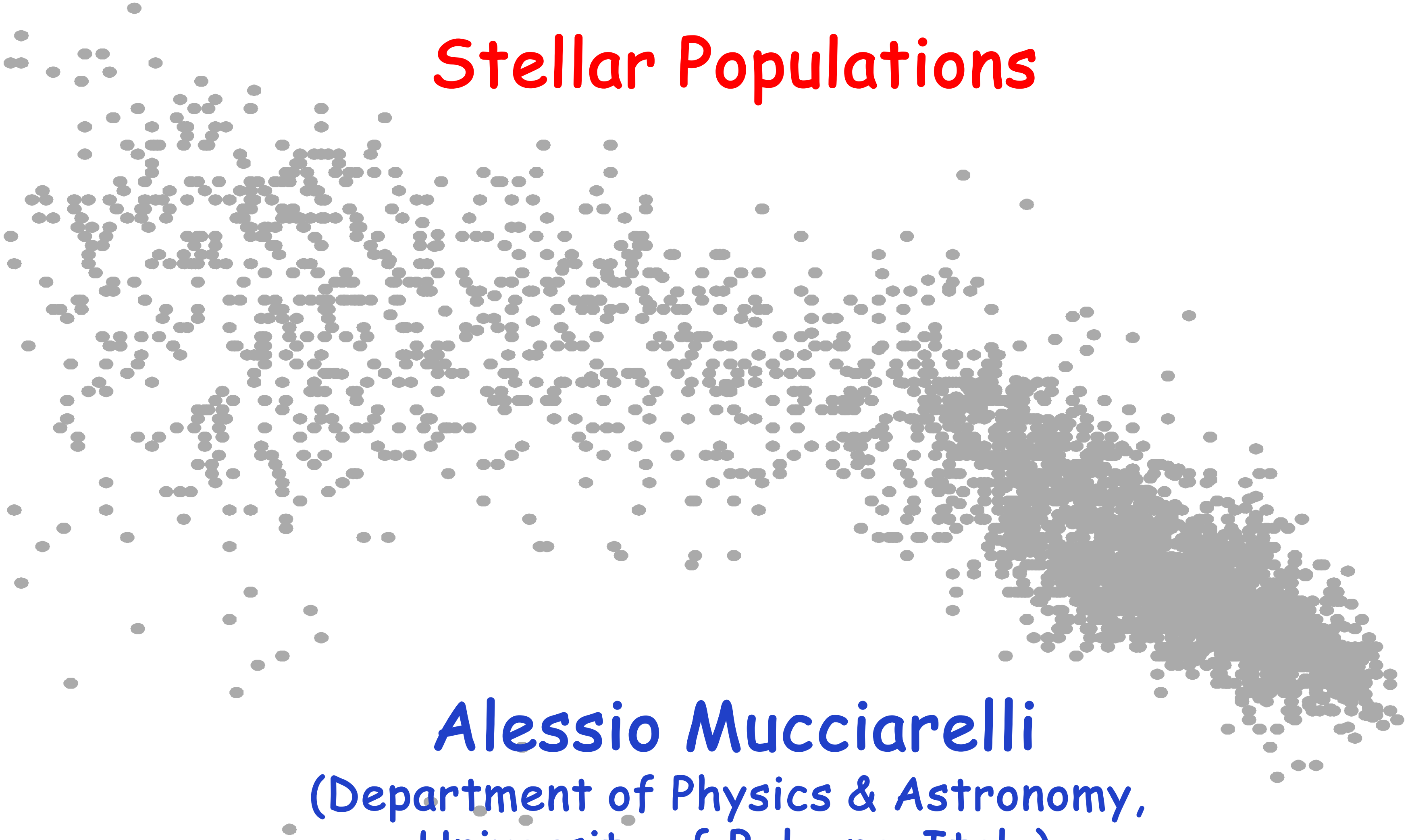


Stellar Populations

Alessio Mucciarelli

(Department of Physics & Astronomy,
University of Bologna, Italy)

Between the lines Workshop – ESO , 2-4 December 2024

Our main aim

Understanding the chemical/dynamical evolution of galaxies

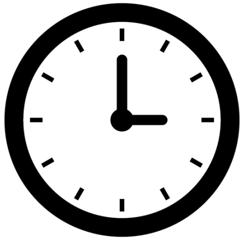
- When, where and how the stars formed
- What are their elemental abundances (chemical evolution)

What we mean with stellar population?

A group of stars sharing some common properties, therefore a common formation and evolution path

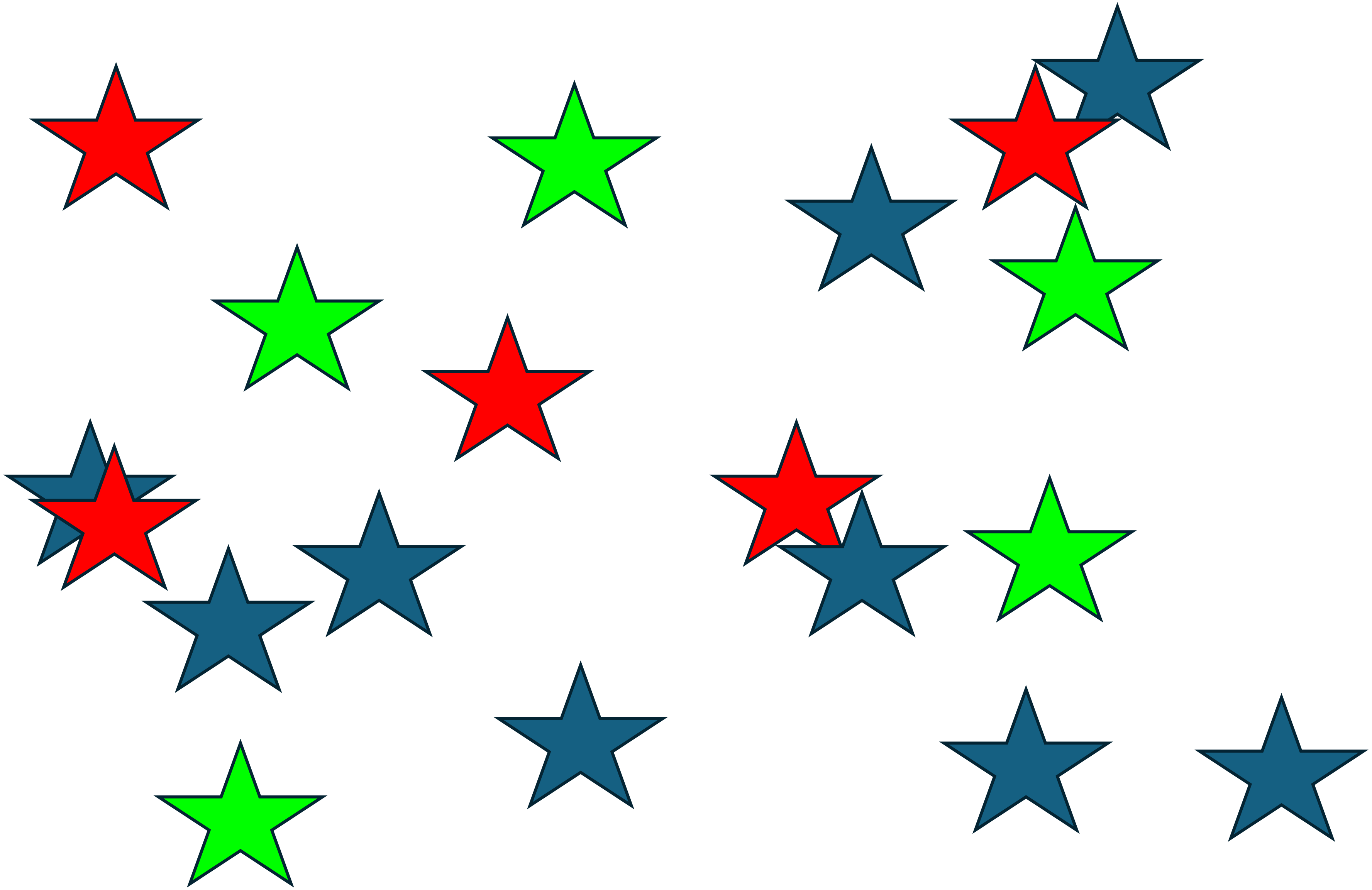
The common properties

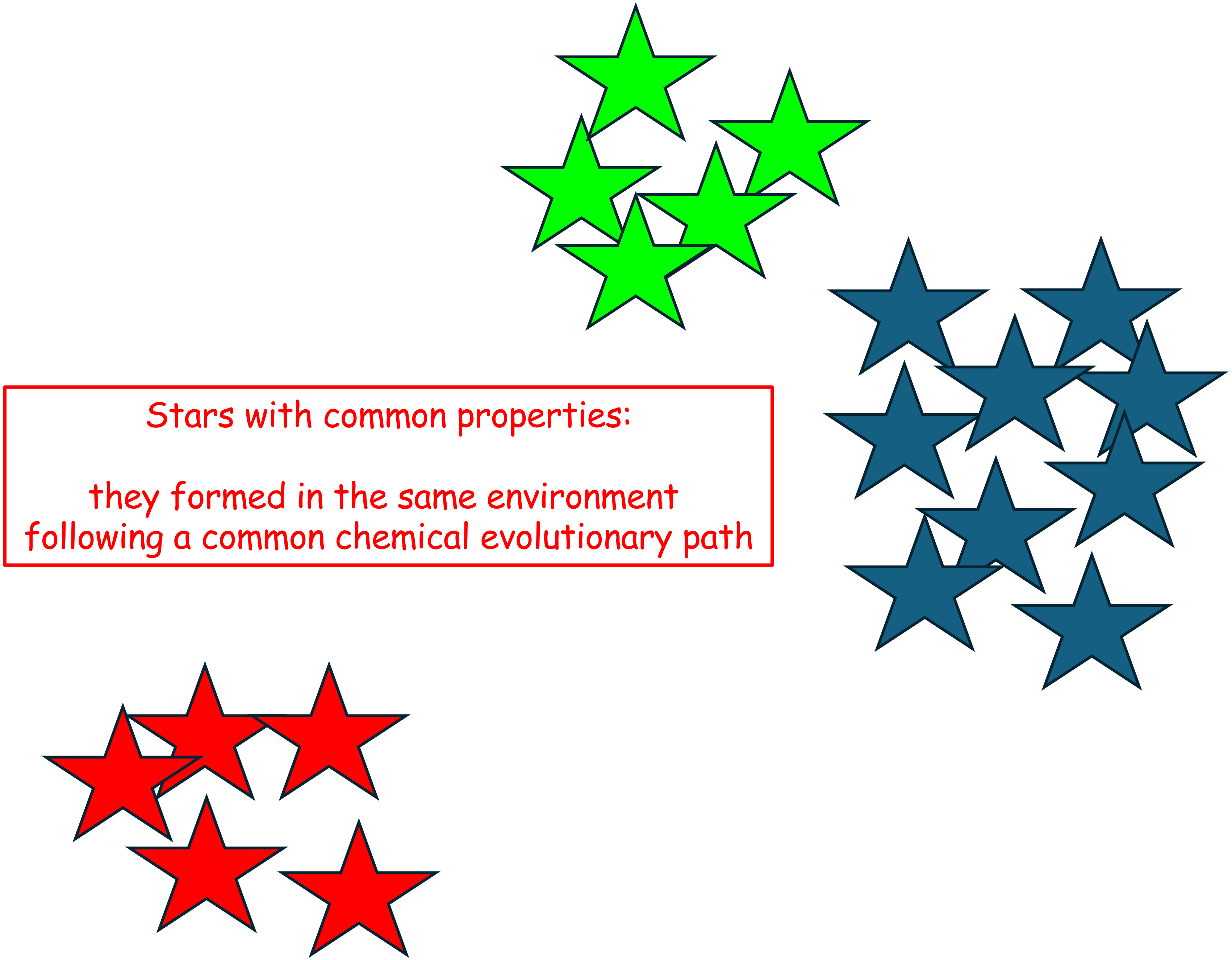
AGE



CHEMICAL COMPOSITION

KINEMATICS



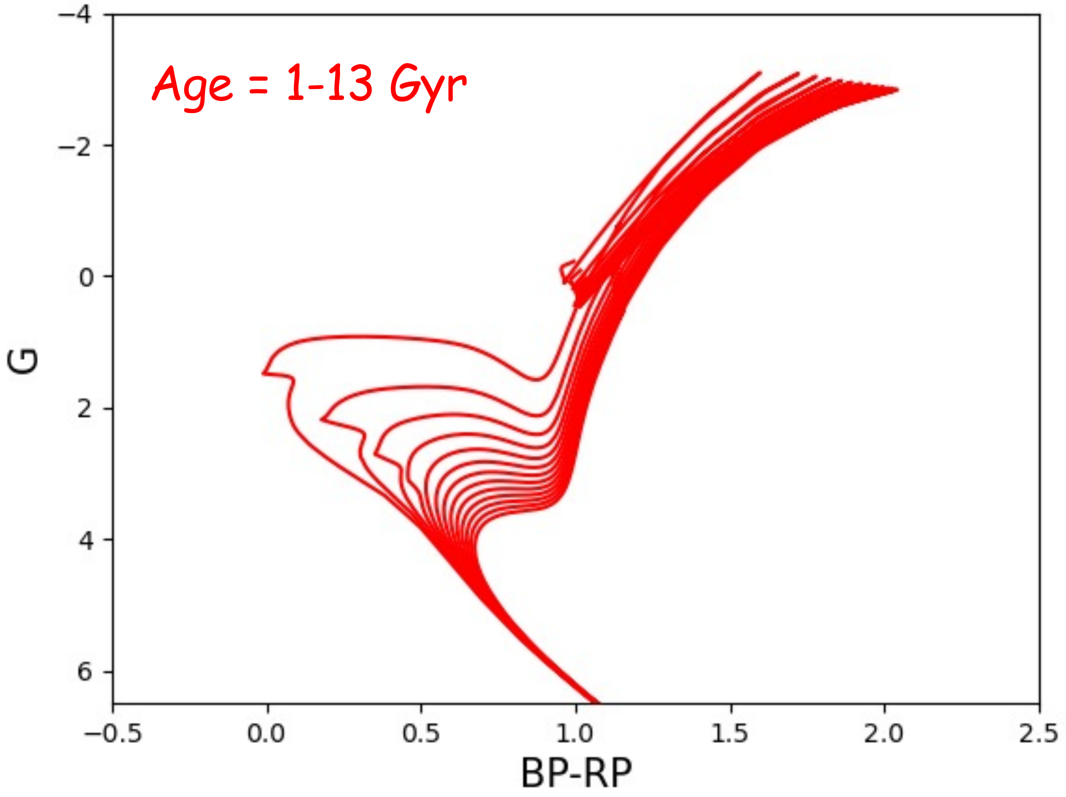


Stars with common properties:

they formed in the same environment
following a common chemical evolutionary path

How to measure ages?

Isochrone fitting: comparison of the position of a star in the Herztsprung-Russell diagram with theoretical isochrones



- Turn-off and Sub-Branch Giant are sensitive to age variation
- Main Sequence and Red Giant Branch are less sensitive to age variation (age-metallicity degeneracy)

How to measure ages?

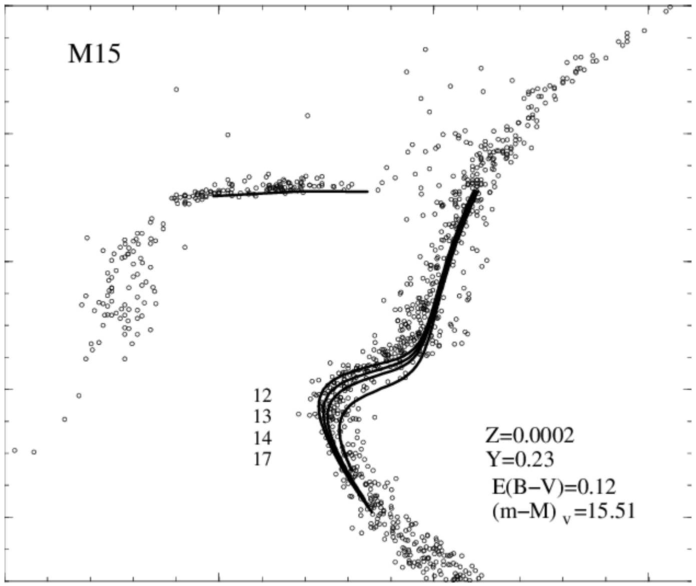
Isochrone fitting: comparison of the position of a star in the Herztsprung-Russell diagram with theoretical isochrones

Problematic for individual stars

We need to know the distance, the reddening and the metallicity (but the Gaia mission helps us) …

Easy for stellar clusters

All the stars at the same distance and with the same [Fe/H] and E(B-V)

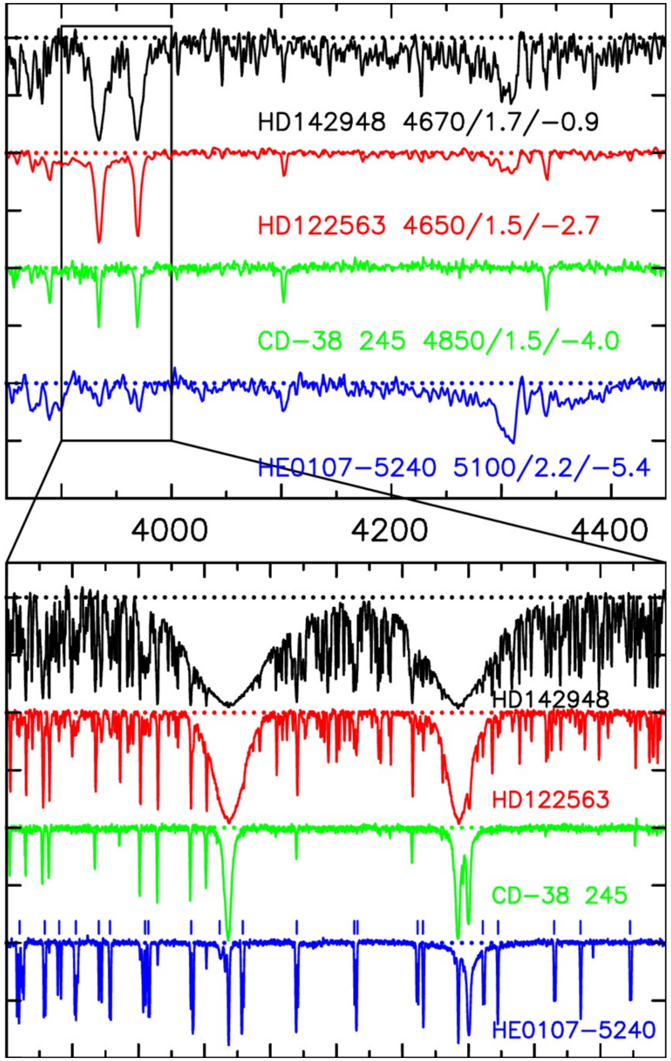


How to measure chemical abundances ?

Using stellar spectra

Low spectral resolution …
Information about global metallicity and some metals

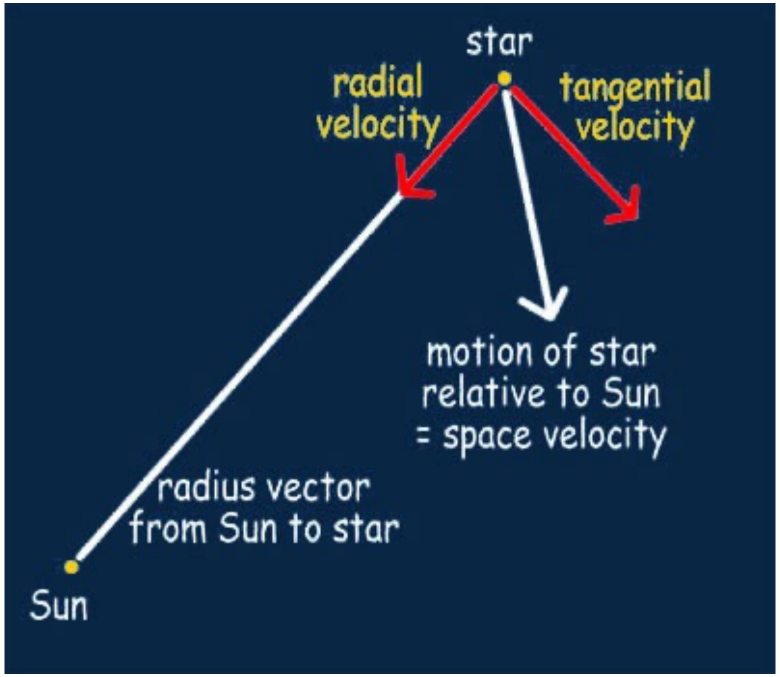
$R \sim 2000$



High spectral resolution …
Detailed abundances for several elements

$R \sim 40000$

How to measure stellar orbits?



Photometry → Tangential velocities (proper motions)

Spectroscopy → Radial velocity

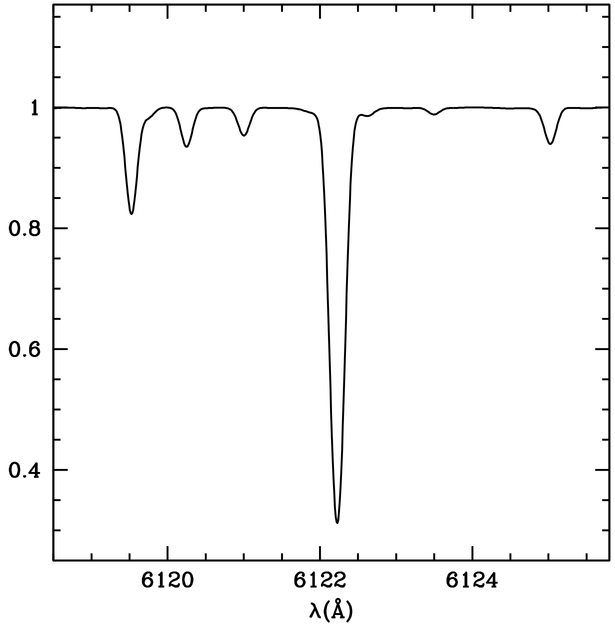
} OBJECT'S MOTION

Radial velocity

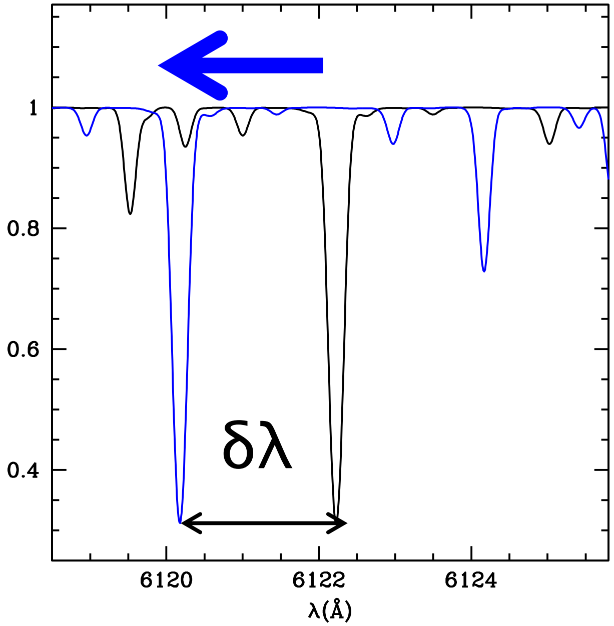
Doppler shift in the non-relativistic case:

$$\frac{\lambda_{OBS} - \lambda_{REST}}{\lambda_{REST}} = \frac{RV}{c}$$

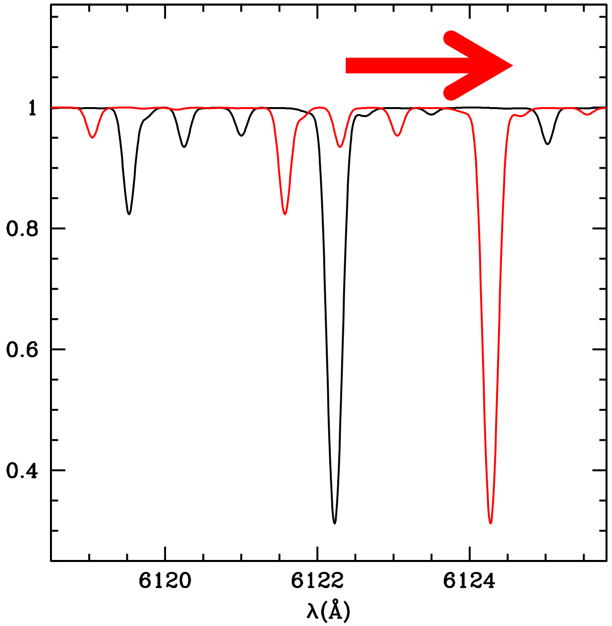
Rest-frame



Blue-shifted

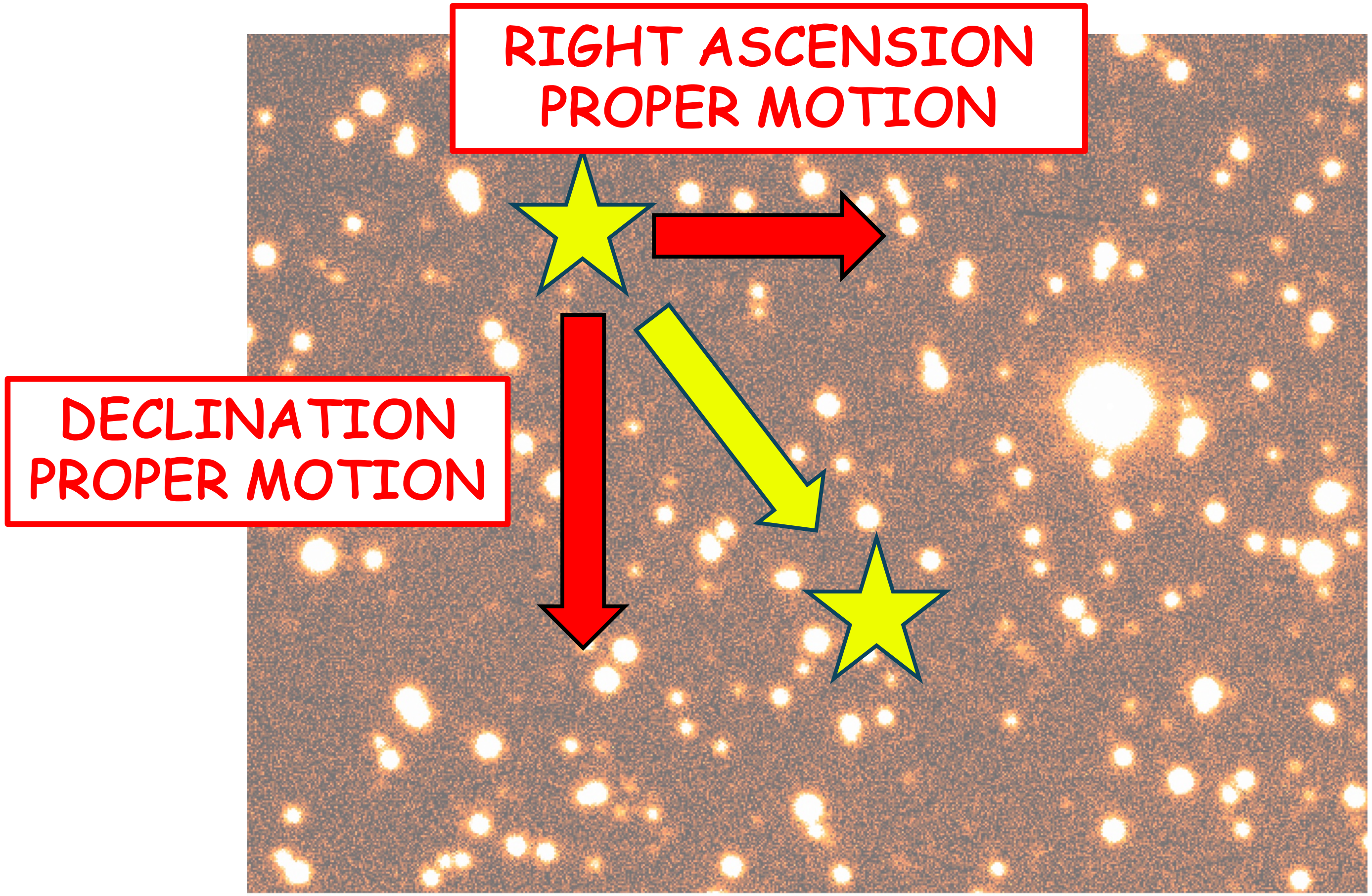


Red-shifted



Proper motions

Measure of the variation of the position on the sky with the time
(typically expressed as mas/year)

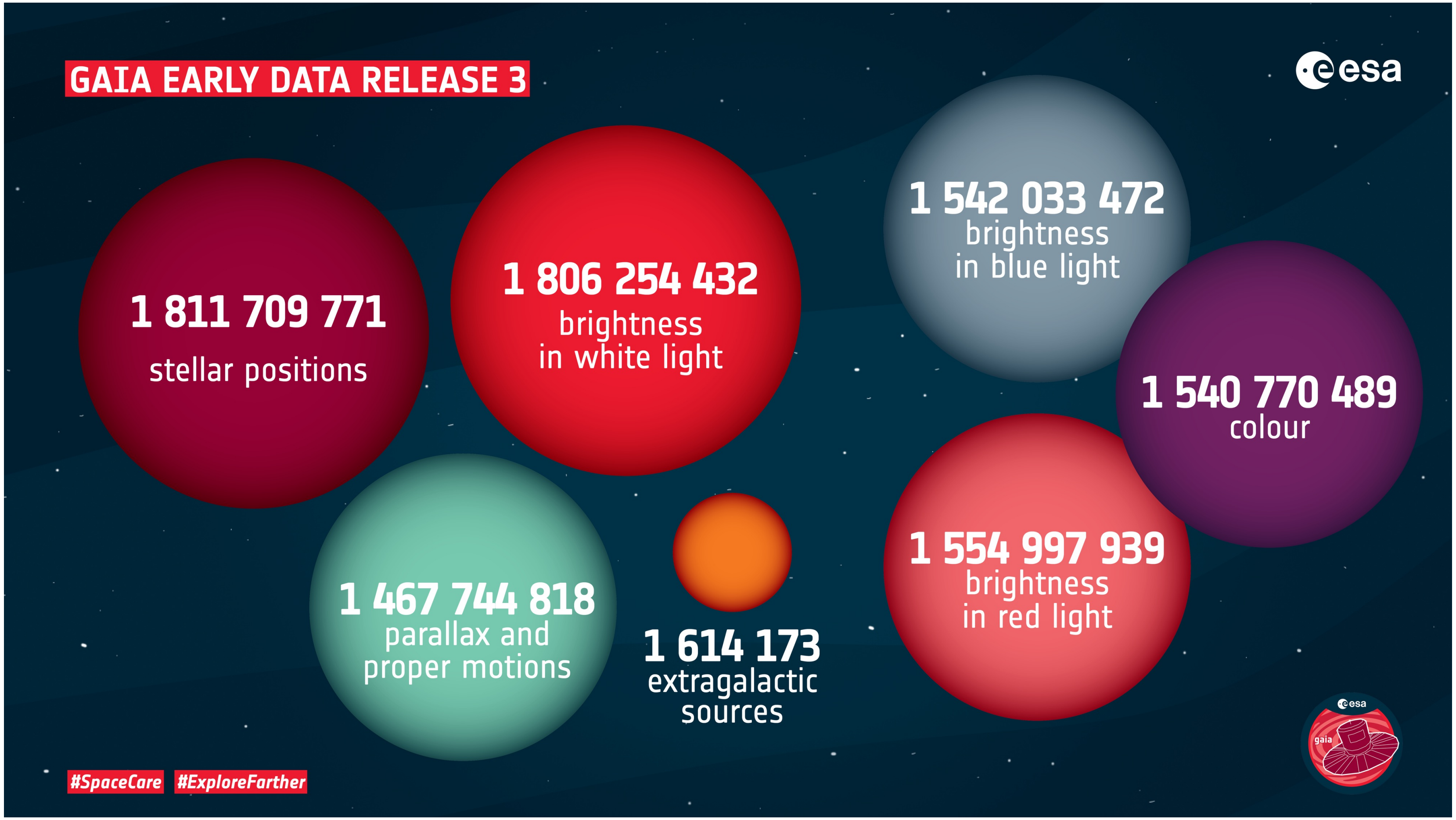


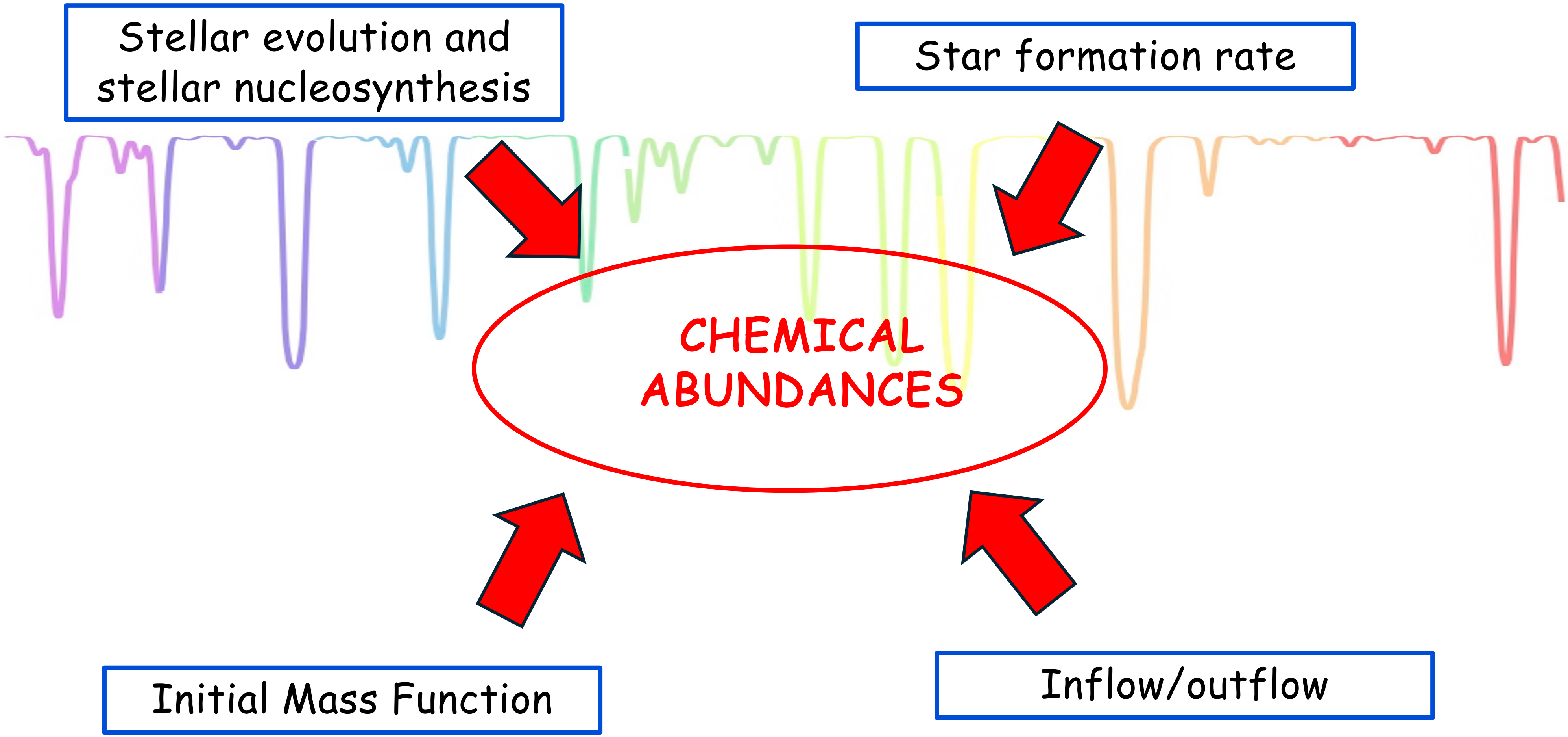
RIGHT ASCENSION PROPER MOTION

DECLINATION PROPER MOTION

GAIA mission

Magnitudes, distances and proper motions for almost 2 billions of stars





Stellar evolution and stellar nucleosynthesis

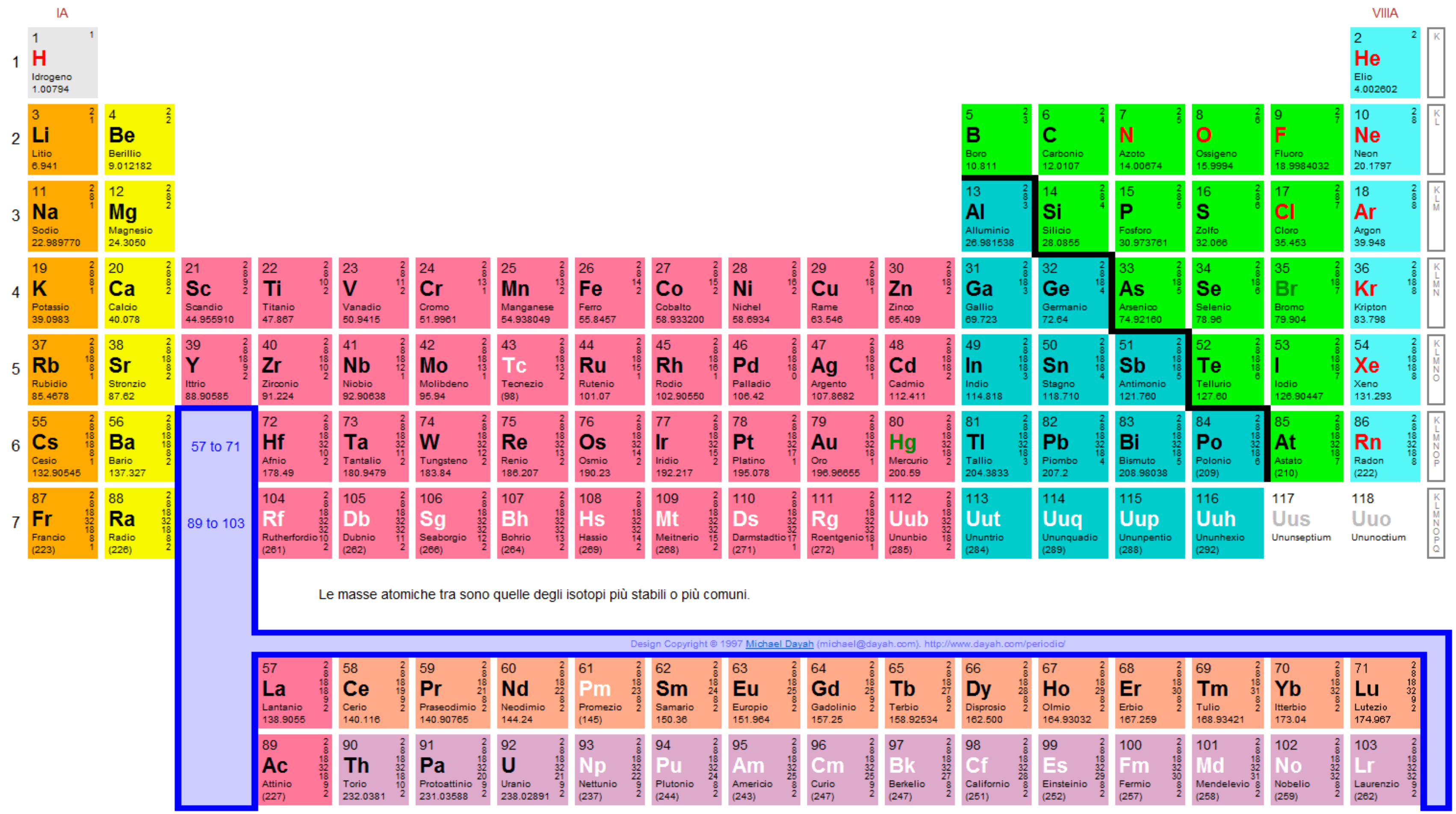
Star formation rate

CHEMICAL ABUNDANCES

Initial Mass Function

Inflow/outflow

Period Table of the Elements



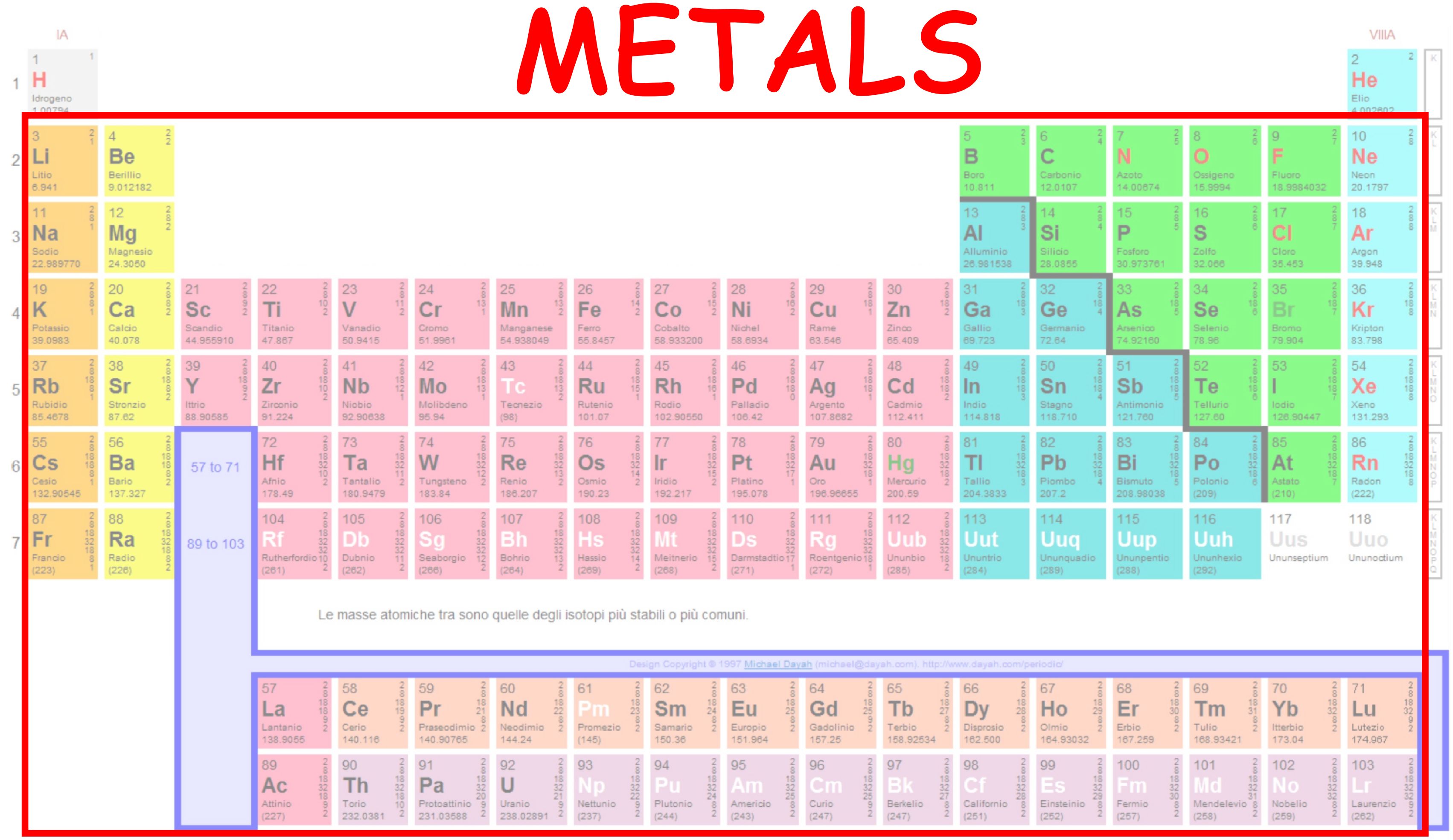
	IA																	VIIIA	
1	1 **H** Idrogeno 1.00794 1																	2 **He** Elio 4.002602 2	K
2	3 **Li** Litio 6.941 2 1	4 **Be** Berillio 9.012182 2 2											5 **B** Boro 10.811 2 3	6 **C** Carbonio 12.0107 2 4	7 **N** Azoto 14.00674 2 5	8 **O** Ossigeno 15.9994 2 6	9 **F** Fluoro 18.9984032 2 7	10 **Ne** Neon 20.1797 2 8	K L
3	11 **Na** Sodio 22.989770 2 8 1	12 **Mg** Magnesio 24.3050 2 8 2											13 **Al** Alluminio 26.981538 2 8 3	14 **Si** Silicio 28.0855 2 8 4	15 **P** Fosforo 30.973761 2 8 5	16 **S** Zolfo 32.066 2 8 6	17 **Cl** Cloro 35.453 2 8 7	18 **Ar** Argon 39.948 2 8 8	K L M
4	19 **K** Potassio 39.0983 2 8 8 1	20 **Ca** Calcio 40.078 2 8 8 2	21 **Sc** Scandio 44.955910 2 8 9 2	22 **Ti** Titanio 47.867 2 8 10 2	23 **V** Vanadio 50.9415 2 8 11 2	24 **Cr** Cromo 51.9961 2 8 13 1	25 **Mn** Manganese 54.938049 2 8 13 2	26 **Fe** Ferro 55.8457 2 8 14 2	27 **Co** Cobalto 58.933200 2 8 15 2	28 **Ni** Nichel 58.6934 2 8 16 2	29 **Cu** Rame 63.546 2 8 18 1	30 **Zn** Zinco 65.409 2 8 18 2	31 **Ga** Gallio 69.723 2 8 18 3	32 **Ge** Germanio 72.64 2 8 18 4	33 **As** Arsenico 74.92160 2 8 18 5	34 **Se** Selenio 78.96 2 8 18 6	35 **Br** Bromo 79.904 2 8 18 7	36 **Kr** Kripton 83.798 2 8 18 8	K L M N
5	37 **Rb** Rubidio 85.4678 2 8 18 8 1	38 **Sr** Stronzio 87.62 2 8 18 8 2	39 **Y** Ittrio 88.90585 2 8 18 9 2	40 **Zr** Zirconio 91.224 2 8 18 10 2	41 **Nb** Niobio 92.90638 2 8 18 12 1	42 **Mo** Molibdeno 95.94 2 8 18 13 1	43 **Tc** Tecnezio (98) 2 8 18 13 2	44 **Ru** Rutenio 101.07 2 8 18 15 1	45 **Rh** Rodio 102.90550 2 8 18 16 1	46 **Pd** Palladio 106.42 2 8 18 18 0	47 **Ag** Argento 107.8682 2 8 18 18 1	48 **Cd** Cadmio 112.411 2 8 18 18 2	49 **In** Indio 114.818 2 8 18 18 3	50 **Sn** Stagno 118.710 2 8 18 18 4	51 **Sb** Antimonio 121.760 2 8 18 18 5	52 **Te** Tellurio 127.60 2 8 18 18 6	53 **I** Iodio 126.90447 2 8 18 18 7	54 **Xe** Xeno 131.293 2 8 18 18 8	K L M N O
6	55 **Cs** Cesio 132.90545 2 8 18 18 8 1	56 **Ba** Bario 137.327 2 8 18 18 8 2	57 to 71	72 **Hf** Afnio 178.49 2 8 18 32 10 2	73 **Ta** Tantalio 180.9479 2 8 18 32 11 2	74 **W** Tungsteno 183.84 2 8 18 32 12 2	75 **Re** Renio 186.207 2 8 18 32 13 2	76 **Os** Osmio 190.23 2 8 18 32 14 2	77 **Ir** Iridio 192.217 2 8 18 32 15 2	78 **Pt** Platino 195.078 2 8 18 32 17 1	79 **Au** Oro 196.96655 2 8 18 32 18 1	80 **Hg** Mercurio 200.59 2 8 18 32 18 2	81 **Tl** Tallio 204.3833 2 8 18 32 18 3	82 **Pb** Piombo 207.2 2 8 18 32 18 4	83 **Bi** Bismuto 208.98038 2 8 18 32 18 5	84 **Po** Polonio (209) 2 8 18 32 18 6	85 **At** Astato (210) 2 8 18 32 18 7	86 **Rn** Radon (222) 2 8 18 32 18 8	K L M N O P
7	87 **Fr** Francio (223) 2 8 18 32 18 8 1	88 **Ra** Radio (226) 2 8 18 32 18 8 2	89 to 103	104 **Rf** Rutherfordio (261) 2 8 18 32 32 10 2	105 **Db** Dubnio (262) 2 8 18 32 32 11 2	106 **Sg** Seaborgio (266) 2 8 18 32 32 12 2	107 **Bh** Bohrio (264) 2 8 18 32 32 13 2	108 **Hs** Hassio (269) 2 8 18 32 32 14 2	109 **Mt** Meitnerio (268) 2 8 18 32 32 15 2	110 **Ds** Darmstadtio (271) 2 8 18 32 32 17 1	111 **Rg** Roentgenio (272) 2 8 18 32 32 18 1	112 **Uub** Ununbio (285) 2 8 18 32 32 18 2	113 **Uut** Ununtrio (284)	114 **Uuq** Ununquadio (289)	115 **Uup** Ununpentio (288)	116 **Uuh** Ununhexio (292)	117 **Uus** Ununseptium	118 **Uuo** Ununoctium	K L M N O P Q

Le masse atomiche tra sono quelle degli isotopi più stabili o più comuni.

57 **La** Lantanio 138.9055 2 8 18 18 9 2	58 **Ce** Cerio 140.116 2 8 18 19 9 2	59 **Pr** Praseodimio 140.90765 2 8 18 21 8 2	60 **Nd** Neodimio 144.24 2 8 18 22 8 2	61 **Pm** Promezio (145) 2 8 18 23 8 2	62 **Sm** Samario 150.36 2 8 18 24 8 2	63 **Eu** Europio 151.964 2 8 18 25 8 2	64 **Gd** Gadolinio 157.25 2 8 18 25 9 2	65 **Tb** Terbio 158.92534 2 8 18 27 8 2	66 **Dy** Disprosio 162.500 2 8 18 28 8 2	67 **Ho** Olmio 164.93032 2 8 18 29 8 2	68 **Er** Erbio 167.259 2 8 18 30 8 2	69 **Tm** Tulio 168.93421 2 8 18 31 8 2	70 **Yb** Itterbio 173.04 2 8 18 32 8 2	71 **Lu** Lutezio 174.967 2 8 18 32 9 2
89 **Ac** Attinio (227) 2 8 18 32 18 9 2	90 **Th** Torio 232.0381 2 8 18 32 18 10 2	91 **Pa** Protoattinio 231.03588 2 8 18 32 20 9 2	92 **U** Uranio 238.02891 2 8 18 32 21 9 2	93 **Np** Nettunio (237) 2 8 18 32 22 9 2	94 **Pu** Plutonio (244) 2 8 18 32 24 8 2	95 **Am** Americio (243) 2 8 18 32 25 8 2	96 **Cm** Curio (247) 2 8 18 32 25 9 2	97 **Bk** Berkelio (247) 2 8 18 32 27 8 2	98 **Cf** Californio (251) 2 8 18 32 28 8 2	99 **Es** Einsteinio (252) 2 8 18 32 29 8 2	100 **Fm** Fermio (257) 2 8 18 32 30 8 2	101 **Md** Mendelevio (258) 2 8 18 32 31 8 2	102 **No** Nobelio (259) 2 8 18 32 32 8 2	103 **Lr** Laurenzio (262) 2 8 18 32 32 9 2

Period Table of the Elements

METALS



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7	87 **Fr** Francio (223)	88 **Ra** Radio (226)	89 to 103	104 **Rf** Rutherfordio (261)	105 **Db** Dubnio (262)	106 **Sg** Seaborgio (266)	107 **Bh** Bohrio (264)	108 **Hs** Hassio (269)	109 **Mt** Meitnerio (268)	110 **Ds** Darmstadtio (271)	111 **Rg** Roentgenio (272)	112 **Uub** Ununbio (285)	113 **Uut** Ununtrio (284)	114 **Uuq** Ununquadio (289)	115 **Uup** Ununpentio (288)	116 **Uuh** Ununhexio (292)	117 **Uus** Ununseptium	118 **Uuo** Ununoctium

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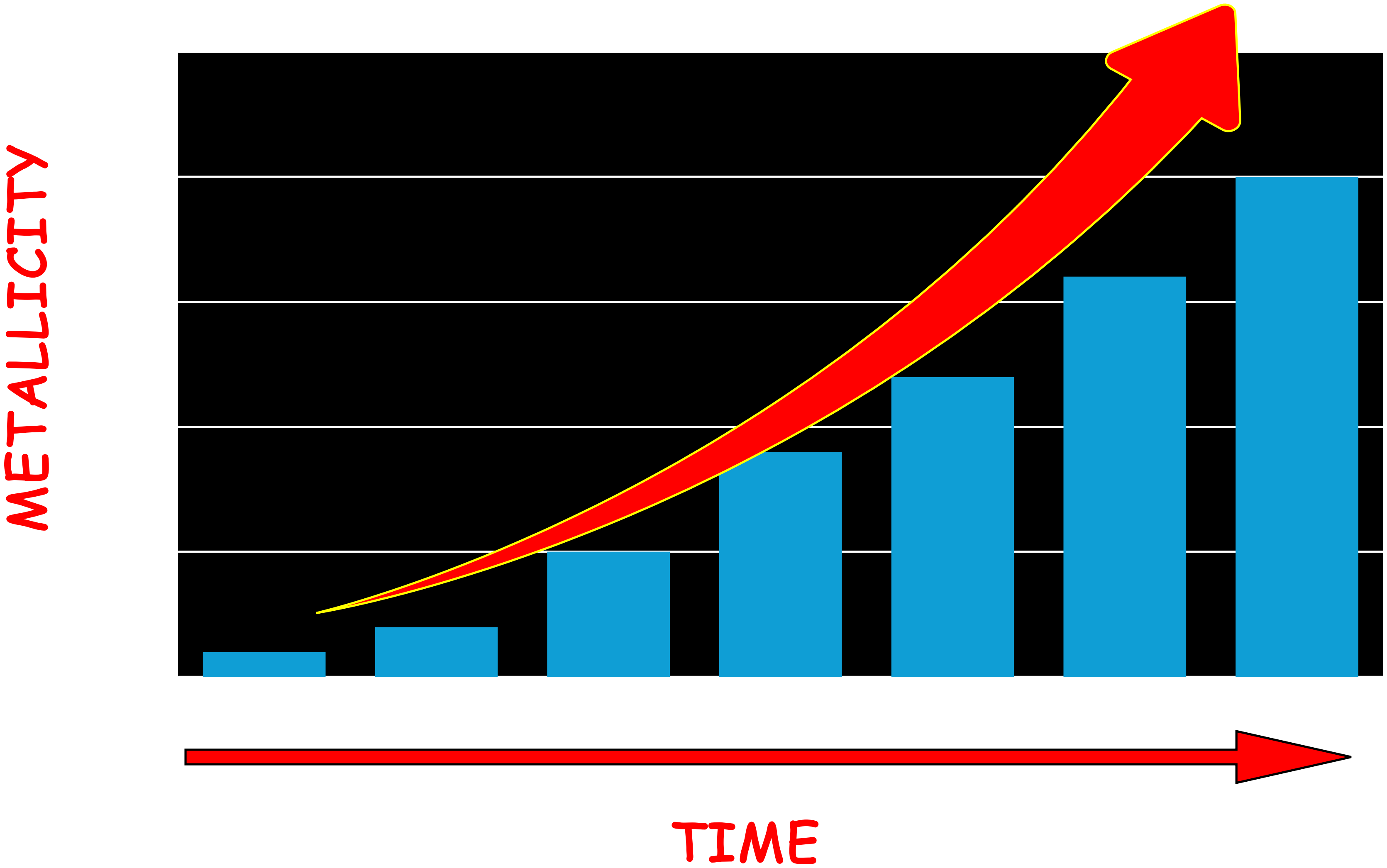
The first stars DO NOT have metals... but they produce them and pass them on to subsequent stars. Each generation of stars is richer in metals than the previous one.


METALLICITY
TIME

We have found a clock to estimate the relative age of stars.

=

The fewer metals we measure ... the older the star is.

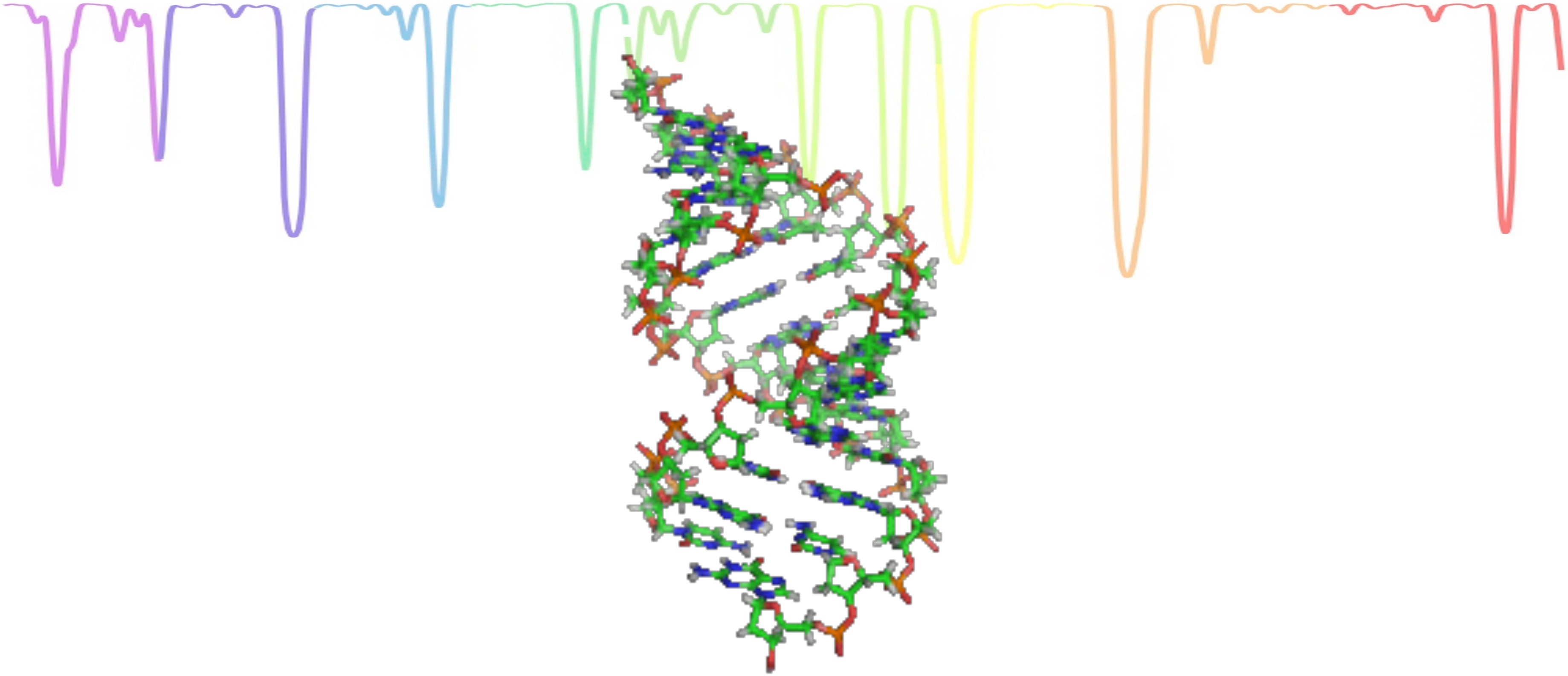
CHEMICAL TAGGING

Chemically tagging groups of stars born
in the same birth cloud (same chemical composition)

The use of chemical tagging in Galactic archaeology was first proposed by Freeman & Bland-Hawthorn (2002), who suggested that the abundances of elements in stars could be used as unique signatures over their lifetime to 'reconstruct' stellar groups that have long since dissolved.

Chemical composition = stellar DNA

The chemical composition reflects the star formation and chemical enrichment of the galaxy where the stars formed … even if a galaxy is accreted by another one and their stars now belong to the major galaxy, we can identify them as "external stars" thanks to their chemistry (the so-called chemical tagging).



An old nomenclature used by astronomers... but still in use:

Population I:
Young, metal-rich stars like the Sun ... 2% of their mass is made of metals.

Population II:
Old, metal-poor stars ... 0.1% or less of their mass is composed of metals.

Population III:
The first stars, completely devoid of metals ... NO METALS AT ALL!!!

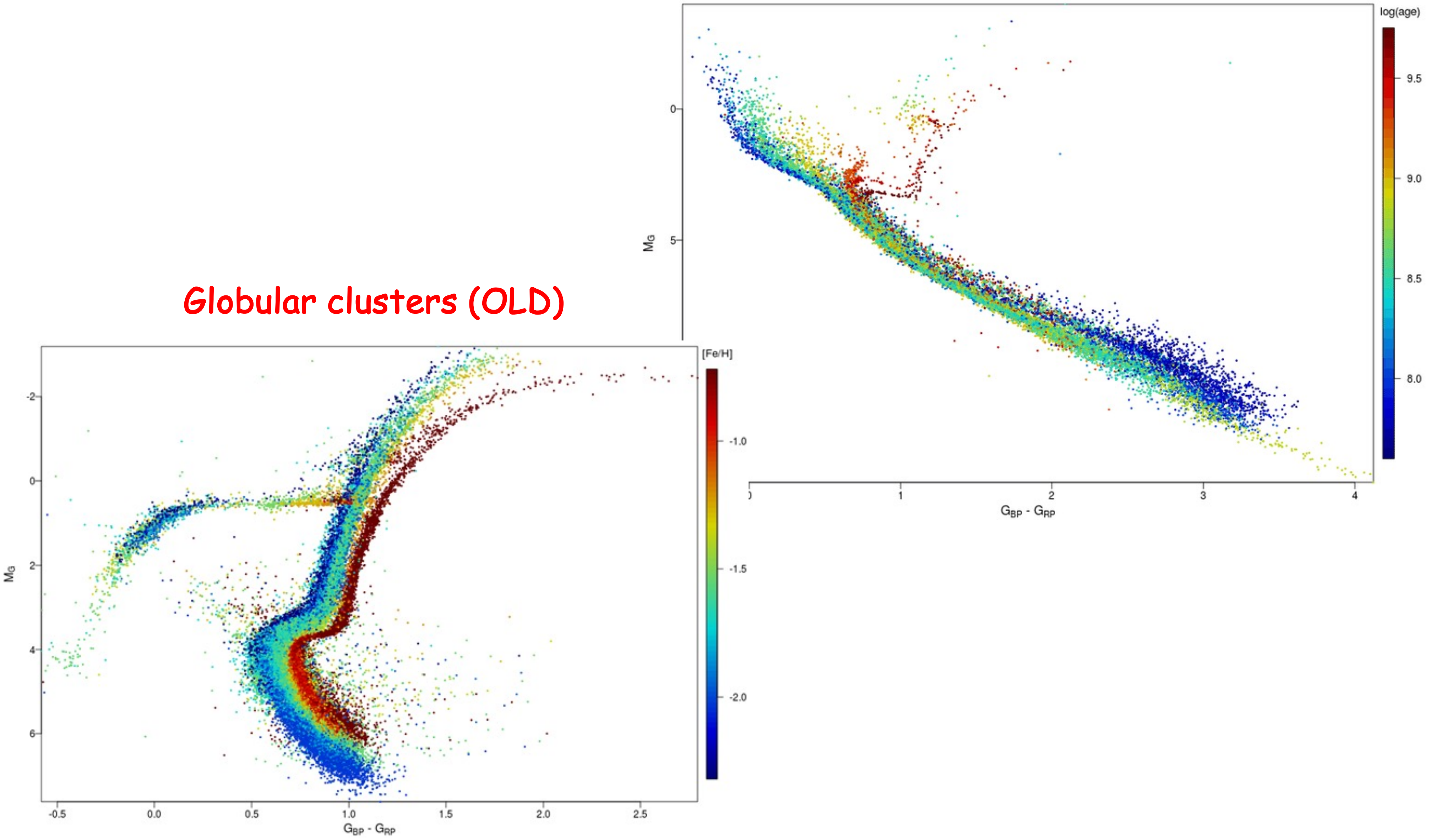
This is a very simplified scheme of the stellar populations in the Milky Way

For instance, the Galactic Bulge is old (like Pop II stars) and metal-rich (like Pop I stars).

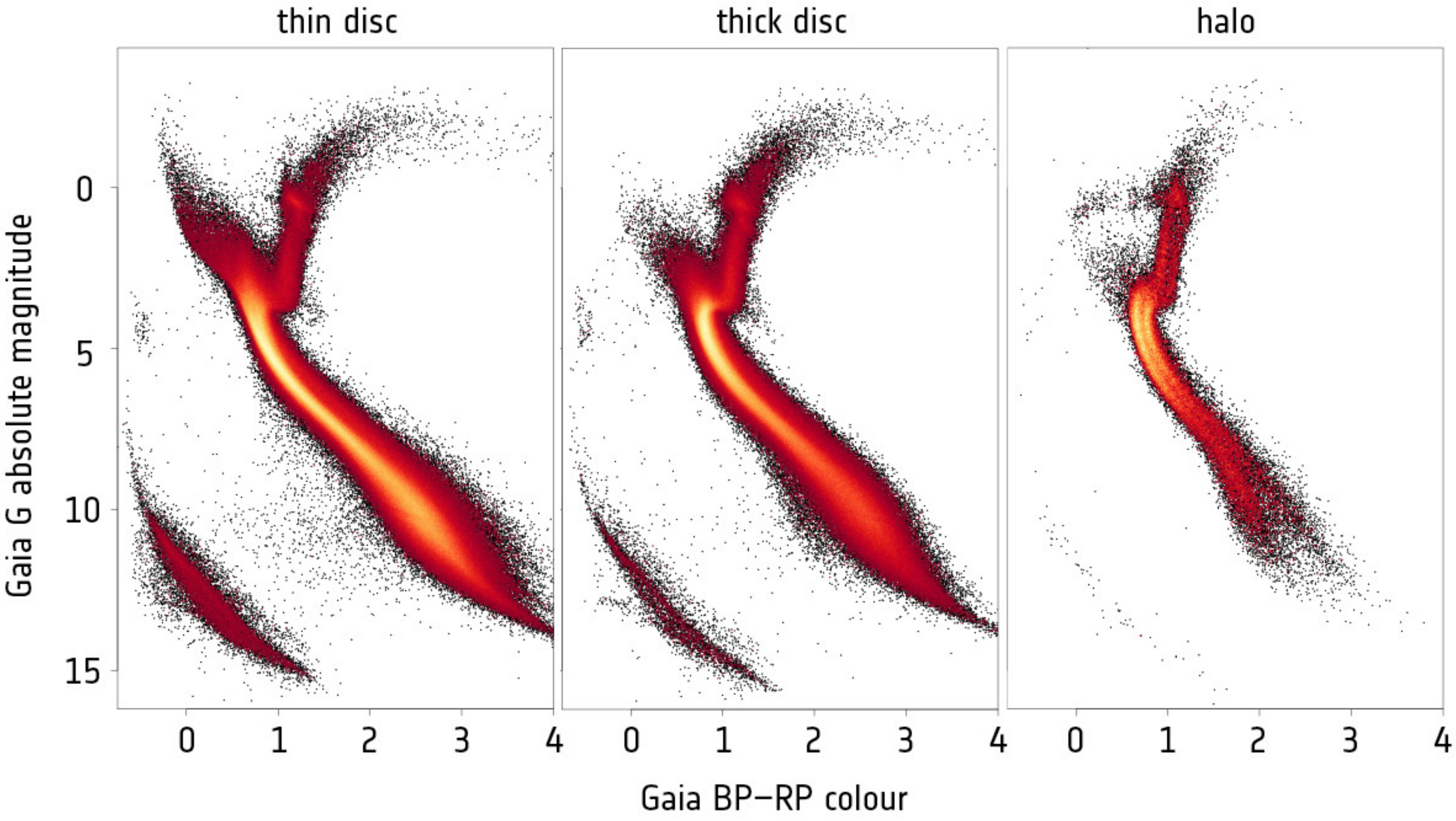
Two main tracers of stellar populations in the Milky Way

Open clusters (YOUNG)

Globular clusters (OLD)



Gaia Mission …
Color-magnitude diagrams of different components of the Milky Way
(different ages)



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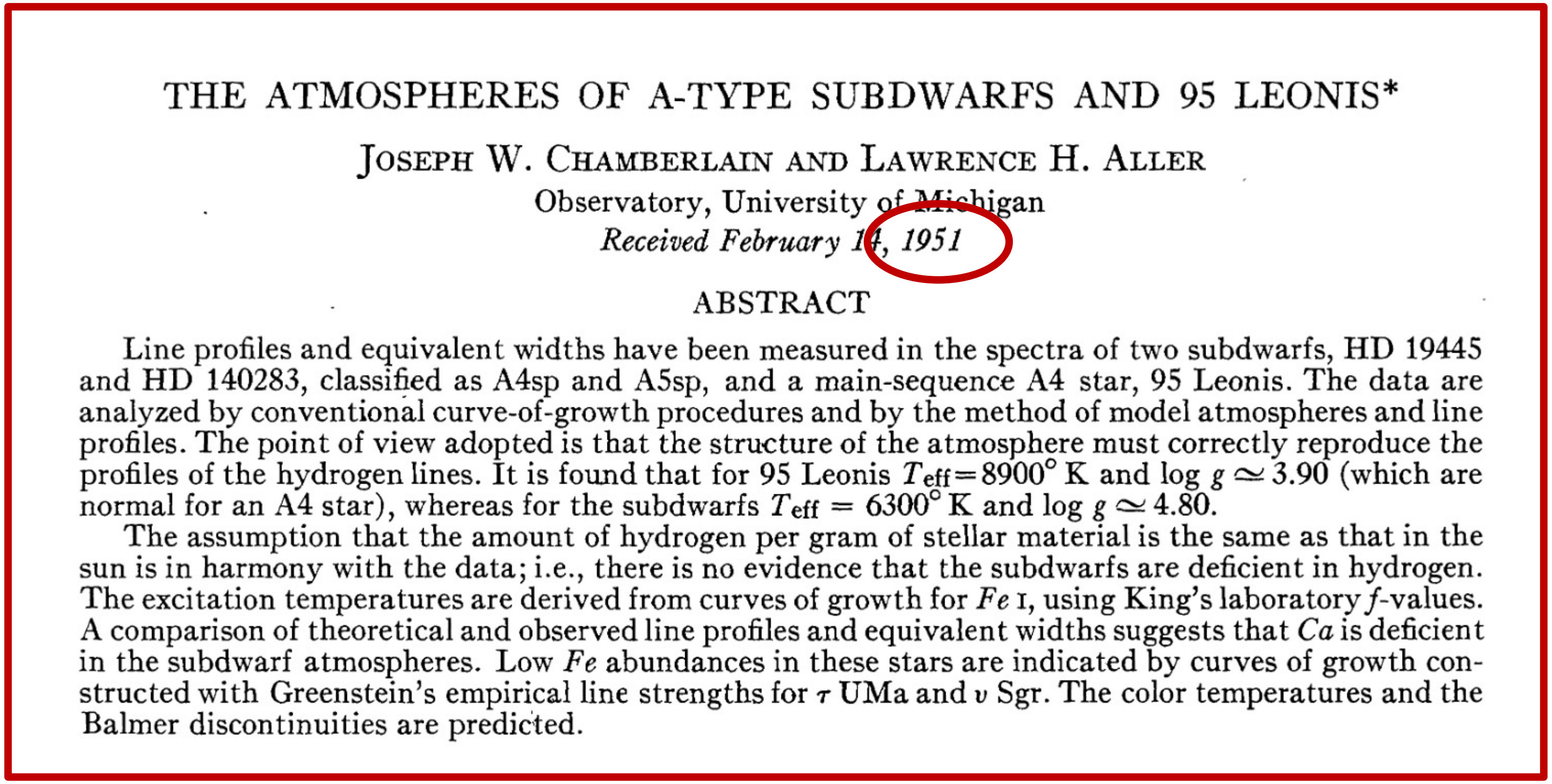
WARNING!!!

Our knowledge of the chemistry of stars today is very detailed,
but it hasn't always been this way...

Until the 1920s, it was believed that all stars had the same chemical composition as the Sun, which was thought to be made entirely of… iron (like the Earth's crust)!!!

Cecilia Payne, PhD Thesis " Stellar Atmospheres" (1925).
One of her results suggests that
the dominant element in the Sun is the hydrogen



THE ATMOSPHERES OF A-TYPE SUBDWARFS AND 95 LEONIS*

JOSEPH W. CHAMBERLAIN AND LAWRENCE H. ALLER
Observatory, University of Michigan

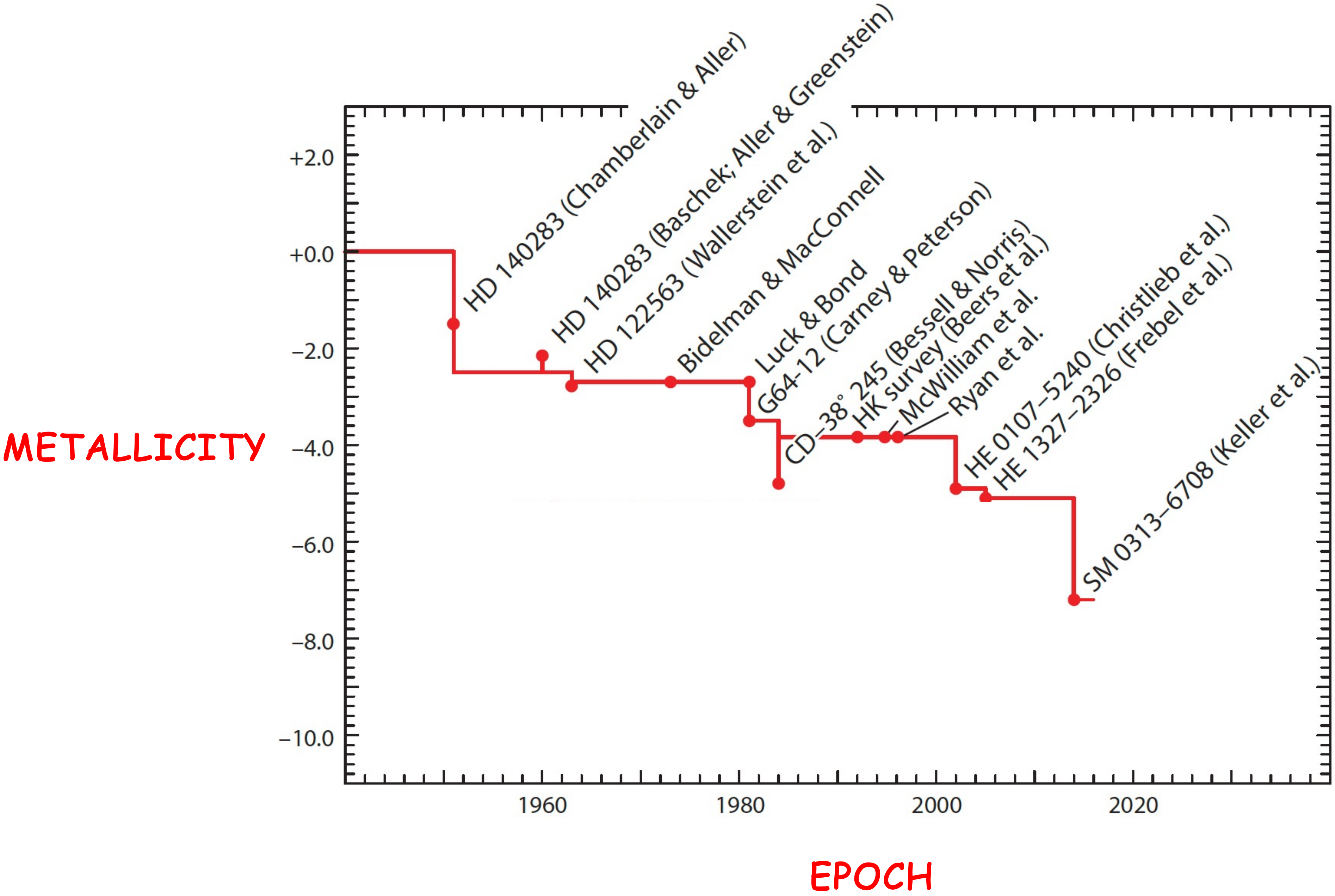
Received February 14, 1951

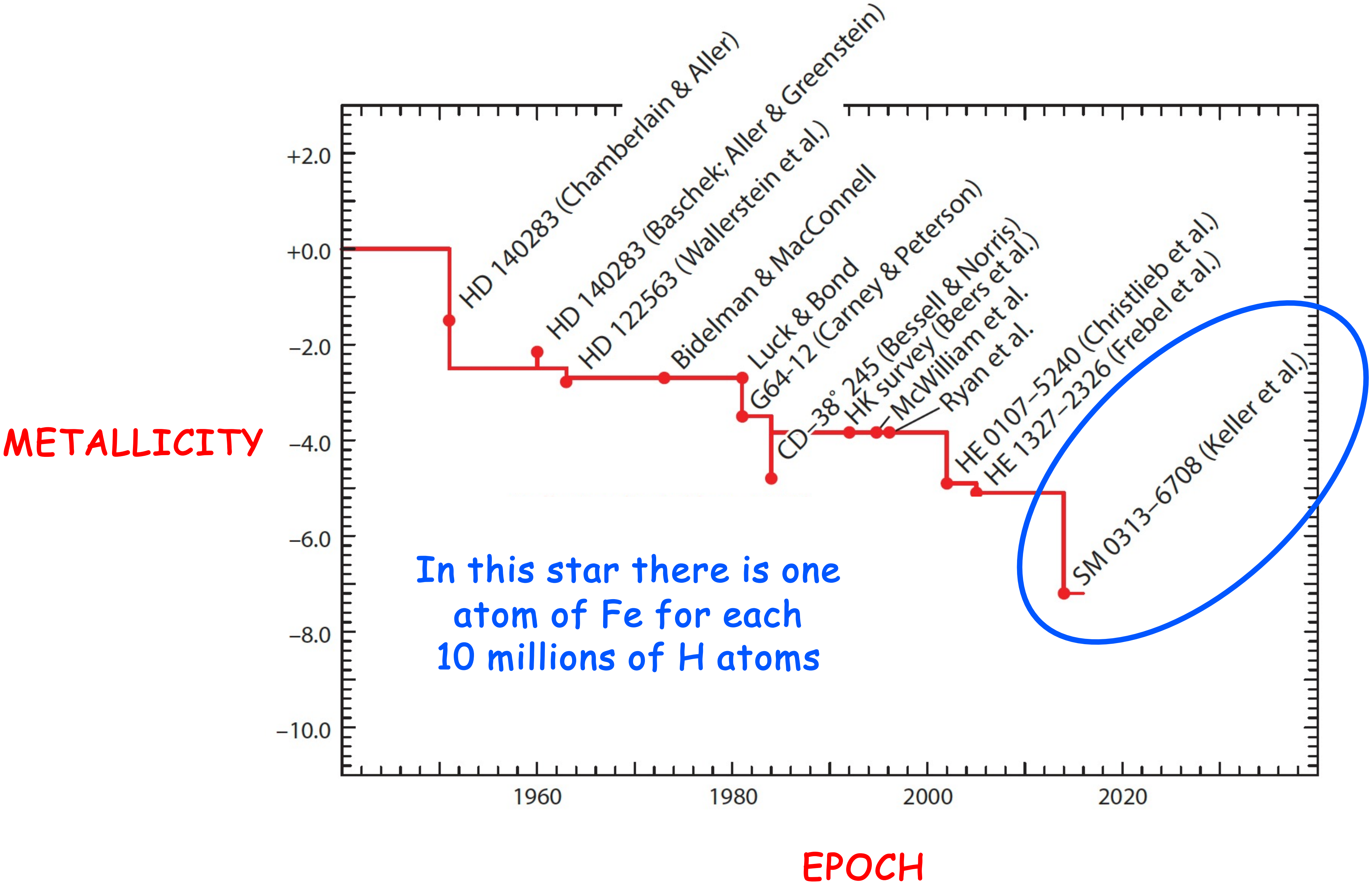
ABSTRACT

Line profiles and equivalent widths have been measured in the spectra of two subdwarfs, HD 19445 and HD 140283, classified as A4sp and A5sp, and a main-sequence A4 star, 95 Leonis. The data are analyzed by conventional curve-of-growth procedures and by the method of model atmospheres and line profiles. The point of view adopted is that the structure of the atmosphere must correctly reproduce the profiles of the hydrogen lines. It is found that for 95 Leonis $T_{\rm eff} = 8900^\circ$ K and $\log g \simeq 3.90$ (which are normal for an A4 star), whereas for the subdwarfs $T_{\rm eff} = 6300^\circ$ K and $\log g \simeq 4.80$.

The assumption that the amount of hydrogen per gram of stellar material is the same as that in the sun is in harmony with the data; i.e., there is no evidence that the subdwarfs are deficient in hydrogen. The excitation temperatures are derived from curves of growth for *Fe* I, using King's laboratory *f*-values. A comparison of theoretical and observed line profiles and equivalent widths suggests that *Ca* is deficient in the subdwarf atmospheres. Low *Fe* abundances in these stars are indicated by curves of growth constructed with Greenstein's empirical line strengths for τ UMa and υ Sgr. The color temperatures and the Balmer discontinuities are predicted.

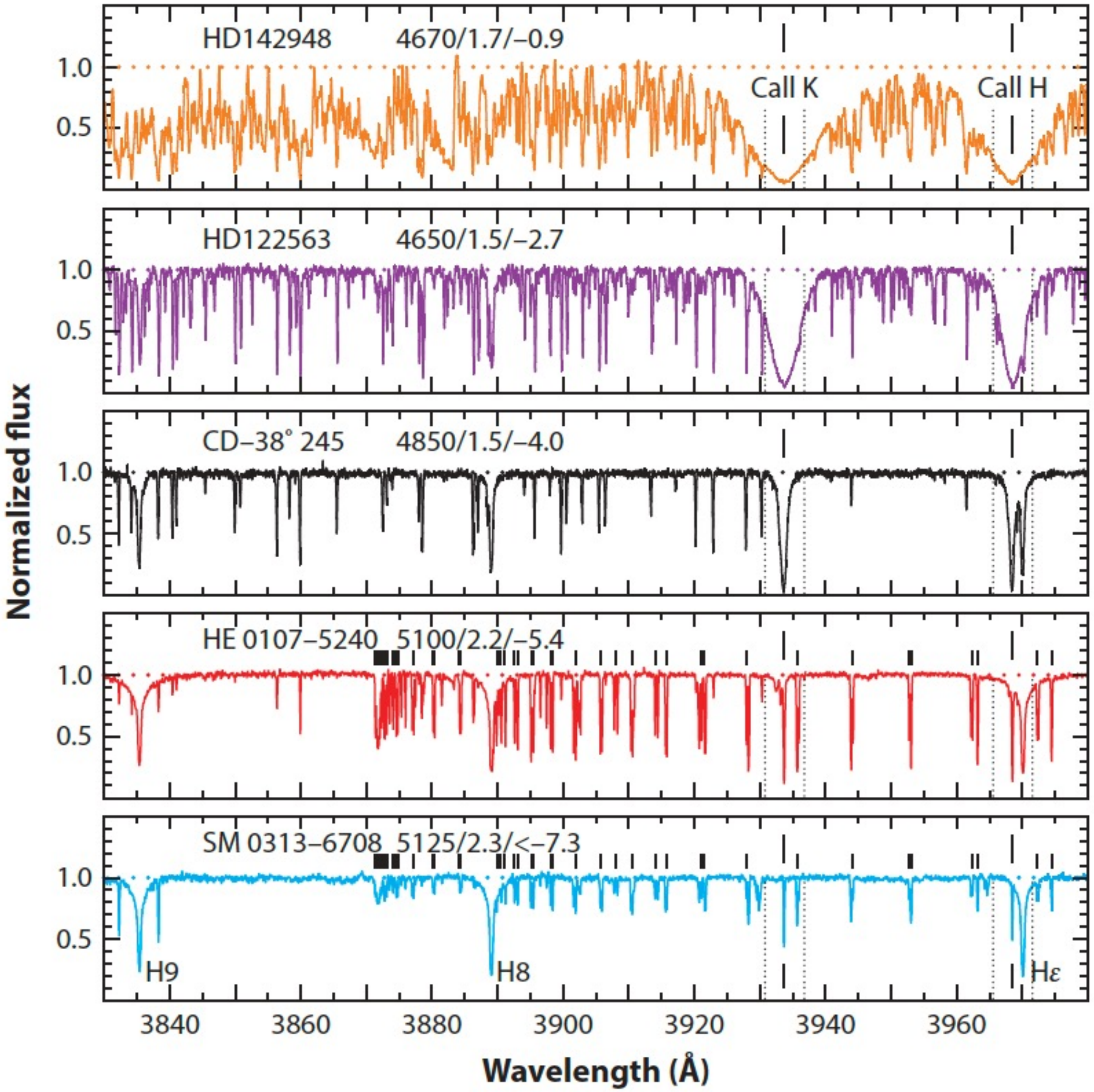
Two stars with chemical abundances one-tenth that of the Sun.


HD 140283 (Chamberlain & Aller)
HD 140283 (Baschek; Aller & Greenstein)
HD 122563 (Wallerstein et al.)
Bidelman & MacConnell
Luck & Bond
G64-12 (Carney & Peterson)
CD−38° 245 (Bessell & Norris)
HK survey (Beers et al.)
McWilliam et al.
Ryan et al.
HE 0107−5240 (Christlieb et al.)
HE 1327−2326 (Frebel et al.)
SM 0313−6708 (Keller et al.)
+2.0
+0.0
−2.0
−4.0
−6.0
−8.0
−10.0
1960
1980
2000
2020
METALLICITY
EPOCH



In this star there is one atom of Fe for each 10 millions of H atoms

METALLICTY


HD142948 4670/1.7/–0.9
CaII K
CaII H
HD122563 4650/1.5/–2.7
CD–38° 245 4850/1.5/–4.0
HE 0107–5240 5100/2.2/–5.4
SM 0313–6708 5125/2.3/<–7.3
H9
H8
Hε
1.0
0.5
Normalized flux
3840
3860
3880
3900
3920
3940
3960
Wavelength (Å)

Metallicity … we use [Fe/H] as a proxy

Is Fe the most abundant metal in the stars? NO

The 10 most abundant elements in the Sun

Oxygen	8.76
Carbon	8.50
Neon	8.05
Nitrogen	7.86
Magnesium	7.54
Silicon	7.53
Iron	7.52
Sulfur	7.16
Argon	6.50
Aluminum	6.46

$$A(Fe) = \log_{10}(\frac{N_{Fe}}{N_H}) + 12$$

Oxygen

Carbon

Neon

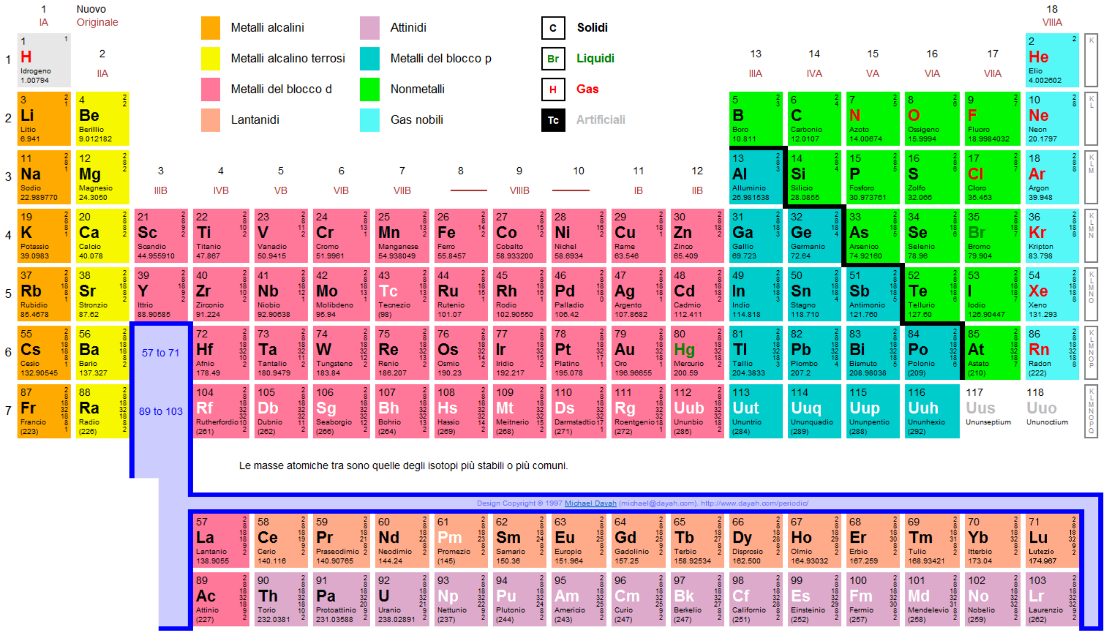
Metallicity … we use [Fe/H] as a proxy

Iron is the element providing the largest number of spectral lines

We measures Fe lines

- At different wavelengths
- At different stellar parameters
- At different metallicities (also in very metal-poor stars)

All the metals provide information about the chemical evolution … timescale, chemical polluters …



α-elements :
mainly produced in SN II
(short timescale)

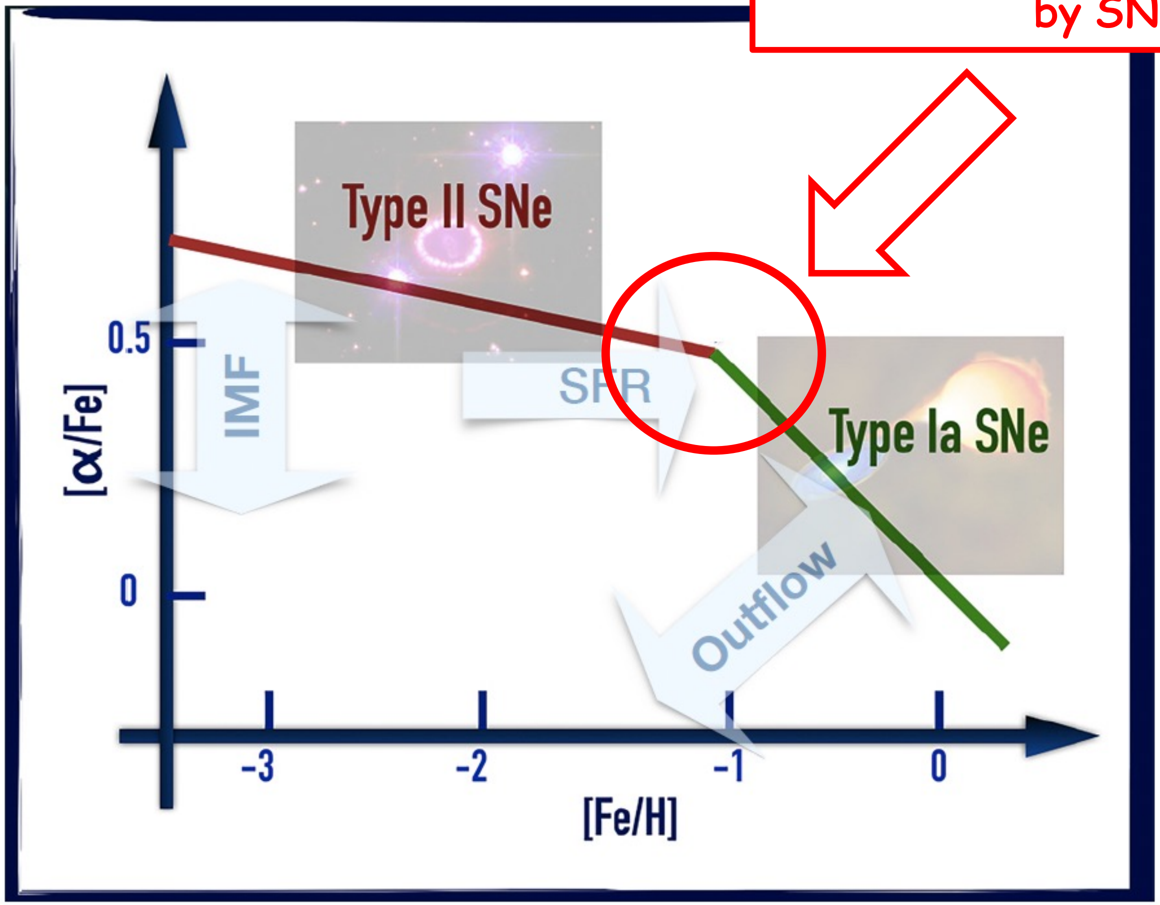
Fe (and iron-peak elements):
mainly produced in SN Ia
(long timescale)

S-process elements:
mainly produced in AGB stars

R-process elements:
mainly produced in neutron stars mergers

Not only Iron …

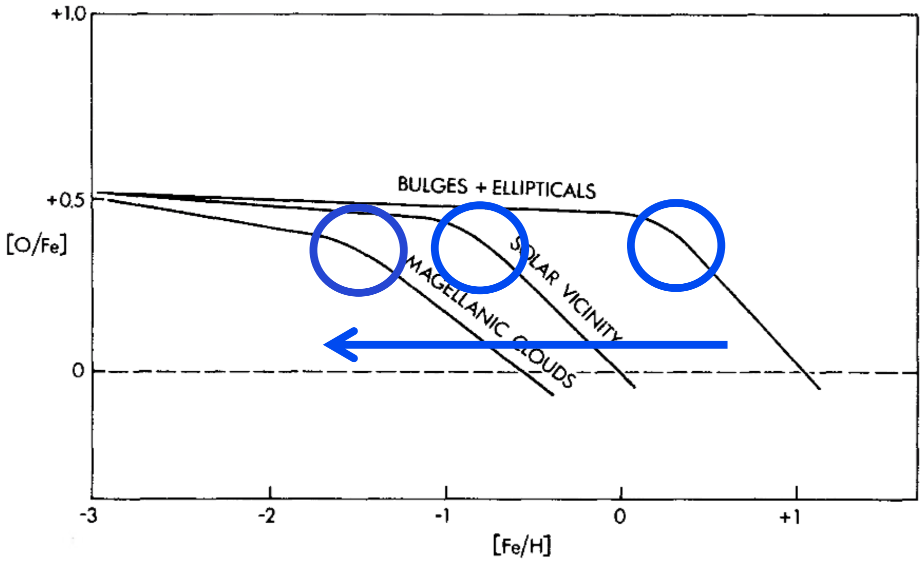
[α/Fe] is the classical diagnostic

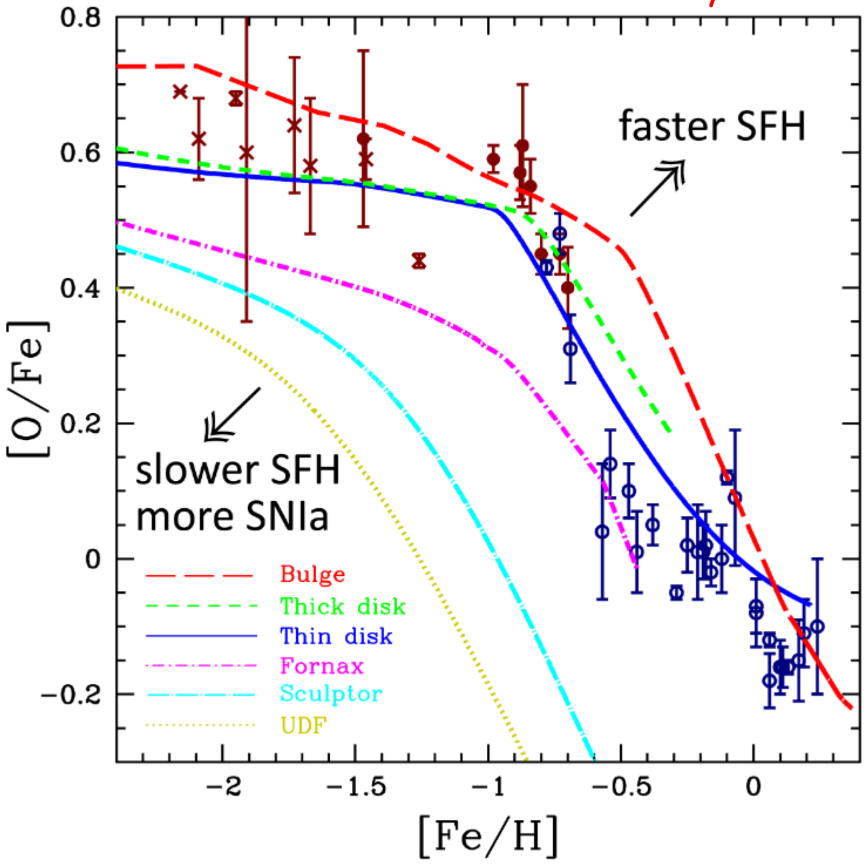


The α $-$*knee*

It marks the onset of the chemical enrichment by SNIa

The knee moves toward lower metallicity in environments with lower SFR

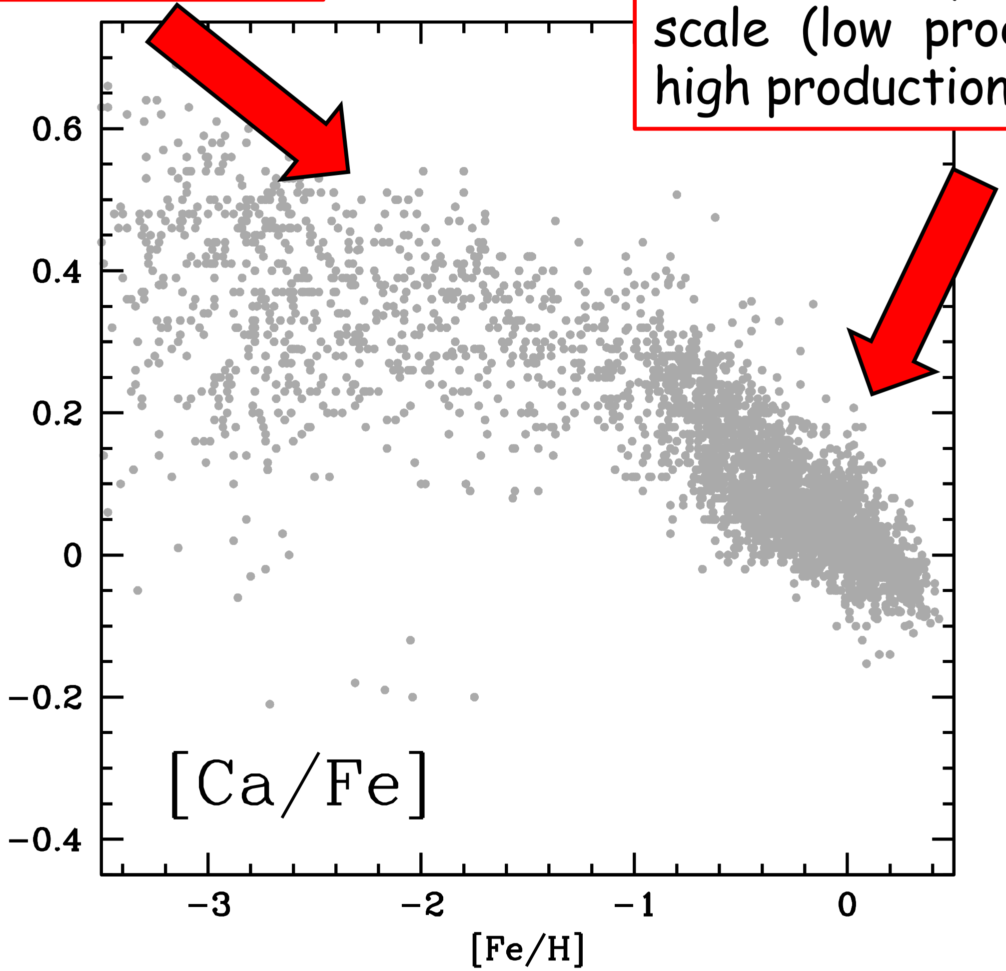

Matteucci & Brocato(1990)


Kobayashi+23

MILKY WAY : HALO

High [α/Fe] :
Production by SN II in short time scale (low production of Fe)

Low [α/Fe] :
Production by SN Ia in long time scale (low production of α and high production of Fe)

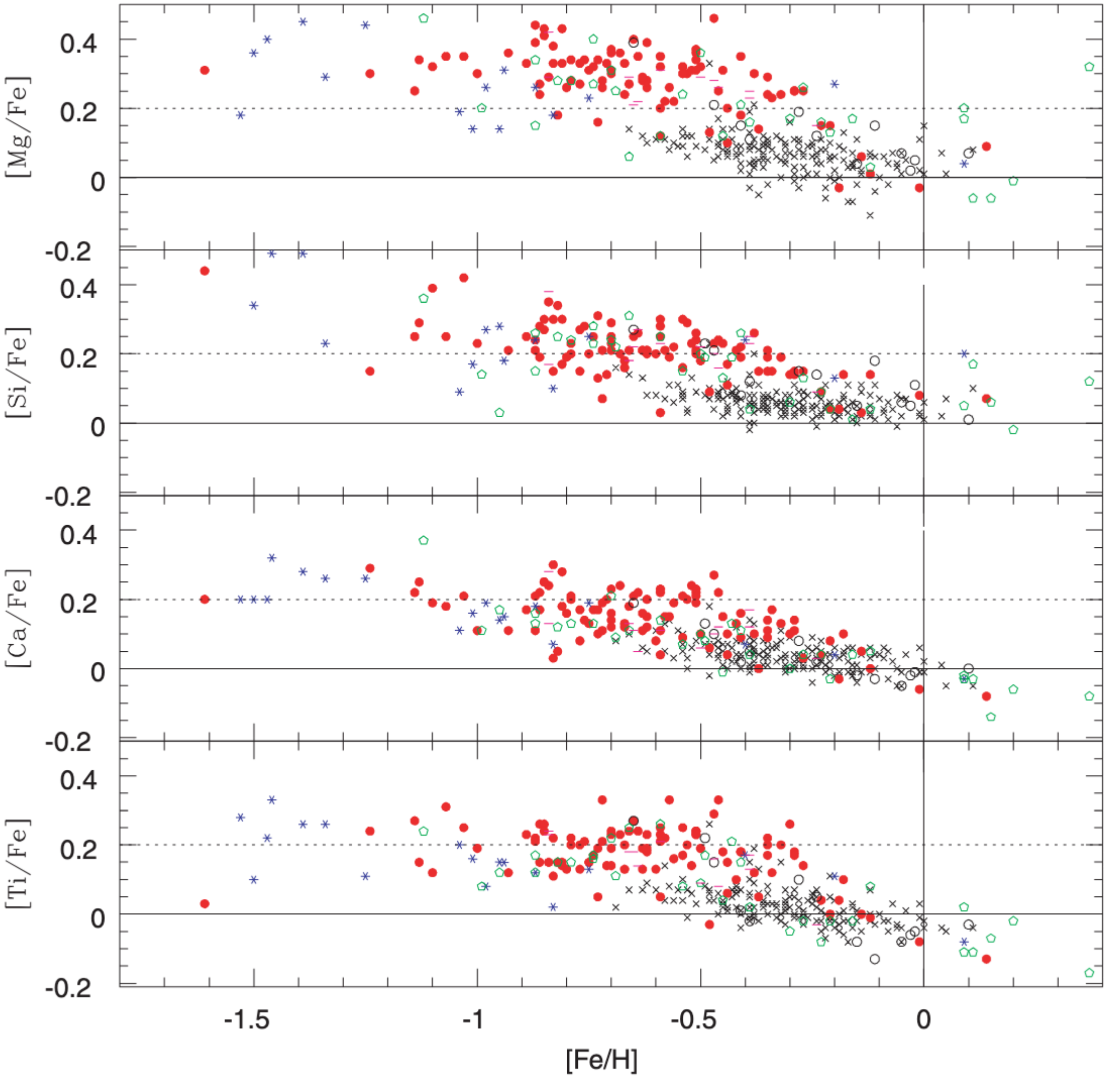


MILKY WAY : THIN/THICK DISK

Thick disk stars

Thin disk stars

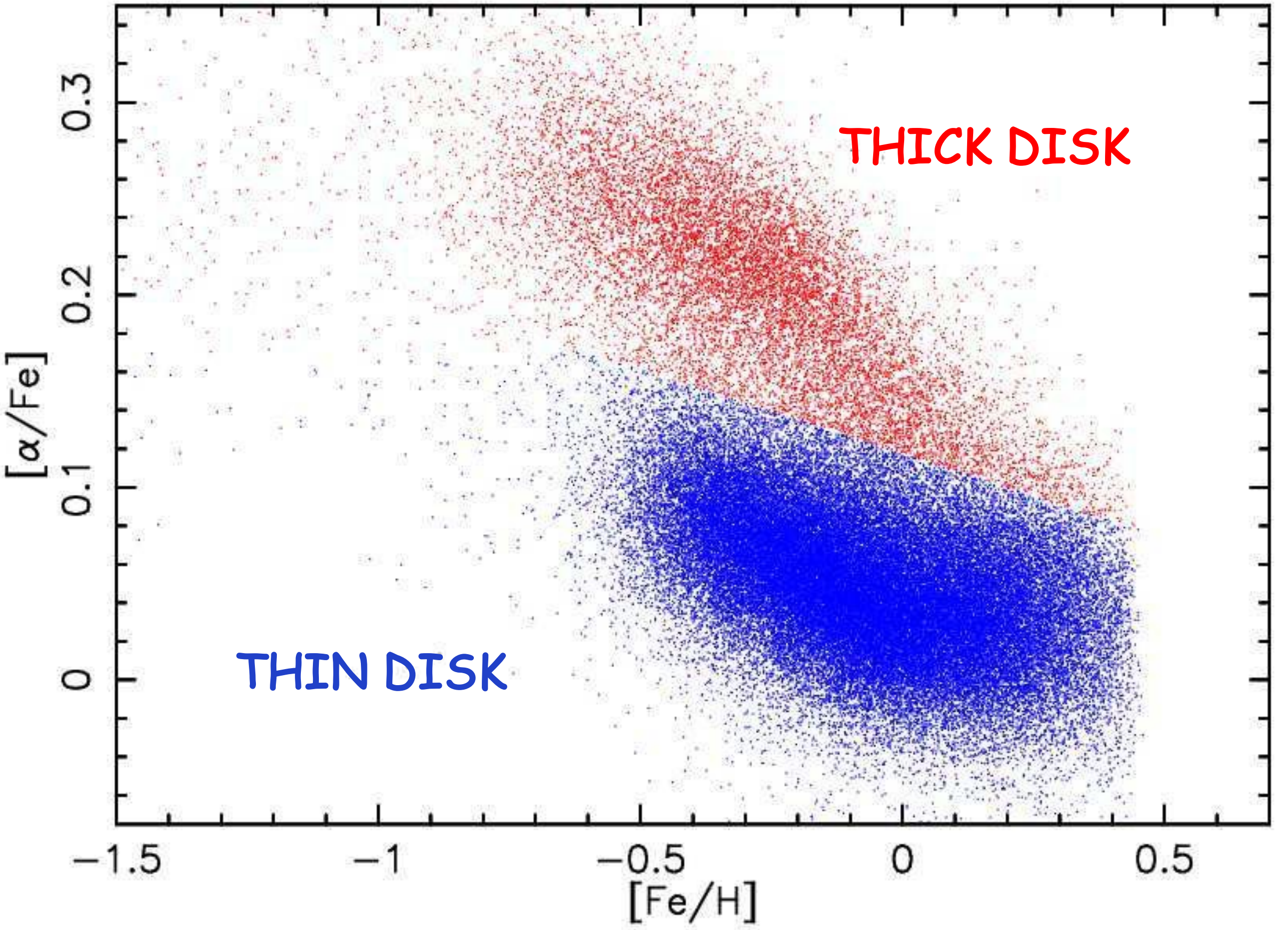
Reddy+06



MILKY WAY : THIN/THICK DISK

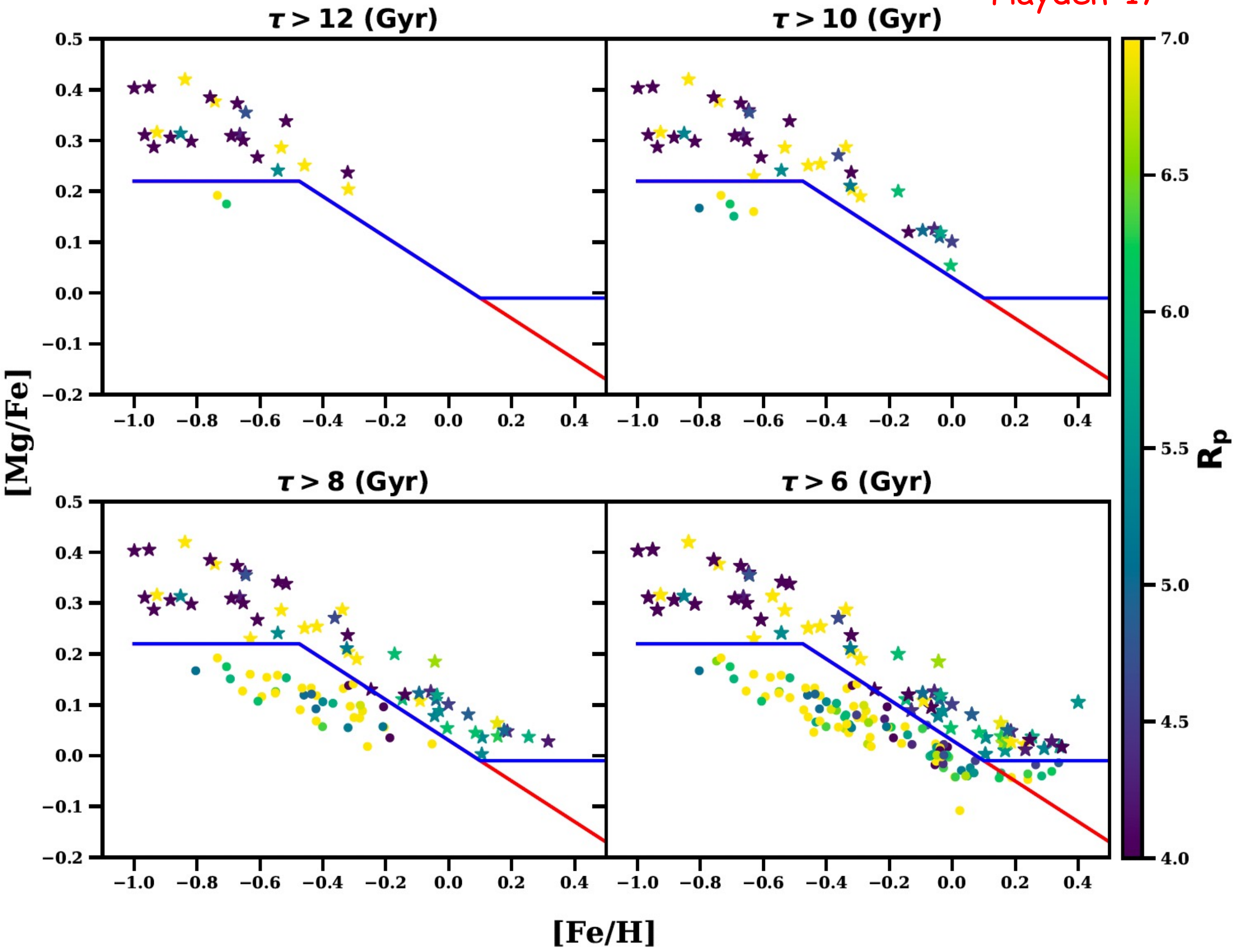
APOGEE

Hayden+15



MILKY WAY : THIN/THICK DISK

Hayden+17

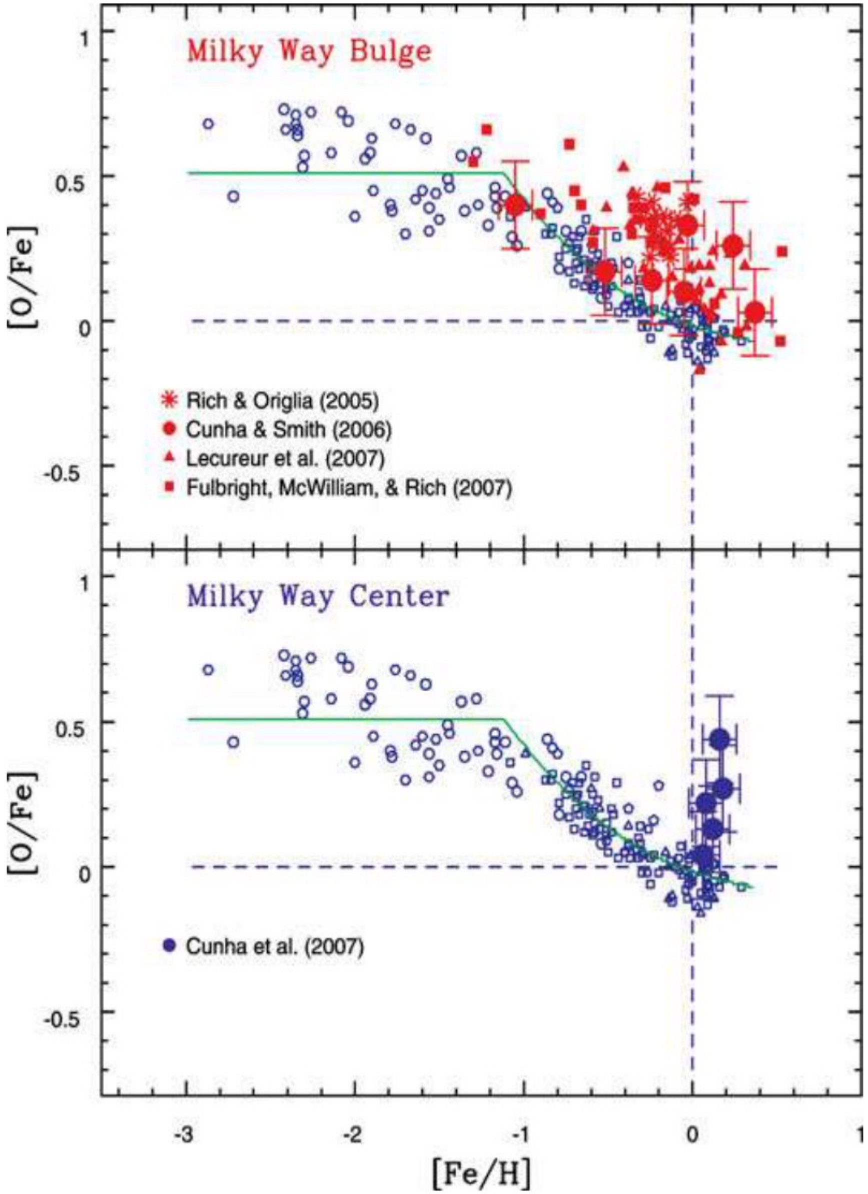


MILKY WAY : BULGE

The Galactic Bulge stars are solar or over-solar and with high [α/Fe] …

The Galatic Bulge is old and with a very efficient star formation rate (fast chemical enrichment)

Cunha+08



AND THE STELLAR POPULATIONS OUTSIDE THE MILKY WAY?

Irregular galaxies

Large and Small
Magellanic Clouds

Dwarf spheroidal
galaxies

Sagittarius,
Sculptor, Fornax …

METALLICITY DISTRIBUTION AND ABUNDANCE RATIOS IN THE STARS OF THE GALACTIC BULGE

FRANCESCA MATTEUCCI[1] AND ENZO BROCATO[2]

Received 1990 March 1; accepted 1990 June 15

If our interpretation is correct, one can also extrapolate these considerations to less evolved systems such as Magellanic Irregulars or the external regions of the disk of the Galaxy. In this case, we should expect that a slower evolution has led the abundance ratios to drop at lower metallicities than in the solar vicinity. In other words, although at the moment we do not have detailed calculations, we can predict that ratios such as [O/Fe] in the Magellanic Clouds should appear less overabundant with respect to the solar neighborhood of our Galaxy at the same [Fe/H]. Indications for a similar behavior come from observations of Russel, Bessel, and Dopita (1988), who instead interpreted this effect as due to preferential loss of ejecta from high-mass stars in low-mass galaxies. In Figure 4 the predicted different evolution of [O/Fe] vs. [Fe/H] in different systems, as due to their different age-metallicity relations is sketched.

METALLICITY DISTRIBUTION AND ABUNDANCE RATIOS IN THE STARS OF THE GALACTIC BULGE

Francesca Matteucci[1] and Enzo Brocato[2]

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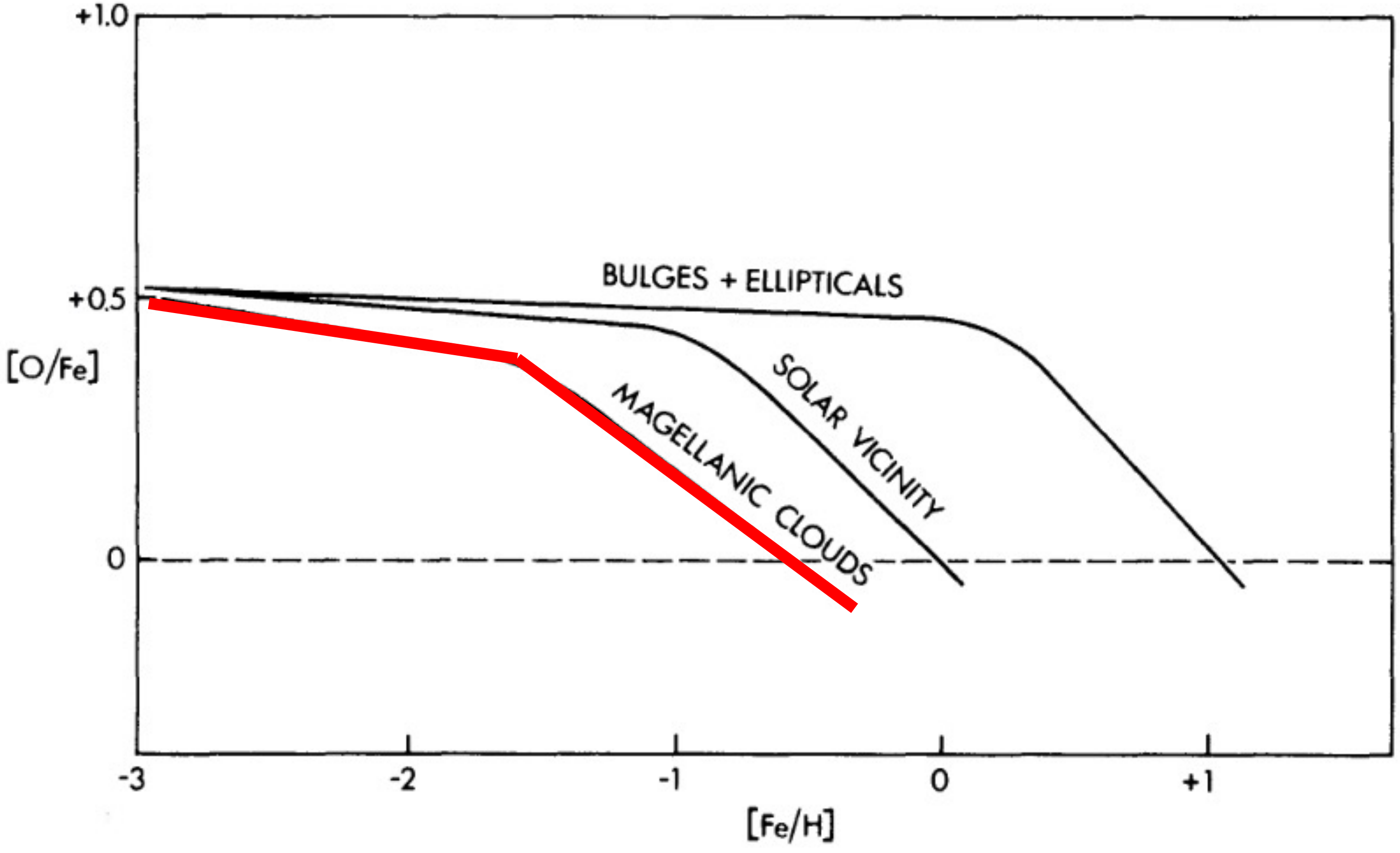
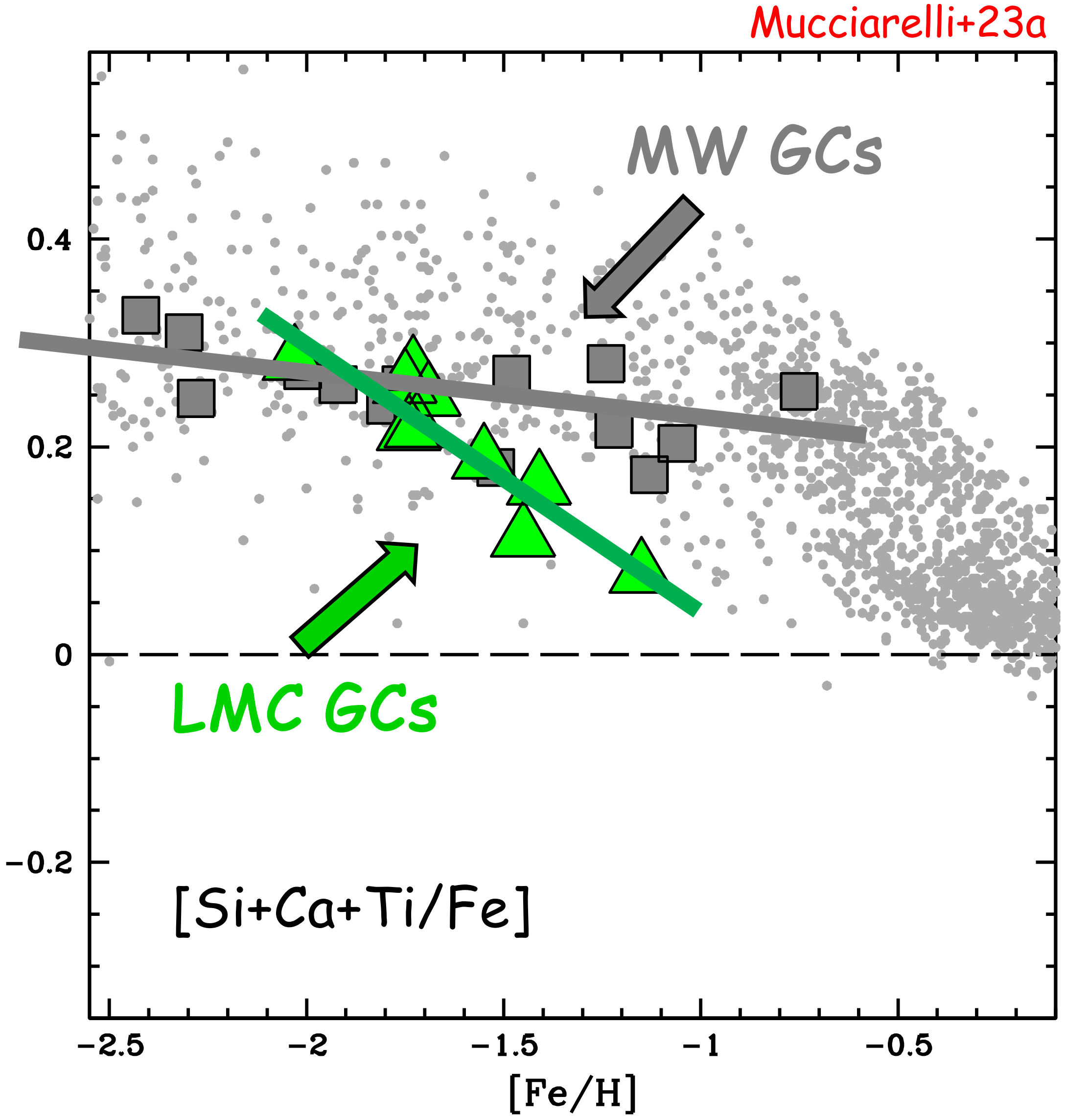


Large Magellanic Cloud

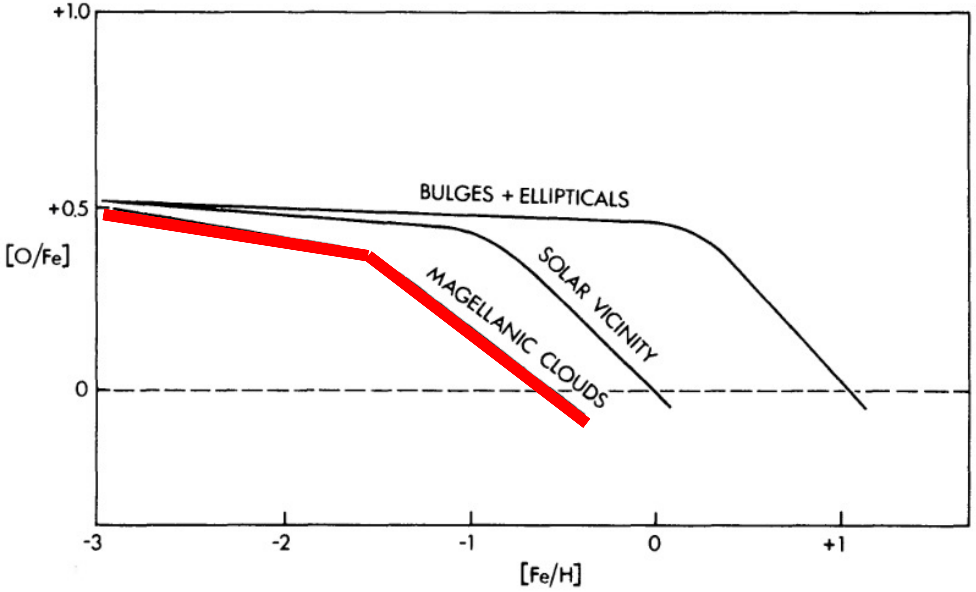


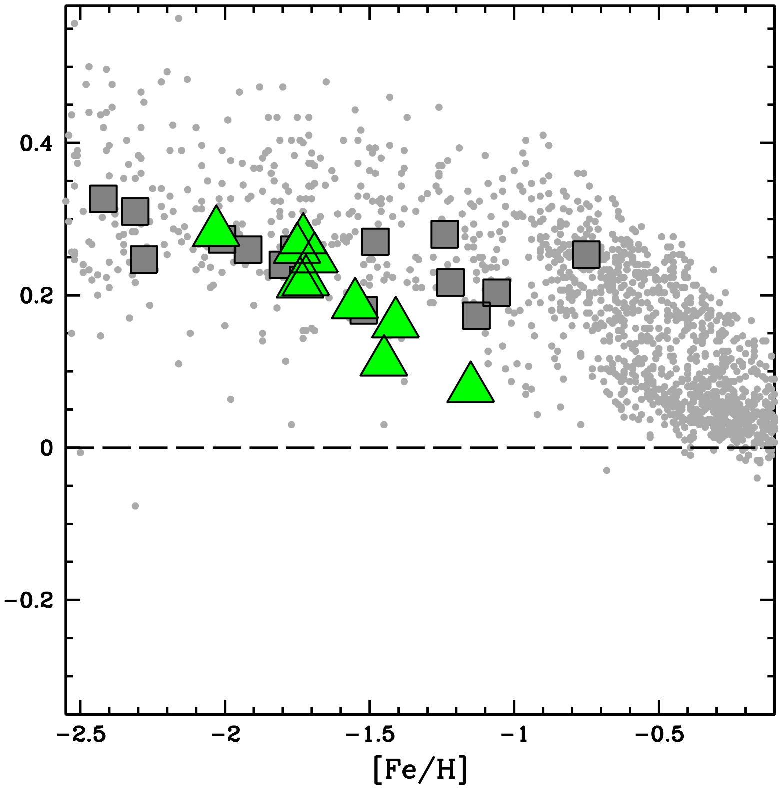
The LMC GCs draw well-defined sequences wrt MW GCs

This reflects the different chemical enrichment histories of the two galaxies

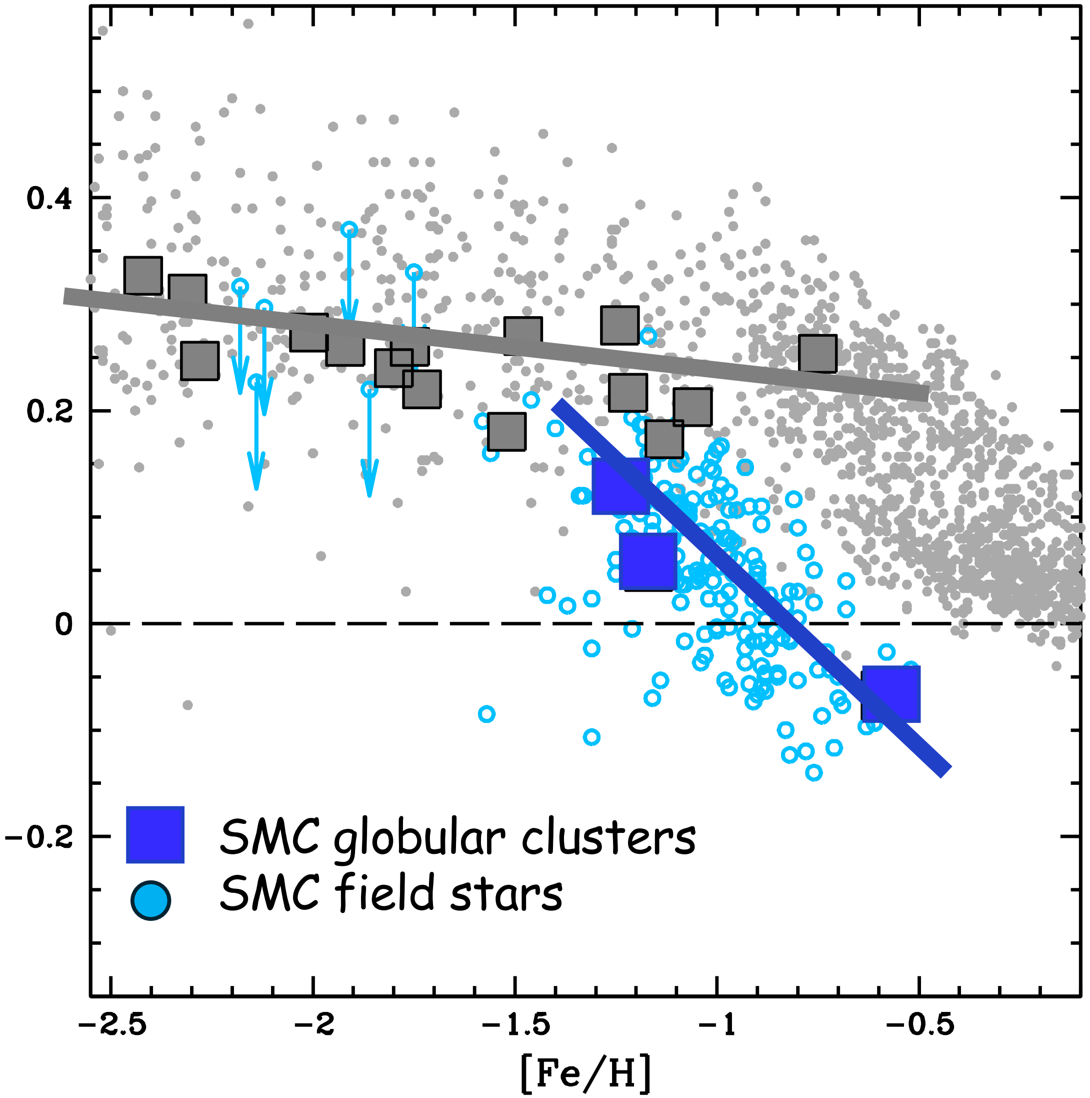
Large Magellanic Cloud

The stellar populations in the Large Magellanic Clouds have an α –knee more metal-poor than the Milky Way





Small Magellanic Cloud



Mucciarelli+23b

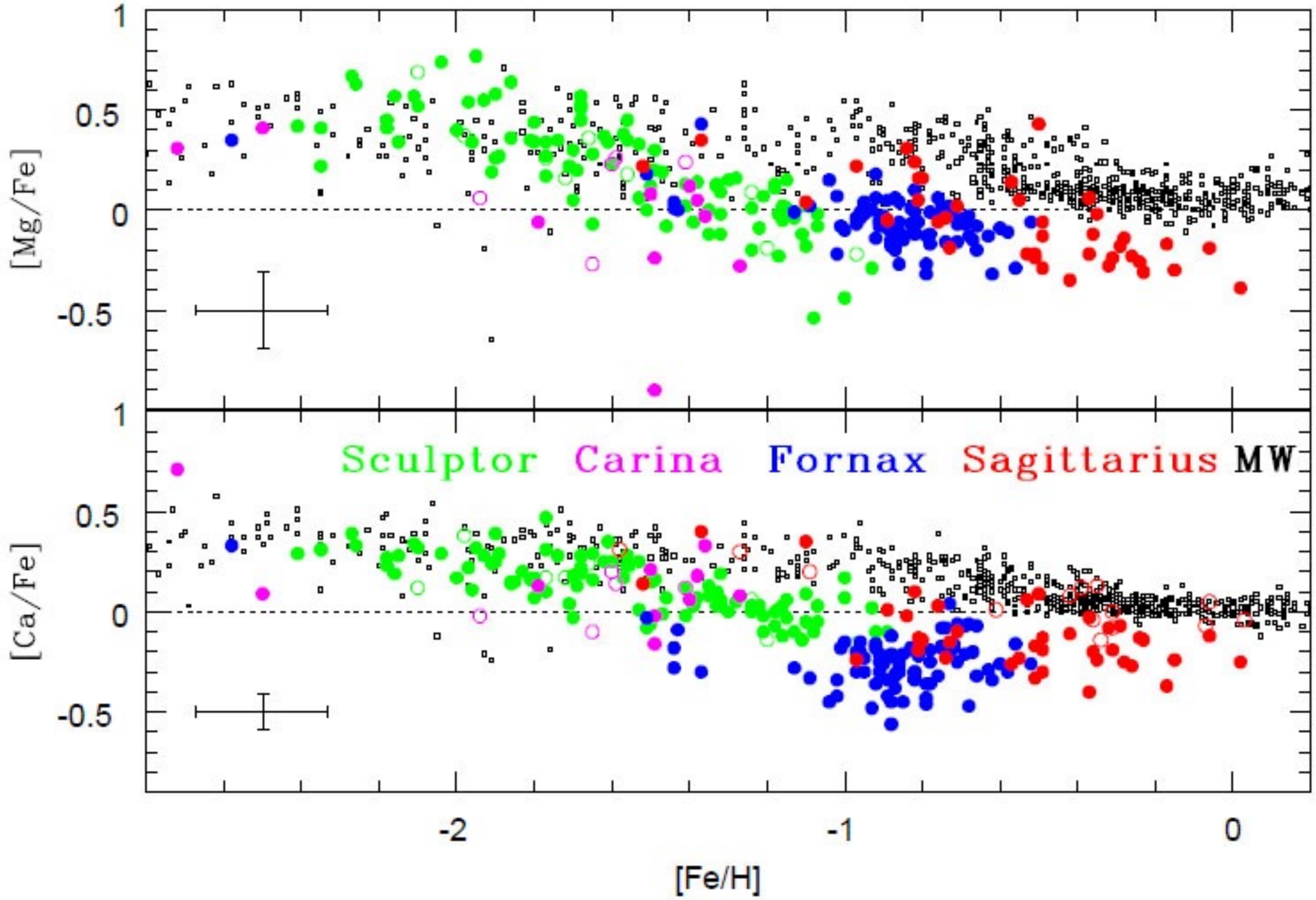
The SMC stars draw well-defined sequences wrt MW stars

This reflects the different chemical enrichment histories of the two galaxies

Dwarf spheroidal galaxies

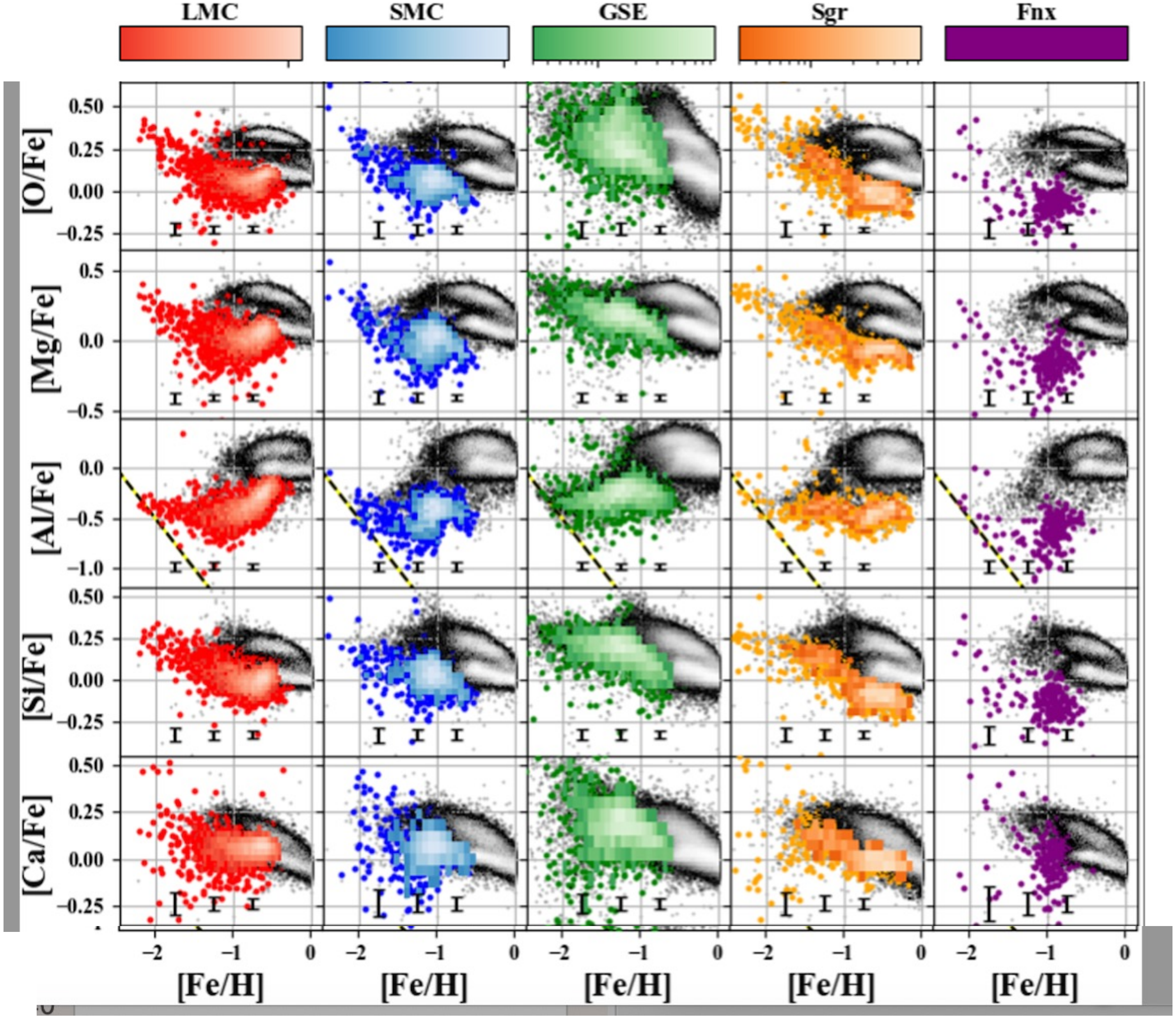
The dwarf spheroidal galaxies have star formation rates slower than that of the Milky Way and they exhibit lower [alfa/Fe] wrt to Milky Way stars of similar [Fe/H].

Tolstoy+09



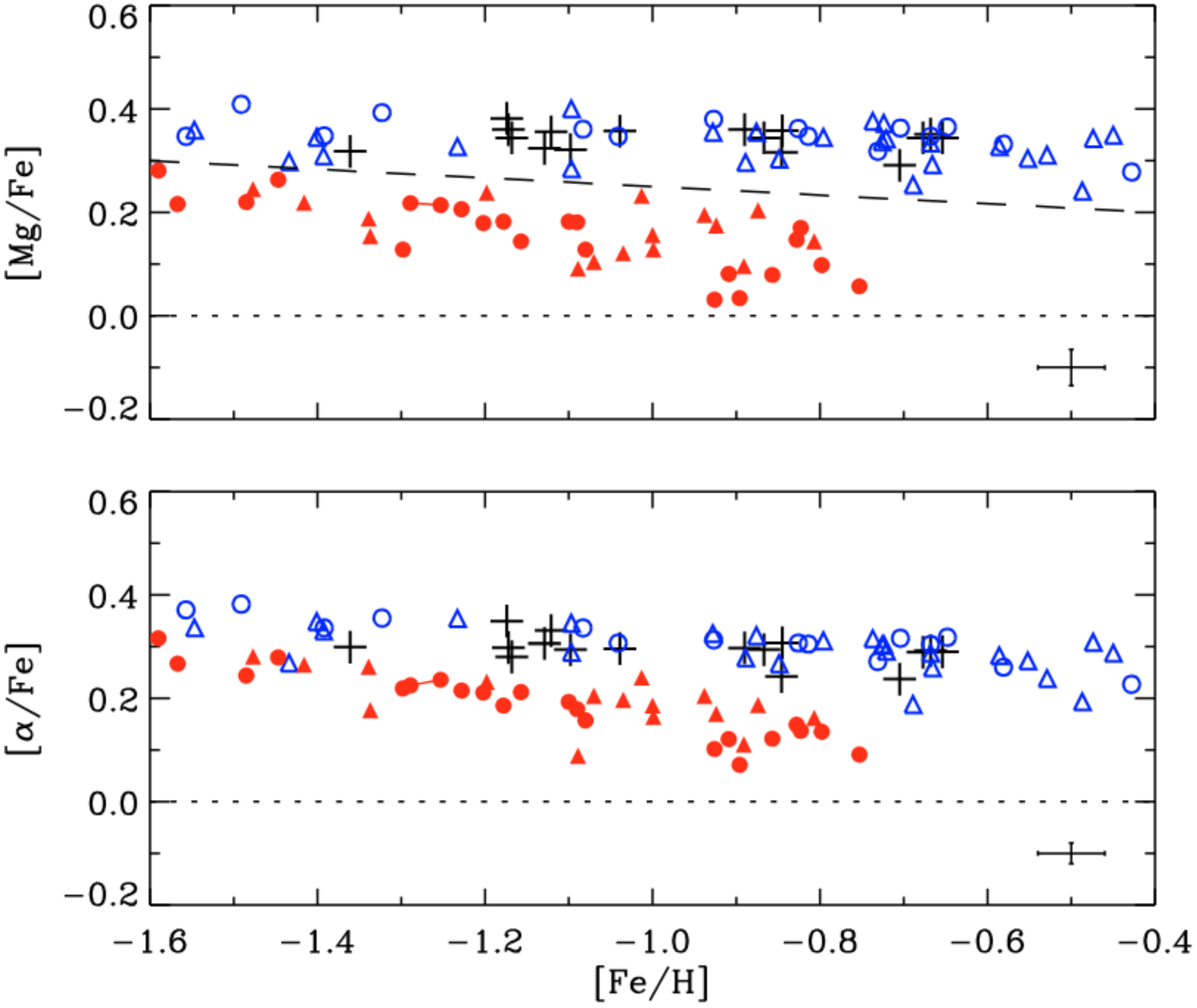
Dwarf spheroidal galaxies

Hasselquist+21



Stellar populations hidden in the Galactic Halo

Nissen & Schuster+10

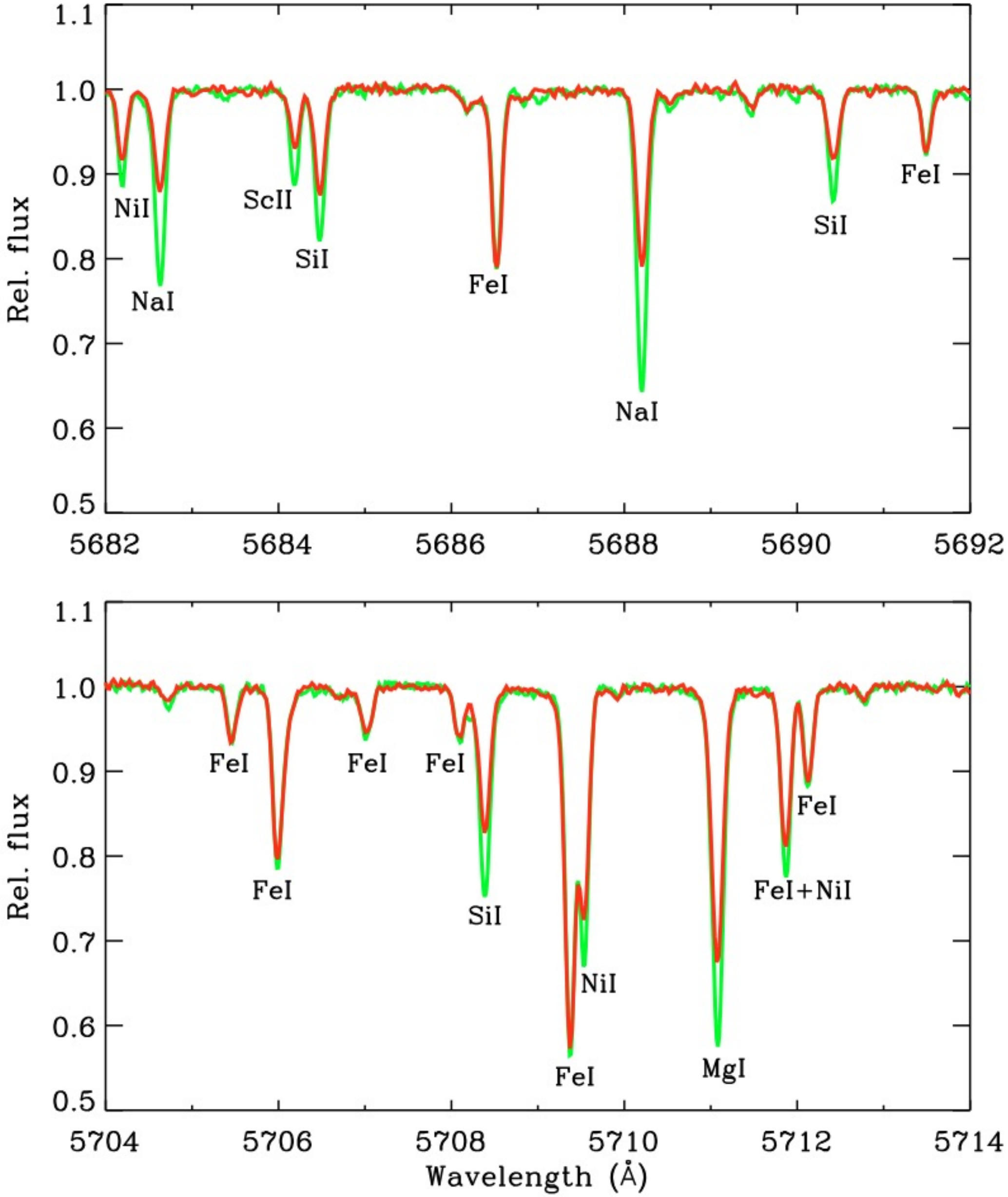


UVES@VLT spectra

R ~ 55,000

SNR > 200

Nissen & Schuster+10



Nissen & Schuster+10

UVES@VLT spectra

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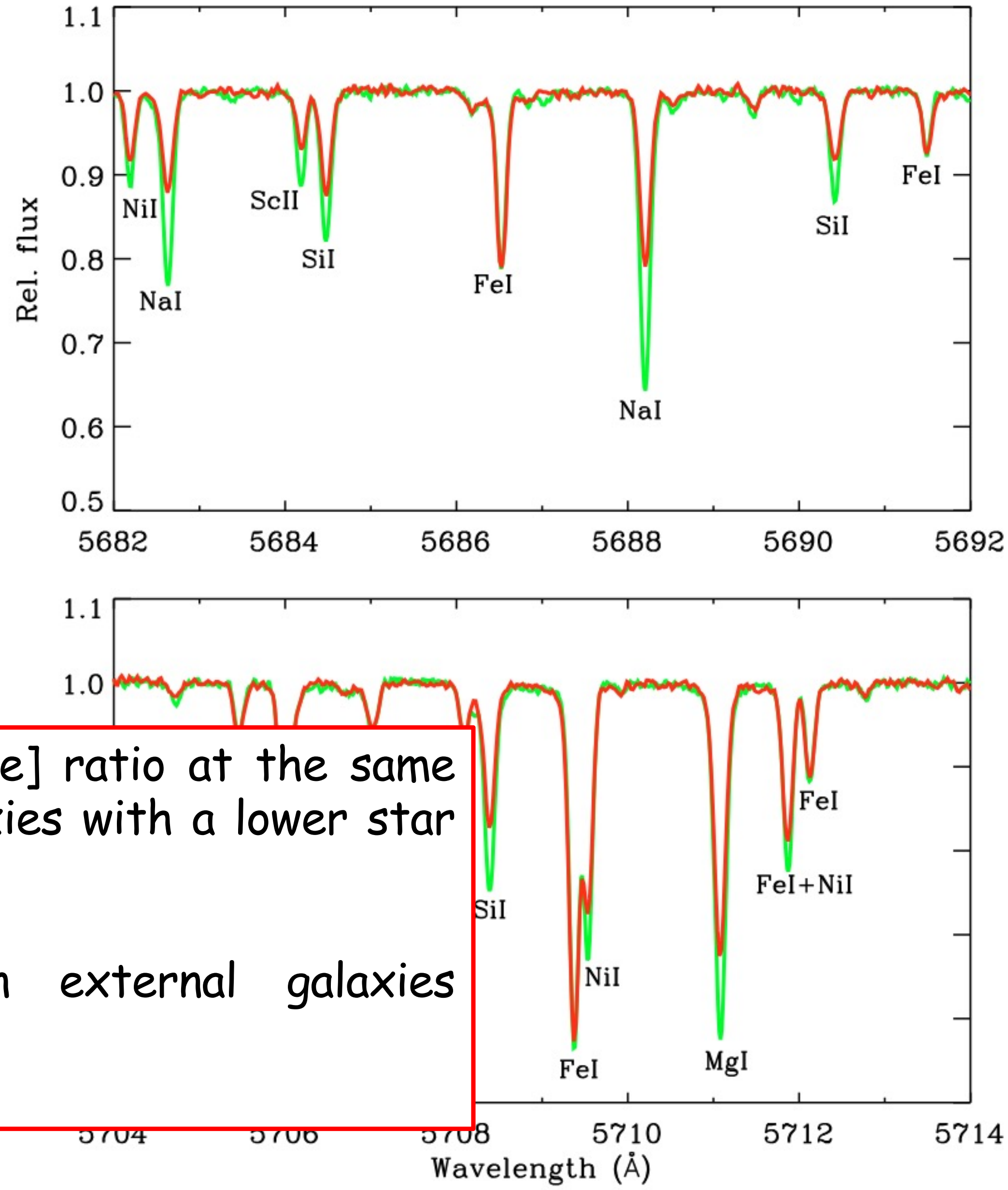
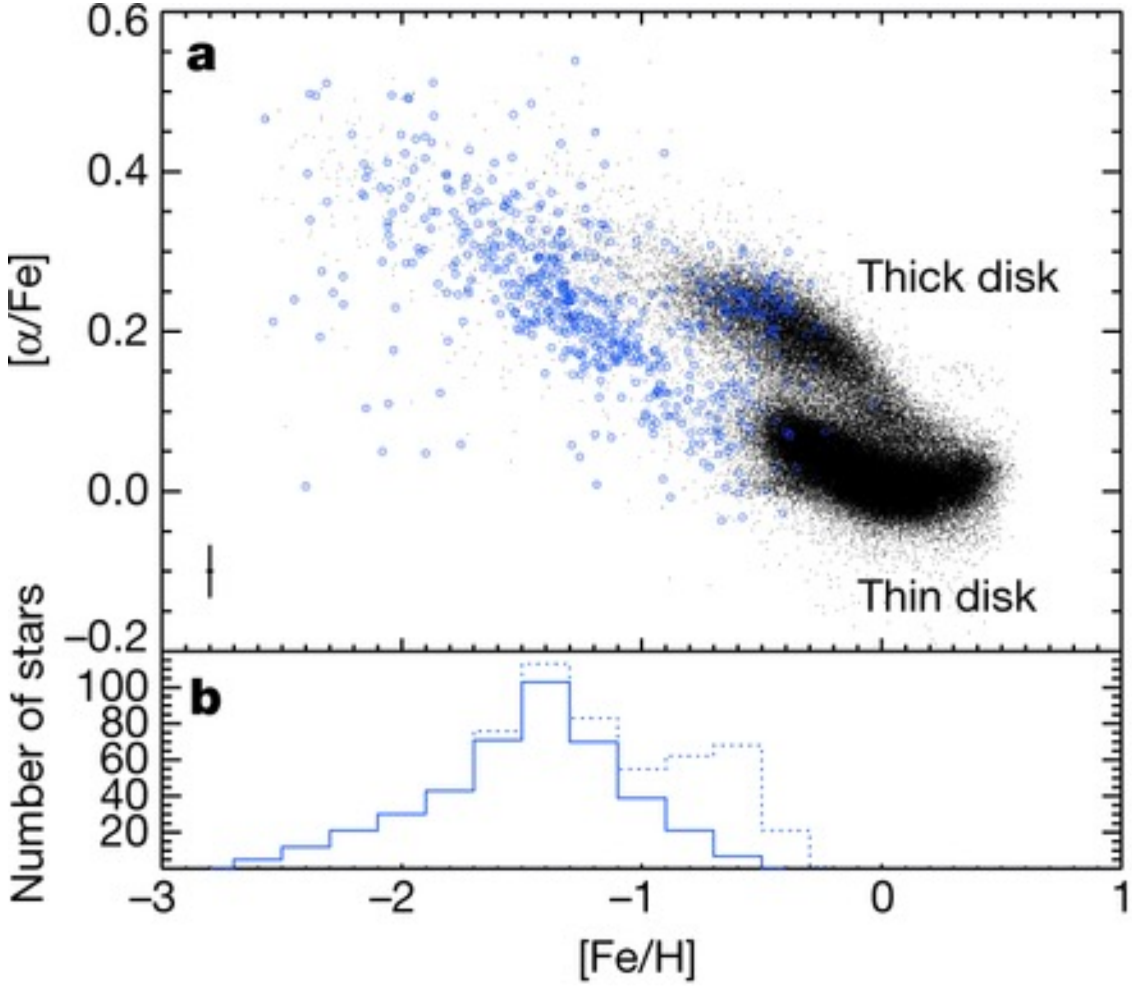


The Halo stars with low [α/Fe] ratio at the same [Fe/H] should formed in galaxies with a lower star formation rate.

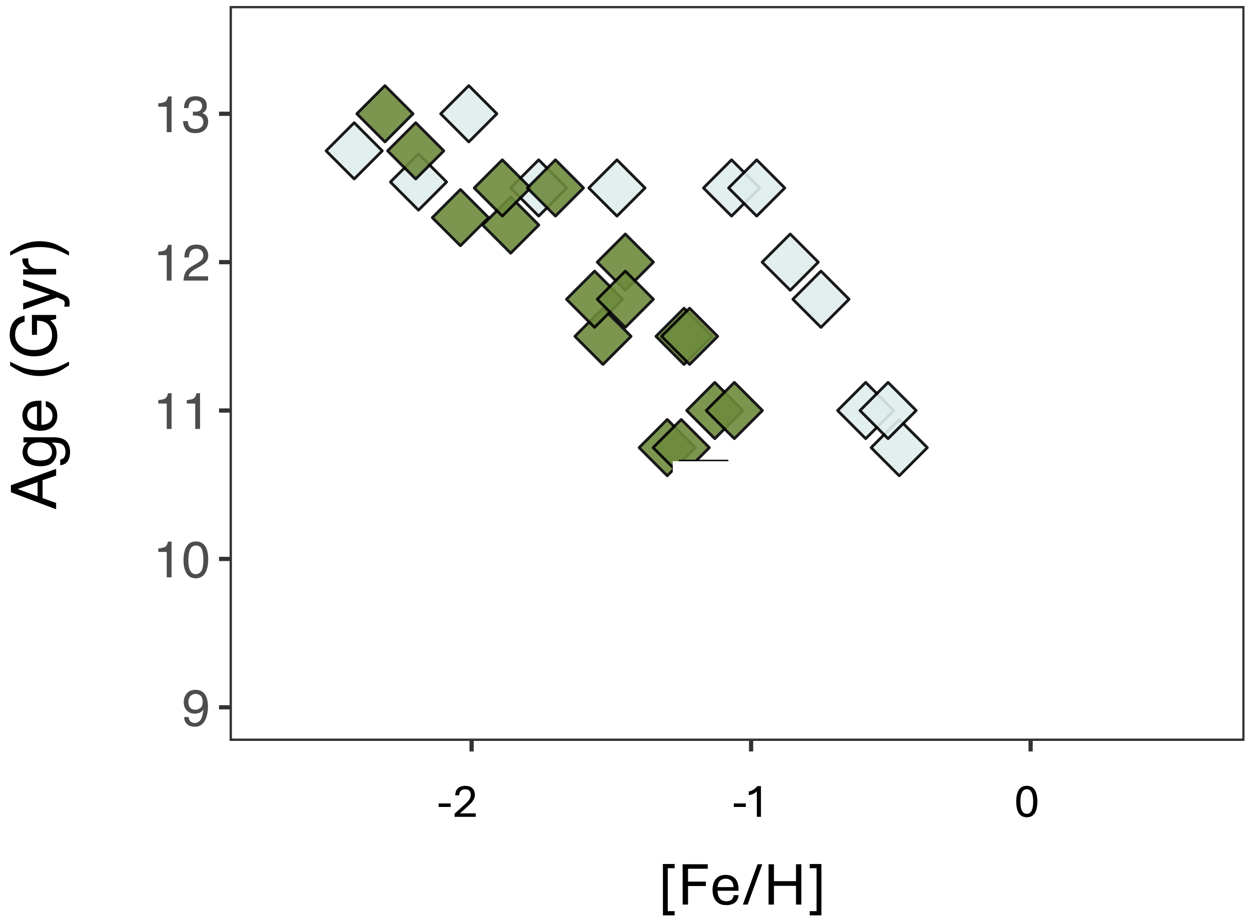
Accreted stars: formed in external galaxies accreted by the Milky Way

The Gaia mission identified Milky Way stars moving on different orbits (thanks to proper motions and parallaxes). These stars have lower [α /Fe] than Milky Way stars with normal orbits. These stars are the remnant of a past merger event with a now disrupted dwarf galaxy (Gaia-Enceladus).

Helmi+18



The age-metallicty relation of in-situ and accreted globular clusters.



◇ In situ MW GCs

◆ Accreted GCs

In situ and accreted globular clusters in the Milky Way trace different age-metallicity relations: different stellar populations

An old nomenclature used by astronomers… but still in use:

Population I:

Young, metal-rich stars like [illegible] Sun … 2% [illegible]eir mass is made of metals.

Population II:

Old, metal-poor stars … 0.1% or les[illegible]heir mass is composed of metals.

Population III:

The first stars, completely [illegible]d of metal[illegible]O METALS AT ALL!!!

The current nomenclature for the stellar populations in the Milky Way

Halo, in-situ stars:
Old, metal-poor stars formed in the early Milky Way

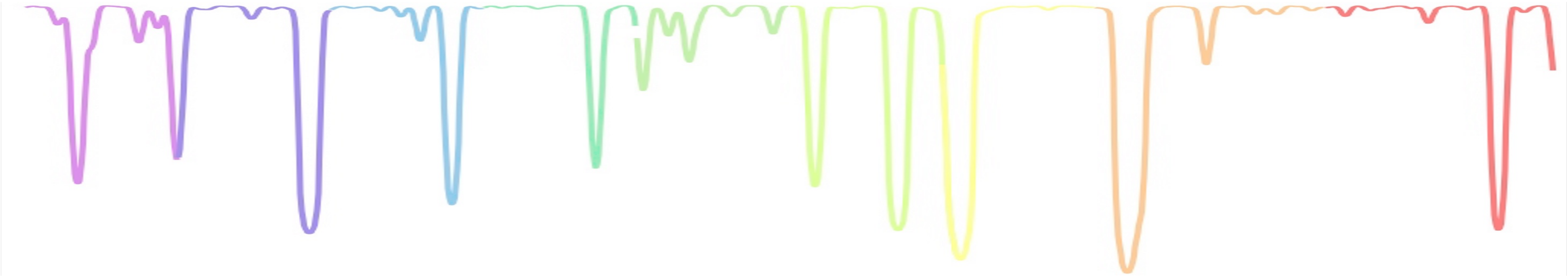
Halo, accreted stars:
Old, metal-poor stars formed in Milky Way satellites (accreted and now disrupted)

Thick disk stars:
Old, metal-intermediate stars

Thin disk stars:
Young, metal-intermediate/metal-rich stars

Galactic Bulge:
Old, metal-rich stars formed in the early Milky Way

Summary



- High-resolution spectroscopy (often together with precise kinematics) allows us to group stars with similar chemical composition (= similar chemical DNA)
- New nomenclature of the stellar populations in our Galaxy thanks to the chemical tagging
- A step towards the future: the use of chemical tagging to identify stellar populations in external galaxies