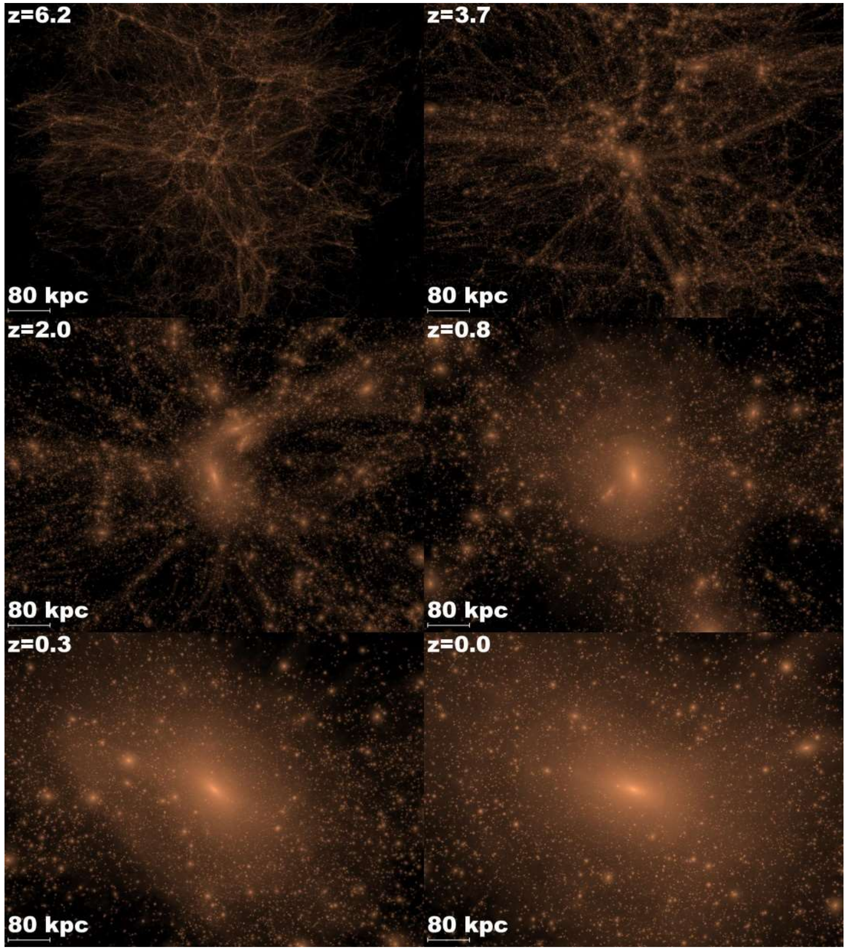
Chap.5 Formation of Galactic Structures

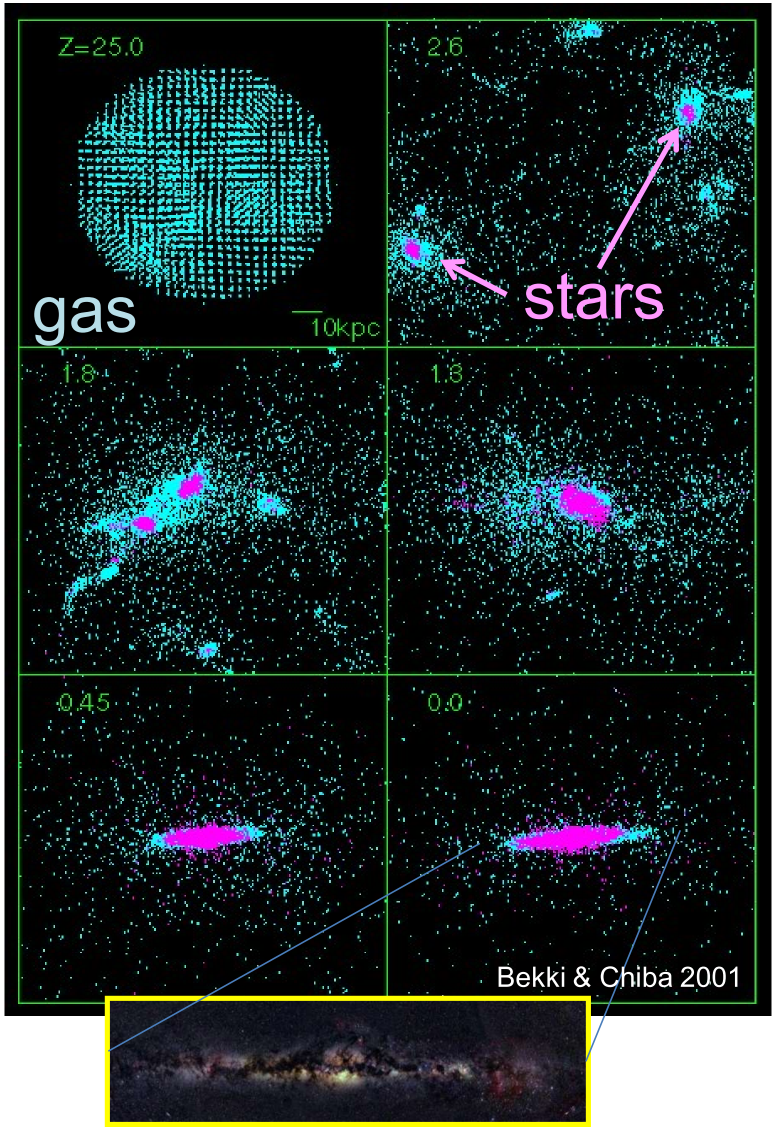
- Overview of galaxy formation
- Classical picture of Galaxy formation
- Formation of the stellar halo: after Hipparcos
- Formation of the stellar halo: after Gaia
- Formation of the thick disk
- Formation of the thin disk
- Formation of satellite galaxies

1. Overview of galaxy formation

Hierarchical assembly of CDM



Via Lactea simulation
(Diemand+07)

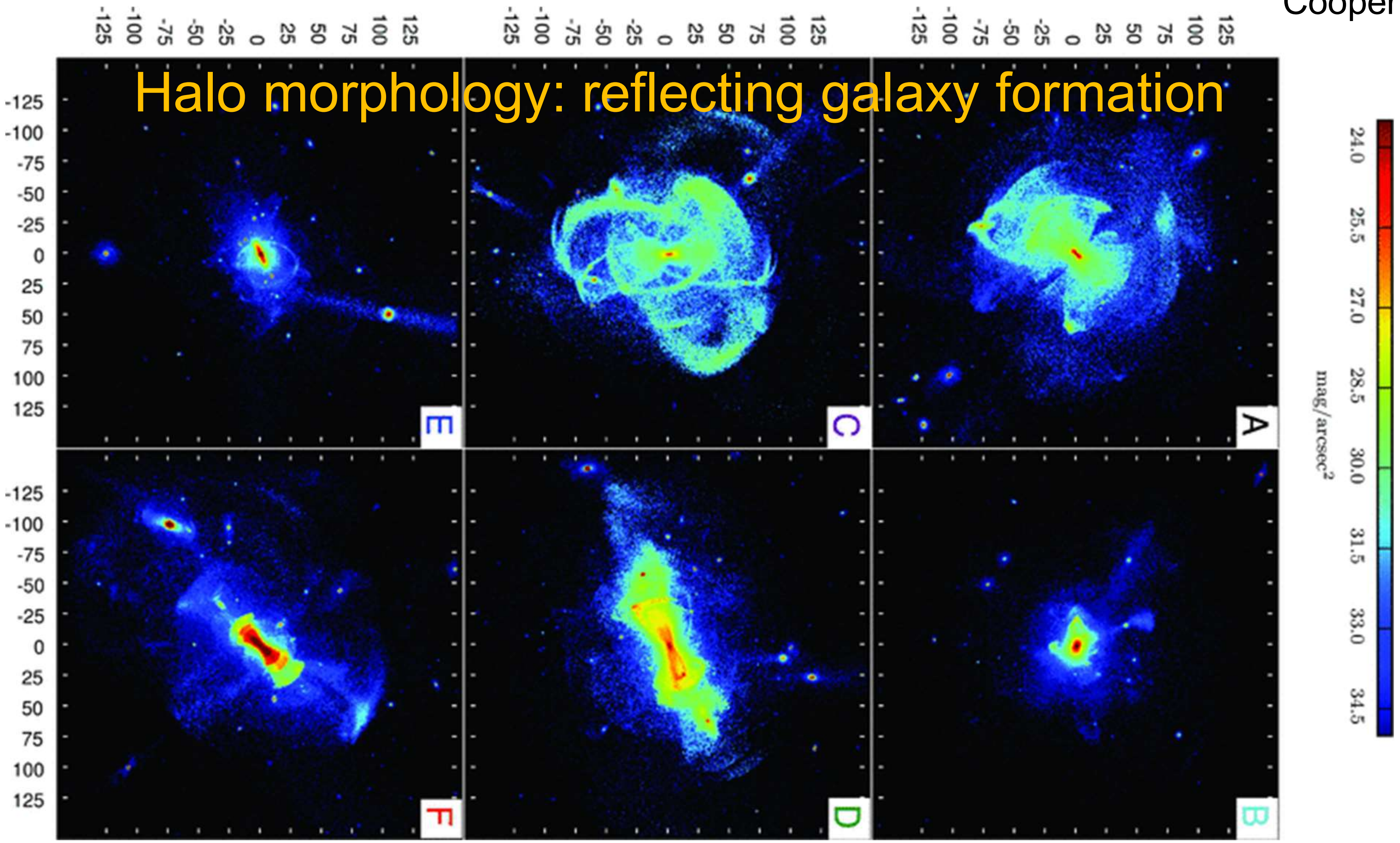


Bekki & Chiba 2001

Stellar halos in various MW-sized halos

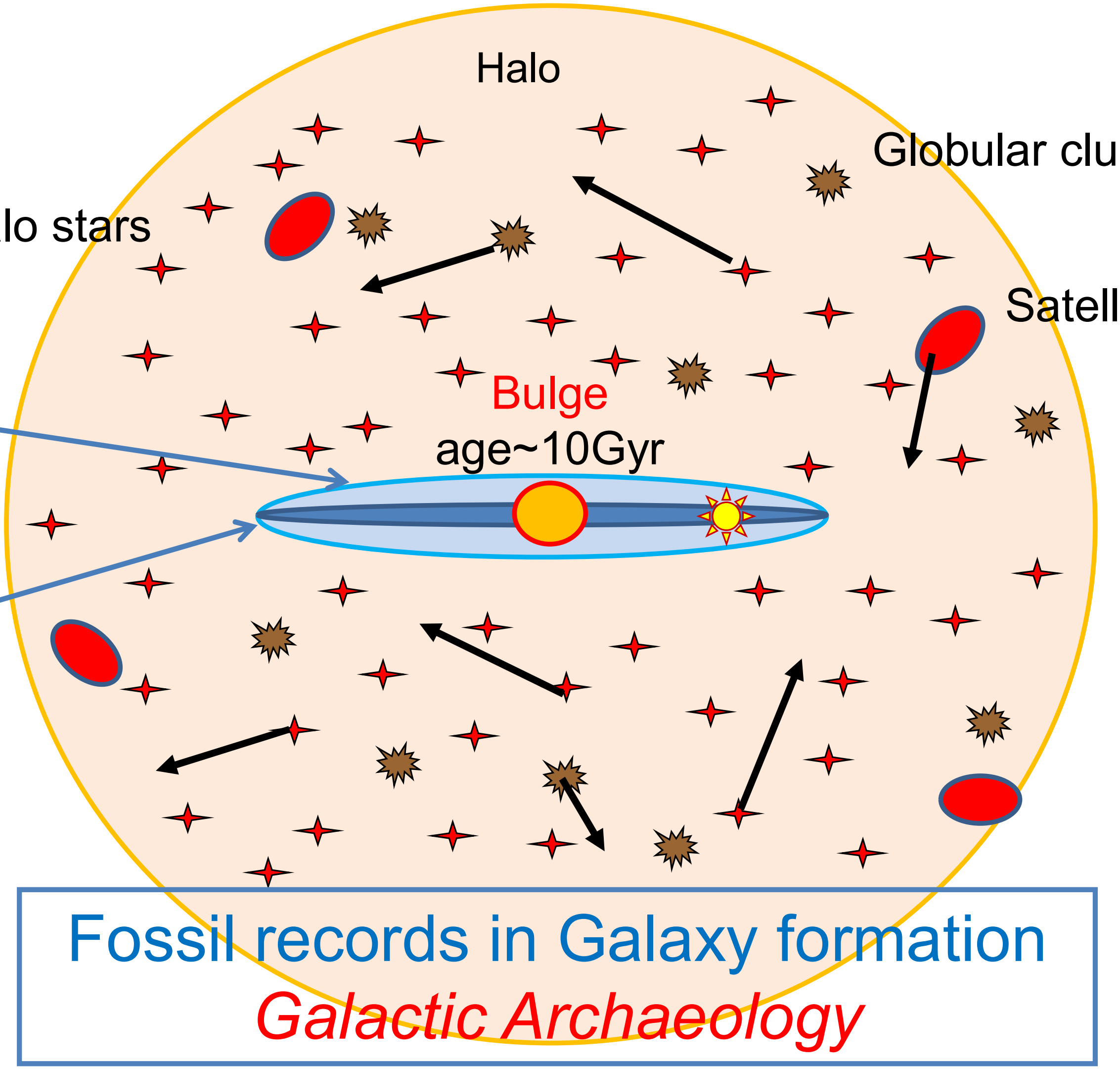
～varieties due to different merging histories～

Cooper et al. 2010



Halo morphology: reflecting galaxy formation

Old stellar components



Thick disk
age > 10 Gyr
(formation
redshift > 2)

Thin disk

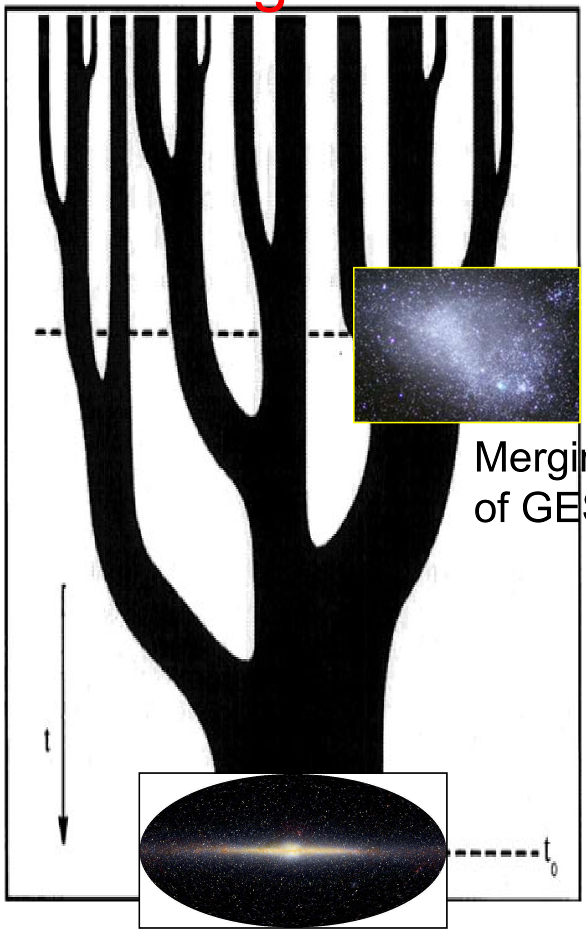
Halo
age > 10 Gyr
(formation
redshift > 2)

Fossil records in Galaxy formation
Galactic Archaeology

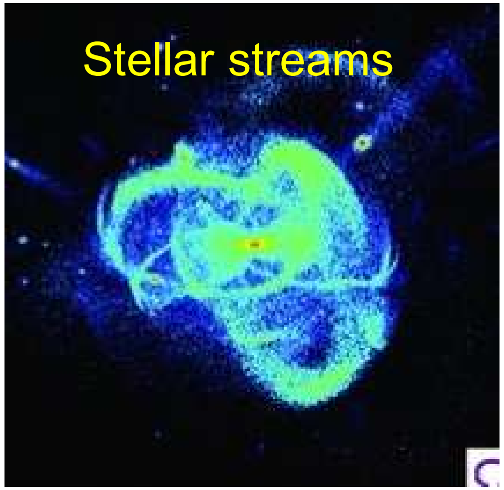
Fossil record of Galaxy formation

Hierarchical merging

Merger tree

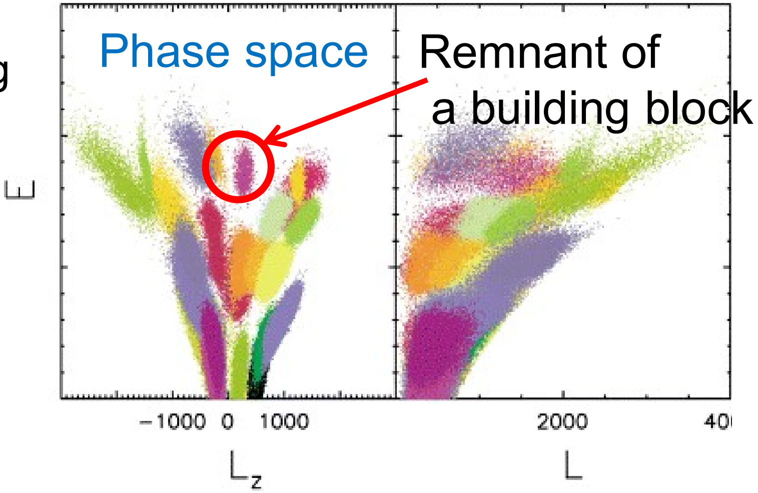


Merging of GES



Stellar streams

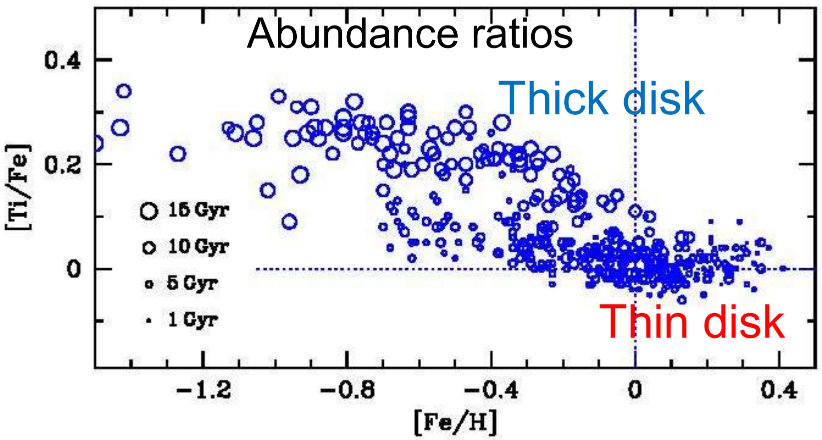
- Spatial distribution and dynamics of stars
  - ✓ Galaxy collapse and merging
- Chemical abundance of stars
  - ✓ Star formation and chemical evolution



Phase space

Remnant of a building block

Helmi & de Zeeuw 2000



Abundance ratios

Thick disk

Thin disk

Bensby et al. 2014

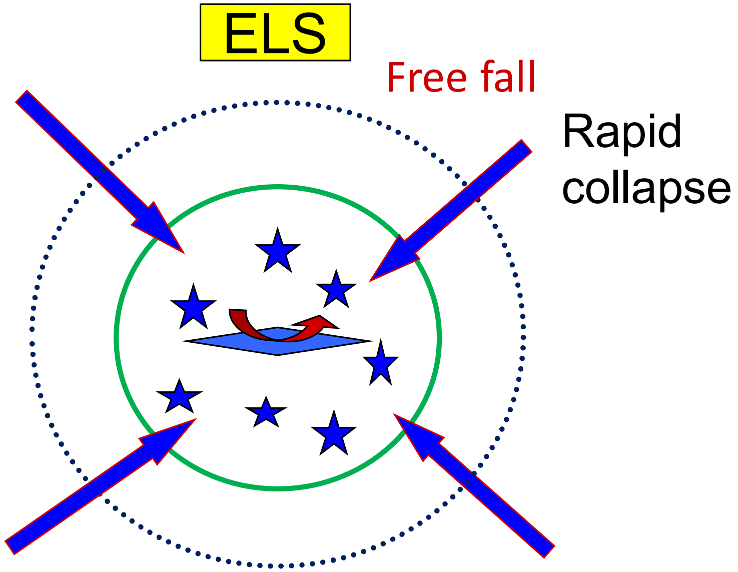
Sampling ancient halo stars

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

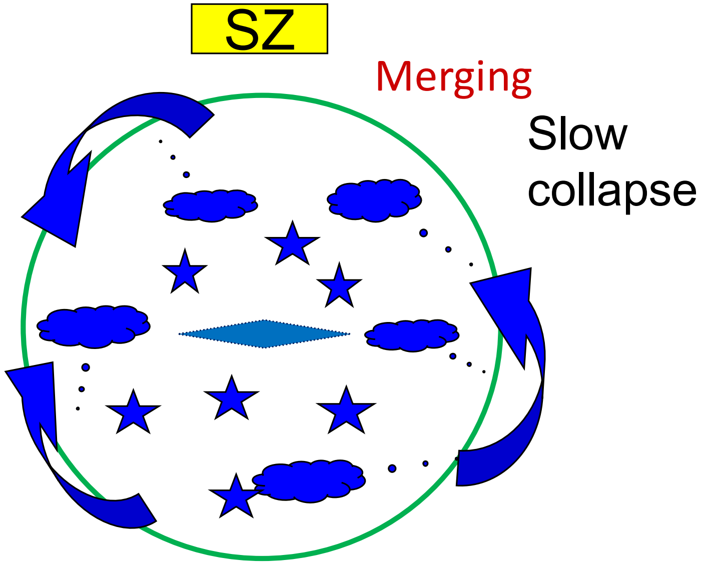
Fraction: ~ 1/1000 near the Sun

2. Classical picture of Galaxy Formation

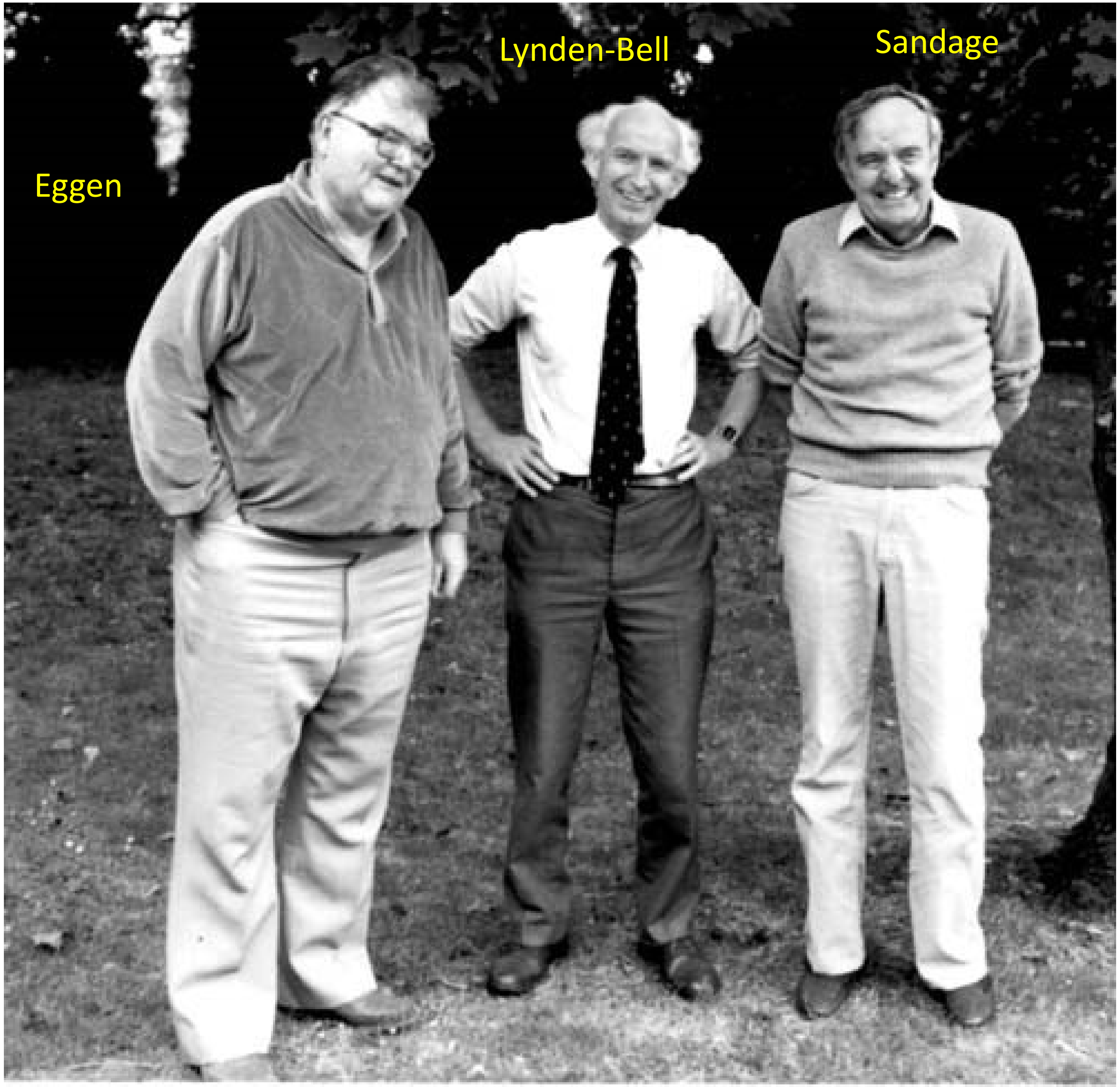
* Monolithic, free-fall collapse
Eggen, Lynden-Bell, Sandage 1962 (ELS)
* Chaotic merging of numerous fragments
Searle, Zinn 1978 (SZ)



Correlation between kinematics
and metal abundances of stars
Metallicity gradient

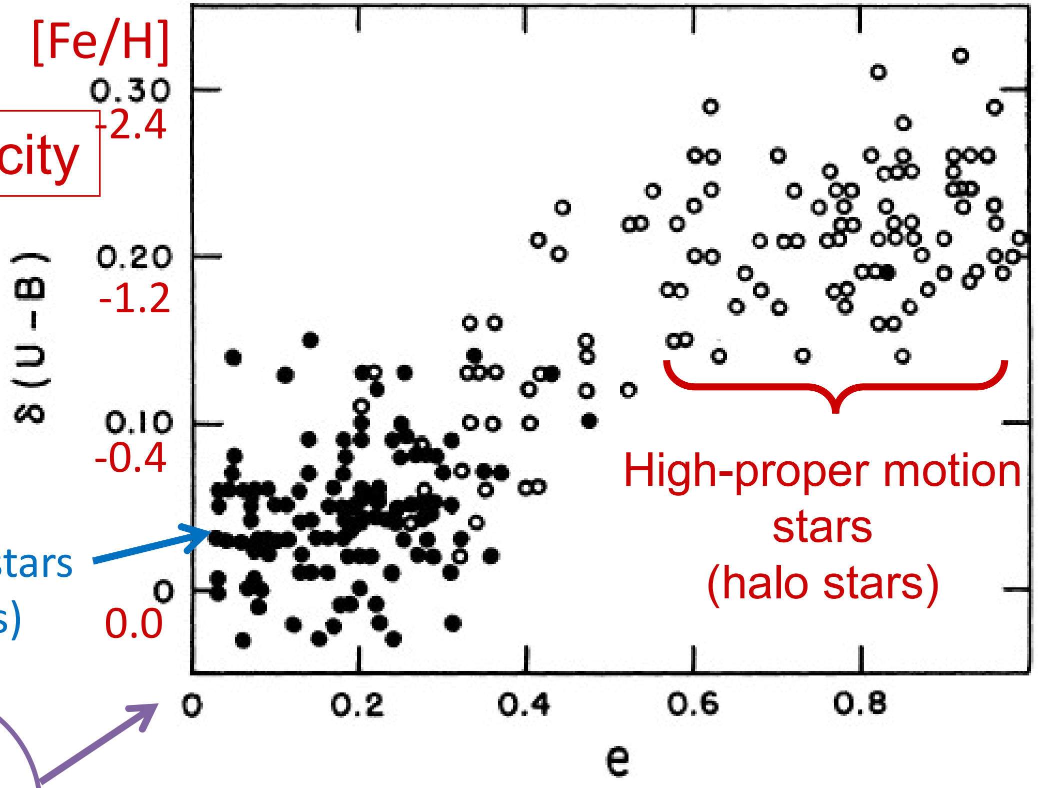


No metallicity gradient
Age spread among
globular clusters


Lynden-Bell
Sandage
Eggen

Physical state of the Protogalaxy

(Eggen,Lynden-Bell & Sandage 1962)



Metallicity

Free-fall collapse !?

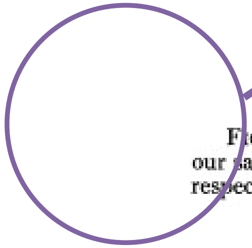
High-proper motion stars (halo stars)

Metal-rich stars (disk stars)

FIG. 4.—The correlation b… tricity, *e*, for our sample of 221 stars. The … d catalogues, respectively.

Orbital eccentricity

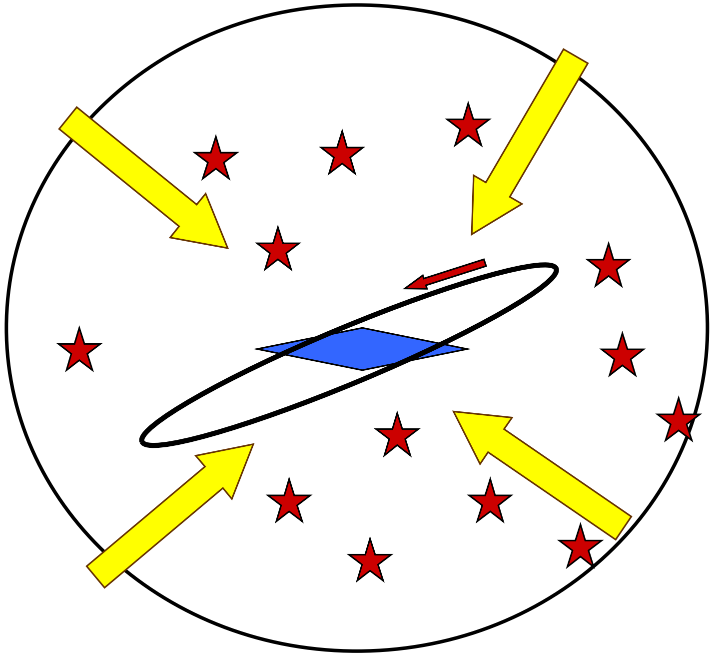
$e = (r_{apo} - r_{peri}) / (r_{apo} + r_{peri})$



Circular orbit

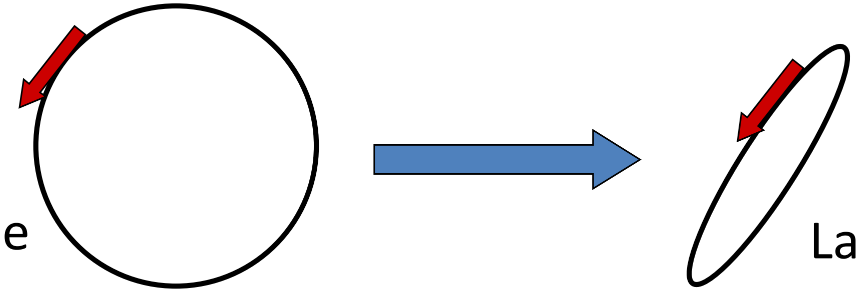
Radial orbit

If free-fall galactic collapse is the case



Large e

Only large-e stars are remaining.



Small e

Large e

If mass inside an orbit is suddenly increased

Note

Action integrals for Kepler motions

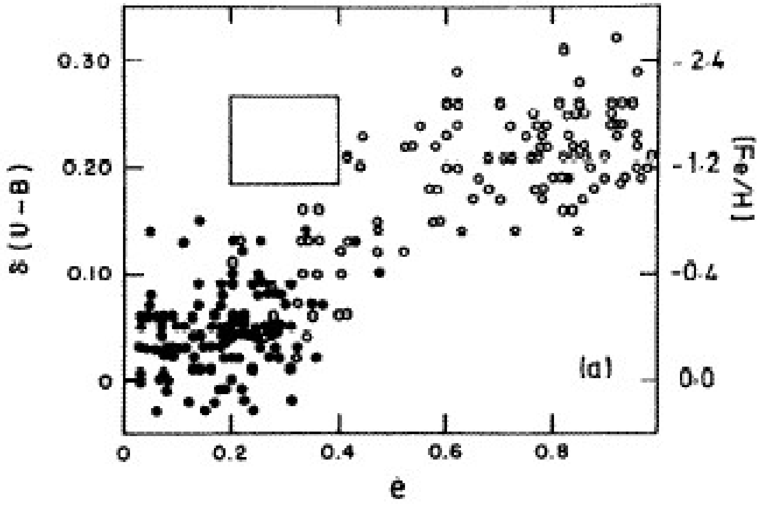
$$J_r = \frac{1}{\pi}\int_{r_{\min}}^{r_{\max}} p_r dr = \frac{\sqrt{2}}{\pi}\int_{r_{\min}}^{r_{\max}} \sqrt{E - \frac{L^2}{2r^2} + \frac{GM}{r}}\,dr = \frac{GM}{\sqrt{2|E|}} - L = L\left[\frac{1}{\sqrt{1-e^2}} - 1\right]$$

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

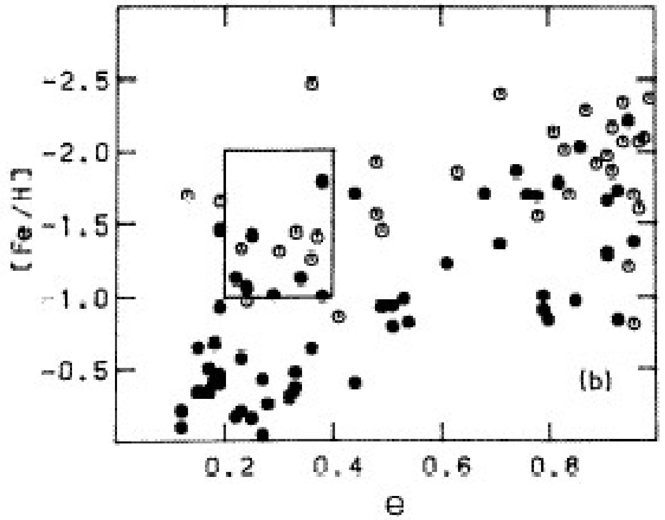
$$J_\phi = \frac{1}{2\pi}\oint p_\phi d\phi = p_\phi$$

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

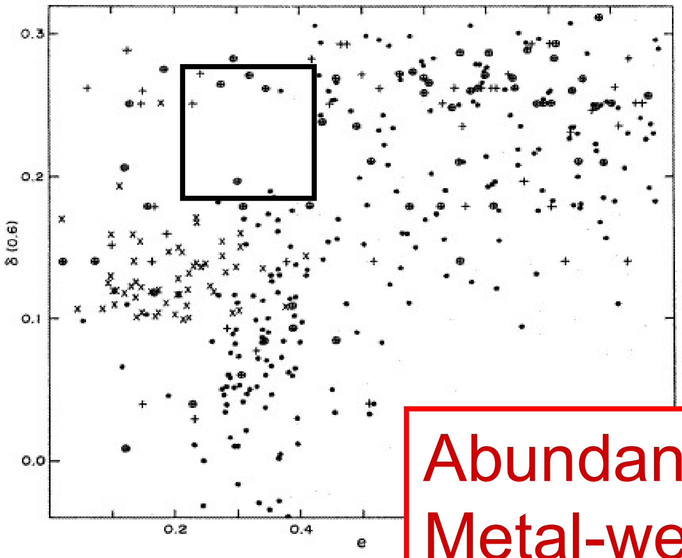
ELS 1962



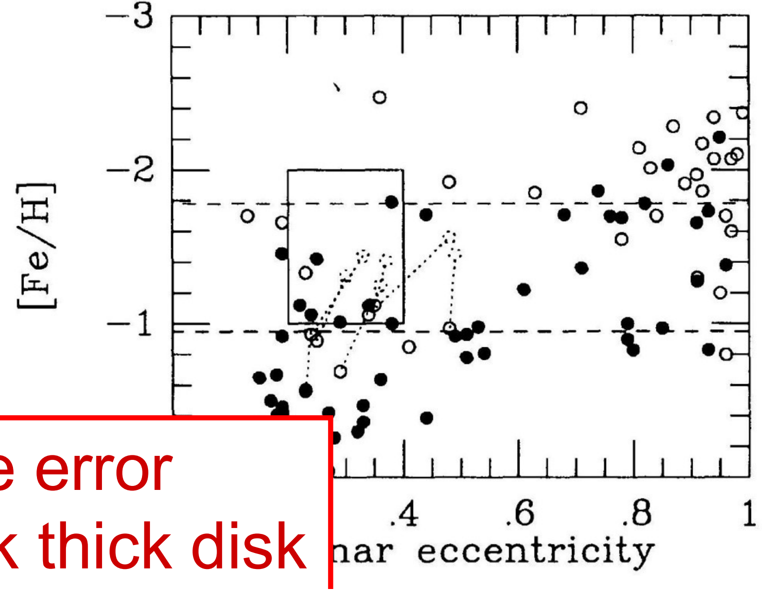
Norris et al. 1985



Yoshii & Saio 1979

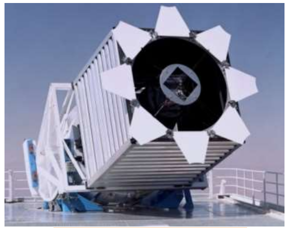


Ryan & Lambert 1995

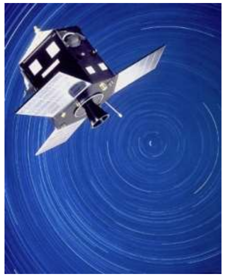


Abundance error
Metal-weak thick disk

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

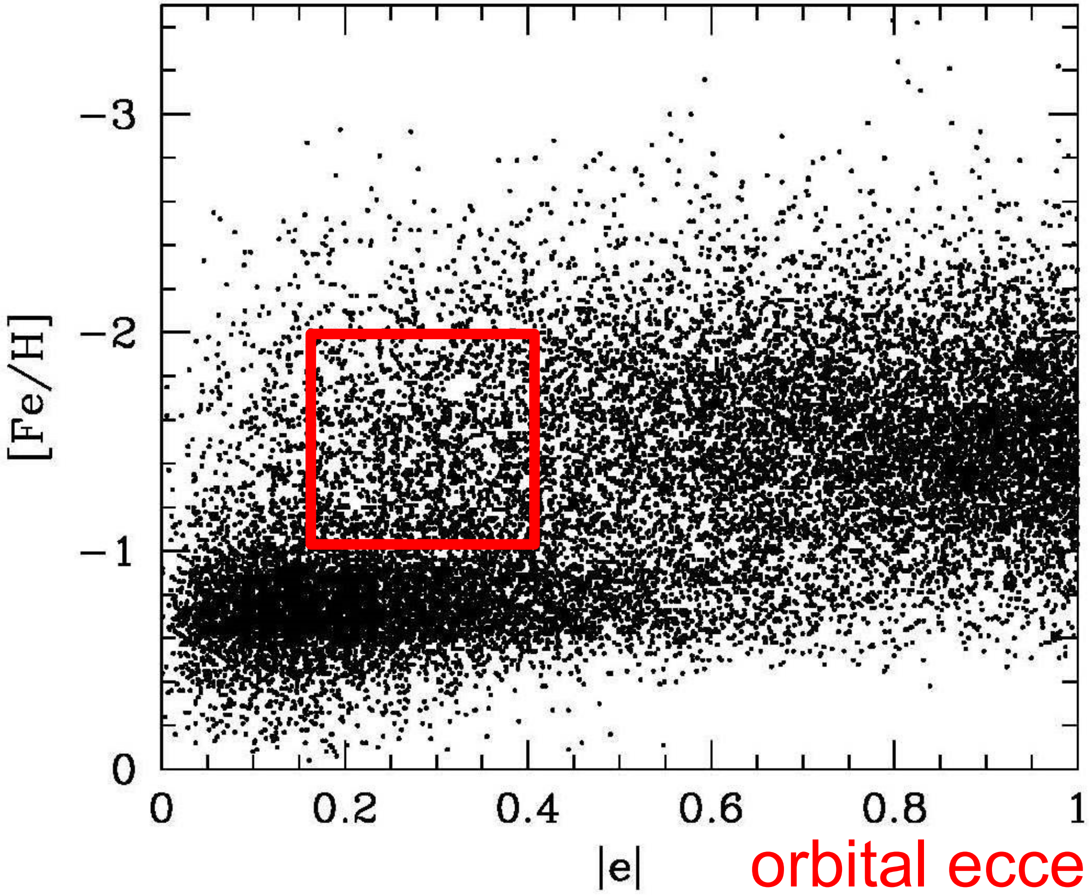


SDSS



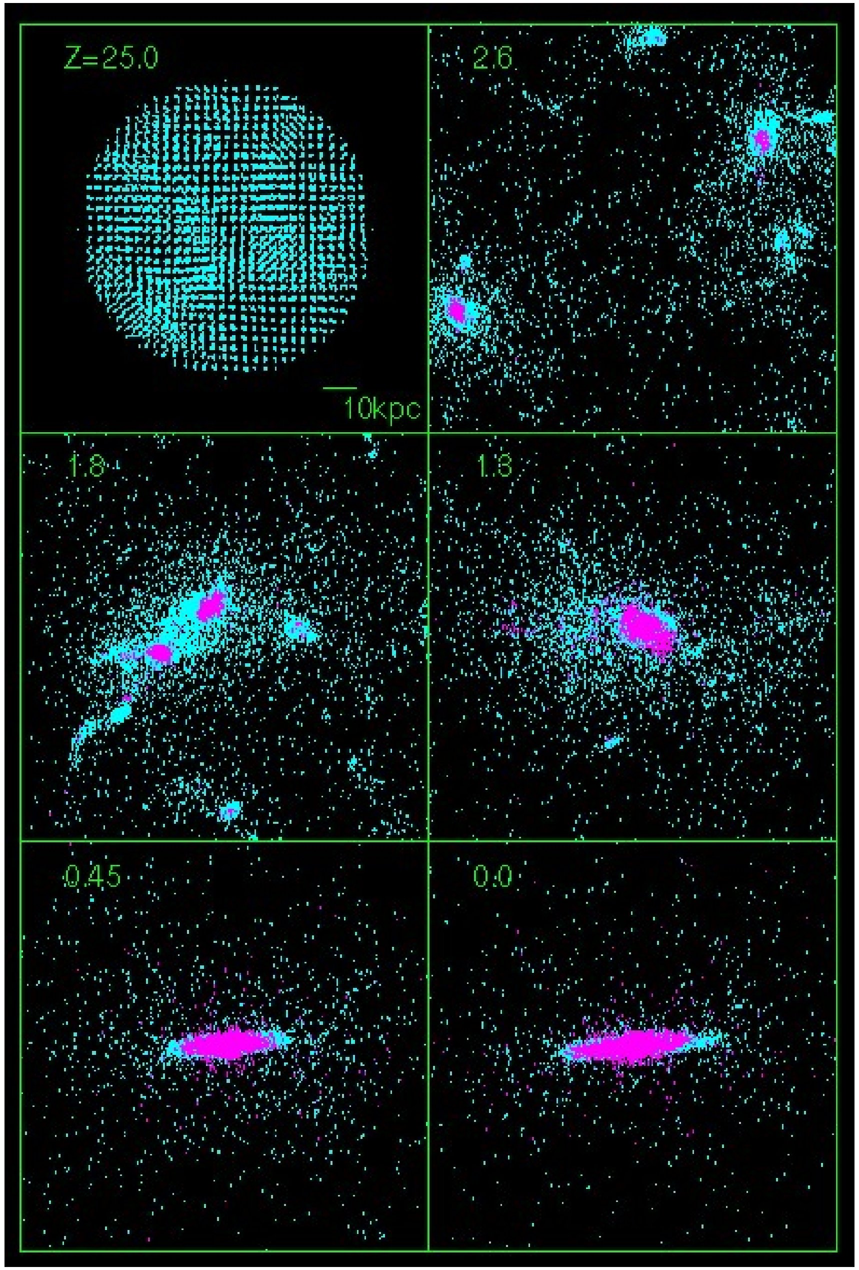
Hipparcos

[Fe/H]



orbital eccentricity

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)

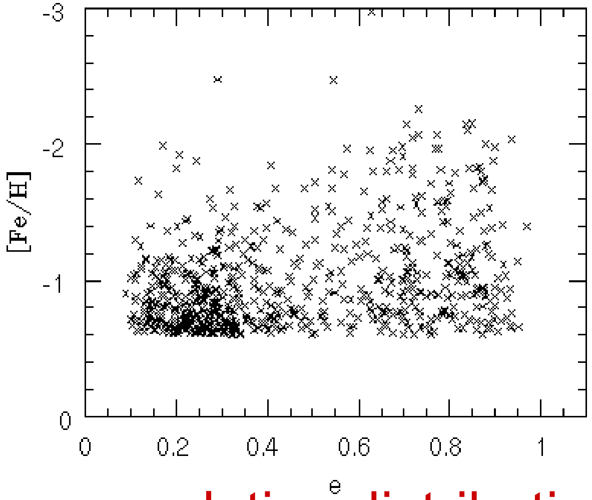
● gas

● star

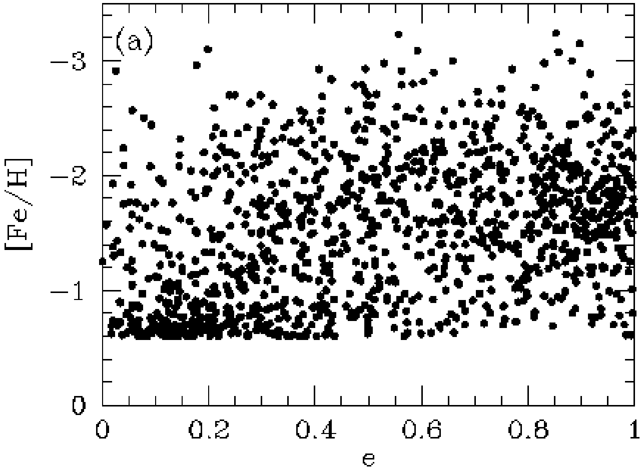
Comparison with simulation results

Bekki & Chiba (2001)

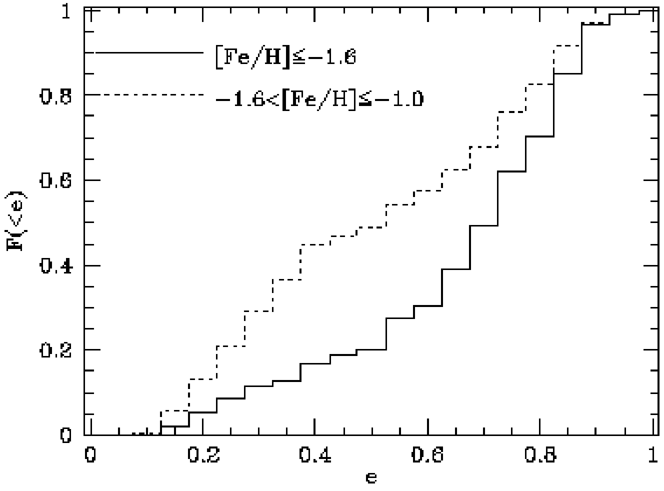
simulation



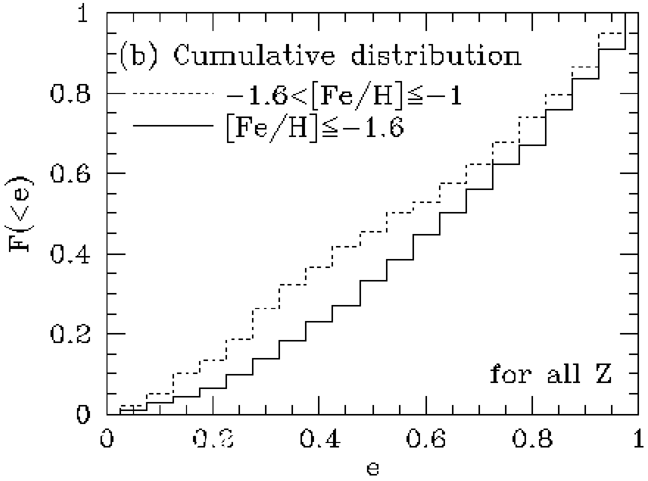
observation



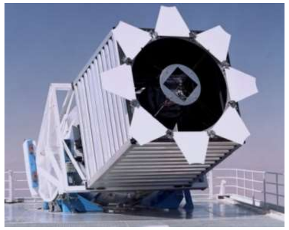
cumulative distribution



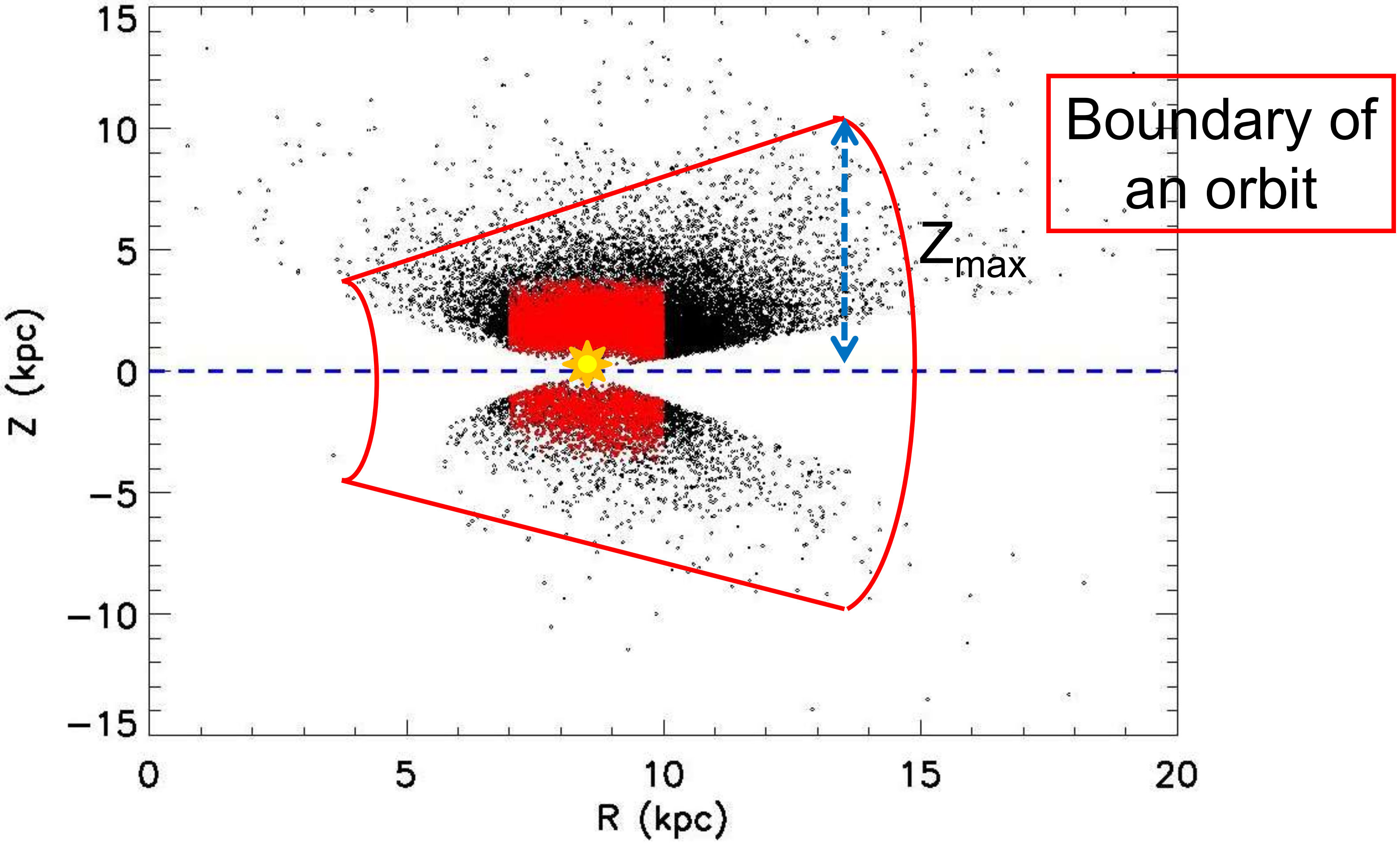
cumulative distribution



Nearby stellar sample from SDSS



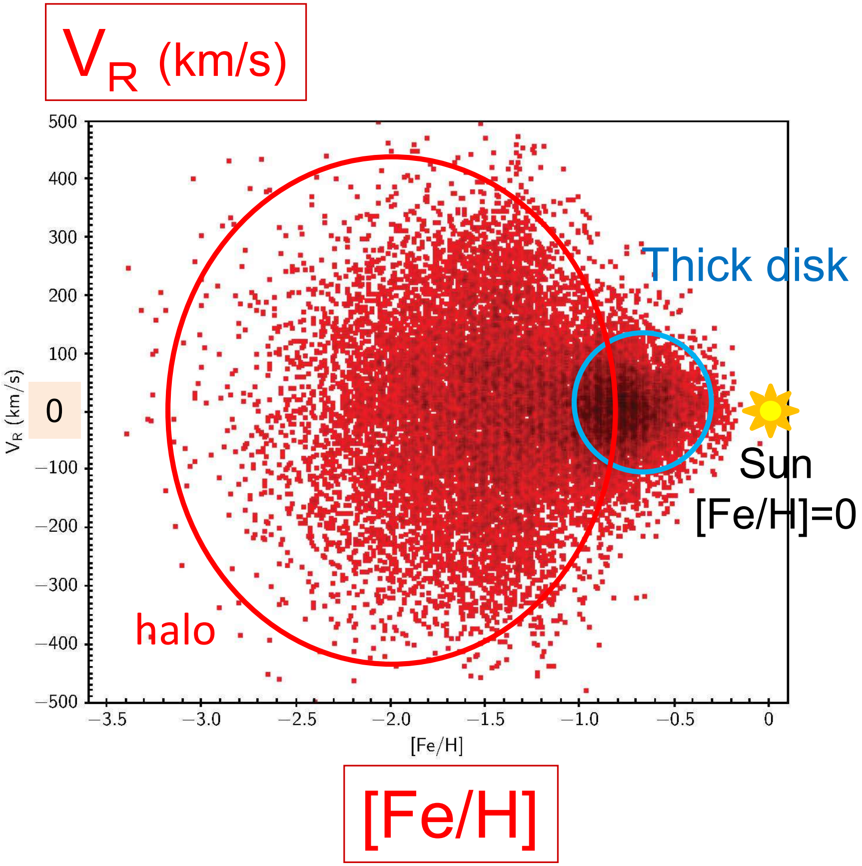
Carollo+2007, 2010

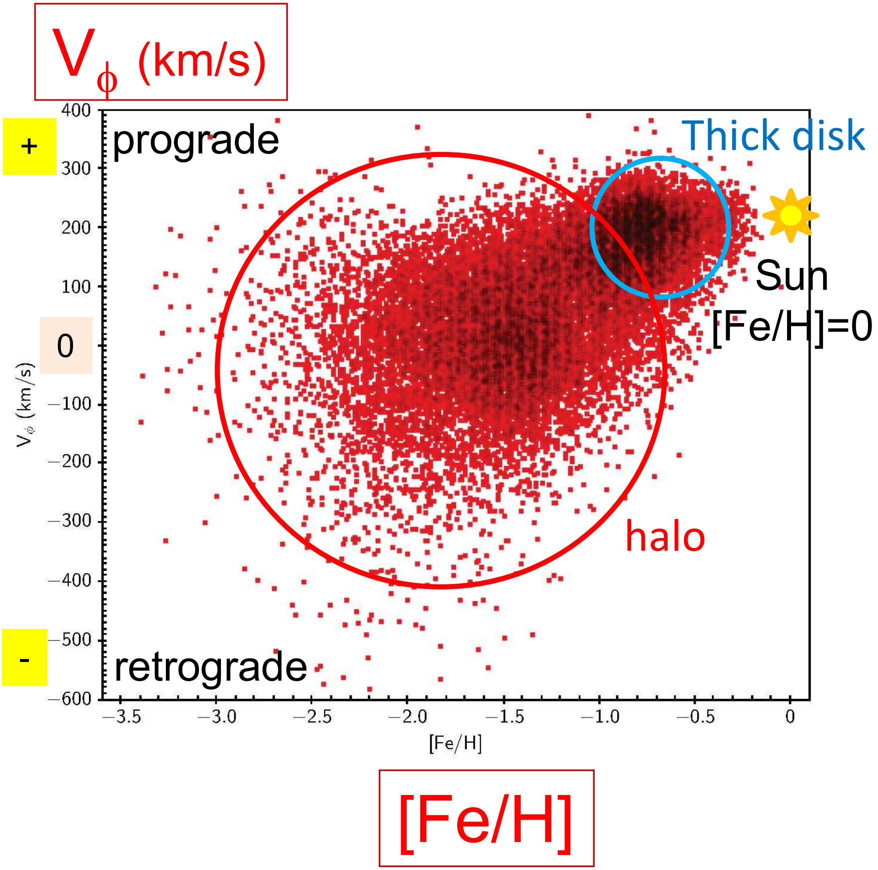


Velocity distribution of nearby stars

Sloan Digital Sky Survey

Carollo+2007, 2010





Velocity distribution of nearby stars

Sloan Digital Sky Survey

Carollo+2007, 2010

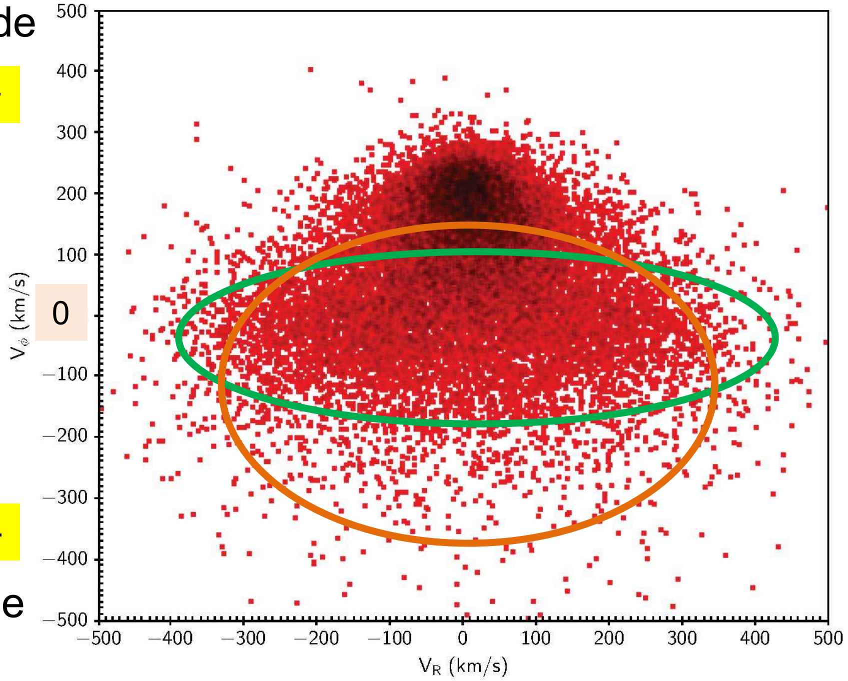
prograde

+

V_ϕ (km/s)

-

retrograde



V_R (km/s)

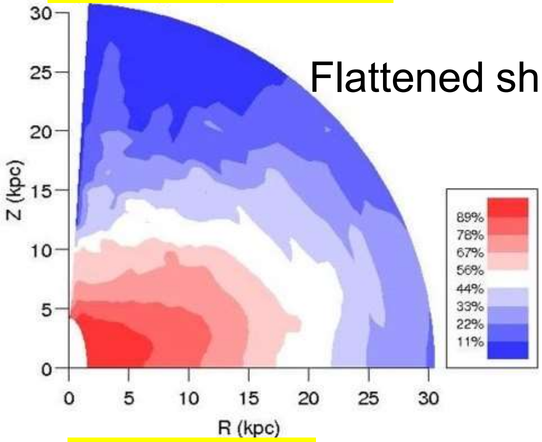
radially anisotropic

mildly anisotropic
presence of stars
with largely negative V_φ

2-halos : from dynamics

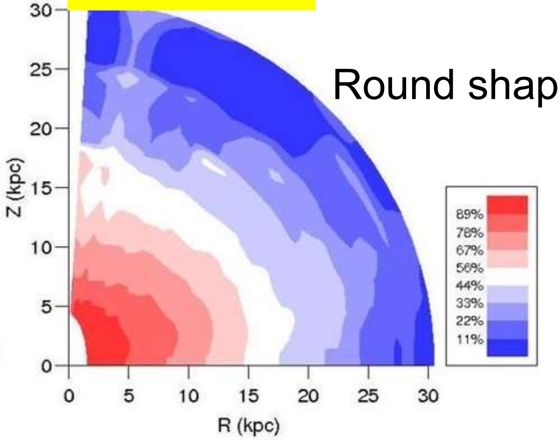
Global halo distribution based on superposition of stellar orbits (Carollo+ 2007)

-1.6<[Fe/H]<-1.4

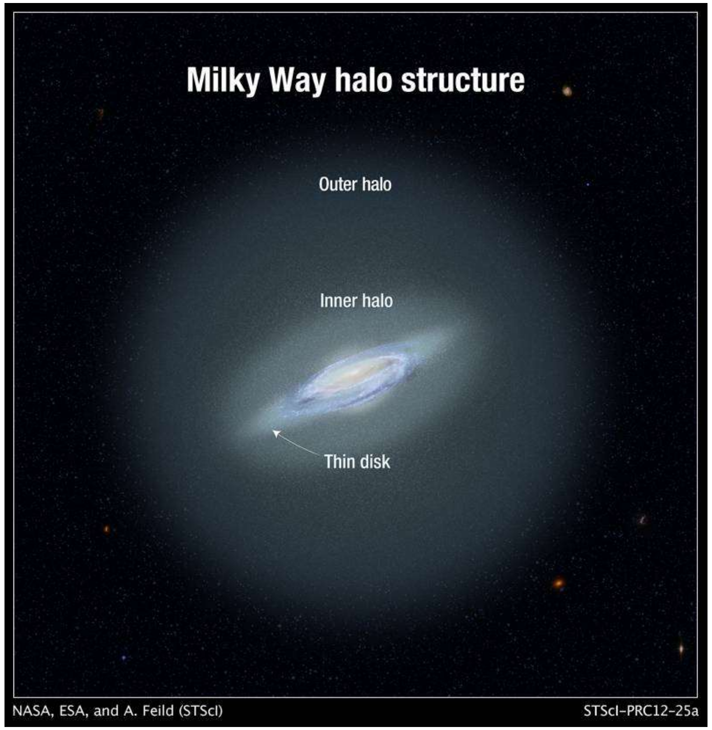


Flattened shape

[Fe/H]<-2.2



Round shape



NASA, ESA, and A. Feild (STScI)

STScI-PRC12-25a

- 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)

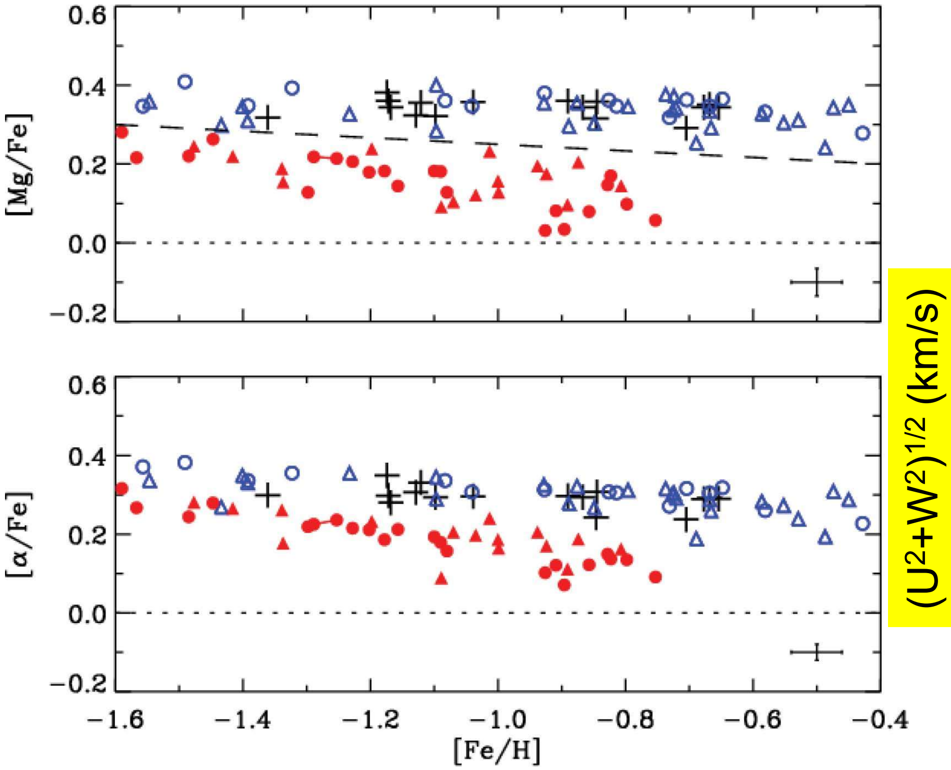
| V_{star} – V_{LSR} | > 180 km/s

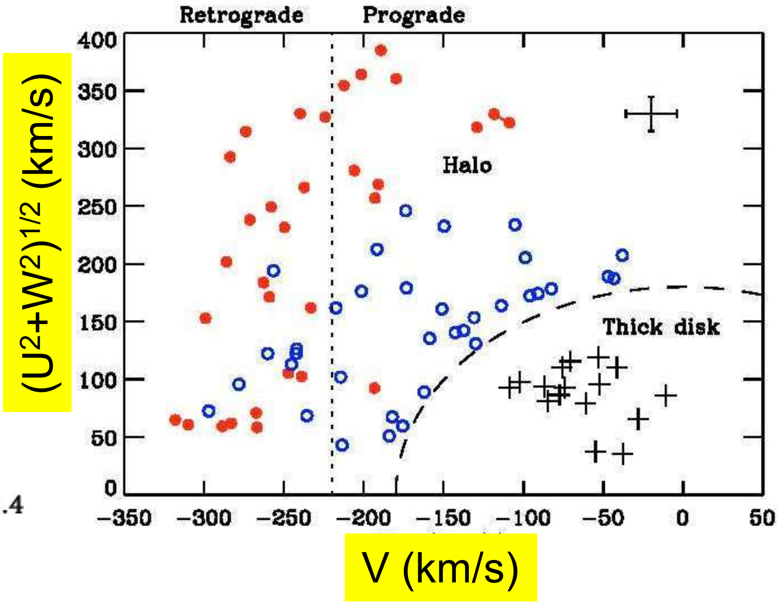
Blue: high-α stars

→ inner (in situ) halo?

Red: low-α stars

→ outer (ex situ) halo?

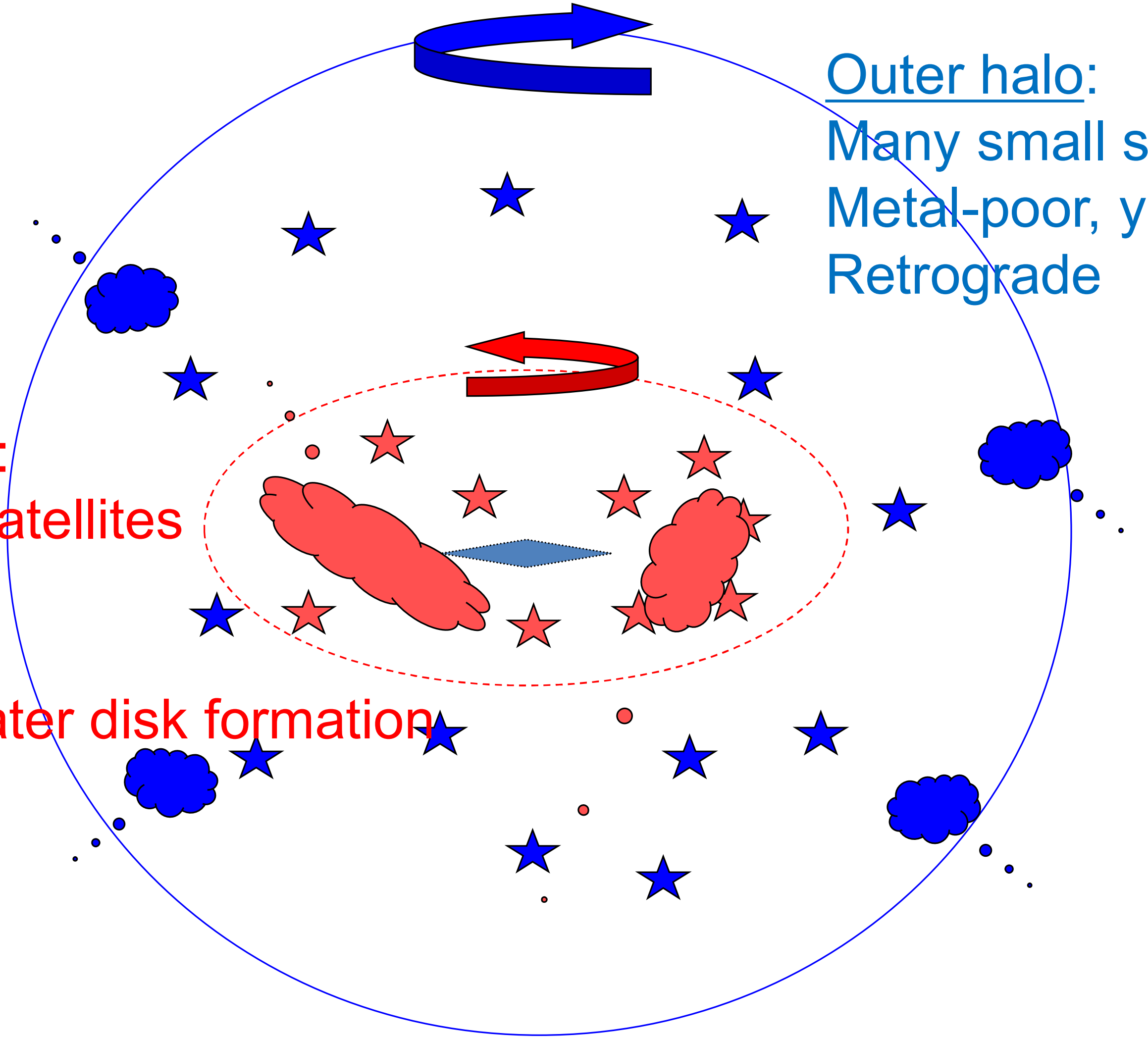




Based on VLT/UVES & NOT/FIES spectra

High-precision calibration with Δ= 0.02 ~ 0.04 dex

How 2-halos have formed?



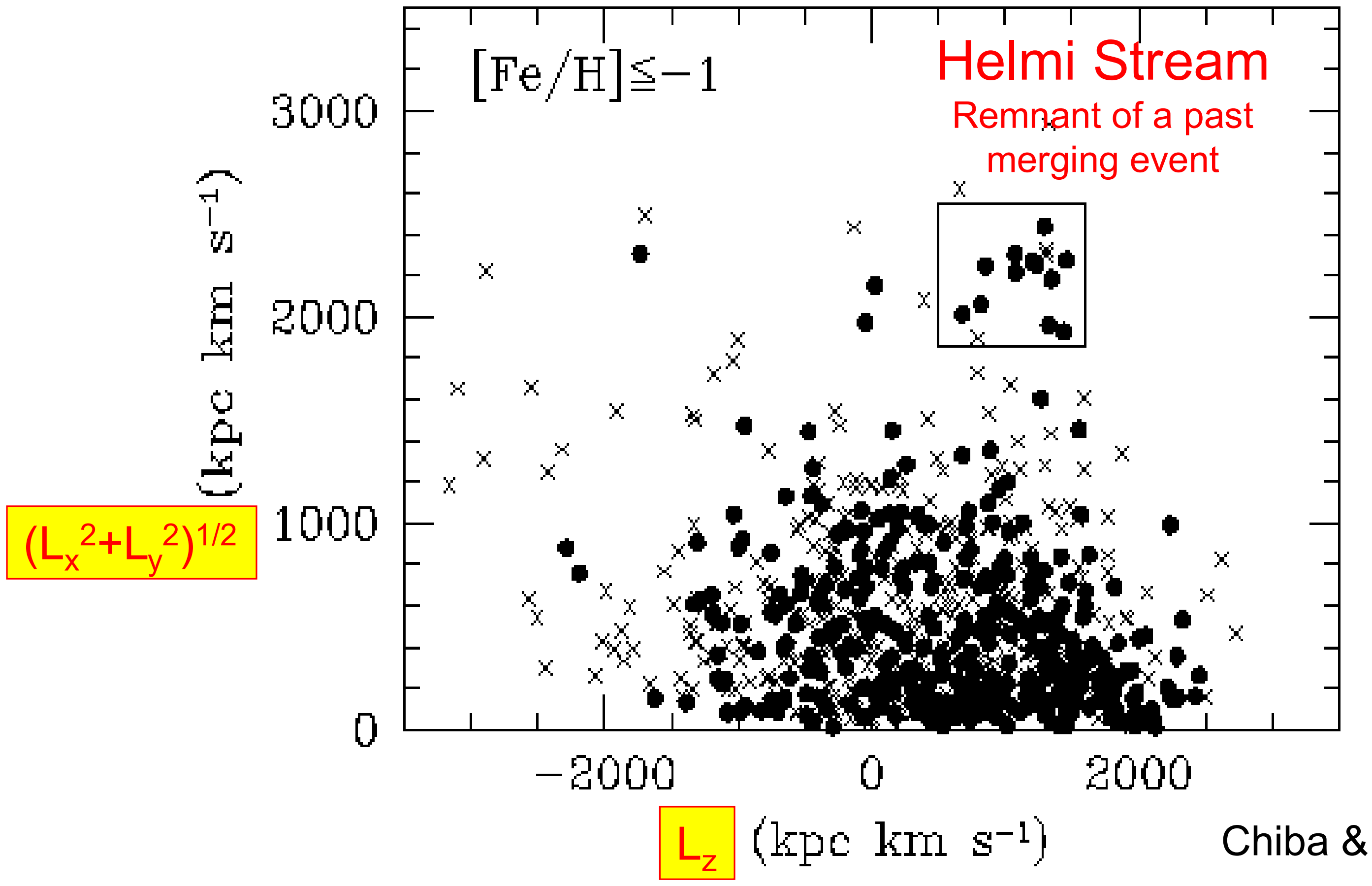
Outer halo:
Many small satellites
Metal-poor, young
Retrograde

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

Substructure in the stellar halo

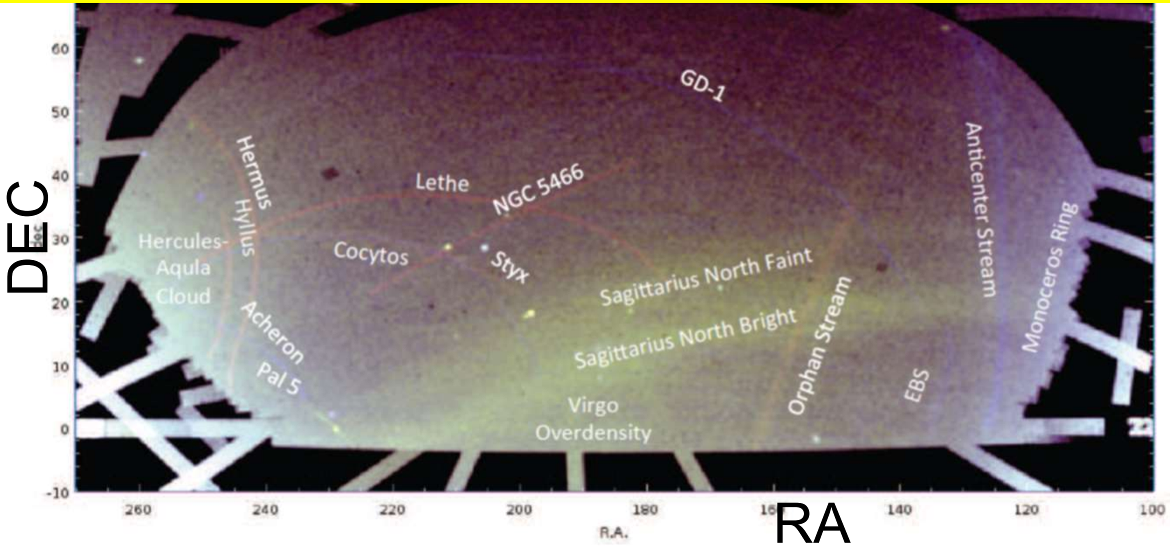
Nearby stars in angular-momentum space

（errors：a few 100 kpc km/s）

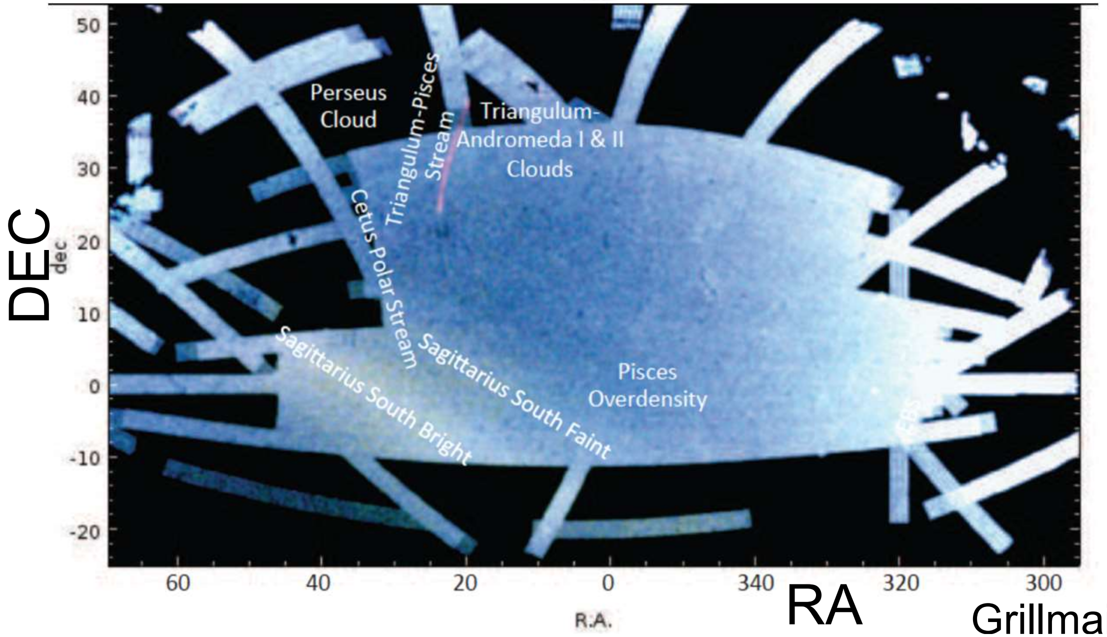


Chiba & Beers 2000

Stellar streams: remnants of merging small galaxies

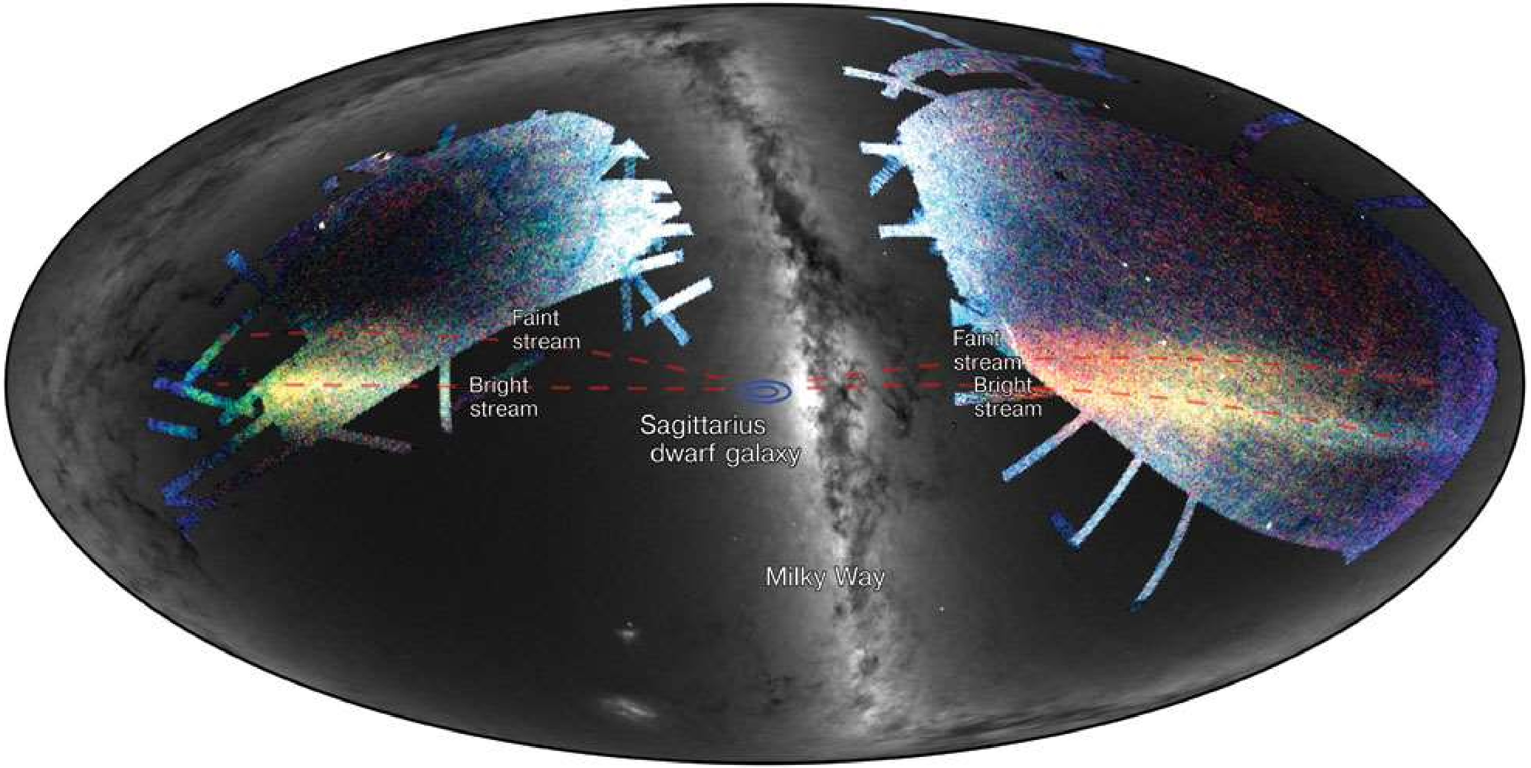


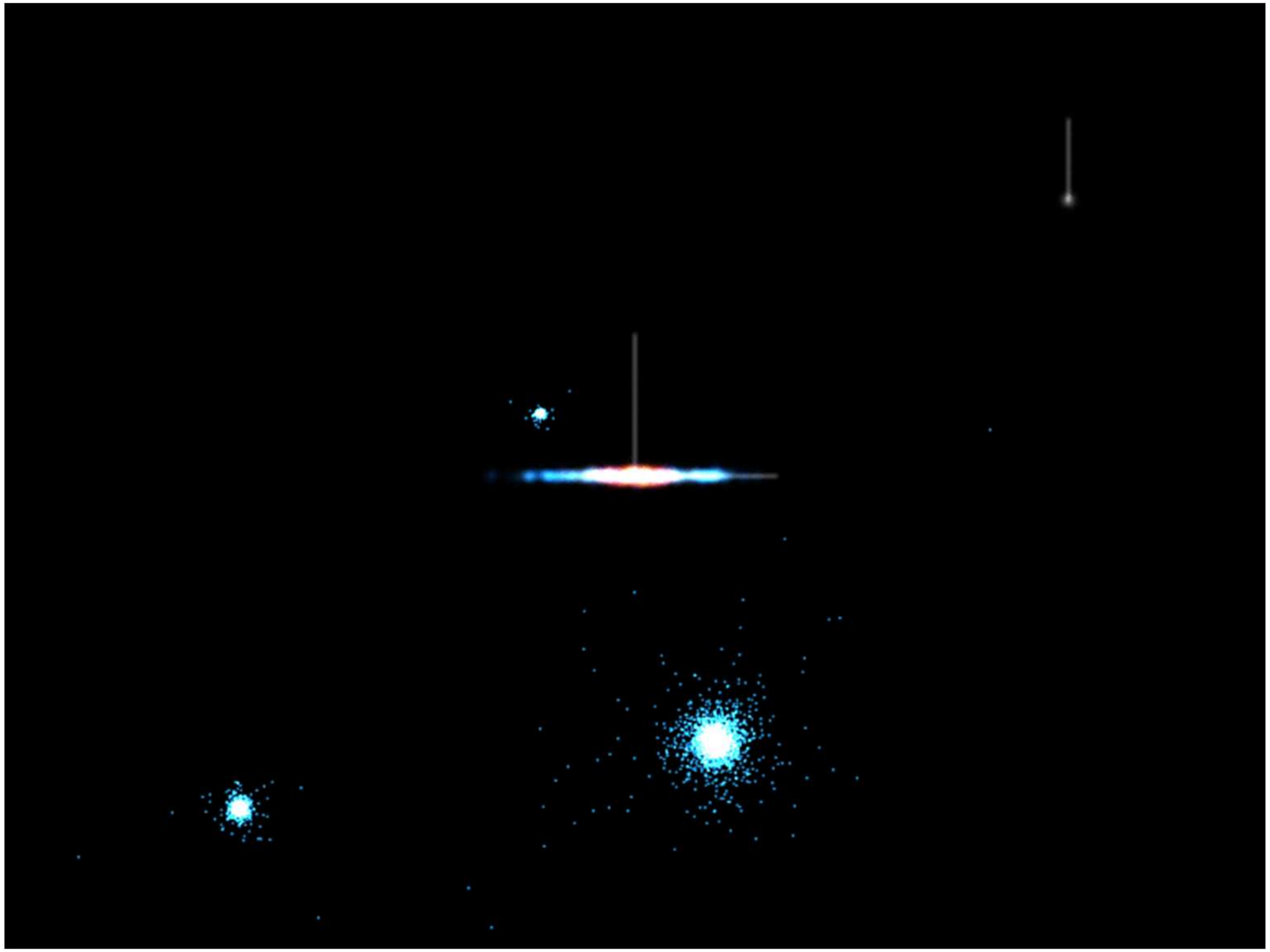
North



South

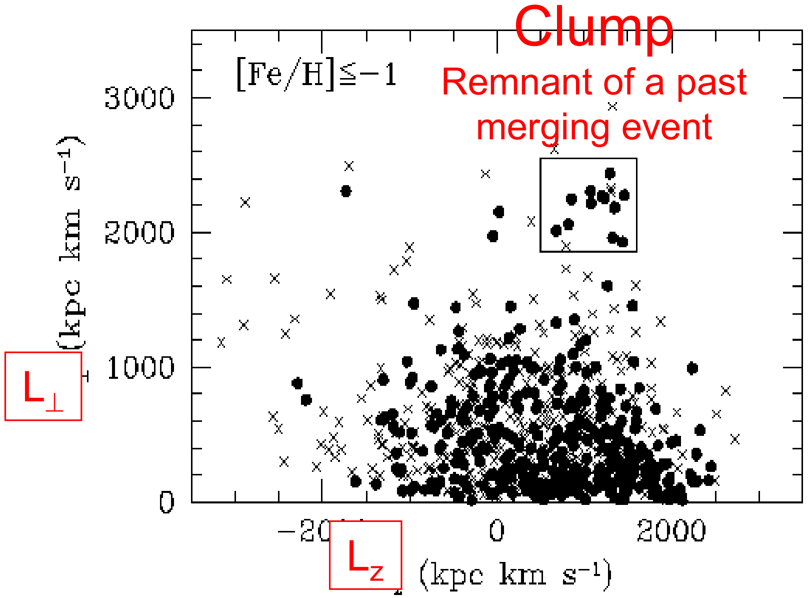
Grillmair & Carlin 2016


Faint stream
Bright stream
Sagittarius dwarf galaxy
Faint stream
Bright stream
Milky Way



Credit: Rensselaer/Benjamin A. Willett

Substructure in the stellar halo



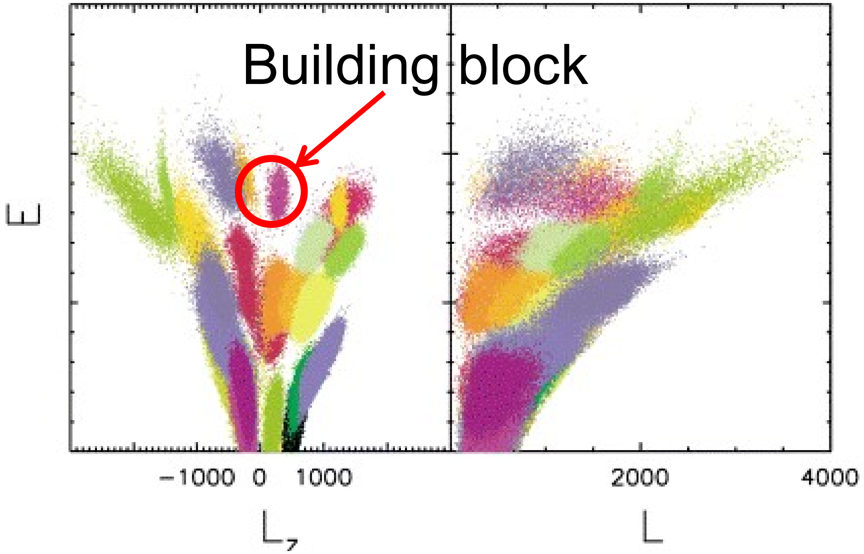
Clump

Remnant of a past merging event

Nearby stars in the angular-momentum space (using Hipparcos data)

- measurement errors of a few 100 (kpc km/s) smear out any possible substructures

MC & Beers 00



Building block

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

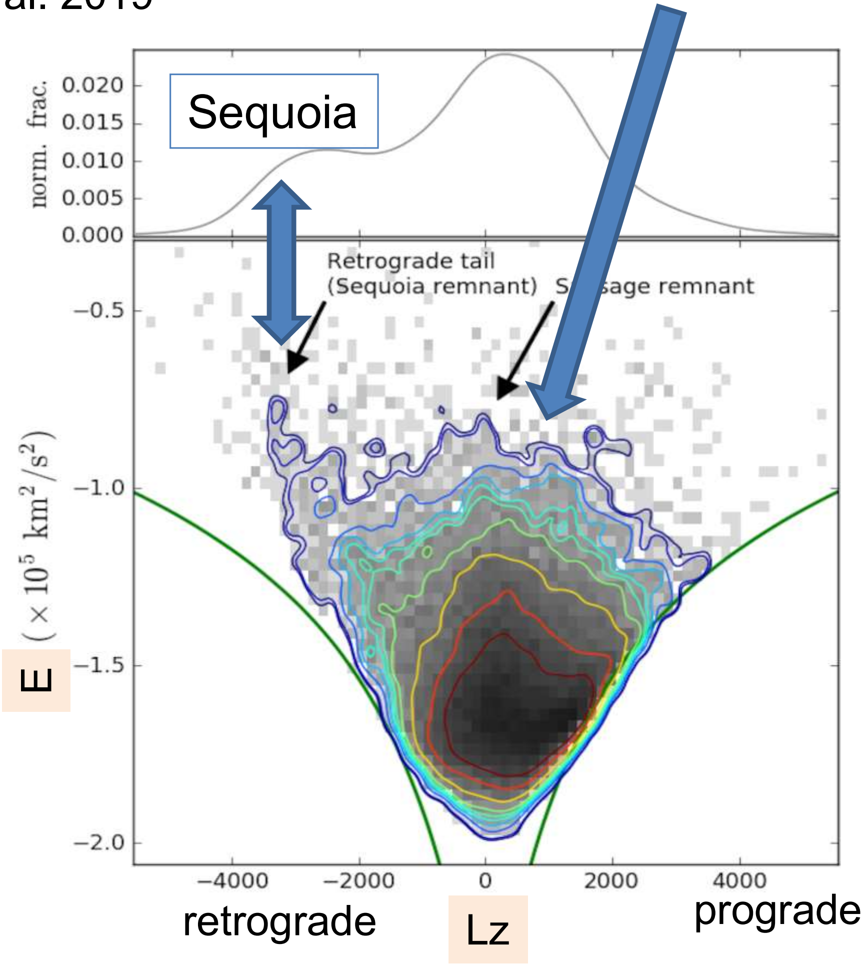
- distinguish each substructure
- SF & Chemical evolution

Helmi & de Zeeuw 00

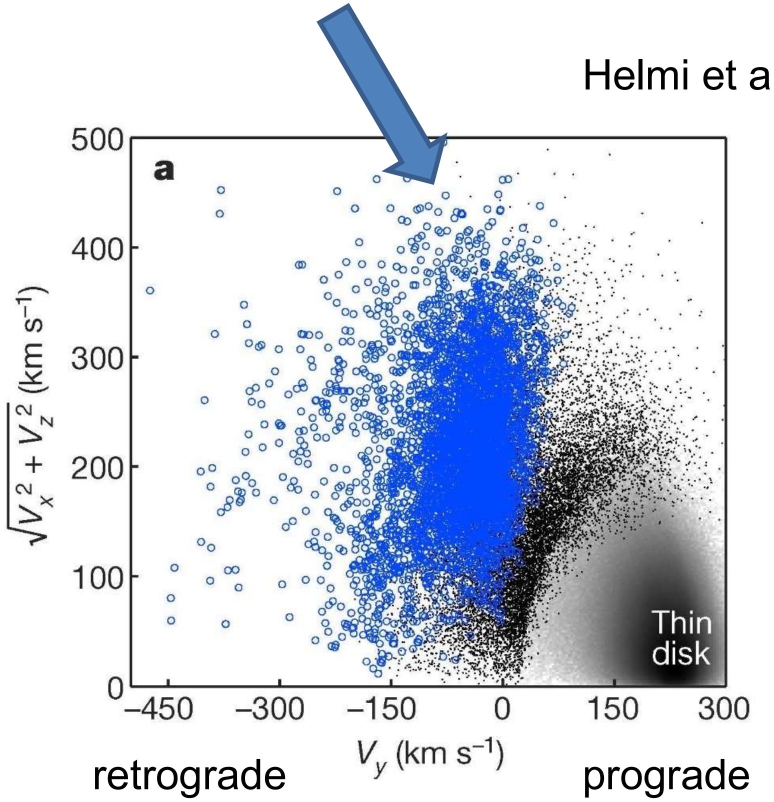
4. Formation of the stellar halo: after Gaia

Gaia-Enceladus/Sausage

Myeong et al. 2019



Helmi et al. 2018, Nature



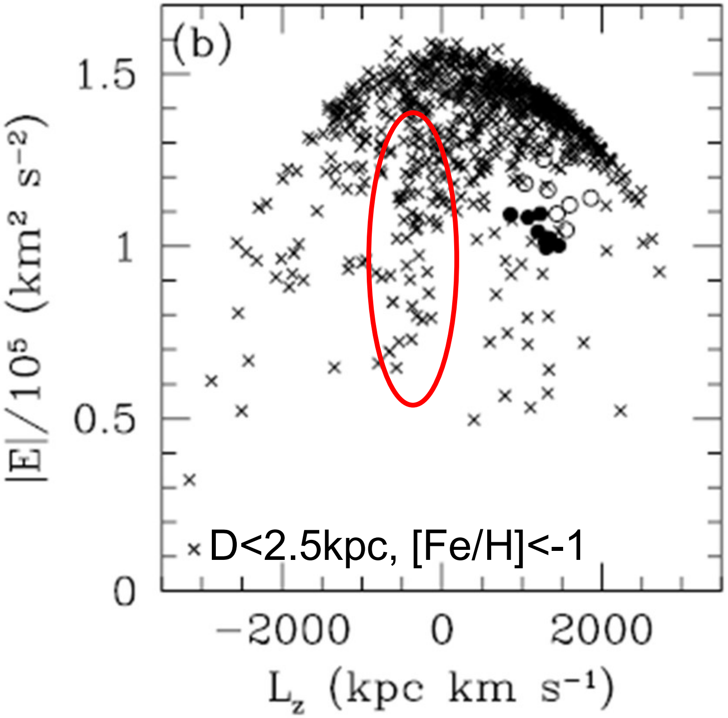
Merging debris of an SMC-class dwarf galaxy 10 Gyrs ago?

Another story …

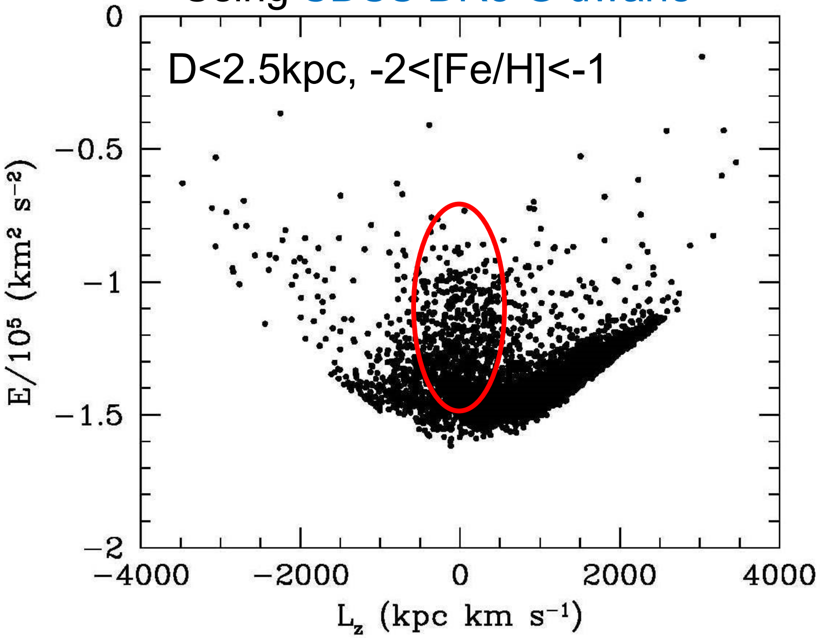
Hipparcos+SDSS-Enceladus?

(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

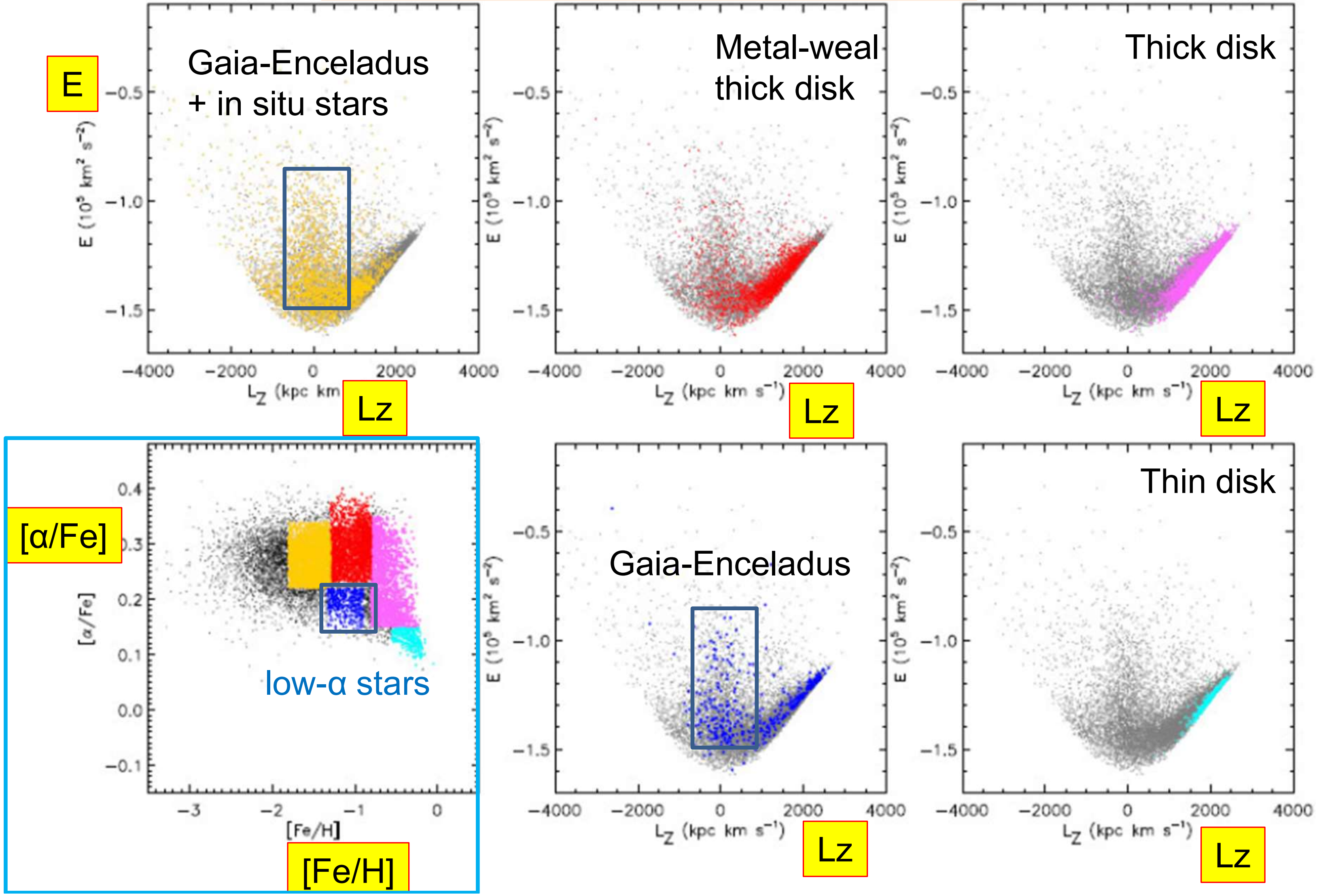
Merging of a dwarf galaxy 10 Gyrs ago?
Gaia-Enceladus

Credit: A. Helmi

Abundance ratios of Gaia-Enceladus

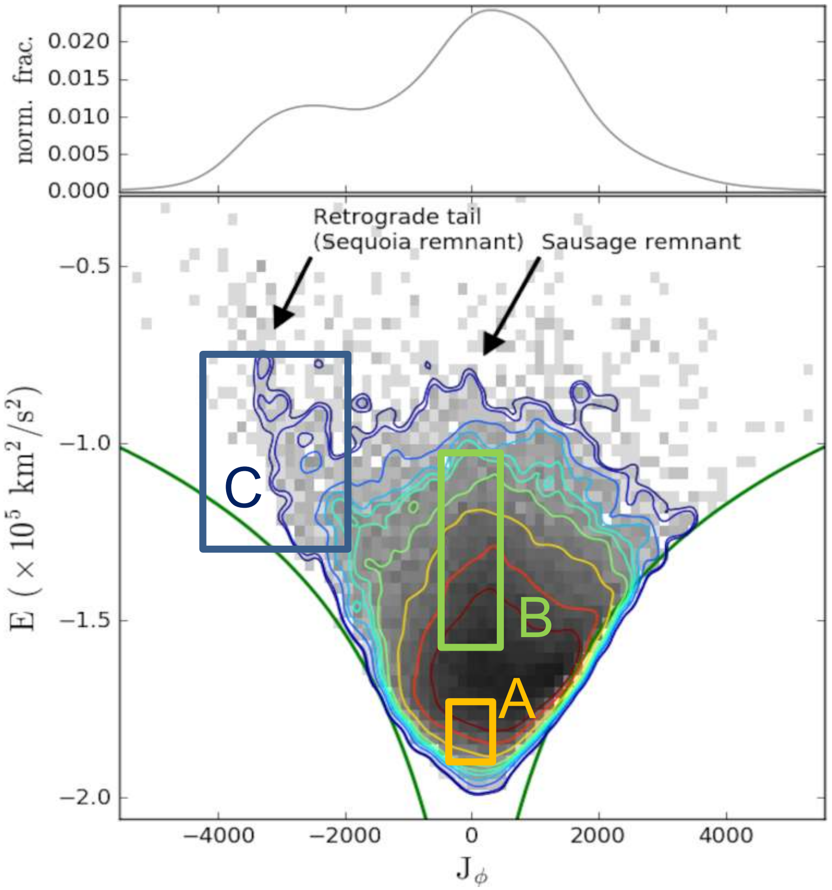
SDSS-DR7 Calibration Stars + Gaia DR2

Carollo & Chiba 2021

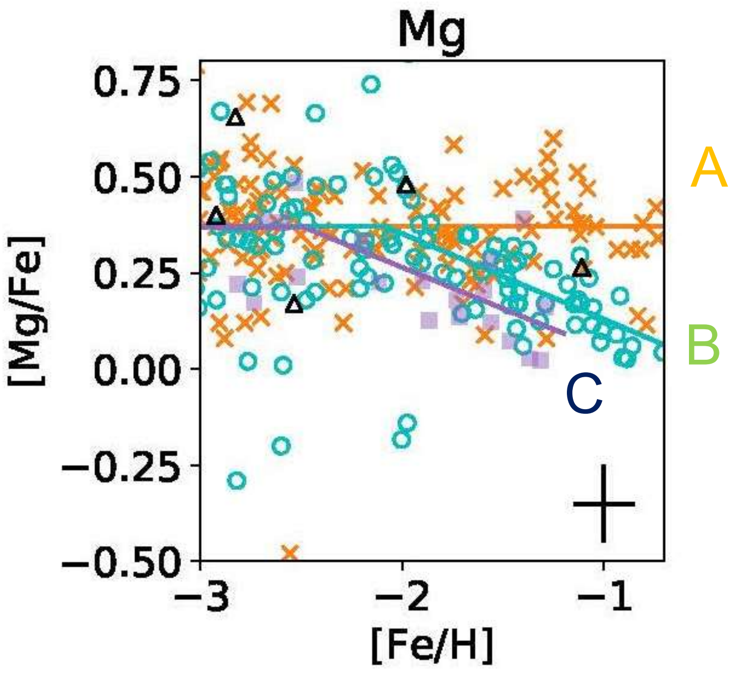


Abundance ratios

Myeong et al. 2019



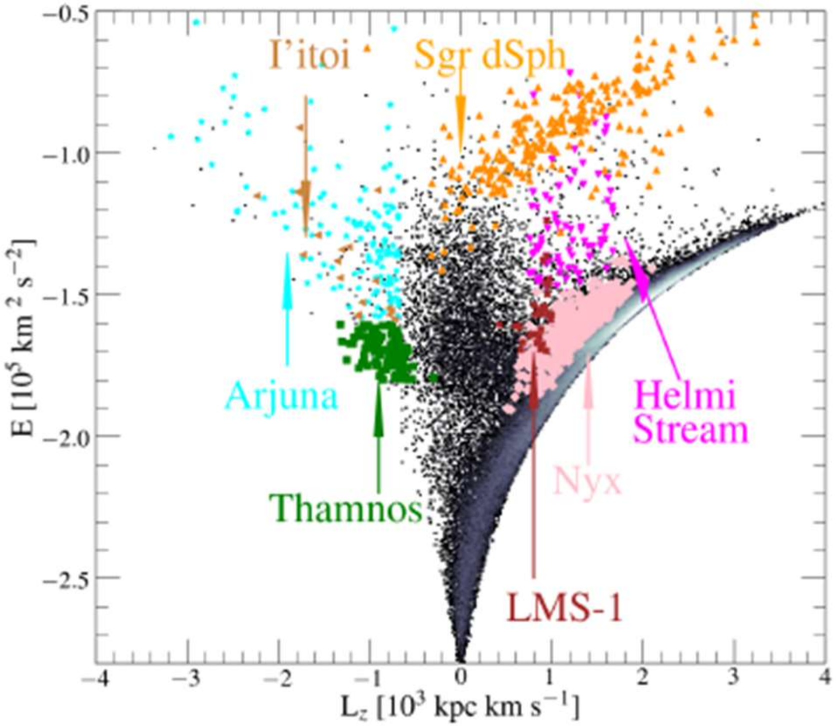
Matsuno et al. 2019
using SAGA & LAMOST

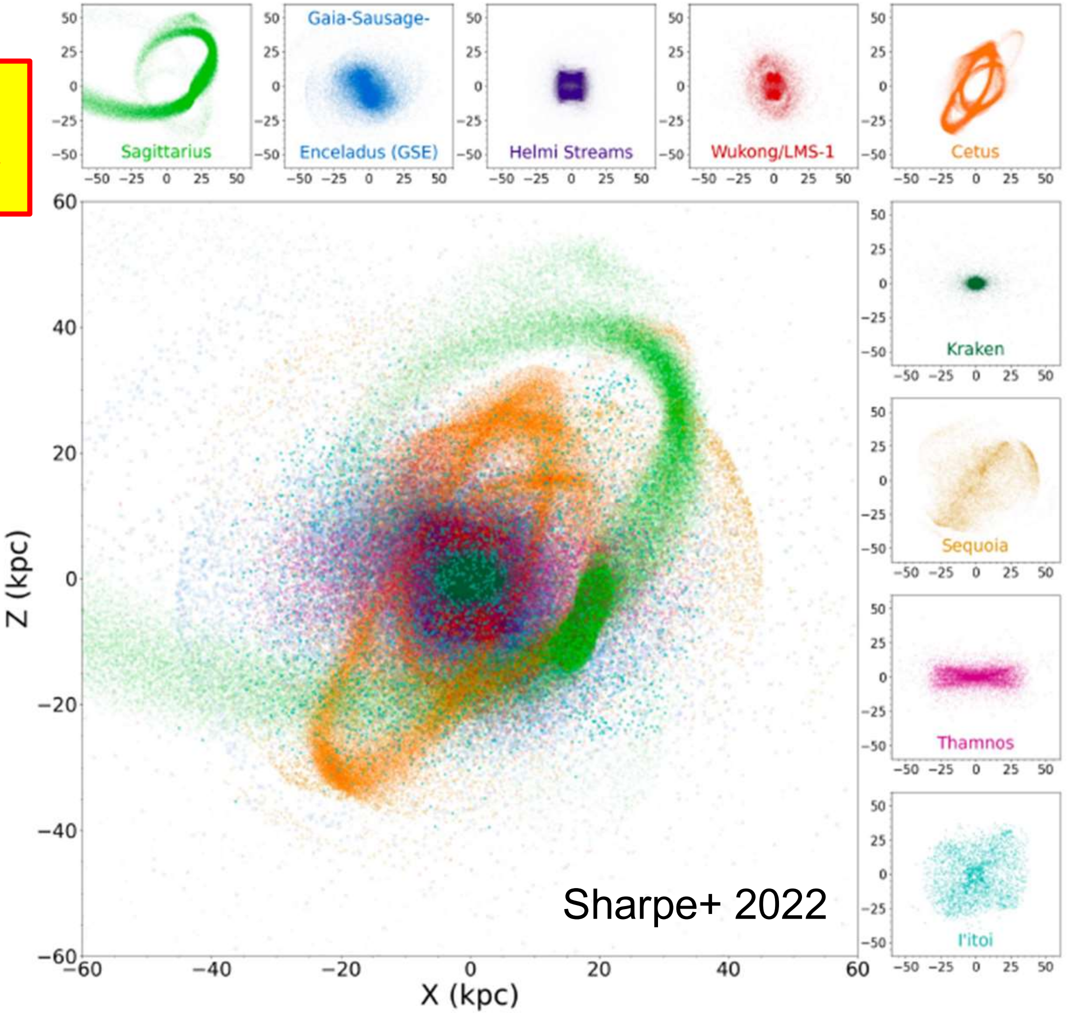


Deciphering merging history of the Galaxy

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

Horta+ 2022



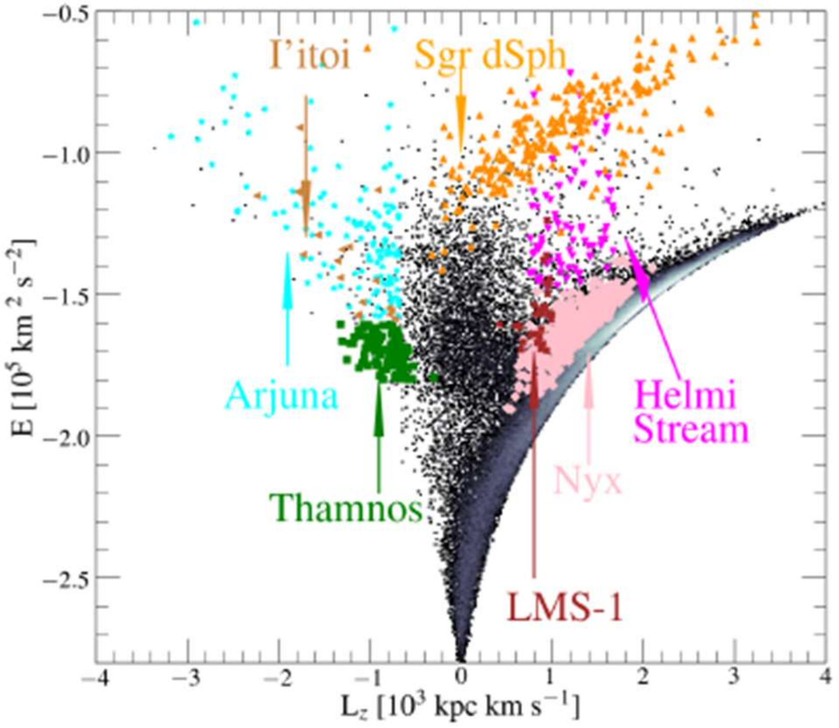


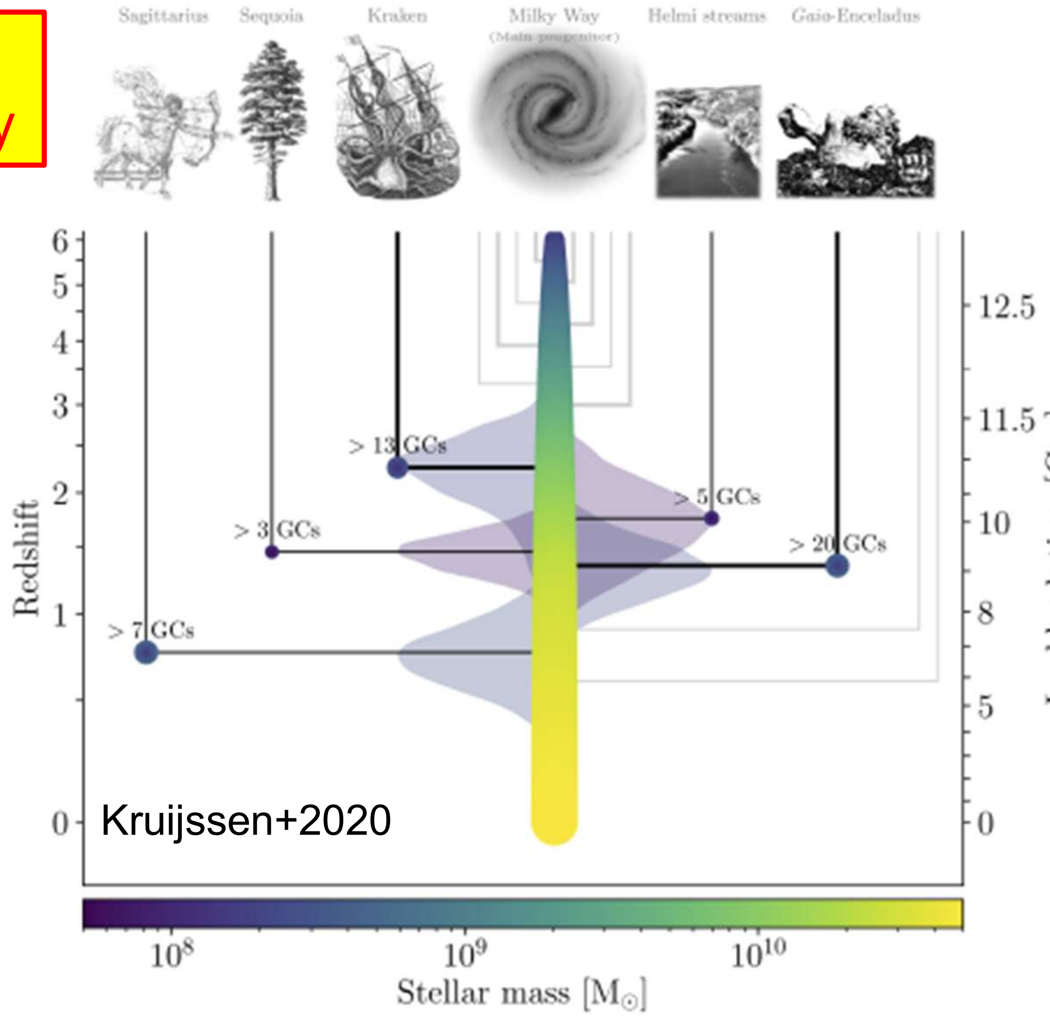
Sharpe+ 2022

Deciphering merging history of the Galaxy

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

Horta+ 2022

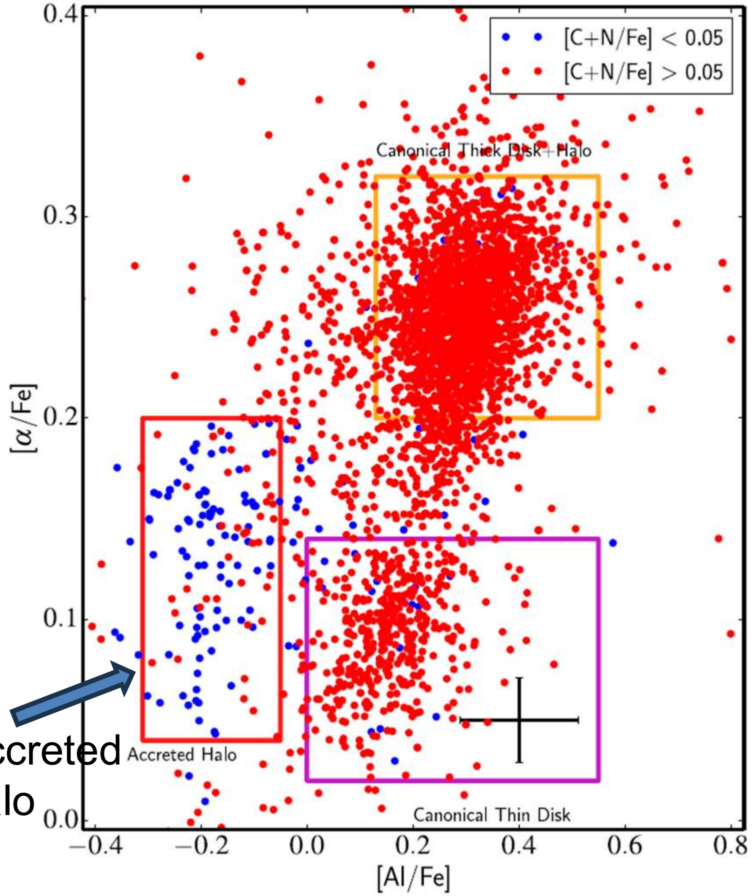




Kruijssen+2020

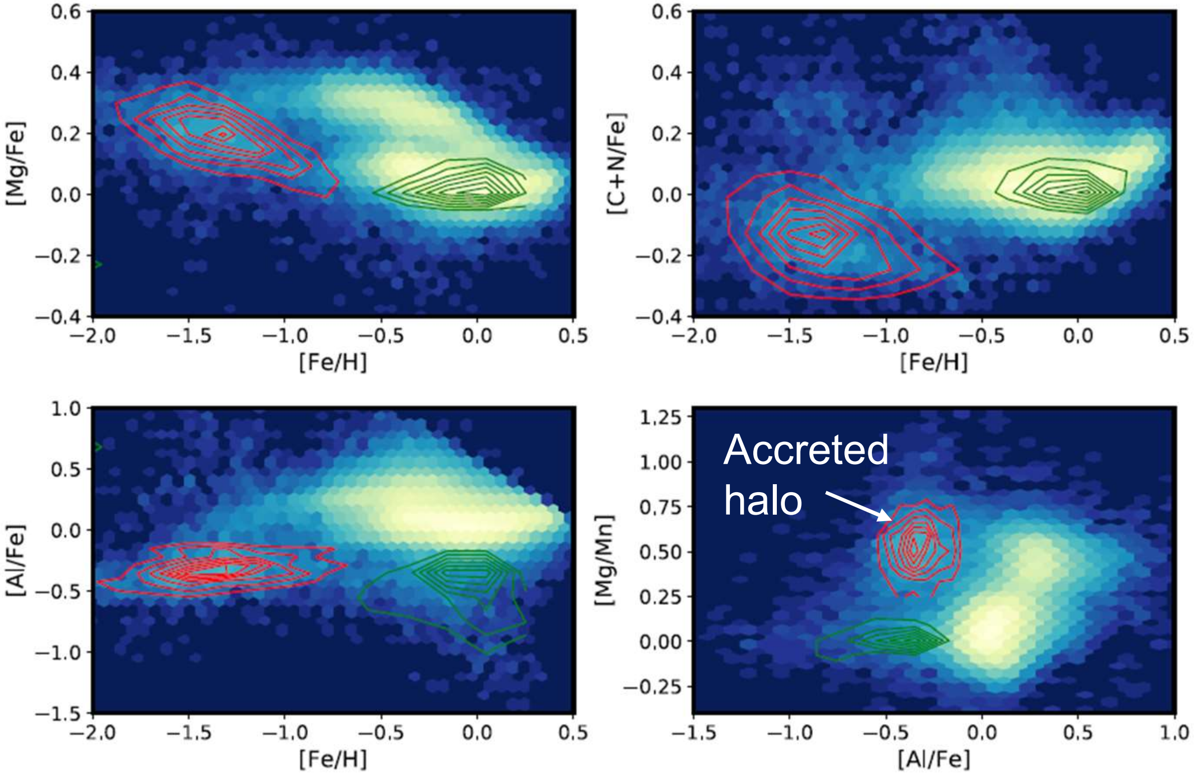
[Al/Fe] as an indicator of accreted/in situ halo

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



Accreted halo

Das et al. 2020 (APOGEE DR14)

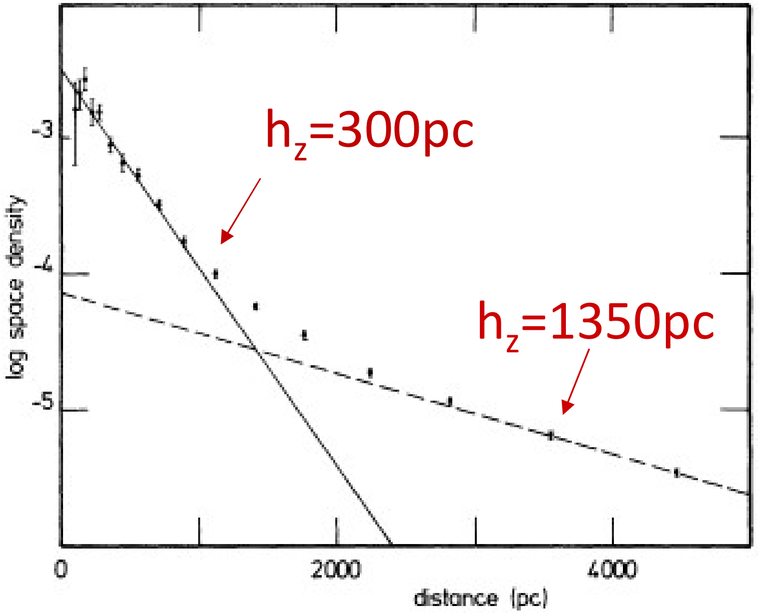


Accreted halo

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

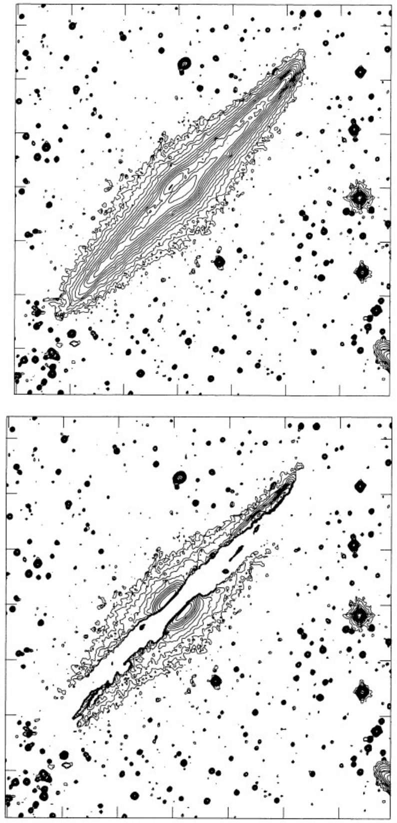
5. Formation of the thick disk

Star counts toward the SGP
Gilmore & Reid 1983



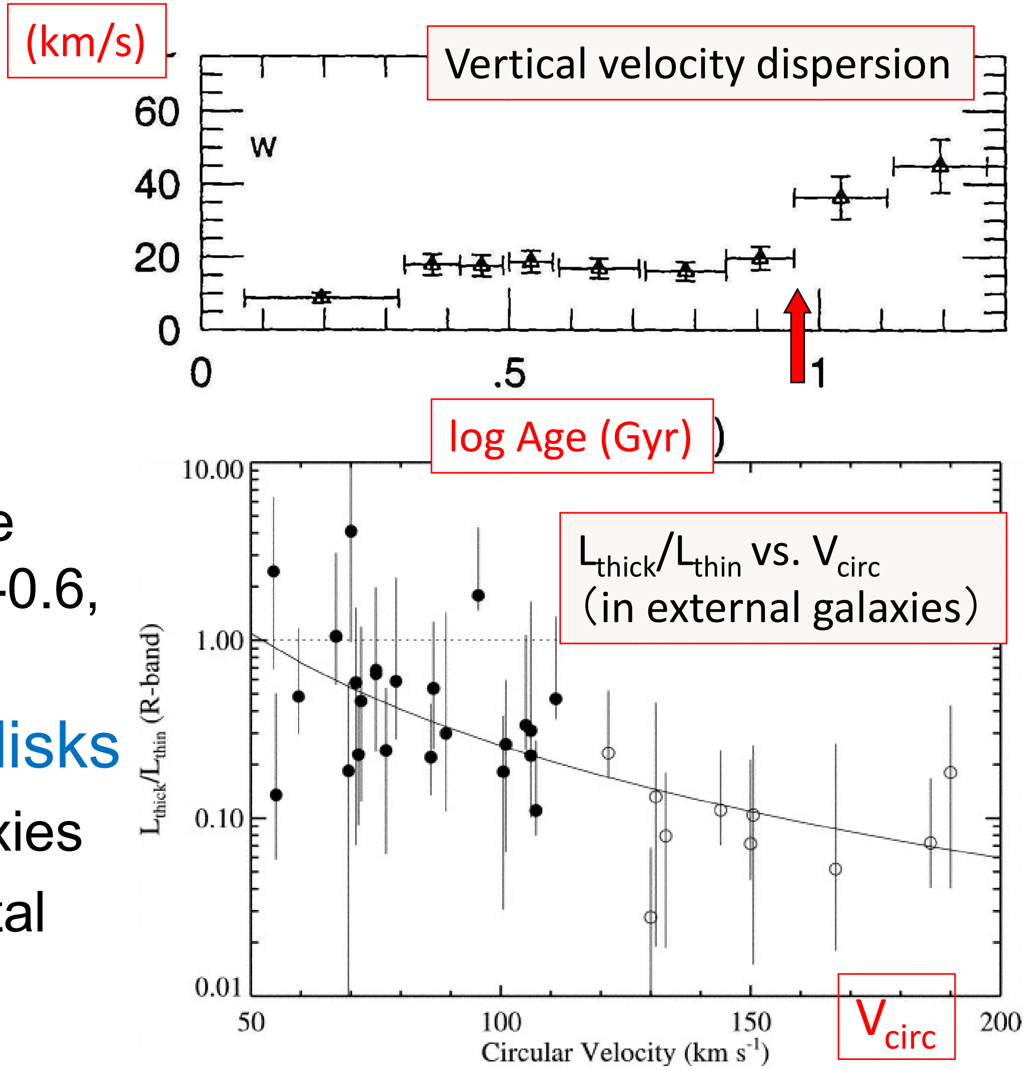
ρ_{thick}~2%ρ_{thin}

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)

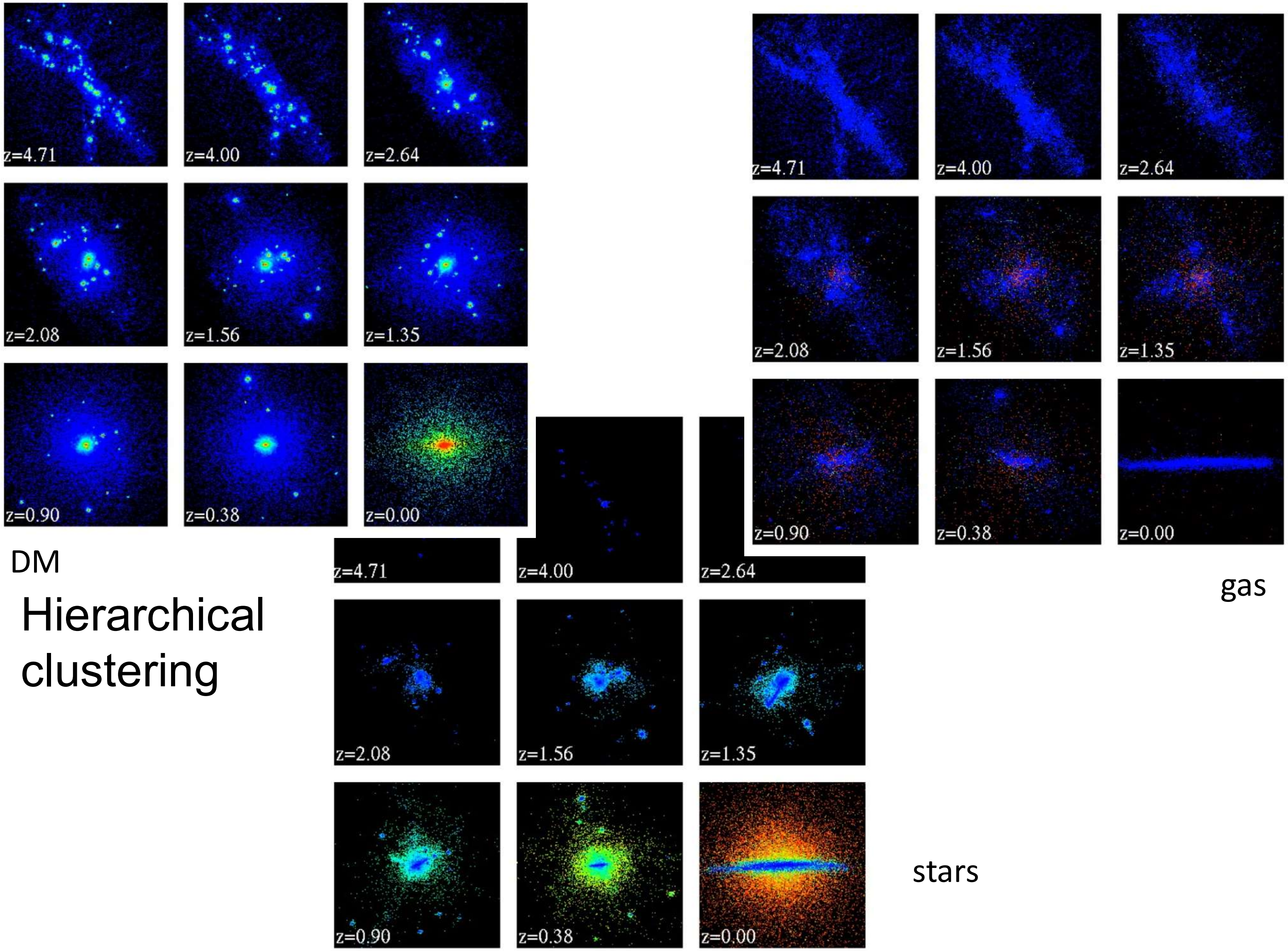
③ Multiple mergers (Brook+2004, 2005)

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



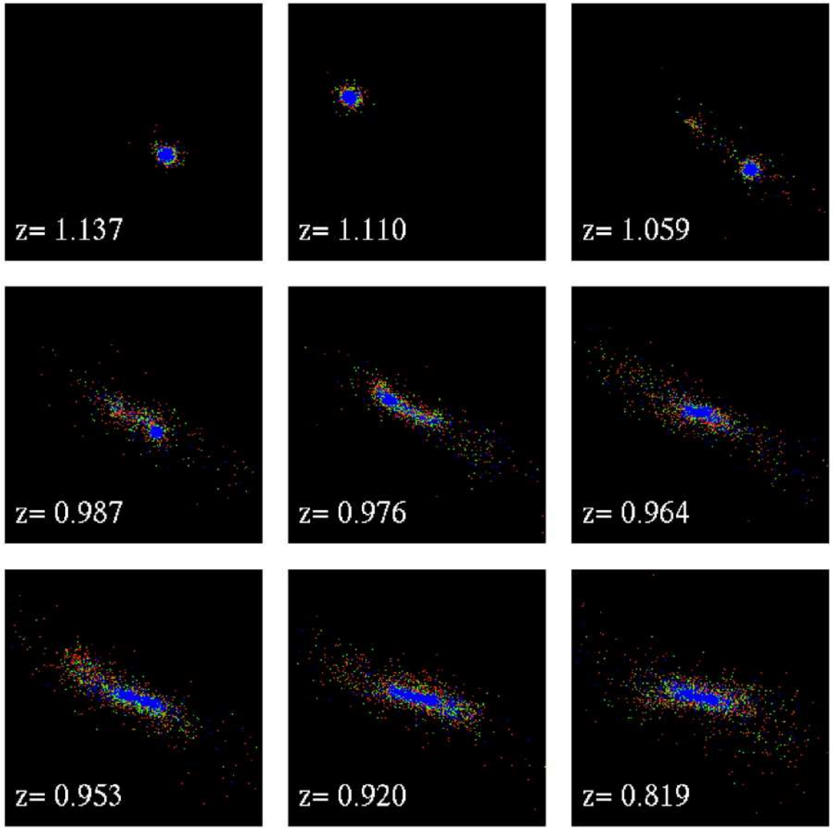
DM

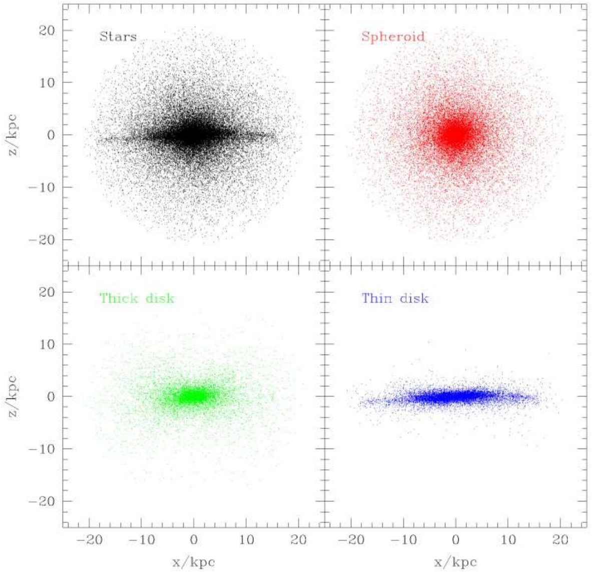
Hierarchical clustering

gas

stars

Shredded satellite → thick disk?



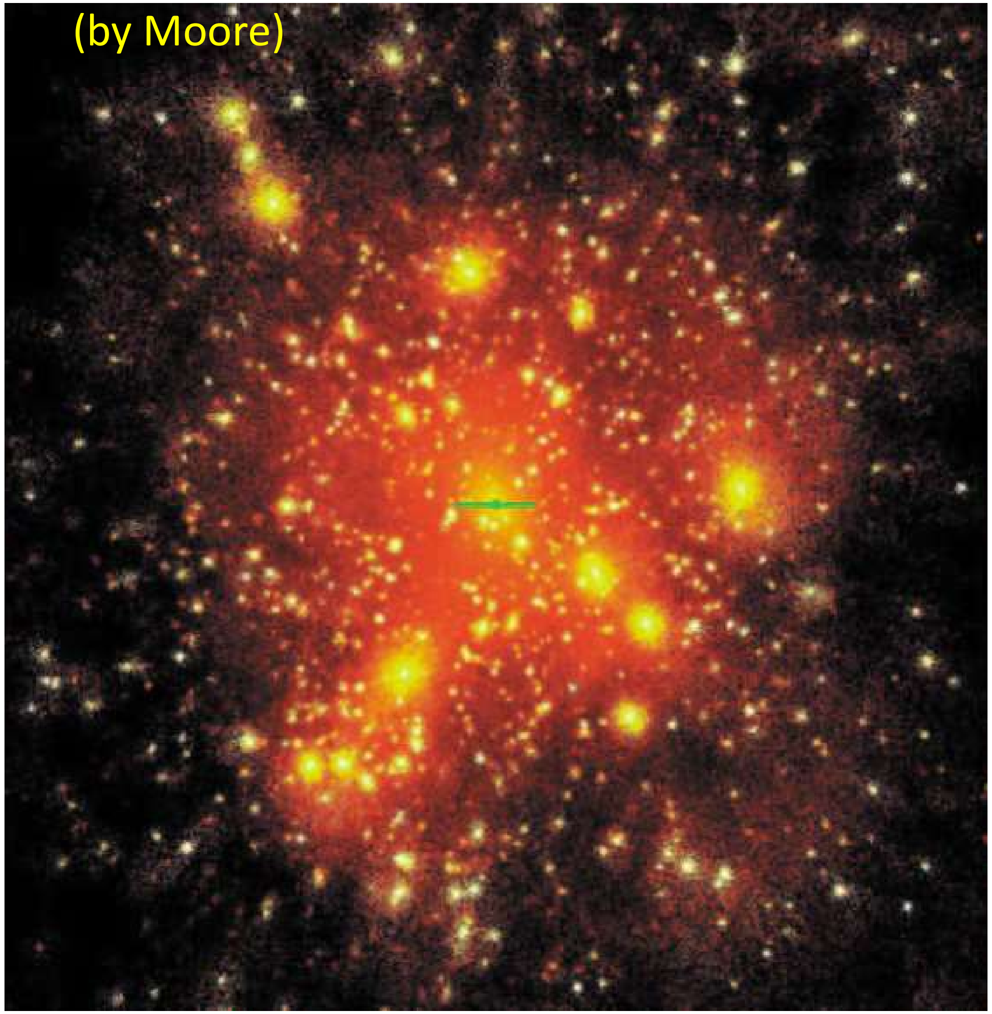


But [Fe/H] and [α/Fe] in satellites are very different from those in the thick disk.

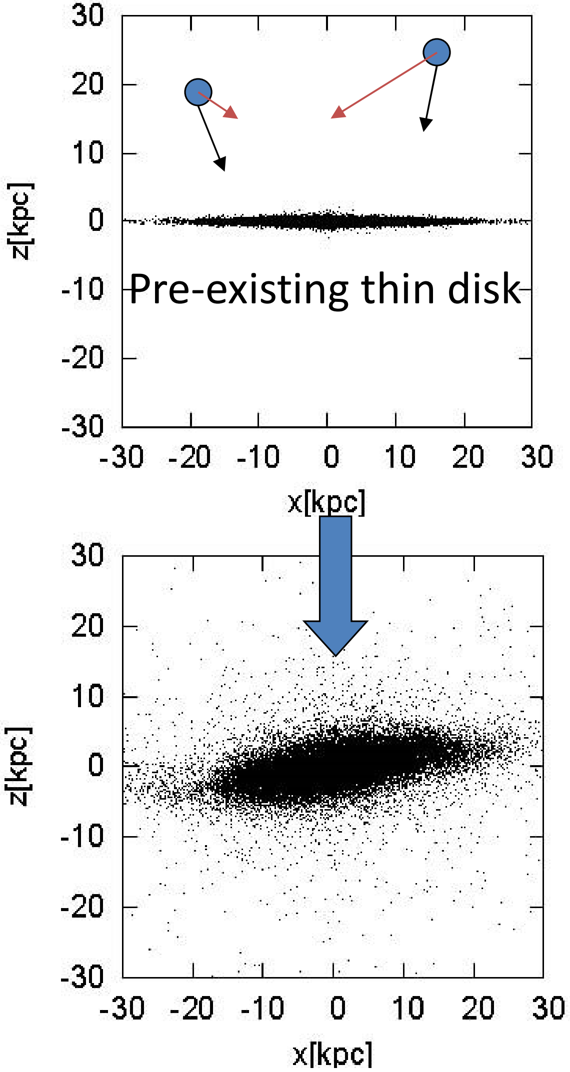
④. Dynamical heating of a thin disk by dark-matter subhalos

(Hayashi & Chiba 2006)

Distribution of dark halos in a galactic scale



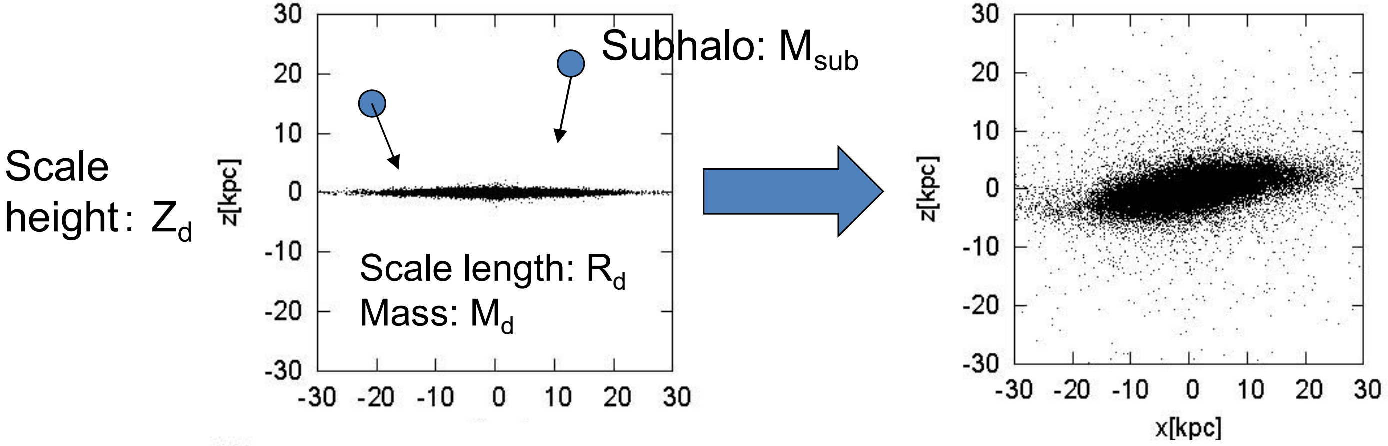
(by Moore)

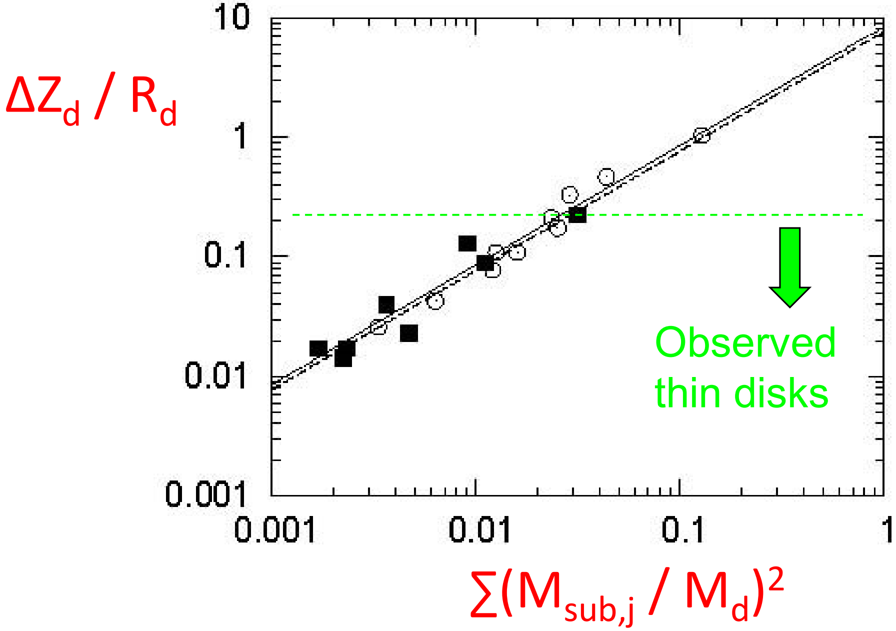


Pre-existing thin disk

Numerical simulation of disk heating

(Hayashi & Chiba 2006)





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

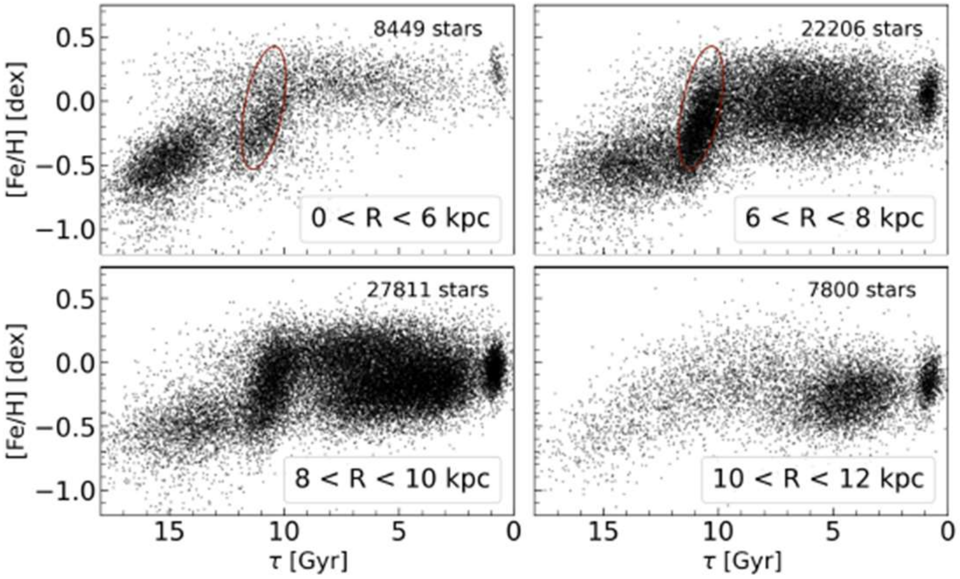
Observed thin disks: $Z_d / R_d < 0.2$
(Kregel et al. 2002)
⇒ accreted subhalo mass
$< 0.15 M_d$

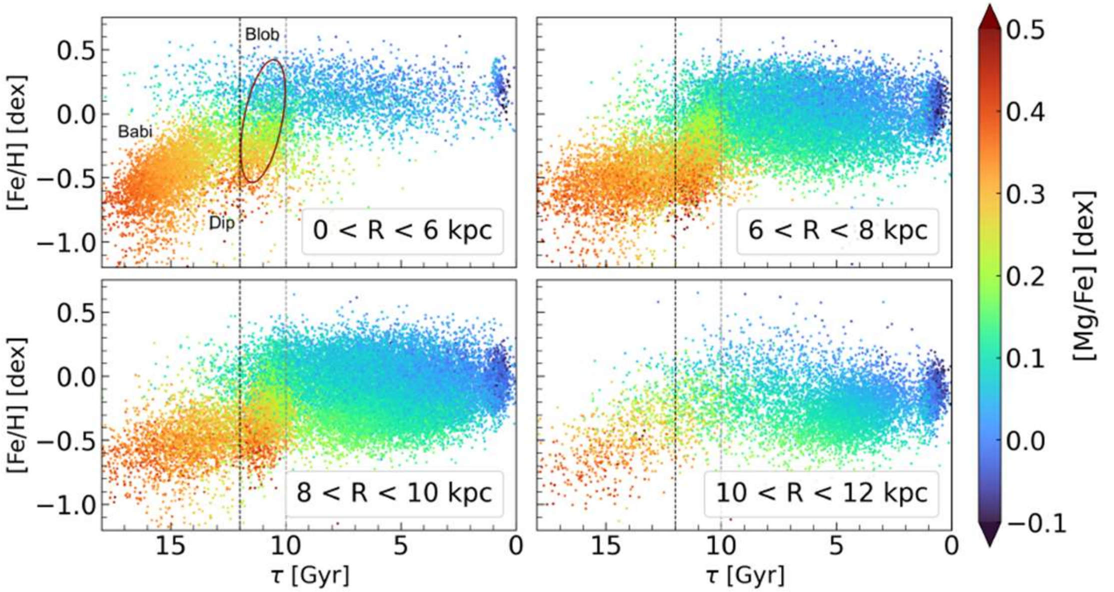
Signature for GES merger on thick disk formation

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]↓

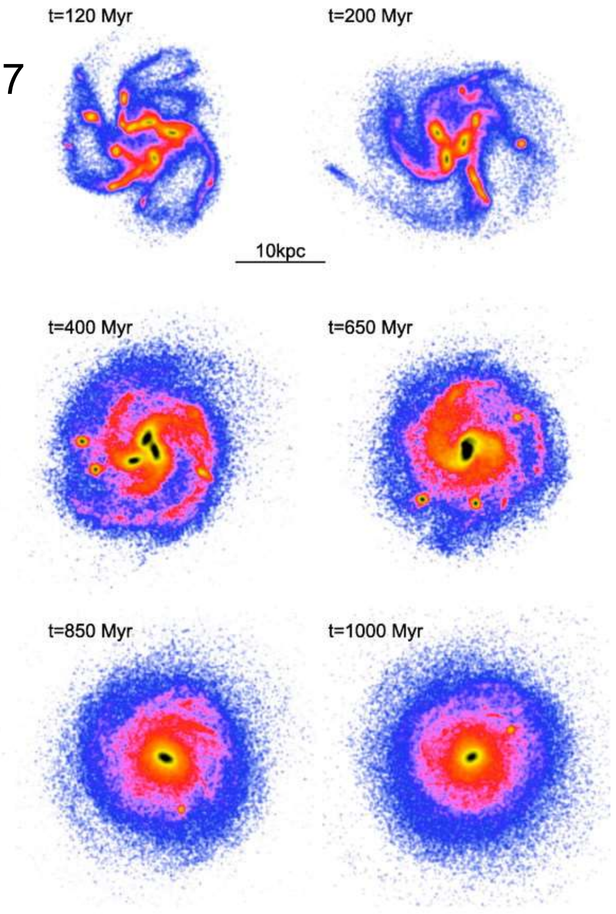
⇒SF + chemical evolution ⇒[Fe/H]↑, [Mg/Fe]↓⇒ metal-rich part of the thick disk

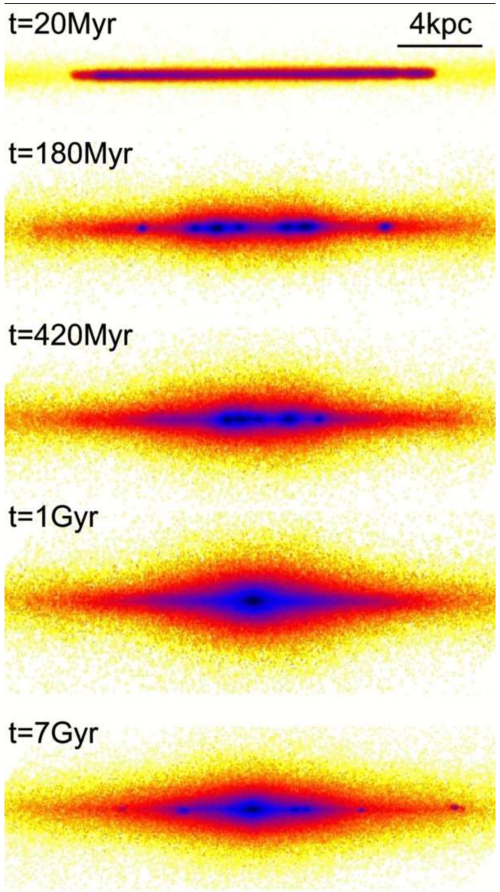
⑤. Clumpy disk evolution

Thick disks as relics of clumpy disk evolution?

(Noguchi 1999; Bournaud+2007; 2009)

Bournaud+2007



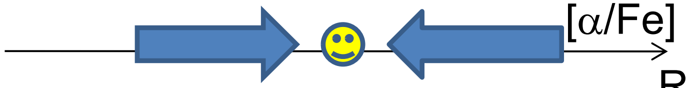


Symmetric structure along z, metal-poor stars?, d<vϕ>/dz?

⑥. Radial migration due to local spiral arms

Radial migration of disk stars
(Schönrich & Binney 2009)

thick disk stars?



Stars getting L_z

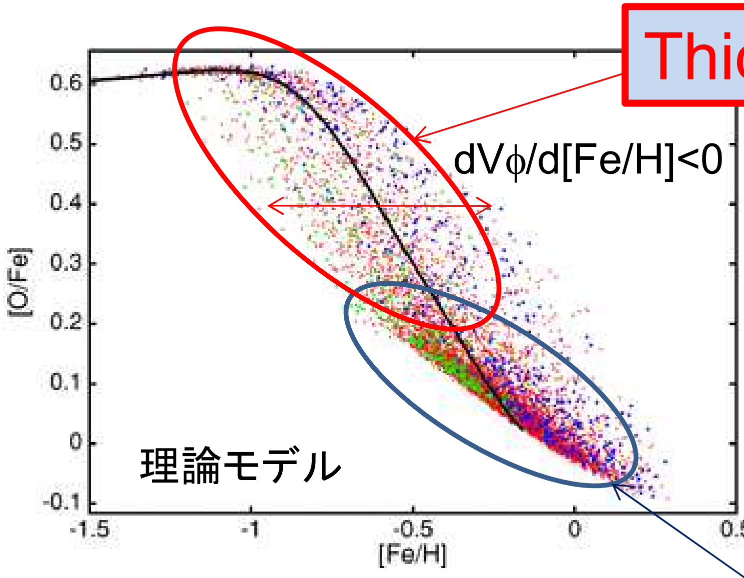
Stars losing L_z

[α/Fe] larger at larger R

R

transient spiral arms etc.

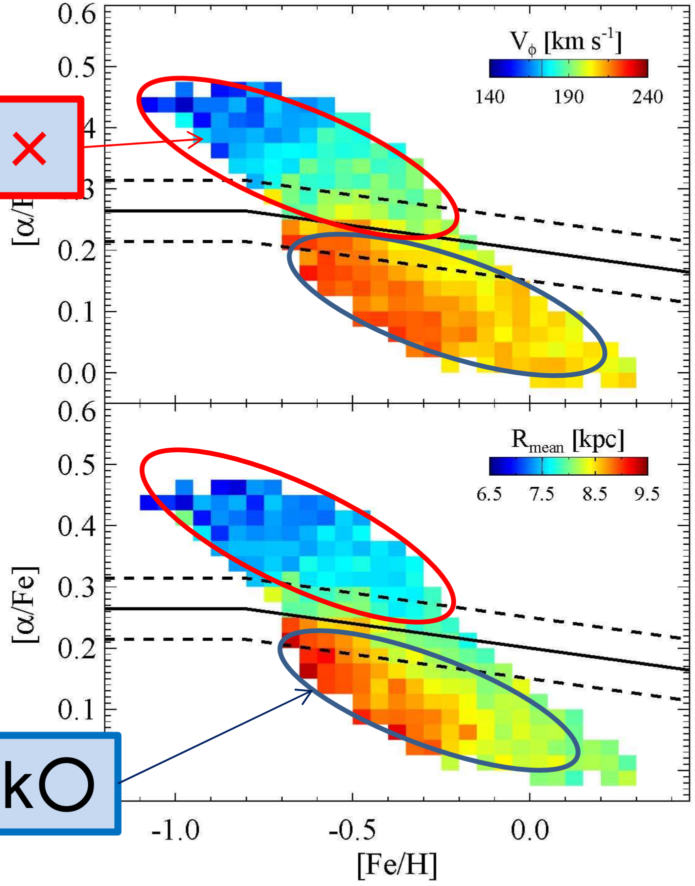
Lee+2010 SDSS sample



理論モデル

dVϕ/d[Fe/H]<0

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



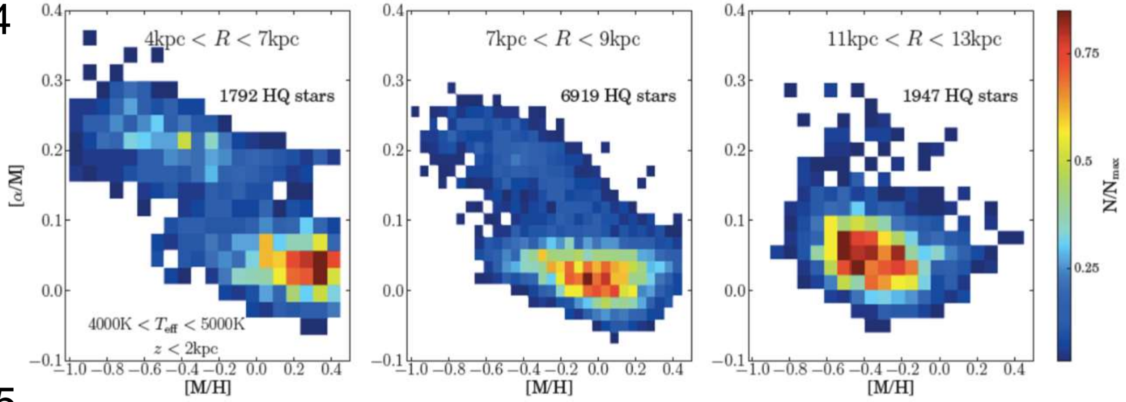
Thick disk ×

Thin disk○

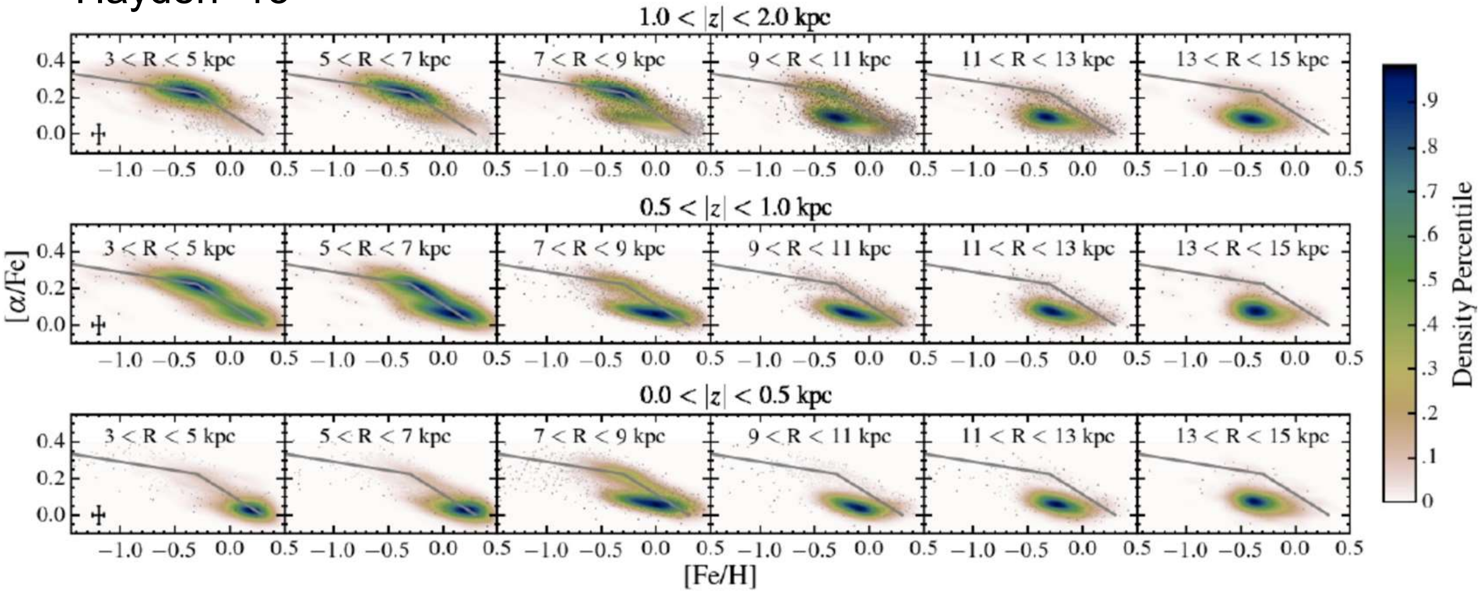
Results of SDSS/APOGEE

Anders+14

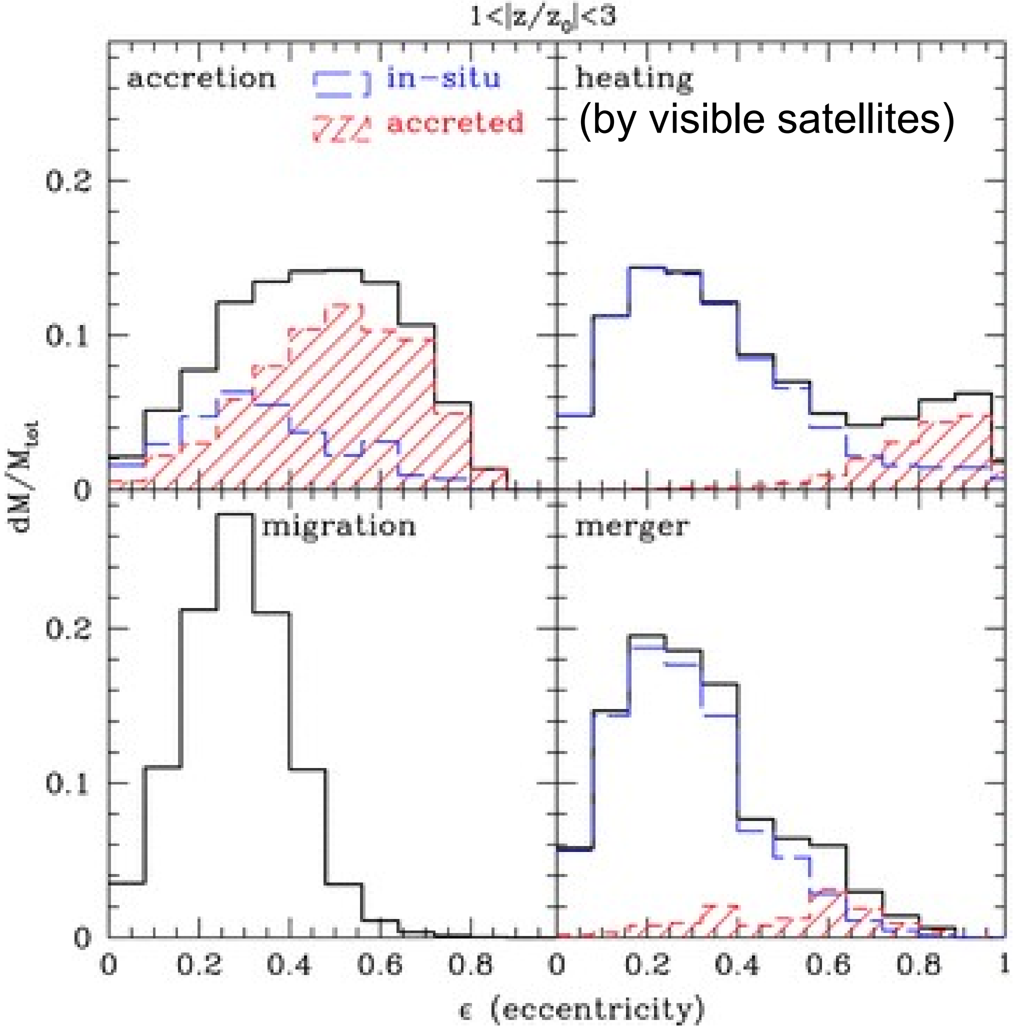
Presence of separate high [α/Fe] + low scale-length component



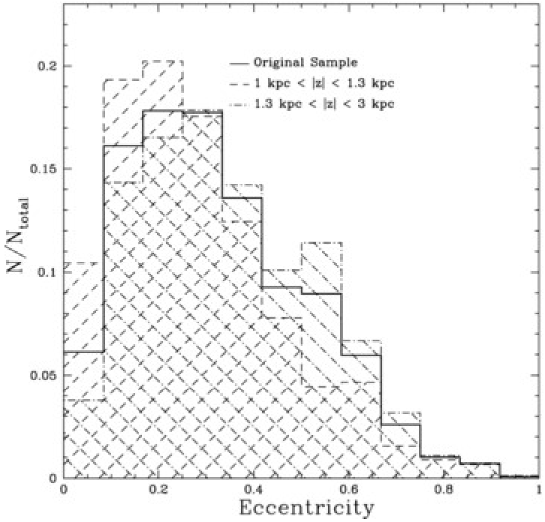
Hayden+15



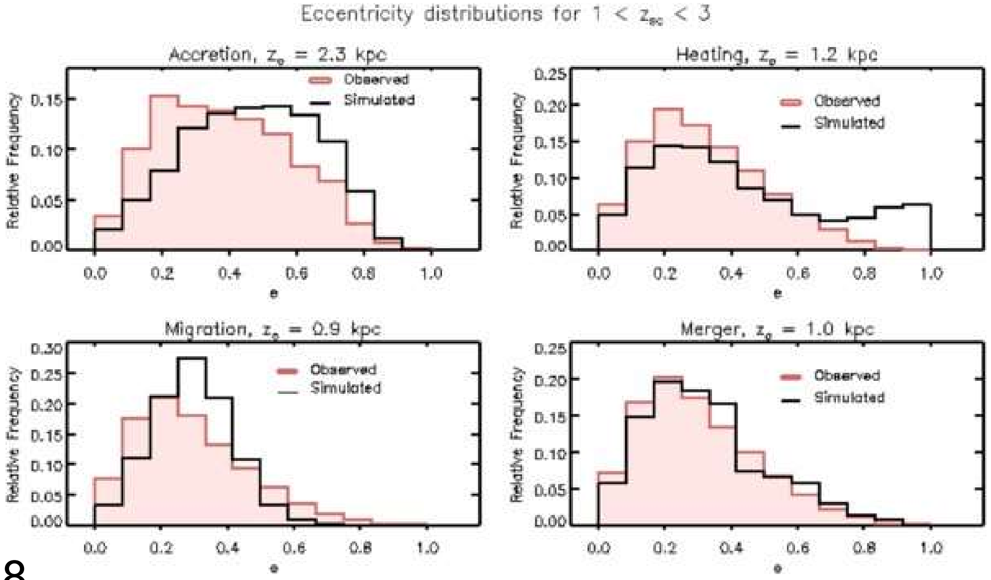
Orbital eccentricity distributions of several models
Sales+ 2009



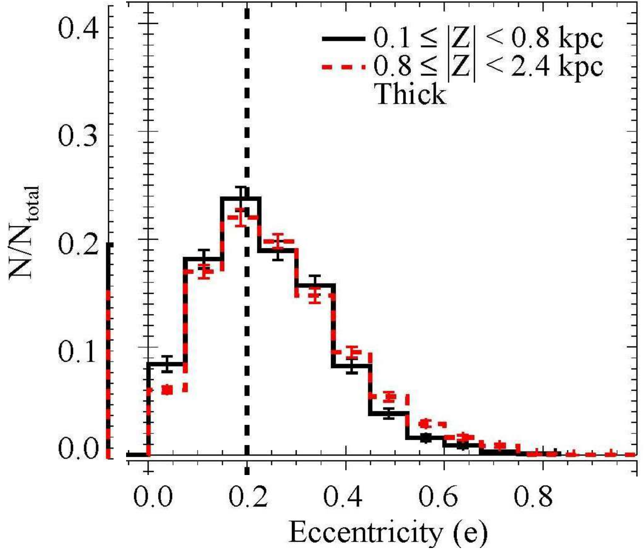
Wilson+2011: RAVE sample



Dierickx+ 2010: SDSS sample DR7



Lee+ 2011: SDSS sample DR8



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

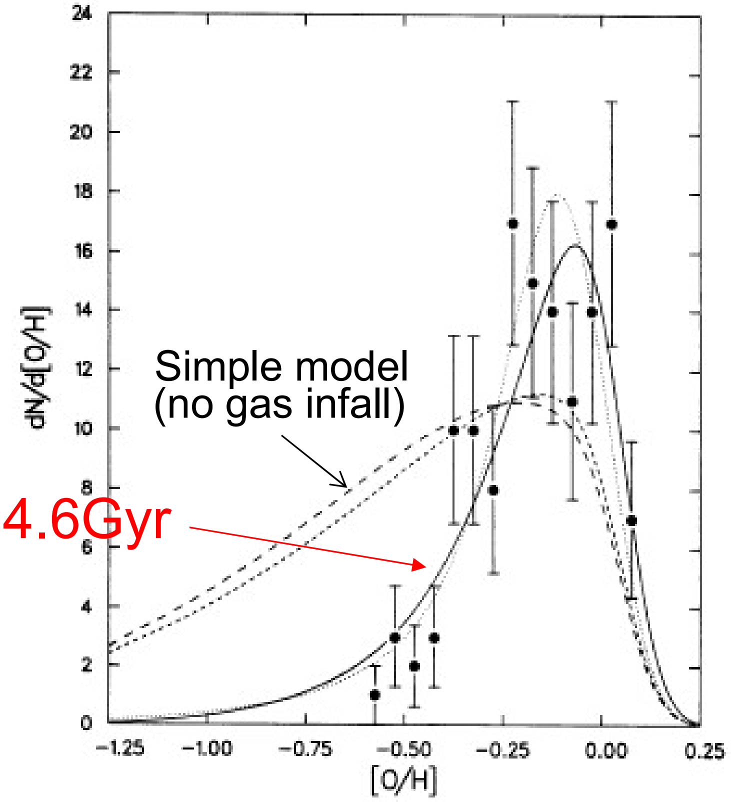
Score sheet for thick-disk formation models

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)

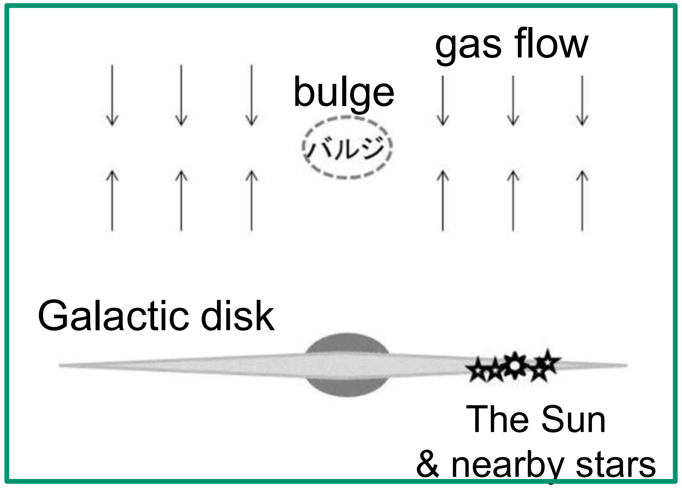


Simple model
(no gas infall)

t_{infall}=4.6Gyr

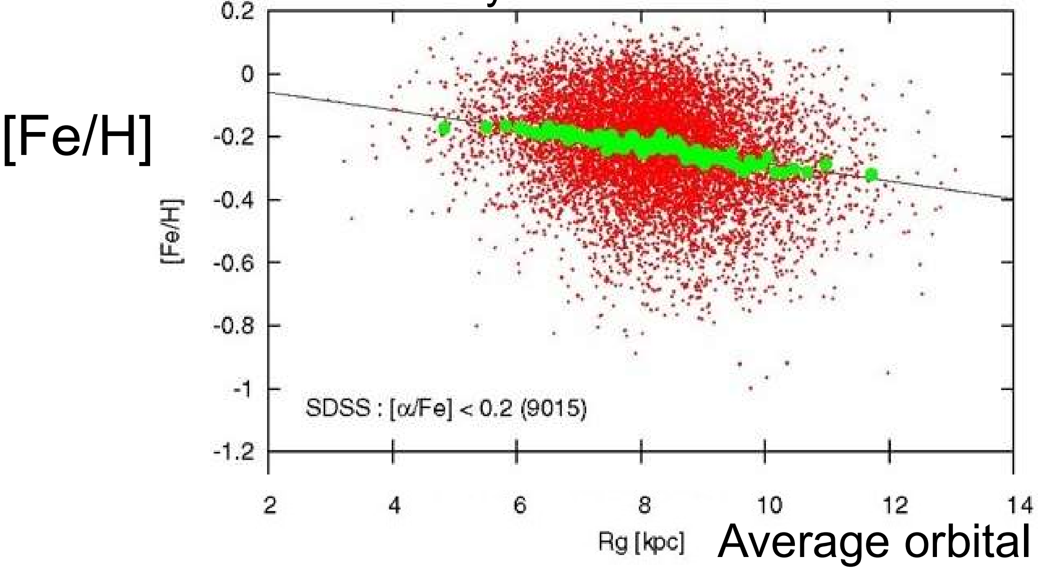
$d\Sigma_{gas}/dt \propto \exp(-t / t_{infall})$
t_{infall}~4-5 Gyr is required

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

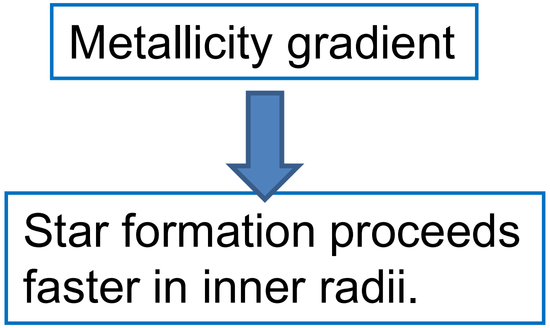


Inside-out formation of the thin disk

Toyouchi & Chiba 2014

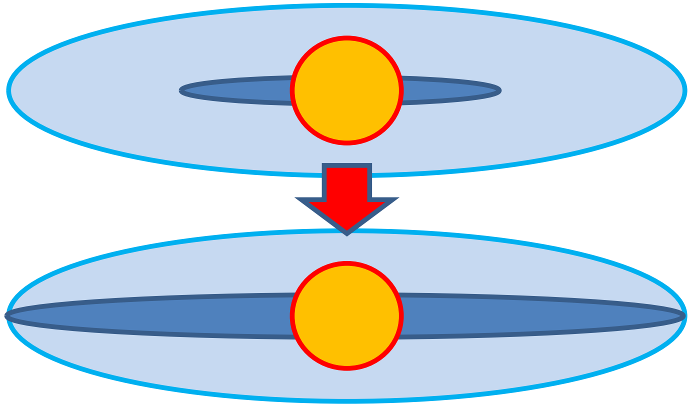


Average orbital radius (kpc)



Metallicity gradient

Star formation proceeds faster in inner radii.



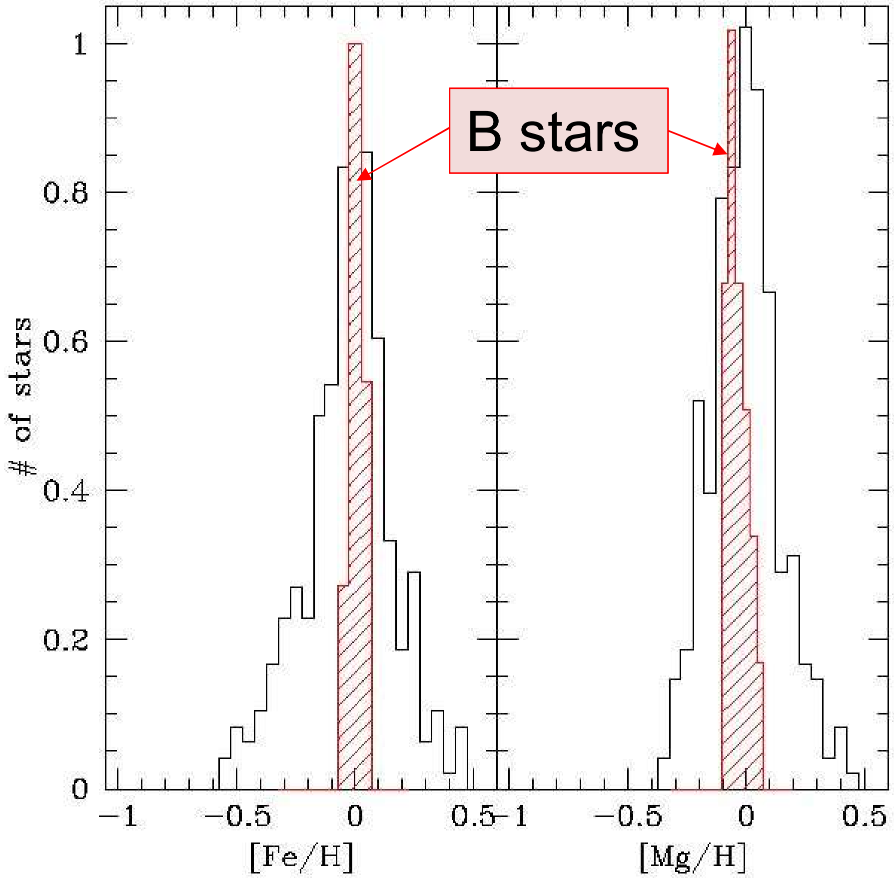
The thin disk has formed from inner to outer radii

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)

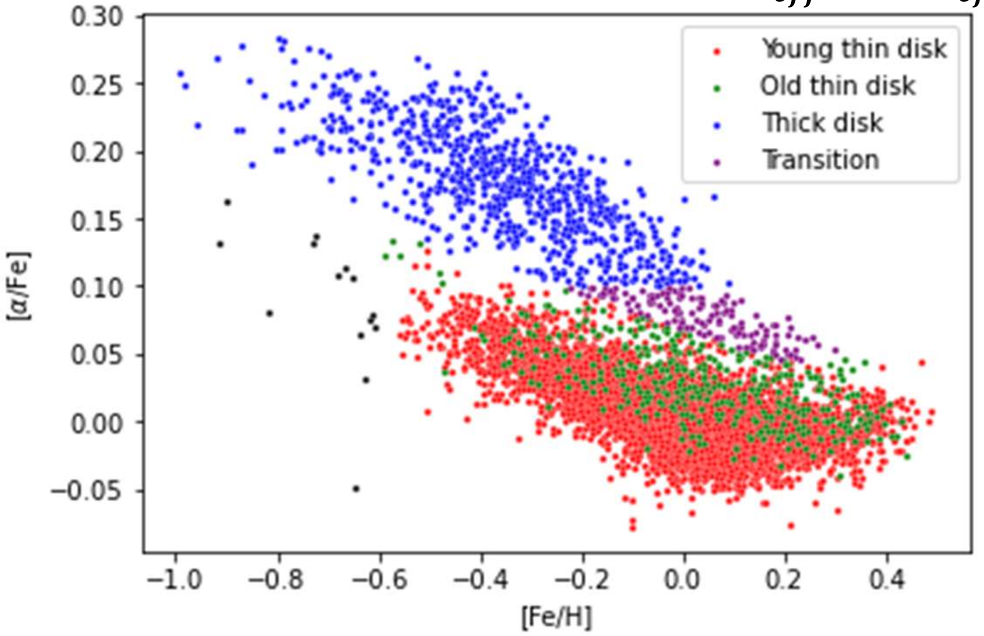
Chang

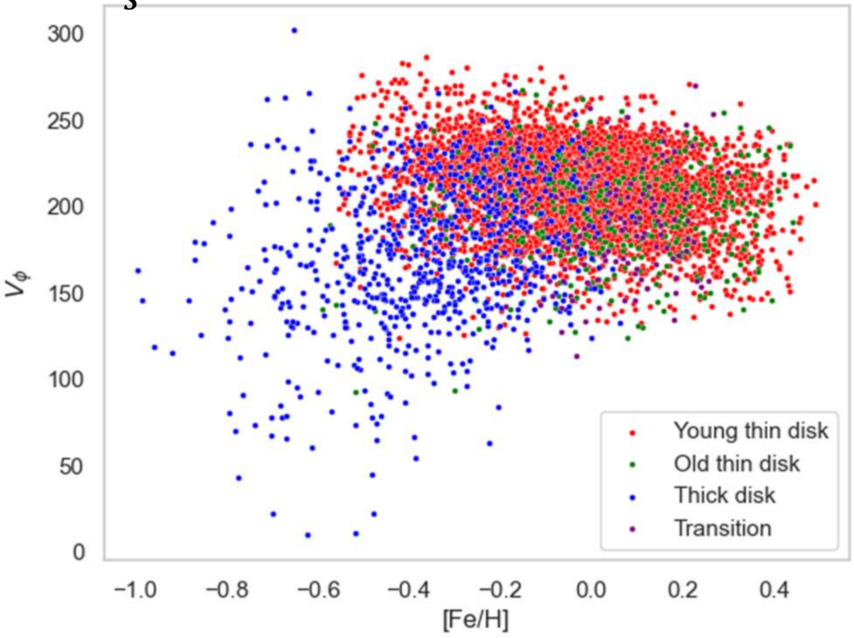
5436 RGBs & RCs (APOKASC-2, APOGEE DR16, Gaia EDR3)

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

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

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



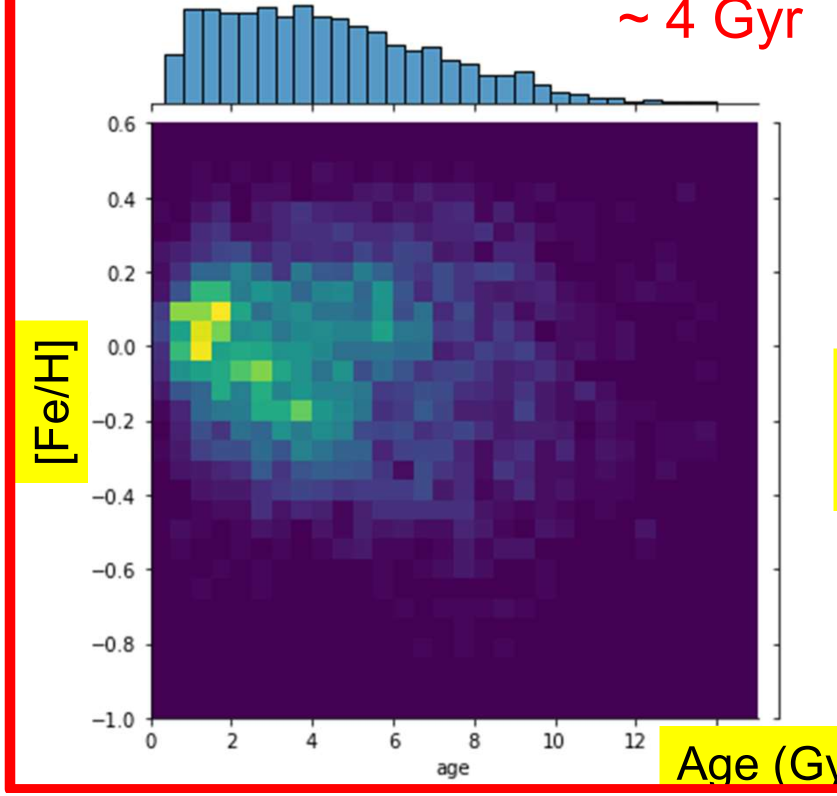


Newly derived AMR

Chang 2022 (Tohoku Univ.)

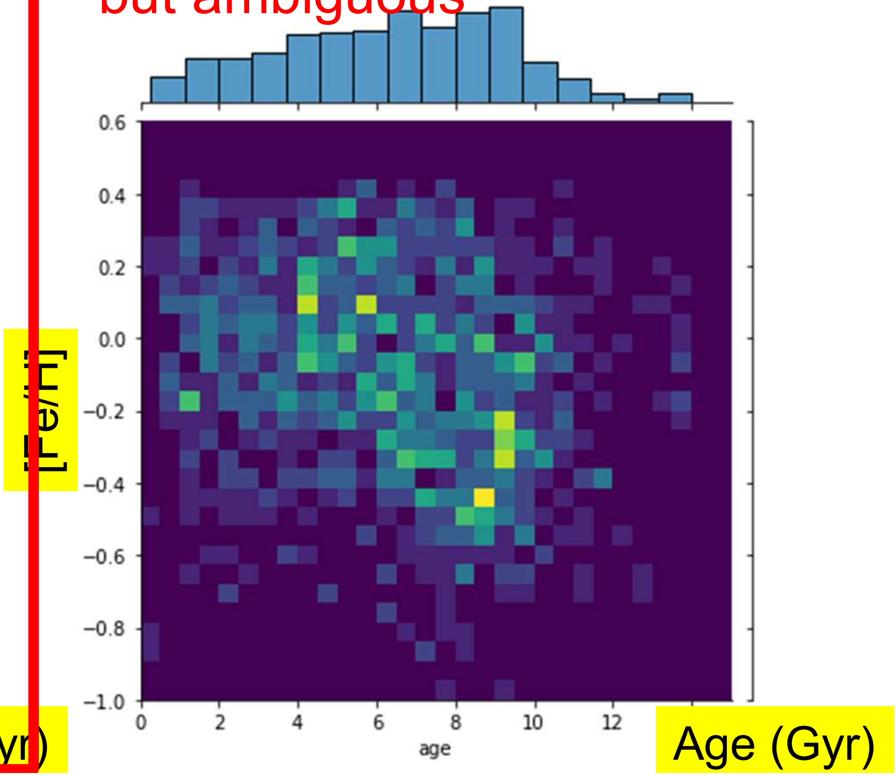
Pop B (thin disk stars)

Peak at ~ 2 Gyr + extended to ~ 4 Gyr



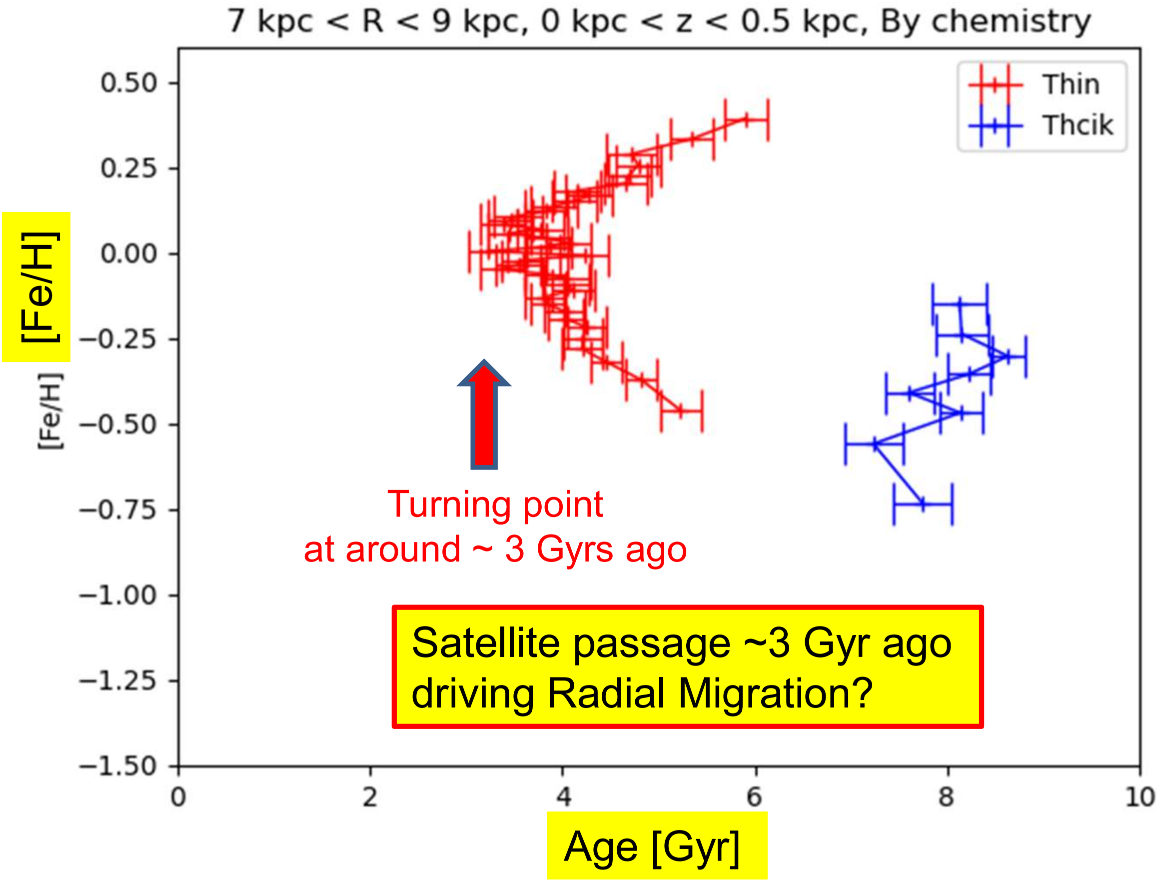
Pop C (thick + old thin disk stars)

Dip-like feature at ~ 8Gyr ago but ambiguous



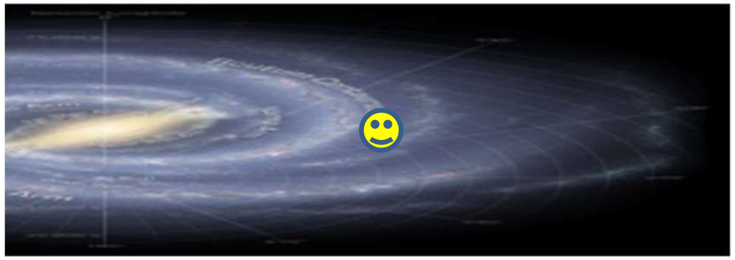
New AMR - Signature for radial migration event

Chang 2022 (RGBs+RCs)



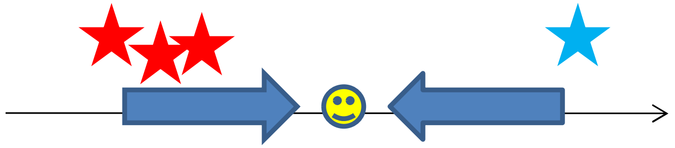
Turning point
at around ~ 3 Gyrs ago

Satellite passage ~3 Gyr ago
driving Radial Migration?



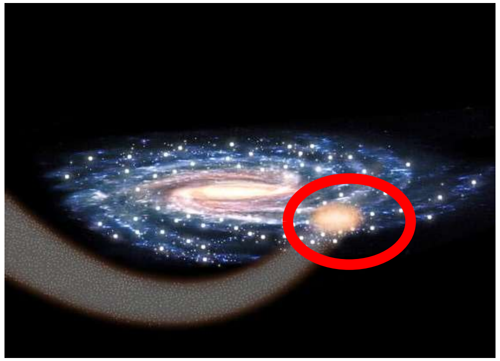
Metal-rich,
older stars

Metal-poor,
younger stars



The effect of satellite infall & radial migration in AMR

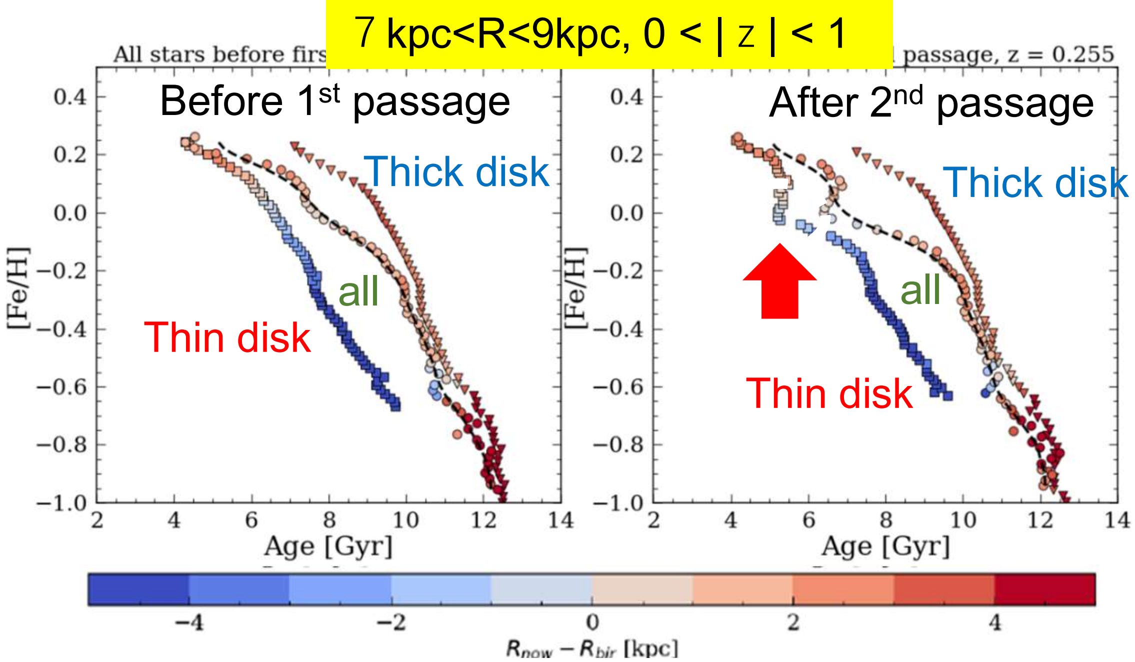
Before 1st passage z = 0.34

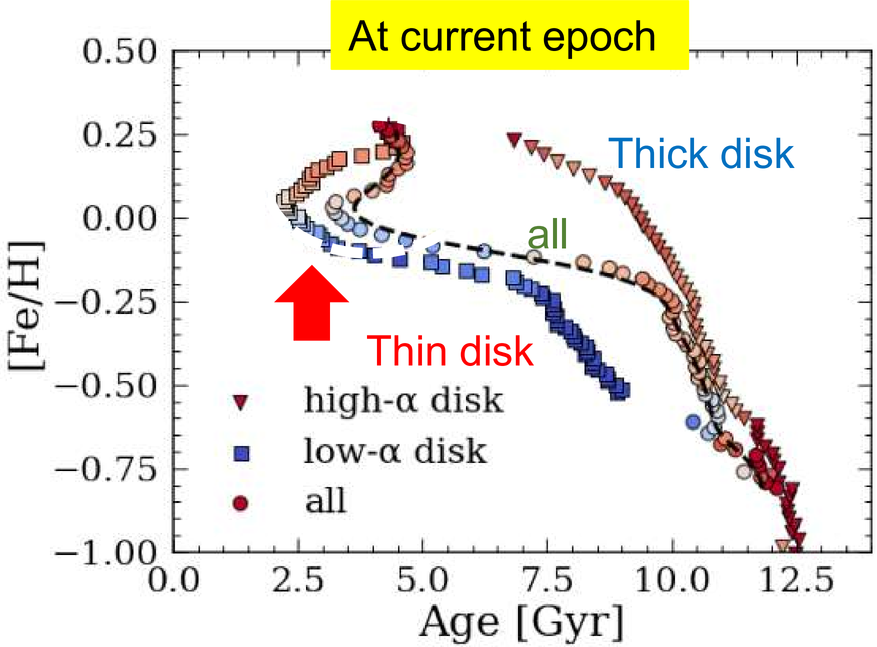


After 2nd passage z = 0.255

Lu et al. 2021 (simulation)

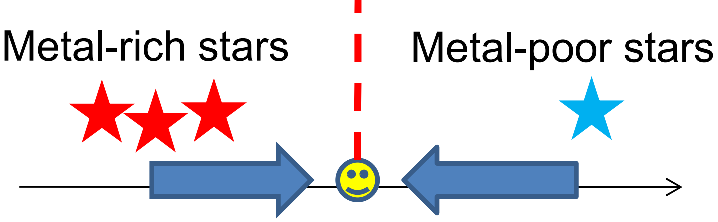
Cosmological simulation with NIHAO-UHD
– Sgr-dwarf like satellite is infalling at z=0.34.
The second passage at z =0.255 yields turning points and radial migration for low-α stars in AMR.





Further evidence for radial migration of stars

Sellwood & Binney 2002, Schoenrich & Binney 2009



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

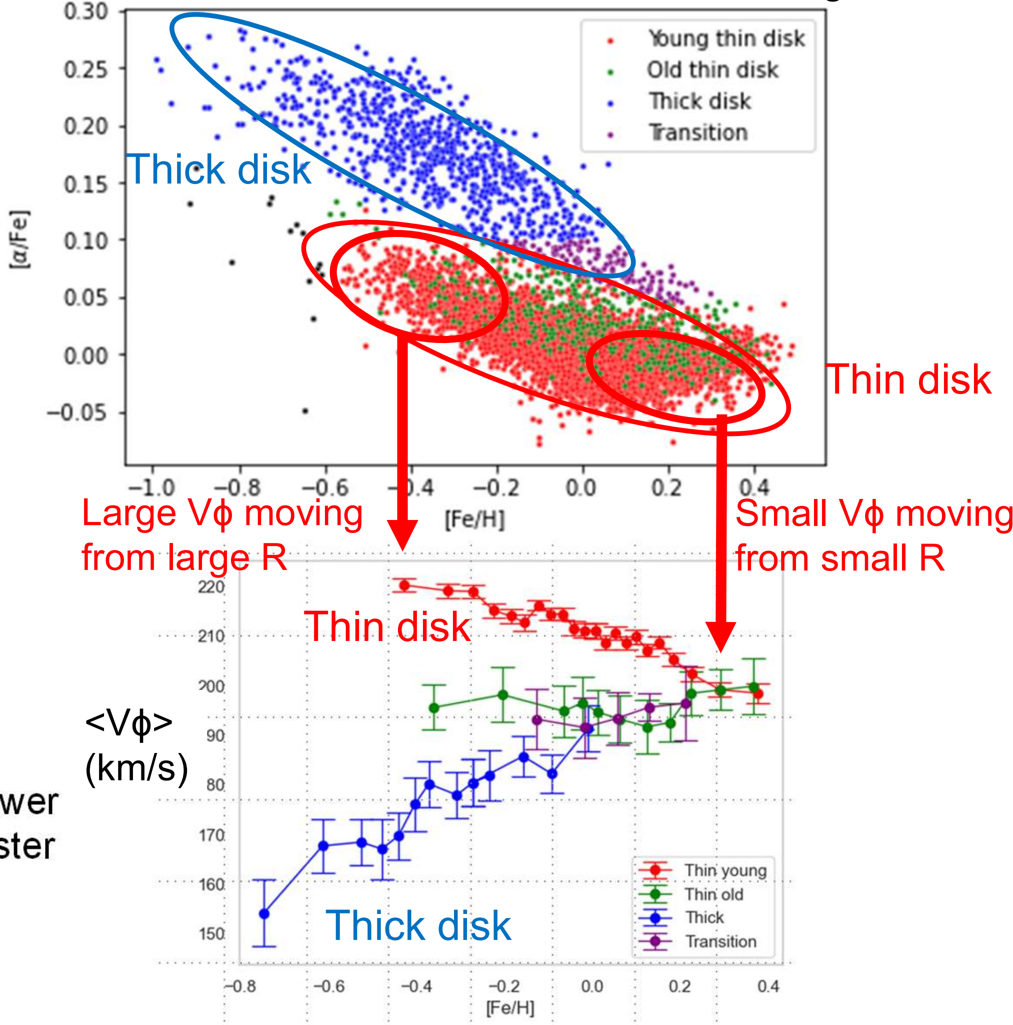
$L_z = V_\varphi R \sim \text{const.}$

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

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

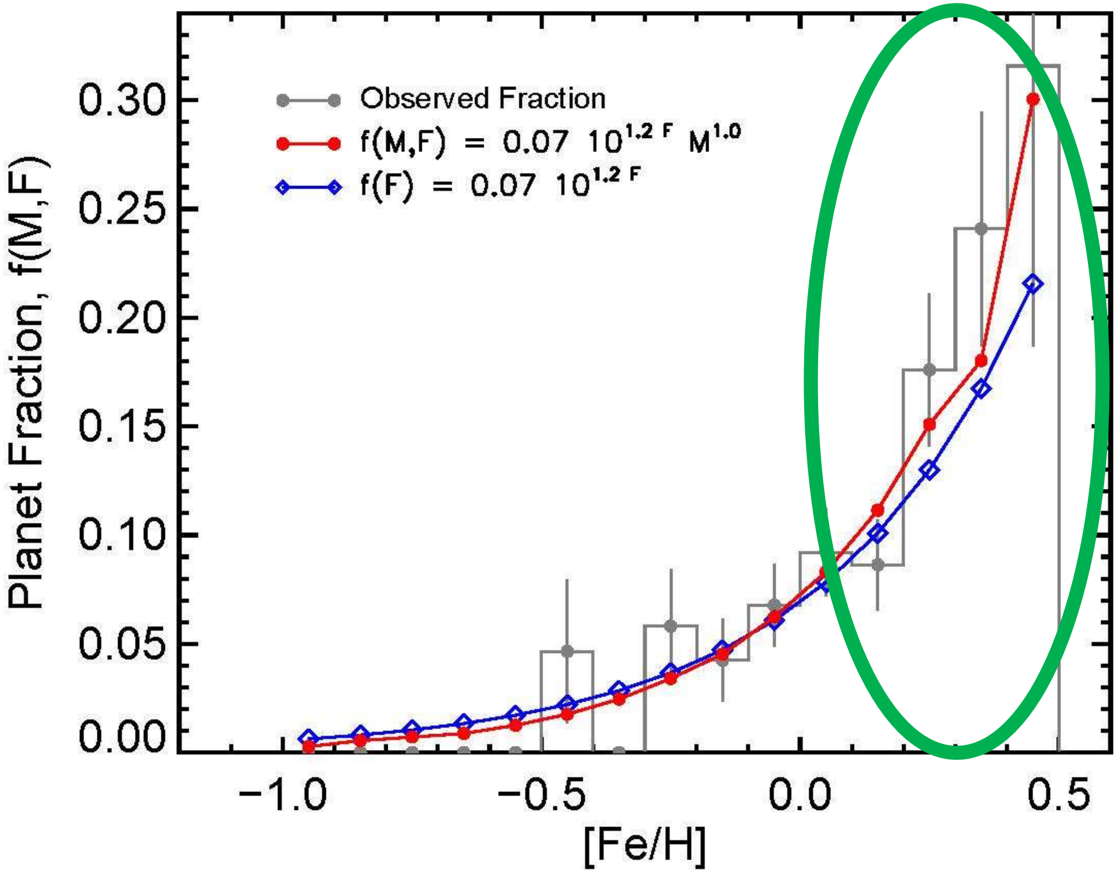
Radial migration of stars driven by satellite infall and associated transient bar/spirals

Chang 2022



MDFs of the stars hosting planets

Johnson et al. 2010



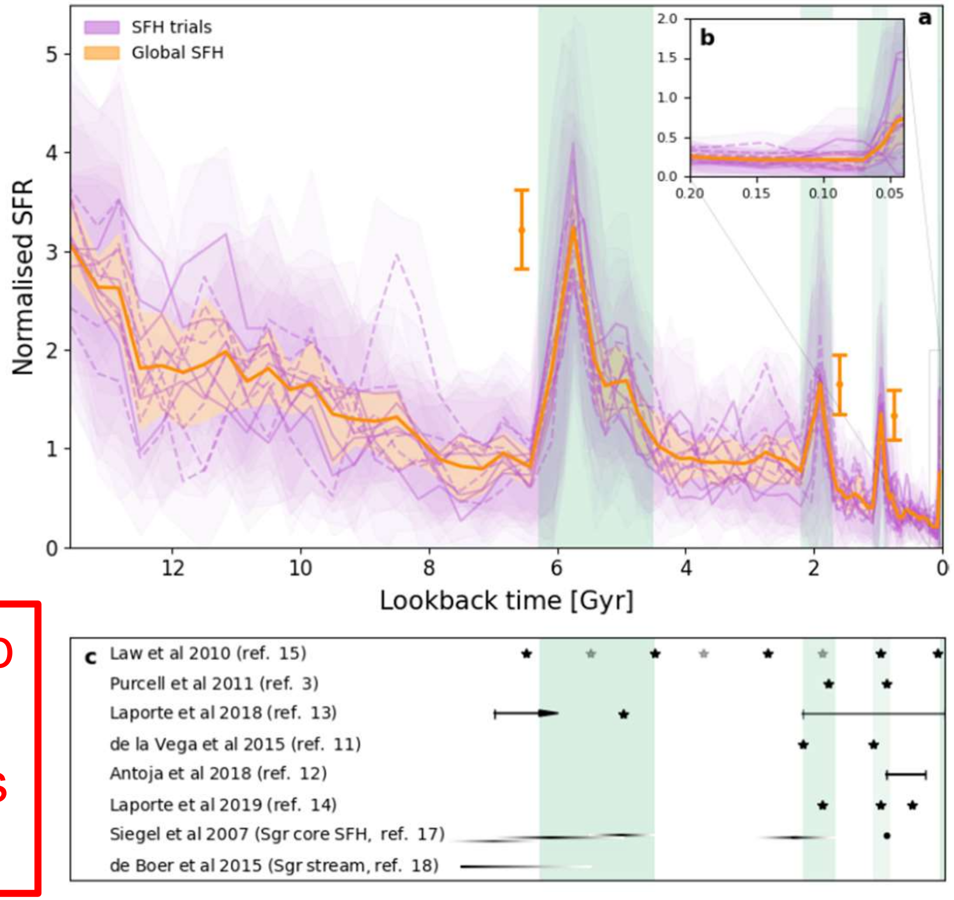
These stars may
have been migrated
from inner R

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

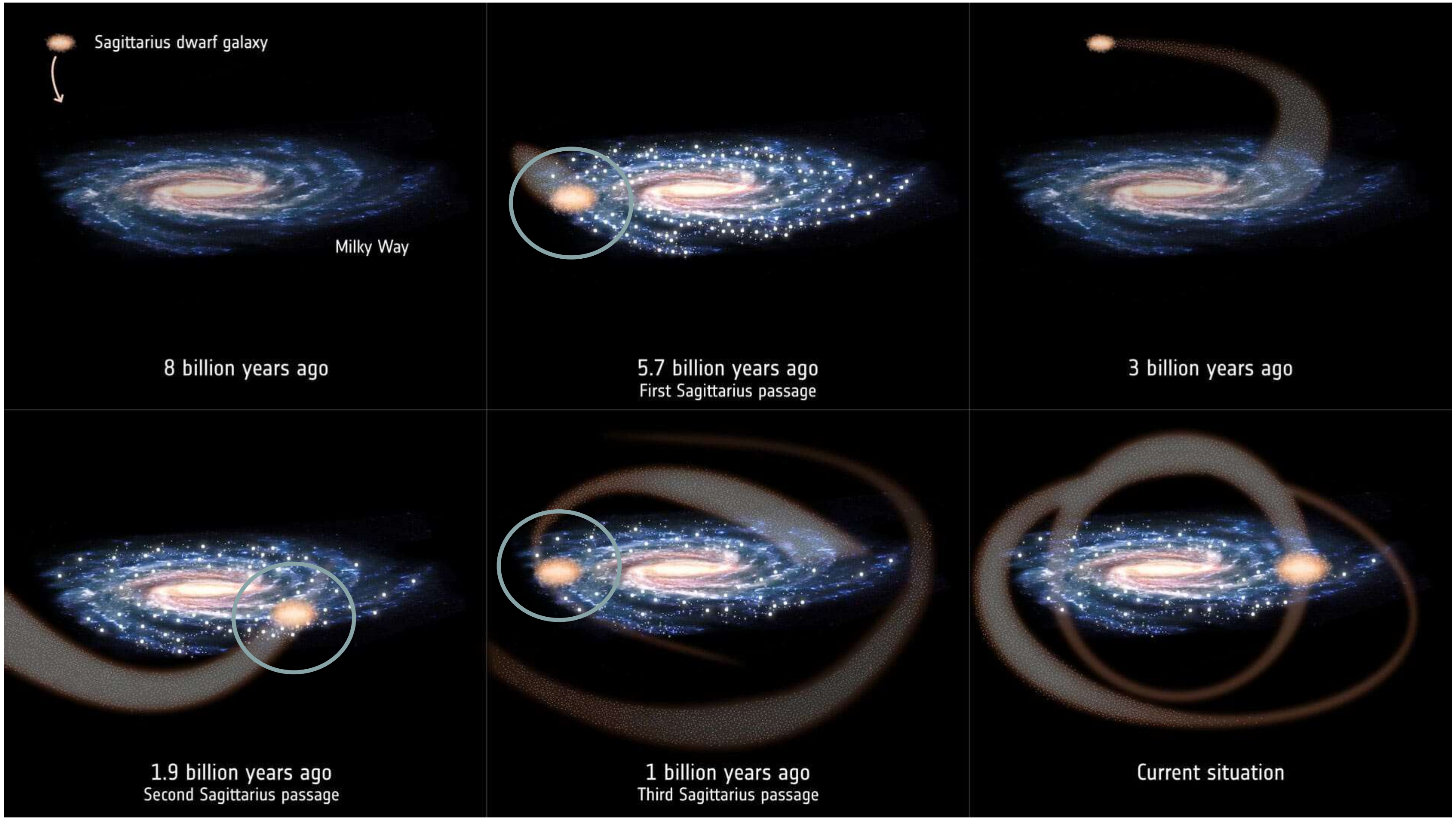
These peaks overlap with the timings of pericentric passages of Sgr dwarf



The orbit of Sgr dwarf

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

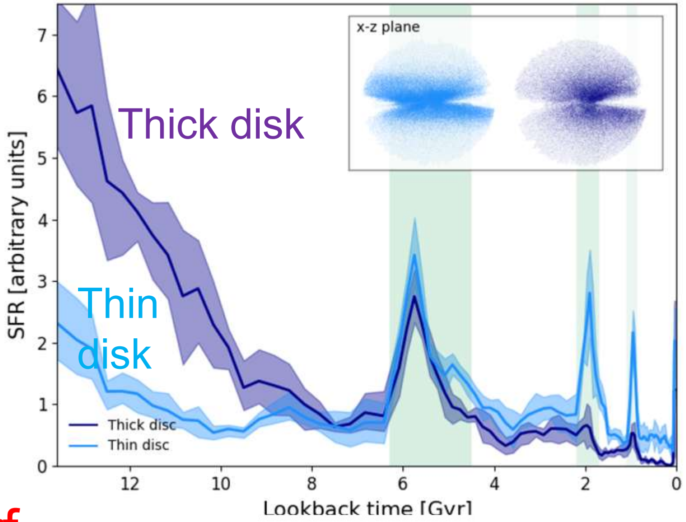
Ruiz-Lara et al. 2020



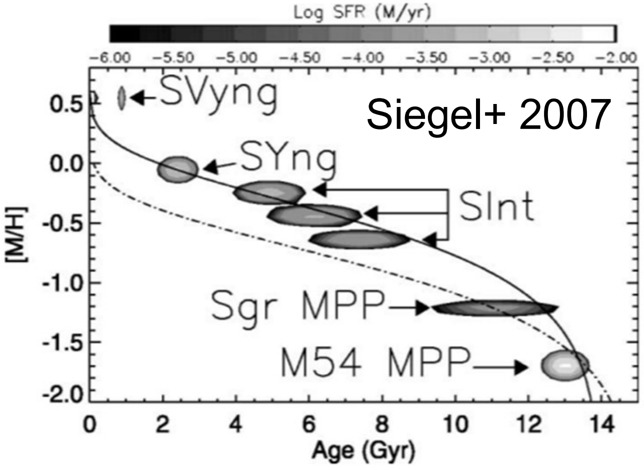
SFHs of thick/thin disks & Sgr dwarf

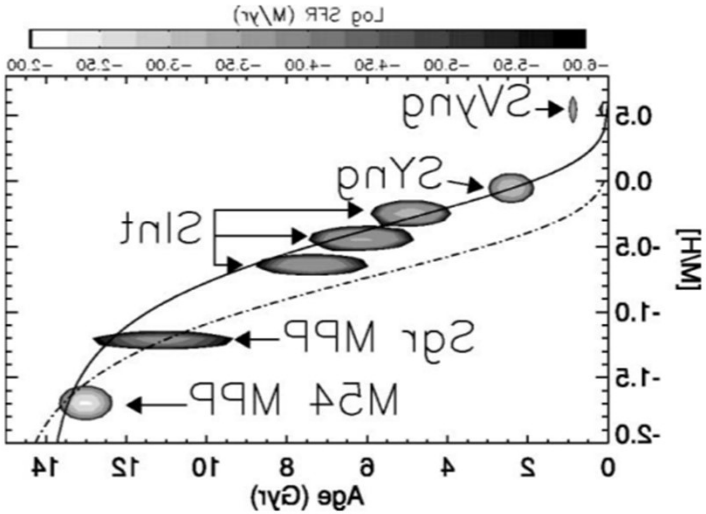
Ruiz-Lara et al. 2020

Peak at 5.7 Gyr exists for both
Thick disk
Thin disk



SFHs of M54 & Sgr dwarf





SFH of Sgr dwarf is also affected