銀河円盤の形成
～厚い円盤の起源～

千葉柾司
（東北大学）

内容

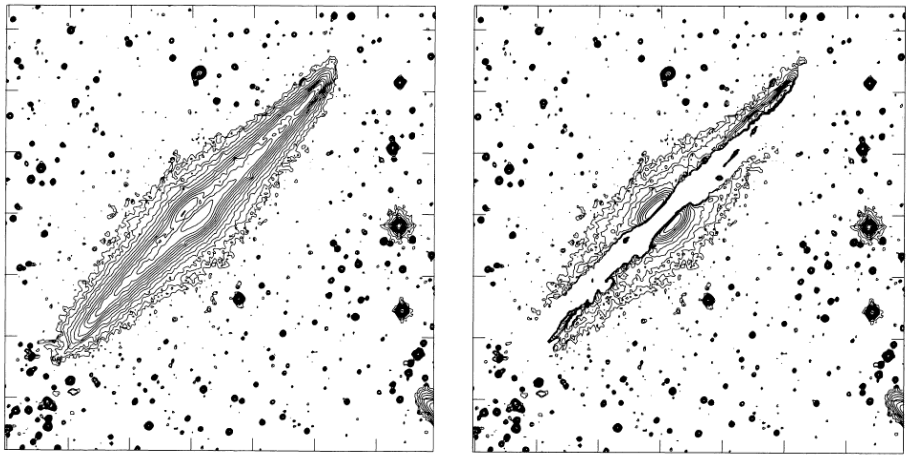
1. 厚い円盤とは何か
2. 厚い円盤の形成シナリオ
3. 今後の展望

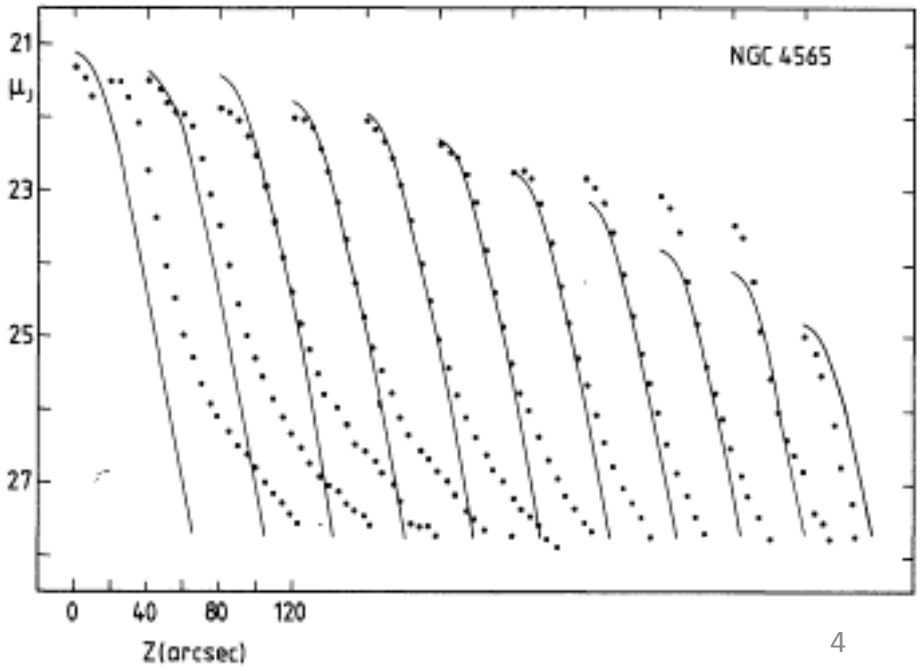
1．厚い円盤とは何か

厚い(銀河)円盤 thick diskの発見

* Tsikoudi 1977 (PhD) : photometry of three edge-on S0 galaxies
  `surrounding envelope'
* Burstein 1979: photometry of five edge-on S0 galaxies
  termed a `thick disk'

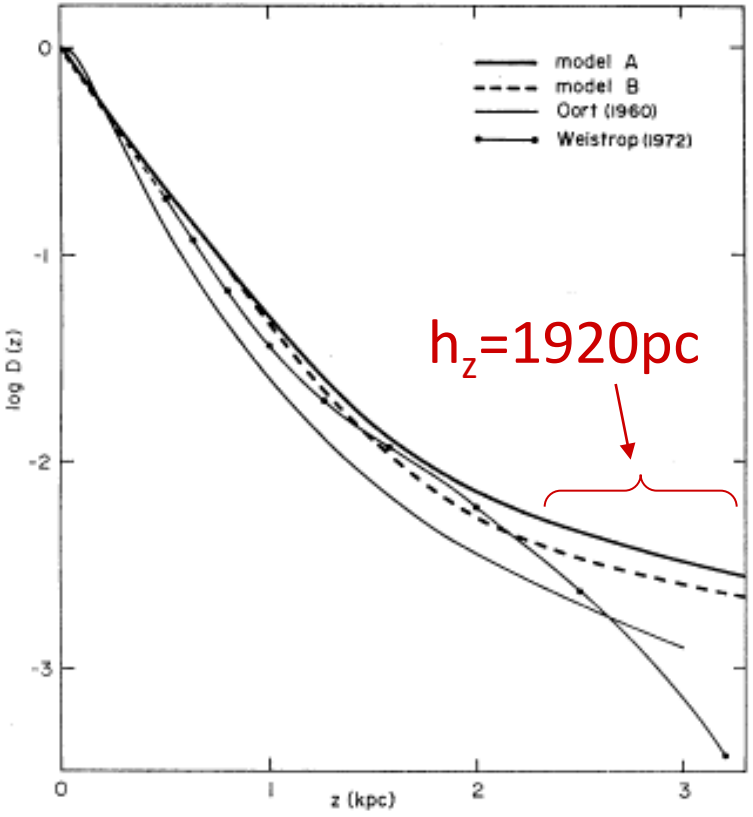
NGC4565(Sab) の光度分布
Van der Kruit & Seale 1981



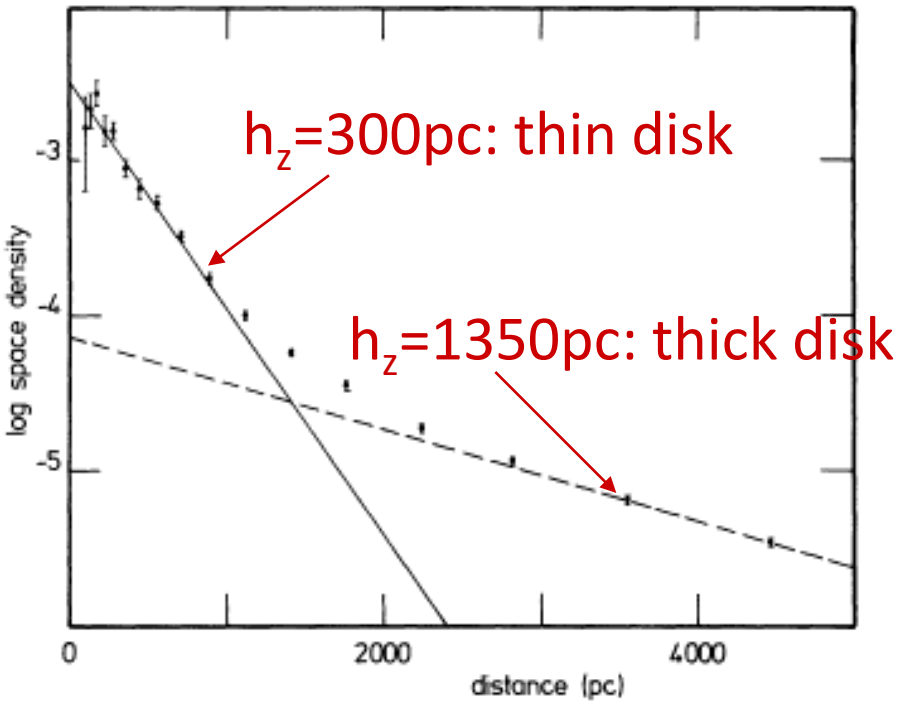


銀河系における厚い銀河円盤

Yoshii 1982
銀河北極方向の恒星計数



Gilmore & Reid 1983
銀河南極方向の恒星計数



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

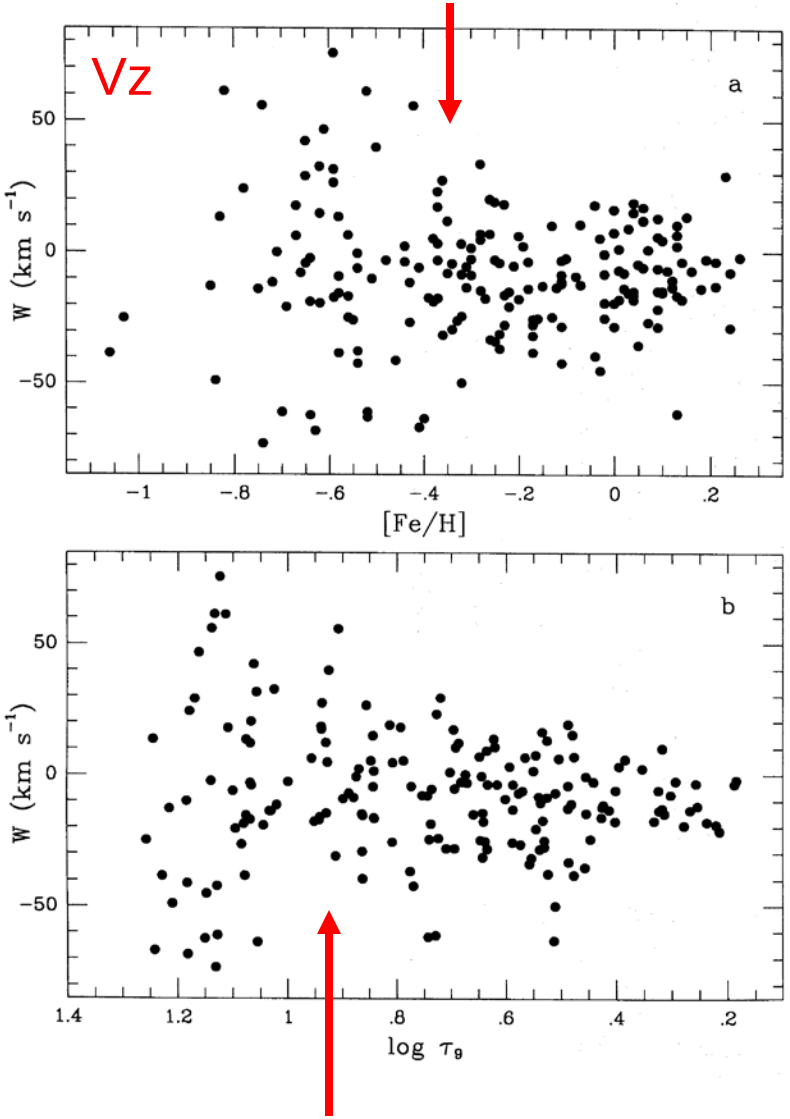
銀河系の厚い円盤の主な特徴

- 幾何学的に厚い。速度分散大。速い回転速度。

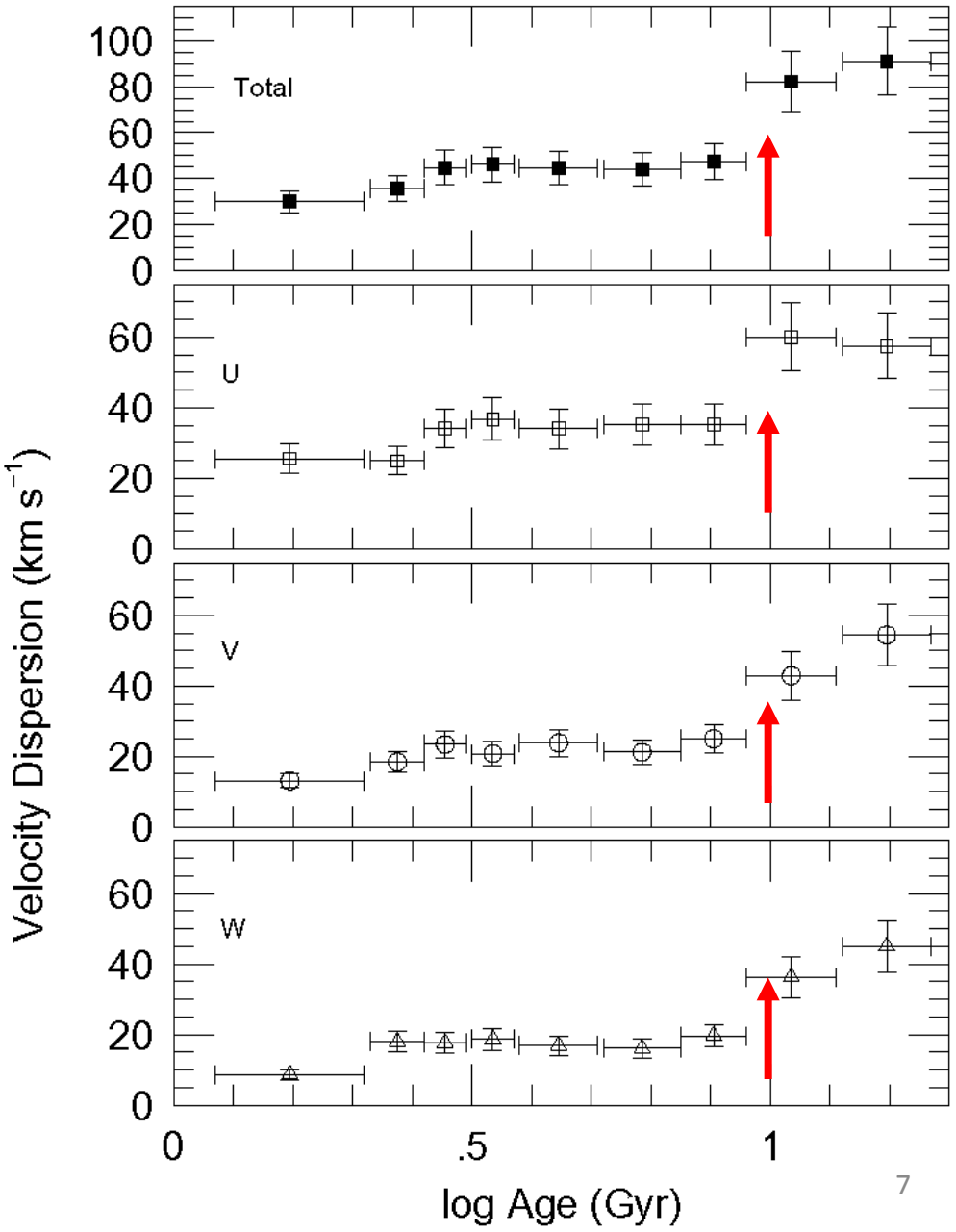
	h_z(kpc)	σ_R(km/s)	σ_z(km/s)	$<V\phi>$(km/s)
Thin disk	~0.3	34	18	~220
Thick disk	~1.0	61	39	~200

  - h_R ~ 4 kpc, M_{thick} ~ 10-20% x M_{thin} ~ $<10^{10}M_{sun}$
- 年齢が古い (≥10 Gyr)。
- 独立した金属量分布。[α/Fe] 比が高い。
  - [Fe/H] = -1 ~ -0.4, [α/Fe] = 0.2 ~ 0.4
  - 金属量の空間依存性（z方向）なし。

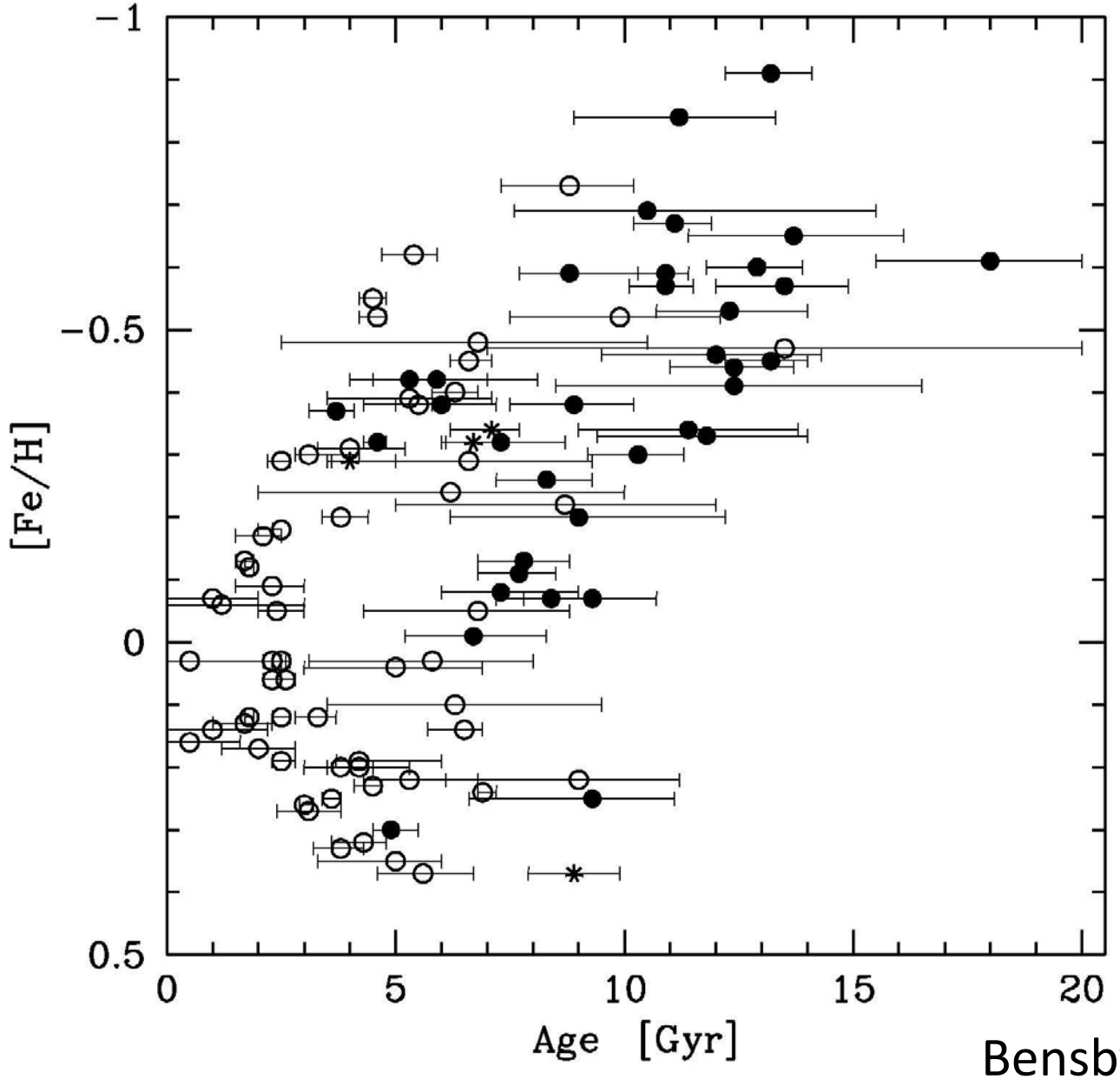
Edvardsson et al. 1993



Quillen & Garnett, astro-ph/0004210



Thick disk stars
at [Fe/H] < -0.4, age >10Gyr



Thick disk

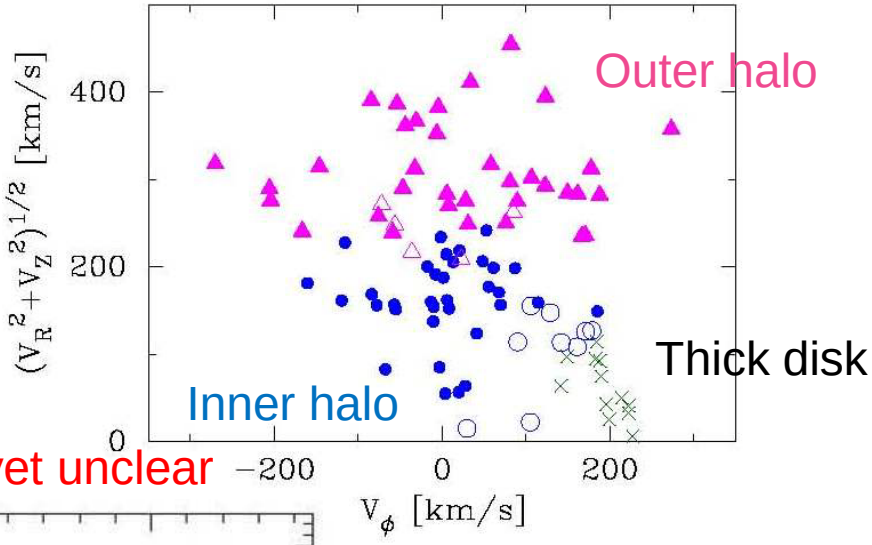
Thin disk

Bensby et al. 2005

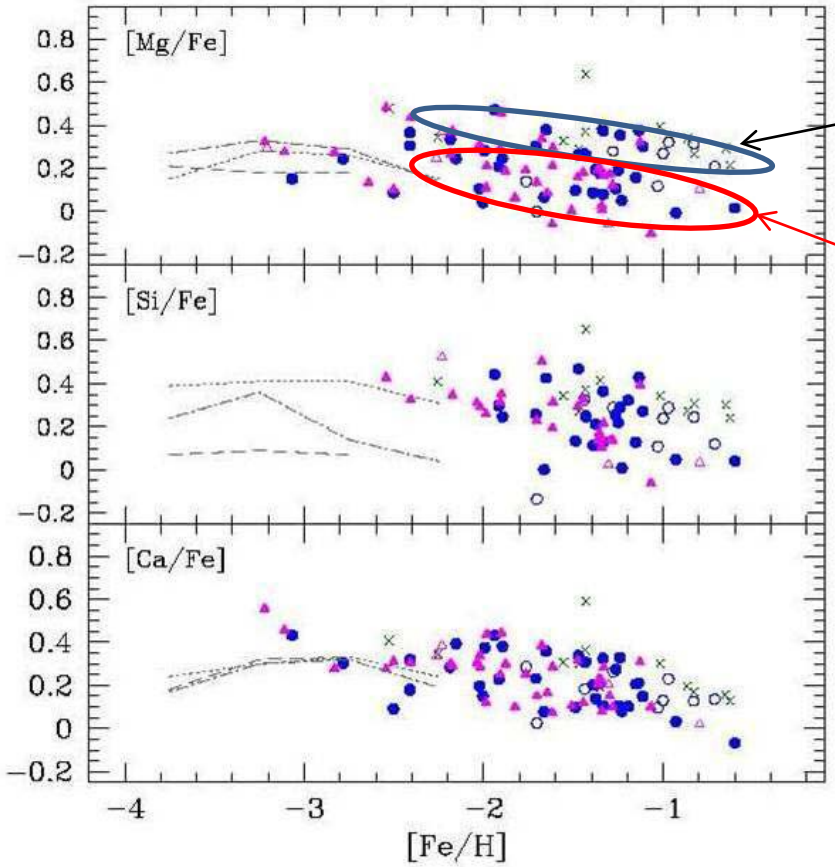
Subaru HDS results (Ishigaki, Chiba, Aoki 2012)

Assignment based on kinematics
- Thick disk: high α
- Halos: mixed in α abundance if selected by kinematics

A clear definition of inner/outer halos is yet unclear



[α/Fe]



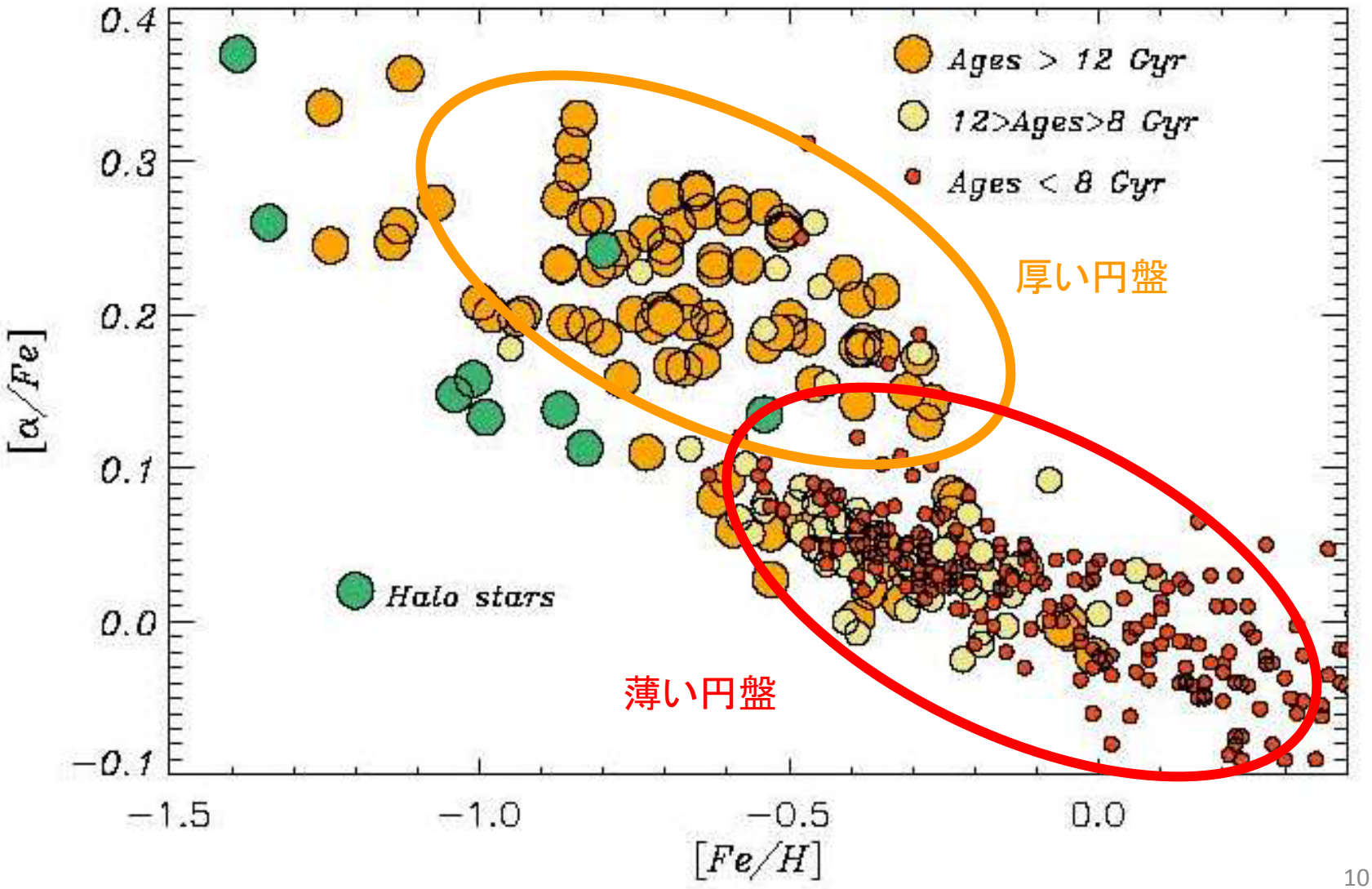
Thick disk

Halo

[Fe/H]

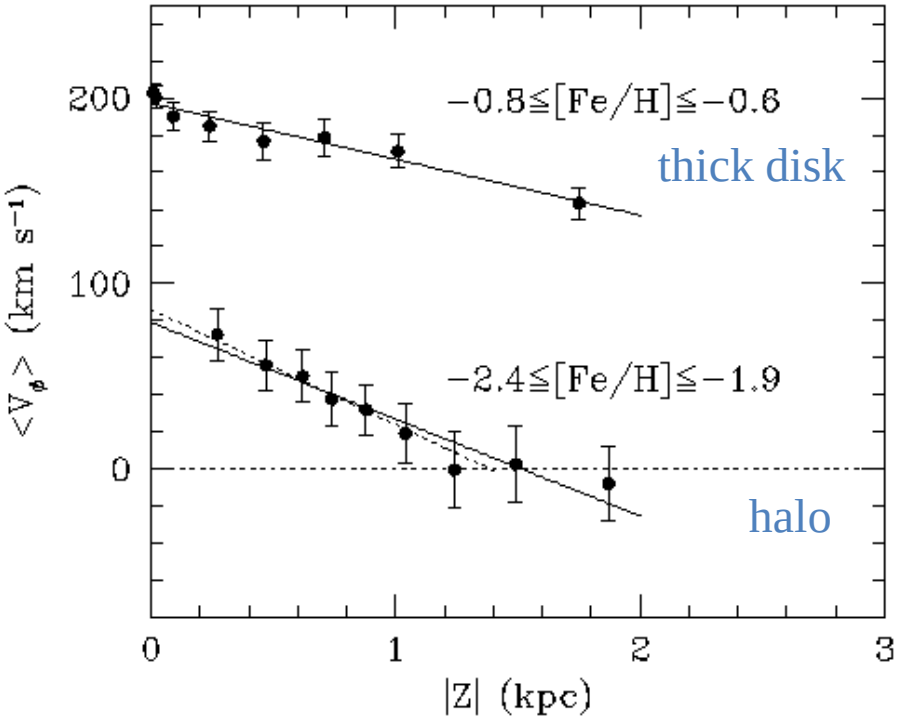
厚い円盤、薄い円盤の[α/Fe]比

(Haywood08, Reddy+03,06, Bensby+05, Gill+06)

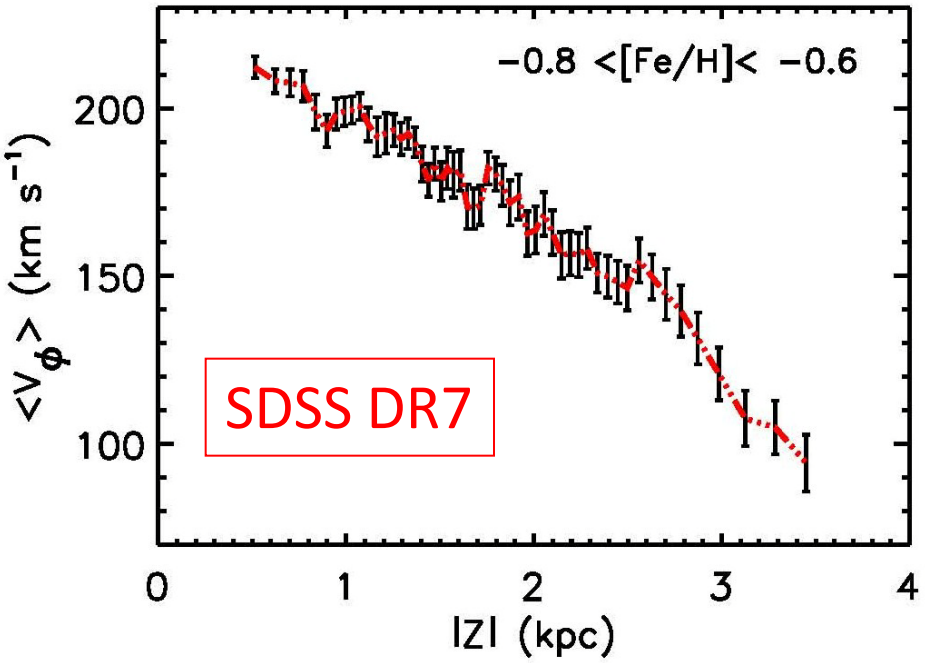


Rotational properties of the thick disk

Hipparcos sample
(Chiba & Beers 2000)



SDSS DR7
(Carollo+ 2010)

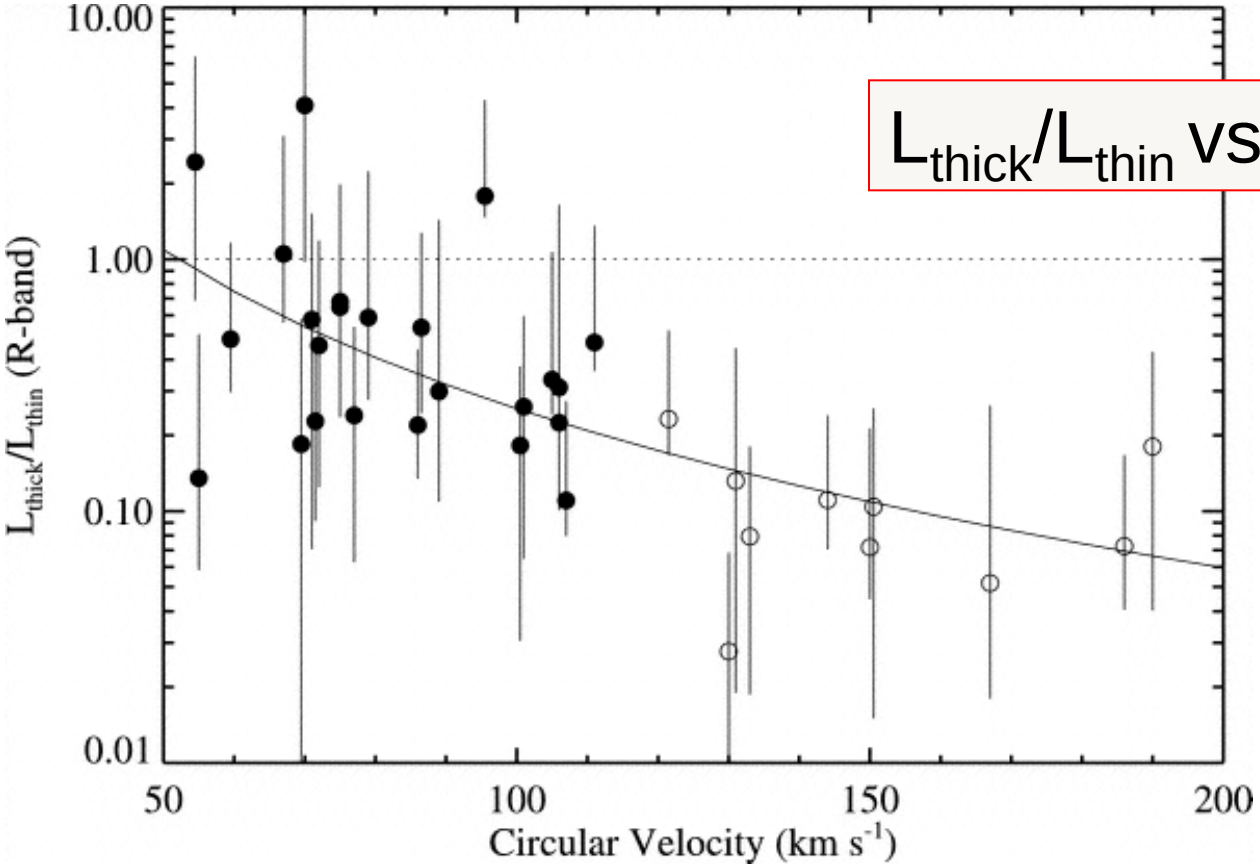


d<Vϕ>/dz < 0 for the thick disk

系外銀河の厚い円盤の特徴

Yoachim & Dalcanton 2006, 2008

- 円盤銀河に普遍。軽い銀河ほど厚い円盤の比が大
- 相対的に古い年齢で金属量が比較的多い

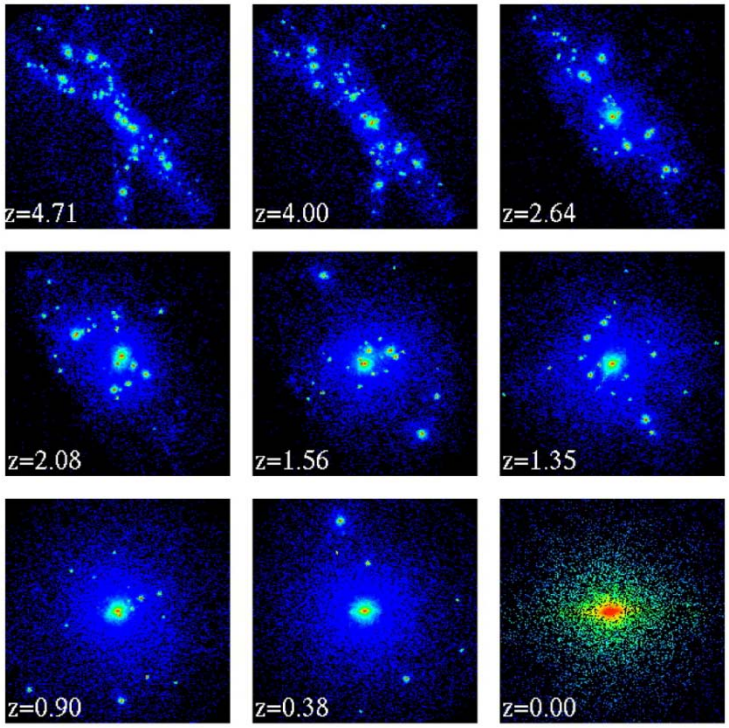


2. 厚い円盤の形成シナリオ

厚い円盤の形成シナリオ

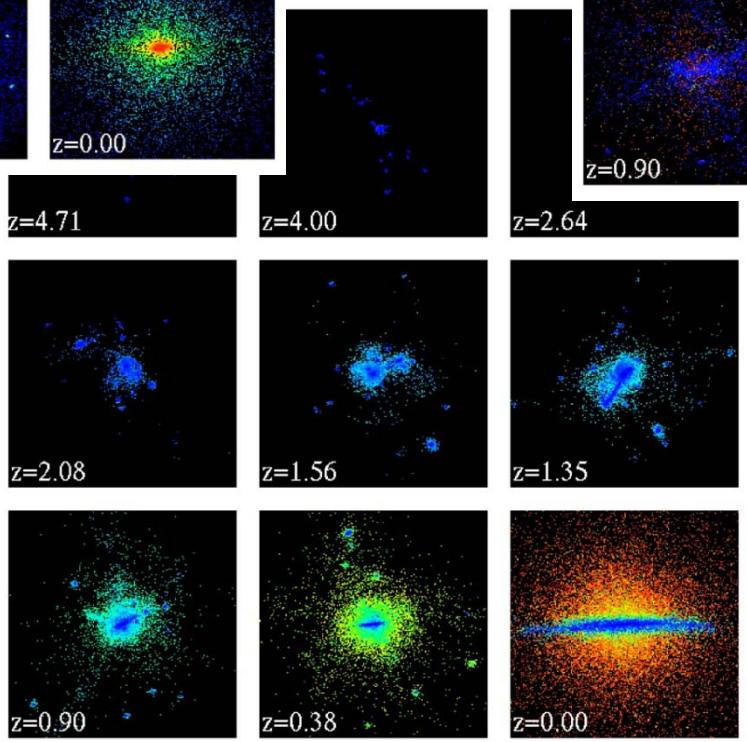
1. ガスエネルギーの散逸を伴う収縮 (Burkert+1992)
   - 金属量勾配あり×, 回転運動に勾配なし×
2. 合体した矮小銀河の破片 (Abadi+2003)
   - 金属量・回転運動に勾配なし×, [α/Fe] が小さい×, 金属量が小さい×
3. 小銀河のmultiple mergers (Brook+2004;2005)
   - 回転運動に勾配なし？
4. 伴銀河やCDM subhalosによる薄い円盤の力学加熱 (Quinn+1993; Veláquez & White 1999; Hayashi & Chiba 2006; Kazantzidis+2009)
   - 金属量勾配なし〇, 回転運動に勾配あり〇
   - 運動状態に非対称性あり, 金属量分布は一様〇
5. 初期のgas rich, clumpy diskの進化によるもの (Bournarud+2007; 2009)
   - 円盤のスケール高が一定〇, 回転運動に勾配なし？, 金属量情報？
6. 薄い円盤内の渦状構造による動径方向の流れ (Haywood 2008; Schönrich & Binney 2009)
   - Migration 機構, [α/Fe] 分布の再現〇
   - 運動状態の不連続性×, 速度分散の加熱機構に難×

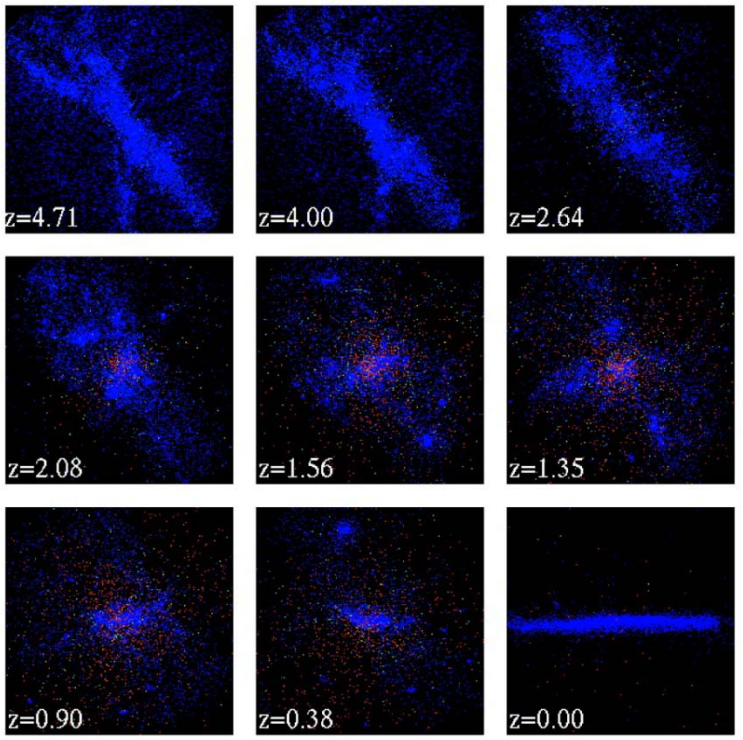
2. 合体した矮小銀河の破片



DM

Hierarchical clustering

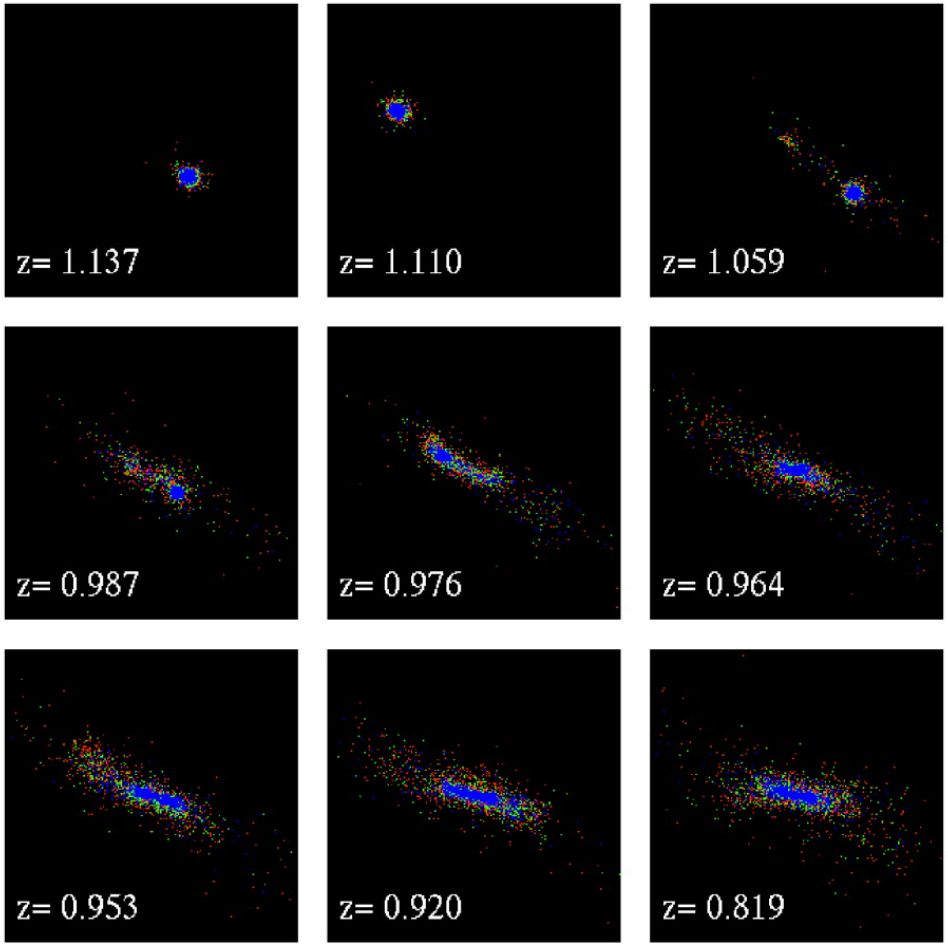


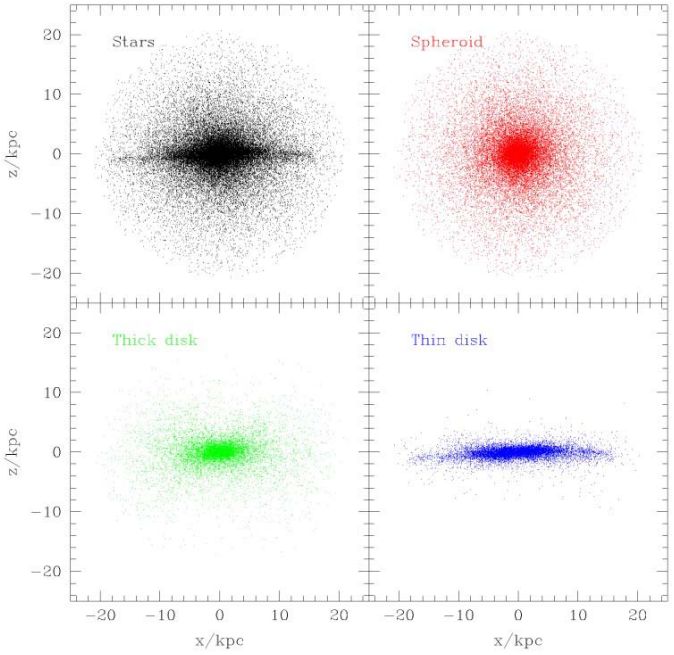


gas

stars

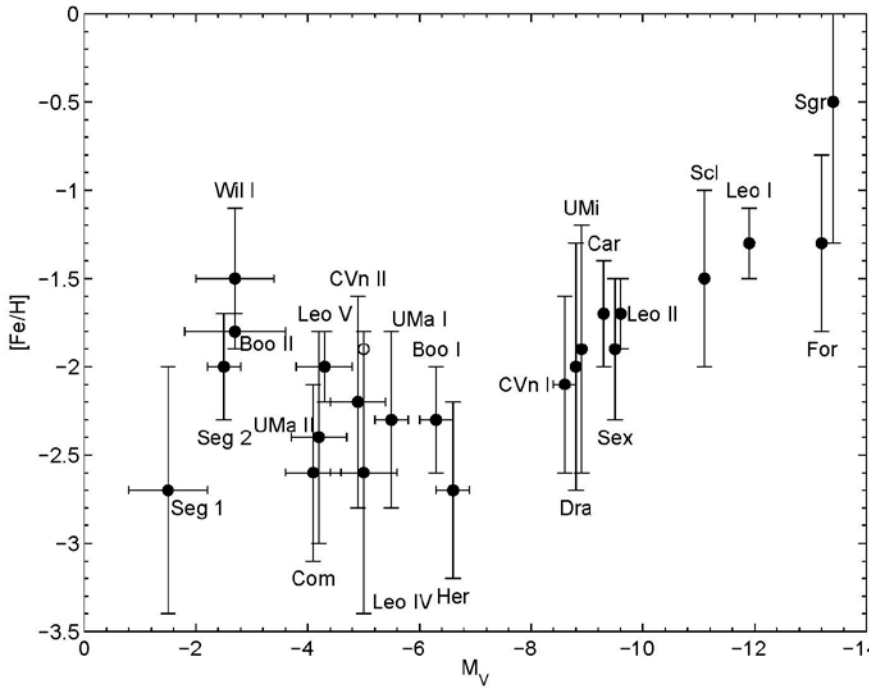
Shredded satellite → thick disk?



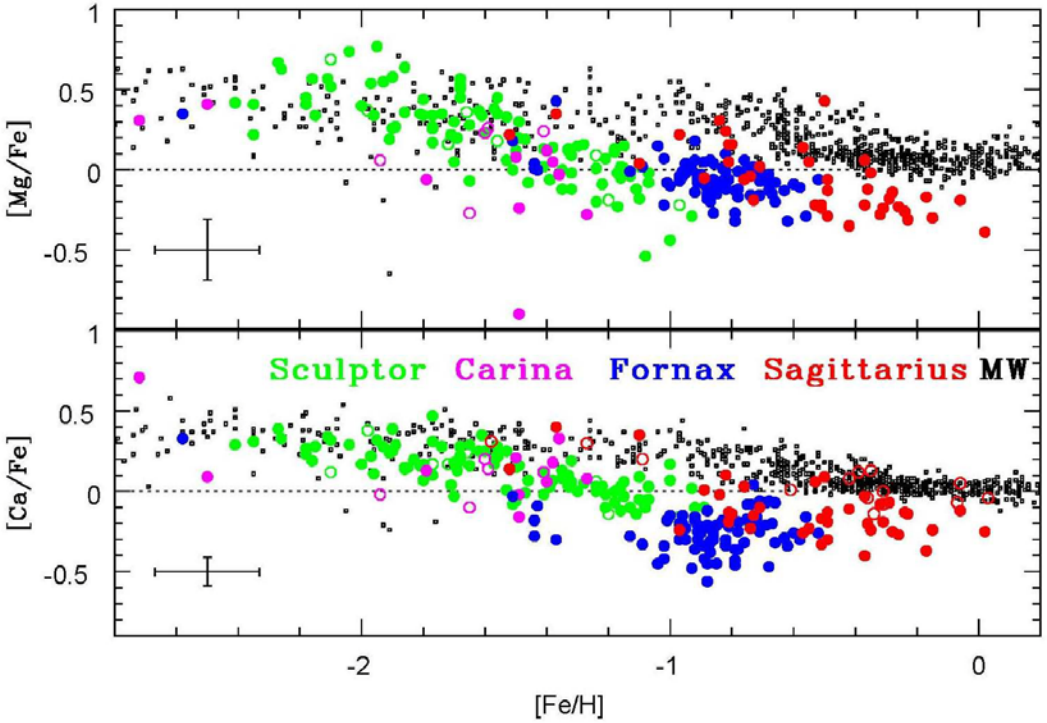


しかし、Dwarf satellites の化学元素量からは、、

Koch 2013



Tolstoy+ 2009

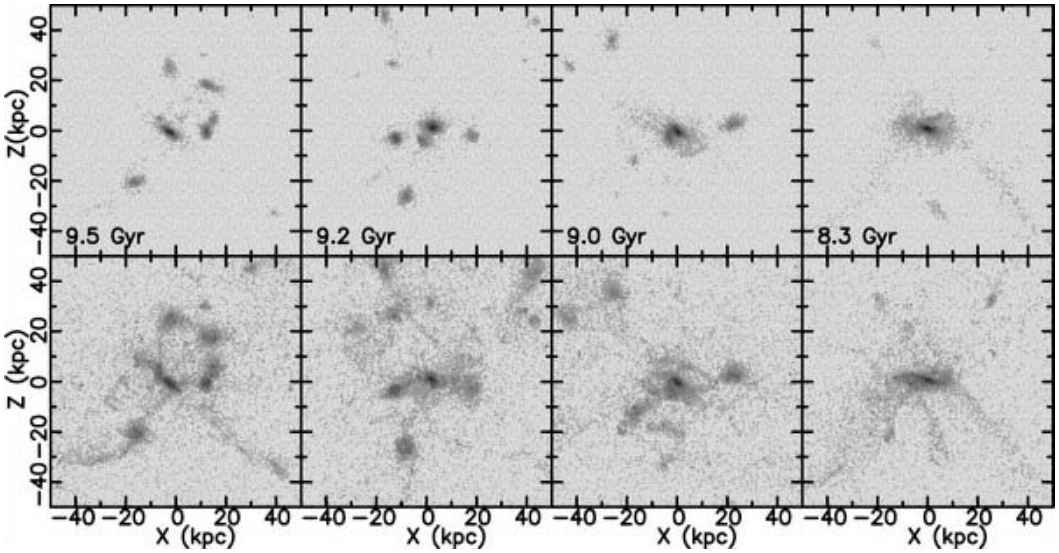


Low [Fe/H] (<-1) and low [α/Fe] (<0.2)
⇒厚い円盤の性質と合わない

3. 小銀河のmultiple mergers

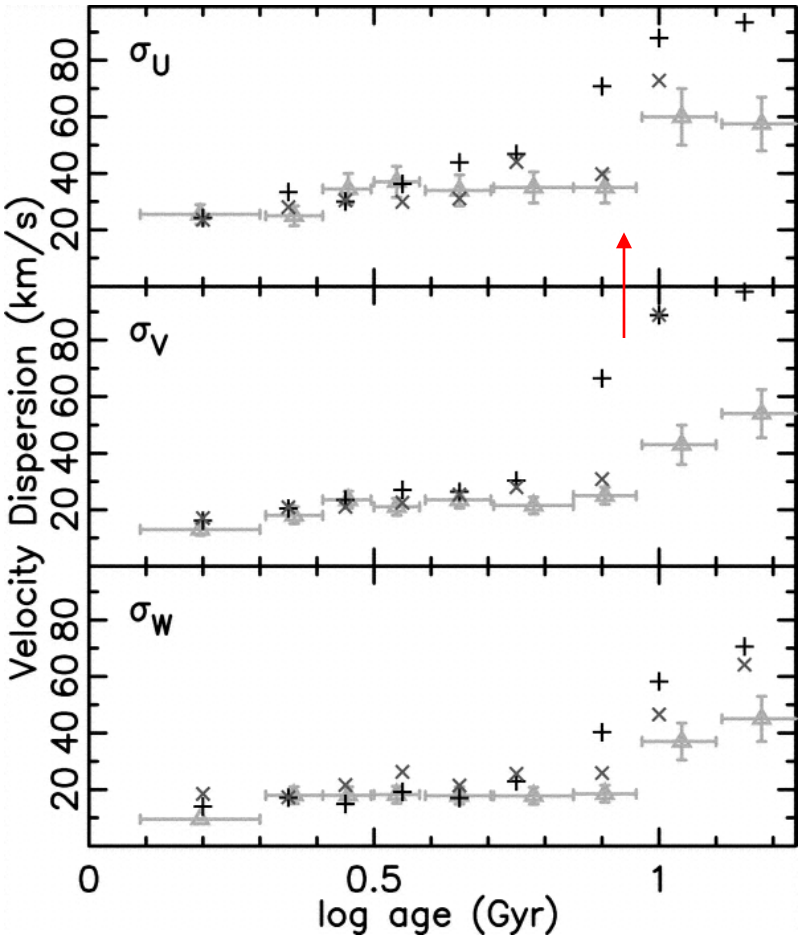
Thick-disk like component emerges from multiple dissipative mergers (Brook et al. 2004)

stars



gas

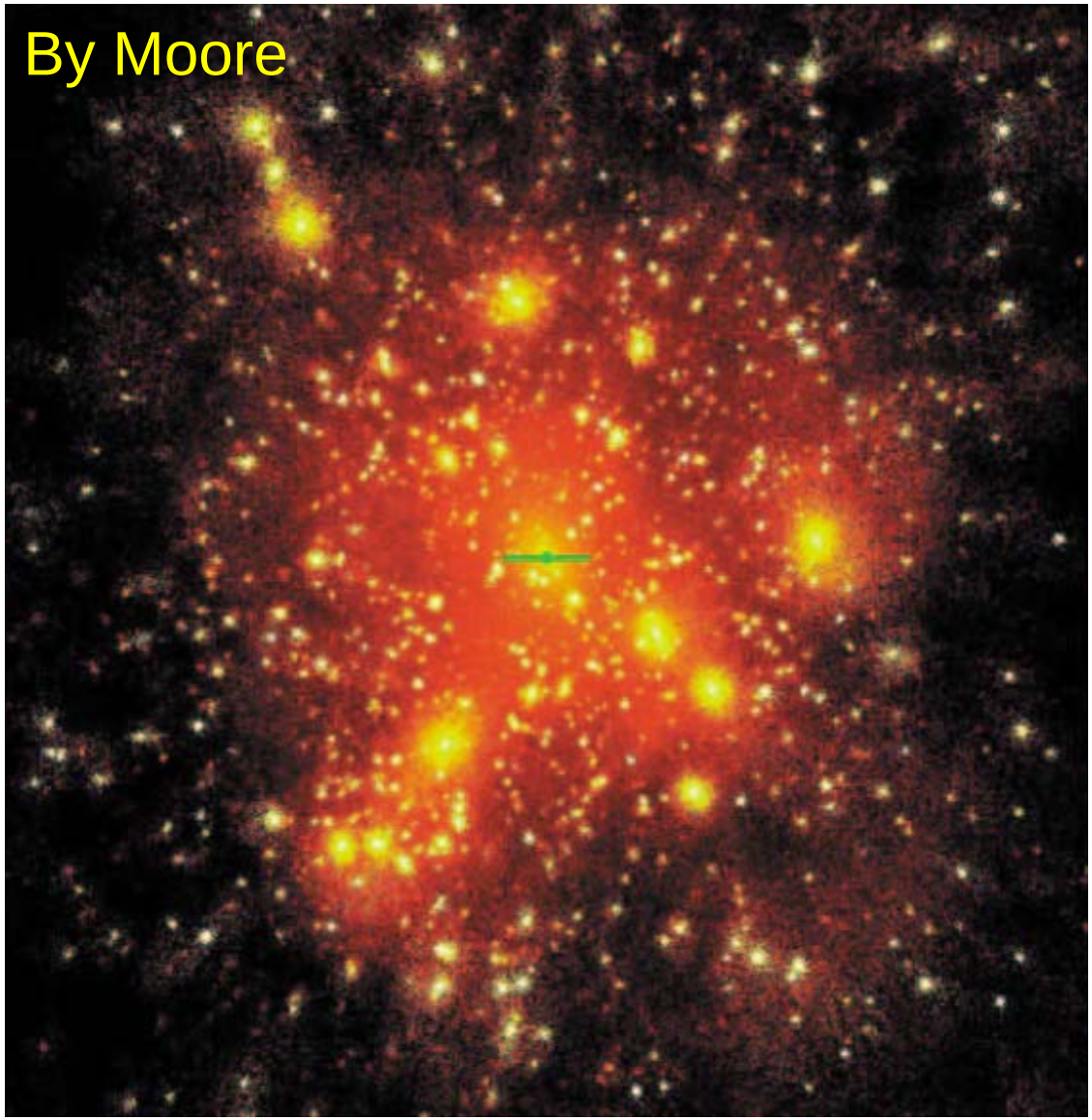
Quillen & Garnett 2001



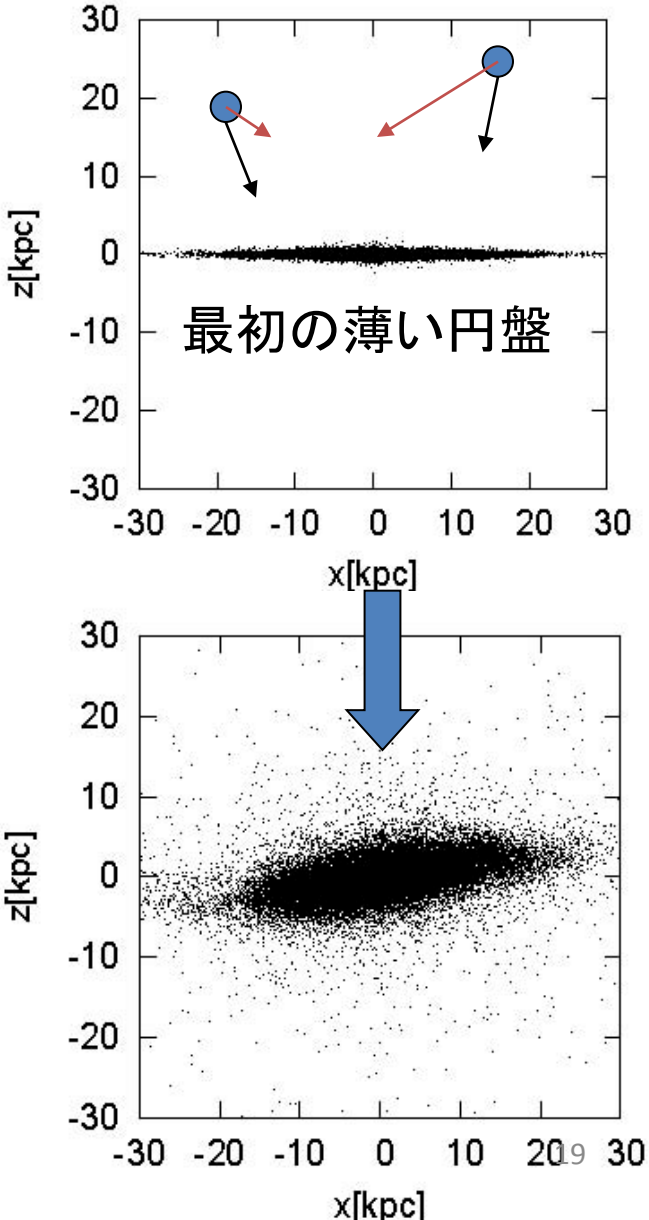
d<Vϕ>/dz < 0 となるか?
全ての円盤銀河で一般的か？

4. ダークマターサブハローによる薄い円盤の力学加熱

Distribution of dark halos in a galactic scale

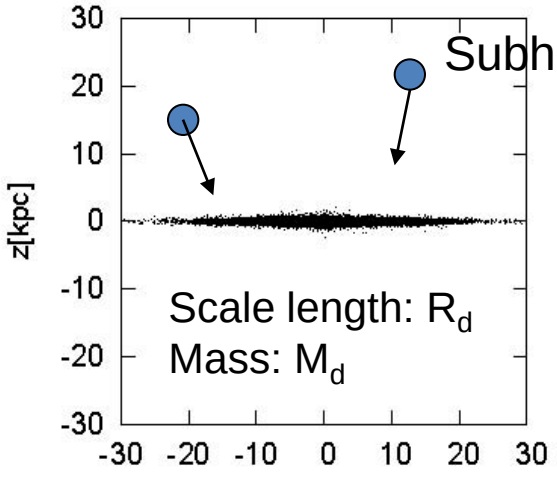


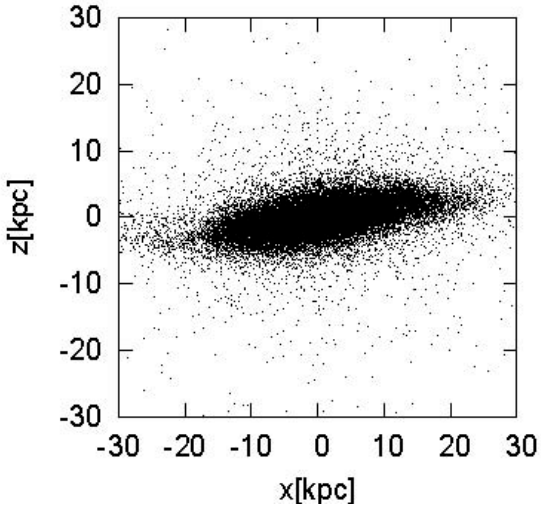
Subhaloによる力学加熱



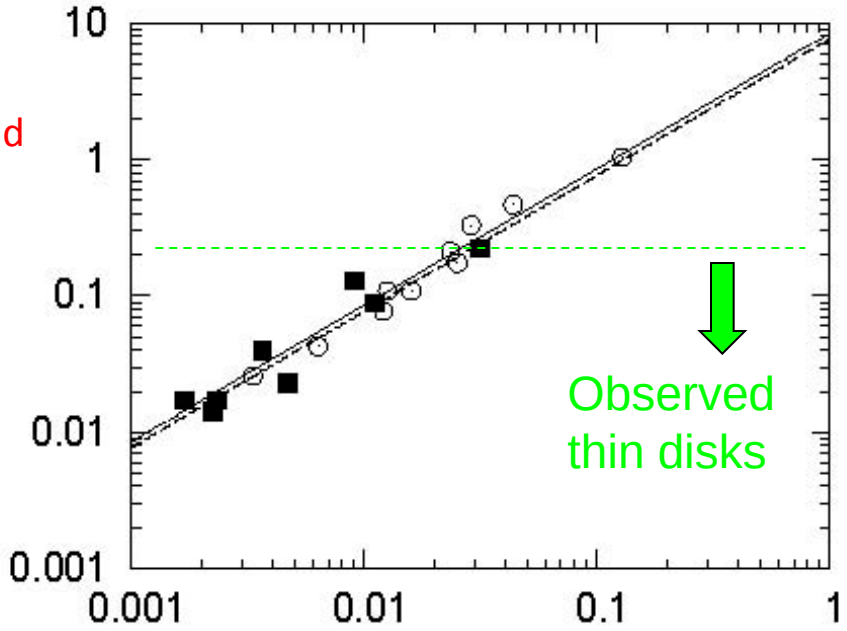
Numerical simulation of disk heating (Hayashi & Chiba 2006)

Scale height: Z_d





$\Delta Z_d / R_d$



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

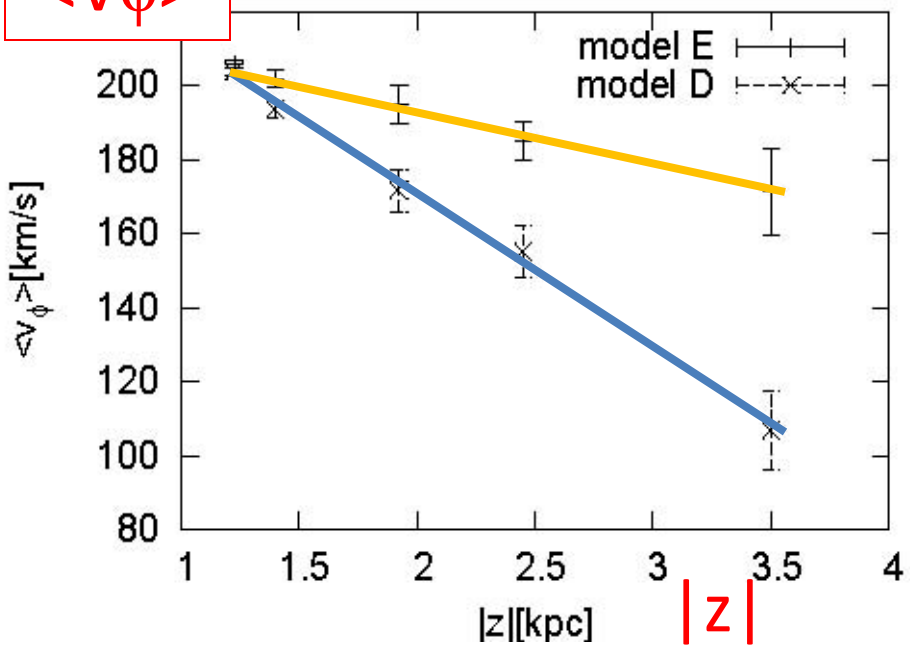
$$\frac{\Delta Z_d}{R_d} = 8\sum_{j=1}^{N}\left(\frac{M_{sub,j}}{M_d}\right)^2$$

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

⇒ accreted subhalo mass $< 0.15\ M_d$

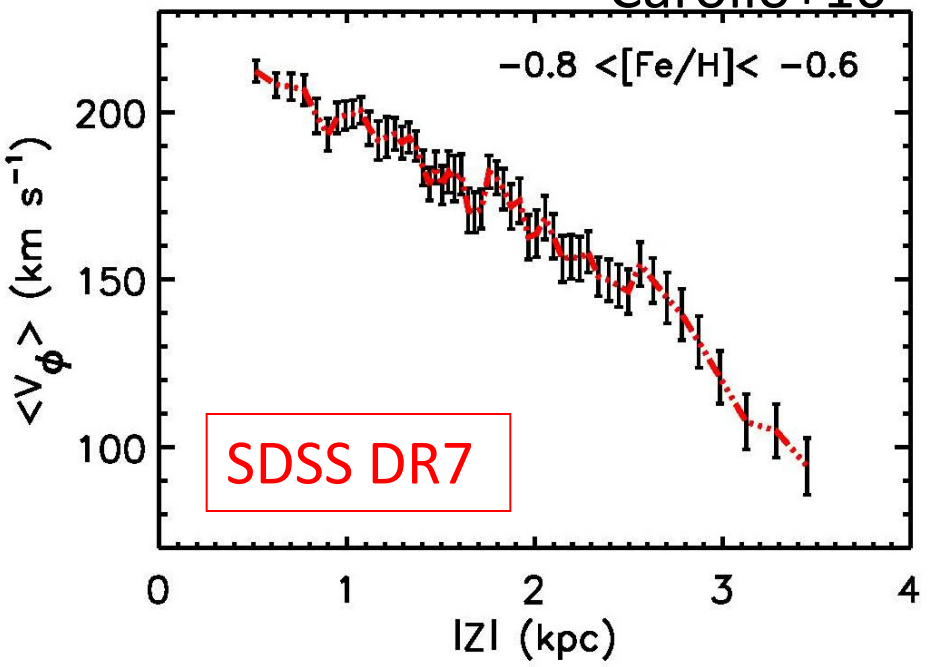
モデル計算結果

<Vϕ>



観測結果

Carollo+10



平均回転速度<V_Φ>のZ方向の勾配

$$\frac{\Delta Z_d}{R_d} \propto \left\langle M_{sub} \right\rangle^2 V_c^{-2}$$

銀河回転速度Vcが小さな系においてより顕著な厚い円盤

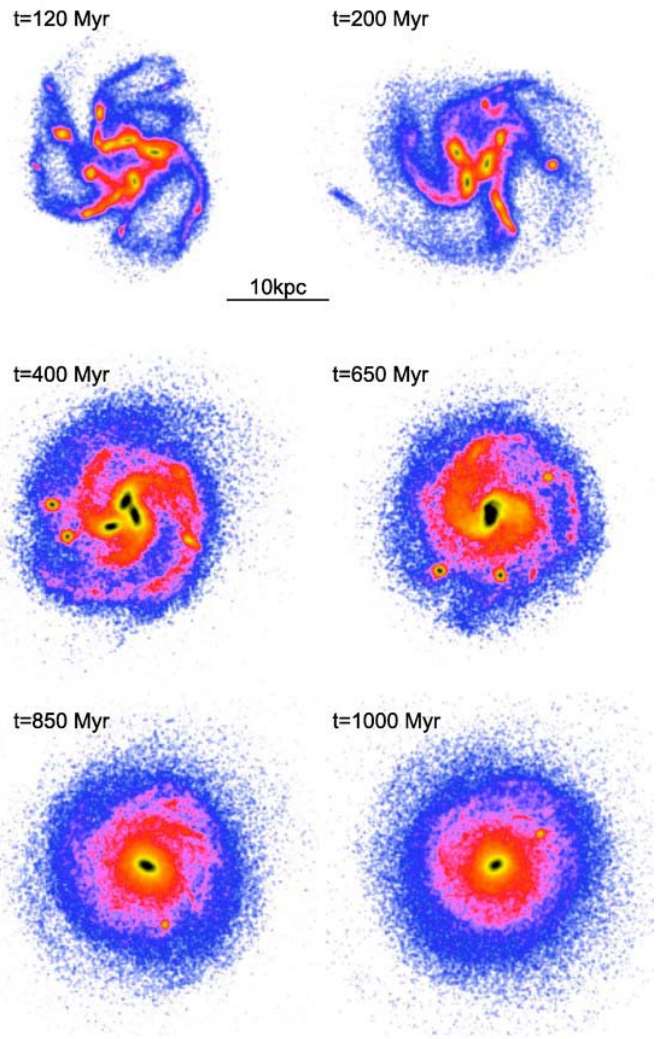
CDMサブハローによる厚い円盤の形成

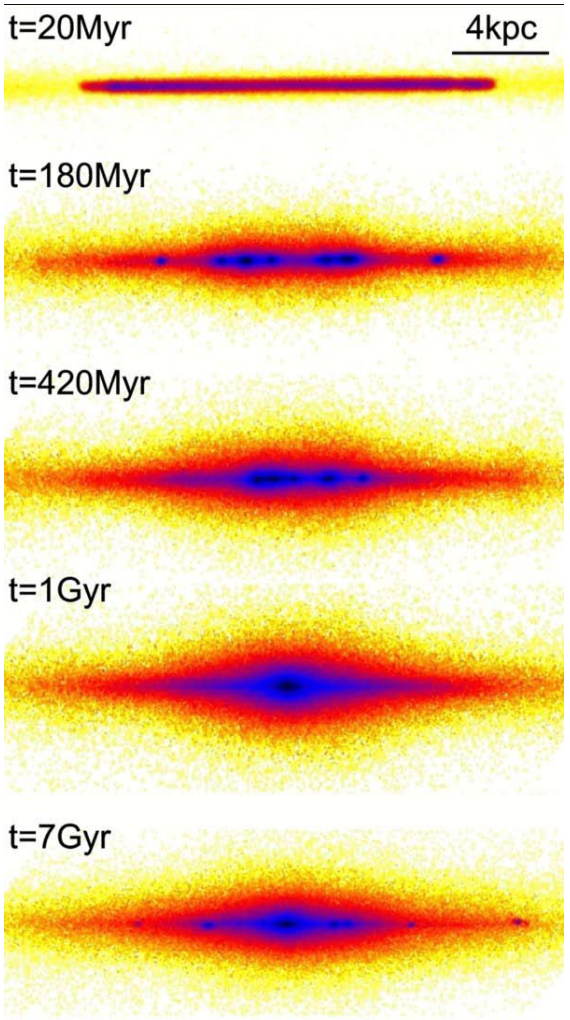
5. 初期のClumpy disk 進化

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. 動径方向の恒星系の流れ

thick disk stars?

Radial migration of disk stars
(Schönrich & Binney 2009)

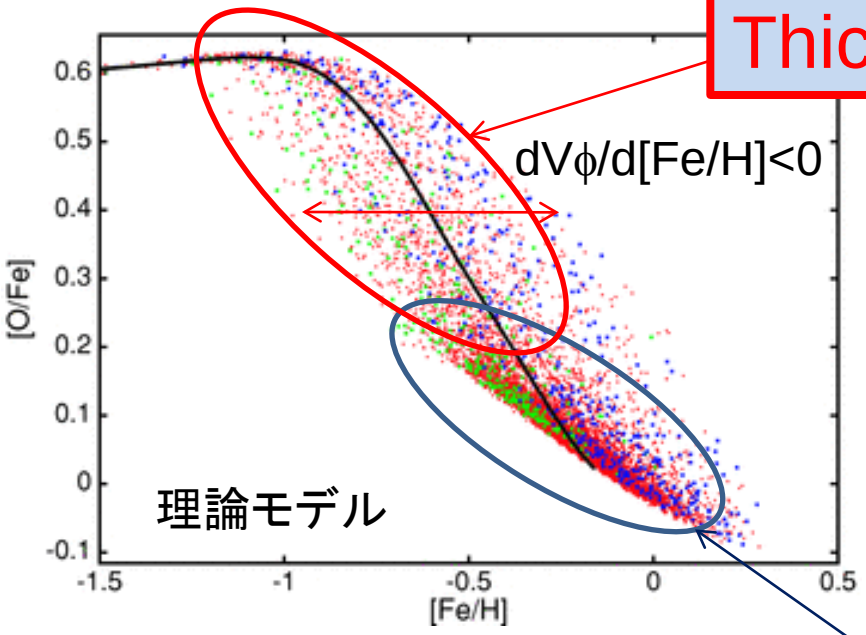
角運動量を得た星　　角運動量を失った星

[α/Fe]が円盤端で最大（？）

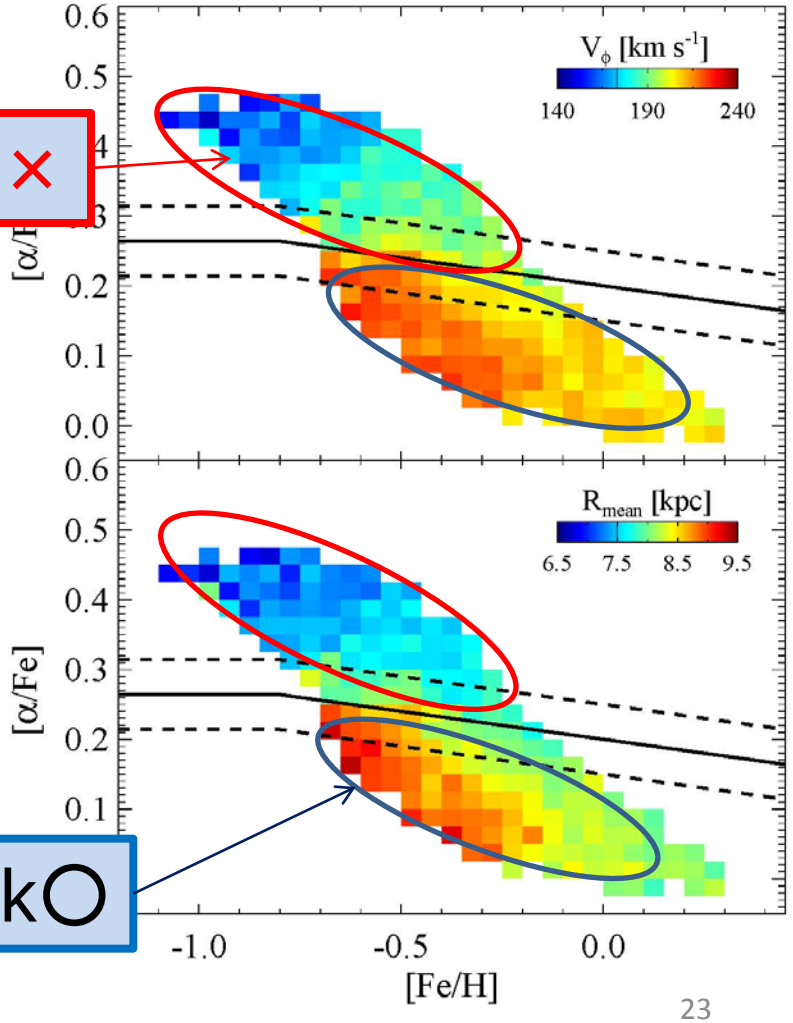
R

transient spiral arms etc.

Lee+2010 SDSS sample



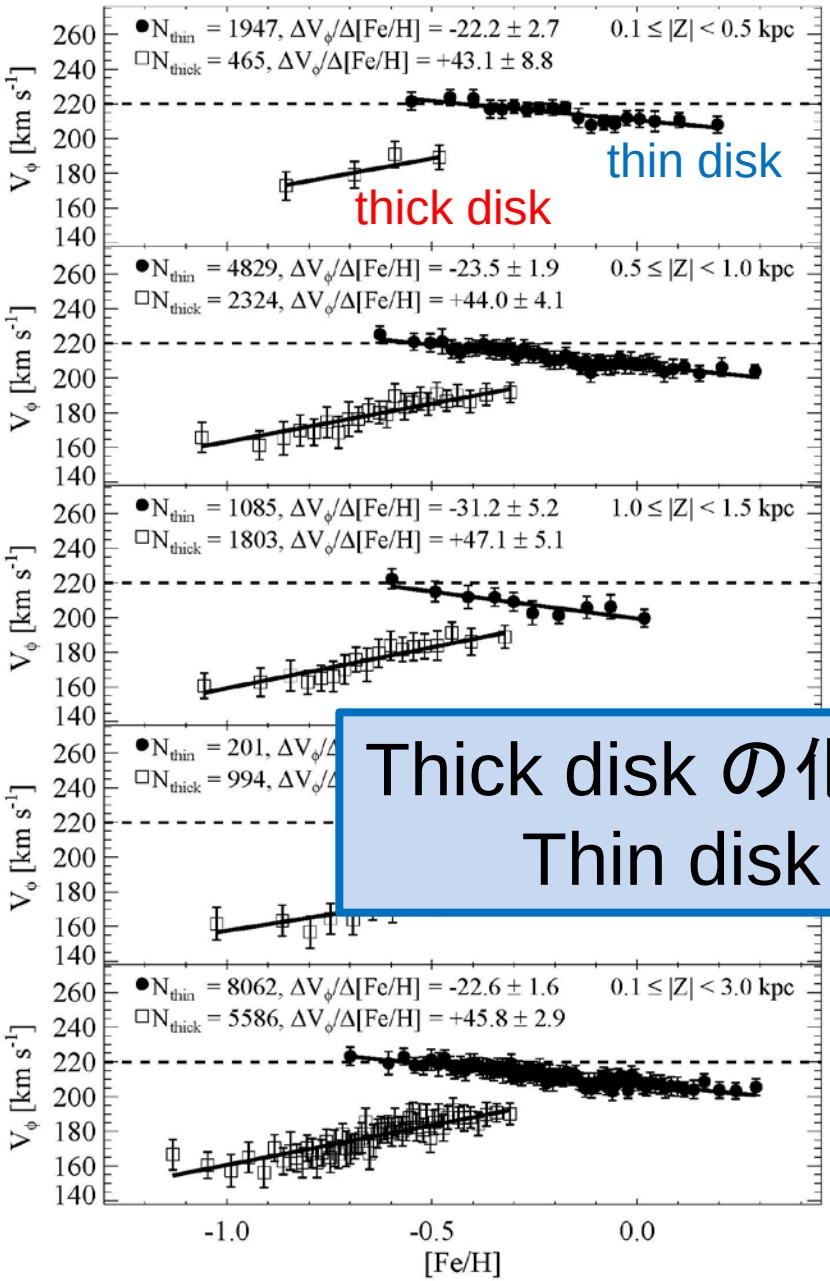
Thick disk ×

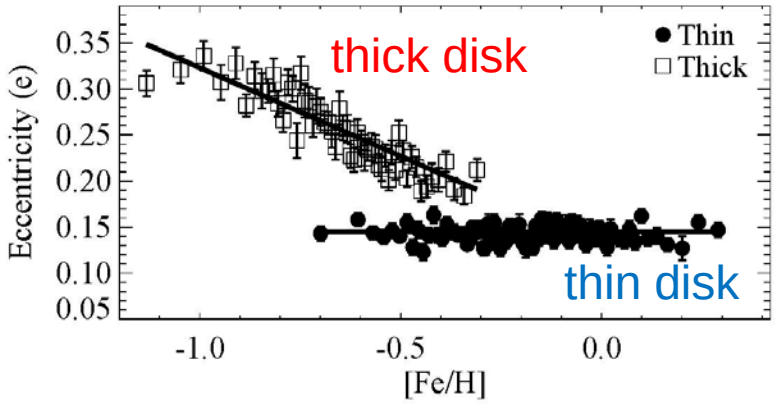


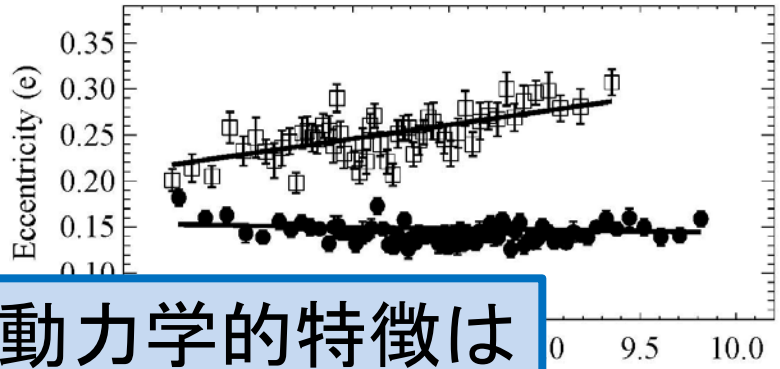
Vϕ < 179 km/s blue
179 < Vϕ km/s < 244 red
Vϕ > 244 km/s green

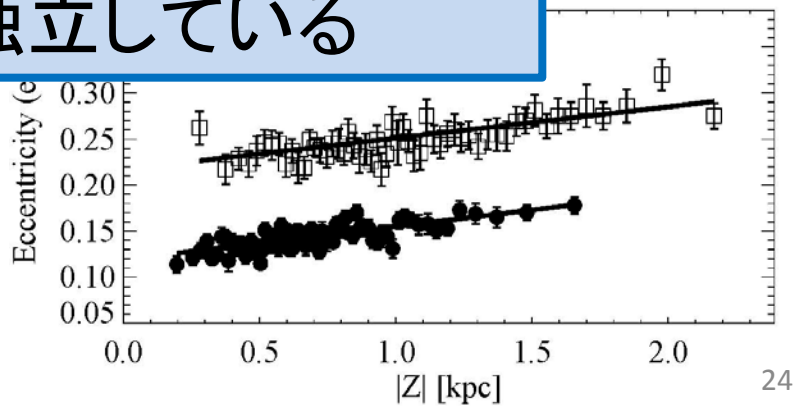
Thin disk○

Lee+2010 SDSS sample



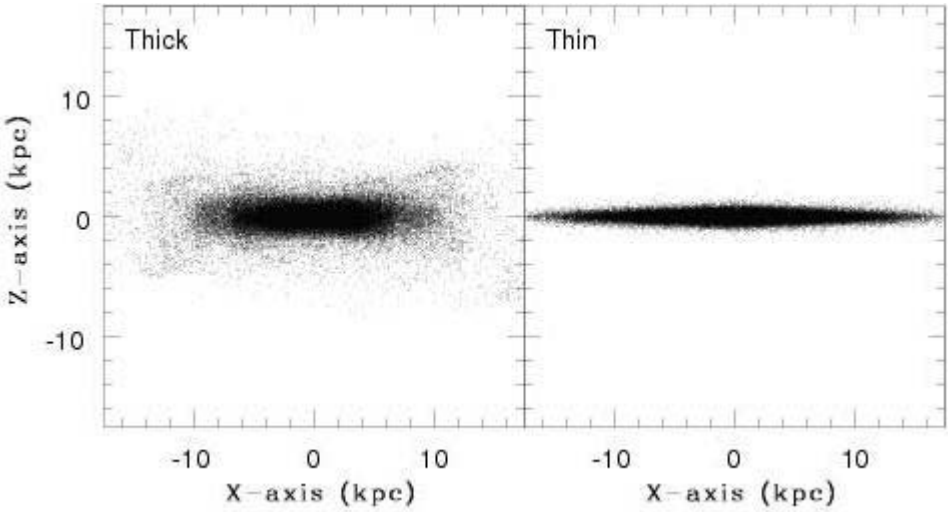


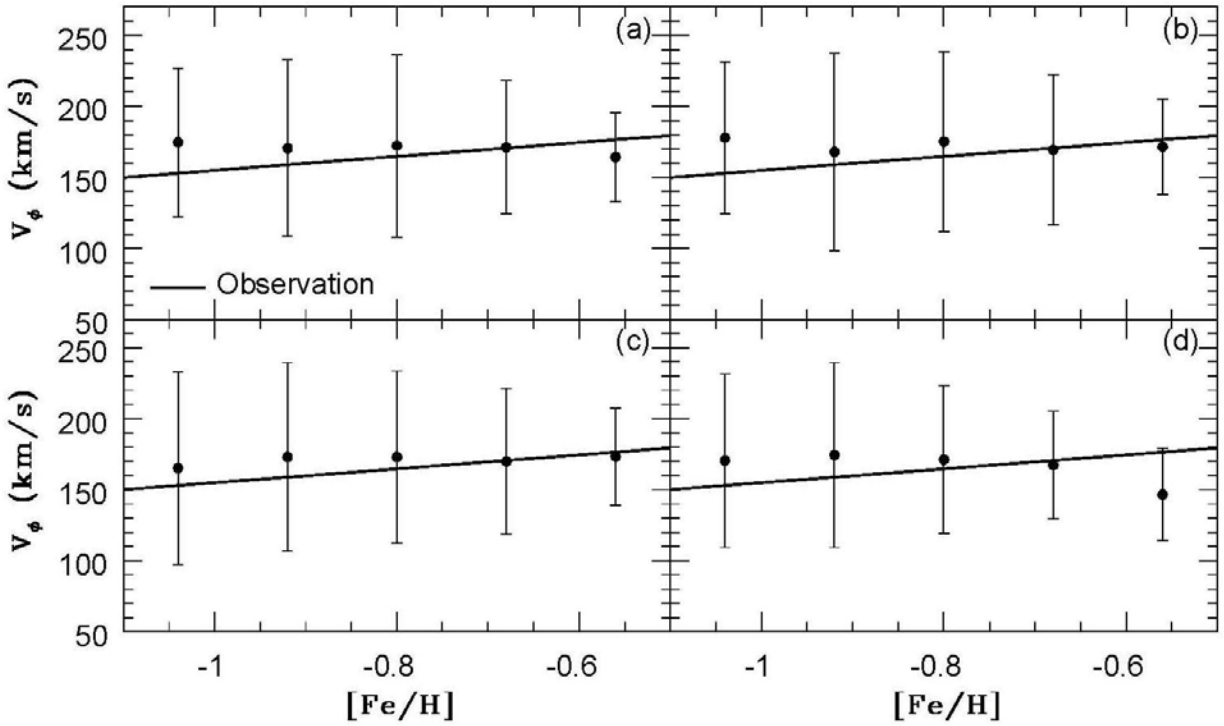




Thick disk の化学動力学的特徴は
Thin disk と独立している

Dynamical heating of a pre-existing disk (with metallicity gradient) driven by the minor merger of a dwarf galaxy (Bekki & Tsujimoto 2011)

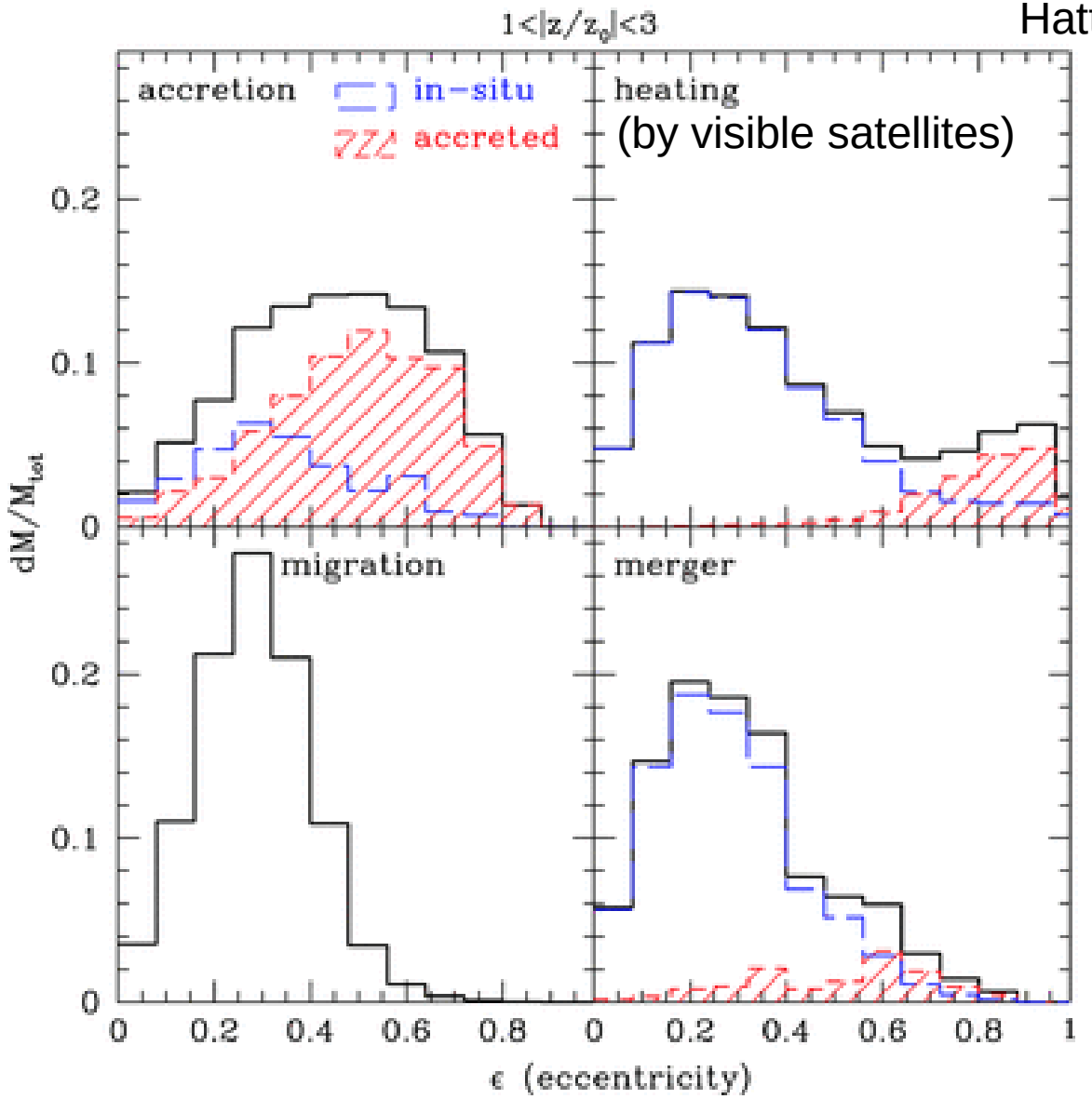




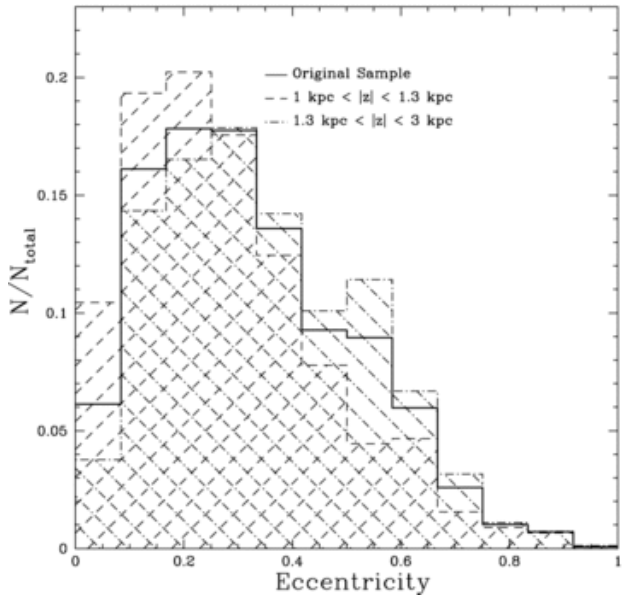
Vϕ vs. [Fe/H] の再現は難しい。

Orbital eccentricity distributions of several models
Sales+ 2009

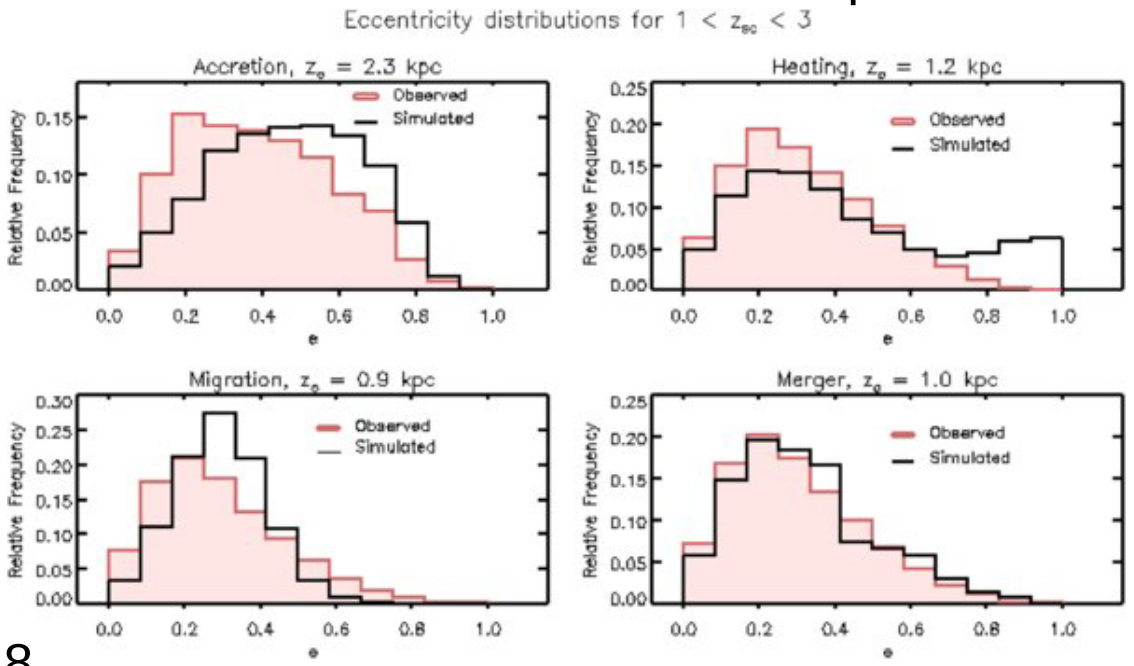
ハローについては
Hattori & Yoshii 2011
を参照



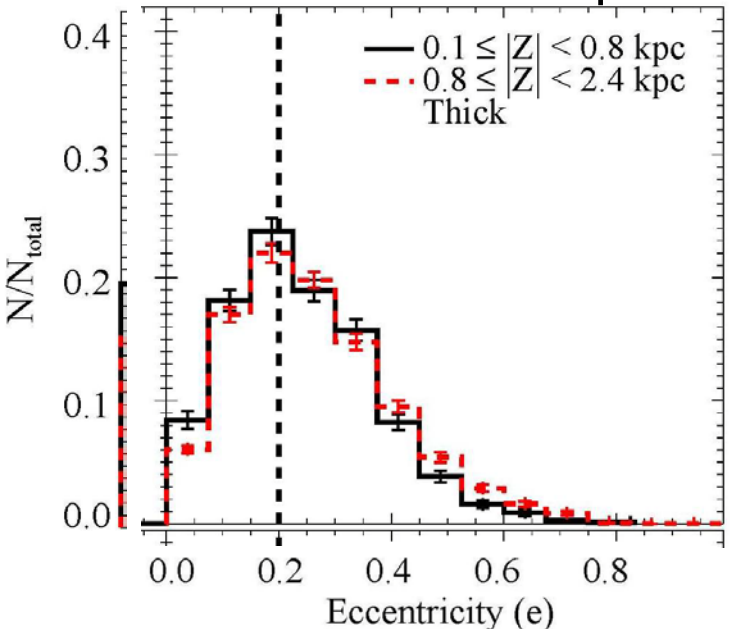
Wilson+2011: RAVE sample



Dierickx+ 2010: SDSS sample DR7



Lee+ 2011: SDSS sample DR8



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

様々なモデルのテスト

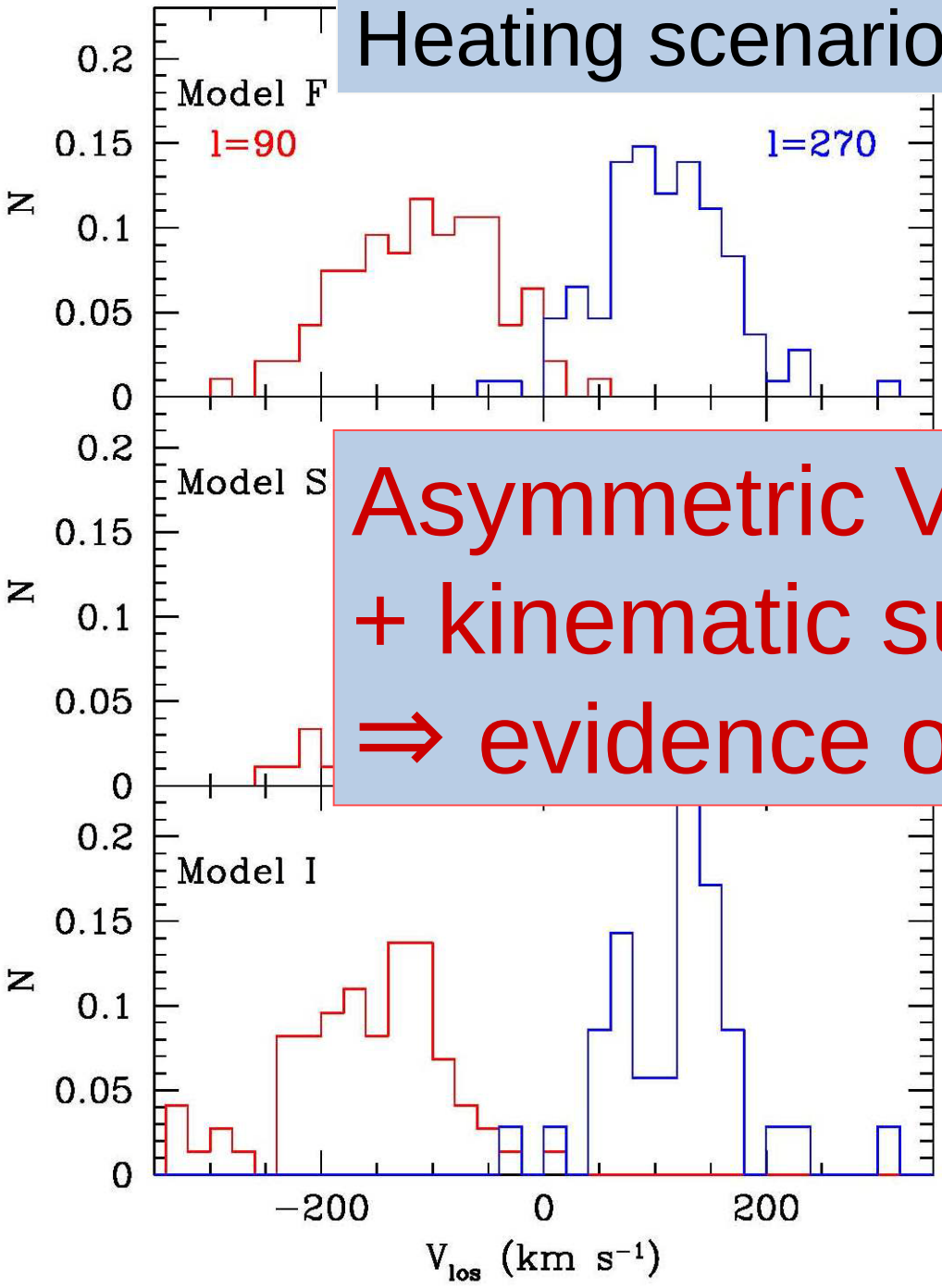
Model	dVϕ/d[Fe/H]	dVϕ/dz	[Fe/H]分布 [α/Fe]分布	Orbital eccentricity
Accretion	N/A	N/A	Failed Failed	Failed
Gas-rich mergers	N/A	Failed	N/A N/A	Passed
Disk heating	? (initial condition)	Passed	? (timing)	Passed
Radial migration	Failed	N/A	Passed? Passed?	Failed
Clumpy disk evolution	N/A	N/A	N/A N/A	N/A

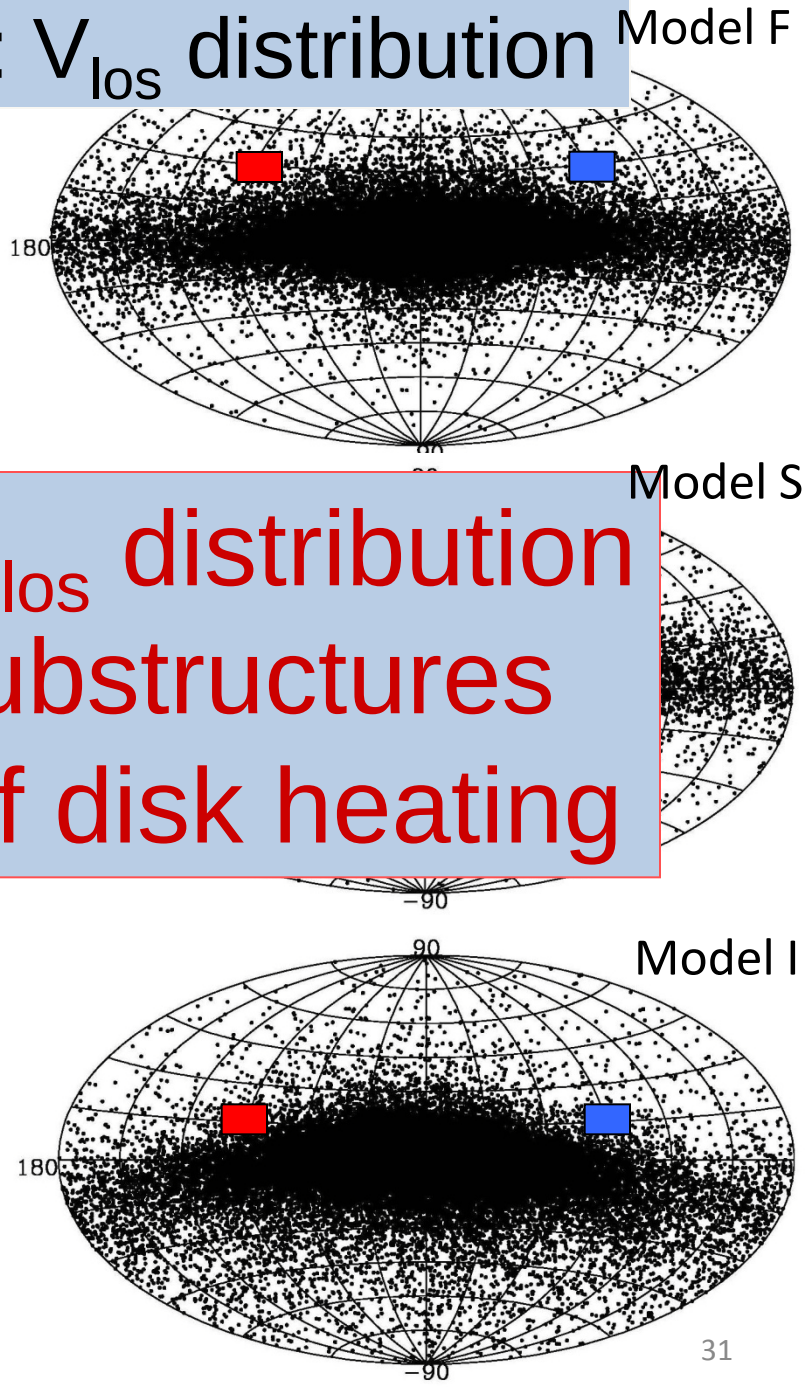
3. 今後の展望

今後必要となる研究内容

- 各シナリオにおける厚い円盤の特徴の解析
  - 速度・軌道分布と空間構造
    - 非対称か否か。サブストラクチャーの存在。
  - 化学元素パターン・金属量分布の空間・運動依存性
    - <Vϕ> vs. [Fe/H], z, R。Metal-weak thick diskの存在割合。
  - Cold accretion + subhalo merging model?
  - ハロー、バルジ、薄い円盤構造 との関連性
- 厚い円盤の詳細な観測と解析
  - 様々な銀河における正確な質量構造
    - 正確な全質量の評価。円盤端の詳細な構造。
  - 太陽近傍以外の場所における速度・軌道分布と化学元素パターン、年齢の分布
    - 非対称か否か。サブストラクチャーの存在。
  - バルジとの関連
  - High-z 銀河にみられる速く回転する円盤部分との関連

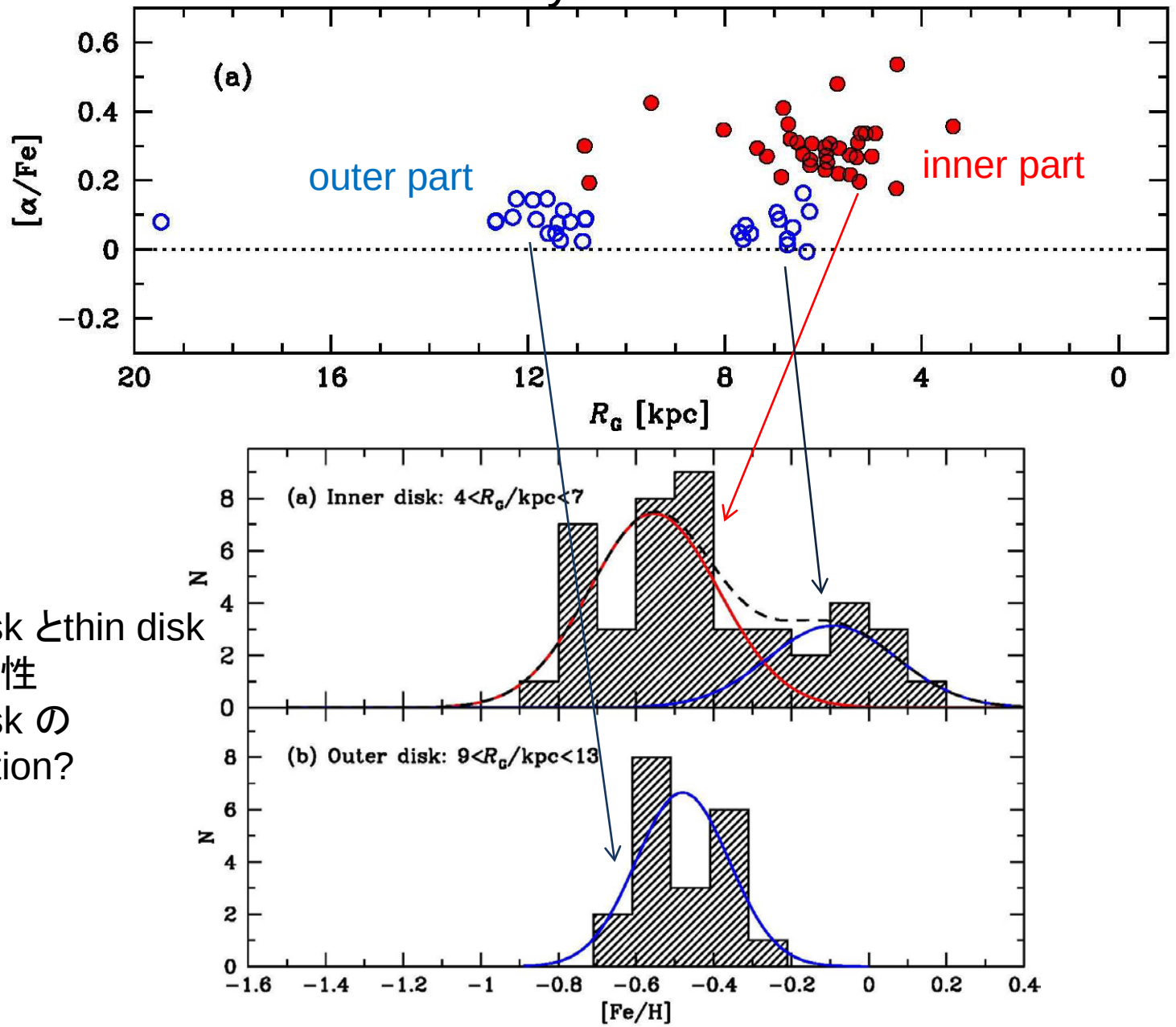
Heating scenario: V_{los} distribution





Asymmetric V_{los} distribution
+ kinematic substructures
⇒ evidence of disk heating

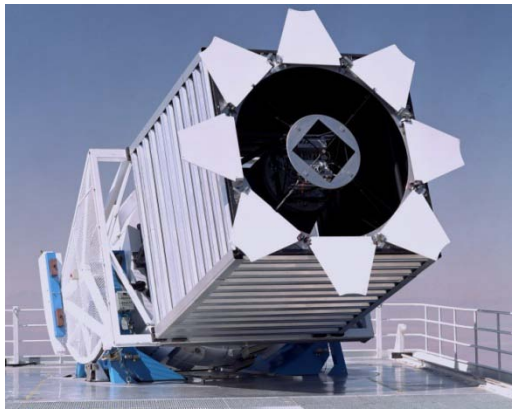
Short scale-length (~ 2kpc) of the thick disk?
Bensby+ 2011



Thick disk とthin disk の独立性

Thick disk の truncation?

今後の展開

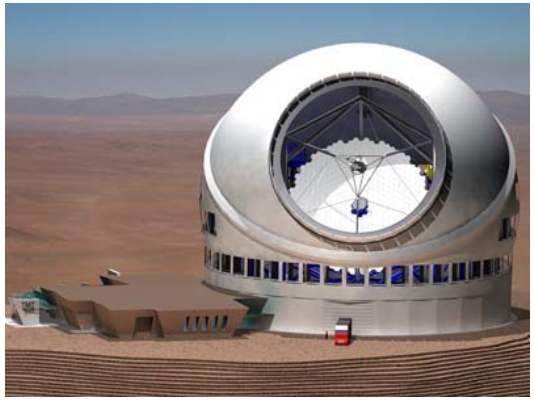


SDSS-III, IV
SEGUE-2
APOGEE
2008~2014

多数のハロー星・円盤星の分光

Subaru
HSC
PFS
2012~2016?

系内・局所銀河星の分光・撮像



TMT
WFOS
HROS
NIRES
2018?

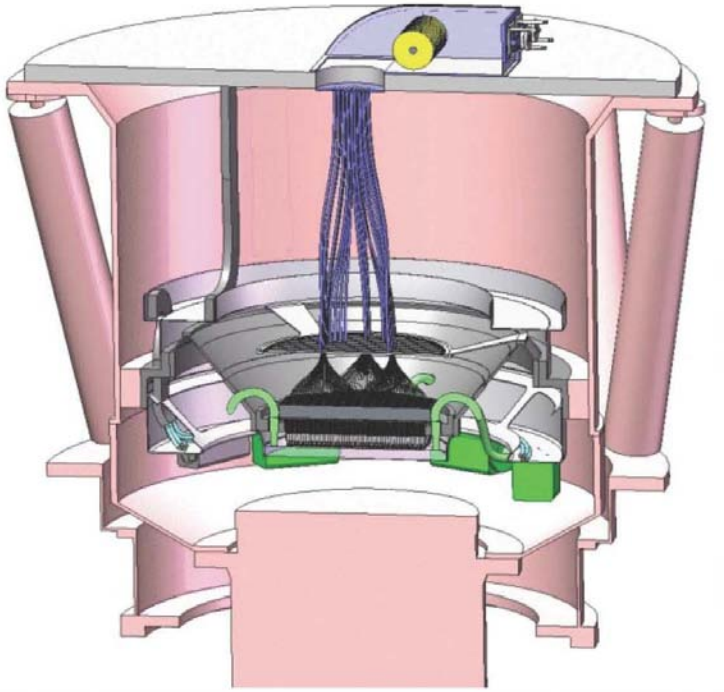
局所宇宙大空間領域の分光・撮像

Gaia
2012~2020?

恒星系の高精度位置天文観測

円盤銀河の形成史の解明へ

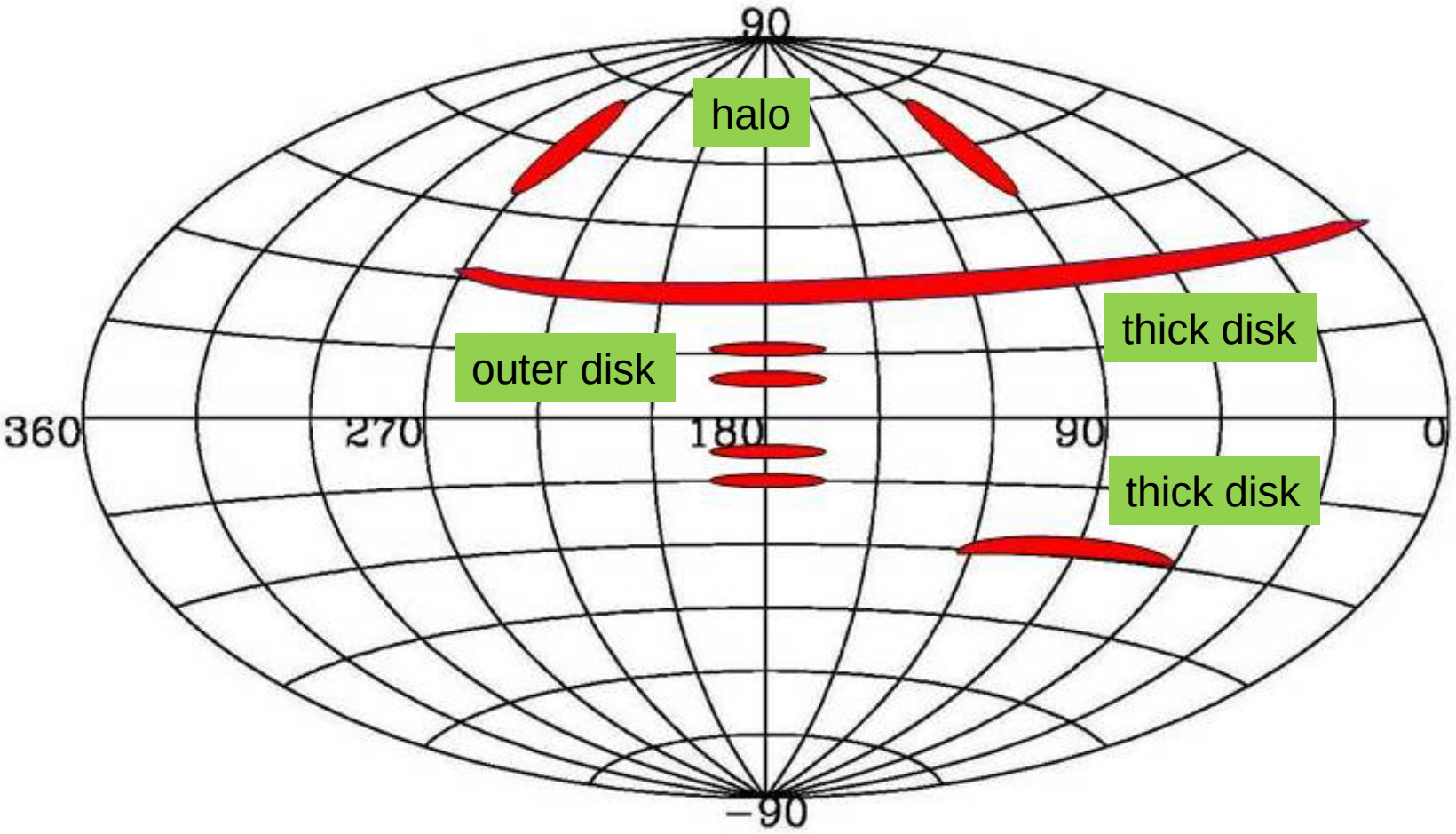
PFS
(Prime Focus Spectrograph)



FOV: 1.77 sq deg
(1.5 deg diameter)
2400 to 3000
fiber positioners
40 sec reconfig. time
λ: 300~1,000nm or more?
R: 3,000 or more?

銀河系の厚い円盤・ハロー、矮小銀河、アンドロメダ銀河にある多数(~10^6)の星を分光⇒金属量、視線速度
＋ Gaia によるアストロメトリ情報

Proposed Survey Fields in the MW



Summary

Thick diskは円盤銀河の形成過程の解明において重要な鍵となる