Chemical Abundances of Stars and Their Impact on the Interior Structure of Rocky Planets

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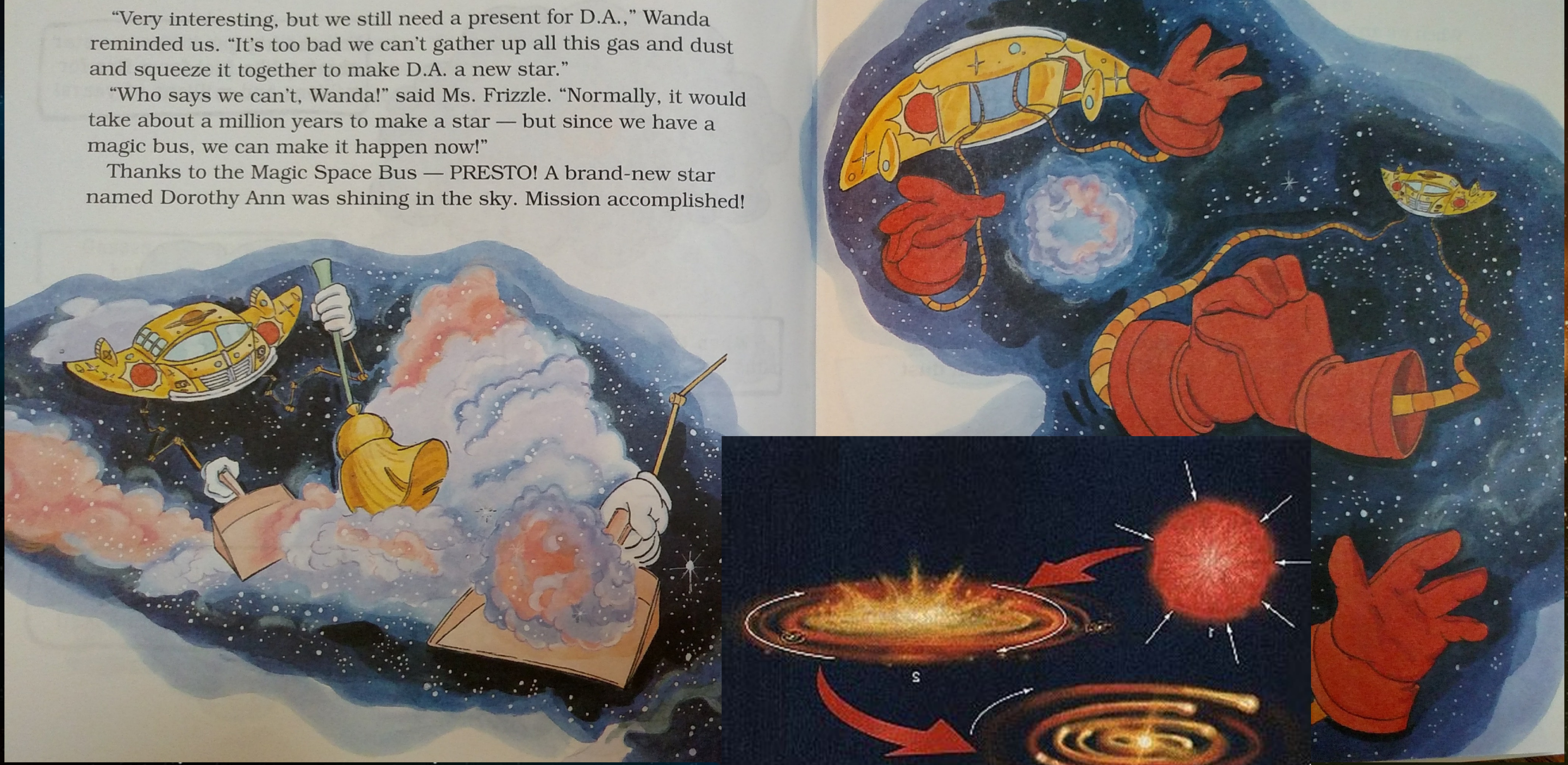
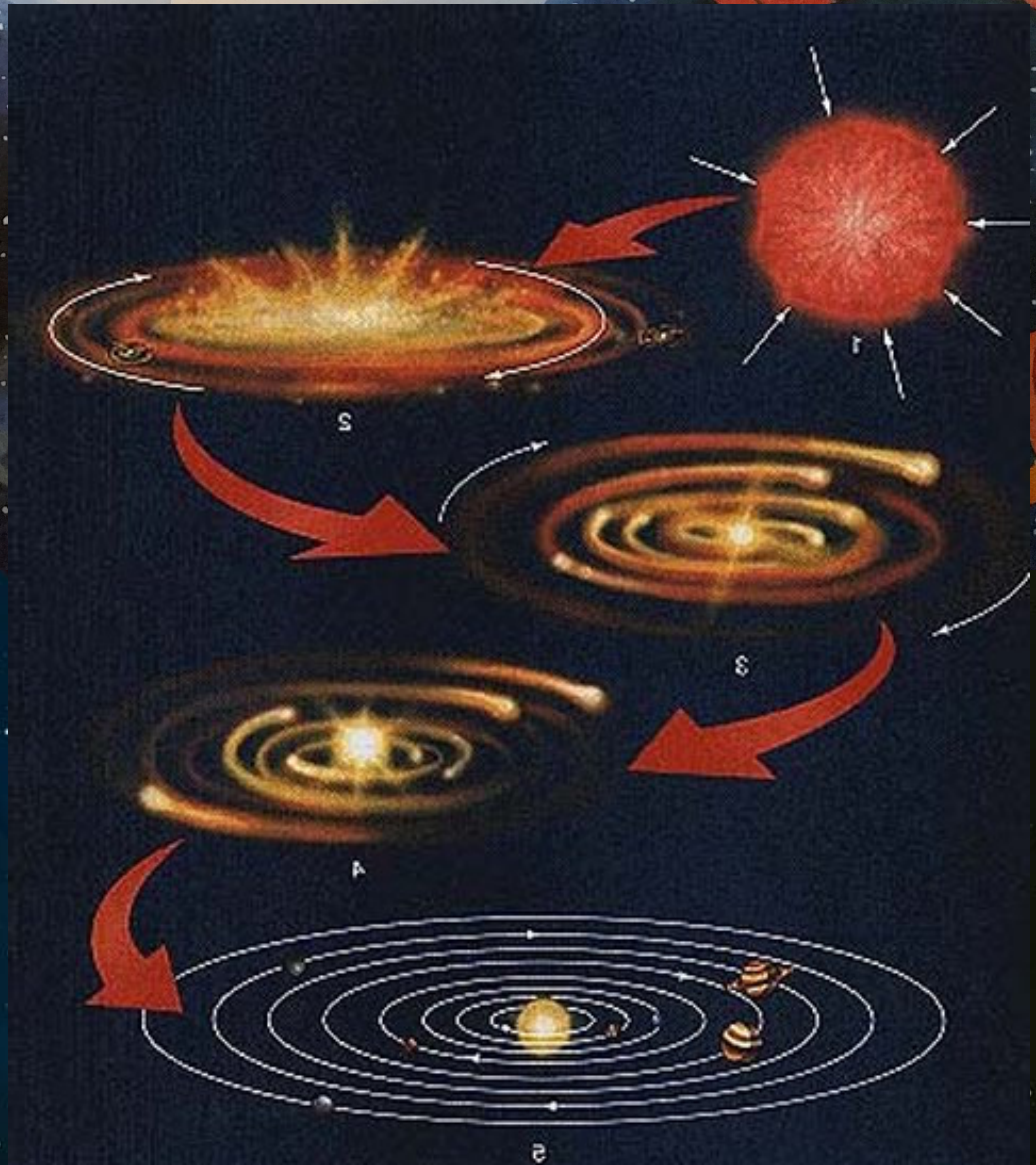


"Very interesting, but we still need a present for D.A.," Wanda reminded us. "It's too bad we can't gather up all this gas and dust and squeeze it together to make D.A. a new star."

"Who says we can't, Wanda!" said Ms. Frizzle. "Normally, it would take about a million years to make a star — but since we have a magic bus, we can make it happen now!"

Thanks to the Magic Space Bus — PRESTO! A brand-new star named Dorothy Ann was shining in the sky. Mission accomplished!



Since stars and planets are formed at the same time… and because there is no other way of assessing planet composition…

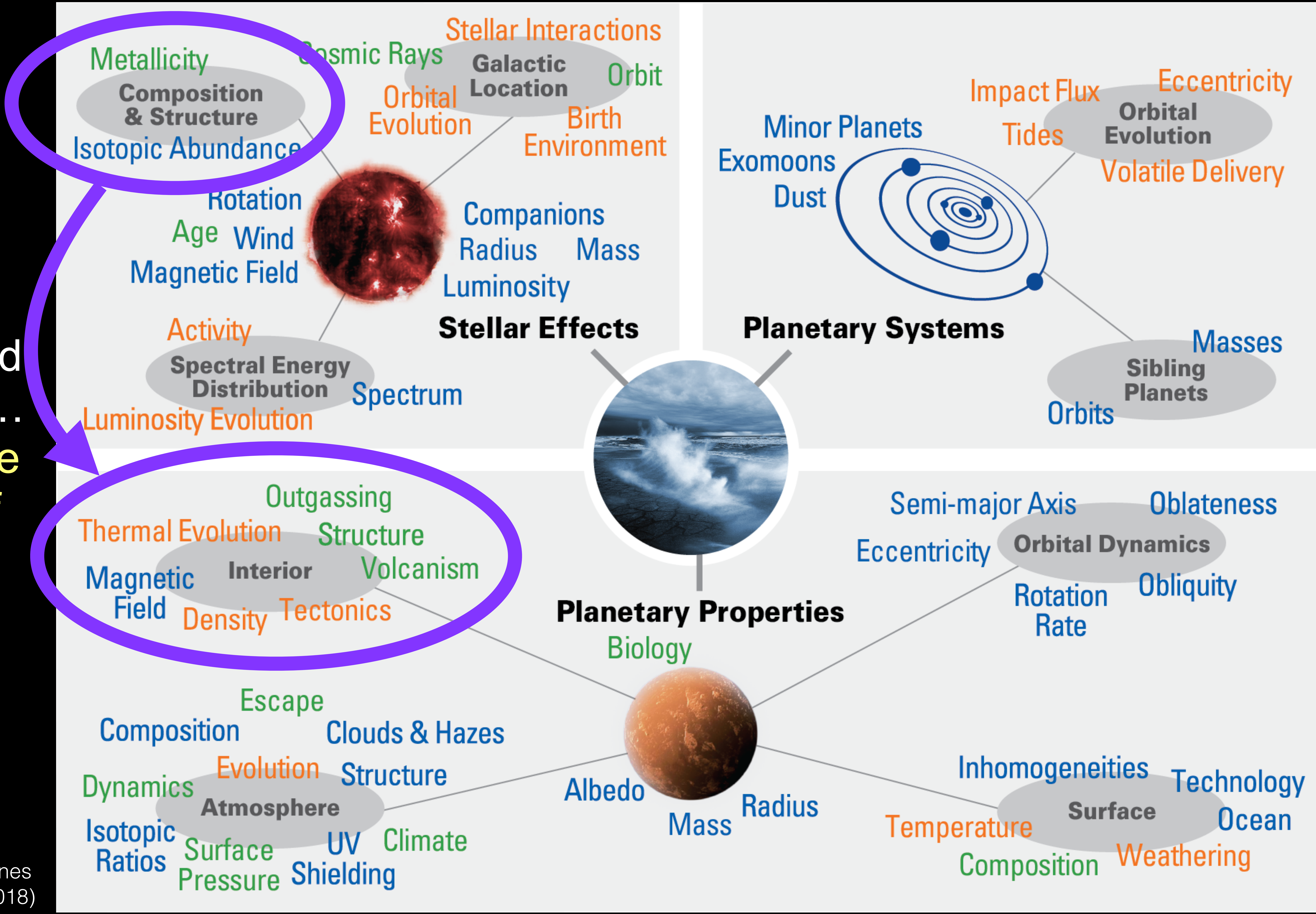
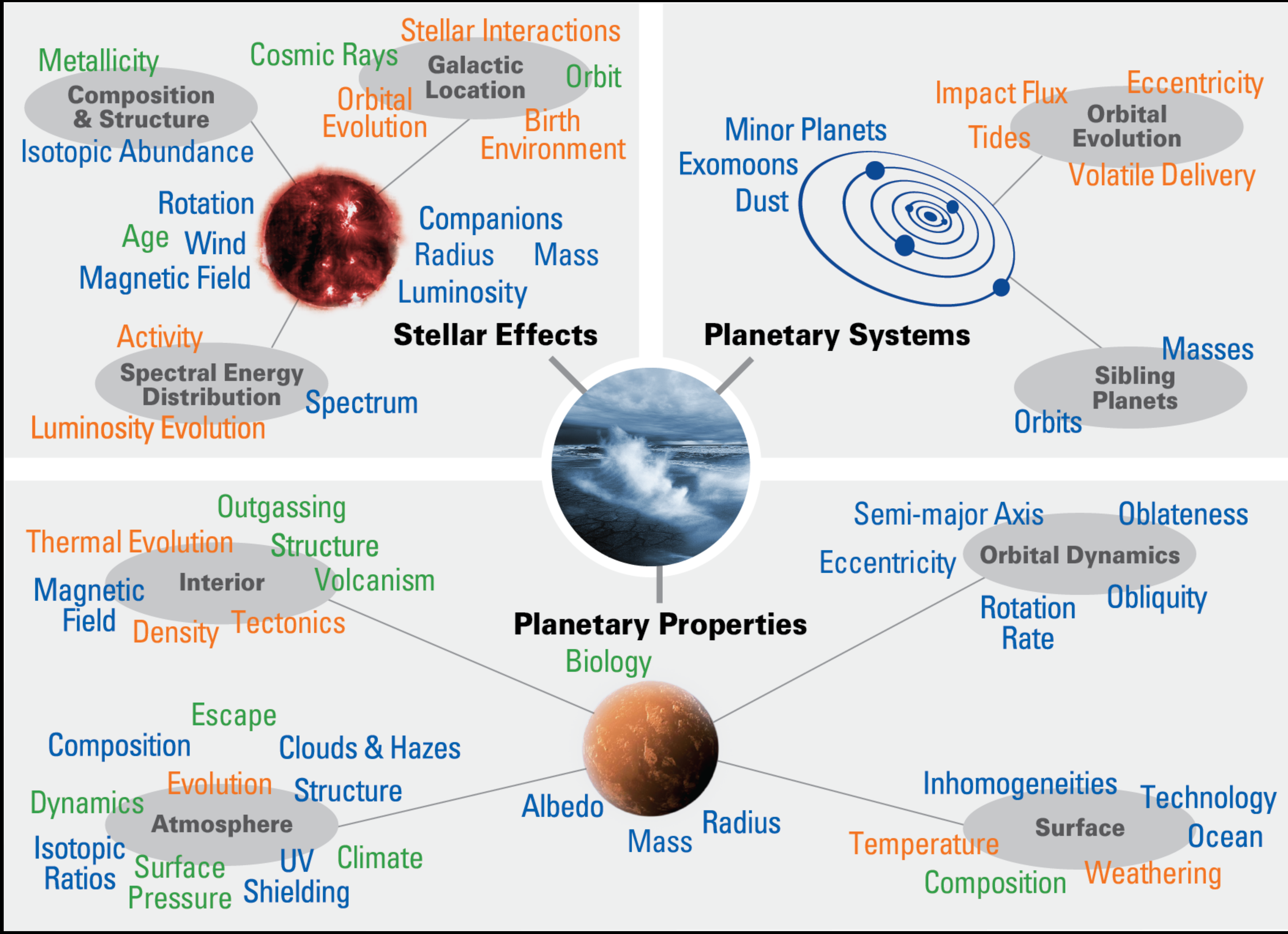


Image per Barnes & Meadows (2018)

It is NOT enough to say a planet is in the HZ, has ~1 M_E or ~1R_E, or has O_2 in the atmosphere.

All of these properties are vital to overall planet habitability.



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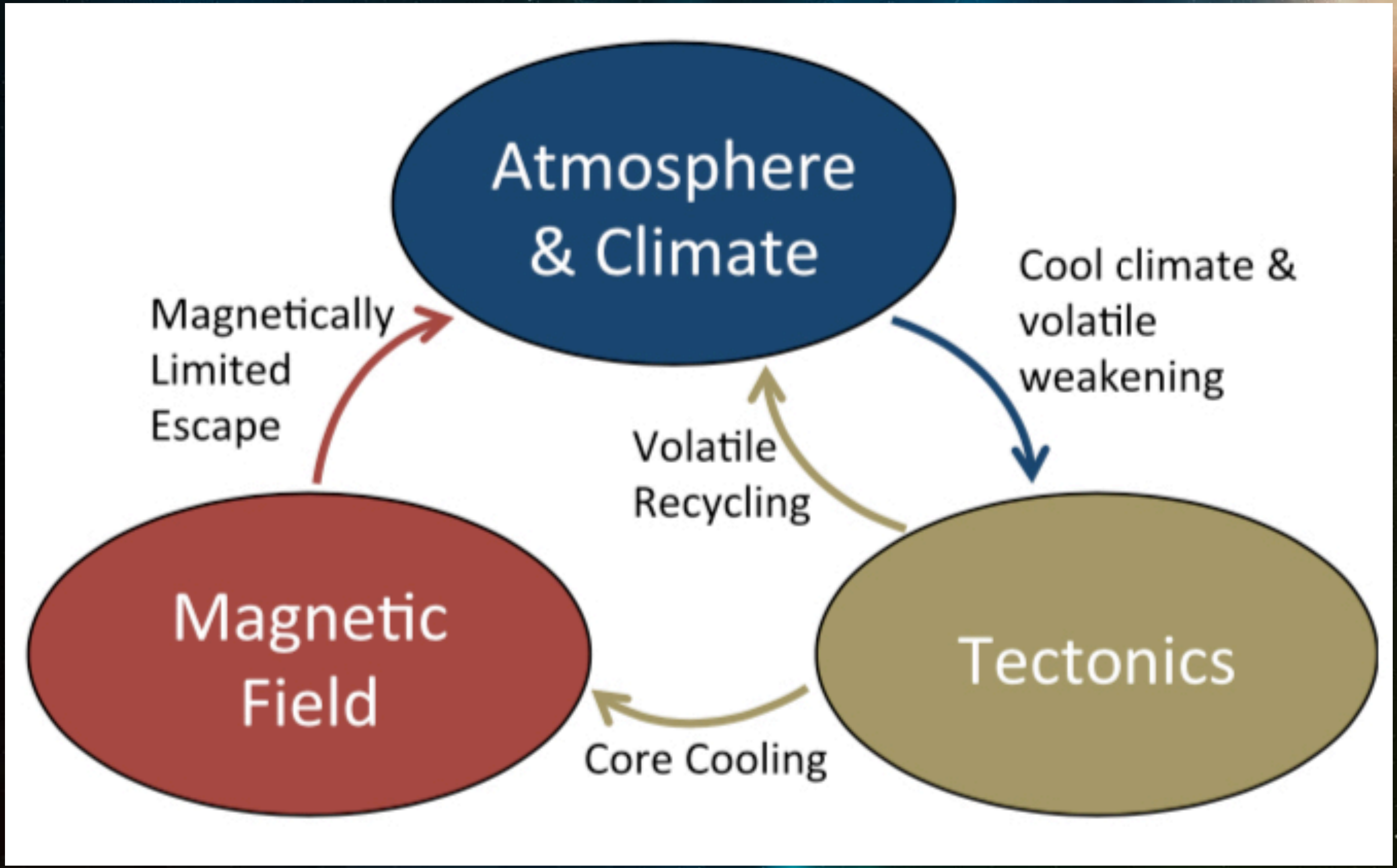
Planets Need to Be Alive

The climate, mantle, and core are coupled to one another on rocky planets.

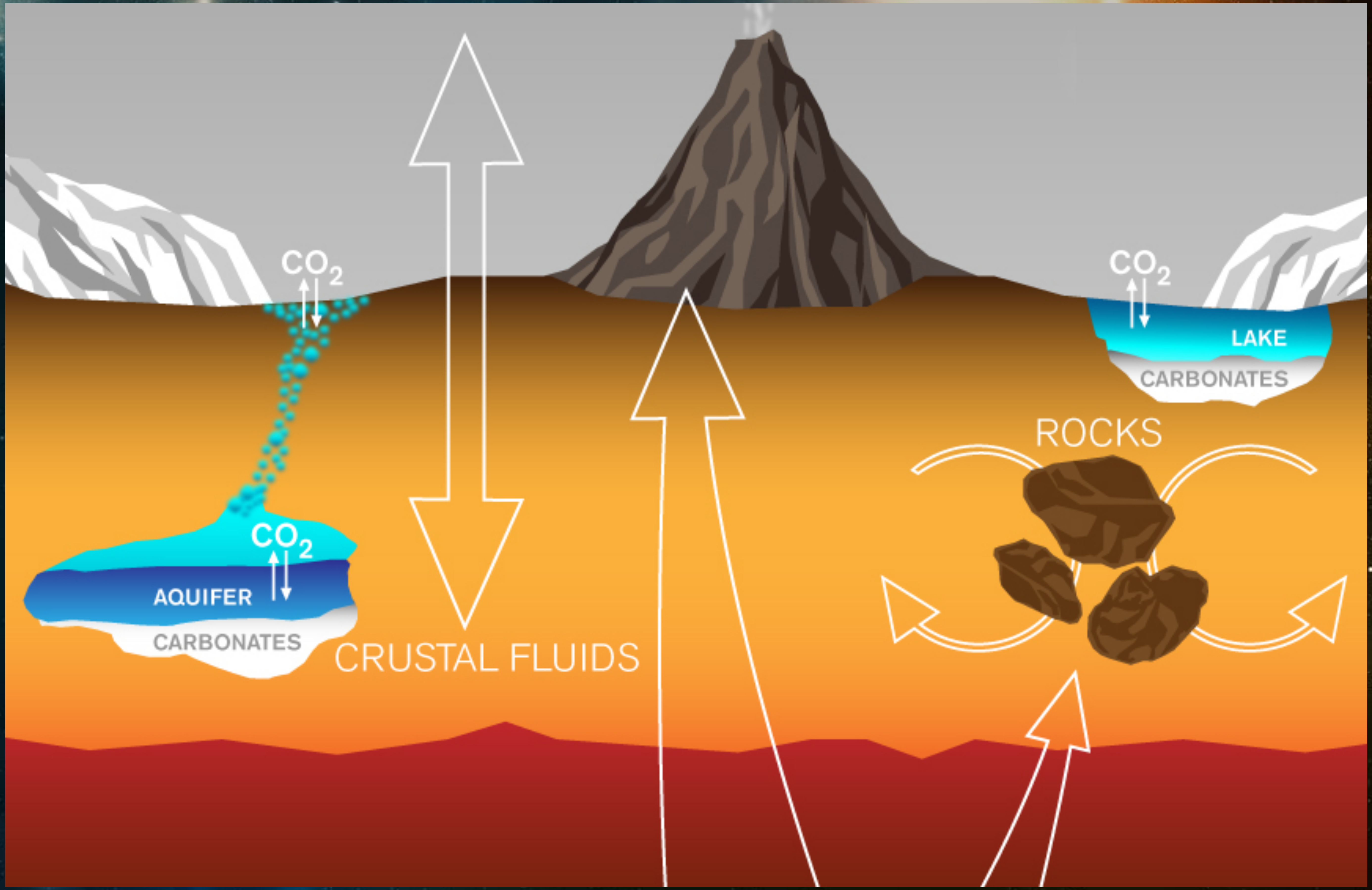


Foley & Driscoll (2016)

Planetary Interiors & Atmospheres

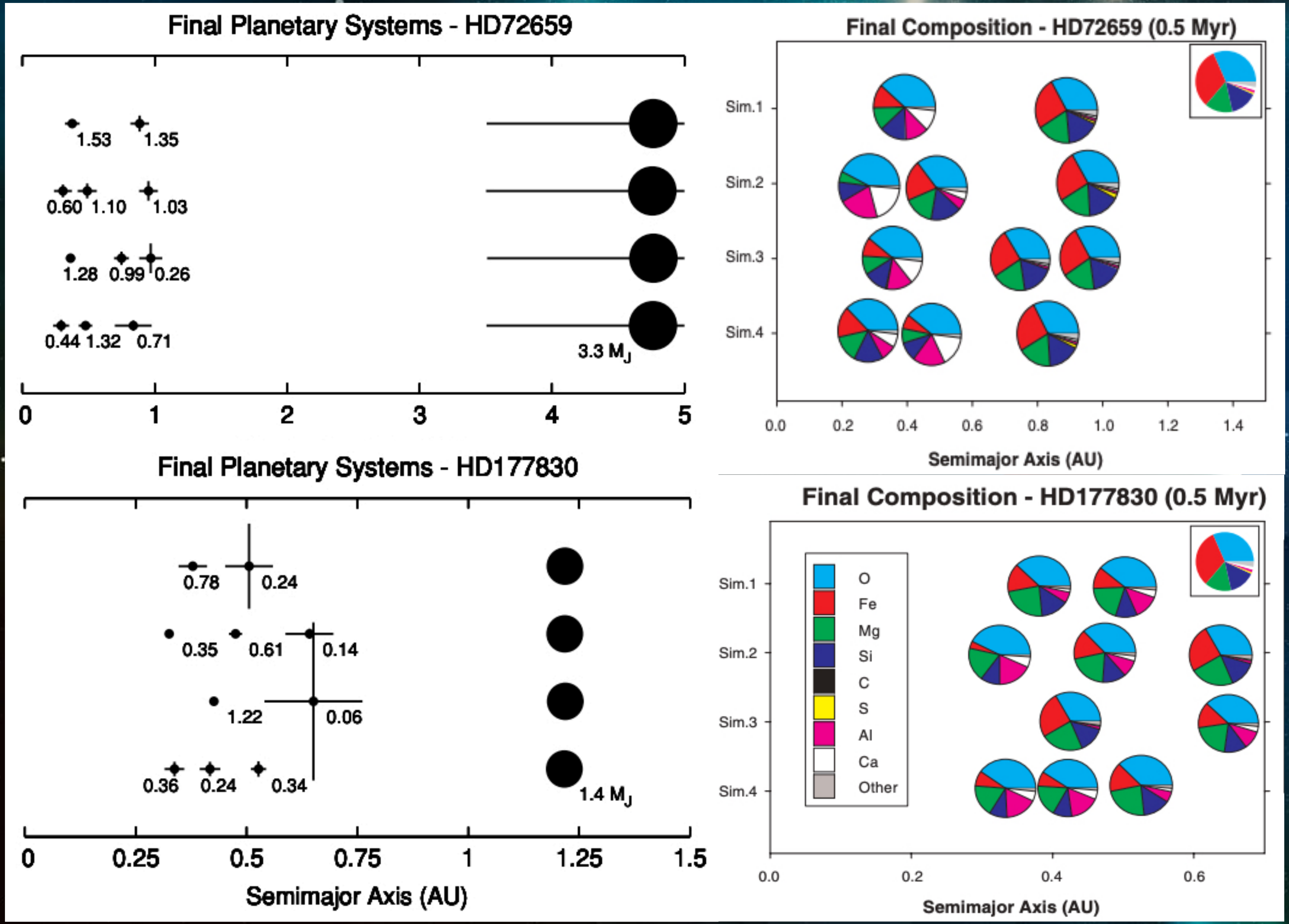
Planets must have active geochemical cycles in order to create a large biome for life to start and take hold.

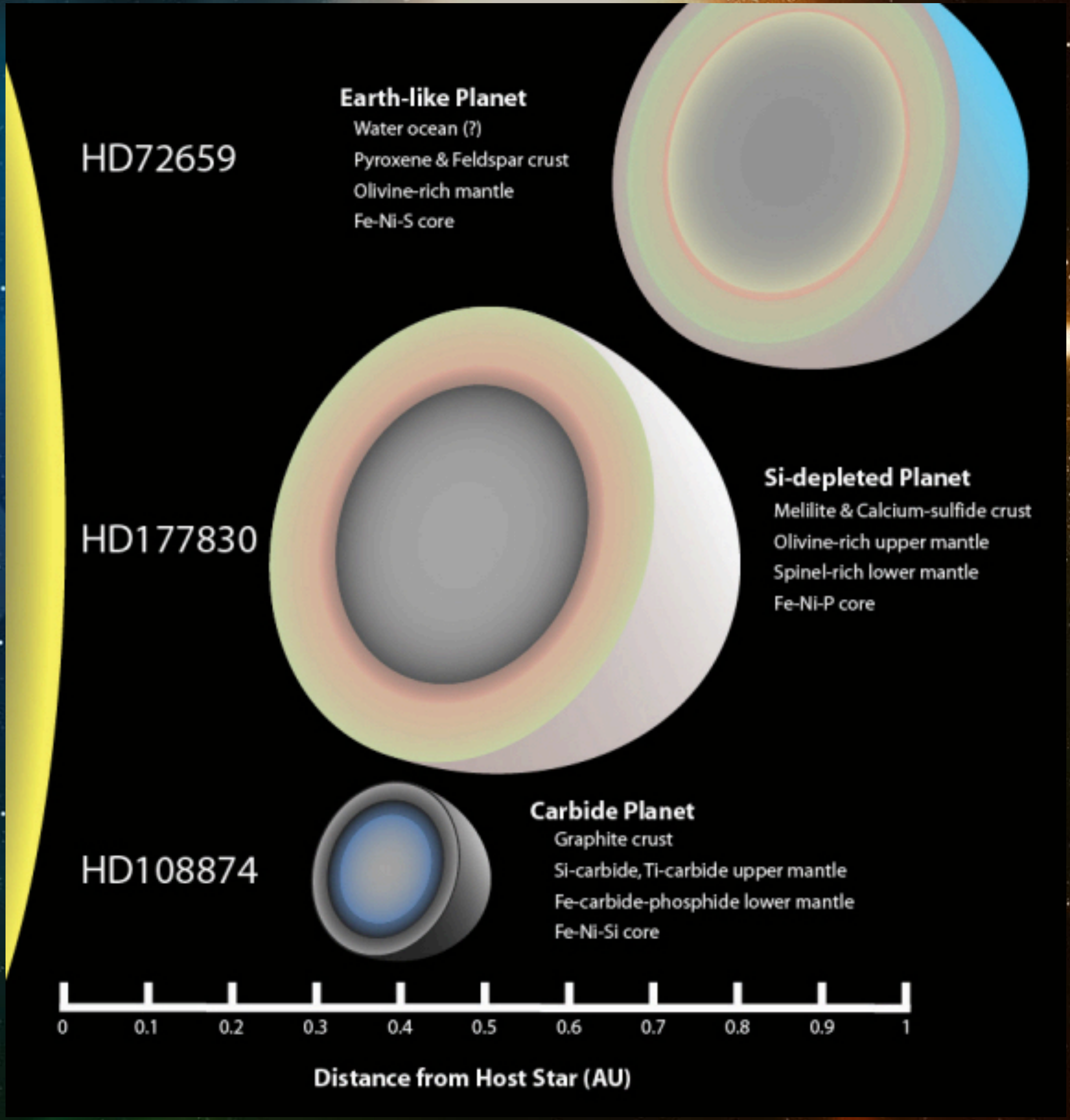
The geochemical processes on the planet can be observed in the composition of the atmosphere for rocky planets, along with bio-signatures. But we need to use the host star composition to understand the interior of rocky exoplanets.



Ahead of Its Time: The Compositional Diversity of Exoplanets

Bond et al. (2010), Delgado Mena et al. (2010)





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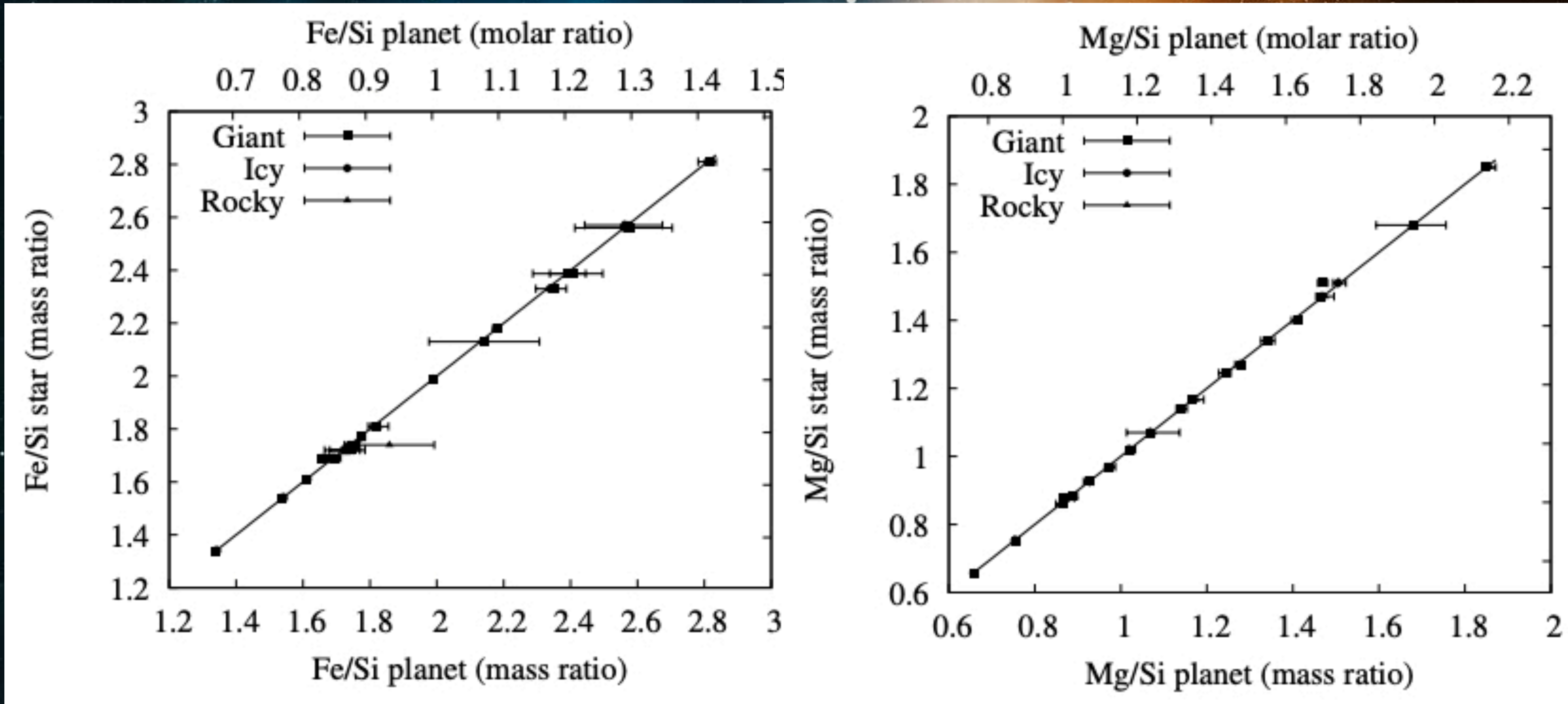
Modeling the Chemical Link Between Stars and Planets

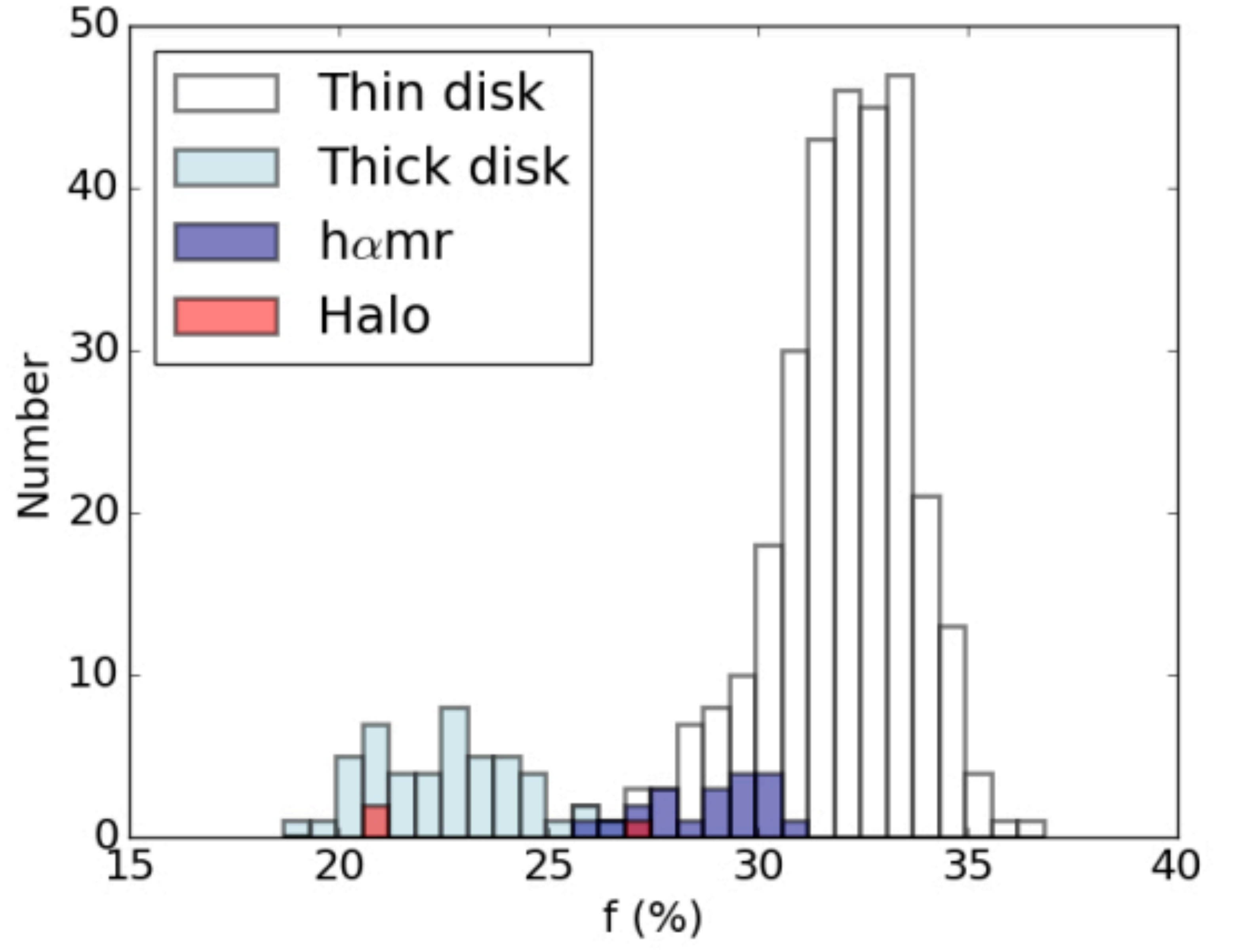
Thiabaud, Marboeuf, Alibert, et al. (2015)

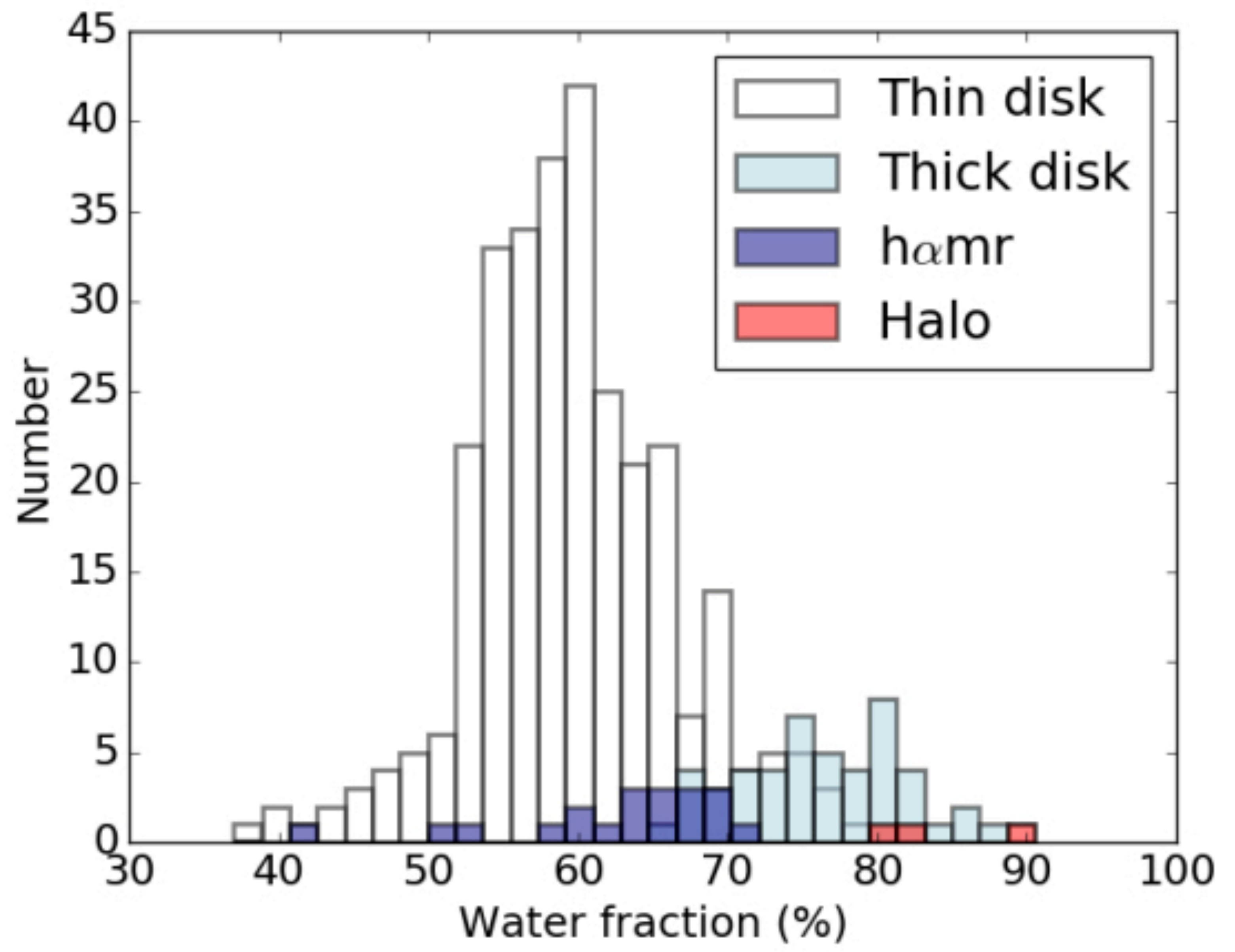
- They quantified the abundance of Mg, Si, and Fe incorporated into 18 planetary systems using different compositions for the stellar nebulae.
- The Fe/Si, Mg/Si, and C/O ratios were derived for rocky, gas giant, and icy planets.
- The planetary ratios were compared to the corresponding stellar abundances and found to correlate along a 1:1 relationship.



Comparing the Iron Mass Fraction of Stars and Planets

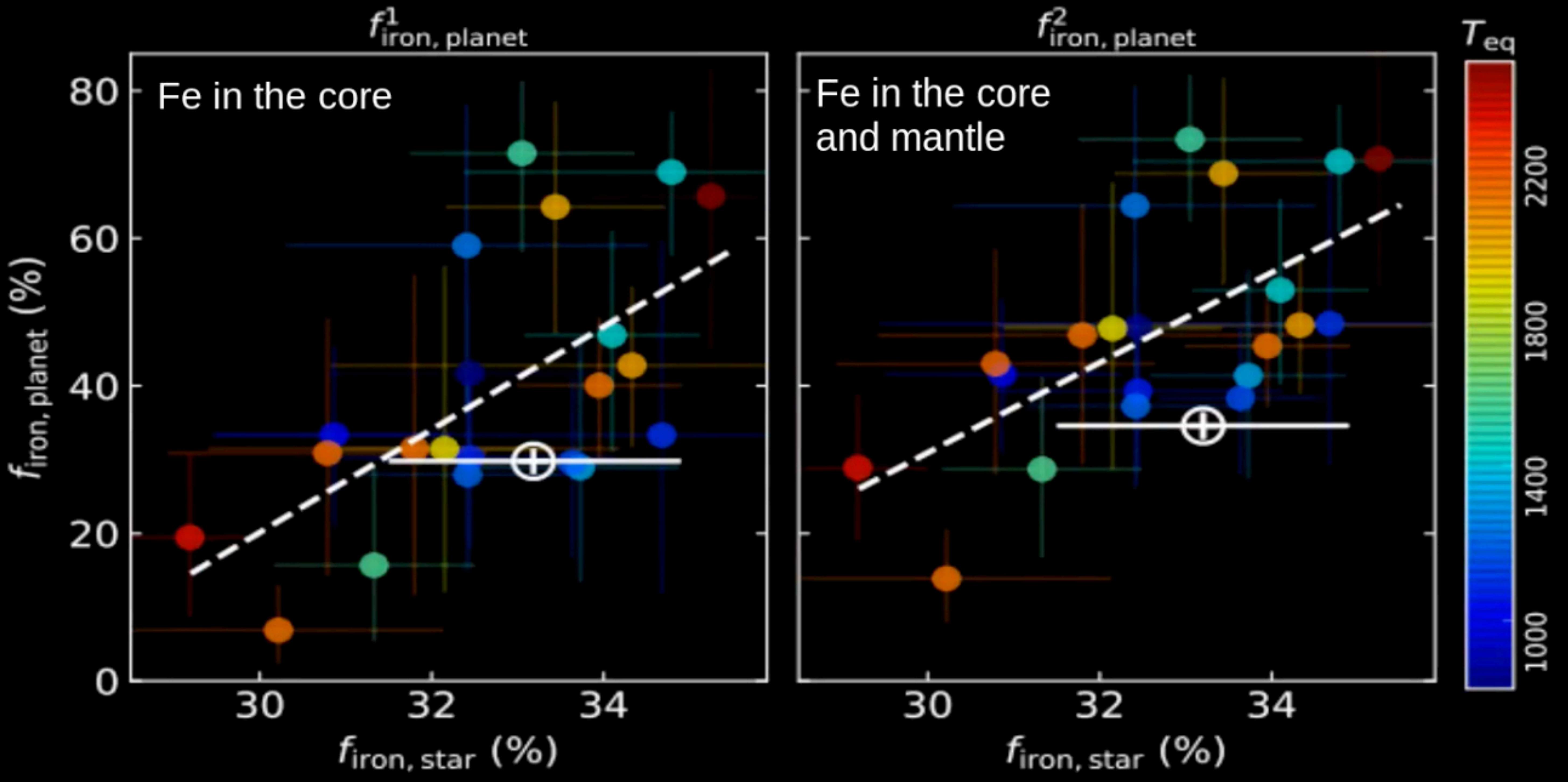
Santos et al. (2015, 2017); Adibekyan et al. (2021)





The correlation is not one-to-one: $f_{\text{iron,planet}}$ is larger than $f_{\text{iron,star}}$!

(planets formed close to rocklines can have an increased proportion of iron – Aguichine et al. 2020)



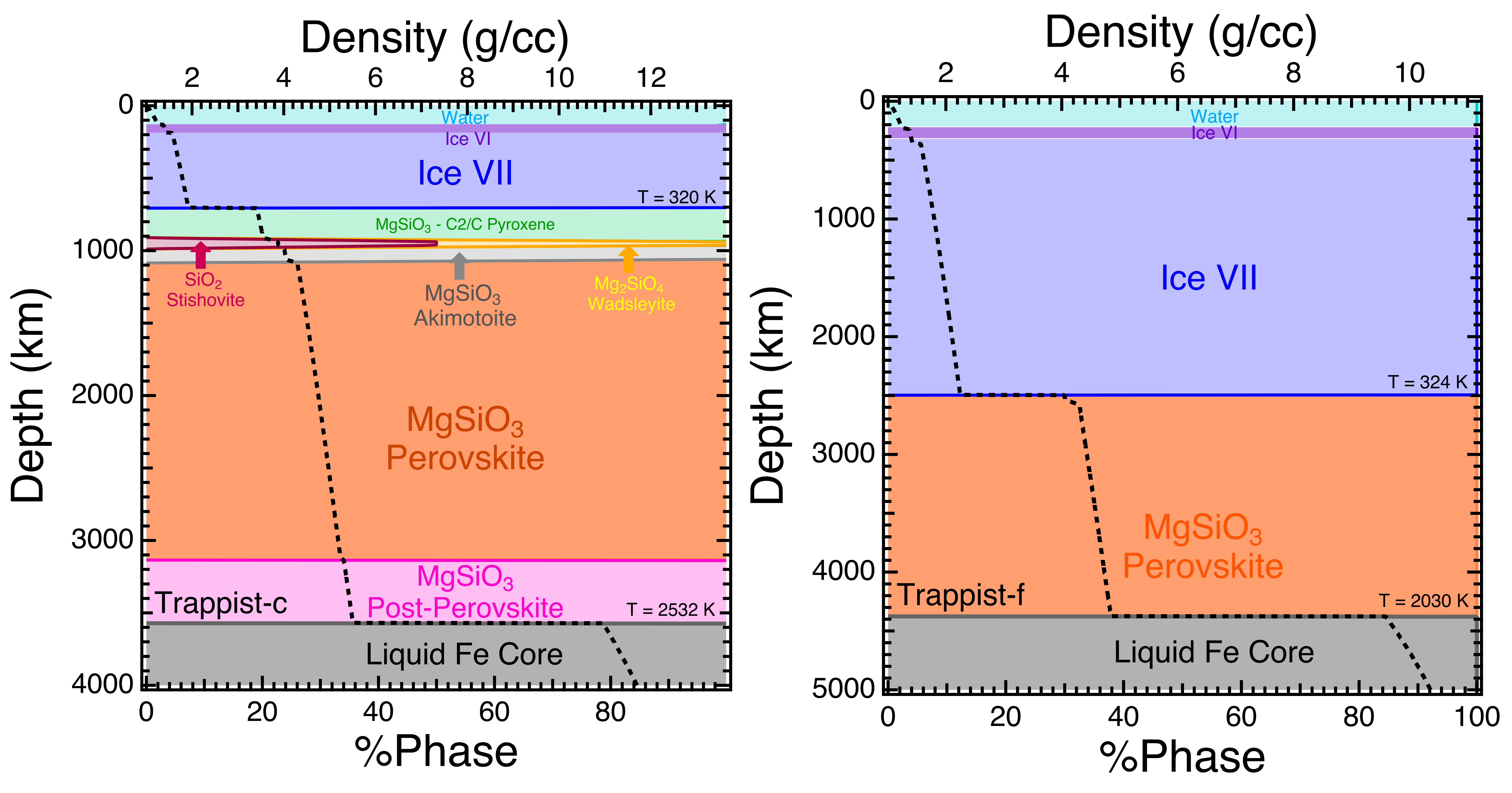
TRAPPIST-1

Unterborn, Desch, Hinkel, Lorenzo (2018)

From their measured mass and volume, all of the planets are very light. But they are also too small for enough gas to explain it = water.

TRAPPIST-1

Unterborn, Desch, Hinkel, Lorenzo (2018)

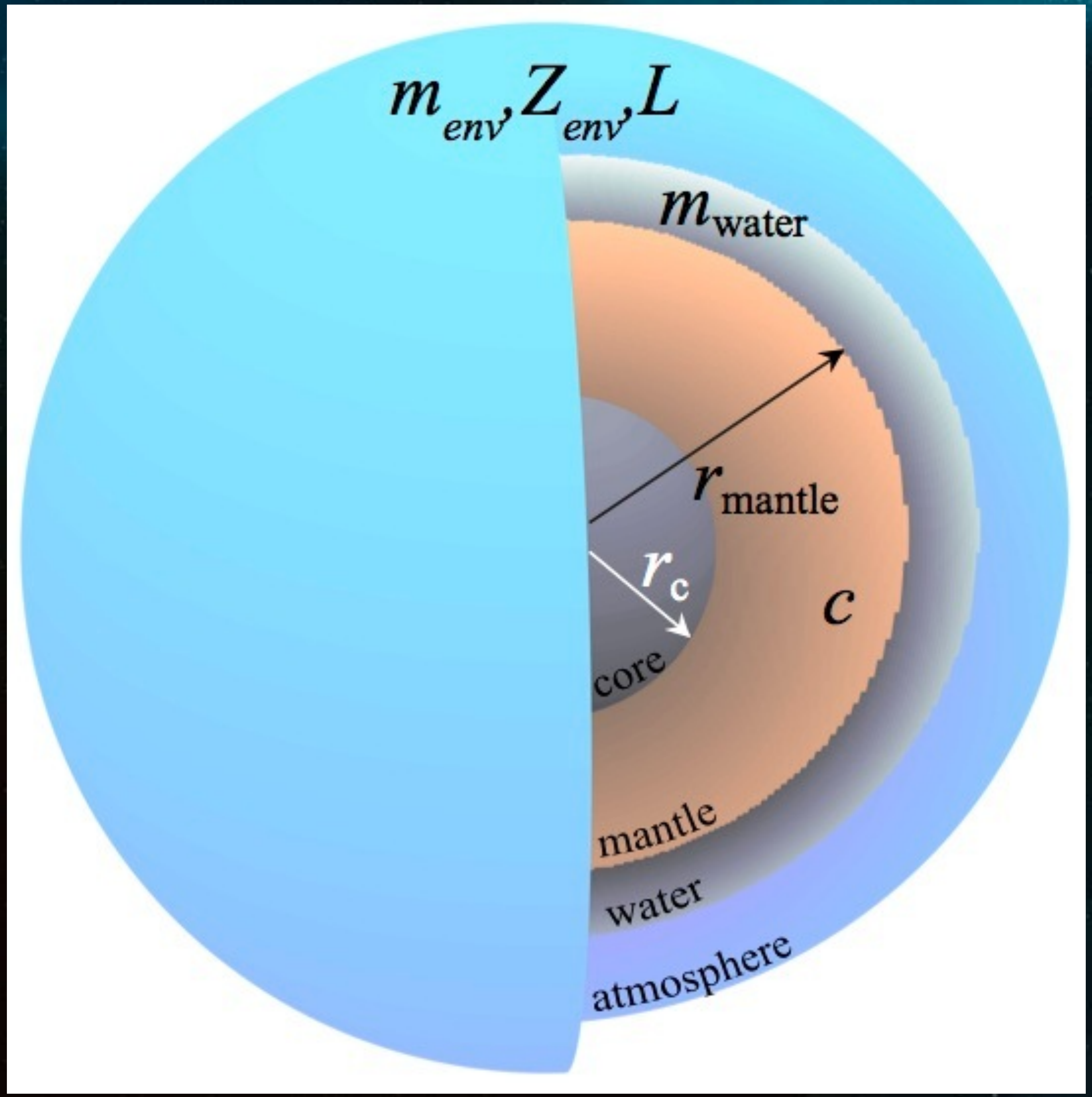


TRAPPIST-1c 8wt% water TRAPPIST-1f 50wt% water

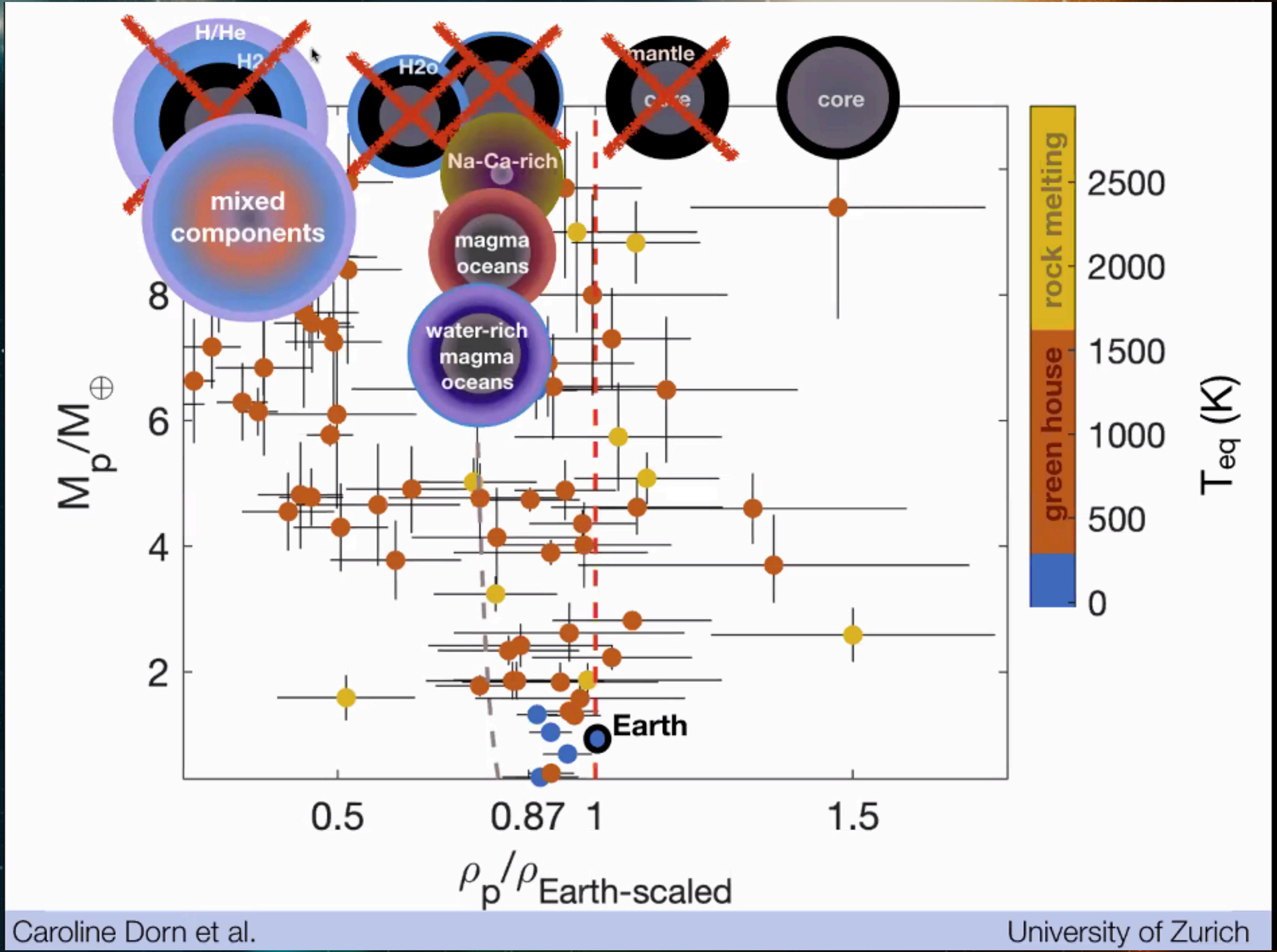
Earth is 0.02wt% water!

Bayesian Analysis of Interiors Using Stellar Abundance Proxies

Dorn et al. (2017a, b); Dorn et al. (2018); Ligi et al. (2019); Otegi et al. (2021)



Na_2O–CaO–FeO–MgO–Al_2O_3–SiO_2



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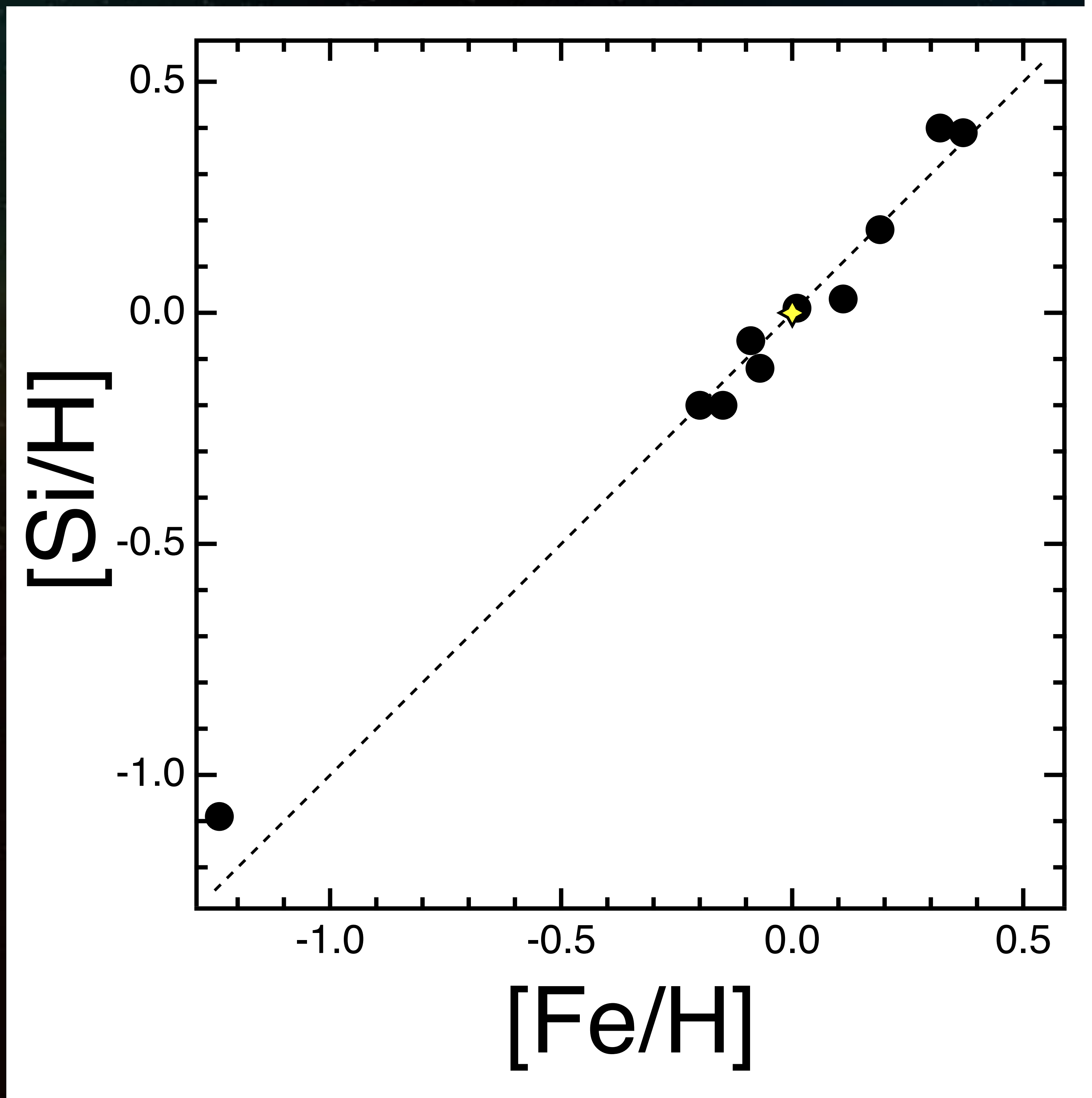
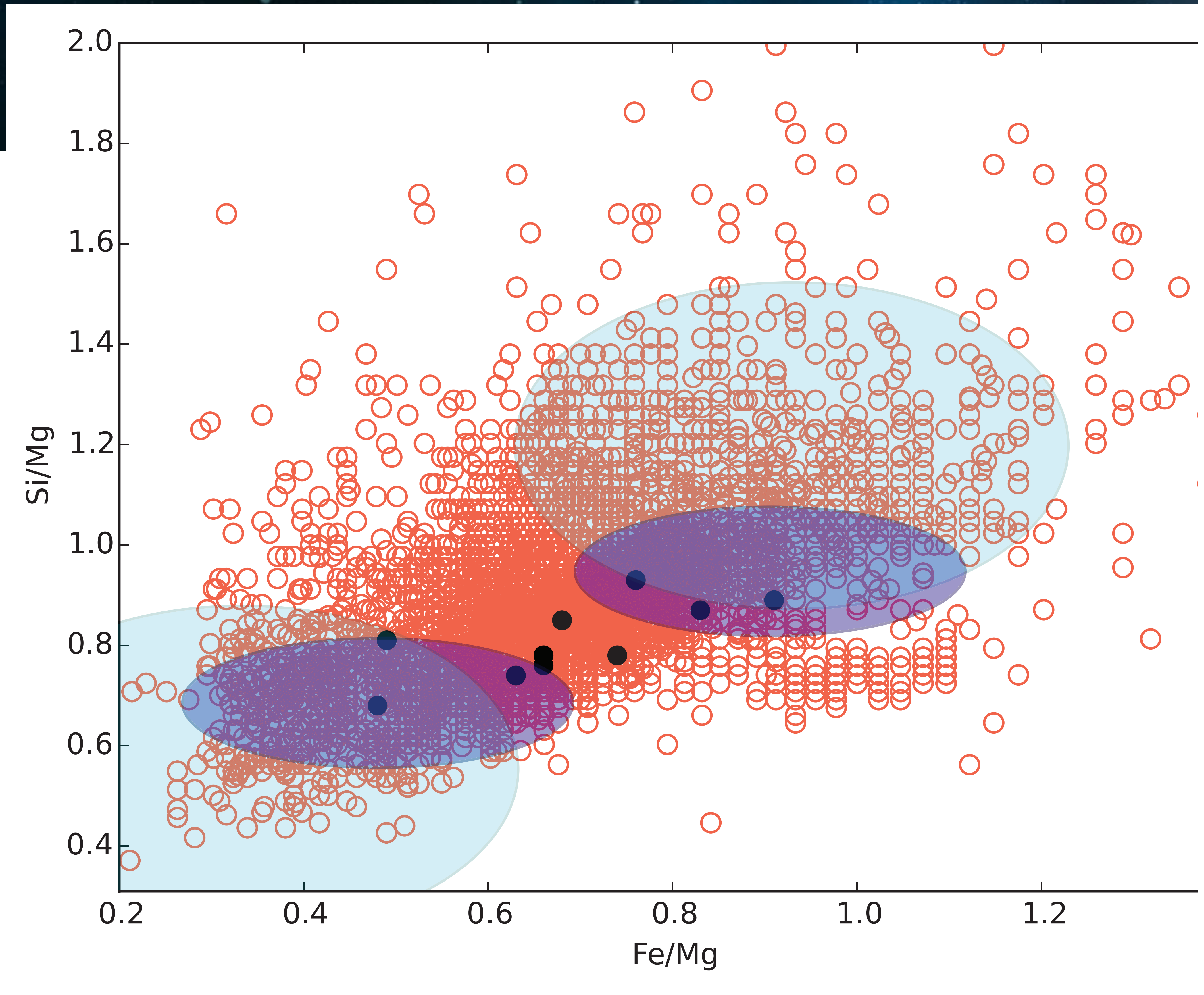
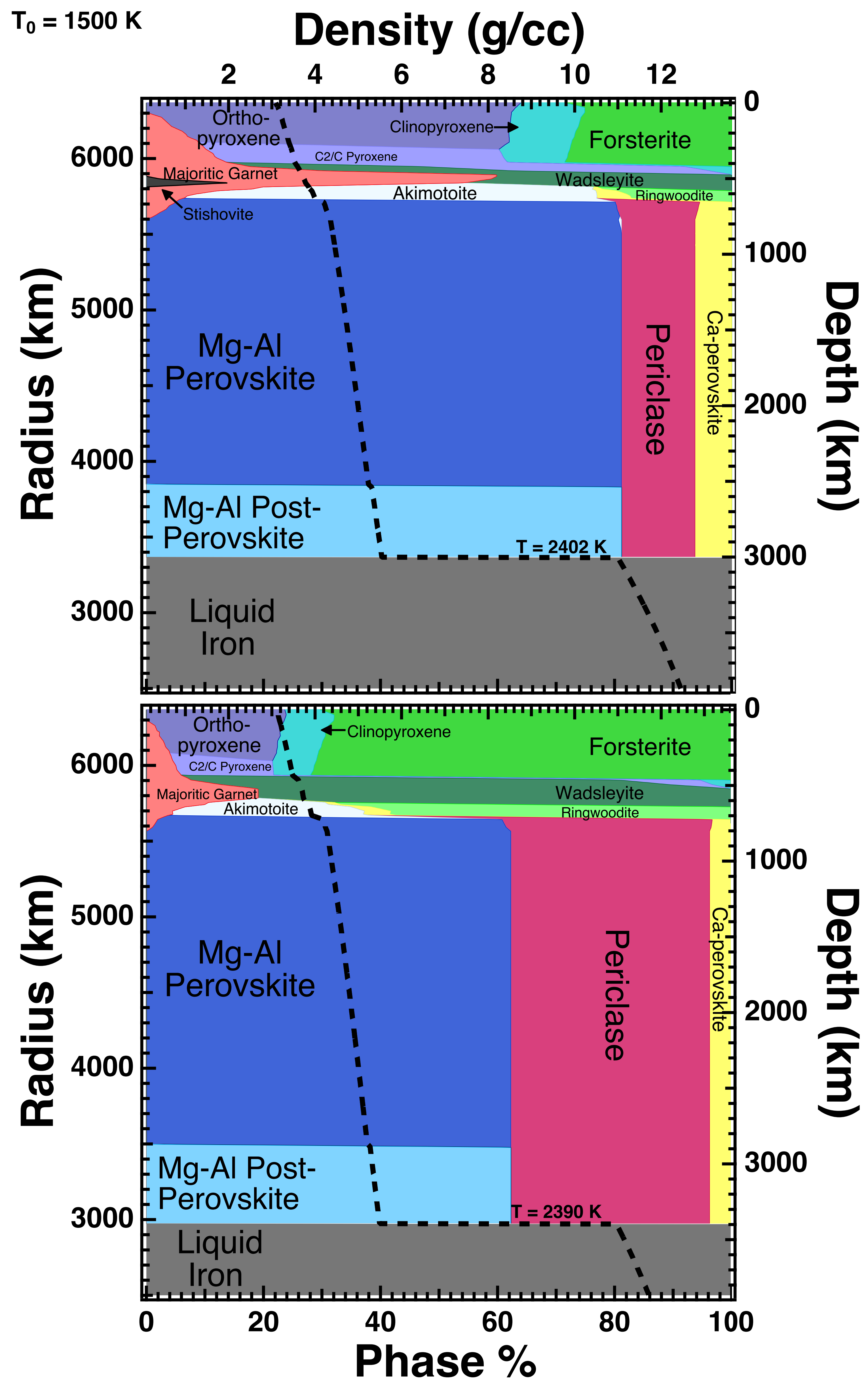
Variations in Rocky Planet Interiors

Hinkel & Unterborn (2018)

Examined the composition of stars (Mg, Al, Si, Ca, Fe) of the 10 nearest stars (which differed) to determine the variation in planet mineralogy from unique populations.

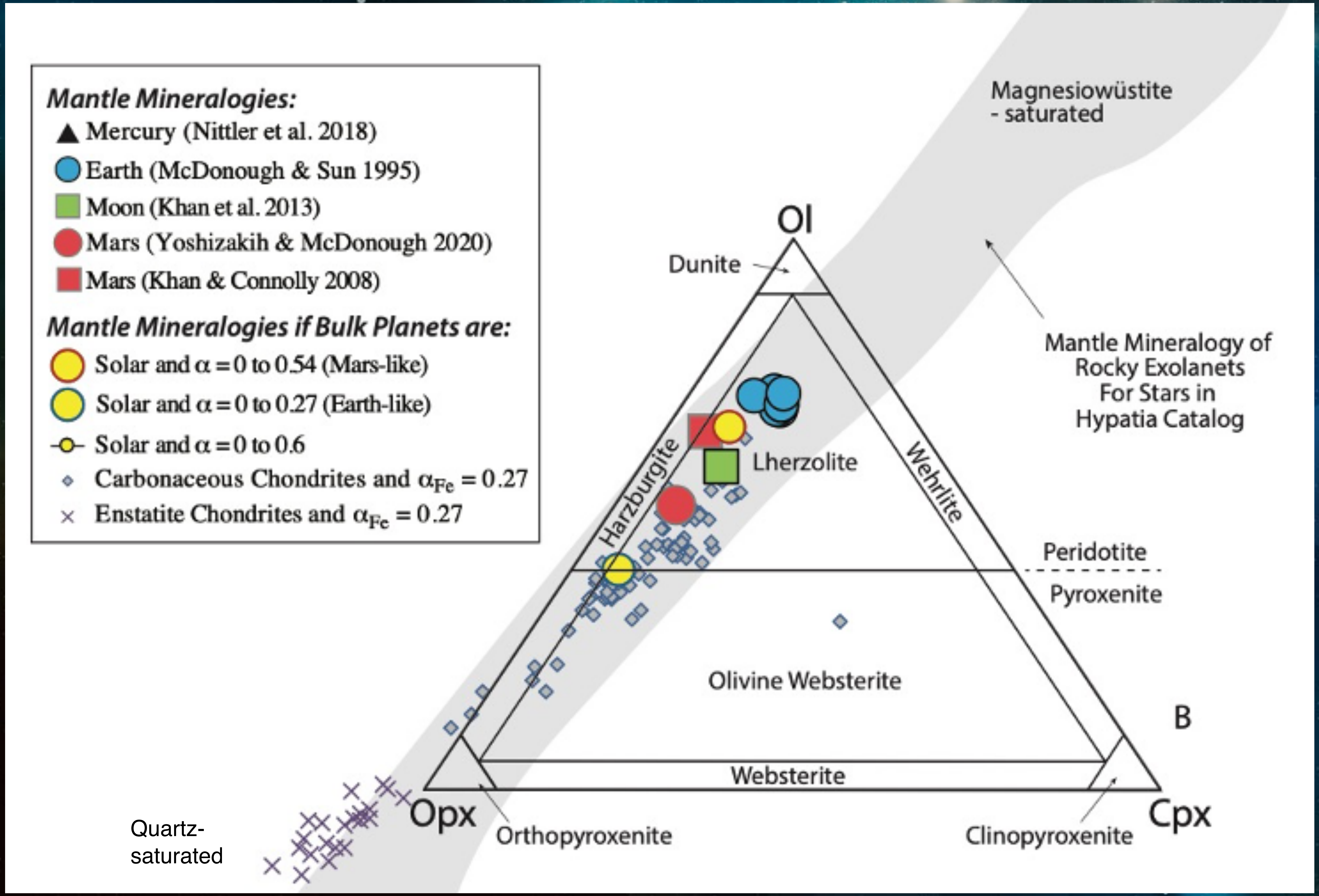






Long-Term Interior-Atmosphere Evolution of Rocky Exoplanets

Putirka & Rarick (2019)



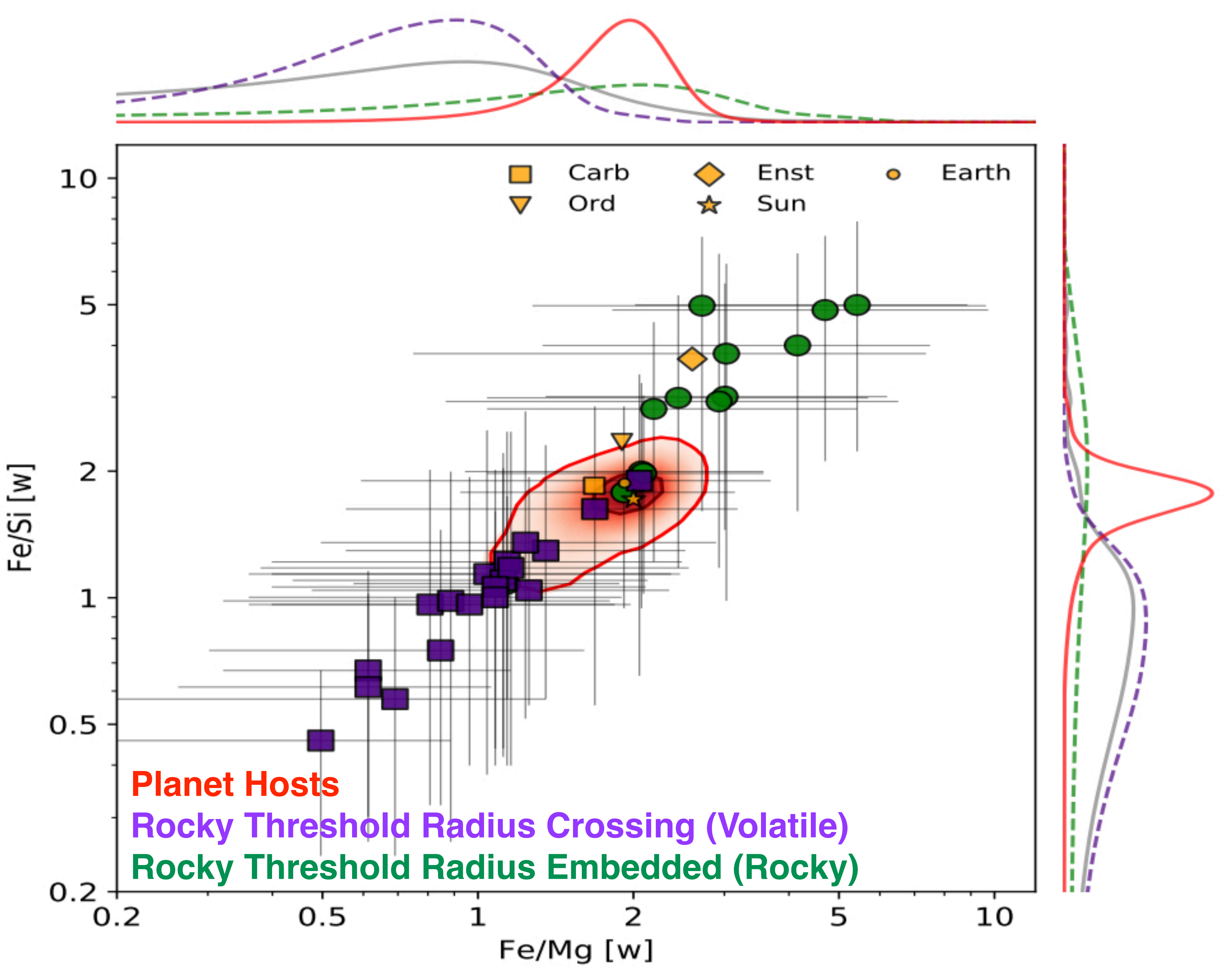
The planet's interior controls plate tectonics, mantle convection, and melting, which depends upon the minerals and elements present in the planet.

They examined > 4000 stellar compositions to determine whether the rocky exoplanets might be geologically similar to the Earth and found that exoplanet mantles are likely dominated by olivine and/or orthopyroxene.

Overall, they predict that exotic planet mineralogies should be rare to absent.

Chemical Formation Fingerprints in the Composition of Rocky Super-Earths

Plotnykov & Valencia (2020)



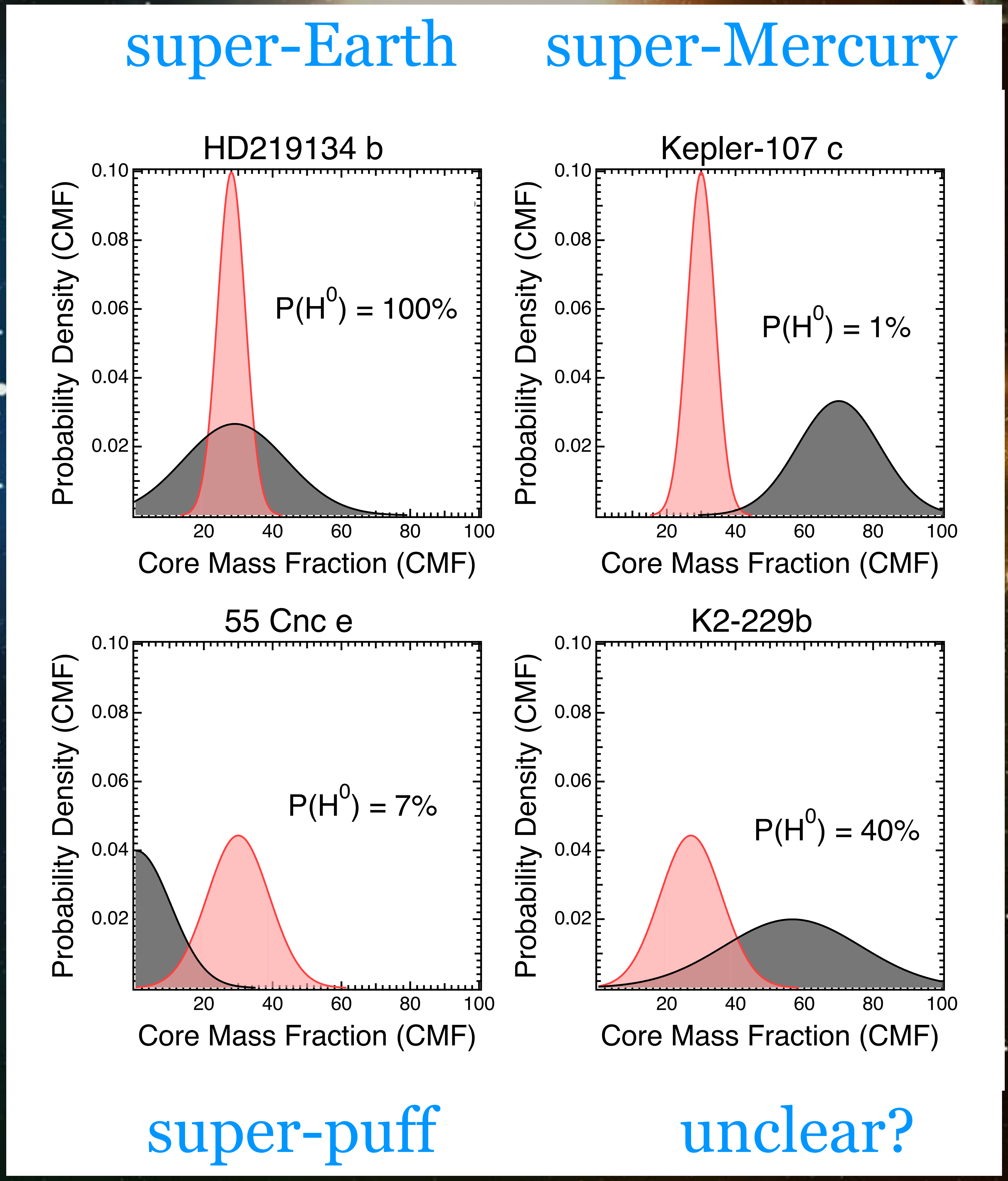
Analyzed 33 exoplanets with mass and radius errors < 25% using SuperEarth (Valencia et al. 2006, 2007):

- The composition of rocky planets spans a wider range than stars, especially highly irradiated planets — some of which are 2x depleted in Fe/Si compared to other stars.
- By employing uncompressed densities — or the density a planet would have if all formation material was decompressed to reference P and T — rocky planets can attain a maximum iron enrichment during planet formation (CMF ~ 0.8).

The Probability that a Rocky Planet's Compositions Reflects the Host Star

Schulze, Wang, Johnson, et al. (2021)

- All mass-radius models are inherently under-constrained when used to determine rocky planet interior compositions.
- However, by adopting the host star composition as an additional constraint (particularly Mg, Si, Fe and Al, Ca), planetary models will have considerably less degeneracy.
- Schulze et al. (2021) tested the (null) hypothesis that stellar composition is a good proxy for bulk rocky planet compositions by comparing mass-radius (gray) and mass-radius-composition (red) models.



Composition is Critical for Life

Hinkel, Hartnett, & Young (2020)

If elements are not present at the correct molar ratios, reactions can't happen!

Photosynthesis has a (fairly) fixed stoichiometry aka the "Redfield Ratio":

$$106\ CO_2 + 16\ NO_3^- + 1\ HPO_4^{2-} + 122\ H_2O + 18\ H^+$$
$$\rightleftarrows C_{106}H_{263}O_{110}N_{16}P_1 + 138\ O_2$$

Crux: *Phosphate*, sourced only via rock weathering, is the limiting reagent for life.

Characteristic C:N:P ratios

	C	N	P
Plankton*, ♧	106	16	1
Earth's Crust, ∩	0.5	0.04	1
Bulk Silicate Earth, ⊕	3.44	0.05	1
Bulk Silicate Mars, ♂	0.11	0.0005	1
Sun, ⊙	2200	550	1
Nearby stars, ★	800	280	1

The planet's composition dictates both its geochemistry and its biochemistry…but we only have P for ~100 stars!

Other Noteworthy Papers

- Wang et al. (2018, 2019): Created a model that devolatilises stellar abundances to infer the rocky planetary bulk composition, based on the Sun and Earth, while incorporating Ni and other light elements. The depletion of volatiles results in varying interiors for Kepler-10, 20, 21, and 100.
- Bitsch & Battistini (2018, 2019): Calculated the composition of solid planetary building blocks around GALAH stars with varying metallicities. Planets formed beyond the ice line (T<150K) have dramatically difference compositions then those interior to the ice line.
- Spaargaren et al. (2020): Used abundances in a geochemical model to simulate the initial compositional profile of the planetary interior and then simulated the long-term thermal evolution. They predict that 50% of rocky exoplanets have whole-mantle convection, while the other 50% exhibit double-layered convection and high Fe, low Mg/Si (cool slowly, lose volatiles).
- Michel et al. (2020): Analyzed the planetary compositions in different populations of the galaxy, per 2 planetary models (Mordasini et al. 2012, Dorn et al. 2015), and inputs from Santos et al. (2017). The stellar abundance variability between populations was confirmed again with this different stellar sample and separation method.

What We’ve Learned

- Going from the star to planet for refractory elements (especially Fe, Mg, and Si) has been tested at length and is viable. But there are more processes at play, for example the role and distribution of volatiles, that are still being explored.

- Bulk planetary density is not sufficient and inherently degenerate. Interior compositions using stellar abundance proxies can improve our understanding and **classification** of the planet.

- Planets formed within different parts of the galaxy (thin disk vs thick disk vs halo) and different areas of the system (interior or beyond the ice line) will have inherently different compositions.

PLATO Science Products

Mission Products

- Transiting planetary parameters, ephemeris of the system, planetary atmospheres, & planetary radius (~3%) for a variety of systems (demographics)
- Asteroseismology analyses including determination of stellar masses (< 10%) radii (~2%), Teff (~1%), and high-precision ages (~10%)
- Stellar rotation rates and activity properties (from light curves)

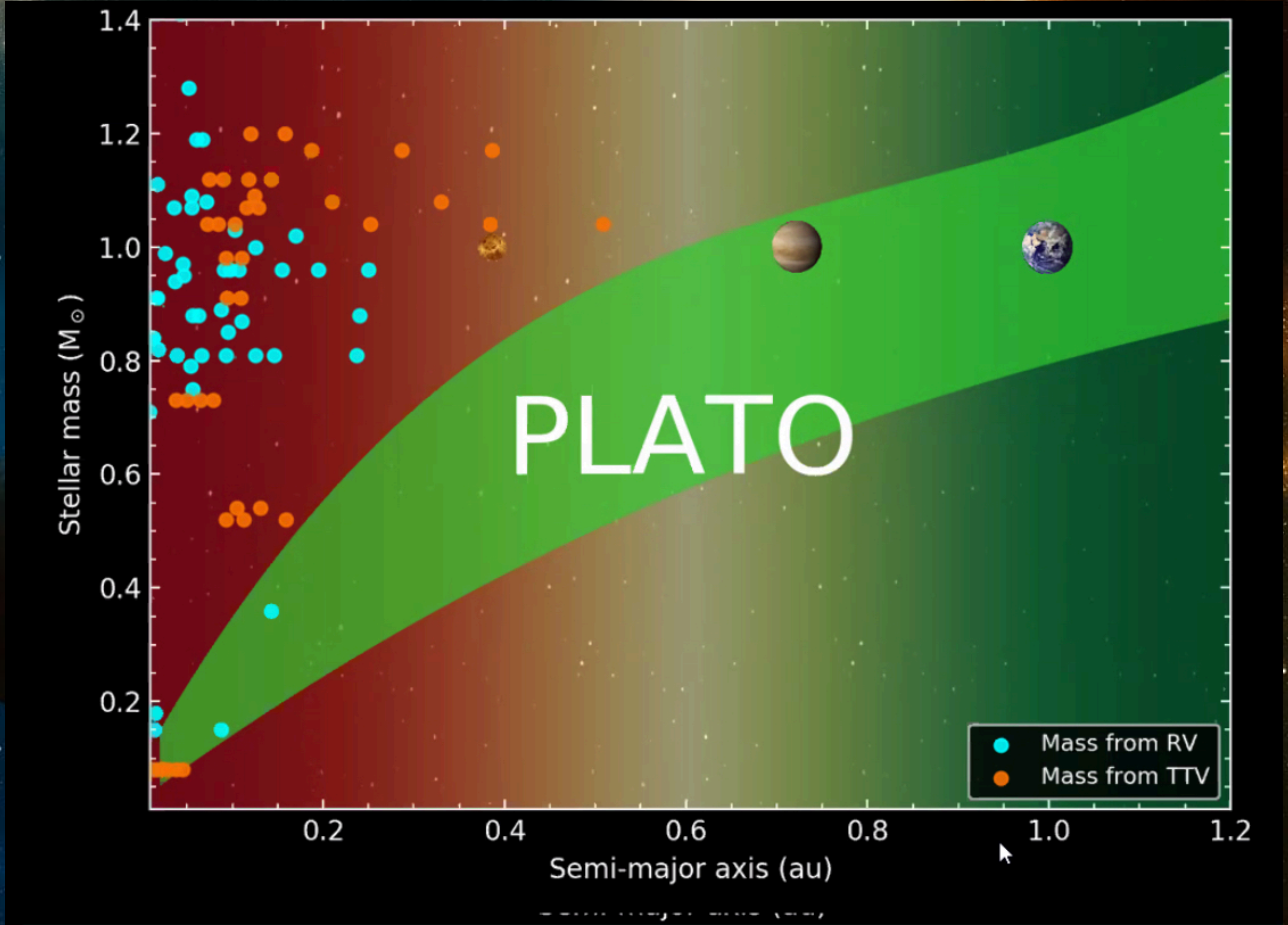
Ground-based Observations

- Filter false-planet transit detections
- Rossiter-McLaughlin observations
- High-resolution spectroscopy for RV determinations, planetary mass (~10%) and mean density, stellar abundances, planetary atmospheric composition

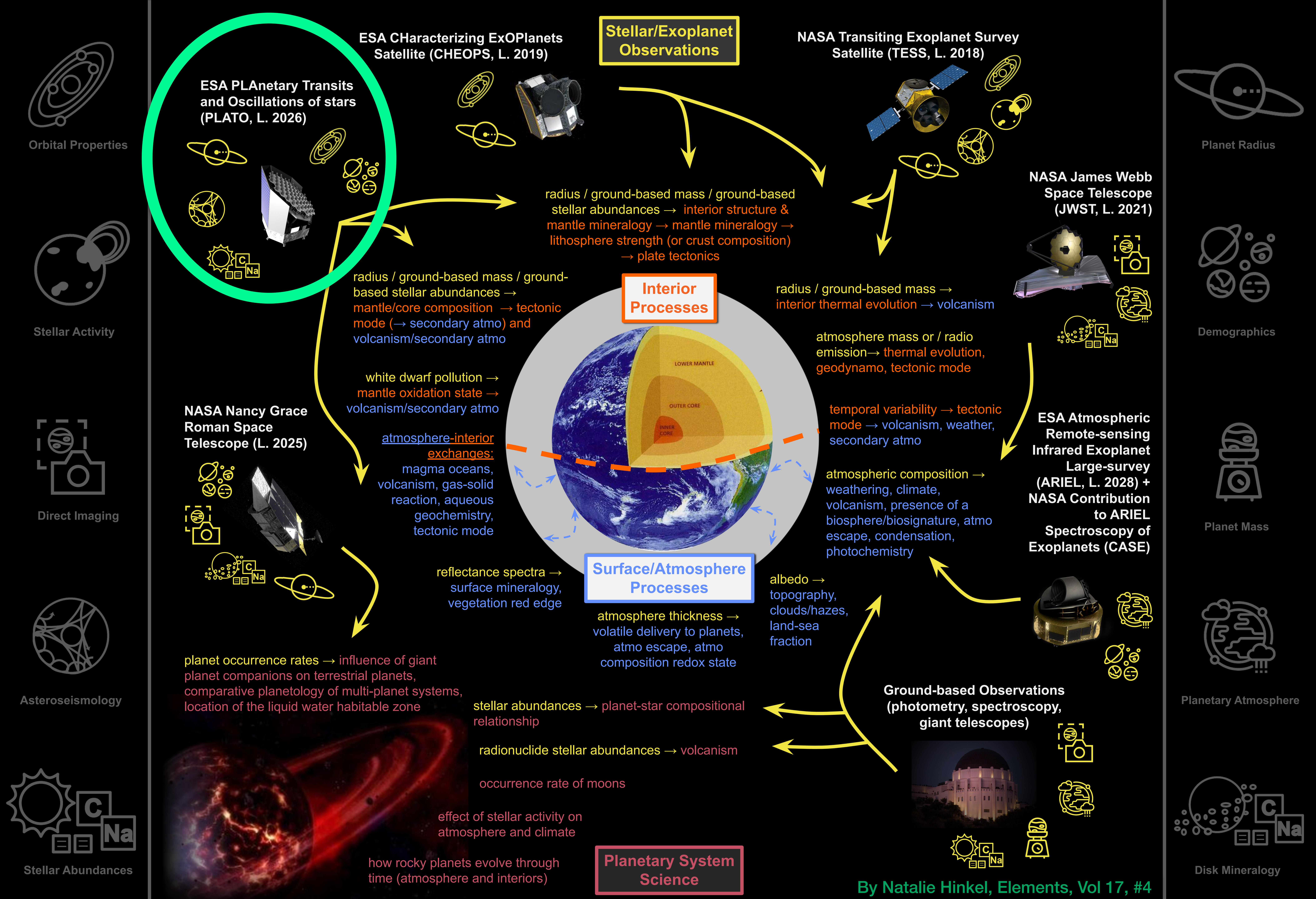
PLATO to Connect Stars and Planets

- 1000s of planet detections and radii measurements for bright, nearby solar-like (F5-K7) and M-dwarfs stars
- Rocky planets with orbits out to +150 days or > 0.3AU

An entirely new dataset with masses and radii for rocky planets orbiting stars with measured elemental abundances.



Dots: Small planets with measured radius and mass.
(less than twice the Earth and less than 10 Earth masses)


Orbital Properties
Stellar Activity
Direct Imaging
Asteroseismology
Stellar Abundances
C
Na
Stellar/Exoplanet Observations
ESA PLAnetary Transits and Oscillations of stars (PLATO, L. 2026)
ESA CHaracterizing ExOPlanets Satellite (CHEOPS, L. 2019)
NASA Transiting Exoplanet Survey Satellite (TESS, L. 2018)
NASA James Webb Space Telescope (JWST, L. 2021)
ESA Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL, L. 2028) + NASA Contribution to ARIEL Spectroscopy of Exoplanets (CASE)
NASA Nancy Grace Roman Space Telescope (L. 2025)
Ground-based Observations (photometry, spectroscopy, giant telescopes)
radius / ground-based mass / ground-based stellar abundances → interior structure & mantle mineralogy → mantle mineralogy → lithosphere strength (or crust composition) → plate tectonics
radius / ground-based mass / ground-based stellar abundances → mantle/core composition → tectonic mode (→ secondary atmo) and volcanism/secondary atmo
radius / ground-based mass → interior thermal evolution → volcanism
atmosphere mass or / radio emission→ thermal evolution, geodynamo, tectonic mode
white dwarf pollution → mantle oxidation state → volcanism/secondary atmo
Interior Processes
LOWER MANTLE
OUTER CORE
INNER CORE
temporal variability → tectonic mode → volcanism, weather, secondary atmo
atmosphere-interior exchanges:
magma oceans, volcanism, gas-solid reaction, aqueous geochemistry, tectonic mode
atmospheric composition → weathering, climate, volcanism, presence of a biosphere/biosignature, atmo escape, condensation, photochemistry
reflectance spectra → surface mineralogy, vegetation red edge
Surface/Atmosphere Processes
albedo → topography, clouds/hazes, land-sea fraction
atmosphere thickness → volatile delivery to planets, atmo escape, atmo composition redox state
planet occurrence rates → influence of giant planet companions on terrestrial planets, comparative planetology of multi-planet systems, location of the liquid water habitable zone
stellar abundances → planet-star compositional relationship
radionuclide stellar abundances → volcanism
occurrence rate of moons
effect of stellar activity on atmosphere and climate
how rocky planets evolve through time (atmosphere and interiors)
Planetary System Science
Planet Radius
Demographics
Planet Mass
Planetary Atmosphere
Disk Mineralogy
By Natalie Hinkel, Elements, Vol 17, #4

Hinkel et al. (2019a),
www.hypatiacatalog.com

In order to understand planetary structure, geochemical cycles, and the availability of resources to life on other planets, we have to first understand important interdisciplinary elements in the host star. Unfortunately, a variety of key elements are difficult to measure in the optical band, meaning they require special time and attention.

Take-Away Messages

The stellar abundances of refractory elements are excellent proxies for the composition of a planet. Insight into the interior of a planet allows us to understand its iron content, water availability, and overall planet classification. However, many planets don't have both mass and radius measurements…

…until PLATO, which will produce a wealth of stellar and planetary information not yet seen in the exoplanet community.

There is much to do in preparation for PLATO and to complement the mission products to holistically characterize the planets.

Thank you!

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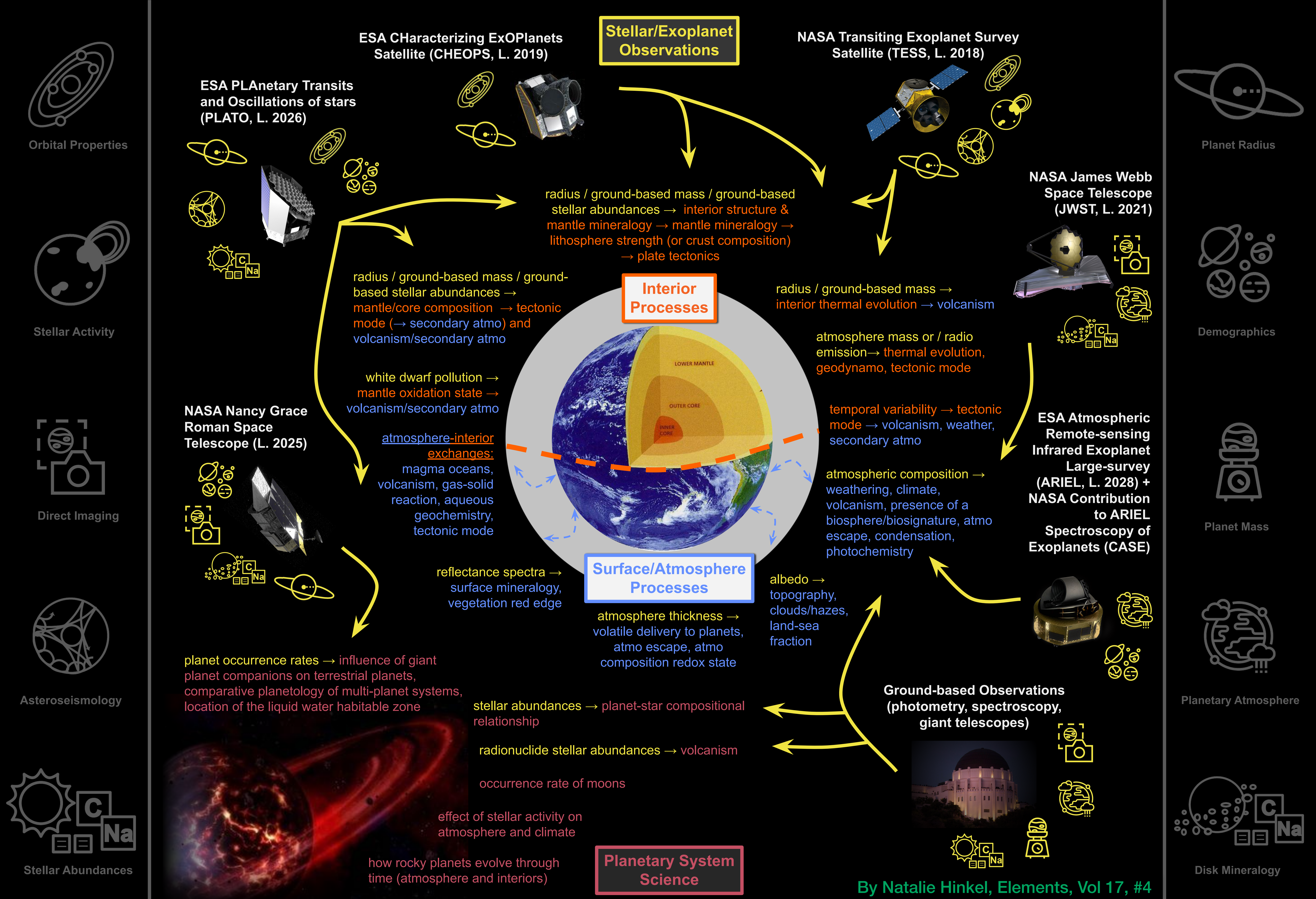
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