GALACTIC CHEMICAL EVOLUTION II.

Lezione X- Fisica delle Galassie
Pagel “Nucleosynthesis and Chemical evolotion of Galaxies”, cap. 8

Laura Magrini

Consequences and applications of Galactic chemical evolution

- The abundance ratios of primary and secondary elements
- The spatial distributions of metallicity: the radial gradients in spiral galaxies
- The Age-metallicity relationship

The simple model

Primary and Secondary elements:

→ We define a <u>**primary element**</u> as an element produced directly from H and He

→ Typical primary elements are carbon or oxygen which originate from the triple α reaction

→ We define a <u>**secondary element**</u> as an element produced from *metals* already present in the star <u>**at birth**</u>

→ It means that some element must previously exist in order to create a secondary element.

→ An example is N, which is produced during the CNO cycle in greater abundance with a larger initial abundance of C (but can also be primary if produced directly from He and H)

The simple model

Primary and Secondary elements:

→ Estimation of the yield (of a primary elements):

The solution of the simple model tells us that:

$Z = p \ln (1/\mu)$

So when $\mu \rightarrow 0$ (gas consumption, stellar population) then

$Z \rightarrow p$

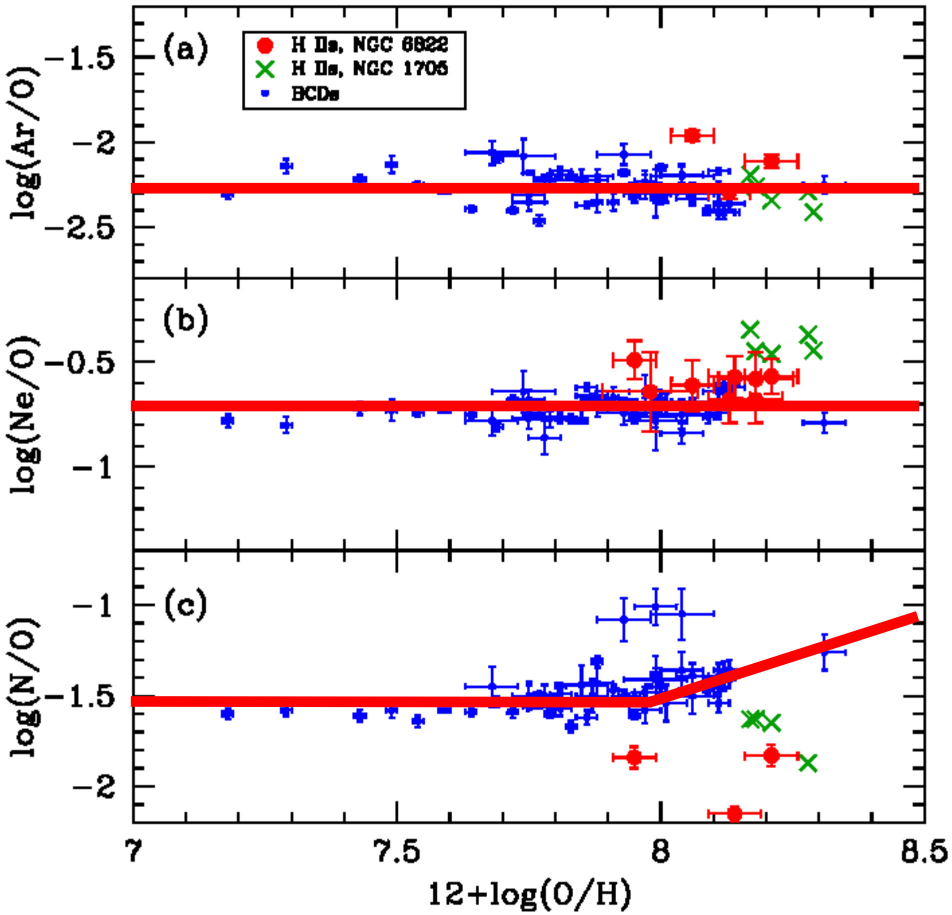
Considering two primary elements, as for instance O, Ne, Ar, S we have that their ratios are:

$$\frac{Z_i}{Z_j} = \frac{p_i}{p_j} = \text{const.}$$

→ The ratio between the abundances of two primary elements is proportional to the ratio of their yields

The simple model

Ratios of primary elements:



Form Lee et al 2006

- → The solution of the Simple model predicts that the ratio between two primary elements is constant (vs. metallicity or the abundance of one of the two elements)
- → It is observed for O, Ar, Ne: all produced in SNII

The simple model

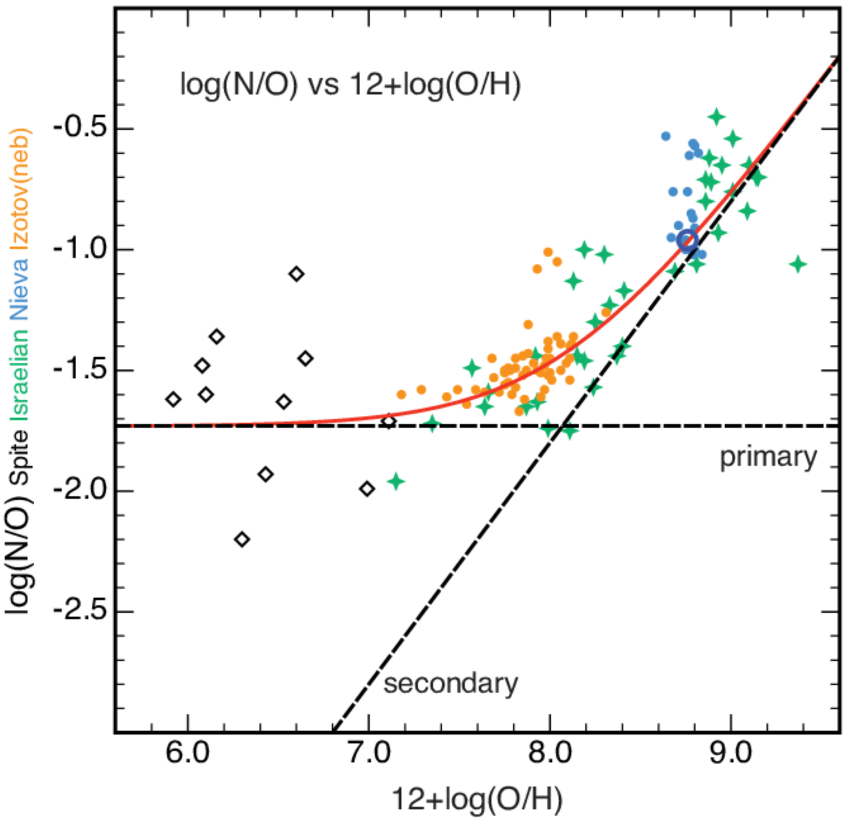
Secondary elements:

→ The solution of the Simple model of chemical evolution for the abundance of a secondary element Xs formed from a seed element Z

→ Xs is proportional to Z^2 (since its yield is proportional to Z-the primary seed)

→ **The ratio Xs/Z is directly proportional to Z**

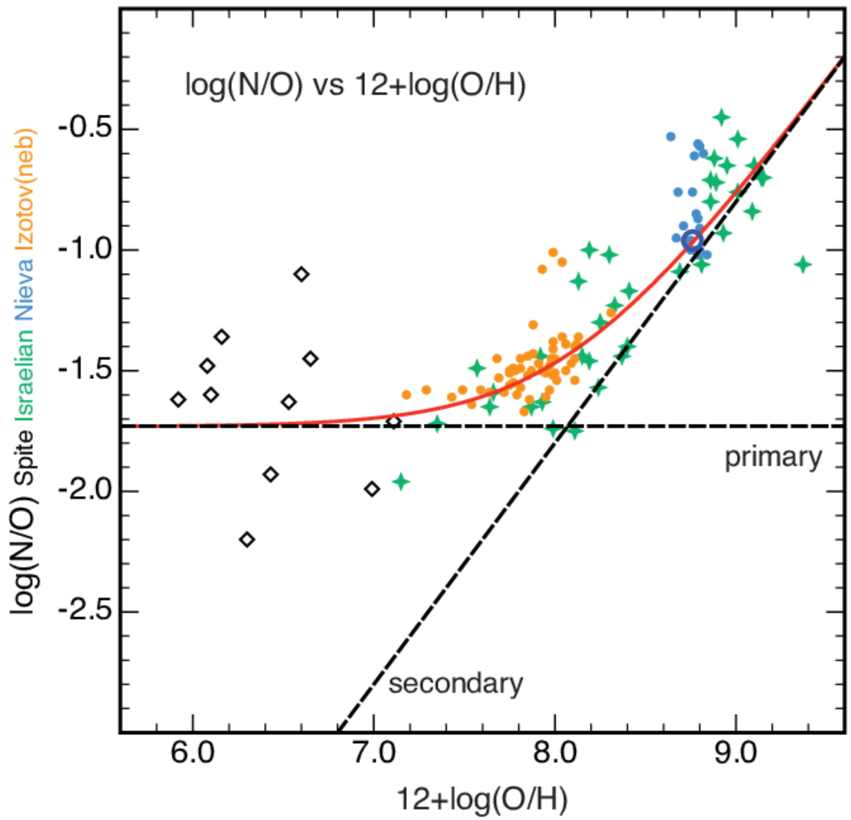
→ In this plot Xs is Nitrogen, and Z is Oxygen



The simple model

Nitrogen as a primary: primary production seems to occur only in the very early phases of galactic evolution, while secondary production appears later, when the metal content of a galaxy is higher

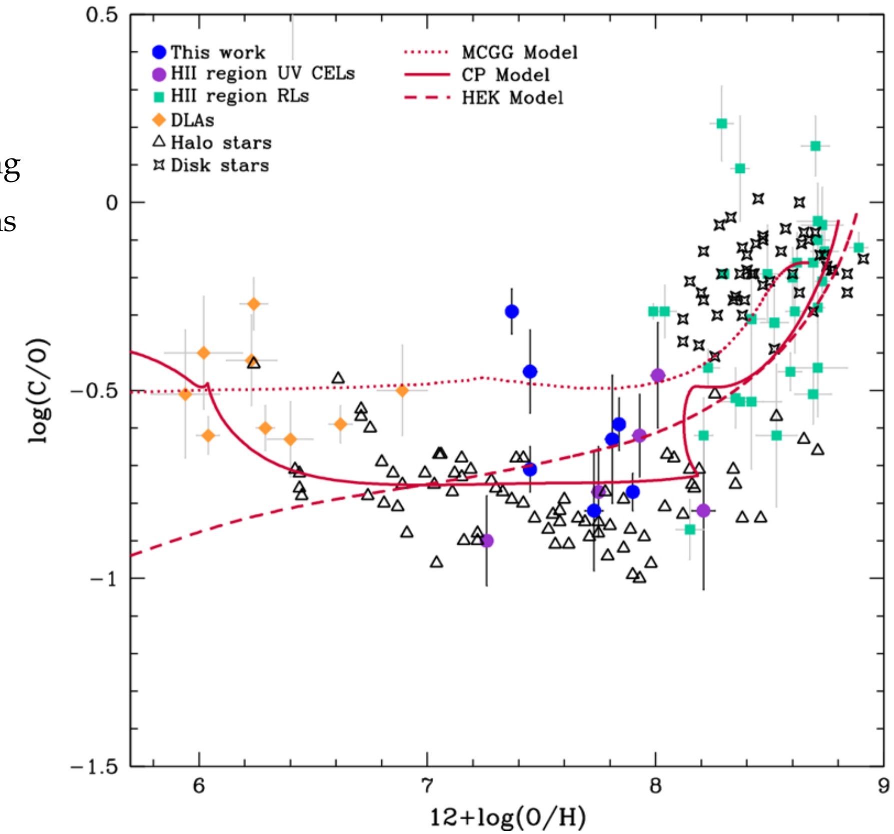
- At low metallicity the abundance ratio N/O vs O/H is constant
- Using models of star evolution with rotation and very low metallicities, typical of the first stellar generations in the Universe (e.g., Meynet & Maeder 2002)
- In these models, some amount of the new carbon synthesized in the core is transported into the hydrogen burning shell, where the CNO cycle will convert it into **primary ^{14}N**
- More efficient rotation can produce such mixing between the H and He shells.



The simple model

Secondary elements: Carbon with the two components

- → in the early stage of our Galaxy, massive stars are the main contributor of carbon (primary).
- → As our Galaxy evolves to the late stage, the long lifetime low and intermediate mass stars begins to play an important role in the enrichment of the ISM (secondary)



From Berg et al. 2016 (extracted from Maiolino & Mannucci 2018)

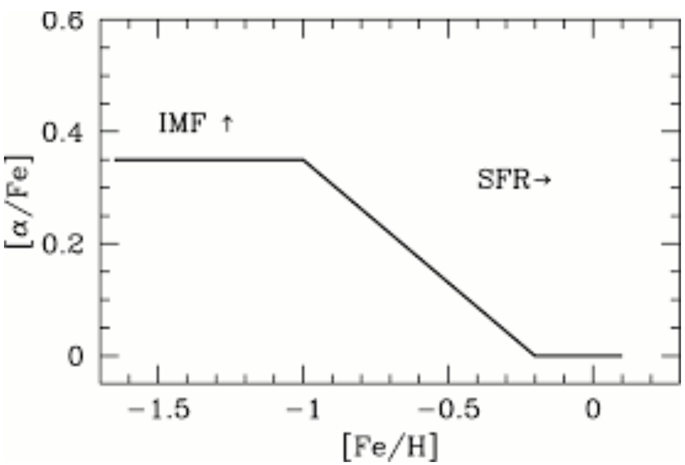
- → C/O resembles the trend observed in the N/O versus O/H diagram, with a flat relation at low metallicity and a steeply increasing abundance at high metallicities.
- → The latter trend has led some authors to suggest that carbon may also have a **secondary production**, i.e., yields that are strongly metallicity-dependent

The simple model

Iron abundance in the Simple model:

An important deviation from constancy in the abundance ratio of elements **supposed to be primary** is displayed by the ratios Fe/O and [Fe/α-elements] in stars, which increase systematically with [Fe/H]

- substantial contribution to the production of iron found in the younger, more metal-rich stars (like the Sun) by SN Ia, which take times of the order of a Gyr to complete their evolution and **therefore cannot be treated in the IRA**



→ [a/Fe] ratio can be viewed as a chronometer (starting to decrease after 1Gyr)

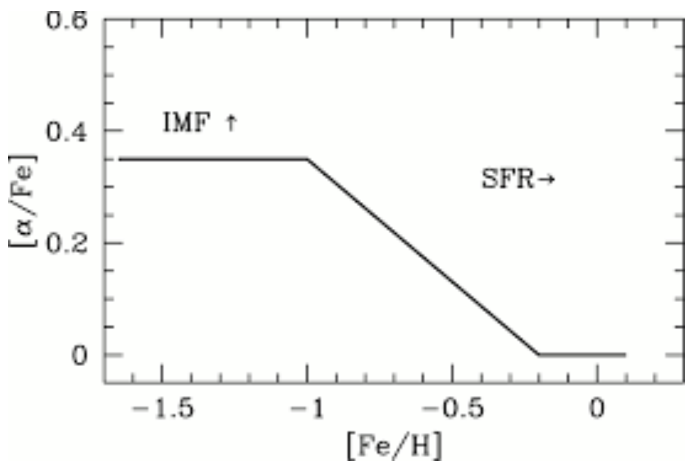
→ [Fe/H] provides the efficiency with which star formation has occurred.

- **SFR:** When the star formation rate (SFR) is high, the gas reaches higher [Fe/H] before the first SN Ia occurs and α-elements start to decrease (the "knee").

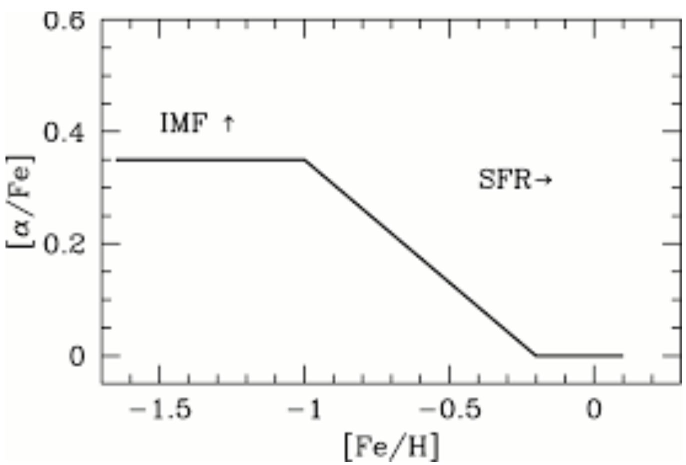
→ The formation efficiency and time scale of a stellar system can be estimated by the position of this "knee"→ **if the SFE is high, we reach higher metallicity**

- **IMF:** Since more massive stars are more efficient in producing a-elements, the level of [a/Fe] at low metallicity (before the "knee") is an indication of the mass of the stars that contributed to enrich the ISM and therefore provides an indirect measure of the IMF.

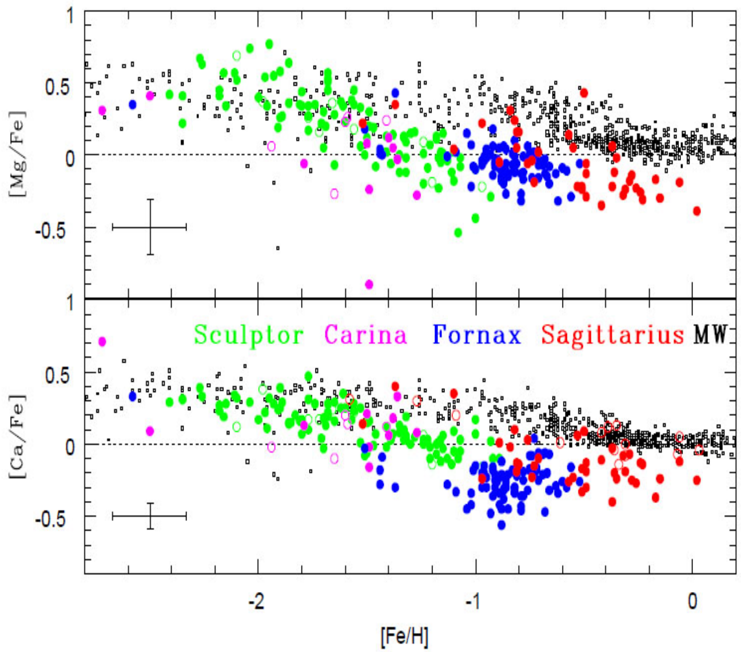
→ **if the IMF is top heavy, we reach higher metallicity**



→ What can we learn from this diagram?



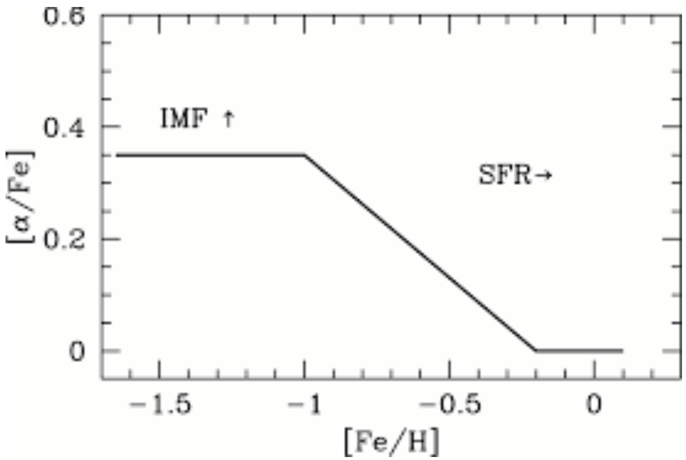
- The position of the knee thus provides information on the star formation rate in a system.
- The fraction of stars at lower [Fe/H] than the [Fe/H] corresponding to the knee gives information on the star formation timescale.



- Different abundance ratios at a given metallicity
- Can the halo be accreted by the present-time dSphs?
- Yes, at low metallicity they are similar to the halo (see Lecture 2)

Colored dots representing different dSph abundances (from Venn et al. 2004)
Black dots represent the MW abundances.

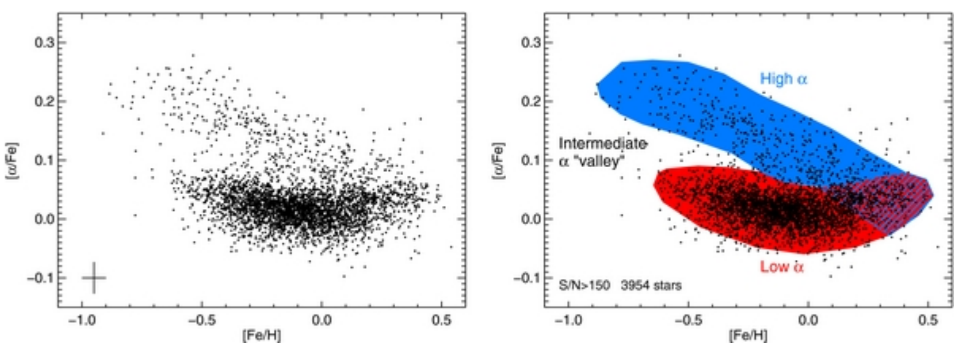
→ What can we learn from this diagram?

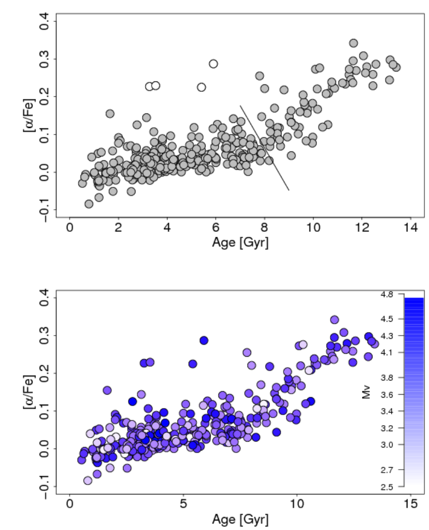


- Different SFR in the evolution of the thin and thick disc
- The two discs are clearly separated in the [alpha/Fe] vs [Fe/H] plane
- There are also strong differences in ages

→ **Remember the possible formation of the thick disc with the merger with a galaxy, called Gaia-Encelado**

The [alpha/Fe] vs. [Fe/H] diagram for APOGEE RC stars with S/N > 150





→ What can we learn from this diagram?

Different ages and different chemical composition
Complex structure of the Galactic discs

Using orbits we can recover the initial radius of the stars

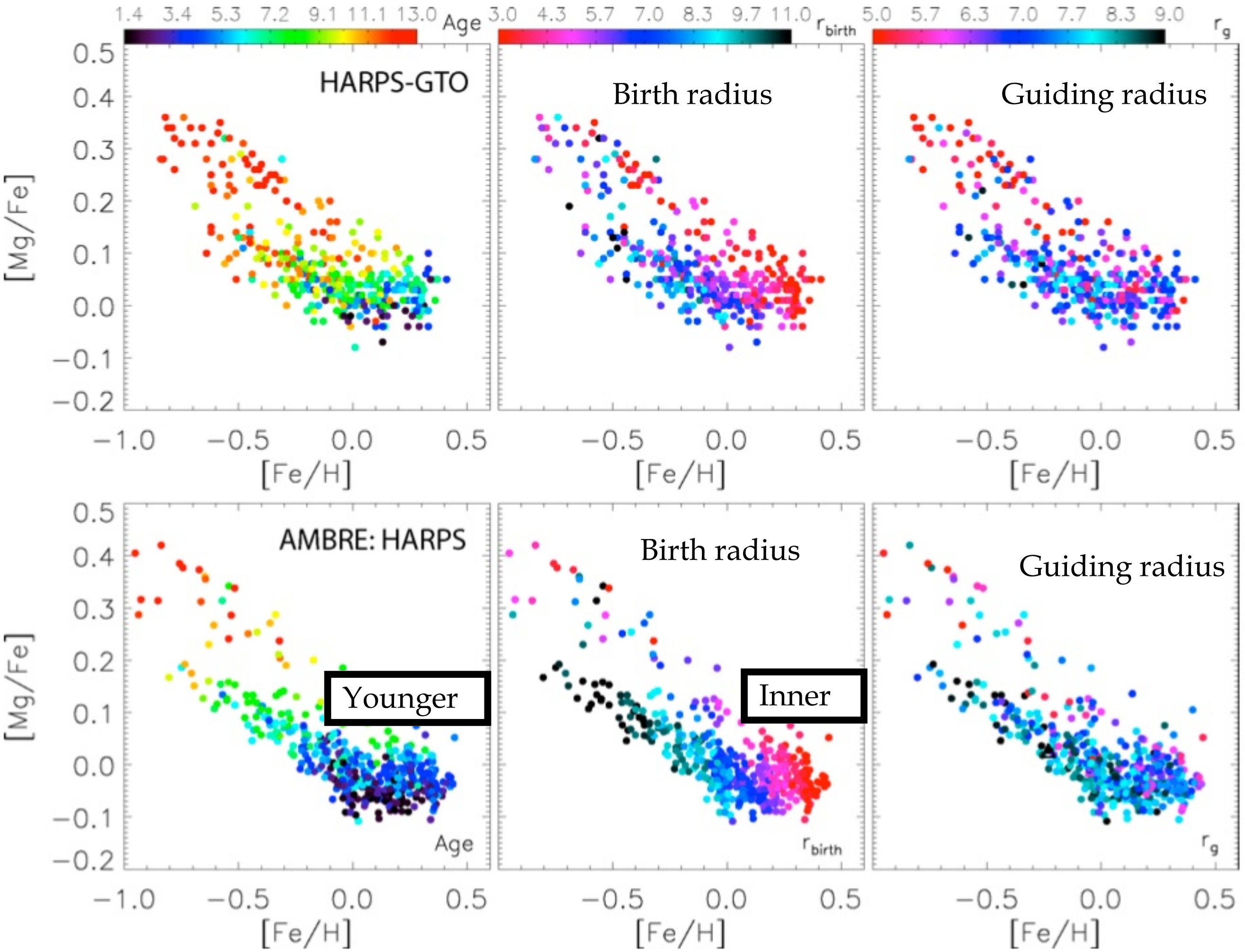


Figure 9. [Mg/Fe]-[Fe/H] plane for the HARPS-GTO sample color-coded by age (left), birth radius (middle) and guiding radius (right). Old stars populate the high-[Mg/Fe] sequence and some of the metal-poor end of the low-[Mg/Fe] sequence. Stars with the smallest birth radii are those with the highest [Fe/H] values. Stars with the largest birth radii belong to the metal-poor end of the low-[Mg/Fe] sequence.

The abundance ratios

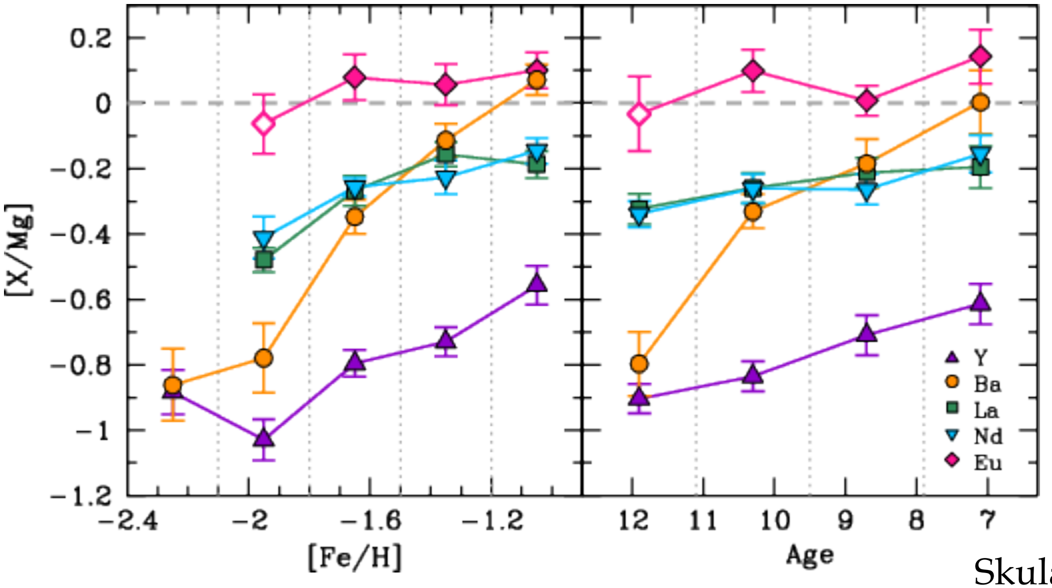
The observed behavior of elements: summary

- Oxygen and α-elements: varies approximately in lockstep and potentially can be described by the instantaneous Simple model.
- C, N, Fe increases from the lowest metallicity systems observed to solar metallicity, relative to the first group → **time-delay effects and secondary production**
- Metals up to Ti show intermediate behavior, which is probably due to varying contributions from massive stars (short time scales) and Type Ia supernovae (longer time scales)
- Heavier metals tend to track iron more or less
- r-process elements like Eu, track oxygen more closely than iron
- s-process elements, like, Ba are also produced by low mass AGB stars and thus have a late production

Using abundance ratios to measure stellar ages

- The abundance ratio of elements produced with different time delays can be used to infer stellar ages

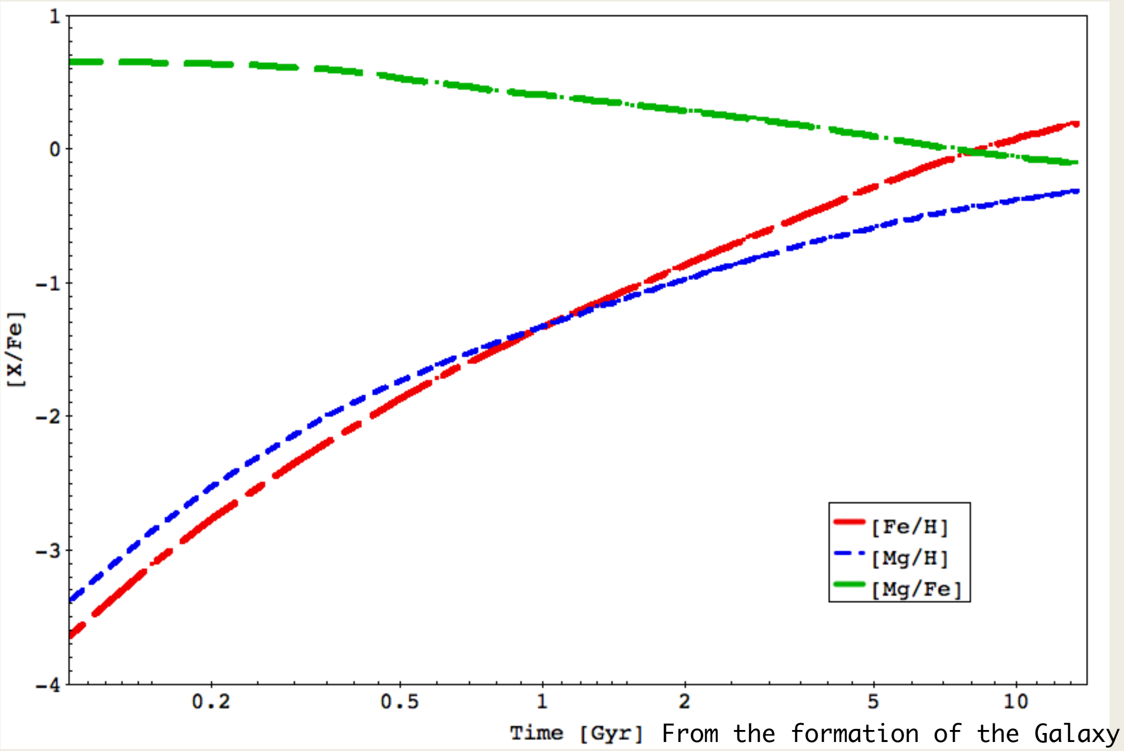
- s-process elements, like, Ba are also produced by low mass AGB stars and thus have a late production
- Compared with elements produced in the early phases of the Galaxy evolution, as Mg



Skuladottir et al. 2019

Magnesium

- Mg is produced mainly by SNII, with shorter timescales than SNIa
- During the first Gyr the production of elements is dominated by SNII, and thus iron is under-produced with respect to Mg
- After ~1 Gyr, SNIa start to explode, over-producing iron (which has both SNI and SNII contributions)
- The final result is a decreasing trend of [Mg/Fe] with age (age of the Galaxy, which is the inverse of stellar ages)

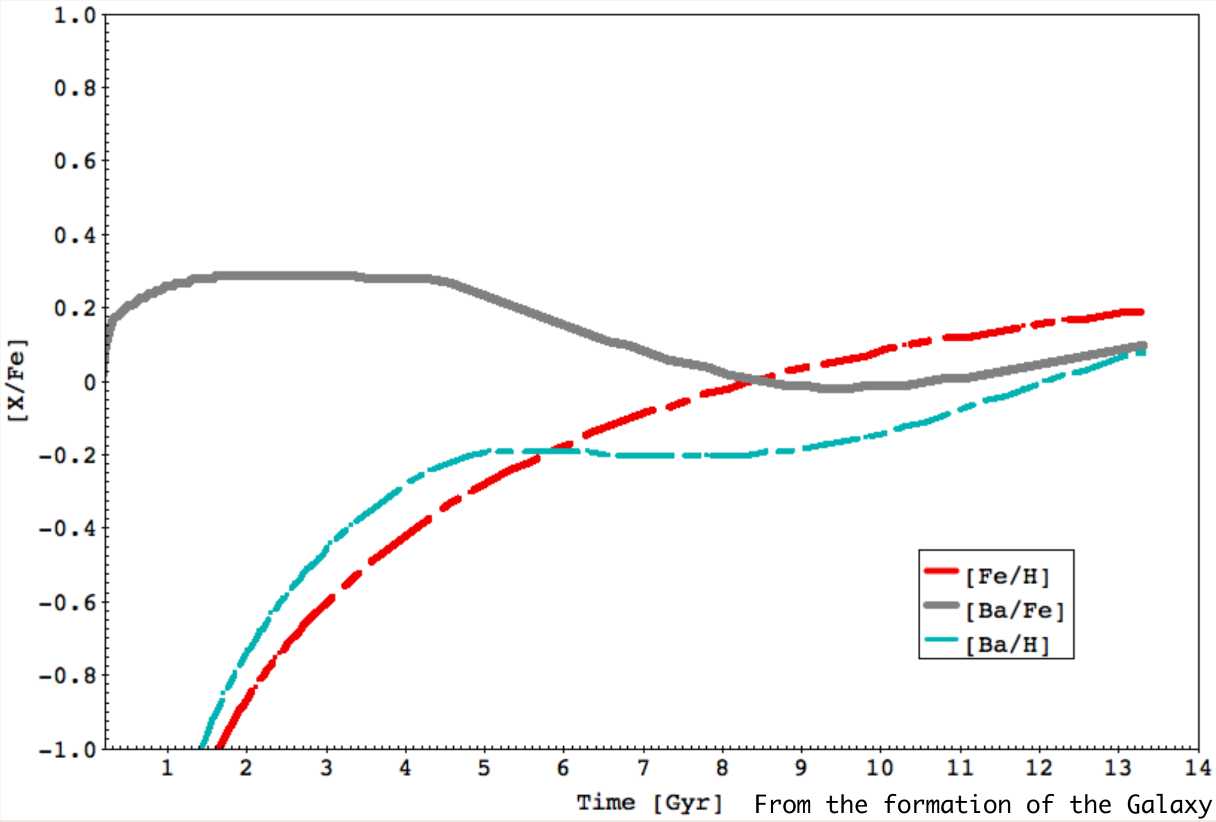


Old stars stars

Young stars

S-process elements

- Ba has a small r component (from SNII) which is responsible of Ba at low metallicity
- At about ~8 Gyr, low mass AGB start to contribute to Ba from s-process, producing the increase [Ba/H] with time, and [Ba/Fe]

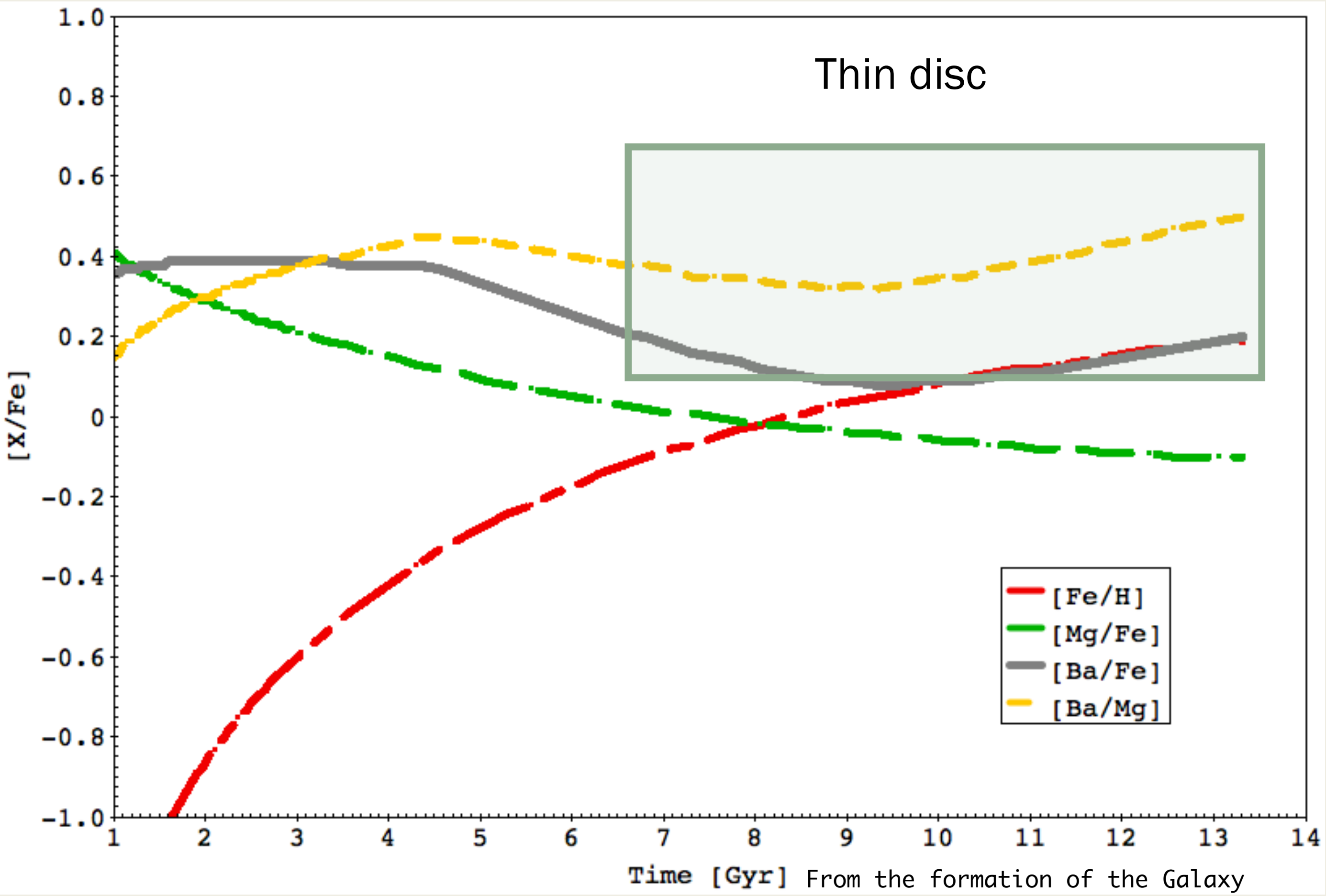


Old stars stars

Young stars

Combining s-process and alpha elements

- The combination of an increasing trend (s-process elements) and of a decreasing trend (alpha elements) produce a steeper increasing trend, e.g. [Ba/Mg] or [Y/Mg]



Old stars stars

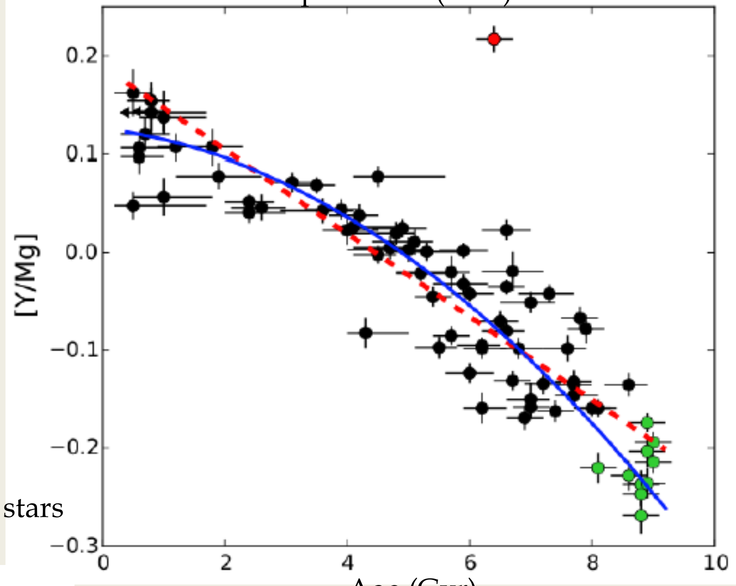
Young stars

Combining s-process and alpha elements

From the observations:

→ if we consider stars very similar (for instance Solar twins-stars with stellar parameters very similar to those of the Sun)

Spina et al. (2018)



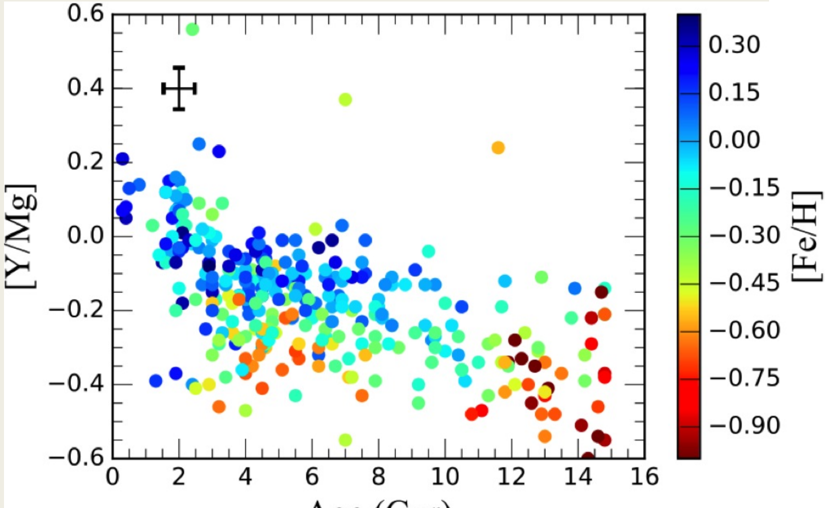
Young stars

Age (Gyr)

Old stars stars

From the formation of the Galaxy

Feltzing et al. (2017)



Young stars

Old stars stars

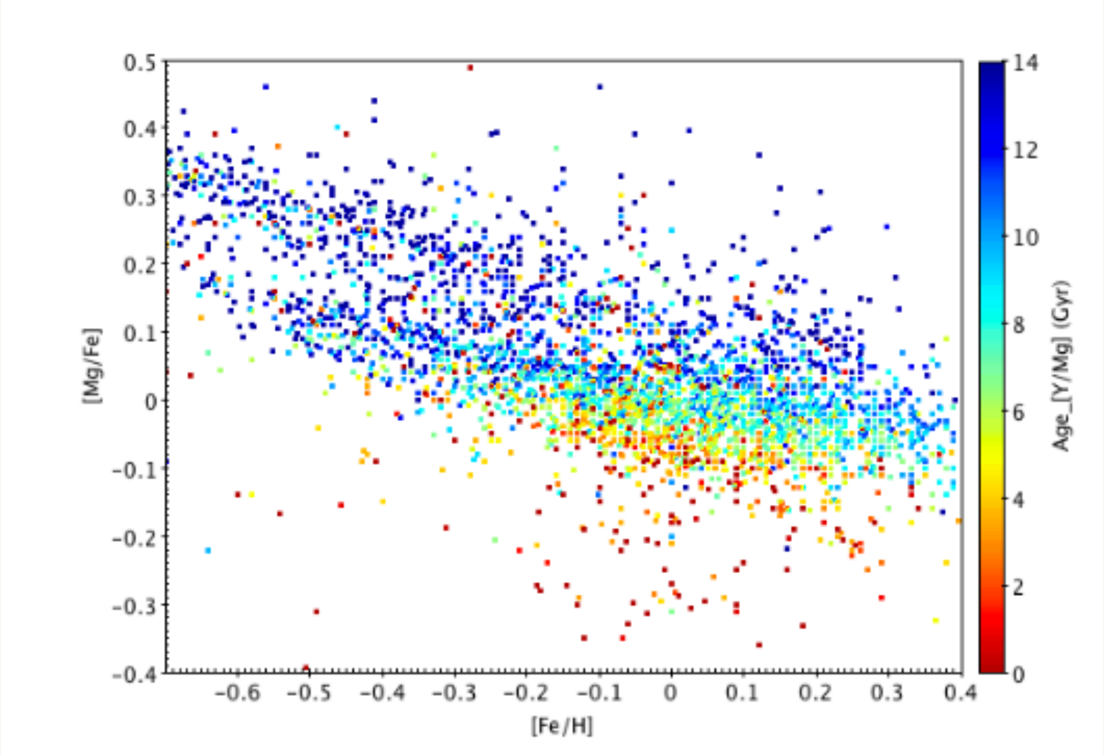
→ if we extend the analysis to a wide range of metallicity, the relationship is less tighter and very dispersed

→ Strong dependence on metallicity

Why does the relationship vary with metallicity?

- The solar neighborhood is populated by stars migrated from the inner and outer disc
- The inner/outer disc had a different star formation history (shorter timescale, and more efficient SF in the inner disc, and viceversa)
- Selecting stars in different metallicity bins means also **selecting stars coming from different regions of the galaxy**
- In addition, the yields of AGB stars for s-process are not monotonic (they have a peak at intermediate metallicity)
- The combination of the maximum production of s-process and the peak of the SF in each annulus of the Galaxy, produces a variation in the age-[s-process/alpha] relationship.

The application of chemical clocks to limited regions of the Galaxy

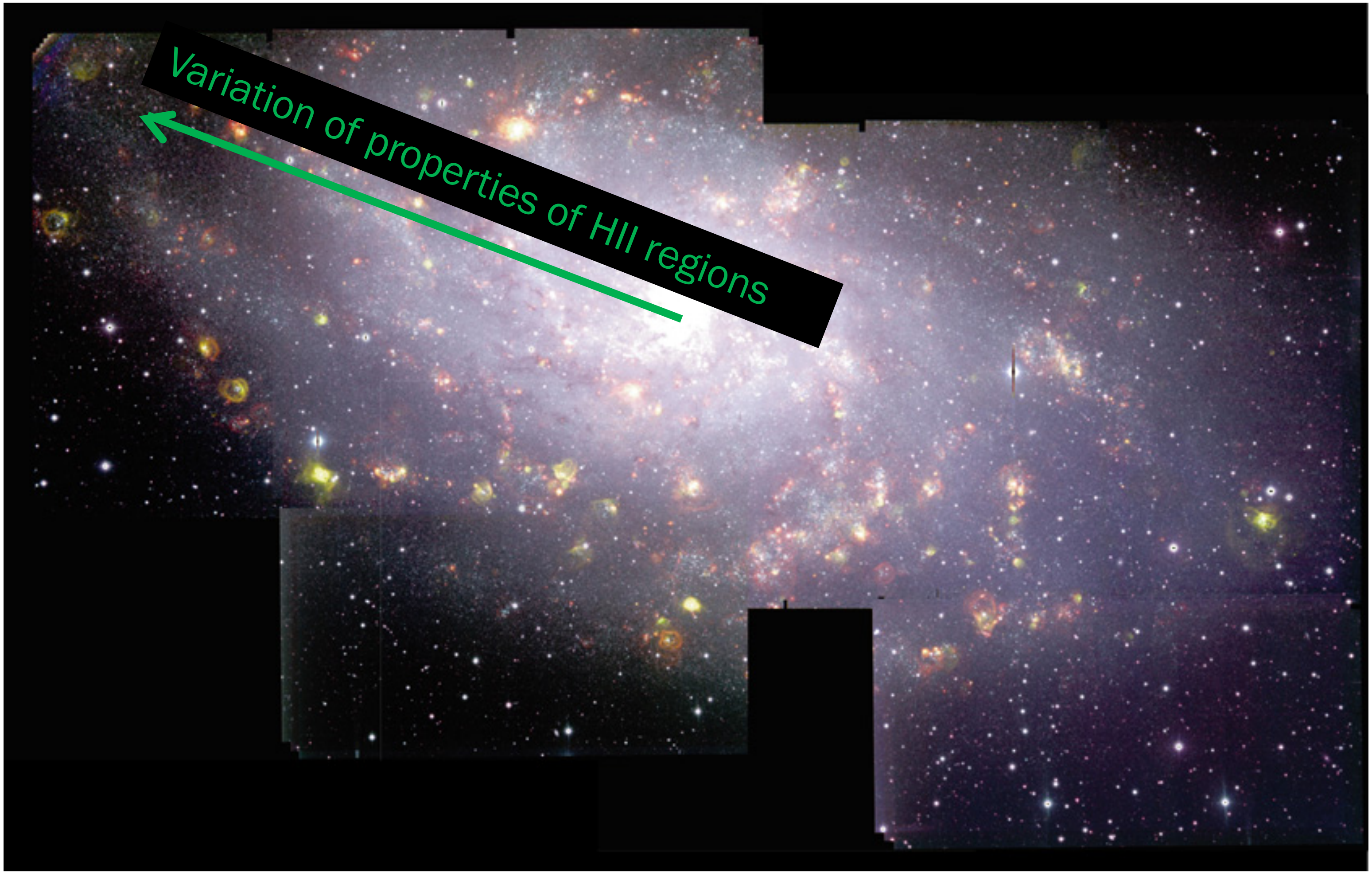


From Casali et al. (in prep.)

- **Ages are derived just using a single abundance ratio**
- Accurate enough to disentangle between the thin and thick disc populations
- But….since the relation varies with the Galactocetric distance, it

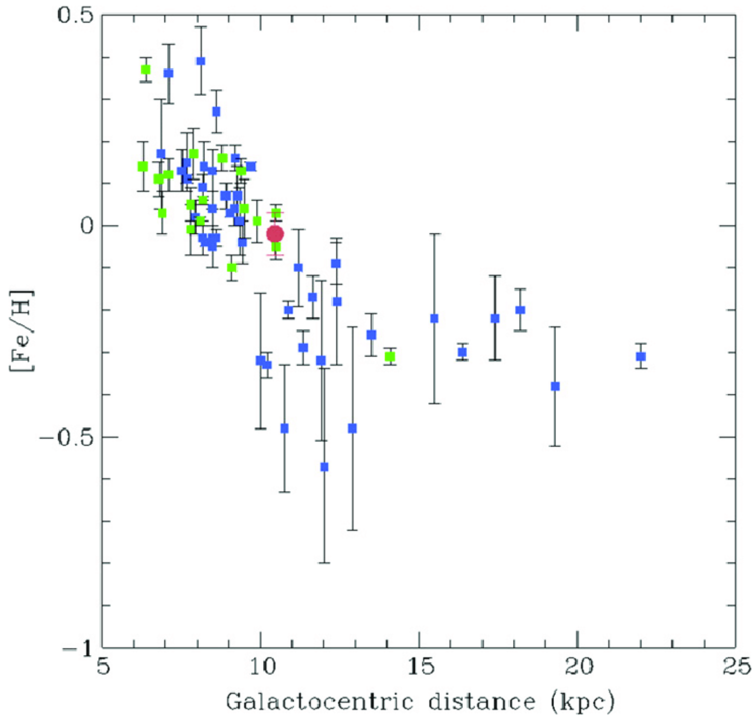
The spatial distribution of abundances

Our Galaxy (and in general spiral galaxies) are not homogeneous in terms of chemical composition



Three-color map of M33 (red-Hα, green [OIII], blue continuum): INT 2.5m telescope

The radial metallicity gradients

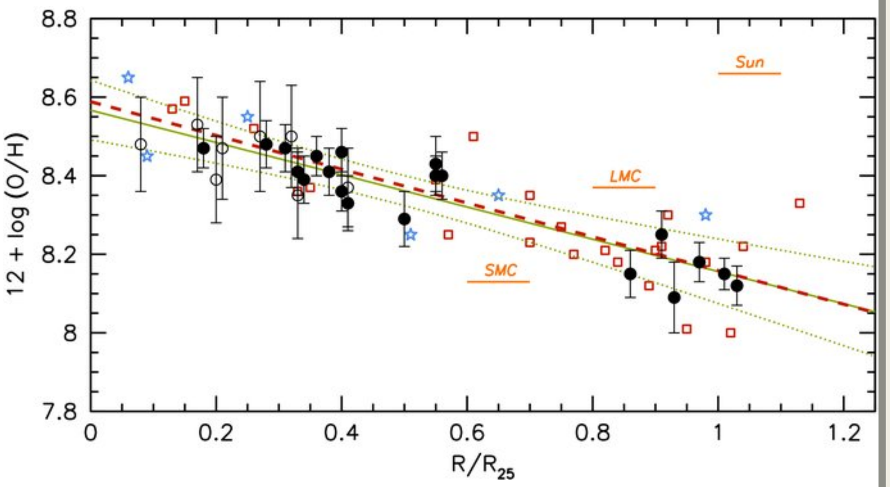


Sales Silva et al. 2015

In our Galaxy

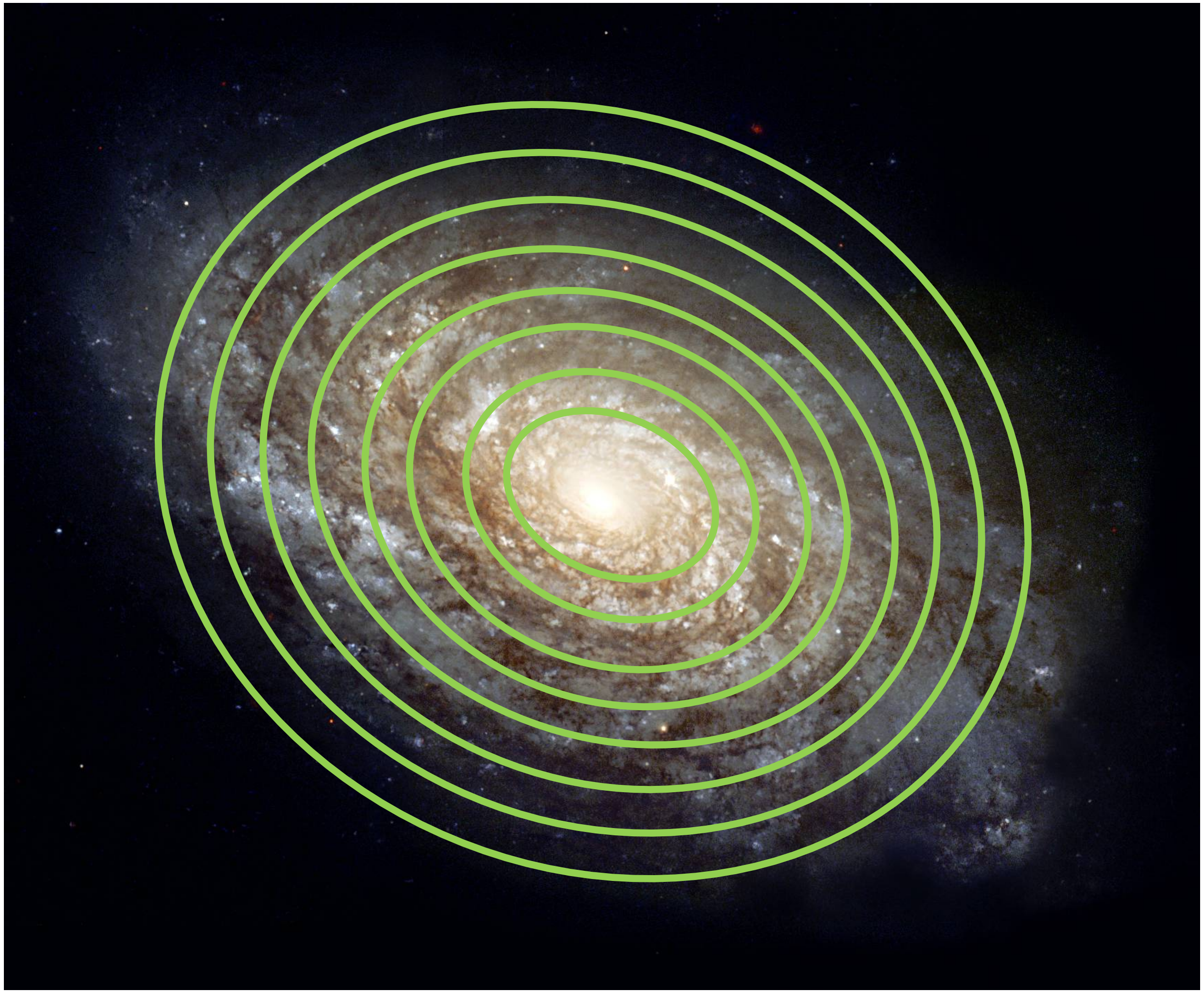
The properties of galaxies varies along the galactic radius

In other spiral galaxies



Bresolin et al. 2009

The multi-zone model



The multi-zone model

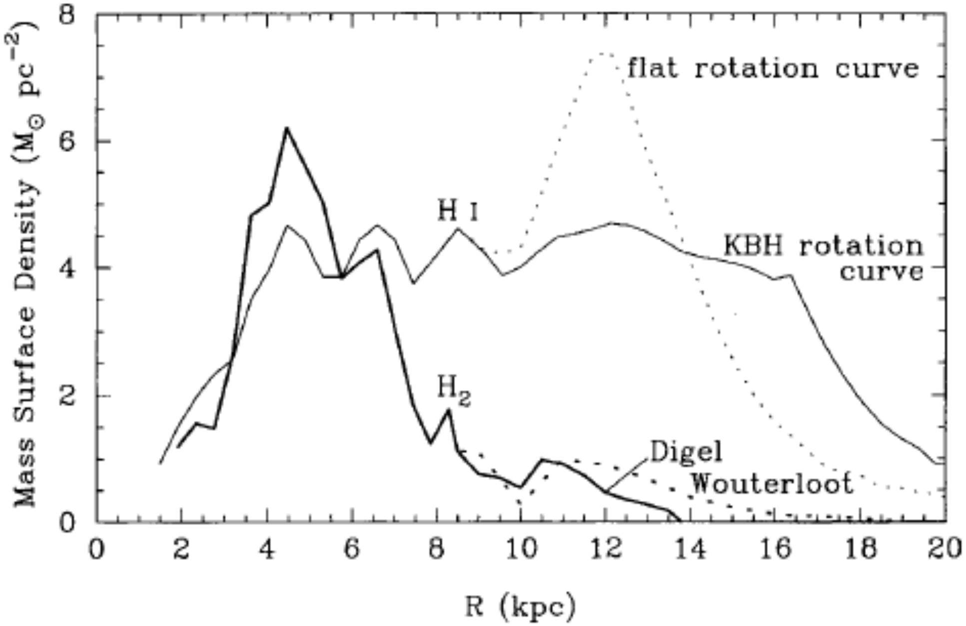


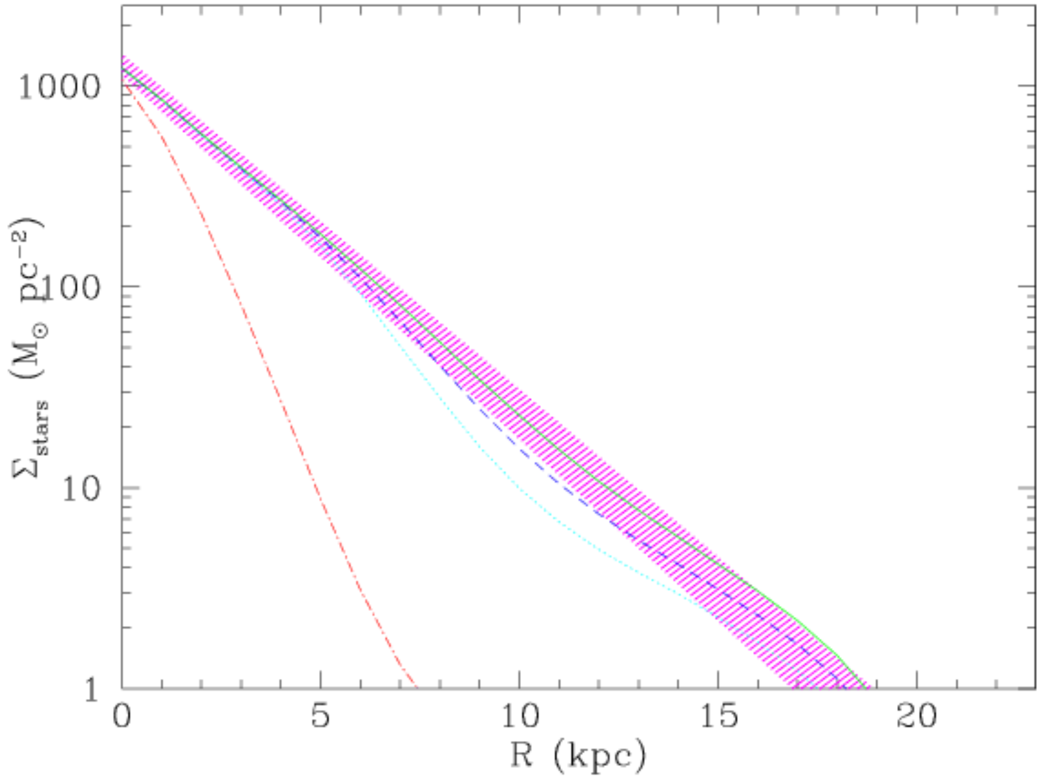
Fig. 8.14. Surface densities of atomic and molecular hydrogen in the Galaxy as a function of Galactocentric distance; the Sun is at 8.5 kpc. Beyond that distance, the deduced surface density depends on the assumed law of Galactic rotation; KBH refers to Kulkarni, Blitz and Heiles (1982). Assuming their rotation curve, the total gas surface density falls by about a factor of 2 between 4.5 and 13 kpc, corresponding to an exponential fall-off with a scale length α_g^{-1} of about 12 kpc. After Dame (1993). Courtesy T. M. Dame.

- Just considering the observational evidences:

→ The mass surface density of the gas (Atomic and Molecular) is not constant along the disc

→ See previous lecture by Simone Bianchi

The multi-zone model



Magrini et al. 2009

- The mass surface density of the stars varies exponentially constant along the disc

  <u>Since the metallicity Z depends on the gas fraction</u>, the combination of the stellar and gaseous densities produces a variation in **<u>the gas fraction</u>**

- → we expect a variation of the metal content along the disc

The radial metallicity gradients in the simple model

In the hypothesis that:

(a) The evolution takes place in isolated concentric zones analogous to the solar cylinder

(b) The gas fraction decreases inwards towards the Galactic centre → faster timescales for conversion of gas into stars in the inner regions → higher metallicity in the gas

$$Z = p \ln \frac{M}{g} = p \ln \frac{s+g}{g} = p \ln \frac{1}{\mu},$$

With scale-lengths of the stars α_*^{-1}=4 kpc and of the gas α_g^{-1}=12 kpc

$$z(R) = -\ln \mu(R_\odot) - (\alpha_* - \alpha_g)(R - R_\odot) + \ln\left(\frac{1 + g(R)/s(R)}{1 + g(R_\odot)/s(R_\odot)}\right)$$
$$\simeq 1.8 - 0.17(R - R_\odot) + 0.0013\, R^2.$$

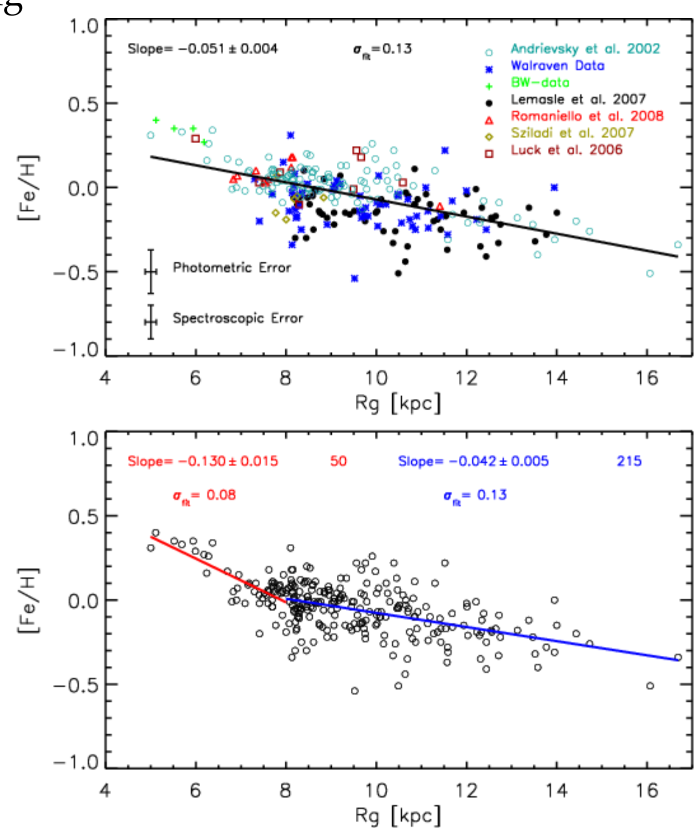
The radial metallicity gradients in the simple model

→ The gradient predicted by the simple model (using the observed surface density profiles) is:

-0.04 dex kpc^{-1}

→ The observed gradient is:

- → steeper in the inner parts
- → flatter in the outskirts



Gradients traced by Cepheid stars (young population)

Pedicelli et al. (2009)

The radial metallicity gradients in the simple model

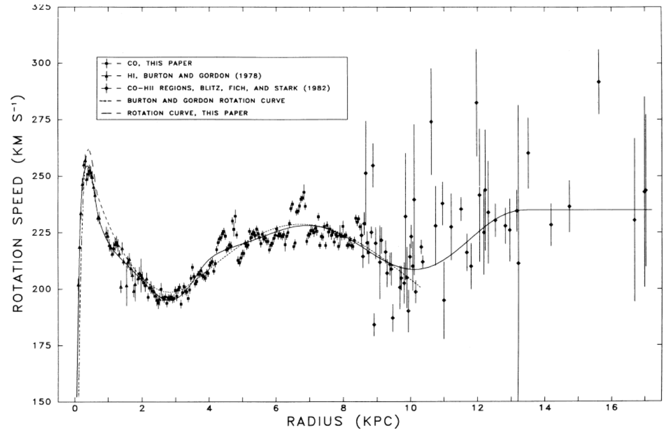
→ Possible origins of the differences from what is predicted by the simple model and the observations

→ **In the inner regions:**

→ **dissipative processes such as inward radial flows of gas driven by viscosity or by a mismatch of angular momentum of inflowing material;**

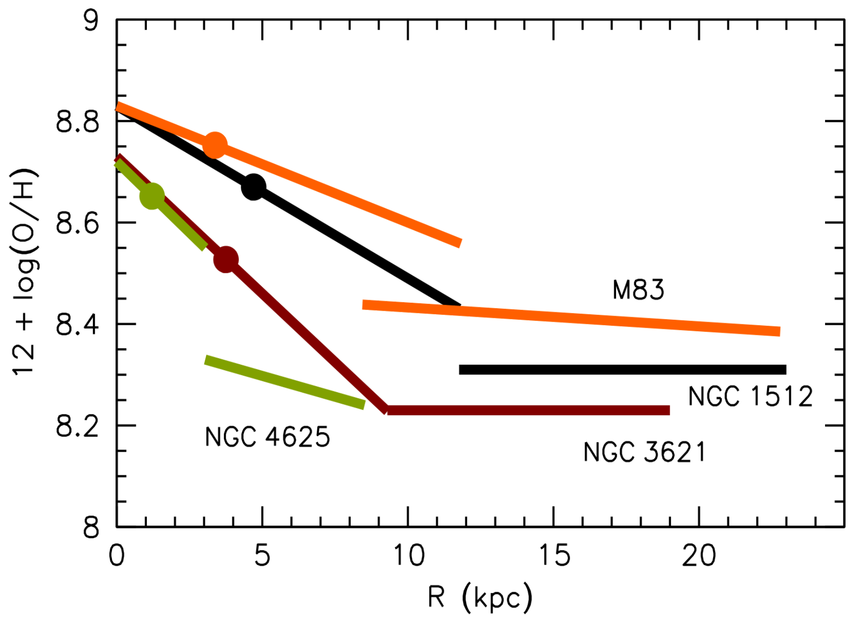
→ **differential effects of inflow of unprocessed material at different radii;**

→ **radial mixing caused by perturbations of axial symmetry, e.g. by a central bar→ the presence of a bar should produce a redistribution of material→ flattening of the gradient**



The radial metallicity gradients in the galaxy outskirts

→ The outskirts of galaxies show often an over-enrichment in metallicity



- → In many external galaxies the radial distribution of O/H from HII regions is flat in the outer regions
- → Bresolin et al (2009) pointed out the extended disk of M83 scan be considered chemically over-enriched given its <u>**large gas mass fraction (approaching unity) when compared to a closed box chemical evolution model**</u>

The radial metallicity gradients in the galaxy outskirts

→ In outer disc of the Milky Way

→ Evidence for a flattening of the abundance gradient in the outer disk of the Milky Way comes from observations of various tracers:

- ❖ H II regions (Vílchez and Esteban 1996; Esteban et al. 2013).
- ❖ Cepheid variables (Korotin et al. 2014)
- ❖ Open clusters (Magrini et al. 2009; Yong, Carney and Friel 2012)

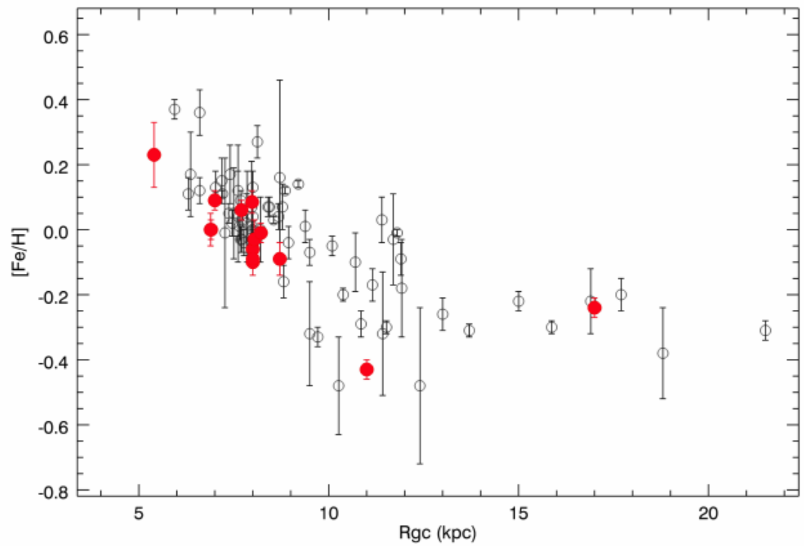
Increasing age

→ This break appears at Galactocentric distances around 12 kpc, extending outwards to 19–21 kpc

→ The open cluster population show a clear bimodal radial gradient in metallicity the outer gradient being quite shallow, with a characteristic outer disk metallicity $[Fe/H] \simeq -0.3 \pm 0.1$.

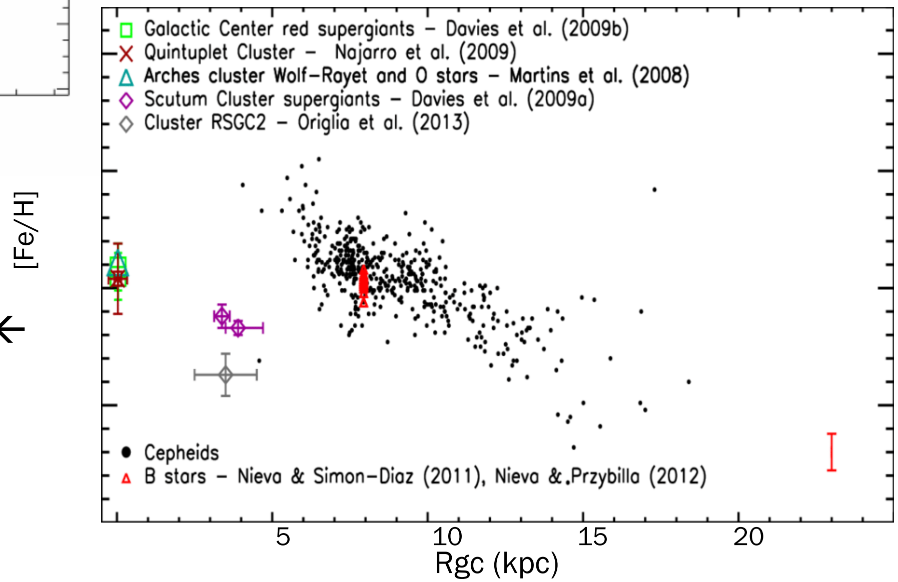
The radial metallicity gradients in the galaxy outskirts

→ In outer disc of the Milky Way



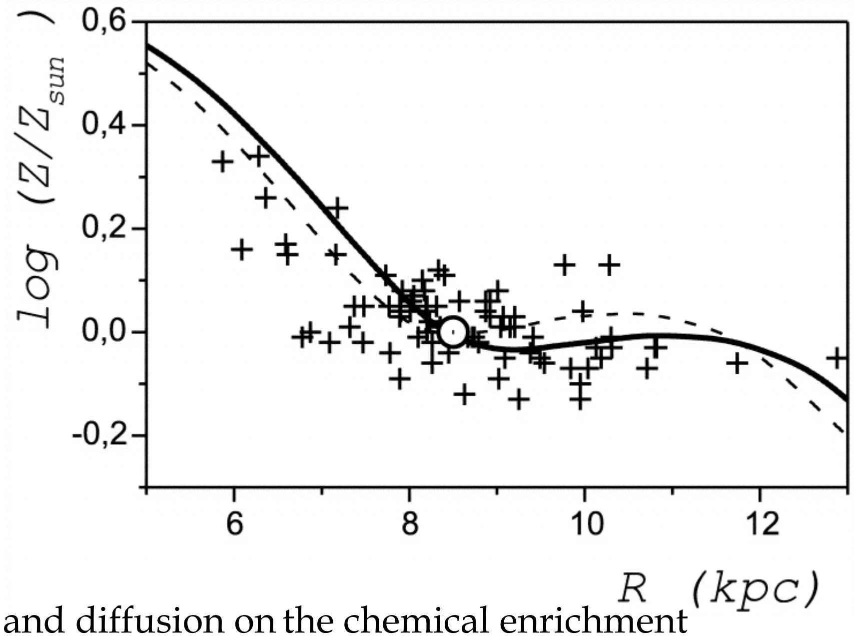
→ Open star cluster (Age 0.1-8 Gyr)

Cepheid variable stars (Age 0.1-0.3 Gyr) ←



The radial metallicity gradients in the galaxy outskirts

→ In outer disc of the Milky Way



The combined effects of spiral arms, corotation, and diffusion on the chemical enrichment of the Galactic disk can indeed explain the bimodal abundance structure.

→ <u>**The corotation radius corresponds to the radius where stars move at the same speed as the spiral arms**</u> (see Lecture 4)

→ Inside it, the stars move faster and outside they move slower than the spiral arms

→ It is the radius where exchange of stars/gas has the higher probability

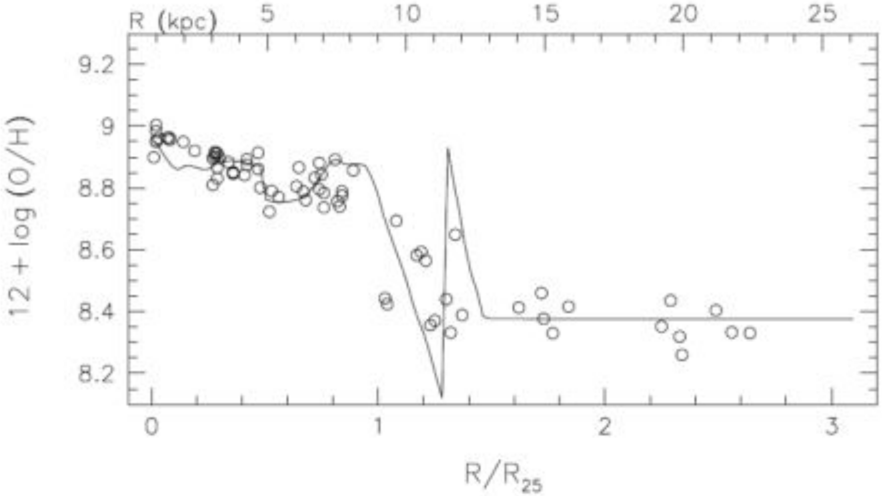
→ Gas enriched in the inner disk might move towards the outer regions

The radial metallicity gradients in the galaxy outskirts

→ In outer disc of the M83 (and in general of spiral galaxies)

Two main categories: mixing and enriched infall:

- Turbulence and convective distribution of metals
- Outward radial flows originating from *viscosity or* by angular momentum redistribution
- Minor merger
- Re-accretion of enriched outflows



→ Model that include an inflow of metal-enriched gas with an oxygen abundance 12 + log(O/H) = 8.20 dex

→ Such an enriched infall is required by the model to reproduce the gas metallicity observed in the extended disk of M83 with the flat distribution arising from the assumed constant star formation efficiency.

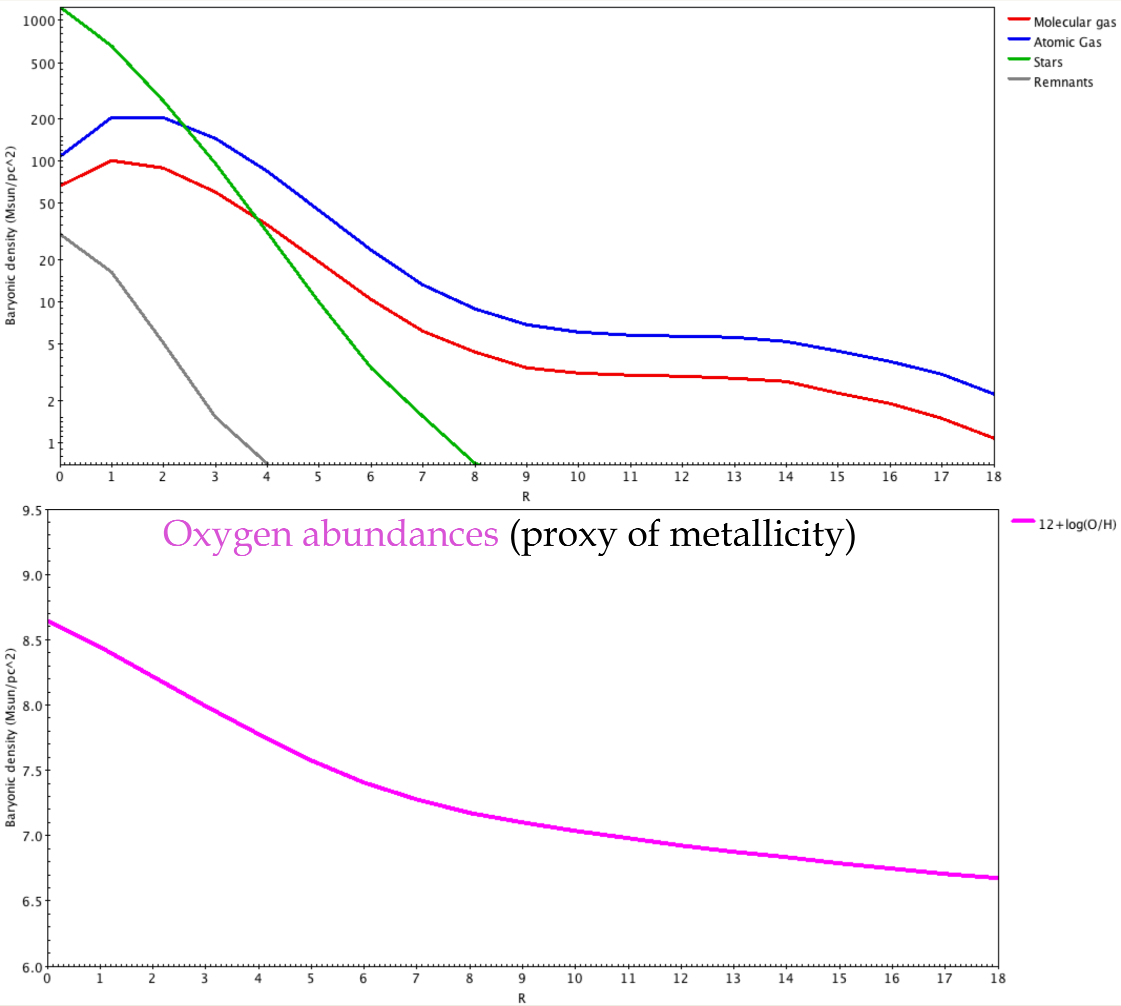
Main drivers of the shape and evolution of the gradients

Gas (atomic and molecular), stars, remnants

Magrini+09
Model of the MW disk

Similar results predicted by many models, e.g.:

- Hou et al. 2000
- Boissier & Prantzos 1999
- Ferrini et al.
- Molla & Diaz 2005
- etc.



What forms the shapes of disks?

- Radial variation of the infall rate
- Radial variation of the star formation efficiency

+ radial migration, gas flows, etc.

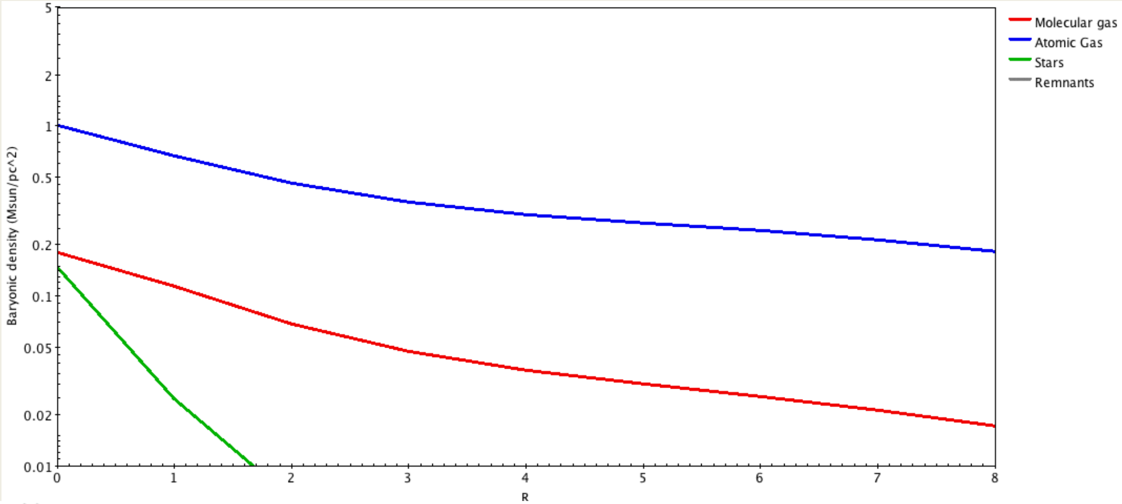
Main drivers of the shape and evolution of the gradients

Gas (atomic and molecular), stars, remnants

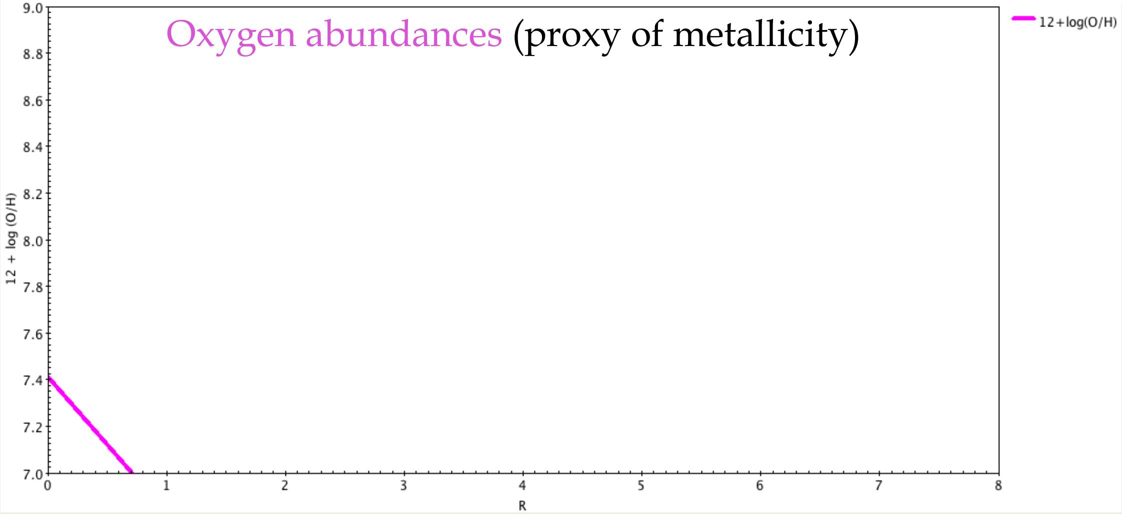
Magrini+07-10
Model of M33 disk

See the differences between the MW and M33:

The shape and evolution of the gradients are also function of the morphological type and mass of the galaxy



Oxygen abundances (proxy of metallicity)



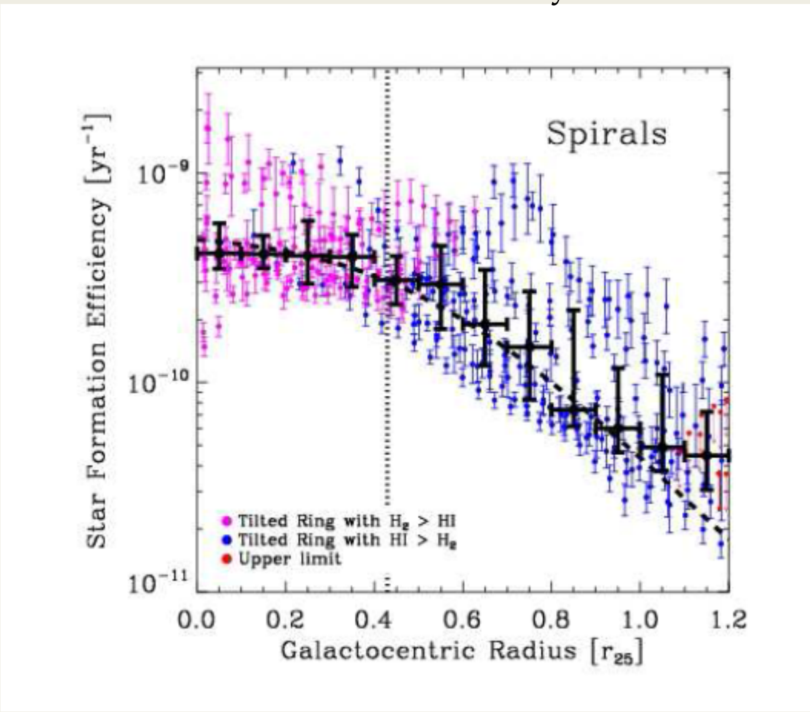
What forms the shapes of disks?

- Radial variation of the infall rate
- Radial variation of the star formation efficiency

+ radial migration, gas flows, etc.

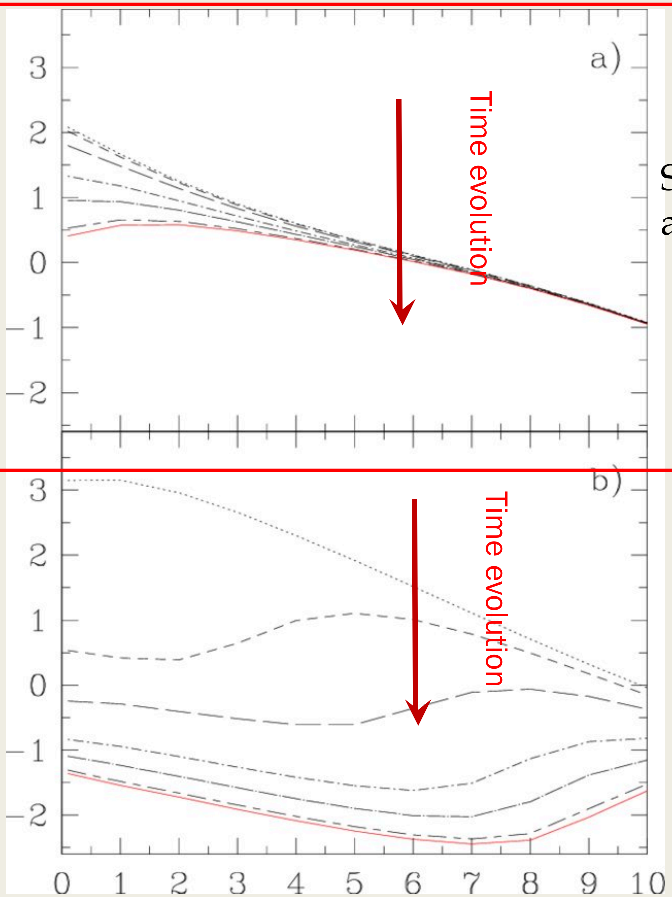
Main drivers of the shape and evolution of the gradients

Observed radial variation of the star formation efficiency



- → More frequent cloud-cloud collapse
- → Higher density
- → **More efficient star formation**

Radial variation of the infall rate (assumed) with its time evolution



Slow accretion

Rapid collapse

Does the radial metallicity gradient evolve with time?

Which kind of time evolution?

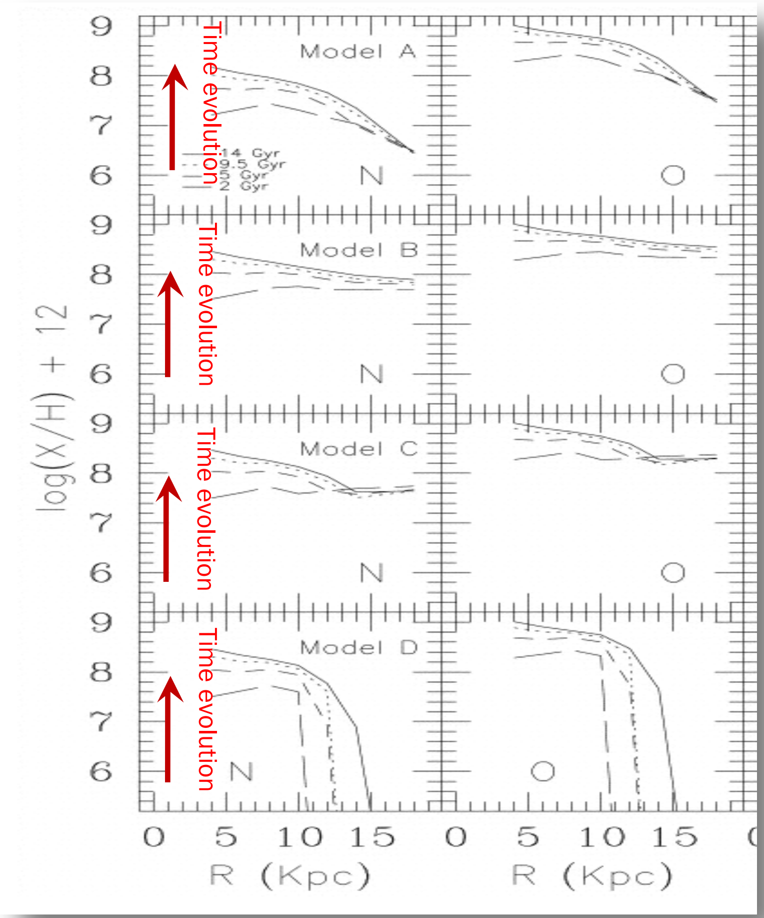
- The models shown in the previous slides predicts a **flattening** with time of the radial metallicity gradient

- This is direct consequence of the **inside-out formation** of the disk:

  - the material from which the disk is formed is not pre-enriched
  - the infall of gas that build up the disk reaches the outer regions at later times (exponentially decreasing infall)
  - The star formation efficiency is lower in the outer regions (radially decreasing→ less cloud collisions)

Does the radial metallicity gradient evolve with time?

- Considering an **inside-out formation** of the disk but
  - A pre-enrichment of the infalling material that forms the disk
  - A threshold in the star formation efficiency (stars are not formed is the density of gas is not sufficiently high)



at $t = 2$ (*long-dashed line*), 5 (*dashed line*), 9.5 (*dotted line*), and 14 (*solid line*) Gyrs for models A to D

- The two infall model by Chiappini+01 (see Lecture 10)
- Four models (A, B, C, D) with different levels of star formation threshold and of halo/thick disc-phase pre-enrichment

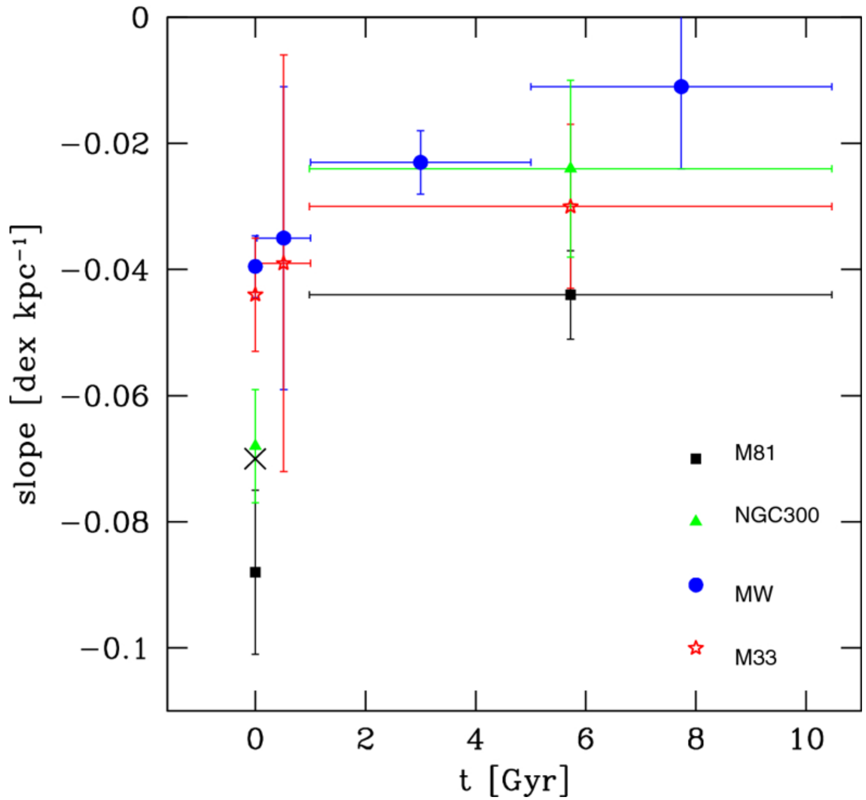
The net effect is a steepening with time of the radial metallicity gradient

→ **The pre-enrichment makes the difference**

Does the radial metallicity gradient evolve with time?
What observations tell us

→ In the MW and in nearby galaxies

- → Observations of stellar population of different ages
- → Comparing their radial gradients to study the time evolution



From Stanghellini et al 2014

- The first naïve interpretation would be that the radial gradients were flatten in the past
- We need to take into account the motions of stars

Taking in to account migration:

we can observe a flatten gradient in the old population even it was steeper just for the effect of radial migration

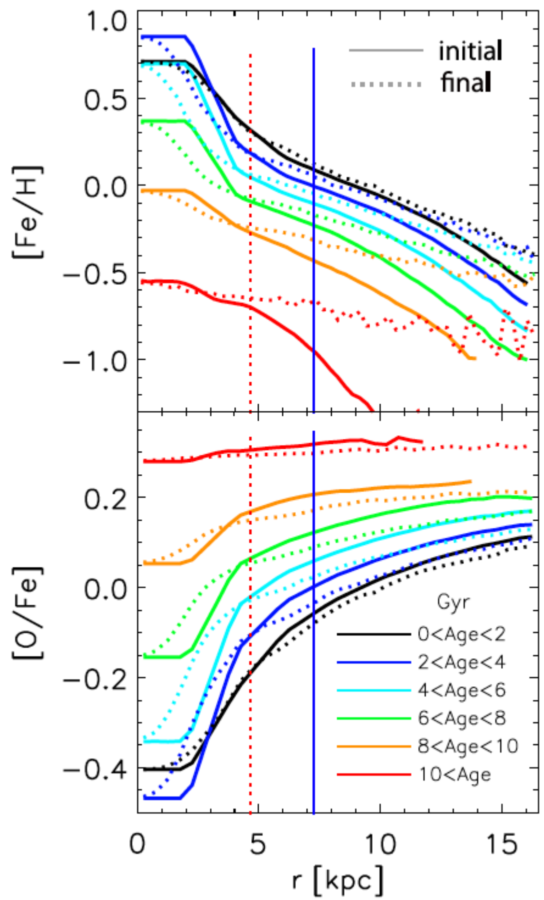


Fig. 5. Effect on the initial [Fe/H] (*top*) and [O/Fe] (*bottom*) gradients for different stellar age groups. The solid and dotted color curves show the initial and final states, respectively. Note that while strong flattening is observed for the older populations, the metallicity gradient for the youngest stars (age <2) is hardly affected at $r \lesssim 12$ kpc, thus justifying the use of our chemical model, which uses this as a constraint.

From Minchev et al. (2013):

- Solid and dotted line-styles represent the initial (chemical) and final (chemodynamical) states→ effect of stellar migration gas in the disk
-
- A strong flattening in [Fe/H] is seen for the older populations, but the younger stars are much less affected.
- For stars younger than 2 Gyr the final gradient is very similar to the initial one out to ~12 kpc.
- There tendency of bringing more stars from the inner disk out, due to a larger bar expected at earlier times.

Taking in to account migration

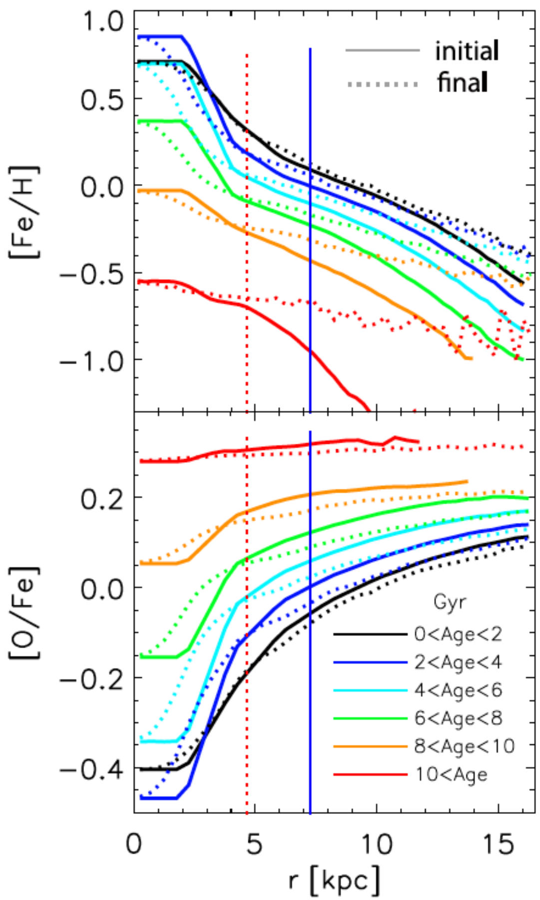


Fig. 5. Effect on the initial [Fe/H] (*top*) and [O/Fe] (*bottom*) gradients for different stellar age groups. The solid and dotted color curves show the initial and final states, respectively. Note that while strong flattening is observed for the older populations, the metallicity gradient for the youngest stars (age <2) is hardly affected at $r \lesssim 12$ kpc, thus justifying the use of our chemical model, which uses this as a constraint.

The effect might be important for very old population but we can still use intermediate age populations, such as **planetary nebulae** and **open clusters** to study the time-evolution of the radial gradients

→ It is important to disentangle the effect of chemical evolution and the dynamical effects

→ We need indeed chemo-dynamical models

The Age-Metallicity relation

The instantaneous Simple model predicts a monotonic increase in the abundance of any robust element with time, which can be quantified **if a star formation law is assumed.**

If, for example, the SFR is assumed proportional to the mass of gas as

$$ds/dt = \omega g$$

with ω constant

The abundance of a primary element (in logarithmic form) increases linearly with time according to

$$z = \omega t$$

The Age-Metallicity relation

More generally, ω may be treated as variable, thus not appealing to any particular star formation law, in which case we still have

$$z(t) = \int_0^t \omega(t')dt' \equiv u,$$

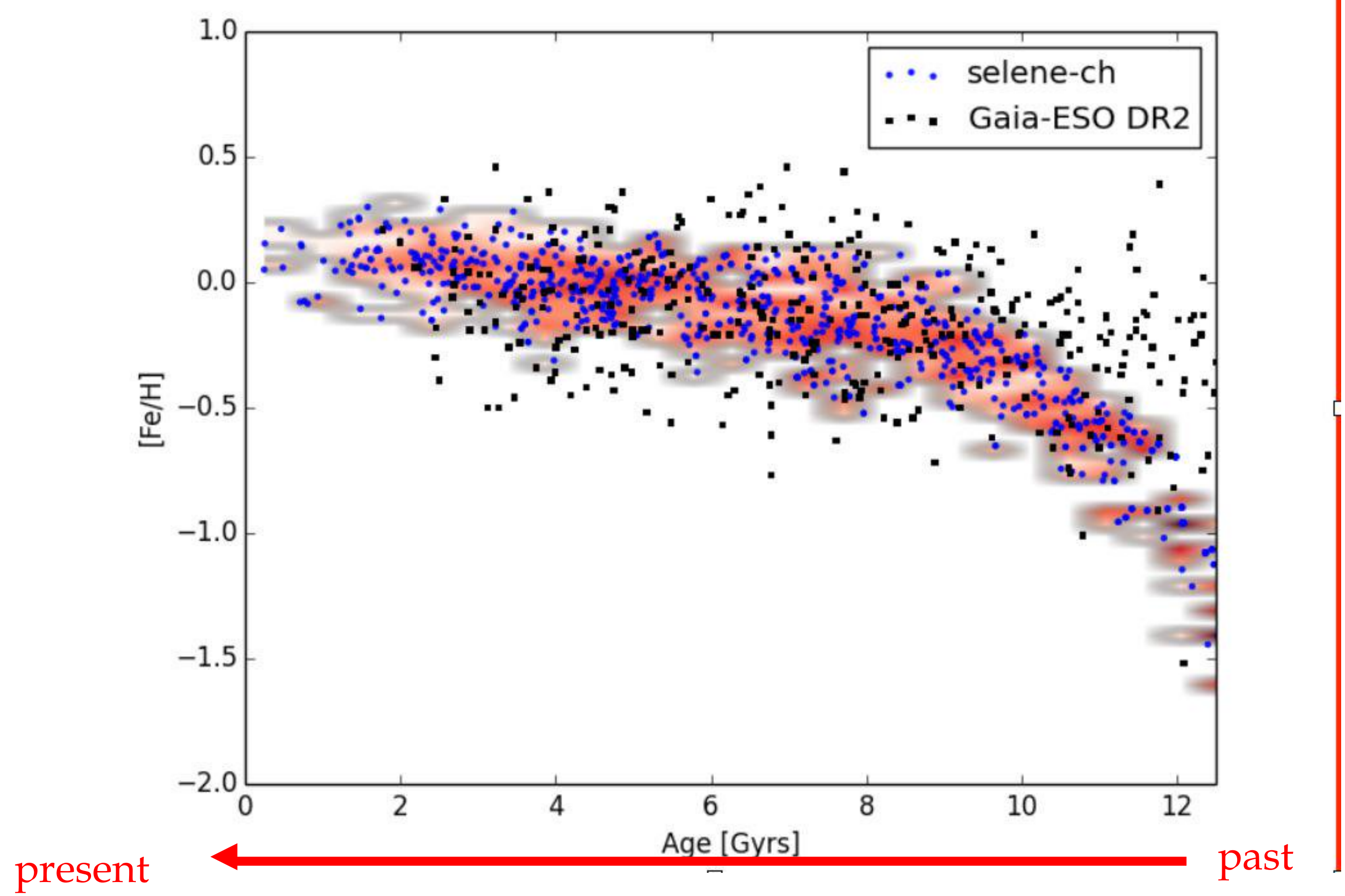
where u is some single-valued **non-decreasing function of time.**

An increase with time is found in a qualitative sense in the low metallicities observed in most stars of the Galactic halo population and in high-redshift absorption-line systems on the line of sight to quasars, including the damped Lyman-α systems which are believed to represent an early form of disk galaxies.

What happens in the stars close to the Sun?

The time evolution of abundances

As time passes, we expect to find more metal rich stars….as a direct consequence of chemical evolution.

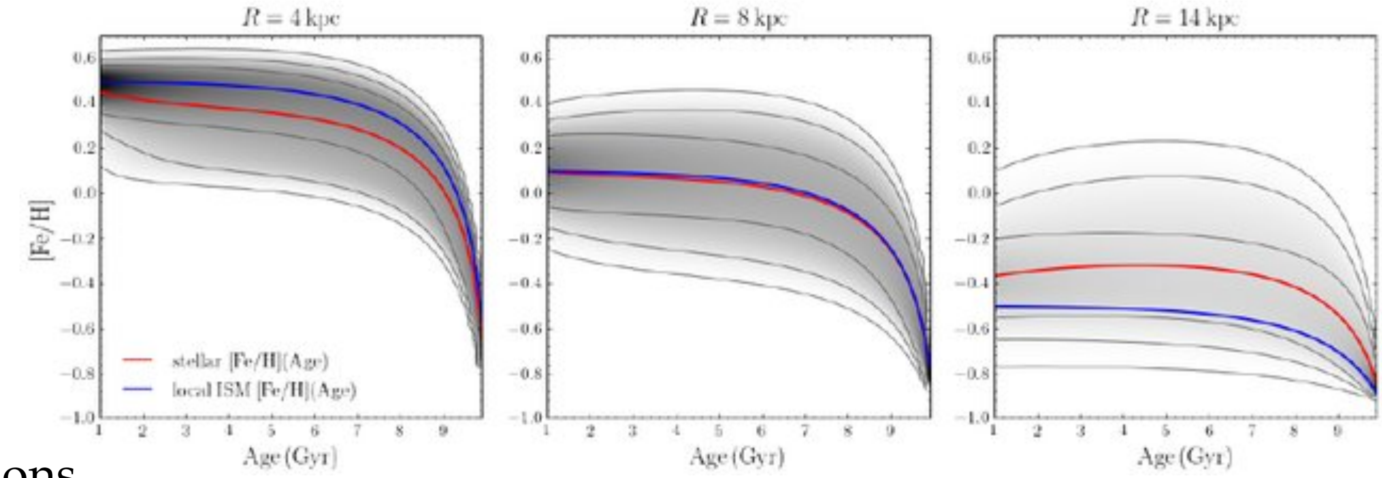


Model and observed age-metallicity relationship in the Galactic disc

The Age-Metallicity relation

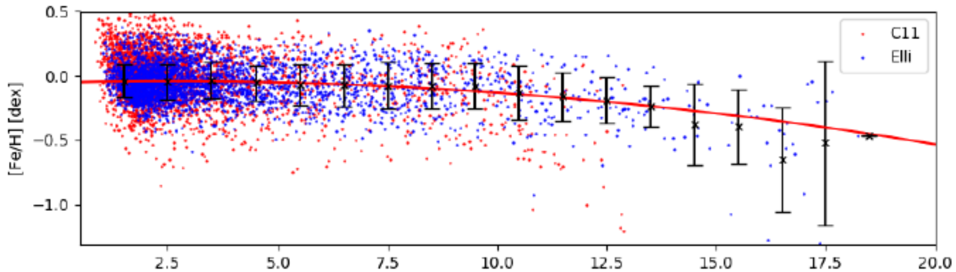
Higher SFE and infall rate → Lower SFE and infall rate

Models



Observations

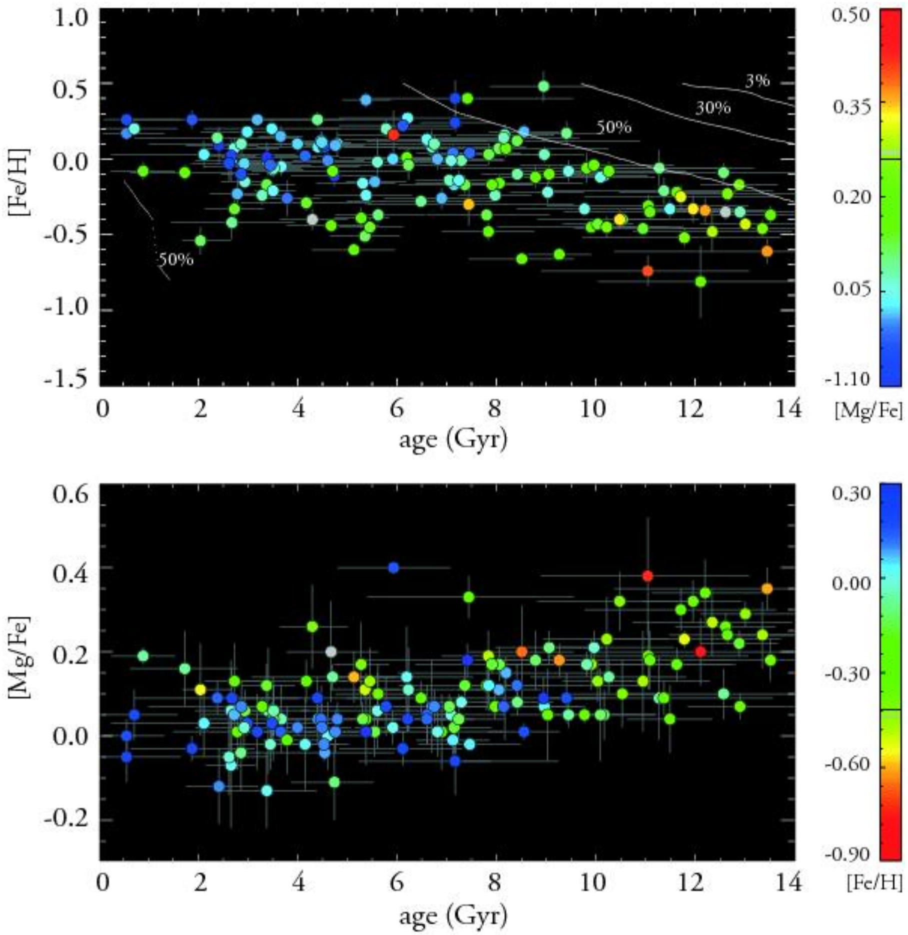
The scatter in the observed relation is due presence in the sample of **stars originating at different Galactocentric distances** with different evolutionary timescales (Edvardsson et al. 1993);



Lin et al. 2016 (Gaia dr1 data)

The Age-Metallicity relation

Observations: decreasing [Fe/H] and increasing [Mg/Fe] with increasing age



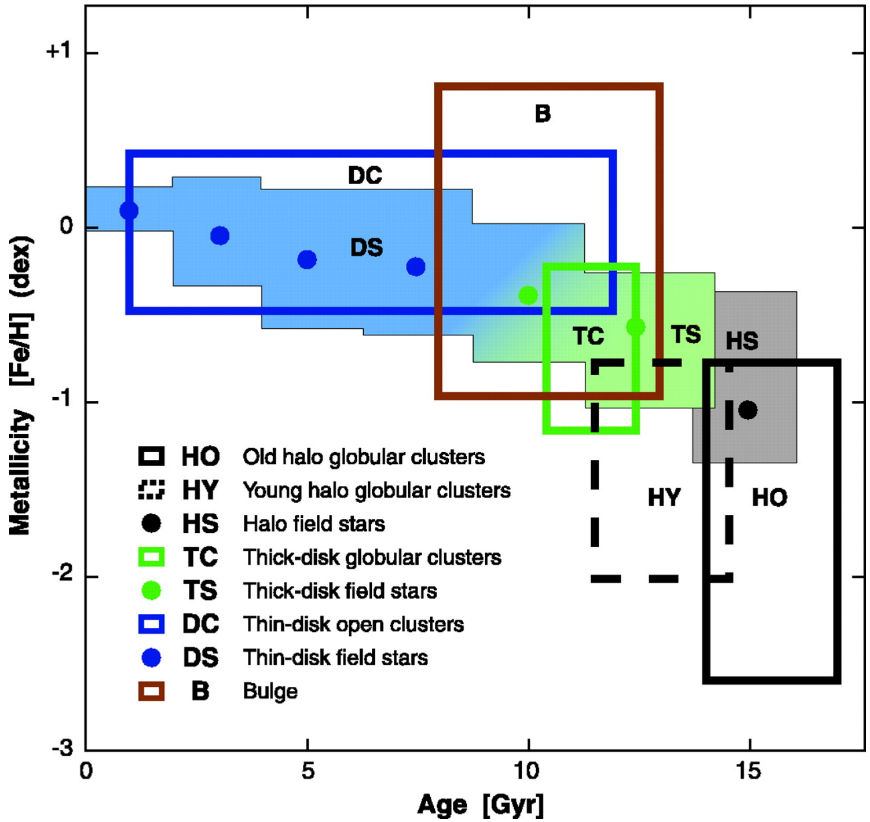
Bergemann et al. 2014

→ The observed relationship is:

- Scattered→ mixing stars born at different radii
- Decreasing [Fe/H] with increasing stellar age: age-metallicity relationship (predicted by chemical evolution)

→ Coupled with the relationship between [Mg/Fe] and age, which implies faster enrichment rates of Mg in the early epochs (most of the iron comes from SN Ia progenitors with significant lifetimes)

The overall **age-metallicity relation in the Milky Way**



The age-metallicity relationship is more evident if we consider all the Galactic components.

The obvious trends of metallicity, [Fe/H], to increase with time and spatial concentration toward the Galactic plane and central region suggest that the components of the Galaxy formed and evolved in a coherent and continuous process.

However, the dispersion of the relation is everywhere so large that for some components, **different independent origins and evolutionary connections are possible**.

From Buser 2000, Science, 287, 5450, 69.

The effect of radial migration: if we can select only non migrating stars…

Non-migrating stars: < 10 % of the whole population

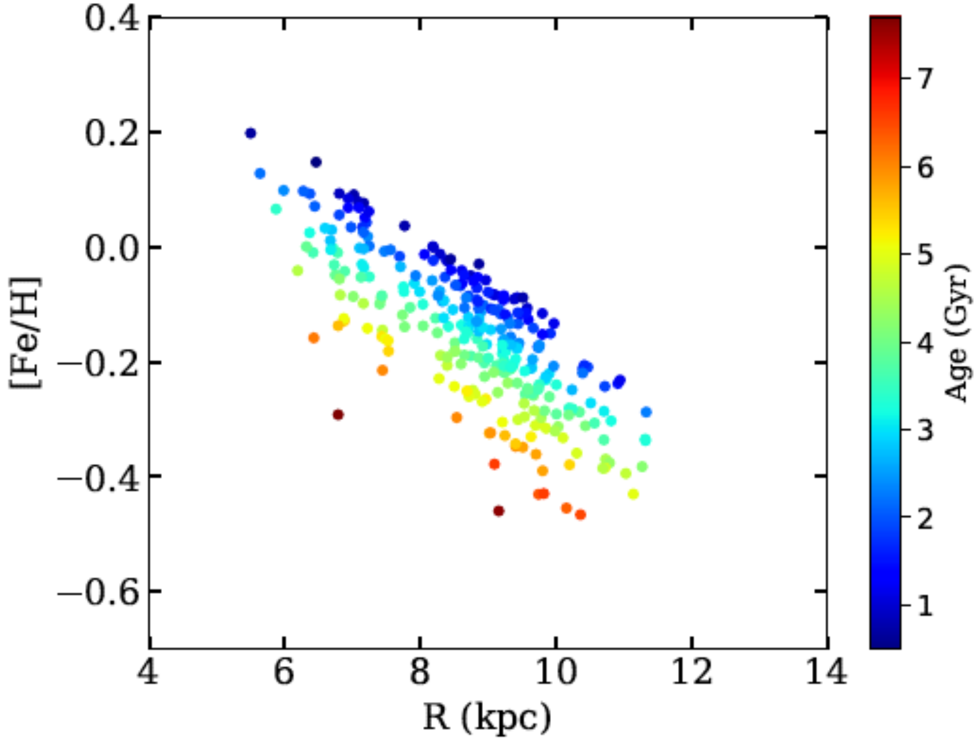


Figure 8. [Fe/H] as a function of Galacto-centric radius for stars that have not moved (for definition refer to Sect. 4.2) away from the radius they formed at. This example is for the model by Frankel et al. (2018). Age is colour coded according to the colour-bar to the right.

From Feltzing et al. 2019

Considering non-migrating stars:

- Metallicity and age appear to correlate well at each radius, such that younger ages are associated with higher metallicities.
- at a given radius there is a tight age-metallicity relation.
- only a **single transient interaction with a spiral arm is required to generate substantial changes to a stars angular momentum** (Sellwood & Binney 2002)

The effect of radial migration: if we can select only non migrating stars…

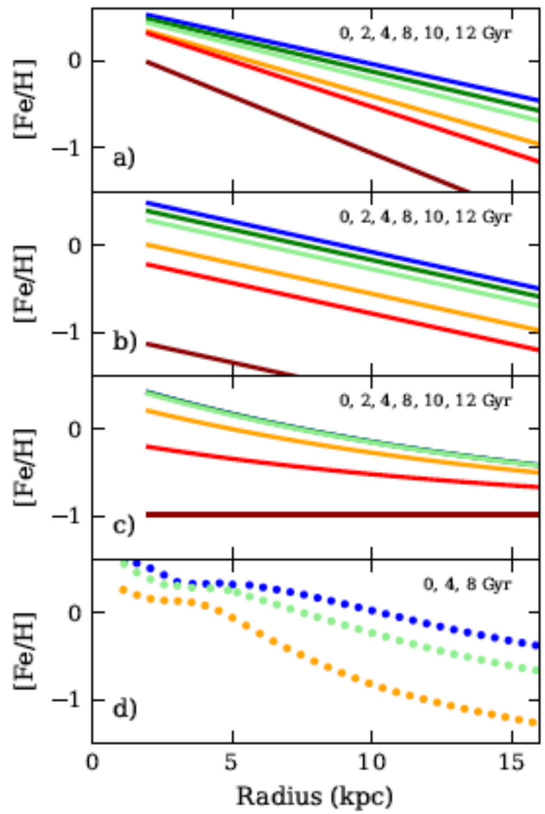
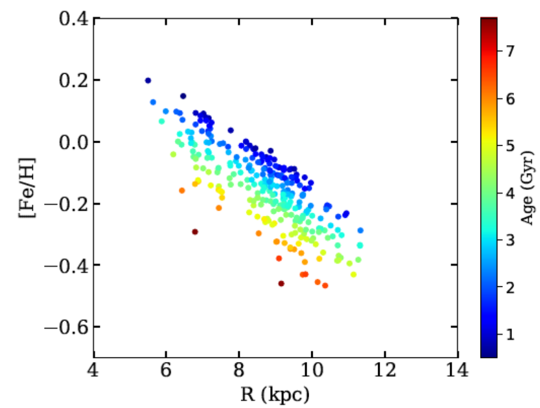


Figure 4. Comparison of radial metallicity gradients for the ISM used in this work. Ages as indicated in the legends (for coloured lines going from blue to brown with increasing age). **a)** (Minchev et al. 2018). **b)** Frankel et al. (2018). **c)** Sanders & Binney (2015). Note that in this model the gradients for ages 0, 2, and 4 Gyr essentially overlap. **d)** Kubryk et al. (2015a).



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There are at least two possibilities:

- Compare observations with models that include the effect of mixing (radial migration of stars, radial flow of gas)
- Select only stars not affected by migration

From Feltzing et al. 2019

Summary of Chemical abundances:

constraints to stellar nucleosynthesis and to galaxy formation and evolution

- Abundance ratios:

→ *reveal the relative time-scales in element production*

→ *reveal the primary to secondary ratio in element production*

- Spatial distribution and temporal evolution of abundances and abundance ratios:

→ *Put constraints on the mechanism of formation of the different Galactic components*

→ *Combined with kinematic information, reveal the role of radial migration in the redistributing stars in the Milky Way*