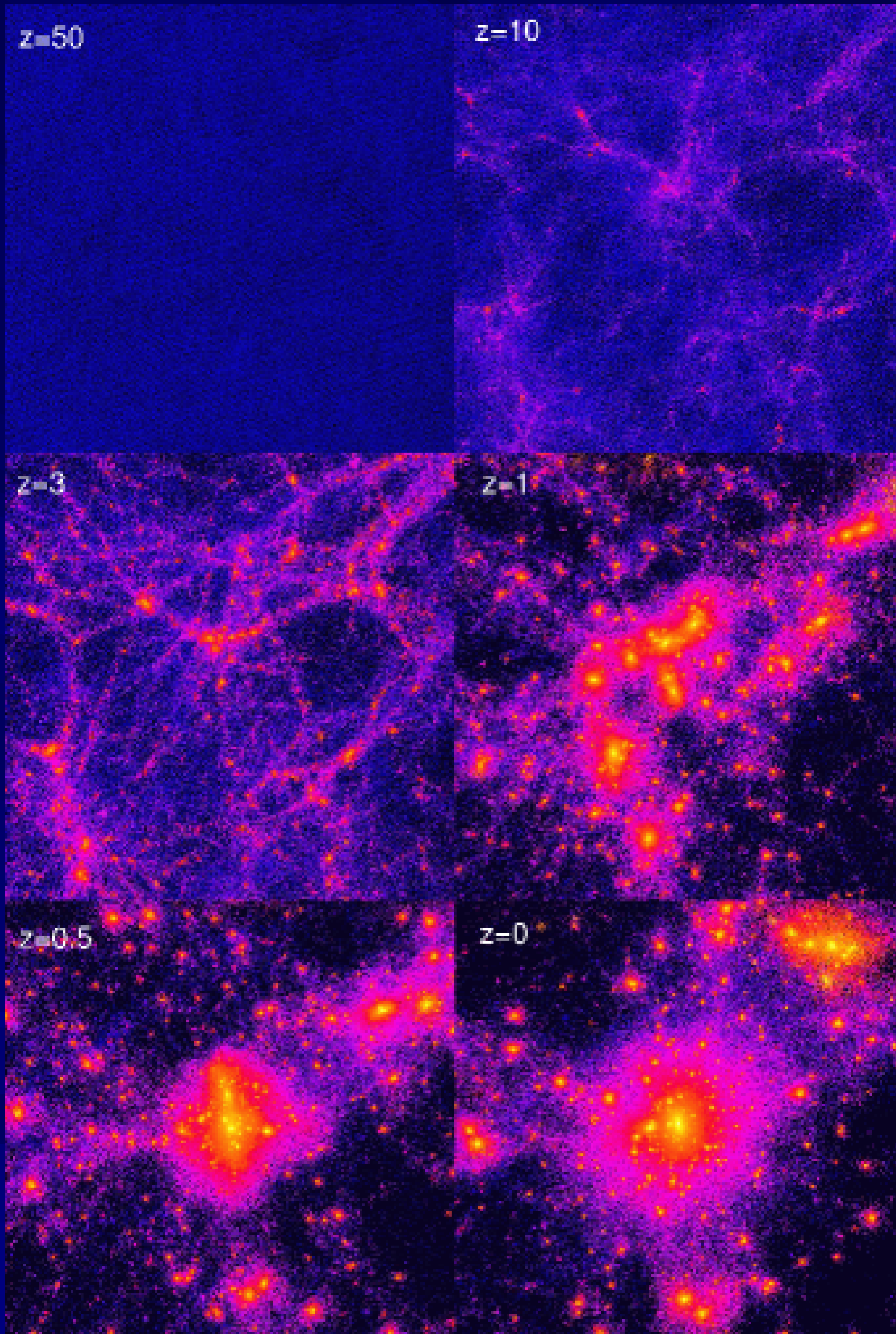
理論天文学のシンポ
～銀河系･近傍銀河研究の進展～

千葉柾司
(東北大学)



Cold Dark Matter

- galaxy formation
- galaxy distribution
- galaxy dynamics
- galaxy morphology

$+\Lambda \Rightarrow \Lambda CDM$

By B.Moore

Issues in ΛCDM-based galaxy formation

Downsizing

Missing satellite problem

UV feedback

Over-merging

NFW profile

AGN feedback

Angular-momentum problem

Substructure

Central cusp problem

講演内容

- その時歴史は動いた！
  - 銀河系天文学を前進させた研究
- 未解決問題と今後

その時歴史は動いた：
まず10年前の状況

- Λは小さいかゼロ？
  – Kochanek 1996　レンズ統計
  – Λ＜0.66 at 95% confidence！
  – Type Ia の初期データも同様の結果
- ダークハローの空間分布？
  – Navarro, Frenk, & White 1996, 1997
  – NFW profile
- ダークハローのオーバーマージング？
  – Cf. Moore et al. 1999, Klypin et al. 1999

10年間の最多引用文献10傑
(Thomson Corp.: ESI, Space Science)

1. 2934 Schlegel et al. 1998
2. 2638 Spergel et al. 2003
3. 2198 Perlmutter et al. 1999
4. 2163 Riess et al. 1998
5. 1401 Bertin & Arnouts 1996
6. 1339 Navarro, Frenk, & White 1997
7. 1278 Bennett et al. 2003
8. 1088 Navarro, Frenk, & White 1996
9. 928 Condon et al. 1998
10. 854 York et al. 2000

11~20位

11. 828 Harris 1996
12. 804 Freedman et al. 2001
13. 790 Madau et al. 1996
14. 778 Cleveland et al. 1998
15. 774 Seljak & Zaldarriaga 1996
16. 728 Magorrian et al 1998
17. 724 Sanders & Mirabel 1996
18. 712 Kennicutt 1998
19. 687 Grevesse & Sauval 1998
20. 676 Steidel et al. 1999

銀河系(恒星系)関連の主な出来事

- 1922: High velocity stars (Oort)
- 1923: M31 as an external galaxy (Hubble)
- 1944: Population I, II (Baade)
- 1962: Galaxy collapse (Eggen, Lynden-Bell, Sandage)
  - 1964: Density wave (Lin, Shu), 1966: Galactic shock wave (Fujimoto)
- 1969: Simulation of galaxy collapse (Larson)
- 1978: Chaotic merging picture (Searle, Zinn)
- 1983: The thick disk (Gilmore, Reid)
  - Cf. 1982: Yoshii
- 1993: MACHO (Alcock et al.)
- 1994: Sgr dwarf (Ibata et al.)
- 1997: Hipparcos Catalogue open to public
  - 1998: MC & Yoshii, 2000: MC & Beers
- 2001: SDSS EDR

銀河系形成のシナリオ

Oort, J. H. 1922: high velocity stars

Netherlands Astronomical Institutes.

BAN

BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

COMMUNICATIONS FROM

THE OBSERVATORY AT LEIDEN, THE OBSERVATORY AT UTRECHT,
THE KAPTEYN ASTRONOMICAL LABORATORY AT GRONINGEN,
THE HELIOPHYSICAL INSTITUTE OF THE UNIVERSITY AT UTRECHT,
THE ASTRONOMICAL INSTITUTE OF THE UNIVERSITY AT AMSTERDAM.

VOLUME I.

Numbers 1—40
1921 November 30 — 1923 July 9.

Printed by JOH. ENSCHEDÉ EN ZONEN
Haarlem

太陽近傍星の運動を系統的に解析

BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

1922 September 1 — No. 23.

COMMUNICATION FROM THE KAPTEYN ASTRONOMICAL LABORATORY
AT GRONINGEN.

Some peculiarities in the motion of stars of high velocity, by *J. H. Oort.*

Among the stars observed for radial velocity a greater number occur of large speed than are to be expected with a Maxwellian distribution. There are at least 16 stars whose radial velocity surpasses 150 *km/sec* whereas according to Maxwell's law with a mean radial velocity of 20 *km/sec* we do not find an average of one of that speed in a million.

The velocities of those stars, when freed from solar motion, are not found to be distributed at random, nor do they show a preference that might originate from either of the two star streams: they are all moving towards one hemisphere of the sky, as has already been demonstrated by W. S. ADAMS and A. H. JOY *).

The principal aim of the present article is to test this result for other stars and to prove that a *sharply defined limit* exists, above which all velocities are directed towards the above mentioned hemisphere, whereas for inferior velocities no preference seems to exist.

The directions of the radial motions of these 47 stars are consequently concentrated whithin the galactic longitudes 130° and 342° or whithin a sector of 212° (see figure 3). The average longitude of the radial velocity vectors *) is 230° and the average latitude −5°.

At first sight we should be inclined to think that the systematic motion of the stars just described is caused by the selection of the observational material. It is undoubtedly true that the fainter stars have been selected on account of their large p. m. and high declination; but it is difficult to imagine how this can have influenced the *sign* of the rad. vel. Also the following arguments may be advanced:

1. Without exception the stars brighter than 4ᵐ.6 Harv. have been observed for rad. vel. Among these occur 9 with a velocity > 65 *km/sec*; they all show the systematic motion very distinctly.

2. If it were a consequence of selection the same phenomenon should show itself in velocities between

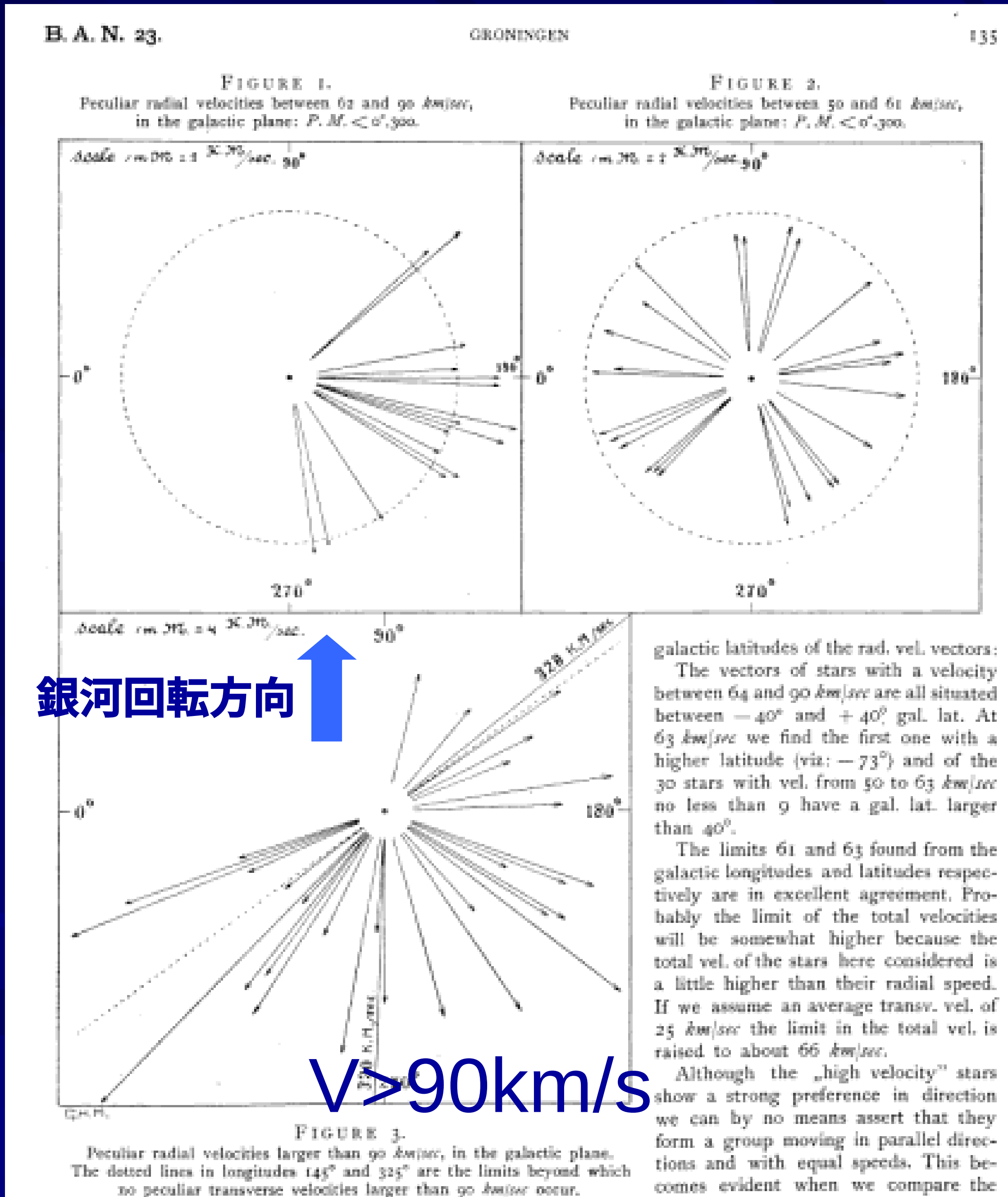


FIGURE 1.
Peculiar radial velocities between 62 and 90 *km/sec*, in the galactic plane: *P. M.* < 0".300.

FIGURE 2.
Peculiar radial velocities between 50 and 61 *km/sec*, in the galactic plane: *P. M.* < 0".300.

FIGURE 3.
Peculiar radial velocities larger than 90 *km/sec*, in the galactic plane. The dotted lines in longitudes 145° and 325° are the limits beyond which no peculiar transverse velocities larger than 90 *km/sec* occur.

galactic latitudes of the rad. vel. vectors:

The vectors of stars with a velocity between 64 and 90 *km/sec* are all situated between −40° and +40° gal. lat. At 63 *km/sec* we find the first one with a higher latitude (viz: −73°) and of the 30 stars with vel. from 50 to 63 *km/sec* no less than 9 have a gal. lat. larger than 40°.

The limits 61 and 63 found from the galactic longitudes and latitudes respectively are in excellent agreement. Probably the limit of the total velocities will be somewhat higher because the total vel. of the stars here considered is a little higher than their radial speed. If we assume an average transv. vel. of 25 *km/sec* the limit in the total vel. is raised to about 66 *km/sec*.

Although the „high velocity" stars show a strong preference in direction we can by no means assert that they form a group moving in parallel directions and with equal speeds. This becomes evident when we compare the

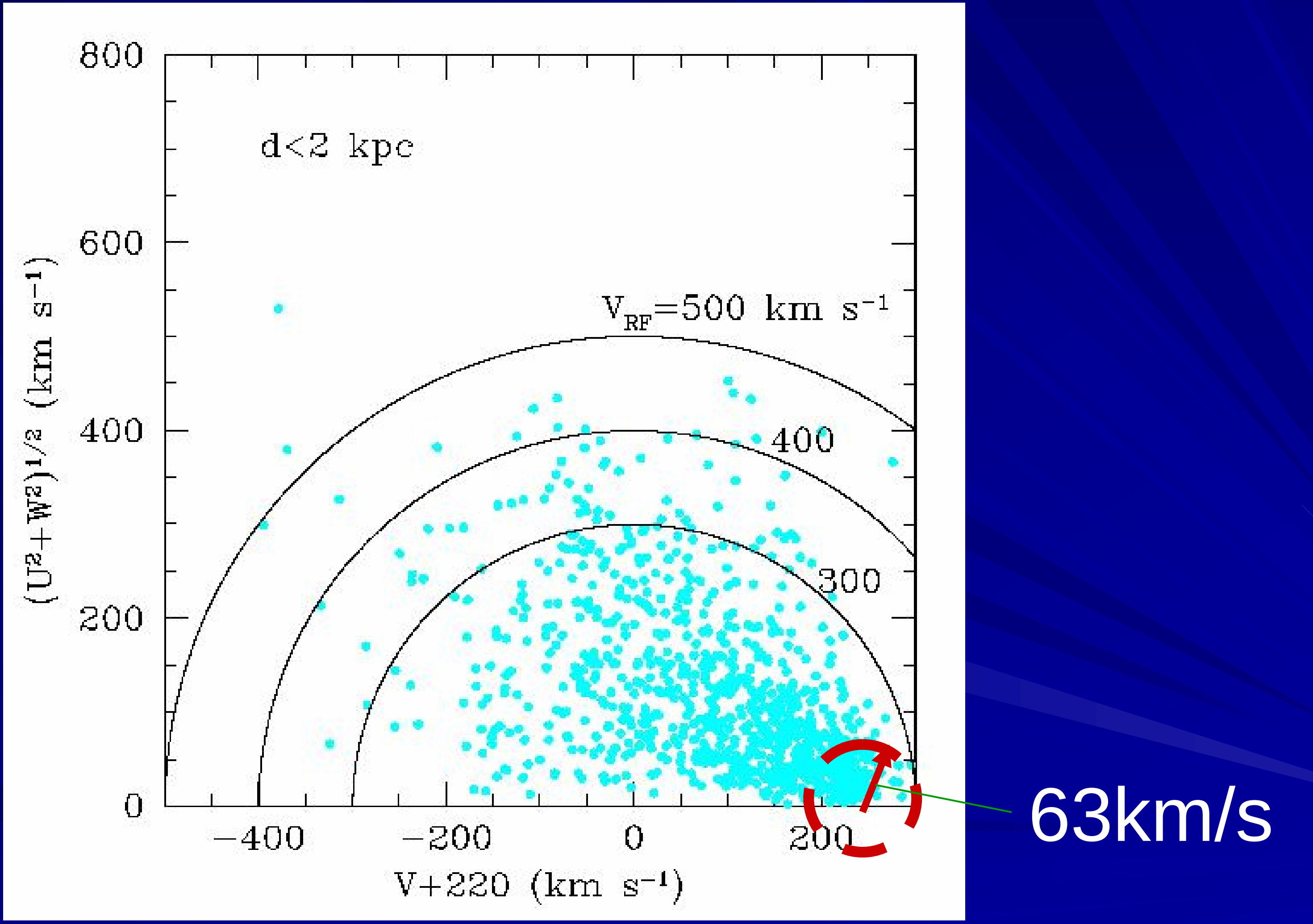
$V < V_{lim}$=90km/s
では、ガウス分布。
速度方向は対称。

$V > V_{lim}$
(high velocity stars)
では、速度方向が
非対称になる。

Oort 1926 にて
V_{lim}=63km/sに改訂。

太陽近傍星の３次元速度分布
(ヒッパルコス衛星データ)

銀河回転に垂直方向の速度



銀河回転方向の速度

Eggen, Lynden-Bell, Sandage 1962

Metallicity

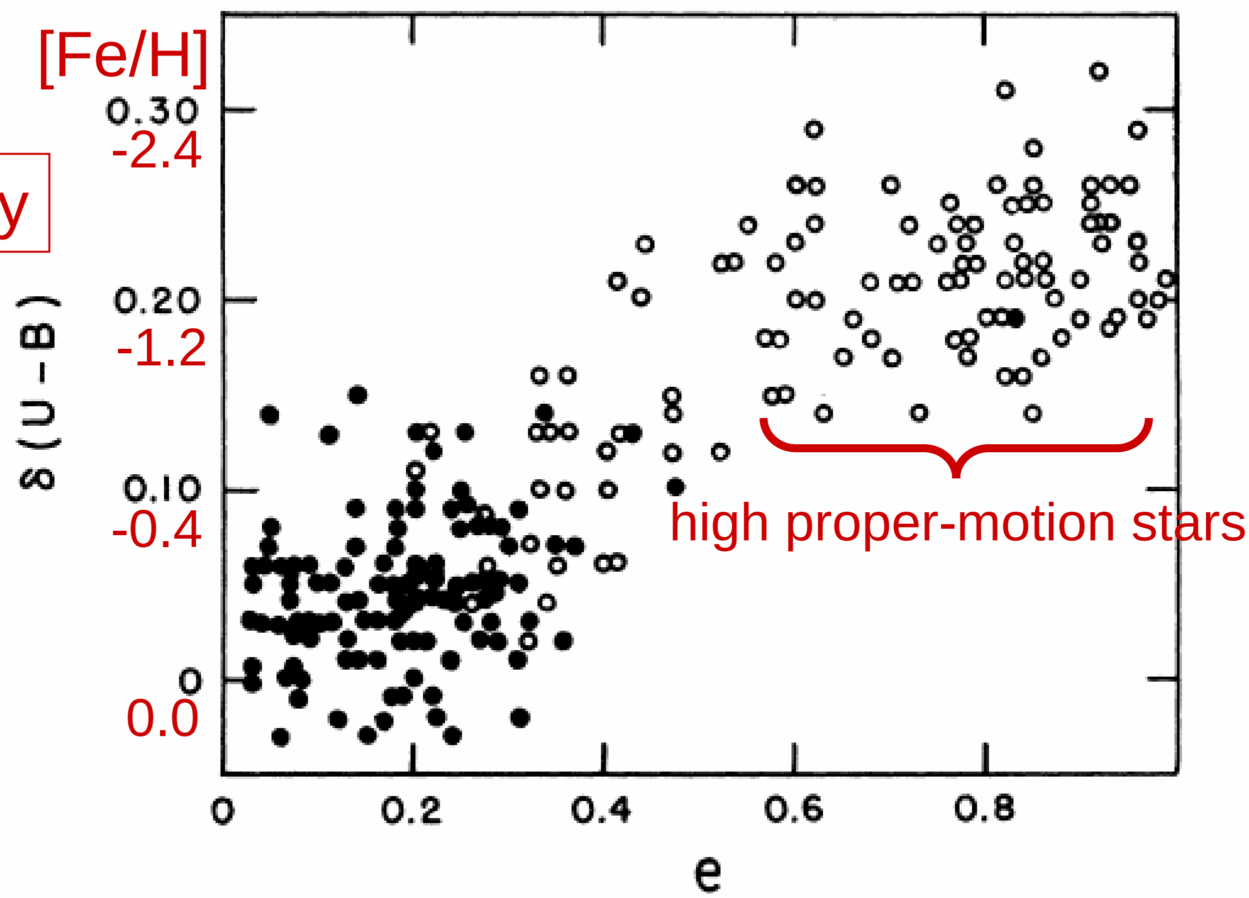
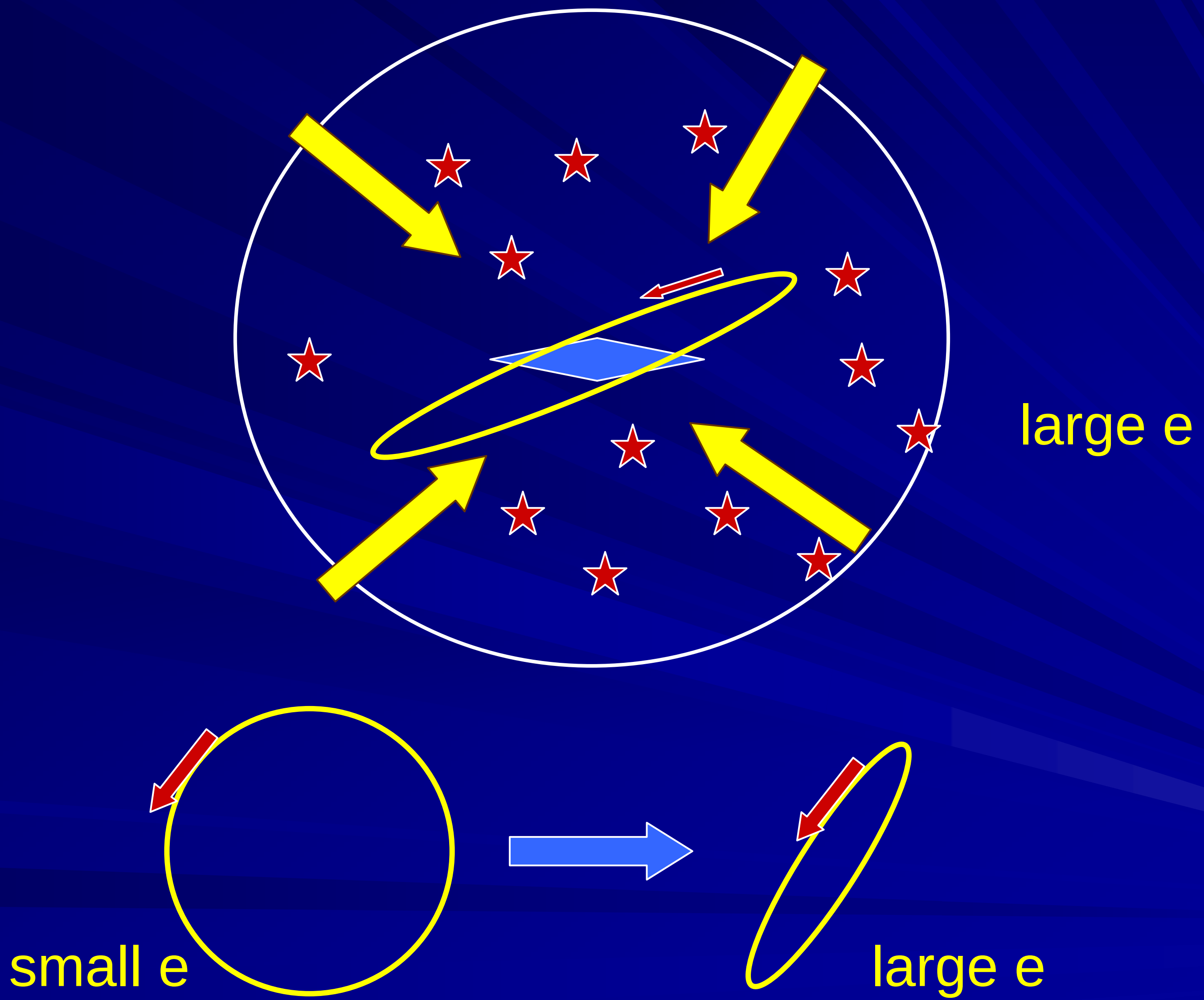


FIG. 4.—The correlation between the ultraviolet excess, δ(U —
our sample of 221 stars. The filled and open circles represent star
respectively.

Free-fall collapse

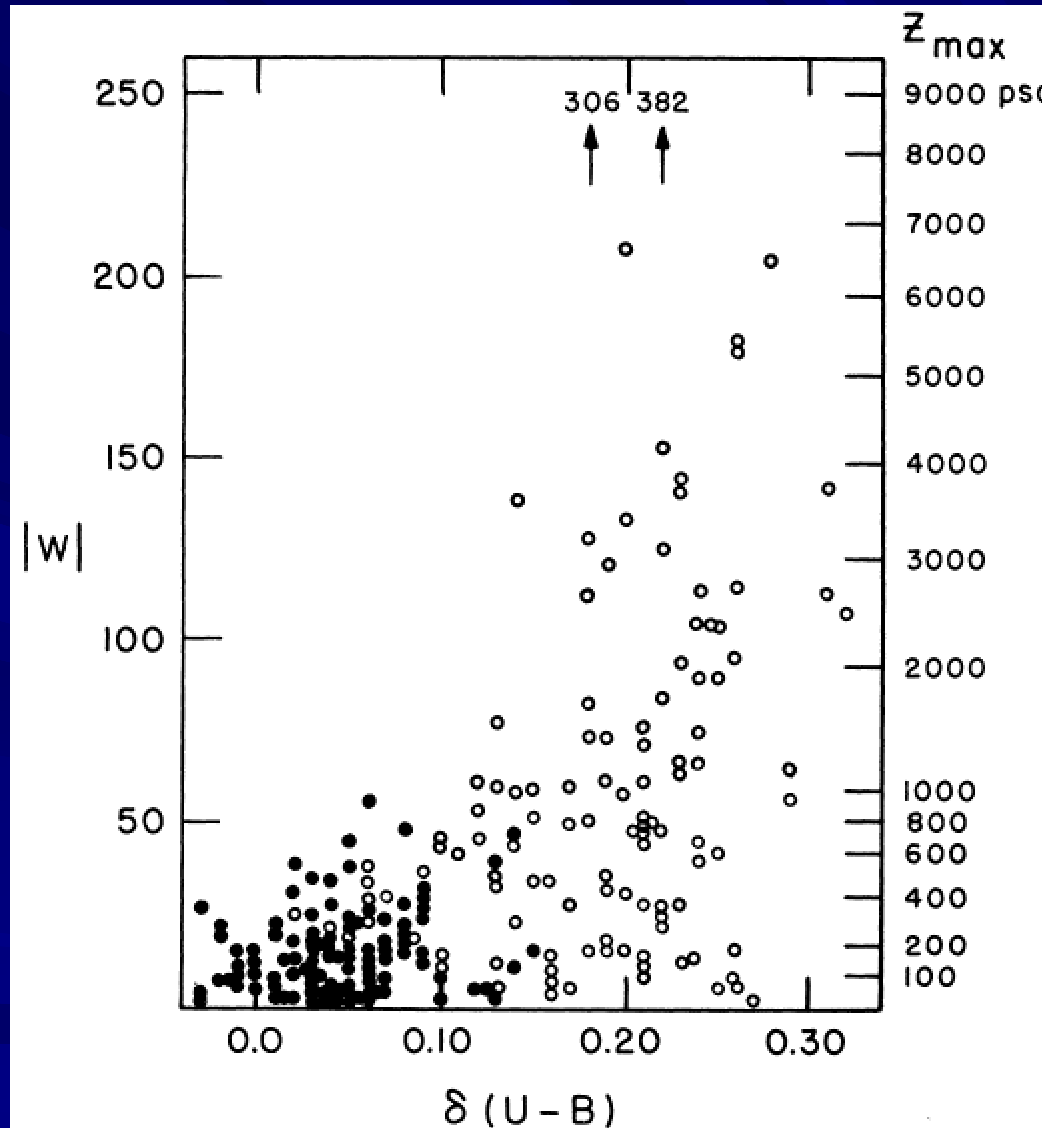
Orbital eccentricity
$e = (r_{ap}-r_{pr}) / (r_{ap}+r_{pr})$

Free-fall collapse



ELS

銀河面に垂直方向（Z）速度



Z方向の到達最高点

金属量

Collapse factor

~25 in Z

~10 in R

Larson 1969: 銀河形成の数値モデル

Mon. Not. R. astr. Soc. (1969) **145**, 405–422.

A MODEL FOR THE FORMATION OF A SPHERICAL GALAXY

Richard B. Larson

(Communicated by P. Demarque)

(Received 1969 March 24)

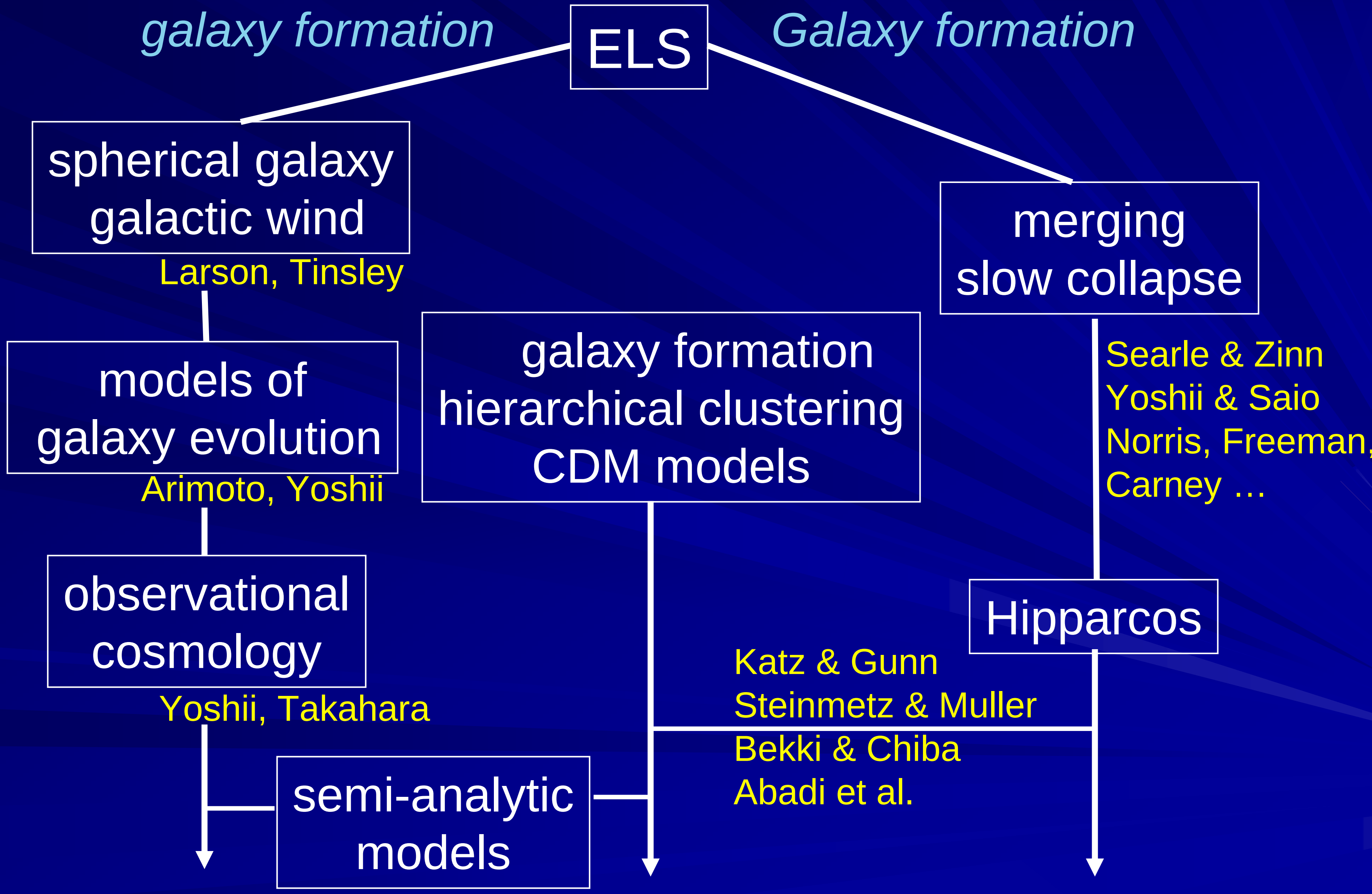
SUMMARY

Numerical calculations have been made for a model representing the collapse of an initially gaseous proto-galaxy and the concurrent transformation of gas into stars. The assumed turbulent motions of the gas are represented by a simple model consisting of discrete colliding clouds, and the star formation rate is assumed to be given as a simple function of the density and turbulent velocity of the gas. The gas clouds and the stars are then treated separately by means of fluid-dynamical equations derived from the Boltzmann equation. It is found that, by assuming reasonable values for the various parameters of the model, it is possible in this way to reproduce reasonably well the observed properties of spherical and nearly spherical galaxies.

1. INTRODUCTION

It is generally believed that galaxies form as the result of the gravitational instability and collapse of condensations in an expanding universe (Field 1969). Evidence that a collapse occurred during the early history of our own galaxy has been provided by the work of Eggen, Lynden-Bell, & Sandage (1962). In the present investigation we adopt the basic picture of formation of galaxies by collapse, and we consider the problem of treating this collapse numerically. A number of calculations of the dynamical collapse of a spherical gas cloud have recently been made in connection with the problem of star formation (see for example Larson 1968, 1969); consequently it is of interest to see whether similar techniques might profitably be applied to the more difficult problem of galaxy formation.

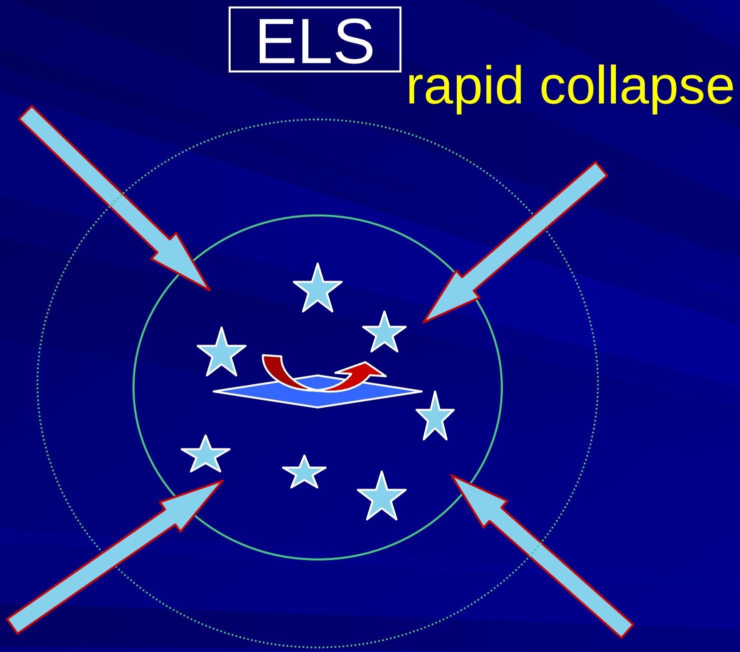
Since ELS …



galaxy formation
ELS
Galaxy formation
spherical galaxy
galactic wind
Larson, Tinsley
merging
slow collapse
models of
galaxy evolution
Arimoto, Yoshii
galaxy formation
hierarchical clustering
CDM models
Searle & Zinn
Yoshii & Saio
Norris, Freeman,
Carney …
observational
cosmology
Yoshii, Takahara
Hipparcos
Katz & Gunn
Steinmetz & Muller
Bekki & Chiba
Abadi et al.
semi-analytic
models

Classical Pictures

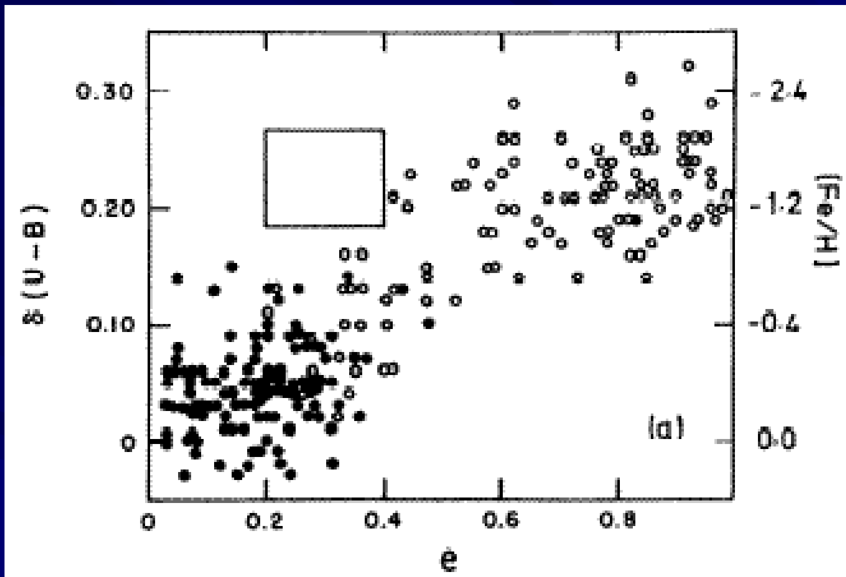
* Monolithic, free-fall collapse
  Eggen, Lynden-Bell, Sandage 1962 (ELS)
* Chaotic merging of numerous fragments
  Searle, Zinn 1978 (SZ)



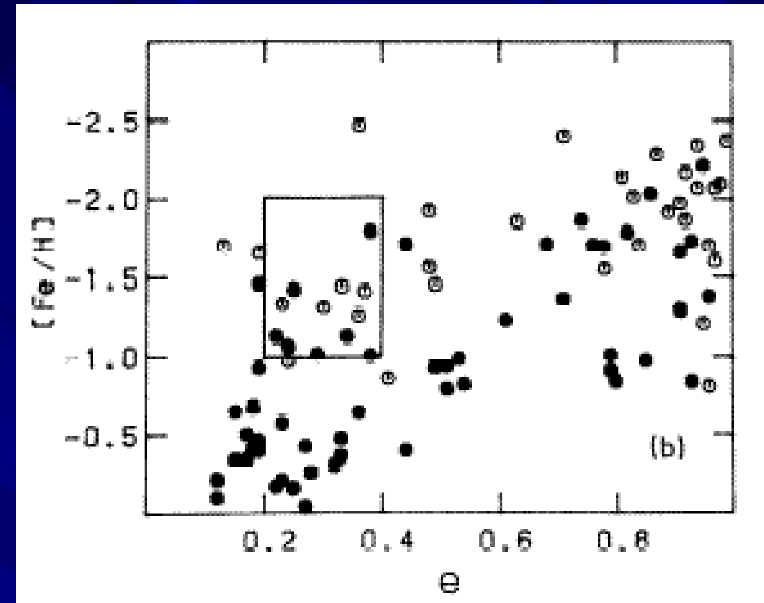
Correlation between kinematics and metal abundances of stars

Age spread among globular clusters
(but how did the disk form?)

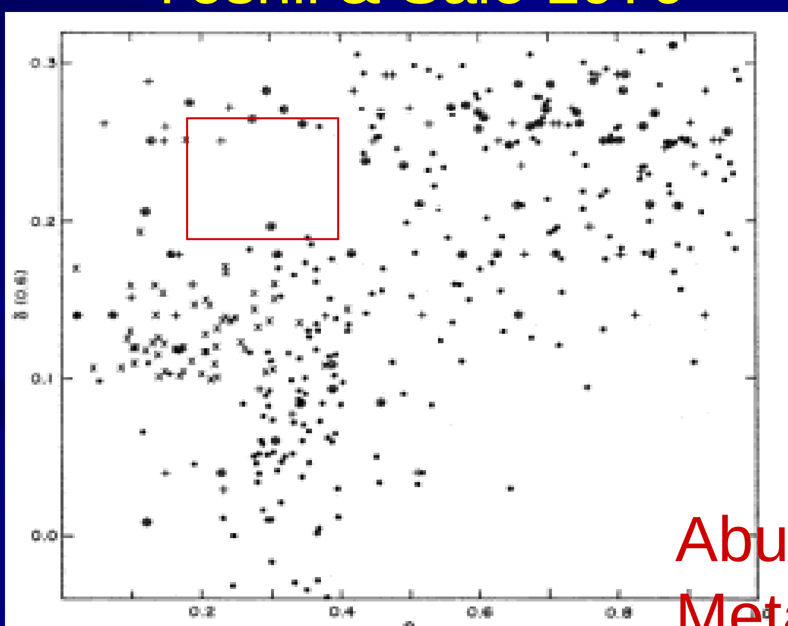
ELS 1962



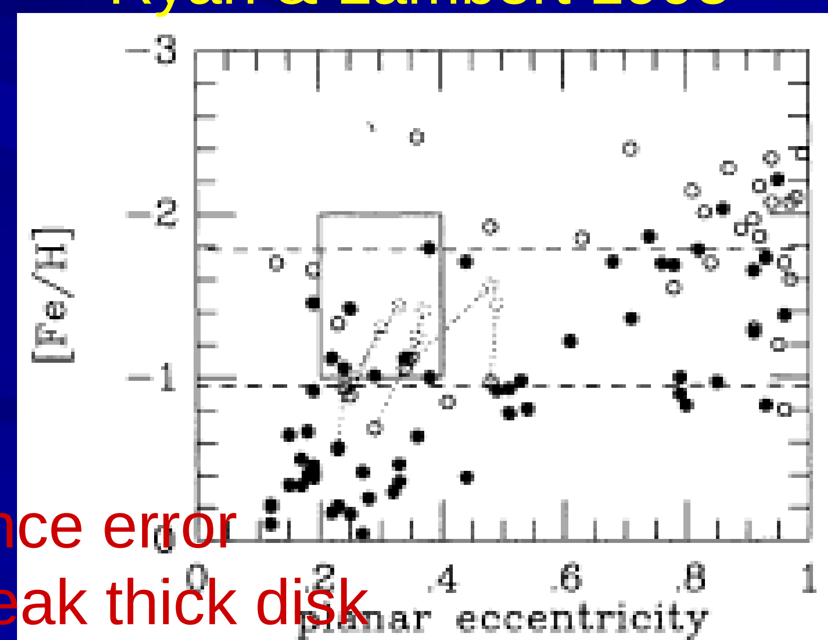
Norris et al. 1985



Yoshii & Saio 1979



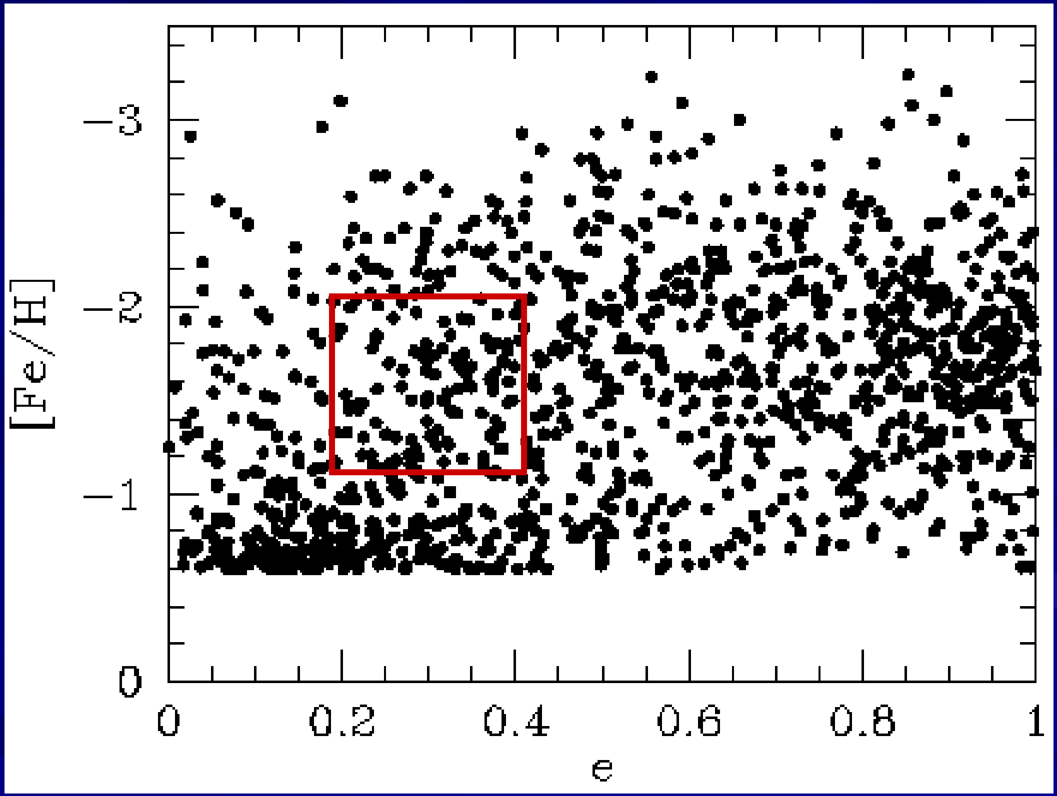
Ryan & Lambert 1995



Abundance error

Metal-weak thick disk

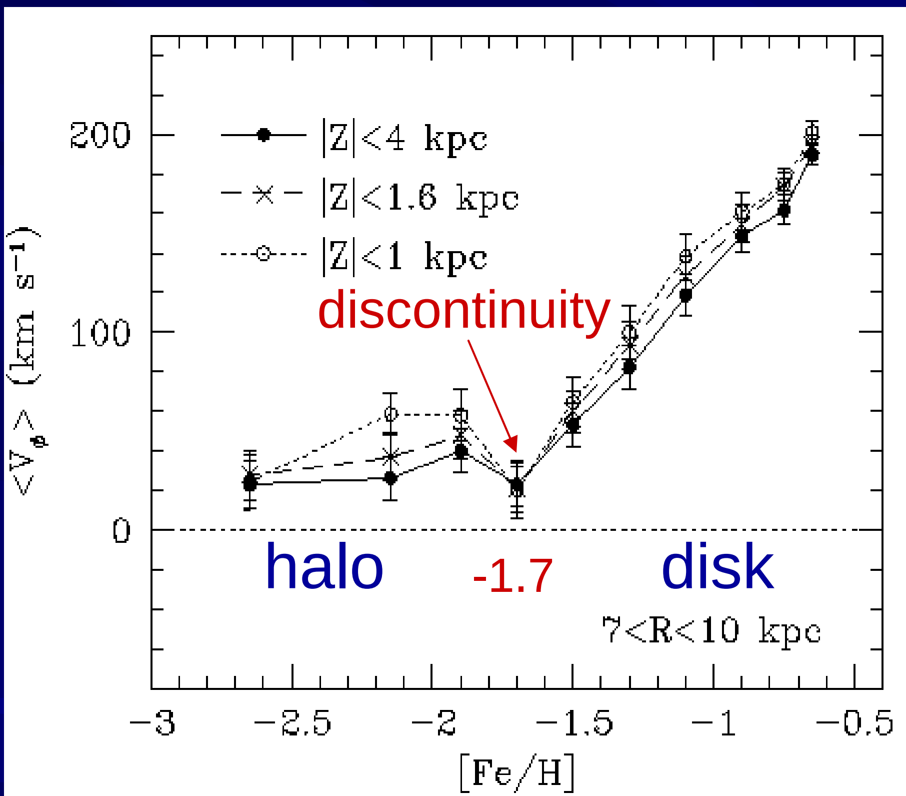
ヒッパルコス衛星の成果
1989年打ち上げ、1993年観測終了、1997年データの一般公開

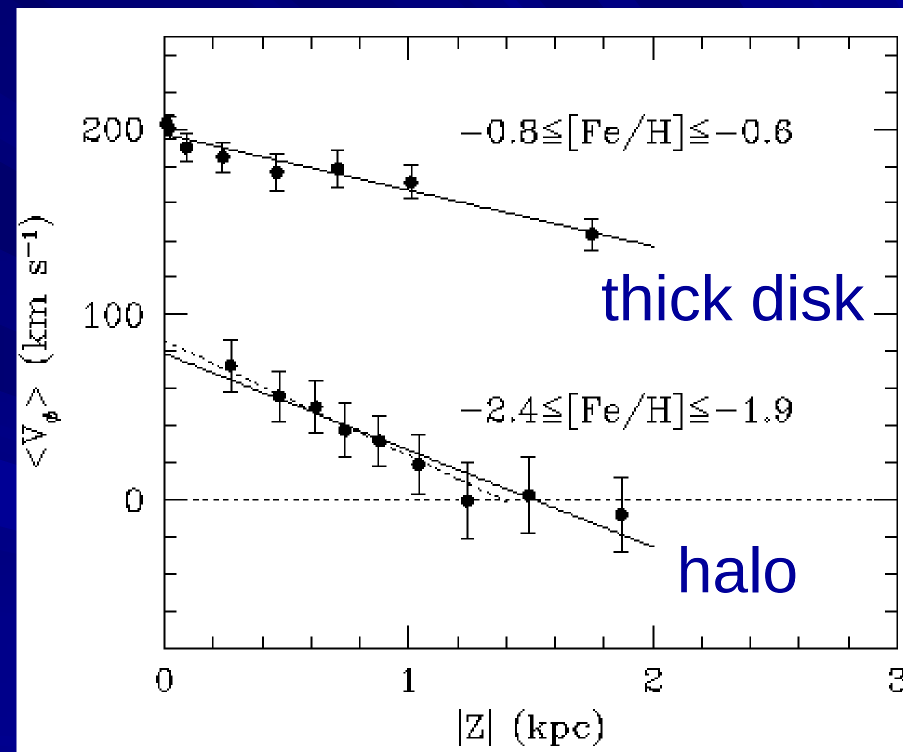


MC & Beers 2000

e: adiabatic invariant

平均回転運動$\langle V_\phi \rangle$の振舞い





MC & Beers 2000

- Halo formation is distinct from disk formation.
- Mean azimuthal rotation decreases with |z|.

厚い銀河円盤の発見

Gilmore. G. & Reid, N. 1983

Mon. Not. R. astr. Soc. (1983) 202, 1025–1047

New light on faint stars – III. Galactic structure towards the South Pole and the Galactic thick disc

Gerard Gilmore *Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ*
Neill Reid *Department of Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ*

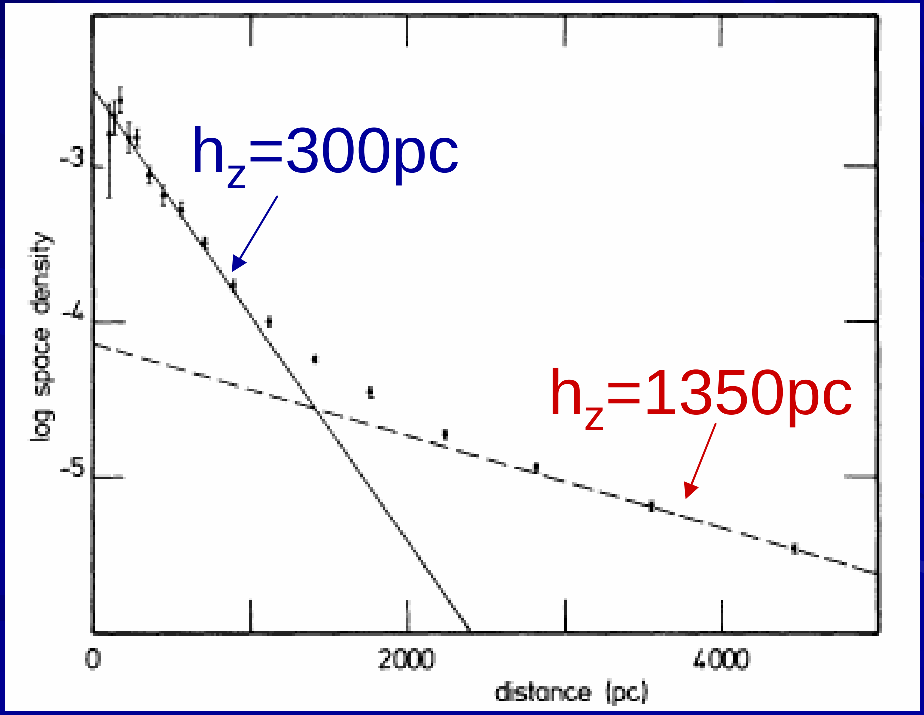
Received 1982 June 11; in original form 1982 March 11

Summary. We have derived absolute magnitudes from photometric parallaxes for a complete sample of ~ 12 500 stars brighter than $I = 18$ in 18.24 square degrees towards the South Galactic Pole. From these data we derive the stellar luminosity function in absolute visual magnitude, bolometric magnitude and mass in the solar neighbourhood for all absolute magnitudes above the thermonuclear burning limit. The total mass in main-sequence stars in the solar neighbourhood is $0.038\, m_\odot\, pc^{-3}$, and the total mass-to-light ratio is $1.2\ (m_\odot/L_{v\odot})$.

We have also derived the density laws with distance from the Galactic plane for each absolute magnitude. The stellar luminosity function shows a systematic change in shape, with stars with $M_v \leq +4$ substantially more concentrated to the plane than fainter stars. The density laws for stars with $M_v \geq +4$ follow a single exponential with scale height ~ 300 pc for $100 \leq z \leq 1000$ pc, and a second exponential with scale height ~ 1450 pc for z distances from ~ 1000 to at least 5000 pc. This second exponential contains ~ 2 per cent of the stars in the solar neighbourhood.

We identify the 300 pc scale height component as old disc, and the 1350 pc scale height component as a Galactic 'thick disc'. The luminosity function and density law of the 'thick disc' are consistent with substantial flattening of the spheroid isodensity contours by the gravitational potential of the Galactic disc, in agreement with recent observations of several external galaxies.

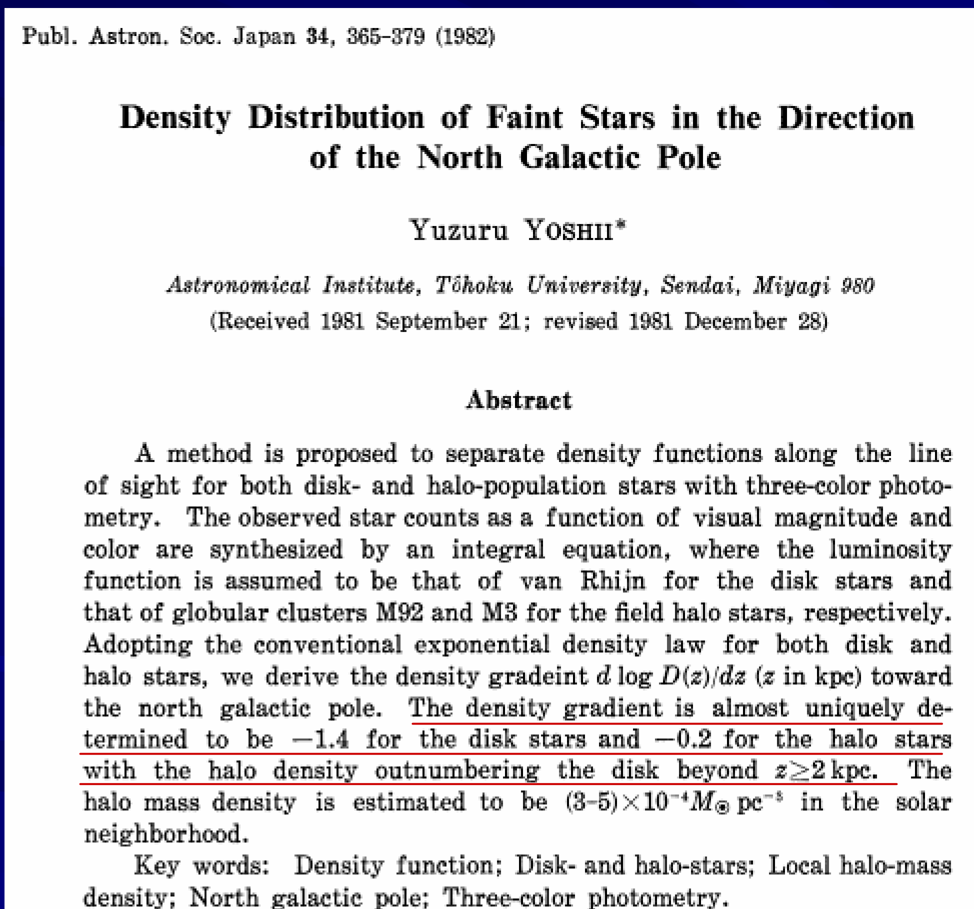
銀河南極方向の恒星計数



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

Yoshii, Y. 1982: signature of the thick disk

銀河北極方向の恒星計数



Publ. Astron. Soc. Japan 34, 365-379 (1982)

Density Distribution of Faint Stars in the Direction of the North Galactic Pole

Yuzuru Yoshii*

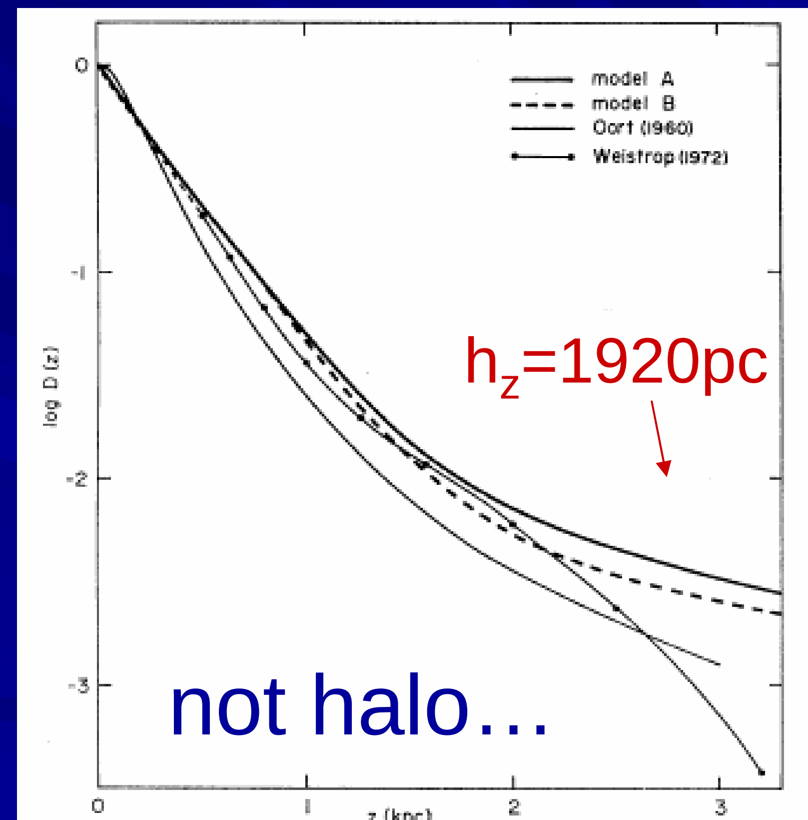
Astronomical Institute, Tôhoku University, Sendai, Miyagi 980

(Received 1981 September 21; revised 1981 December 28)

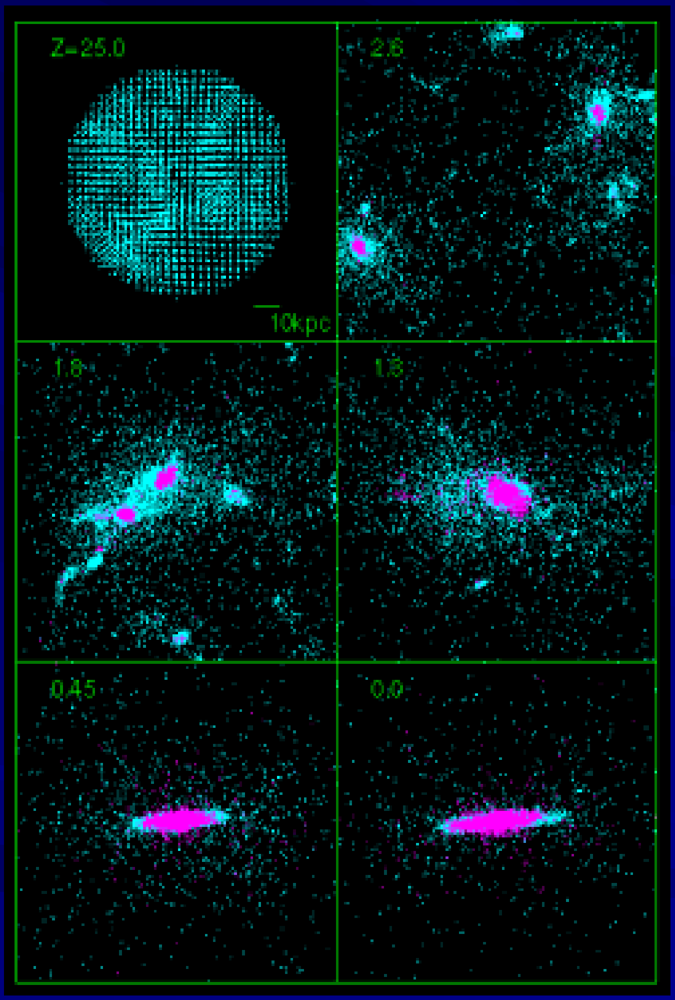
Abstract

A method is proposed to separate density functions along the line of sight for both disk- and halo-population stars with three-color photometry. The observed star counts as a function of visual magnitude and color are synthesized by an integral equation, where the luminosity function is assumed to be that of van Rhijn for the disk stars and that of globular clusters M92 and M3 for the field halo stars, respectively. Adopting the conventional exponential density law for both disk and halo stars, we derive the density gradeint $d \log D(z)/dz$ (z in kpc) toward the north galactic pole. The density gradient is almost uniquely determined to be -1.4 for the disk stars and -0.2 for the halo stars with the halo density outnumbering the disk beyond $z \geq 2$ kpc. The halo mass density is estimated to be $(3\text{-}5)\times 10^{-4} M_\odot\ \mathrm{pc}^{-3}$ in the solar neighborhood.

Key words: Density function; Disk- and halo-stars; Local halo-mass density; North galactic pole; Three-color photometry.

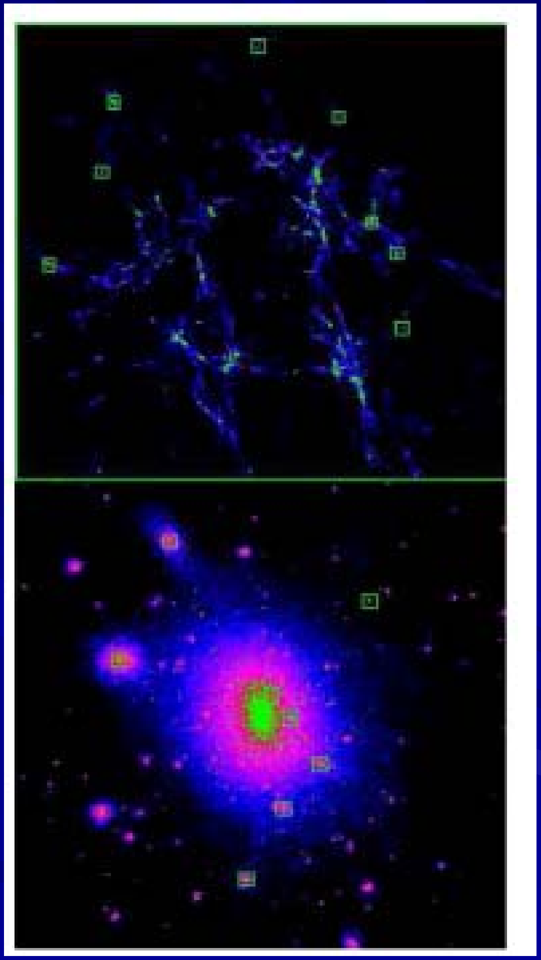


CDMに基づく銀河系収縮とハロー



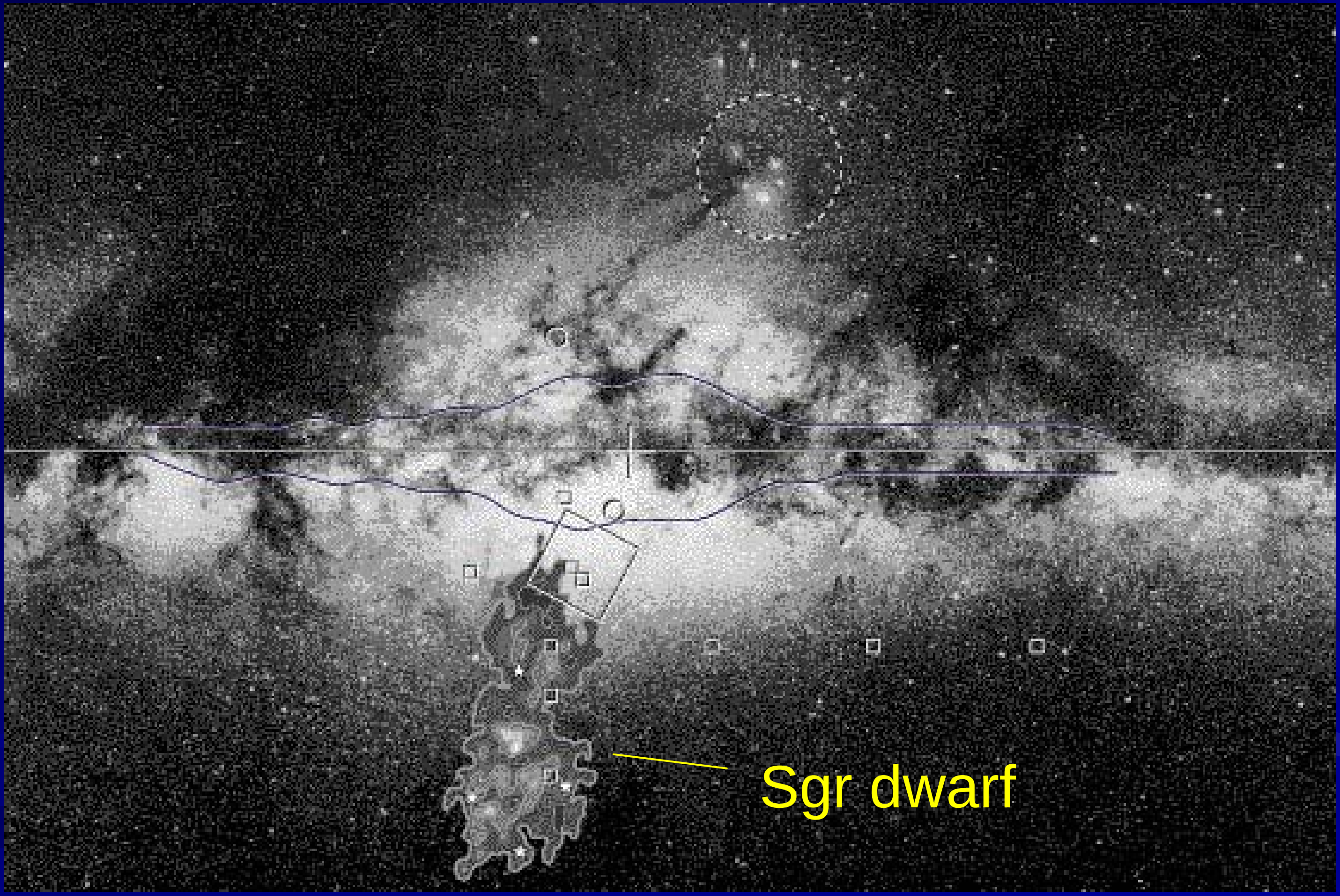
- gas
- star

Bekki & MC 2001



(green: $M=10^8\text{-}10^{10}M_{sun}$, $T>10^4K$)
Moore et al. 2005, astro-ph/0510370

Ibata et al 2004: Sgr dwarf



“Field of Streams” in SDSS data (Belokurov et al. 2006)

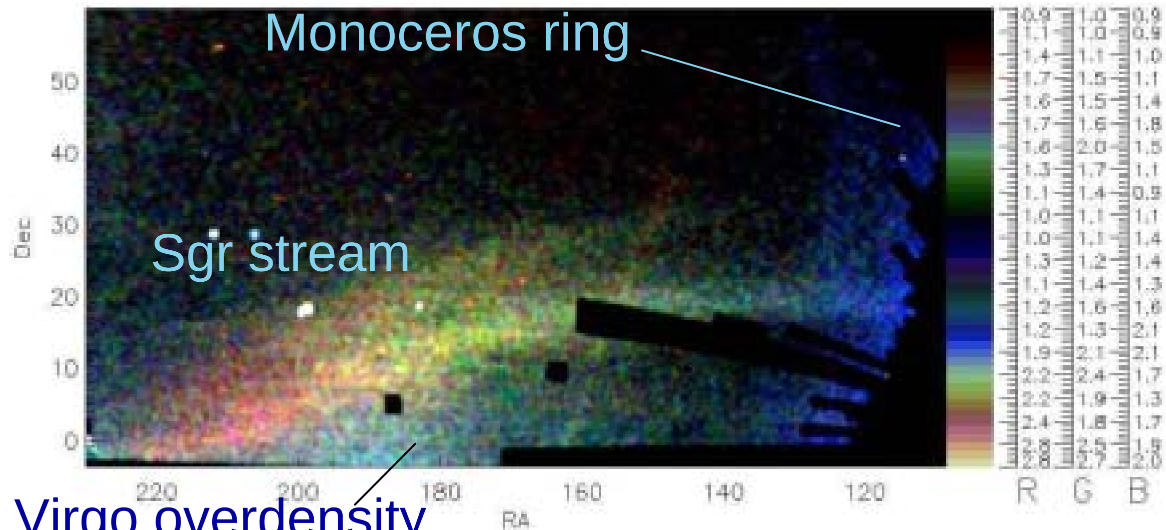


FIG. 1.— The spatial density of SDSS stars with $g - r < 0.4$ around the North Galactic Cap in equatorial coordinates, binned 0.5×0.5 arcdegrees. The color plot is an RGB composite with blue for the most nearby stars with $20.0 < r \leq 20.66$, green for stars with $20.66 < r \leq 21.33$ and red for the most distant stars with $21.33 < r \leq 22.0$. Note the bifurcation in the stream starting at $\alpha \approx 180°$. Further structure that is visible includes the Monoceros Ring at $\alpha \approx 120°$, and a new thin stream at $150° \lesssim \alpha \lesssim 160°$ and $0° \lesssim \delta \lesssim 30°$. The color bar shows a palette of 50 representative colors labeled according to the stellar density (in units of 100 stars per square degree) red, green and blue components. The displayed density ranges are 102 to 330 (red), 107 to 304 (green) and 98 to 267 (blue).

2MASS
(M giants)

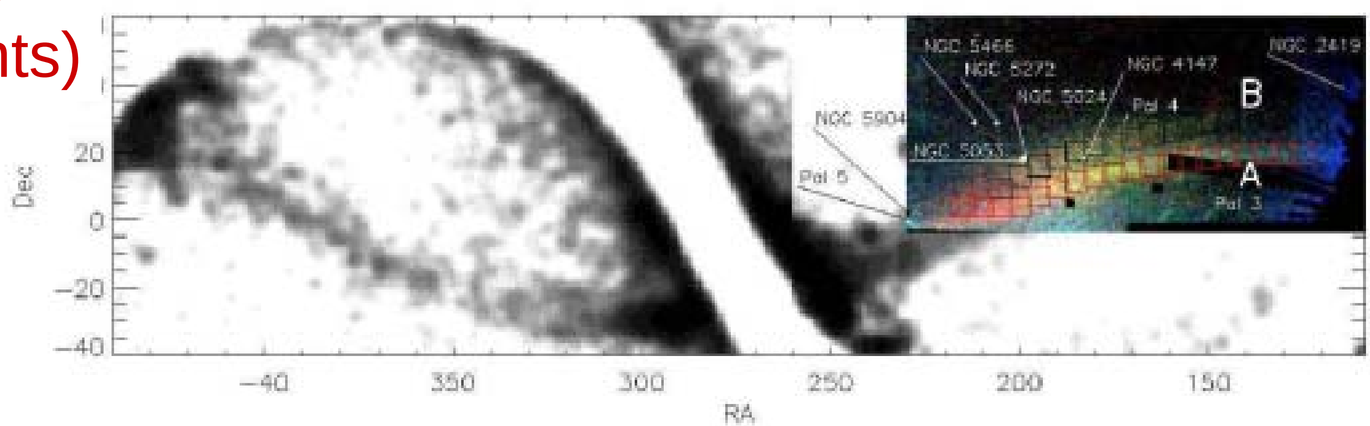


FIG. 2.— A panoramic view of the Sgr stream, obtained by combining the 2MASS M stars. Marked on the figure are branches A and B of the stream, together with some of th in red and black are the on-stream fields used in the analysis of Section 3 (see main text).

Majewski et a. 2003

Sgr stream

Majewski et al.

Stream is confined onto an orbital plane

⇒ round dark halo at 20 < r < 50 kpc

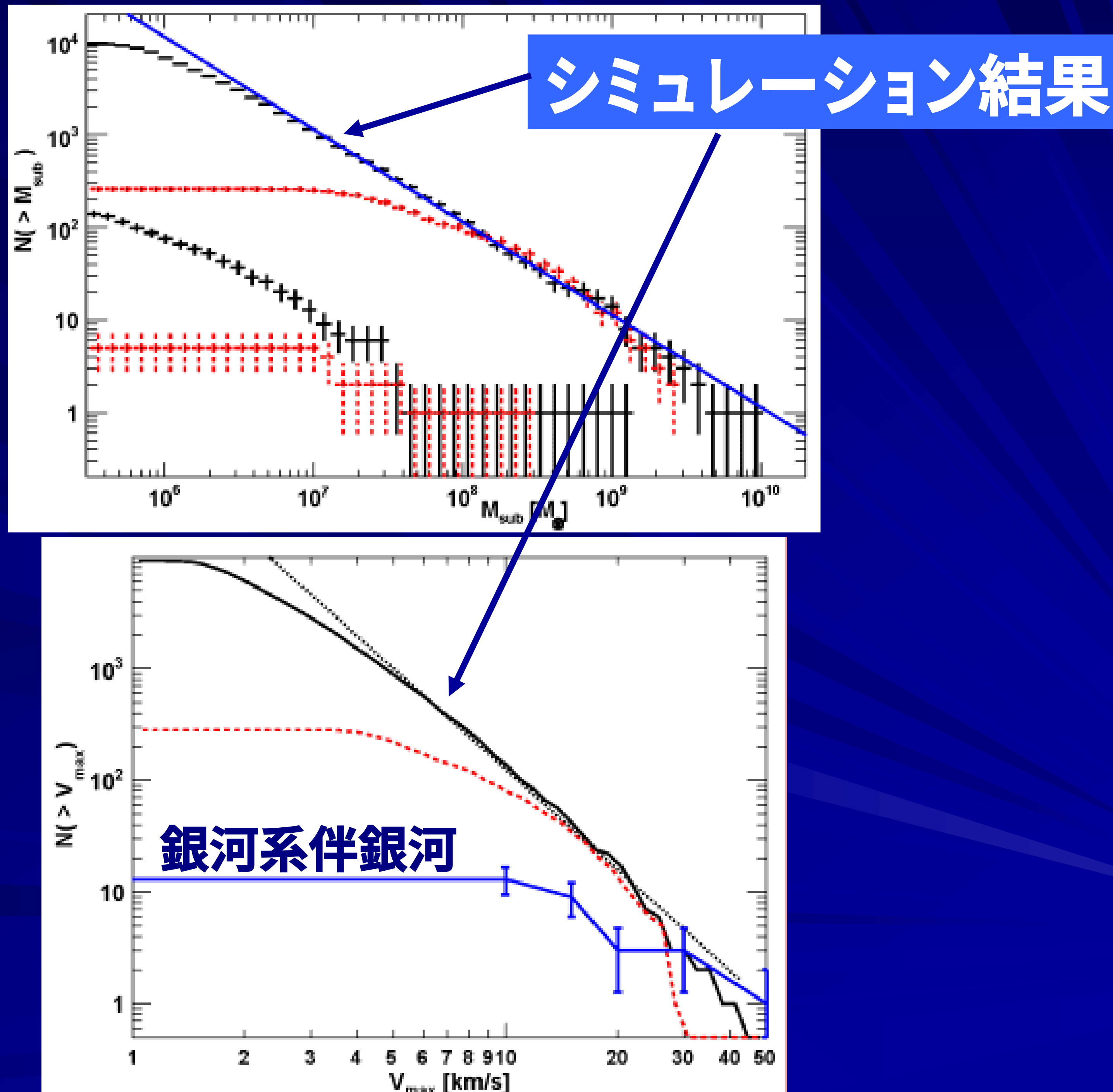
未解決問題
（10年以内に解決？）

- ミッシングサテライト問題
  - 矮小銀河の性質
  - 高速度H I雲の性質
  - ハロー星の速度分布
  - 銀河系内のサブハロー分布
- Thick disk の起源
  - 銀河合体過程
  - Thin disk との関係
- アンドロメダ銀河と銀河系
  - 古成分の相違
  - 銀河合体過程
  - アンドロメダのサブハロー分布

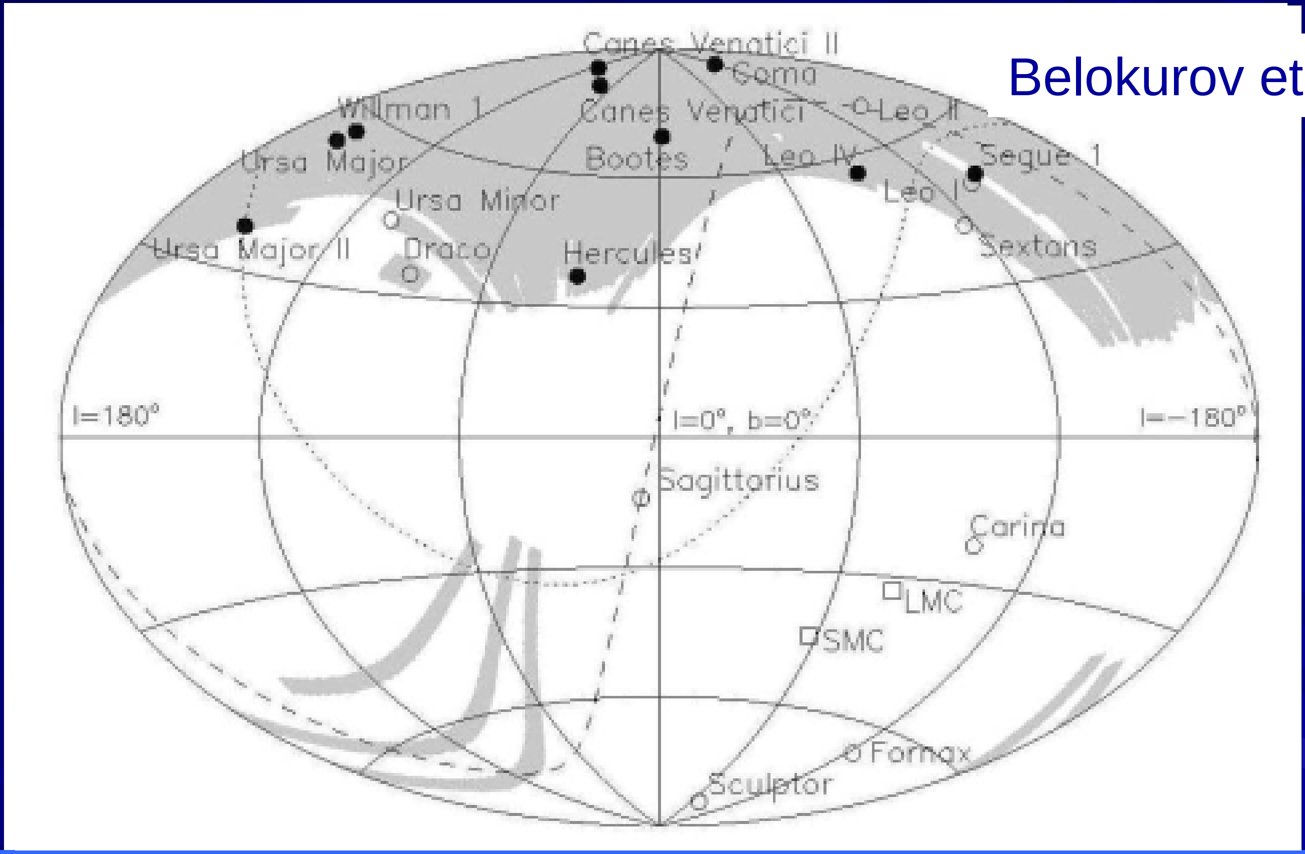
ミッシングサテライト問題

Diemand et al. 2006

2.1×10^4 M_{sun}/particle!


シミュレーション結果
銀河系伴銀河
N(> M_sub)
M_sub [M_⊙]
10^4
10^3
10^2
10
1
10^6
10^7
10^8
10^9
10^10
N(> V_max)
V_max [km/s]
10^3
10^2
10
1
1
2
3
4
5
6
7
8
9
10
20
30
40
50

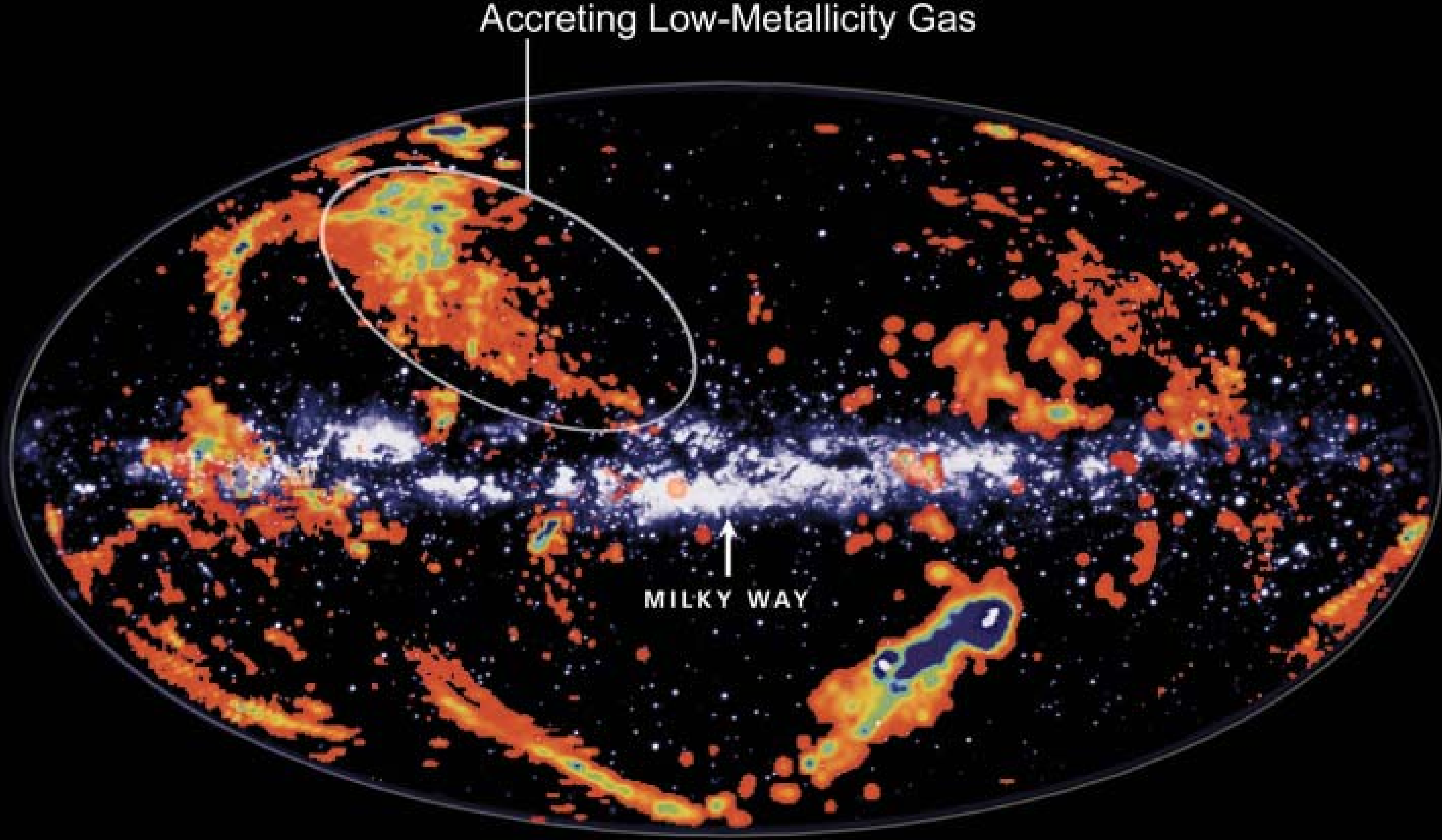
A new, faint and old stellar system @ D=150kpc
Sakamoto & Hasegawa 2006



Belokurov et al. 2006

The number of newly found satellites is increasing
Insights on missing satellite problem

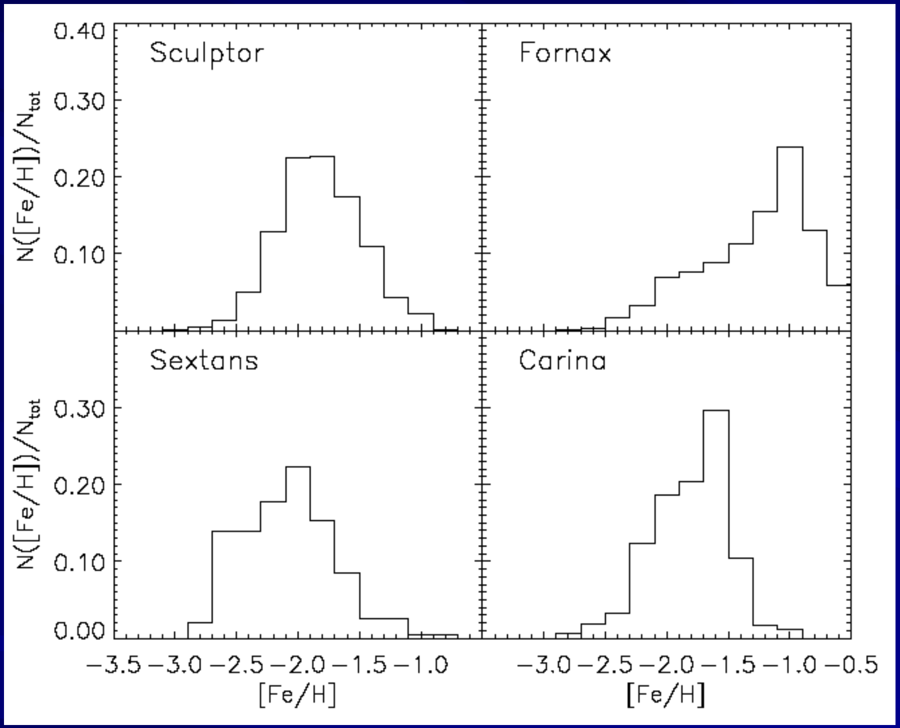
High Velocity Clouds

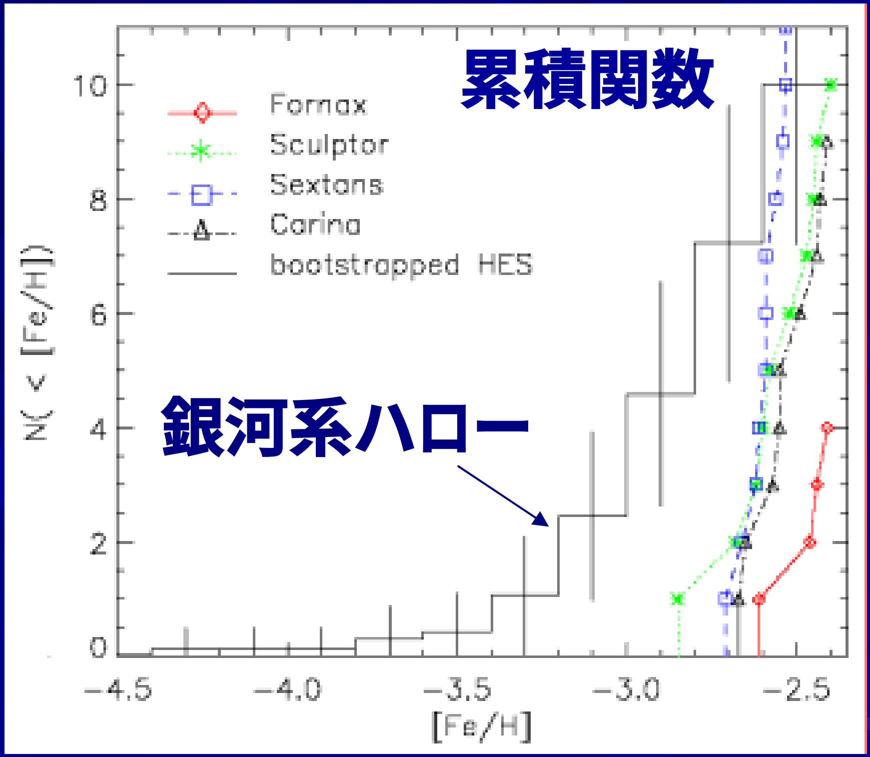


NASA and B. Wakker (University of Wisconsin-Madison) • STScI-PRC99-46

矮小銀河の金属量分布

Helmi et al. 2006



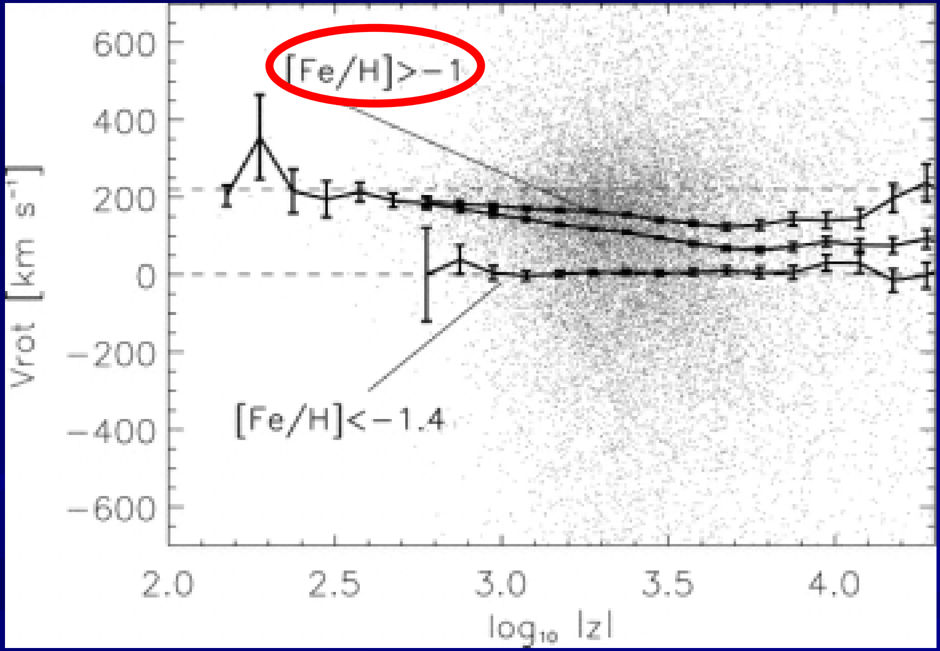


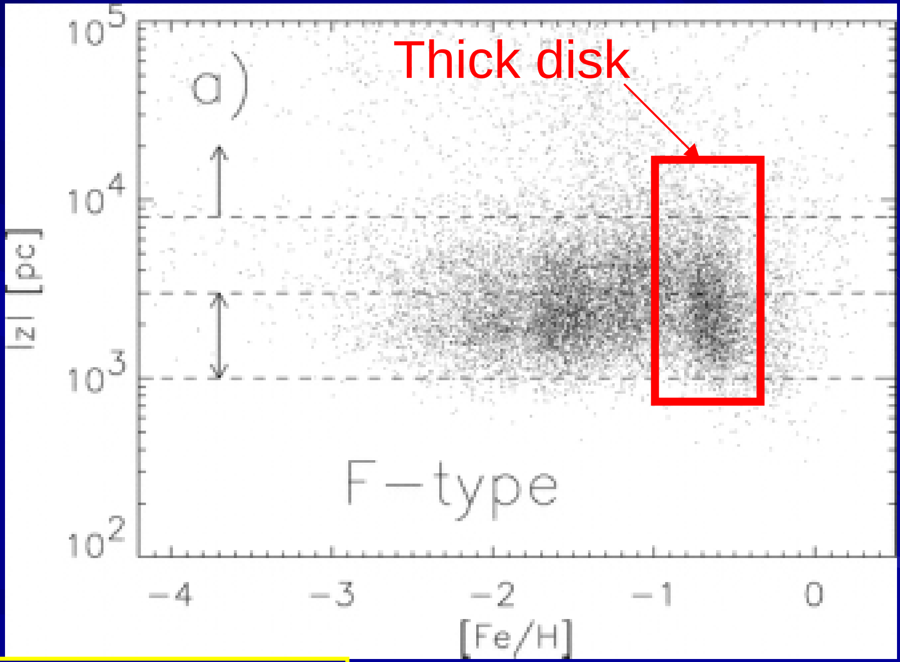
現在の矮小銀河を集めても
銀河系ハローは再現できない

Thick disk の起源

-1 < [Fe/H] < -0.4
scale height ~ 1 kpc

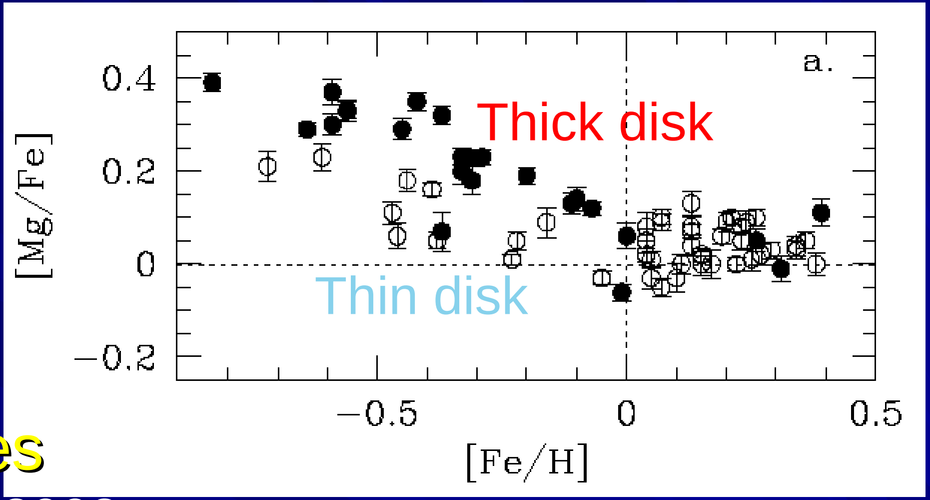
Thick disk revealed from F- and G- stars in SDSS DR3
(Allende Prieto et al. 2006)





• V_{rot} ↓ as |z| ↑ (confirmed)
• no metallicity gradient

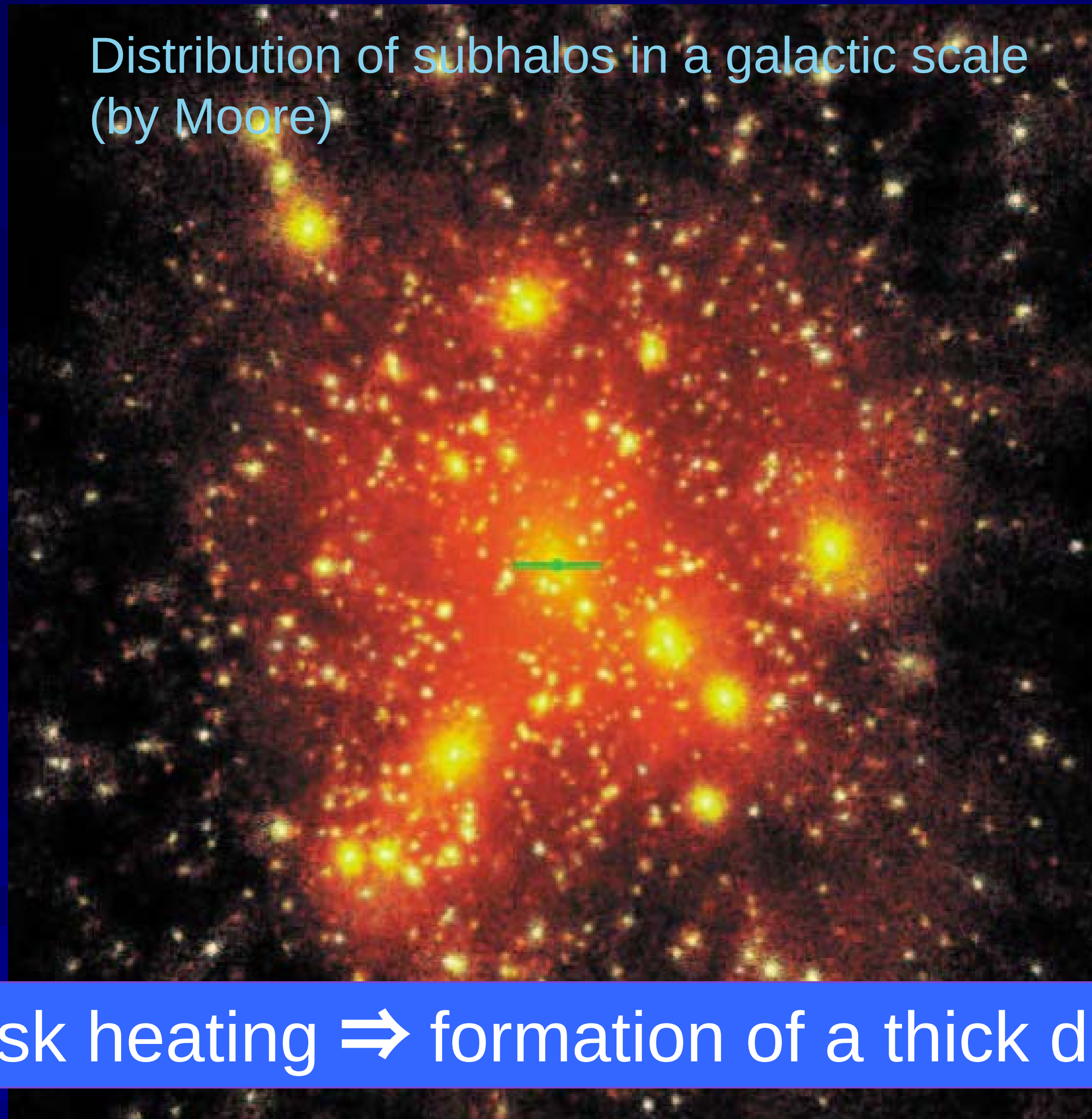
Thick disk 形成のシナリオ



Feltzing et al. 2003

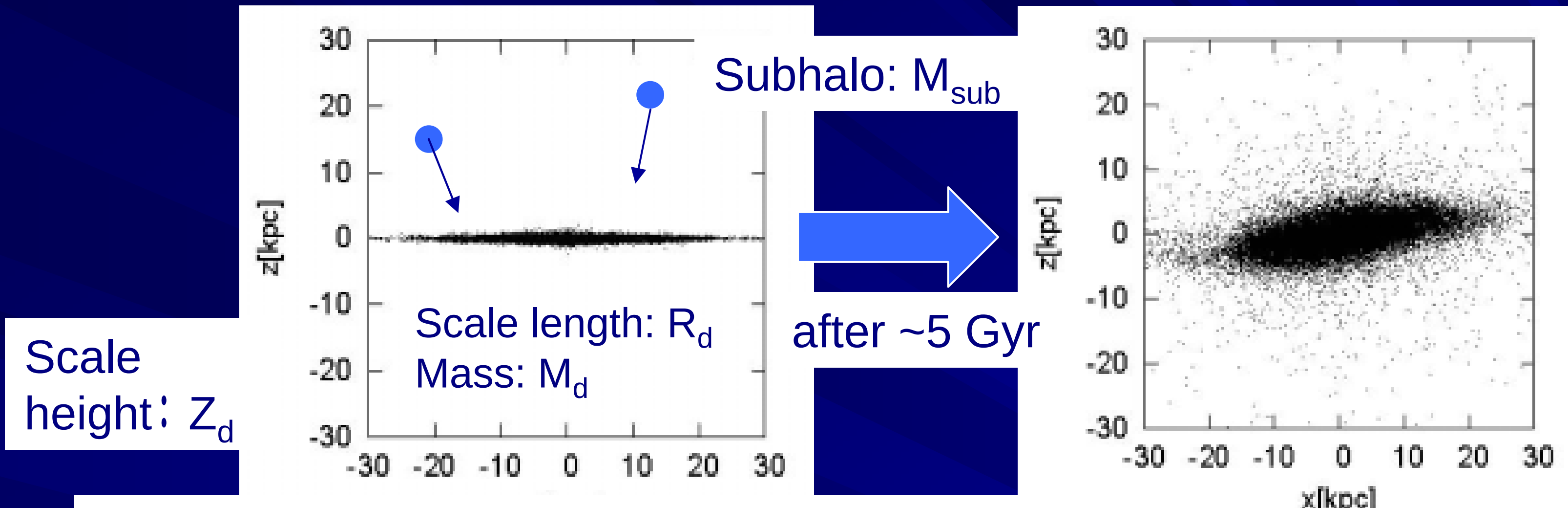
- Dissipative collapse
  - Burkert et al. 1992
  - Thick diskの独立性×
  - 金属量勾配が存在 ×
- Merging of luminous satellites
  - Quinn et al. 1993, Abadi et al. 2003
  - [α/Fe] が小さくなる×
  - 金属量が小さく、多種の恒星種族の混合となる ×
- Multiple mergers of building blocks
  - Brook et al. 2004
  - V_{rot} が z に依存しない×
- Disk heating triggered by merging of CDM subhalos
  - Hayashi & Chiba 2006

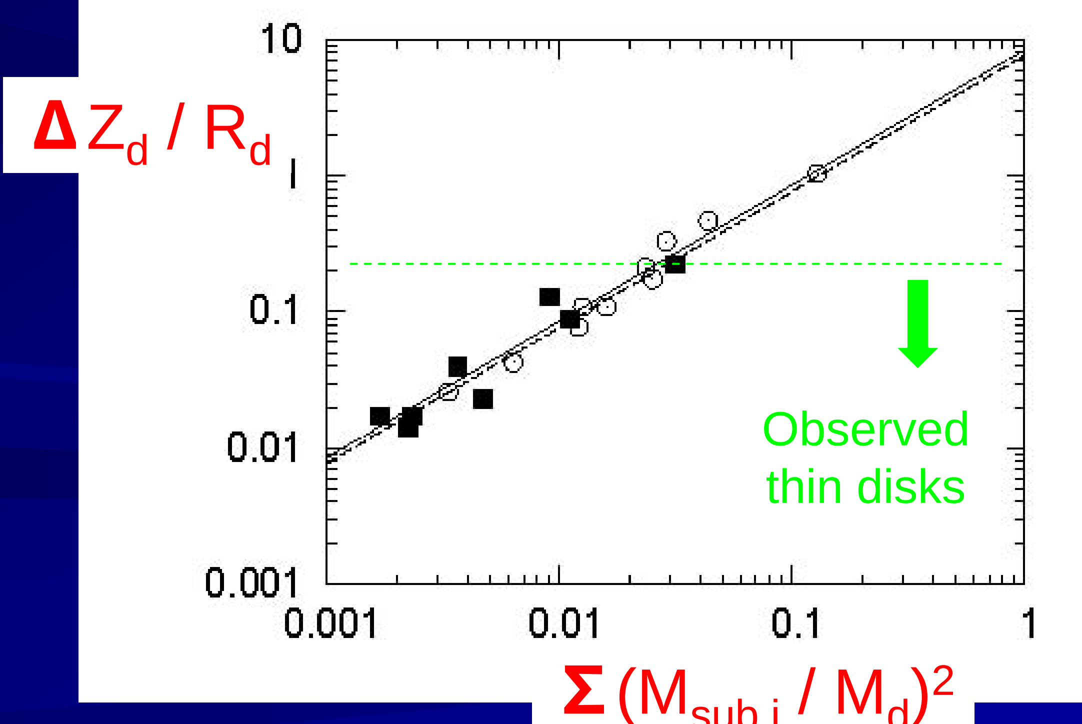
Dynamical effects of CDM subhalos on a (pre-existing) galactic disk



Disk heating ⇒ formation of a thick disk?

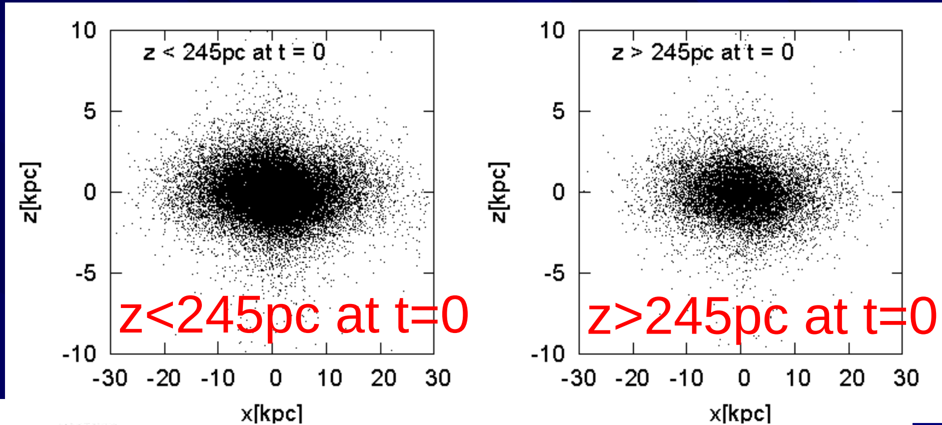
Numerical simulation of disk heating
(Hayashi & Chiba 2006)



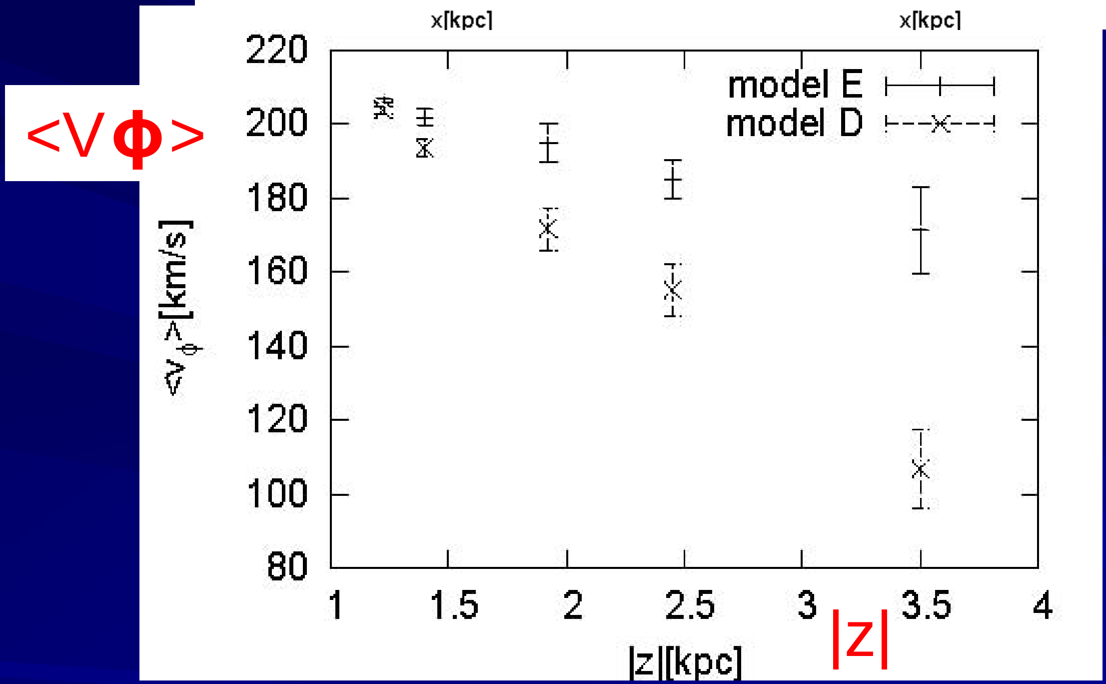


$$\frac{\Delta Z_d}{R_d} = 8 \sum_{j=1}^{N} \left(\frac{M_{sub,j}}{M_d} \right)^2$$

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



No metallicity gradient



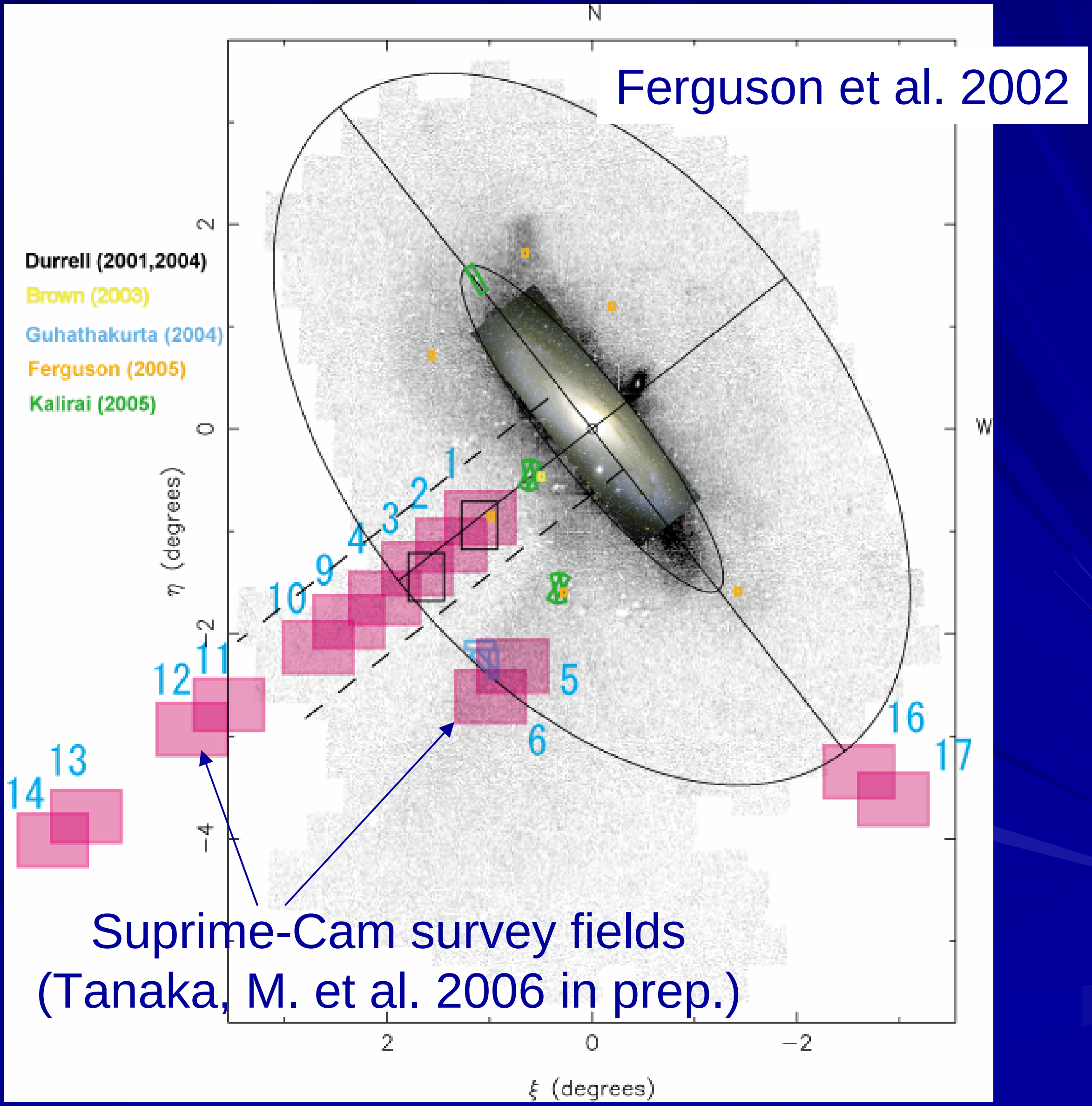
Vertical gradient
in mean rotation

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

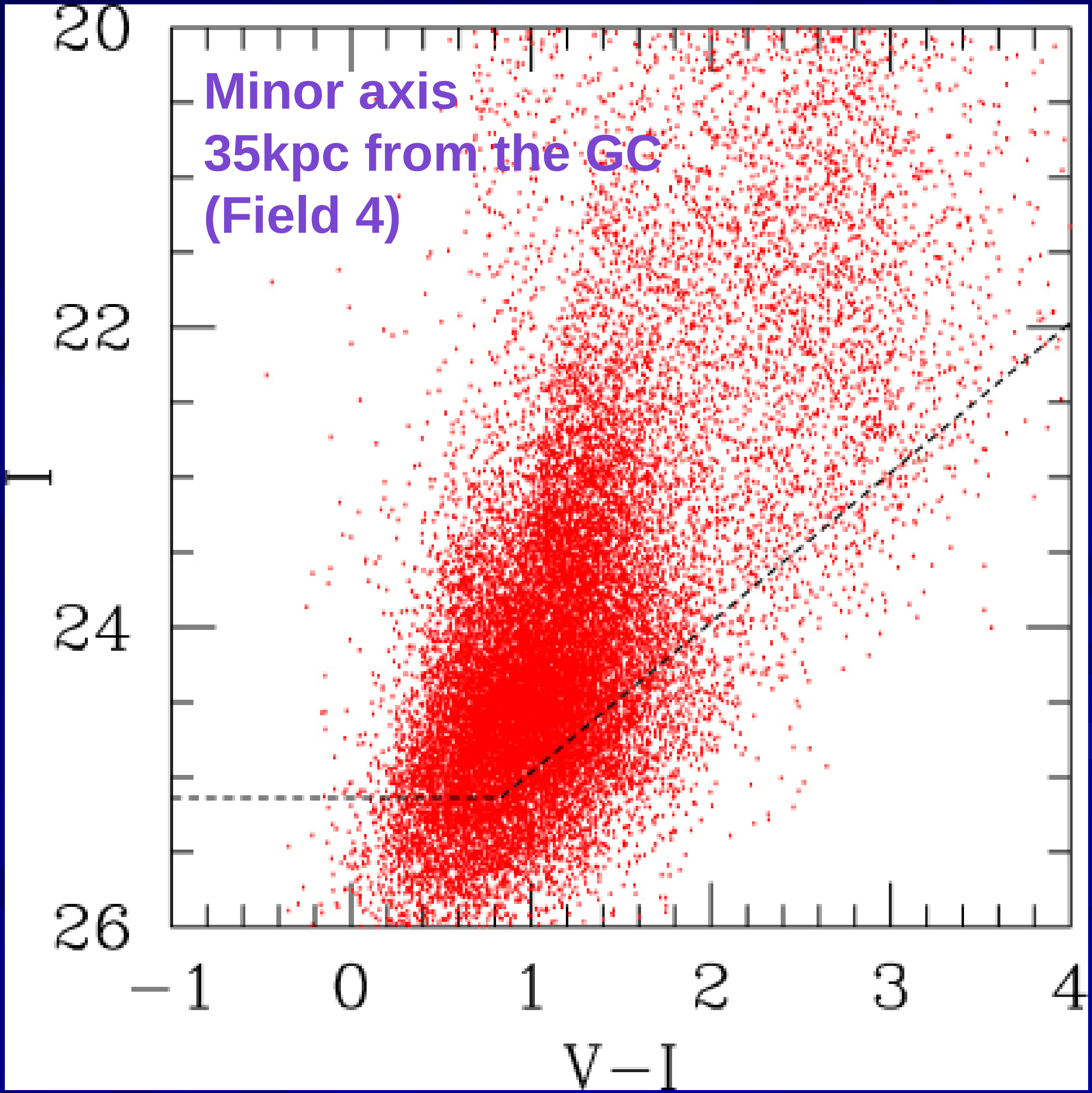
More massive thick disk
for smaller V_c disk system

CDM subhalos はthick diskの形成において重要

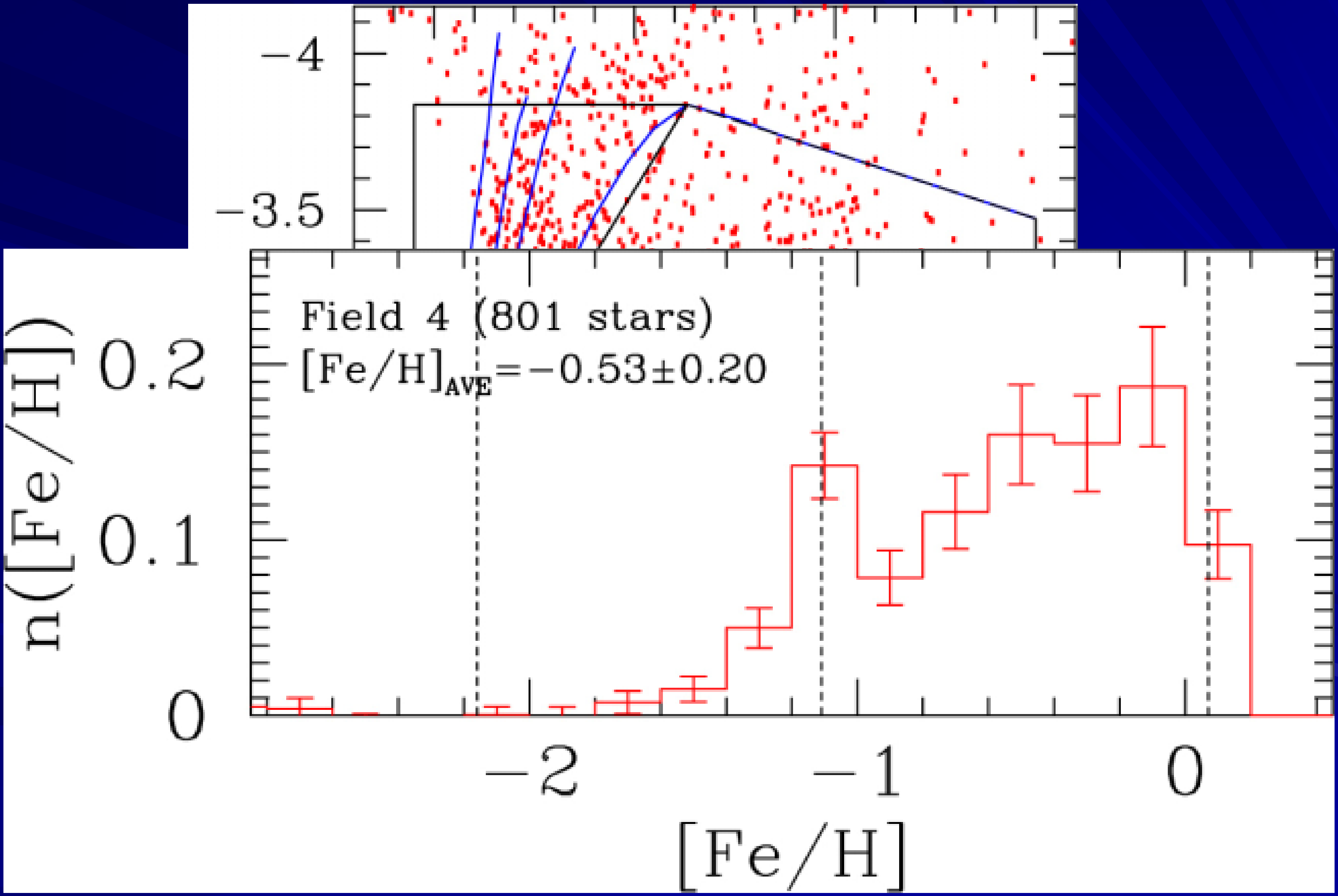
アンドロメダ銀河の恒星系ハロー



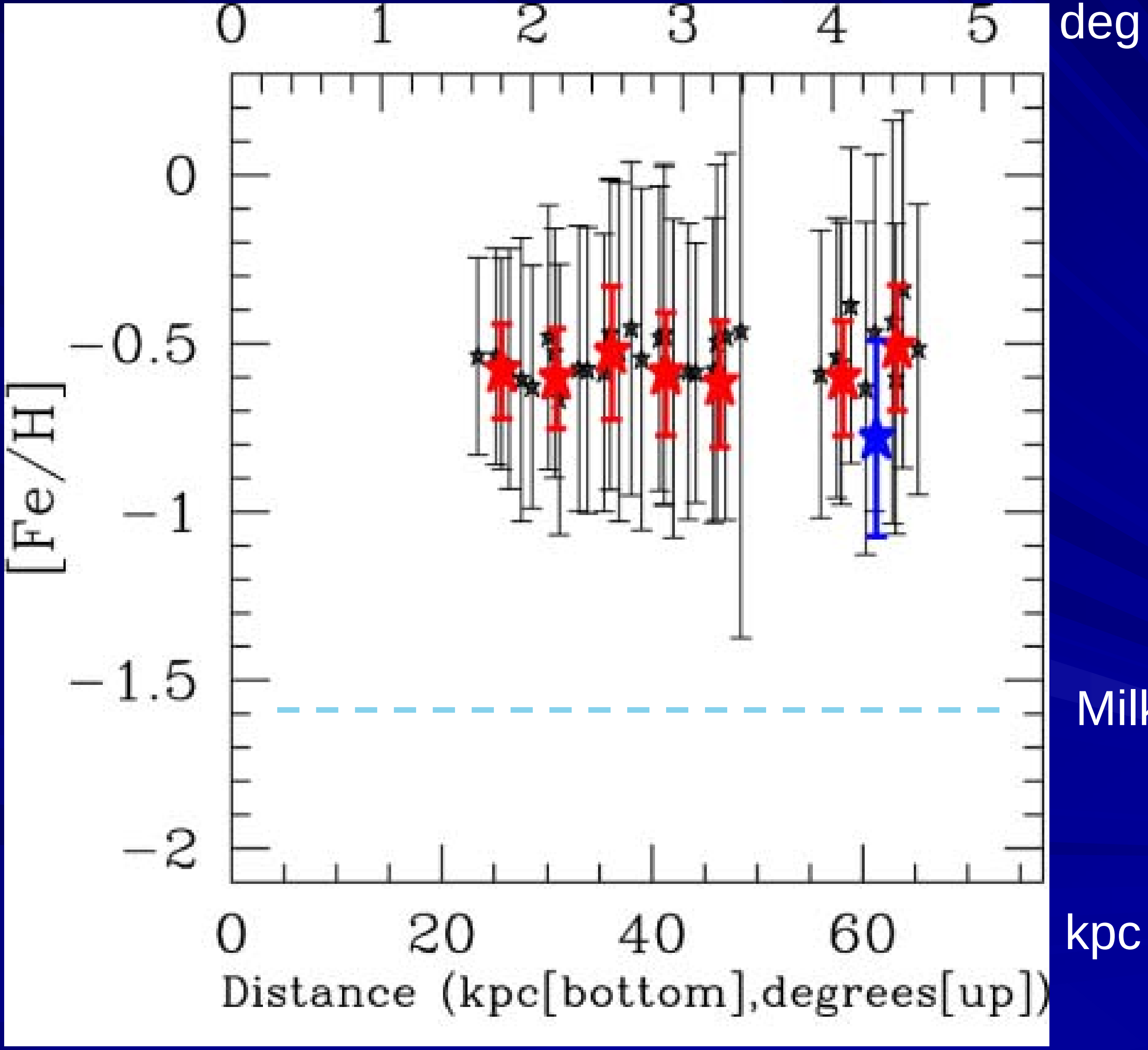
Color-magnitude diagram



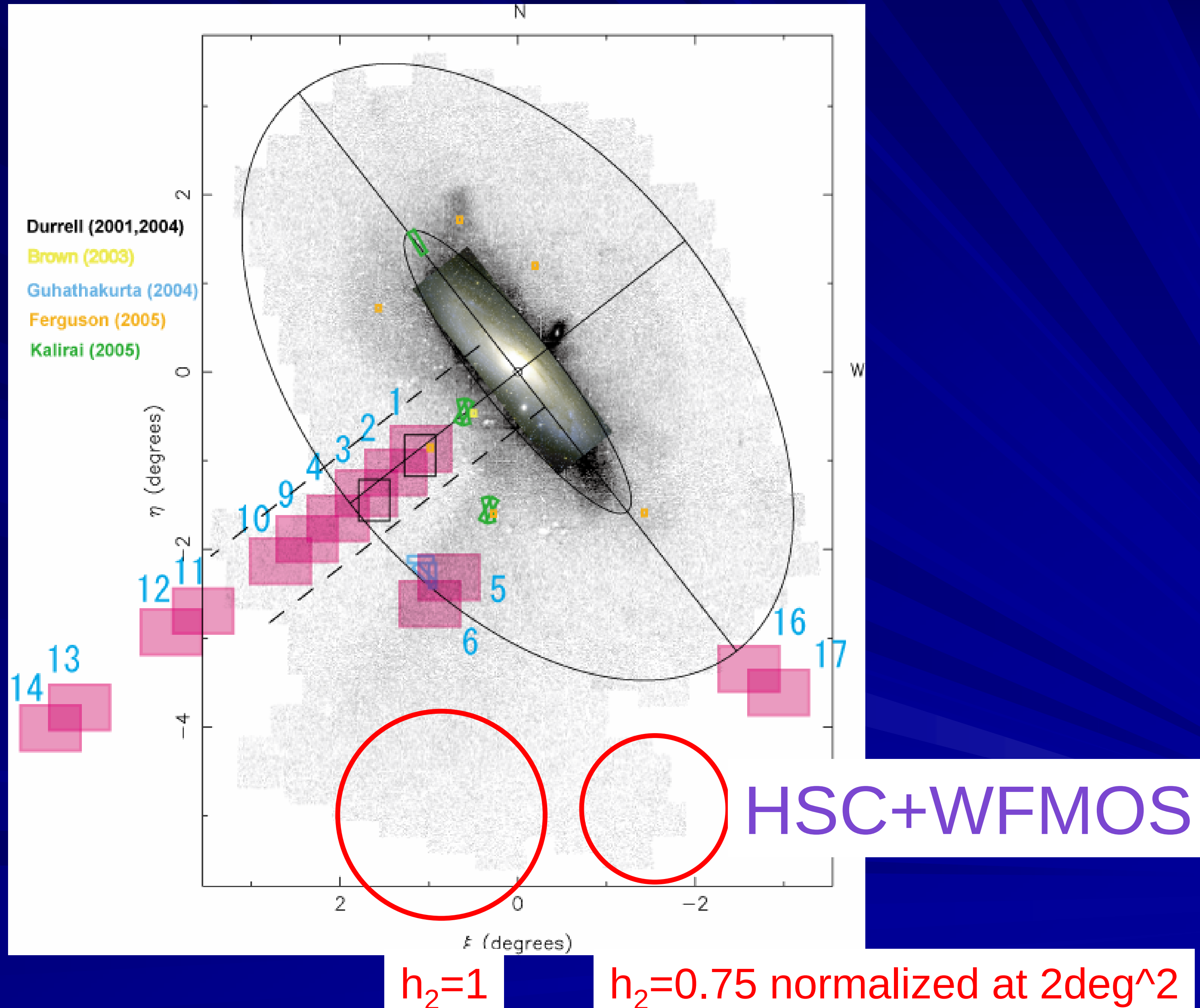
Getting metallicity distribution



Mean metallicity along the minor axis



HyperSprime Survey of the Andromeda Halo (down to HB)



結論

- CDMに基づく銀河系・局部銀河群形成理論の完成。
- RAVE, GAIA, JASMINE + HyperSprime, WFMOS on Subaru + ELTによる観測との比較検証。
- 今年一年ごくろうさまでした。

終了