On the Compositional Links Between Exoplanets and their Host Stars

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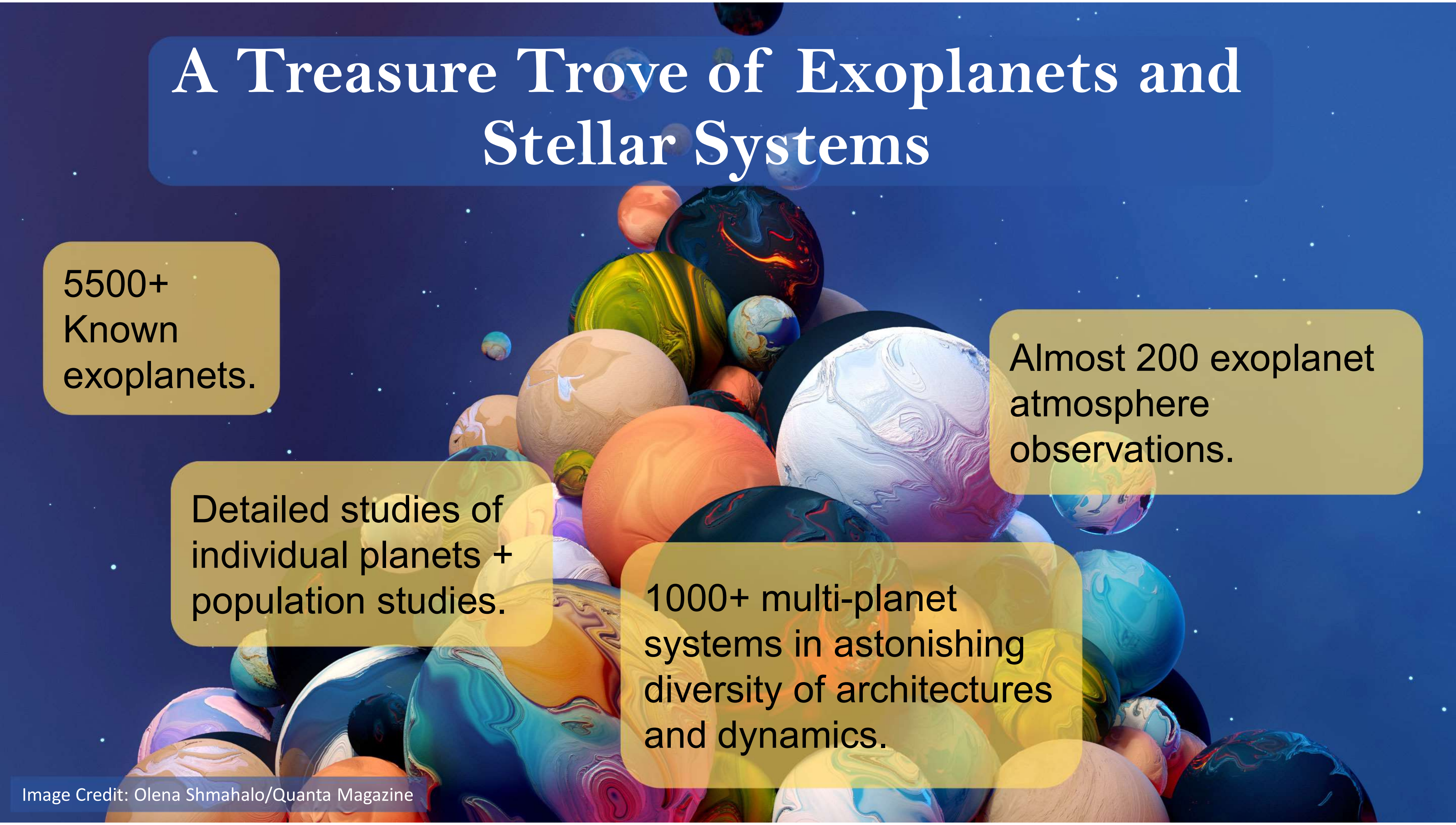
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

A Treasure Trove of Exoplanets and Stellar Systems



5500+ Known exoplanets.

Almost 200 exoplanet atmosphere observations.

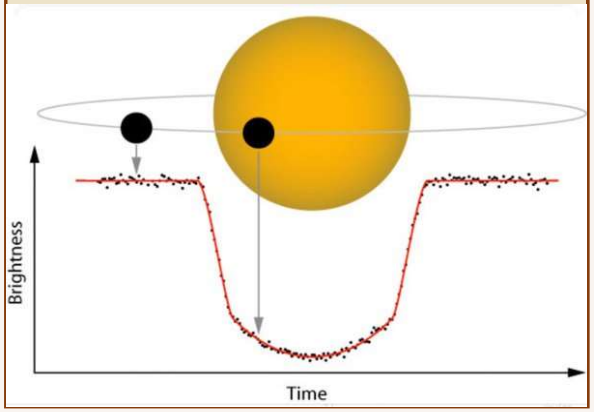
Detailed studies of individual planets + population studies.

1000+ multi-planet systems in astonishing diversity of architectures and dynamics.

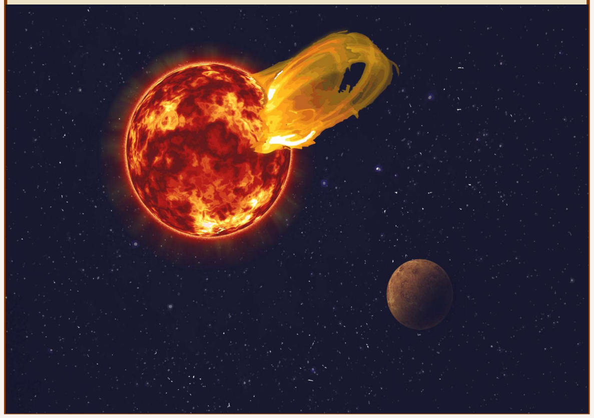
Image Credit: Olena Shmahalo/Quanta Magazine

Know thy Star, Know thy Planet: The Star-Planet Connection

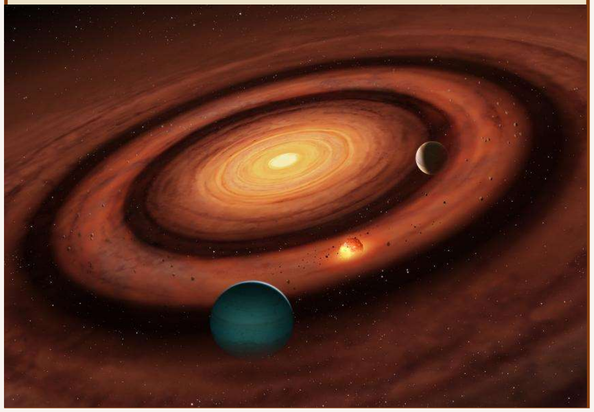
Measuring a planet's bulk physical properties hinges upon knowledge of the properties of the host star.



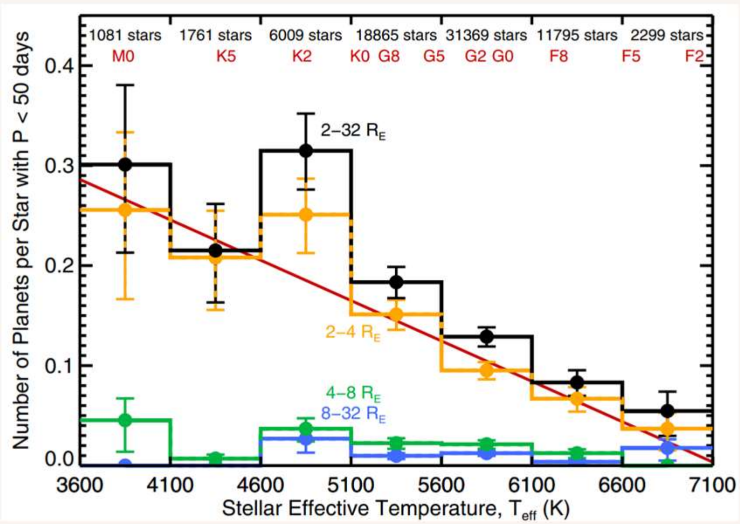
Stellar radiation as well as magnetic activity impacts the atmosphere and properties of orbiting planets.



Planets can inherit characteristics of their host star, which are visibly imprinted in the planets' properties.

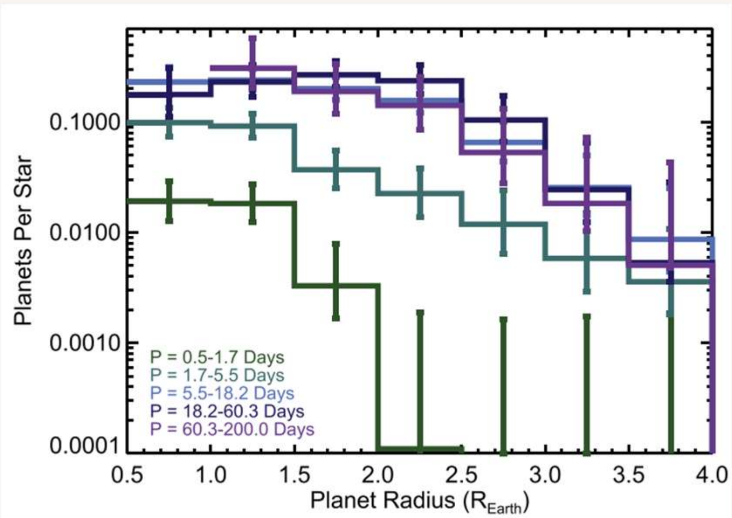


The number of low-mass planets *increases* with *decreasing* stellar mass.



Howard et al. 2012

Howard+2012 found an increase in planet occurrence with decreasing stellar temperature.

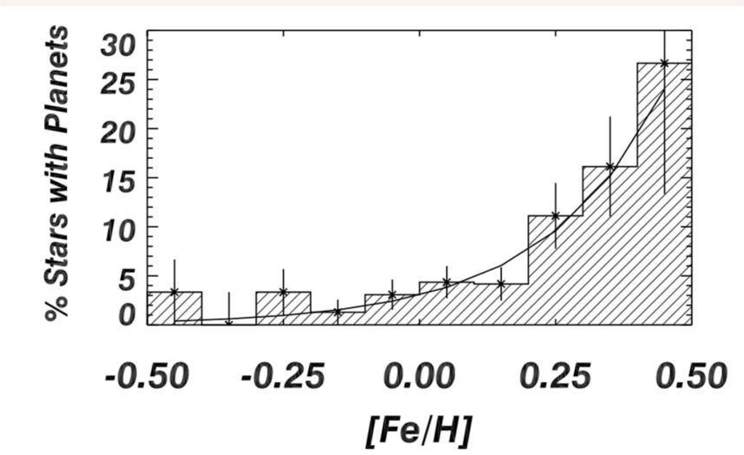


Dressing and Charbonneau 2015

Dressing & Charbonneau found that the average M dwarf hosts $\mathbf{2.5 \pm 0.2}$ **planets per star** within 200 days.

Stellar metallicity and planet occurrence

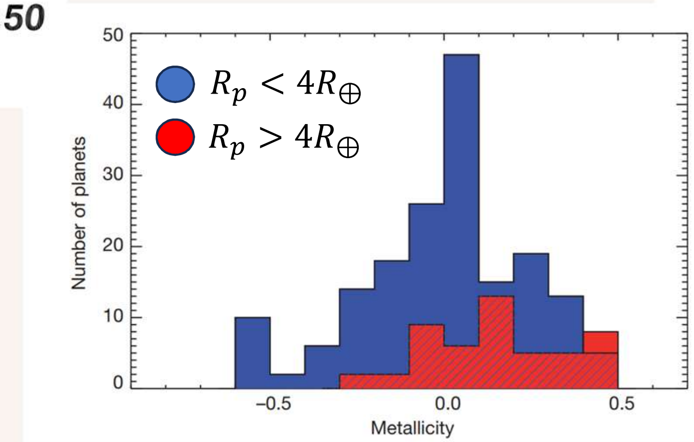
Sunlike stars

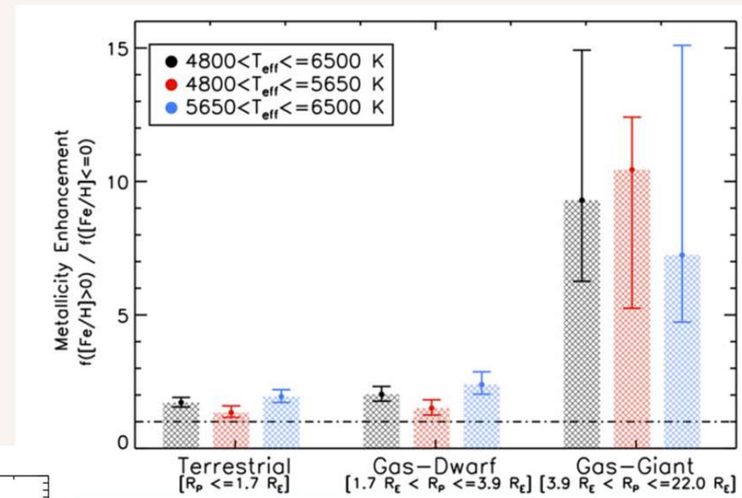


Fischer and Valenti 2005

Giant planets are more common around metal-rich (high [Fe/H]) stars.

Buchhave et al. 2012





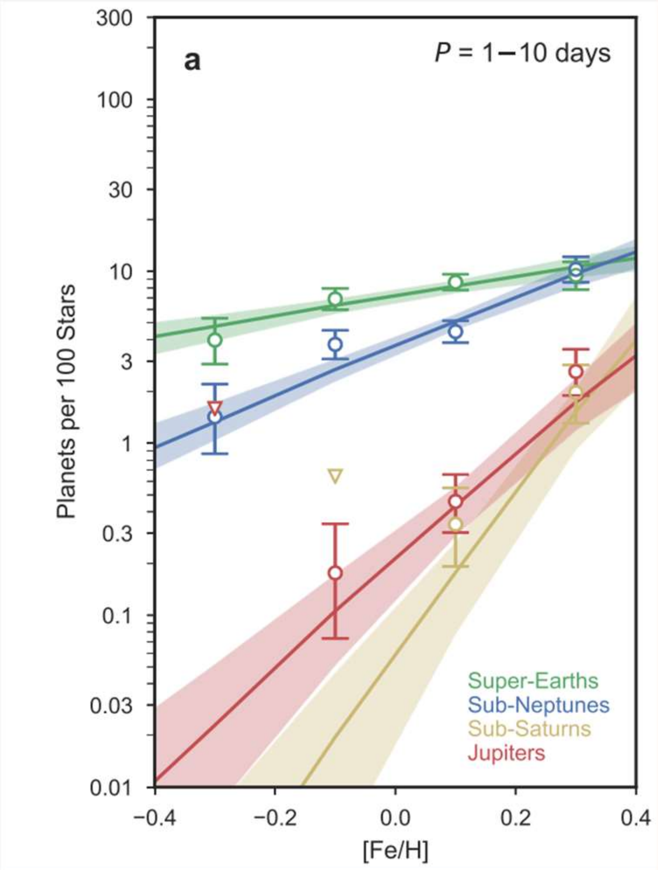
Wang and Fischer 2015

Not only are giant planets more common around metal-rich Sunlike stars, but **gas-dwarfs and terrestrial planets** are statistically **more prevalent** around **metal-rich** stars as well.

Stellar metallicity and planet occurrence

- **Petigura et al. 2018** confirmed that planet occurrence strongly depends on metallicity for giants like exo-Jupiters and Sub-Saturns.

- Metallicity dependence is **much weaker** for smaller planets. There is still no clear consensus on the planet-metallicity link for smaller planets.

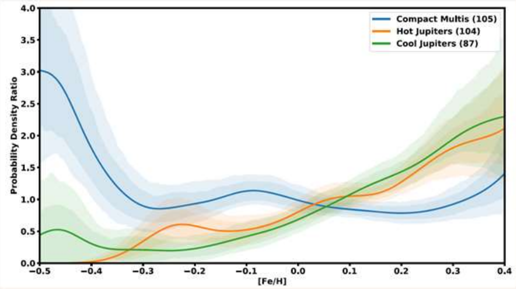


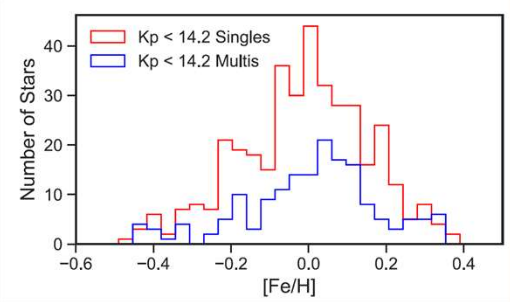
Petigura et al. 2018

Higher prevalence of compact multiplanet systems around metal-poor stars

Sunlike Stars

Brewer et al. 2018





Weiss et al. 2018

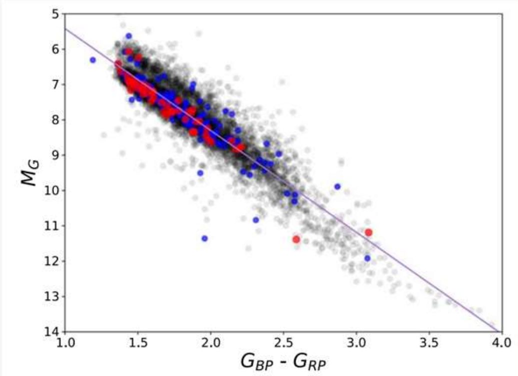
Top. Hot/Cool Jupiter occurrence rises with host star metallicity. However, **compact multiplanet systems occur more frequently around** increasingly **lower metallicity stars.**

Bottom. Metallicity distribution of single- and multi-planet hosting stars are indistinguishable.

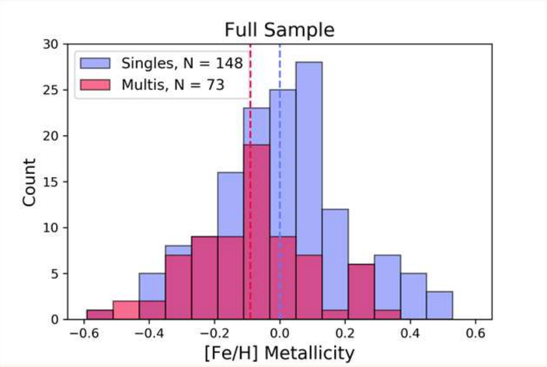
Low-Mass Stars

Compact**, multiplanet systems** are more likely to come from **metal-poor M- and K-dwarf** populations.

Metal-rich M dwarfs are more likely to host a **single planet** rather than multiple.



Anderson et al. 2018



Rodríguez Martínez et al. 2023

What about metallicity and planet composition?

Composition is necessary to constrain theories of **planet formation.**

A planet's composition and measured properties partially constrain the planet's dynamical history and **evolution.**

Determining a planet's composition is a vital first step to constrain its potential **habitability.**

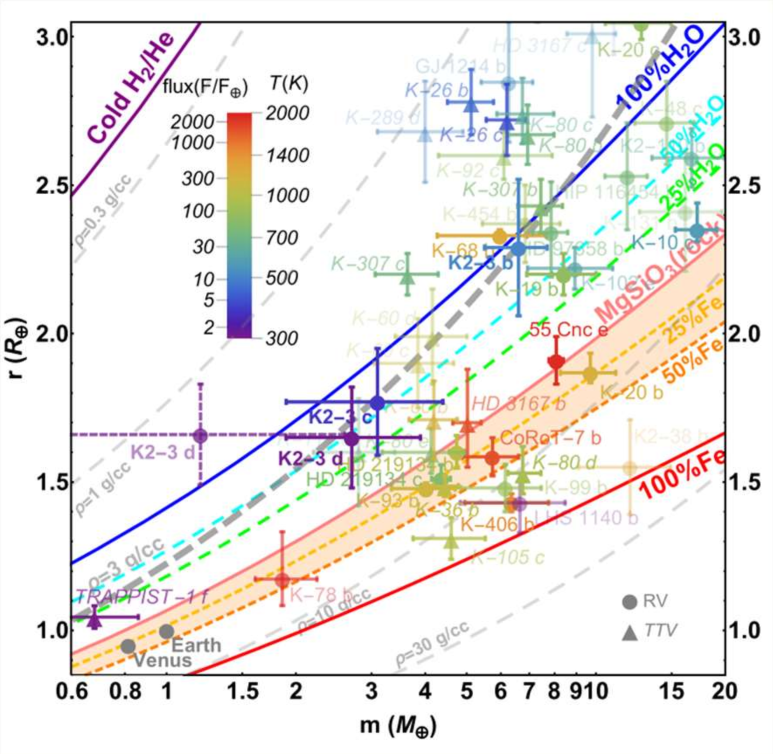
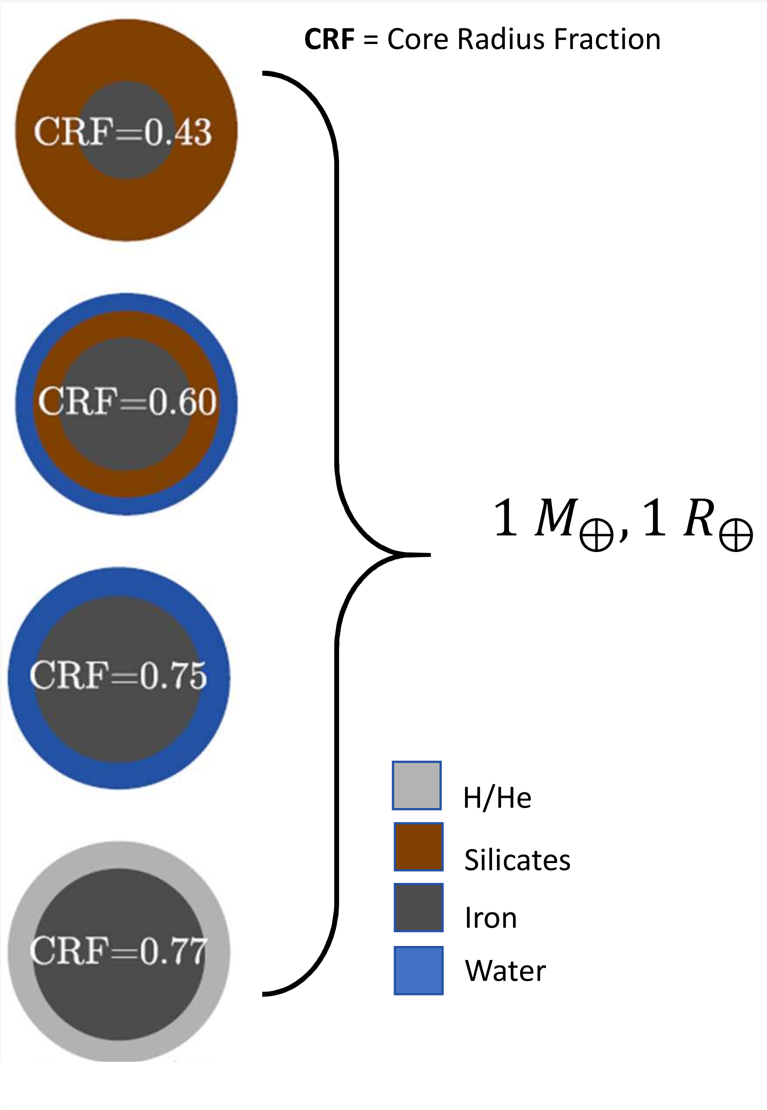


Figure from Damasso et al. 2018

Schematic from Suissa et al. 2018

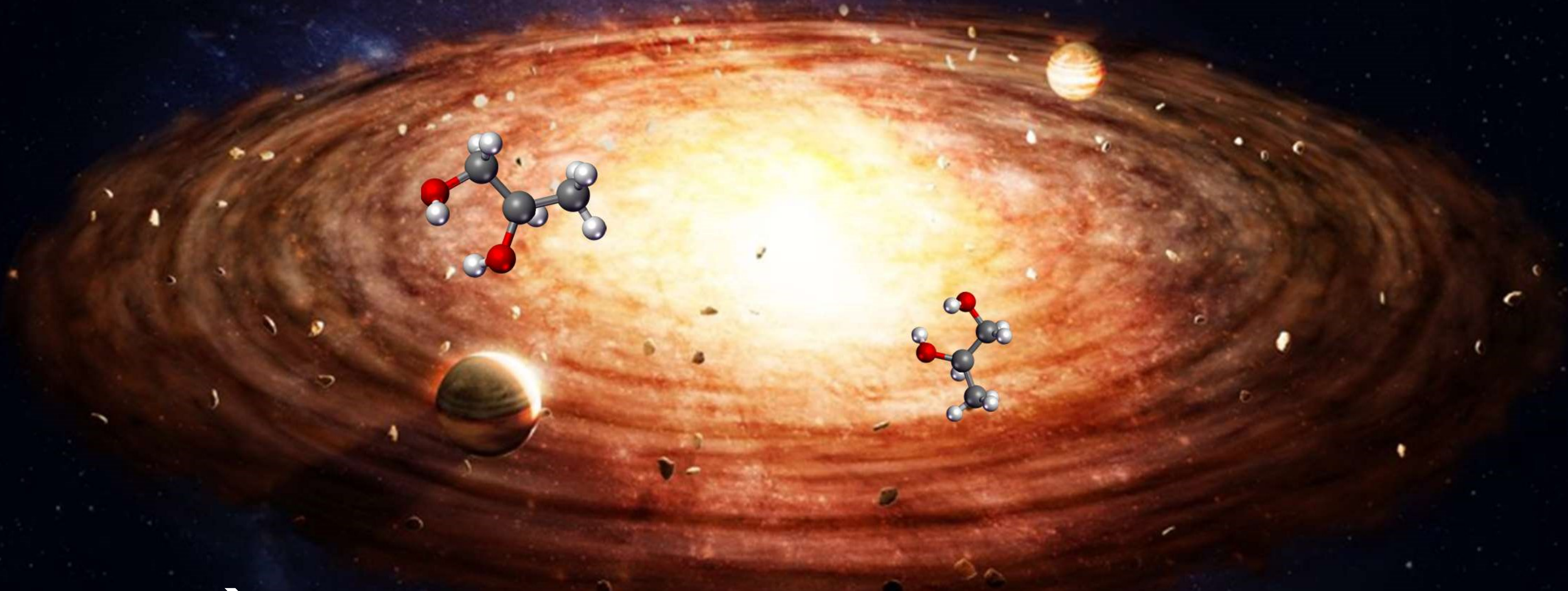


Small planets suffer from a degeneracy in **density** and **composition.**

Uncertainties in the **equations of state also complicate our inferences about a planet's composition.**

Planetary mass and radius alone **are not enough** to constrain interior composition.

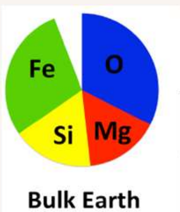
Stars and planets form from the same molecular cloud.

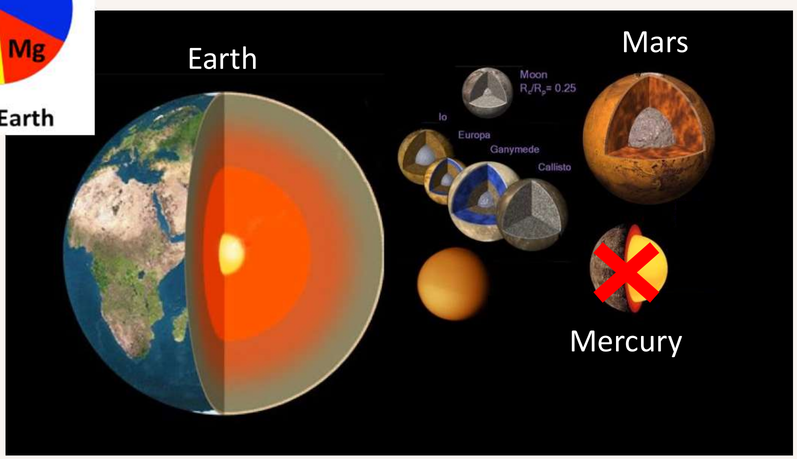


→ Planets should reflect the chemical composition of their host stars.

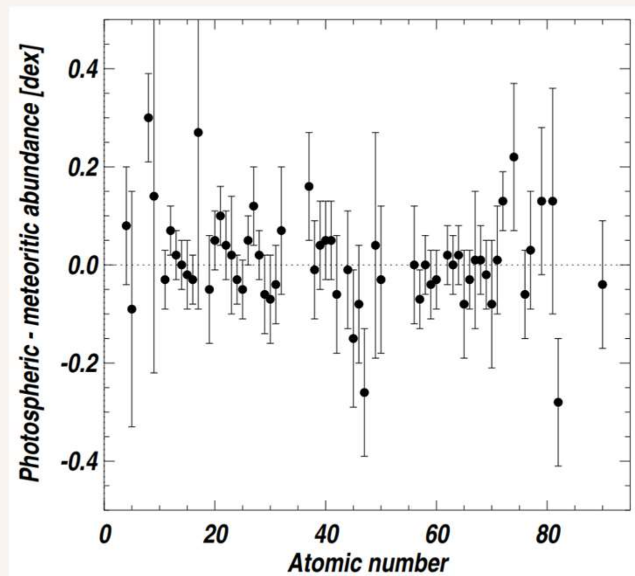
Connections in the Solar System

The bulk compositions of Earth and Mars* reflect the relative abundances of the major rock-forming elements (Fe, Mg, Si) in the Sun. Fe/Mg and Si/Mg ratios are similar to the Sun's to within 10%.





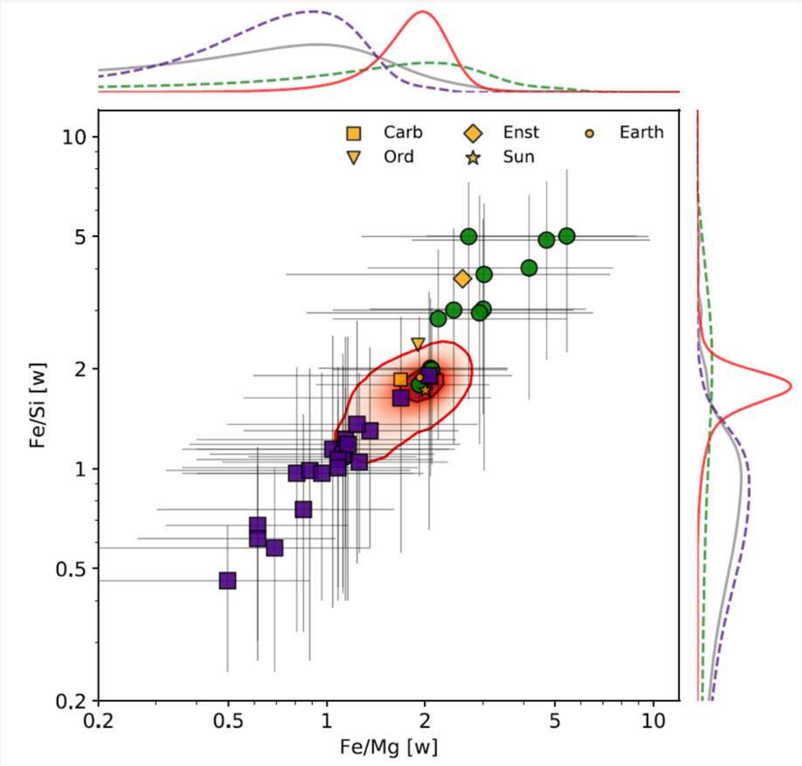
*Not the case for Mercury, which has a much larger core (~70%). Composition of Venus is not well understood.



Difference between the abundances from the Sun and CI carbonaceous chondrites as a function of atomic number.

Asplund et al. 2009

Inferring composition from elemental abundances

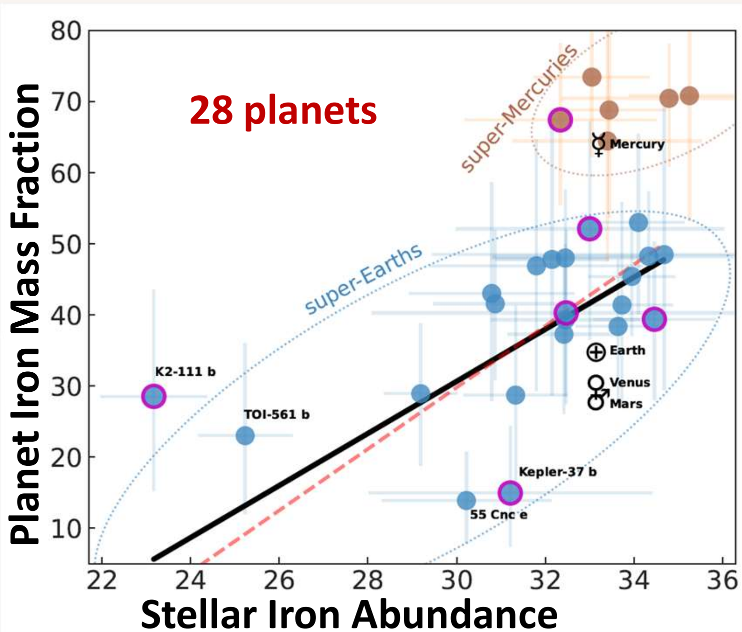


Plotnykov & Valencia 2020

Plotnykov & Valencia 2020 computed Fe/Si and Mg/Si ratios of stars and the core mass fractions of their orbiting planets and found that planets span a much wider range of compositions than their stars.

See also: Dorn+2015, Brugger+2017, Hinkel & Unterborn 2018, Unterborn+2016, Spaargaren+2020, Scora+2020.

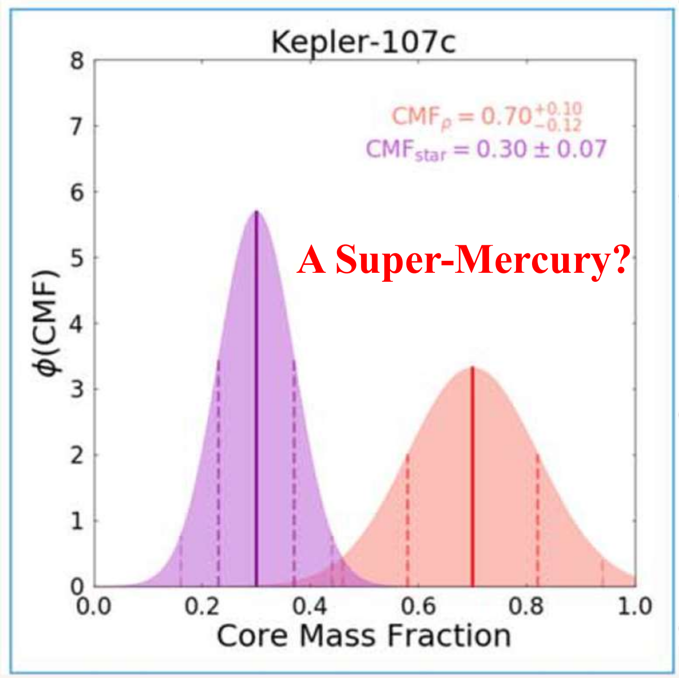
Rocky planets mirror the composition of their stars



Adibekyan et al. 2021

Adibekyan et al. 2021 found a strong correlation (but not a one-to-one relationship) between the iron mass fraction and the composition of their hosts.

** Stellar Iron Abundance = Fe/(Mg + Si) **

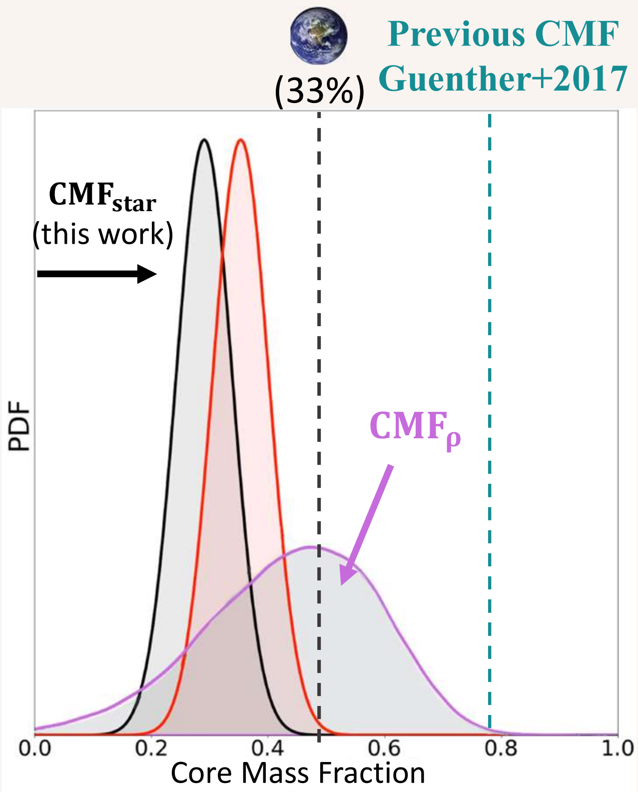


Schulze et al. 2021

Rocky planets generally reflect the Fe/Mg ratios of their host stars.

Deviations from the expected solar composition gives clues as to the evolution of the orbiting planets.

Reevaluation of the putative Super-Mercury K2-106b



Rodríguez Martínez et al. 2022

We find that the Core Mass Fraction (based on planet density) is consistent with the Core Mass Fraction (from the star) for K2-106b, implying that the planet **does not significantly deviate** from the chemical composition of its star.

→Likely NOT a Super-Mercury.*

This underscores the importance of considering stellar elemental abundances to make more physically motivated planet classifications.

*Here we define a Super-Mercury by a planet that is iron-enriched relative to its host star, regardless of its bulk density.

Measurement uncertainties

- Our precision on planetary structure is limited by the precision on $\boldsymbol{R_p}$, $\boldsymbol{M_p}$, Fe, Mg, and Si.
- Mass and radius uncertainties of $\boldsymbol{\Delta M_p/M_p \lesssim 20\%}$ **and** $\boldsymbol{\Delta R_p/R_p \lesssim 10\%}$ are good enough to characterize interiors (see Schulze et al. 2021).
- Literature values quote uncertainties in refractory elements **[X/H] of ~0.01 dex and Fe/Si ratio uncertainties of a few percent.**
- Hinkel and Unterborn 2016 show that abundance uncertainties need to be on the order of **[Fe/H]** $\boldsymbol{< 0.02}$**, [Si/H]** $\boldsymbol{< 0.01}$ **dex** to distinguish between different planet populations.
- These are difficult but achievable with high resolution spectra.
- The majority of planet host stars do not have Fe/Mg/Si abundance measurements. **More abundances are needed to quantify the compositional diversity of small planets!**

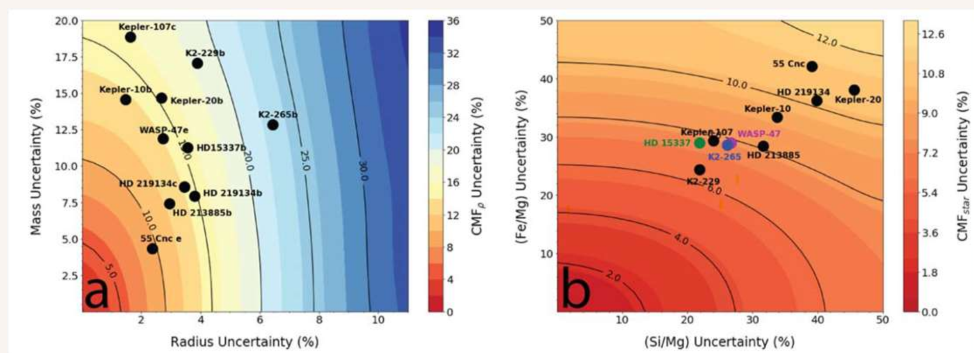


Figure from Schulze et al. 2021

Can we use stellar abundances to constrain the composition of a planet's atmosphere?

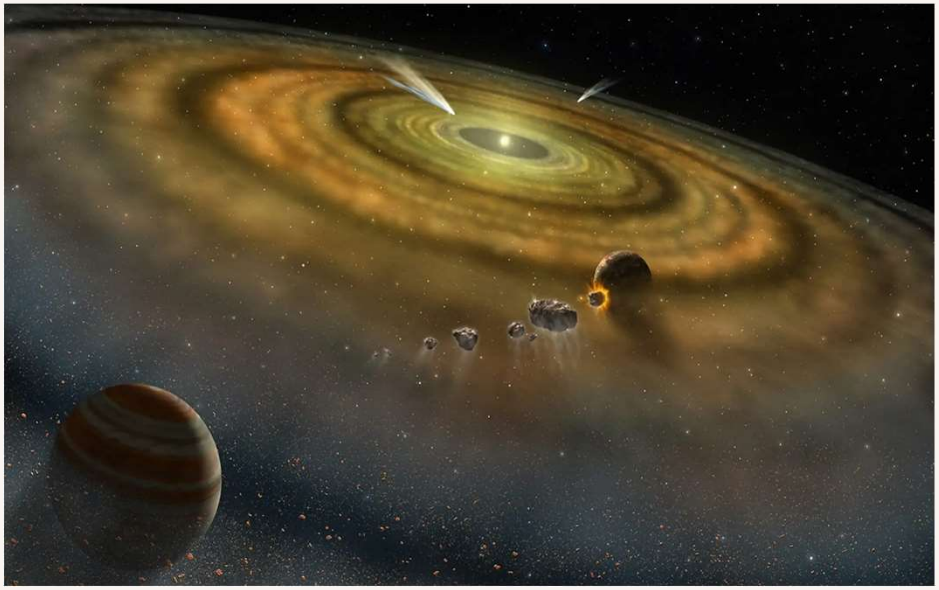
Can we use planetary atmospheric composition to constrain a planet's *origin and formation*?

Planetary atmospheres can partially constrain planet formation

Assumption: the initial composition of a protoplanetary disk in which a planet is formed is the same as that of the host star.

Thus, to first order, the chemical composition of a planet depends on the location and time when it formed in the protoplanetary disk.

C/O ratio is a tracer of planet formation and migration history.



C/O ratio as a tracer of planet formation

Rationale:

Different molecules evaporate and sublimate at different temperatures or locations in the disk (their ‘icelines’), and thus planets will be enriched in certain elements depending on where they form.

C/O increases → distance from host star

Implications:

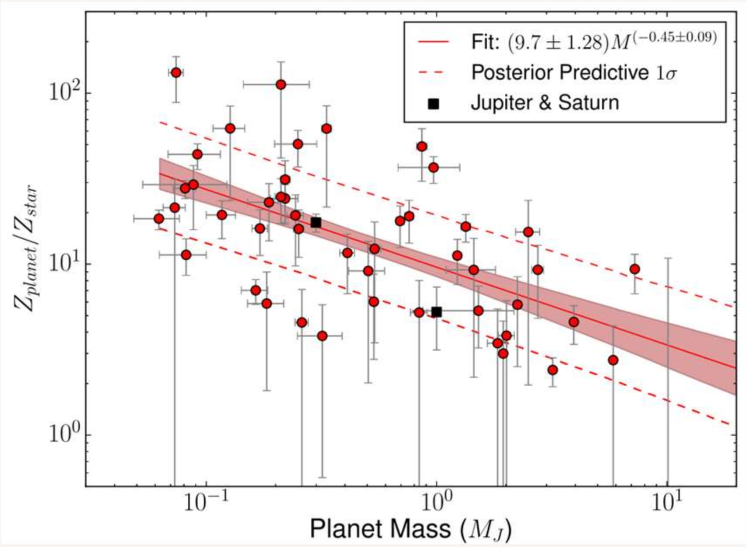
- Giants formed via core accretion with significant accretion will likely have supersolar metallicities and C/O < 0.5 (oxygen rich).
- Planets formed beyond the CO/CO_2 lines will be carbon rich with C/O approaching 1.

Caveats:

- As a planet forms, it can migrate, thus accreting different materials as it sweeps across the disk. Thus, its final composition is dependent upon both initial chemistry and evolution.
- Disks have gaps and overdensities that can complicate this simple picture. (Madhusudhan 2019)
- The C/O ratio can be altered with time by different processes.

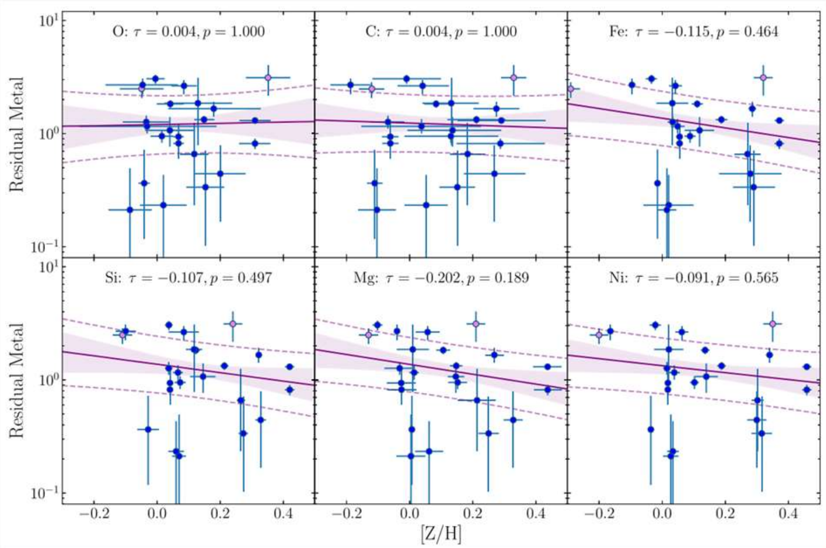
Check out: Oberg+2011 Mordasini+2016, Brewer+2017, Espinoza+2017, Bitsch and Battistini 2019, Madhusudhan 2019.

Links between atmospheres and metallicity



Thorngren et al. 2016

- The heavy element enrichment compared to the host star decreases with planet mass.
- In addition, more massive planets are more enriched in heavy elements. Sample of 47 cool ($T_{eq} < 1000$ K), giant exoplanets.

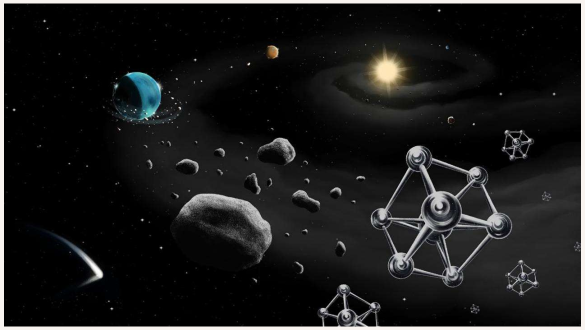


Teske et al.

Teske et al. 2019 found no correlation between stellar metallicity and residual metallicity (observed vs expected planet metallicity from the mass alone) for a sample of 22 giants.

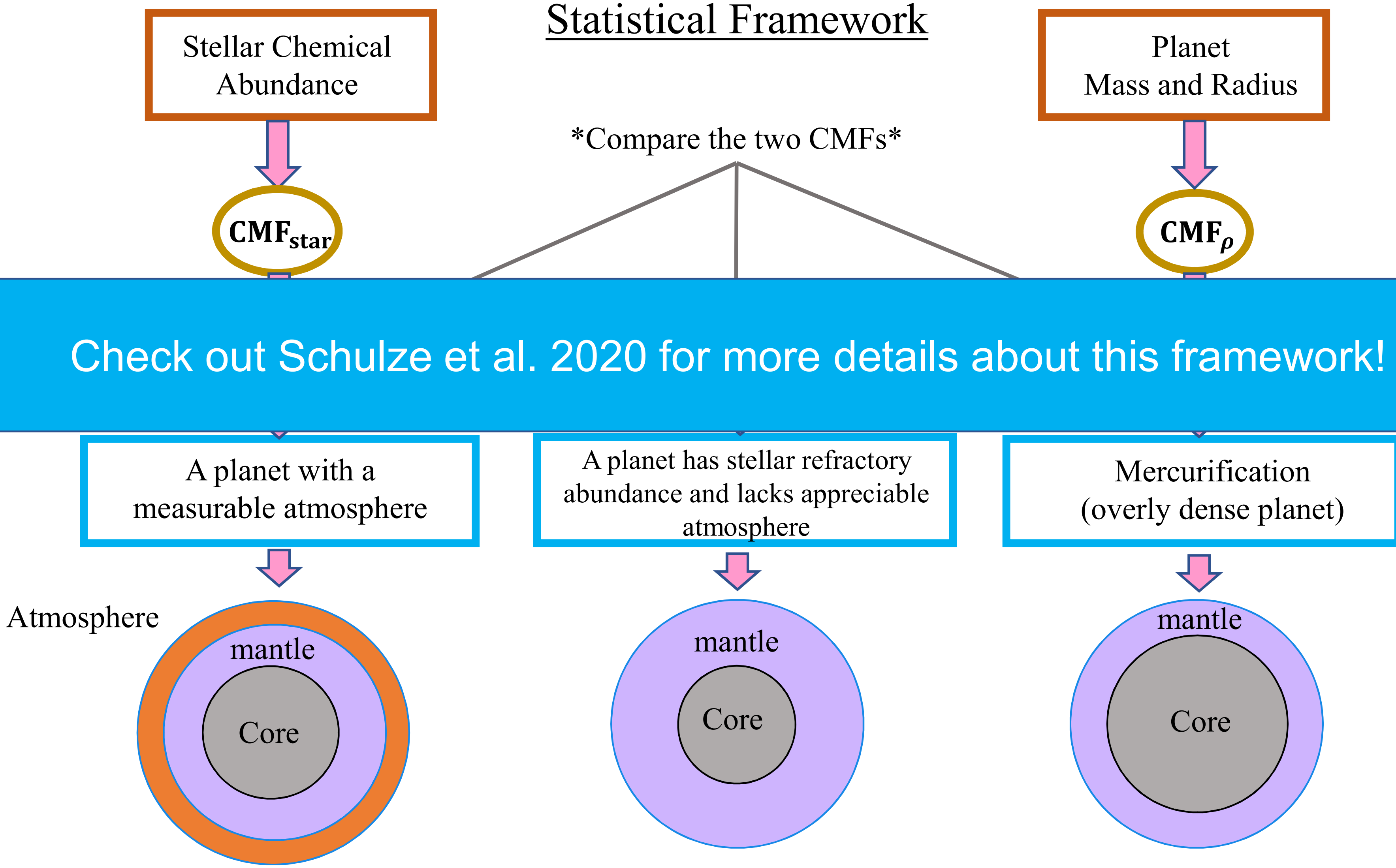
Takeaways

- There **are strong links between planetary and stellar composition**:
  - Rocky planets mirror the composition of their host stars, but span a wider range of compositions.
  - The cases in which they do not match gives clues as to different evolutionary scenarios.
  - Giant planets and single planets appear to be more common around metal-rich stars.
  - **The abundances of the refractory elements are fundamental to constrain planetary composition.**
- **The vast majority of Sunlike, planet-hosts do not have Mg and Si abundance measurements.**
- **We need more abundance measurements** of both the planet-building elements Fe, Si, and Mg to constrain the structure of low-mass planets, as well as C, N, O to possibly constrain formation pathways for larger, farther out planets.



Thank you for listening!

Statistical Framework



Check out Schulze et al. 2020 for more details about this framework!

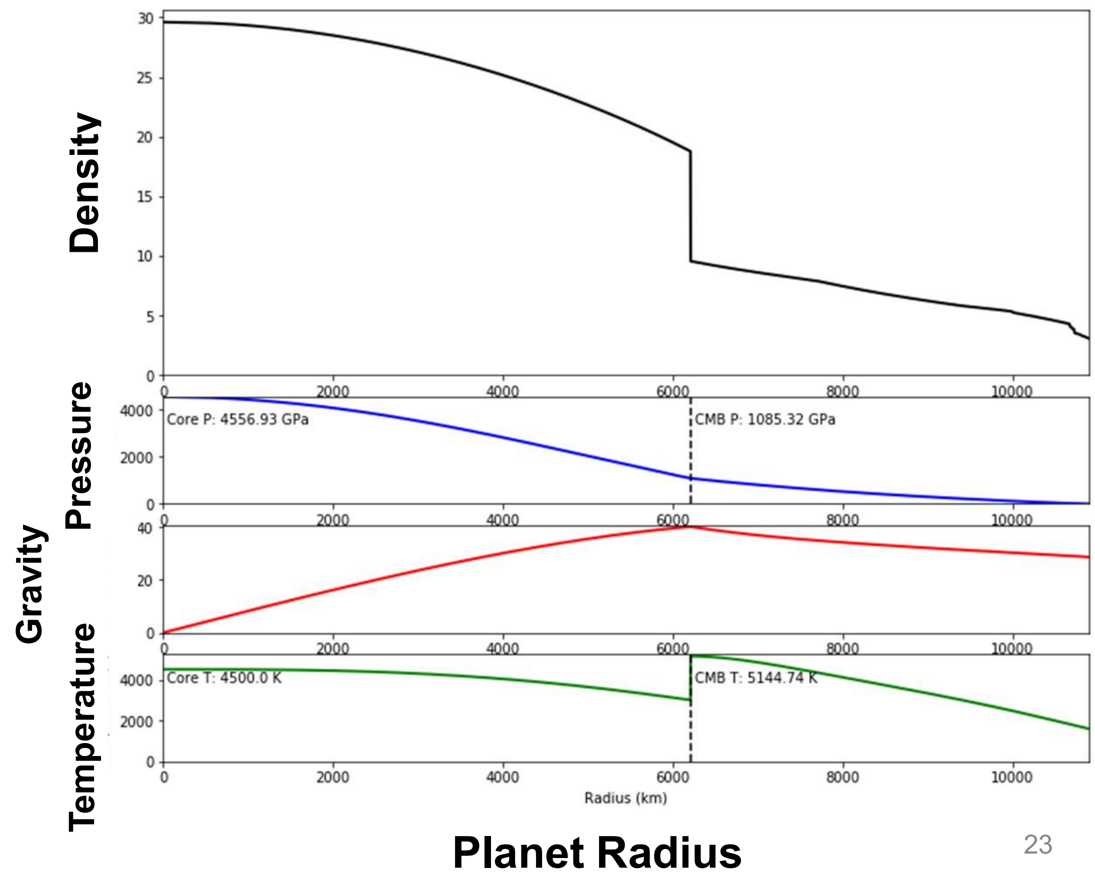
Calculating CMF_ρ

ExoPlex: Calculates the depth-dependent density, mantle, pressure, gravity profiles of planets. (Unterborn et al. 2018).

Assumes planet with Fe core and silicate mantle.

We obtain a CMF_ρ for K2-106 of $\mathbf{45^{+14}_{-16}}\%$

*Earth's CMF is **32%***



Calculating $\mathrm{CMF}_{\mathrm{star}}$

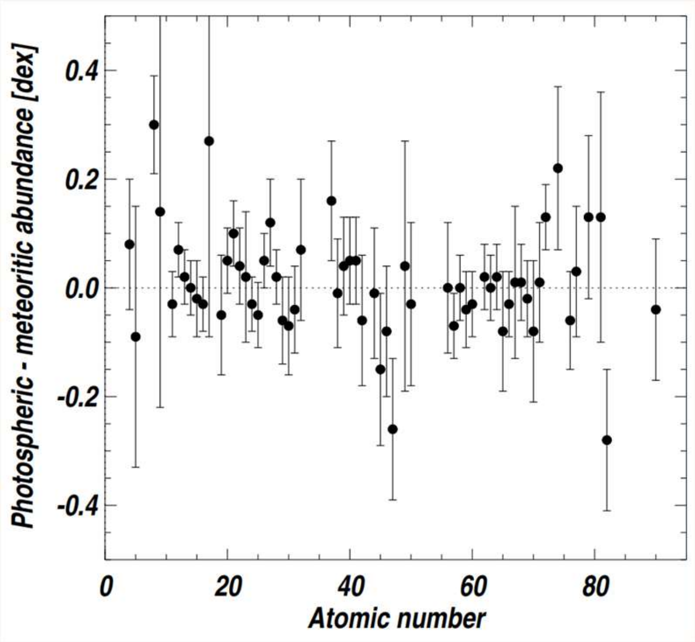
Molar refractory ratios. Requires **[Fe/H], [Si/H], [Mg/H]** abundances

$$\mathrm{CMF}_{\mathrm{star}} = \frac{\left(\frac{Fe}{Mg}\right) m_{Fe}}{\left(\frac{Fe}{Mg}\right) m_{Fe} + \left(\frac{Si}{Mg}\right) m_{Si}{}_{\ 2} + m_{MgO}}$$

m_i is the molar mass of species i.

- CMFρ/CMFstar < 0.5 => Low Density Small Planets (LDSPs)
- 0.5 < CMFρ/CMFstar < 1.4 => Indistinguishable from their host star.
- CMFρ/CMFstar > 1.4 => iron-rich super-Mercuries

The composition of the oldest meteorites closely matches the Sun's.

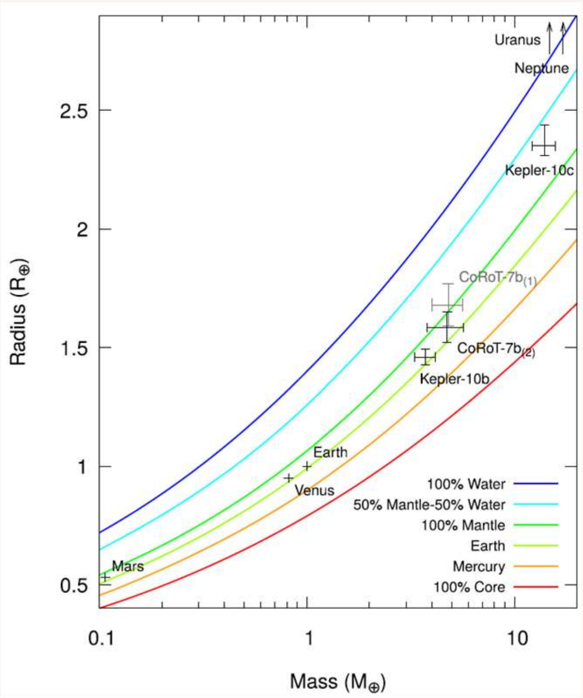


Asplund et al. 2009

Difference between the abundances from the Sun and CI carbonaceous chondrites as a function of atomic number.

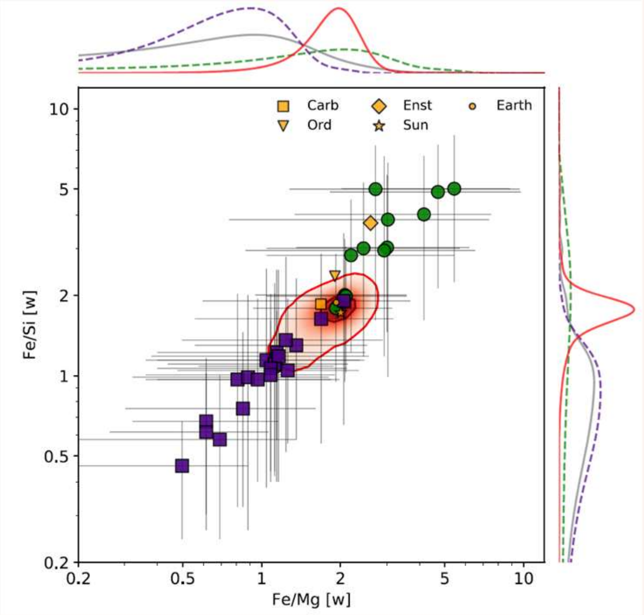
CI chondrite meteorite. Their pristine composition resembles the Sun's more than any other type of meteorite.

Inferring composition from stellar abundances



Brugger et al. 2017

Brugger et al. 2017 used the Fe/Si ratios of planet-hosting stars to reduce the degeneracy in their composition and **update mass-radius relationships** for small planets to provide a first estimate composition based on density.



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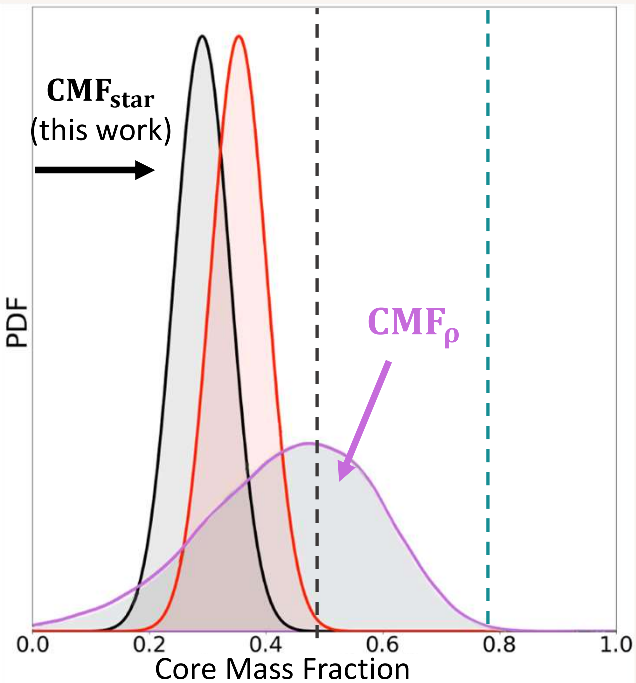
Reevaluation of the putative Super-Mercury K2-106b

Previous CMF Guenther+2017

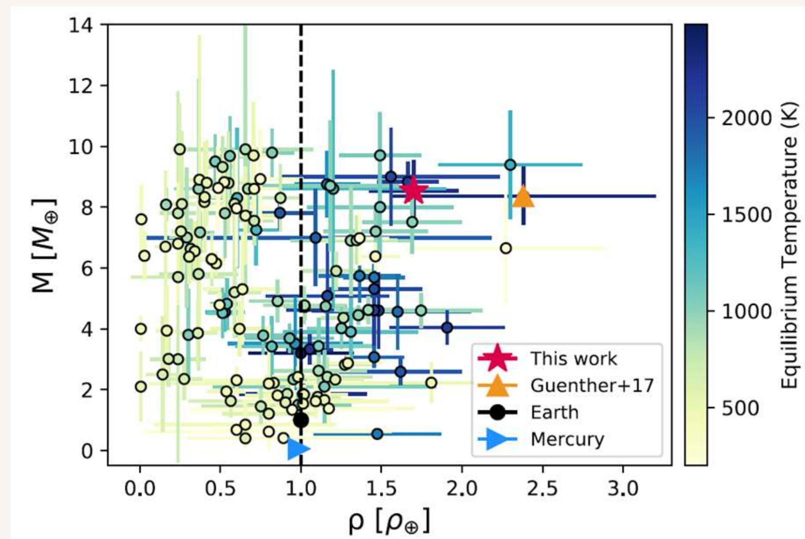


Rodríguez Martínez et al. 2022

We find that $CMF_{star} \sim CMF_{\rho}$ for K2-106b, implying that the planet **does not significantly deviate** from the chemical composition of its star.

→ NOT a Super-Mercury!

This highlights the importance of considering stellar elemental abundances to make more physically motivated planet classifications.



Rodríguez Martínez et al. 2022

There is a remarkably **broad range** of observed bulk densities for small planets.

Measurement uncertainties

- Our precision on planetary structure is limited by the precision on planet mass, radius, and uncertainties in the abundances of Fe, Mg, and Si.
- Mass and radius uncertainties of $\boldsymbol{\Delta M_p / M_p \lesssim 20\%}$ **and** $\boldsymbol{\Delta R_p / R_p \lesssim 10\%}$ are good enough to characterize interiors. (see Schulze et al. 2021)
- M_p, R_p need to be more precise than abundances to achieve the same precision on core mass fraction (Schulze et al. 2021).
- Literature values quote uncertainties in refractory elements **[X/H] of ~0.01 dex and Fe/Si ratio uncertainties of a few percent.**
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- The majority of planet host stars do not have Fe/Mg/Si abundance measurements. **More observations are needed!!!**

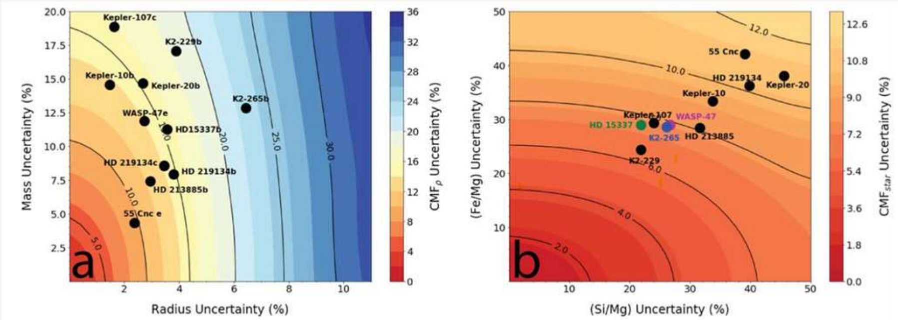
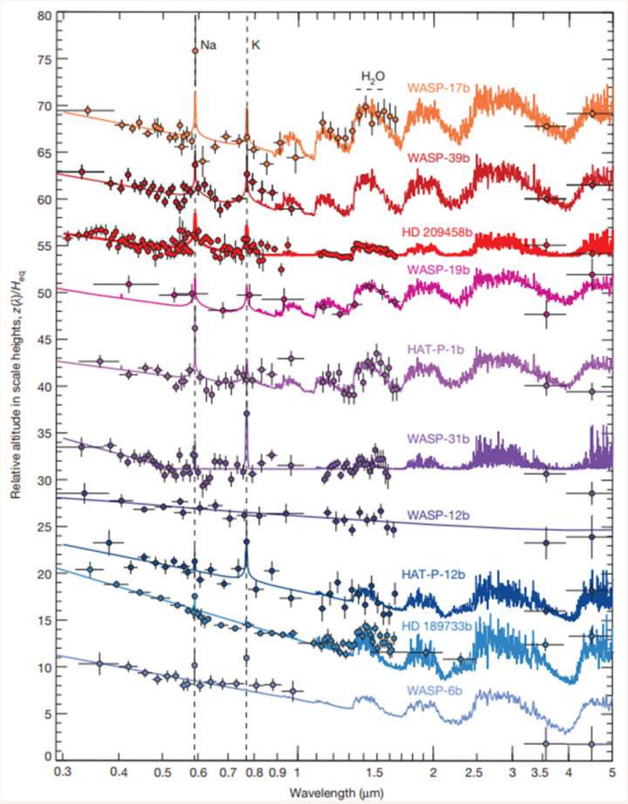


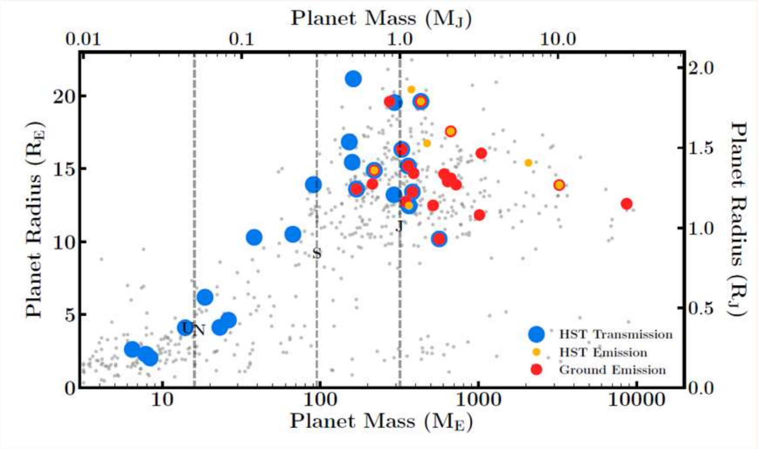
Figure from Schulze et al. 2021

Exoplanet atmospheres



Sing et al. 2016

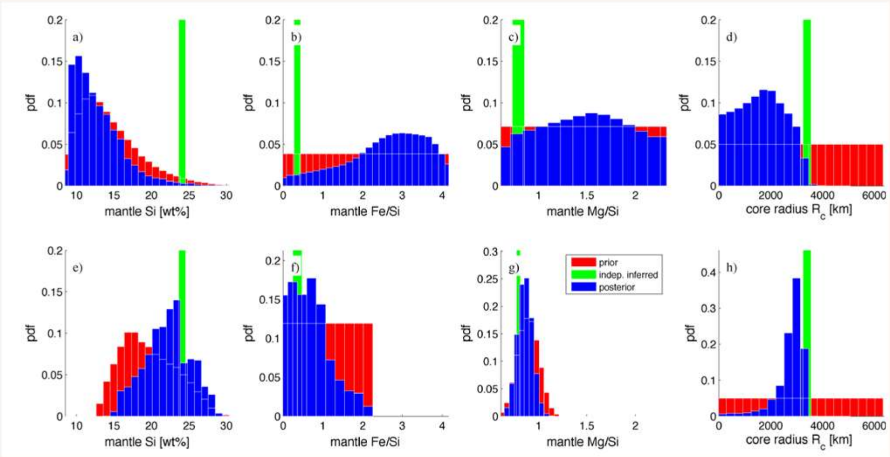
- 5500+ discovered exoplanets.
- Almost 200 different planets have atmosphere measurements.
- They span a wide range of radii ($0.6 < R_p/R_\oplus < 258$)
- 50+ different species/molecules detected, incl. H_2O, Na, CO, CH_4 , etc.



Madhusudhan 2019

Inferring composition from stellar abundances

1. Mass and radius observations are enough to constrain core size.
2. **Precise stellar abundances (of Fe, Si, Mg) are fundamental to constrain planet composition.**
3. The degeneracies composition not only depends on measurement accuracies but on the size and density of the planet.



Dorn et al. 2015