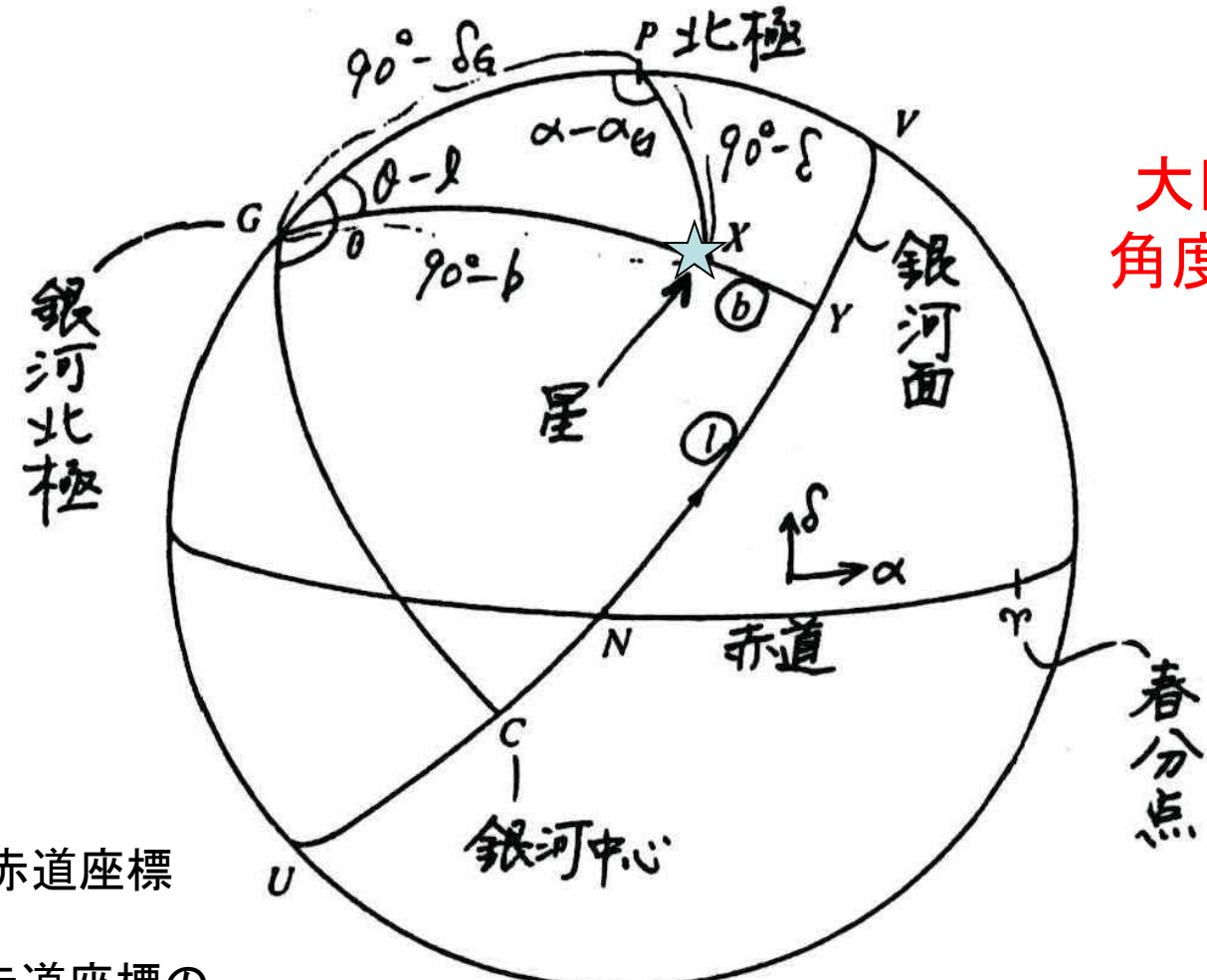


Chapter 1. 銀河宇宙物理の基礎



大円上で  
角度を取る

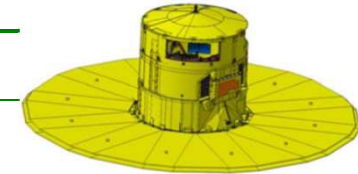
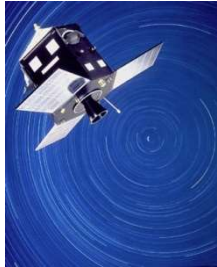
- ・銀河北極の赤道座標  $(\alpha_G, \delta_G)$
- ・銀河中心と赤道座標の北極のなす角  $\theta$

$$(\alpha, \delta) \rightarrow (l, b)$$

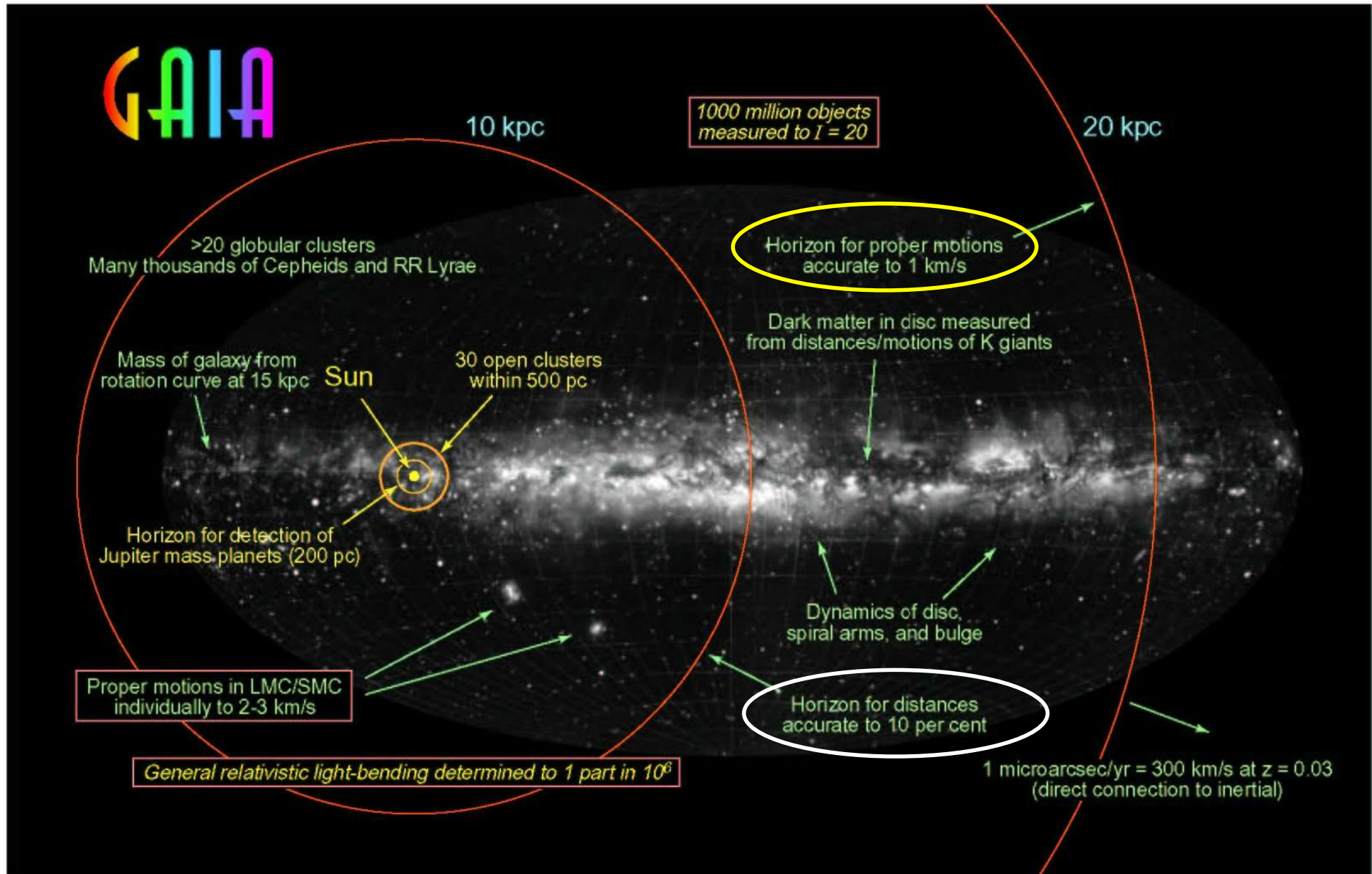
赤道座標

銀河座標

# Astrometry Satellites



	1989~1993	2013~2021
	<b>Hipparcos</b>	<b>Gaia</b>
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	6 mag
Number of objects	120,000	26 million to V = 15 250 million to V = 18 1000 million to V = 20
Effective distance	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1.000.000
Accuracy	1 milliarcsec	7 $\mu$ arcsec at V = 10 10 – 25 $\mu$ arcsec at V = 15 300 $\mu$ arcsec at V = 20
Photometry	2-colour (B and V)	Low-res. spectra to V = 20
Radial velocity	None	15 km s <sup>-1</sup> to V = 17
Observing	Pre-selected	Complete and unbiased



Gaia:  $10\mu\text{as} = 10\%$  error @distance 10kpc,  $10\mu\text{as/yr} = 1\text{km/s}$  @20kpc  
 Hipparcos:  $1\text{mas} = 10\%$  error @distance 100pc,  $1\text{mas/yr} = 5\text{km/s}$  @ 1kpc

# Photometric Systems

M. Bessel 2005 ARAA, 43, 293

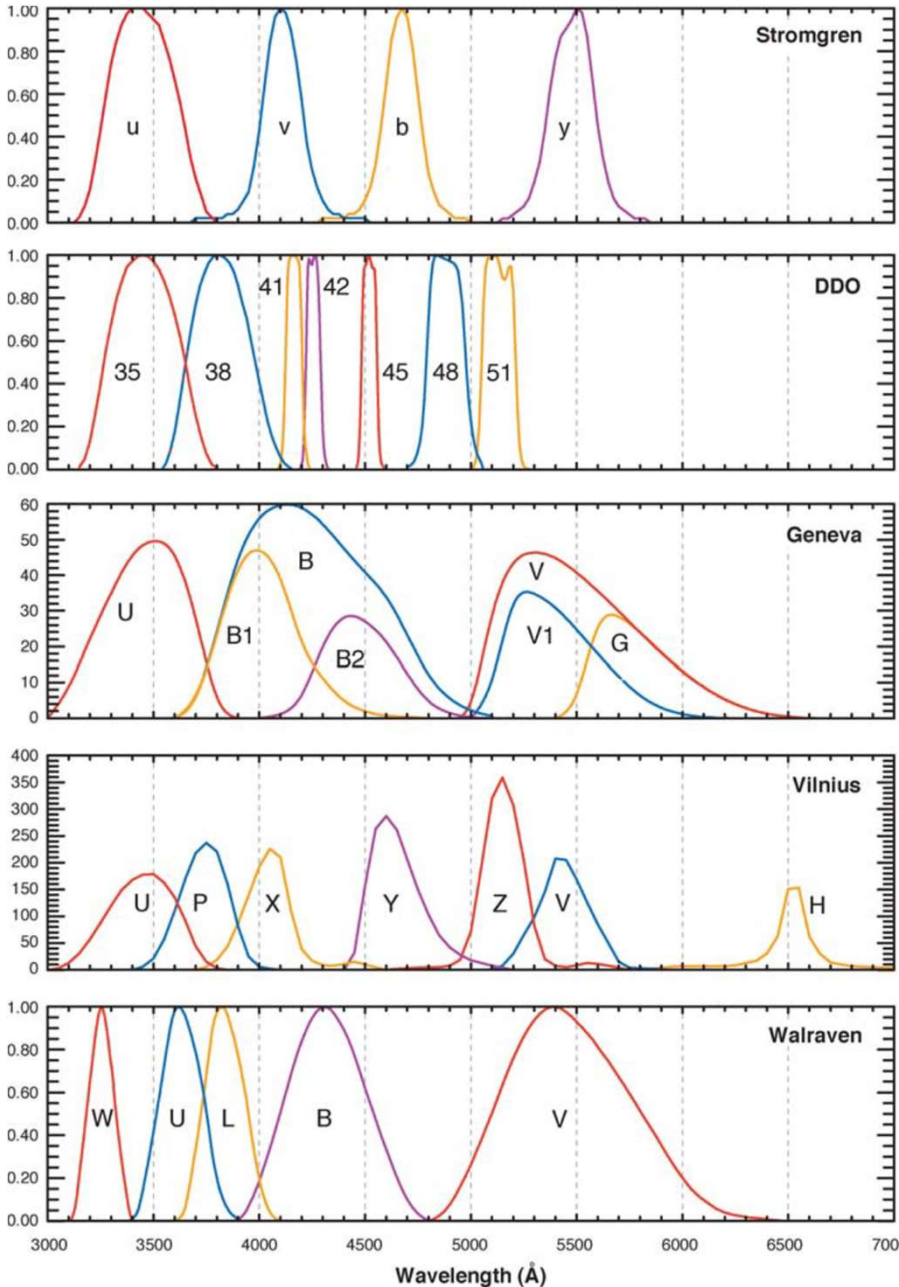
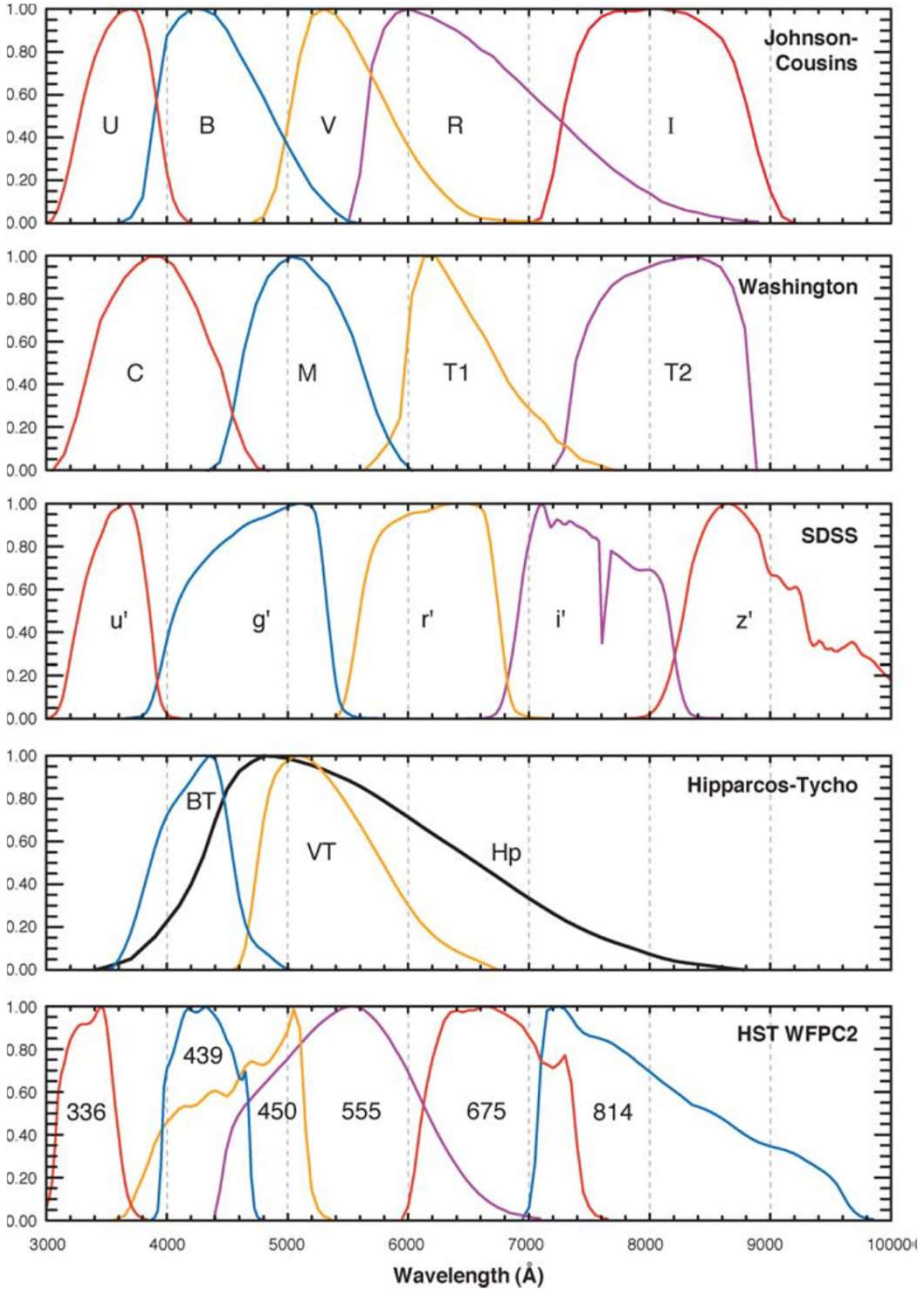
**TABLE 1** Wavelengths ( $\text{\AA}$ ) and widths ( $\text{\AA}$ ) of broad-band systems

<b>UBVRI</b>			<b>Washington</b>			<b>SDSS</b>			<b>Hipparcos</b>			<b>WFPC2</b>		
$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$	
<i>U</i>	3663	650	<i>C</i>	3982	1070	<i>u'</i>	3596	570	<i>H<sub>P</sub></i>	5170	2300	F336	3448	340
<i>B</i>	4361	890	<i>M</i>	5075	970	<i>g'</i>	4639	1280	<i>B<sub>T</sub></i>	4217	670	F439	4300	720
<i>V</i>	5448	840	<i>T<sub>1</sub></i>	6389	770	<i>r'</i>	6122	1150	<i>V<sub>T</sub></i>	5272	1000	F555	5323	1550
<i>R</i>	6407	1580	<i>T<sub>2</sub></i>	8051	1420	<i>i'</i>	7439	1230				F675	6667	1230
<i>I</i>	7980	1540				<i>z'</i>	8896	1070				F814	7872	1460

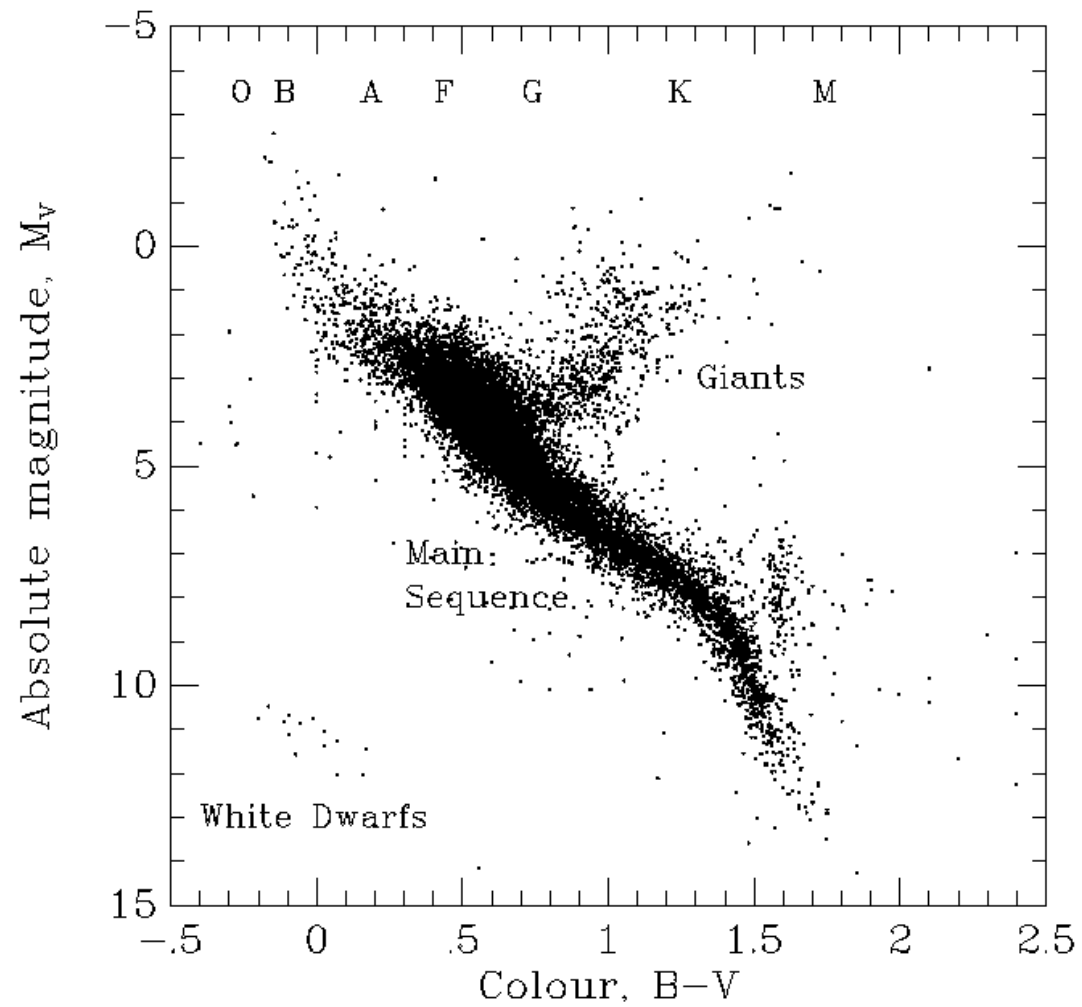
**TABLE 3** Wavelengths ( $\text{\AA}$ ) and widths ( $\text{\AA}$ ) of intermediate-band systems

<b>Strömgren</b>			<b>DDO</b>			<b>Geneva</b>			<b>Vilnius</b>			<b>Walraven</b>		
$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$		$\lambda_{\text{eff}}$	$\Delta\lambda$	
<i>u</i>	3520	314	35	3460	383	<i>U</i>	3438	170	<i>U</i>	3450	400	<i>W</i>	3255	143
<i>v</i>	4100	170	38	3815	330	<i>B</i>	4248	283	<i>P</i>	3740	260	<i>U</i>	3633	239
<i>b</i>	4688	185	41	4166	83	<i>B1</i>	4022	171	<i>X</i>	4050	220	<i>L</i>	3838	227
<i>y</i>	5480	226	42	4257	73	<i>B2</i>	4480	164	<i>Y</i>	4660	260	<i>B</i>	4325	449
$\beta_w$	4890	150	45	4517	76	<i>V</i>	5508	298	<i>Z</i>	5160	210	<i>V</i>	5467	719
$\beta_n$	4860	30	48	4886	186	<i>V1</i>	5408	202	<i>V</i>	5440	260			
			51	5132	162	<i>G</i>	5814	206	<i>S</i>	6560	200			



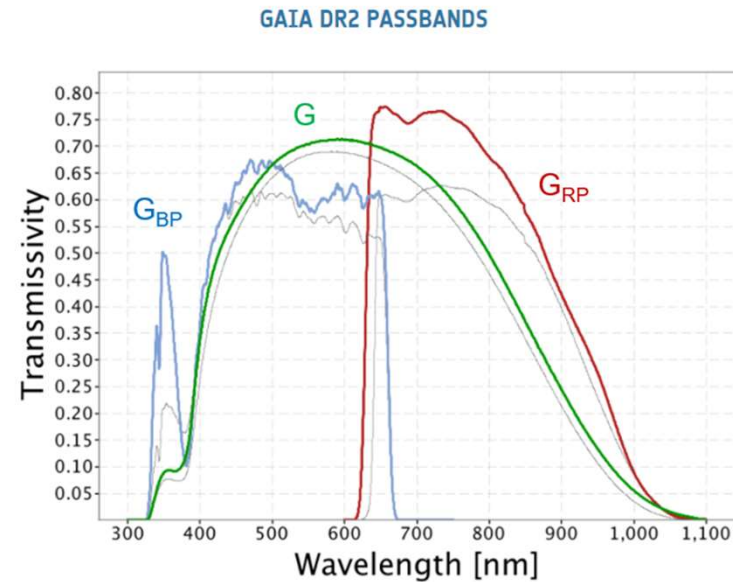
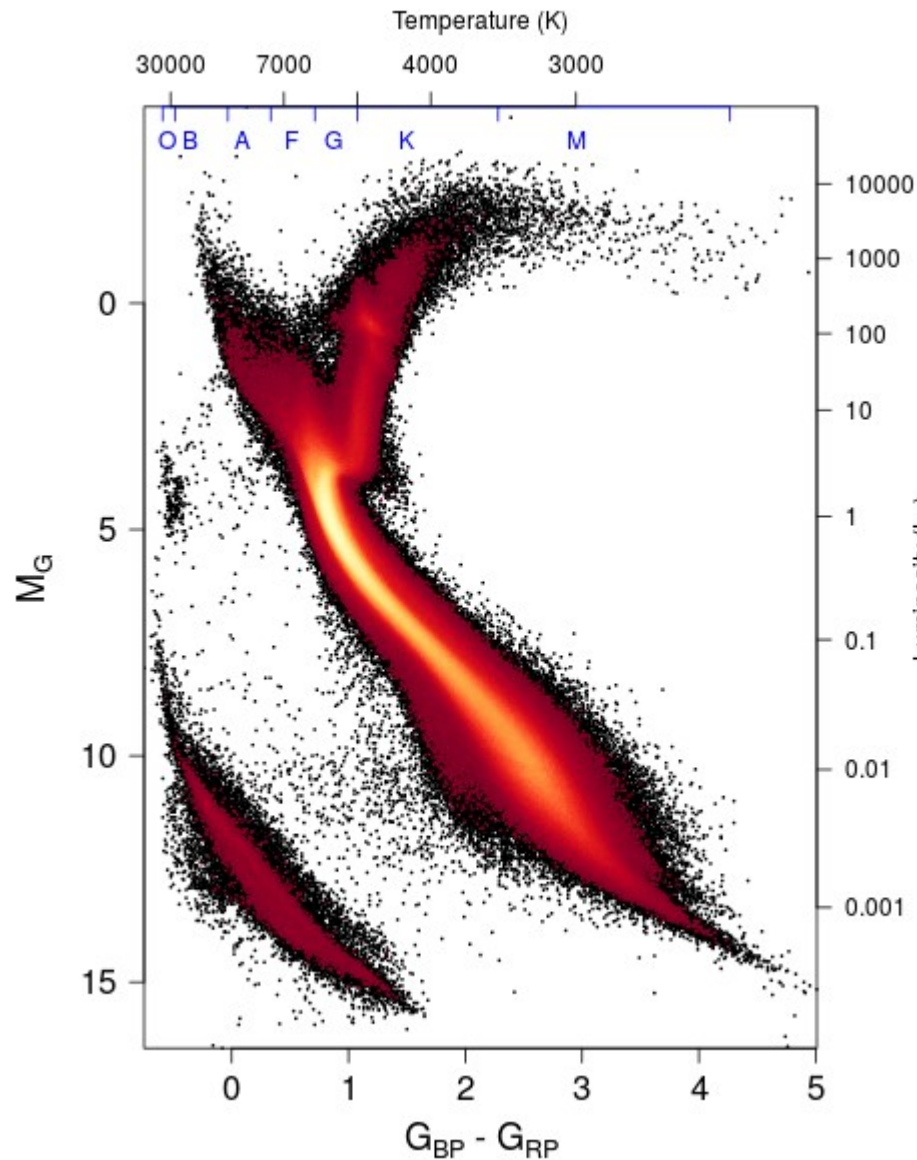


## ヒッパルコス衛星による太陽近傍星の色一等級図



三角視差の相対エラー < 10%

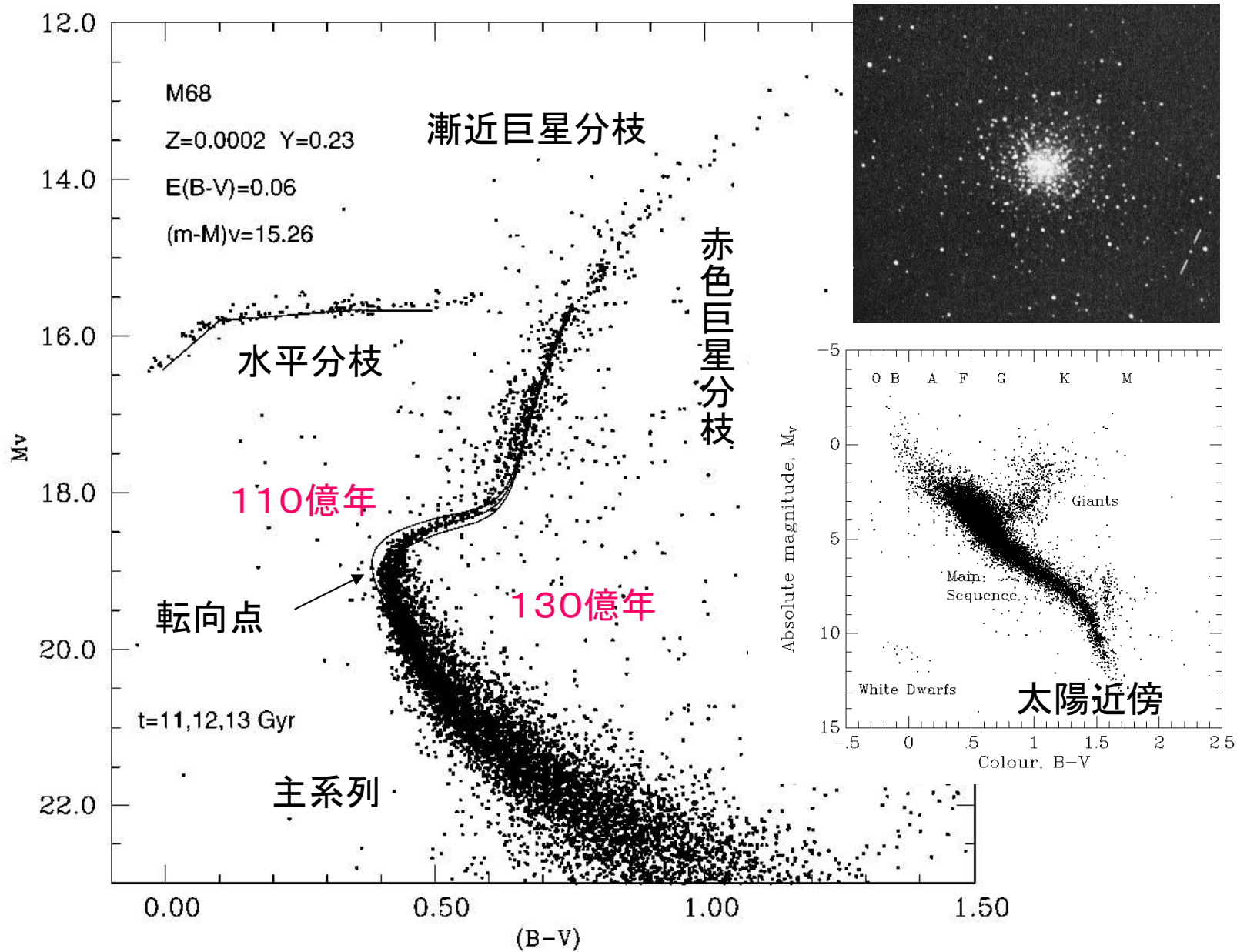
# ガイア衛星による太陽近傍星の色一等級図



The coloured lines in the figure show the revised passbands for G,  $G_{BP}$  and  $G_{RP}$  (green: G; blue:  $G_{BP}$ ; red:  $G_{RP}$ ), defining the Gaia DR2 photometric system. The thin, grey lines show the nominal, pre-launch passbands published in Jordi et al. 2010, used for Gaia DR1.

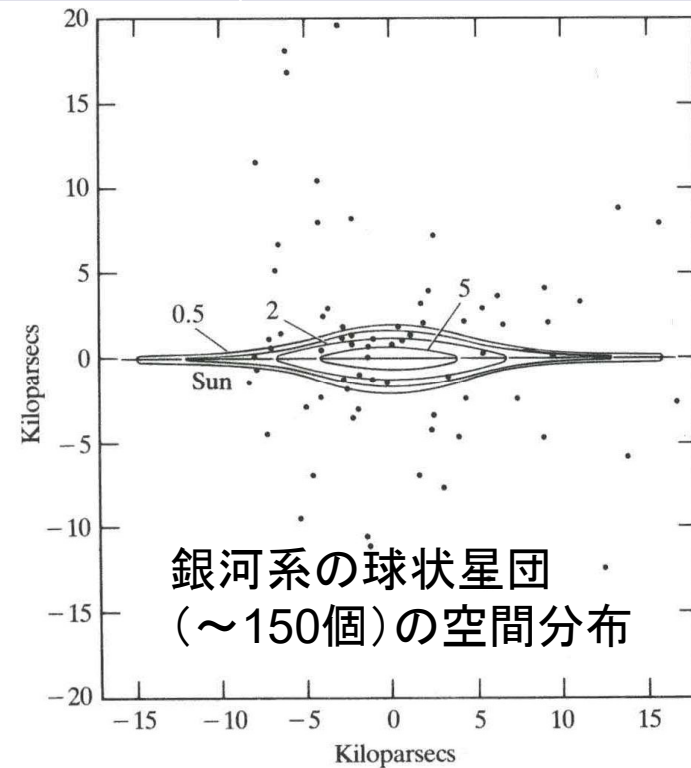
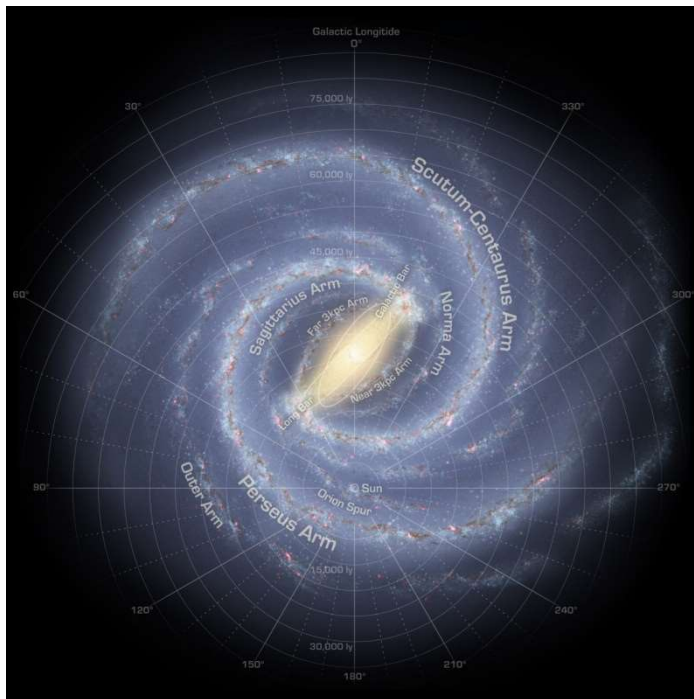
Gaia HRD of sources with low extinction ( $E(B - V) < 0.015$  mag) satisfying the filters described in Sect. 2.1 (4,276,690 stars). The colour scale represents the square root of the density of stars. Approximate temperature and luminosity equivalents for main-sequence stars are provided at the top and right axis, respectively, to guide the eye.

# ハローにある球状星団内の色一等級図

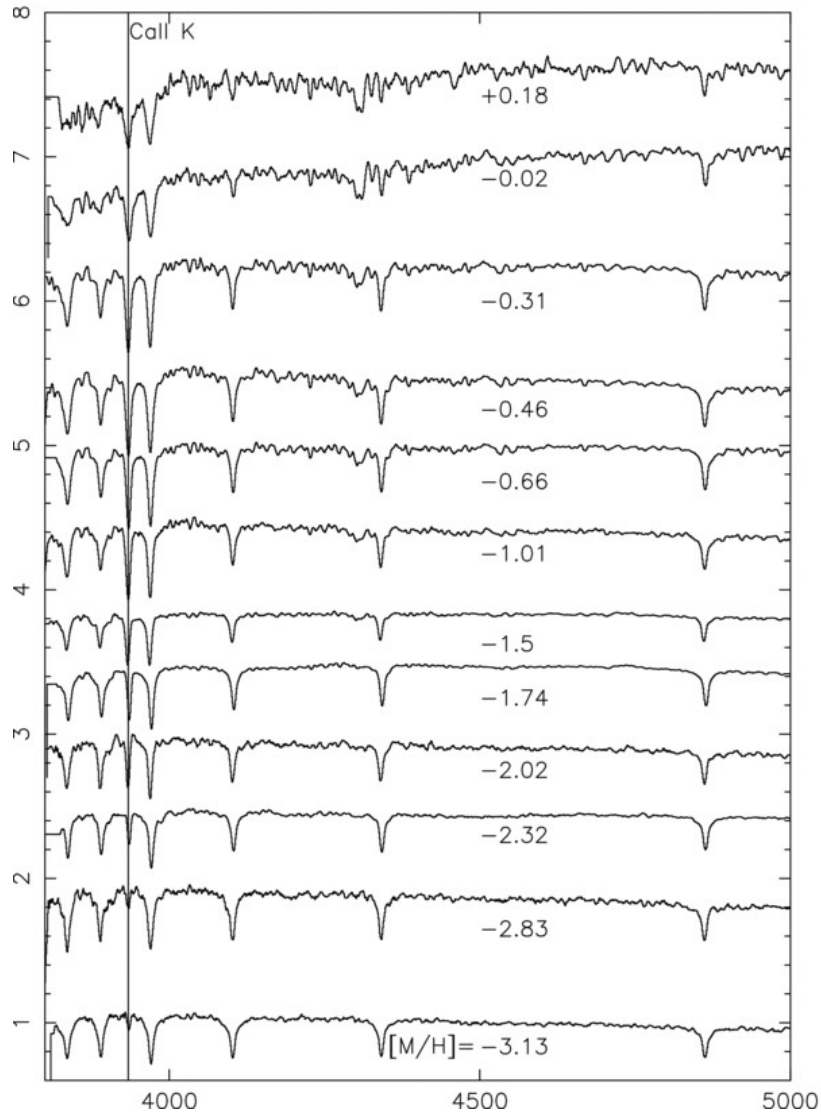




恒星の種族	年齢	空間運動	空間分布	金属量 (ヘリウムよりも重い元素量)
種族I (Population I) 渦状腕, 散開星団	若い	ほぼ円軌道	平坦	多い
種族II (Population II) バルジ, ハロー, 球状星団	古い	ランダム	球状	少ない(バルジを除く)
種族III (Population III)	古い	?	?	ゼロ

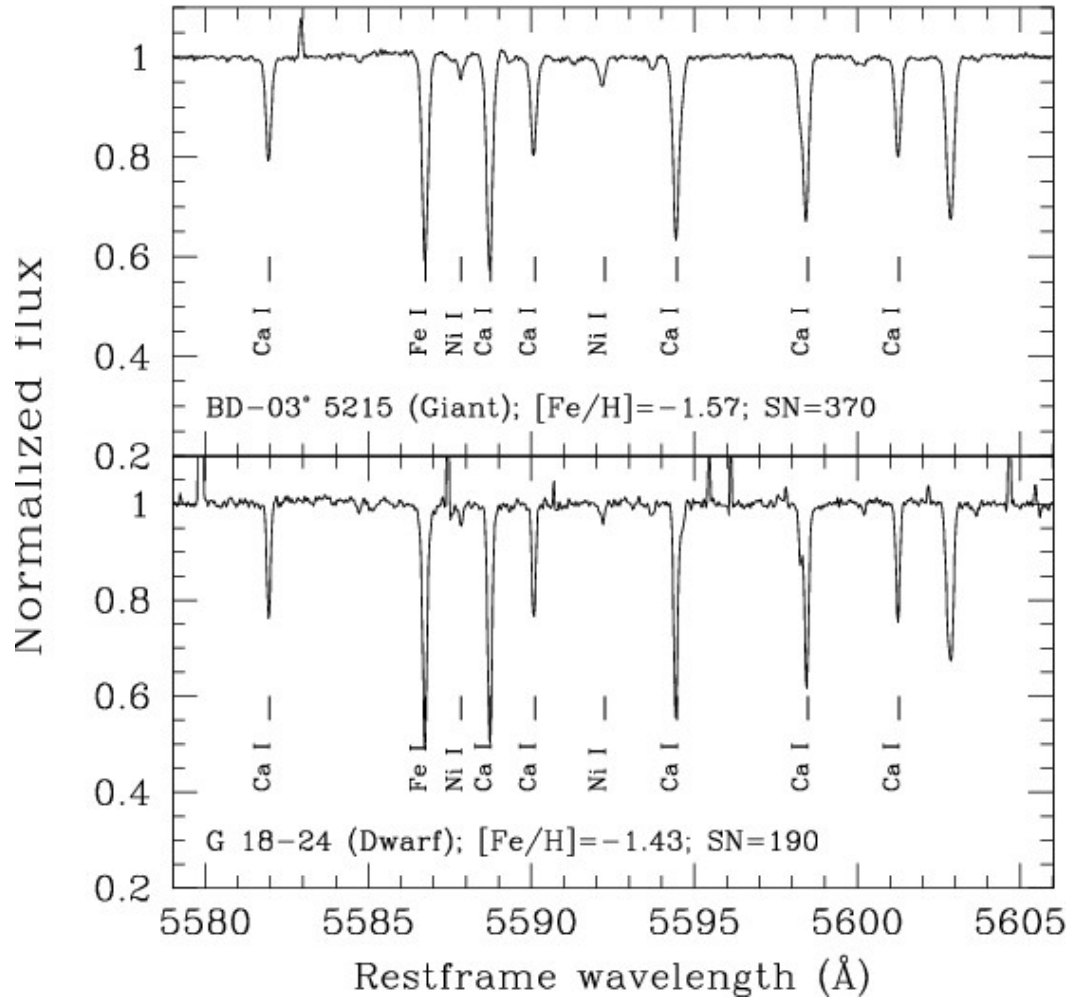


# SDSSによる銀河系F型星の 低分散スペクトル



# すばる望遠鏡による銀河系 ハロー星の高分散スペクトル

High Dispersion  
Spectrograph (HDS)



# 太陽のX, Y, Z ( $X+Y+Z=1$ )

Asplund et al. 2009, ARAA

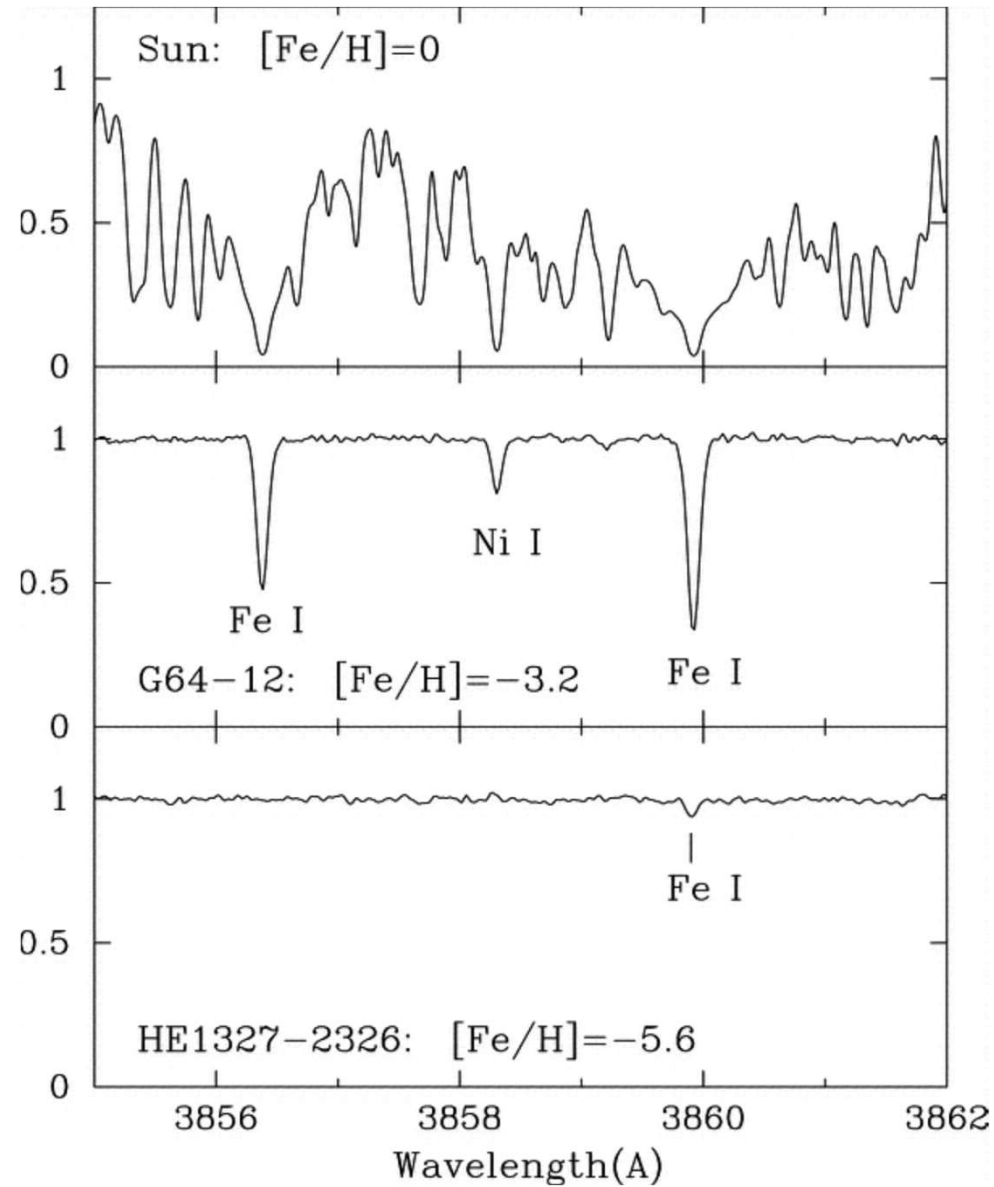
Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
<b>Present-day photosphere:</b>				
Anders & Grevesse (1989) <sup>a</sup>	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993) <sup>a</sup>	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
<b>Proto-solar:</b>				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

<sup>a</sup> The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).

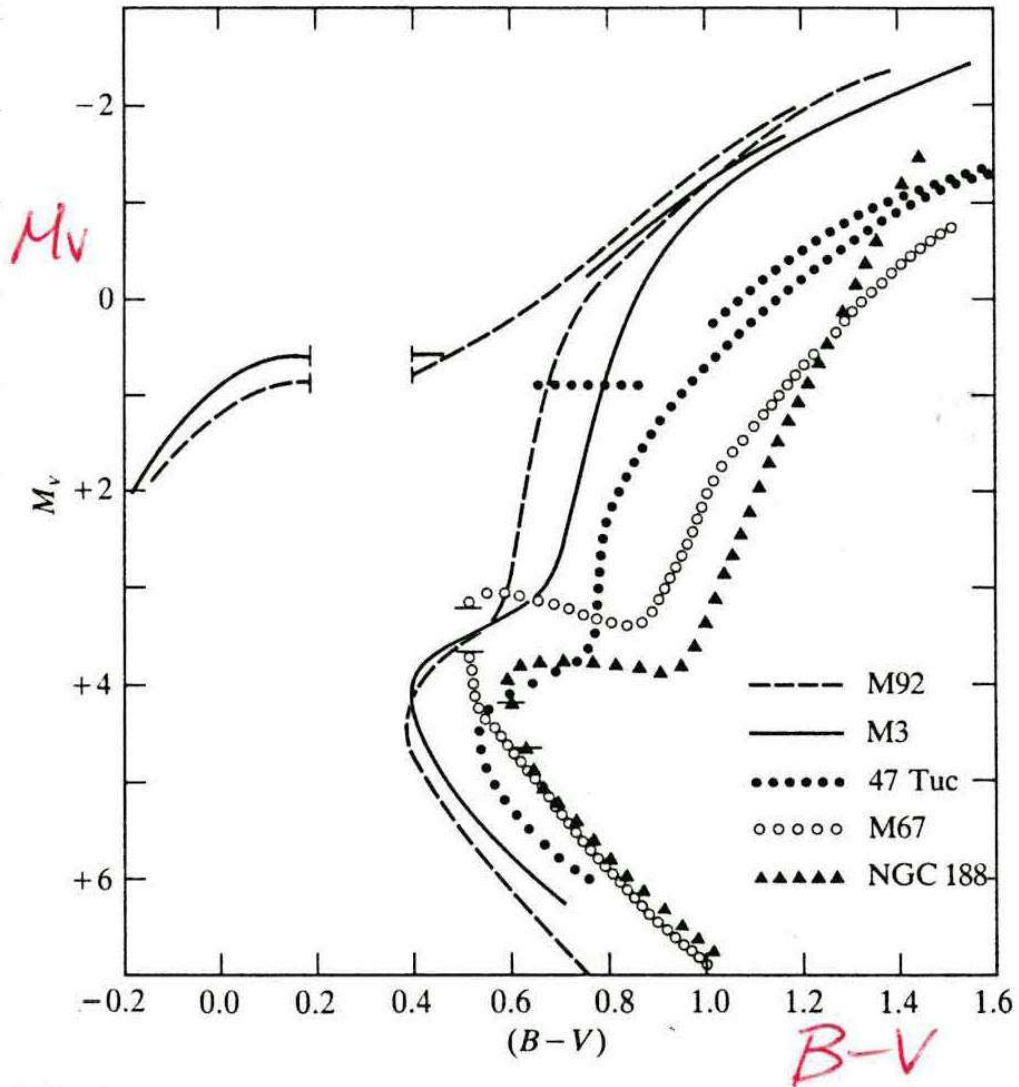
# 非常に金属量が少ない星(超金属欠乏星)

$[\text{Fe}/\text{H}] \leq -2.5$



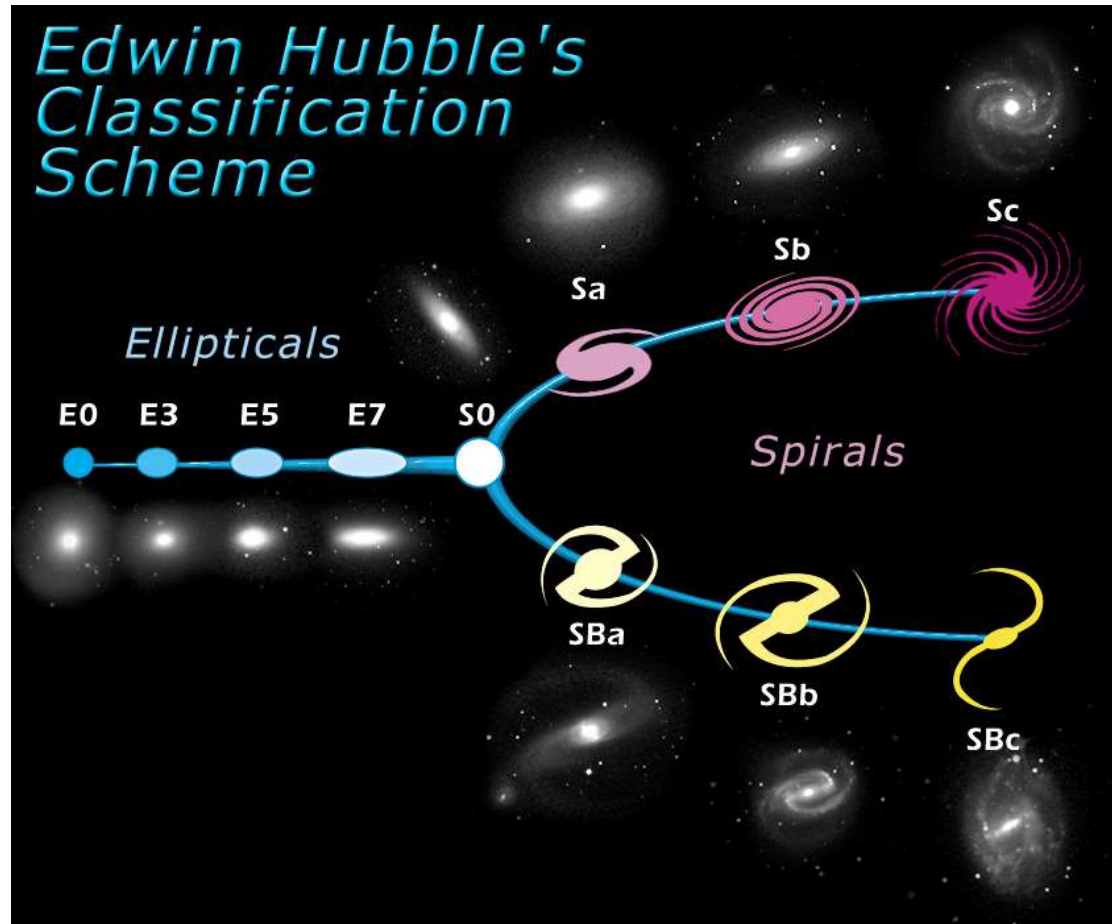


# 様々な球状星団の色一等級図



星団名	[Fe/H]
M92	-2.24
47 Tuc	-0.71
NGC188	-0.06

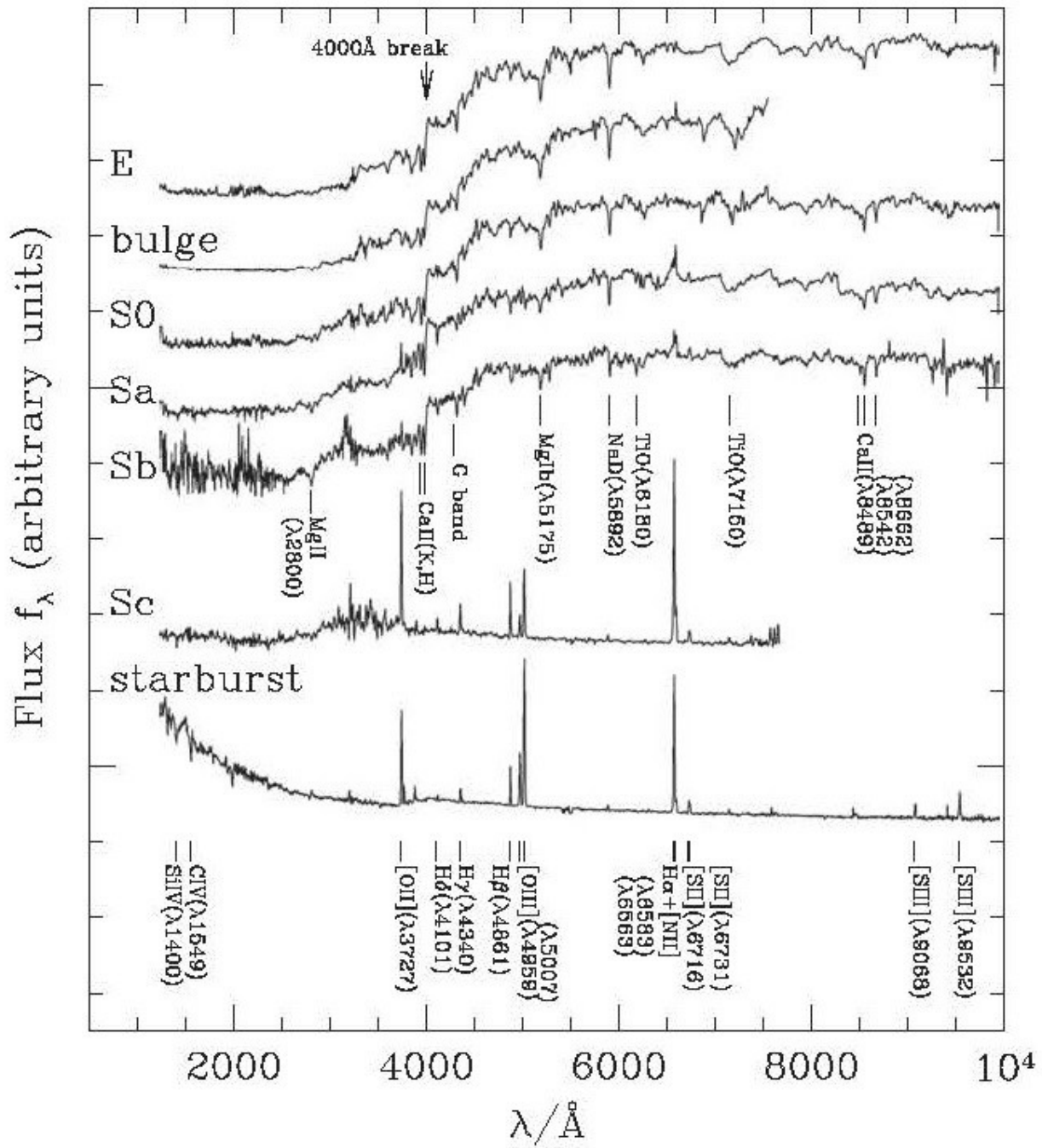
銀河の形態分類  
ハッブルの音さ図 (Tuning Fork)



早期型  
early-type

晩期型  
late-type

→  
星間ガスの量多い  
L\_bulge/L\_disk が小さい  
腕 (arm) の巻き込みがゆるい  
色が青い (B-V ↓)



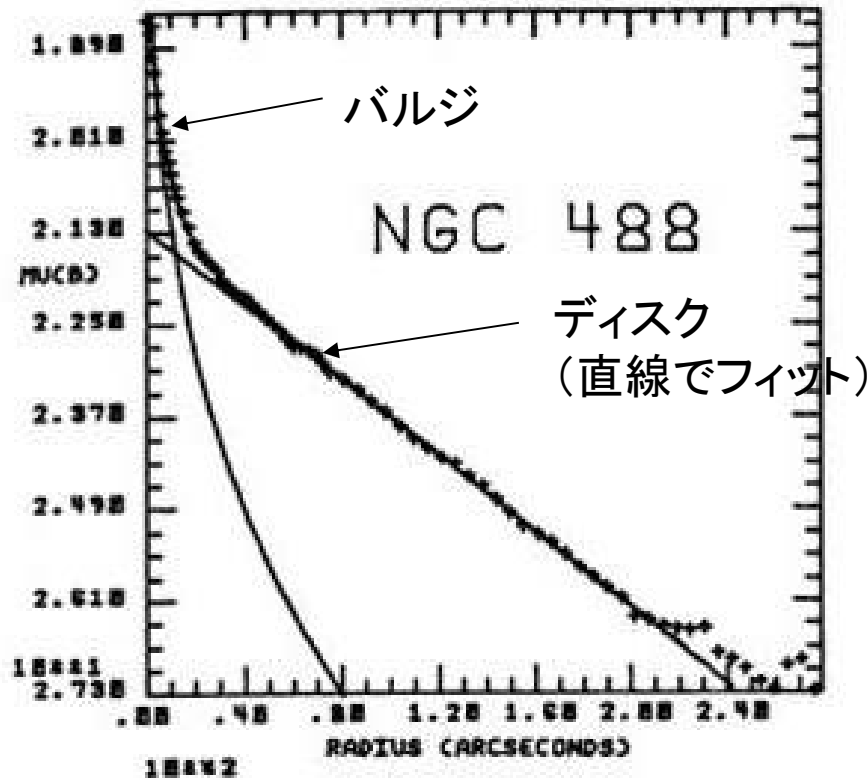
# 円盤銀河の表面輝度分布

$$I(R) = I_0 \exp(-R / R_d) \quad \text{Exponential disk}$$

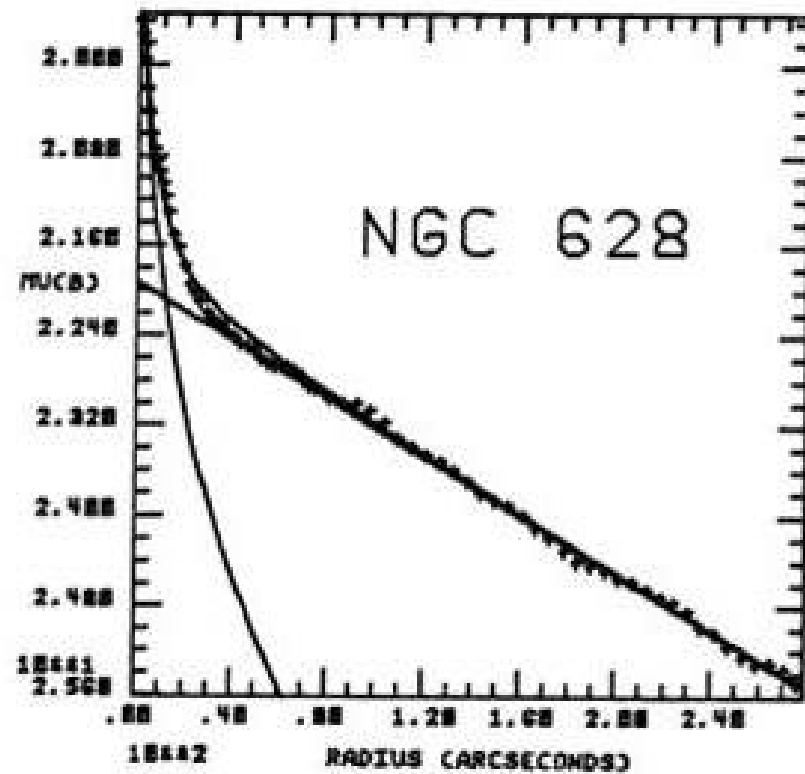
$$\rightarrow \mu \propto -\frac{5}{2} \log_{10} I \propto R / R_d$$

Boroson 1981  
ApJS, 46, 177

表面輝度  $\mu$  (等級/面積)



中心からの距離(角度秒)



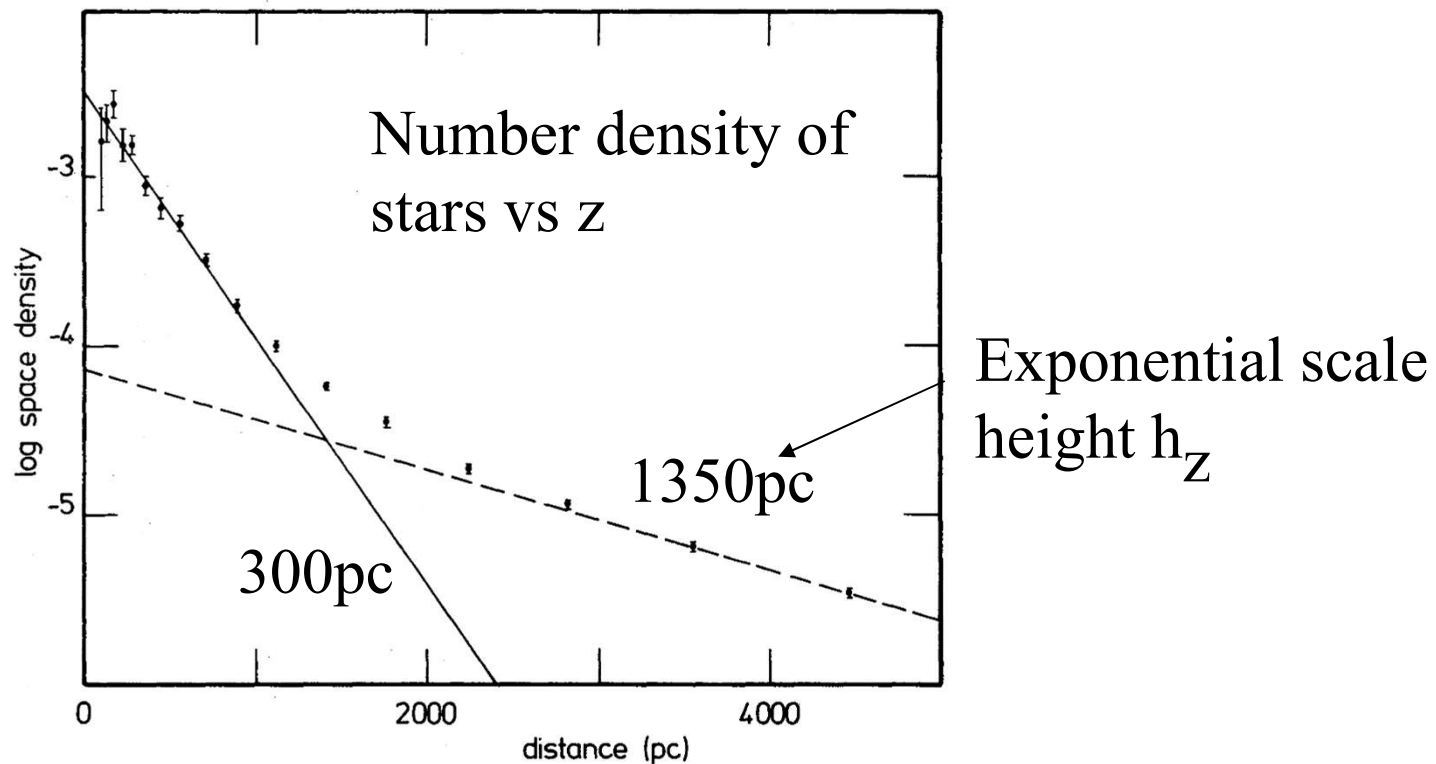
中心からの距離(角度秒)



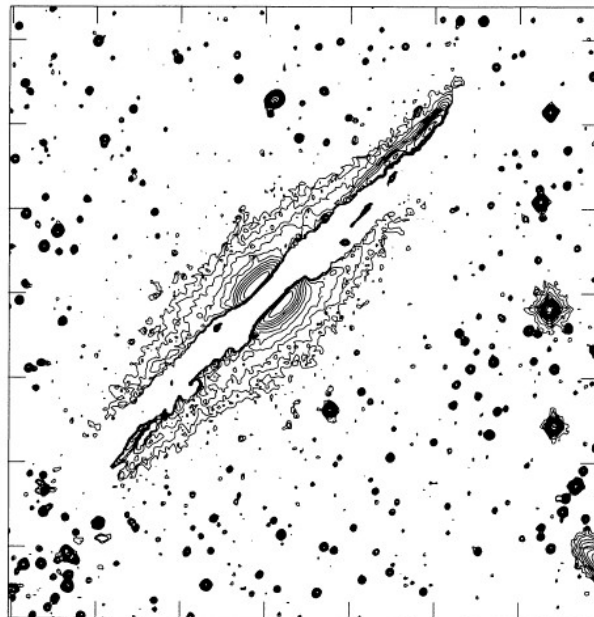
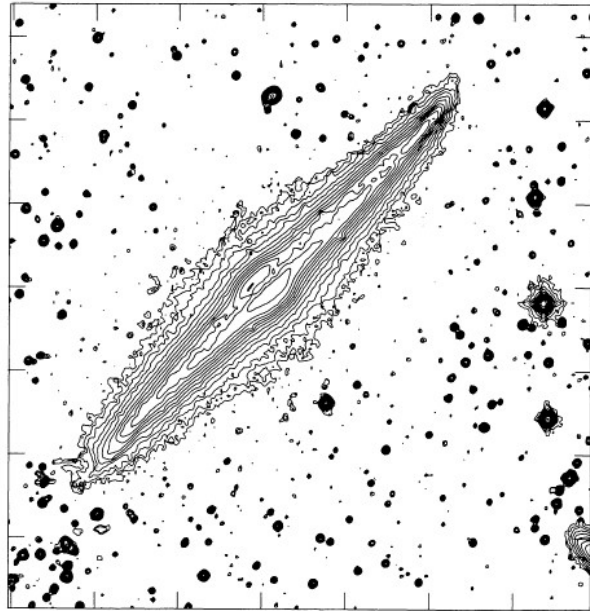
# 銀河面に垂直方向の星の密度分布

Gilmore & Reid 1983, MN, 202, 1025

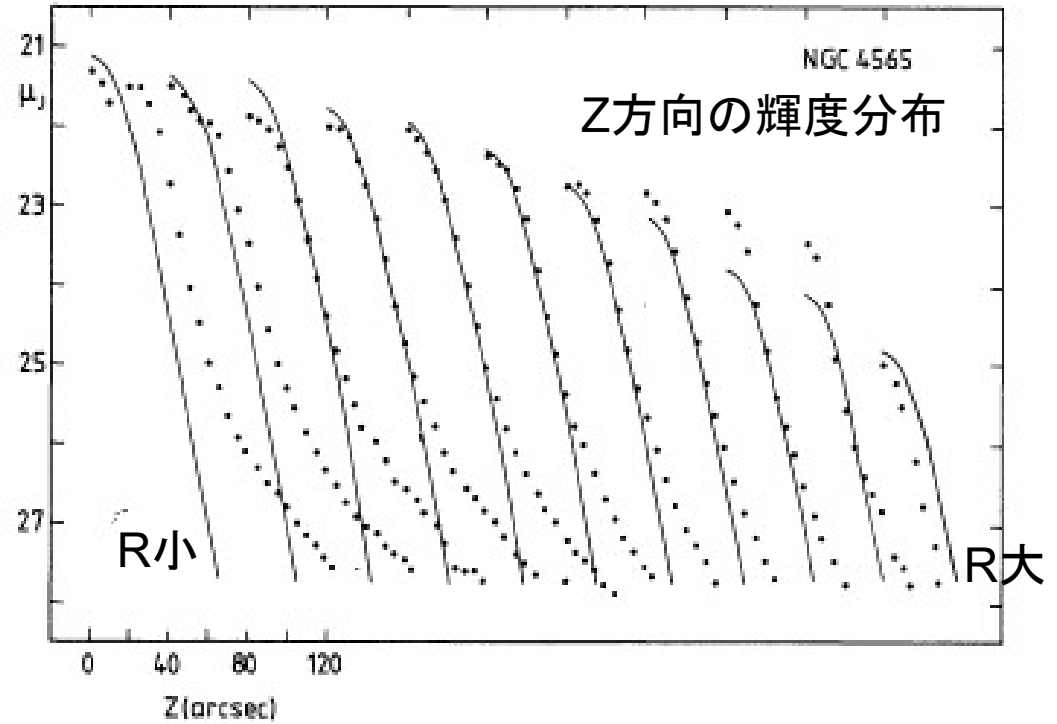
Discovery of the thick-disk component



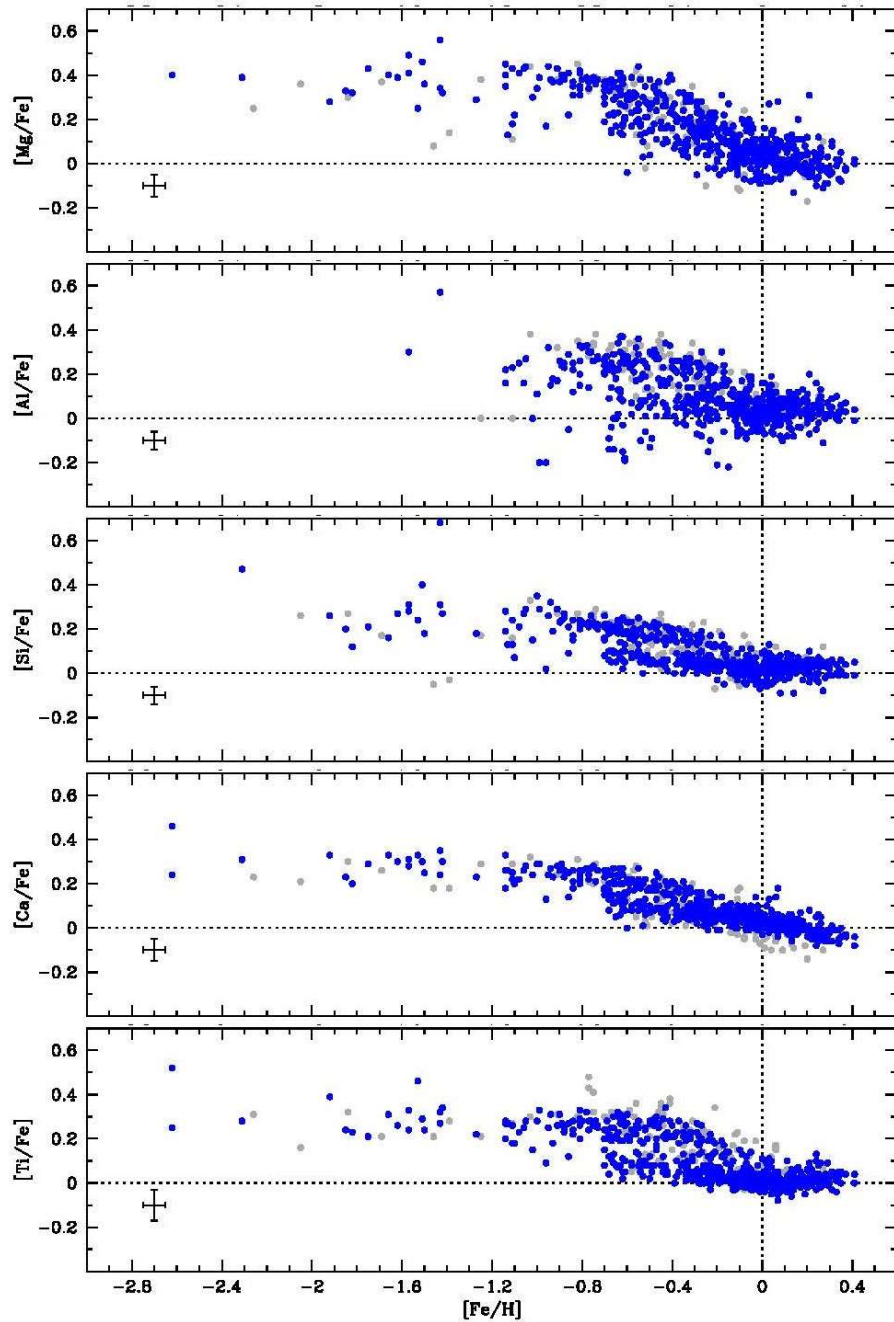
	$h_z$ (kpc)	$\sigma_R$ (km/s)	$\sigma_z$ (km/s)	$\langle V_\phi \rangle$ (km/s)
Thin disk	$\sim 0.3$	34	18	220
Thick disk	$\sim 1.0$	61	39	200



# NGC4565

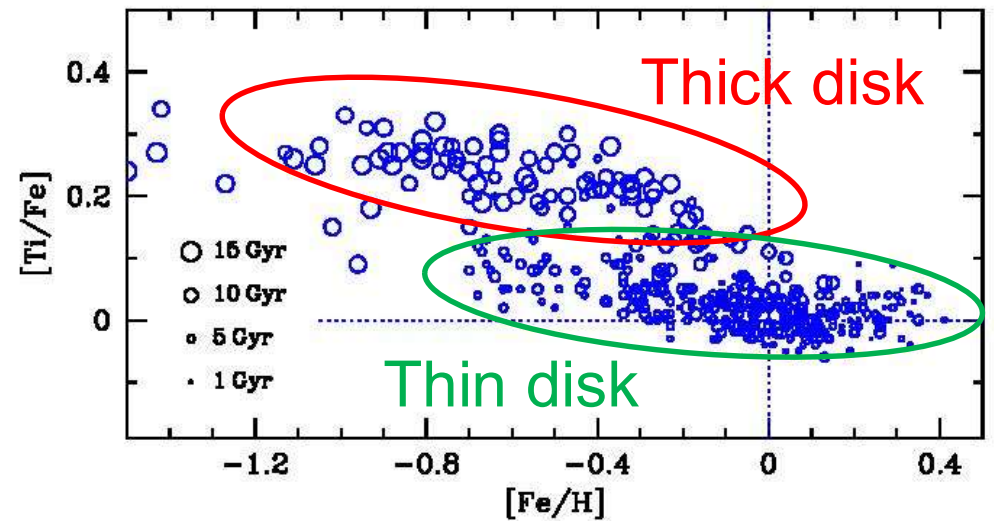


**Fig. 12.** The complete set of model and observed z-profiles after rectangle smoothing for NGC 4565. Note that from the third profiles outward the observed profiles have a linear part that is fitted in brightness and slope by the model. The shallowing of the observed profiles at fainter levels is similar to those of Burstein's "thick disks"

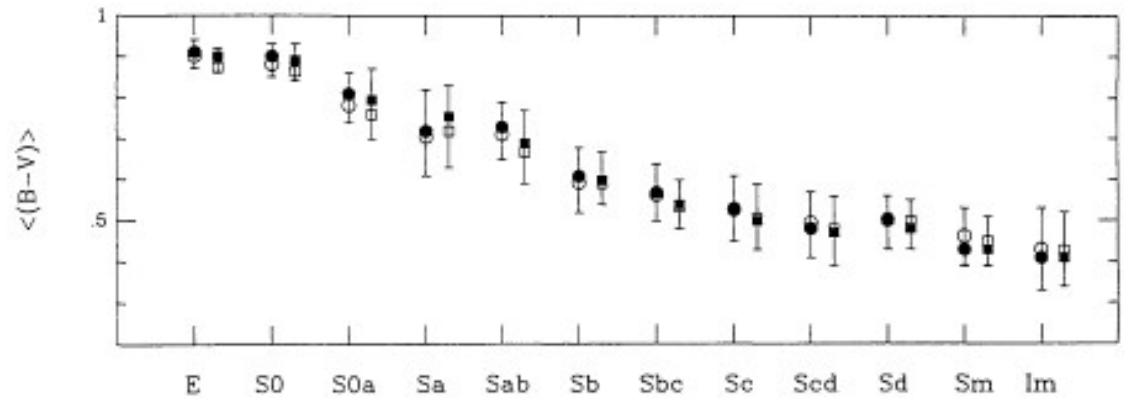


[alpha-elements/Fe]  
= Type II SNe / Type Ia SNe

Chemical clock diagram



Bensby+ 2014

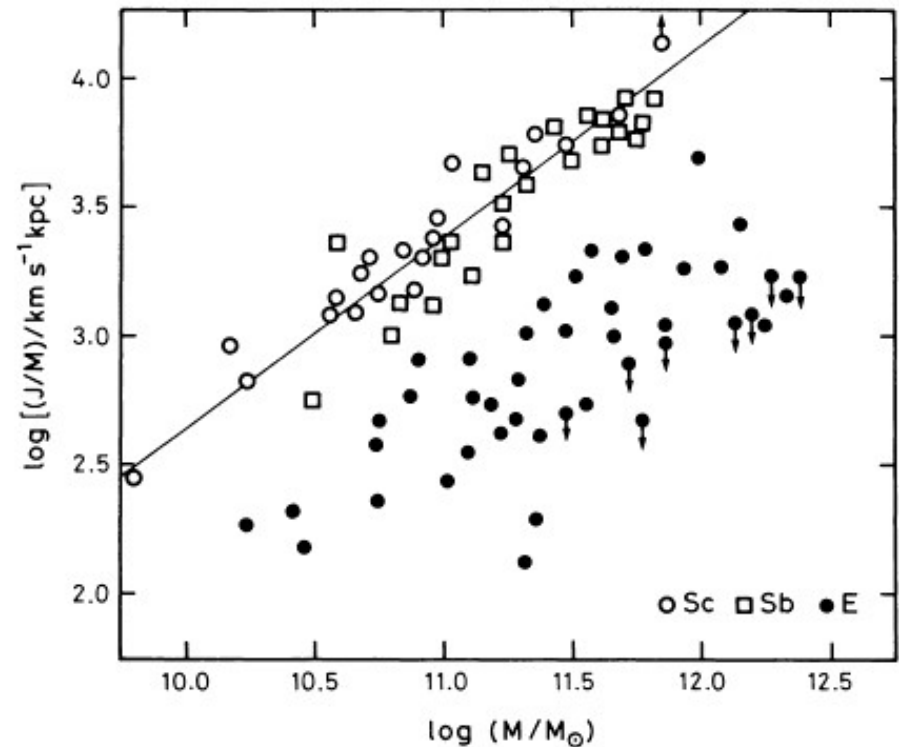


RC3, UGC  
catalogs

Roberts & Haynes,  
1994, ARAA, 32, 115

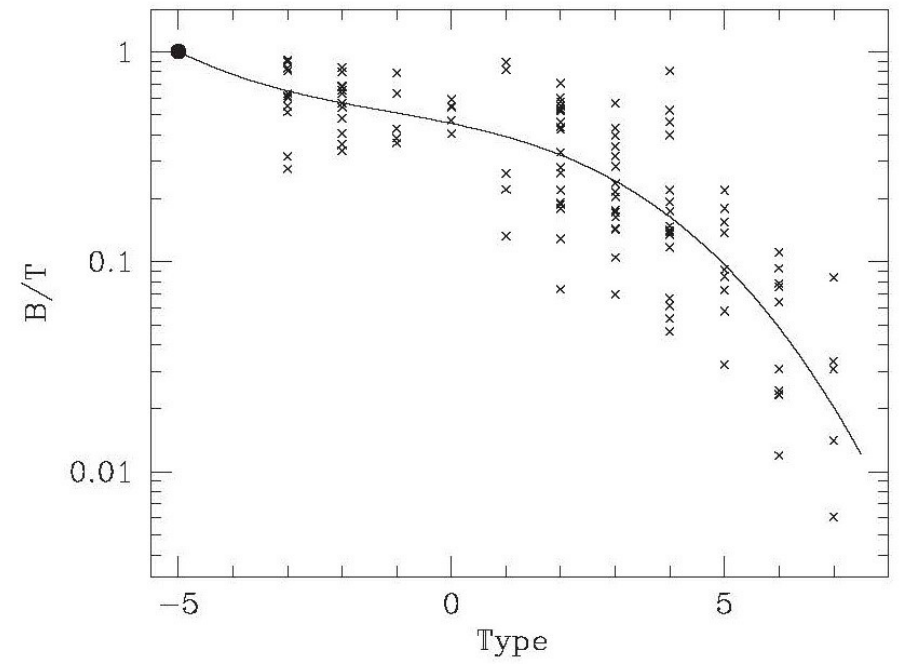
Figure 5 (B - V) color vs morphological type. (Same symbols as in Figure 2.)

単位質量あたりの角運動量 (J/M)  
vs. 光っている部分の質量 (M)



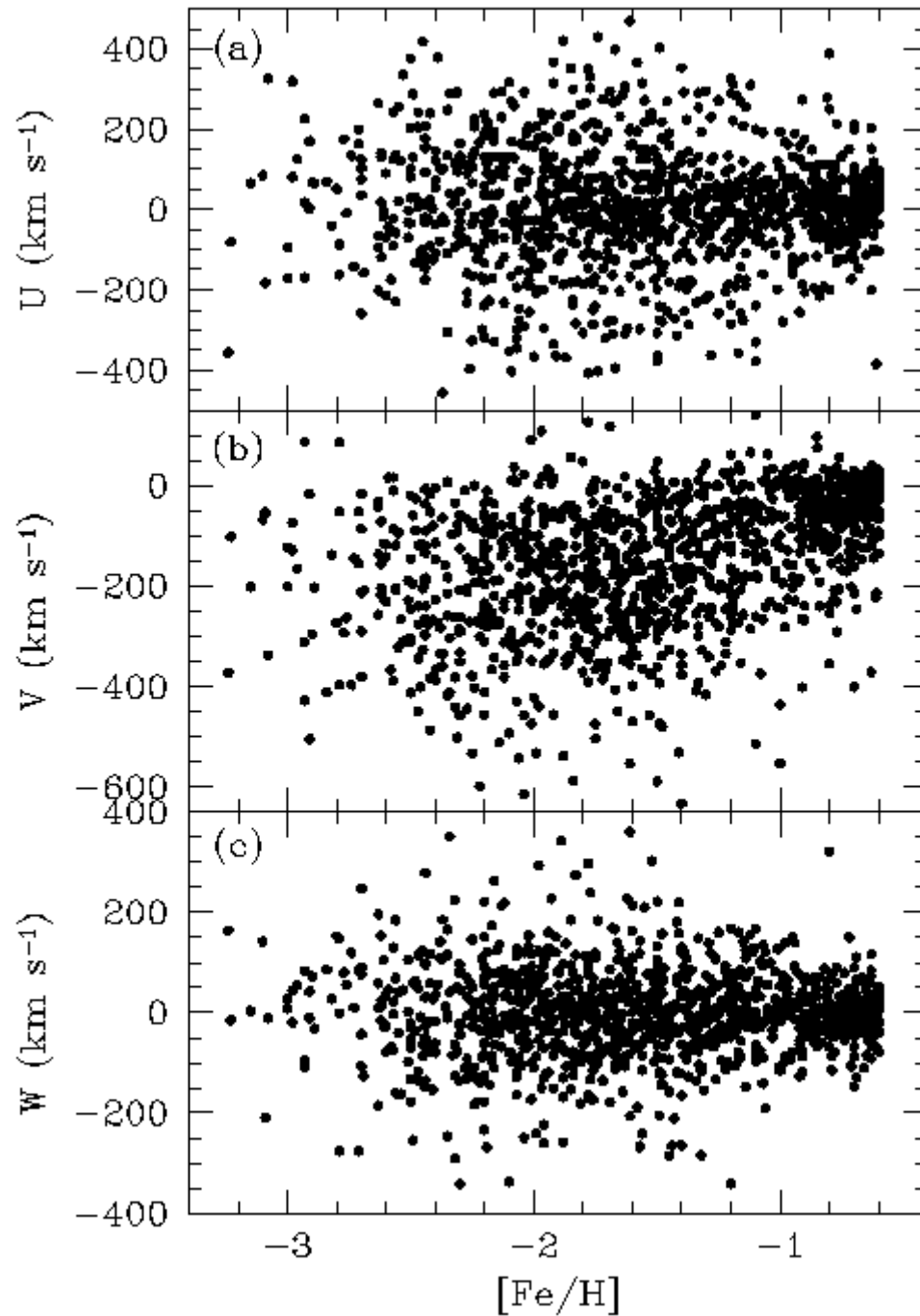
Fall 1983, in IAU 100, 391

Bulge L / Total L

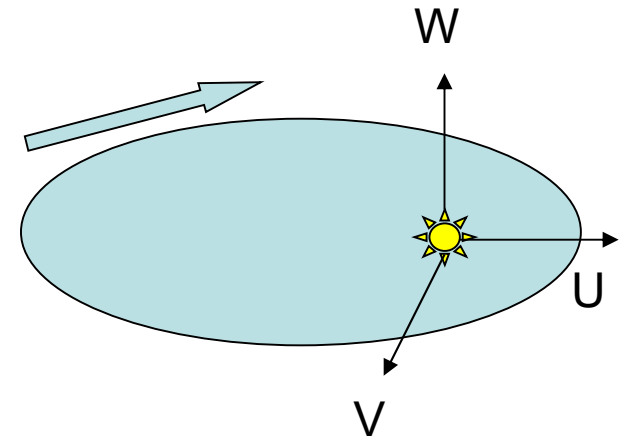


Simien & de Vaucouleurs 1986



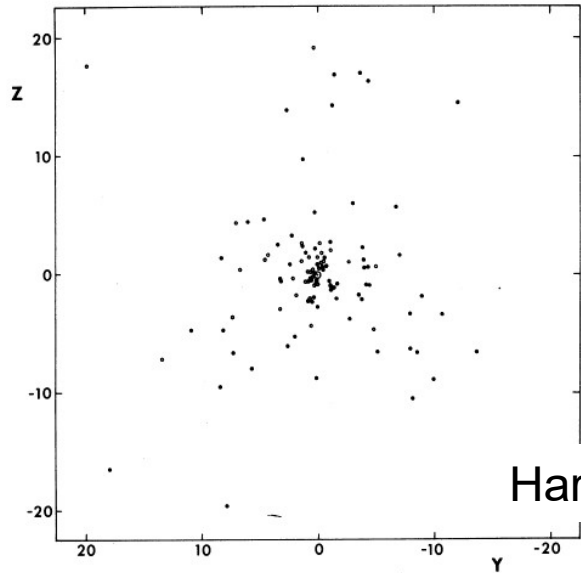


太陽近傍にある  
金属欠乏星の  
3次元速度分布

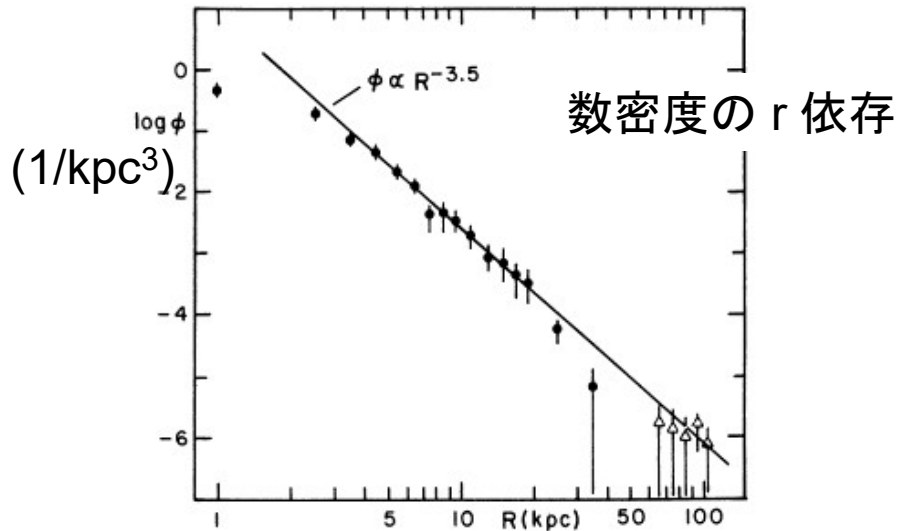


( U, V, W ) 速度成分:  
約220km/sで円運動する系  
局所静止基準  
Local Standard of Rest (LSR)  
からみた速度

# 球状星団の空間分布



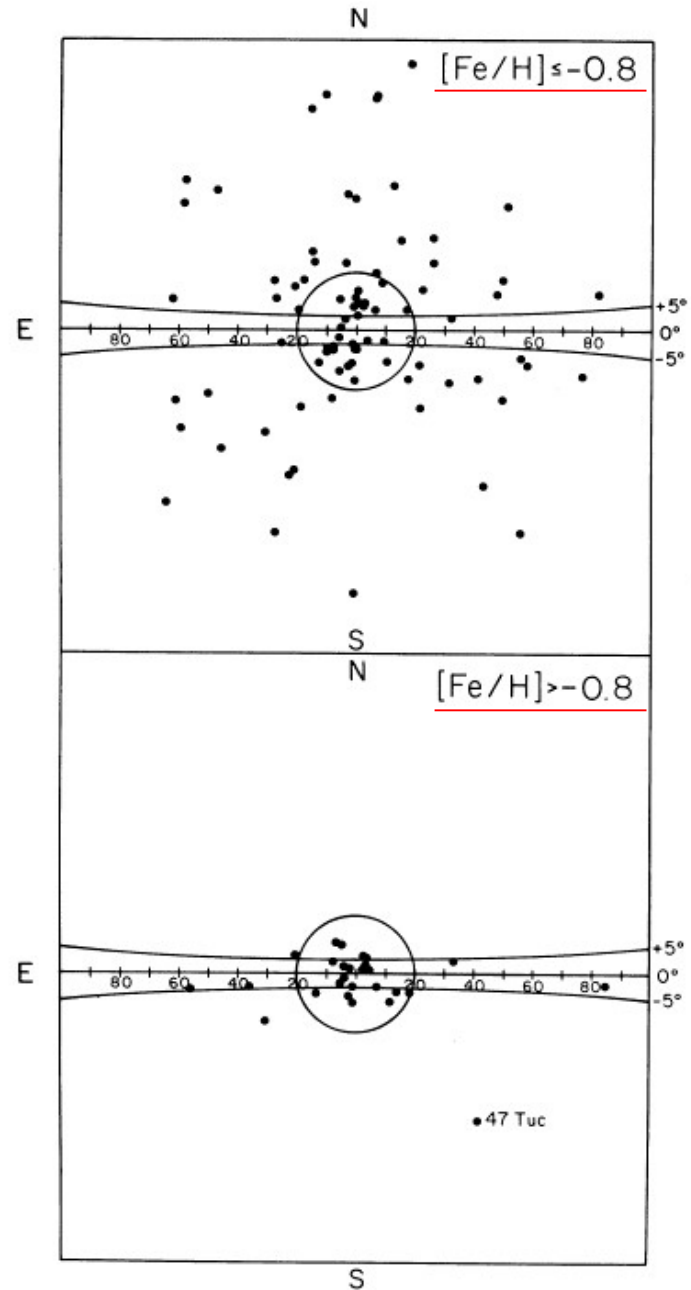
Harris 1976



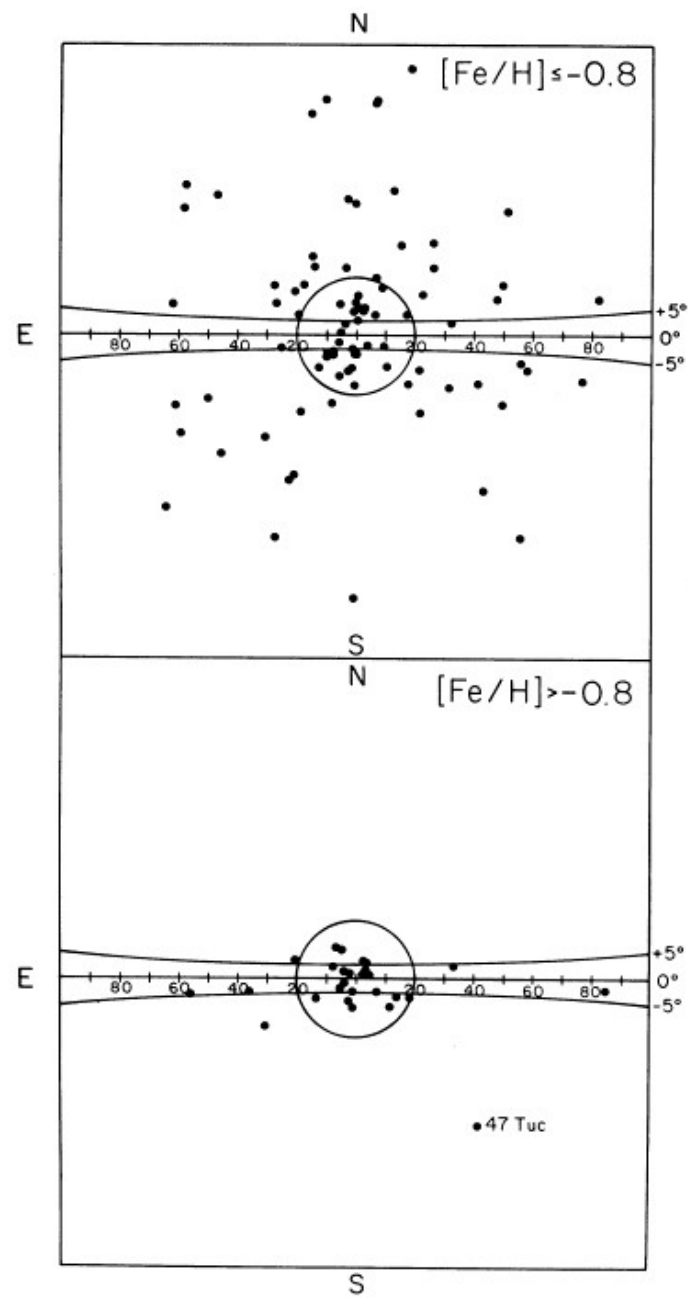
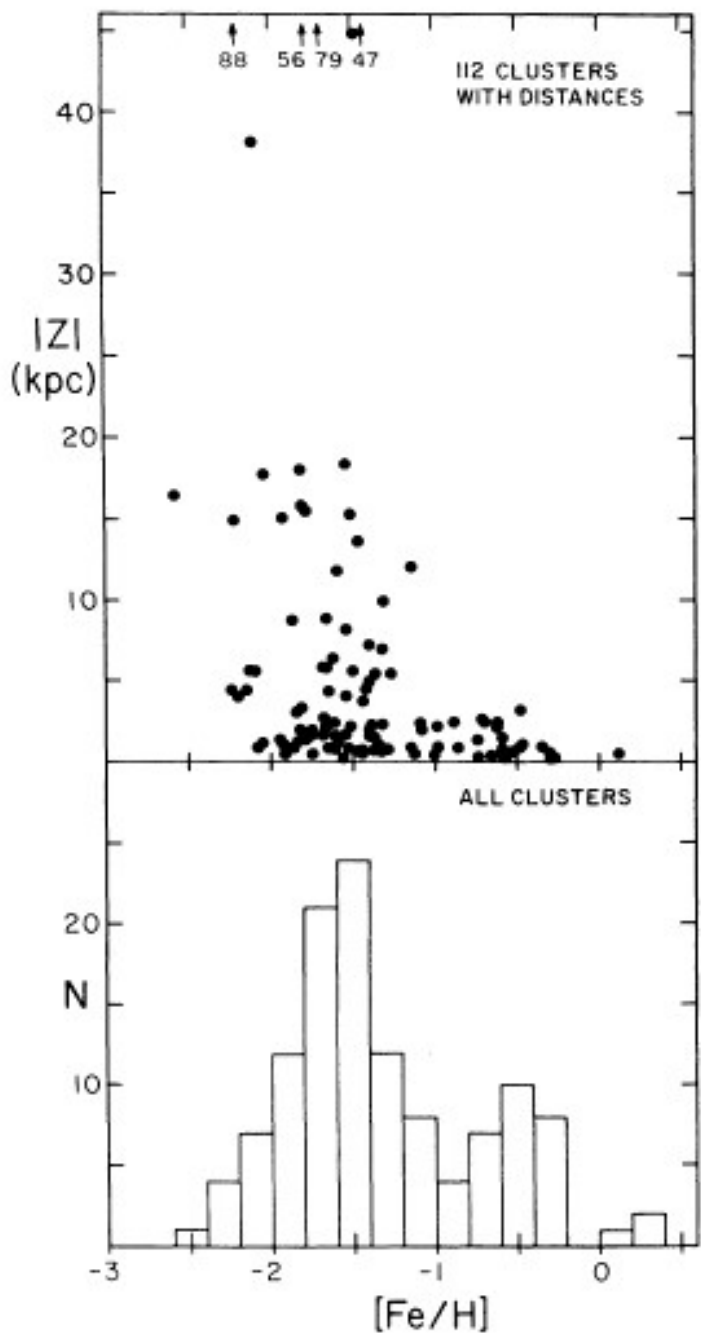
# 数密度の r 依存

FIG. 2.—The number of clusters per cubic kiloparsec ( $\phi$ ) is plotted against galactocentric distance ( $R$ ). The solid circles represent the clusters with  $|Z| < 20$  kpc; the open triangles represent the clusters with  $|Z| > 37$  kpc. There are no clusters in the zone  $33 < R < 60$  kpc.

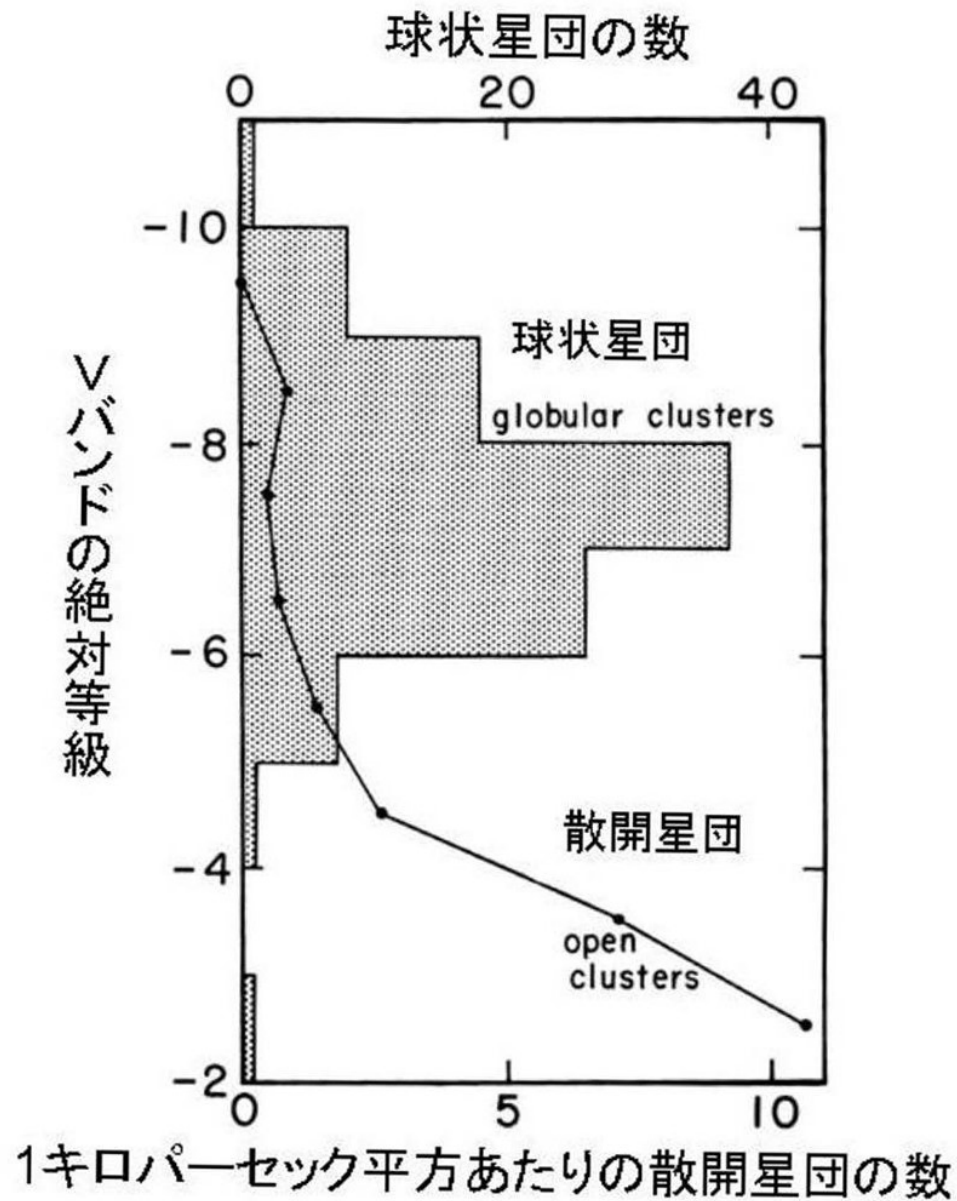
Zinn 1985



Zinn 1985



Zinn 1985



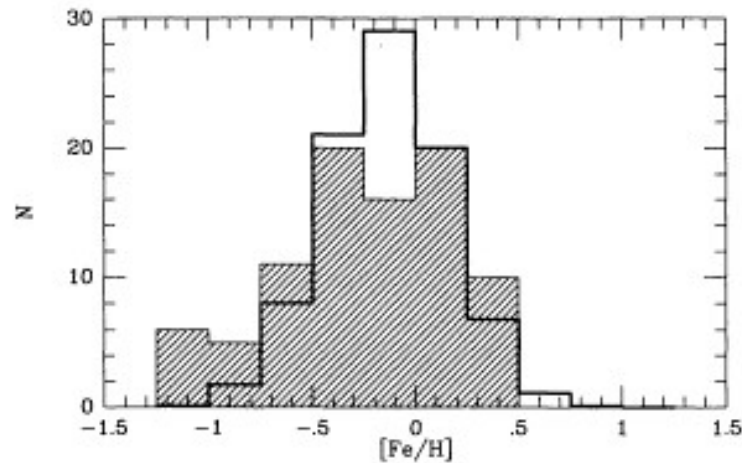
球状星団 Omega Centauri



散開星団 NGC290



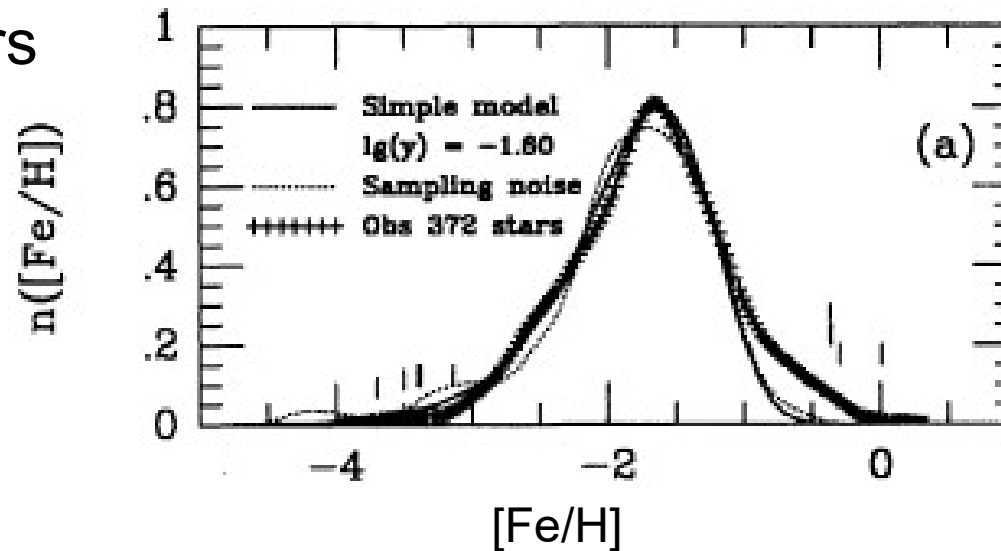
## Bulge



McAilliam & Rich 1994

FIG. 17.—The hatched area represents a frequency histogram of Rich (1988) solution 1  $[Fe/H]$ , corrected for the regression relation found here. The solid histogram outline represents the solar neighborhood GK giant distribution found by McWilliam (1990), smoothed by a Gaussian of  $\sigma = 0.25$  dex. Note that the bulge giants have a similar mean  $[Fe/H]$  but a slightly broader distribution and more very metal-poor stars.

## Halo stars



Ryan & Norris 1991

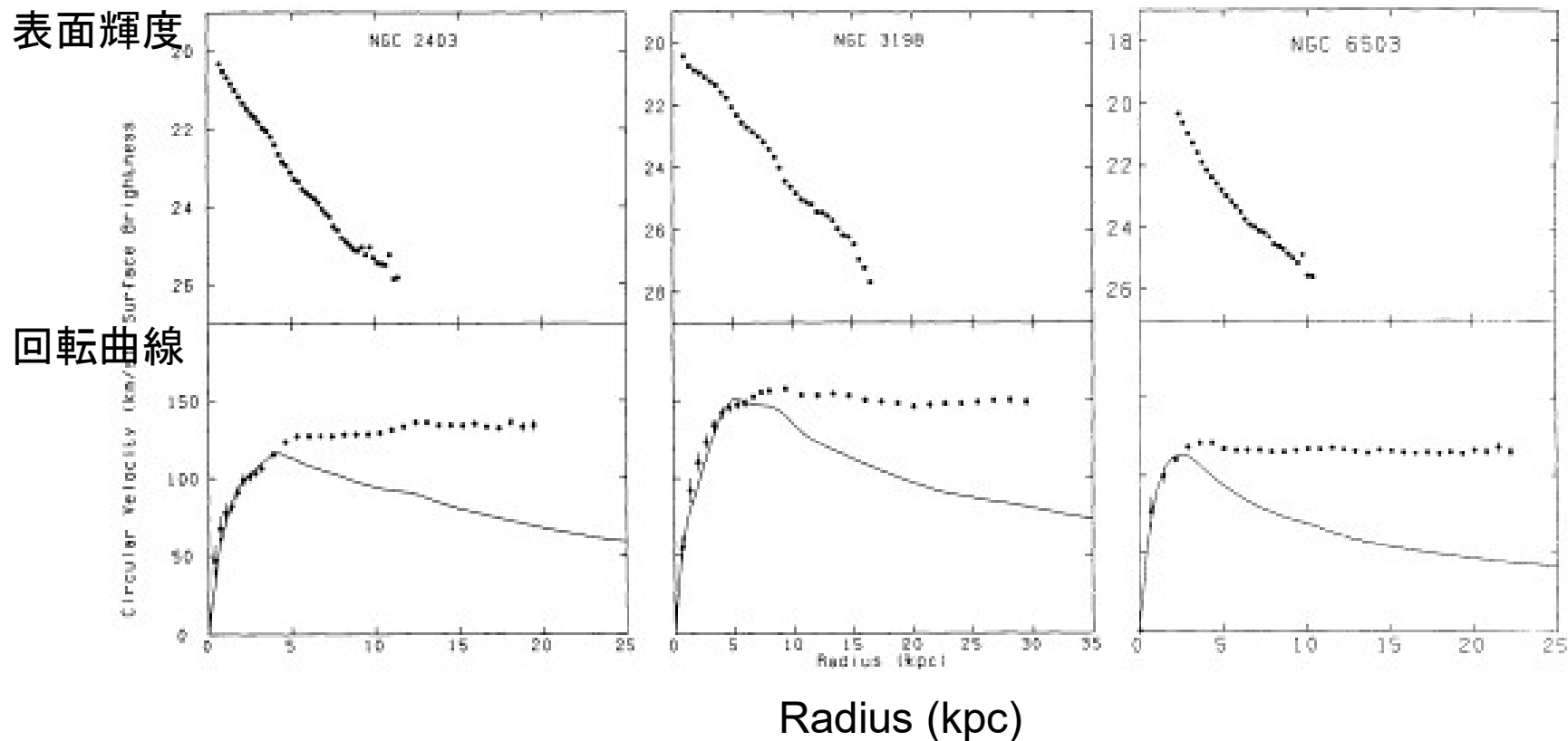
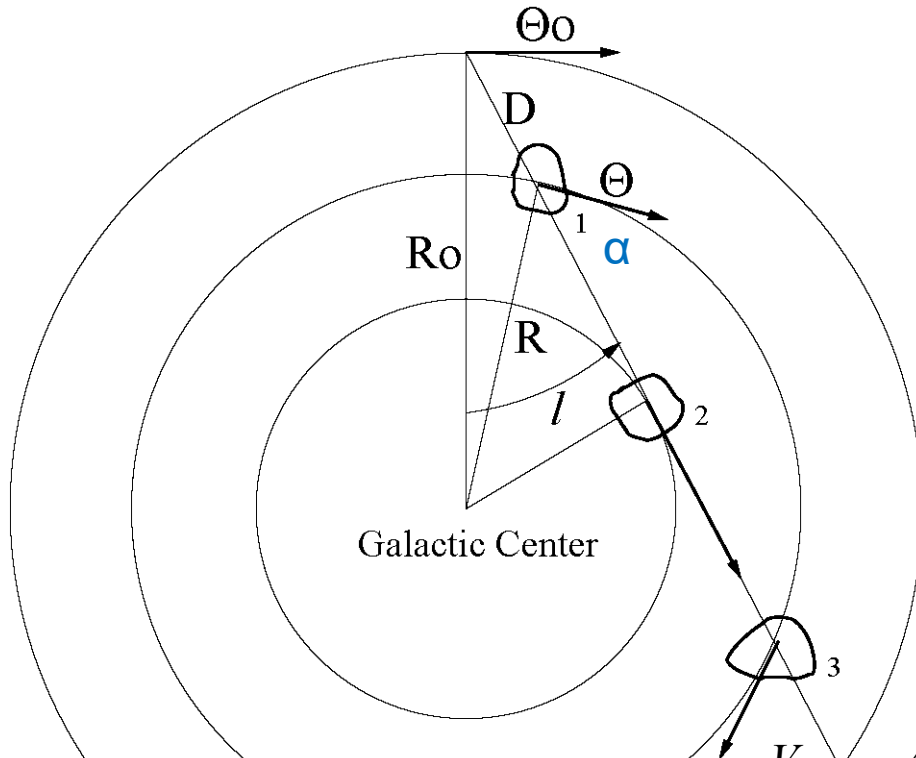


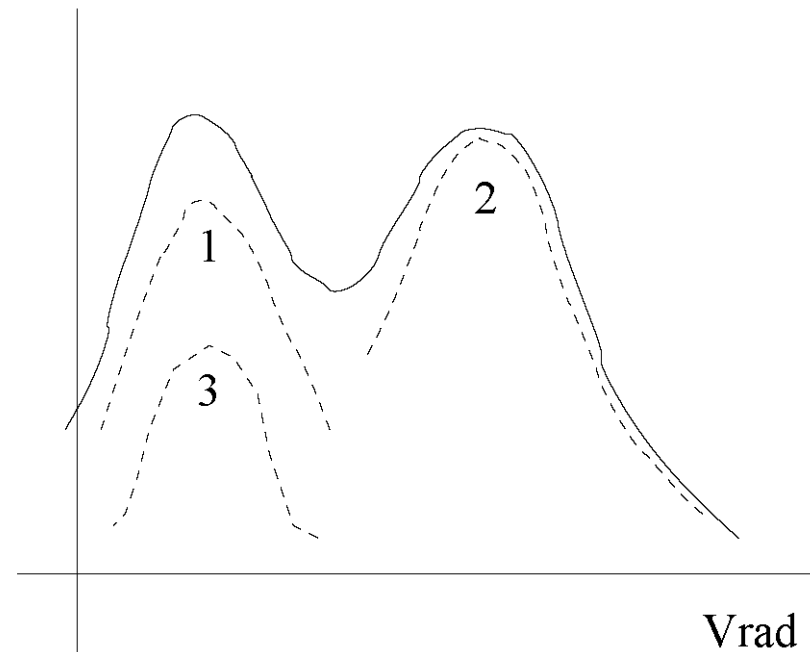
Figure 2. Light profiles and rotation curves for three spiral galaxies with extended, symmetrical HI disks. Upper panels: luminosity profiles from Wevers (1984). Lower panels: HI rotation curves (dots with error bars, Begeman 1986) and curves representing the circular velocity of stars and gas (solid line). The light contribution has been calculated from the luminosity profile by assuming that  $M/L$  is constant with radius and has the maximum value allowed by the observed rotation curve.

Sancisi & van Albada 1987, IAU 117

# Determination of the rotation curve



Radio intensity



$$V_{rad} = \Theta \cos \alpha - \Theta_0 \sin l$$

$$V_{tan} = \Theta \sin \alpha - \Theta_0 \cos l$$

$$\sin l / R = \sin(90 + \alpha) / R_0 = \cos \alpha / R_0$$

$$R \cos(90 - \alpha) = R \sin \alpha = R_0 \cos l - D$$

$$V_{rad} = (\Omega - \Omega_0) R_0 \sin l$$

$$V_{tan} = (\Omega - \Omega_0) R_0 \cos l - \Omega D$$

$$\Rightarrow (R_0 - R) / R_0 \ll 1 \Rightarrow$$

$$V_{rad} = AD \sin 2l$$

$$V_{tan} = D(A \cos 2l + B)$$

$$\mu_l = \frac{A \cos 2l + B}{4.74}$$

$$A \equiv \frac{1}{2} \left[ \frac{\Theta_0}{R_0} - \left( \frac{d\Theta}{dR} \right)_{R_0} \right]$$

$$B \equiv -\frac{1}{2} \left[ \frac{\Theta_0}{R_0} + \left( \frac{d\Theta}{dR} \right)_{R_0} \right]$$

$$\Omega_0 = \Theta_0 / R_0 = A - B$$

$$\left( \frac{d\Theta}{dR} \right)_{R_0} = -(A + B)$$

$V_{rad}$  is max at  $R = R_0 \sin l \Rightarrow \Theta(R)$

$$\frac{\partial V_{rad}}{\partial D} = 0 \Rightarrow \partial R / \partial D = 0$$

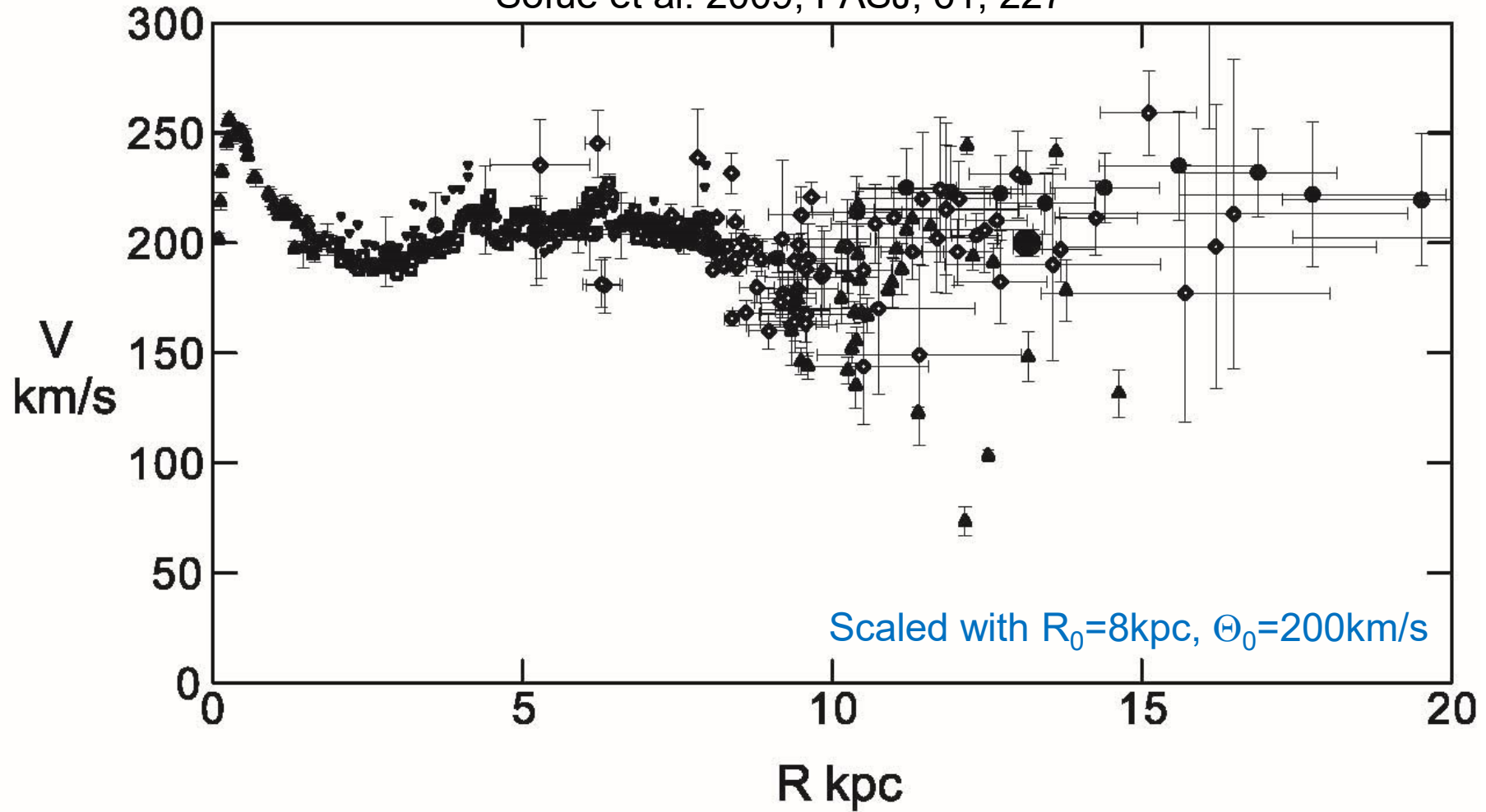
$$R^2 = D^2 + R_0^2 - 2DR_0 \cos l$$

$$\Rightarrow D = R_0 \cos l \Rightarrow R = R_0 \sin l$$

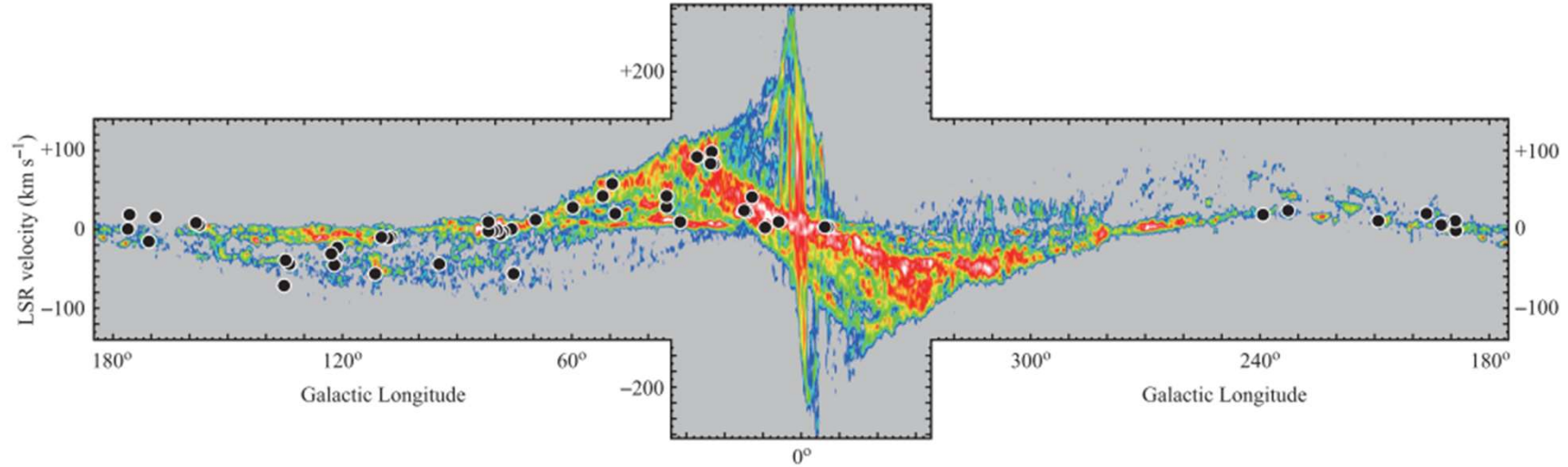
A, B: Oort Constants

# Rotation curve of the Milky Way

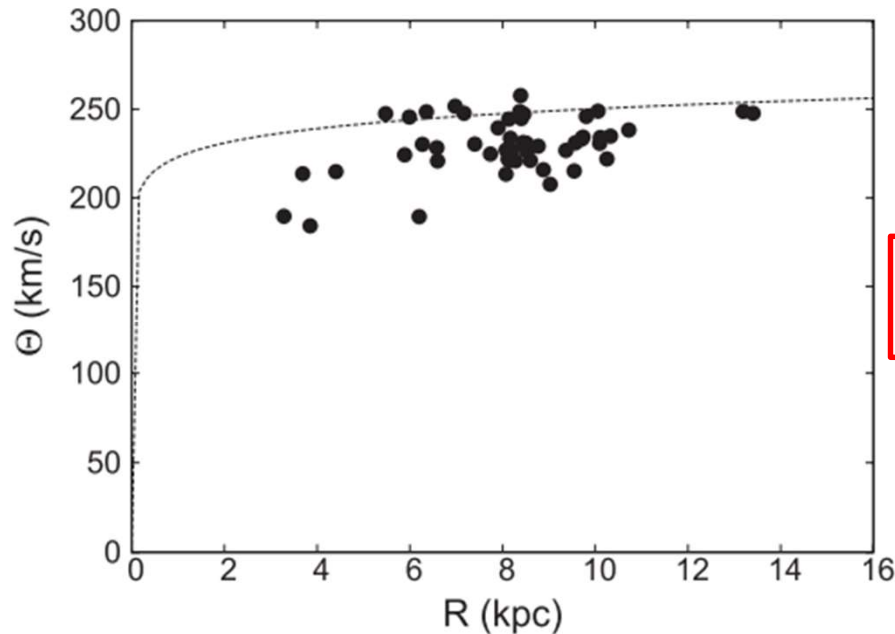
Sofue et al. 2009, PASJ, 61, 227



See also, Gunn, Knapp, Tremaine 1979, AJ, 84, 1181;  
Fich & Tremaine 1991, ARAA, 29, 409



**Fig. 1.** Location of 52 maser sources for which accurate astrometric data are available (table 1), superposed on the longitude–velocity diagram of CO (Dame et al. 2001).



**Fig. 6.** Rotation curve plot for result 1 (52 sources). Filled circles correspond to the observed sources. Values of  $R_0$  and  $\Theta_0$  are taken from the relevant results in table 1 ( $R_0 = 8.27 \text{ kpc}$ ,  $\Omega_0 = 29.98 \text{ km s}^{-1} \text{ kpc}^{-1}$  and thus  $\Theta_0 = R_0 \times \Omega_0 = 248 \text{ km s}^{-1}$ ). Here error bars are not shown because in most cases they are invisibly small in this plot (but note that the systematic effect is considerably large as described in the text). Dotted line shows a rotation curve with  $\Theta_0 = 248 \text{ km s}^{-1}$  and a power-law index  $\alpha = 0.05$ . Note that here  $V_\odot = 5.25 \text{ km s}^{-1}$  is adopted and hence the lag of SFRs against Galactic rotation is prominent (by  $\sim 15 \text{ km s}^{-1}$ ), with most of data points located below the model rotation curve.



楕円銀河・バルジの輝度分布

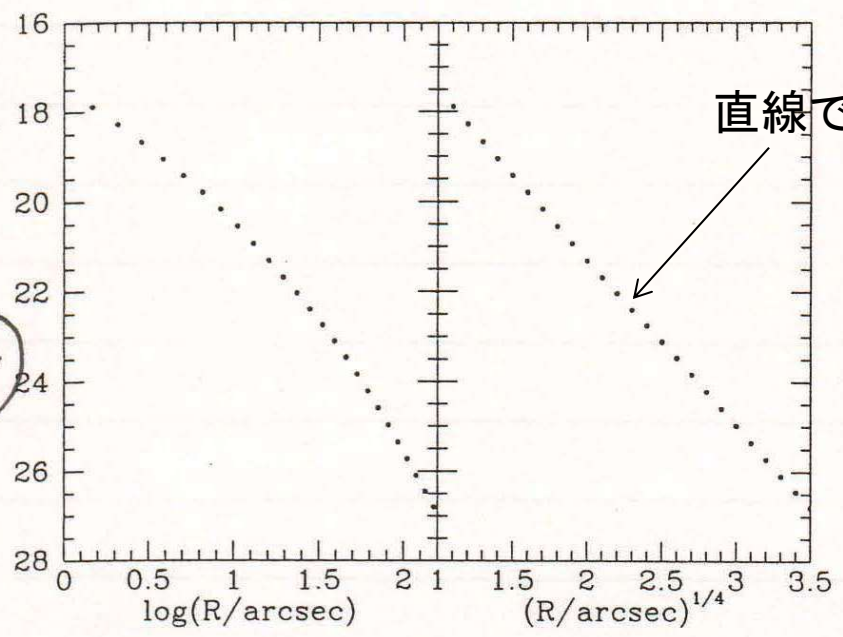
$$I(R) = I_0 \exp(-kR^{1/4})$$



$$\mu \propto -\frac{5}{2} \log_{10} I \propto R^{1/4}$$

表面輝度

$\mu_B$   
(mag/arcsec<sup>2</sup>)



R<sup>1/4</sup>-law

楕円銀河における内部運動と光度の関係

中心の速度散  
log  $\sigma_p$   
(km/s)

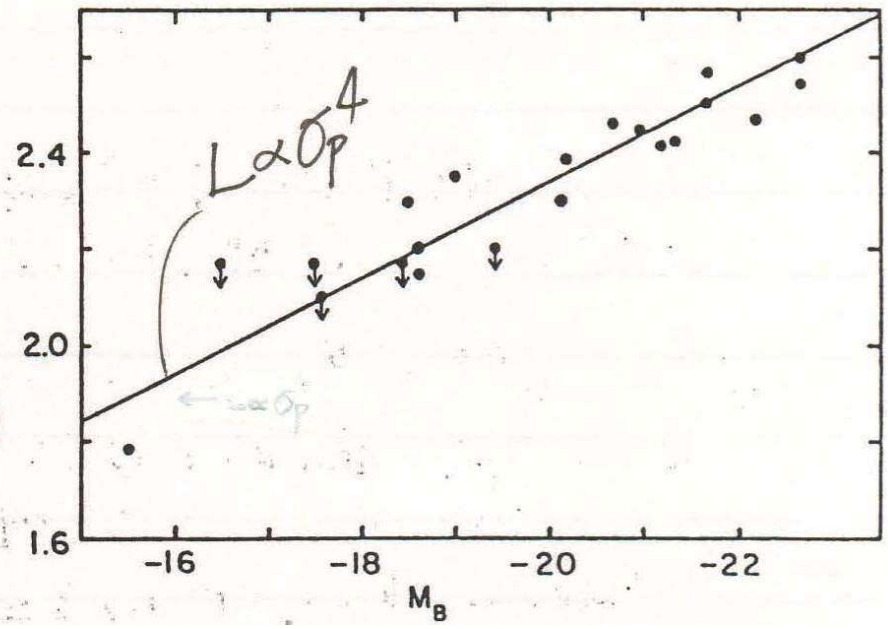


Figure 4.25 The major-axis brightness profile of NGC 1700 plotted against (a)  $\log r$  and (b)  $R^{1/4}$ . [From data published in Capaccioli, Piotto & Rampazzo (1988)]

# 二色図

## Two-color diagram

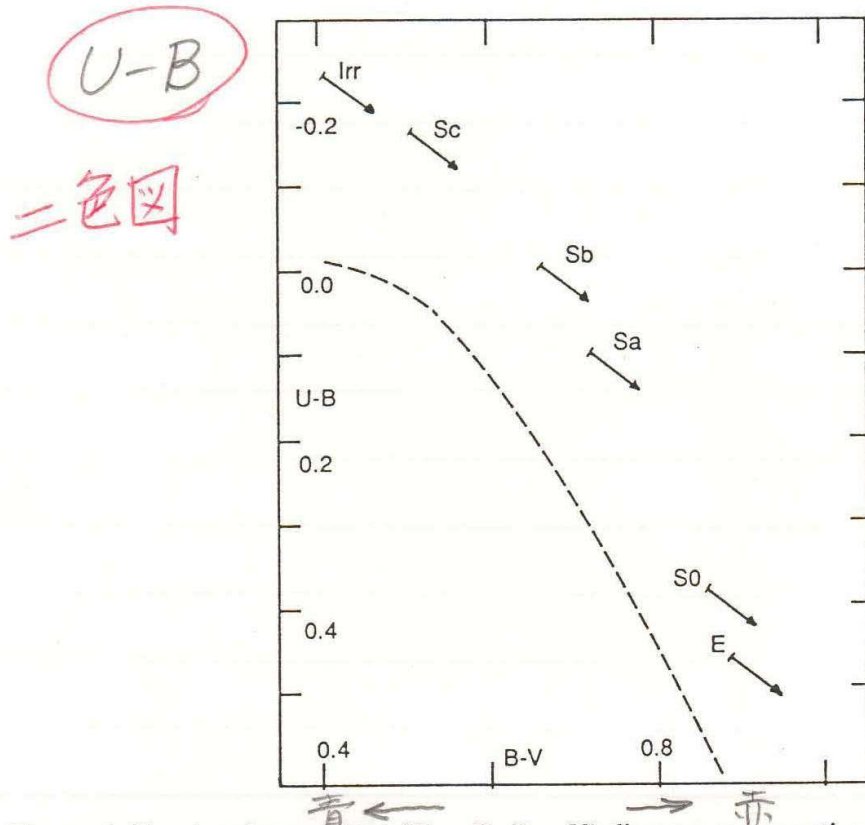
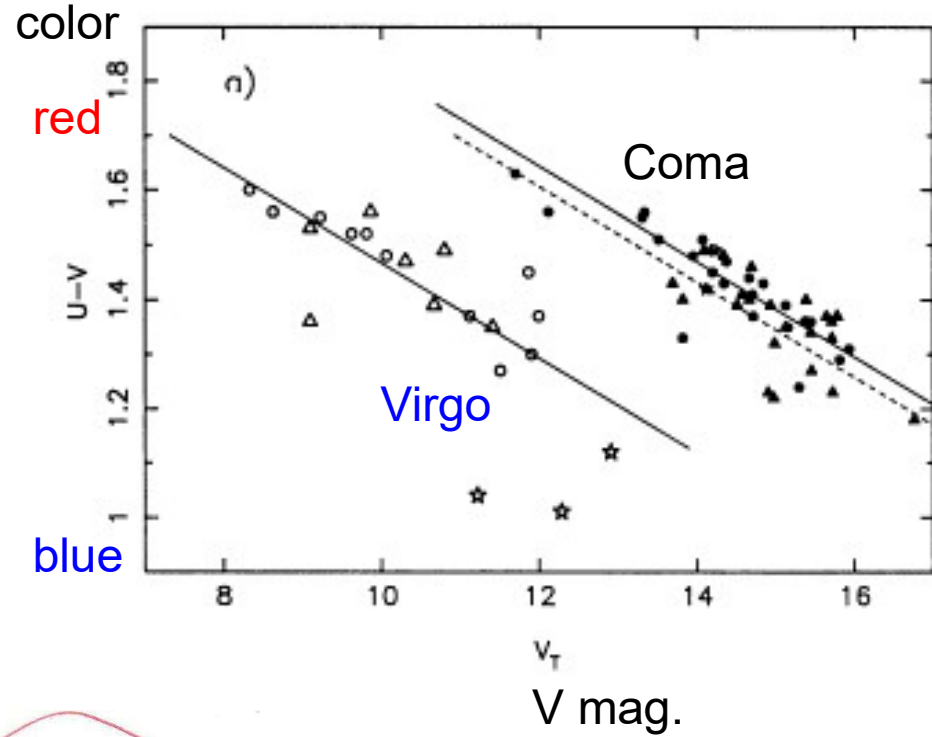


Figure 1.10 A colour-colour ( $U - B$ ,  $B - V$ ) diagram representing the position of normal galaxies (points) and the main sequence of stars (dashed line). The arrows indicate the effect obtained by correcting for galactic reddening,  $E(B - V) = 0.06$ .

# 色一等級関係

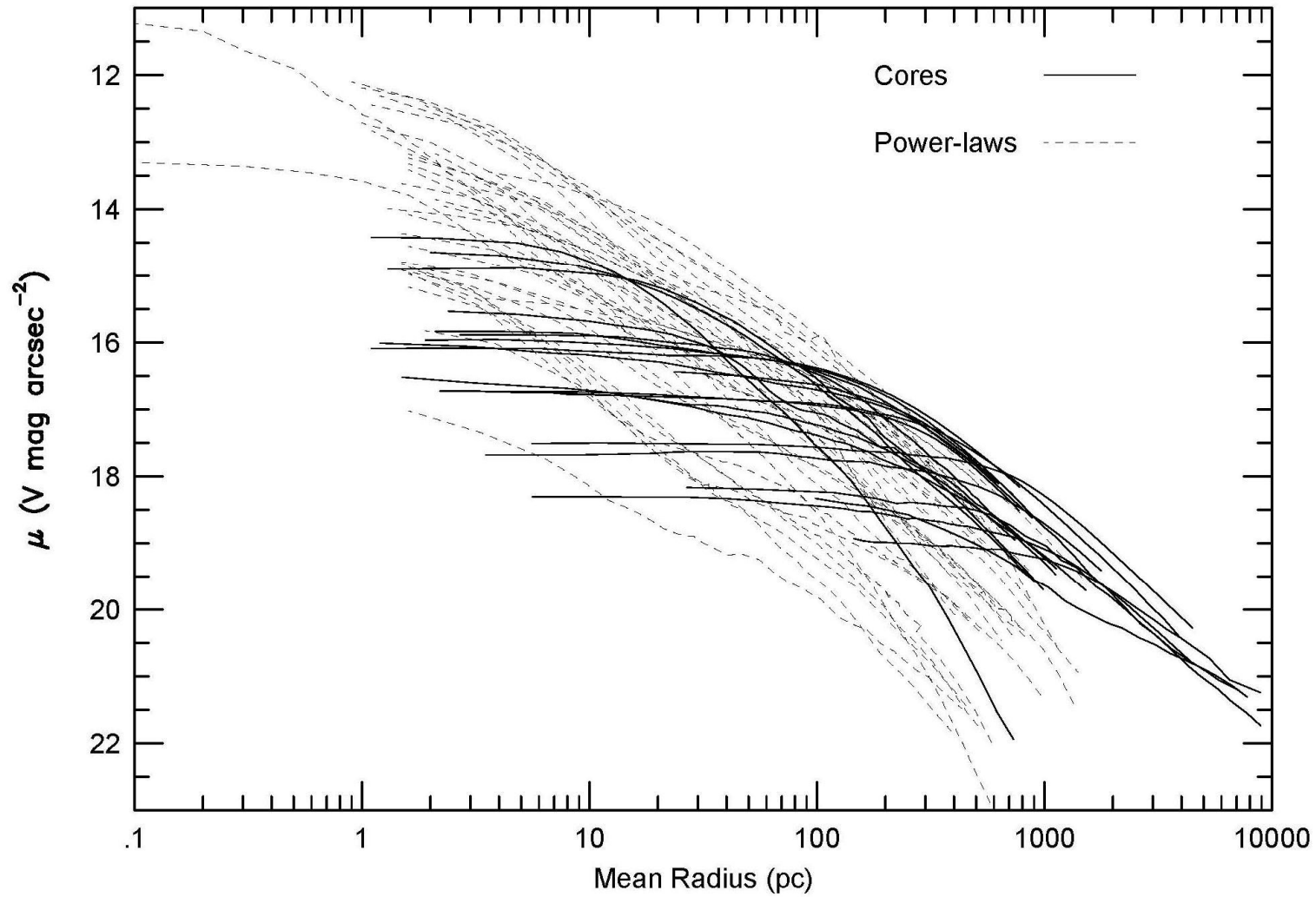
## Color-magnitude relation



# 楕円銀河の中心輝度プロファイル

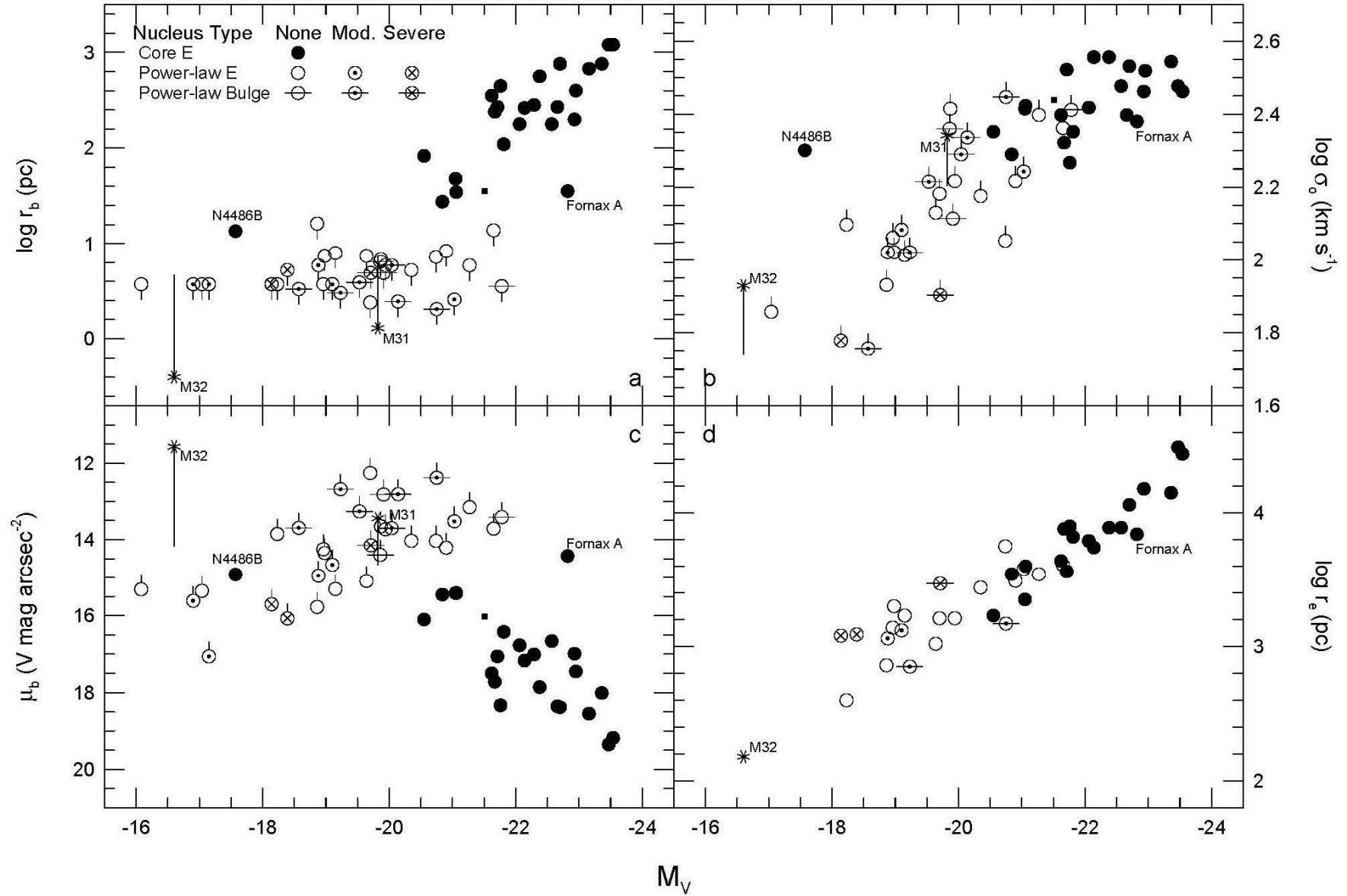
Faber et al. 1997

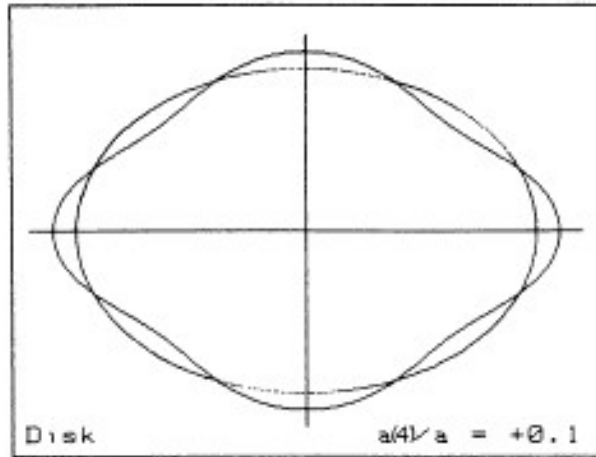
Fig. 1: Inner Profiles of 55 Ellipticals and Bulges



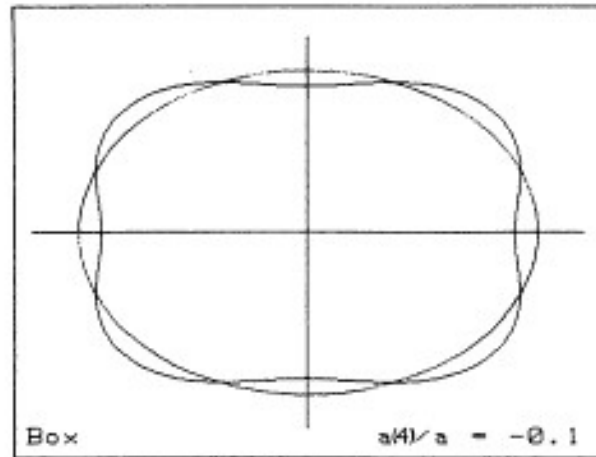
$r_b$  : break radius,  $\mu_b$  :  $\mu$  at break radius

Fig. 4. Central Parameters vs. Absolute Magnitude





Disky E



Boxy E

FIGURE 5. — Schematic drawing illustrating isophotes with  $a(4)/a = +0.1$  and  $a(4)/a = -0.1$ .

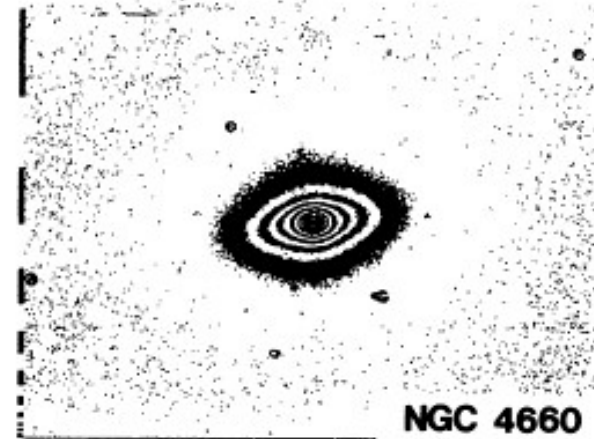


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ( $a(4)/a \sim +0.03$ ).

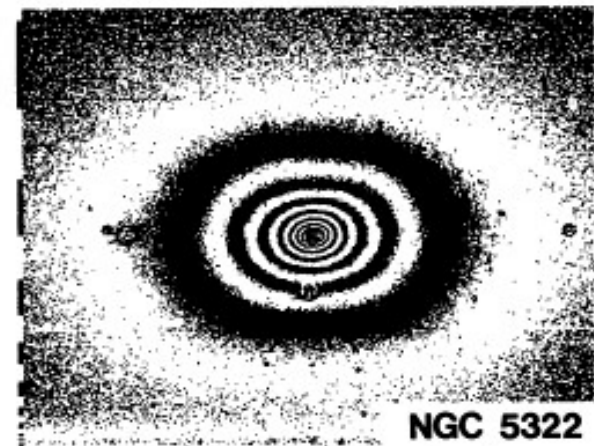


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ( $a(4)/a \sim -0.01$ ).



# Fundamental Plane

3-d space:  $(\sigma_0, r_e, \langle I \rangle_e)$

$$\log R_e = a \log \sigma_0 + b \log \langle I \rangle_e + \text{constant},$$

$a \approx 1.5, b \approx -0.8$

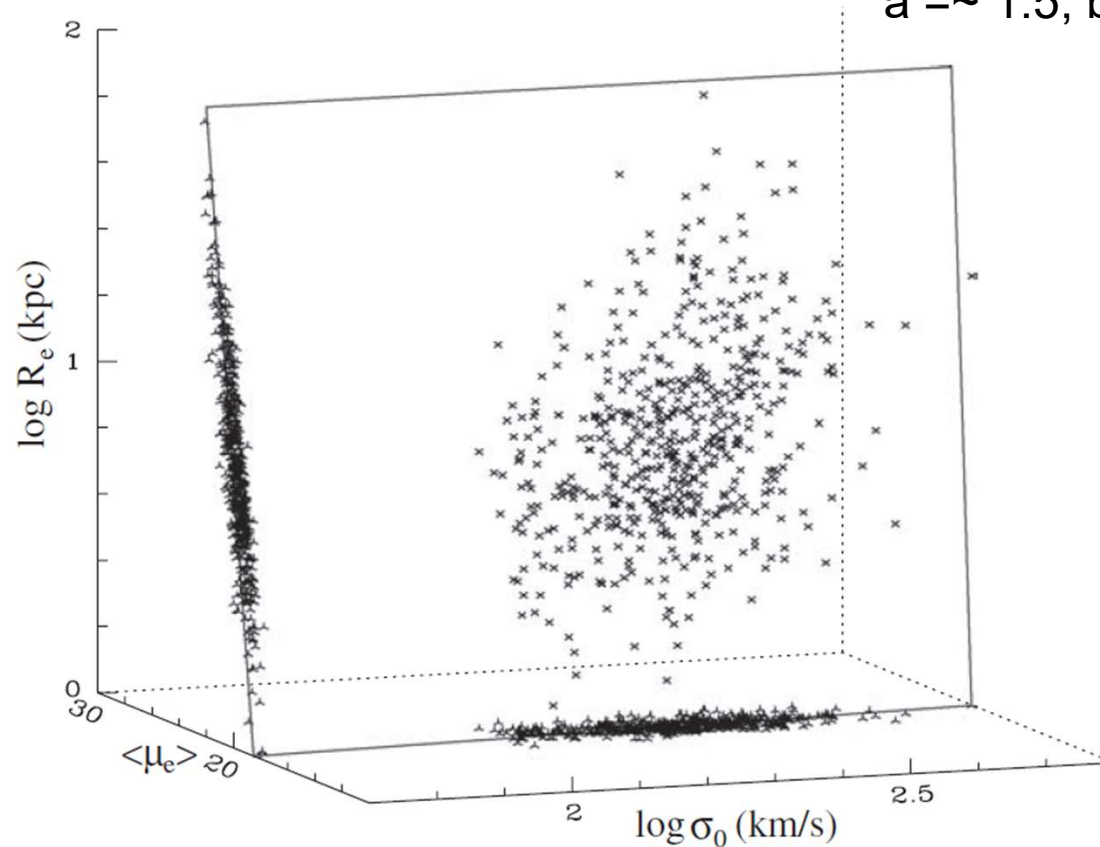
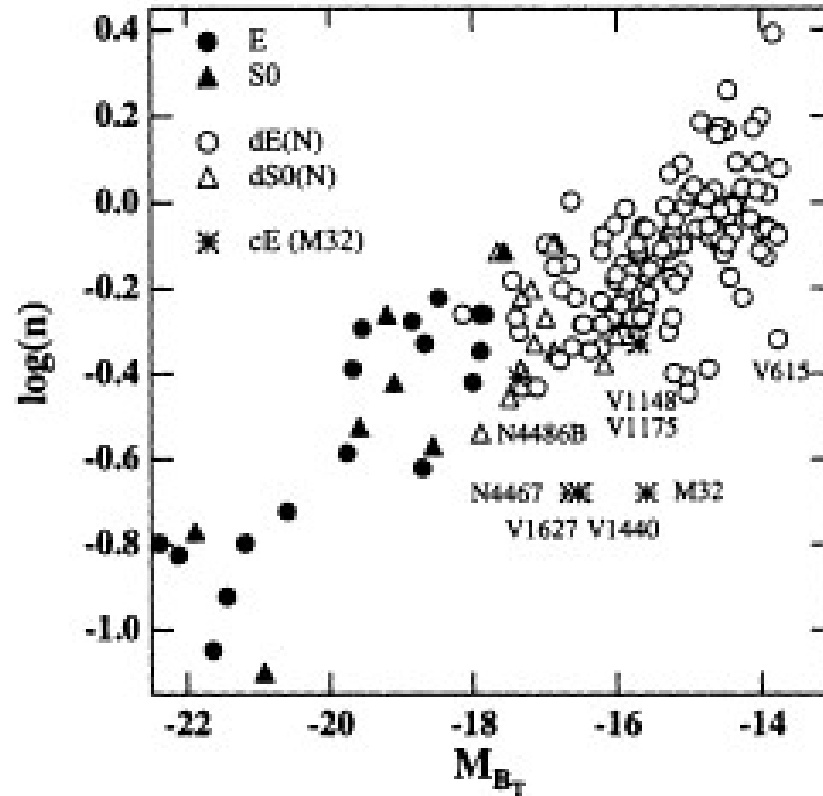
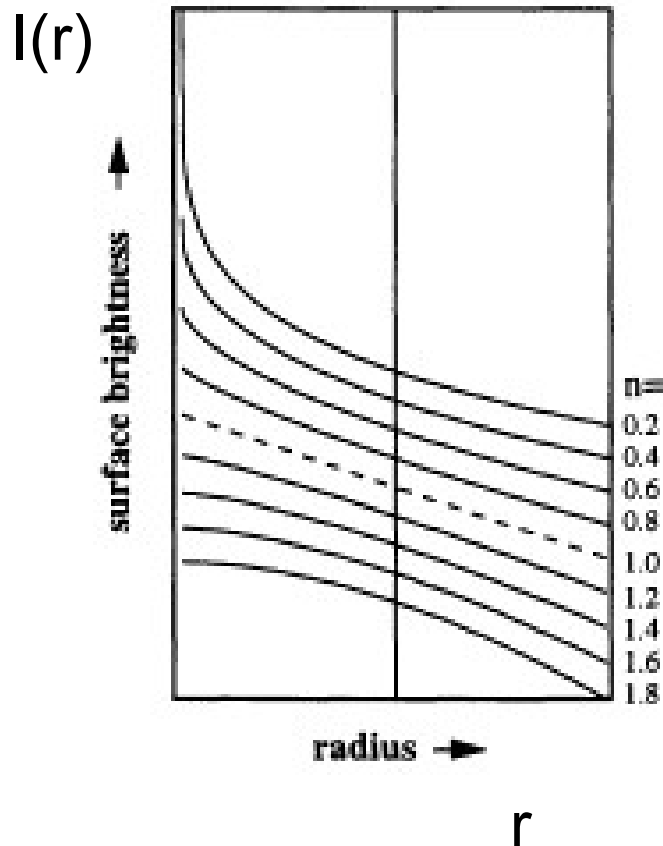


Fig. 2.18. The fundamental plane of elliptical galaxies in the  $\log R_e$ - $\log \sigma_0$ - $\langle \mu \rangle_e$  space ( $\sigma_0$  is the central velocity dispersion, and  $\langle \mu \rangle_e$  is the mean surface brightness within  $R_e$  expressed in magnitudes per square arcsecond). [Plot kindly provided by R. Saglia, based on data published in Saglia et al. (1997) and Wegner et al. (1999)]

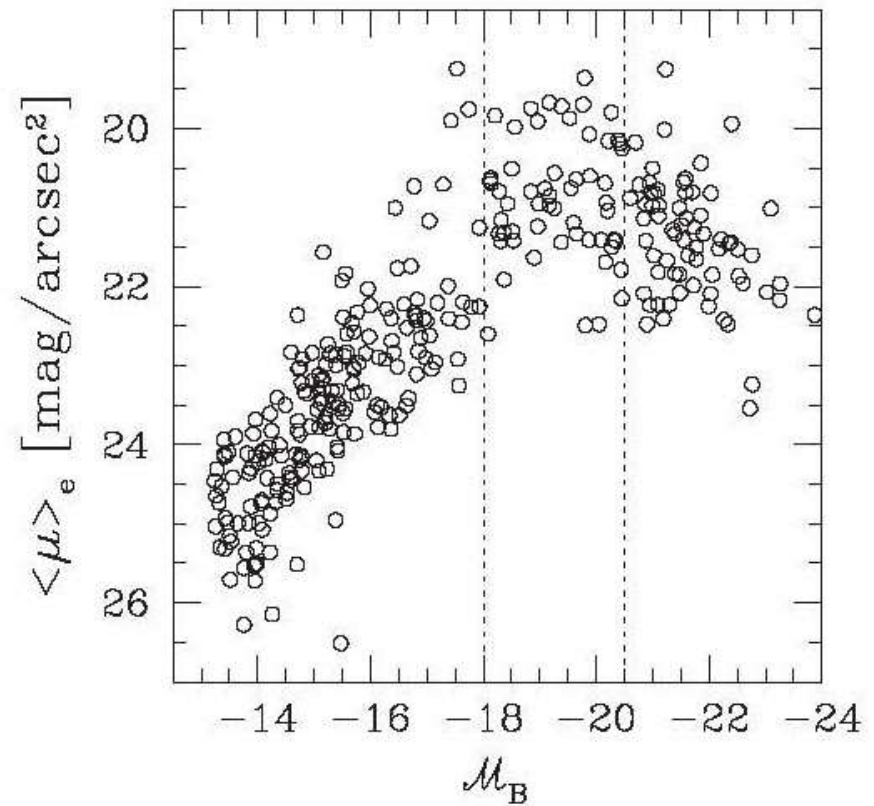
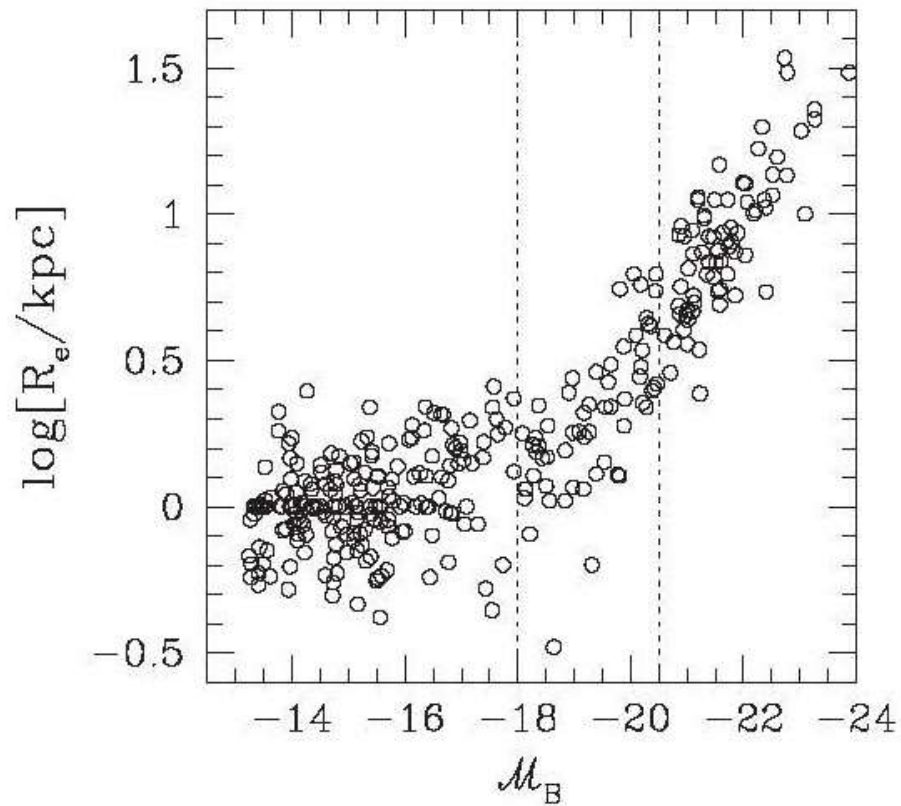
# 矮小銀河、楕円銀河の輝度分布

$$I(r) \propto \exp(-r^n)$$



Jerjen & Binggeli 1997  
In ASP conf, vol. 116

# Scaling relations for spheroidal systems



# Dwarf galaxies

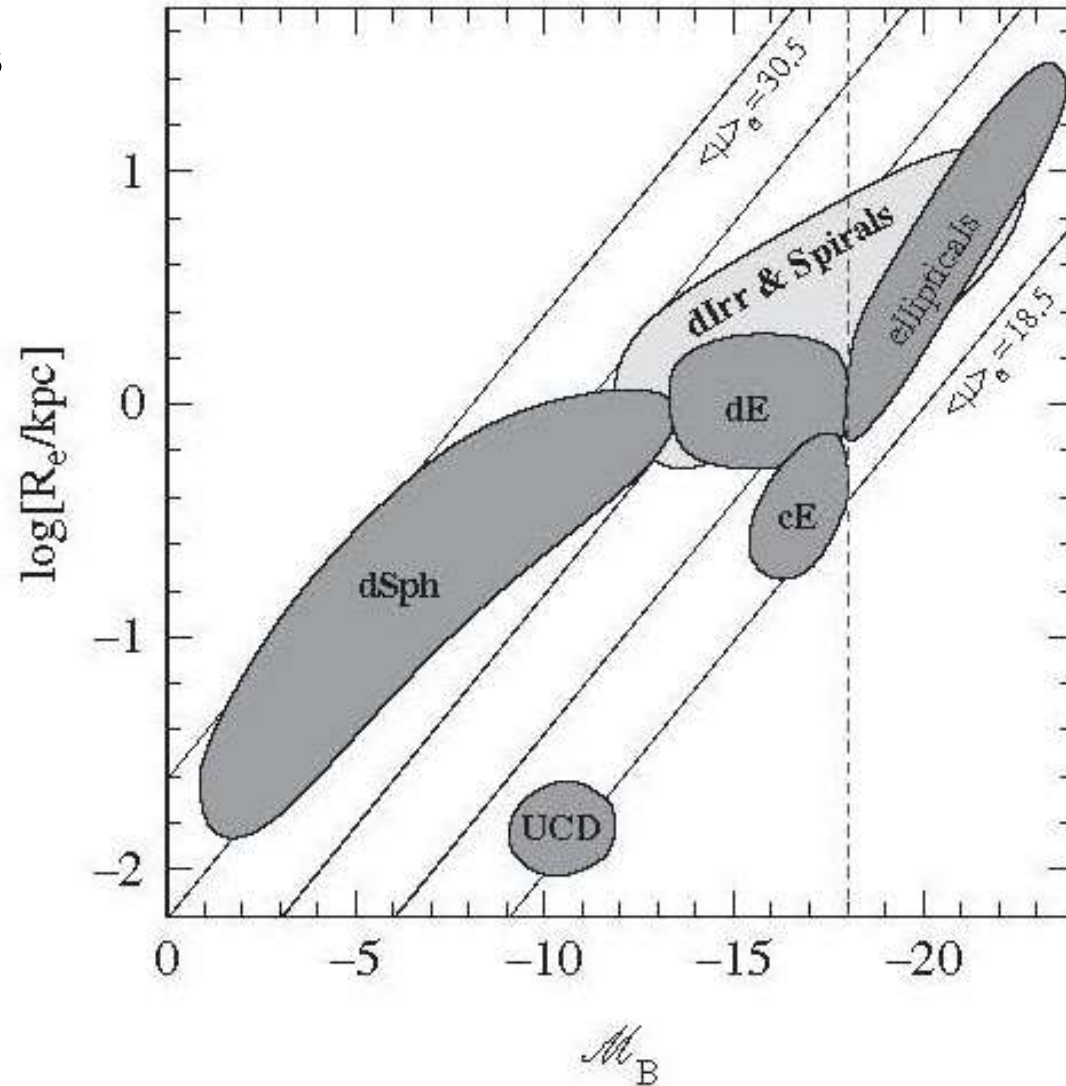
dwarf spheroidal galaxies  
(dSphs 矮小橢圓體銀河)



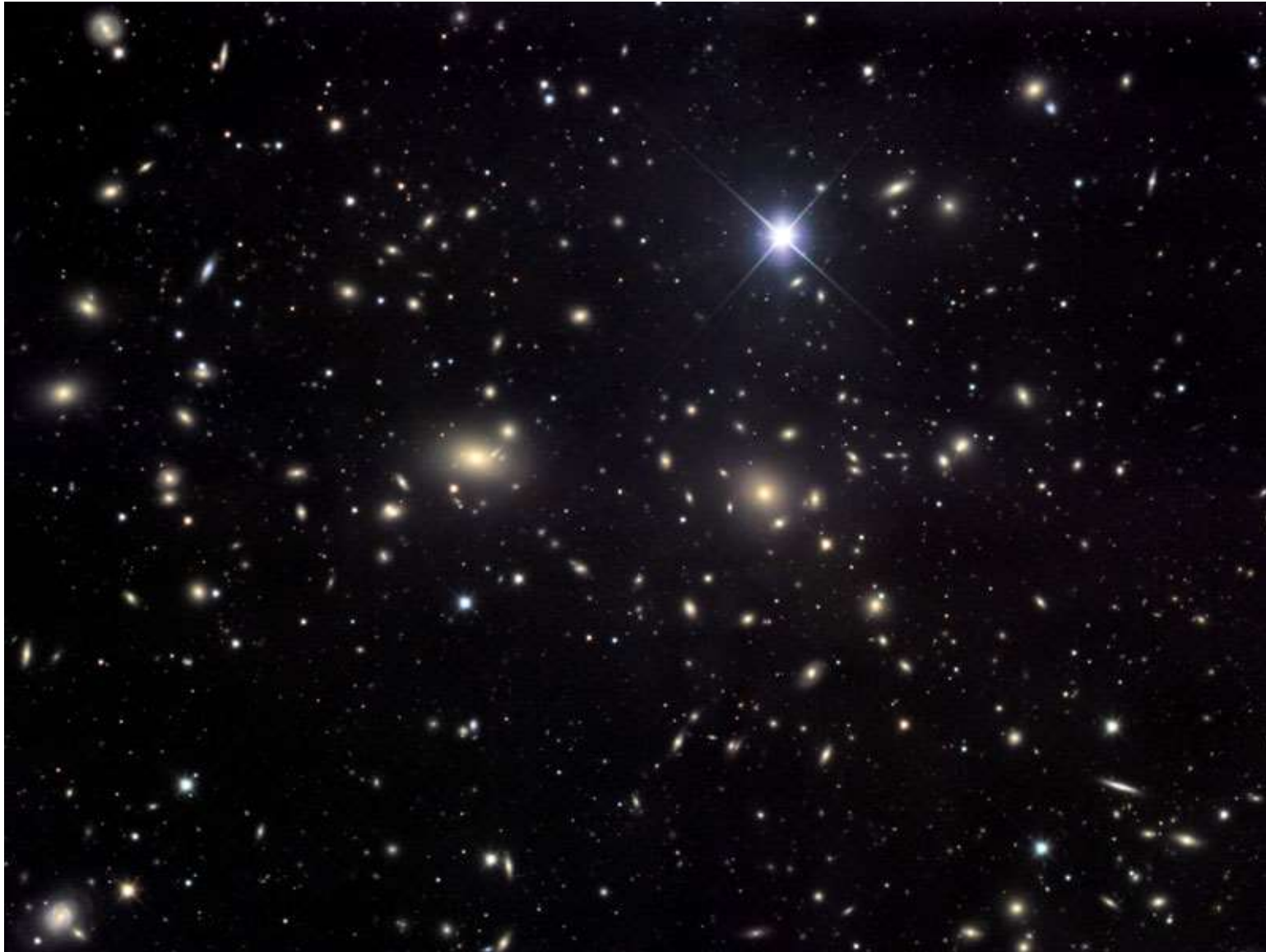
Leo I



Carina



# 銀河団

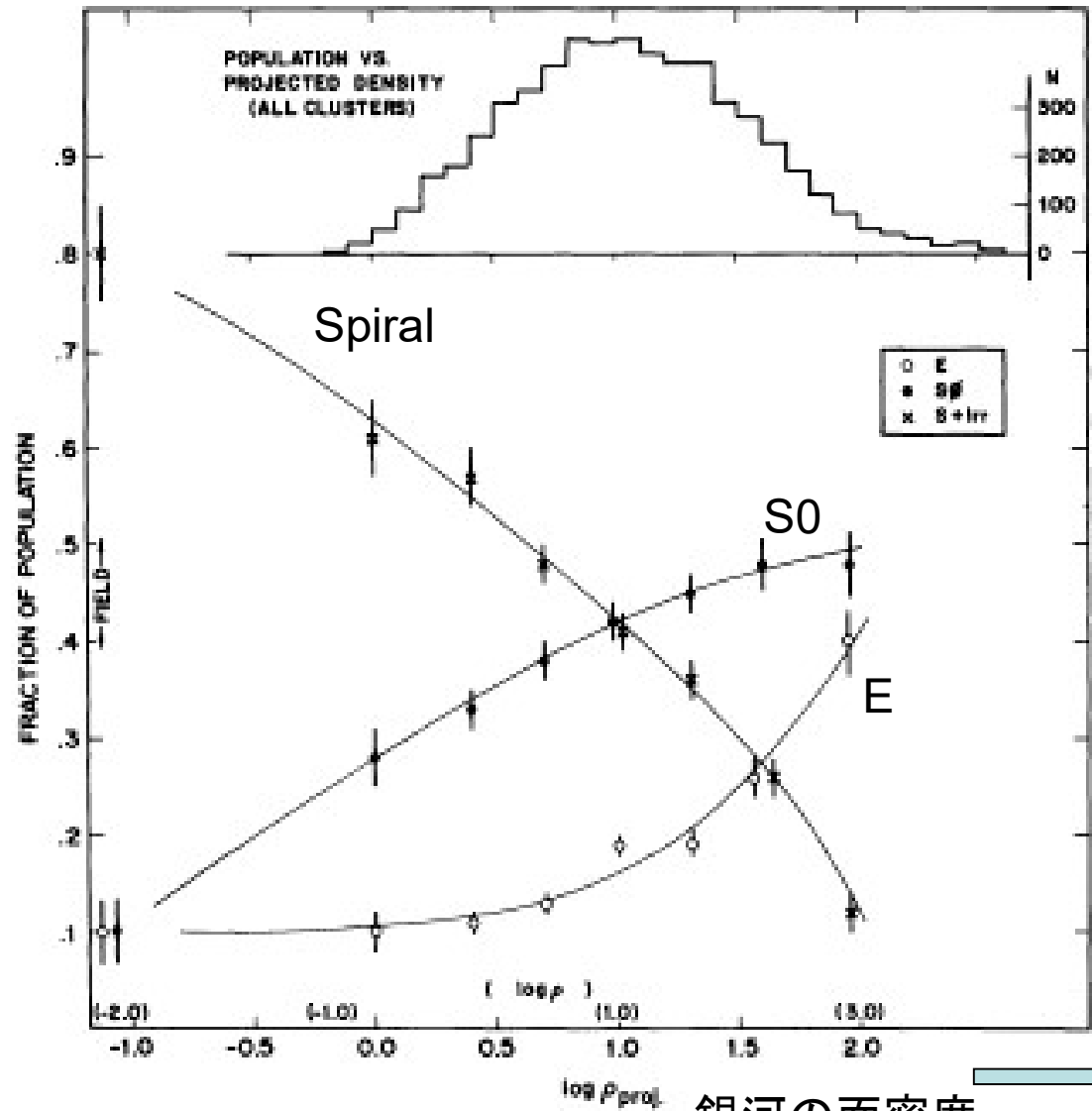


かみのけ座銀河団 Coma cluster



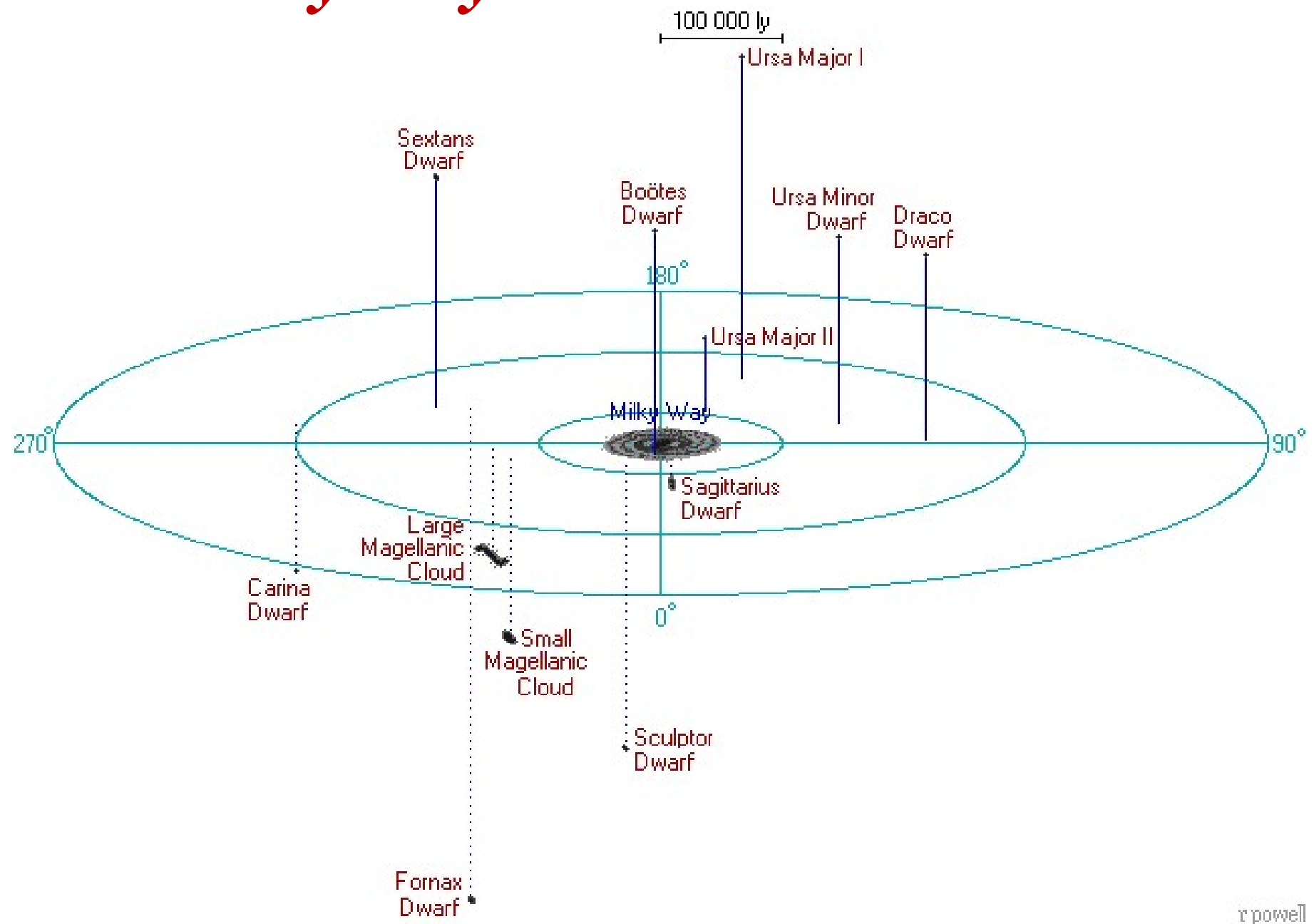
# Morphology-density relation

銀河形態の割合

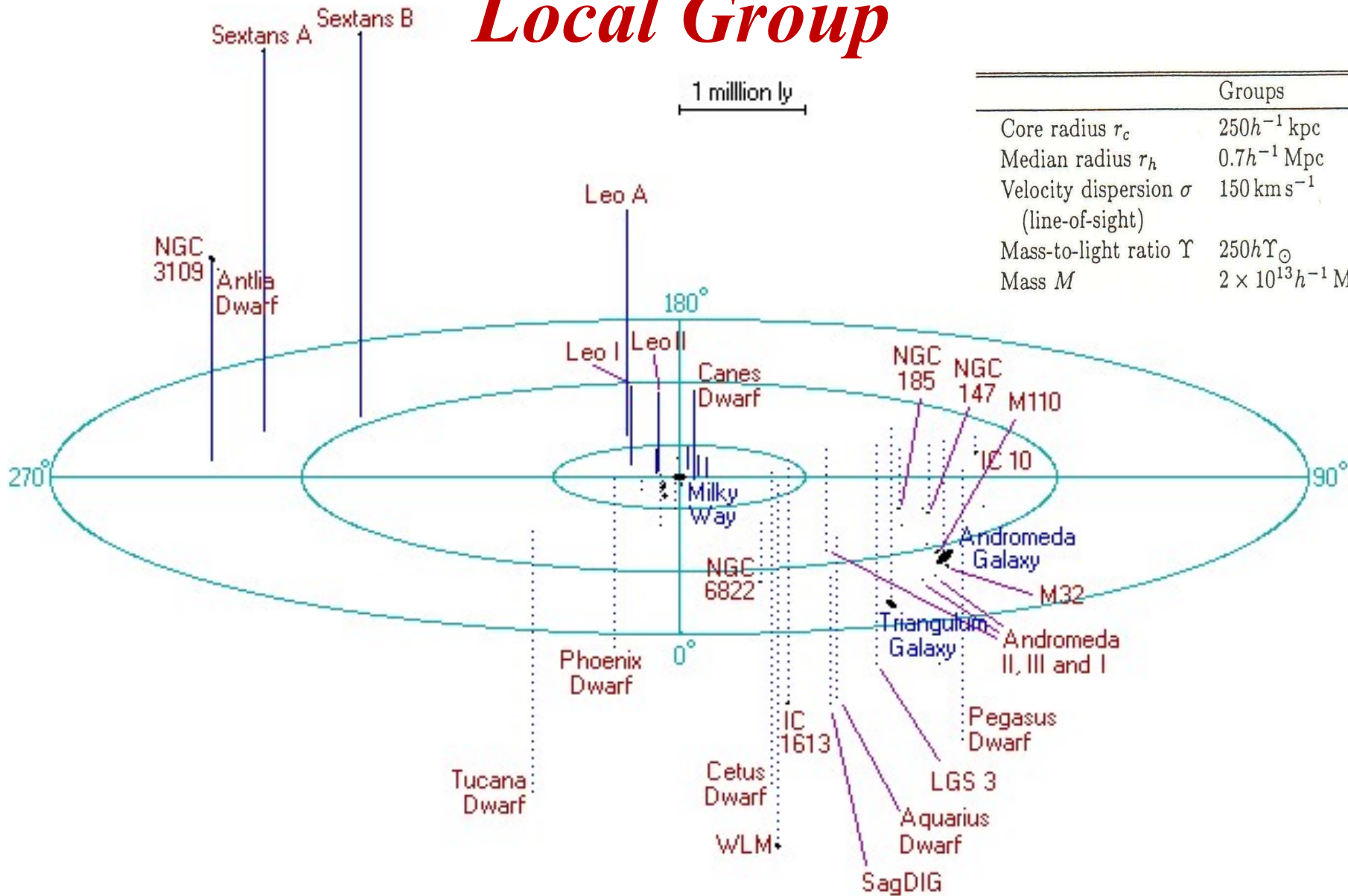


Dressler et al. 1980

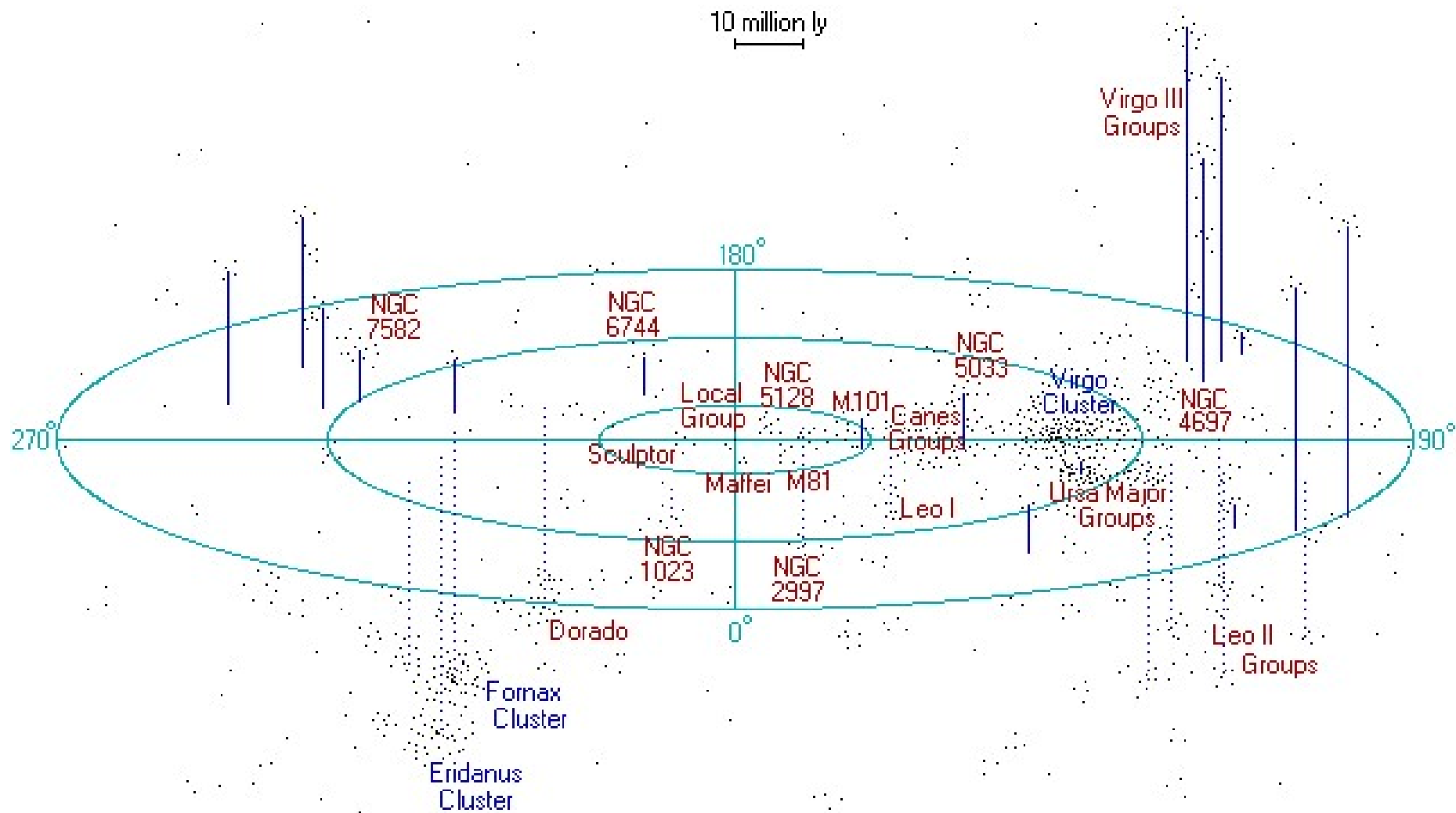
# Milky Way & Galactic satellites



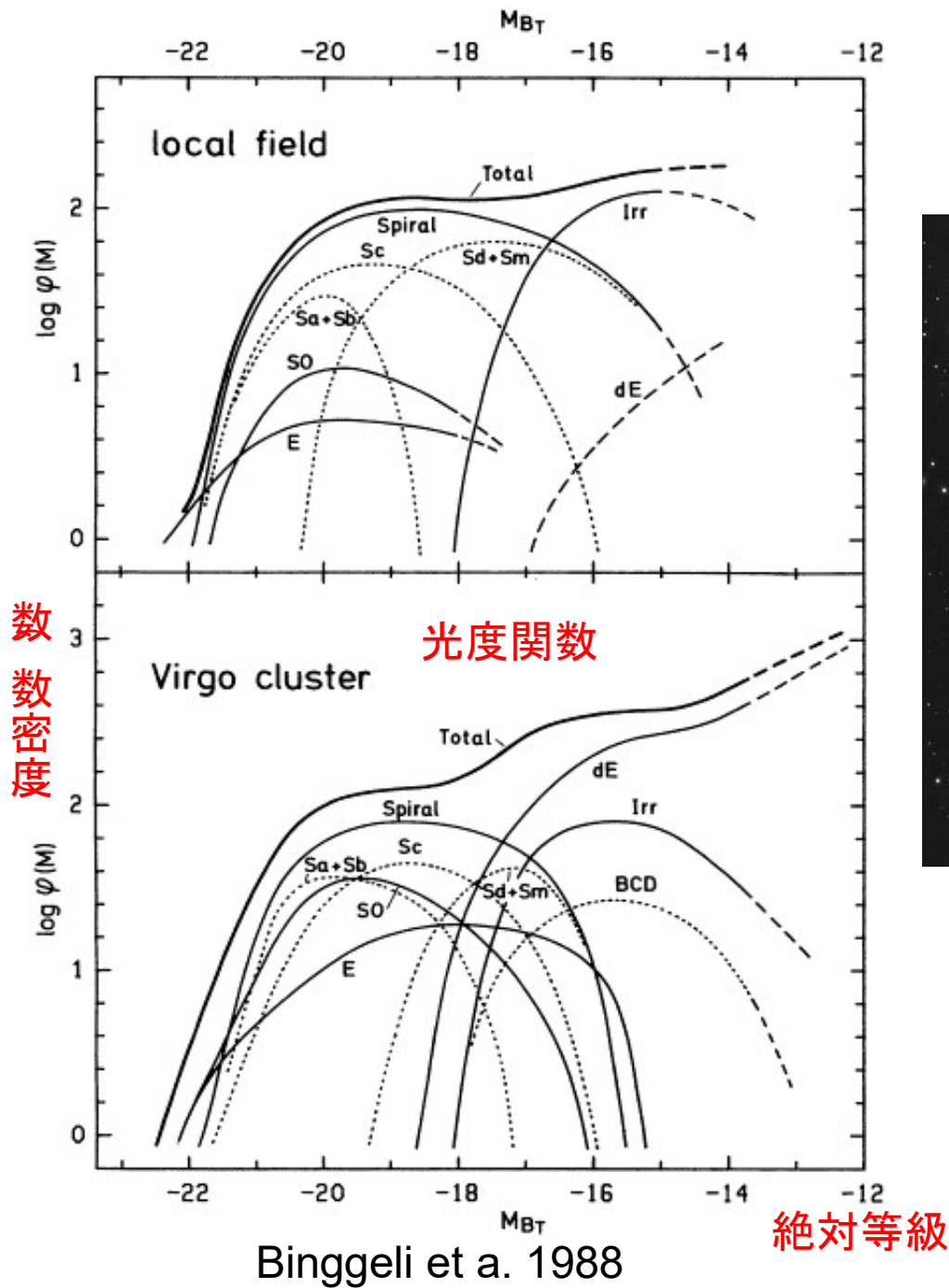
# Local Group



	Groups	Clusters
Core radius $r_c$	$250h^{-1}$ kpc	$250h^{-1}$ kpc
Median radius $r_h$	$0.7h^{-1}$ Mpc	$3h^{-1}$ Mpc
Velocity dispersion $\sigma$ (line-of-sight)	$150 \text{ km s}^{-1}$	$800 \text{ km s}^{-1}$
Mass-to-light ratio $\Upsilon$	$250h\Upsilon_{\odot}$	$250h\Upsilon_{\odot}$
Mass $M$	$2 \times 10^{13}h^{-1} M_{\odot}$	$10^{15}h^{-1} M_{\odot}$



# おとめ座銀河団 Virgo cluster



## Schechter form

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*}\right)^\alpha \exp\left(-\frac{L}{L^*}\right) dL$$

$$L^* \sim 10^{10} L_\odot$$

$$\Phi^* \sim 10^{-2} \text{Mpc}^{-3}$$

$$\alpha \sim -1.0$$



# CfA Survey

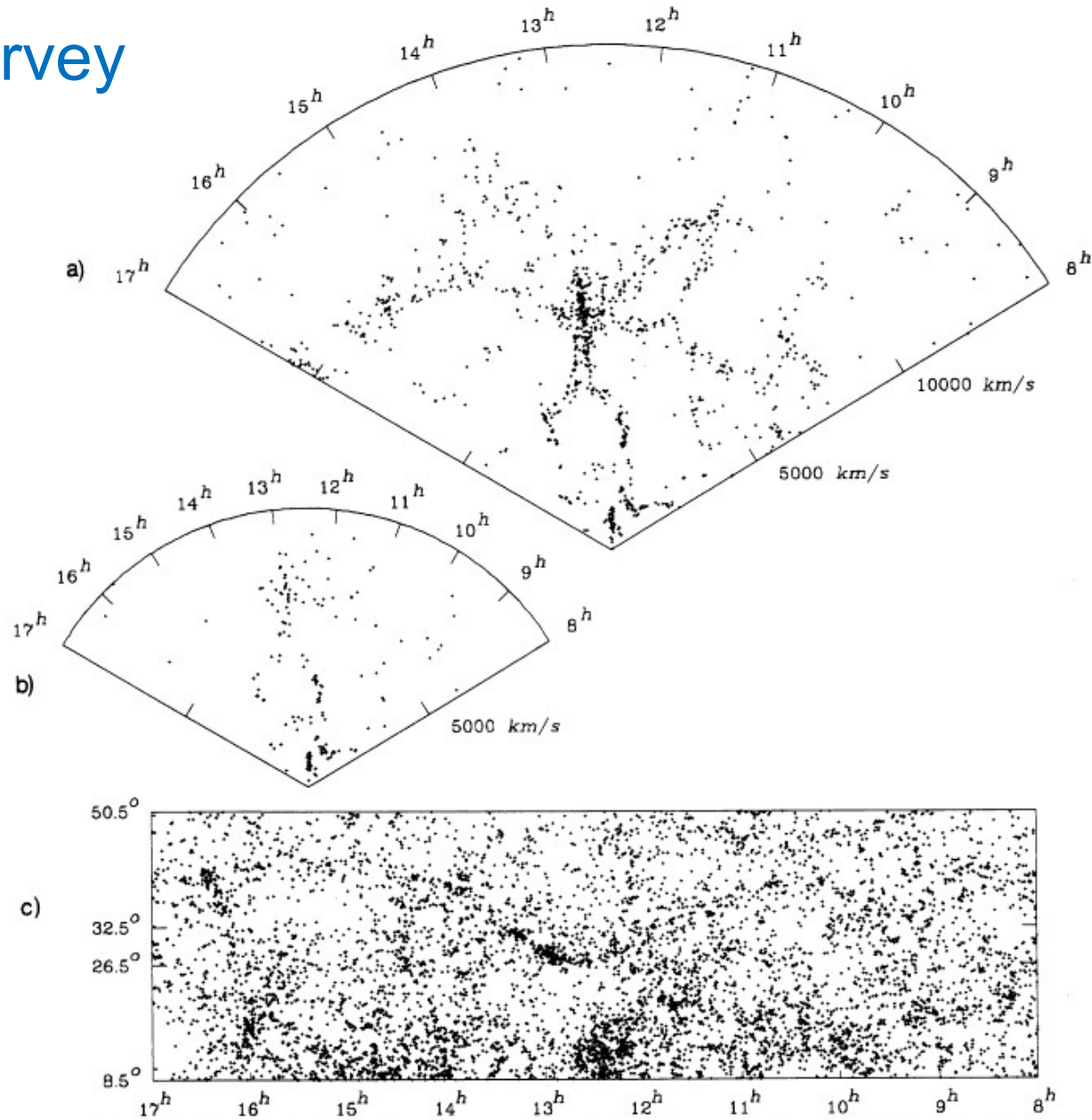
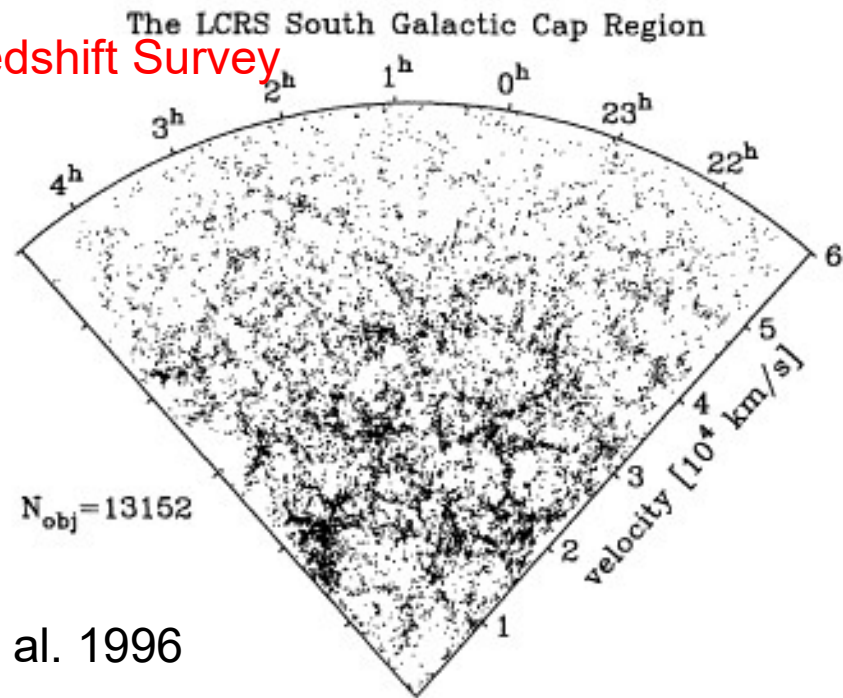
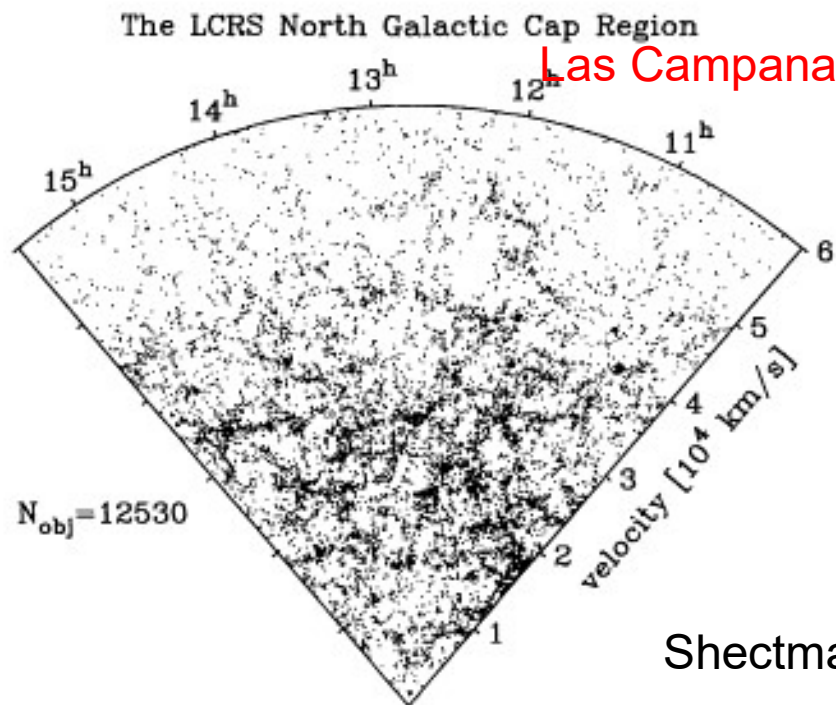


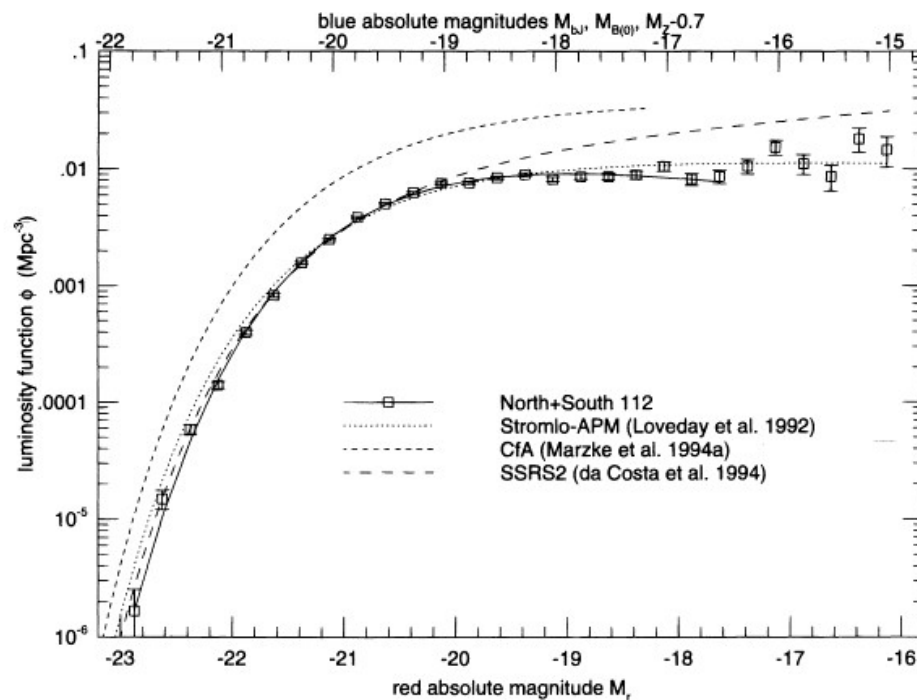
FIG. 1.—(a) Map of the observed velocity plotted vs. right ascension in the declination wedge  $26.5^\circ \leq \delta \leq 32.5^\circ$ . The 1061 objects plotted have  $m_B \leq 15.5$  and  $V \leq 15,000 \text{ km s}^{-1}$ . (b) Same as Fig. 1a for  $m_B \leq 14.5$  and  $V \leq 10,000 \text{ km s}^{-1}$ . The plot contains 182 galaxies. (c) Projected map of the 7031 objects with  $m_B \leq 15.5$ , listed by Zwicky *et al.* in the region bounded by  $8^h \leq \alpha \leq 17^h$  and  $8.5^\circ \leq \delta \leq 50.5^\circ$ .

Las Campanas Redshift Survey



Shectman et al. 1996

数密度  
( $1/\text{Mpc}^3$ )



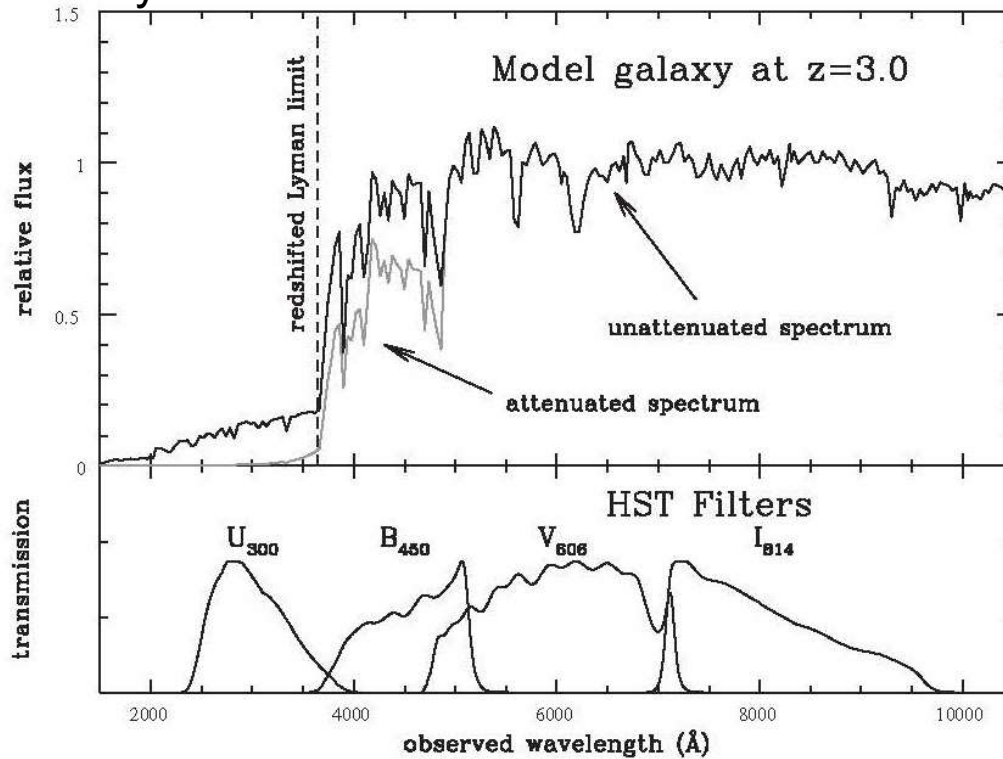
Lin et al. 1996

絶対等級

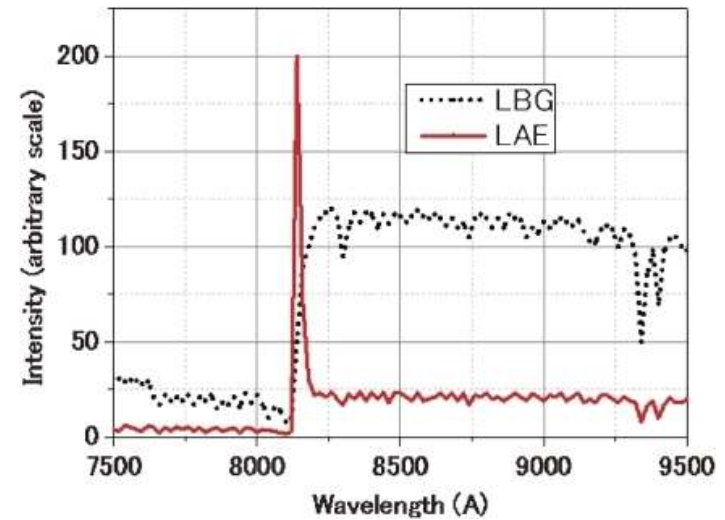
# Galaxies at high redshifts

## Lyman Break Galaxies (LBG)

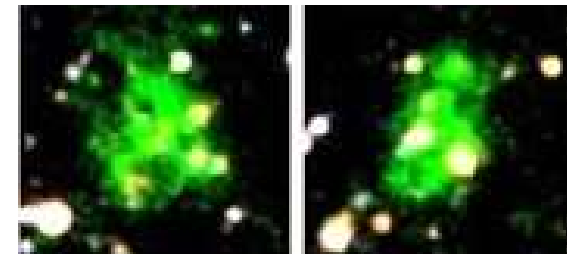
Lyman limit: 912 Å



## Lyman alpha Emitters (LAE)



## Lyman alpha Blob (LAB)



様々な観測から求められた宇宙における星形成史  
Madau & Dickinson (2014)

