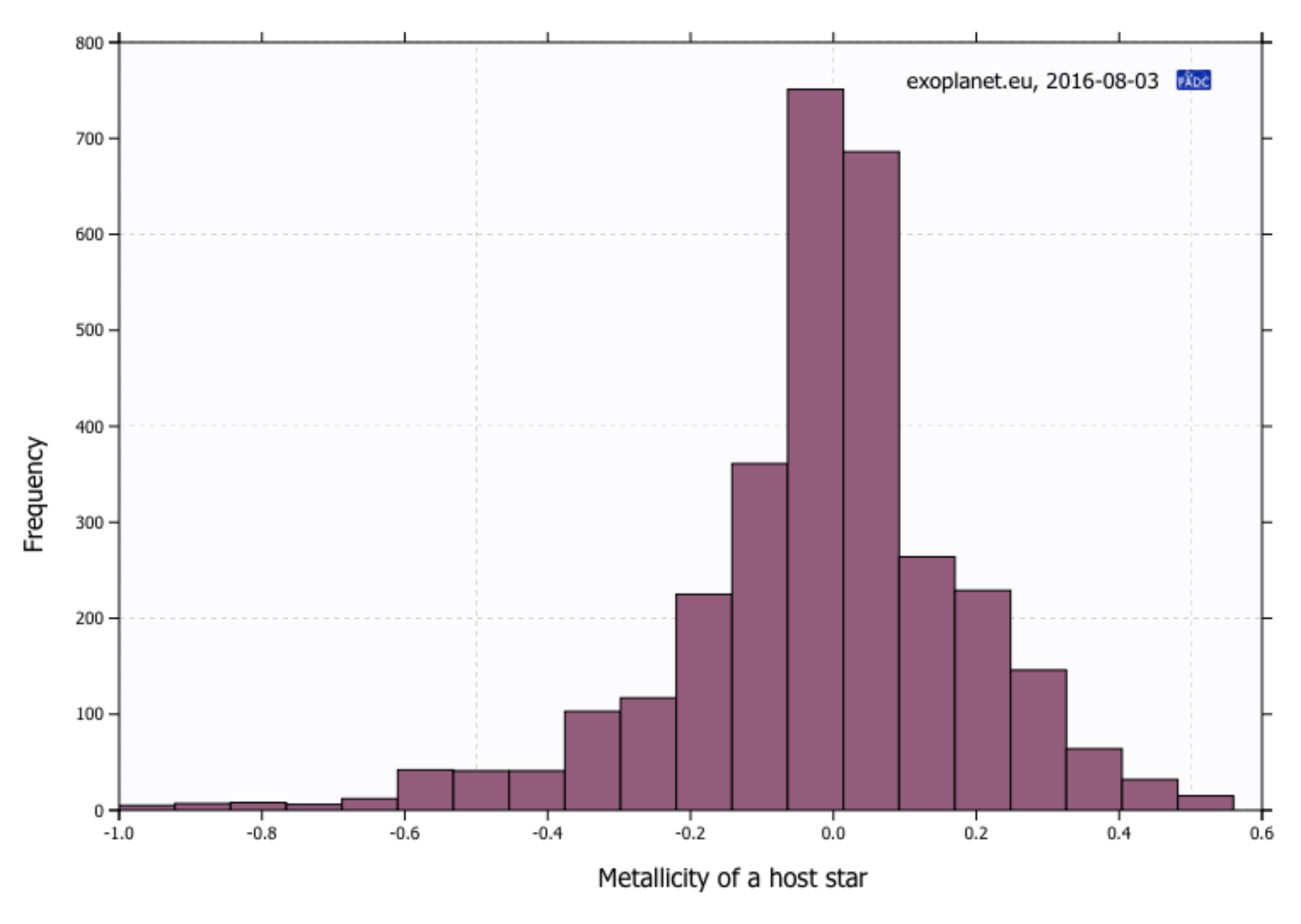
Luminosity of host star

Distance to host star





By now, a representative range of stellar metallicities have been observed



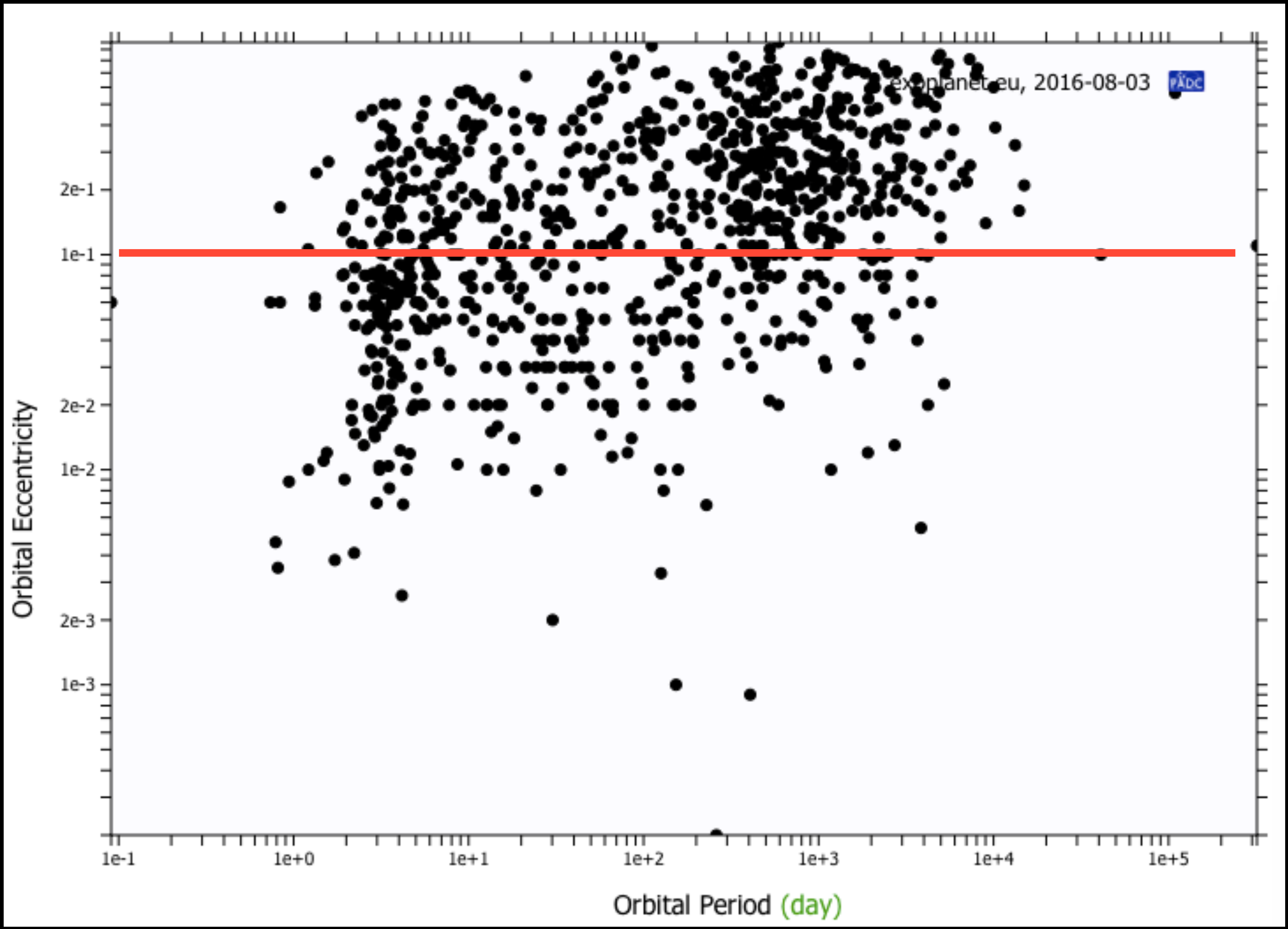
Which stellar properties would you explore next?

The **Planet** properties

Period - Eccentricity

Planet eccentricities and periods

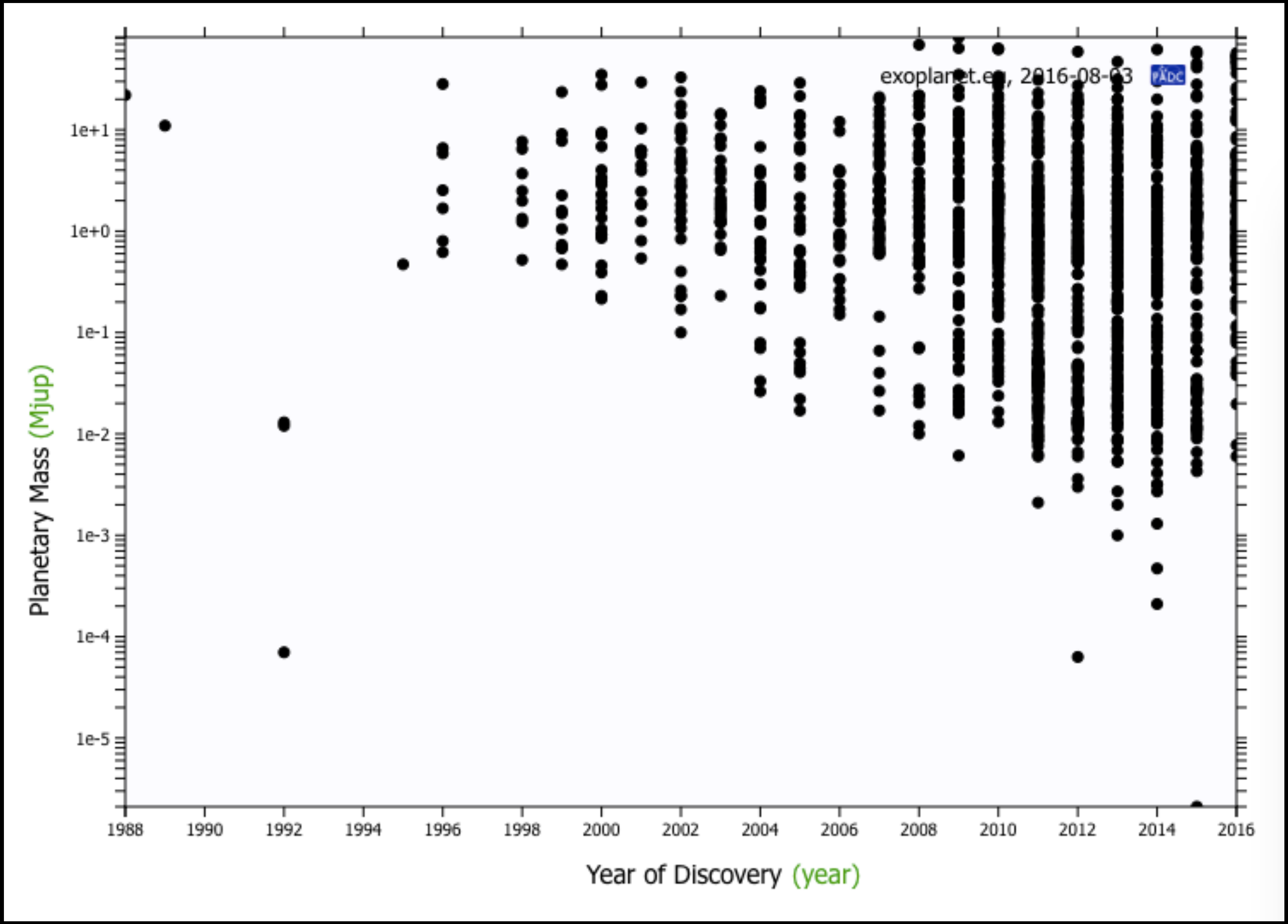
Planets with high eccentricities are not unusual



Mass and Radius

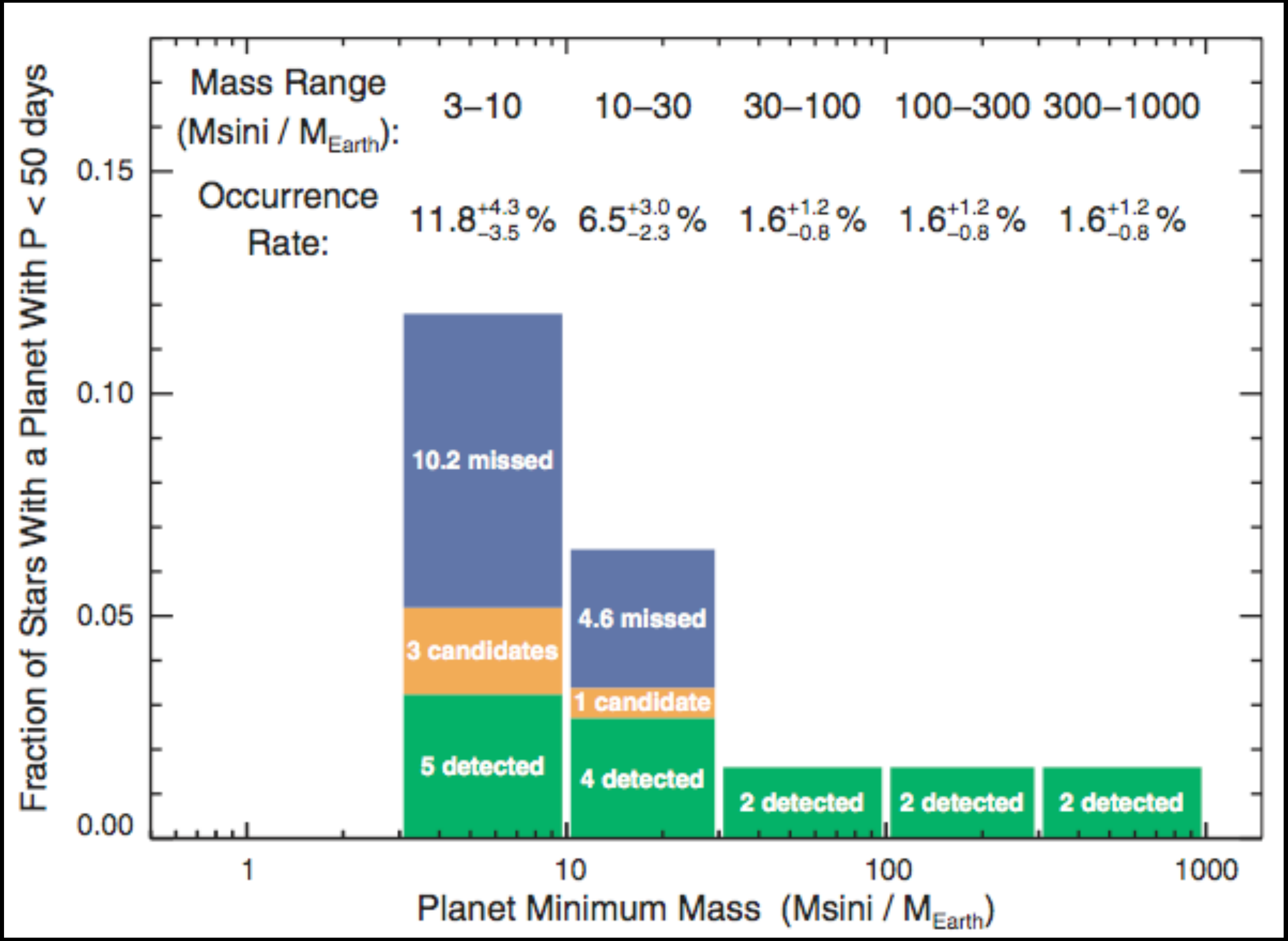
Mass distribution

Measured **masses** are still limited by observational methods



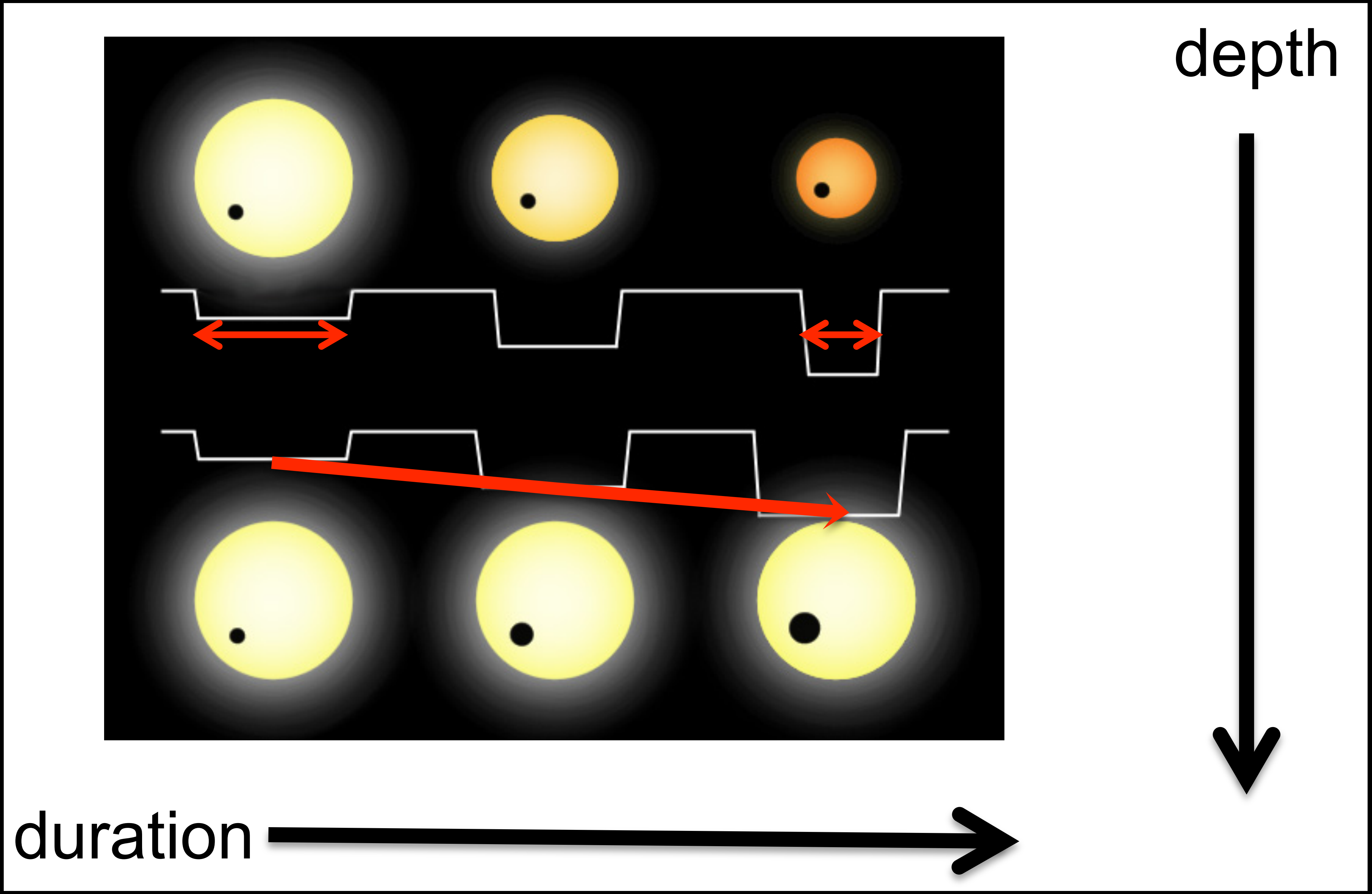
Mass distribution

After correcting for observational biases,
low-mass planets out-number the giant ones

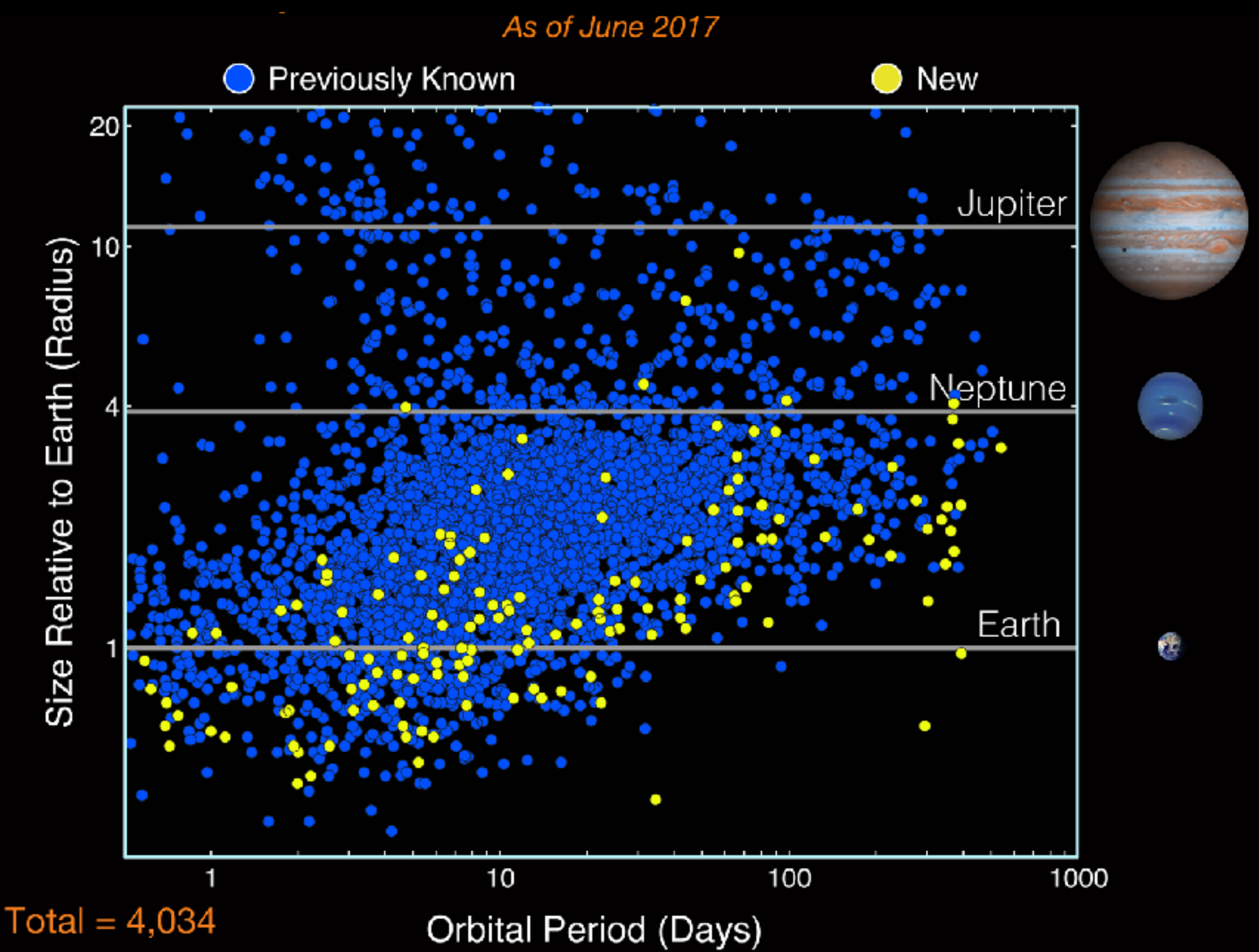


Planet **Radius** distribution

Radii are only available for transiting planets
(and require known stellar radii)



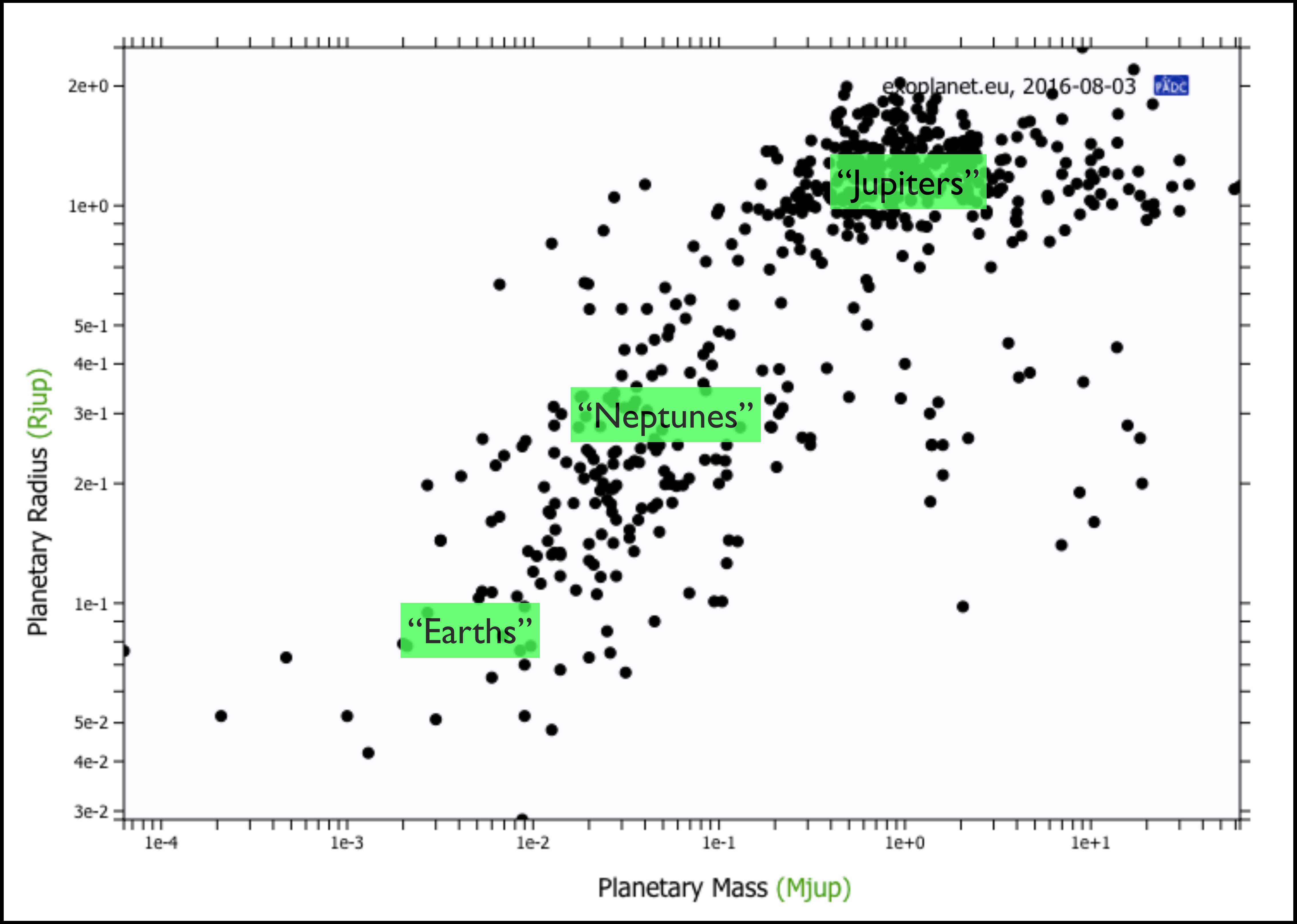
Planet **Radius** distribution



Mass and Radius = Density

Mass - Radius relation

To date, ~600 planets have mass and radius measurements…

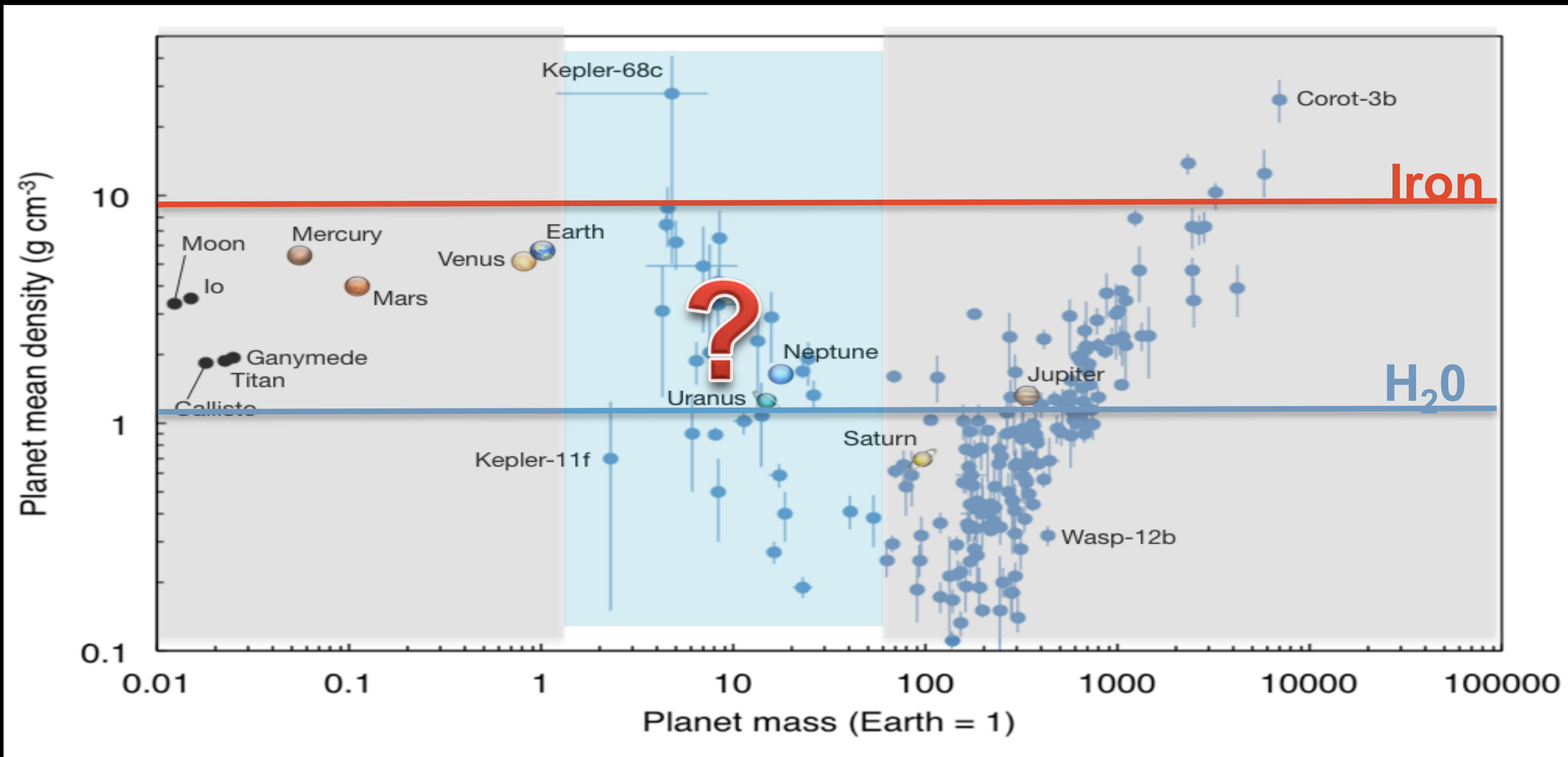


Which densities should the planets be compared with?

Propose two g/cm^3 boundaries

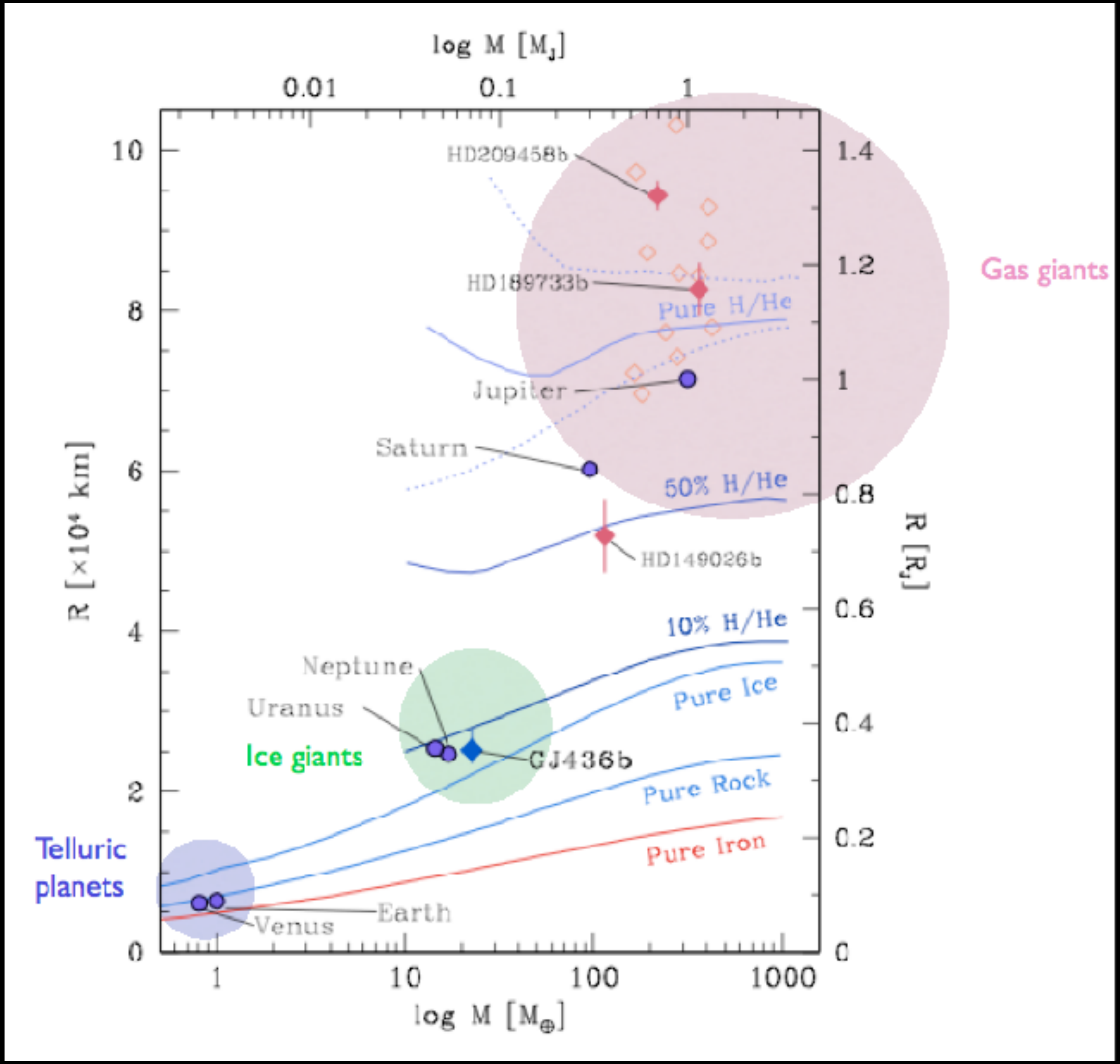
Mass - Radius relation

Mass and Radius allow to derive Density, i.e. Composition



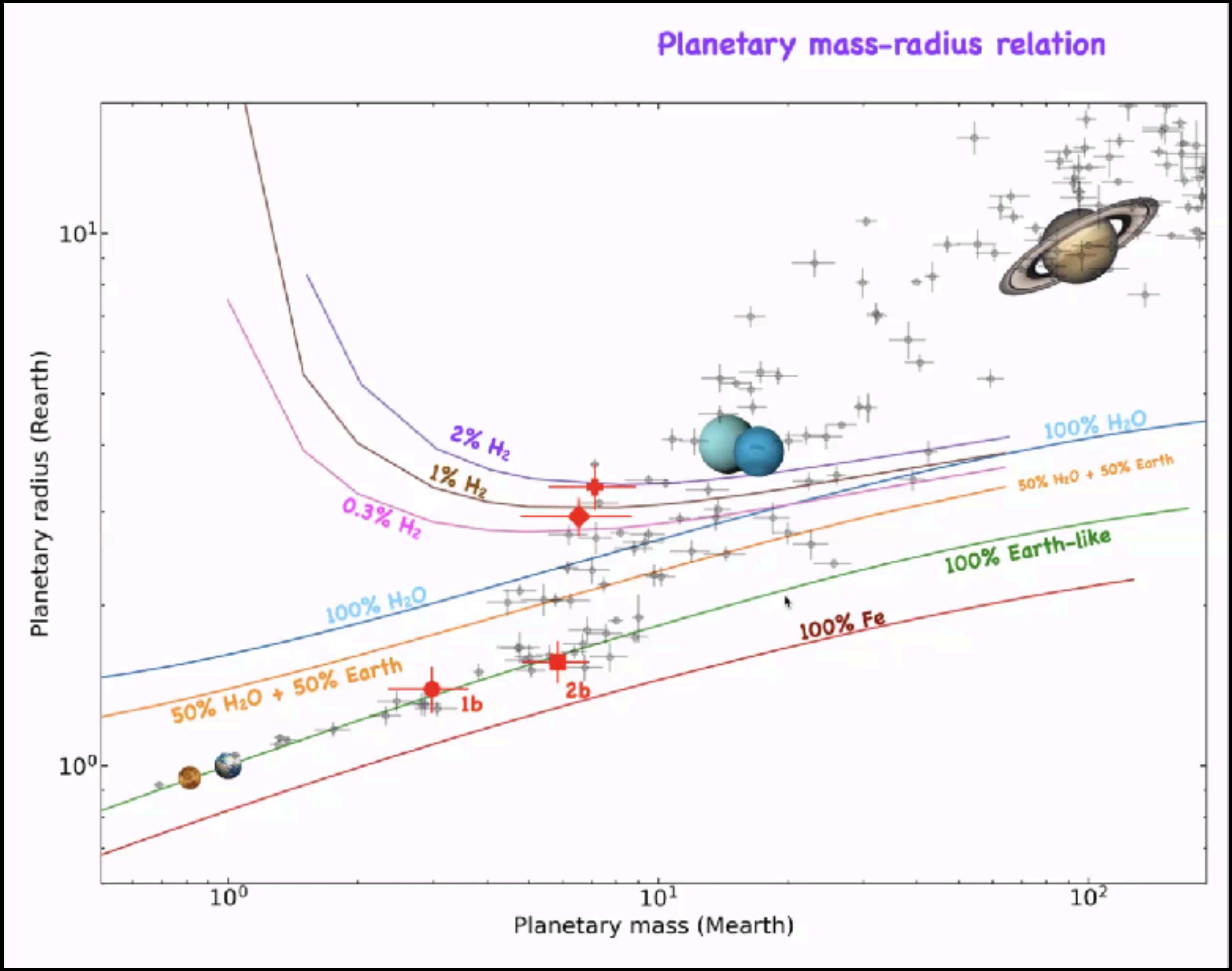
Mass - Radius relation

Mass and Radius allow to derive Density, i.e. Composition

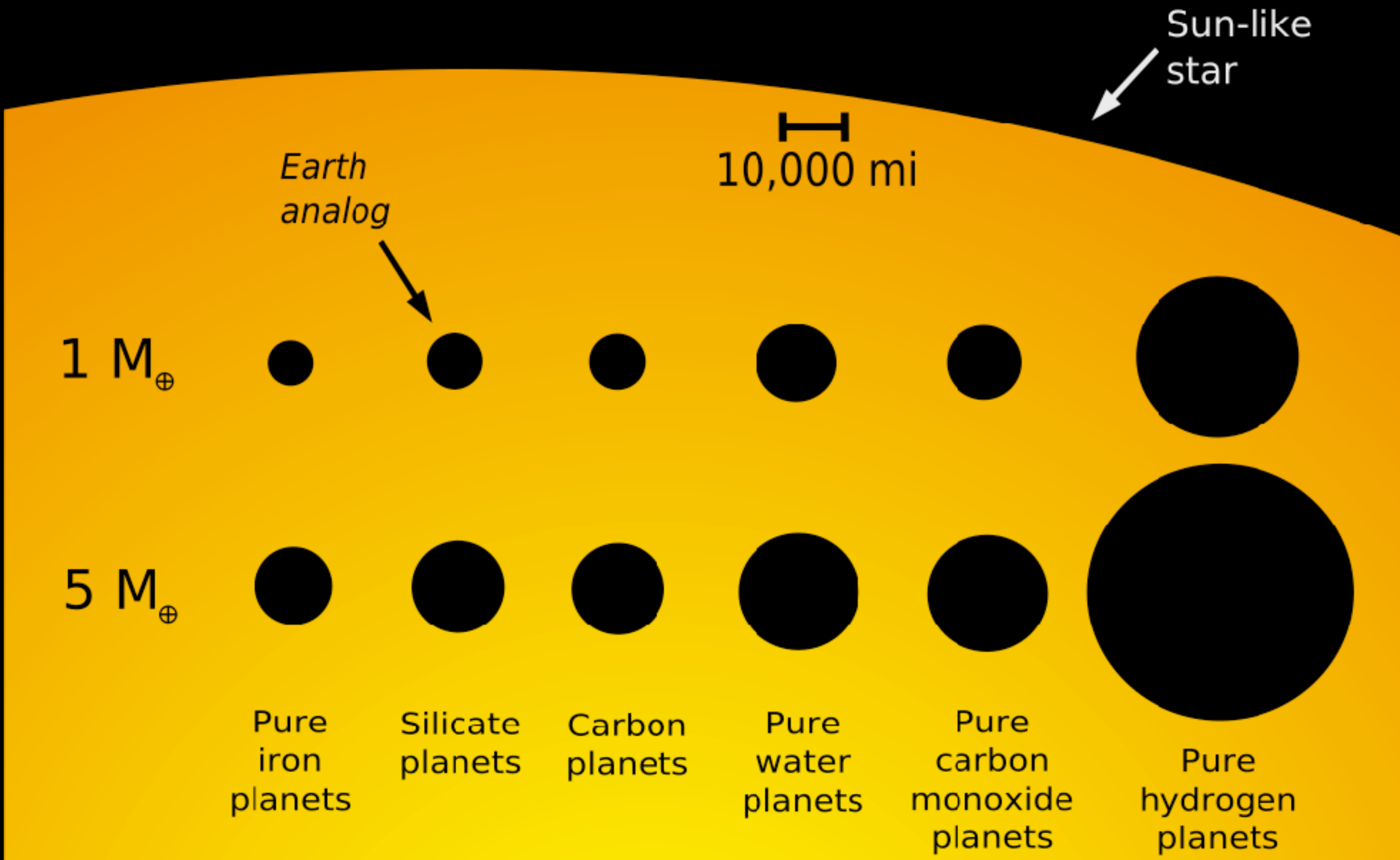


Mass - Radius relation

Mass and Radius allow to derive Density, i.e. Composition



Predicted sizes of different kinds of planets



Lunch break…

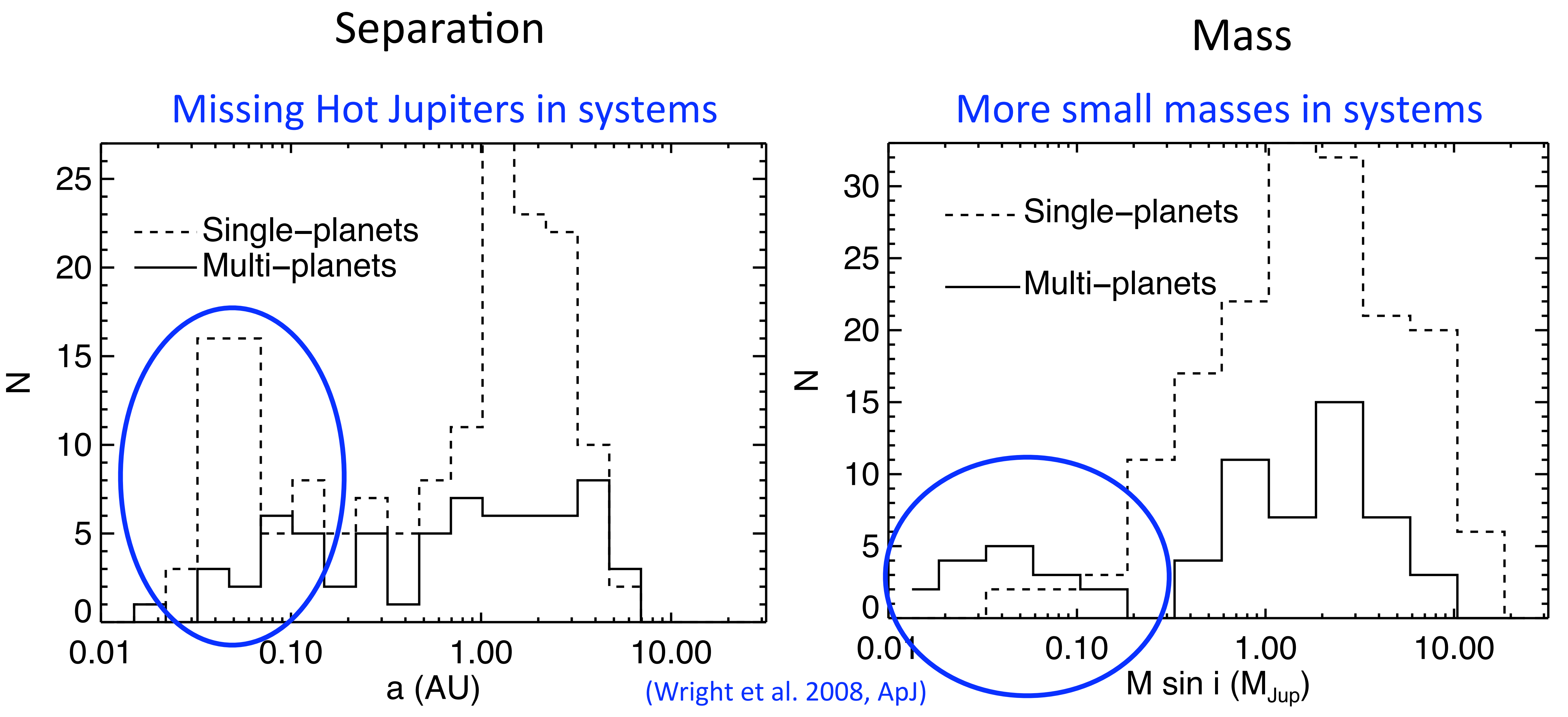
Multi-planetary systems

Can you guess a property of multi-planet systems, given what you know about the formation of the Solar System?

Multiple systems

Systems with >3 are now routinely found

Properties of multi-planet vs single systems



(Wright et al. 2008, ApJ)

Summary of what we know today about stars and planets

What do we know today from >5000 exoplanets?

(mostly from HARPS and KEPLER)

- 50-80% of stars host at least one planet of any kind
- 1% of the stars have hot Jupiter,
  more frequently around metal-rich stars
- 10% of the stars host a gas giant at any period,
  more frequently around metal-rich stars
- ‘Small’ stars rarely host giant planets
- 30% of the stars have a planet <30 M_{Earth} with <100 day period
- Most of the small/light planets occur in multiple systems
- More than 70% of the systems with one <30 M_{Earth} planet include more than one planet

Characterization of Exoplanets

(atmosphere, surface, interior)

Exoplanet atmospheres

- ★ Planetary atmospheres are currently the only way to infer whether or not a planet is habitable or likely inhabited

- ★ The planetary atmosphere is our window into temperatures, habitability indicators and biosignature gases

Atmospheres in the Solar System

Atmosphere around planets in our Solar System are know since the 19th century

1927: The atmosphere of Venus does not contain oxygen!

1934: giant planets have methane in their atmospheres

1937: terrestrial planets have CO_2 in their atmospheres

1944: Titan has an atmosphere

MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY.

Vol. XXIII. *June* 12, 1863. No. 8.

C. B. Vignoles, Esq., Vice-President, in the Chair.

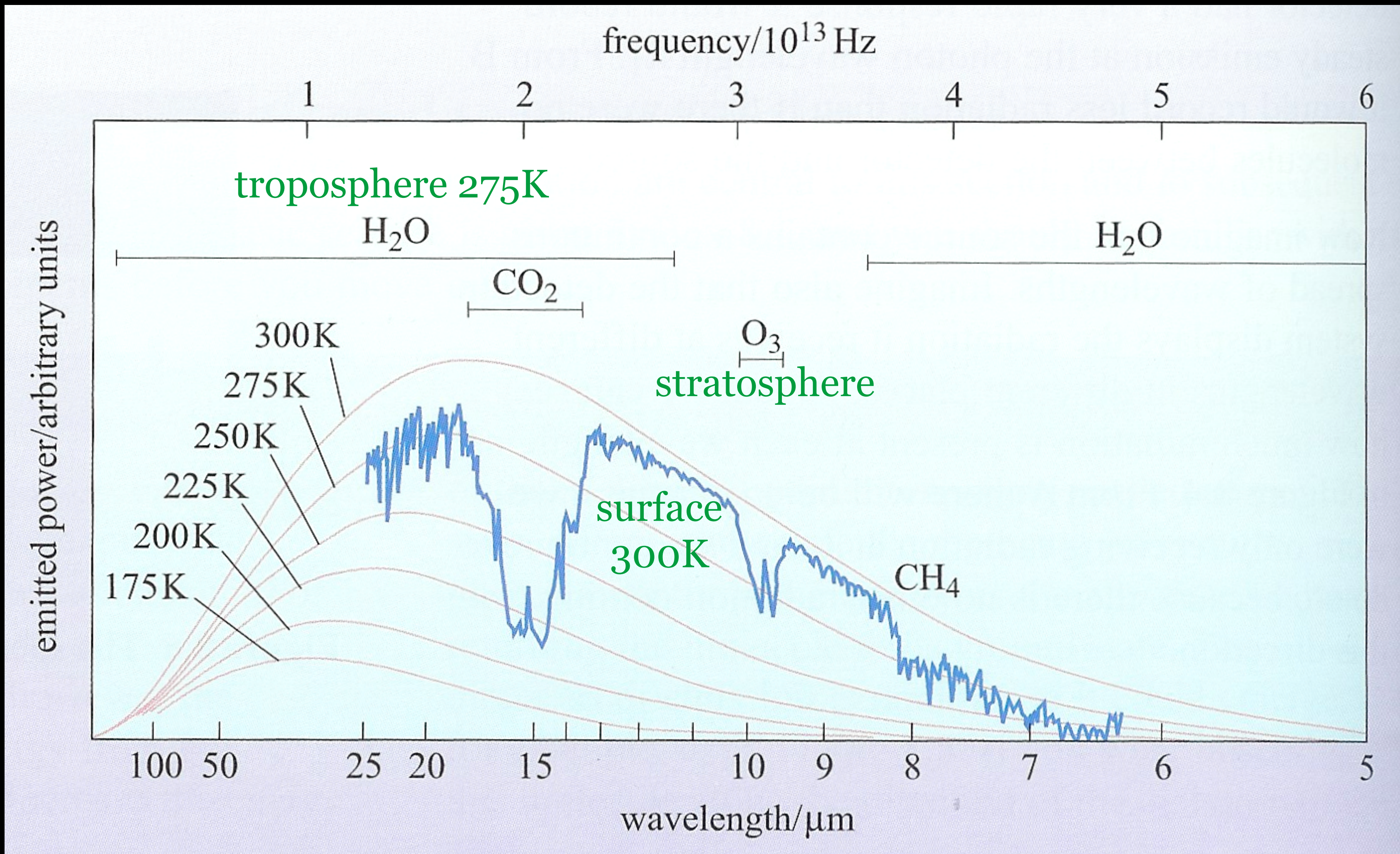
The Ven. Archdeacon Garbett, Chichester, was balloted for and duly elected a Fellow of the Society.

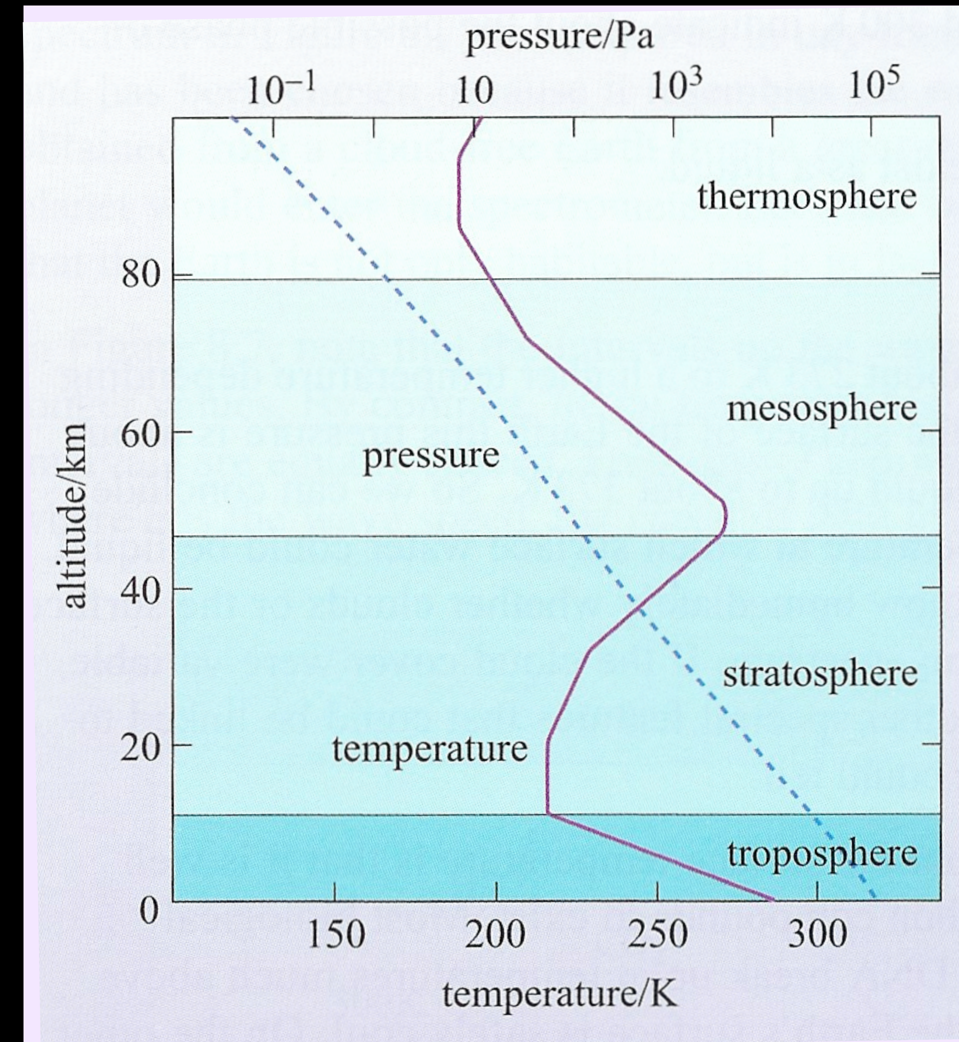
On the Indications by Phenomena of Atmospheres to the Sun, Moon, and Planets. By Professor Challis.

As the Earth has an atmosphere, it is not unlikely that the other bodies of the solar system are similarly furnished, and the knowledge we have of our own atmosphere may reasonably be employed in inquiring whether the existence of other atmospheres of the same kind is indicated by phenomena. I propose, therefore, in this communication to discuss generally the possible effects, observable from a distant position, of an atmosphere constituted like the Earth's, with the view of ascertaining whether such effects have been actually observed.

The most notable effect of the Earth's atmosphere is the refraction of the rays of light which pass through it. In consequence of this refraction, the apparent magnitude of the Earth, as seen by a distant spectator, would be in some degree greater than the apparent magnitude of the globe deprived of its atmosphere, because the rays which pass from the periphery of the globe to the position of the spectator must have a curved course concave to the straight line joining that position and

What does Earth's atmosphere show?





Nimbus satellite: 1970s day-time, western Pacific

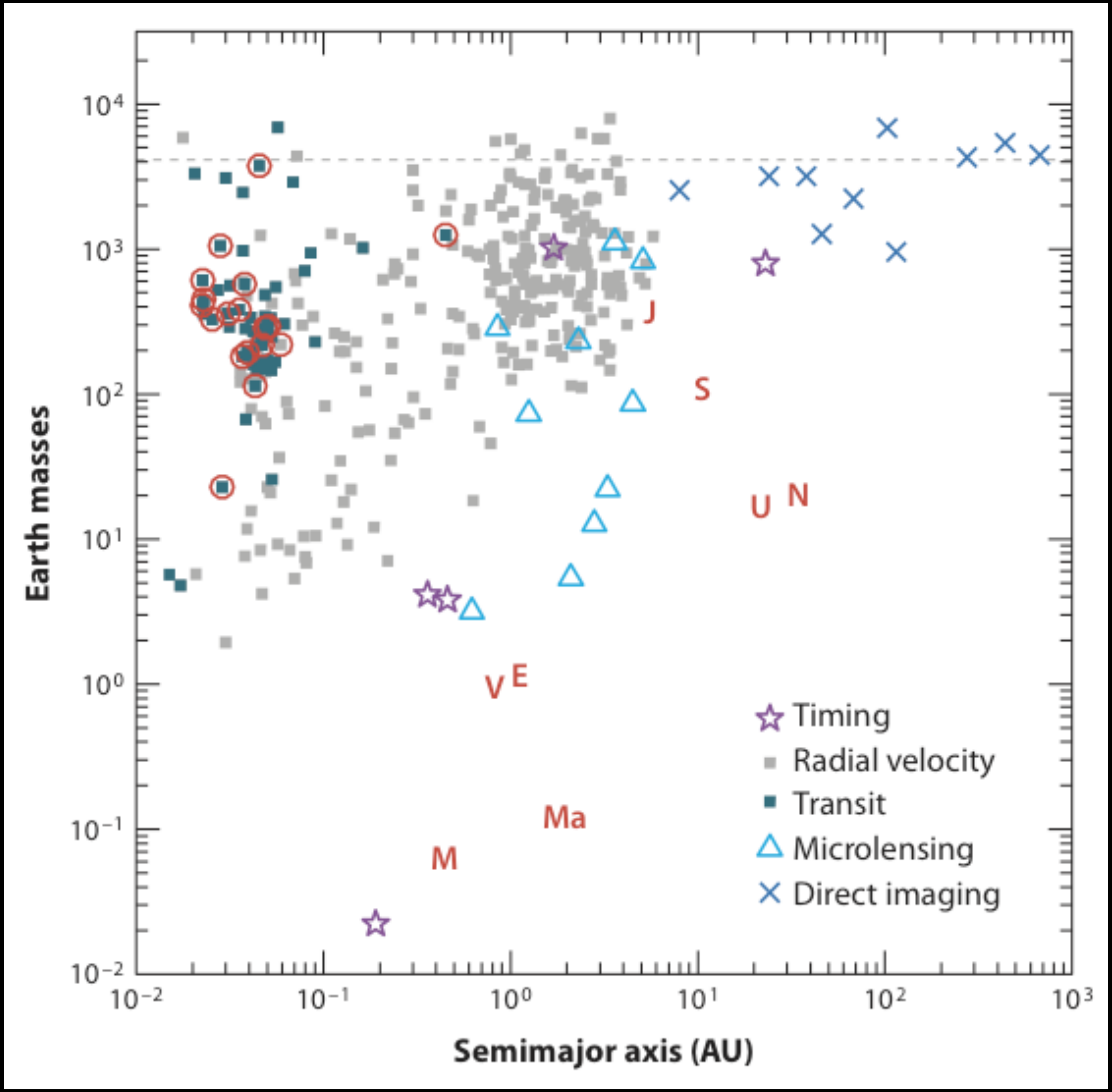
- Cloud free surface at ~300K
- H_2O at 275K at a few kilometers height
- CO_2 at 220K in the upper tropopause (0.035%, 15µm flux blocked)
- O_3 at 270K from the stratosphere (strong → large amounts of O_2)
- CH_4 visible at only 1.6ppm (together with O_2 → biosphere)

What type of exoplanets have studied atmospheres?

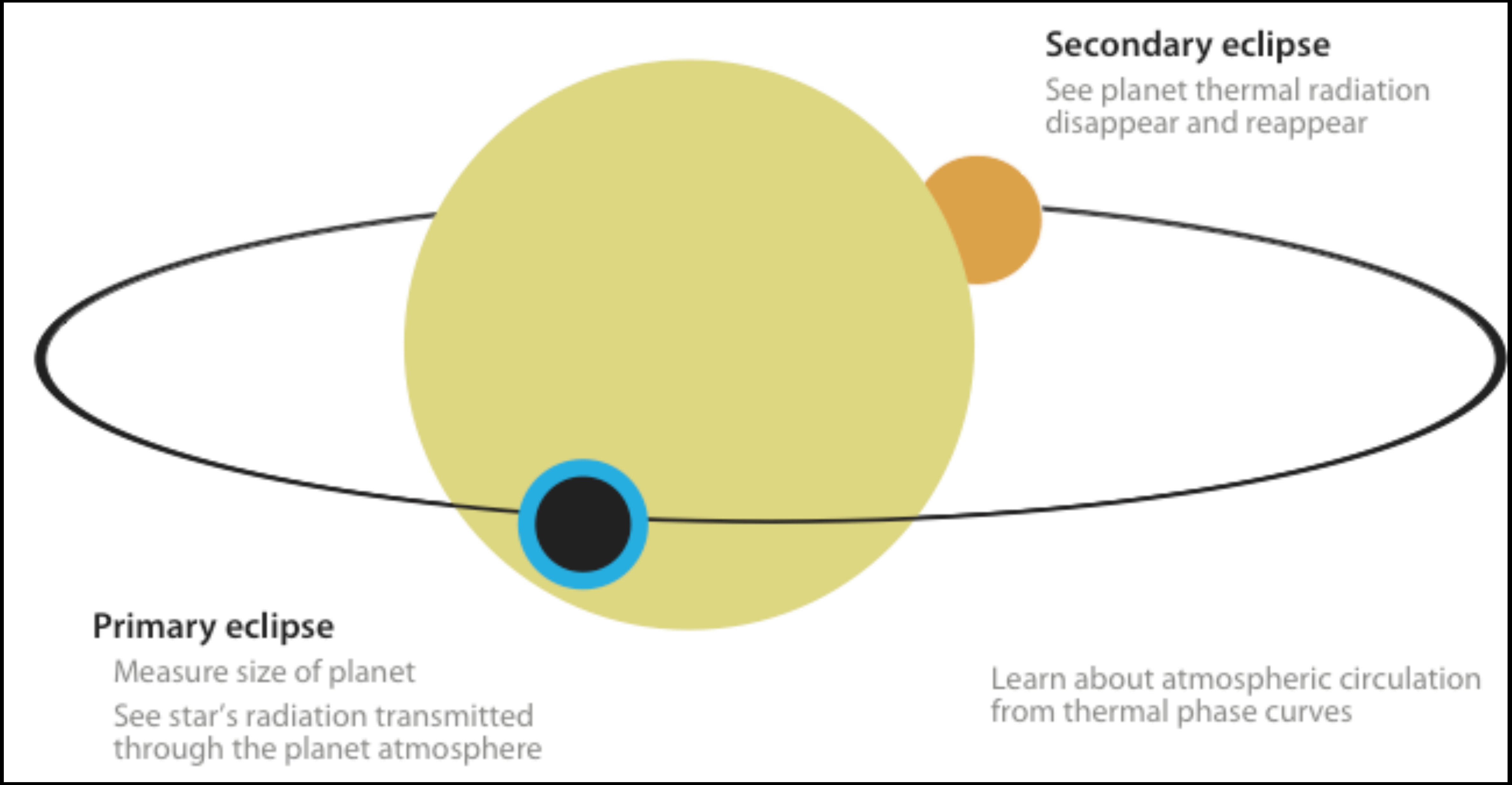
Exoplanets with measured atmospheres

Over 20 exoplanets have measured atmospheres today

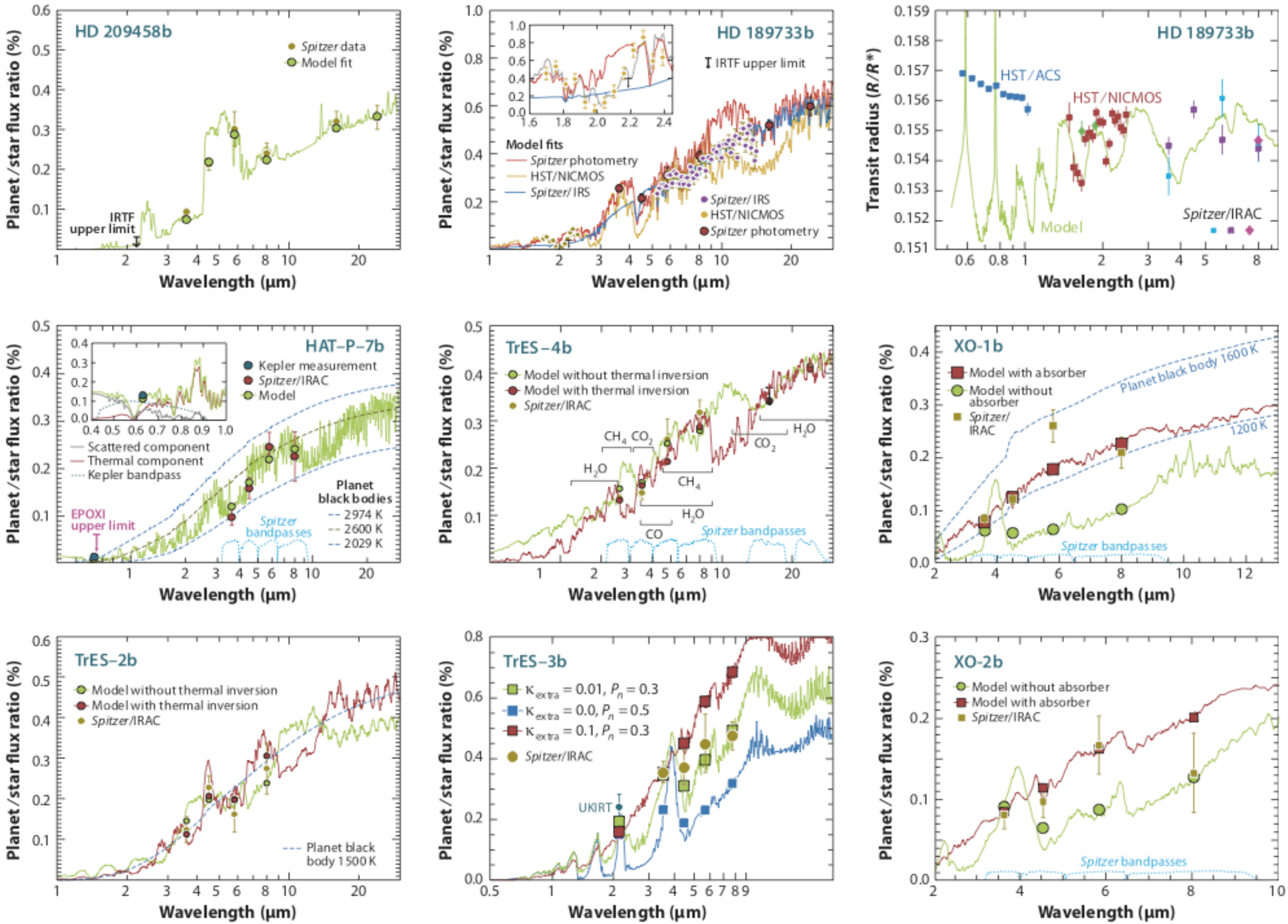
(more than Solar system objets!)



Secondary eclipse:
we see the planet in emission
(albedo, composition, temperature)



Primary eclipse:
allows to obtain spectra in transmission

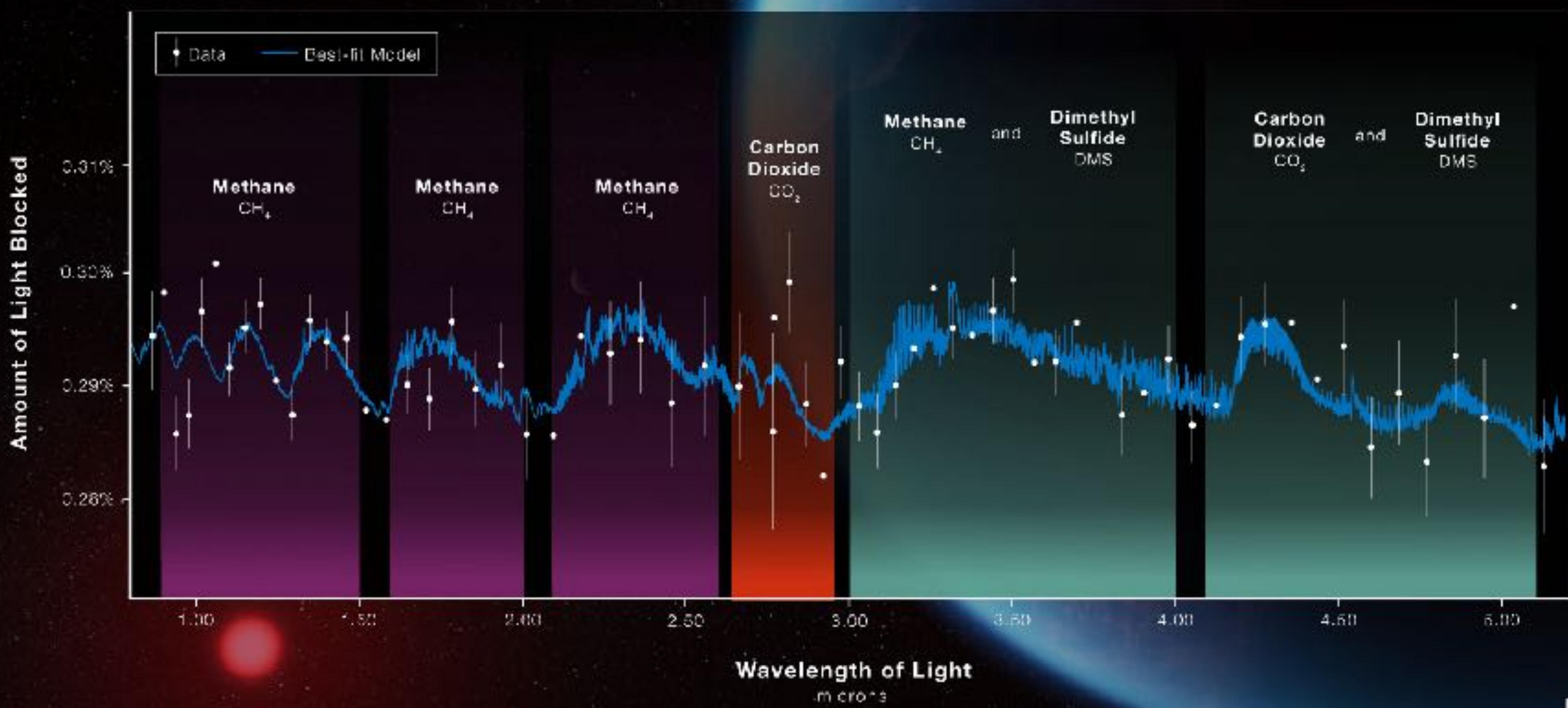


HD 209458b
Spitzer data
Model fit
IRTF upper limit
Planet / star flux ratio (%)
Wavelength (μm)
HD 189733b
IRTF upper limit
Model fits
Spitzer photometry
HST/NICMOS
Spitzer/ IRS
Spitzer/ IRS
HST/NICMOS
Spitzer photometry
HD 189733b
HST / ACS
HST / NICMOS
Spitzer/IRAC
Model
Transit radius (R/R*)
HAT–P–7b
Kepler measurement
Spitzer/IRAC
Model
Scattered component
Thermal component
Kepler bandpass
Planet black bodies
2974 K
2600 K
2029 K
EPOXI upper limit
Spitzer bandpasses
TrES–4b
Model without thermal inversion
Model with thermal inversion
Spitzer/IRAC
H2O
CH4
CO2
CH4
H2O
CO
CO2
H2O
Spitzer bandpasses
XO-1b
Model with absorber
Model without absorber
Spitzer/ IRAC
Planet black body 1600 K
1200 K
Spitzer bandpasses
TrES–2b
Model without thermal inversion
Model with thermal inversion
Spitzer/IRAC
Planet black body 1500 K
TrES–3b
κextra = 0.01, Pn = 0.3
κextra = 0.0, Pn = 0.5
κextra = 0.1, Pn = 0.3
Spitzer/IRAC
UKIRT
XO-2b
Model without absorber
Model with absorber
Spitzer/IRAC
Spitzer bandpasses

EXOPLANET K2-18 b

ATMOSPHERE COMPOSITION

NIRISS and NIRSpec (G395H)



WEBB
SPACE TELESCOPE

Categories of atmospheres

- Dominated by **H and He** (captured proto-planetary material)
- Outgassed atmospheres dominated by **H** (incl. H_2O, CH_4, CO)
- Outgassed atmospheres dominated by **CO_2** (lost H and He)
- Hot super-Earth **lacking volatiles** (>1500K → H,C,N,O,S gone)
- **Atmosphere-free** planets (e.g. Mercury)

What we have learned so far about Hot Jupiters:

- Hot Jupiters are hot (>1000K) and absorb the stellar light to re-emit it in the infrared (albedo « 0.2)
- As expected, hot atmospheres are dominated by the most active gas: H_2O (H_2 is more difficult to detect). Also detected: Na, CH_4, CO, CO_2
- Day-Night temperature gradients of ΔT=1000-2000K (due to tidally locked hot Jupiters)
- H escape (in form of comet-like coma) from the atmosphere
- Indications for temperature inversion ("stratospheres") in Hot Jupiters [not expected as no CH_4 haze or O_3 should be present; and model dependent]

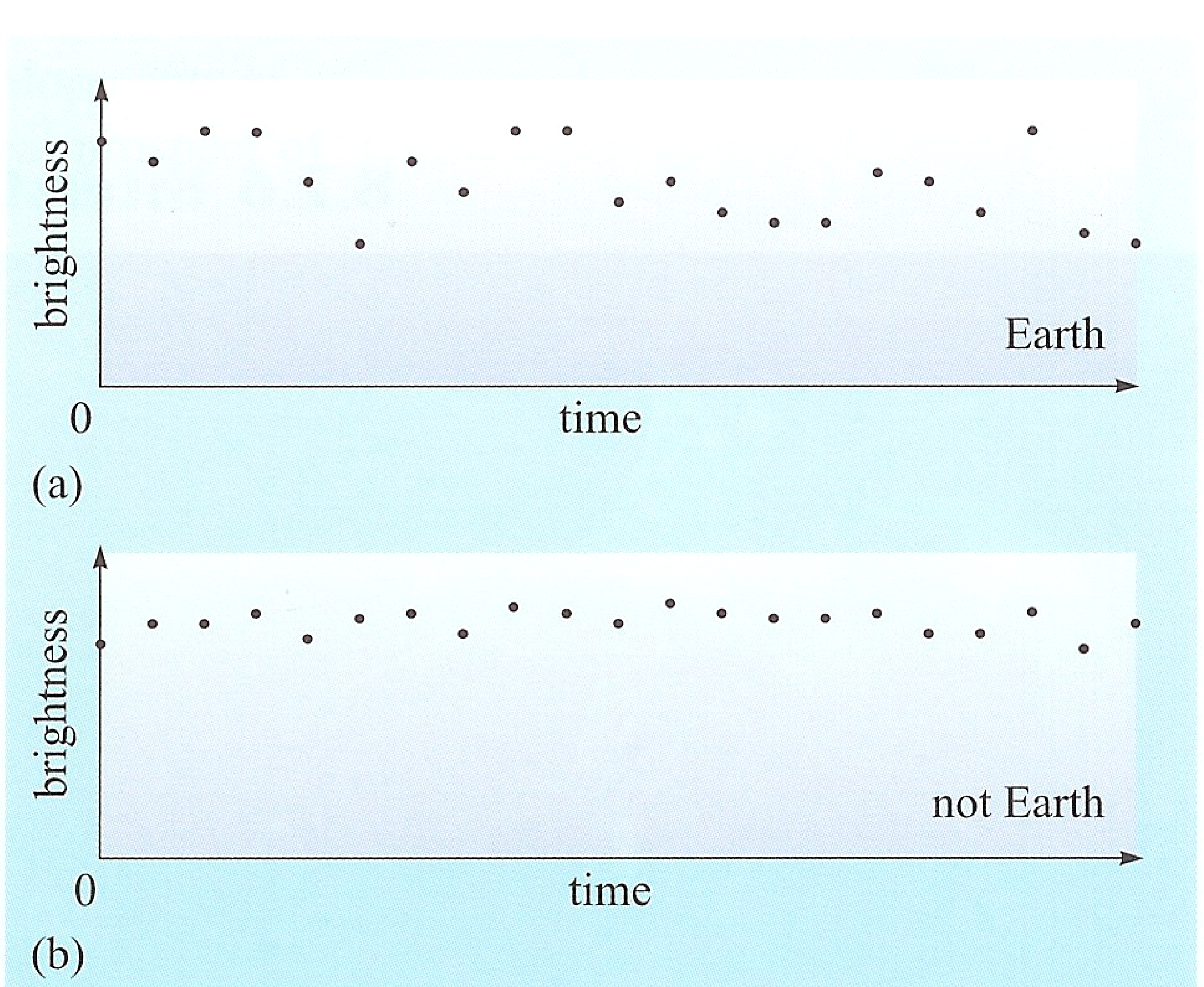
Exoplanet “surface”

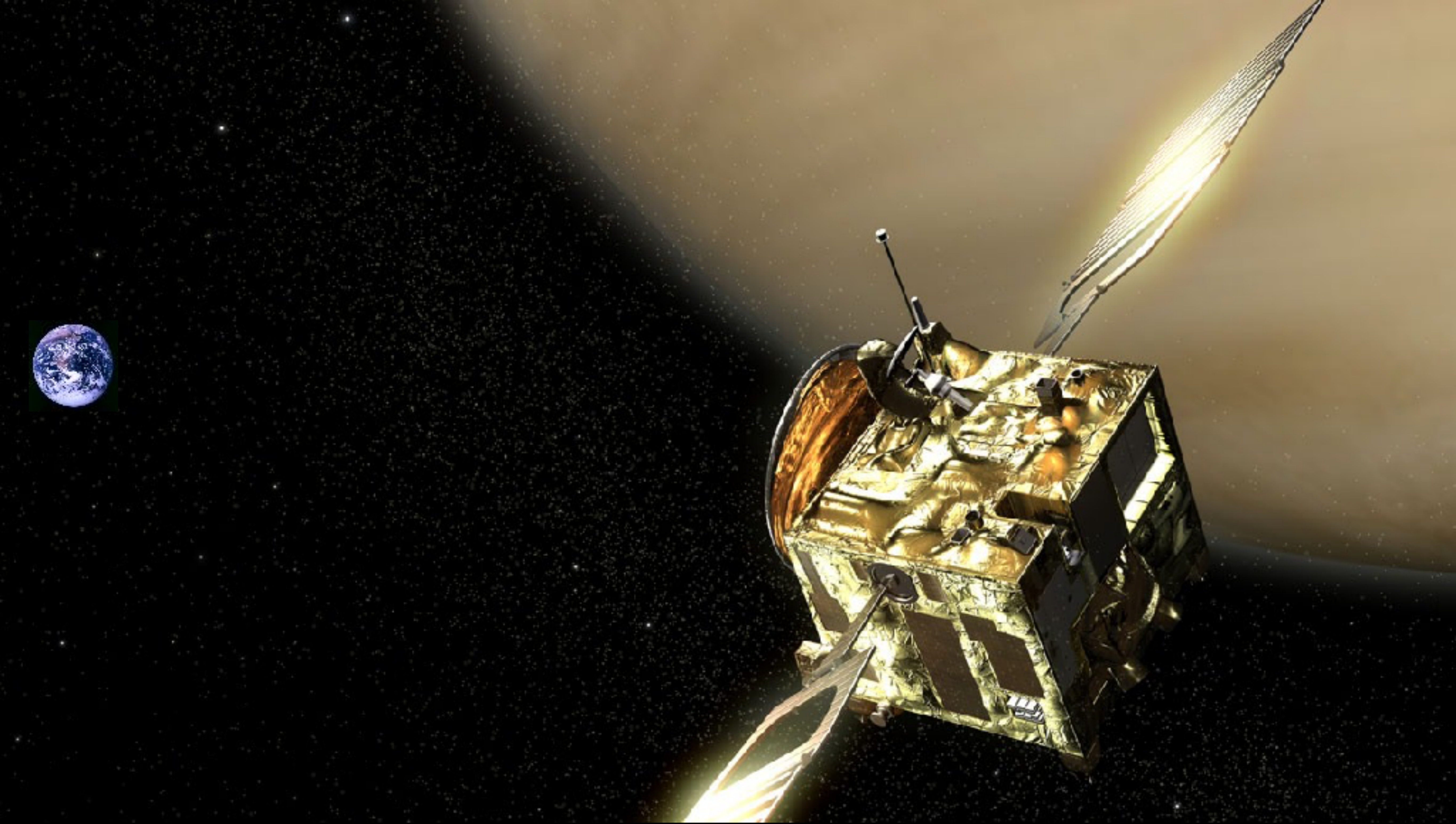
As direct imaging becomes feasible, variation of the reflected sunlight will indicate variations in albedo (±20%), i.e. cloud coverage, surface composition

These measurement can be combined with spectroscopy of the atmosphere

Albedo:

Ocean	10%
Land	30%
Snow/Ice	60%





Venus Express (ESA) frequently looked back at Earth

Biosignatures

Is there Life on Earth?

The Galileo Spacecraft

Launched to study Jupiter and Europa
It looked back on Earth in 1990 and 1992

What might Galileo have seen?

A search for life on Earth from the Galileo spacecraft

Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

* Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
‡ Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
§ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

At ranges varying from ~100 km to ~100,000 km, spacecraft have now flown by more than 60 planets, satellites, comets and asteroids. They have been equipped variously with imaging systems, photometric and spectrometric instruments extending from ultraviolet to kilometre wavelengths, magnetometers and charged-particle detectors. In none of these encounters has compelling, or even strongly suggestive, evidence for extraterrestrial life been found. For the Moon, Venus and Mars, orbiter and lander observations confirm the conclusion from fly-by spacecraft. Still, extraterrestrial life, if it exists, might be quite unlike the forms of life with which we are familiar, or present only marginally. The most elementary test of these techniques—the detection of life on Earth by such an instrumented fly-by spacecraft—had, until recently, never been attempted.

Galileo is a single-launch Jupiter orbiter and entry probe currently in interplanetary space and scheduled to arrive in the Jupiter system in December 1995. It could not be sent directly to Jupiter; instead, the mission incorporated two close gravitational assists at the Earth and one at Venus. This greatly lengthened the transit time, but it also permitted close observations of the Earth. The

Infrared spectrometer

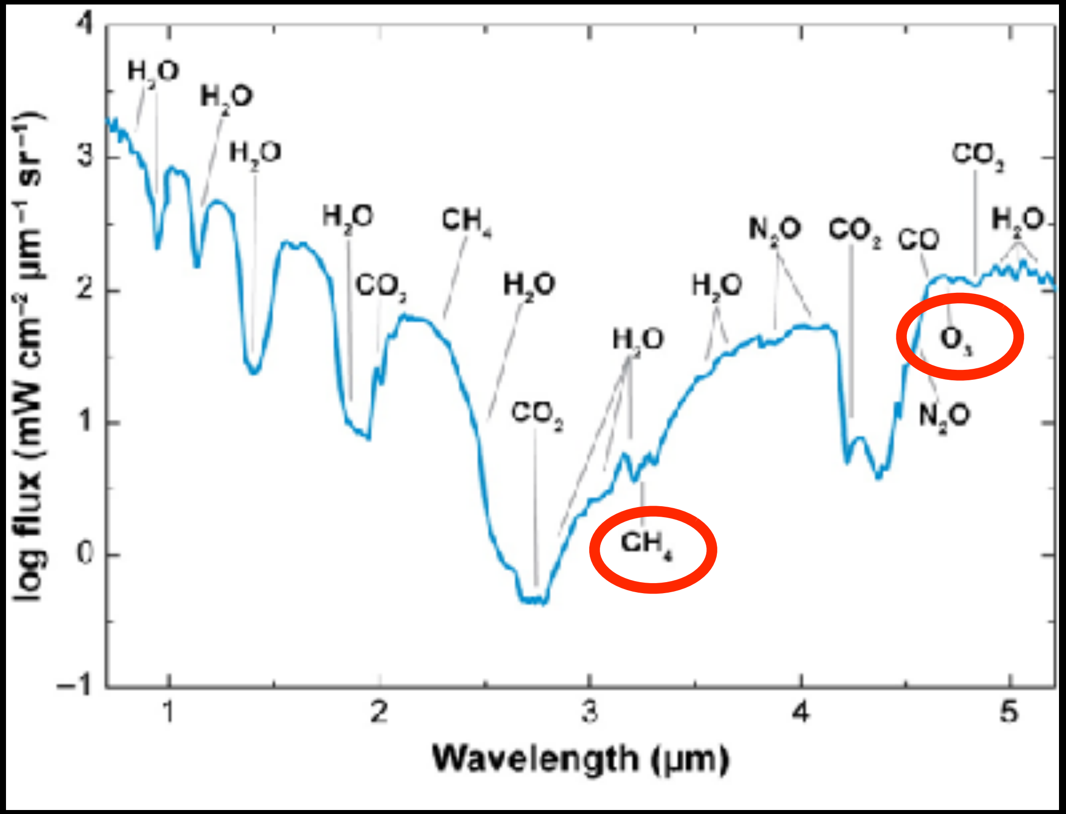
Detected O_3 (i.e. O_2) and CH_4 simultaneously

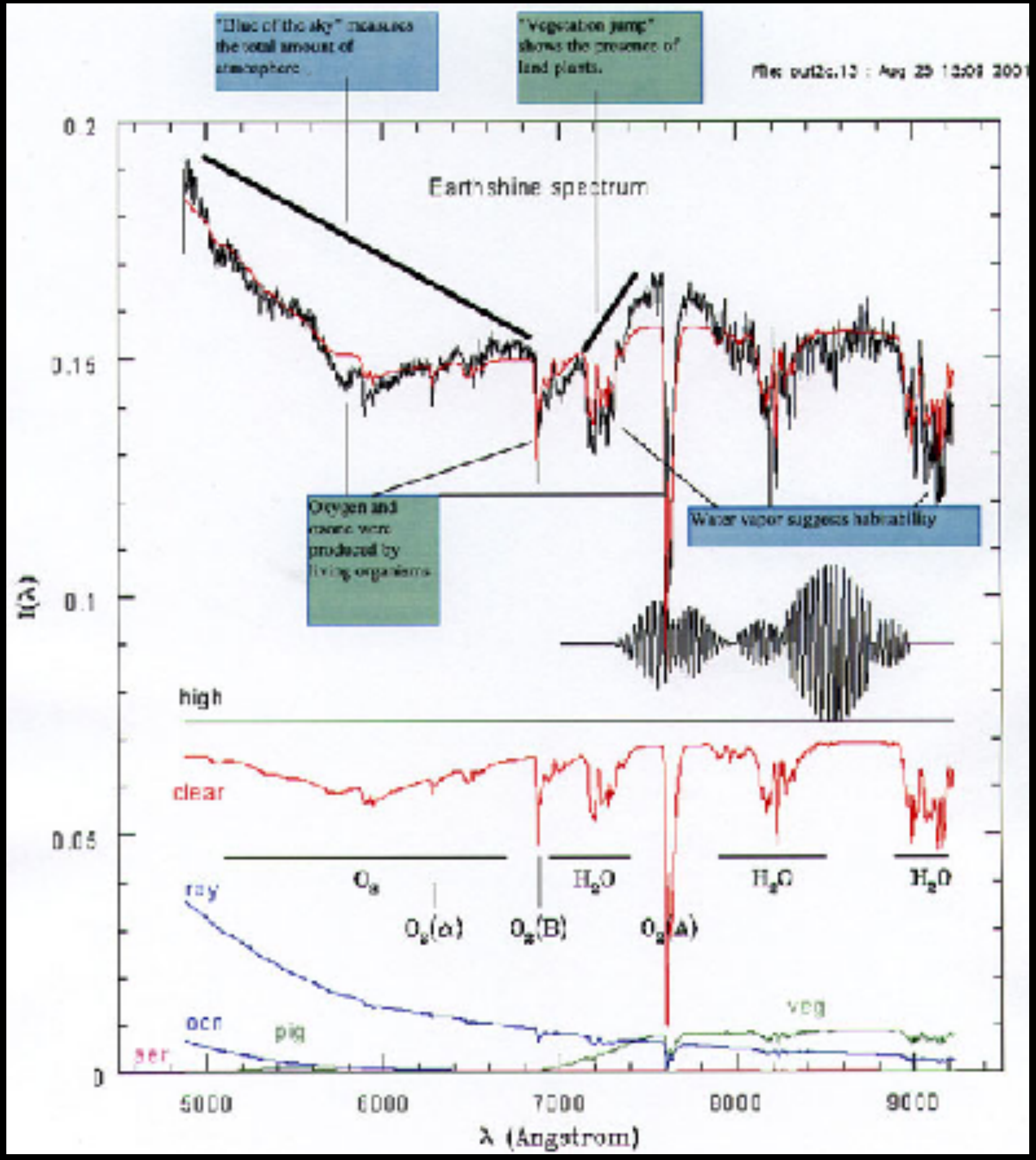
Optical spectrometer

Reflectance spectrum of the Earth (Earthshine): Vegetation “red-edge”

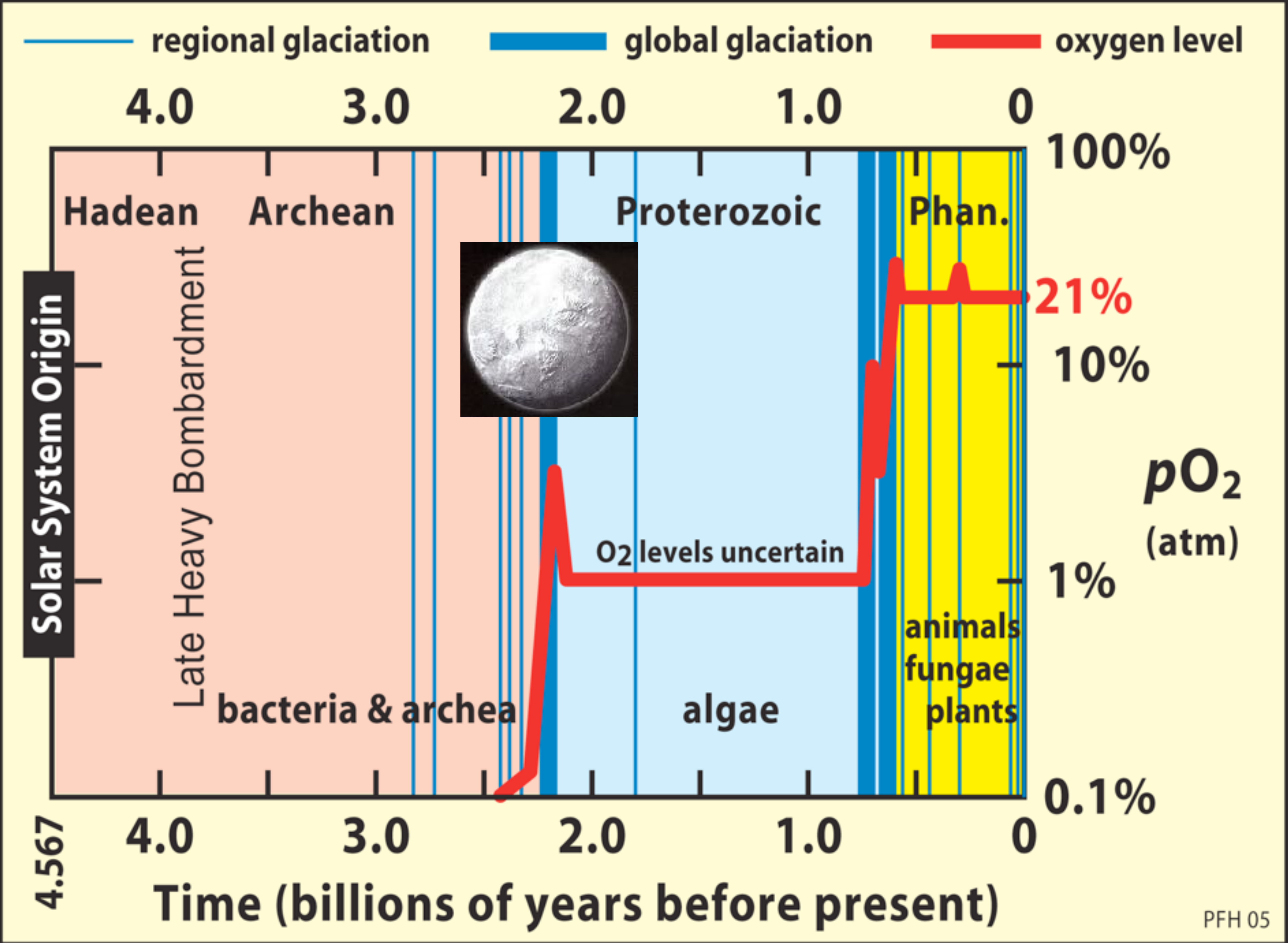
Radio receiver

strong radiation in narrow wavelength ranges (radio + TV) not explained by natural processes: *intelligent life*



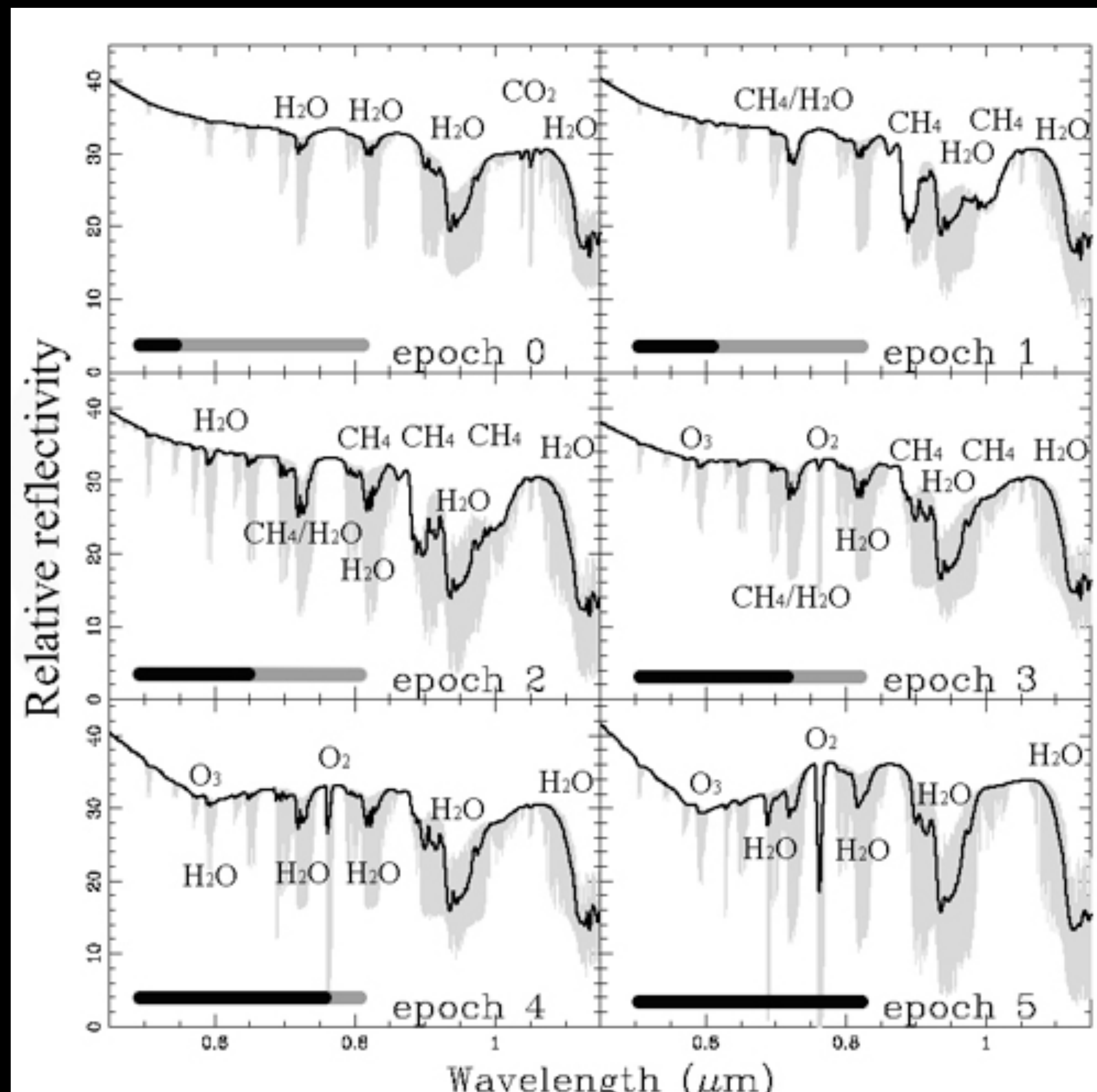


Was there Life on Earth?



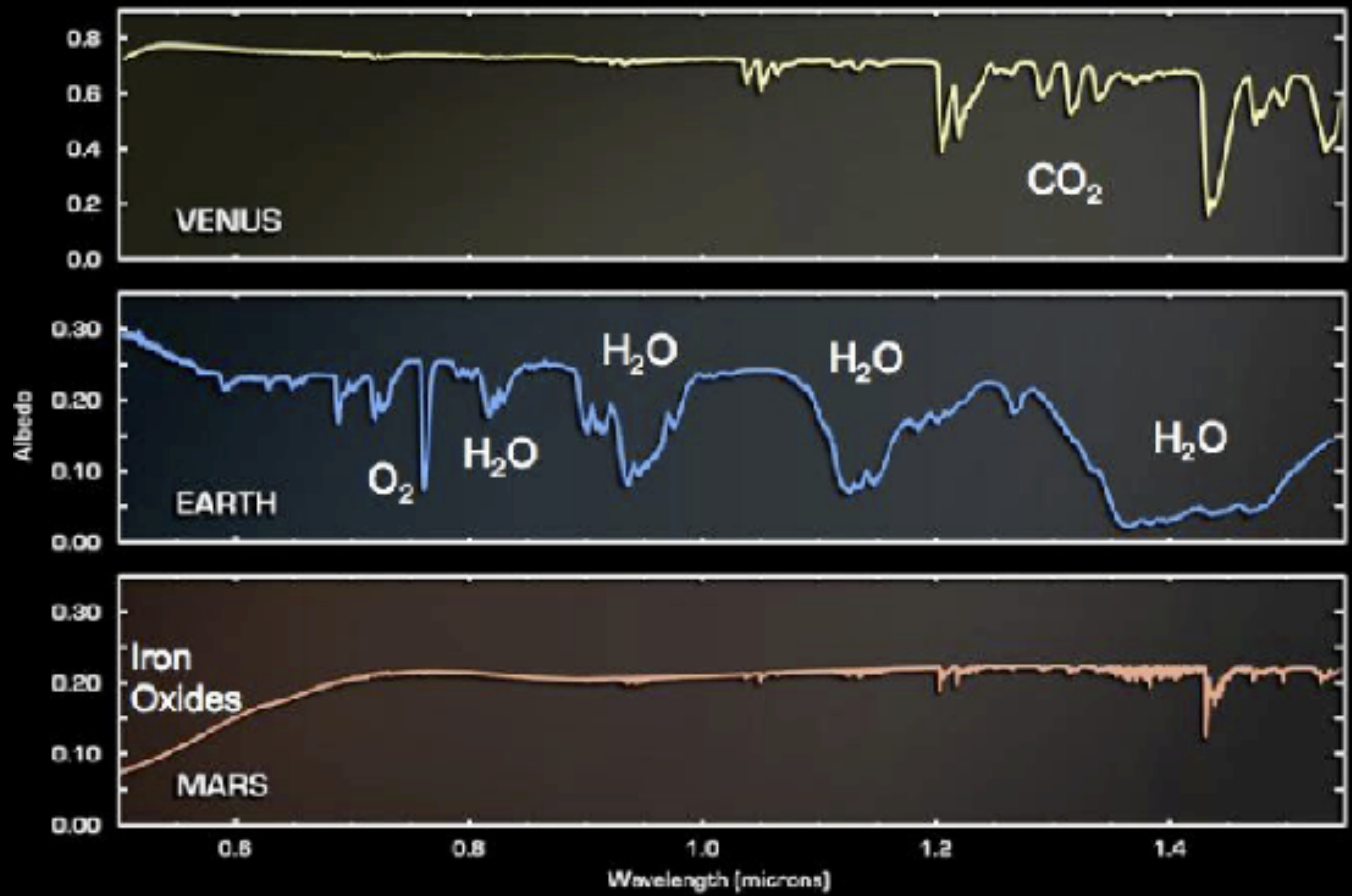
regional glaciation
global glaciation
oxygen level
4.0
3.0
2.0
1.0
0
100%
Hadean
Archean
Proterozoic
Phan.
Solar System Origin
Late Heavy Bombardment
21%
10%
pO_2
(atm)
O_2 levels uncertain
1%
animals
fungae
plants
bacteria & archea
algae
0.1%
4.567
4.0
3.0
2.0
1.0
0
Time (billions of years before present)
PFH 05

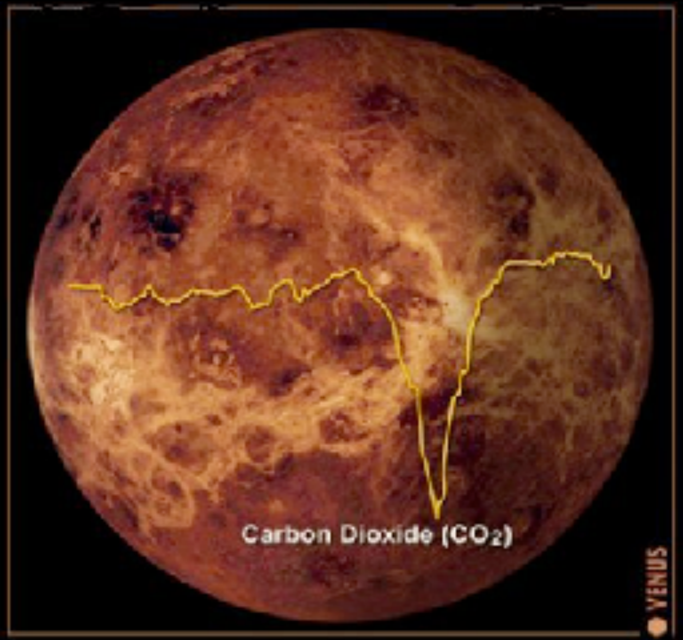
As Life and Climate evolved, biosignatures evolved

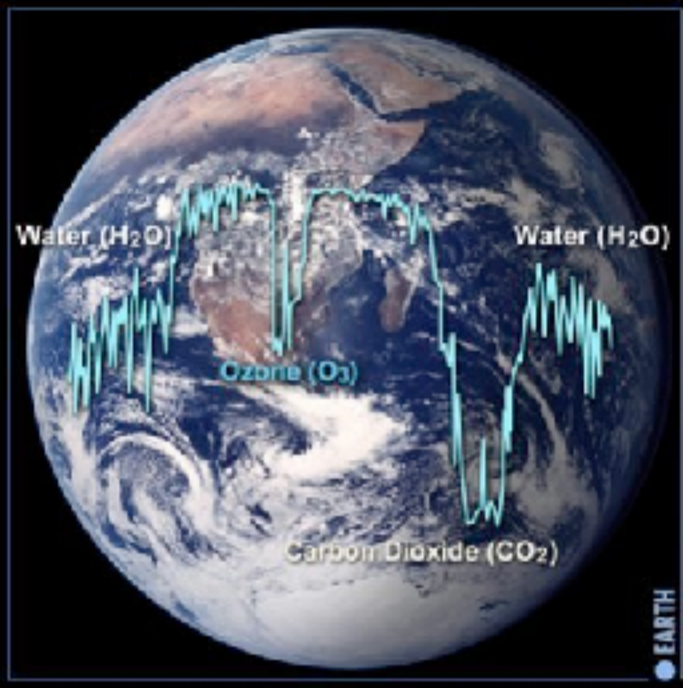


Biosignatures / Biomarkers

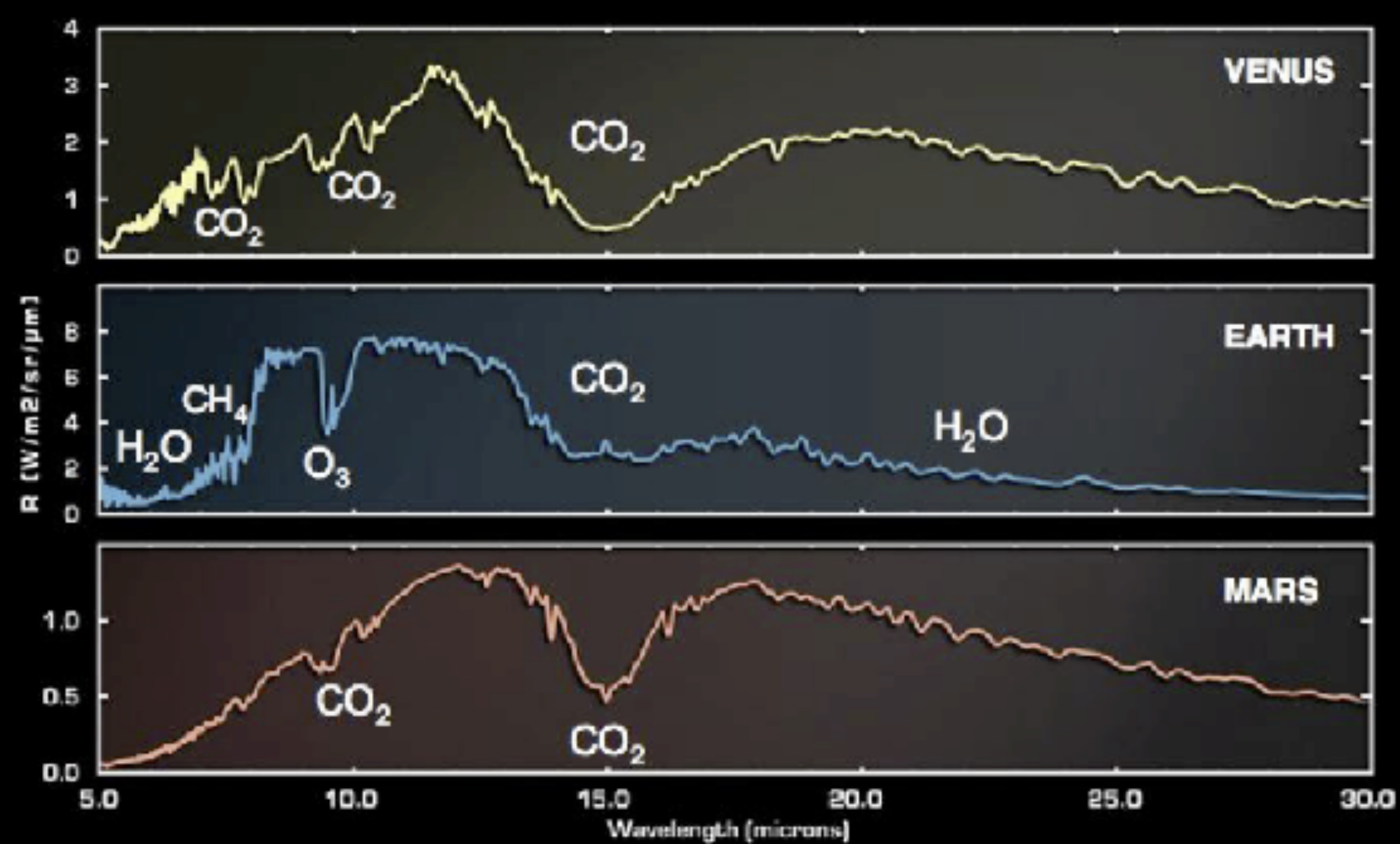
Optical

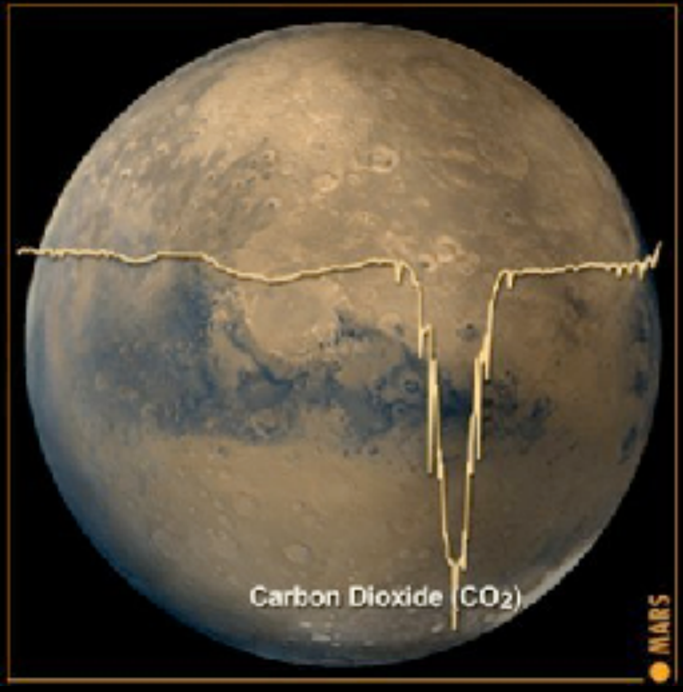






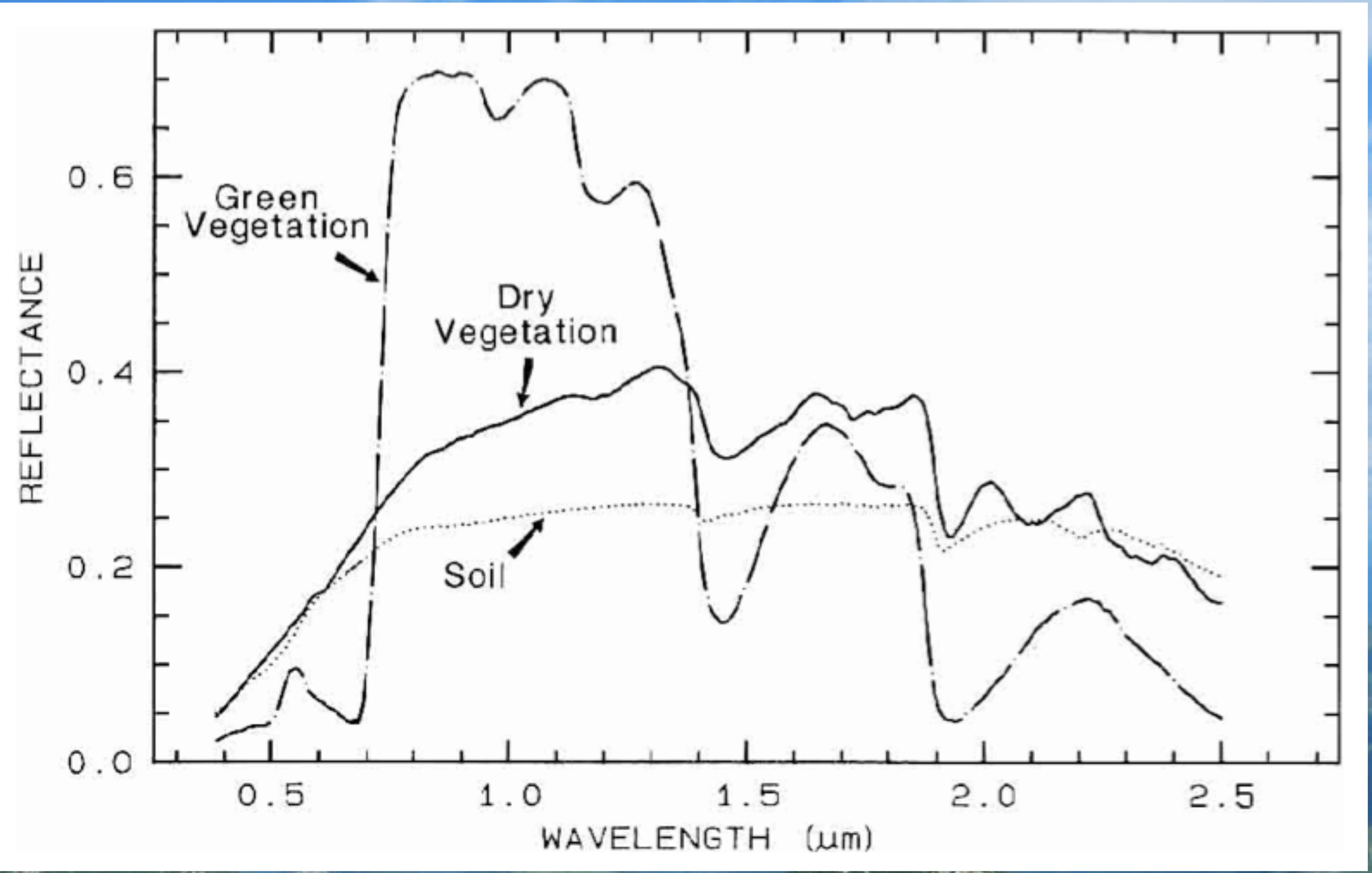
Near-infrared





What is the cause for the vegetation ‘Red-edge’?

Vegetation is a surface biomarker



Biosignature Thermodynamics

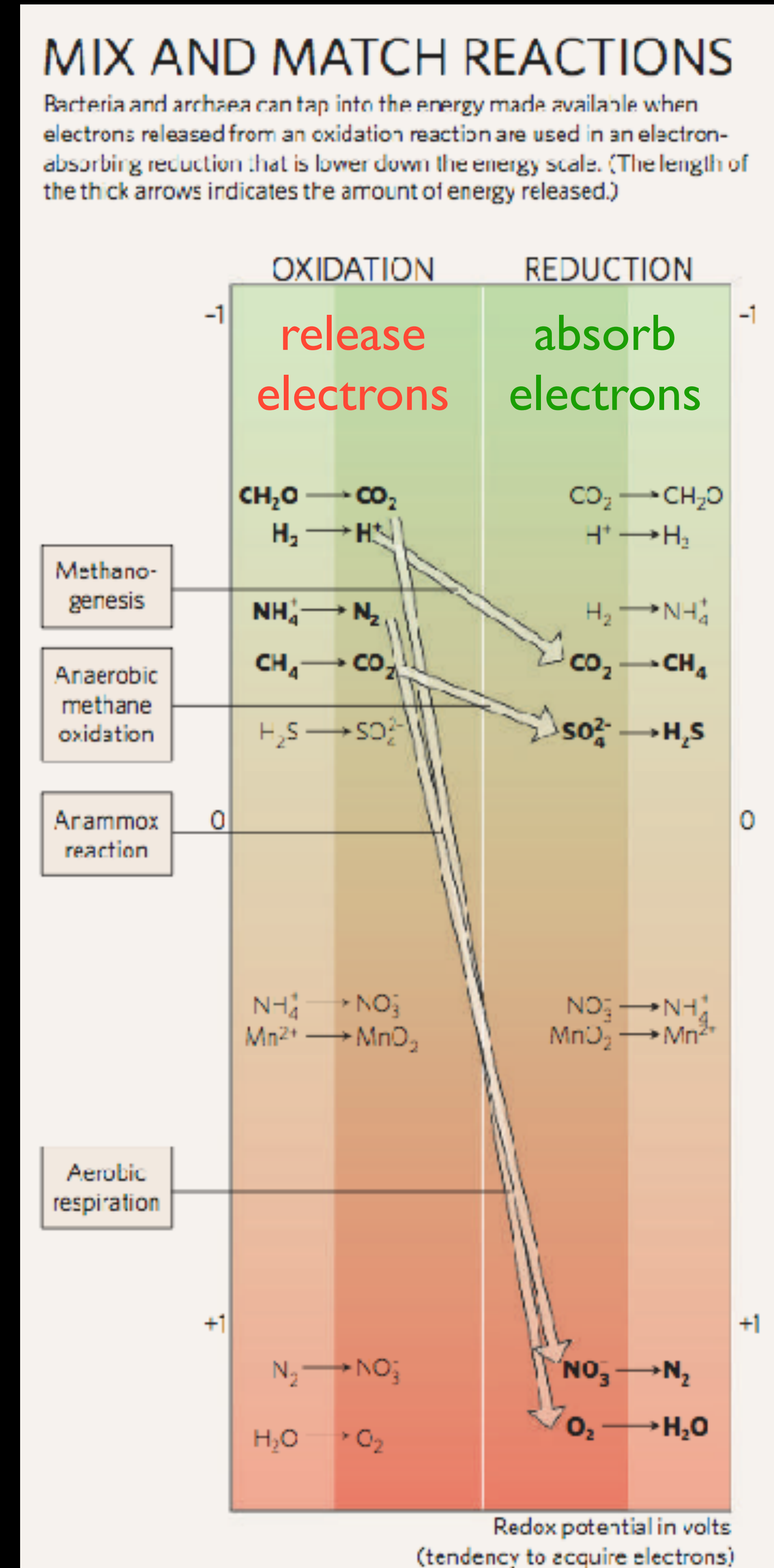
The major net chemical transformations performed by life on Earth and the product gases:

Metabolic reactions are redox reactions (either to generate energy or biomass)
Search for gases in (redox) disequilibrium

e.g. Respiration:
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6\ H_2O$
30 ATP per glucose

Anaerobic metabolism:
1-2 ATP per glucose

See Review by Seager, Schrenk & Bains 2012



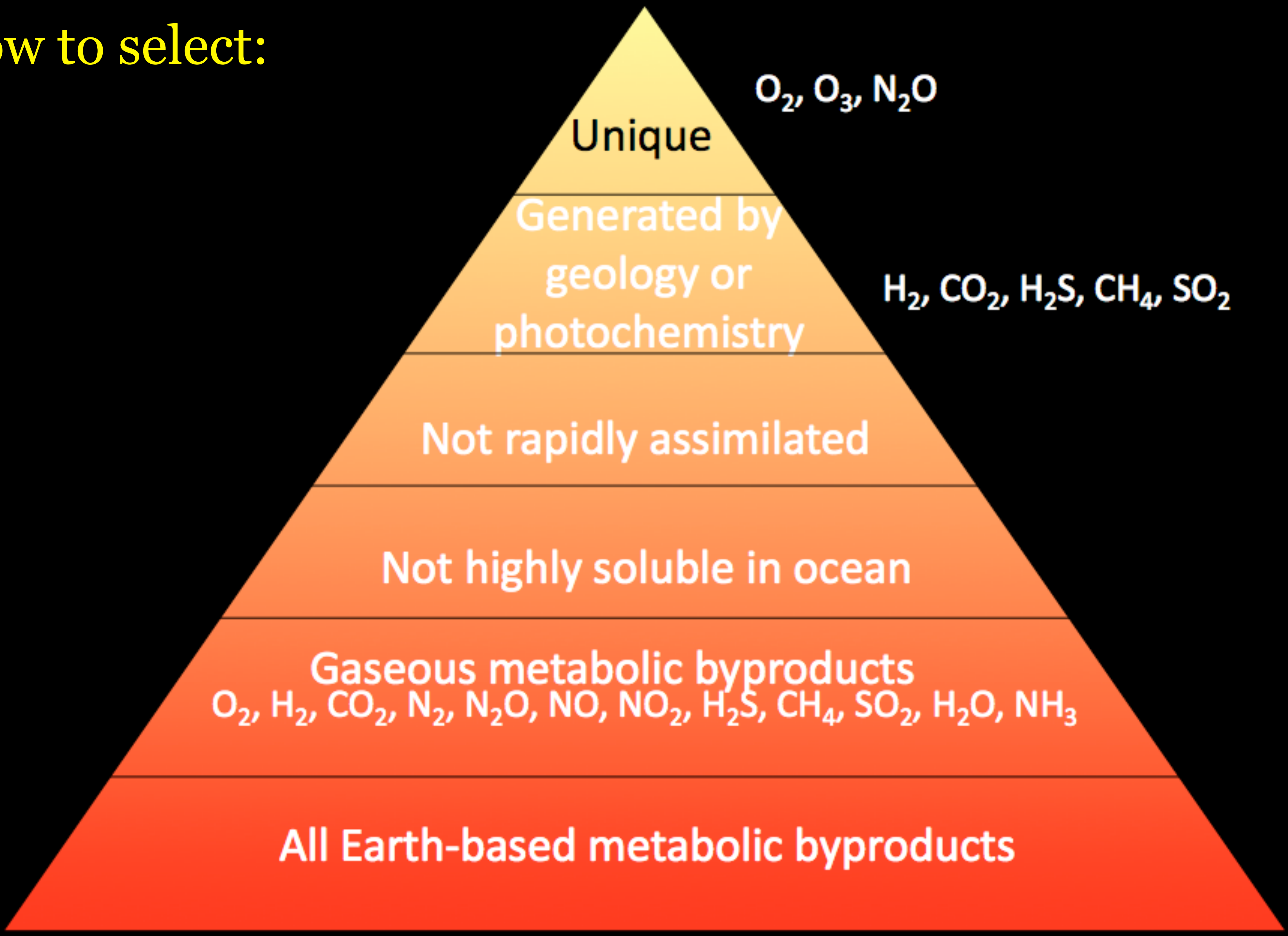
Different atmospheres, different stellar fluxes could have different biosignatures…

How to select:

All Earth-based metabolic byproducts

Different atmospheres, different stellar fluxes could have different biosignatures…

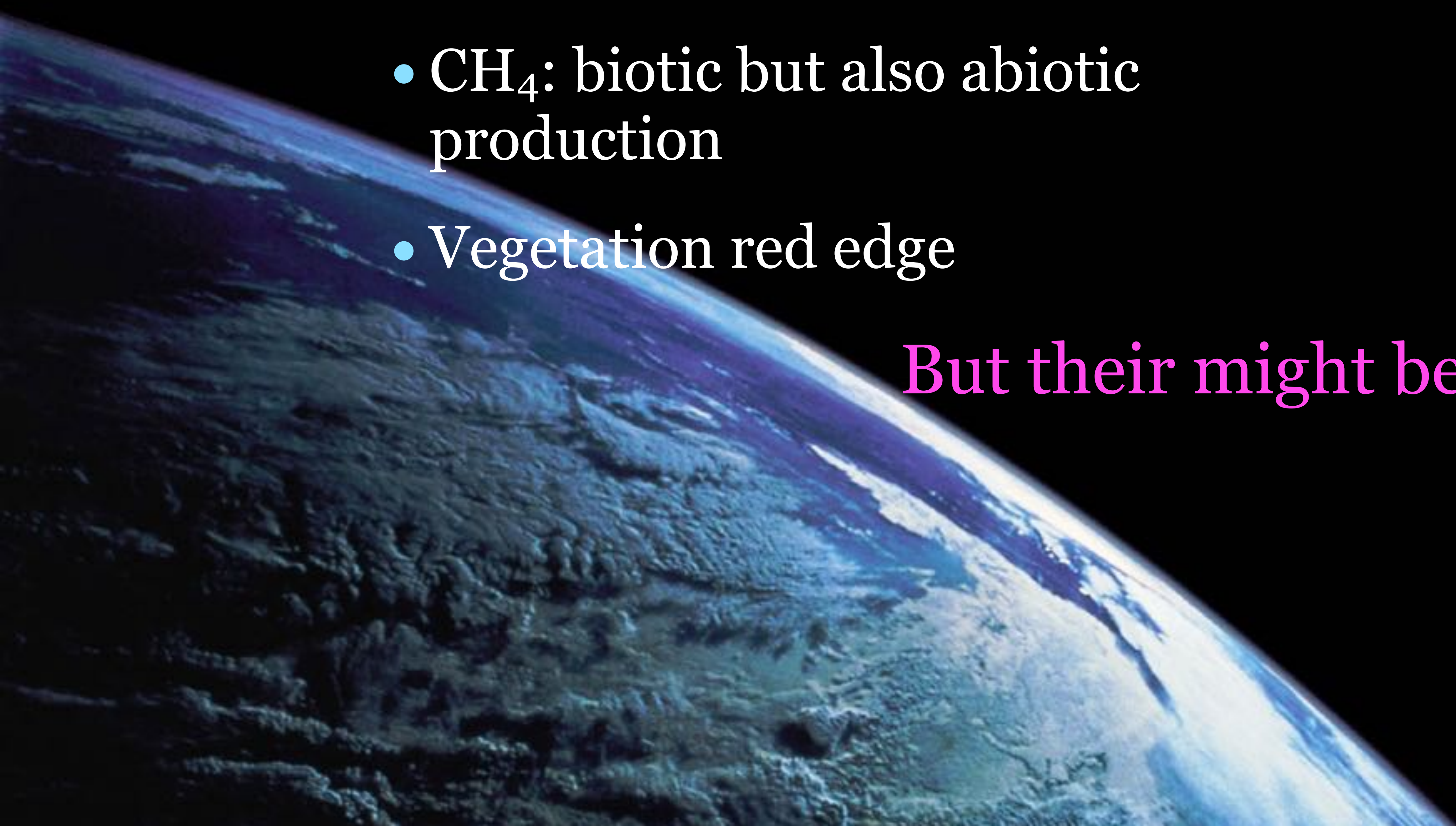
How to select:



Terracentric Biosignatures:

- O_2/O_3 : oxygen based metabolism
- N_2O: biological but weak signature
- H_2O: evidence for liquid water
- CH_4: biotic but also abiotic production
- Vegetation red edge

But their might be more…



Take home ideas

- Almost all stars host planets
- Stars < $1M_{\odot}$ are better suited for life
- Over 5000 exoplanets are know to date, through transiting (radius) and radial velocity methods (mass)
- Hundreds of densities measured
- Spectroscopy of giant planet attempt atmospheres is possible
- Biosignatures in atmospheres are derived from metabolic redox reactions

Homework:

- iOS: download the app ‘Exoplanet’ and play
- Android: download the app ‘Exoplanet Explorer’ (3US$) and play

Monday November 20	Day 1: Definition of Life; Origin of Life; Evolution of Life; Limits of Life 10:00-12:00 & 13:00-14:00 ✔
Tuesday November 21	Day 2: Earth Climate History; Mars and Venus Climates 10:00-12:00 & 13:00-14:00 OLD SEMINAR ROOM ✔
Wednesday November 22	Day 3: Habitable Places in the Solar System; Mars; Moons of Giant Planets 10:00-12:00 & 13:00-14:00 ✔
Thursday November 23	Day 4: Habitable Places beyond the Solar System; Exoplanets properties; Biosignatures 10:00-12:00 & 13:00-14:00 ✔
Friday November 24	Day 5: Search for Extraterrestrial Intelligence; Alien Biochemistry 10:00-12:00 & 13:00-14:00

The End for Today

Thank you!