Are open clusters chemically homogeneous?

Fan Liu

Collaborators: Martin Asplund, David Yong, Sofia Feltzing, Jorge Melendez, Ivan Ramirez

August 1st 2018

Australian National University

Lund University

Why open clusters are important?

- Open clusters

--- basic Galactic building blocks

--- form together, coeval

--- chemically identical

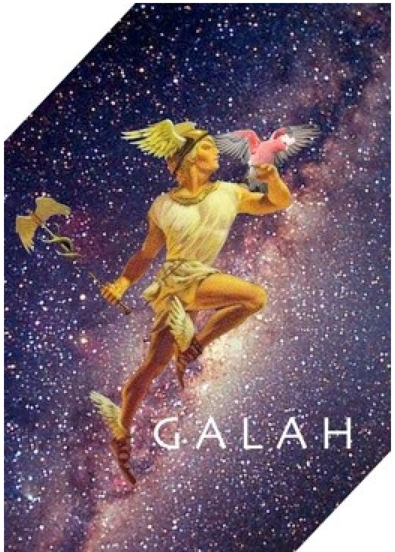
Is it true?

- Assumption for concept of chemical tagging

(Freeman & Bland-Hawthorn 2002)

- Clues for Galactic archeology

GaiaESO



Should OCs be chemically homogeneous?

- Inhomogeneous mixing of proto-cluster cloud

  Yes/small scatter (Feng & Krumholz 2014)

  No element-to-element variation

  Intrinsic scatter ~ 0.01 – 0.03 dex

- Chemical signature of planet formation

  Probably not (Melendez et al. 2009)

  Trend with condensation temperature

- Varying amount of atomic diffusion in stars

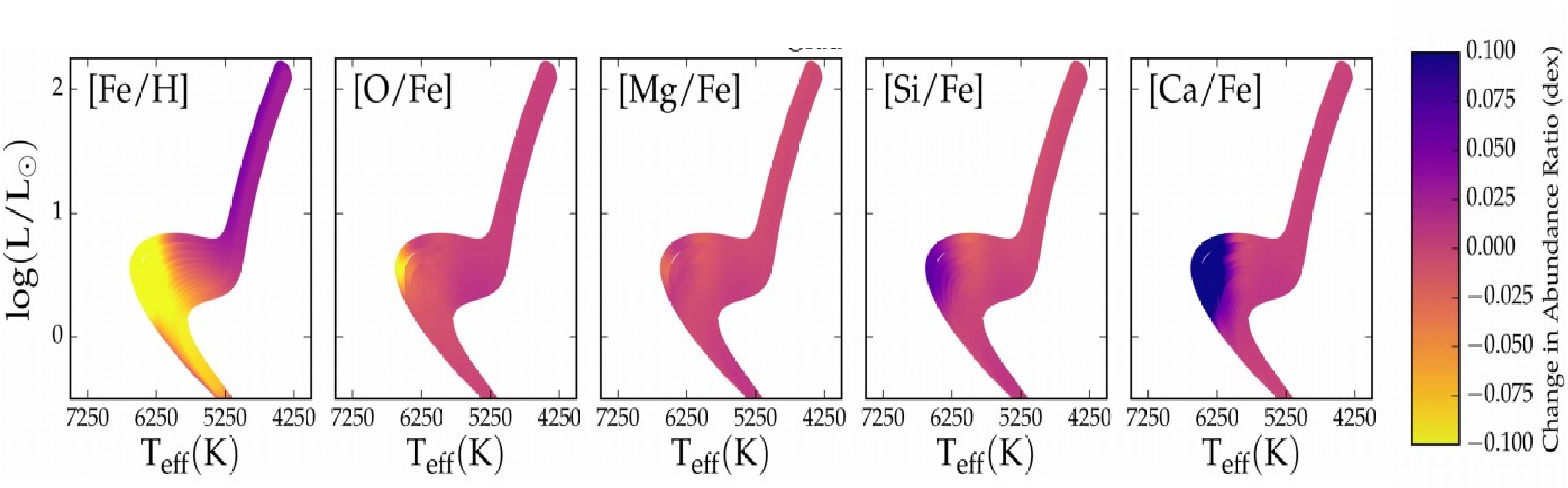
  No (Dotter et al. 2017)

  Trend with stellar evolutionary phase

Atomic diffusion

- Atomic diffusion: gravitational settling + radiative levitation
- Surface and convection zone abundances change with time
- Trend with stellar evolutionary phase

Dotter et al. 2017



Extremely high precision in abundance

- Intrinsic uncertainties: ~ 0.05 dex is the 'floor' (e.g., Asplund 2009)
- Strictly line-by-line differential approach

Require high quality spectra (R > 50,000; S/N > 300) using 'stellar twins'

Systematic errors cancel
-> Line-by-line cancel errors in gf-values
-> Weak dependence on model atmospheres

Very precise relative abundance ratios (0.01 – 0.02 dex, 2% - 5%)

Hyades observations

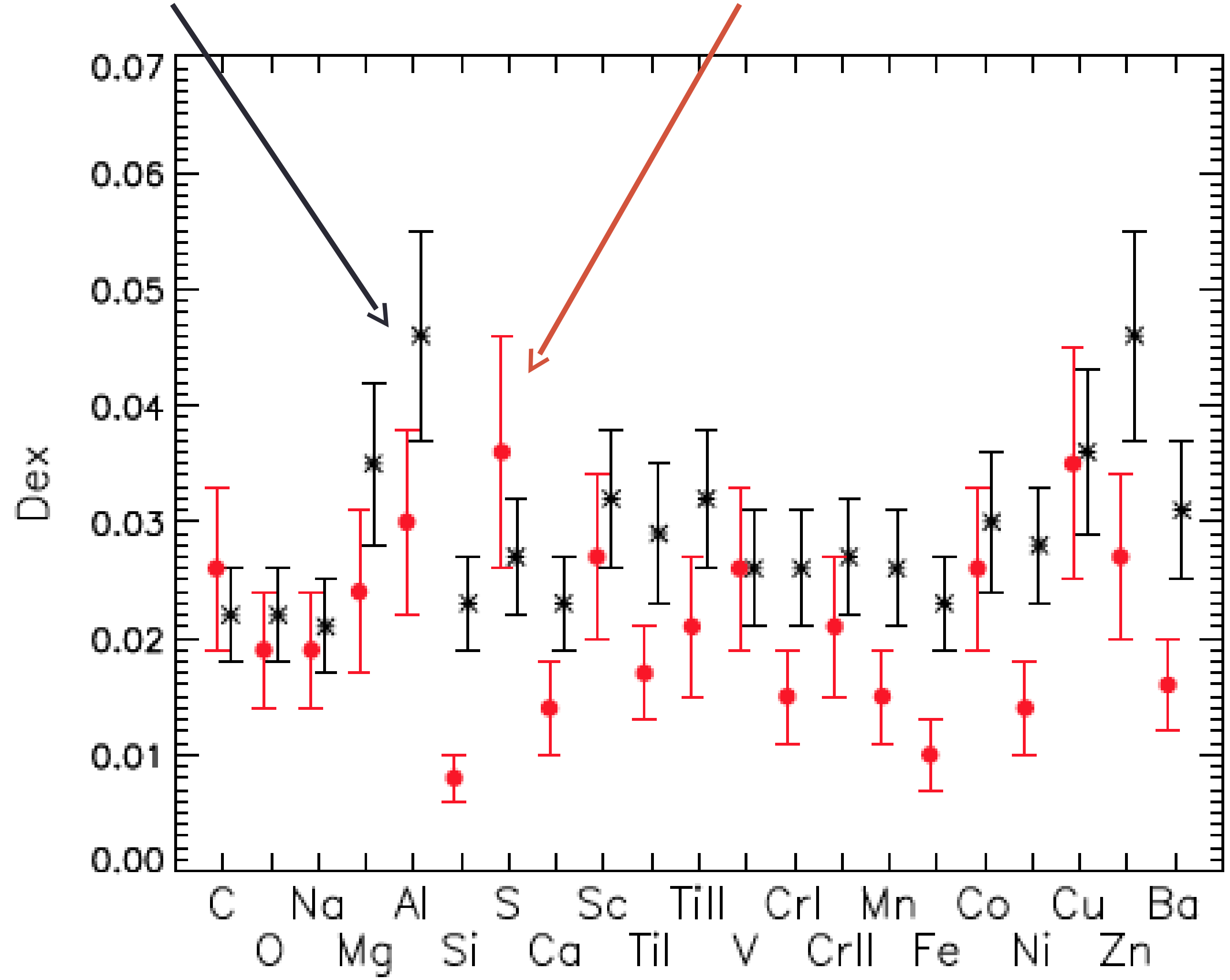
- McDonald/2.7m/TS2 echelle spectra
- R = 60,000, S/N ~ 350
- Wavelength coverage (3700 – 10,000 Å)
- 16 solar-type stars (5600 - 6200 K) from Paulson et al. 2003

- Extremely high precision differential abundance analysis
  σTeff = 20 K, σlogg = 0.03, σ[Fe/H] = 0.01, σ[X/H] = 0.02

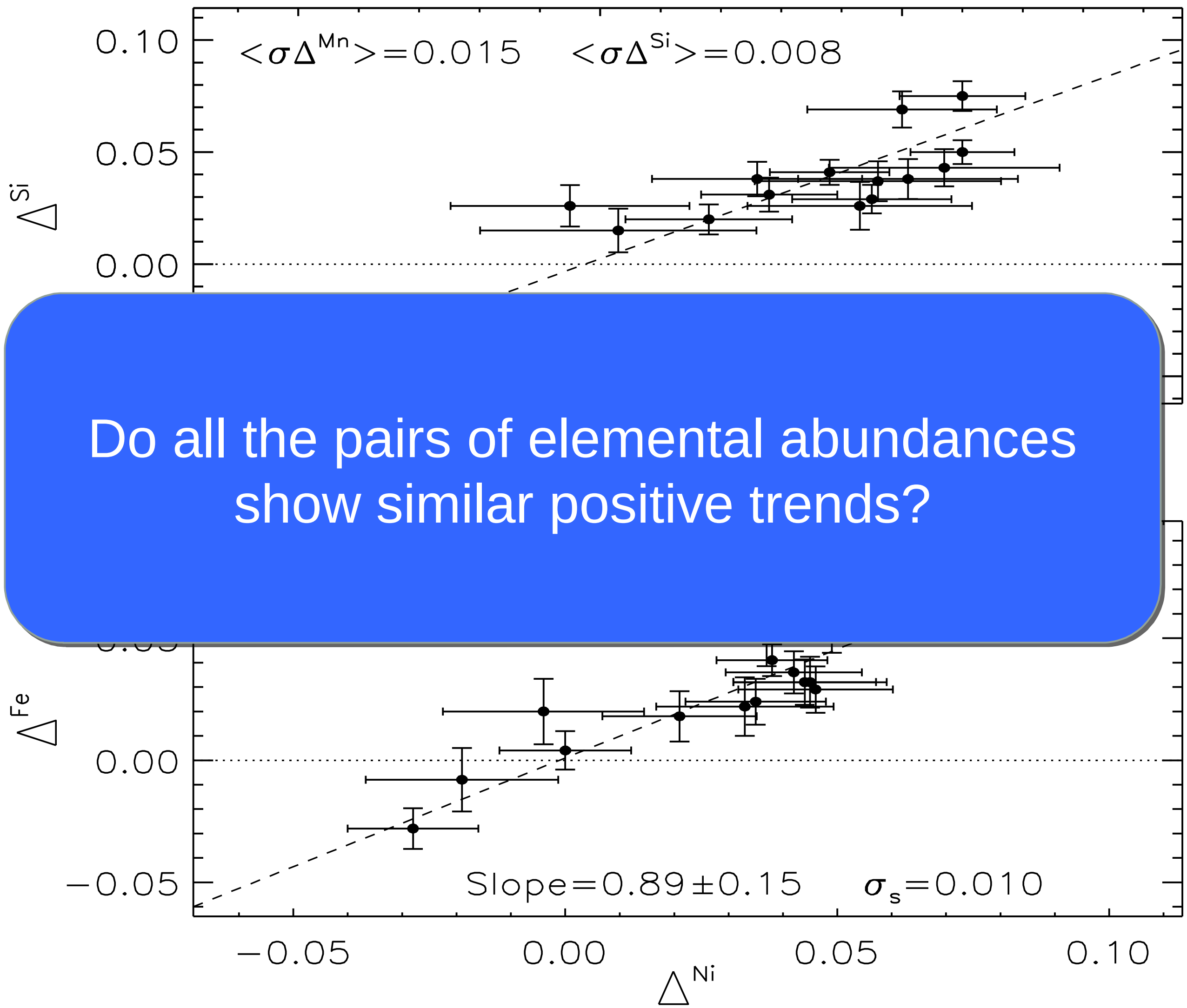
Chemical inhomogeneity in the Hyades?

Observed scatter larger than expected uncertainties for most elements

Liu et al. 2016a

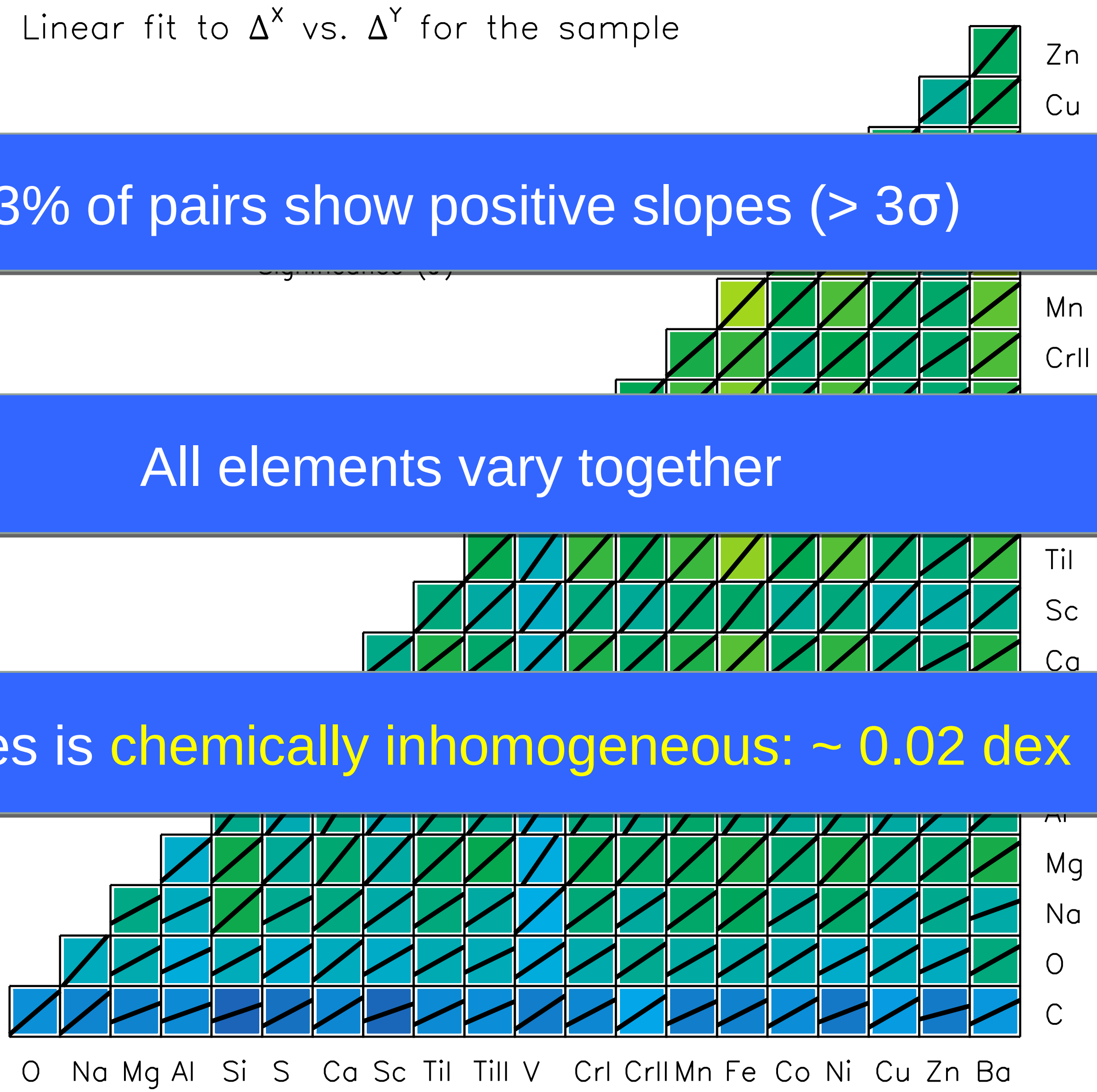


Differential elemental abundances



Do all the pairs of elemental abundances show similar positive trends?

Abundance correlations



83% of pairs show positive slopes (> 3σ)

All elements vary together

Hyades is chemically inhomogeneous: ~ 0.02 dex

Possible explanations

- Underestimation of systematic errors?

  Unlikely

  Require at least 3 times larger errors

- Supernova ejection in the proto-cluster cloud

  Can’t reveal all the measured abundance patterns

- *Pollution of metal-poor gas before the complete mixing*

  Possibly, worth for further exploration

M67 Keck program

V ~ 14 mag
Age ~ 3.5 – 4.8 Gyr
(Yadav et al. 2008)

Solar metallicity (-0.04 - +0.03)
(Yong et al. 2005; Randich et al. 2006)

- Was the Sun born from M67?

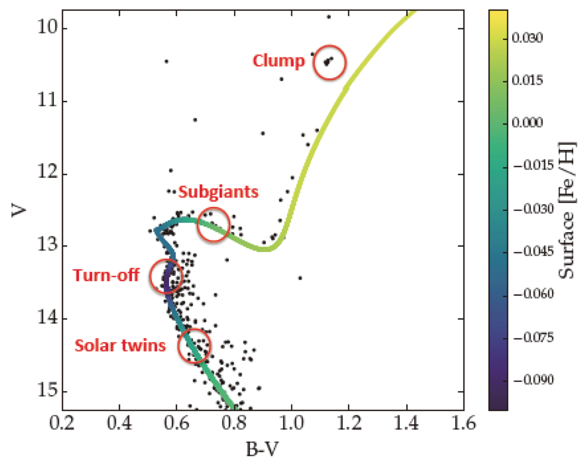
  (e.g., Gustaffsson et al. 2016, 2018)
- Chemical signature of planet in M67?

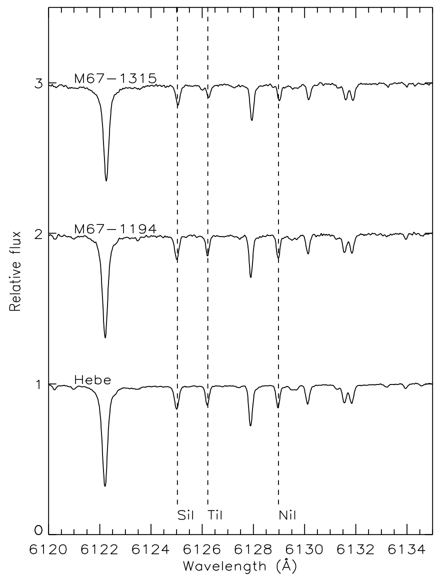
  (HJs in M67, Brucalassi et al. 2016)
- Effect of atomic diffusion in M67?

  (e.g., Souto et al. 2018, Gao et al. 2018, Bertelli Motta et al. 2018)

M67 observations

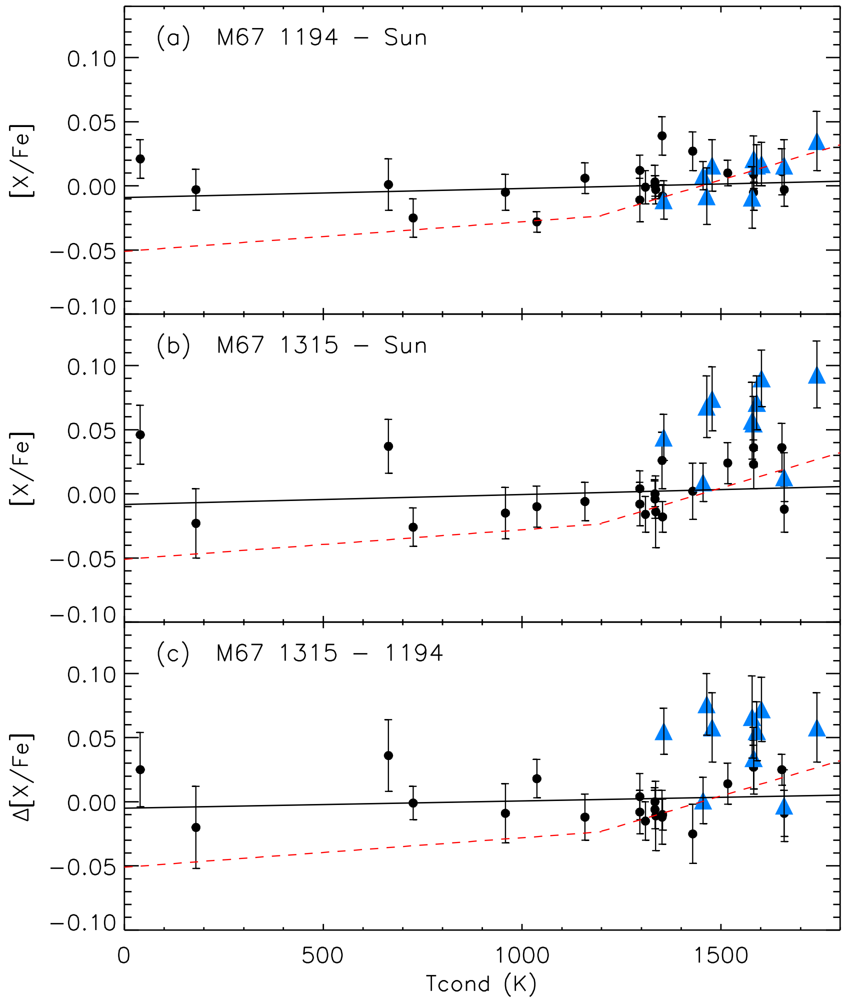
- Keck/HIRES: 3.5 nights
- 2 solar twins, 3 turn-off stars, 3 subgiants, 5 clump stars
- R = 50,000, S/N ~ 270 - 350
- Wavelength coverage (4200 – 8500 Å)
- Precise differential abundance analysis
  σTeff = 30 K, σlogg = 0.04,
  σ[Fe/H] = 0.015, σ[X/H] = 0.025





Solar twins: 1194 & 1315

Liu et al. 2016b



1194 is identical to the Sun

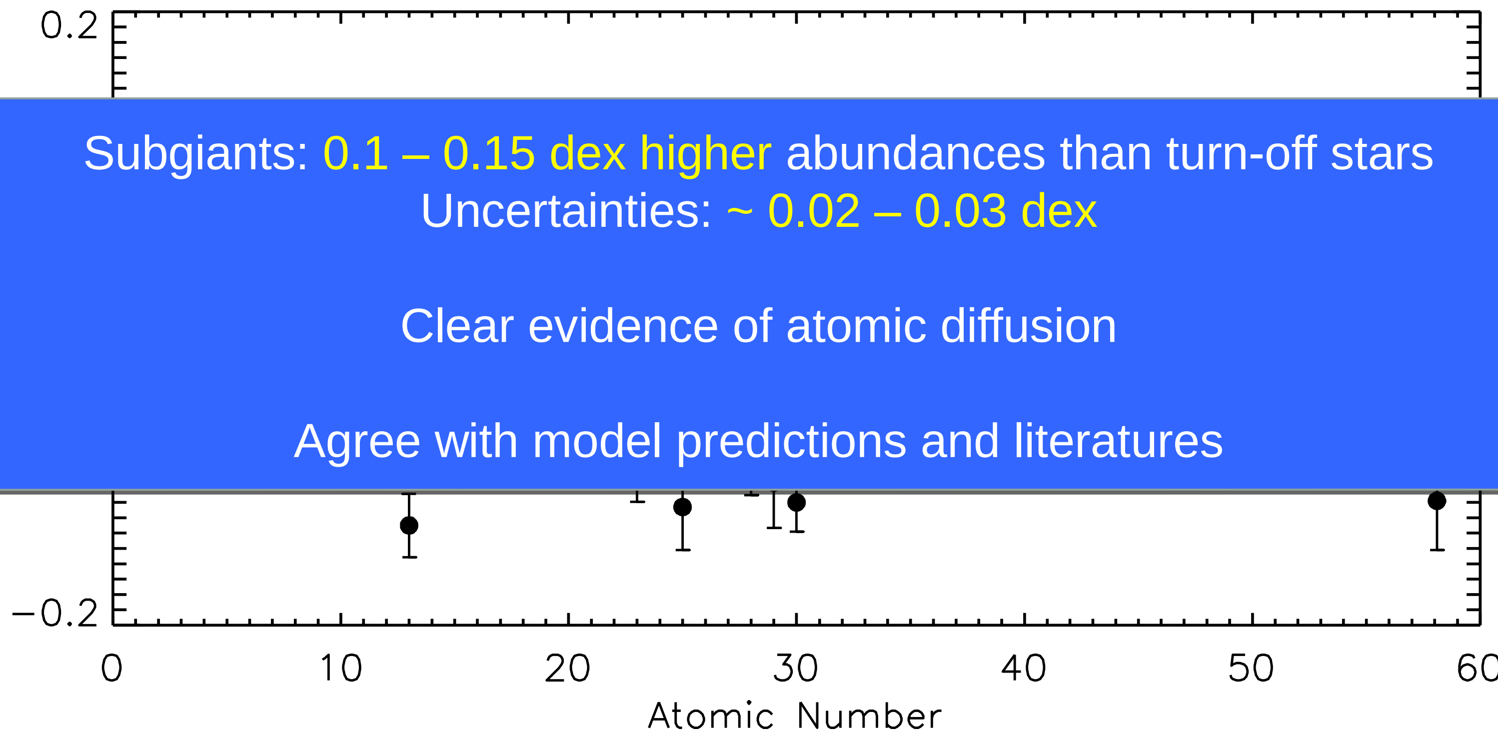
1315 is similar to the Sun and 1194 for Z <= 30

1315 is enriched in neutro-capture elements ([X/Fe]) by ~ 0.05 dex

Turn-off stars & Subgiants

Liu et al. 2018, in prep

<SG> & <TO> - Sun



Subgiants: 0.1 – 0.15 dex higher abundances than turn-off stars
Uncertainties: ~ 0.02 – 0.03 dex

Clear evidence of atomic diffusion

Agree with model predictions and literatures

Summary

- The Hyades is not chemically homogeneous at ~ 0.02 dex level

- M67 solar twins are identical to the Sun (Z <= 30)
- Effect of atomic diffusion in M67 (~ 0.1 dex)

- Stars in an open cluster are coeval and not chemically identical

- Abundance variation and atomic diffusion are present and should be taken into account for chemical tagging

Questions?

Future work

Are all the open clusters inhomogeneous?

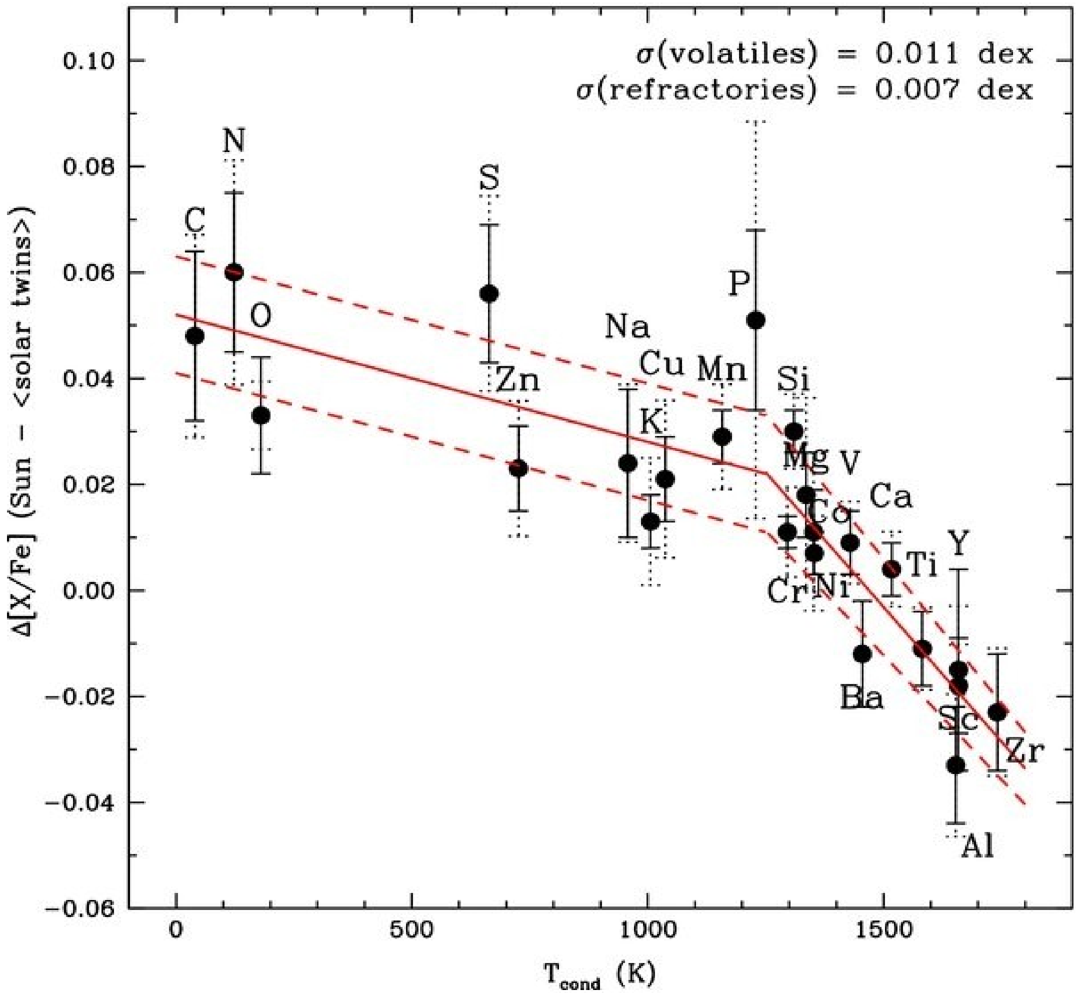
- Large number of open cluster stars cover a range of ages and metallicities (Ruprecht 147, NGC 3680, NGC 6253 etc.)
- Intrinsic chemical inhomogeneity level for different elements

Is each open cluster unique?

- ‘Cluster-to-cluster’ abundance differences

Chemical signature of planet formation

Melendez et al. 2009



Sun differs from most otherwise solar twins

Chemical signature imprinted by terrestrial planet formation?

Trend with condensation temperature

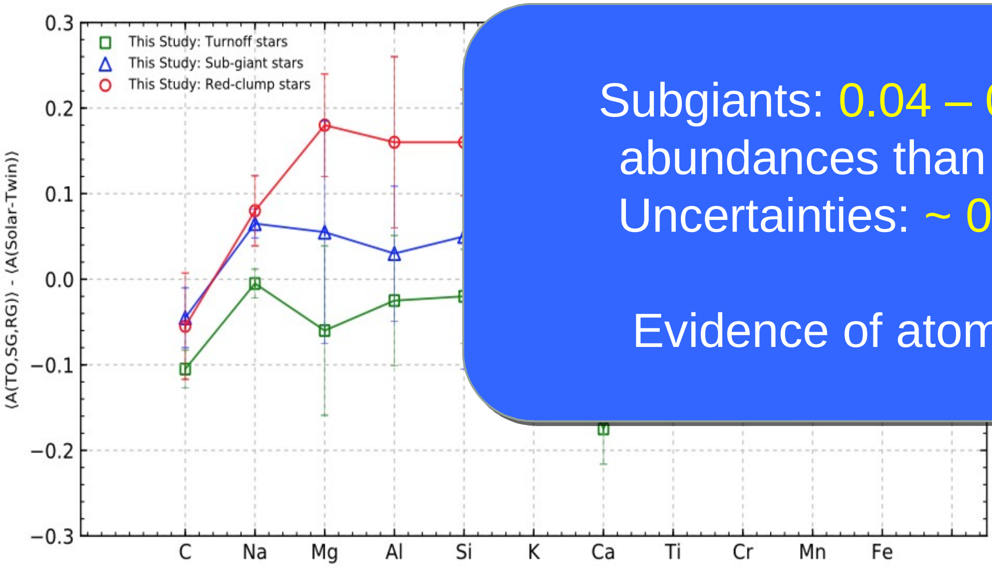
Atomic diffusion in M67?

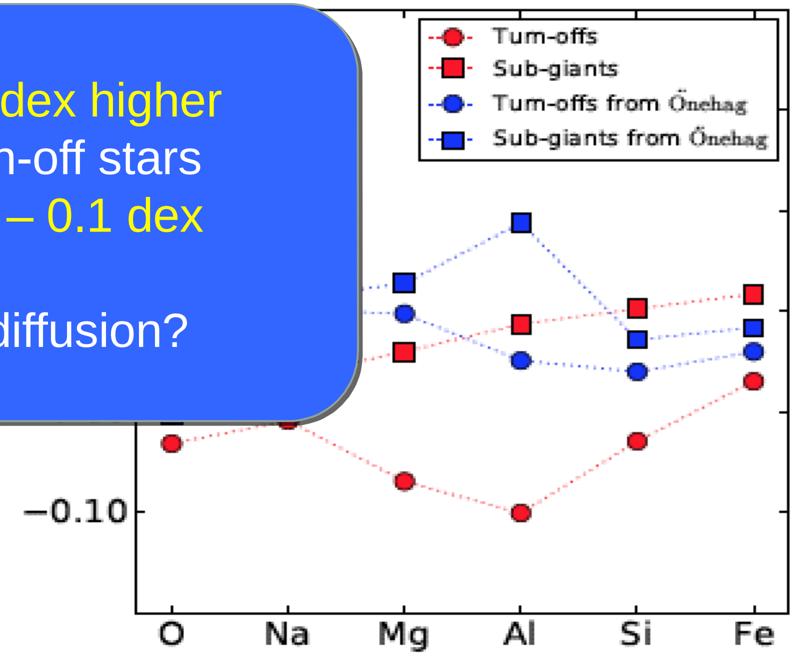
APOGEE spectra
R = 22,500, S/N ~ 100 – 200

Souto et al. 2018

GALAH-HERMES spectra
R = 42,000, S/N > 50

Gao et al. 2018





Subgiants: 0.04 – 0.1 dex higher abundances than turn-off stars
Uncertainties: ~ 0.05 – 0.1 dex

Evidence of atomic diffusion?

See also Bertelli Motta et al. 2018 (Gaia-ESO, UVES/FLAMES spectra)

Methodology

Careful selection of clean spectral lines

↓

Measurements of equivalent width (differential)

↓

Derivation of (relative) stellar atmospheric parameters

↓

Strictly line-by-line differential abundances

Error analysis

Based on Epstein et al. 2010, Bensby et al. 2014

$$o_i = o_i^0 + \sum_{j=1}^{4} b_{ij}(m_j - m_j^0) \Rightarrow b_{ij} = \partial o_i / \partial m_j$$

Partial derivatives

$$C_{ik} = b_{ij}^{-1}$$

Covariance Matrix

$$\sigma(m_j) = \sqrt{\sum_{k=1}^{4} C_{ik}^2 \sigma_k^2}$$

$$X = X_0 + \sum_{j=1}^{4} \kappa_j (m_j - m_j^0) = X_0 + \sum_{j=1}^{4} \alpha_j (o_j - o_j^0) \Rightarrow \kappa_j = \partial X / \partial m_j \Rightarrow \alpha_j = \sum_{k=1}^{4} \kappa_k \times c_{kj}$$

$$\sigma_X = \sqrt{\sigma_{X_0}^2 + \sum_{k=1}^{4} \alpha_k^2 \times \sigma_k^2}$$

$$\sigma_{XY} = \sqrt{\sigma_X^2 + \sigma_Y^2 - 2\sum_{k=1}^{4} \alpha_{K,X} \times \alpha_{K,Y} \times \sigma_k^2}$$