When the Milky Way turned-off the lights

APOGEE provides evidence of star formation quenching in our Galaxy

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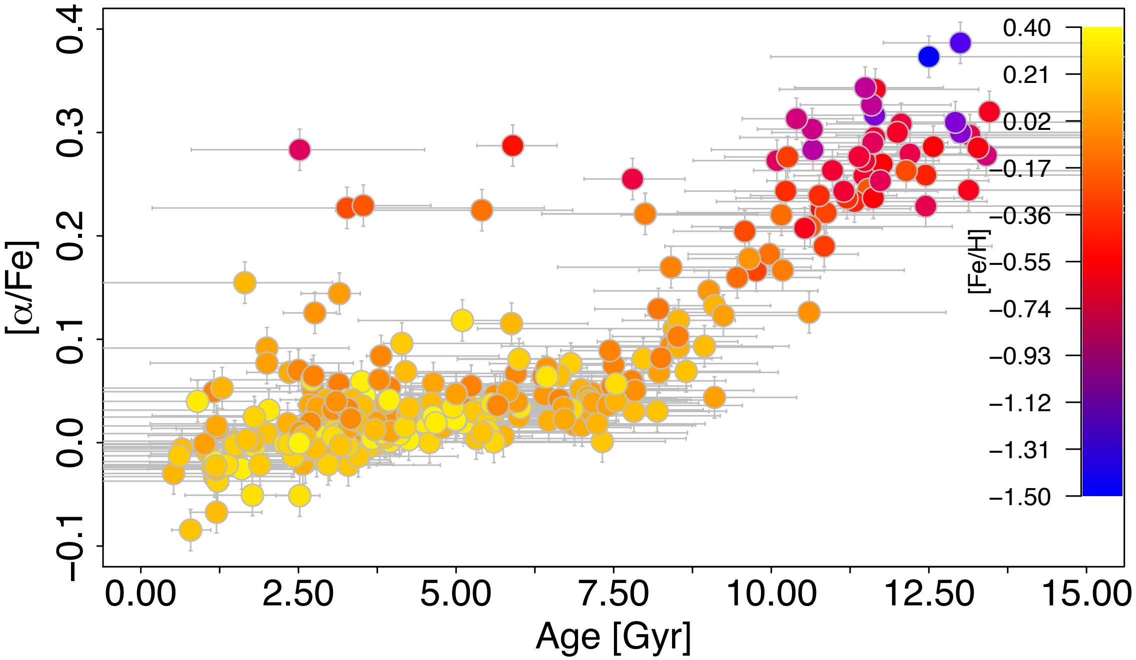
Sesto 2016, Galactic Surveys: New Results on the Formation, Evolution, Structure and Chemical evolution of the Milky Way

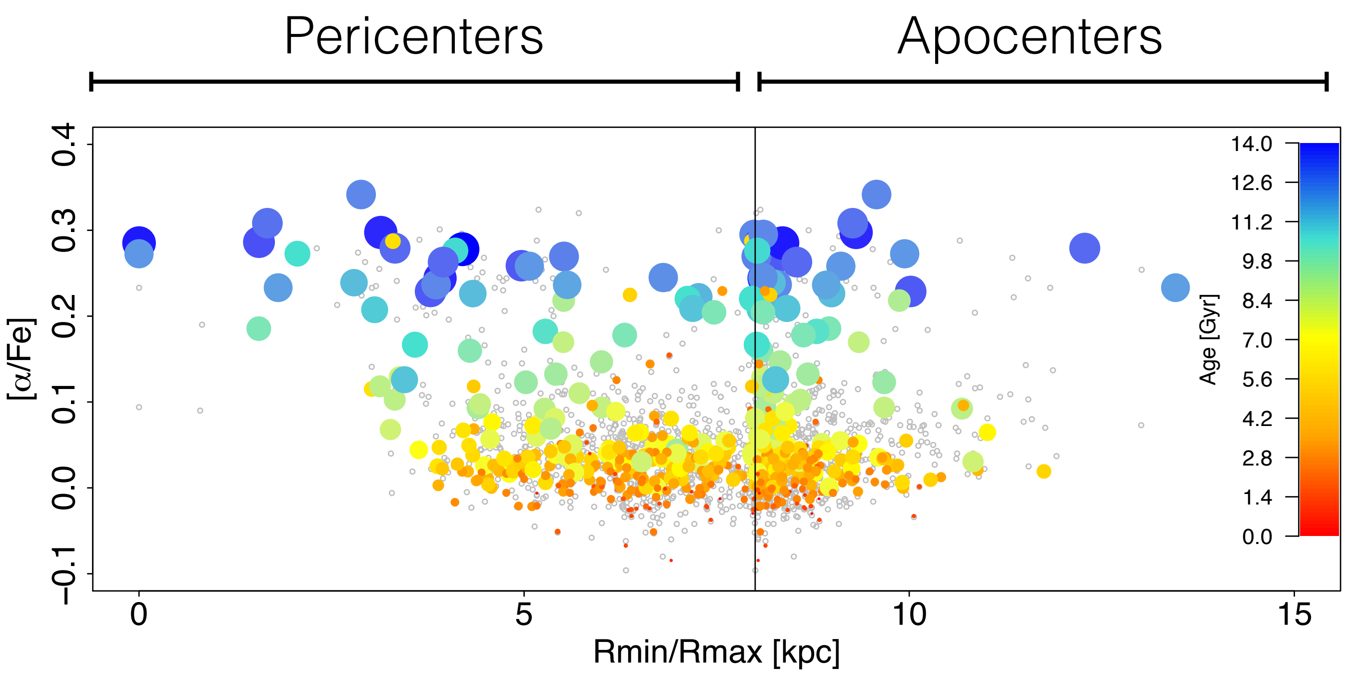
The inner disk age-alpha relation



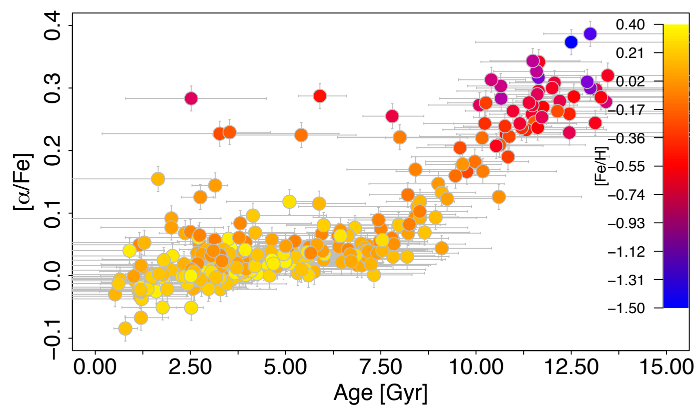
HAYWOOD et al 2013, 2015

Local sample of stars
Adibekyan et al. 2012

Two segments corresponding to two distinct populations: the thin and thick disks

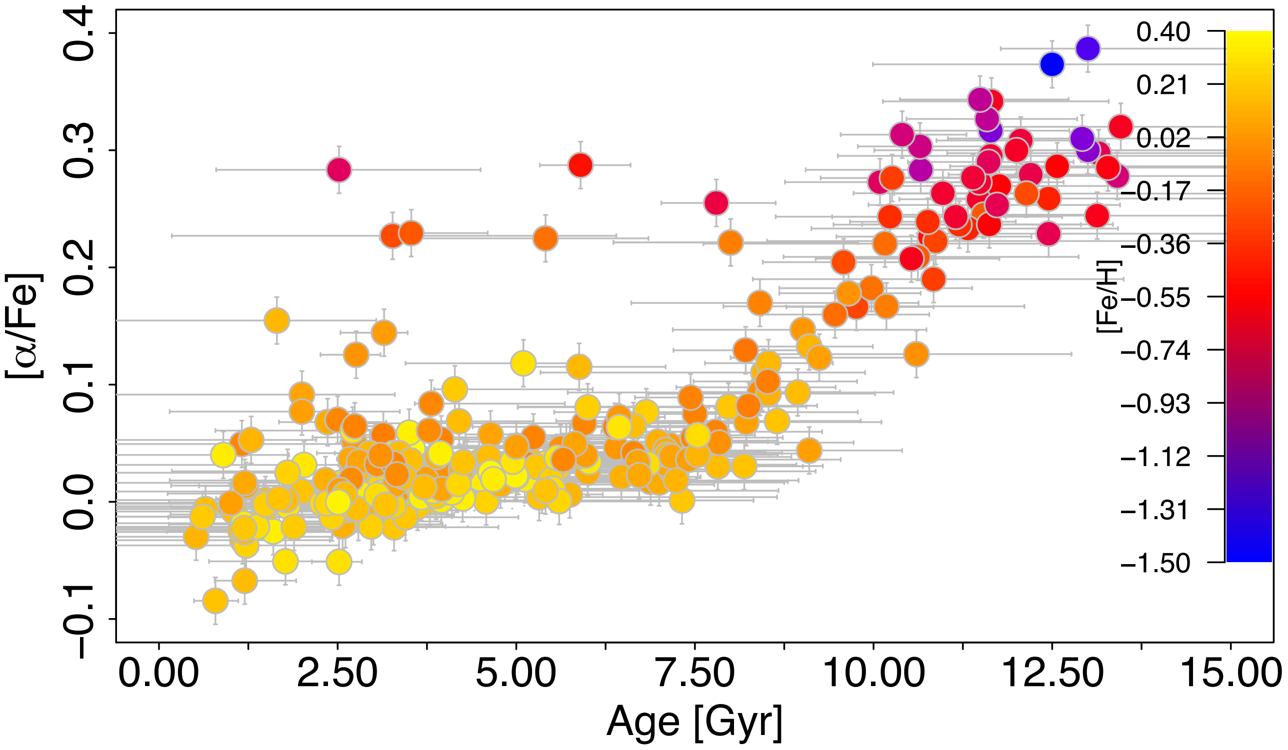


High-α stars have pericentres that can reach R<2kpc,
stars originate from all over the inner disk (0-10kpc).



A local sample, but a general relation

Combined with the small dispersion, implies an homogeneous chemical evolution



HAYWOOD et al 2015

The slope of the age-alpha relation is proportional to the intensity of the SFR

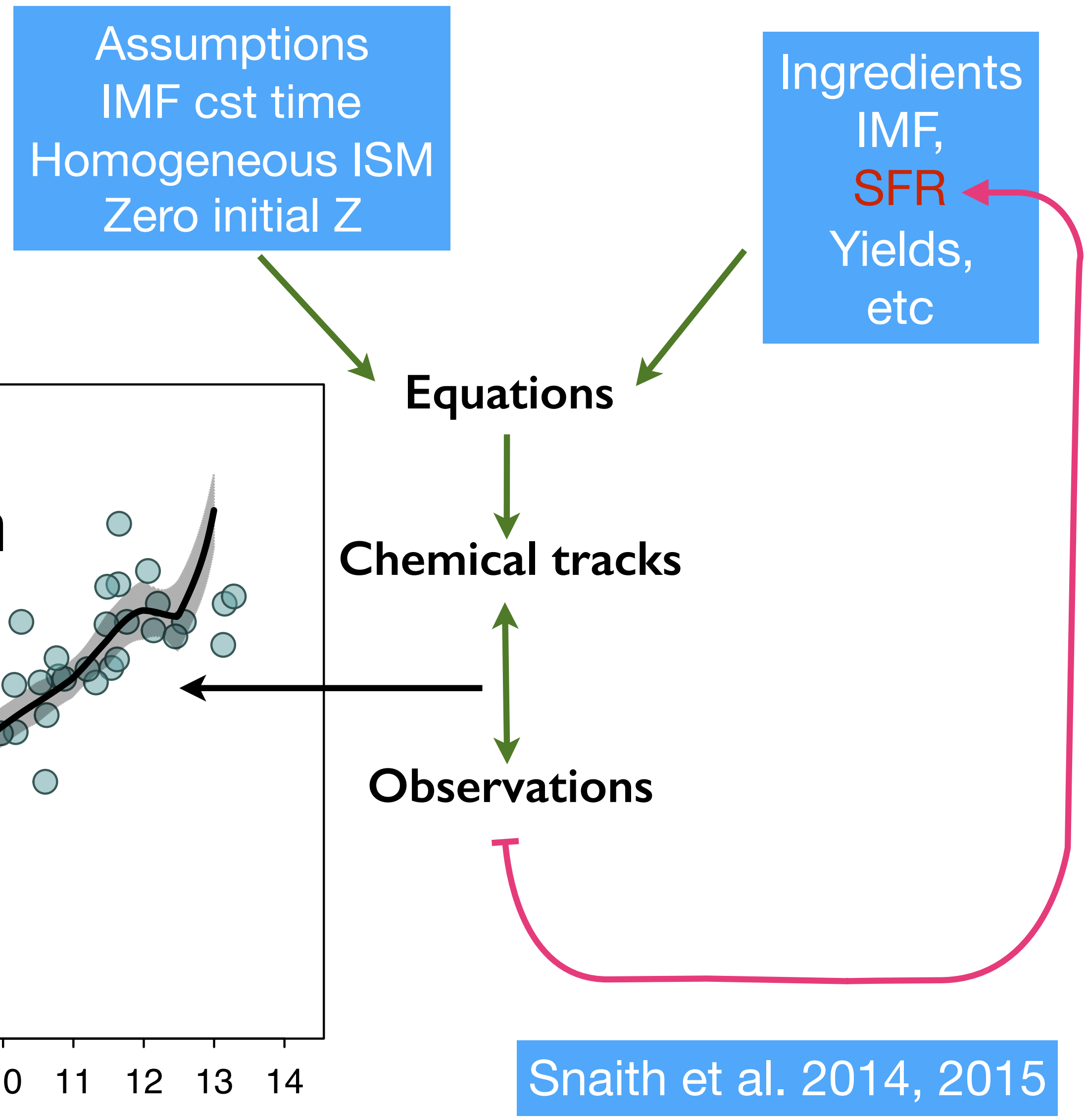
➡ Fitting the age-alpha relation allows one to recover the SFH of the MW.

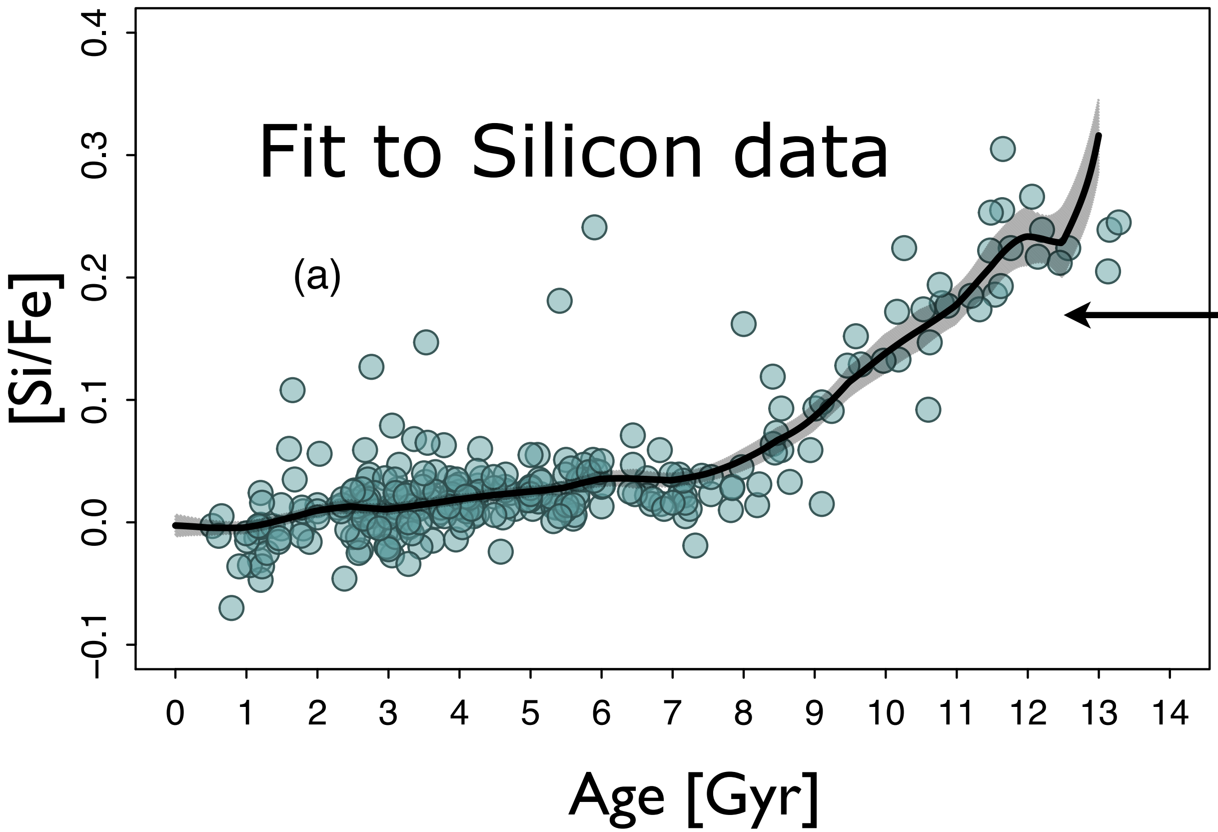
If the age-alpha relation is general, so is the recovered SFH

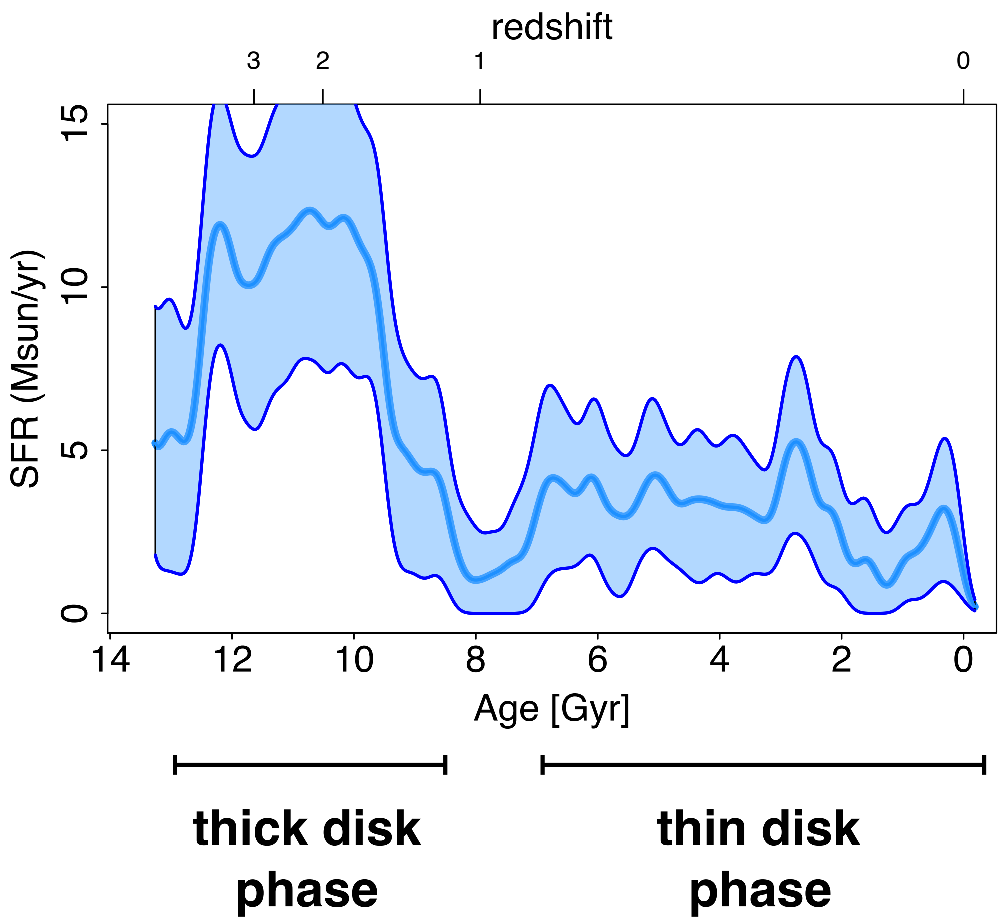
Two slopes ➡ two phases of star formation

Chemical evolution modelling, Snaith et al. 2015

The inner disk (R<8-10kpc) as a closed box
= independent of gas accretion
=most of the gas was accreted
before significant star formation
started







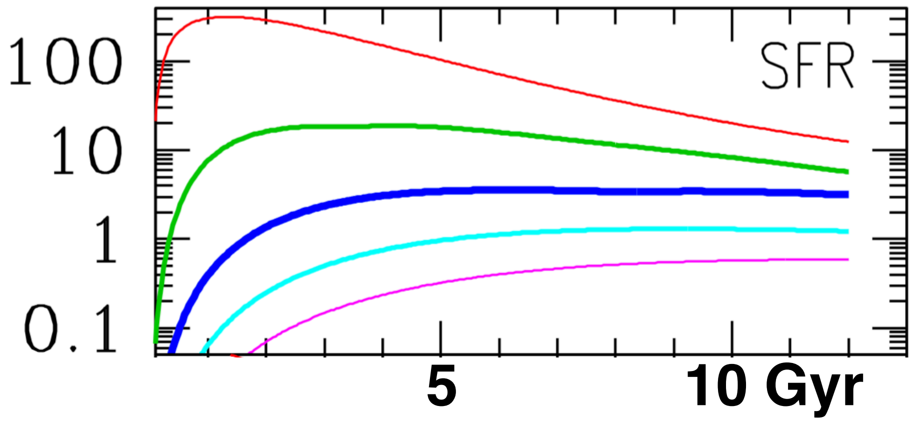
SNAITH et al 2015

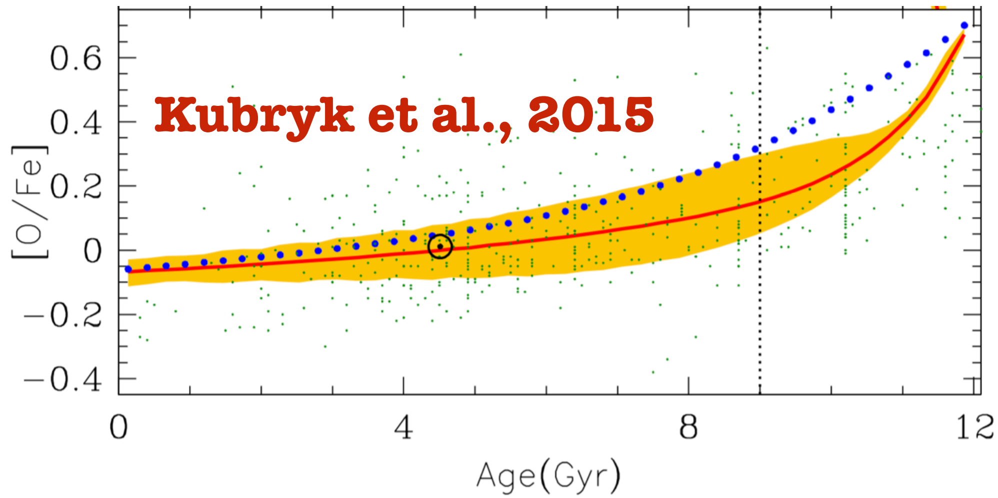
The method provides a SFH valid for the whole inner disk of the Milky Way (at the price of having to assume a GCE model)

The thick disk represents ~50% of the disk stellar mass

Confirmed by structural parameters of the MW (short scale length, Bovy+2015, Bovy+2012, Bensby+2011)

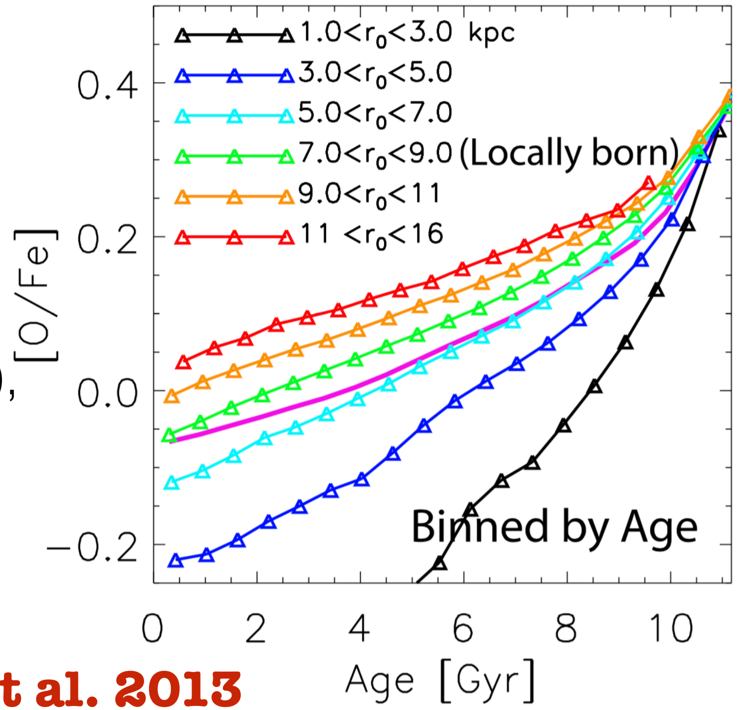
What are the implications ?



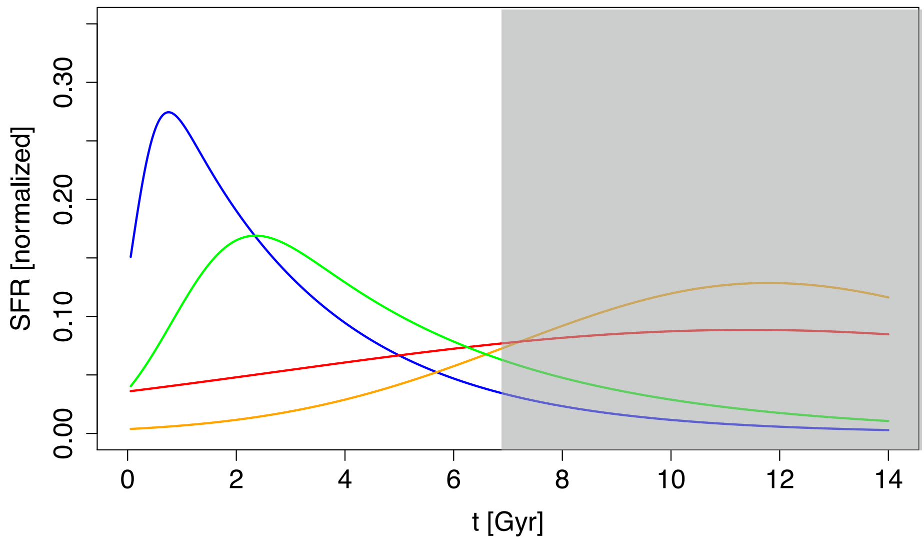


In a closed-box model (no radially dependent gas accretion), the nucleosynthesis is uniform, small dispersion of alpha abundances

In inside-out models, accretion depends on radius, the SFH is radially dependent (inside-out formation), generating dispersion in alpha **incompatible with the observed relation**

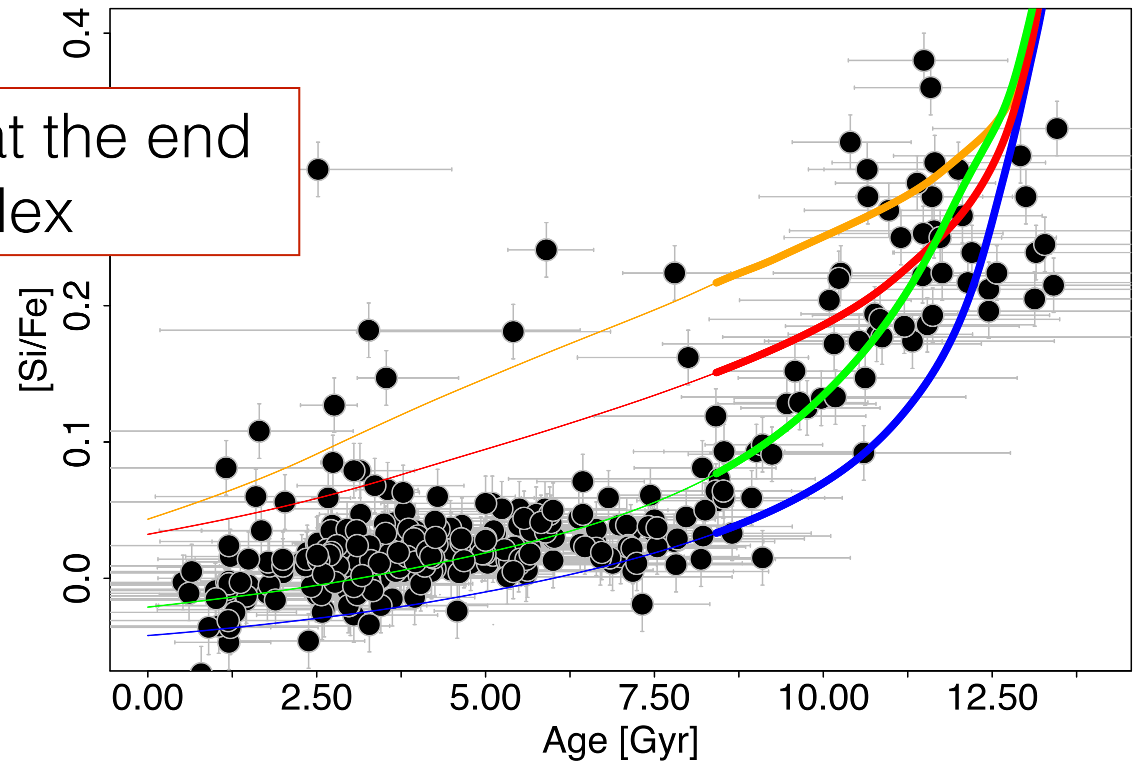


Minchev et al. 2013



HAYWOOD et al 2015

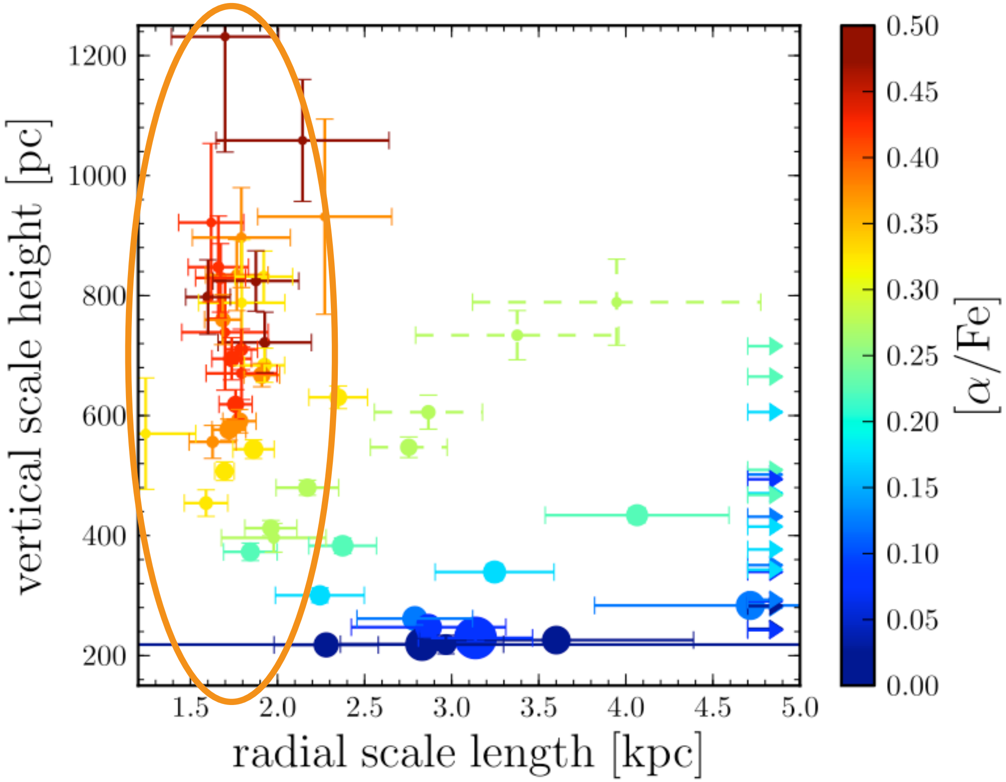
The observed spread in alpha at the end of the thick disk phase is <0.1 dex



Compatible with a variation of x2 in the SF intensity, not a factor of a few 10s

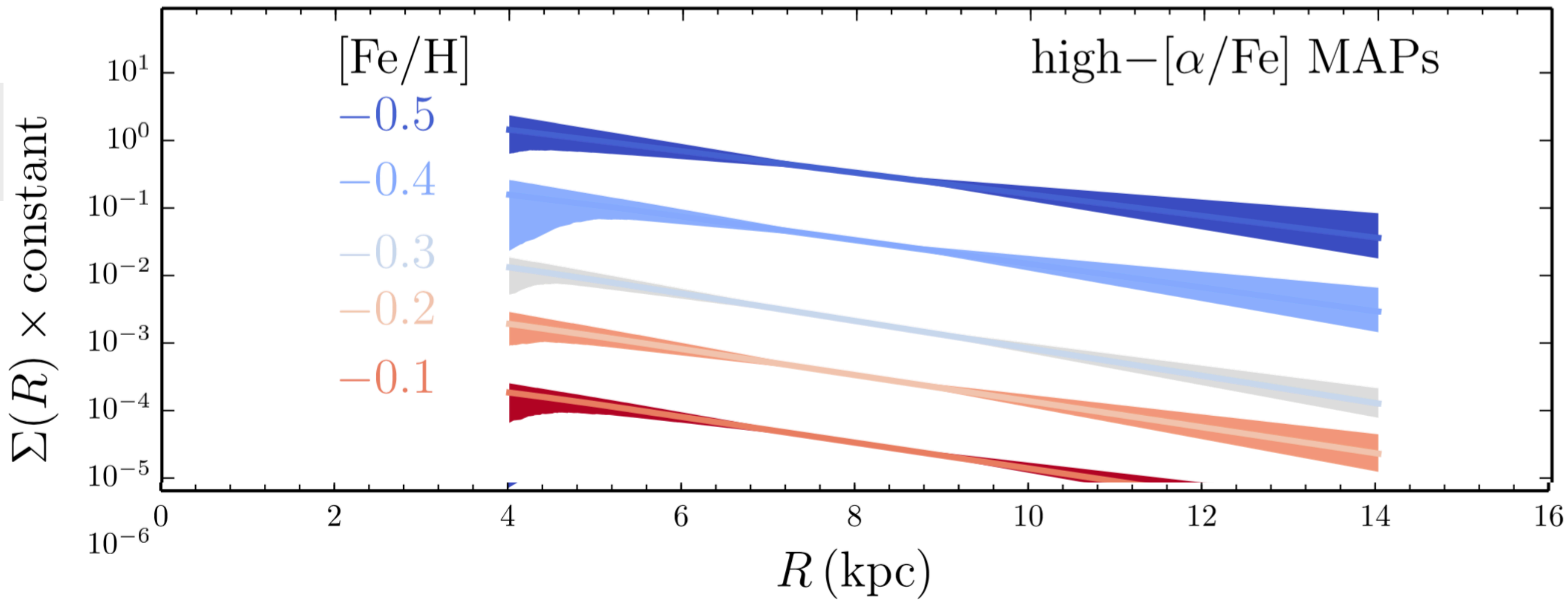
The SFH in the thick disk was not radially dependent

Consistent with the no-evolution of the thick disk scale length



SEGUE data, Bovy et al. 2012

APOGEE data, Bovy et al. 2015



Conclusions

- The chemical trends (small dispersion in age-alpha relation)
- The structural parameters
- Absence of metallicity gradients in the thick disk (Cheng et al. (2012))

…. are not consistent with an inside-out formation of the thick disk

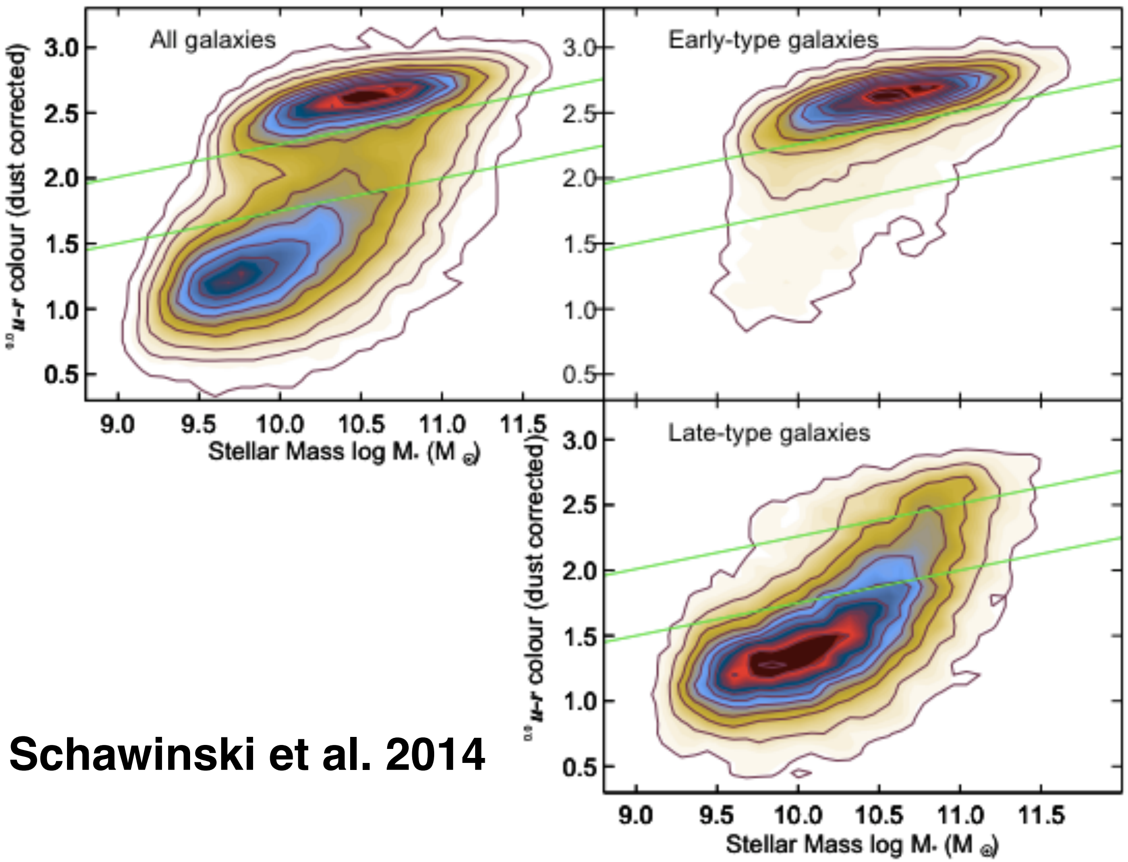
Confirms the weak dependence of the (thick) disk formation on a radially dependent accretion of gas

Compatible with the observation of MW analogs at high redshift, which form in a self-similar way, see van Dokkum et al. 2013, Morishita et al. 2015

Massive galaxies ($M_{*}>10^{11}$Msun), M31 type, formed inside-out, van Dokkum et al. (2010) Morishita et al. (2015)

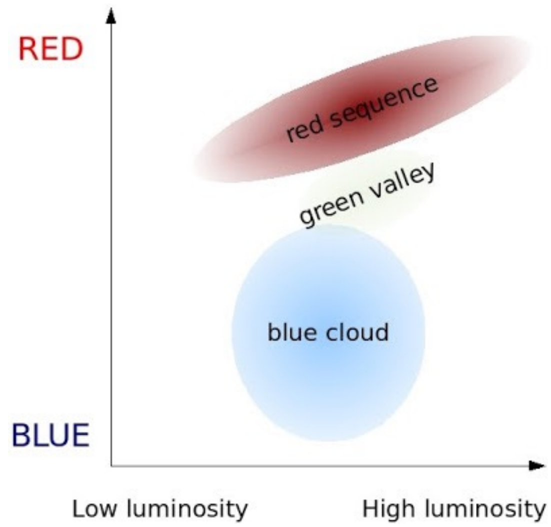
APOGEE provides evidence of star formation quenching in our Galaxy
Haywood et al. astro-ph

Quenching in galaxies: a few generalities



Schawinski et al. 2014

Transition from the blue cloud to the red sequence

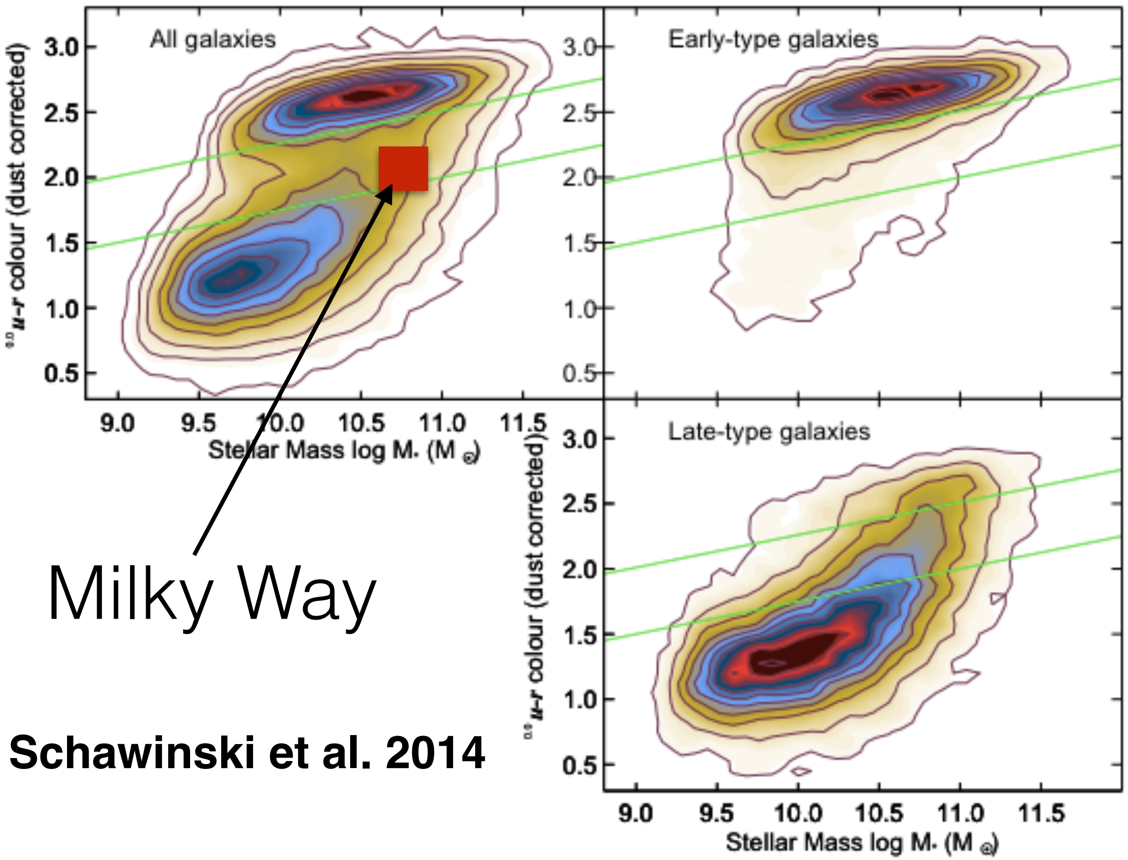


- Transition from the blue cloud to the red sequence is usually thought to be rapid (~ 1 Gyr)
- But quenching timescale for spiral discussed
- Perhaps accompanied by morphological transformation

(from disks-dominated to spheroid or bulge-dominated)

Massive galaxies are observed to quench first

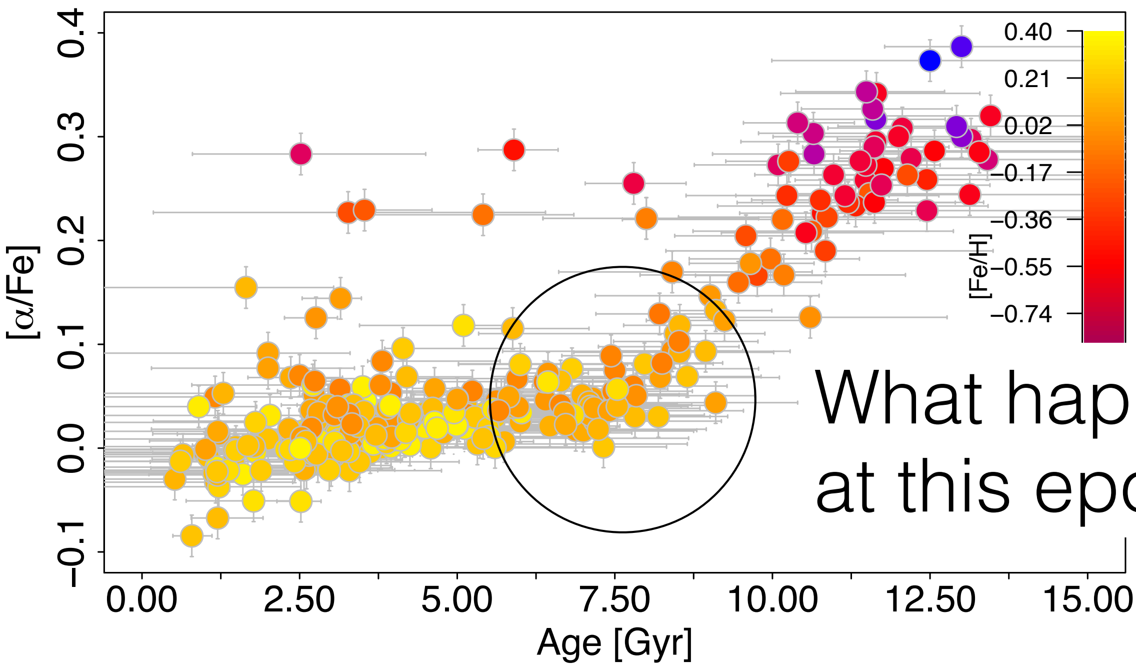
For Milky Way type galaxies, quenching occurs at z=1.6 (Morishita et al. 2015)



Schawinski et al. 2014

Milky Way in the green valley,

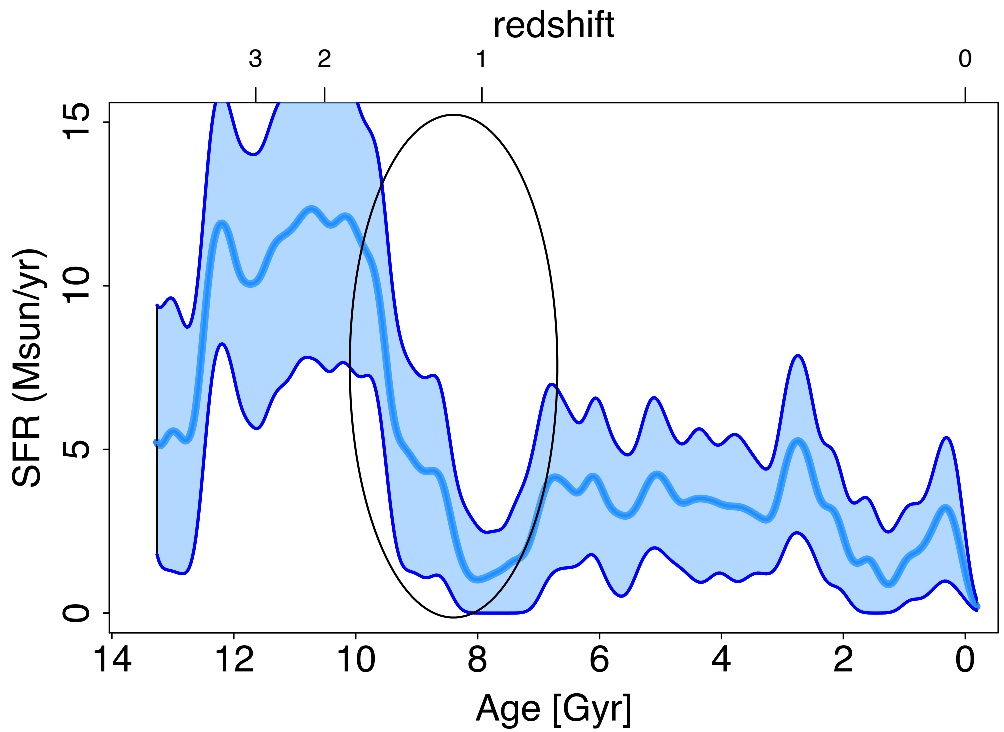
see Licquia et al. 2015, or Mutch et al. 2011

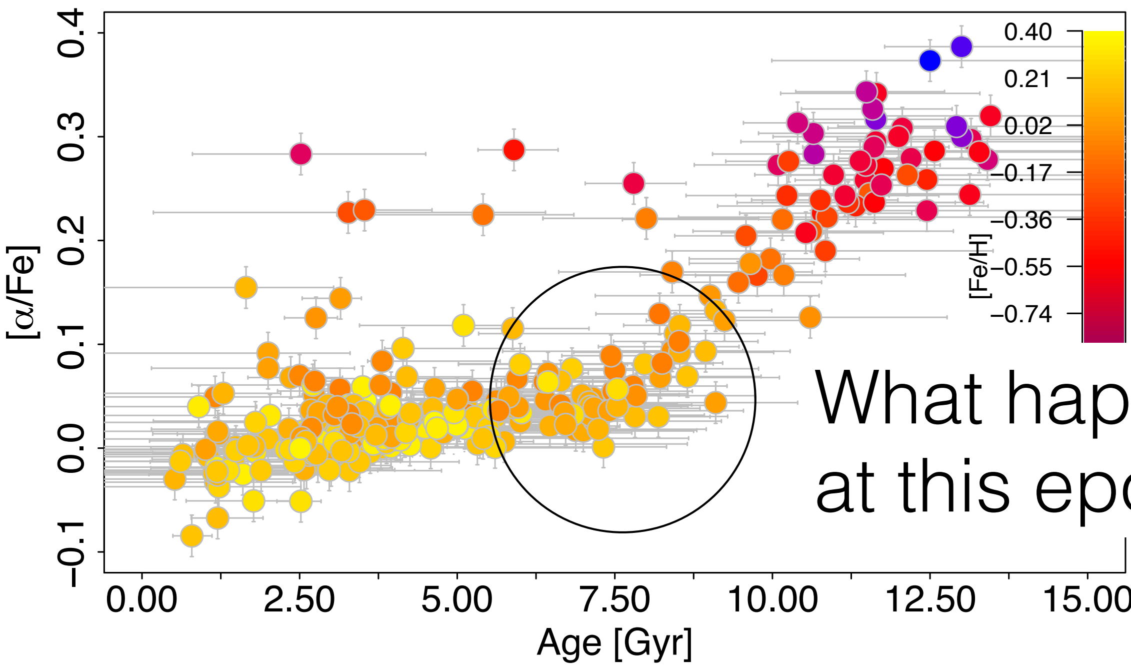


HAYWOOD et al 2015

What happened in the Galaxy at this epoch (z~1) ?

The MW SFR decreased by more than x10 in less than 2 Gyr

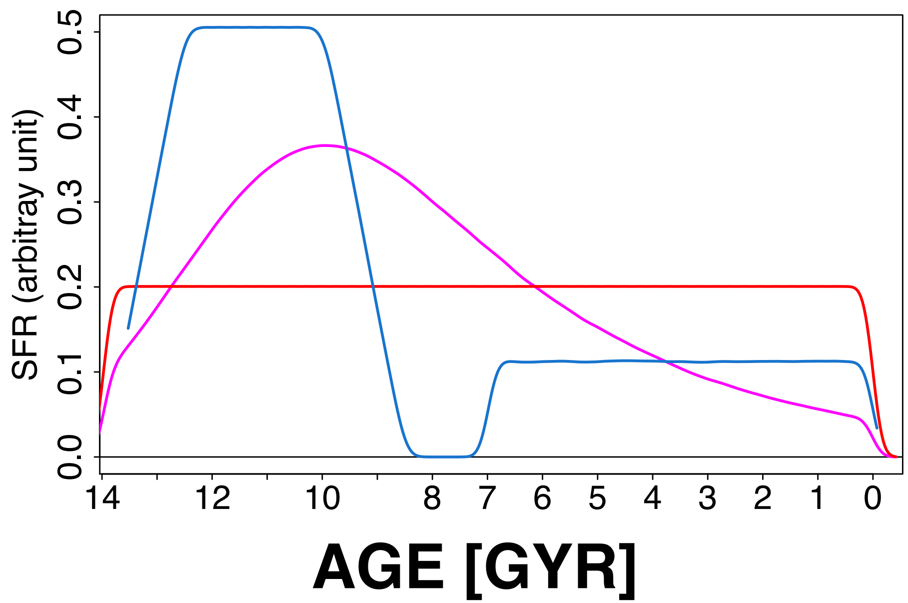


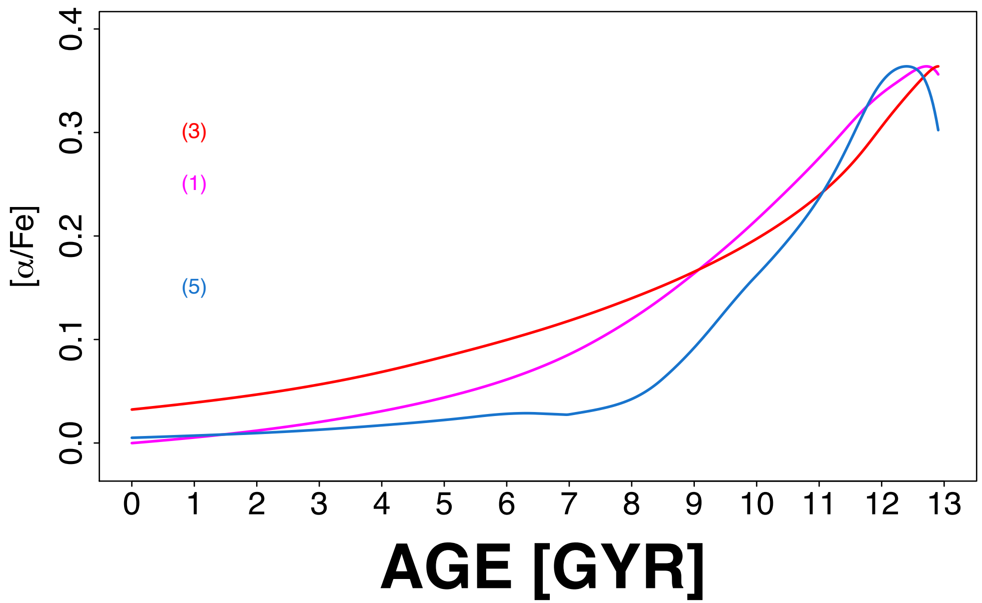


HAYWOOD et al 2015

What happened in the Galaxy at this epoch (z~1) ?

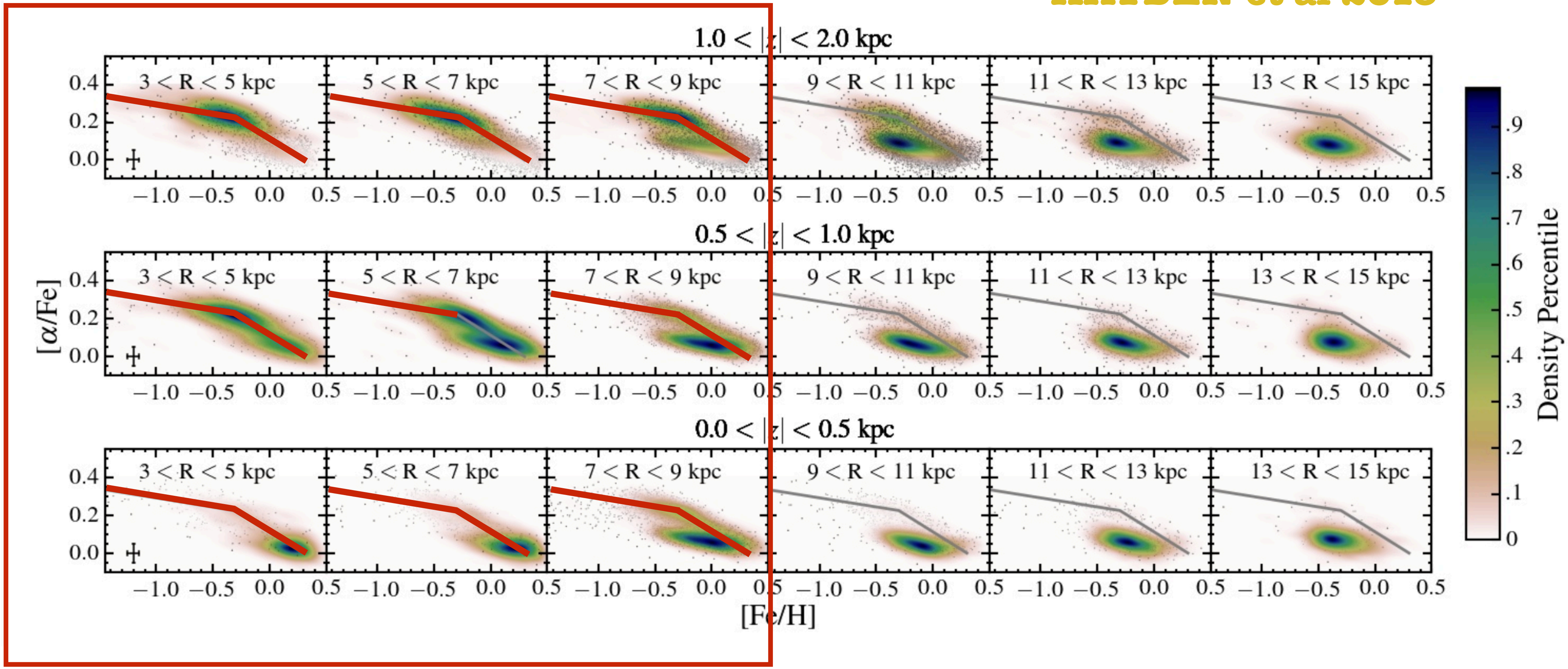
The knee in the relation is evidence that the Galaxy rapidly changed its intensity of star formation.



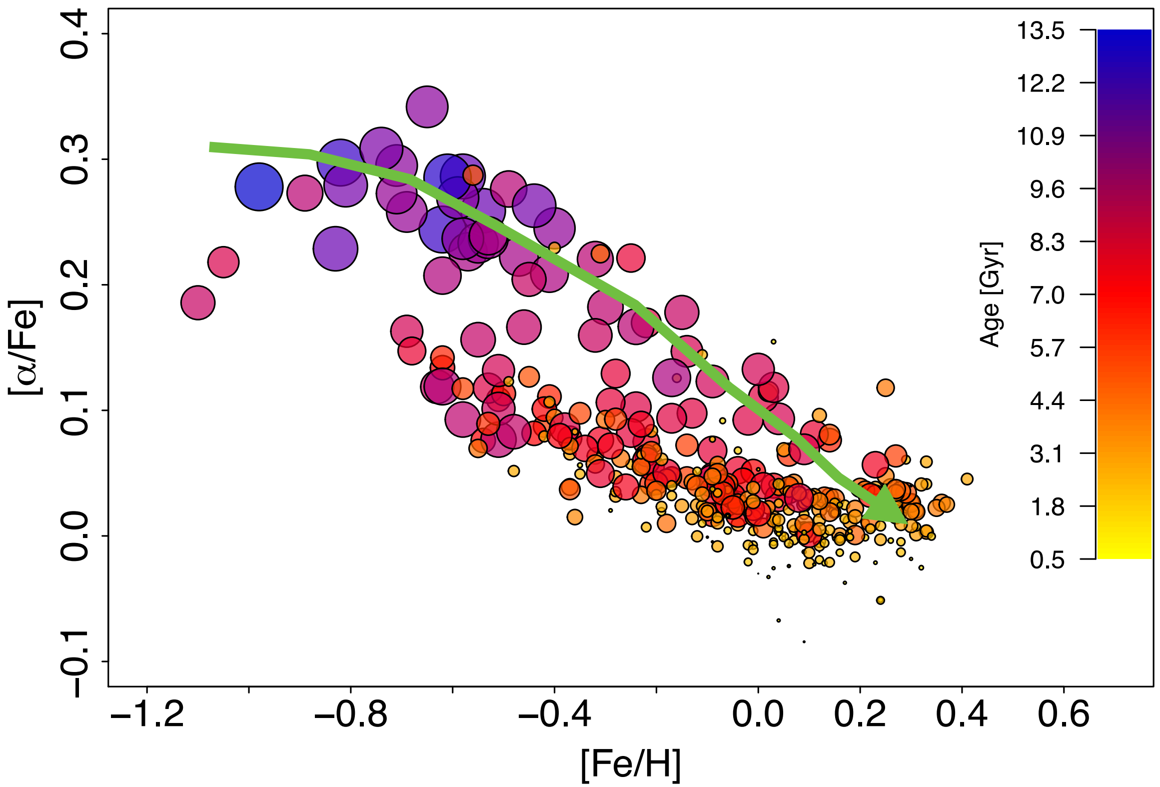


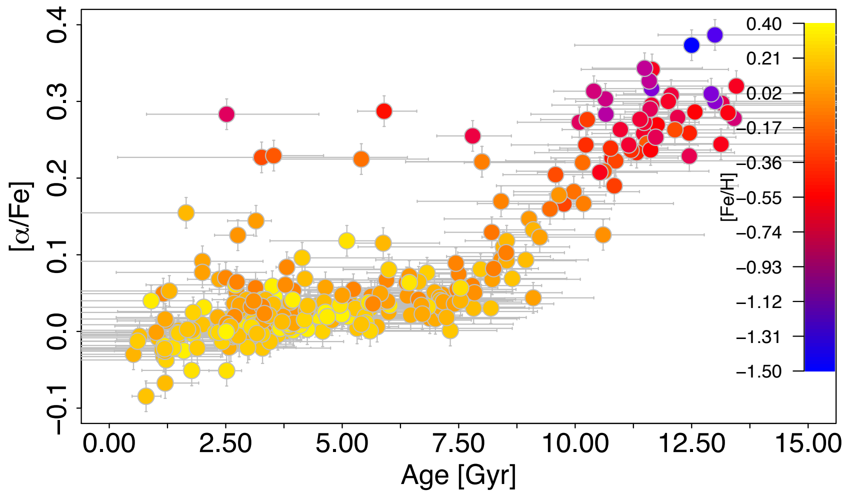
Any large scale signature of this event ?
APOGEE data (Holtmann+2015, Majewski+2015)

HAYDEN et al 2015



Where do we want to measure the SF variations ?

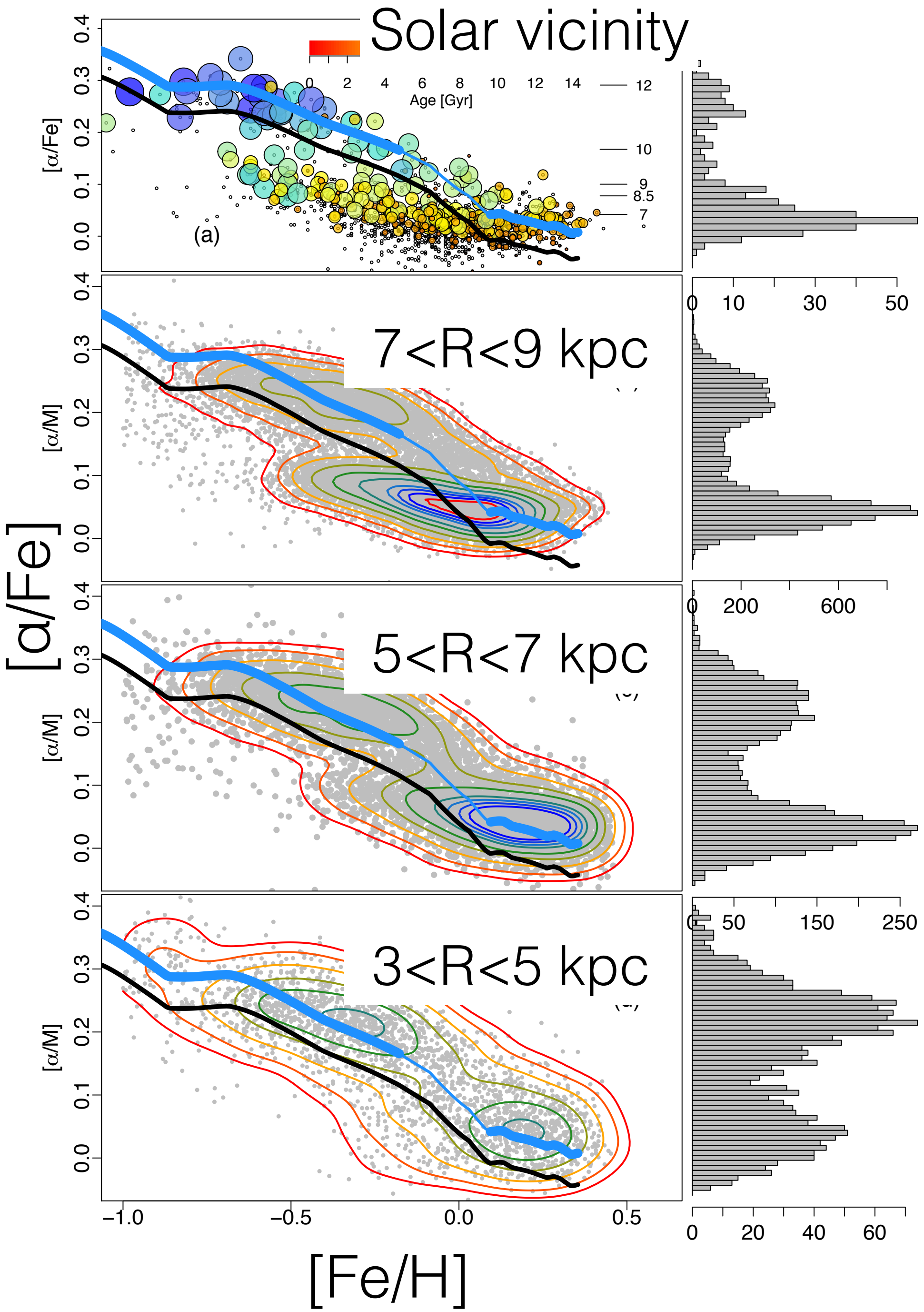




[α/Fe] correlates well with age

Quenching is measured along the inner disk sequence

Stellar counts in [α/Fe] directly reflect the SFH

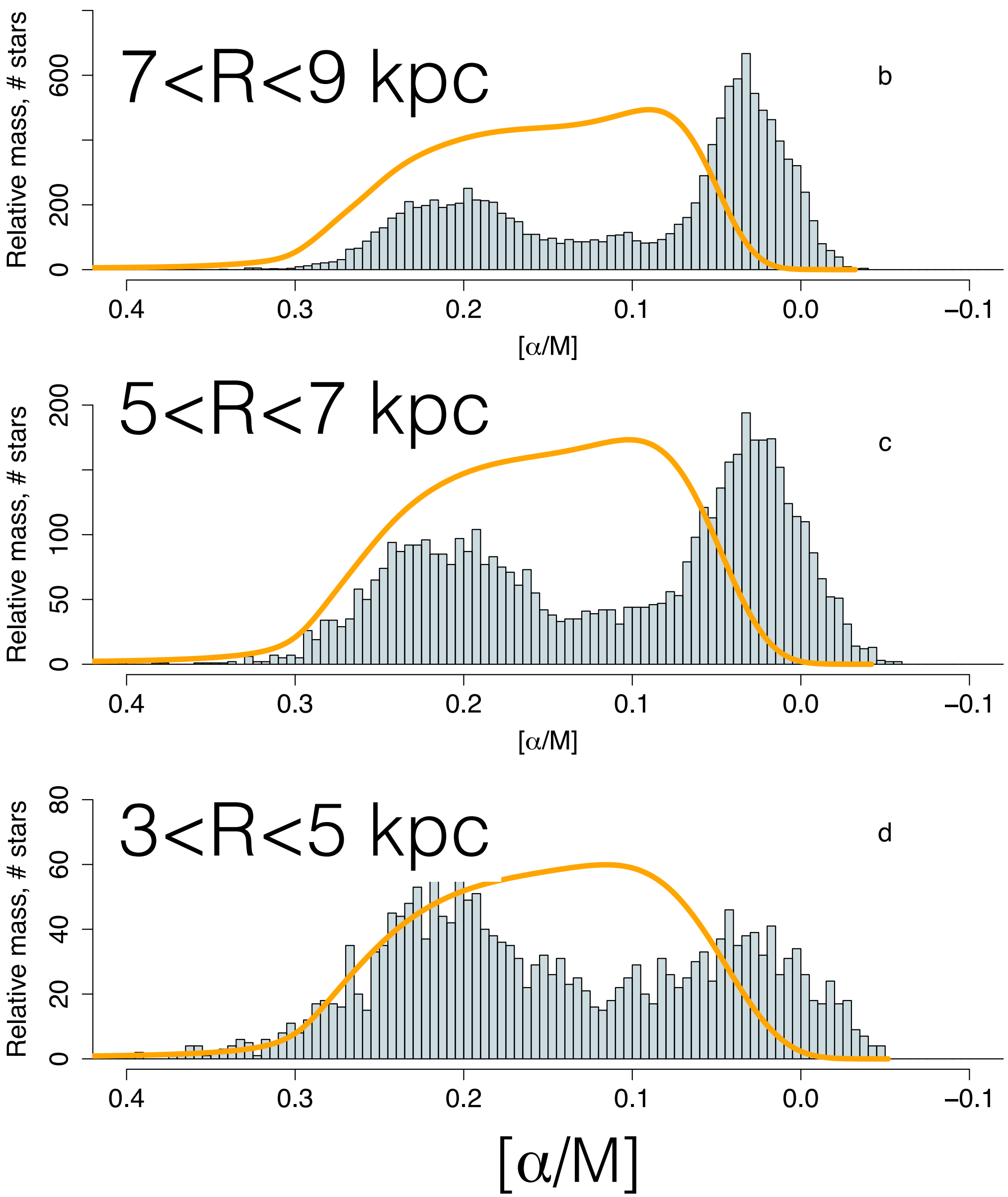


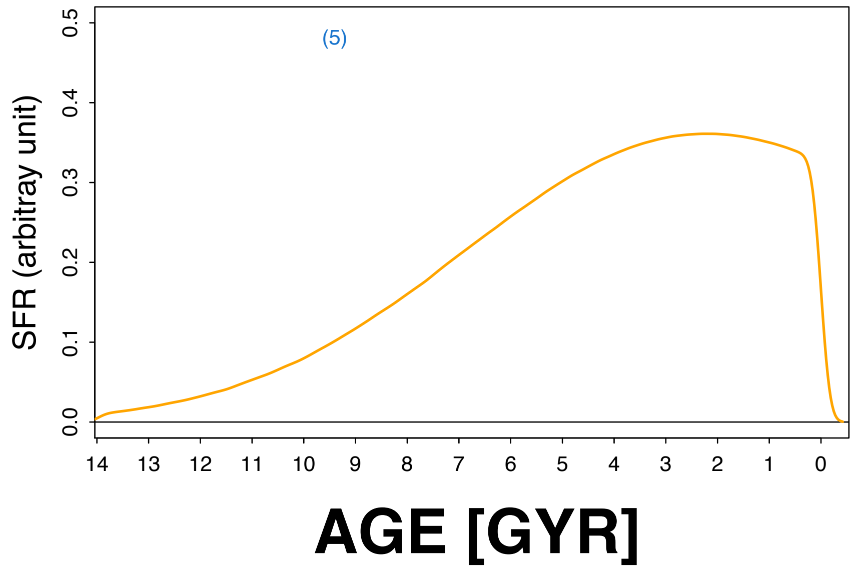
Selection from APOGEE same as Hayden et al (2015), no bias expected in the alpha abundance distribution

Distances derived by Schultheis et al. (2014), accuracy to 30-40%

What Star Formation History is needed to reproduce the (bimodal) [α/M] stellar counts?

Increasing SFR with time

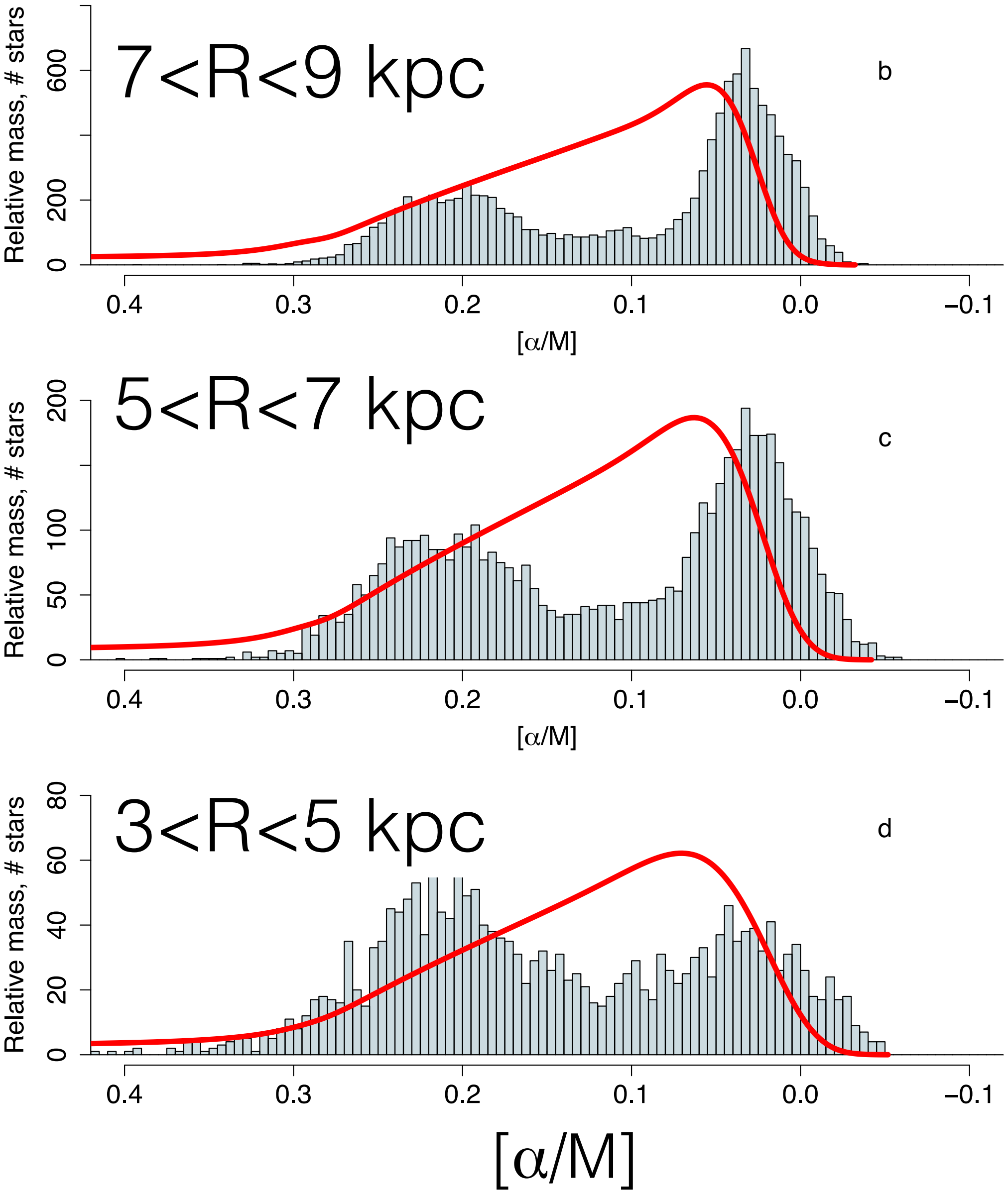


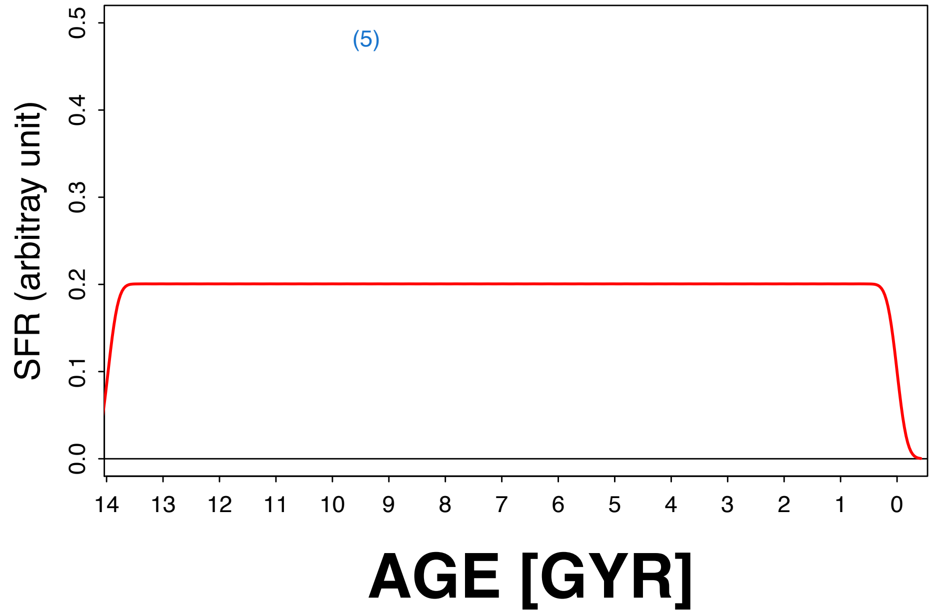


Two difficulties:

- The dip is absent
- The initial nucleosynthesis not enough to produce low-alpha stars

Constant SFR

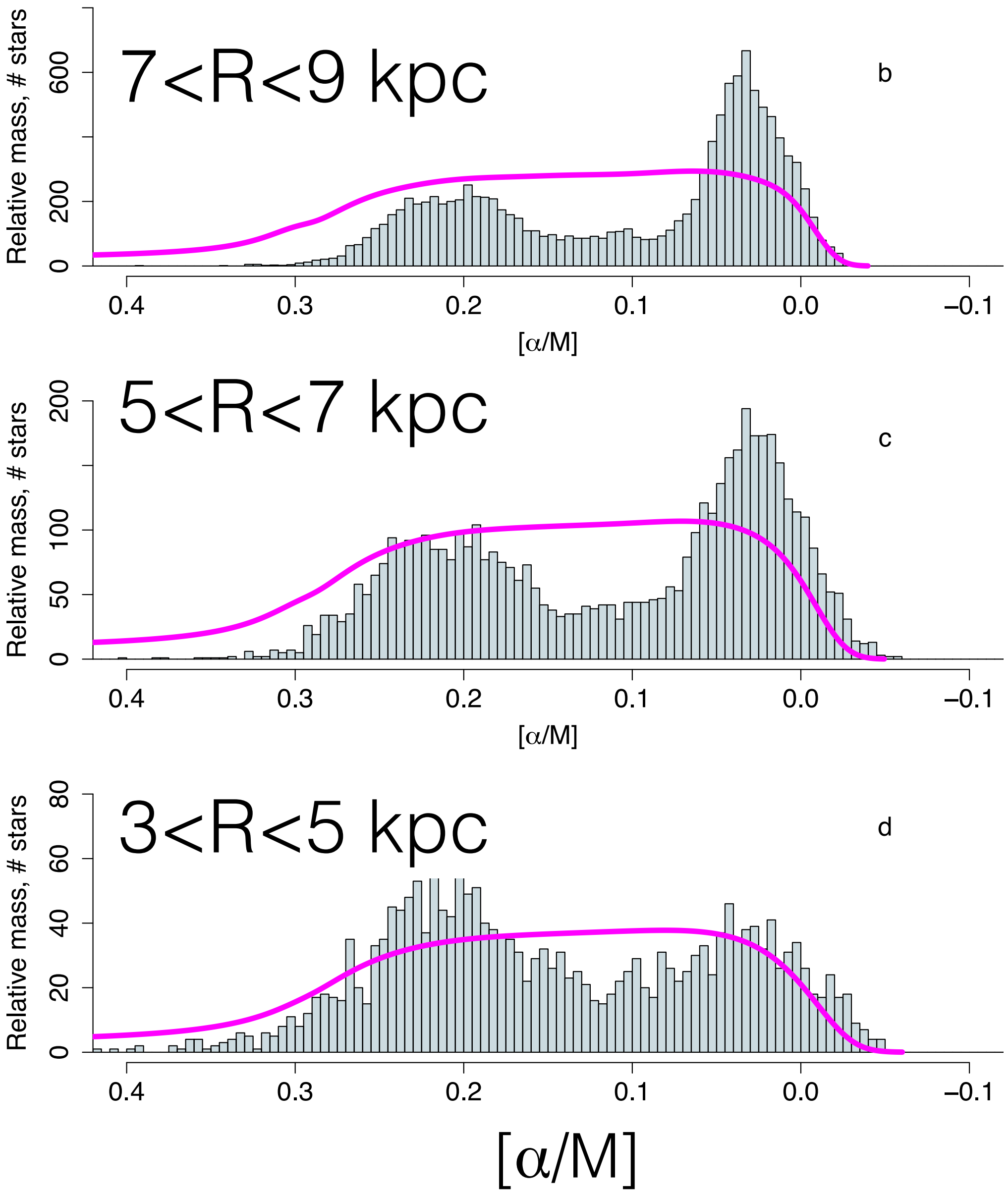


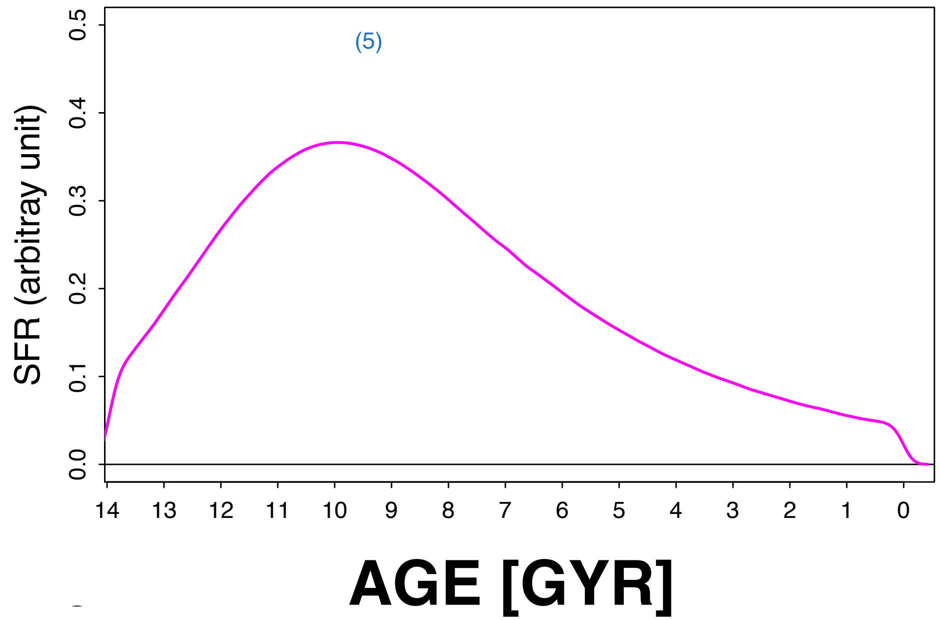


Two difficulties:

- The dip is absent
- Initial nucleosynthesis barely enough to produce low-alpha stars

Decreasing SFH

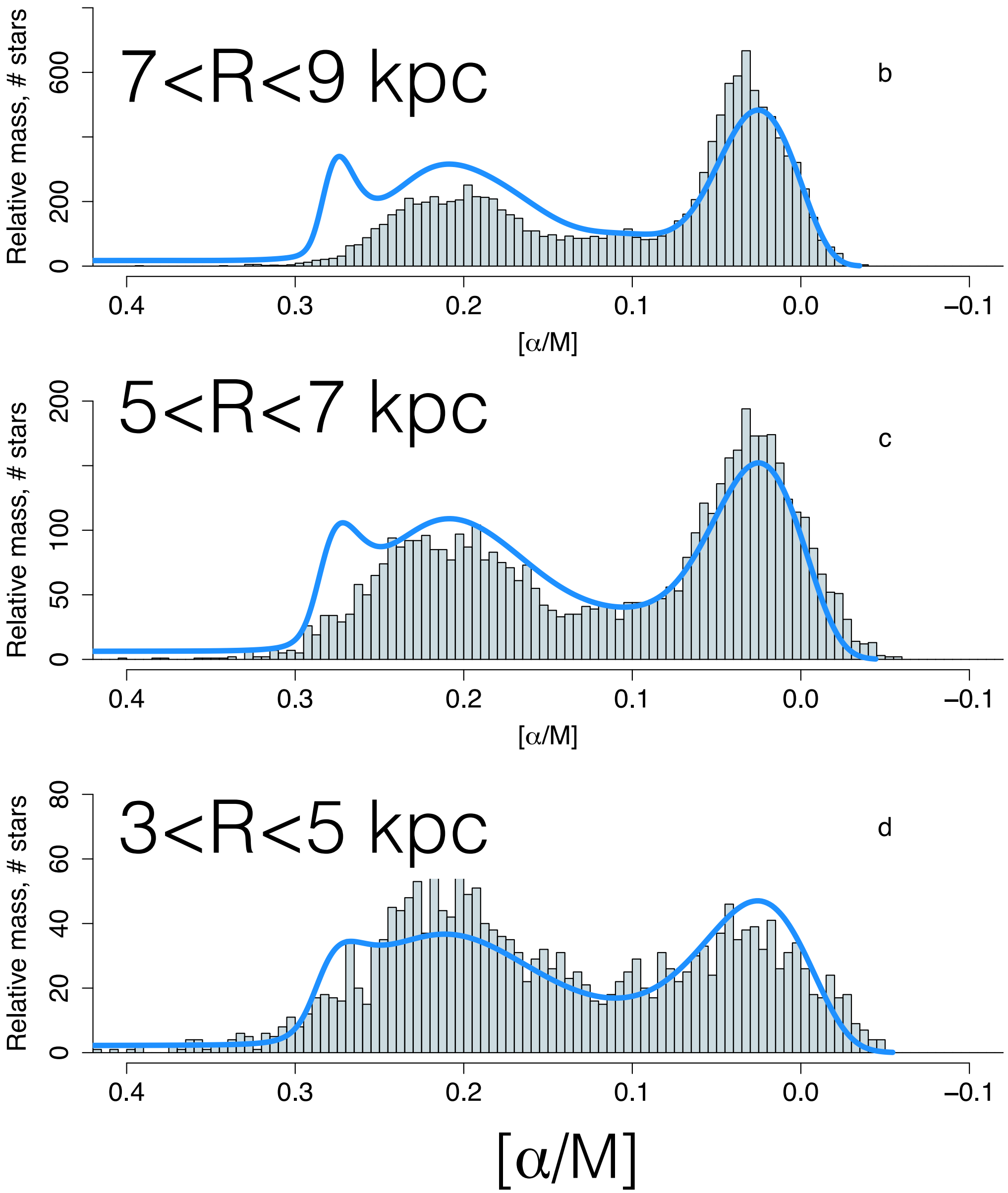


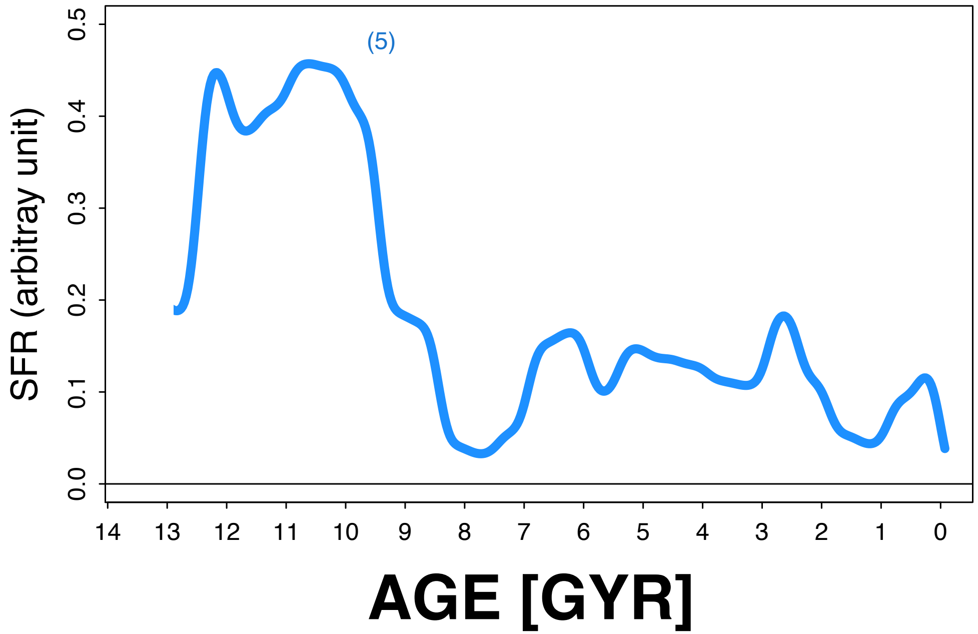


Low-alpha stars are present

- But the dip is absent

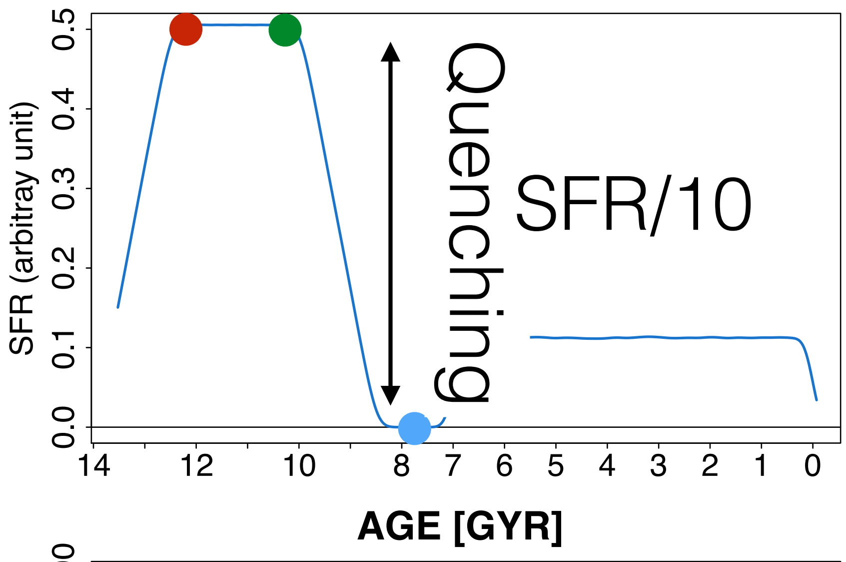
SFH from Snaith et al. (2015)

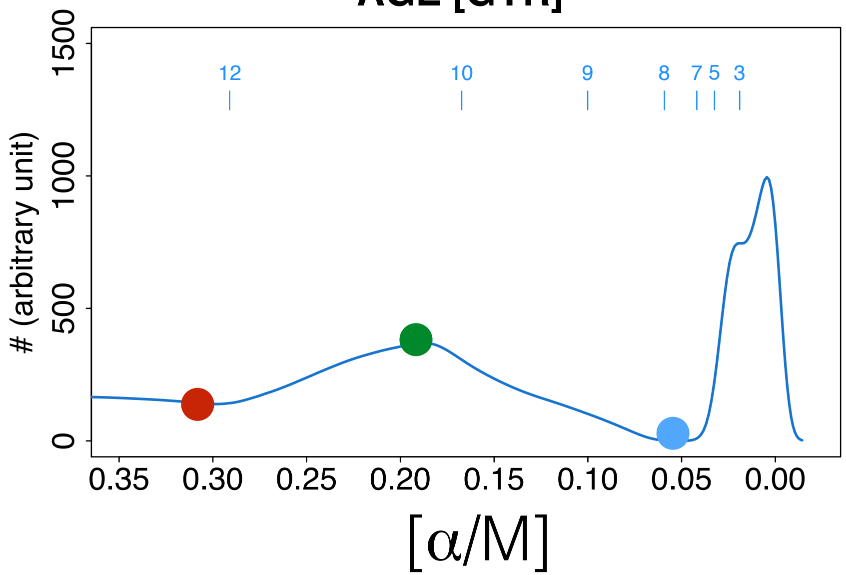




A fast decrease of the SFR must occur in order to reproduce the dip at [α/Fe]~0.1

Why is the alpha distribution bimodal ?





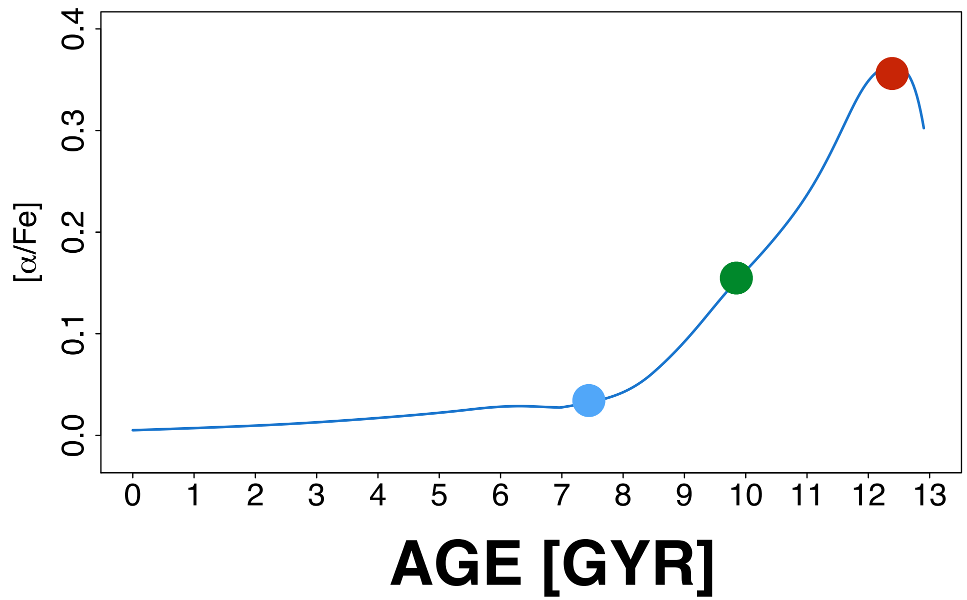
Two effects :

Alpha-rich peak (thick disk):

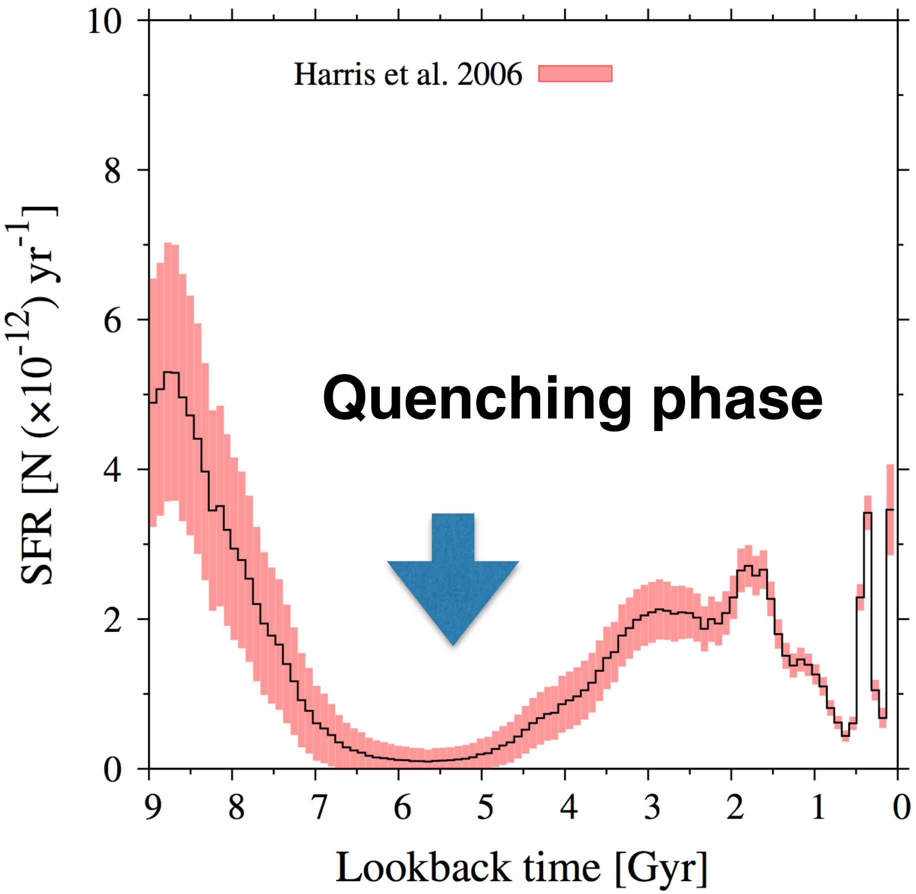
Caused by the important SFR at early times and drop between 10 and 8 Gyr

Alpha-poor peak (thin disk):

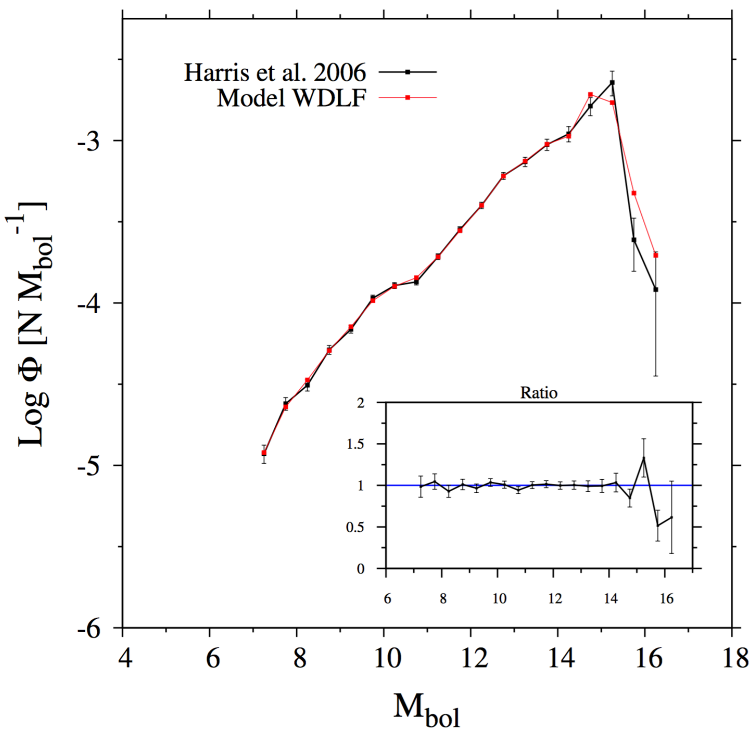
Caused by the slope of the age-alpha relation at age<7Gyr : stars accumulate at the same [α/M]



Other signatures of this « quenching » phase ?



Derivation of the SFH from the white dwarf luminosity function, Rowell (2013)
See also inversions of the HR diagram, Cignoni et al. (2006)



The age scale is different, but the same feature is present

Is it quenching ? probably yes

- It is *strong suppression* of the SF activity (x10 decrease),
- *Related to the thick to thin disk transition*
- *Occurs at the same epoch/high redshift MW analogues (z=1.6)*

What is the origin of this quenching episode?

- The quenching in the Milky Way occurred on a relatively short time scale. The star formation activity decreased by an order of magnitude to almost zero within less than 2 Gyr.
- The phase of total quenching (SFR=0) itself lasted about 1.5 Gyr.
- There is chemical continuity between the populations formed before and after the quenching episode.
- In extragalactic studies, quenching is often associated to the bulge (but are these really bulges?), in the Milky Way, it is associated to the thick disk.

The chemical continuity between the thin and thick disks implies that gas has not been re-accreted to form the thin disk after the quenching episode

Quenching in the MW was apparently not caused by gas exhaustion

Connection with the bar ? Extragalactic evidence

Epoch of bar formation for MW-type galaxies z~ 1 (8 Gyr) (Sheth et al. 2008, Melvin et al. 2014): precisely the epoch of the quenching episode in the MW

Also compatible with other clues observed on local galaxies:

- Gas rich galaxies hosting a strong bar are optically redder than similar gas rich galaxies without bars (Masters et al. 2012)

- Bars seem to be responsible for a « star formation desert » (James & Percival, 2015, 2016) inside corotation

What origin?

Gas funneled to the galactic center? cf Athanassoula et al. (2013) , Gavazzi et al. (2015). Would imply gas replenishment, and high mass concentration in the center: not likely

Could the strong bar maintain high turbulence in the gas and prevent SF activity for some time ? Needs further study, both numerical simulations and observations.

Conclusions :

The MW thick disk did not formed inside-out

The Milky Way quenched its star formation 10-7 Gyr ago

The origin of this quenching episode is not known, but possibly related to the bar

About the continuity of the thick and thin disks:

- there is continuity because the thick and thin disk have continuous chemical properties: the thin disk inherited the chemical traits of the thick disk, they are parent populations
- but they are separated populations, formed at distinct epochs