# Dissecting a Milky Way - like galaxy from the inside

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# Outline

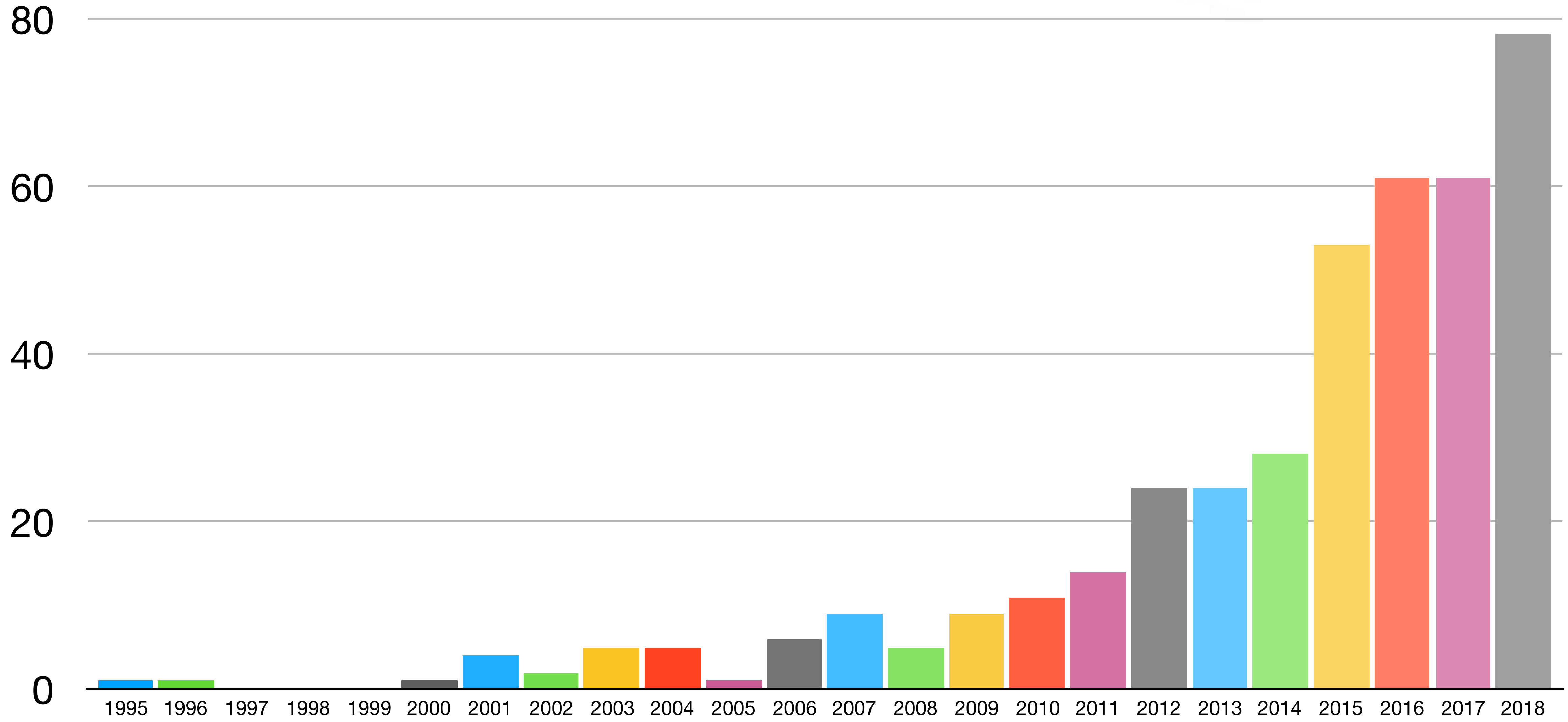
1 - Why are we interested in MW-like galaxies?

2 - What populations made the mass growth of the MW?

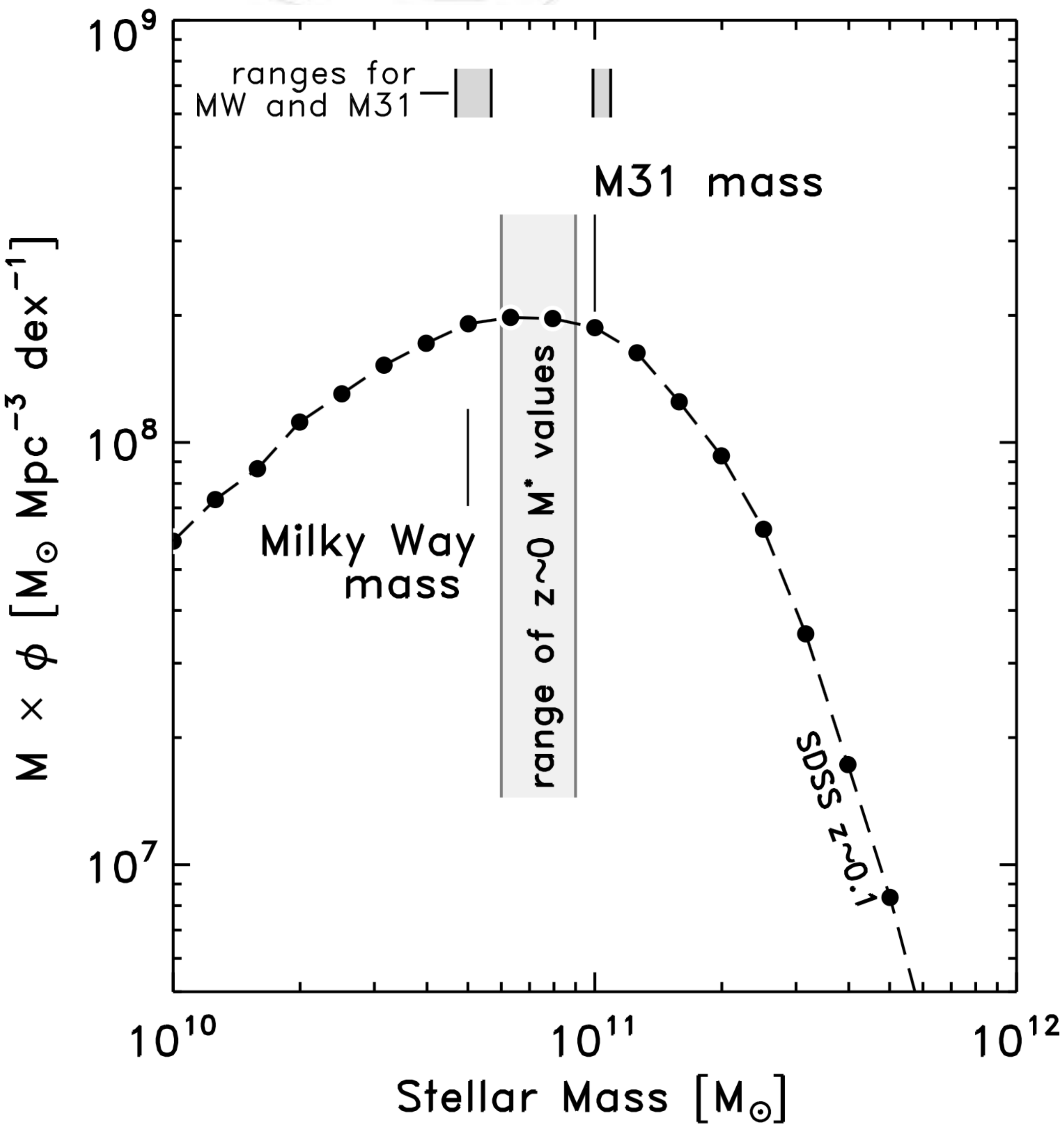
3 - Highlight from Gaia: searching for the in situ halo of the MW

# 1 - Why are we interested in MW-like galaxies?

## ADS ‘Milky Way-like’ matches in abstracts since 1995



# Why are Milky Way-like galaxies interesting?




**The stellar mass of the MW is ~ 5. $10^{10}$ $M_\odot$**

**'A randomly chosen star in today's Universe is most likely to live in a galaxy with a stellar mass between that of the Milky Way and Andromeda.', Nelson et al. 2018**

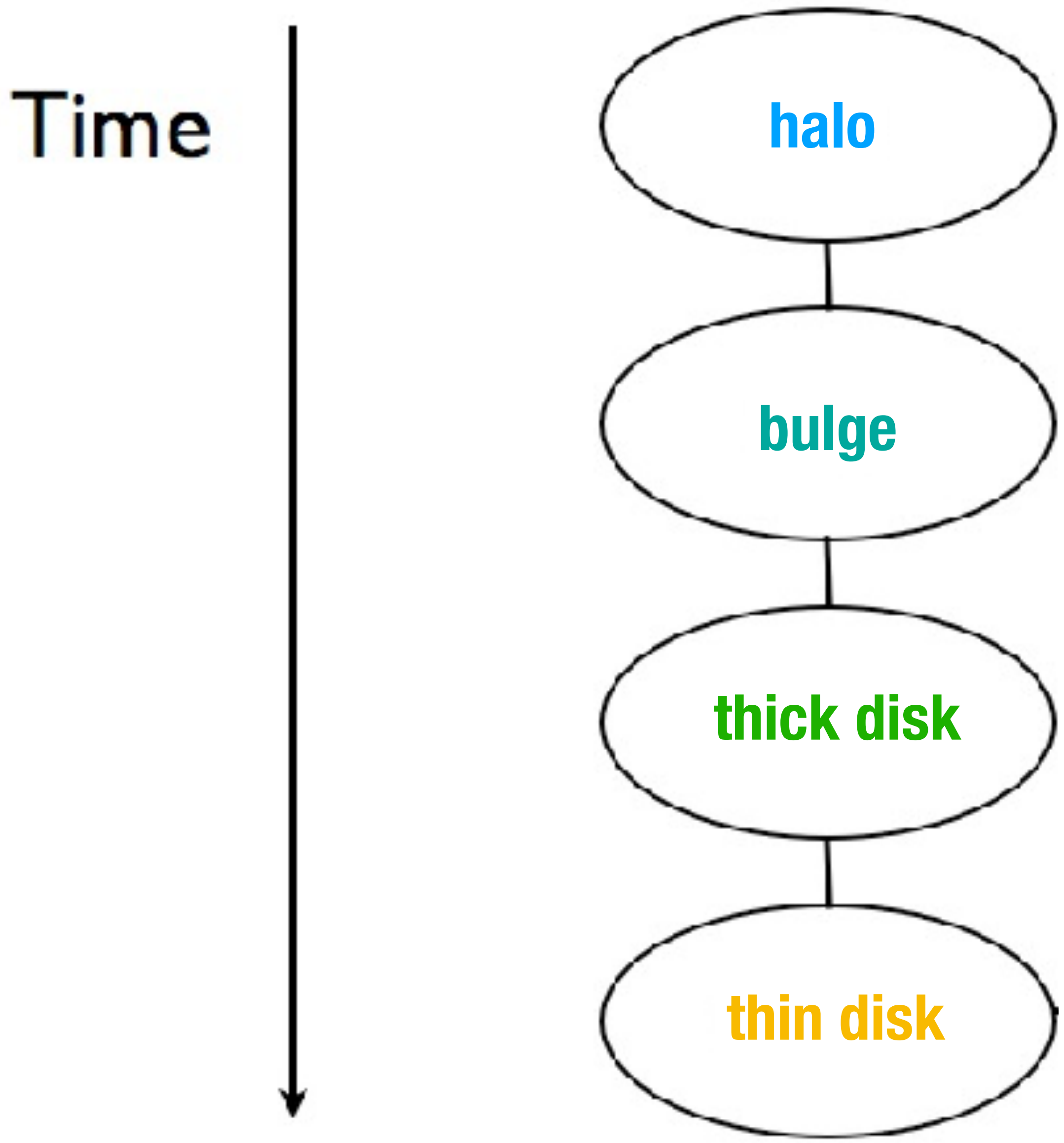
Stellar-mass density distribution of galaxies

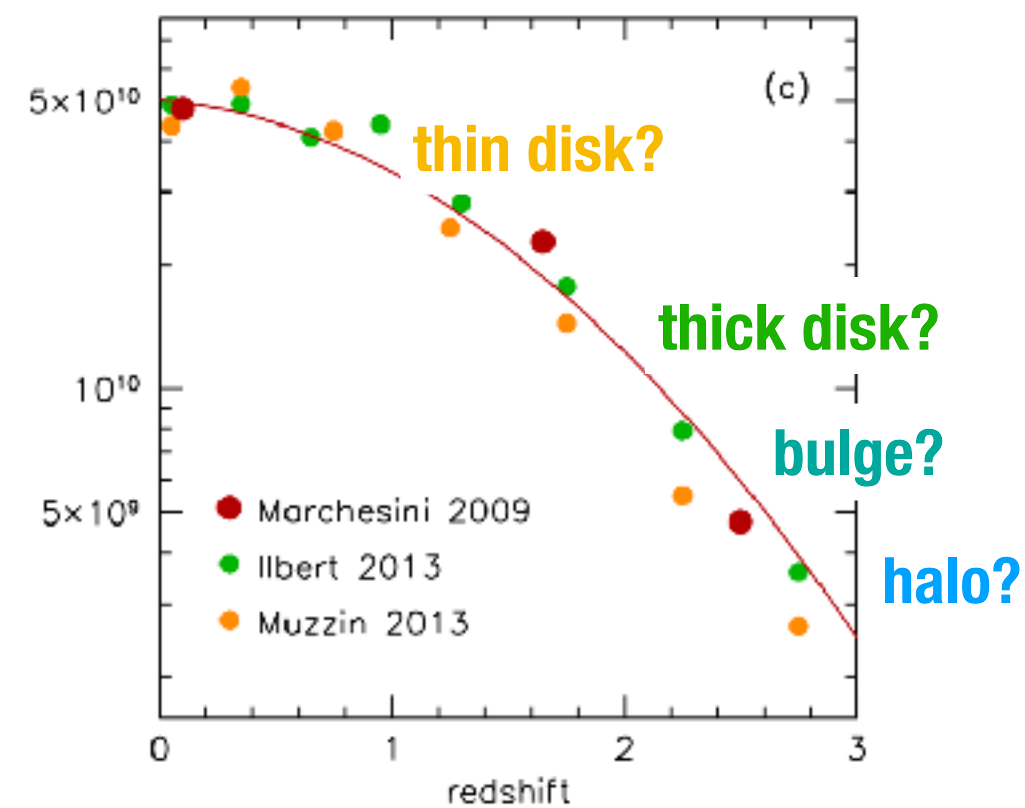
**Papovich+2015**

**In the local universe, most stellar matter is in ~ MW-mass galaxies**

- **We want to know how they form**

# A Milky Way like galaxy?

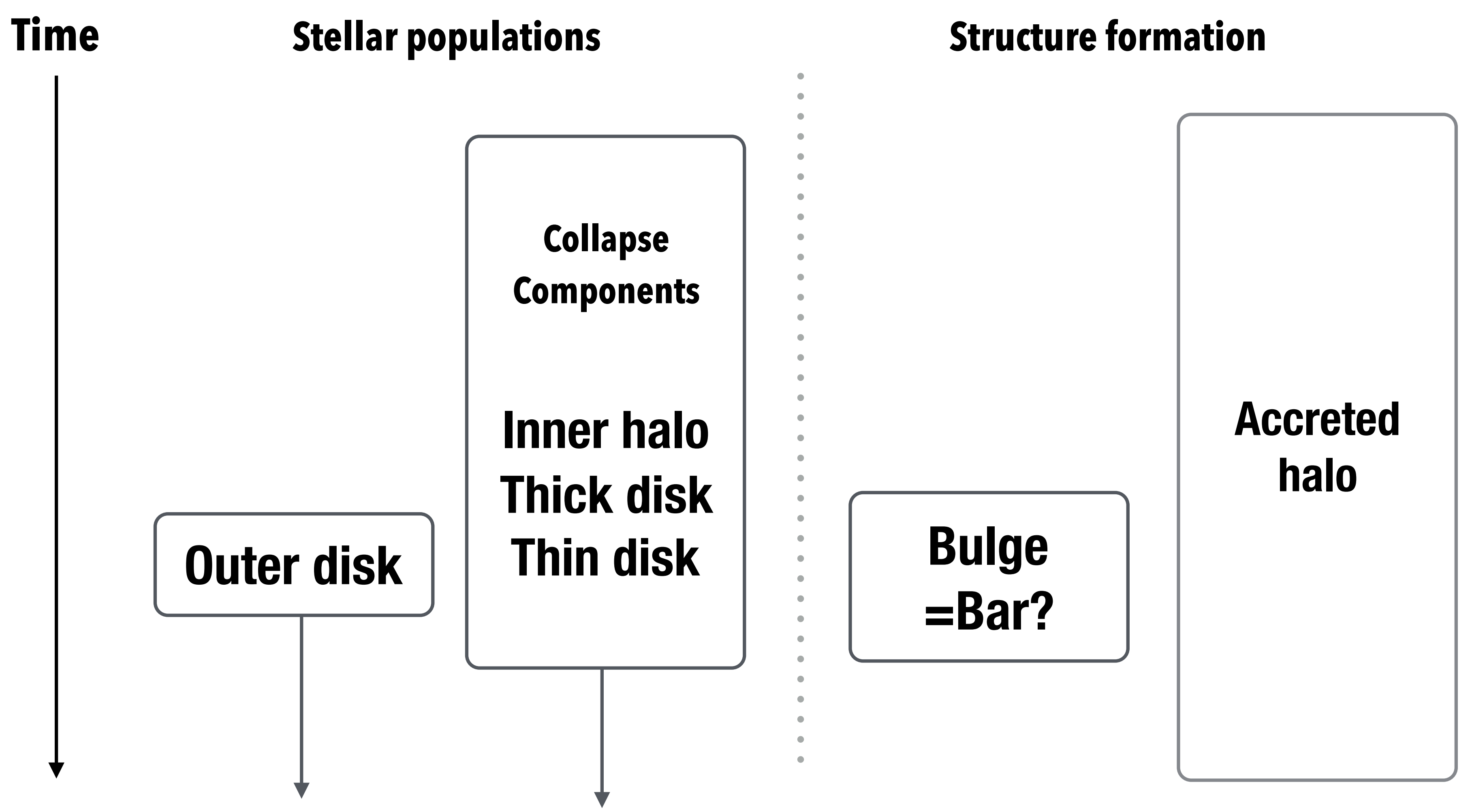


# The Milky Way

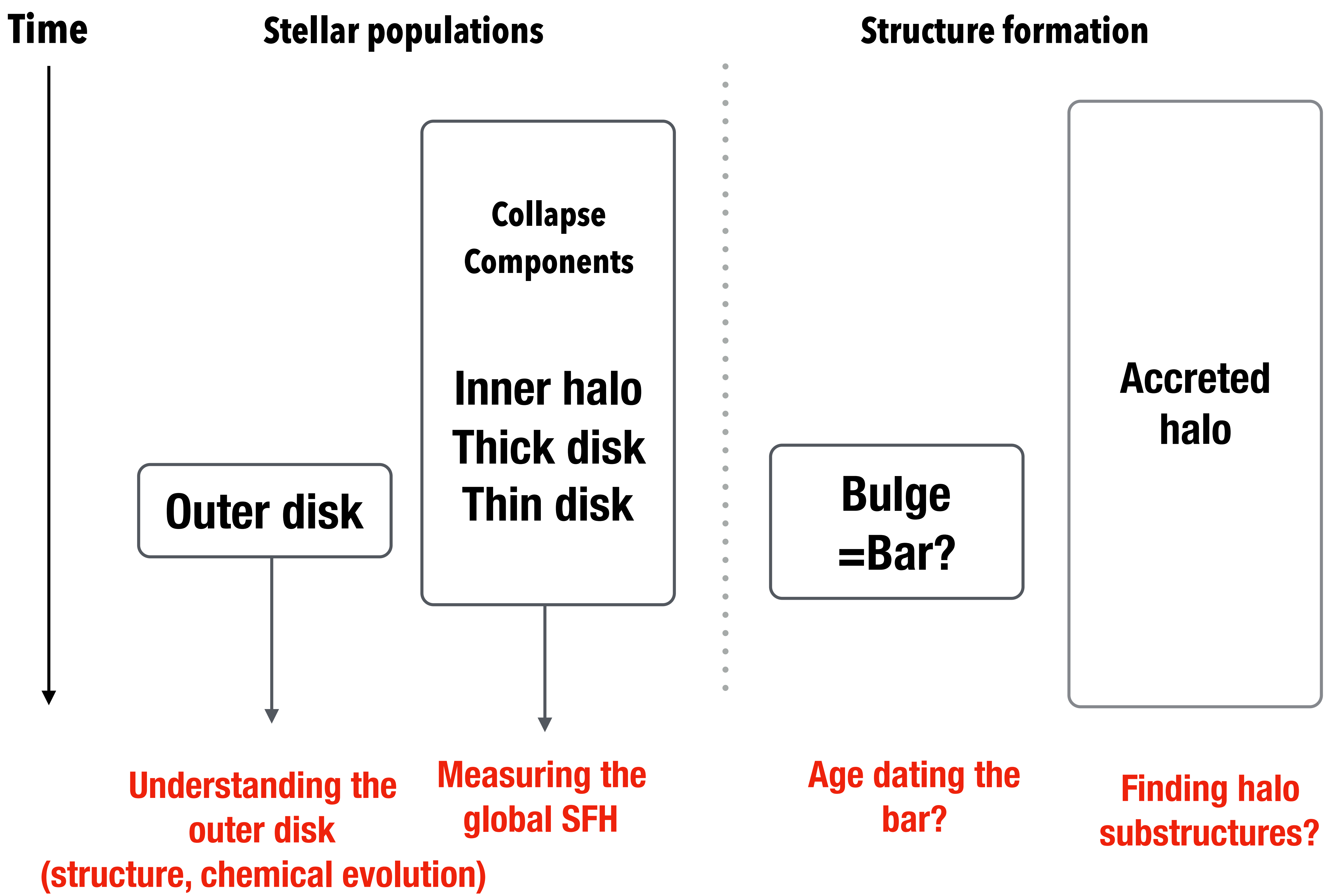
Gas history (accretion, consumption)

Stars history (accretion, redistribution)




**What we have been doing in the last 20 years is largely to (try) deconvolve the in situ / ex situ components**

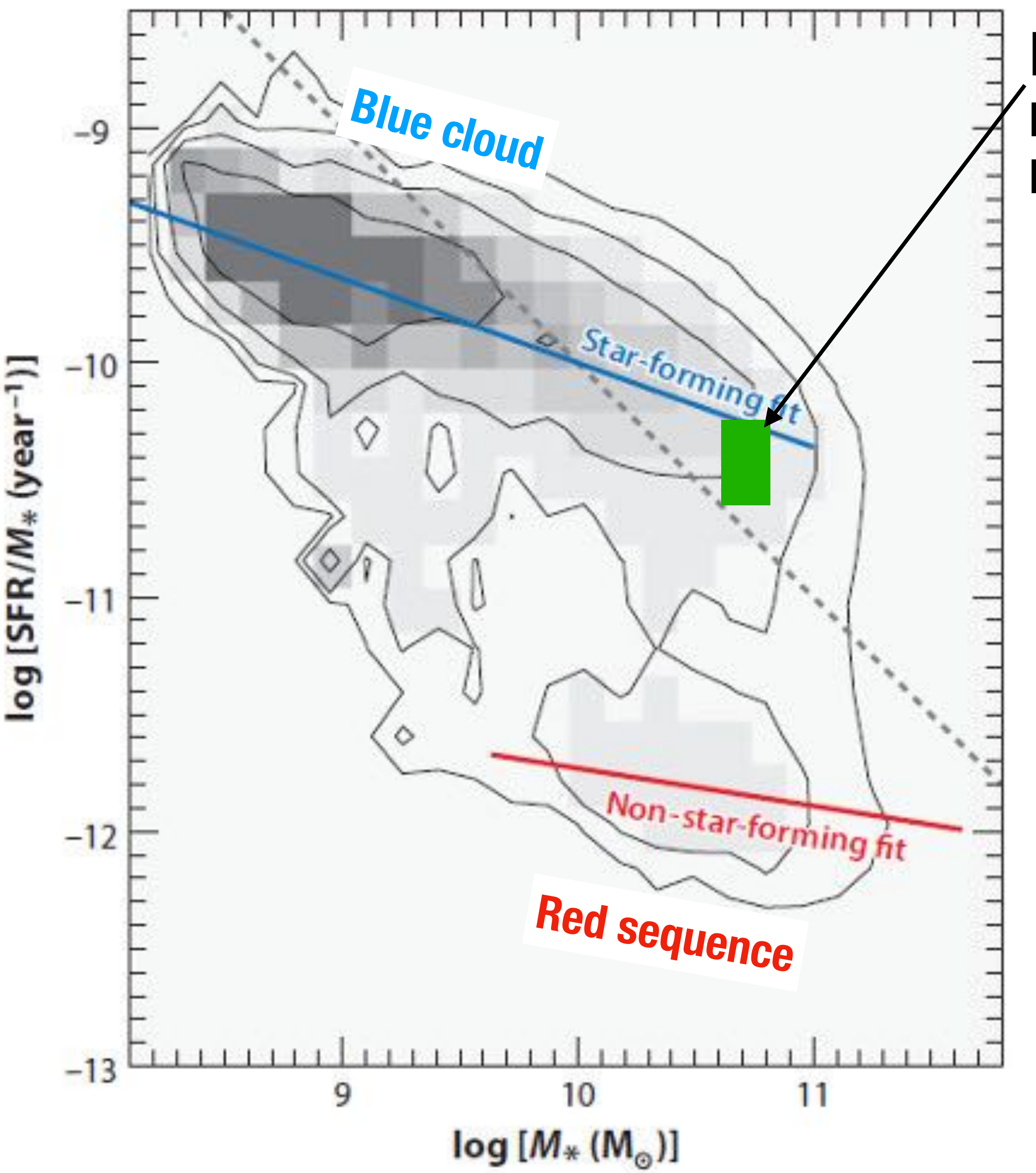
# Some of my favorite questions where Gaia will help us



## 2 - What populations made the mass growth of the MW?

## Measuring the Star Formation History of the Milky Way

# MW: present star formation properties




**Milky Way**

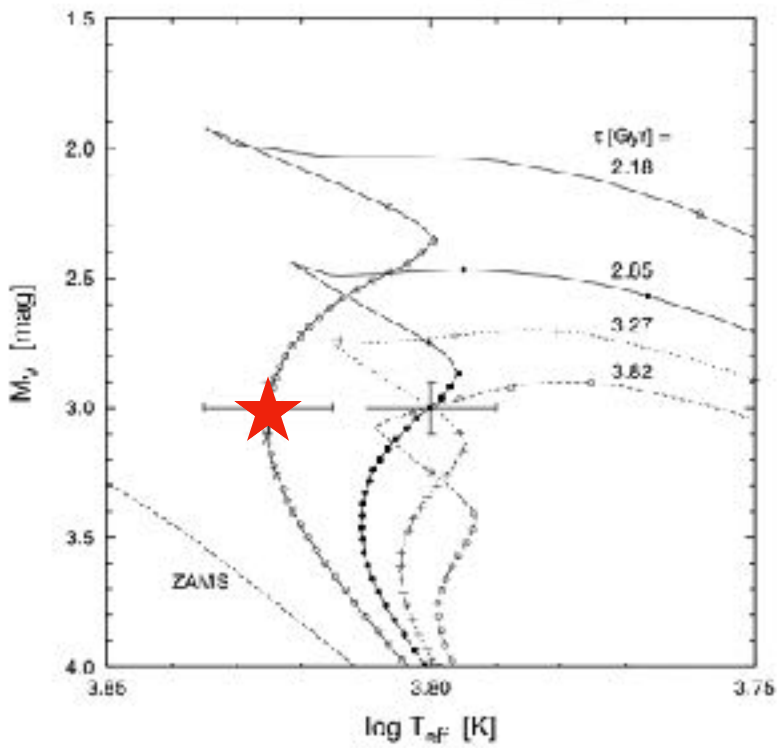
**log(M(M☉))= 10.69**

**log(SFR/M$_{MW}$(year$^{-1}$)) ~ -10.22**

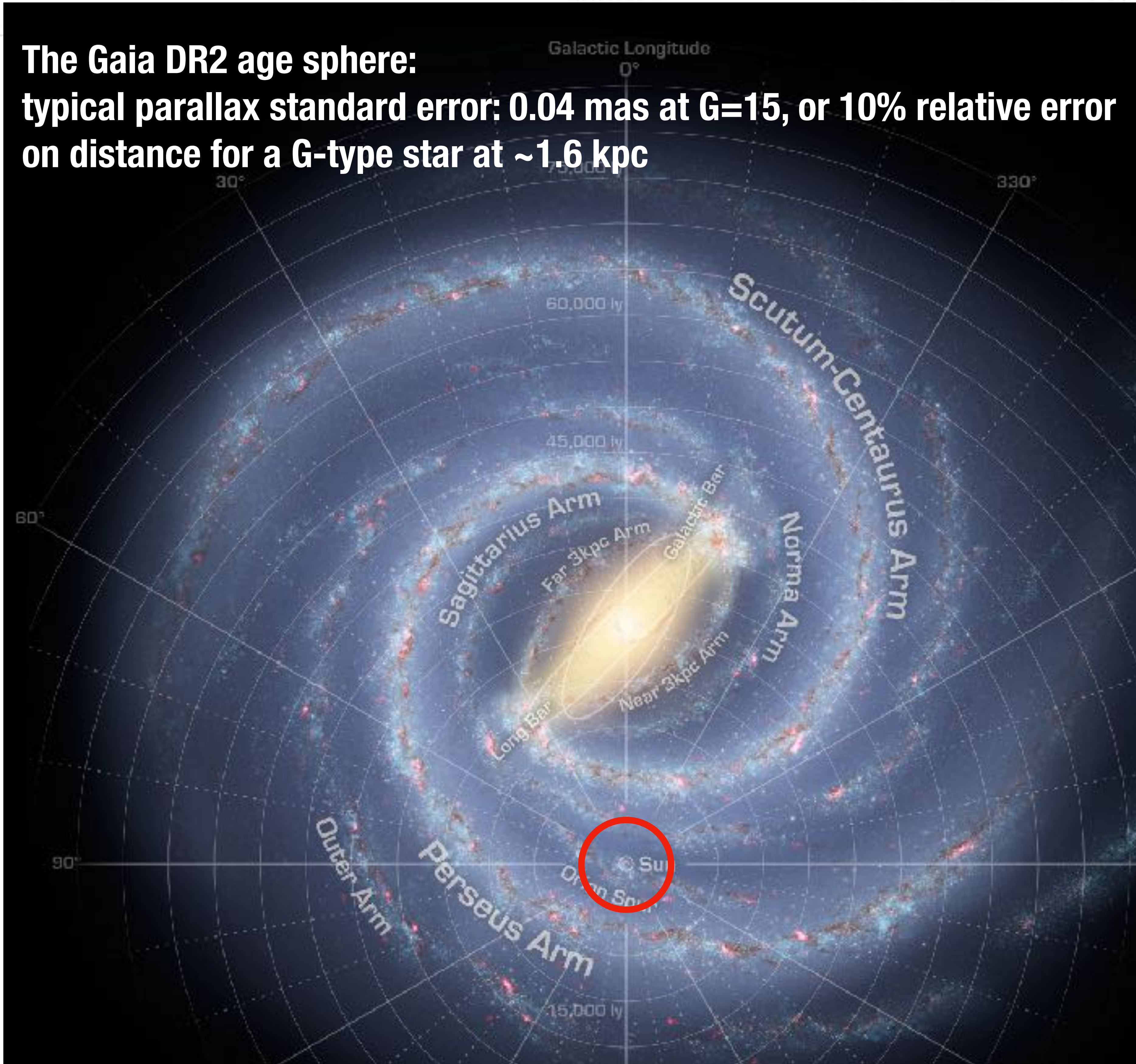
**The MW is on the low side of star forming galaxies: it has almost finished forming stars (SFR~1-3 M☉.yr$^{-1}$), increasing its stellar mass by only a few % per Gyr**

**How do we measure the Star Formation History of the MW?**

# From stellar ages: Even with Gaia, this is going to be difficult. WHY?




**The Gaia DR2 age sphere:**
**typical parallax standard error: 0.04 mas at G=15, or 10% relative error on distance for a G-type star at ~1.6 kpc**



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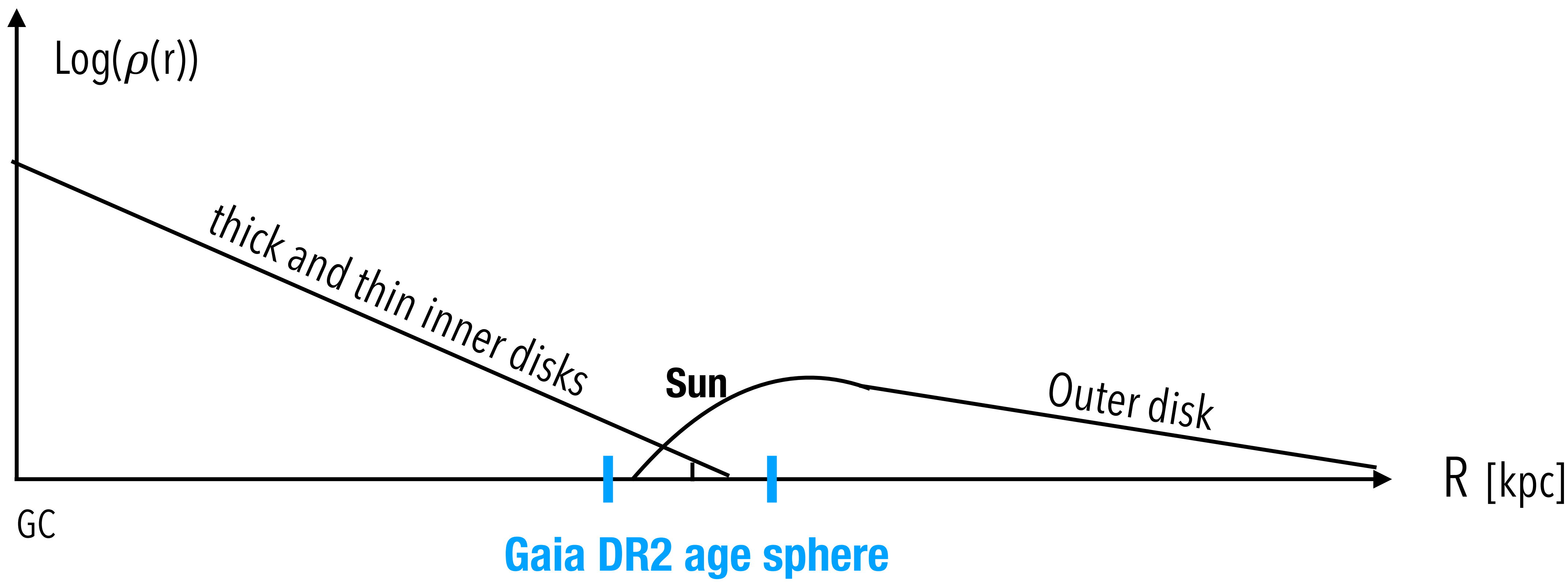
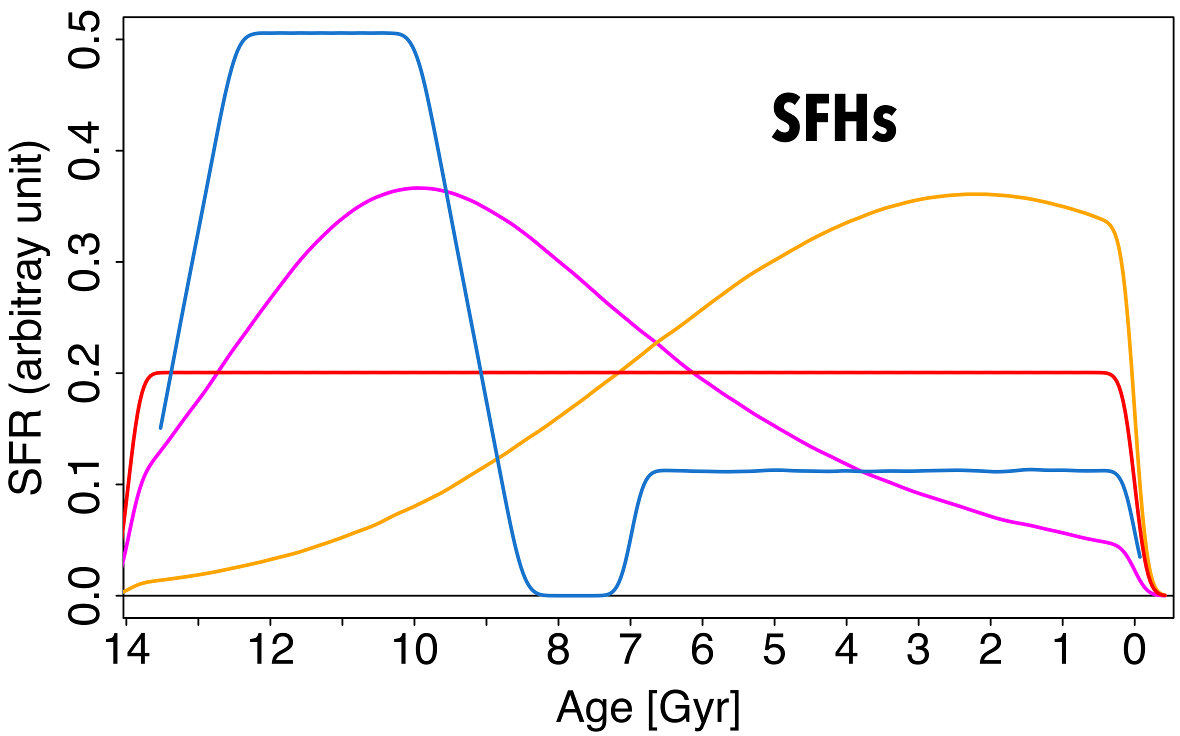


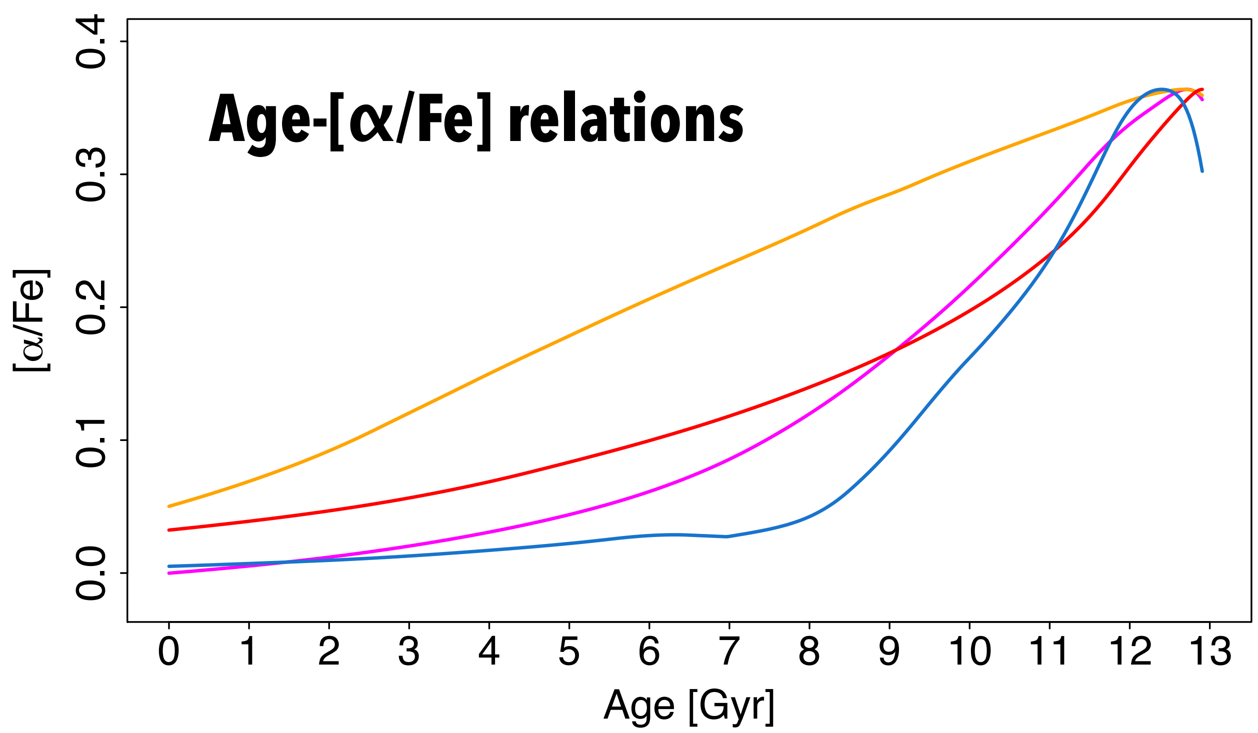

**Local age distribution strongly biased against old stars**

**The inner disk, which makes up most of the mass of the MW, is only a few % at the solar vicinity**

**Go for galactic archeology from spectroscopy ➡ the intensity of the past SFR is imprinted in stellar abundances**

# The SFH of the MW is encrypted in chemical abundances of its stars



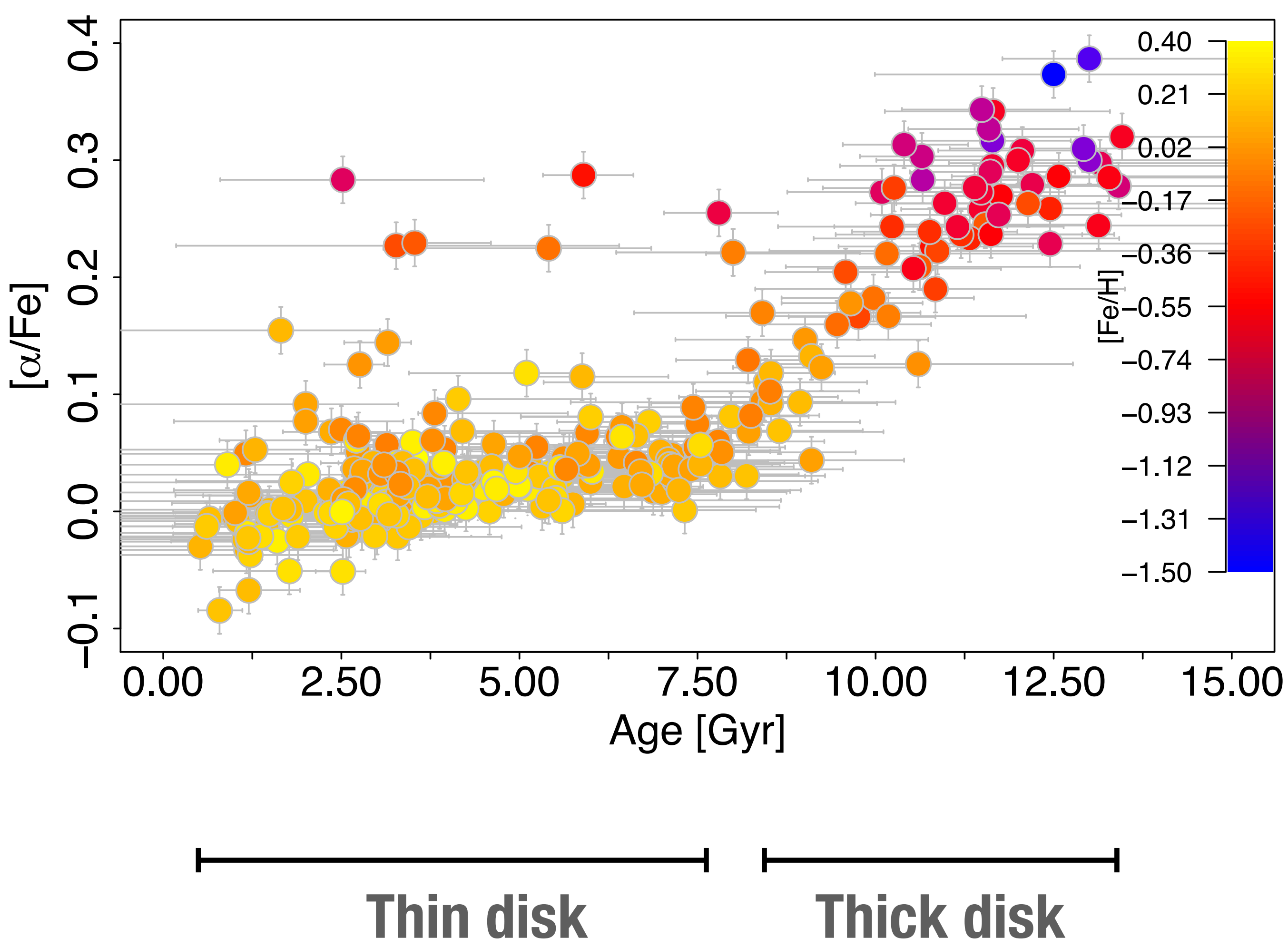




**The higher the SFR, the steeper the age-[alpha/Fe] relation**

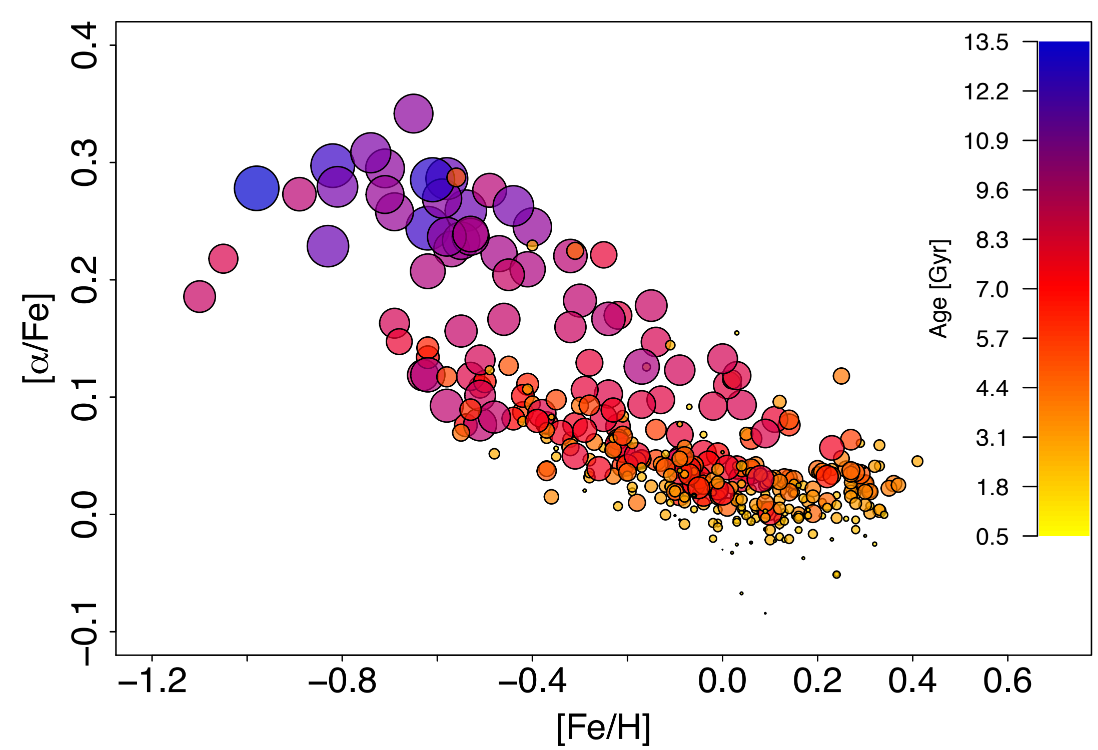
# The Star Formation History from stellar abundances

## Observed age-alpha relation from the solar vicinity, Haywood et al. 2013

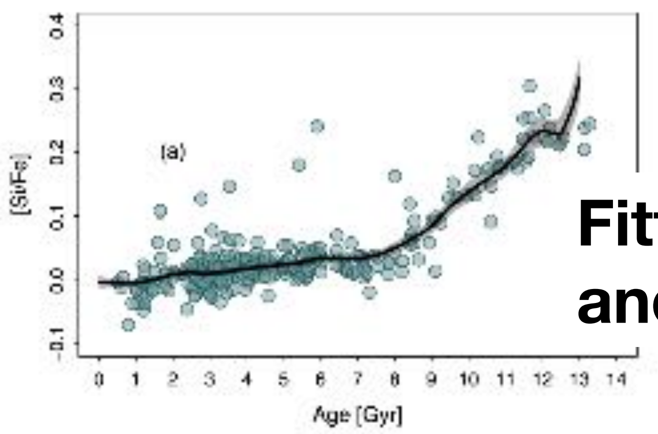
**From a sample of solar vicinity F,G stars at the solar vicinity:**
**and accurate spectroscopy from Adibekyan et al. (2012)**




**Two phases, corresponding to two separate phases of the SFH**

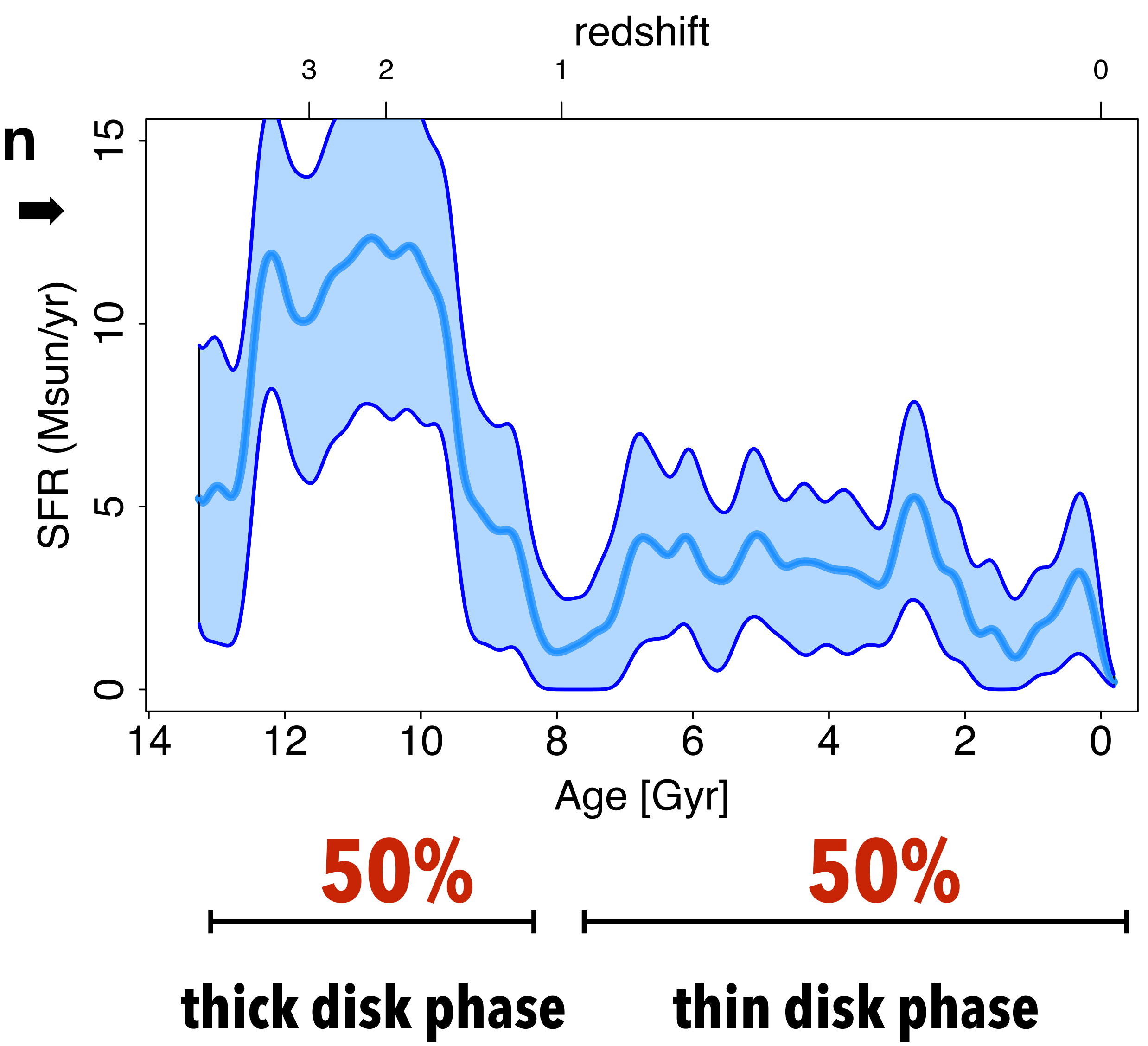


# The Star Formation History from stellar abundances




Fitted age-[α/Fe] relation and corresponding SFH ➡

Snaith et al. 2014, 2015

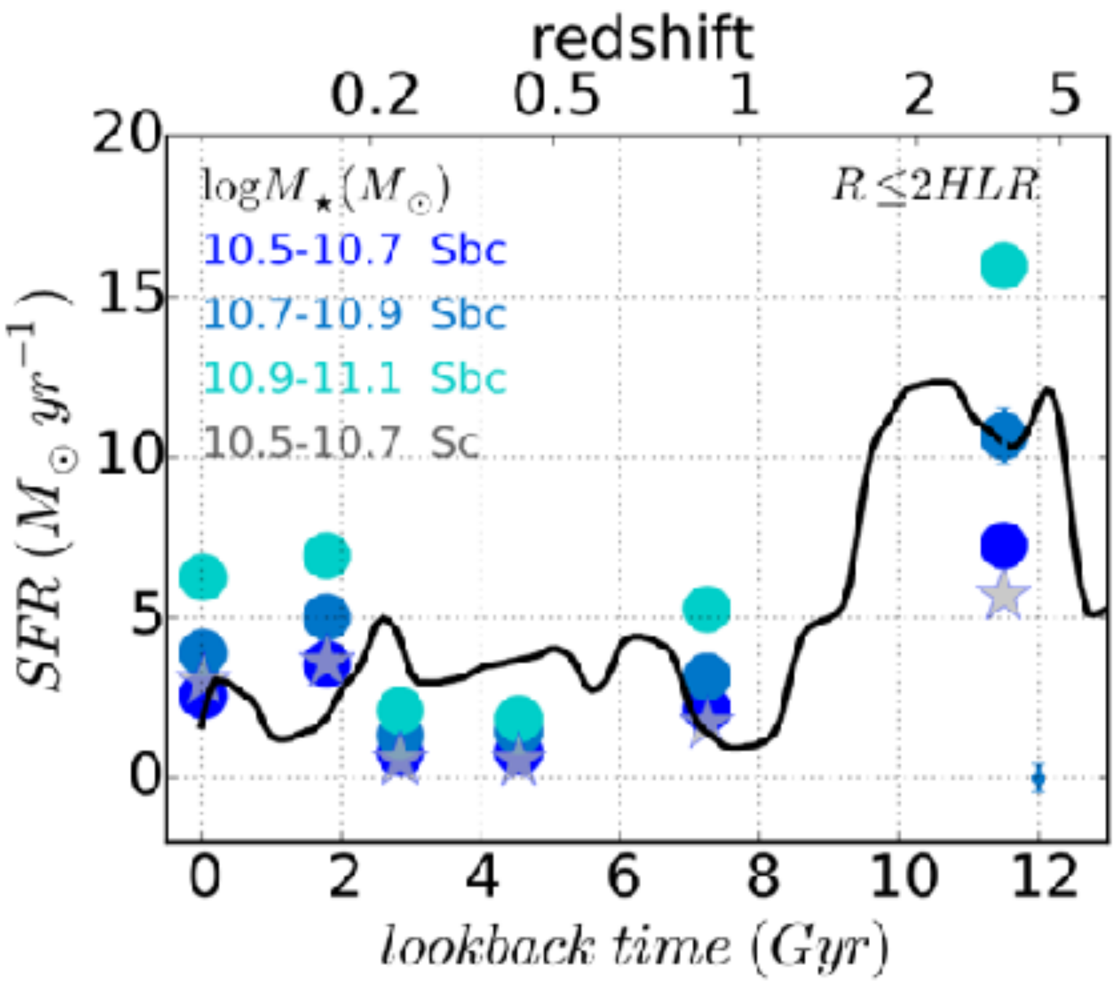



## Two results:

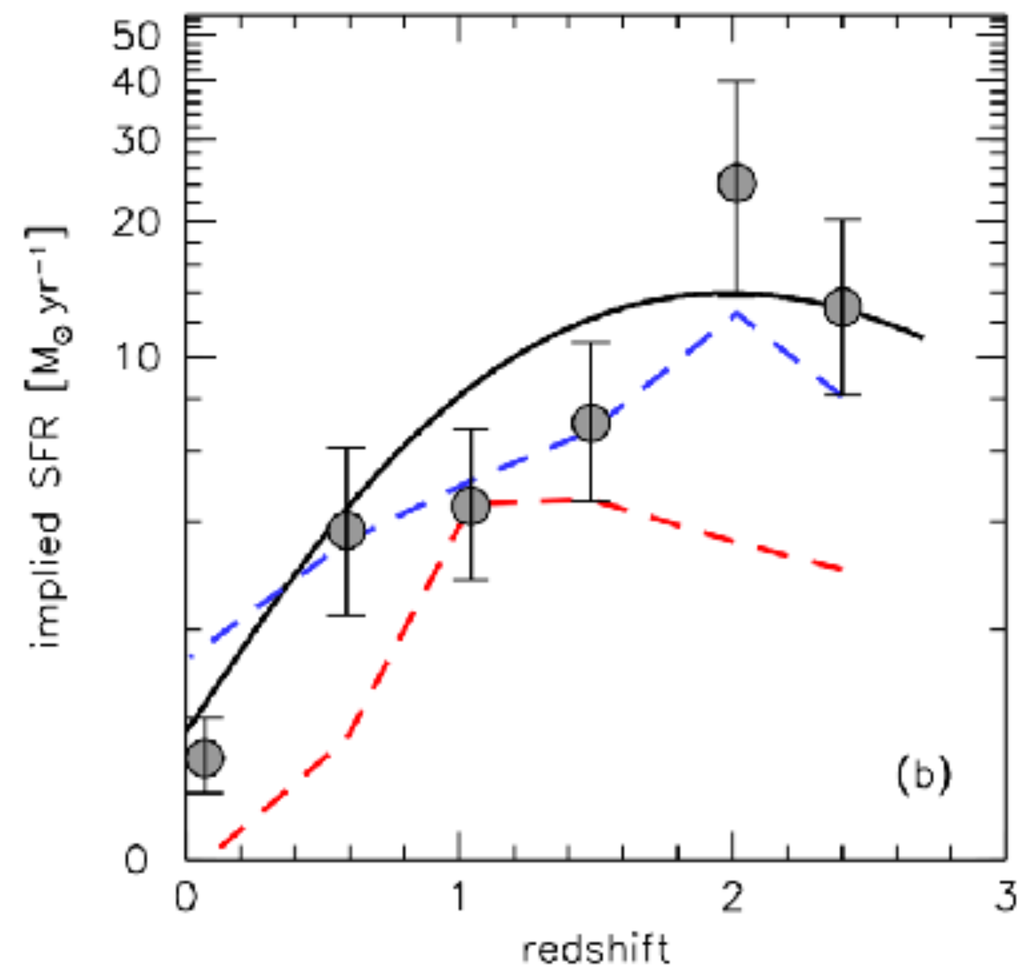
- The TD represents ~ 50% of the MW stars
- The TD formed stars at a rate of about 10-12 M⊙/yr

**The thick disk was the dominant epoch of star formation in the MW**

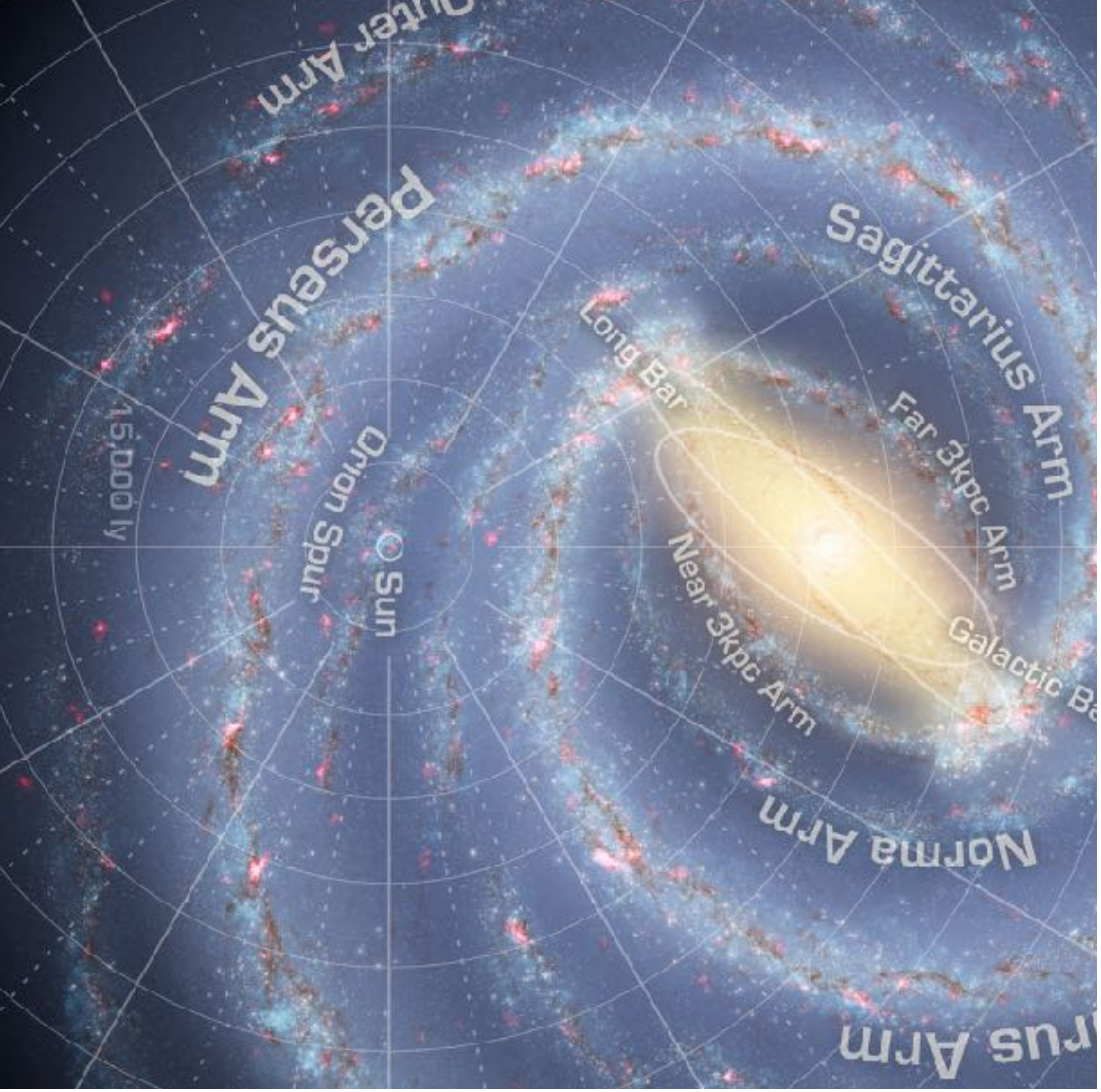
# Typical level of SFR for a MW-mass galaxy (~ 5. $10^{10}$ M⊙)



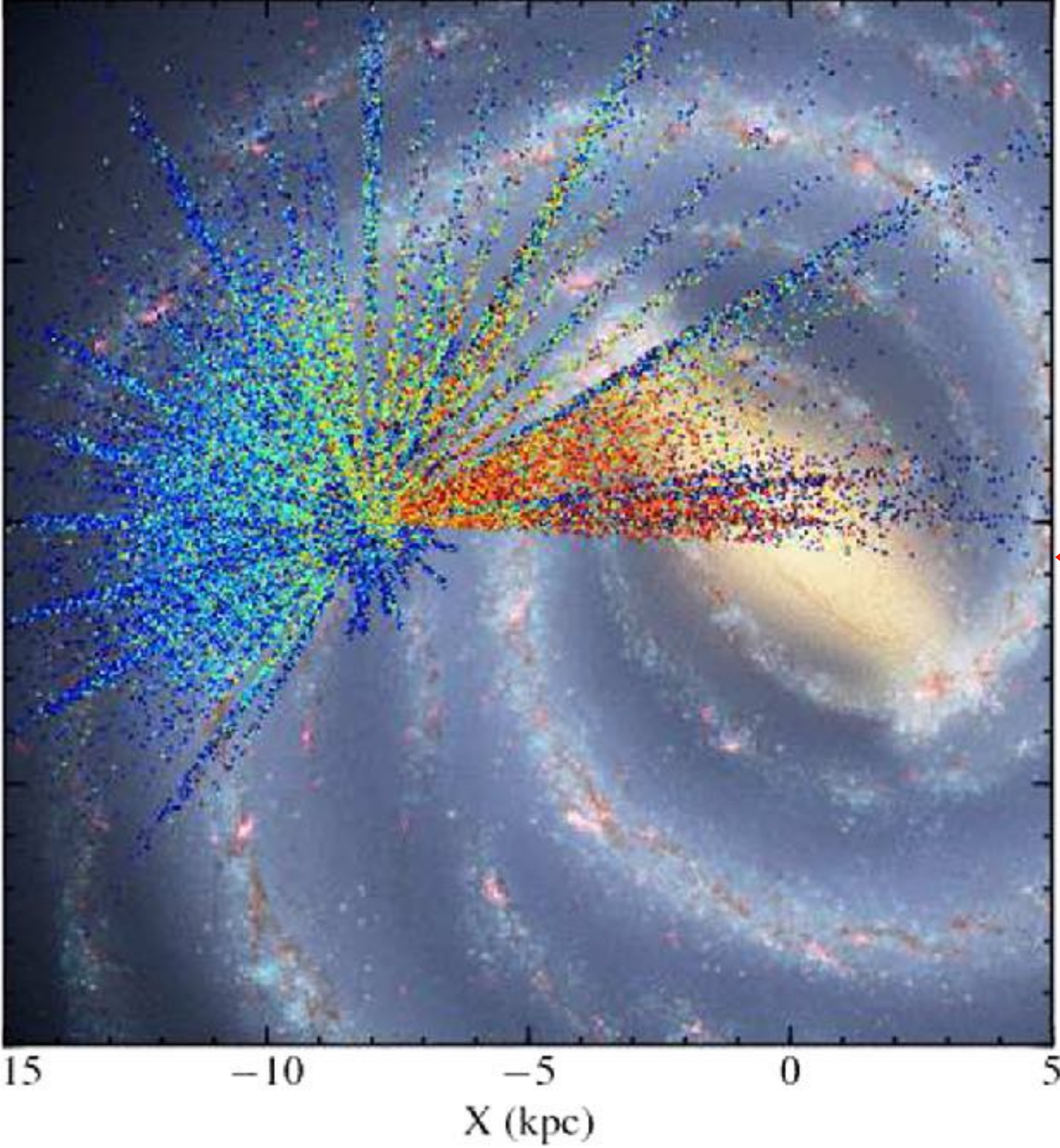

González Delgado+2017, CALIFA survey




van Dokkum+2013,
MW-like galaxies vs redshift




## What constraints on a larger scale?




# What constraints on a larger scale?

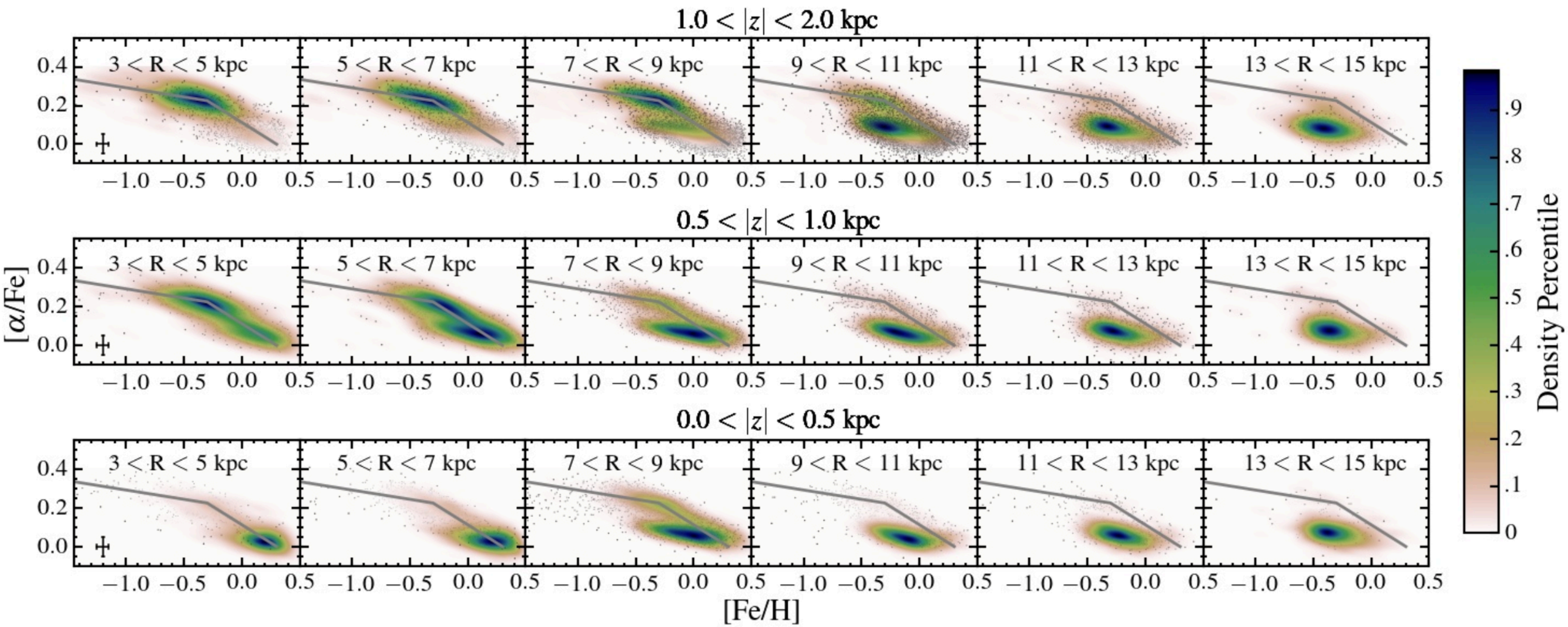
**APOGEE survey,**
**Majewski et al. 2017**

**High resolution, S/N>100**
**near infrared spectroscopy**
**APOGEE 1, 146000 science targets**

**APOGEE 2 (on-going),**
**300 000 science targets**

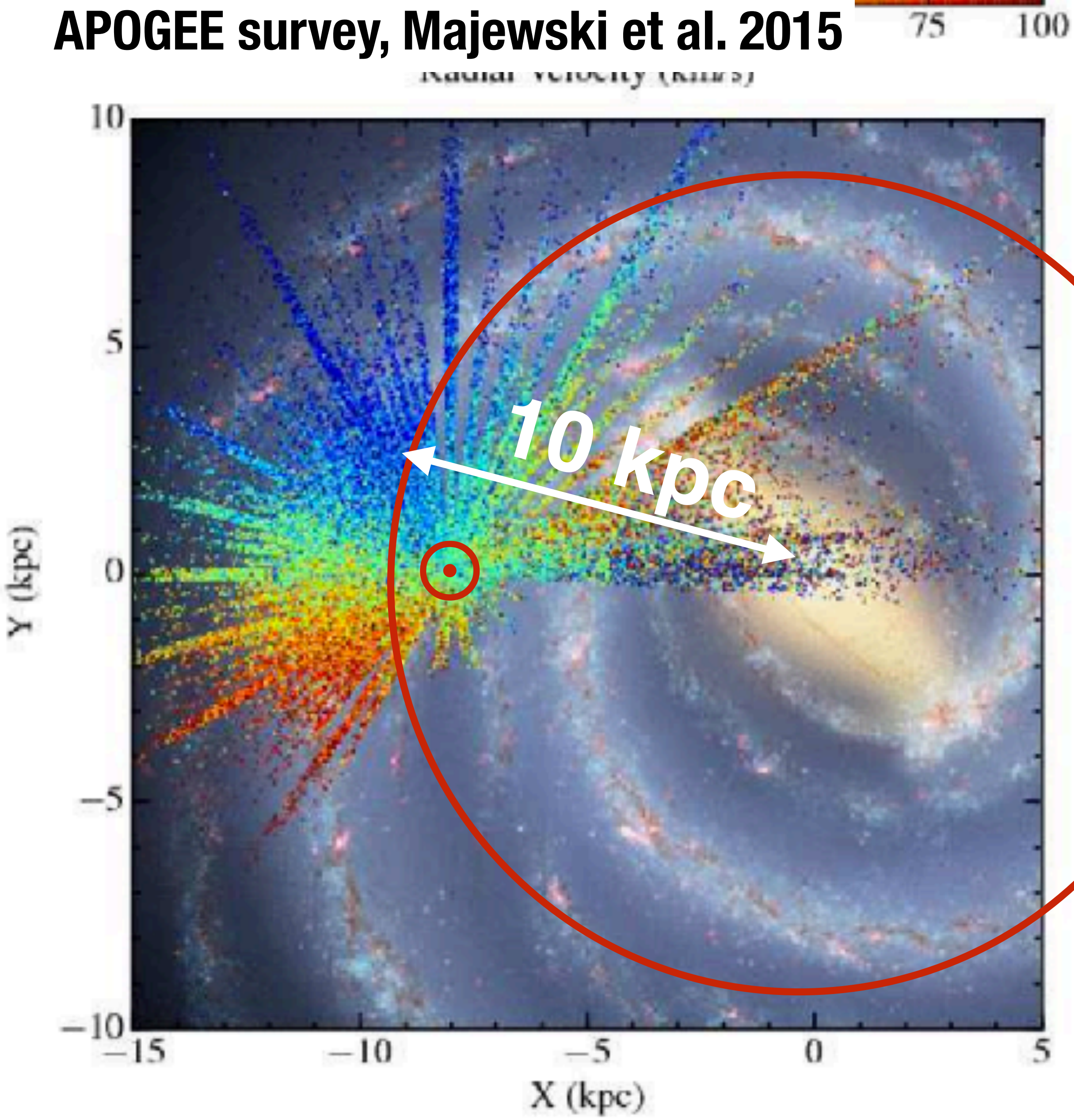
**The thick disk chemical pattern can be traced well beyond solar vicinity:**

**APOGEE shows that the alpha-rich sequence is present and strong at R<10kpc but is essentially absent from the outer disk (R>11 kpc)**

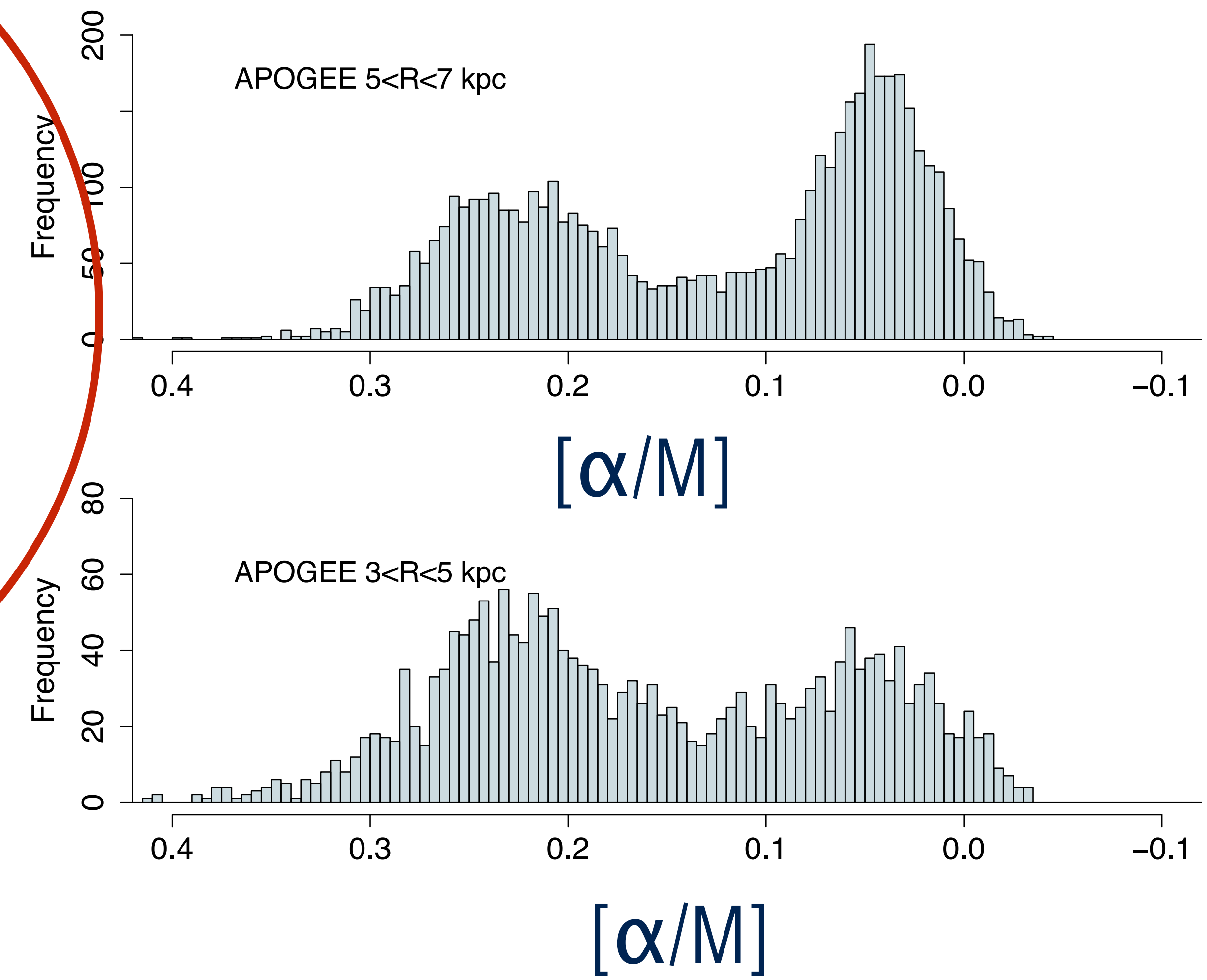



APOGEE survey, Hayden et al. 2015

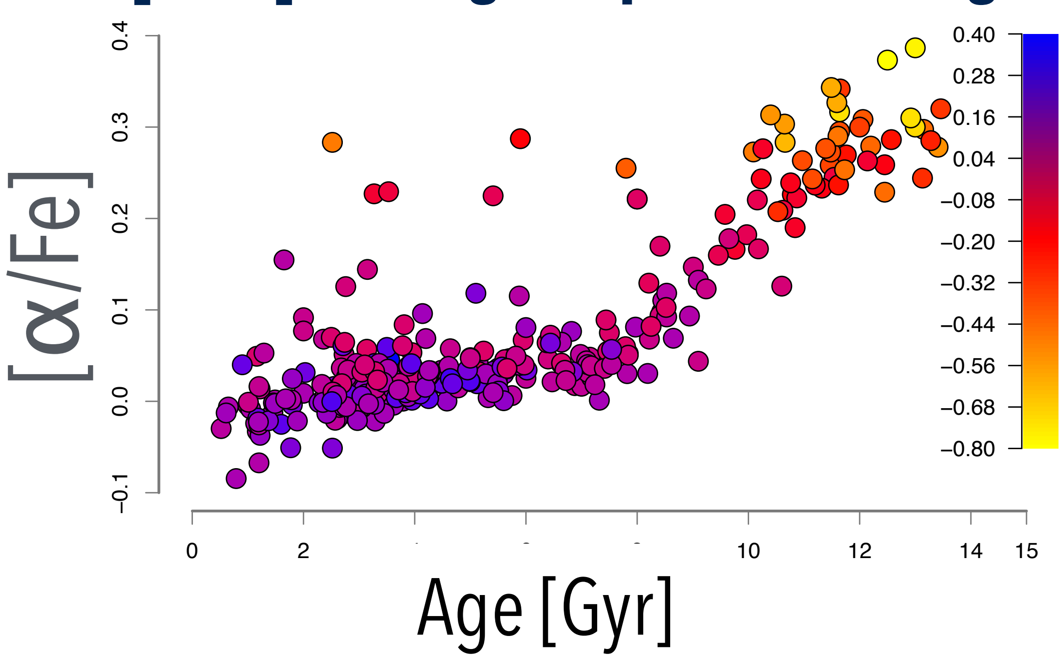
APOGEE survey, Majewski et al. 2015



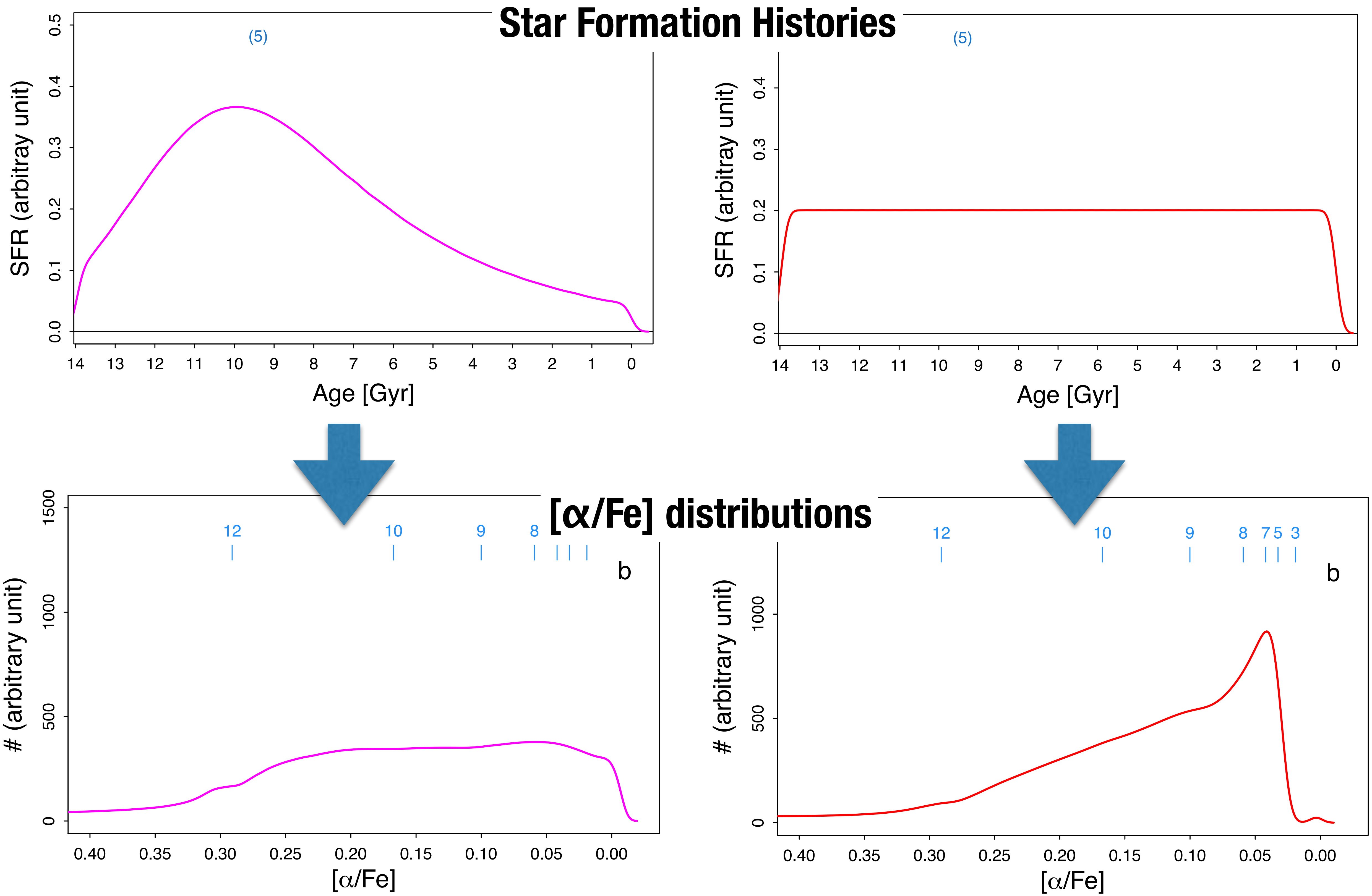

The [α/M] distribution is bimodal in all the inner disk



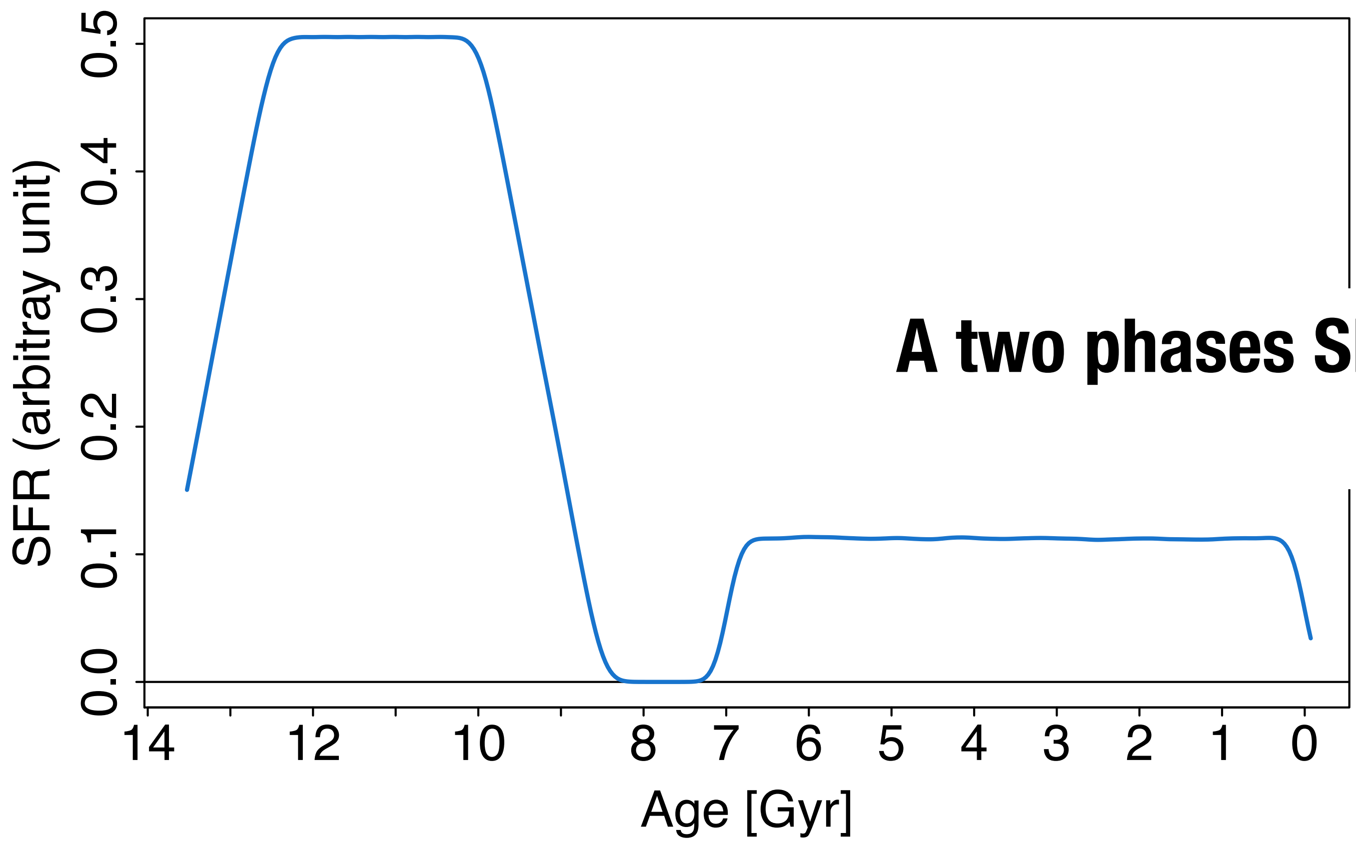

[α/M]s are good proxies for age



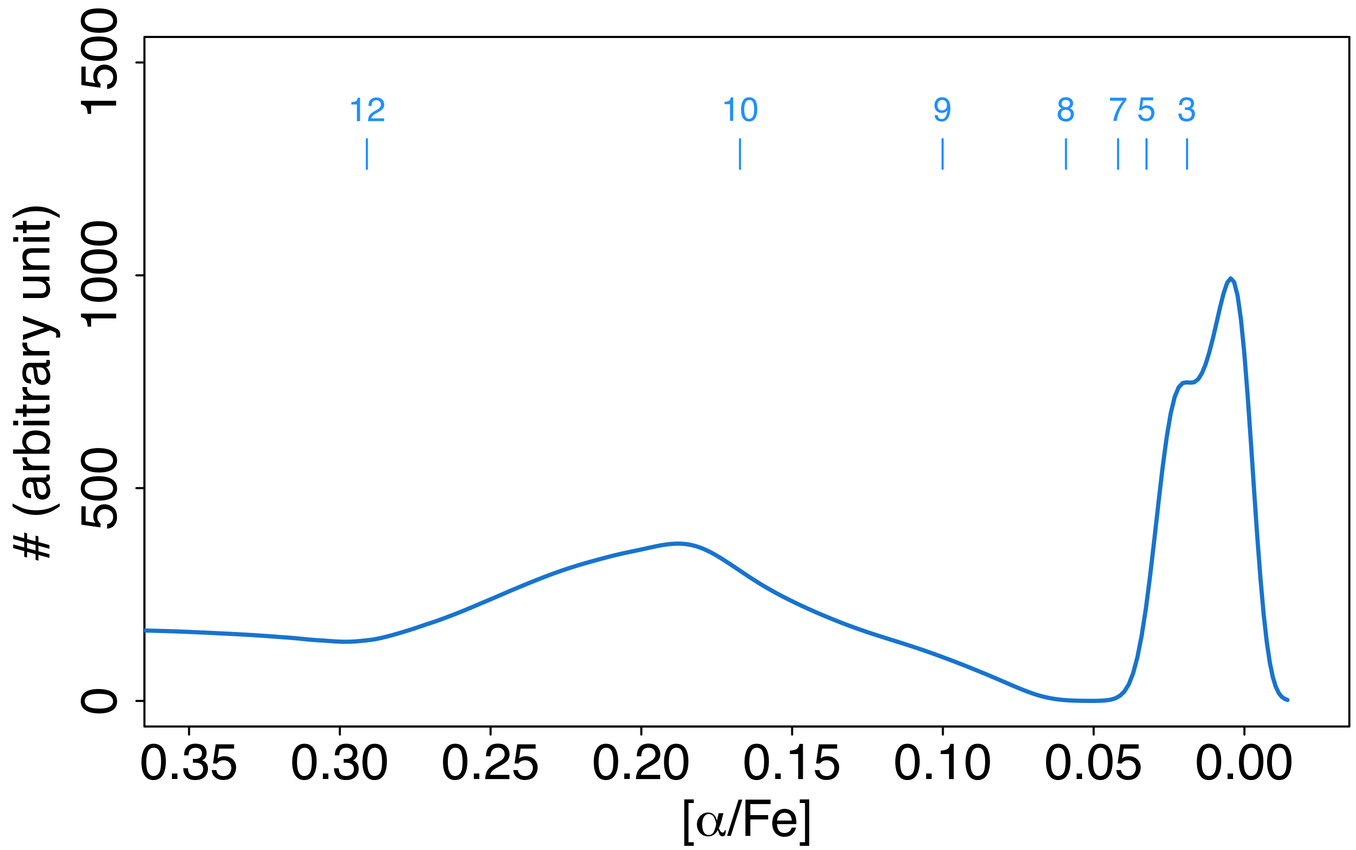

[α/M] distributions reflect the SFH




# A bimodal [α/Fe] distribution requires a very specific SFH

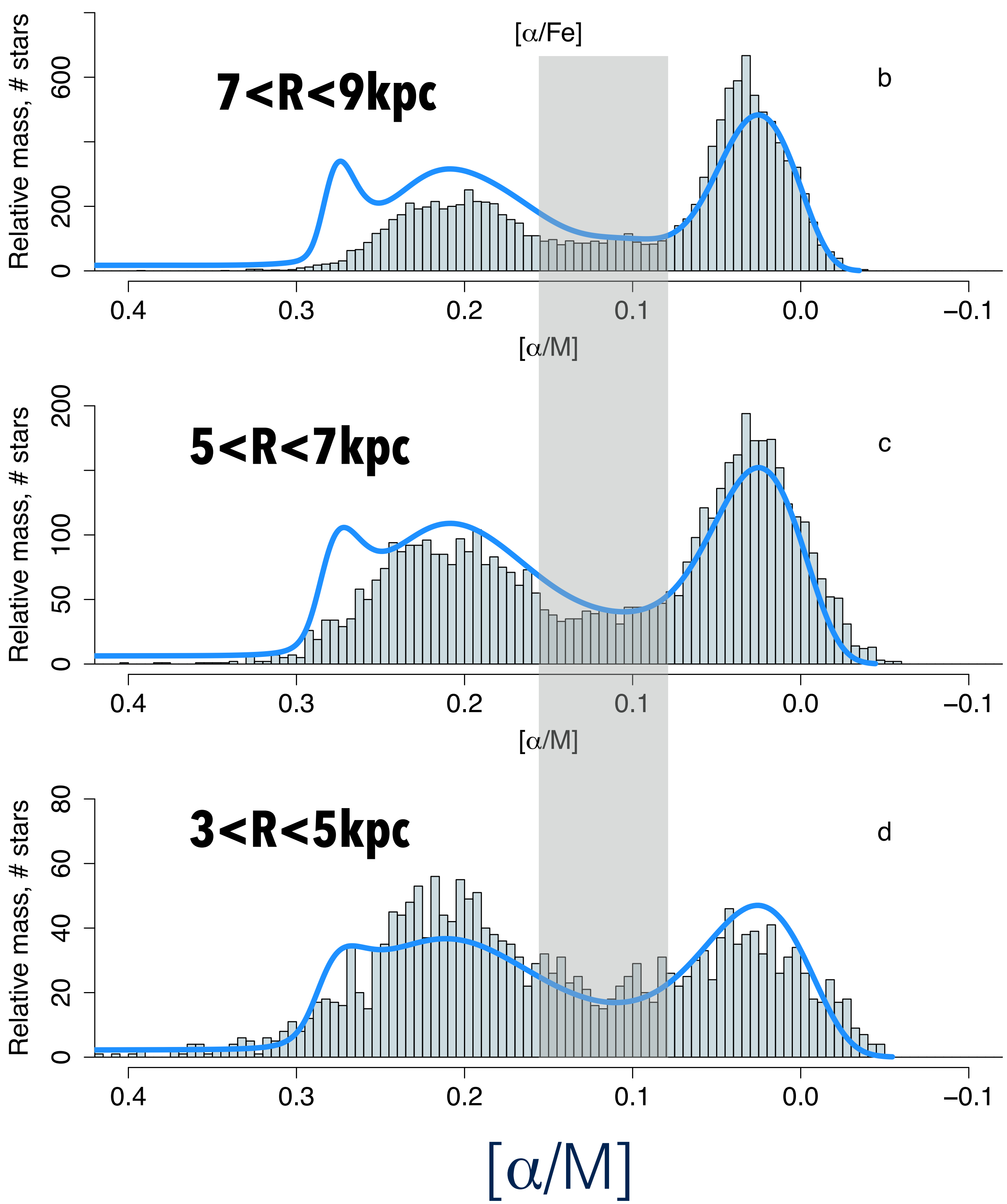



A two phases SFH generates…




…a bimodal distribution

# APOGEE data



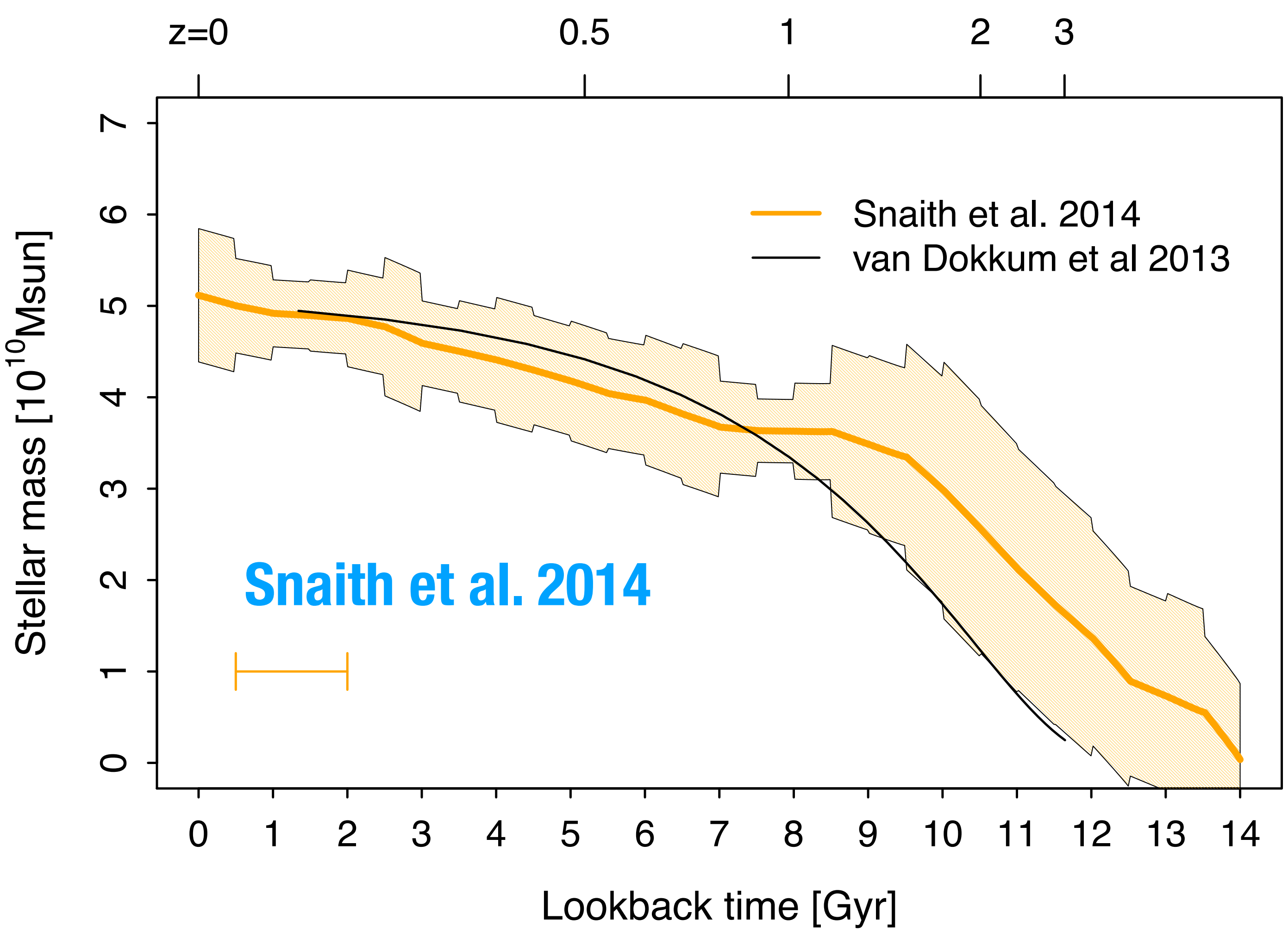


- The SFH deduced from solar vicinity data is a good match to large scale chemical data
- The minimum in the [α/M] distribution is associated to a 'quenching' episode experienced by our Galaxy about 10 Gyr ago (Haywood et al 2016)

# MW MASS GROWTH: the importance of the thick disk

**14% (of the total disk) (Bland-Hawthorn & Gerhard ARAA2016) ?**

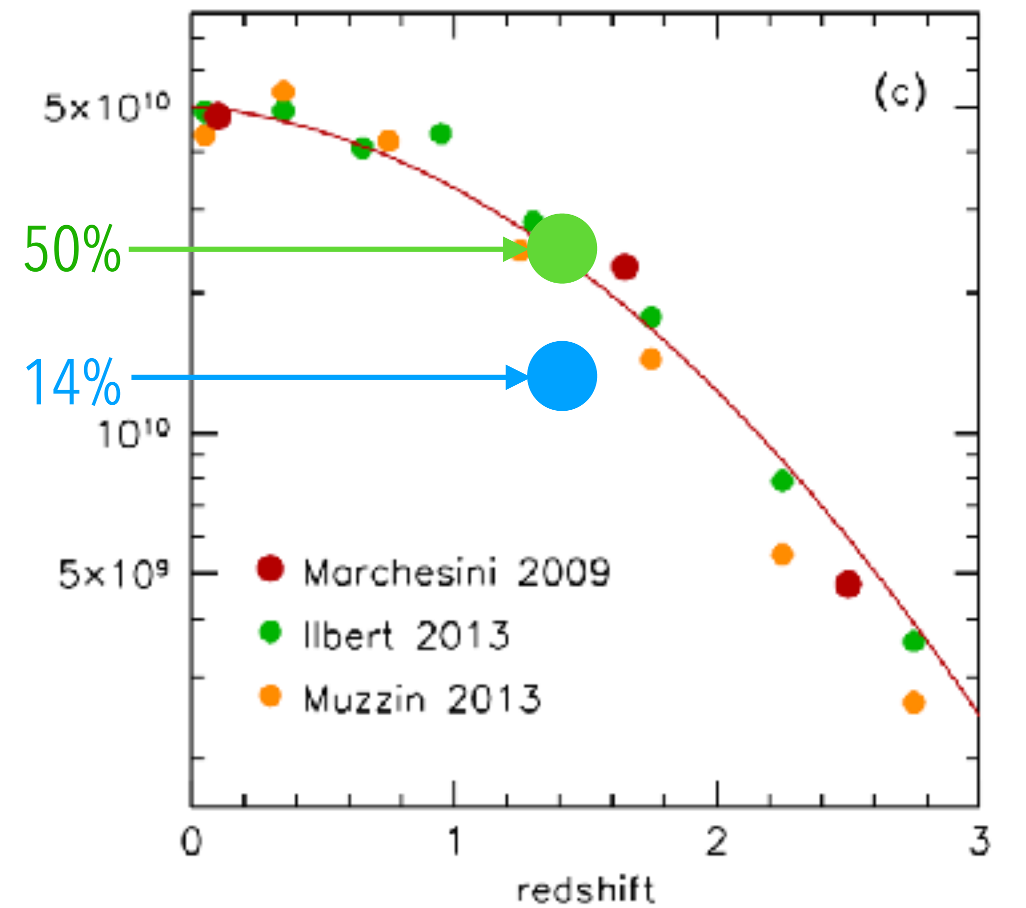
**50% Snaith et al. (2014, 2015) ?**




**thick disk phase**

**Mass growth of MW-type galaxies**

**van Dokkum+2013, cf also Papovitch+2015**

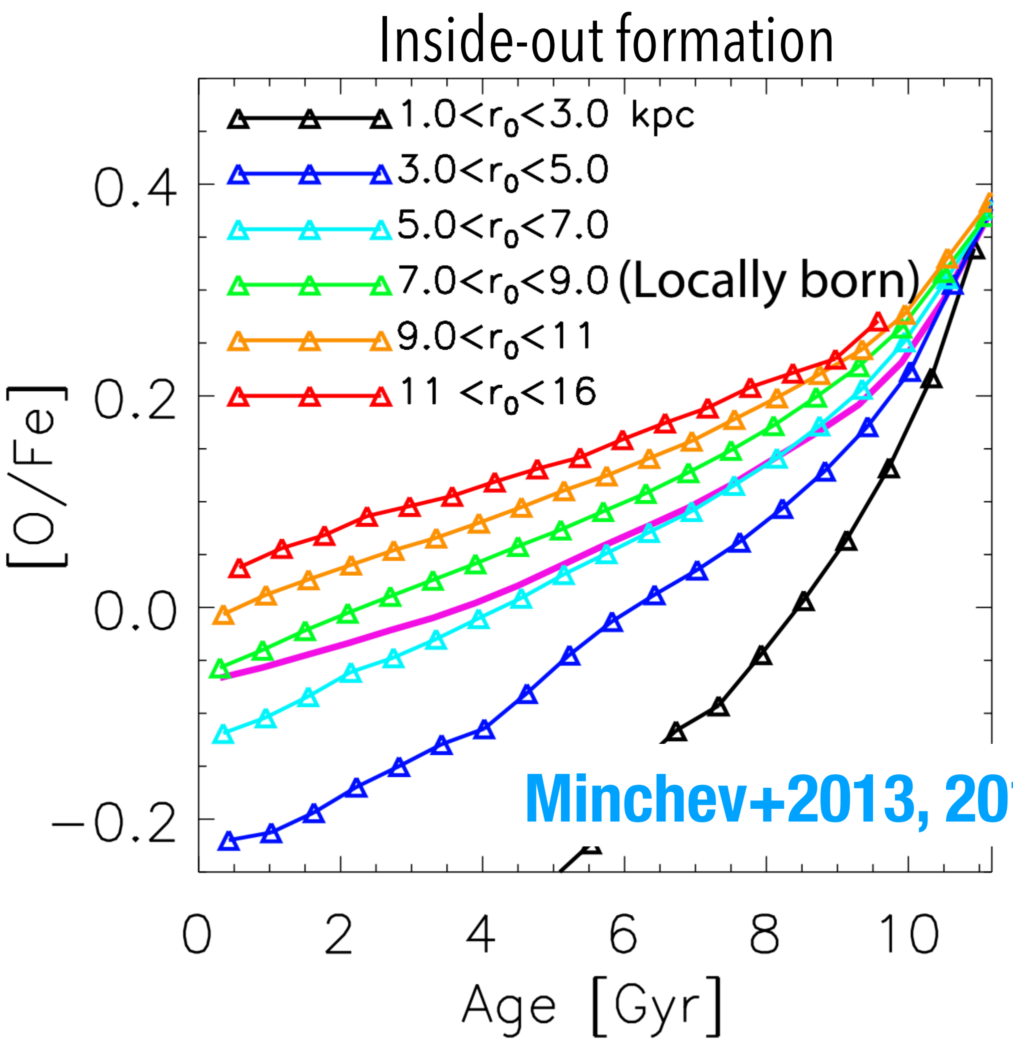


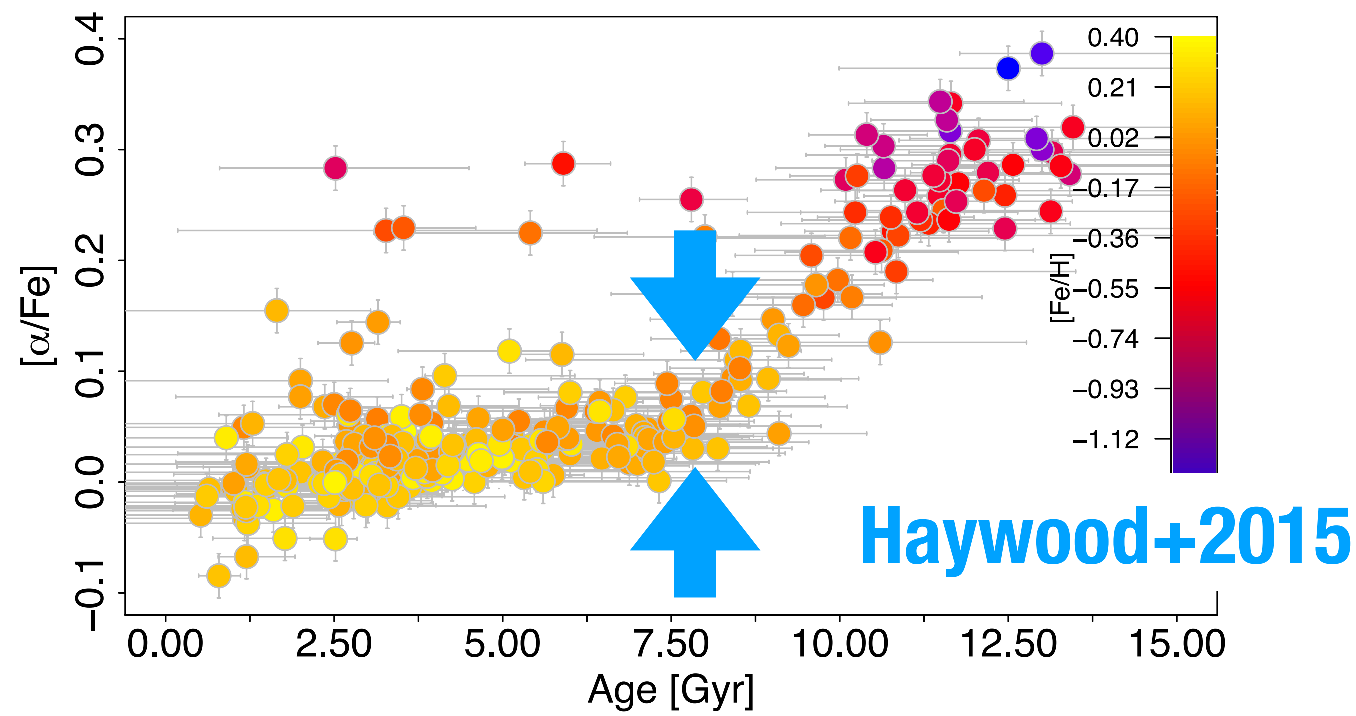

**At 14%, the MW is an outlier of the evolution of MW type galaxies**

## It is the formation of a massive thick disk that allows the MW to follow the general evolution of MW-mass galaxies

# ABUNDANCES as tests of INSIDE-OUT FORMATION

**Inside-out disk formation leaves specific signatures in chemical abundances that are not observed:**
**the spread in [α/Fe] is expected to be significant (>0.2 dex), it is <0.1 dex**



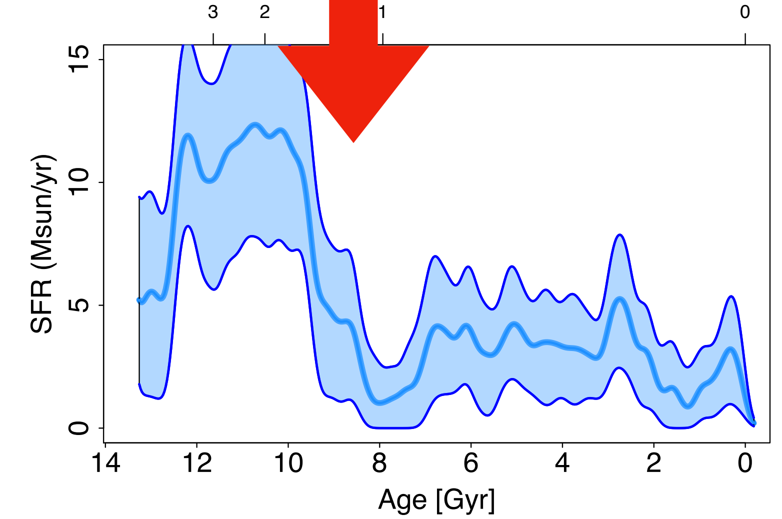




Significant spread in [α/Fe] is not observed (<0.1dex)

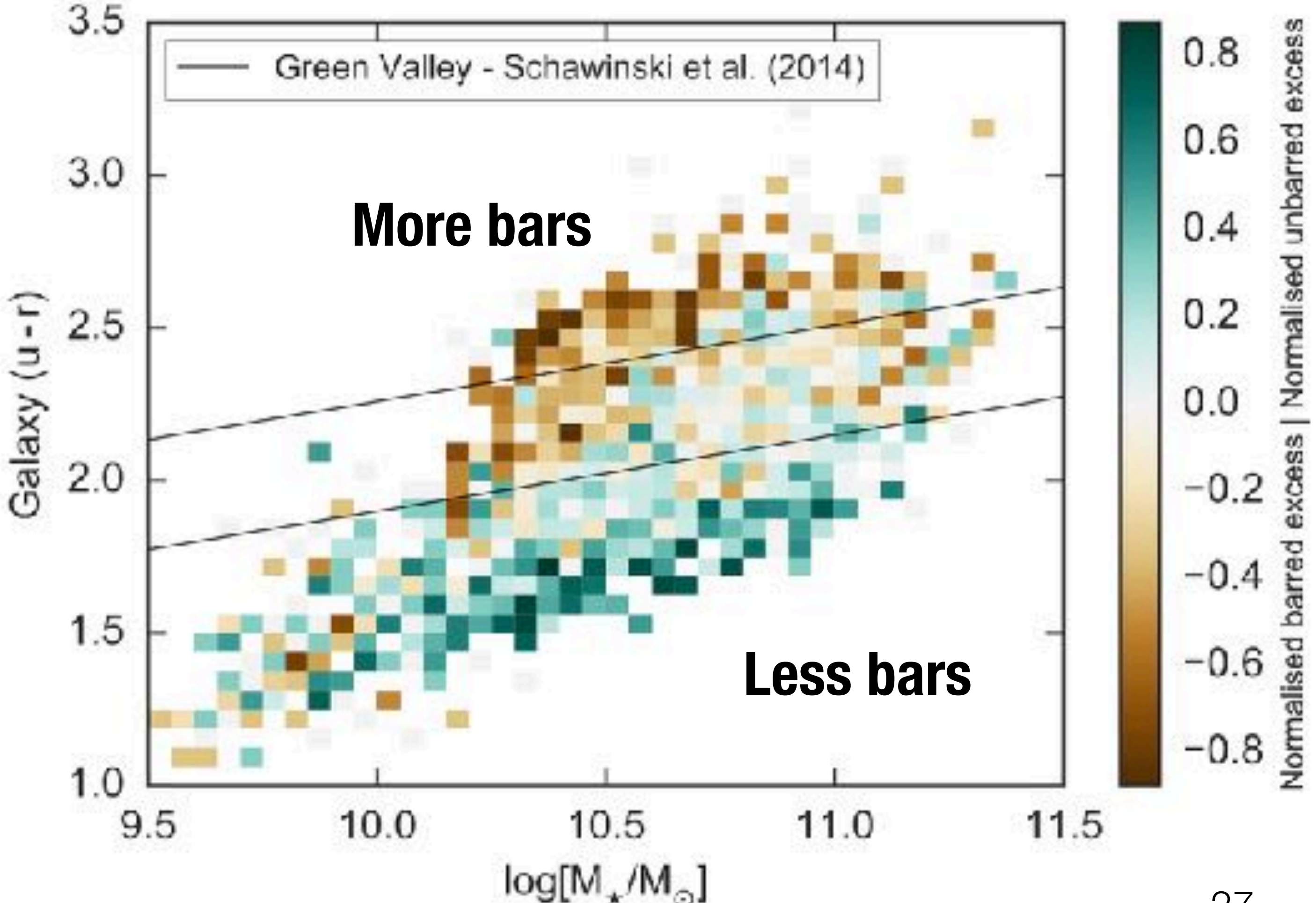
**The thick disk did not formed inside-out and is chemically homogeneous at any given time**
**=> the TD formation was a general process (10 kpc scale) that included strong mixing**

**What put an end to the formation of the thick disk?**

# After the thick disk: What put an end to the formation of the thick disk?




**Depletion of fuel for star formation?**
**Not favored because MW-like galaxies show substantial amount of molecular gas at z~1 (Tacconi et al., 2013; Saintonge et al. 2013; Zavadsky et al. 2015)**
**A possibility:**
**Formation of a strong bar?**

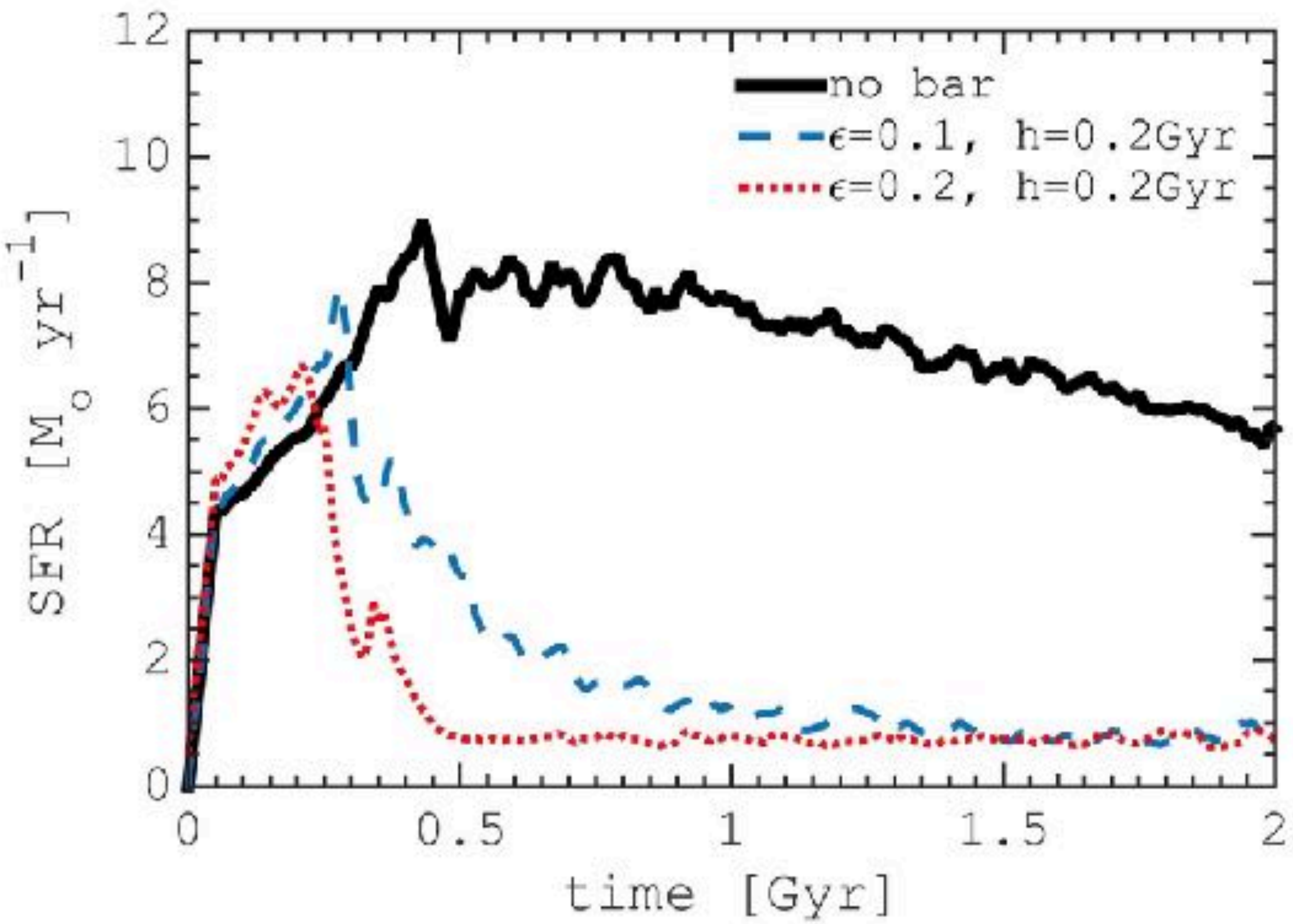



**Kruk et al., 2017**

**At a given mass, galaxies with bar are redder, i.e, have less star formation see also James & Percival, 2018 on nearby galaxies**

# After the thick disk: What put an end to the formation of the thick disk?

**The epoch of thick disk end is the epoch of bar formation for Milky Way-mass galaxies, or z=1-1.5, see Sheth et al. 2008; Melvin et al. 2014**
**Could the bar have played a role?**

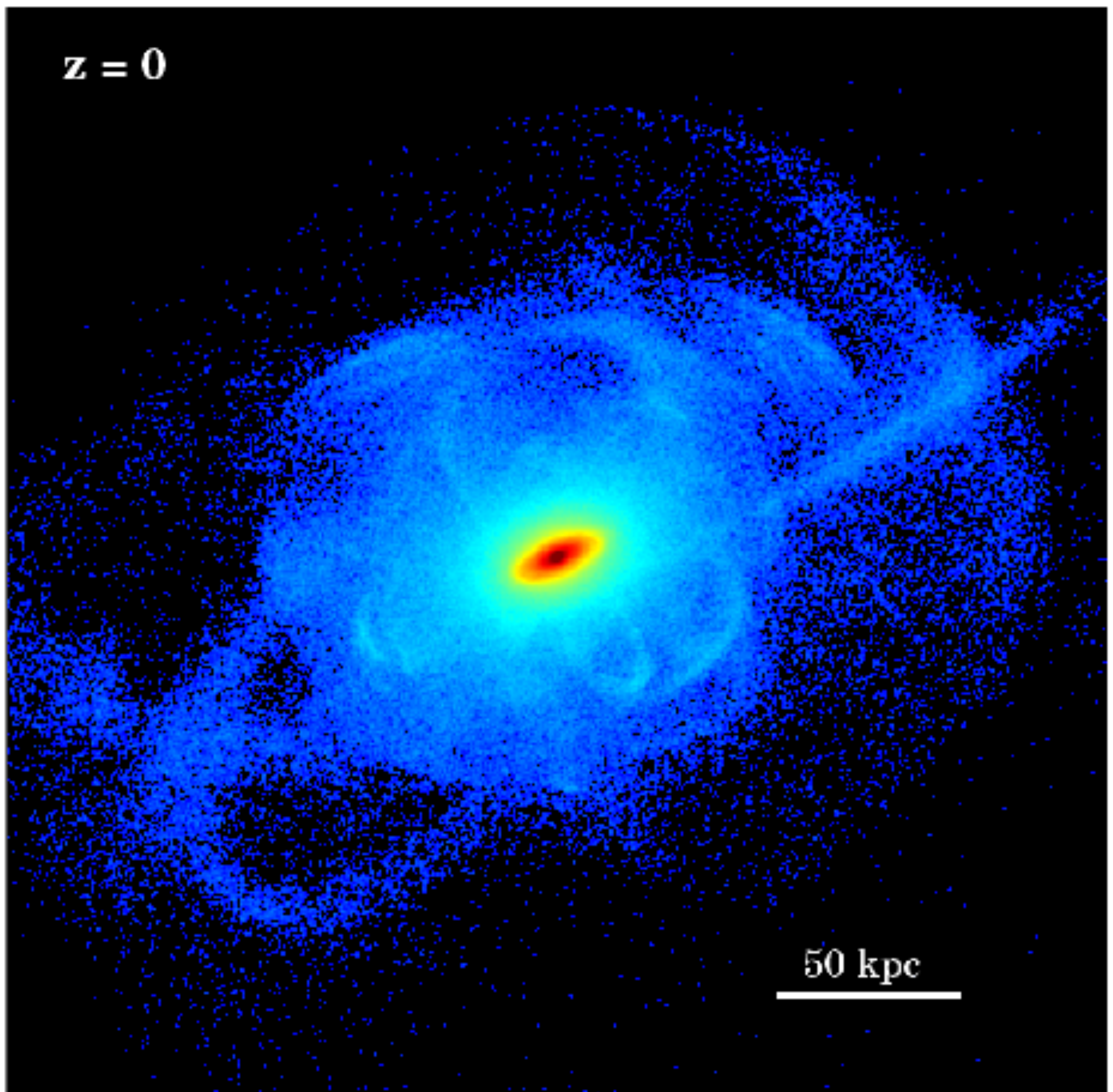



**Khoperskov et al. 2018**

**Simulations of gas rich disks with bar formation: The bar increases the random motion of the gas, stabilizing the gas layer against fragmentation, suppressing star formation**

**A strong bar is able to decrease the SFR by a factor of ~ 10, in less than 1 Gyr**

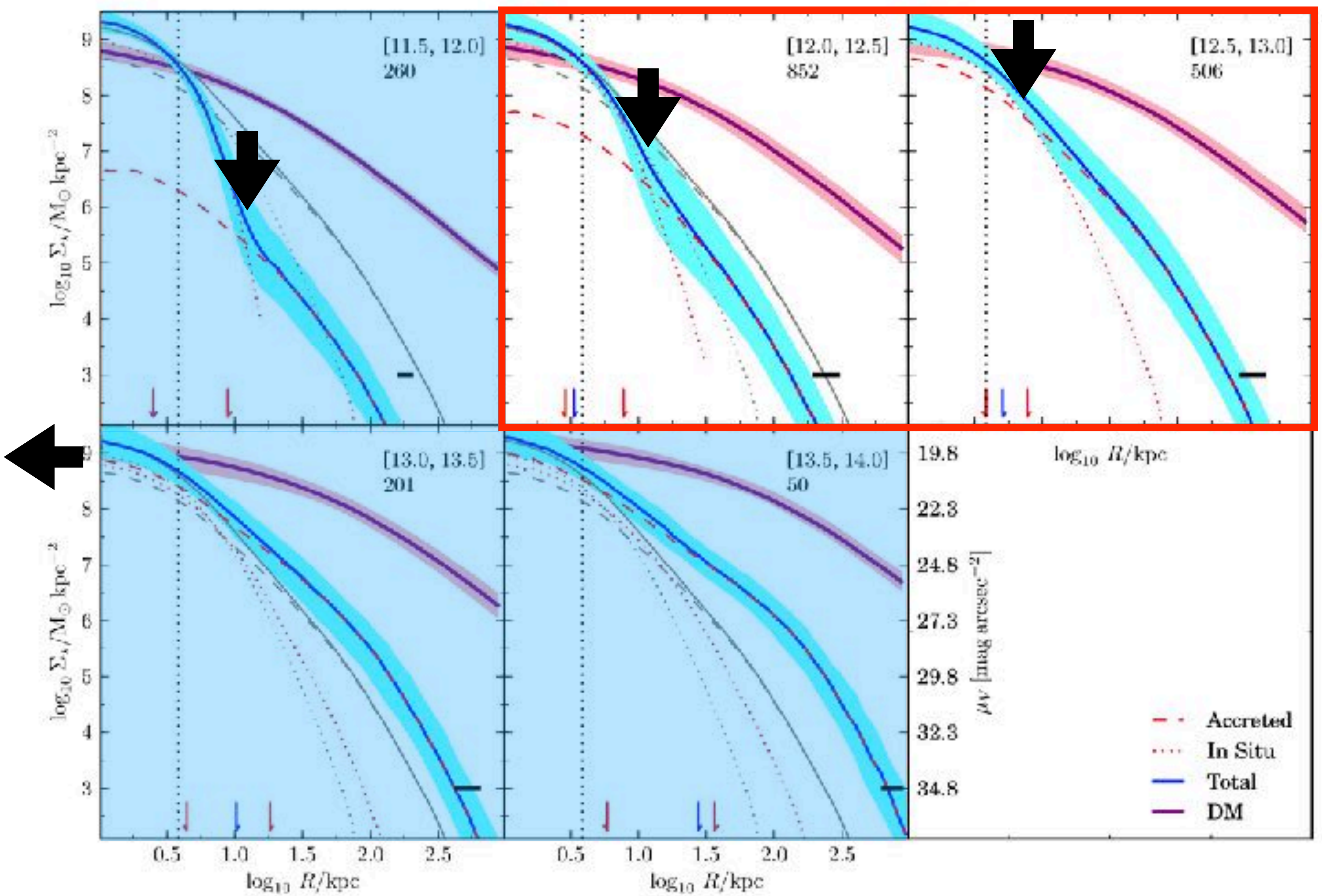
# 3 - Highlight from Gaia: searching for the in situ halo of the MW




(or: the Galactic halo before and after Gaia)
see Haywood et al. 2018

ERIS simulation of a MW-like stellar halo

# Milky Way-like stellar halo density distributions




Cooper et al. 2013

**Stellar density break at the passage between in situ and accreted halo stars**

MW-like galaxies are expected to have a halo made of both in situ and accreted stars

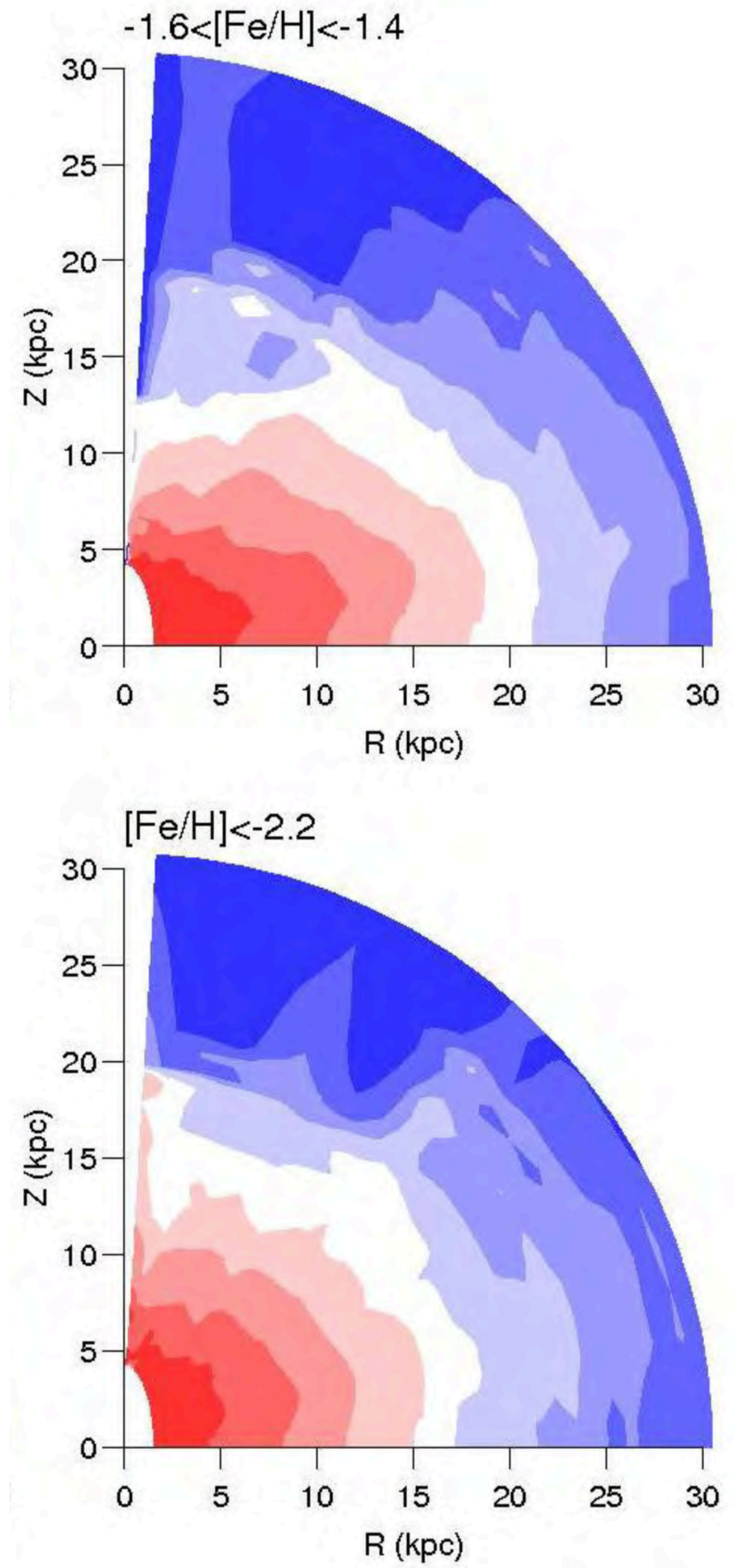
# Standard view of the Milky Way Galactic halo (before Gaia)

## See Carollo et al. (2007), Belokurov (2013)

**Two components:**

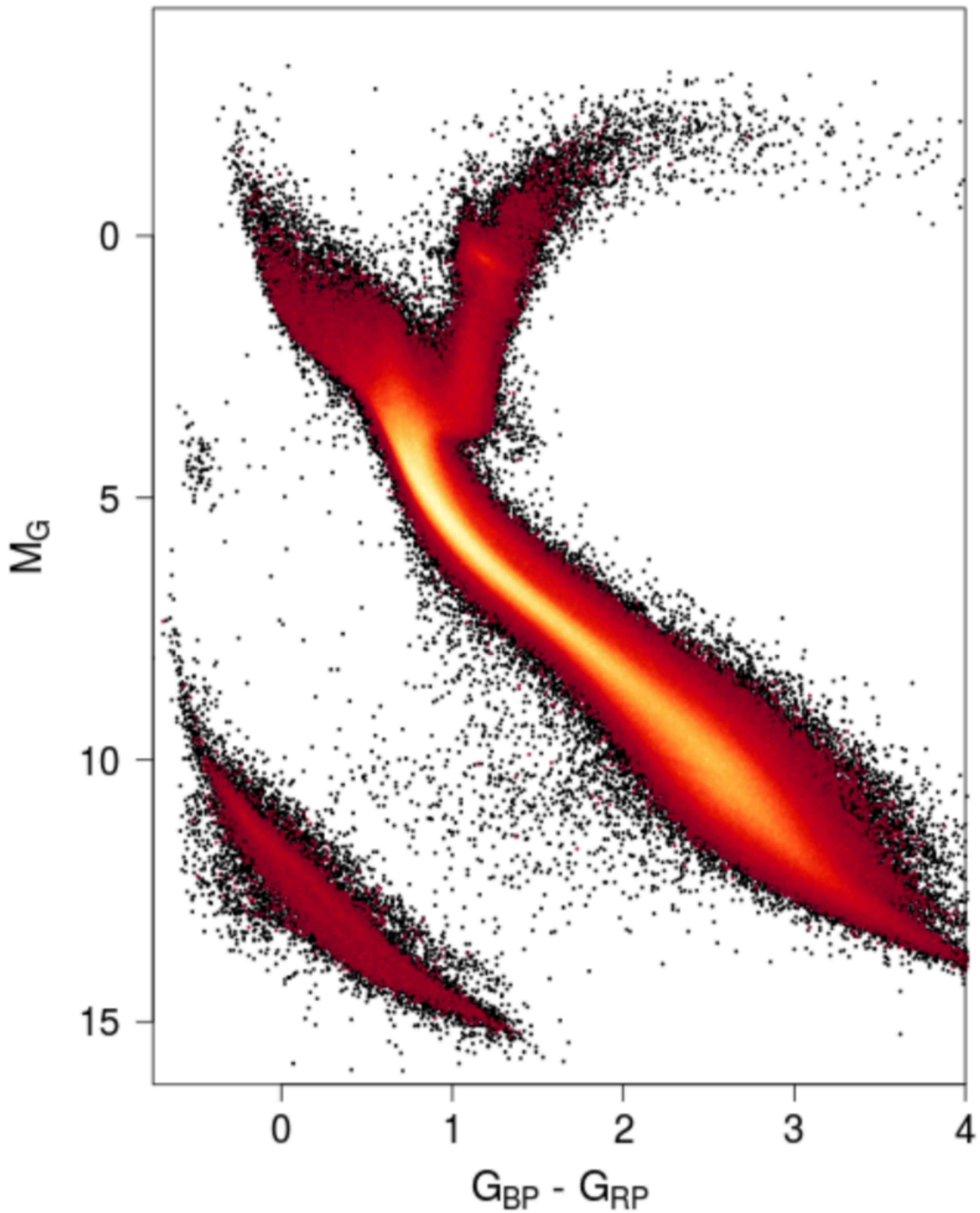
- In-situ, dominating the inner halo (<15-20kpc)
- MDF peaks at [Fe/H]~-1.5
- Age > 10 Gyr
- Flattened distribution

- Accreted, dominating at > 20kpc
- Dominate at [Fe/H]<-2.0
- Younger ages
- Spherical distribution




Density profiles for the in situ (top)
and accreted (bottom), according to Carollo et al. (2007)

# GAIA COLOR-MAGNITUDE DIAGRAM




**Disk stars**

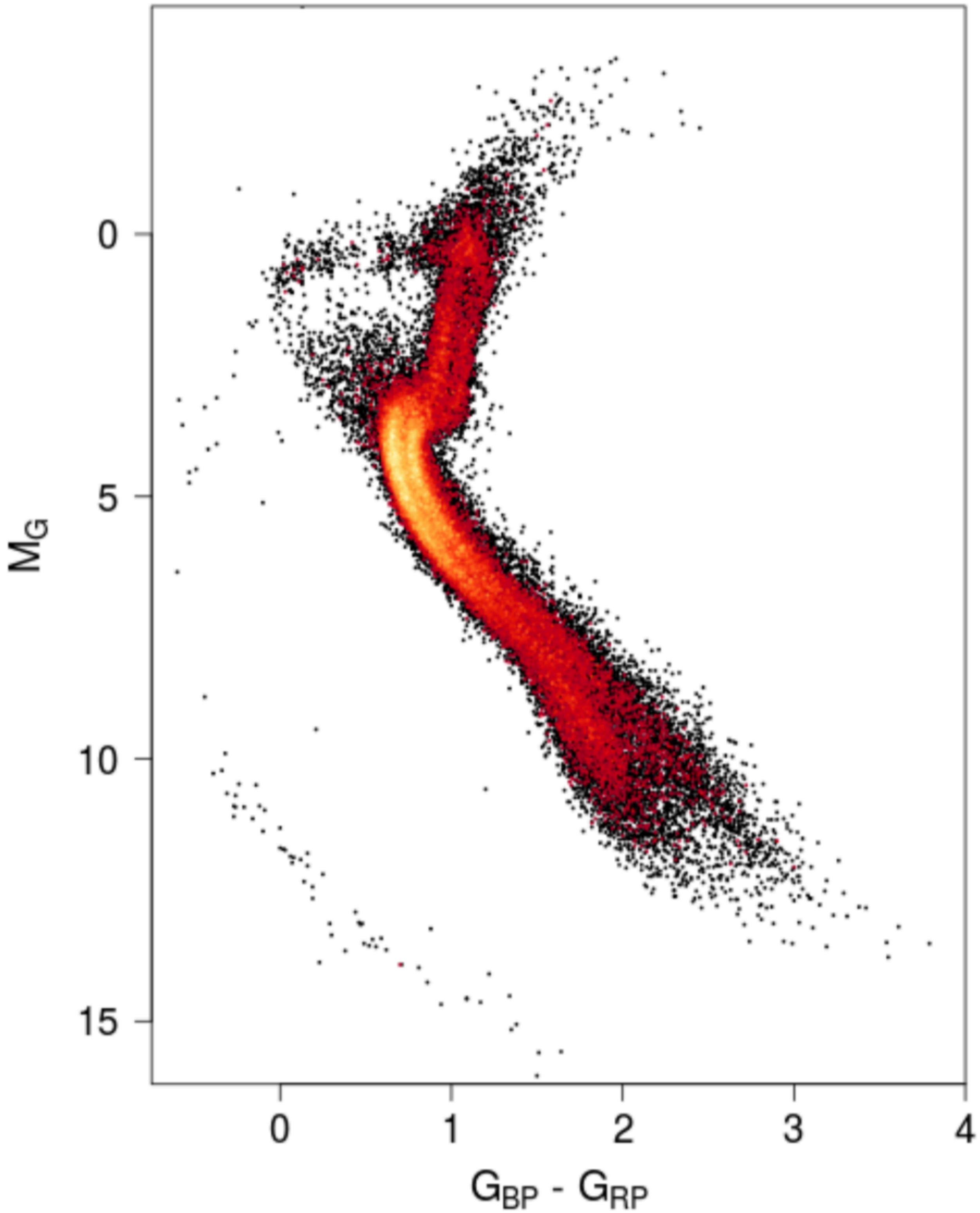
**Tangential velocities $V_T < 40 km.s^{-1}$**

**(velocities perpendicular to the line of sight)**

**~$1.8\times10^6$ stars**

Gaia Collaboration, Babusiaux et al. 2018

## One of the Gaia highlights:
## The first colour-magnitude diagram of the thick disk and halo




**High velocity stars**

**Tangential velocities $V_T > 200 km.s^{-1}$**

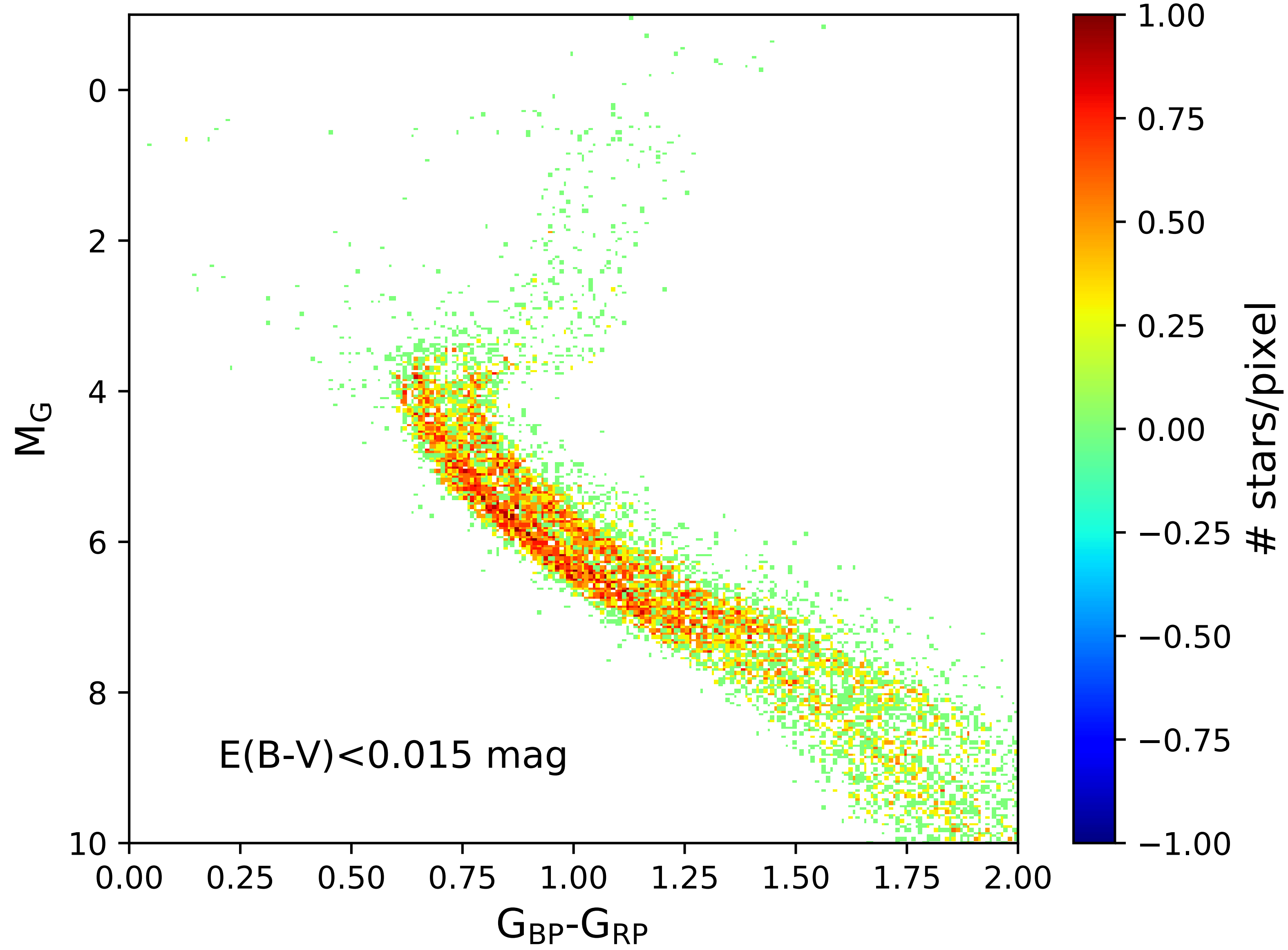
**(velocities perpendicular to the line of sight)**

**~64700 stars**

Gaia Collaboration, Babusiaux et al. 2018

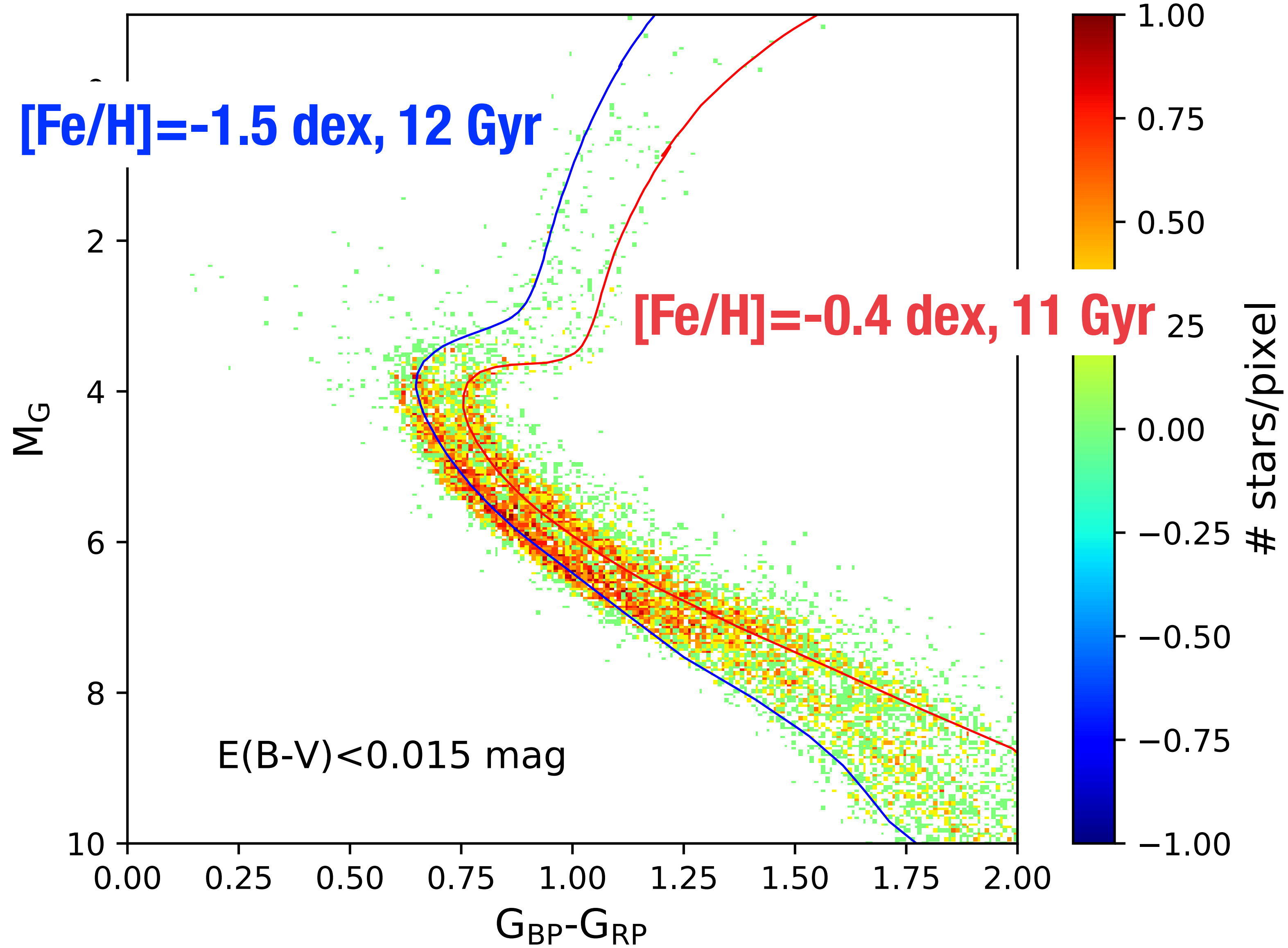
# One of the Gaia highlights:
# The first colour-magnitude diagram of the thick disk and halo

## Cleaner sample (stars with low extinction)




Extinction from Lallement et al, 2018

# One of the Gaia highlights:
# The first colour-magnitude diagram of the thick disk and halo



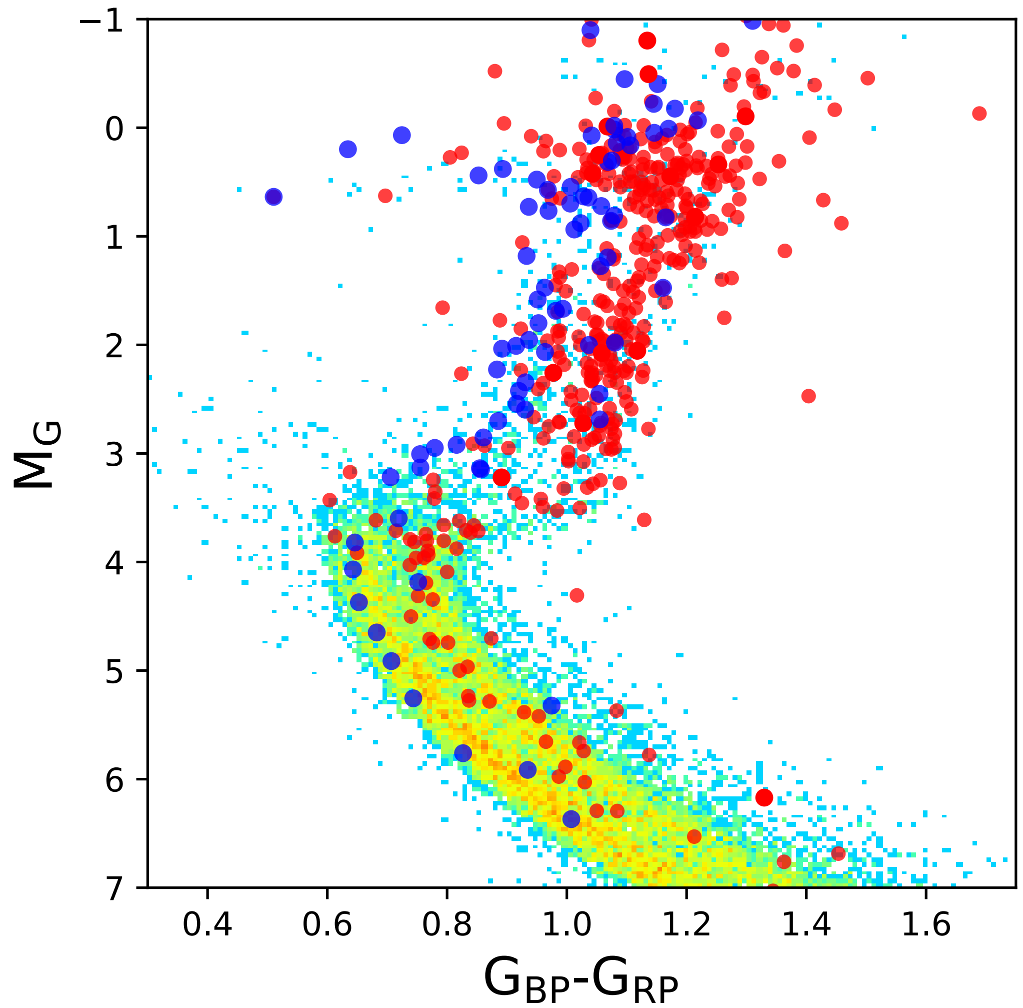

Isochrones from PARSEC library, Marigo et al. 2017

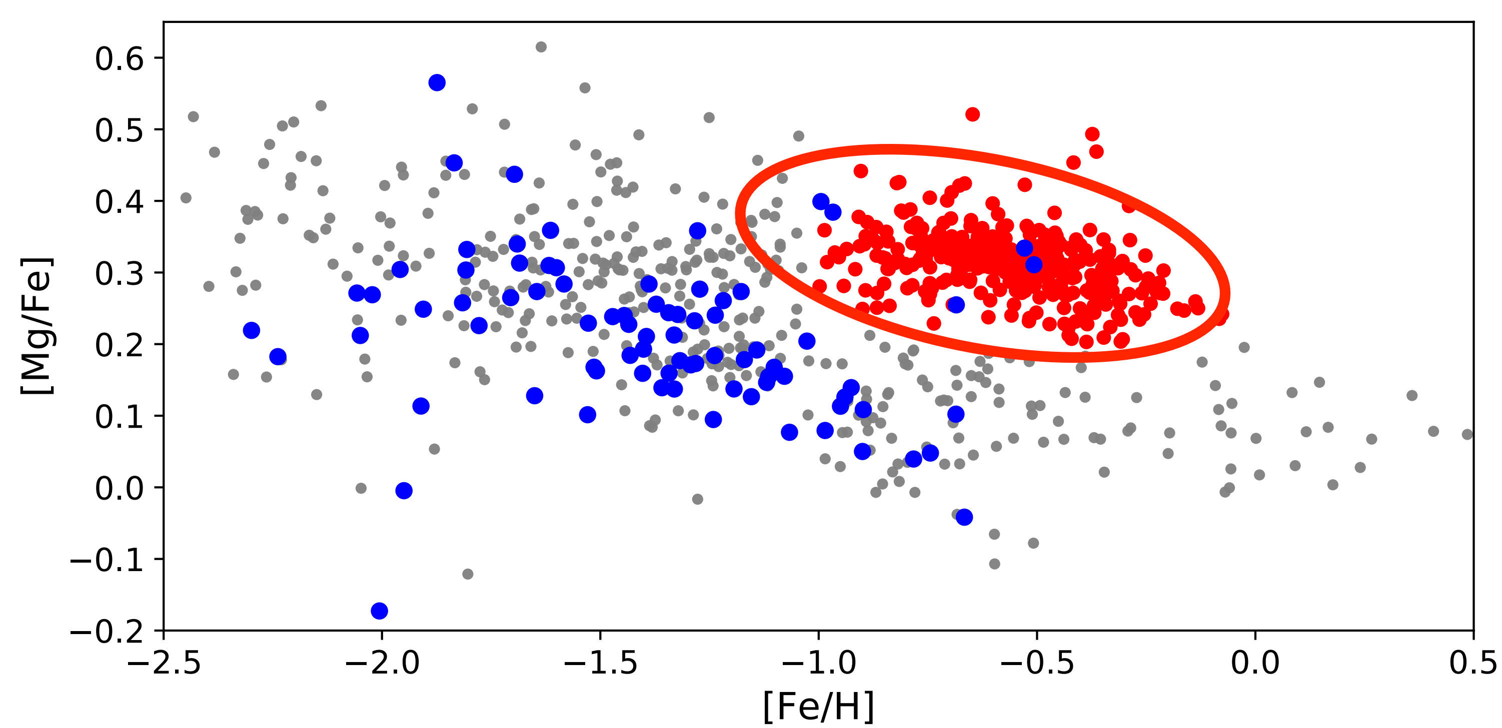
**Gaia collaboration et al. :~1dex metallicity separation between the two sequences**

**Blue sequence: stellar halo**

**Red sequence: thick disk**

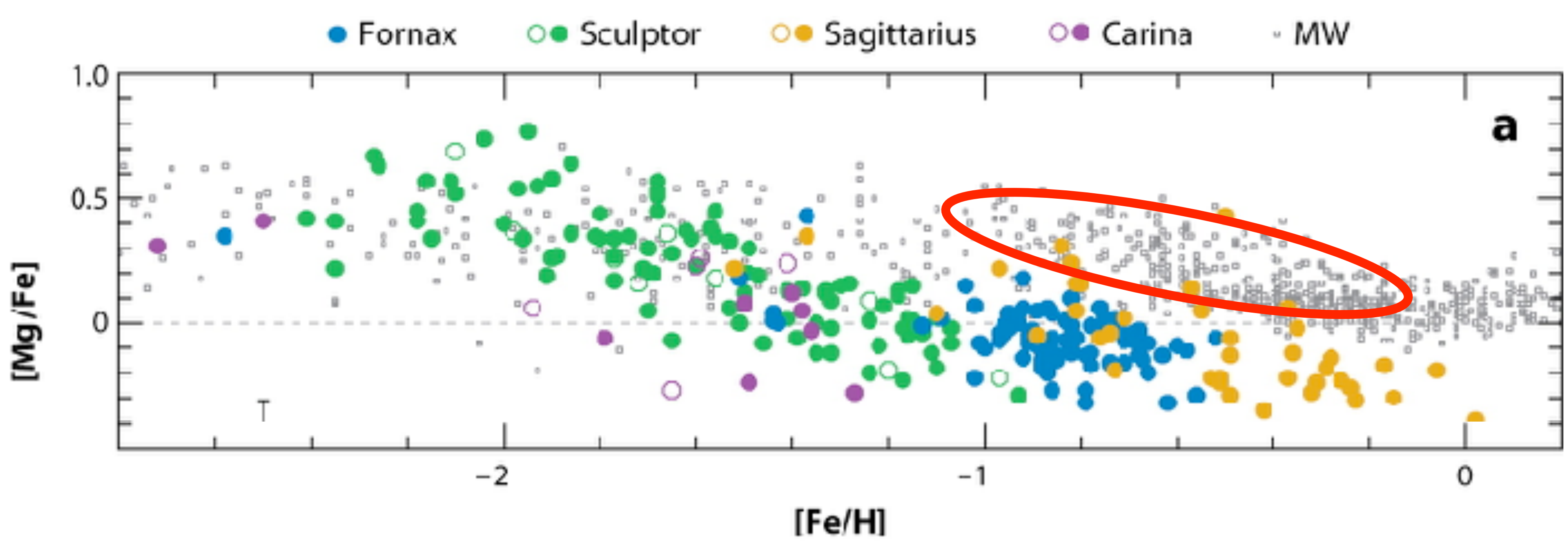
# High velocity stars with chemistry from the APOGEE survey



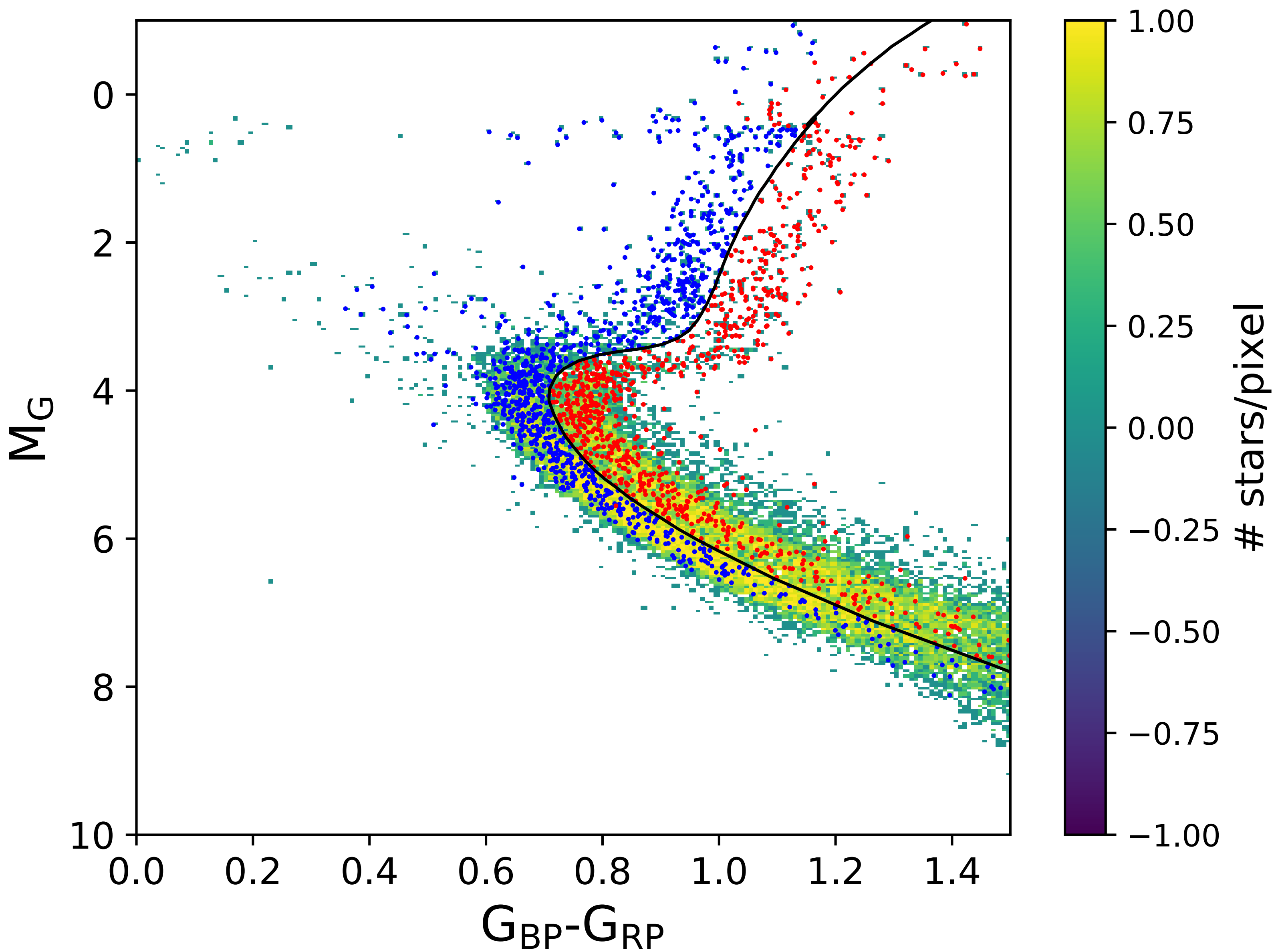




**Low star formation efficiency chemical sequence**

**Chemistry strongly suggest that these stars are most possibly accreted**



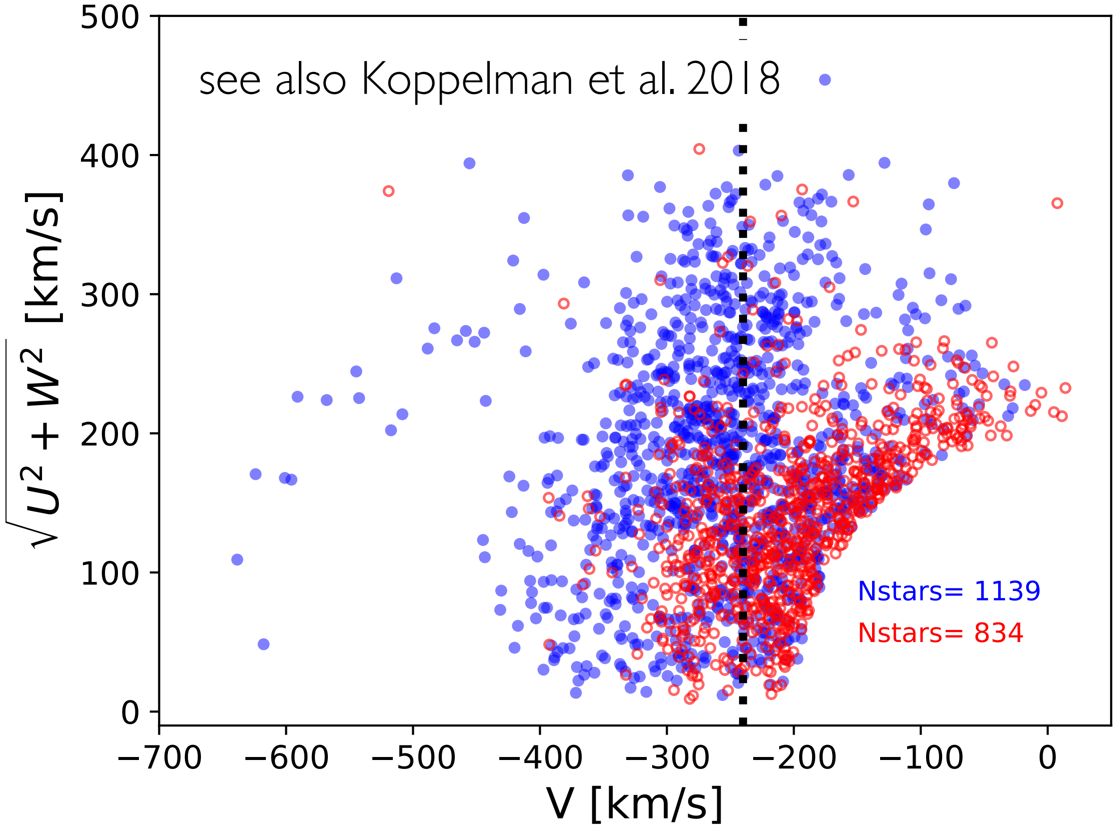
# What is the kinematics of these two groups?



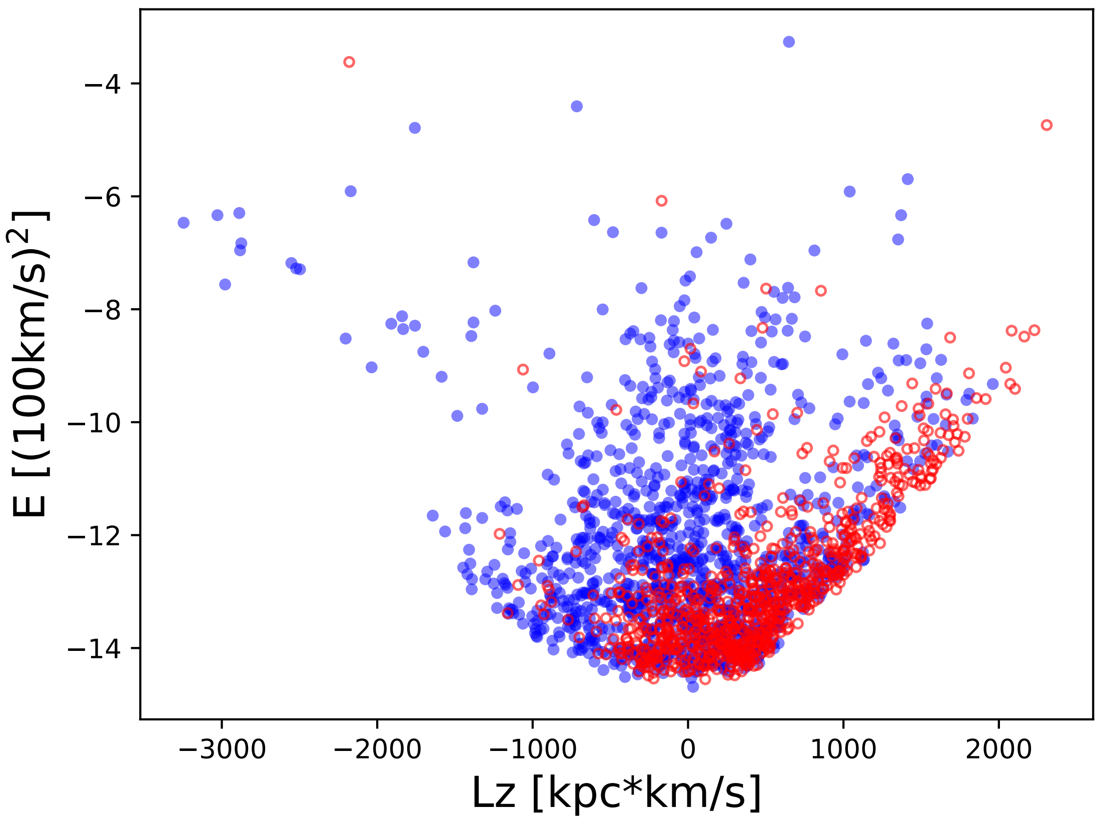

**Stars with radial velocities (in blue and red on the figure) + Gaia proper motions**
**Full 3D velocities + orbit calculations**

# KINEMATICS OF GAIA HRD BLUE AND RED SEQUENCES

## Toomre diagram



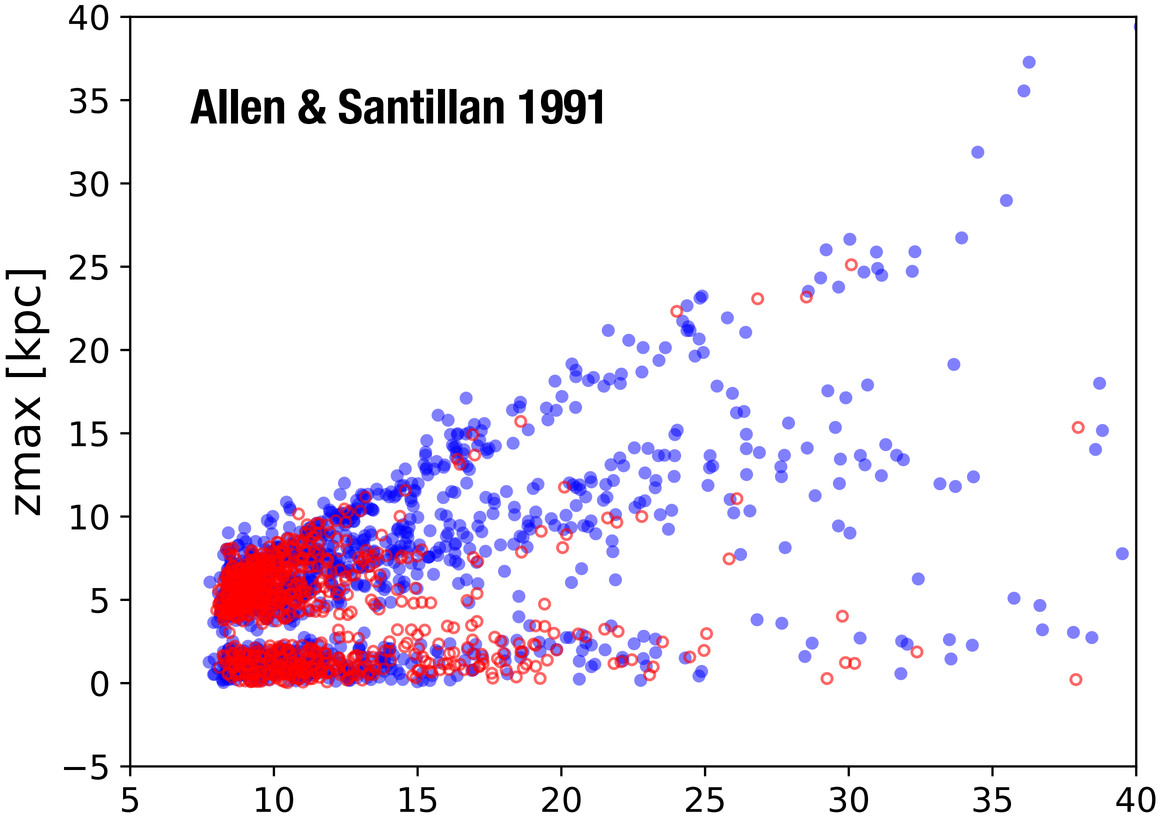

## Energy-Angular momentum diagram

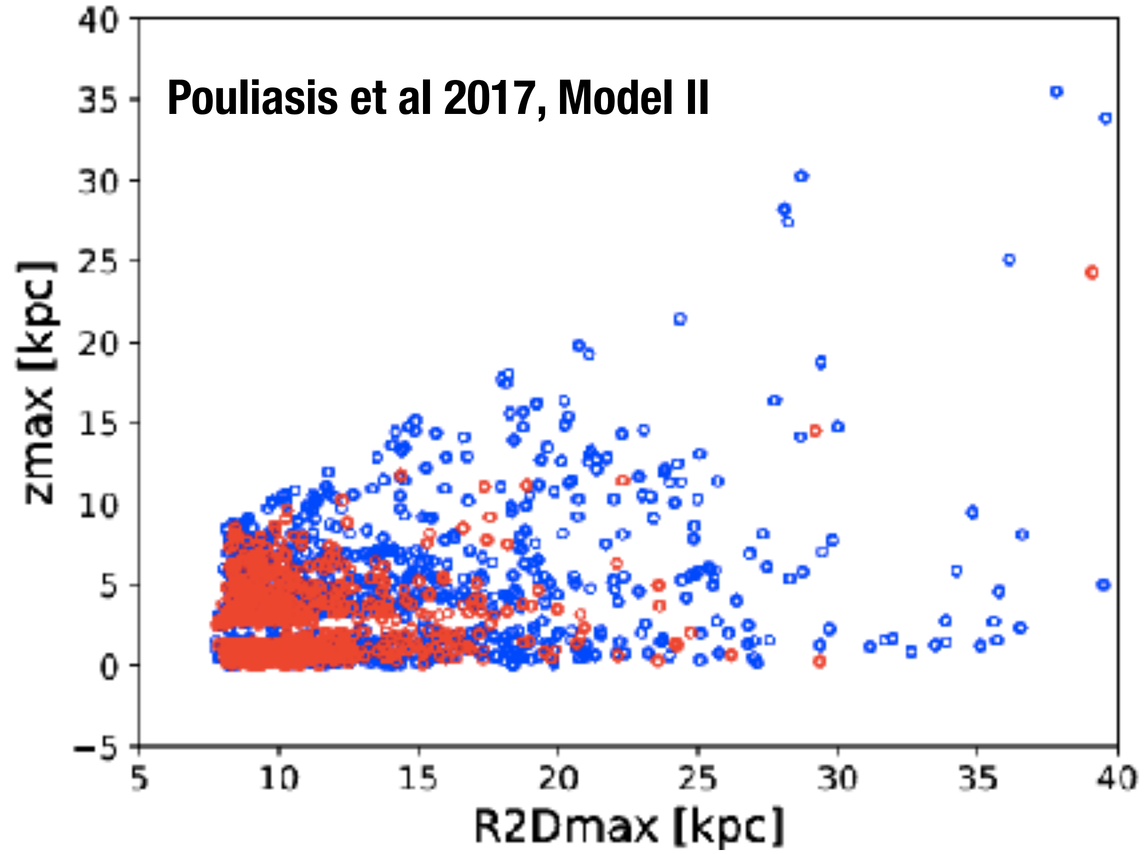


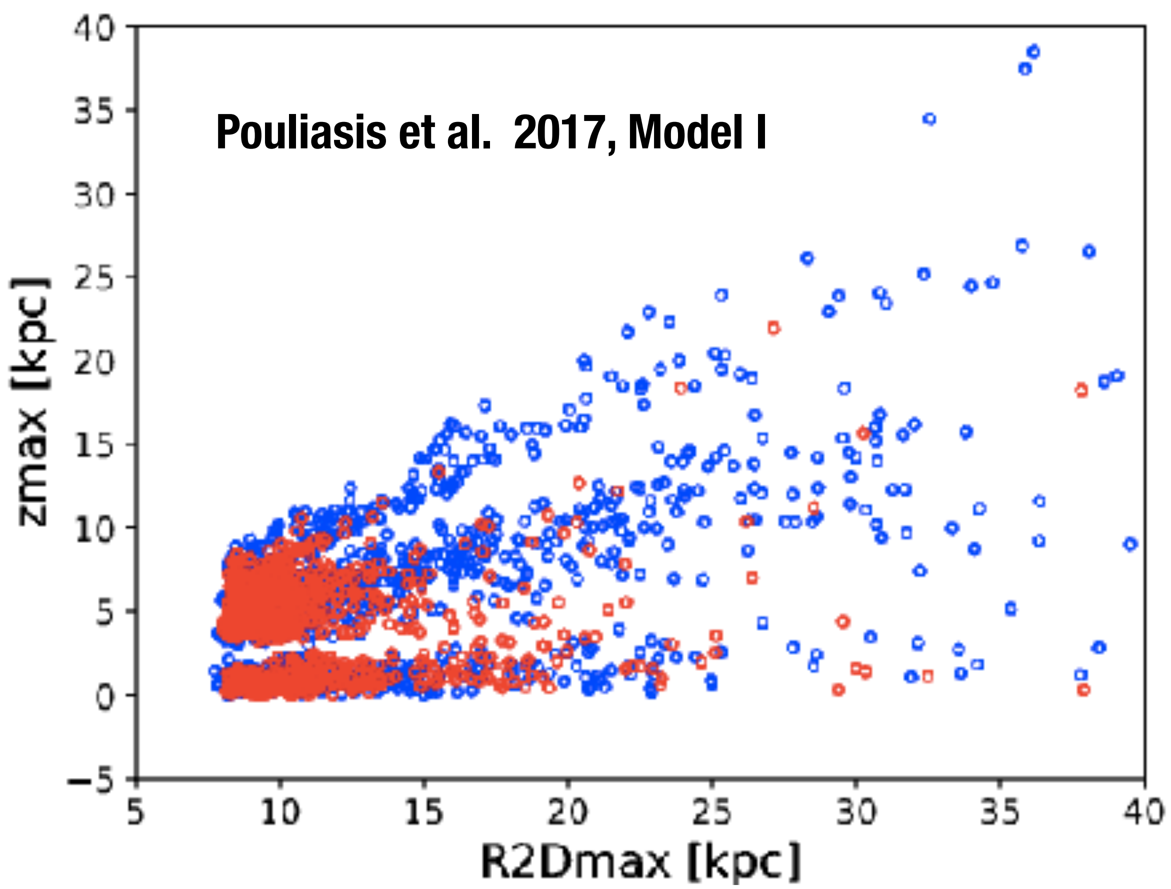

- The stars in the red sequence are the high-velocity tail of the thick disk
Some are counter-rotating:
could be the consequence of an interaction,
see Jean-Baptiste et al. 2018

- Stars in the blue sequence form a blob at high-energy, no-rotation

# ORBITAL PARAMETERS OF THE HRD BLUE AND RED SEQUENCE STARS

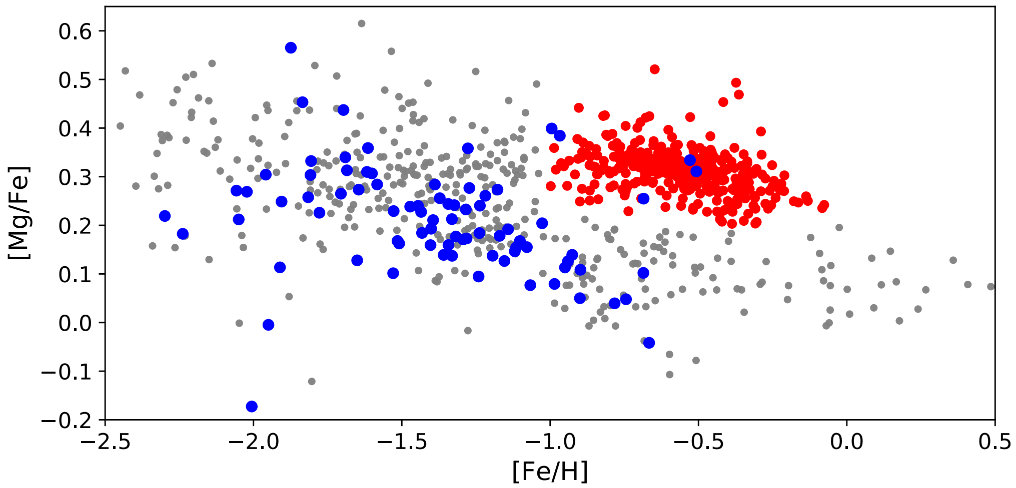


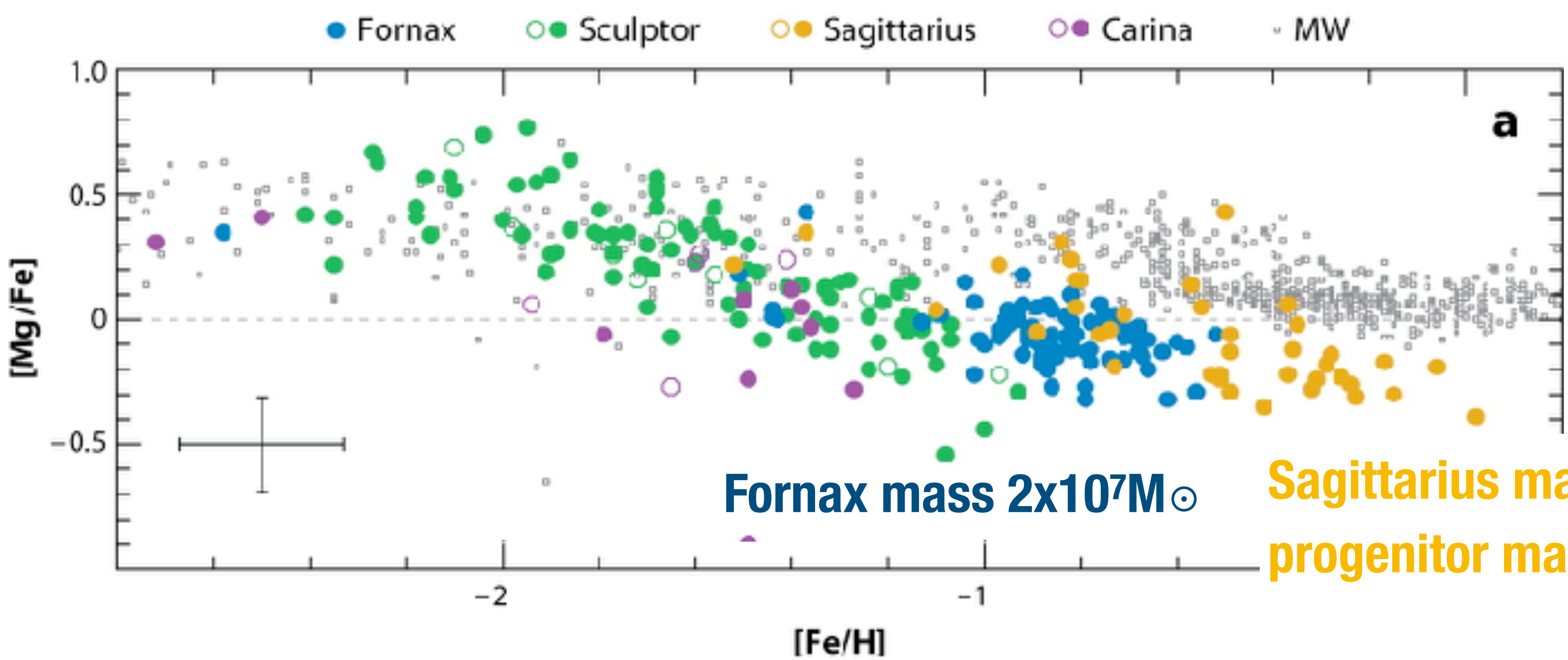




- **Blue sequence dominates at R2Dmax > 15-20kpc**
- **Wedges are seen in both the thick disk and 'halo' stars. What are they?**

# What was the mass of the progenitor?




Fornax mass $2x10^7 M_\odot$

Sagittarius mass= $2x10^7 M_\odot$
progenitor mass ~ $7.10^8 M_\odot$

**Does it have a name? Several:**
**'Gaia sausage', Belokurov et al., 2018**
**'Gaia Enceladus', Helmi et al., 2018**

**Possibly 8 associated globular clusters, Myeong et al. 2018**

# Conclusions I

The Galactic stellar halo:

- What we thought was the in situ inner halo is probably dominated by the remnants of a single, massive, merger, *not* by an in-situ population

- We are still looking to identify a possible in situ component that pre-dated the thick disk

# Conclusions II

## The Thick disk:

- Is not a fortuitous (accretion or interaction-like event) component of the MW: it formed during an epoch of active star formation

- Is massive, and dominated the first Gyrs of the formation of the MW

- Puts the MW mass growth in accord with that of MW mass galaxies

- Did not form inside-out

Several features of the thick disk of the MW could be generic to thick disk formation in general:

- massive component
- chemical homogeneity
- Star formation 'quenched' due to the bar permitted the transition of the thin disk

Need to investigate these in Milky Way-like galaxies !