GES 2014
Gaia-ESO Survey Second Science Meeting

the formation and evolution of the Milky Way disks from stellar abundances

Misha Haywood, Paris Observatory

Porto, nov. 2014

Outline.

1 - Defining stellar populations

2 - The Star Formation History of the disk

3 - The structuration of the disk

4 - Why are thick disks important ?

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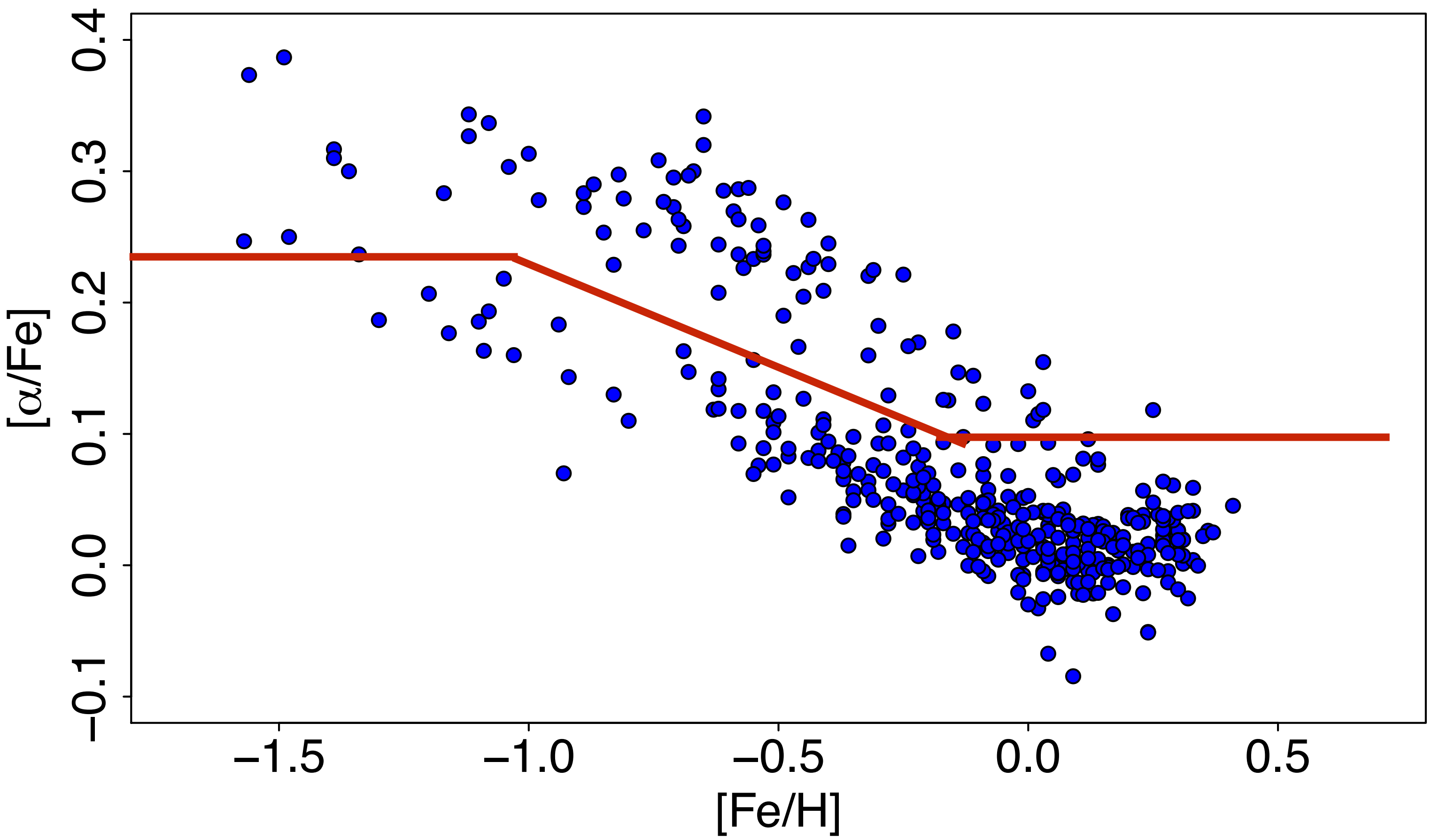
Defining stellar populations

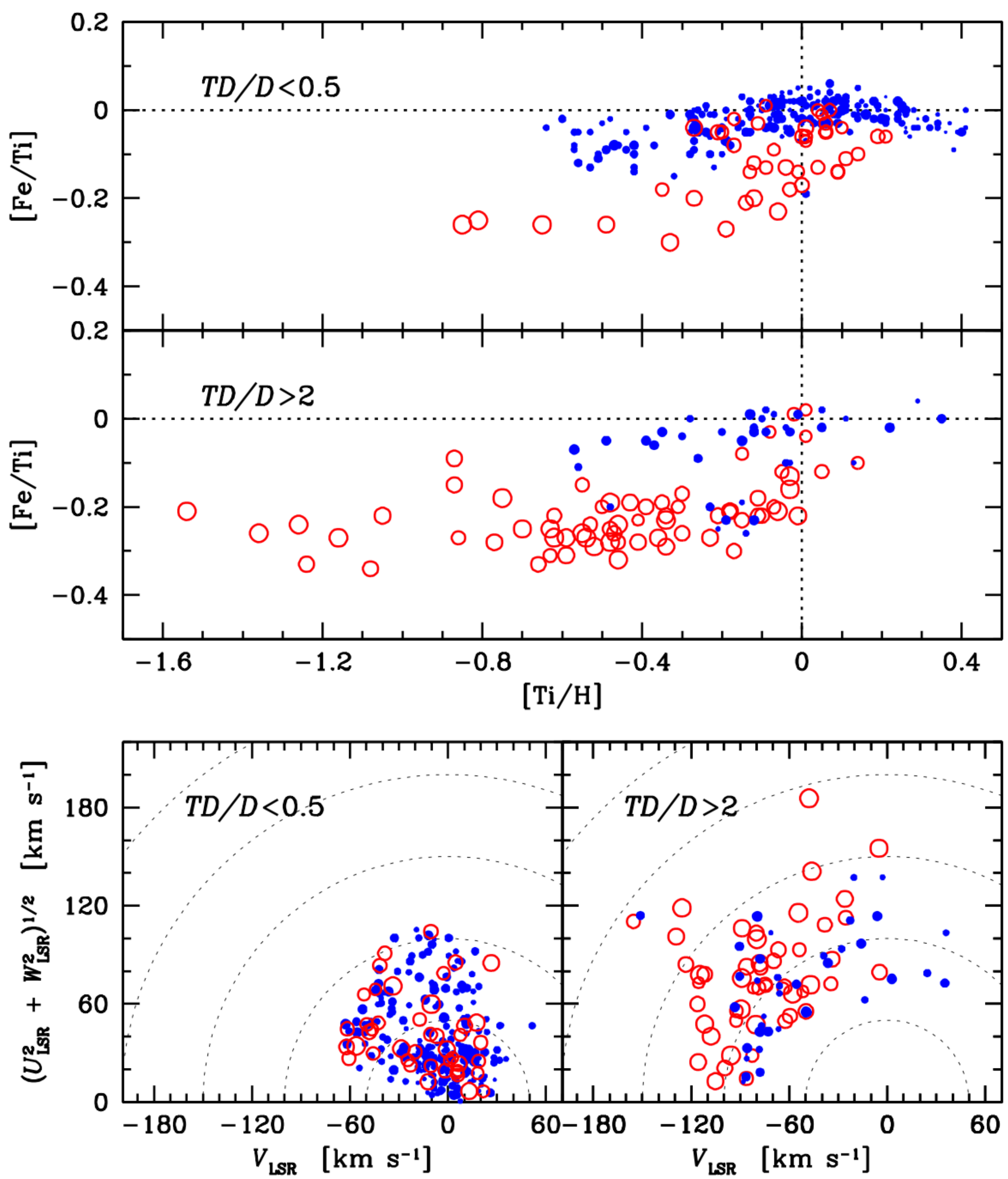


Abundances from :
Adibekyan et al 2012,
Nissen & Schuster 2010

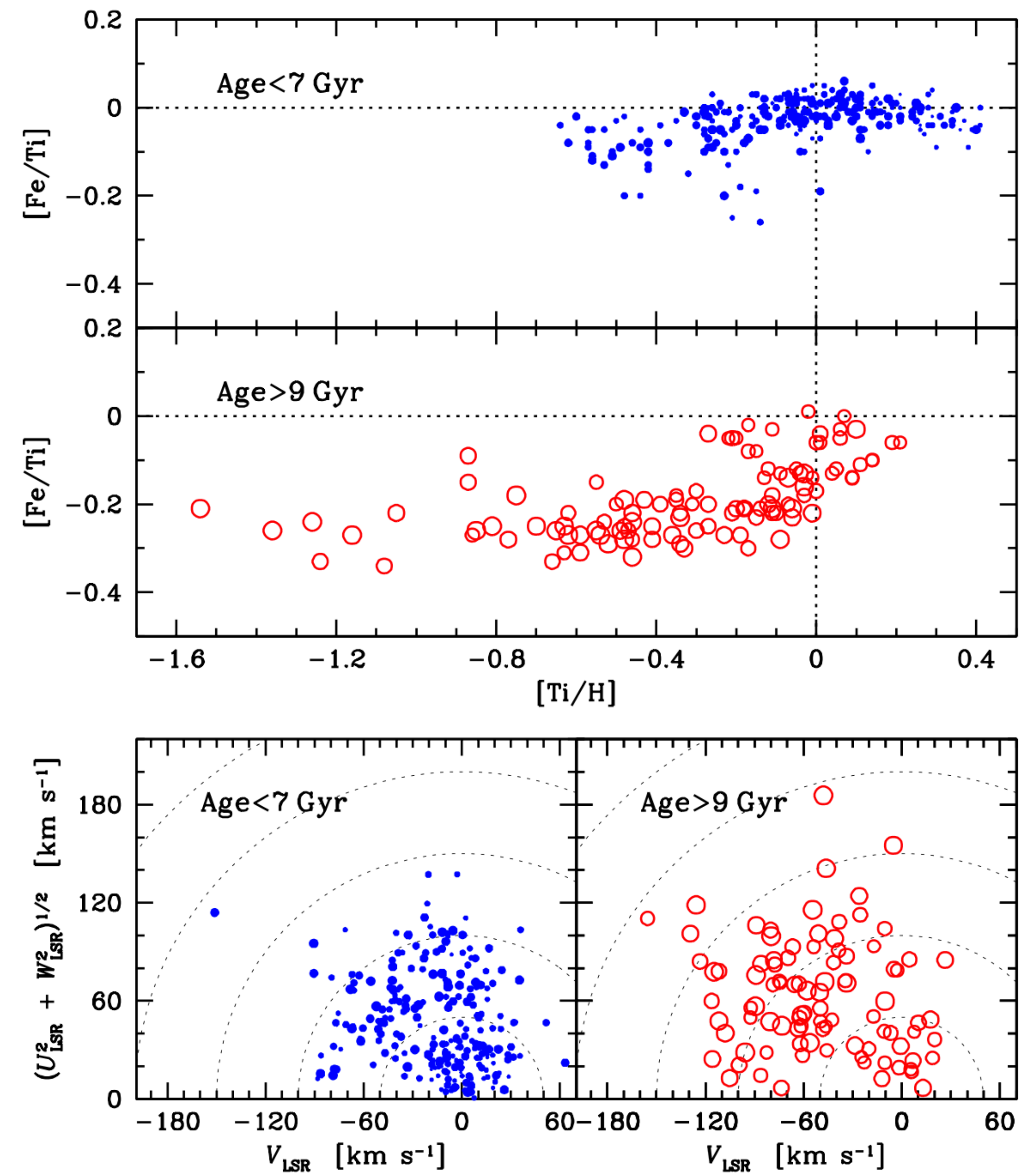
F & G dwarfs in the solar vicinity
High S/N, high resolution sample from Adibekyan et al. 2012 and Nissen & Schuster 2010

Separating the thick and thin disk in alpha abundances is difficult because we don't really understand the interface between the two populations

Definition based on kinematics



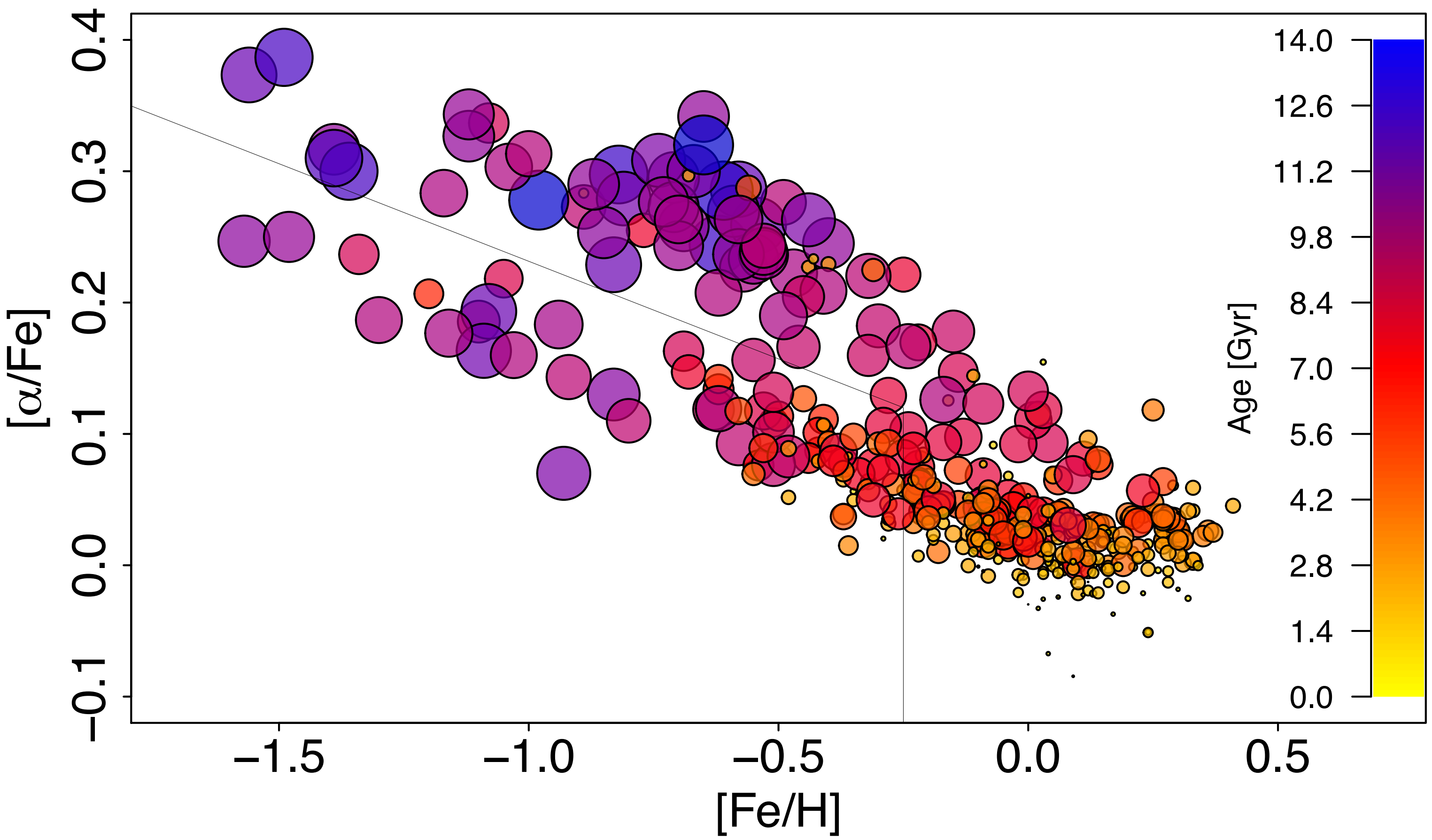
Definition based on age



Bensby et al. 2014

- Thick and thin disk sequences much more cleanly defined when age information is known

Defining stellar populations



Ages from Haywood et al. 2013

Abundances from :
Adibekyan et al 2012,
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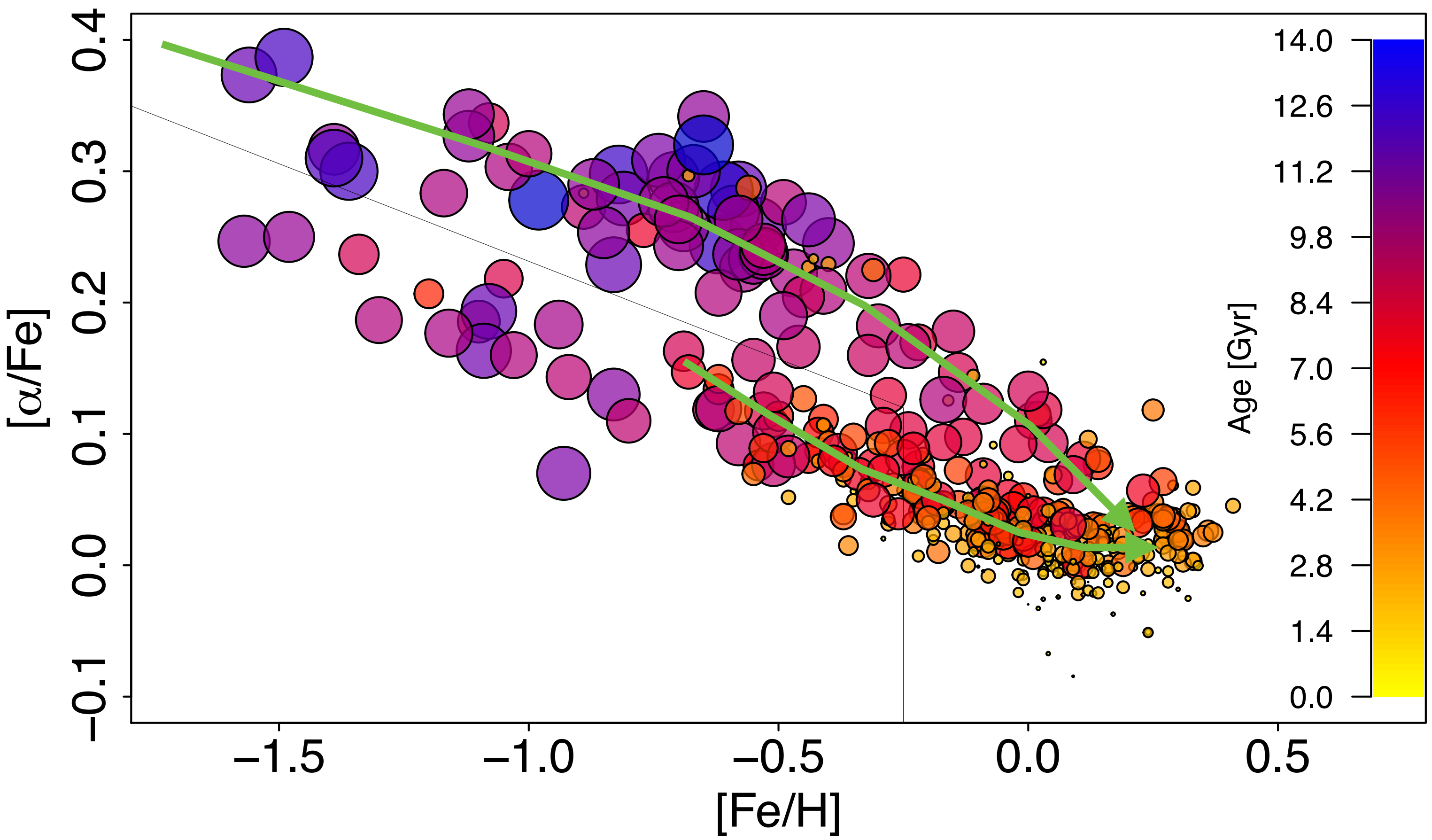
Even with the age information, how do we read the evolution from this plot ?

Defining stellar populations



Ages from Haywood et al. 2013

Abundances from :
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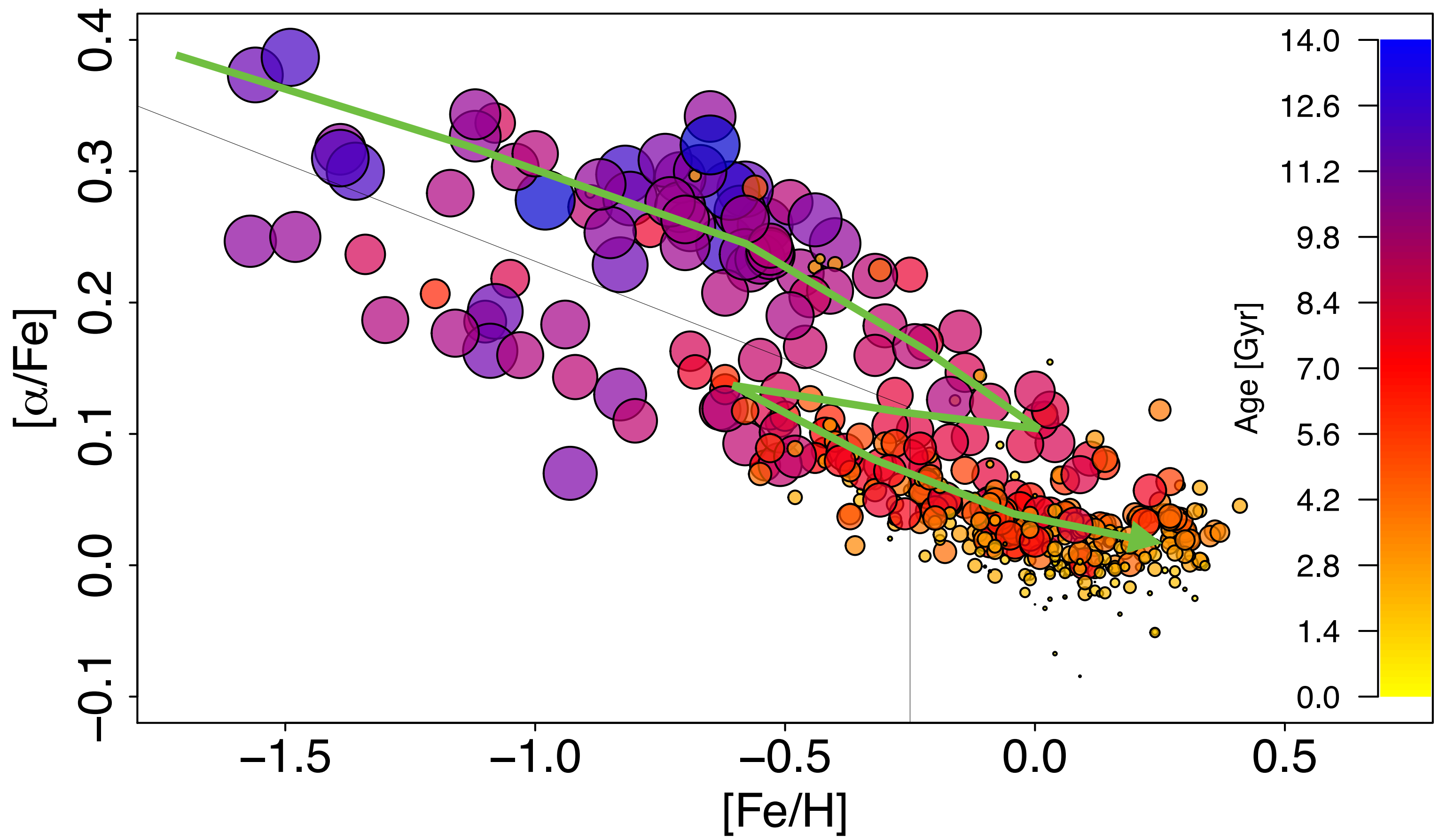
Even with the age information, how do we read the evolution from this plot ?

Two separate evolutions of the thick and thin disks?

Defining stellar populations



Ages from Haywood et al. 2013

Abundances from :
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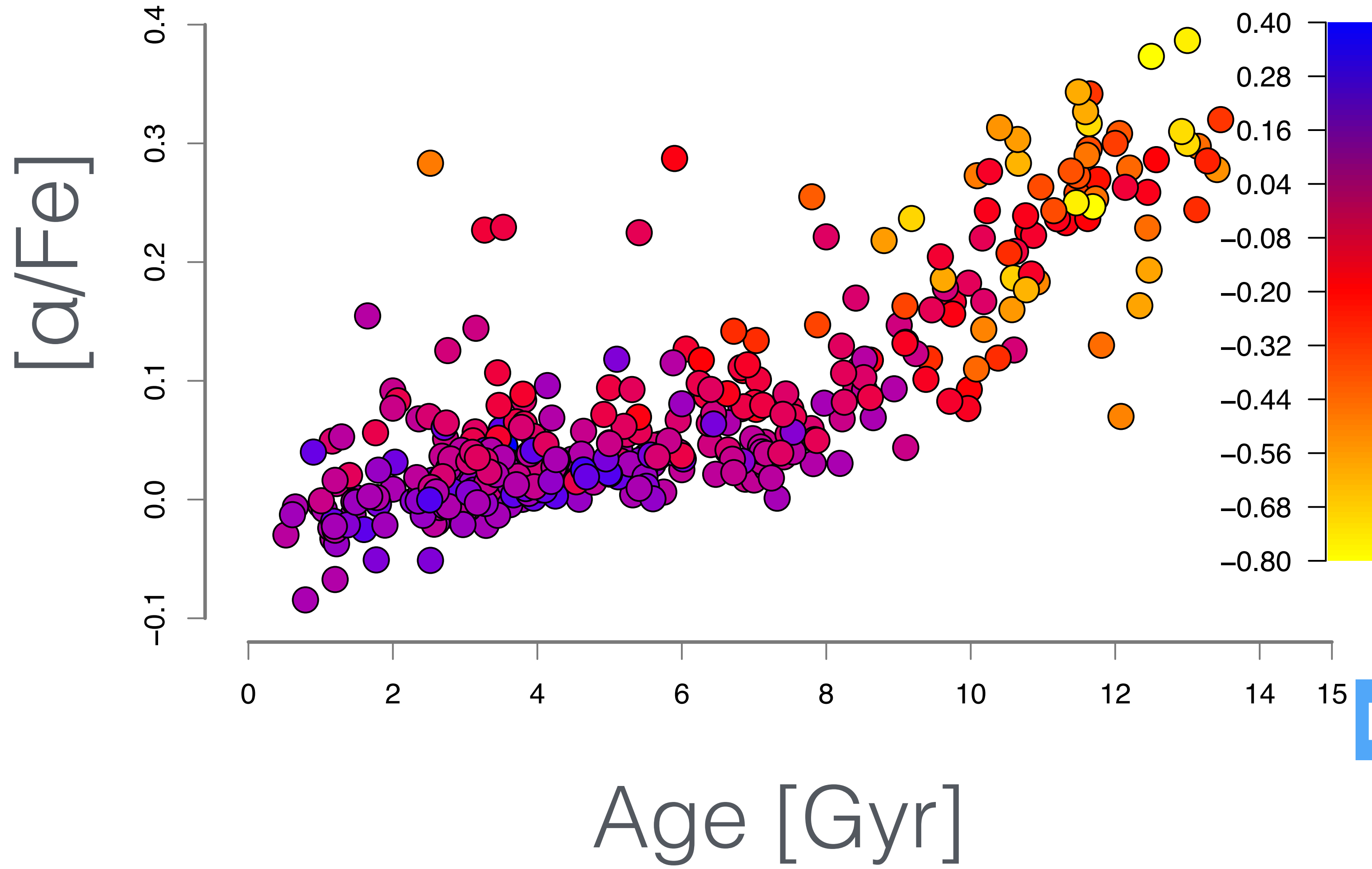
Nissen & Schuster 2010

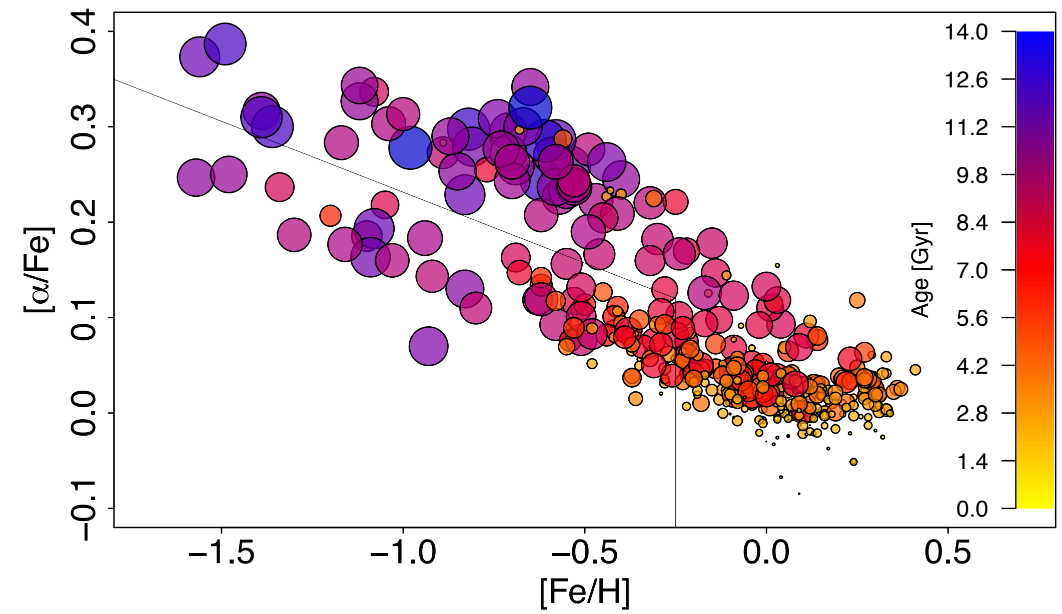
Even with the age information, how do we read evolution from this plot ?

A unique track ?

➡ More information is needed

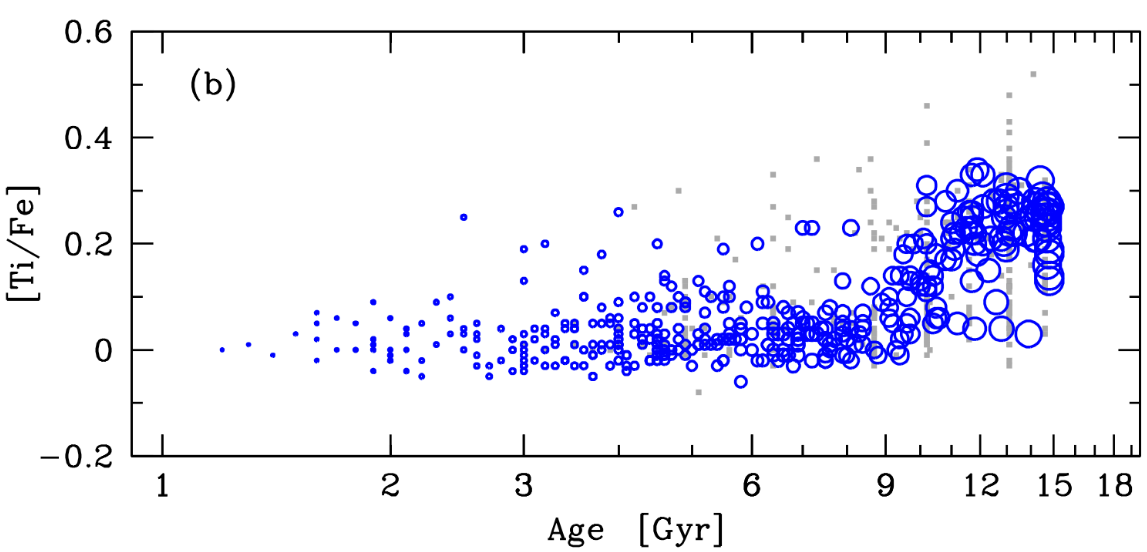
Defining stellar populations

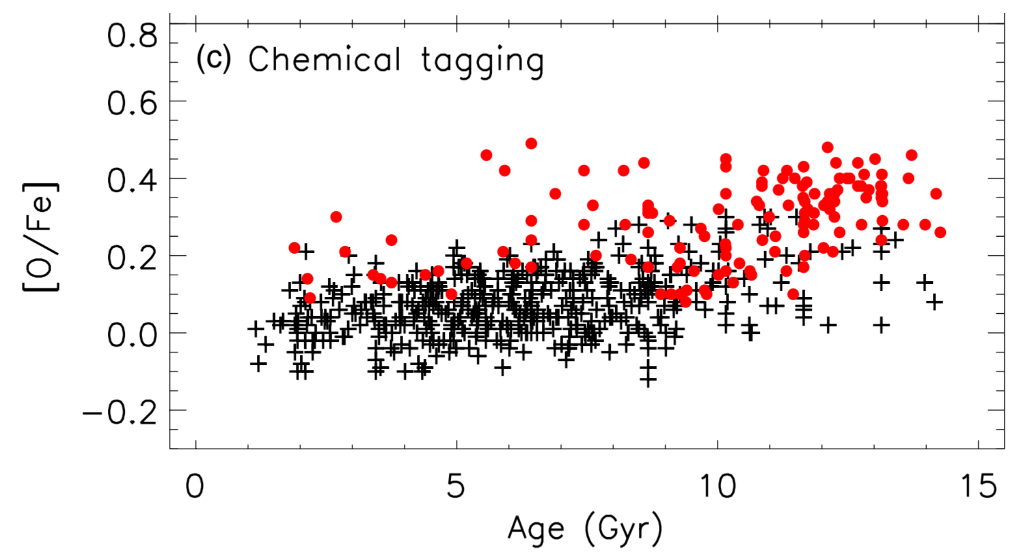




Haywood et al. 2013

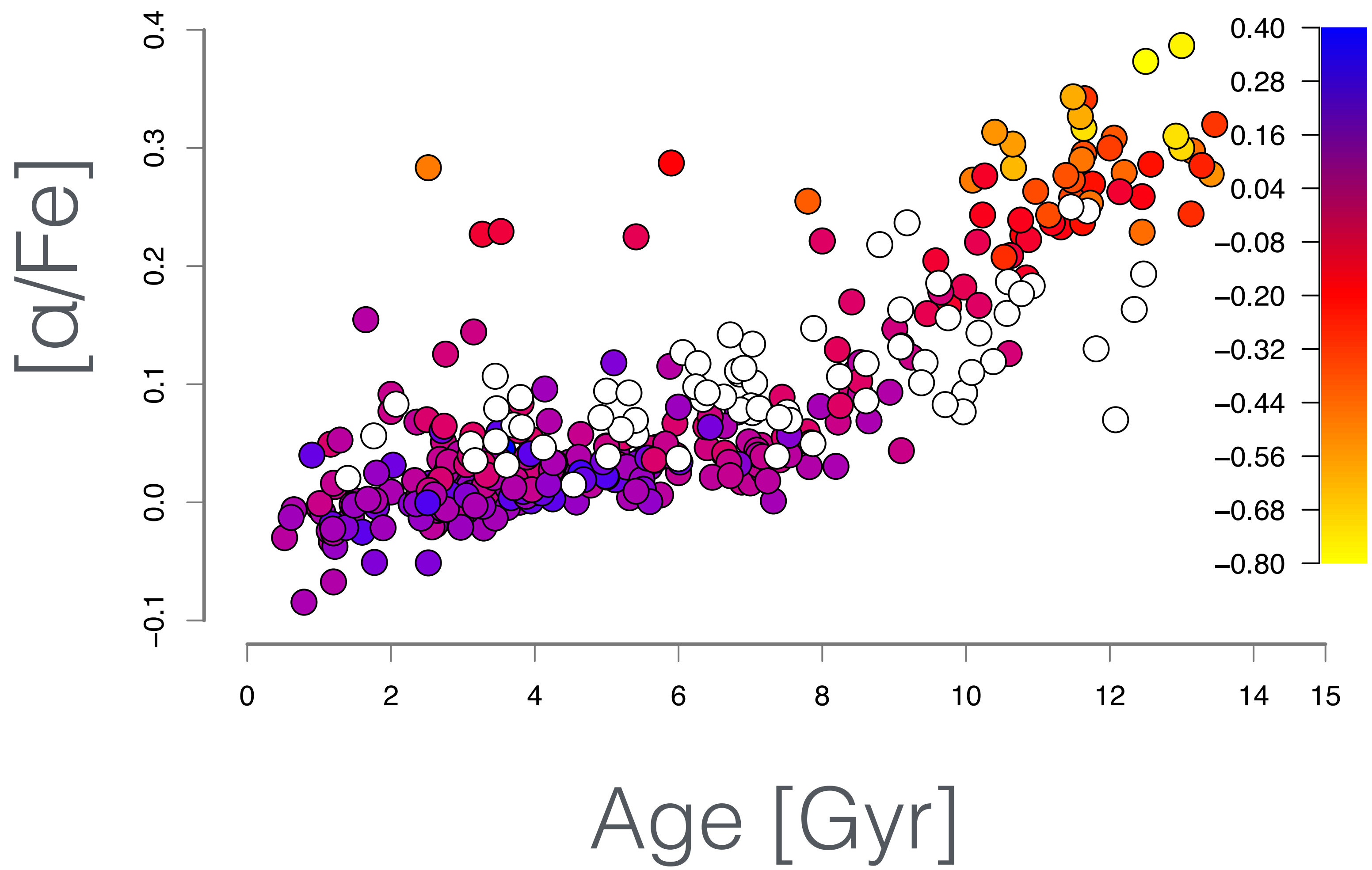
Ramirez et al. 2013

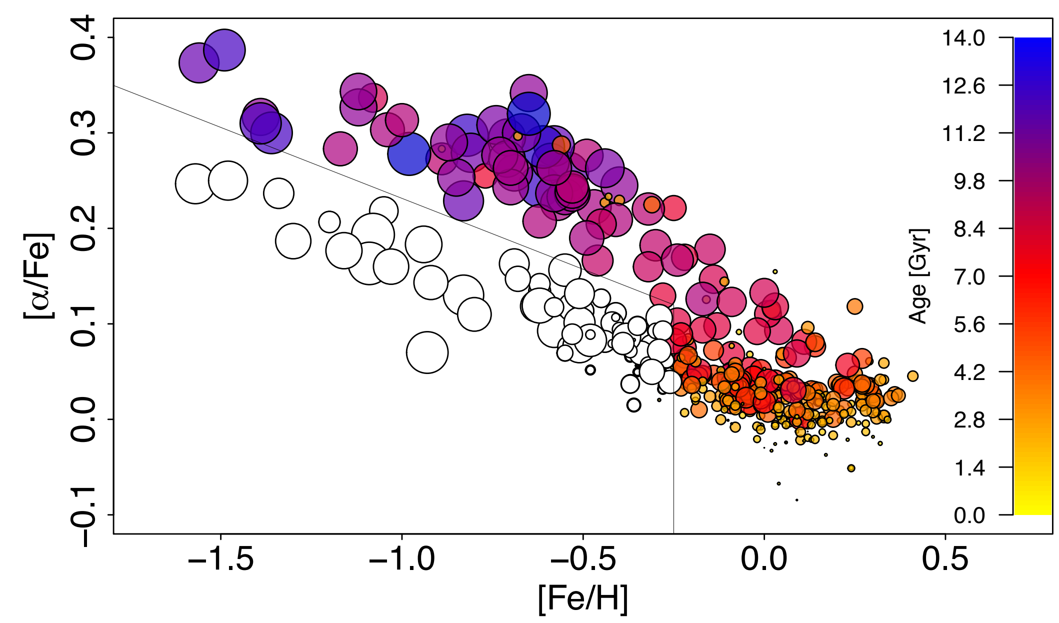


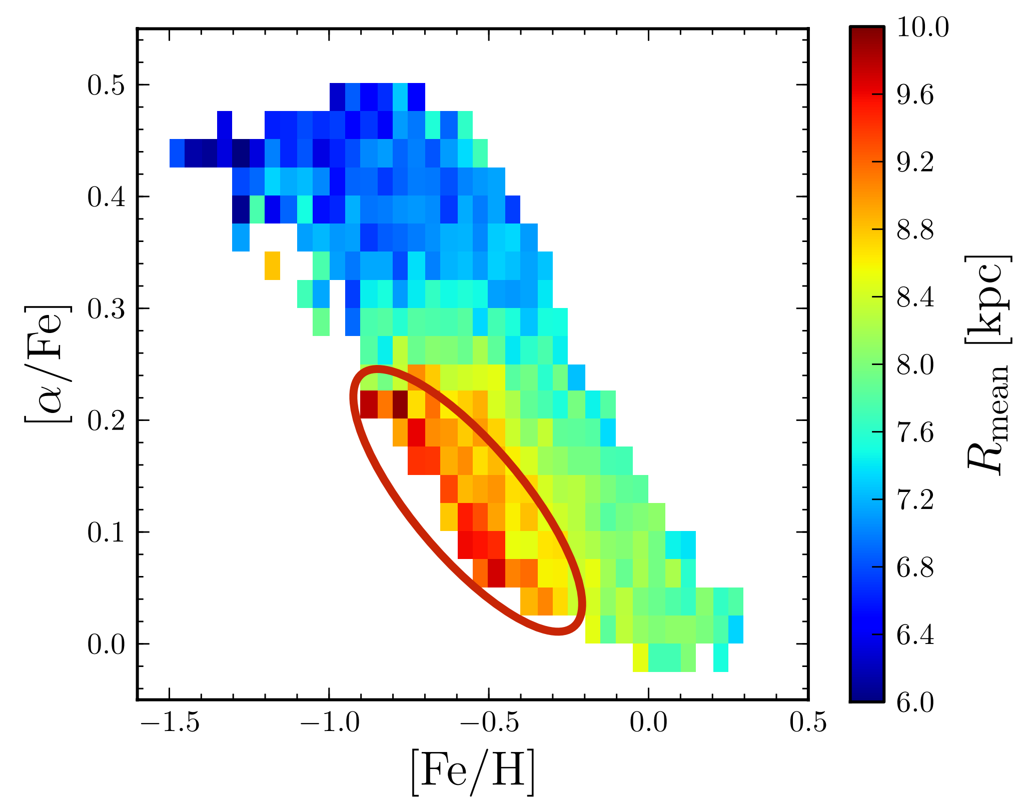


Bensby et al. 2014

Defining stellar populations

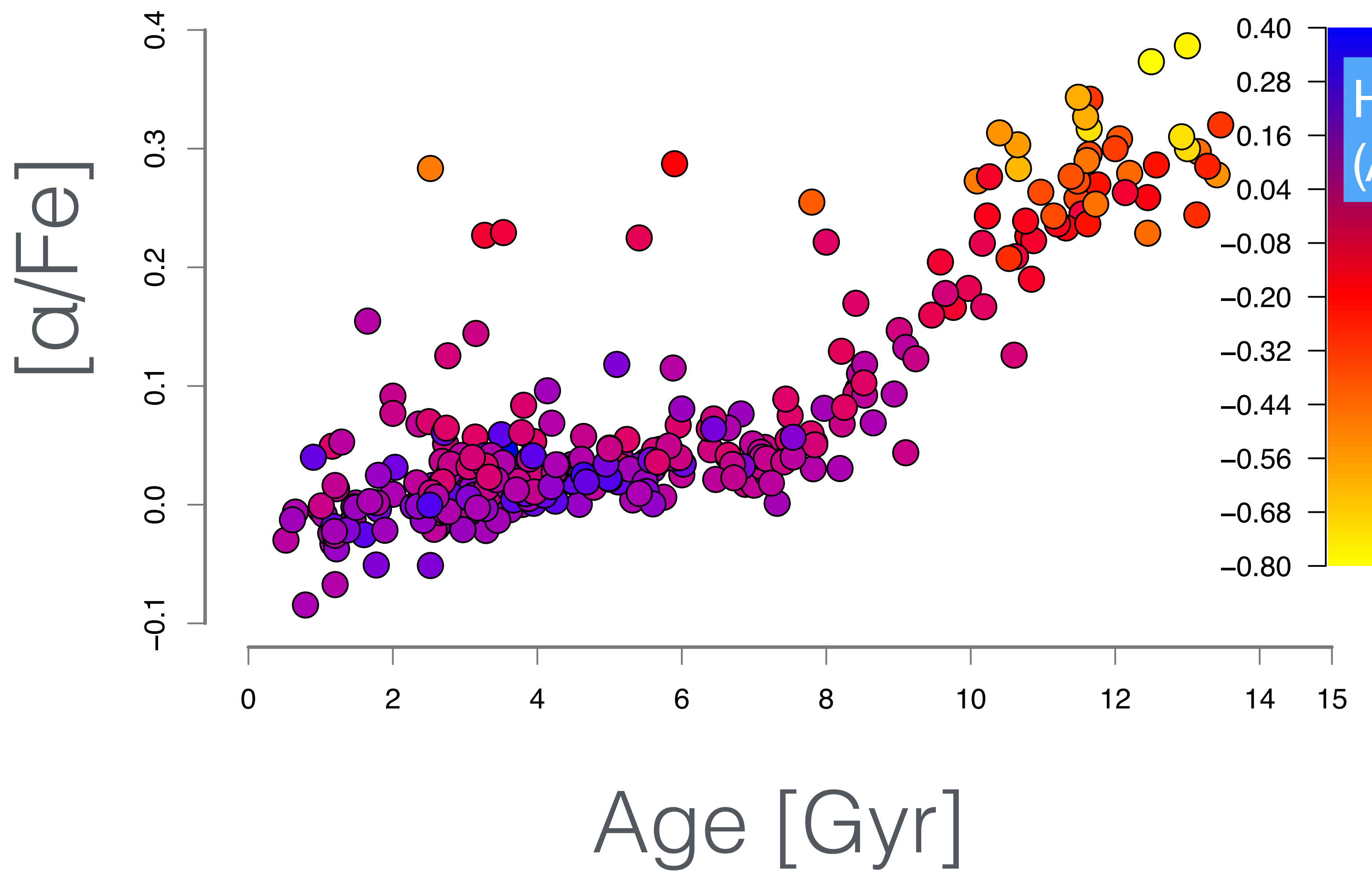






Using extra information:
Metal-poor thin disk stars are not part of the inner disk (R<7kpc):
they are outer disk (R> 9kpc)objects
(Haywood 2008; Bovy et al. 2012)

Defining stellar populations



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

The inner disk sequence

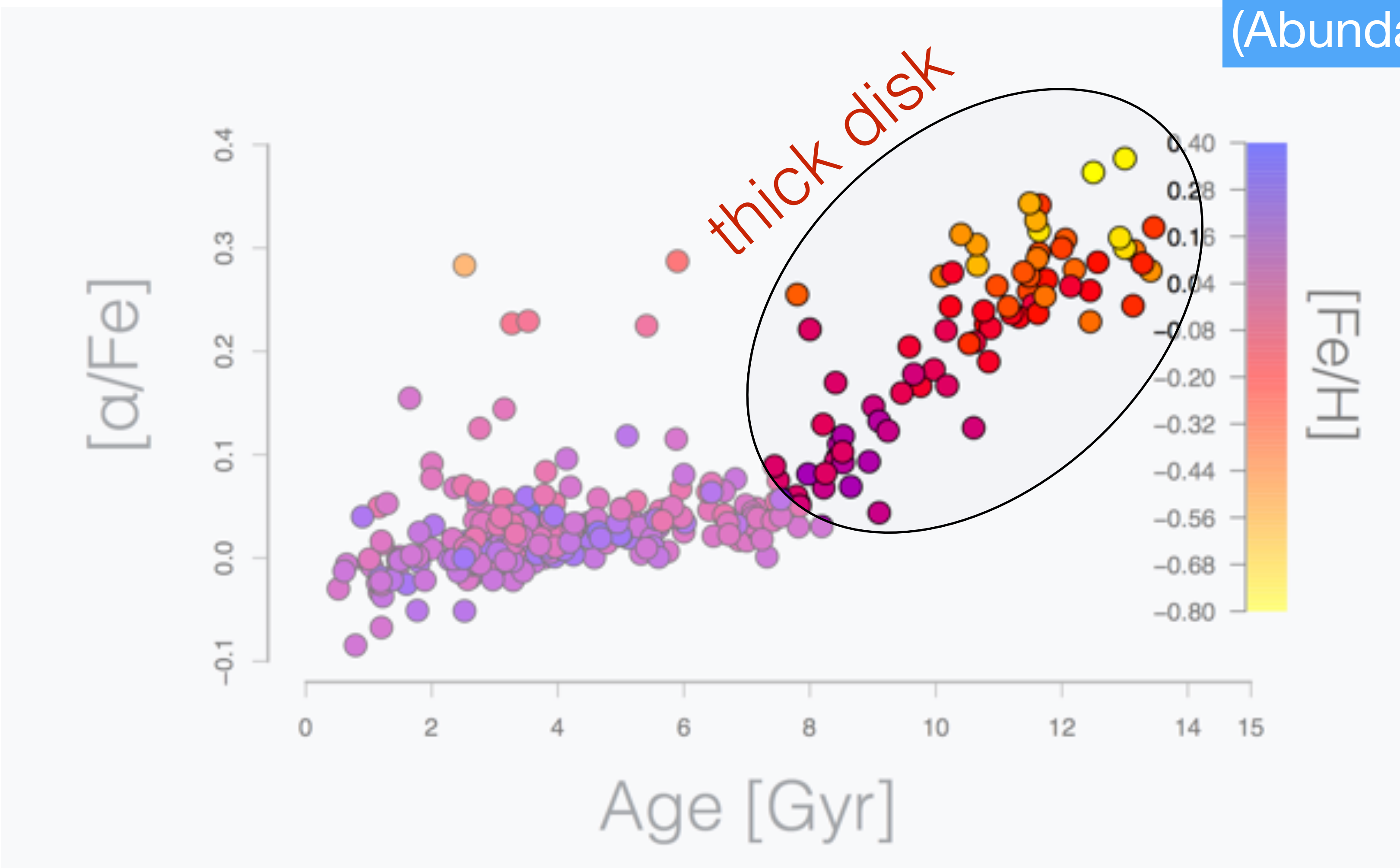
Advantages of using alphas as population tracers:

1/ They correlate with age (Bovy et al. 2013, Haywood et al. 2013)

2/ Their variation with age correlates with the SFR intensity

Defining stellar populations

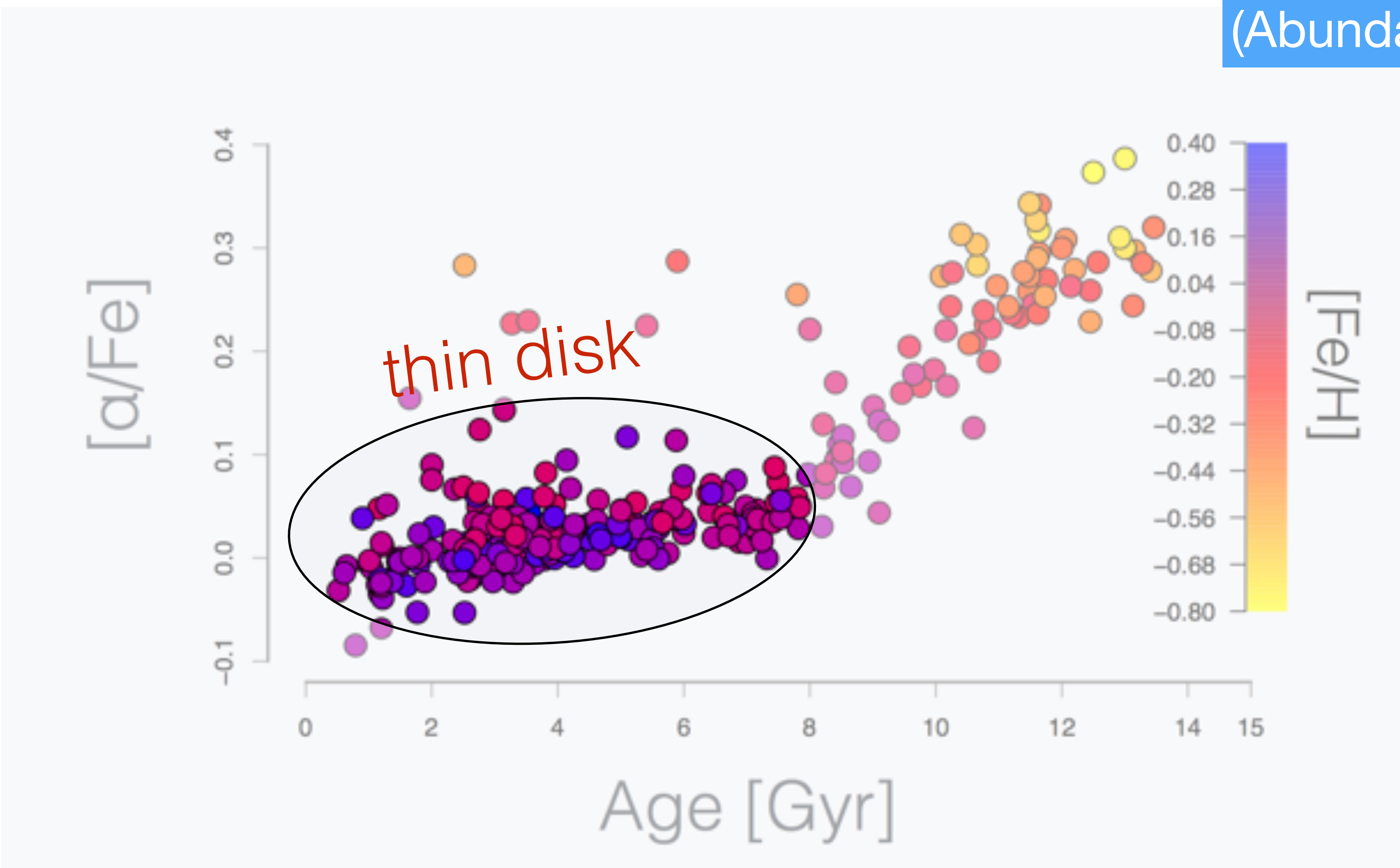
Haywood et al. 2013
(Abundances from Adibekyan et al 2012)



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

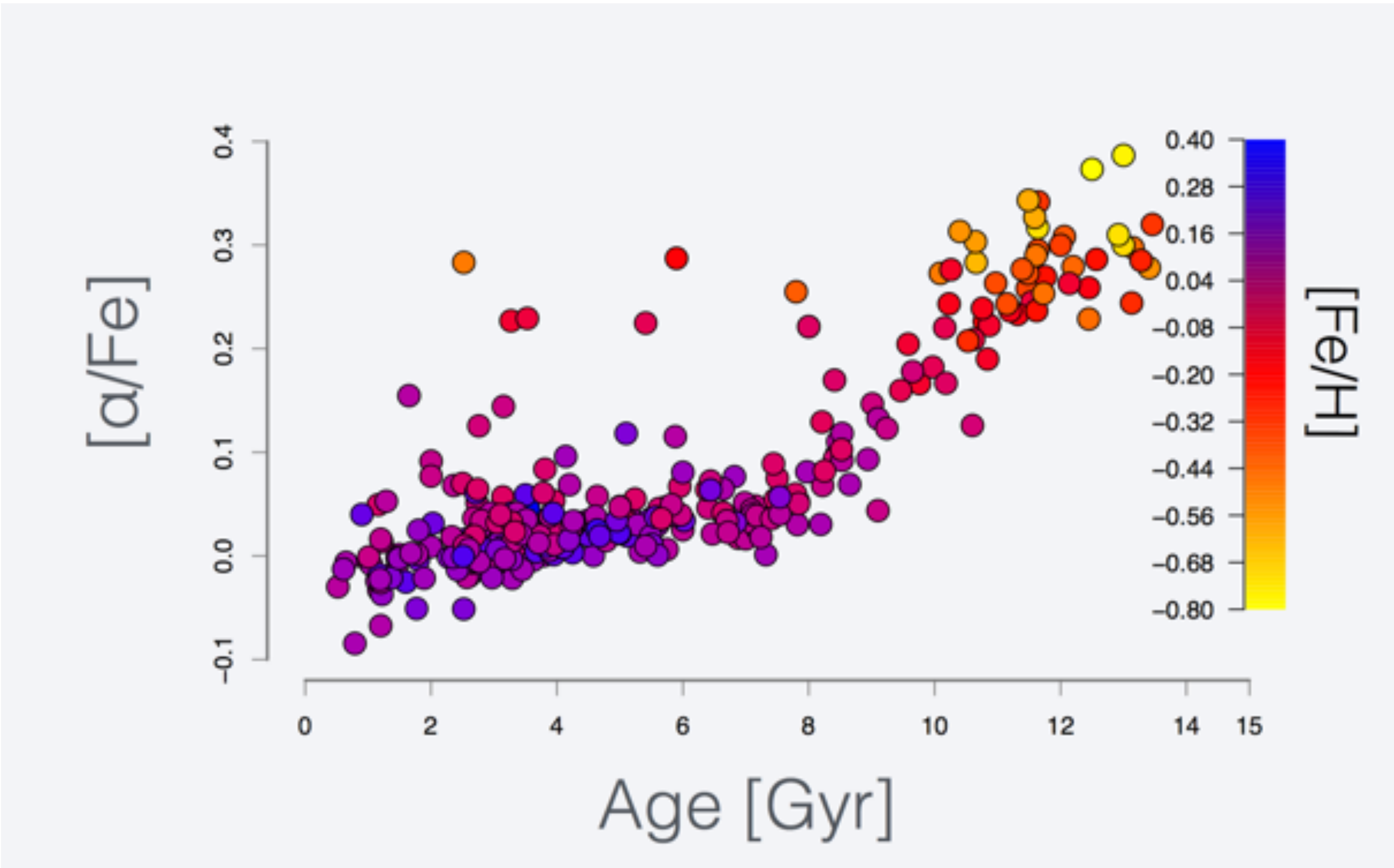
Defining stellar populations

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



- 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***

Defining stellar populations



Different α-enrichment regimes correspond to different SFR intensity

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

Outline.

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4 - Why are thick disks important ?

What model ?

We want huge quantities of gas available for consumption in the first Gyrs of evolution. Why ?

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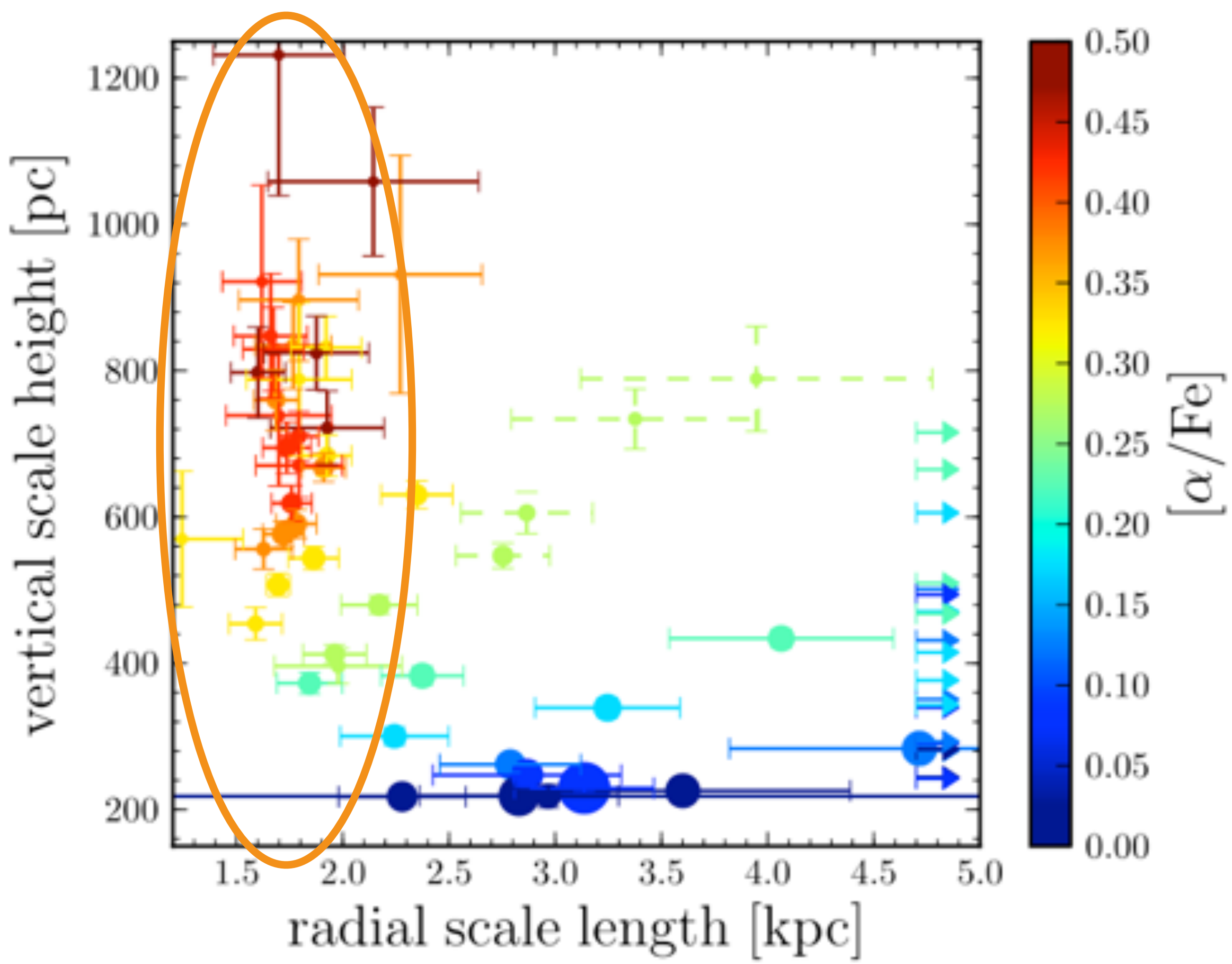
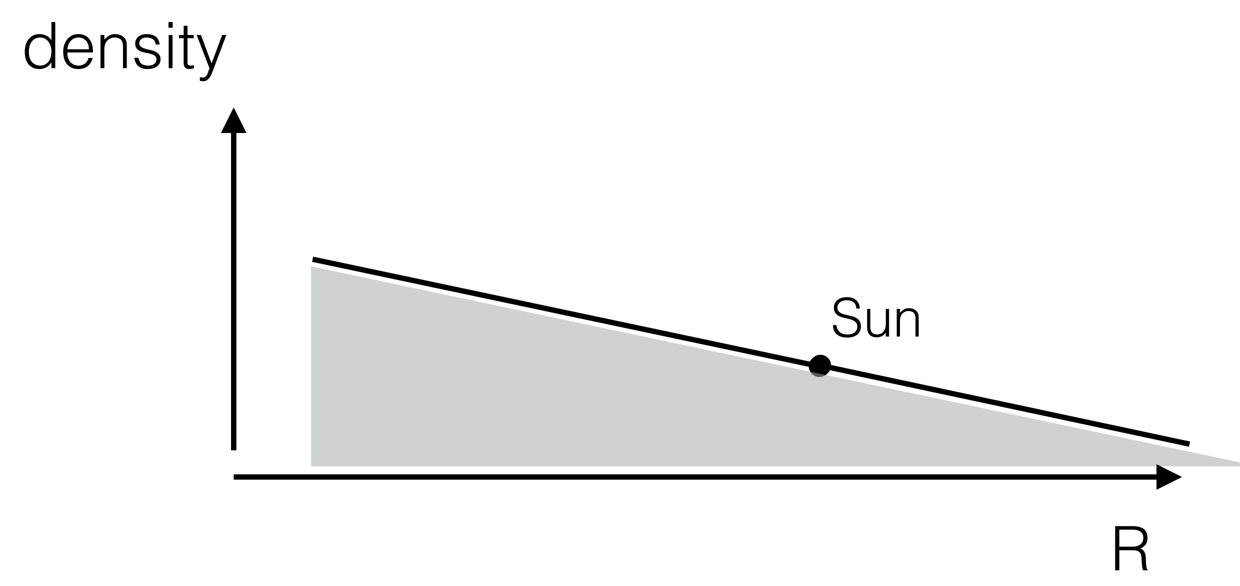


Vertical scale height versus radial scale length, color coded by [alpha/Fe]
SEGUE data, Bovy et al. 2012



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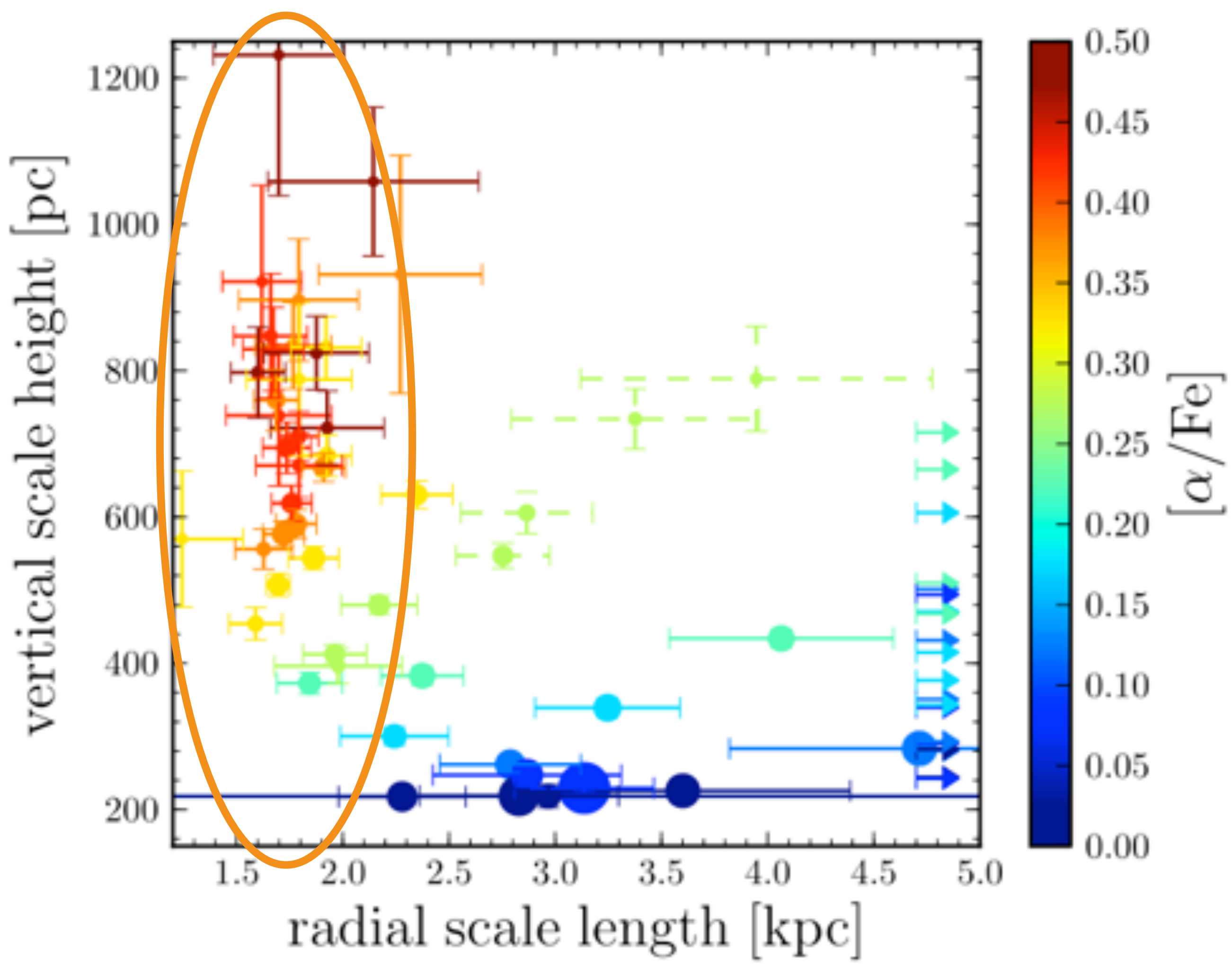
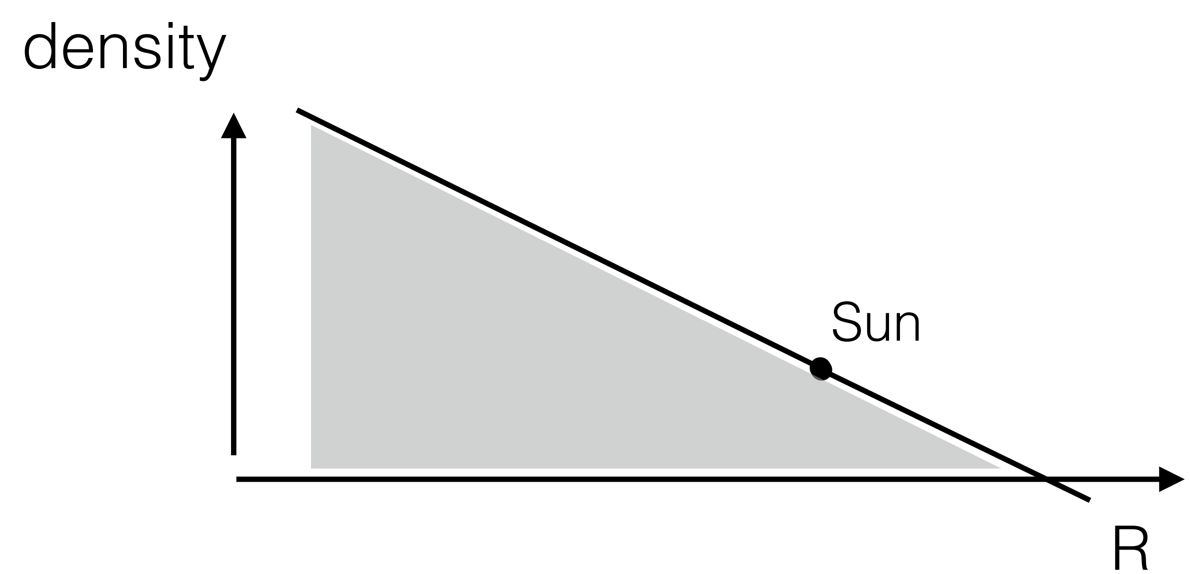


Vertical scale height versus radial scale length, color coded by [alpha/Fe]
SEGUE data, Bovy et al. 2012

The thick disk has a short scale length



- it implies that it is massive

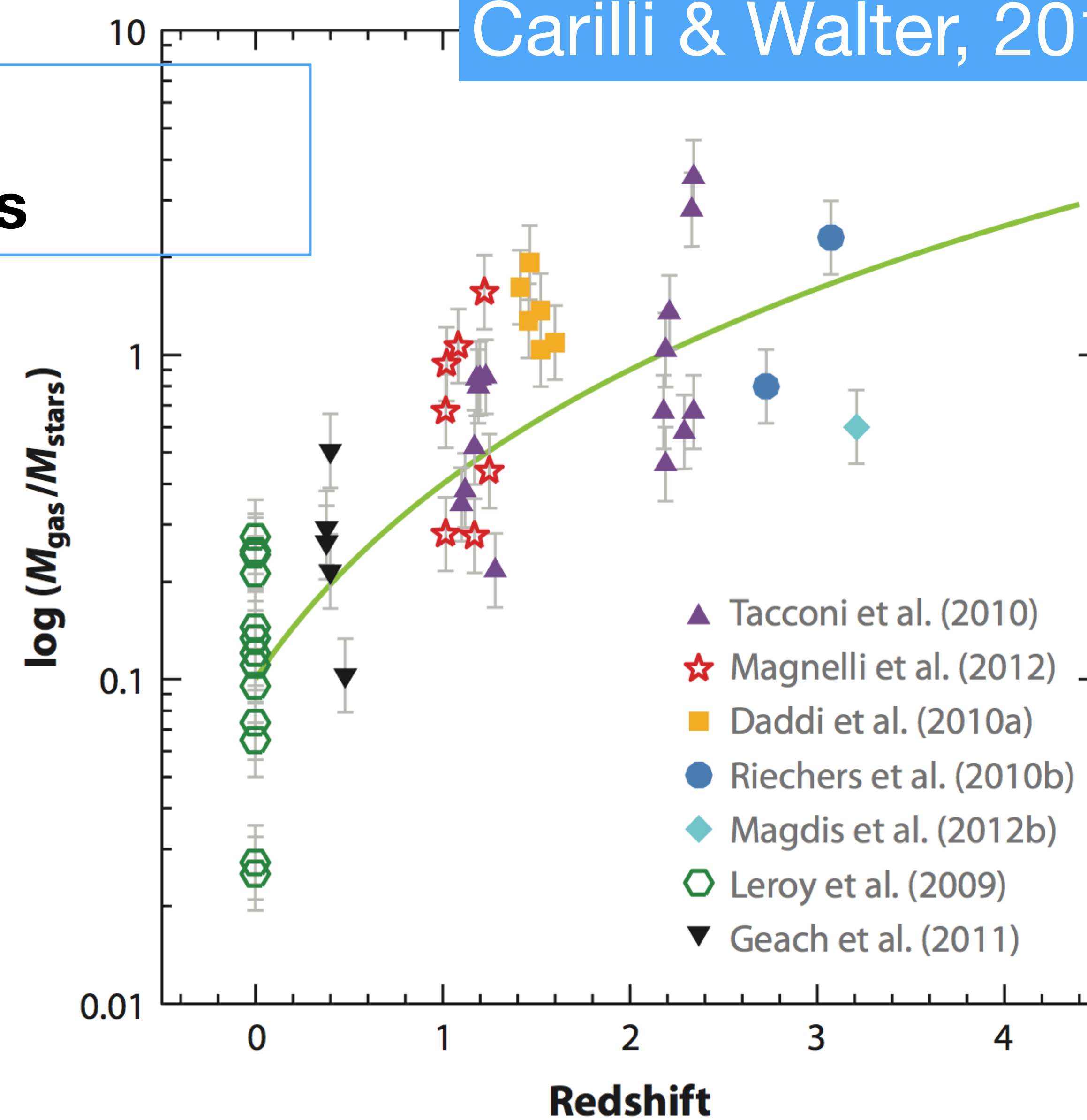
The thick disk could be as massive as the thin disk

What model ?

We want huge quantities of gas available for consumption in the first Gyrs of evolution. Why ?

Carilli & Walter, 2013

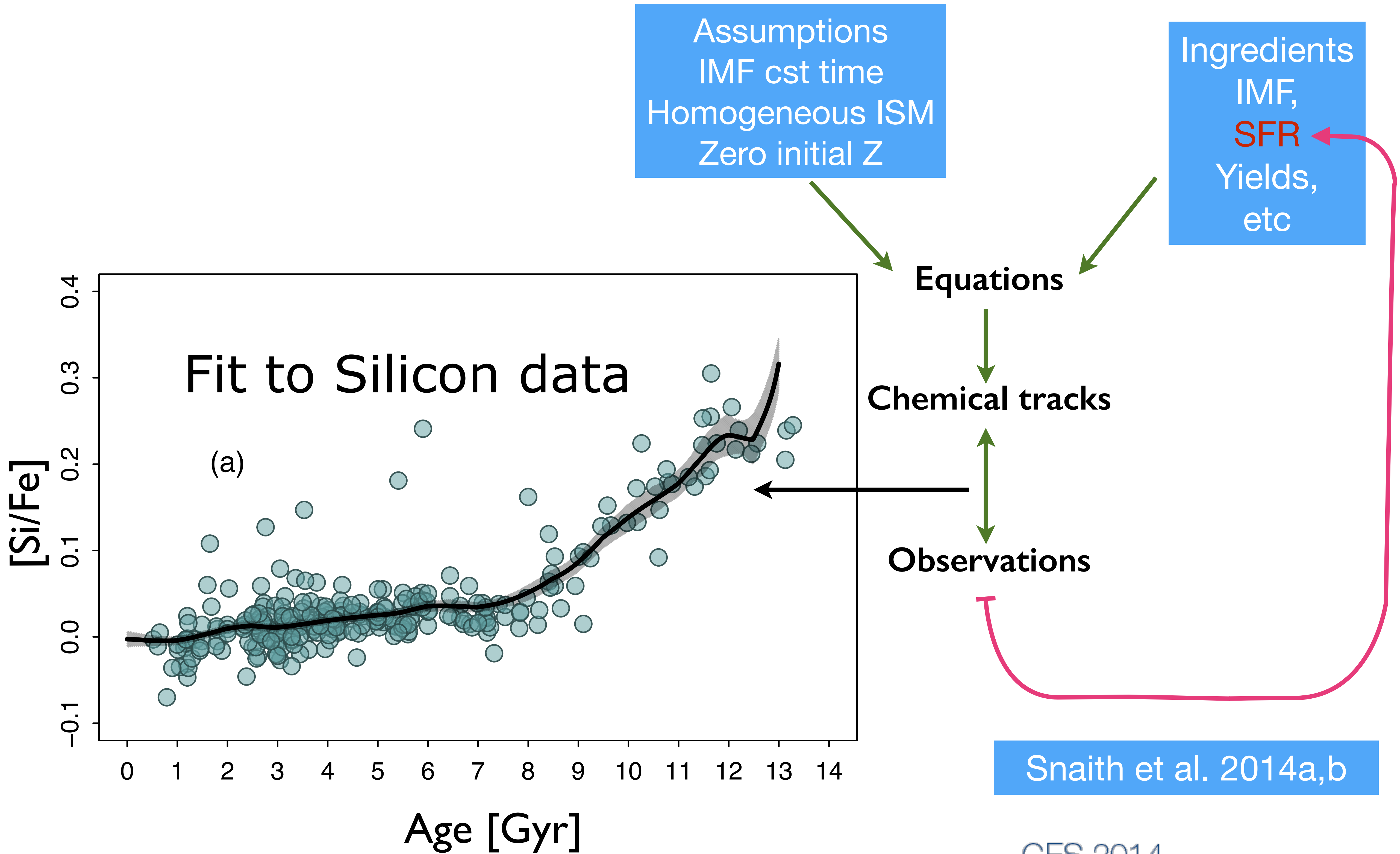
Disks at high z (z>2) have a **high (≳50%) fraction of gas**



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

The model that maximizes the amount of gas at early times is the Closed-box

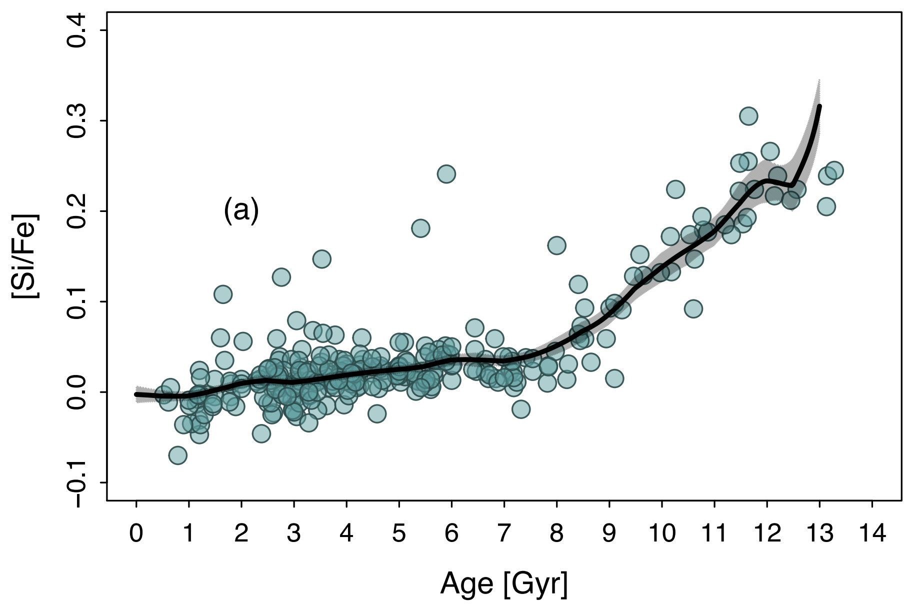
Recovering the SFH from the data…



Snaith et al. 2014a,b

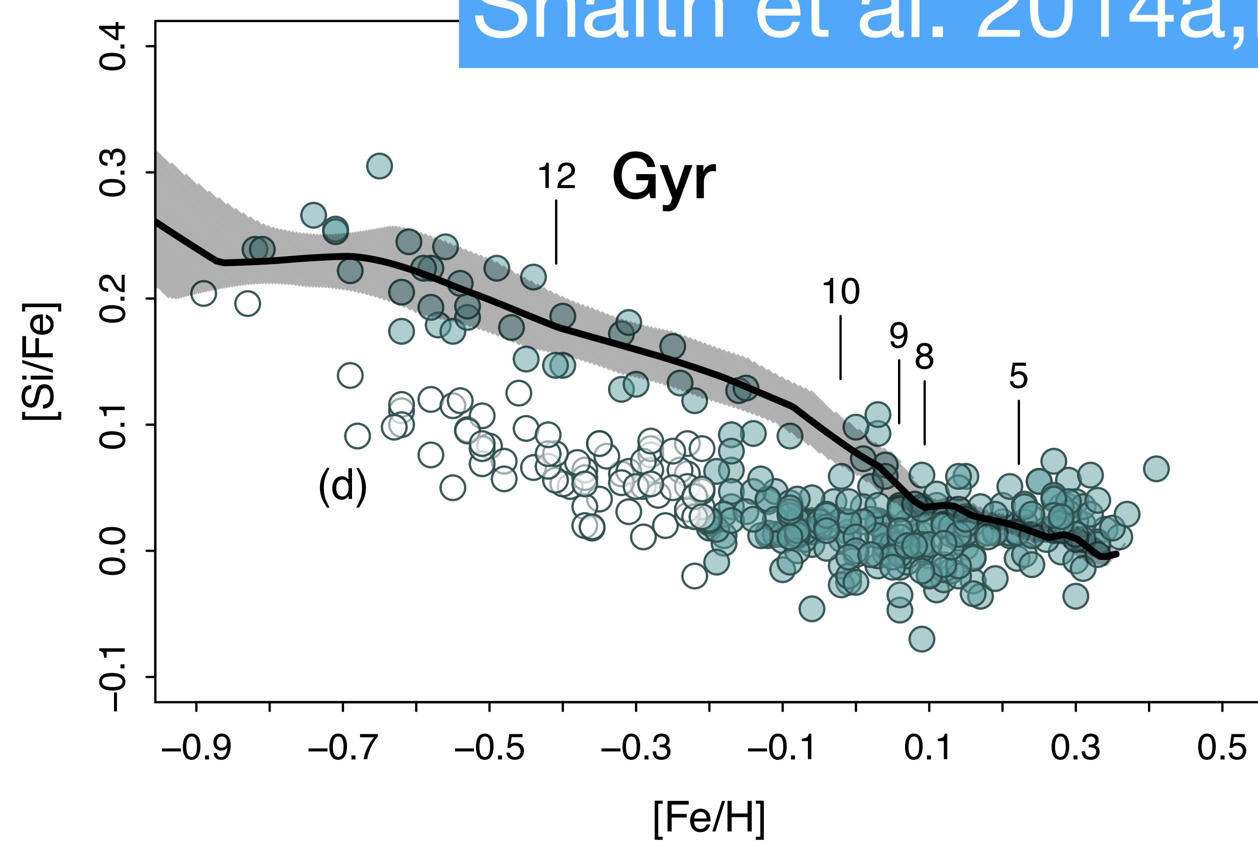
The Star Formation History of the disk

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



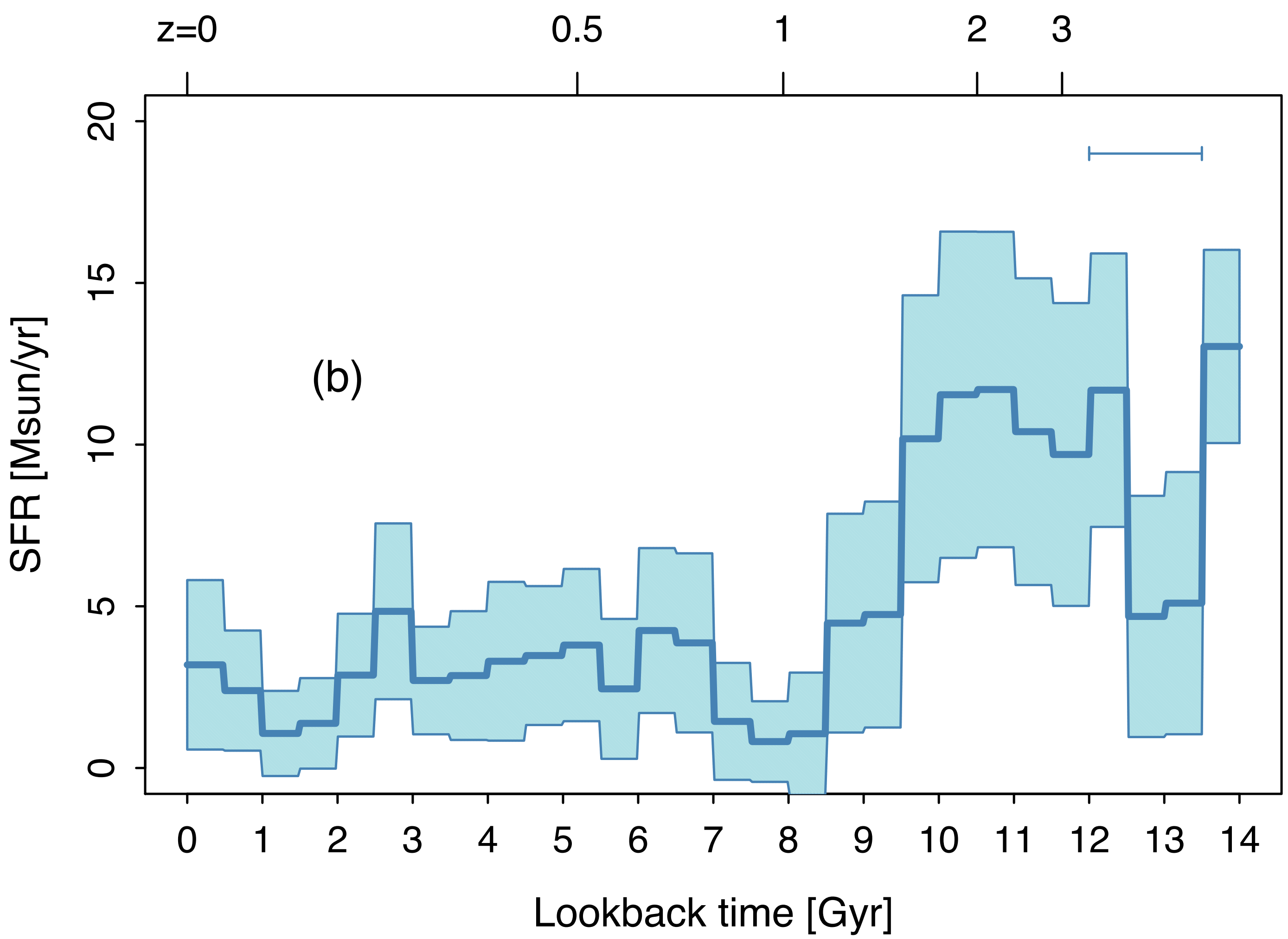
... **a good match (not a fit !)** to the [Si/Fe]-[Fe/H] distrib.

Snaith et al. 2014a,b



the thick disk sequence is a temporal sequence

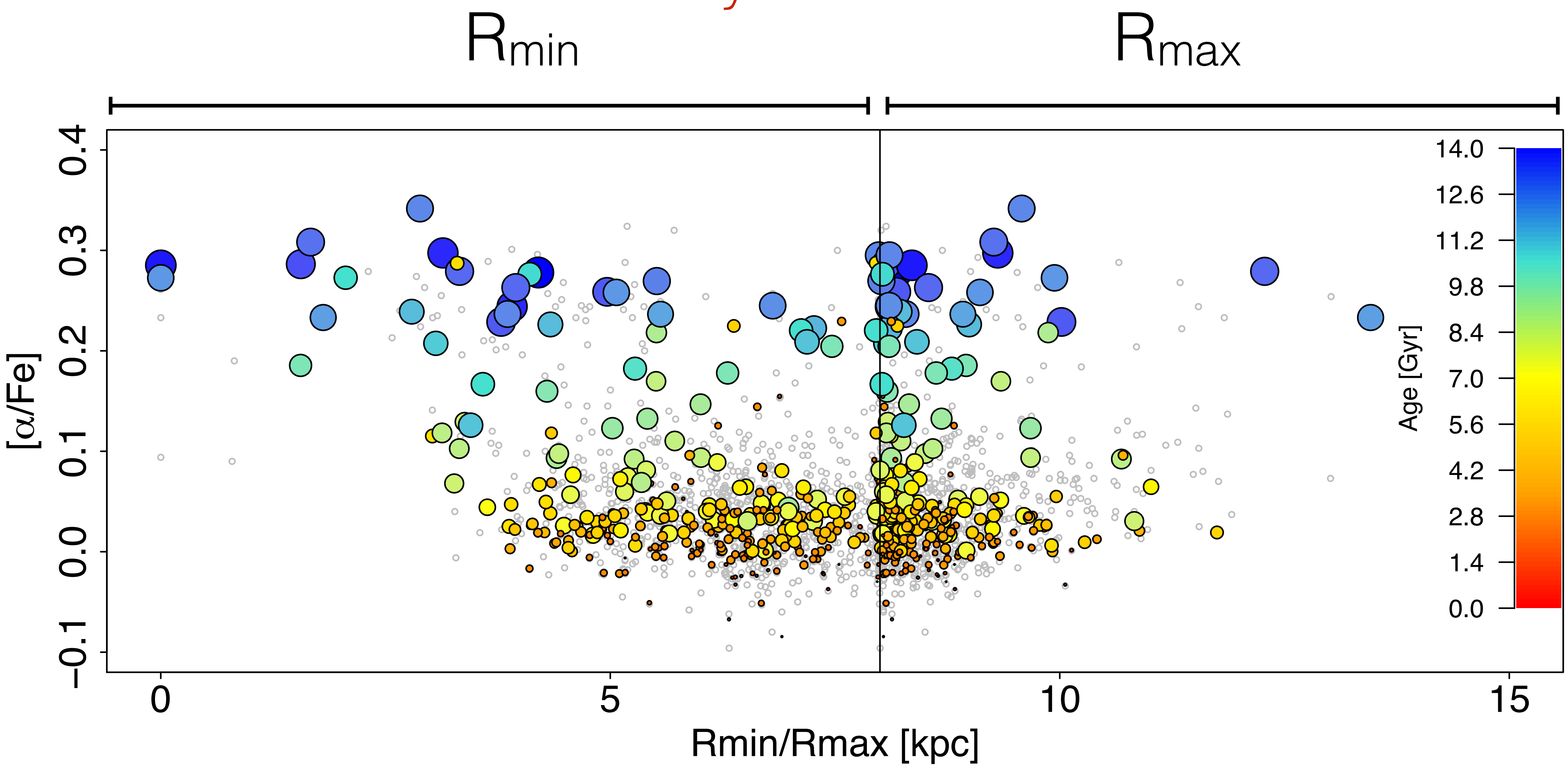
The Star Formation History of the disk



Snaith et al. 2014a
Snaith et al. just 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

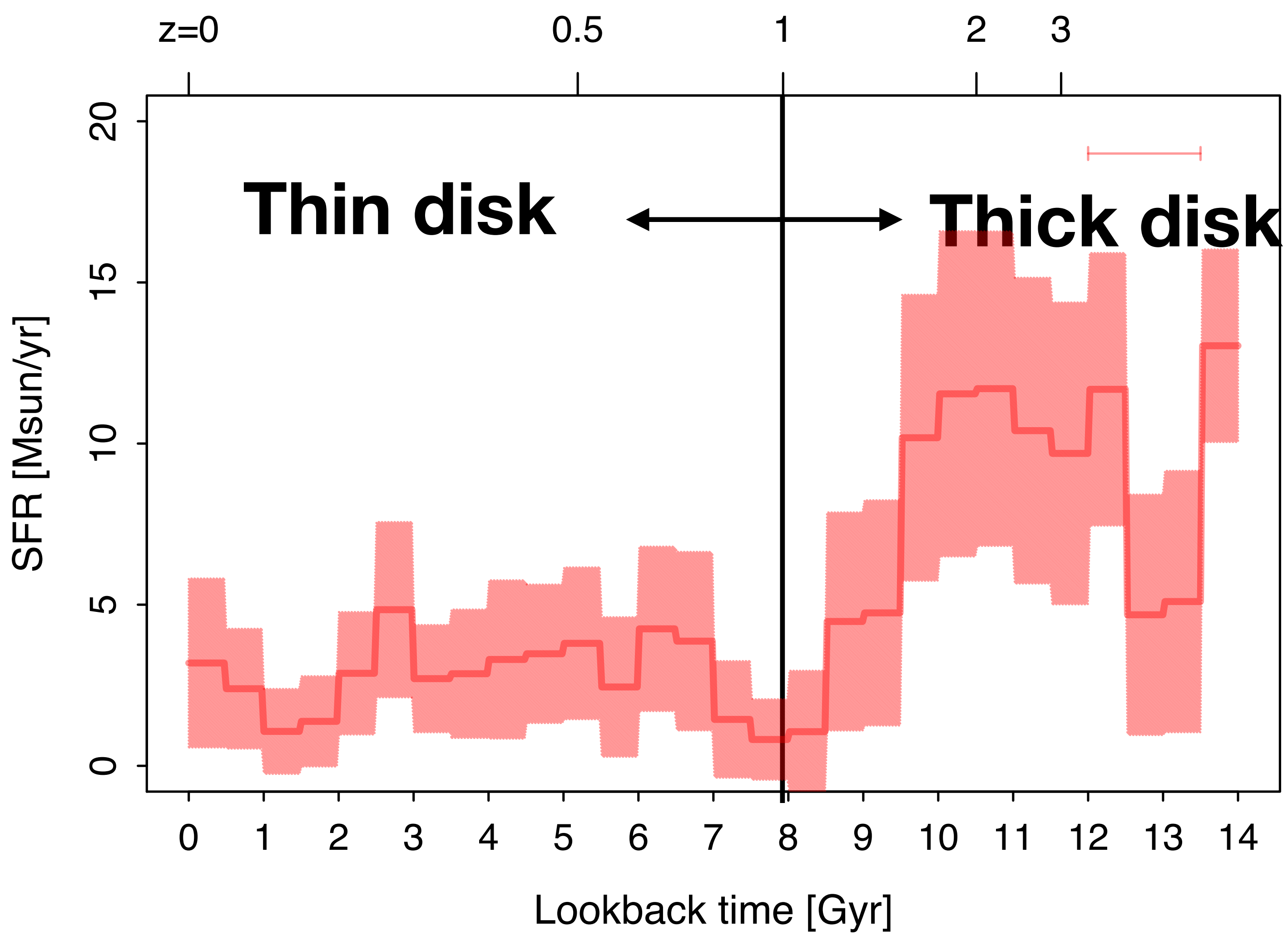


High-α stars pericentres reach R<2kpc

- 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

The main characteristics of the MW star formation history



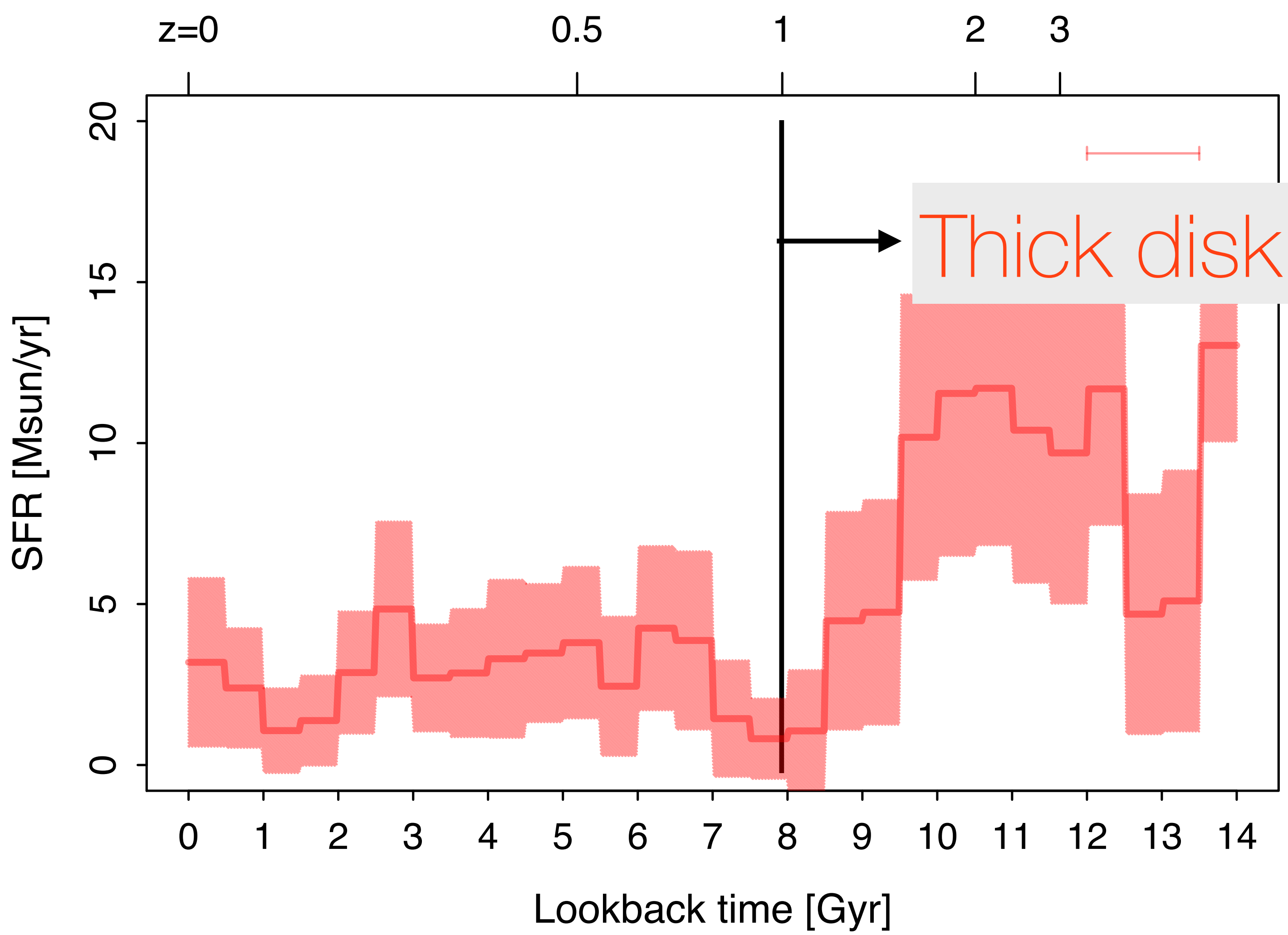
Two main periods of SFR corresponding to:

1/ 13.5-8.5 Gyr :
thick disk at SFR ∼12 M⊙/yr
2/ 7.5 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

The main characteristics of the MW star formation history



Thick disk ~ 50% of stellar mass

Consistent with :

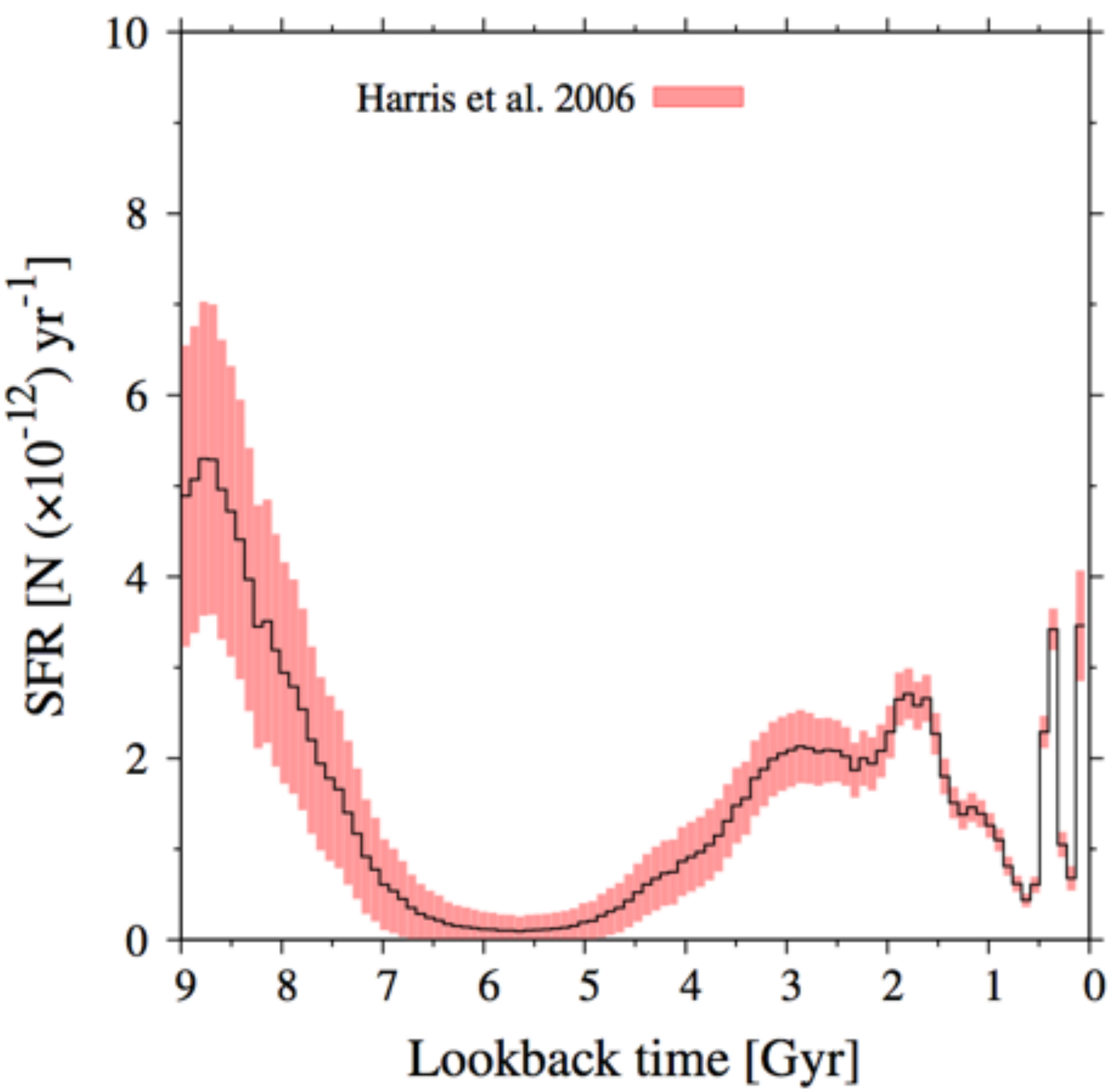
1/ the mass estimate for a thick disk scale length of ~ 2 kpc

2/ the finding that most of the mass in the bulge is due to the thick disk
See talk by P. Di Matteo tomorrow

The Star Formation History of the disk

Is the dip in the SFH real ?

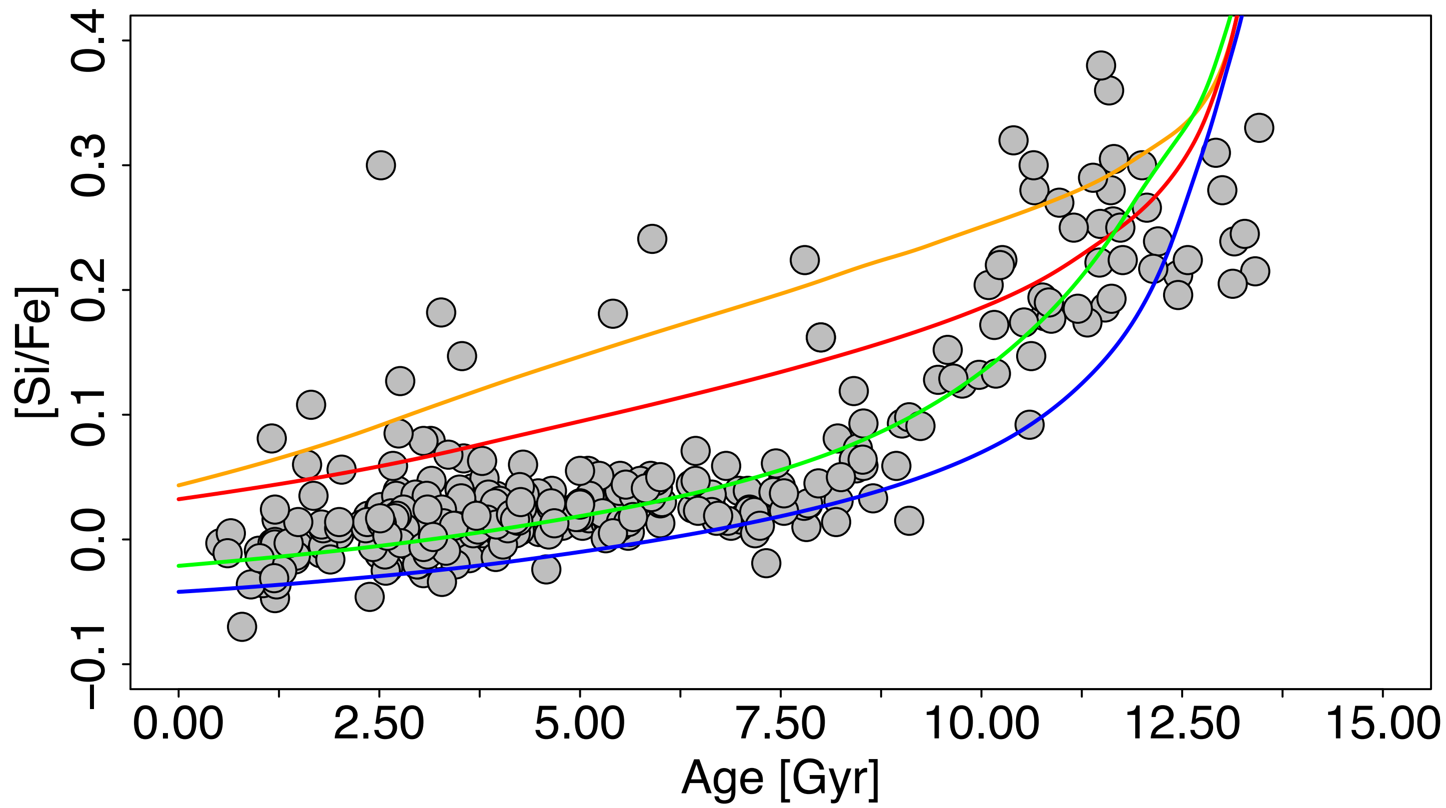
The age scale is different, but the SFHs are qualitatively similar

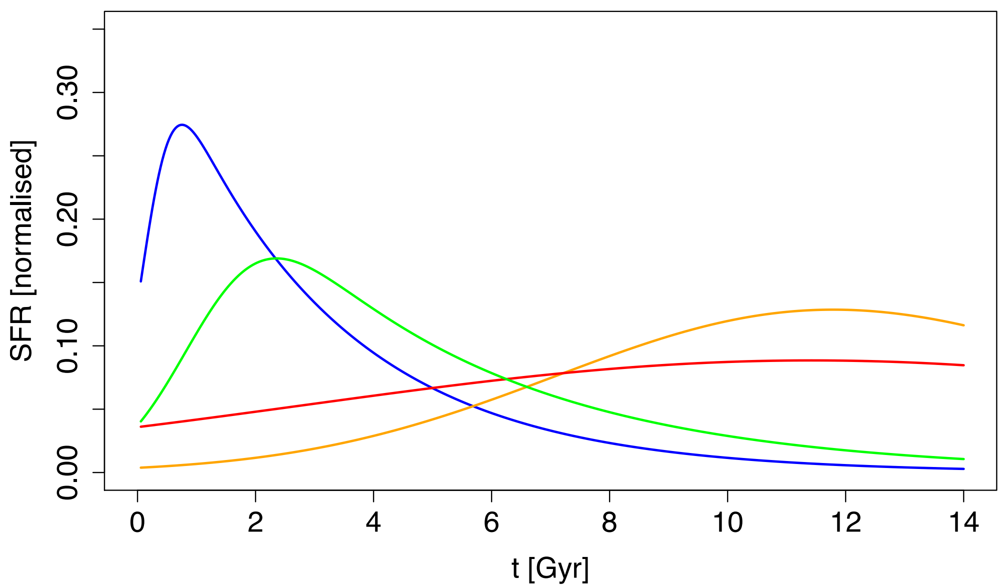


A dip is also present in the SFH derived from the WDLF

SFH from the WD luminosity function, Rowell 2012

The Star Formation History of the disk





Star formation in the thick disk was an homogeneous and general process, Haywood et al. *submitted*

- In agreement with the lack of gradient in the thick disk

SEGUE: Cheng et al. 2012

GES: Recio-Blanco et al. 2014, Mikolaitis et al. 2014

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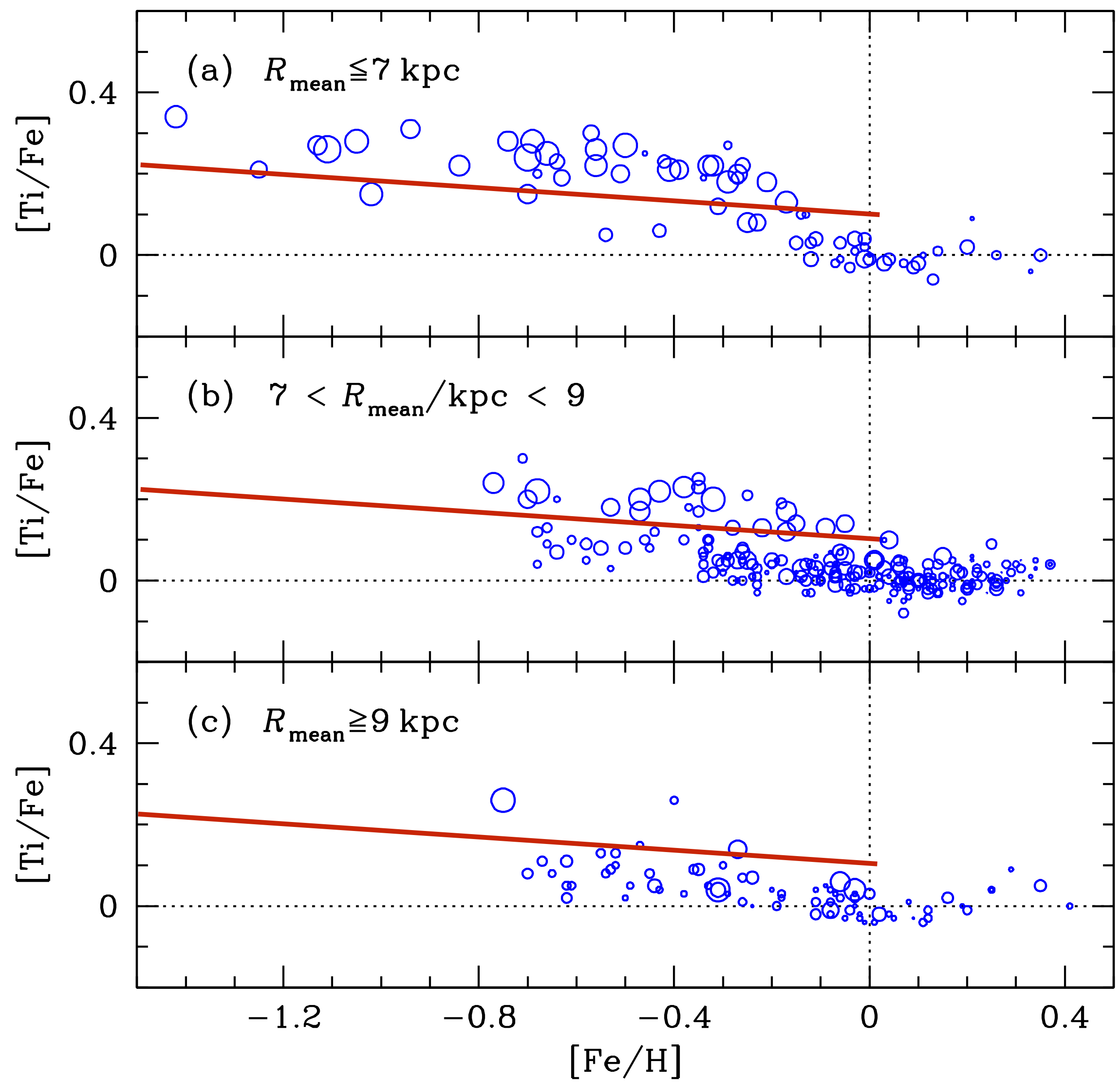
4 - Why are thick disks important ?

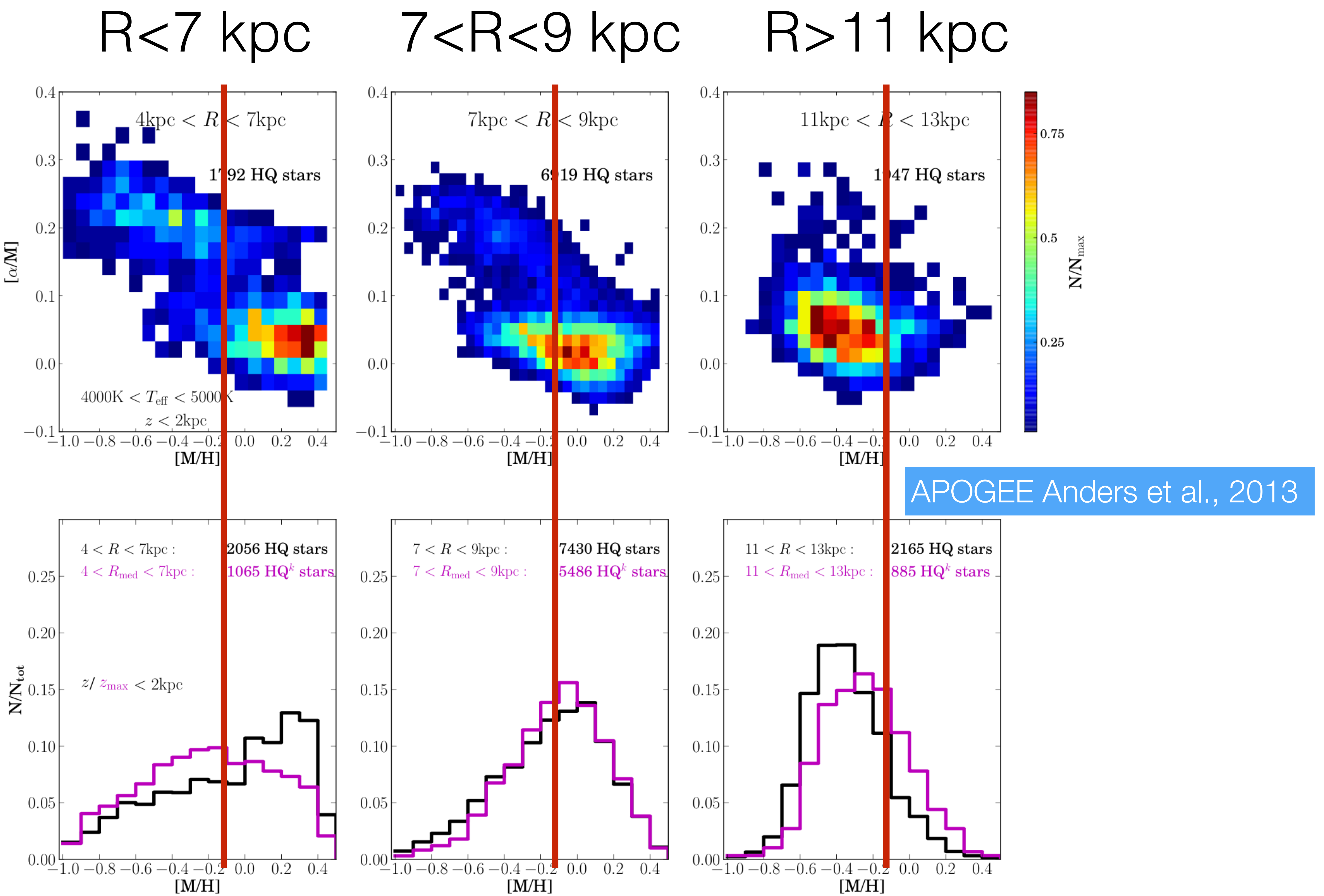
the structuration of the disk is radial, not vertical

Bensby et al. 2014



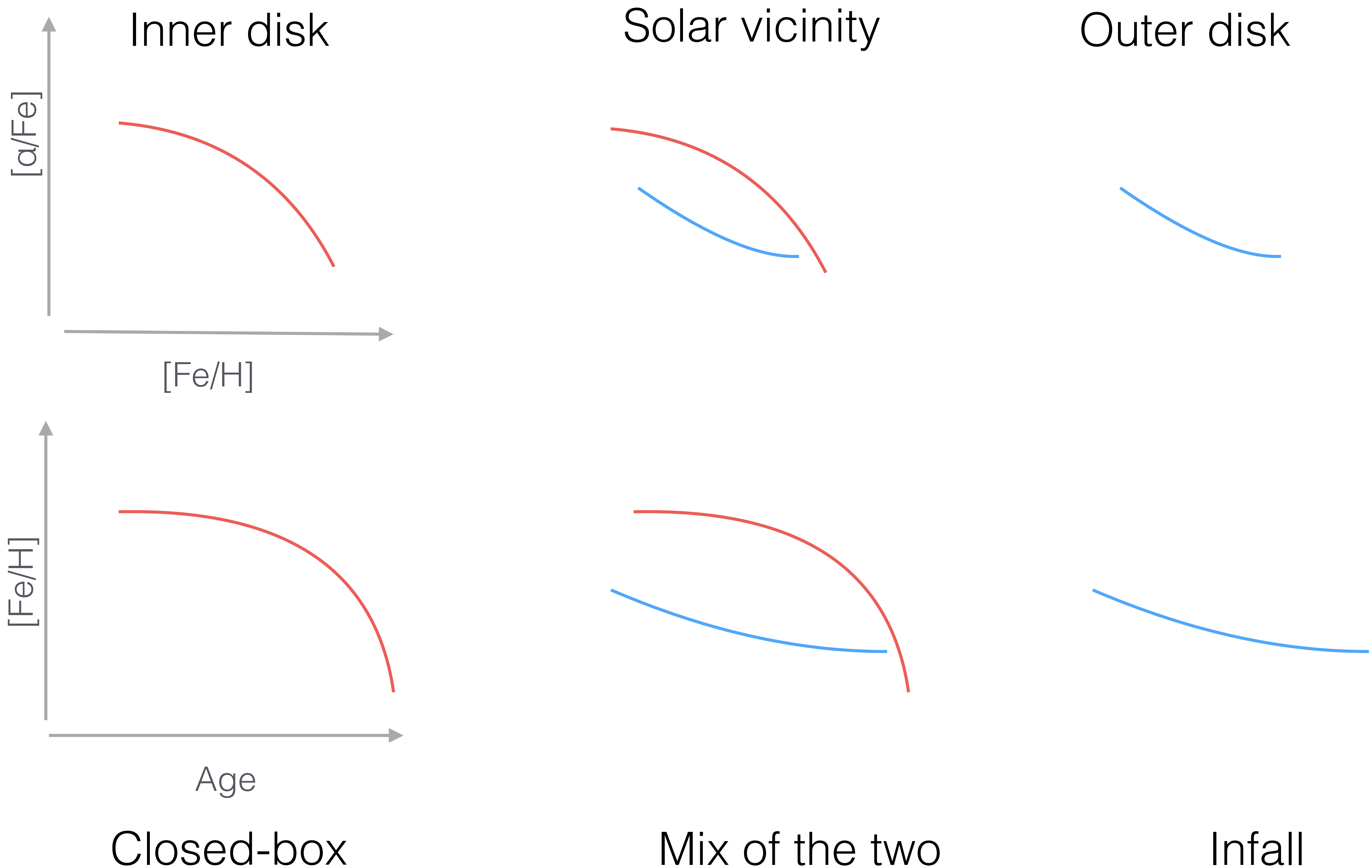
The solar ring (7-9 kpc) is a transition zone between the inner and outer disks

No evidence for radial mixing across the solar ring, otherwise we would not see such structuration



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

The inner and outer disks had different chemical evolutions, Haywood et al. 2013, Snaith et al. 2014



the structuration of the disk

thick disk

thin disk

inner disk + outer disk

The structuration of the disk is not vertical, but radial

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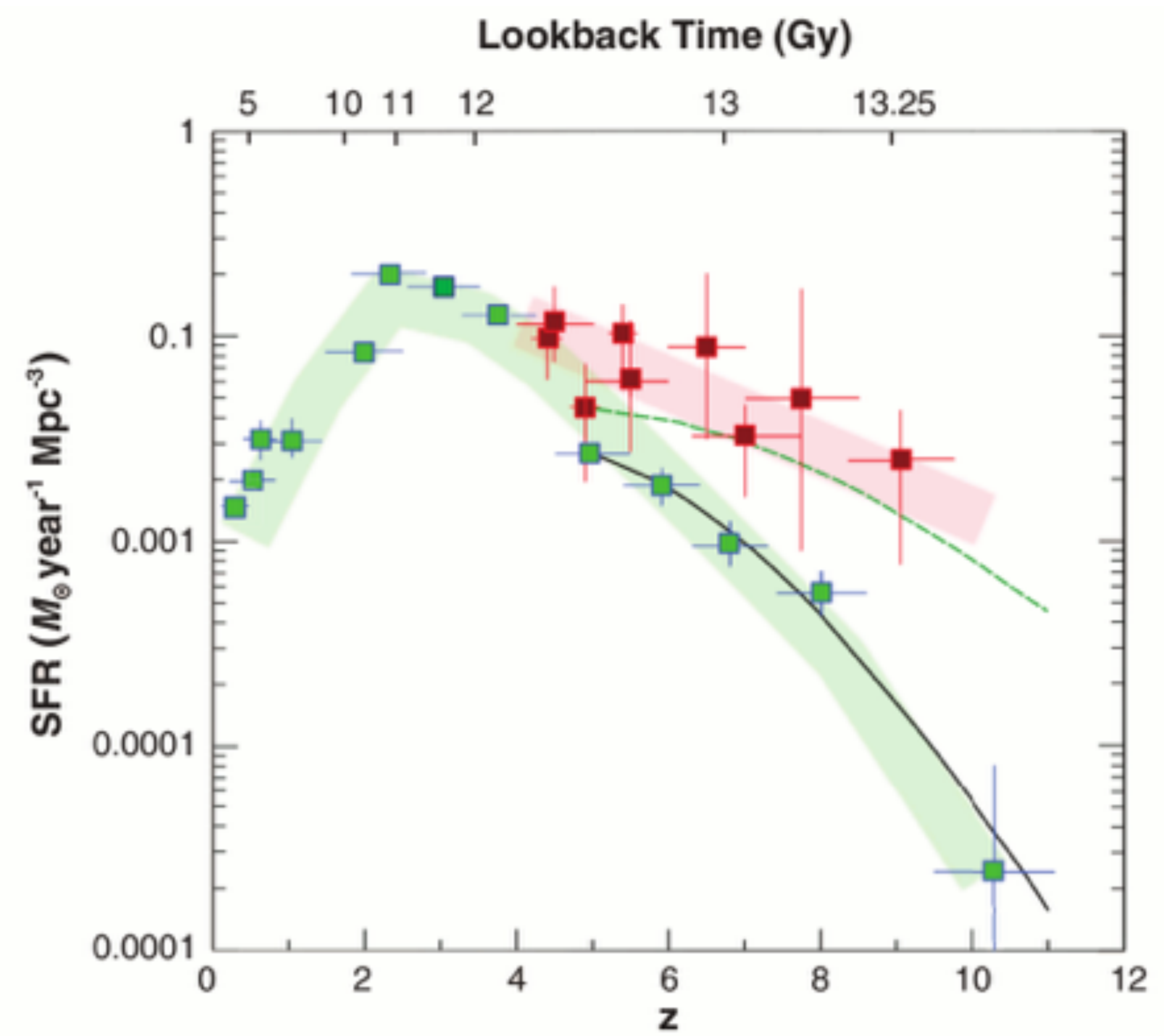
Why are thick disks important?

The SFH reaches its maximum between z=4 and 1 (e.g. Madau & Dickinson, 2013)

Candidate structures to form at this epoch are:

- Classical bulges
- Thick disks



Thick disks are common in galaxies (Dalcanton, 2007; Comeron et al. 2011)

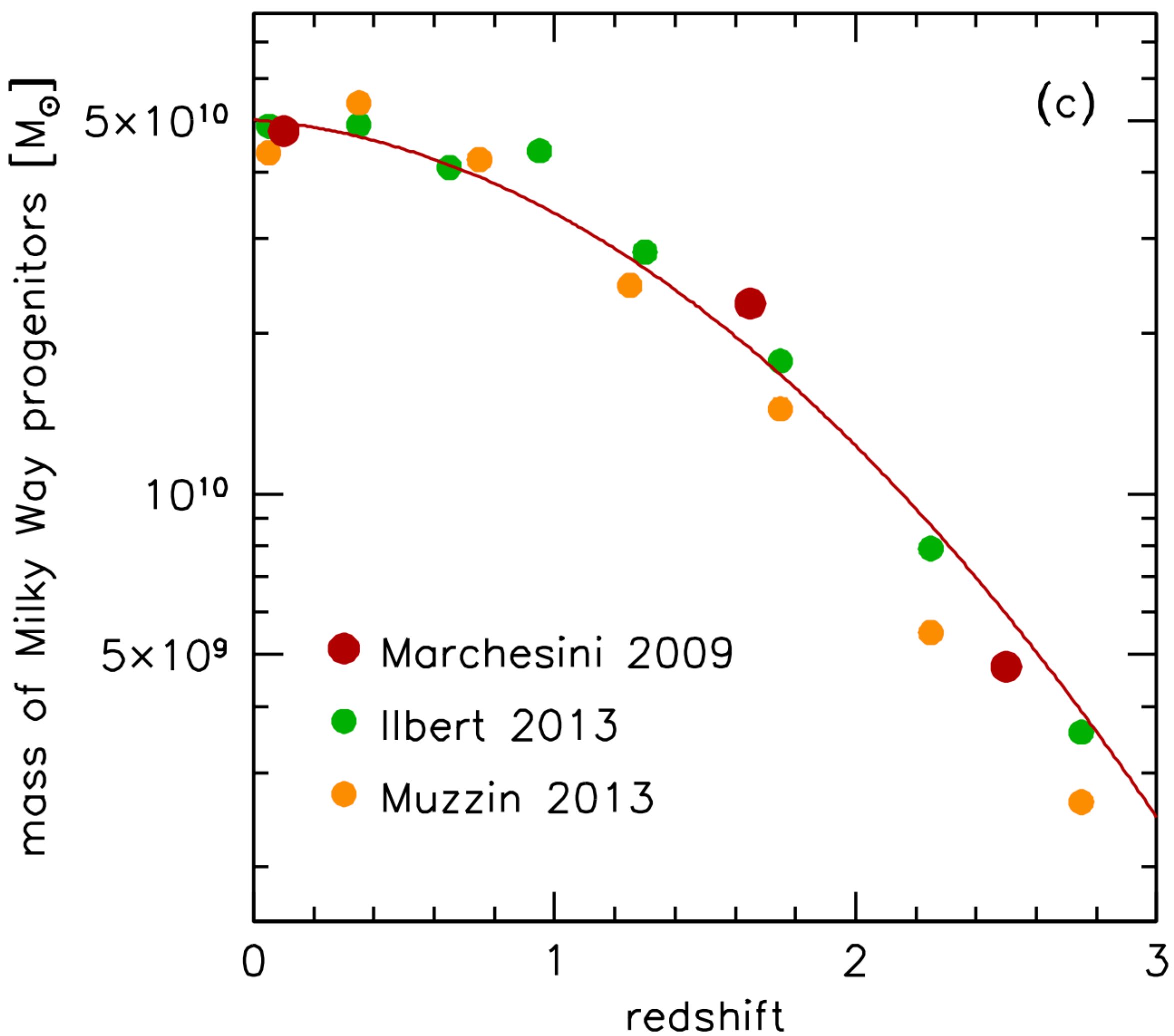
Most galaxies in the local universe are pure disks (no classical bulges), see Kormendy et al. (2010), Fisher & Drory (2010), Laurikainen et al. (2014)

- Thick disks may be the most important component to form at z>1

The Astrophysical Journal Letters, 771:L35 (7pp), 2013 July 10
doi:10.1088/2041-8205/771/2/L35

THE ASSEMBLY OF MILKY-WAY-LIKE GALAXIES SINCE $z \sim 2.5$

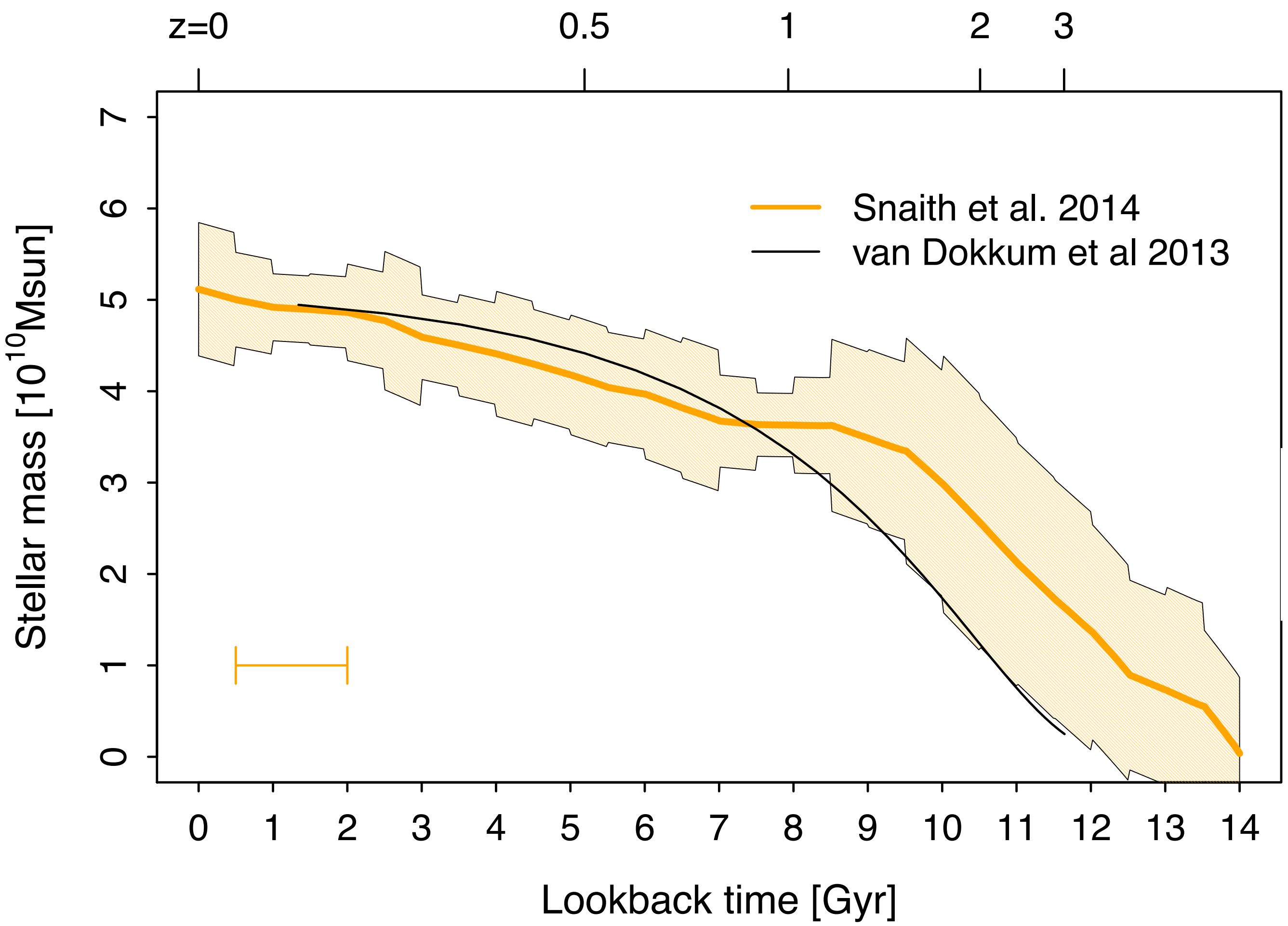
Pieter G. van Dokkum[1], Joel Leja[1], Erica June Nelson[1], Shannon Patel[2], Rosalind E. Skelton[1], Ivelina Momcheva[1], Gabriel Brammer[3], Katherine E. Whitaker[4], Britt Lundgren[5], Mattia Fumagalli[2], Charlie Conroy[6], Natascha Förster Schreiber[7], Marijn Franx[2], Mariska Kriek[8], Ivo Labbé[2], Danilo Marchesini[9], Hans-Walter Rix[10], Arjen van der Wel[10], and Stijn Wuyts[7]
[1] Department of Astronomy, Yale University, New Haven, CT 06511, USA
[2] Leiden Observatory, Leiden University, Leiden, The Netherlands
[3] European Southern Observatory, Alonson de Córdova 3107, Casilla 19001, Vitacura, Santiago, Chile



« More than half the present day mass was assembled in 3 Gyr between z=2.5 and z=1 »

van Dokkum et al., 2013

the evolution of the MW *vs* Milky Way type galaxies



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 thick disk that makes the mass growth evolution of the MW similar to its progenitors

Conclusions:

- The thick disk is not an isochrone population (single age, unique set of structural parameters), it formed over 4-5 Gyr

- It formed during the most intense phase of star formation experienced by the Milky Way in the last 13 Gyr, representing ~50% of the stellar mass

- The formation of a massive thick disk makes the evolution of the MW comparable to the evolution of MW type galaxies

- The structuration of the disk is radial, not vertical, the Sun is in a transition zone between the inner and outer disks

- It requires the modeling of two different chemical evolutions (inner disk (thin+thick) / outer disk)