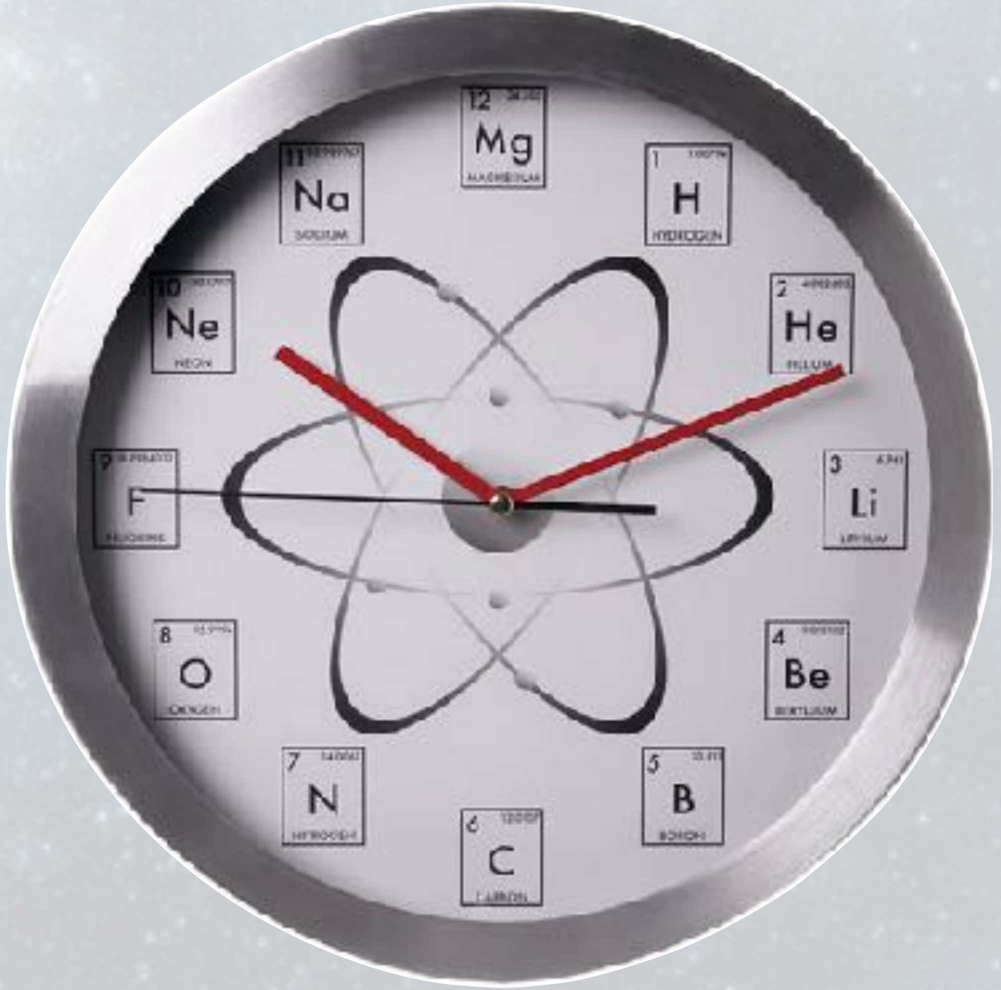
Unlocking Stellar Ages with S-Process Elements: Calibrating Chemical Clocks Using Kepler Data

Giada Casali

Australian National University

In collaboration with: Montalbán, Miglio, Casagrande, Chiappini, Magrini et al.



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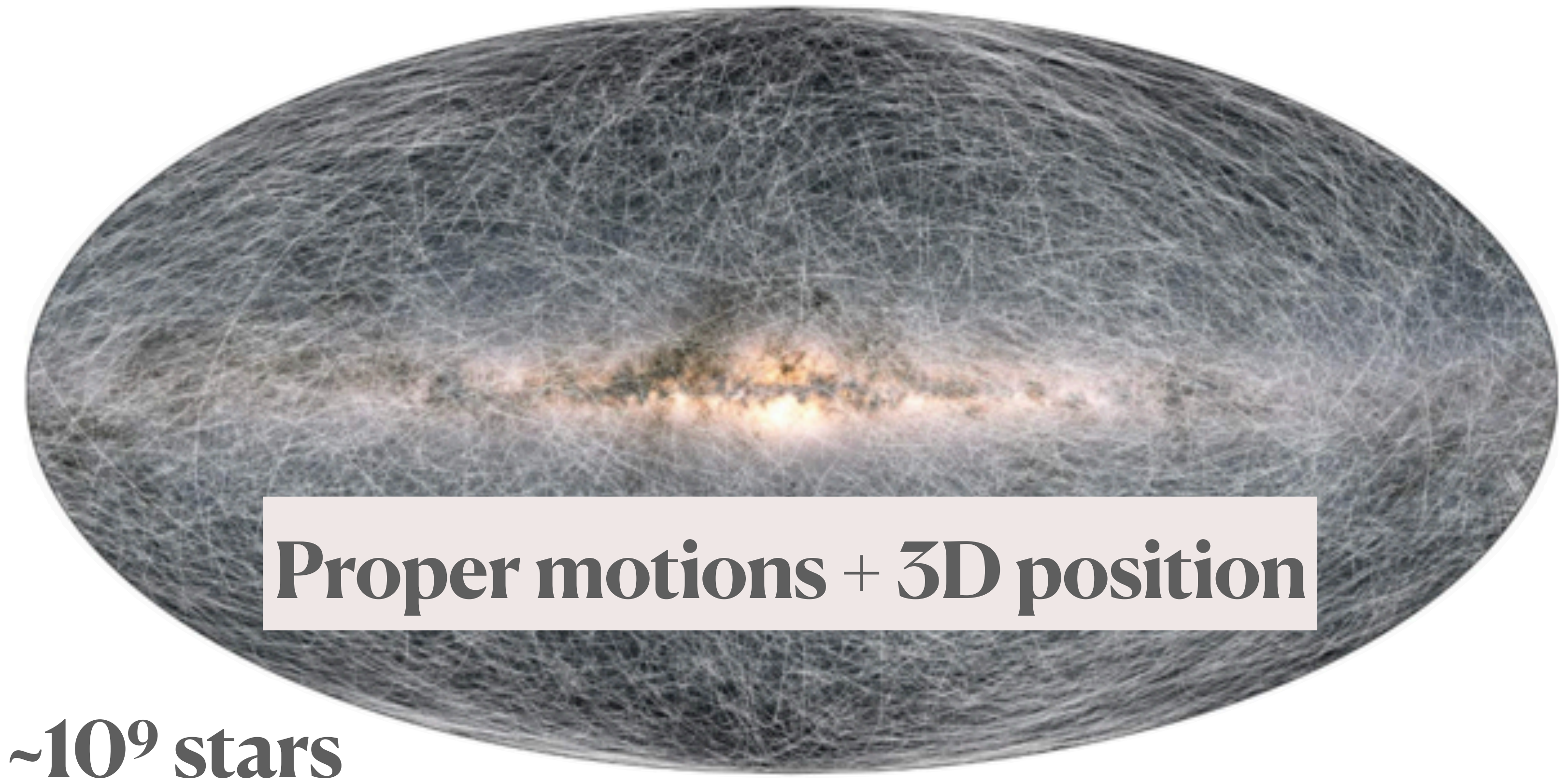
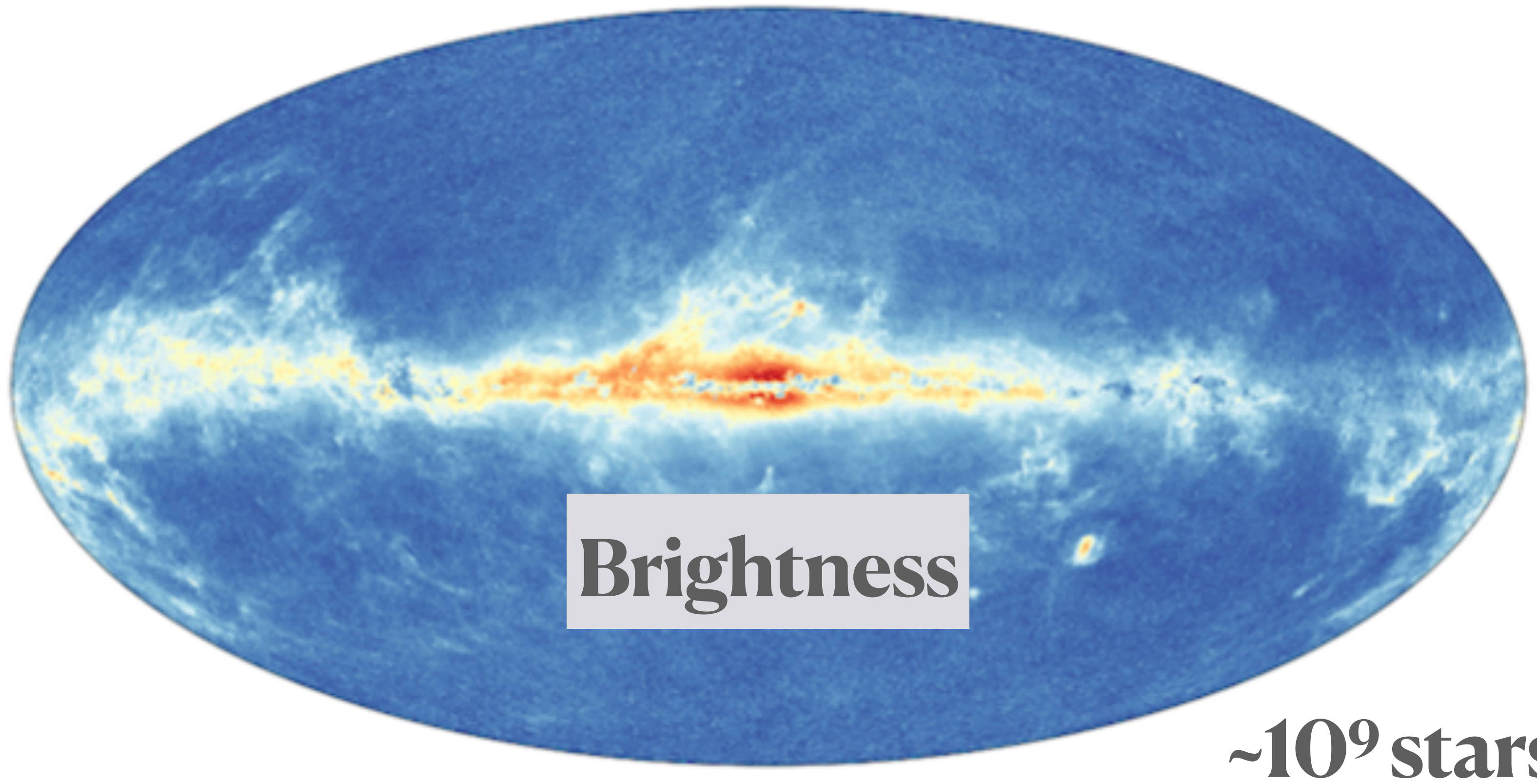
ASTERO CHRONOMETRY

sirEN conference - Giulianova, 13 June 2025

Galactic archaeology in the Gaia era



~10^9 stars



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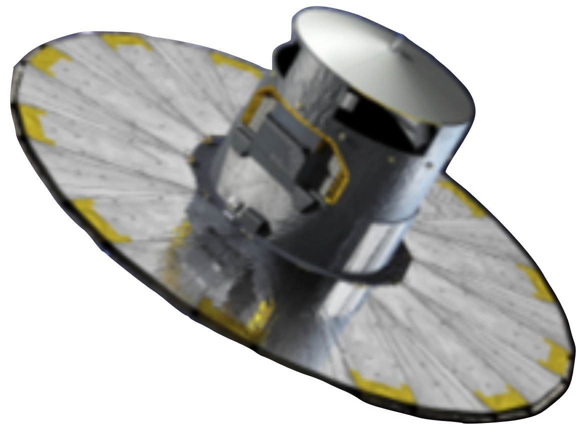
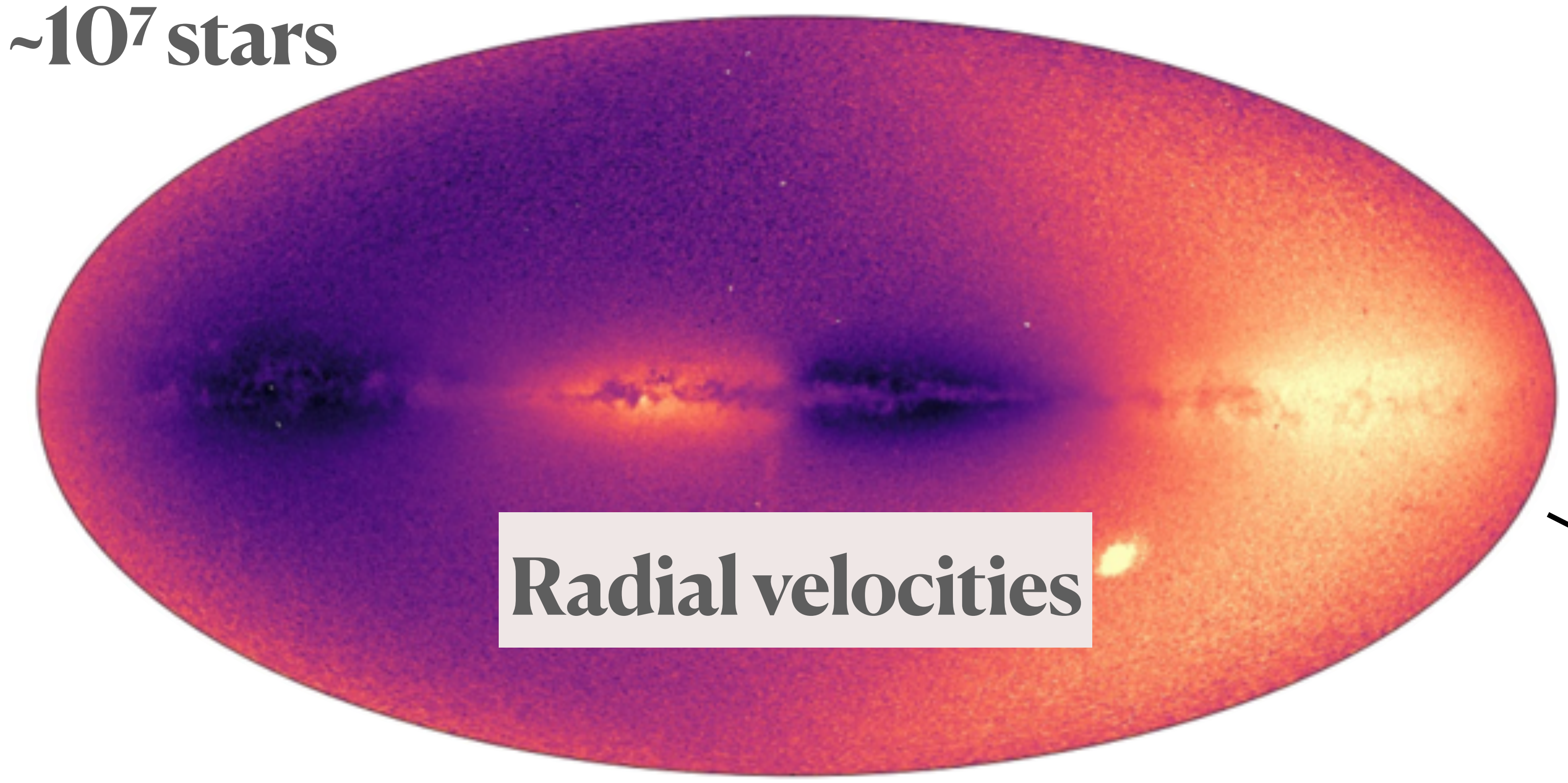
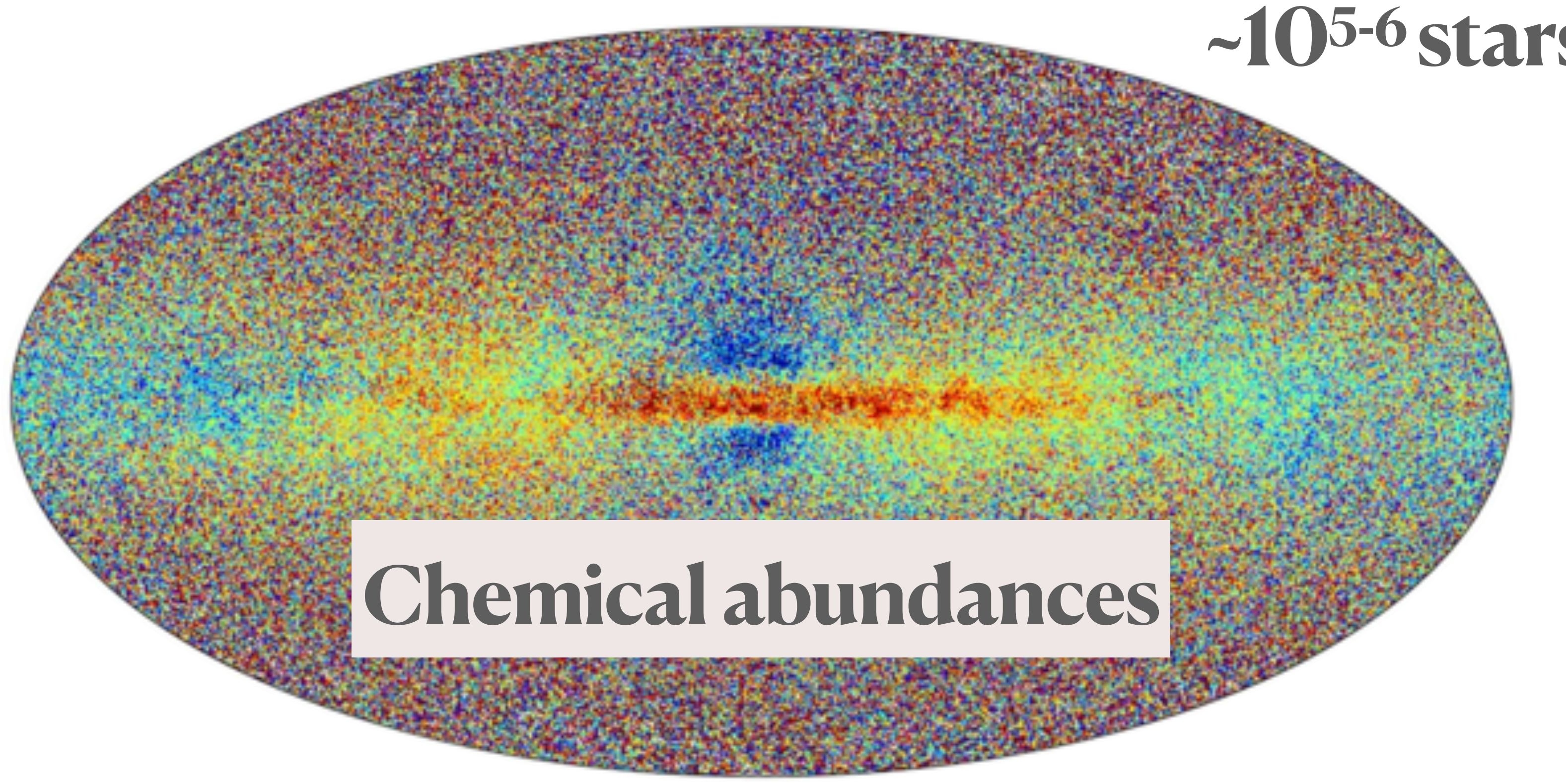


~10^7 stars



~10^{5-6} stars



+
Large spectroscopic surveys

Credit: ESA/Gaia/DPAC

https://www.cosmos.esa.int/web/gaia/dr3

Stellar age - the missing piece of the Galactic puzzle

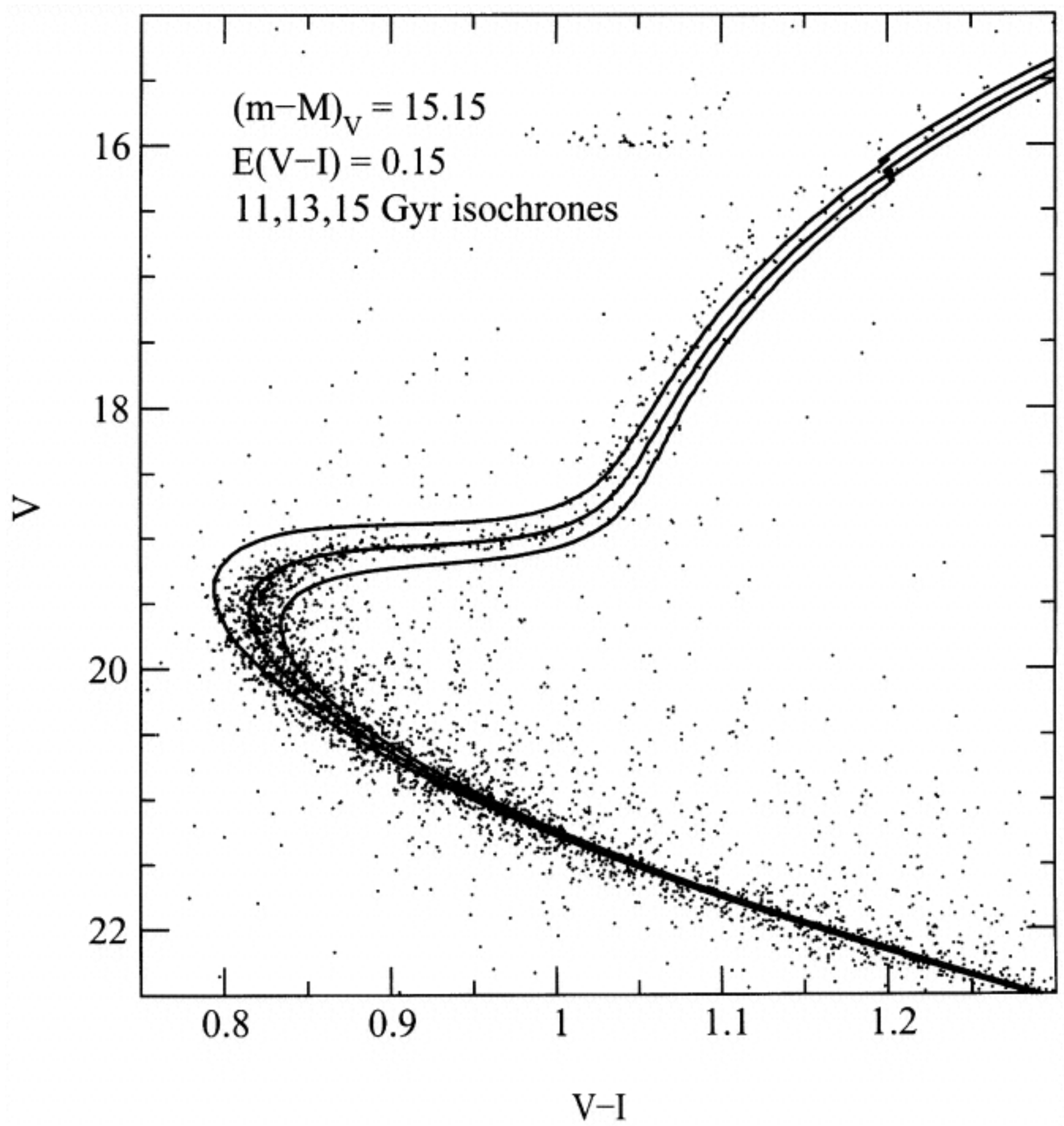
- Age determination of individual stars is important to study how our Galaxy formed and evolved to its present-day structure

- However, stellar ages are elusive and cannot be directly measured

- Estimating stellar ages is indeed one of the most difficult tasks of astrophysics

Methods to infer ages

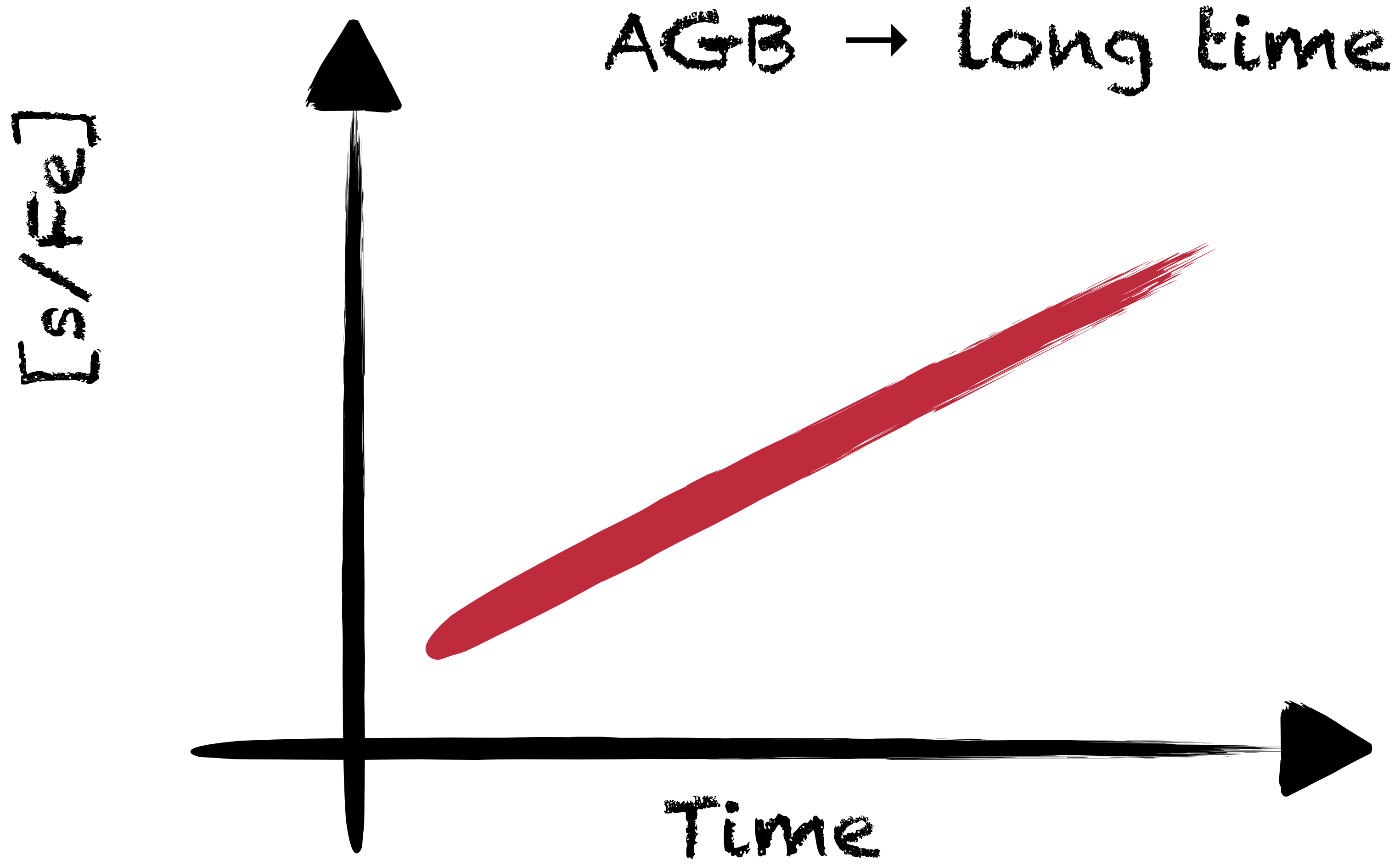
- MODEL-DEPENDENT:
    - Isochrone fitting
    - Asteroseismology
    - Lithium depletion boundary
- SEMI-FUNDAMENTAL:
    - Kinematic age
- EMPIRICAL:
    - Gyrochronology & stellar activity



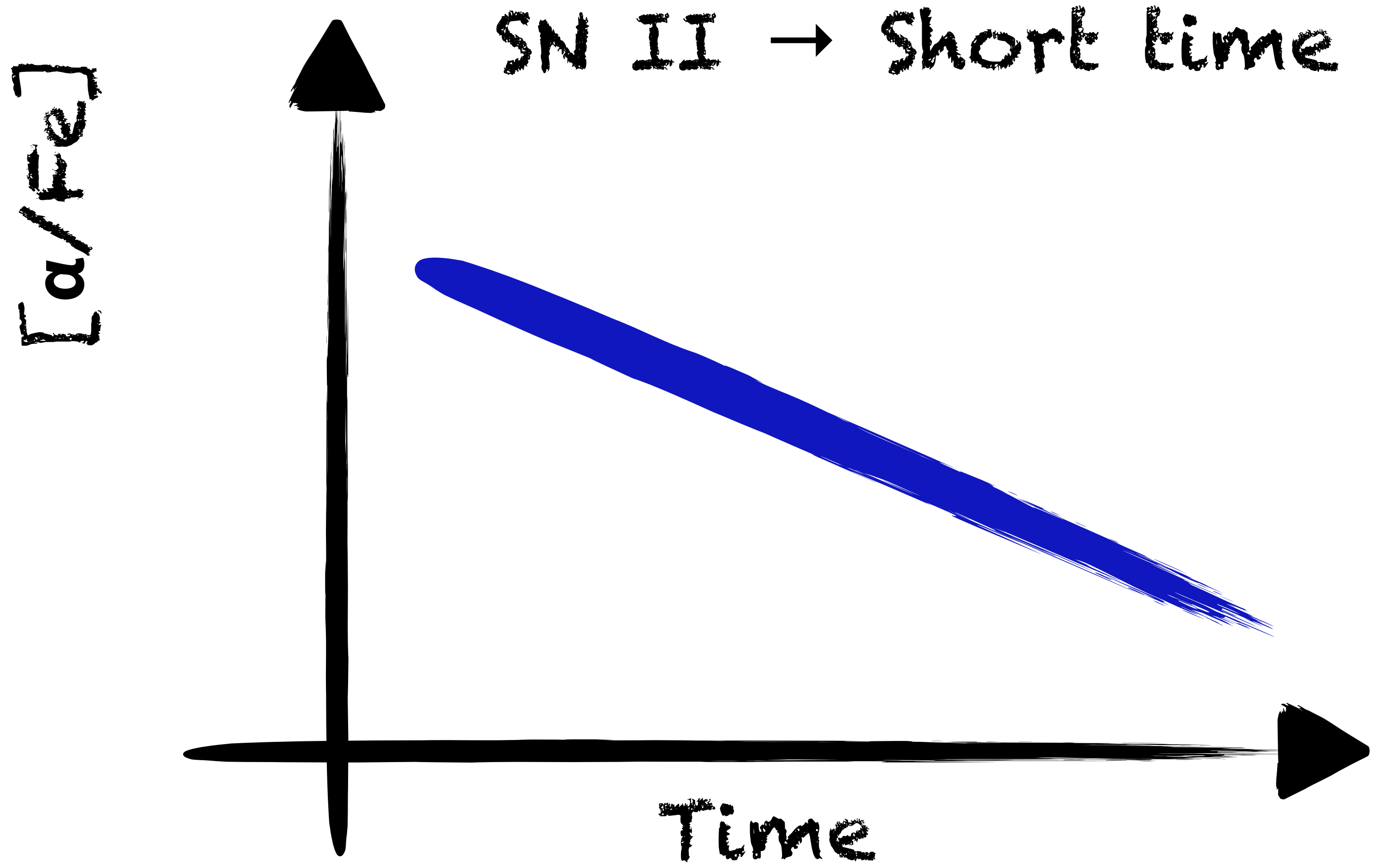
(See Soderblom+10 for a review)

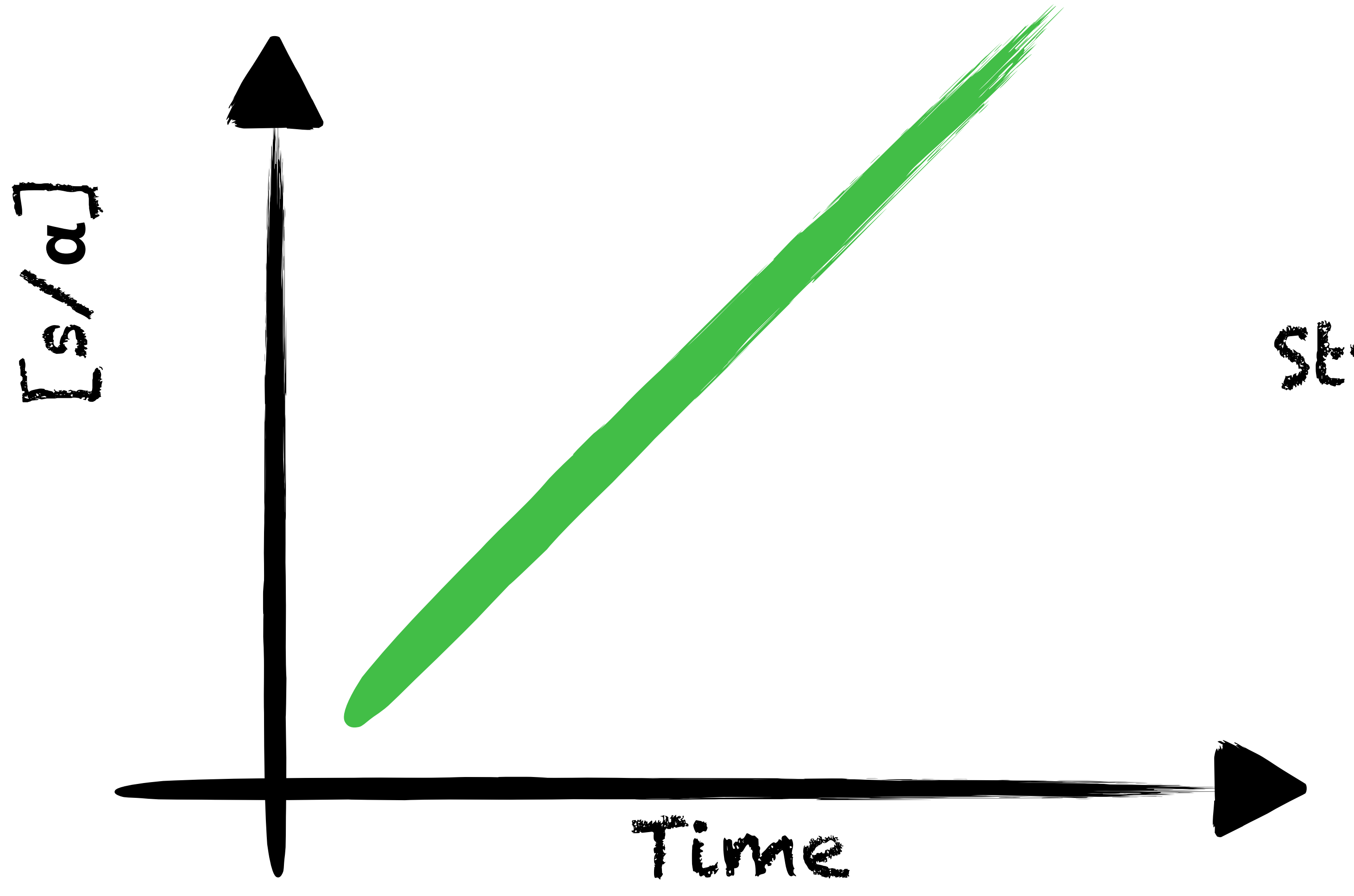
Innovative method: chemical clocks

AGB → long time scale



SN II → Short time scale

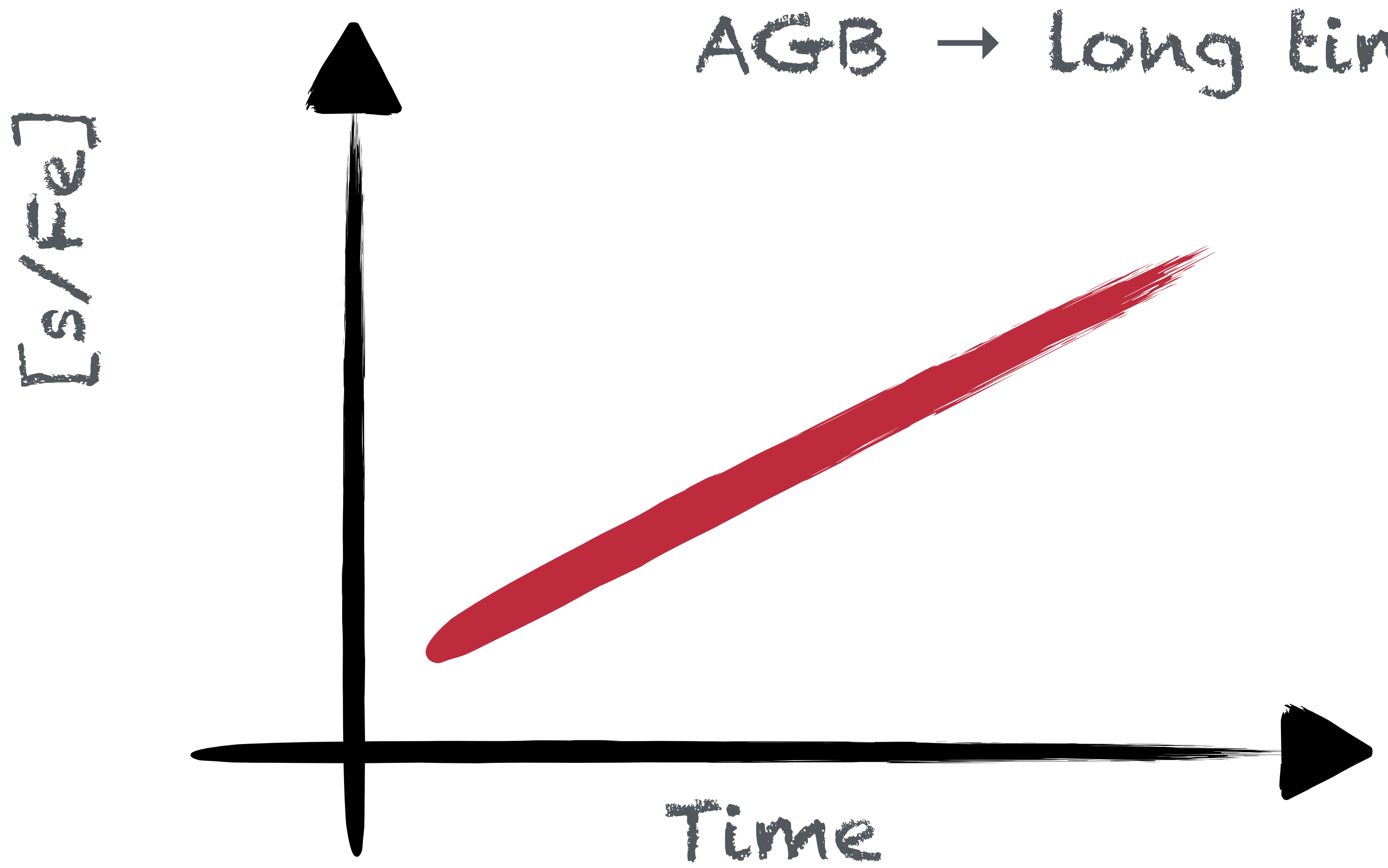




The combination of the abundances of an *s*-process element with other elements with opposite behaviour (α elements) maximise their correlation with stellar age.

Strongest trend -> best age tracers

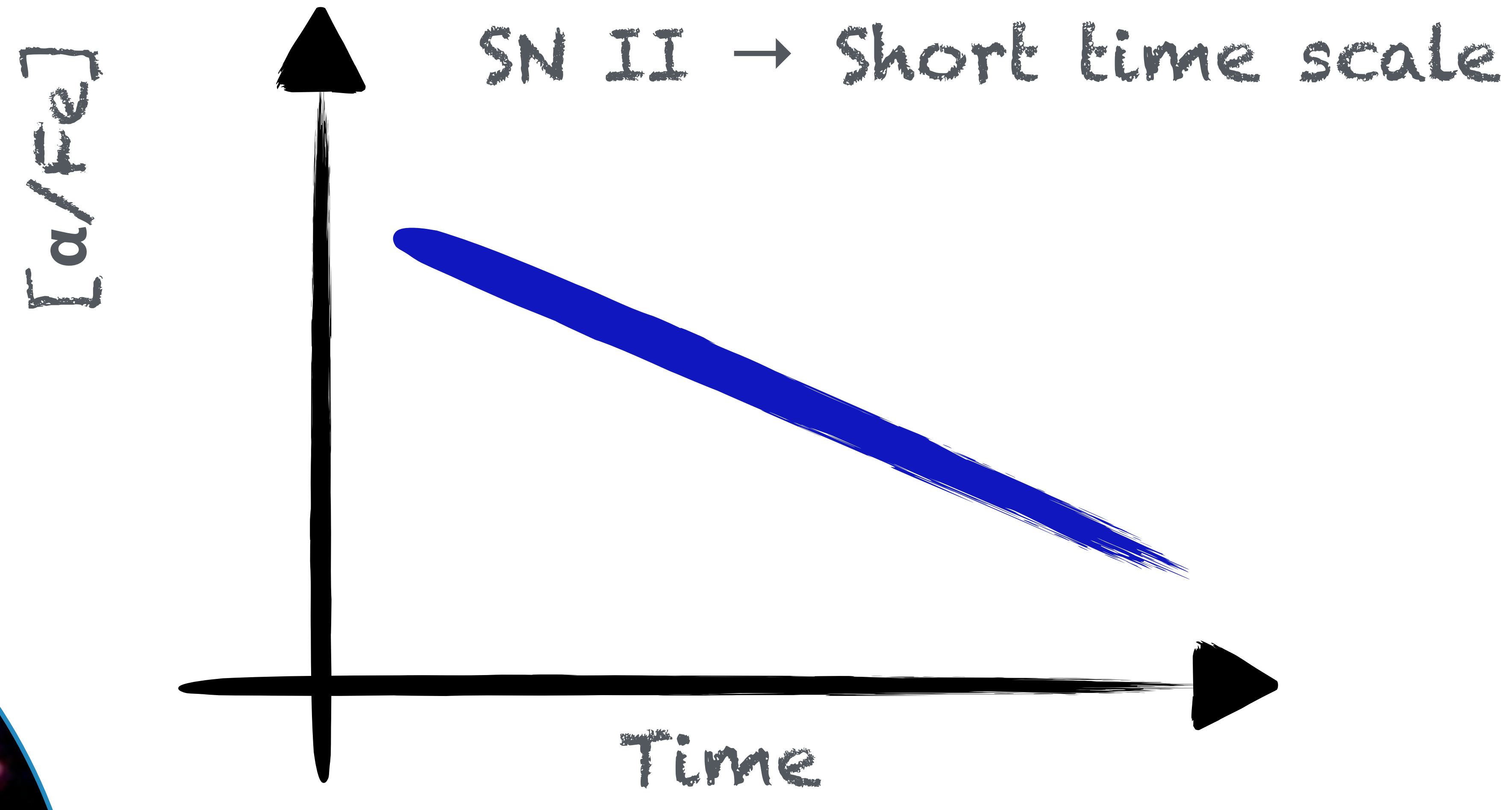
Innovative method: chemical clocks



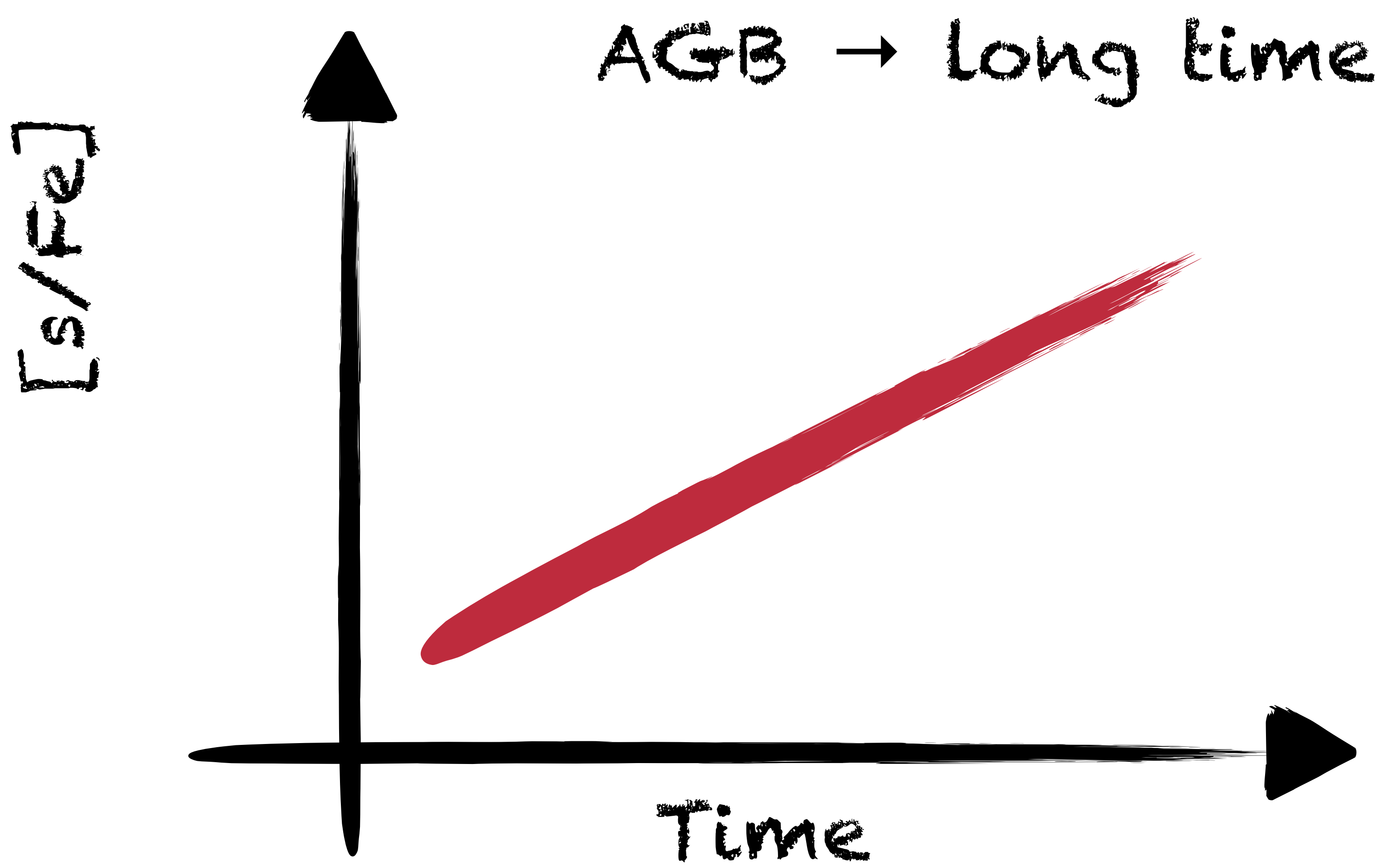
- Low/intermediate mass stars ($M < 8$ $M_\odot$) evolve as AGB stars, dying as planetary nebulae
- They eject mainly s-process elements (Y, Ba, Zr).
- They have a delayed contribution to the Galactic chemical enrichment, with timescale decreasing with their mass (0.5 -10 Gyr)

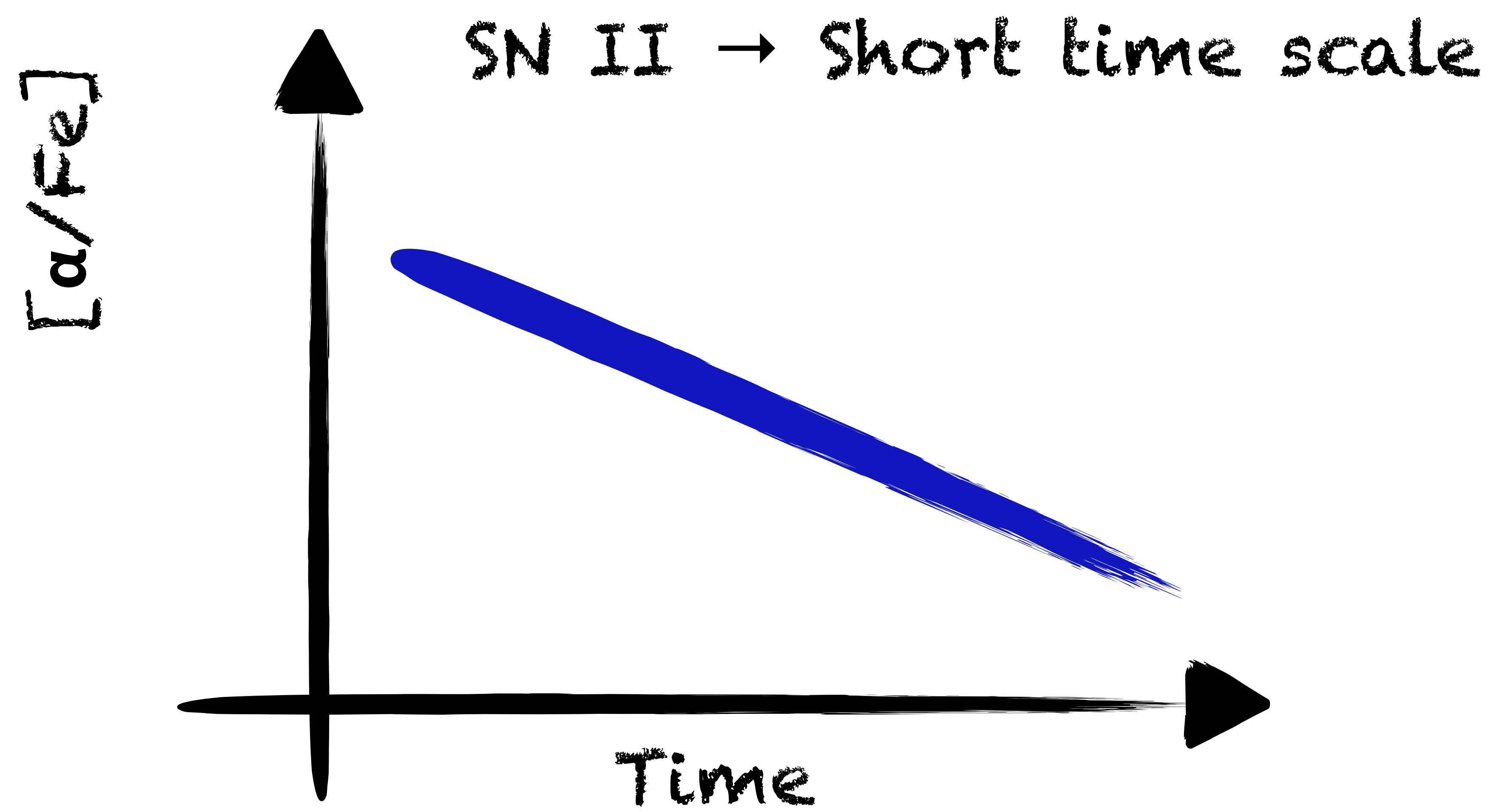
Innovative method: chemical clocks

- Massive stars ($M > 8\,M_\odot$) explode as SNe II
- They eject α-elements (Mg, Si, S, Ti) in ISM
- Shot timescale: $t < 10^{-2}$ Gyr
- Remnants: NS, BH
- They have an early contribution to the Galactic chemical enrichment



Innovative method: chemical clocks





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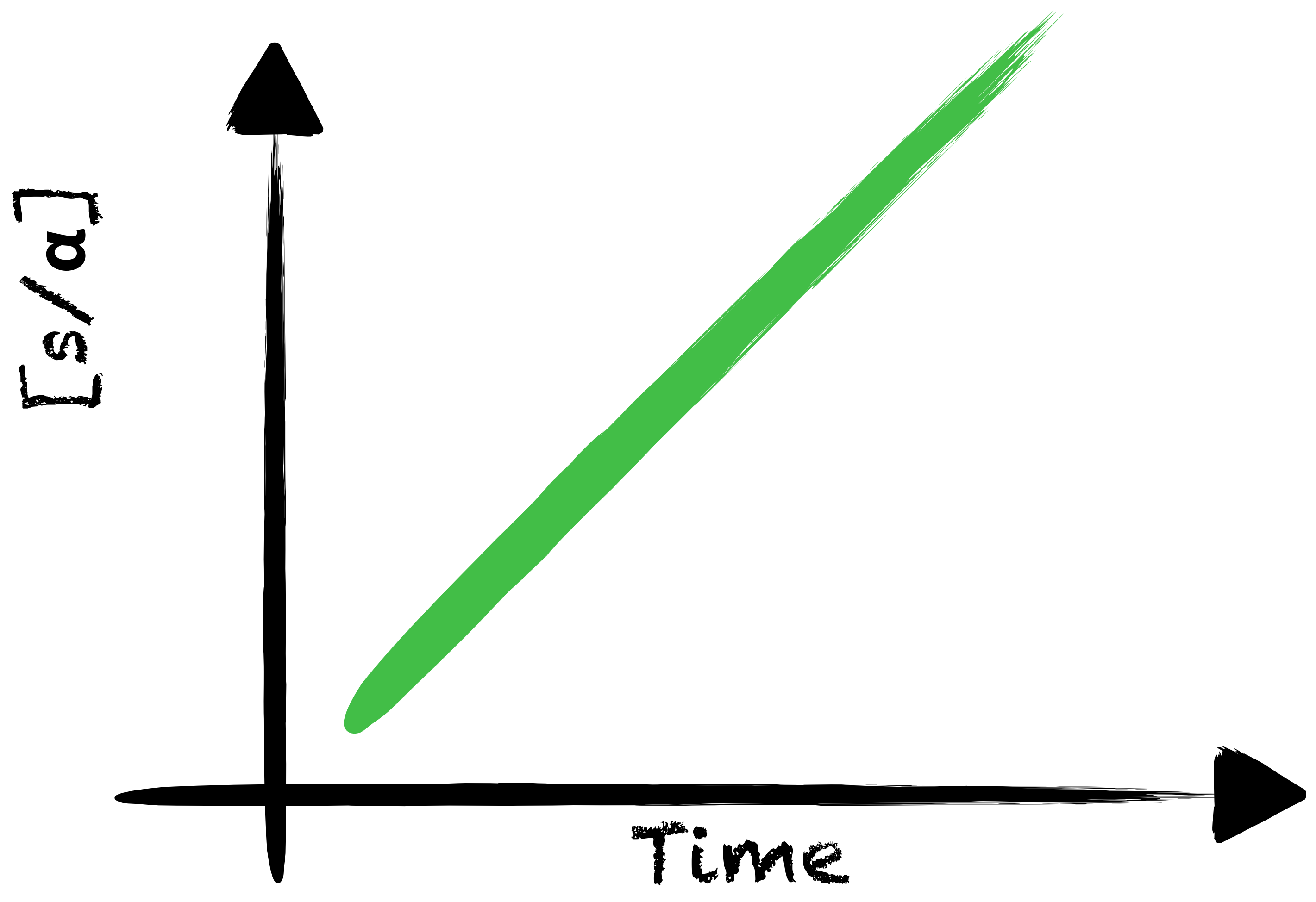
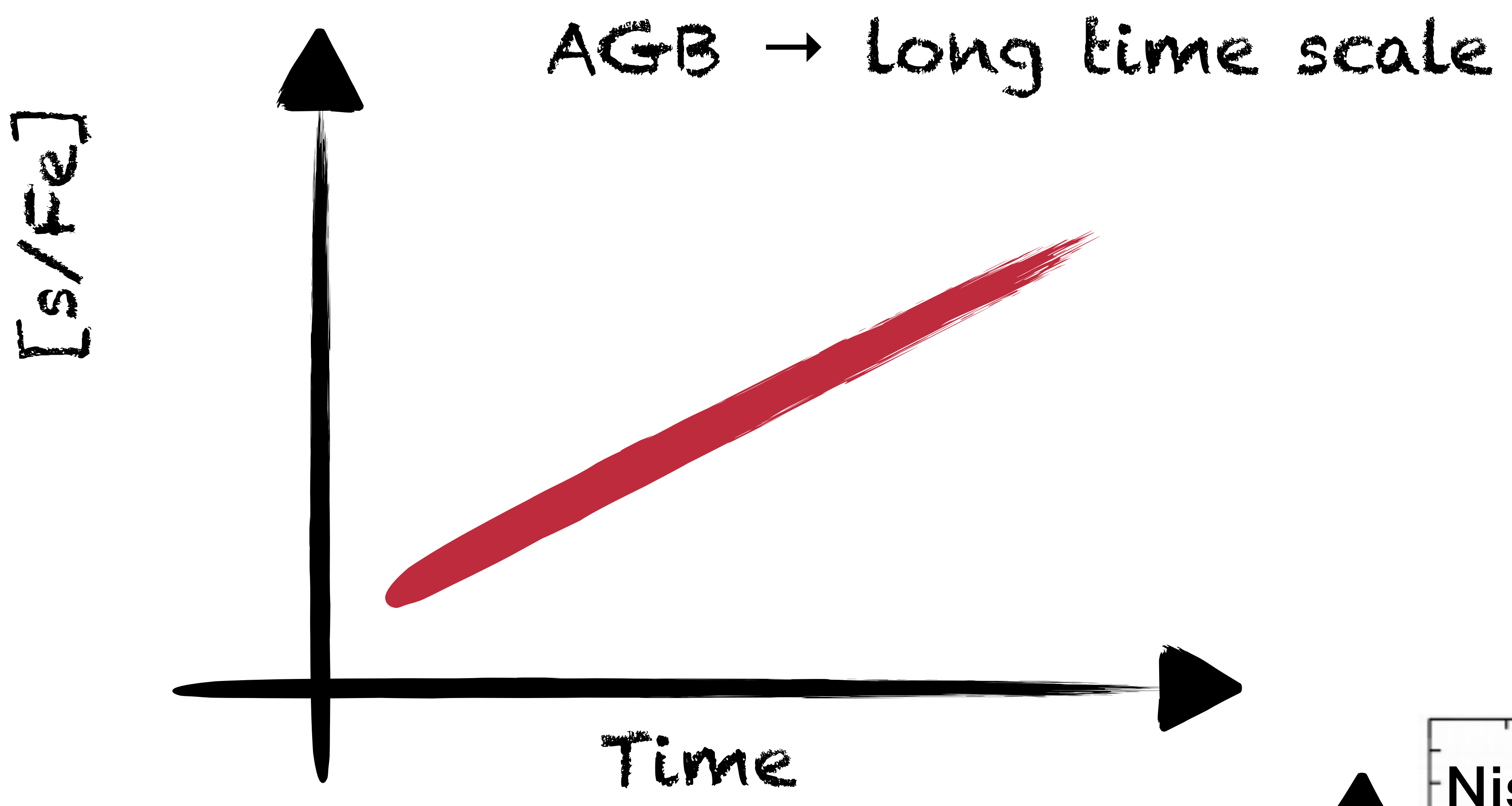
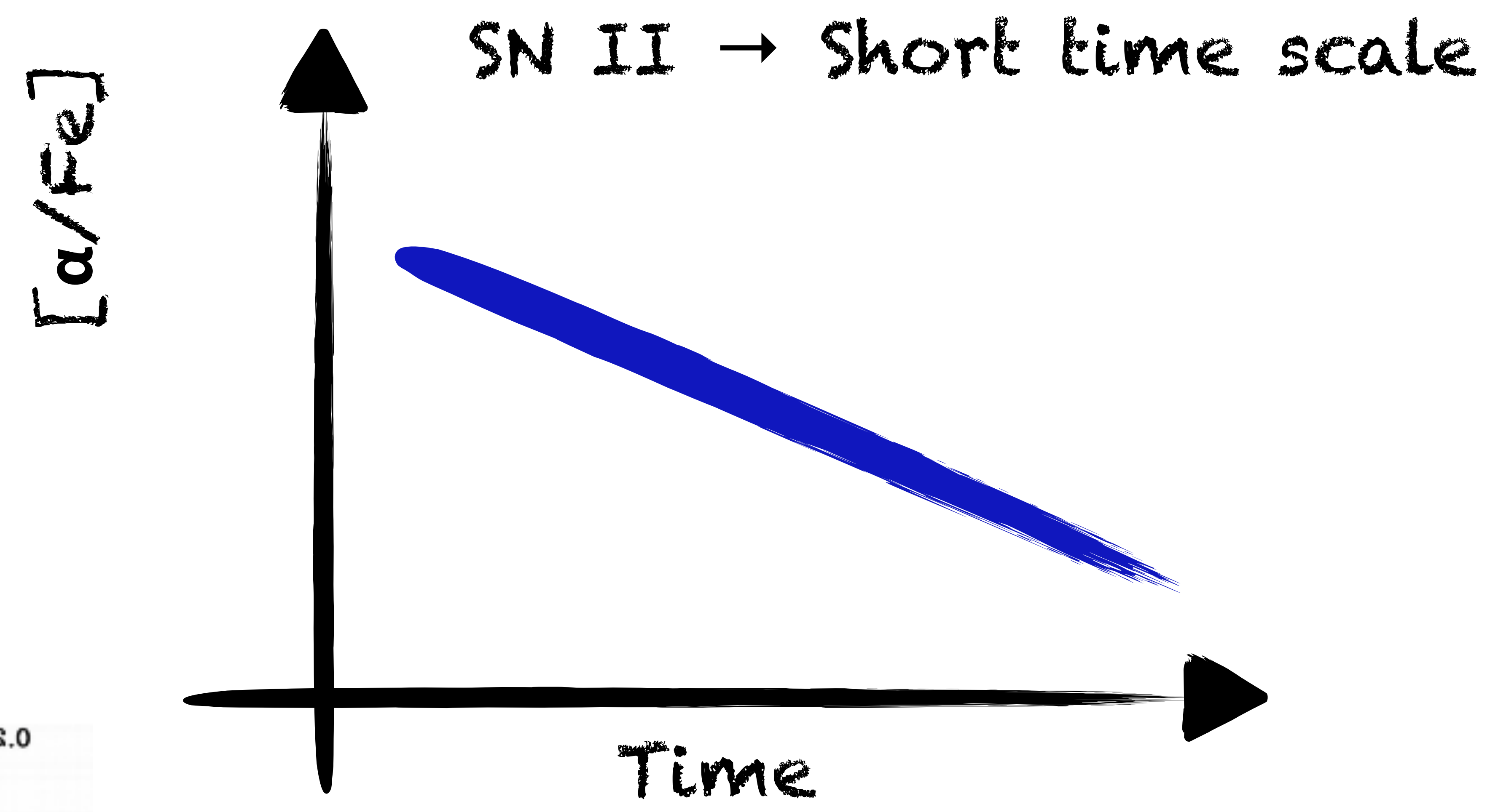


Strongest trend -> best age tracers

Innovative method: chemical clocks





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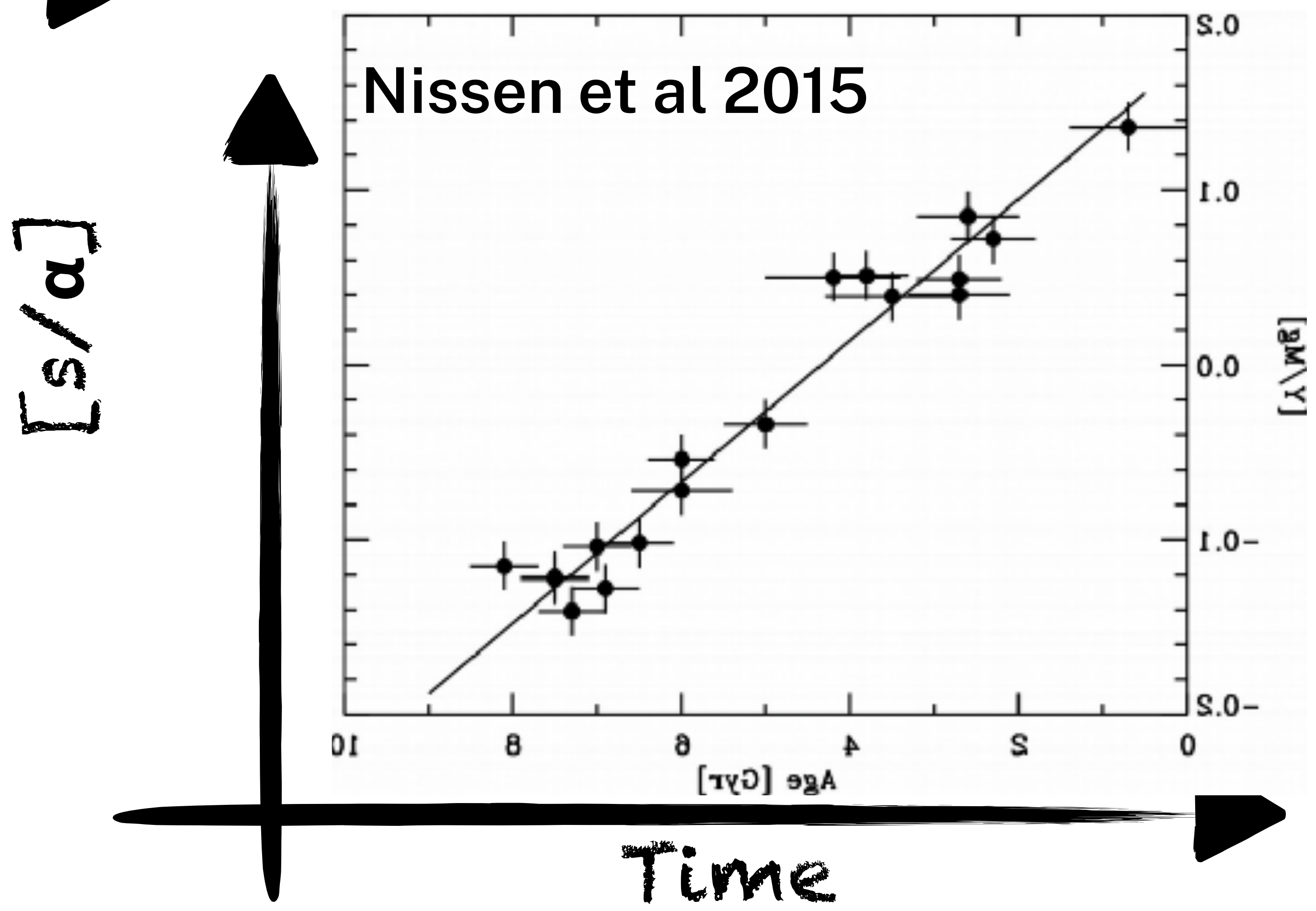


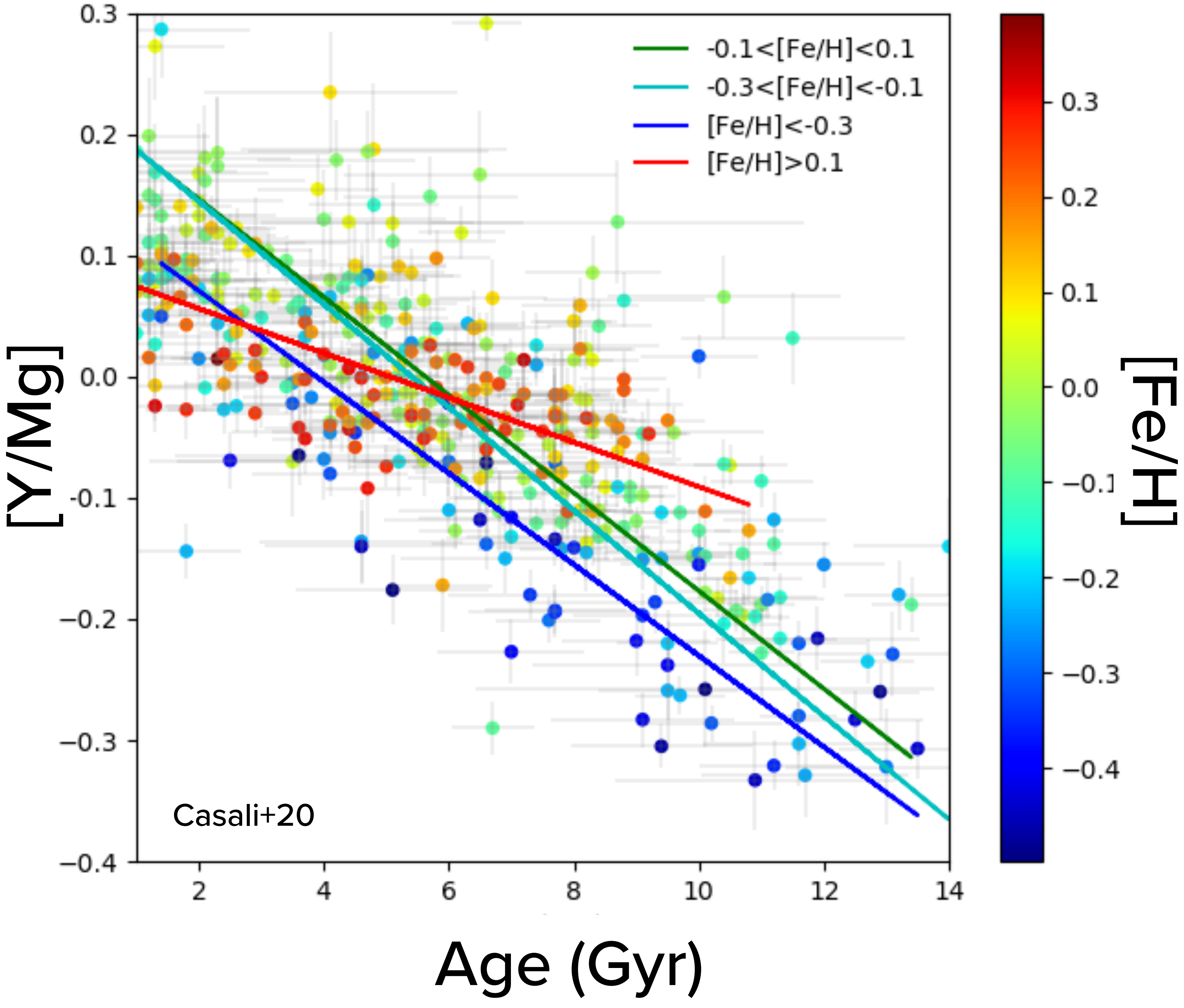
Strongest trend -> best age tracers

These abundance ratios, calibrated on stars with well-known ages, allow us to derive ages of large sample of stars through empirical relations

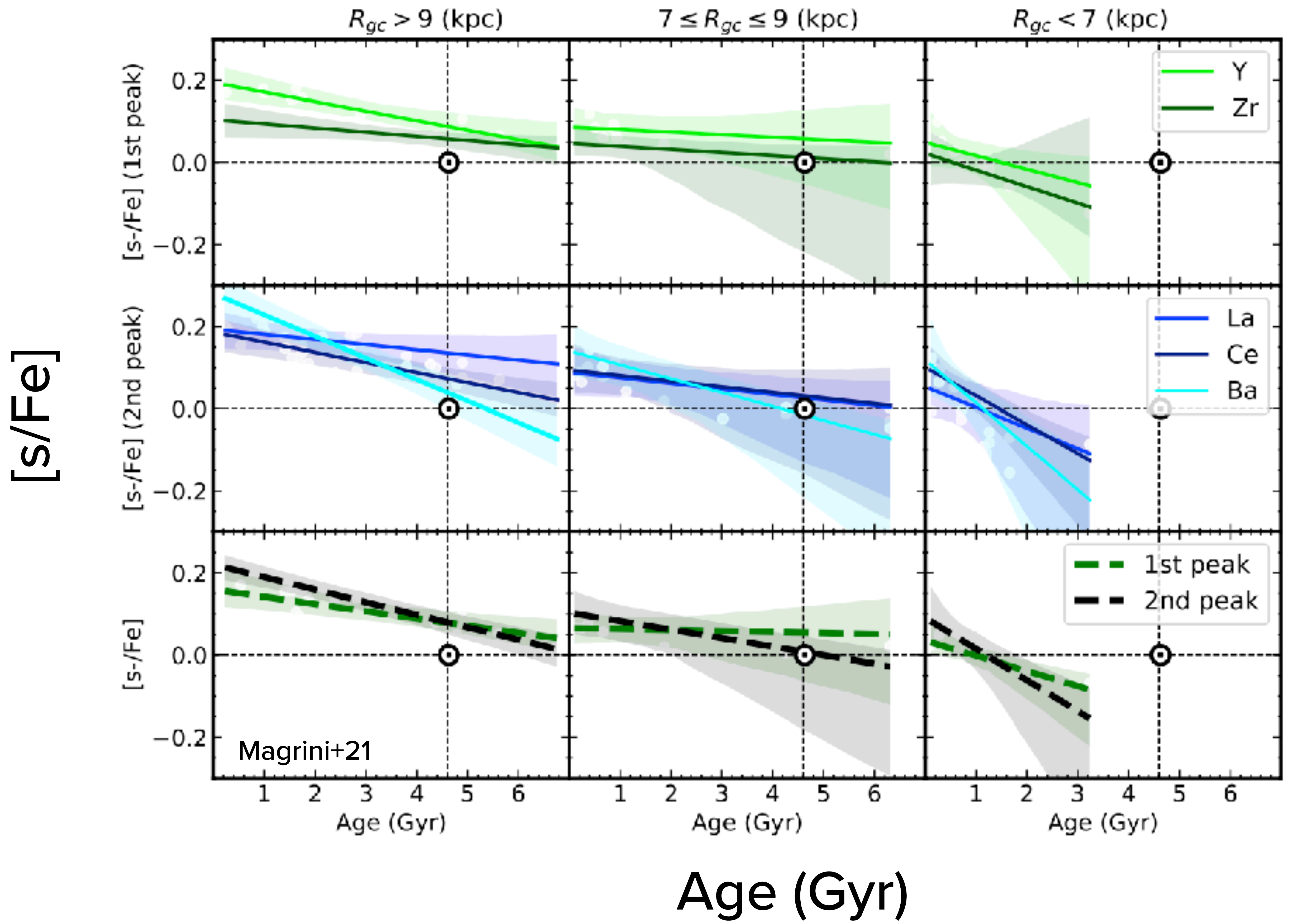
Innovative method: chemical clocks

Applicability

Relationship not applicable to wider range of metallicity!



Non-universality of the chemical clock relations in the Galactic disc!!



Innovative method: chemical clocks

CALIBRATORS

- Stars with well known ages
- Precise s- and α-elements abundances ($\sigma \lesssim 0.05$ dex):
  - HR (> 20,000)
  - High SNR (> 60 in blue part)
- Visible wavelengths

Relation →

TEST SAMPLE

- Abundances: s- and α-elements
- Uncertainties on elements $\lesssim$ 0.1 dex

Calibrators

- FGK dwarfs → age from isochrone fitting (Delgado Mena+19, Moya+22, Titarenko+19, Feltzing+17)
- Solar twins → High precision spectroscopy ⇒ Precise age from isochrone fitting (Nissen+15, Spina+16, Spina+18, Casali+20, Jofré+20, Nissen+20)
- Open clusters → Precise age from isochrone fitting (Casali+19, Casamiquela+20, Viscasillas Vázquez+22)
- Stars with asteroseismic age → Measuring the internal frequencies of a star allows reaching a high precision on the inferred ages (Morel+21, Casali+23)

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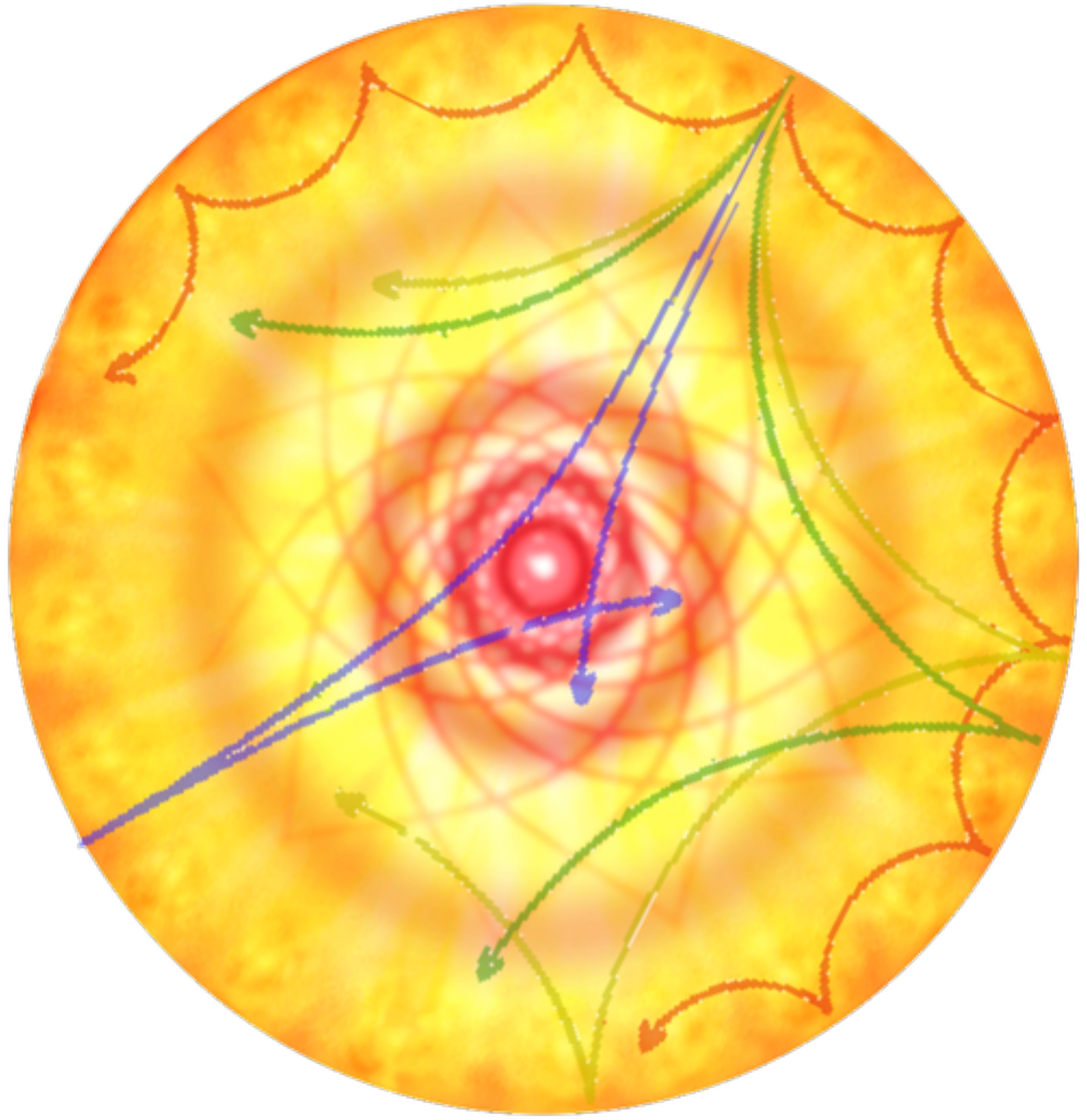
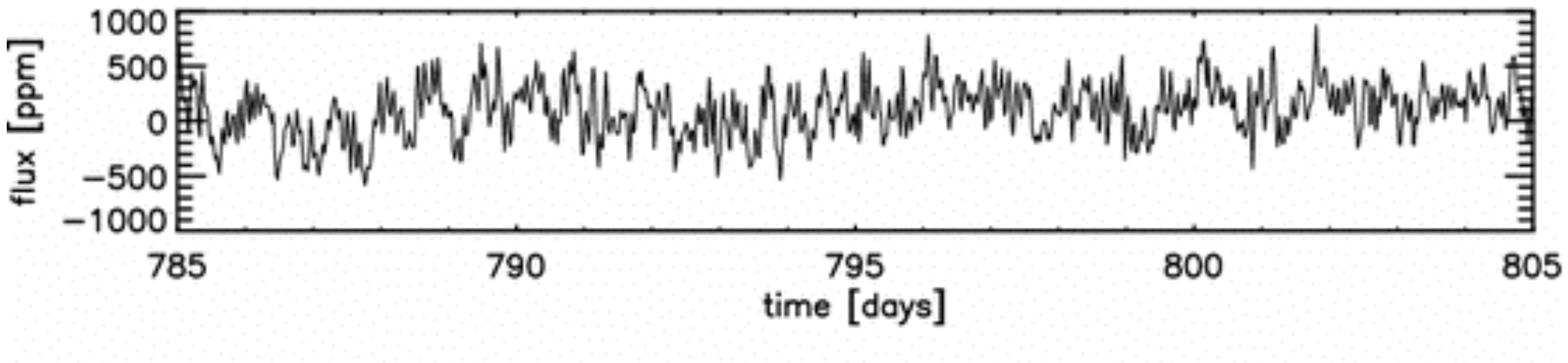
Age from asteroseismology



Credits: IAC

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

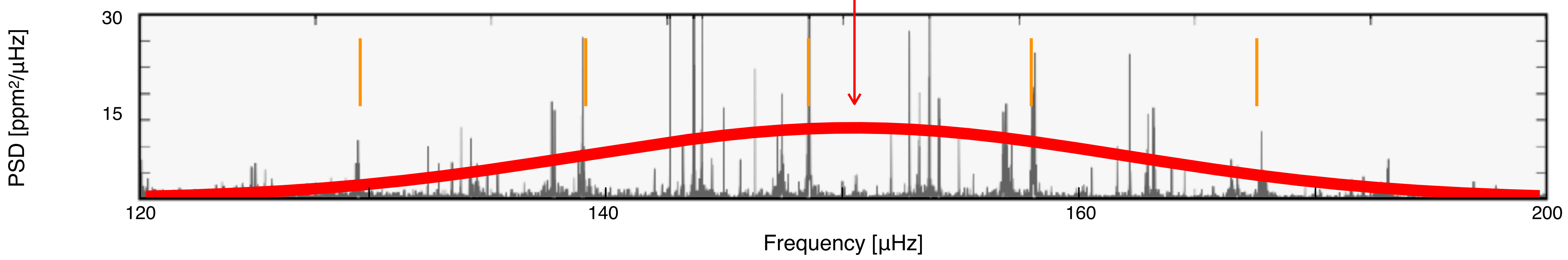


We can detect these oscillations by measuring the changes in the brightness, which we can measure over time in a time series. We can then perform a Fourier transform on the time series data and get the power spectrum

Age from asteroseismology

- average seismic parameters

$\Delta\nu$ $\quad$ ν_{max} $\quad$ 2 constraints, $\sigma \sim 10^{-2}$



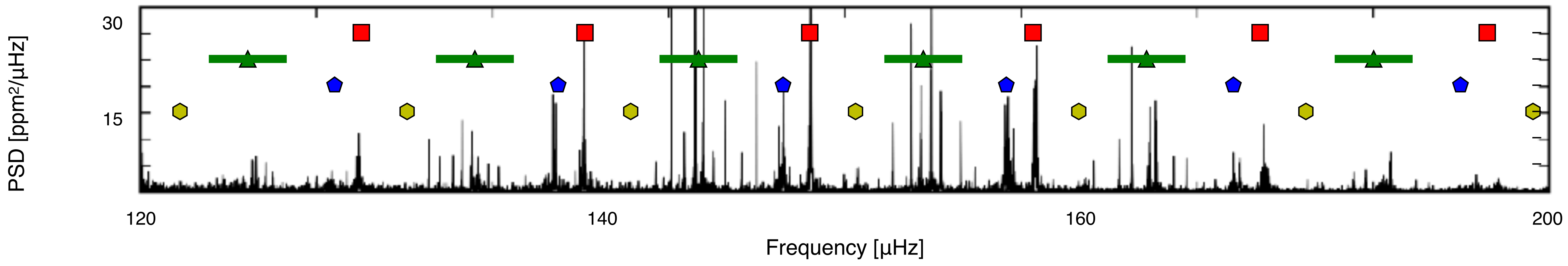
$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3/2}$$

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

Age, logg, distance

- individual mode frequencies

ν_i $\quad$ tens of constraints, $\sigma_i \sim 10^{-4}$



→ Montalban+21, Nat. As.

Kepler only

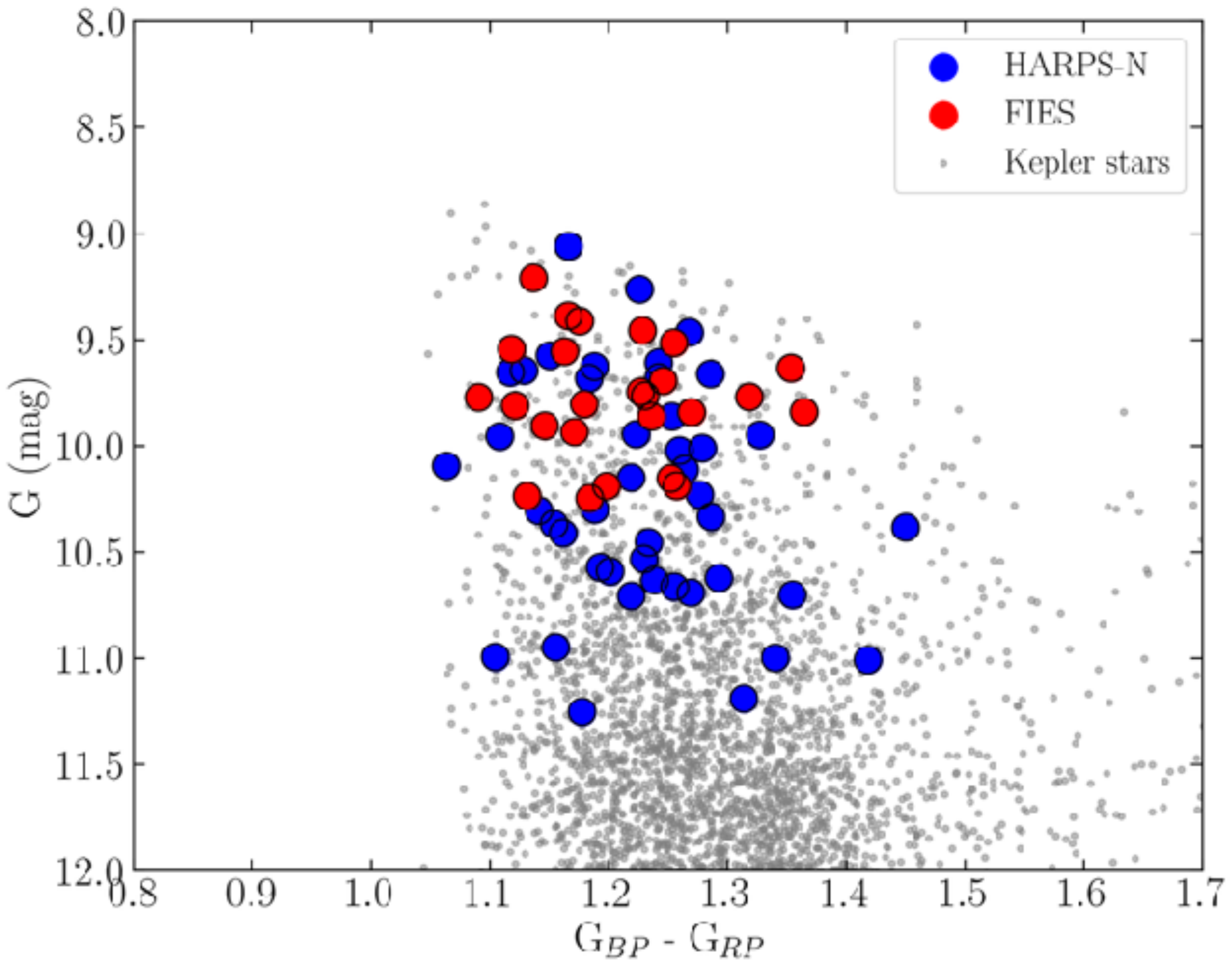
(Plato in the future)

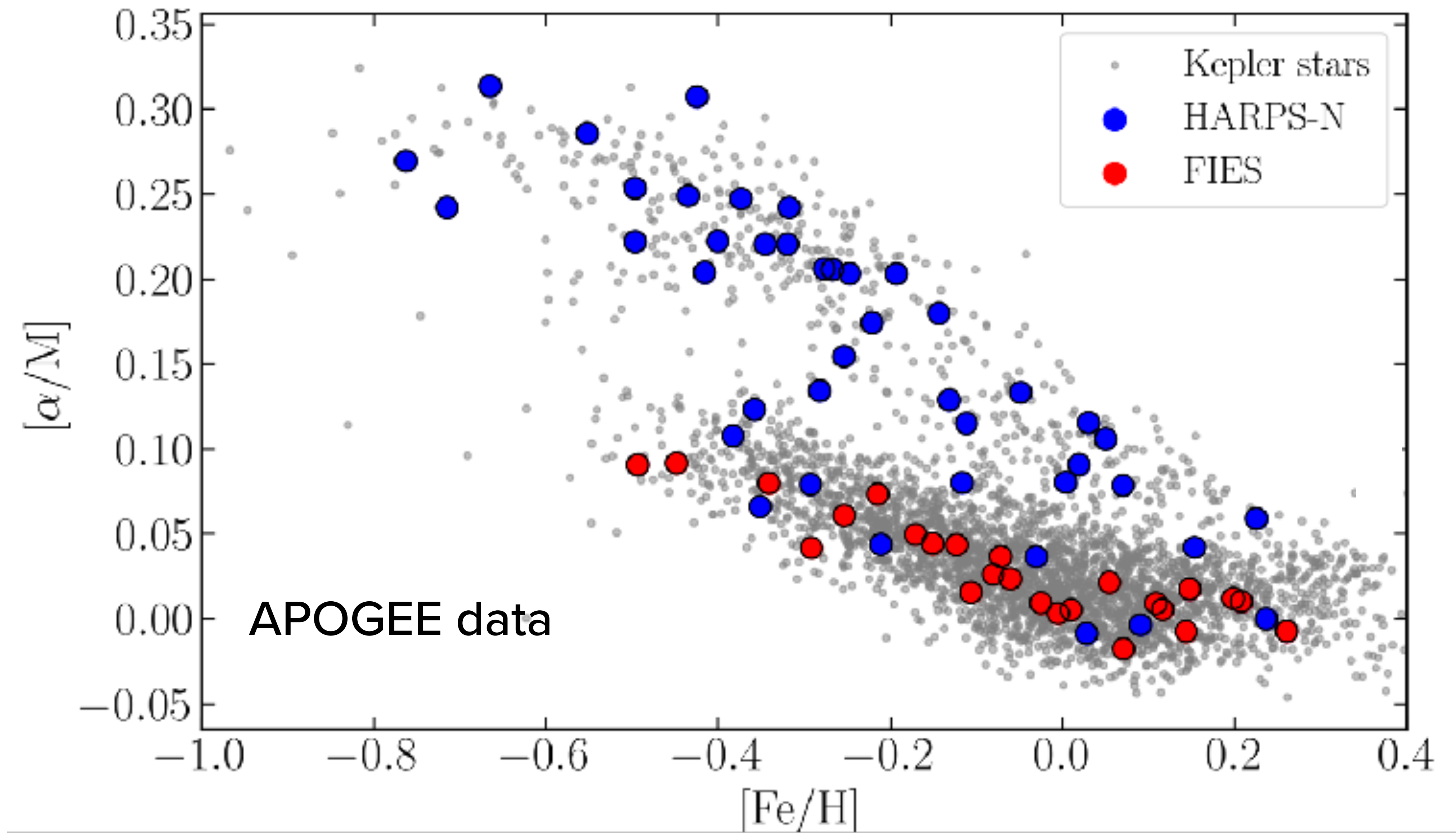
(e.g. papers by Anders et al., Joergensen et al., Miglio et al., Montalban et al, Pinsonneault et al., Rendle et al., Sharma et al., Silva Aguirre et al., Stello et al., Valentini et al., Tailo et al., ...)

Stars with asteroseismic age

OBSERVATIONS of 68 Kepler RGB stars:

- HARPS-N@TNG (R ~ 115,000, λ ~ 385-691 nm)
  - 59h
  - 47 RGB
- FIES@NOT (R ~ 67,000, λ ~ 370-830 nm)
  - 11h
  - 25 RGB



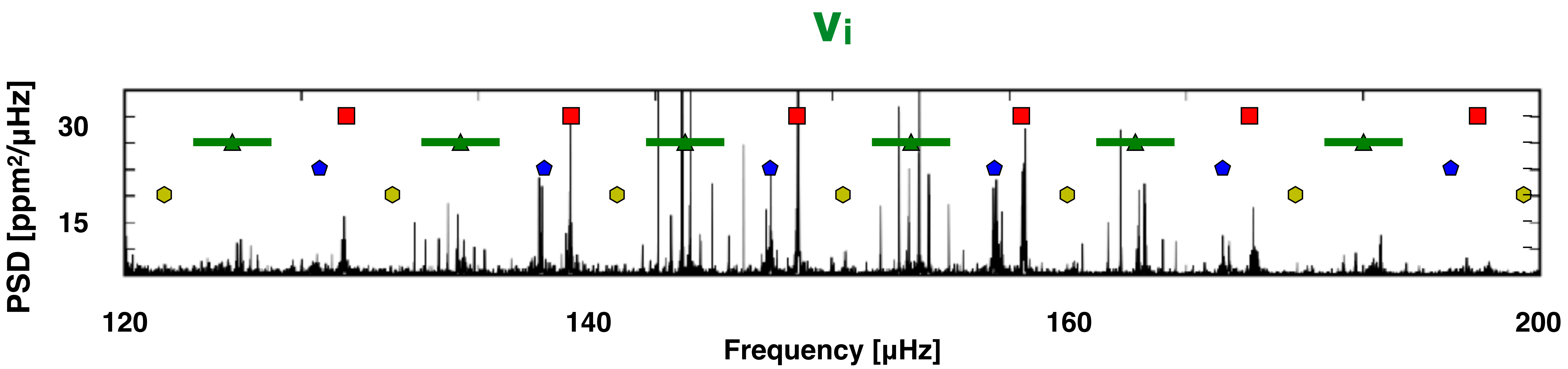


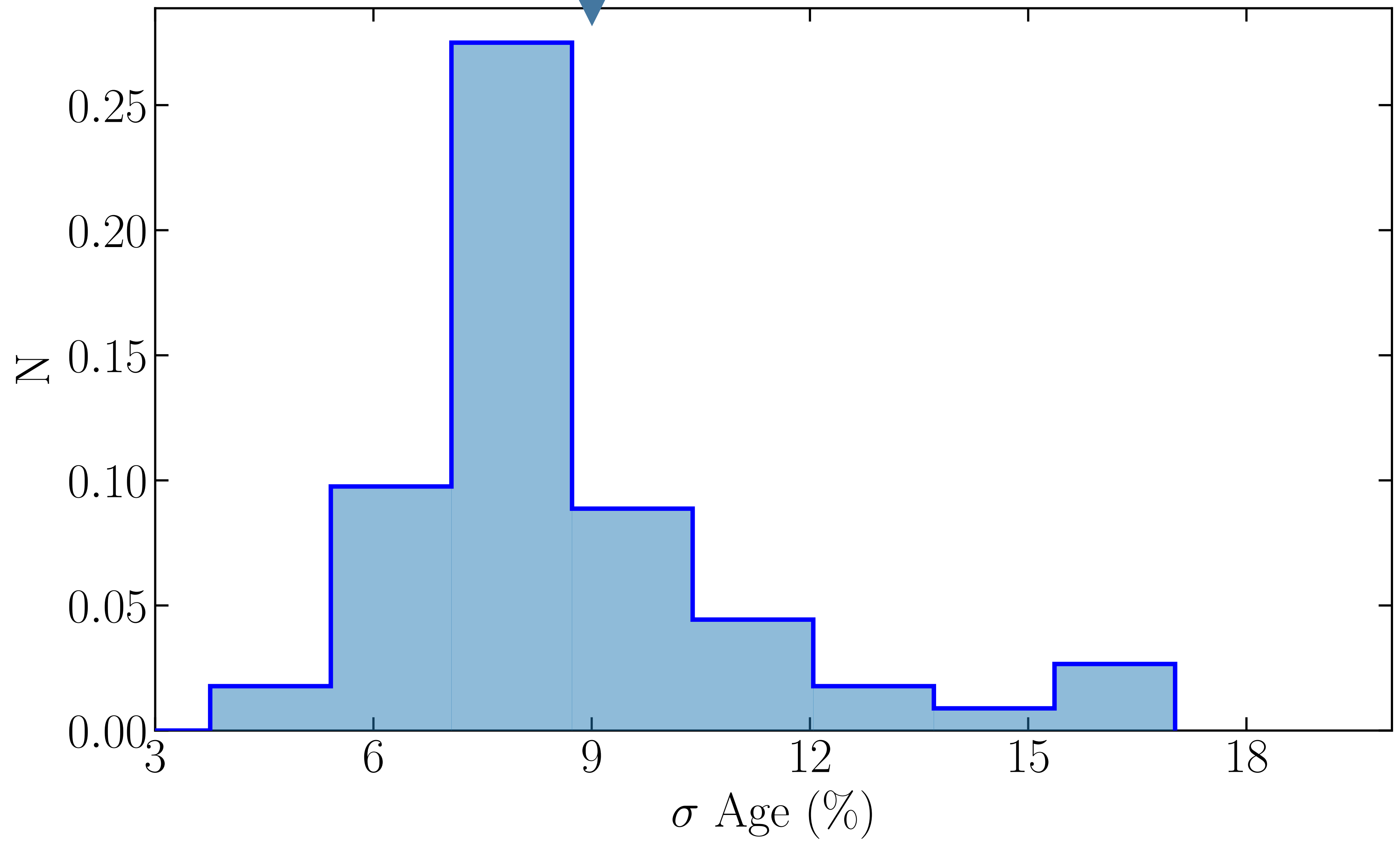
Casali+25 in review

Age from asteroseismology

Typical mean uncertainties ~ 9%

Individual mode frequencies (Montalbán in prep.)



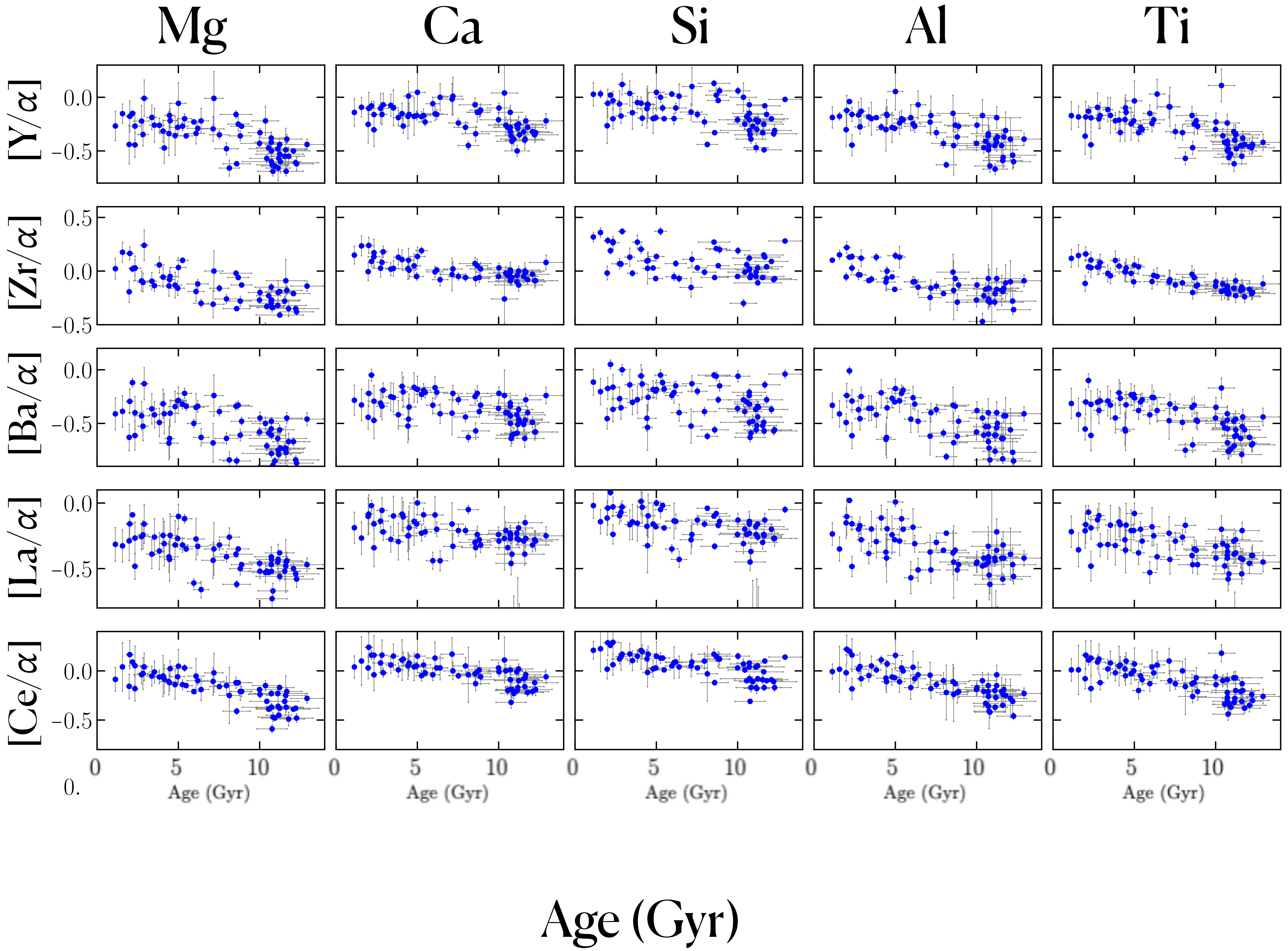


Chemical clocks

s: Y, Zr, La, Ba, Ce

α: Mg, Ca, Si, Ti, (Al)

The tightest relations are for chemical clocks composed by Zr and Ce



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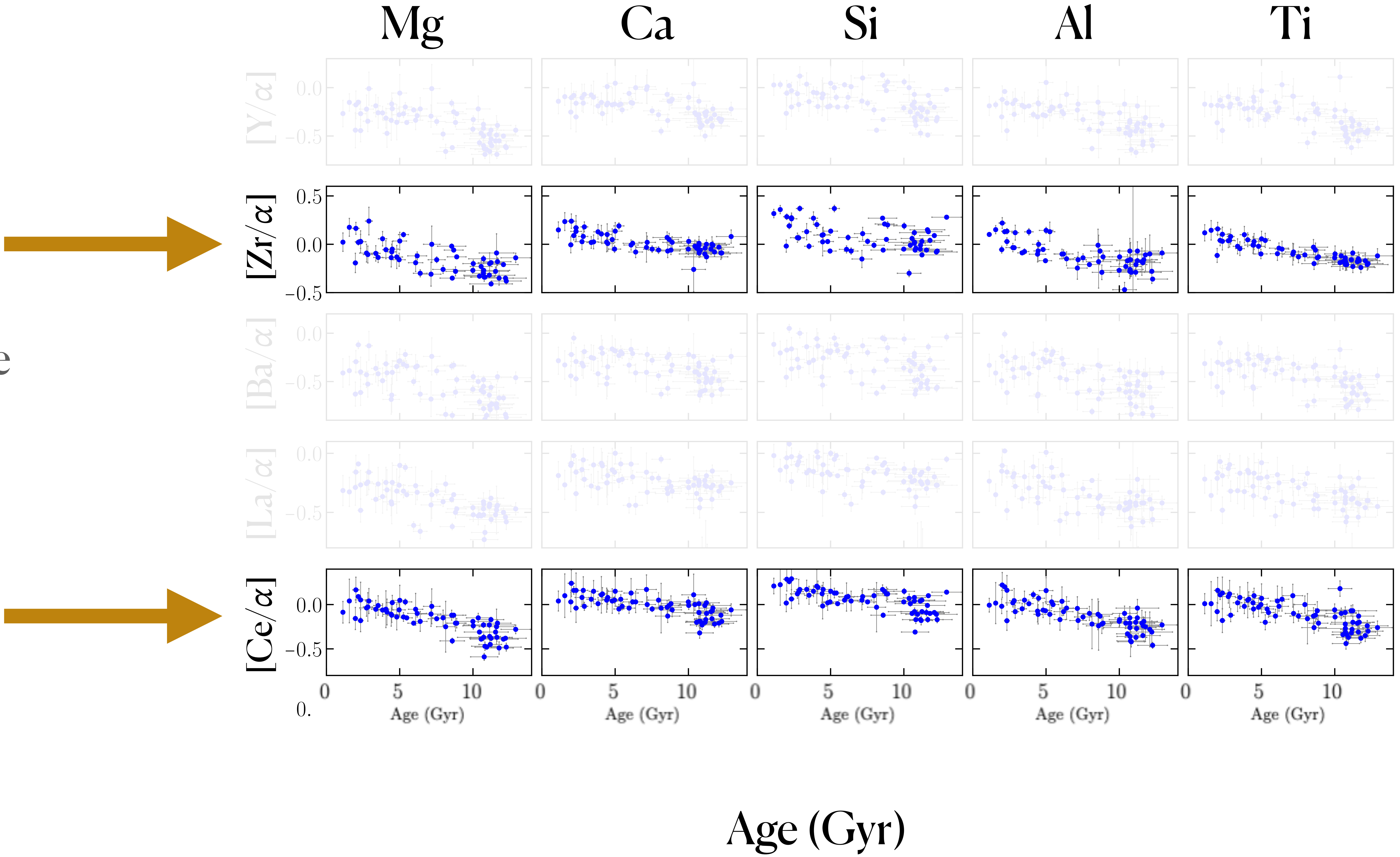

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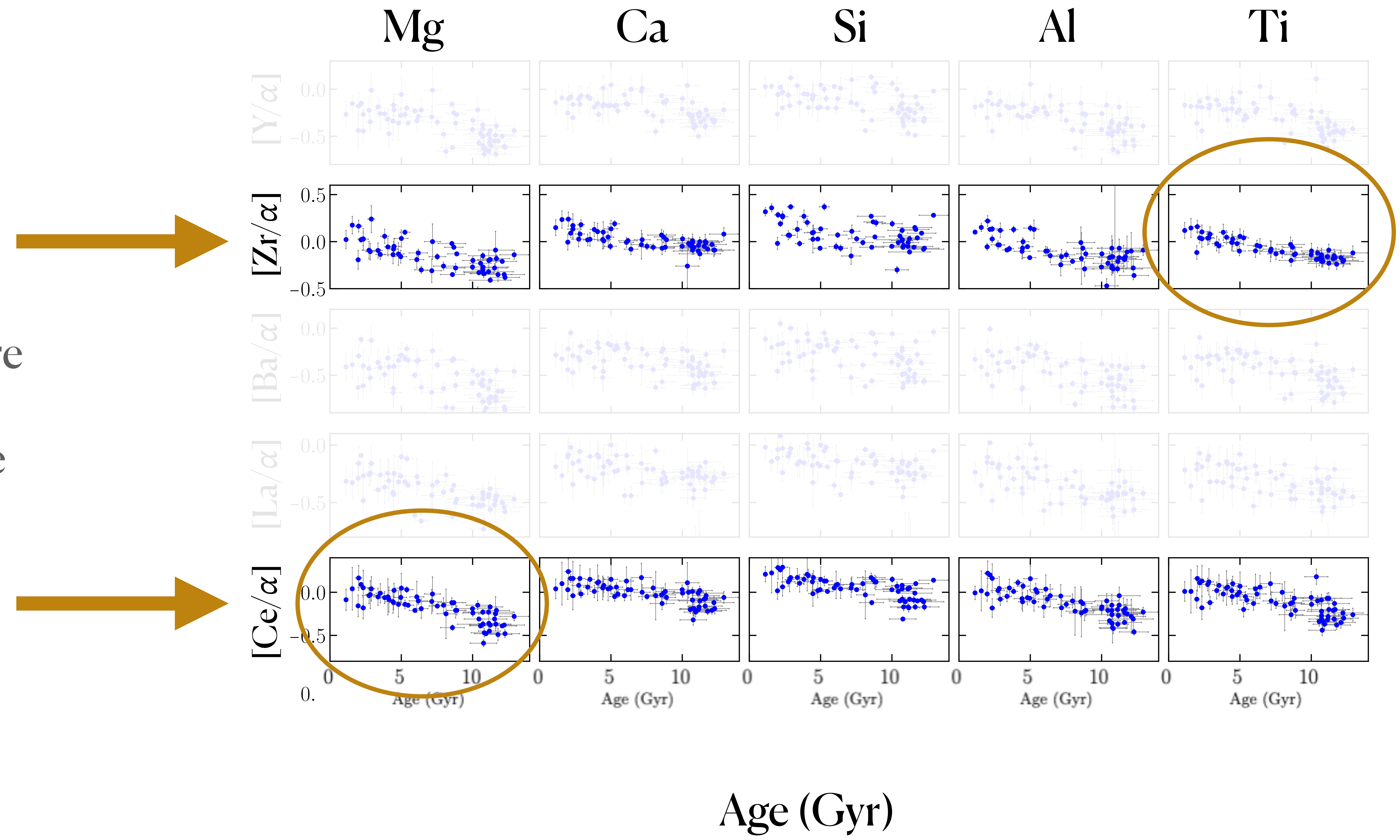
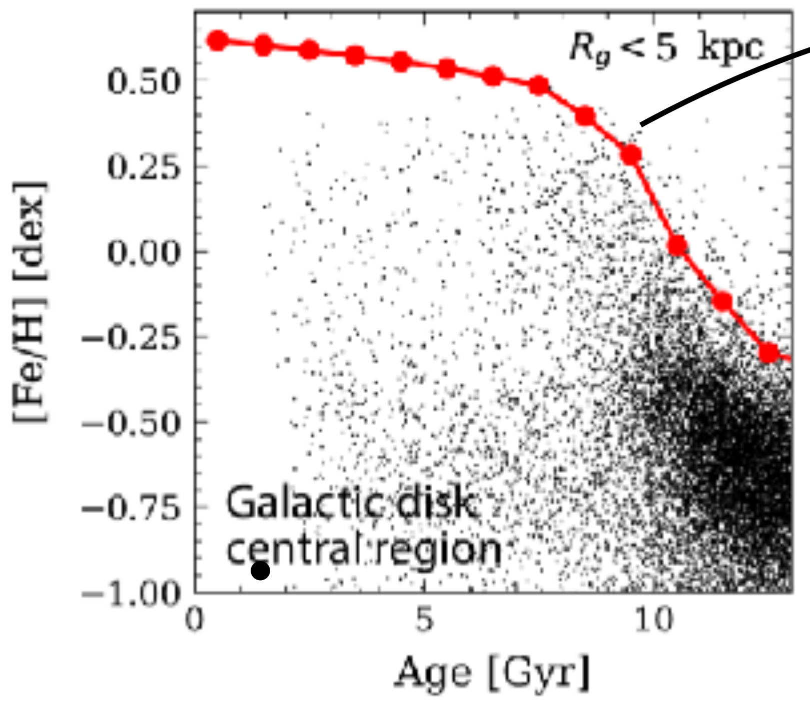


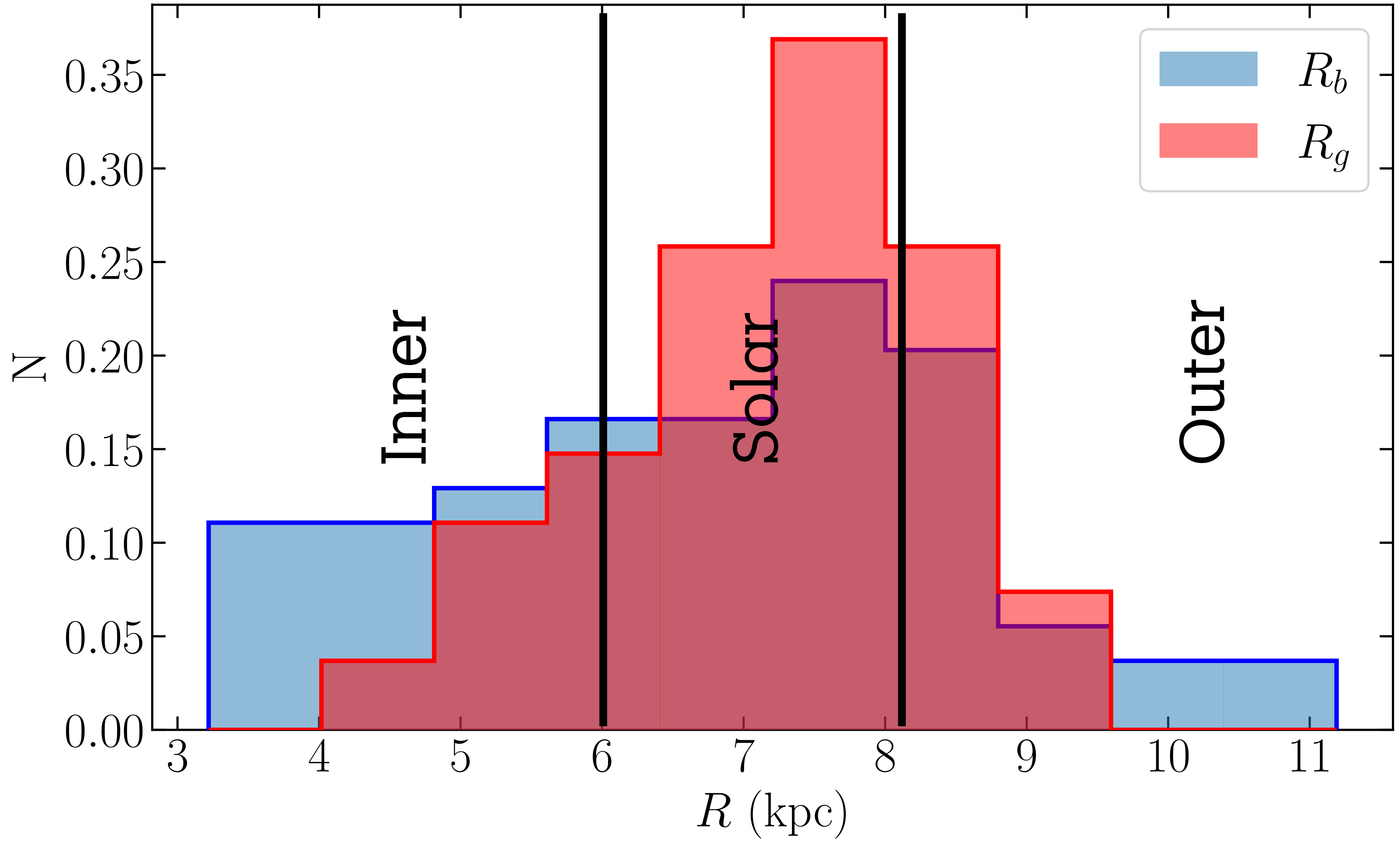
Spatial distribution

- **Guiding radius R_g**: it can mitigate the "blurring" effect of radial migration
- **Birth radius R_b**: it can mitigate the effect of radial migration knowing age and metallicity of stars (Lu+24)



$$R_b = \frac{[Fe/H] - AMR(Lu + 22)}{-0.08 * Range[Fe/H] - 0.07}$$

$$Range[Fe/H] = 95\,\%\,[Fe/H] - 5\,\%\,[Fe/H]$$



Rg: radius of a circular orbit with specific angular momentum

Blurring: circular orbits becoming less circular with time. Increase the eccentricity, while maintaining the guiding radius

[Zr/Ti] at different R_g & R_b bins

$[Zr/Ti] = a \cdot Age + b \cdot [Fe/H] + c$

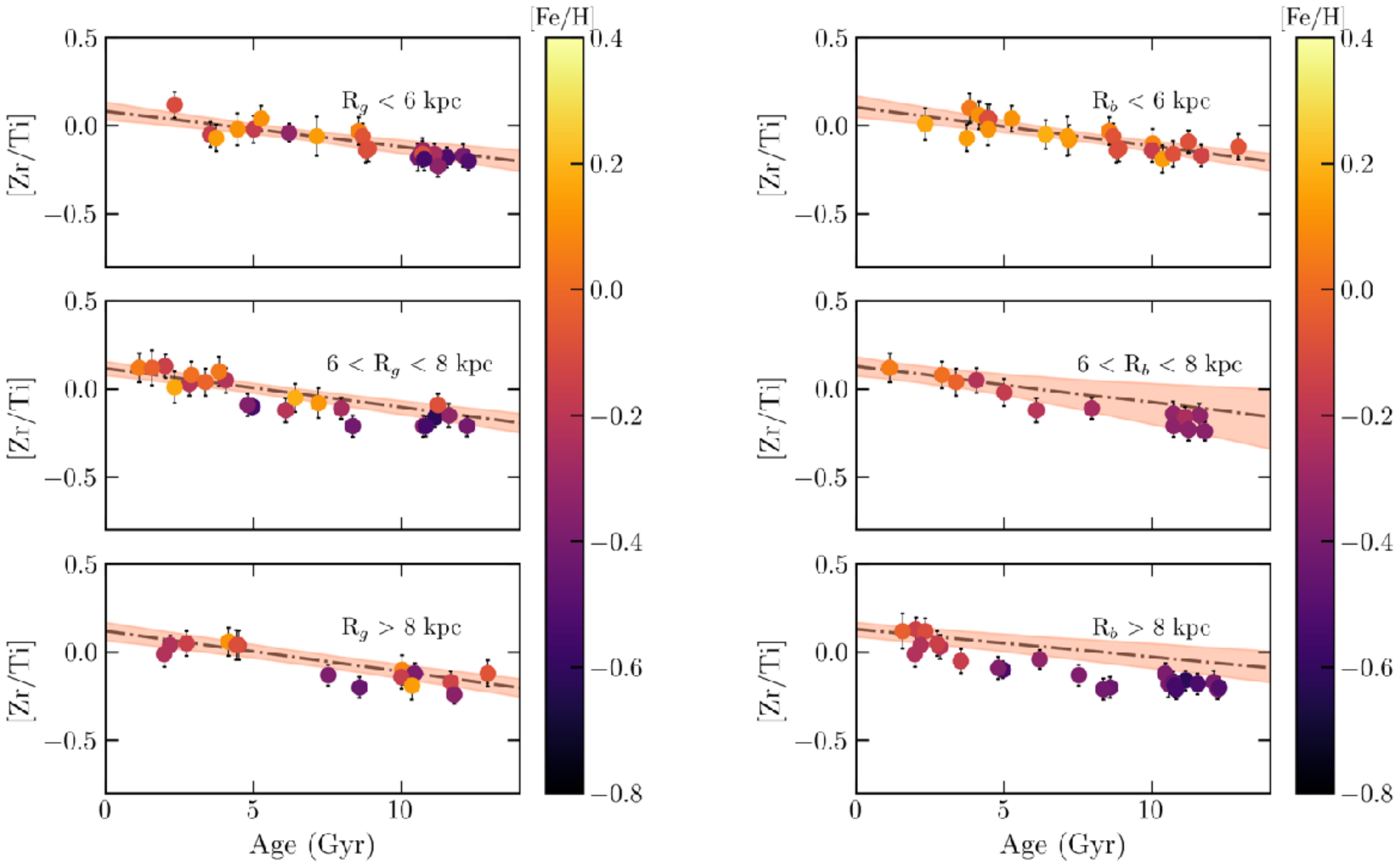
MCMC modelling

R_g R_b

Inner

Solar

Outer



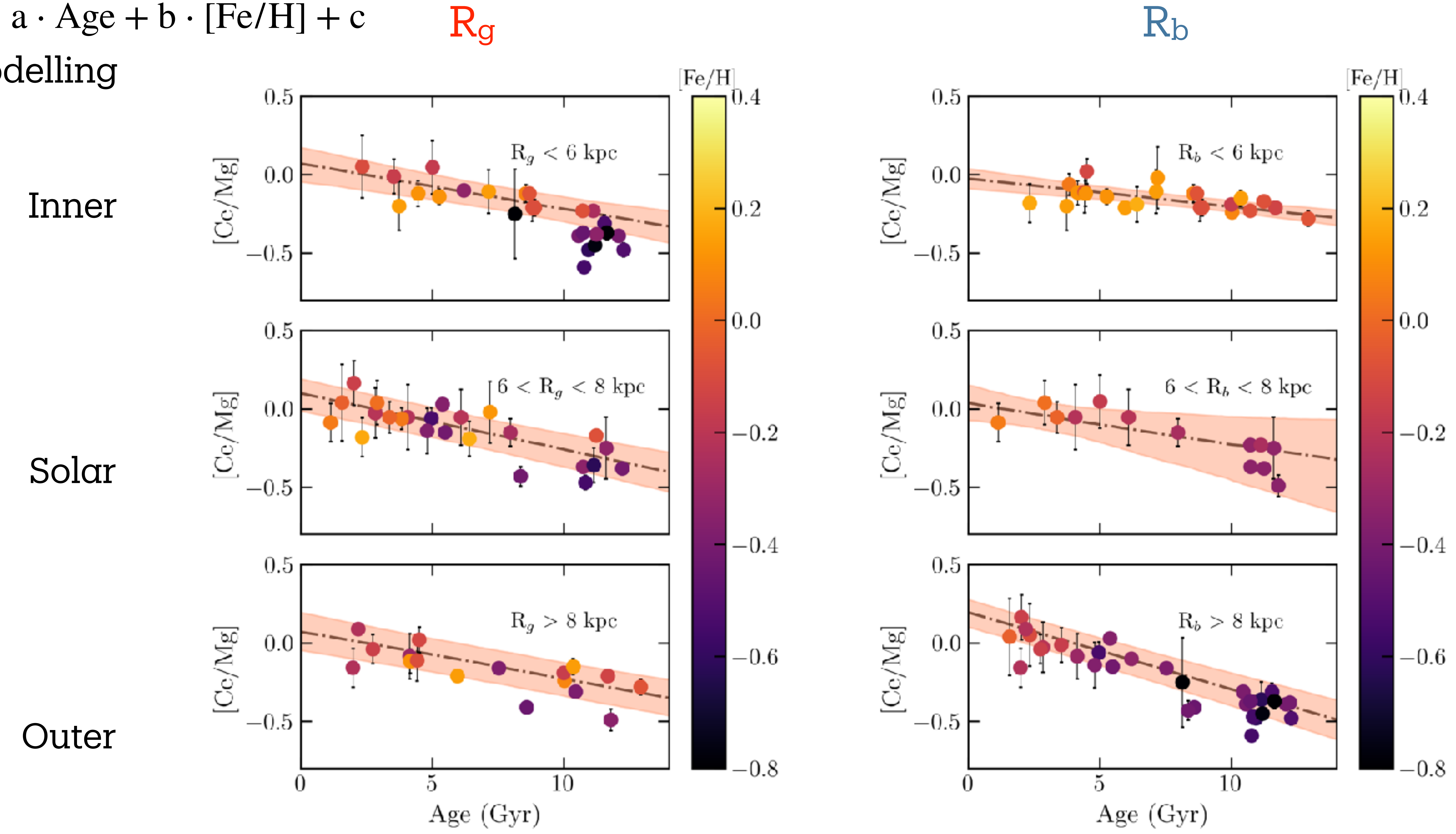
Large intrinsic scatter for Rb

Similar trends

[Ce/Mg] at different R_g & R_b bins

$[Ce/Mg] = a \cdot Age + b \cdot [Fe/H] + c$

MCMC modelling



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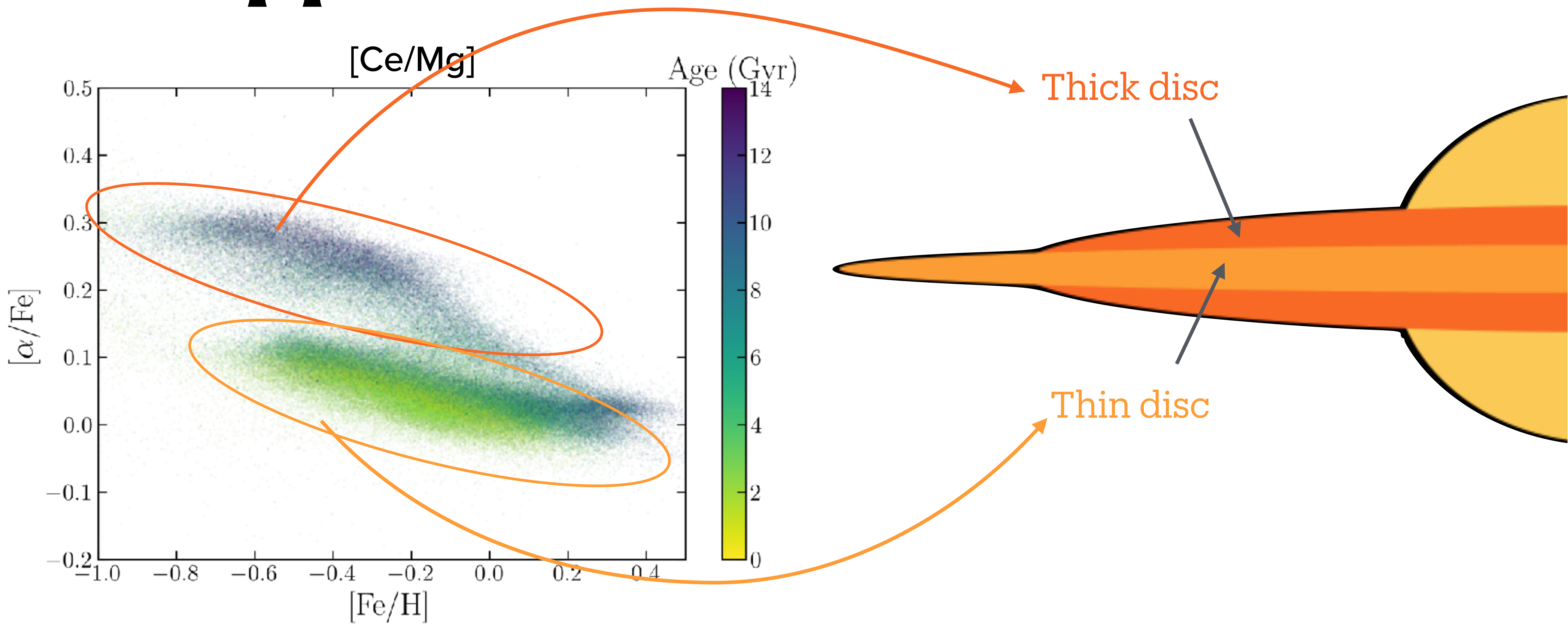
Similar trends

Applications to APOGEE

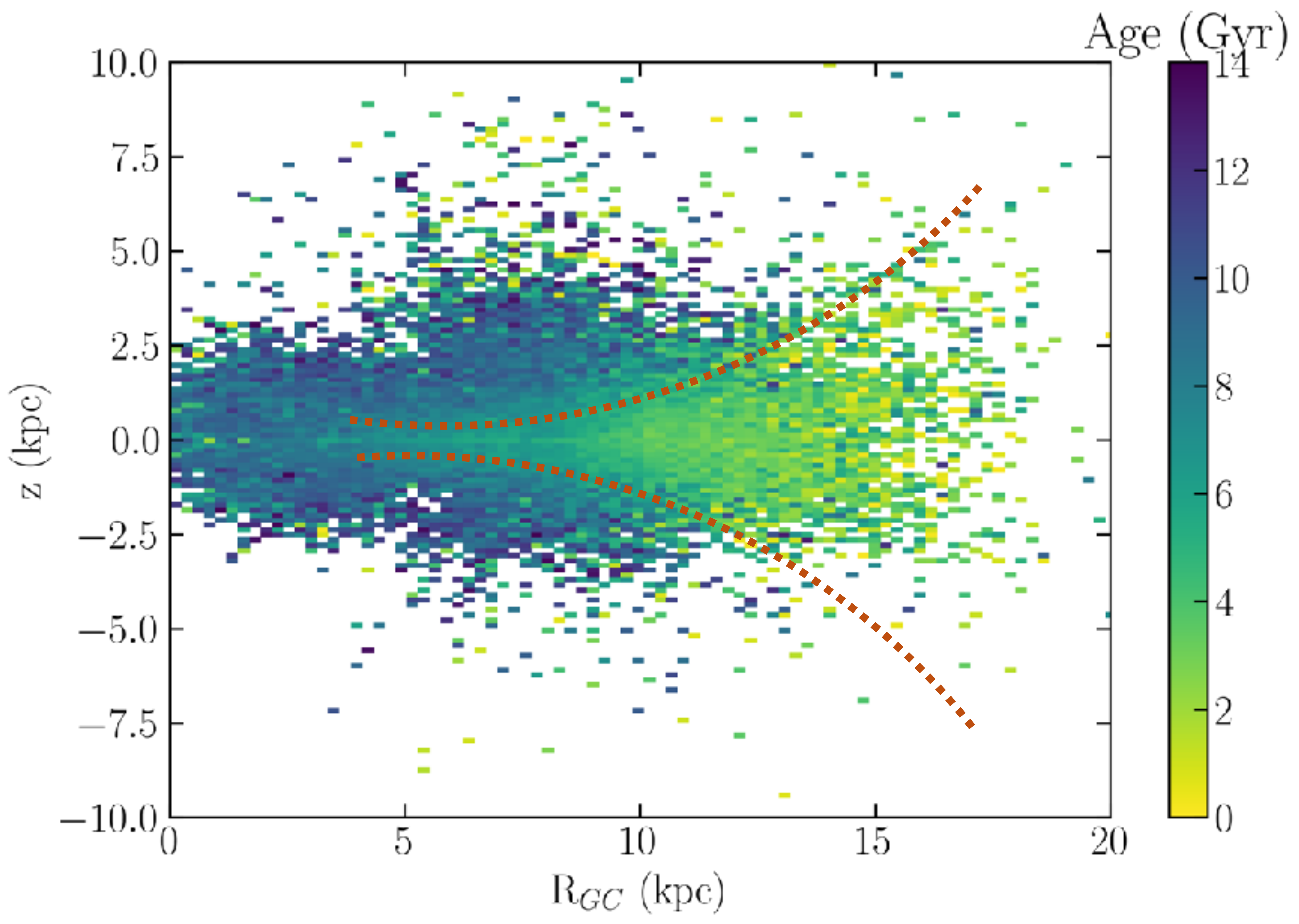


Applications to APOGEE

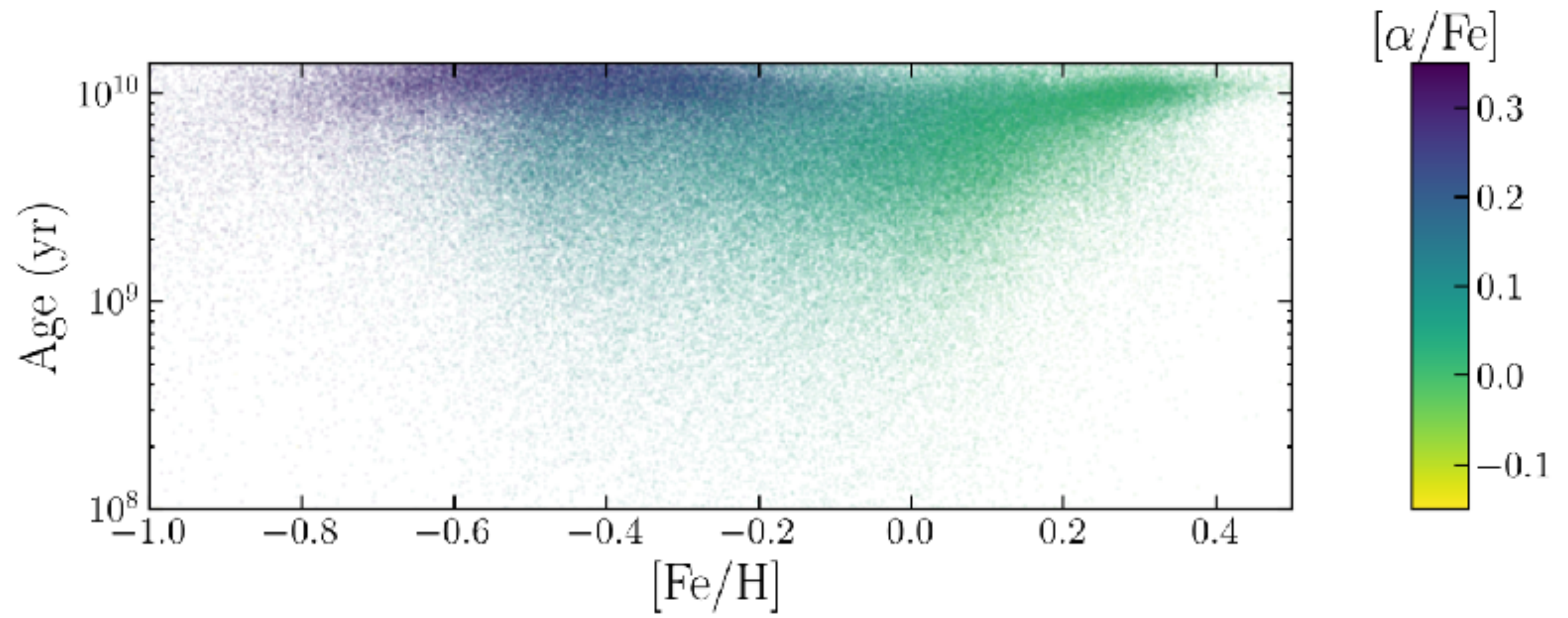
APOGEE stars

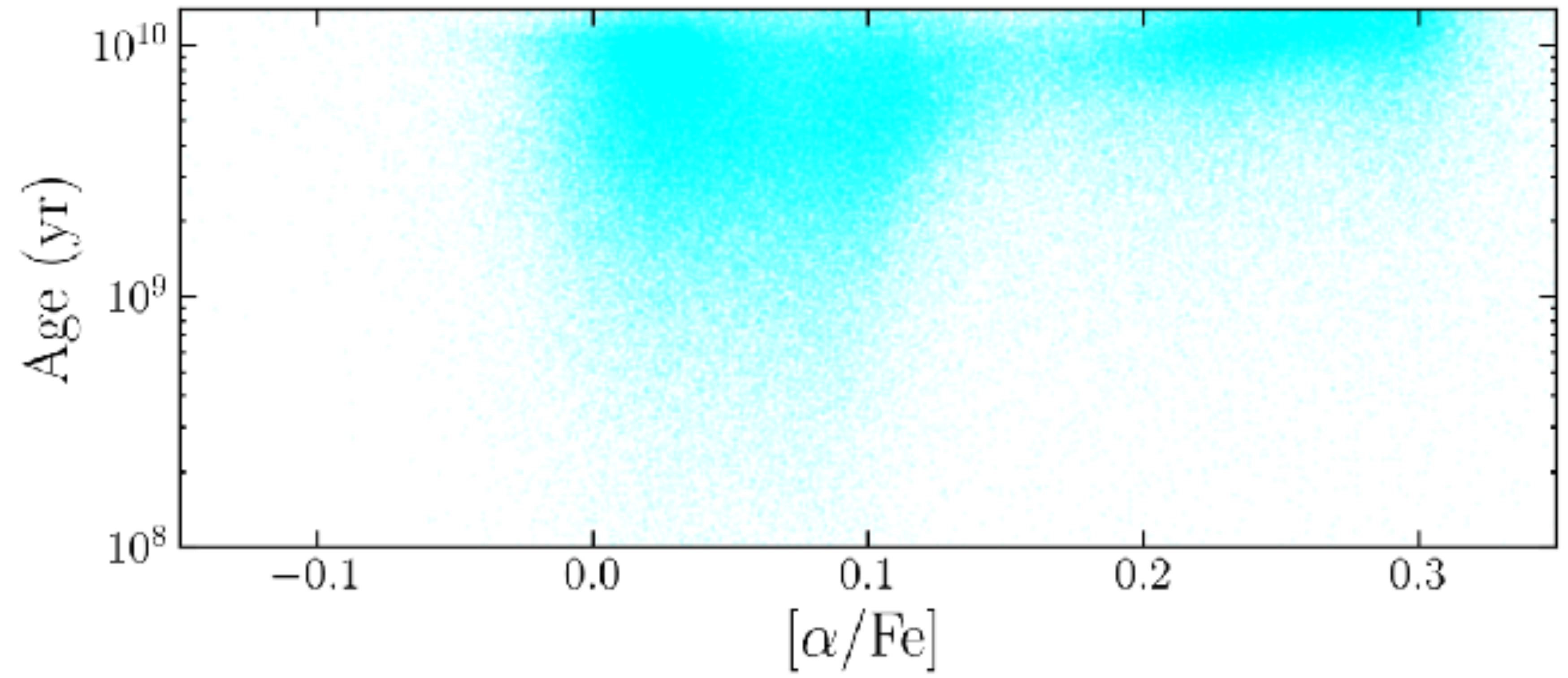
Chemical age from [Ce/Mg]

Disc flaring:



Age-Metallicity relation:



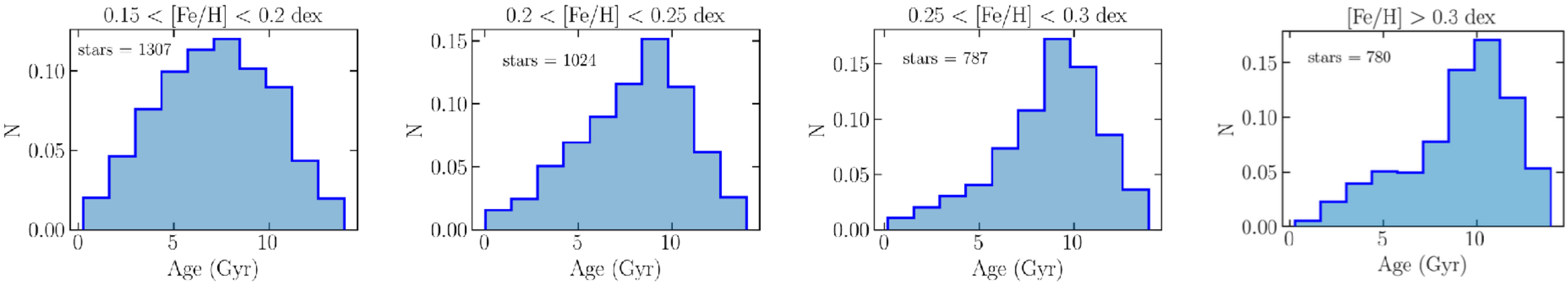


Applications to APOGEE

APOGEE stars

Chemical age from [Ce/Mg]

Old metal-rich stars:



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26th - 27th June

- Ages from Isochrones in the Era of Gaia: Models, Simulations, and Machine Learning
- Ages from Isochrones in the Era of Gaia: Challenges and Insights from Large Surveys
- Ages from Asteroseismology
- Ages from Empirical methods: chemical clocks, gyrochronology, variable stars
- Ages for Cosmology: Cosmochronometry and Stellar Population Studies
- The accretion history of the Milky Way

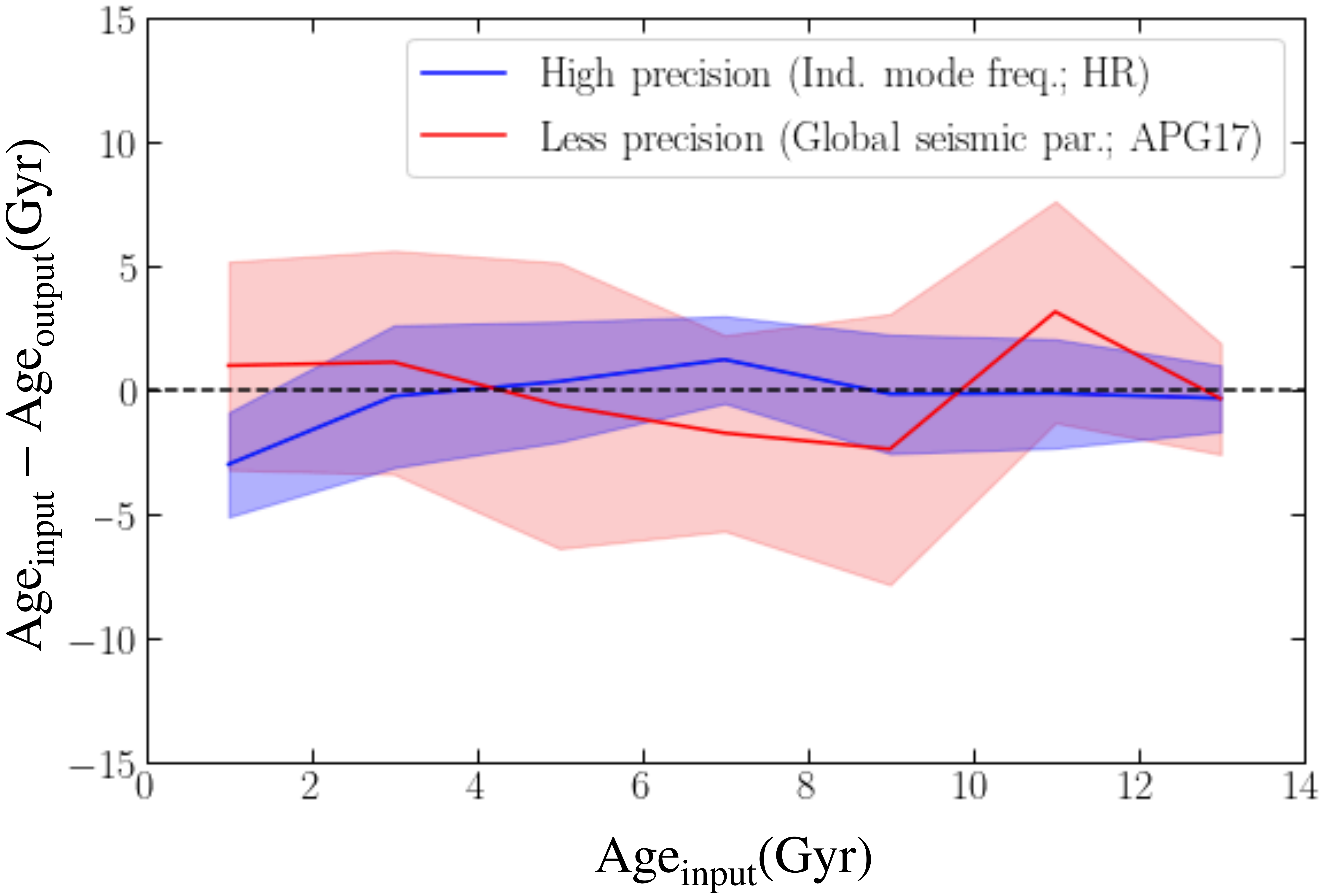
Conclusions

- Chemical clocks: innovative method to date a huge number of stars present in large spectroscopic surveys
- Our sample: Kepler RGB stars with high-precision spectroscopy and high-precision age from asteroseismology
- Relations: the best relations are for [Ce/Mg] and [Zr/Ti]
- Application to field stars: chemical ages for all APOGEE and Gaia-ESO surveys → [a/Fe] vs [Fe/H], disc flaring, age-metallicity relation, old metal rich stars

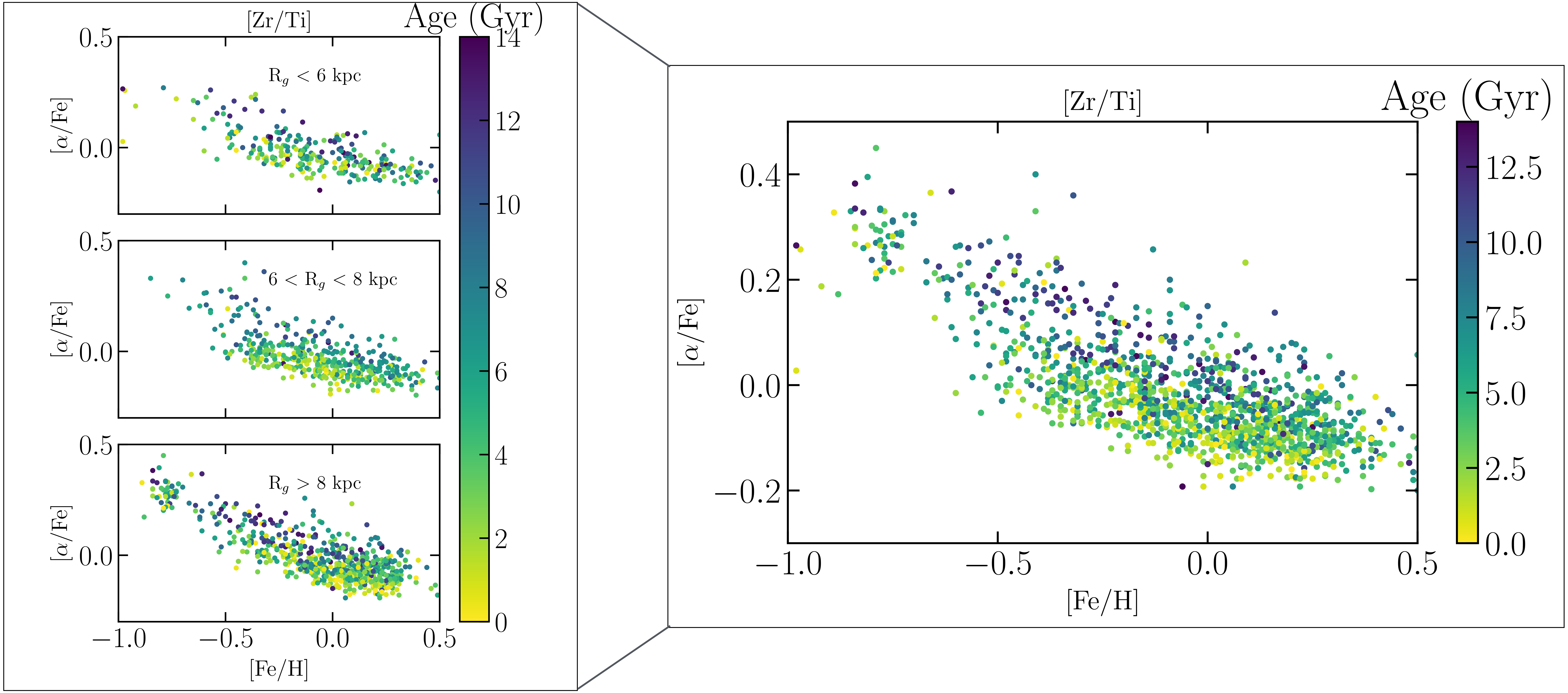
High precision for calibrators

TEST for the 68 Kepler RGB stars:

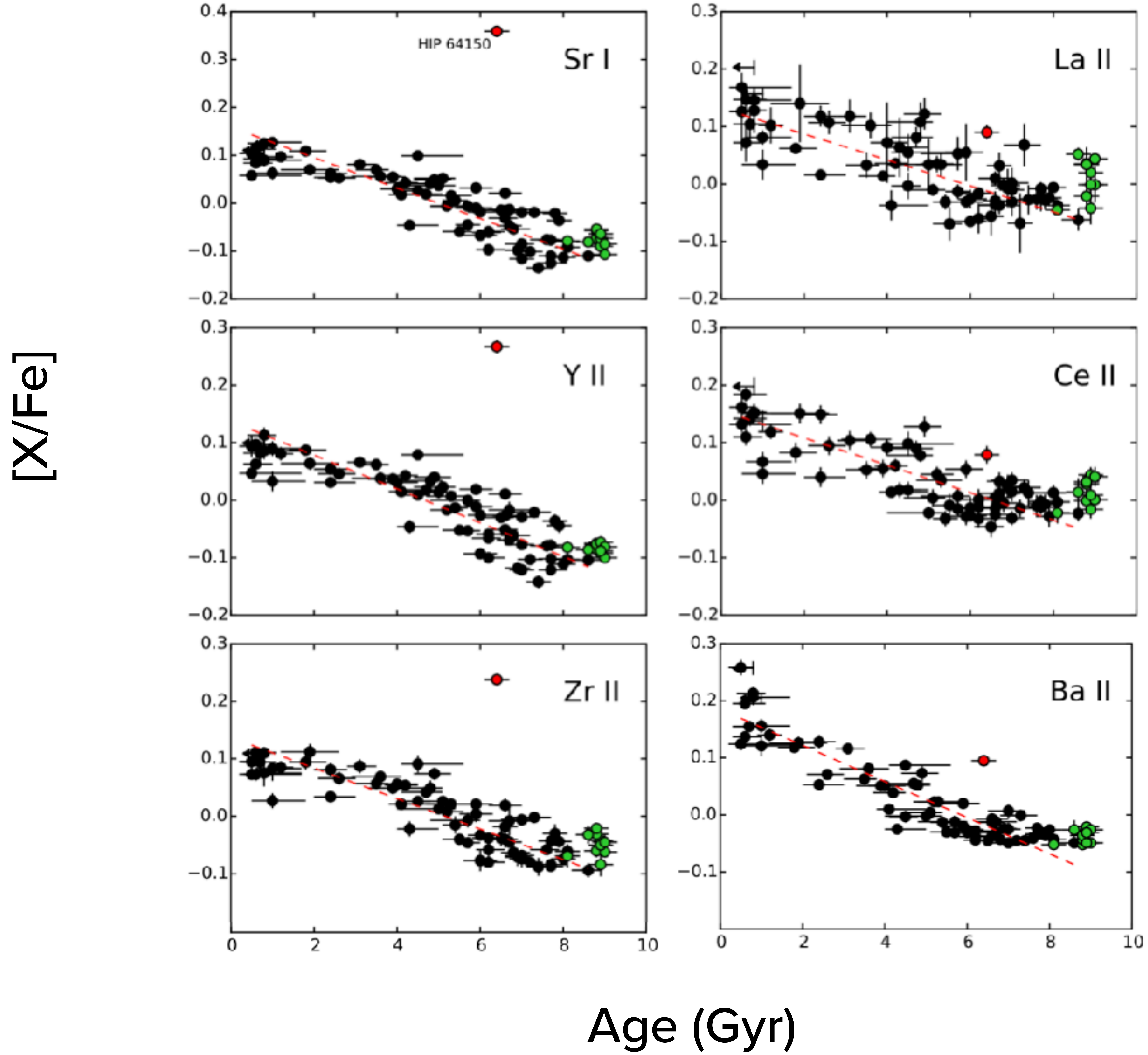
- Age from individual mode frequency (9%) + abundances HR (~0.05)
- Age from global seismic parameters (18%) + abundances APG17 (~0.1)



Applications to Gaia-ESO



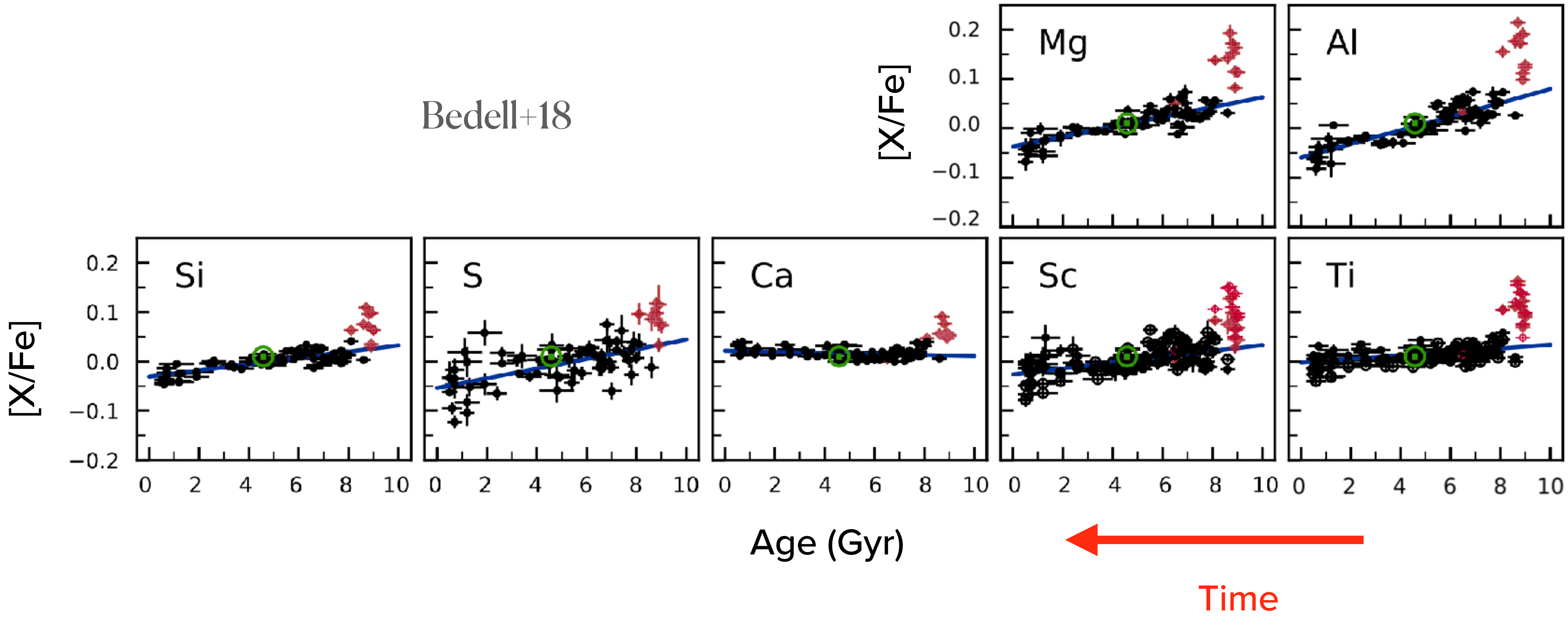
Innovative method: chemical clocks



Spina+18

Innovative method: chemical clocks

Bedell+18



Methods to infer ages

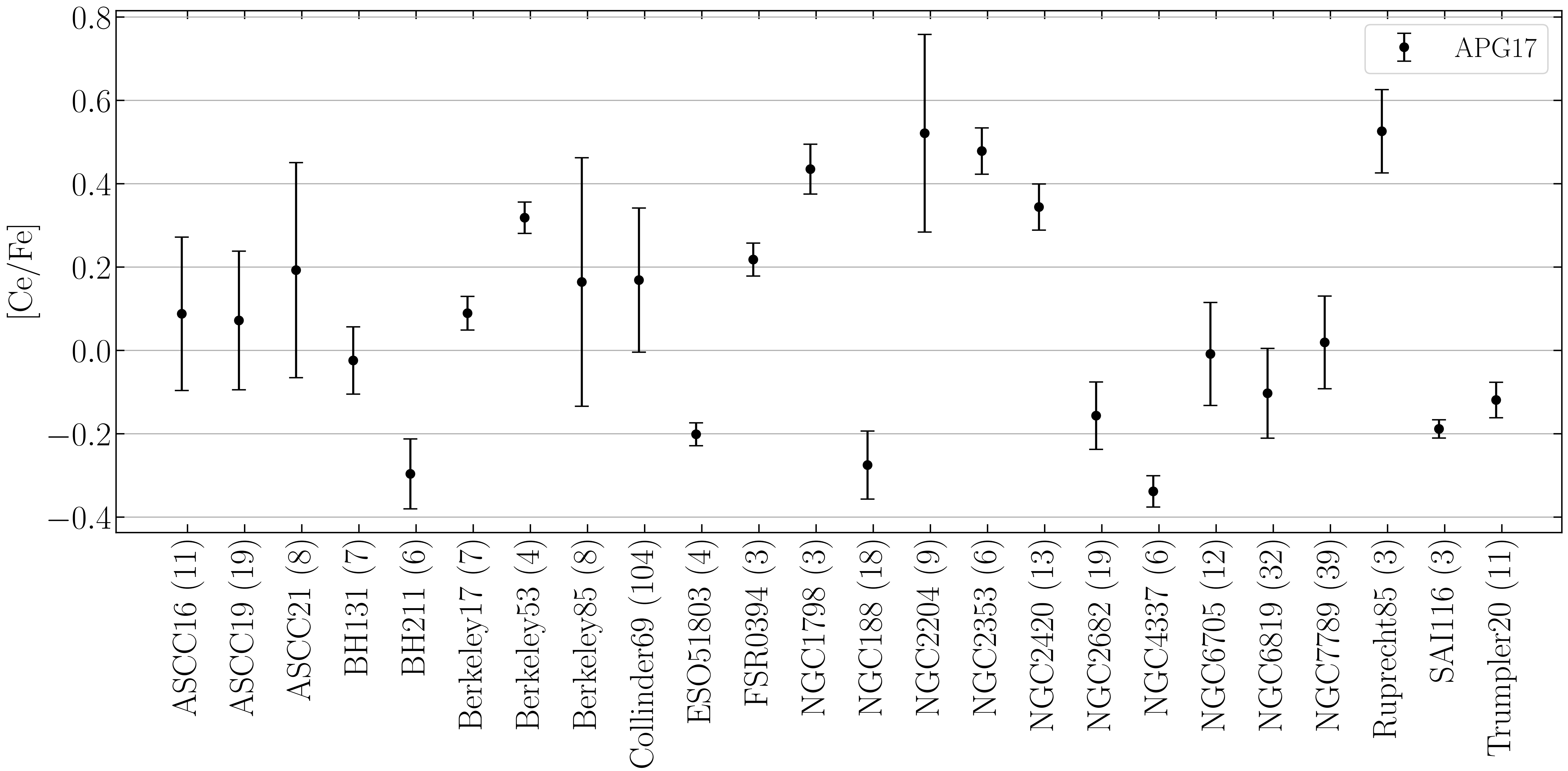
	PMS	ZAMS	MS	Giants
Isochrone fitting	E, i	E	E, i	E
Asteroseismology			i	I
LDB	E	E		
Kinematics	E			
Gyrochronology	E	E	E, I	
Stellar activity	E	E	i	

(No old stars)

Adopted from Soderblom+10

I and i refer to individual stars, E to ensembles. Suitability is indicated in increasing order of usefulness by i, I respectively

Mean [Ce/Fe] in open clusters



- σ is large for almost all clusters, showing a spread in the Ce measurements among the member stars of the same cluster, which is not expected since they should be homogeneous
- Such large σ indicate that the Ce uncertainties are likely underestimated

σ ~ 0.1 dex
Typical Ce uncertainties in APOGEE ~ 0.07 dex