The formation and evolution of the galactic disks

Misha Haywood, Paris Observatory

with

P. Di Matteo, O. Snaith, M. Lehnert

Sesto, 19-23 jan. 2015

1 - The new conditions of GCE

2 - A « new » model: the closed-box

3 - The evolution of the inner disk

5 - Conclusions

Current GCE models are based on the following assumptions:

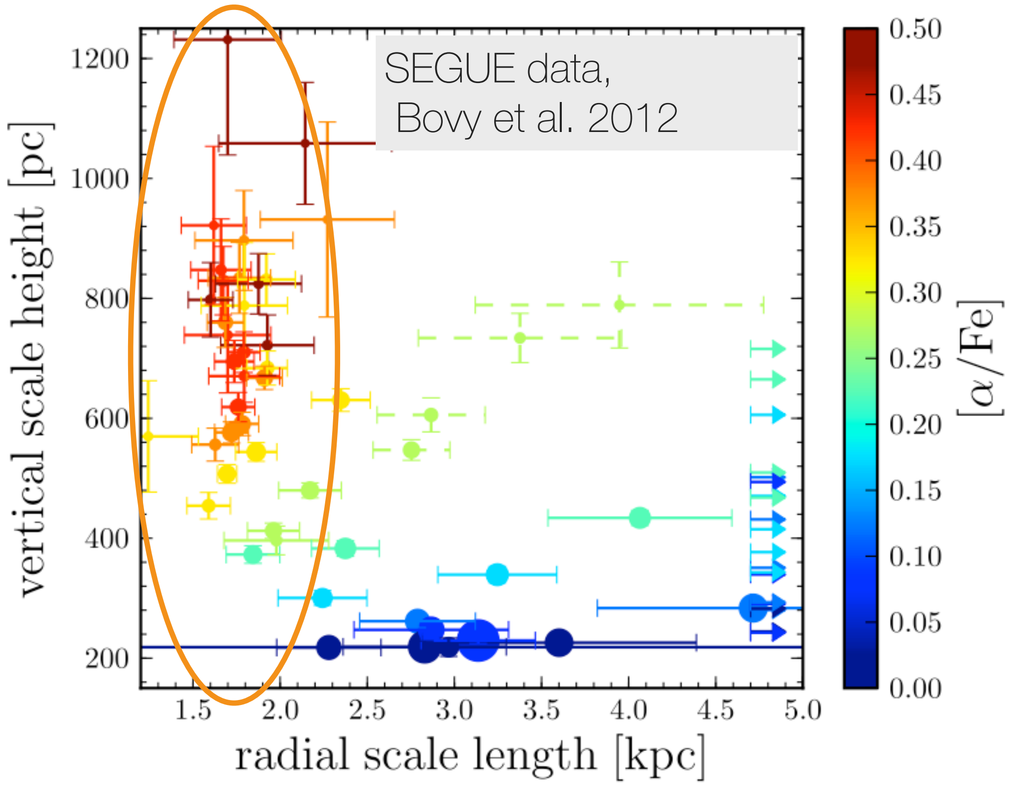
1. The lack of metal poor stars at the solar vicinity necessitates of long term infall
2. Long-term infall dependent on the distance to the Galaxy center, and so does the SFH
3. The disk is a unique system, inner and outer disks are in chemical continuity

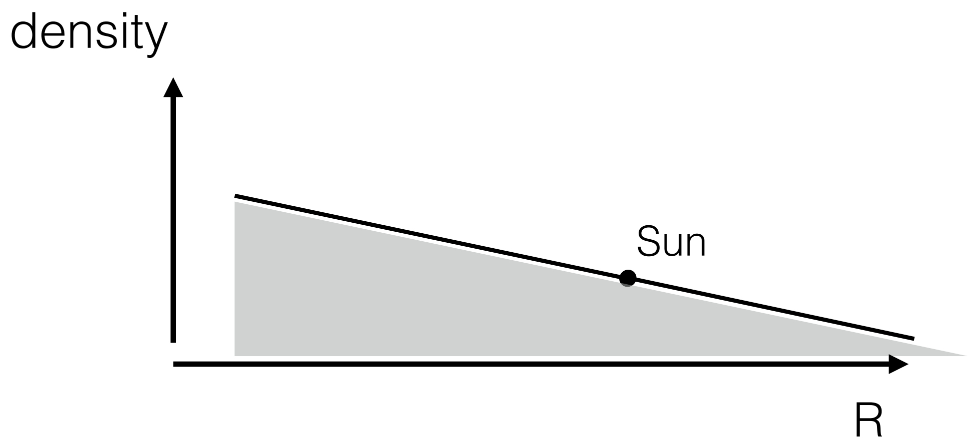
Why we need to change these assumptions:
1/ Large gas reservoir is needed at early times

The thick disk dominates the inner Galaxy

1/ The thick disk has a short scale length

(Bensby et al. 2011; Bovy et al. 2012)





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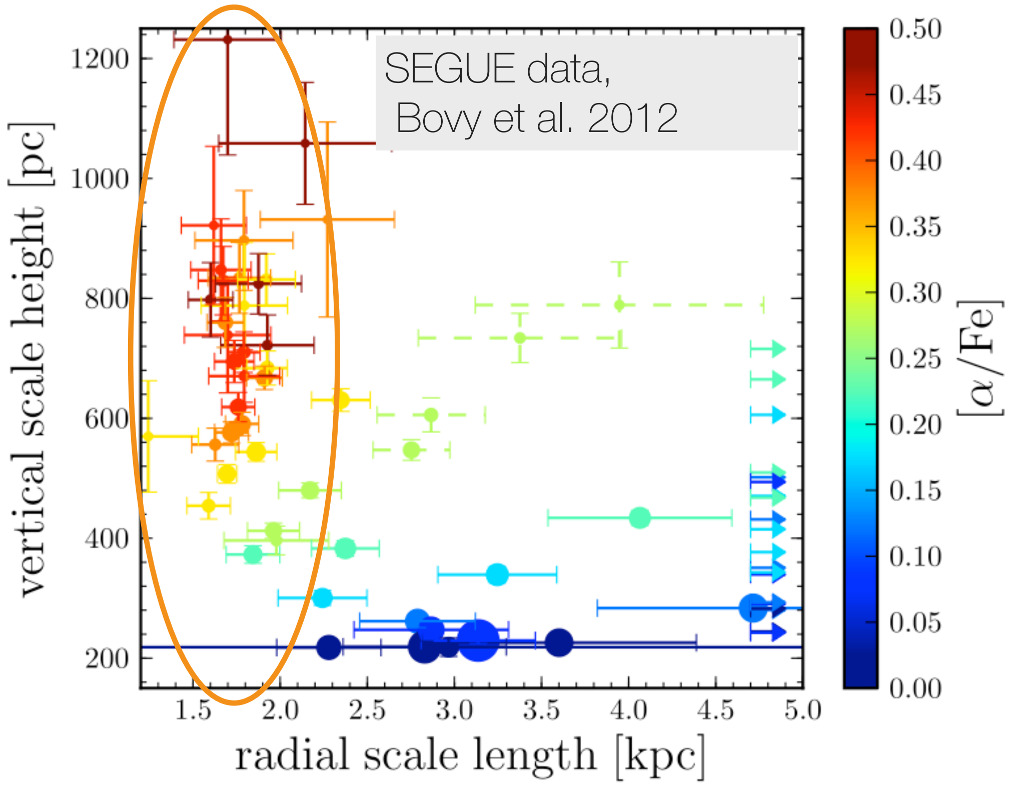
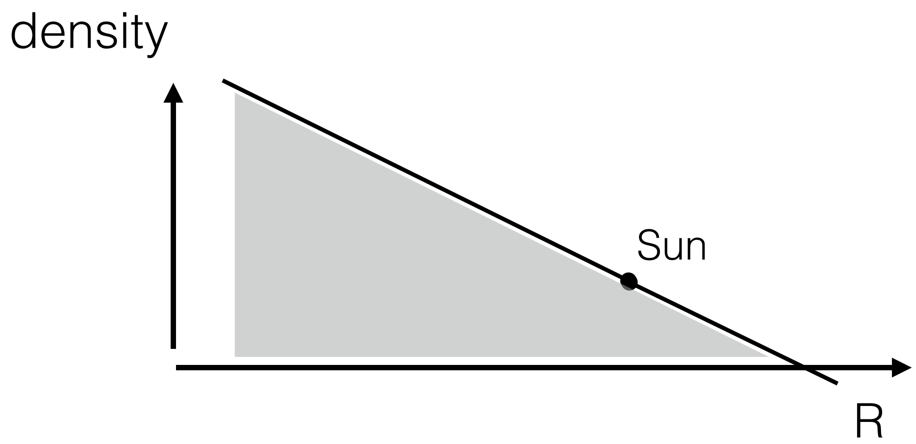


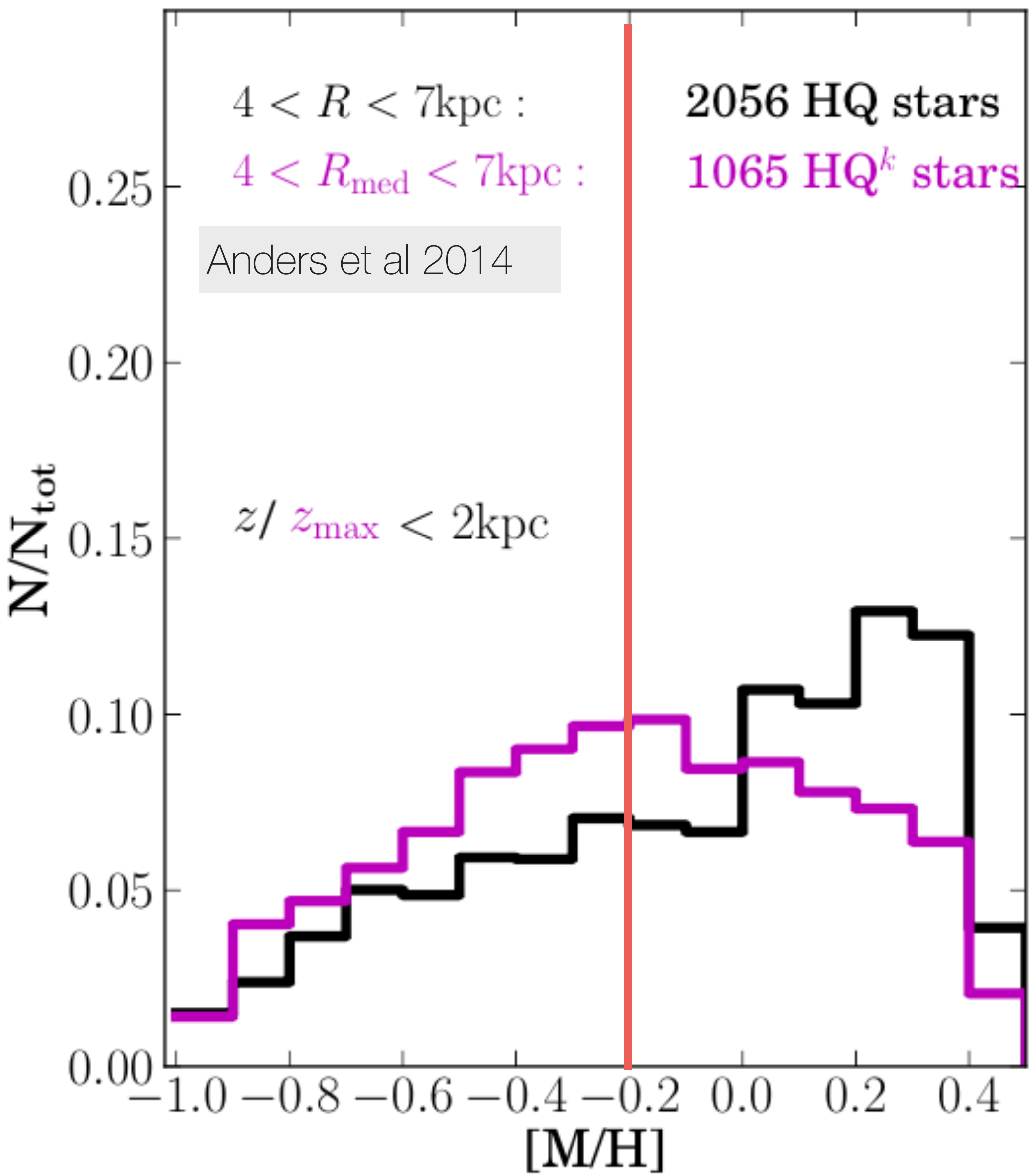


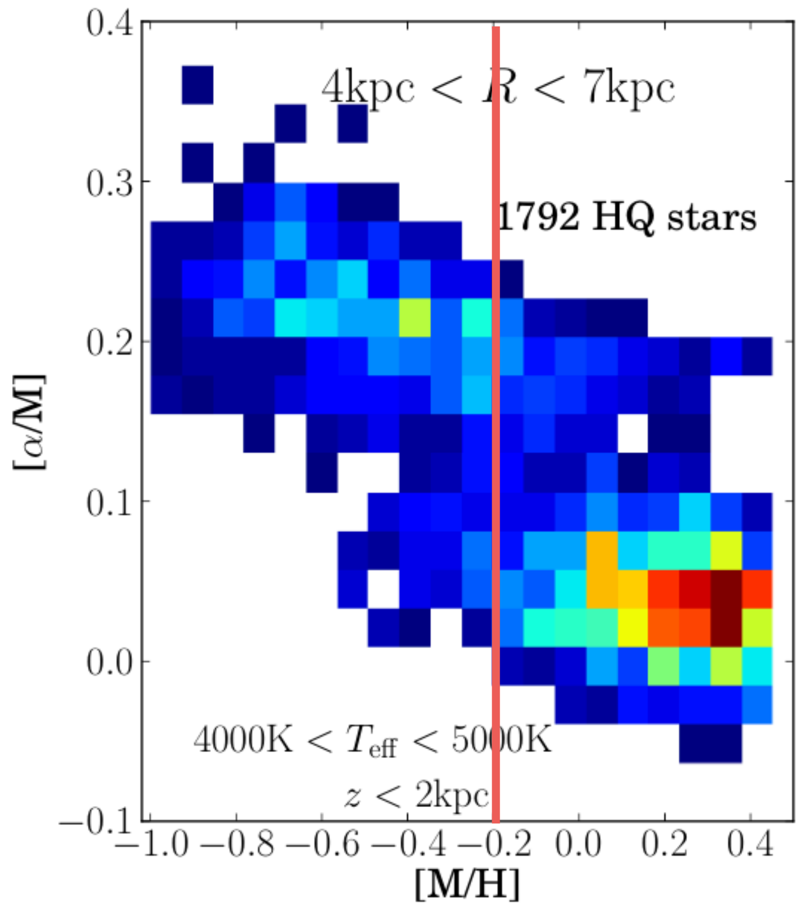
It implies that

- the solar radius is not representative of the whole thick disc population
- most of the thick disc is confined in the inner Galaxy
- it is massive (see later on)

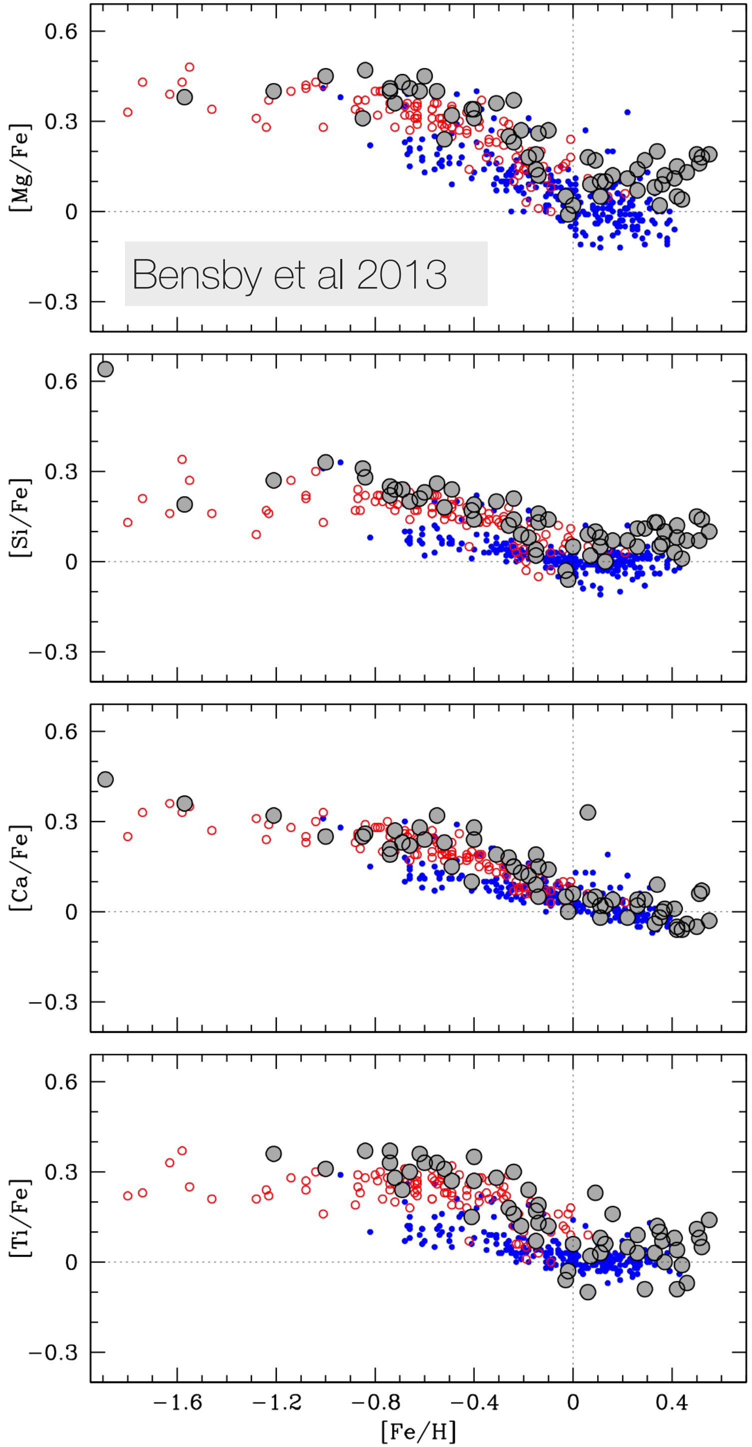
The thick disk dominates the inner Galaxy

APOGEE survey, Inner disk, 4-7 kpc





The thick disk dominates the inner Galaxy



… and the bulge

- Several indications that the metal-poor population in the bulge is not a classical spheroid (Shen et al 2010, Kunder et al 2012, Di Matteo et al 2014a)
- Kinematic properties of a disk-like component (Ness et al 2013)
- Chemical similarity with the thick disk (Bensby et al 2013, Gonzalez et al 2011)

The need for a large gas reservoir at early times

1/ The thick disc dominates the inner regions
2/ It is old and formed in the first 3-4 Gyr of evolution of the MW (see Haywood et al 2013)
3/ It is massive, as massive as the thin disk
(see Snaith et al 2014a,b)

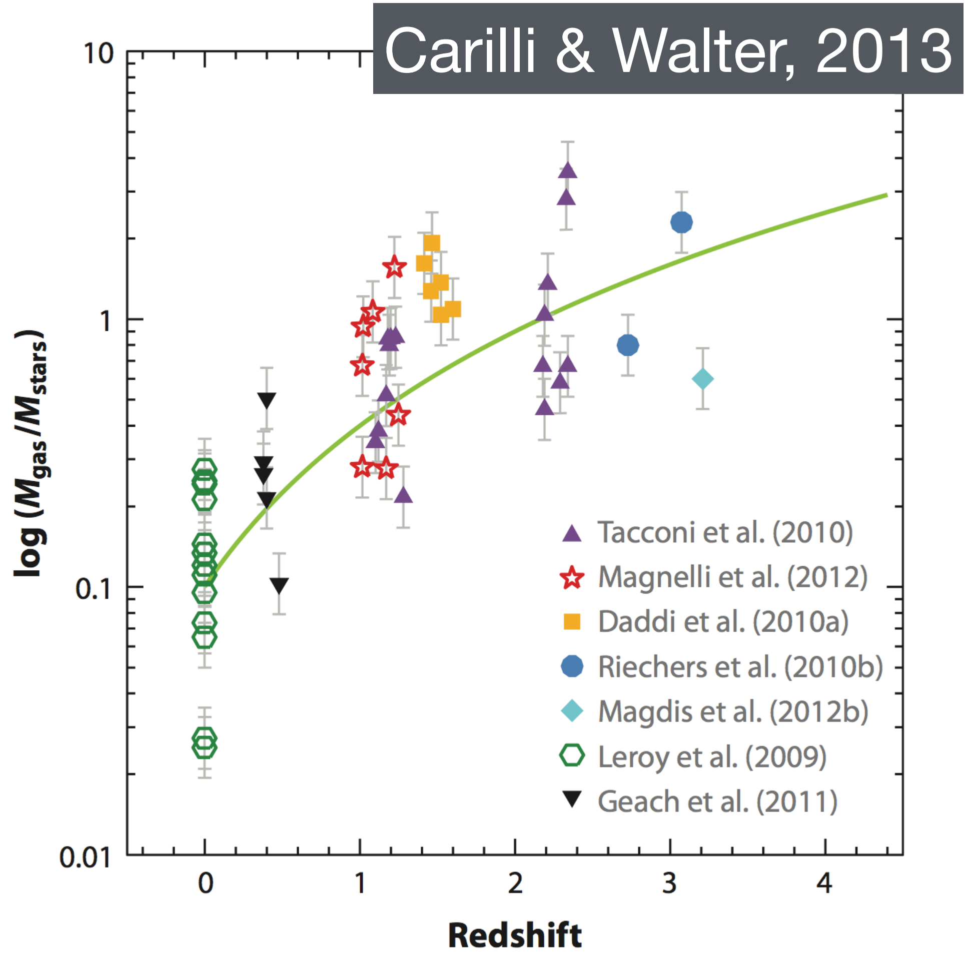
➡ **The Milky Way contains a huge amount of intermediate metallicity stars hidden in the inner disk (and bulge)**
« the G-dwarf problem » is a local problem

To form 50% of its mass at early times, the Galaxy must have had large reservoir of gas at $z > 1$

The need for a large gas reservoir at early times

Disks at z>2 have a
high (≳50%) fraction of gas

➡ **Instead of minimizing the amount of gas** (= choice done by infall models to overcome the G-dwarf problem) **we should try to maximize it**



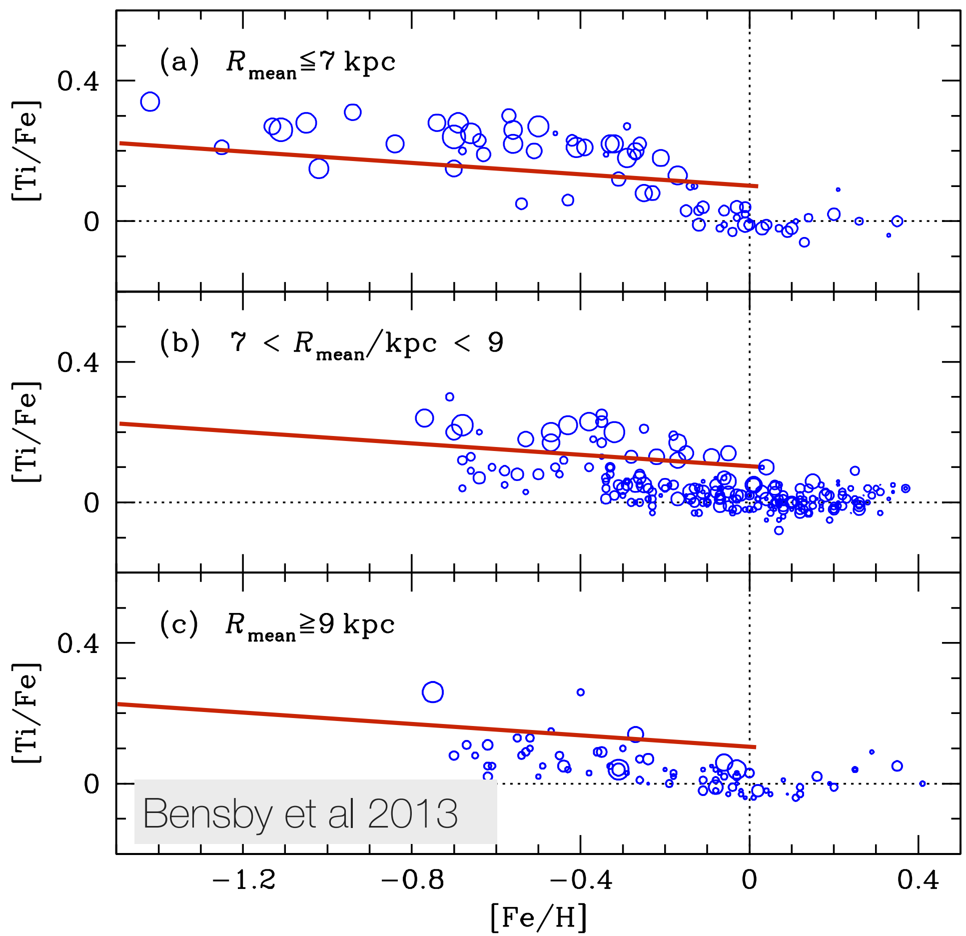
Why we need to change these assumptions:

1/ No chemical continuity between the inner and the outer disk

Why we need to change these assumptions

2/ The inner and outer disks are chemically distinct

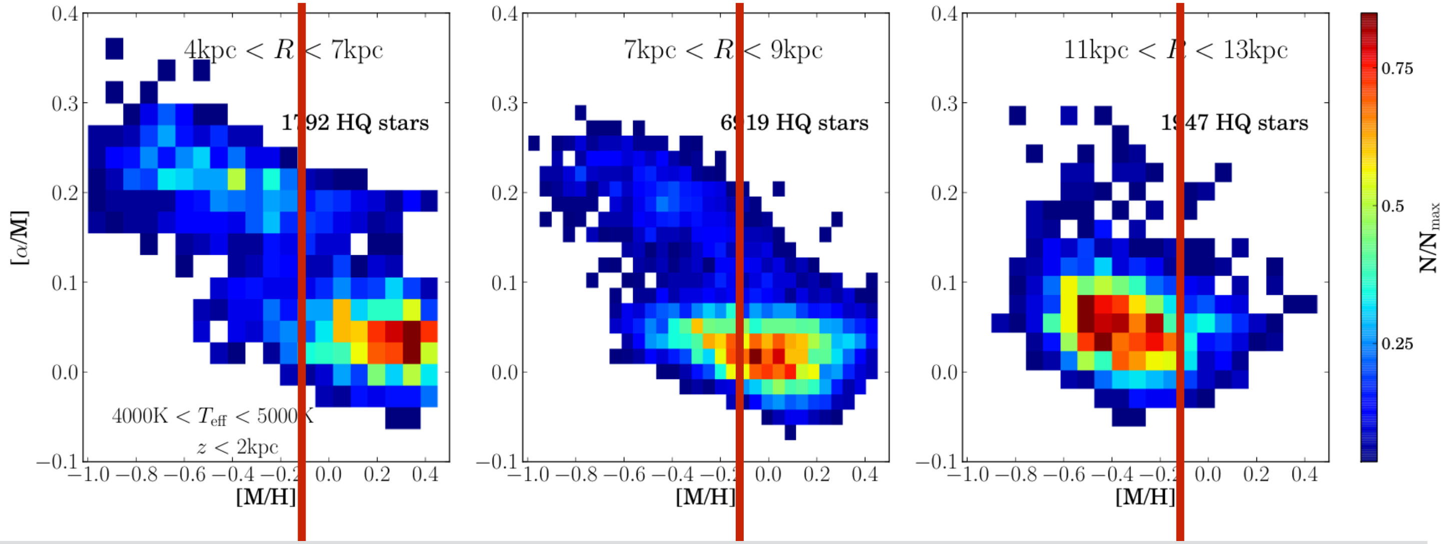
The solar ring (7-9 kpc) is a transition zone between the inner and outer disks



Why we need to change these assumptions

2/ The inner and outer disks are chemically distinct

APOGEE, Anders et al 2014



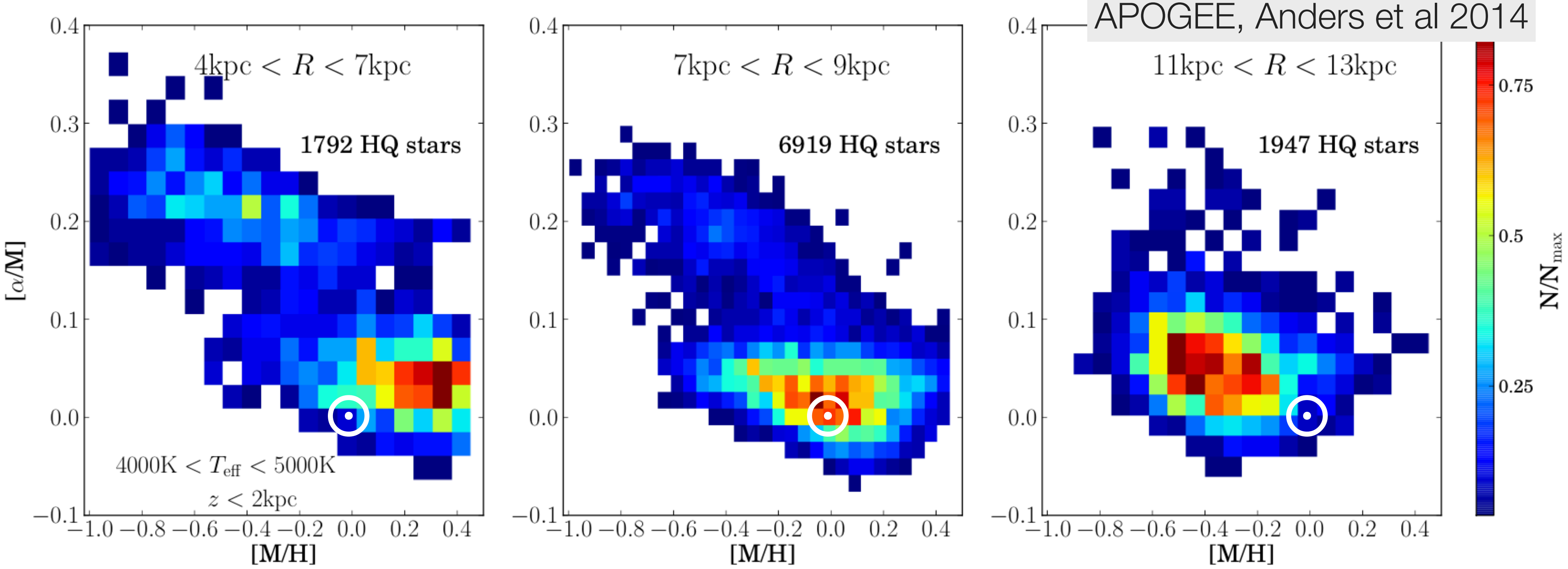
The solar ring (7-9 kpc) is a transition zone between the inner and outer disks

- The inner disk is composed of the thick disk and the metal-rich thin disk only
- The outer disk is made of a metal-poor thin disk only

This suggests also a revision of the effects and borders of radial migration

Hallé et al 2015, arXiv

APOGEE, Anders et al 2014



Haywood et al, 2015

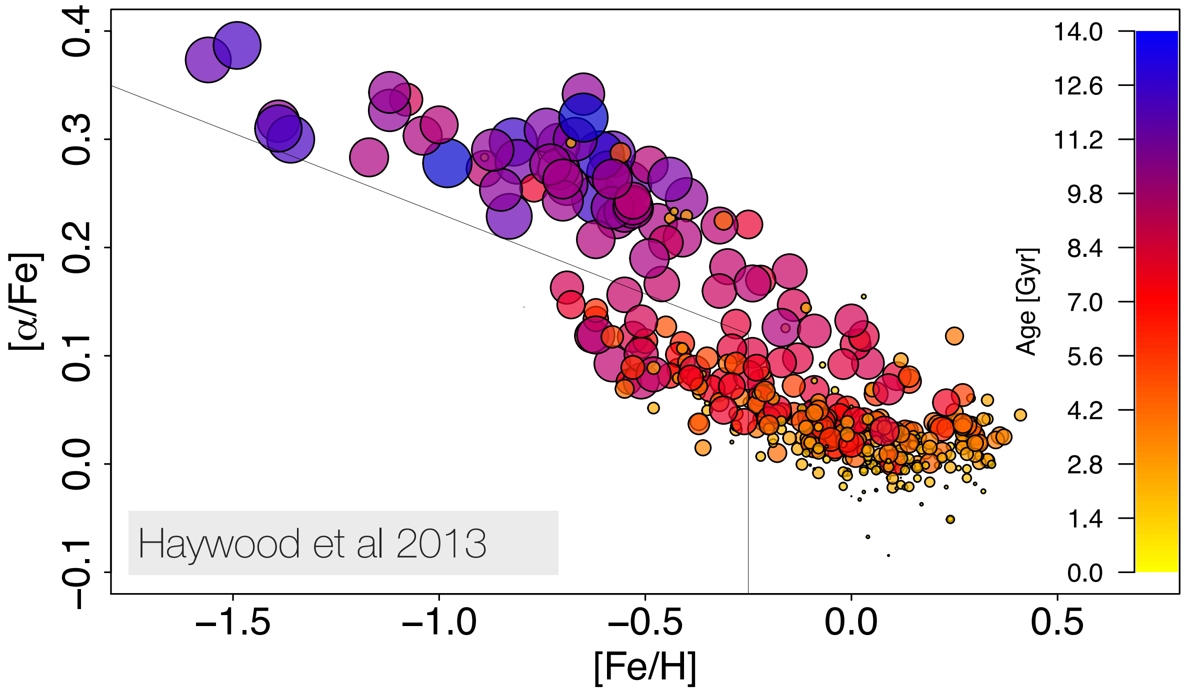
1/ The Sun is probably not an inner nor an outer disk star !

2/ Effect of the OLR of the bar ? see P. Di Matteo's talk tomorrow

Why we need to change these assumptions

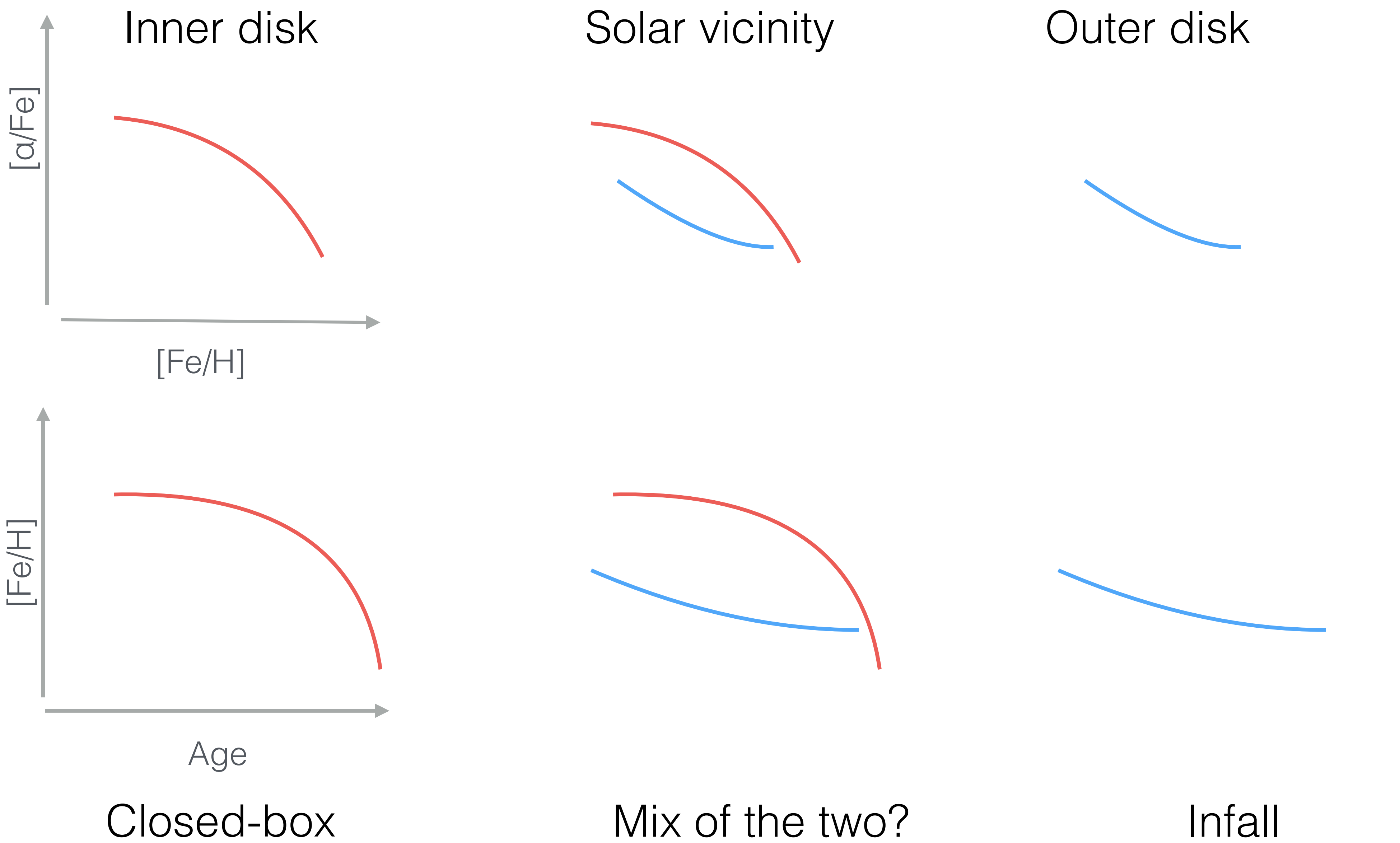
2/ The inner and outer disks are chemically distinct

At the same epoch, inner & outer disks were forming stars with significantly different chemistry (see Haywood et al 2013)



Different GCE models required to describe inner and outer disks

Haywood et al. 2013, Snaith et al. 2014



A « new » GCE model for the inner disk: the closed-box model

The evolution of the inner disk : a closed box GCE model

Haywood et al. 2013, Snaith et al. 2014

Closed box is here meant to assume that the quantity of gas in the disk is such as the SFR is not dependent on infall

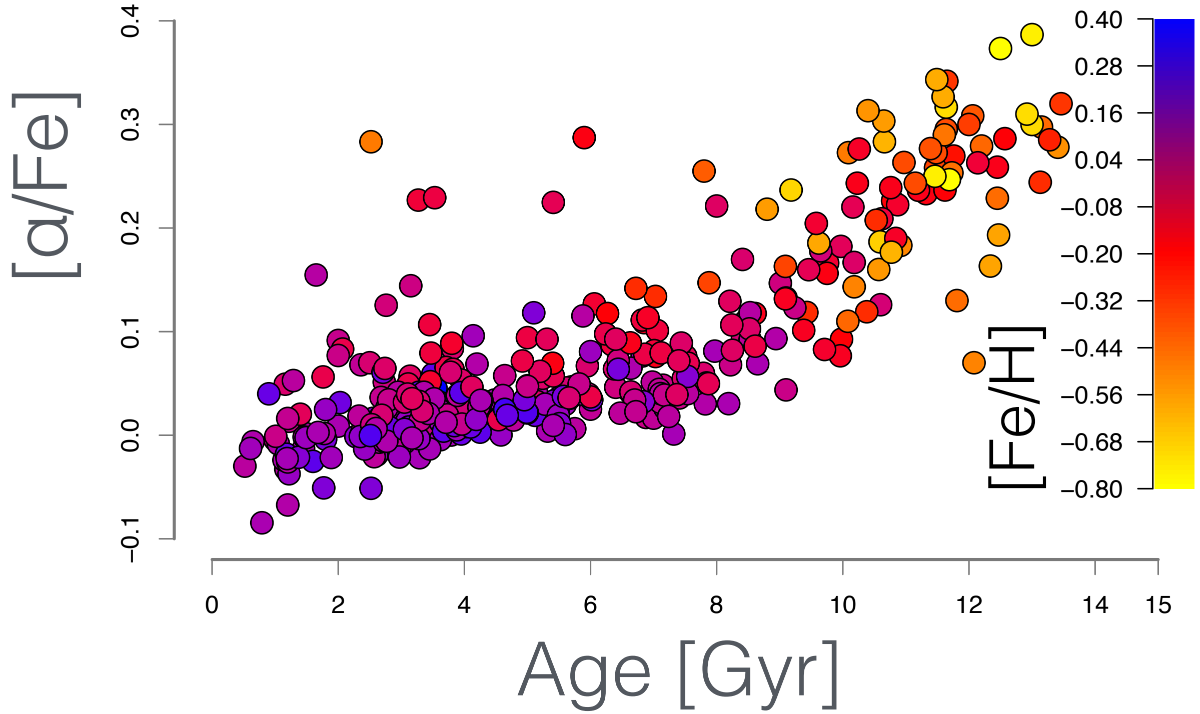
➡ either infall has been massive at early times (in the inner disk)

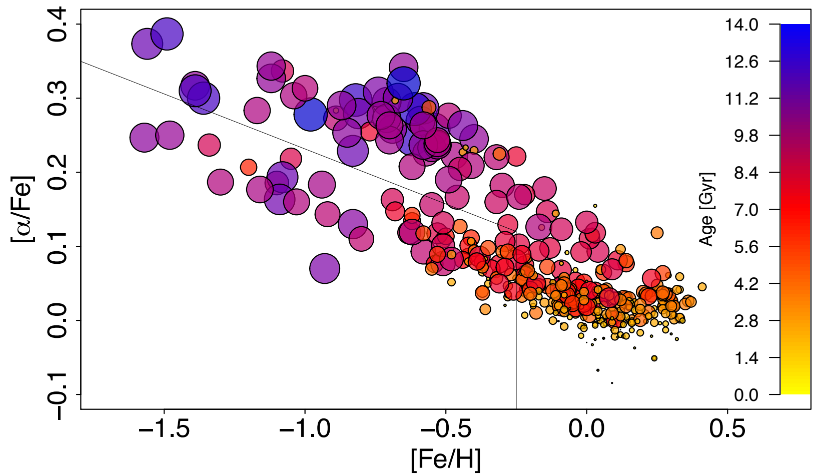
or

➡ infall is not connected to the SFR for some other physical process (e.g. feedback, see Hopkins et al 2014) dominating the ISM

Defining stellar populations

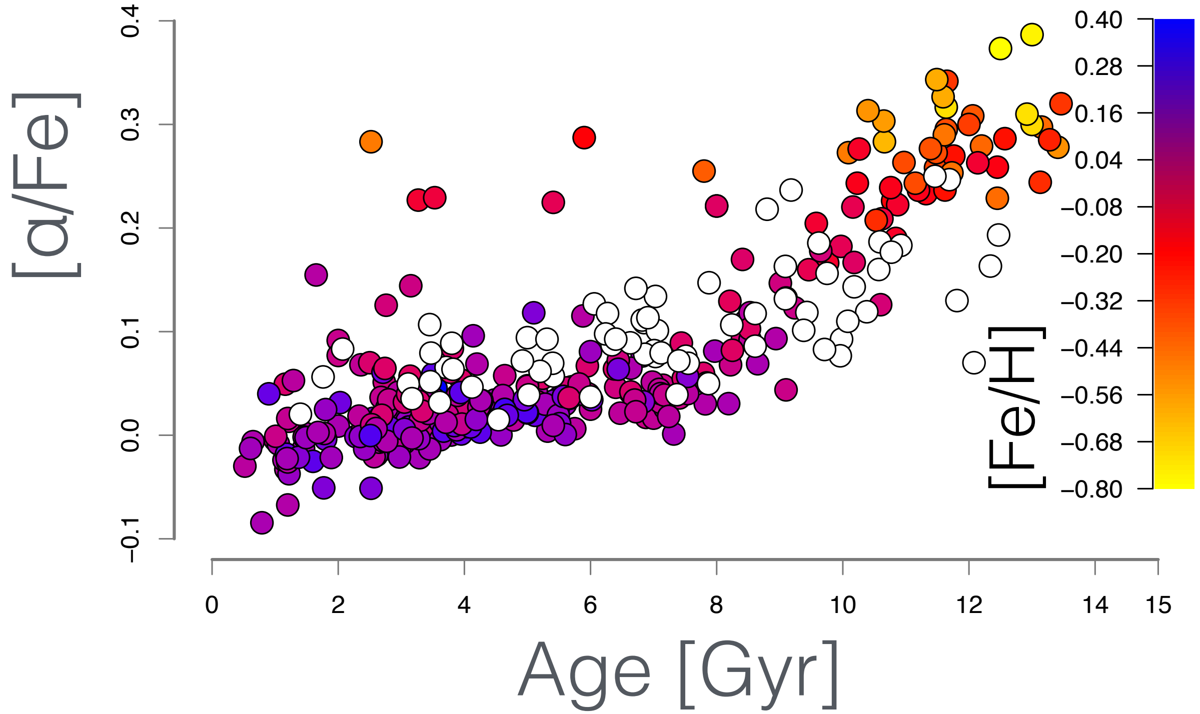
Haywood et al. 2013
(Abundances from Adibekyan et al 2012)

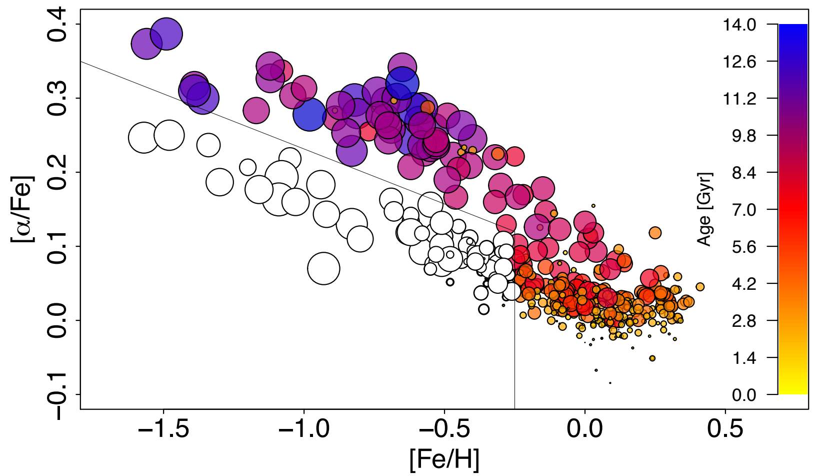




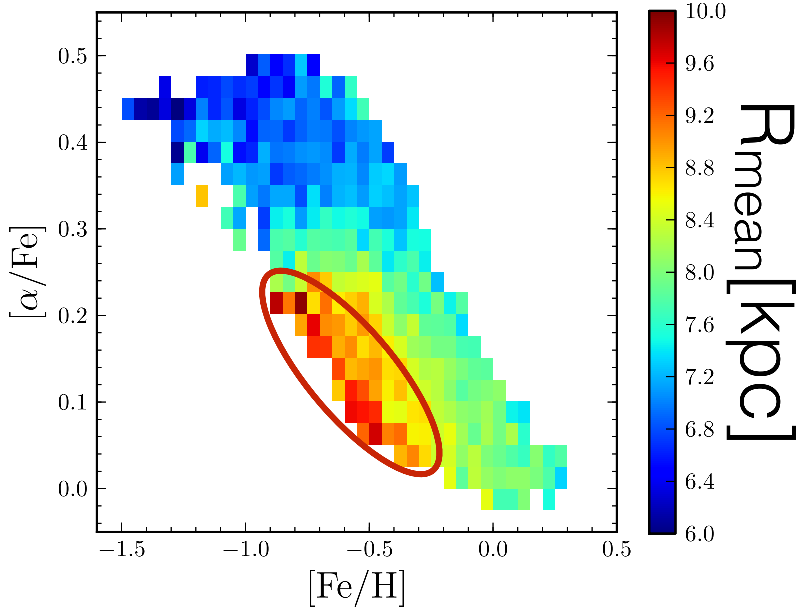
F&G stars in the solar vicinity

Defining stellar populations



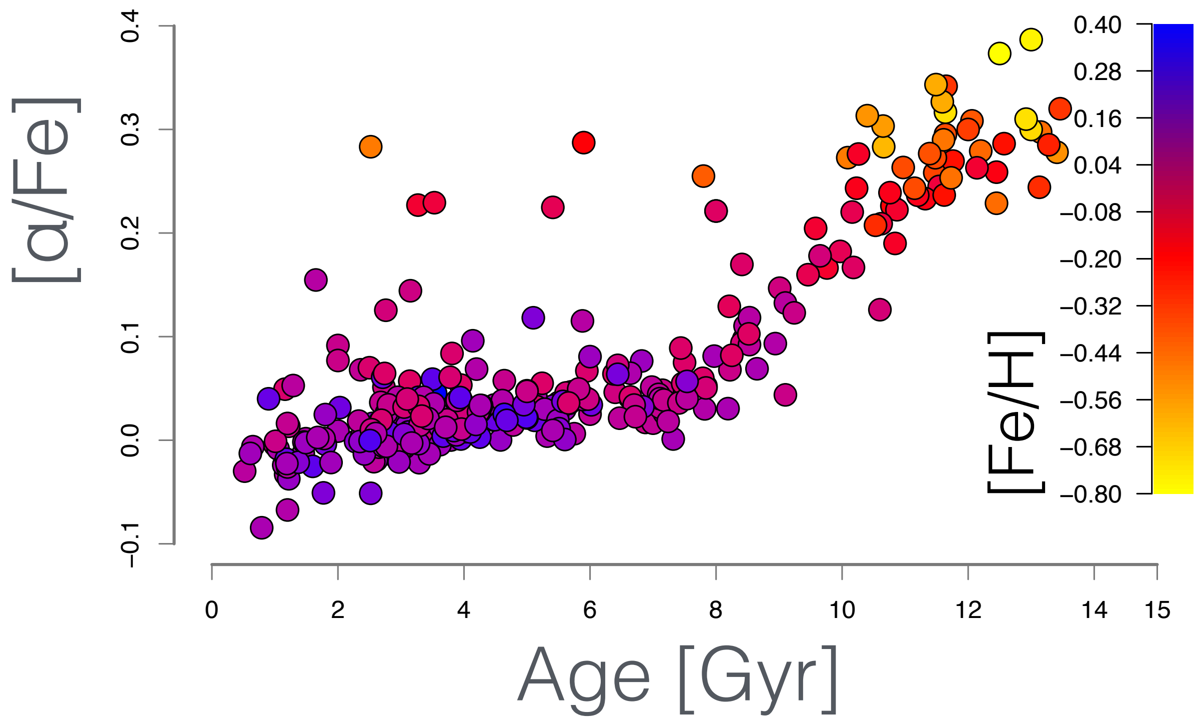


Metal-poor thin disk stars are not part of the inner disk (R<7kpc):
they are outer disk (R> 9kpc) objects
(Haywood 2008; Bovy et al. 2012)



Bovy et al. 2012

Defining stellar populations: The inner disk sequence



Haywood et al. 2013
(Abundances from Adibekyan et al 2012)

Defining stellar populations: The inner disk sequence

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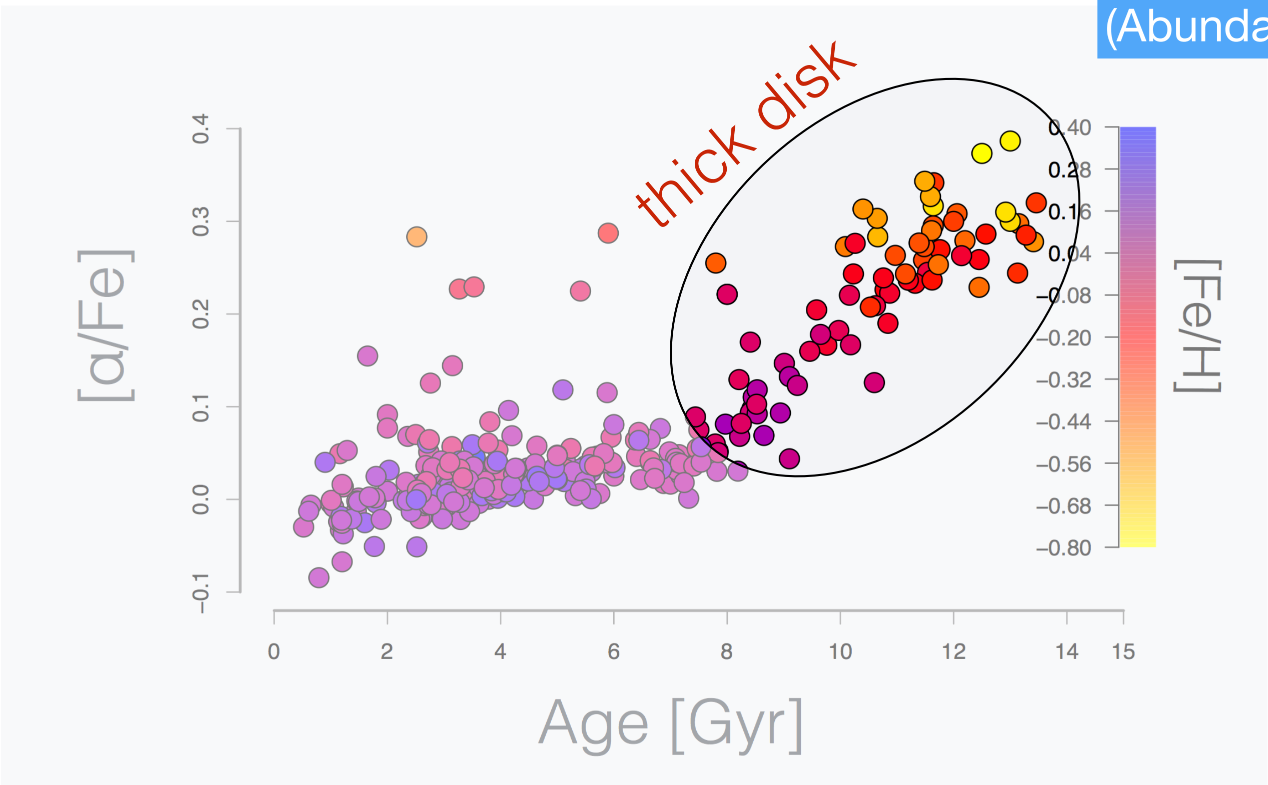

- The thick disk was formed over a period of 4-5 Gyr
- The thick disk formation was an homogeneous process

Defining stellar populations: The inner disk sequence

Haywood et al. 2013
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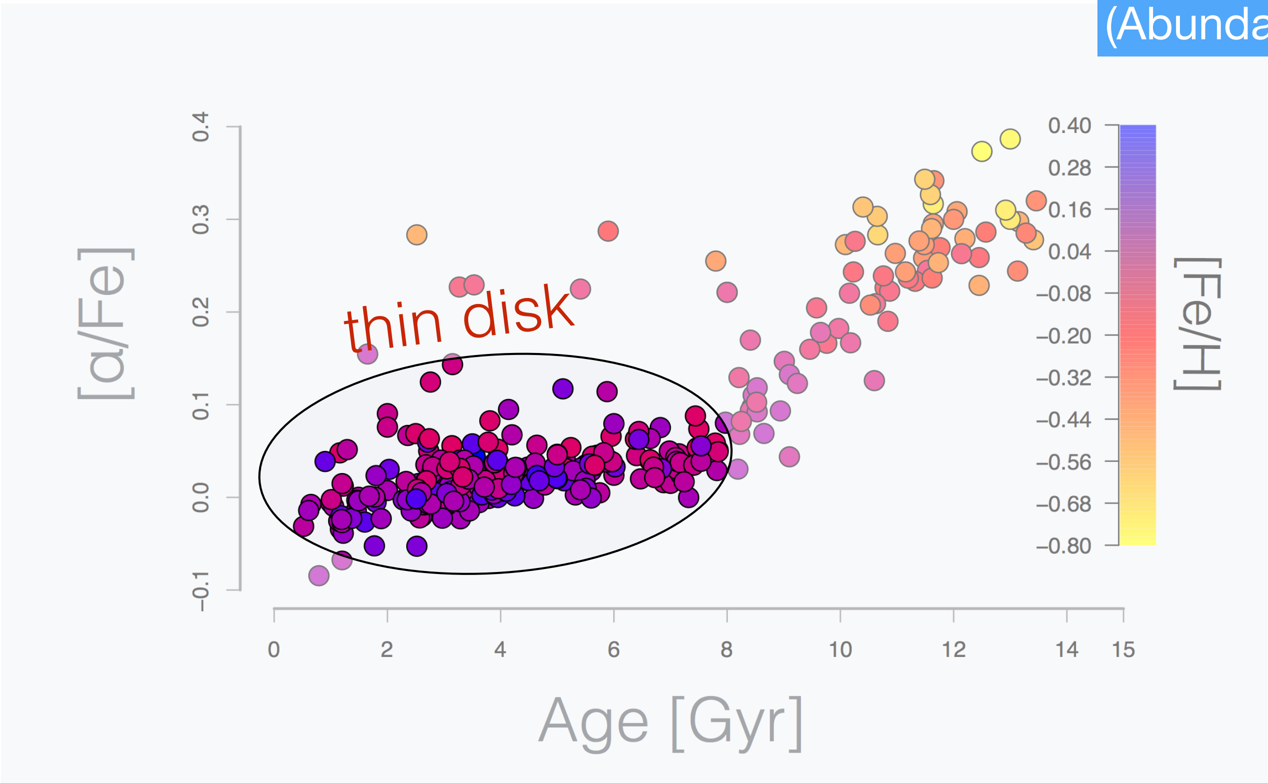
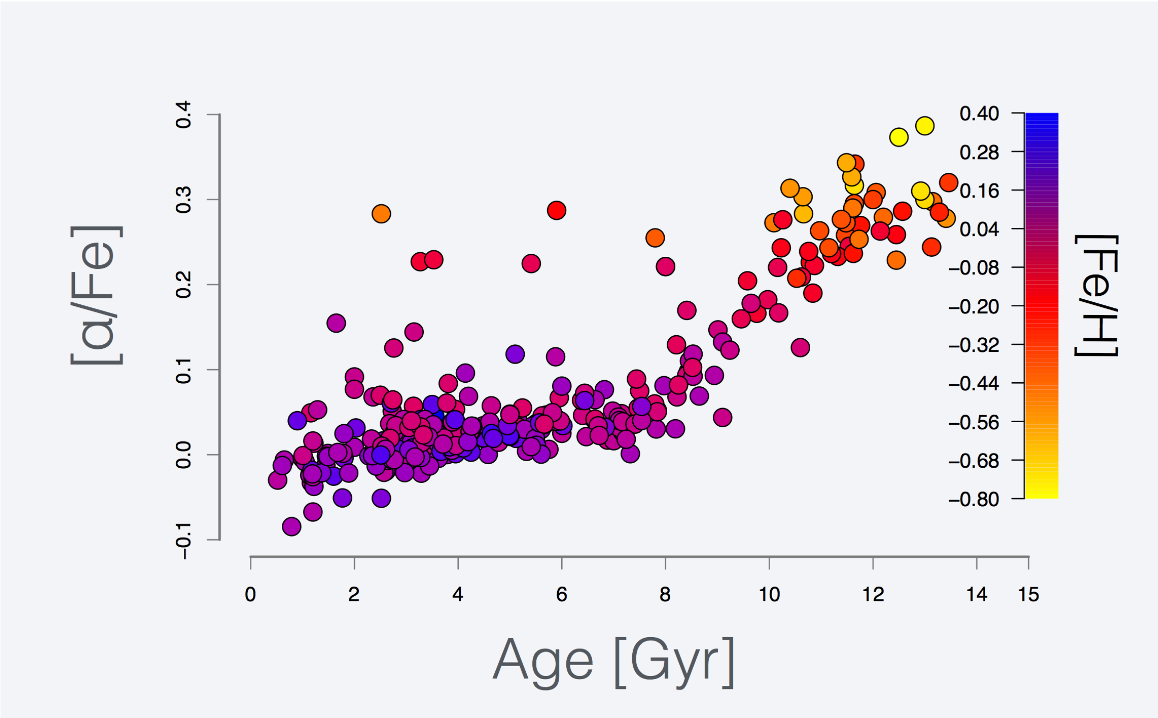


- The thick disk was formed over a period of 4-5 Gyr
- The thick disk formation was an homogeneous process
- The thick disk set the initial conditions from which the thin disk was formed. There is ***continuity between the two***

The Star Formation History of the disk

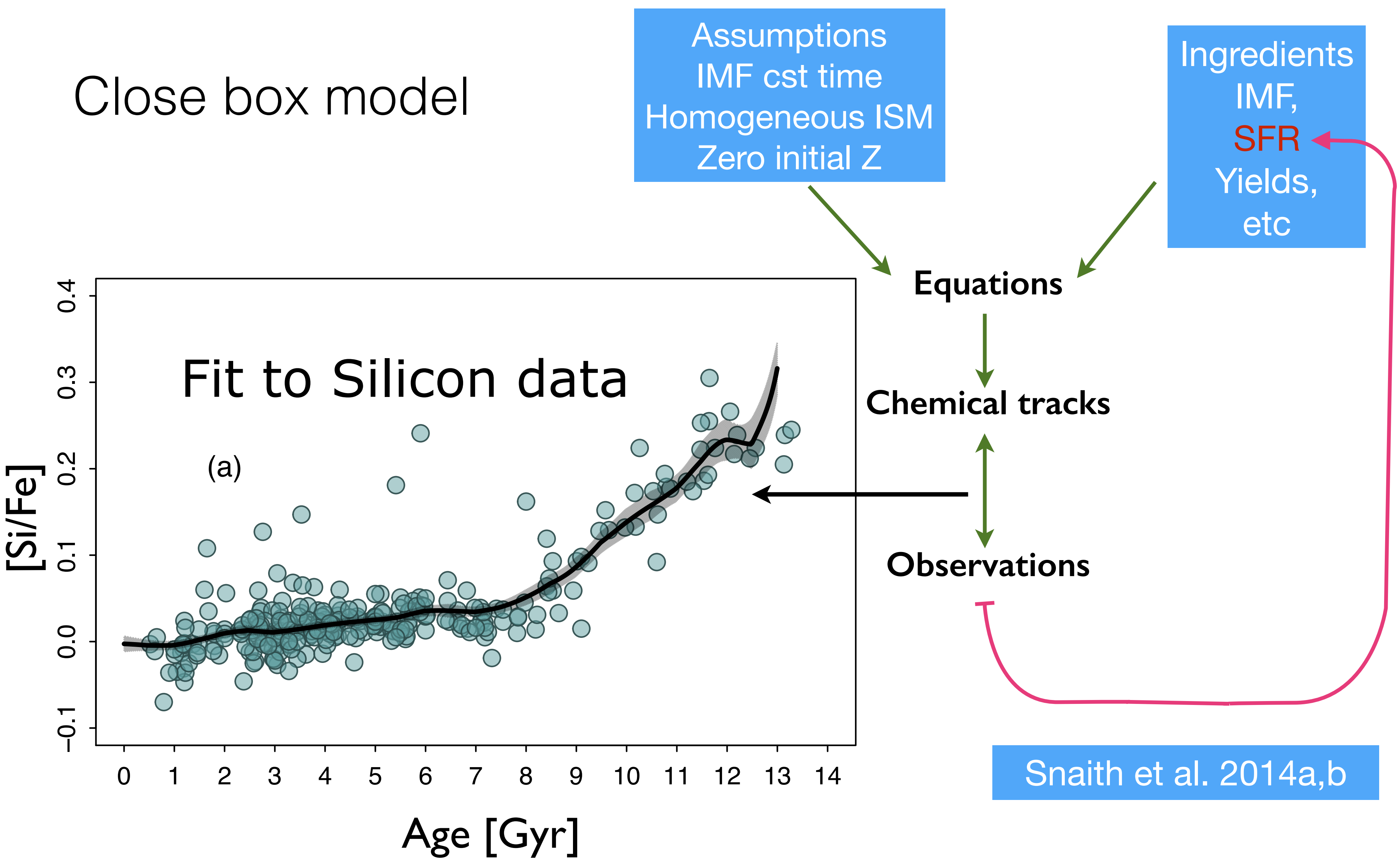


Different α-enrichment regimes correspond to different SFR intensity

Fitting chemical tracks to the α-age relation yields the SFH ➡ we need a model

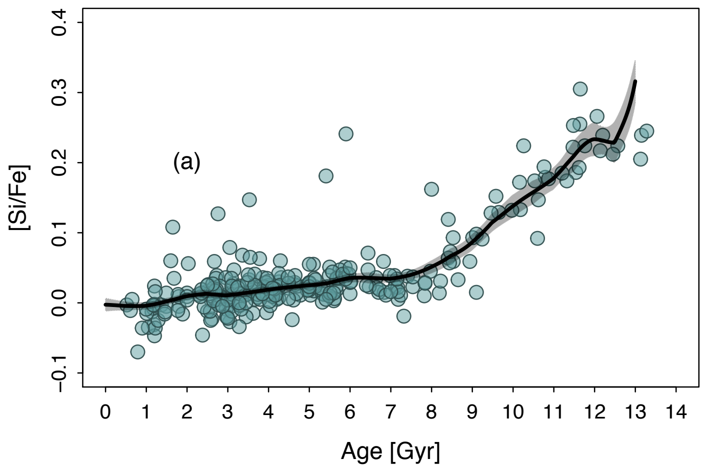
Recovering the SFH from the data… Snaith et al. (2014, 2015)

Close box model



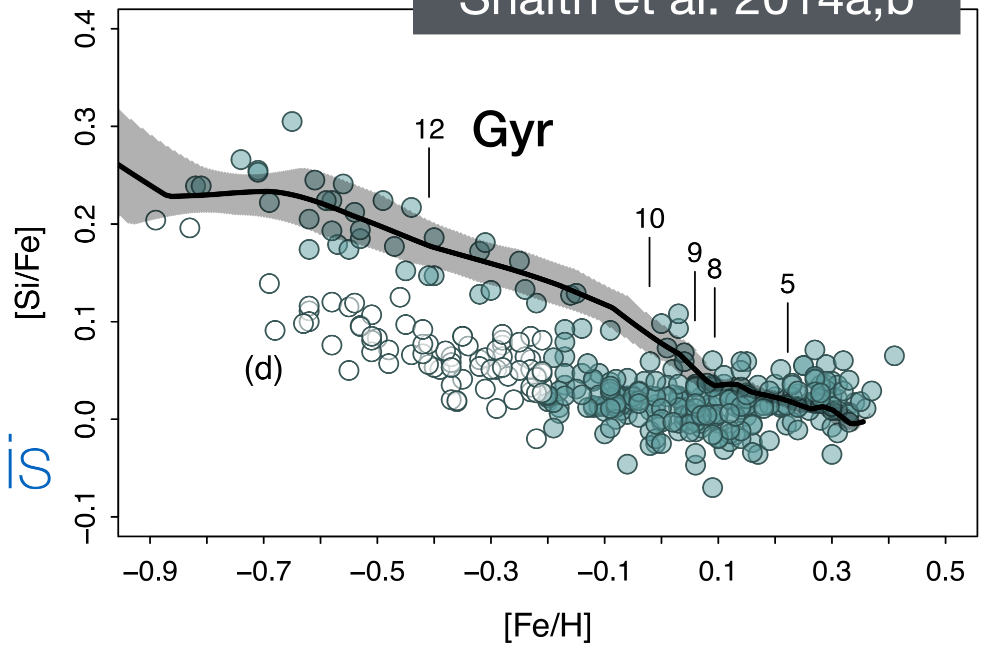
Snaith et al. 2014a,b

The fit to the [Si/Fe]-age relation gives also ...



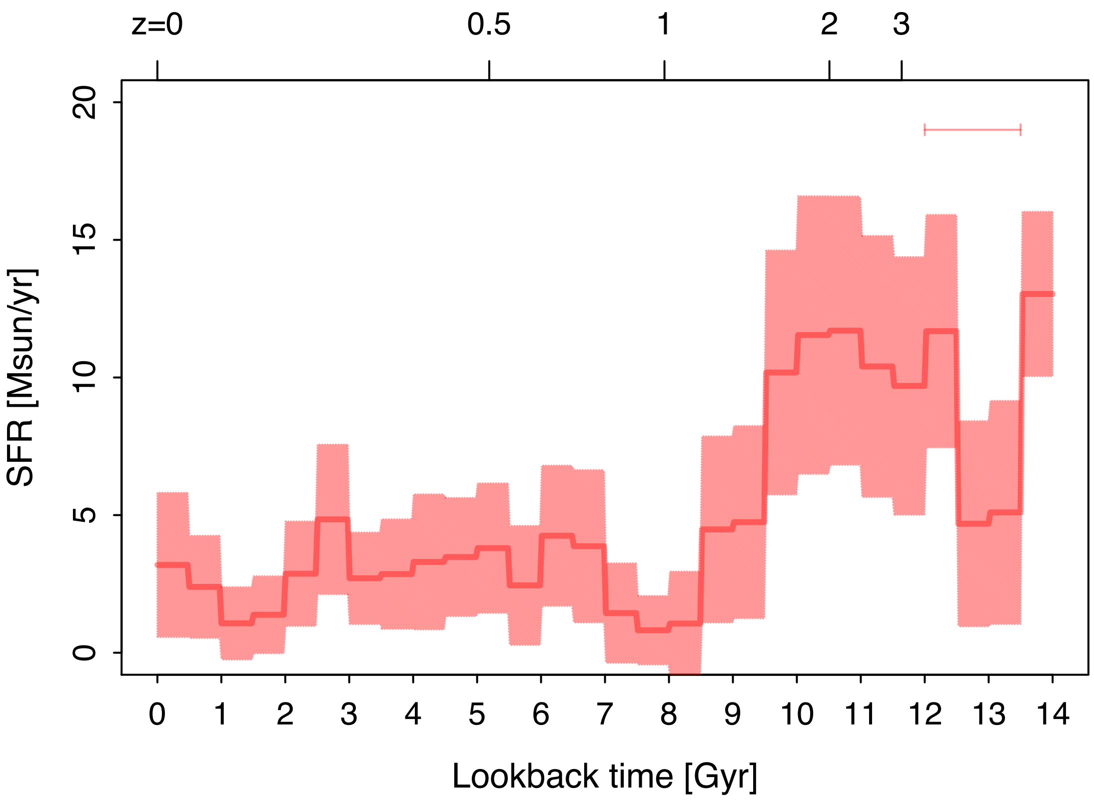
... **a good match (not a fit !)** to the [Si/Fe]-[Fe/H] distrib.

Snaith et al. 2014a,b



the thick disk sequence (in the [α/Fe]-[Fe/H] plane) is a temporal sequence

The Star Formation History of the disk

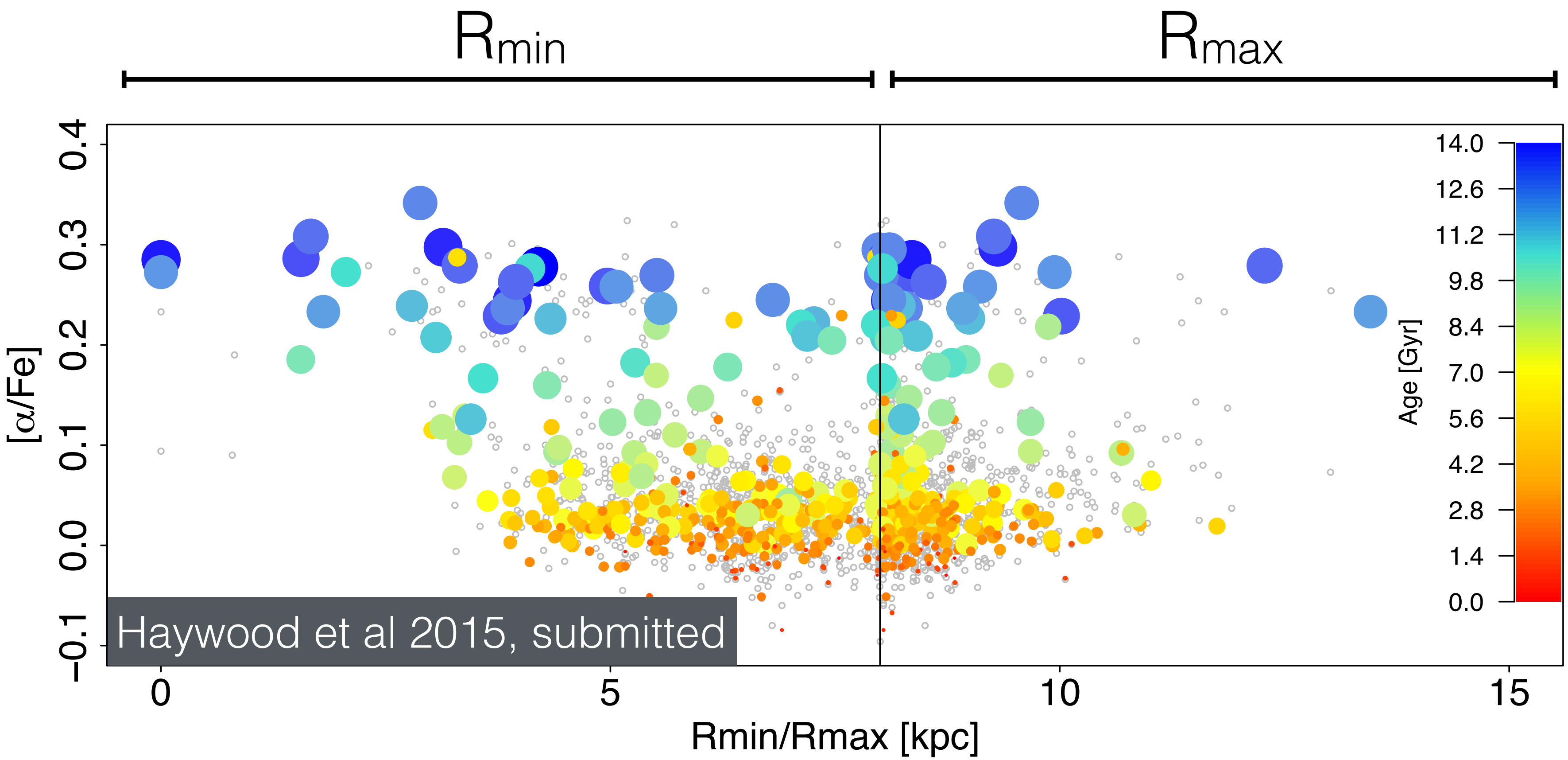


Snaith et al. 2014a
Snaith et al. accepted,
astro-ph 1410-3829

The method provides the SFR with high accuracy
on the first Gyrs (at the price of having to assume a GCE model)

The Star Formation History of the disk

Note that even if found by analyzing solar vicinity stars, **this is not a local SFR**

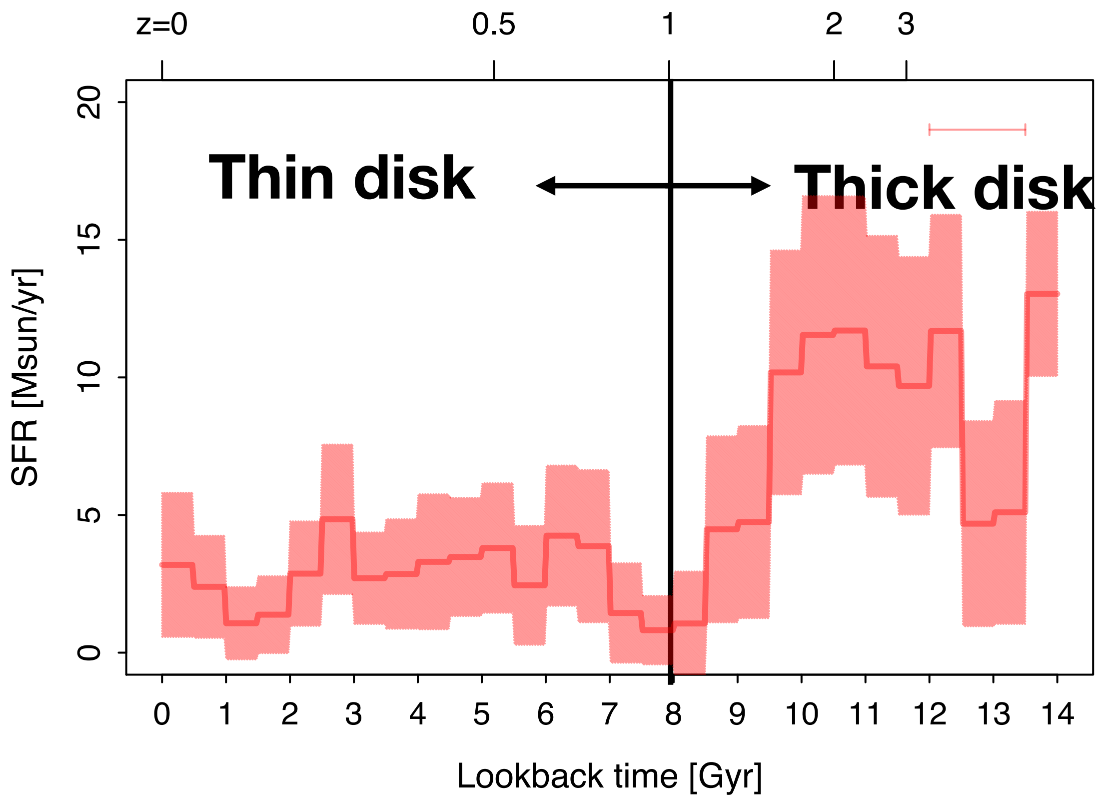


High-α stars have pericentres that can reach R<2kpc

➡ Solar vicinity thick disk covers the whole inner disk (0-10kpc)

The SFH in the thick disk phase is valid for the entire disk

The Star Formation History of the disk : main characteristics

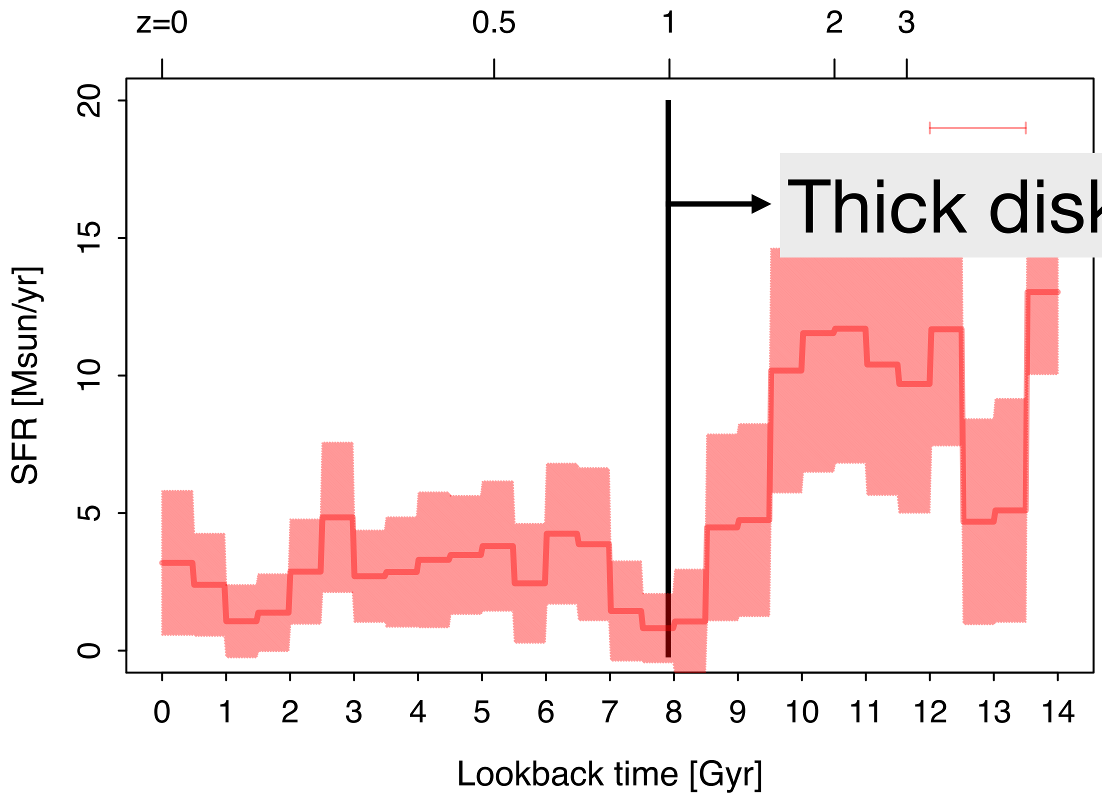


Two main periods of SFR corresponding to:

1/ 13-8.5 Gyr :
thick disk at SFR ∼12 M⊙/yr
2/ 7 Gyr - Now
thin disk at SFR ∼2-3 M⊙/yr

(Normalized to have an integrated stellar mass of 5. 10^{10} M⊙,
Flynn et al. 2006, McMillan 2011)

The Star Formation History of the disk : main characteristics



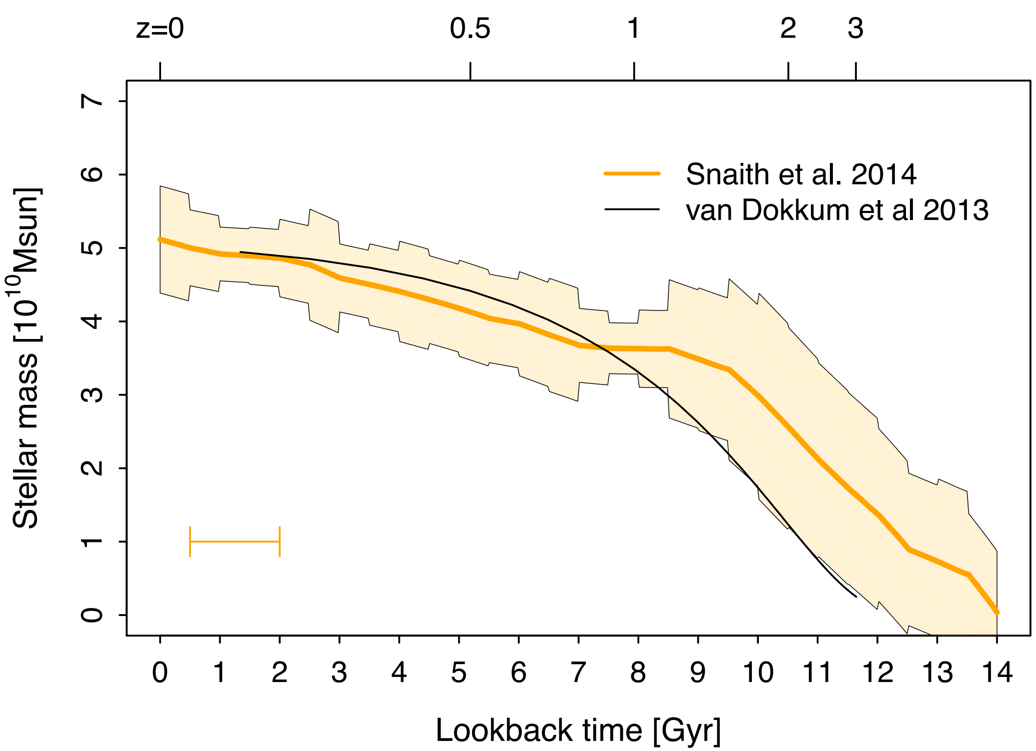
Thick disk ∼ 50% of stellar mass

Consistent with :

1/ the mass estimate for a thick disk scale length of ~ 2 kpc

2/ the finding that most of the mass in the bulge is due to the thick disk

The Star Formation History of the disk :implied mass growth



van Dokkum et al 2013 (selection of MW-type progenitors by abundance matching):

The implied star formation rate is approximately constant at 10–15 $M_\odot$ yr^{-1} from $z \sim 2.5$ to $z \sim 1$ and then decreases rapidly to $\lesssim 2\, M_\odot$ yr^{-1} at $z = 0$. The form of this star formation

.. and also :

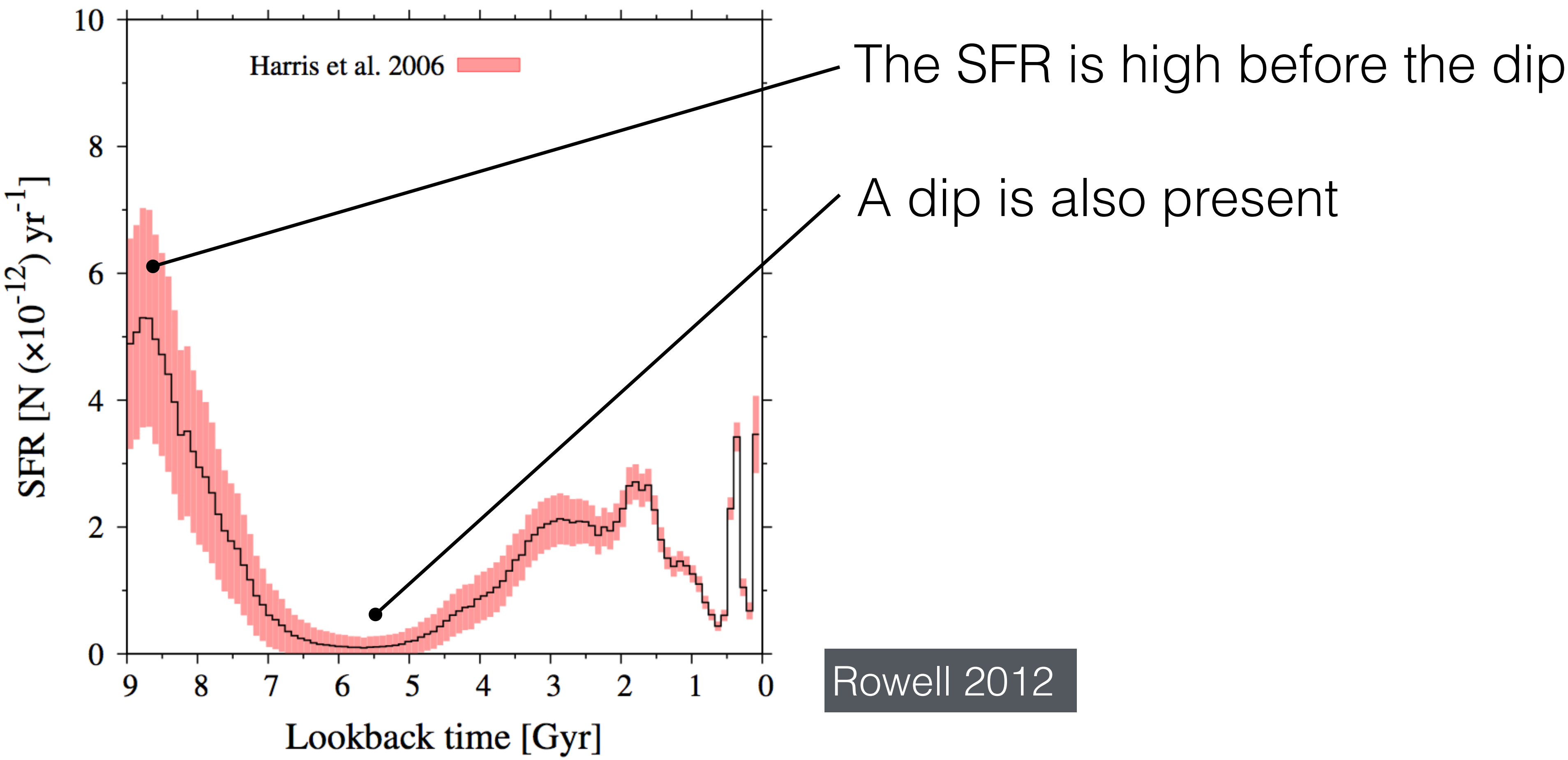
much as the disks, particularly at $z > 1$. We do *not* see high-density "naked bulges" at $z \sim 2$ around which disks gradually assembled. Instead, the central densities at $z \sim 2$ were much lower than the central densities at $z \sim 0$. We quantify this result

It is the formation of the (massive) thick disk that makes the mass growth evolution of the MW similar to its progenitors

The Star Formation History of the disk : main characteristics

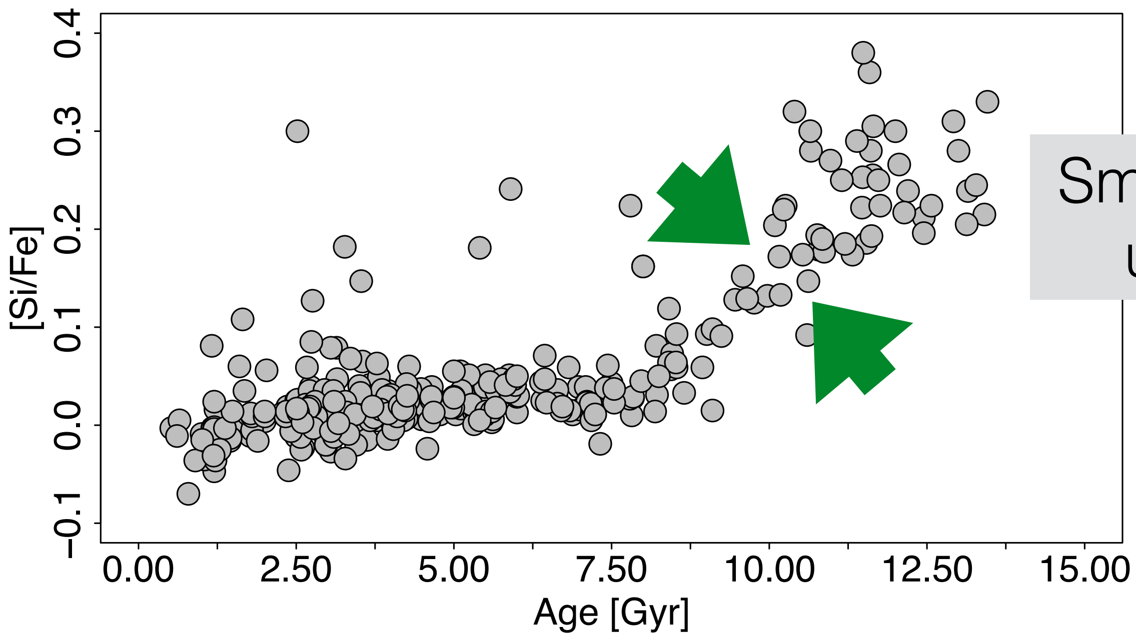
Is the dip in the SFH real ?

SFH from the White Dwarf luminosity function, shows that, although the SFHs are qualitatively similar (but no volume corrections)



Rowell 2012

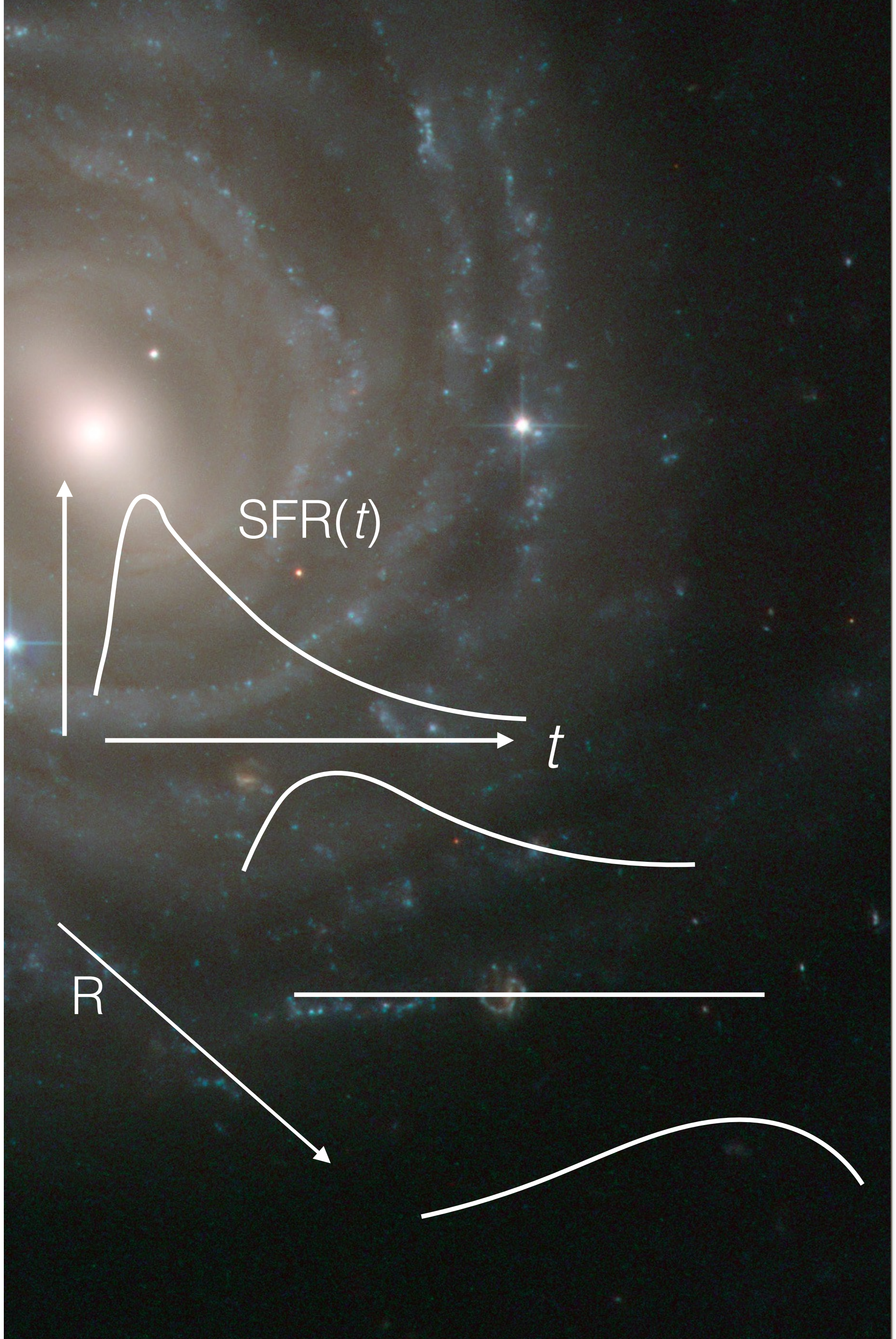
The Star Formation History of the disk : main characteristics



Small dispersion compatible with uncertainties on stellar ages

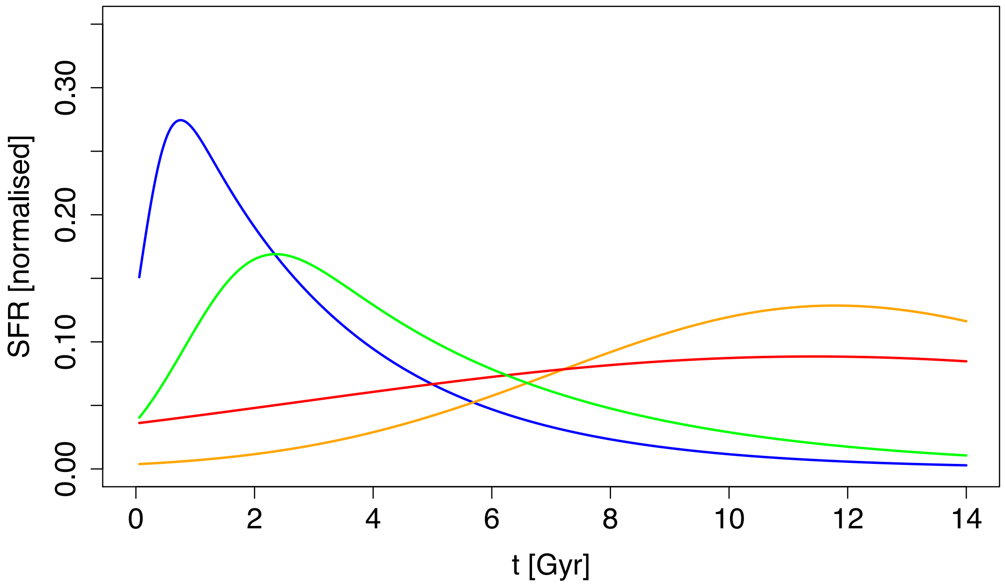
Very homogeneous abundances for thick disk stars
in spite of the various origins of the stars

➡ **Very efficient mixing of metals, possibly due to turbulence** (see Lehnert et al. 2014)

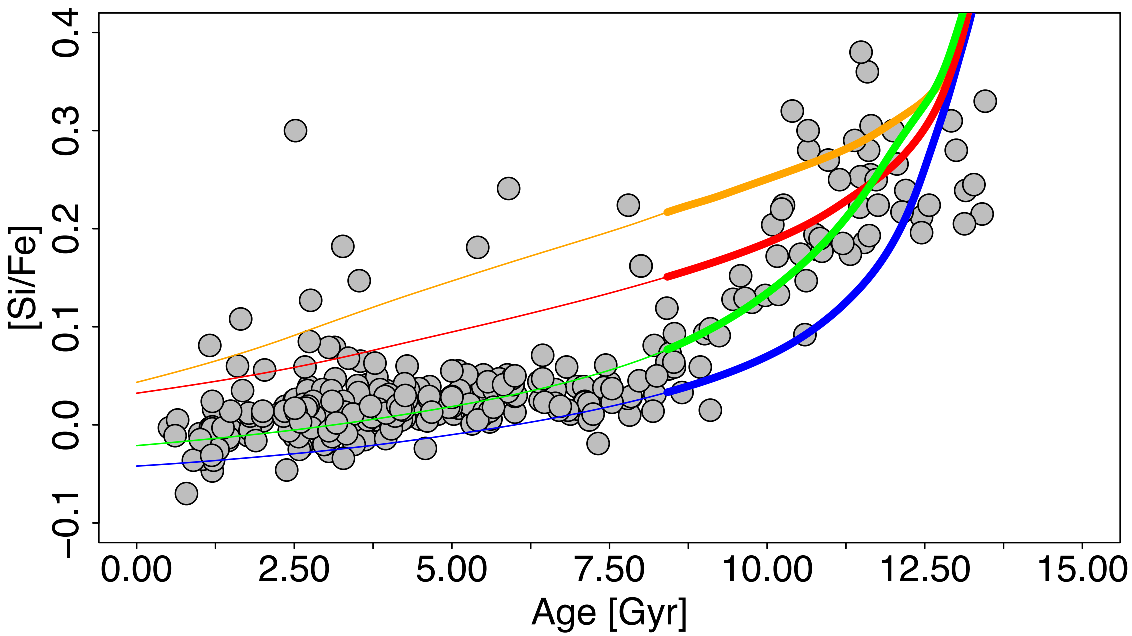


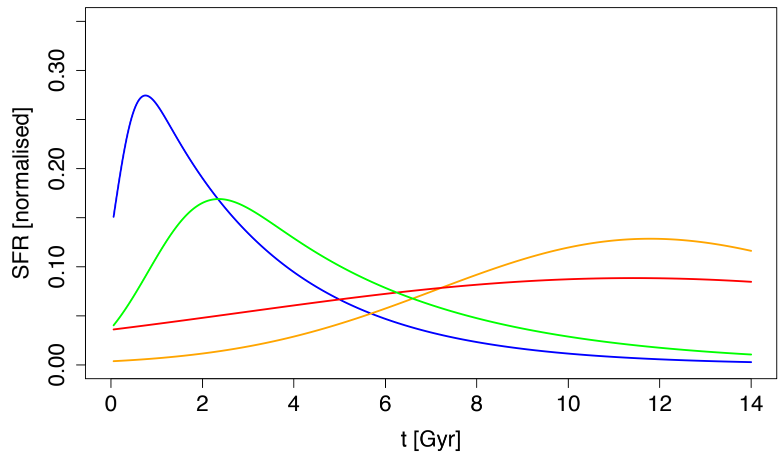
On the homogeneous abundances of thick disk stars

To obtain an inside-out formation process, classically **GCE models assume a radially dependent infall**. This implies **a radially dependent SFH**



On the homogeneous abundances of thick disk stars





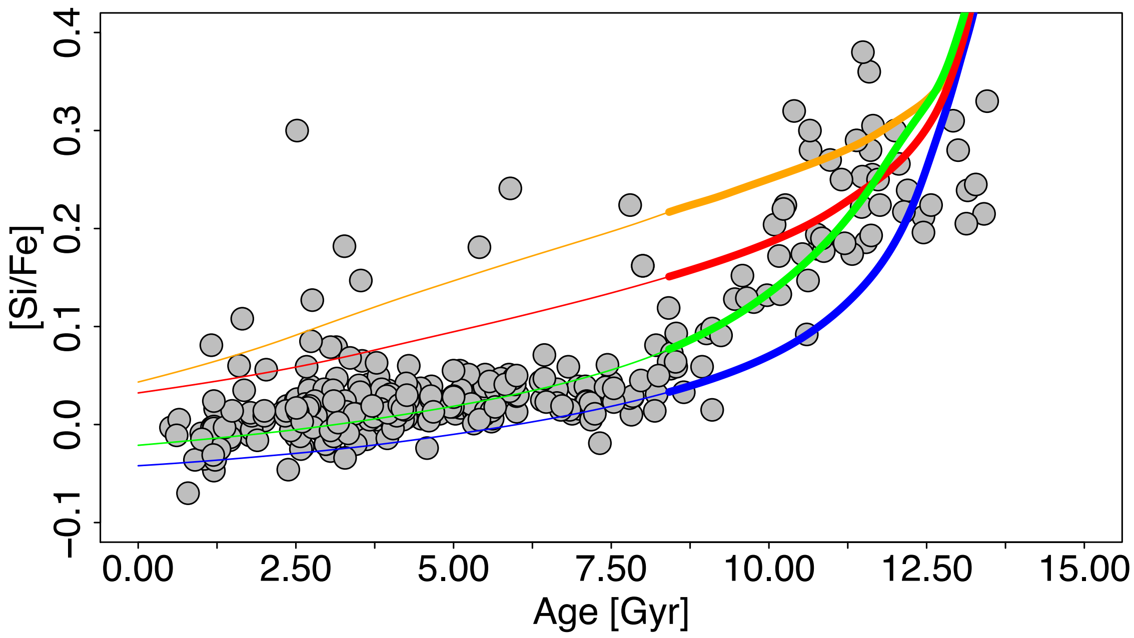
Haywood et al. *submitted*

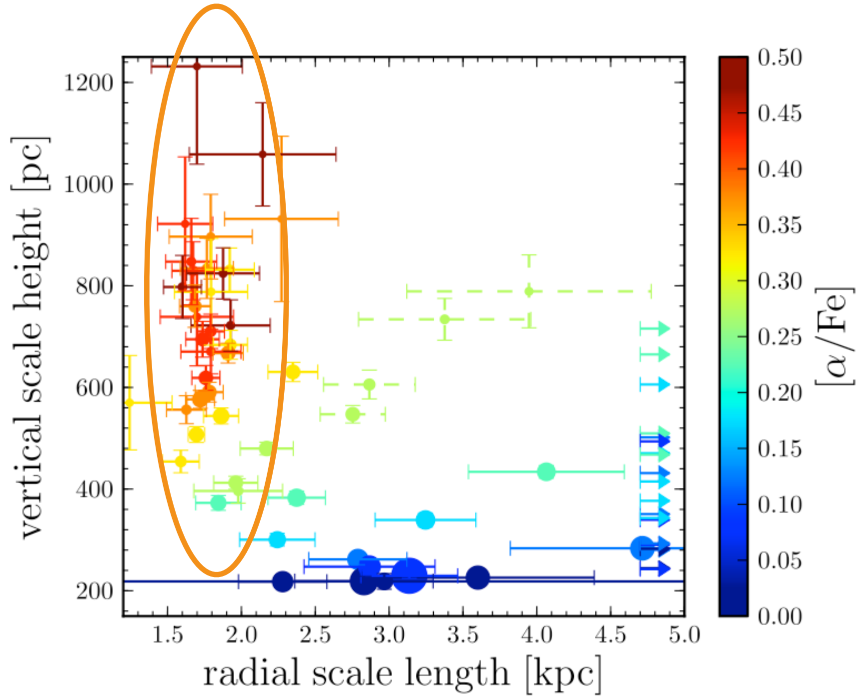
If the SFH was dependent on radius,

we should find significant variation in the SFR incompatible with the chemistry

The lack of gradient in the thick disk (Cheng et al. 2012) **is not due to stellar radial mixing, but to well mixed ISM during the thick disk formation** (Haywood+2013). **Star formation in the thick disk was an homogeneous process on large spatial scales**

On the homogeneous abundances of thick disk stars



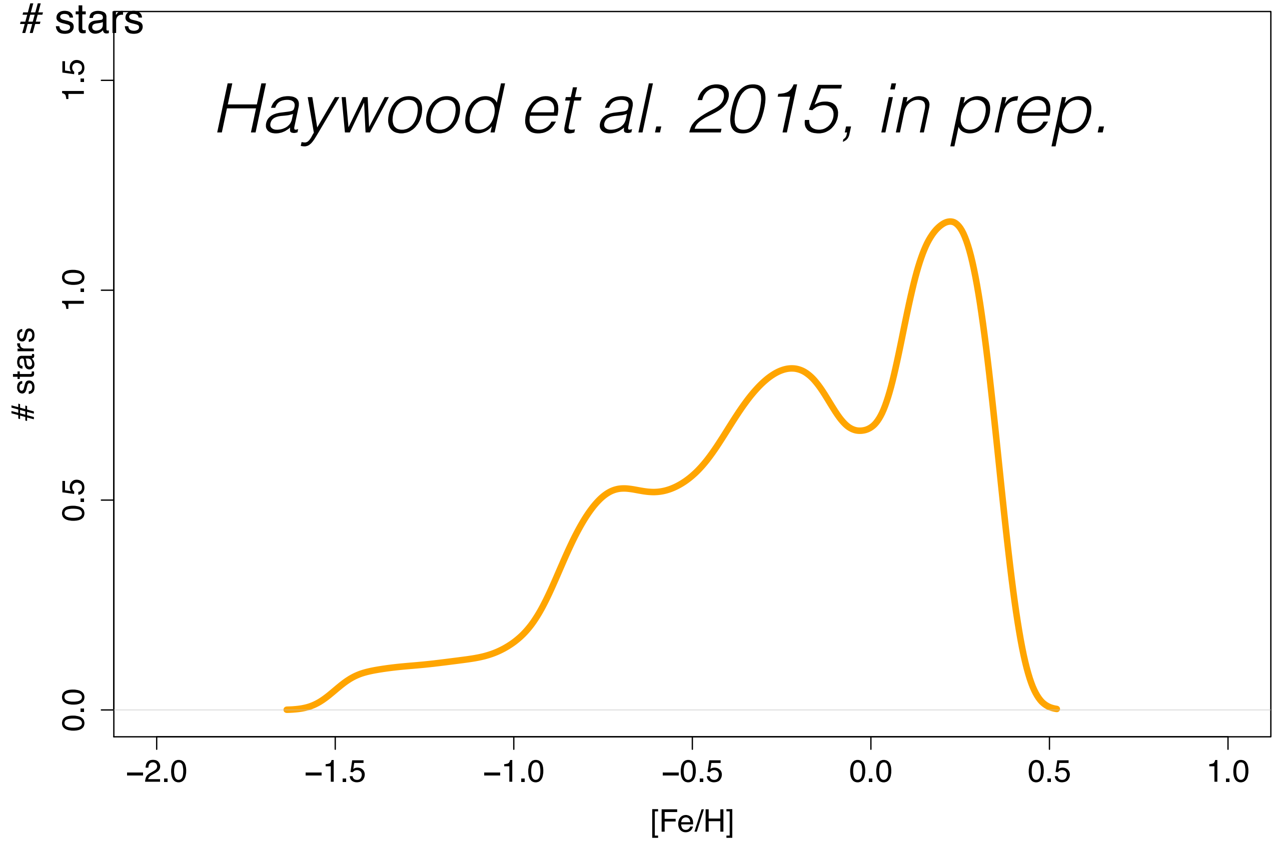


Moreover, the lack of a dependence of the SFH with radius
suggests no inside-out evolution during the thick disk phase

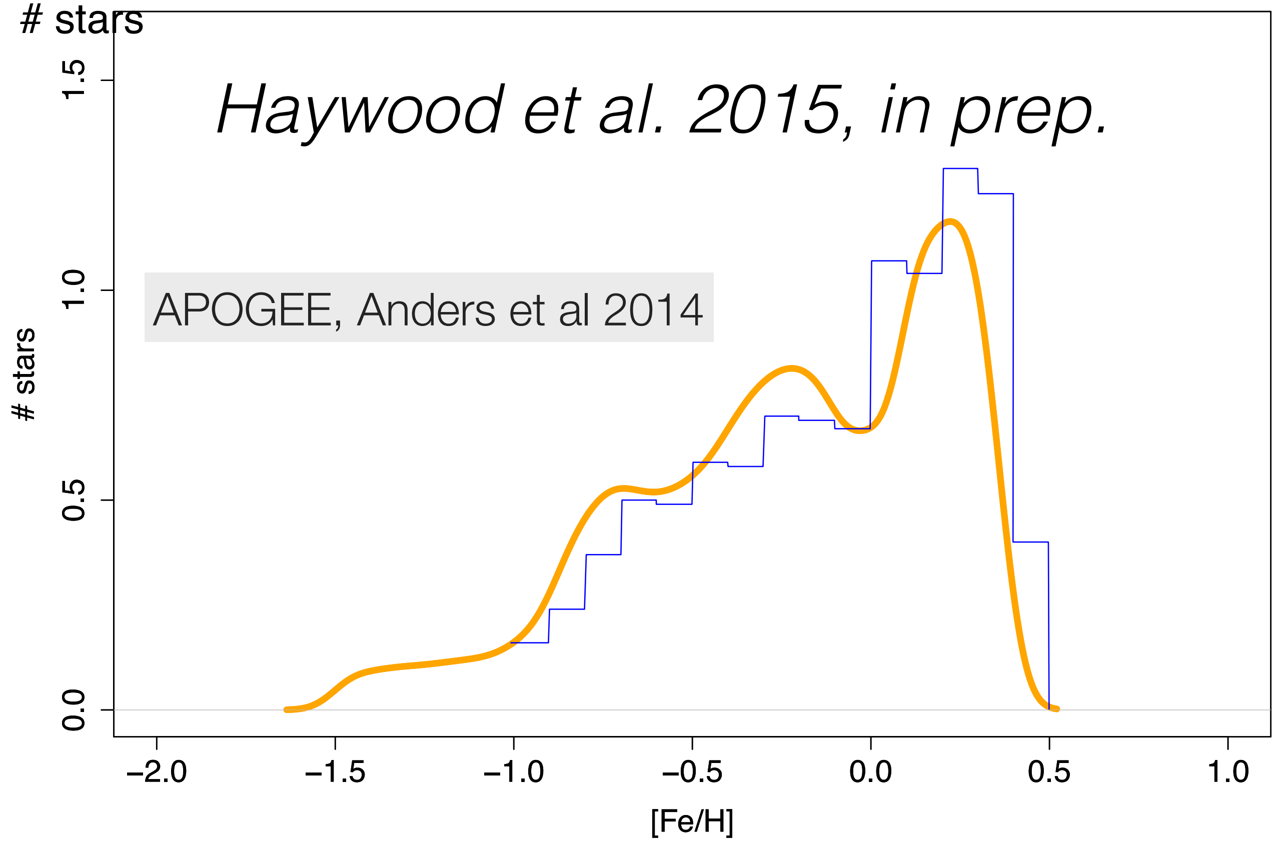
1/ In agreement with the constant scale length in the thick disk
(Bovy et al. 2012)

2/ In agreement with the growth of MW-type galaxies at redshifts > 1
(van Dokkum et al 2013)

The MDF of the inner disk



The MDF of the inner disk



work in progress…

Conclusions

Important differences with standard infall models:
(e.g. Naab & Ostriker 2006, Minchev et al., 2014, Kubryk et al. 2014)

➡ The thick disk is as massive as the thin disk and old. Its formation requires **huge quantities of gas in the Galaxy at early epochs**

➡ **SF in the thick disk phase is a homogeneous process over a large spatial extent.** In particular :

1/ The SFH is a not a function of radius in the thick disk phase
2/ No radial gradient in the thick disk (observed)
3/ No inside-out in the thick disk (observed)

➡ **The inner and the outer disk are not in chemical continuity**

1/ no smooth variation of the chemical patterns of the disk with R
2/ the region between ~7-9 kpc is a transition region
3/ The Sun has a chemistry typical of this region, i.e. **the Sun is an OLR star, not an inner disk star**