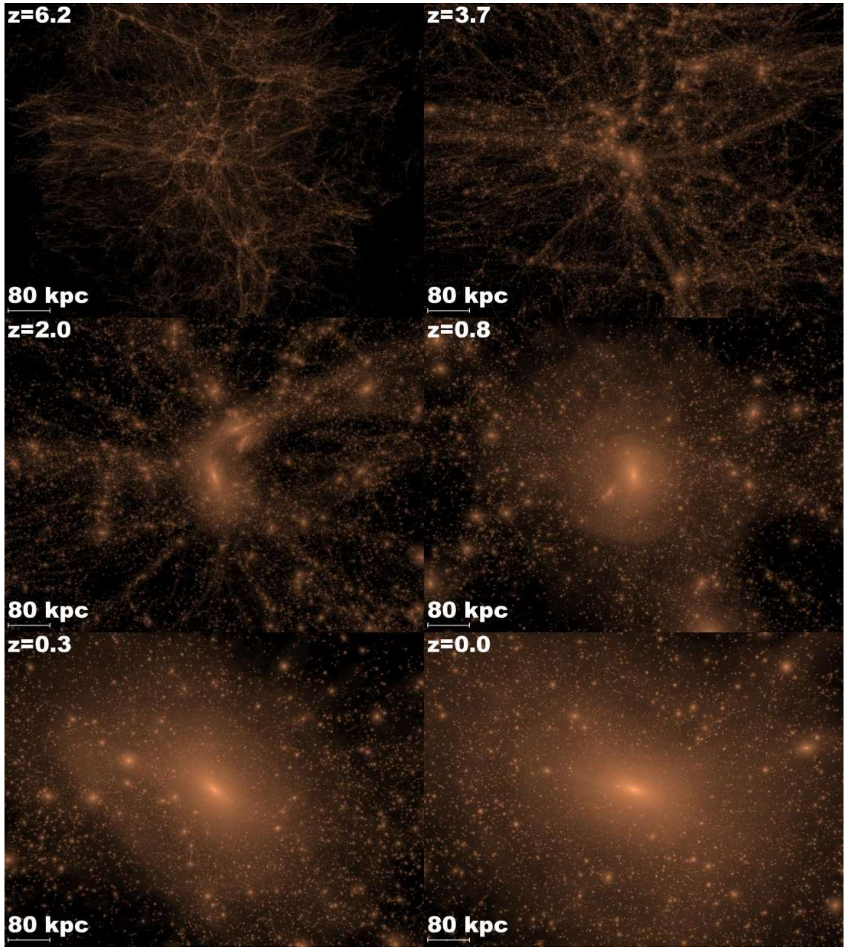
Chap.5 Formation of Galactic Structures

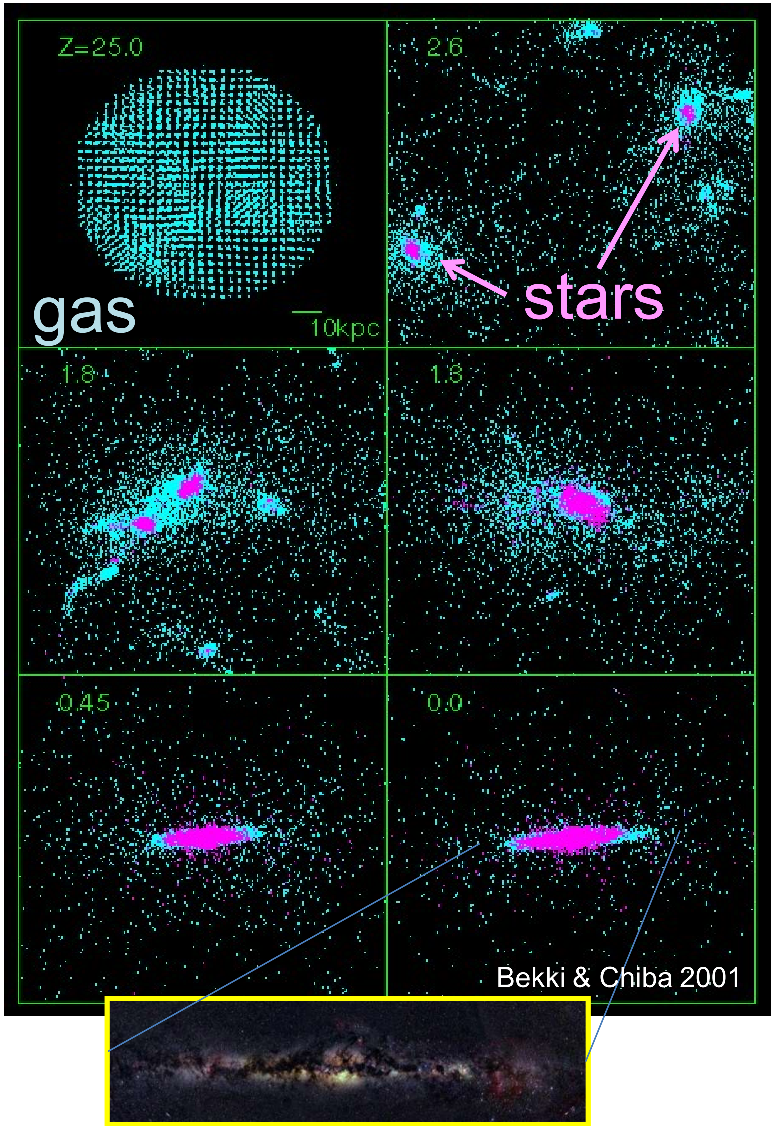
- Overview of galaxy formation
- Classical picture of Galaxy formation
- Formation of the stellar halo: after Hipparcos
- Formation of the stellar halo: after Gaia
- Formation of the thick disk
- Formation of the thin disk
- Formation of satellite galaxies

1. Overview of galaxy formation

Hierarchical assembly of CDM



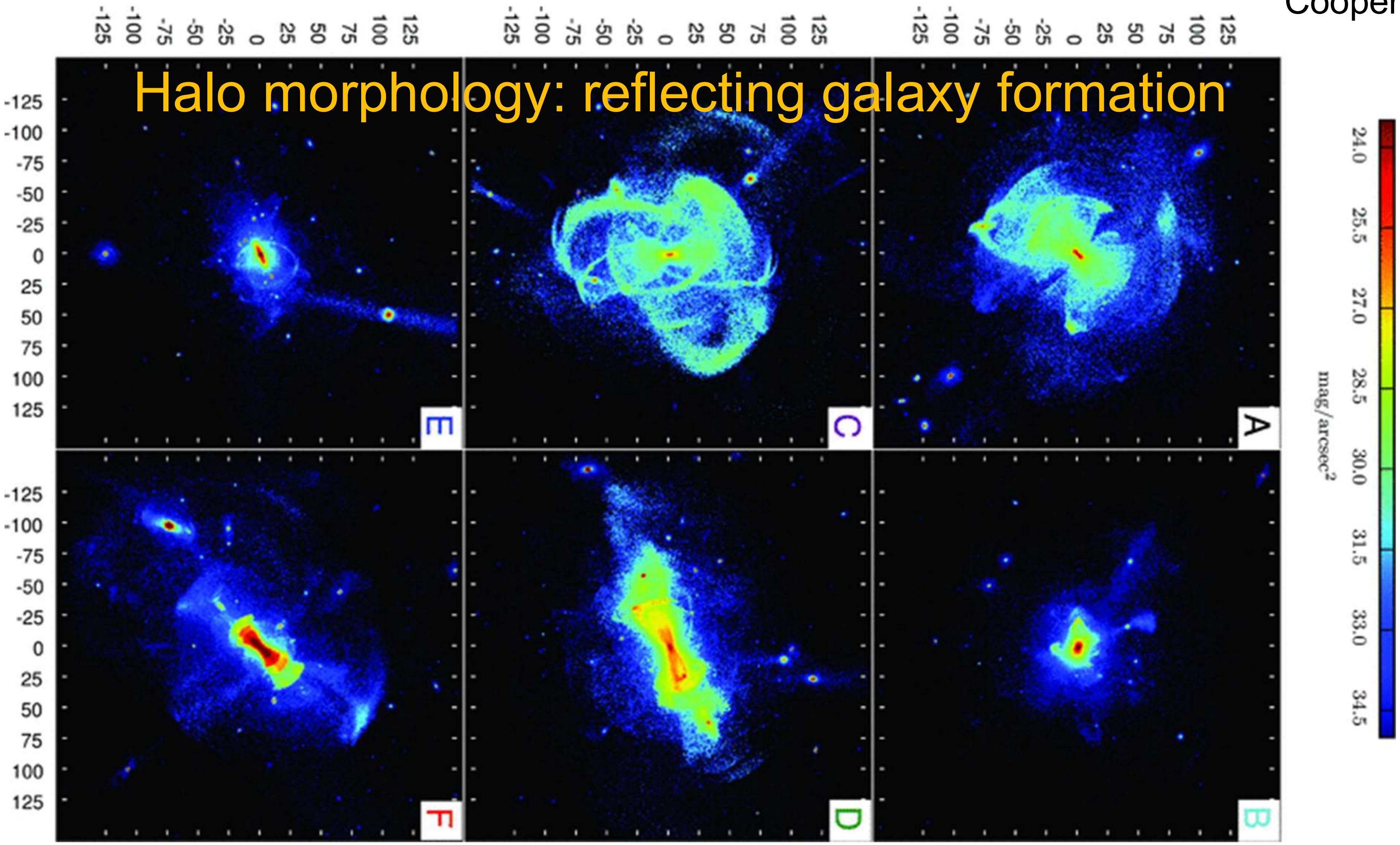
Via Lactea simulation
(Diemand+07)



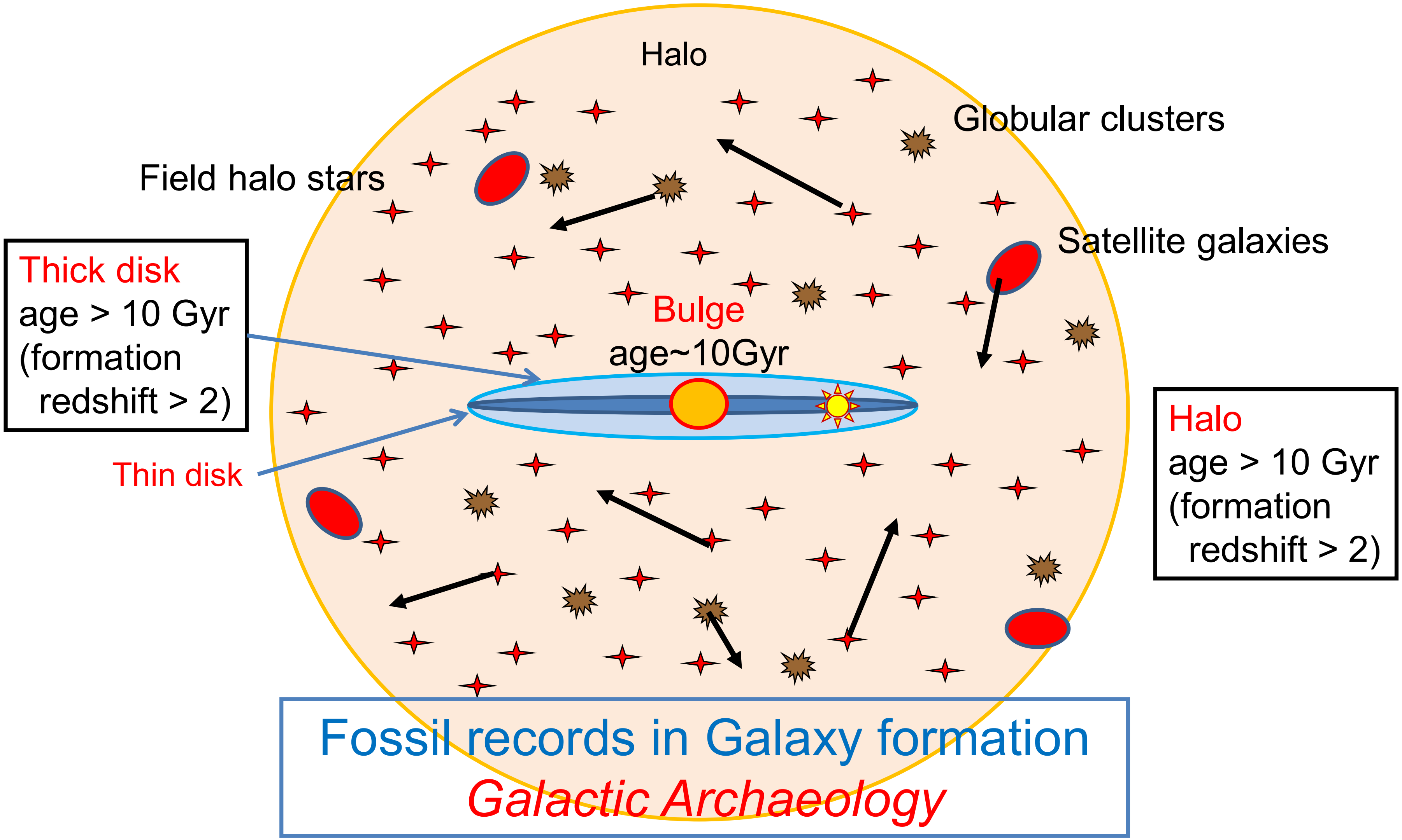
Stellar halos in various MW-sized halos

~varieties due to different merging histories~

Cooper et al. 2010



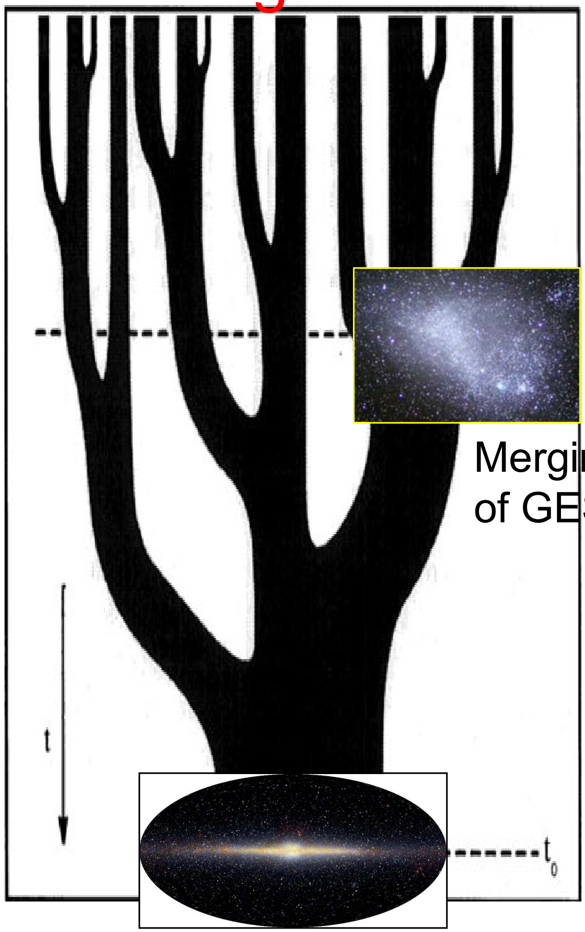
Old stellar components

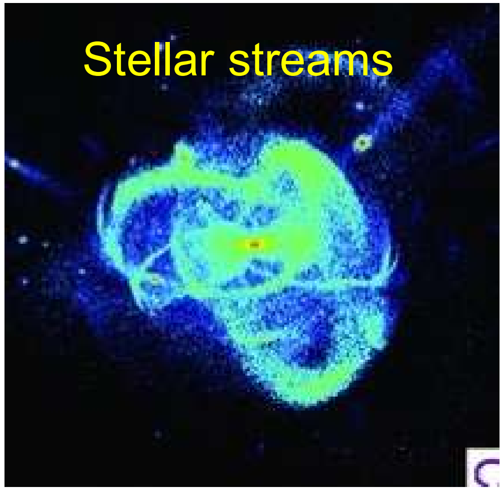


Fossil record of Galaxy formation

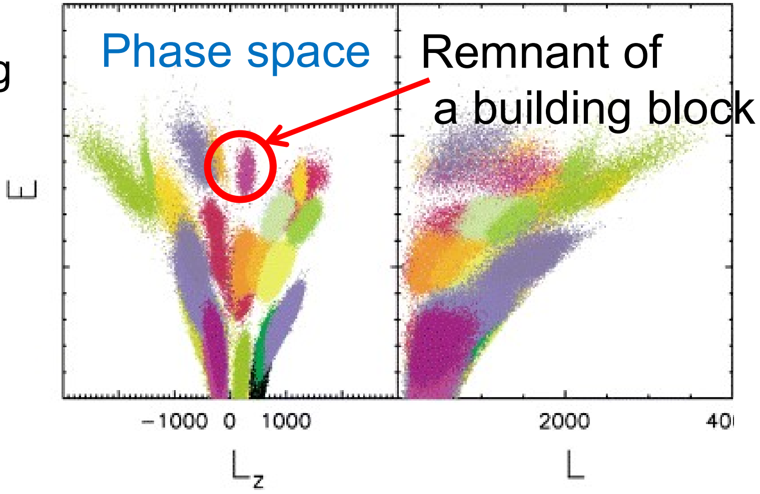
Hierarchical merging

Merger tree

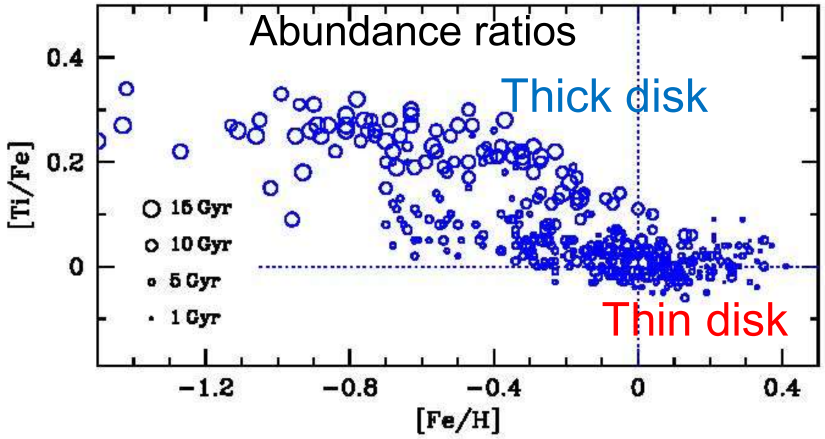




- Spatial distribution and dynamics of stars
  - ✓ Galaxy collapse and merging
- Chemical abundance of stars
  - ✓ Star formation and chemical evolution



Helmi & de Zeeuw 2000



Bensby et al. 2014

Sampling ancient halo stars

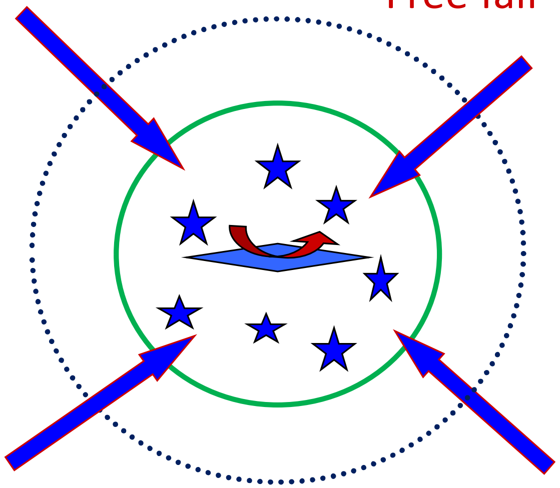
- Metal-poor sample (metallicity biased)
  - e.g. : [Fe/H] < -1
  - Suitable for kinematic analysis
- High-velocity sample (kinematically biased)
  - e.g. : $| V_{star} – V_{LSR} | > 180$ km/s
  - Suitable for metallicity analysis

Fraction: ~ 1/1000 near the Sun

2. Classical picture of Galaxy Formation

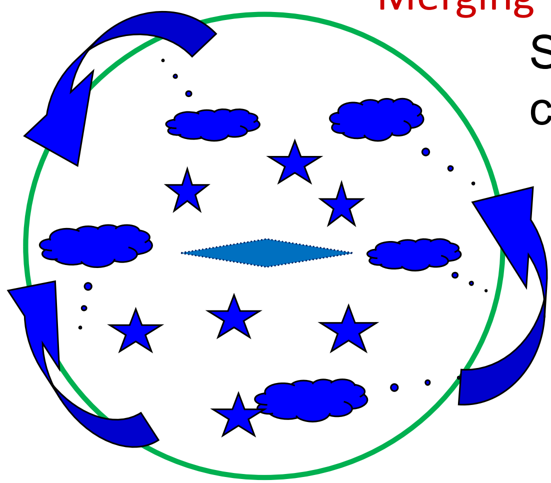
* Monolithic, free-fall collapse
Eggen, Lynden-Bell, Sandage 1962 (ELS)
* Chaotic merging of numerous fragments
Searle, Zinn 1978 (SZ)

ELS

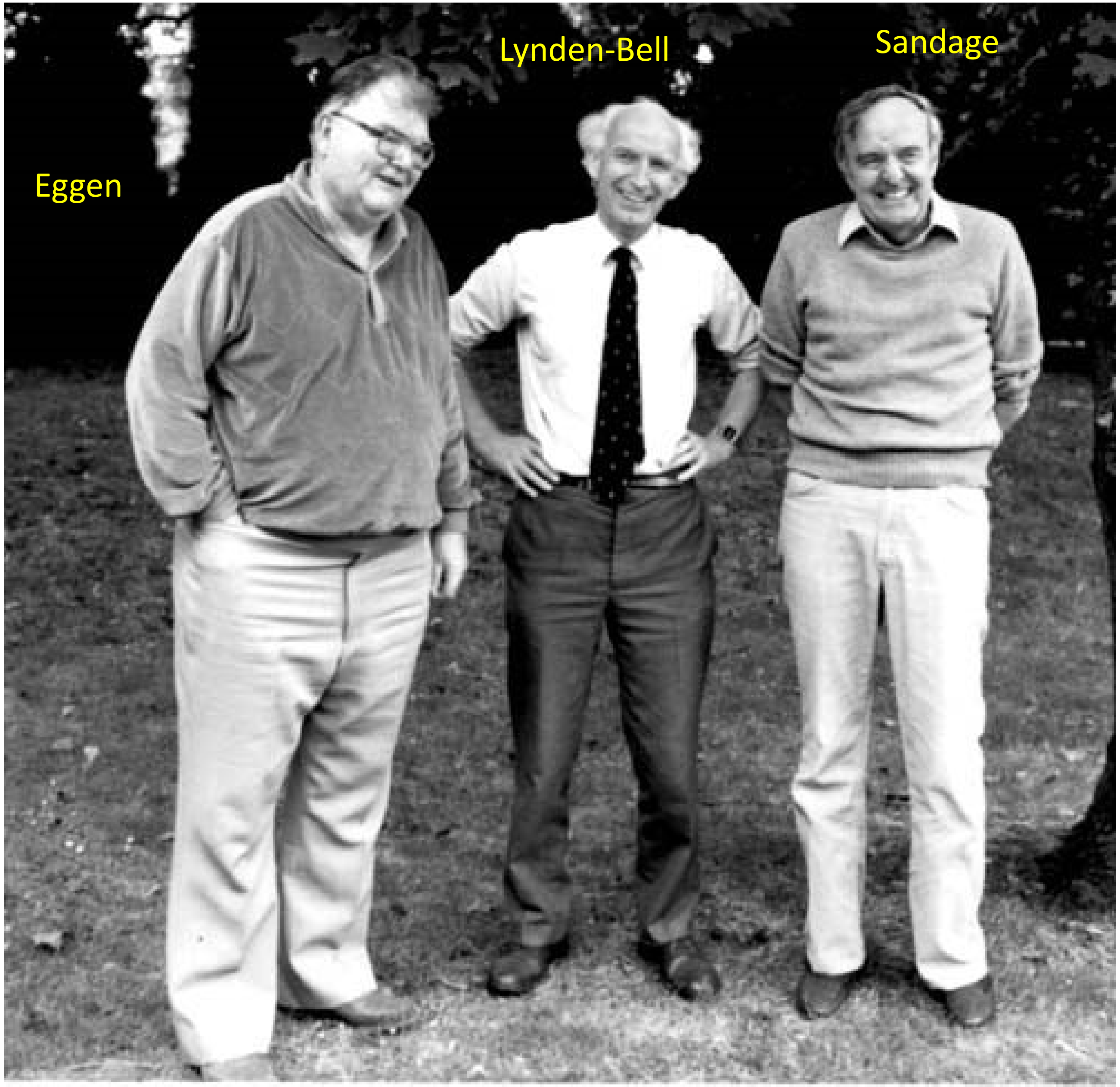


Correlation between kinematics and metal abundances of stars
Metallicity gradient

SZ

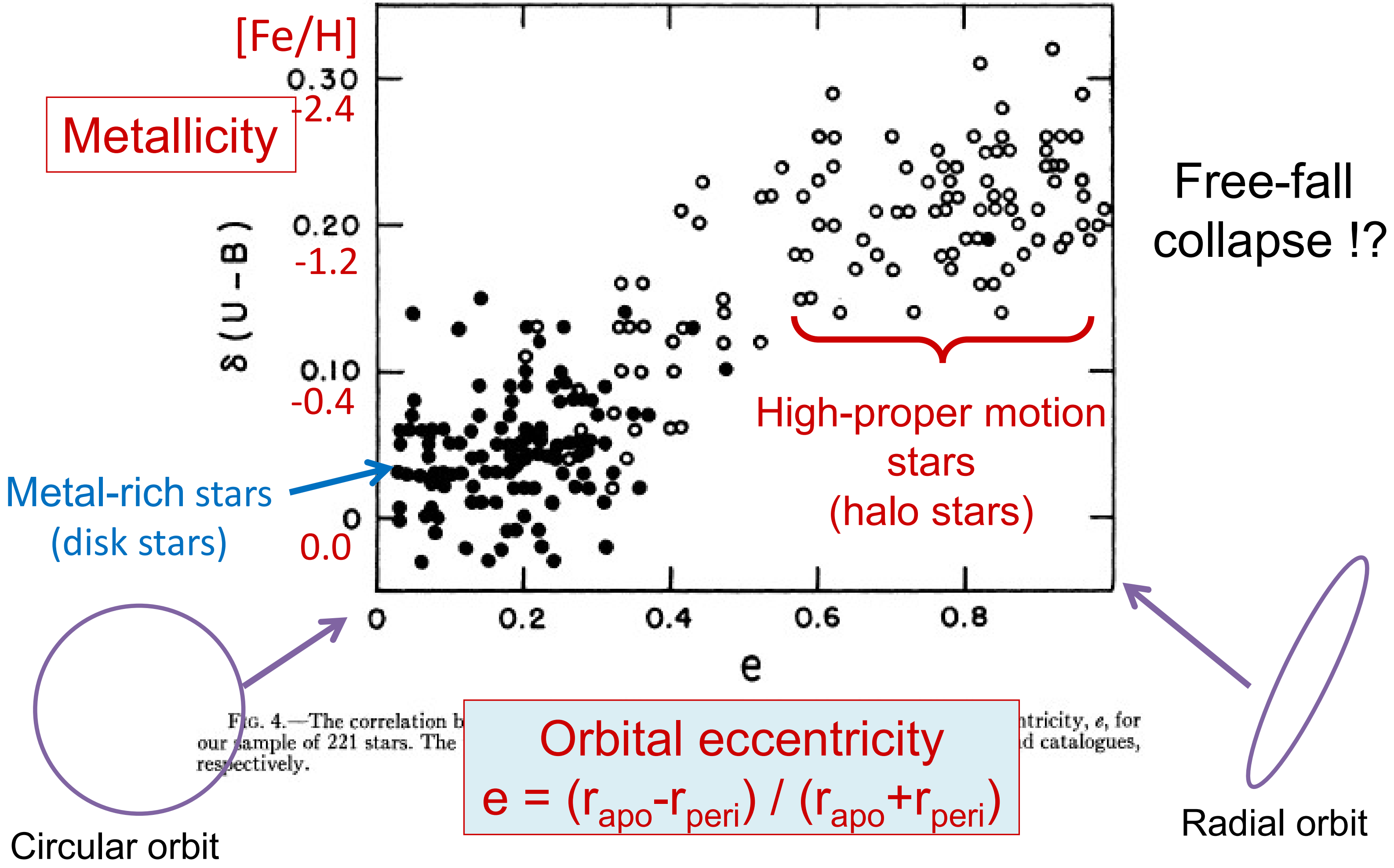


No metallicity gradient
Age spread among globular clusters

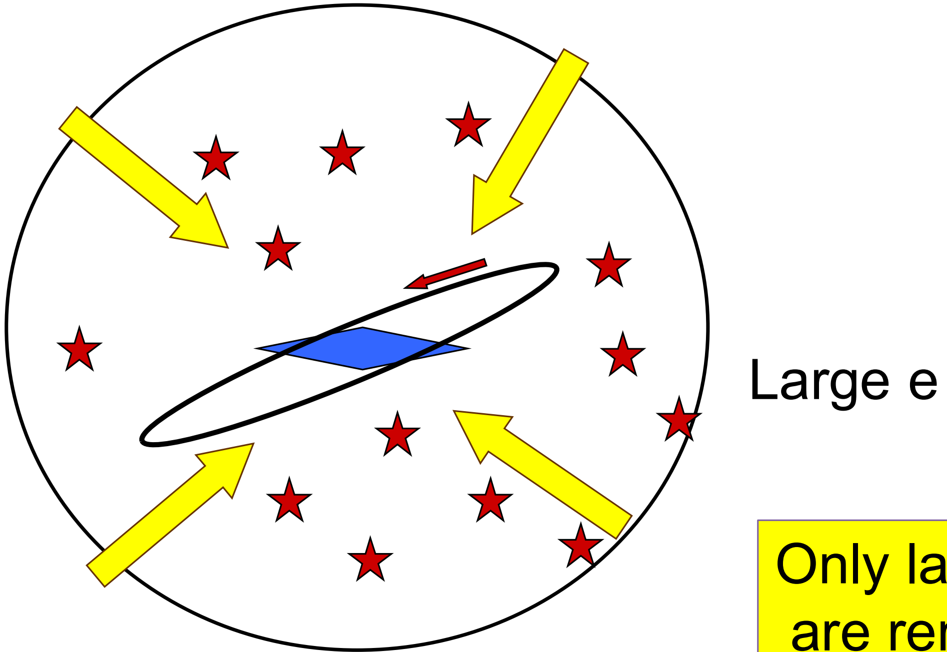

Eggen
Lynden-Bell
Sandage

Physical state of the Protogalaxy

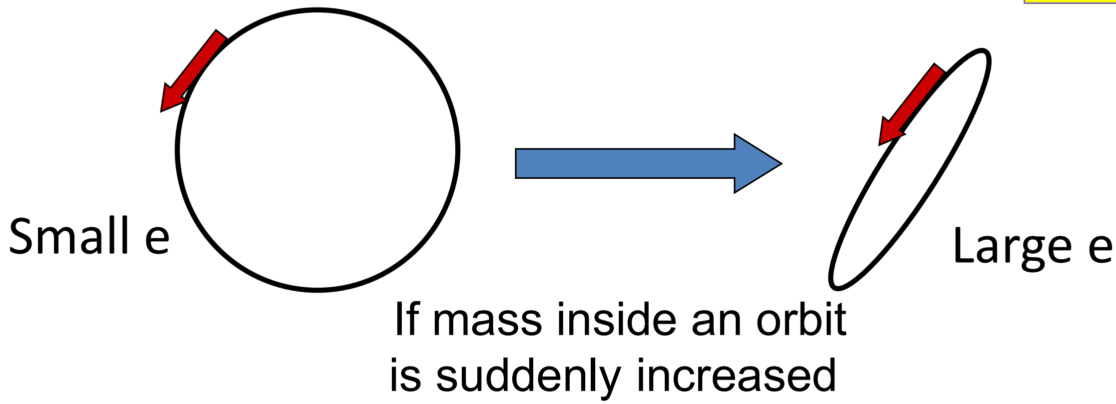
(Eggen,Lynden-Bell & Sandage 1962)



If free-fall galactic collapse is the case



Only large-e stars are remaining.



Note

Action integrals for Kepler motions

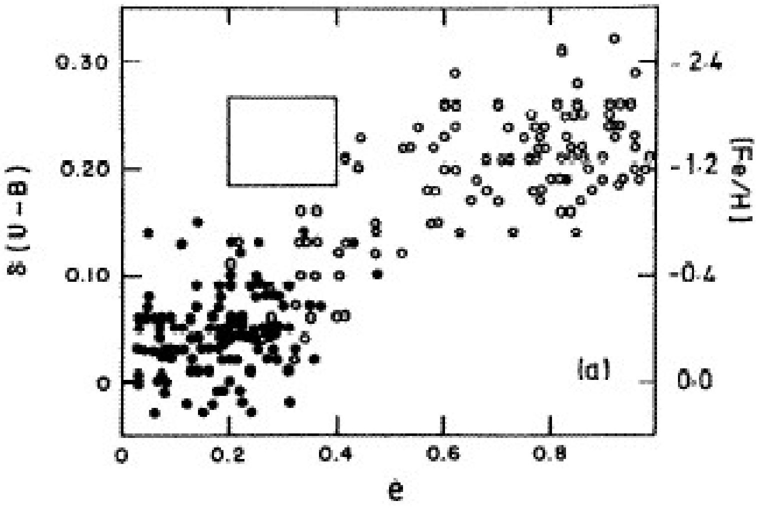
$$J_r = \frac{1}{\pi}\int_{r_{\min}}^{r_{\max}} p_r dr = \frac{\sqrt{2}}{\pi}\int_{r_{\min}}^{r_{\max}} \sqrt{E - \frac{L^2}{2r^2} + \frac{GM}{r}}\, dr = \frac{GM}{\sqrt{2|E|}} - L = L\left[\frac{1}{\sqrt{1-e^2}} - 1\right]$$

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

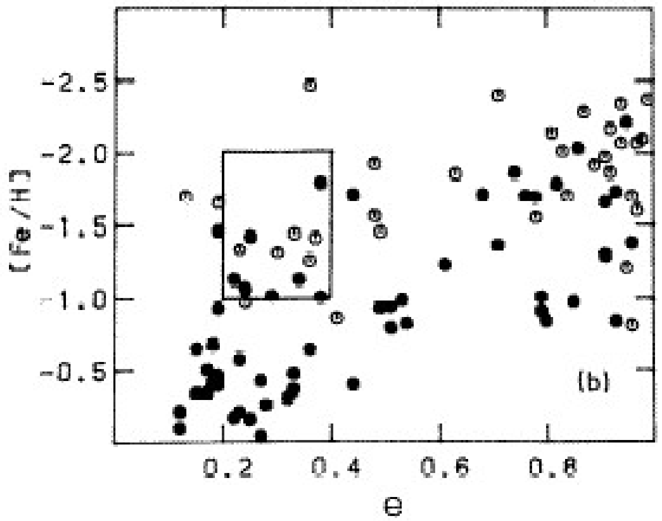
$$J_\phi = \frac{1}{2\pi}\oint p_\phi d\phi = p_\phi$$

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

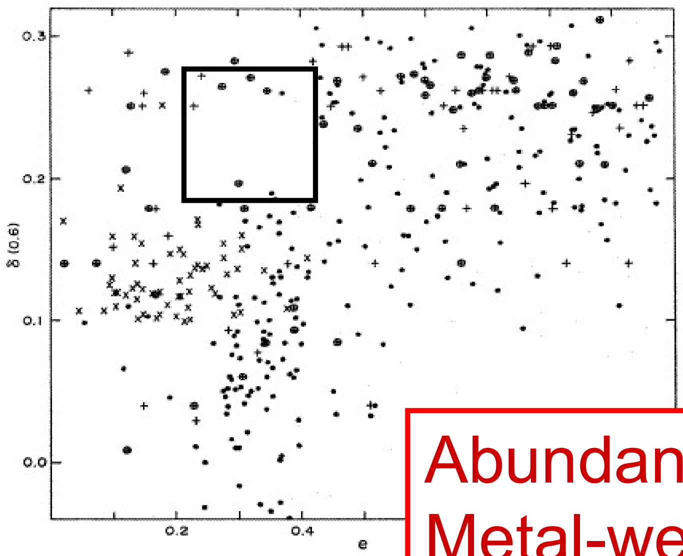
ELS 1962



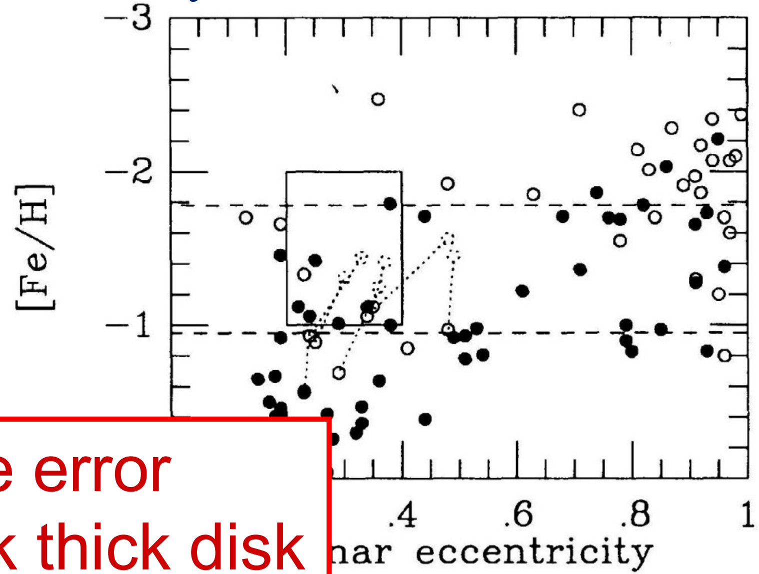
Norris et al. 1985



Yoshii & Saio 1979



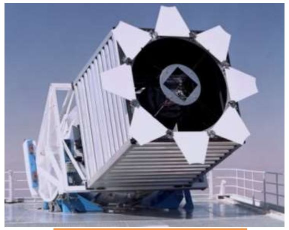
Ryan & Lambert 1995



Abundance error

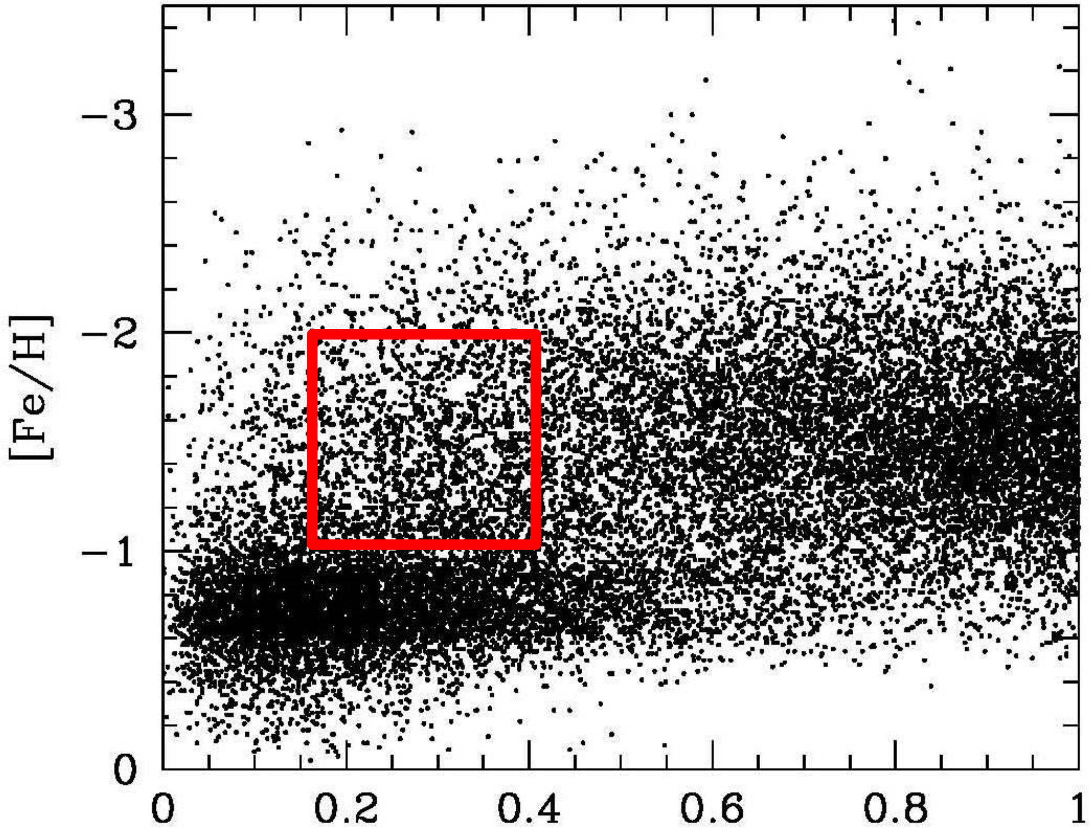
Metal-weak thick disk

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

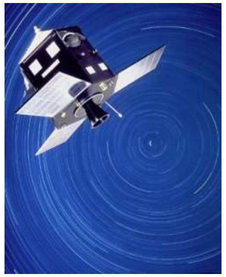


SDSS

[Fe/H]

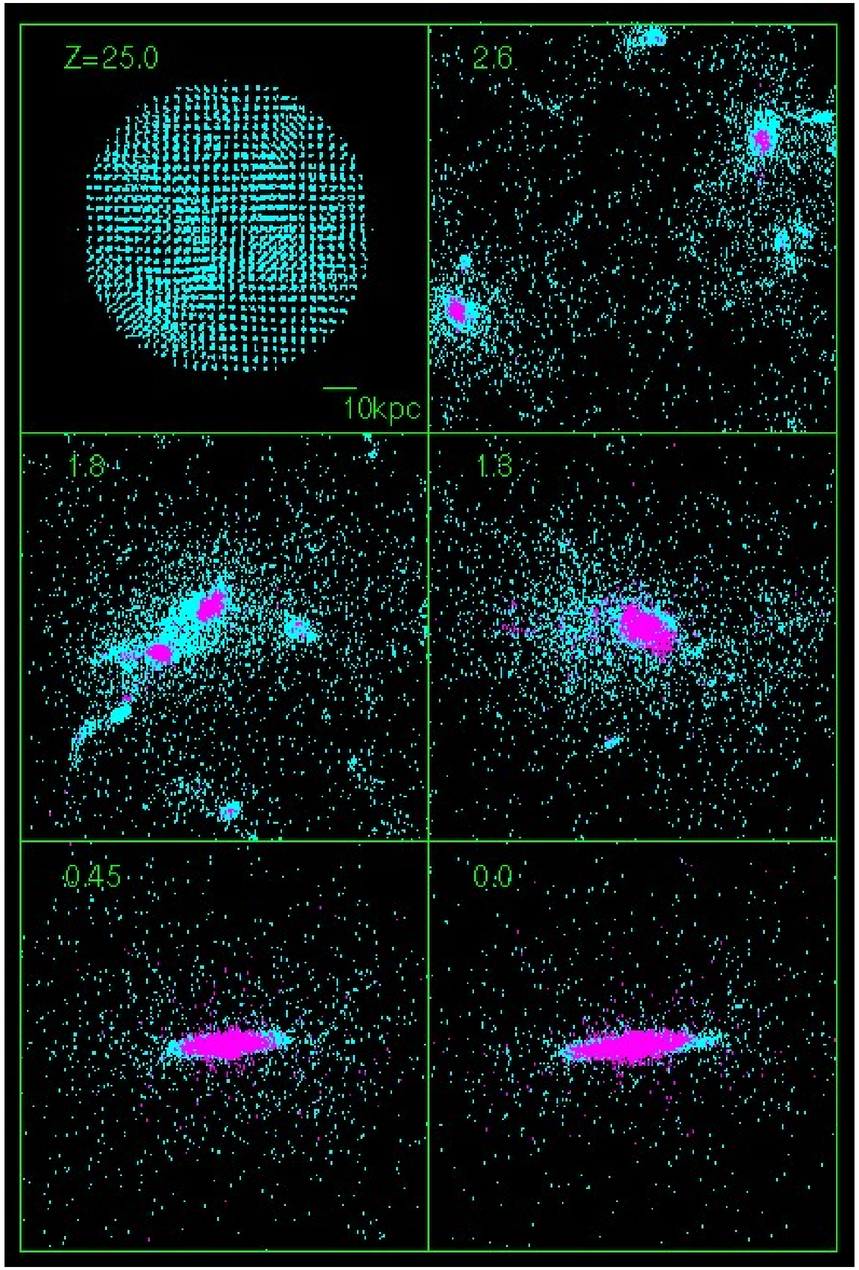


orbital eccentricity



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)

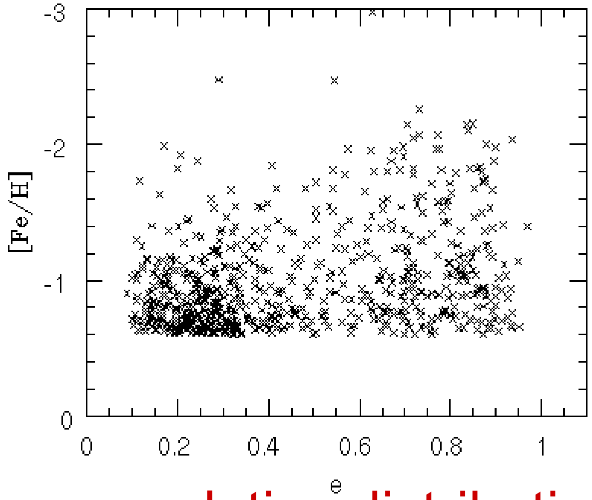
gas

star

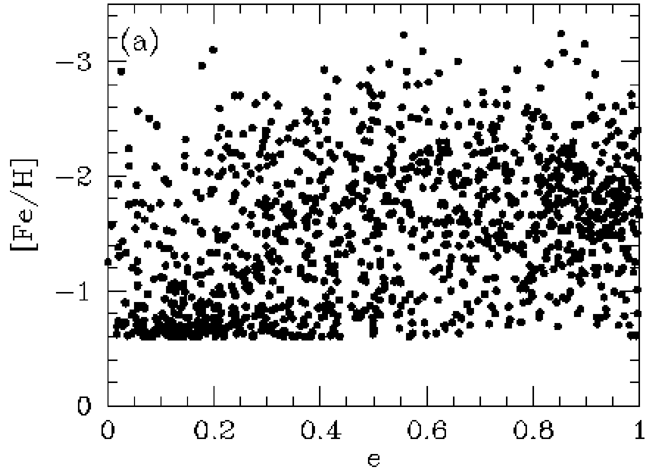
Comparison with simulation results

Bekki & Chiba (2001)

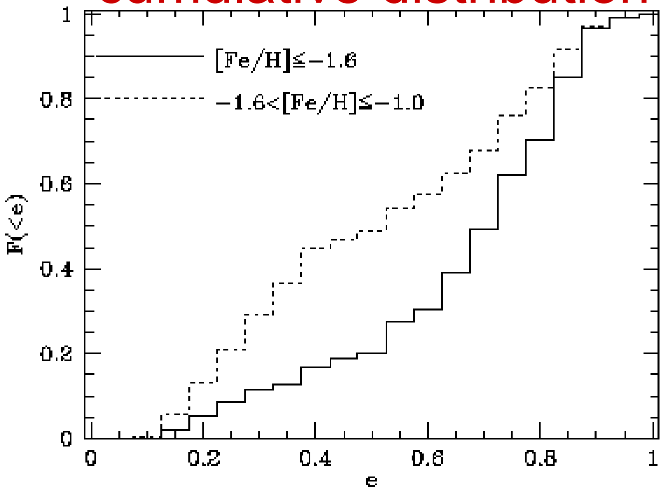
simulation



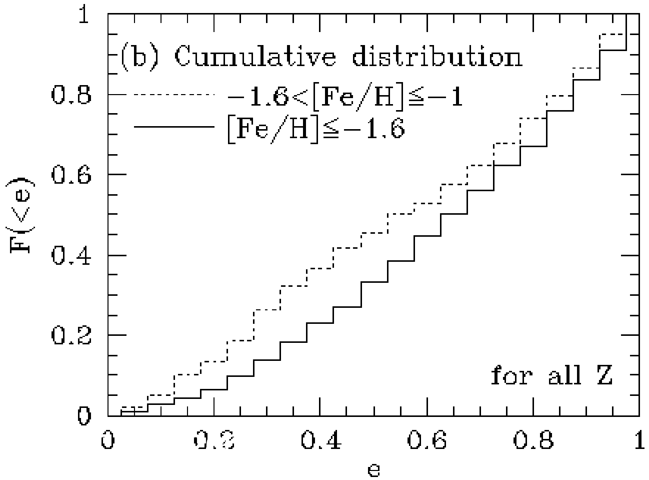
observation



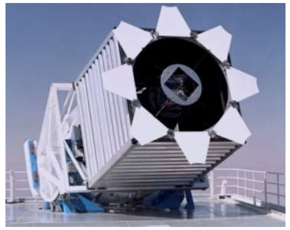
cumulative distribution



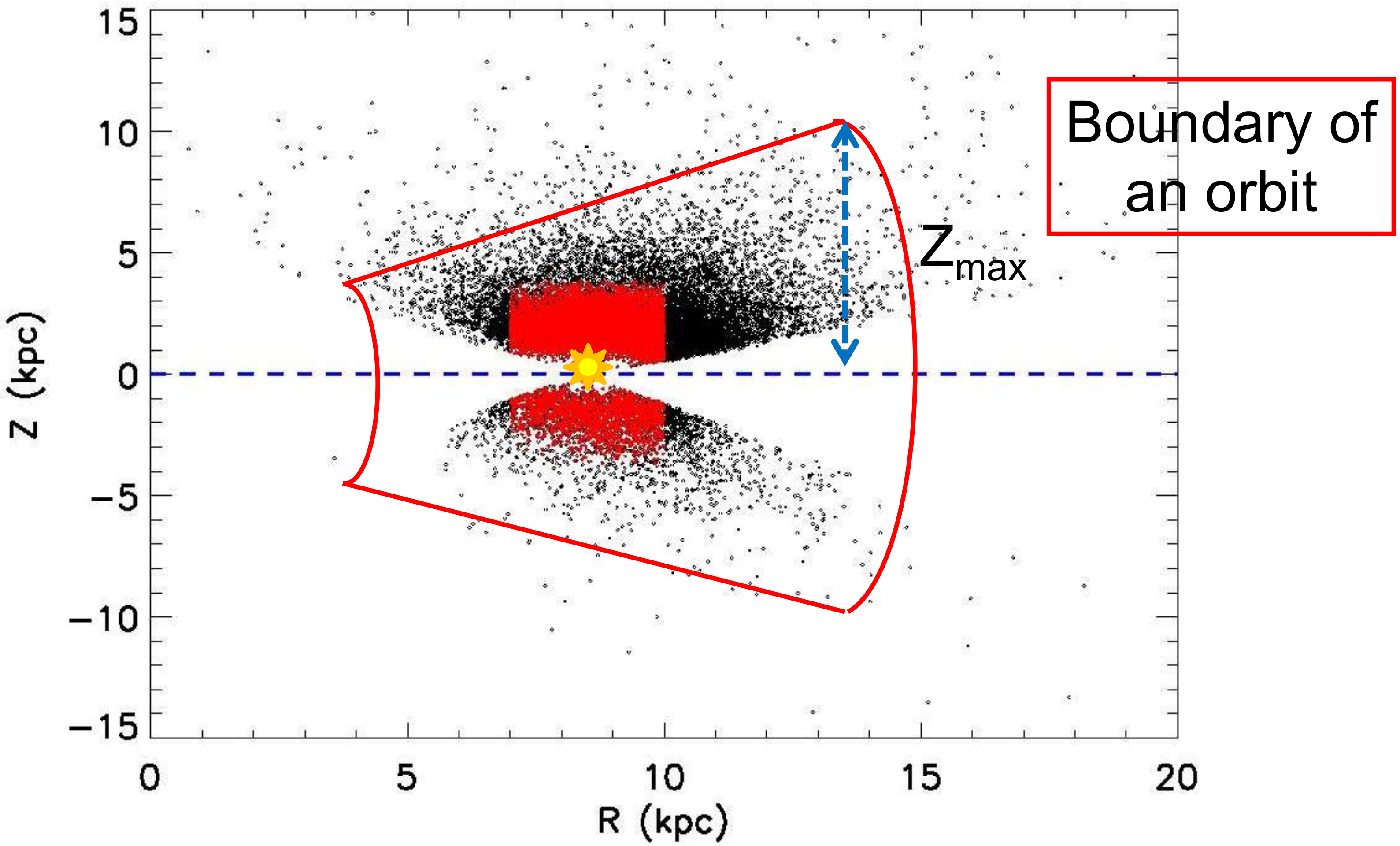
cumulative distribution



Nearby stellar sample from SDSS



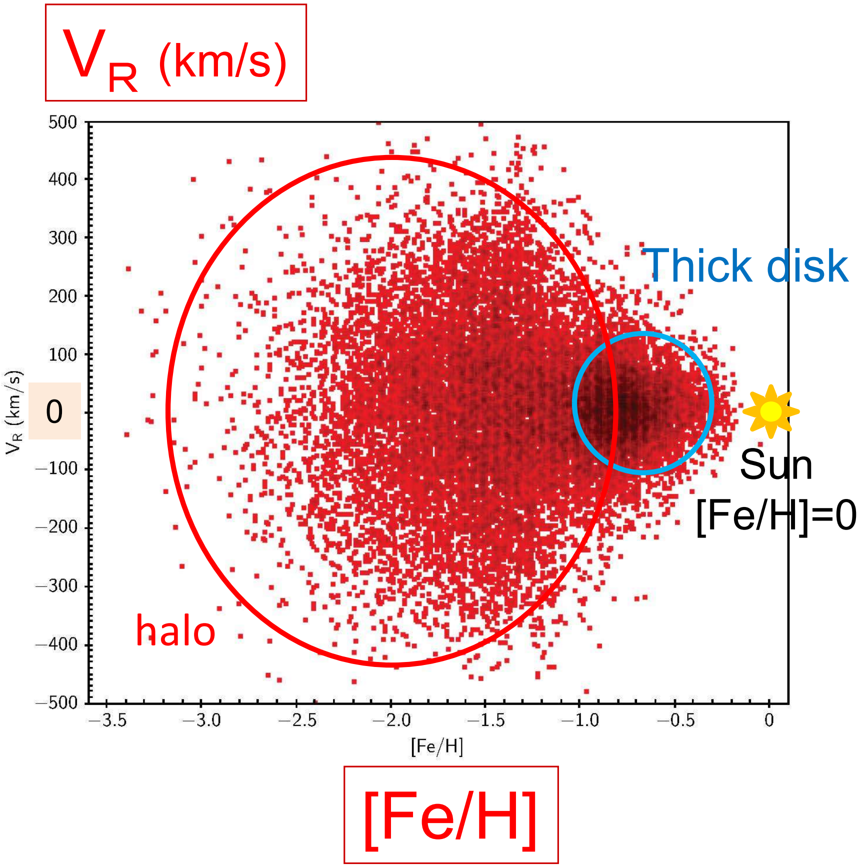
Carollo+2007, 2010

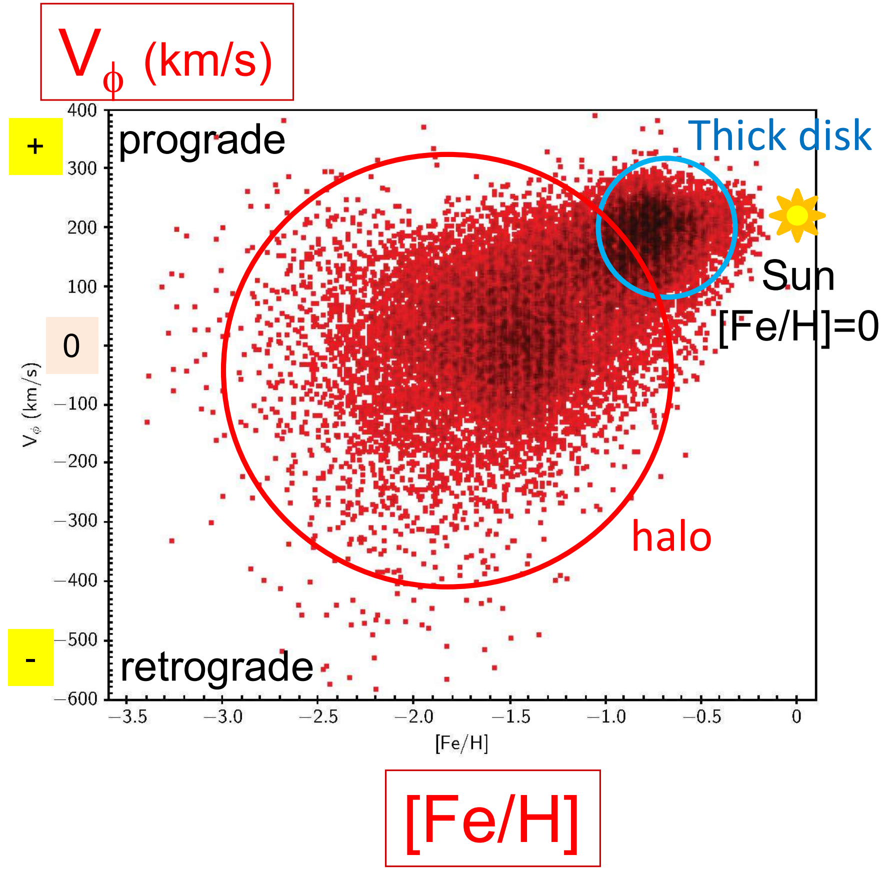


Velocity distribution of nearby stars

Sloan Digital Sky Survey

Carollo+2007, 2010





Velocity distribution of nearby stars

Sloan Digital Sky Survey

Carollo+2007, 2010

prograde

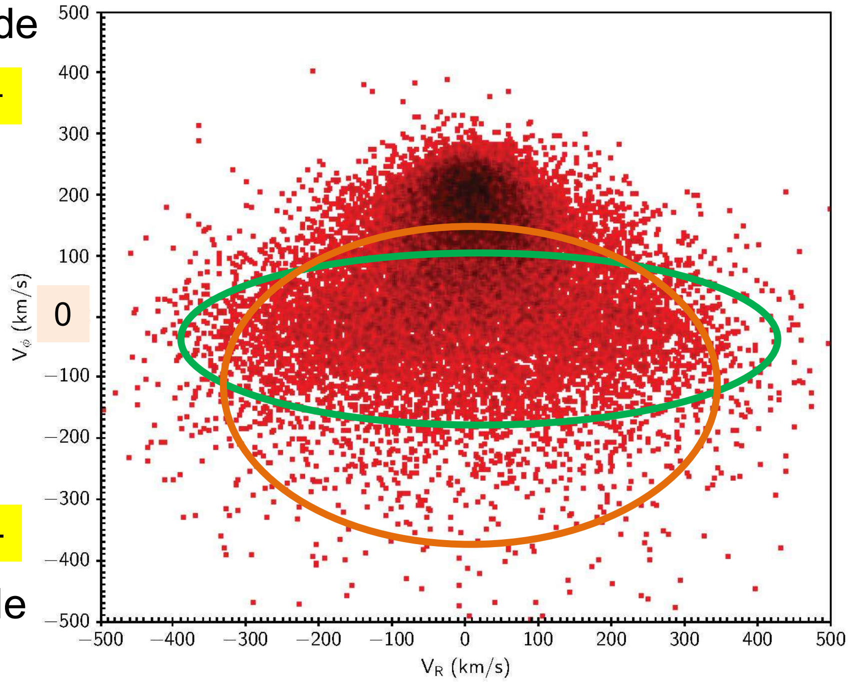
+

V_{ϕ} (km/s)

0

-

retrograde



V_R (km/s)

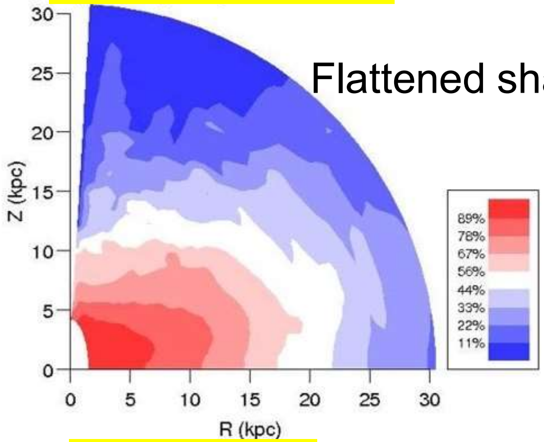
radially anisotropic

mildly anisotropic
presence of stars
with largely negative V_{φ}

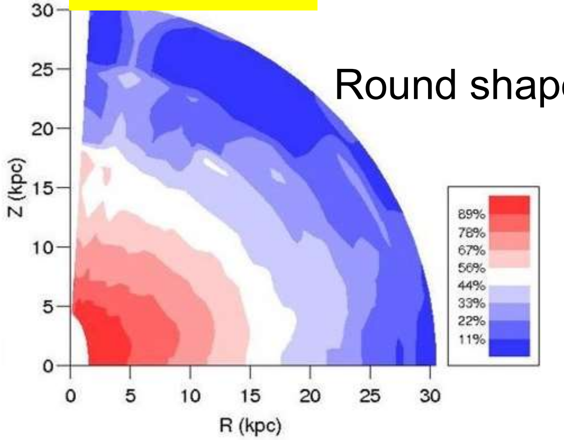
2-halos : from dynamics

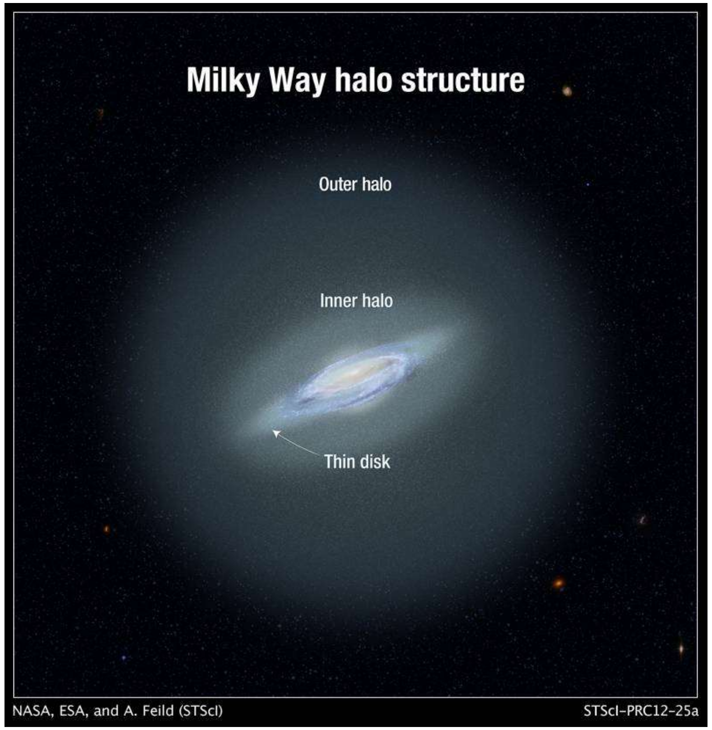
Global halo distribution based on superposition of stellar orbits (Carollo+ 2007)

-1.6<[Fe/H]<-1.4



[Fe/H]<-2.2



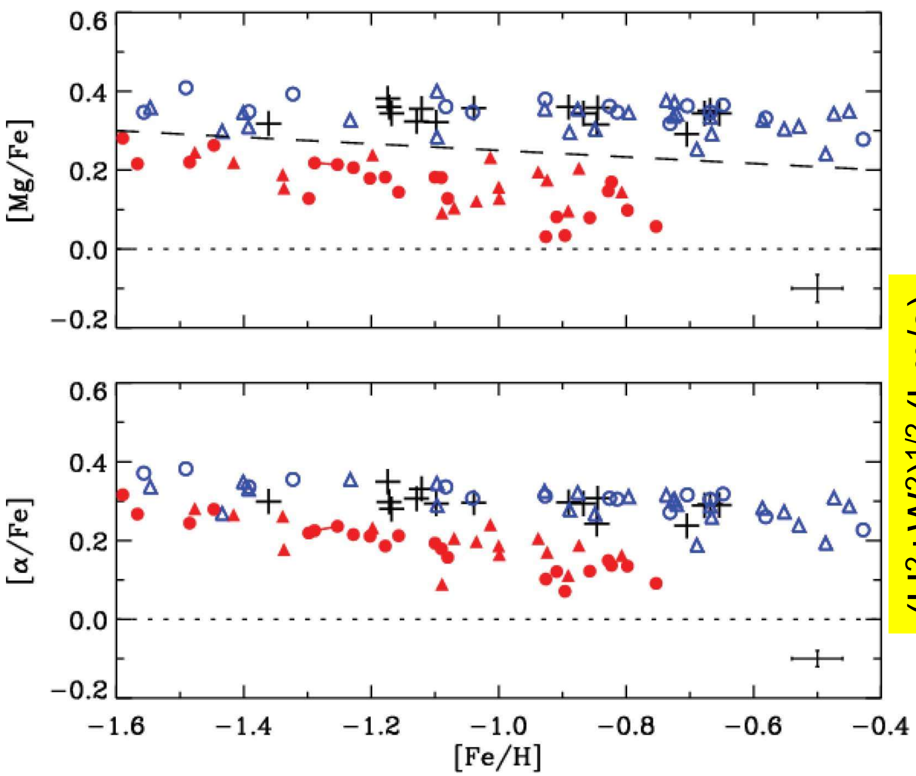


- Inner halo -> in situ halo
  - Flattened shape, -1.6<[Fe/H]<-1
- Outer halo -> ex situ halo
  - Round shape, [Fe/H]<-2

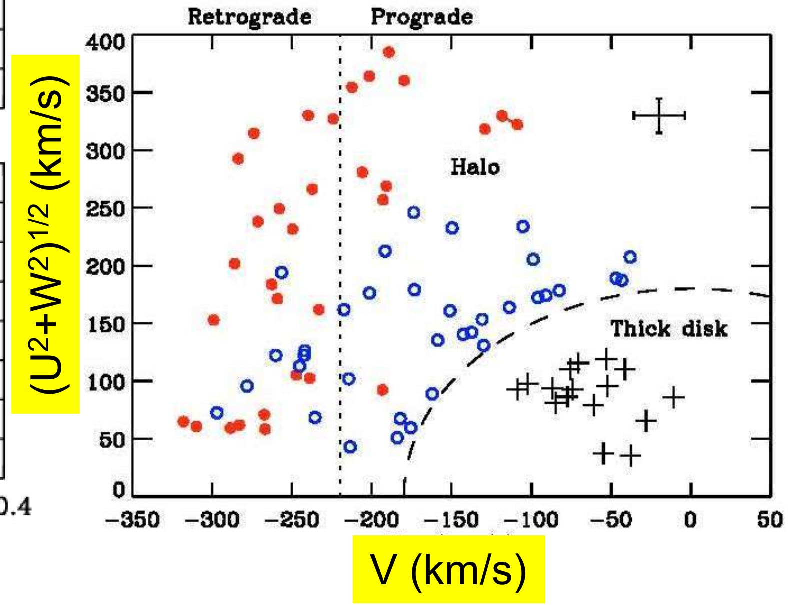
2-halos : from chemical abundance

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

| V_{star} – V_{LSR} | > 180 km/s

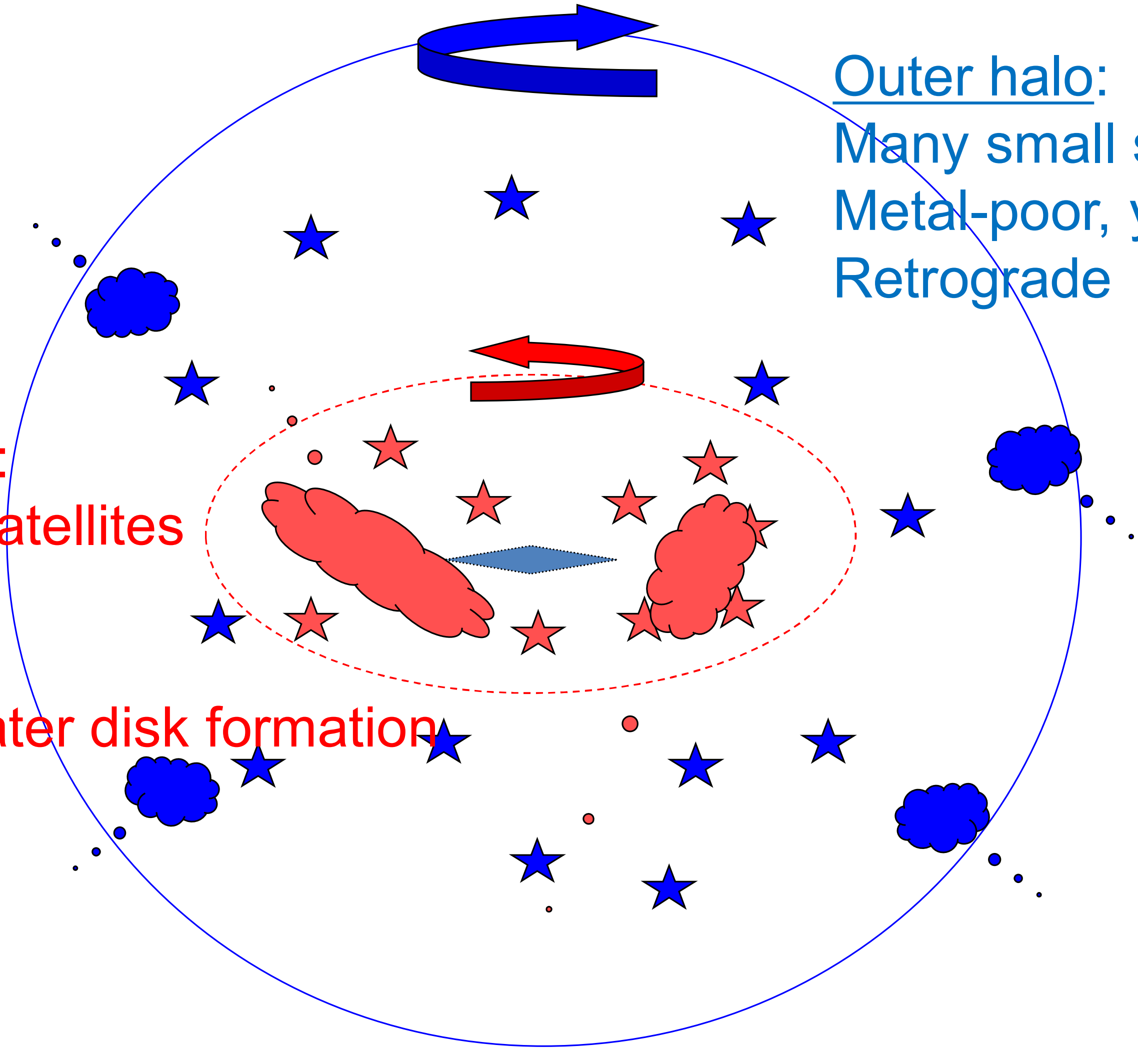


Blue: high-α stars
→ inner (in situ) halo?
Red: low-α stars
→ outer (ex situ) halo?



Based on VLT/UVES & NOT/FIES spectra
High-precision calibration with Δ= 0.02 ~ 0.04 dex

How 2-halos have formed?

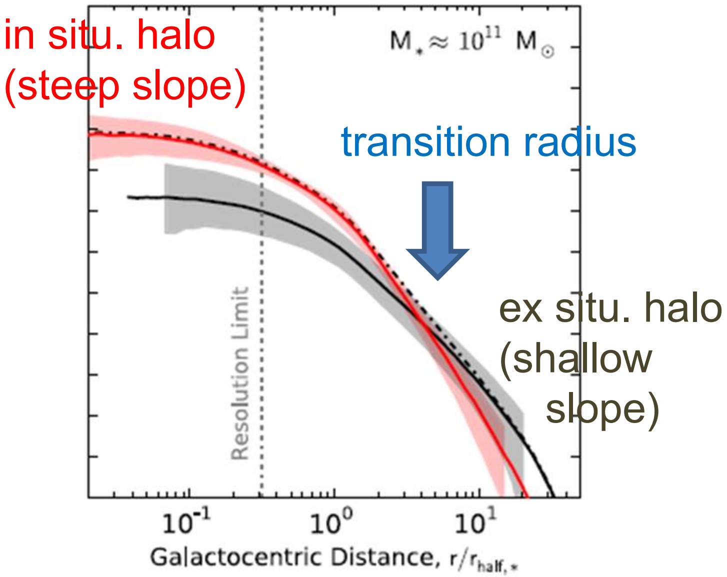


Outer halo:
Many small satellites
Metal-poor, young
Retrograde

Inner halo:
Massive satellites
Metal-rich
Prograde
Effect of later disk formation

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

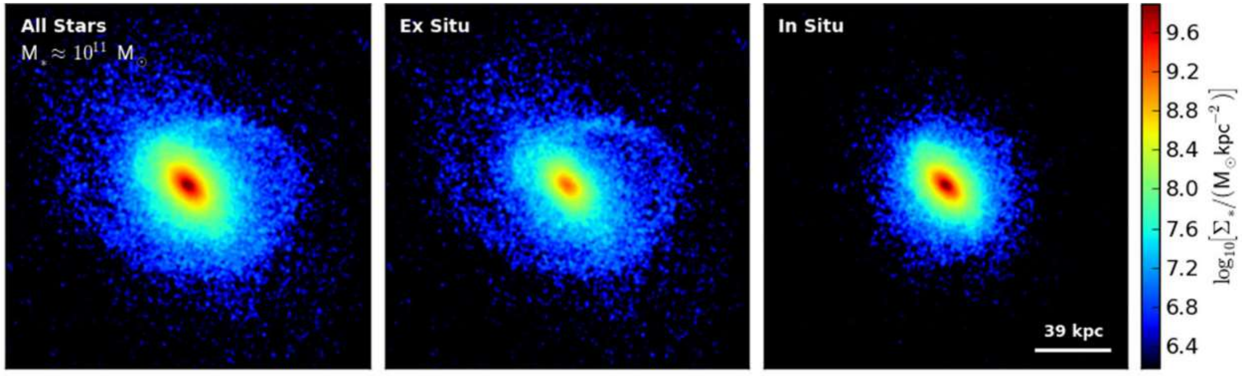
Radial profile of halo stars



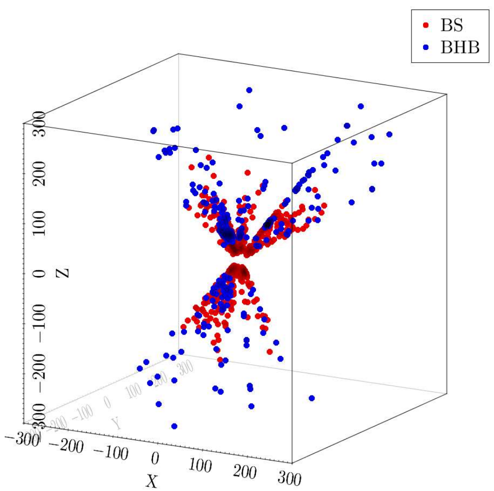
Illustris simulation

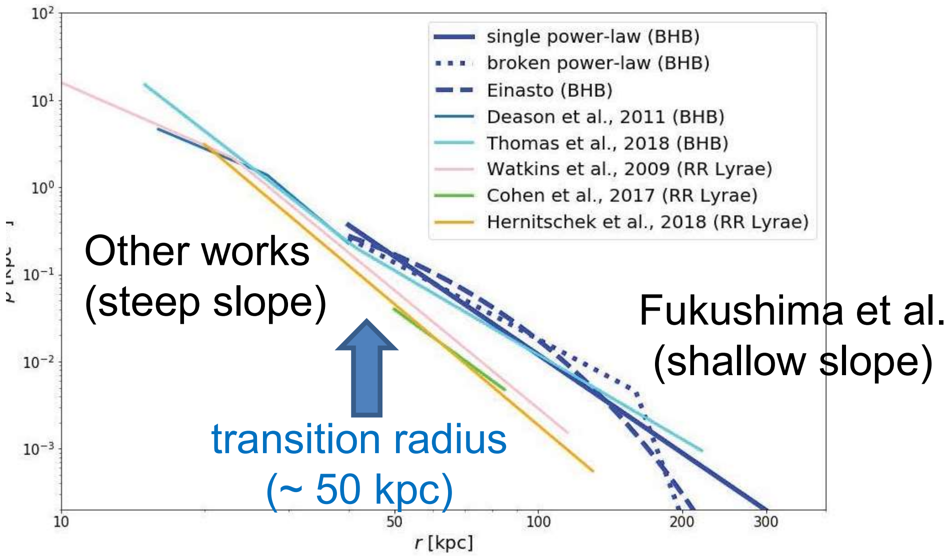
Rodriguez-Gomez+2016

all stars ex situ. in situ.

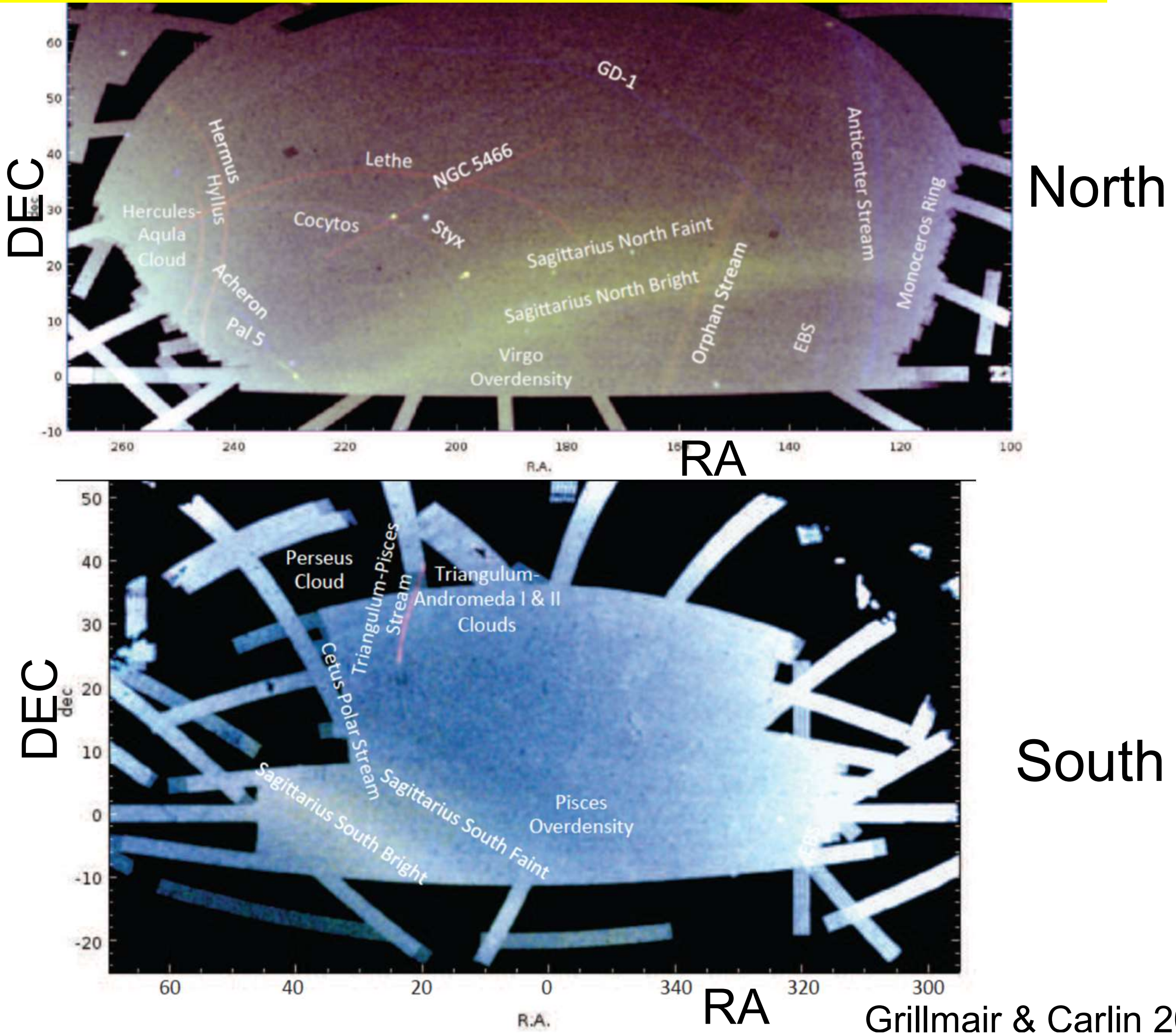


Distribution of Blue-Horizontal Branch Stars from Subaru/HSC (Fukushima et al. 2019)



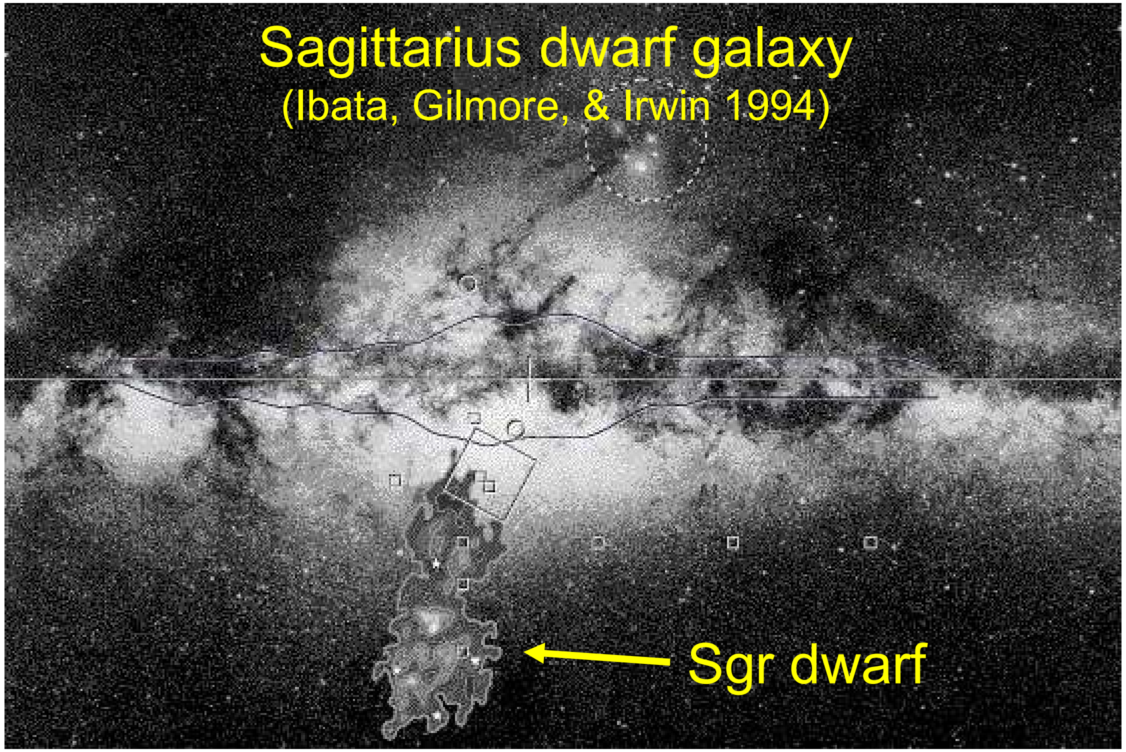


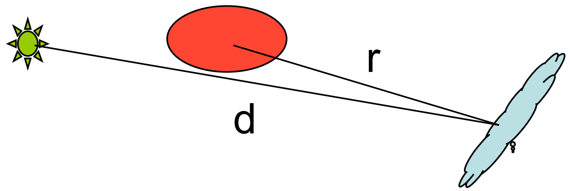
Stellar streams: remnants of merging small galaxies



Grillmair & Carlin 2016

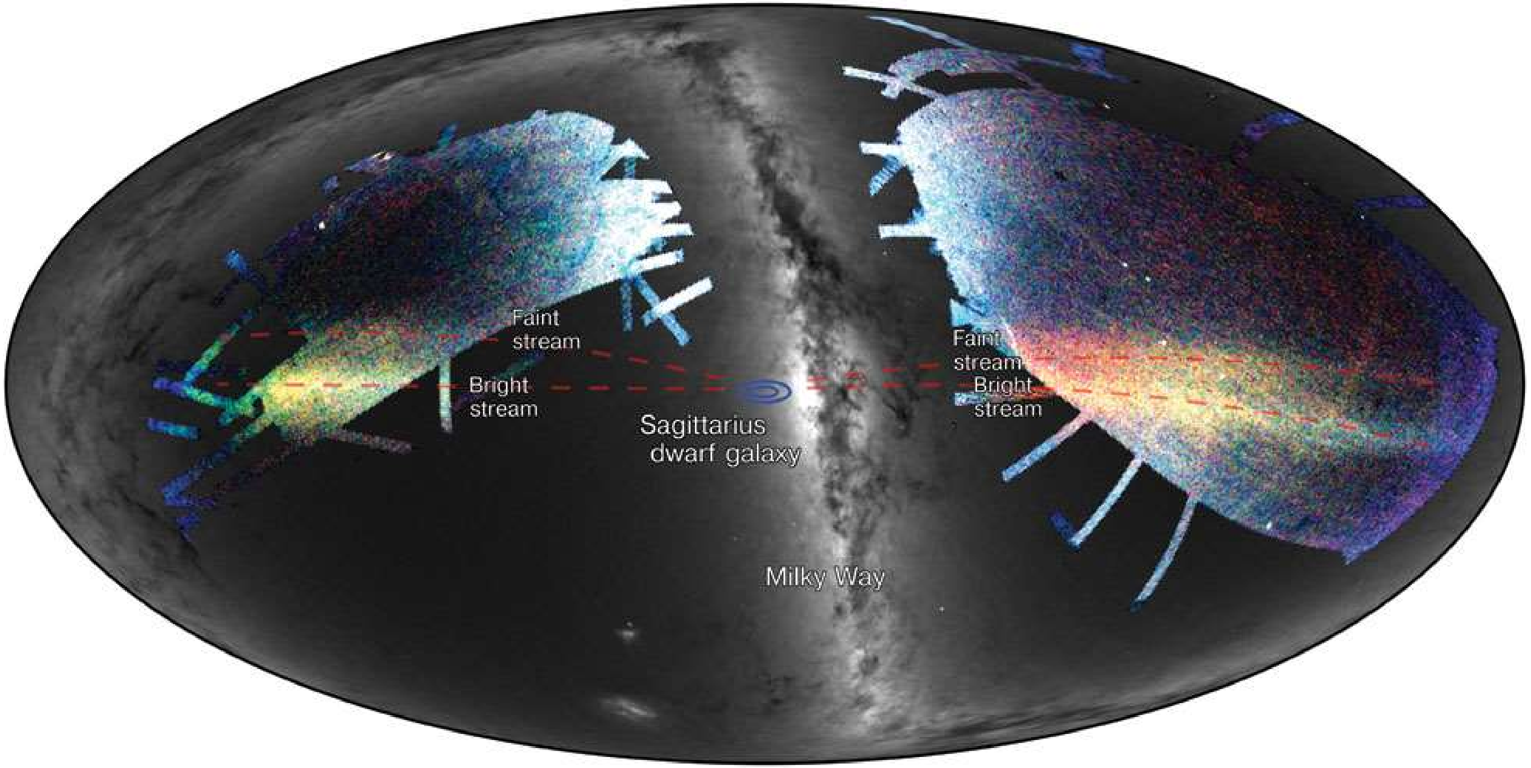
Sagittarius dwarf and stream





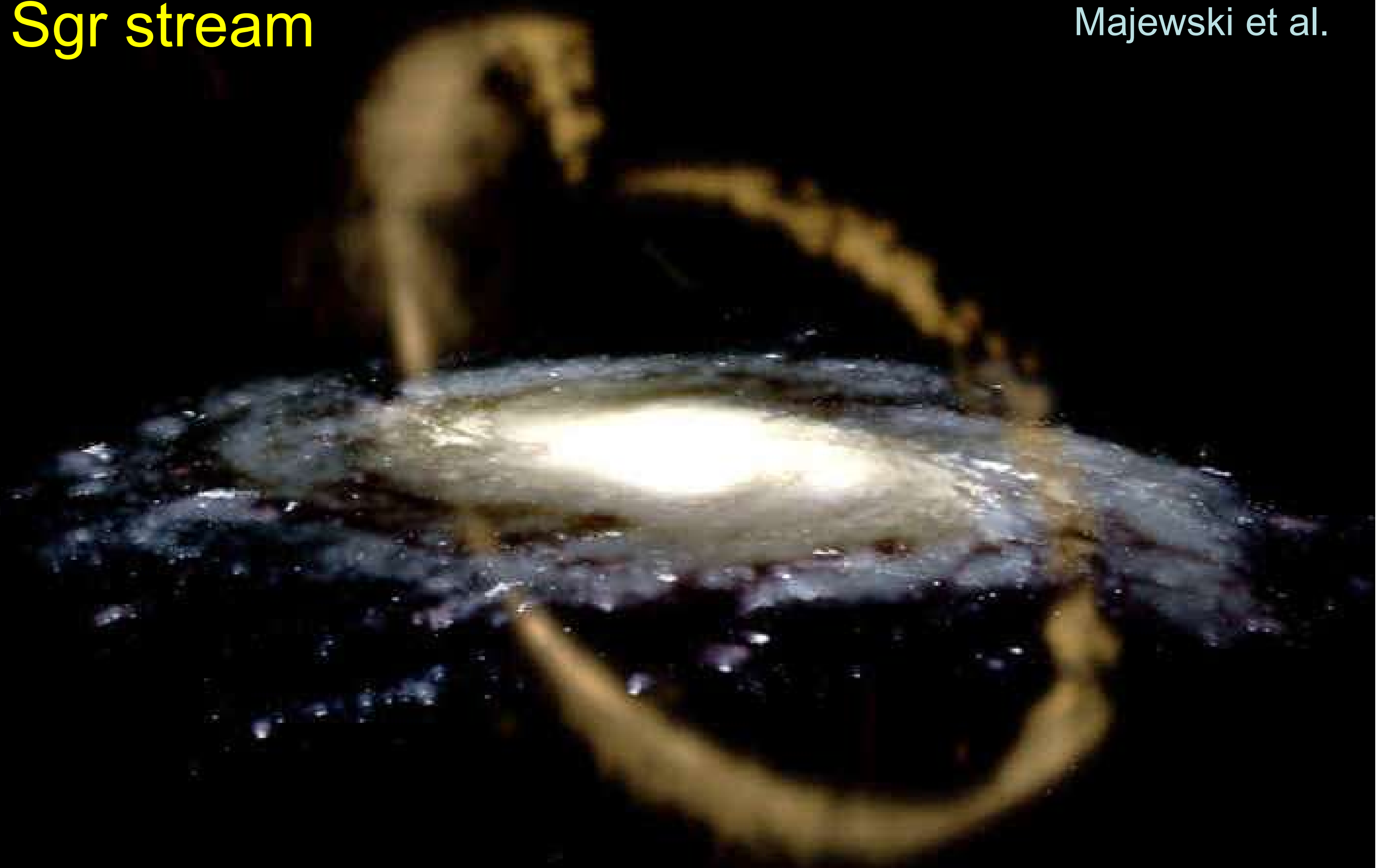
d ~ 24 kpc
r ~ 16 kpc

Sagittarius stream



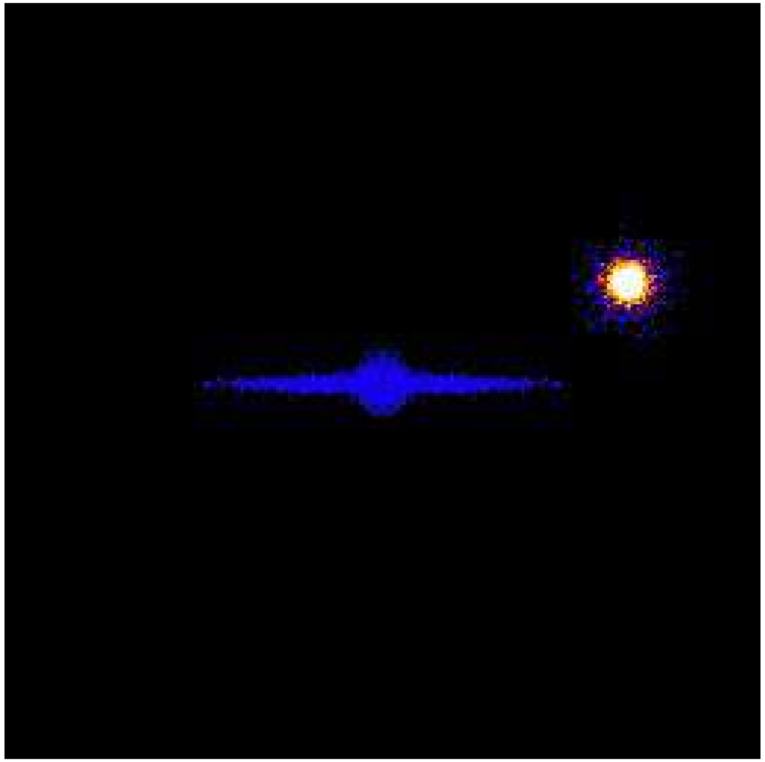
Sgr stream

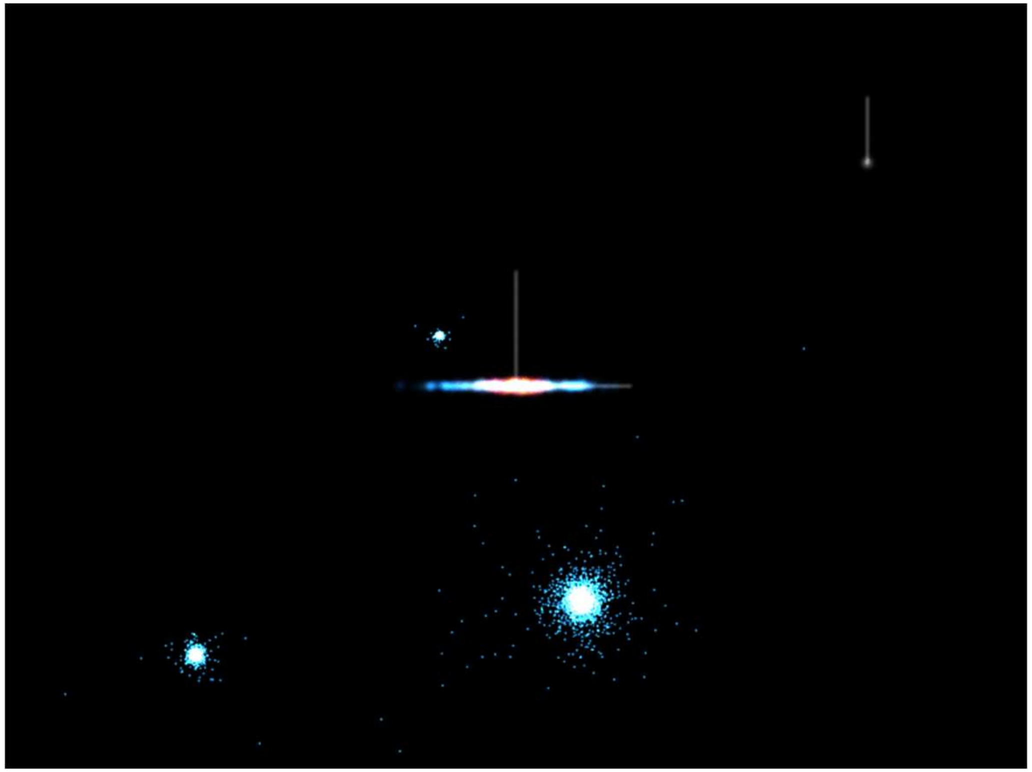
Majewski et al.



Stream is confined onto an orbital plane
⇒ round dark halo at 15 < r < 60 kpc

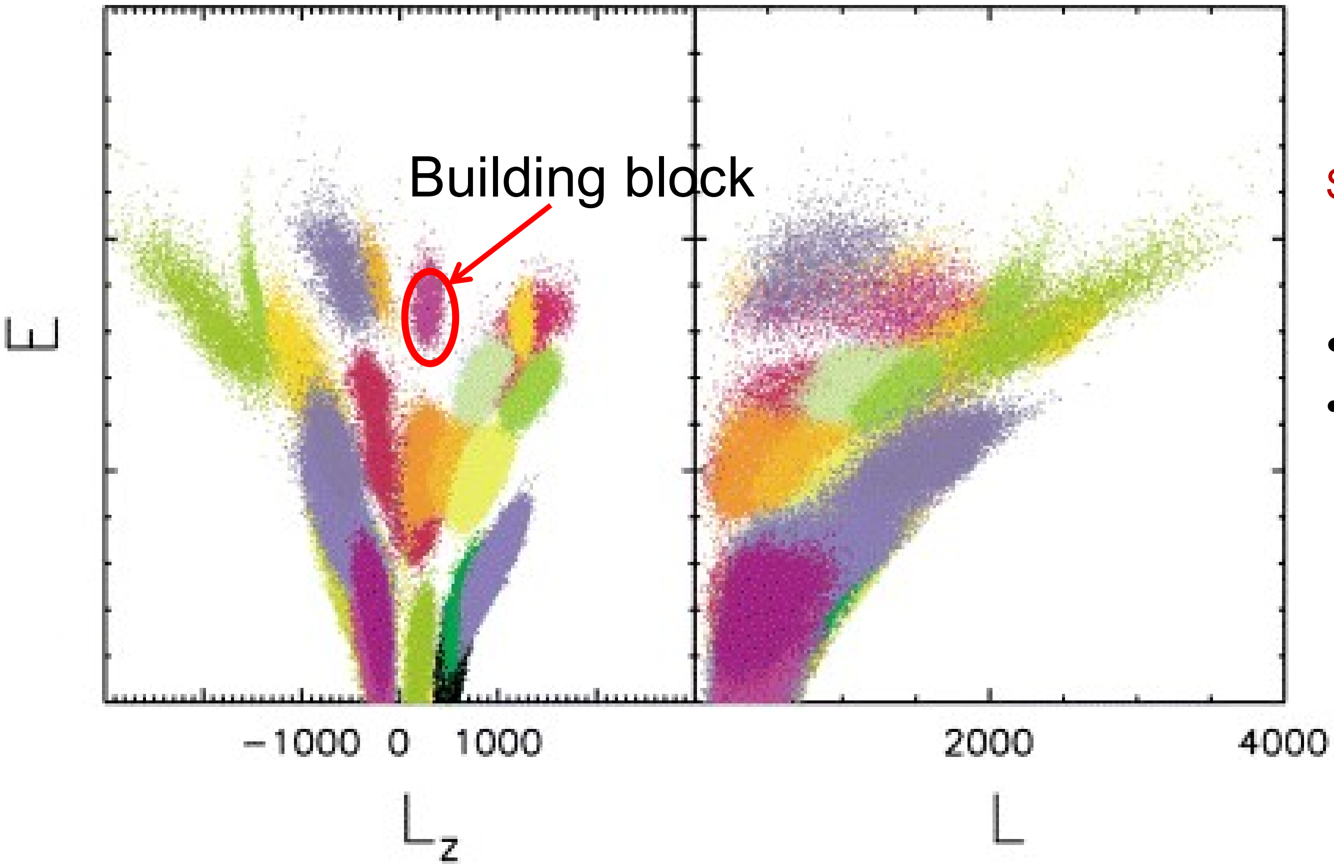
Formation of stellar streams (by tidal force)





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_{rad} & [Fe/H]

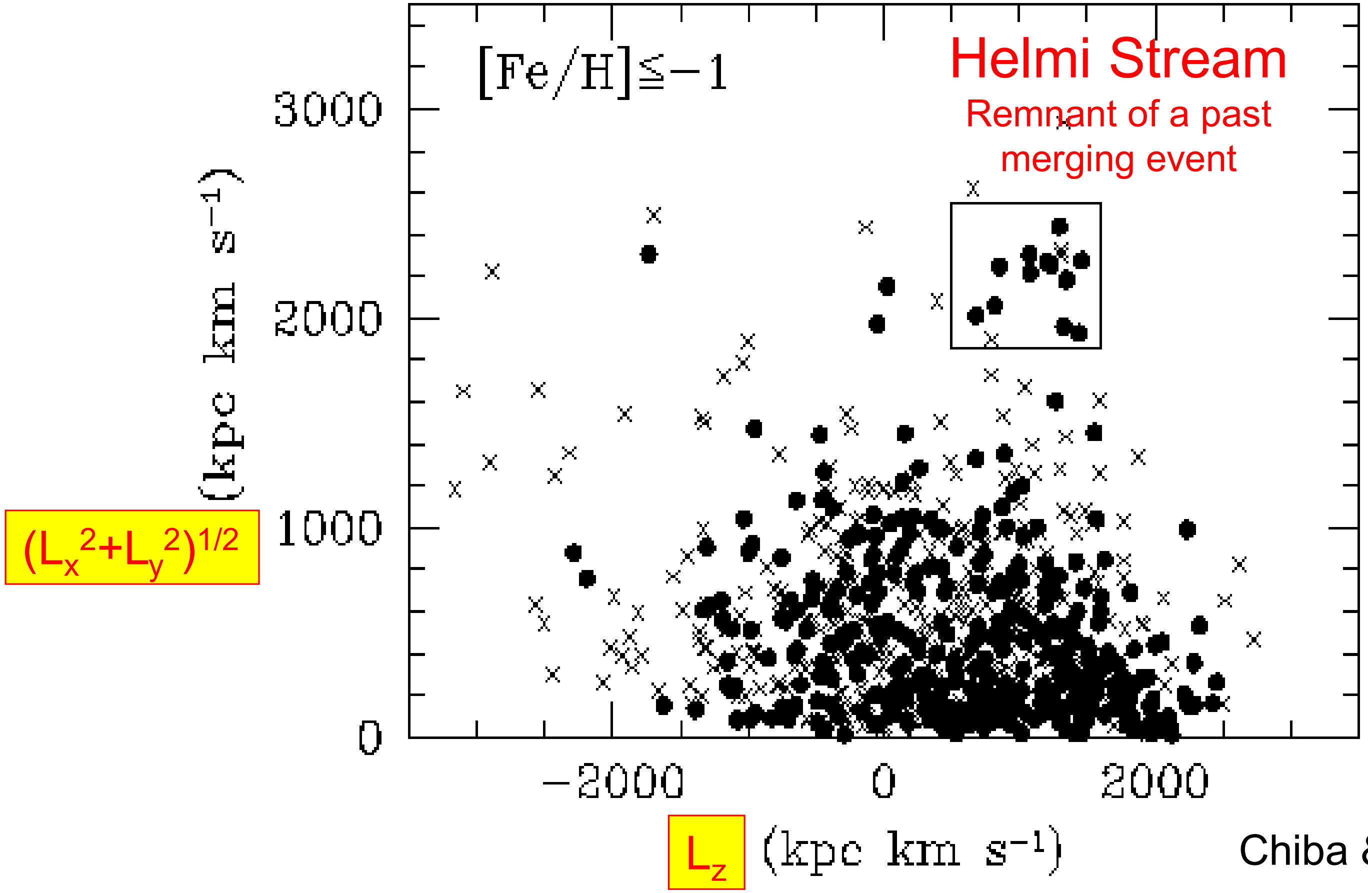
- distinguish each substructure
- SF & Chemical evolution

Helmi & de Zeeuw 00

Substructure in the stellar halo

Nearby stars in angular-momentum space

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

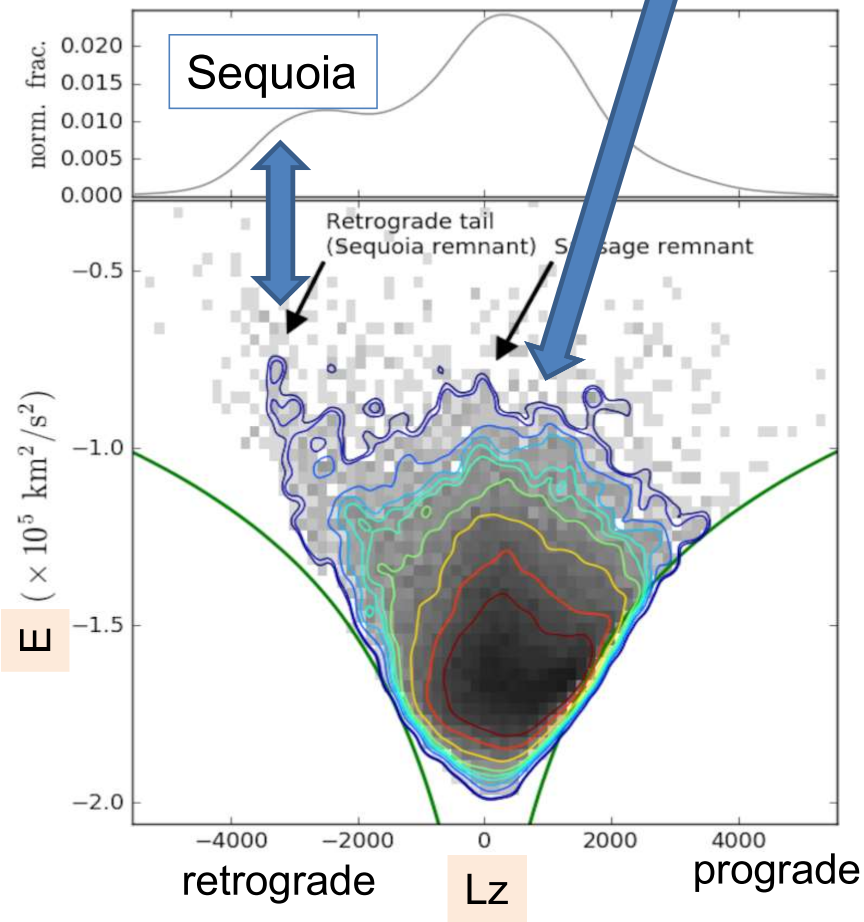


Chiba & Beers 2000

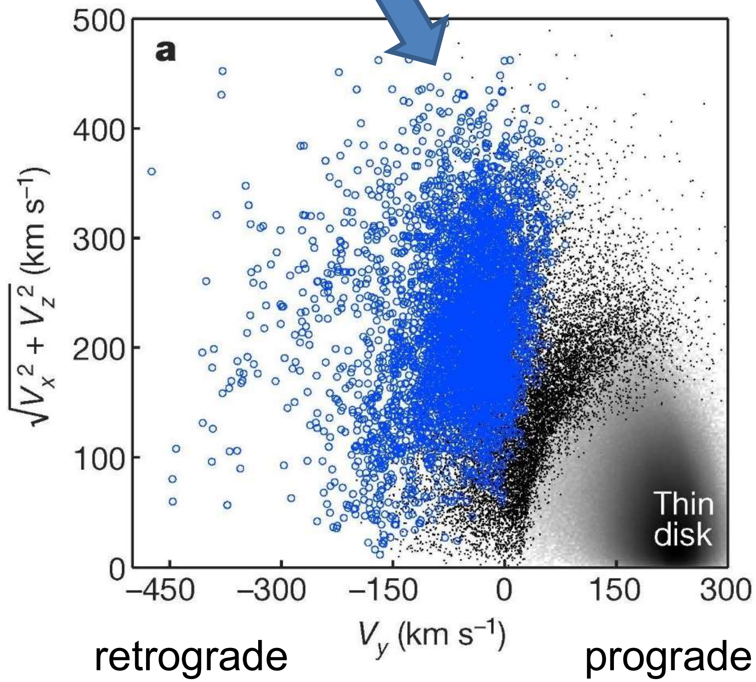
4. Formation of the stellar halo: after Gaia

Gaia-Enceladus/Sausage

Myeong et al. 2019



Helmi et al. 2018, Nature



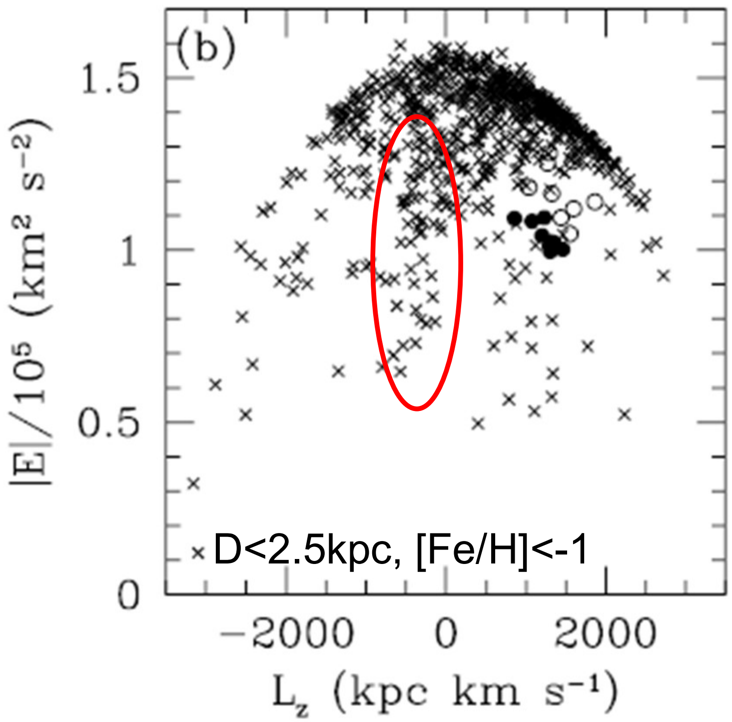
Merging debris of an SMC-class dwarf galaxy 10 Gyrs ago?

Another story …

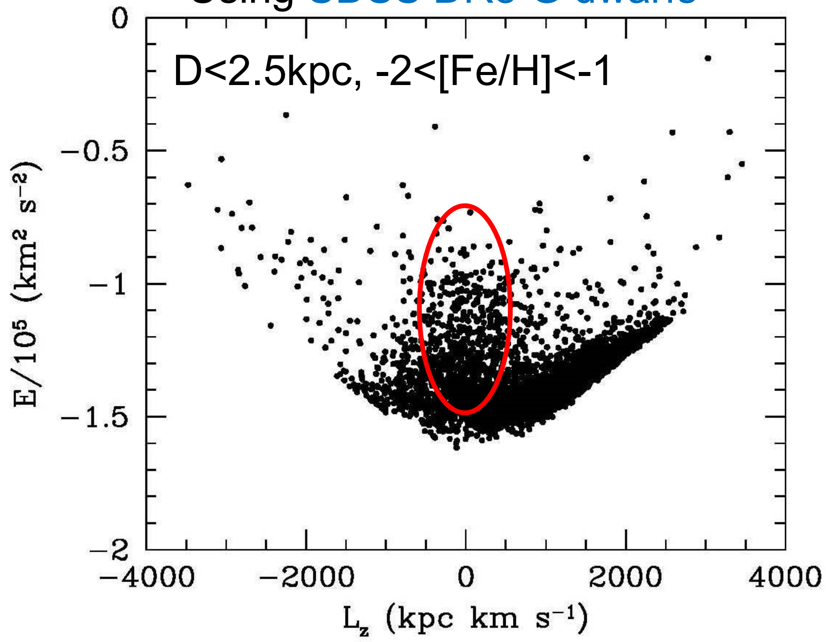
Hipparcos+SDSS-Enceladus?

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

Chiba & Beers 2000
Using Hipparcos sample



Chiba 2012 (IAP conf. poster)
Using SDSS DR8 G dwarfs



This feature was thought to be a tidal remnant of a dSph containing ωCen

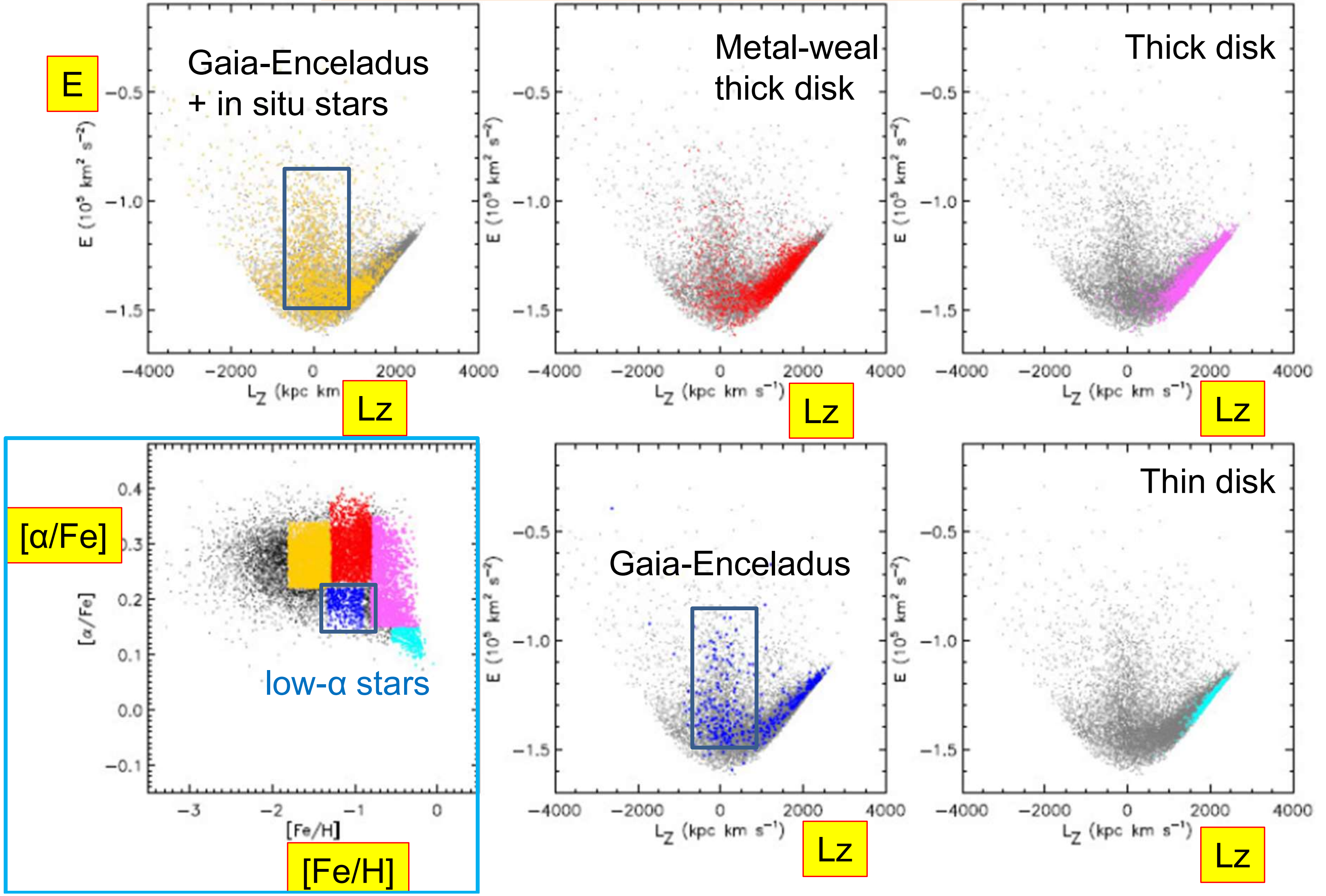
Merging of a dwarf galaxy 10 Gyrs ago?
Gaia-Enceladus

Credit: A. Helmi

Abundance ratios of Gaia-Enceladus

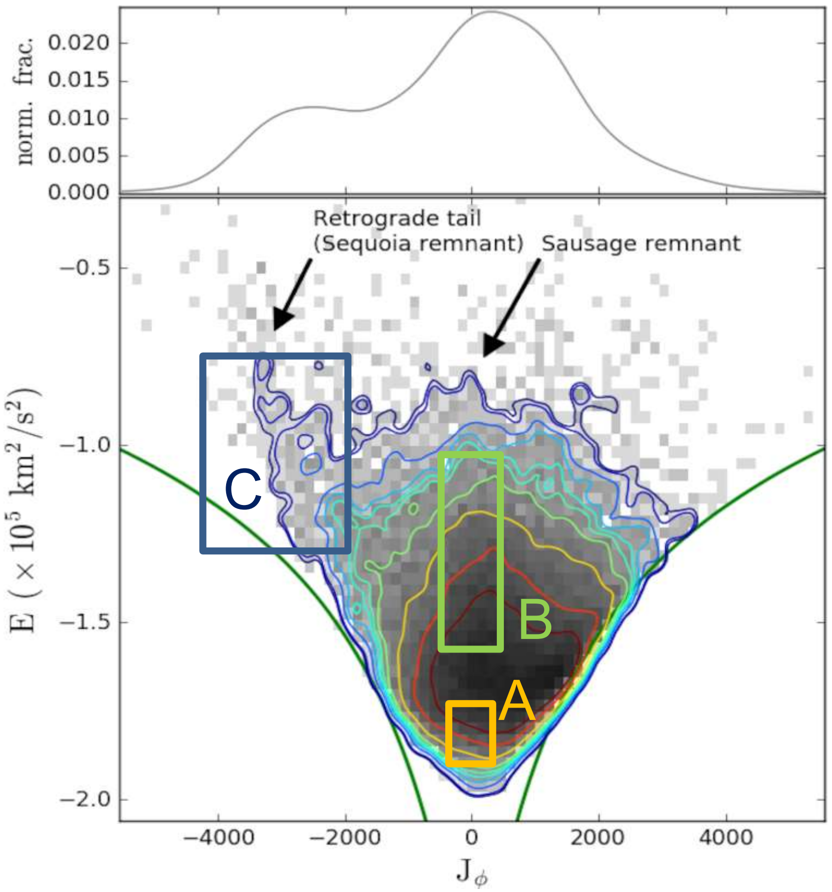
SDSS-DR7 Calibration Stars + Gaia DR2

Carollo & Chiba 2021

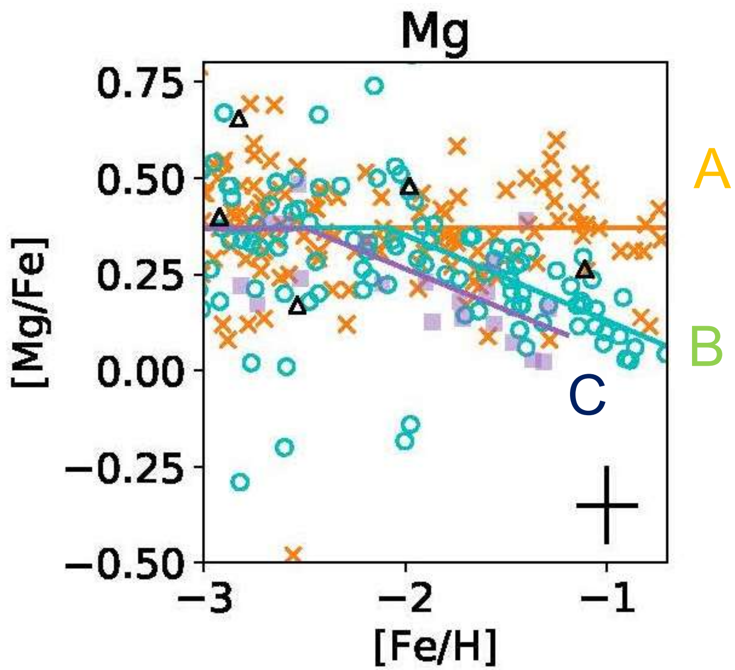


Abundance ratios

Myeong et al. 2019



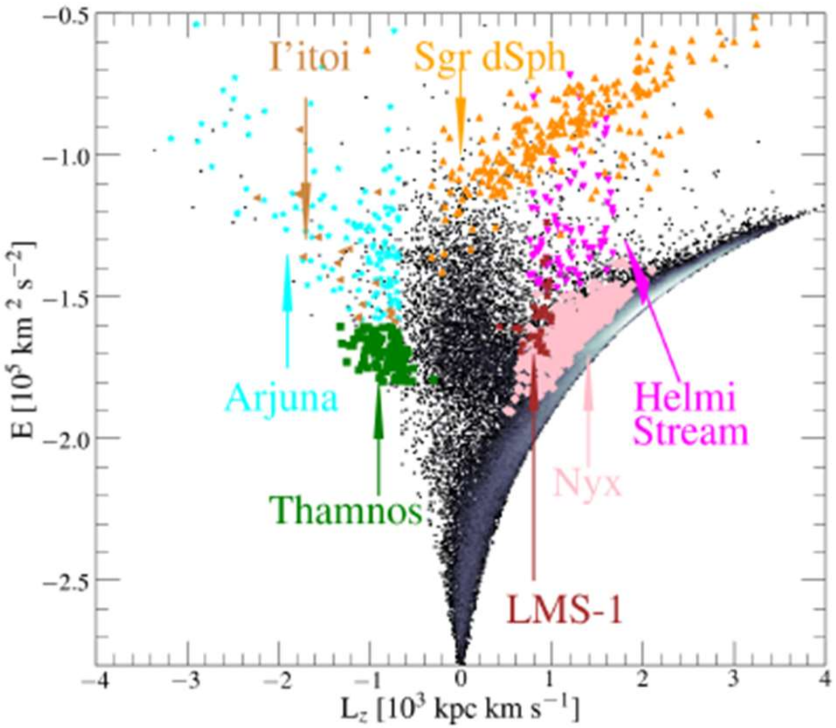
Matsuno et al. 2019
using SAGA & LAMOST

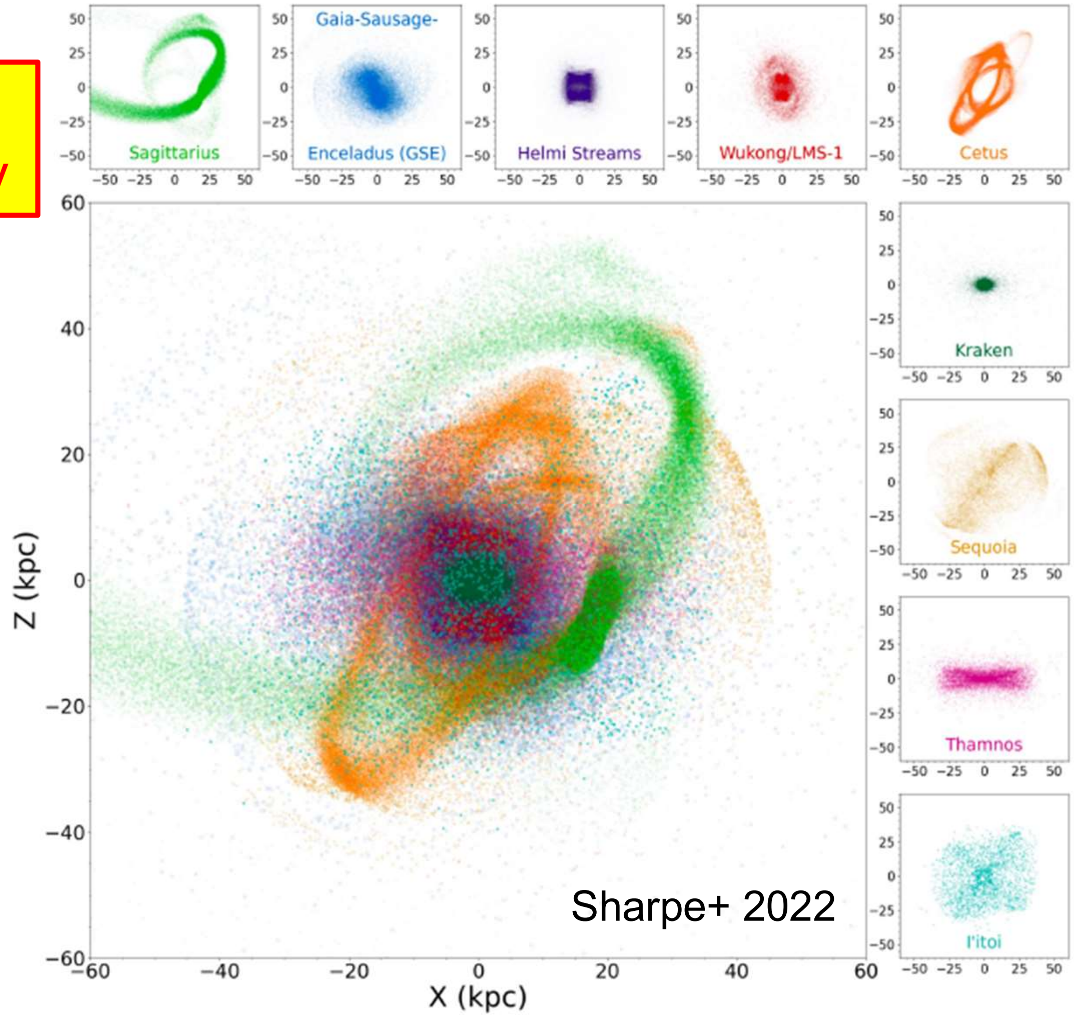


Deciphering merging history of the Galaxy

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

Horta+ 2022





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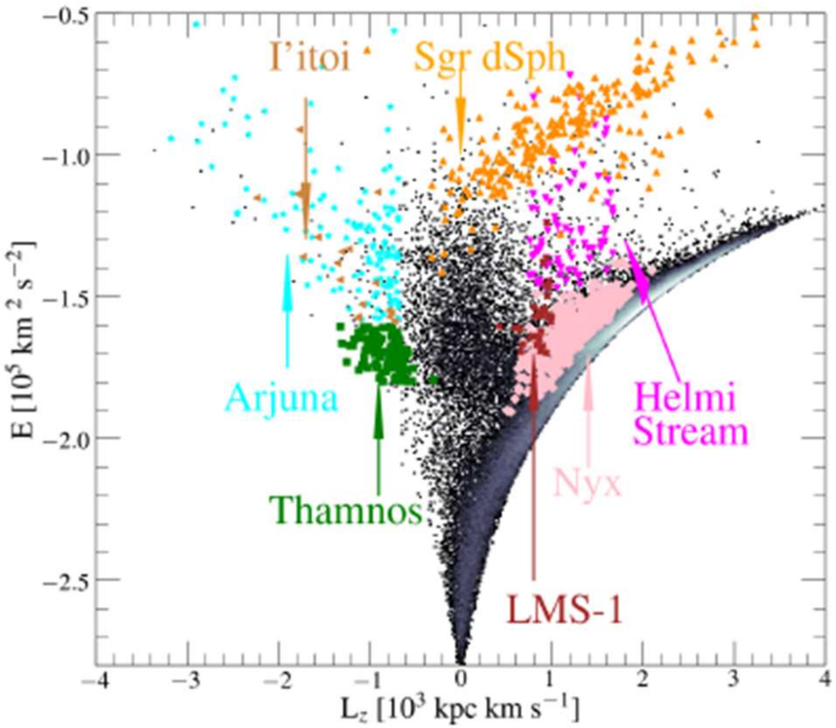
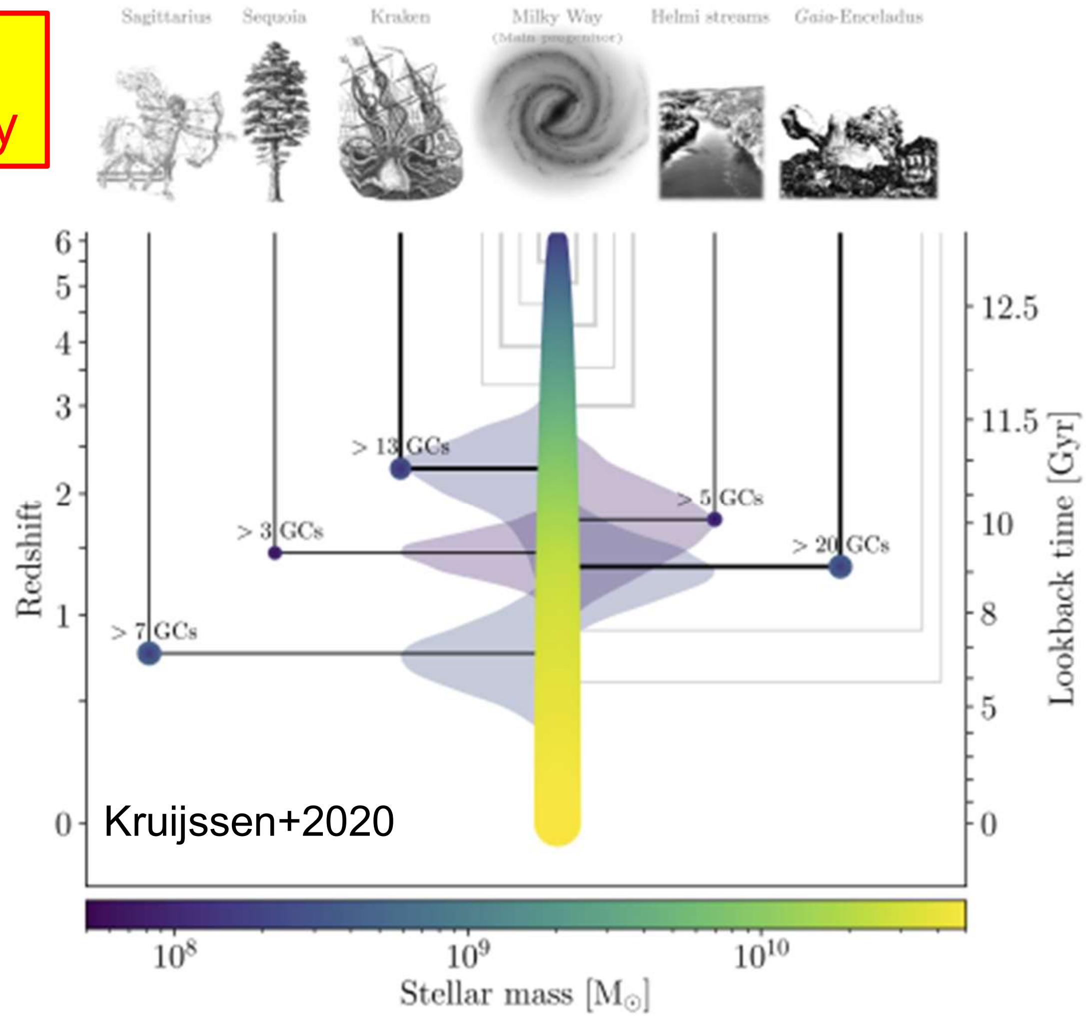
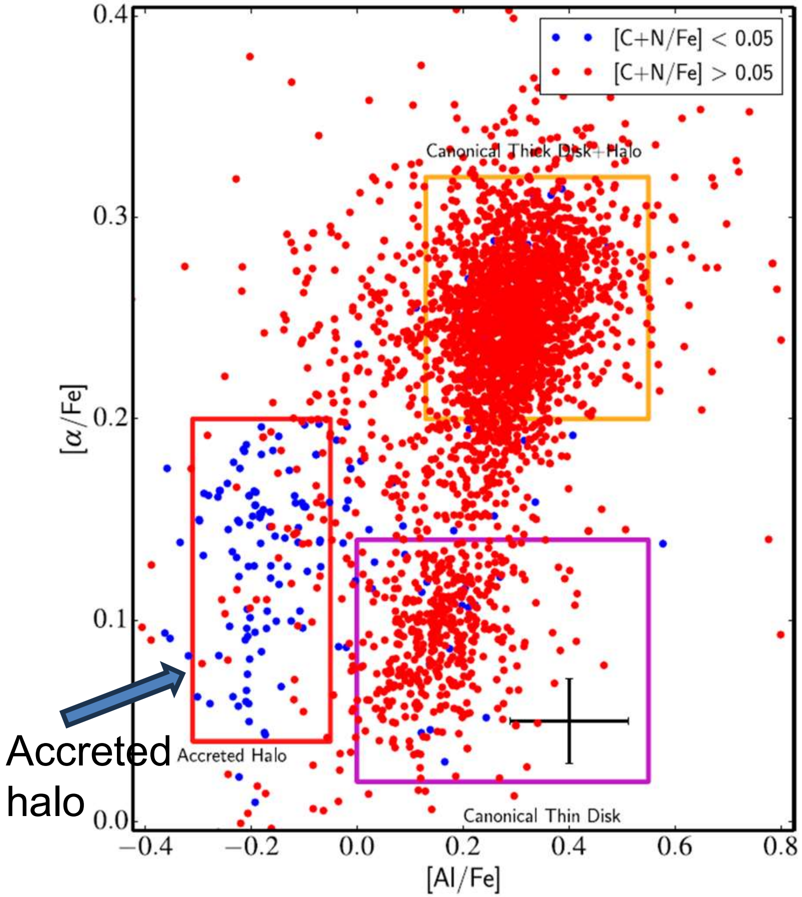
Horta+ 2022



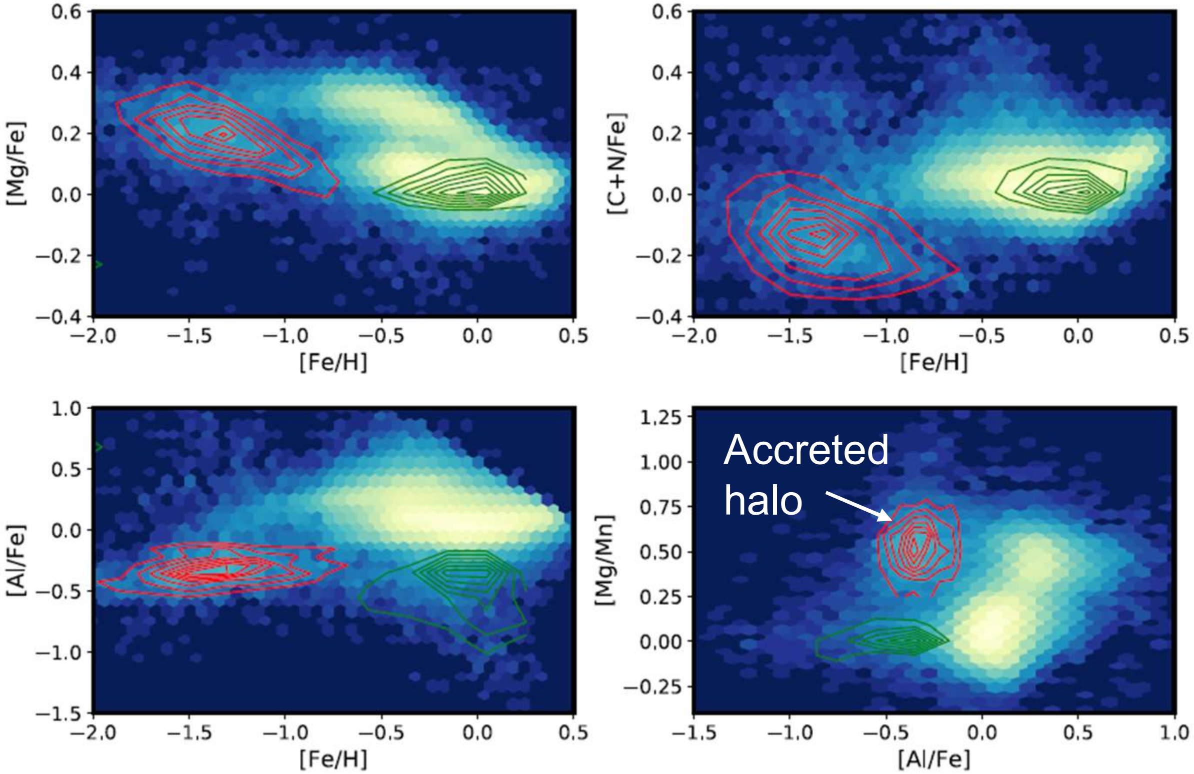


[Al/Fe] as an indicator of accreted/in situ halo

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



Das et al. 2020 (APOGEE DR14)

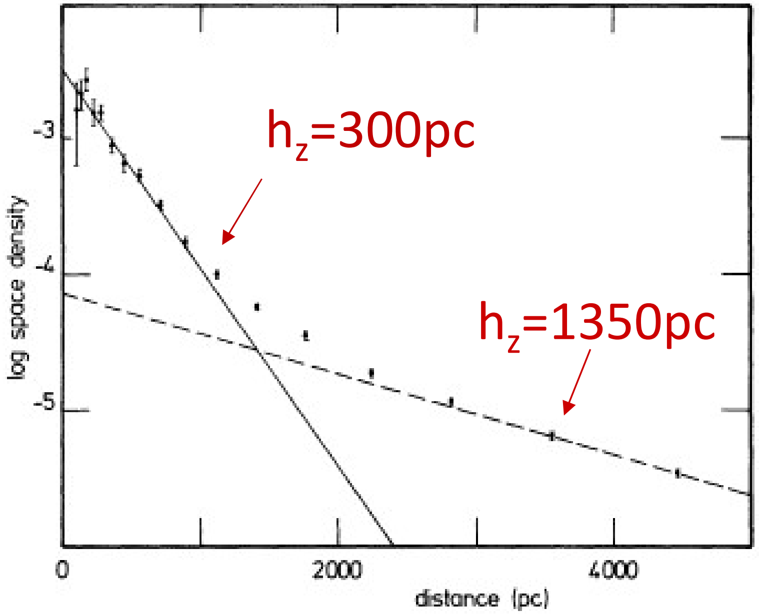


Al from SNII and is sensitive to initial C+N abundance

5. Formation of the thick disk

Star counts toward the SGP

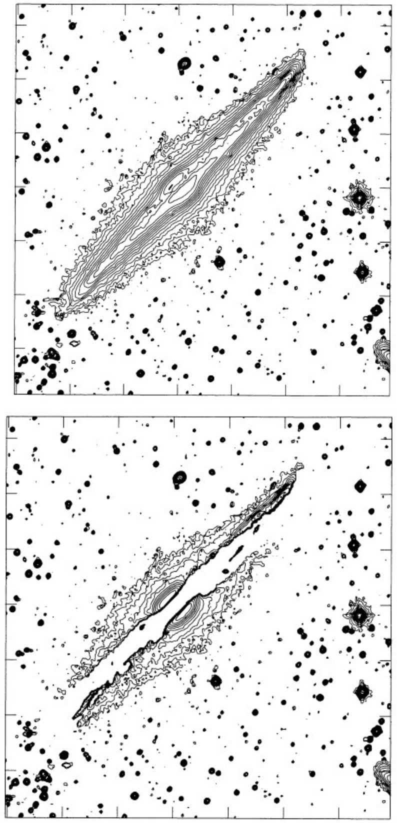
Gilmore & Reid 1983



ρ_{thick}~2%ρ_{thin}

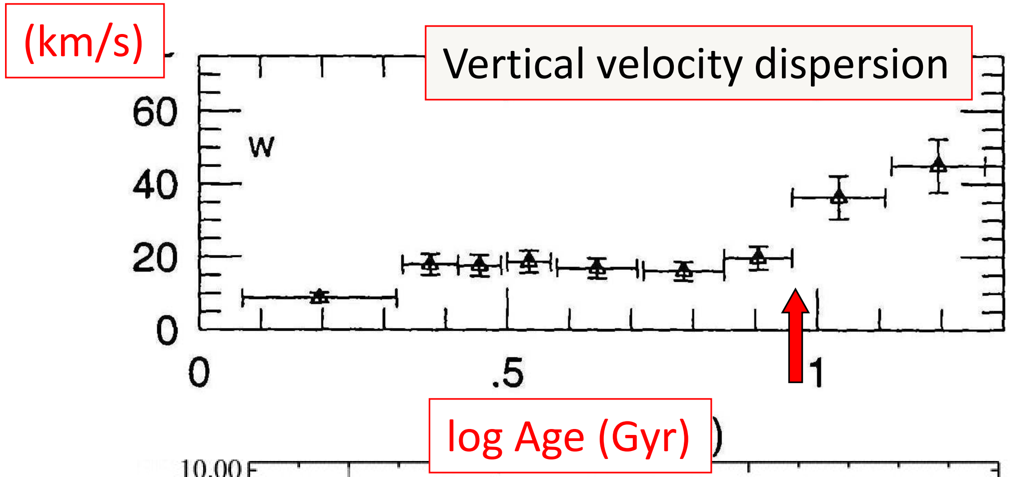
Luminosity distribution of NGC4565

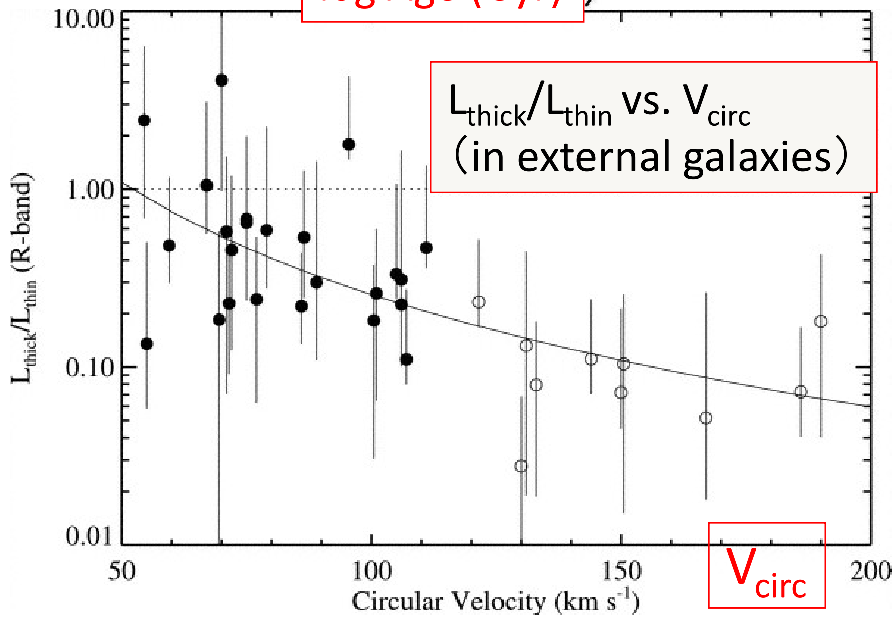
Van der Kruit & Seale 1981



Thick disk(s)

- **Milky Way thick disk**
  - ✓ distinct kinematics, chemistry, and age: <u>independent Galactic component</u>
  - ✓ dynamically hot, large scale height, [Fe/H]~ -0.6, old age (~10Gyr)
- **Extra-galactic thick disks**
  - ✓ common in disk galaxies
  - ✓ relatively old and metal poor

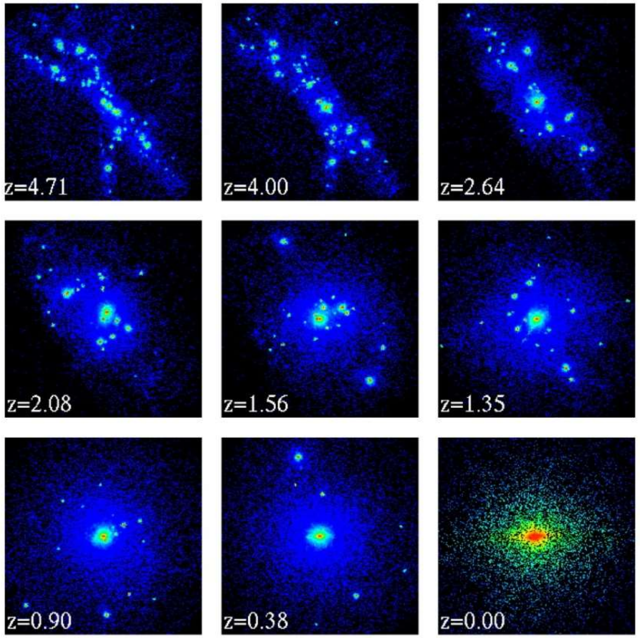




Formation scenarios of the thick disk

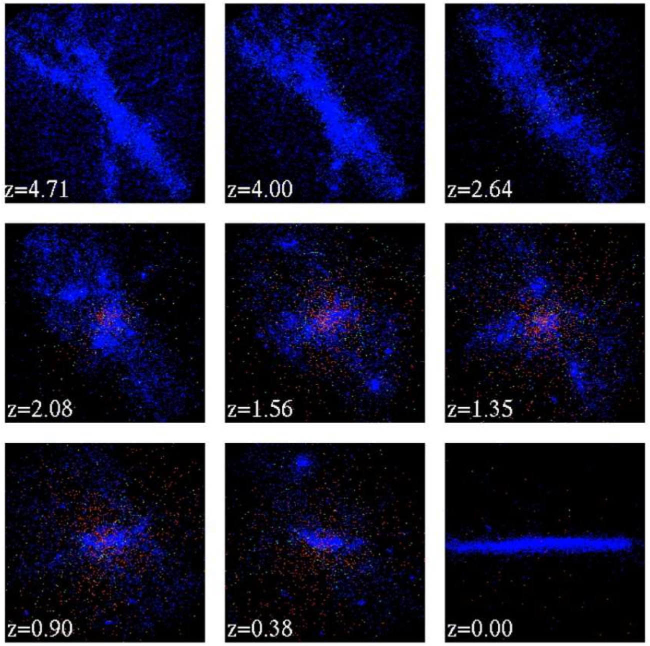
① Dissipative collapse (Burkert+1992)
② Direct accretion of thick-disk material (Abadi+200s)
③ Multiple mergers (Brook+2004, 2005)
④ Dynamical heating of a pre-existing thin disk by satellites or subhalos (Quinn+1993; Veláquez & White 1999; Hayashi & Chiba 2006; Kazantzidis+2009), by merging of Gaia-Enceladus?
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

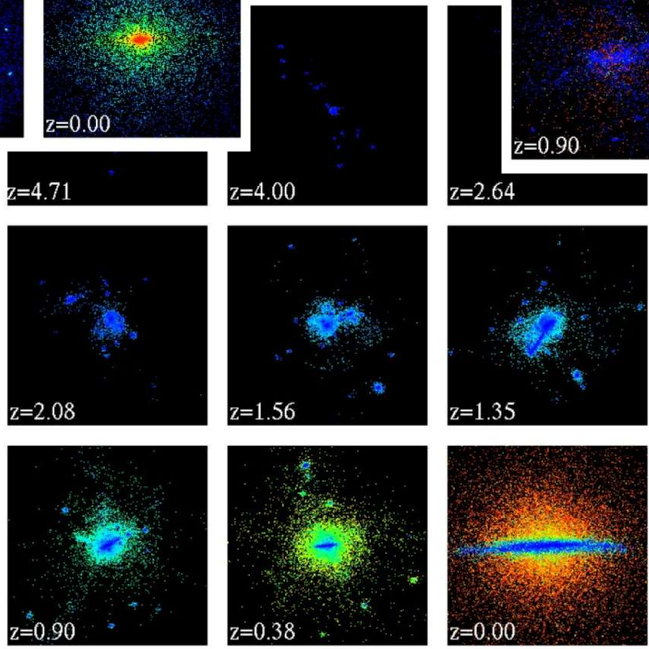


DM

Hierarchical clustering

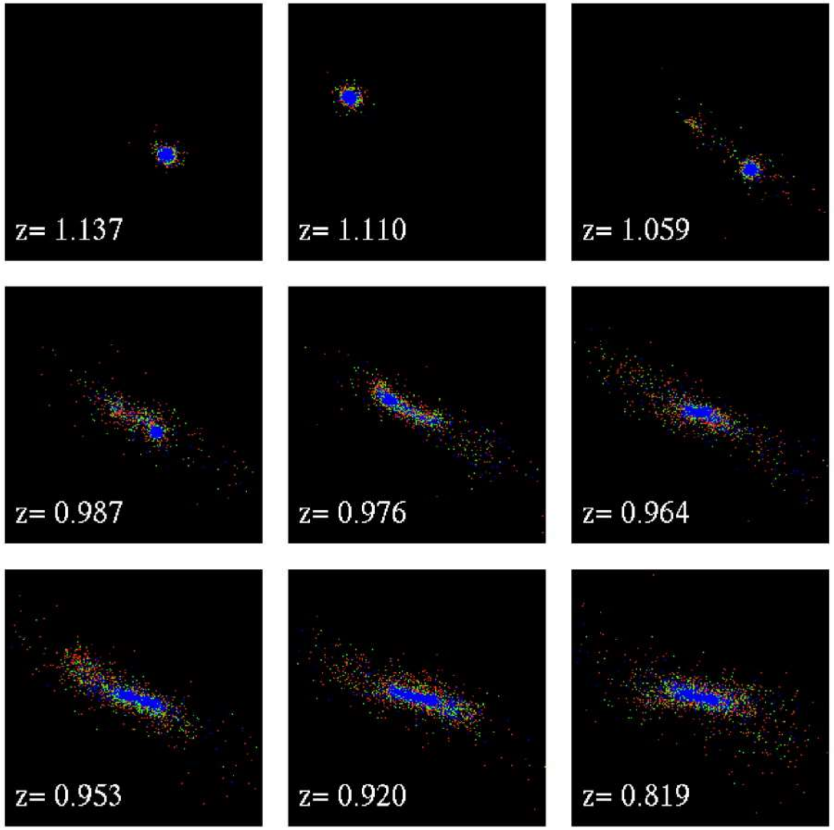


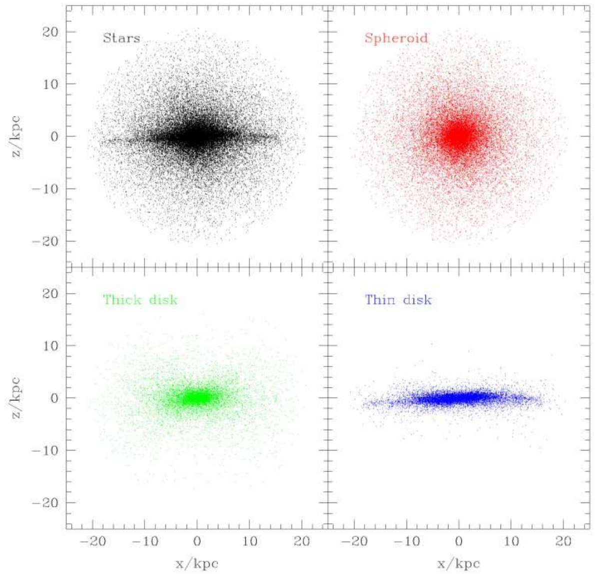
gas



stars

Shredded satellite → thick disk?

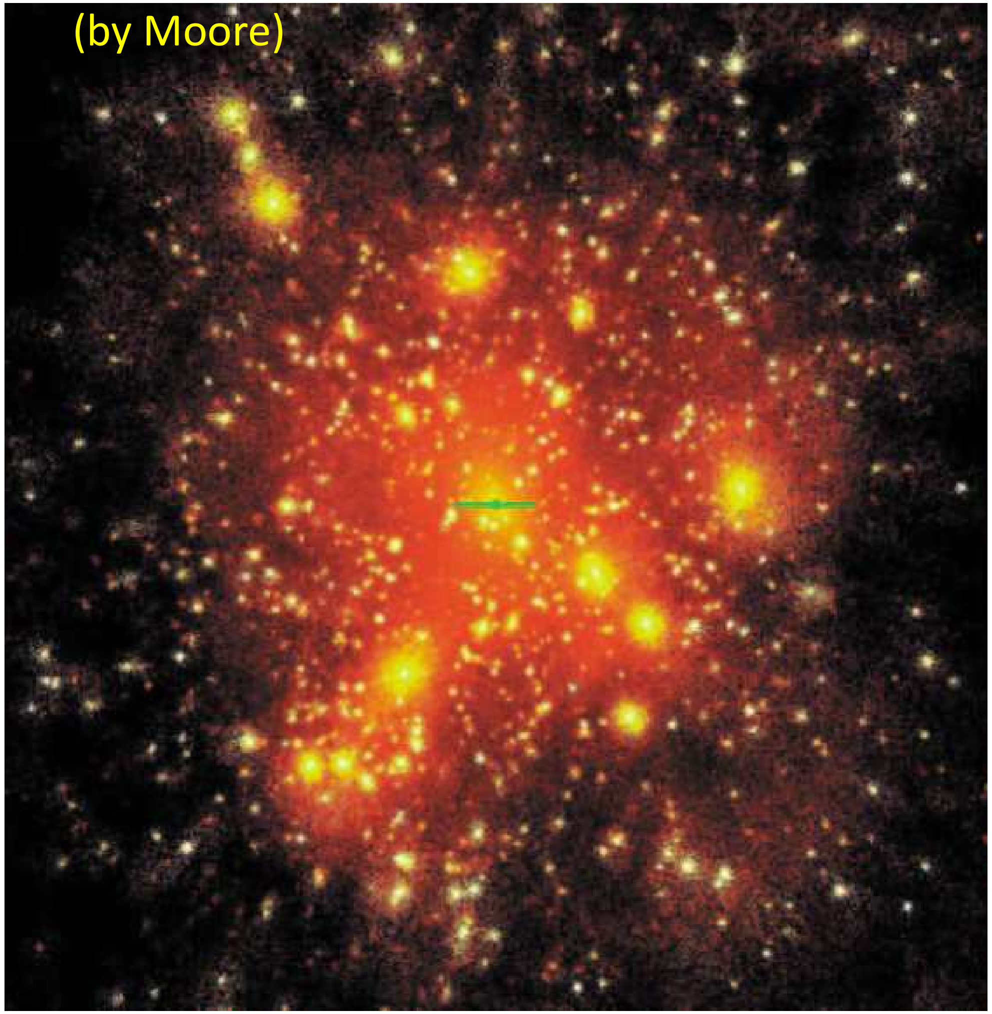


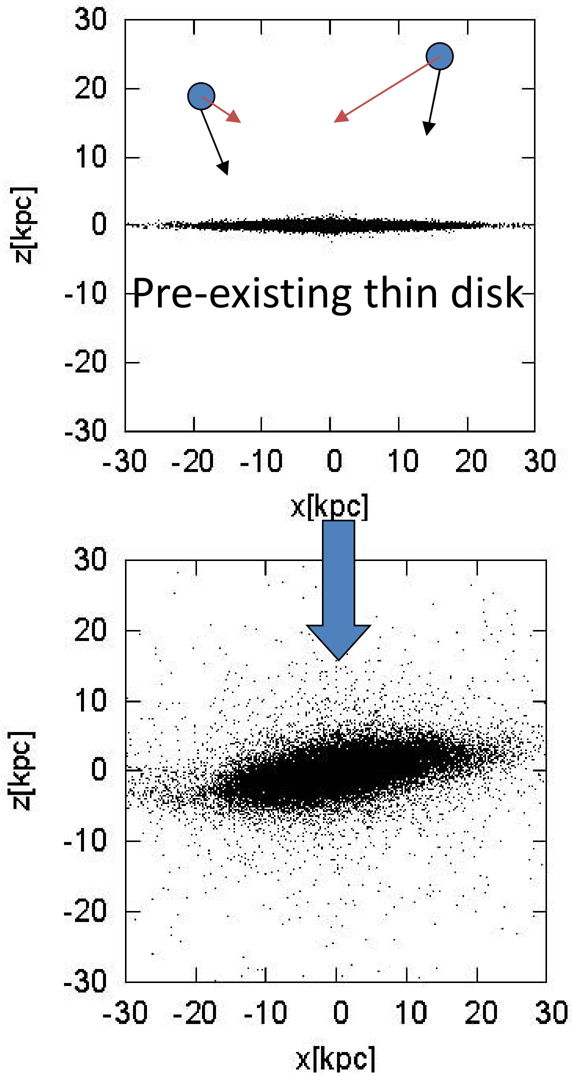


But [Fe/H] and [α/Fe] in satellites are very different from those in the thick disk.

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

Distribution of dark halos in a galactic scale

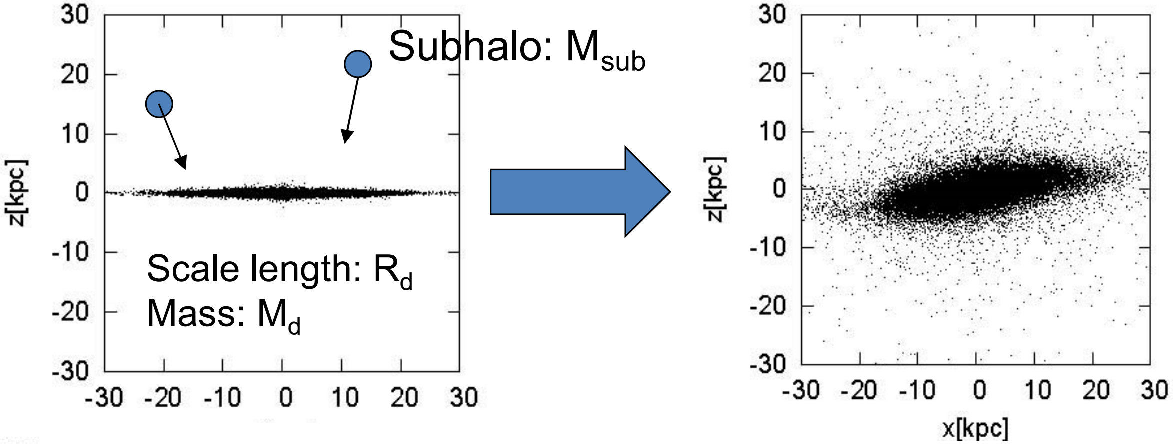




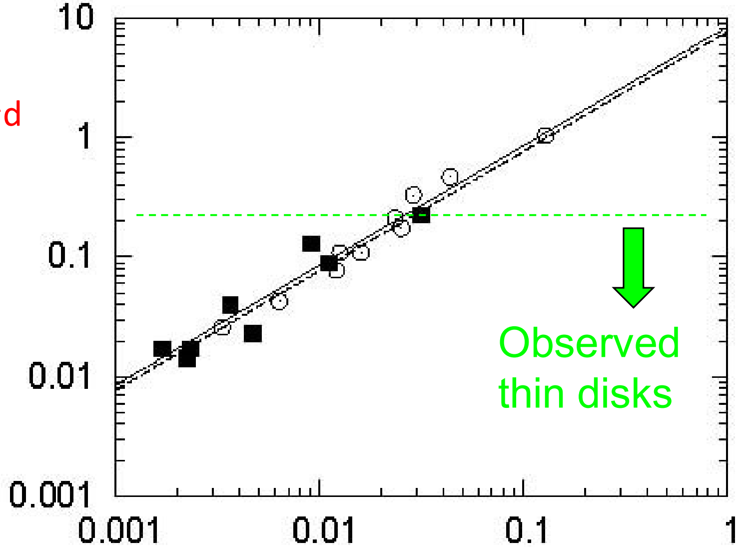
Numerical simulation of disk heating

(Hayashi & Chiba 2006)

Scale height: Z_d



$\Delta Z_d / R_d$



$\sum(M_{sub,j} / M_d)^2$

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

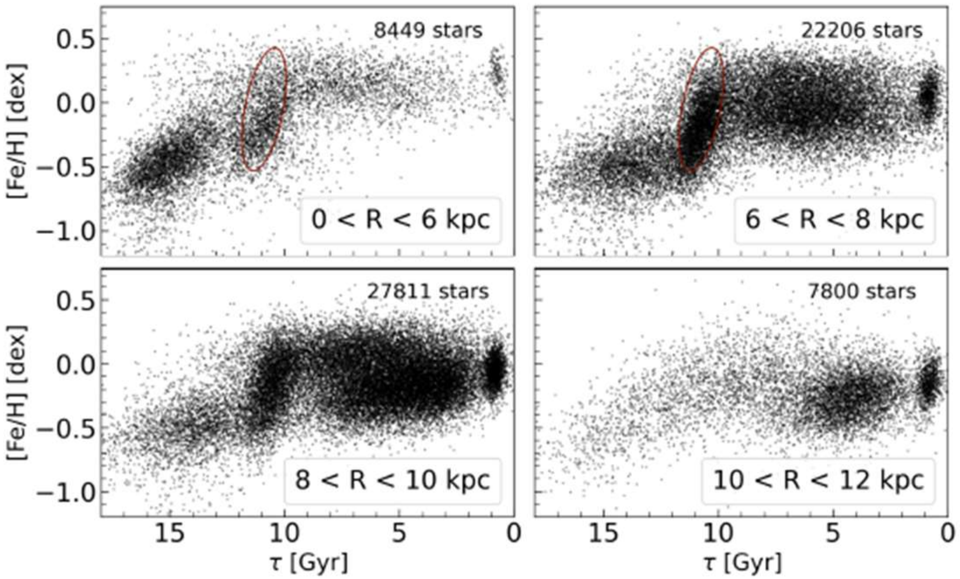
Observed thin disks: $Z_d / R_d < 0.2$
(Kregel et al. 2002)
⇒ accreted subhalo mass
$< 0.15\ M_d$

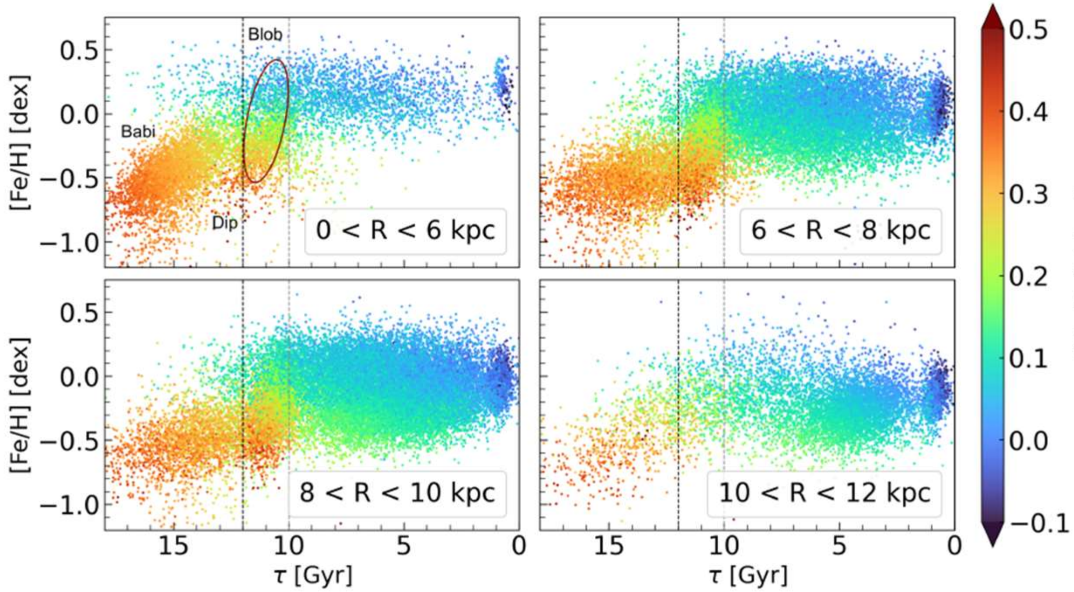
Signature for GES merger on thick disk formation

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) ⇒dilution [Fe/H]↓

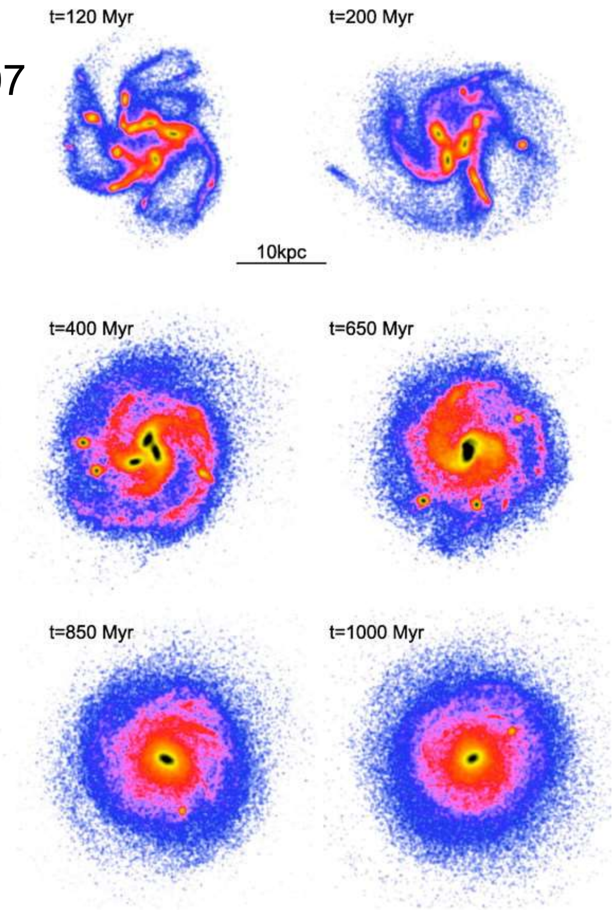
⇒SF + chemical evolution ⇒[Fe/H]↑, [Mg/Fe]↓⇒ metal-rich part of the thick disk

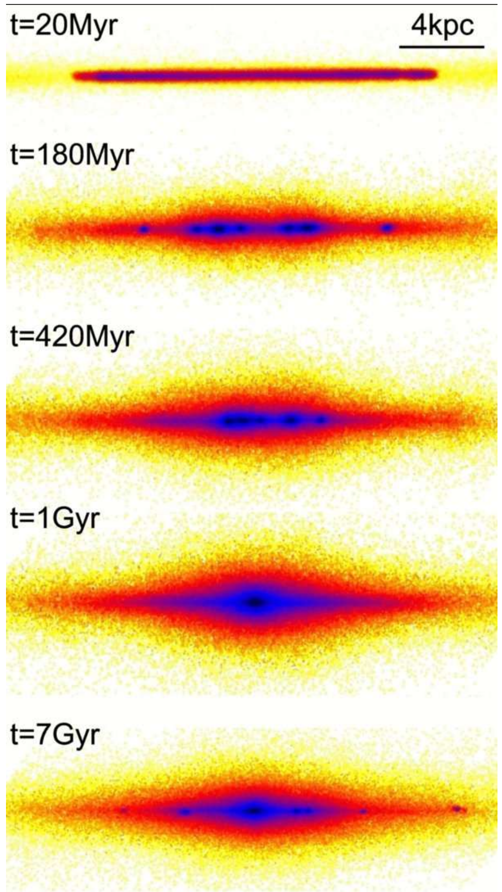
⑤. Clumpy disk evolution

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

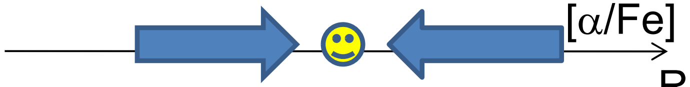
Radial migration of disk stars
(Schönrich & Binney 2009)

thick disk stars?

Stars getting L_z

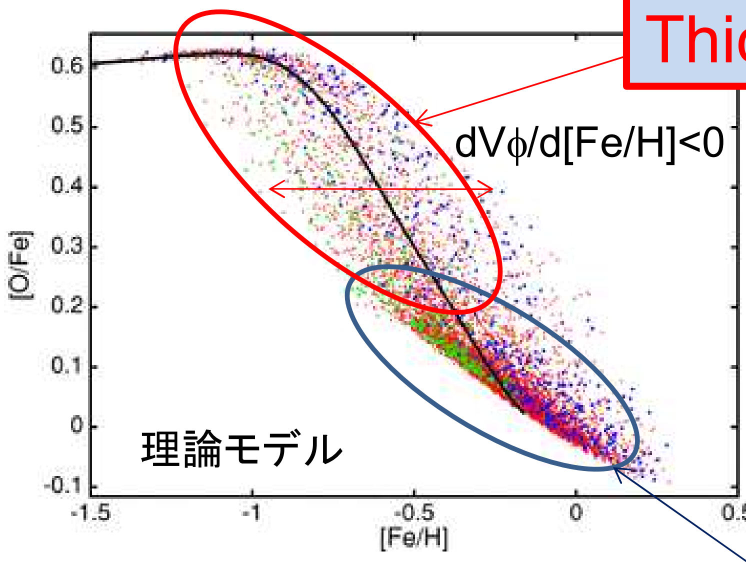
Stars losing L_z

[α/Fe] larger at larger R



transient spiral arms etc.

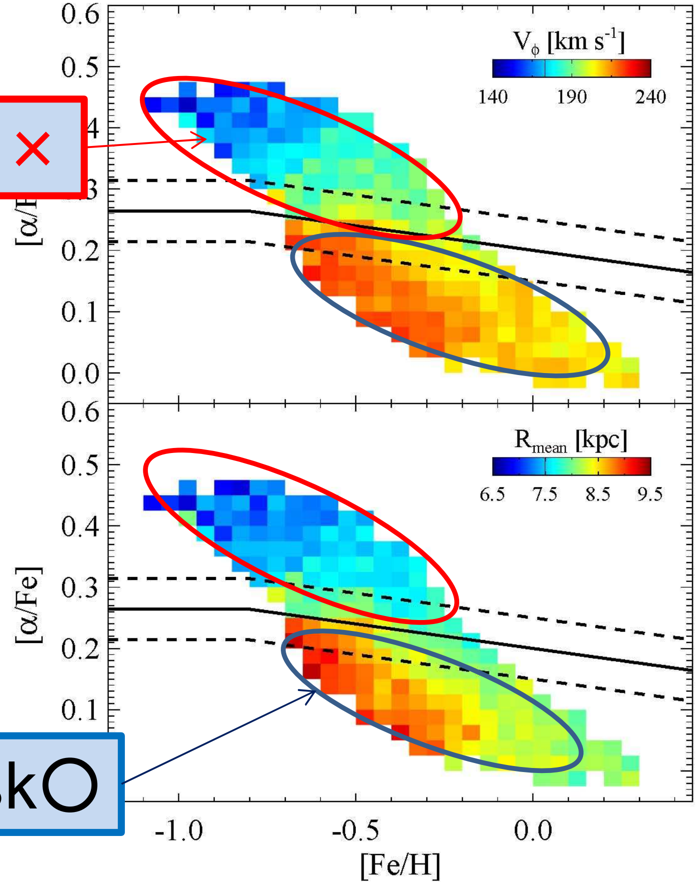
Lee+2010 SDSS sample



Vϕ < 179 km/s blue
179 < Vϕ km/s < 244 red
Vϕ > 244 km/s green

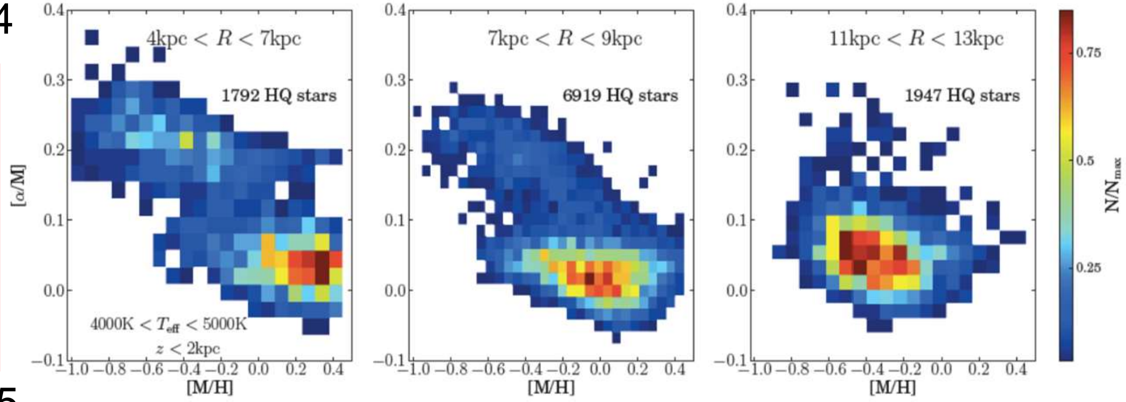
Thick disk ×

Thin disk○



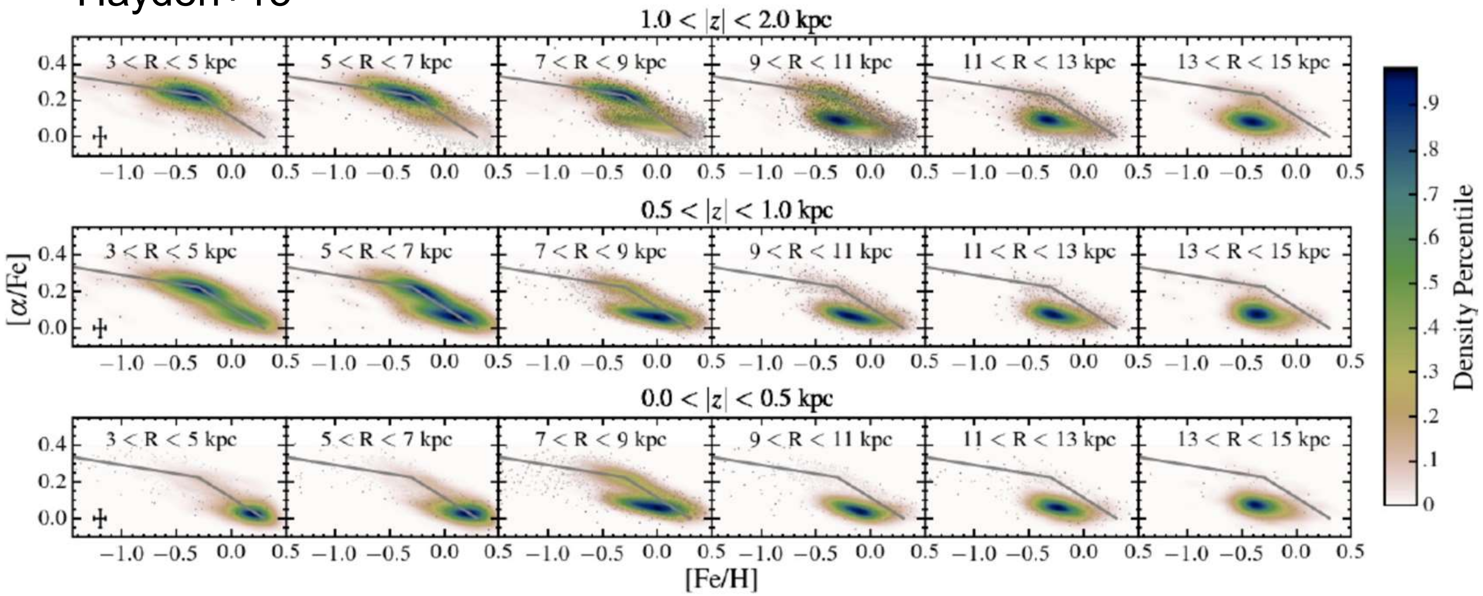
Results of SDSS/APOGEE

Anders+14

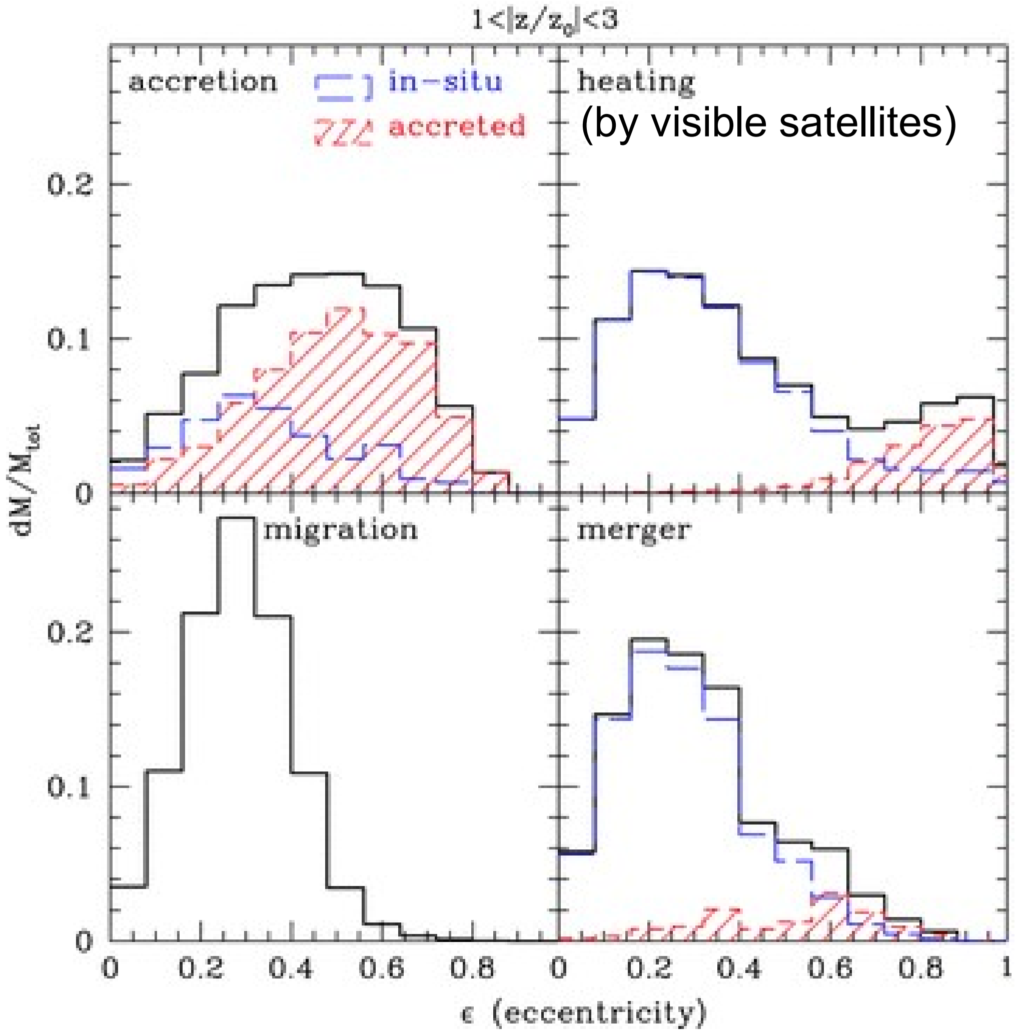


Presence of separate high [α/Fe] + low scale-length component

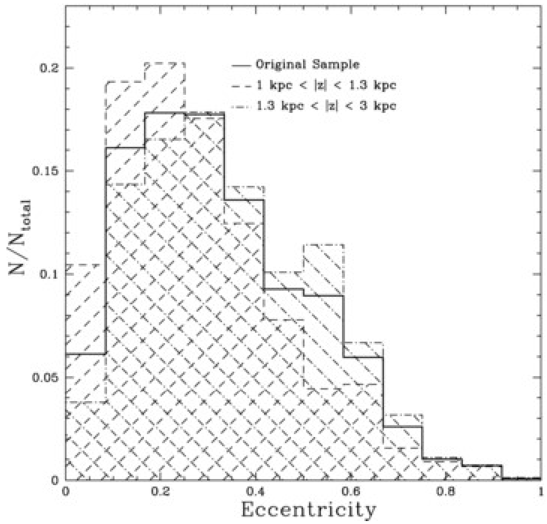
Hayden+15



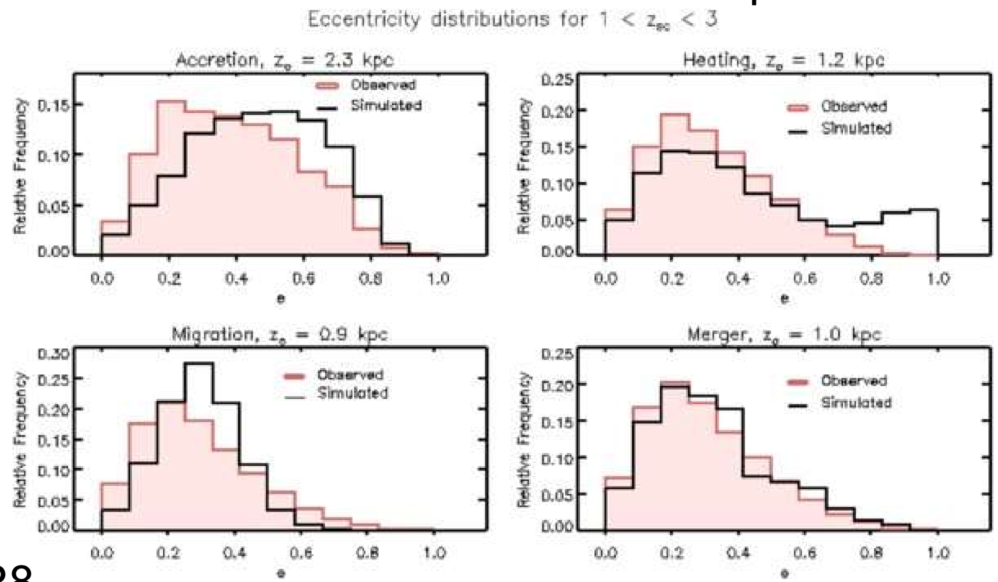
Orbital eccentricity distributions of several models
Sales+ 2009



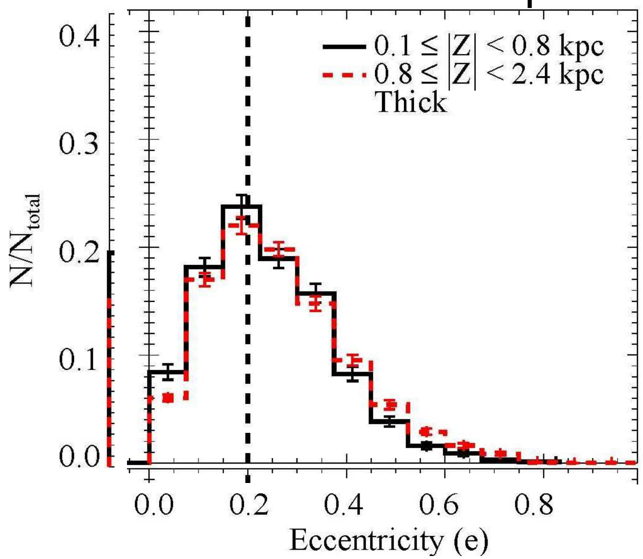
Wilson+2011: RAVE sample



Dierickx+ 2010: SDSS sample DR7



Lee+ 2011: SDSS sample DR8



Scenarios of both
- Heating by dark satellites
- Multiple mergers

are favorable.

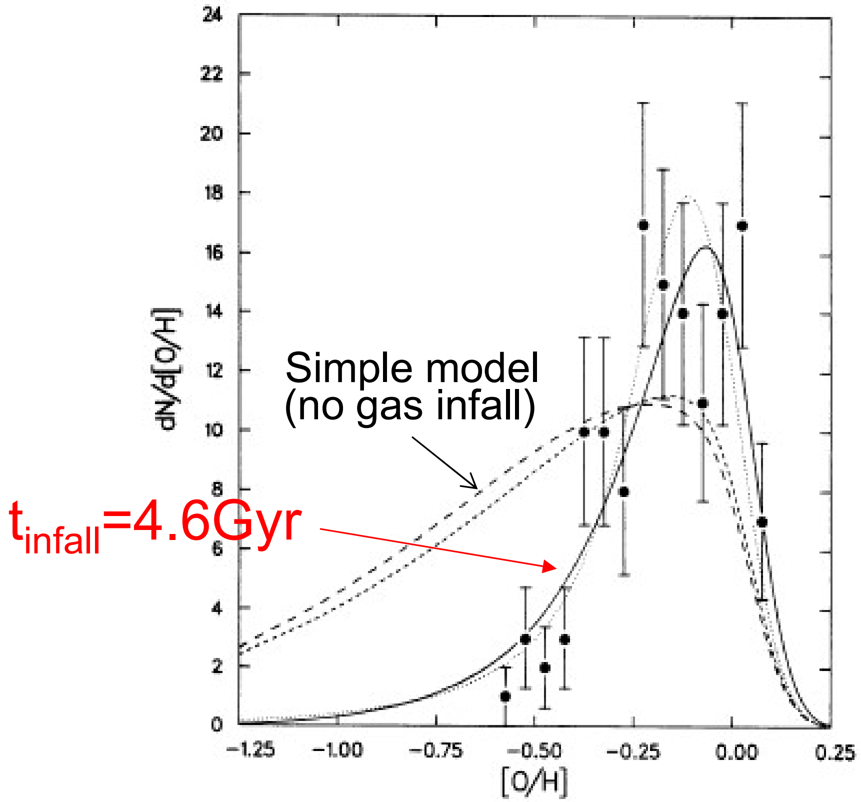
Score sheet for thick-disk formation models

Model	dVϕ/d[Fe/H]	dVϕ/dz	[Fe/H] [α/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!

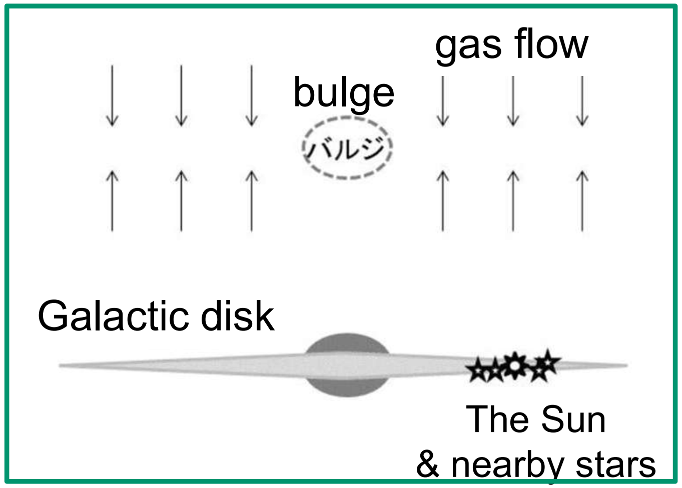
6. Formation of the thin disk

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



$d\Sigma_{gas}/dt \propto \exp(-t\ /\ t_{infall})$
t_{infall}~4-5 Gyr is required

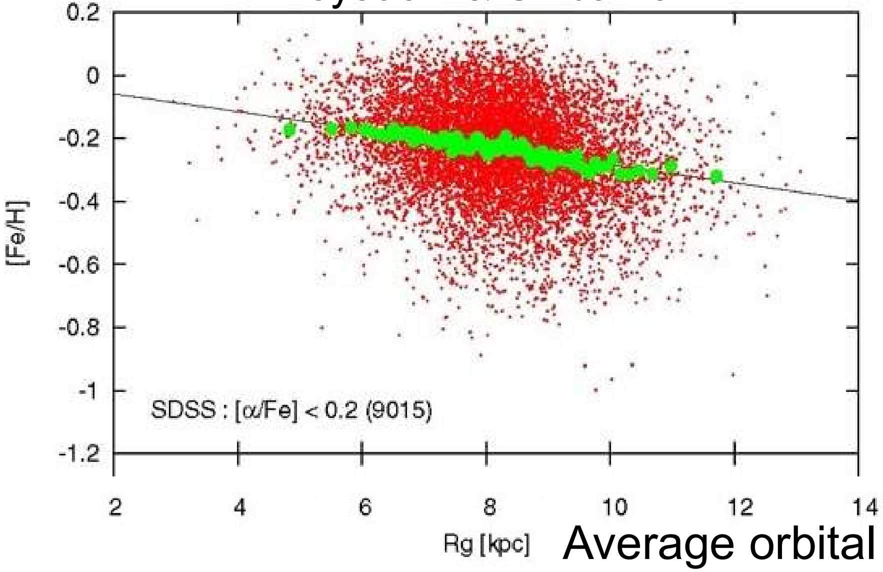
The Galactic (thin) disk formed slowly over 4-5 Gyr.



Inside-out formation of the thin disk

Toyouchi & Chiba 2014

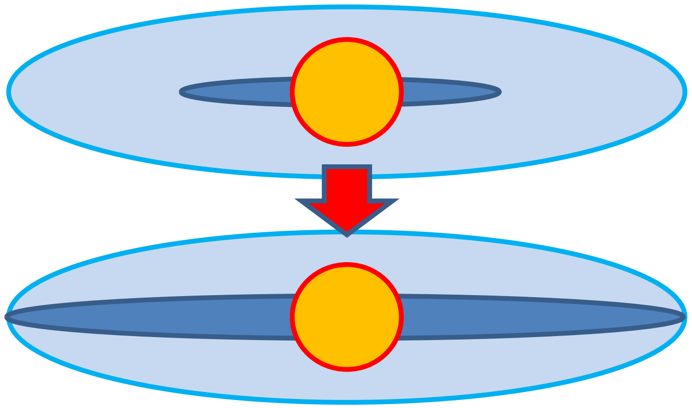
[Fe/H]



Average orbital radius (kpc)

Metallicity gradient

Star formation proceeds faster in inner radii.

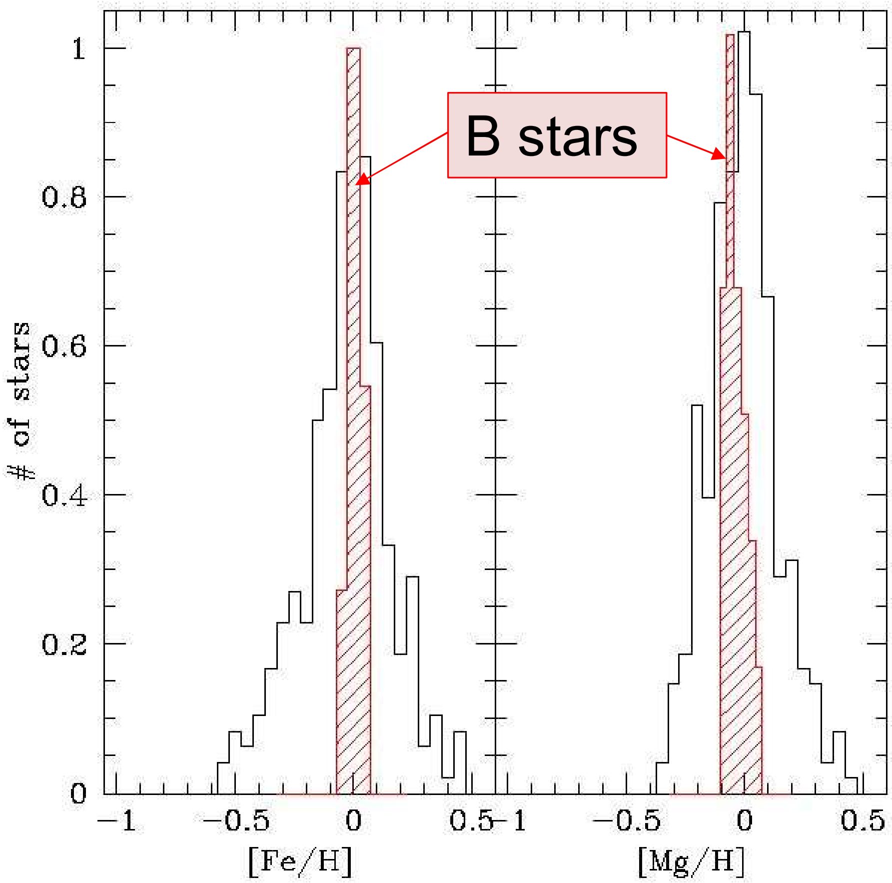


The thin disk has formed from inner to outer radii

Inside-out formation

Origin of very metal-rich stars with [Fe/H] > +0.2 near the Sun
~ Metallicity distribution of F, G dwarfs near the Sun ~

Feltzing & Chiba (2013)



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

Very meal-rich stars with [Fe/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)

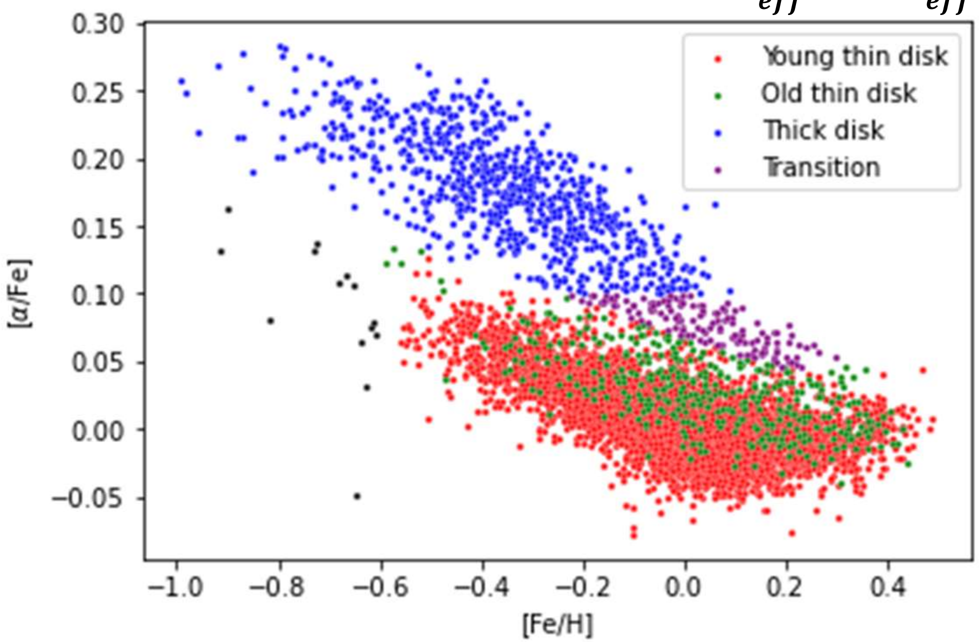
Chang

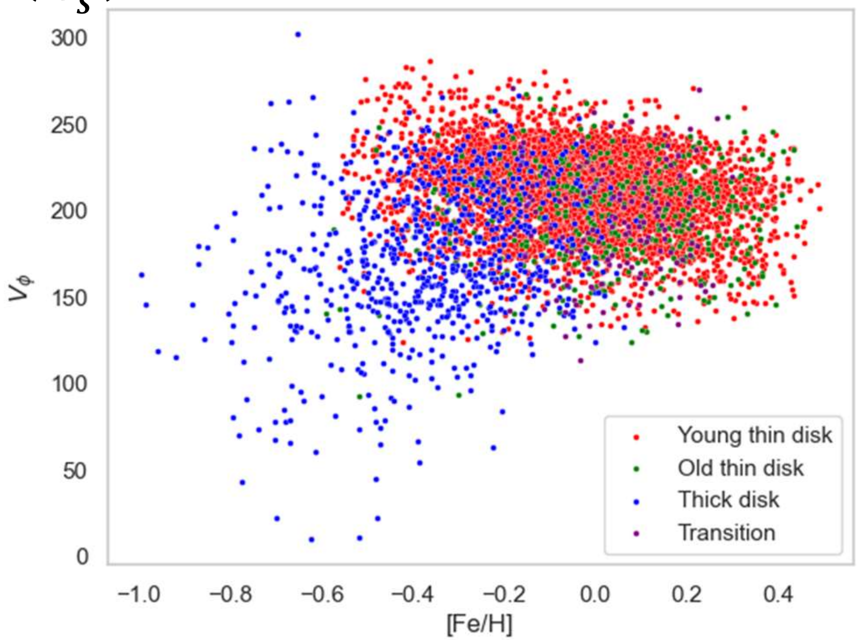
5436 RGBs & RCs (APOKASC-2, APOGEE DR16, Gaia EDR3)

Ages from Kepler seismology data (frequency -> mass -> age)

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{\frac{1}{2}} \propto \sqrt{\rho} \propto \left(\frac{R}{C_s}\right)^{-1}$$

$$\nu_{max} \propto \frac{g}{T_{eff}^{0.5}} \propto \frac{1}{T_{eff}^{0.5}}\frac{M}{R^2} \propto \left(\frac{H}{C_s}\right)^{-1}$$



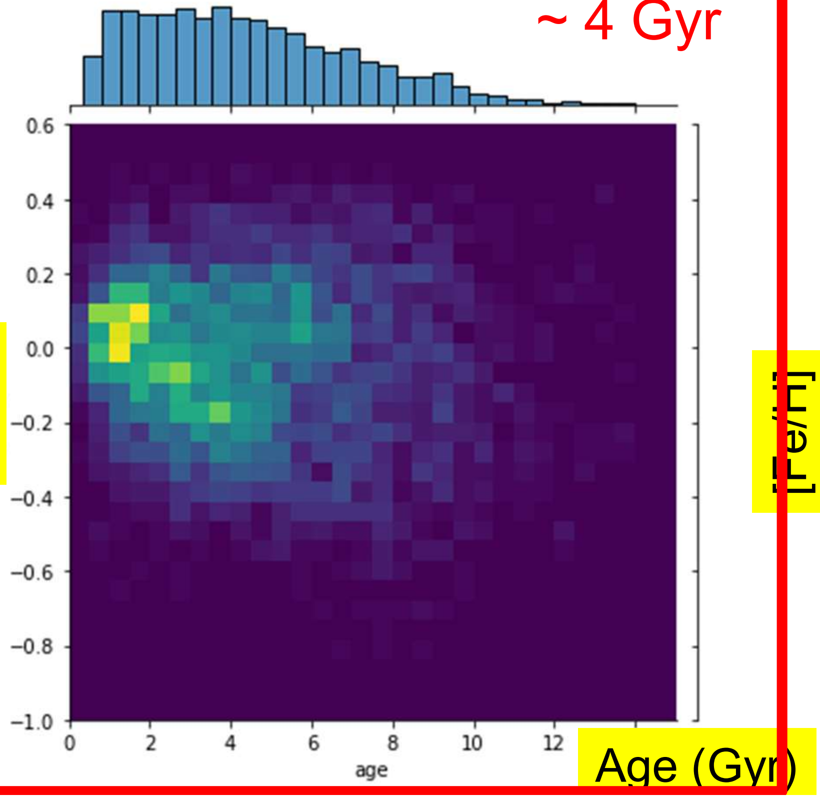


Newly derived AMR

Chang 2022 (Tohoku Univ.)

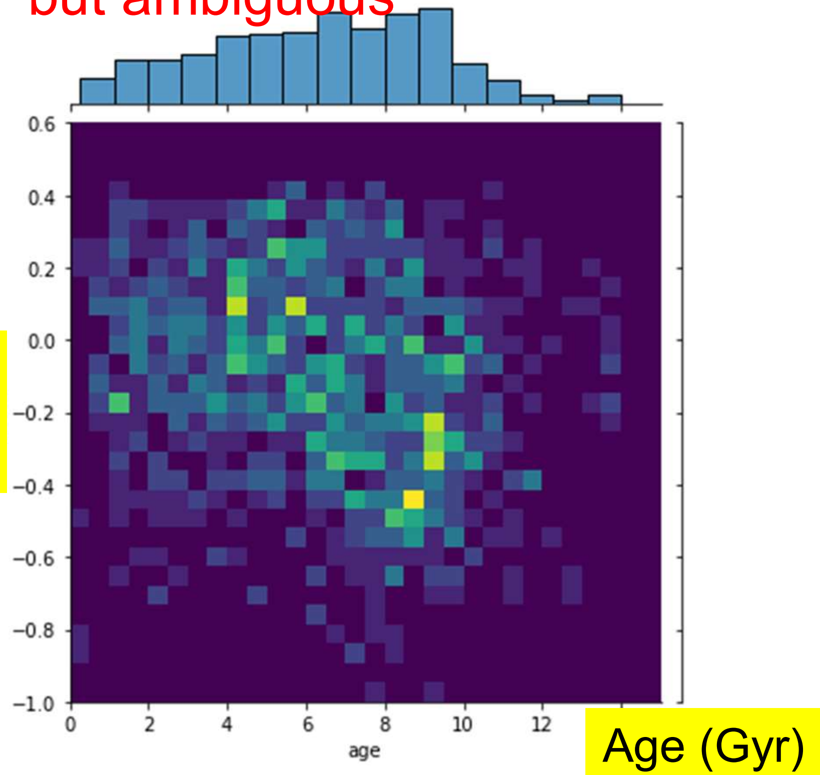
Pop B (thin disk stars)

Peak at ~ 2 Gyr + extended to ~ 4 Gyr



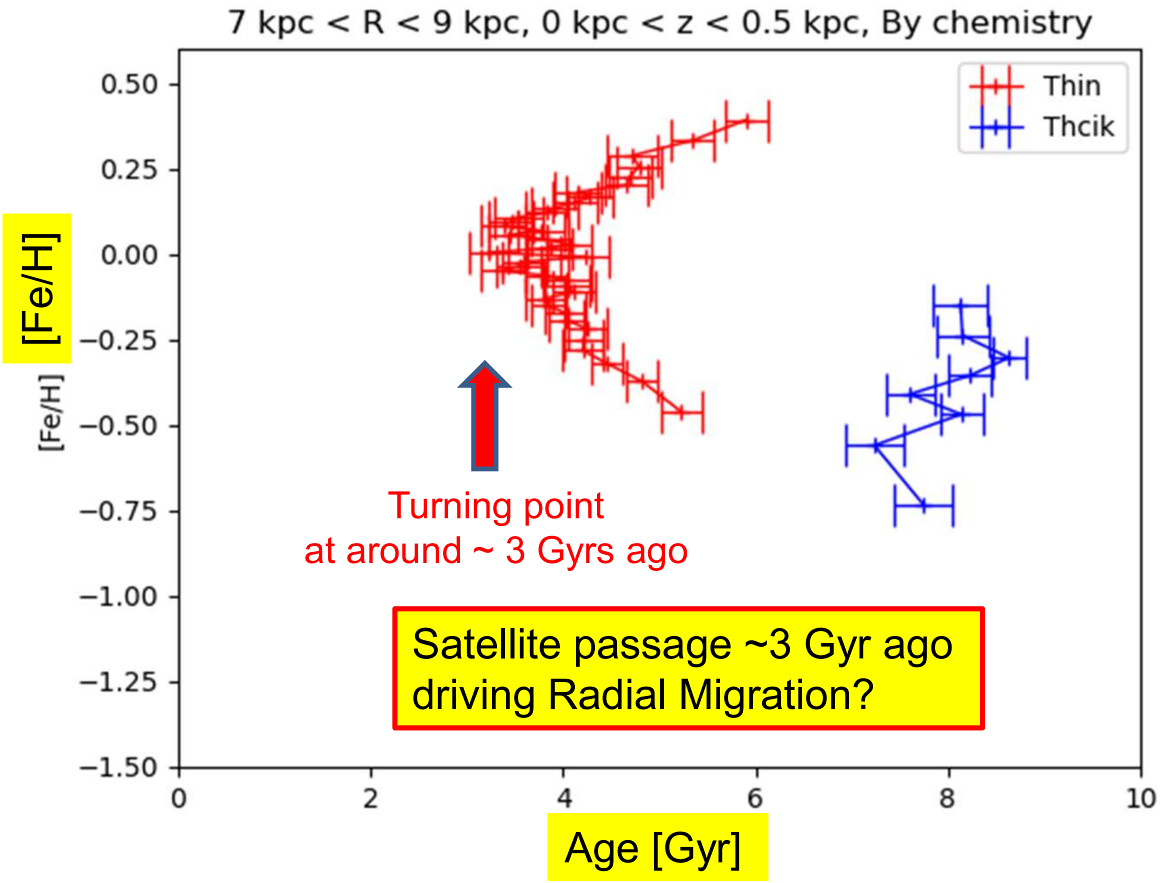
Pop C (thick + old thin disk stars)

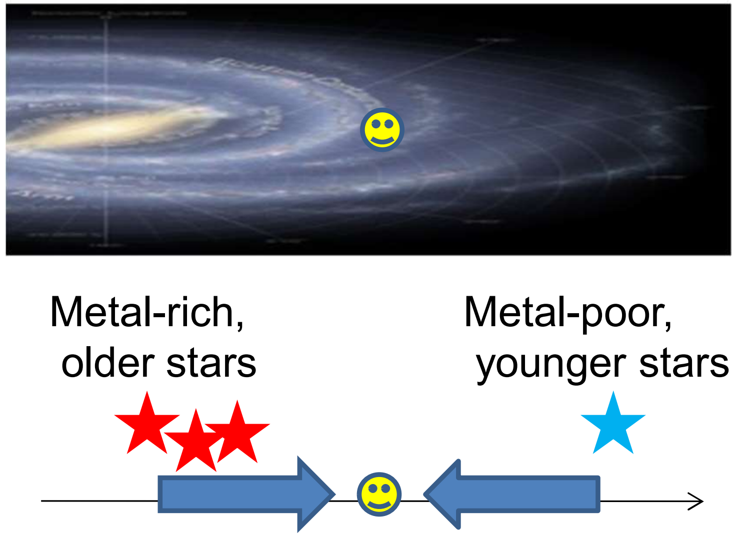
Dip-like feature at ~ 8Gyr ago but ambiguous



New AMR - Signature for radial migration event

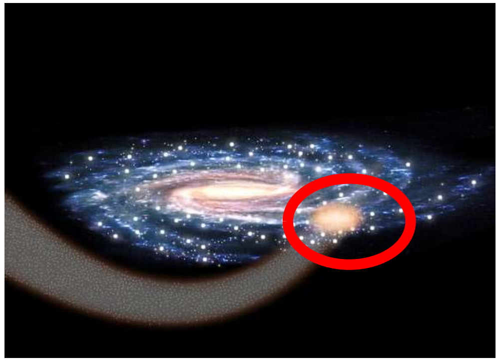
Chang 2022 (RGBs+RCs)





The effect of satellite infall & radial migration in AMR

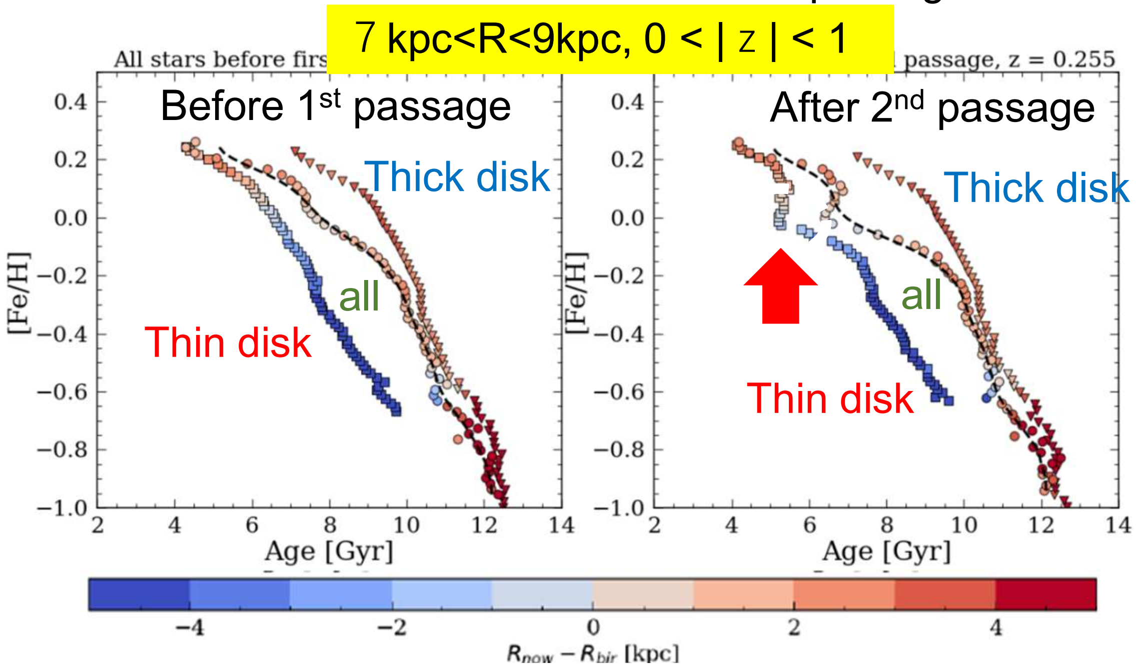
Before 1st passage z = 0.34

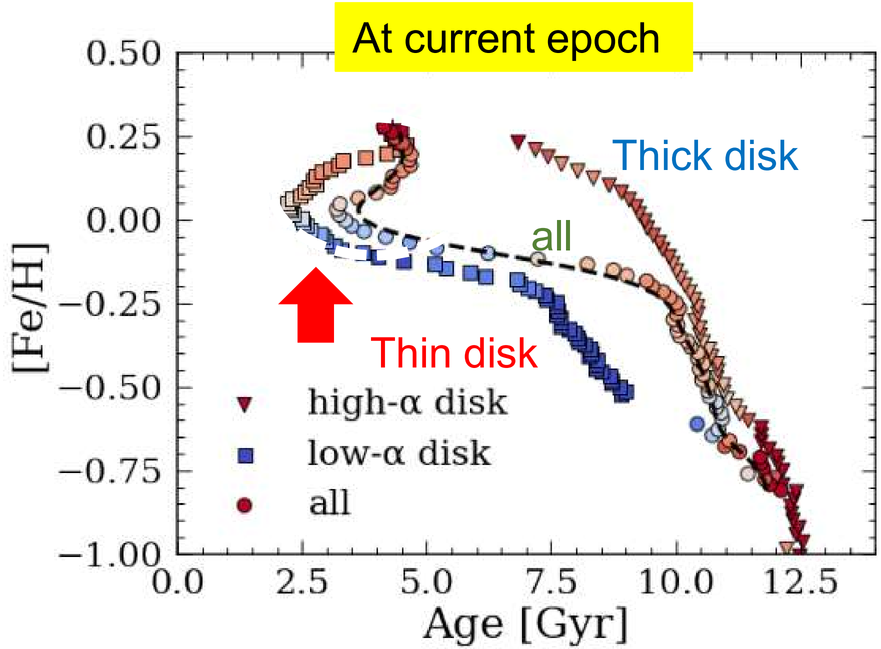


After 2nd passage z = 0.255

Lu et al. 2021 (simulation)

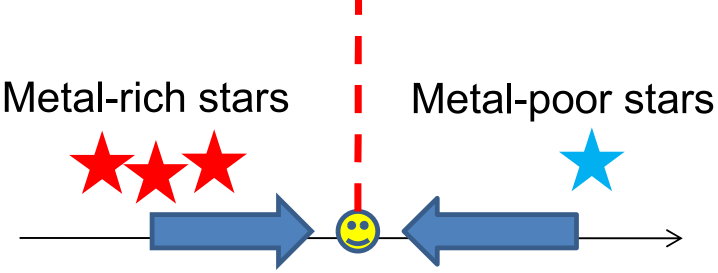
Cosmological simulation with NIHAO-UHD
– Sgr-dwarf like satellite is infalling at z=0.34.
The second passage at z =0.255 yields turning points and radial migration for low-α stars in AMR.





Further evidence for radial migration of stars

Sellwood & Binney 2002, Schoenrich & Binney 2009



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

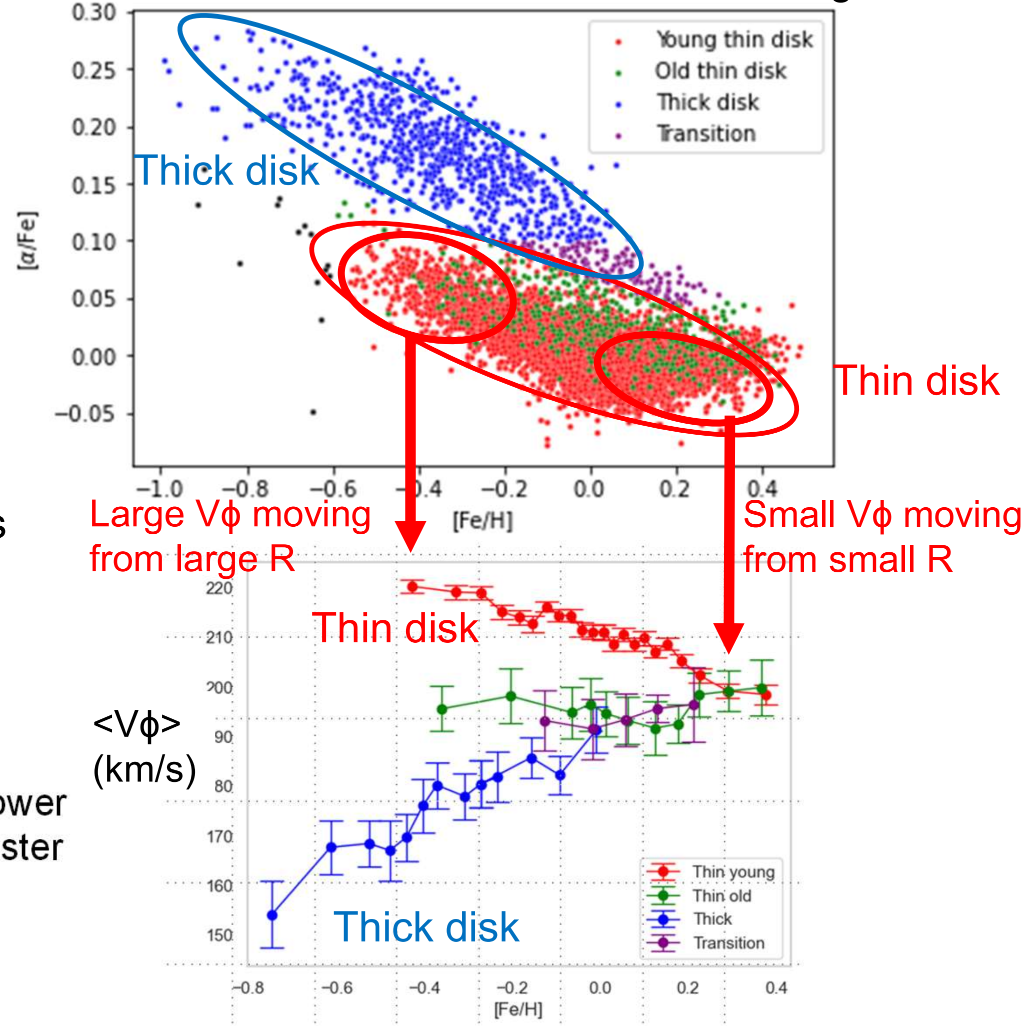
$L_z = V_\varphi R \sim$ const.

(Metal-rich) star moving from inner R: V_φ is slower

(Metal-poor) star moving from outer R: V_φ is faster

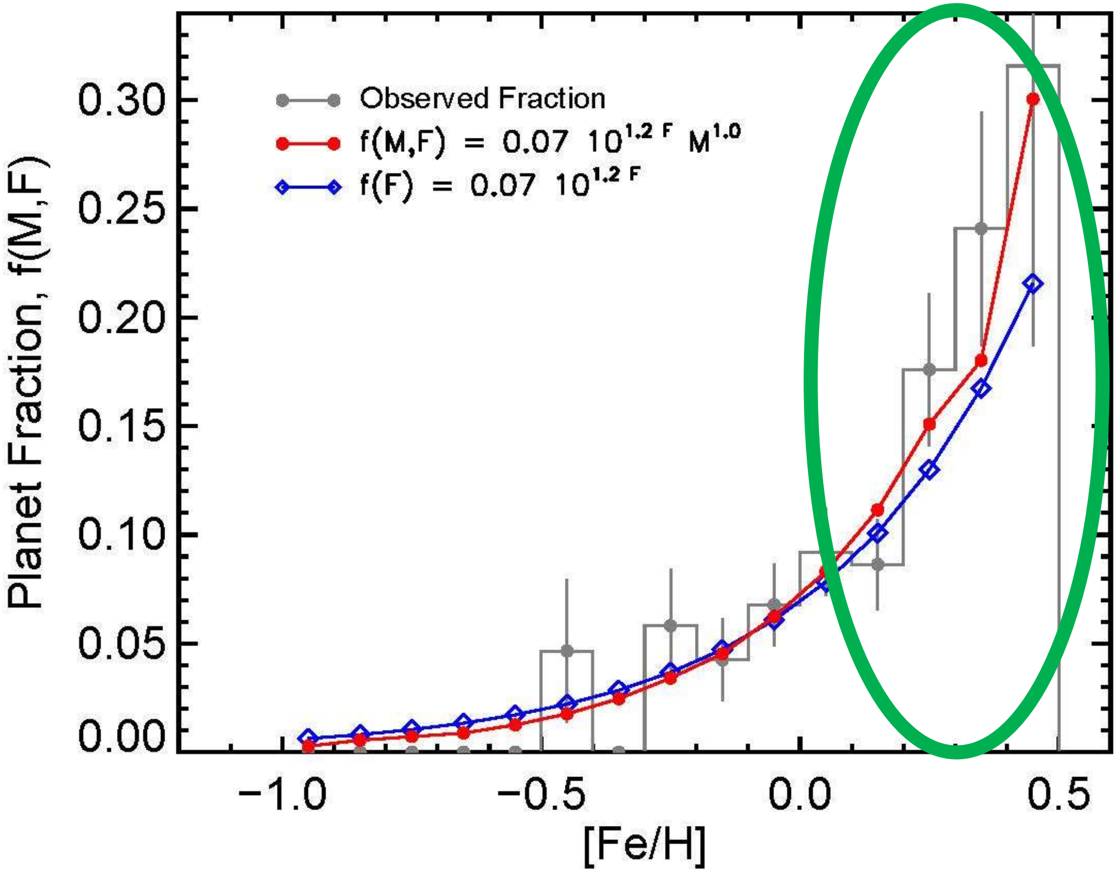
Radial migration of stars driven by satellite infall and associated transient bar/spirals

Chang 2022



MDFs of the stars hosting planets

Johnson et al. 2010

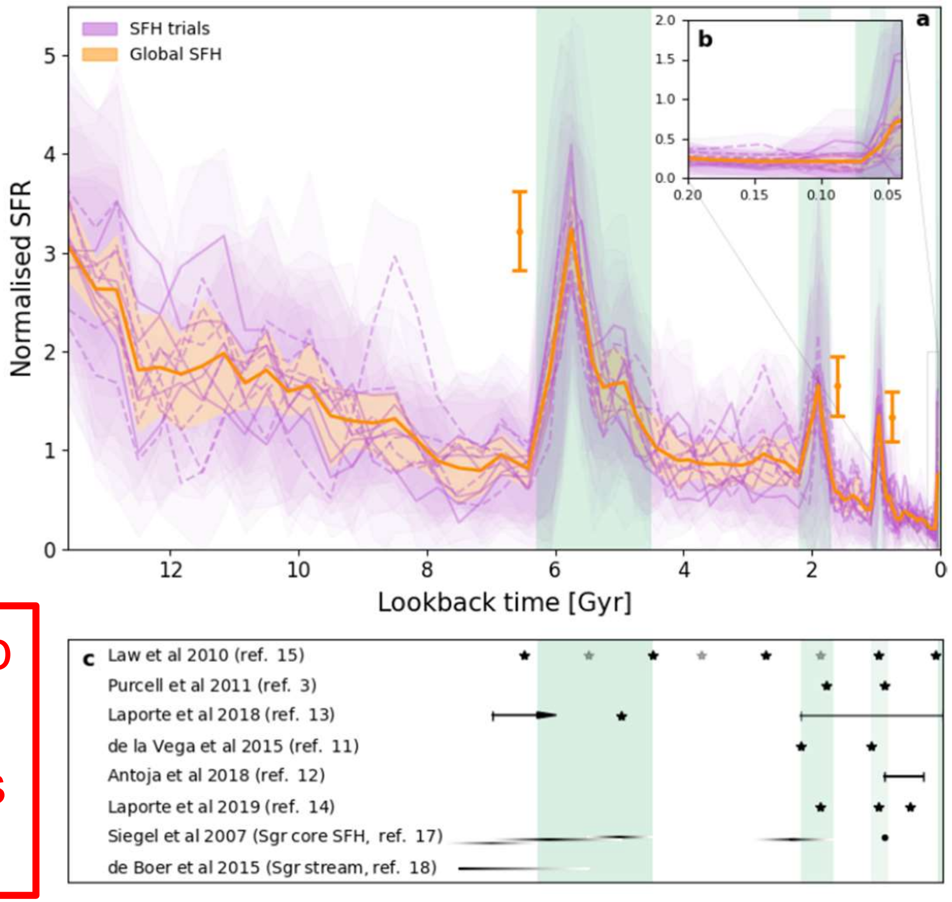


These stars may have been migrated from inner R

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

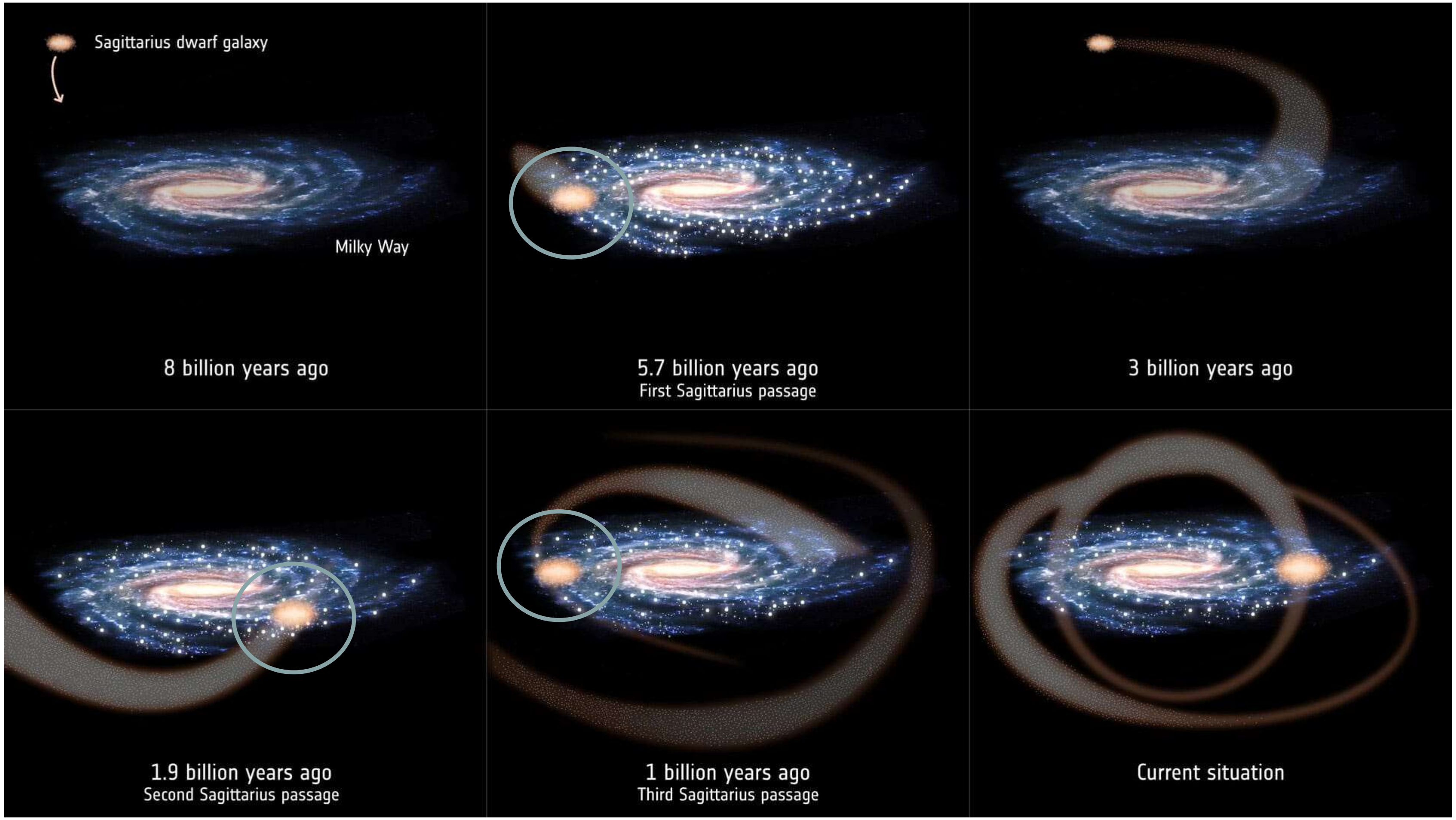


These peaks overlap with the timings of pericentric passages of Sgr dwarf

The orbit of Sgr dwarf

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

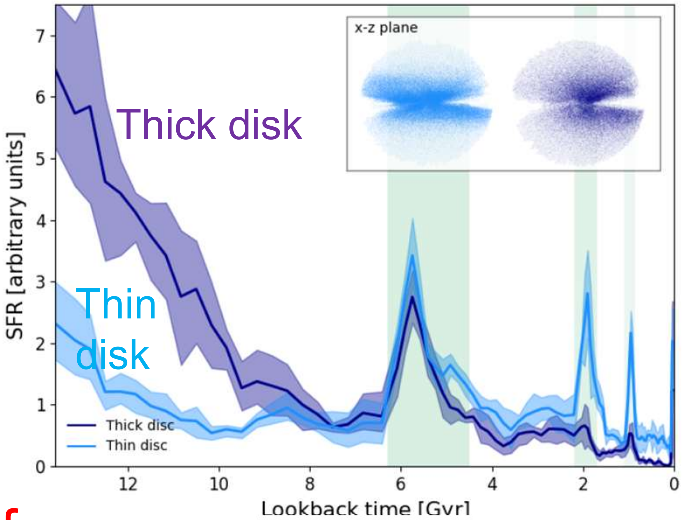
Ruiz-Lara et al. 2020



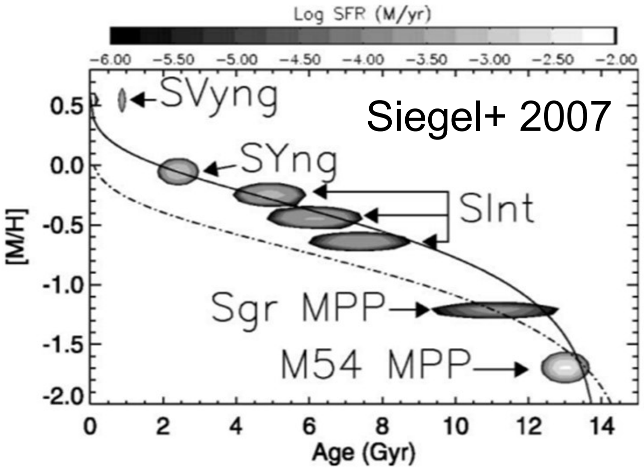
SFHs of thick/thin disks & Sgr dwarf

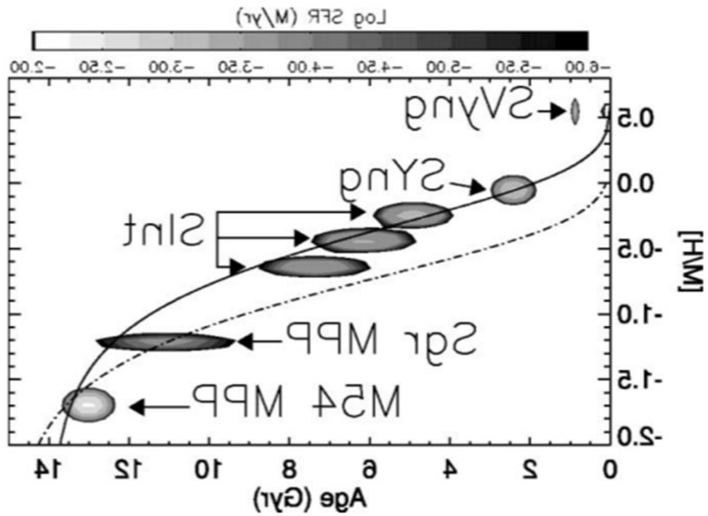
Ruiz-Lara et al. 2020

Peak at 5.7 Gyr exists for both
Thick disk
Thin disk



SFHs of M54 & Sgr dwarf





SFH of Sgr dwarf is also affected