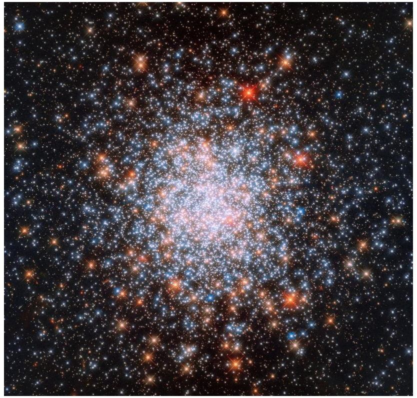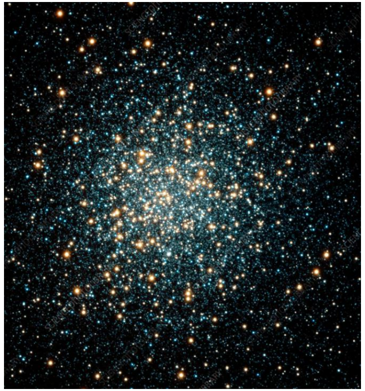

Evidences of transport processes in stellar interiors

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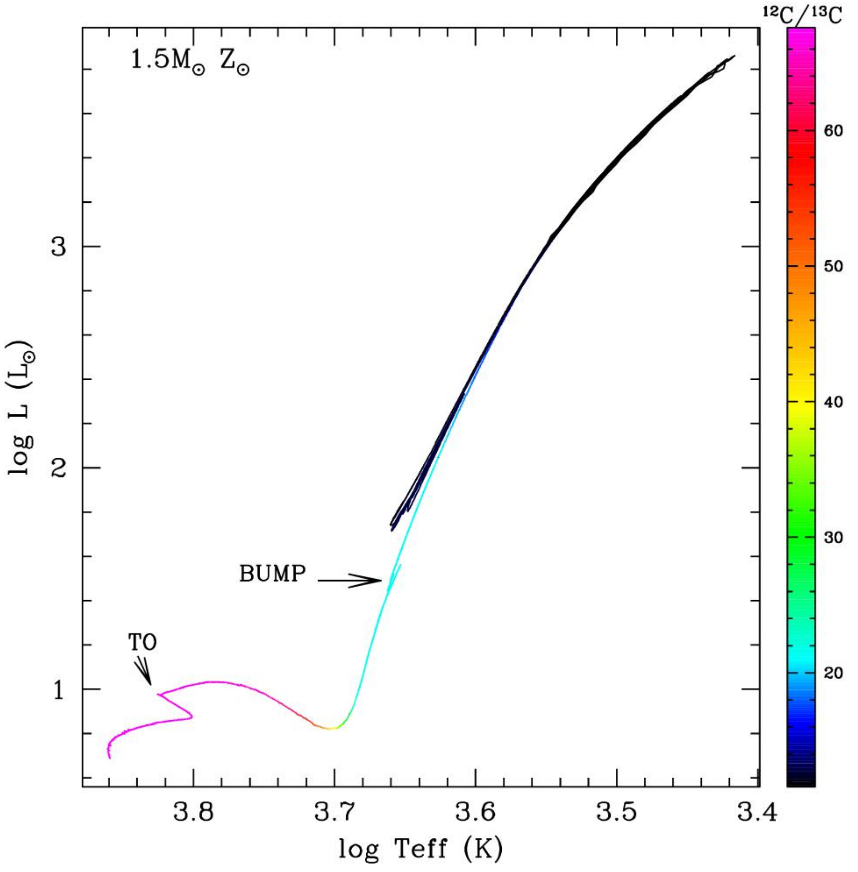
1^{st} dredge-up (Iben 1965)

^{12}C decreases by 30 %
^{14}N increases by 80 %
^{16}O unaltered

$^{12}C/^{14}N = 3.98 \rightarrow 2.0$
$^{12}C/^{13}C = 90 \rightarrow 20 – 30$

Extra mixing

Deep mixing is a non convective circulation process that begins at the RGB luminosity bump when the RGB star's hydrogen-burning shell crosses the deepest point reached by the first dredge-up, and continues for the entire RGB lifetime of the star.



The change in the $^{12}C/^{13}C$ ratio during the evolution of a star. Figure taken from Lagarde et al. (2015)

Carbon, nitrogen, and oxygen (CNO):

- Comprise in stars most of the mass of elements heavier than helium.
- Are among the first elements to form in the nucleosynthesis chain.
- Play important roles in stellar interiors as sources of opacity and energy production through the CNO cycle, and thus affect the star’s lifetime, its position in the Hertzsprung-Russell diagram, and its heavy-element yields.

The exact mechanism for deep mixing is not known, and theoretical arguments have been made for:

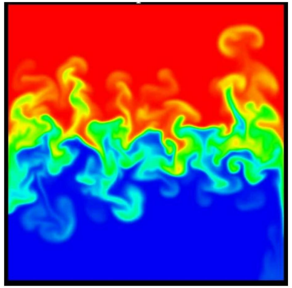
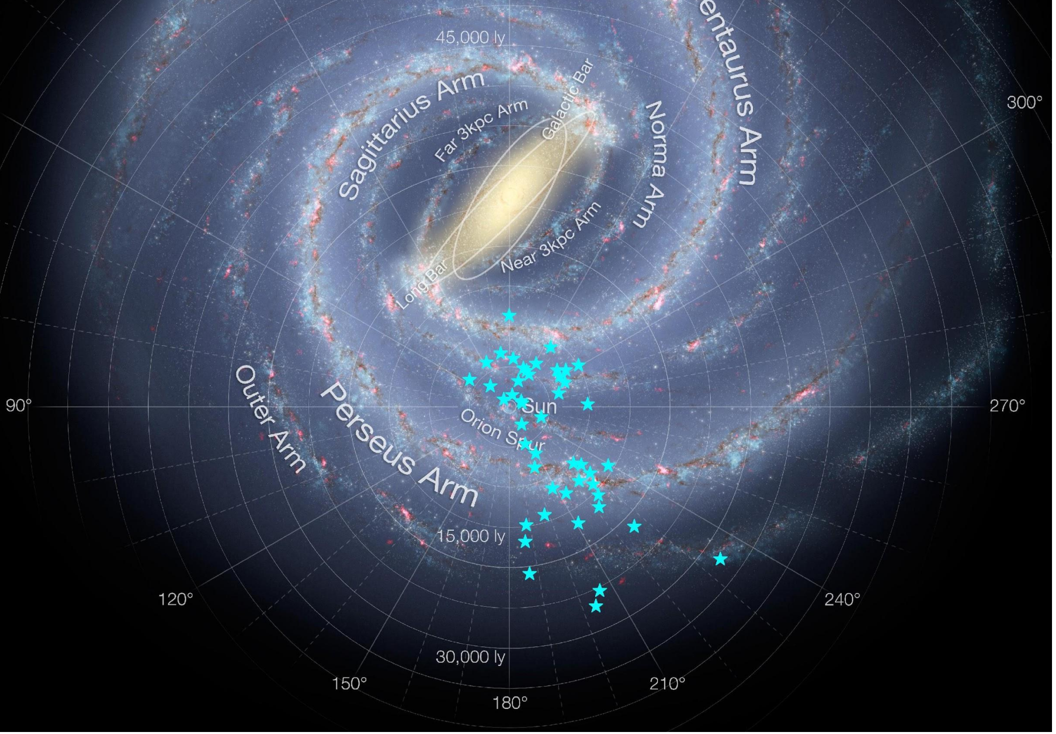


Image credit: Mohamad M. Nasr-Azadani

- **rotational mixing** (Sweigart & Mengel 1979; Palacios et al. 2003; Chanamé et al. 2005; Denissenkov et al. 2006)
- **magnetic fields** (Hubbard & Dearborn 1980; Busso et al. 2007; Nordhaus et al. 2008; Palmerini et al. 2009)
- **rotation and magnetic fields** (Eggenberger et al. 2005)
- **internal gravity waves** (Zahn et al. 1997; Denissenkov & Tout 2000)
- **thermohaline mixing** (Ulrich 1972; Eggleton et al. 2006, 2008; Charbonnel & Zahn 2007; Cantiello & Langer 2010; Charbonnel & Lagarde 2010; Lagarde et al. 2017, 2019)
- **combination of thermohaline mixing and magnetic fields** (Busso et al. 2007; Denissenkov et al. 2009)
- **combination of thermohaline mixing and rotation** (Charbonnel & Lagarde 2010; Lagarde et al. 2012; Charbonnel et al. 2017)

Open and globular star clusters

- Are important in giving us the opportunity to investigate stellar evolution
- Have a number of stars of essentially the same age, distance, and origin, as cluster stars are most likely formed in the same proto-cloud of gas and dust
- Chemical compositions of cluster members initially were identical

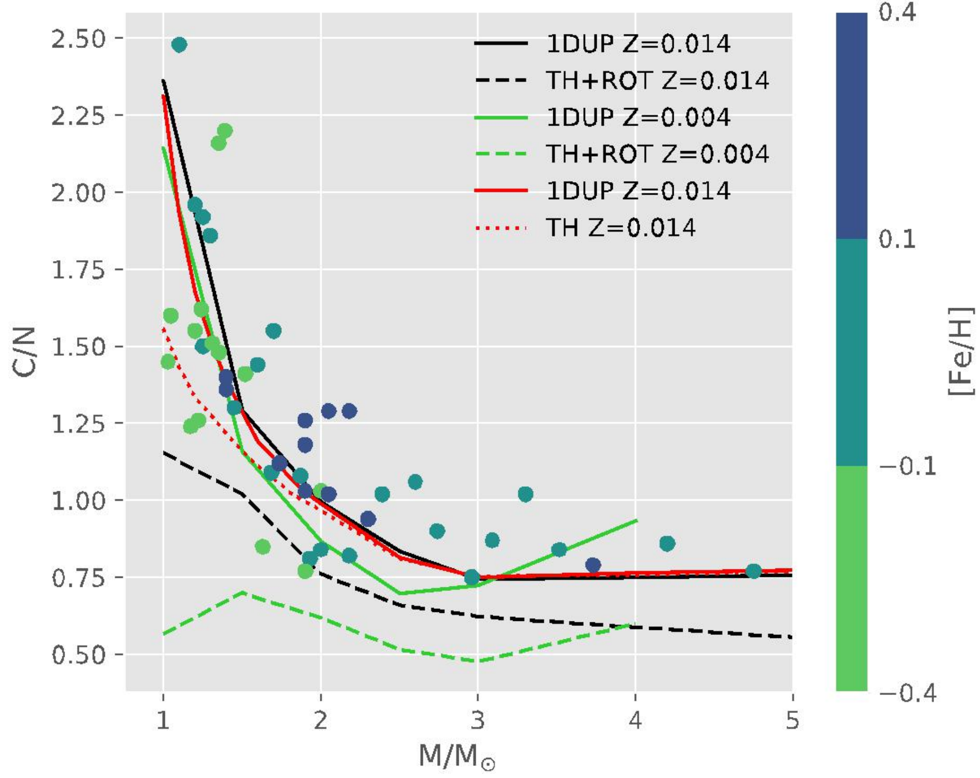


CNO investigations in the Gaia-ESO Spectroscopic Survey

- iDR6
- ~90 open and globular clusters

Tautvaišienė et al. 2015, A&A, 573, 35
Magrini et al. 2018, A&A, 618, 102
Lagarde et al. 2019, A&A, 621, 24
Casali et al. 2019, A&A, 629, 62

GES iDR4 45 open clusters

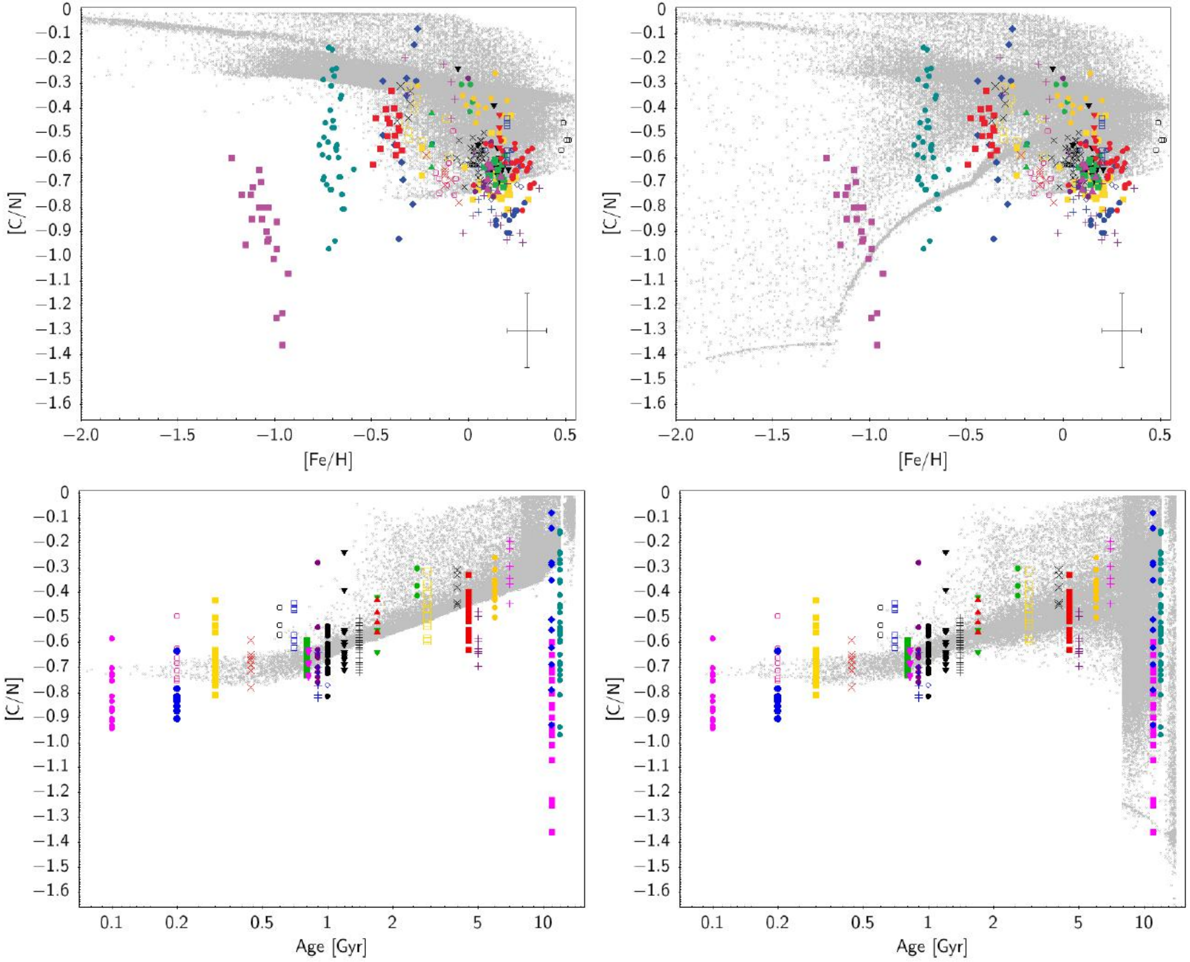


Gaia-ESO Survey

Red curves – the first dredge-up and thermohaline mixing models by Lagarde et al. (2017).
Black and green curves – models in which thermohaline- and rotation-induced mixing act together.

A role of rotation-induced mixing is seemingly overestimated.

(iD6 in preparation)



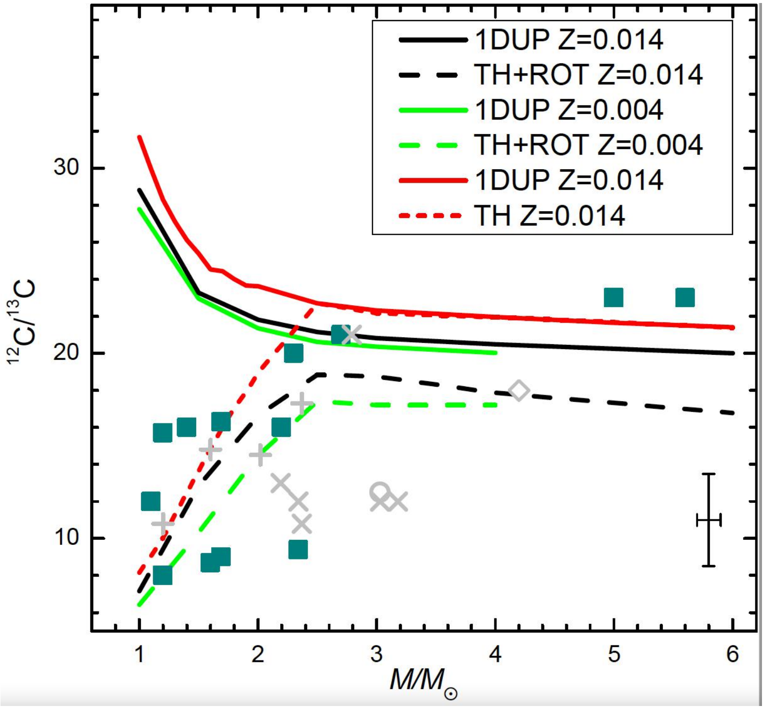
Gaia-ESO Survey

[C/N] as a function of [Fe/H] and age for synthetic populations computed **with thermohaline induced mixing** (right panel) and without (left panel).

[C/N] for our sample of UVES giant stars members of open and globular clusters are also shown (each symbol represents a cluster.

Taken from Lagarde et al. (2019) (iDR2, iDR4, iDR5)

Average $^{12}C/^{13}C$ in clump stars of open clusters



- $^{12}C/^{13}C$ ratios in stars with turn-off masses <2 $M_{\odot}$ agree well with the theoretical models which take into account thermohaline-induced mixing (Lagarde et al. 2017, red lines) or with the model where both the thermohaline-and-rotation-induced mixing act together (Charbonnel et al. 2017, black and green lines).
- For turn-off masses ≥ 2.0 $M_{\odot}$ the mean $^{12}C/^{13}C$ values agree with the first dredge up models. They are not lowered as much as predicted by the model where thermohaline- and rotation-induced mixing act together.
- Investigations should be continued.

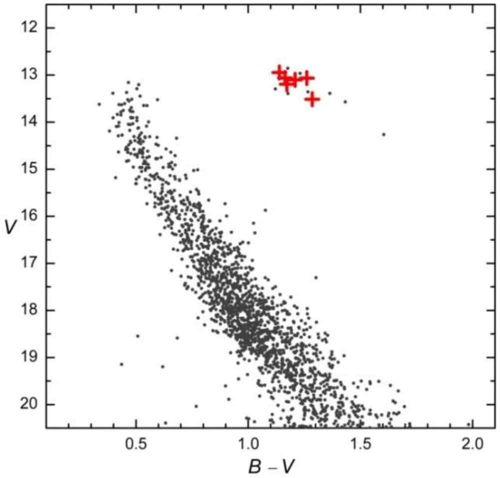
Squares indicate results by Tautvaisiene et al. (2000, 2005, 2016); Mikolaitis et al. (2010, 2011a,b, 2012); Drazdauskas et al. (2016a,b). Other symbols include results from Gilroy (1989) – pluses, Luck (1994) – open circles, Smiljanic et al. (2009) – crosses, Santrich et al. (2013) – open diamond.

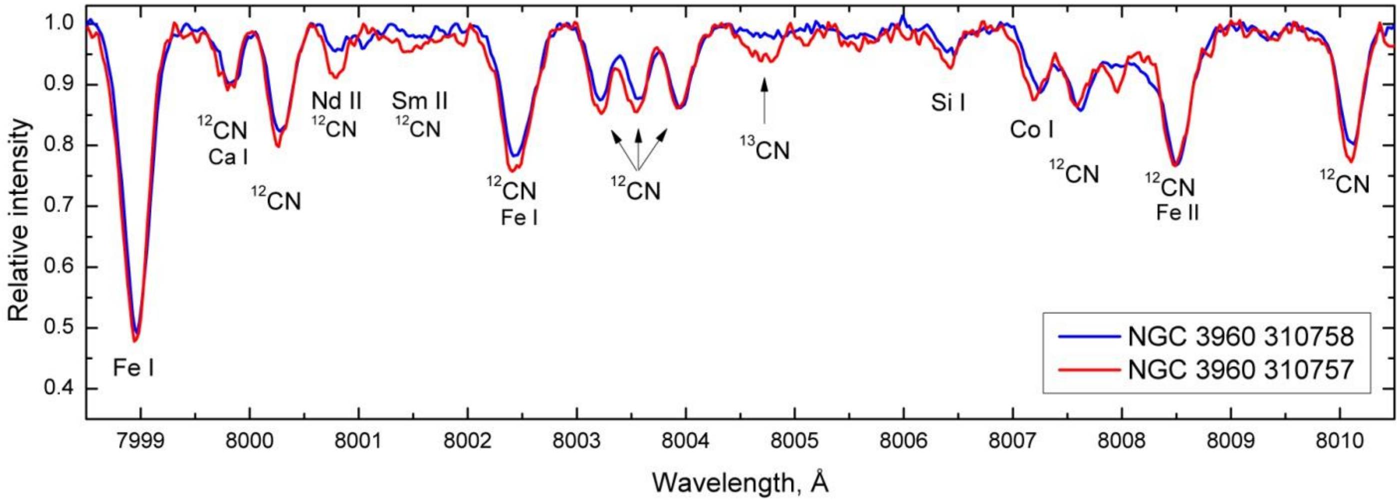
Inhomogeneities

The $^{12}C/^{13}C$ ratios in the investigated clump stars of NGC 3960 (turn-off mass is about 2 $M_{\odot}$) are not homogeneous.

Other extra-mixing mechanisms may act.

Tautvaišienė et al. 2016, A&A, 595, 16





NGC 1851 has two subgiant branches

Two generations of stars, the first being primordial, while the second one being born from the ejecta of a fraction of the stars of the first population (e.g., Pancino et al. 2010)

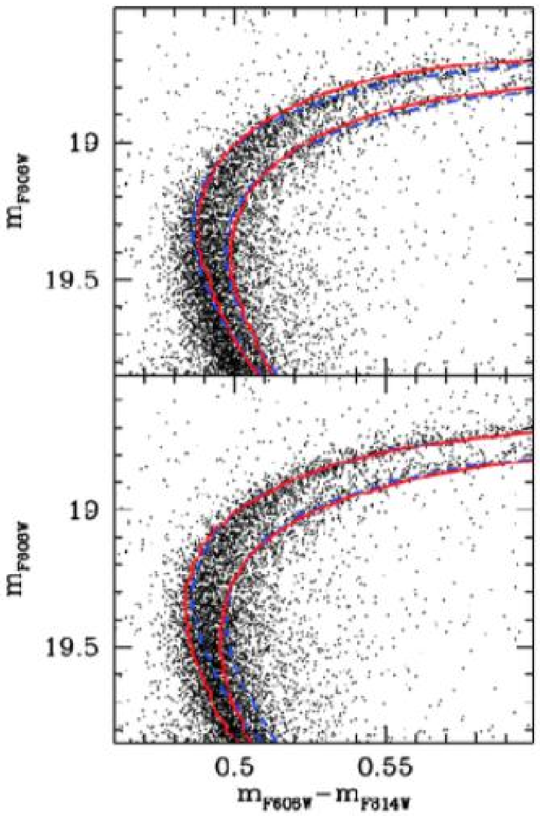
The two branches have slightly different metallicity (Carretta et al. 2010, 2011; Gratton et al. 2012)

NGC 1851 originated by merging of two globular clusters (e.g. Campbell et al. 2012)

NGC 1851 is a naked nucleus of a captured and disrupted dwarf galaxy (e.g. Bekki & Yong 2012; Marino et al. 2014)

NGC 1851 may have been formed by the merger between parental globulars that were once located within a dwarf spheroidal galaxy (van den Bergh 1996; Carretta et al. 2010)

Those questions can be answered by the robust investigation of C, N, O, and other element abundances.



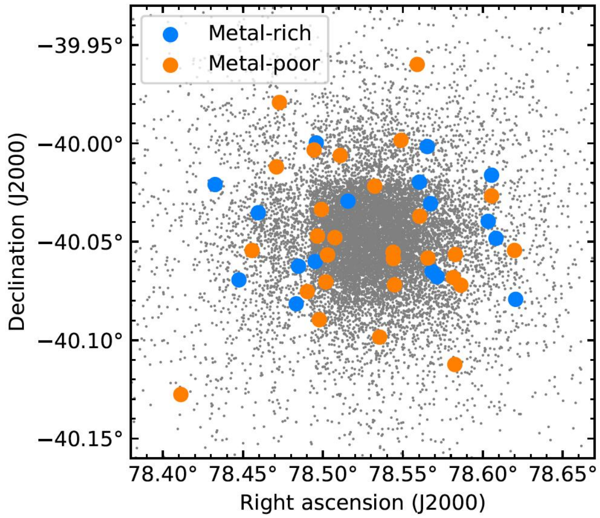
Gaia-ESO Spectroscopic Survey

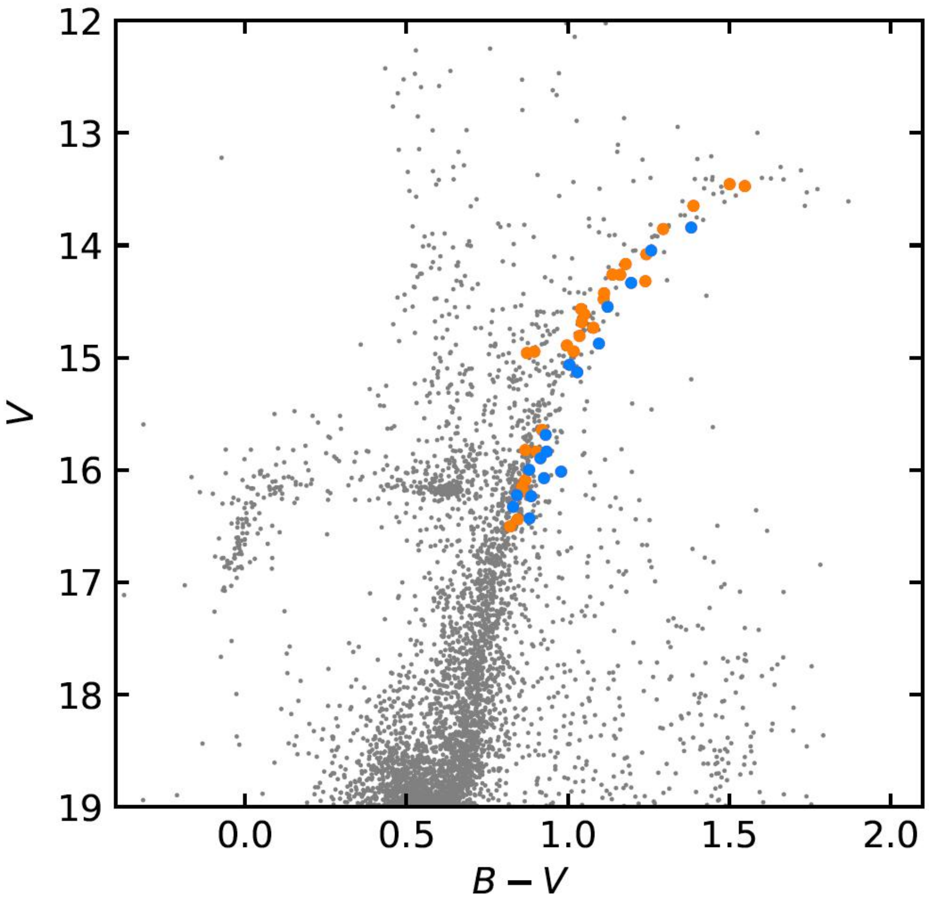
8.2 m VLT telescope

UVES, Resolution 47 000

4700–6840 Å, S/N ≈ 40 – 180

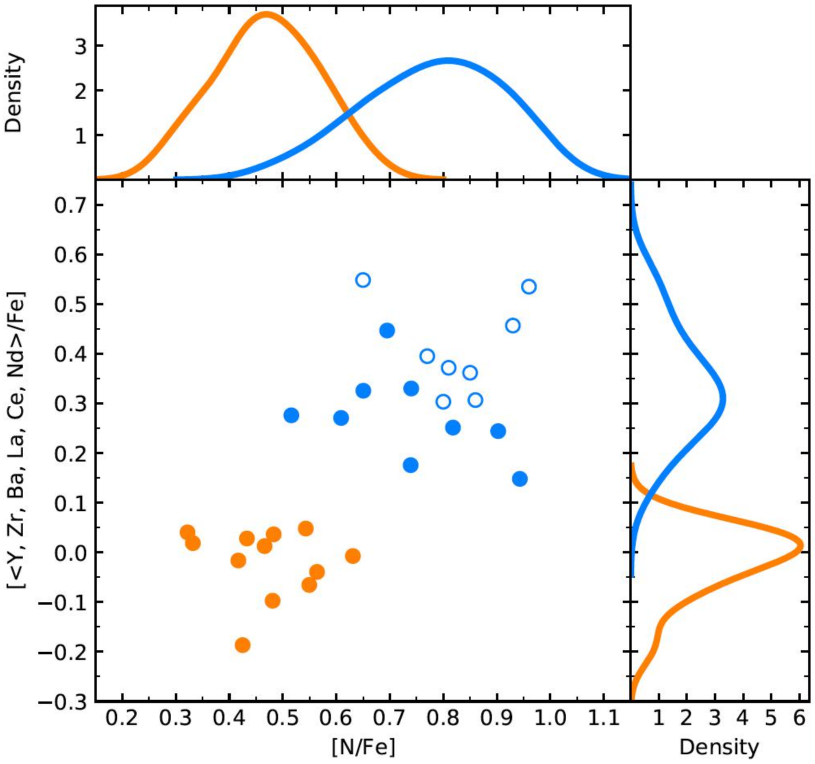
45 giants: metal-rich metal-poor

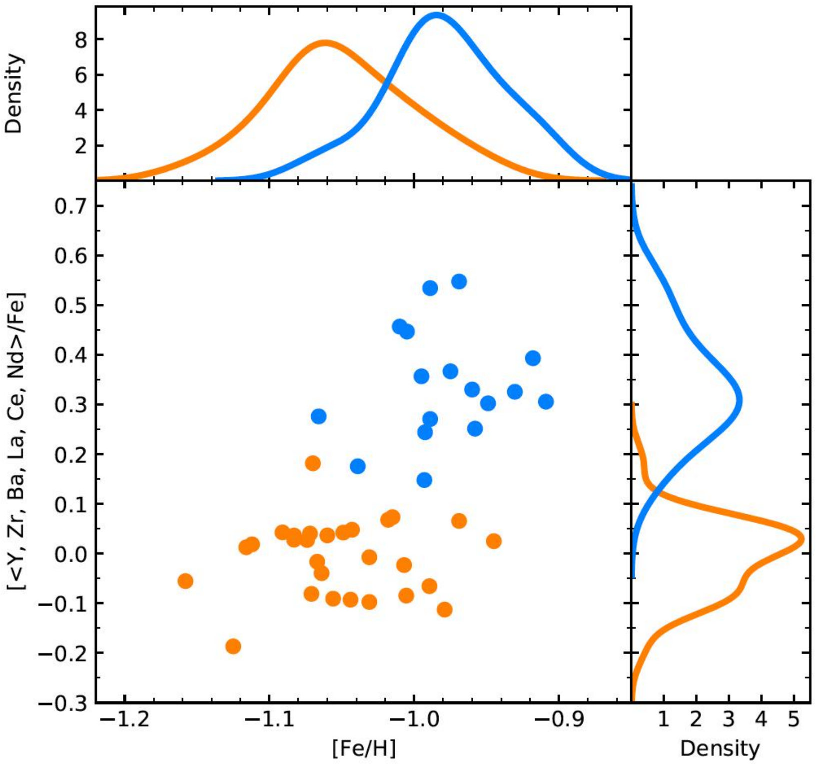




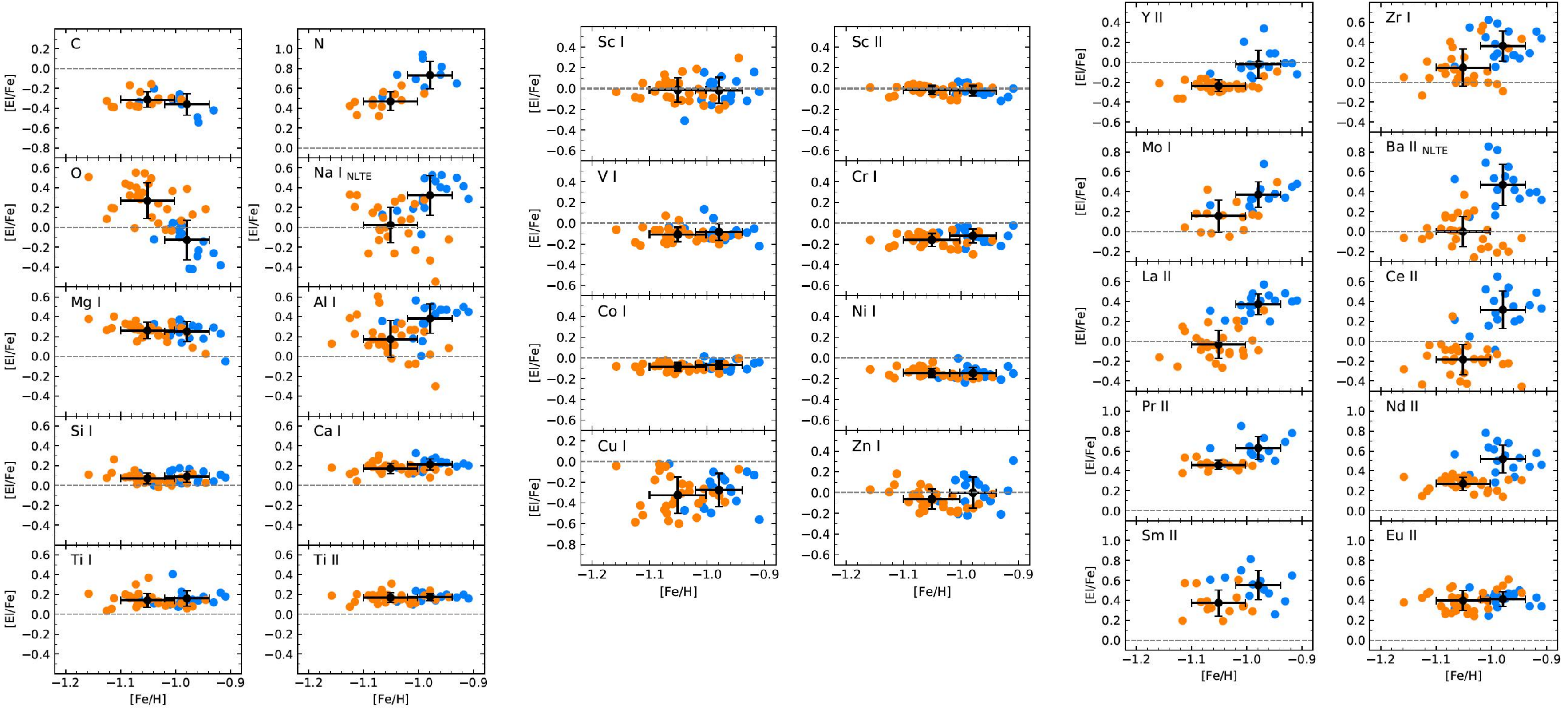
Tautvaišienė et al. (submitted)

The investigated stars were divided into subsamples of 17 metal-rich and 28 metal-poor stars with averaged metallicities of -0.98 ± 0.04 dex and -1.05 ± 0.05 dex, respectively.



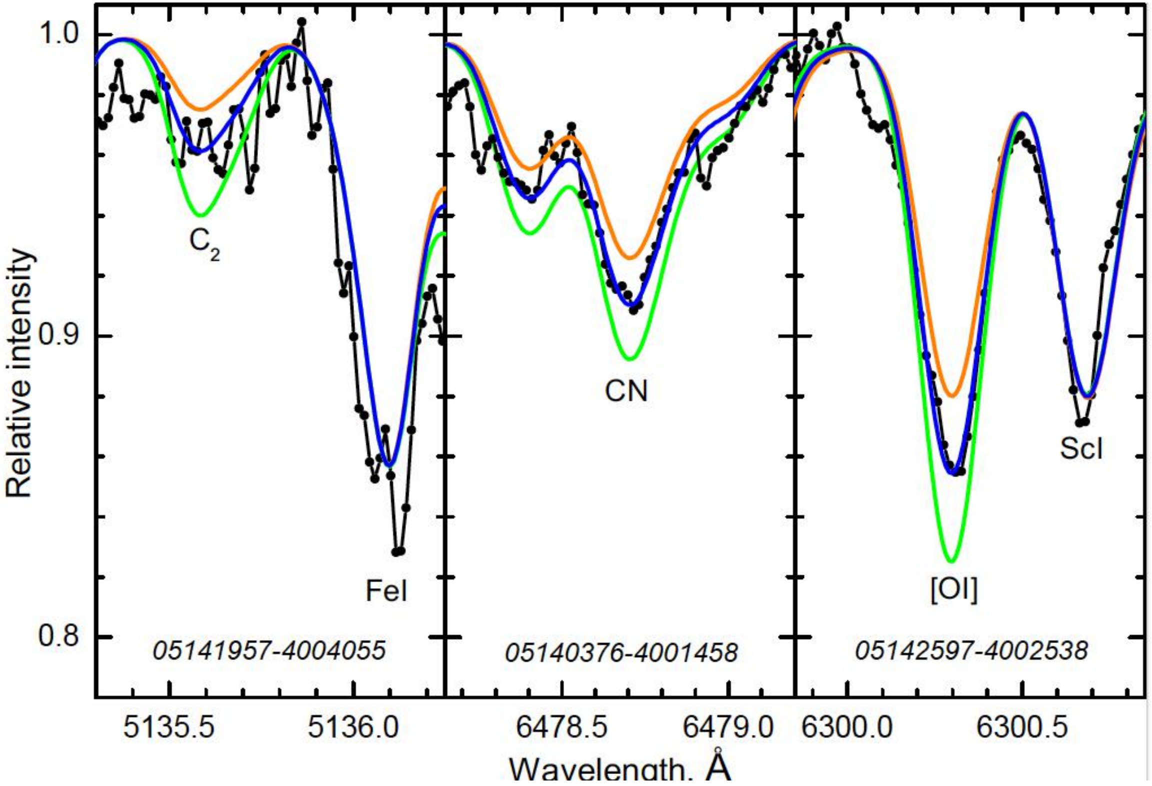


Abundances of 29 chemical elements in 45 giants of the globular cluster NGC1851

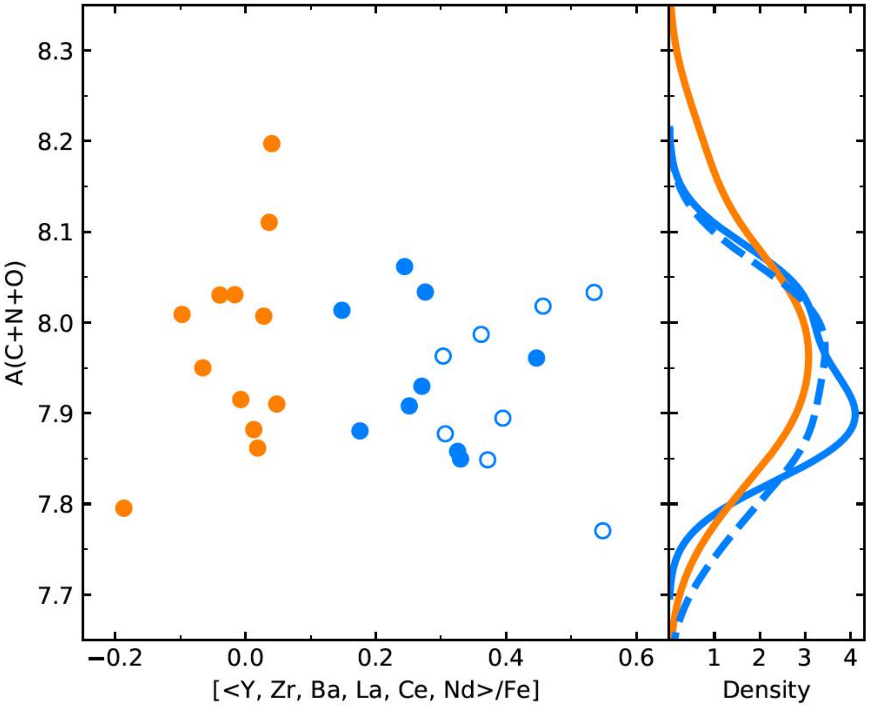


Knowing the *A*(C+N+O) abundance it is possible to answer the question whether a spread in the subgiant branch is caused by the difference in *A*(C+N+O) or in age.

The observed spectra are shown as black lines with dots. The best-fit synthetic spectra are the blue lines with 0.1 dex changes in corresponding abundances shown as orange and green lines.



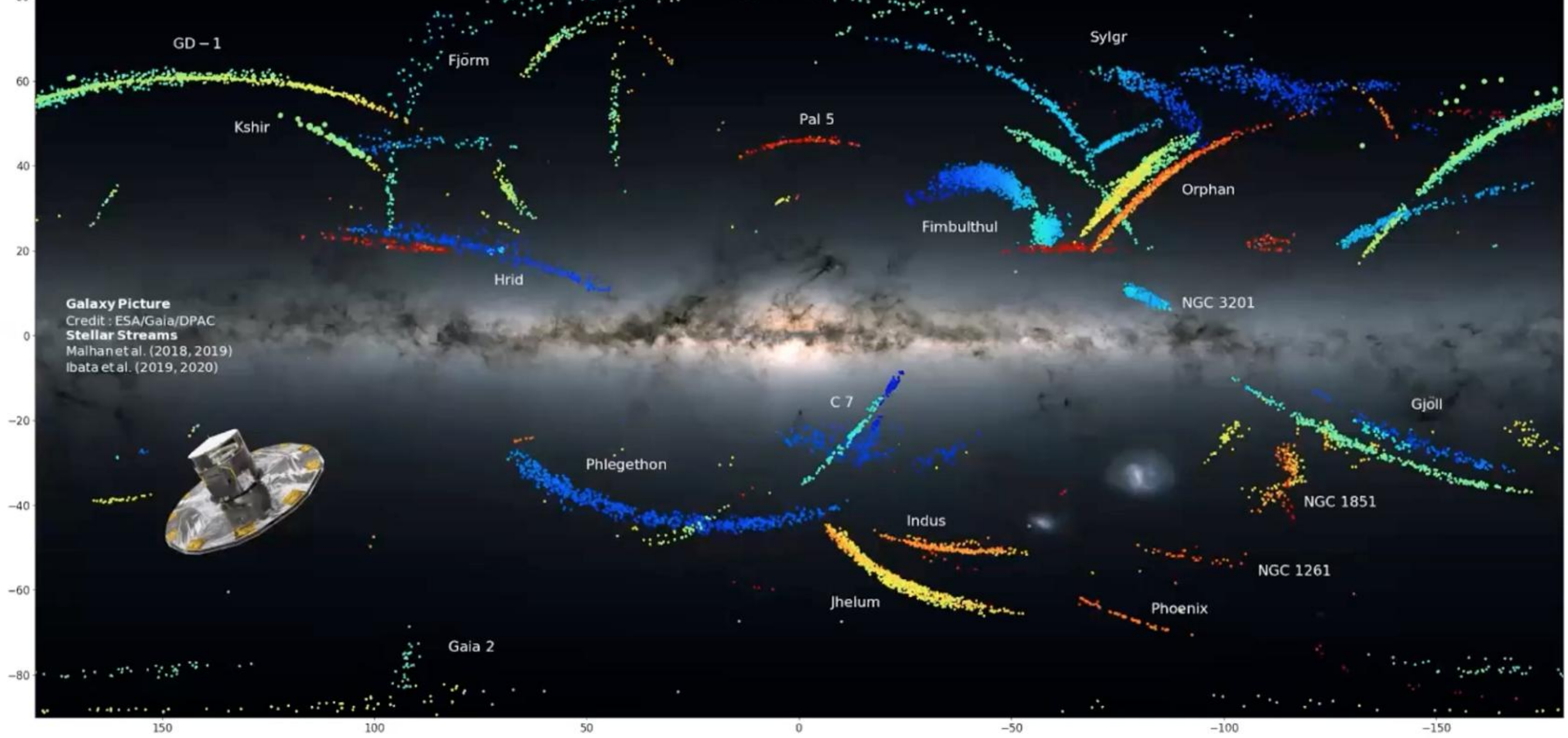
Formation scenario for NGC1851



Our study shows that there is a spread of about 0.1 dex in A(C+N+O) in both populations, however the averaged values between the populations do not differ.

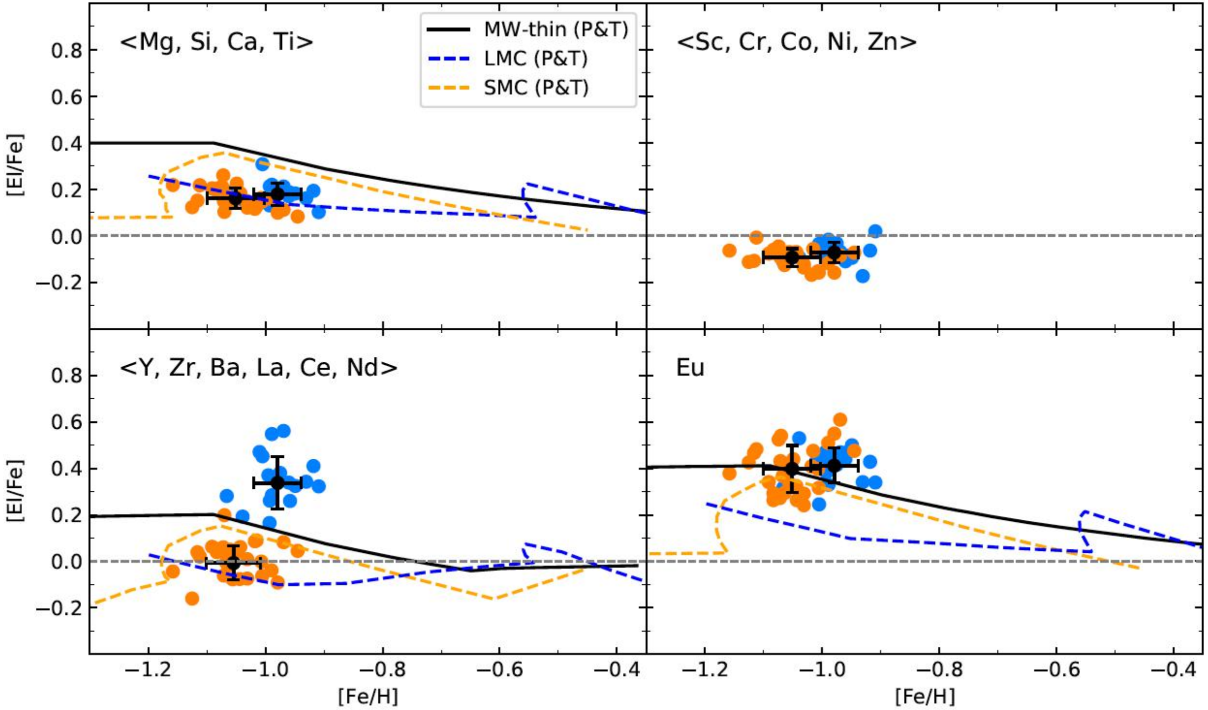
Gratton et al. (2012c) evaluated that the metal-rich subsample would be older by 0.6 Gyr than the metal-poor if the total A(C+N+O) abundance is the same in both subsamples.

NGC1851 is composed of two clusters, the metal-rich cluster being by about 0.6 Gyr older than the metal-poor one.



Based on the Gaia space mission kinematics, Massari et al. (2019) attributed NGC1851 to the Gaia-Enceladus which merged to the Milky Way.
According to Helmi et al. (2018), the Gaia-Enceladus was slightly more massive than the Small Magellanic Cloud.

Chemical composition supports the extragalactic origin



Comparison of mean abundances of chemical elements dominated by different nucleosynthesis processes with the corresponding models of the Milky Way, Large and Small Magellanic Clouds evolution by Pagel & Tautvaisiene (1995, 1997, 1998).

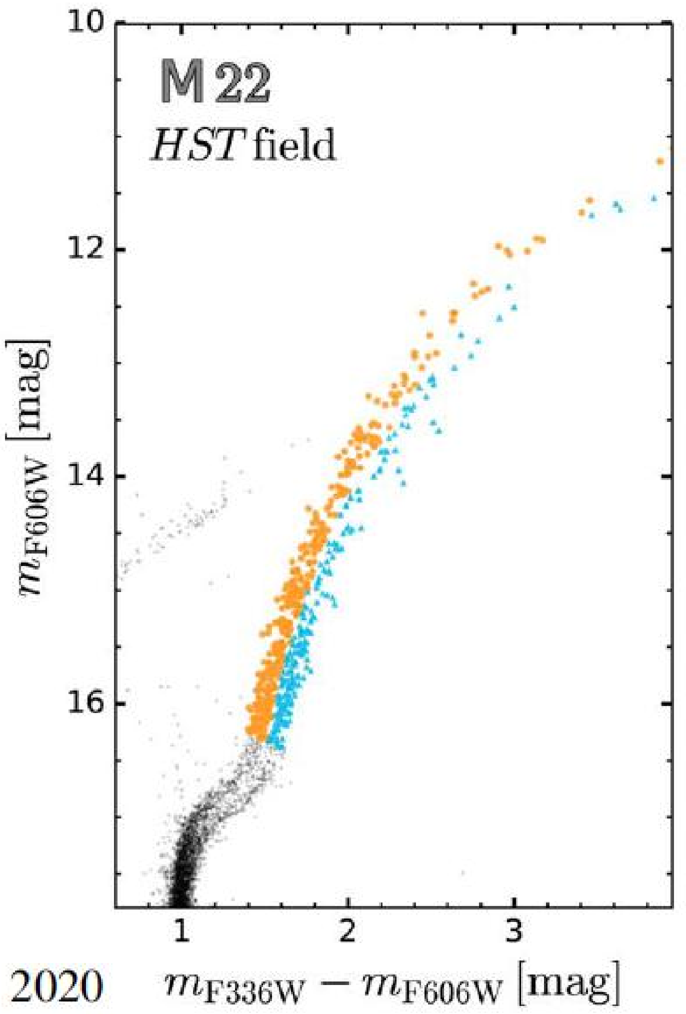
According to its chemistry, NGC1851 fits to the Gaia-Enceladus parent galaxy and even may be its nucleus as suggested by Bekki & Yong (2012) and Forbes (2020).

M 22

Lee et al. (2020) have found five populations in M22 from Ca-CN-CH photometry.

The metal-poor stars were divided into **two subpopulations and the metal-rich stars into three subpopulations.**

They support the idea that M22 was formed via a merger of two globular clusters.



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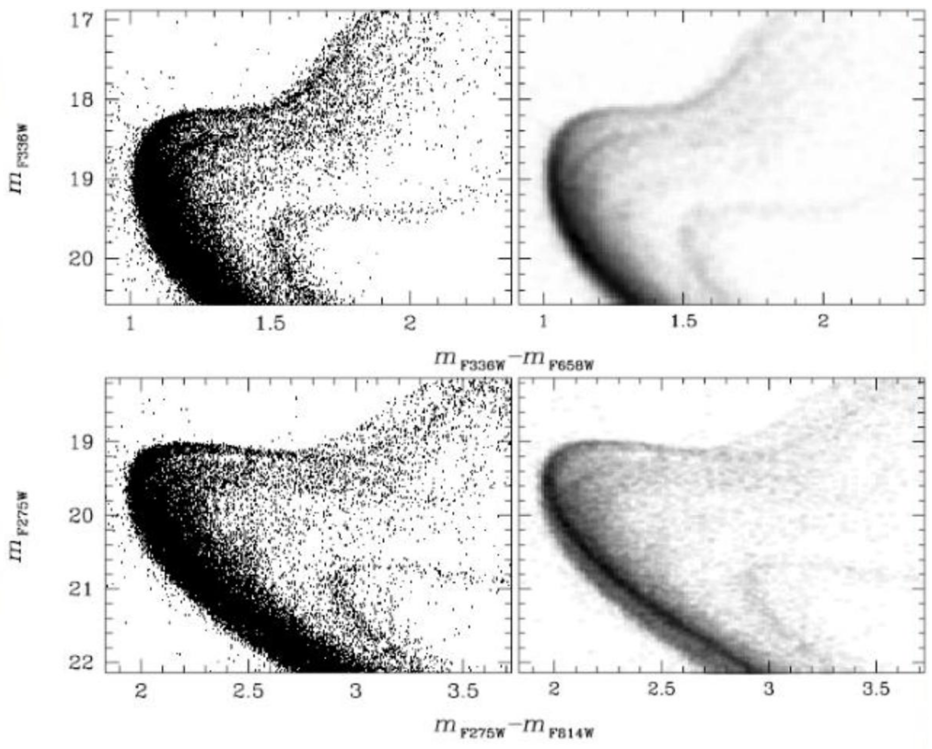
ω Centauri

Mészáros et al. (2021) investigated multiple populations of ω Centauri by analysing APOGEE spectra and found **seven populations** based on stellar [Fe/H], [Al/Fe], and [Mg/Fe] abundances as well as increased *A*(C+N+O) with increased metallicity.

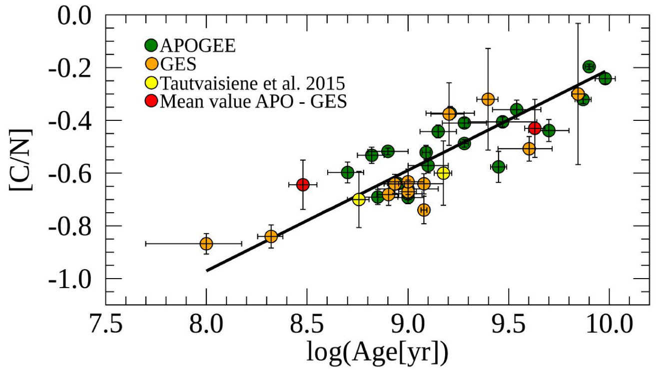


[C/N] as age indicator

Age indicators can be related to stellar evolution and alterations of [C/N] in particular

- Salaris et al. 2015, A&A, 583, A87;
- Masseron & Gilmore 2015, MNRAS, 453, 1855;
- Martig et al. 2016, MNRAS, 456, 3655;
- Ness et al. 2016, ApJ, 823, 114;
- Ho et al. 2017, ApJ, 841, 40;
- Feuillet et al. 2018, MNRAS, 477, 2326.

Especially helpful for the low-mass red giant stars.



Preliminary results from 36 Gaia-ESO and APOGEE open clusters in Casali et al. (A&A, 629, 62, 2019)

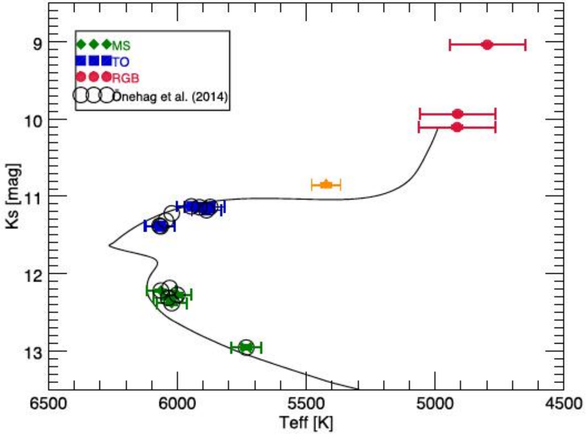
Atomic diffusion

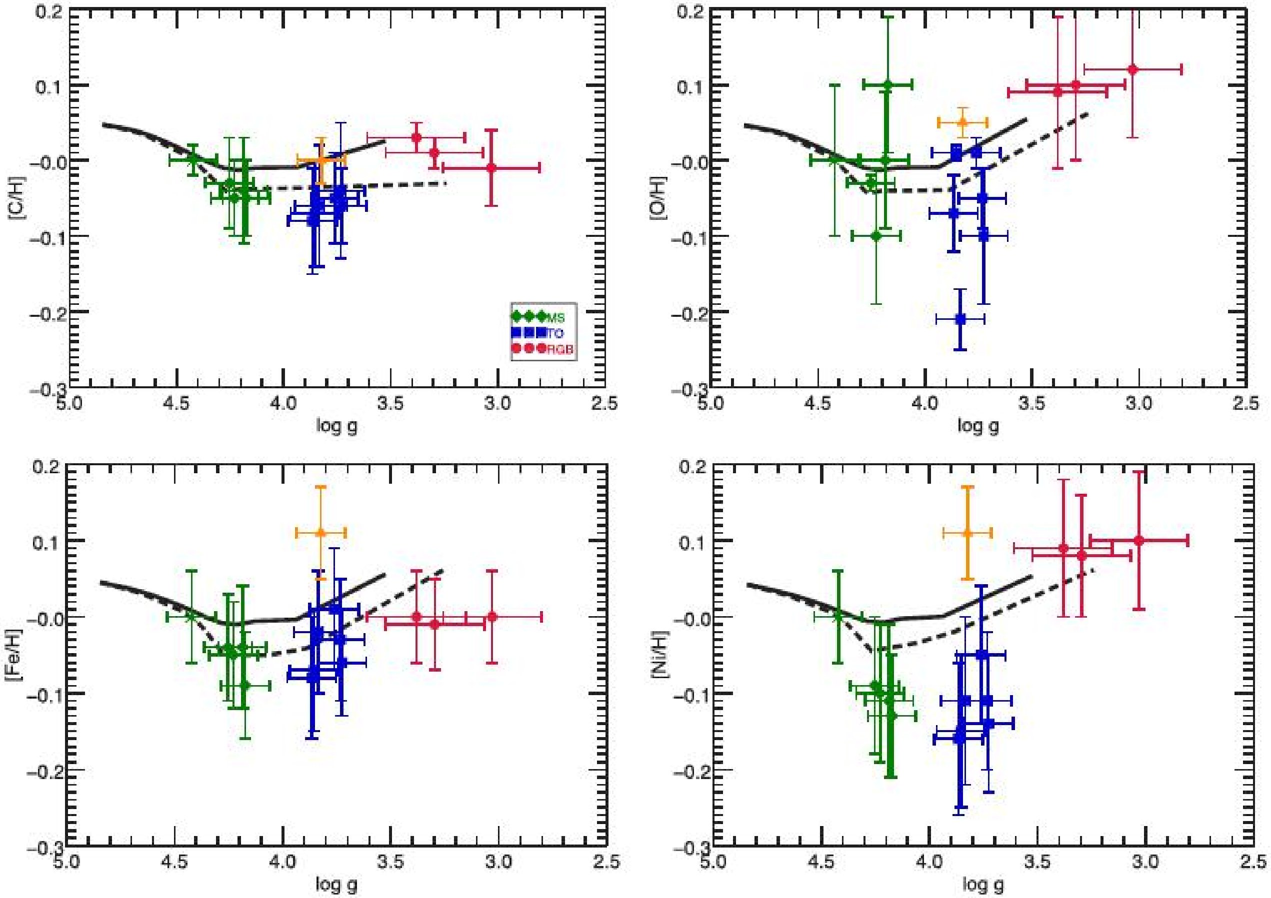
- Atomic diffusion can cause surface abundances to vary as a function of stellar evolutionary phase.
- The elemental abundances in the surface layers decrease when the star evolves along the main sequence until they reach the turn-off point where the maximum effect is seen.
- As the star evolves from the turn-off point to the subgiant and red giant branches, the surface abundances return to nearly their original values due to the deepening of the surface convection zone.
- Material transport effects must be studied with high precision and taken into account in chemical evolution studies.
- Few studies exist as a high precision analysis is required: in globular clusters: NGC 6397 - Korn et al. (2007); Lind et al. (2008); Nordlander et al. (2012); NGC 6752 - Gruyters et al. (2013); in open clusters: M67 - Bertelli Mota et al. (2018), Liu et al (2019), Souto et al. (2019); NGC 6633 - Bertelli Mota et al. (2018)
- As it operates in the main sequence stars - should be taken into account while studying the Galactic chemical evolution.

M 67

Bertelli Motta et al. (2018)

Gaia-ESO Survey
Abundances of C, O, Mg, Al, Na, Si, Ca, Ti, Cr, Mn, Fe, and Ni investigated.





M 67

Liu et al. (2019)

C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr, Y, Ba, and Ce

3 turn-of and 3 subgiant stars

HIRES and 10 m Keck I telescope

The effects of atomic diffusion could be as large as 0.1–0.2 dex

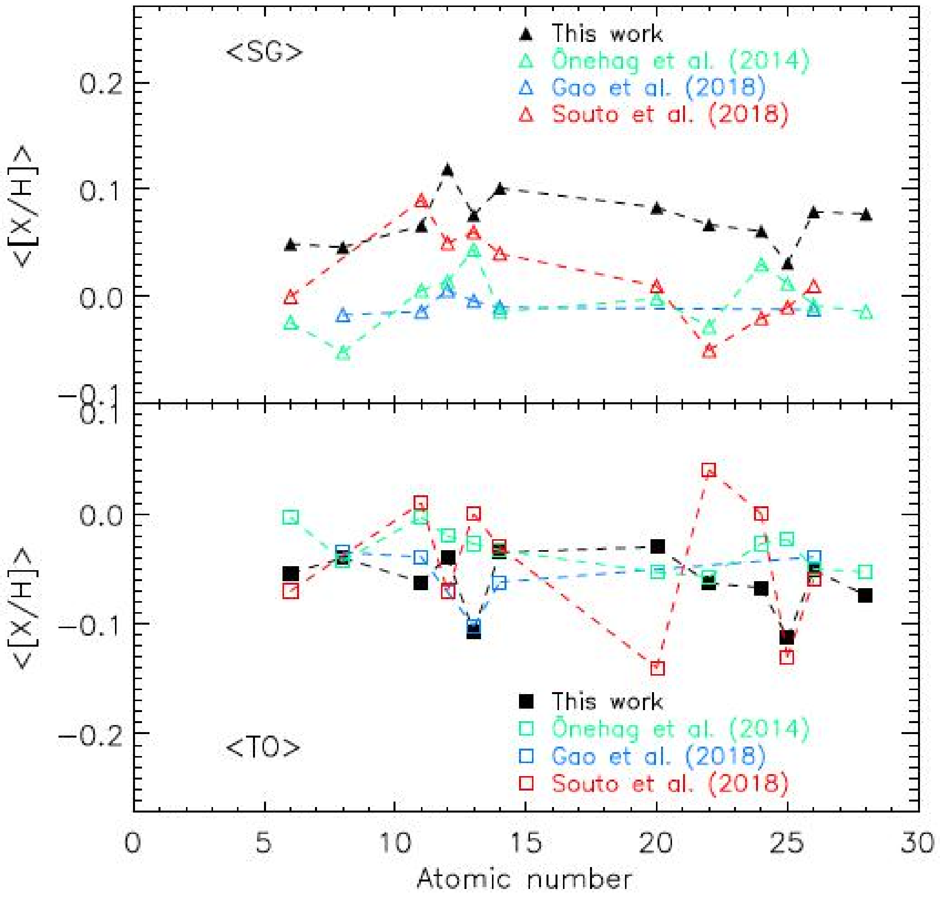


Fig. 8. Comparison of our results with those from Önehag et al. (2014), Gao et al. (2018), and Souto et al. (2018) for the average elemental abundances for subgiant and turn-off stars. *Top panel*: comparison of the average elemental abundances for the subgiant stars. *Bottom panel*: comparison of the average elemental abundances for the turn-off stars (black, green, blue, and red symbols represent the results from this work, Önehag et al. 2014, Gao et al. 2018, and Souto et al. 2018, respectively).

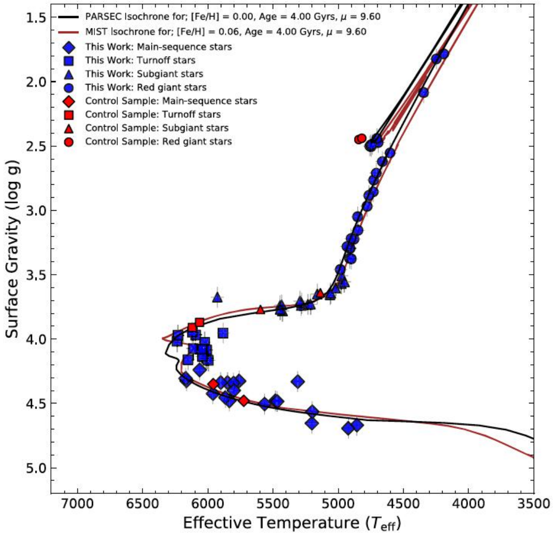
M 67

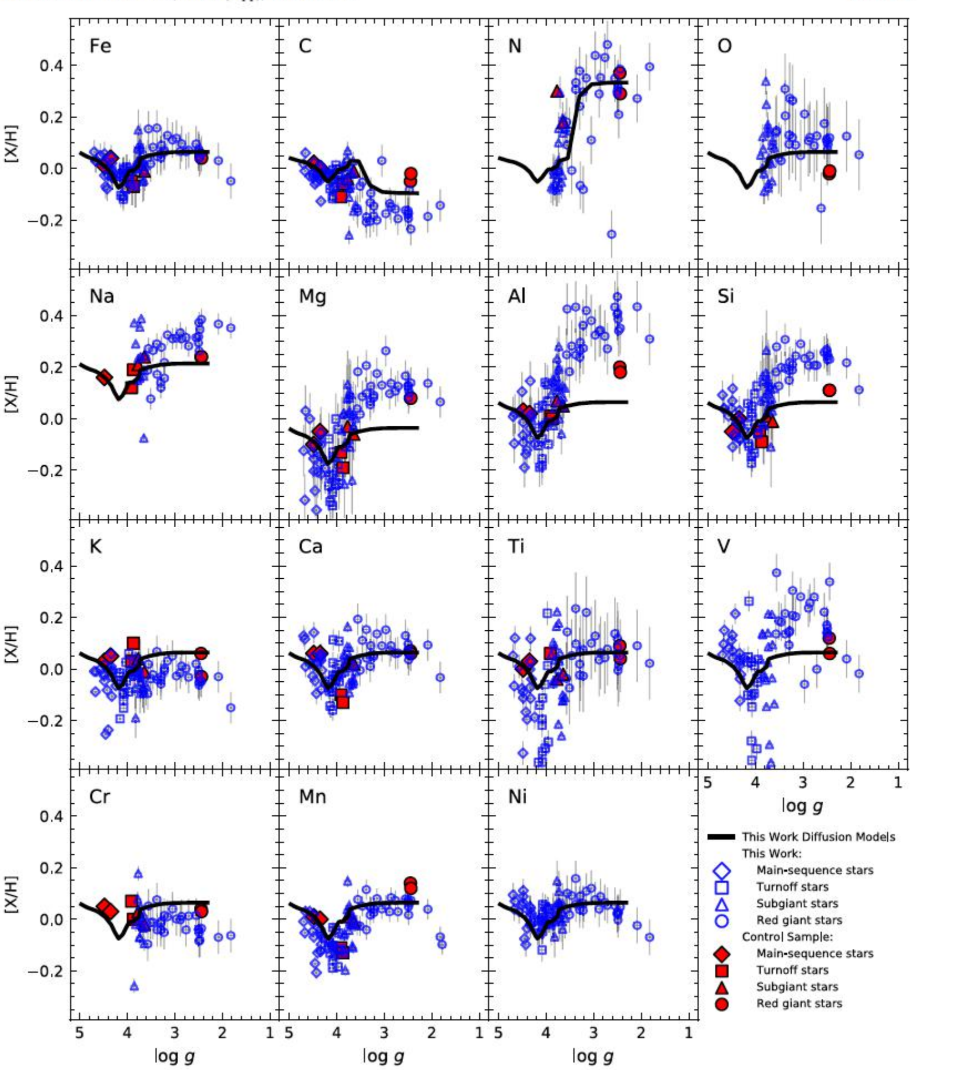
Souto et al. (2019) analysed SDSS-IV/APOGEE spectra

C, N, O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, and Ni

19 main sequence, 15 turnoff, 20 subgiant, and 29 red giants

Abundance differences of up to 0.30–0.40 dex

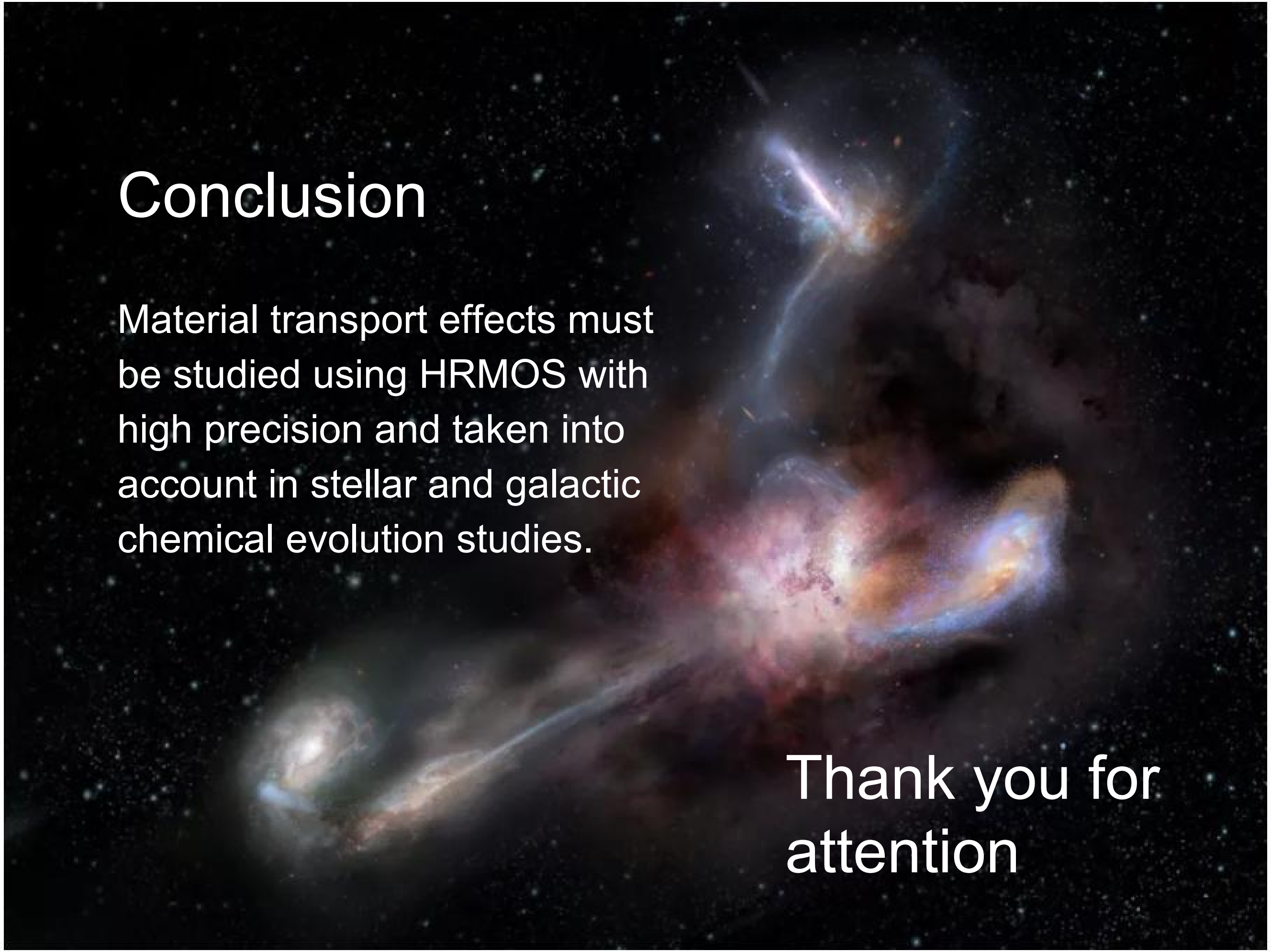




Conclusion

Material transport effects must be studied using HRMOS with high precision and taken into account in stellar and galactic chemical evolution studies.

Thank you for attention



(Image credit: NRAO/AUI/NSF, S. Dagnello)