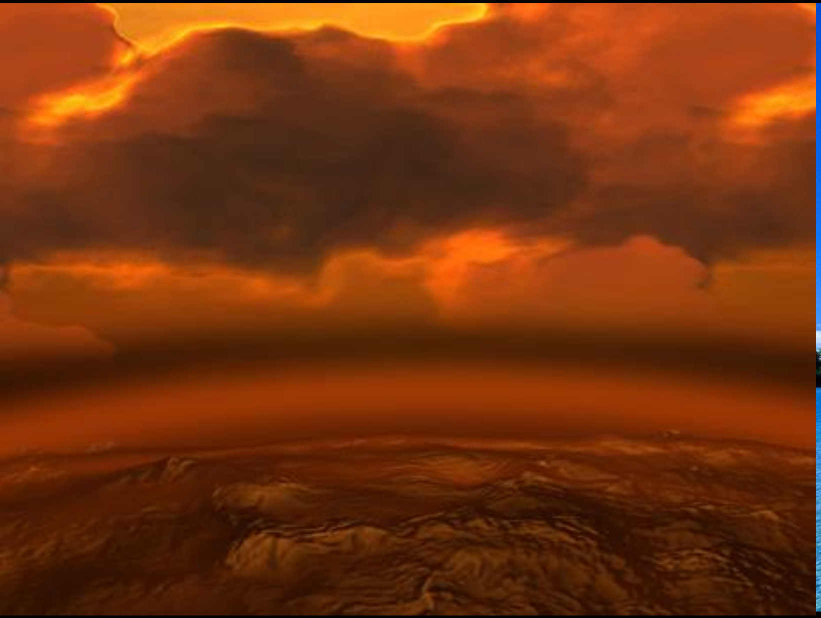
Planetary Habitability I



Dave Brain
U. Colorado

1. Habitability

Question

What is life? What are its essential characteristics?

You have 3 minutes

-

Requirements for life

All ~8.7 million species of life on Earth require three things:

<u>Building blocks</u>

C, H, N, O, P, S

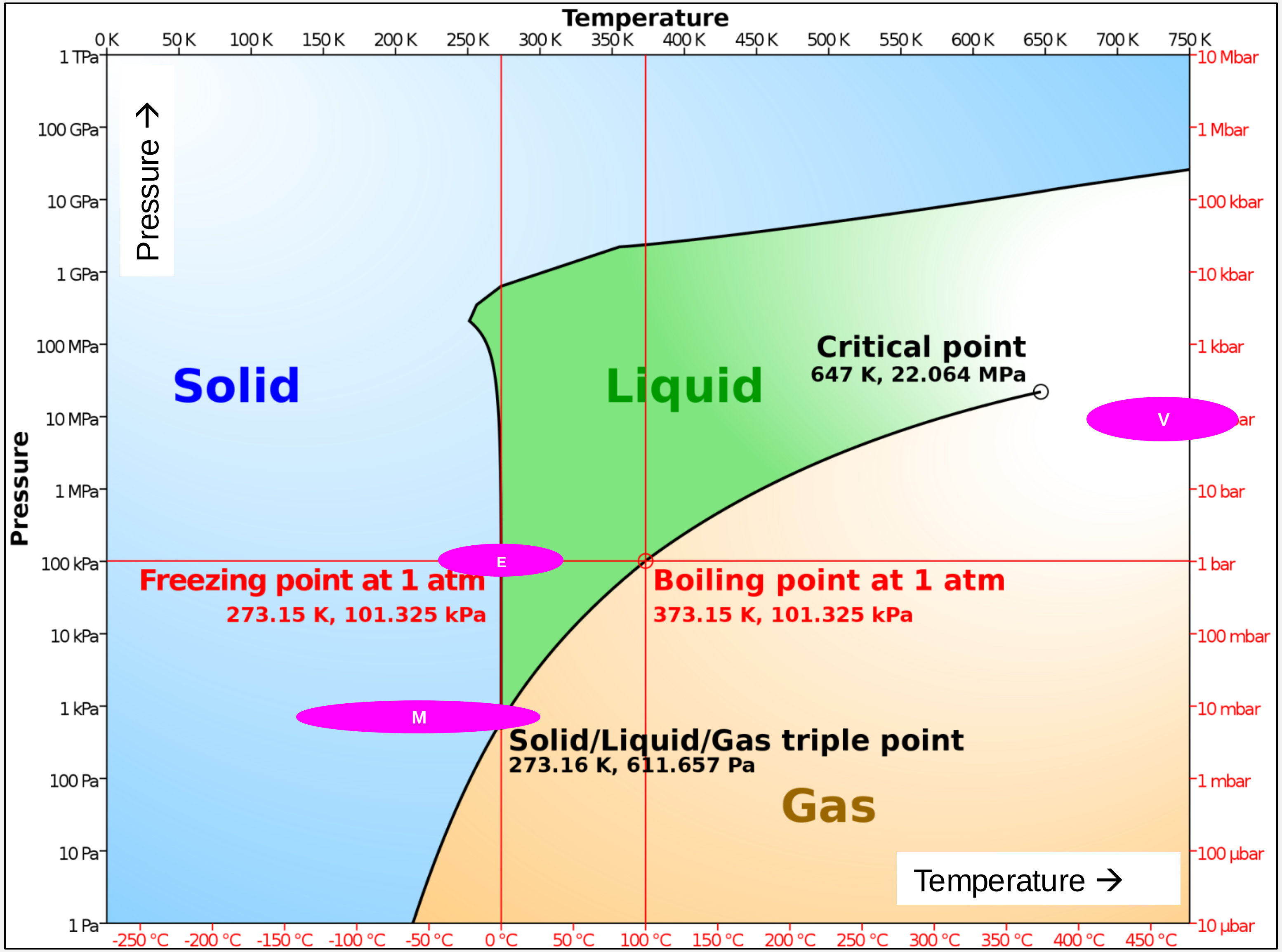
<u>Source of energy</u>

sunlight
chemical reactions
heat

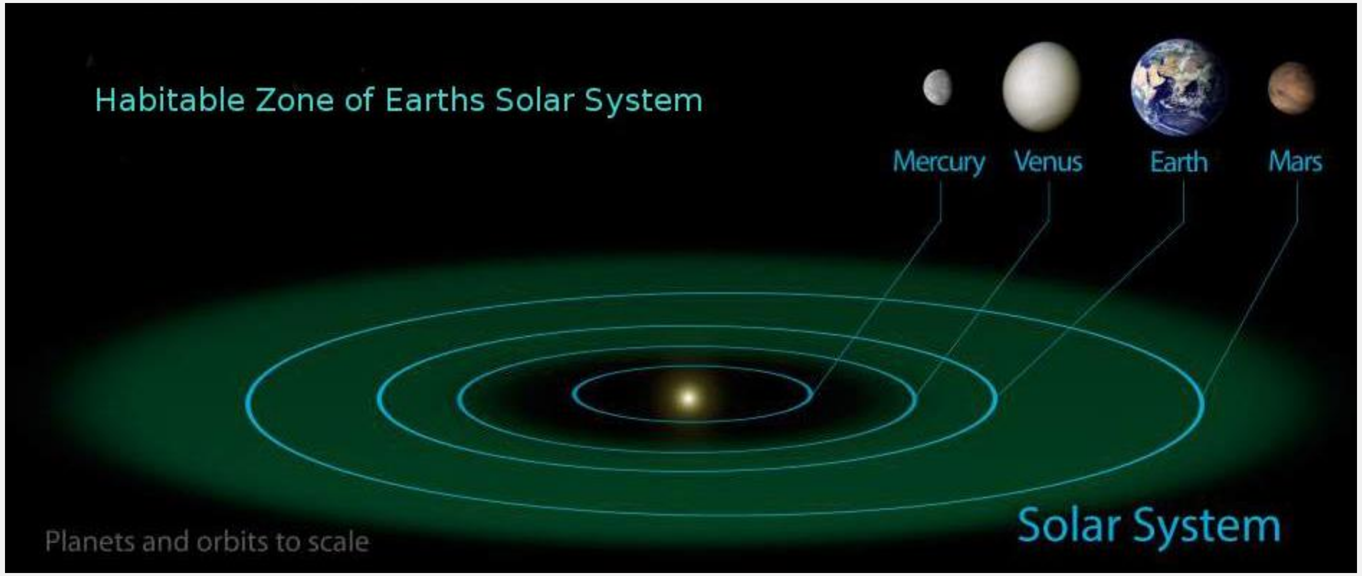
<u>Liquid water</u>

good solvent
'Polar' molecule

Liquid water requires the right temperature and pressure



Habitable zone



Liquid water requires $T_{surface} > \sim 273\ K$

Recall:

$$T_{surface}^4 = (1+\tau)\, T_{effective}^4 \qquad T_{effective}^4 = \frac{S}{4\varepsilon\sigma}\,\frac{1-A}{d^2}$$

So solar luminosity, albedo, and amount of greenhouse gases all play a role in *where* water can be liquid

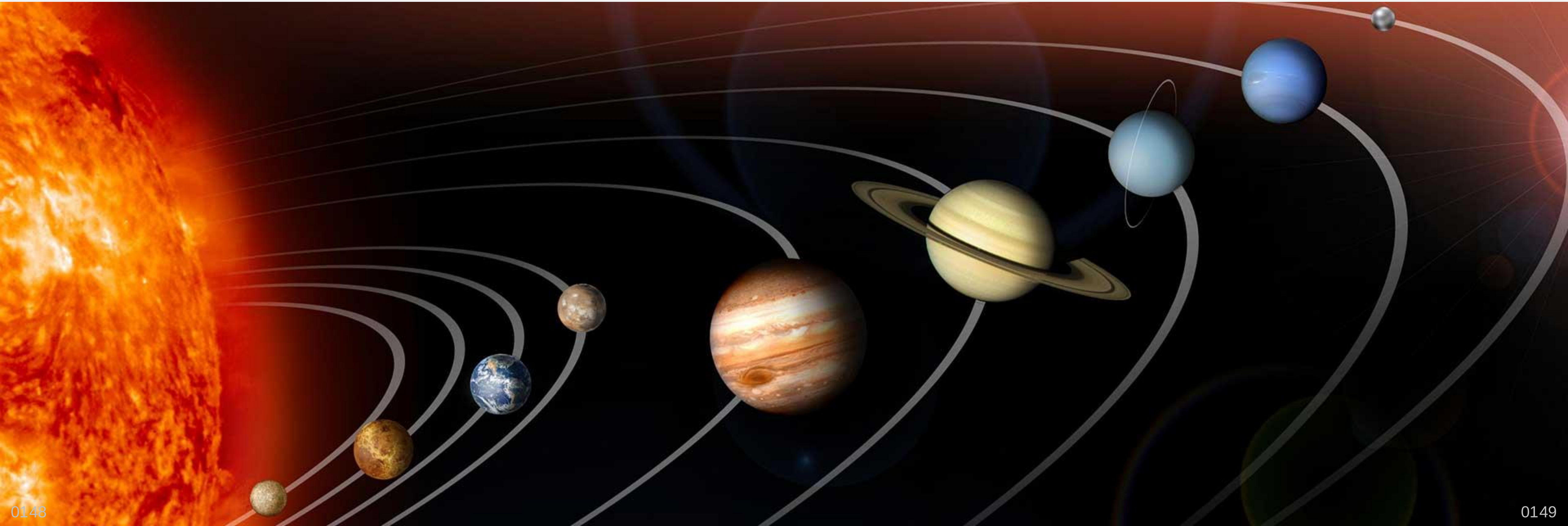
'Habitable Zone' refers to the distance from a star, *d*, where water might exist as liquid on a planetary surface

Habitable zone

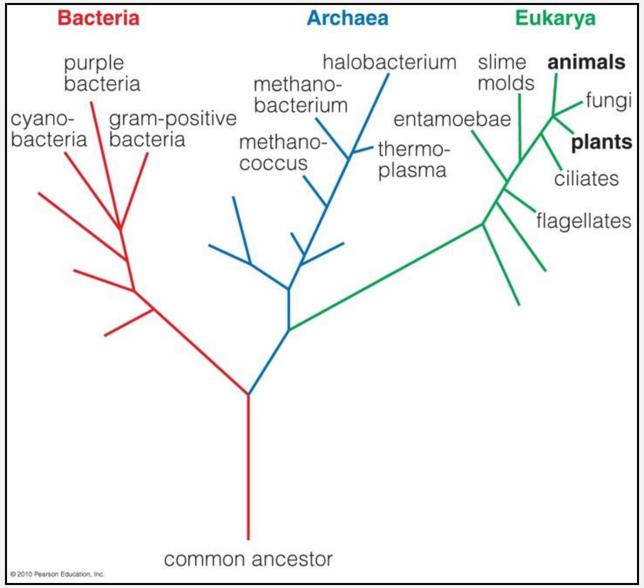
Estimating the HZ distance depends upon the assumptions you make

Inner Edge (AU)	Outer Edge (AU)	Authors
0.725	1.24	Dole, 1964
0.95	1.01	Hart et al., 1979
0.95	1.37	Kasting et al., 1993
0.75		Abe et al., 2011
	10	Pierrehumbert and Gaidos, 2011
0.99	1.70	Kopparapu et al., 2013
0.95	2.4	Ramirez and Kaltenegger, 2017

2. Solar System Habitability

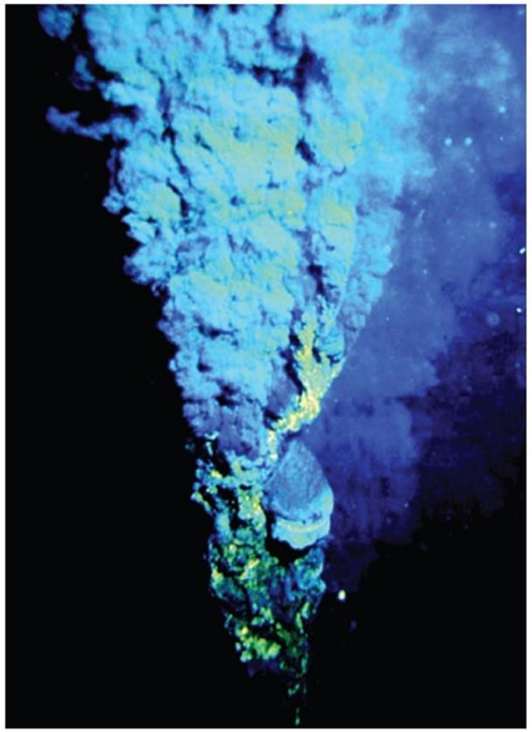


Earth



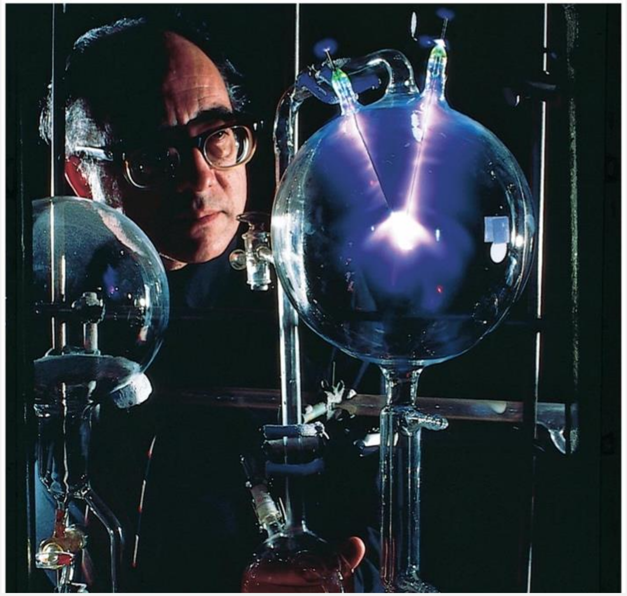
When

- Fossils by 3.5 Gya
- Isotope signatures back to 3.85 Gya
- ➢ Started quickly after impact bombardment



Where

- Tree of life → common ancestor
- Microbes near seafloor vents are good option
- Seafloor environment is harsh but sheltered
- Today we find life nearly everywhere we look, including extreme environments



How?

- Miller-Urey experiment → sparking early Earth chemicals yields organic molecules
- Other scenarios are promising, too

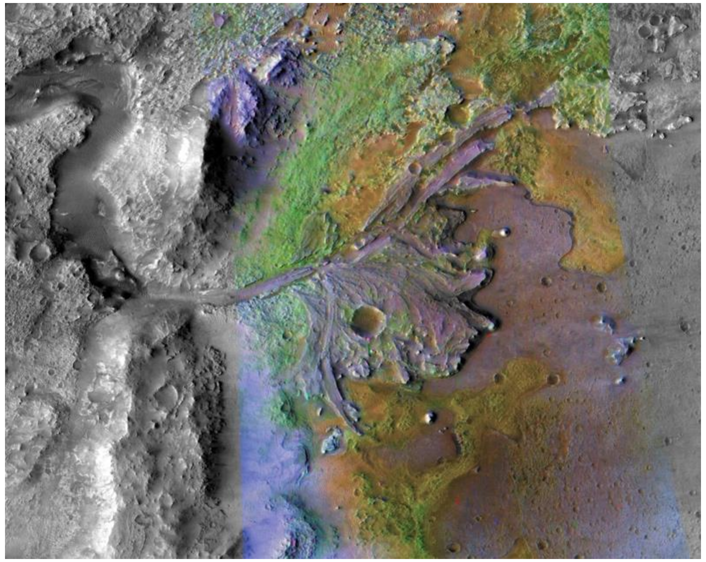
Mars

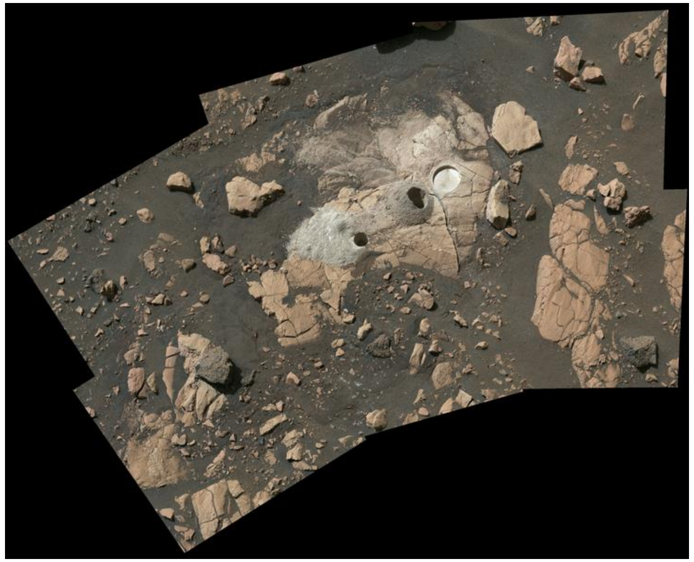
Abundant evidence for stable past liquid surface water

- → Mars was habitable
- → Evidence for past life may be present, and more accessible than at other solar system objects

Is life active today?

- Controversial evidence for atmospheric methane
- Suggestions for past subsurface hydrothermal systems, with speculation they could exist today





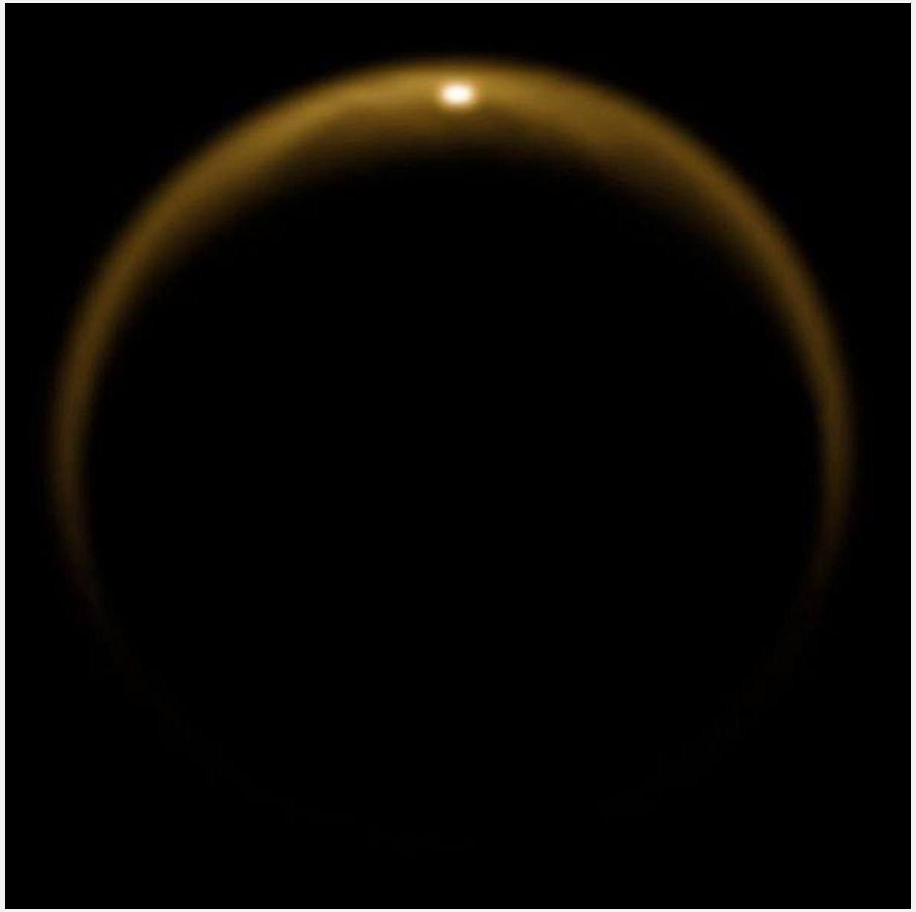
Titan

Requirements for life *may* be met at the surface

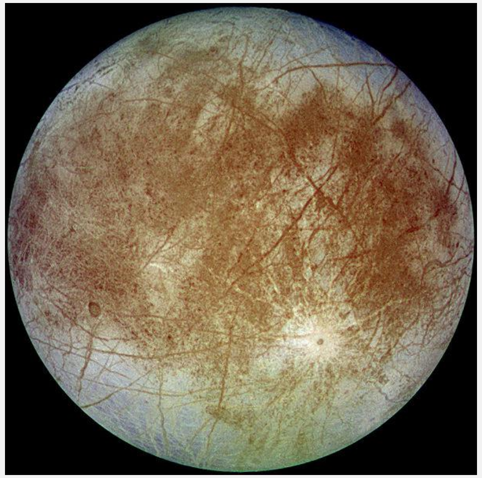
- No liquid water, but lakes of liquid methane and ethane
    - Methane and ethane are not polar, not good solvents
- Rich atmospheric chemistry, with organic compounds

The subsurface may be a better option

Future Titan may be better!



Icy moons

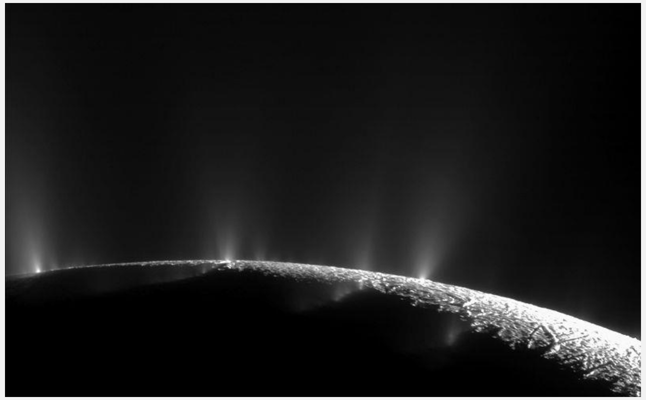
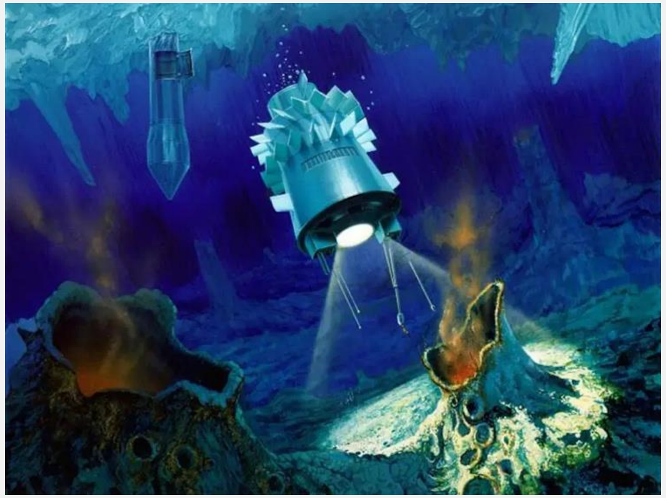
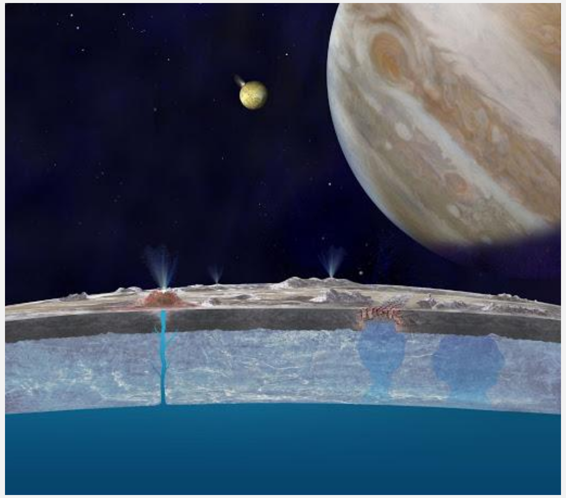


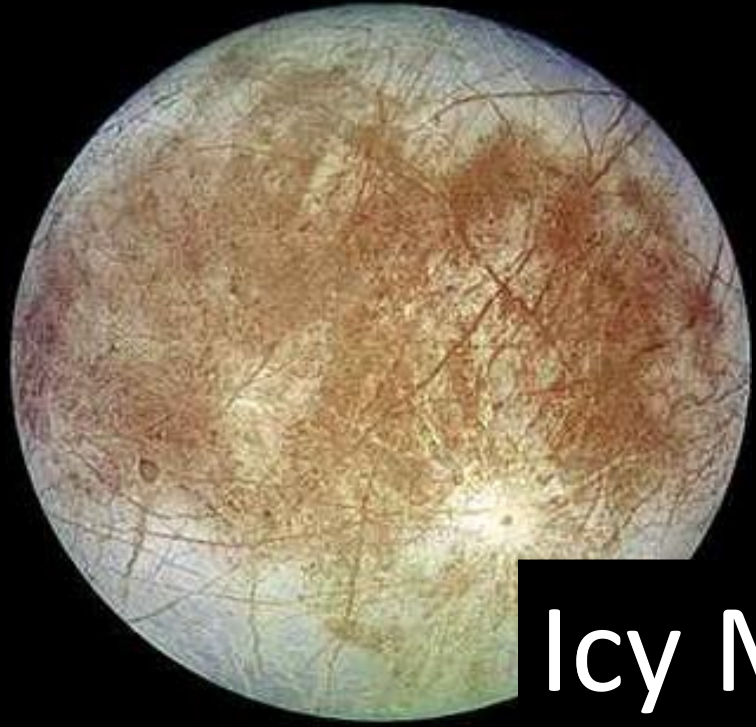
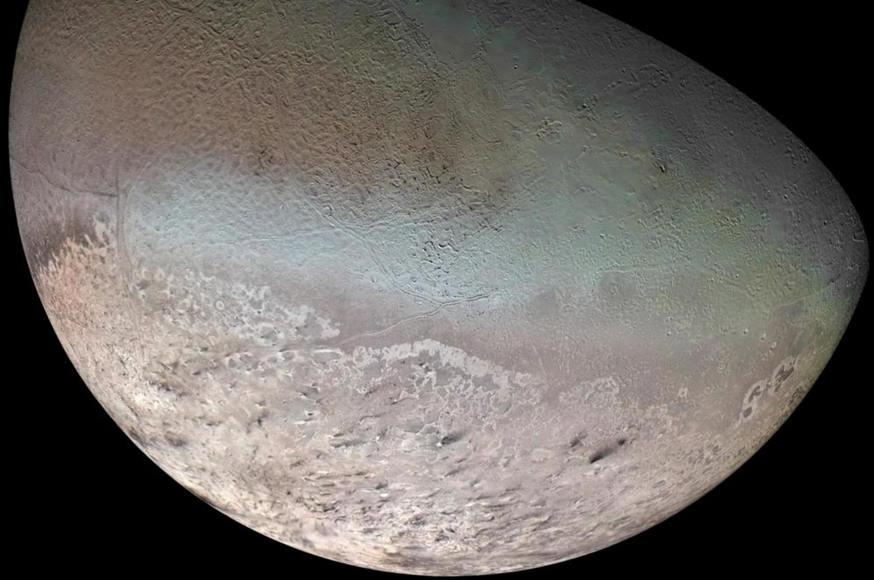
Requirements for life are met

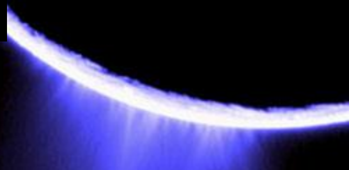
- Liquid water under icy shells
- Heat source from tides for many

Accessibility is an issue

- These may be the most likely places to find other life in our solar system
- But getting to it is hard (geyser exception?)
- Icy moons in other solar systems can only be explored remotely

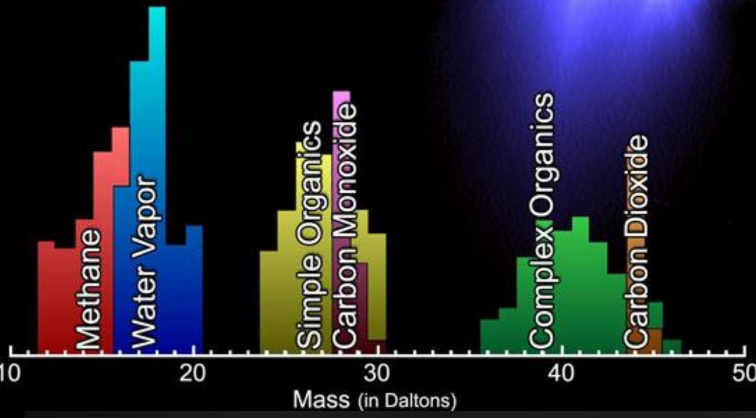





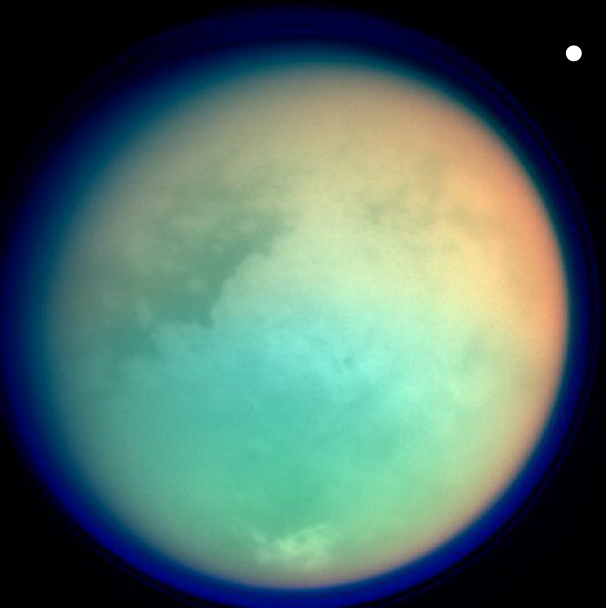
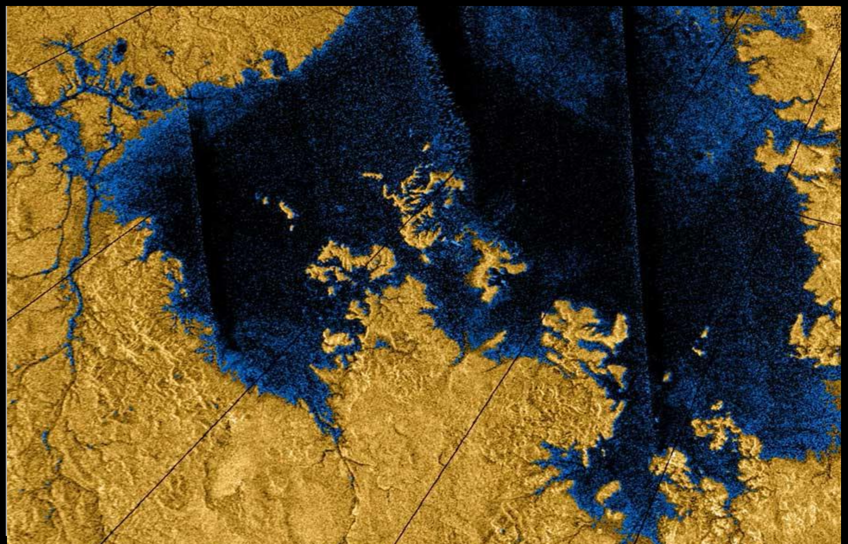
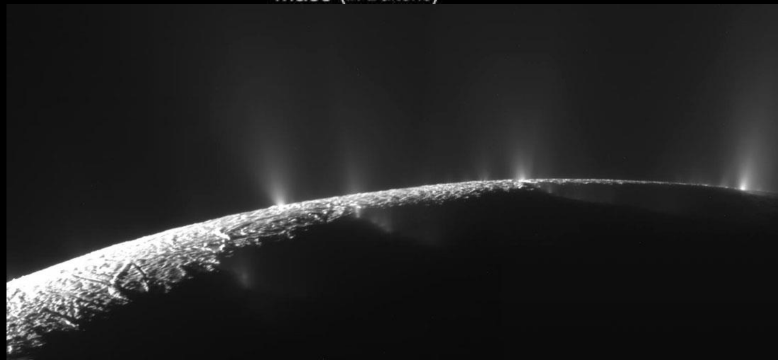





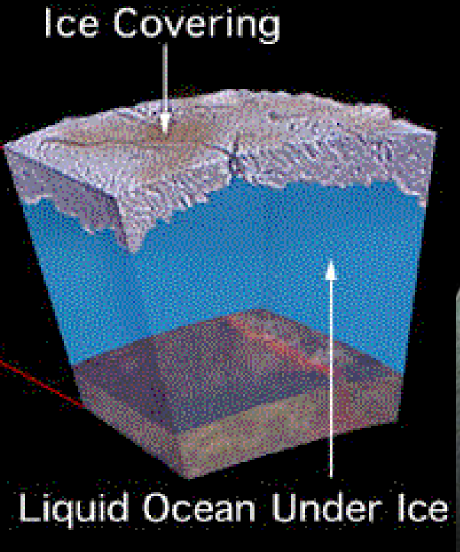
Icy Moons

- Outside "habitable zone"
- Most likely place to find extra-terrestrial life

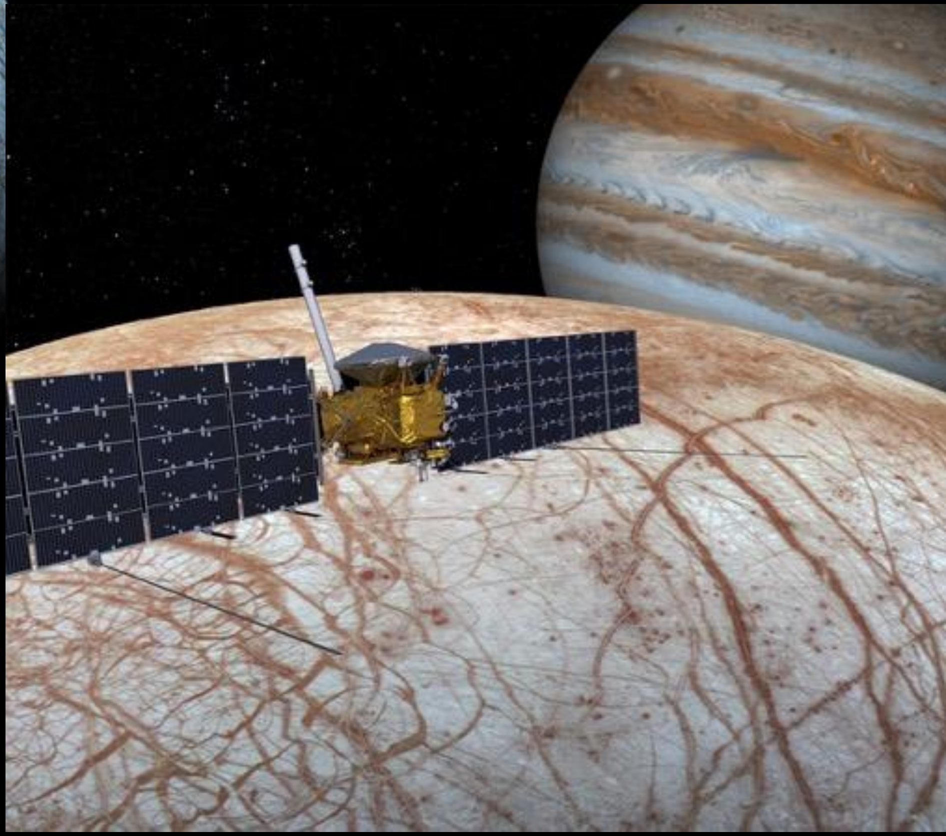


Europa



NASA's Europa Clipper Mission



- What's the brown gunk?
- How thick is ice?
- Does water reach surface?
- What's in the water??
- If Life, what kind of Life?!

Launch Oct 2024

Venus

nature astronomy

ARTICLES

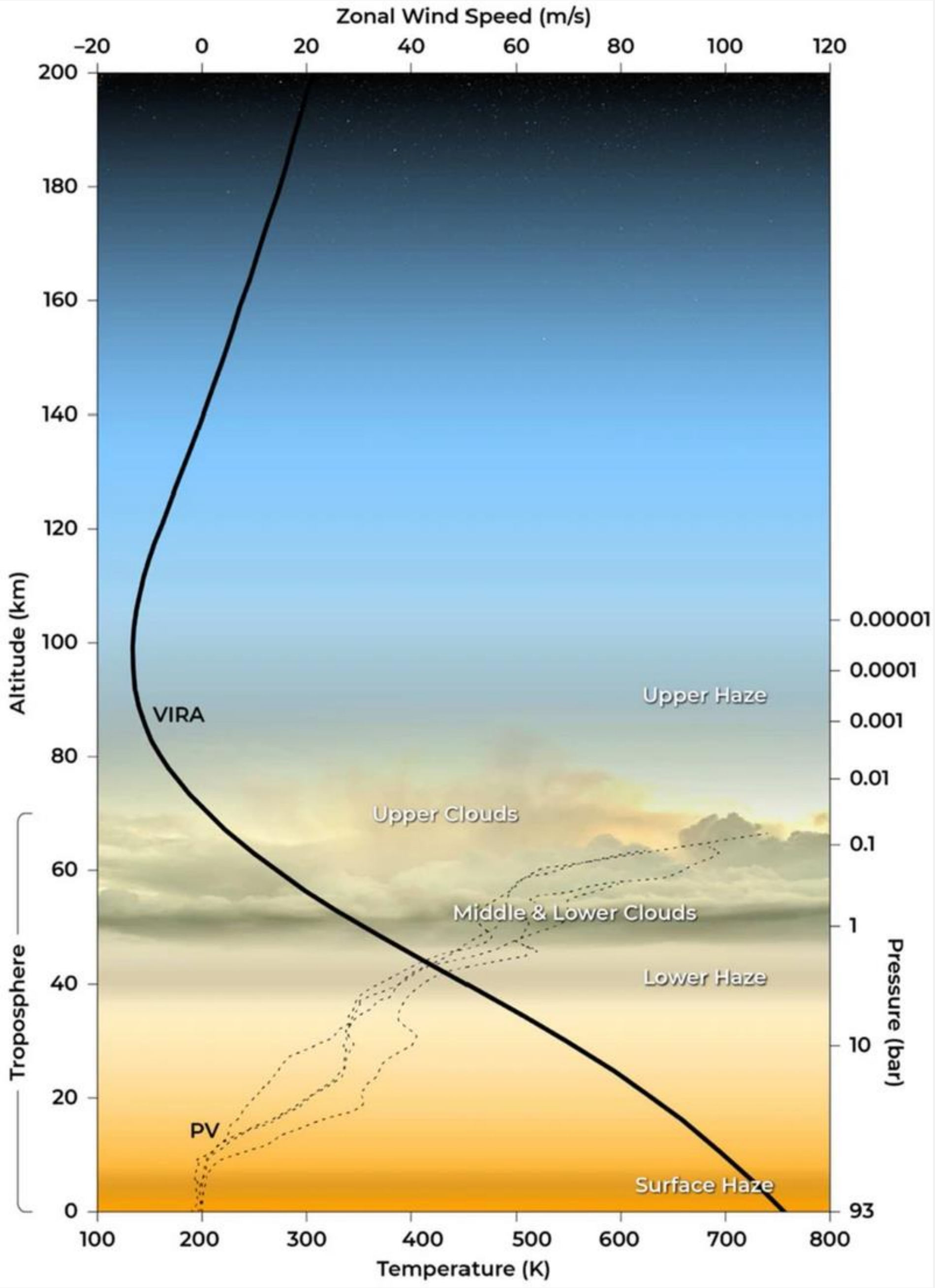
https://doi.org/10.1038/s41550-020-1174-4

Check for updates

Phosphine gas in the cloud decks of Venus

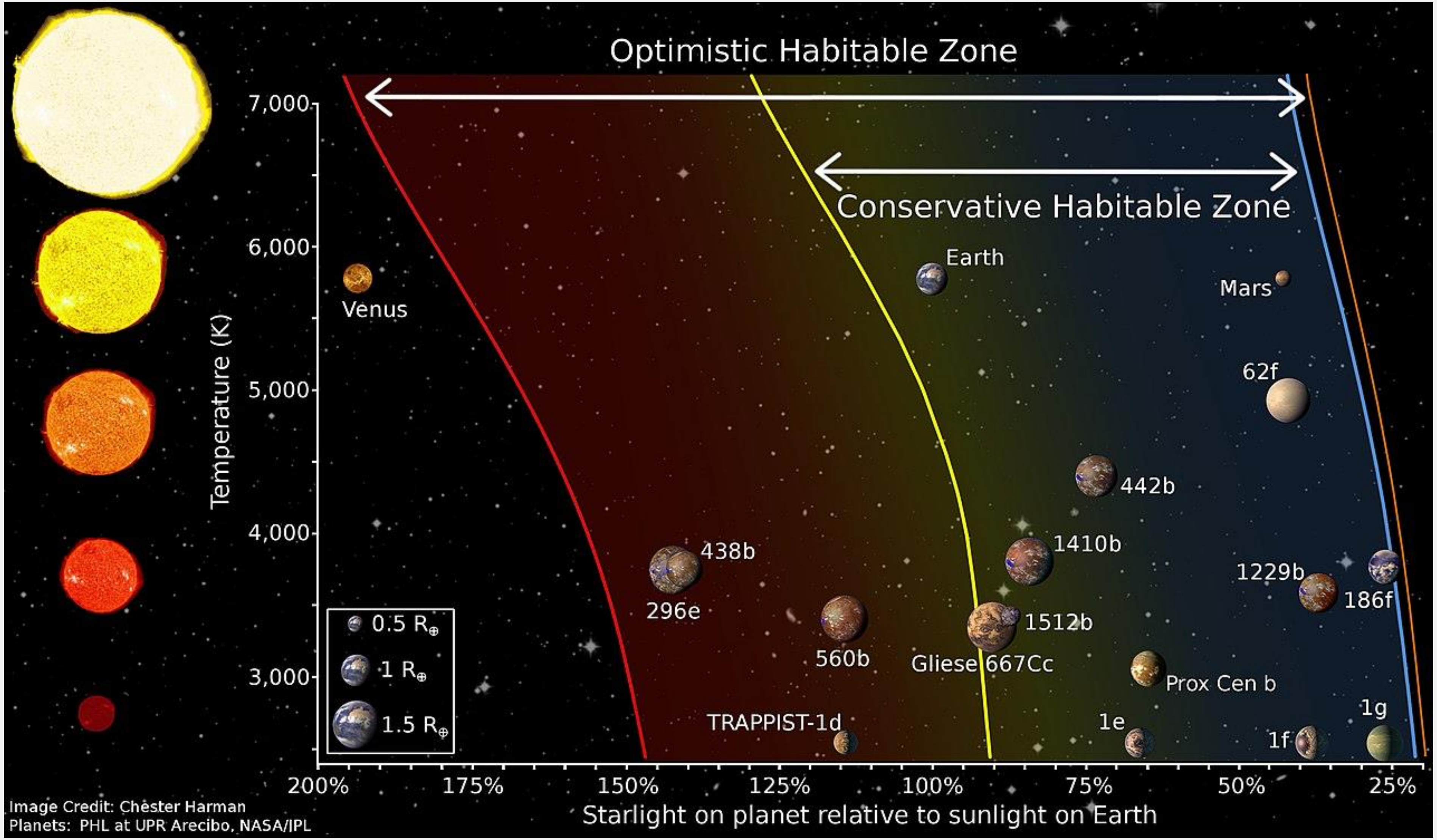
Jane S. Greaves[1,2], Anita M. S. Richards[3], William Bains[4], Paul B. Rimmer[5,6,7], Hideo Sagawa[8], David L. Clements[9], Sara Seager[4,13,14], Janusz J. Petkowski[4], Clara Sousa-Silva[4], Sukrit Ranjan[4], Emily Drabek-Maunder[1,10], Helen J. Fraser[11], Annabel Cartwright[1], Ingo Mueller-Wodarg[9], Zhuchang Zhan[4], Per Friberg[12], Iain Coulson[12], E'lisa Lee[12] and Jim Hoge[12]

Measurements of trace gases in planetary atmospheres help us explore chemical conditions different to those on Earth. Our nearest neighbour, Venus, has cloud decks that are temperate but hyperacidic. Here we report the apparent presence of phosphine (PH_3) gas in Venus's atmosphere, where any phosphorus should be in oxidized forms. Single-line millimetre-waveband spectral detections (quality up to ~15σ) from the JCMT and ALMA telescopes have no other plausible identification. Atmospheric PH_3 at ~20 ppb abundance is inferred. The presence of PH_3 is unexplained after exhaustive study of steady-state chemistry and photochemical pathways, with no currently known abiotic production routes in Venus's atmosphere, clouds, surface and subsurface, or from lightning, volcanic or meteoritic delivery. PH_3 could originate from unknown photochemistry or geochemistry, or, by analogy with biological production of PH_3 on Earth, from the presence of life. Other PH_3 spectral features should be sought, while in situ cloud and surface sampling could examine sources of this gas.



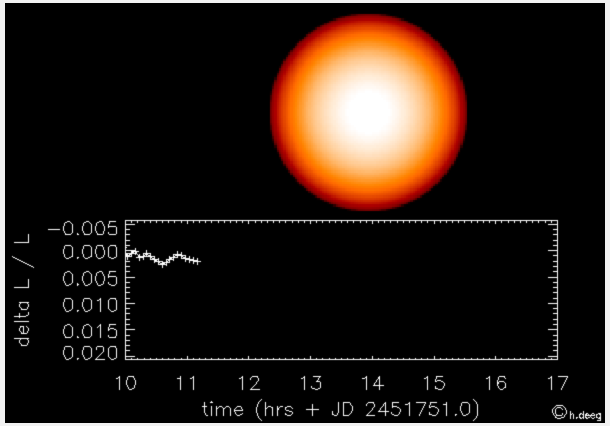
3. Exoplanets and Habitability

Stellar habitable zones



Exoplanet detection methods

Transit



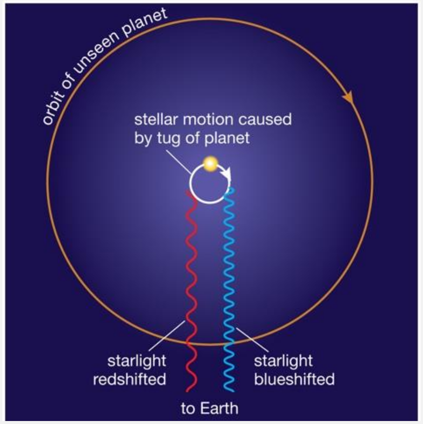
Infer

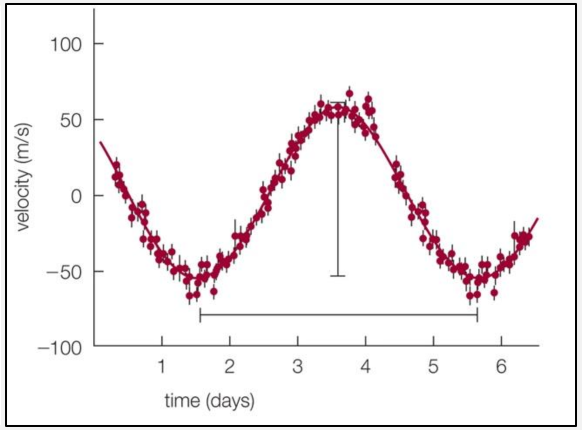
- Size
- Orbital period & distance
- Atmosphere

Bias

- Large, close planets
- Systems edge-on as viewed from Earth

Radial Velocity





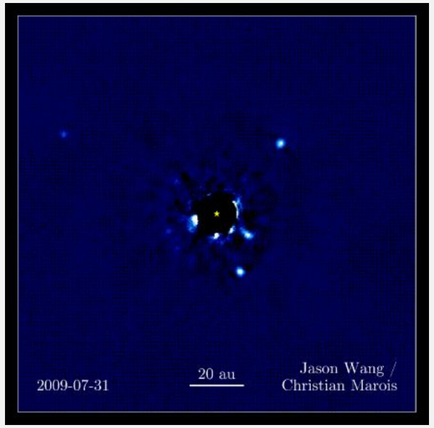
Infer

- Mass
- Orbital period & distance
- Eccentricity

Bias

- Large, close planets
- Systems edge-on as viewed from Earth

Direct Imaging



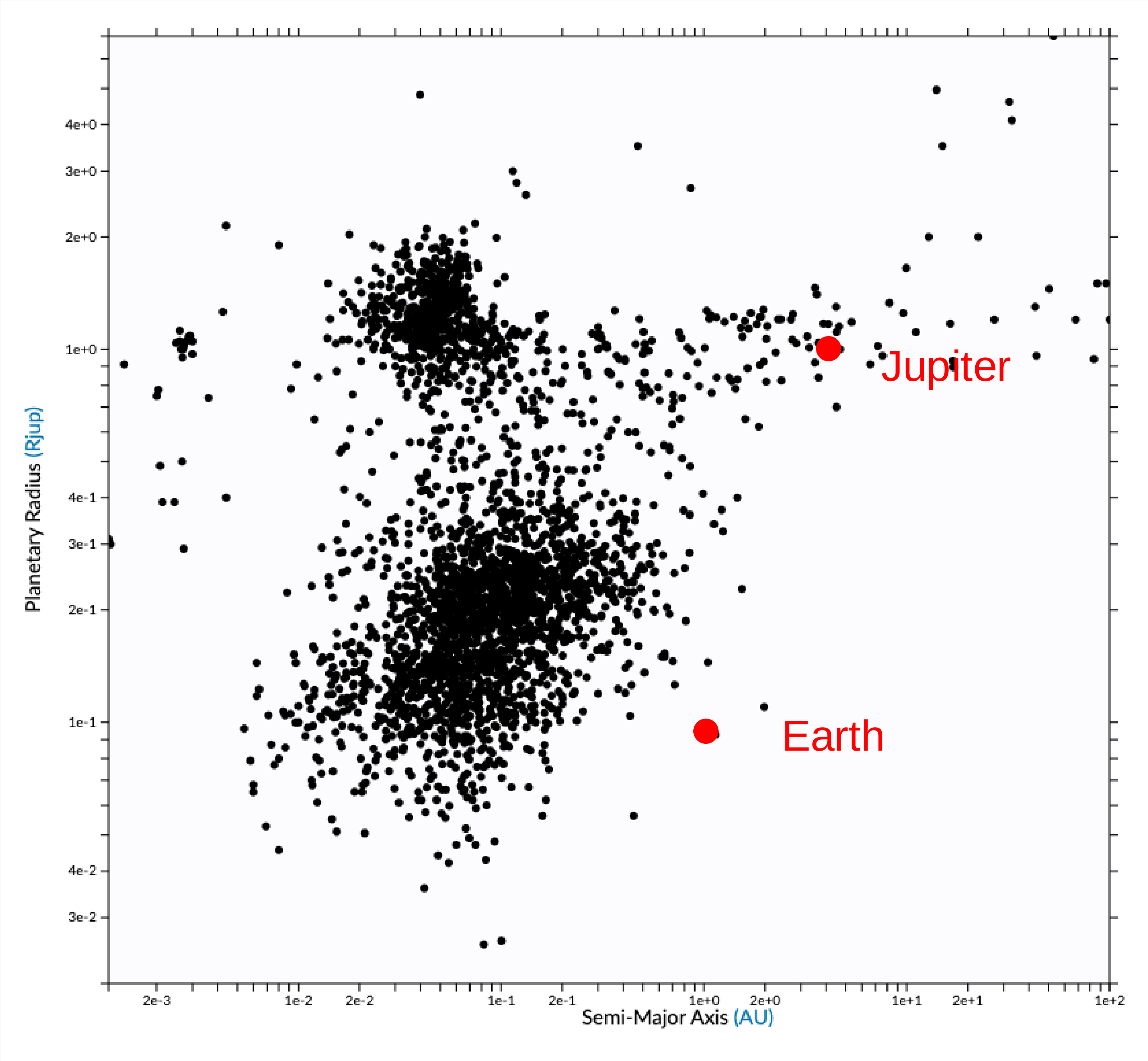
Infer

- ~Mass, ~size
- Orbital period & distance
- Atmosphere

Bias

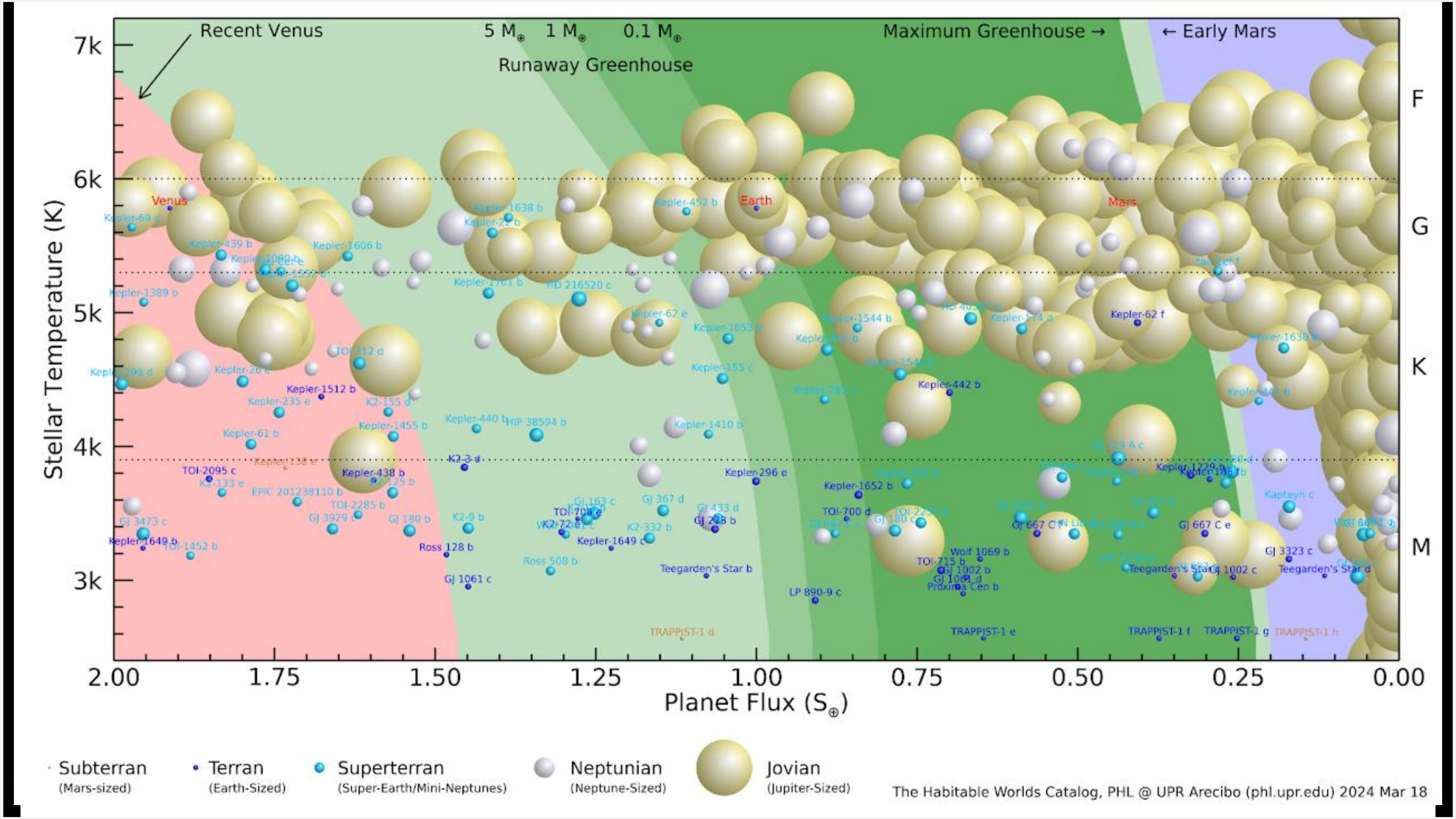
- Large, bright, distant planets
- Systems face-on as viewed from Earth

Known exoplanets



exoplanets.eu

Potentially habitable exoplanets

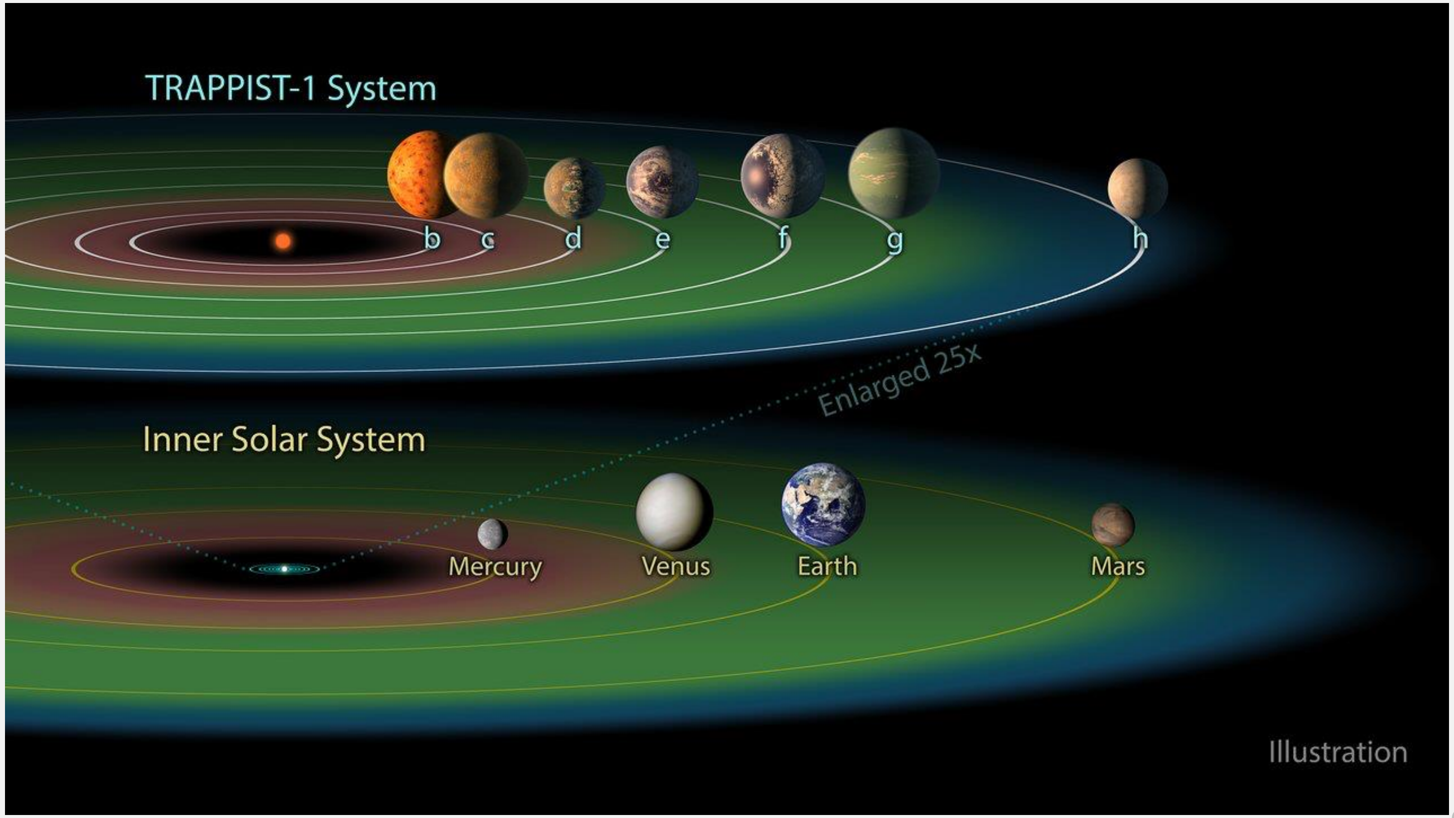


Trappist-1

39.5 ly away

7-planet system, all roughly Earth-sized, including 3 in the "Habitable Zone"
Compact system → could see surface features on other planets!
Planets all in resonance with each other

Discovered: 2015-2017
Orbital period: 1.5-18.8 days
Orbital distance: .01-.06 AU
Size: ~0.7-1.1 M_E



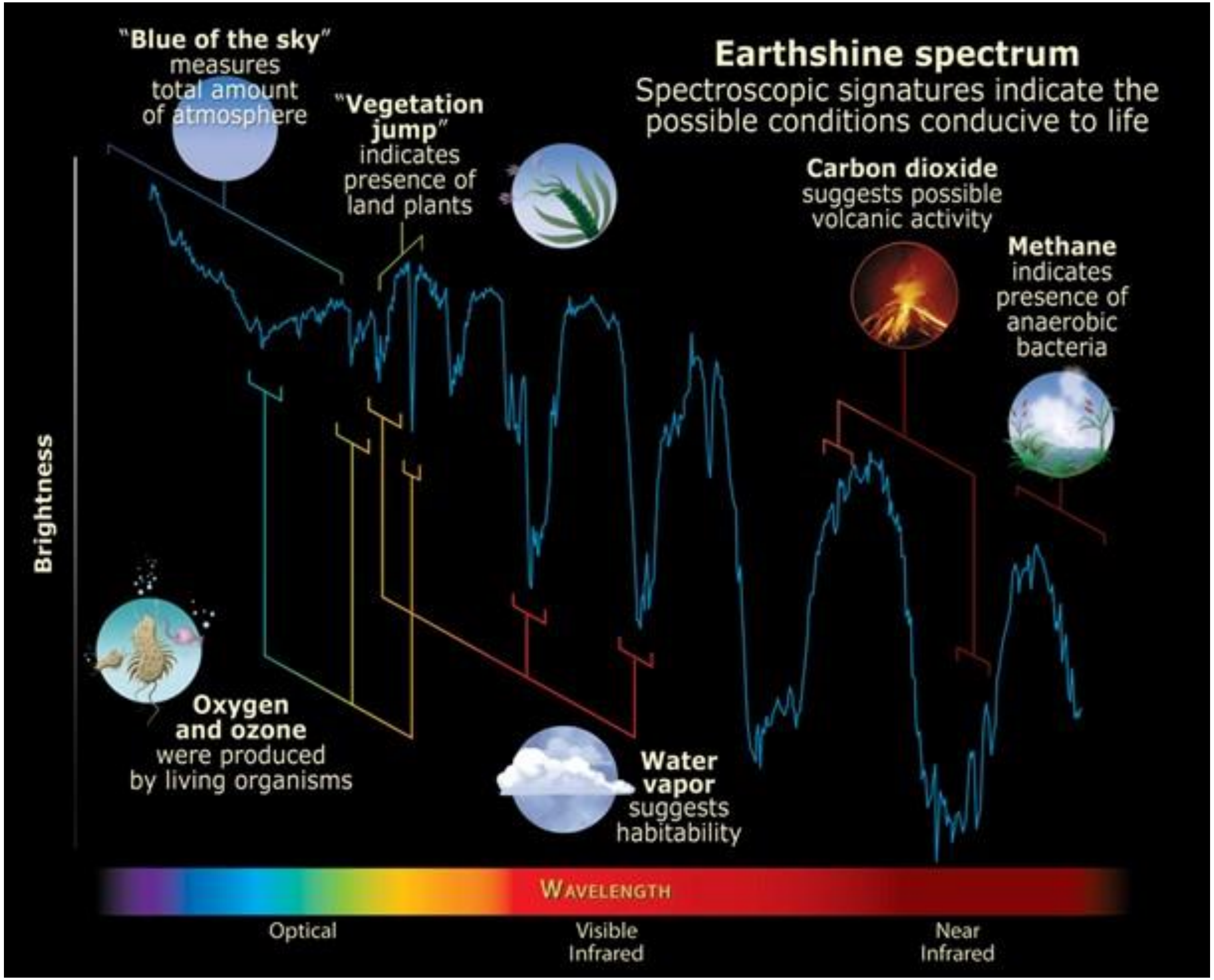
Proxima Centauri b

4.25 ly away

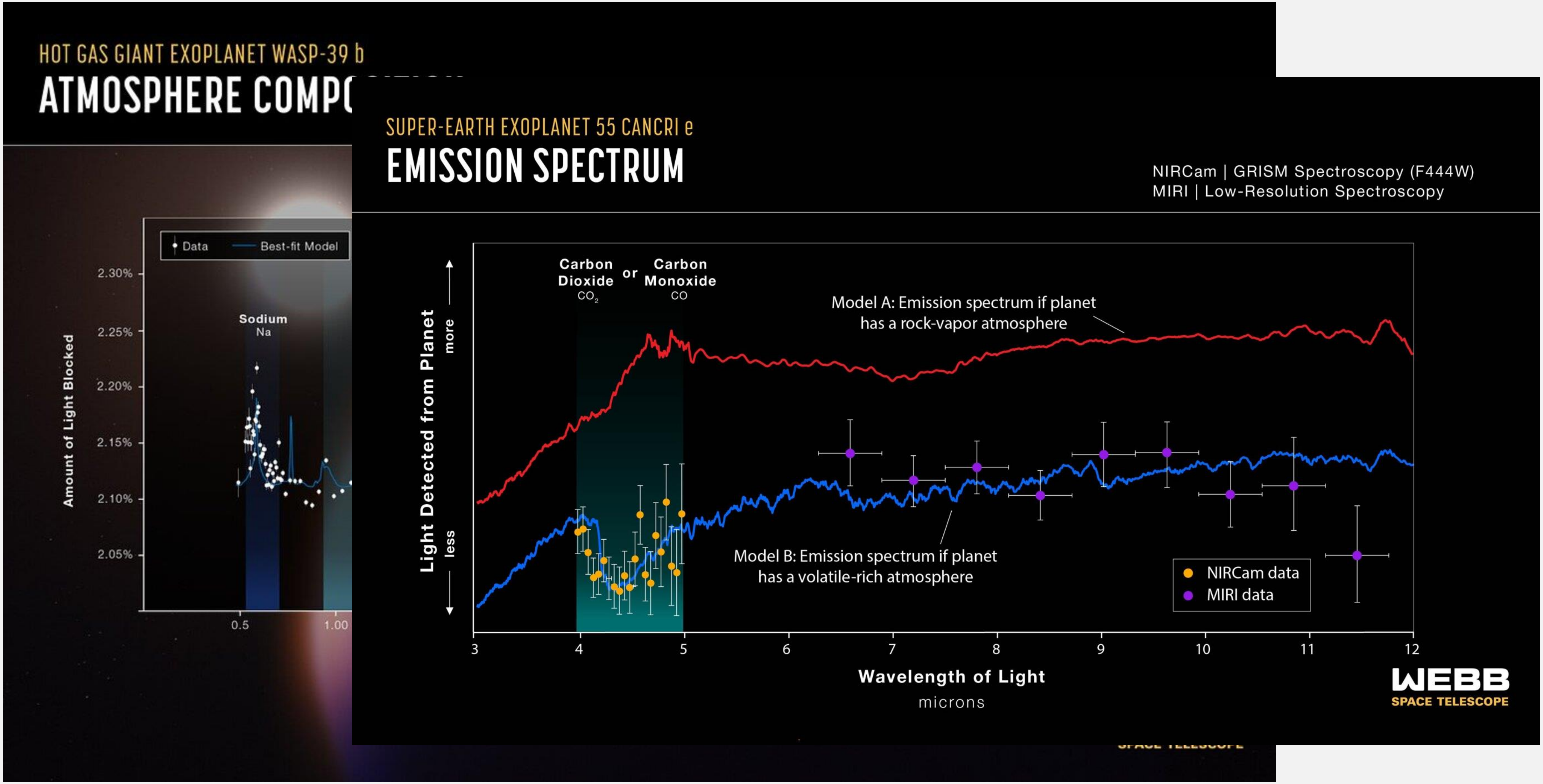
Earth-mass exoplanet orbiting our closest star

Discovered: August 2016 via Doppler technique
Orbital period: 11 days
Orbital distance: .05 AU
Effective Temperature: ~234 K
Mass: ~1.27 M_E

Biosignatures



Atmospheric spectra



4. Planetary Influence on Habitability

Question

What properties of a planet influence its habitability?

-

5. Stellar Influences on Habitability

Stellar energy sources for planets

Photons

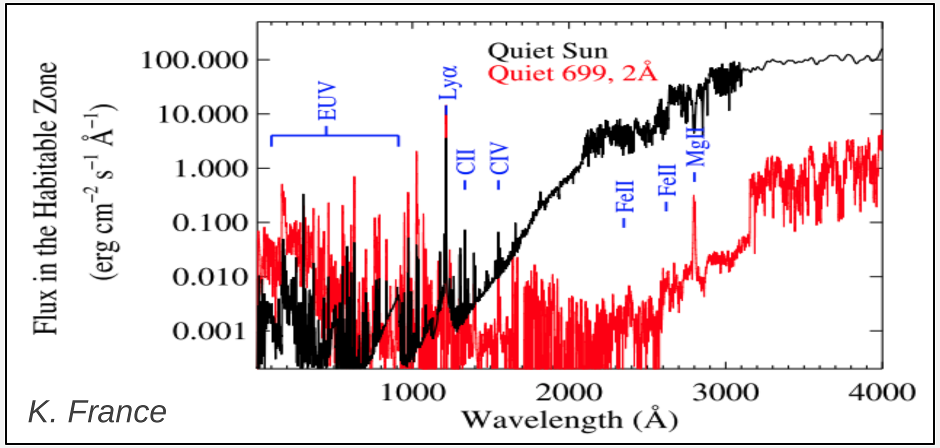
- Total luminosity (warms planet's surface)
- UV (drives chemistry, damages DNA)
- EUV / Xray (upper atmosphere heating, ionization, escape)

Particles

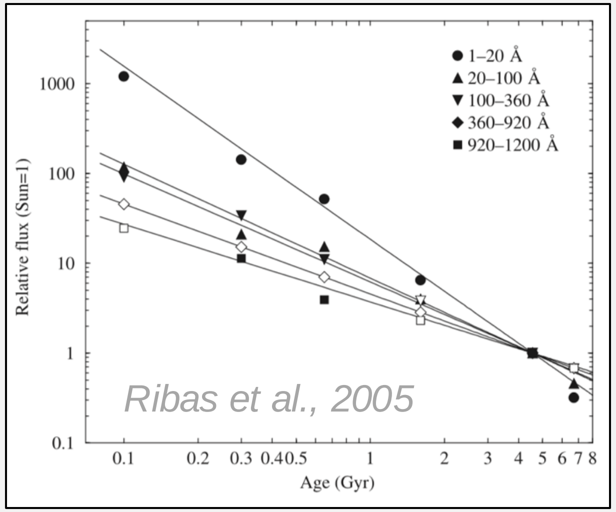
- Stellar wind (drives escape, deposits particles)
- Stellar energetic particles (heating and escape, chemistry, radiation)

Fields

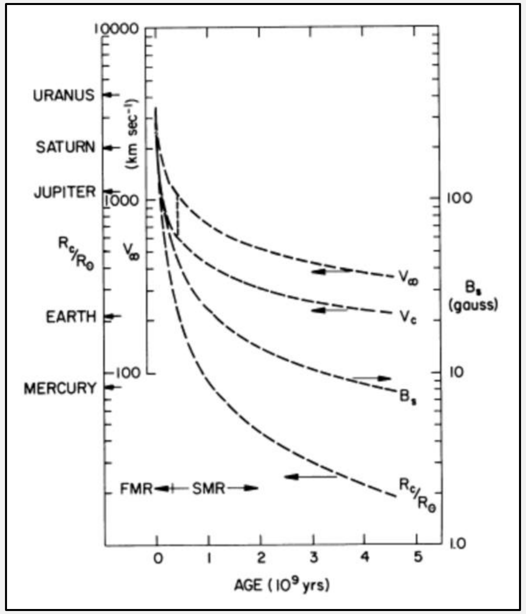
- Interplanetary magnetic field*



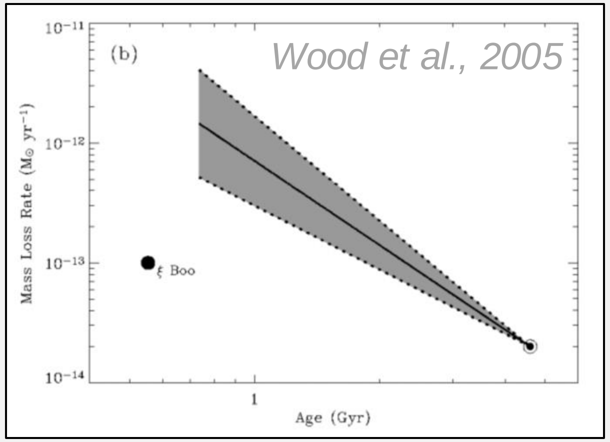
K. France



Ribas et al., 2005



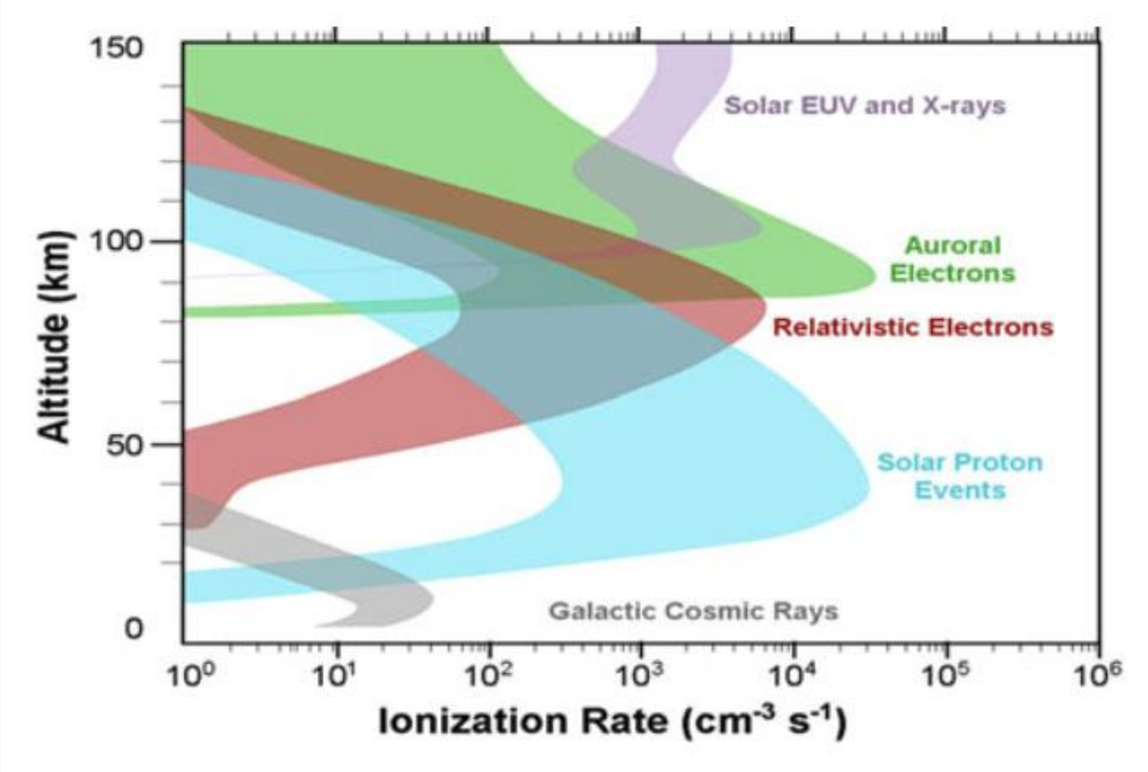
Newkirk Jr., 1980



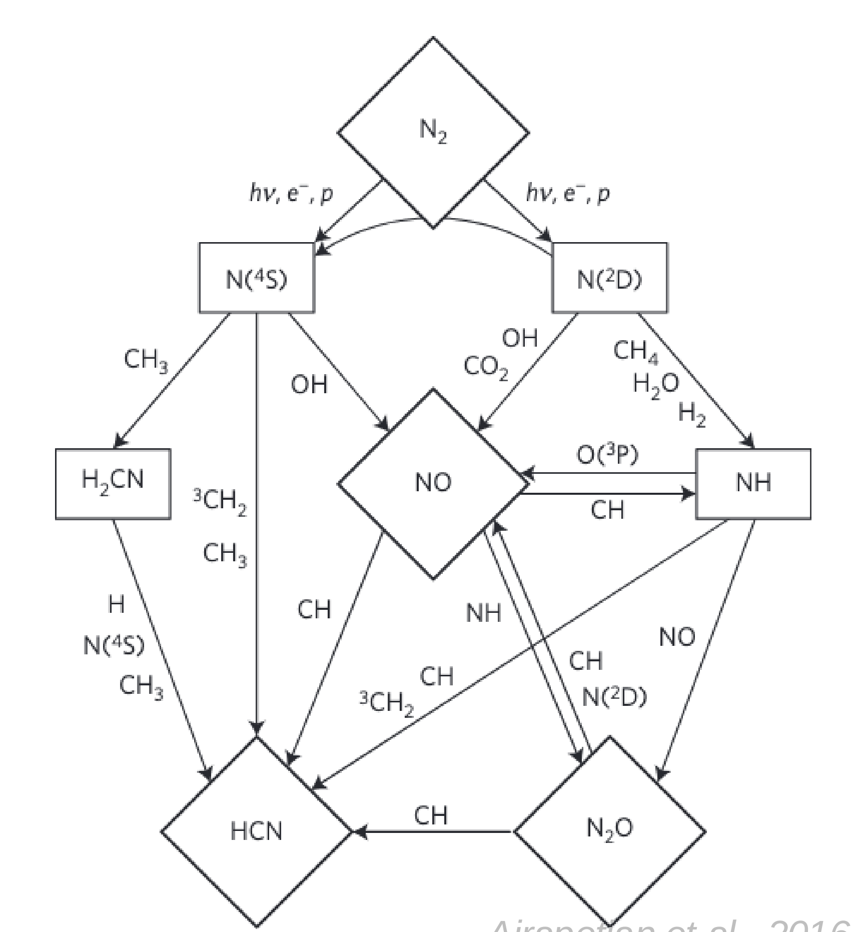
Wood et al., 2005

* Requires accompanying plasma velocity to be energy source

Particle inputs for Earth



Airapetian et al., 2020



Airapetian et al., 2016

Kobayashi et al., 1998

Production of amino acids by irradiating mixture of CO, N_2 and H_2O with 3 MeV protons

Magnetosphere and atmospheric chemistry modeling suggests nitrogen could be fixed abiotically on early Earth by SEPs

There are now many interdisciplinary conferences about exoplanets and habitability.

Few heliophysicists attend.

GOLDSCHMIDT 2024 Chicago 18–23 August

geochemical society

EAG European Association of Geochemistry

My Goldschmidt

Exoplanets: Compositions, Mineralogy, Evolution

This is a two-day, in-person workshop (Aug 17-18) that comprises the short course portion of the Reviews in Mineralogy and Geochemistry (RiMG) volume, "Exoplanets: Compositions, Mineralogy, Evolution," edited by Natalie Hinkel, Keith Putirka, and Siyi Xu. Because the study of exoplanets lies at the boundary of geology and astronomy, our goal is to expand communications between geologists – especially mineralogists and petrologists – and astronomers. Astronomers are able to measure the radius, mass, and hence density of small exoplanets as current and upcoming space missions (e.g., JWST and Roman) are providing measurements of exoplanetary atmospheric compositions. Astronomers and geologists have also used the compositions of nearby Sun-like stars and polluted white dwarf stars to translate these into mineral proportions and rock types of their small planets' interiors, which can be used to hypothesize exoplanetary tectonic behavior. The ability to estimate exoplanet bulk compositions and densities provides extraordinary opportunities for mineralogists, petrologists and geochemists to profoundly expand on exoplanet characterization. The hope for our workshop is to spur conversations and initiate collaborations, as well as explain the current state of the field and teach one another about our respective fields. Registration fees include lunch and coffee for both days as well as a copy of the RiMG volume (early career students who would prefer a physical softbound copy, in addition to online access, should register under the full price).

The following is a list of the workshop presentations and associated RiMG chapters. The schedule will allow time for a 20 min presentation for each topic followed by a 20 min Q&A, in addition to open discussions at the end of both days:

- Host Stars and How Their Compositions Influence Exoplanets (Hinkel, Youngblood, & Soares-Furtado)
- Chemistry in Protoplanetary Disks (Zhang & Trapman)
- Planet Formation (Mordasini & Burn)
- Meteorites and Planetary Formation (Jones)
- The Evolution and Delivery of Rocky Extra-Solar Materials to White Dwarfs (Veras, Mustill, & Bonsor)
- The Chemistry of Extra-Solar Materials from White Dwarf Planetary Systems (Xu, Rogers, & Blouin)
- Exoplanet Mineralogy: Methods & Error Analysis (Putirka)
- Exoplanetary Mantles, Melts, and Crusts (Shorttle & Sossi)
- A Beginner's Guide to Tectonics – Plate and Otherwise (Putirka)
- A Framework of Deep Volatile Cycles in Rocky Exoplanets (Dasgupta, Pathak, & Maurice)
- Exoplanetary Magnetic Fields (Brain & Kao)
- Transiting Exoplanet Atmospheres in the Era of JWST (Kempton & Knutson)
- An Overview of Exoplanet Biosignatures (Schwieterman & Leung)
- The Early Earth as an Analogue for Exoplanetary Biogeochemistry (Stueeken, Olsen, Moore, & Foley)
- Exoplanet Geology: What Can We Learn From Current and Future Observations? (Foley)

Important concept interlude

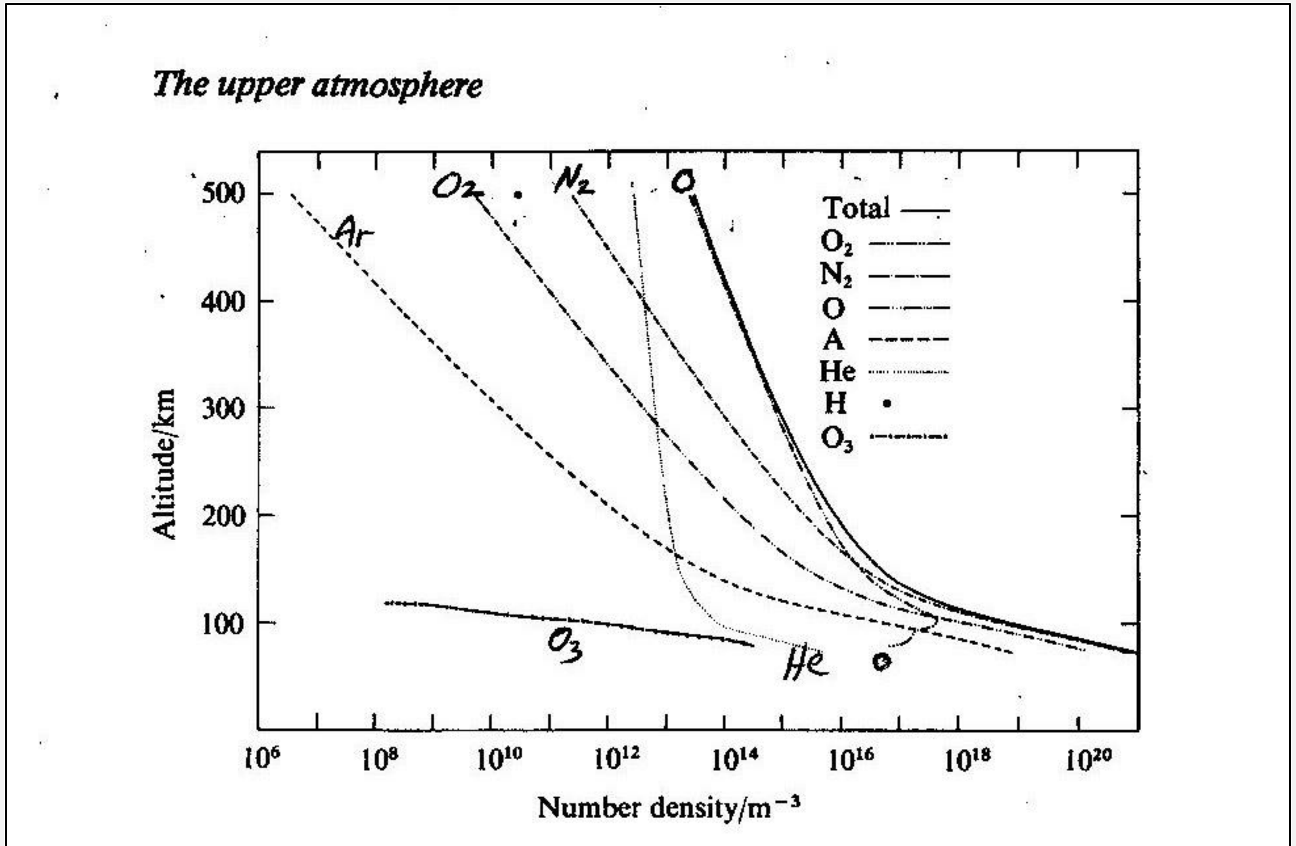
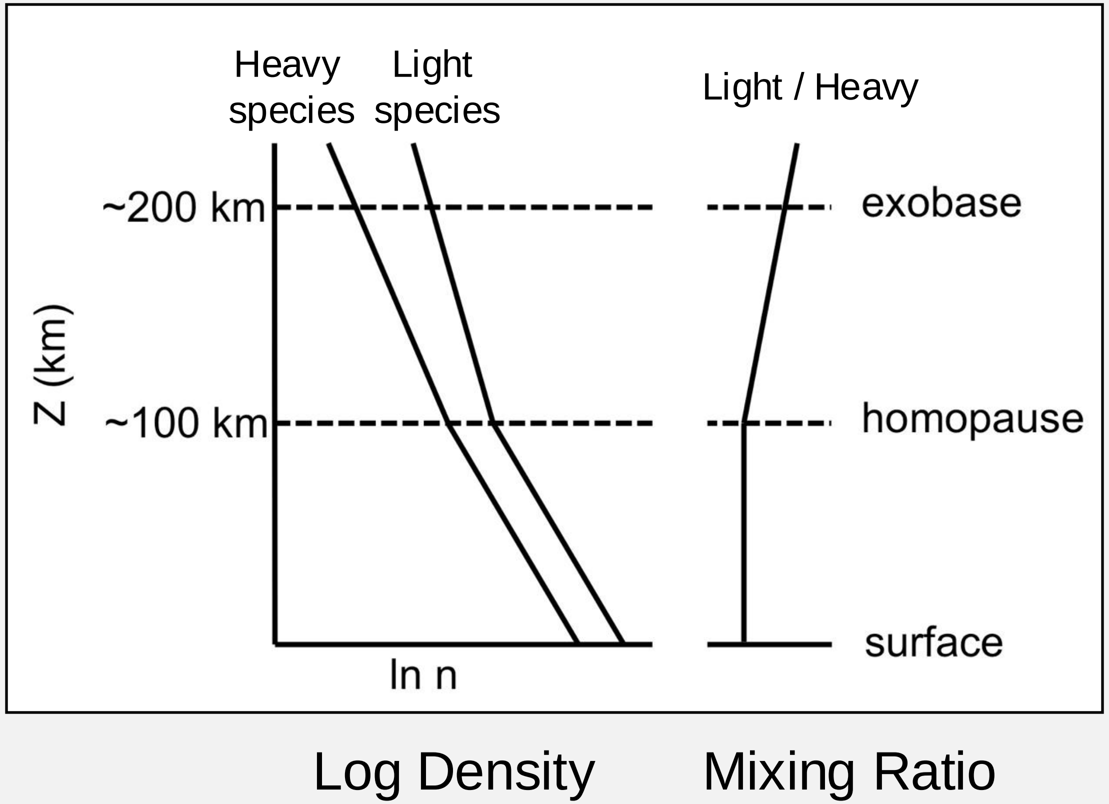


Fig. 5.2. Total number density and number densities of various constituents for mean atmospheres (from COSPAR, 1972).

Look at the decline of each species with altitude. There's a trend!

Important concept: Diffusive separation

- At high altitudes each species has its own characteristic vertical density structure ($H_i = {}^{k\,T}/_{m_i\,g}$)
- With less frequent collisions than the lower atmosphere, heavier species experience a stronger gravitational force and tend to 'sink'
- This leaves the uppermost portions of an atmosphere enriched in lighter species
- This also means that the 'mixing ratio' (relative abundance) for each species varies with altitude in this region



Diffusive separation and atmospheric escape

- Isotopes of a species differ only in mass – otherwise they behave in all the same ways
- The uppermost parts of atmospheres, where escape occurs are enriched in light isotopes
  - ➢ Light isotopes should escape more readily than heavy isotopes
  - ➢ Light isotopes also escape more readily due to the smaller mass
- Atmospheres where escape has been an important process should be enriched in heavy isotopes