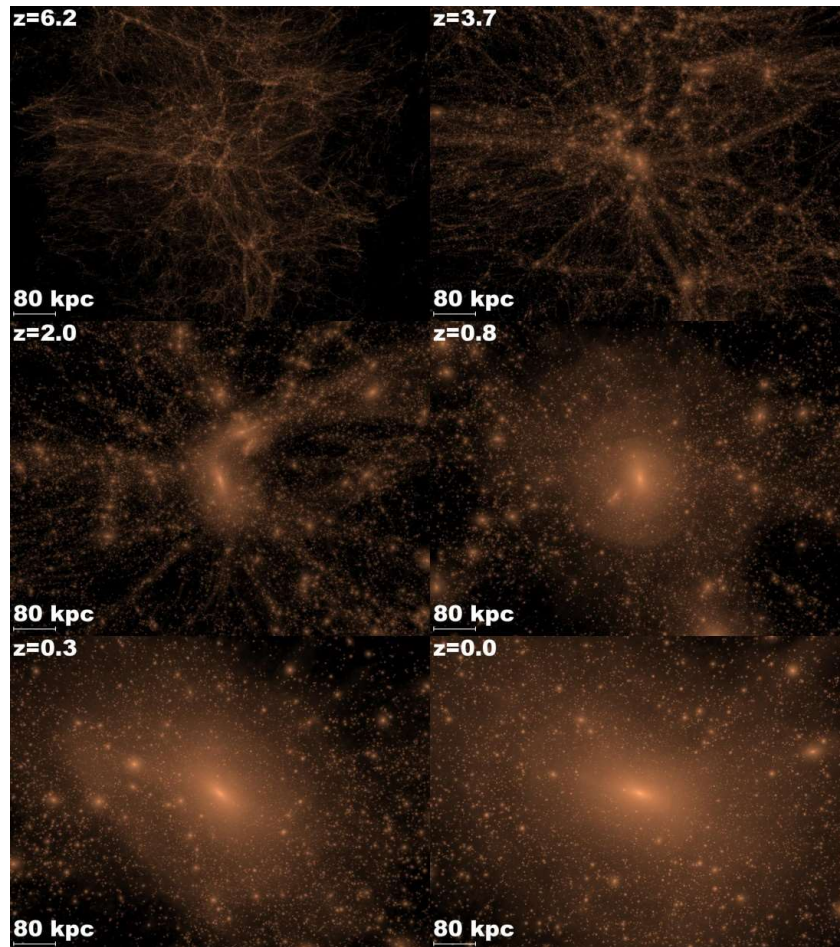


# Chap.5 Formation of Galactic Structures

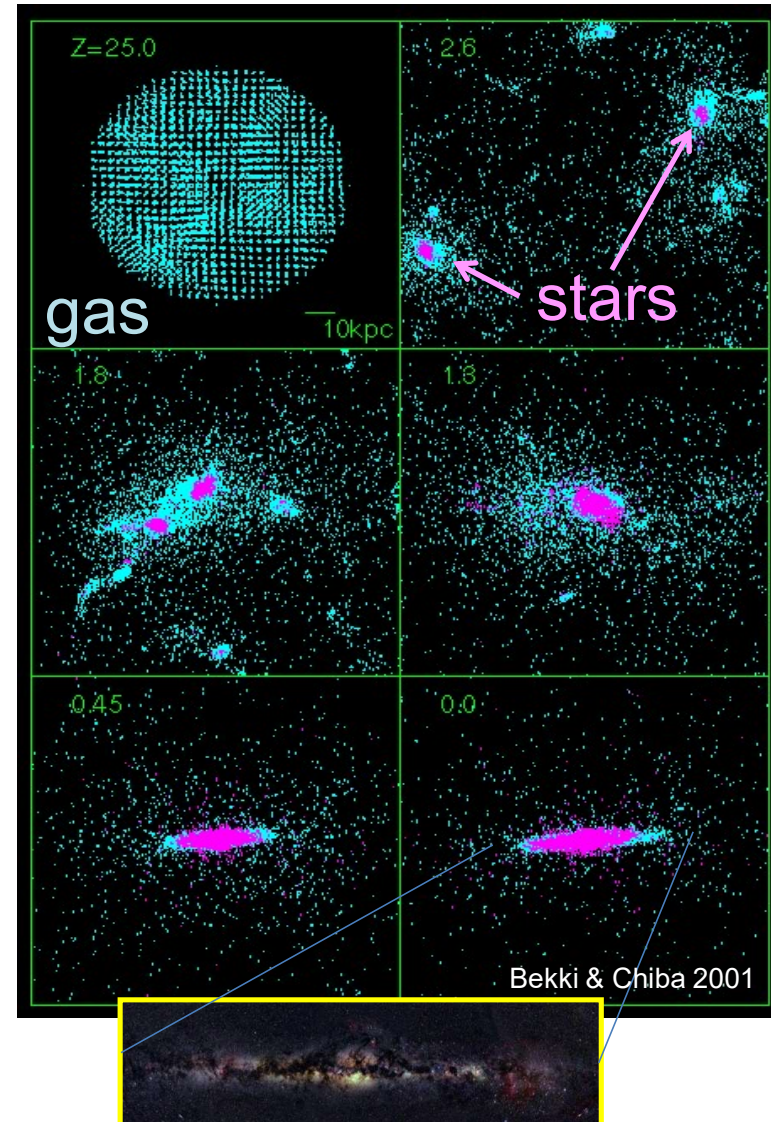
- Overview of galaxy formation
- Classical picture of Galaxy formation
- Formation of the stellar halo: after Hipparcos
- Formation of the stellar halo: after Gaia
- Formation of the thick disk
- Formation of the thin disk

# 1. Overview of galaxy formation

Hierarchical assembly of CDM



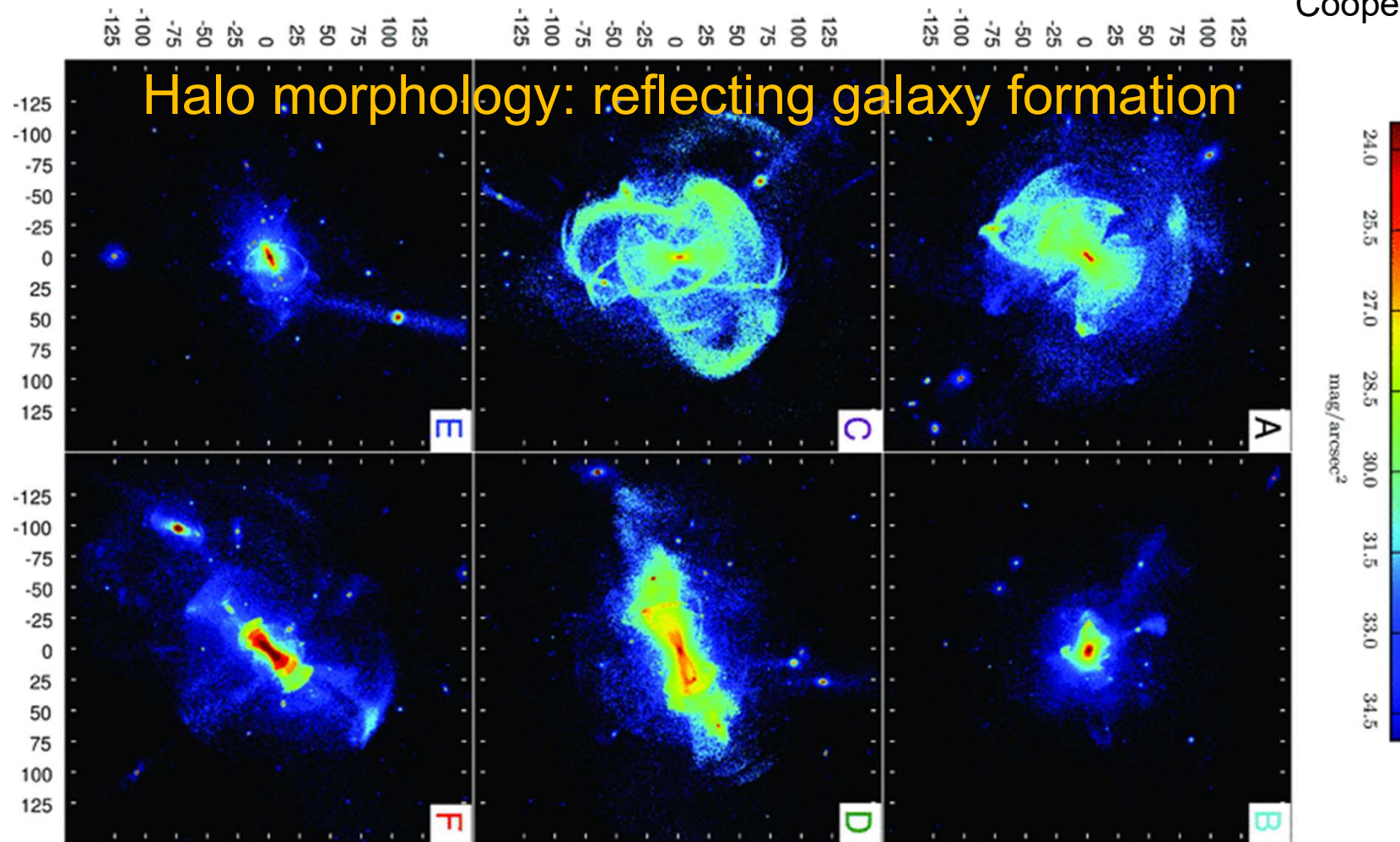
Via Lactea simulation  
(Diemand+07)



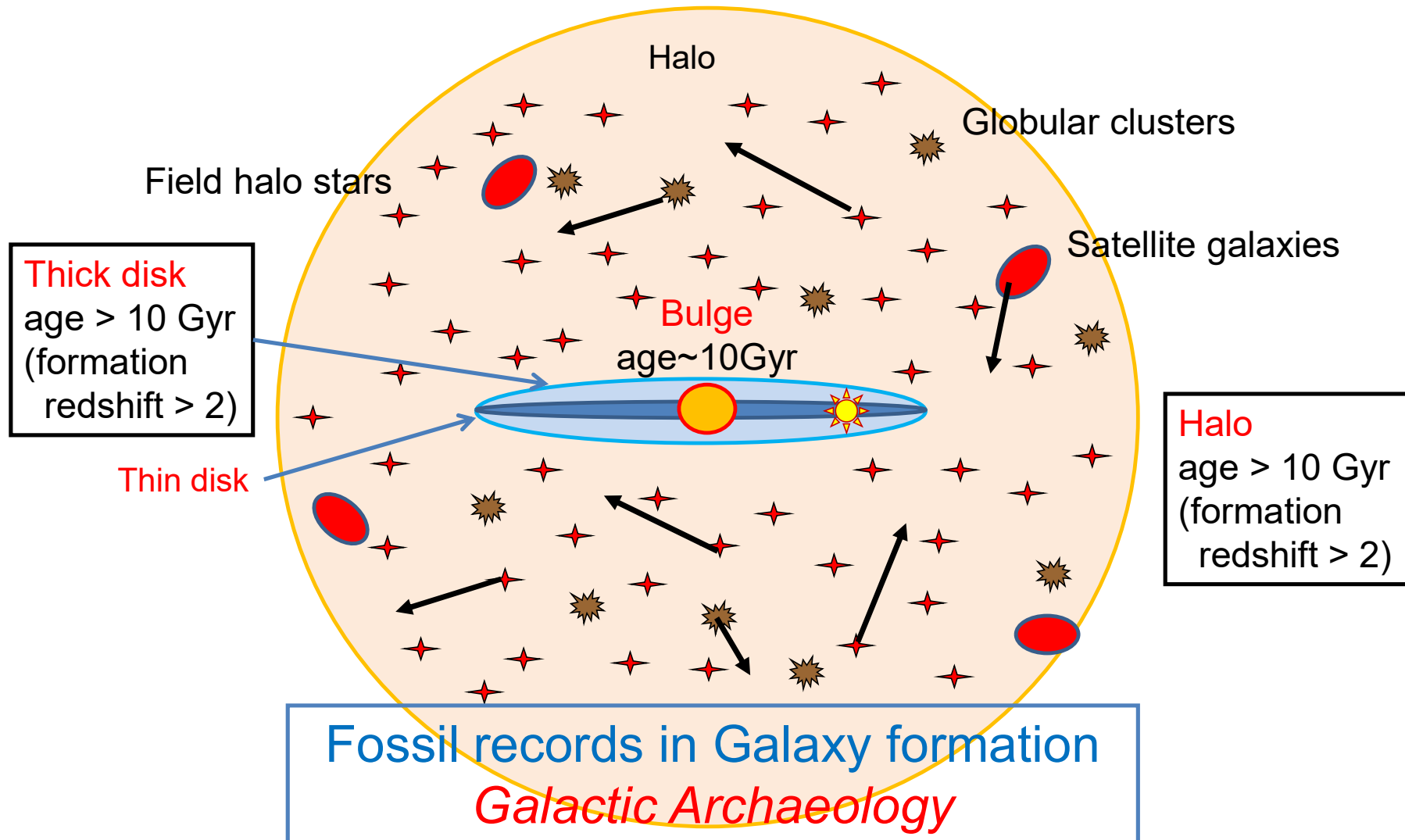
# Stellar halos in various MW-sized halos

~varieties due to different merging histories~

Cooper et al. 2010



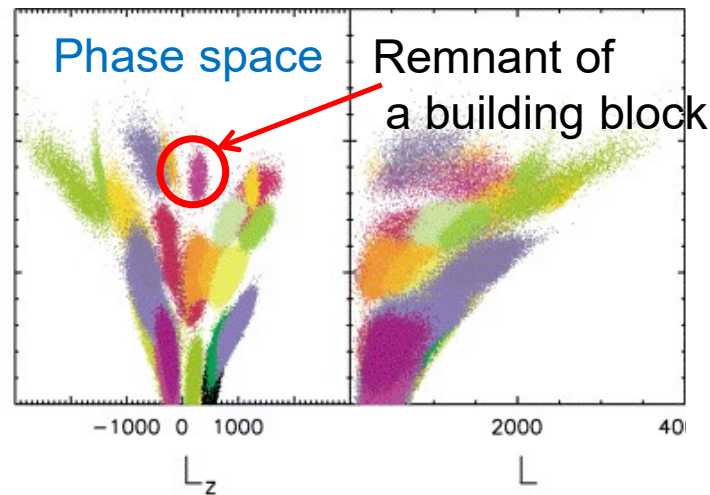
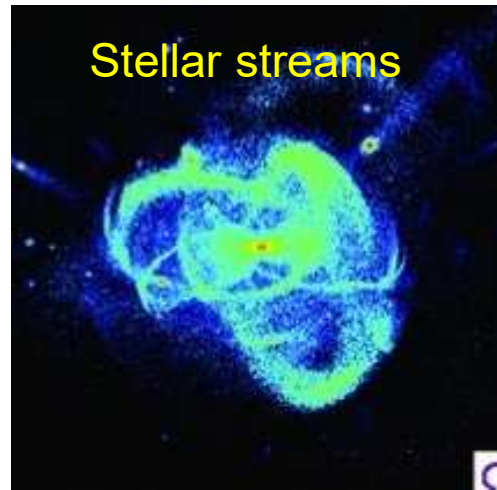
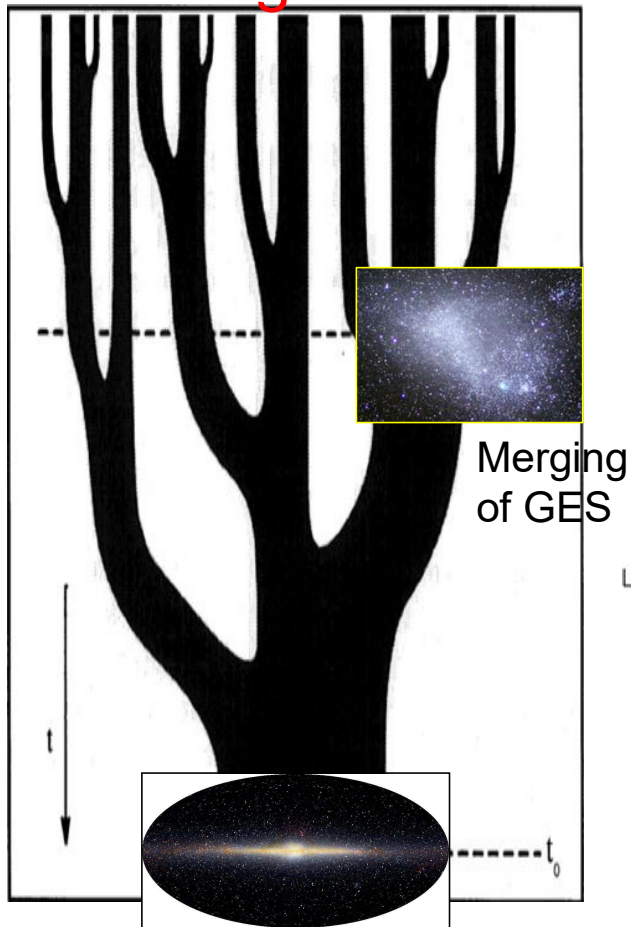
# Old stellar components



# Fossil record of Galaxy formation

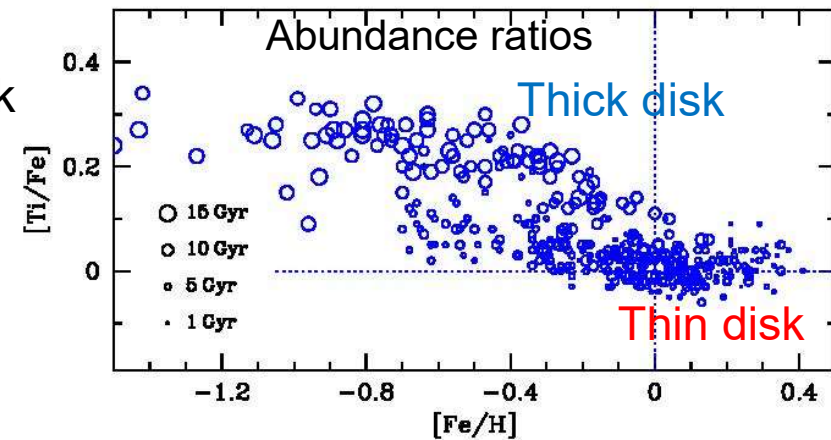
Hierarchical merging

Merger tree



Helmi & de Zeeuw 2000

- Spatial distribution and dynamics of stars
  - ✓ Galaxy collapse and merging
- Chemical abundance of stars
  - ✓ Star formation and chemical evolution



Bensby et al. 2014

# Sampling ancient halo stars

- Metal-poor sample (metallicity biased)
  - e.g.:  $[\text{Fe}/\text{H}] < -1$
  - Suitable for kinematic analysis
- High-velocity sample (kinematically biased)
  - e.g.:  $|V_{\text{star}} - V_{\text{LSR}}| > 180 \text{ km/s}$
  - Suitable for metallicity analysis

Fraction:  $\sim 1/1000$  near the Sun

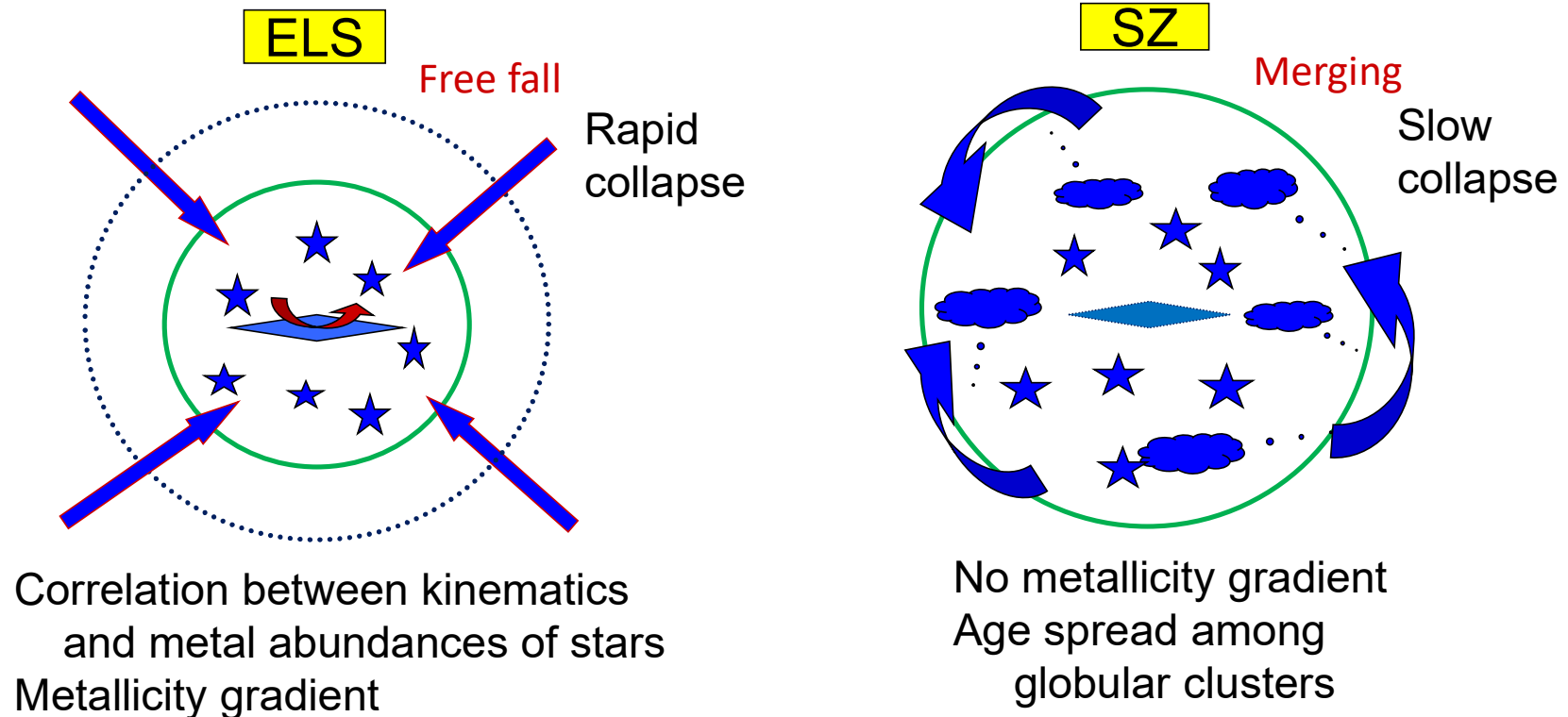
## 2. Classical picture of Galaxy Formation

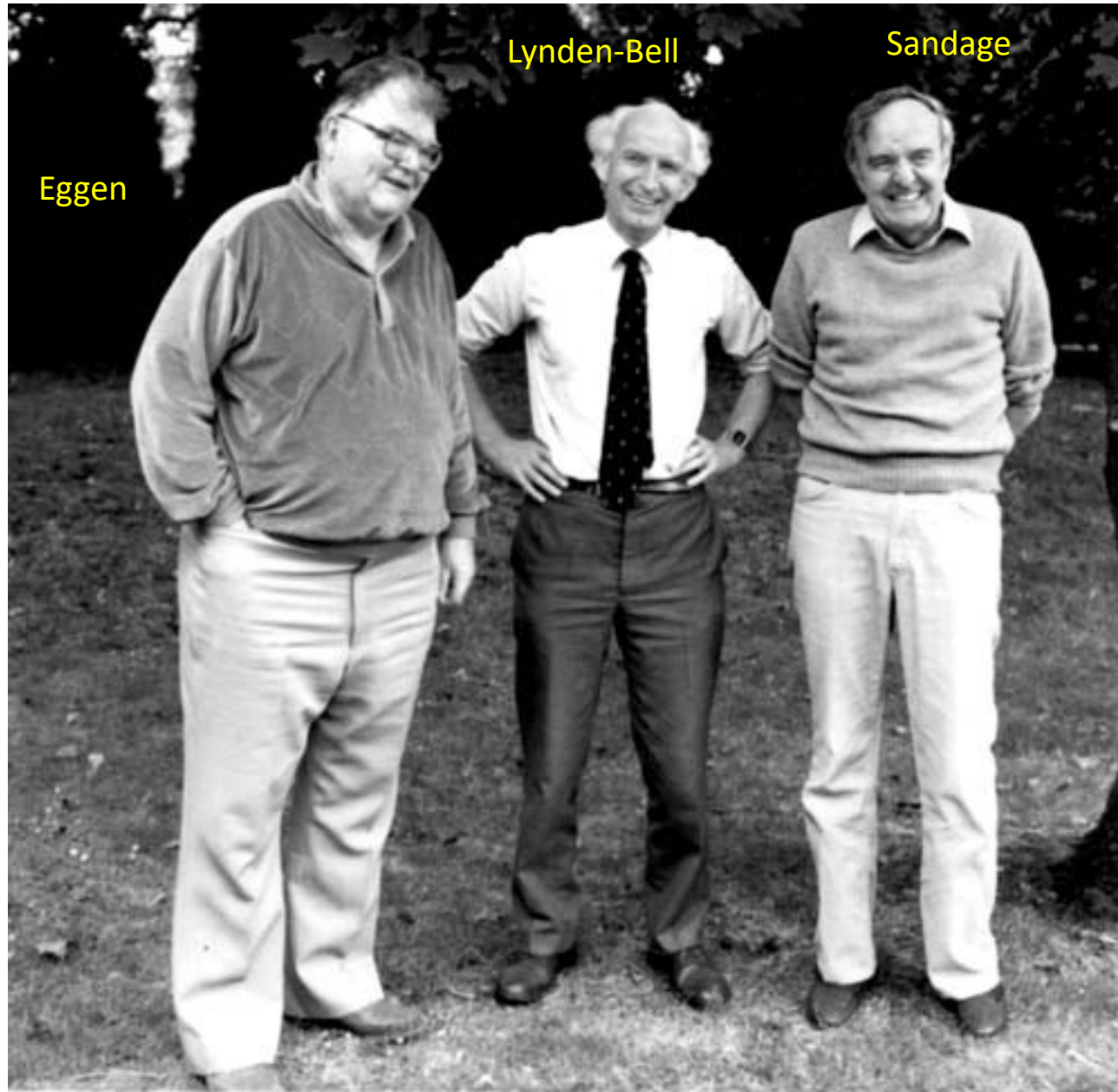
\* **Monolithic, free-fall collapse**

Eggen, Lynden-Bell, Sandage 1962 (ELS)

\* **Chaotic merging of numerous fragments**

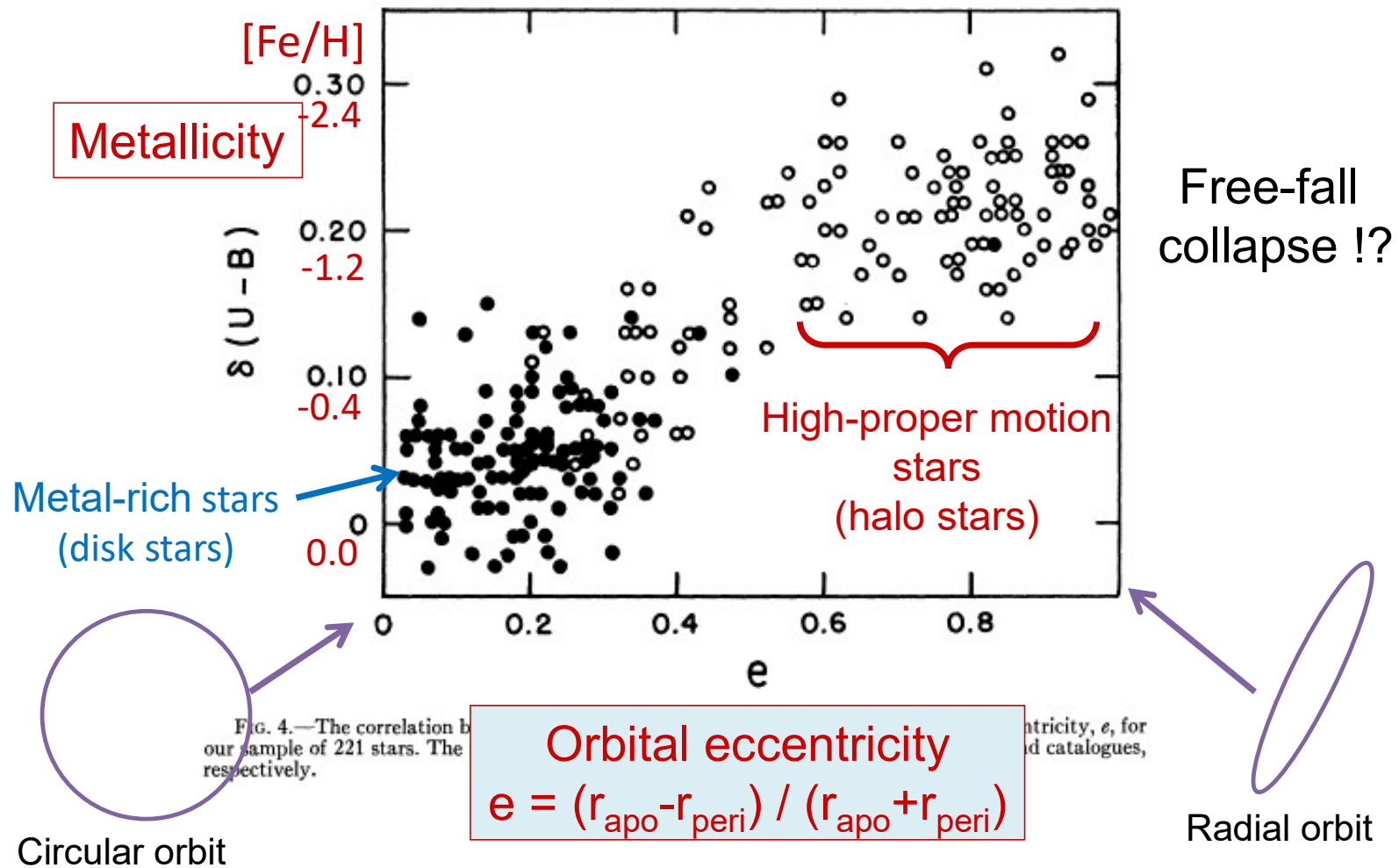
Searle, Zinn 1978 (SZ)



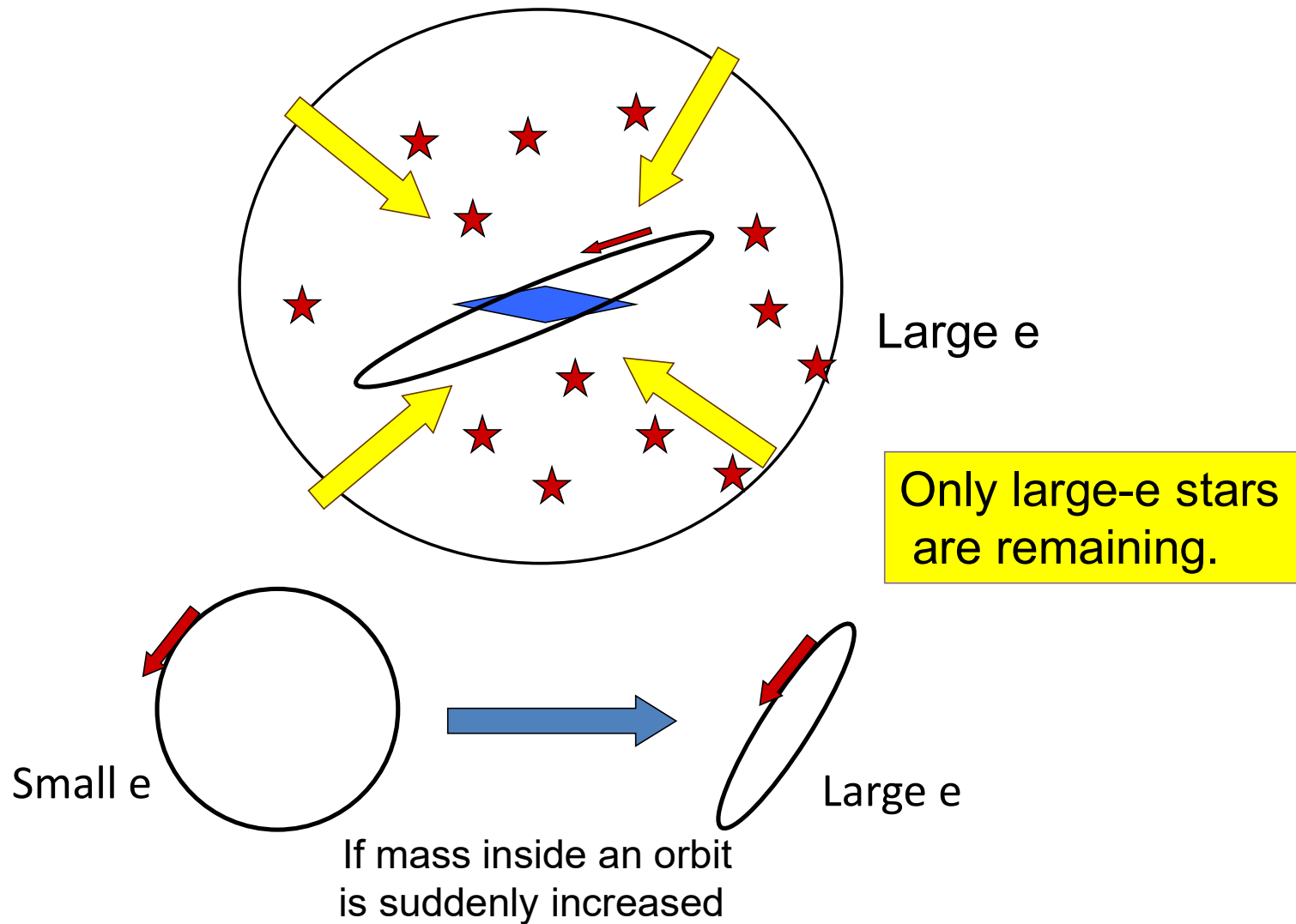


# Physical state of the Protogalaxy

(Eggen, Lynden-Bell & Sandage 1962)



# If free-fall galactic collapse is the case



## Note

### Action integrals for Kepler motions

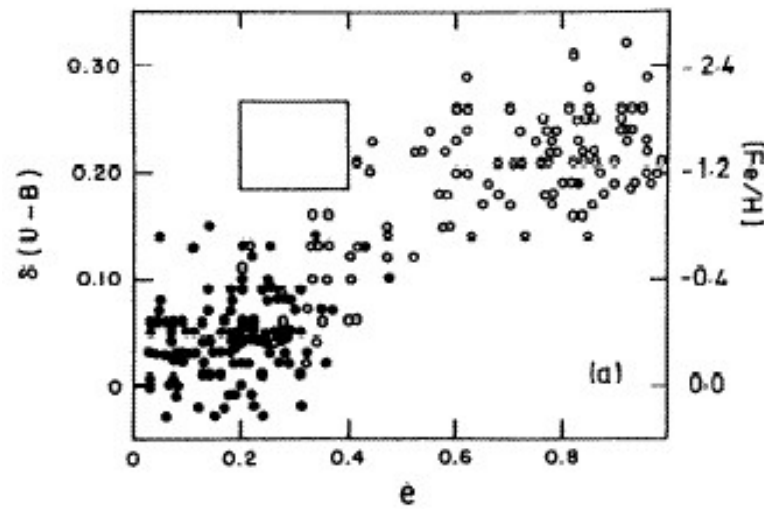
$$J_r = \frac{1}{\pi} \int_{r_{\min}}^{r_{\max}} p_r dr = \frac{\sqrt{2}}{\pi} \int_{r_{\min}}^{r_{\max}} \sqrt{E - \frac{L^2}{2r^2} + \frac{GM}{r}} dr = \frac{GM}{\sqrt{2|E|}} - L = L \left[ \frac{1}{\sqrt{1-e^2}} - 1 \right]$$

$$J_\theta = \frac{1}{\pi} \int_{\theta_{\min}}^{\theta_{\max}} \sqrt{L^2 - \frac{p_\phi^2}{\sin^2 \theta}} d\theta = L - |J_\phi|$$

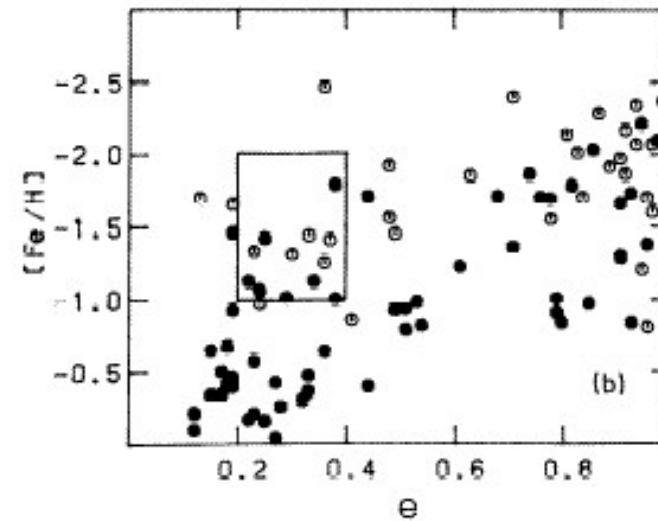
$$J_\phi = \frac{1}{2\pi} \oint p_\phi d\phi = p_\phi$$

$L = |J_\phi| + J_\theta$  : conserved  
 $e$  : conserved as well  
 $\Rightarrow$  adiabatically invariant  
(also nearly invariant  
for non-Kepler motions)

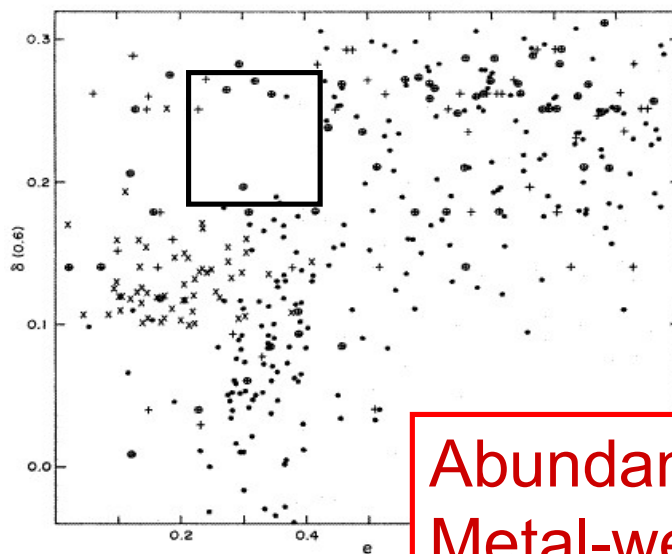
ELS 1962



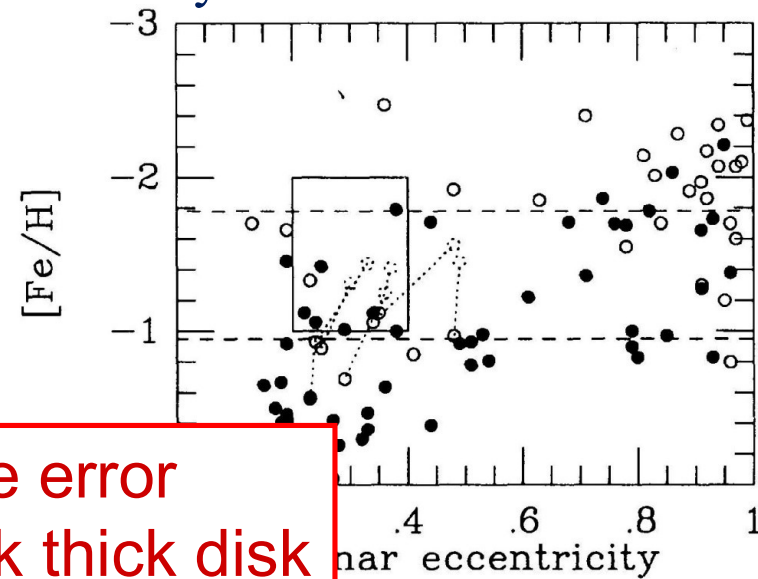
Norris et al. 1985



Yoshii & Saio 1979

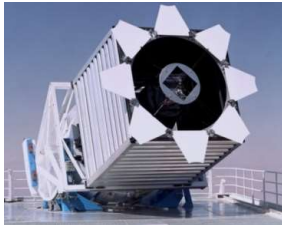


Ryan & Lambert 1995



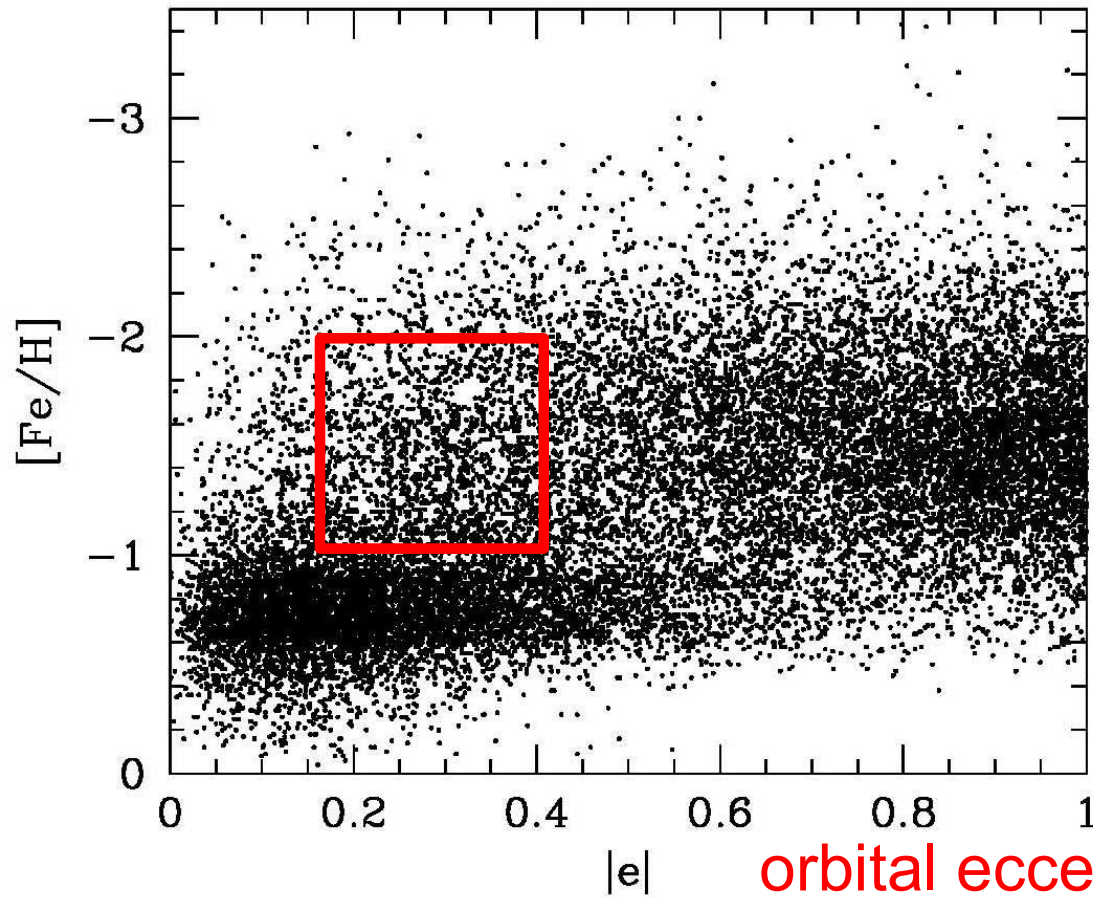
Abundance error  
Metal-weak thick disk

### 3. Formation of the stellar halo: after Hipparcos (& before Gaia)



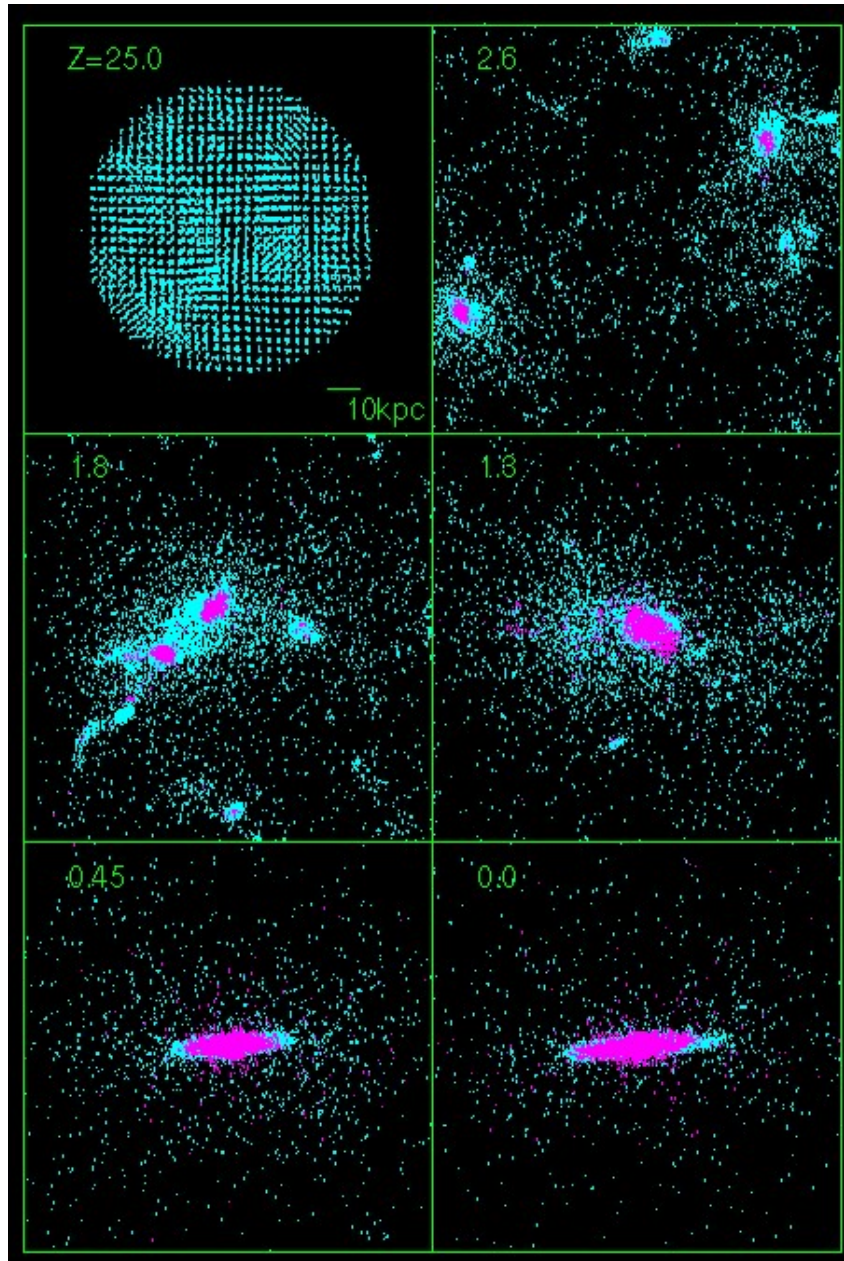
SDSS

[Fe/H]



Hipparcos

Carollo, Beers, Lee, Chiba,  
Norris et al. 2007, Nature



Monolithic collapse  
or chaotic merging?



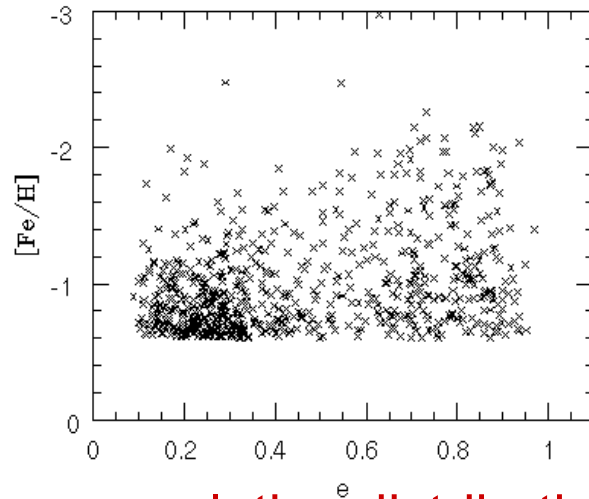
Comparison with numerical  
simulation based on CDM model  
Bekki & Chiba (2001)

- gas
- star

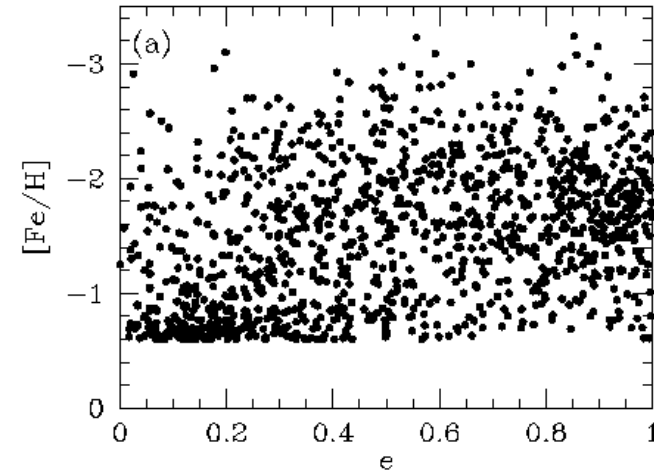
# Comparison with simulation results

Bekki & Chiba (2001)

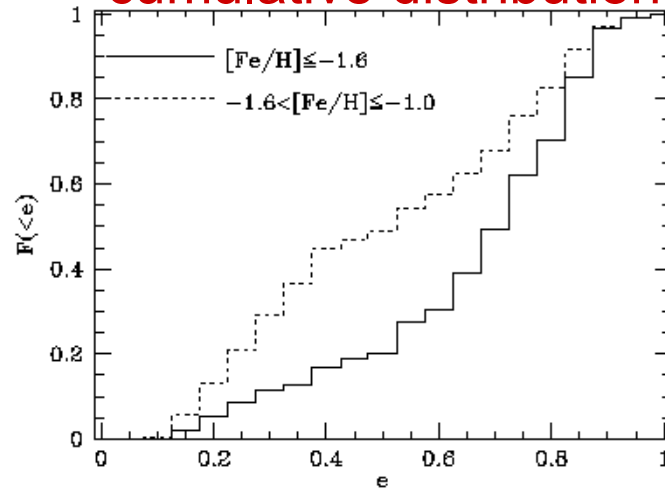
simulation



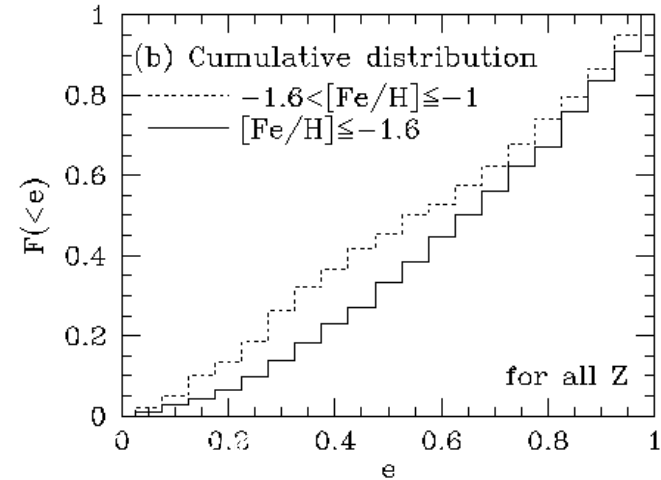
observation



cumulative distribution

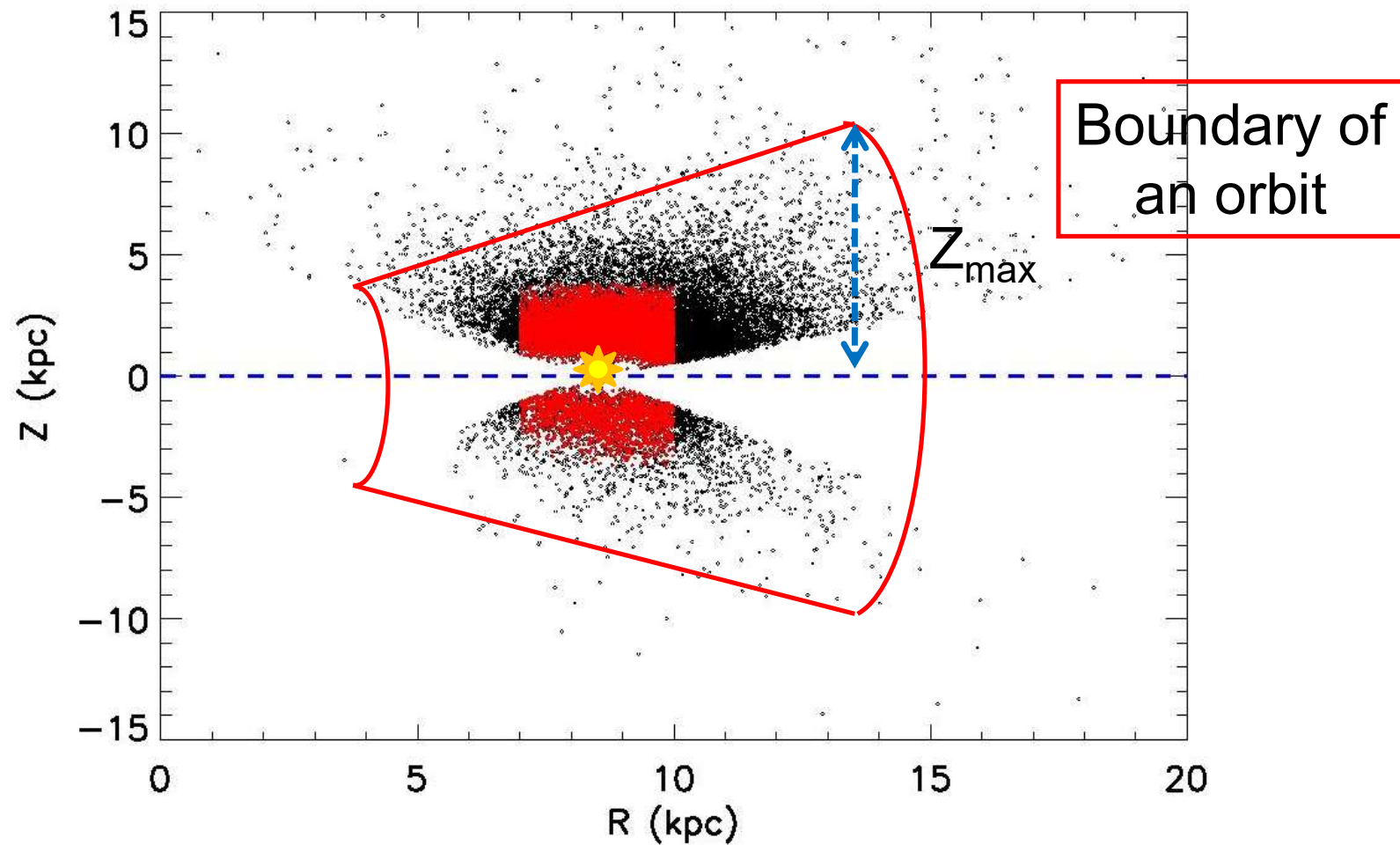
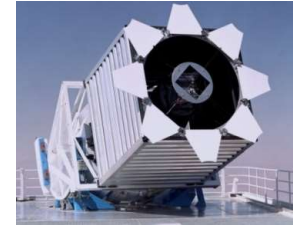


cumulative distribution



# Nearby stellar sample from SDSS

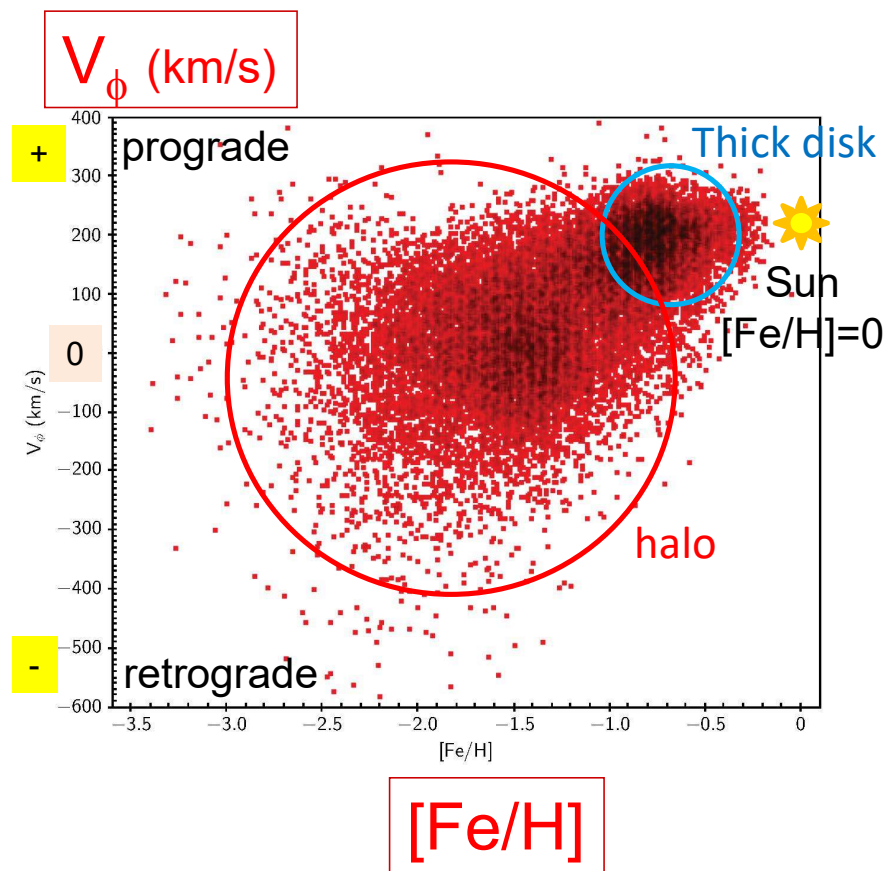
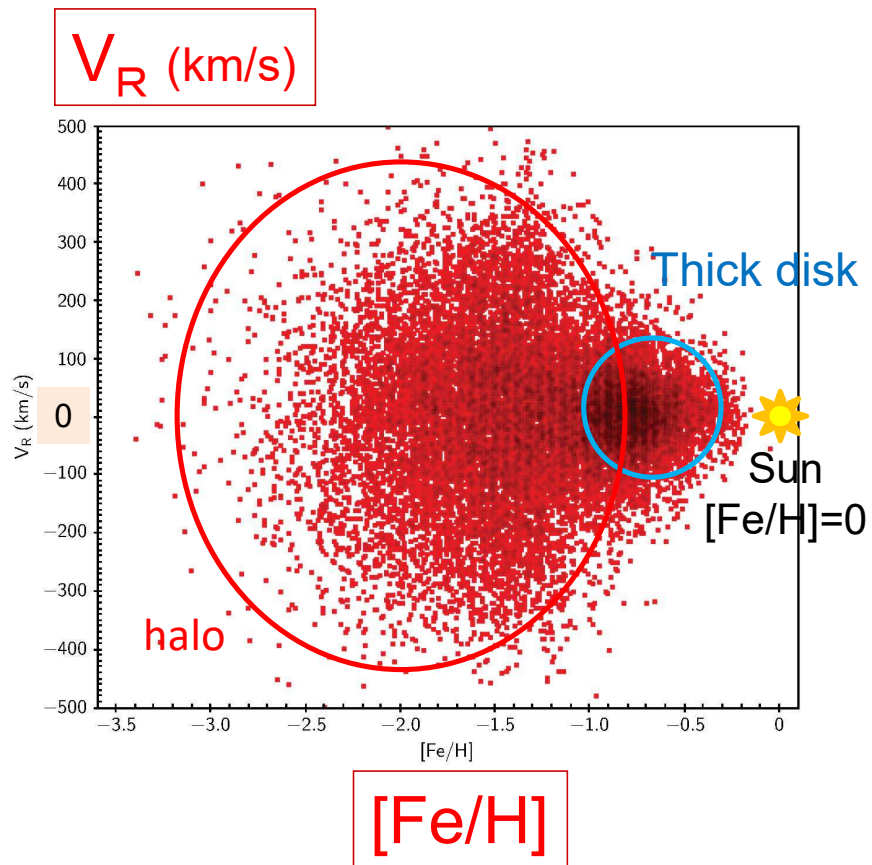
Carollo+2007, 2010



# Velocity distribution of nearby stars

## Sloan Digital Sky Survey

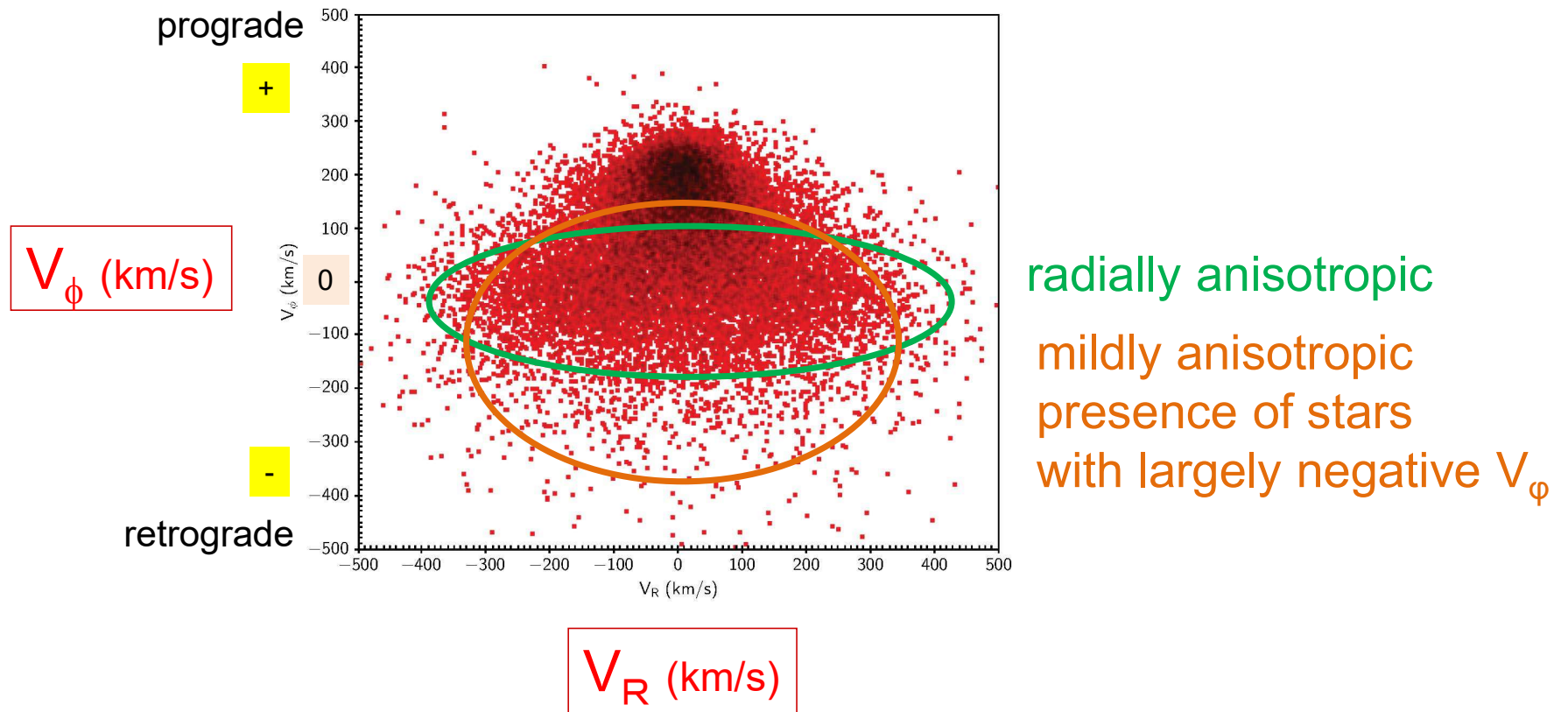
Carollo+2007, 2010



# Velocity distribution of nearby stars

## Sloan Digital Sky Survey

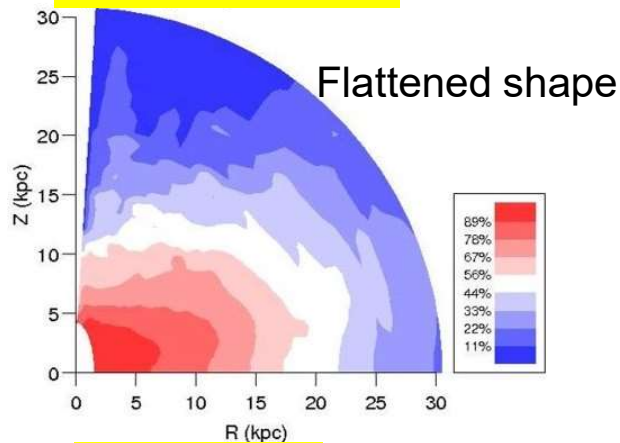
Carollo+2007, 2010



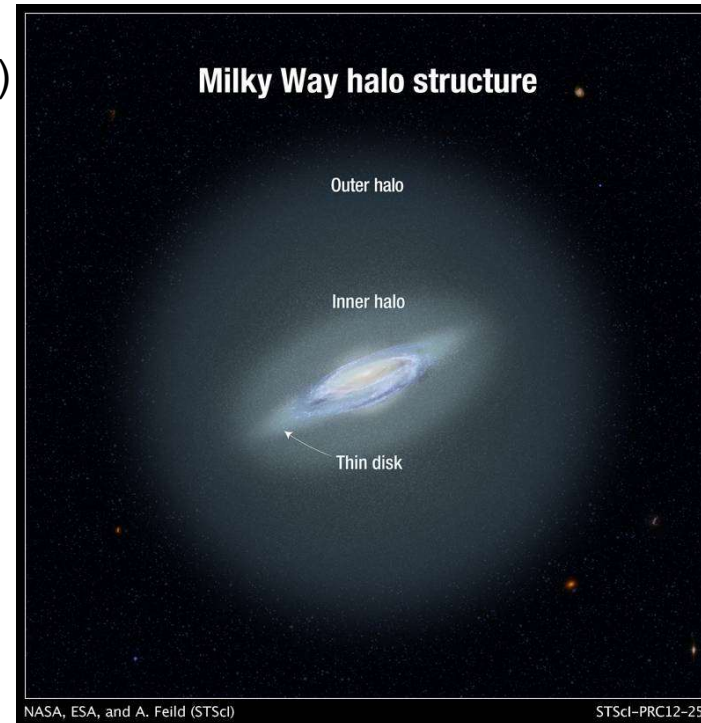
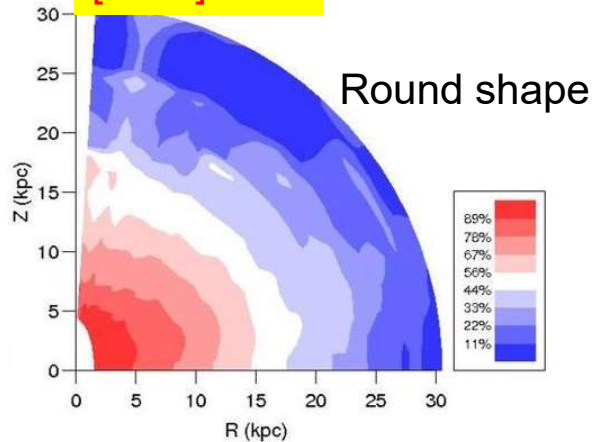
# 2-halos : from dynamics

Global halo distribution based on superposition of stellar orbits (Carollo+ 2007)

$-1.6 < [\text{Fe}/\text{H}] < -1.4$



$[\text{Fe}/\text{H}] < -2.2$

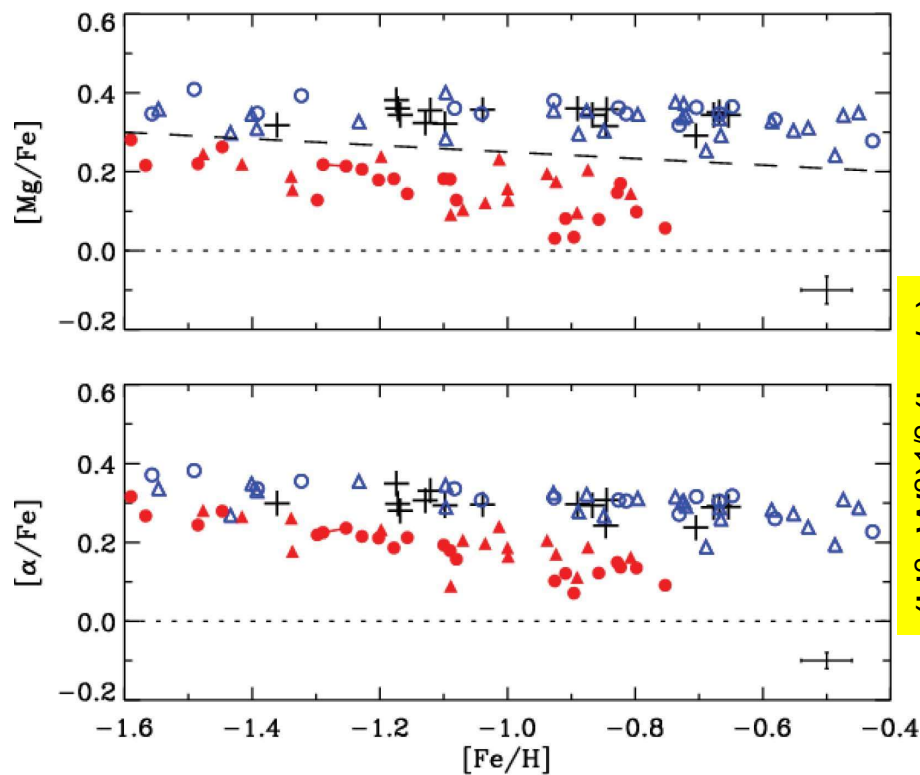


- Inner halo -> in situ halo
  - Flattened shape,  $-1.6 < [\text{Fe}/\text{H}] < -1$
- Outer halo -> ex situ halo
  - Round shape,  $[\text{Fe}/\text{H}] < -2$

# 2-halos : from chemical abundance

Abundance ratios for high-velocity stars (Nissen & Schuster 2010)

$$|V_{\text{star}} - V_{\text{LSR}}| > 180 \text{ km/s}$$



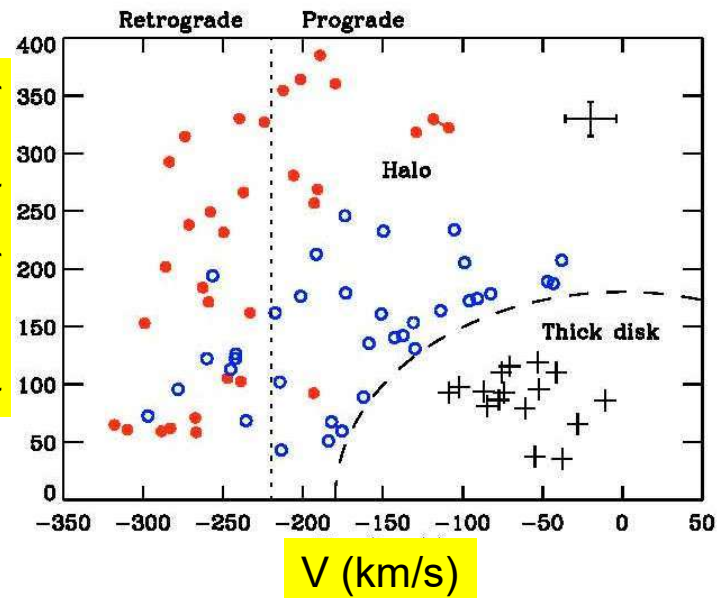
Blue: high- $\alpha$  stars

→ inner (in situ) halo?

Red: low- $\alpha$  stars

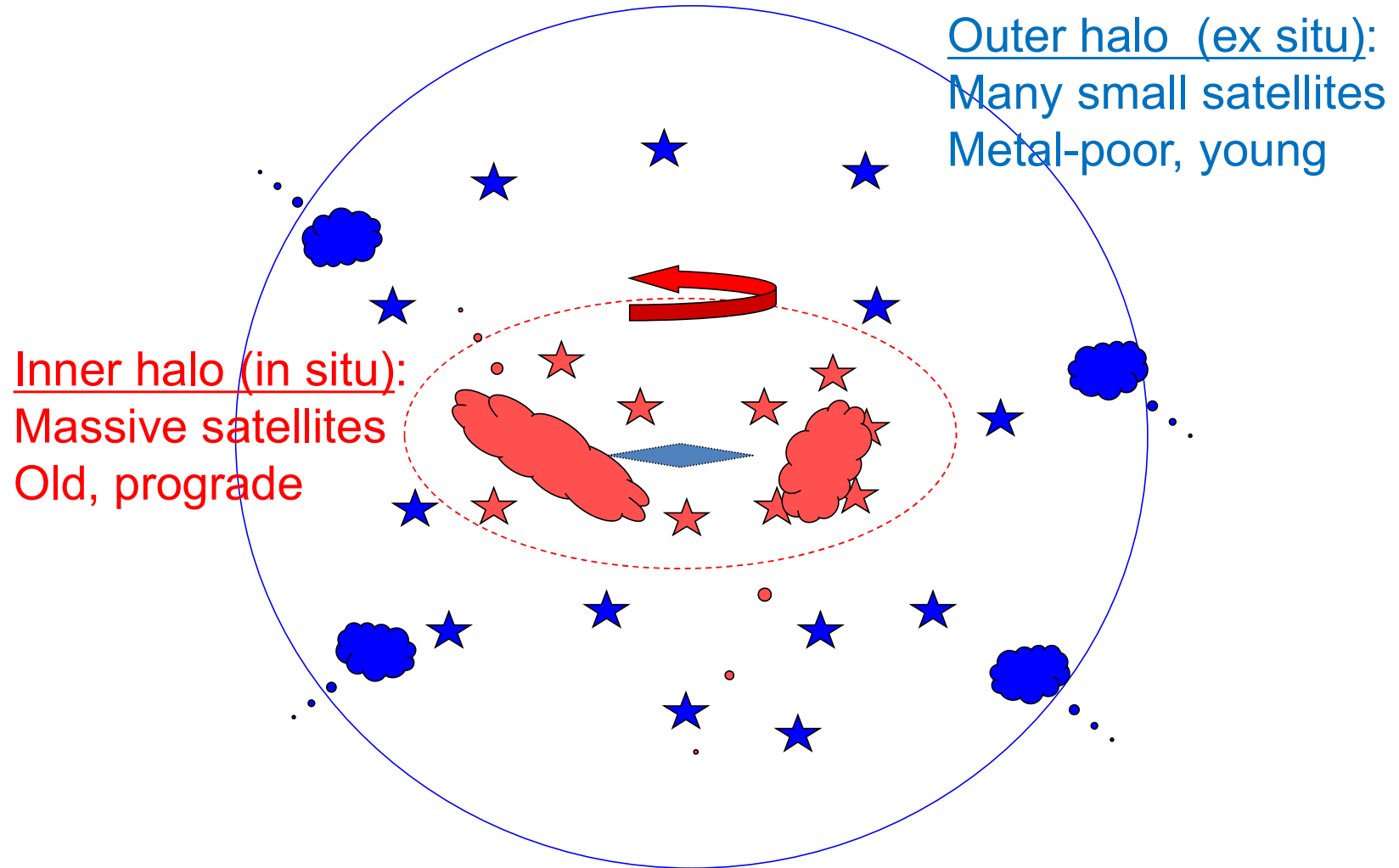
→ outer (ex situ) halo?

$(U^2 + W^2)^{1/2}$  (km/s)



Based on VLT/UVES & NOT/FIES spectra  
High-precision calibration with  $\Delta = 0.02 \sim 0.04$  dex

# How 2-halos have formed?



## Emergence of *in situ*. and *ex situ*. halos from numerical simulation

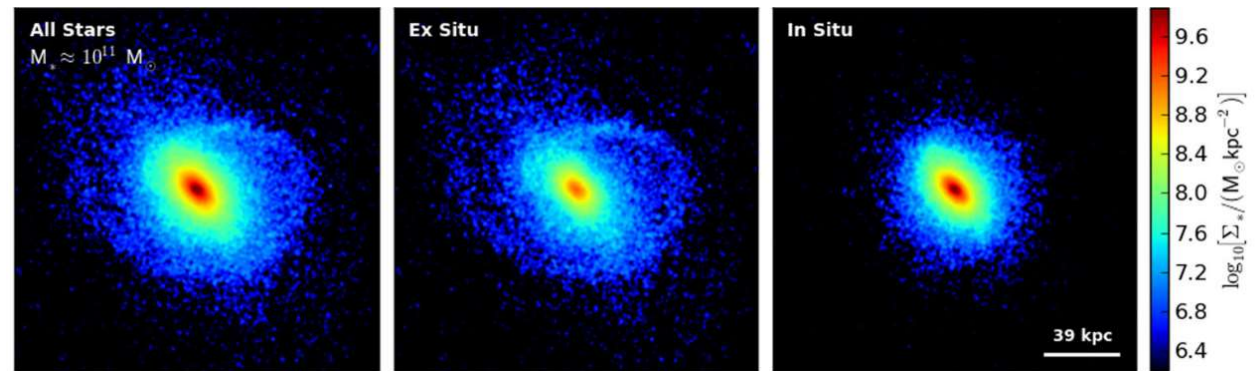
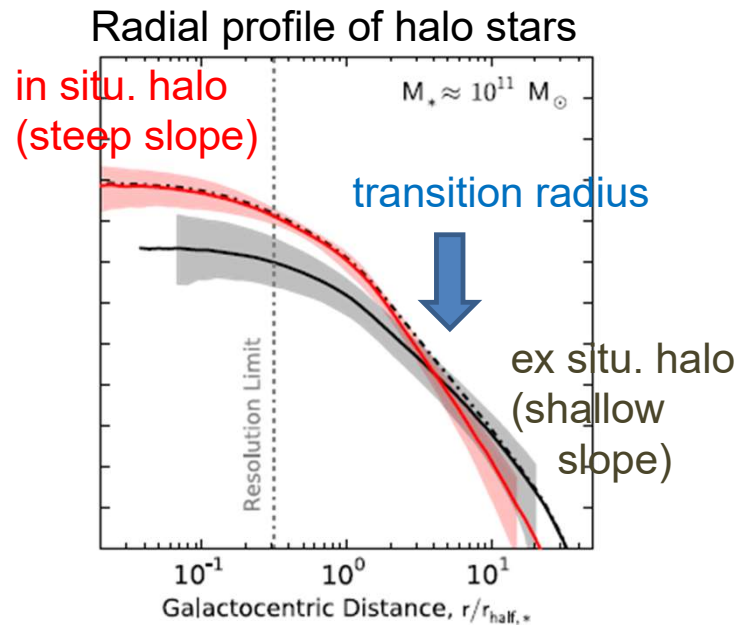
Illustris simulation

Rodriguez-Gomez+2016

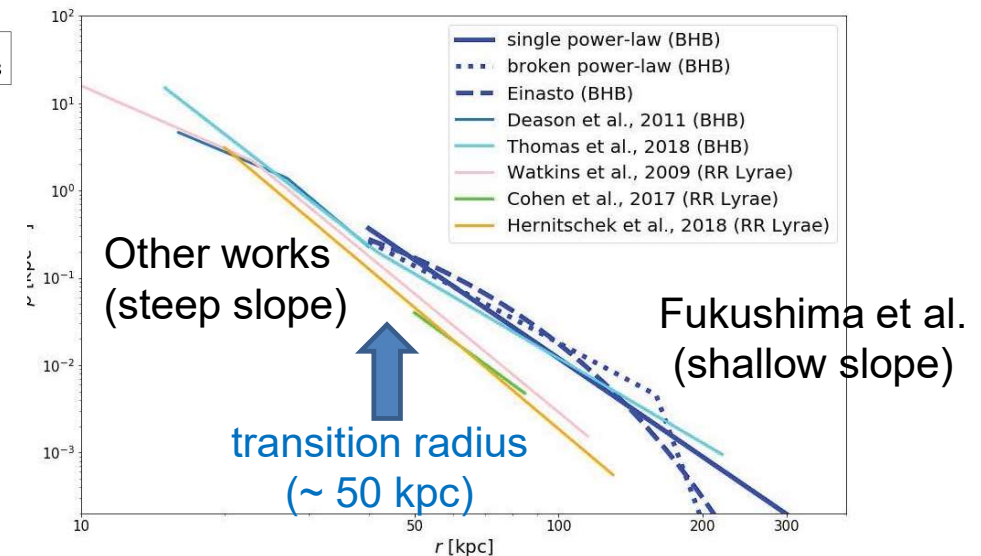
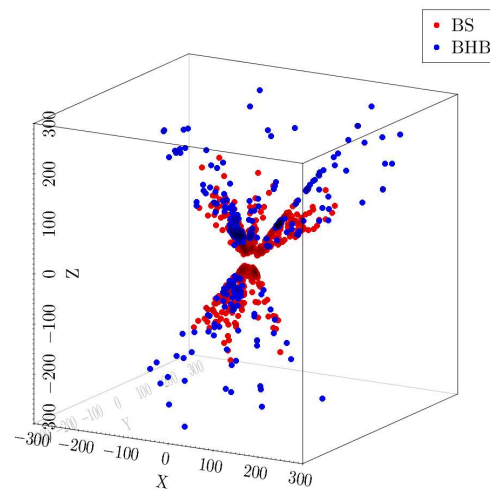
all stars

*ex situ*.

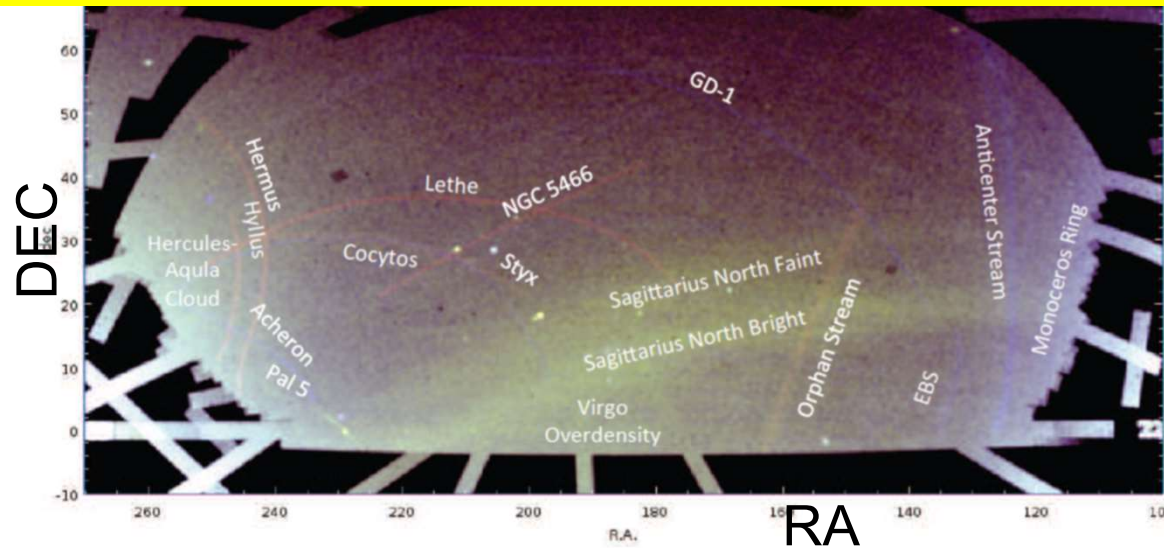
*in situ*.



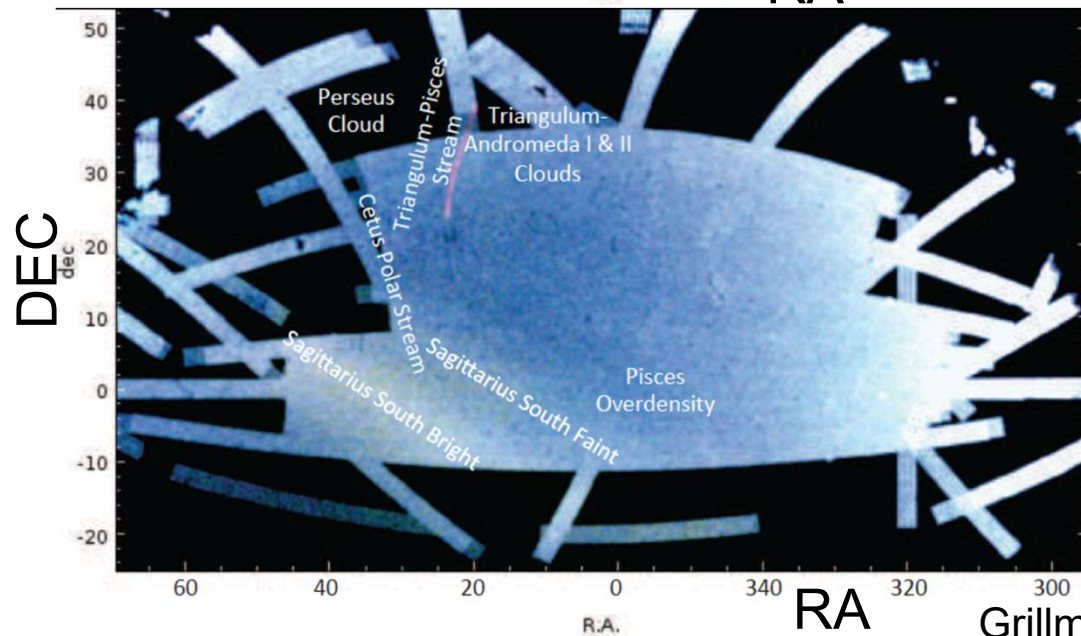
Distribution of Blue-Horizontal Branch Stars from Subaru/HSC (Fukushima et al. 2019)



## Stellar streams: remnants of merging small galaxies



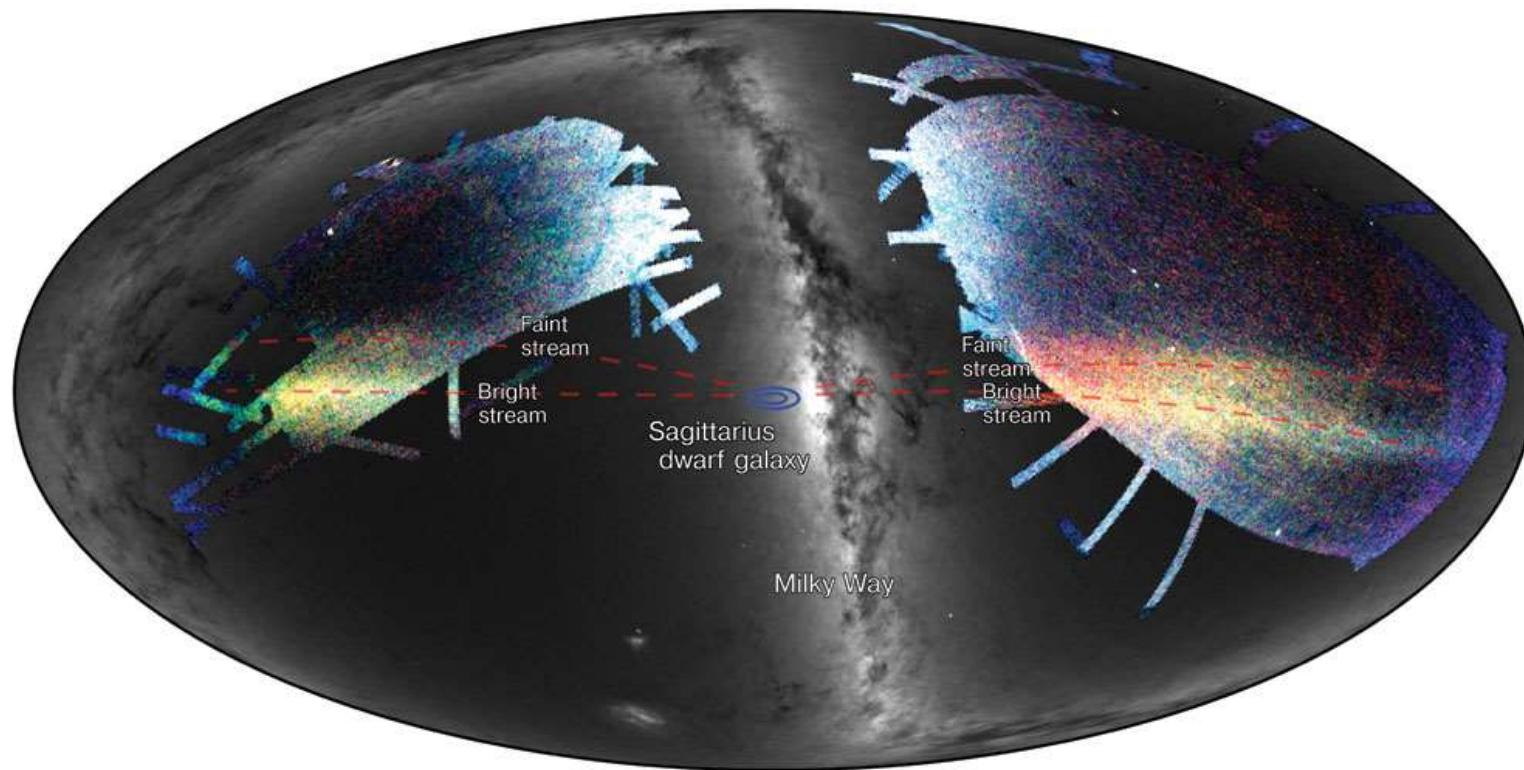
North



South

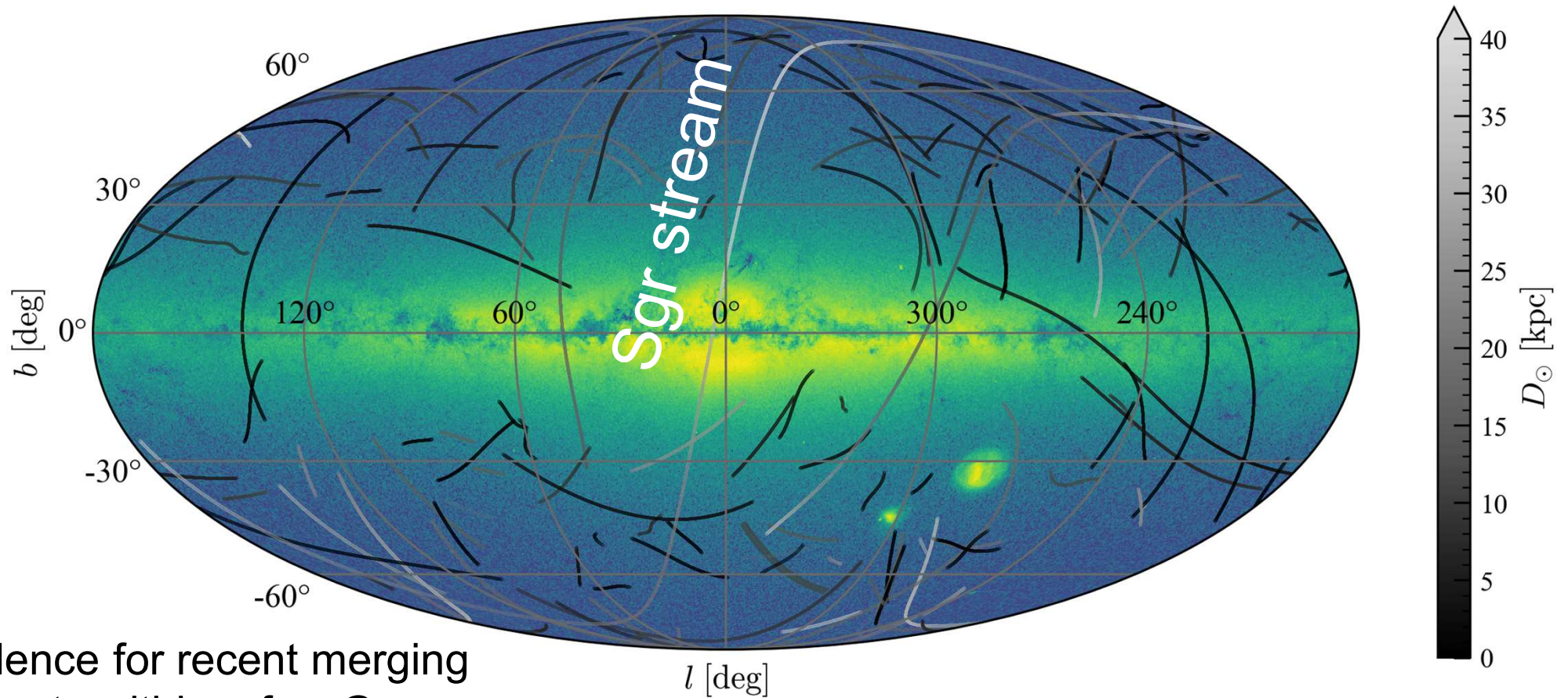
Grillmair & Carlin 2016

# Sagittarius stream



# Sgr stream and other stellar streams

(incl. those found after Gaia)

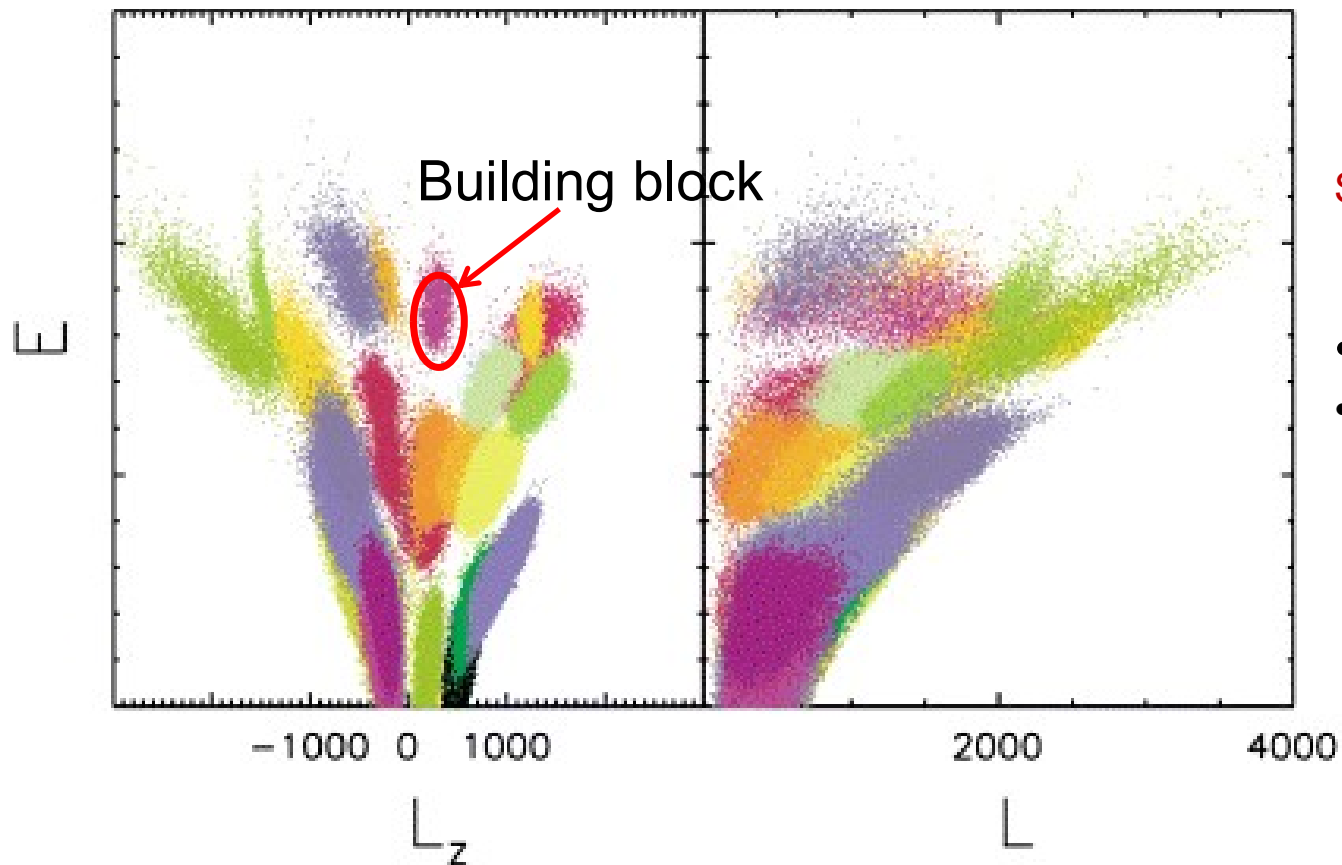


Evidence for recent merging  
events within a few Gyrs

Credit: Y. Suzuki

# Probing merging events at much earlier epochs

These substructures remain due to a long relaxation time



Simulation result of satellite accretion:  
Gaia (precise distance and proper  
motion) + observation of  $V_{\text{rad}}$  &  $[\text{Fe}/\text{H}]$

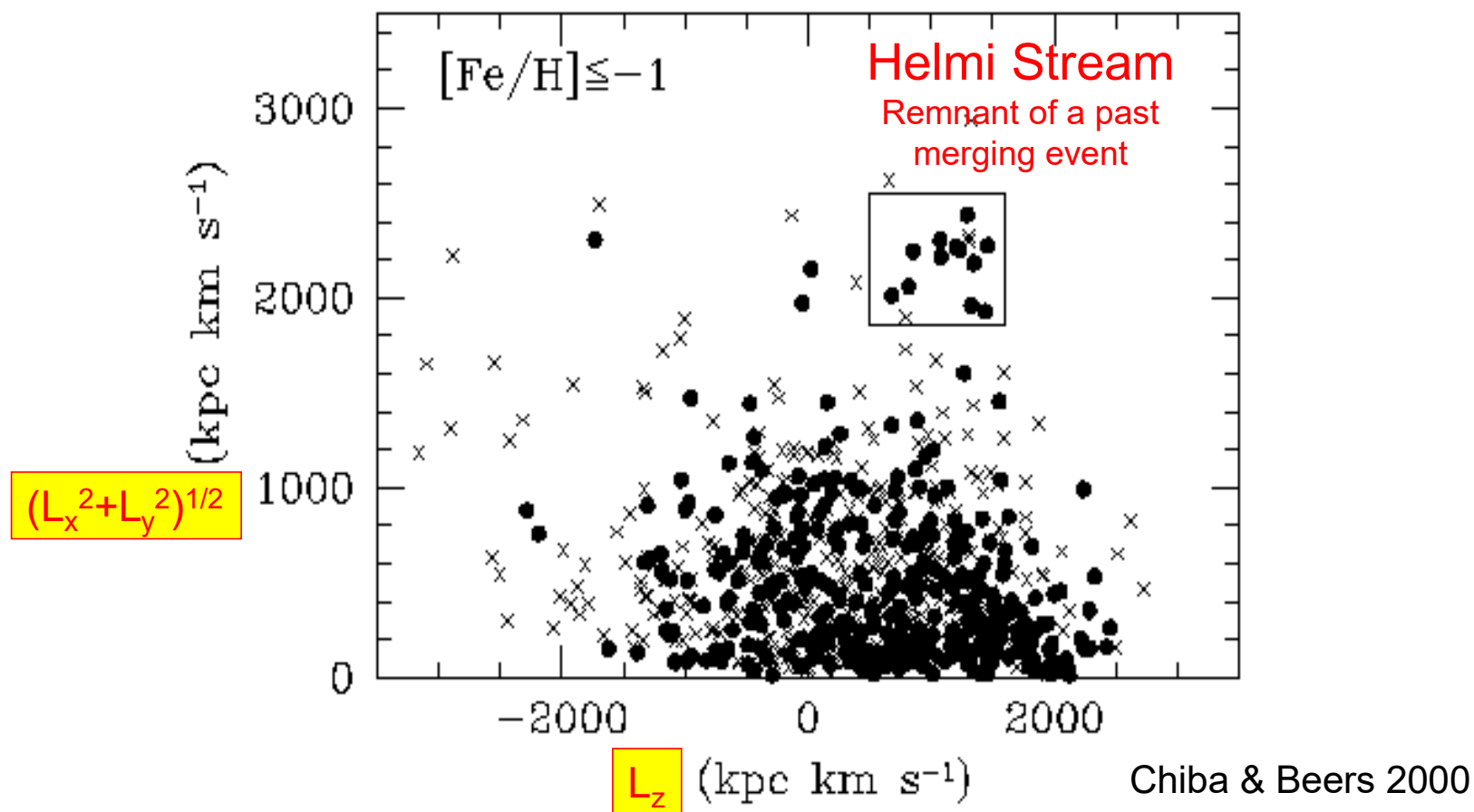
- distinguish each substructure
- SF & Chemical evolution

Helmi & de Zeeuw 00

# Substructure in the stellar halo

Nearby stars in angular-momentum space

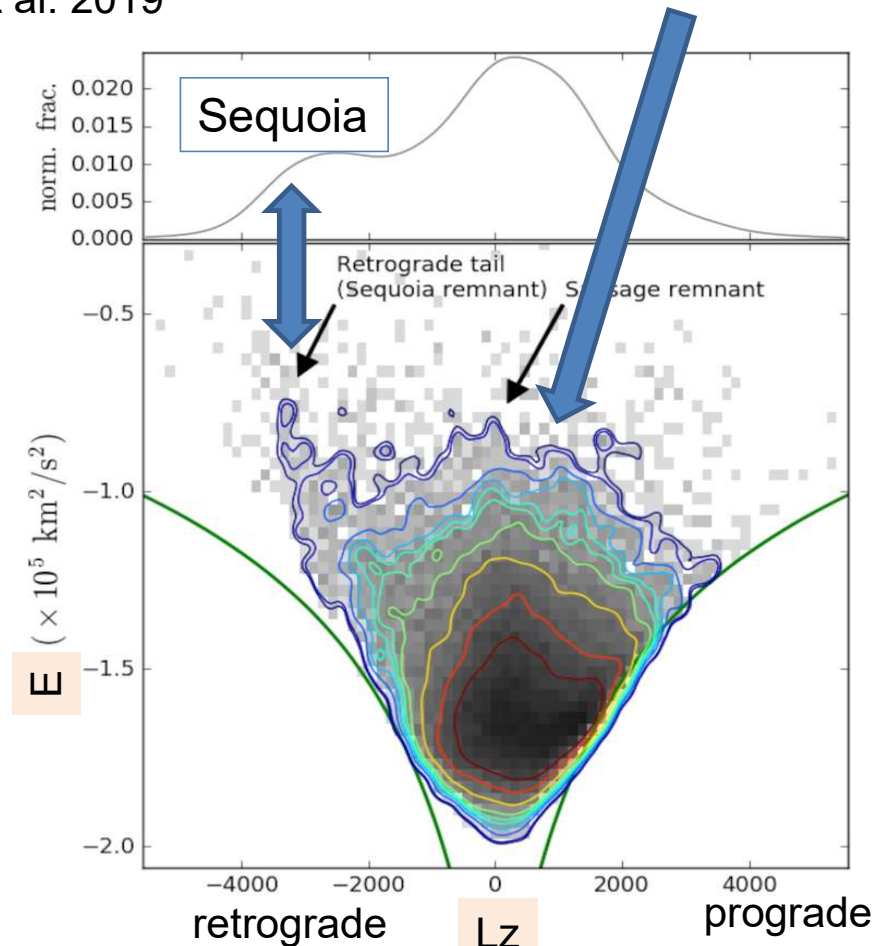
(errors: a few 100 kpc km/s smear out any possible substructures)



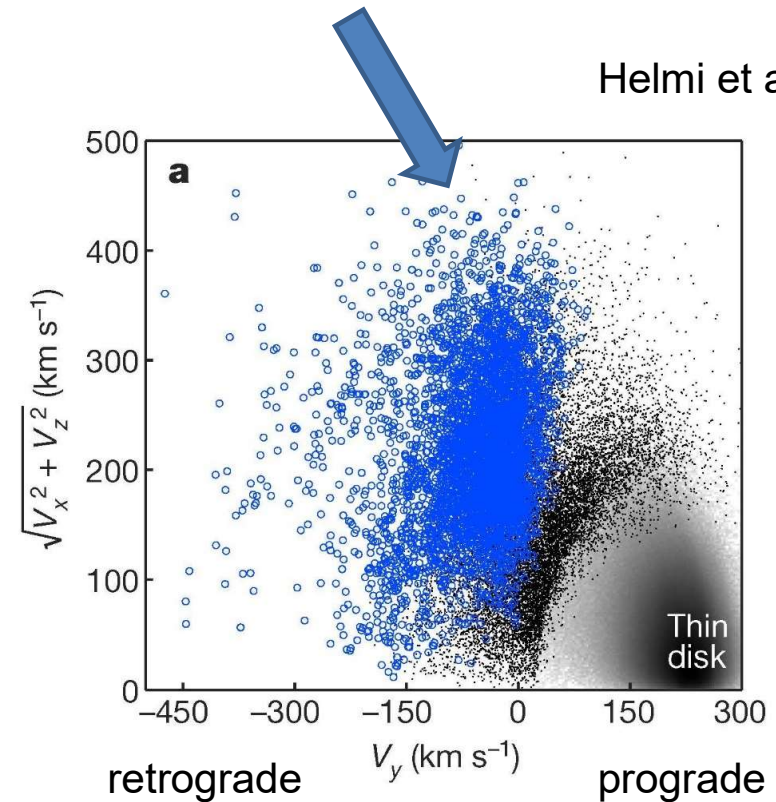
## 4. Formation of the stellar halo: after Gaia

### Gaia-Enceladus/Sausage

Myeong et al. 2019



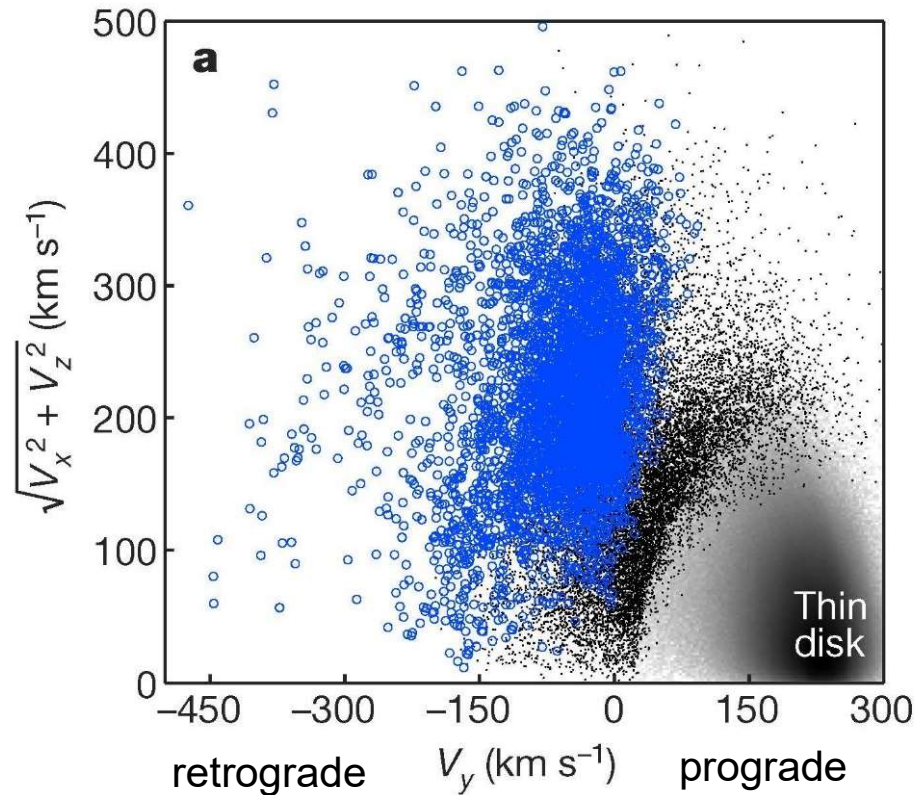
Helmi et al. 2018, Nature



Merging debris of an SMC-class dwarf galaxy 10 Gyrs ago?

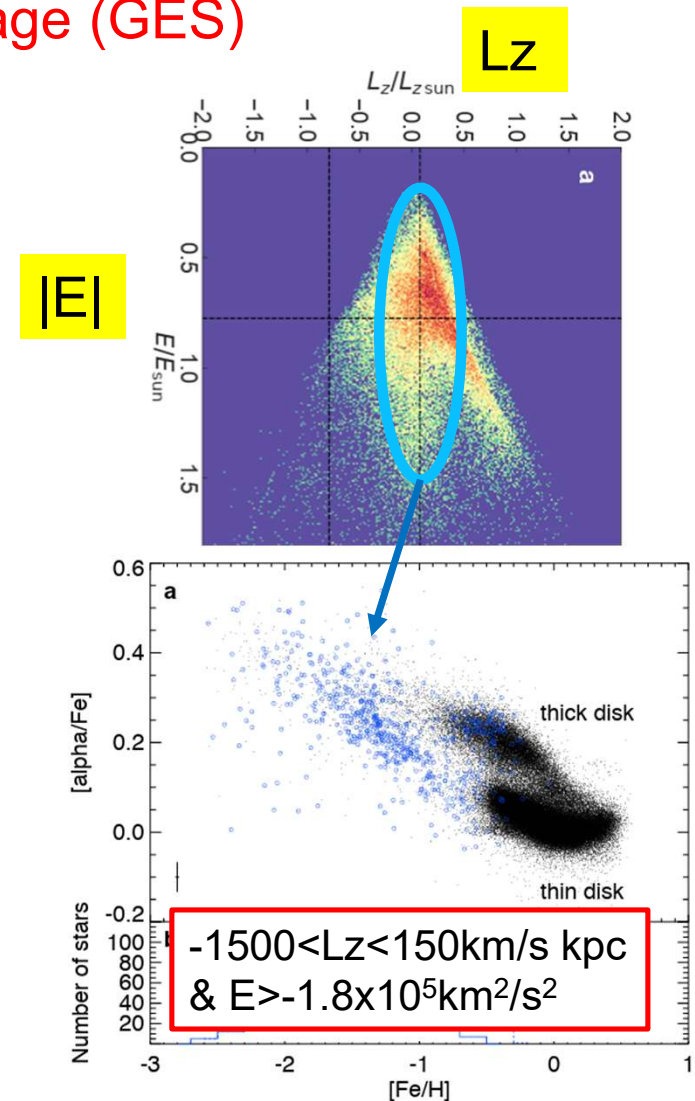
## 4. Formation of the stellar halo: after Gaia

Helmi et al. 2018 **Gaia-Enceladus/Sausage (GES)**



**GES dominates the inner halo.**

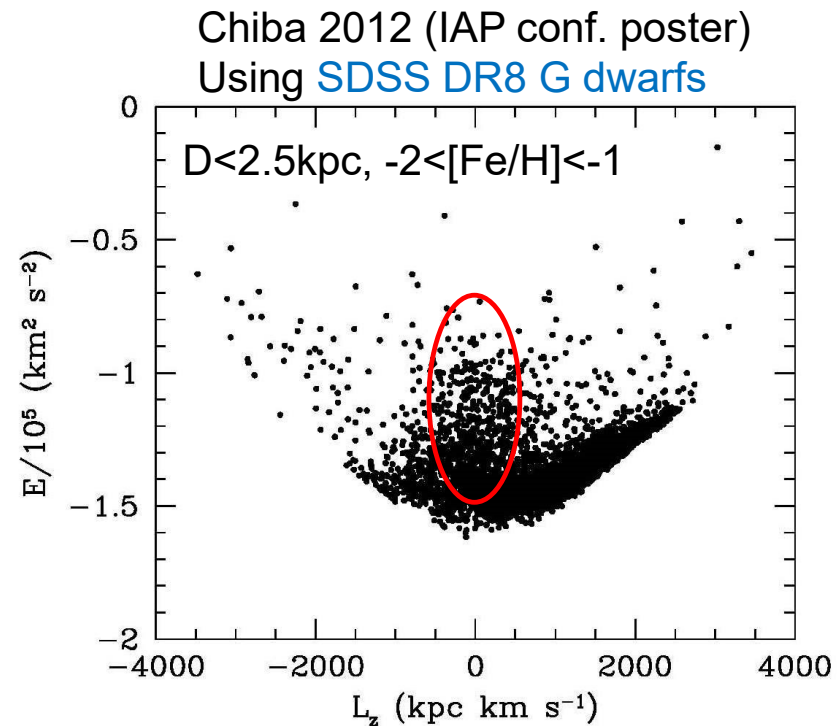
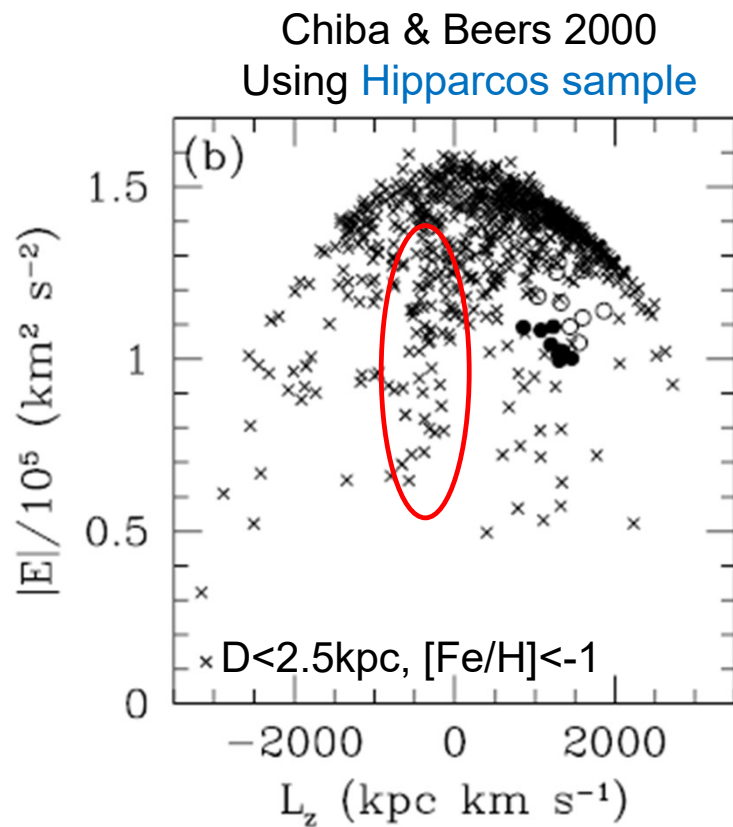
Merging debris of an SMC-class dwarf galaxy 10 Gyrs ago?



Another story ...

# Hipparcos+SDSS-Enceladus?

(This feature was already present in previous samples, but only weakly due to the small number of sample stars.)



This feature was thought to be a tidal remnant of a dSph containing  $\omega\text{Cen}$

# Merging of a dwarf galaxy 10 Gyrs ago? Gaia-Enceladus

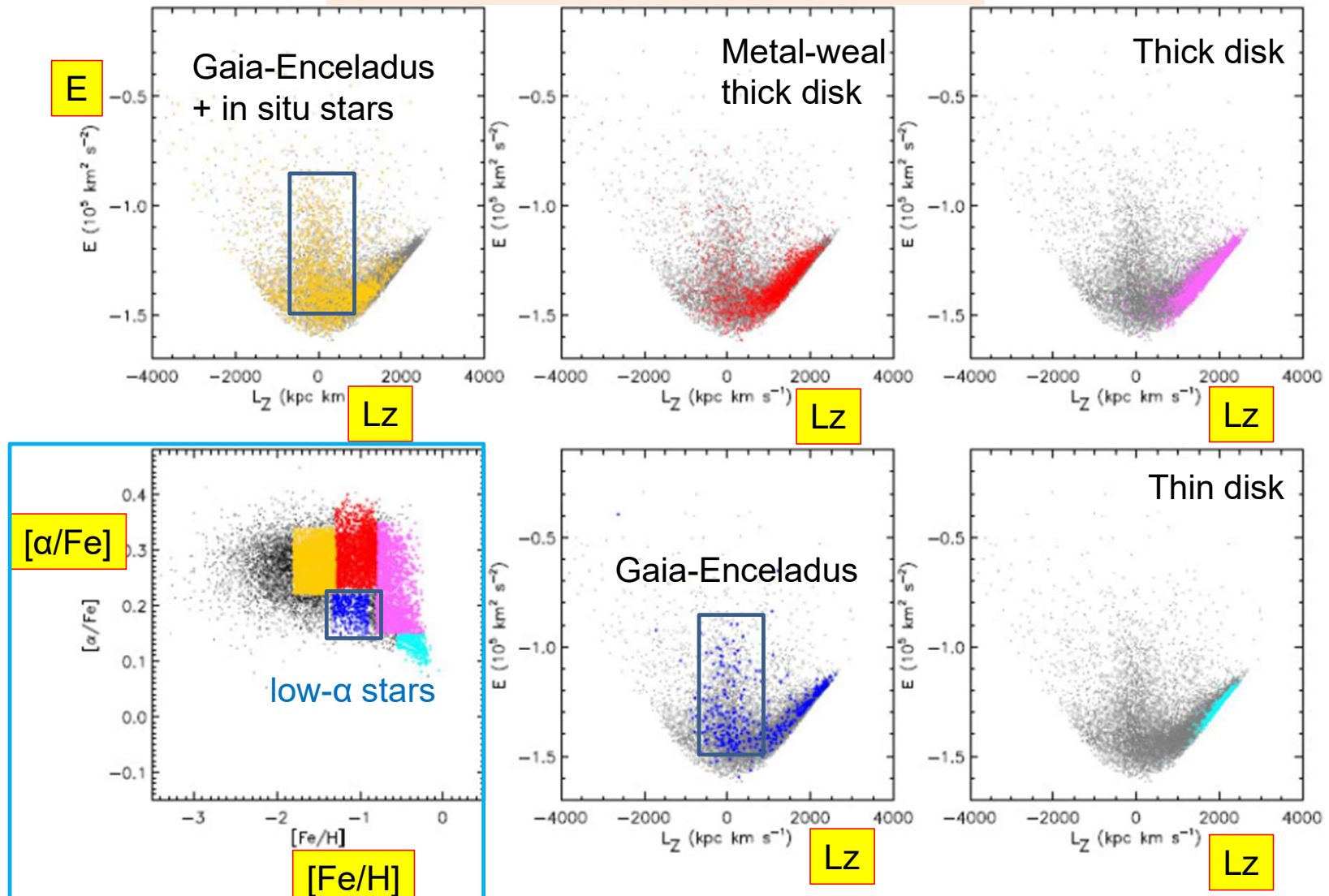


Credit: A. Helmi

# Abundance ratios of Gaia-Enceladus

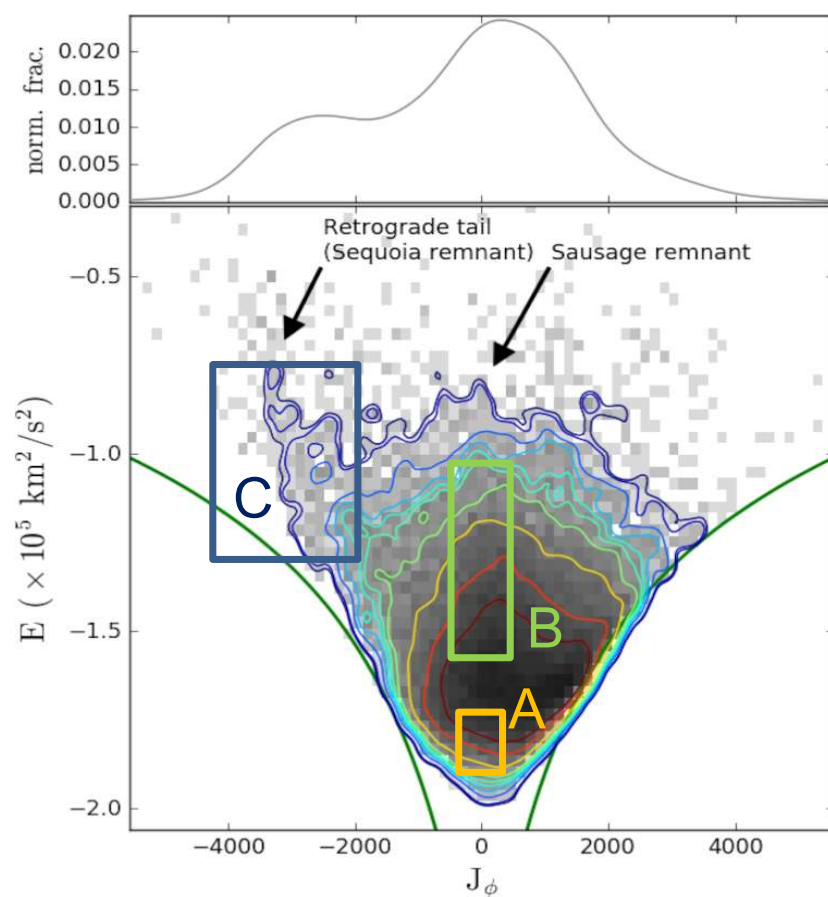
SDSS-DR7 Calibration Stars + Gaia DR2

Carollo & Chiba 2021

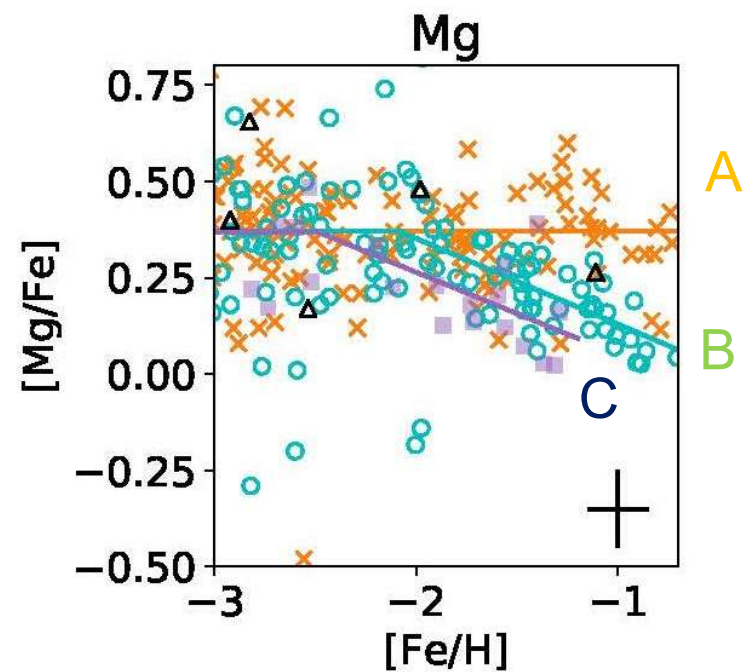


# Abundance ratios

Myeong et al. 2019



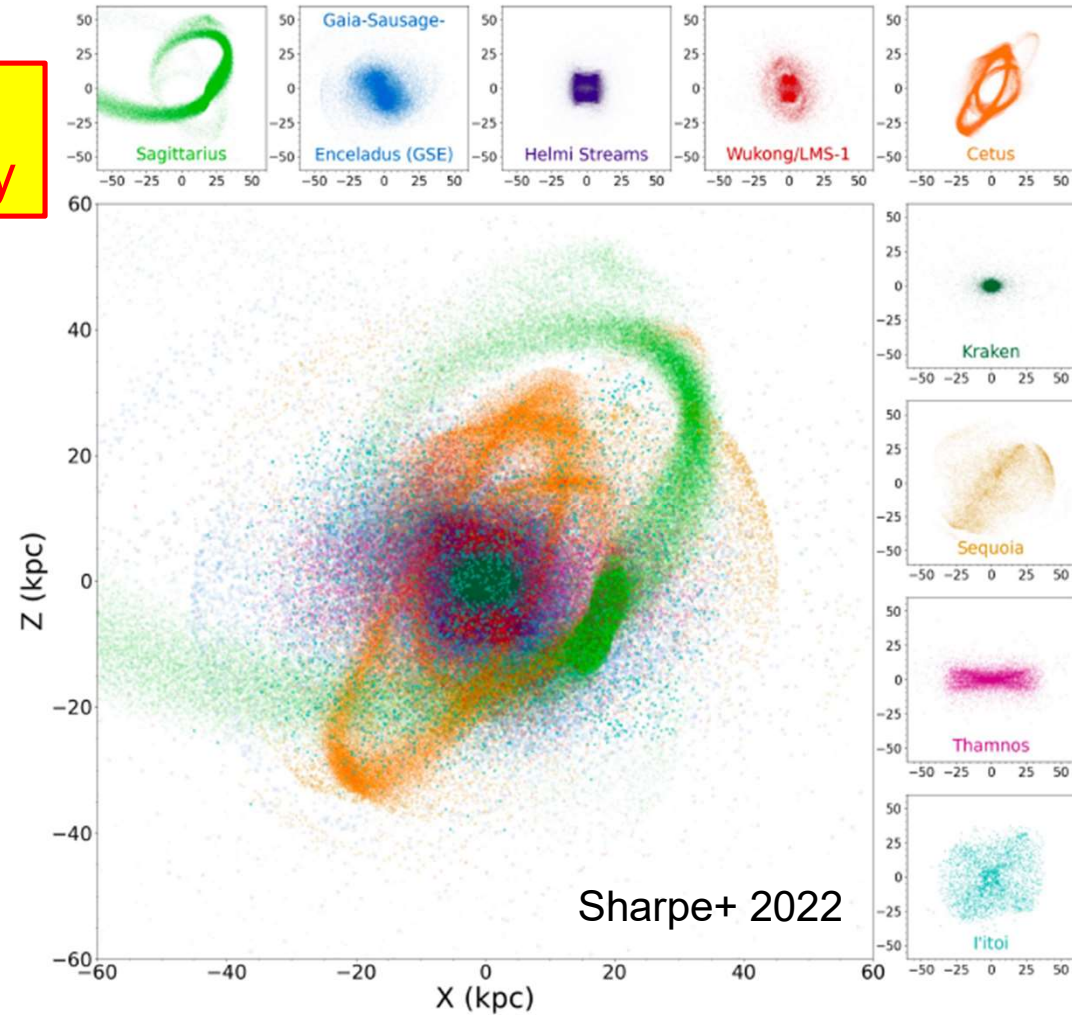
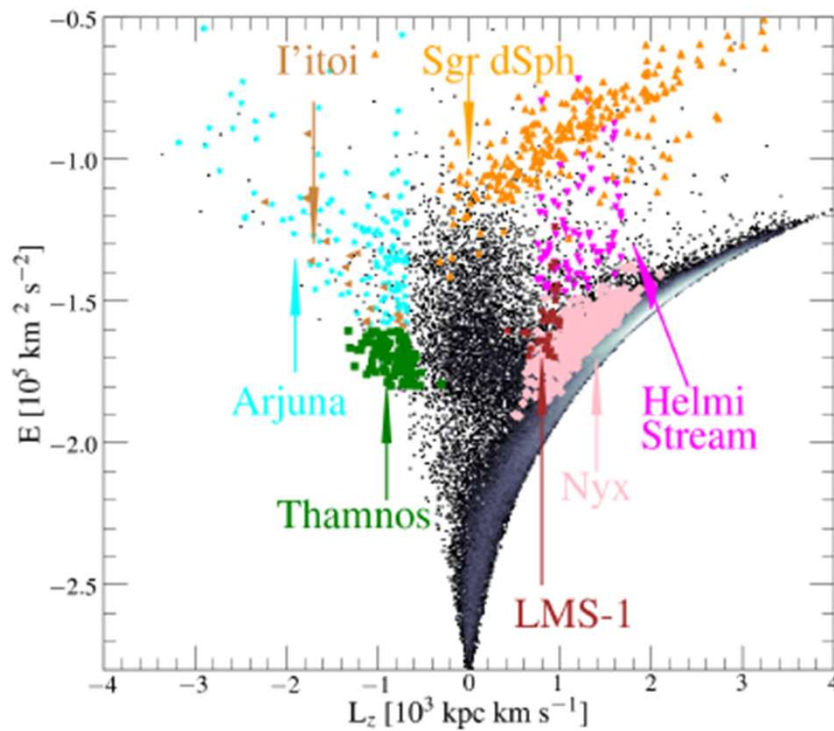
Matsuno et al. 2019  
using SAGA & LAMOST



# Deciphering merging history of the Galaxy

More substructures discovered in the nearby halo phase space reveal past merging history

Horta+ 2022

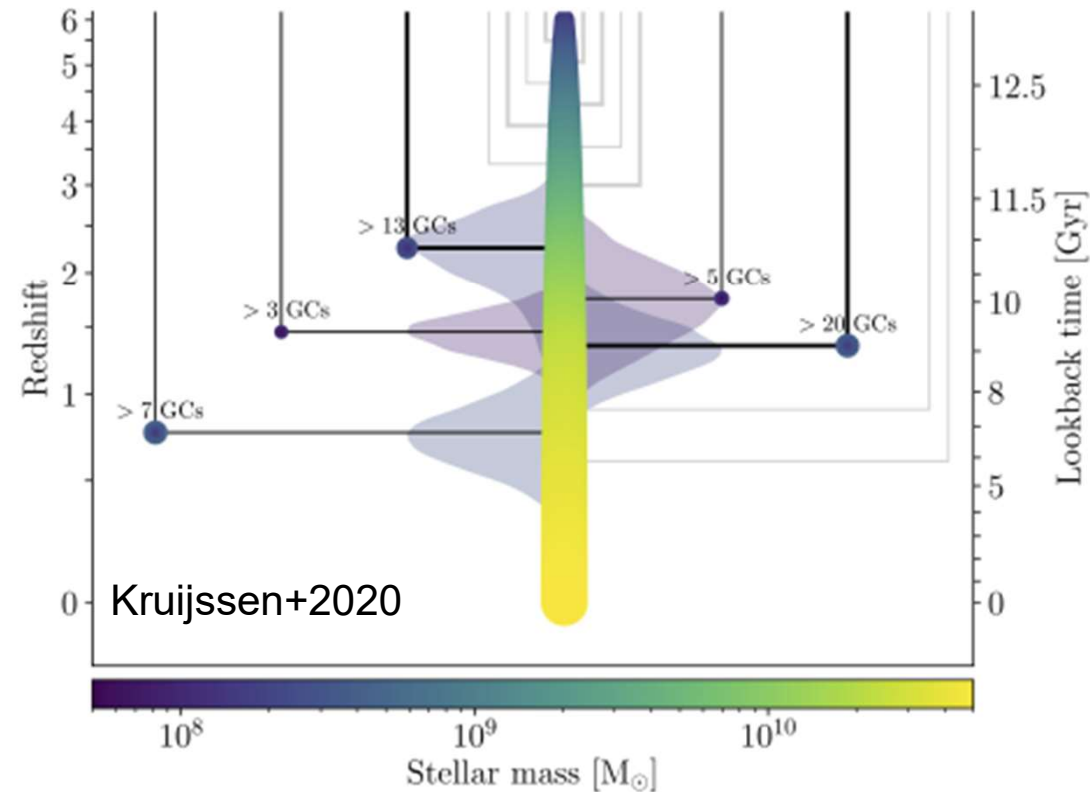
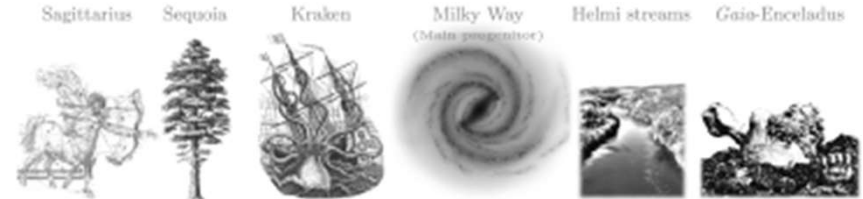
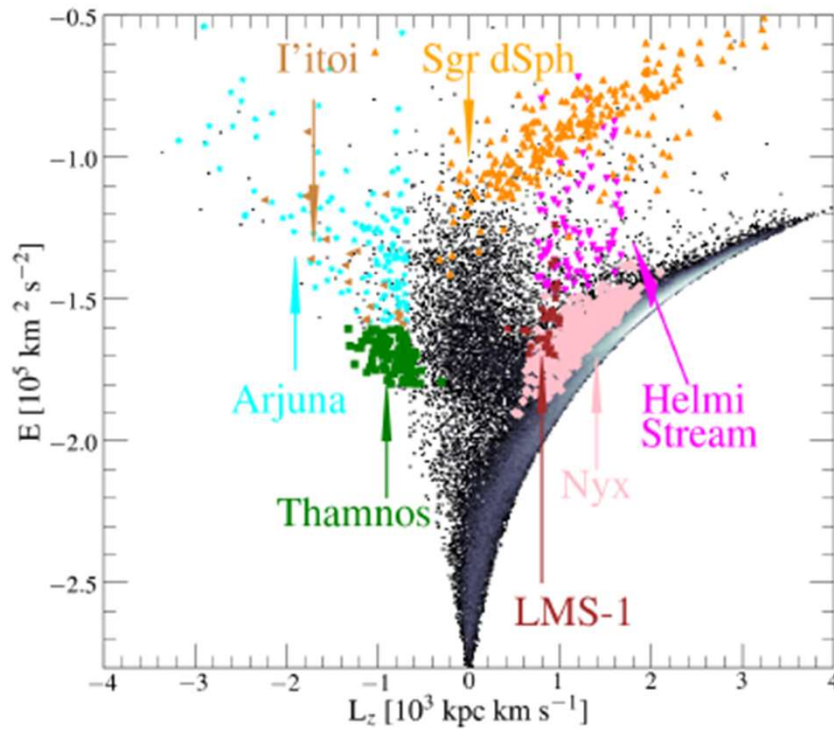


Sharpe+ 2022

# Deciphering merging history of the Galaxy

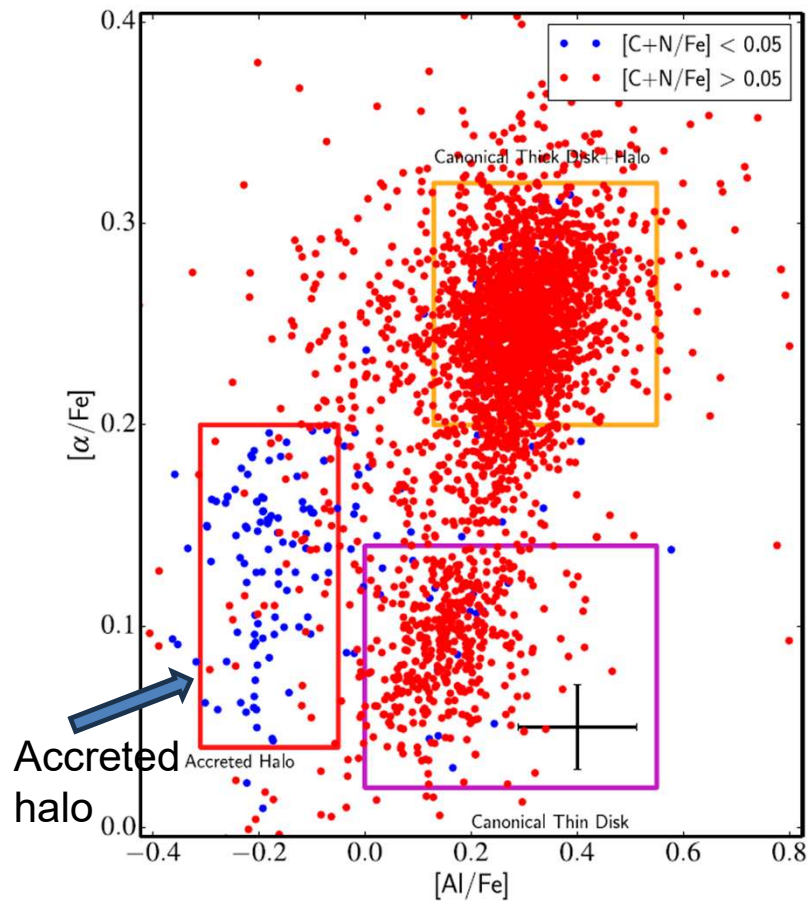
More substructures discovered in the nearby halo phase space reveal past merging history

Horta+ 2022

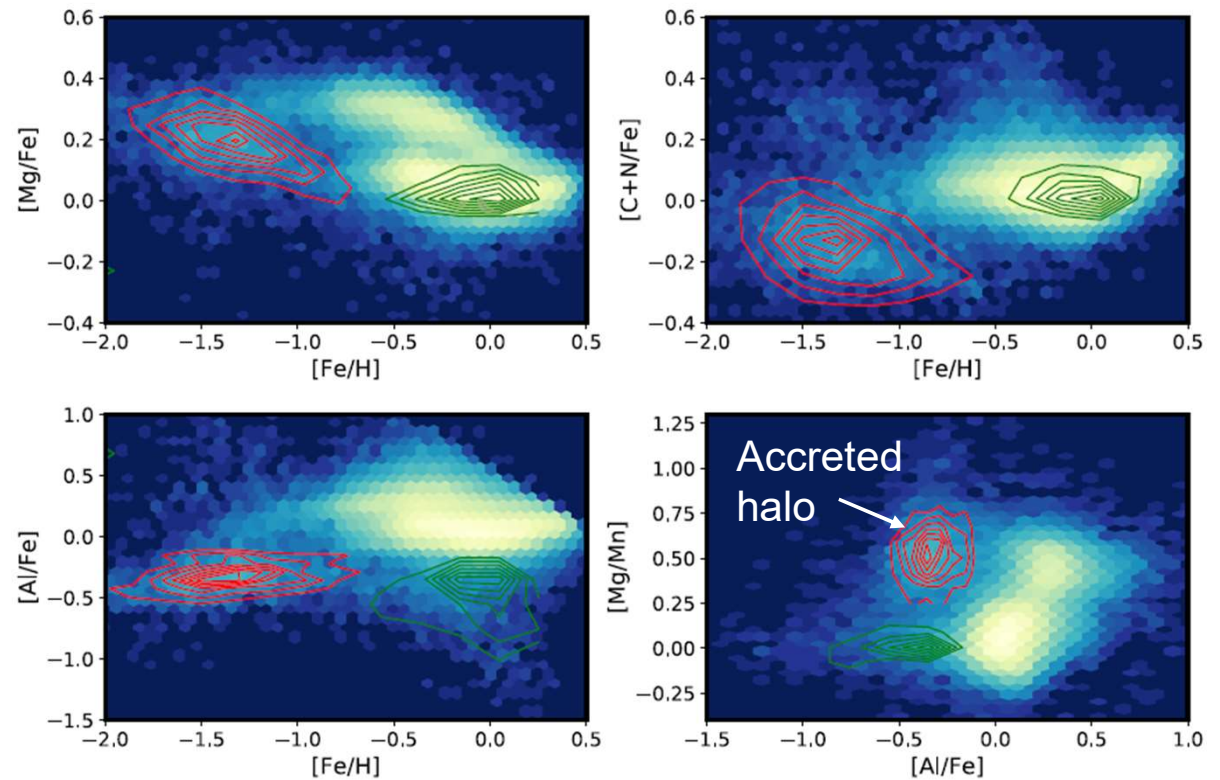


# [Al/Fe] as an indicator of accreted/in situ halo

Hawkins et al. 2015 for  $-1.20 < [\text{Fe}/\text{H}] < -0.55$



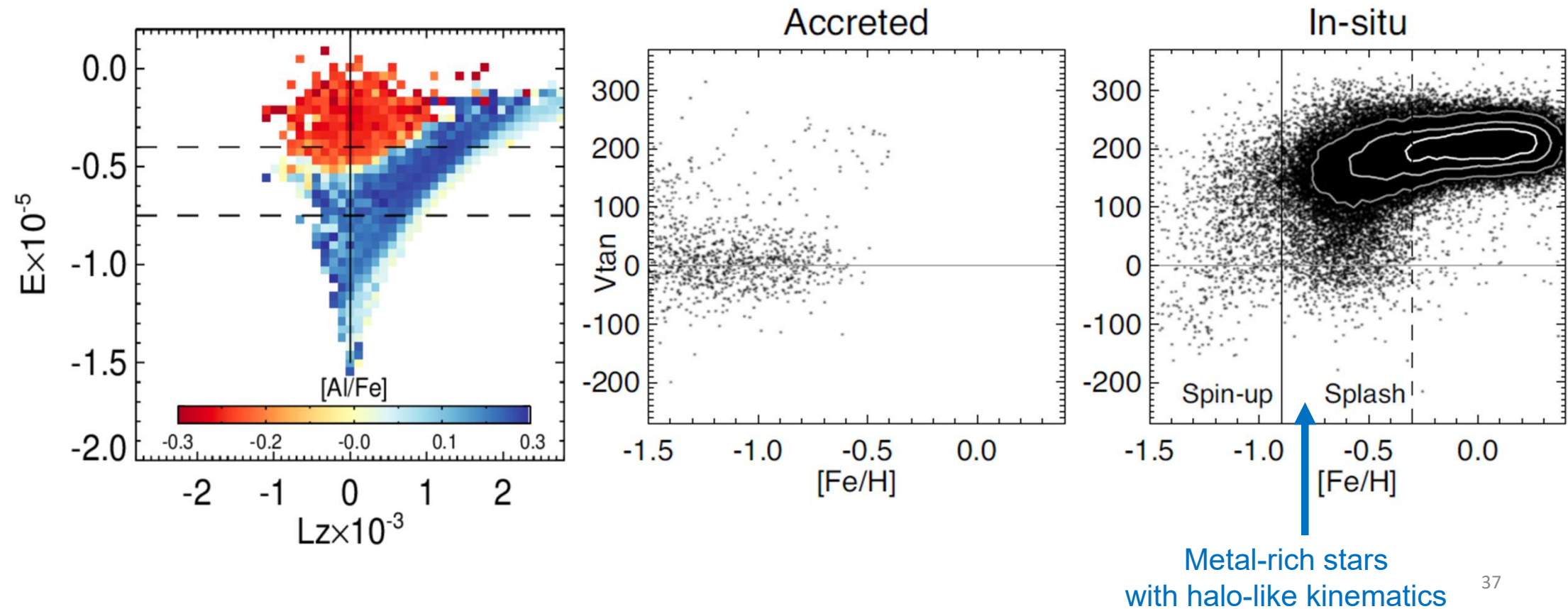
Das et al. 2020 (APOGEE DR14)



Al from SNIa and is sensitive to initial C+N abundance

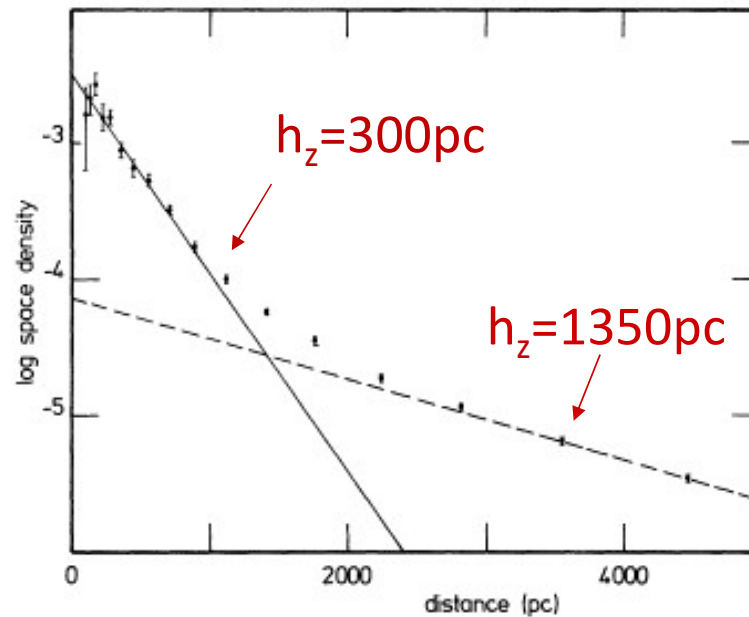
# $[Al/Fe]$ as an indicator of accreted/in situ halo

Belokurov & Kravtsov (2022) using APOGEE DR17 + Gaia EDR3



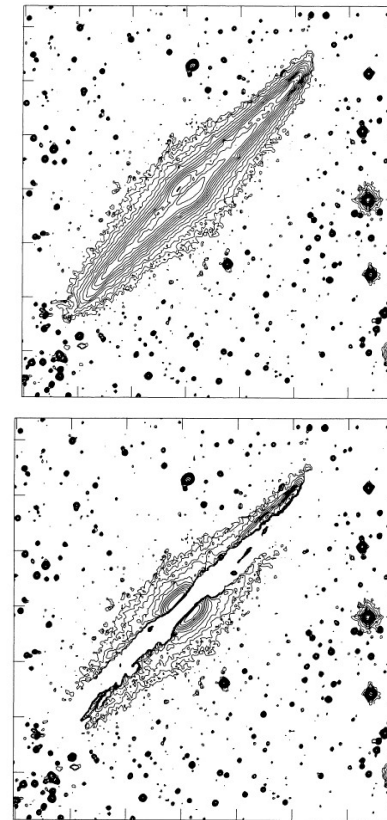
## 5. Formation of the thick disk

Star counts toward the SGP  
Gilmore & Reid 1983



$$\rho_{\text{thick}} \sim 2\% \rho_{\text{thin}}$$

Luminosity distribution  
of NGC4565  
Van der Kruit & Seale 1981



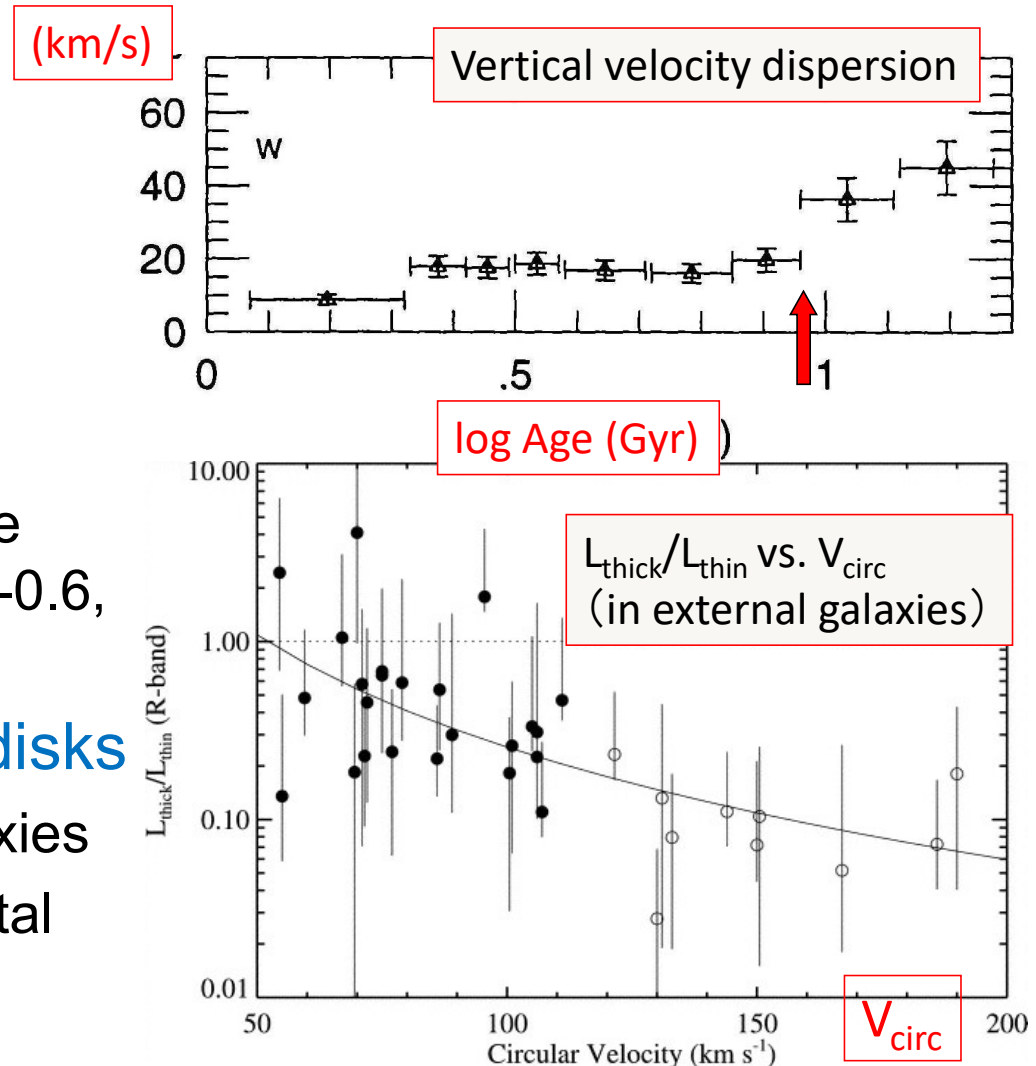
# Thick disk(s)

## ◆ Milky Way thick disk

- ✓ distinct kinematics, chemistry, and age: independent Galactic component
- ✓ dynamically hot, large scale height,  $[Fe/H] \sim -0.6$ , old age ( $\sim 10$  Gyr)

## ◆ Extra-galactic thick disks

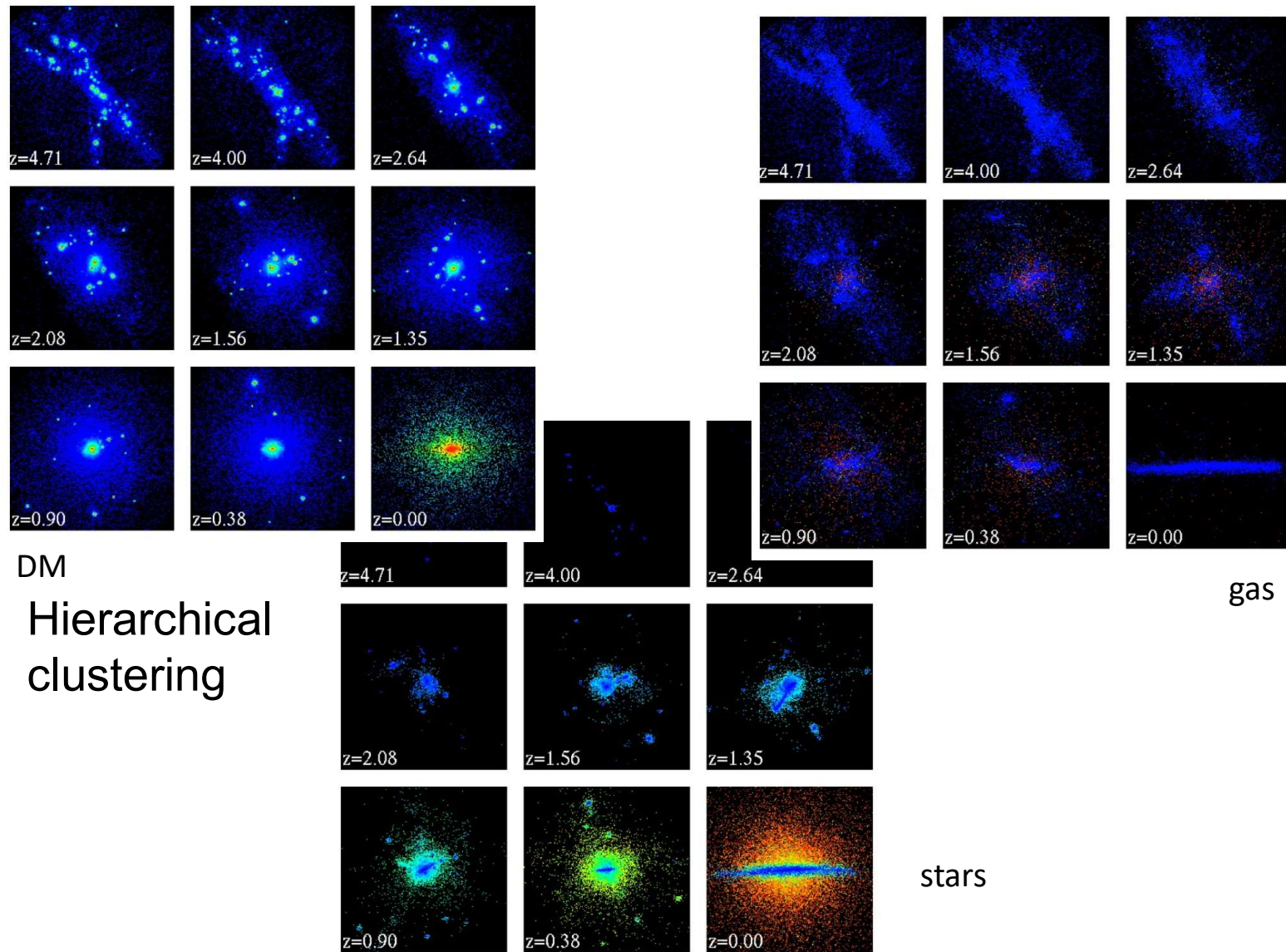
- ✓ common in disk galaxies
- ✓ relatively old and metal poor



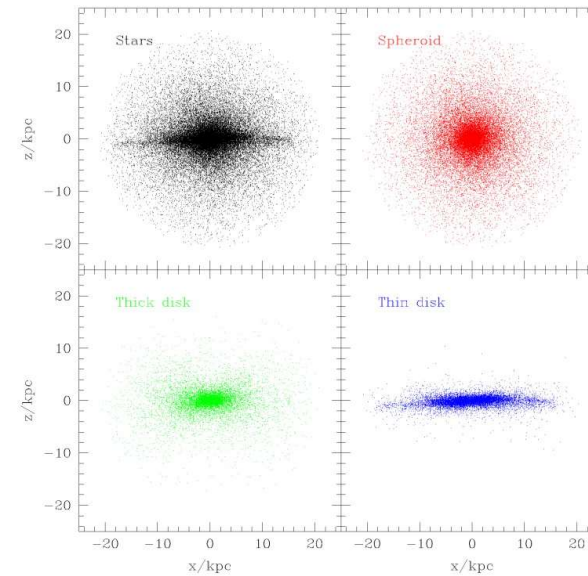
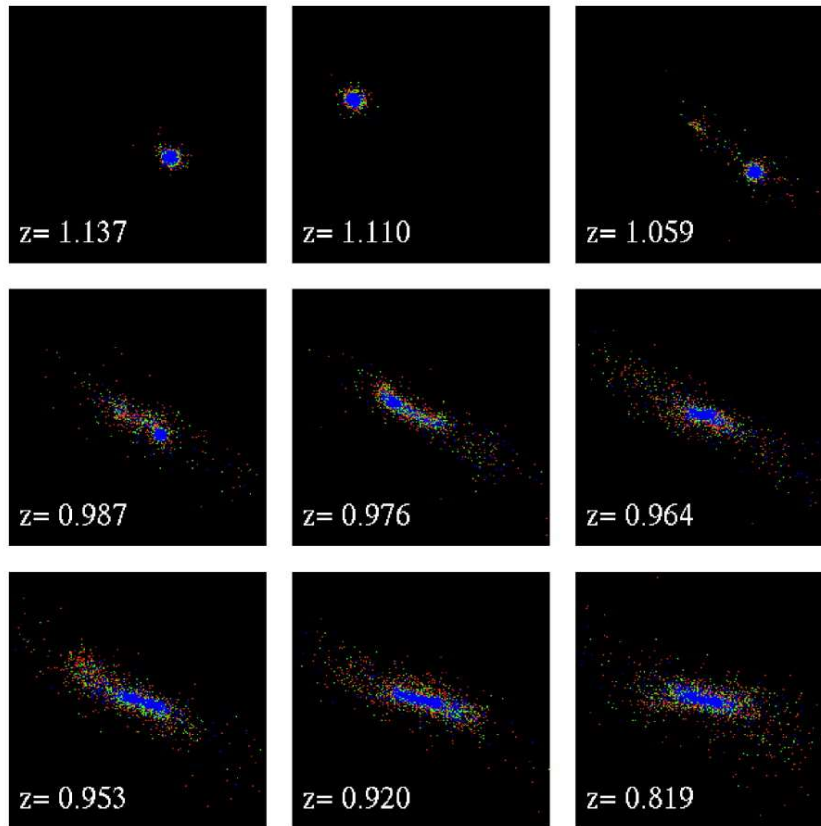
# Formation scenarios of the thick disk

- ① Dissipative collapse (Burkert+1992)
- ② Direct accretion of thick-disk material (Abadi+200s)
- ③ Multiple mergers (Brook+2004, 2005)
- ④ Dynamical heating of a pre-existing thin disk by satellites or subhalos (Quinn+1993; Velázquez & White 1999; Hayashi & Chiba 2006; Kazantzidis+2009), **by merging of Gaia-Enceladus?**
- ⑤ Clumpy disk evolution (Noguchi 2009; Bournarud+2007; 2009)
- ⑥ Radial migration due to local spiral arms (Haywood 2008; Schönrich & Binney 2009)

## ②. Direct accretion of thick-disk material



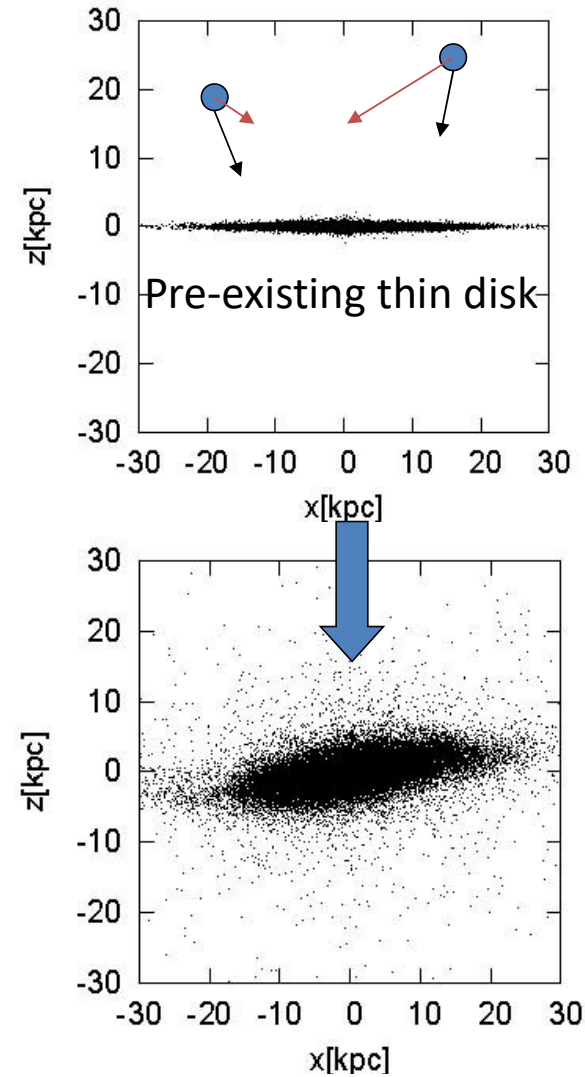
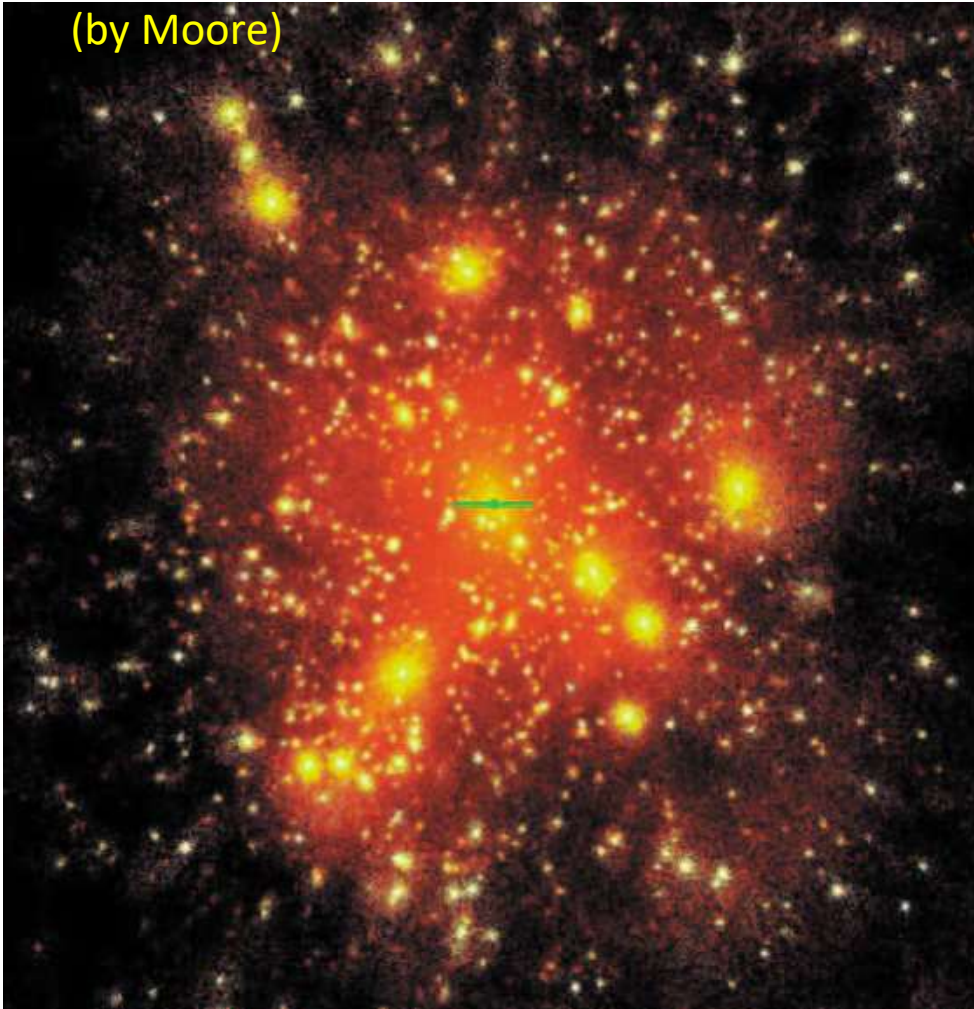
## Shredded satellite → thick disk?



But  $[\text{Fe}/\text{H}]$  and  $[\alpha/\text{Fe}]$  in satellites  
are very different from those  
in the thick disk.

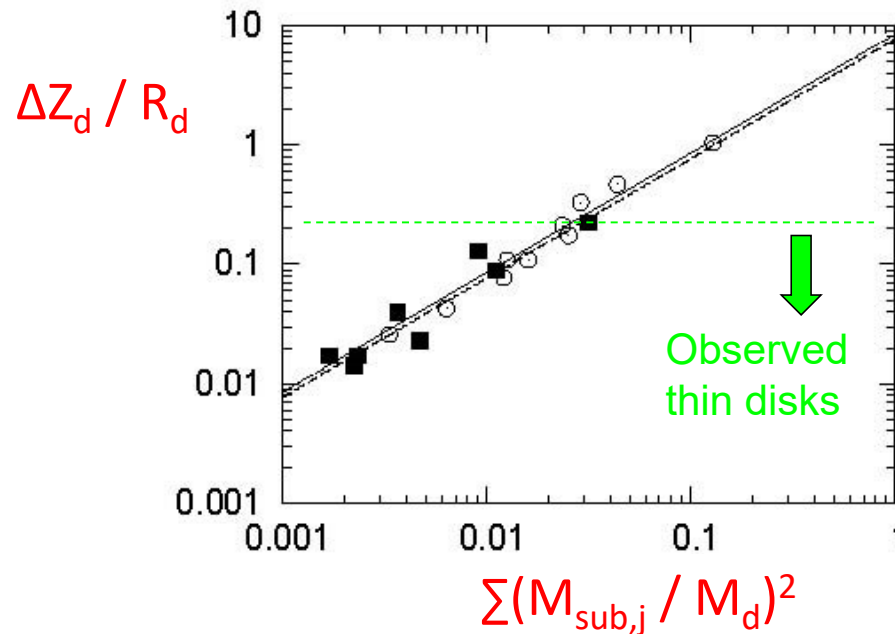
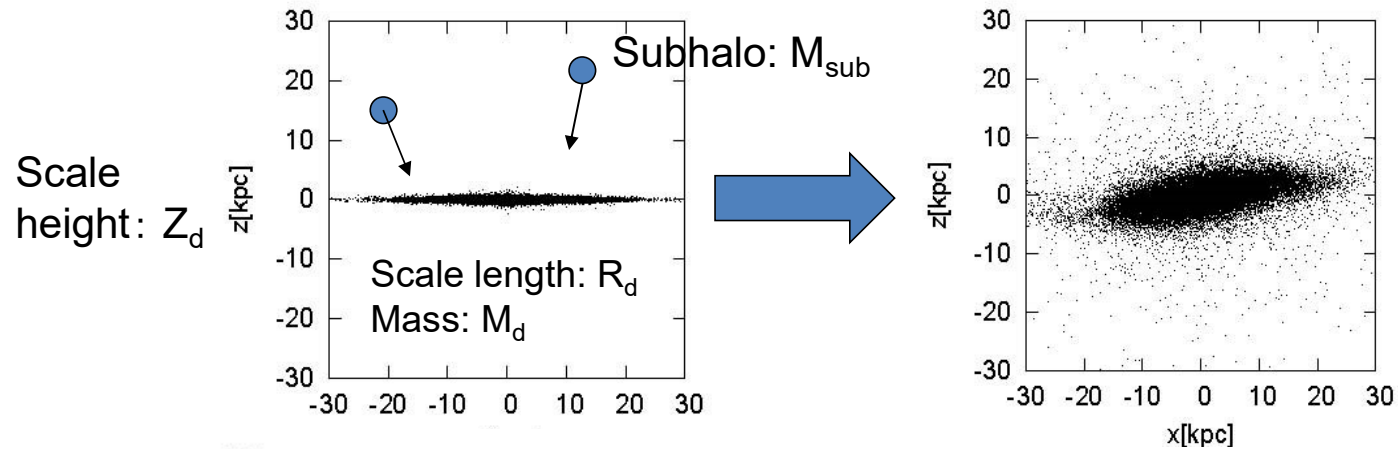
#### ④. Dynamical heating of a thin disk by dark-matter subhalos (Hayashi & Chiba 2006)

Distribution of dark halos in a galactic scale  
(by Moore)



# Numerical simulation of disk heating

(Hayashi & Chiba 2006)



$$\frac{\Delta Z_d}{R_d} = 8 \sum_{j=1}^N \left( \frac{M_{sub,j}}{M_d} \right)^2$$

Observed thin disks:  $Z_d / R_d < 0.2$   
(Kregel et al. 2002)

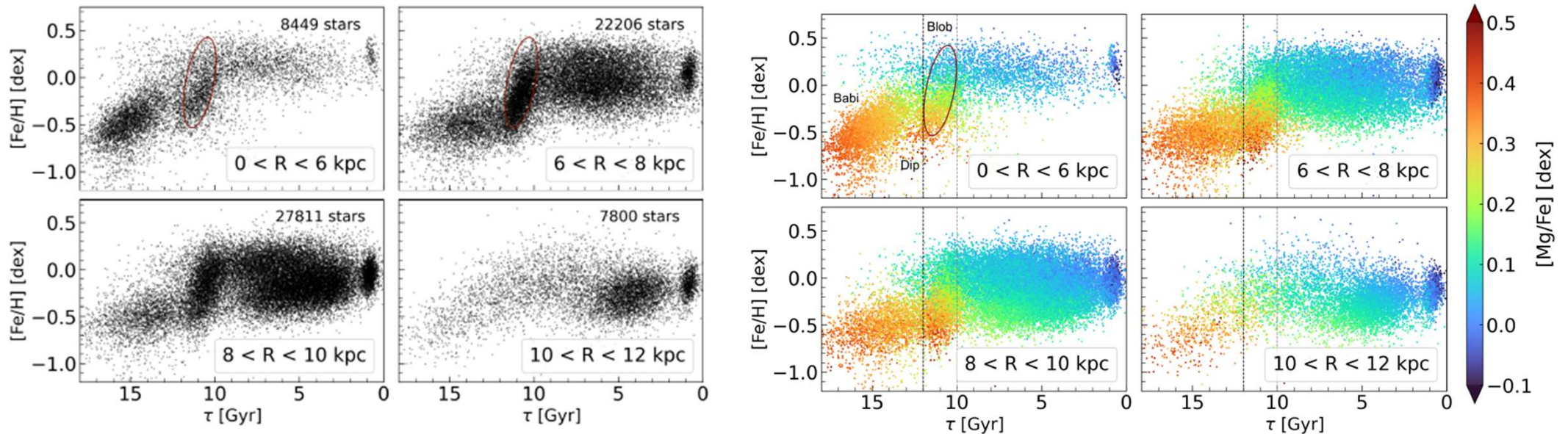
$\Rightarrow$  accreted subhalo mass  
 $< 0.15 M_d$

# Signature for GES merger on thick disk formation

Ciuca, Kawata,, Baba et al 2022

68360 RGBs and Red Clumps from APOGEE-2 + APOKASC-2

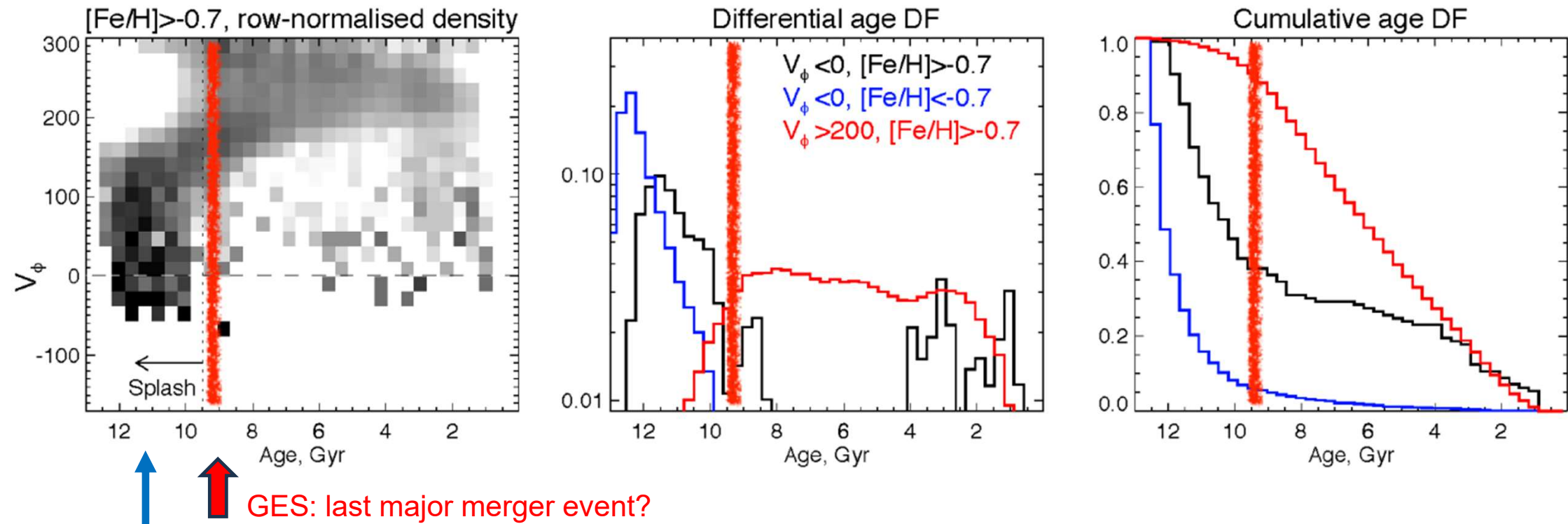
Machine learning



Early-epoch gas-rich merger (GES merger)  $\Rightarrow$  dilution  $[\text{Fe}/\text{H}] \downarrow$   
 $\Rightarrow$  SF + chemical evolution  $\Rightarrow [\text{Fe}/\text{H}] \uparrow$ ,  $[\text{Mg}/\text{Fe}] \downarrow \Rightarrow$  metal-rich part of the thick disk

# Splash: a signature of last major merger

Belokurov et al. 2020 using Gaia DR2



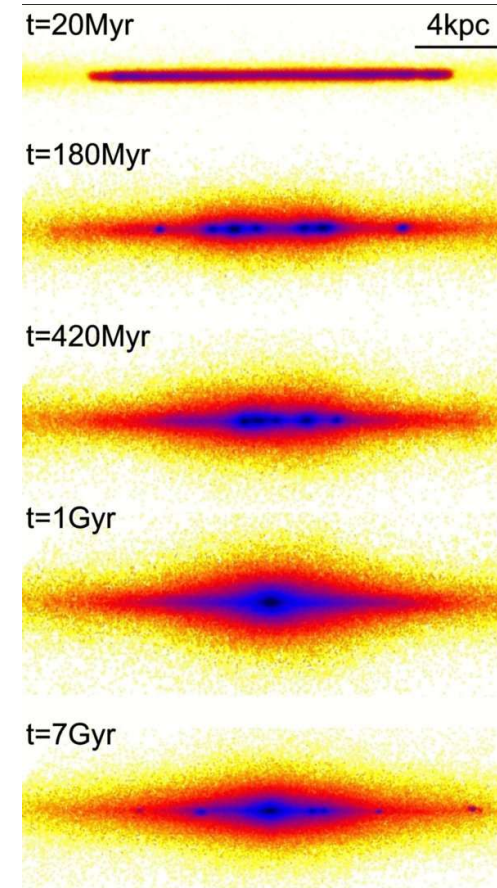
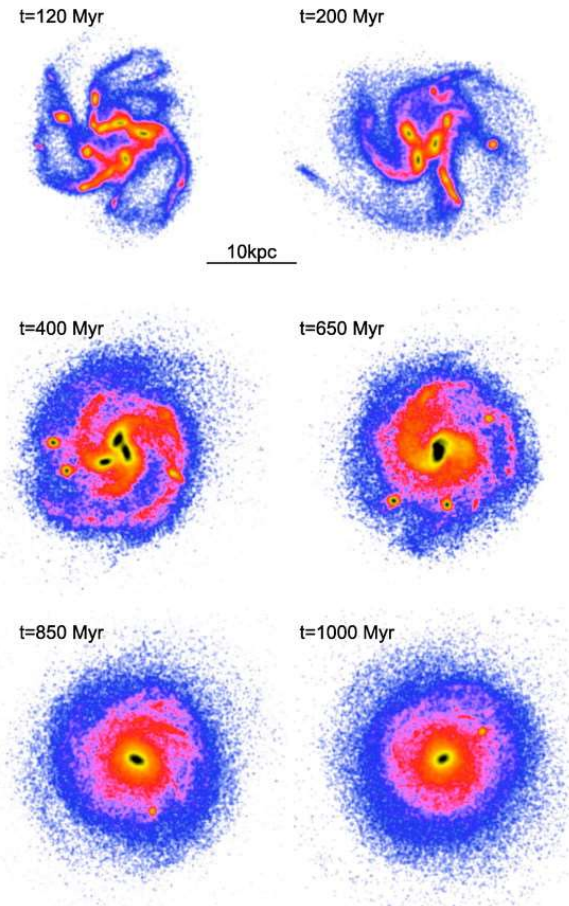
Metal-rich stars  
with halo-like kinematics

## ⑤. Clumpy disk evolution

Thick disks as relics of clumpy disk evolution?

(Noguchi 1999; Bournaud+2007; 2009)

Bournaud+2007



Symmetric structure along  $z$ , metal-poor stars?,  $d\langle v_\phi \rangle / dz$ ?

## ⑥. Radial migration due to local spiral arms

Radial migration of disk stars  
(Schönrich & Binney 2009)

thick disk stars?

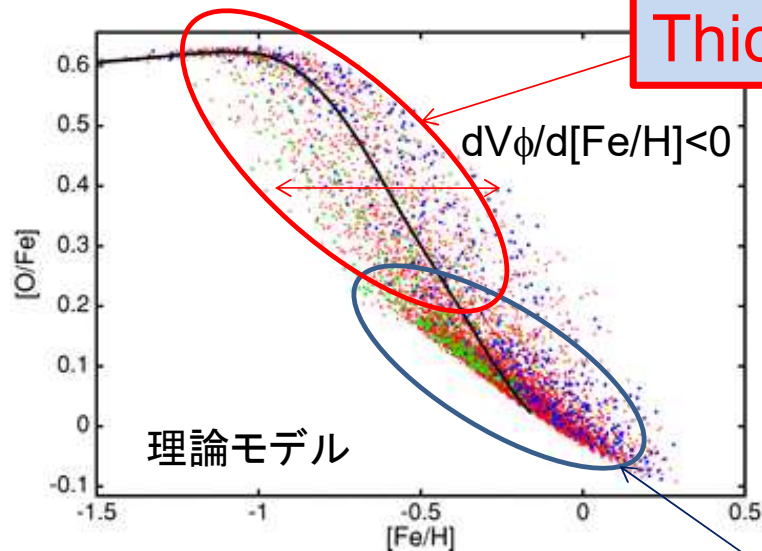
Stars getting  $L_z$

Stars losing  $L_z$

$[\alpha/\text{Fe}]$  larger at larger  $R$

Lee+2010 SDSS sample

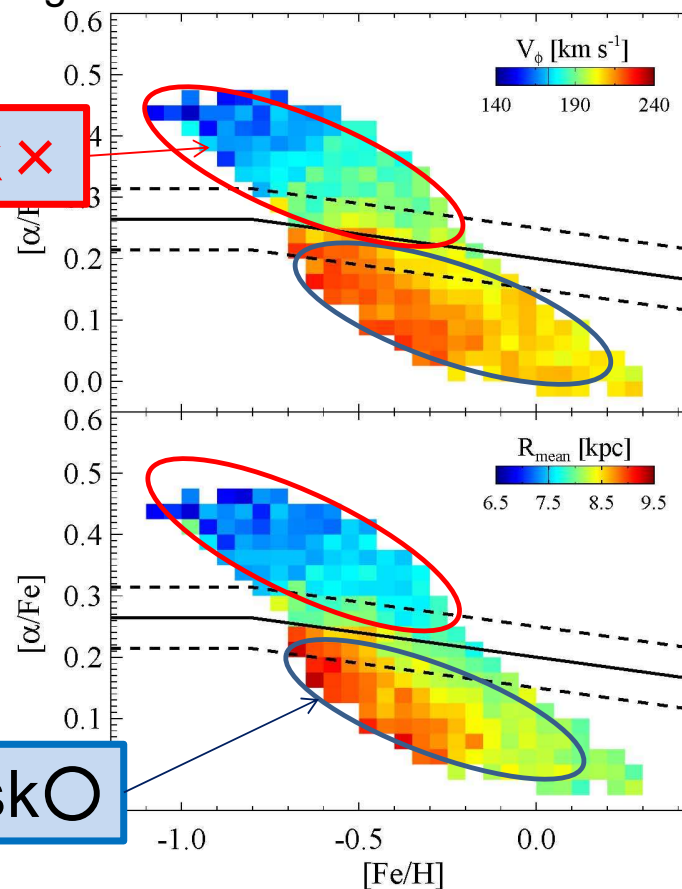
transient spiral arms etc.



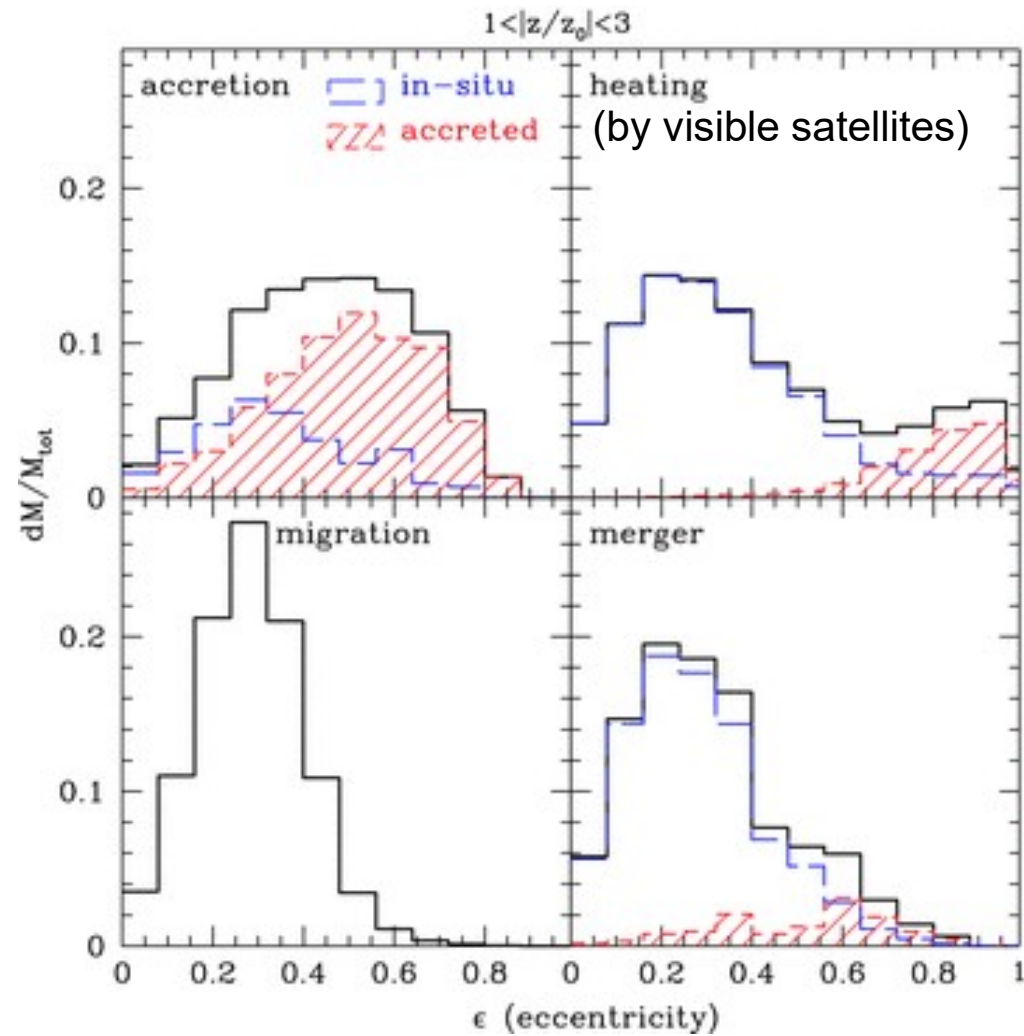
$V_\phi < 179 \text{ km/s}$  blue  
 $179 < V_\phi \text{ km/s} < 244$  red  
 $V_\phi > 244 \text{ km/s}$  green

Thick disk ×

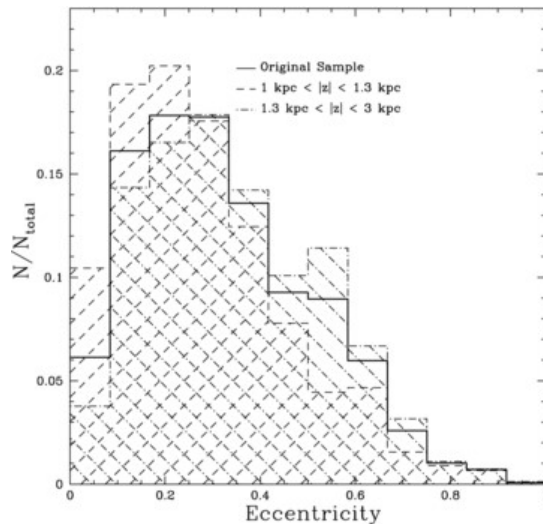
Thin disk ○



# Orbital eccentricity distributions of several models Sales+ 2009

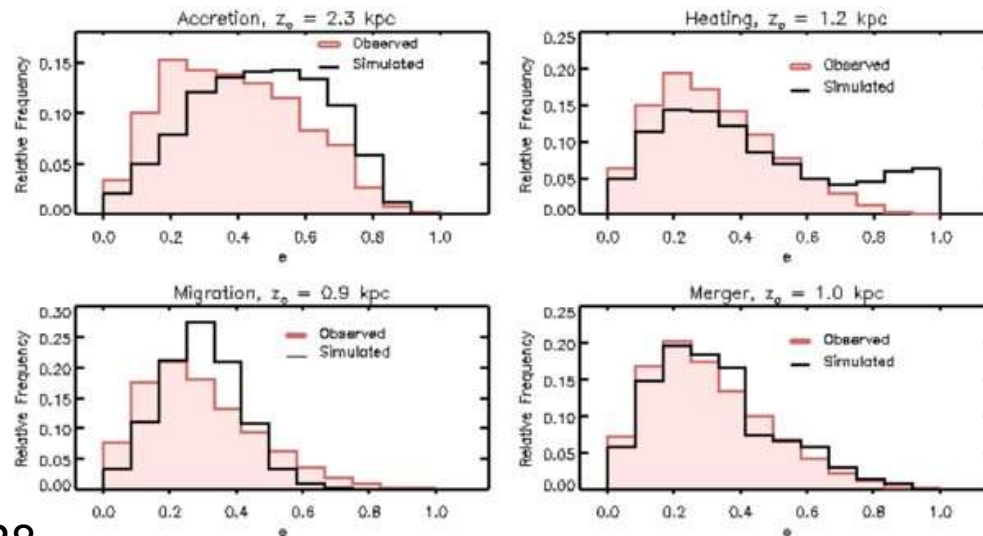


## Wilson+2011: RAVE sample

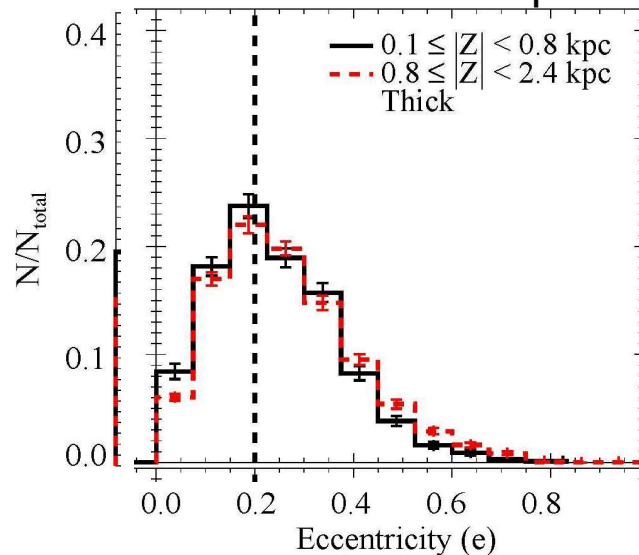


## Dierickx+ 2010: SDSS sample DR7

Eccentricity distributions for  $1 < z_{\text{pc}} < 3$



## Lee+ 2011: SDSS sample DR8



Scenarios of both  
Heating by dark satellites  
Multiple mergers  
are favorable.

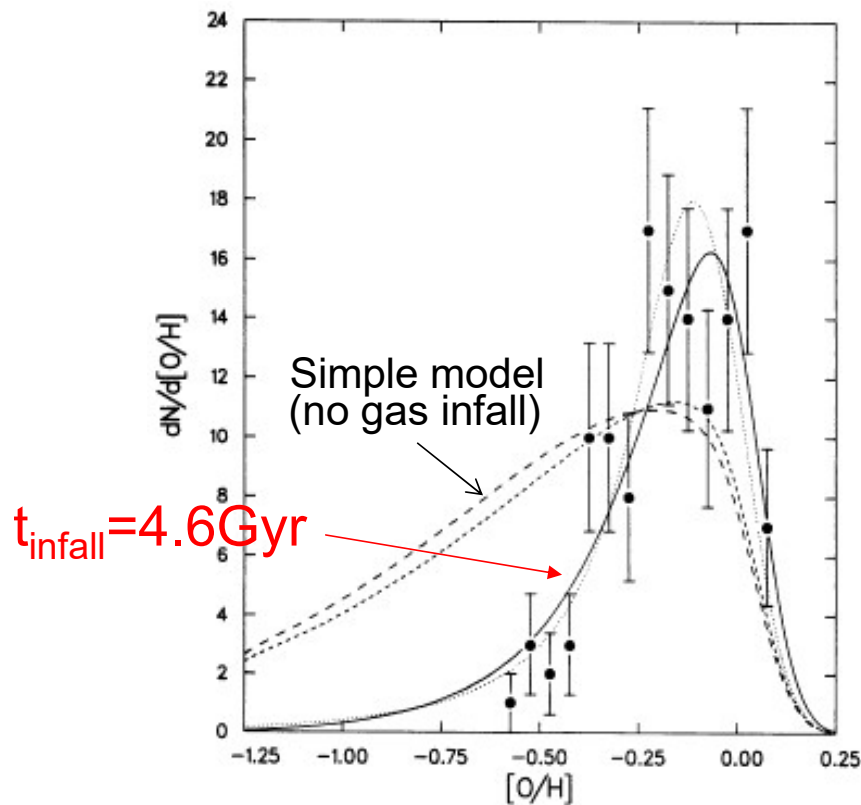
## Score sheet for thick-disk formation models

Model	$dV\phi/d[\text{Fe}/\text{H}]$	$dV\phi/dz$	$[\text{Fe}/\text{H}]$ $[\alpha/\text{Fe}]$	Orbital eccentricity
Accretion	N/A	N/A	Failed Failed	Failed
Gas-rich mergers	N/A	Failed	N/A N/A	Passed
Disk heating	? (initial condition)	Passed	? (timing)	Passed
Radial migration	Failed	N/A	Passed? Passed?	Failed
Clumpy disk evolution	N/A	N/A	N/A N/A	N/A

More theoretical and observational  
studies are needed!

## 6. Formation of the thin disk

G-dwarfs in the solar neighborhood  
(model: Sommer-Larsen & Yoshii 1990, MN, 243, 468)

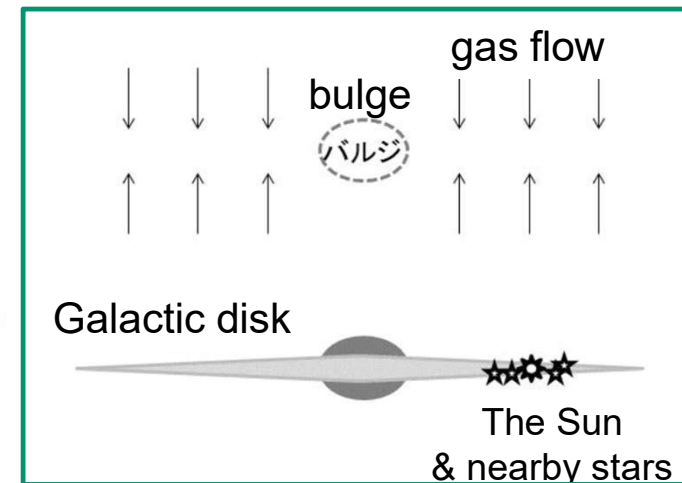


$$\frac{d\Sigma_{\text{gas}}}{dt} \propto \exp(-t / t_{\text{infall}})$$

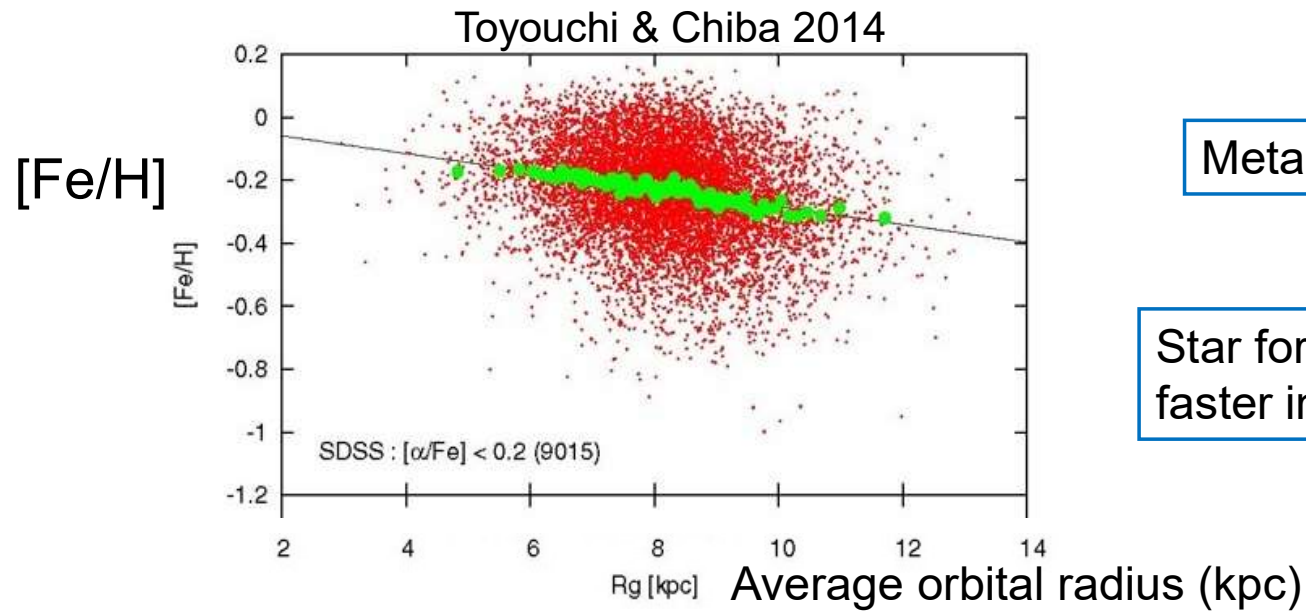
$t_{\text{infall}} \sim 4\text{-}5 \text{ Gyr}$  is required



The Galactic (thin) disk  
formed slowly over 4-5 Gyr.



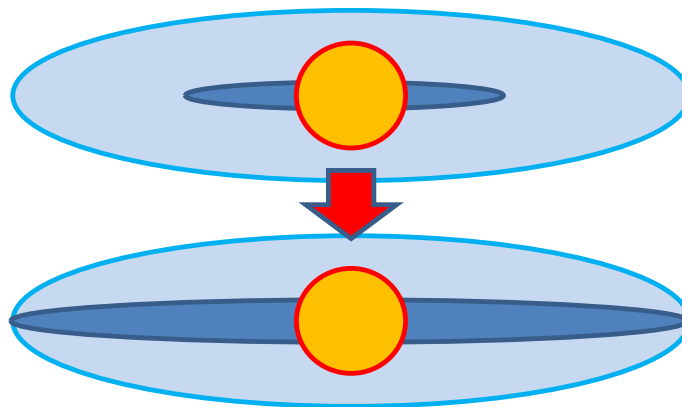
# Inside-out formation of the thin disk



Metallicity gradient



Star formation proceeds faster in inner radii.

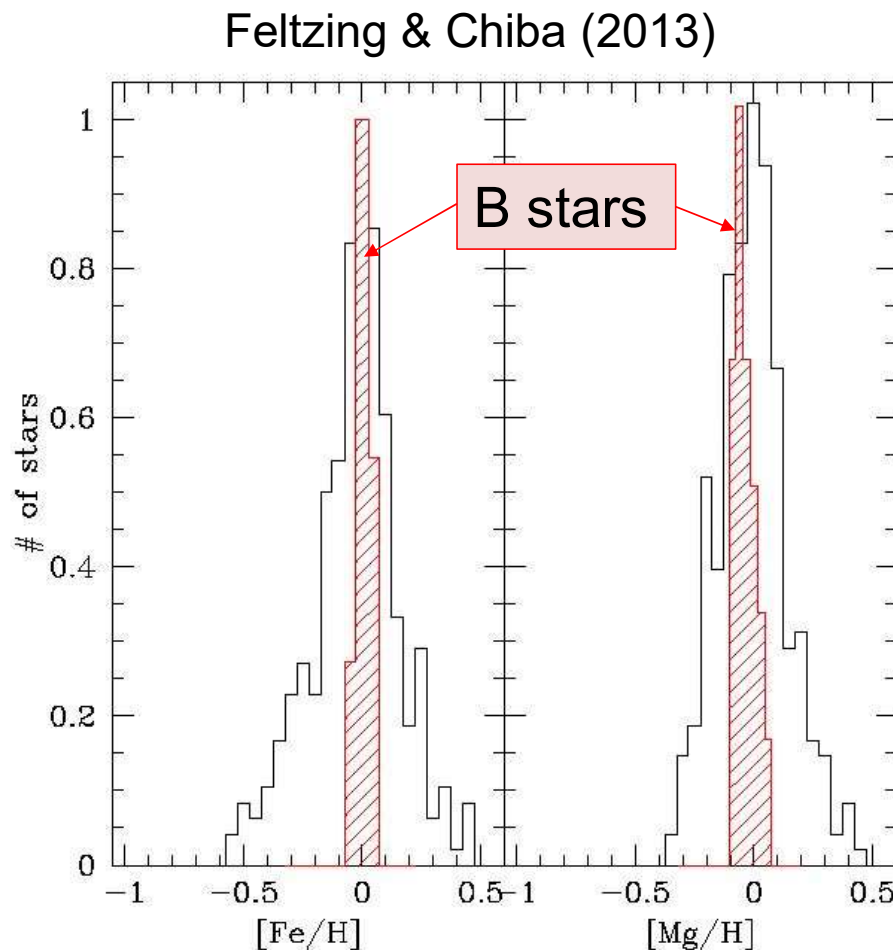


The thin disk has formed from inner to outer radii

*Inside-out formation*

# Origin of very metal-rich stars with $[\text{Fe}/\text{H}] > +0.2$ near the Sun

~ Metallicity distribution of F, G dwarfs near the Sun ~



MD of B-type stars  
reflects that of ISM  
near the Sun



Very metal-rich stars  
with  $[\text{Fe}/\text{H}] > +0.2$   
cannot be formed  
near the Sun



These very metal-rich stars  
(possibly having exo-planets)  
are migrated from inner radii

# New aspects using Gaia

Chang 2022 (Master Thesis, Tohoku U)

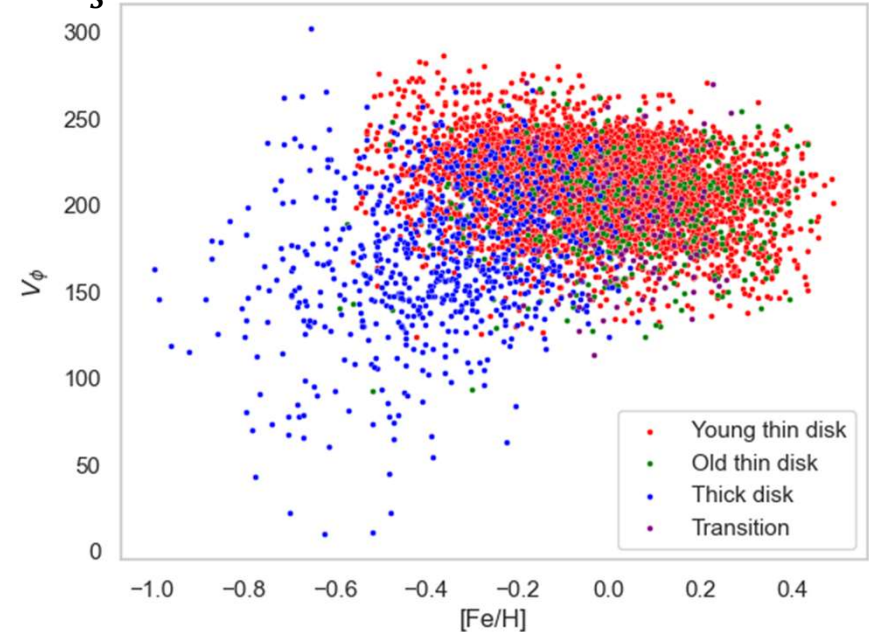
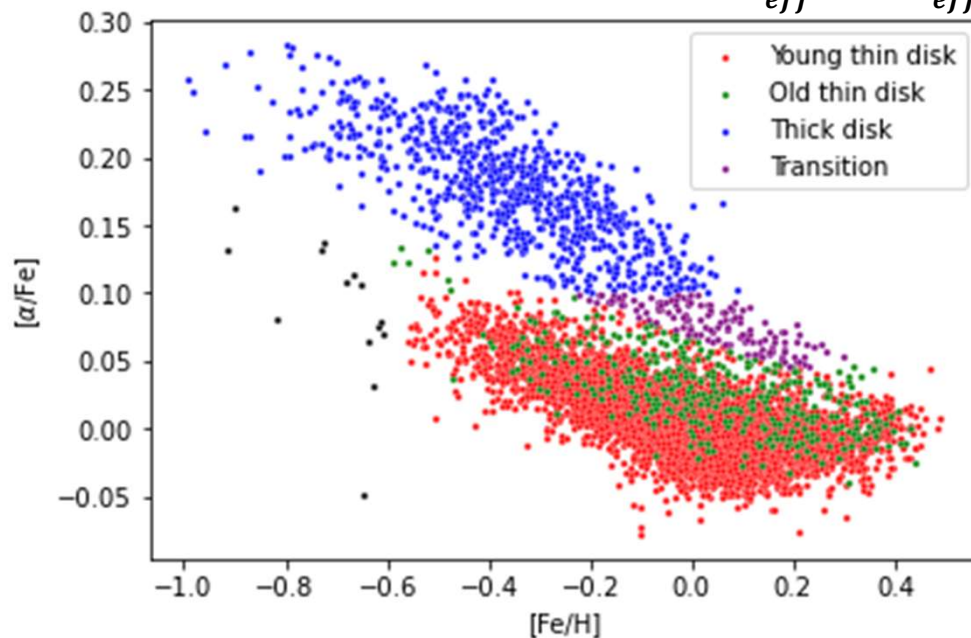


Chang

5436 RGBs & RCs (APOKASC-2, APOGEE DR16, Gaia EDR3)

Ages from Kepler seismology data (frequency  $\rightarrow$  mass  $\rightarrow$  age)

$$\Delta \mathbf{v} \propto \left( \frac{M}{R^3} \right)^{\frac{1}{2}} \propto \sqrt{\rho} \propto \left( \frac{R}{C_s} \right)^{-1}$$
$$\mathbf{v}_{\max} \propto \frac{g}{T_{\text{eff}}^{0.5}} \propto \frac{1}{T_{\text{eff}}^{0.5}} \frac{M}{R^2} \propto \left( \frac{H}{C_s} \right)^{-1}$$



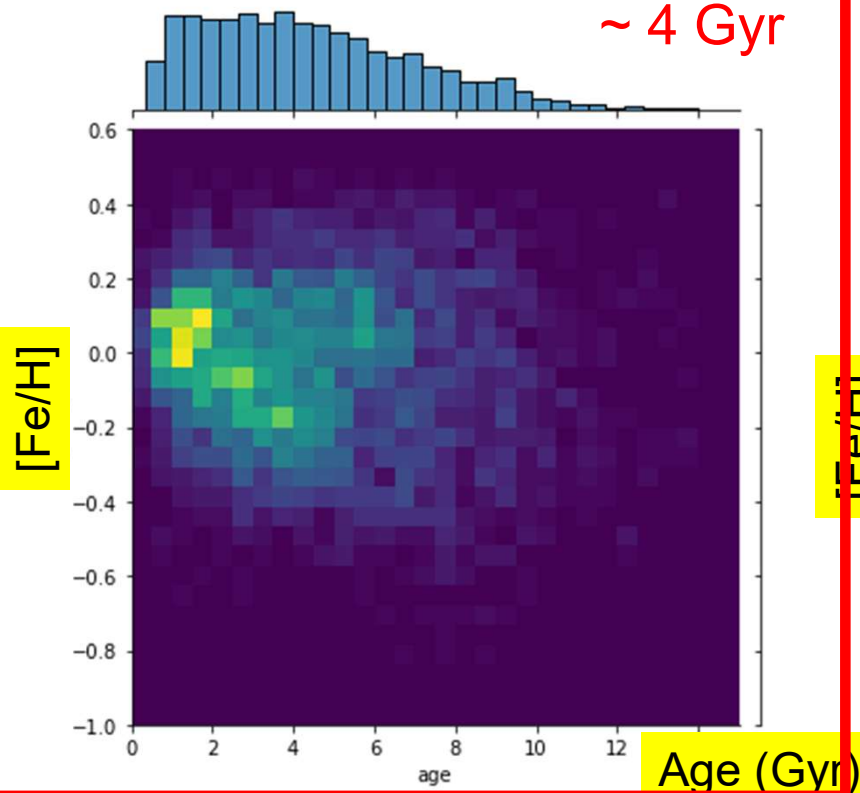
# Newly derived AMR

Chang 2022 (Tohoku Univ.)



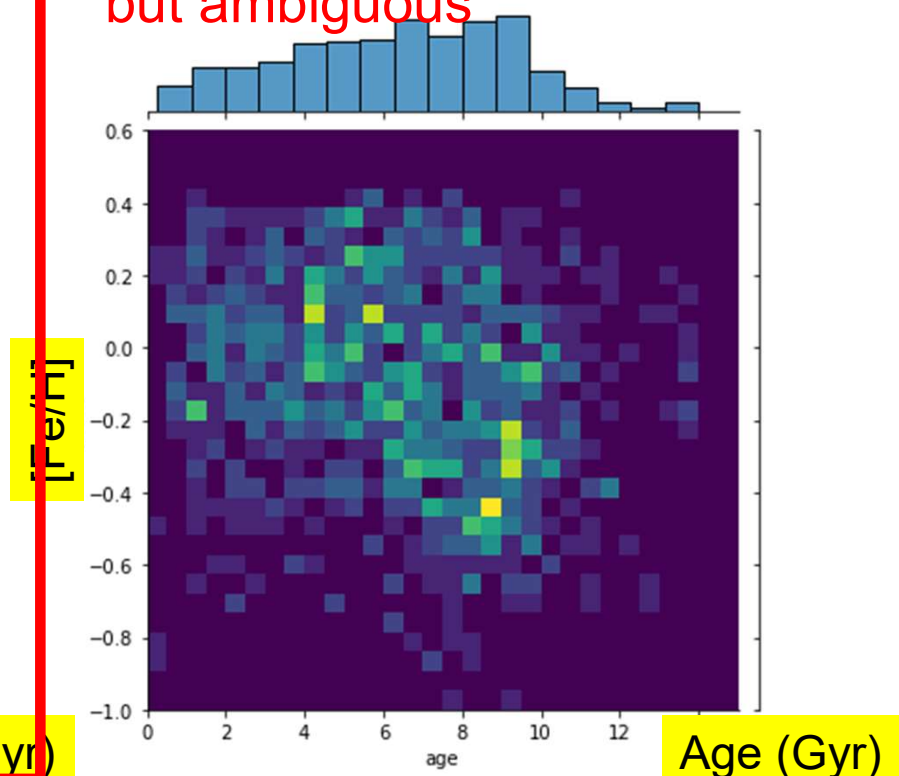
Pop B (thin disk stars)

Peak at  $\sim 2$  Gyr + extended to  
 $\sim 4$  Gyr



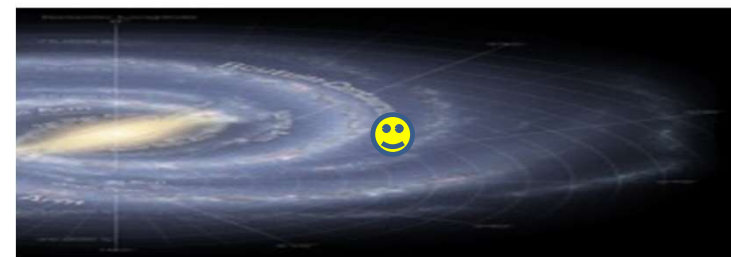
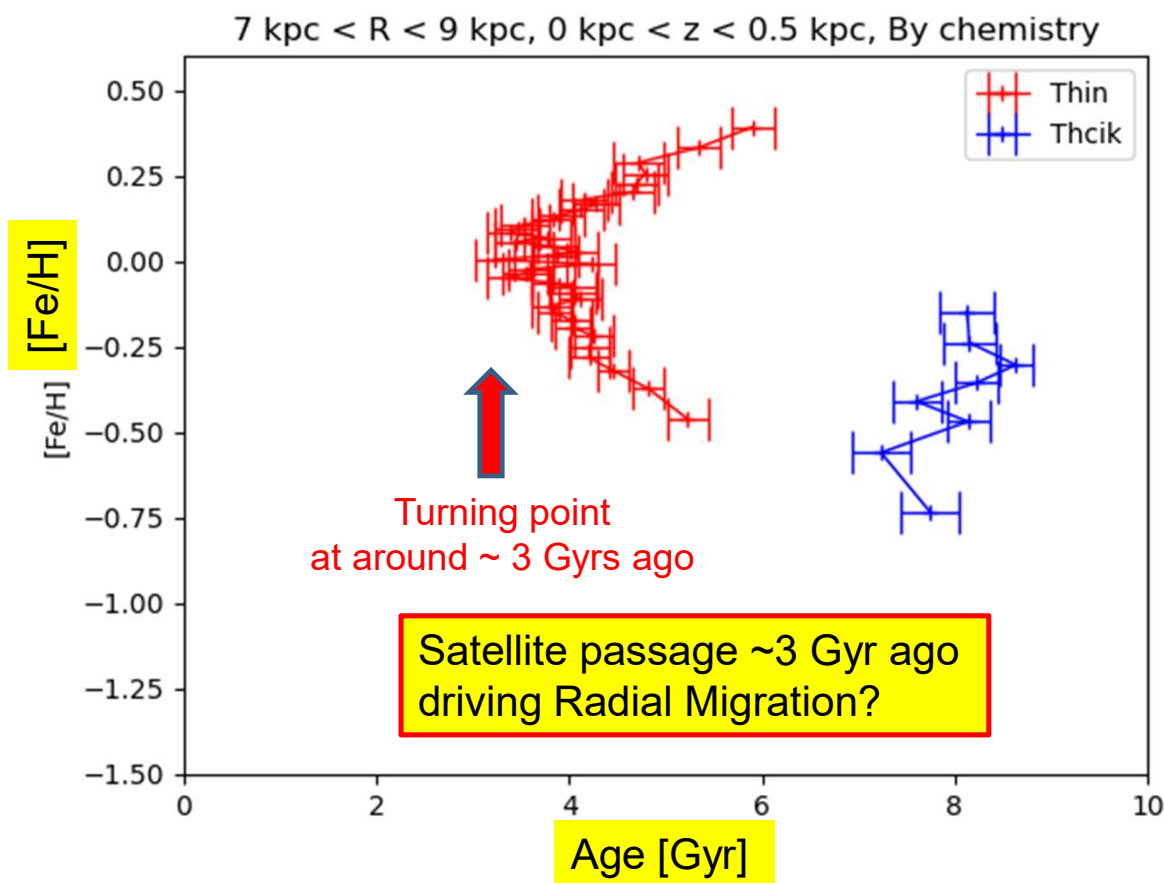
Pop C (thick + old thin disk stars)

Dip-like feature at  $\sim 8$  Gyr ago  
but ambiguous



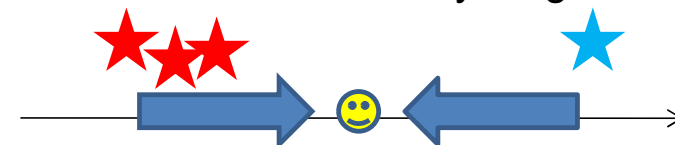
# New AMR - Signature for radial migration event

Chang 2022 (RGBs+RCs)



Metal-rich,  
older stars

Metal-poor,  
younger stars



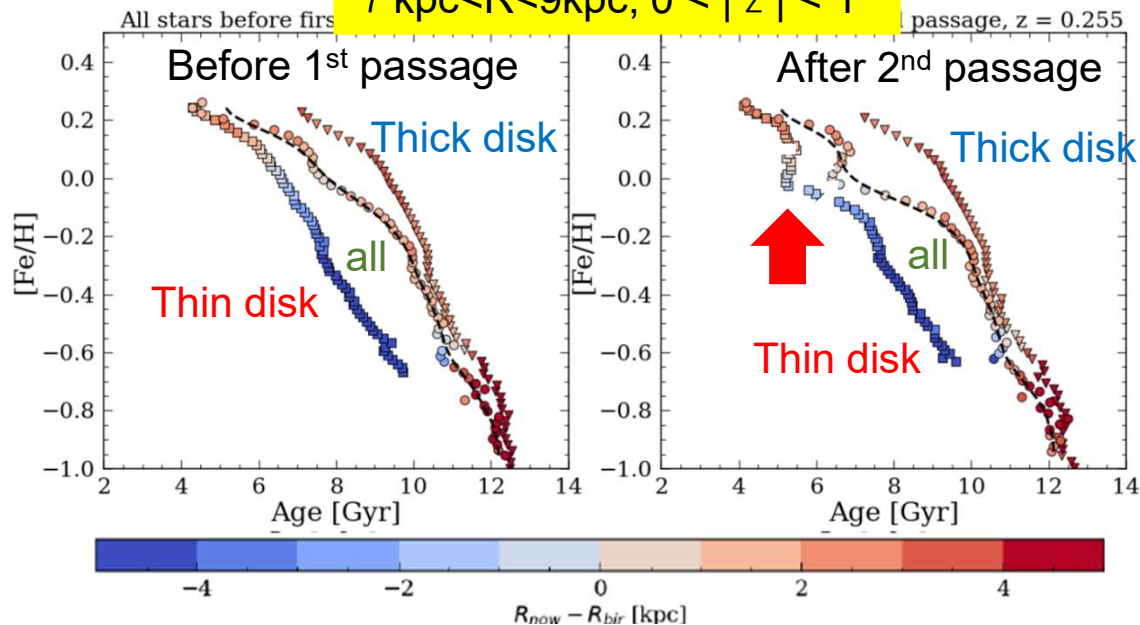
# The effect of satellite infall & radial migration in AMR



Before 1<sup>st</sup> passage  $z = 0.34$

After 2<sup>nd</sup> passage  $z = 0.255$

$7 \text{ kpc} < R < 9 \text{ kpc}, 0 < |z| < 1$

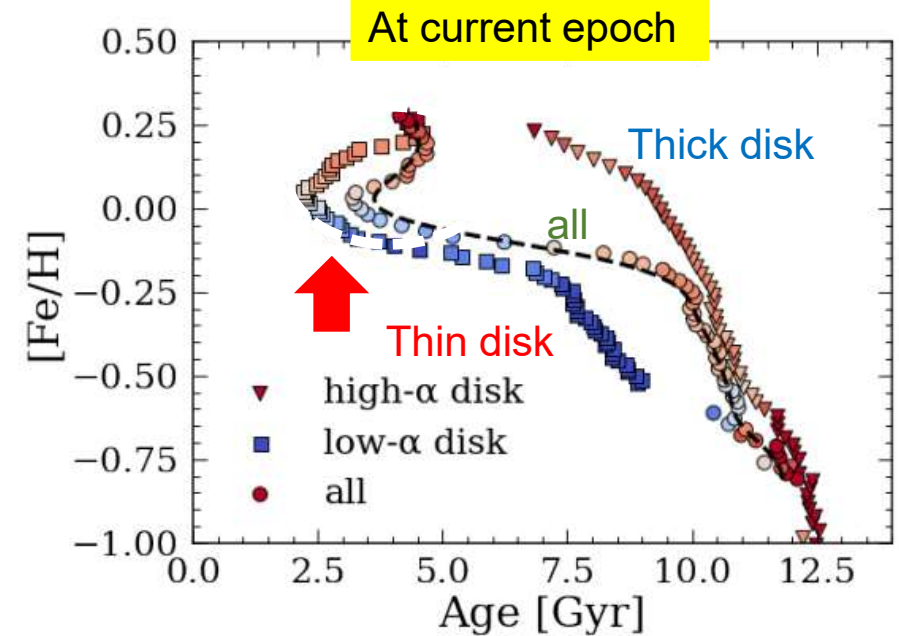


Lu et al. 2021 (simulation)

Cosmological simulation with NIHAO-UHD

– Sgr-dwarf like satellite is infalling at  $z=0.34$ .

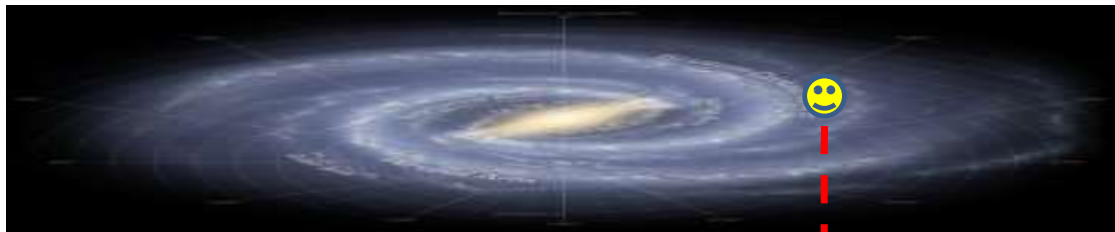
The second passage at  $z = 0.255$  yields turning points and radial migration for low- $\alpha$  stars in AMR.



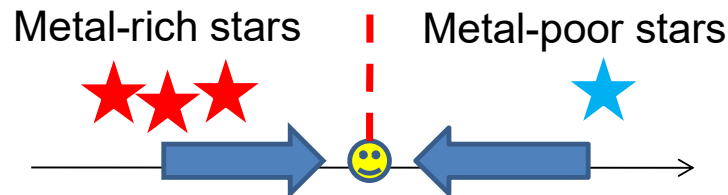
# Further evidence for radial migration of stars

Chang 2022

Sellwood & Binney 2002, Schoenrich & Binney 2009

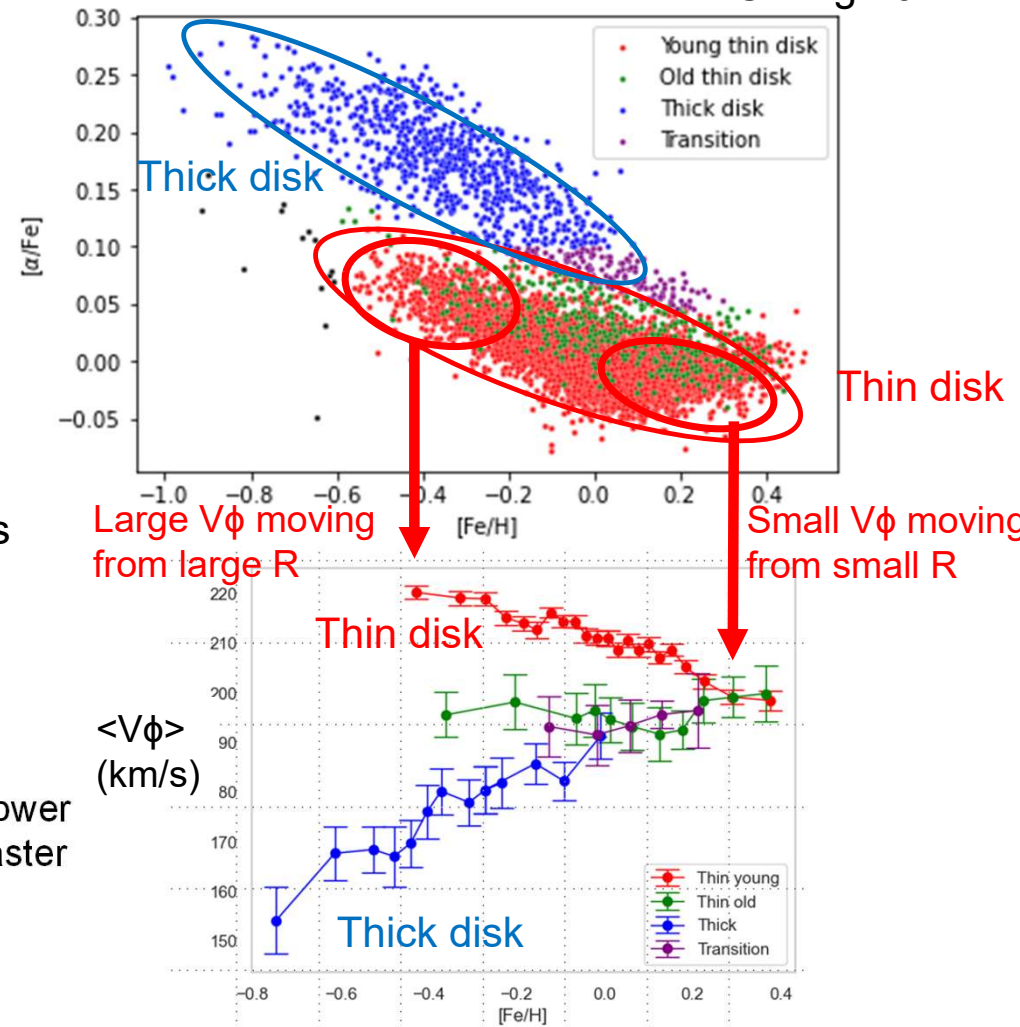


- Epicycle motion
- Angular-momentum transfer by transient spiral arms

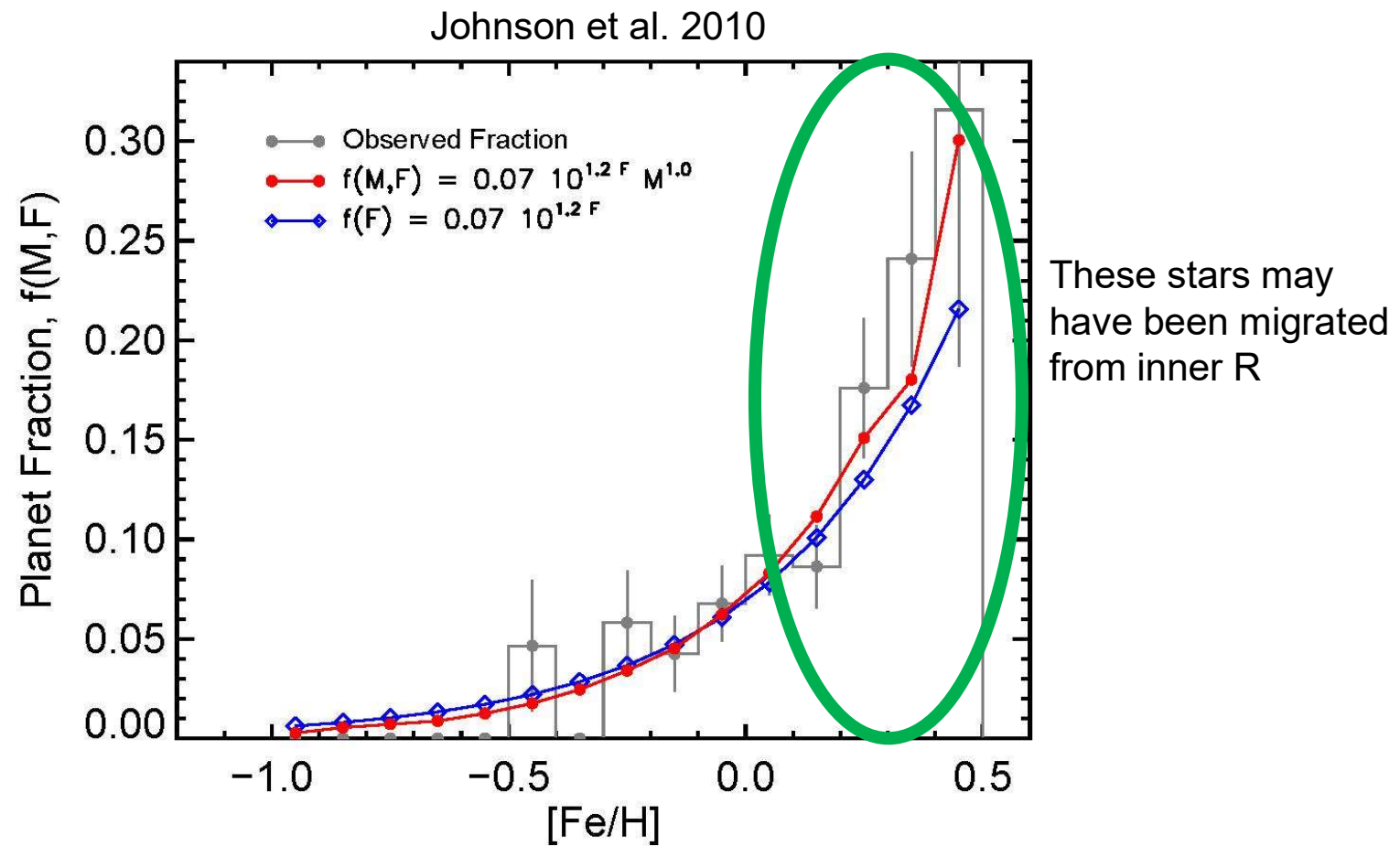


$L_z = V_\phi R \sim \text{const.}$   
 (Metal-rich) star moving from inner  $R$ :  $V_\phi$  is slower  
 (Metal-poor) star moving from outer  $R$ :  $V_\phi$  is faster

Radial migration of stars driven by satellite infall and associated transient bar/spirals



# MDFs of the stars hosting planets

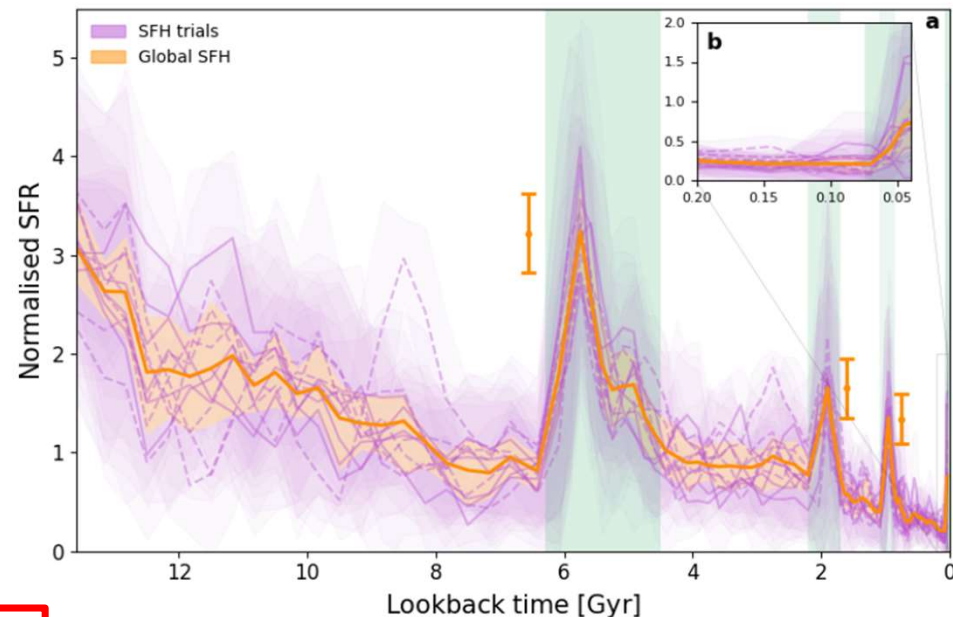


# SFH of disk stars within 2kpc from the Sun using Gaia DR2

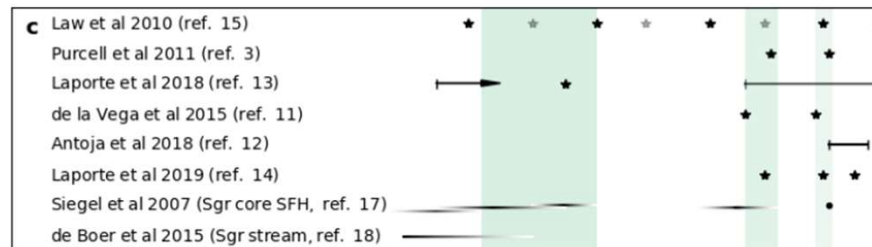
Ruiz-Lara et al. 2020 Nature Astronomy

Peaks at  
lookback t of

- 5.7 Gyr  
(incl. Sun formation)
- 1.9 Gyr
- 1.0 Gyr



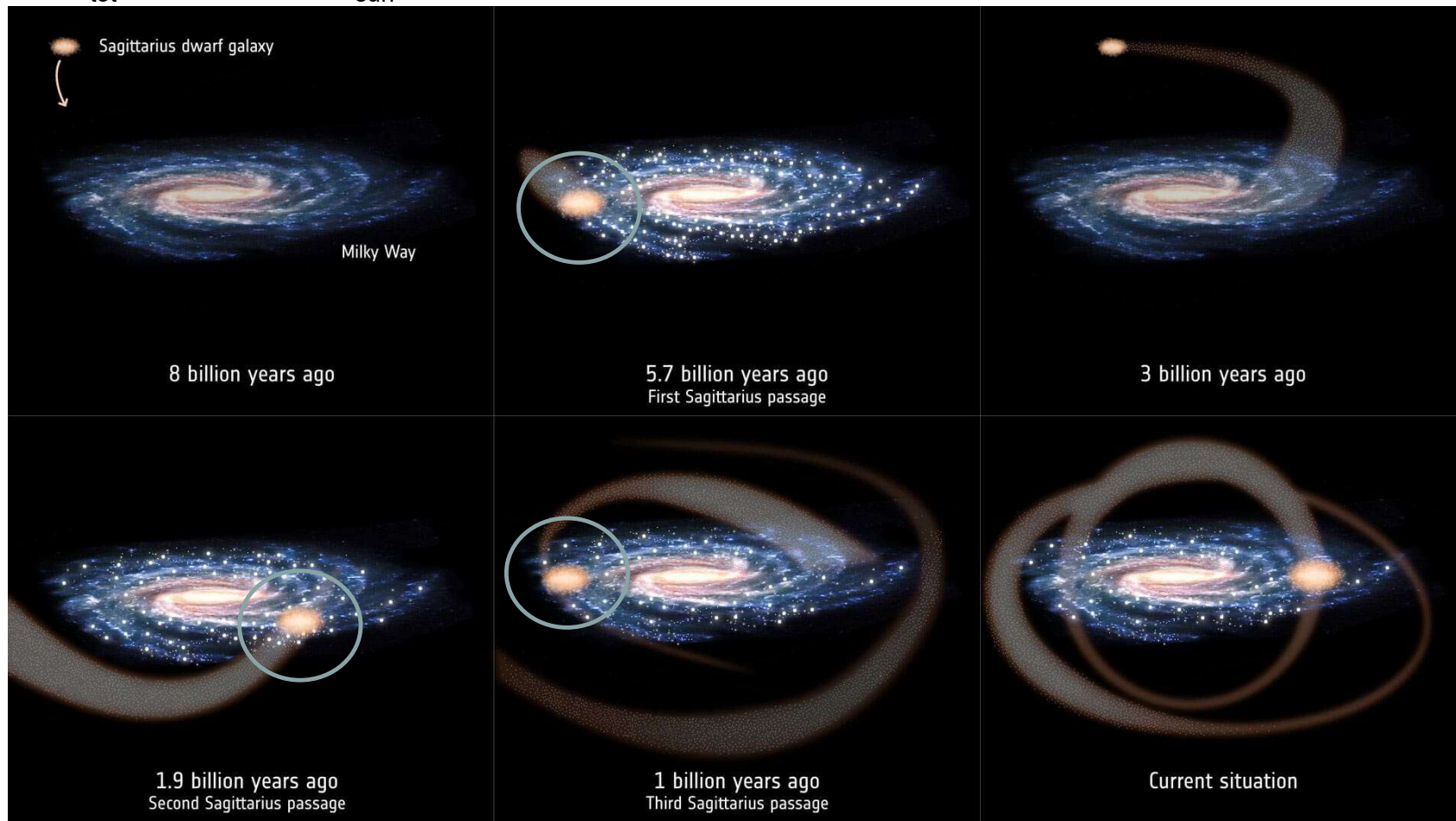
These peaks overlap  
with the timings of  
pericentric passages  
of Sgr dwarf



# The orbit of Sgr dwarf

$$M_{\text{tot}} \sim 2.5 \times 10^{10} M_{\text{sun}}$$

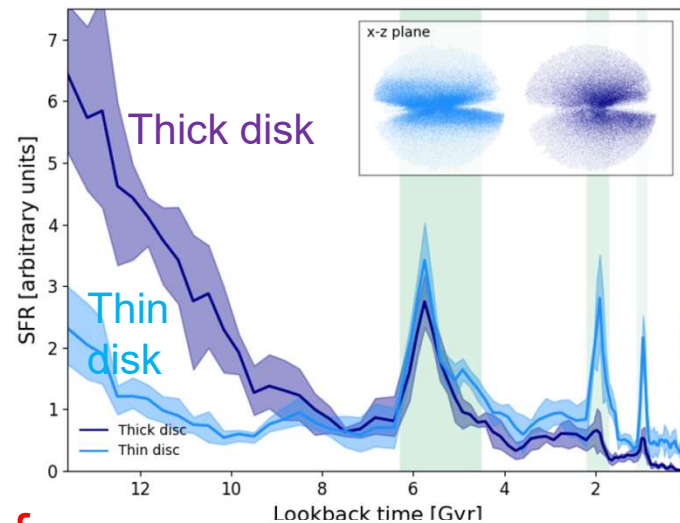
Ruiz-Lara et al. 2020



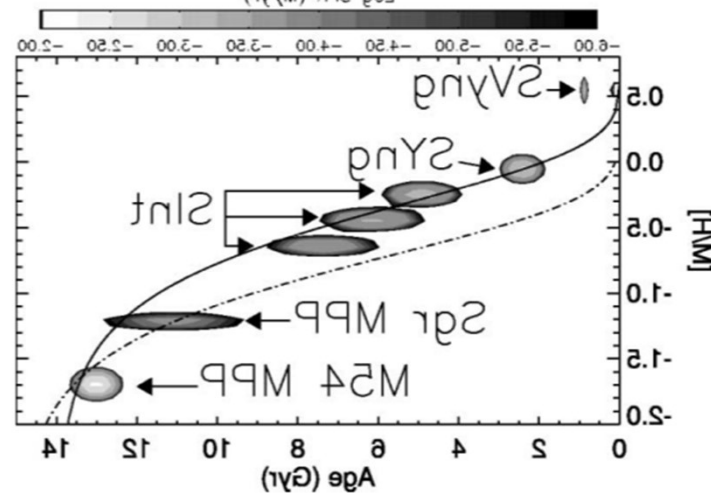
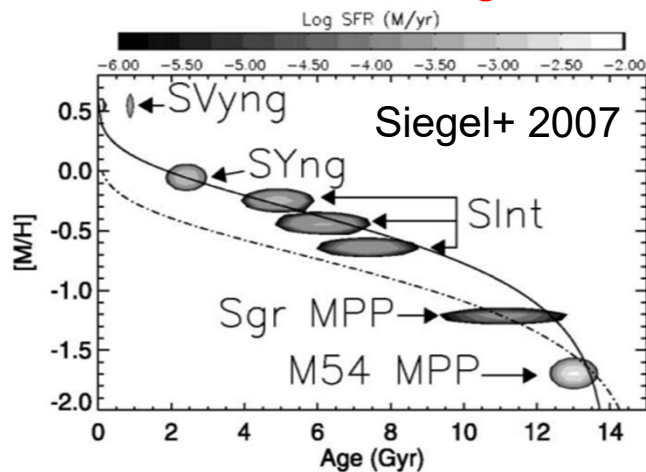
# SFHs of thick/thin disks & Sgr dwarf

Ruiz-Lara et al. 2020

Peak at 5.7 Gyr  
exists for both  
Thick disk  
Thin disk



## SFHs of M54 & Sgr dwarf



SFH of  
Sgr dwarf  
is also  
affected

# Summary: formation history of the Galaxy

