CHEMICAL COMPOSITION OF STARS AND ROCKY EXOPLANETS

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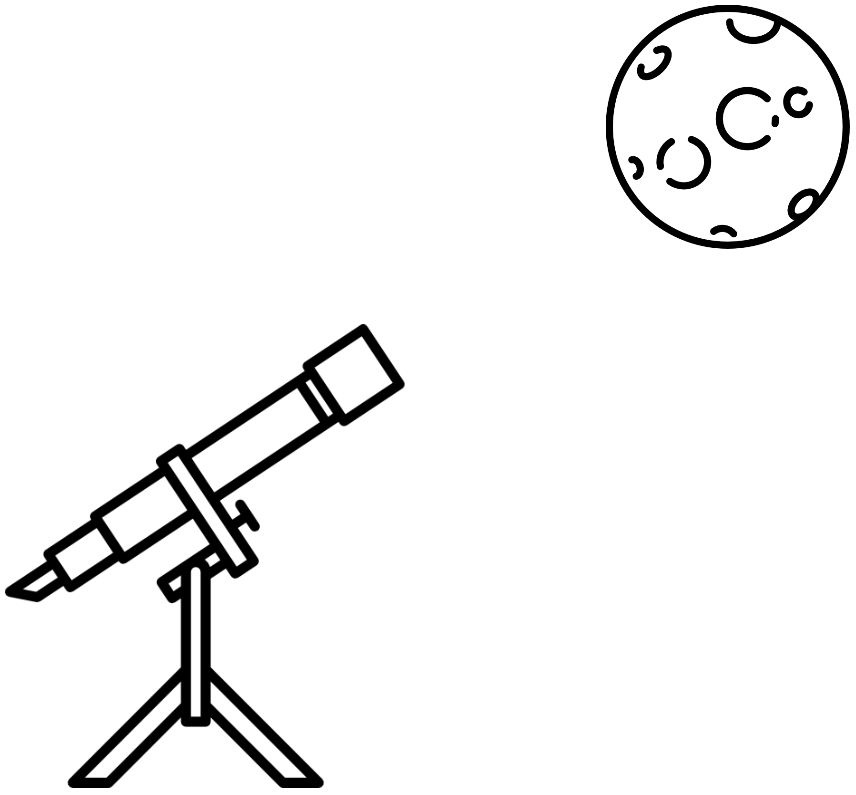
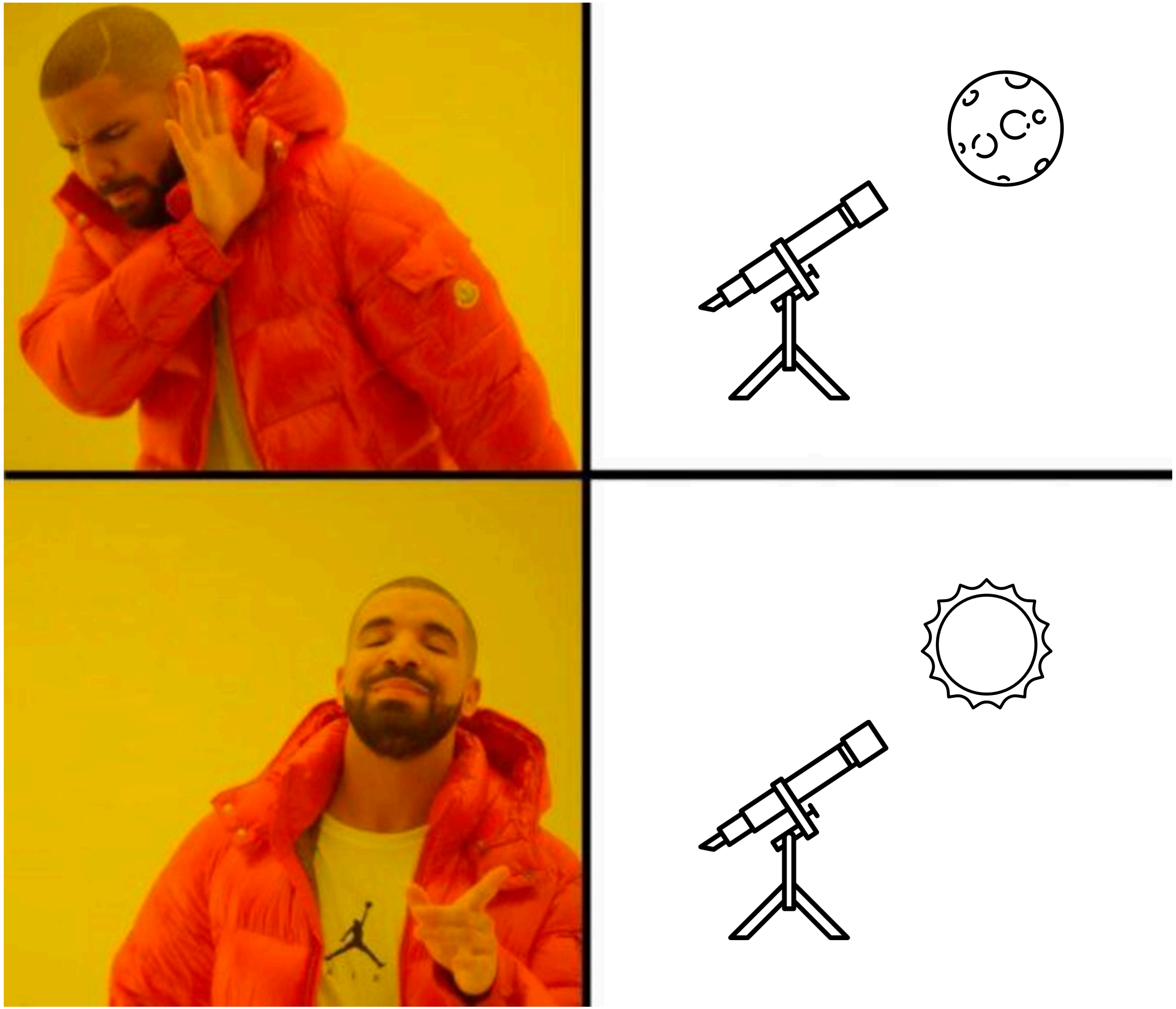
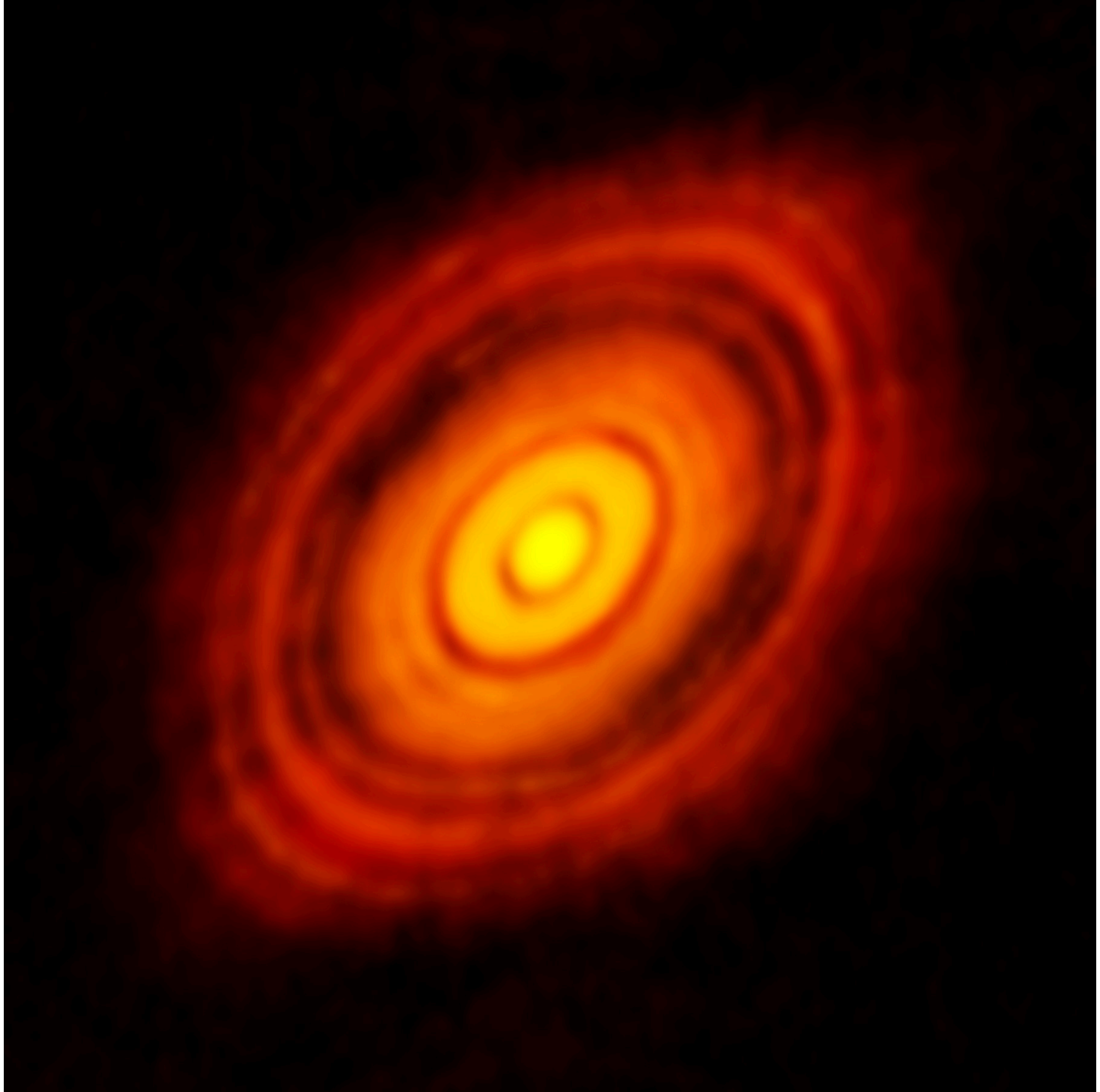
What are exoplanets made of?





What can
stellar compositions
tell us about
planet compositions?

stars & planets form side-by-side from the same primordial nebulae

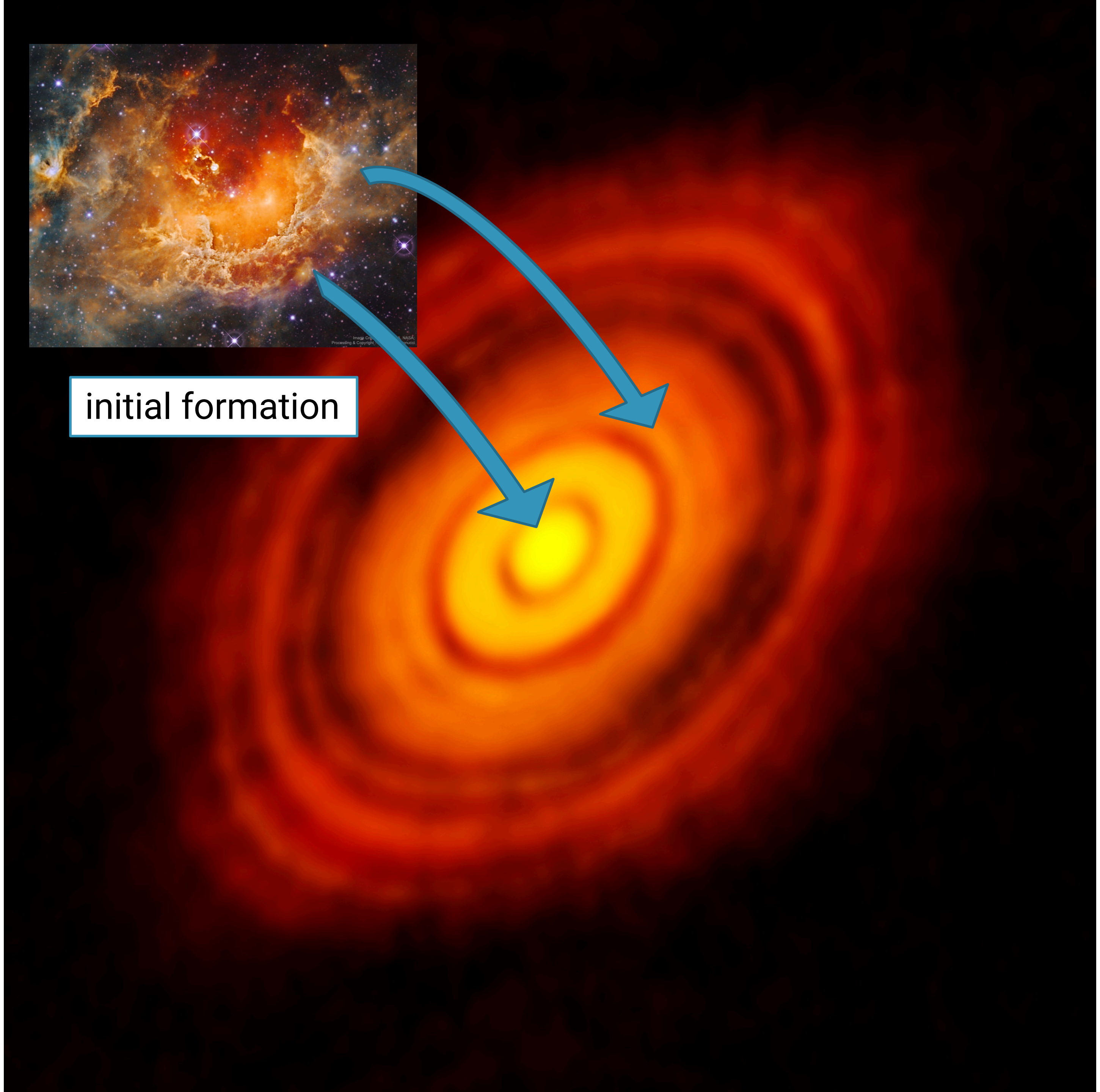


HL Tau,
ALMA image

stars & planets form side-by-side from the same primordial nebulae

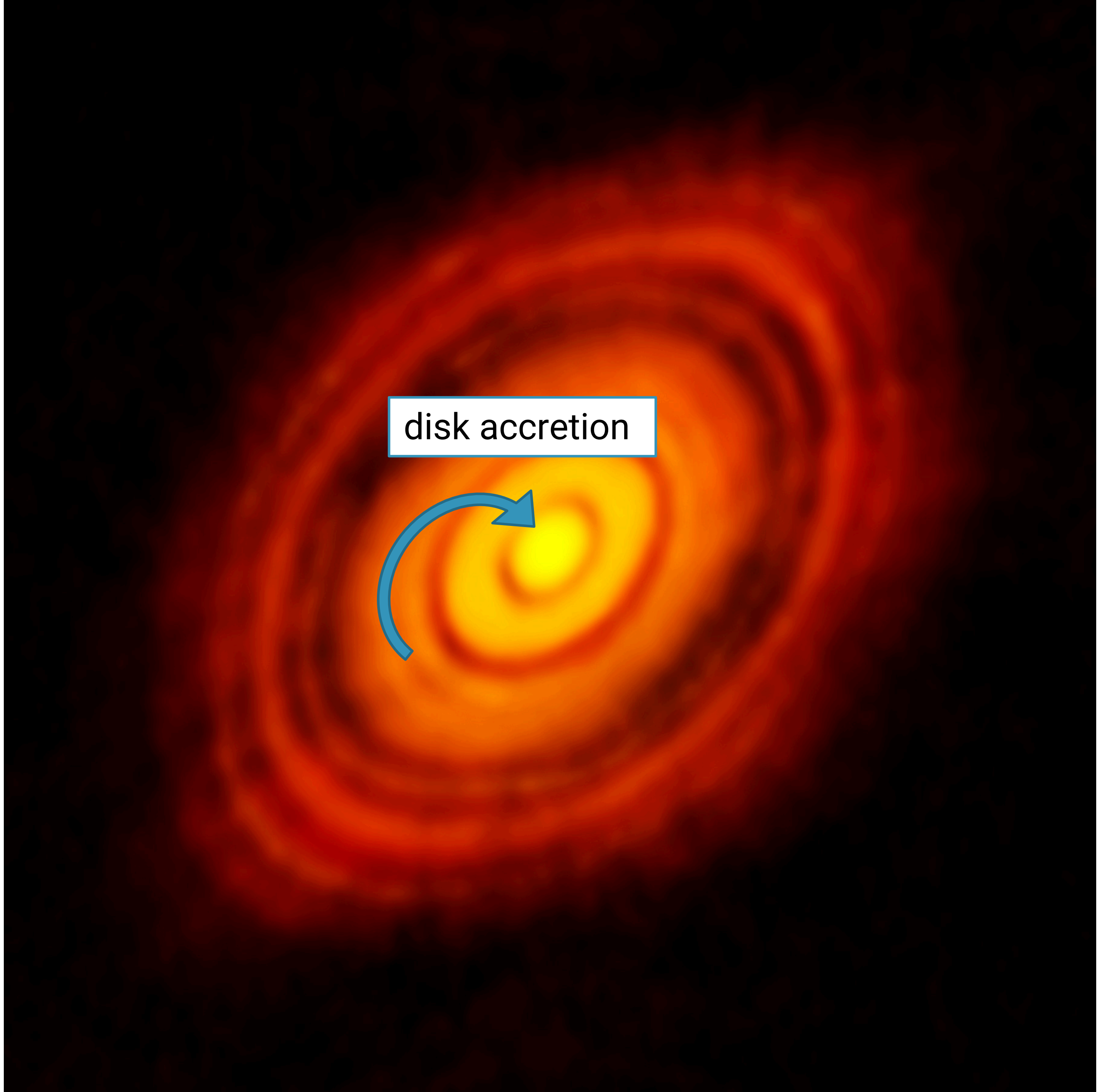
… so host stars reflect the starting conditions for exoplanets

HL Tau,
ALMA image



stars & planets form side-by-side from the same primordial nebulae

... so exoplanets imprint a (tiny) signature on their host star



HL Tau,
ALMA image

How do you measure the **composition of a star**?

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{\mathrm{N_{Fe}}}{\mathrm{N_{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{\mathrm{N_{Fe}}}{\mathrm{N_{H}}}\right)_{\mathrm{sun}}$$

STELLAR* ABUNDANCES CHEAT SHEET

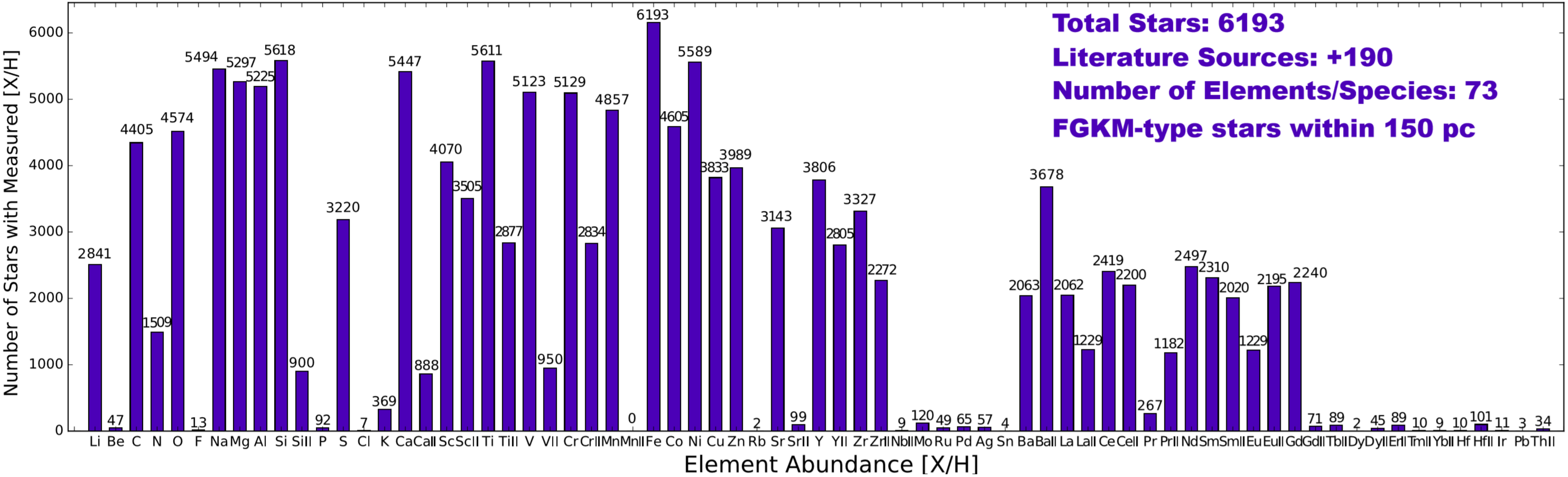
easy to measure: Fe

can measure precisely given a high-quality spectrum:
Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Y, Zr, …

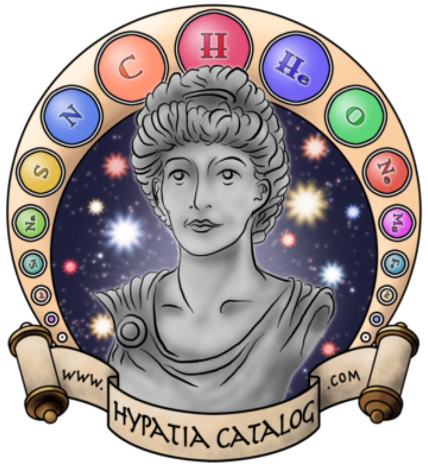
hard but possible to measure: Li, C, N, O, K, …

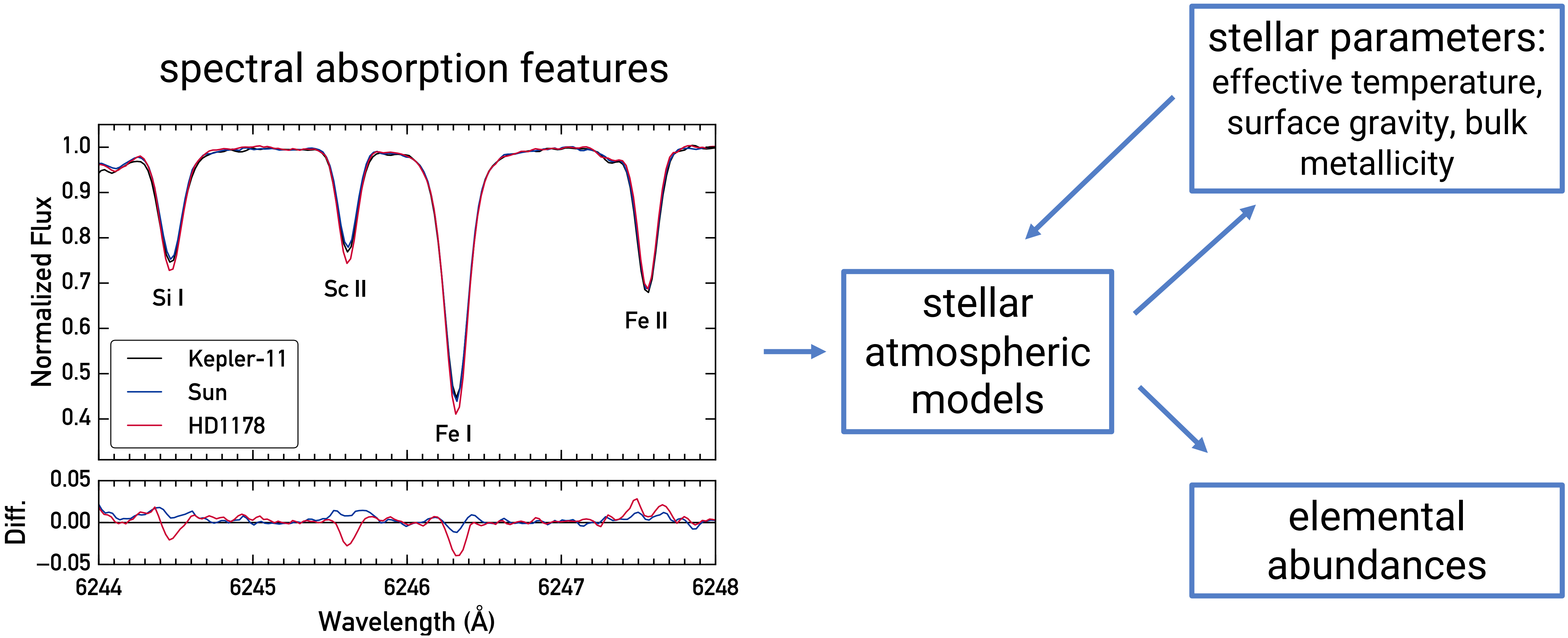
forget about it: H, He, B, Ne, P, Cl, Ar, …

* Mostly valid for main-sequence FGK stars observed in the optical/NIR.
Terms & conditions may apply.



Hypatia Catalog
made by Natalie Hinkel
www.hypatiacatalog.com





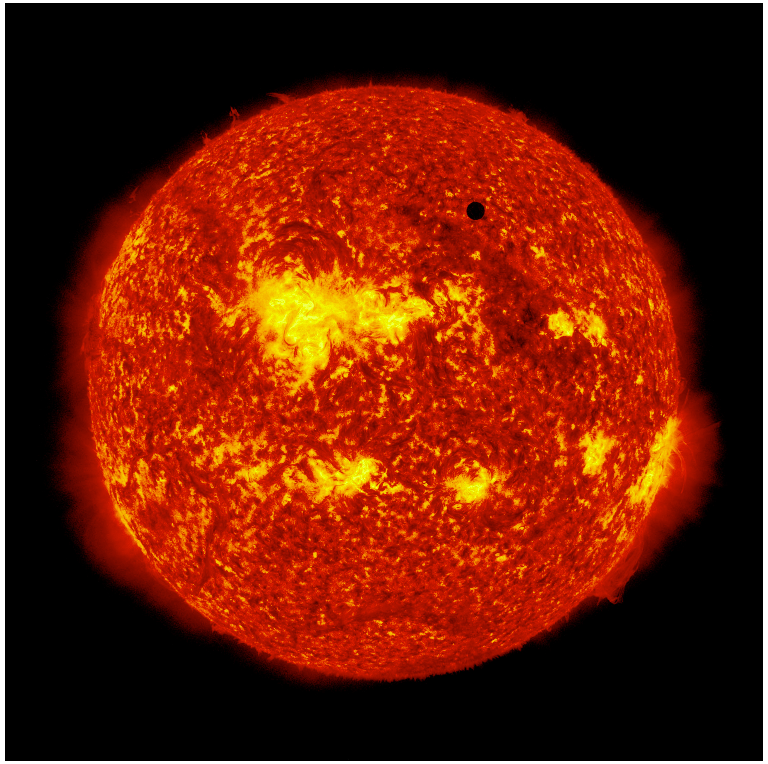
spectral absorption features
Normalized Flux
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Si I
Sc II
Fe I
Fe II
Kepler-11
Sun
HD1178
Diff.
0.05
0.00
−0.05
6244
6245
6246
6247
6248
Wavelength (Å)
stellar atmospheric models
stellar parameters:
effective temperature, surface gravity, bulk metallicity
elemental abundances

STELLAR MODEL ATMOSPHERES

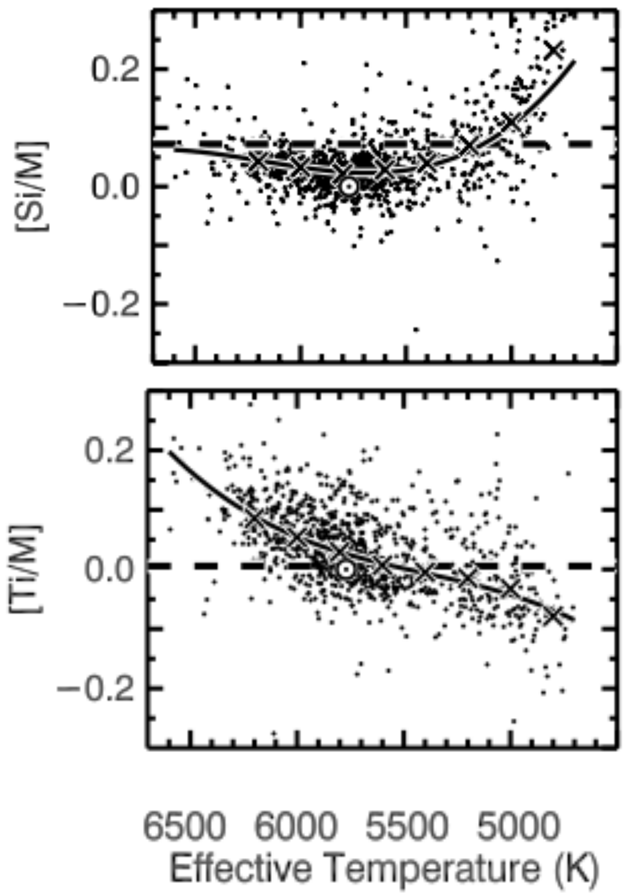
COMMON ASSUMPTIONS

- stellar surface is homogenous
- single source function (i.e. opacity is the same no matter which way you look)
- does not evolve in time
- no mass loss
- no rotation
- no magnetic field

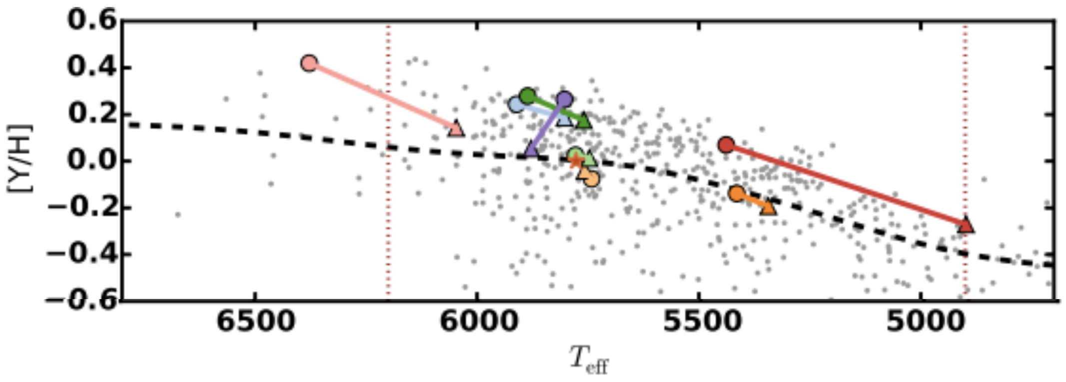
REALITY



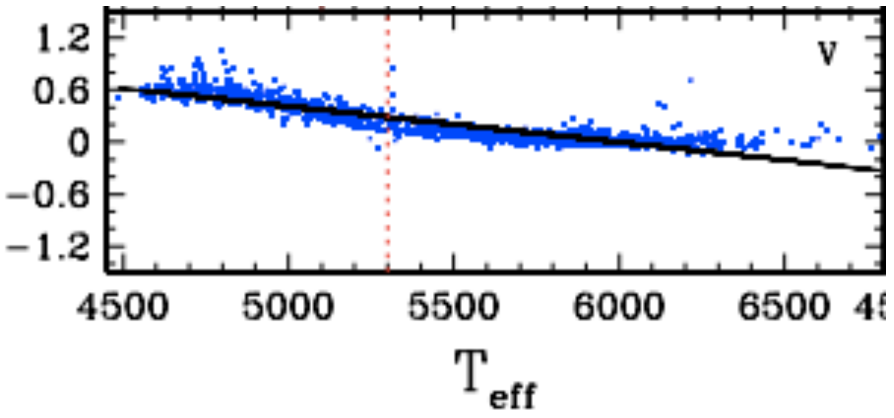
Issues with stellar models lead to issues with stellar abundances (up to a factor of ~2)



Valenti & Fischer 2005



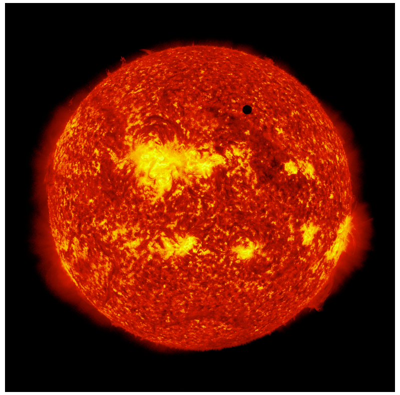
Brewer+2016



Adibekyan+2012

DIFFERENTIAL TWIN STAR SPECTROSCOPY

A pair of "twin stars" use (almost) **the same stellar model**.



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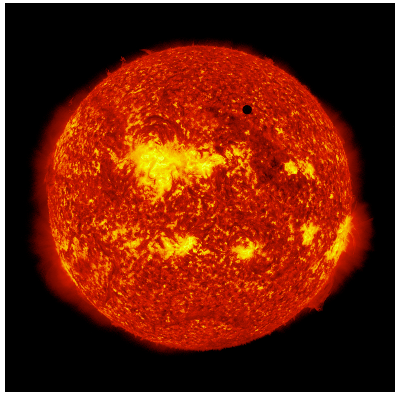


Typical definition:

$\Delta T_{eff} \lesssim 100$ K,
$\Delta \log(g) \lesssim 0.1$ dex,
$\Delta[Fe/H] \lesssim 0.1$ dex

By minimizing error introduced by models, we can achieve **0.01 dex or 2% precision on abundances** – a factor of 5 better than a typical spectroscopic analysis!

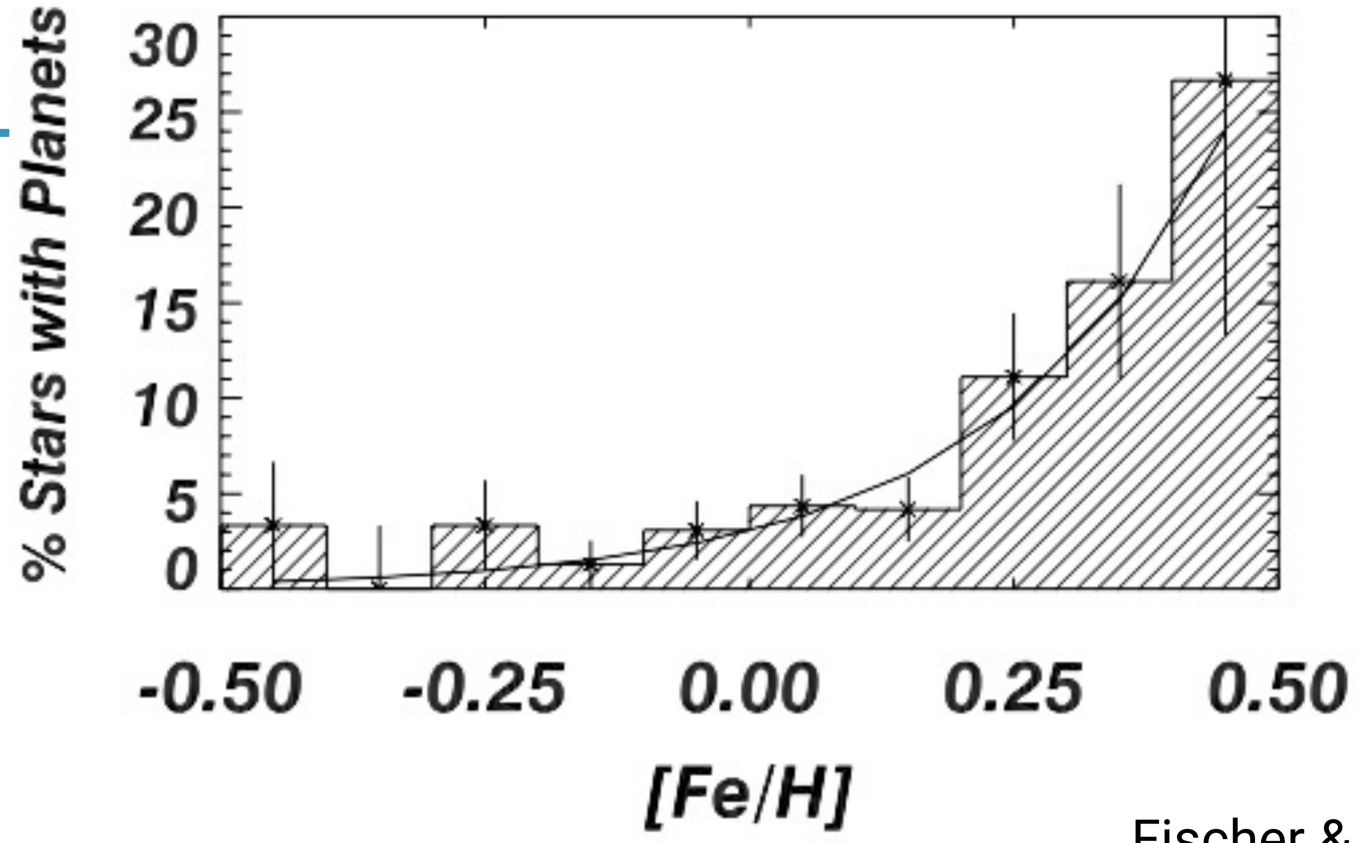
Stellar **metallicity**

+

planets

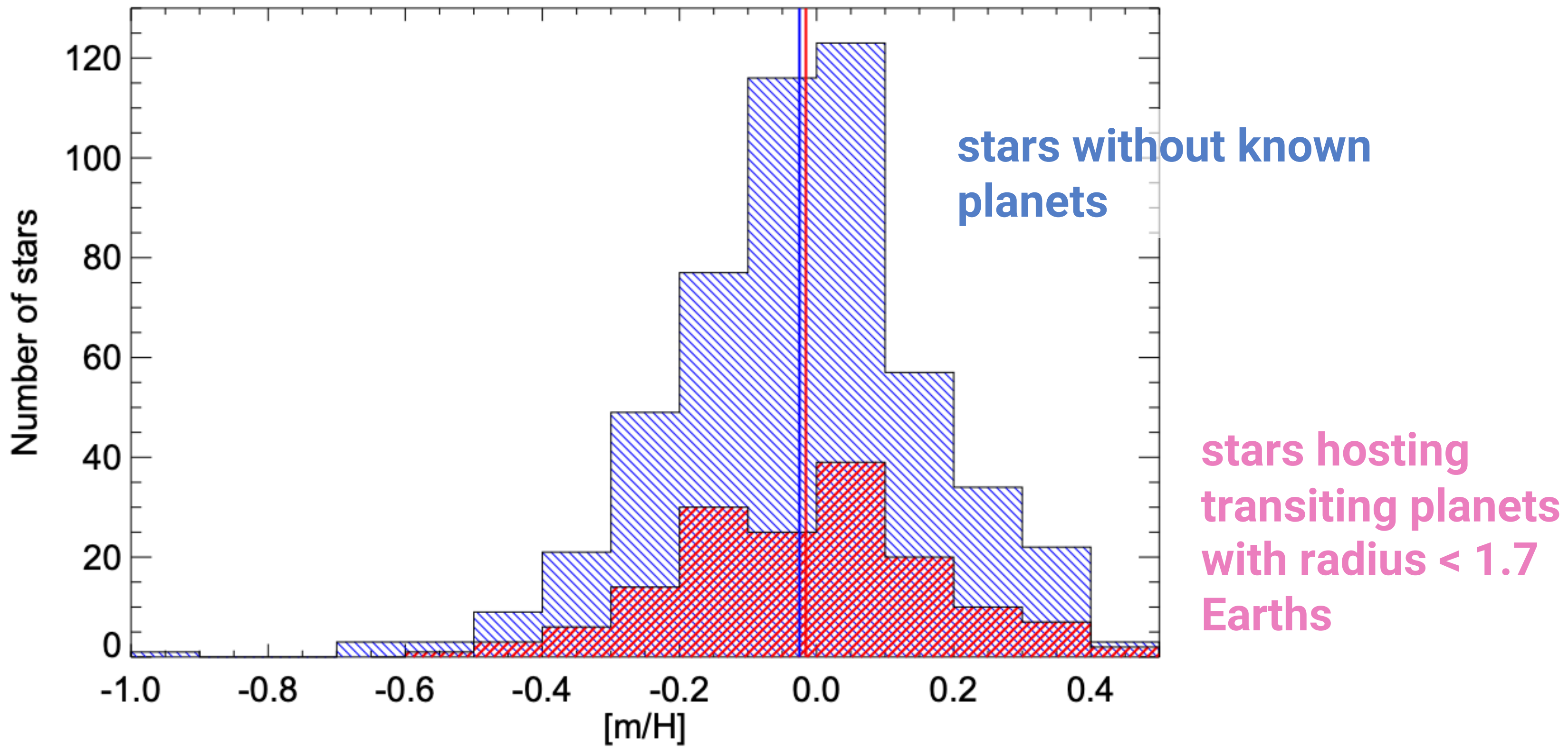
Jupiters are hosted by iron-rich stars…

(with orbital period < 4 years & RV semi-amplitude K > 30 m/s)



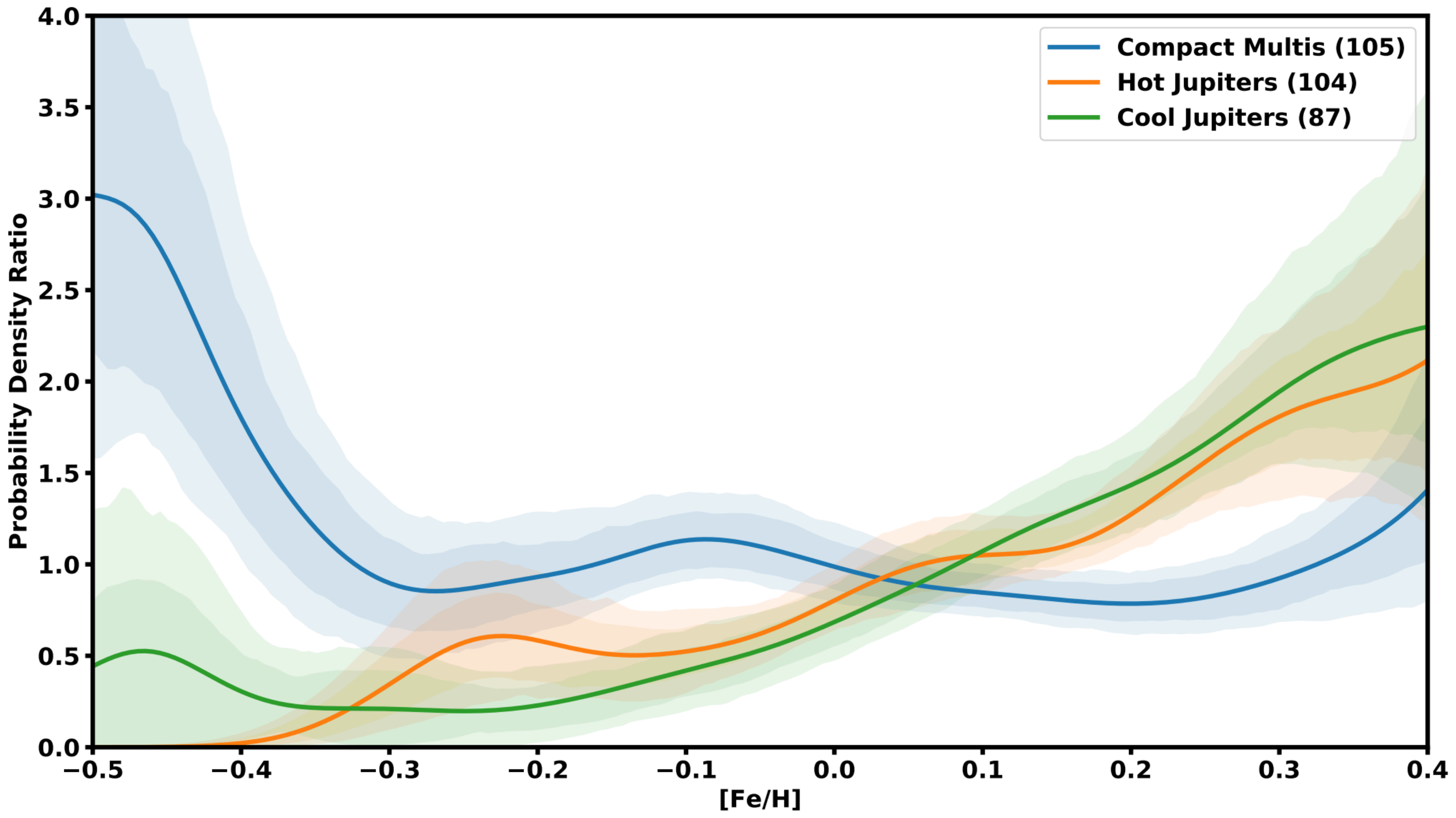
Fischer & Valenti (2005)

… but Earths may not care about stellar metallicity.



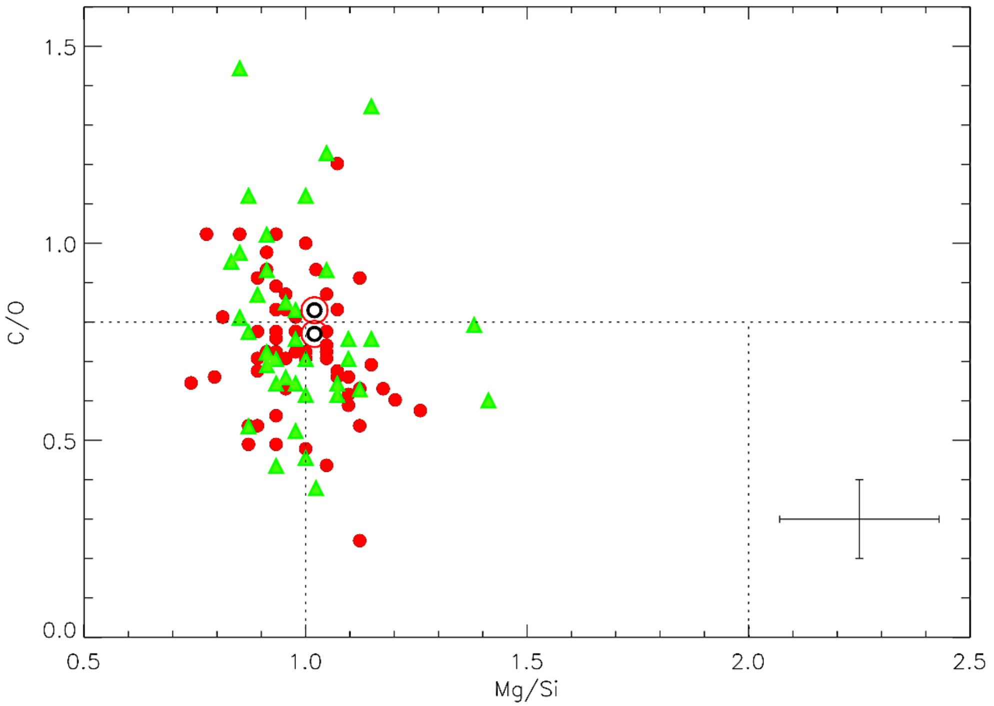
Buchhave & Latham (2014)

And compact multi-planet systems might prefer low-metallicity hosts!



Brewer+2018

Planet-forming elements in stars

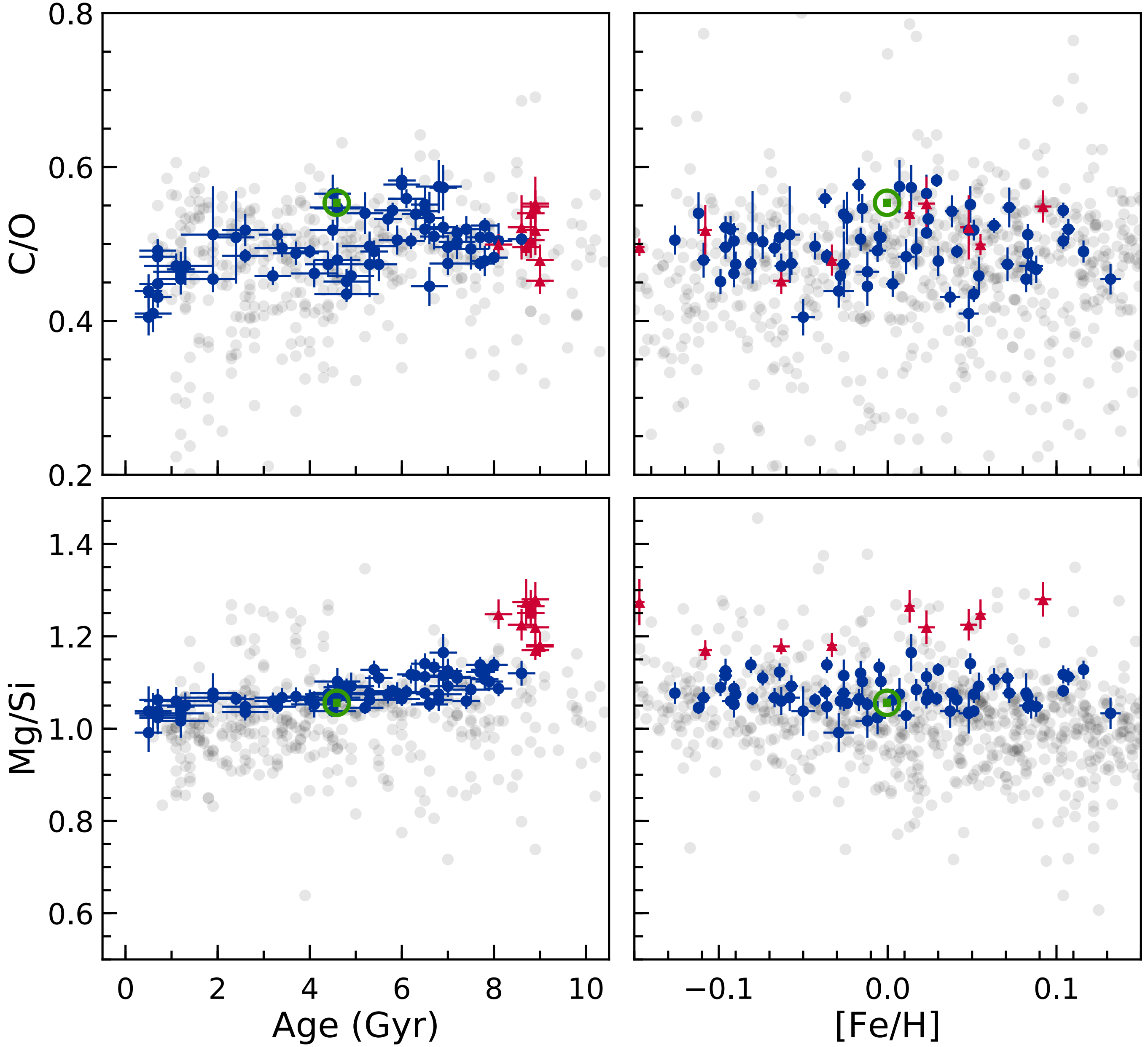


Considerable diversity in planetary building blocks…

Table 2: C/O and Mg/Si distributions for stars with planets

Ratio	Percentage	Principal Composition
C/O > 0.8	34%	graphite, TiC and solid Si as SiC
C/O < 0.8	66%	solid Si as $SiO_4{}^{4-}$ or SiO_2
Mg/Si < 1	56%	pyroxene, metallic Fe and excess Si as feldspars
1 < Mg/Si < 2	44%	equal pyroxene and olivine
Mg/Si >2	0%	olivine and excess Mg as MgO

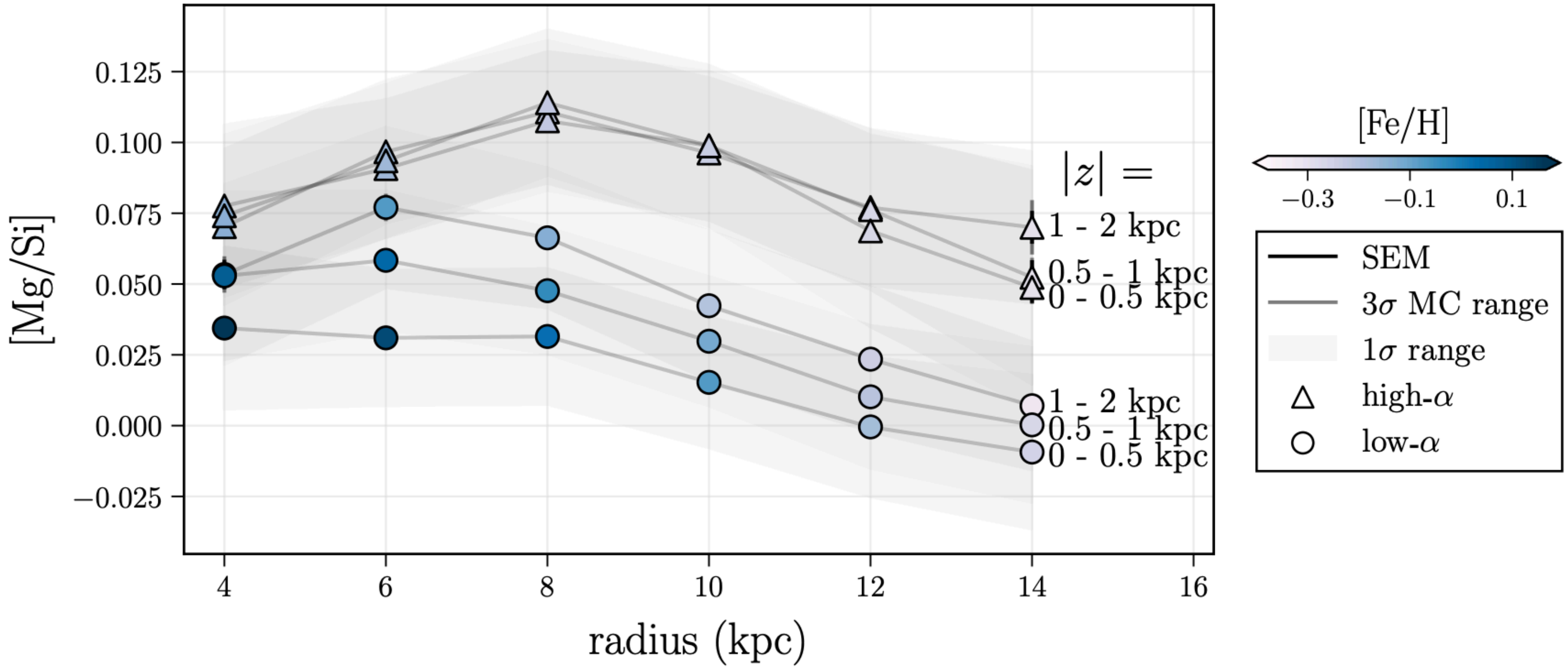
Delgado Mena+2010



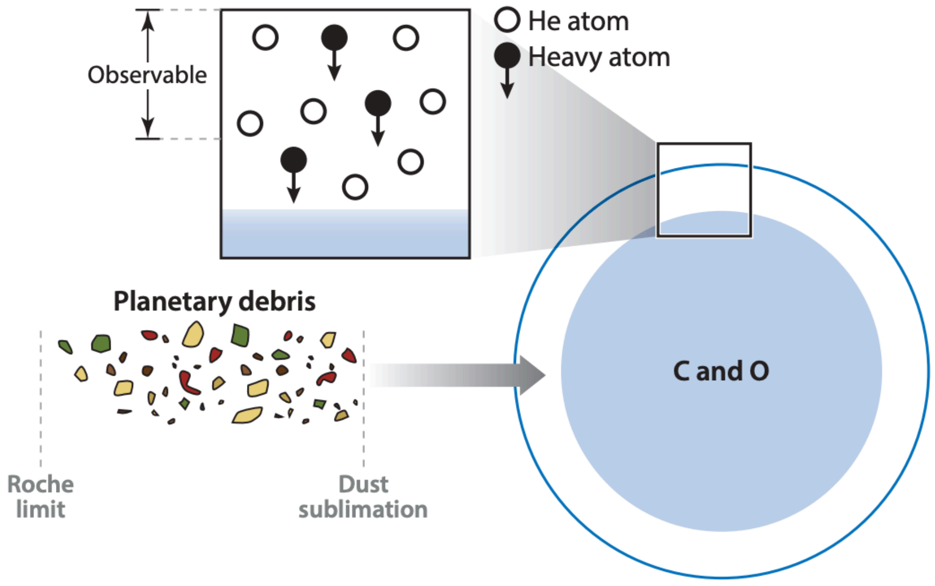
...or not.

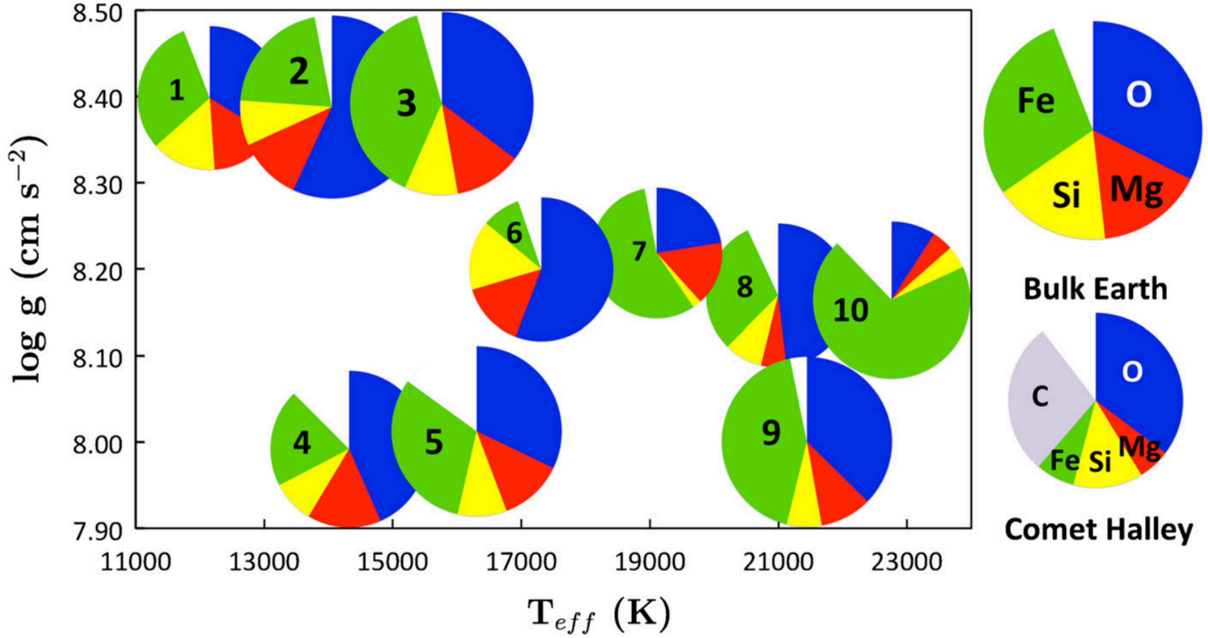
Bedell+2018

Could stars in other parts of the Galaxy host very different planets?



Blancato+2019



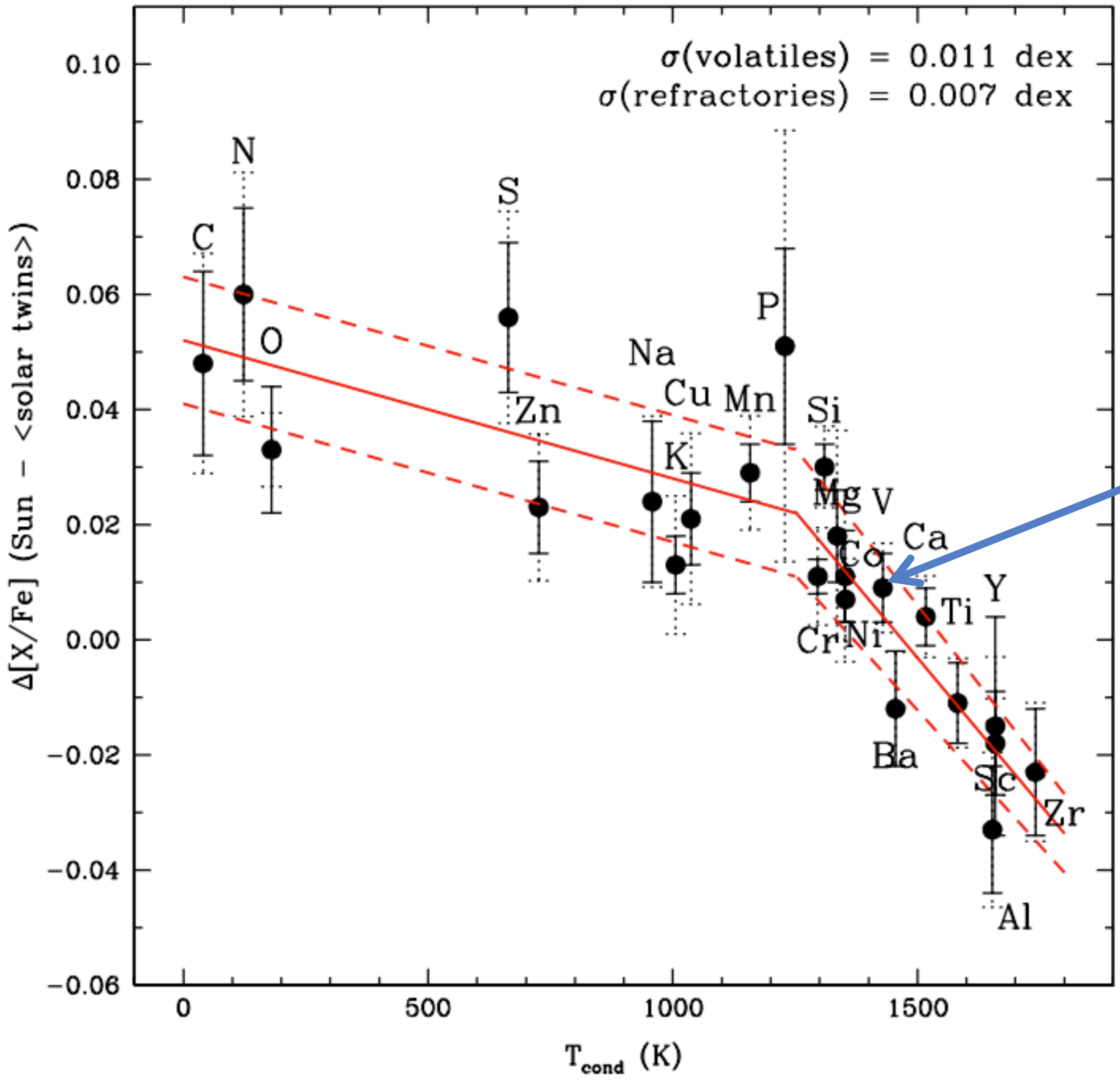


White dwarf pollution: a direct(?) probe of extrasolar planetesimal compositions

Jura+2014 (top);
Xu+2014 (bottom)

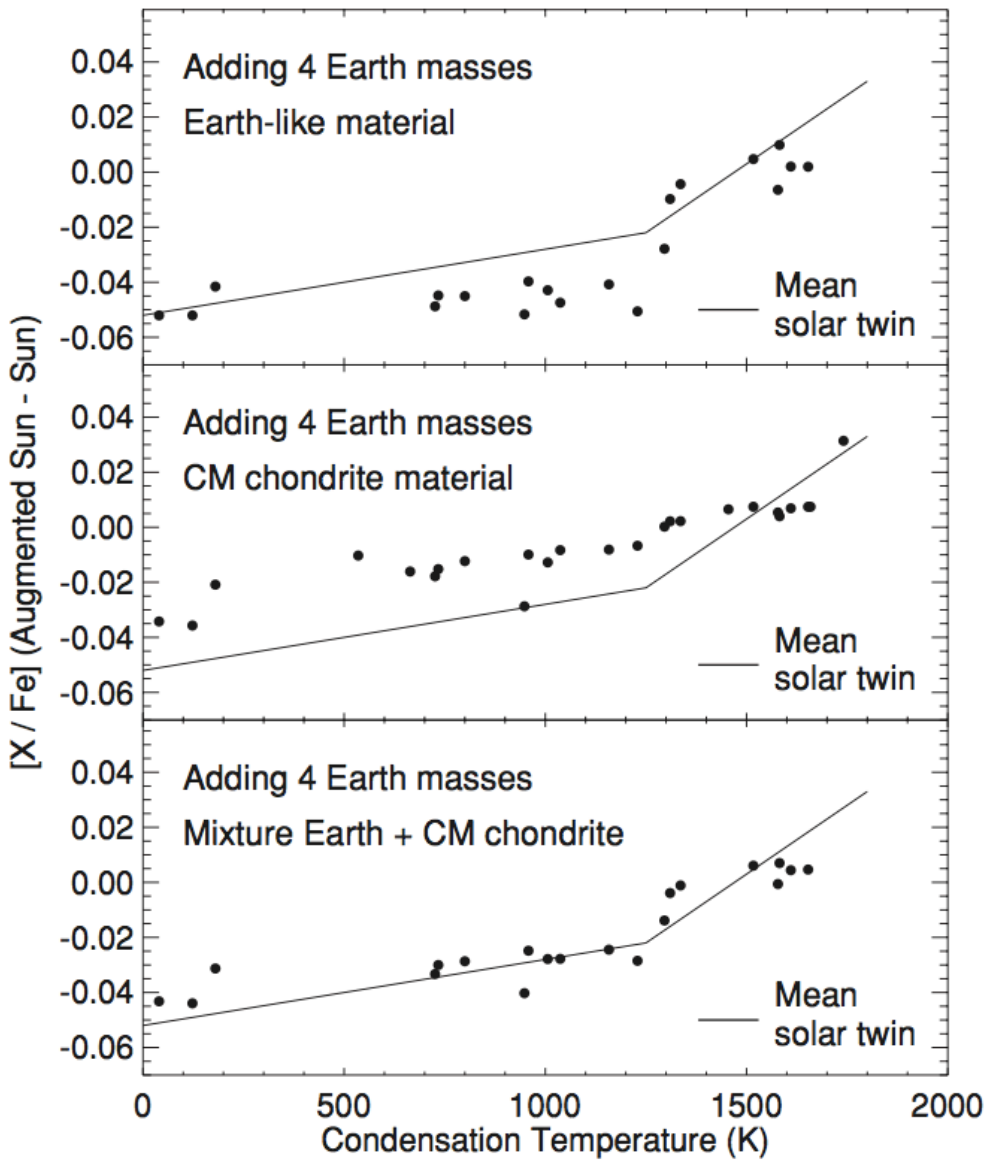
Can we observe the **imprints of planet formation** on stars?

Comparing the Sun to an average Sun-like star…



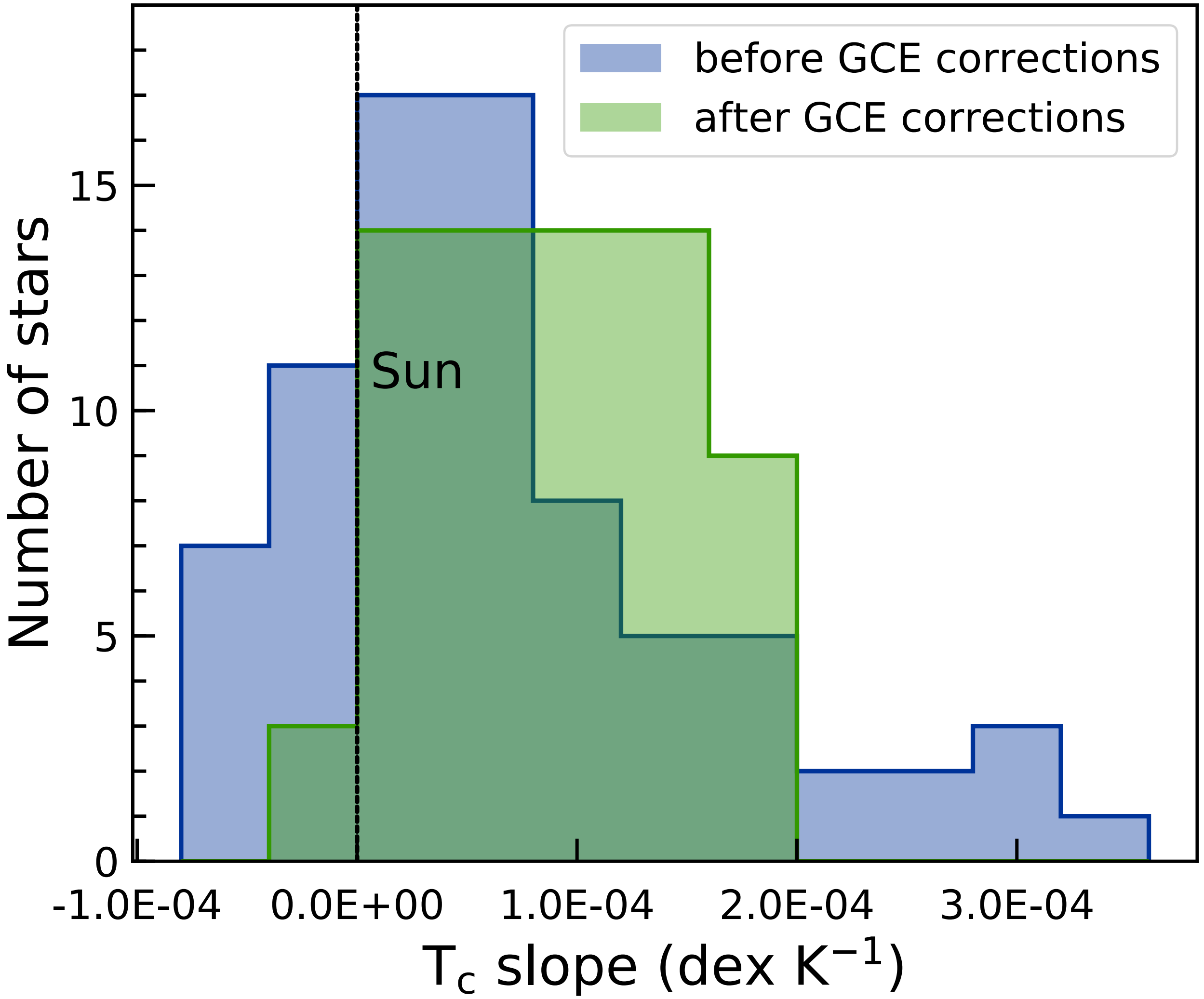
…refractory elements are preferentially depleted in the Solar photosphere.

Meléndez+2009



This can be explained if the Sun contains **4 Earths' worth less planet material** than the average solar twin.

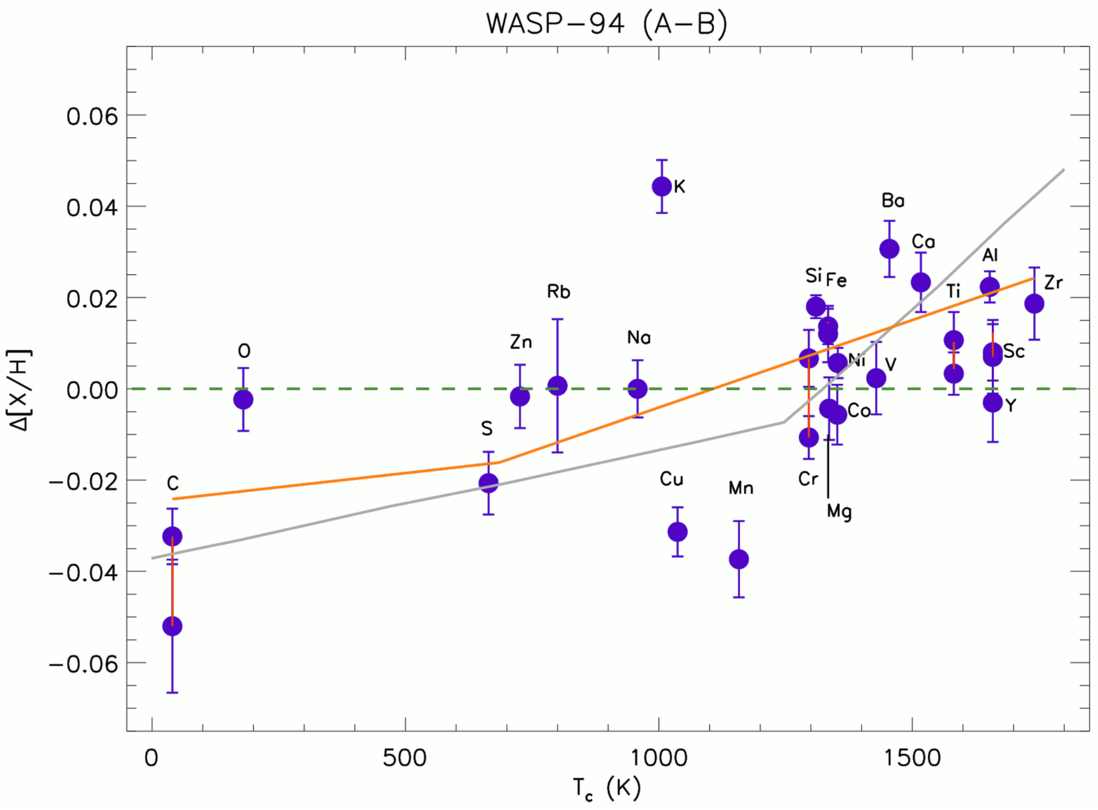
Chambers 2010



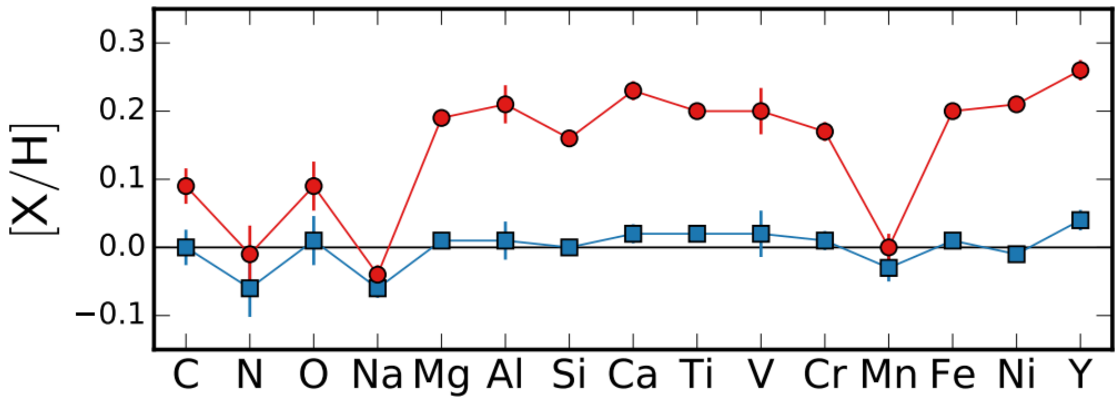
~90% of solar twins contain a higher concentration of rocky materials than the Sun does.

Bedell+2018

A controlled laboratory: **binary star systems**

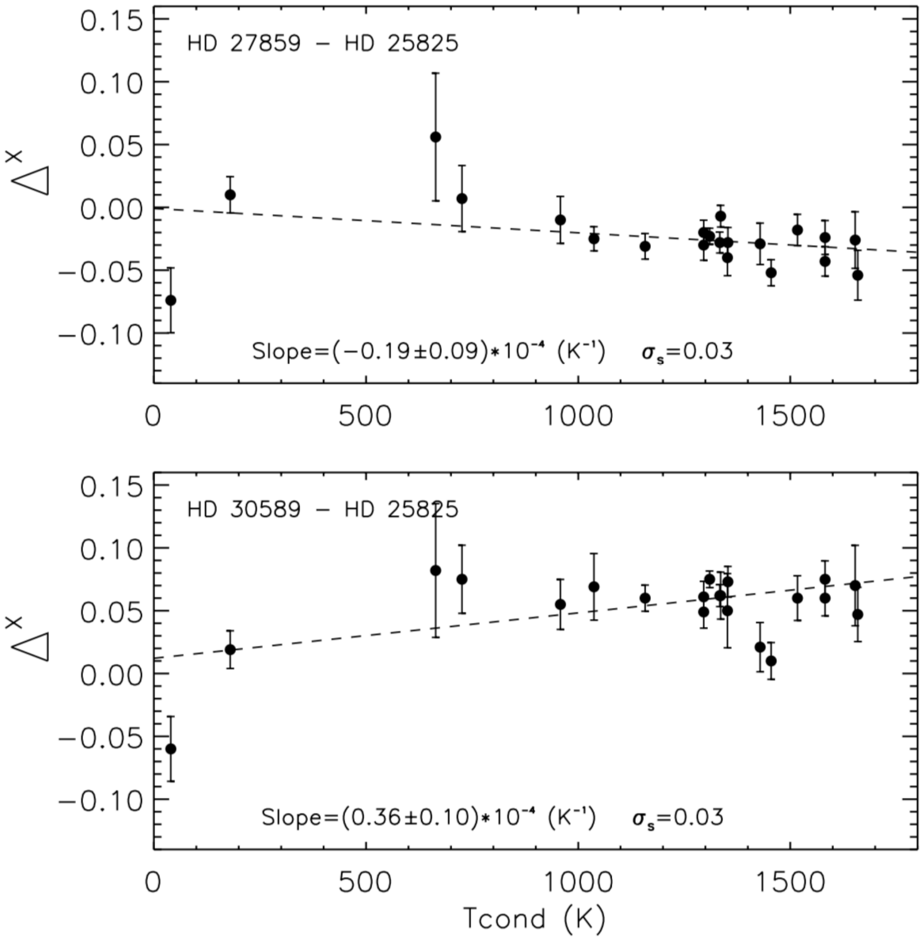


WASP-94 -- Teske+2016

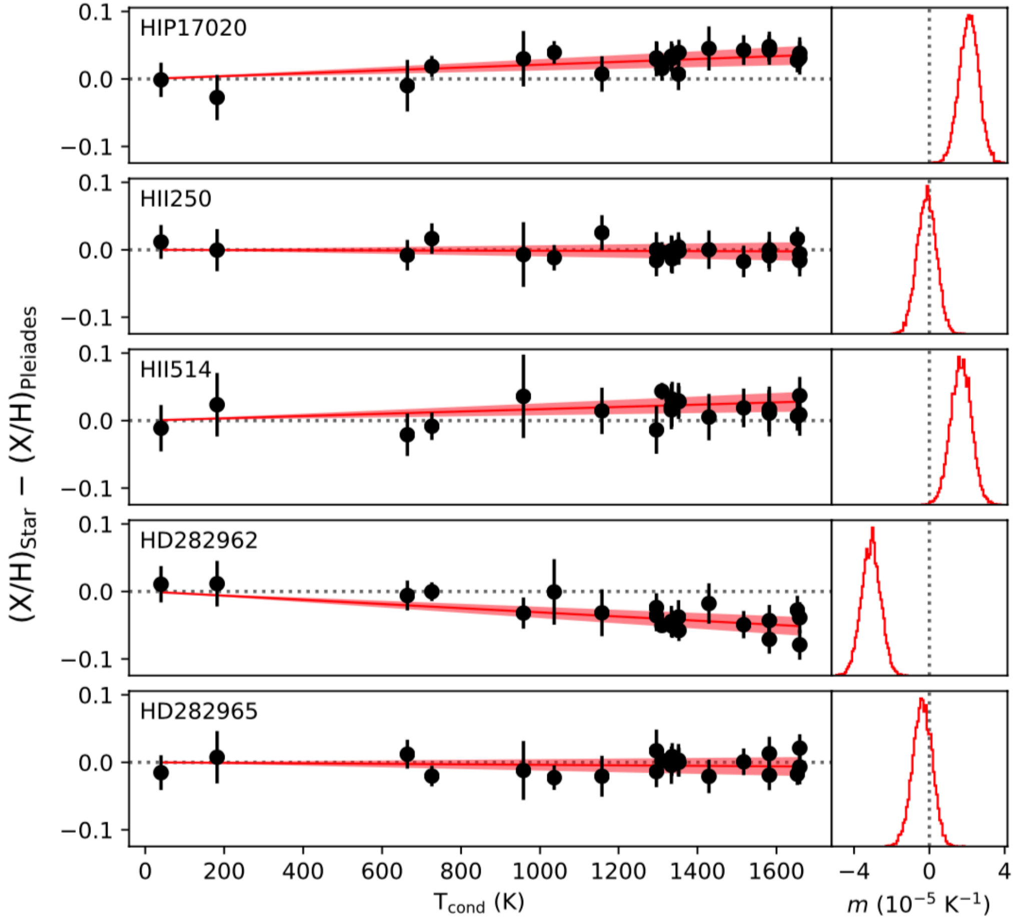


Kronos & Krios -- Oh+2018

See also: **star clusters**



Hyades -- Liu+2016



Pleiades -- Spina+2018

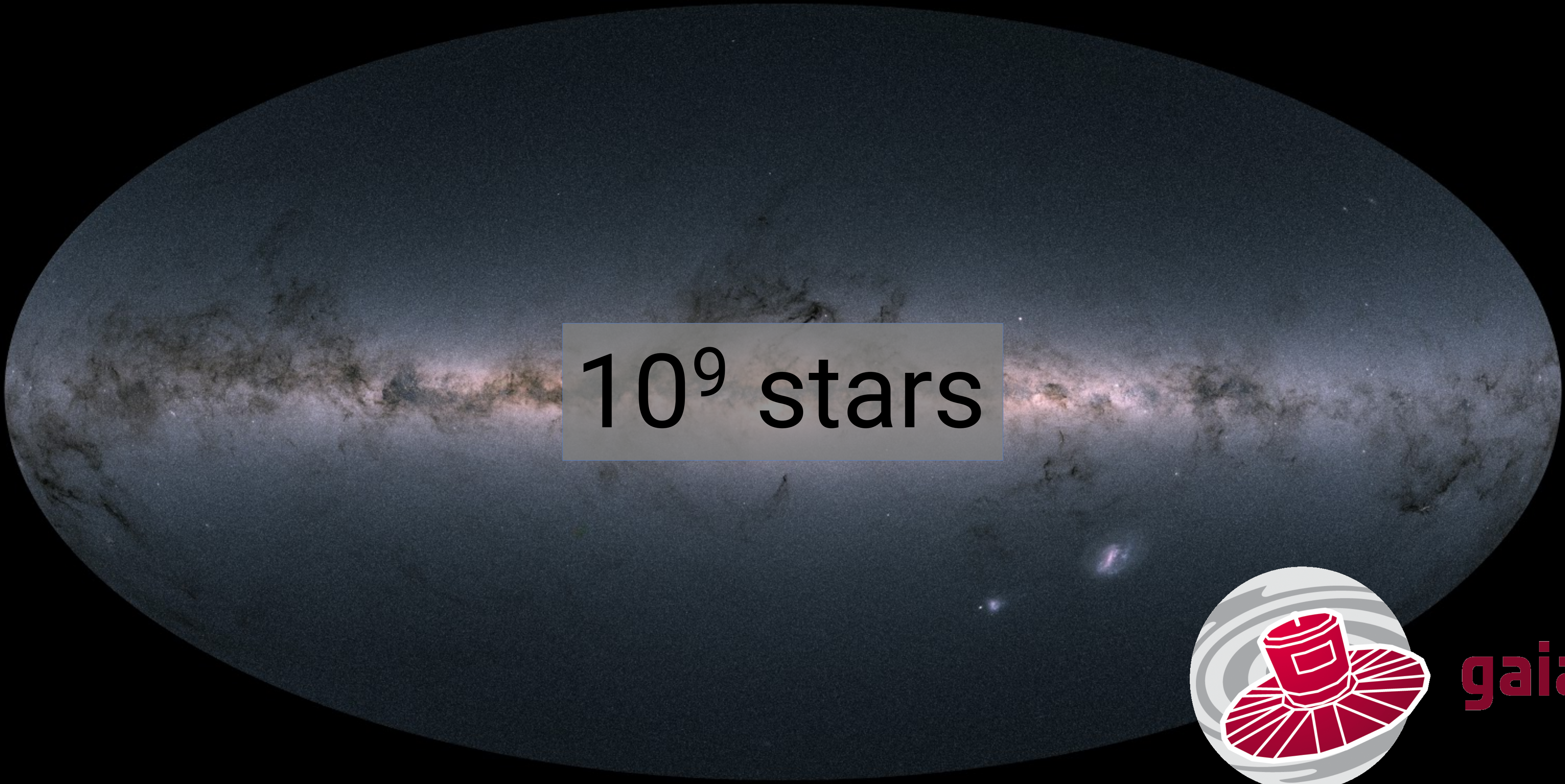
CAVEATS:

1. Our data are not (yet) ideal; we need knowledge of planetary system architectures & very precise abundances for the same stars

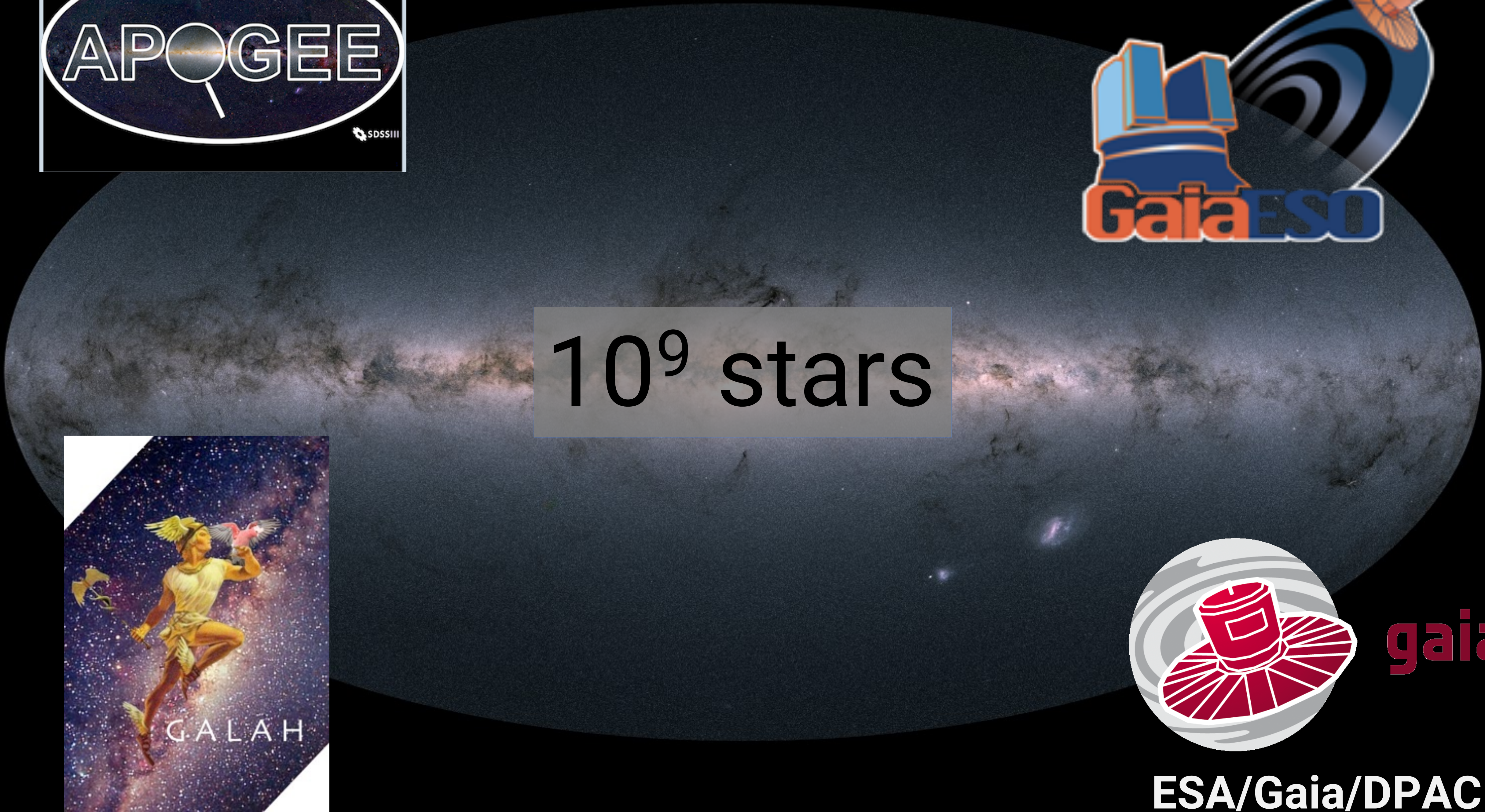
2. Our models are not (yet) ideal; a linear T_c trend is semi-arbitrary

3. Interpretation is inherently degenerate & may not be planets at all!

What's **next**?



ESA/Gaia/DPAC



10^9 stars

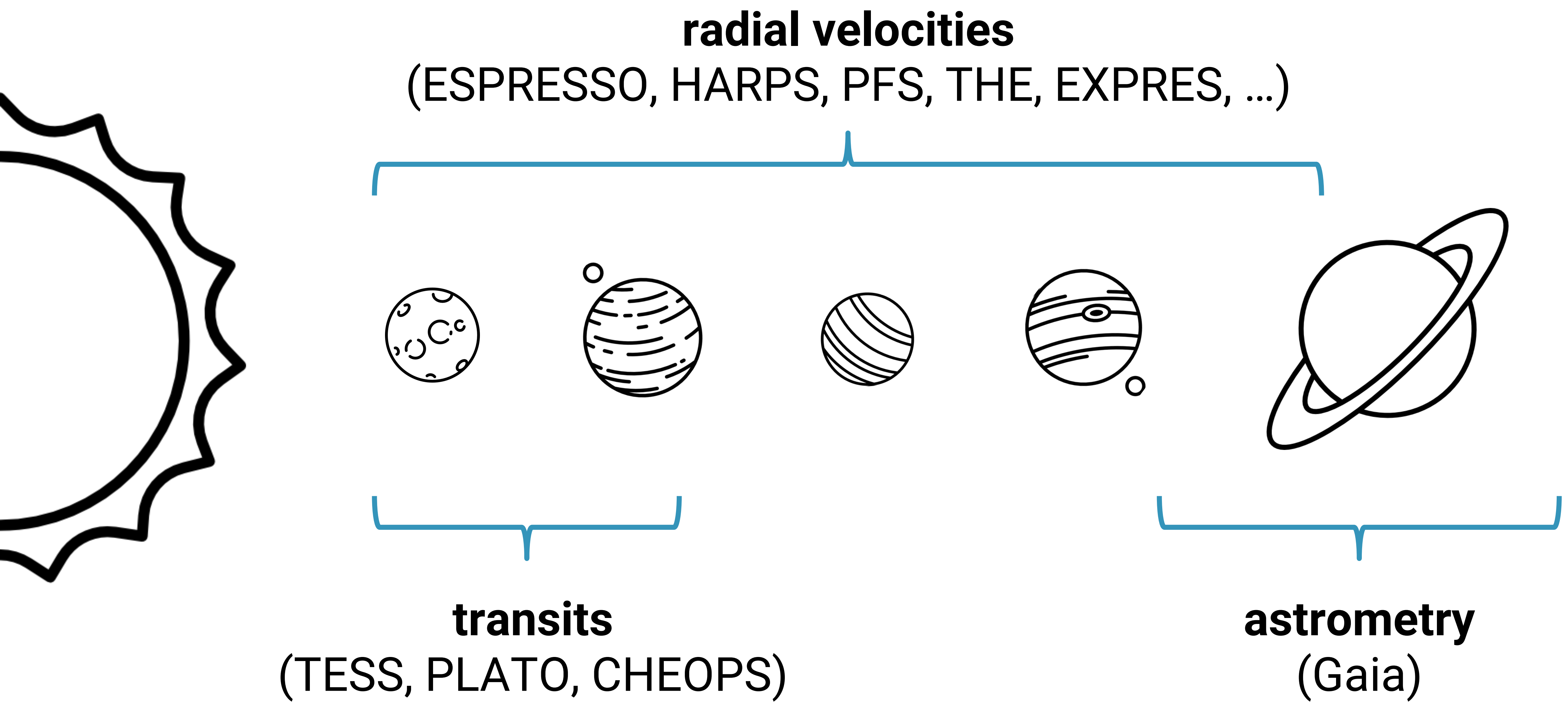
APOGEE

SDSSIII

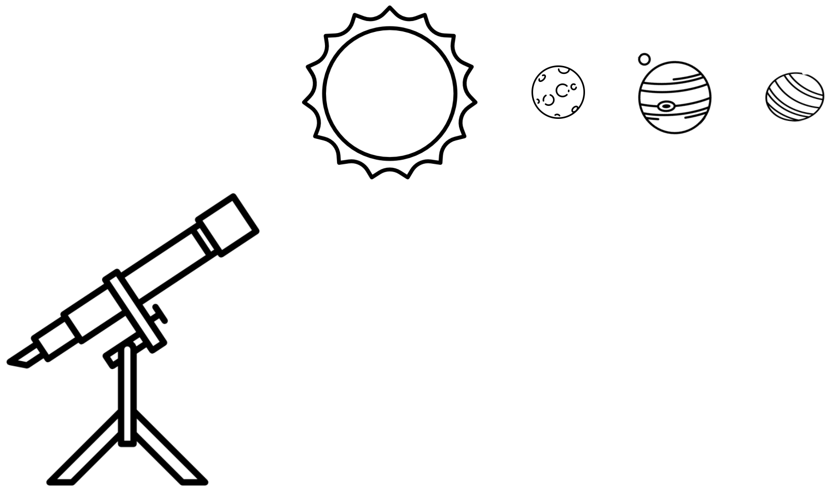
GaiaESO

gaia

ESA/Gaia/DPAC


radial velocities
(ESPRESSO, HARPS, PFS, THE, EXPRES, ...)
transits
(TESS, PLATO, CHEOPS)
astrometry
(Gaia)

Large populations of stars with precise abundance measurements & strong constraints on their planetary systems are coming soon!



TAKE–AWAY POINTS

1. Precise stellar spectroscopy gives us multiple indirect probes of exoplanet composition.

2. Both the observations & the interpretation of the results can get complicated fast!

3. We’re getting closer to an ideal sample of stars with extensively measured compositions hosting a range of planet types.