Extrasolar planets: recent advances and future challenges

J. Cabrera, M. Godolt, J. L. Grenfell, N. Katyal, J. MacKenzie, M. Scheucher, F. Wunderlich, H. Rauer

Institute of Planetary Research
German Aerospace Center (DLR)
Berlin

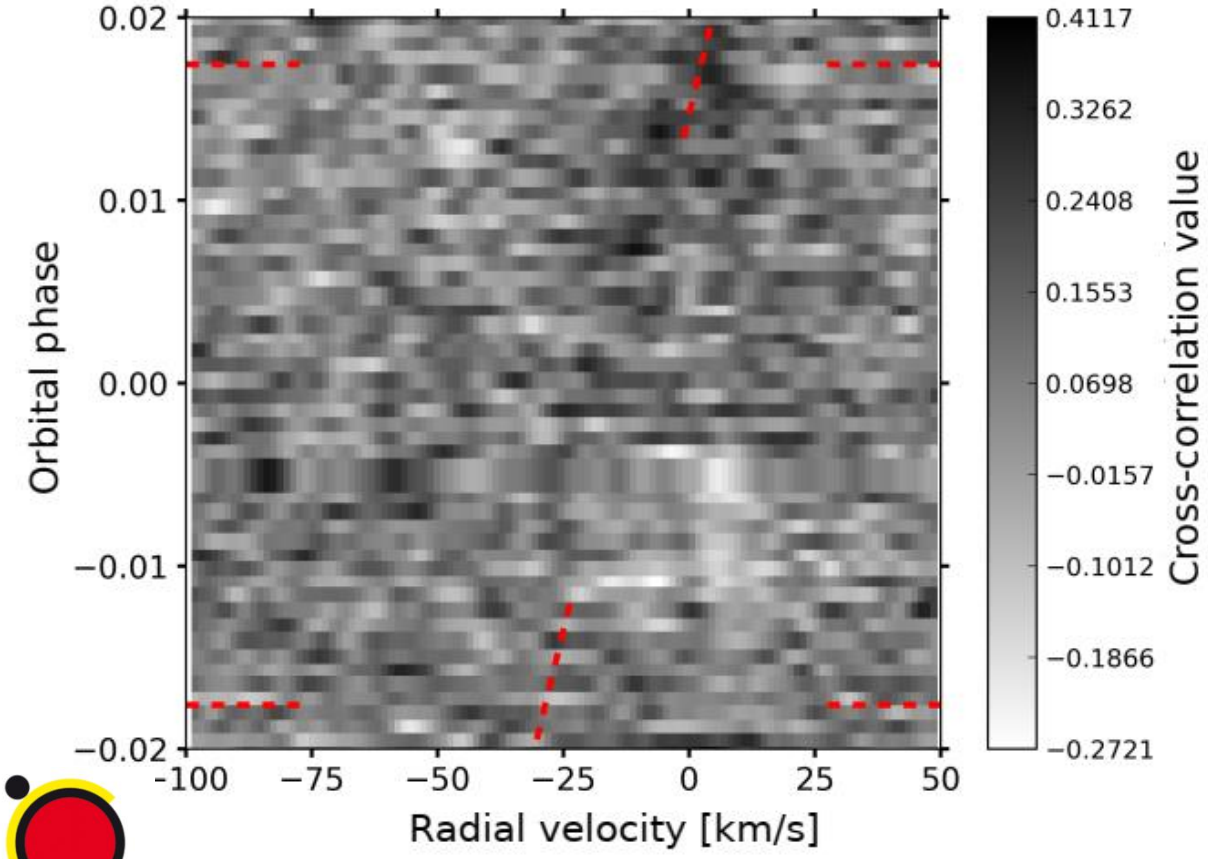
Zentrum für Astronomie und Astrophysik
Technische Universität Berlin

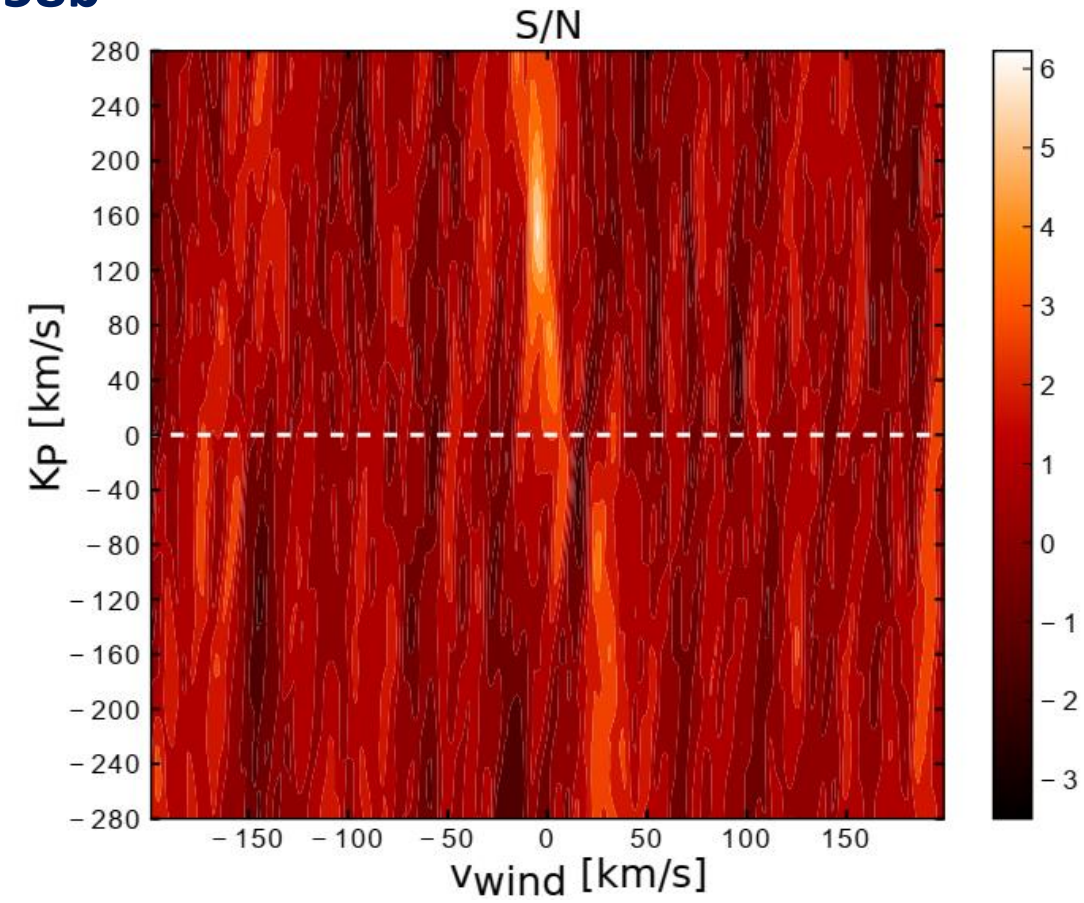
Institut für Geologische Wissenschaften
Freie Universität Berlin

DLR

Water in the atmosphere of exoplanets

HD 209458b





Sánchez-López et al. 2019, A&A, 630, A53

K2-18b: water vapour in the atmosphere of a super-Earth in the HZ

transit depth:
Kepler: 0.3% (3 mmag)

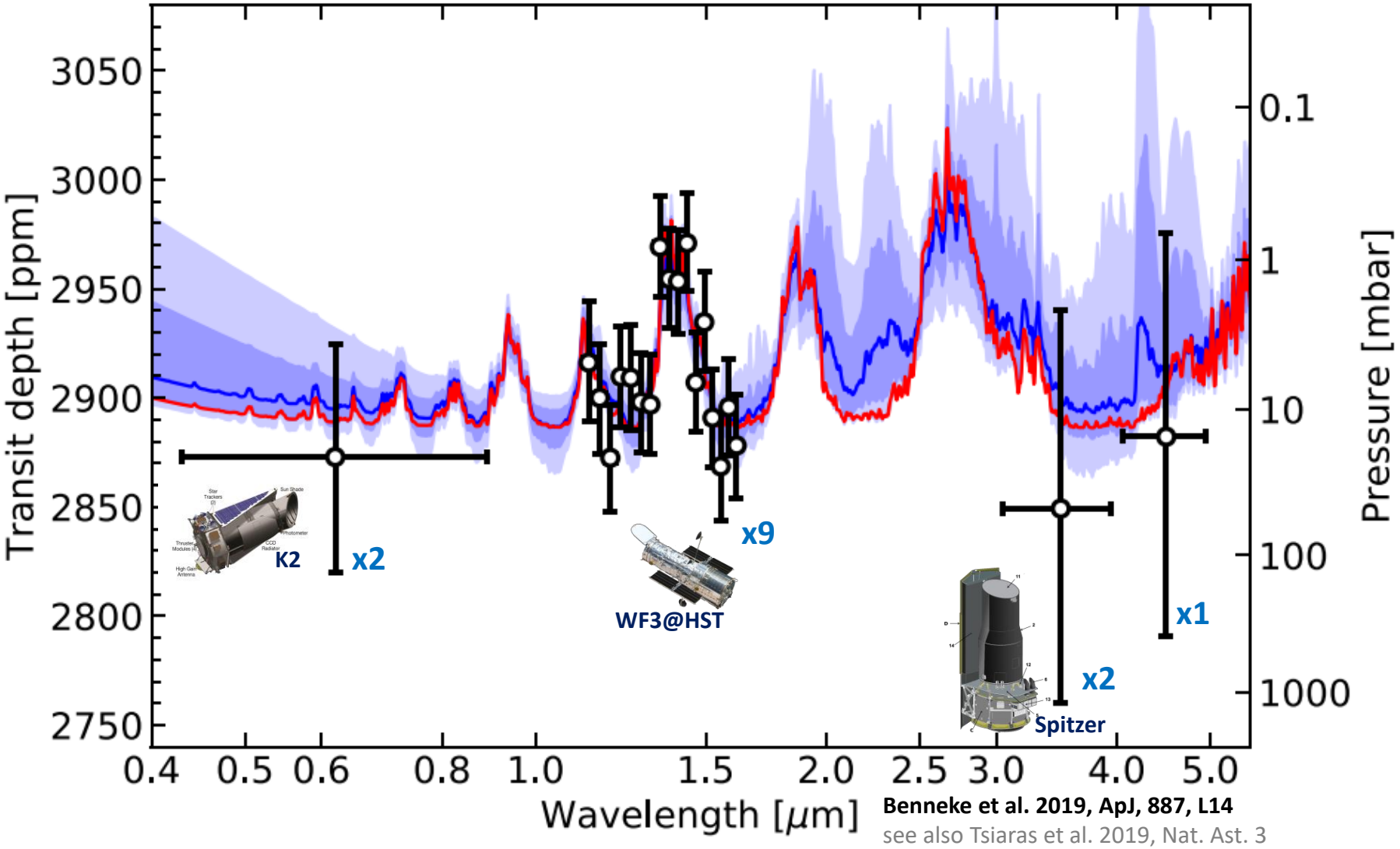
uncertainty in depth:
Kepler: ~3%

uncertainty in radius ratio:
Kepler: ~6%

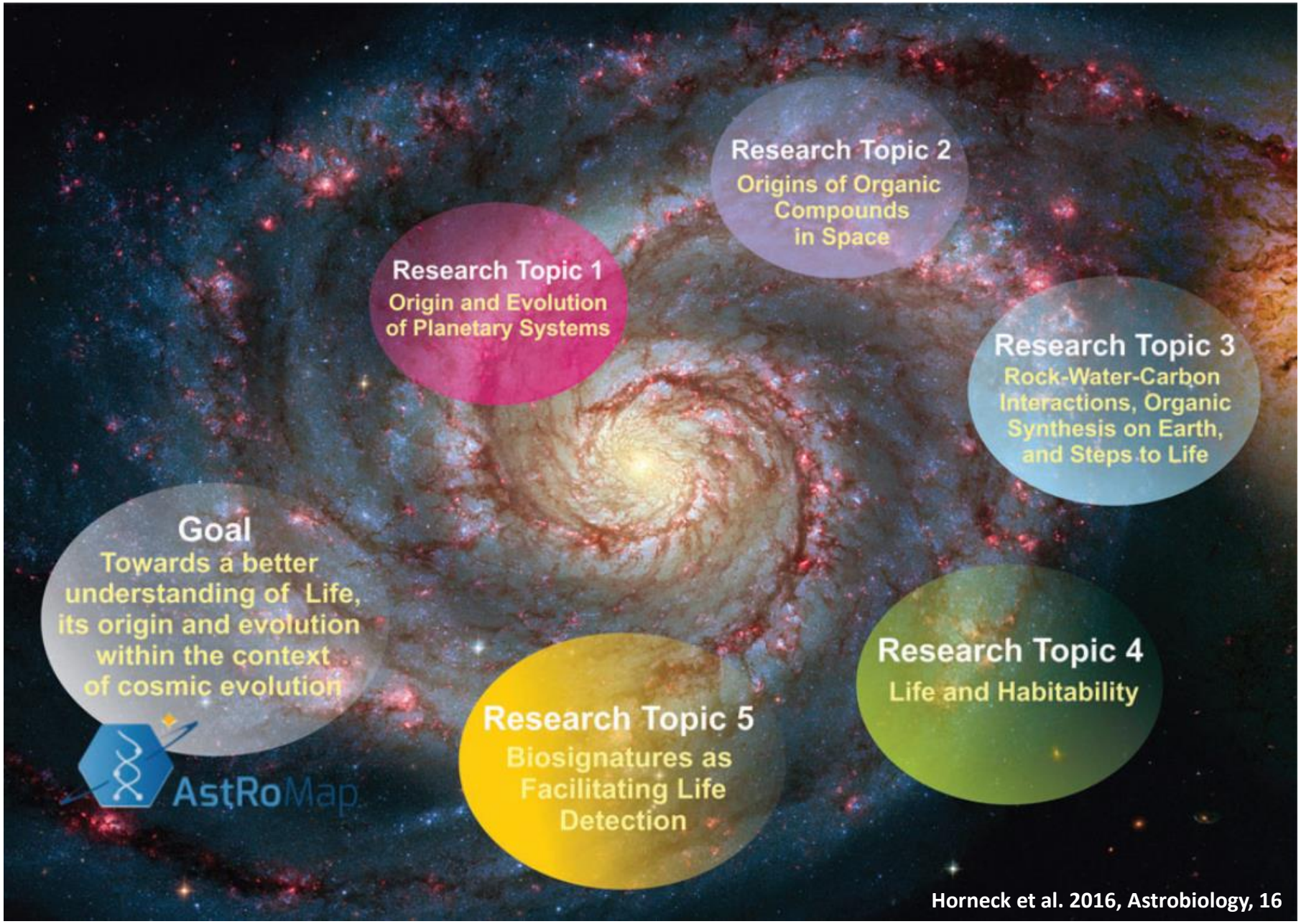
uncertainty in radius:
(see next slides)

uncertainty in composition:
(see next slides)

orbital period: 32.9 days
host star M2.5V (V=13.5; J=9.



Benneke et al. 2019, ApJ, 887, L14
see also Tsiaras et al. 2019, Nat. Ast. 3



Horneck et al. 2016, Astrobiology, 16

For a recent review on issues like the definition of **life**, see Walker et al. 2018, Astrobiology, 18 (you might also enjoy Cleland, 2012 and Schneider, 2013)

For a recent review on exoplanetary **biosignatures** see Grenfell (2019), in 'Biosignatures for Astrobiology', Cavalazzi B., Westall F. (eds), Springer.

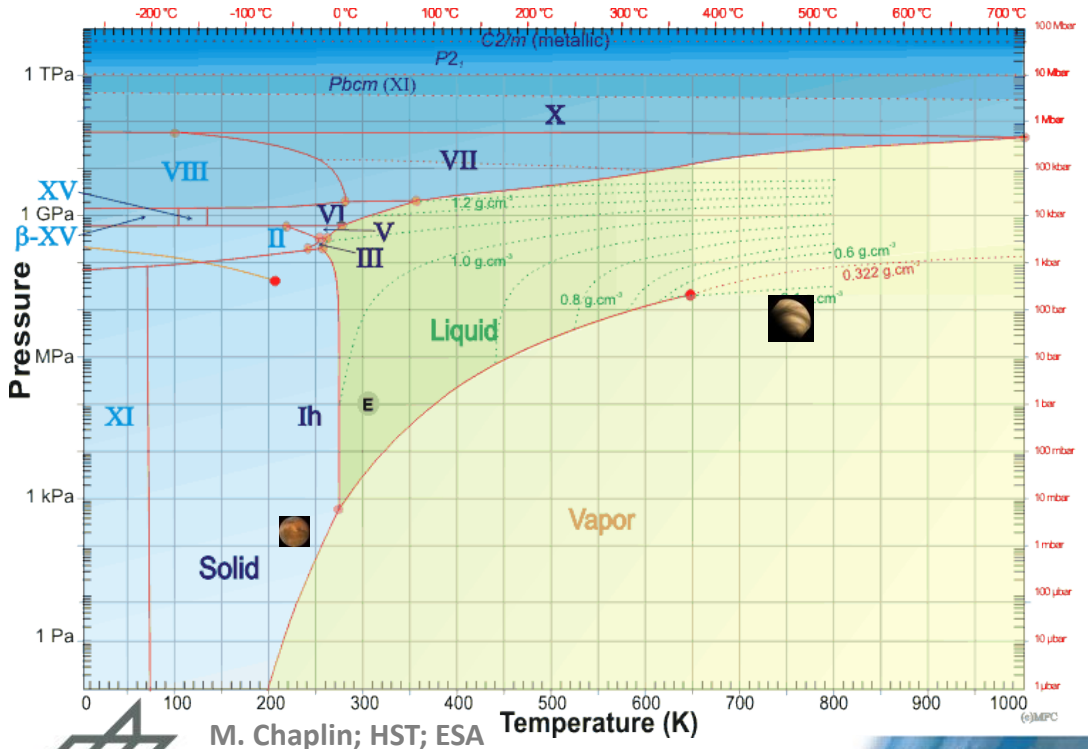
For strong criticism of the approach chosen for this talk, see Stevenson (2018) [*thanks to A. García Muñoz for bringing up the latter*].

Basic notions on habitability

"Habitability refers to the potential of an environment to sustain life (see Cockell, 2016)."

"The classical HZ (Huang, 1959; Kasting et al. 1993) is defined to be the annulus region around a star where liquid water can exist on a rocky planet's surface."

Grenfell (2019)



M. Chaplin; HST; ESA

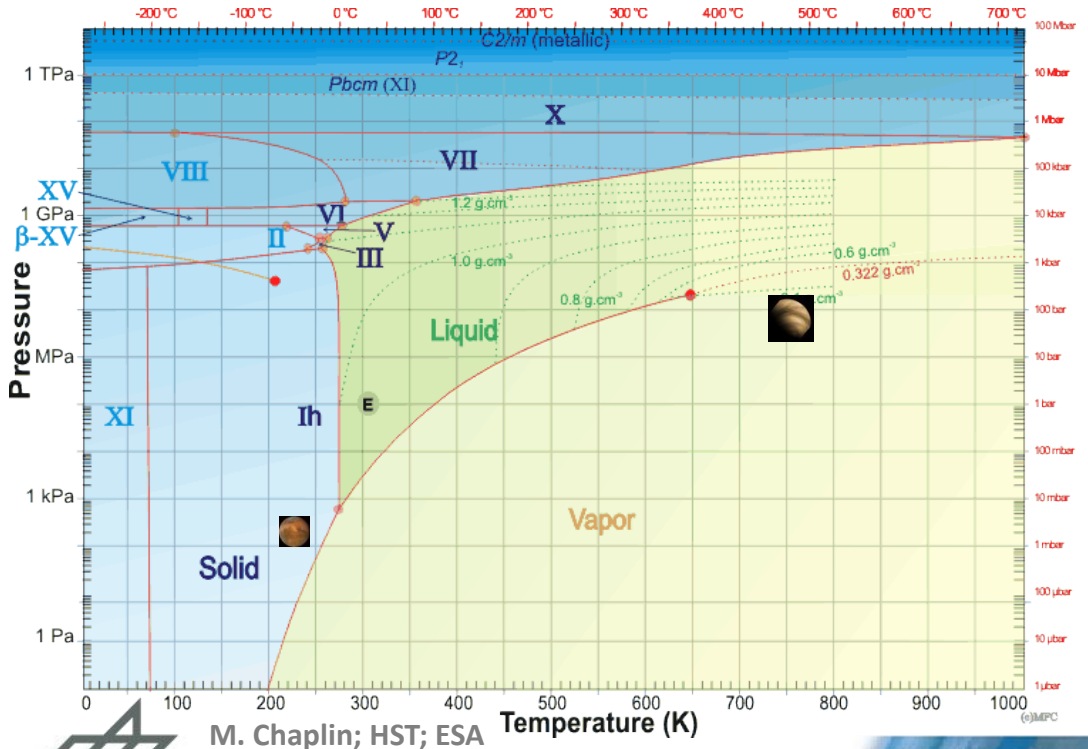
DSCVR, NASA

Basic notions on habitability

"Habitability refers to the potential of an environment to sustain life (see Cockell, 2016)."

"The classical HZ (Huang, 1959; Kasting et al. 1993) is defined to be the annulus region around a star where liquid water can exist on a rocky planet's surface."

Grenfell (2019)



M. Chaplin; HST; ESA

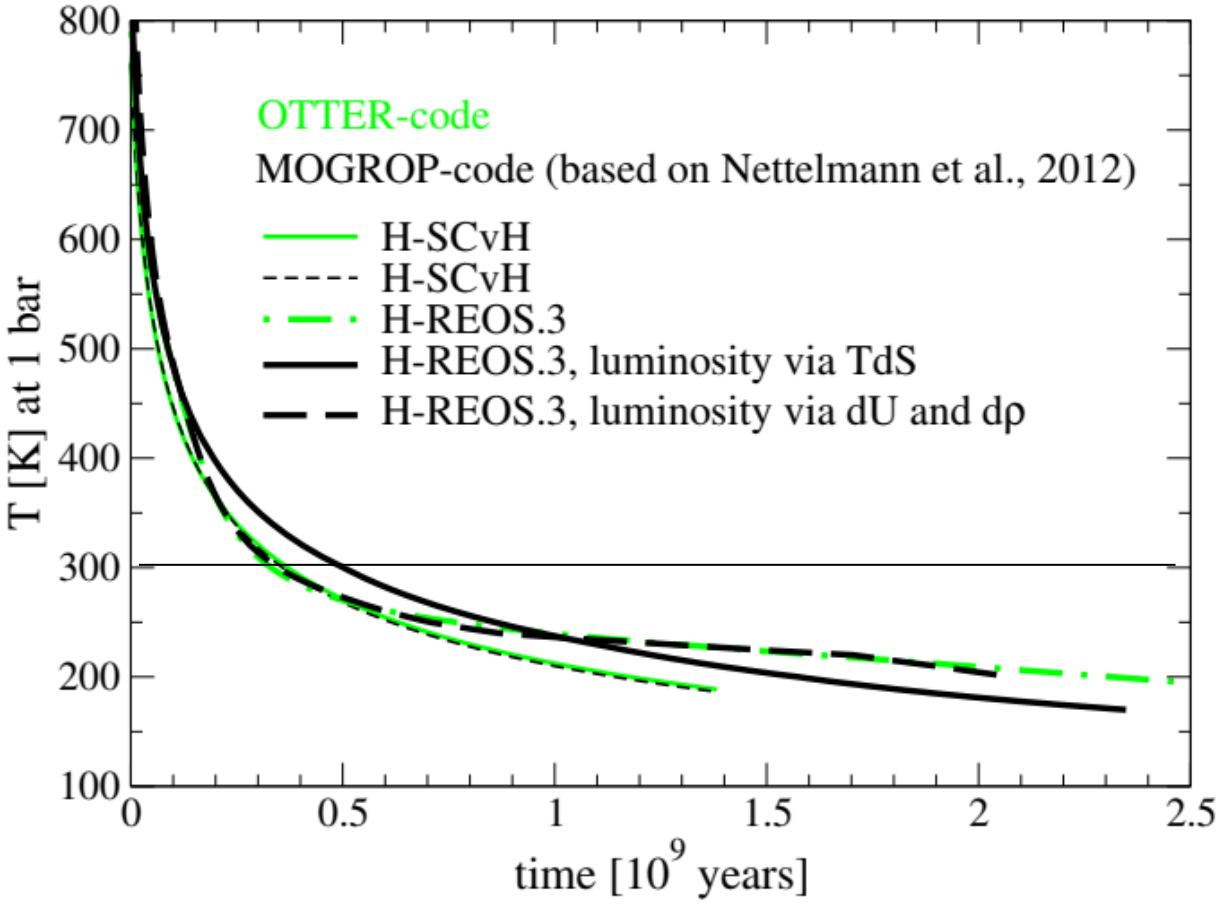


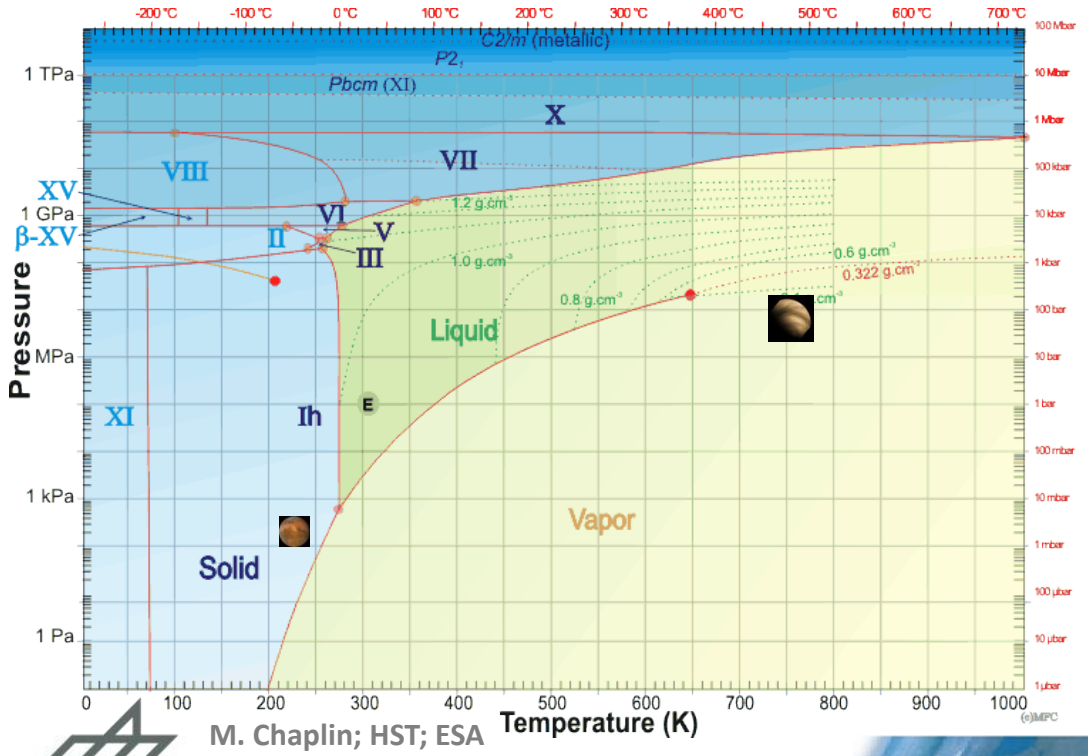
Fig. 1. Evolution of a 300 M_E planet with a 2 M_E rock core and an adiabatic hydrogen envelope. Shown are comparisons between the OTTER code (red, this work) and the MOGROP code (black, Nettelmann et al. 2012) for two different hydrogen equations of state–thin: SCvH-EOS (Saumon et al. 1995); thick: REOS.3 (Becker et al. 2014)–and, for MOGROP, different ways of calculating the luminosity. Scheibe et al. (2019)

Basic notions on habitability

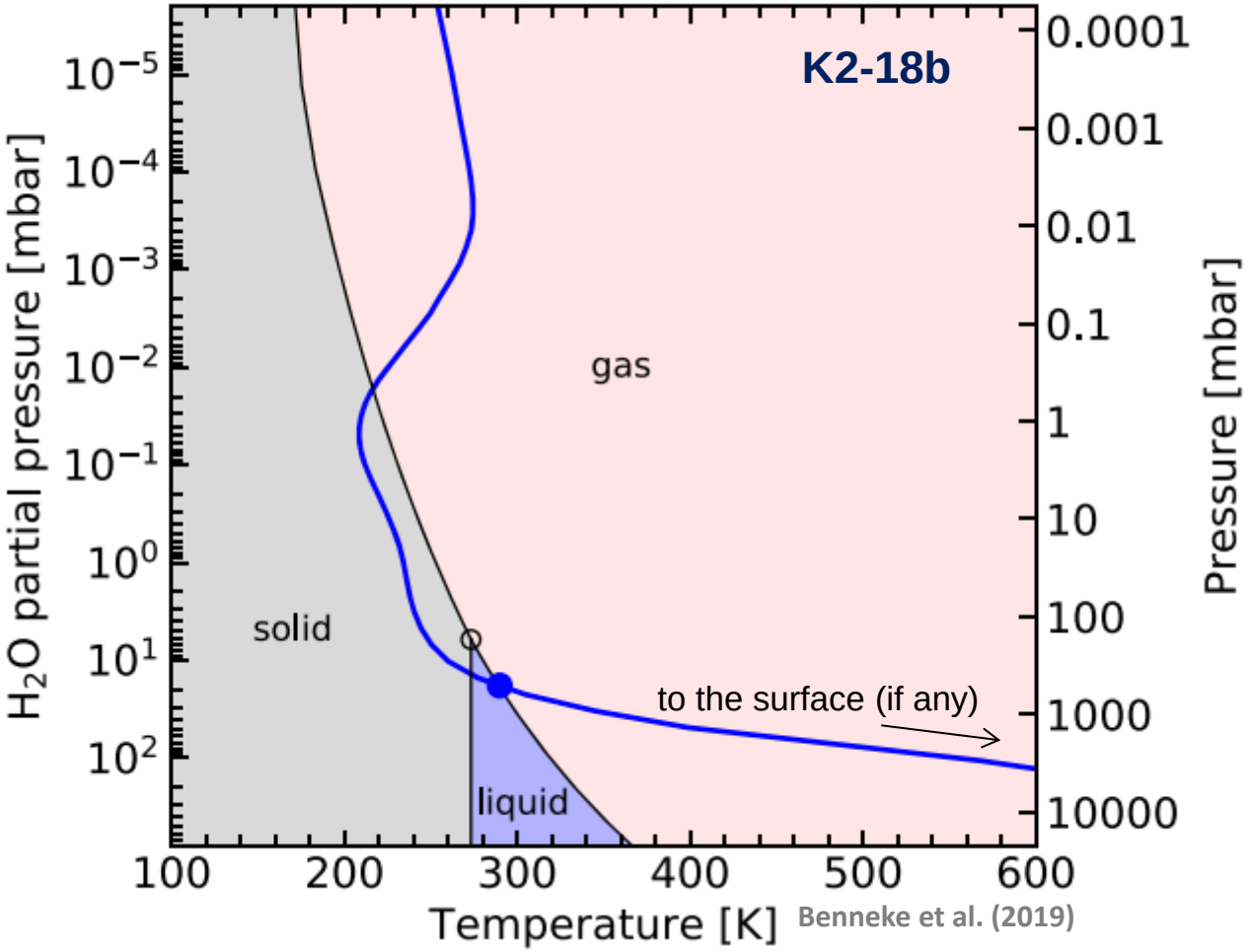
"Habitability refers to the potential of an environment to sustain life (see Cockell, 2016)."

"The classical HZ (Huang, 1959; Kasting et al. 1993) is defined to be the annulus region around a star where liquid water can exist on a rocky planet's surface."

Grenfell (2019)



M. Chaplin; HST; ESA

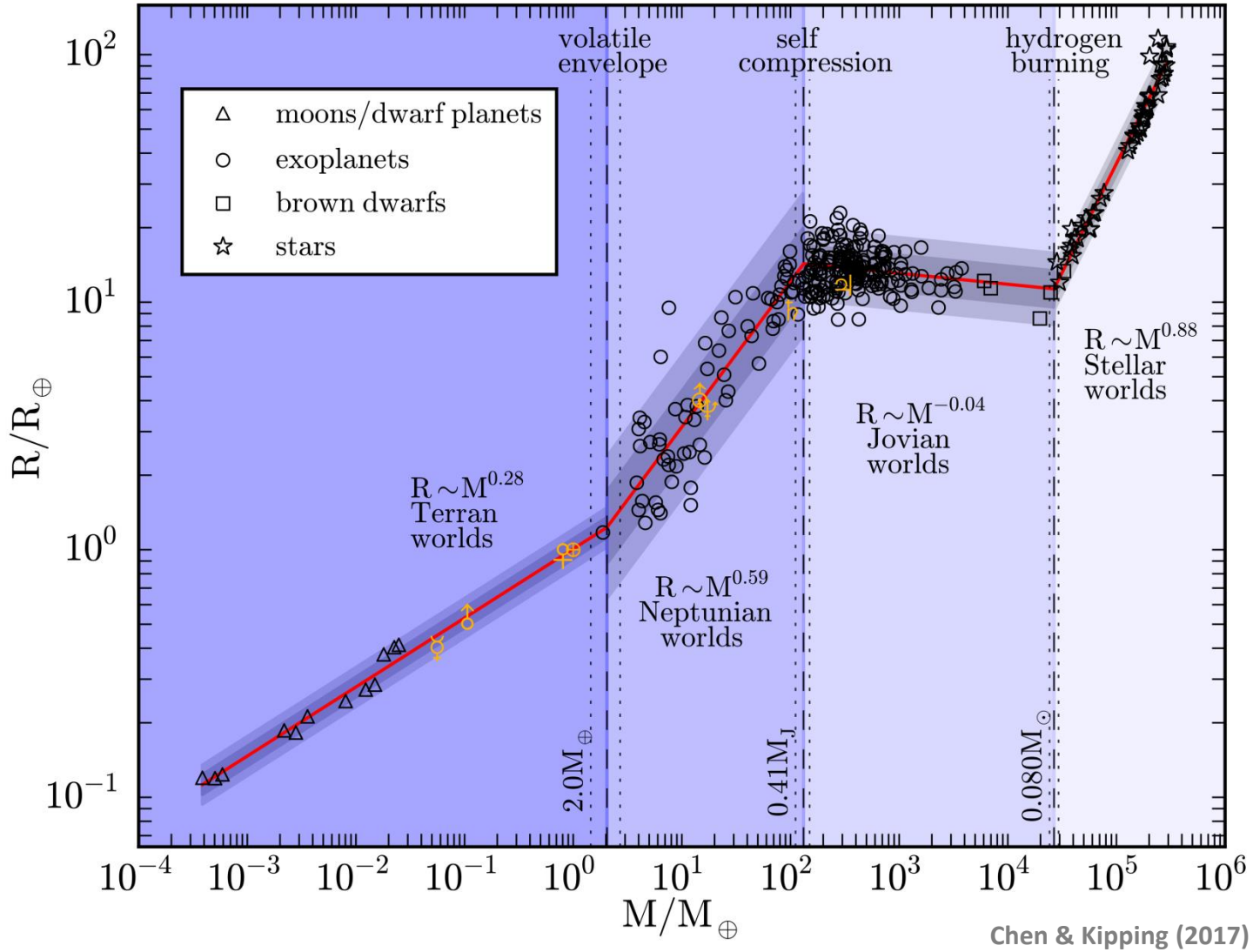


Benneke et al. (2019)

K2-18b is a very different kind of planet than what we find in our Solar System. The conditions on the surface (whatever 'surface' means for K2-18b) are very different than on Venus, Mars, or Earth.

What kind of planets exist?

Planet characterization



Chen & Kipping (2017)

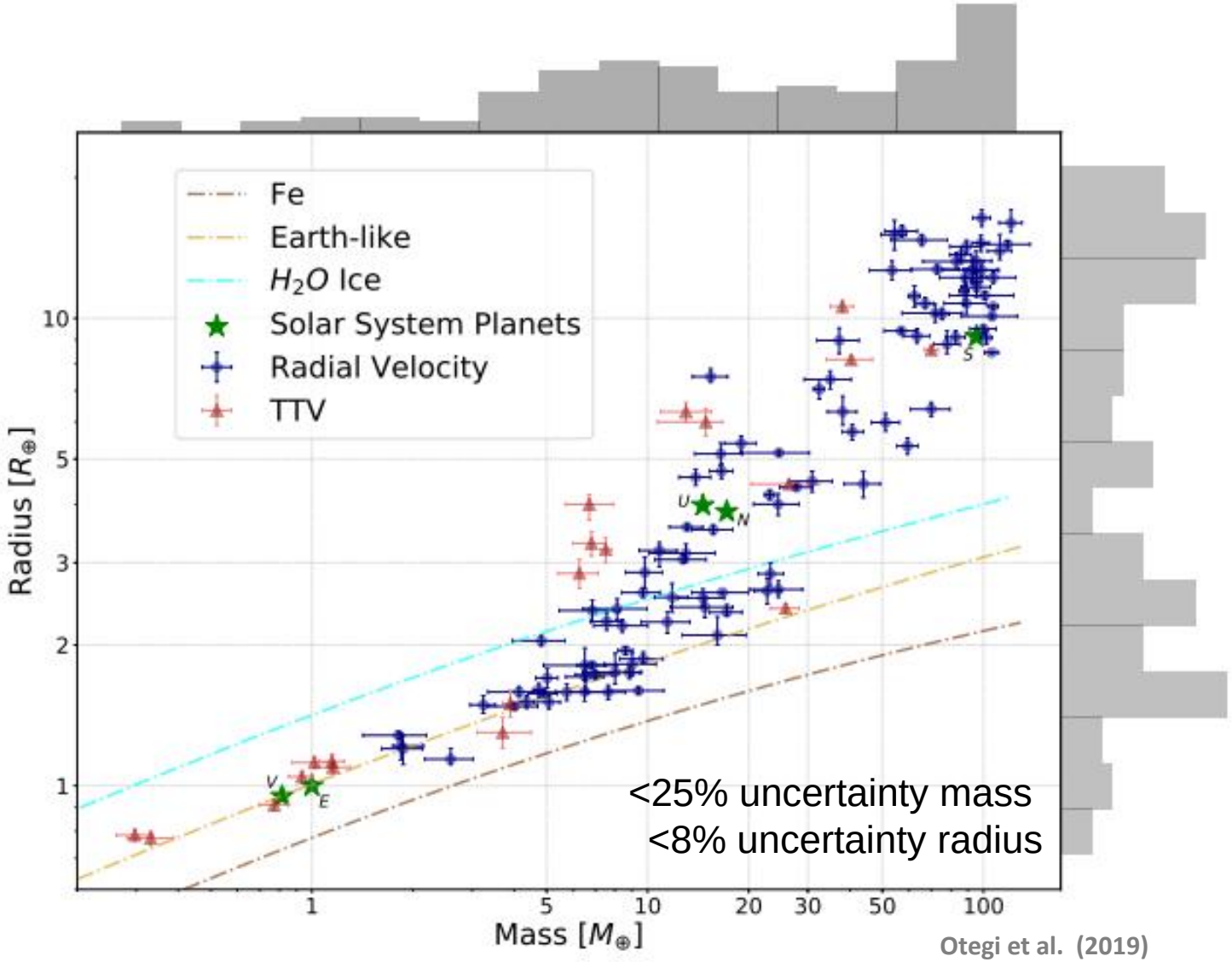
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Otegi et al. (2019)

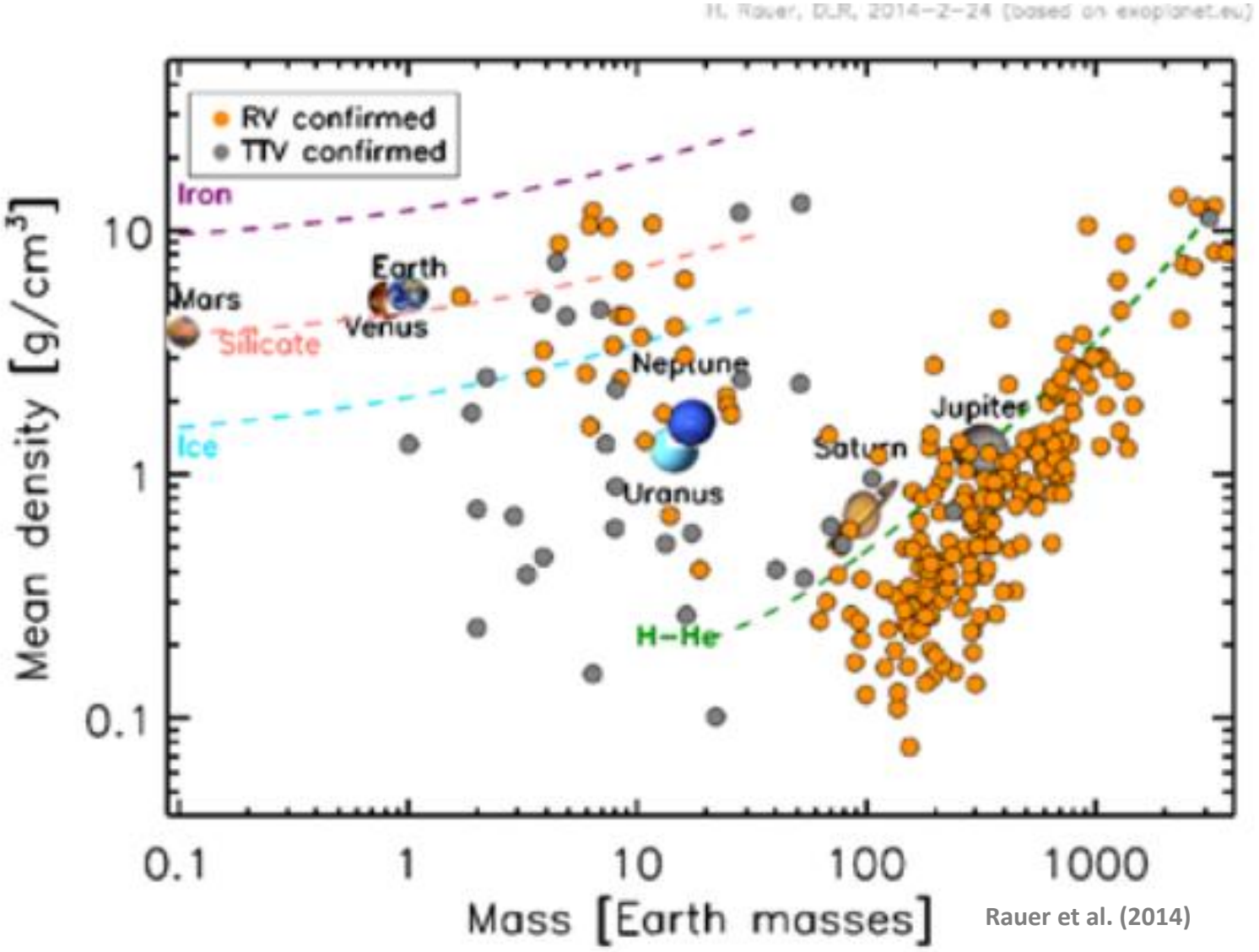
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Rauer et al. (2014)

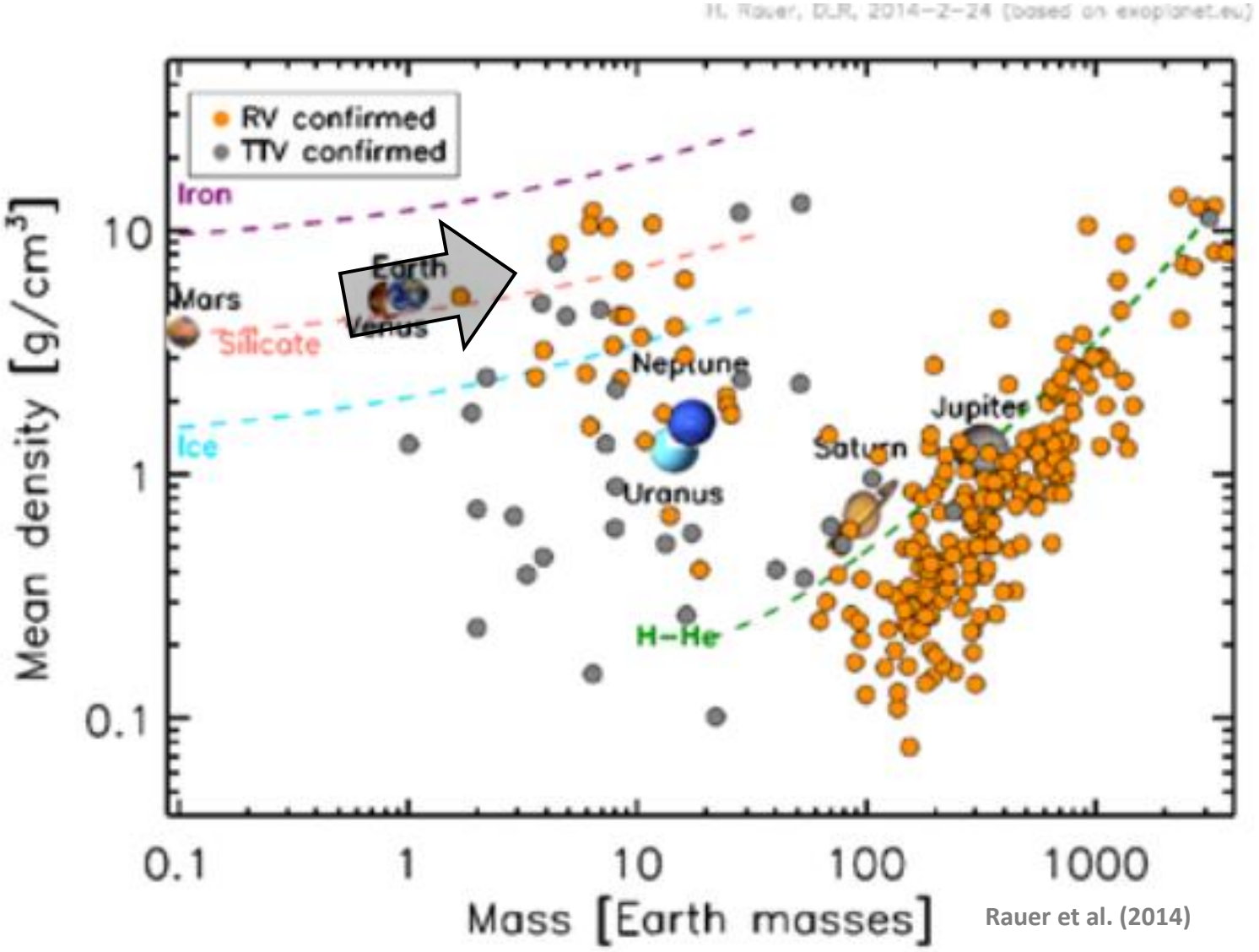
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Rauer et al. (2014)

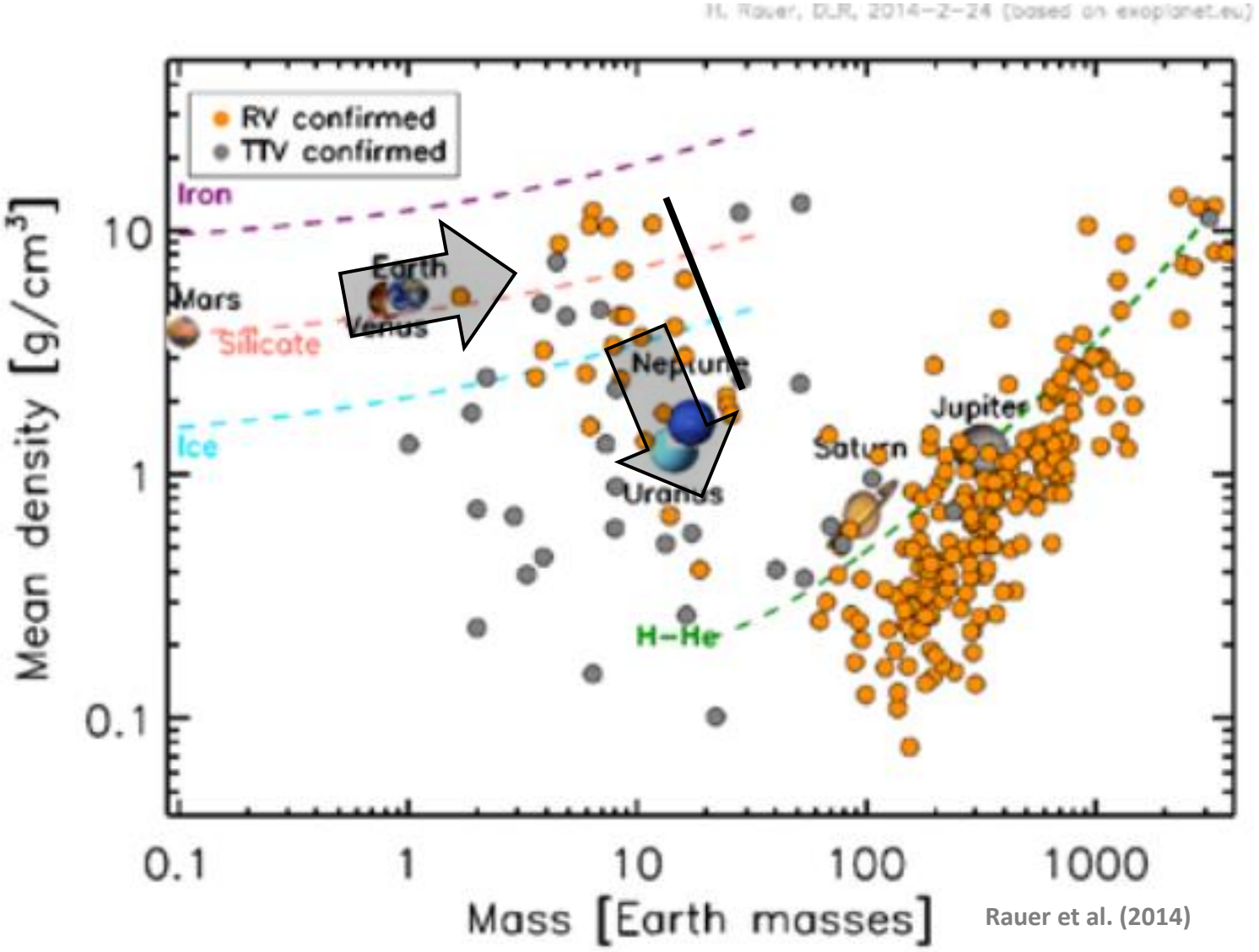
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Rauer et al. (2014)

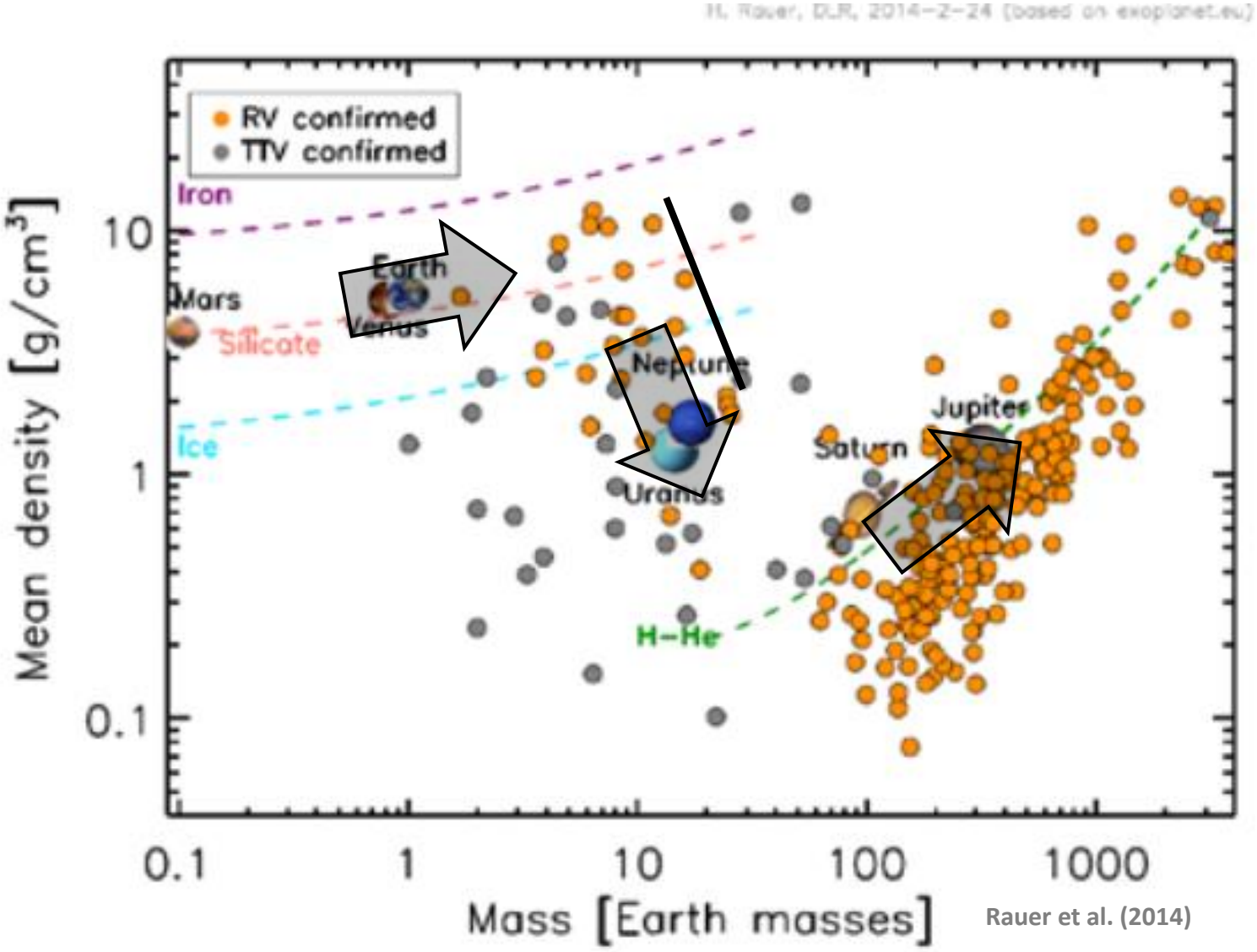
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Rauer et al. (2014)

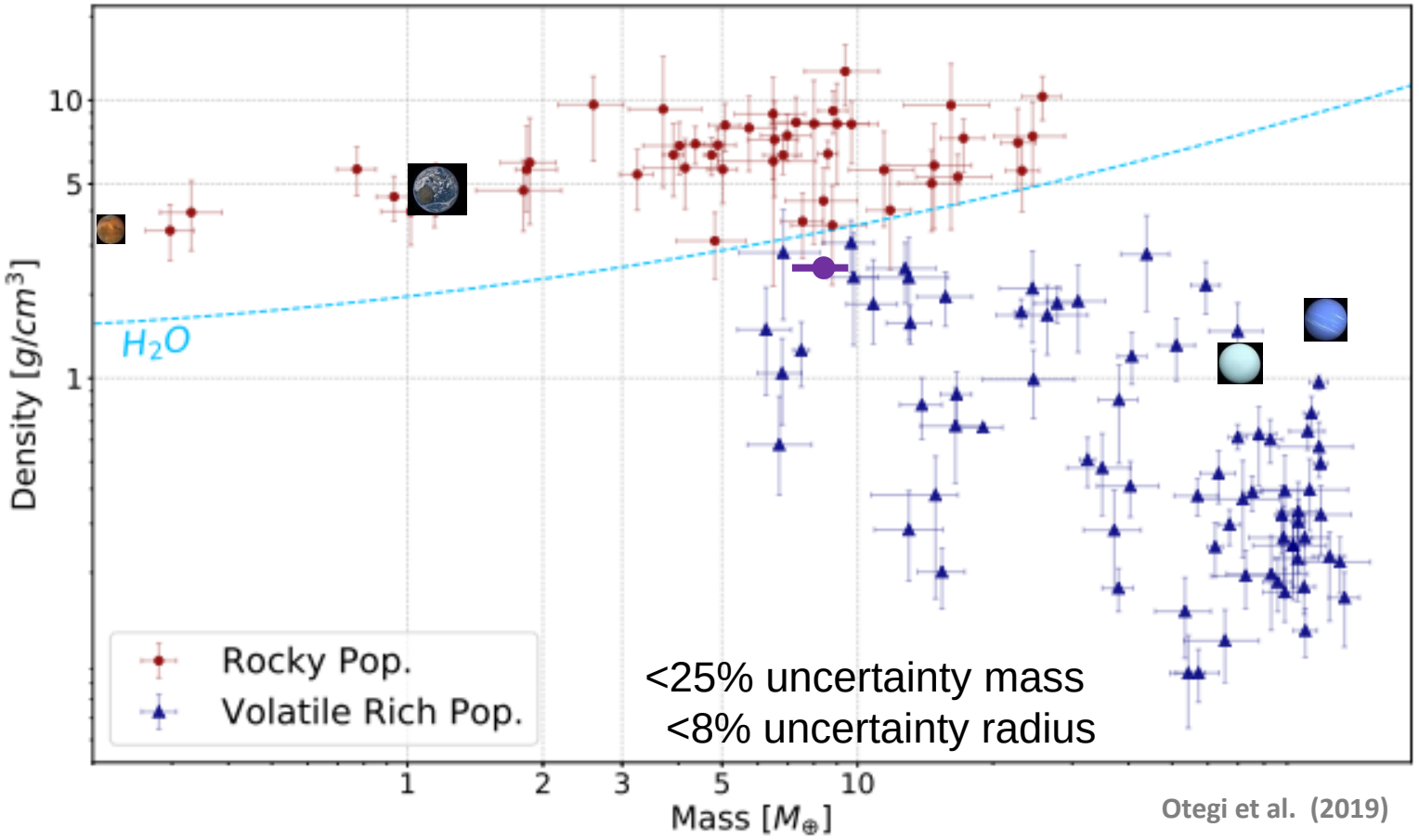
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Otegi et al. (2019)

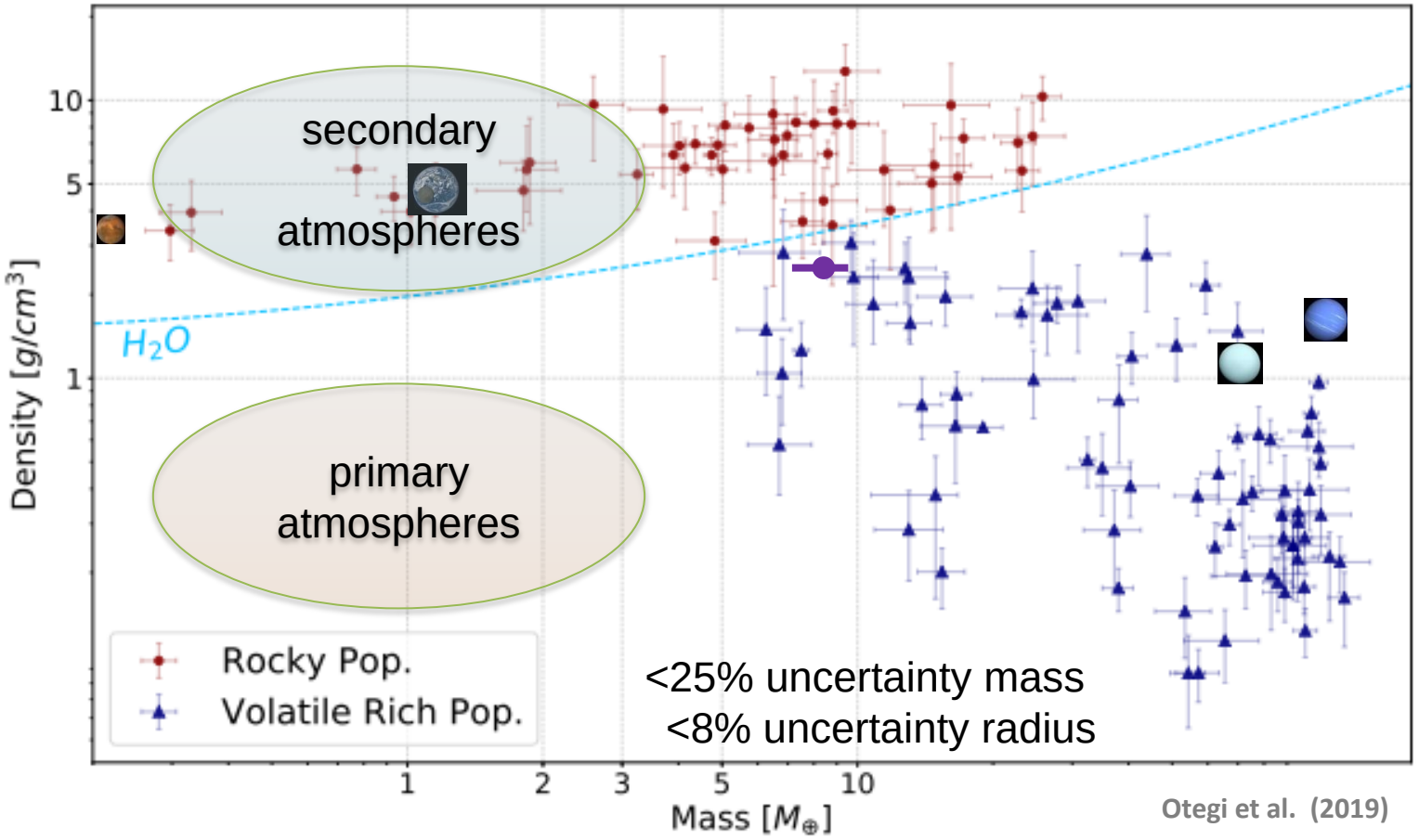
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet characterization



Otegi et al. (2019)

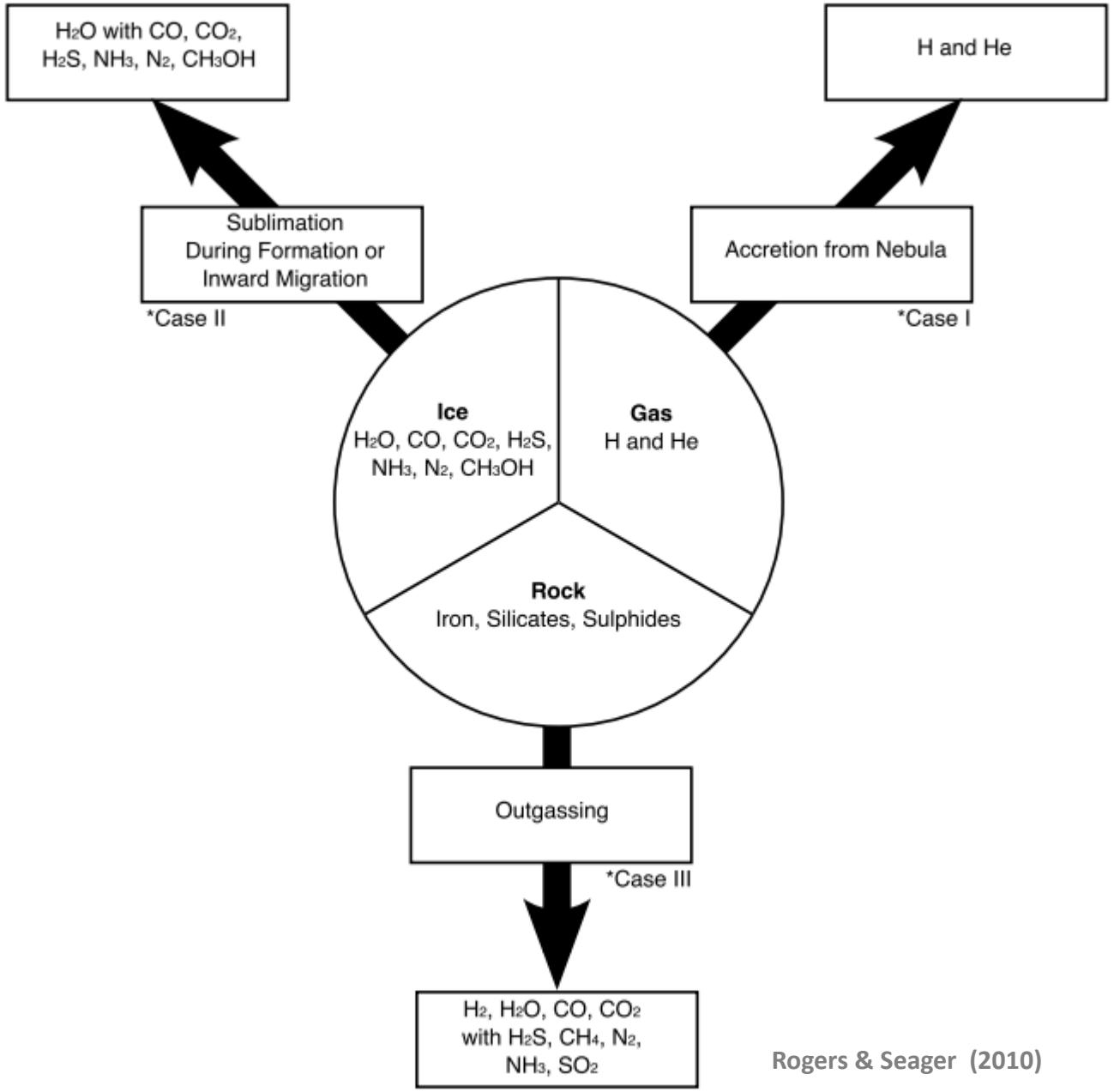
To first order, the only information that we have on extrasolar planets are its bulk properties: mass, radius, and density.

In the Solar System there is a clear correlation between density and distance to the Sun. It is also relatively straightforward to find power laws for mass and radii. This is great for planet formation theories.

Extrasolar planets are far more diverse than solar system planets.

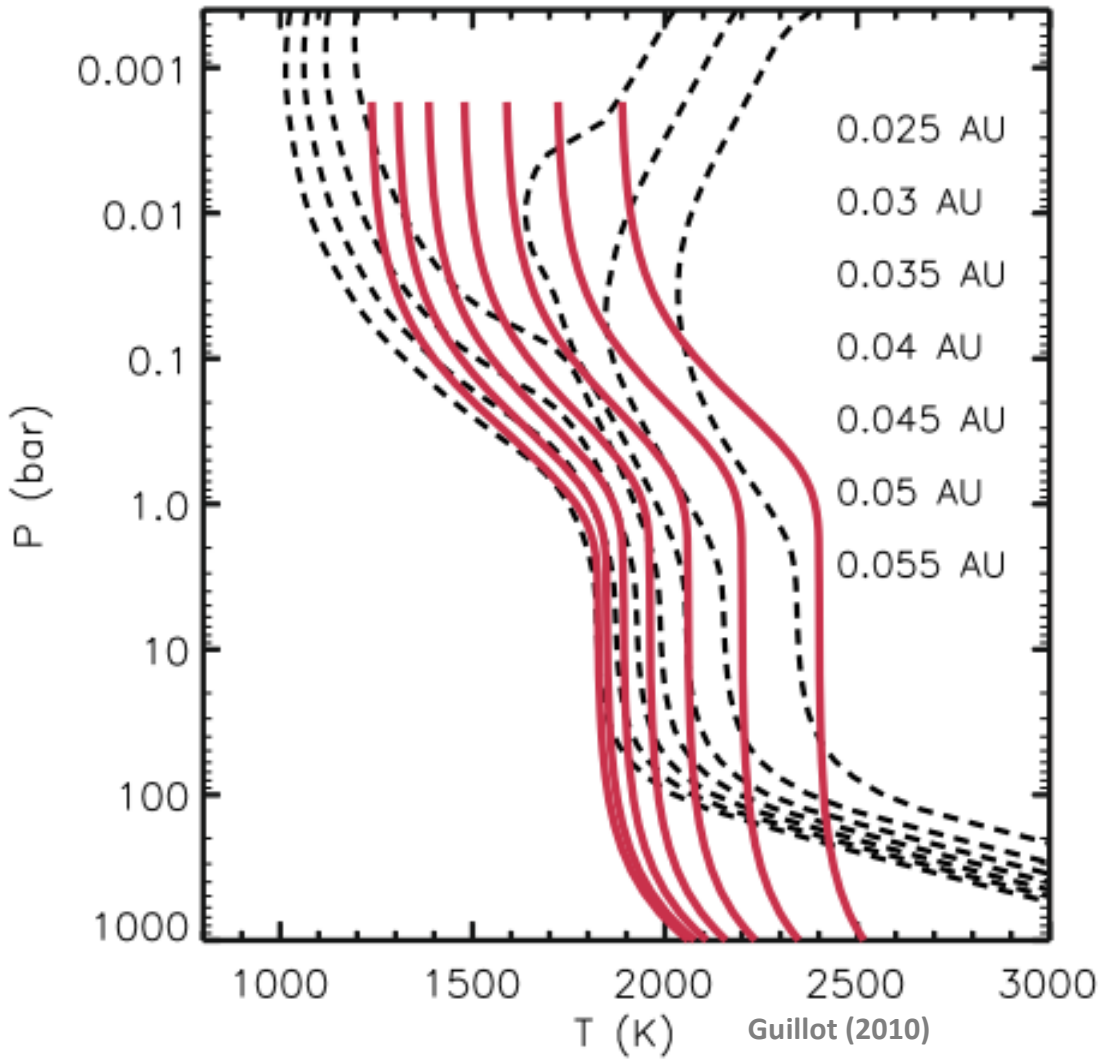
Part of the 'diversity' might be linked to observational biases and uncertainties, but a good part of it is real (i.e. K2-18b).

Planet interior



Rogers & Seager (2010)

Degeneracies in planetary atmospheres



Guillot (2010)

Effective temperature of the atmosphere, which is only representative of a small part of the atmosphere (see left).
Changing the temperature also changes the chemistry.
The dependency on the albedo is weak (a power of 0.25).
It ranges from ~2 000K (*) to 100K with uncertainty ~10%.
Most known planets between ~300 and ~1 500K.

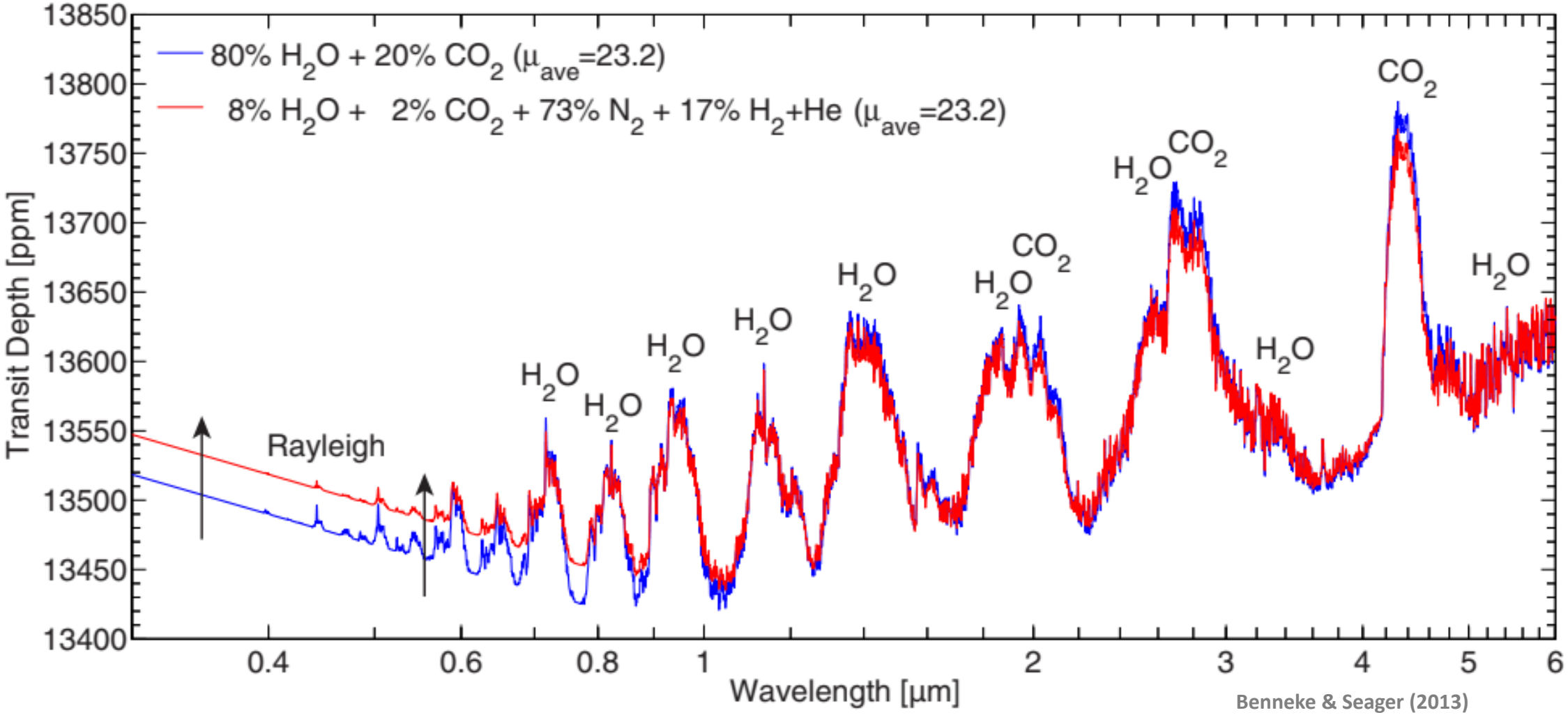
(*) But see KELT-9b!

$$H = \frac{k_B T}{g\mu}$$

Mean molecular weight of the atmosphere.
The chemical composition of the atmosphere is hidden here.
It ranges from 2 (H_2) to anything (H_2O is 18; CO_2 is 44).

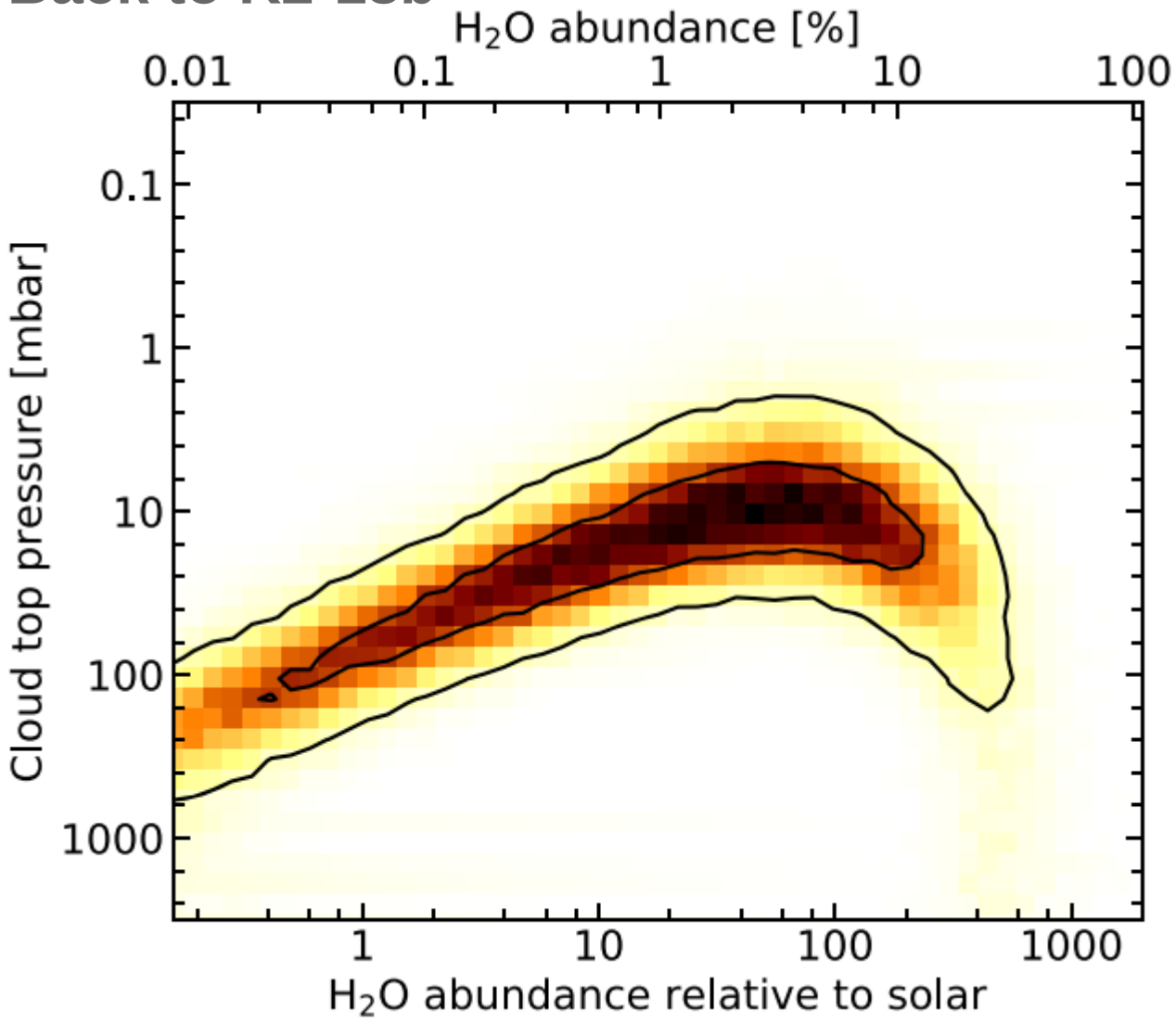
Degeneracies in planetary atmospheres

$$H = \frac{k_B T}{g\mu}$$



Benneke & Seager (2013)

Back to K2-18b



Benneke et al. 2019, ApJ, 887, L14

There is enough observational support to think that the atmosphere of K2-18b is hydrogen dominated:

- Bulk properties.
- Retrieval studies of transmission spectroscopy.

However, the composition of the atmosphere is highly degenerate: i.e. water abundance ranging from 0.033% to 8.9% with 68% confidence level.
Note that 8.9% corresponds to 162 times the solar abundance, indicating strong enrichment in volatiles with respect to the original nebula.

The bulk properties are affected by some uncertainties (see next slides).

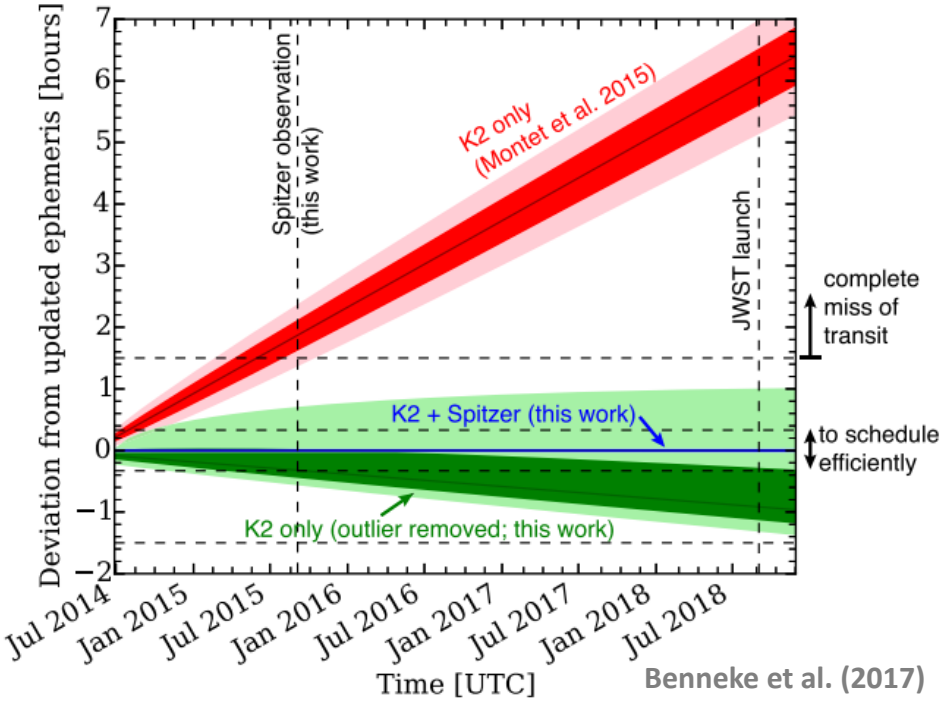
Back to K2-18b

	stellar radius [Rs]	stellar mass [Ms]	planet radius [RE]	planet mass [ME]	planet density [gcm-3]
Montet et al. (2015)	0.394±0.038	0.413±0.043	2.24±0.23 (10%)	-	-
Benneke et al. (2017)	0.411±0.038	0.359±0.047	2.38±0.22 (9%)	-	-
Cloutier et al. (2017)	0.411±0.038	0.359±0.047	2.38±0.22 (9%)	7.96±1.91 (24%)	3.3±1.2 (36%)
Cloutier et al. (2019)	0.469±0.010	0.495±0.004	2.711±0.065 (2.4%)	8.63±1.35 (16%)	2.4±0.4 (17%)

The uncertainty in the orbit and ephemeris was secured with Spitzer observations by Benneke et al. (2017) [see later slides on CHEOPS].

The uncertainty in the radius is driven by the uncertainty in the stellar parameters, which was driven by the uncertainty in the distance to this M dwarf. It changed from 34±4 pc to 38.025±0.079 pc with the second data release of Gaia (Cloutet et al 2019) [see later slides on PLATO].

The uncertainty in the mass is so far driven by the RV measurements and will certainly improve in the future.



Benneke et al. (2017)

Back to K2-18b

Mass-radius relationship for known exoplanets.

Dashed lines represent mass-radius relationships for planets of (unrealistically) homogeneous compositions.

Note the position of K2-18b in the corner where a significant amount of hydrogen is needed to account for the bulk properties.

Note the large uncertainty of the planetary parameters which makes it difficult to relate the bulk properties to the internal composition (see later slides on PLATO).

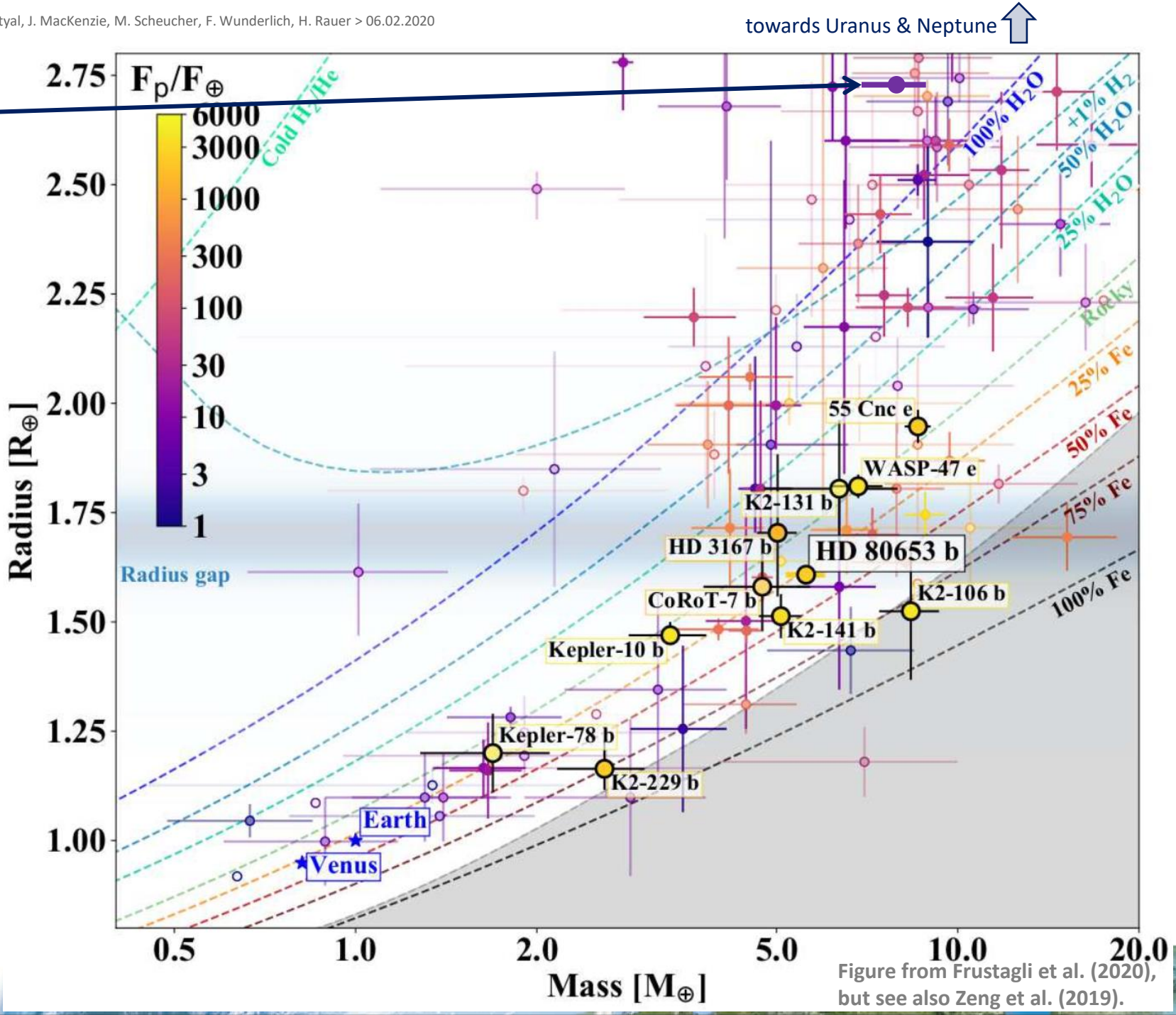
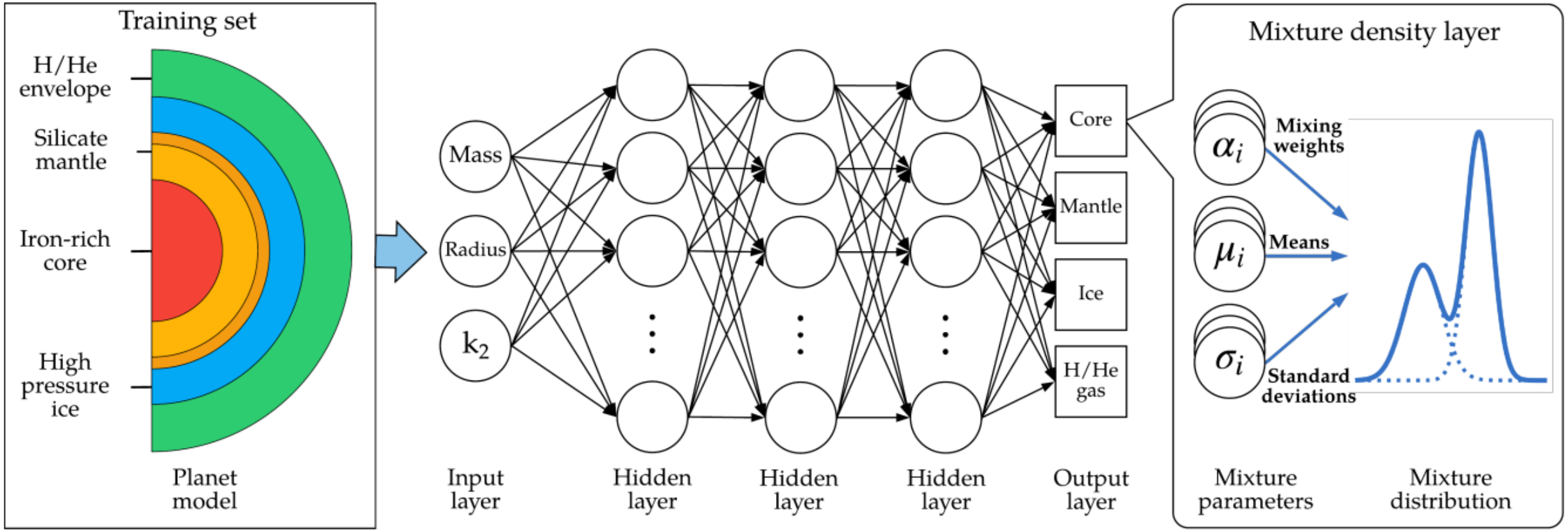


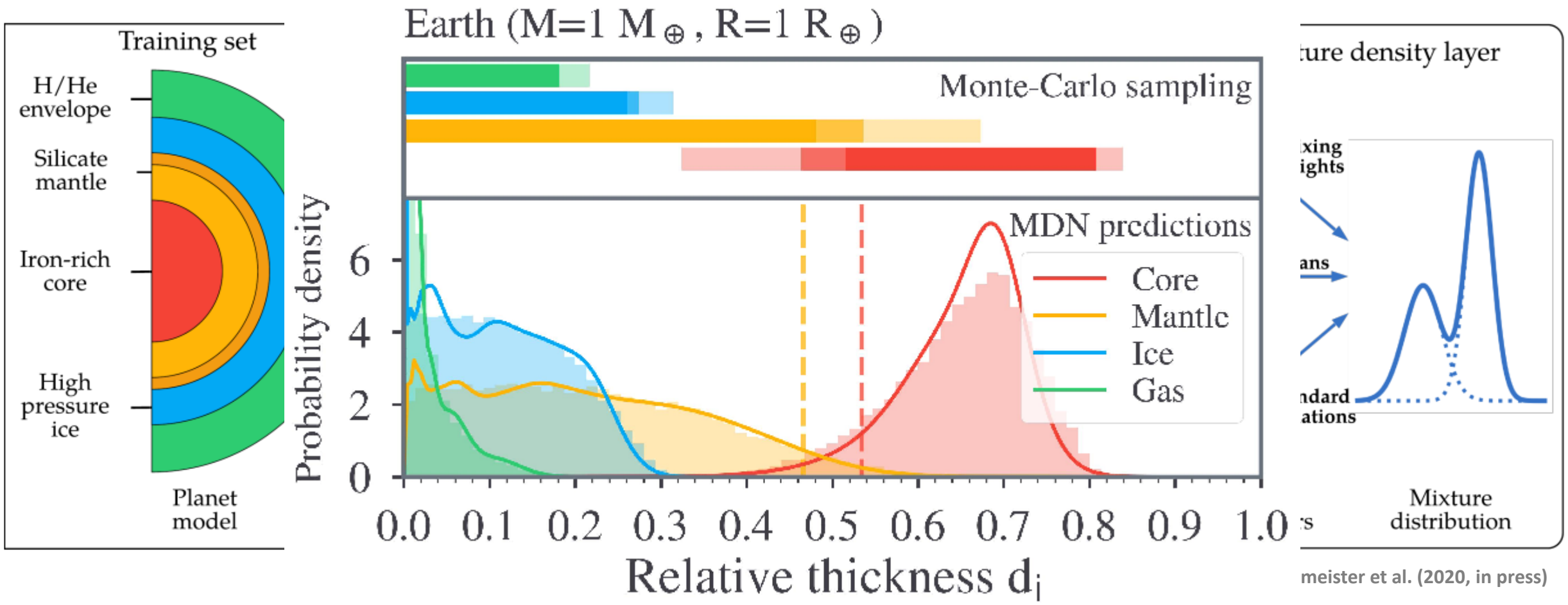
Figure from Frustagli et al. (2020), but see also Zeng et al. (2019).

Breaking the degeneracies



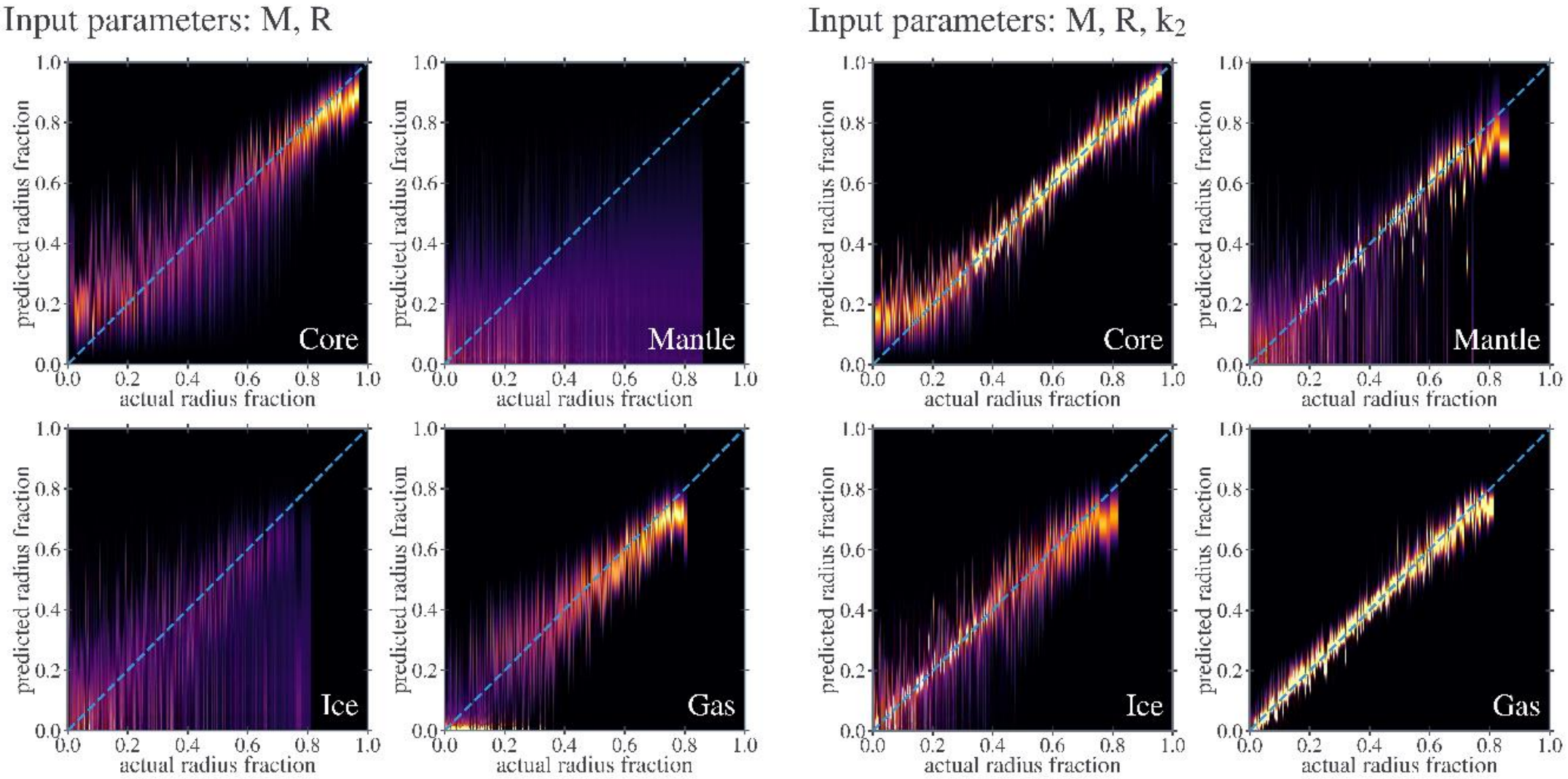
Baumeister et al. (2020, in press)

Breaking the degeneracies



meister et al. (2020, in press)

Breaking the degeneracies



Baumeister et al. (2020, in press)

Breaking the degeneracies: Love number

$$V_t = \frac{Gm_s}{d}\sum_{j=2}^{\infty}\left(\frac{R_p}{d}\right)^j P_j(\lambda),$$

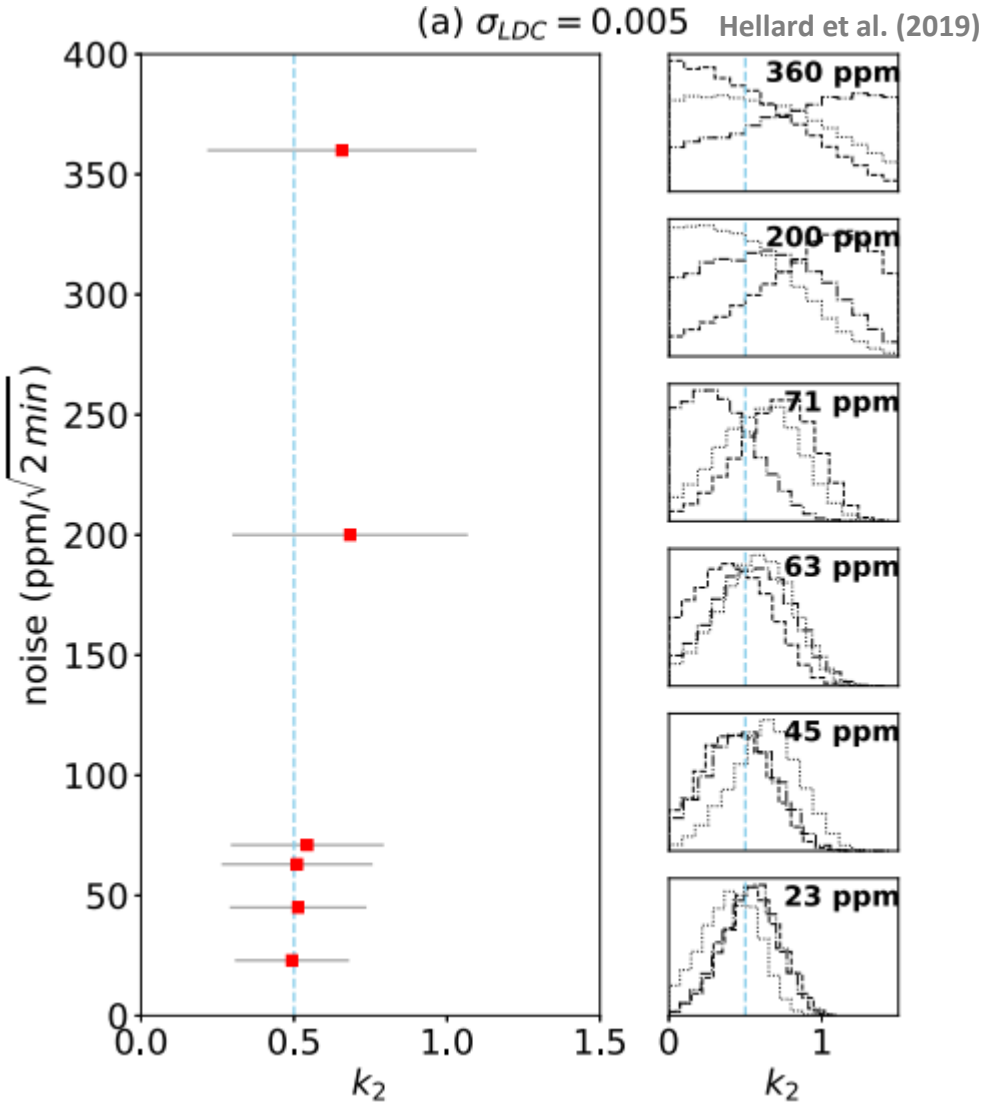
tidal potential

$$r(\theta,\phi) = R_p\left(1 + q\sum_{j=2}^{4} h_j P_j(\lambda)\left(\frac{R_p}{d}\right)^{j+1} - \frac{1}{3}h_2(1+q)F_p^2\left(\frac{R_p}{d}\right)^3 P_2(\cos(\Theta))\right).$$

surface shape

The fluid Love number is k_j with $h_j=1+h_j$.

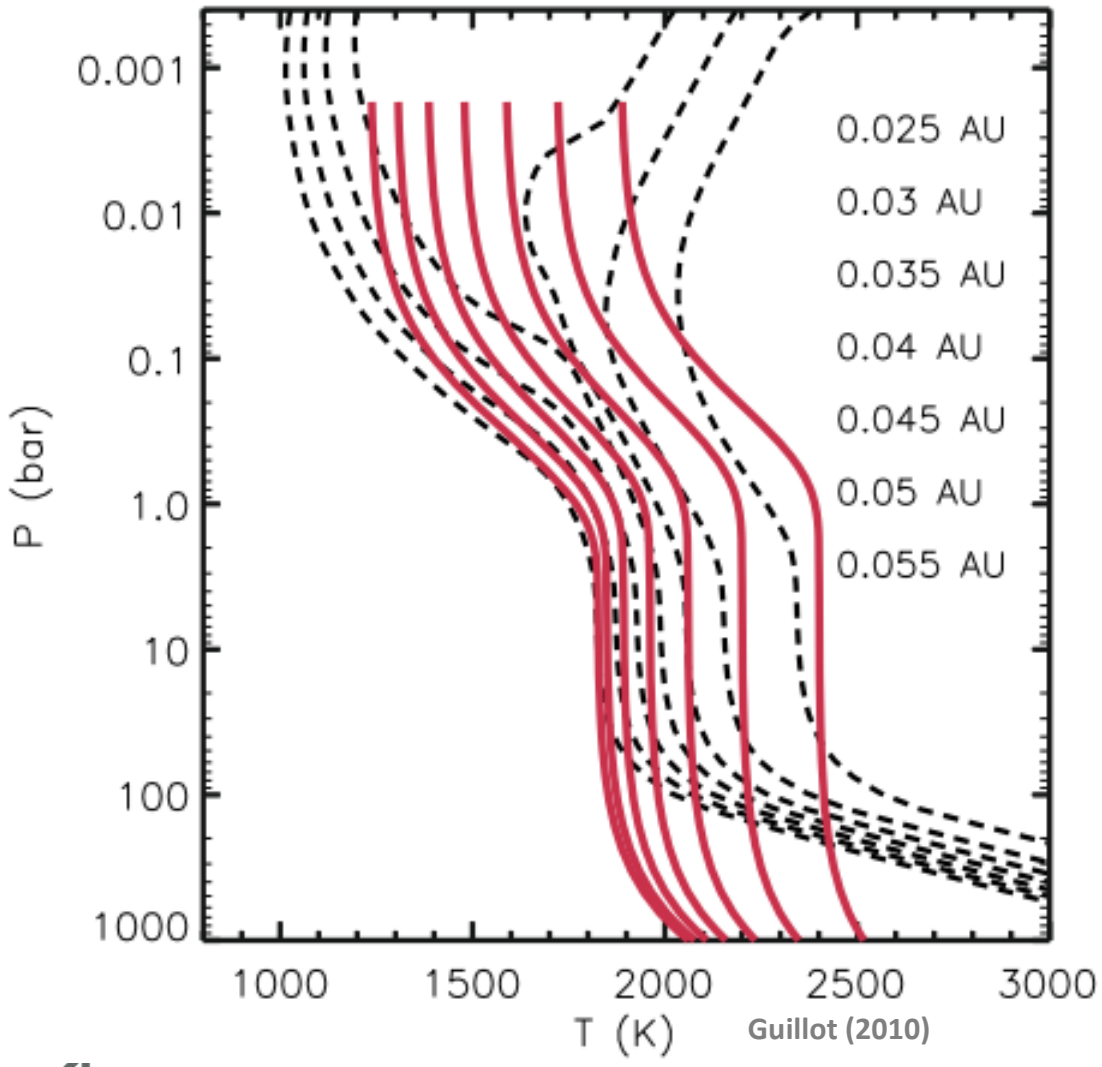
The second degree fluid Love number, k2, is proportional to the concentration of mass toward the body's center, hence providing valuable additional information about the planetary internal structure (see Hellard et al. 2019).



Synthetic data for WASP-121b with k2=0.5 observed by different facilities (JWST, Kepler, PLATO, CHEOPS, TESS). Average values (left) and posterior distributions of k2 (right)

$$H = \frac{k_B T}{g\mu}$$

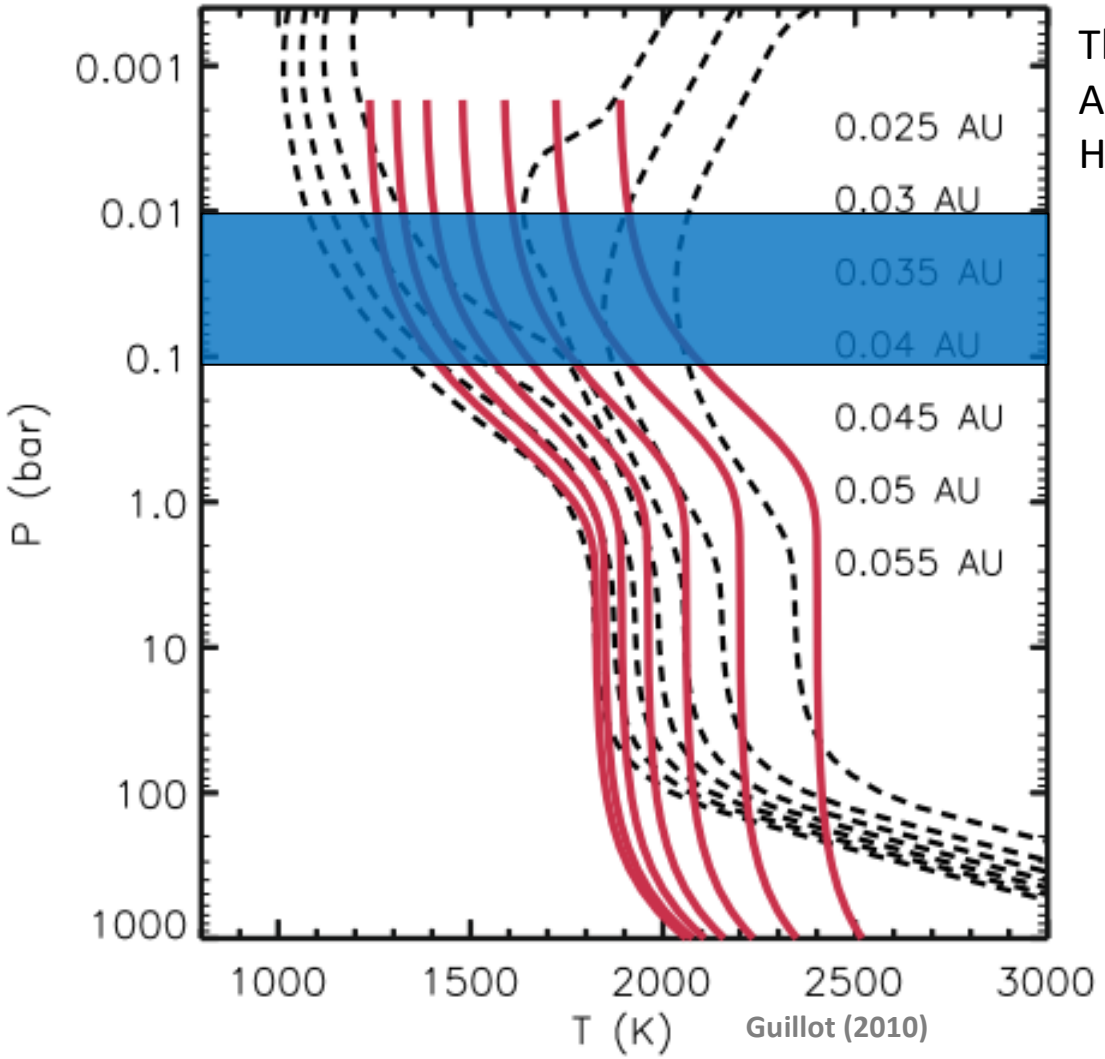
Degeneracies in planetary atmospheres



Guillot (2010)

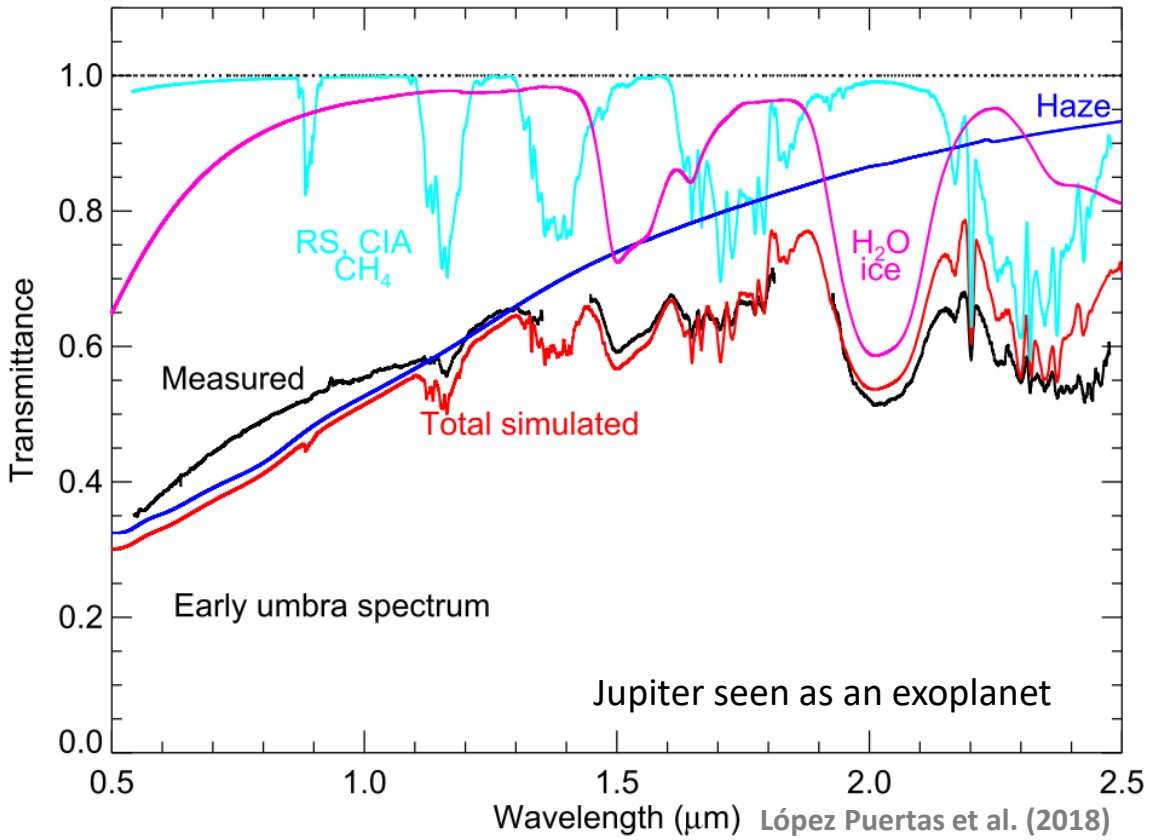
$$H = \frac{k_B T}{g\mu}$$

Degeneracies in planetary atmospheres



Guillot (2010)

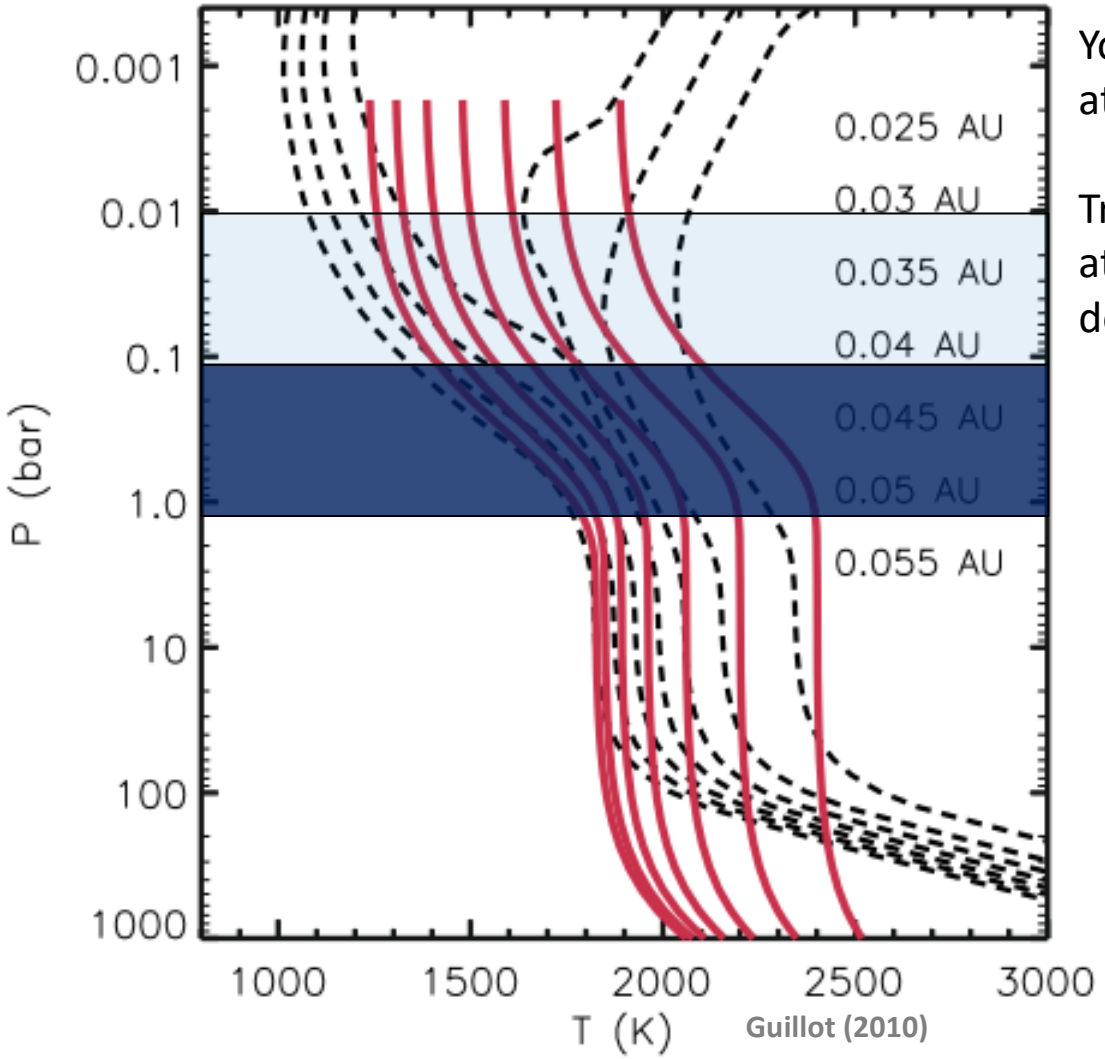
This is the regime typically proved by transmission spectroscopy.
An isothermal atmosphere is not a bad approximation.
Hazes might mask your observations.



López Puertas et al. (2018)

$$H = \frac{k_B T}{g\mu}$$

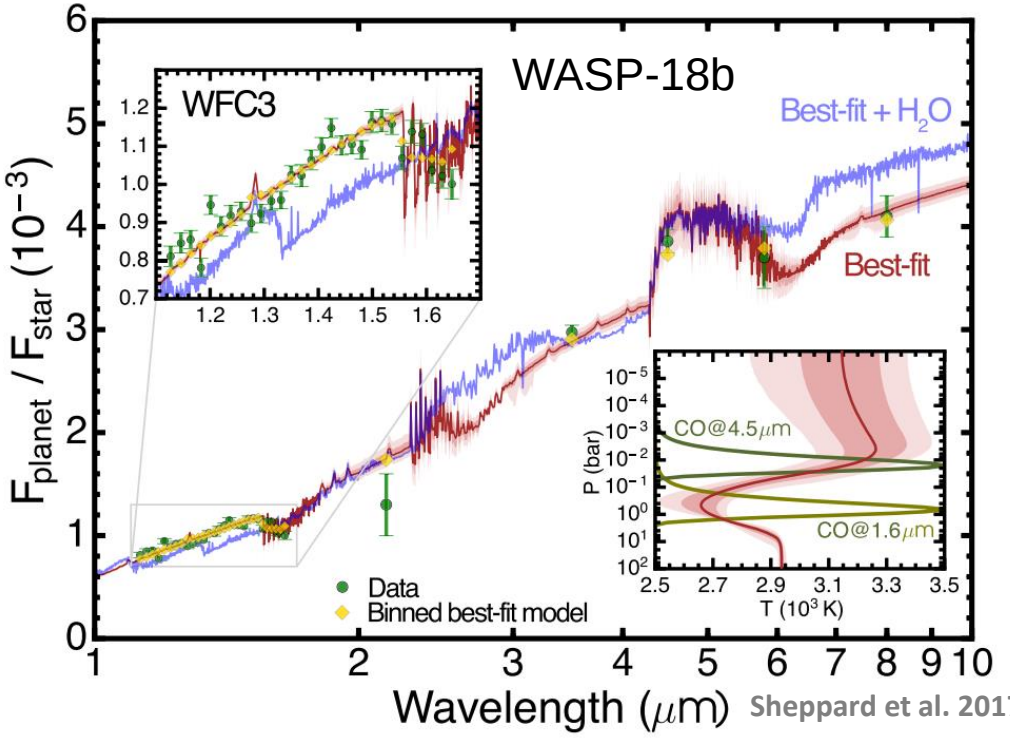
Degeneracies in planetary atmospheres



Guillot (2010)

You might reach this regime in emission, depending on the planet and its atmosphere.

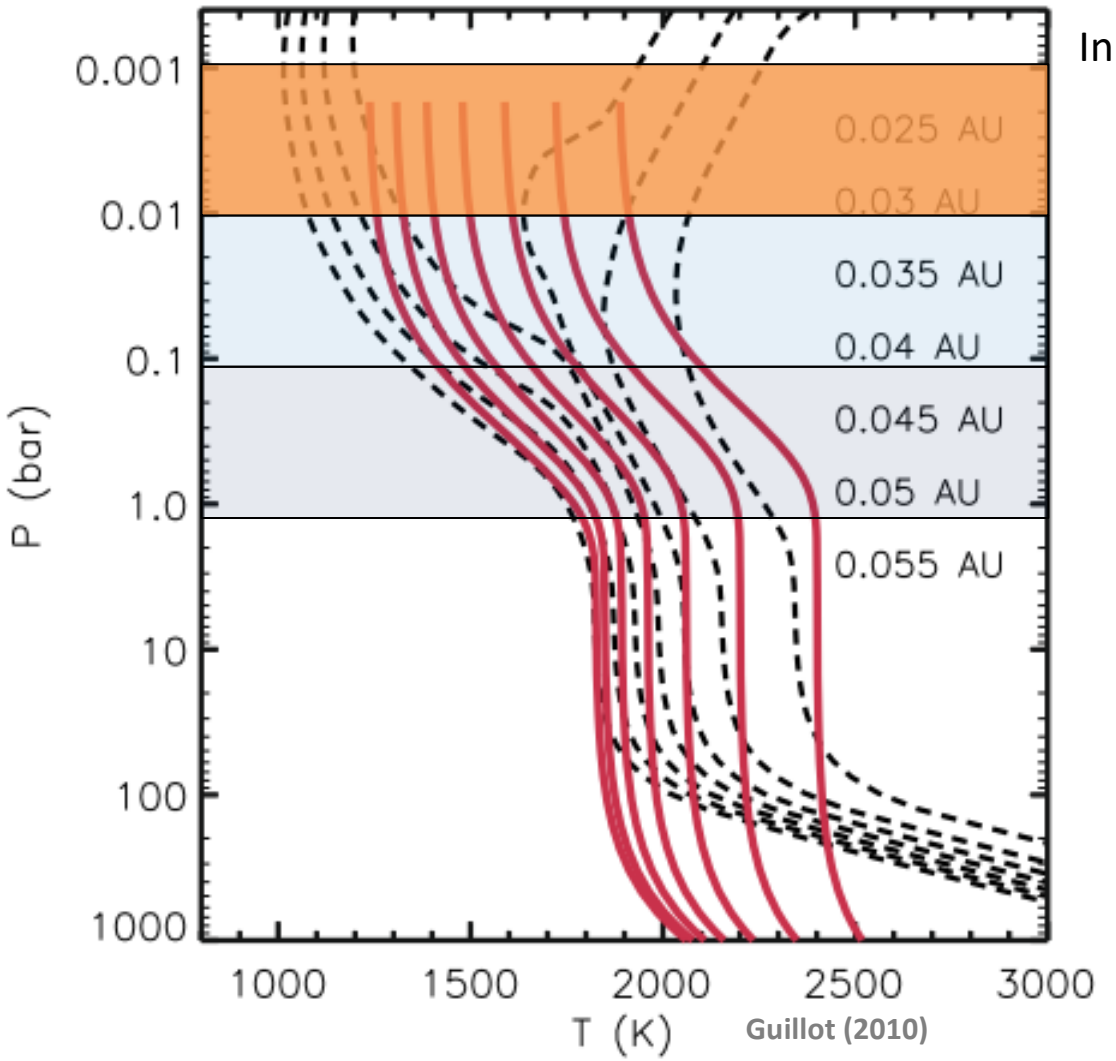
Transport and quenching redistribute the composition of your atmosphere above the adiabatic region, where equilibrium chemistry dominates.



Sheppard et al. 2017

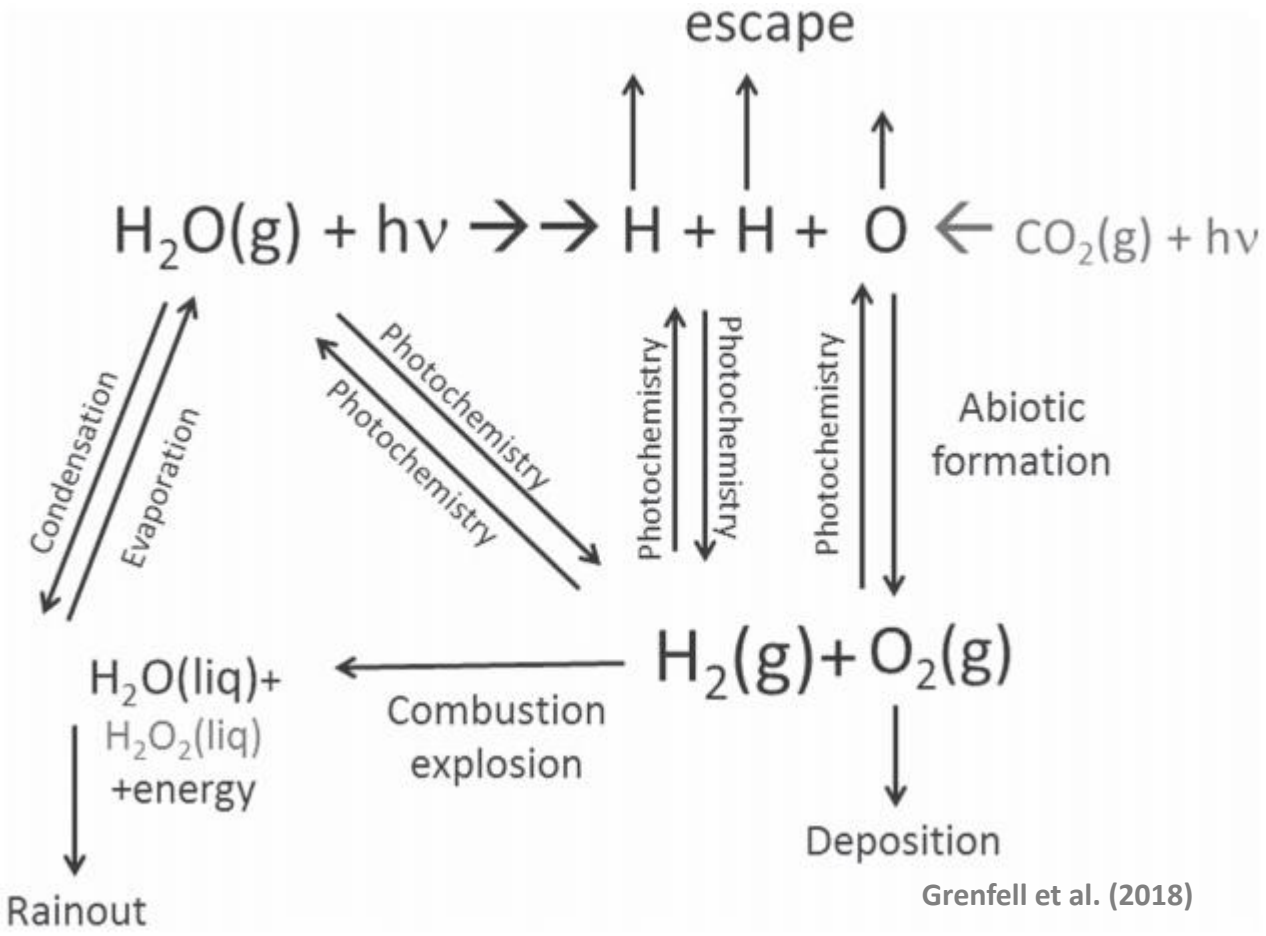
$$H = \frac{k_B T}{g\mu}$$

Degeneracies in planetary atmospheres



Guillot (2010)

In this regime photochemistry dominates.

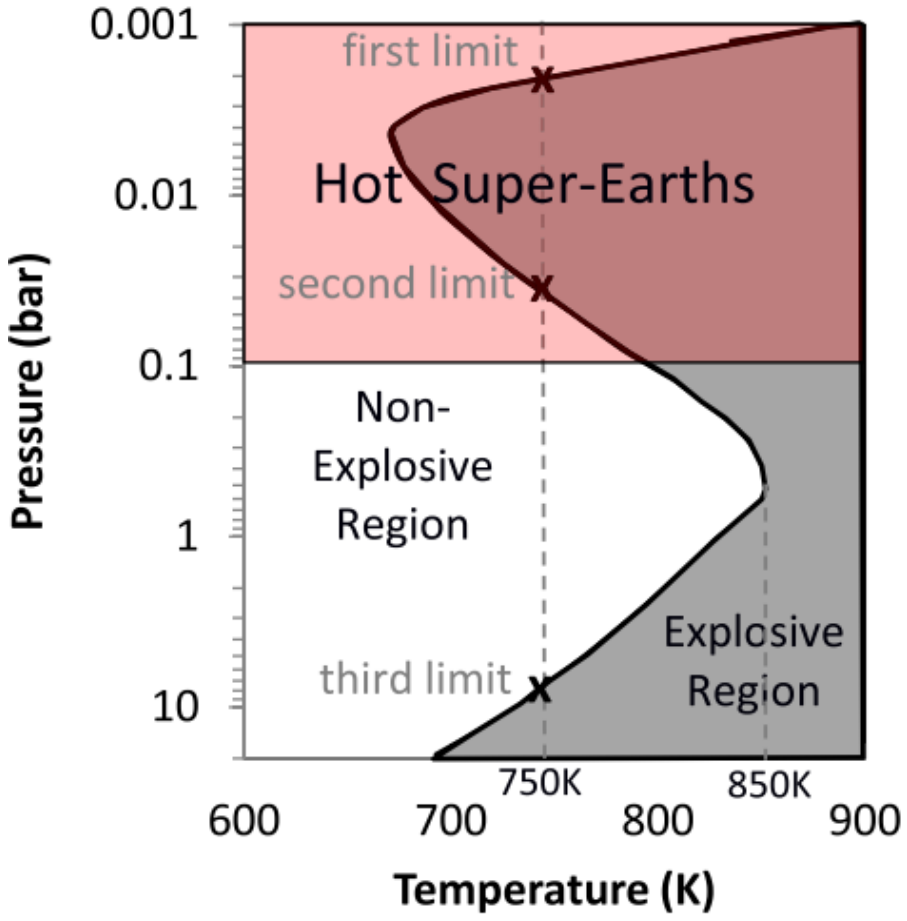


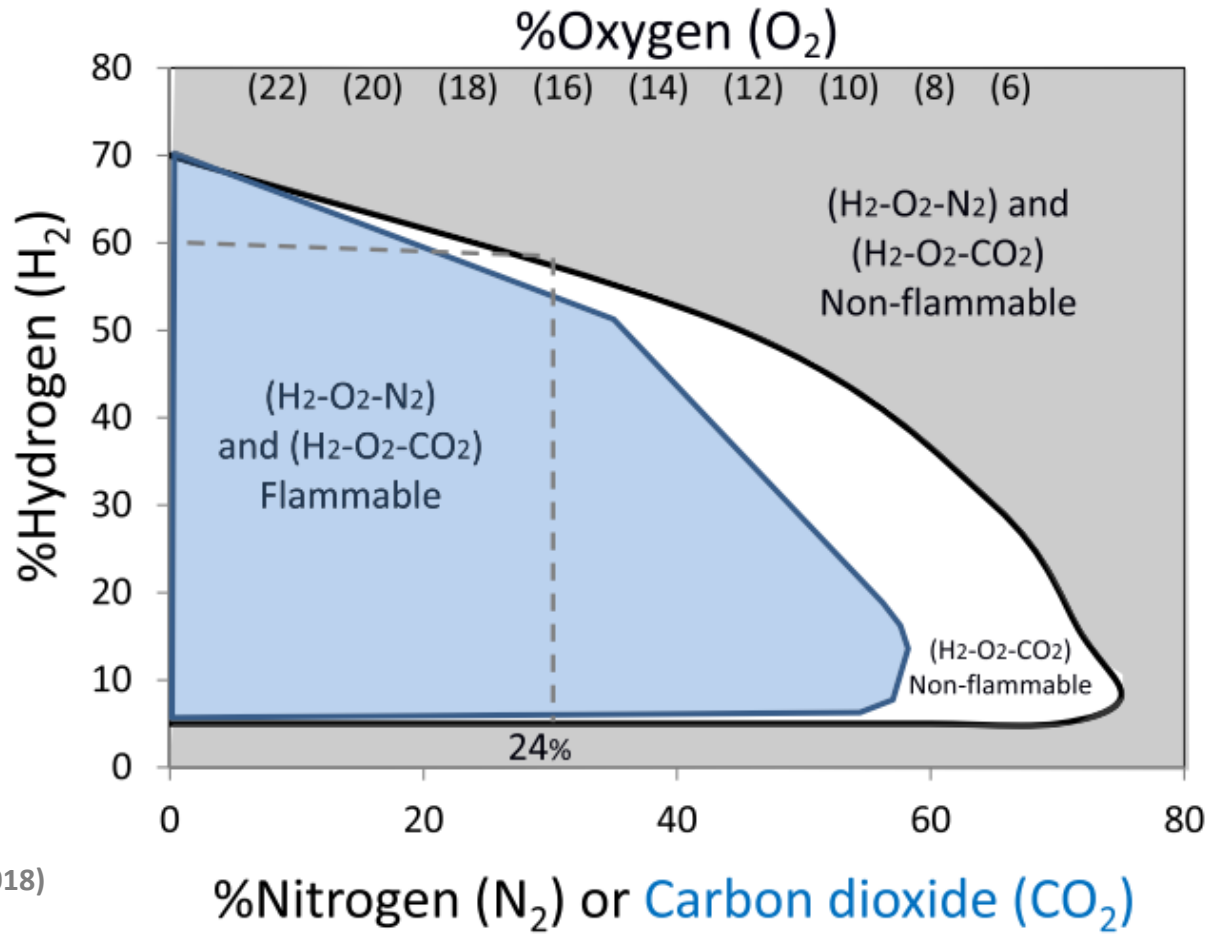
Grenfell et al. (2018)

$$H = \frac{k_B T}{g\mu}$$

Degeneracies in planetary atmospheres

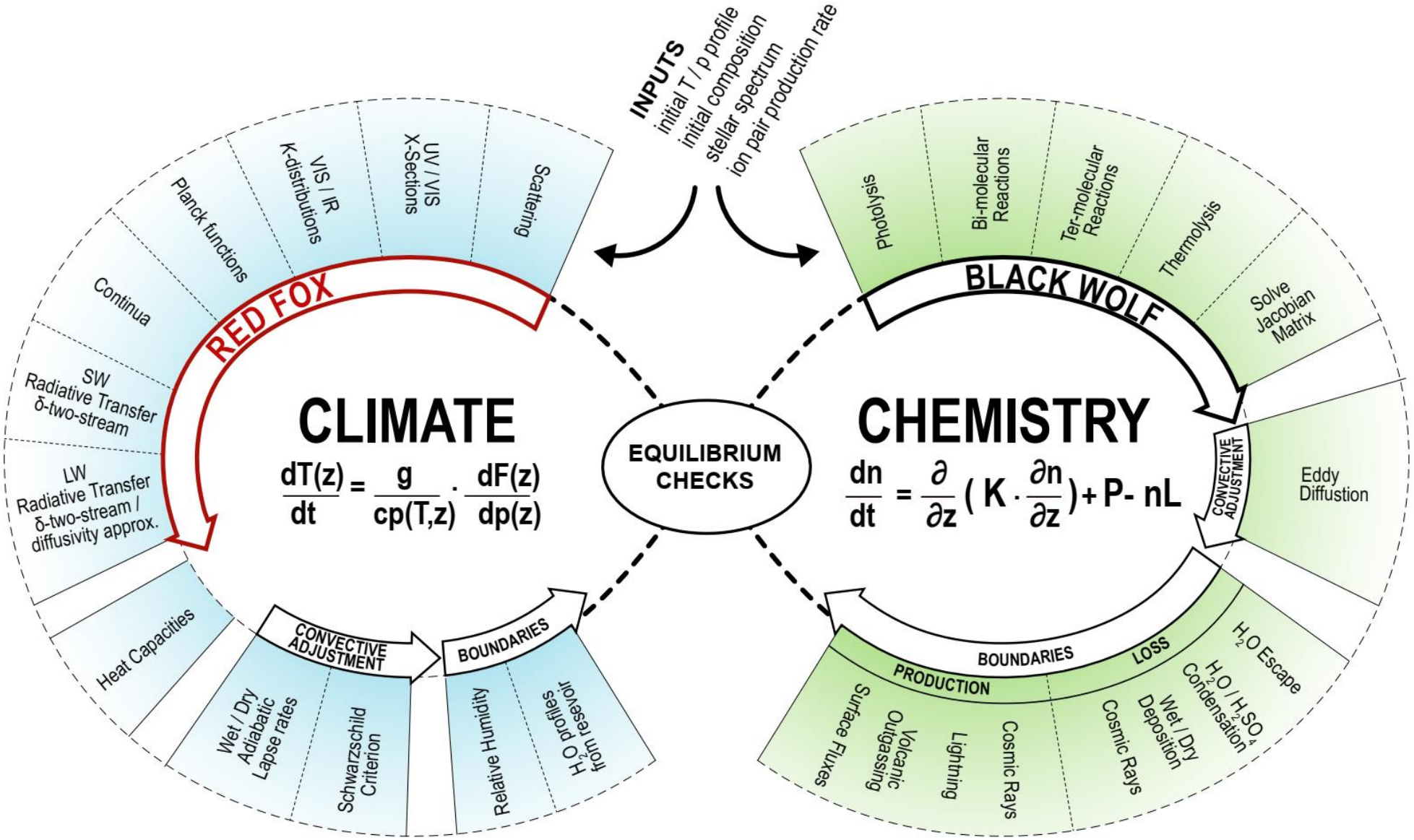
In this regime photochemistry dominates.





Grenfell et al. (2018)

Planetary atmospheres model



1D-TERRA

See Scheucher et al. 2020 (submitted) and references therein (Rauer et al. 2011, Grenfell et al. 2012...)

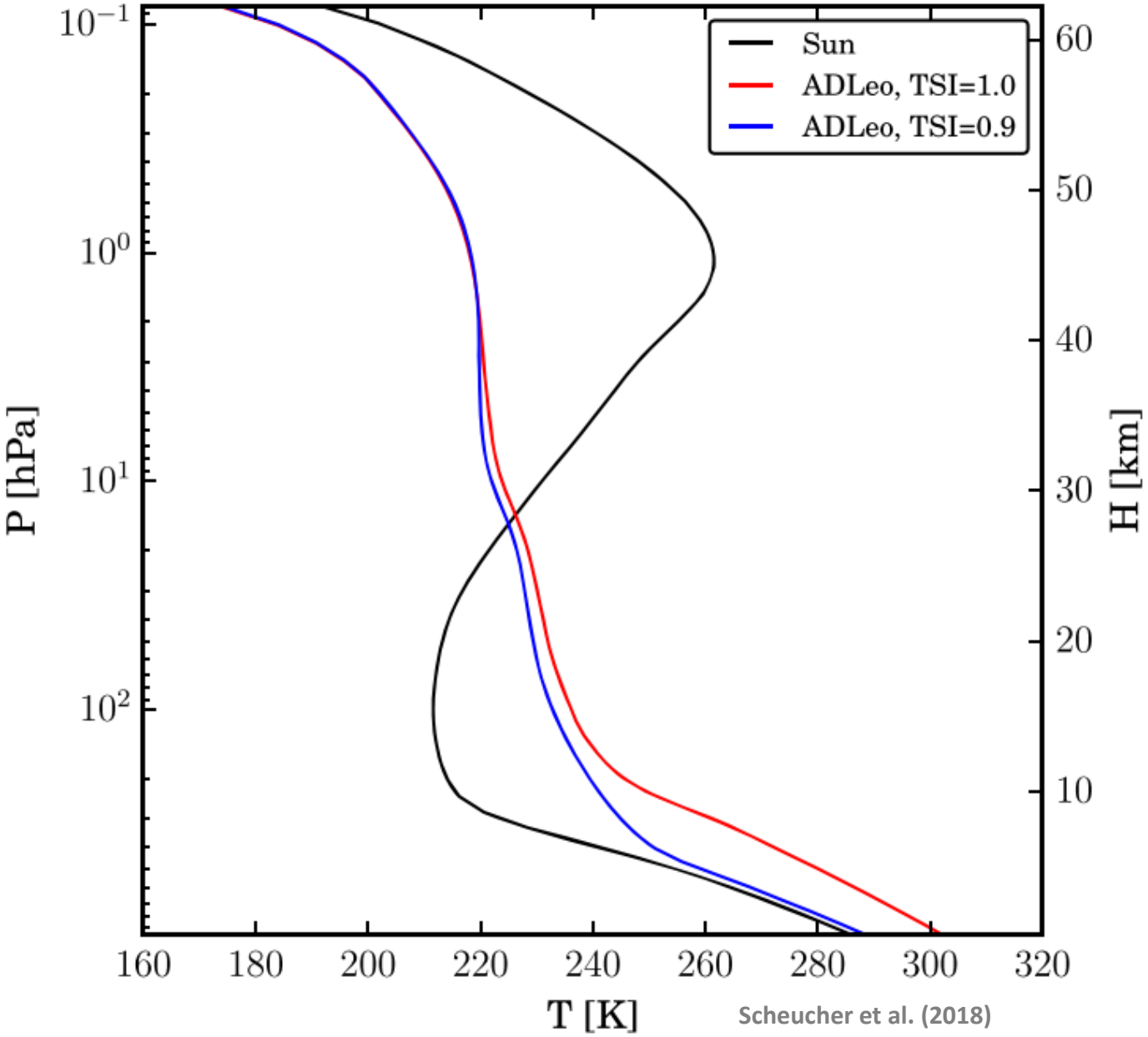
Planetary atmospheres in the Solar System and abroad

A typical exercise is to take the planet Earth and put it (metaphorically speaking) in orbit of a M dwarf.

The same atmosphere (in terms of mass and composition) with the same temperature surface has a completely different structure because of the different energy input.

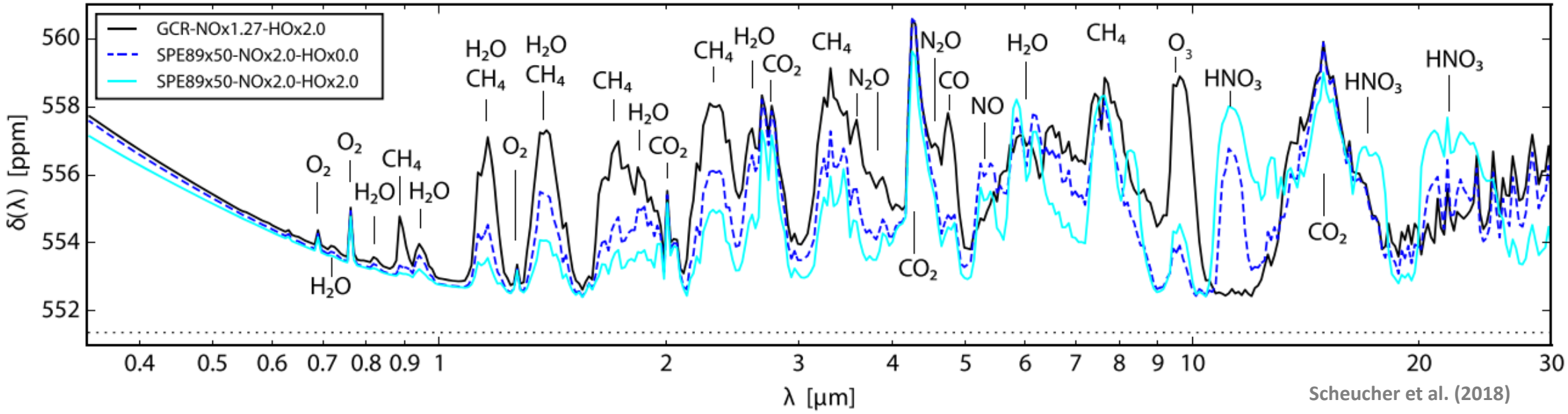
The photochemistry is also affected resulting in a different chemical composition (for the same amount of elements in mass).

The changes are larger the larger the difference of the stellar spectrum to the Sun (in the example of the right, the active M dwarf AD Leo).



Scheucher et al. (2018)

Planetary atmospheres in the Solar System and abroad



Scheucher et al. (2018)

Models must include the influence of cosmic rays and stellar flares if they want to reflect realistically the environment of planets orbiting M dwarfs.

Flares (see blue curves) weaken the role of CH_4 in the heating of the middle atmosphere so that H_2O absorption. Stratospheric O_3 is destroyed by cosmic rays, but smog O_3 can build up in the lower atmosphere (because of the relatively lower UVB flux).

Uncertainties in production rates of NO_x and HO_x still challenge our interpretation of planetary spectra (Scheucher et al. 2018).

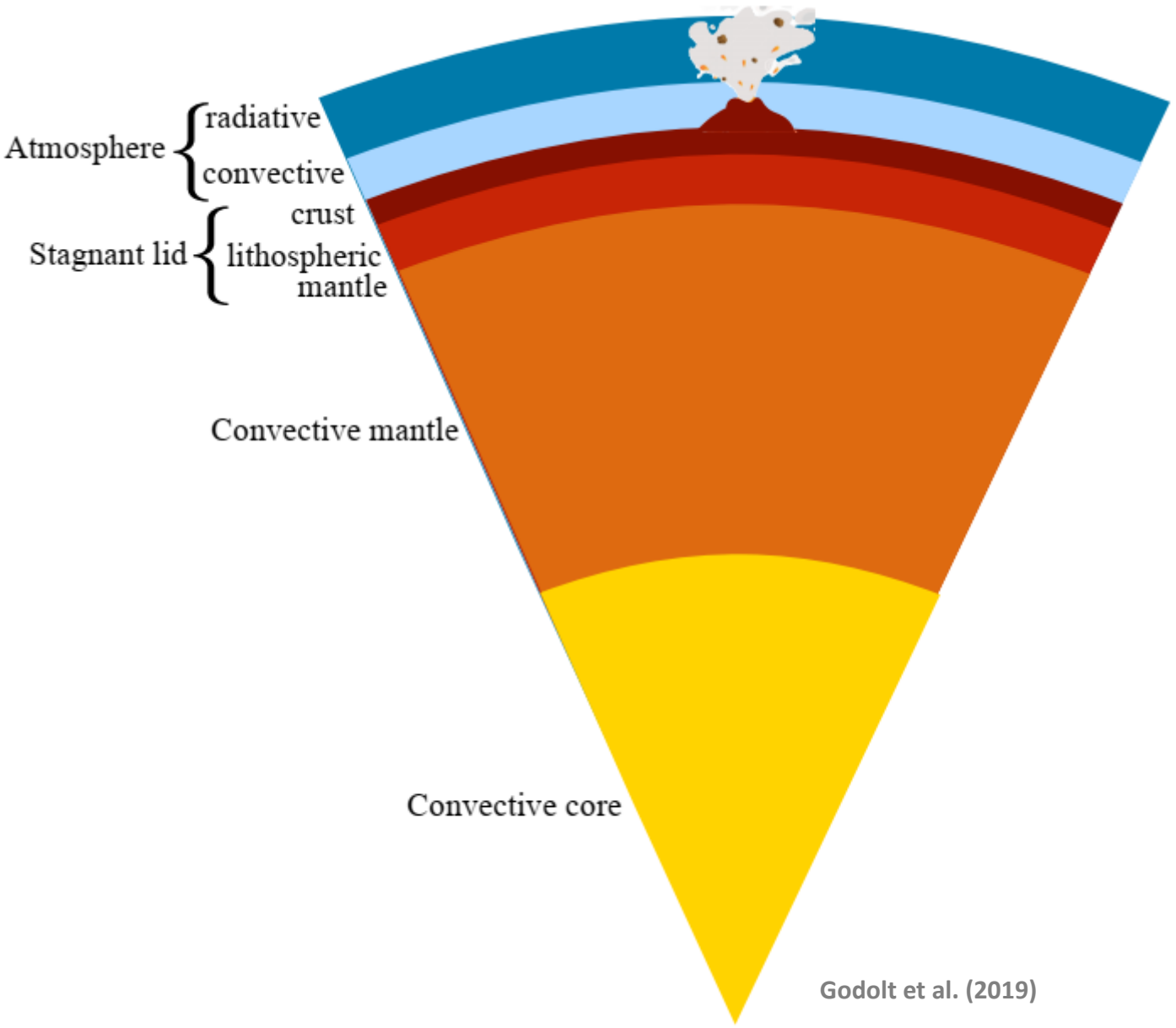
Planetary atmospheres in the Solar System and abroad

For ice and gas giants there is a continuum between the atmosphere and the interior, with all degeneracies that have been mentioned before.

Terrestrial planets have a solid surface, but the atmosphere is still linked to the interior via, e.g. outgassing.

Outgassing can have a significant impact on the atmospheric composition and evolution of a planet (see next slides).

Atmospheres can have a significant impact on the cooling history of the planet and hence on its thermal evolution.



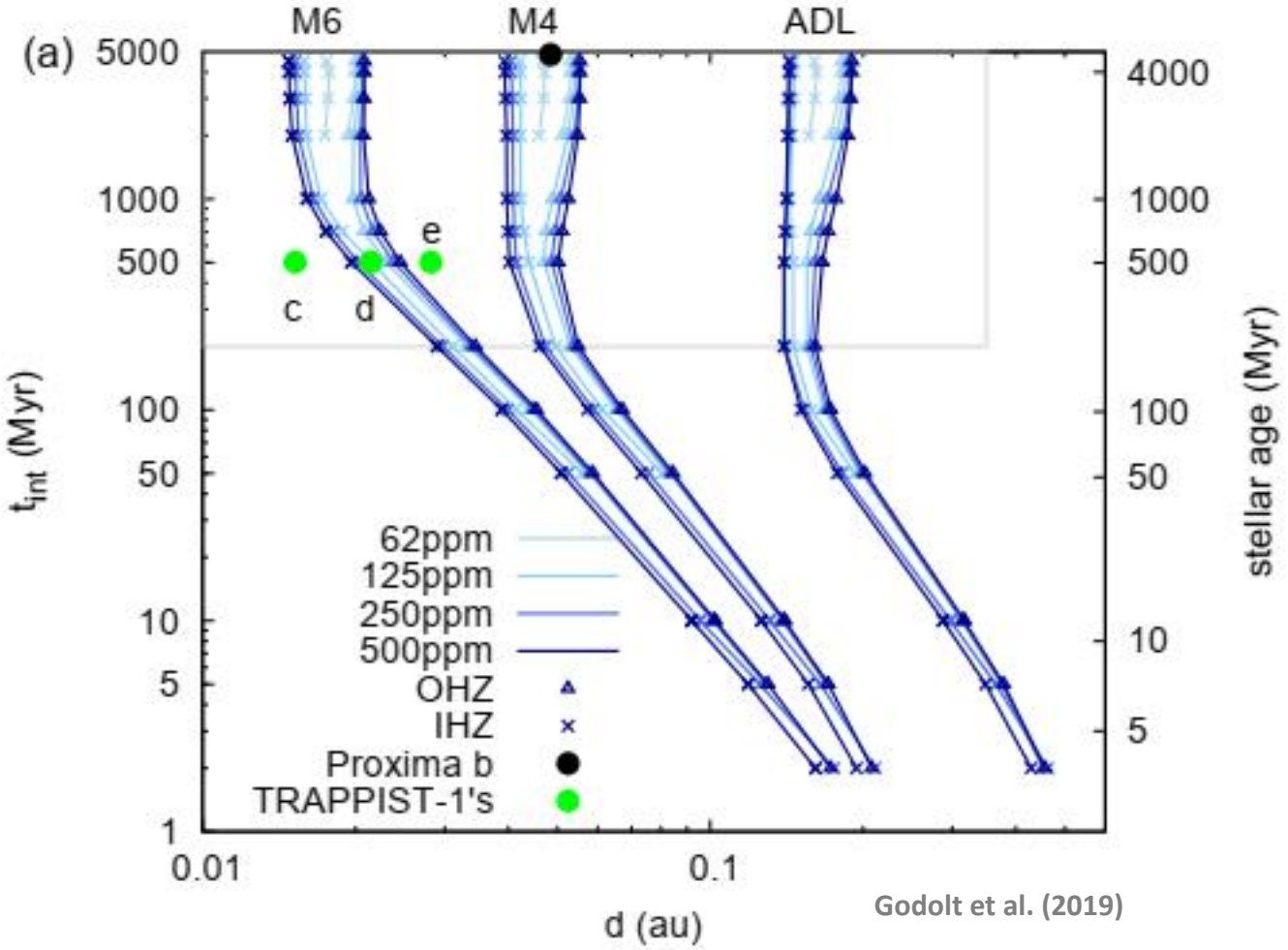
Godolt et al. (2019)

Planetary atmospheres in the Solar System and abroad

M dwarfs can host habitable planets in orbital configurations which are favorable for their remote characterization. However, M dwarfs have increased stellar luminosities and stellar activity phases during the pre-main sequence phase when compared to solar-like stars.

In the past, concerns had been raised that these properties of M dwarfs could compromise the long-term survival of liquid water on planetary surfaces, making those planets actually inhabitable.

Godolt et al. (2019) showed for the first time that outgassing from the interior can rebuild a water reservoir large enough to allow for habitable surface conditions at a later evolutionary stage, which is a very promising result for the understanding of habitability conditions on these systems.



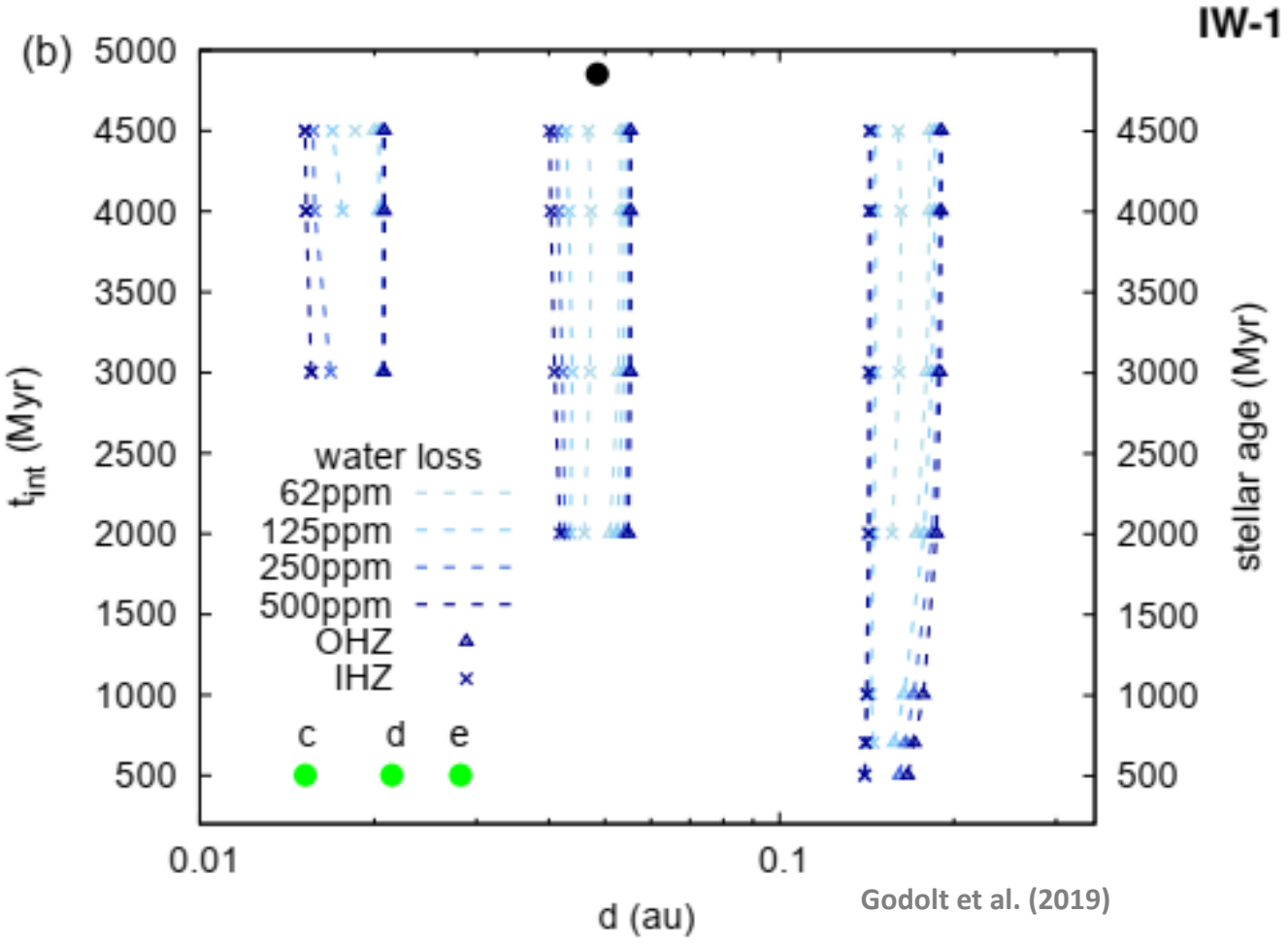
Godolt et al. (2019)

Planetary atmospheres in the Solar System and abroad

M dwarfs can host habitable planets in orbital configurations which are favorable for their remote characterization. However, M dwarfs have increased stellar luminosities and stellar activity phases during the pre-main sequence phase when compared to solar-like stars.

In the past, concerns had been raised that these properties of M dwarfs could compromise the long-term survival of liquid water on planetary surfaces, making those planets actually inhabitable.

Godolt et al. (2019) showed for the first time that outgassing from the interior can rebuild a water reservoir large enough to allow for habitable surface conditions at a later evolutionary stage, which is a very promising result for the understanding of habitability conditions on these systems.



Godolt et al. (2019)

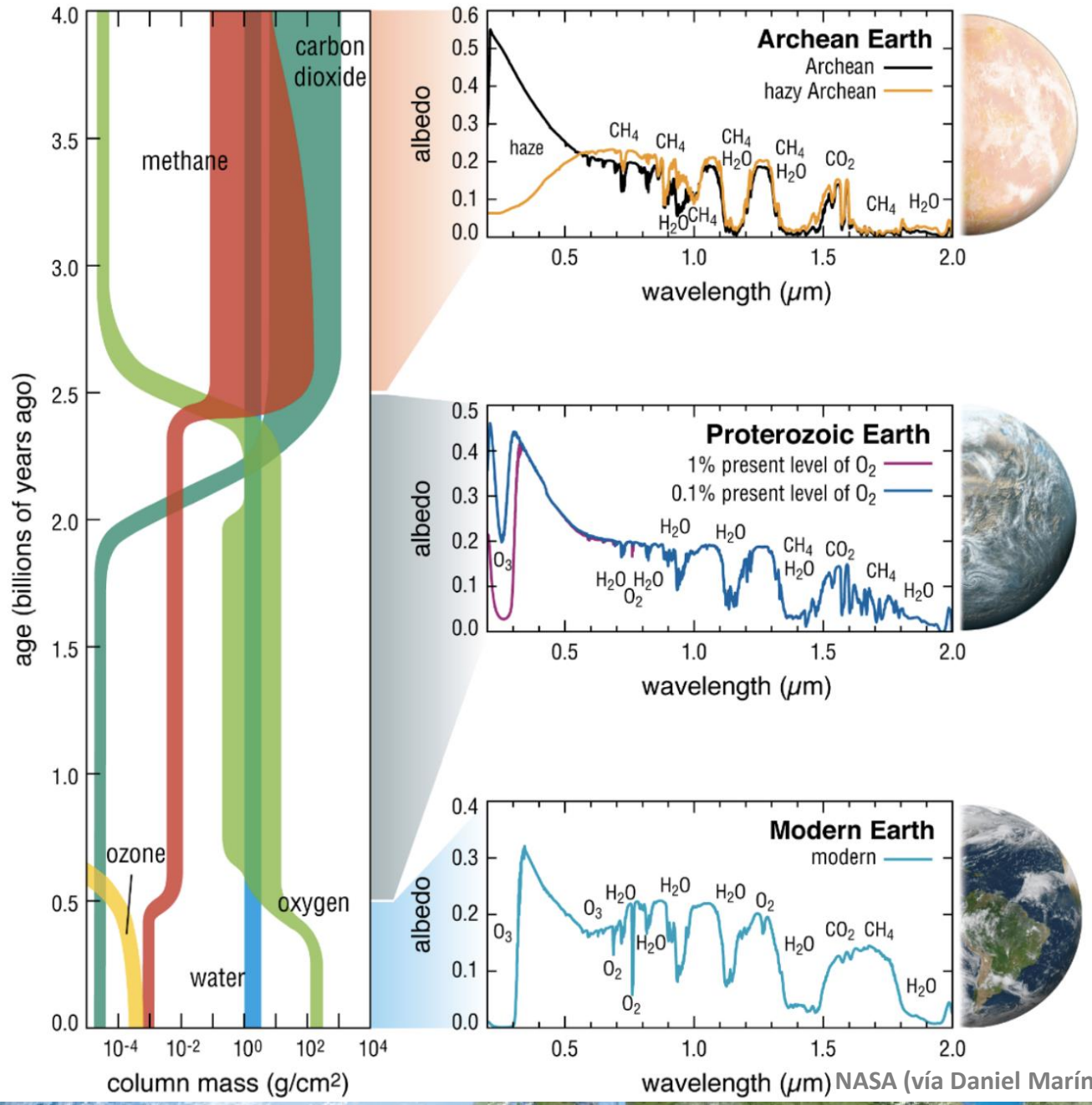
Planetary atmospheres in the Solar System and abroad

It is also relevant to study the properties of Earth's atmosphere in time.

The composition of Earth's atmosphere has changed dramatically since the formation of the planet.

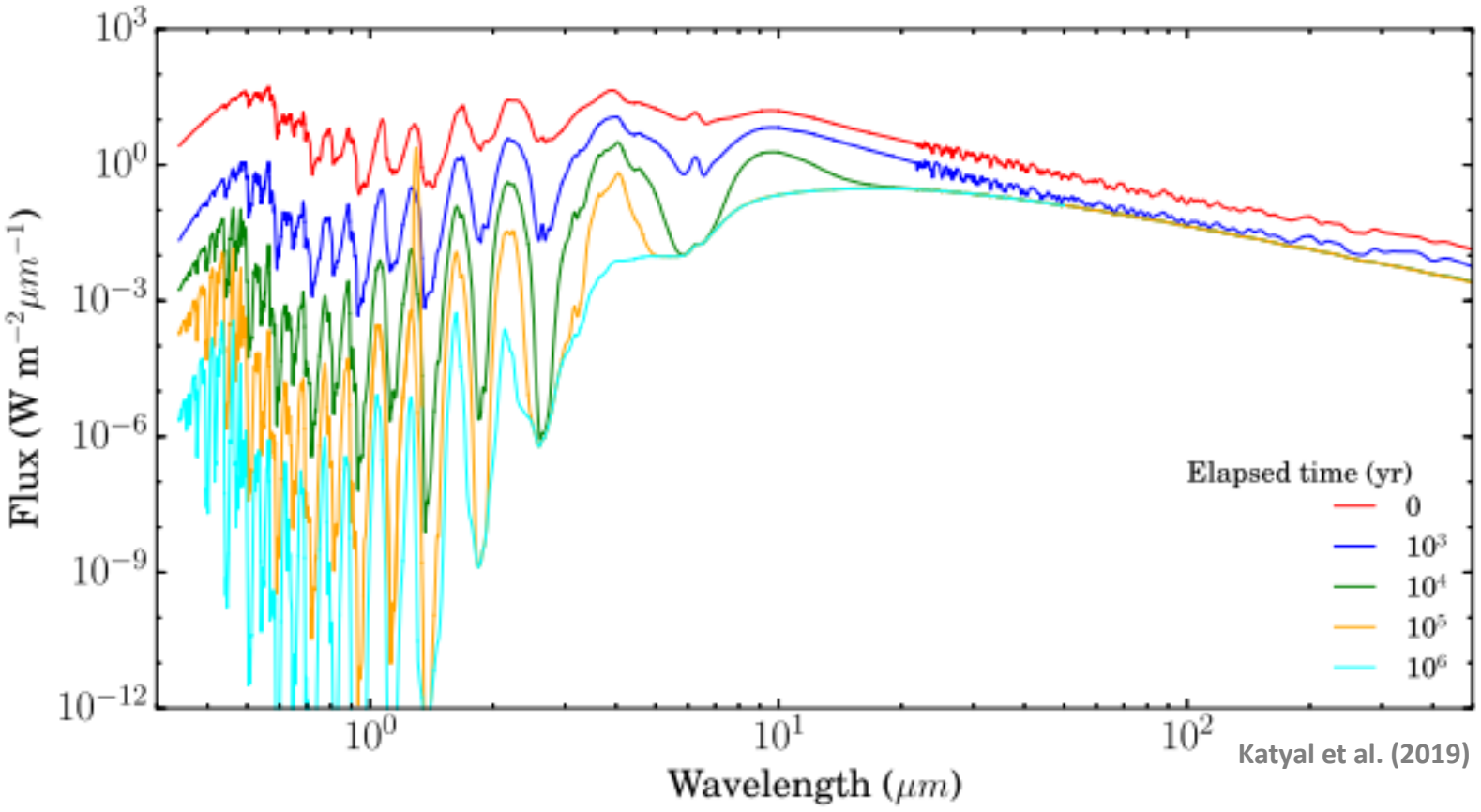
These changes are reflected on the spectral signature of the planet.

Different planetary processes are dominant at different epochs (outgassing, emergence of life...).



NASA (vía Daniel Marín)

Planetary atmospheres in the Solar System and abroad



Katyal et al. (2019)

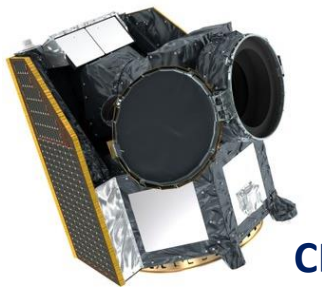
At the very early stages of Earth's history (hadean) there was a magma ocean on the surface of the planet.

The magma ocean was covered by a steam atmosphere (i.e. no liquid water on the surface, but significant amounts of water on the atmosphere).

The atmosphere regulates the energy balance of the planet with water being quantitatively a key molecule for the process.

Our model (see left) studies consistently the surface and interior (outgassing) conditions together with the atmosphere and key atmospheric processes (like photochemistry) to put observational constraints on magma ocean phases on extrasolar planets.

Next steps for planet characterization



CHEOPS

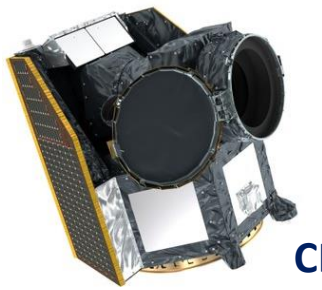
Understanding planetary formation and evolution starts by knowing what are planets made of. This requires the **precise characterization of the bulk properties of known planetary systems**.

But understanding evolution requires observing planets with different ages, and ages are poorly constrained for field stars. Additionally, planetary parameters are as accurate as the parameters of the host star. The breakthrough method to obtain ages and accurate stellar parameters is **asteroseismology**. Understanding planetary evolution, for **planets down to the size of the Earth, orbiting stars like the Sun, with orbital periods up to 1 year**, requires precisely measuring how planetary mass and radius vary with orbital distance (and system architecture) and stellar properties (spectral type, metallicity, age).

The detailed characterization of **atmospheres** will further constrain the evolutionary paths of planets.

Finally we might be able to characterize the atmospheres of **terrestrial habitable planets**.

Next steps for planet characterization



CHEOPS

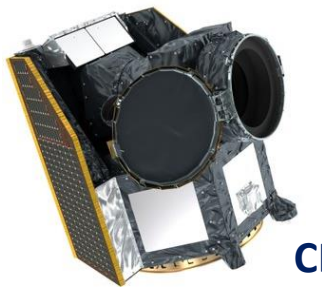
Understanding planetary formation and evolution starts by knowing what are planets made of. This requires the **precise characterization of the bulk properties of known planetary systems**.

But understanding evolution requires observing planets with different ages, and ages are poorly constrained for field stars. Additionally, planetary parameters are as accurate as the parameters of the host star. The breakthrough method to obtain ages and accurate stellar parameters is **asteroseismology**. Understanding planetary evolution, for **planets down to the size of the Earth, orbiting stars like the Sun, with orbital periods up to 1 year**, requires precisely measuring how planetary mass and radius vary with orbital distance (and system architecture) and stellar properties (spectral type, metallicity, age).

The detailed characterization of **atmospheres** will further constrain the evolutionary paths of planets.

Finally we might be able to characterize the atmospheres of **terrestrial habitable planets**.

Next steps for planet characterization

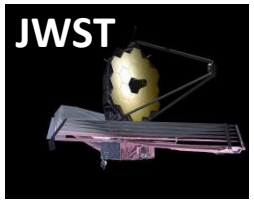


CHEOPS

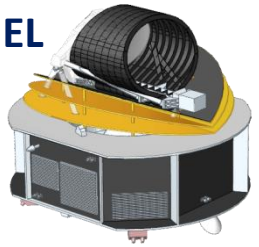
Understanding planetary formation and evolution starts by knowing what are planets made of. This requires the **precise characterization of the bulk properties of known planetary systems**.

But understanding evolution requires observing planets with different ages, and ages are poorly constrained for field stars. Additionally, planetary parameters are as accurate as the parameters of the host star. The breakthrough method to obtain ages and accurate stellar parameters is **asteroseismology**. Understanding planetary evolution, for **planets down to the size of the Earth, orbiting stars like the Sun, with orbital periods up to 1 year**, requires precisely measuring how planetary mass and radius vary with orbital distance (and system architecture) and stellar properties (spectral type, metallicity, age).

The detailed characterization of **atmospheres** will further constrain the evolutionary paths of planets.

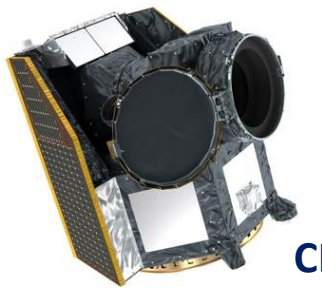


ARIEL



Finally we might be able to characterize the atmospheres of **terrestrial habitable planets**.

Next steps for planet characterization



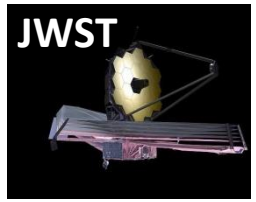
CHEOPS

Understanding planetary formation and evolution starts by knowing what are planets made of. This requires the **precise characterization of the bulk properties of known planetary systems**.

But understanding evolution requires observing planets with different ages, and ages are poorly constrained for field stars. Additionally, planetary parameters are as accurate as the parameters of the host star. The breakthrough method to obtain ages and accurate stellar parameters is **asteroseismology**. Understanding planetary evolution, for **planets down to the size of the Earth, orbiting stars like the Sun, with orbital periods up to 1 year**, requires precisely measuring how planetary mass and radius vary with orbital distance (and system architecture) and stellar properties (spectral type, metallicity, age).

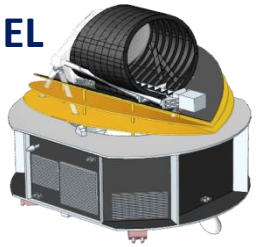
The detailed characterization of **atmospheres** will further constrain the evolutionary paths of planets.

Finally we might be able to characterize the atmospheres of **terrestrial habitable planets**.



JWST

ARIEL



LIFE

HabEx

LUVOIR