The Connection between Planets and the Stellar Chemical Composition

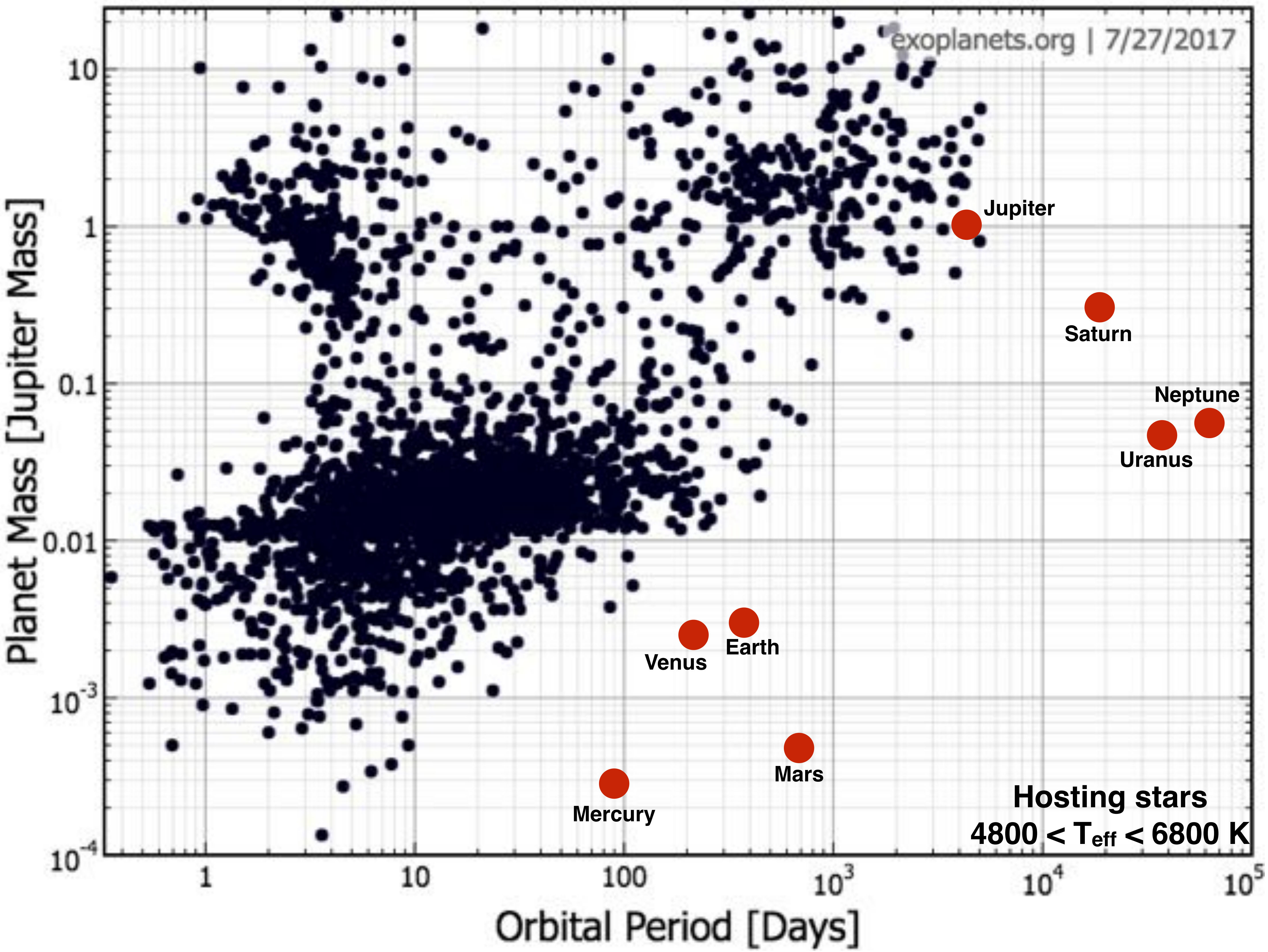
Lorenzo Spina

Universidade de São Paulo, IAG,
Departamento de Astronomia - Brazil

SAMPA
Stellar Atmospheres Planets and Abundances

FAPESP

Credits: NASA



A big diversity

- in the architectures of planetary systems
- in the processes of dynamical evolution

Are we special?

Our current instruments are not precise enough to answer this question

How special is our Solar System?

The architecture of the Solar System

A quiet solar type star

Inner small rocky planets

Outer giant gaseous planets

Absence of super-Earths or mini-Neptune inside the orbit of Mercury

Orbits with moderate eccentricities that never cross

Let’s design more precise instruments!

Does the presence of planets imprint signatures in the properties of stars that can easily detectable?

- Unveil new details on the process of planet formation
- Understand the possible connections between the hosting star and its planets
- Identify primary targets that could host a *Solar System 2.0*

Planet - metallicity connection

The stellar metallicity–giant planet connection

Guillermo Gonzalez★

Department of Astronomy, University of Texas, Austin, TX 78712, USA

Accepted 1996 September 24. Received 1996 September 23; in original form 1996 August 1

ABSTRACT

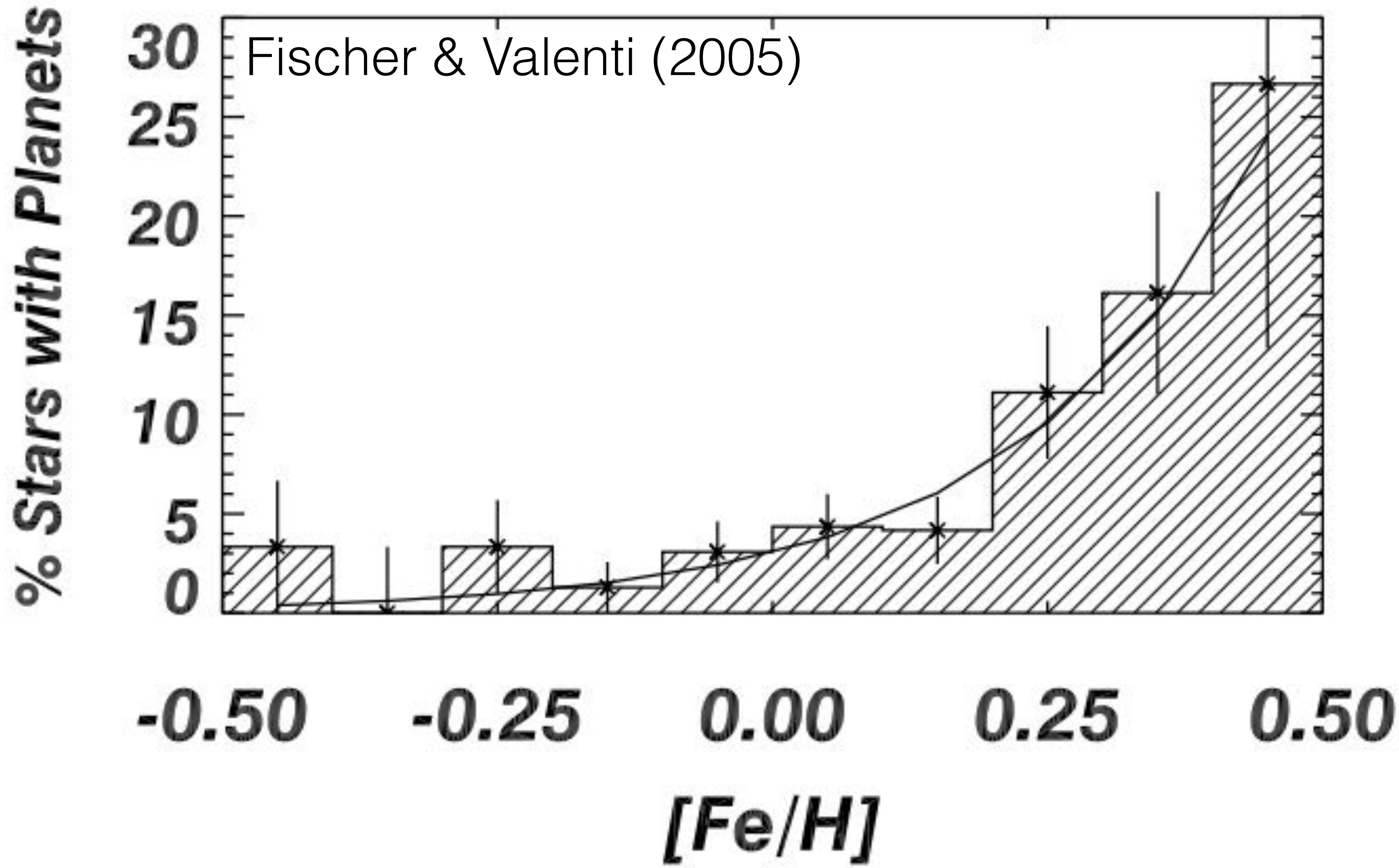
The parent stars of the recently announced planetary system candidates are far from typical in terms of their chemical compositions. In this study we report on spectroscopic abundance analyses of υ And and τ Boo. Both stars are metal-rich relative to the Sun, with a mean [Fe/H] value near 0.25. These findings follow the trend set by two other planetary system candidates, ρ^1 55 Cnc and 51 Peg, which also display metallicities much higher than the average for nearby dwarfs. In addition, their companions share similar orbital characteristics. Given these observations, we propose that the current metallicities of these four stars are not representative of that of the original interstellar clouds from which they formed but, rather, are the result of self-pollution during the planet formation epoch early in their histories.

What is the nature of this link? Is the high metallicity a prerequisite for the formation of giant planets, or does the planet formation process alter the stellar surface abundances, or is it a combination?

Planet - metallicity connection

Metal rich stars ([Fe/H] > 0 dex) have an higher probability to host giant planets

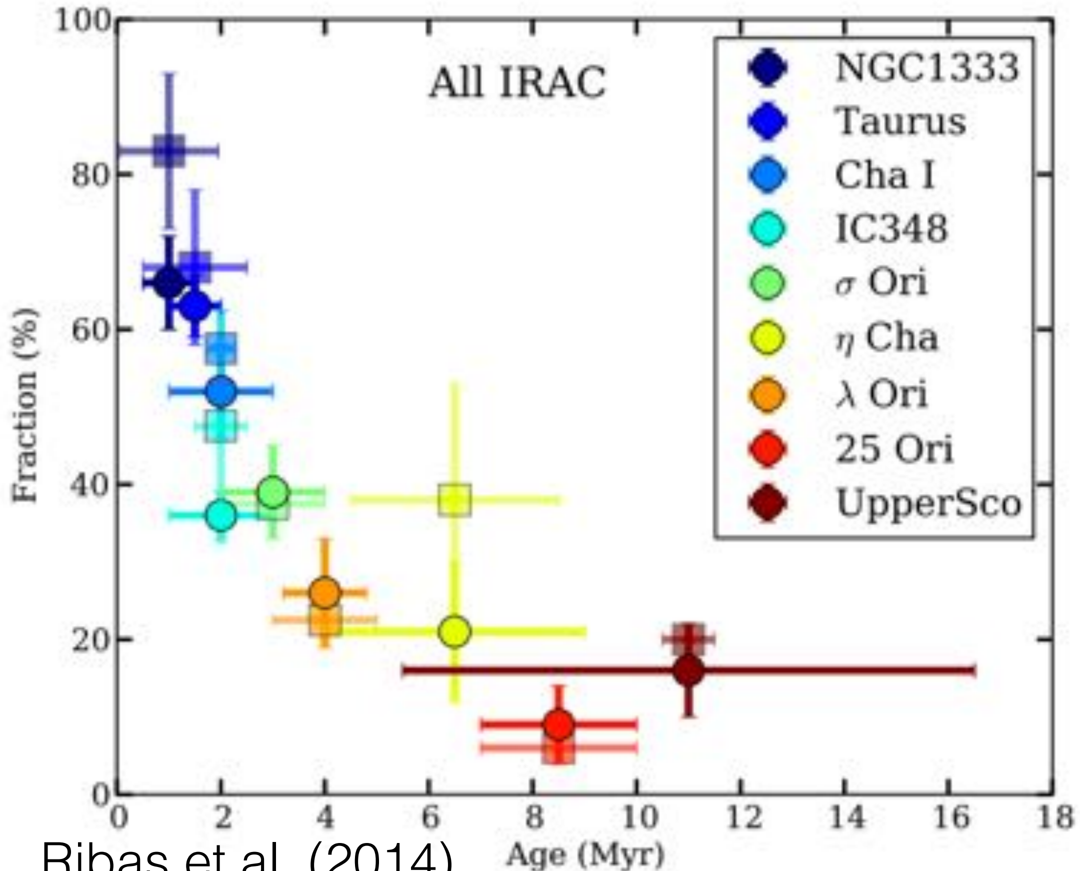
Santos et al. (2004), Fischer & Valenti (2005), Johnson et al. (2010), Schlaulfman & Laughlin (2011), Everett et al. (2013) , Buchhave et al. (2012, 2014)



The metallicity of the circumstellar disk determines the structure of the planetary system that forms.

The metallicity of the Sun may not be especially promotive to the formation of planets.

Planet - metallicity connection



Ribas et al. (2014)

The typical lifetime of a circumstellar disk is shorter than 10 Myr.

Two main processes of disk dispersal:

- photo-evaporation
- planet formation

An **higher metallicity** implies that the disk disposes of and **higher amount of dust**

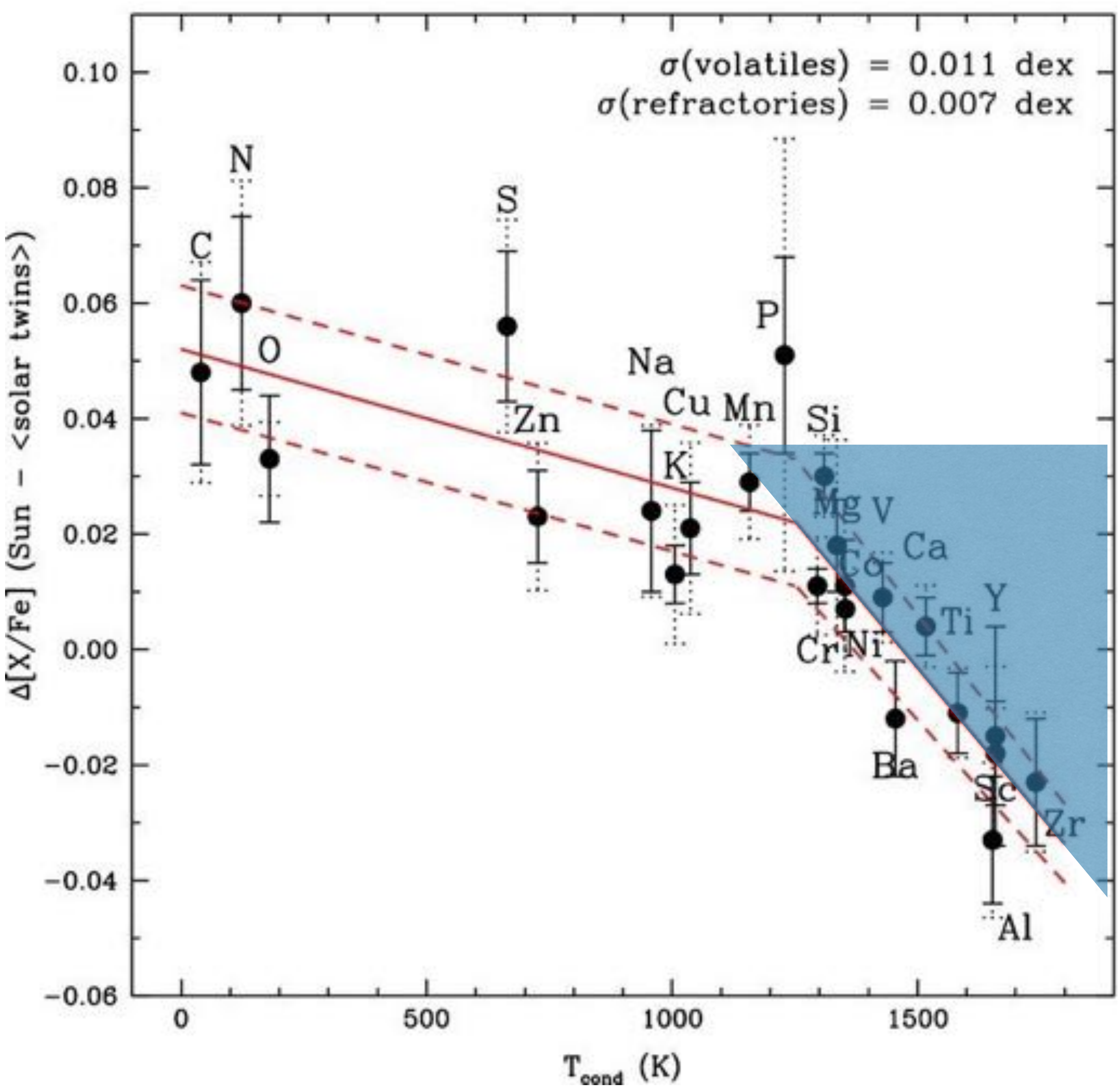
Speeds up the growth of grains → the planetesimal formation is able to start earlier (see Drazkowska & Dullemond 2014, Fletcher & Nayakshin 2016)

- **In metal-rich systems**, rocky cores can form and start the gas accretion before the gas disc dissipates, so they quickly become gas giants.
- **In metal-poor systems**, rocky cores form in gas-free environment and hence do not make gas giants.

Chemical signatures of rocky planet formation?

Melèndez et al. 2009 ApJ 704 L66

Line-by-line differential analysis of 11 solar twins relative to the solar spectrum: very high precision in atmospheric parameters ($\Delta T_{eff} \leq 5$K, $\Delta \log g \leq 0.02$, Δ[Fe/H]≤ 0.005 dex) and abundances (≤ 0.01 dex).

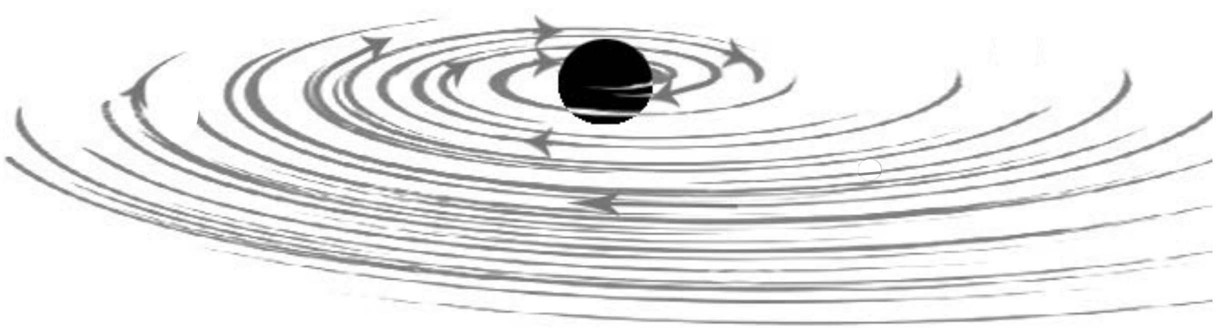


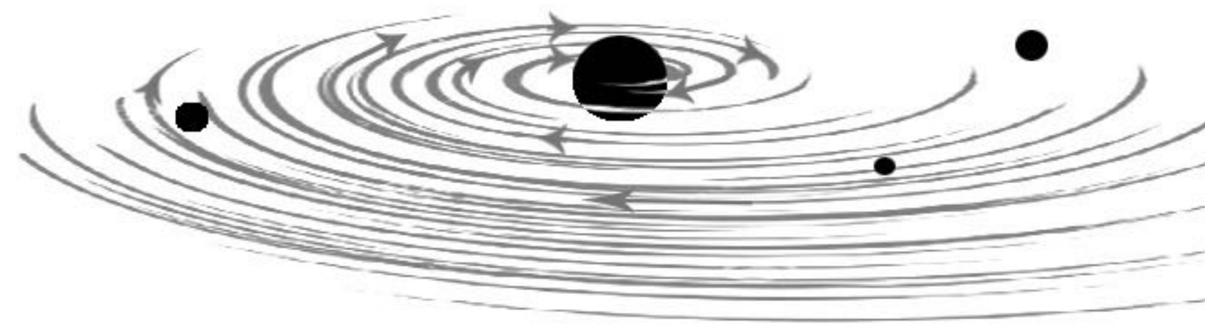
The refractory elements are though to be the main component of the solids that populate our solar system.

The Solar anomaly could be a signature of rocky planet formation

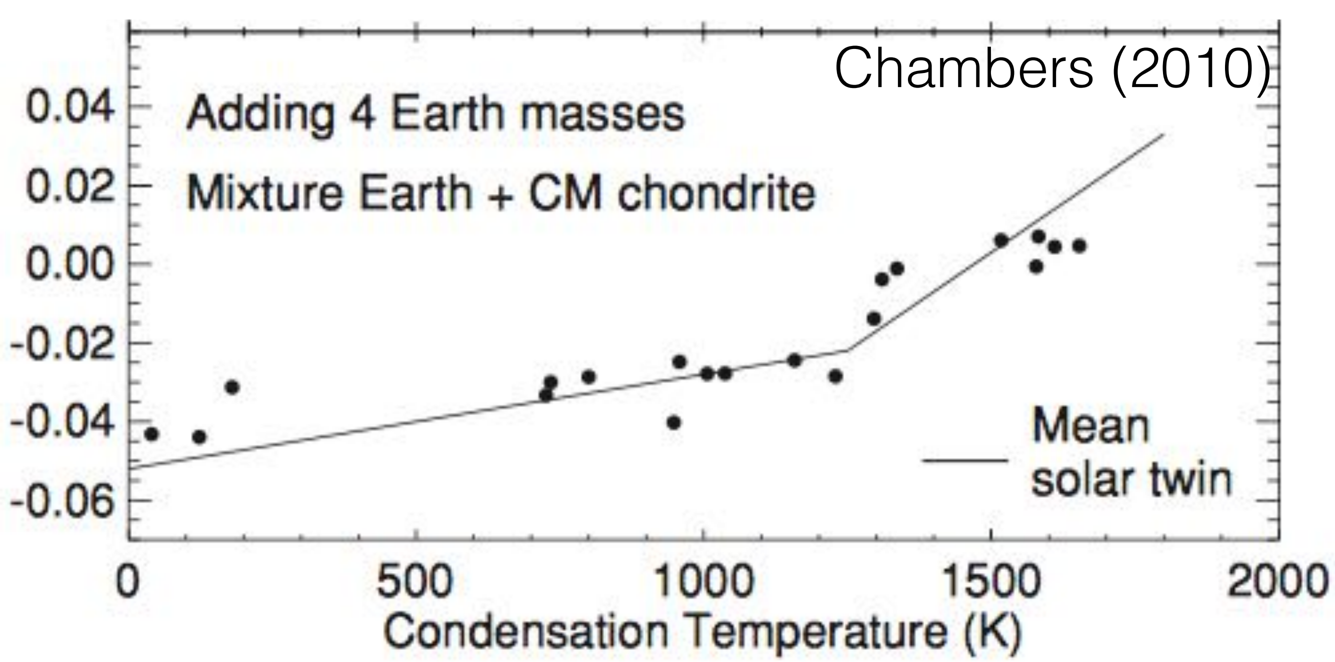
Chemical signatures of rocky planet formation?

- If the **star does not form planets**, it accretes most of the material in the disk (volatiles + refractories, without distinction).
- If the **star forms planets**, the refractories are locked into the rocky planets and the star will accrete the volatiles.



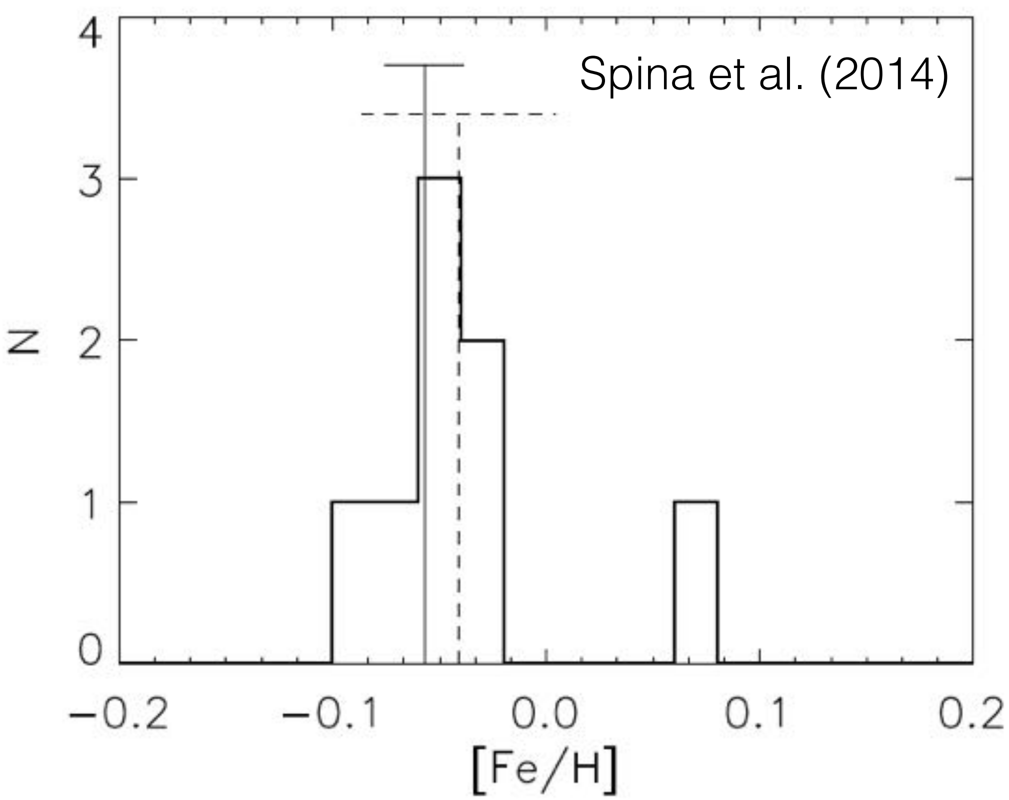


The star with rocky planets is poorer of refractories than the star without planets.

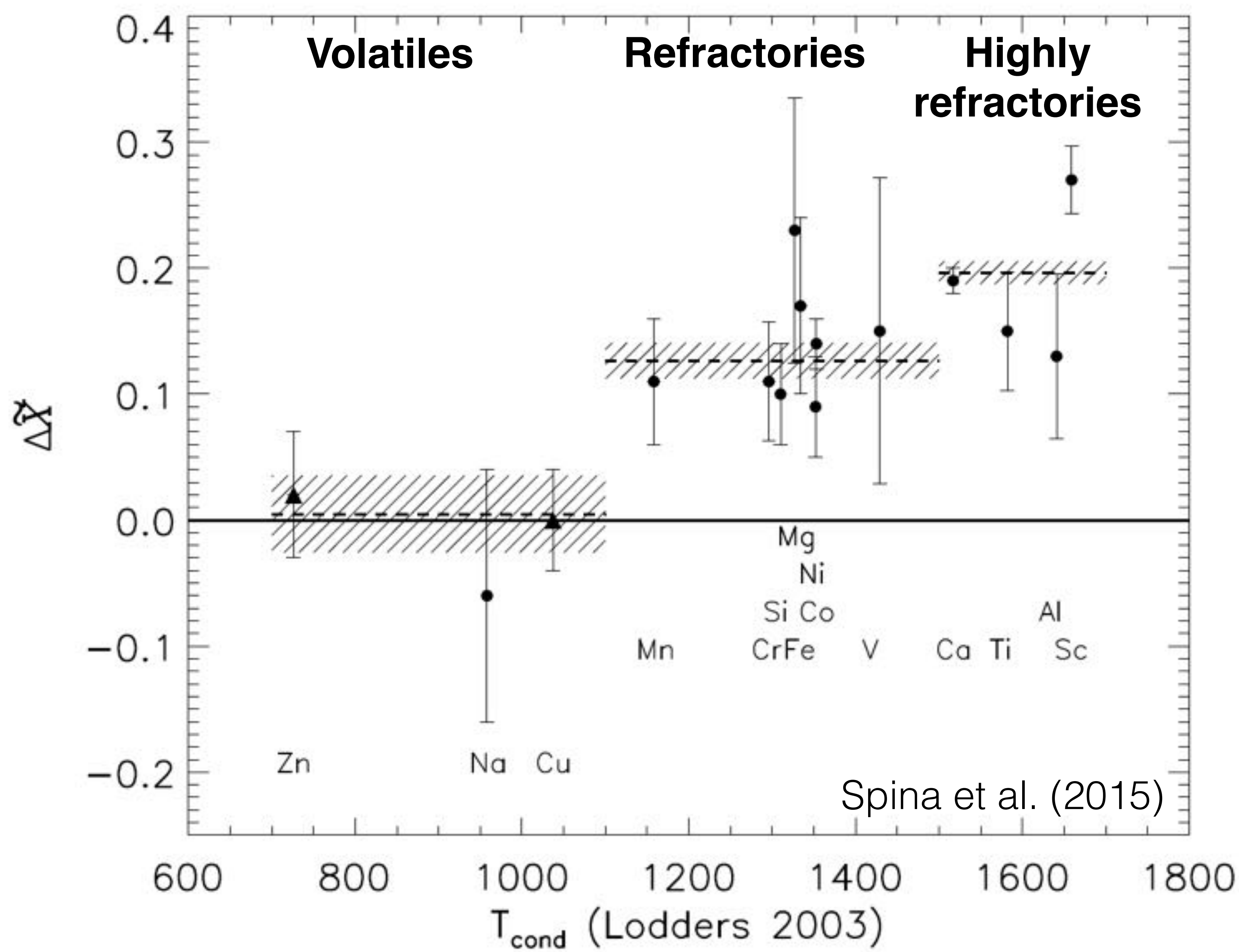


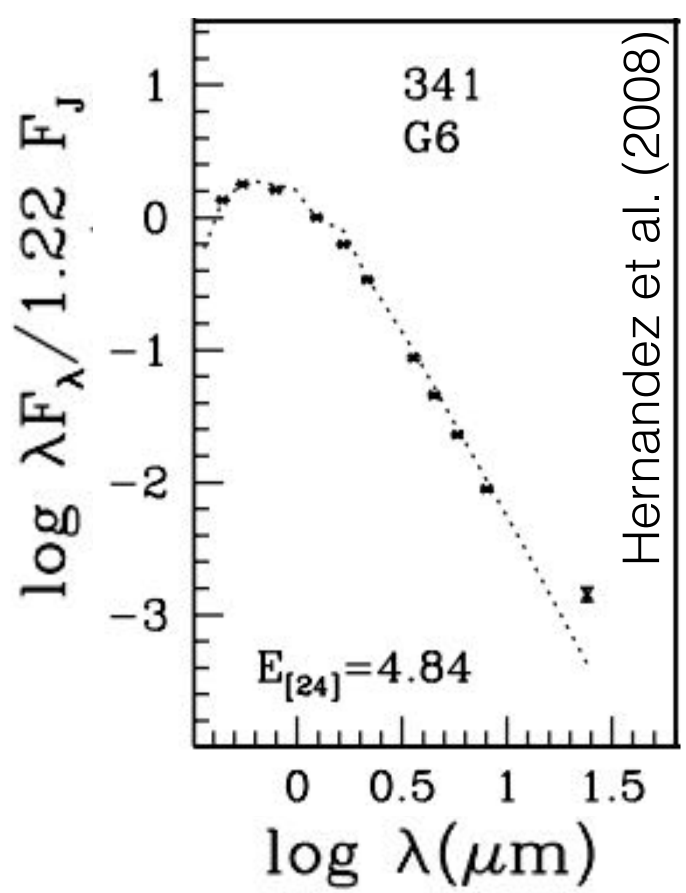
The missing refractories in the Sun are a mixture of Earth-like material and meteoritic material.

Chemical signatures of planetary engulfment?



Gamma Velorum cluster (15 Myr):
2MASS J08095427-4721419 (1.3 $M_\odot$) is +0.13 dex richer of iron respect to the cluster average (~2σ).

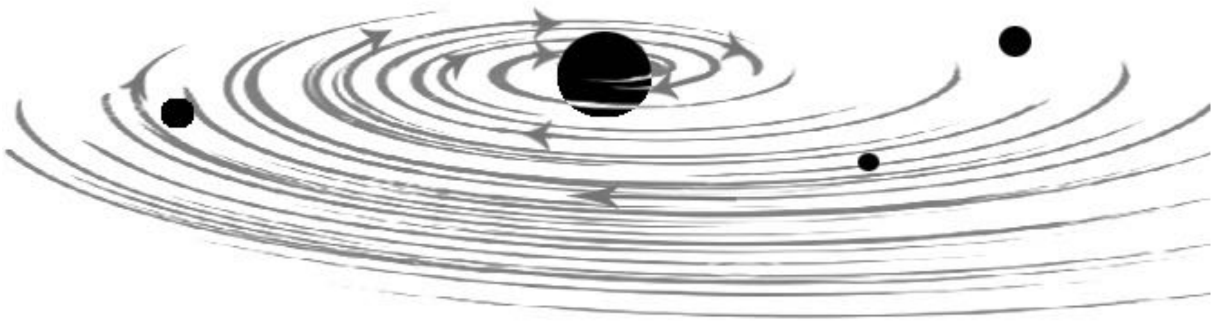




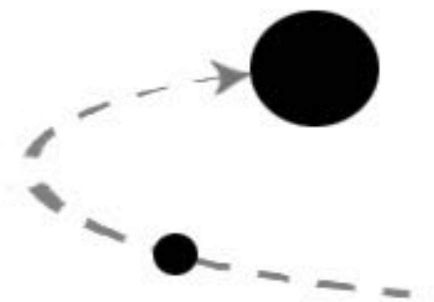
Likely the star has formed planets.
An evidence of a planetary engulfment event.

The Sun is poorer of refractory elements than the majority of the solar twin stars (Melèndez et al. 2009)

Signature of **rocky planet formation** around the Sun



Signature of **planet engulfment events** occurred for the majority of the solar twins



Material falls onto the star, is diluted into the external layer (convective zone) and selectively pollute the stellar atmosphere of determined elements

Early accretion: <10 Myr

Occurrence of planet formation: the formation of rocky planets is a rare event.

Late accretion: >10 Myr

Architecture of planetary systems: stable planetary systems (like our own) are rare.

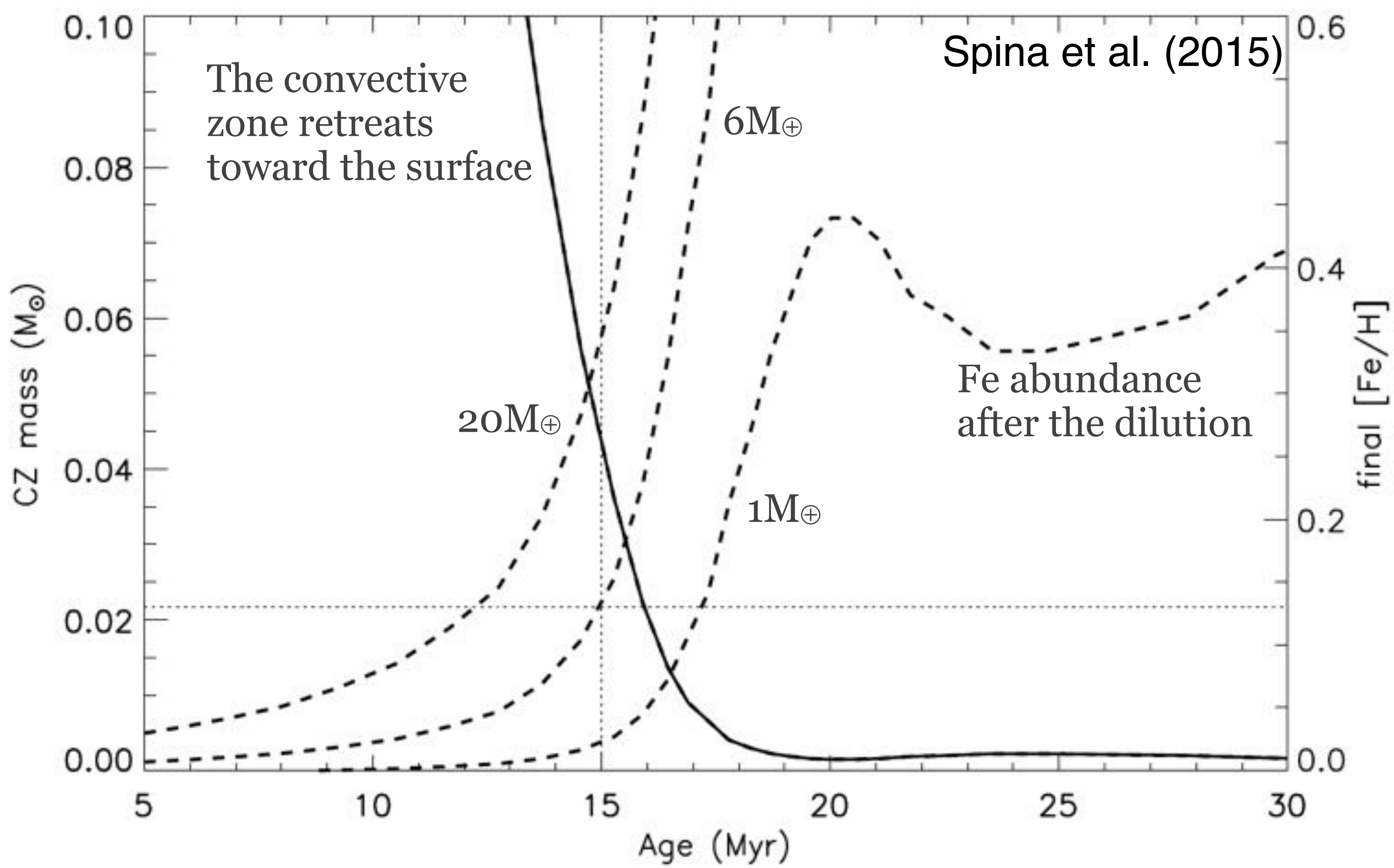
It could also be a combination of the two scenarios.
In both the cases, a Sun-like chemical pattern could be indicative of a solar-like planetary system.

The dilution matters

If the accreted mass is too diluted into the stellar material, the stellar enhancement will be modest. → The mass enclosed in the envelope layer of the star is a critical parameter!

During the PMS phase solar type stars undergo a process of internal readjustment. Younger stars have thicker convective zones.

Models:
Siess et al. (2000)
for a
1.3 $M_\odot$ star



The accretion of material during the first 10 Myr does not produce a significant enhancement of the stellar atmosphere.

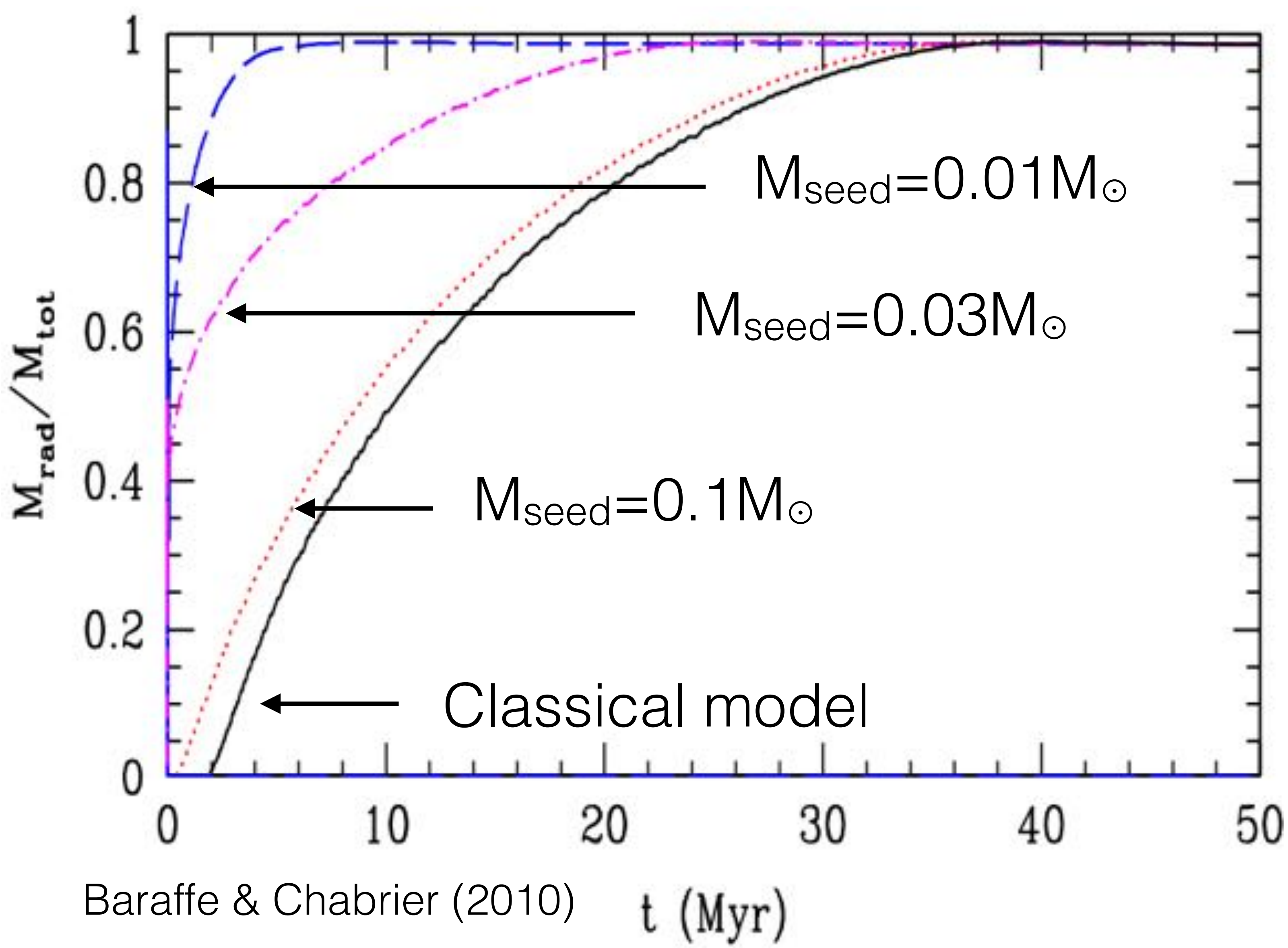
Models with episodic accretion

Very young stars accrete material from the progenitor cloud and from the disk.

The key ingredients:

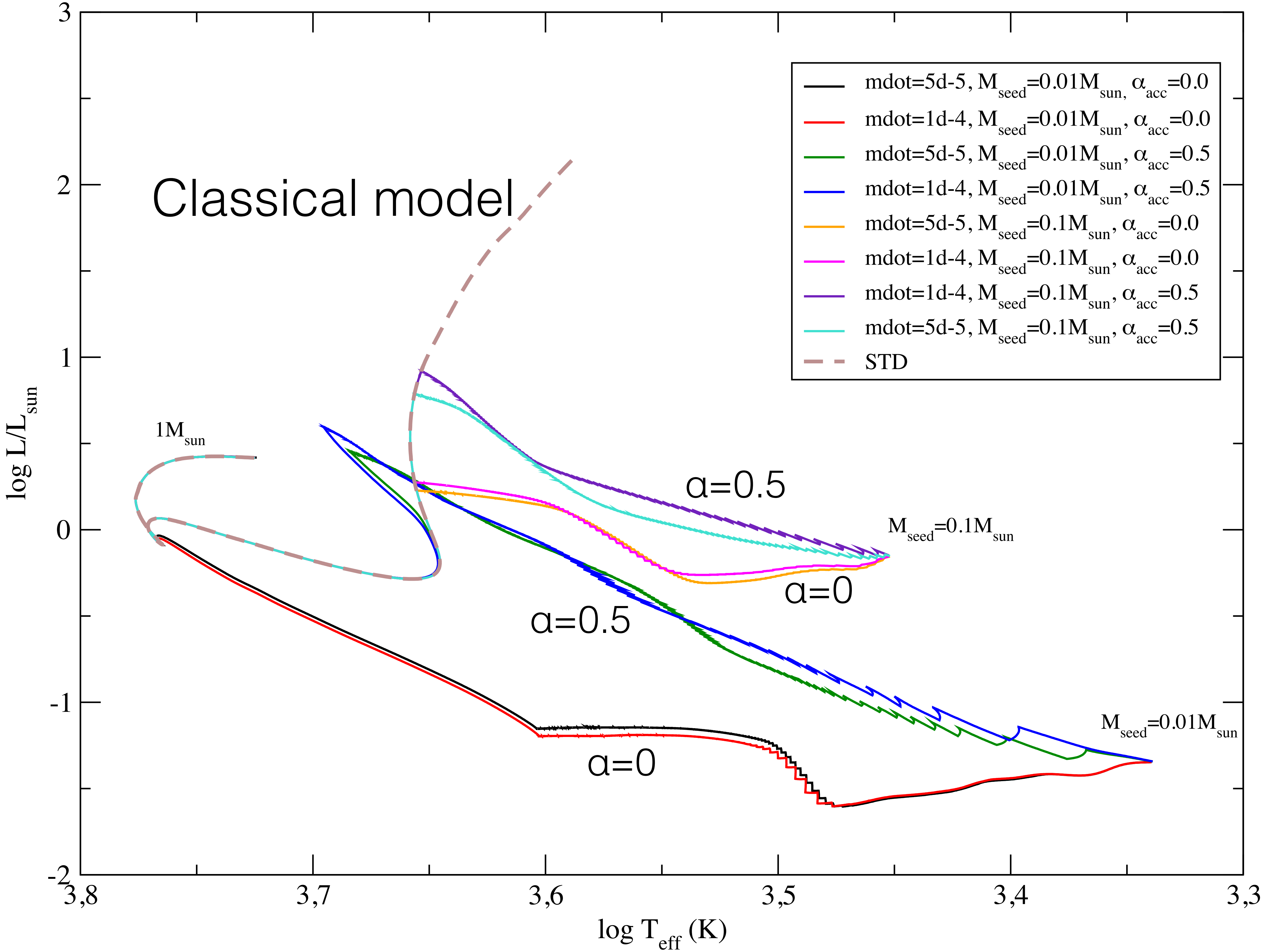
- M_{seed}: the initial mass of the protostar
- $\dot{M}_{acc}$:the mass accretion rate
- α: the fraction of energy absorbed by the proto-star

$\dot{M}_{acc}=5x10^{-4}\ M_\odot/yr$; $\alpha=0$; $\Delta t_{acc}=100$ yr; $\Delta t_{quiet}=1000$ yr



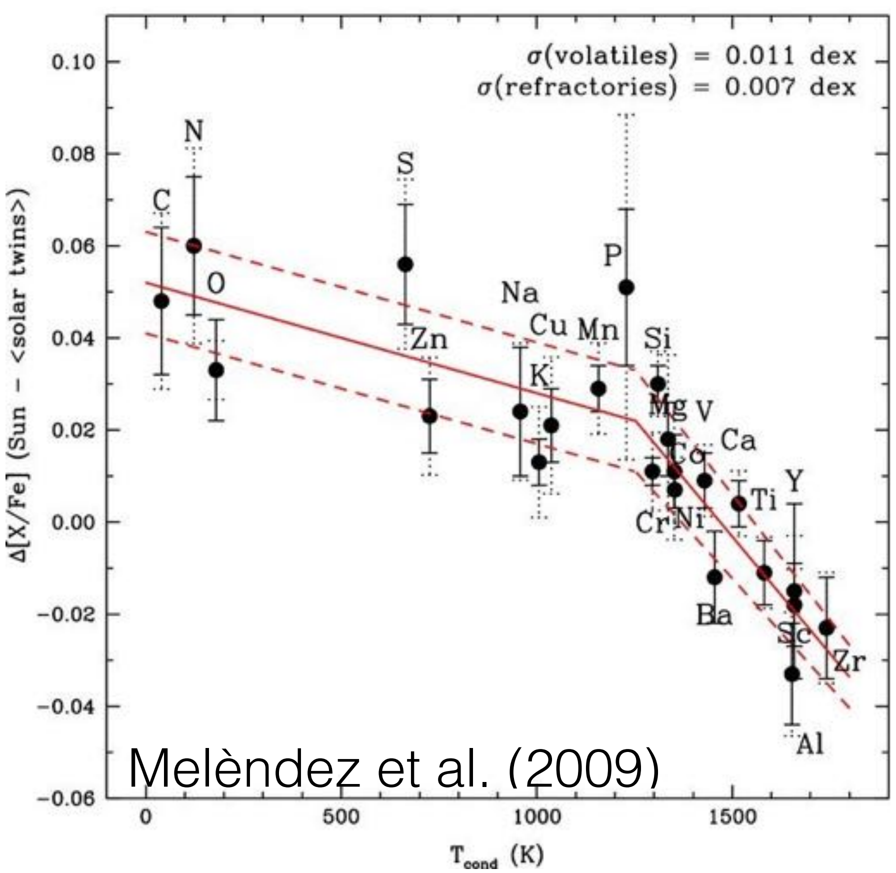
Baraffe & Chabrier (2010)

Models with episodic accretion

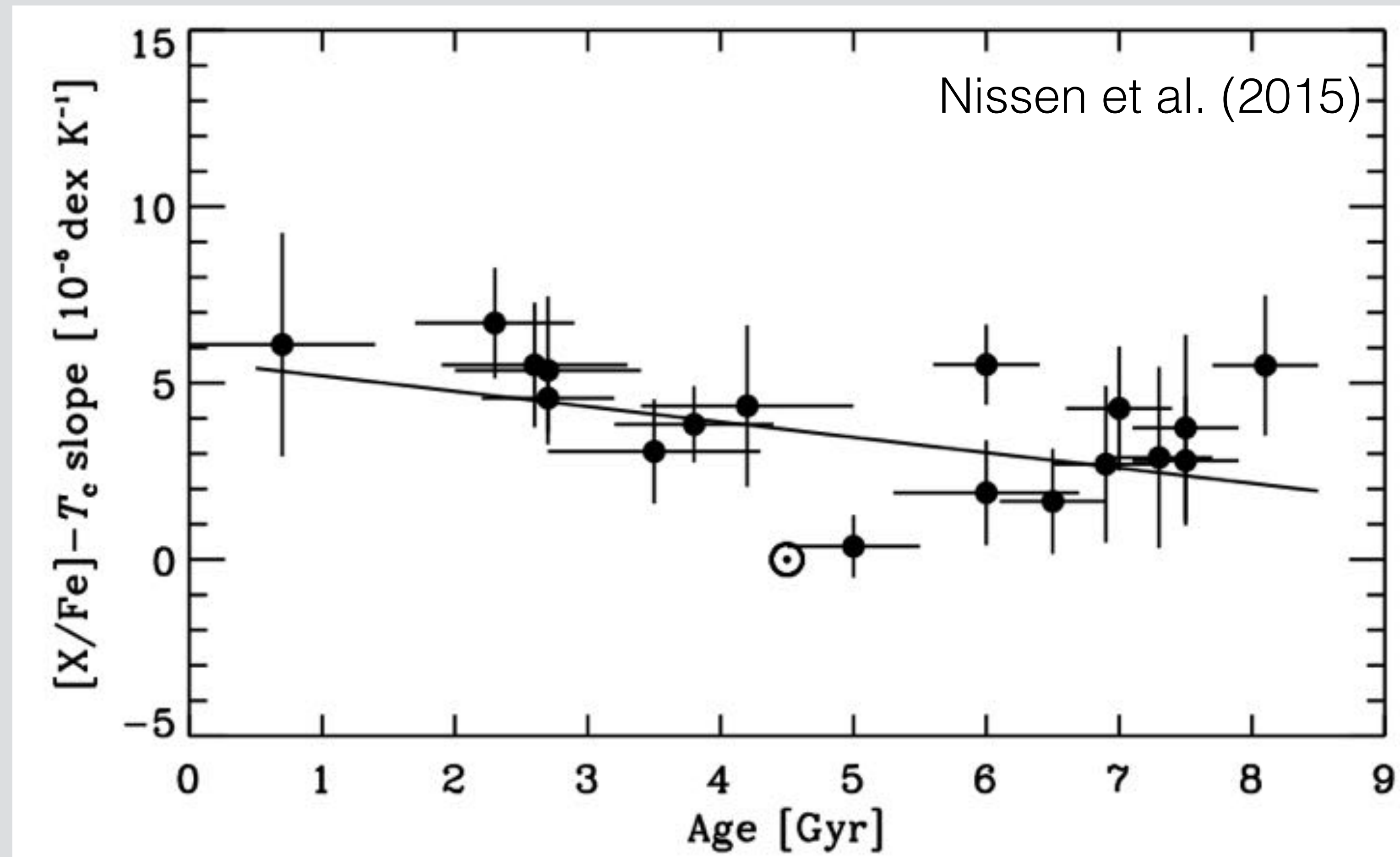


Thanks to E. Tognelli and S. Degl'Innocenti (University of Pisa)

An alternative interpretation not related to planets



An effect of the Galactic chemical evolution?
Old stars are poorer in refractories than younger stars (Adibekyan et al. 2014).

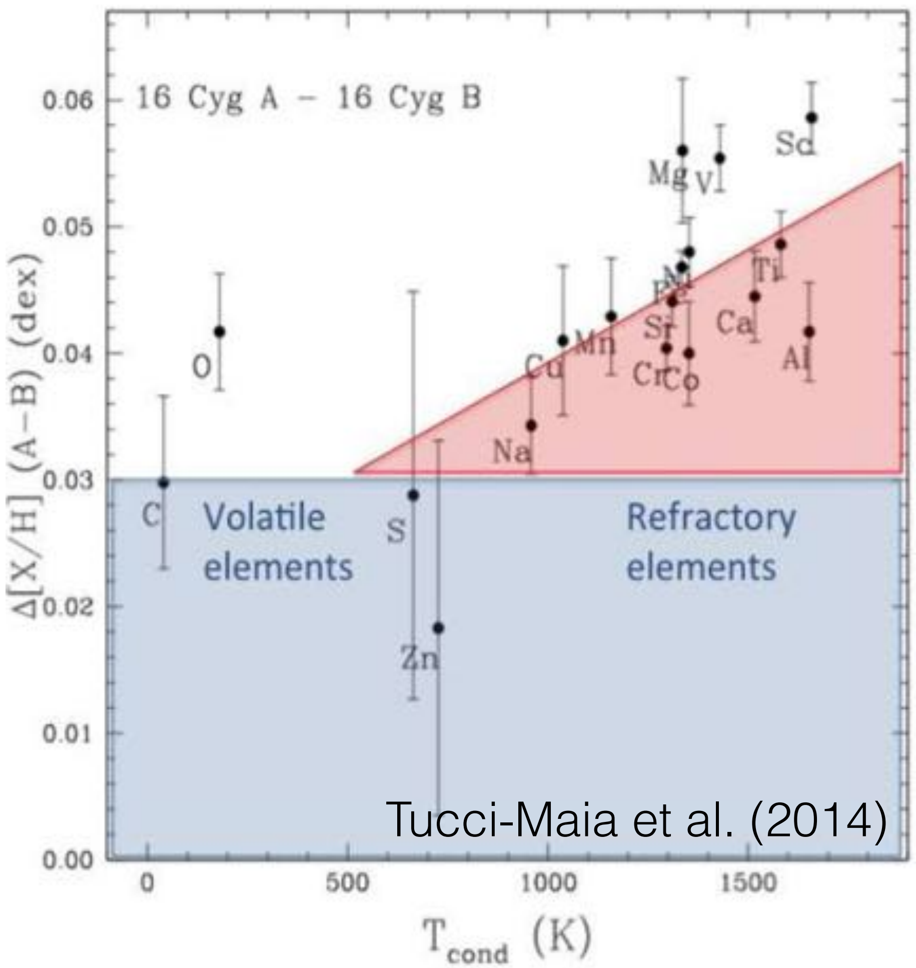


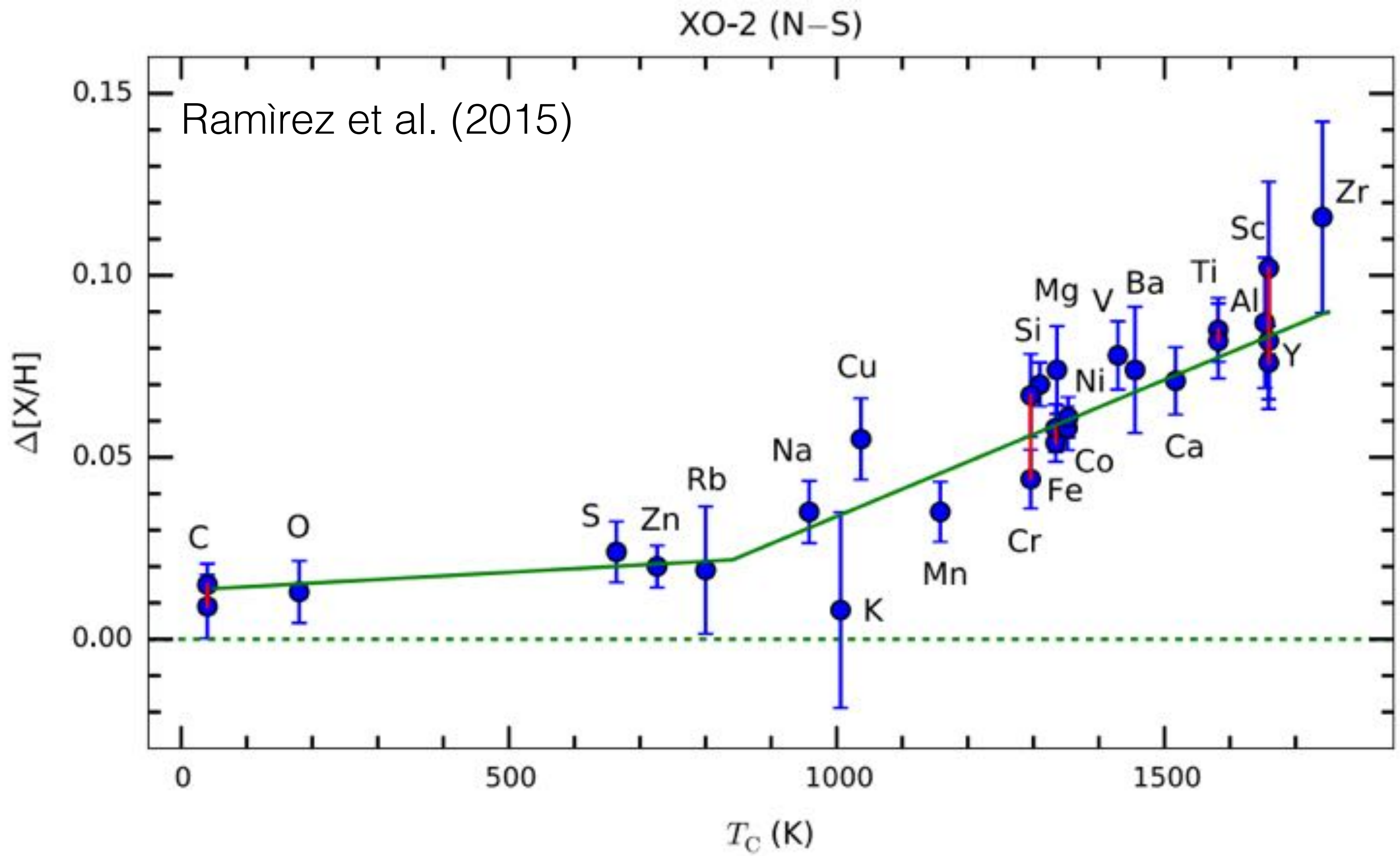
Are these trends between differential abundances and condensation temperature only due to the chemical evolution of the Galaxy?

Compare the chemical pattern of solar twins formed by the same gas.

Chemical anomalies in binary pairs

Trends between [X/H] and T_{cond} have been found between stars in binary systems.

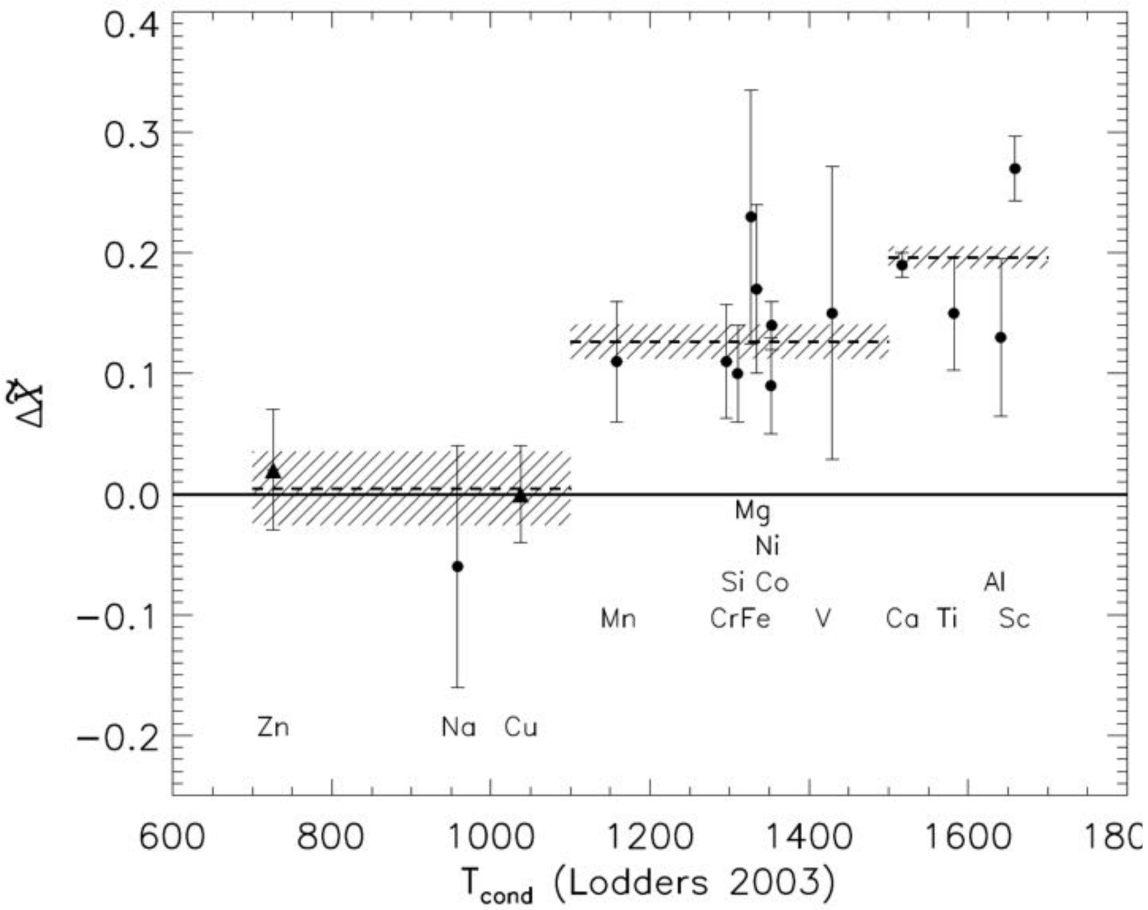




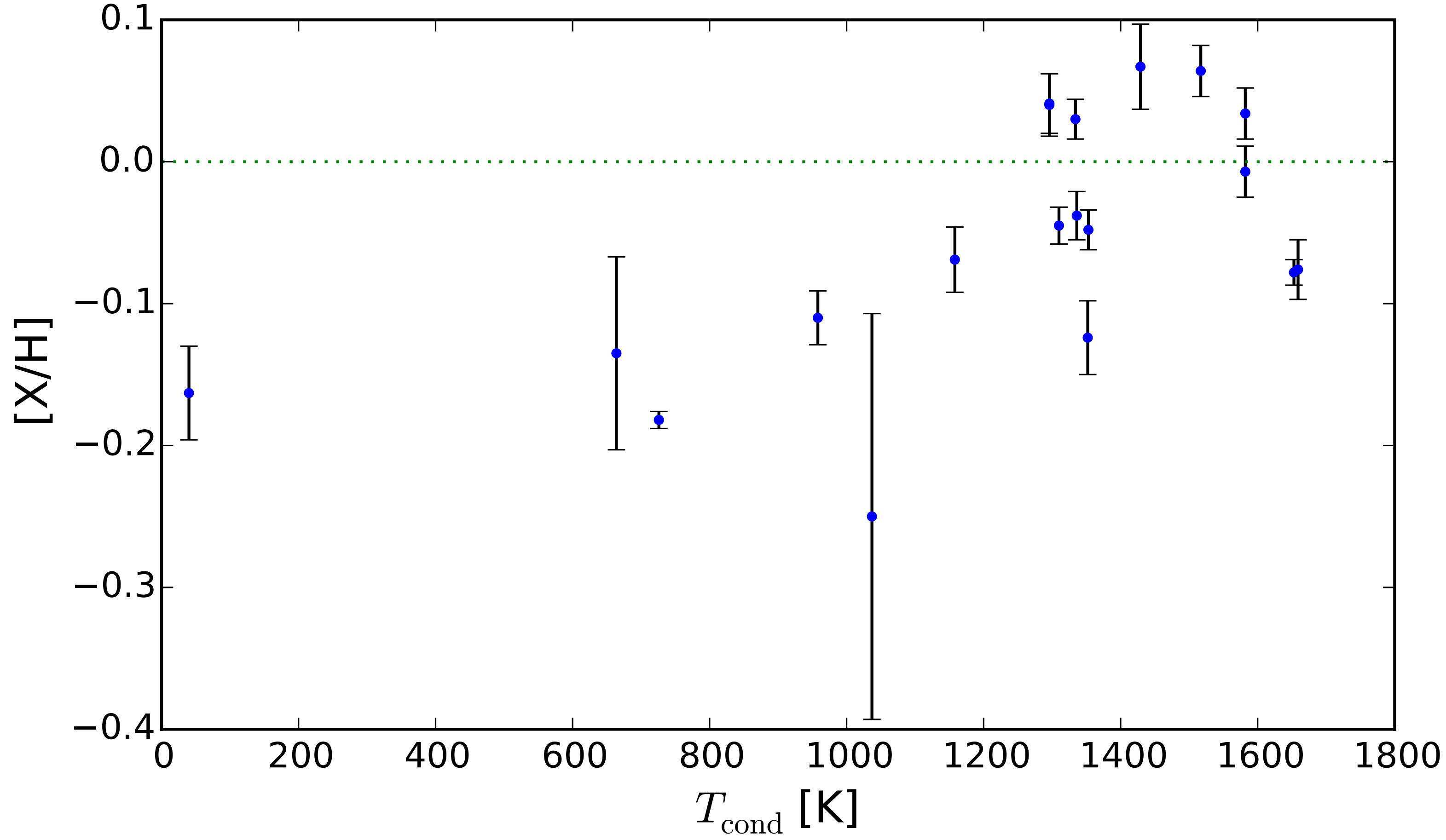
- So far, five stars in binary systems have showed chemical anomalies related to the condensation temperature. These anomalies have been confirmed by several authors (Tucci-Maia et al. 2014; Ramirez et al. 2015; Biazzo et al. 2015; Saffe et al. 2016; Teske et al. 2016a, 2016b; Adybekian et al. 2016)
- There are other binary pairs that do not show any chemical variation (e.g., Liu et al. 2014)

Chemical anomalies in open clusters

Gamma Vel - Spina et al. (2015)



Pleiades - Spina et al. (in prep.)

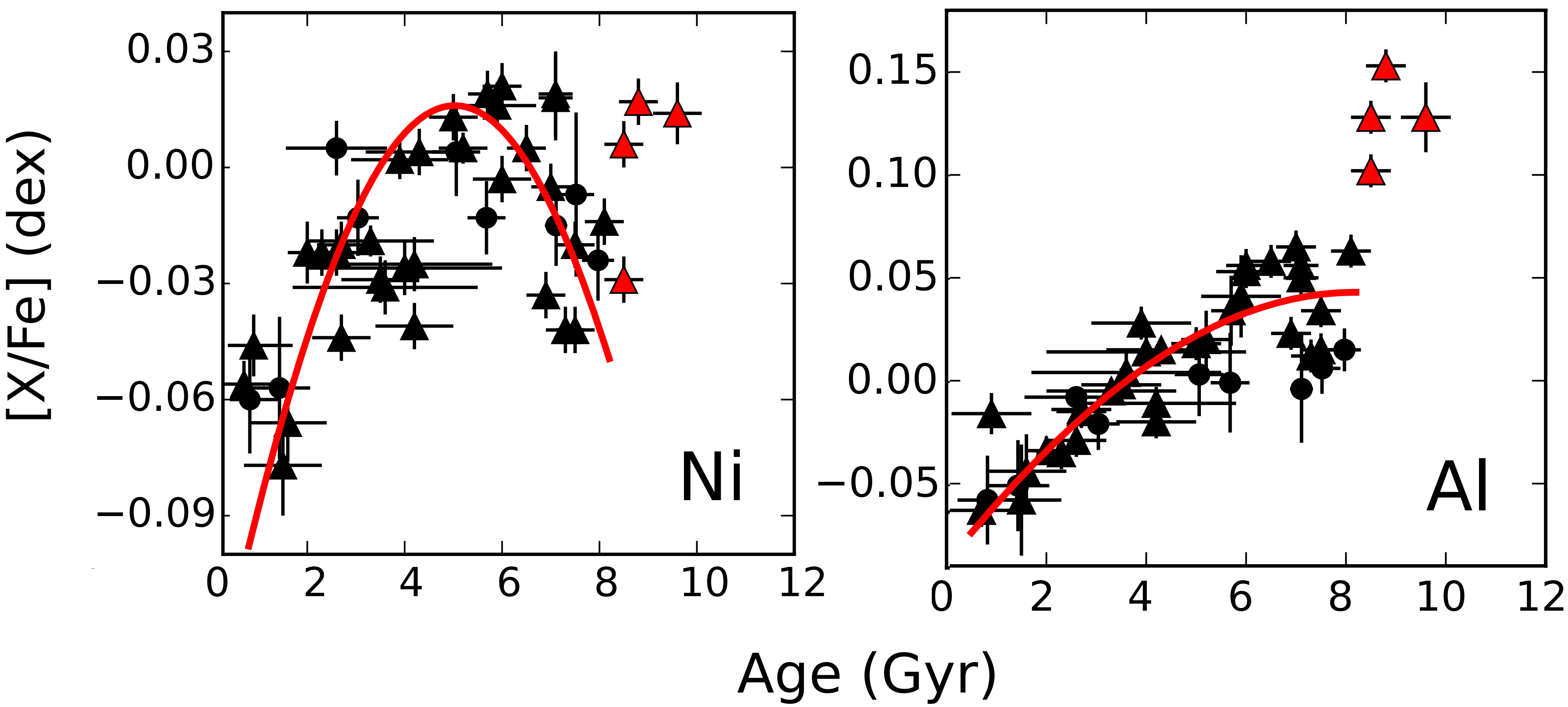


Chemical anomalies found in Hyades and M67, but without relations to the T_{cond} (Liu et al. 2014; 2016)

Other possibilities are not ruled out, such as the gas-dust segregation in the circumstellar disks (Gaidos et al. 2015)

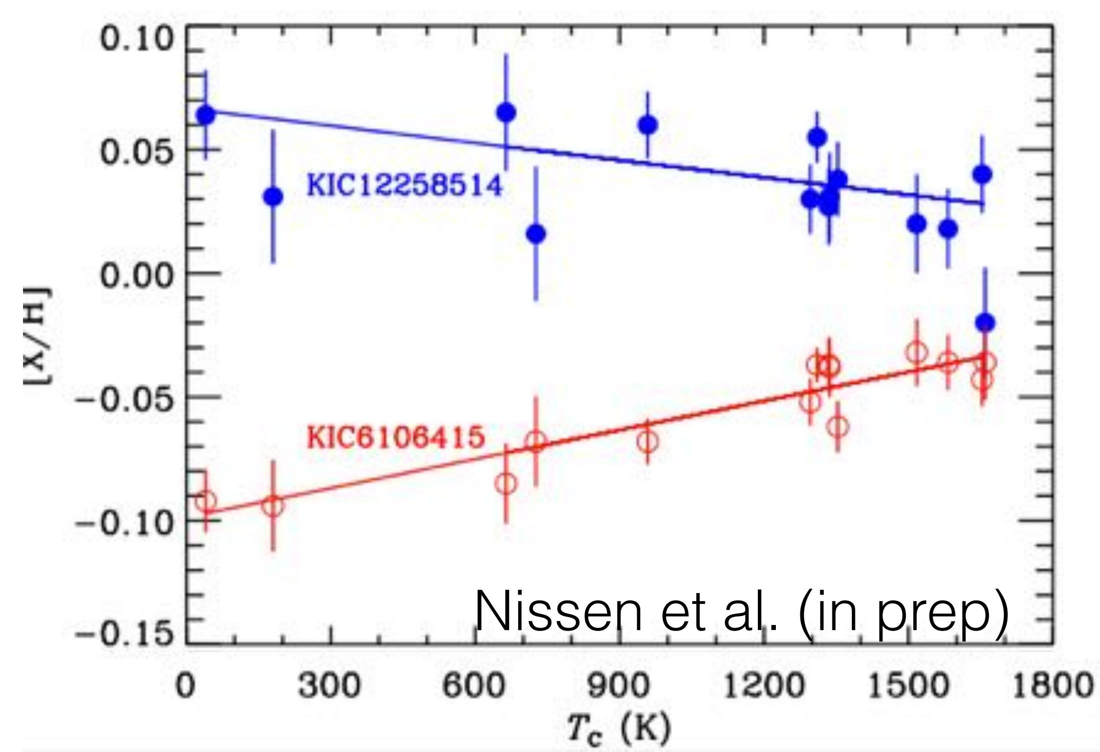
These results are challenging the possibility to associate stars to determined native environments on the basis of abundance ratios.

Subtracting the chemical evolution of the Galaxy

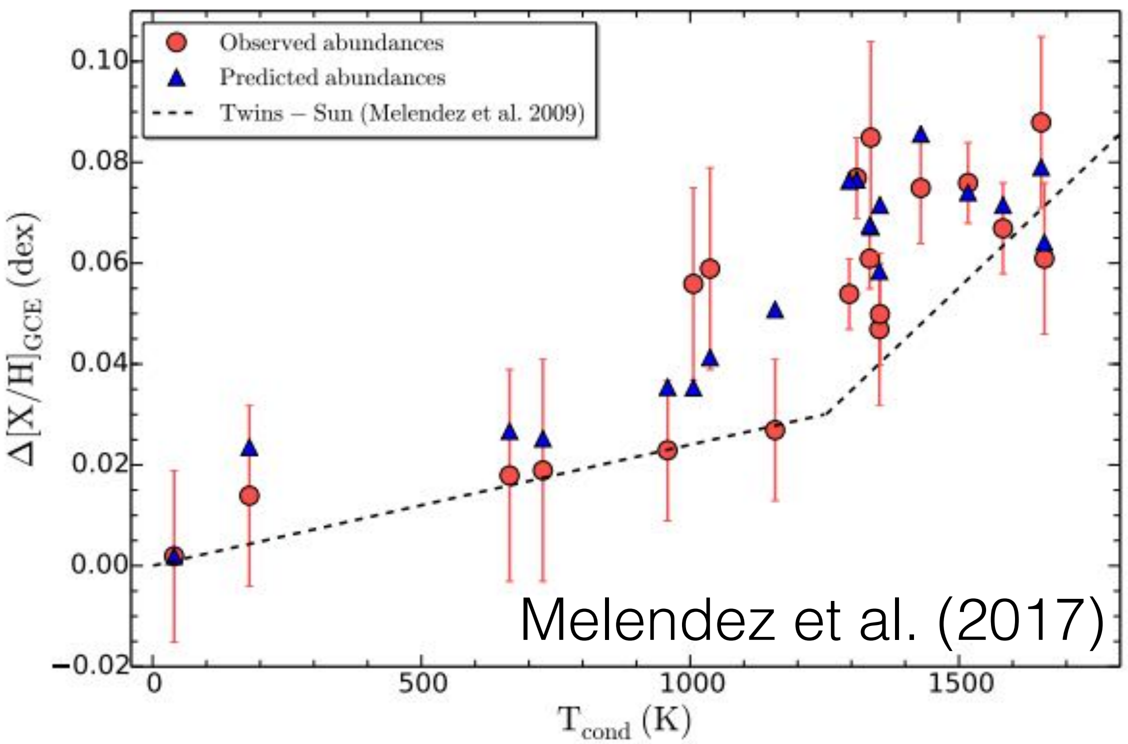


High-precision abundances in solar twins allow studies of the [X/Fe]-Age correlations (see Nissen 2015, 2016, Spina 2016ab)

We can subtract the effect of the chemical evolution of the Galaxy in order to reveal secondary effects related to the presence of planets (Spina et al. 2016a).



A chemically anomalous solar twin: HIP 68468



The star has two Planets:

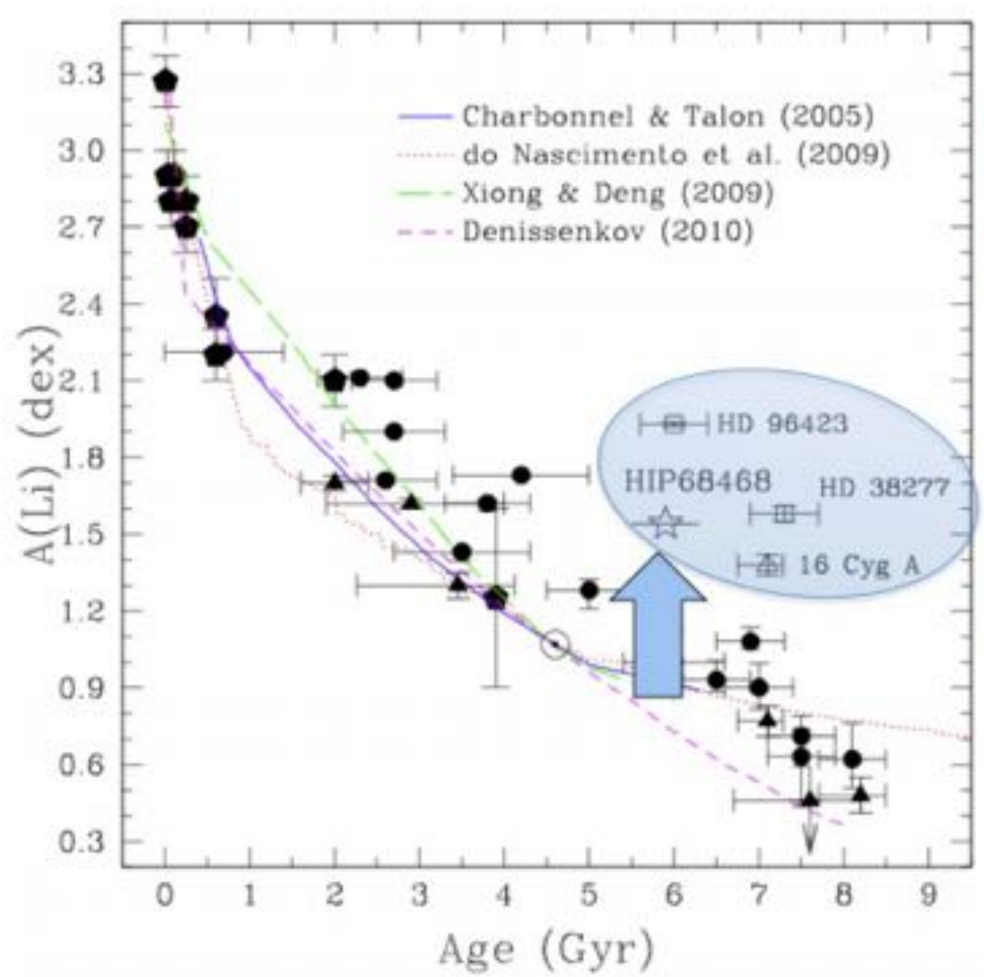
- 26±4 $M_\oplus$ at 0.66AU
- 2.9±0.8 $M_\oplus$ at 0.03 AU

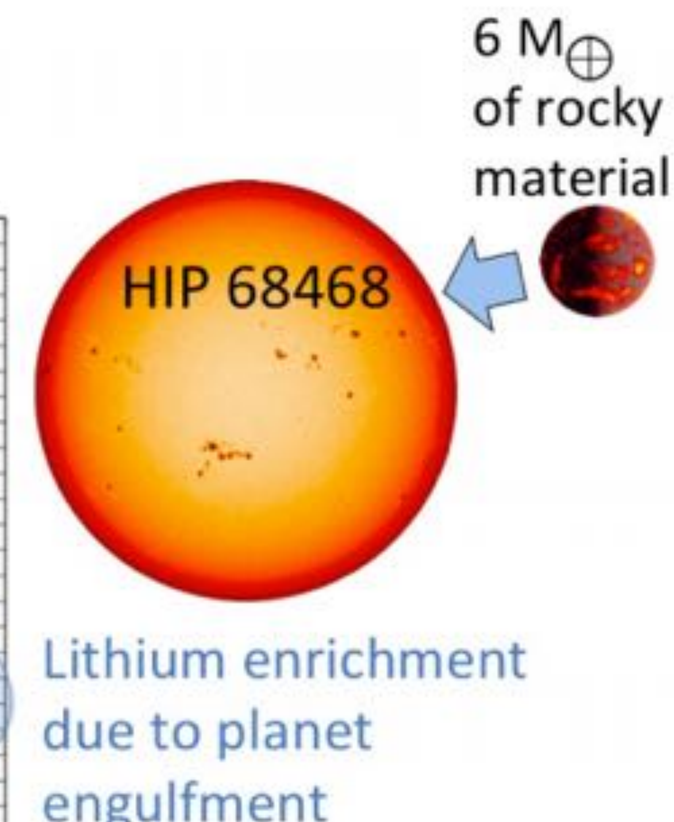
The chemical pattern corrected for the Galactic chemical evolution shows a clear trend with the condensation temperature. The overabundance of refractories is equal to 6 $M_\oplus$ of rocky material.

The star is also enhanced in Li.

↓

A strong evidence of planetary engulfment event





Carlos et al. (2016)

Melèndez & Ramìrez et al. (2016)

What is the nature of this link? Is the high metallicity a prerequisite for the formation of giant planets, or does the planet formation process alter the stellar surface abundances, or is it a combination?

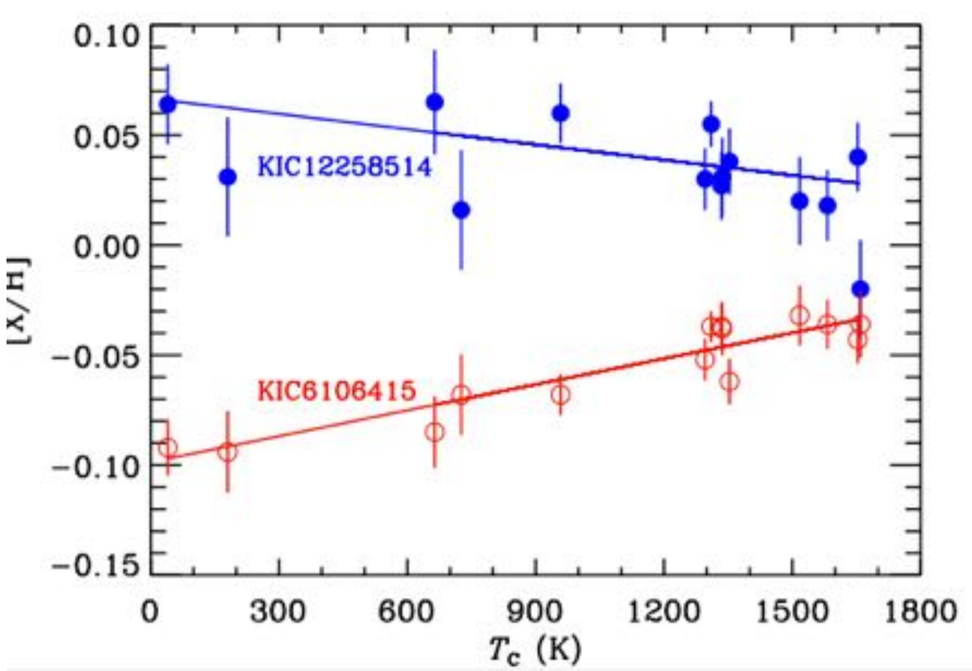
Planet-metallicity connection	**Trend [X/H] - T_{cond}**
High-precision is not required	High-precision abundances are required ($\sigma_{[Fe/H]}$<0.01 dex)
It is a statistical correlation (large samples of stars)	Observed when comparing stars sharing a similar history
Process of giant planet formation	Its nature is not fully understood. Very likely it is related to determined events that polluted the stellar atmospheres
The Sun is a typical star	The Sun probably is an anomalous star

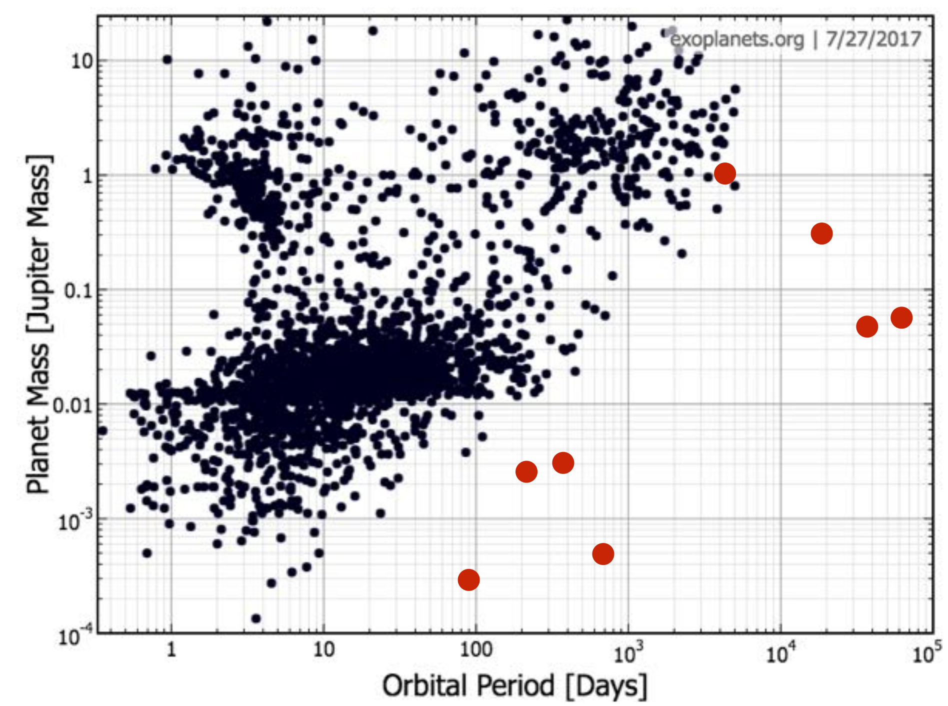
My open questions about the [X/H]-T_{cond} trends

- When does the star has been polluted?
  During or after the planet formation?

- Which is the frequency of chemically anomalous stars in binary pairs and open clusters?

- Are these [X/H] - T_{cond} trends connected with the big diversity observed among planetary systems?





- If so, is it possible to identify stars that could host a Solar System 2.0 from their chemical composition?