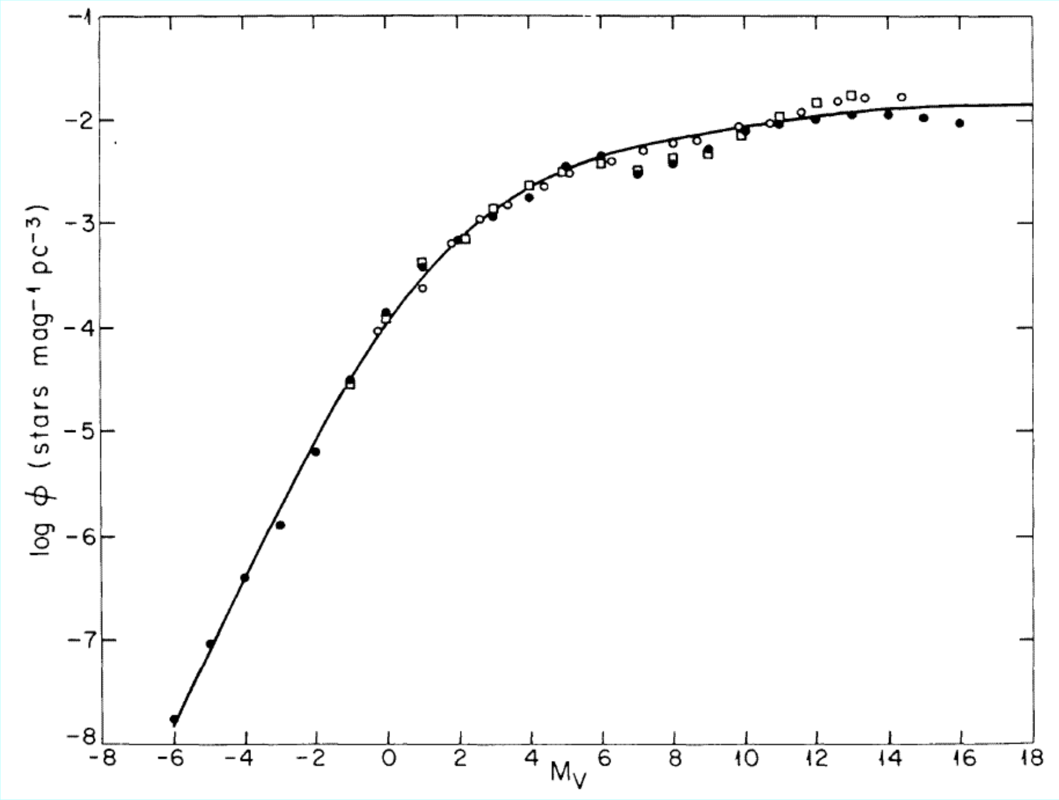
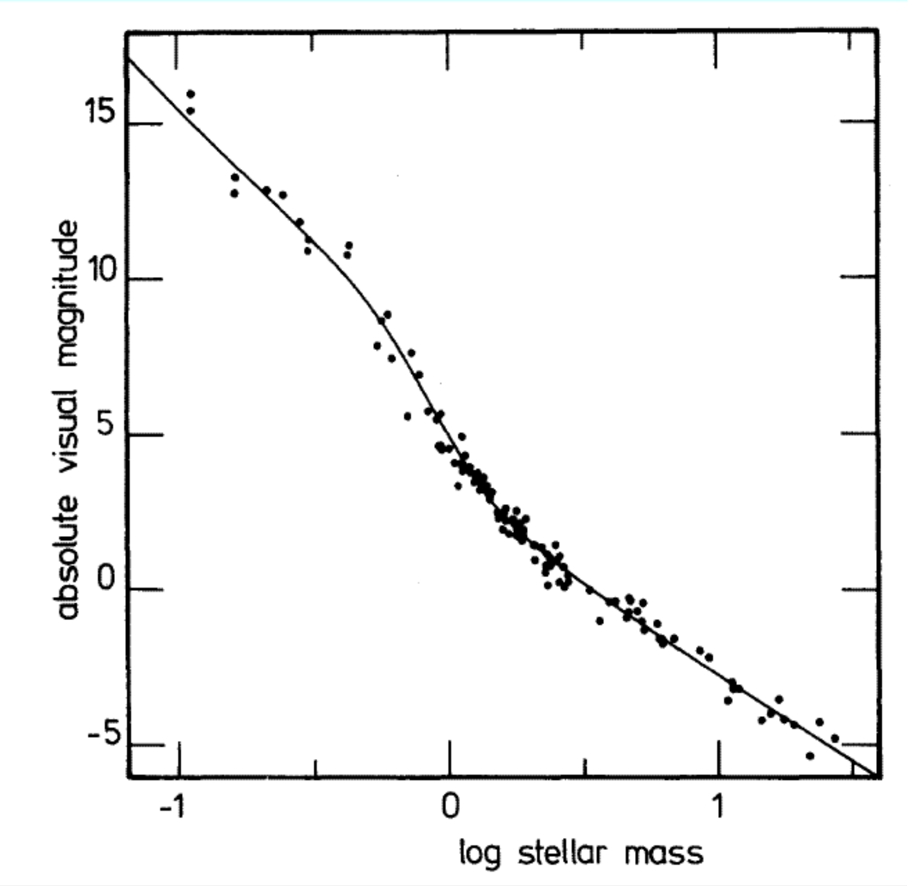
STRUCTURE OF GALAXIES

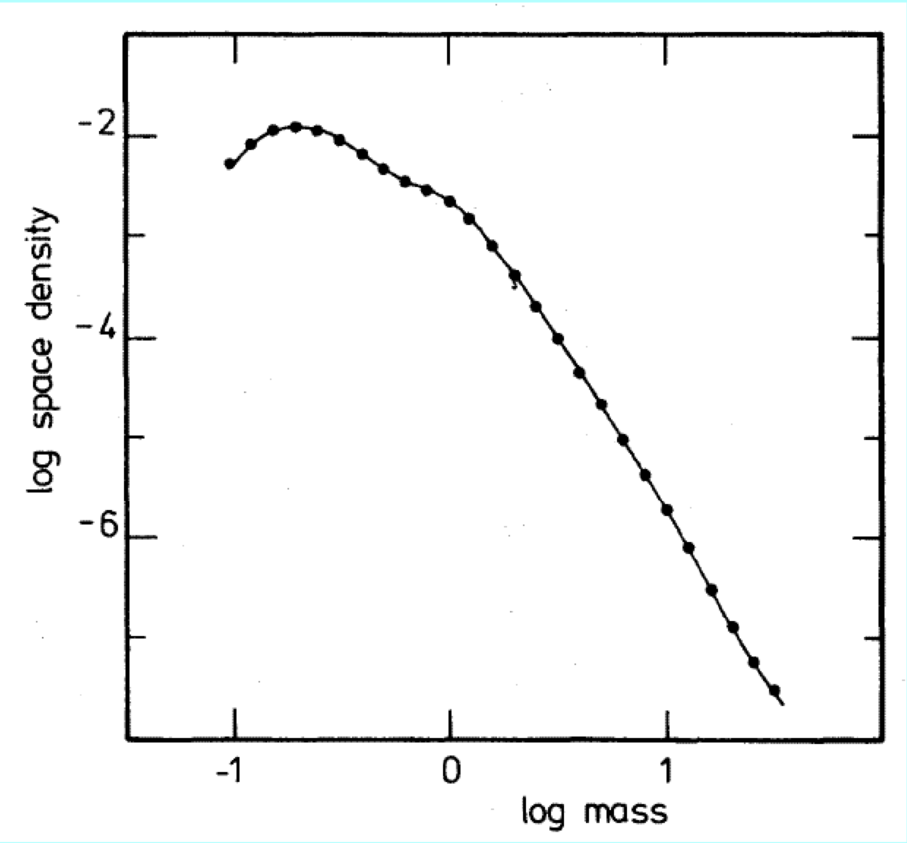
Lecture 7. Our Galaxy compared to others.

The disk population.

The local Mass Function (density in $M_\odot$ pc^{-3} per mass interval of 0.1 log $M_\odot$ as a function of stellar mass) derives from the observed Luminosity Function (number of stars per magnitude interval per pc^3) using the Mass-Luminosity Relation.




15
10
5
0
-5
-1
0
1
absolute visual magnitude
log stellar mass


-2
-4
-6
-1
0
1
log space density
log mass

The stellar mass density in the solar neighborhood is then $0.038\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ and the corresponding mass-to-light ratio is 1.2*.

The (surface) density distributions can be derived from dynamical studies.

Take a tracer population of objects with density distribution ν and velocity dispersions σ_{xy}

$$\sigma_{\mathrm{xy}} = \langle V_{\mathrm{x}} V_{\mathrm{y}} \rangle^{1/2}$$

The hydrodynamical equation then describes how the distribution and kinematics of this tracer population relates to the vertical gravitational force.

$$-K_{\mathrm{z}} = \frac{1}{\nu}\frac{\partial}{\partial z}(\nu\sigma^2_{\mathrm{zz}}) + \frac{1}{\nu R}\frac{\partial}{\partial R}(\nu R\sigma^2_{\mathrm{Rz}})$$

The second term can usually be neglected and if the tracer population is isothermal then

$$K_{\mathrm{z}} = \sigma^2_{\mathrm{zz}}\frac{\partial}{\partial z}\ln\nu(z)$$

*Gilmore & Reid, Mon.Not.R.A.S. 202, 1025 (1983)

The Poisson equation relates the gravitational field to the total density distribution ρ.

At small distances z from the plane these equations can be combined to give

$$4\pi G\rho_\circ = \frac{\partial}{\partial z}\left[\frac{1}{\nu}\frac{\partial}{\partial z}(\nu\sigma_{\mathrm{zz}}^2)\right]$$

One can use samples of for example K giants or (older) F dwarfs to this. This idea goes back to Kapteyn* and Oort†.

Modern analyses of this kind have been done by Bahcall‡ and Kuijken & Gilmore§.

Bahcall finds for the space density in the solar neighborhood 0.21 ± 0.04 $\mathrm{M}_\odot \mathrm{pc}^{-3}$.

*Ap.J. 55, 302 (1922)

†Bull.Astron.Inst.Neth. 6, 249 (1932)

‡Ap.J. 276, 156 and 169, Ap.J. 287, 926 (1984)

§Mon.Not.R.A.S. 239, 571, 605 and 651 (1989)

Observed are the following contributions.

Component	density
Main sequence stars	0.044
Subgiants and giants	0.002
White dwarfs	0.005
ISM (atomic & molec. gas, dust)	0.045
Population II	0.0001
Total	0.096

So in this case a total of about $0.1\ M_{\odot}pc^{-3}$ is unaccounted for. This problem has been known for many years and is known as the "Oort limit".

Large numbers of brown dwarfs or stellar remnants cannot completely be ruled out.

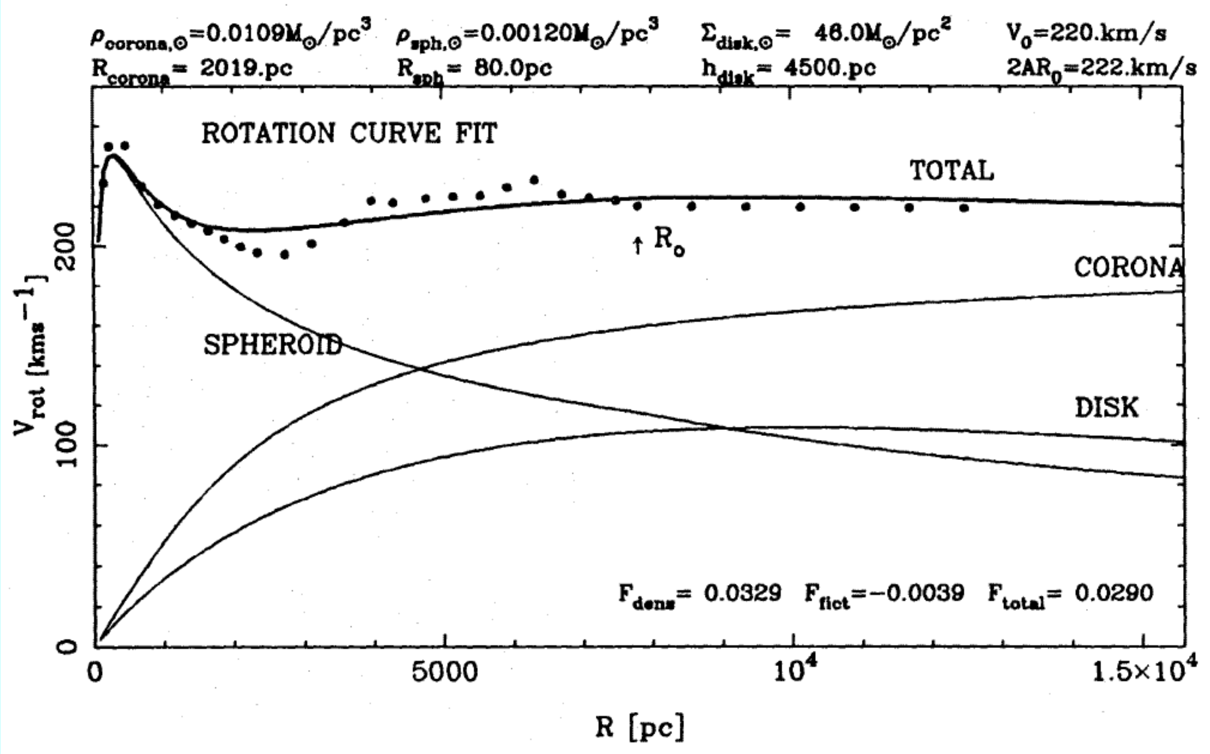
Kuijken & Gilmore on the other hand find that the local density is about $0.10\ M_{\odot}pc^{-3}$ and that there is no convincing evidence for missing matter.

In terms of surface density of the Galactic disk, Bahcall finds a value of $66 \pm 8\ \mathrm{M_\odot pc^{-2}}$. This is distributed as follows:

Component	mass $\mathrm{M_\odot pc^{-2}}$	luminosity $\mathrm{L_\odot pc^{-2}}$
Main sequence stars	23.9	9.7
Subgiants and giants	1.0	13.3
White dwarfs	3.6	0.0
Interstellar medium	4.5	0.0
Unseen matter	33.0	0.0
(Population II)	(3.0)	(1.5)
Total	66.0	23.0

Kuijken & Gilmore find a total surface density of $46 \pm 9\ \mathrm{M_\odot pc^{-2}}$, of which $35 \pm 5\ \mathrm{M_\odot pc^{-2}}$ is in stars and $13 \pm 3\ \mathrm{M_\odot pc^{-2}}$ in gas and dust.

They also propose the following fit to the rotation curve of the Galaxy.



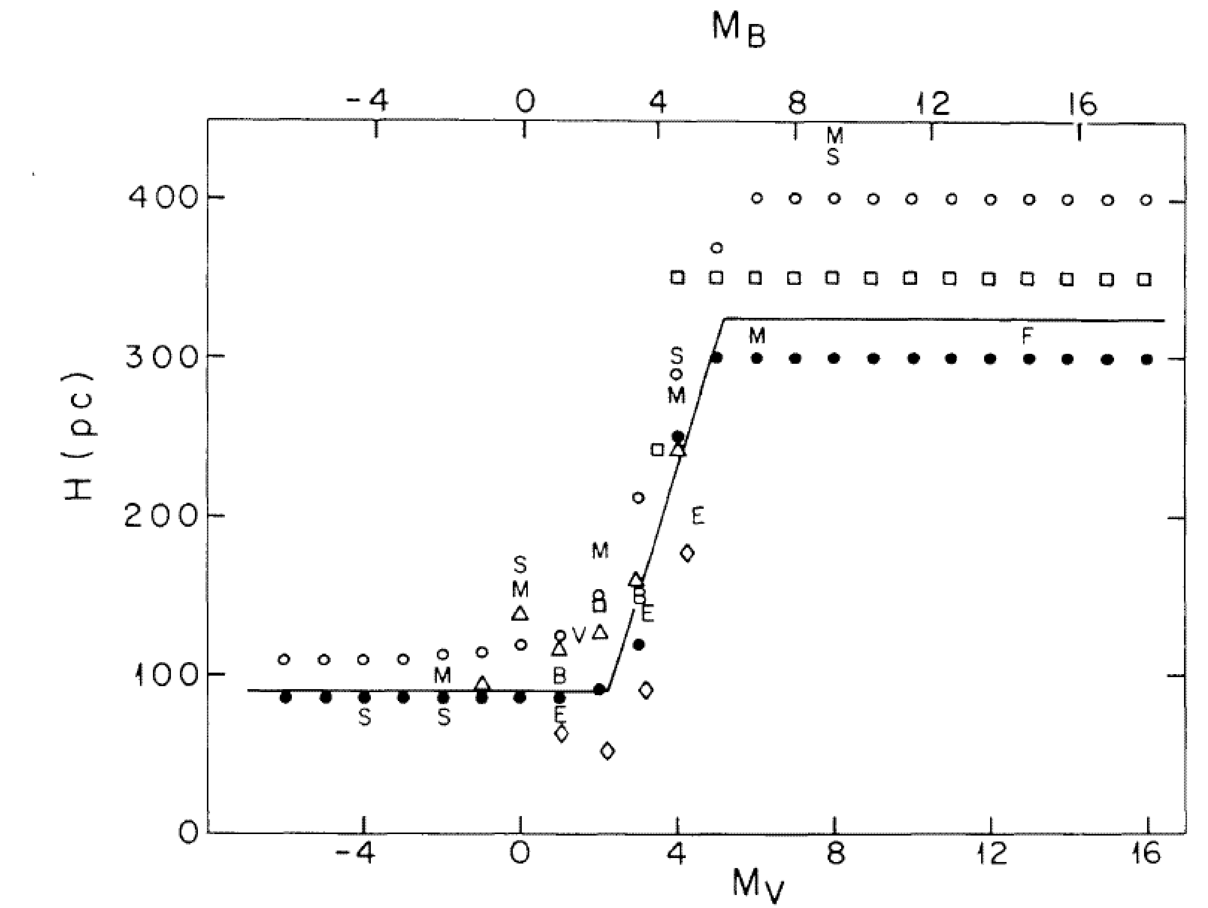
It follows that the Galaxy is NOT maximum disk.

With $\kappa \sim 31$ km sec^{-1} kpc^{-1} and $\sigma_{RR} \sim 40$ km sec^{-1} the Toomre parameter can be determined as

$$Q \sim 2.1.$$

Disk stars have varying vertical distributions, according to the velocity dispersion – age relation (see lecture 6).

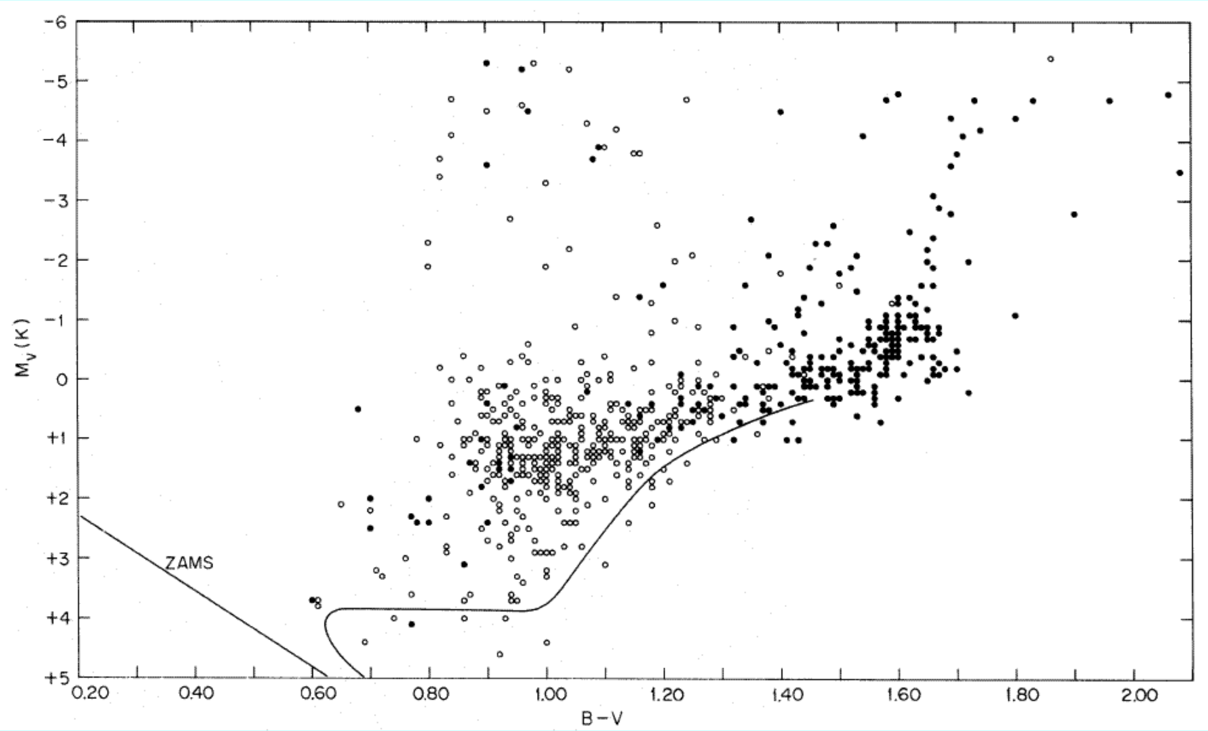
This is also reflected in the (exponential) scaleheight derived from counts as a function of absolute magnitude.



The old disk scaleheight is about 325 pc.

Subgiants and giants have emission ("chromospheric") components in the CaII K-line. The strength of this component gives the absolute magnitude and hence the distance.

This has been done for a sample of about 700 bright stars*.



The line in the figure is the (sub-)giant branch of NGC 188 (age $\approx 10 \times 10^9$ years).

This shows that the old disk population contains stars with ages at least up to that age.

*Wilson, Ap.J. 205, 823 (1976)

ELS and the collapse of the Galaxy.

This classical paper ELS* contains a study of properties of samples of high- and low-velocity dwarfs.

These samples have determinations of parallax, proper motion, radial velocity and photometry and spectral type.

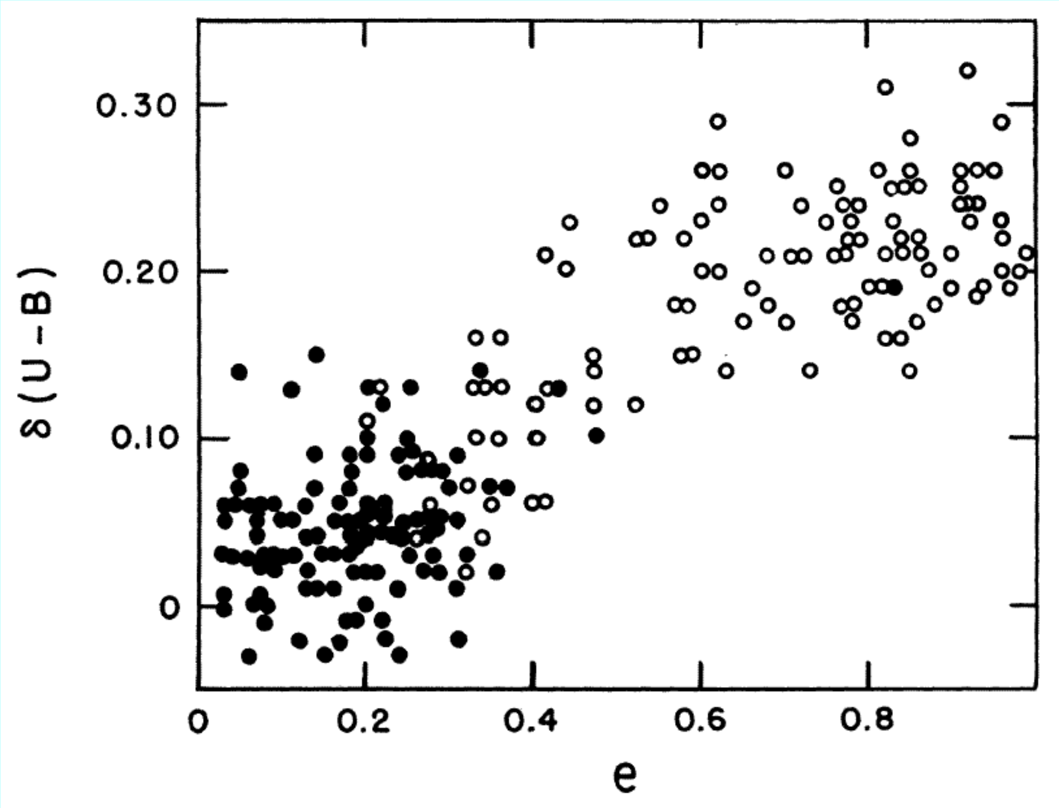
They determined the three components of the space velocity and computed from that the "excentricity" (from the radial excusion in the plane) and the angular momentum.

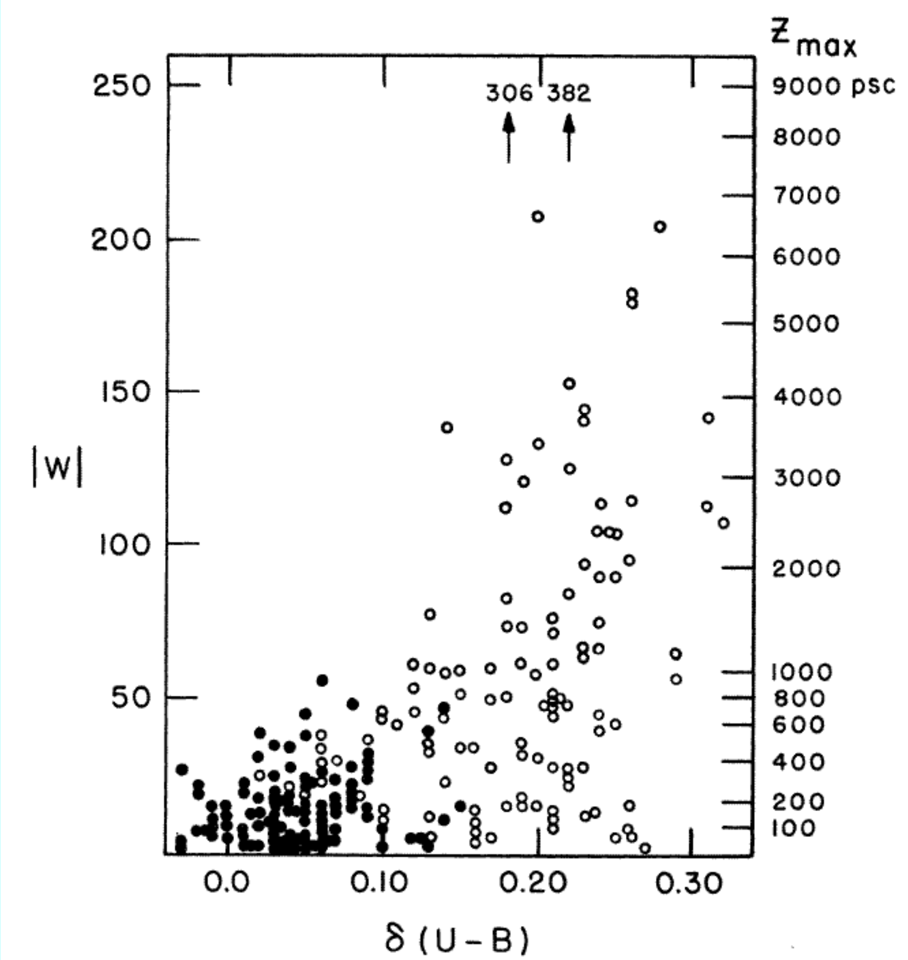
The ultraviolet excess $\delta(U-B)^{\dagger}$ is an indication of the metallicity, since for these stars it results from line blanketing (more absorption lines in the UV than in the visual).

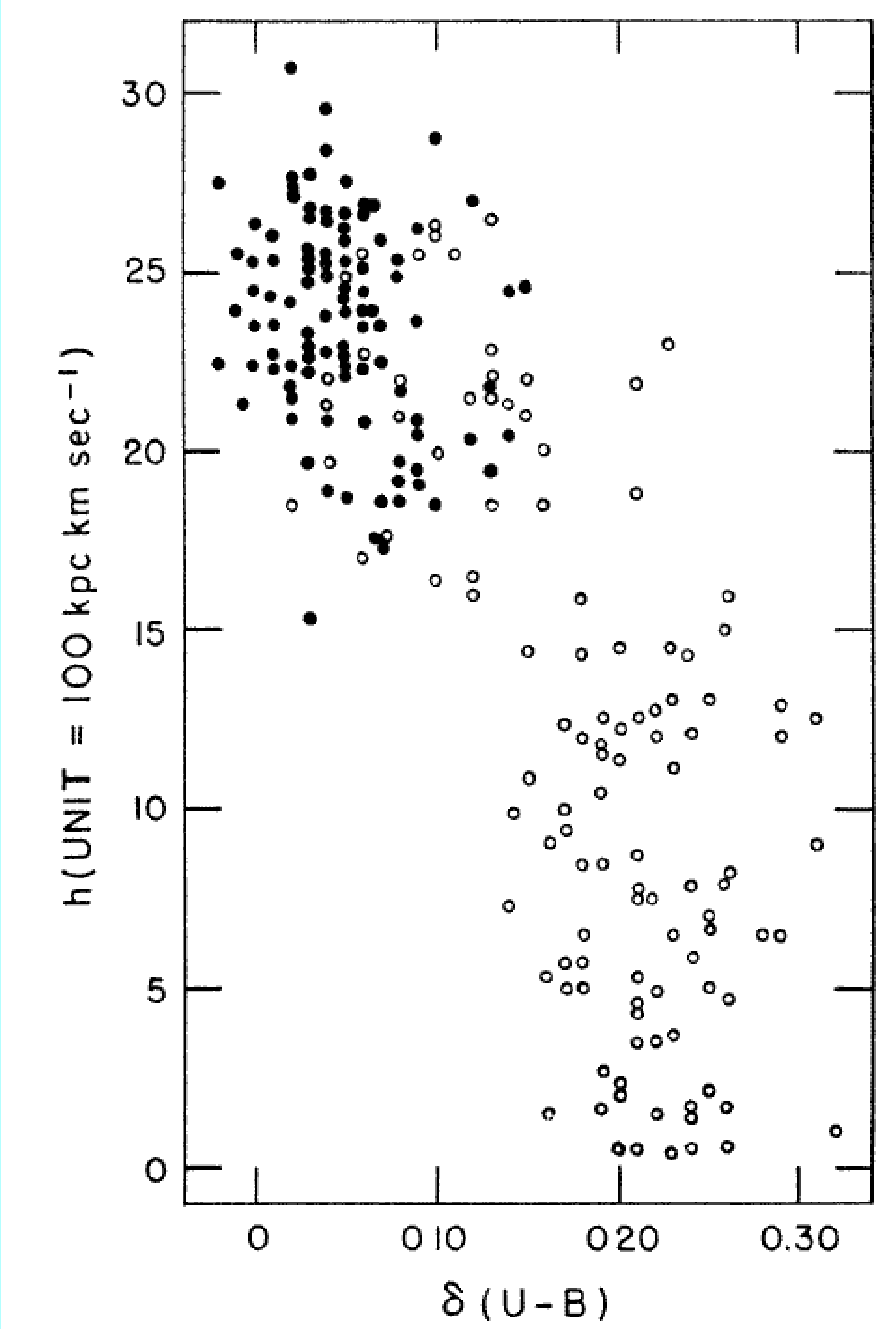
- The vertical velocity, orbital excentricity and angular momentum correlate with the UV-excess.

*Eggen, Lynden-Bell & Sandage, Ap.J. 136, 748 (1962)

†difference in color observed from that expected on the basis of the spectral type


0.30
0.20
0.10
0
δ (U – B)
0
0.2
0.4
0.6
0.8
e


Z max
250
200
150
100
50
|W|
306
382
9000 psc
8000
7000
6000
5000
4000
3000
2000
1000
800
600
400
200
100
0.0
0.10
0.20
0.30
δ (U – B)



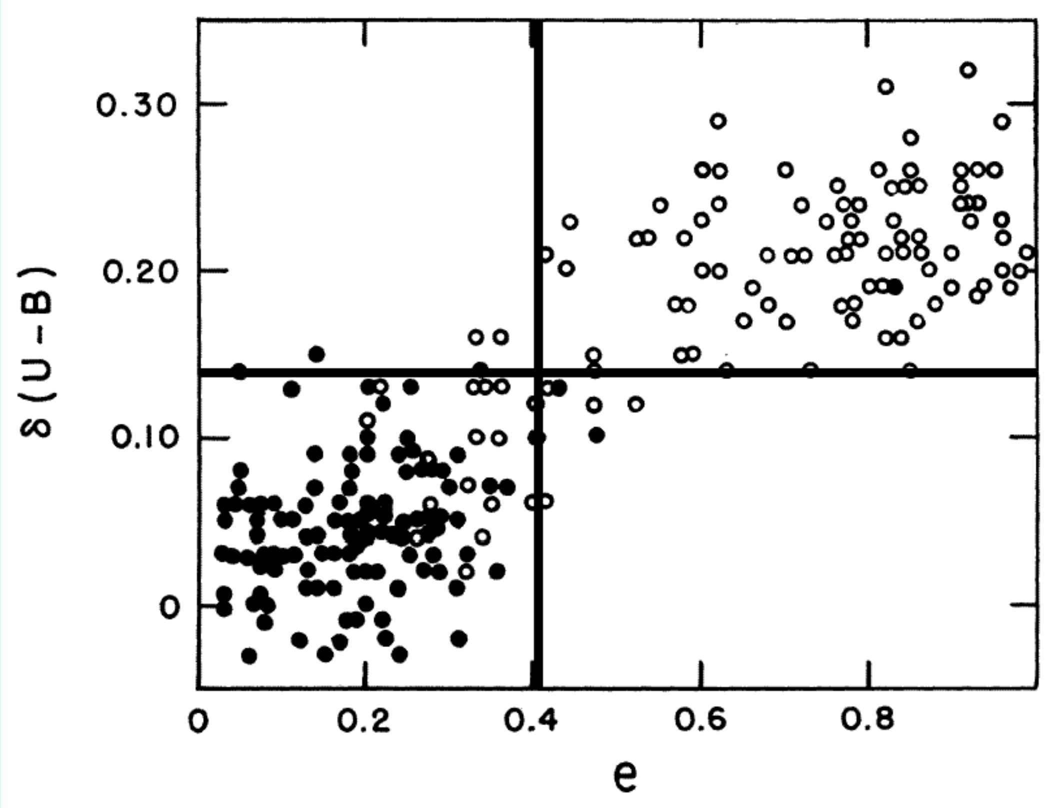
• The continuous progression of metal content from halo to disk stars provides evidence that the Galaxy collapsed.

• Metal-poor stars go up to $z \approx 10$ kpc while the old disk only goes up to $z \approx 400$ pc. The vertical collapse is thus about a factor 25.

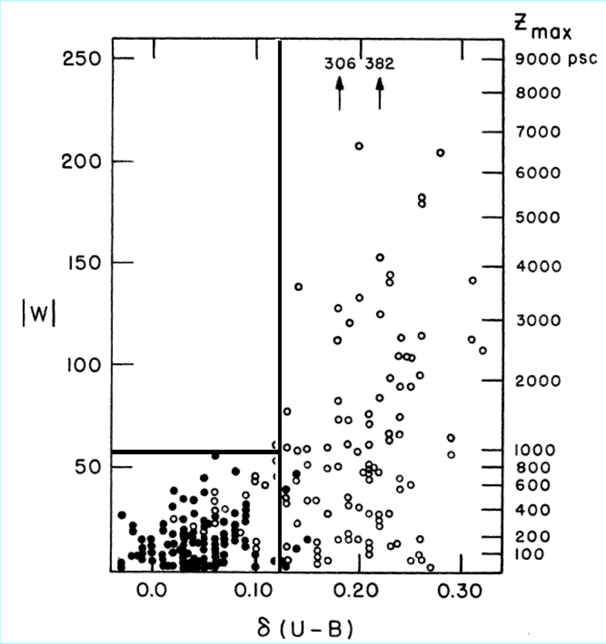
• The occurence of very high excentricities among halo stars indicates rapid disk collapse. A strong increase in gravitation will elongate circular orbits when the collapse proceeds on timescale less than the orbital period ($\approx 10^8$ years).

• From the observed angular momentum the estimated radial collapse factor is about 10.

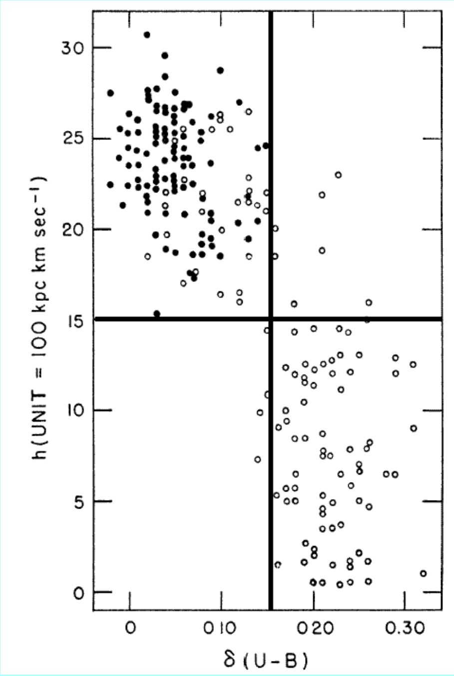
ELS described the process as a continuous one, but even their figures can be interpreted as showing two discrete components.



0.30
0.20
0.10
0
δ (U − B)
0
0.2
0.4
0.6
0.8
e



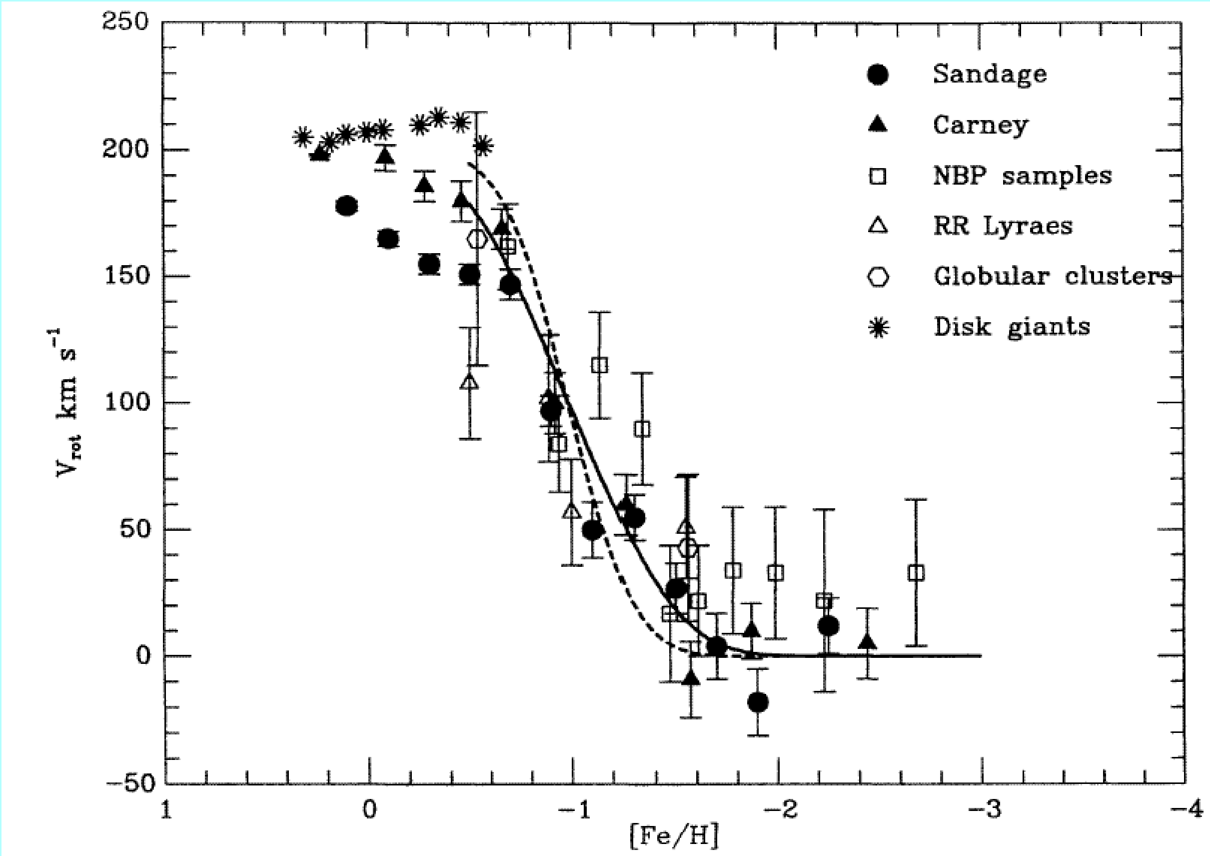
250
200
150
100
50
|W|
z max
9000 psc
8000
7000
6000
5000
4000
3000
2000
1000
800
600
400
200
100
306
382
0.0
0.10
0.20
0.30
δ (U − B)



30
25
20
15
10
5
0
h(UNIT = 100 kpc km sec⁻¹)
0
0.10
0.20
0.30
δ (U − B)

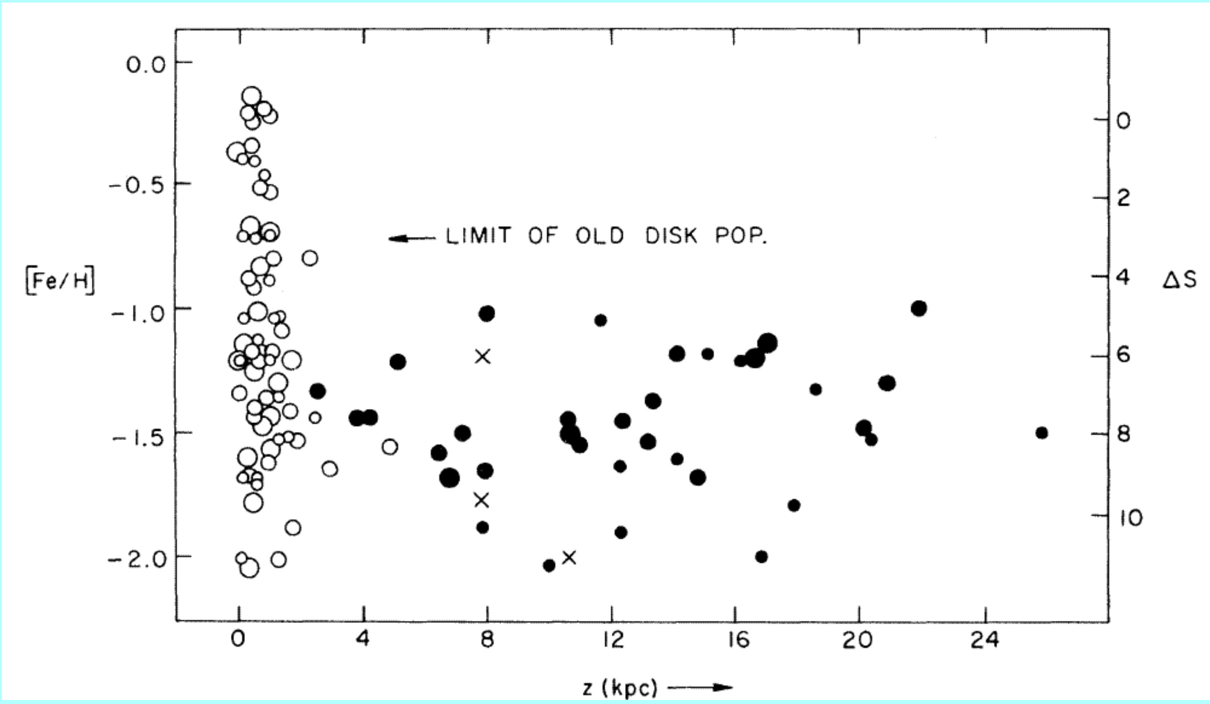
There is more evidence for the basic discreteness of Galactic structure.

One example is the asymmetric drift (the lagging behind in rotation of components with higher velocity dispersion) as a function of metallicity [Fe/H].



Here we see the rotation velocity with respect to an inertial frame.

Also the upper limit of the distribution of metallicity of disk and halo RR Lyrae stars* does not show a gradual decline with height above the plane.

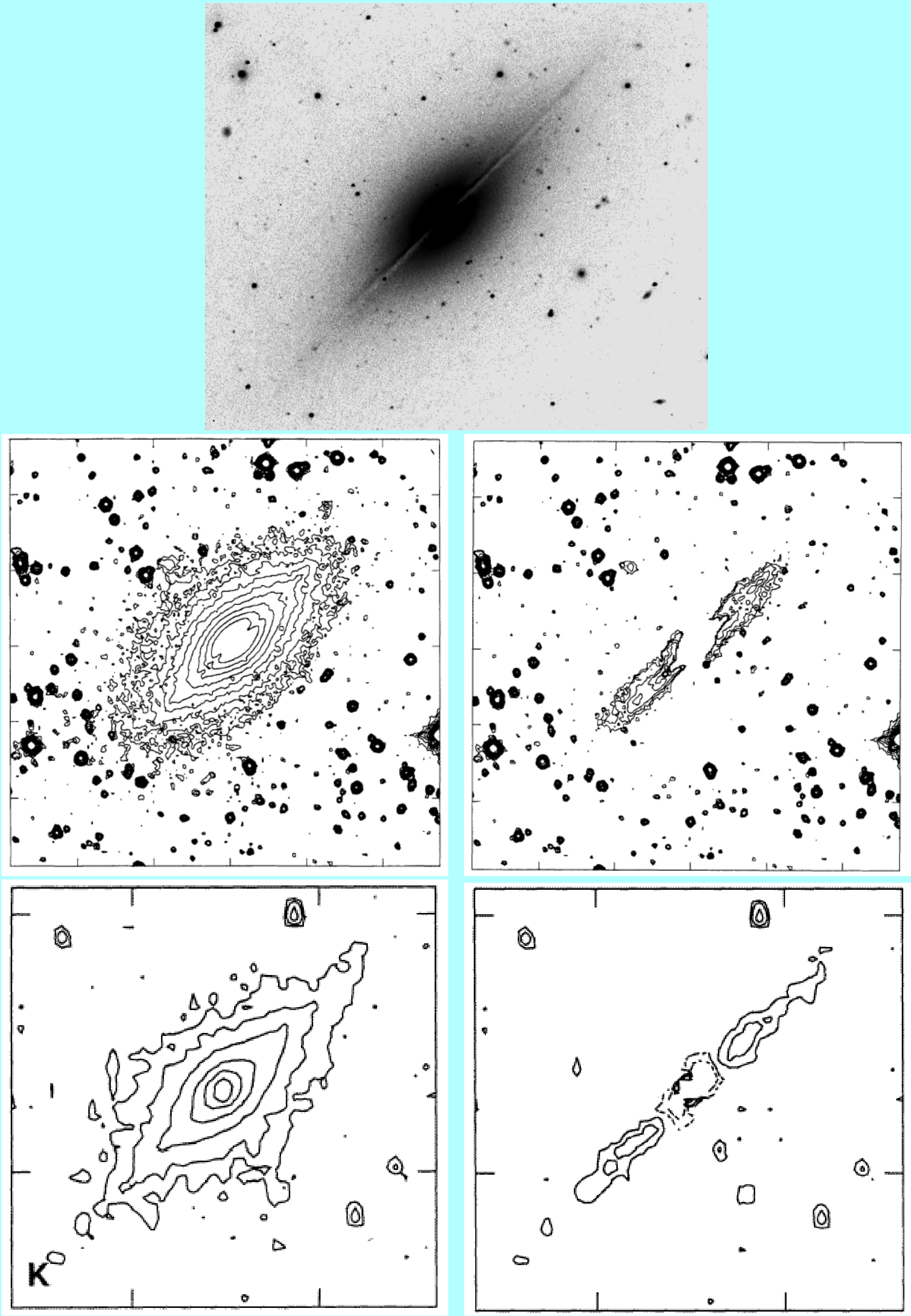


The surface photometry of NGC 7814 (see lecture 2) showed that it was possible to separate the bightness distribution into two components (spheroid and disk) with discretely different flattenings.

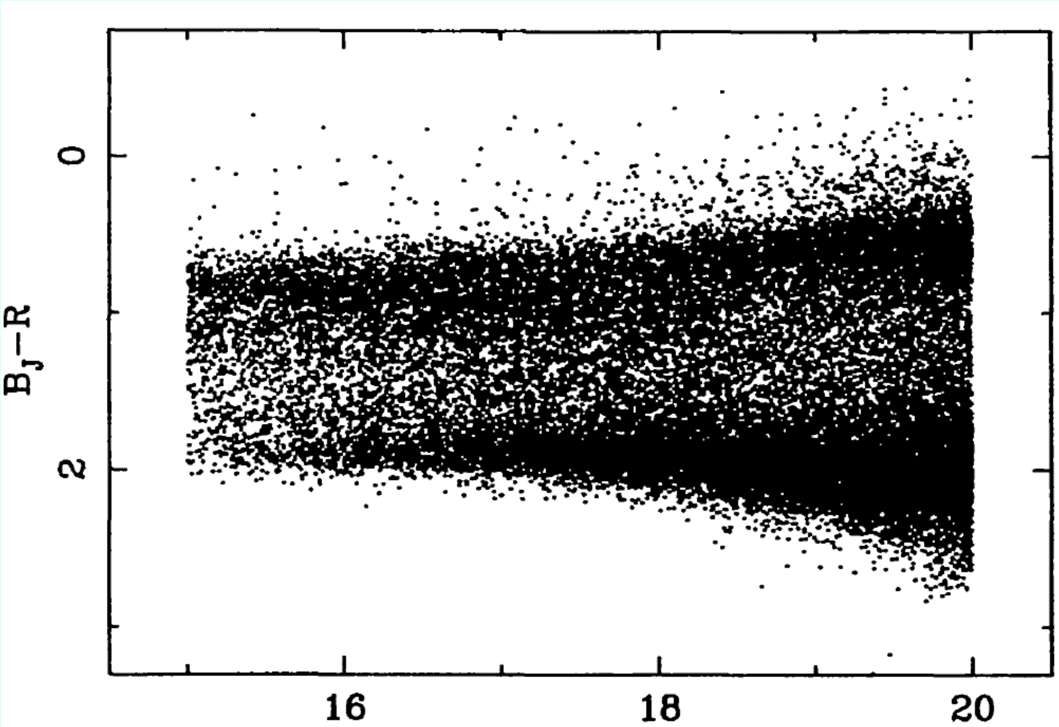
This seemed to indicate† that star formation occured in two discrete epochs, one before and one after disk collapse.

*Butlet, Kinman & Kraft, A.J. 84, 993 (1979)

†van der Kruit & Searle, A.&A. 110, 79 (1982)


K

We see also the basic two-component structure in the colors at faint star counts.



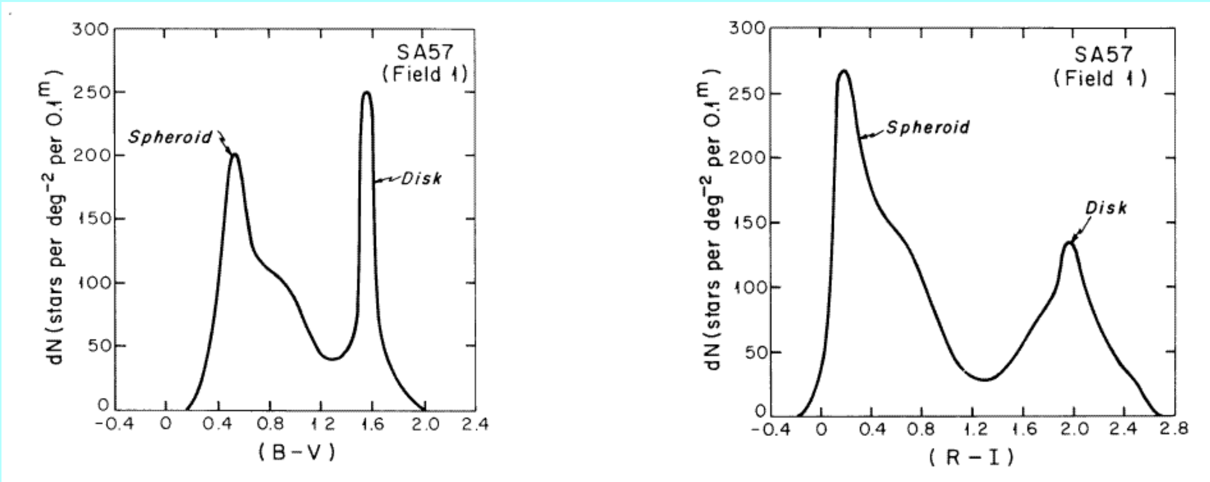
- Few stars bluer than $(B - V) \sim 0.4$. This corresponds to the MS turn-off of the extremely metal-poor halo population.
- The peak at $(B - V) \sim 0.6$. This is the MS turn-off of the halo population.
- The peak at $(B - V) \sim 1.5$. This is the cool MS of the disk population.
- The absence of stars redder than $(B-V) \sim 2.0$. This indicates the absence of large amounts of M-dwarfs to provide the missing local mass.

The "thick disk".

The old situation (before about 1980) was that there was no clear evidence for a substabtial Intermediate Population II and there were basically two discrete components (halo and disk).

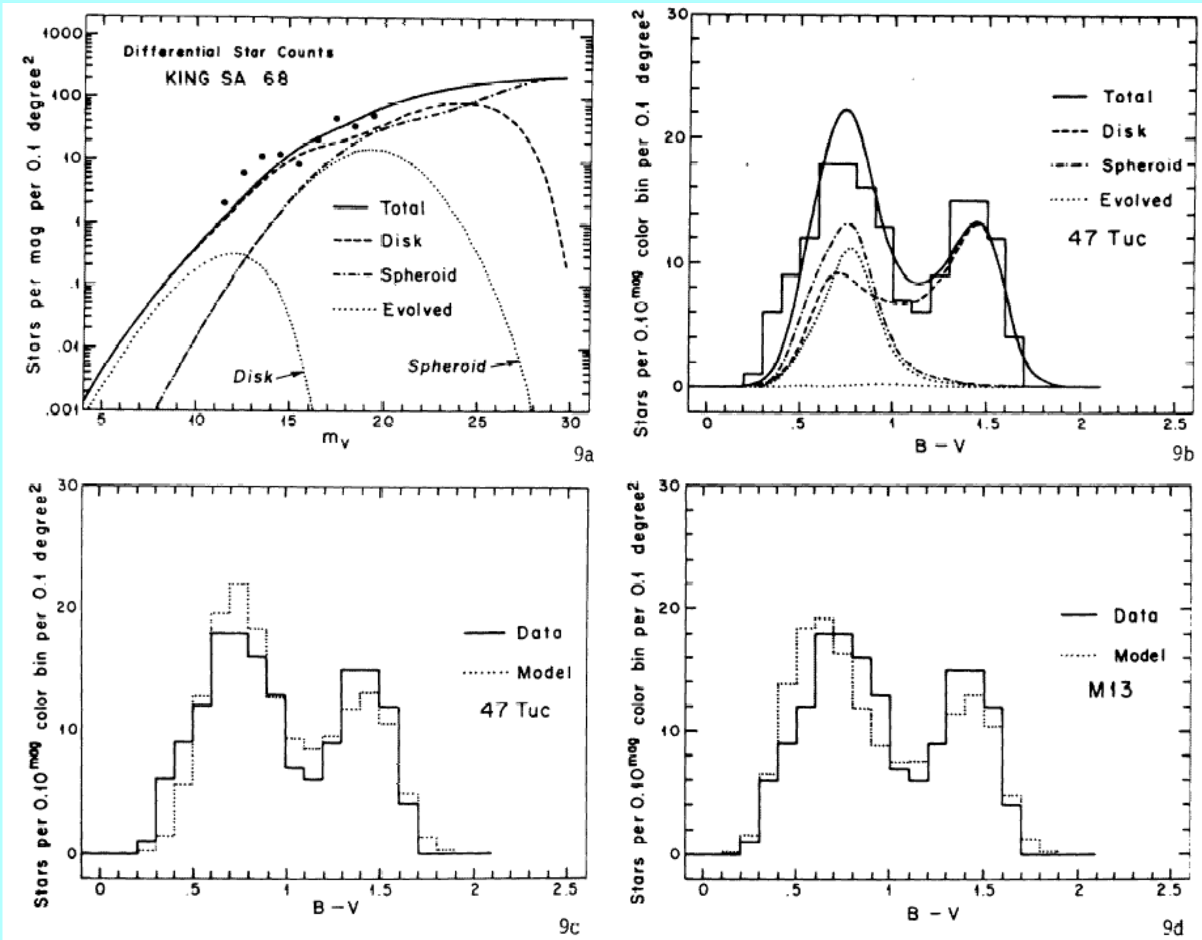
Bahcall & Soneira* built a Galaxy model with distinct disk and halo components. This was later improved as the Standard Galaxy Model†.

They showed that it could very well reproduce faint star counts and color distributions in two "Selected Areas", for which deep data were available, namely SA 57 (l, b) = (65,86) and SA 68 (111,-46).



*Ap.J. Suppl. 44, 73 (1980)

†Bahcall & Soneira, Ap.J.Suppl. 55.67 (1984)



Gilmore & Reid* did deep star counts in South Galactic Pole.

They selected only those stars near the MS turn-off on the basis of their colors.

For these turn-off and subgiants they determined photometric parallaxes.

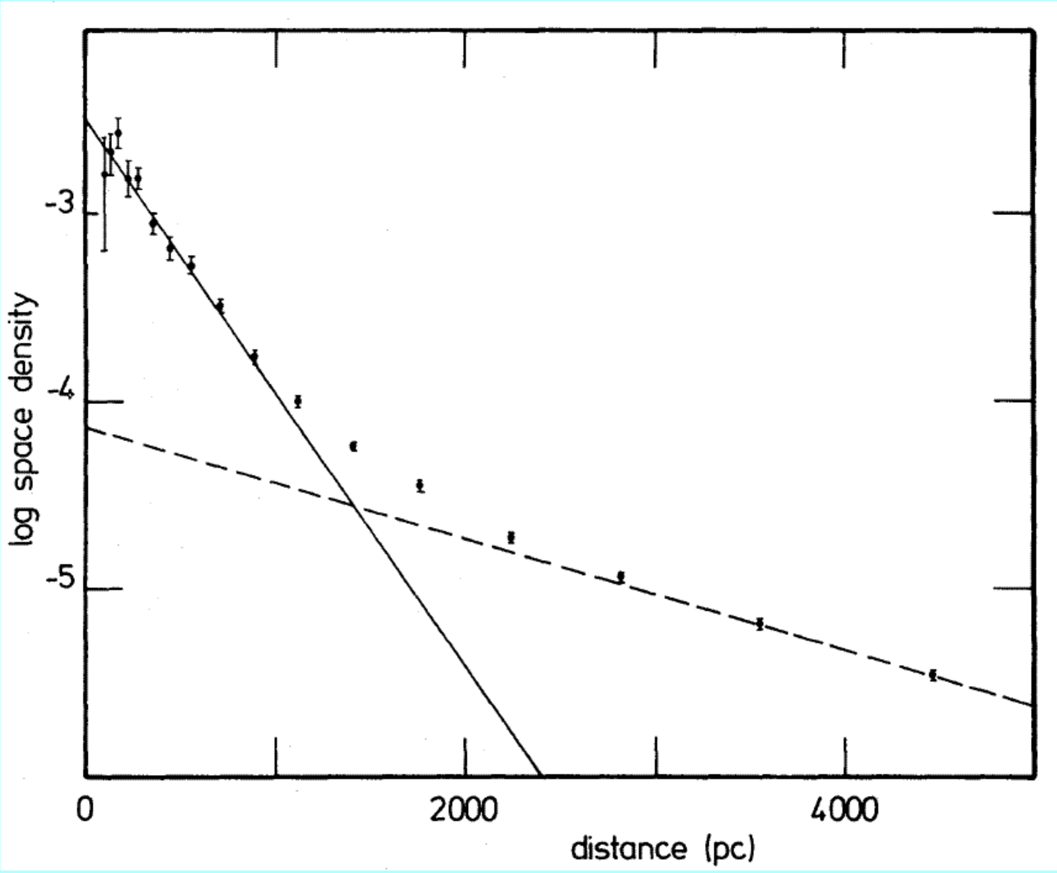
*Mon.Not.R.A.S. 202, 1025 (1983)

They found two components in the disk:

• The "thin disk" (really the old disk) with exponential scaleheight $h_z \approx 300$ pc

• A new component that they called the "thick disk" with $h_z \approx 1350$ pc.

• The local normalisation was such that the thick disk has in the plane $\approx 2\%$ of the stars and this corresponds to $\approx 9\%$ of the face-on surface brightness.



Bahcall and collaborators* conclude that the Standard Galaxy Model BS84 is consistent with counts in all fields available and inconsistent with a model including a thick disk and inconclusive when a metal-rich Luminosity Function (LF) is used for a thick disk.

Gilmore and collaborators† propose a model with a thick disk (G84) and claims consistency with the count. For the thick disk they use the LF of the globular cluster 47 Tuc ([Fe/H] ≈ -0.7).

So earlier disagreement due to choice of the LF of the intermediate component; BS84 and G84 reproduce star counts only if the LF of metal-rich globular cluster is used for it.

Star counts alone are not conclusive evidence for a thick disk or Intermediate Population II.

*Bahcall & Soneira, Ap.J.Suppl. 55, 67 (1984) (BS84); Bahcall *et al.*, 299, 616 (1985)

†Gilmore, Mon.Not.R.A.S. 207, 223 (1984) (G84); Gilmore *et al.*, Mon.Not.R.A.S. 213, 257 (1085)

External galaxies.

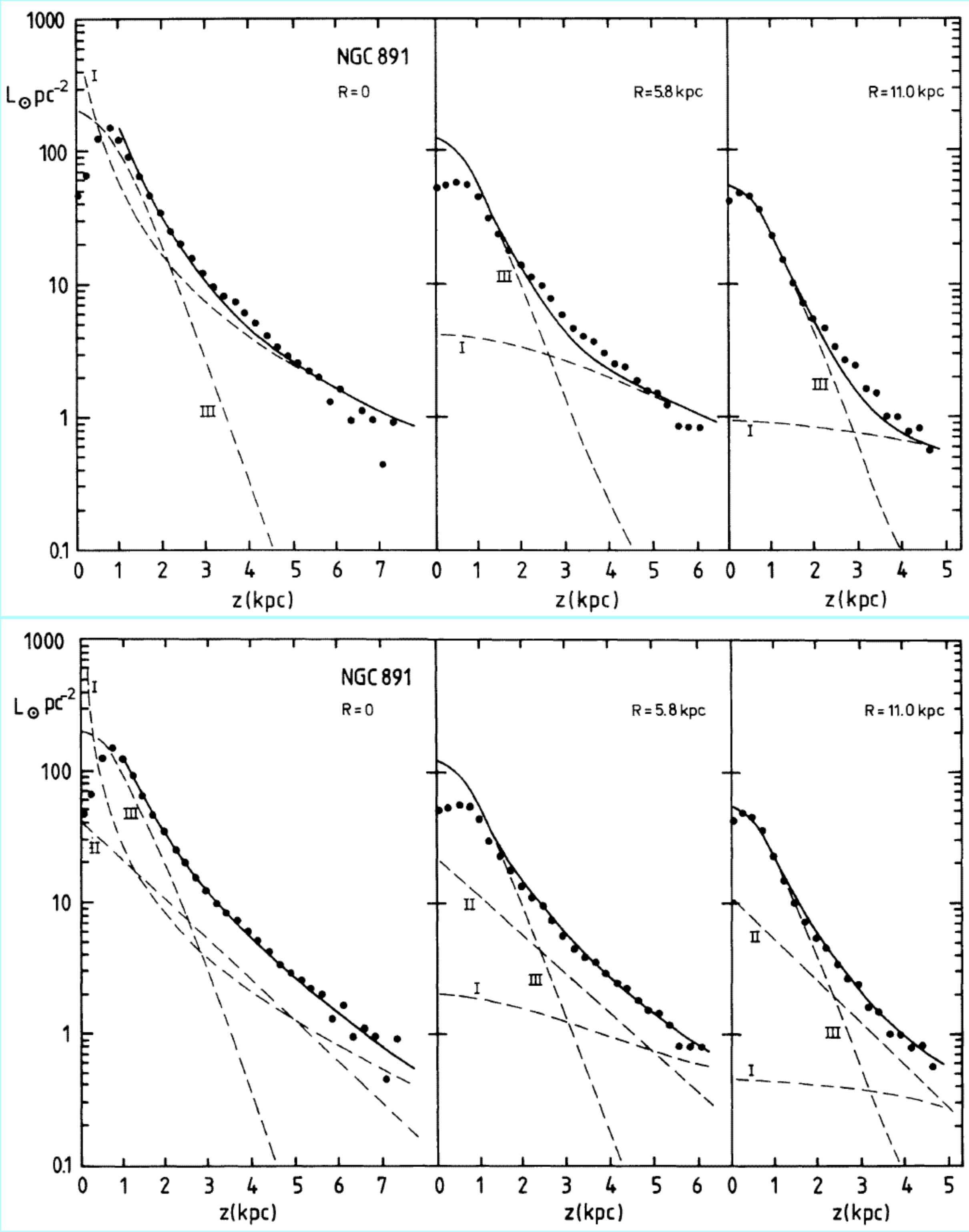
We can look at edge-on external galaxies, such as NGC 891, which is very similar to our Galaxy*.

On can construct equivalent "BS84" and "G84" models for NGC 891.

	Galaxy	NGC 891
"BS84" old disk		
h (kpc)	4.5 - 5	4.9
z_0 (kpc)	0.6 - 0.7	0.99
$R_{\rm max}$ (kpc)	22	21
$L_{\rm tot}$ ($L_\odot$)	$(1.0 - 1.2) \times 10^{10}$	6.7×10^{10}
"BS84" spheroid		
$R_{\rm e}$ (kpc)	~ 2.7	2.3
$(1 - e^2)^{1/2}$	~ 0.7	~ 0.6
$L_{\rm tot}$ ($L_\odot$)	$\sim 1.5 \times 10^9$	1.2×10^9
"G84" old disk		
	as above	as above
"G84" thick disk		
$h_{\rm R}$ (kpc)	~ 4.5	5
$h_{\rm z}$ (kpc)	~ 1.3	1.5
$L_{\rm tot}$ ($L_\odot$)	$\sim 2 \times 10^8$	2×10^8
"G84" spheroid		
$R_{\rm e}$ (kpc)	~ 2.7	2.3
$(1 - e^2)^{1/2}$	~ 0.7	~ 0.6
$L_{\rm tot}$ ($L_\odot$)	$\sim 1.0 \times 10^9$	4.9×10^8

*van der Kruit, A.&A. 140, 470 (1984)

Both these models fit the surface photometry well.

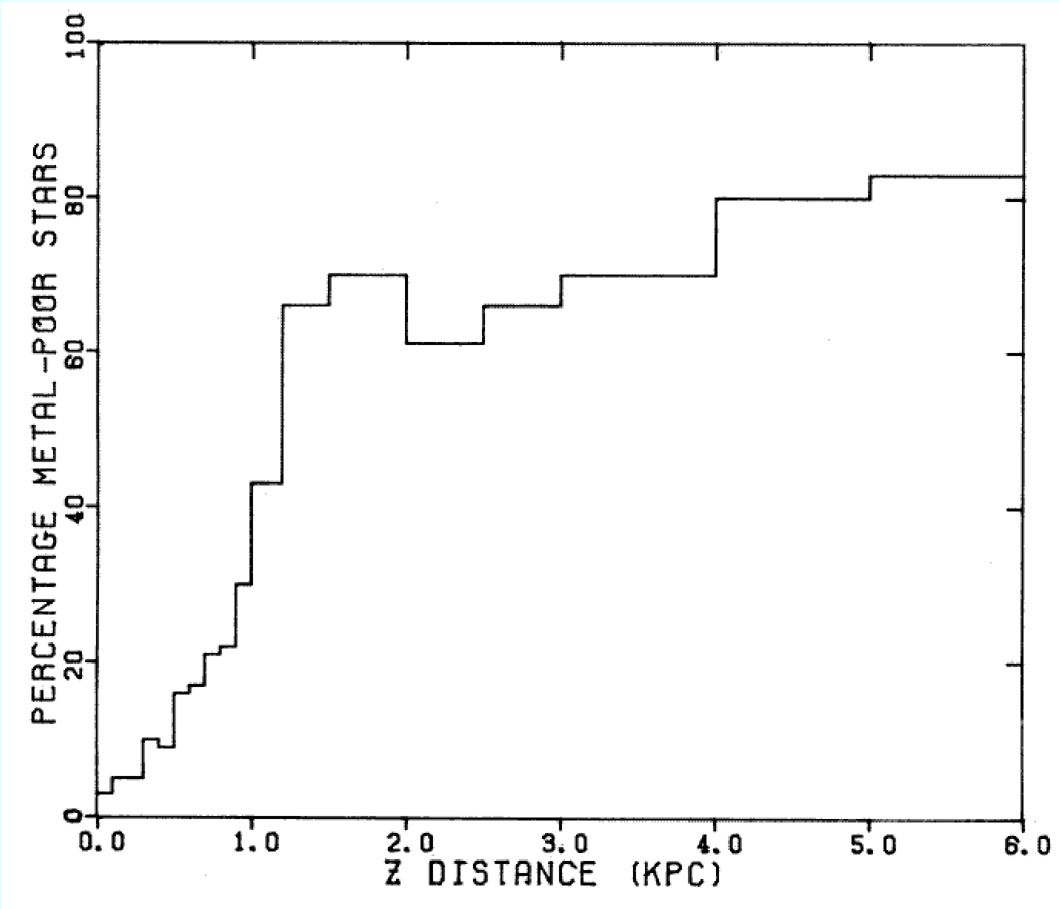


Kinematical evidence for a thick disk.

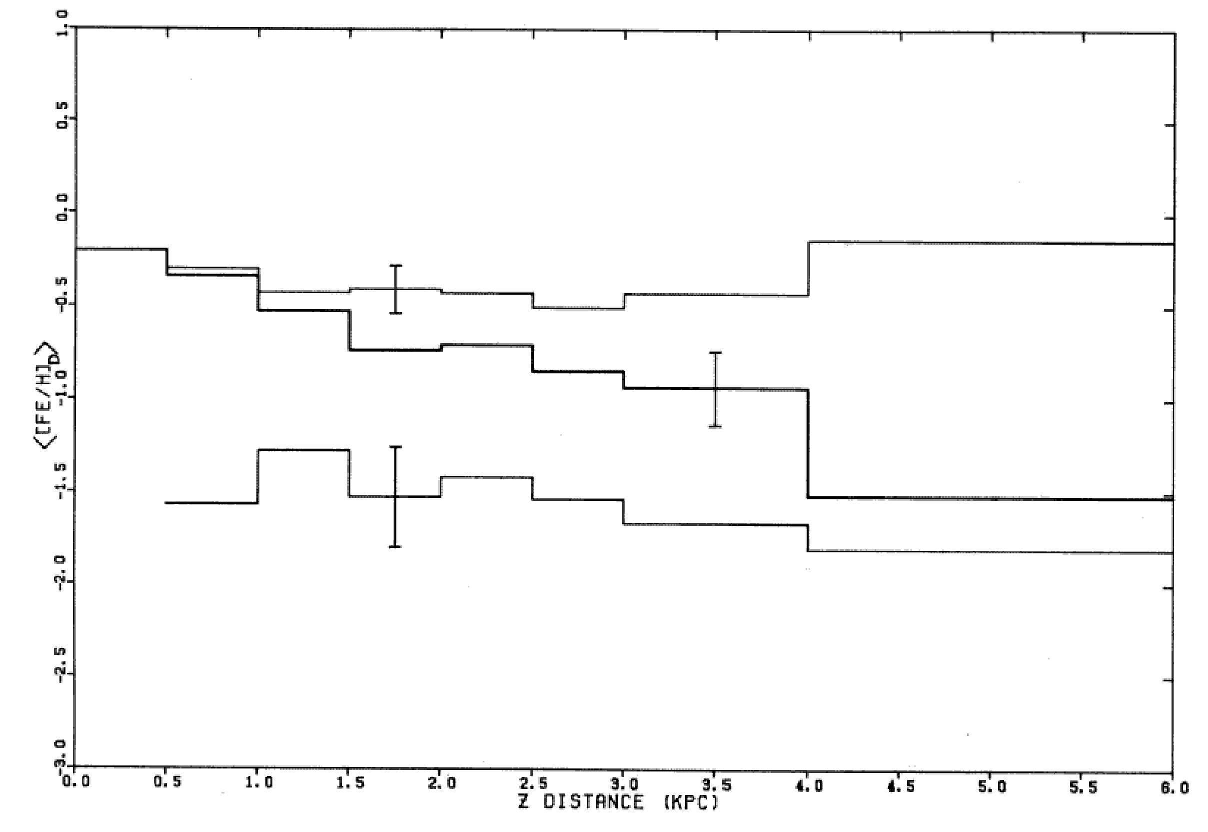
Hartkopf & Yoss* compiled DDO photometry and vertical velocities of G & K giants.

The distribution is separable into two components, each about isothermal:

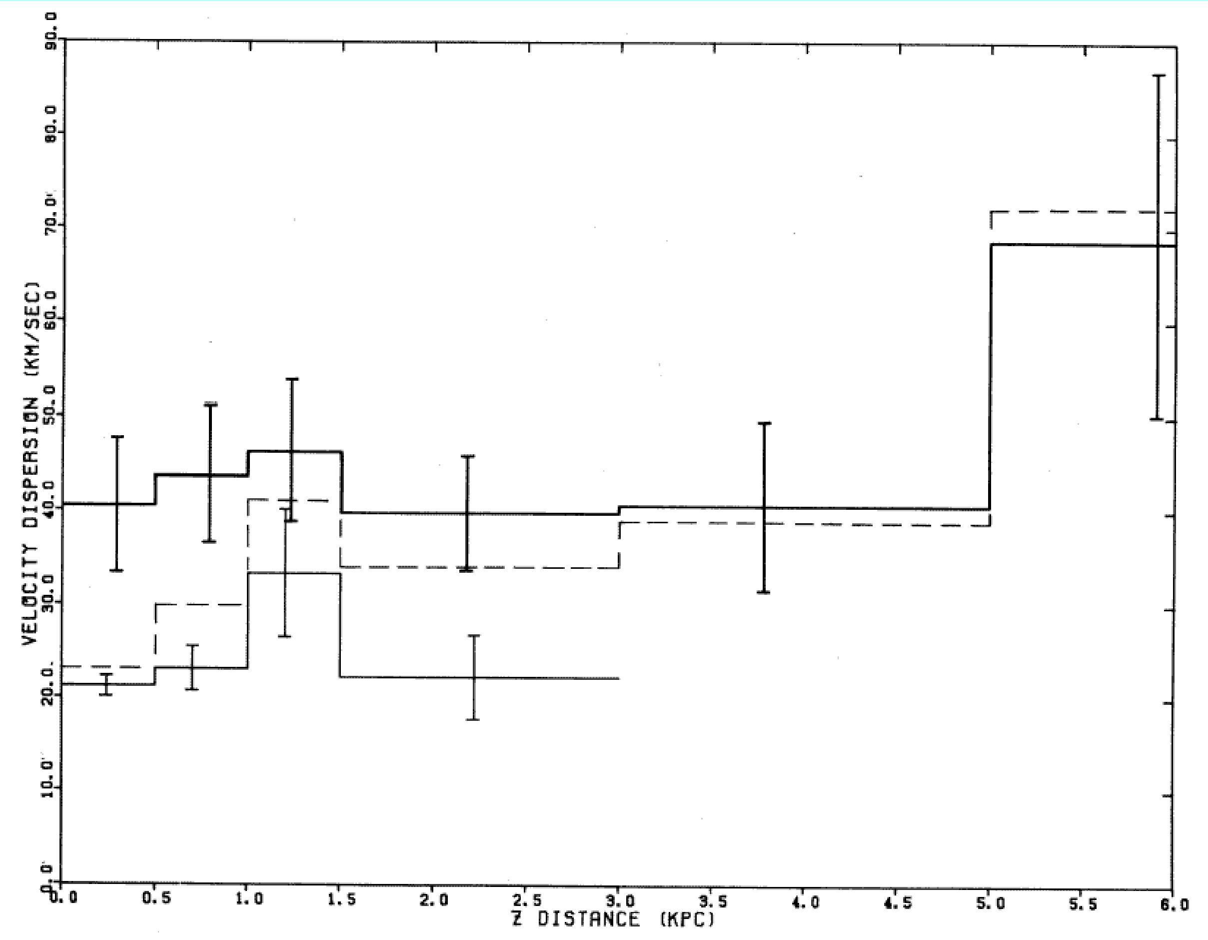
- $\langle[\mathrm{Fe/H}]\rangle \approx -0.4$; $\langle W^2\rangle^{1/2} \approx 20$ km s^{-1}
- $\langle[\mathrm{Fe/H}]\rangle \approx -1.5$; $\langle W^2\rangle^{1/2} \approx 40$ km s^{-1}



*A.J. 87, 1679 (1982)



1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
⟨[FE/H]$_D$⟩
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Z DISTANCE (KPC)



90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
VELOCITY DISPERSION (KM/SEC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Z DISTANCE (KPC)

Rose* found Red Horizontal Branch stars in the North Galactic Pole field similar to the ones in globular cluster M71 ([Fe/H] ~ -0.6).

These are too metal poor to be old disk stars.

They constitute 5% of all non-halo giants in the field and have $h_z \lesssim 0.5$ kpc and $\langle W^2 \rangle^{1/2} \sim 40$ km s^{-1}.

This is fully consistent with the thick disk of Gilmore & Reid.

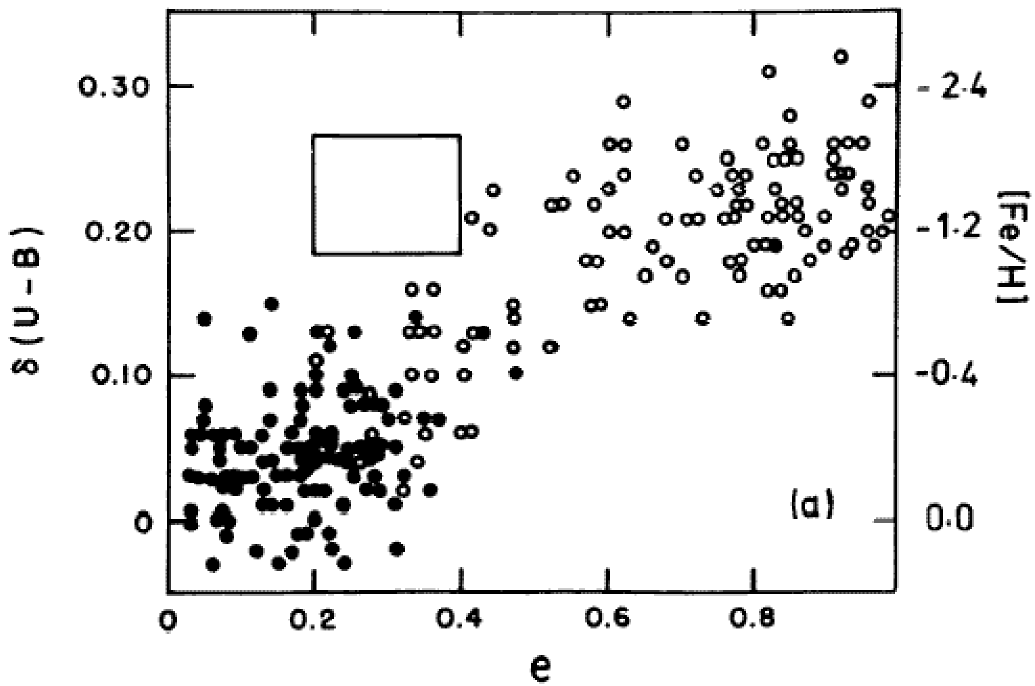
Norris *et al.*† found stars with [Fe/H] ≤ -1.0 ; $e \leq 0.4$.

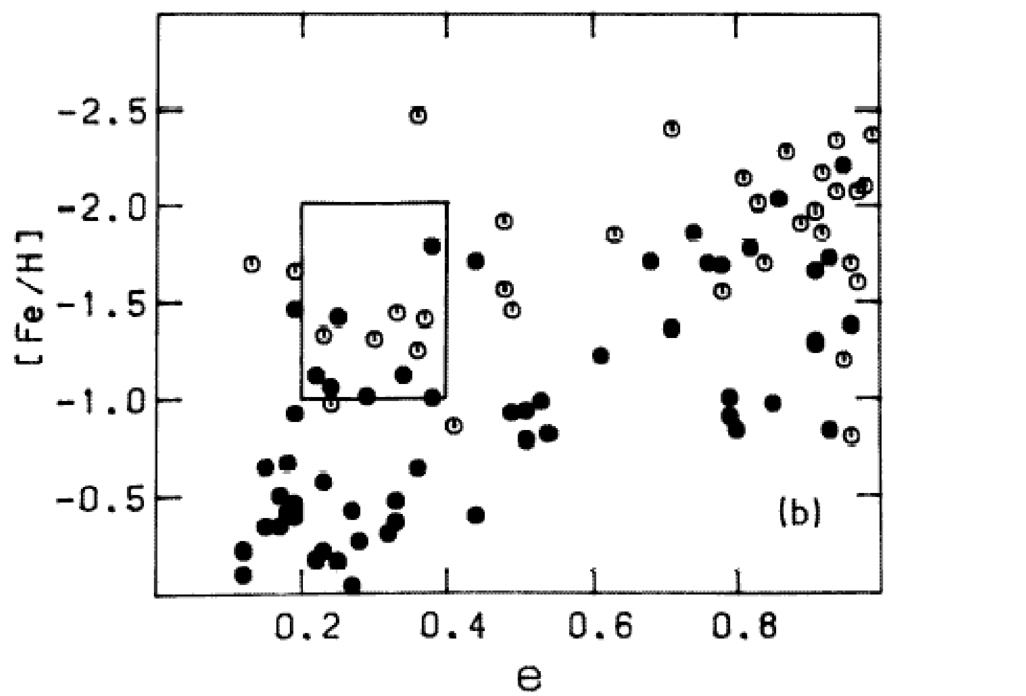
This area is empty in the ELS study and would correspond to positions of stars in an Intermediate Population II.

These stars have $\langle W^2 \rangle^{1/2} = 61 \pm 9$ km s^{-1}.

*A.J. 90, 787 (1985)

†Norris, Bessel & Pickles, Ap.J.Suppl. 58, 463 (1985)





At the top the ELS diagram. The rectangle gives corresponding areas in both diagrams.

The thick disk is real and could be an Intermediate Population II.

It is probably discrete from the Old Disk Population and possibly also from the Halo Population II

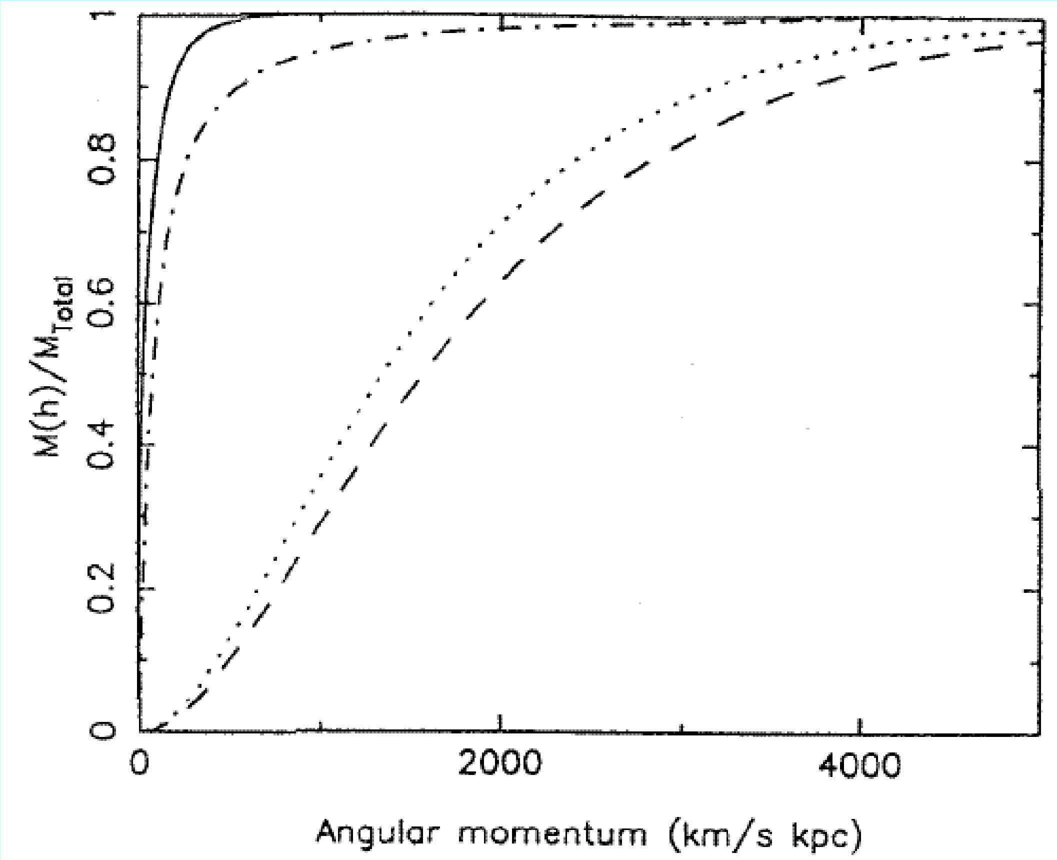
In face-on surface brightness is only of the order of 10% compared to the disk in the solar neighborhood.

So we may distinguish the following components* (lengths in kpc and velocities in km/s).

Component	Pop I	Old Disk	Thick disk	Halo
h_z	0.1	0.3	$\sim$ 1.5	$\sim$ 4
$\langle$[Fe/H]$\rangle$	$\sim$ 0.0	-0.3	-0.6	-1.5
$\sigma_{[Fe/H]}$	$\sim$ 0.15	$\sim$ 0.2	$\sim$ 0.3	$\sim$ 0.5
Asym. Drift	small	$\sim$ 10	$\sim$ 40	$\sim$ 150
$\langle W^2\rangle^{1/2}$	$\sim$ 10	25	45	100

*see also Gilmore, Wyse & Kuijken, Ann.Rev.A.&A. 27, 555 (1989)

It is possible to make an estimate of the cumulative distribution $M(h)/M_{\text{total}}$ of specific angular momentum* h in each of these components.



The solid line is the bulge, the dashed-dotted line the halo, the dotted curve the thick disk and the dashed curve the old (thin) disk.

The bulge is related to the halo, but the thick disk to the disk.

*angular momentum per unit mass

Globular clusters.

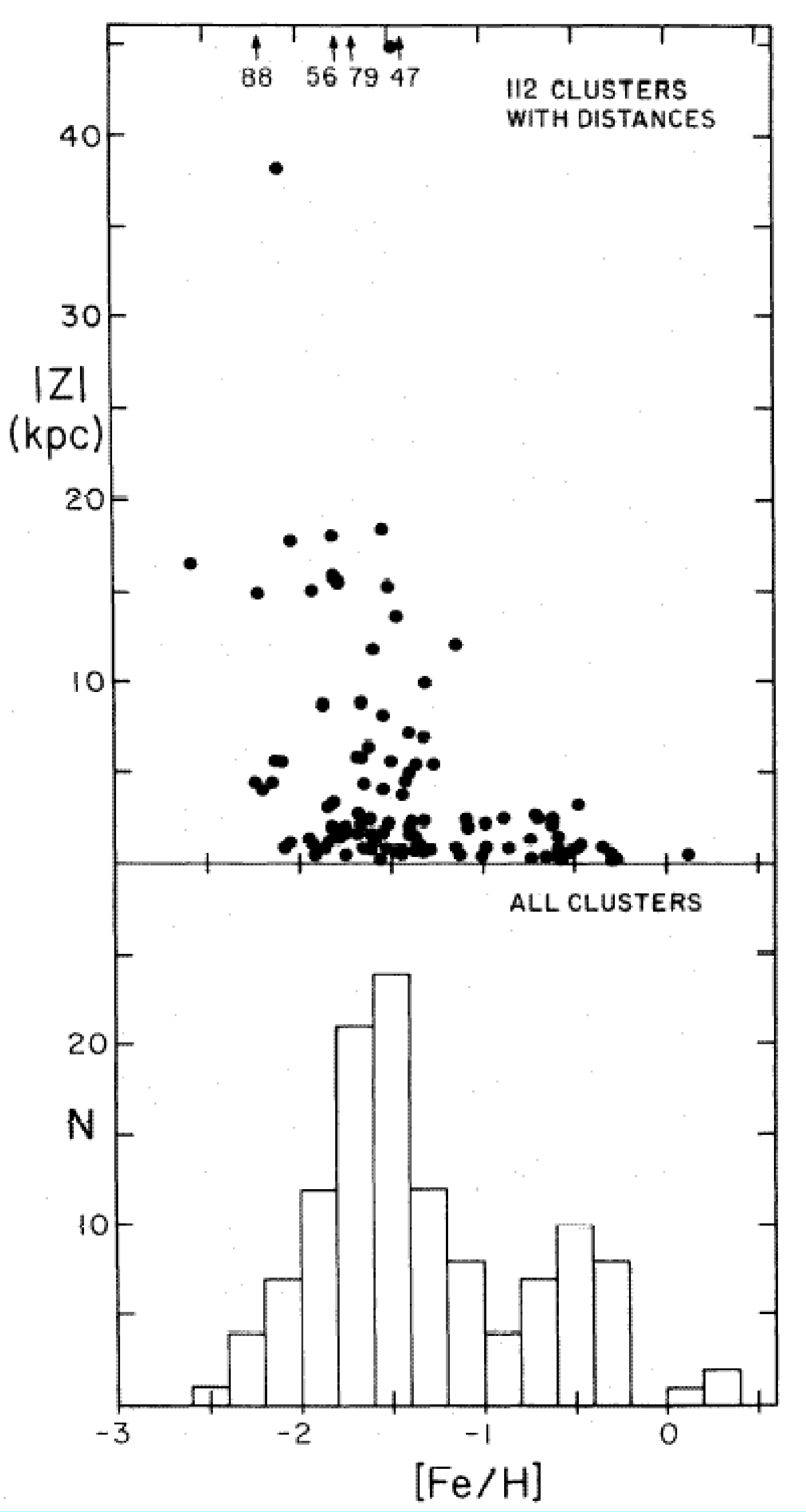
Globular clusters have long been known to be made up of two sub-systems, one following the traditional halo and with metal-poor clusters and one flattened and with less metal-poor systems.

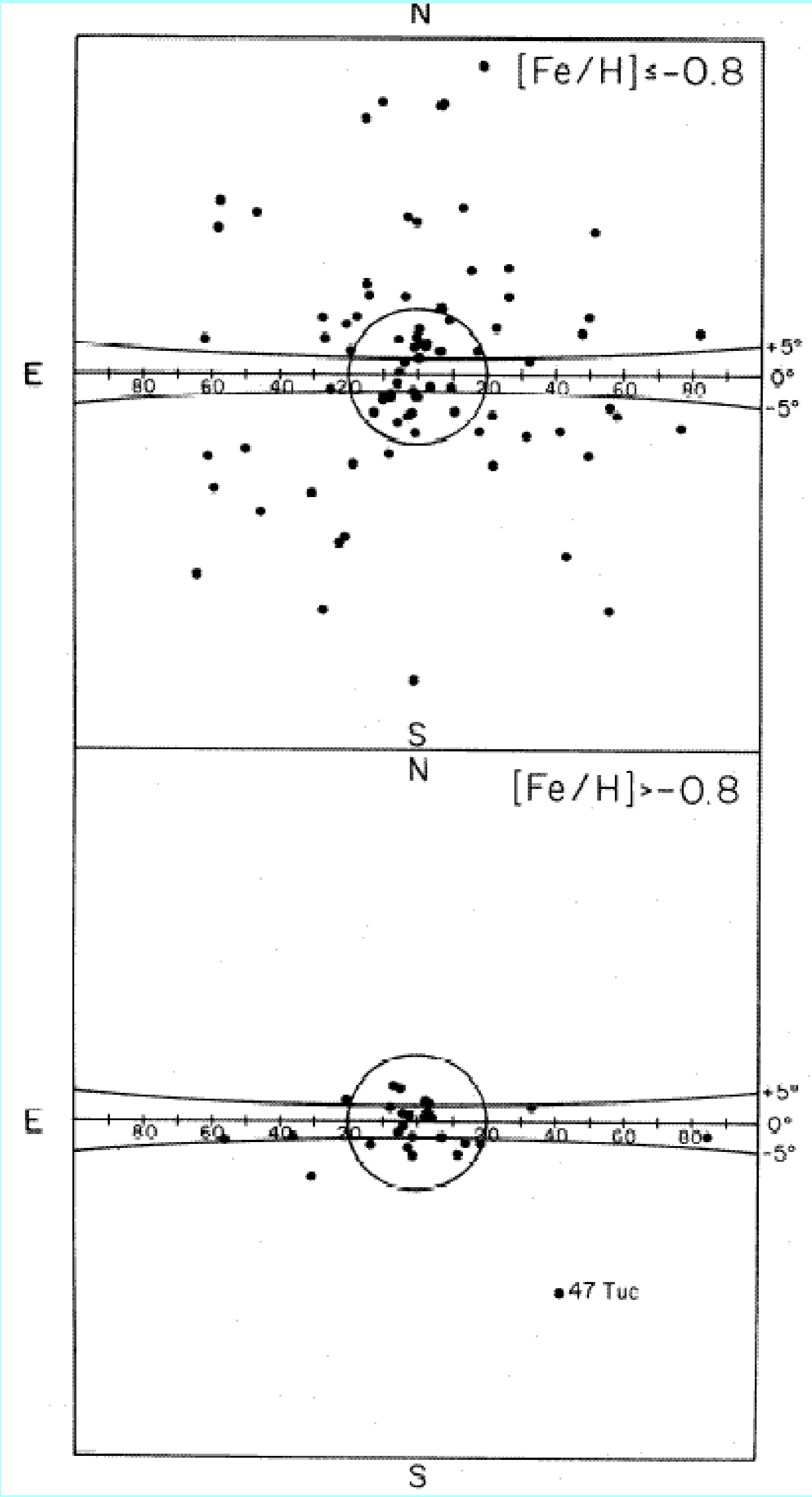
These have been called G- and F-clusters or disk- and halo-clusters.

They also display a bi-modal metallicity distribution with a division at [Fe/H] ≈ -0.8.

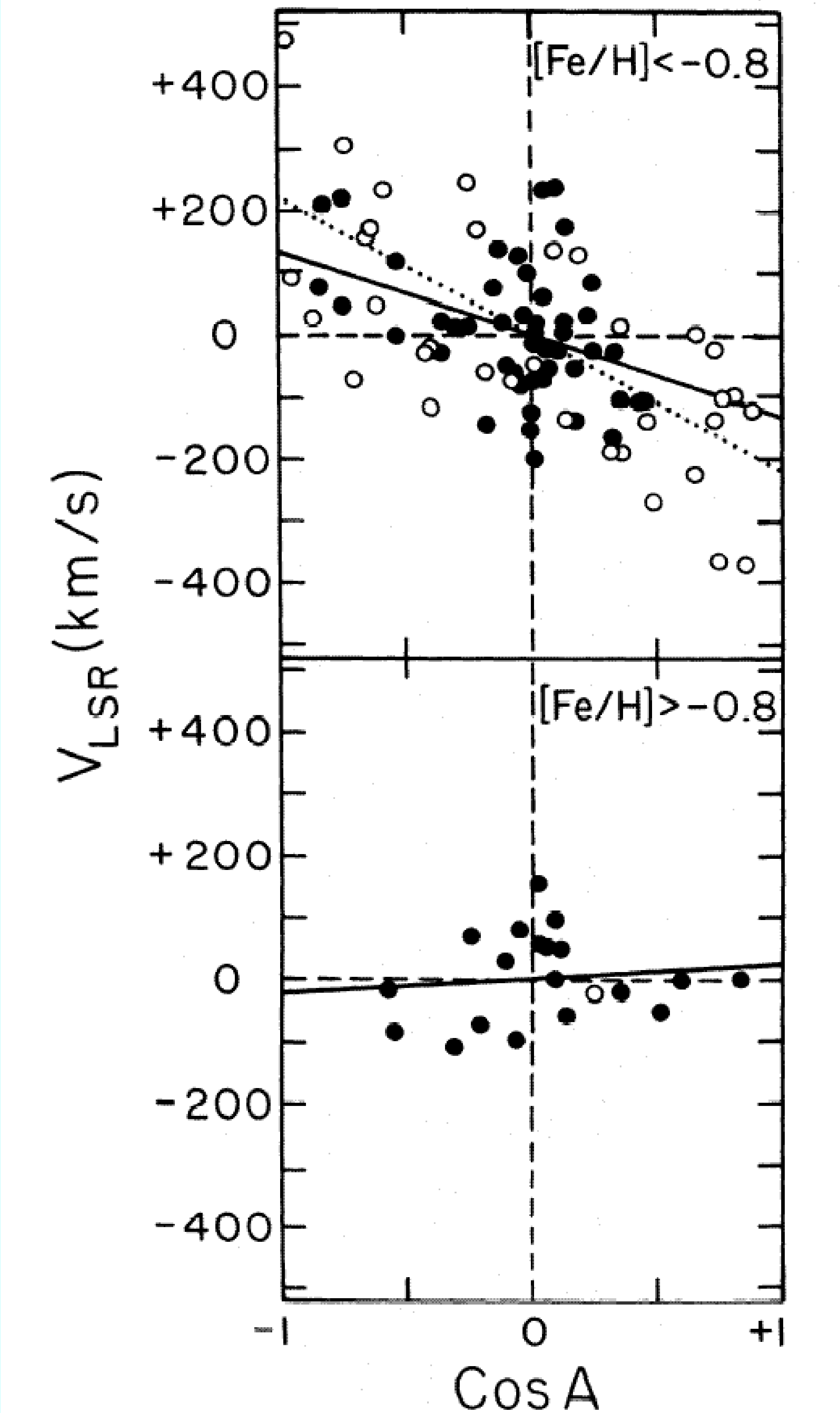
Also there is a clear difference in asymmetric drift (or rotation velocity of the group as a whole) and velocity dispersion.

This is seen in the radial velocity with respect to the Local Standard of Rest (LSR) as a function of the angle A with the apex of the LSR.

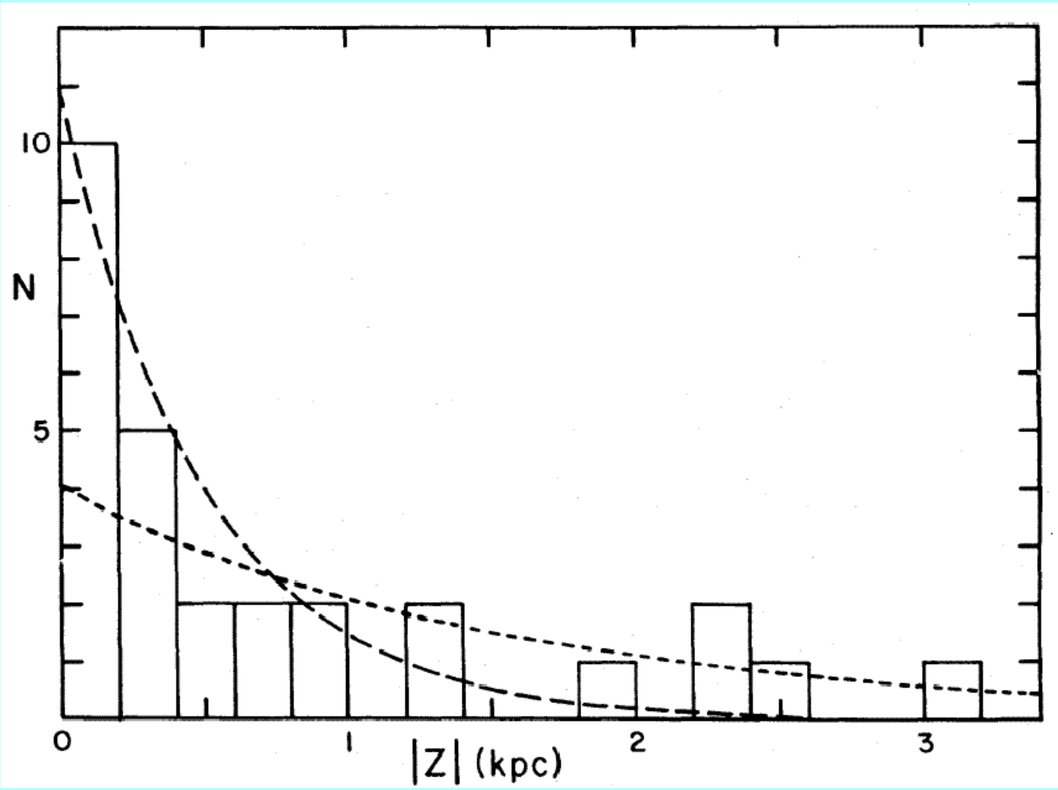

88
56
79
47
112 CLUSTERS
WITH DISTANCES
|Z|
(kpc)
40
30
20
10
ALL CLUSTERS
N
20
10
-3
-2
-1
0
[Fe/H]



N
[Fe/H]≤-0.8
E
80
60
40
20
20
40
60
80
+5°
0°
-5°
S
N
[Fe/H]>-0.8
E
80
60
40
20
20
40
60
80
+5°
0°
-5°
47 Tuc
S



[Fe/H]<-0.8
[Fe/H]>-0.8
+400
+200
0
-200
-400
V_{LSR} (km/s)
-1
0
+1
Cos A

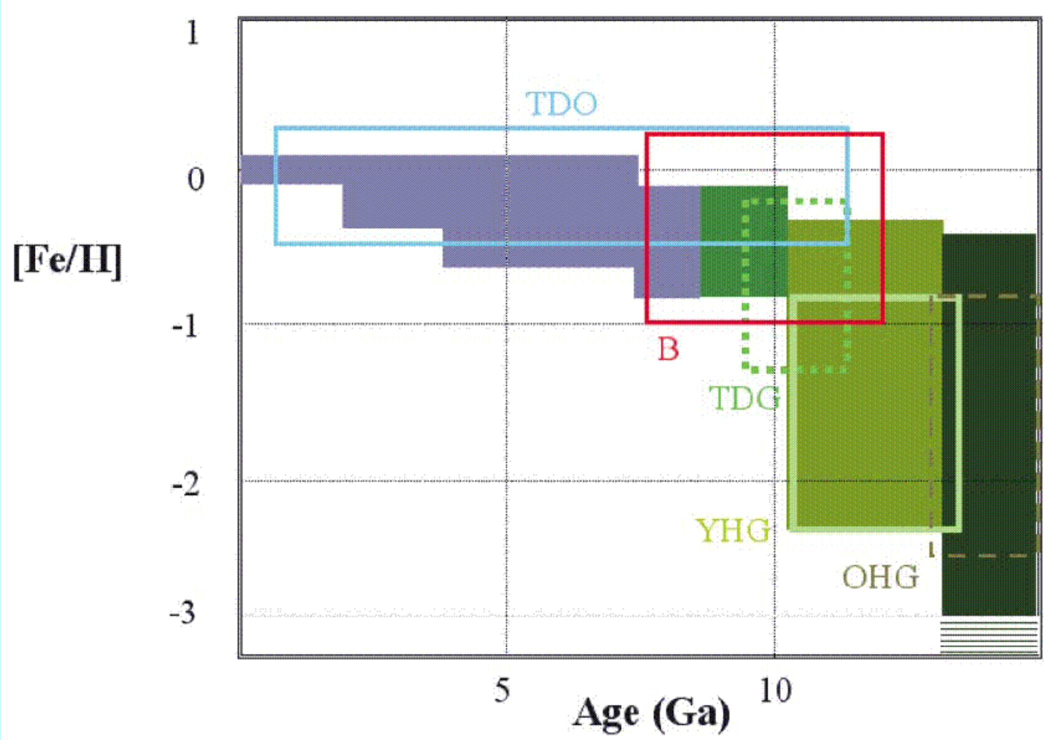


The metal-rich clusters form a disk-system with properties much like the thick disk*.

	disk-clusters	halo-clusters
[Fe/H]	> -0.8	< -0.8
h_z (kpc)	0.5-1.5	–
$V_{\rm rot}$ (km/s)	152 ± 29	50 ± 23
$\sigma_{\rm los}$ (km/s)	72 ± 11	116 ± 9

*Zinn, Ap.J. 293, 424 (1985)

A summary picture of the structure of the Galaxy is given in this age-metallicity relation*.



TDO = thin disk open clusters

TDG = thick disk globular clusters

B = bulge

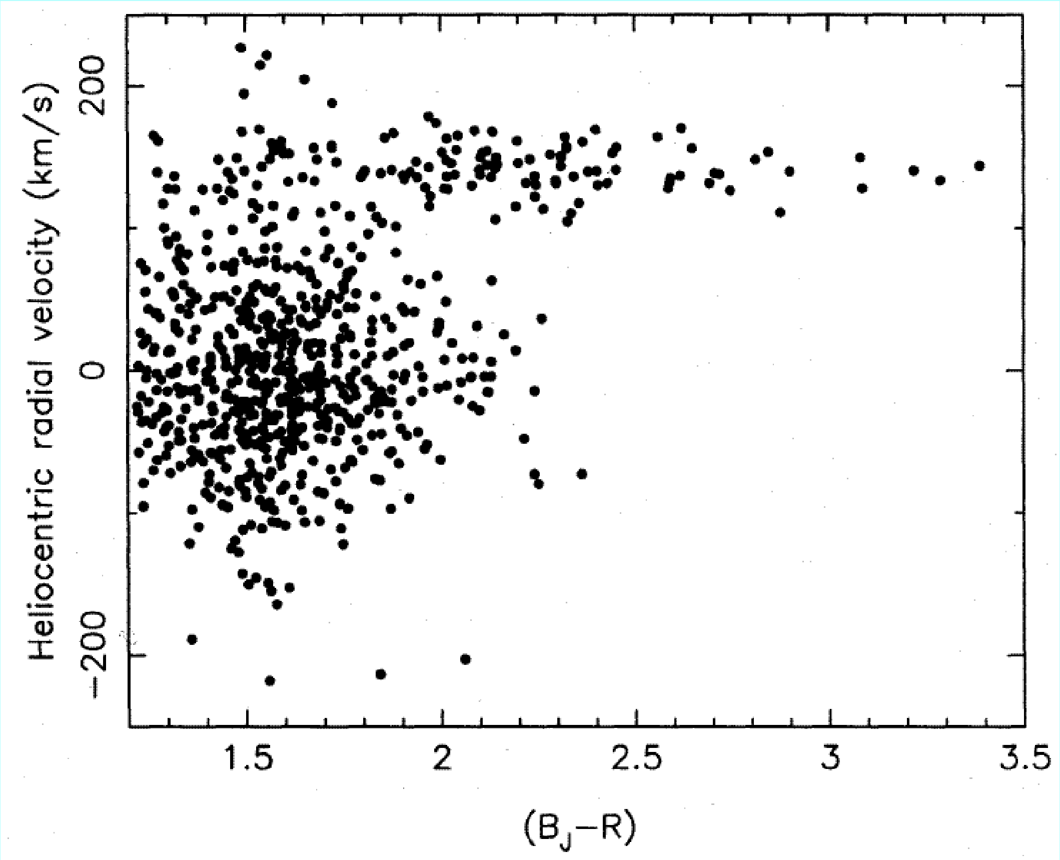
YHG = young halo globular clusters

OHG = old halo globular clusters

*Freeman & Bland-Hawthorn, Ann.Rev.A.&A. 40, 487 (2002)

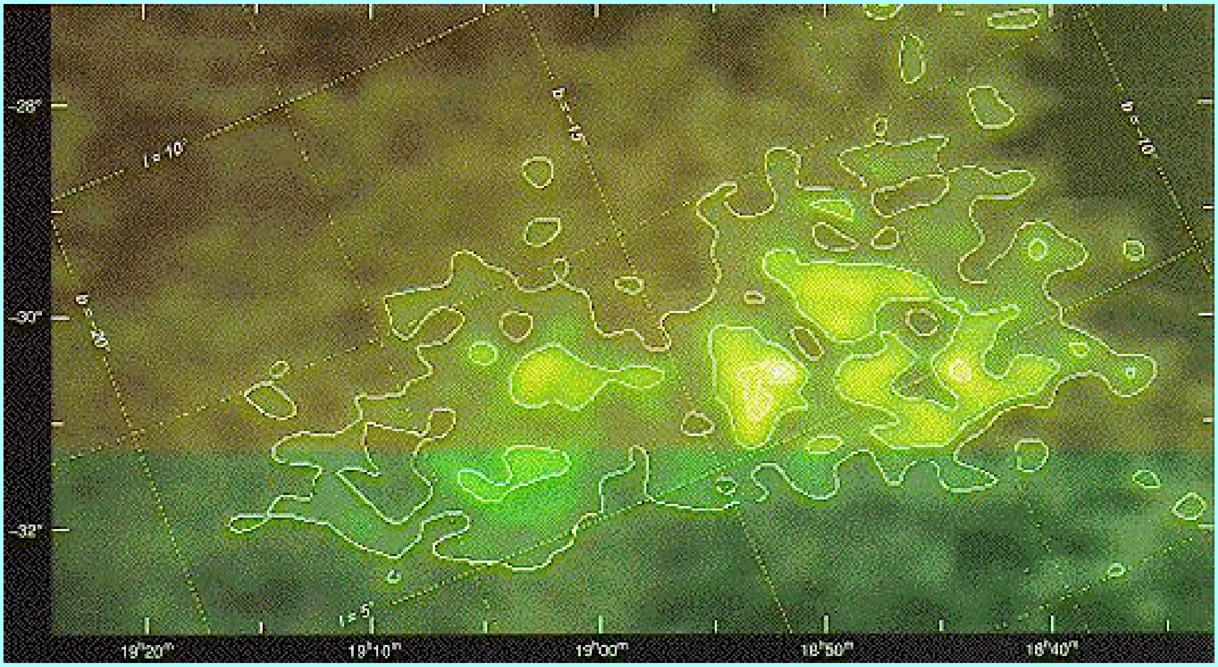
The Sagittarius Dwarf.

In the course of a study of the kinematics of a sample of stars in the Galactic bulge* a curious feature in the distribution was found.



Tracing it accross the sky mapped out the Sagittarius Dwarf.

*Ibata, Gilmore & Irwin, Mon.Not.R.A.S. 277, 781 (1995)

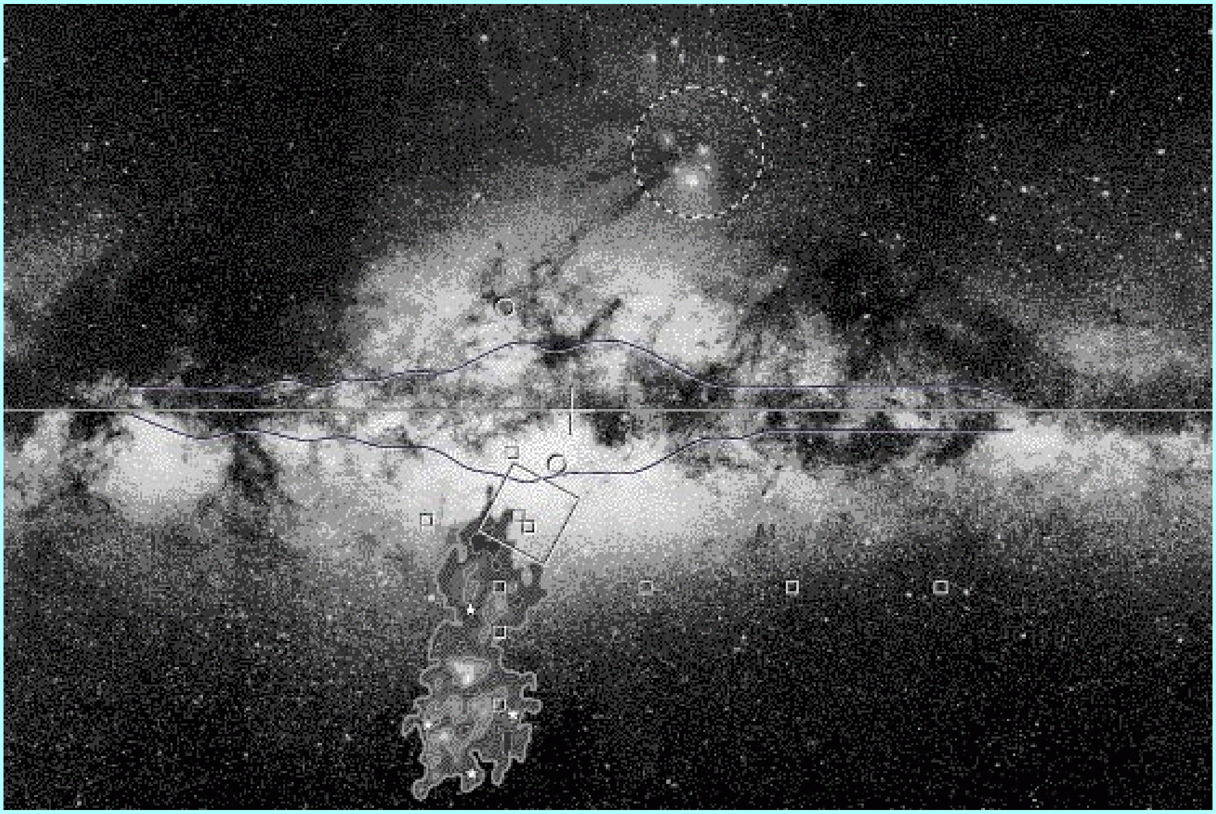


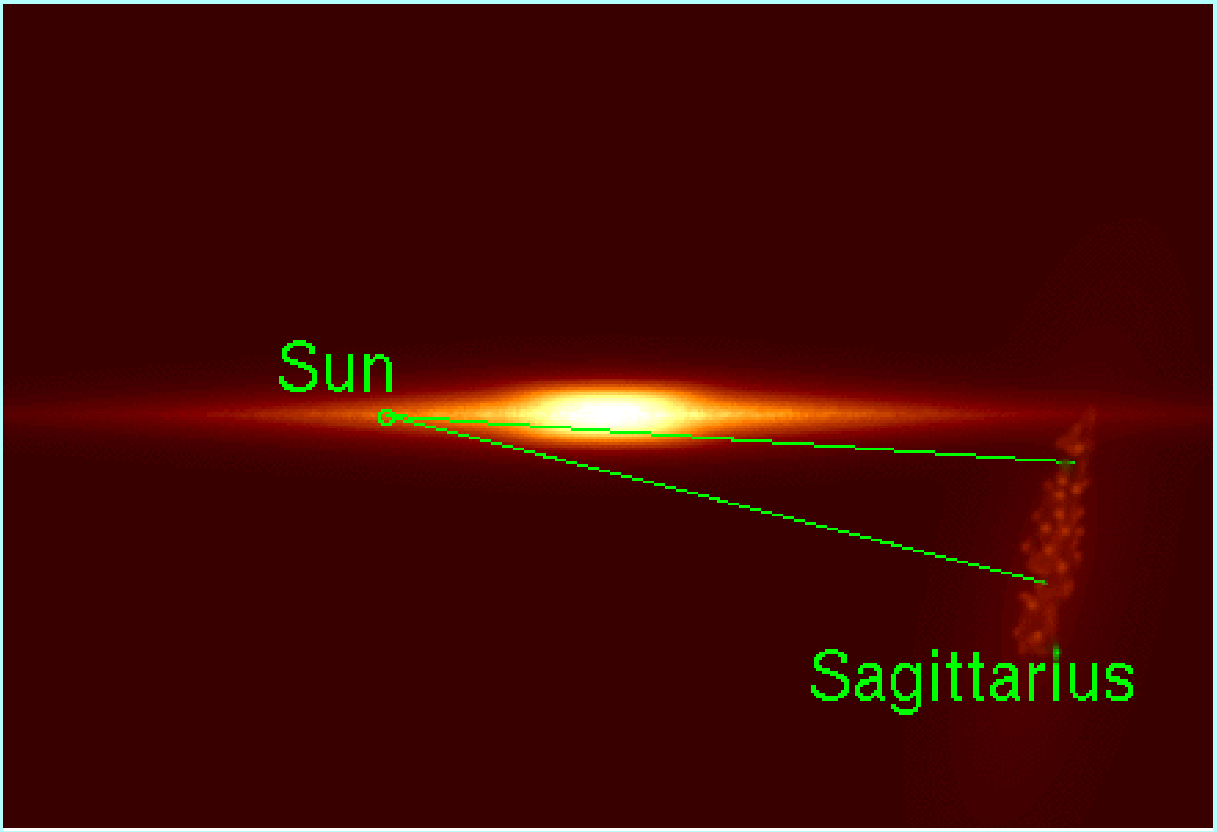
The distance is about 24 kpc and it is comparable in size and luminosity to a large dwarf spheroidal galaxy.

It apparently is approaching the disk of the Galaxy.

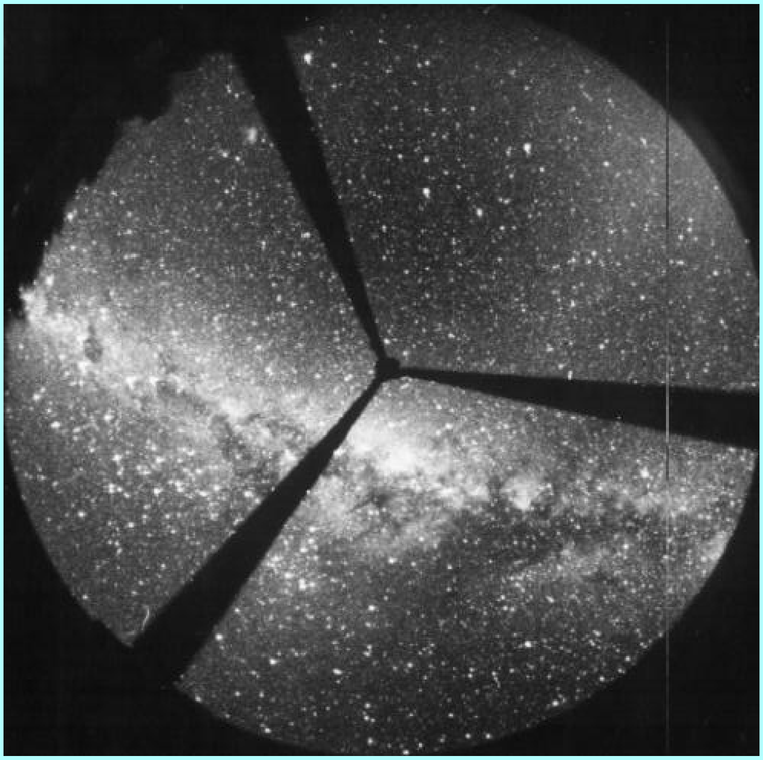
Detailed follow-up studies* indicate that it is on an orbit with a period of about 1 Gyr and it must have gone through the disk a few times before.

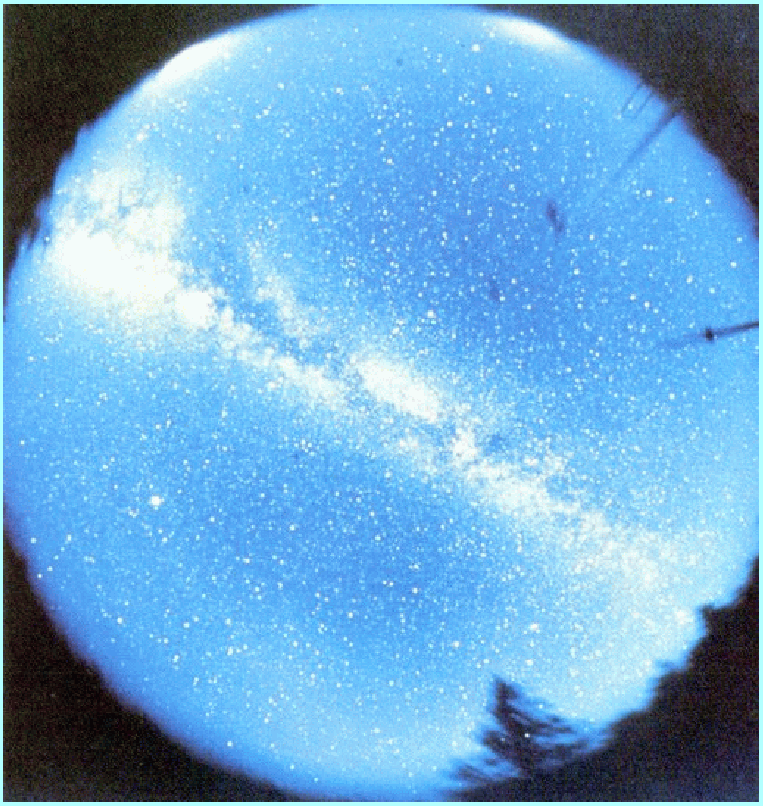
*Ibata, Wyse, Gilmore, Irwin & Suntzeff, A.J. 113, 634 (1997)




Sun
Sagittarius

The Hubble type of the Galaxy.





Various ways have been devised in the past:

• From the scalelength of the HII-regions: Sb or Sc

• From the disk color index $(B-V) = 0.85 \pm 0.15$: Sb?

• The HI-surface density – surface brightness ratio at $3h$; the log of that value is -0.5 ± 0.3. Compare with the Wevers sample: Sb

• The bulge-to-disk ratio: Sb or Sc

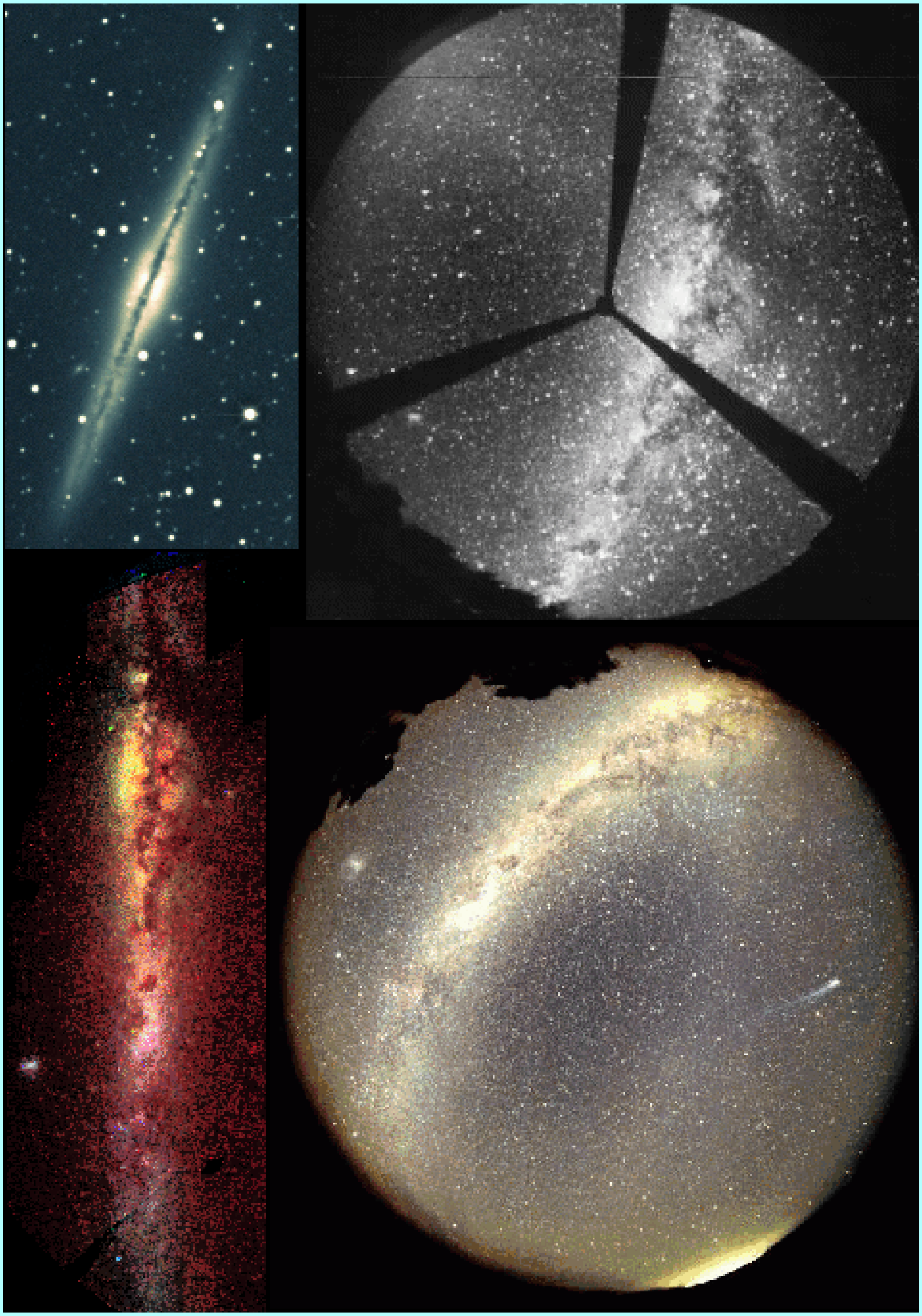
• The CO-distribution: Sb

• The similarity to NGC 891: Sb

In the Virgo 6°-core:

	$h < 4$ kpc	$h > 4$ kpc
I, I-II	0	6
II	20	5

Most likely Hubble type: SbI-II



Galaxies similar to our own.

Criteria: • Disk scalelength h = 4 - 6 kpc

• Disk color $(B - V)$ = 0.6 - 0.8

• Bulge luminosity / total luminosity L/L_{tot} = 0.10 -0.20

• Bulge effective radius R_{e} = 2 - 3 kpc

• Rotation velocity V_{rot} = 210 - 230 km/s

• HI-mass $M_{\text{HI}} = (4 - 10) \times 10^9 M_\odot$

Closest in these parameters* (for NGC 891 disk luminosity parameters refer only to the old disk).

	The Galaxy	NGC 891	NGC 5033
Type	SbI-II	Sb	SbcI-II
Bulge R_{e} (kpc)	2.7	2.3	2.9
Bulge b/a	$\sim$ 0.7	0.7	?
$L_{\text{bulge}}(L_\odot)$	2×10^9	1.5×10^9	4×10^9
Disk $\mu_{0,\text{B}}$	22.1	22.9	22.0
Disk h (kpc)	5	4.9	5
$L_{\text{disk}}(L_\odot)$	1.7×10^{10}	6.9×10^9	1.7×10^{10}
Disk $(B - V)$	0.8	0.9	0.6
Disk R_{max} (kpc)	20 - 25	21	22
$L_{\text{bulge}}/L_{\text{tot}}$	0.12	0.07	0.19
V_{rot} (km s^{-1}	220	225	215
$M_{\text{HI}}(M_\odot)$	8×10^9	4×10^9	4×10^9

*using H = 75 km s^{-1} Mpc^{-1}