Galaxies, Cosmology and Dark Matter

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Chapter 2

Galaxy Morphology and Classification

2.1 Galaxy Classification Schemes

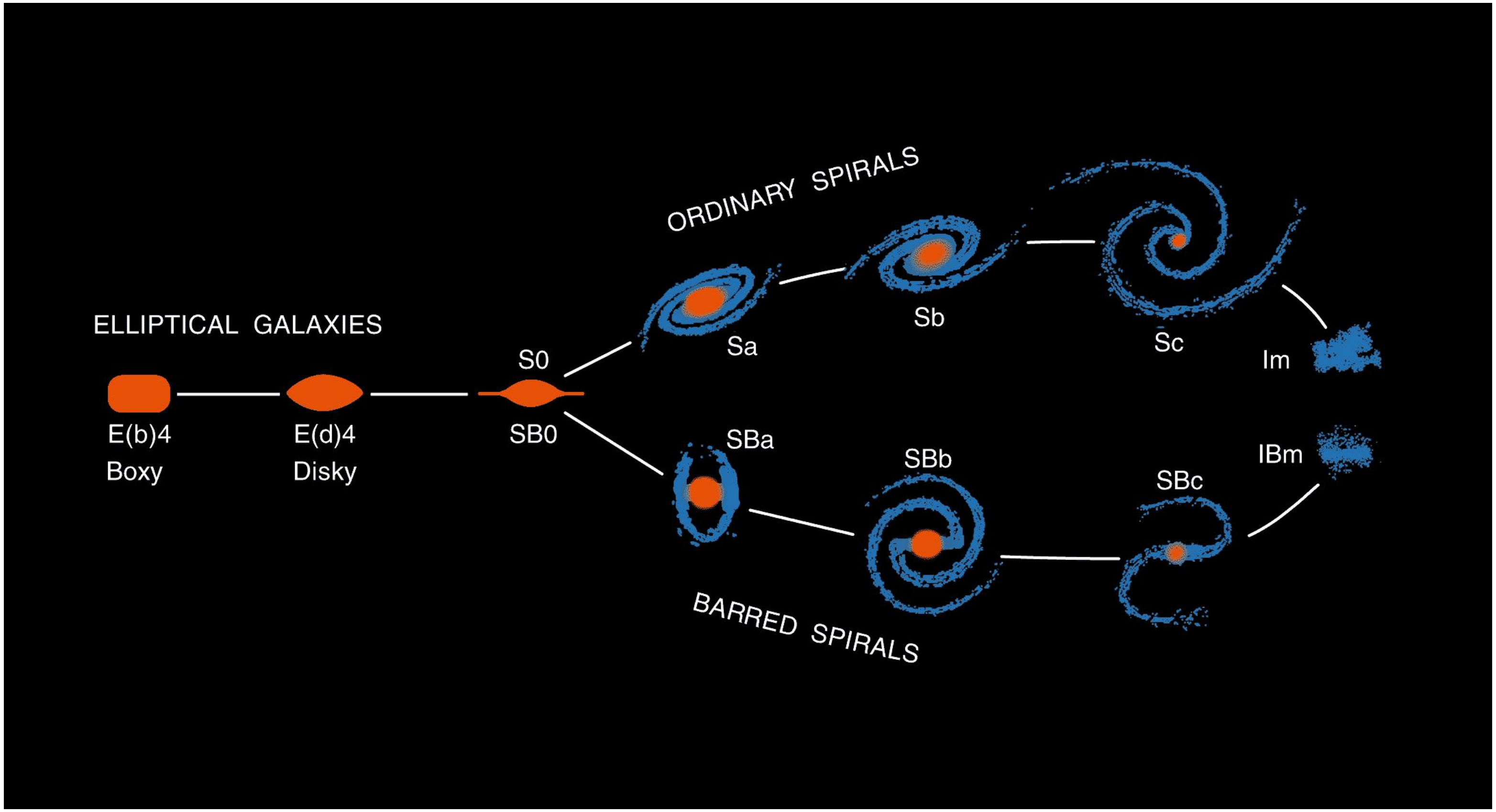
- Classification schemes usually based on a restricted and incomplete set of information (e.g. morphology in blue-band photography).
- Classical classifications schemes have biases of various sorts: optical bias, surface brightness bias, luminosity bias.
- Classification not always well-defined or unique.
- Nevertheless morphological classification is useful: The isolation of some fundamental properties of galaxies provides guidance to pose questions that result in quantitative analysis and better physical understanding of the objects.

- Examples of classification schemes:
  - Hubble-Sandage (1936)
  - de Vaucouleurs (1959)
  - van den Bergh (1960/66)
  - Yerkes (Morgan, 1957 ff)
  - ...
- Primary classification criteria of commonly used Hubble-Sandage system:
  - Disk-to-bulge ratio
  - Opening angle of spiral arms
  - Bars

Classification Schemes:

System	Principal criteria	Symbols	Examples
Hubble-Sandage (Sandage (1961-1995))	barrishness; openness of arms/disk-bulge ratio; degree of resolution of arms into stars	E, S0, S, SB, Irr a, b, c	M87=E1 M31=Sb M101=Sc LMC=Irr I
De Vaucouleurs (de Vaucouleurs (1959))	barrishness; openness of arms/disk-bulge ratio; rings or s shapes	E, S0, S, SA, SB, I a, b, c, d, m (r), (s)	M87=E1P M31=SA(s)b M101=SAB(rs)cd LMC=SB(s)c
Yerkes (Morgan (1958-1970))	central concentration of light; barishness/smoothness	k, g, f, a E, R, D, S, B, I	M87=kE1 M31=kS5 M101=fS1 LMC= afI2
DDO (van den Bergh (1960-1976))	richness of disk in young stars; barrishness; central concentration of light; quality and length of arms	E, S0, A, S, Ir B a, b, c I, II,. . . , V	M87=E1 M31=Sb I-II M101=Sc I LMC=Ir III-IV

Hubble Sequence (Revised for Ellipticals):



see: Kormendy J., Bender R. (1996) *ApJ*, **464**, L119

de Vaucouleurs' Classification Scheme:

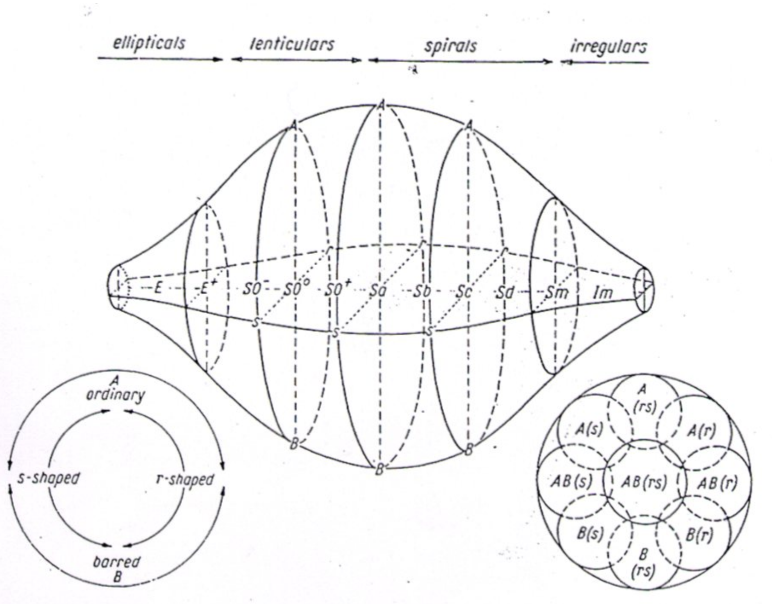


Figure 1. - The basic Hubble-Sandage-de Vaucouleurs classification scheme. Hubble's (1936) well known tuning-fork diagram (upper panel) was a two-dimensional classification. The lower panel shows the three-dimensional classification volume envisaged by de Vaucouleurs (1959a). There is a continuous sequence of classes (E, S0, Sa-m, Im) horizontally, families (SA, SAB, SB) vertically and varieties [(r), (rs), (s)] perpendicular to the page. For classification purposes this continuum is somewhat arbitrarily divided into discrete cells (lower right).

see: Kormendy J. (1982) *12th Saas-Fee Course*

de Vaucouleurs' Numeric Type:

Stage t	Type T	q_0	Notes
-6	E^{-}	0.33	Compact E
-5	E		Plus dE
-4	E^{+}	0.29	Morgan cD's
-3	L^{-}	0.26	Lenticulars
-2	L^{0}	0.23	Lenticulars
-1	l^{+}	0.21	Lenticulars
0	S0/a	0.19	also IO's
1	Sa	0.17	
2	Sab	0.15	
3	Sb	0.13	
4	Sbc	0.12	
5	Sc	0.11	
6	Scd	0.09	
7	Sd	0.08	
8	Sdm	0.12	
9	Sm	0.16	
10	Im	0.20	plus dIm
11	Im^{+}	$\ldots$	Compact Im

Type	LC=	I	II	III	IV	V	VI
Sb	$M_p =$	-20.4	-19.4	-18.0			
Sc, Irrl	$M_p =$	-20.0	-19.4	-18.3	-17.3	-16.1	-15

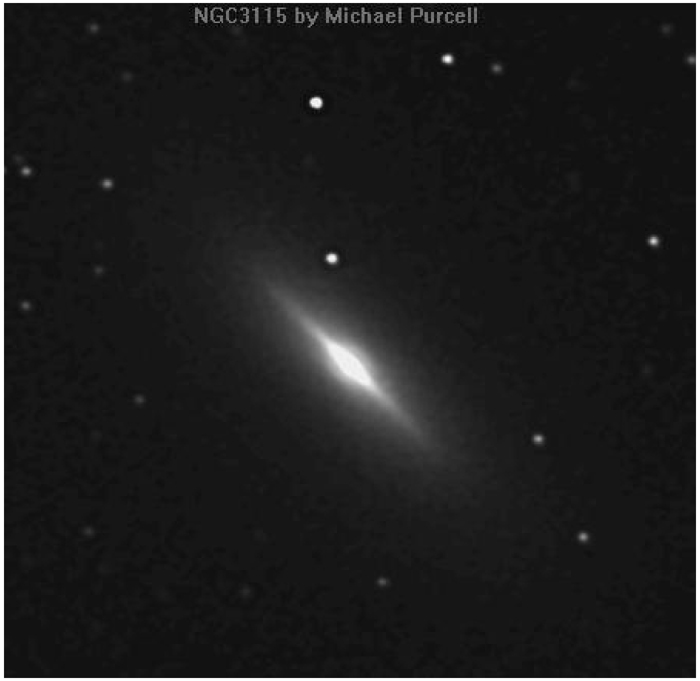
Examples for Normal Galaxies:

Elliptical (E) Galaxies:

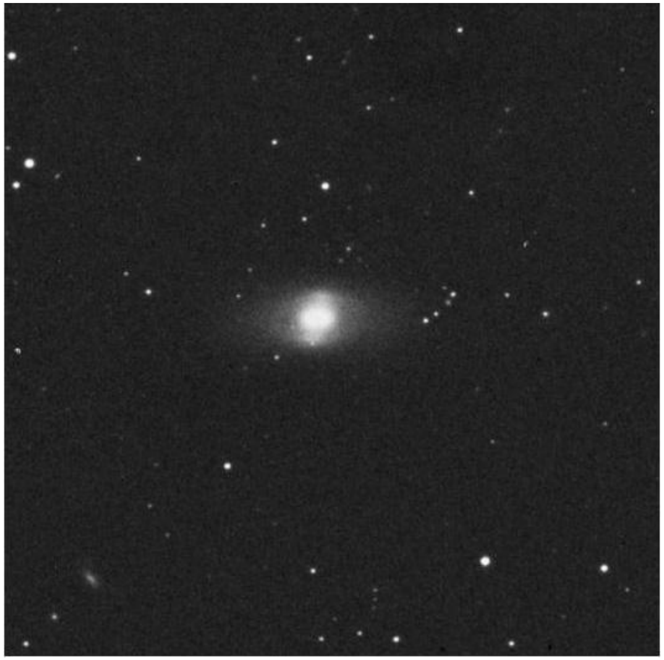
M 87: E0-galaxy

M 110: E6-galaxy

Lenticular (S0) Galaxies:



NGC 3115: S0-galaxy



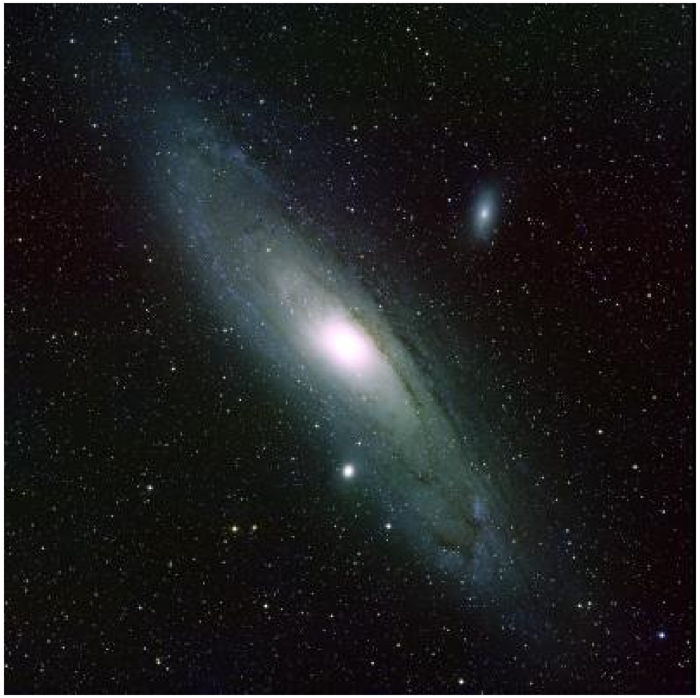
NGC 4371: SB0-galaxy

Spiral (Sa) Galaxies:

NGC 3223: Sa-galaxy

M 104 (Sombrero), Sa-galaxy
(P. Barthel, VLT)

Spiral (Sb) Galaxies:



M 31 (Andromeda-galaxy):
Sb-galaxy

M 81: Sb-galaxy

Spiral (Sc) Galaxies:

M 51: Sc-galaxy

courtesy: C. Gössl, Wendelstein Observatory, USM

M 101: Sc-galaxy

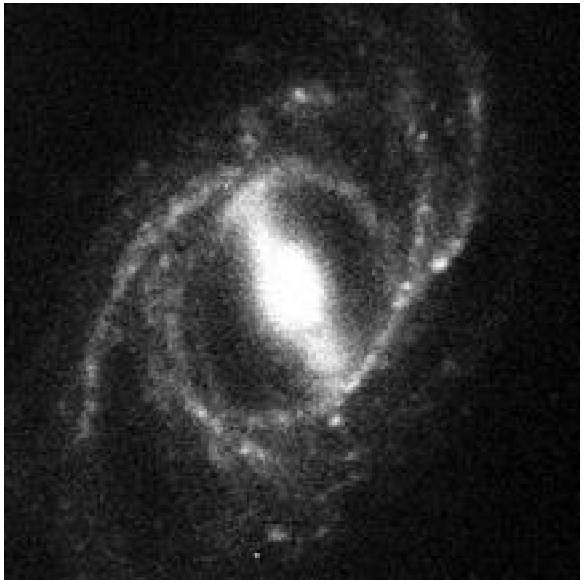
courtesy: C. Gössl, Wendelstein Observatory, USM

Barred-Spiral (SBa) Galaxies:

M 83 (Southern Pinwheel):
SBa-galaxy

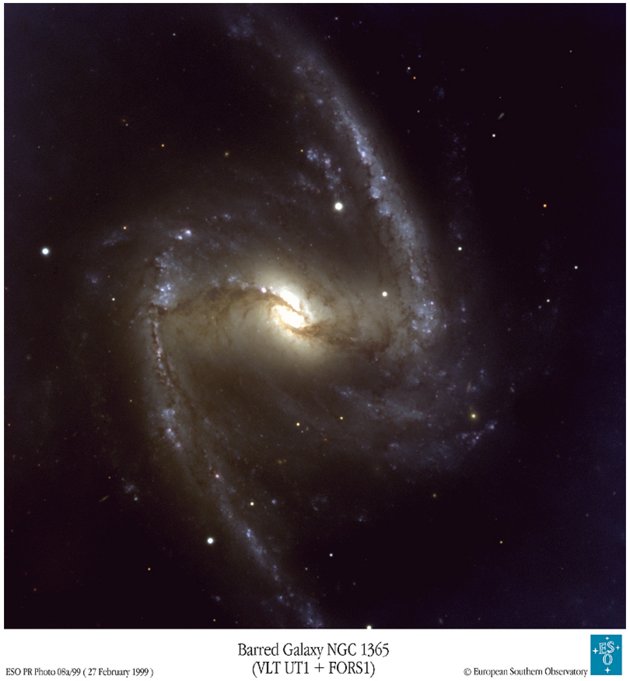
Barred-Spiral (SBb) Galaxies:

M 95: SBb-galaxy



NGC 2523: SBb-galaxy

Barred-Spiral (SBc) Galaxies:



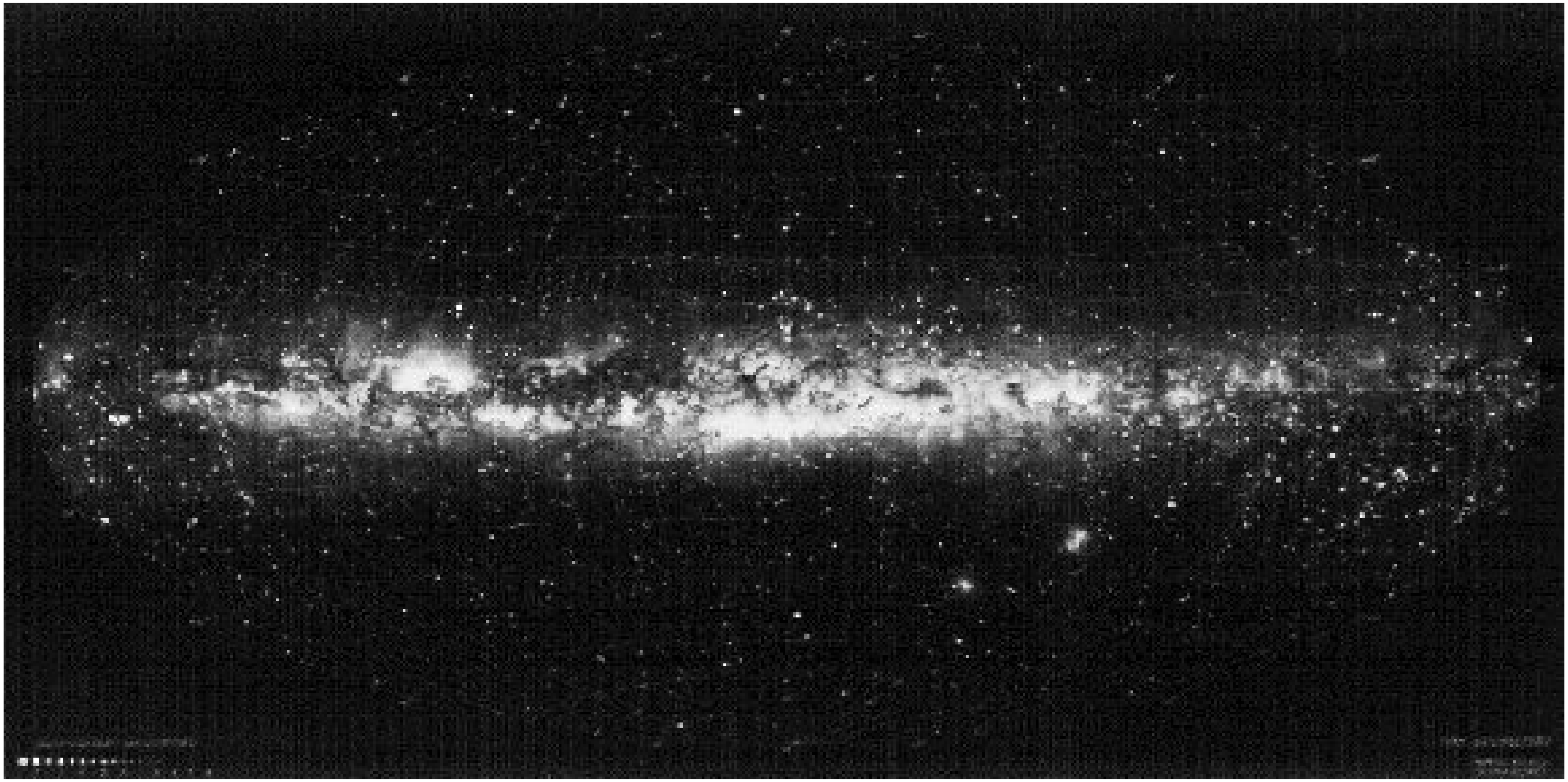
NGC 1365: SBc-galaxy

NGC 613: SBc-galaxy

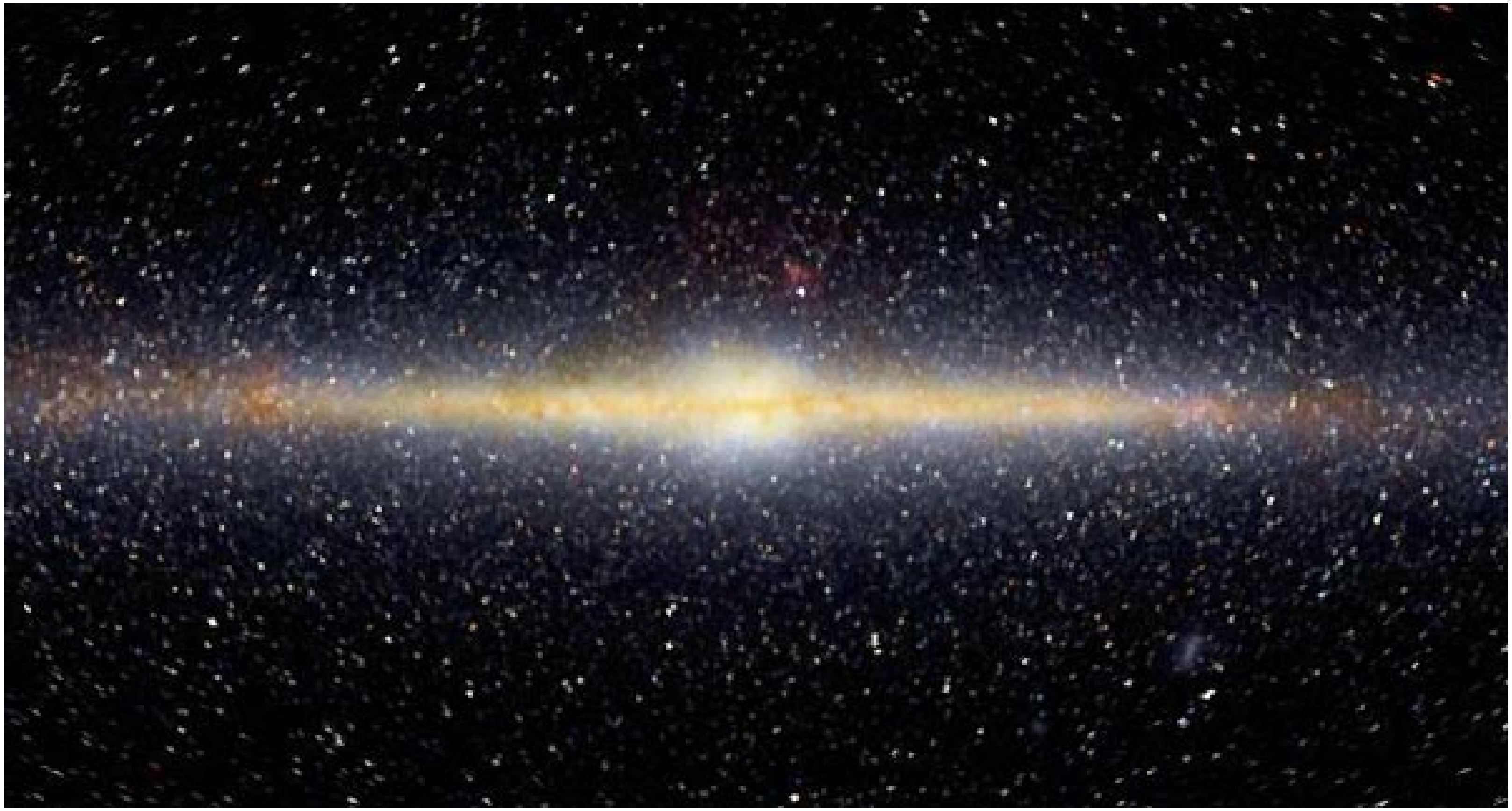
Irregular (Irr) Galaxies:

LMC: Irr-galaxy

SMC: Irr-galaxy



Milky Way, Sbc-galaxy (all-sky projection in optical)



Milky Way, Sbc-galaxy (all-sky projection in near IR, COBE satellite)

2.2 Luminosities of Bulges and Disks

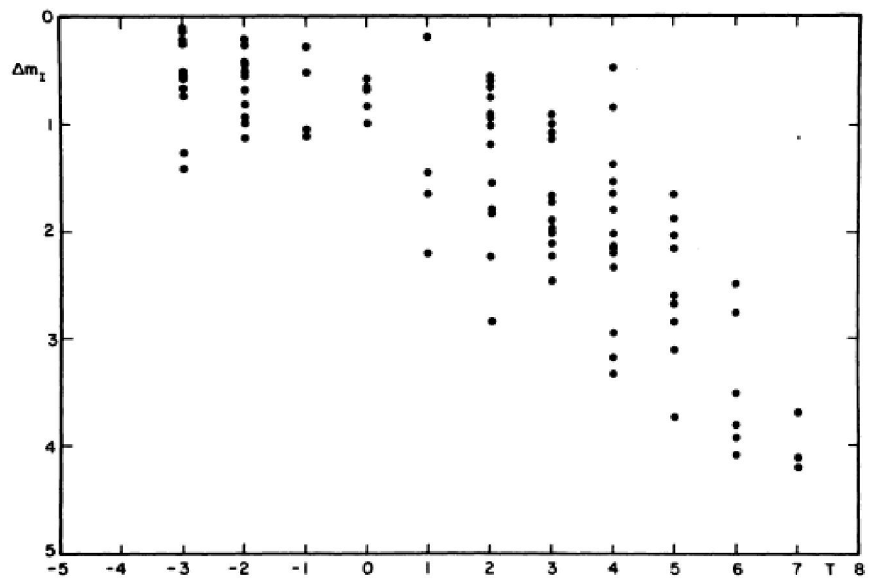


FIG. 2.—Fractional luminosity of spheroidal component expressed as magnitude difference $\langle \Delta m_I \rangle$ between spheroid and galaxy as a whole. Individual values vs. morphological type T (stage along revised Hubble sequence). Most of the scatter ($\sigma \approx 0.7$ mag) is due to photometric and decomposition errors, with little contributions from classification errors or cosmic scatter.

see: Simien, de Vaucouleurs (1986) *ApJ*, **302**, 564

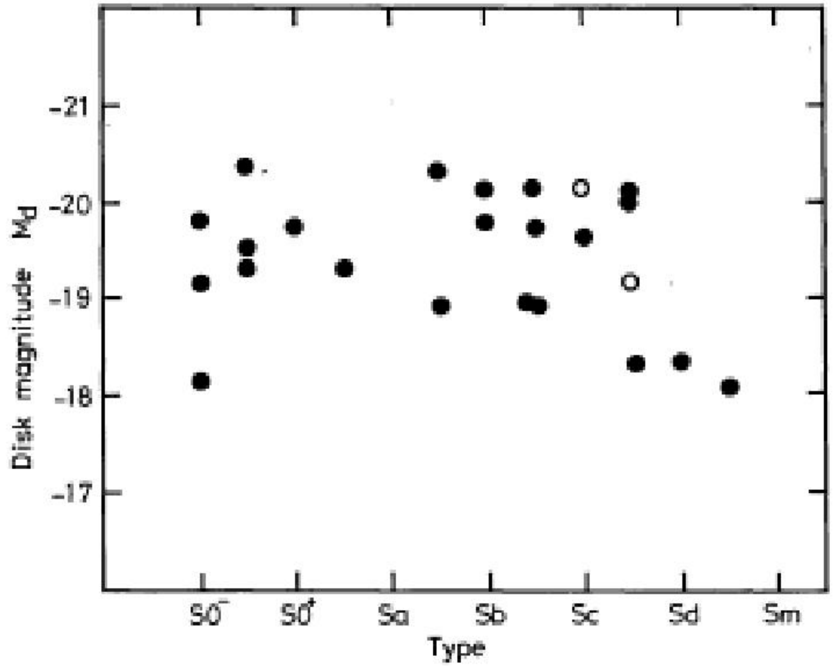


Fig. 1. Absorption-free, absolute magnitude of the disk, M_d, defined by Eq. (2), against the morphologic type. Open circles are of type II luminosity profile

see: Yoshizawa, Wakamatsu (1975) *A&A*, **44**, 363

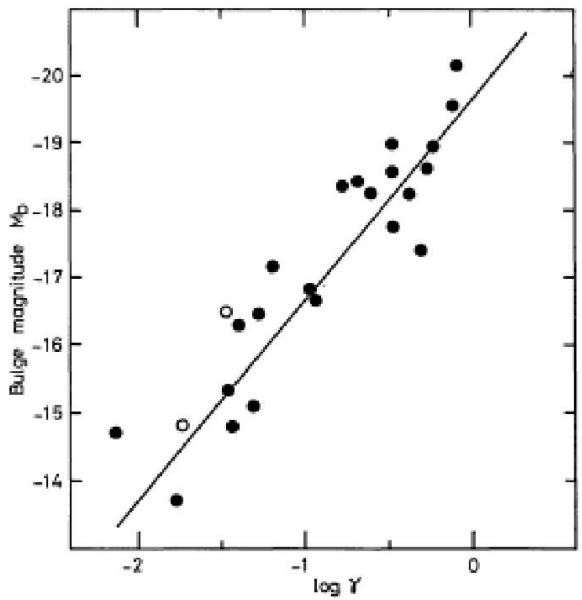


Fig. 3. Absorption-free, absolute magnitude of the bulge, M_b, plotted against log γ. Straight line represents the least squares fit [Eq. (3)]. Open circles are of the same meaning as in Fig. 1 and are omitted in the least squares fit

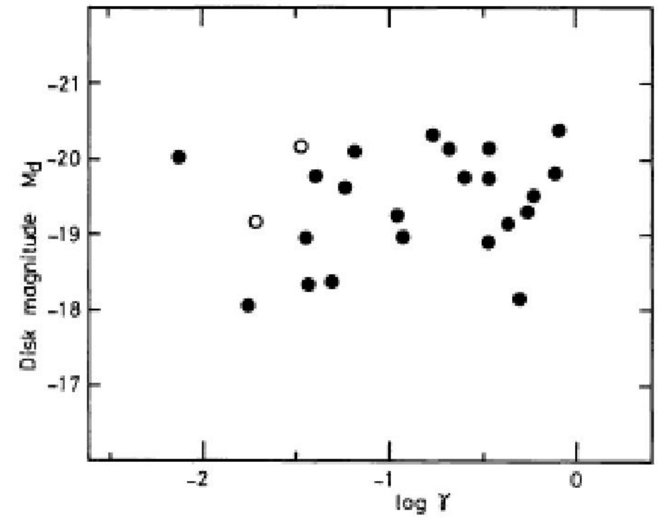


Fig. 4. Absorption-free, absolute magnitude of the disk, M_d, plotted against log γ. Open circles are of the same meaning as in Fig. 1. Note that no correlation can be seen in contrast to in Fig. 3

$$\gamma = \frac{\text{bulge luminosity}}{\text{total luminosity}}$$

see: Yoshizawa, Wakamatsu (1975) *A&A*, **44**, 363

From these figures (fig1, fig3, fig4) it follows, that the Hubble sequence is primarily a bulge sequence

2.3 Pitch Angle as a Function of the Hubble-Type

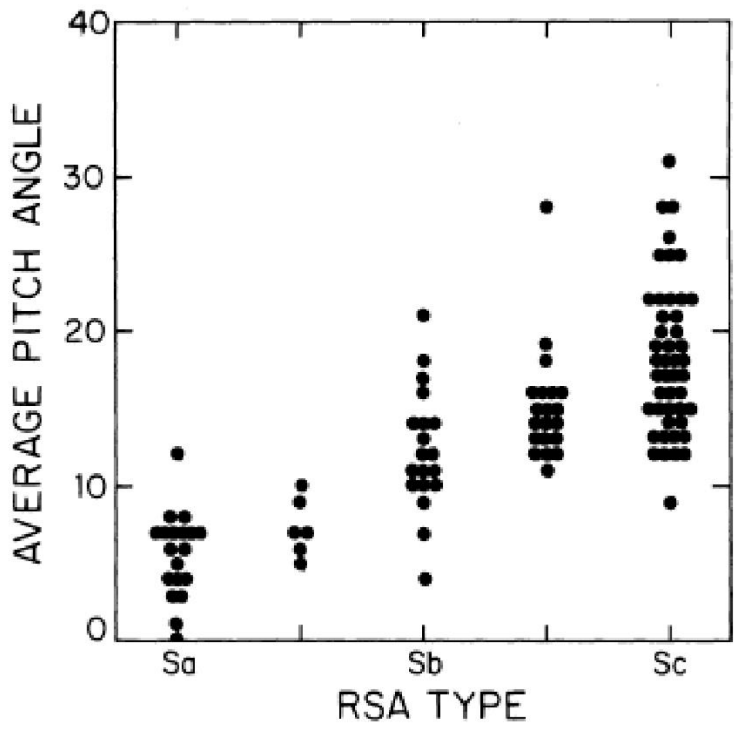


FIG. 7. Measured pitch angle vs Hubble type, the latter from Sandage and Tammann.

see: Kennicutt (1981) *AJ*, **86**, 1847

2.4 Other Galaxy Types

Classical classification systems are incomplete regarding:

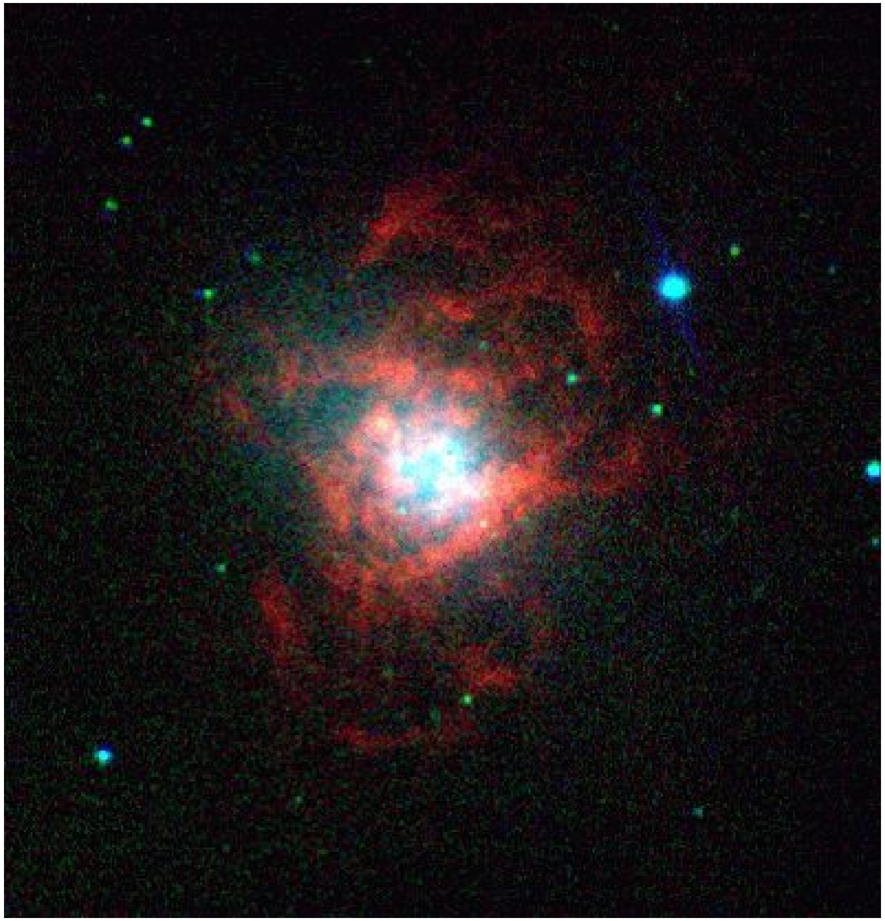
- dwarf galaxies:
  dE: dwarf ellipticals or dwarf spheroidals, similar to E but low luminosity and low surface brightness
  BCD: Blue Compact Dwarfs, concentrated starburst, few old stars
- some extreme types:
  cD-galaxies: Yerkes classification for “extra (c) large and diffuse (D)” galaxies, found in the centers of clusters and groups
  low surface brightness (LSB) galaxies: luminous but very low surface brightness disks
- active galaxies: radio galaxies; galaxies with unusual nuclear emission lines and/or extreme nuclear luminosity (QuasiStellarObjects-QSOs, Seyfert galaxies) and/or with powerful non-thermal radio emission (radio galaxies, quasars)
- interacting, merging and starbursting galaxies

Dwarf Galaxies:

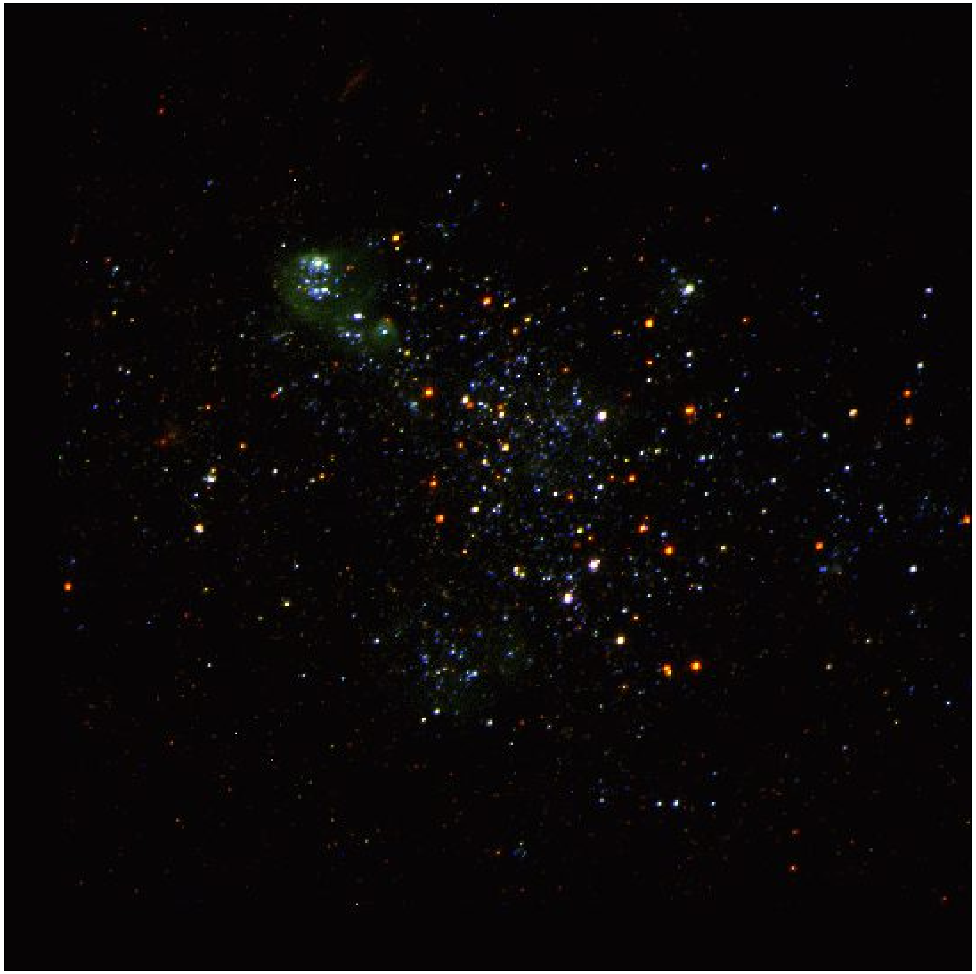
Leo 1, dwarf elliptical (dwarf spheroidal) companion of Milky Way

Sculptor dwarf,
dwarf elliptical
companion of Milky Way

from: Anglo Australian Observatory



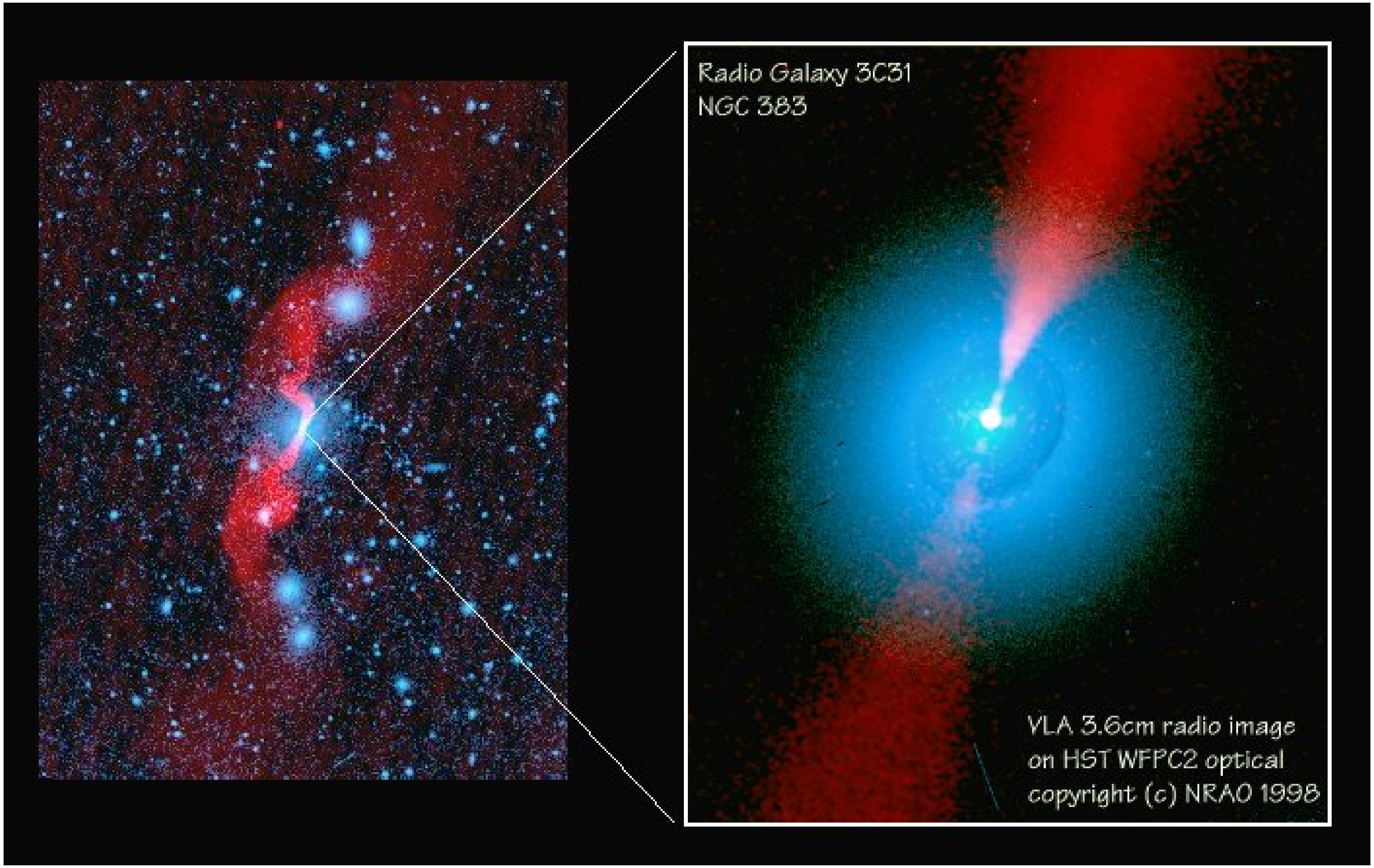
Blue Compact Dwarf (BCD) NGC 1705, blue: blue continuum, green: red continuum, red: Hα (G. Meurer)



UGC 6456, nearby irregular dwarf, real color (U. Hopp)

Active Galaxies:

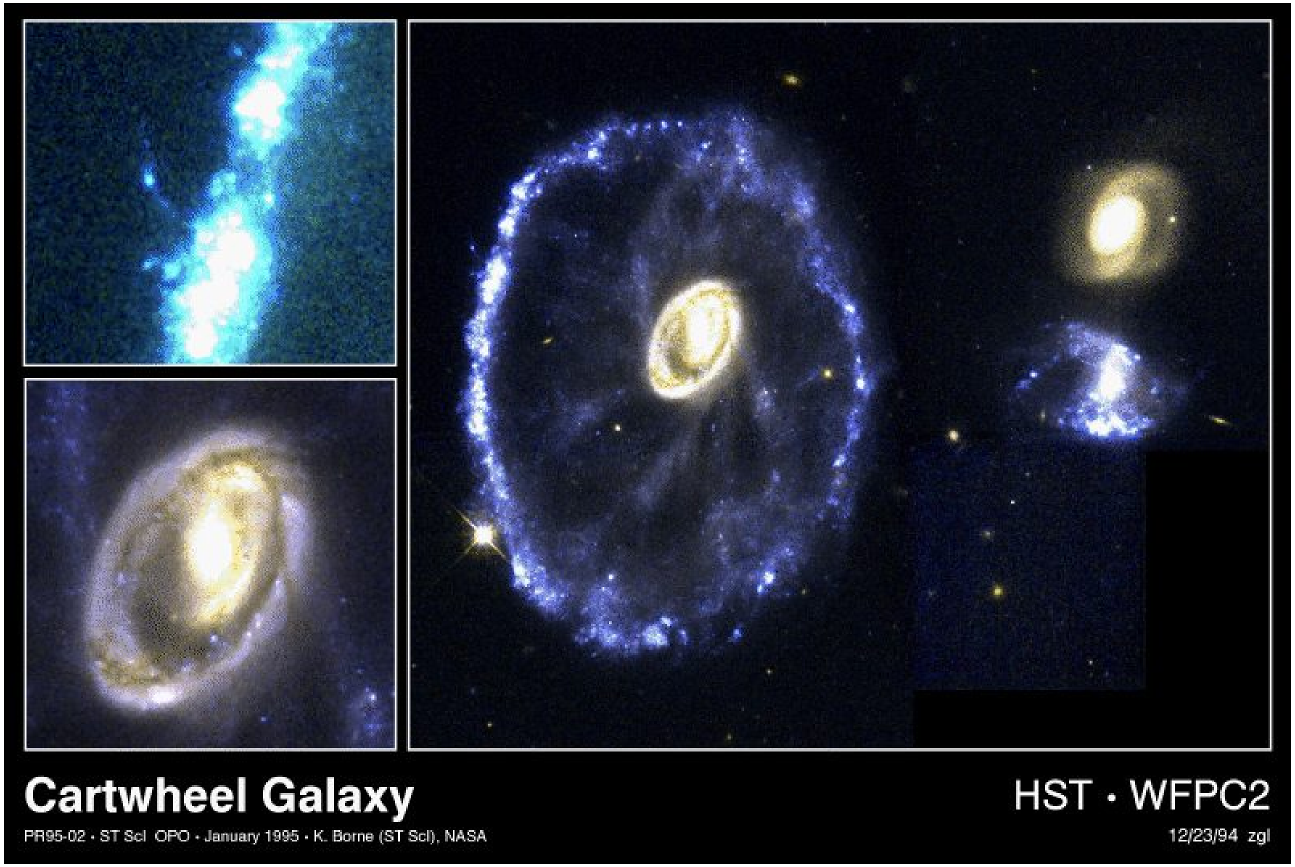
NGC 7742, a Seyfert galaxy



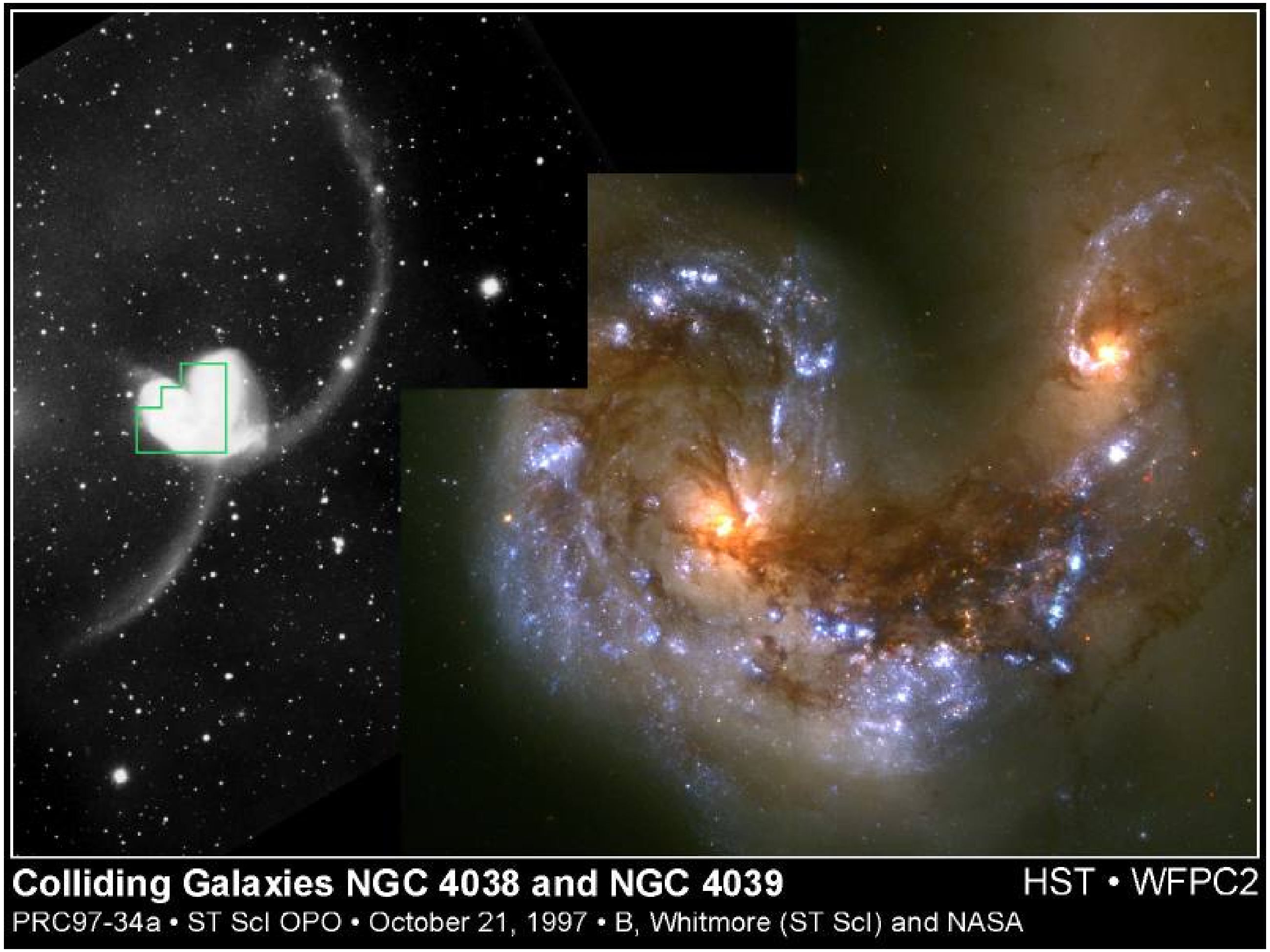
NGC 383 (= 3C31), a radio galaxy, blue: optical, red: radio (A. Bridle)

The currently most distant object known,
a quasar at redshift 5.8 (April 2000, Sloan Digital Sky Survey)

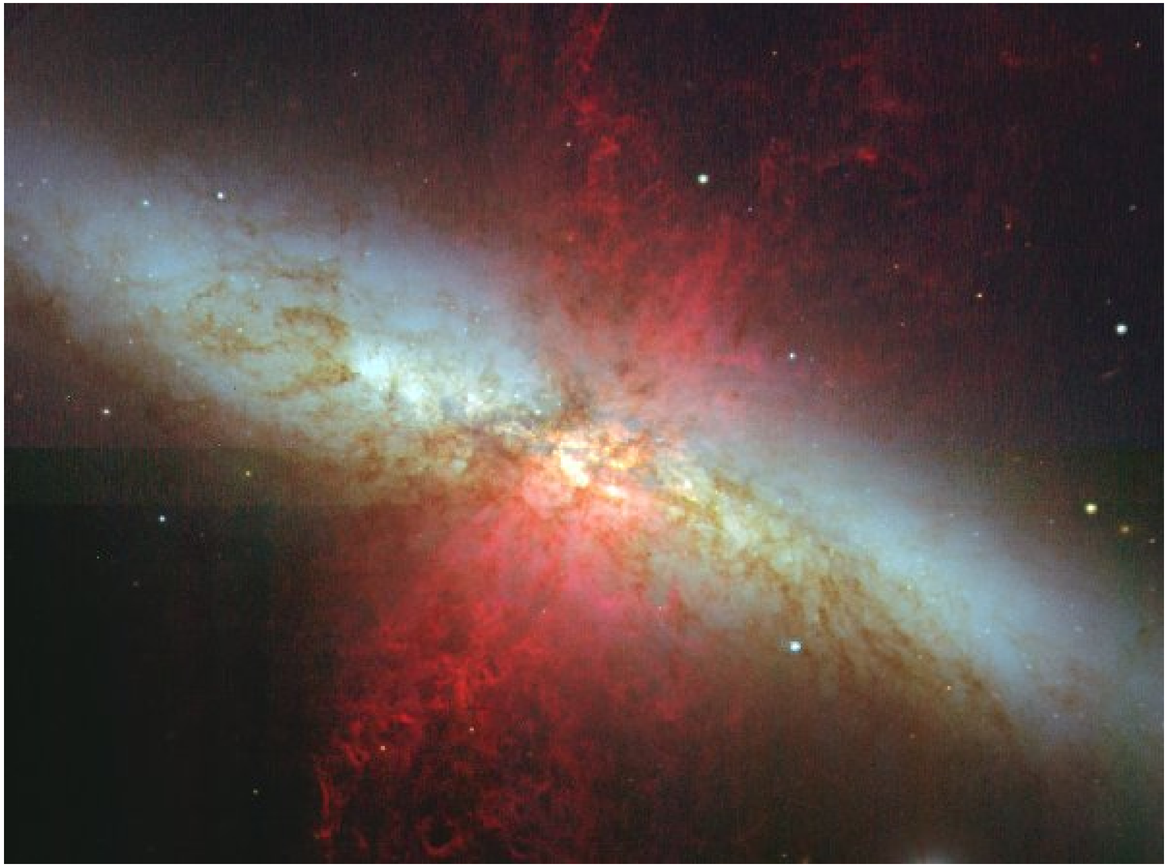
Interacting, Merging and Starbursting Galaxies:



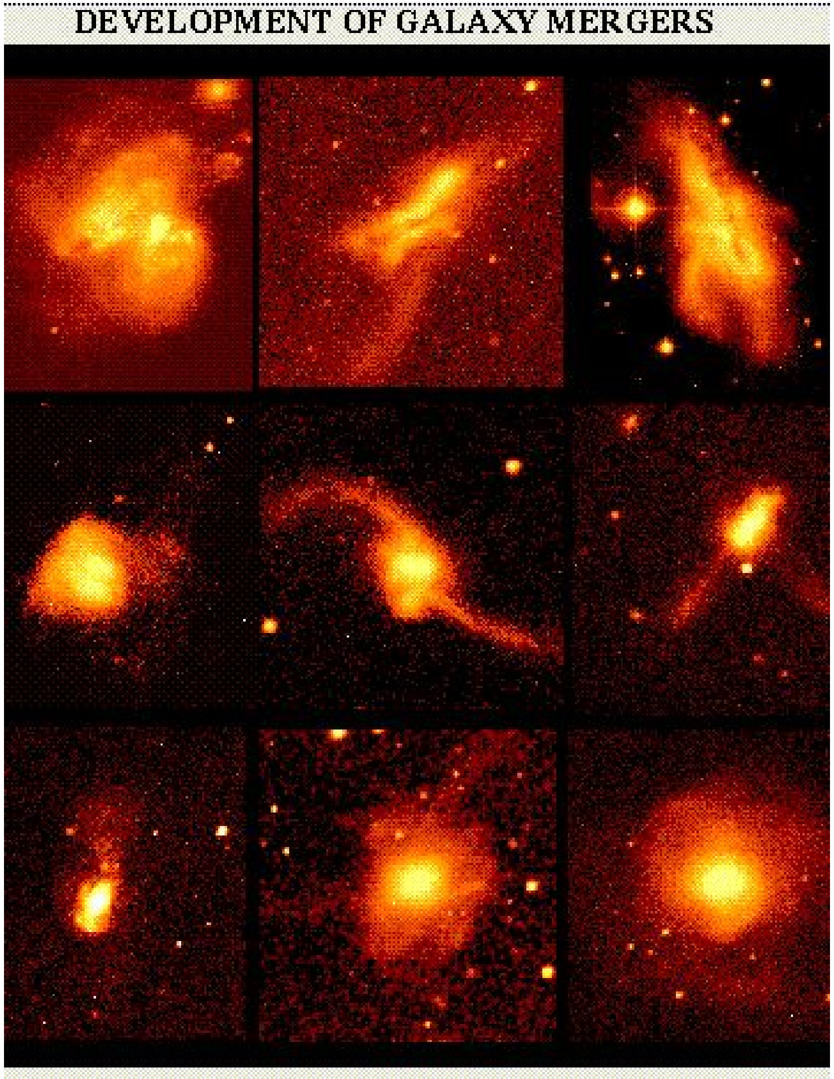
Cartwheel galaxy



Antenna galaxies



M 82, a starburst galaxy, white/brown: stellar light and dust, red: hot expanding gas in Hα (Subaru telescope)



Various evolutionary steps of spiral-spiral mergers

Luminosity and Surface Brightness Bias:

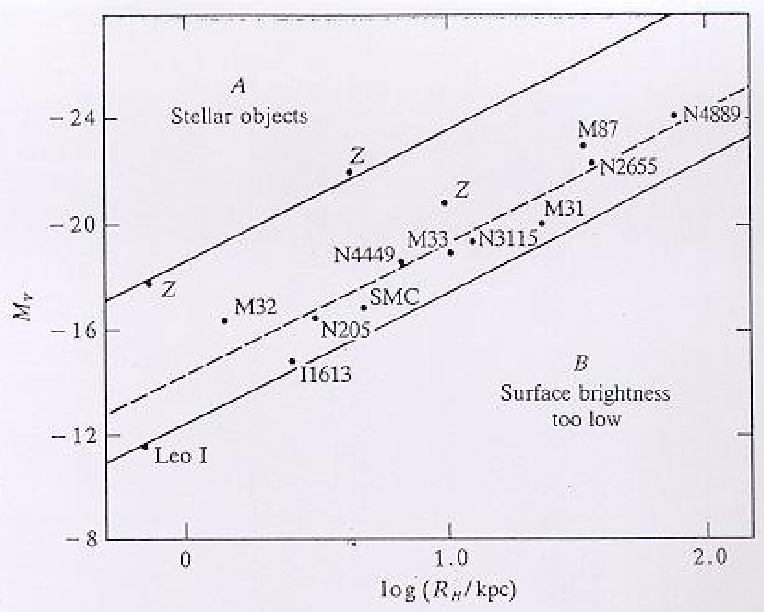
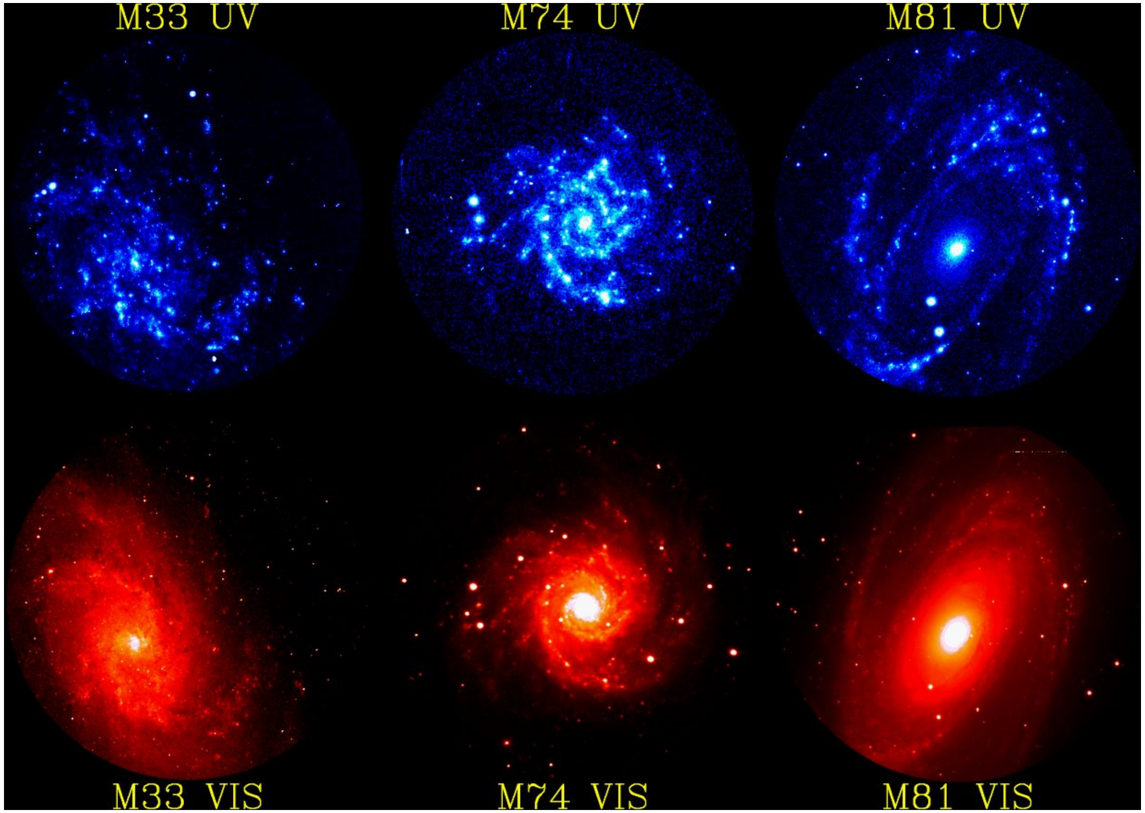


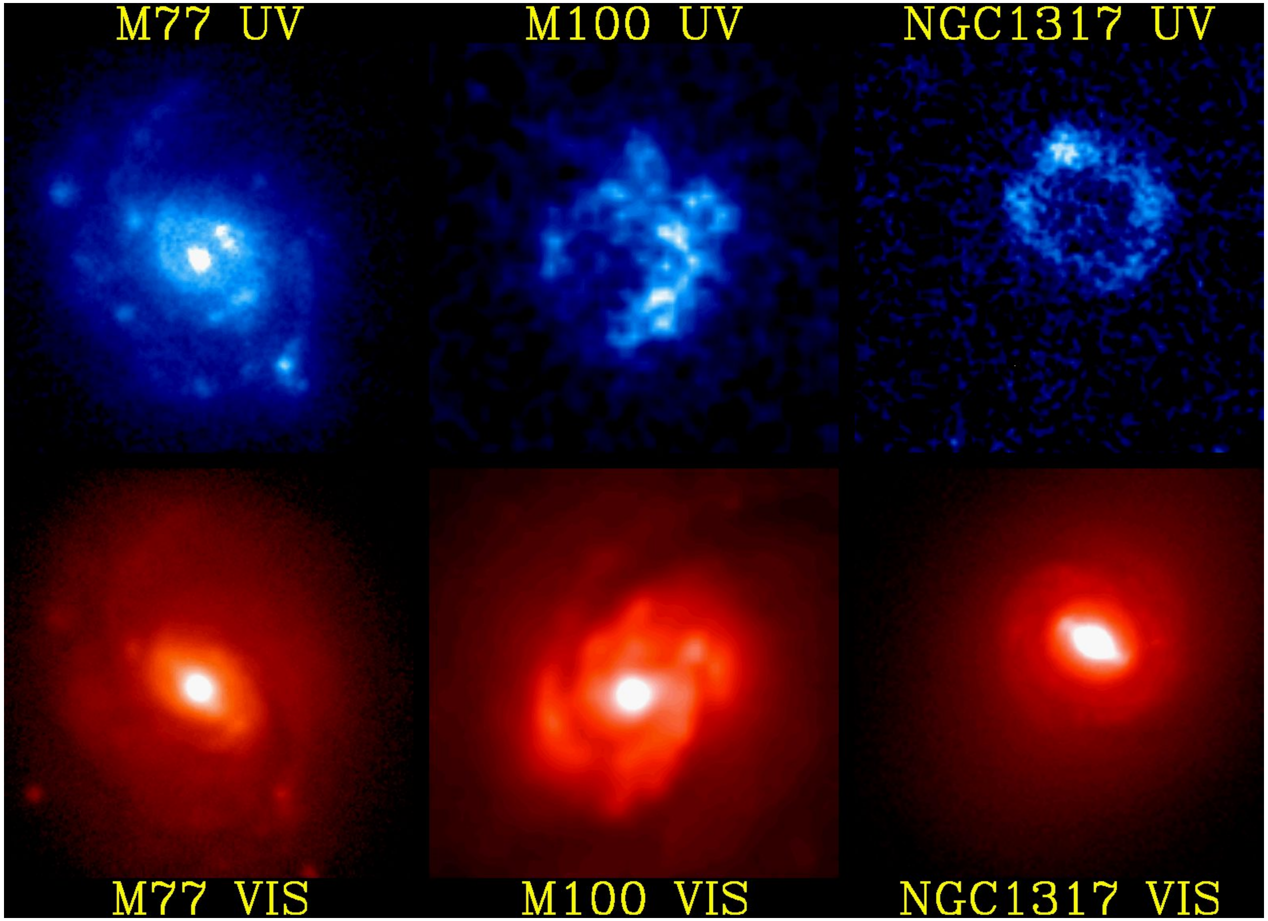
Figure 5-47. Observed galaxies might not be typical of all extragalactic objects. Here we plot the absolute magnitude of a number of galaxies against their Holmberg radii (both based on a Hubble constant $H = 50$ km s^{-1} Mpc^{-1}). Most objects whose representative points fell in region *A* would be indistinguishable from stars, while objects whose representative points fall in region *B* will not be visible against the brightness of the night sky. Notice that the swath of detectibility is well populated. The points marked *Z* are compact galaxies discovered by Zwicky (Z2). [After (A7).]

see: Mihalas / Binney: Galactic Astronomy

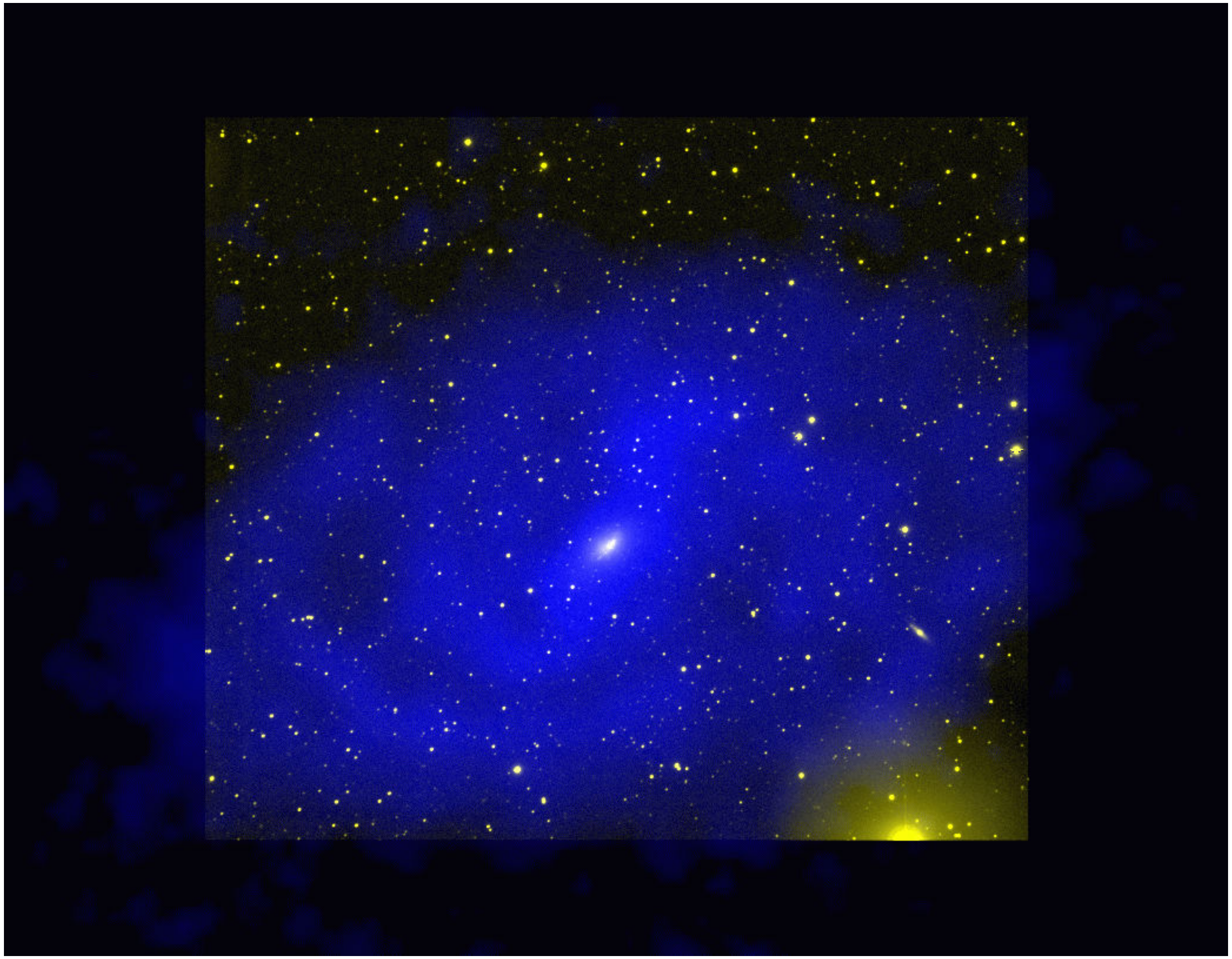
Galaxies at Non-optical Wavelengths:



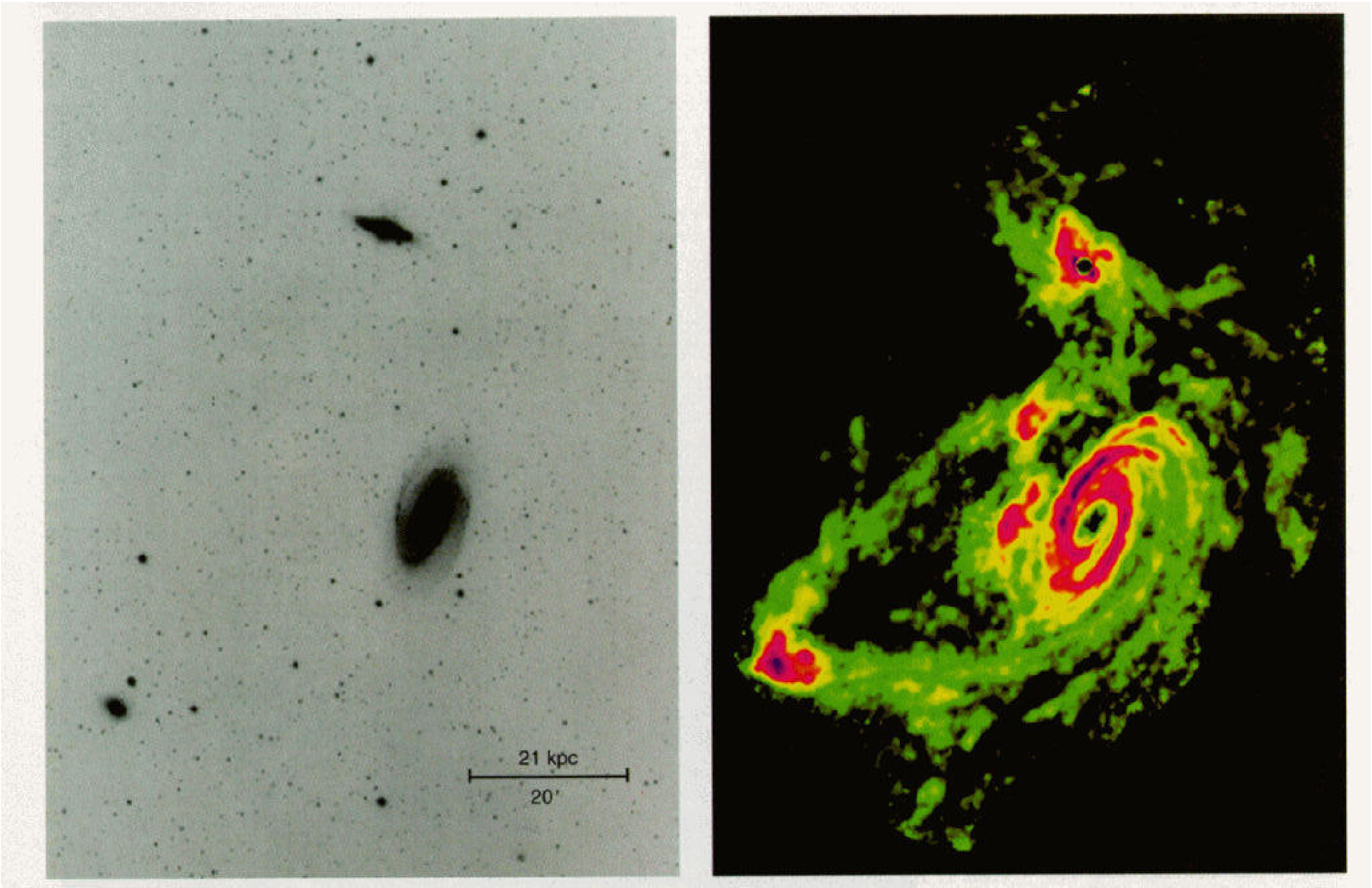
Spirals in ultraviolet (dominated by massive stars) and visual (average population), Ultraviolet Imaging Telescope, Astro mission.



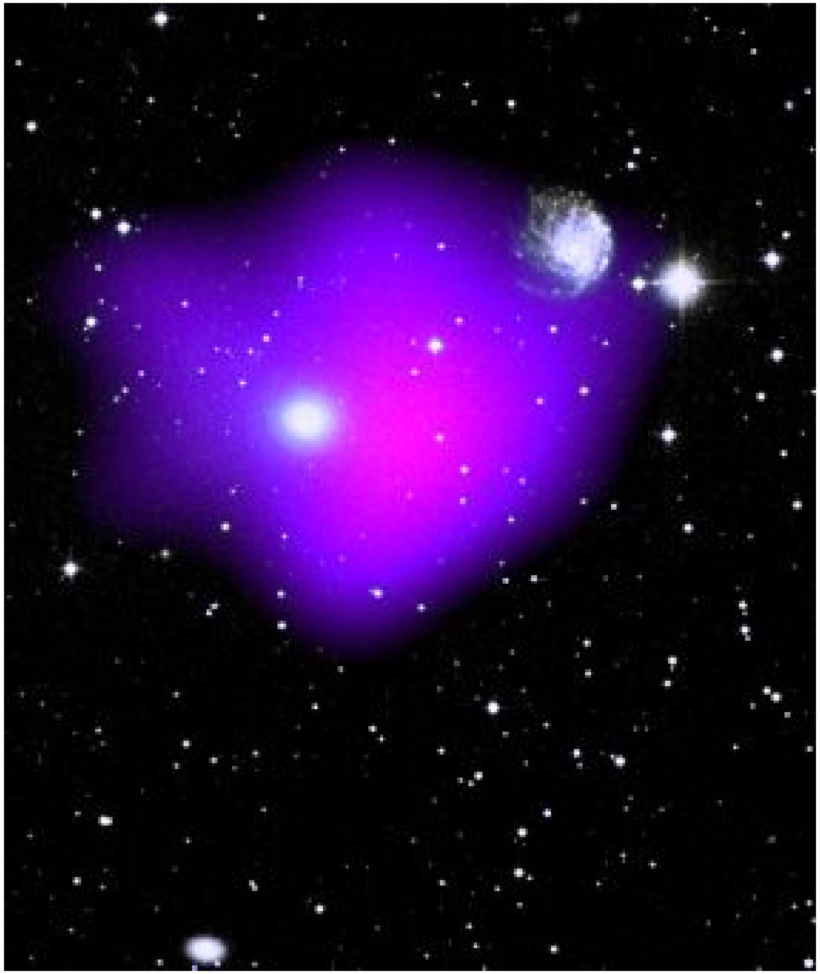
Spirals in ultraviolet (dominated by massive stars) and visual (average population), Ultraviolet Imaging Telescope, Astro mission.



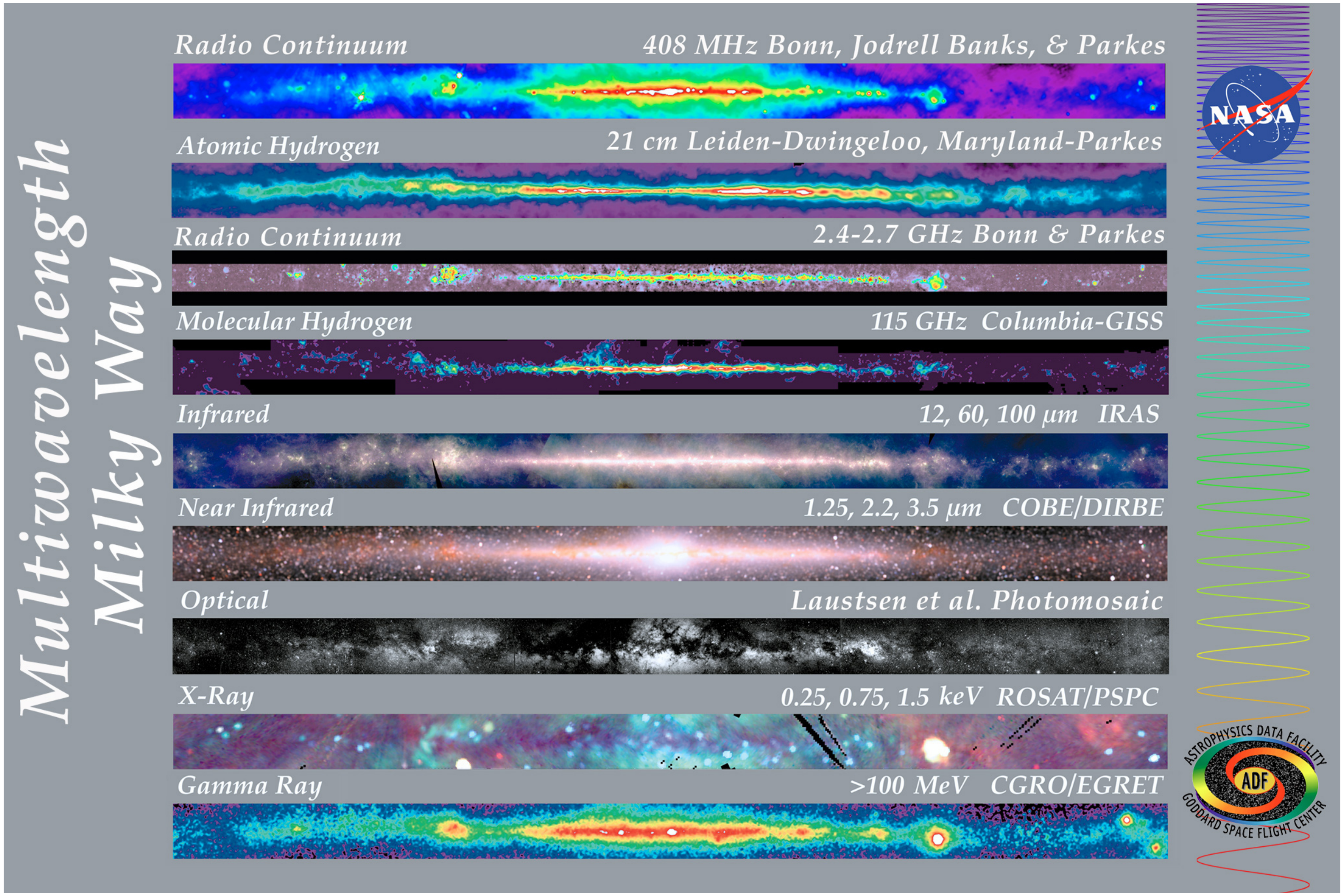
Dwarf irregular NGC 2915, yellow: optical, blue: HI



optical M81-group HI



NGC 2300 group, black&white: optical, blue/pink: X-rays



Milky Way (Sbc-galaxy) in different wavebands

Colours of Galaxies:

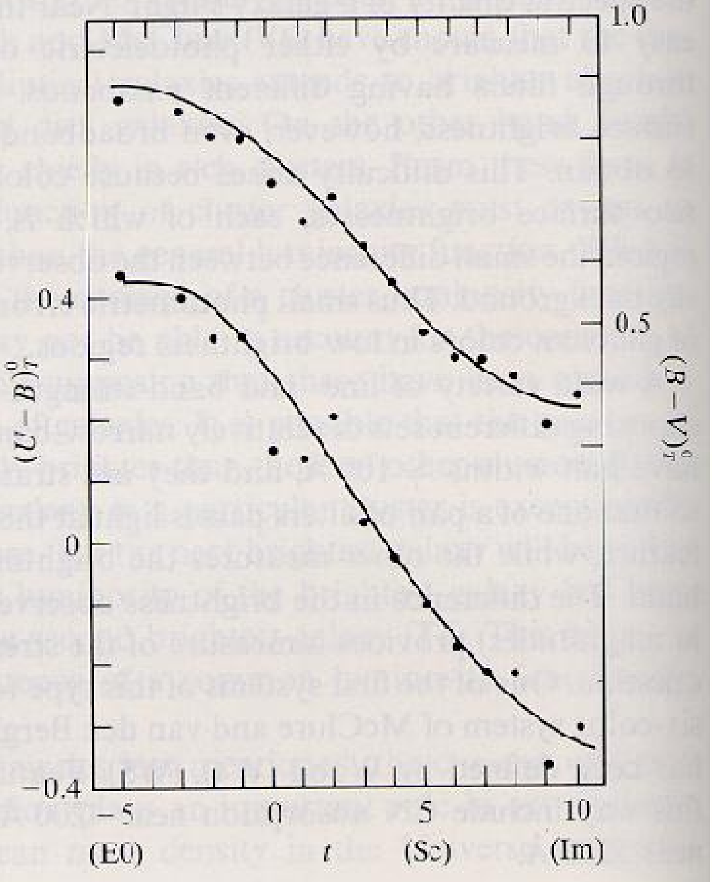


Figure 5-36. Early-type galaxies are redder than late-type systems. This plot shows the mean corrected color indicies $(U-B)_T^0$ and $(B-V)_T^0$ of all galaxies of a given morphological type in the Second Reference Catalogue (**D7**). The dispersion of color within each Hubble class is typically $0^m.1$. [From (**D4**) by permission.]

2.5 Mass-Luminosity Ratios

Usually with reference to the luminosity in B (L_B) or the visual luminosity (L_V) and normalized to the sun.

$$\text{sun} : \quad \frac{M}{L} = 1 \frac{M_\odot}{L_{B,\odot}}$$

$$\text{stars} : \quad \log \frac{L}{L_\odot} \simeq 3.8 \log \frac{M}{M_\odot}$$

star with mass $M = 0.5 M_\odot$: $\frac{M}{L} \simeq 10 \frac{M_\odot}{L_\odot}$

star with mass $M = 2 M_\odot$: $\frac{M}{L} \simeq 0.1 \frac{M_\odot}{L_\odot}$

$\Rightarrow$ In star systems the luminosity is dominated by massive stars, the mass by low-mass stars (due to their longer lifetime and greater number).

The luminous parts of “normal” galaxies usually have:

$$\frac{M}{L} \simeq 6 \frac{M_\odot}{L_{V,\odot}} \simeq 10 \frac{M_\odot}{L_{B,\odot}}$$

This is also valid for the mean stellar-population in the solar neighborhood. Older populations and populations with higher metallicities have a higher $\frac{M}{L}$, younger and metal-poor populations have a lower $\frac{M}{L}$.

maximum range:

$$\boxed{2 \leq \frac{M}{L_B} \leq 20}$$

2.5.1 Luminosity Function of Schechter

see: Schechter P. (1976) *ApJ*, **203**, 297

- global fitting function for all galaxies
  (individual types do not follow the Schechter-function)

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

- typical values (averaged over large volumes)

$$\begin{aligned} L_* &\simeq 10^{10} L_{B,\odot} h^{-2} \\ \text{or:} \quad M_{B,*} &\simeq -19.5 + 5\log h \\ \Phi_* &\simeq 0.01 Mpc^{-3} h^3 \\ \alpha &\simeq -1 \ldots -1.3 \quad \text{(see Peebles 1993)} \end{aligned}$$

with: $h = \frac{H_0}{100 \frac{km/s}{Mpc}}$ and $M_B = -2.5 \log \frac{L}{L_{B,\odot}} + 5.48$

- $\Phi\left(\frac{L}{L_*}\right) dL$ is the number density of galaxies with luminosities in the range $(L, L + dL)$
(strong variation of Φ_* depending on environment)

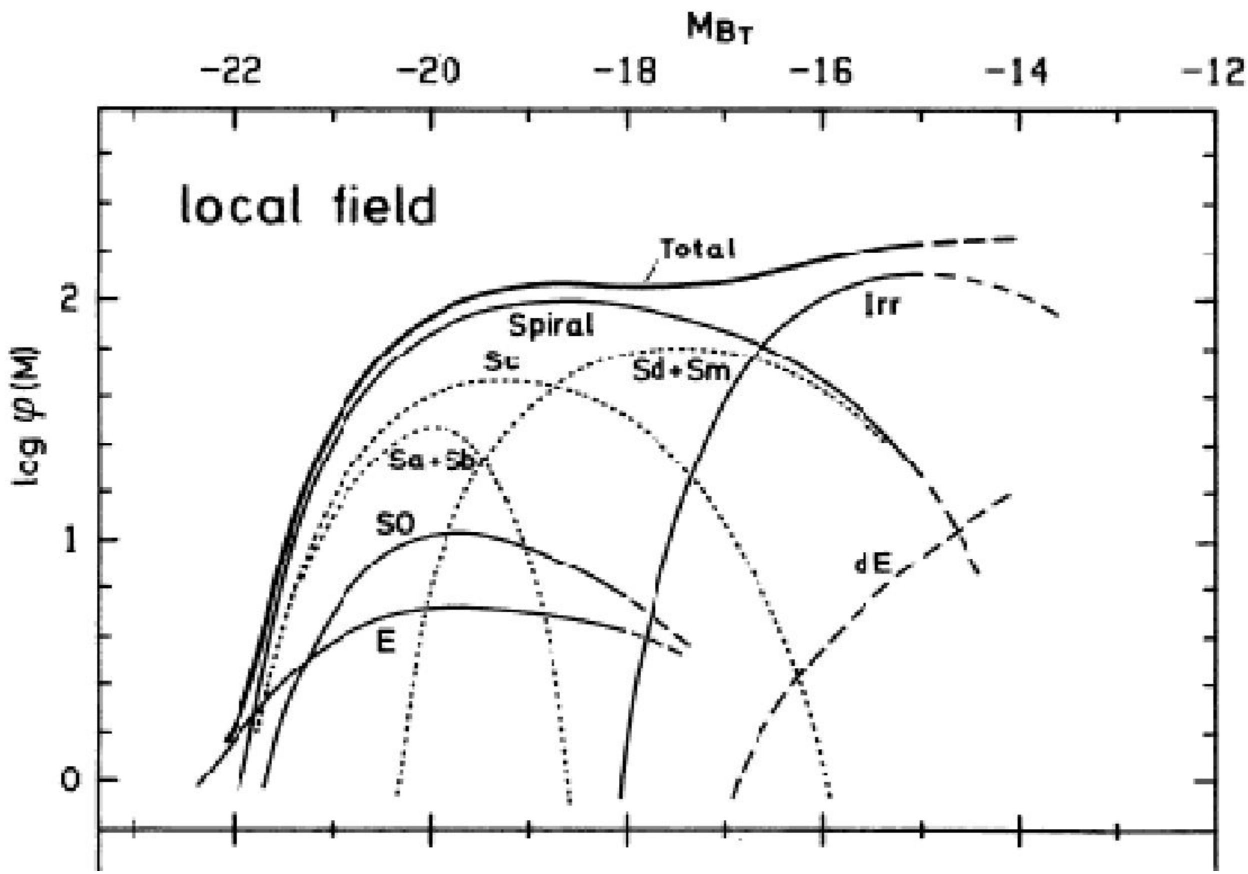
- averaged luminosity per volume:

$$j = \int_0^\infty L\,\Phi\left(\frac{L}{L_*}\right) d\left(\frac{L}{L_*}\right) = \Gamma(\alpha+2)\Phi_* L_*$$

$$\Rightarrow \quad j \simeq 10^8 \frac{L_\odot}{Mpc^3}$$

Using $\frac{M}{L} \simeq 10$ yields a mass density of $\rho_* \simeq 10^9 \frac{M_\odot}{Mpc^3} \quad \Rightarrow \quad \Omega_* \simeq 0.004$

Luminosity Function $\Phi(M)$ versus Absolute Blue Magnitude M_{B_T}:



see: Binggeli, Sandage, Tammann (1988) *ARAA* **26**

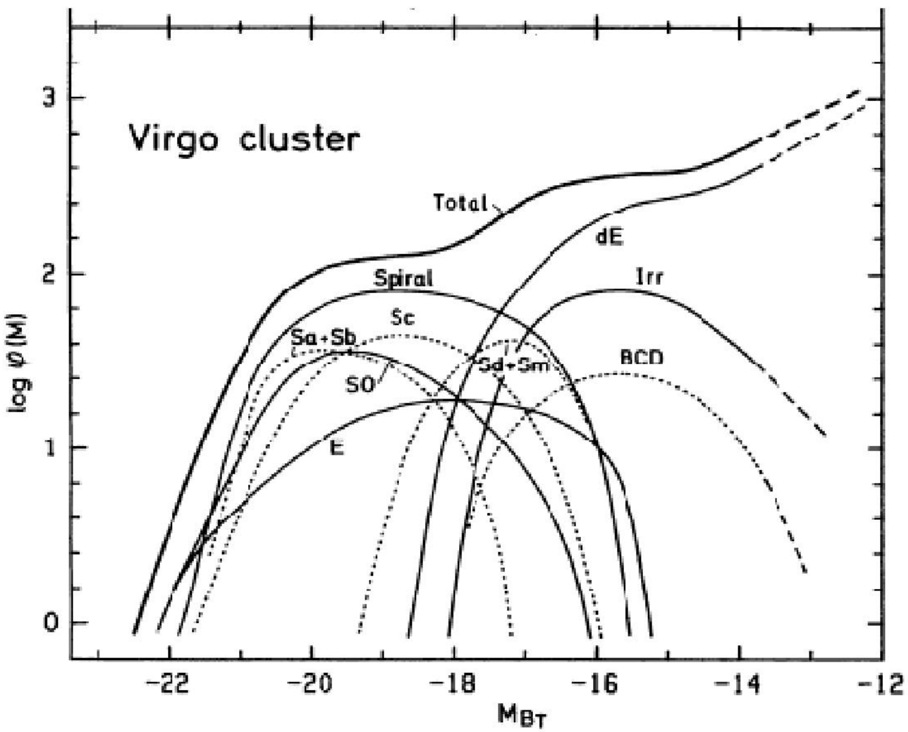
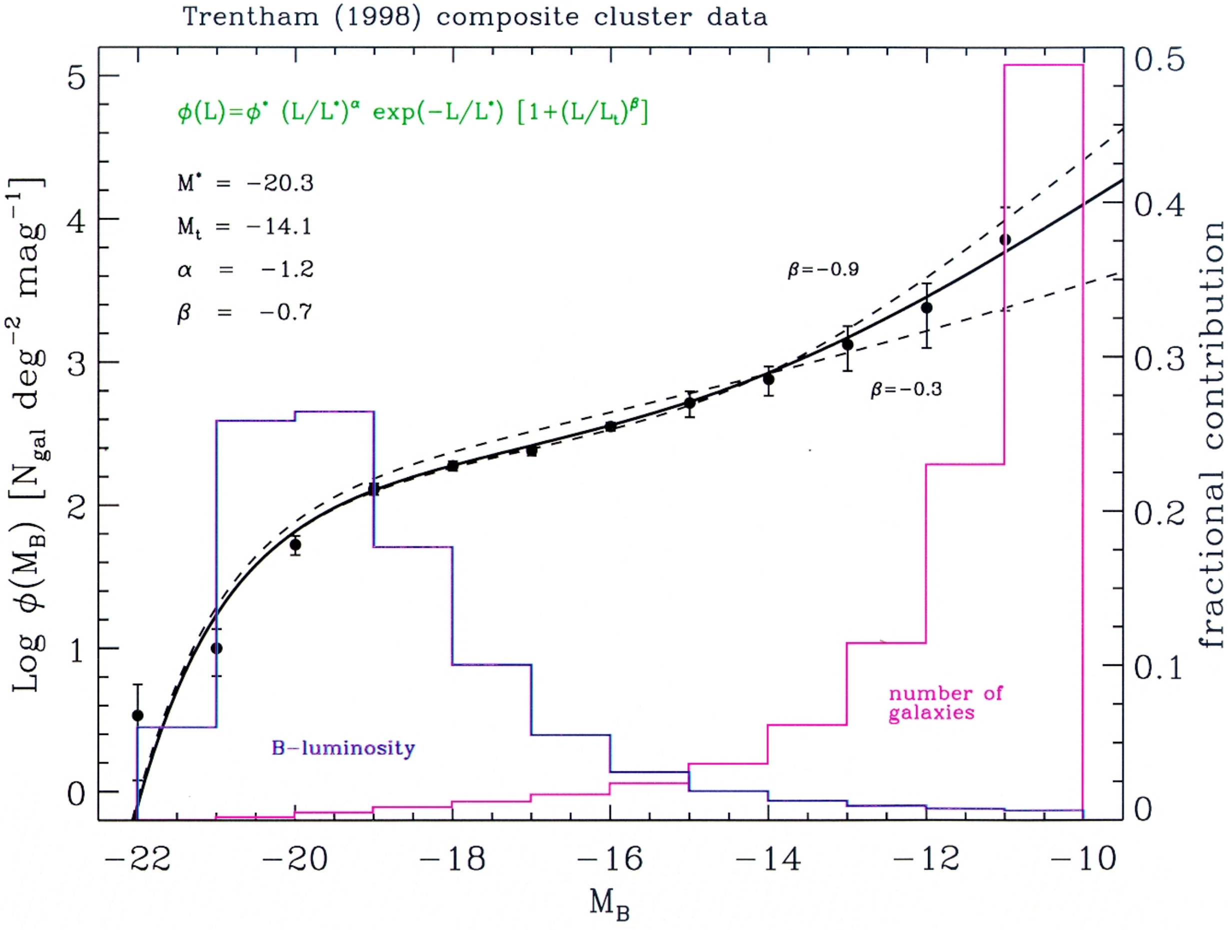


Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa+Sb, Sc, and Sd+Sm are also shown as dotted curves. The LF of Irr galaxies comprises the Im and BCD galaxies; in the case of the Virgo cluster, the BCDs are also shown separately. The classes dS0 and "dE or Im" are not illustrated. They are, however, included in the total LF over all types (heavy line).

see: Binggeli, Sandage, Tammann (1988) *ARAA* **26**



see: Thomas (1999) *ESO Astrophysics Symposia*