Núcleo de Astrofísica Teórica

Chemical Evolution Models for Dwarf Spheroidal Galaxies

Gustavo A. Lanfranchi
Núcleo de Astrofísica Teórica - Universidade Cruzeiro do Sul

F. Matteucci, G. Cescutti. H. Monteiro, A. Caproni

Chemical evolution in the Universe: the next 30 years, Castiglione della Pescaia,September 15 – 20, 2013

Introduction

Dwarf galaxies are the most common type of galaxy in the universe: dominant in the number (~ 40 in the Local Group).

Classic dwarf spheroidal galaxies are characterized by low luminosities ($-18 < M_B < -9$), low masses ($10^6 M_\odot – 10^9 M_\odot$), small sizes ($R_c = 0{,}09$ - $0{,}9$ *kpc*), and, normally, a low metal content (from ~ 0.1 to 0.001 solar) (Mateo 98, Hill et al. 2009).

They are dark matter dominated and made of mostly primordial material.

They exhibit very complicated star formation histories (SFH) and chemical enrichment – complex systems with varied evolution ruled by yet unknown physical mechanisms.

dSph – formation and evolution

How do they evolve? What physical processes control their evolution?

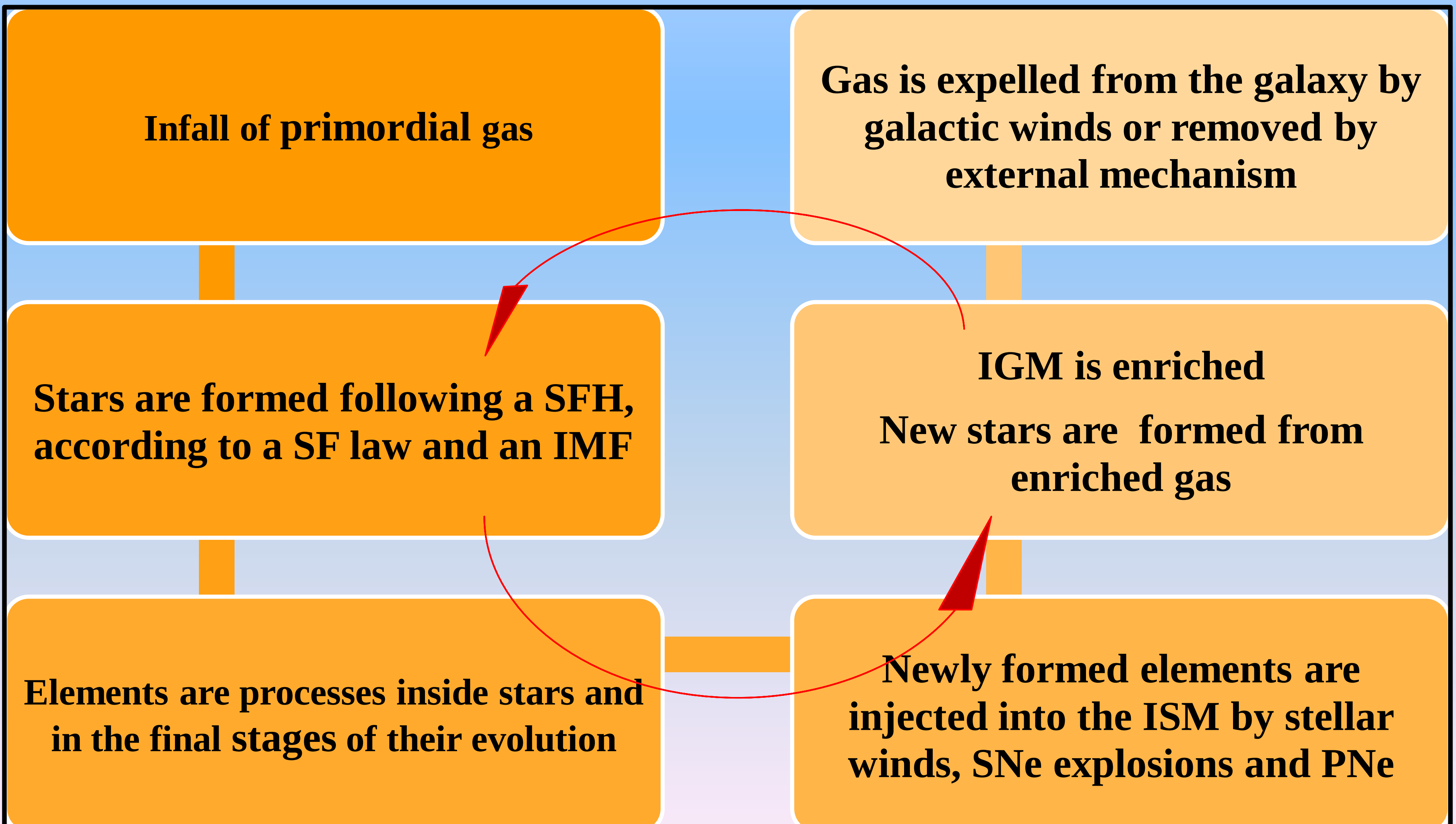
The SFRs are generally low and in long episodes and a fraction of the gas is removed from the galaxy by unknown mechanisms: internal or external (Marcolini et al. 2006, Fenner et al. 2006, Lanfanchi & Matteucci 2006, Lanfranchi et al. 2008, Revaz et al. 2010, Salvadori et al. 2010).

How much gas can be removed by winds? Is there also external mechanism (ram pressure, tidal stripping, etc.)?

What defines the observed patterns of the abundance ratios and the shape of the SMDs?

Chemical Evolution

The study of chemical enrichment and formation of elements are very important tools in the understanding of how galaxies form and evolve.



Chemical Evolution

A very important tool in chemical evolution are abundance ratios of key elements.

Different elements, produced in different timescales, can be used as “chemical clocks” and impose constraints in the SFH and SFR of a galaxy, for instance.

Besides that, the stellar metallicity distribution, the age-metallicity relation, present day mass, SNe rate and other observables can be compared to chemical evolution models, which provide clues to the formation and evolution of the system analysed.

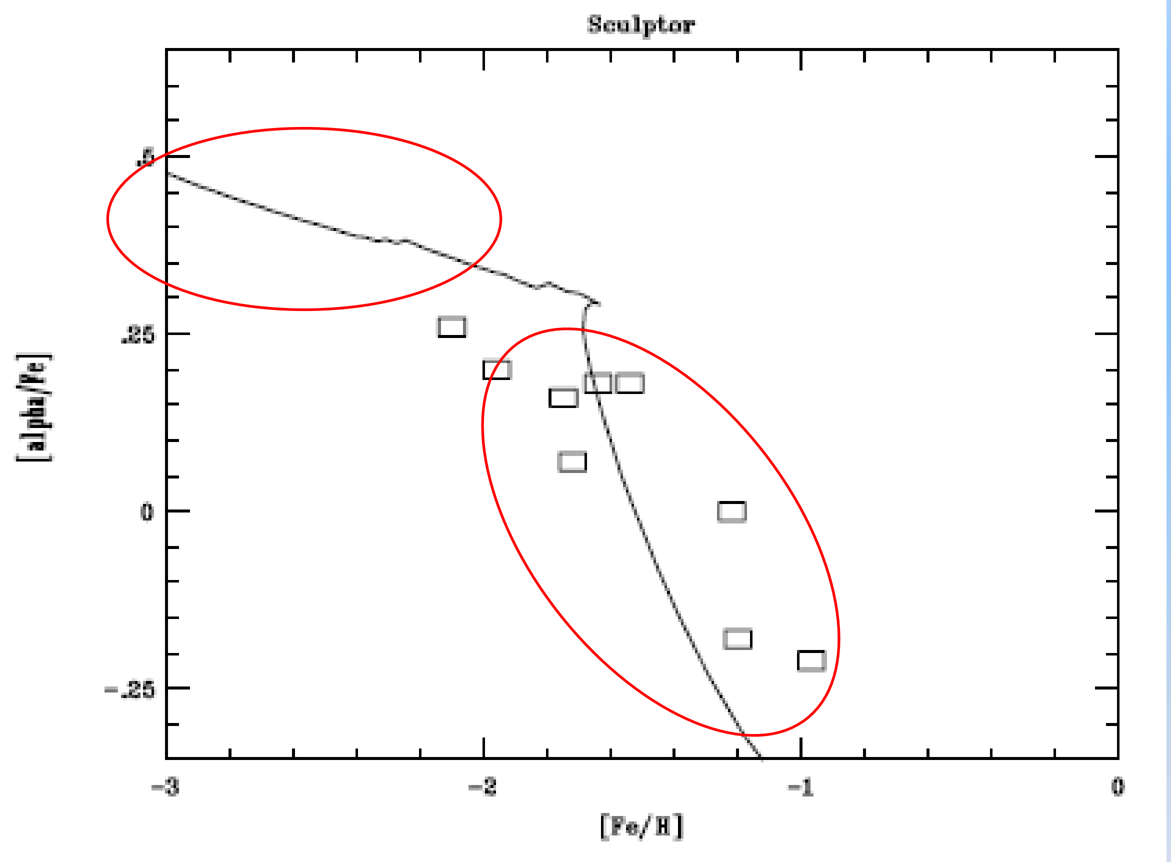
Alpha and Fe-peak Elements

Alpha elements are produced mainly in SNe II ($M > 8\ M_o$) in short timescales: from 10^7 - 10^8 yr depending on the initial mass.

Fe-peak elements on the other hand are injected into the ISM in a much longer timescale (10^8 - 10^{10} yr), since their main production site is SNe Ia.

The [alpha/Fe] ratio can be used to constrain the SFR, SFH and other parameters, such as galactic wind rate.

Alpha and Fe-peak Elements



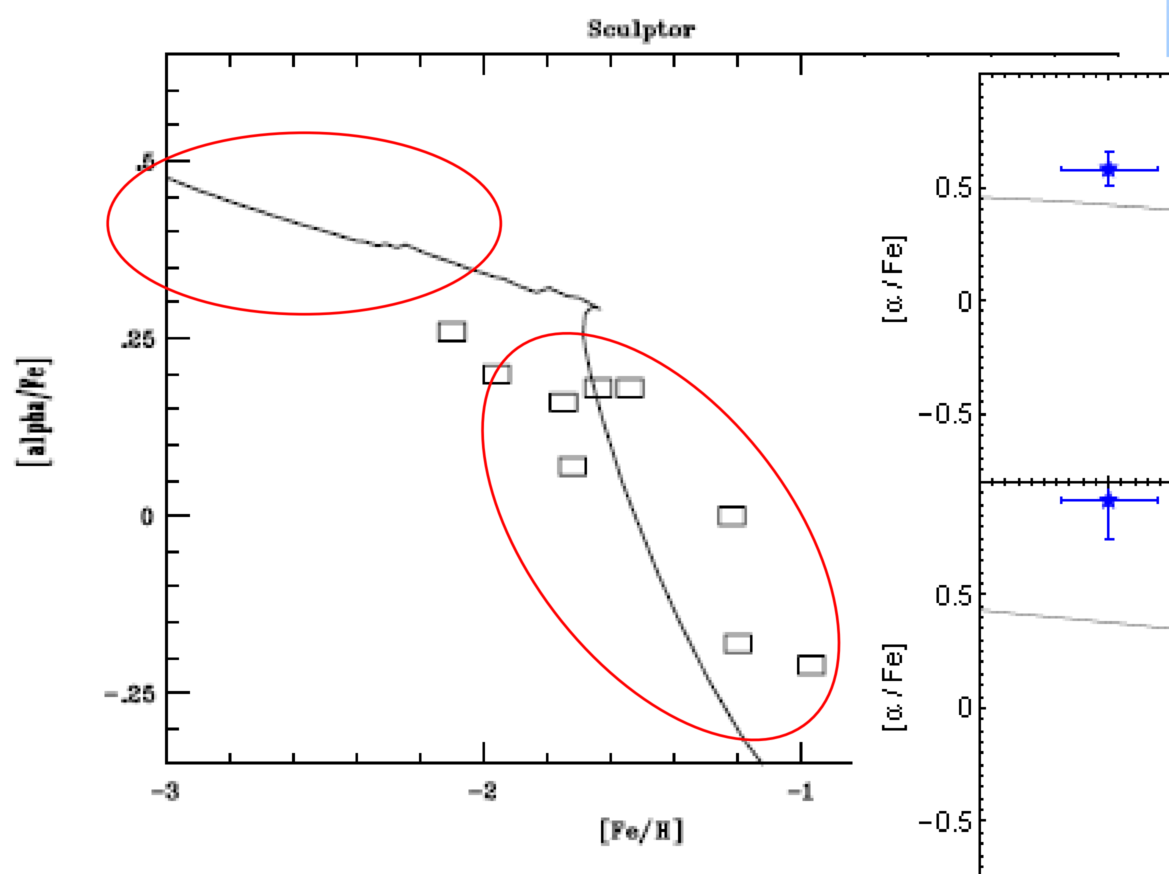
Geisler et al. 2007

Early injection in the ISM of α elements by SNe II – high values at low metallicities ([Fe/H] < -2.0).

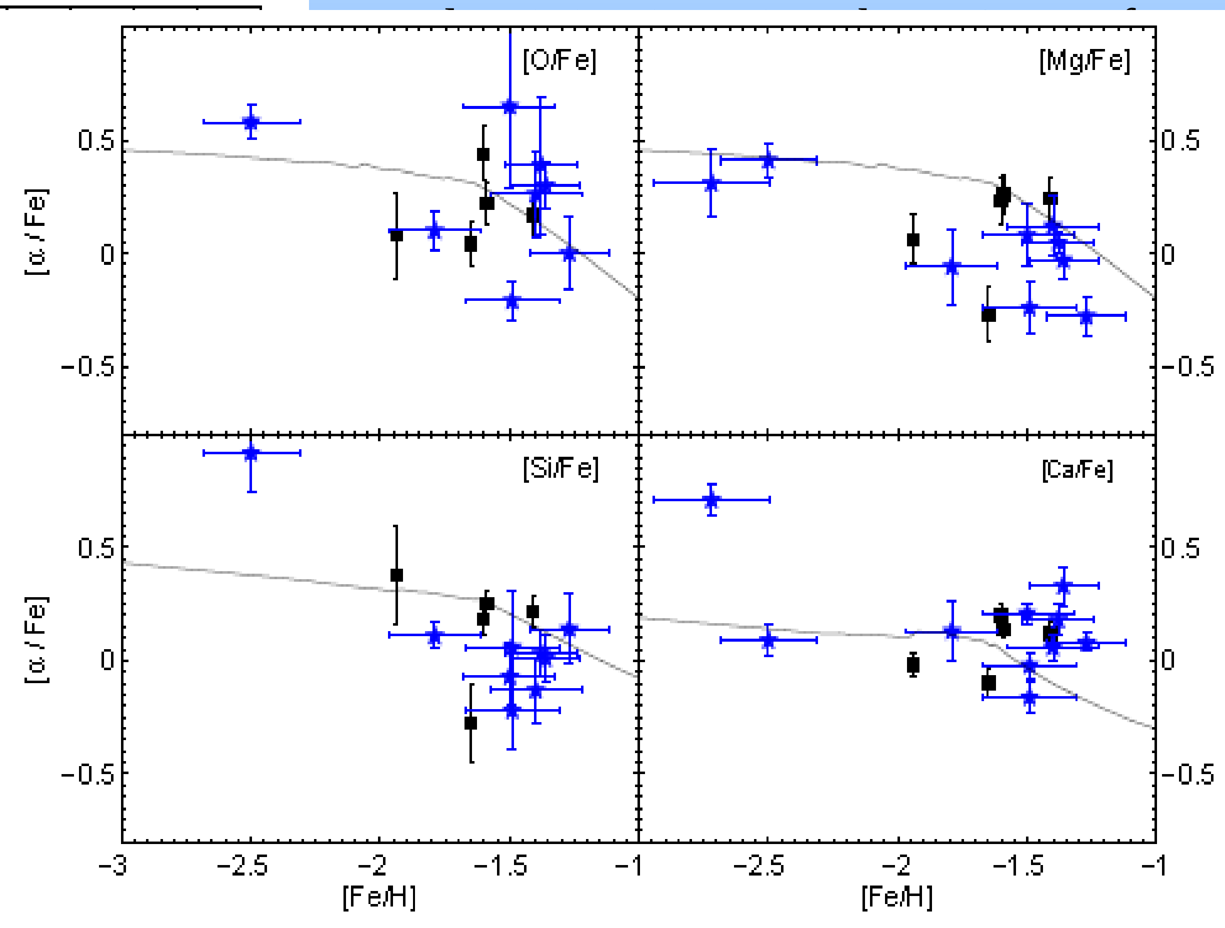
Sharp decrease at [Fe/H] < -1.6 due to low SFR and intense galactic wind.

Gas is removed from the ISM and the SFR decreases substantially, almost halting the production of α elements, whereas Fe continues to be injected in the ISM by SNeIa.

Alpha and Fe-peak Elements



Geisler et al. 2007



Koch et al. 2008

Neutron Capture Elements

Neutron capture elements can be produced by two different processes (r and s-process), that take place in different sites.

The r-process is assumed to take place in massive stars in a large range of masses ($M = 10 - 30\ M_o$) whereas the s-process is believed to occur in low and intermediate mass stars (LIMS), with masses in the range $1 - 3\ M_o$.

The analysis of the abundance ratios of neutron capture elements over Fe and between themselves can impose constraints in their nucleosynthesis.

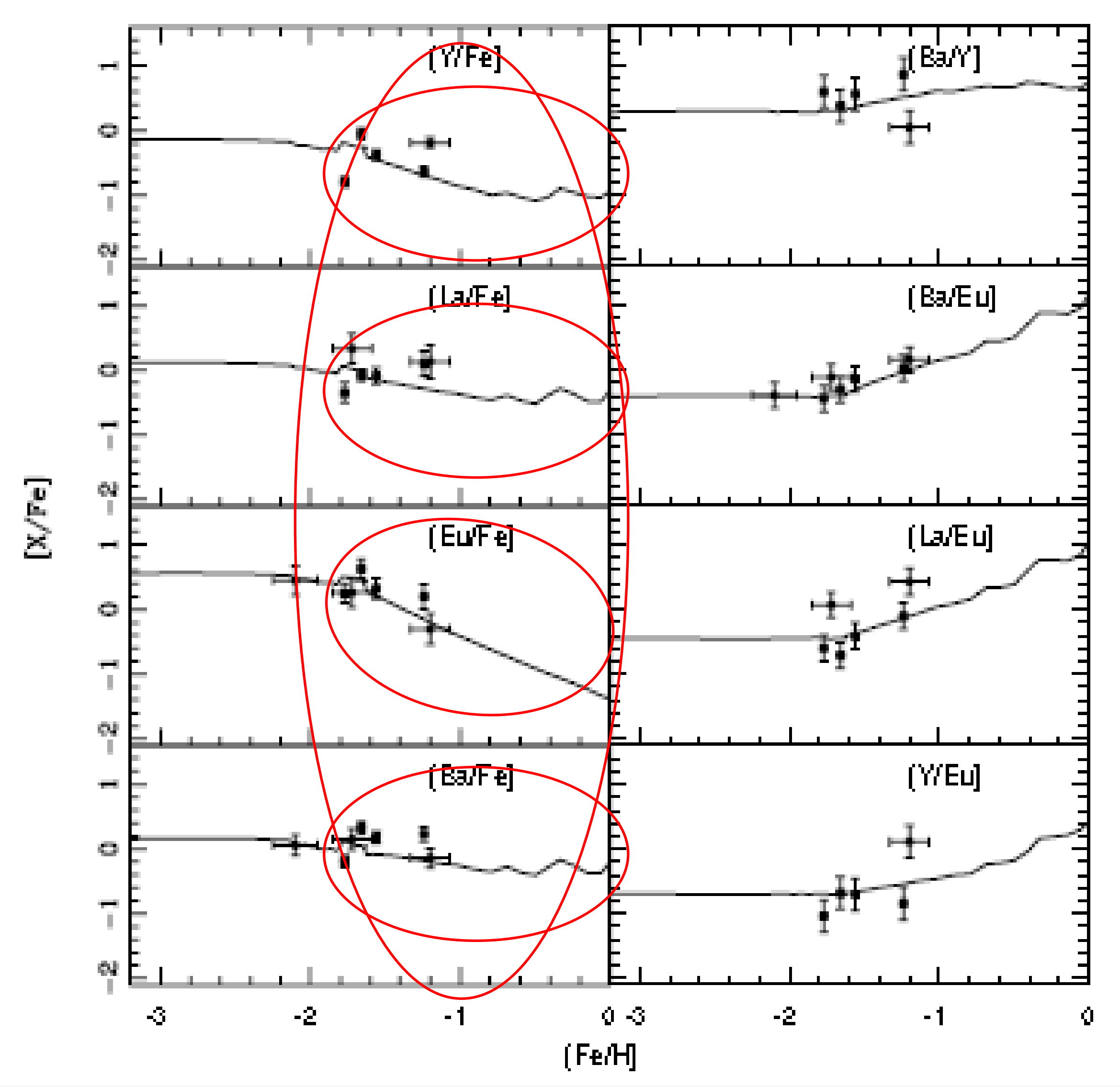
Neutron Capture Elements

Sculptor model – Busso et al. 2001 and Cescutti et al. 2006 yields for r- and s-process

Decrease of [Y,Ba,La,Y/Fe] at high [Fe/H] due to the galactic wind.

[Eu/Fe] – sharper decrease since Eu is assumed to be produced only in massive stars.

[La,Ba,Y/Fe] – smoother decrease due to the s-production in LIMS.



Lanfranchi & Matteucii 2009

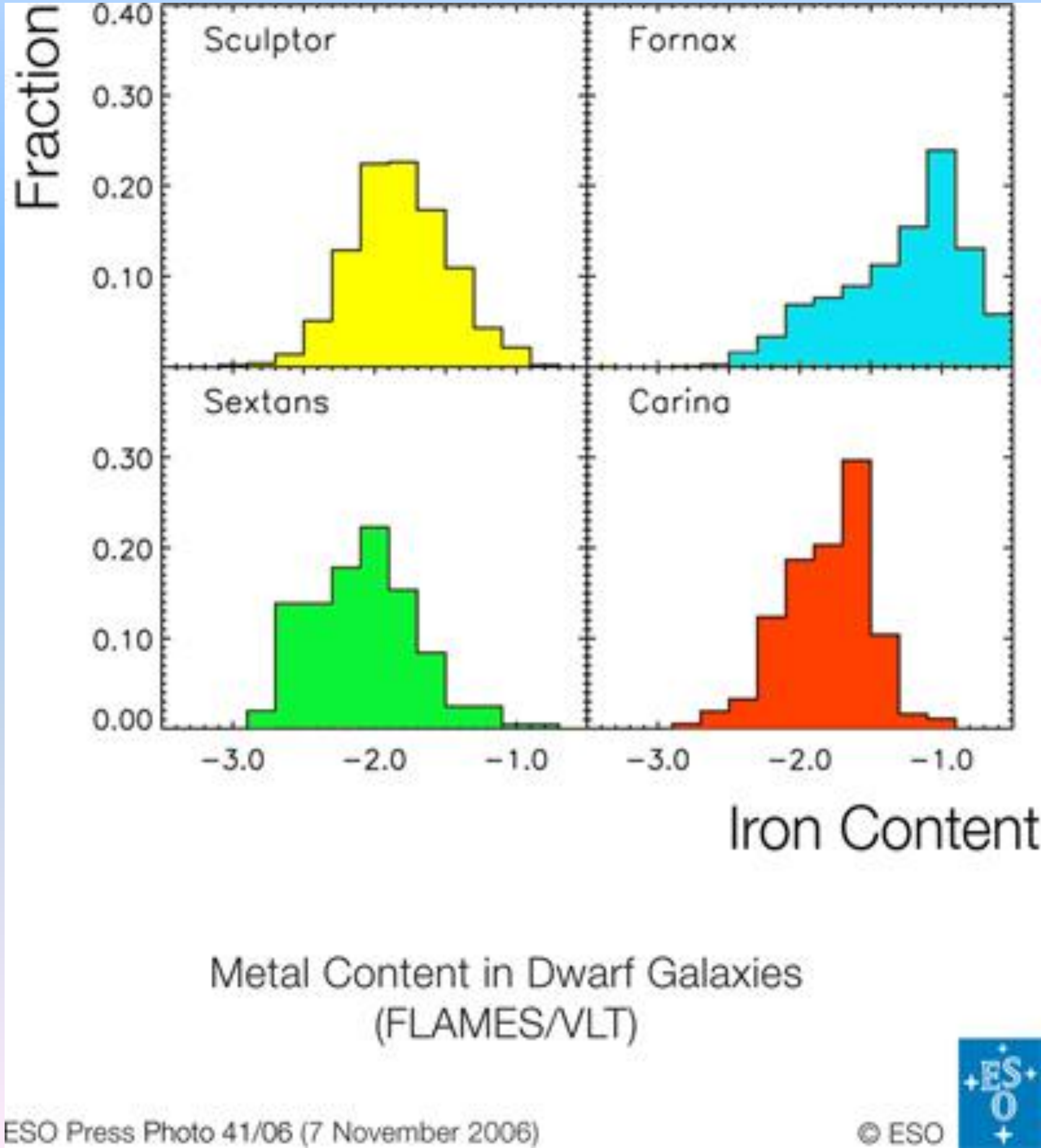
Stellar metallicity distribution

One of the most robust constraint in chemical evolution studies.

Reflects the chemical enrichment and evolution of the galaxy.

In local dSph galaxies, the peak of the distributions are located much below the solar [Fe/H] (~ -1.5 to -2.0 dex) → slow evolution and low SFR

At the high metallicity tail there is a sharp drop in several cases → lost of gas.



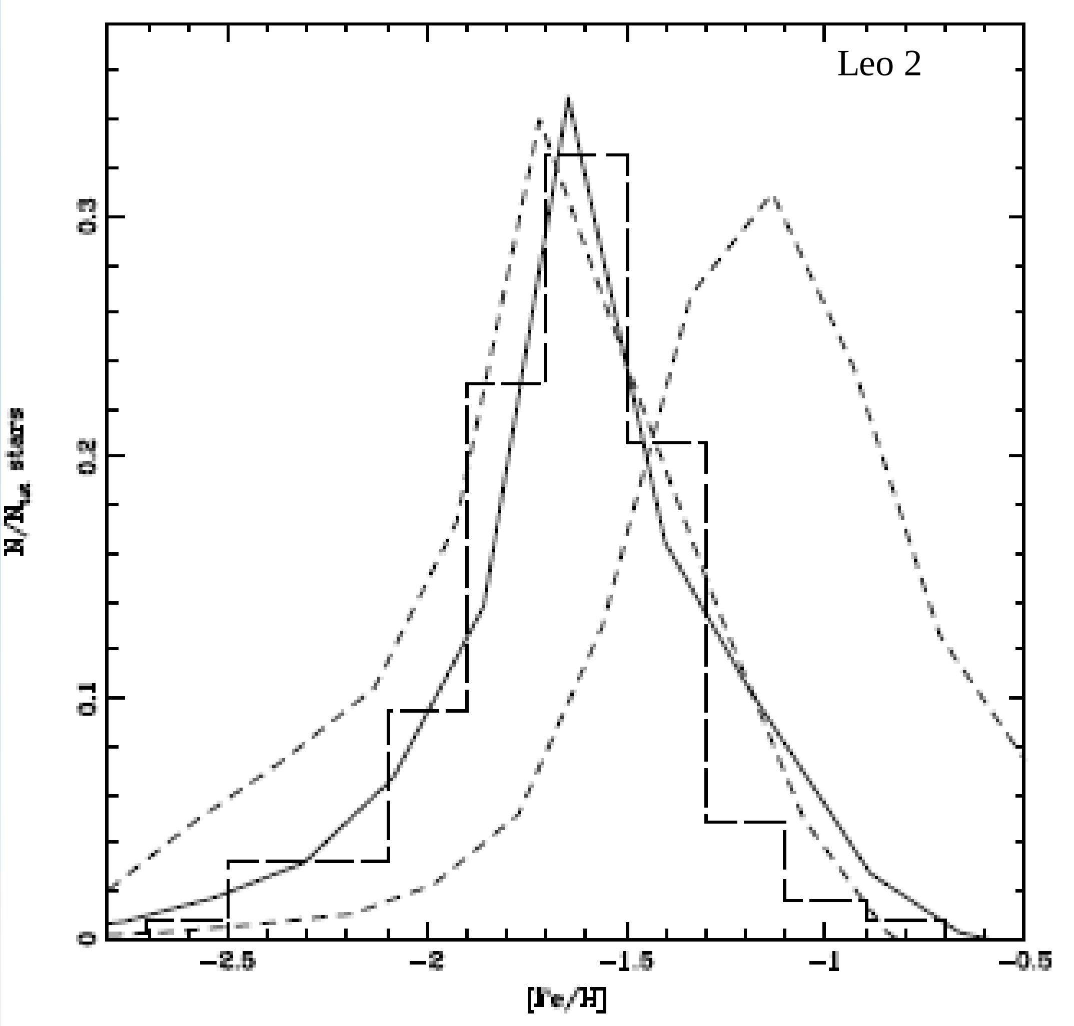
Stellar metallicity distribution

One of the most robust constraint in chemical evolution studies.

Reflects the chemical enrichment and evolution of the galaxy.

In local dSph galaxies, the peak of the distributions are located much below the solar [Fe/H] (~ -1.5 to -2.0 dex) → slow evolution and low SFR

At the high metallicity tail there is a sharp drop in several cases → lost of gas.



Lanfranchi & Matteucci 2010

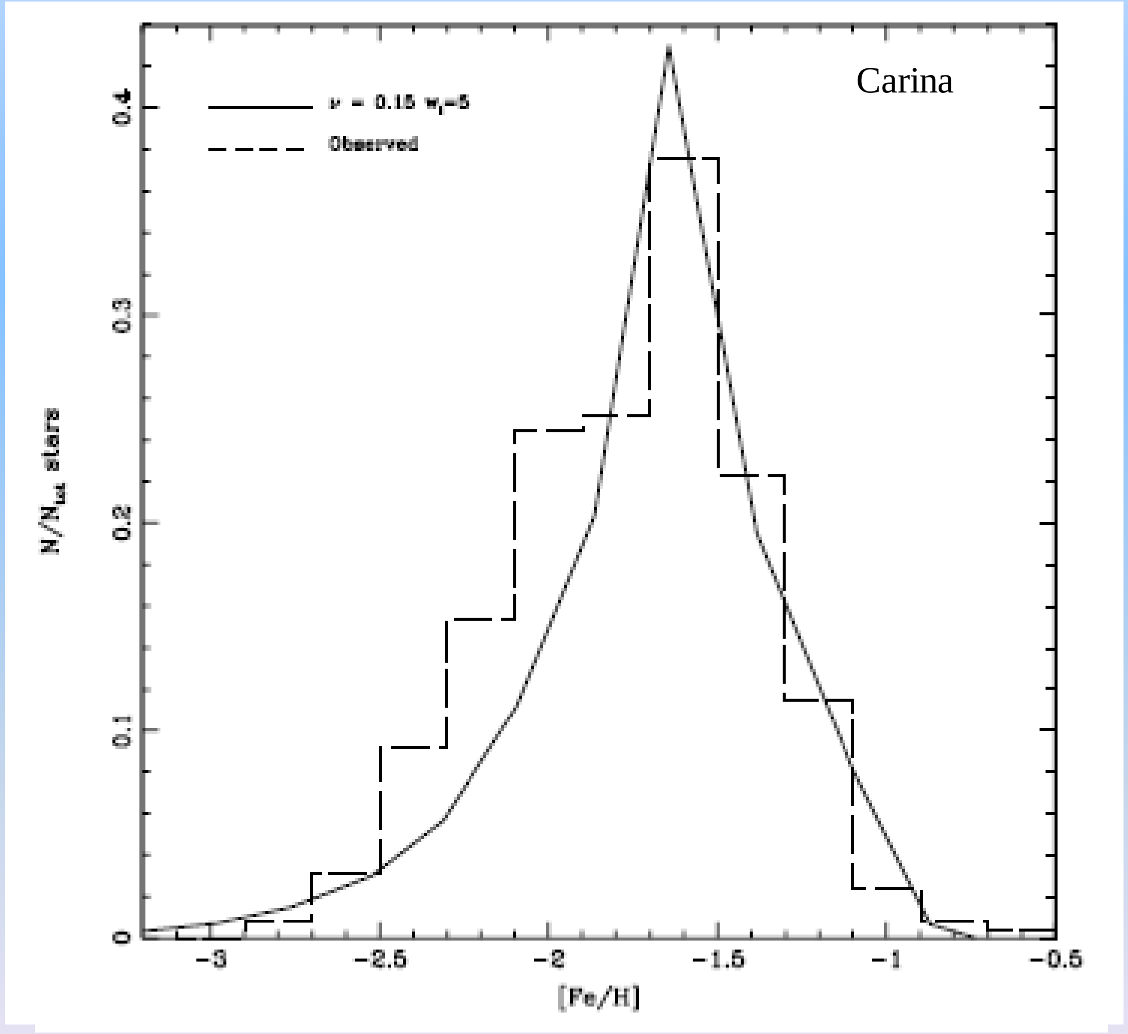
Stellar metallicity distribution

One of the most robust constraint in chemical evolution studies.

Reflects the chemical enrichment and evolution of the galaxy.

In local dSph galaxies, the peak of the distributions are located much below the solar [Fe/H] (~ -1.5 to -2.0 dex) → slow evolution and low SFR

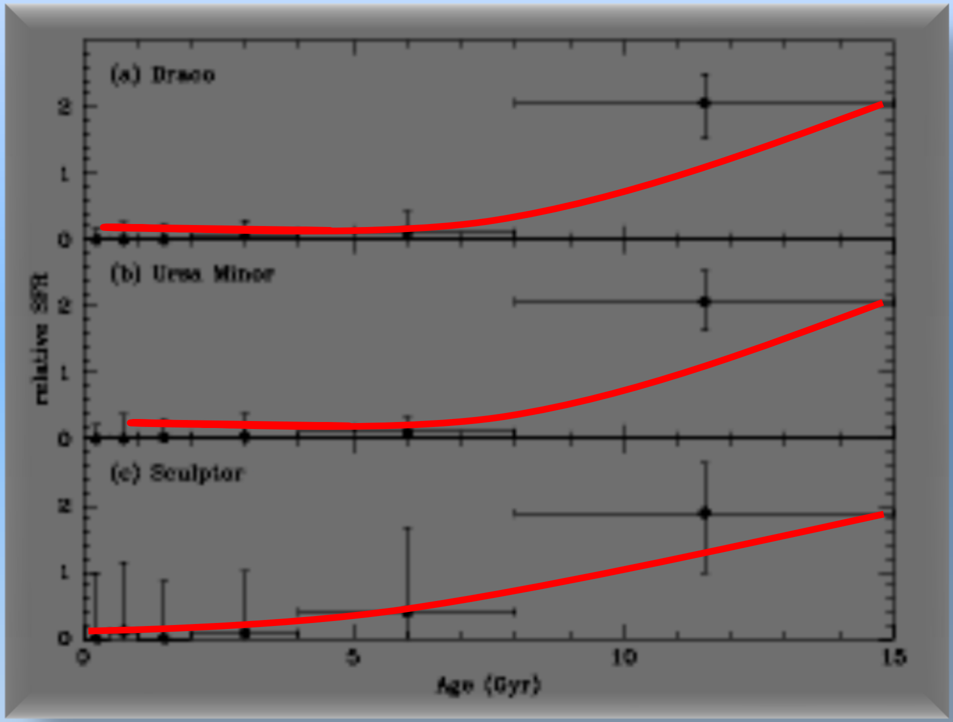
At the high metallicity tail there is a sharp drop in several cases → lost of gas.

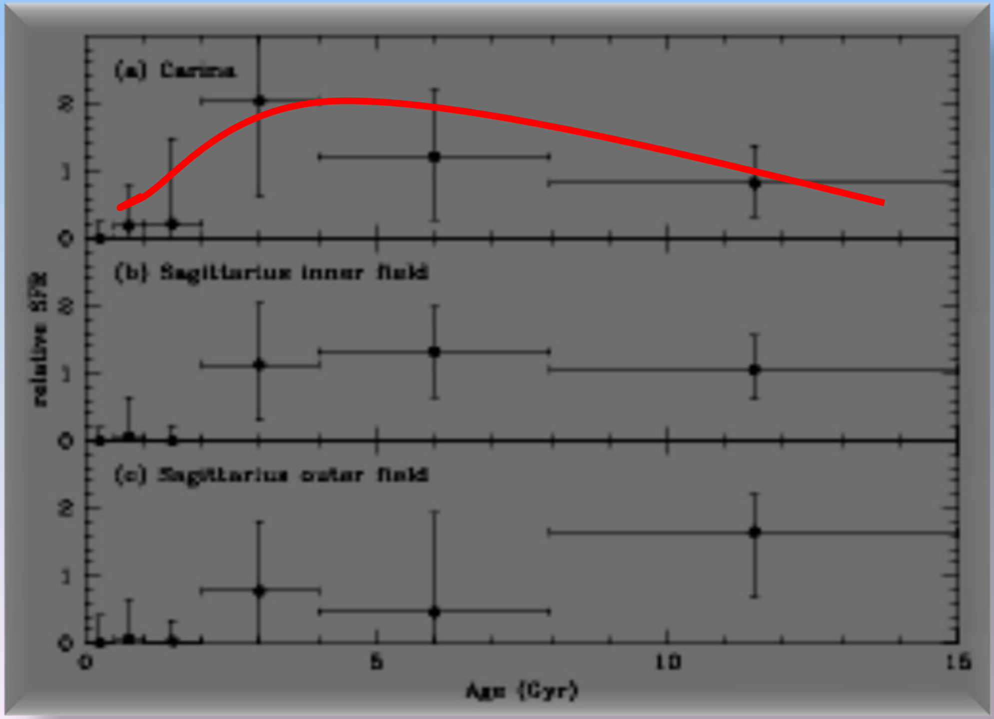


Lanfranchi & Matteucci 2009

Lanfranchi & Matteucci 2010

Star Formation History





Fornax

One of the most distant (135 kpc - Rizzi et al. 2007) and most luminous dSph galaxy believed to be associated with the Milky Way, with a total mass around 10^8 M_o (Walker et al. 2007).

Characterized by a complex star formation history with the majority of stars formed at intermediate galactic age (from 2 to 8 Gyr ago), but also at early epochs (more than 10 Gyr ago) and more recently (Dolphin et al. 2005, Battaglia et al. 2006, Coleman & de Jong 2008, de Boer et al. 2012).

Low iron content : $<$[Fe/H]$>$ ~ -1.0, extending below [Fe/H] ~ -2.0 and above [Fe/H] ~ -0.4 (Pont et al. 2004).

Majority of the observed stars exhibit values of [α/Fe] below the ones observed on Milky Way stars at the same [Fe/H] (Letarte et al. 2006, 2010; Kirby et al. 2010).

Fornax – Chemical Evolution Model

Model of Lanfranchi & Matteucci (2003, 2004) developed to reproduce local dSph galaxies. Main properties:

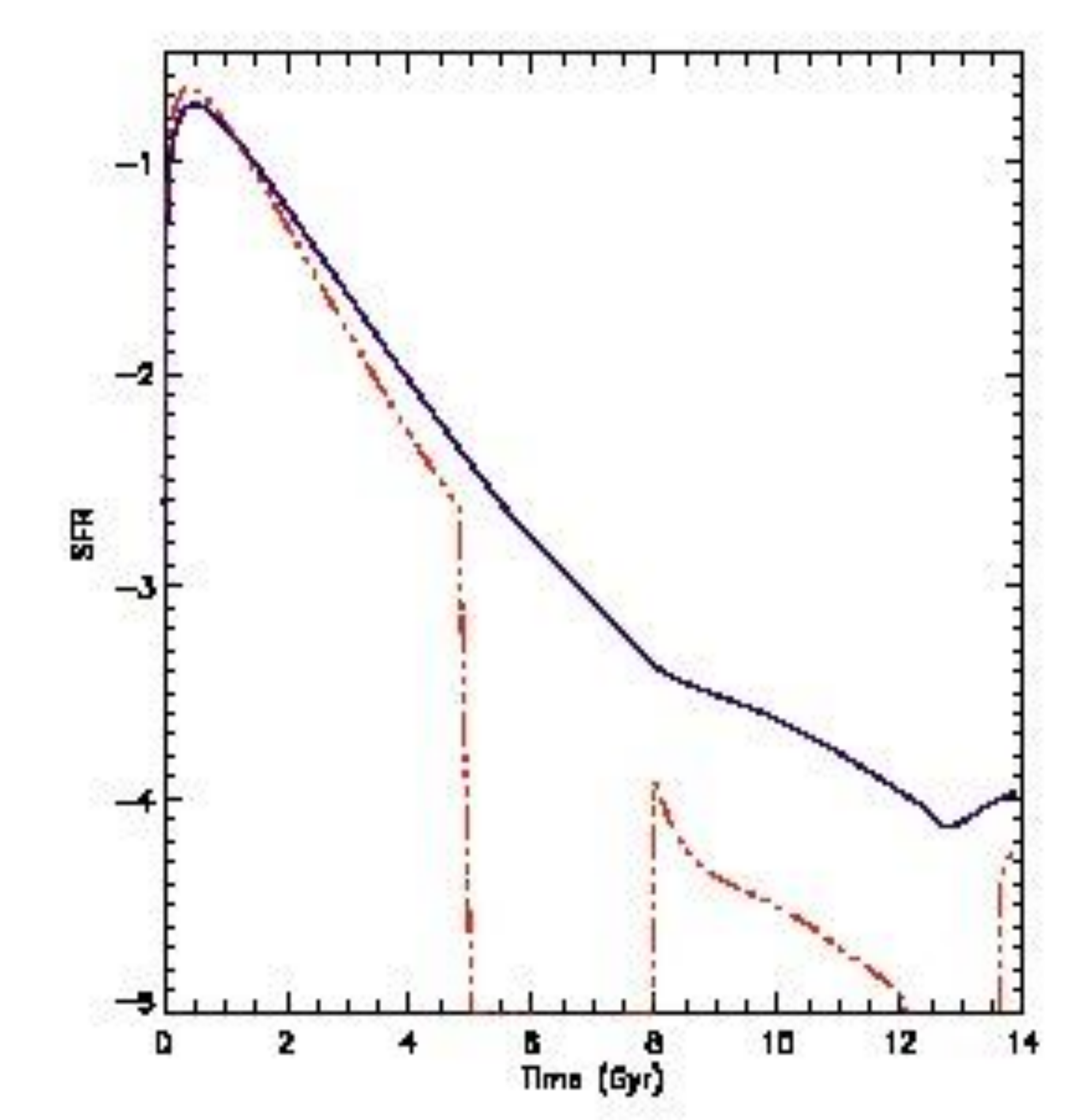
- one zone, with no instantaneous recycling approximation: stellar lifetimes are taken into account;
- Salpeter IMF (0.1 – 100 M_o);
- SFR is proportional to the gas mass and determined by its efficiency;
- Yields: Woosley & Weaver (95) for massive stars, Nomoto et al. (97) for SNeIa, van den Hoek & Groenewegen (97) for IMS, Busso et al. (2001) and Cescutti et al. (06) for *s* and *r* process elements;
- a galactic wind develops when the thermal energy of the gas is equal or higher than the binding energy of the galaxy ($E_{th} \geq E_b$);
- two SFH: one with three episodes of activity occurring from 0 to 5 Gyr, 7 to 10 Gyr and from 13.6 to 13.8 Gyr; and a continuos one;
- the main parameters (SF and wind efficiencies and infall timescale) were adjust by a statistical tool – cross-entropy method.

Results - SFH

Dashed-dotted line – model 1 with 3 episodes (Dolphin et al. 2005, Battaglia et al. 2006, Coleman & de Jong 2008).

Solid line – model 2 with continuous SF (de Boer et al. 2012).

SF efficiencies:
Model 1 – 1.10, 0.39, and 0.86 Gyr^{-1}
Model 2 – 1,01 Gyr^{-1}



Fornax - mass

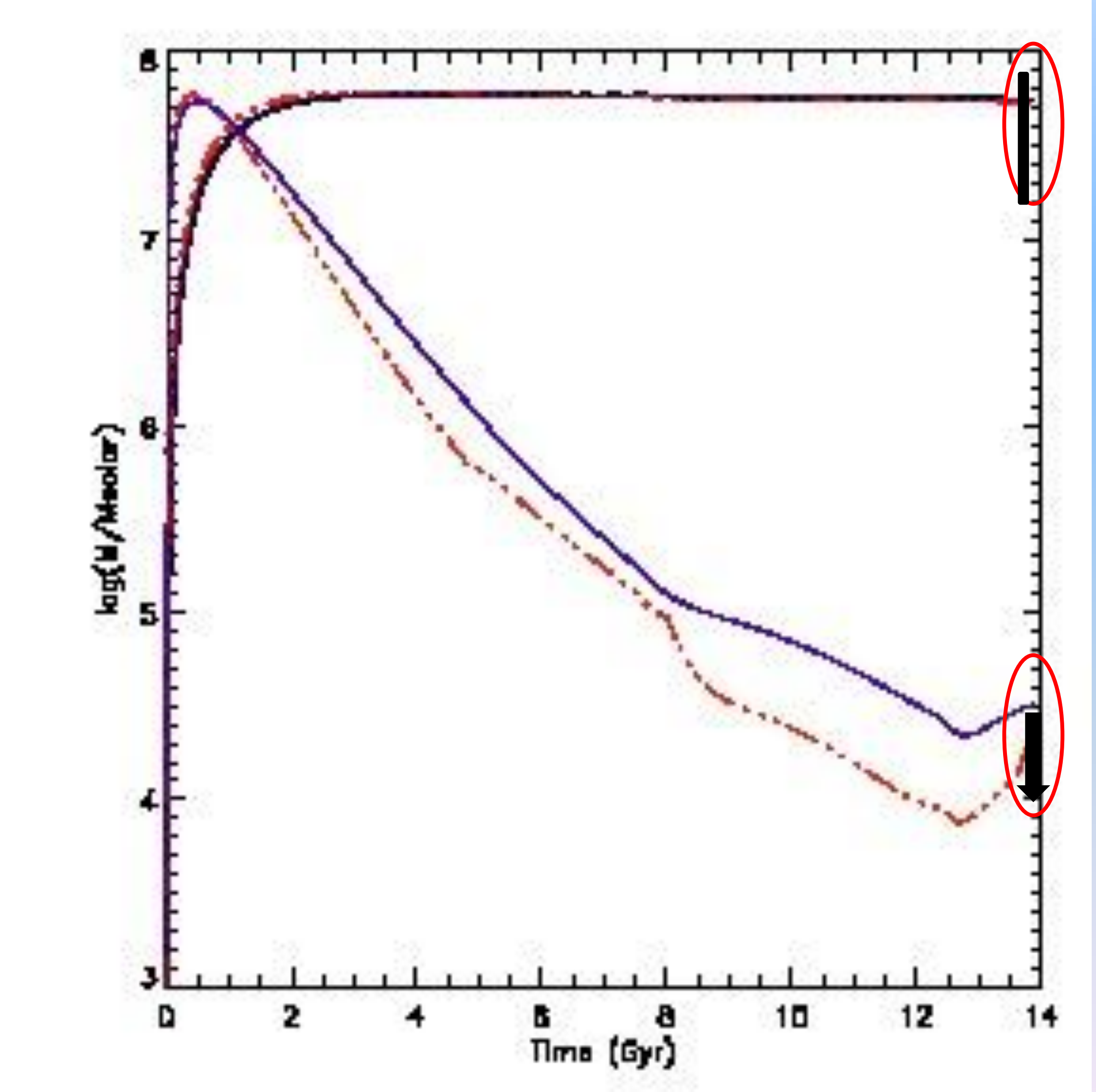
Stellar mass and gas mass

The gas and stellar masses predicted by the models (thin and thick lines, respectively) fits the present day observed values.

Gas mass – initial increase due to infall and subsequent decrease due to the consumption of gas by the SF and to the removal of gas by the galactic wind.

Stellar mass – slow initial increase due to the slow SFR. After the onset of the wind, the SFR decreases to almost zero, maintaining the stellar mass constant.

0.2 - 0.8 x10^8 M_o and 10^4 M_o (Walker et al. 2007).



Fornax - [alpha/Fe]

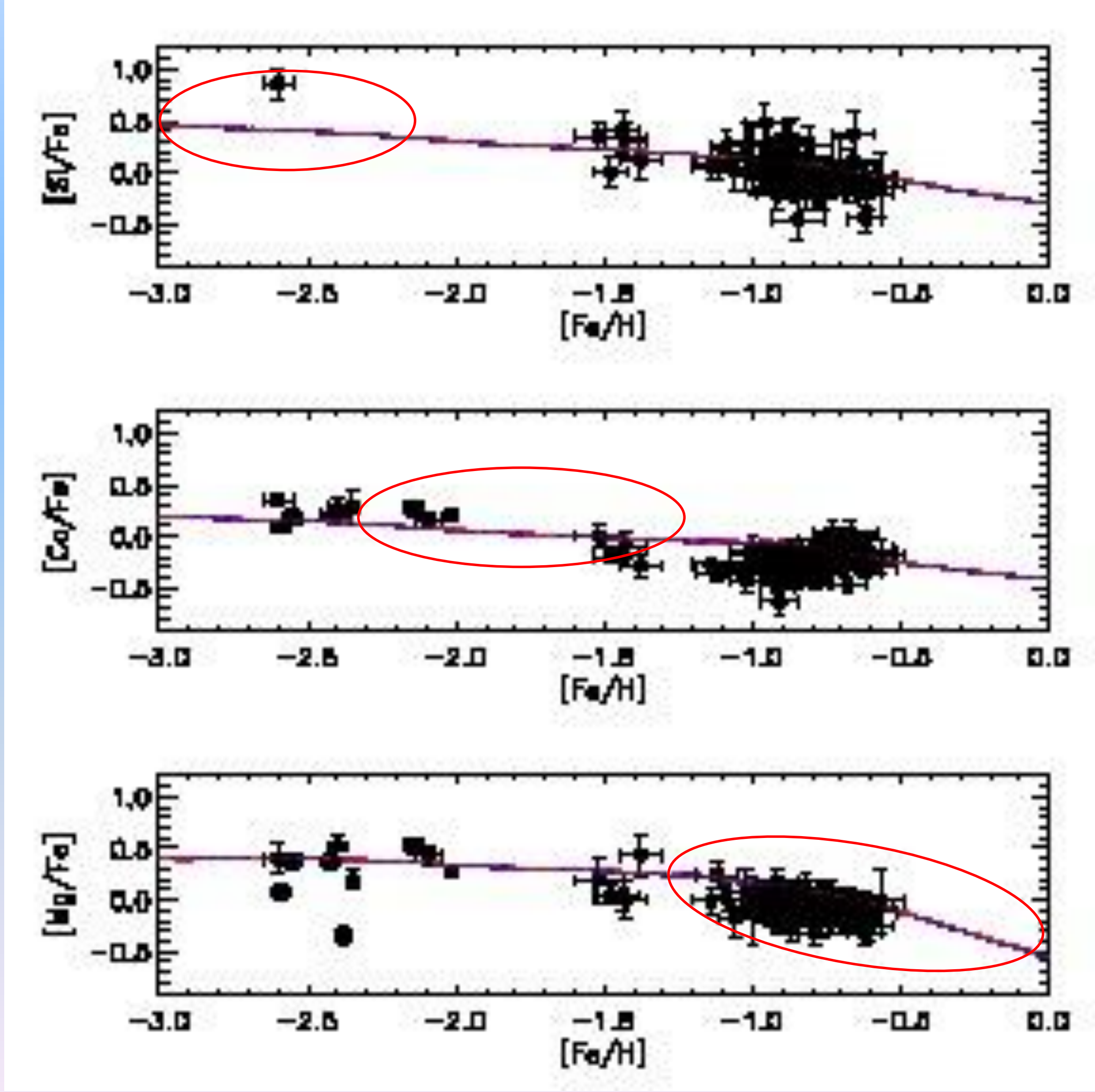
[α/Fe] ratios

High values at low metallicities ([Fe/H] < -2.0) due to the fast injection in the ISM of α elements by SNe II.

At intermediate metallicities a slow decrease can be noticed due to the injection in the ISM of Fe by SNe Ia.

At [Fe/H] > -1.3 a sharp decrease is caused by the effects of the galactic wind on the SFR.

The SFR decreases substantially due to the removal of gas, almost halting the production of α elements. Fe continues to enrich the ISM by SNeIa.



Data from Letarte et al. 2010 and 2006

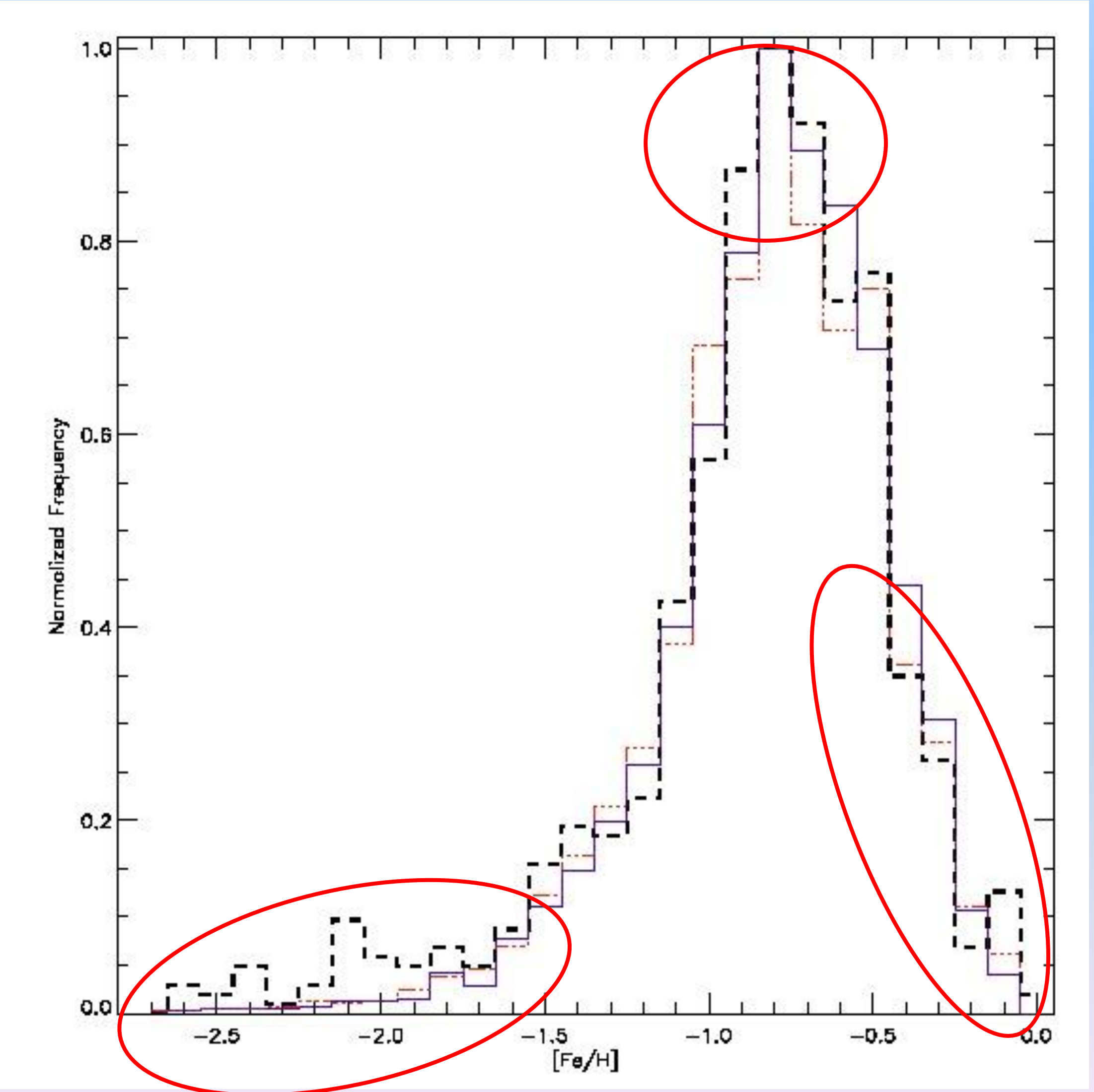
Fornax - SMD

Stellar metallicity distribution

Low metallicities – good agreement with a slightly lower number of stars predicted by the model.

High metallicities - a sharp decrease due to the onset of galactic wind, which prevents stars with higher metallicities to be formed.

Peak at around [Fe/H] ~ -0.8.
This value is determined by the low SFR and by the occurrence of the galactic wind.

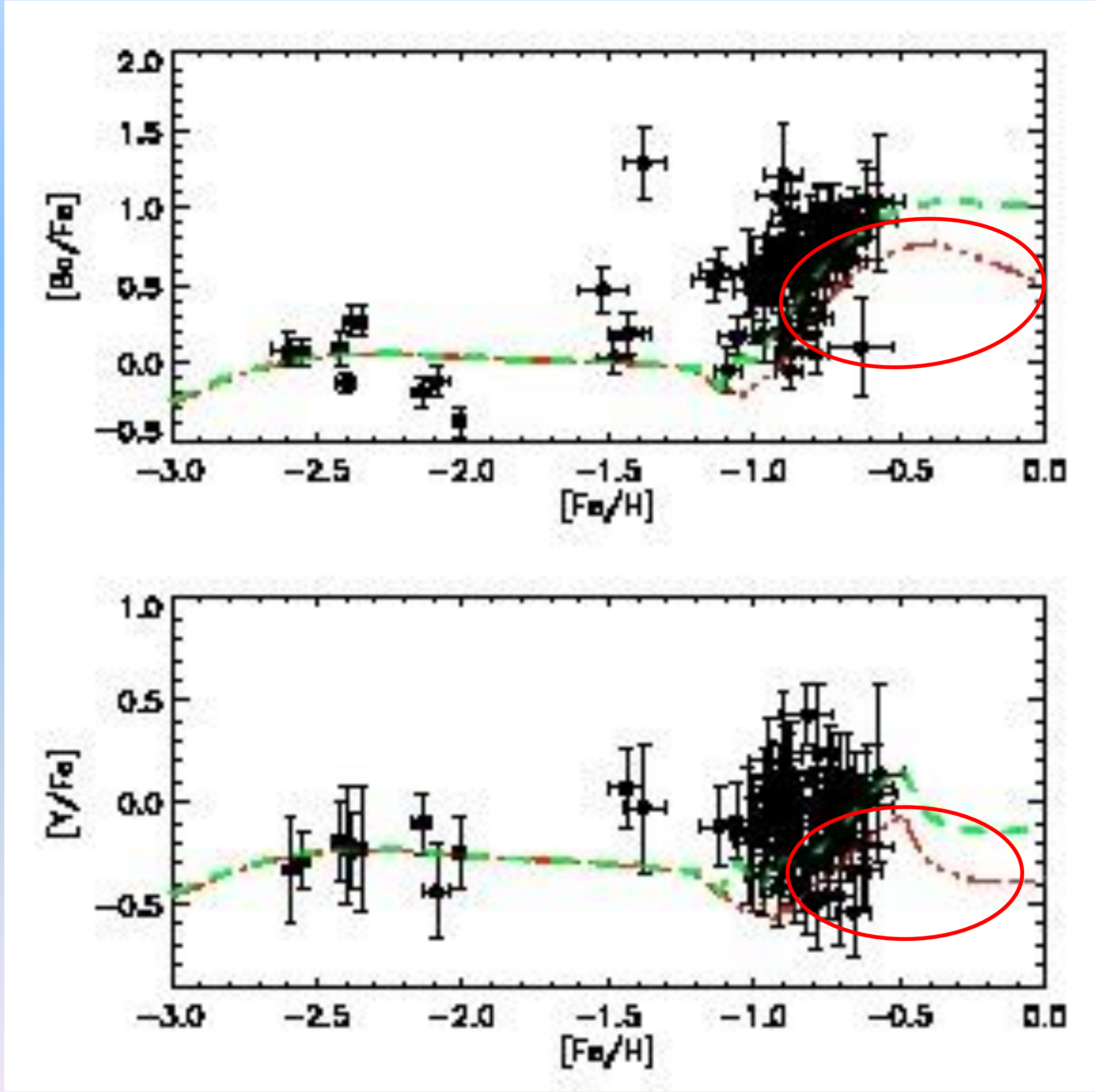


Observations from Kirby et al. 2010 and Letarte et al. 2006

Fornax – neutron capture

[Ba/Fe] and [Y/Fe] ratios

At high [Fe/H] (above -1.0), the predictions of the models lie below the data of the four elements: Ba, Y, La, and Eu.



Fornax – neutron capture

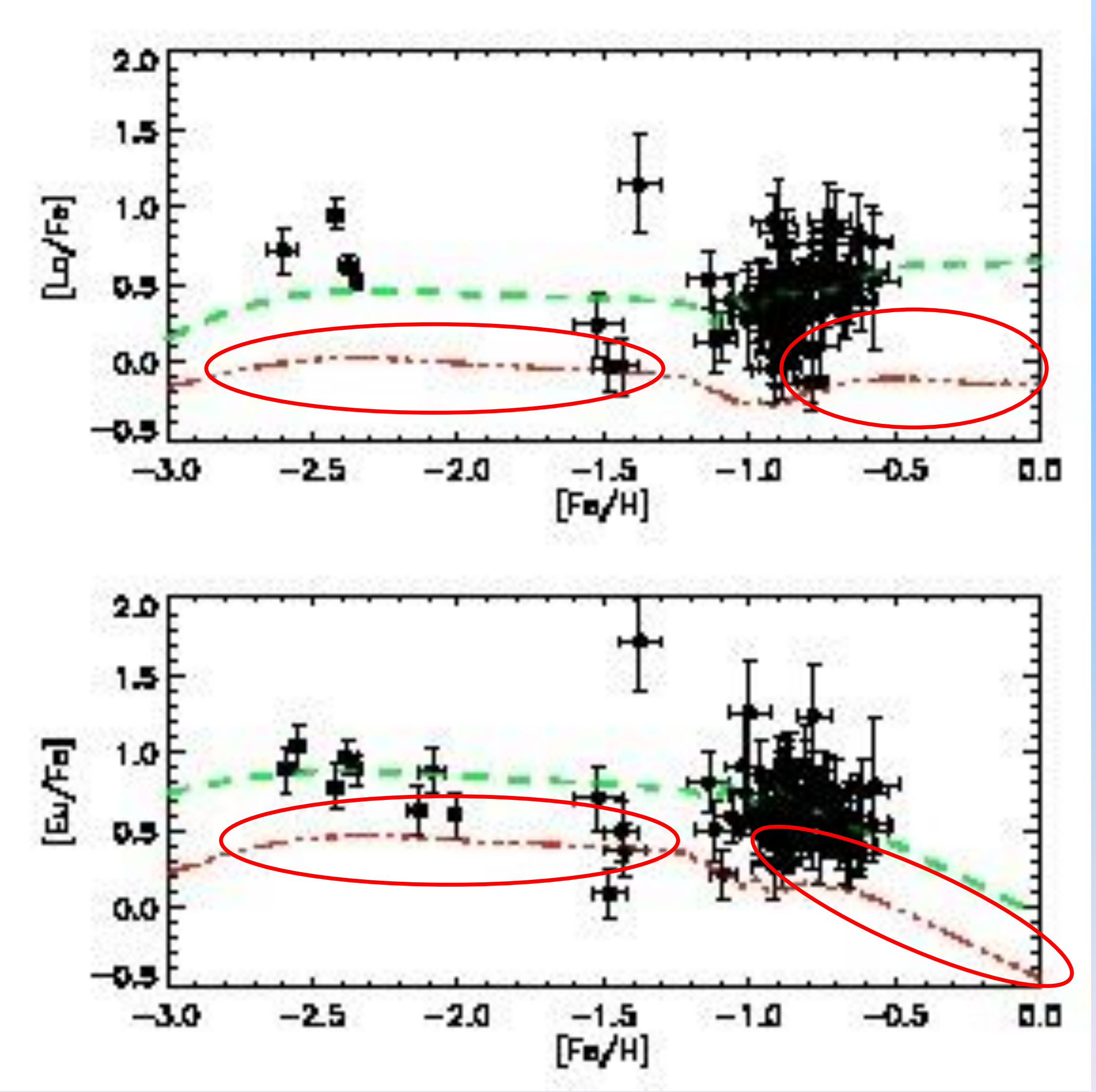
[Eu/Fe] and [La/Fe] ratios

At high [Fe/H] (above -1.0), the predictions of the models (blue line) lie below the data of the four elements: Ba, Y, La, and Eu.

At lower [Fe/H] there is also an undepredriction for [Eu/Fe] and [La/Fe].

This could be related to SFR, wind efficiency, stellar yields …

The values adopted for the main parameters of the chemical evolution models assures a very good fit to the observed data - yields.



Fornax – neutron capture

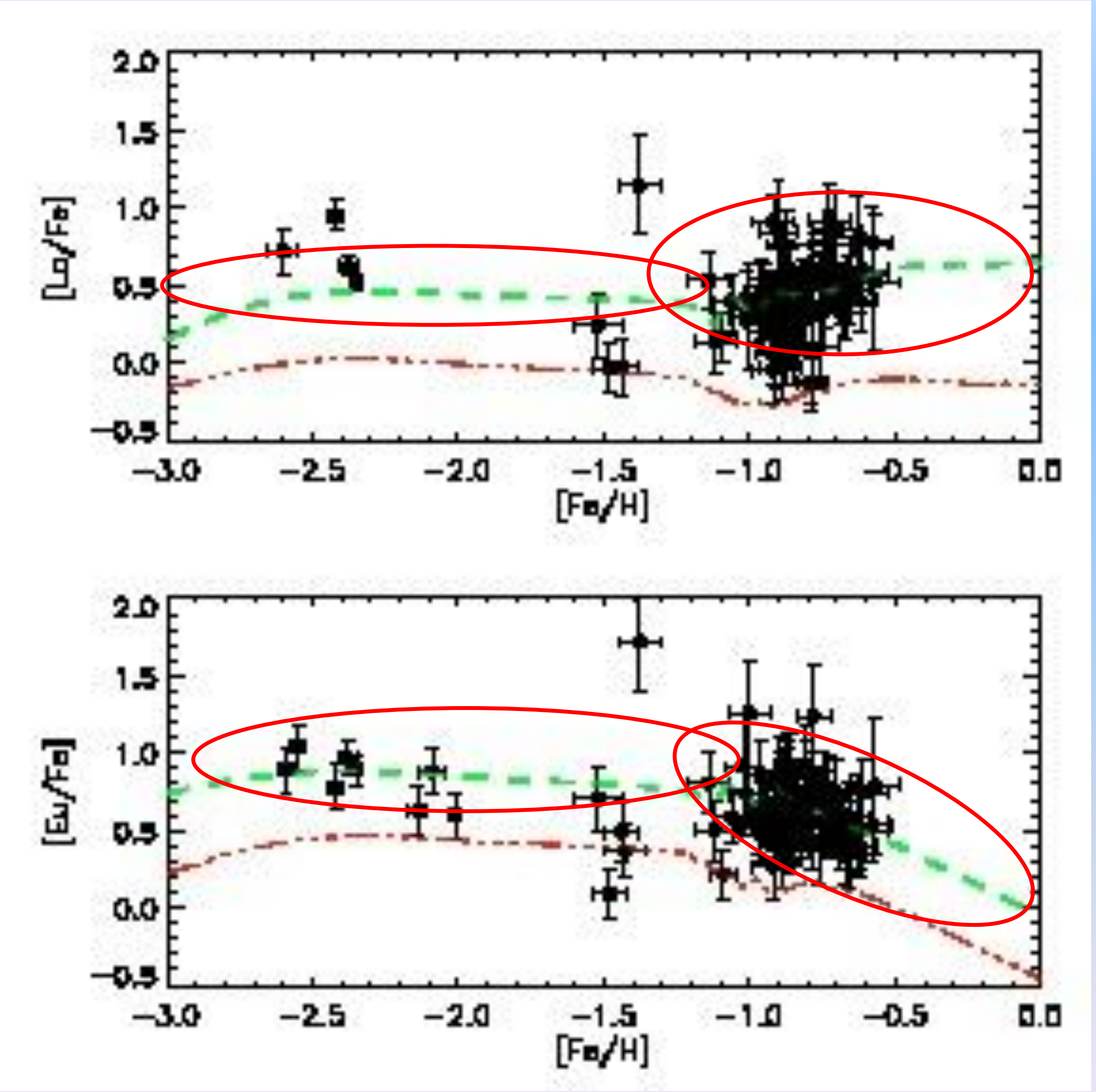
[Eu/Fe] and [La/Fe] ratios

An increase in r-process yields gives rise to higher [La/Fe] and [Eu/Fe] at low [Fe/H]. It continues high at higher values of Fe.

[Eu/Fe] - pattern similar to [α/Fe], a sharp decrease caused by the effects of the galactic wind on the SFR in agreement with stellar values.

At high [Fe/H] s-process plays a major role (LIMS).

Increased yields of s-process for La gives a nice fit to the data



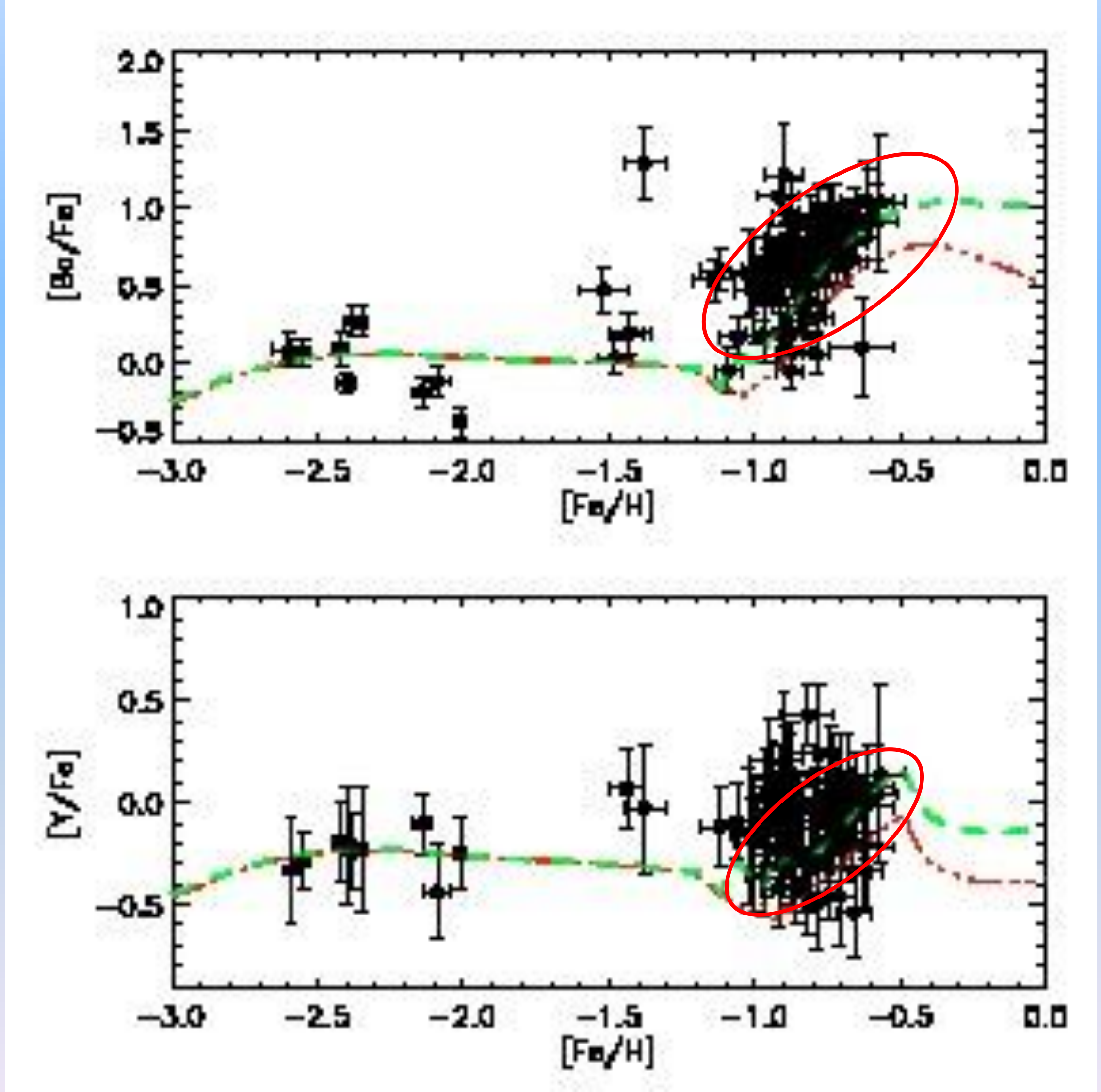
Fornax – neutron capture

[Ba/Fe] and [Y/Fe] ratios

The same increase in the s-process yields for Ba and Y allows a better fit at high [Fe/H].

It could reflect the uncertainties in the yields > model parameters, site of production, etc.

Does it work with [s/r]?

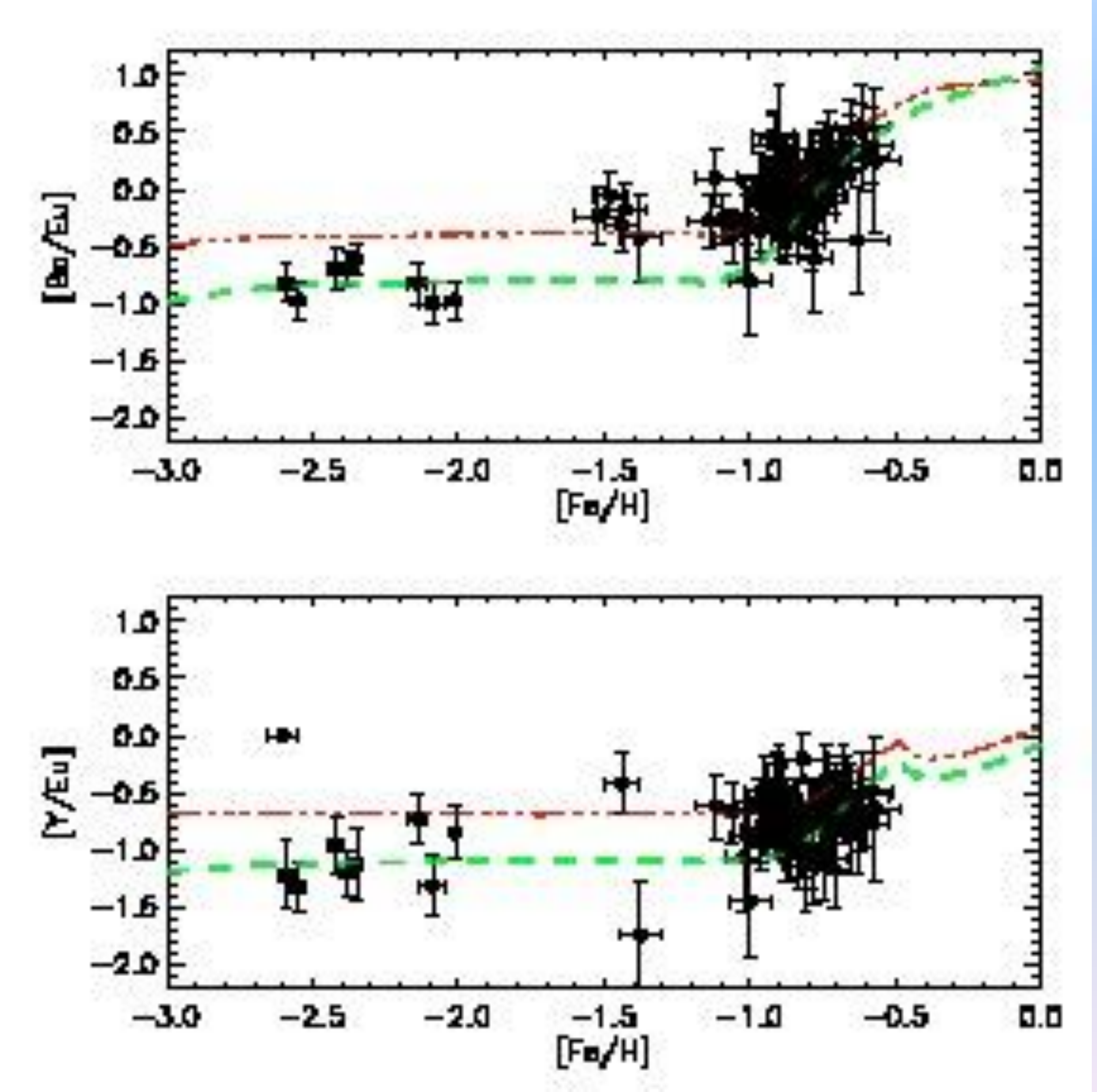


Fornax – neutron capture

[Y/Eu] and [Ba/Eu] ratios

Yes, it does. The model with increased yields reproduces very well all observed ratios.

At [Fe/H] > -1.0, s-process become important, whereas the r-process are halted by galactic winds, causing the increase in the values of these two ratios.

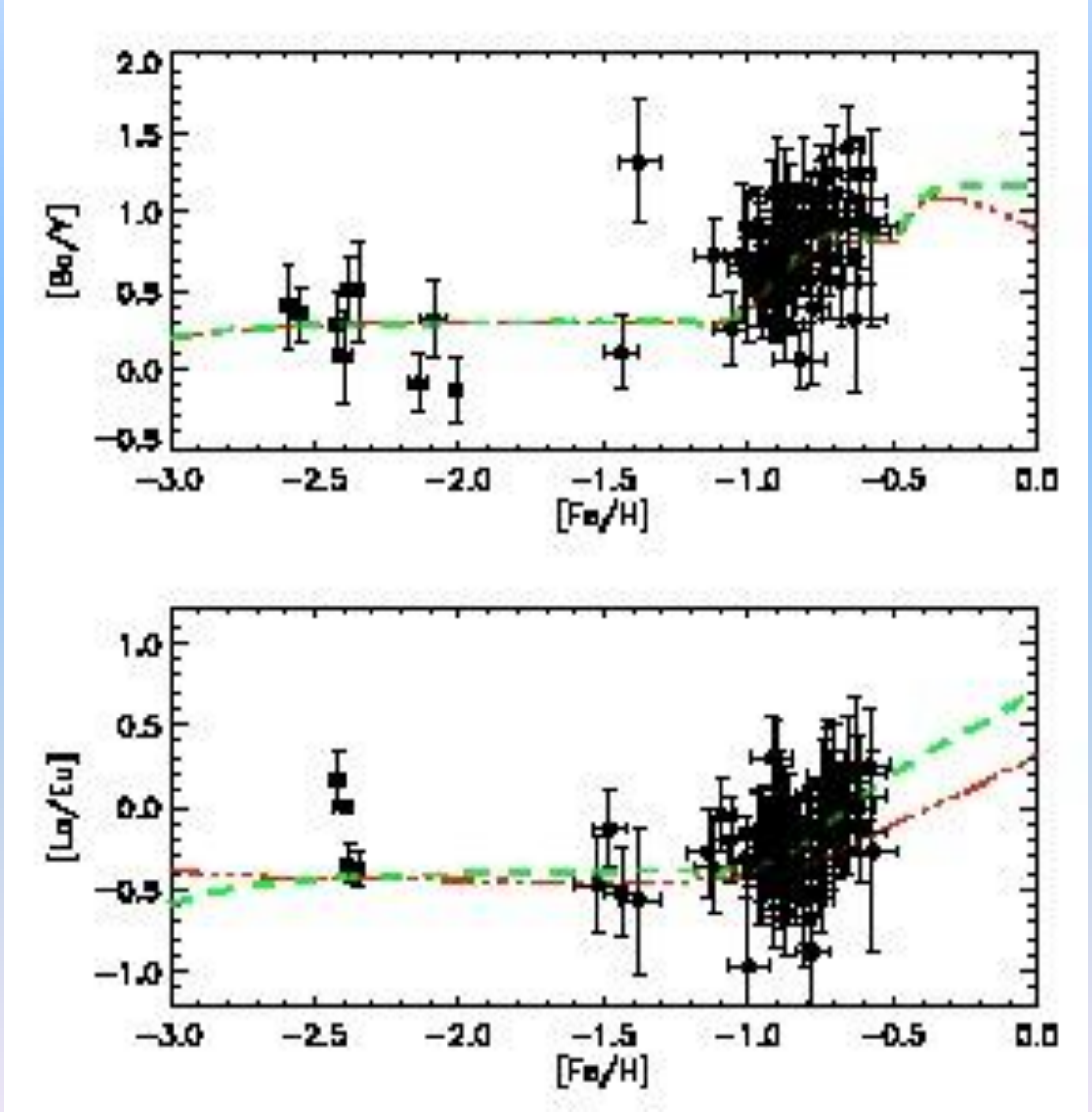


Fornax – neutron capture

[La/Eu] and [Ba/Y] ratios

[La/Eu]: similar behaviour as the one in [Y/Eu] and [Ba/Eu].

[Ba/Y]: less intense increase due to the lower fraction of Y formed through s-process when compared to Ba.



Conclusions

✓The combination of a low SF efficiency and a high wind efficiency are the main responsables for the observed chemical properties of dSph.

✓The [α/Fe] ratios, stellar metallicity distribution, and present day total and gas masses of the Fornax are very well reproduced by two similar chemical evolution models, but with different star formation histories.

✓The major fraction of the stars in Fornax is formed in the first Gyr after the formation of the galaxy, but young and intermediate stars are also present.

✓The model with ”standard” yields for neutron process elements are not capable of reproducing the abundance ratios of neutron capture elements such as Ba, La, Y, and Eu.

✓A model with increased yields of r- and s-process elements can account for the observed values.

Thank You!

Conclusions

Acknowledgements: G. Lanfranchi thanks the Brazilian Agency FAPESP financial support (proj. 2013/06722-8).