Chemical abundances of stars hosting planets

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Chemical abundances from stars

- Formation of the Galaxy
- Nucleosynthesis processes → Galactic chemical evolution
- Classification of stellar populations (chemical tagging)
- Asteroseismology and stellar activity
- Determination of ages
- Detection and characterization of exoplanets

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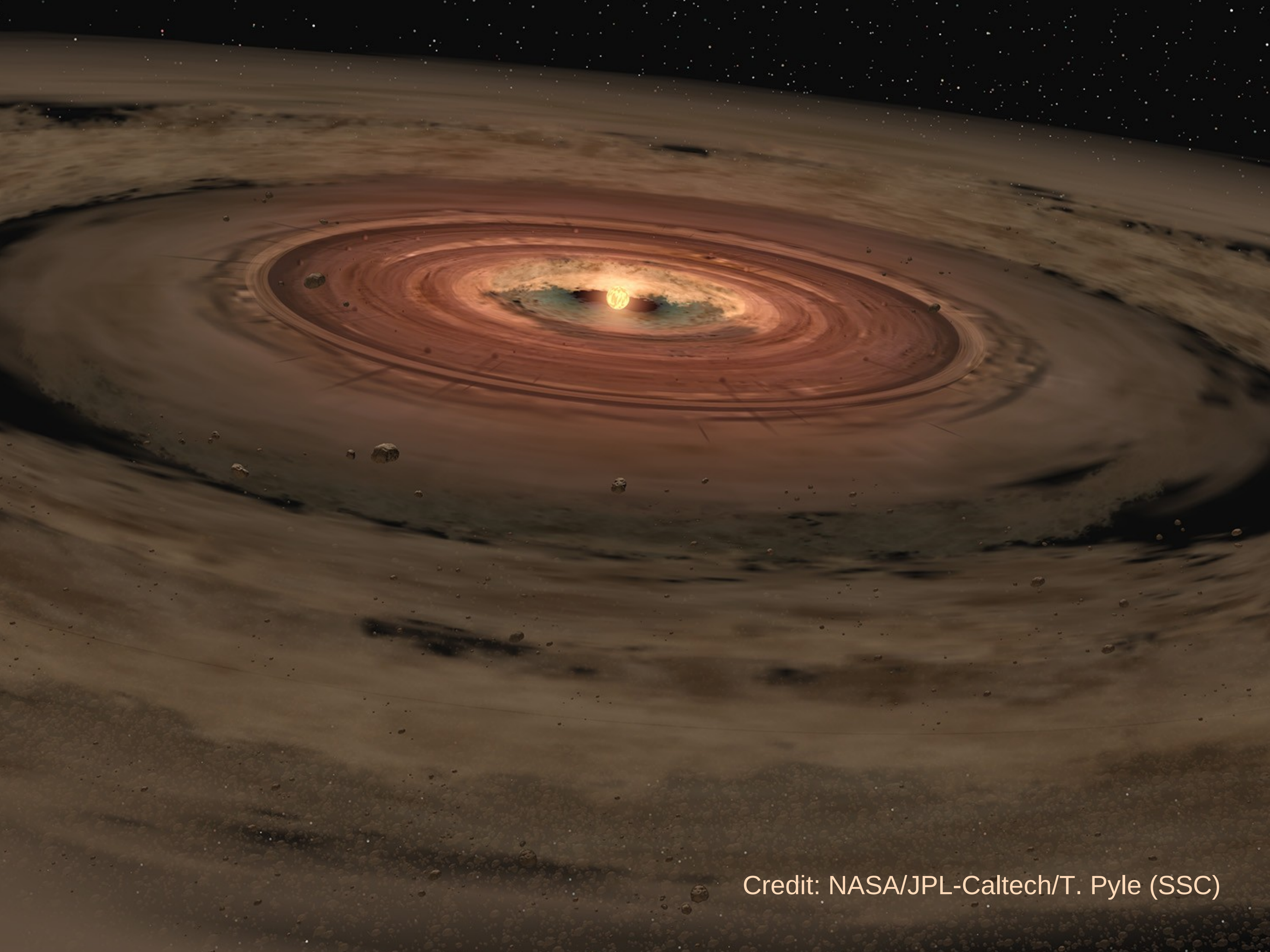
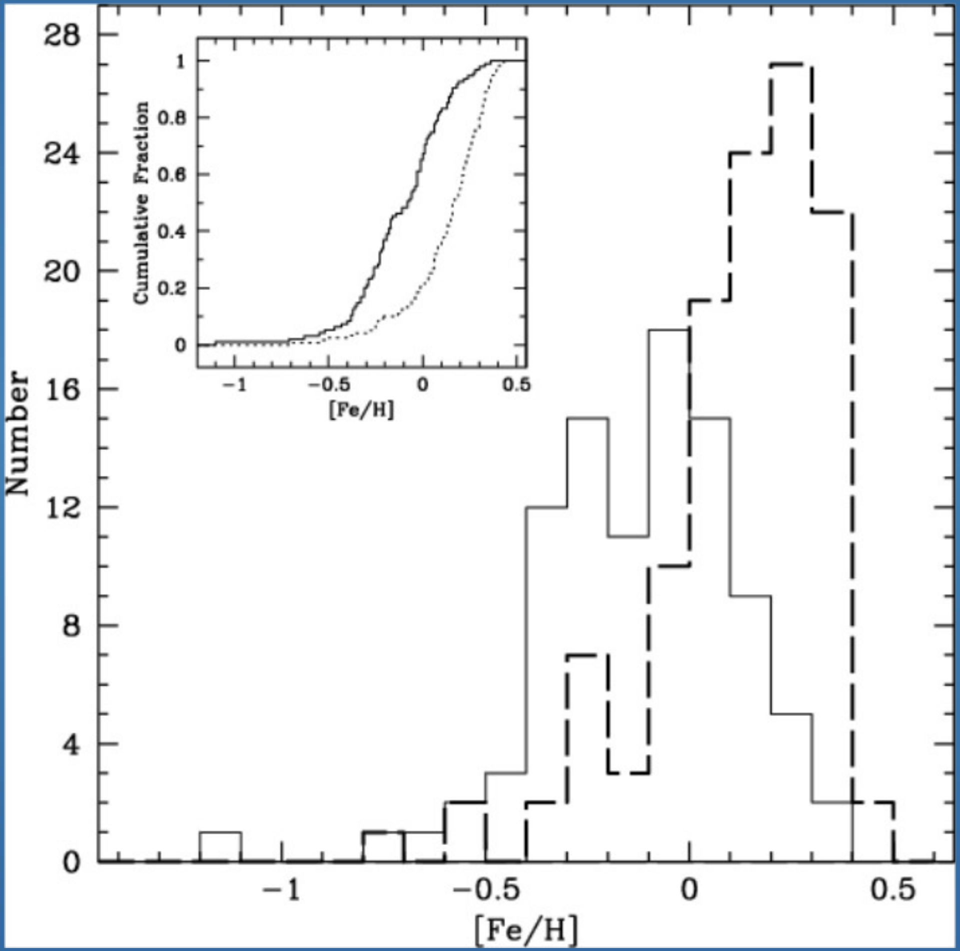
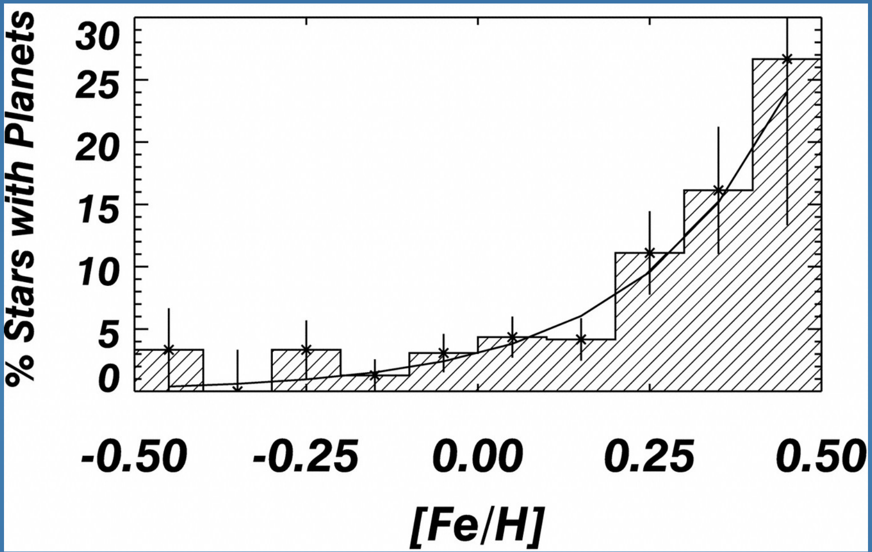
To infer the bulk chemical composition of exoplanets, understand their atmospheres and constrain formation processes


Credit: NASA/JPL-Caltech/T. Pyle (SSC)

Early studies: Metallicity excess

First found by Gonzalez (1997) – self pollution scenario
Later confirmed with larger samples – primordial hypothesis

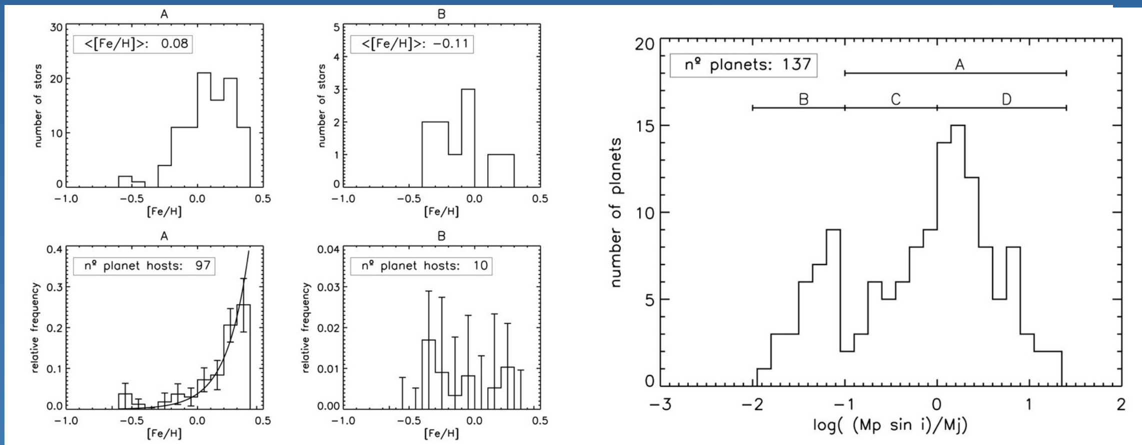


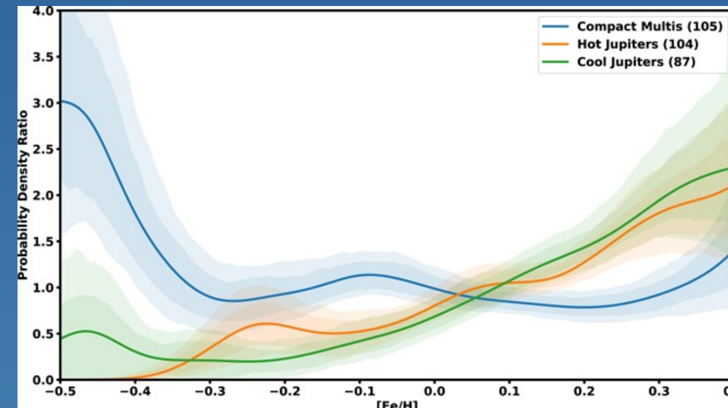


Fisher & Valenti (2005)

Metallicity excess for giant planet hosts
(Santos et al. 2004, 2005)

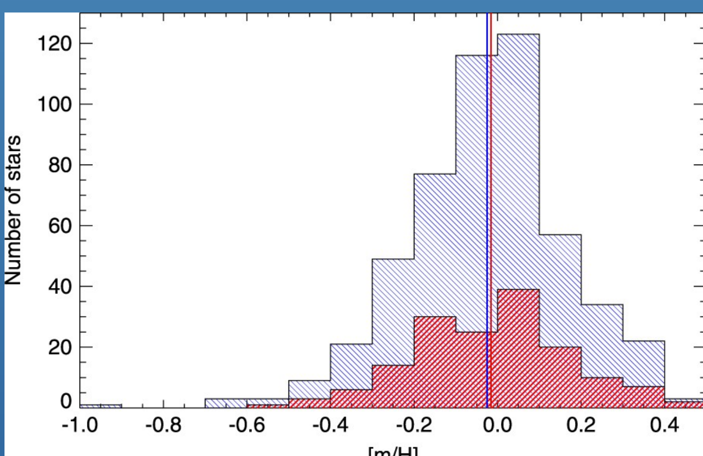
Metallicity excess for low-mass planet hosts?

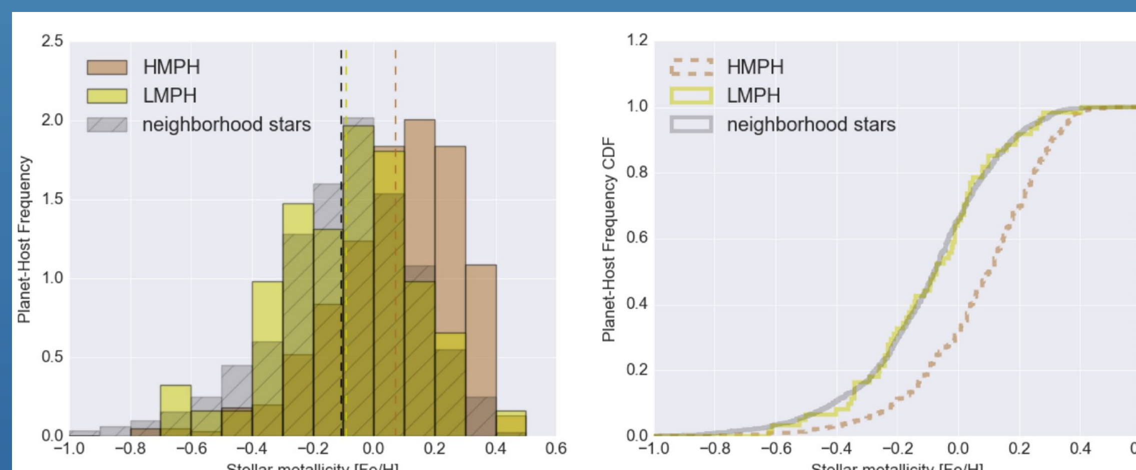




Brewer et al. (2018)

Metallicity distribution of HARPS and CORALIE samples (Sousa et al. 2011)





Buchhave & Latham (2015)
Kepler small radii hosts (red)

Sousa et al. (2018)

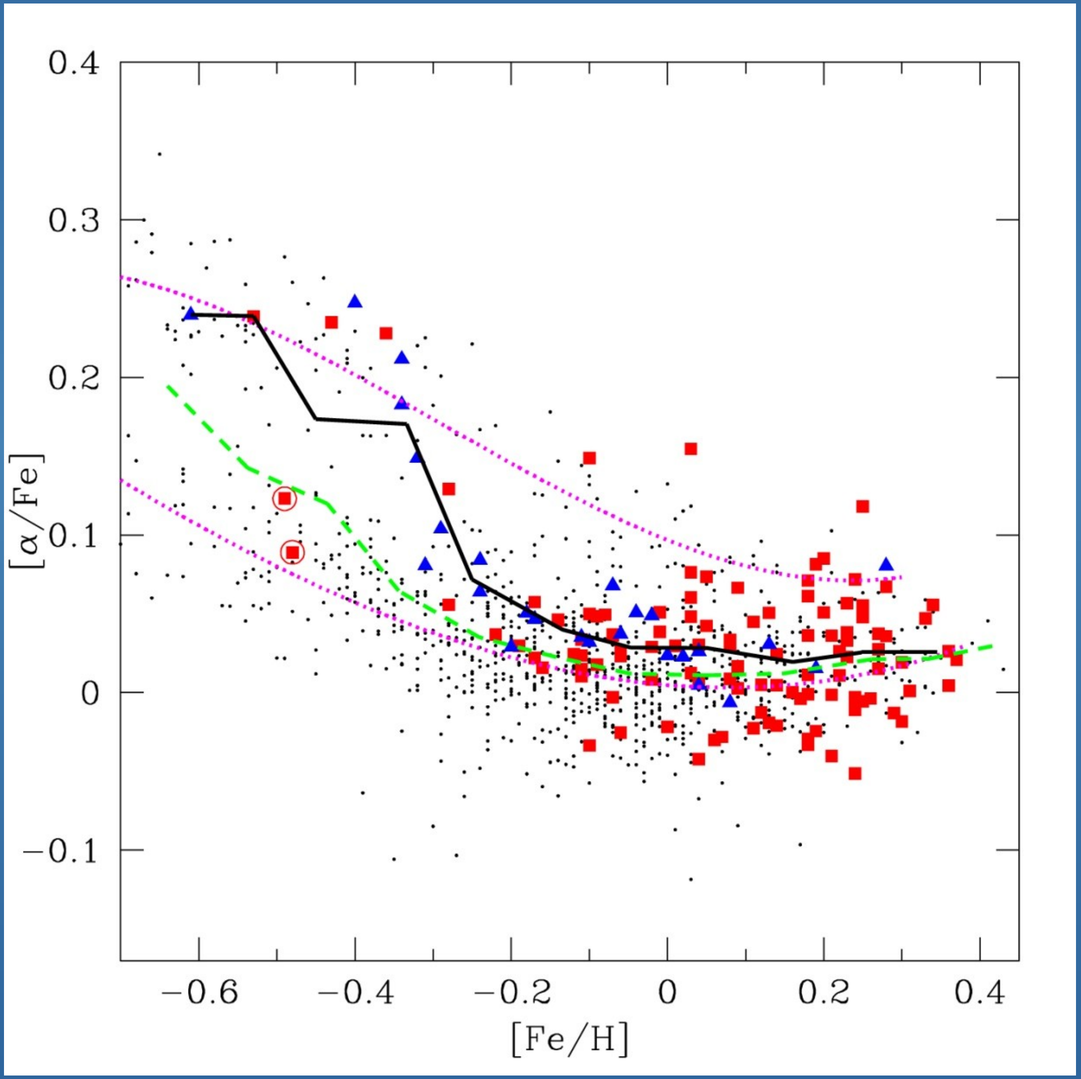
From iron to other species: Alpha elements

Planet hosts at lower [Fe/H] show an enhancement in α elements
(Adibekyan et al. 2012)

Most important elements for planet formation: Fe, O, Si, Mg.

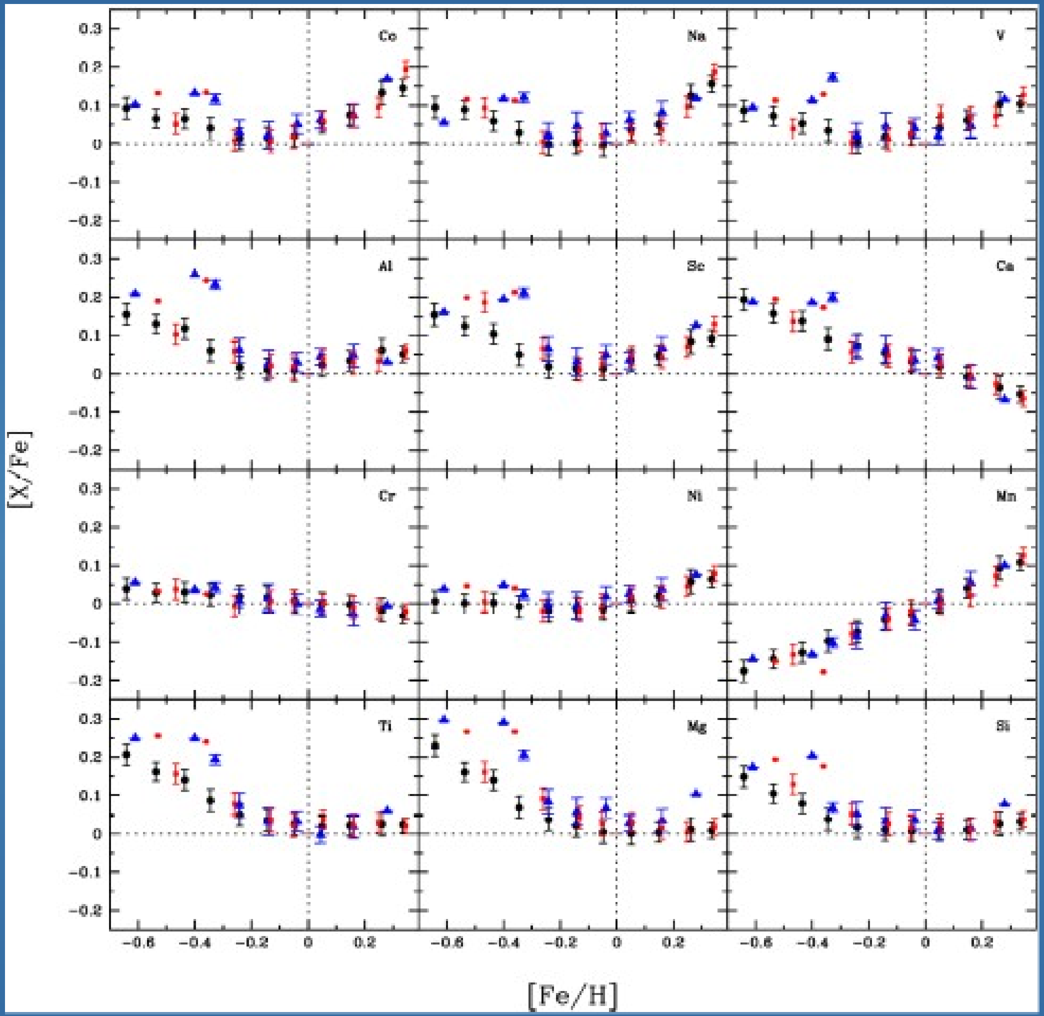
109 stars hosting **Jupiter** type planets, **26 stars** with **Neptunian** planets and **634 comparison stars**

Also seen in later works: e.g. Sharma+2024



[X/Fe] ratios of refractory elements in planet hosts

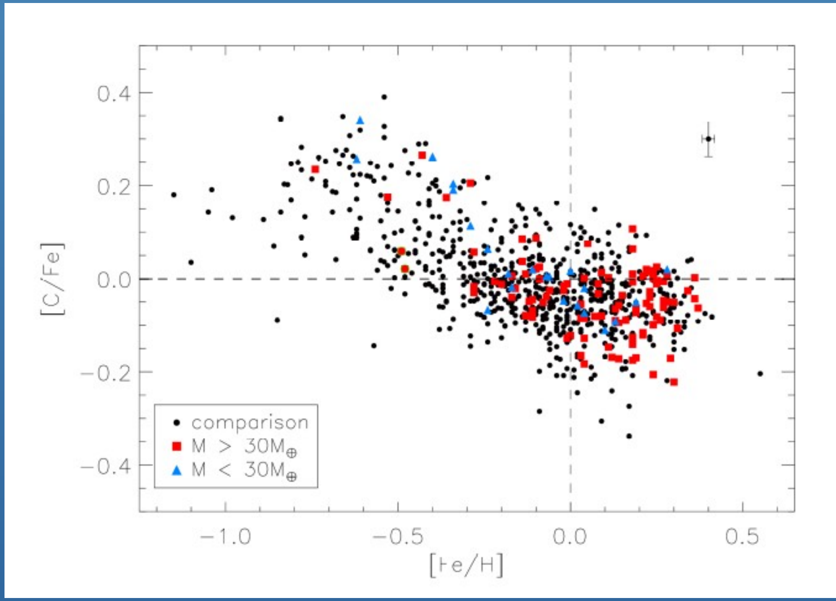
- The work by Adibekyan et al. (2012) using the HARPS GTO sample (109J+26N) found an **overabundance of Mg, Al, Si, Sc, Ti in planet hosts** when compared to single stars of the same metallicity, for [Fe/H] < -0.2-0.1
- The work by Delgado Mena et al. (2018) found a similar overabundance of Zn for planet hosts: **GCE of Zn similar to alpha elements**
- Underabundances of Ba in planets hosts found by Mishenina et al. (2016) and Delgado Mena et al. (2018)

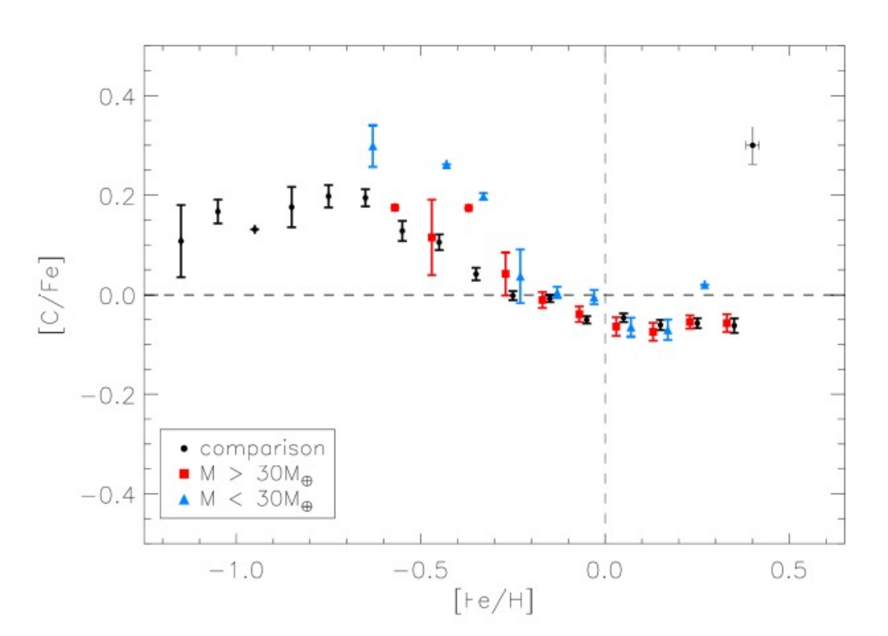


Adibekyan et al. (2012)

[C/Fe] in planet hosts

- [C/Fe] ratios are higher for planet hosts at [Fe/H] < -0.2 dex (see also Sharma+2024)
- Planet hosts at low metallicity tend to be **formed in the thick disk** (Haywood+09, Bashi&Zucker 2019)
- Planet hosts seem to have **higher carbon** when compared with single stars **only in the thick disk** → to be confirmed with a larger number of stars, also the trends with oxygen
- Need to consider the Galactic context for comparison purposes

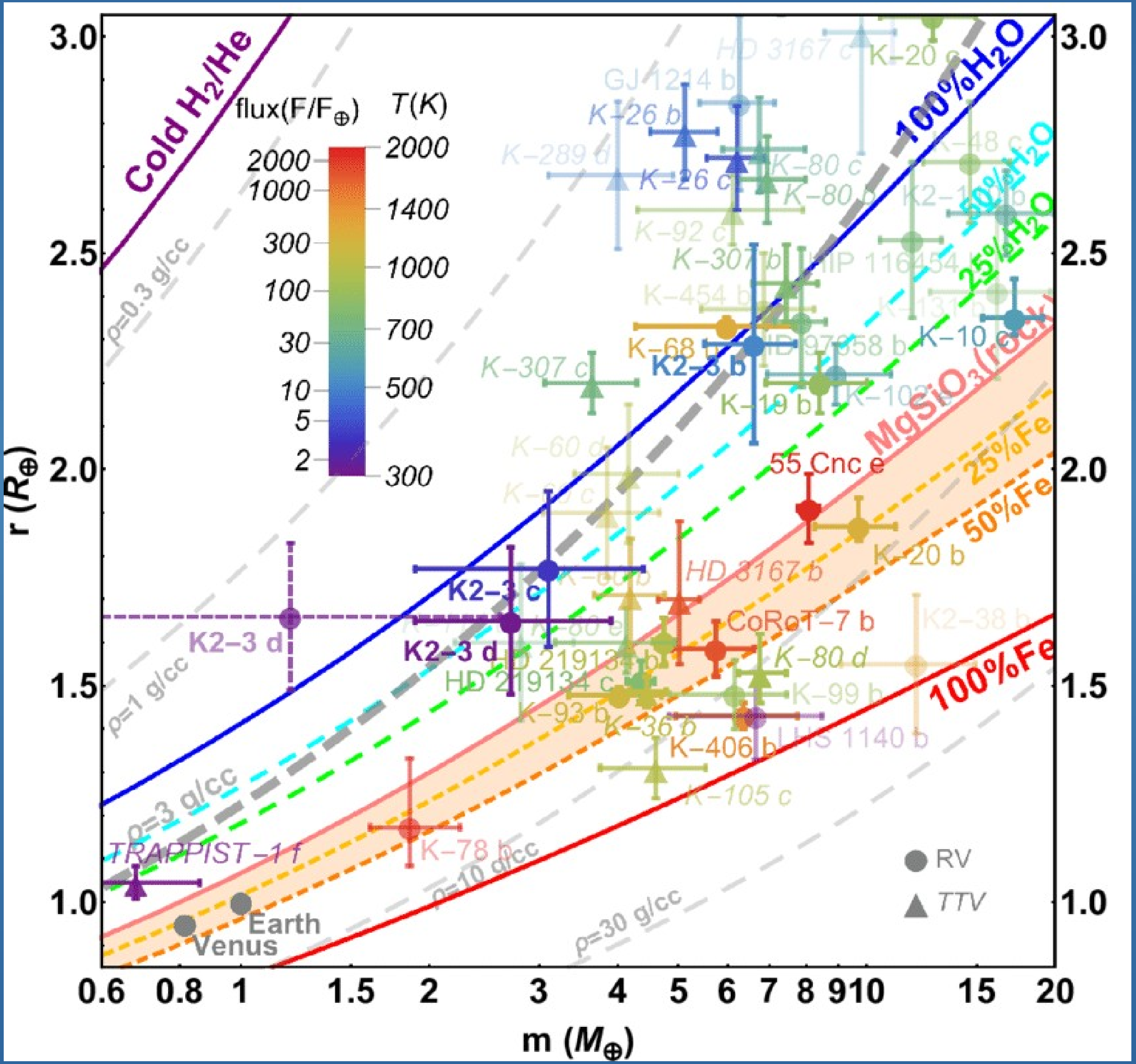




Delgado Mena et al. (2021)

Exoplanets Mass-Radius diagram

Stellar chemical composition can help to understand the different densities of planets --> different internal structure and bulk composition

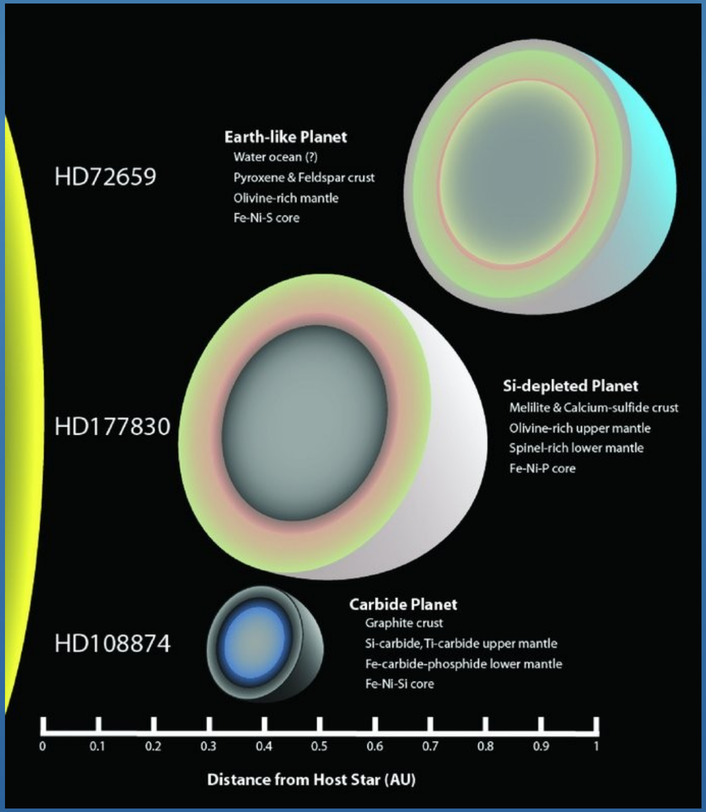


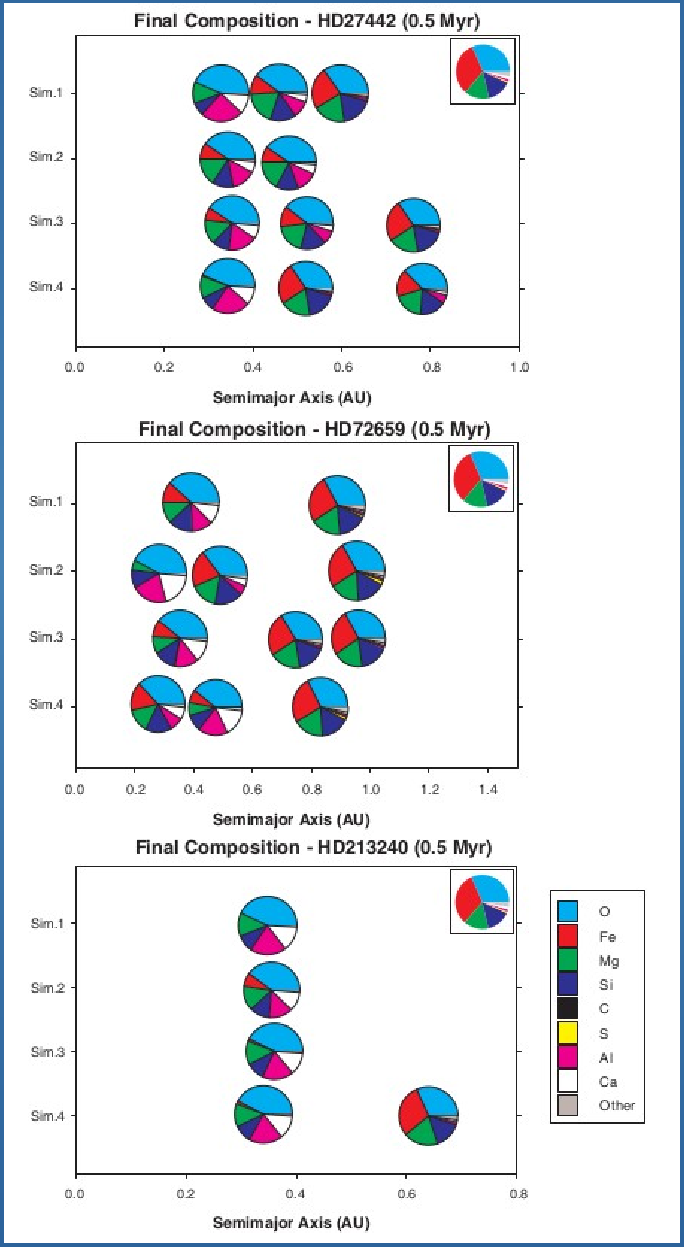
Damasso et al. (2018)

Bulk composition of exoplanets: first models

Bond et al. 2010: dynamical+chemical n-body simulations of planetary embryos using stellar abundances. Determine bulk compositions of planets at different orbital distances

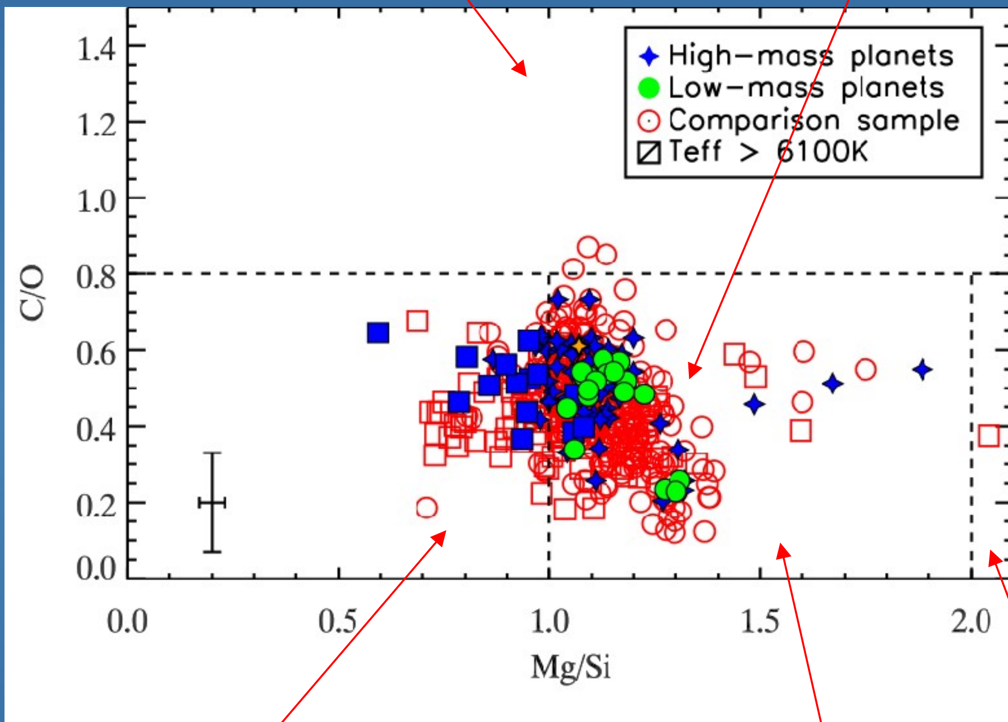
Strong influence of C/O and Mg/Si ratios (carbon planets? e.g. Seager&Kuchner 2005)





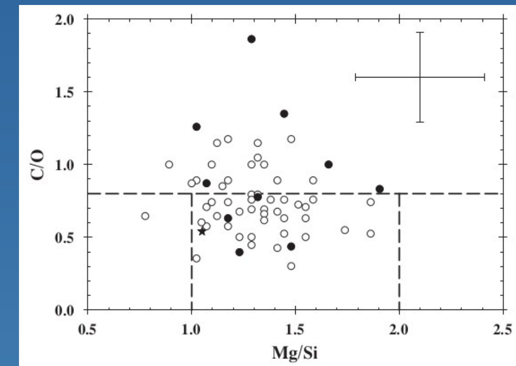
C-rich phases such as graphite, SiC and TiC

Si mainly present as SiO_2

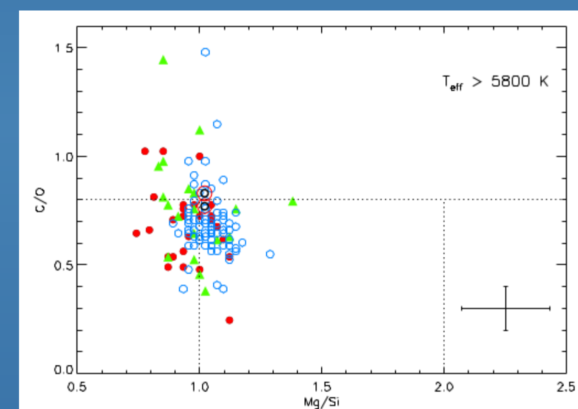


Suárez-Andrés et al. (2018)

Oxygen abundandes from Bertran de Lis (2015)



Bond et al. (2010)



Delgado Mena et al. (2010)

Mg as pyroxene ($MgSiO_3$) and excess Si as feldspars

Mg mainly distributed as olivine and pyroxene

All Si as olivine (Mg_2SiO_4), MgO

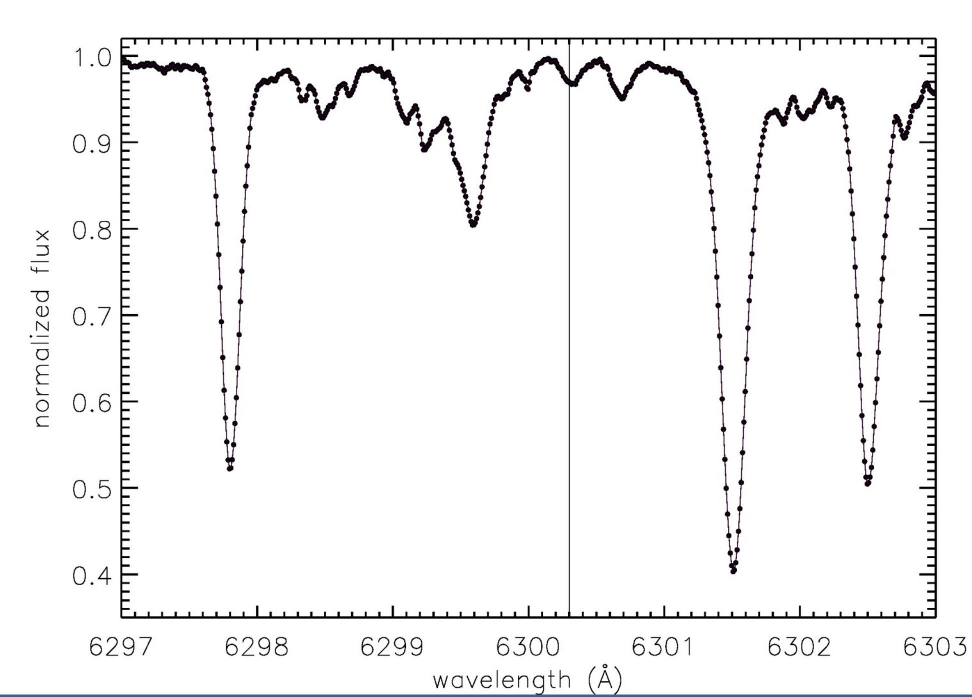
Caution with some stellar abundances - oxygen

[OI] line - 6300Å - weak and blended

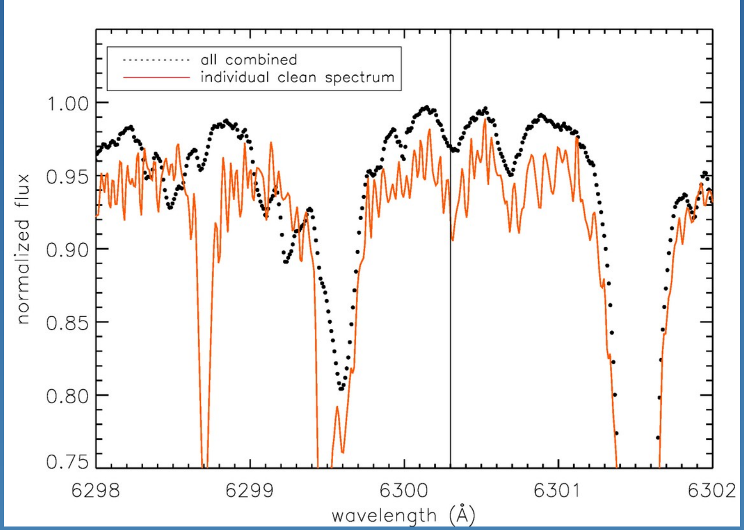
OI line - 6158Å - very weak

OI triplet - 7770Å - affected by NLTE

78 HARPS co-added spectra for a G2V star. S/N=650



Caution with some stellar abundances - oxygen



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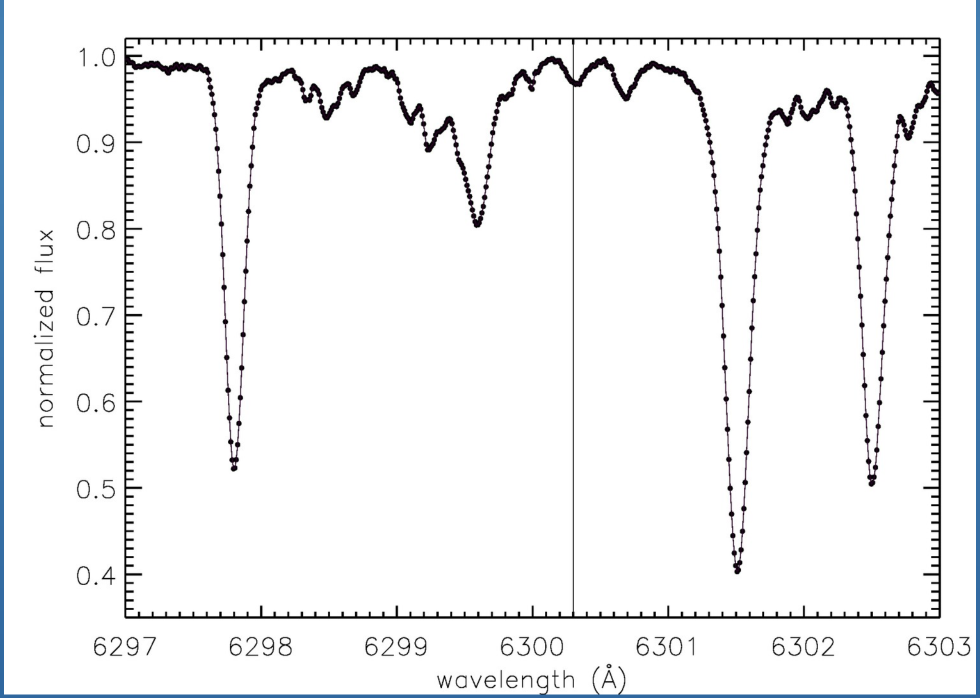
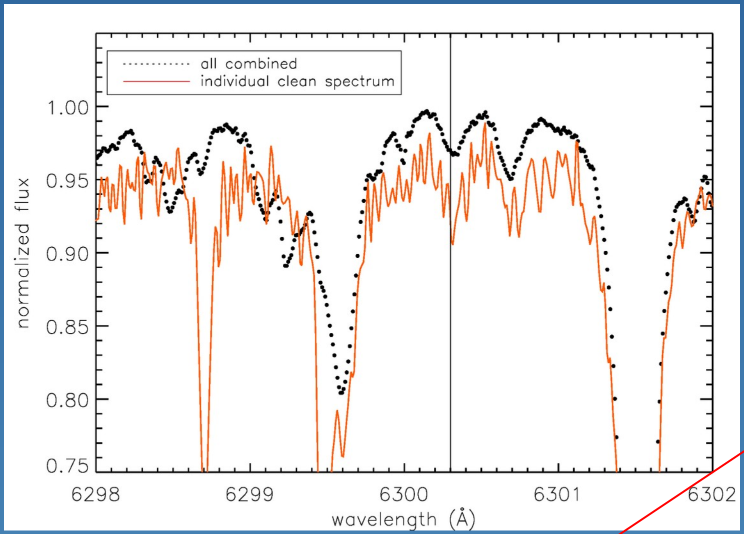
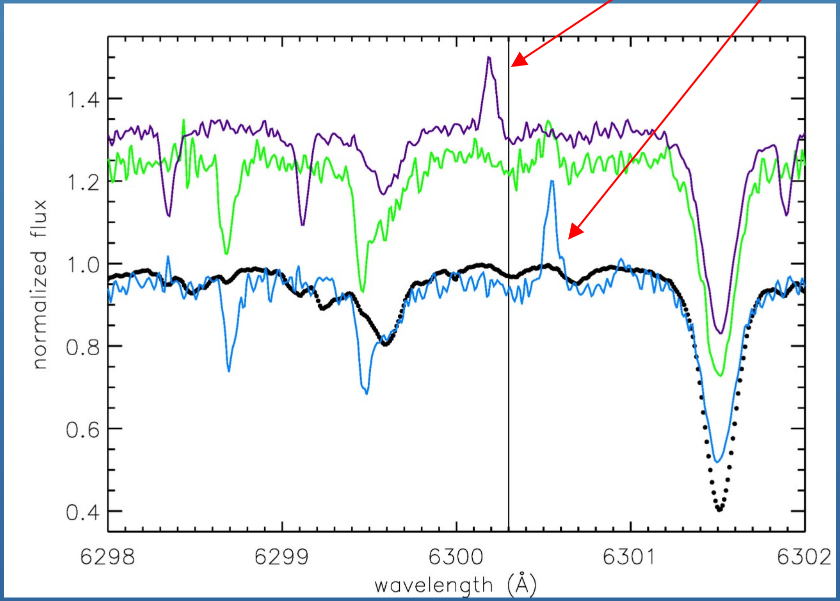
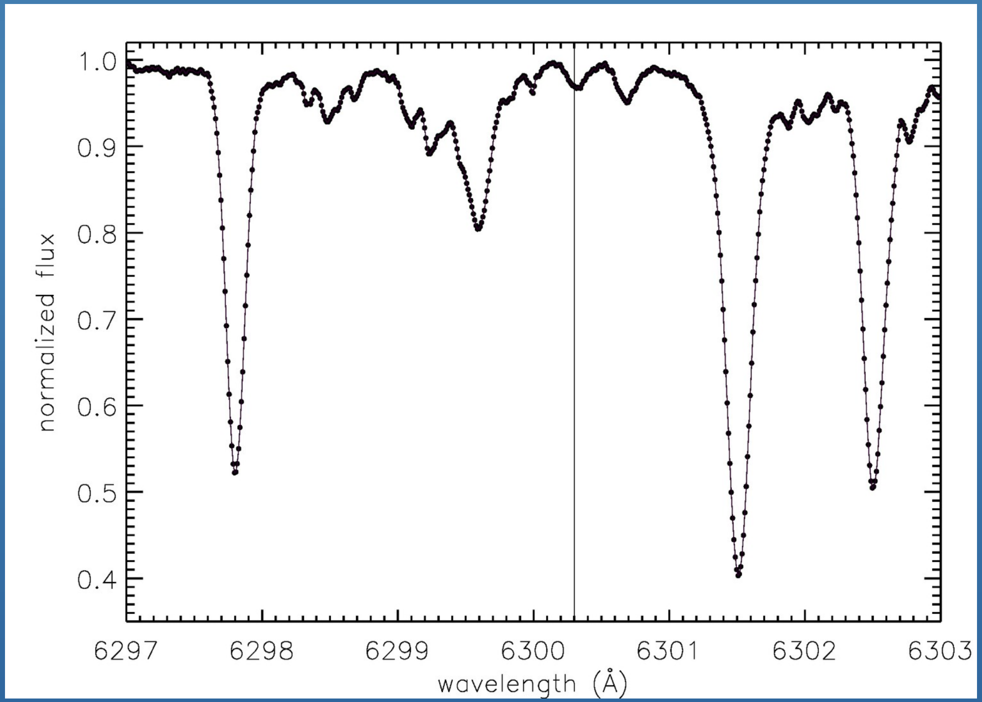


Caution with some stellar abundances - oxygen

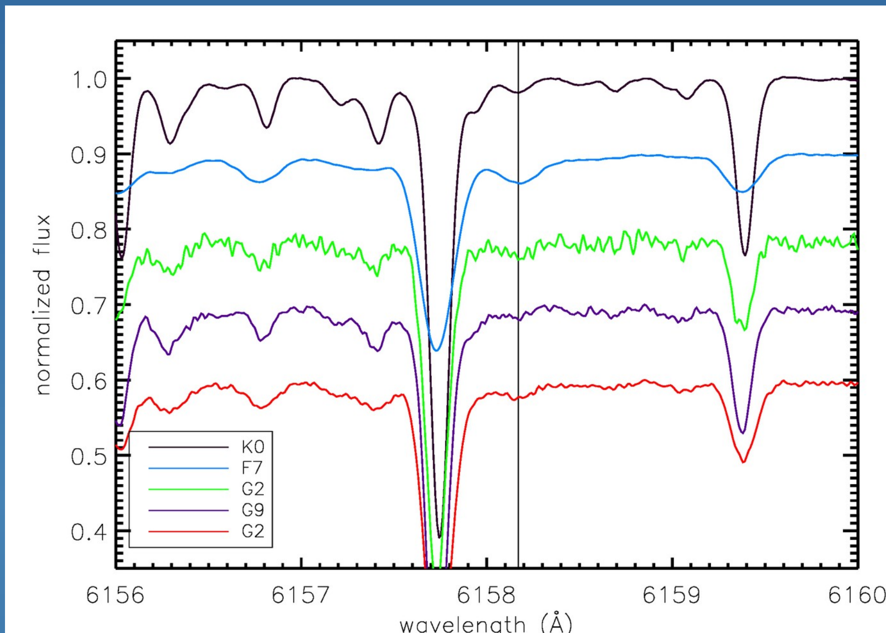


WARNING: Contamination by an oxygen airglow



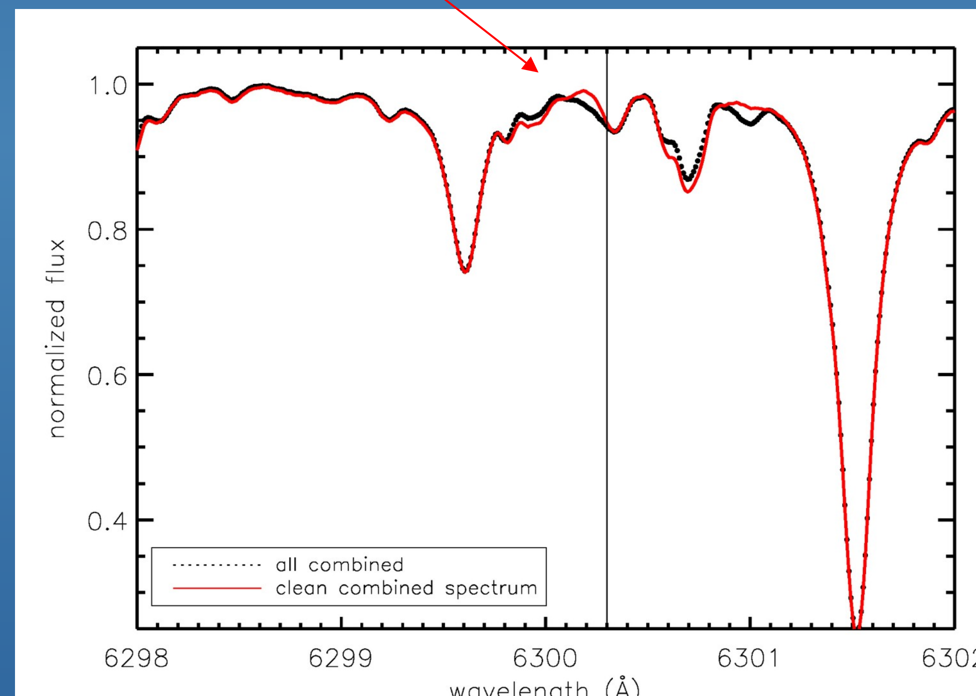


Caution with some stellar abundances - oxygen



OI line at 6158Å can only be measured at very high S/N and for not very cool stars.

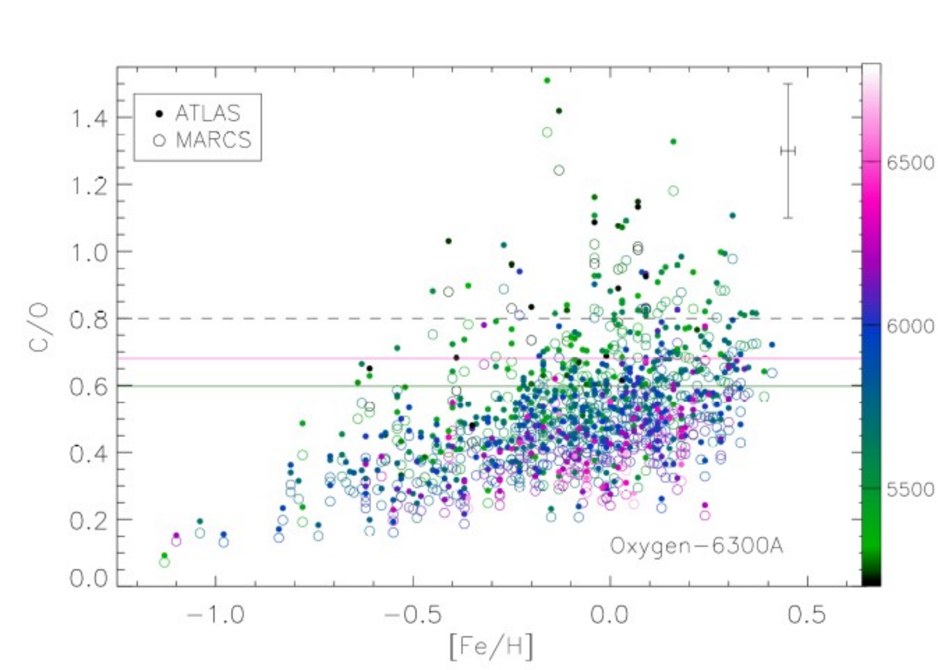
Tellurics can also affect the 6300Å oxygen line

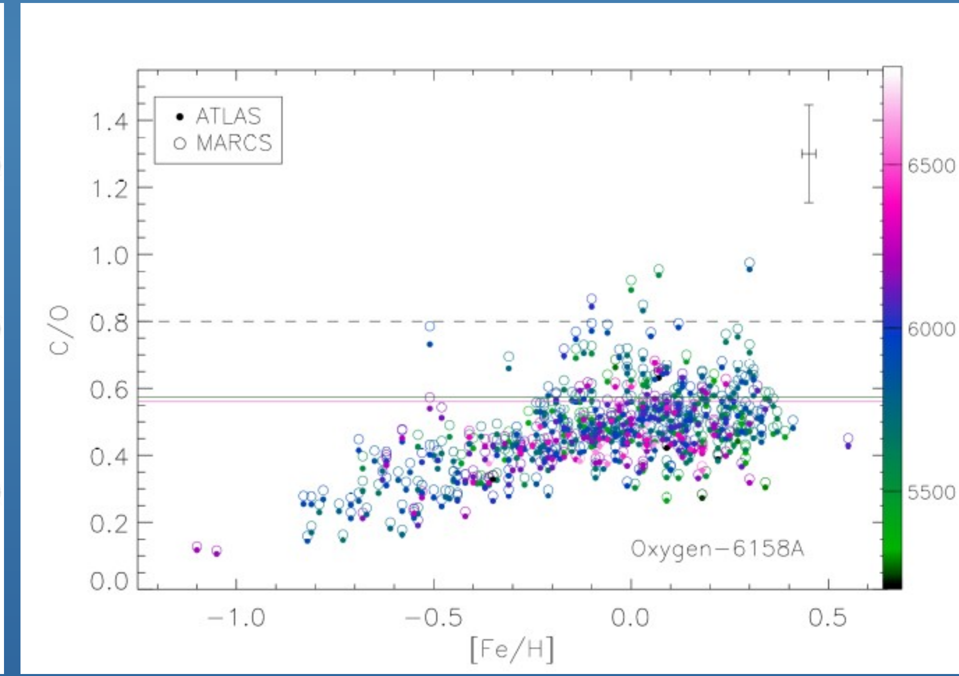


83 ESPRESSO co-added spectra for a K0V. S/N=960

Caution with some stellar abundances – C/O ratios

- C/O ratios derived with oxygen-6300Å line have a slight dependence on Teff, better to use oxygen line at 6158A (which is also of high excitation potential as CI lines)
- Larger difference between model atmospheres for the 6300A line (up to 0.18 dex)
- **Calculate [C/O] ratios for your stars based on your solar spectra** and then transform them to C/O using the desired solar reference value



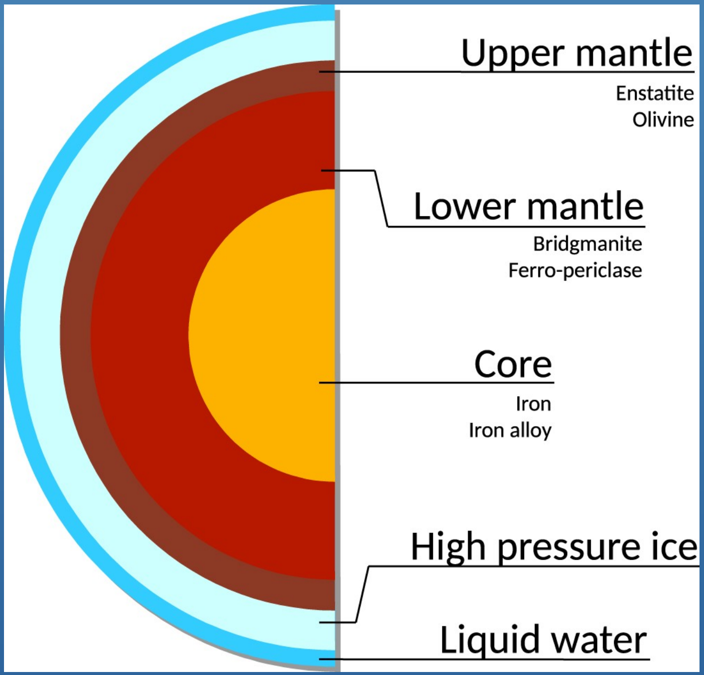


Delgado Mena et al. (2021)

Bulk composition of exoplanets: elemental ratios

Low condensation temperatures of the light elements carbon and oxygen make the planetary C/O ratio more dependent on the distance to the star where the planet was formed (e.g. **Thiabaud et al. 2015; Brewer et al. 2017**).

Use of Fe/Mg and Fe/Si ratios (e.g. **Dorn et al. 2015, Santos et al. 2015**) → similar ratios for the Sun, Mars, Venus and Earth → critical to reduce degeneracies of planet interiors and constrain the mantle composition



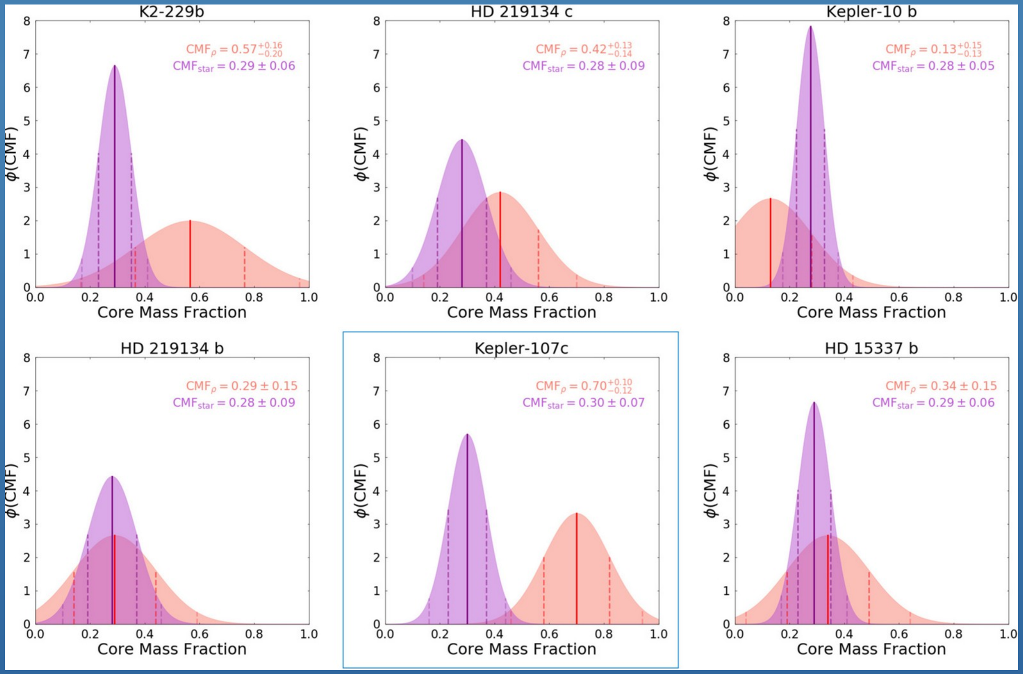
Brugger et al. (2017) - *assumption that the bulk Fe/Si ratio of a planet is similar to that of its host star allows to significantly reduce the existing degeneracy and more precisely constrain the planet's composition*

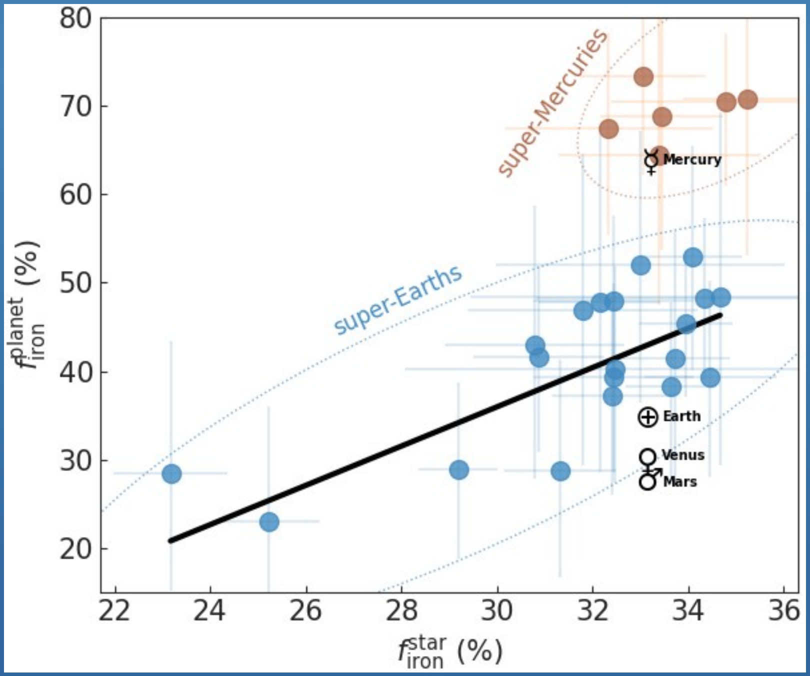
See also **Hinkel&Unterborn (2018), Dorn et al. (2017)**

Can we use stellar abundances as direct proxy of bulk composition?

Schulze et al. (2021)
Comparison of CMF from stellar abundances and CMF from planet mass and radius, assuming a planet with a solid Fe core and a mantle with oxidized silicates (no Fe)

Only in 2 planet hosts out of 11 they found a different CMF
Kepler-107 c: CMF_planet > CMF_star → Super Mercury planet?
55 Cnc e: CMF_star > CMF_planet → low density small planet





Shulze et al. (2021)

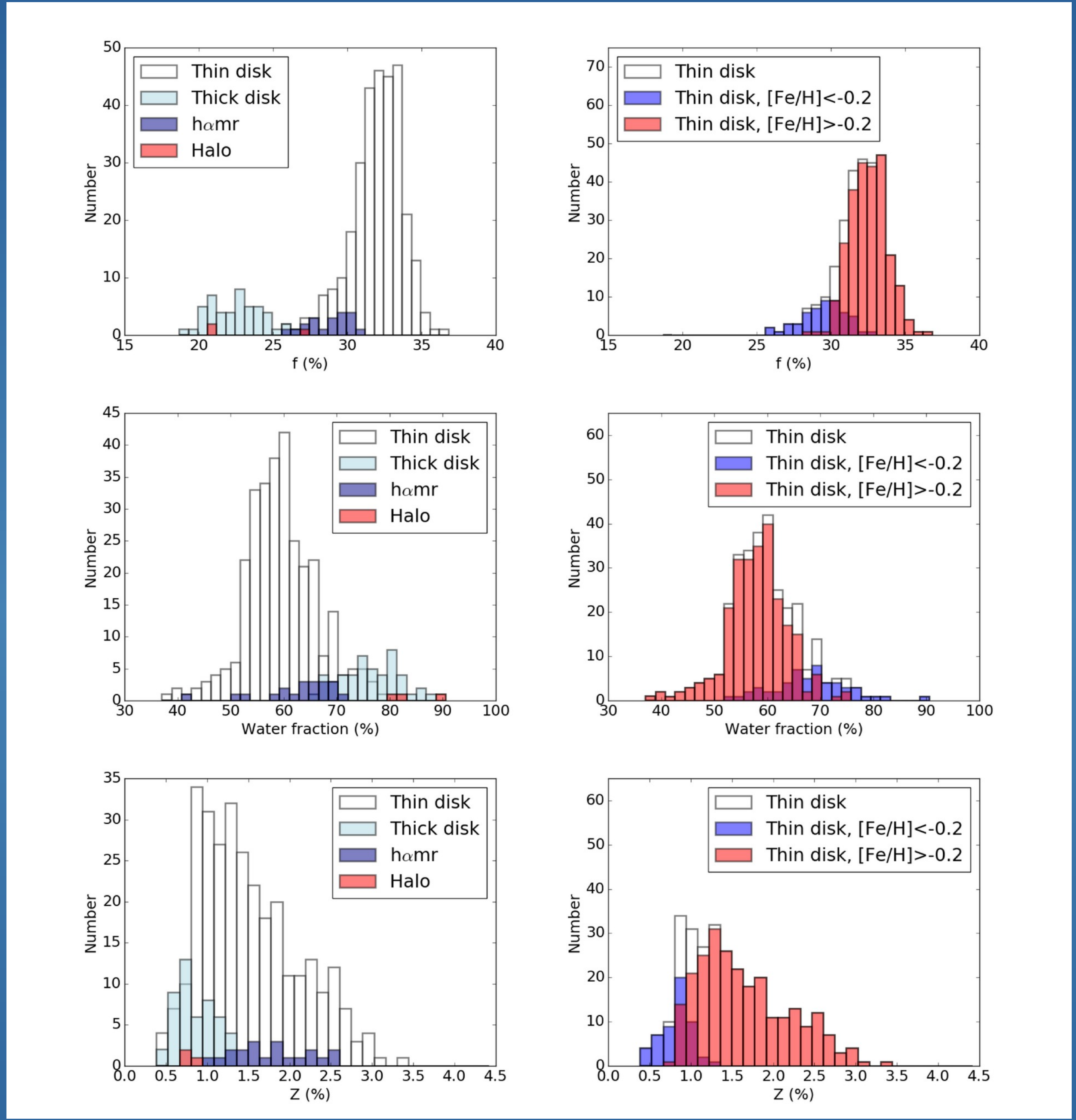
Adibekyan et al. (2021)

Planetary bulk composition in the Galactic context

Homogeneous abundances of Fe, Mg, Si, C, O to derive core-mass fractions and water mass fraction (assuming a simple stoichiometric models with a Fe core and silicates in mantle)

Different Galactic populations show different compositions in their planetary systems

Thick disk stars have larger water mass fraction



Santos et al. (2017)

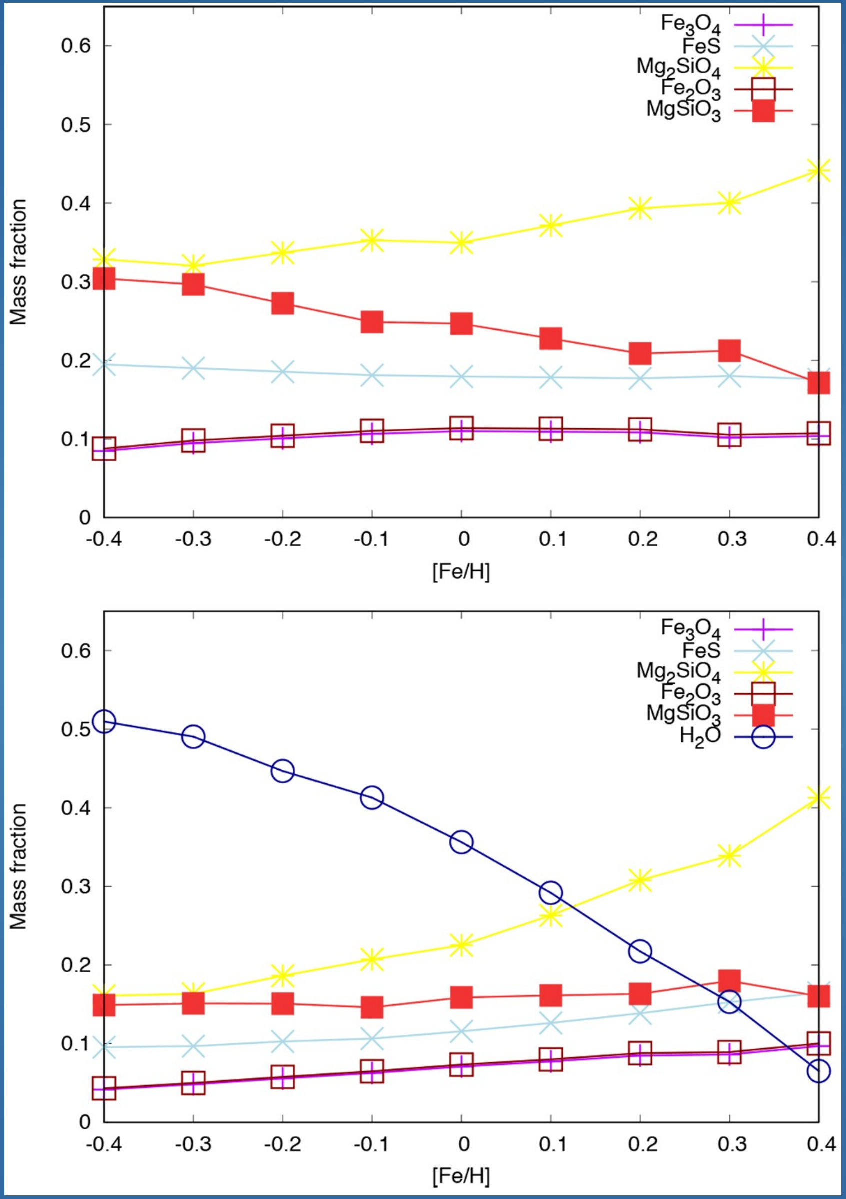
Planetary bulk composition in the Galactic context

Stellar abundances from GALAH to derive mass fractions of different compounds

Solids formed interior to the water ice line (upper panel) → rise in the Mg_2SiO_4 fraction and decline in the $MgSiO_3$ fraction is visible, caused by the increase of Mg/Si for increasing [Fe/H].

Solid planetary building blocks formed exterior of the water ice line (lower panel) → reduced water ice fraction with increasing [Fe/H], which is then compensated by an increase in Mg_2SiO_4.

→ see also the more recent works by **Cabral+2023 and Nielsen+2023**



Bitsch & Battistini et al. (2020)

Radioactive nucleides

Abundances of radioactive nucleides (K, Th, U) in the Earth are critical for the plate techtonics and vulcanism which in turn can impact planet habitability

Unterborn et al. (2015), Botelho et al. (2019) – abundances of Th in solar twins

Wang et al. (2020) – use of Eu abundances as a proxy for radiogenic heat

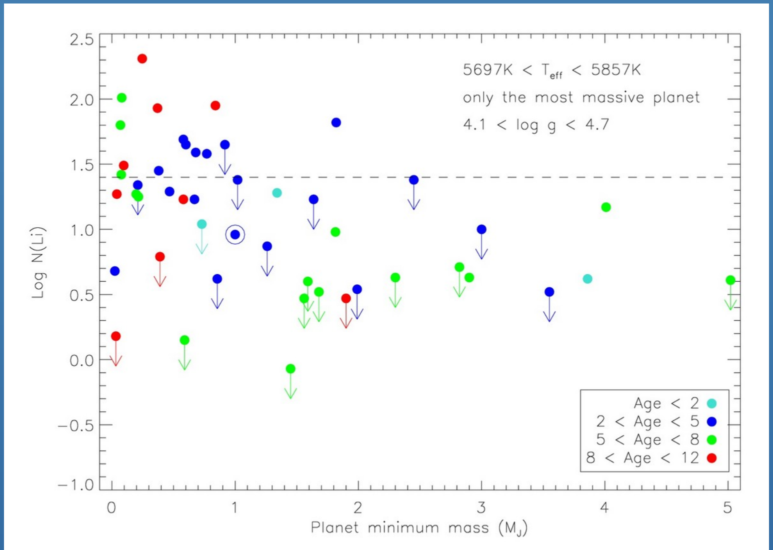
Planet formation effects on stellar abundances?

Light elements provide information regarding the distribution and mixing of matter within a star.

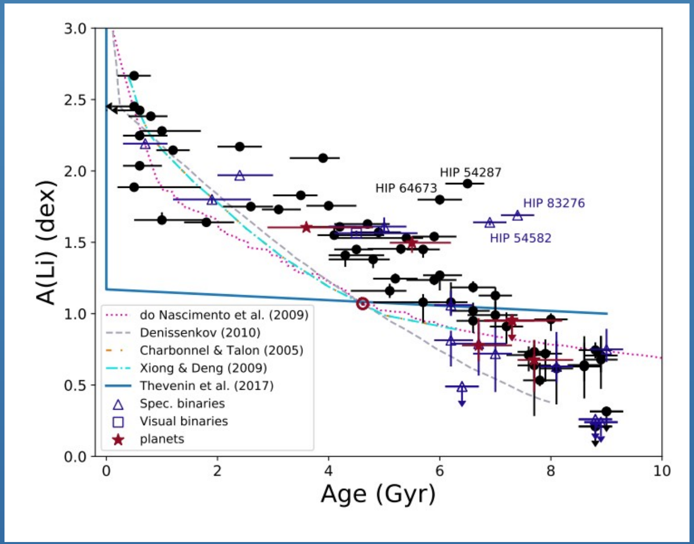
Li is depleted at a temperature of 2.5 million K primarily during the PMS but it can also be destroyed in stellar envelopes if any mixing process exists (e.g. Dumont et al. 2021)

→ Enhanced depletion of Li on planet hosts only in the solar Teff range (Israelian et al. 2009, Delgado Mena et al. 2014, Gonzalez et al. 2015)

→ Li depletion is only an age effect (Baumann et al. 2010, Carlos et al. 2019)



Delgado Mena et al. (2014)



Carlos et al. (2019) → most lithium-depleted stars also have fewer refractory elements

Neptunes → higher dispersion → no planet effect

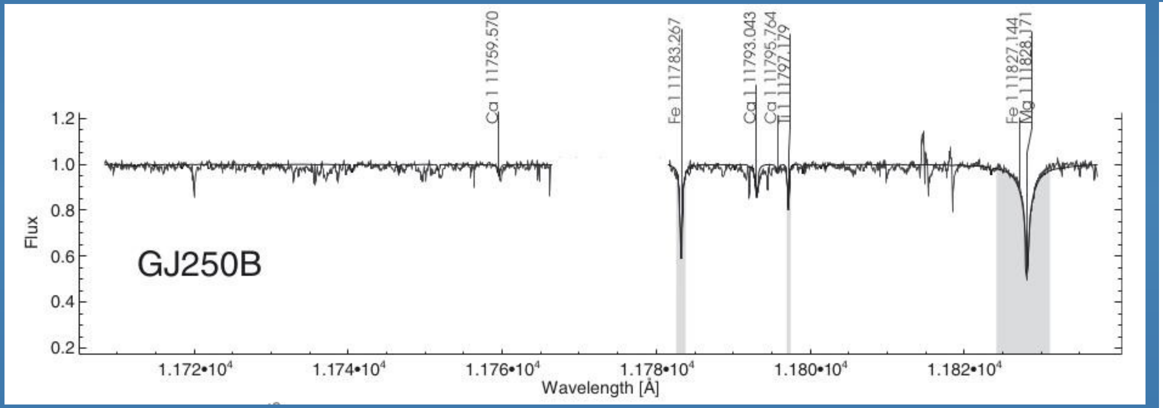
Jupiters → longer disk lifetime → major destruction (Bouvier 2008)

more frequent and violent accretion bursts--> major destruction (Baraffe&Chabrier 2010)

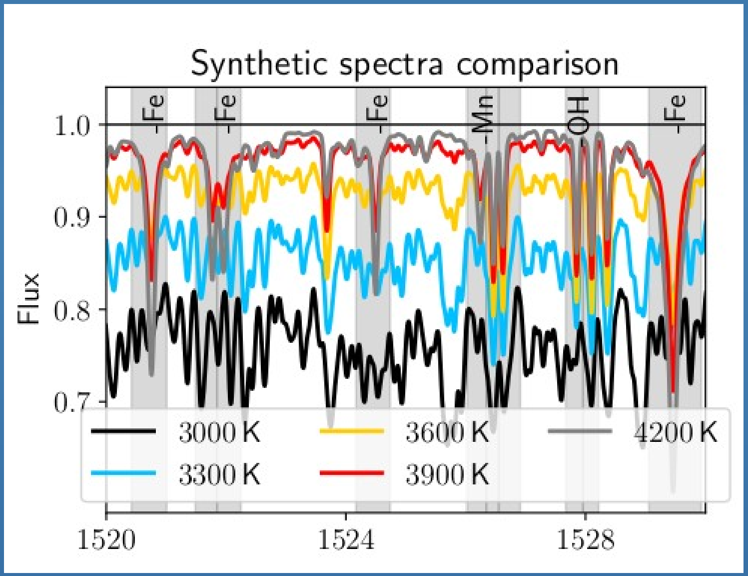
Future prospects

Improve characterization of M dwarfs

Stellar parameters with medium or high-resolution spectra: e.g. Onehag+2012, Lindgren+2016, Veyette+2017, Passegger+19, Souto+2020, Sarmento+21, Marfil+21, Olander+21, Cristofari+22)



Onehag et al. (2012)

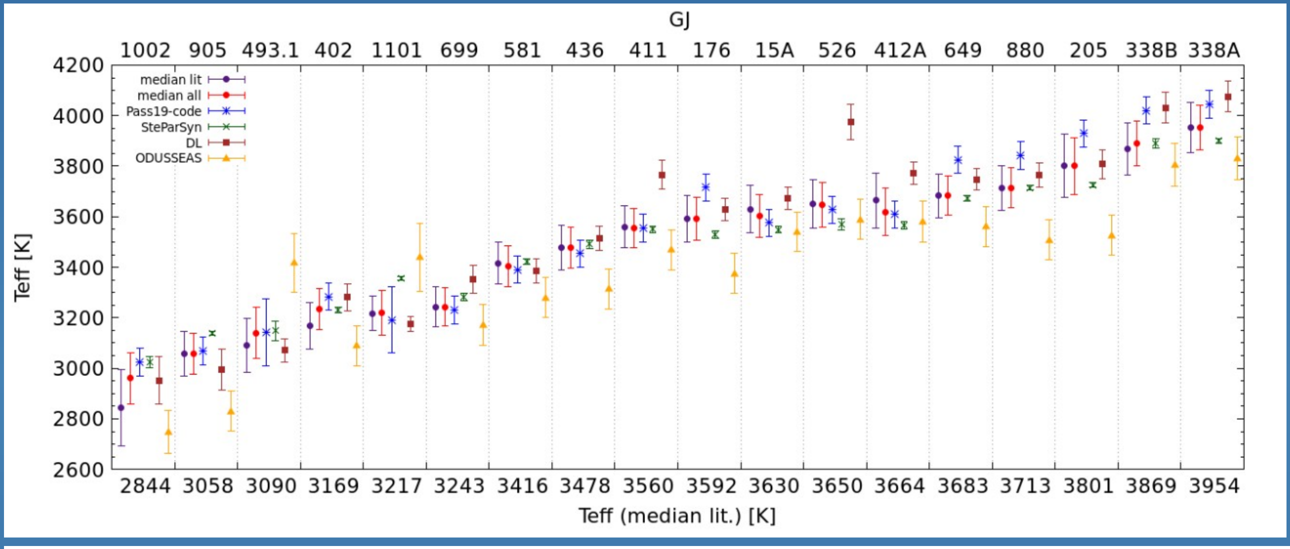


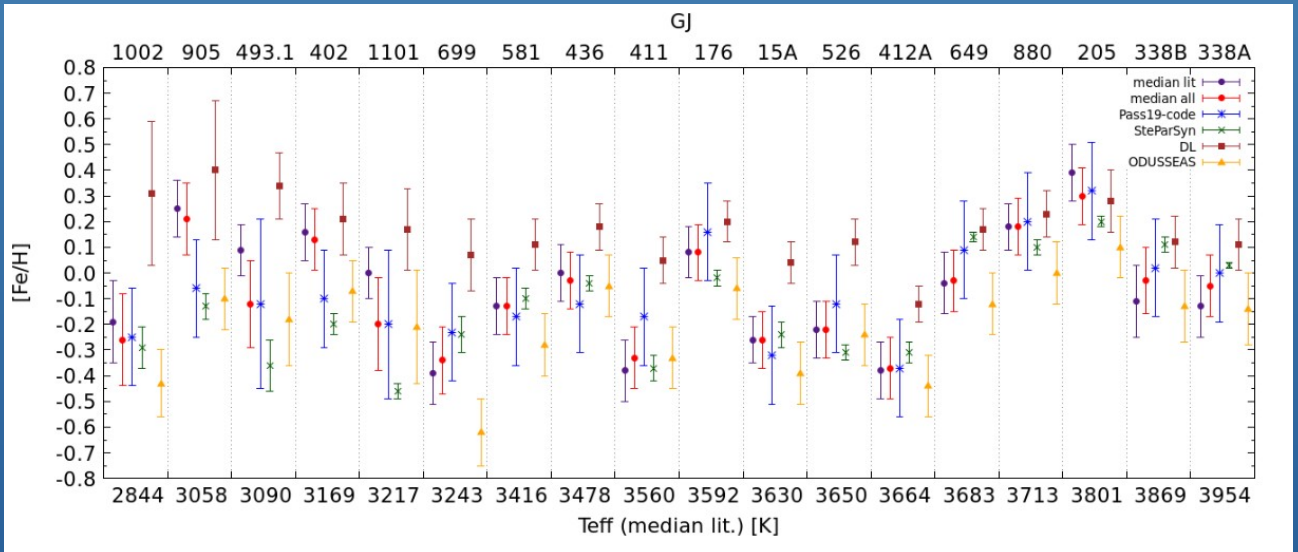
Sarmento et al. (2021)

Future prospects

Improve characterization of M dwarfs

NIR high resolution spectrographs will be a major advance: CARMENES, Spirou, NIRPS, CRIRES+

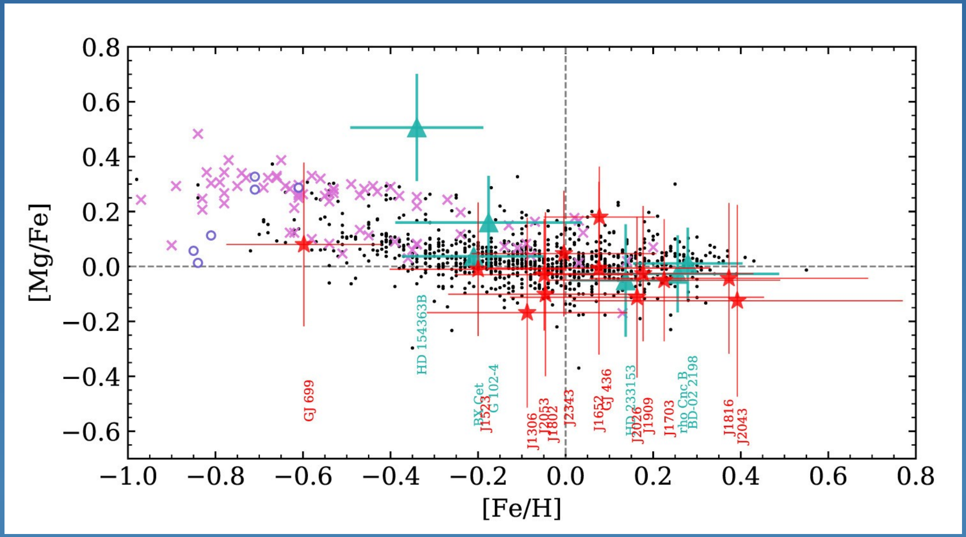


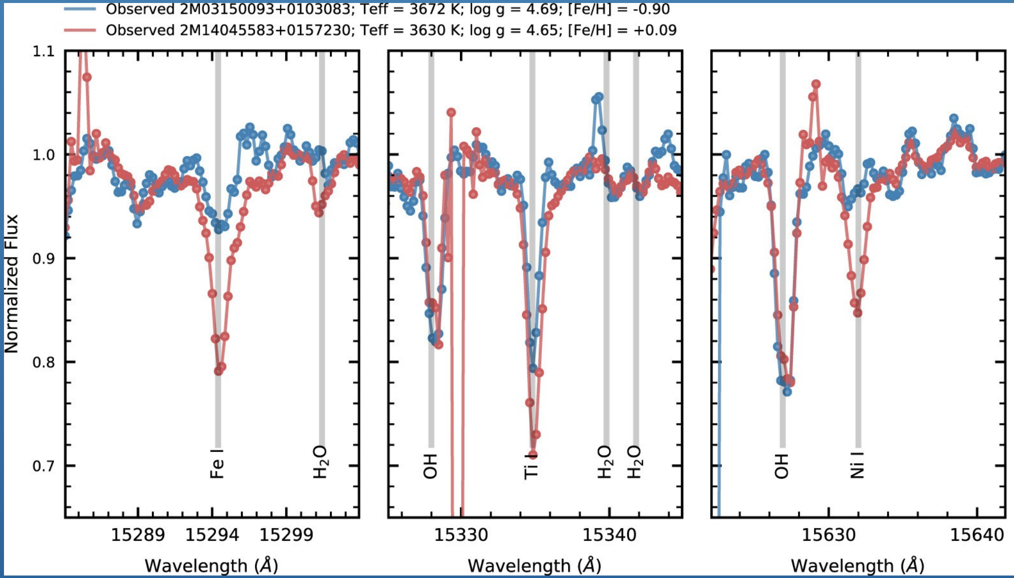


Passegger et al. (2022)

Future prospects

Improve characterization of M dwarfs





Ishiwaka et al. (2020,2022)

Spectra from CARMENES and Subaru/IRD

Abundances of Na, Mg, Si, K, Ca, Ti, V, Cr, Mn, Fe for 19 M dwarfs

Most atomic lines are sensitive to changes in abundance not only of the corresponding elements but also of other elements, especially dominant electron donors such as Na and Ca

Souto et al. (2022)

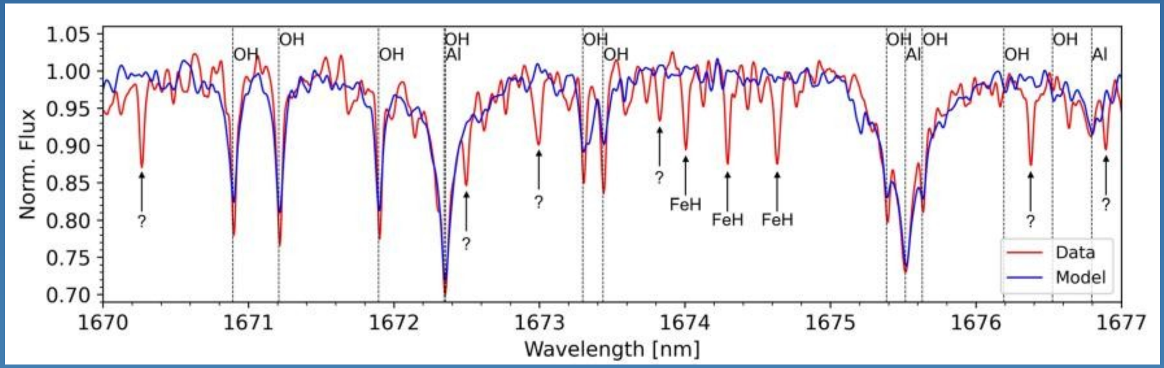
Spectra from APOGEE

Abundances of C, O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, and Ni for 11 M dwarfs in FGK binaries

Offset in stellar parameters but not [X/Fe] ratios with respect to ASPCAP

Future prospects

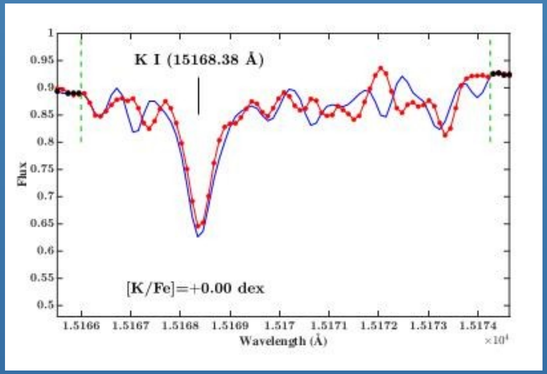
Improve characterization of M dwarfs

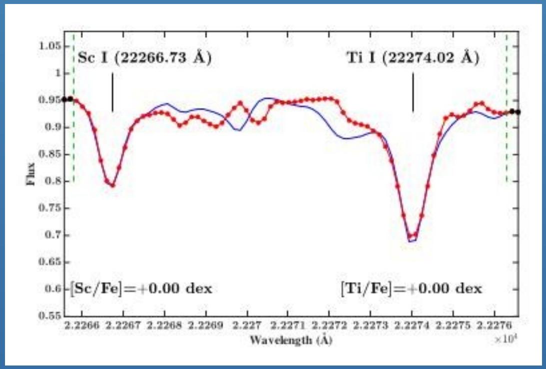


Jahandar et al. (2024)

Very high S/N spectra from SPIRou to obtain parameters and abundances of 15 elements

Need to improve models to identify missing lines



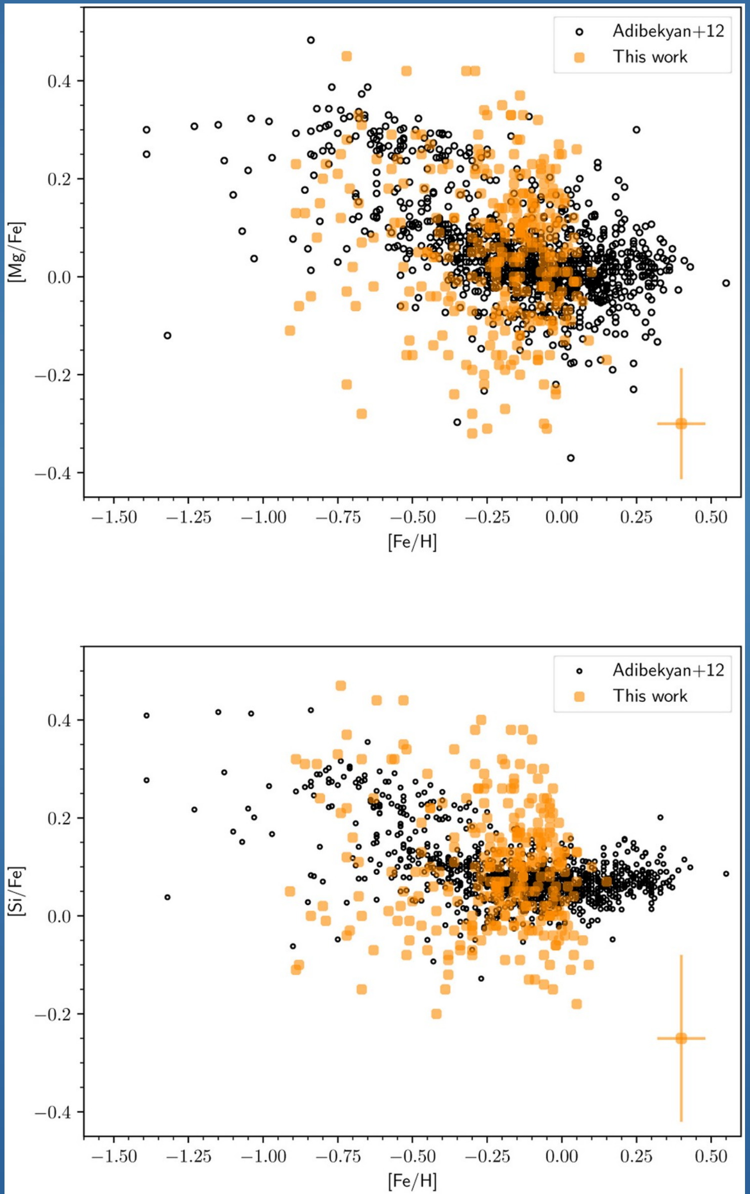


Hejazi et al. (2024)

Abundances of 10 elements using IGRINS spectra (R~45000) for the planet host K2-18b

Future prospects

Improve characterization of M dwarfs



Tabernero et al. (2024)

Spectra from CARMENES

Abundances of Mg, Si for 314 dwarf stars with spectral types K7.0–M5.5

High dispersion compared to FGK stars but compatible abundances for stars in multiple systems.

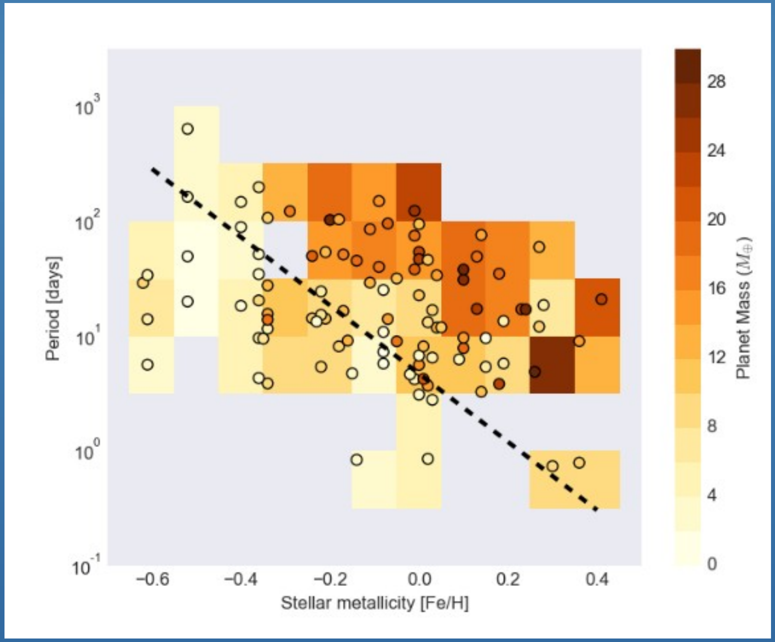
Not possible to determine abundances for M6.0V and later spectral types

Sweet-Cat: a catalogue for stellar parameters of exoplanets

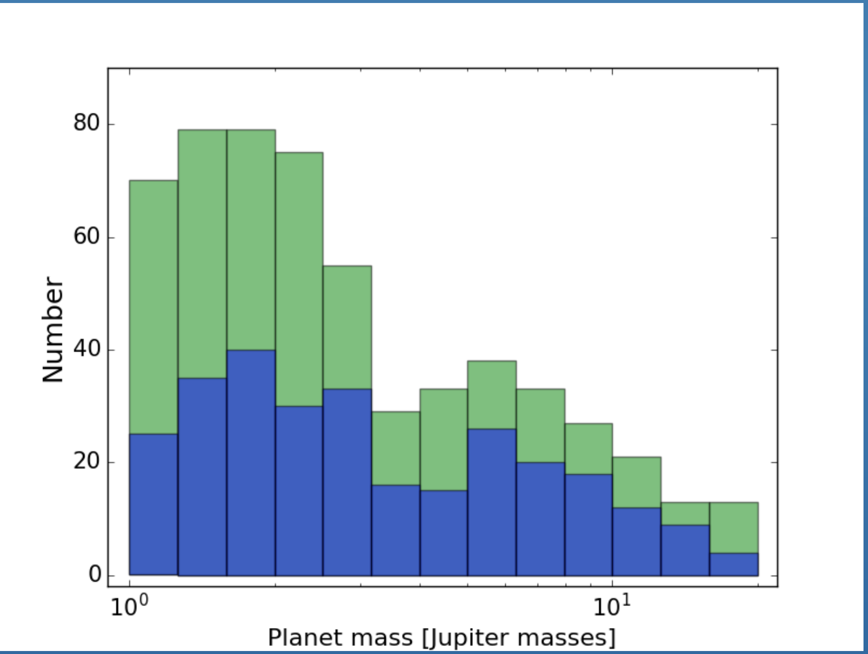
http://sweetcat.iastro.pt/

Homogeneous parameters for 68% FGK planet hosts with V<12 (mostly with HARPS and UVES *R*>100000 spectra) → Santos+2013, Sousa+2021, Sousa+2024

To be complemented with stellar abundances of C, O, Mg and Si



Sousa et al. 2019: Period-metallicity-mass correlation for low mass planets



Santos et al. 2017: planet hosts with planets>$4M_J$ have lower metallicities and are more massive

Ariel stellar characterization

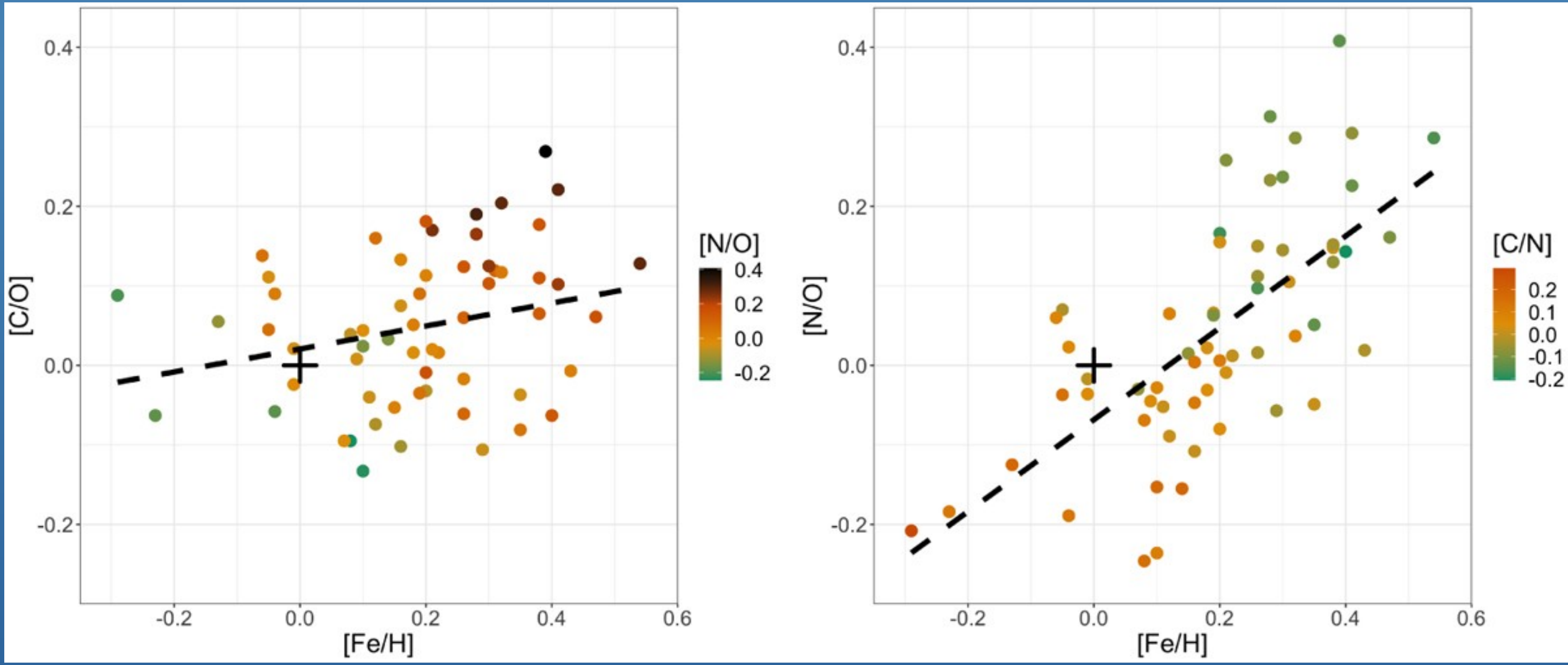
Homogeneous parameters and abundances for Ariel targets are needed to understand the exoplanet atmospheres

Stellar parameters:

Magrini et al. (2022) + Tsantaki et al. (2024) (fast rotators) + M dwarfs (in prep.)

Chemical abundances:

CNO: da Silva et al. (2024) + refractories+S: Delgado Mena et al. (in prep)



Da Silva et al. (2024)

Conclusions

- Precise stellar characterization is required to discover planets and to understand their formation and composition

- The chemical composition of the protostellar cloud conditions the formation of planets: stars need to have a minimum quantity of metals in order to form planets around them

- Certain elements are clue to unveil the bulk internal composition and structure of exoplanets (Fe, Mg, Si, C, O, radioactive elements)

- Chemical abundances can be affected by planet formation


Thanks