Probing dynamics with chemistry: young open clusters in the inner disc

....

and other evidences of the importance of radial migration in Local Universe galaxies

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Outline of the talk:

Observational evidences of radial migration

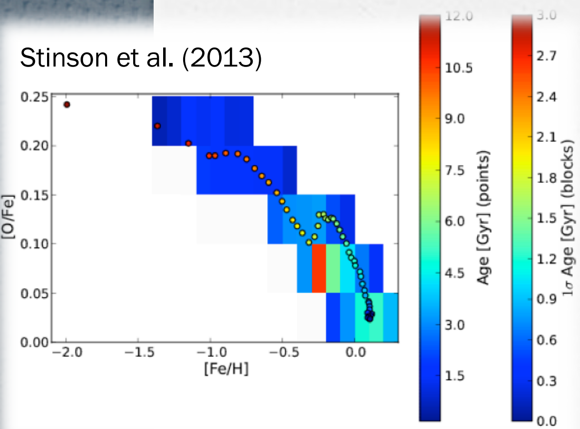
1. The discovery of a young Mg-enhanced population in the inner regions of the Milky Way: the case of young open clusters

    ....[confirmed also by field stars]

2. The time evolution of radial metallicity gradients in nearby galaxy: effects of chemical evolution and/or of radial migration?

The α-elements over Fe: the 'classical' Galactic clock

- In the absence of other age determinations, the abundance in α-elements, [α/Fe], is often adopted as a proxy for age.
- Simulations showed that mono-abundance and mono-age populations are roughly equivalent [e.g., Stinson et al. (2013)] .
- The large majority of α-rich stars are found to be older than 8–9 Gyr, both in simulations and observations (e.g., Haywood+13; Bensby+14; Bergemann+14).



The sites of production

The shorter time scales of, e.g., Oxygen and Magnesium (produced by massive stars) then that of Iron (produced by SNIa) make of [α/Fe] a good indicator of the time of star formation.

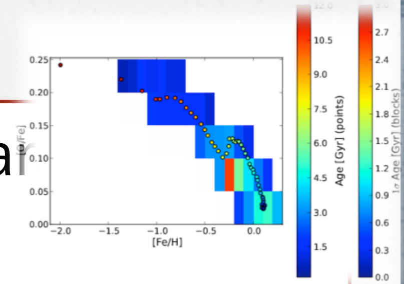
Table 8. Stellar nucleosynthesis.

From ML+14

Element	Main production site	Mechanism	Yield(SN Ia/SN II)
^{16}O	Massive Stars	Helium burning	8%
^{24}Mg	Massive Stars	C, Ne burnings	10%
^{28}Si	Massive Stars	explosive and non-explosive O burning	60%
^{40}Ca	Massive Stars	explosive and non-explosive O burning	67%
^{45}Sc	Massive Stars	C, Ne burnings, α and ν-wind (neutrino-powered wind)	49%
^{48}Ti	Massive Stars and SNIa	explosive Si burning and SNIa with He detonation	63%
^{51}V	Massive Stars and SNIa	explosive Si and O burnings, SNIa with He detonation, and α and ν	88%
^{52}Cr	Massive Stars and SNIa	explosive Si burning, SNIa with He detonation, and α	84%
^{56}Fe	Massive Stars and SNIa	explosive Si burning and SNIa	88%
^{58}Ni	Massive Stars (and SNIa)	α (α-rich freeze-out from nuclear statistical equilibrium) and SNIa	75%
^{50}Y	Massive Stars	He-burning s-process, and ν-wind	–
^{153}Eu	Massive Stars, compact binary merger	ν-wind	–

Many elements are produced by both SNII and SNIa, selecting the most ‘pure’ ones –dominated by a single channel of production– allows us to have the best ‘stellar clock’.

The discovery of new classes of α-enhanced stars



- HAMR stars (e.g., Adibekyan+13)→ old sta

- 'Young'* α-enhanced stars (e.g., Martig+15, Chiappini +15)

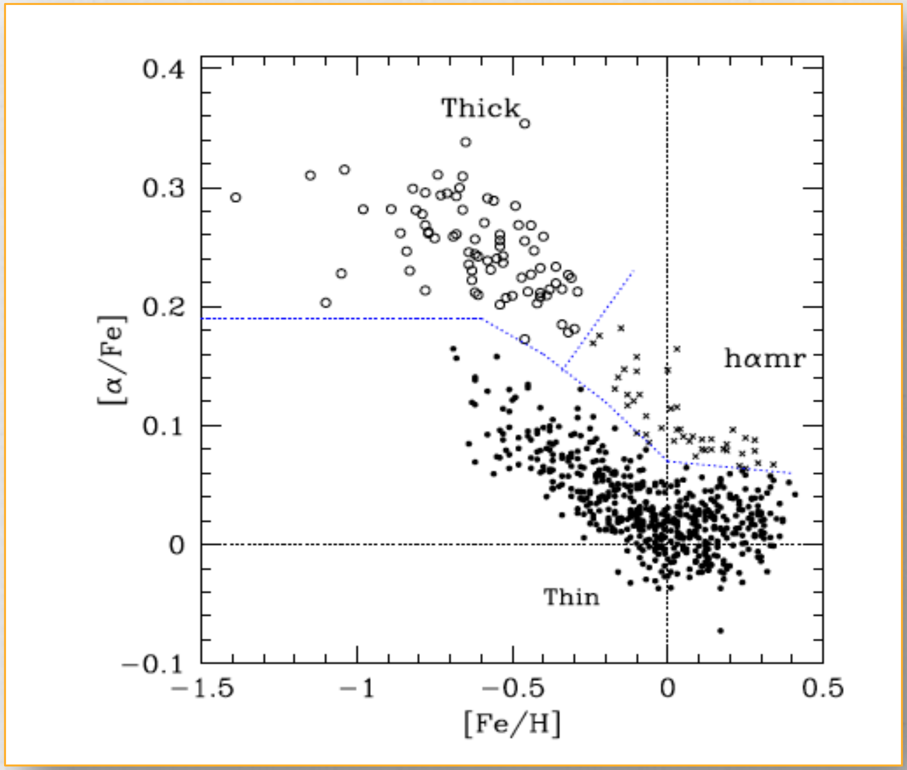
- 'Young'** open clusters located in the inner thin disc (Magrini+15)

*   < 4 Gyr

** <=1.5 Gyr

The discovery of new classes of α-enhanced stars

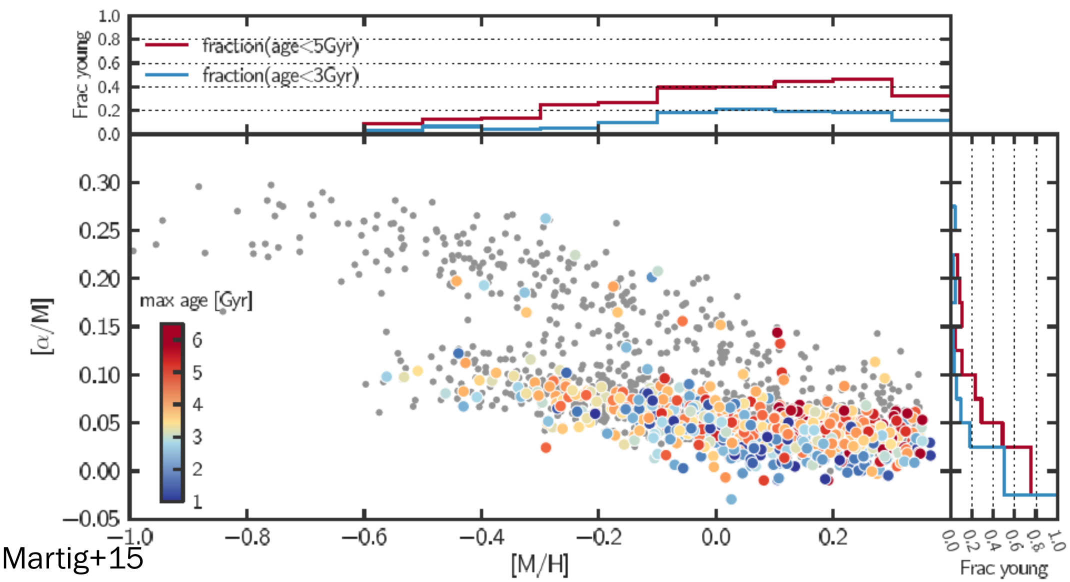
- HAMR stars (e.g., Adibekyan+13)



- Most of the HAMR stars have thin disk kinematics
- They are old stars, with ages 8-9 Gyr

The discovery of new classes of α-enhanced stars

- ‘Young’ α-enhanced stars (e.g., Martig+15, Chiappini+15)



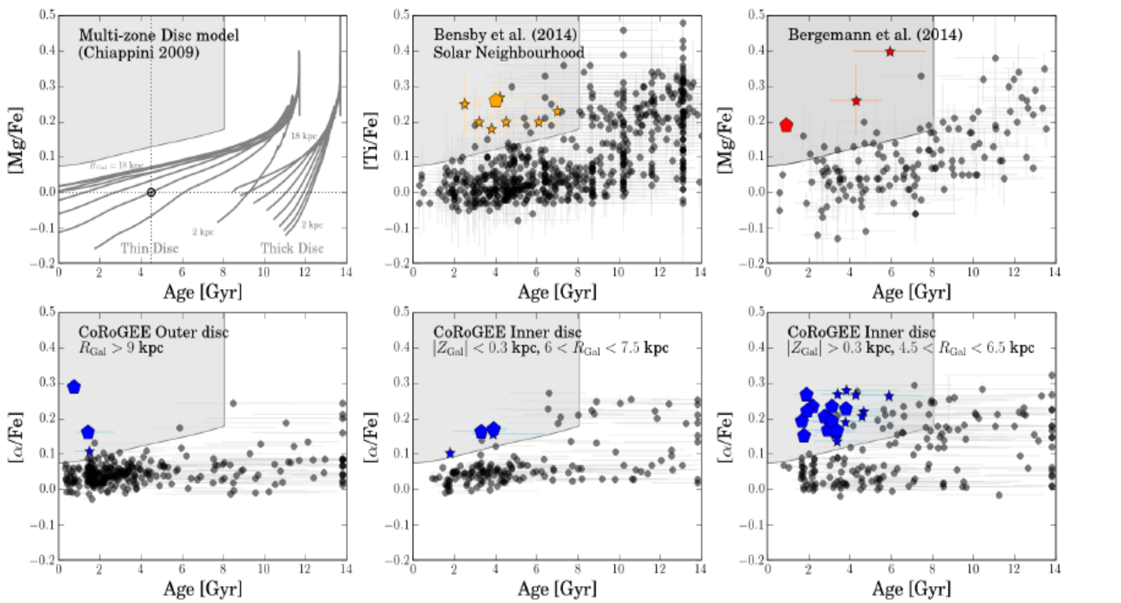
Martig+15

Figure 7. Age and abundances for stars in our APOKASC sample. The main panel shows the distribution of the APOKASC sample in the [α/M] versus [M/H] plane. Small grey dots represent stars for which ages are not measured (i.e. stars with a mass smaller than 1.2 $M_{\odot}$) and coloured dots represent stars younger than 7 Gyr (the colour encodes the maximal age of each star). The two histograms show the fraction of stars younger than 5 and 3 Gyr in different bins of [M/H] (top) and [α/M] (right).

- ‘Young’ α-enhanced stars in the APOKASC sample
- Ages < 4 Gyr
- Most of them are located at high altitudes from the Galactic plane |z| > 0.3 kpc

The discovery of new classes of α-enhanced stars

- ‘Young’ α-enhanced stars (e.g., Martig+15, Chiappini+15)

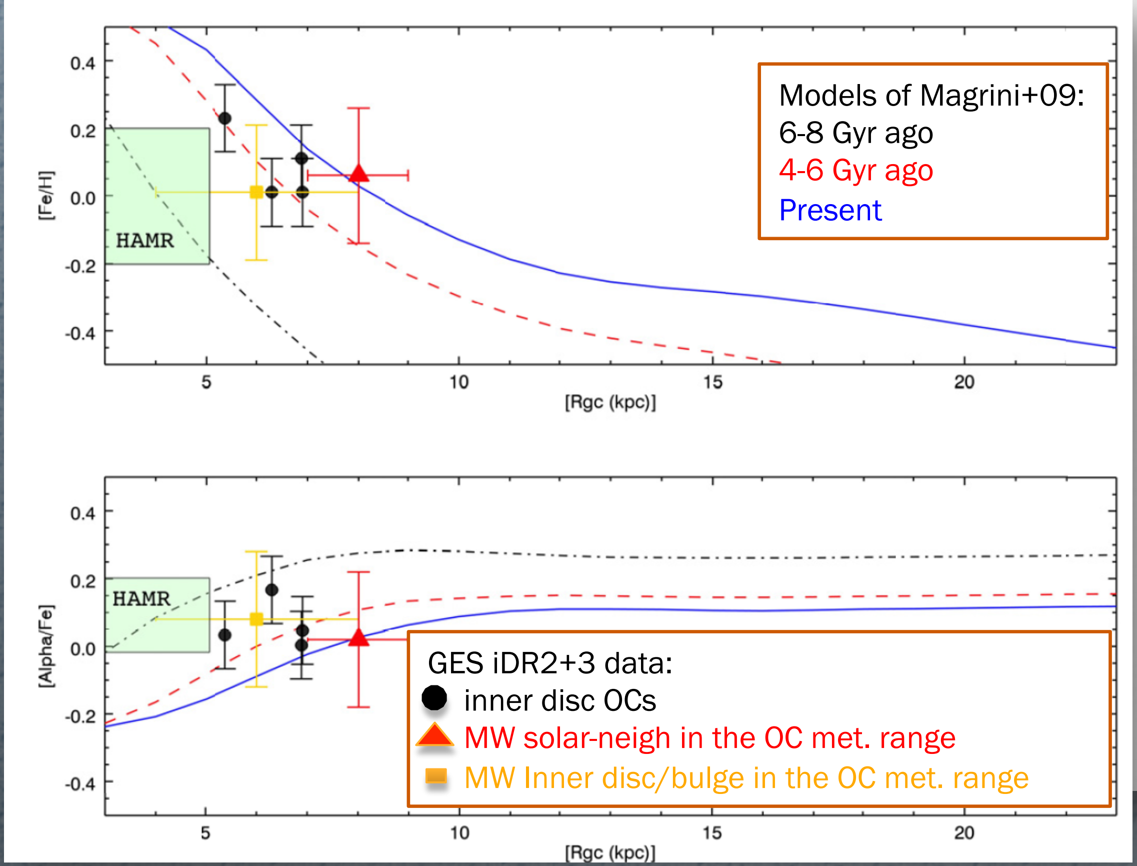


Chiappini+15

- ‘Young’ α-enhanced stars in the CoRoGEE sample
- Ages < 4 Gyr, with several around 2 Gyr
- Most of them are located at high altitudes from the Galactic plane |z| > 0.3 kpc and in the inner disc

The discovery of new classes of α-enhanced stars

- Young open clusters located in the inner thin disc (Magrini+15)

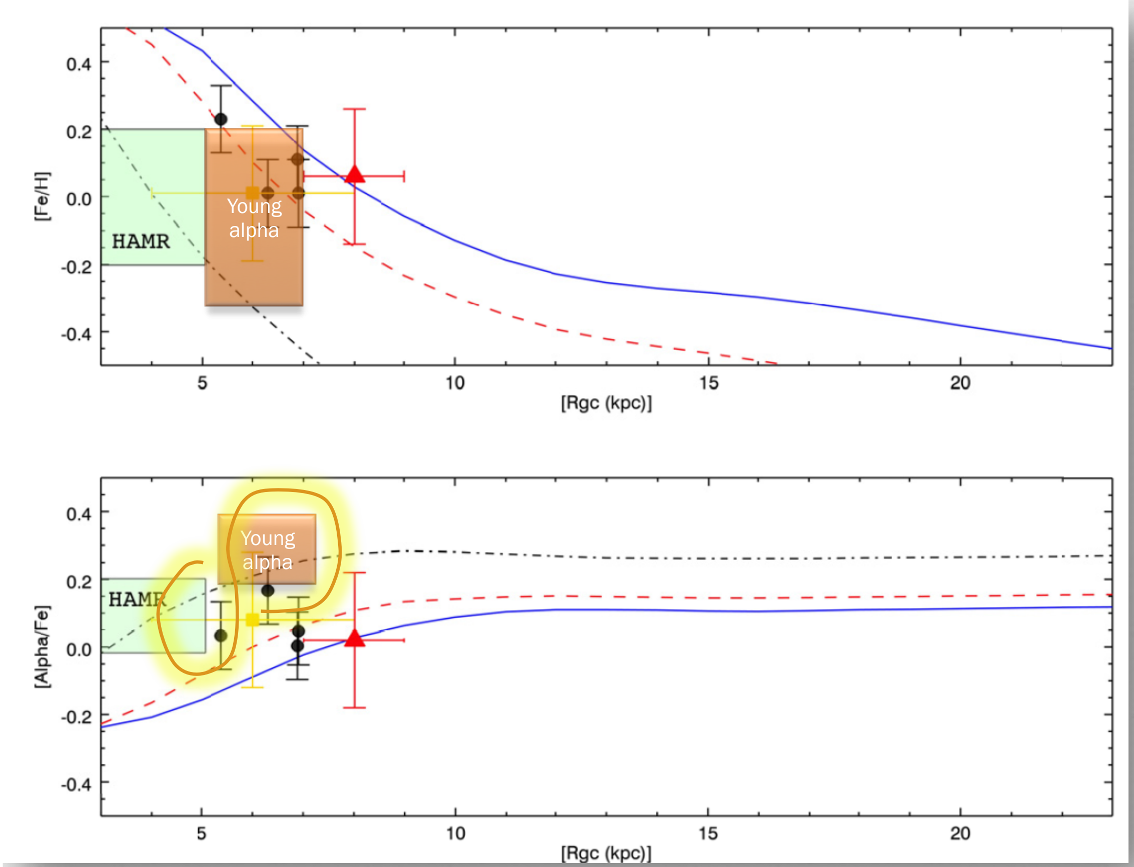


- α-enhanced, especially in Mg, and/or with higher [α/Fe] than expected by chemical evolution
- Ages ≤ 1 Gyr

ML+15

In the chemical evolution framework

HAMR can be explained in the CEM framework as old stars born in the inner disc



What about the young stars and clusters (e.g. NGC6705 and Be81)?

- Their abundance ratios are not consistent with the measured ages

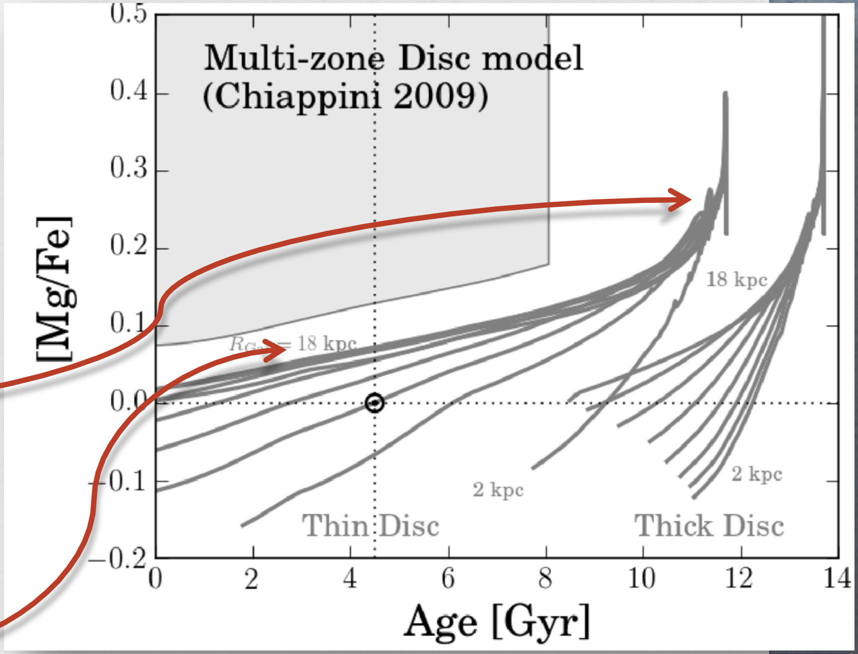
The metal rich α-enriched young stars

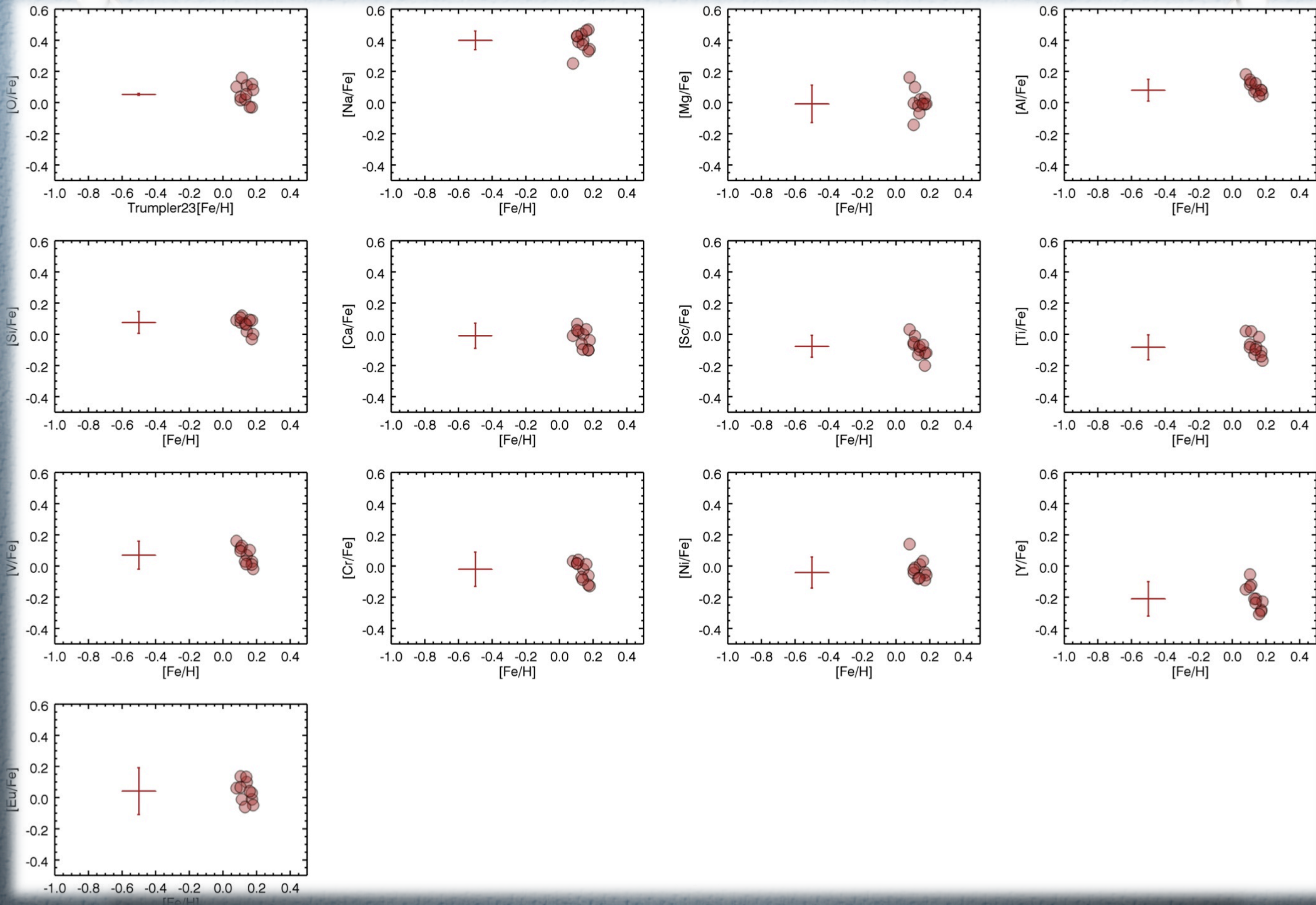
- This combination of high [α/Fe] and young ages is not predicted by standard chemical evolution models (CEMs) of the Galaxy.

- In most CEMs:

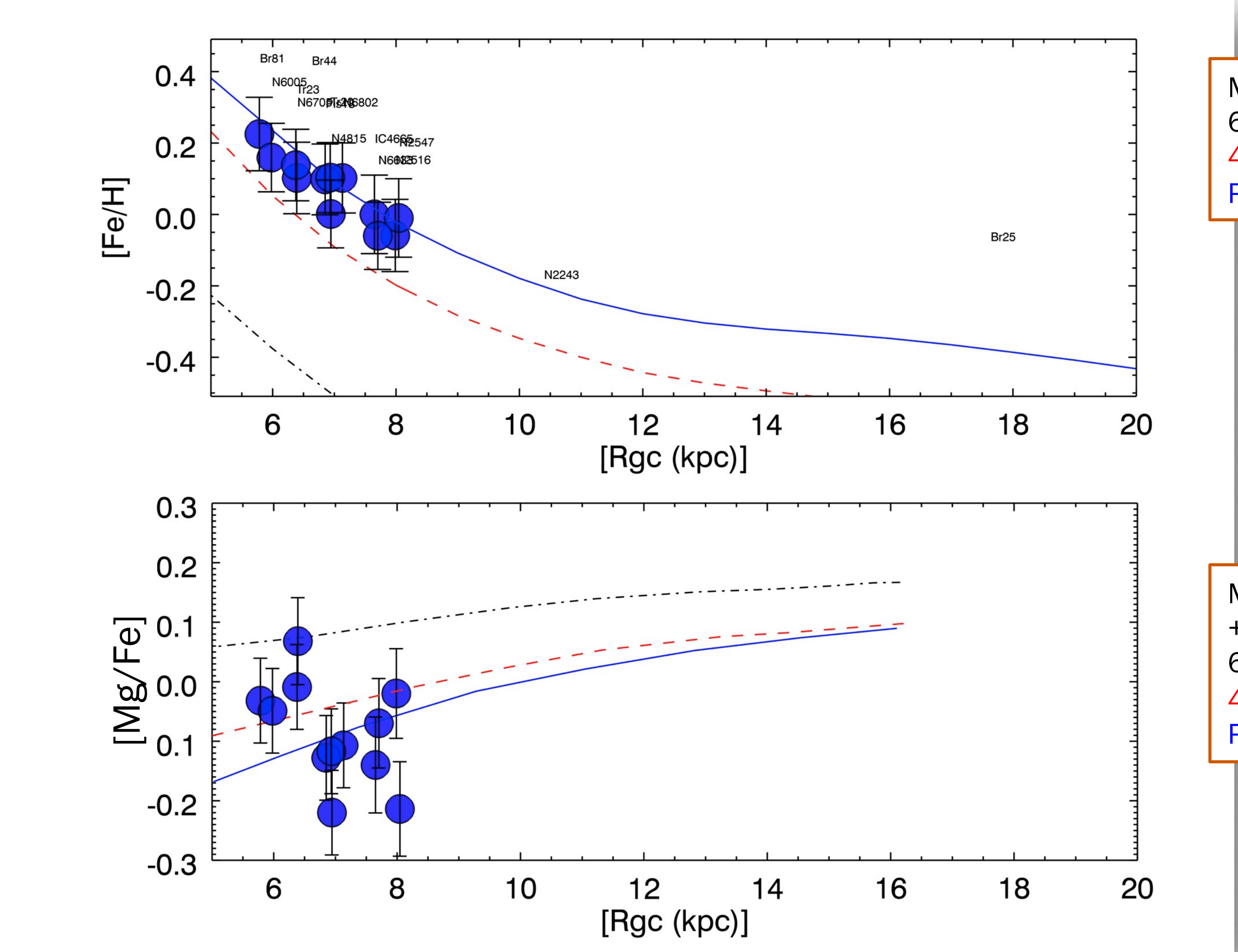
  - Stars with [α/Fe]> 0.2 are all older than 7Gyr, whatever their location at birth;

  - Stars with positive [α/Fe] can be young but they should be originated in the very outer disc with [Fe/H] <−0.5




[O/Fe]
Trumpler23[Fe/H]
[Na/Fe]
[Mg/Fe]
[Al/Fe]
[Si/Fe]
[Ca/Fe]
[Sc/Fe]
[Ti/Fe]
[V/Fe]
[Cr/Fe]
[Ni/Fe]
[Y/Fe]
[Eu/Fe]
[Fe/H]
0.6
0.4
0.2
0.0
-0.2
-0.4
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4

Open clusters in the GES sample (iDR4)



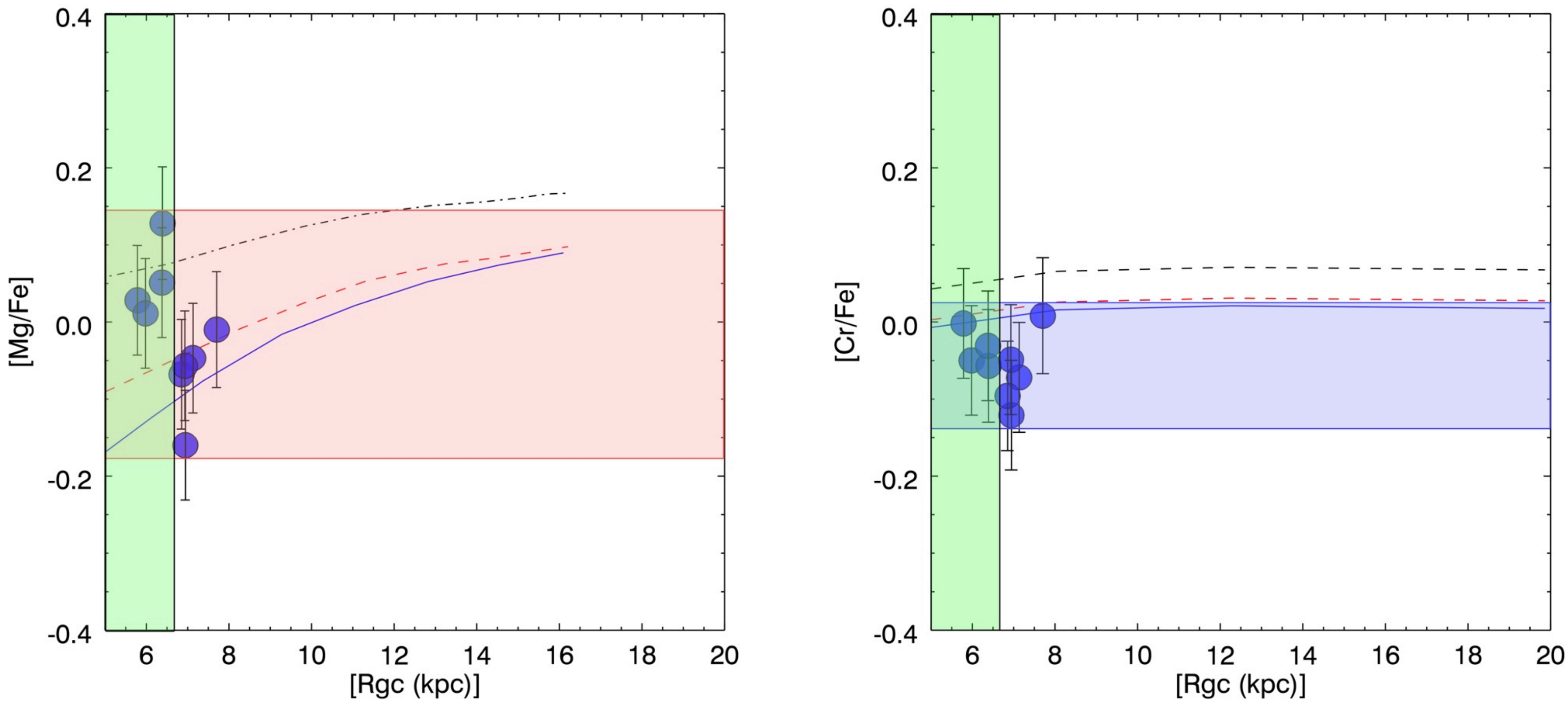
Models of Magrini+09:
6-8 Gyr ago
4-6 Gyr ago
Present

Models of Minchev +13:
6-8 Gyr ago
4-6 Gyr ago
Present

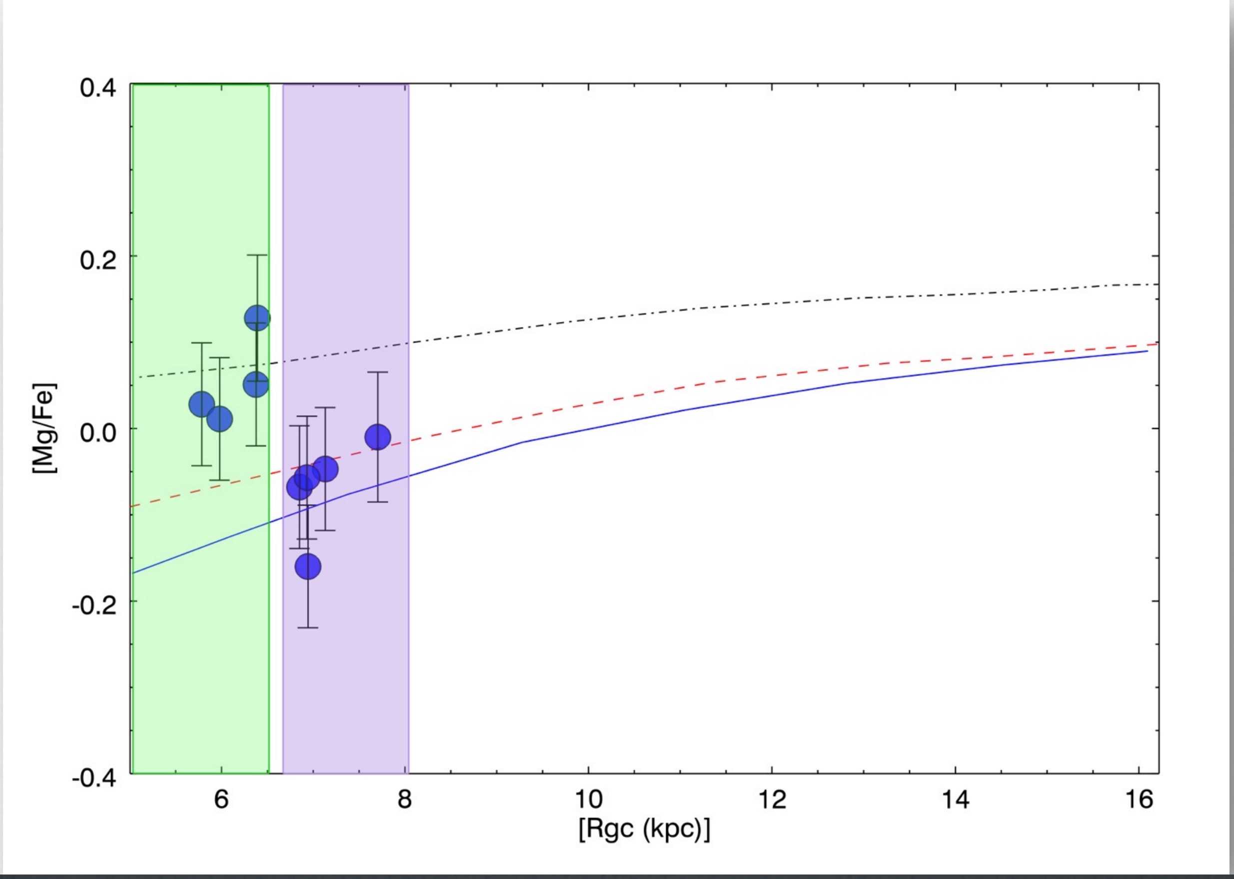
‘Young’ open clusters in the GES sample (iDR4)

Mg (90% from SNII)

Cr (84% from SNIa)



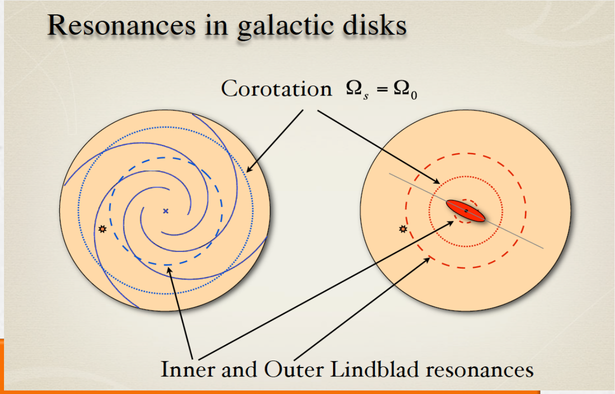
What happens at ~6 kpc?



Dynamics to understand chemistry?

The MW is a barred spiral galaxy with a boxy barred bulge:

- Bulge → 0-2 kpc
- Bar → 2-4 kpc
- Disc → exponential profile outside 4 kpc
- Four arms



From observations in the MW galaxy:

- The Galactic bar rotates rapidly, with co-rotation at about halfway between the Galactic centre and the Sun.

- The Galactic spiral arms rotate with a distinctly slower pattern speed, with its co-rotation at about Solar radius.

[From Gerhard 2008]

Dynamics to understand chemistry?

Several models now try to couple dynamics with chemistry
(e.g. Sellwood & Binney 2002; Lepine, Acharova & Mishurov 2003; Roskar et al. 2008; Schonrich & Binney 2009; Minchev & Famaey 2010, Minchev et al. 2013, Kubryk et al. 2013, Snaith et al. 2015).

→ Effect of transient spiral arms
→ Coupling of bar and spiral patterns
→ Effect of grand design spiral arms
→ Epicyclic motions ('blurring') and migration ('churning')

The Kubryk+13's model:

a fully self-consistent, high-resolution *N*-body+ smoothed particle hydrodynamics (SPH) simulation of MW-like barred galaxy + chemical evolution model, non IRA (instantaneous recycling approximation)

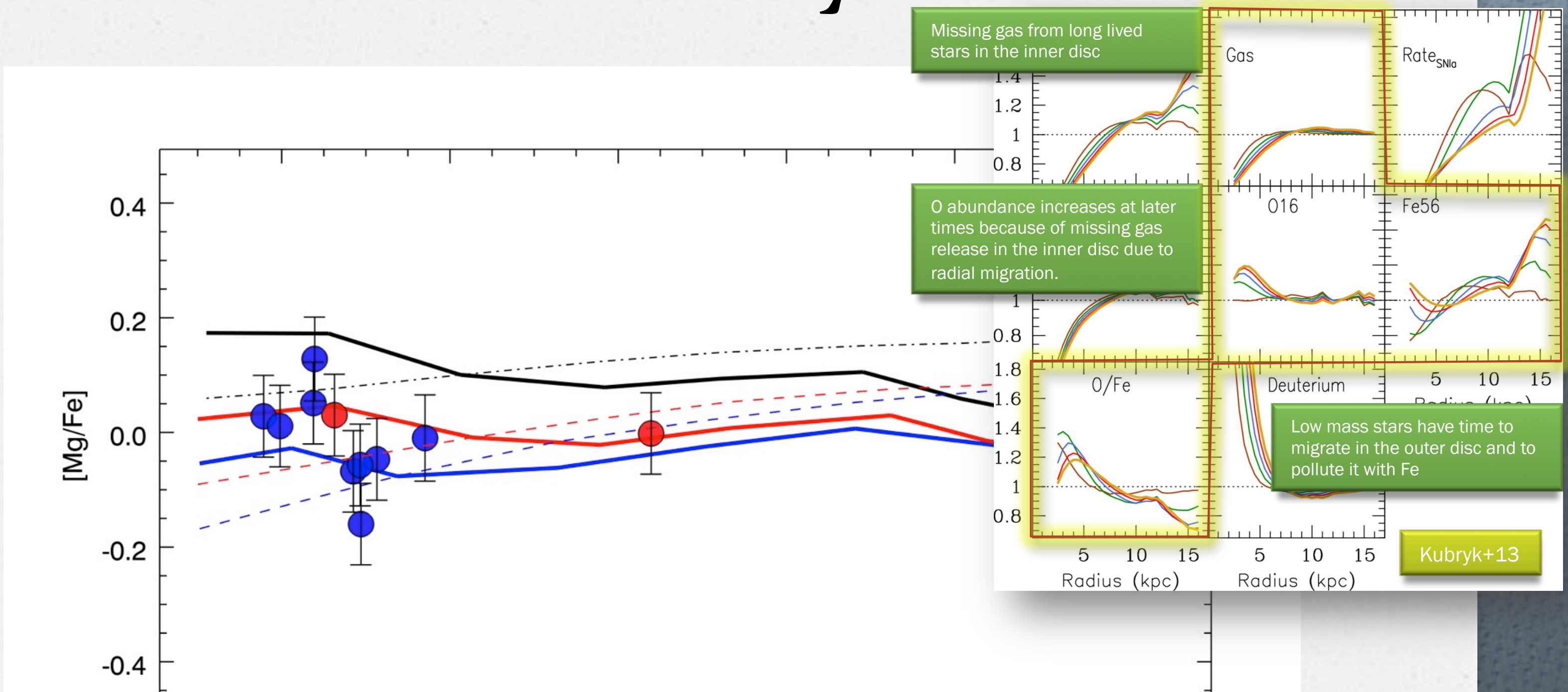
Dynamics to understand chemistry?

Radial migration of stars impacts on chemical evolution both:

- directly by moving around the long-lived agents of nucleosynthesis, like e.g. SNIa or asymptotic giant branch stars, and thus altering the abundance profiles of the gas

- Indirectly by moving around the long-lived tracers of chemical evolution and thus affecting stellar metallicity profiles, local age–metallicity relations and metallicity distributions of stars, etc..

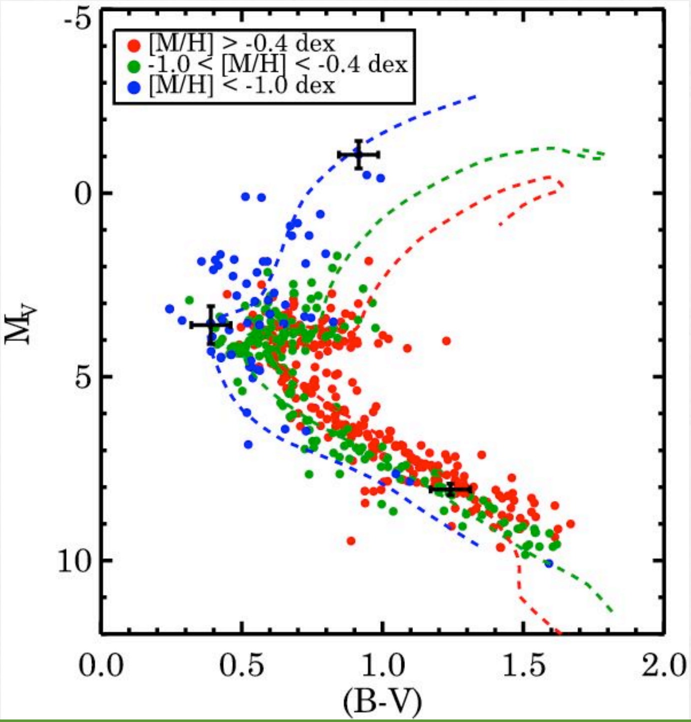
Dynamics to understand chemistry?



Radial migration of long-lived stars (including SNIa) makes the O/Fe ratio larger in the inner disc (by up to 20 per cent) and smaller in the outer one (by 30 per cent) → this might be the gas from which young clusters where formed

Deriving ages and Distances of field stars (Kordopatis+2011, 2015)

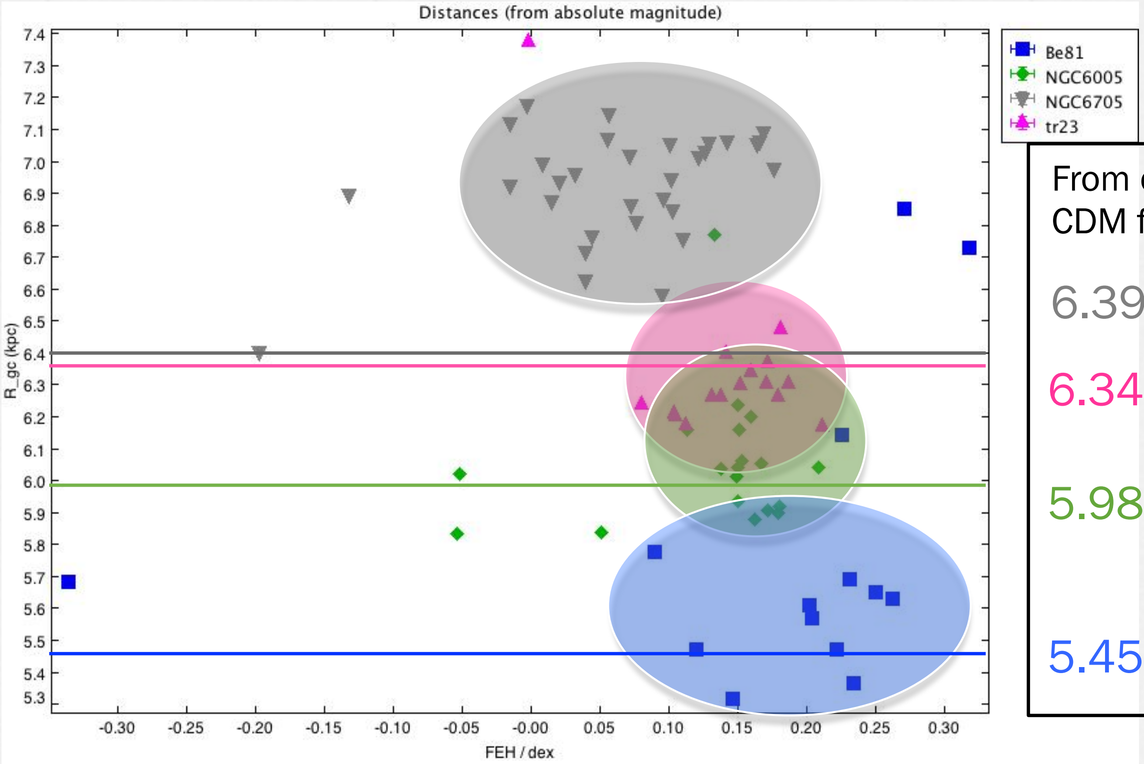
- Grid of isochrones (Padova) in ages and metallicity
- Absolute magnitude M_V → most likely values of the stellar parameters weighted considering the time spent by a star in each region of the HR diagram
- Distances → observed magnitudes and colours were de-redenned (Schlegel et al. 1998).



- Distances have a mean uncertainty of 15%
- Ages have much higher errors (~50%)

What can we infer from field stars: distances

- Distances are on average correct, with some exception
- (NGC6705…but its younger than the minimum isochrones adopted)



From cluster CDM fitting

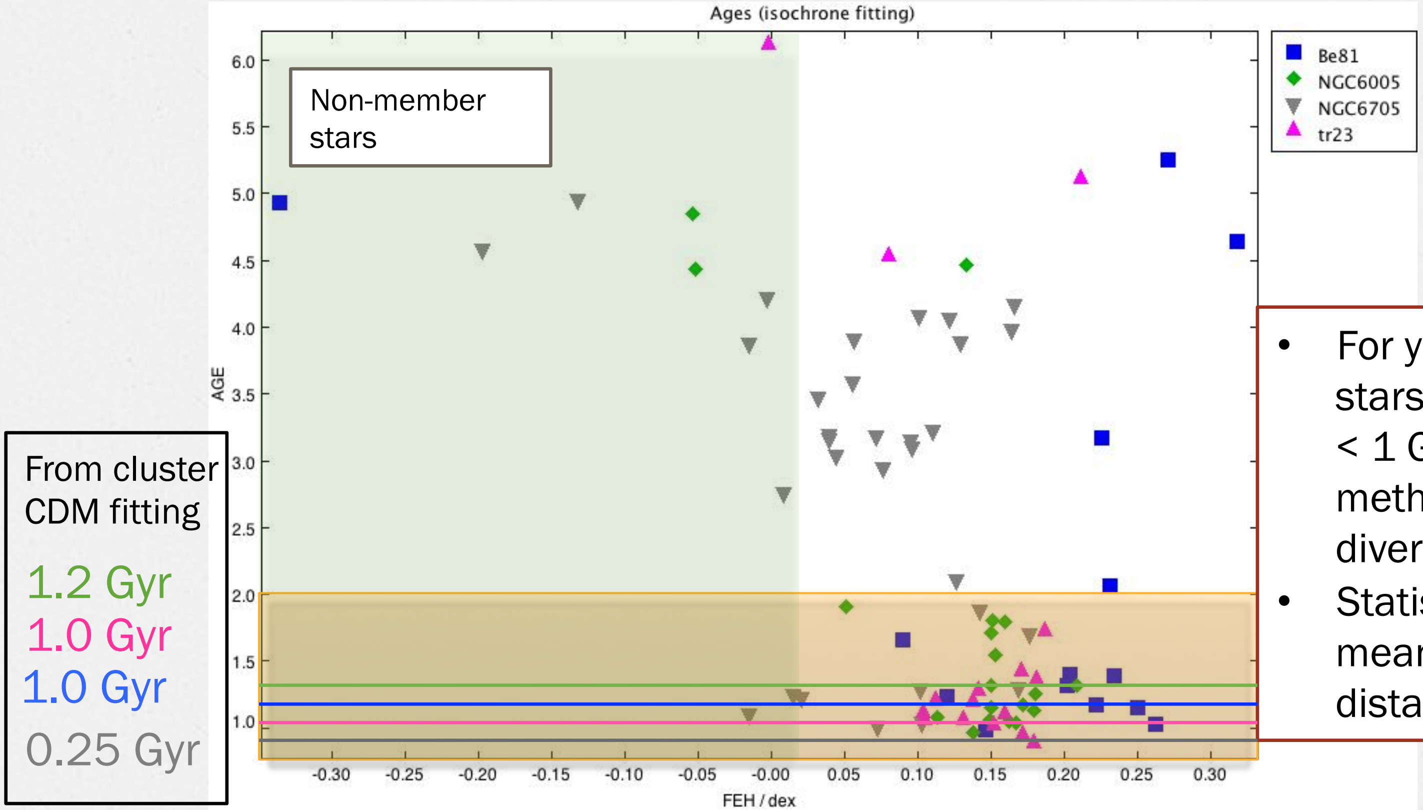
6.39 kpc

6.34 kpc

5.98 kpc

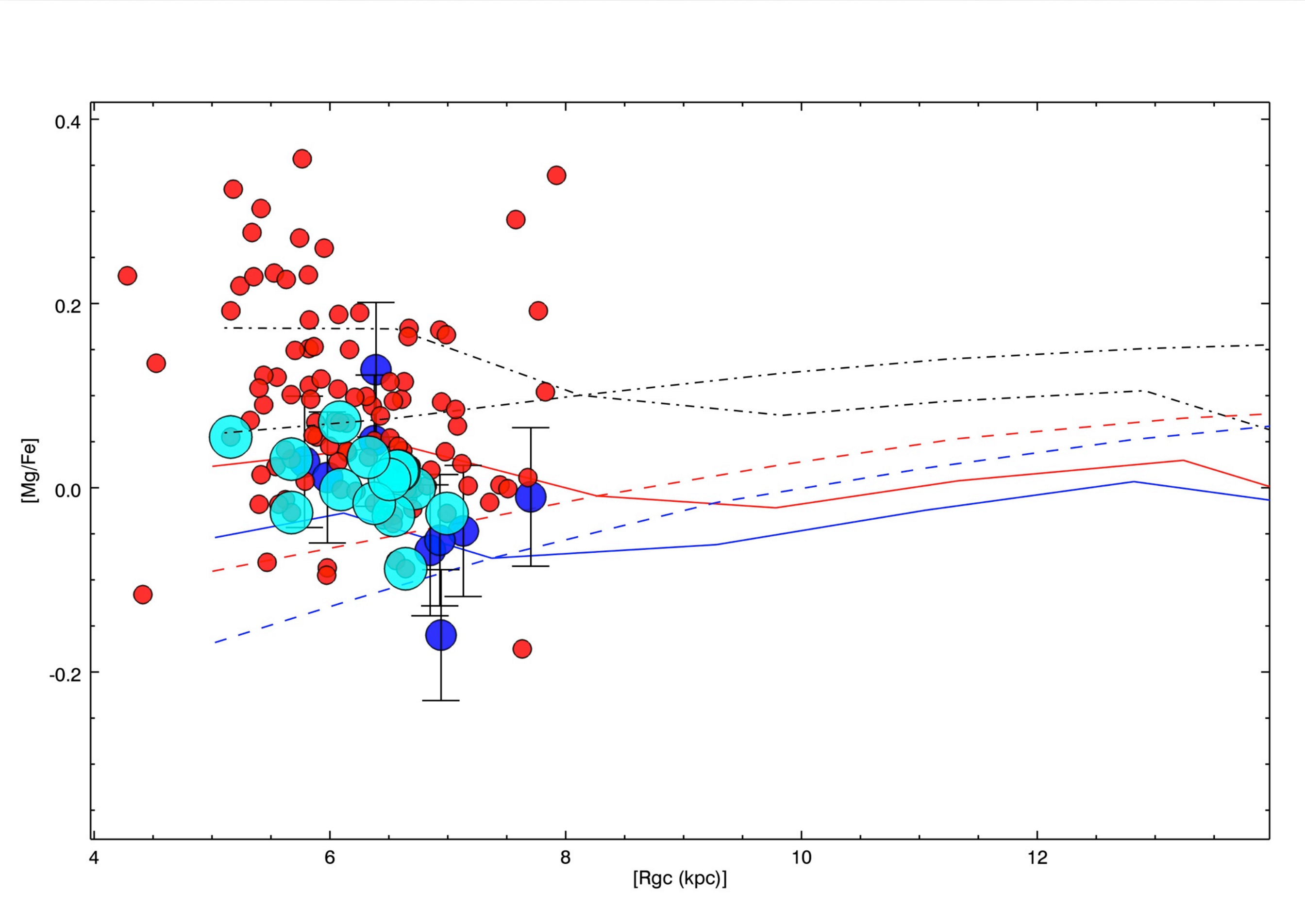
5.45 kpc

What can we infer from field stars: ages



- For young stars (age < 1 Gyr) the method can diverge
- Statistically meaningful distances

Clusters vs. field stars



Conclusions:

- iDR4 very inner-disc (R_{GC} < 6 kpc) clusters and field stars are on average enhanced in [Mg/Fe] with respect to the prediction of chemical evolution, but, at the same time, they are young and metal rich.

- Classical chemical evolution cannot explain the combination of their age and composition [neither of the Chiappini+15 and Martig+15 stars]

- We need chemo-dynamical models to explain their existence
  - → the perturbing effects of bar/spiral pattern on gas and stars might explain their abundance ratios
  - → the best agreement with a model including a strong bar (Kubryk +13)

Metallicity gradients in Local Universe galaxies: time evolution and effects of radial migration

Laura Magrini
With
Lodovico Coccato, Letizia Stanghellini, Viviana Casasola, Daniele Galli
INAF, ESO, NOAO

The origin of radial metallicity gradients

The spatial distribution of metals in a disc galaxy provides insights about the mass assembly history, the star formation history, the balance between outflow/inflow.

What we know about gradients:

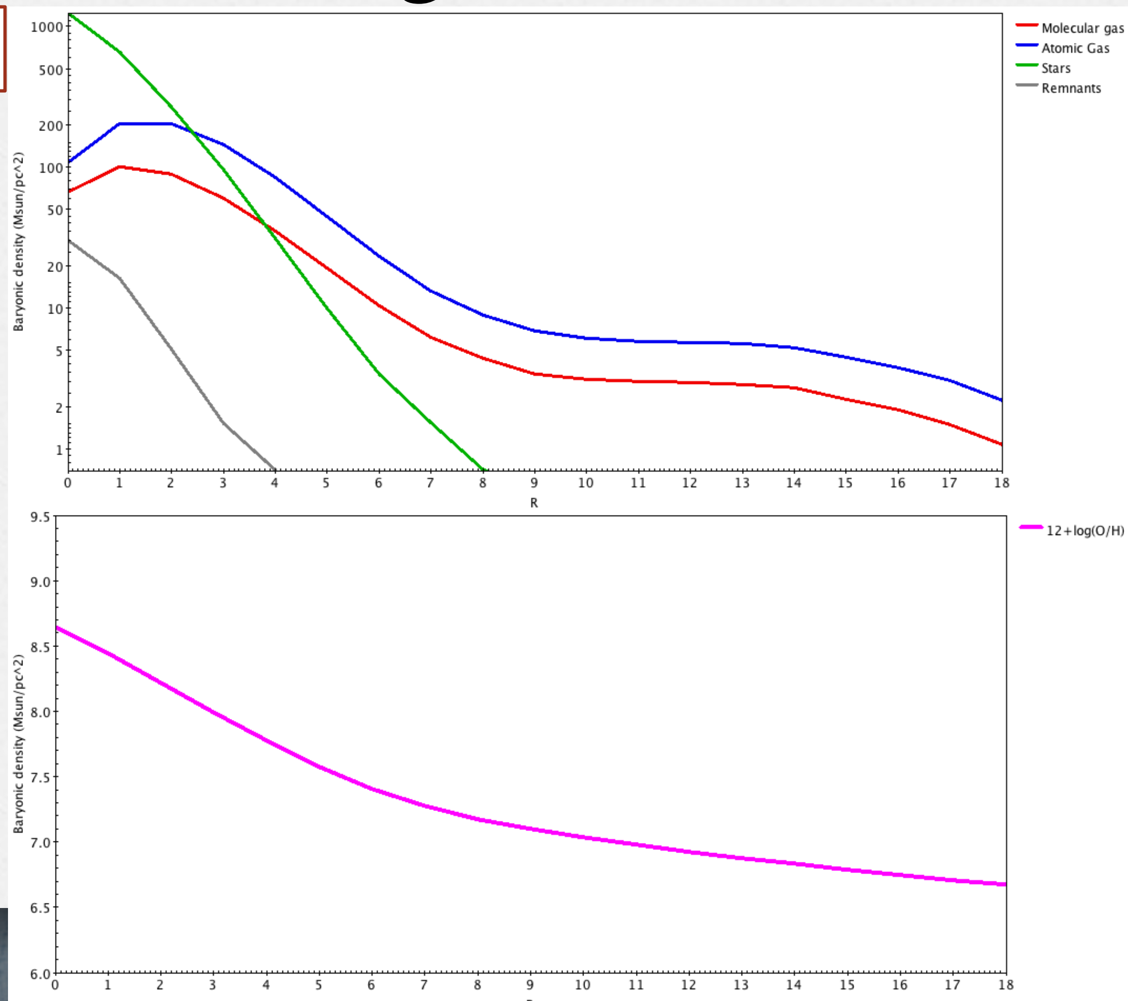
- Disc galaxies in the local Universe universally exhibit negative metallicity gradients (e.g. Zaritsky+94; Moustakas+10; Rupke+10; Sánchez+14).
- The metallicity gradients flatten in the outer discs, suggesting inner-to-outer transportation of metals via mechanisms such as galactic fountains or radial mixing (e.g., at co-rotation).
- Mergers of disc galaxies present shallower metallicity gradients than isolated disc galaxies due to effective gas mixing.

Main drivers of the shape of the gradients

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

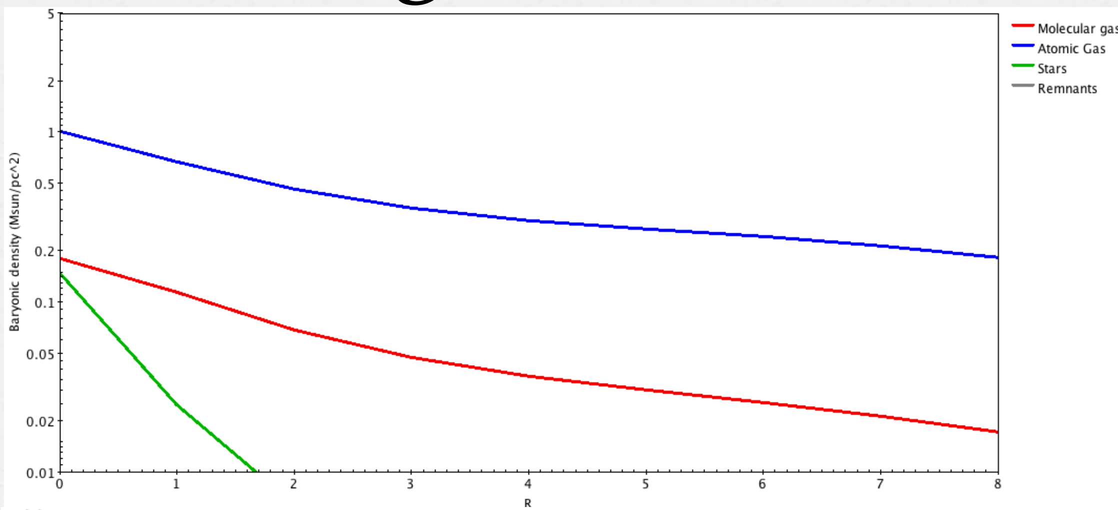
+ radial migration, gas flows, etc.

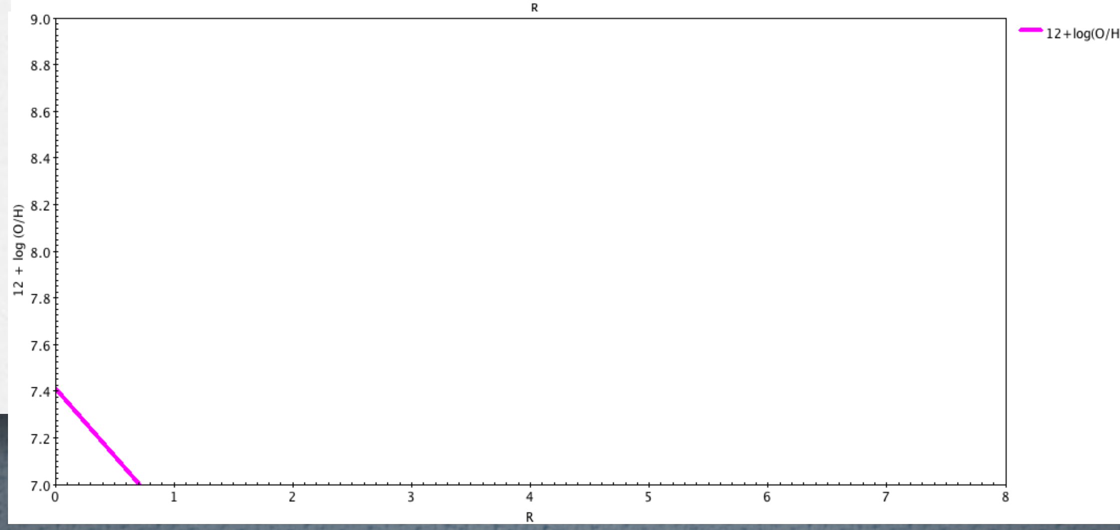
Main drivers of the shape of the gradients

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





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

What kind of time evolution for the radial metallicity gradient?

- This class of models predict 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
  - The star formation efficiency is lower in the outer regions (radially decreasing → less cloud collisions)

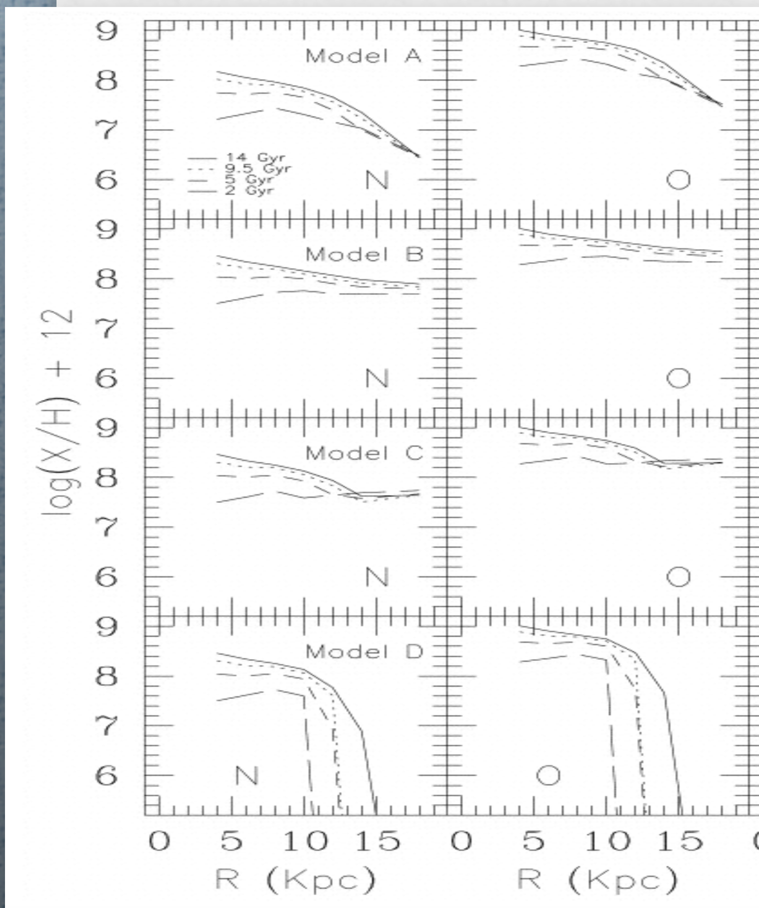
Main drivers of the shape and evolution of the gradients

What kind of time evolution for the radial metallicity gradient?

- What happens is we consider an <u>inside-out formation</u> of the disk but
  - A pre-enrichment of the infalling material that forms the disk
  - A threshold in the star formation threshold (stars are not formed is the density of gas is not sufficiently high)

?

Main drivers of the shape and evolution of the gradients

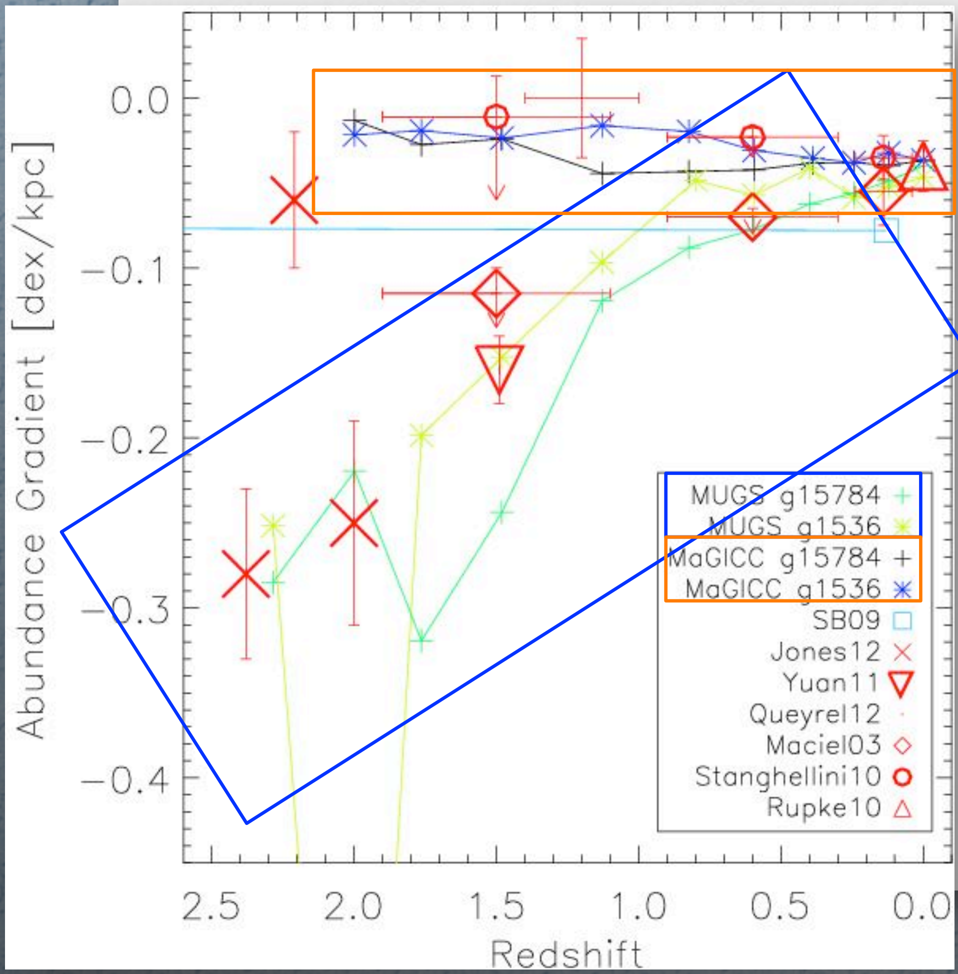


at $t = 2$ (*long-dashed line*), 5 (*dashed line*), 9.5 (*dotted line*), and 14 (*solid line*) Gyrs for models A to D

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

The net effect is a <u>steepening with time of the radial metallicity gradient</u>

Gradients in the cosmological contest



From Gibson et al. (2013):

While negative abundance gradients today provide a boundary condition for galaxy evolution models, in support of inside-out disc growth, empirical evidence as to whether abundance gradients steepen or flatten with time remains highly contradictory.

Abundance gradients and age-metallicity relations within a sub-set of cosmological hydro-dynamical disc simulations:

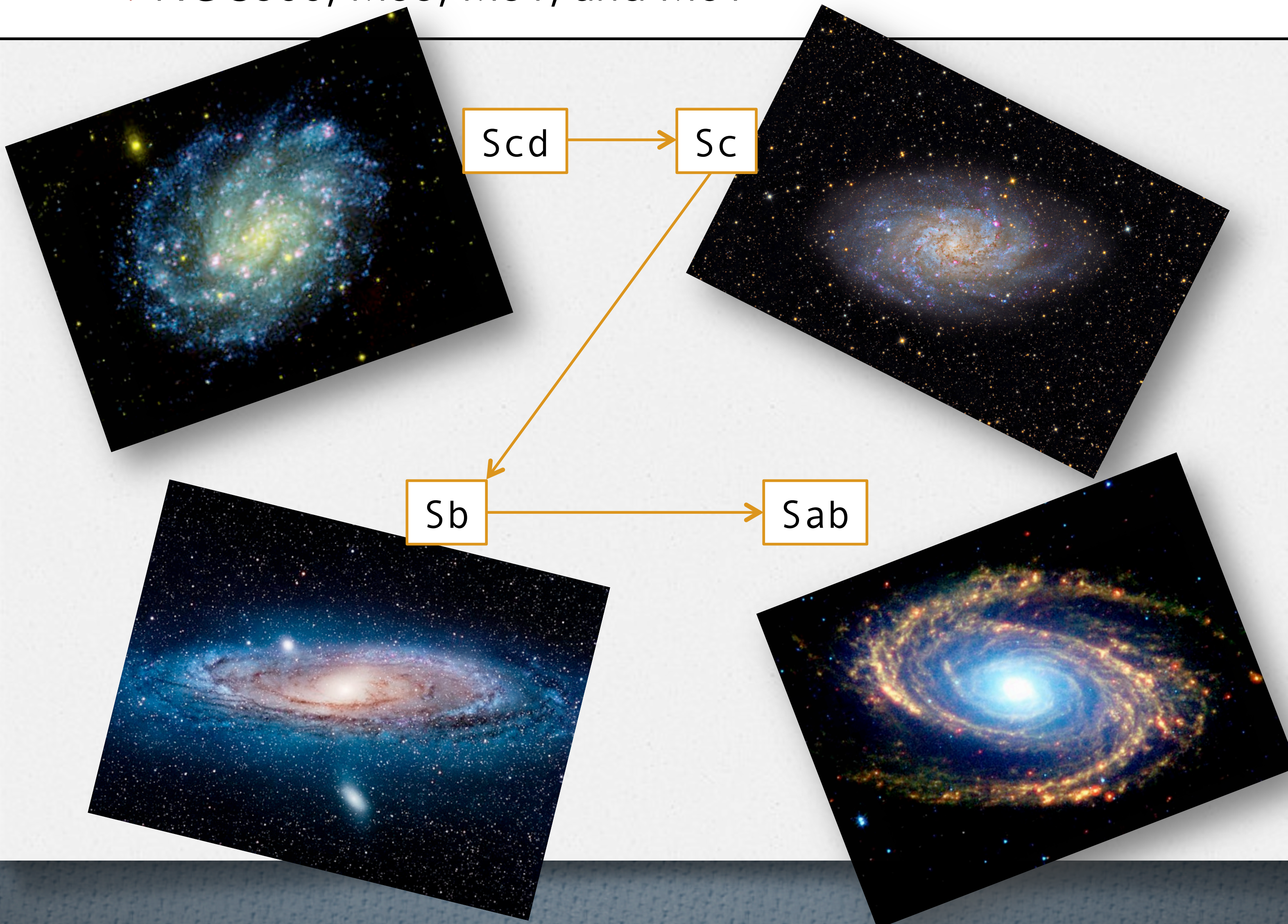
- MUGS (McMaster Unbiased Galaxy Simulations; Stinson et al. 2010)
- MaGICC (Making Galaxies in a Cosmological Context; Brook et al. 2012b).

Re-analysis of the metallicity gradients from HII regions and PNe:

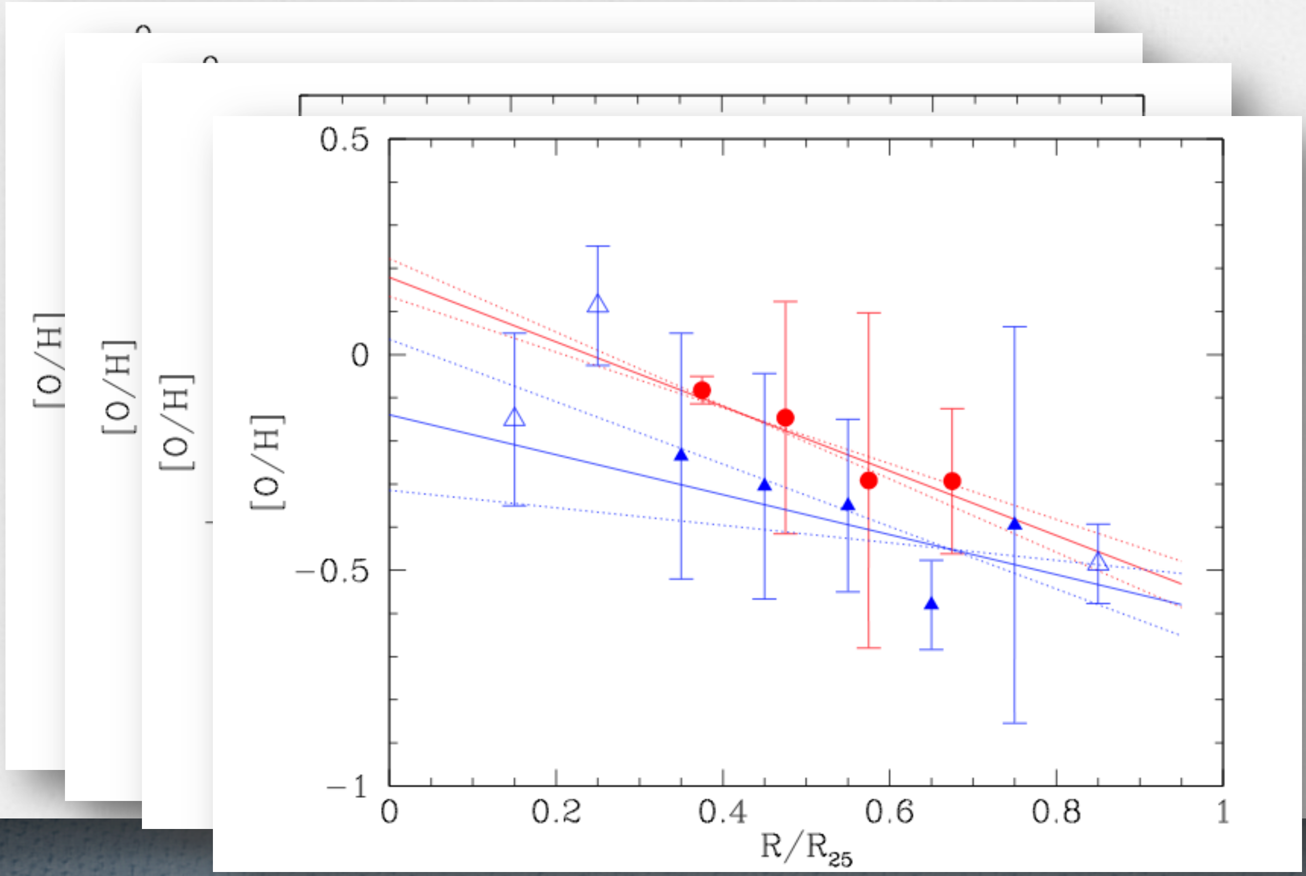
- The homogenization :
  - Elemental abundances from *direct*-method for both populations
  - Normalization to a common radial scale (R_{25})
  - Binning the data and comparing similar radial range
- The sample:
  - NGC300, M33, M31, and M81

The sample:

- NGC300, M33, M31, and M81



Time-evolution of the slopes of the gradients:



General findings:

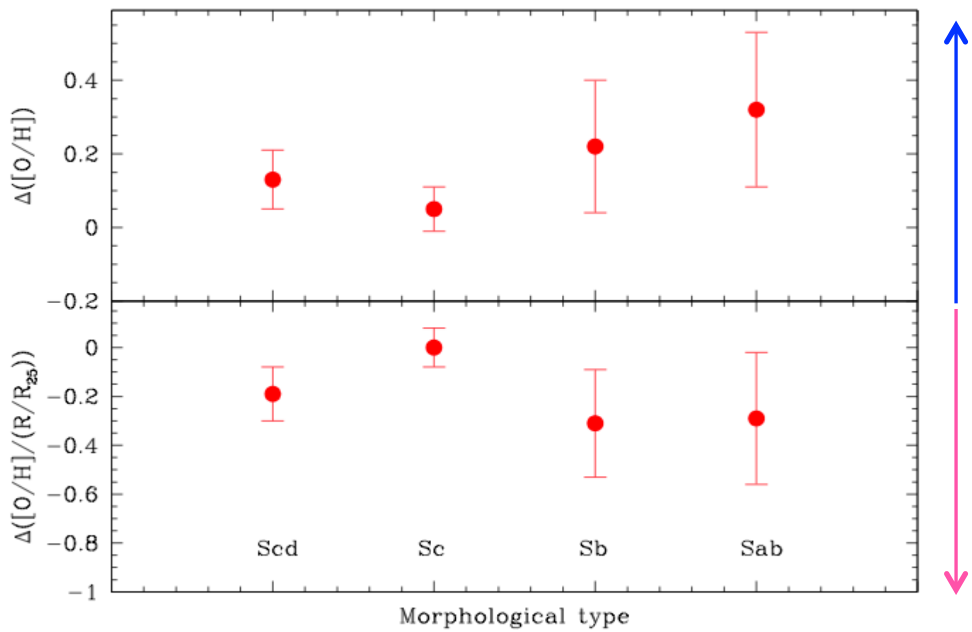


Fig. 10. Global enrichment (upper panel) and variation of the slope of the metallicity gradient (lower panel) as a function of the morphological type.

Global enrichment

Positive values → Enrichment with time

Evolution of the gradient slope

Negative values → Steepening with time

But…how much of the slope variation is due to radial migration?

Since the PN progenitors have resided in the galaxy for several Gyr, it is essential to quantify their radial migration.

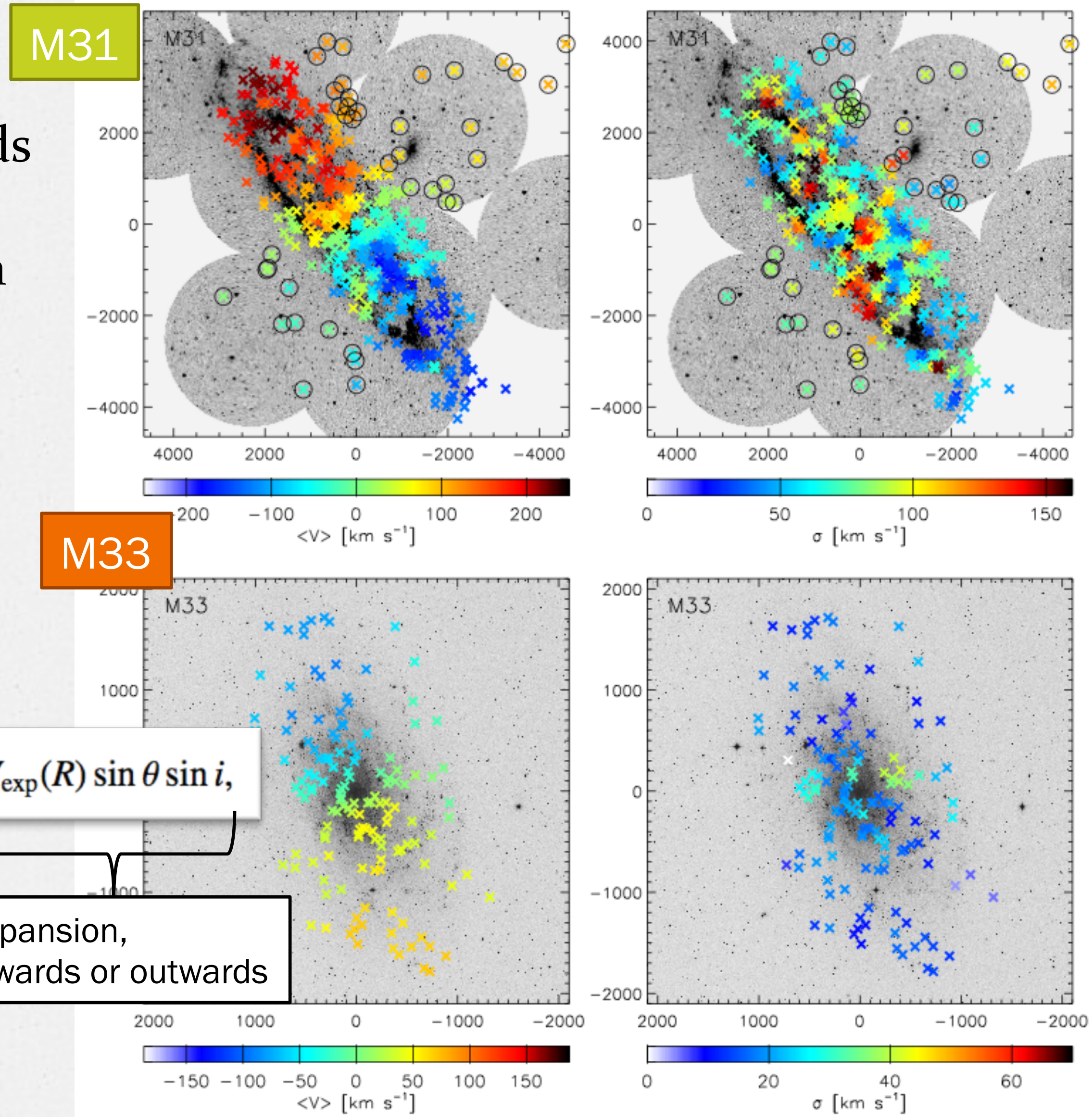
- Signatures of radial motions in the two-dimensional velocity field of the PN population
- PNe that deviate from a simple rotational-disc model

These quantities can be estimated in two galaxies→ M33 and M31 having accurate radial velocity measurements

Signatures of radial motions in the two-dimensional velocity field of the PN population

→ The 2D reconstructed fields of velocity and velocity dispersion for M31 and M33

→ Each cross represents the location of a detected PN



Formalism of Teuben+02

$$\langle V(x,y)\rangle = V_{sys} + V_{rot}(R)\cos\theta\sin i + V_{exp}(R)\sin\theta\sin i,$$

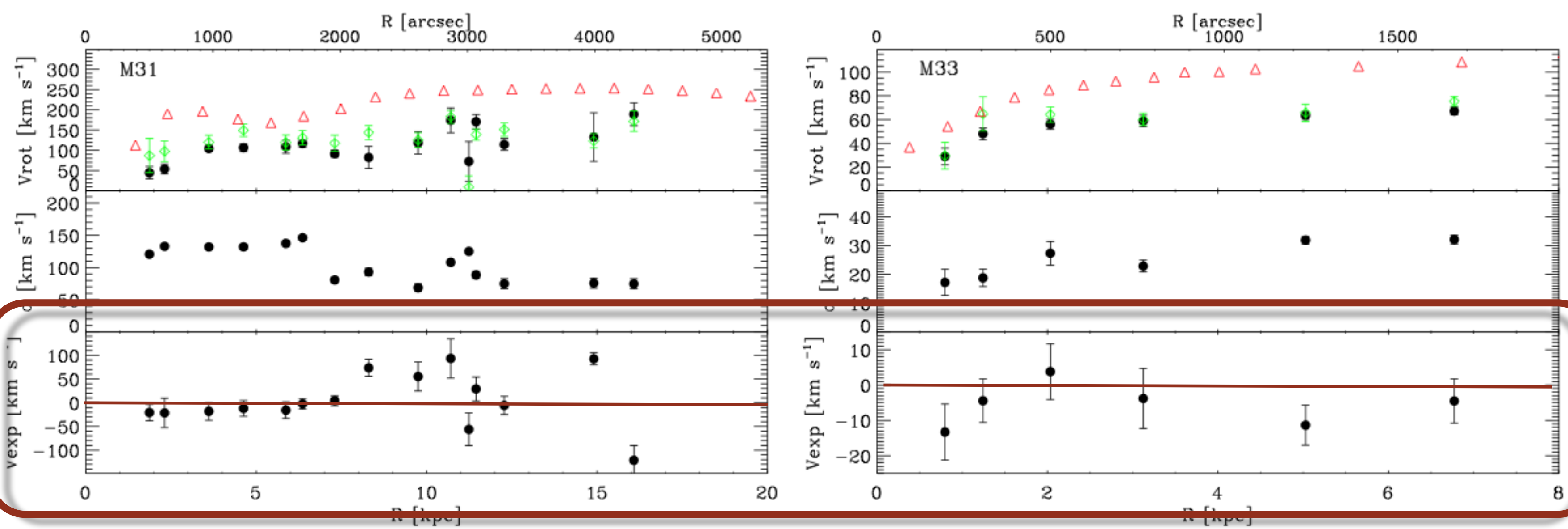
Rotation

Expansion,
Inwards or outwards

$$\langle V(x,y)\rangle = V_{sys} + V_{rot}(R)\cos\theta\sin i + V_{exp}(R)\sin\theta\sin i,$$

M31

M33



Outward motions→ positive values of V_{exp} in both galaxies

PNe that deviate from a simple rotational-disc model

M33

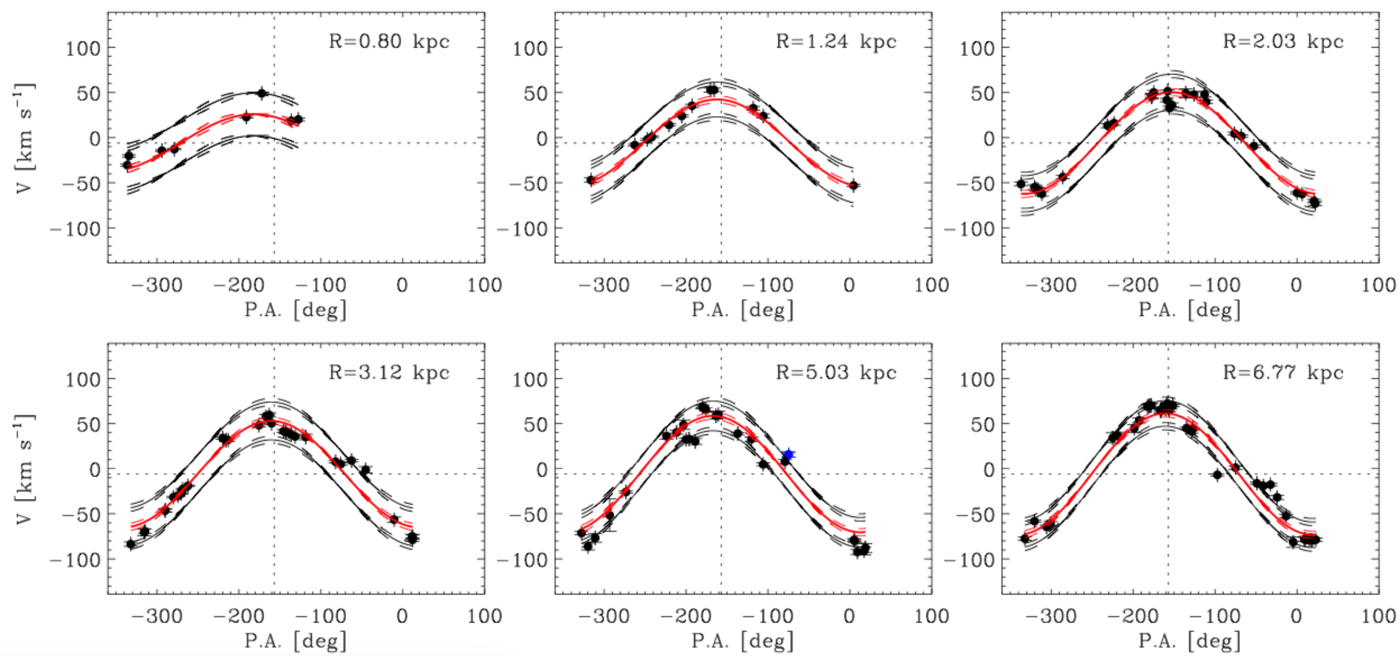


Table 4. Same as Table 3 for M33.

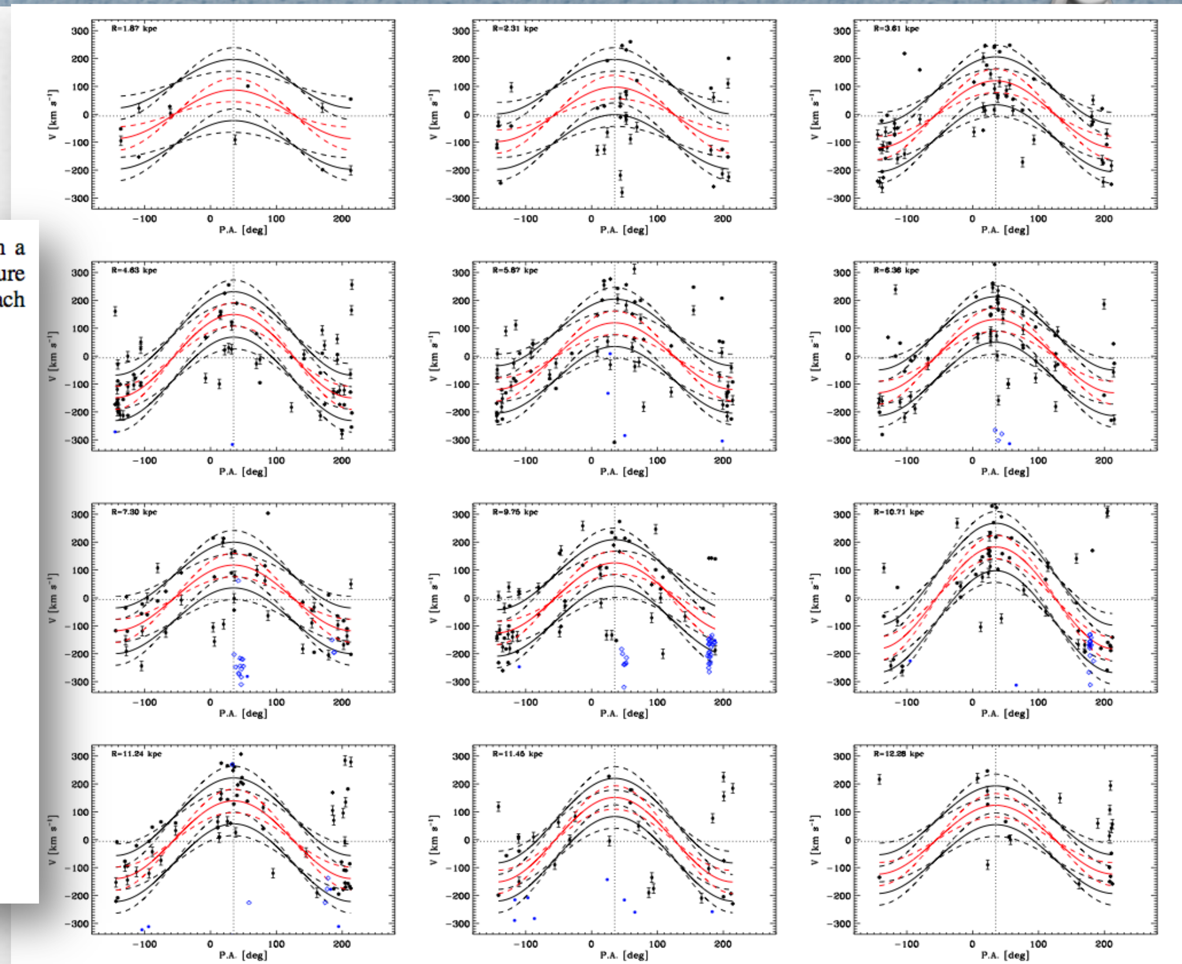
bin	R (kpc)	Outside 1σ	Expected
1	0.80	2	2.6
2	1.24	3	4.0
3	2.03	9	8.6
4	3.12	10	10.2
5	5.03	9	8.3

PNe that deviate from a simple rotational-disc model

M31

Table 3. Number of PNe in M31 that deviate more than 1σ from a pure rotating thin disc model compared with that expected from a pure Gaussian distribution for the elliptical bins. The semi-major axis of each bin is indicated in the second column.

bin	R (kpc)	Outside 1σ	Expected
1	1.87	4	4.0
2	2.31	23	13.0
3	3.61	26	21.1
4	4.63	28	24.1
5	5.87	37	24.4
6	6.36	26	21.1
7	7.30	20	18.5
8	8.30	34	20.5
9	9.75	30	20.5
10	10.71	24	19.5
11	11.24	37	31.0
12	11.45	21	10.2
13	12.28	15	7.9
14	14.90	7	4.0
15	16.08	3	1.7



Constraints to cosmological models

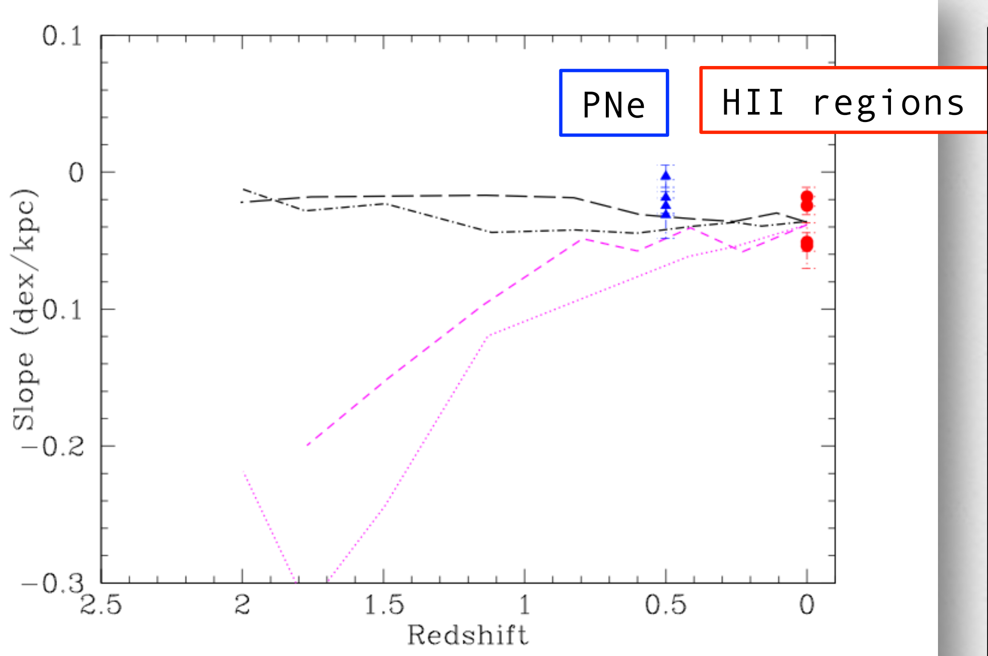


Fig. 12. Comparison of the redshift evolution of the gradient with the chemical evolution models of Gibson et al. (2013): black (dashed and dot-dashed) lines are models with enhanced feedback from SNe, magenta (short-dashed and dotted) lines are models with normal feedback.

- Favoring models with mild/no evolution of the slope (enhanced SNe feedback)
- Radial migration can mimic in some cases flatter gradients in the past

Conclusions

- The effect of radial migrations can be important and might vary from galaxy to galaxy

- In galaxies where it is negligible (at present), mild/no evolution of the gradient are favoured