# Cerium in the *Kepler* and TESS fields

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The 13th Torino workshop, 24 June 2022

European Research Council
Established by the European Commission

ASTERO CHRONOMETRY

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

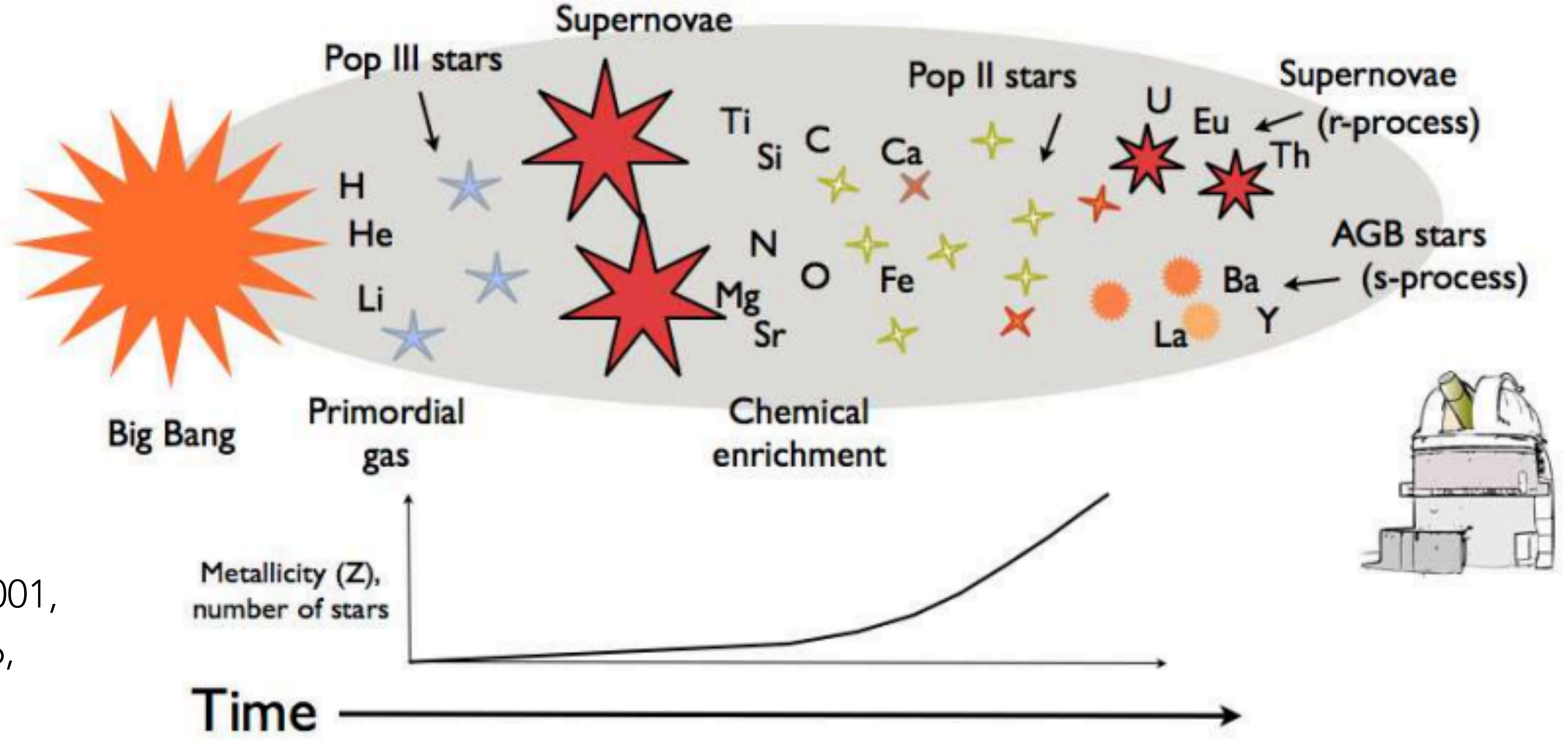
# S-process elements

- The **neutron-capture processes** are responsible for the production of about half the abundances of elements heavier than iron in the Galaxy

- s-process elements are produced by:

  1. Massive stars
     (weak process; e.g. Heil+2007, Pignatari+2008,2010)

  2. AGB stars
     (main process; e.g., Busso & Gallino 1997, Busso+2001, Lugaro+2003, Cristallo+2018, Karakas & Lugaro 2016, Busso+2021)

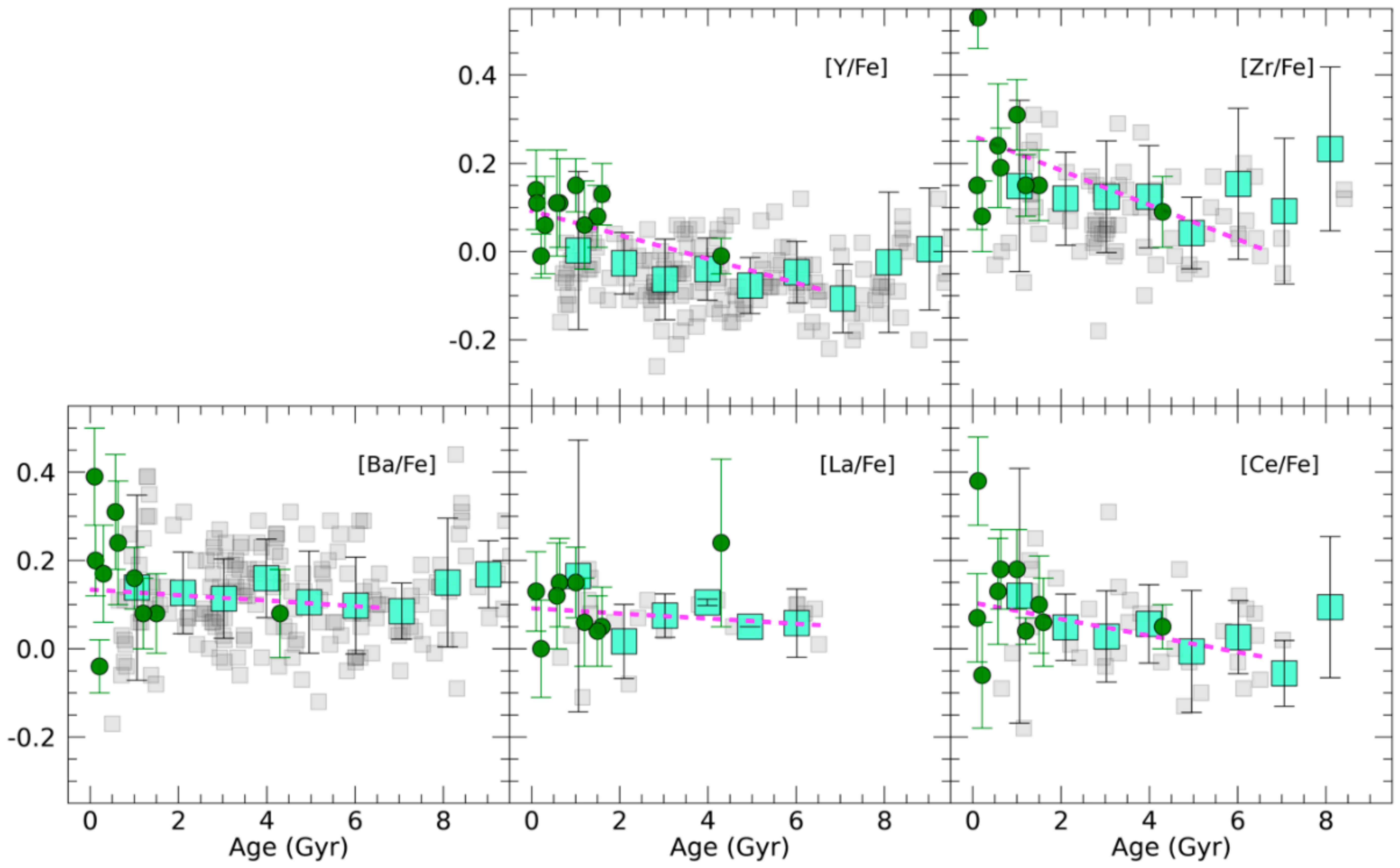



Jacobson & Frebel 2014

# Temporal evolution of s-elements

- These elements show an increasing trend with decreasing age. The rise is likely:
    - The result of elemental synthesis in AGB stars
    - Observational effects/stellar characteristics at youngest ages (Spina+2020, Baratella+2020)

See Baratella's talk




Magrini et al 2022

# Calibrators for the temporal evolution

- In order to investigate the temporal evolution of these elements, we need precise ages:

    A. Star clusters → Precise age from isochrone fitting (e.g., Casamiquela+20, Viscasillas Vázquez+22, Sales-Silva+22)

    B. Solar twins → High precision spectroscopy ⇒ Precise age from isochrone fitting (e.g., Nissen+15, Spina+16, Spina+18, Casali+20, Jofré+20)

    C. Stars with asteroseismic age → Measuring the global frequencies of a star allows reaching a high precision on the inferred ages

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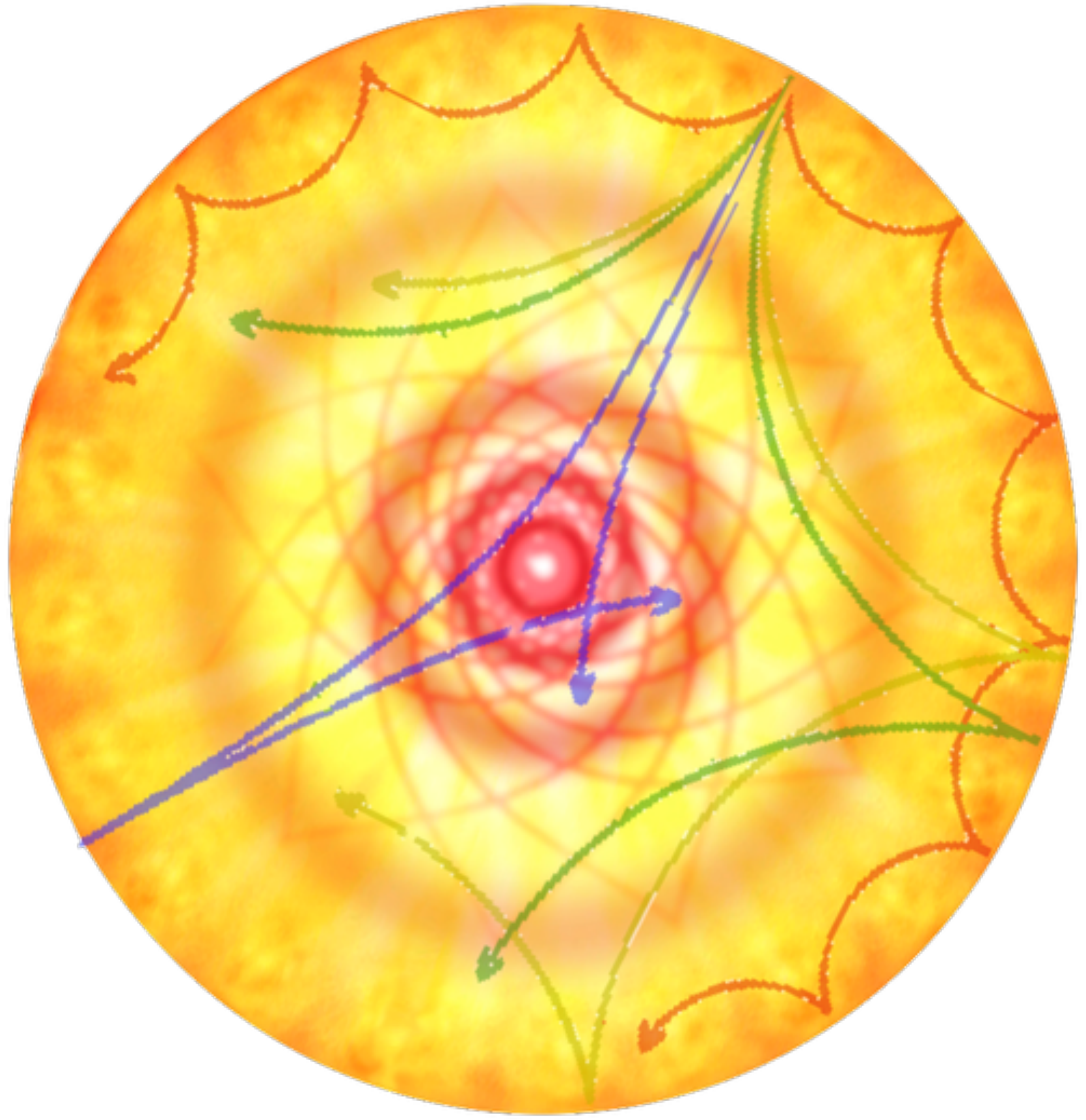
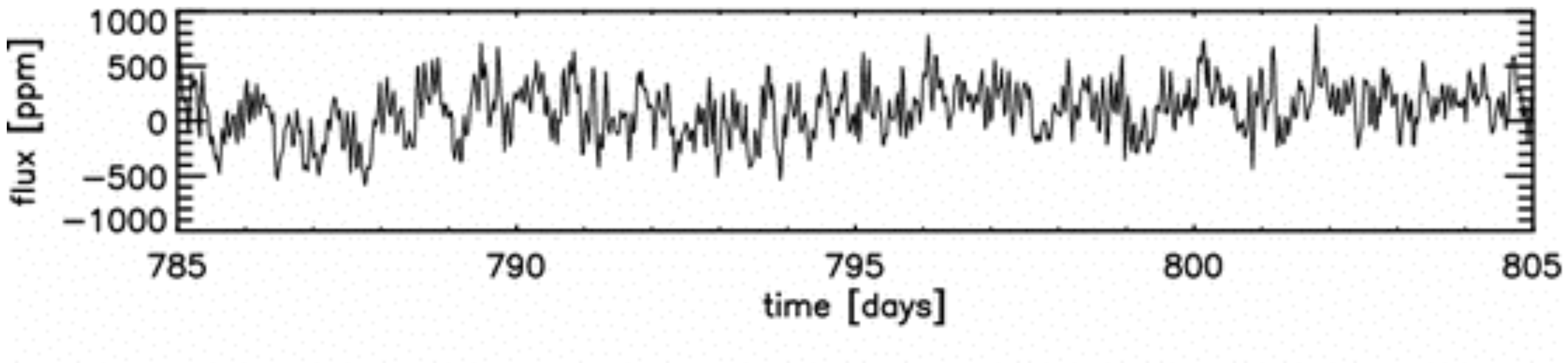
# Age from asteroseismology



Credits: IAC

Asteroseismology is the study of stellar pulsations, directly related to physical properties

Hekker & Christensen-Dalsgaard (2017)

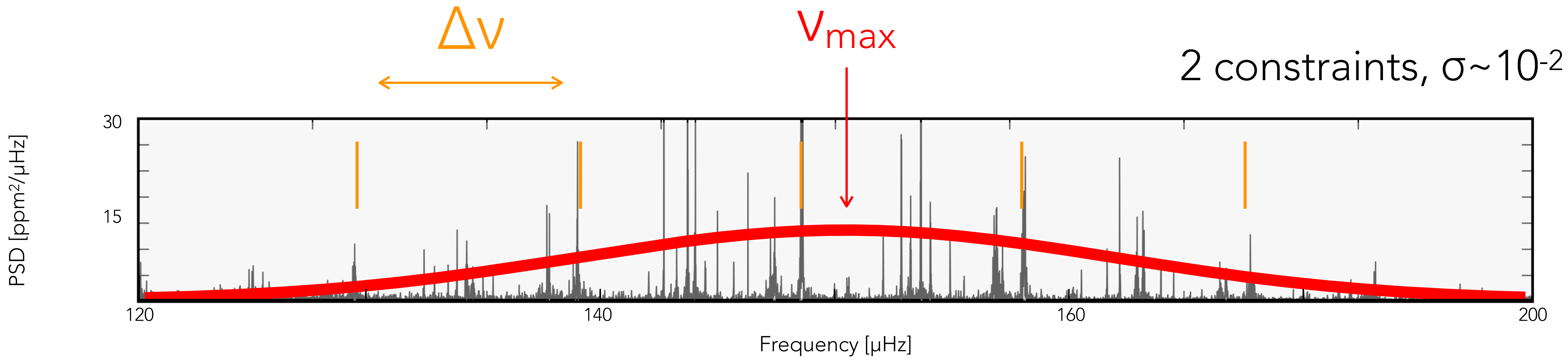



We can detect these oscillations by measuring the changes in the brightness, which we can measure over time in a time series. We can then perform a Fourier transform on the time series data and get the power spectrum

# Age from asteroseismology

- average seismic parameters

2 constraints, σ~10$^{-2}$



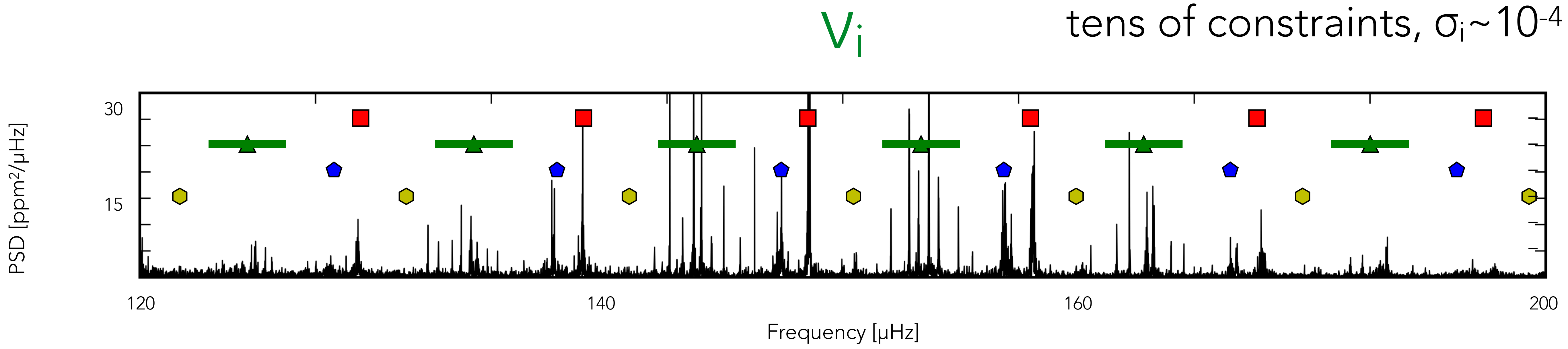

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2},$$

Age, logg, distance

- individual mode frequencies

tens of constraints, $\sigma_i$~10$^{-4}$




→ Montalban, Mackereth, Miglio et al., 2021, Nat. As.

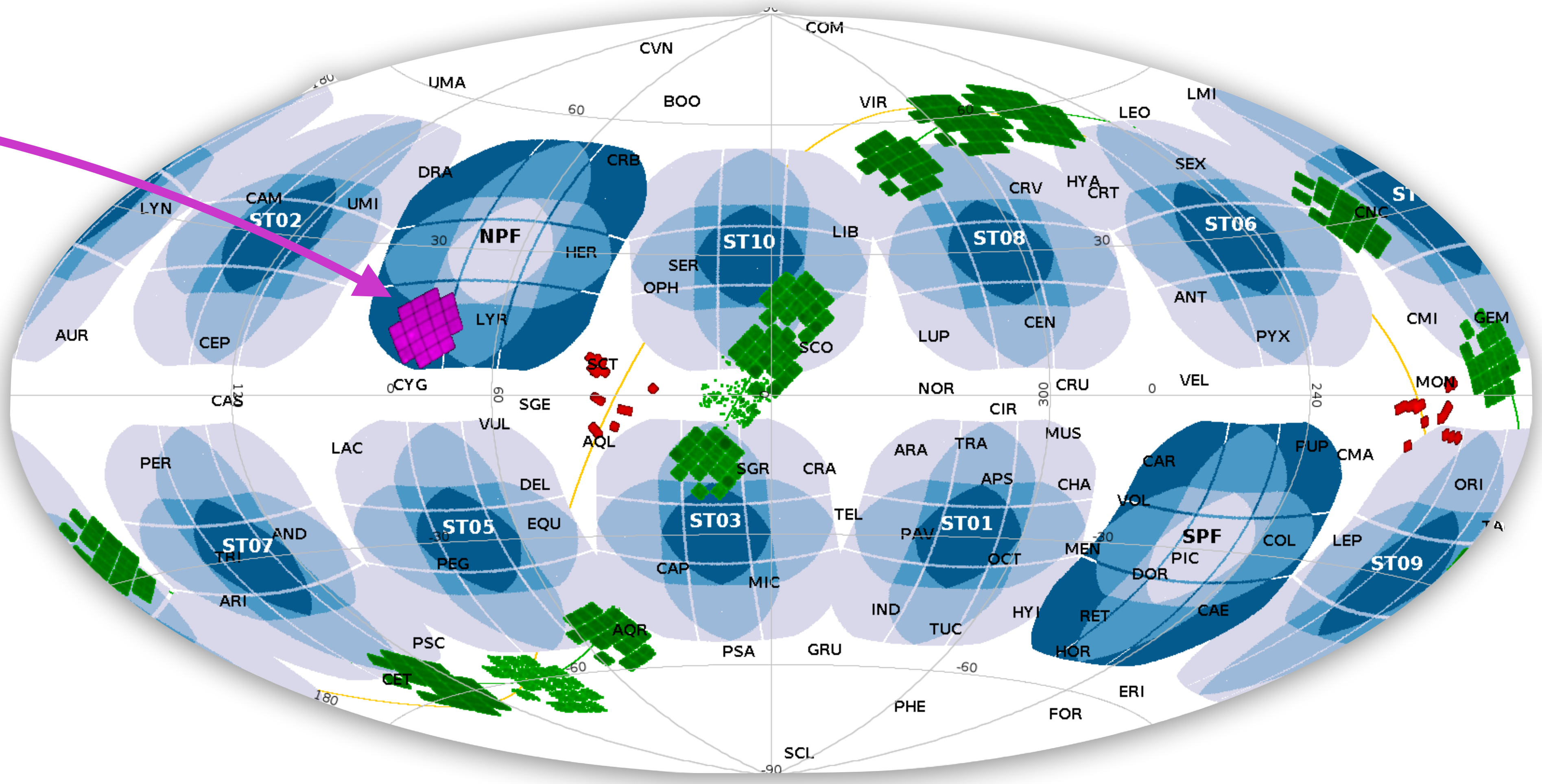
(e.g. papers by Anders et al., Joergensen et al., Miglio et al., Montalban et al, Pinsonneault et al., Rendle et al., Sharma et al., Silva Aguirre et al., Stello et al., Valentini et al., …)

# Stars with asteroseismic age

<u>Data samples (giants):</u>

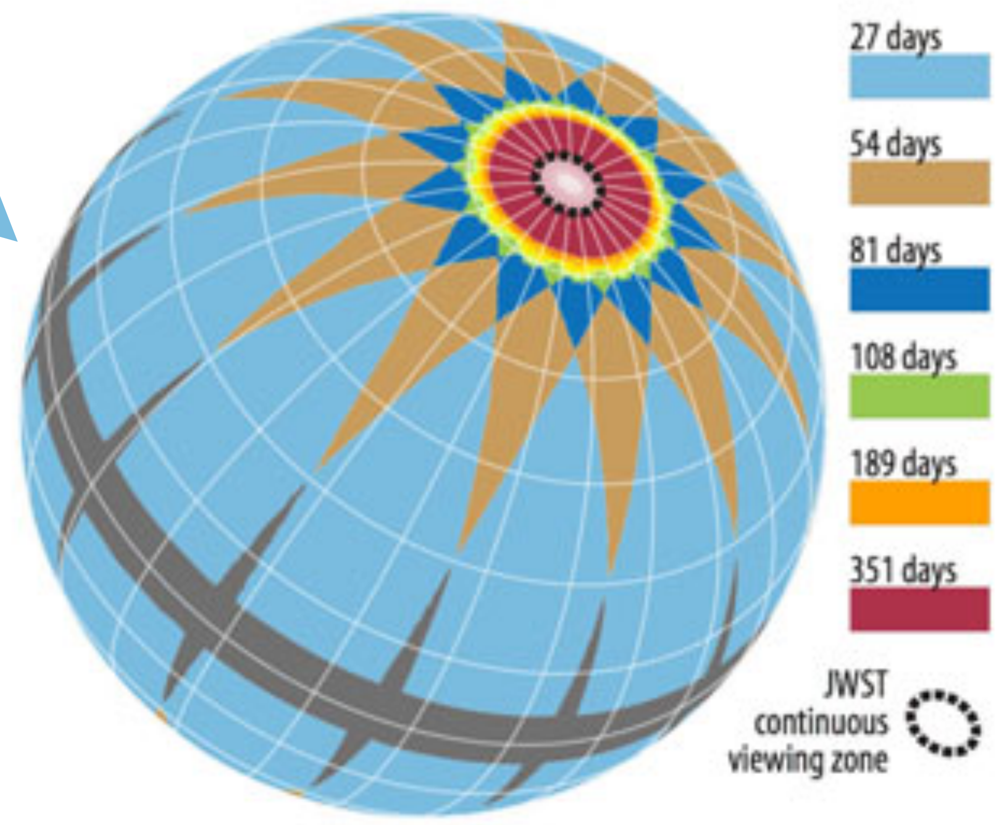
1. *Kepler* + APOGEE DR17

2. TESS + APOGEE DR17




For all of them, stellar age was computed using PARAM tool (Rodriguez et al 2017)

σ(Age)~10-20% *Kepler* (sample by Miglio et al 2021)
σ(Age)~20-30% TESS (sample by Mackereth et al 2021)




Local volume: 7.5 < Rgc < 8.5 kpc

# TESS/*Kepler* + APOGEE

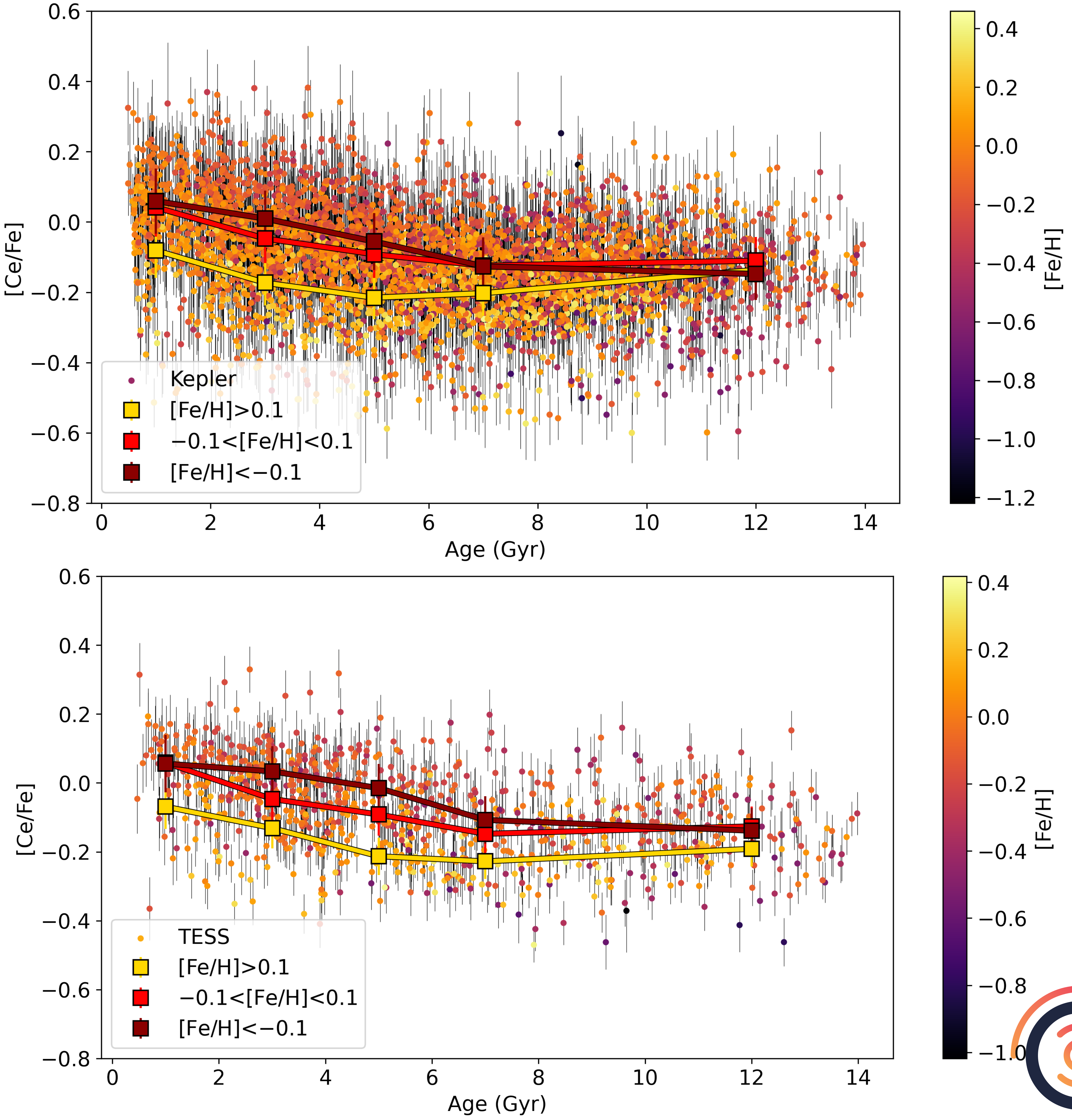
- The only s-process element in APOGEE is Cerium
- [Ce/Fe] vs Age
- [Ce/Fe] vs [Fe/H]
- [Ce/α] vs Age → additional tool to date stars

# [Ce/Fe] vs Age

- Increase of [Ce/Fe] at recent epochs → the enrichment from AGB stars is predominant in latest MW evolution
- Metal-rich stars have lower [Ce/Fe] than metal-poor stars

<u>From a nucleosynthesis point of view:</u>

- Important step in understanding the late-time contribution in the Ce production by low-mass AGB stars ($M < 1.5\ M_{\odot}$)



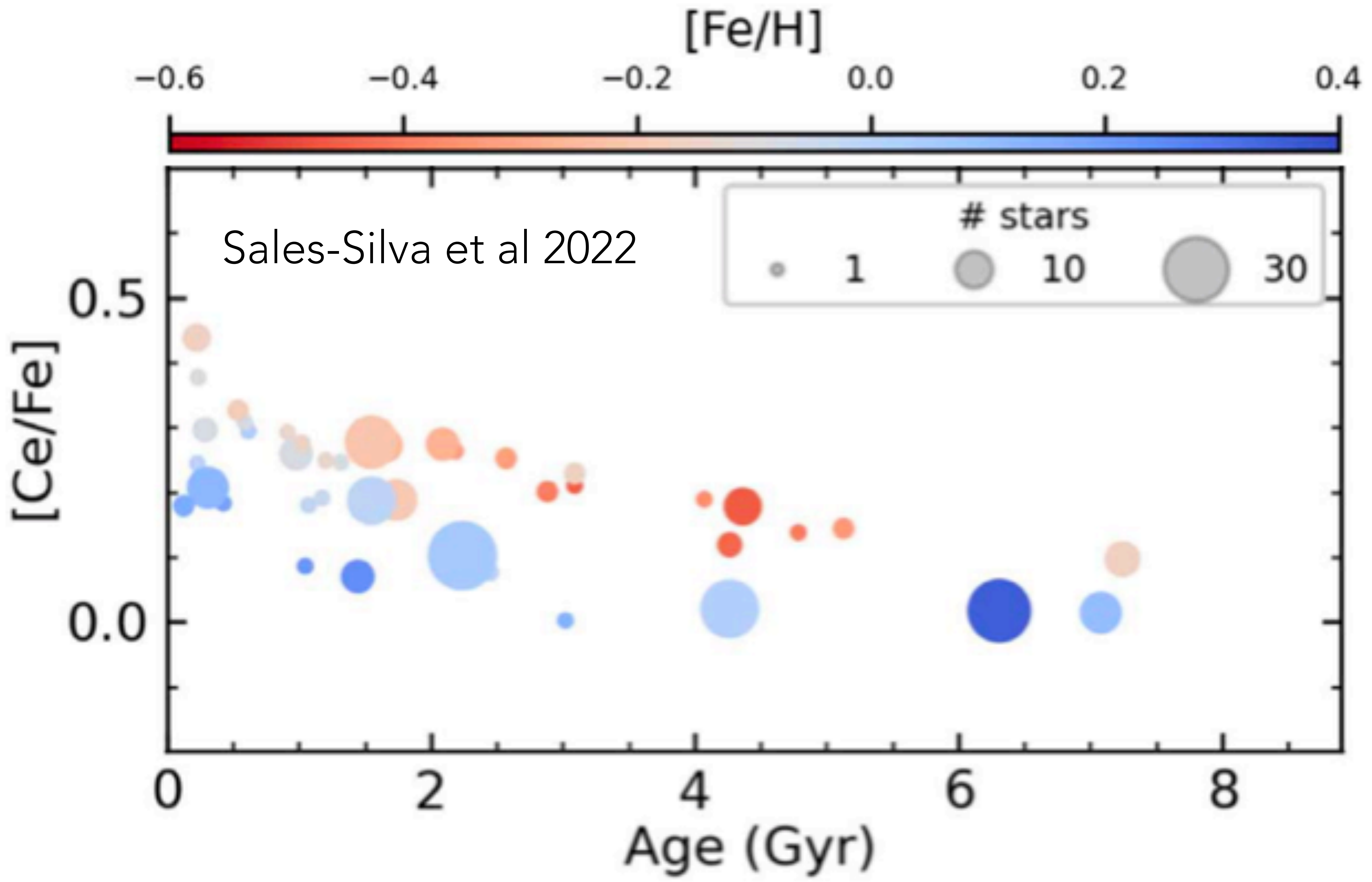
# [Ce/Fe] vs Age

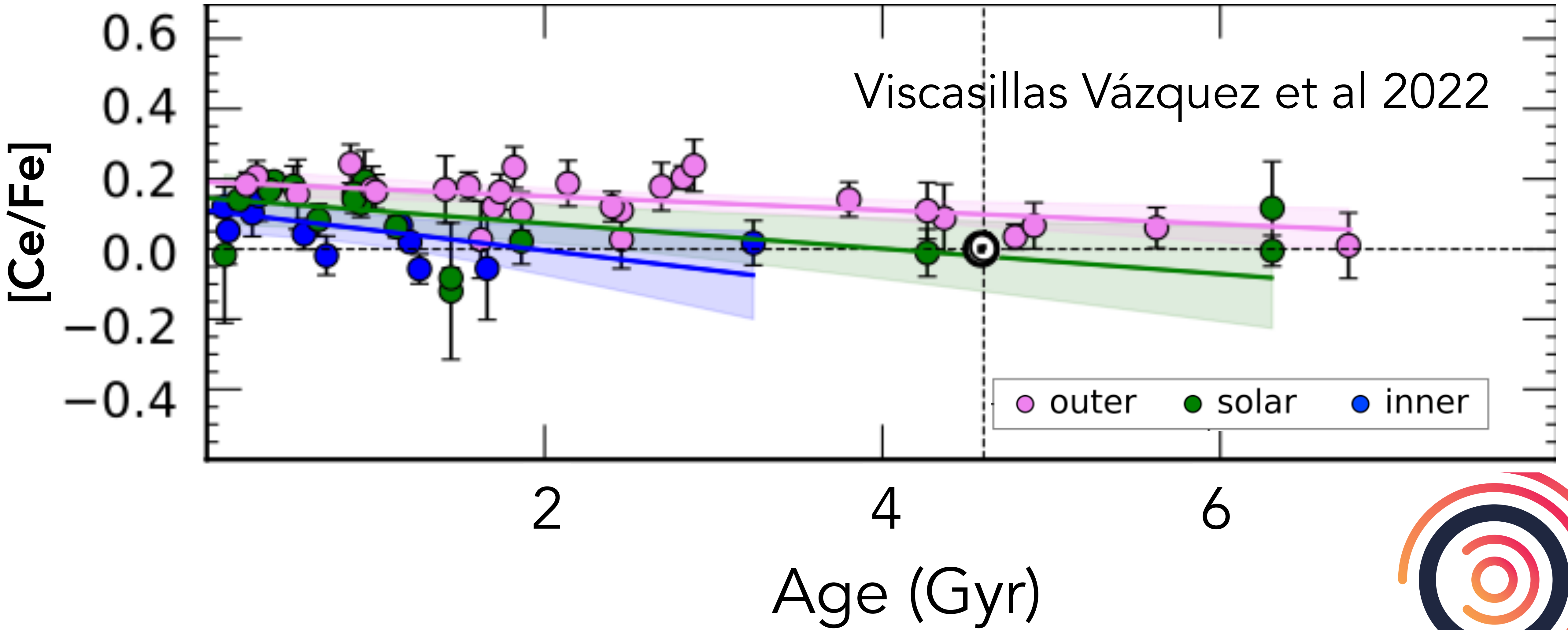
- Recent works on Ce in open clusters:

  A. <u>Sales-Silva+22:</u> 42 OCs in APOGEE DR16 analysed by BACCHUS

  B. <u>Viscasillas Vázquez+22:</u> 62 OCs in Gaia-ESO iDR6

- We see a similar trend with our data sample



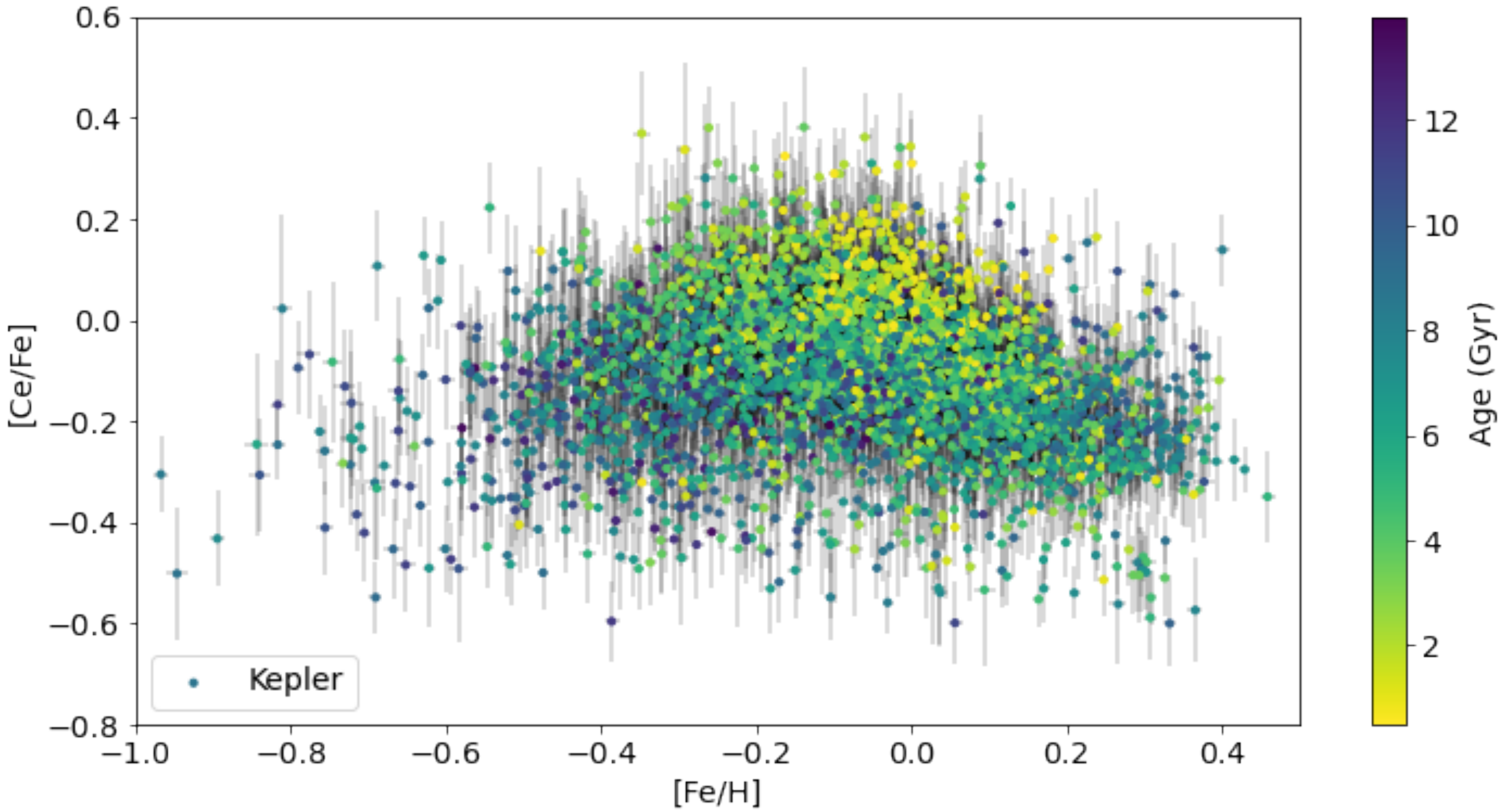

Cons of OCs: No open clusters older than 7 Gyr
Limited number wrt field stars

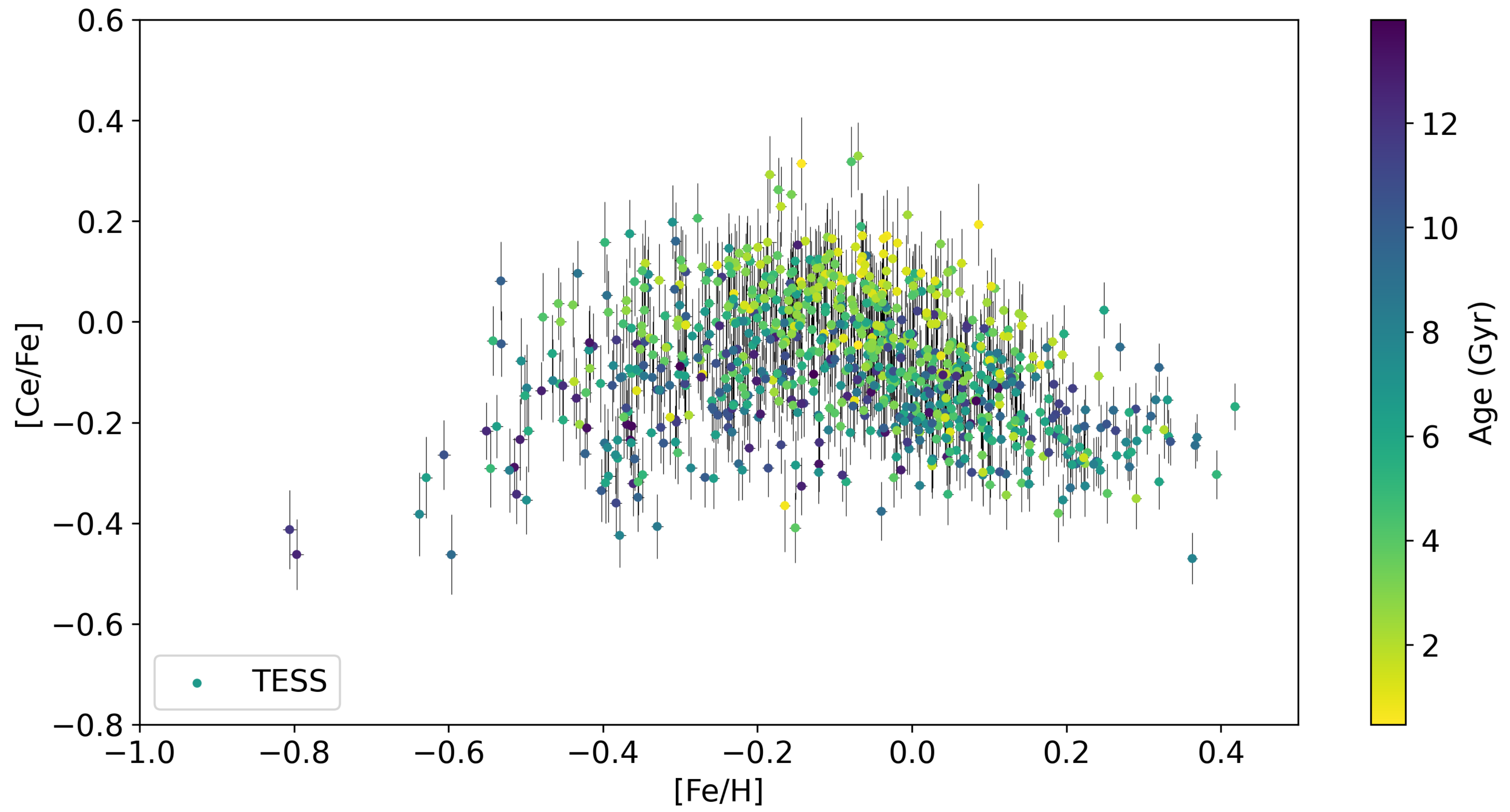
# [Ce/Fe] vs [Fe/H]

- "Banana" shape for [Ce/Fe] with a peak at −0.2 in [Fe/H]
- Younger stars have larger [Ce/Fe]

<u>From a nucleosynthesis point of view:</u>

- The yields of s-process elements are highly dependent on metallicity, in a non-monotonic way



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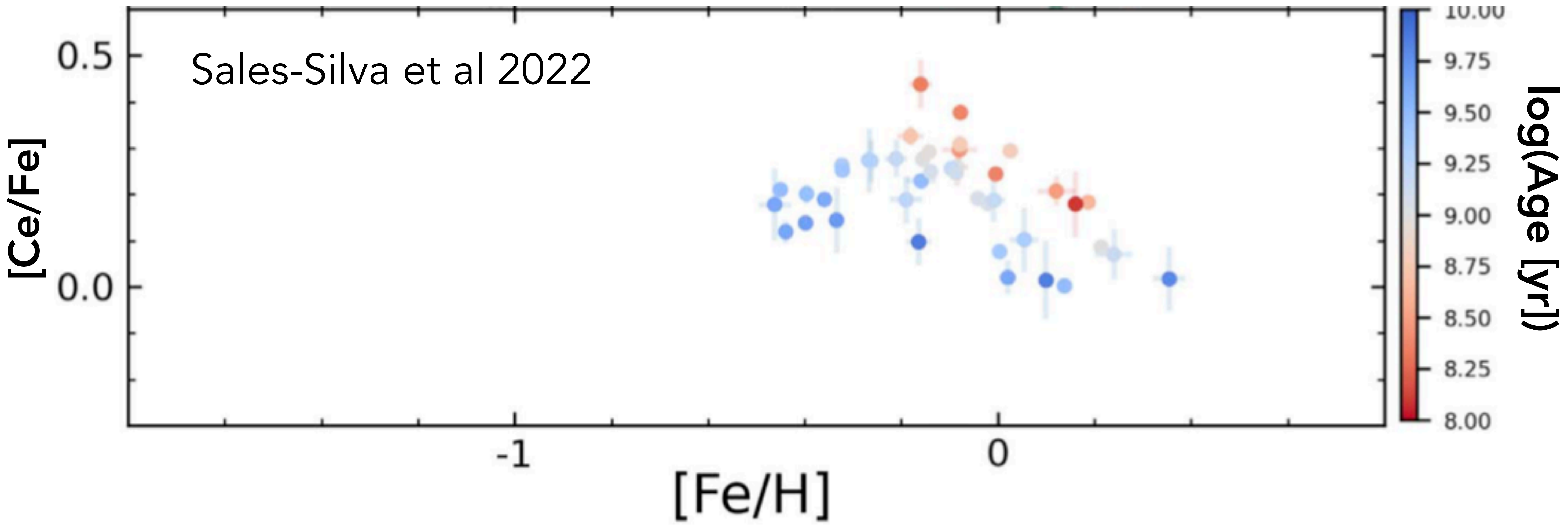
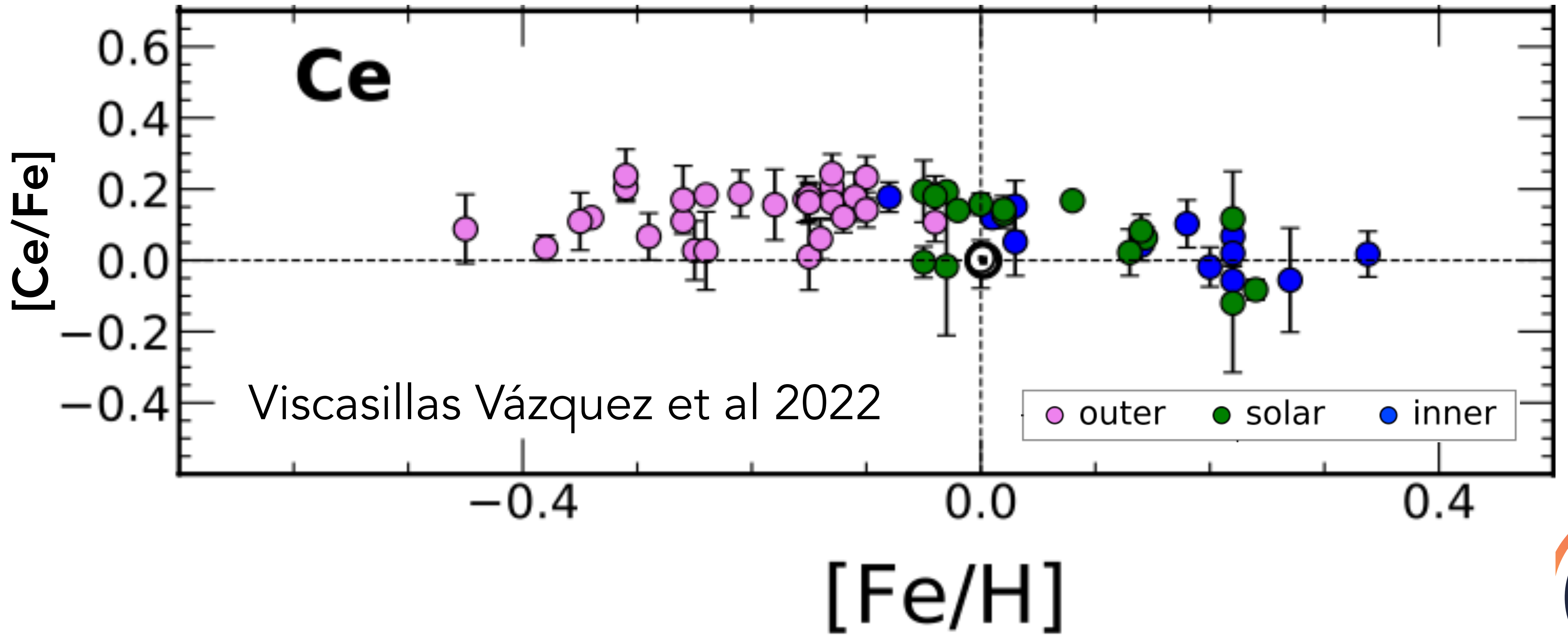
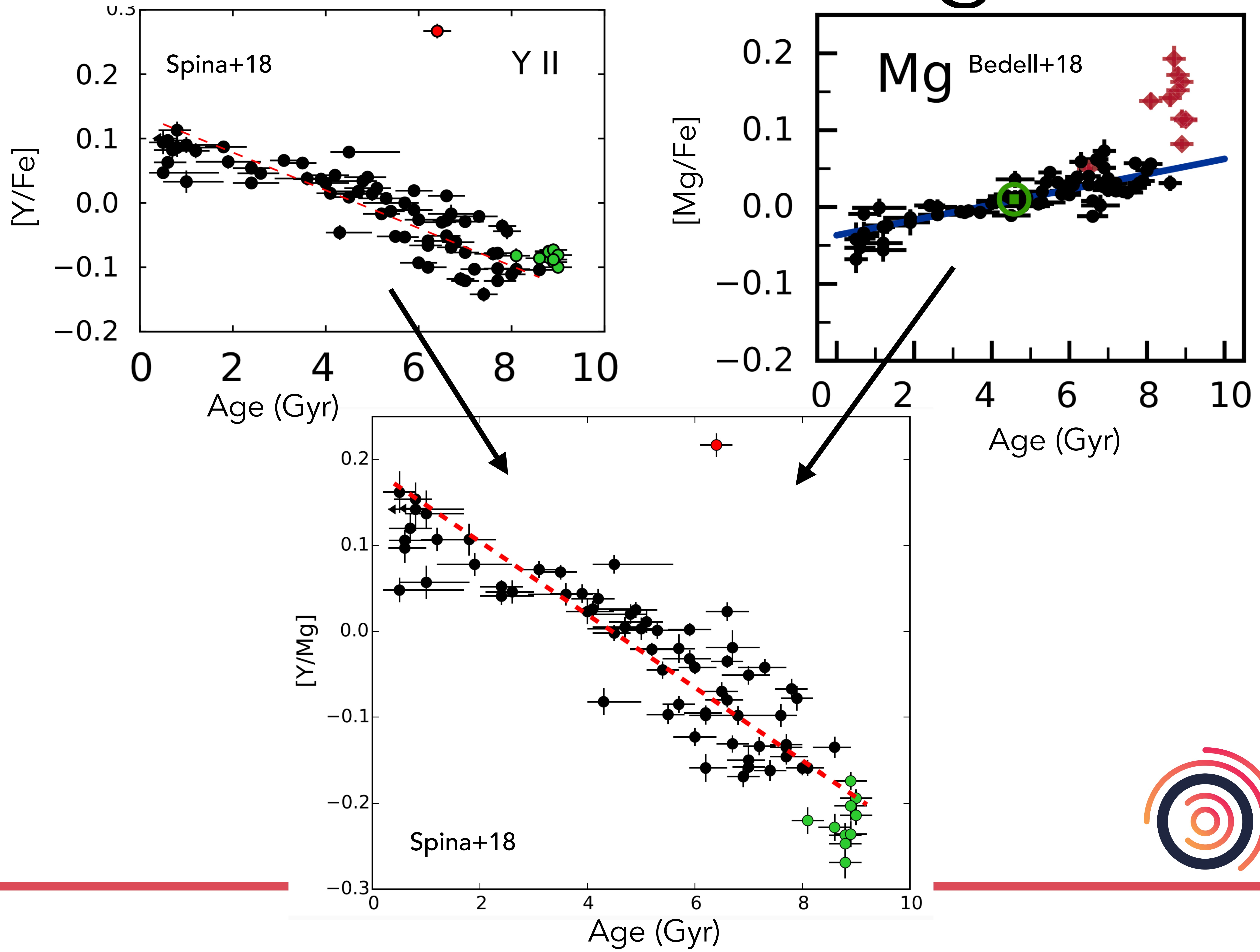


# Chemical clocks: [Ce/$\alpha$] vs Age

What they are?

A combination of the abundances of an ***s*-process** element with other elements with opposite behaviour (**α elements**) that maximises their correlation with stellar age



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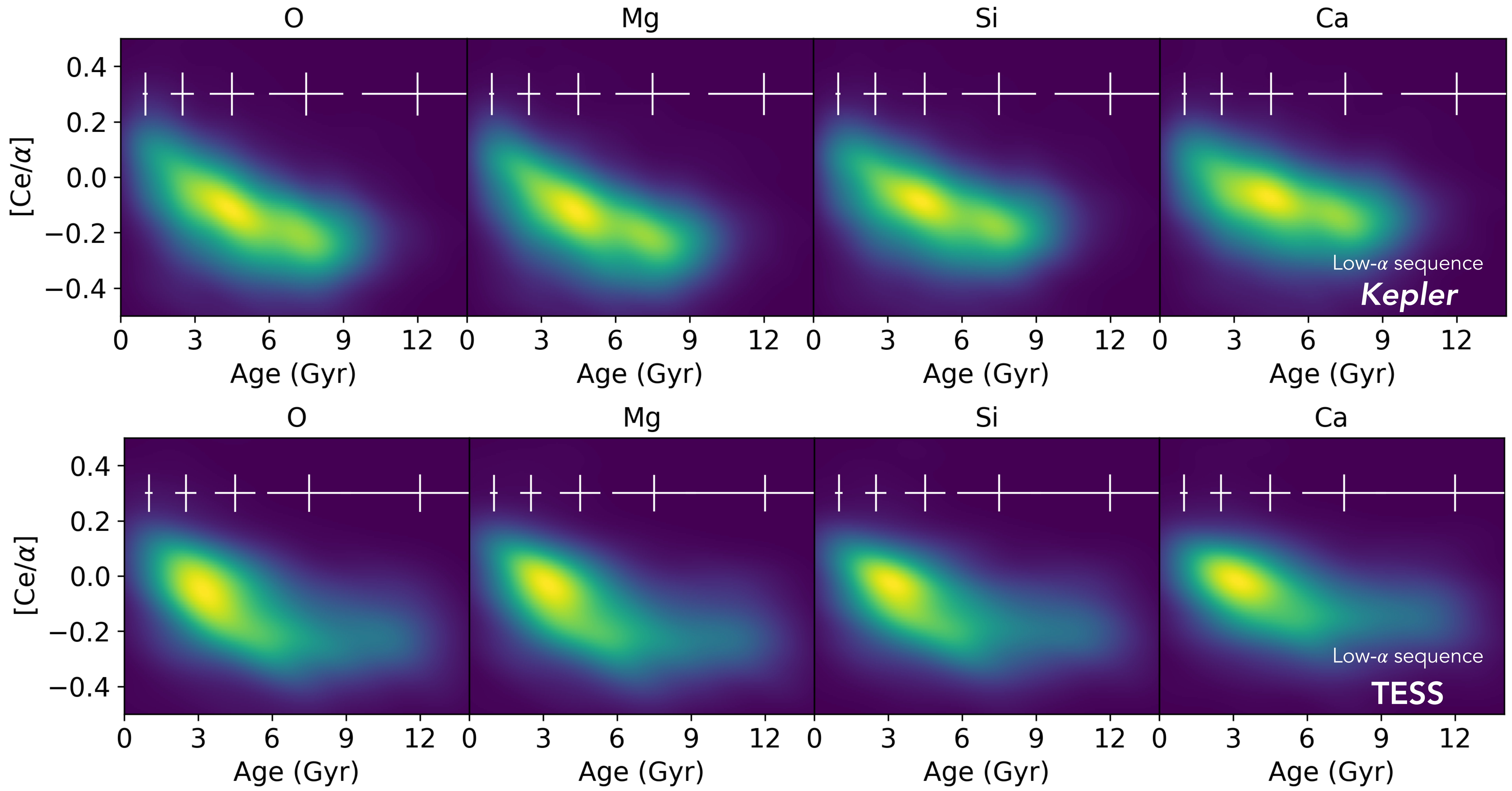
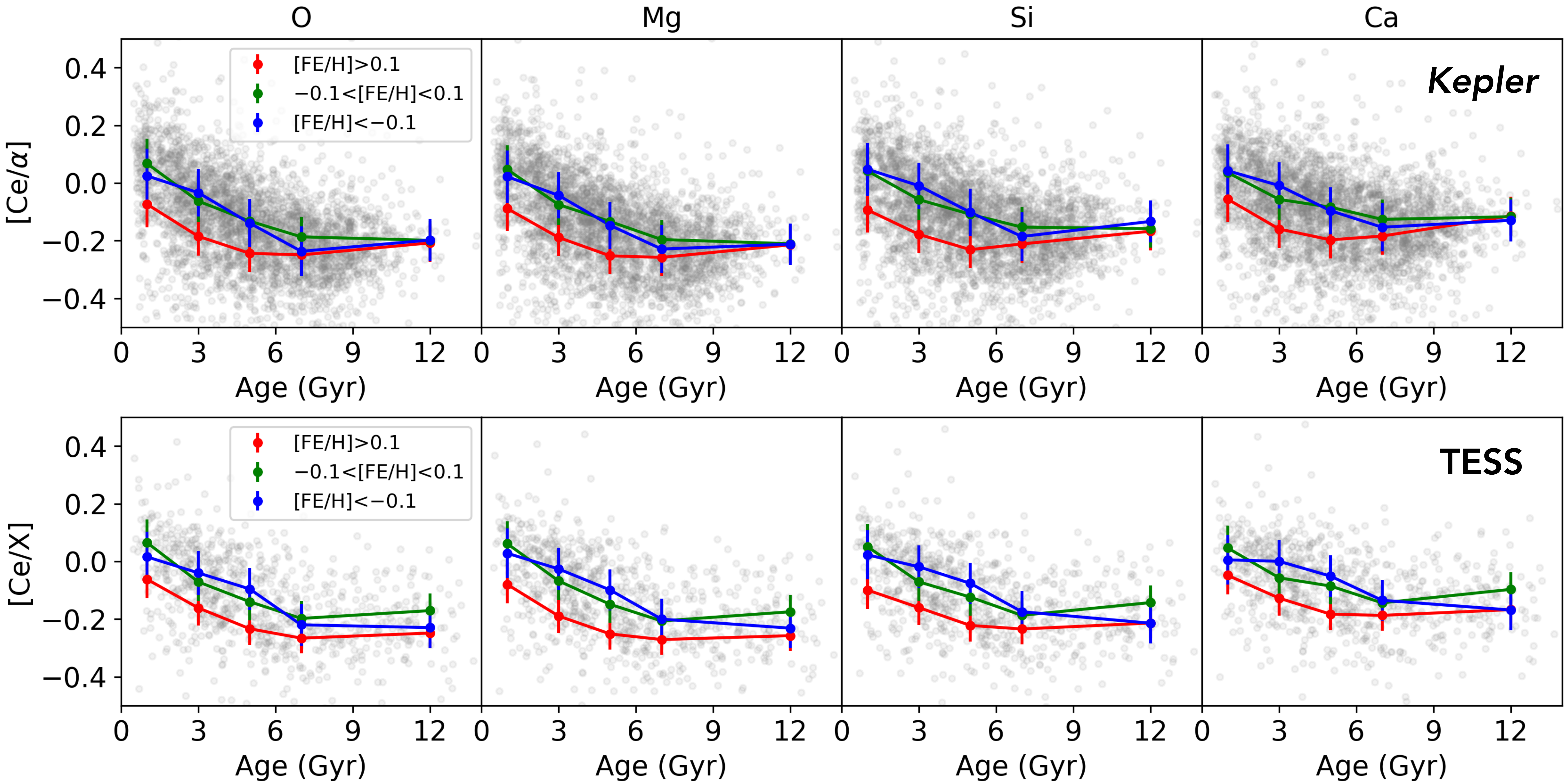


# Chemical clocks: [Ce/$\alpha$] vs Age

Metallicity dependence of chemical clocks:



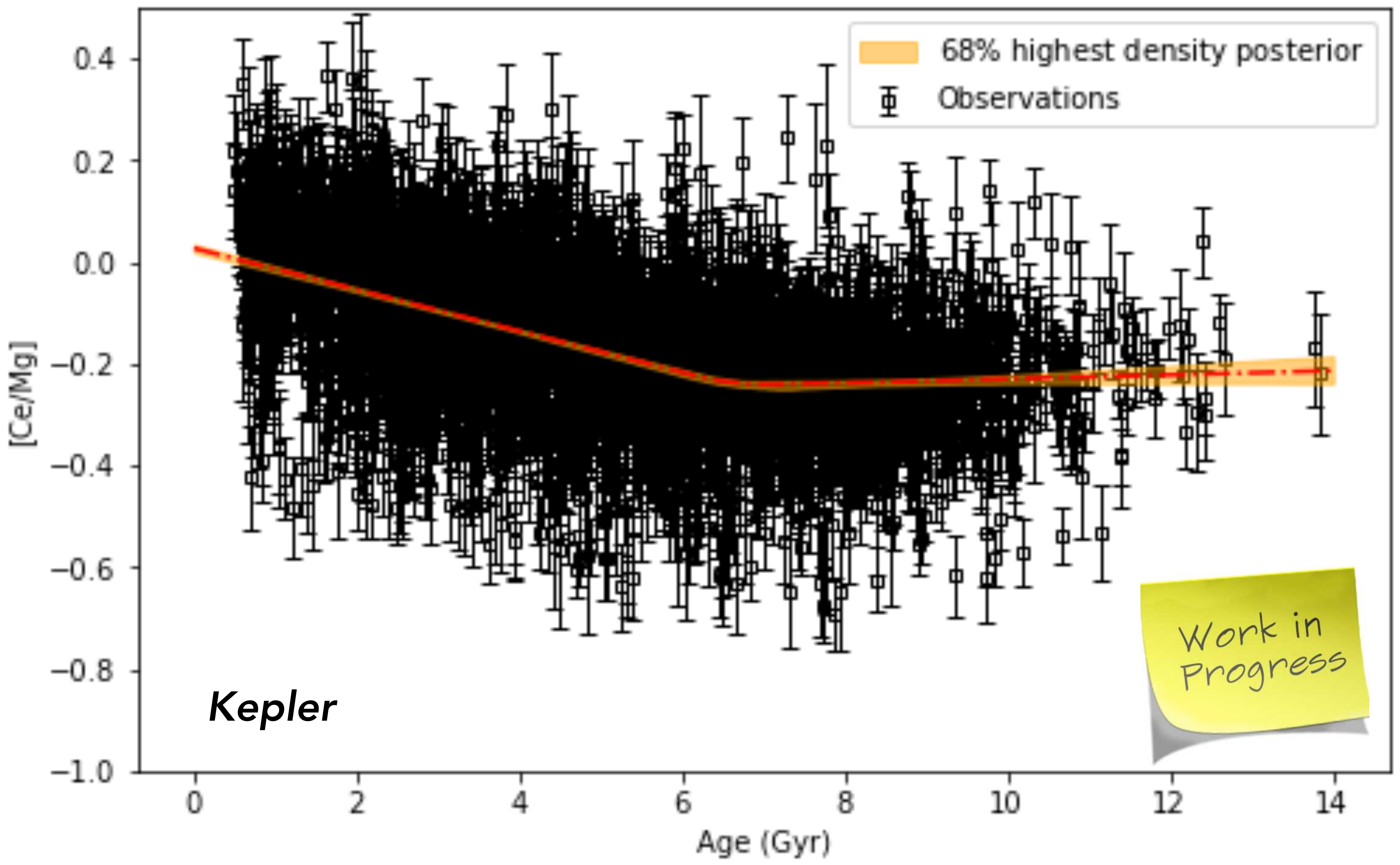
# Chemical clocks: MCMC fitting

Through a MCMC simulation, we derive the probability density distributions of the parameters in Equation:

$$[Ce/\alpha] = m_1 \cdot Age + m_2 \cdot [Fe/H] + c \qquad x <= k$$
$$[Ce/\alpha] = n_1 \cdot (Age - k) + (m_1 \cdot k + m_2 \cdot [Fe/H] + c) \qquad x > k$$

Uniform priors for all parameters: $m_1$, $m_2$, c, $n_1$, k, $\boldsymbol{\varepsilon}$

Free parameter $\varepsilon$ which accounts for the intrinsic scatter of the relation



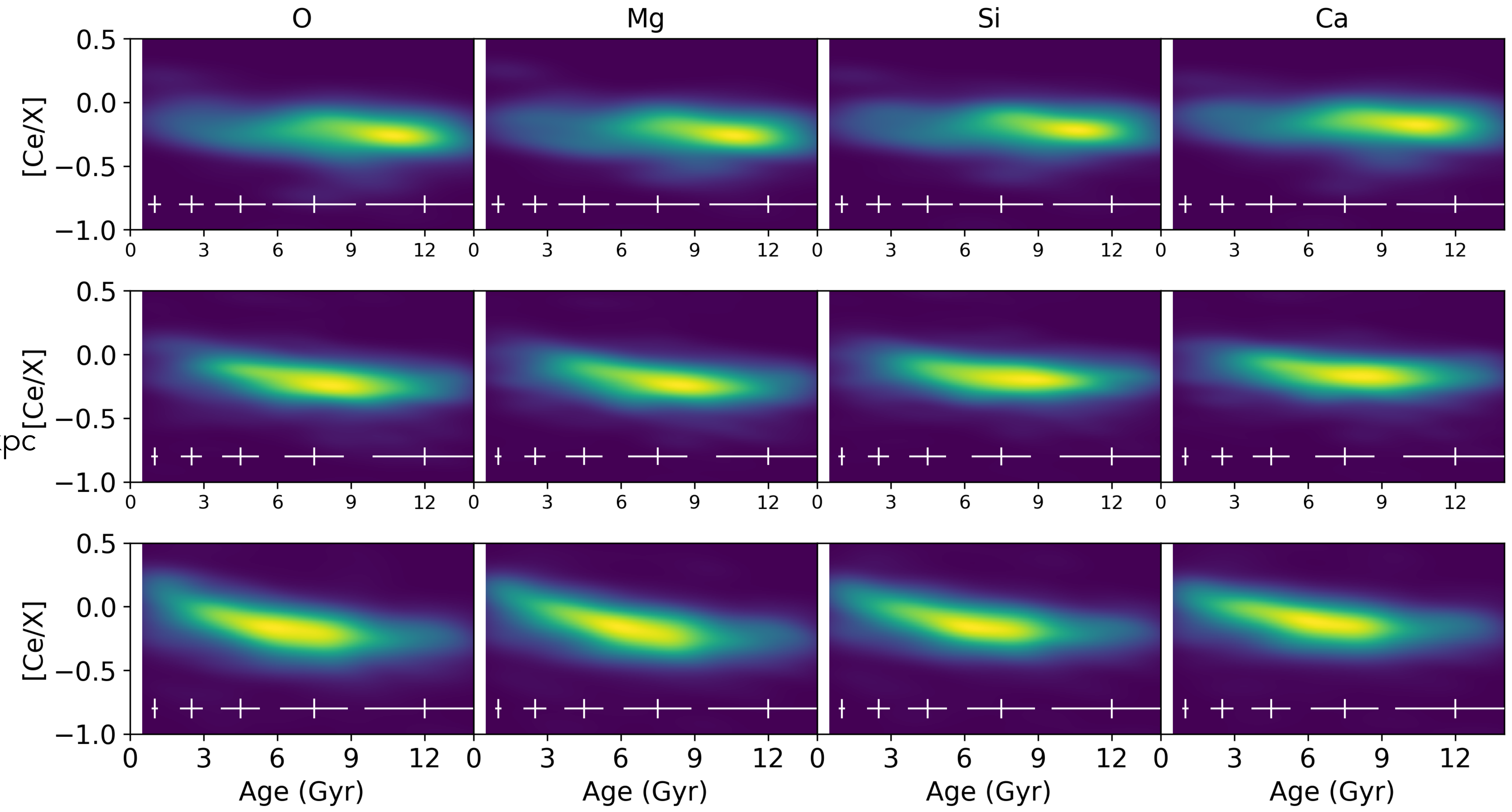
# Different temporal evolution at different $R_{GC}$: K2

Low-α

**Inner regions**
Rmean < 7 kpc

**Solar regions**
7 < Rmean < 9 kpc

**Outer regions**
Rmean > 9 kpc



# Summary

- The investigation of the temporal evolution of s-process elements (in this case, Ce) is fundamental for the comprehension of the nucleosynthesis of AGB stars
- Asteroseismology unveils the temporal evolution of these elements and their application as age tracers
- We study two data samples: *Kepler* and TESS with abundances from APOGEE DR17
- [Ce/Fe]-[Fe/H]: [Ce/Fe] increases as the metallicity decreases, with a possible downturn in the trend at roughly −0.2 in [Fe/H]
- [Ce/Fe]-Age, [Ce/α]-Age: [Ce/Fe] and [Ce/α] increase with decreasing age
- [Ce/α] can be use as an additional tool to date stars
- Future plan: to move from local volume to other regions of the MW disc: K2 dataset