I*M*P*R*S on ASTROPHYSICS at LMU Munich

Astrophysics Introductory Course

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Powerpoint version with the help of Hanna Kotarba

Fall 2007

Chapter 6

Basic properties of galaxies

6.1 History

- Around 1610:
  Galilei resolves the Milky Way into many faint stars (discovery due to introduction of telescopes; other discoveries: Jupiter moons, sun spots).

- Around 1750:
  Building on a popular summary of Thomas Wright's first (bizarre) ideas about the structure of the MilkyWay, Immanuel Kant concludes that the appearance of the MilkyWay is best explained by a disk of stars. Furthermore he claims that the faint elliptical nebulae observed by de Maupertuis are very distant 'island universes' resembling in shape and composition our own Milky Way.

- Late 18th century:
  Herschel uses systematic star counts to determine the flattening of the Milky Way and obtains 1:5. He compiles a list of nebulae and discriminates between nebulae with embedded stars (like the Orion nebula) and others which appear to be 'a shining fluid of a nature totally unknown to us'.

- Middle of 19th century:
  William Parsons discovers spiral structures in some nebulae and concludes that they rotate.

- Late 19th century:

  Photographic plates revolutionize astronomical observations. Kapteyn, von Seeliger and van Rijn discuss the structure of the Milky Way in a new quantitative way based on reliable star counts on plates. Kapteyn concludes that the Milky Way has a radius of a few kiloparsecs and that the sun is at its center. At the same time Shapley reasons that the sun is located at 15kpc distance from the center because of the distribution of globular clusters in the sky. (This contradiction is later resolved by the discovery of interstellar extinction.)

- 1916:

  Albert Einstein finds the theory of General Relativity.

- 1923/24:

  With the new 100inch telescope on Mount Wilson (and building on previous results), Edwin Hubble uncovers the true nature of the ’nebulae’. He resolves M31 and M33 into faint stars, and confirms that these systems are galaxies like the MilkyWay. He identifies Cepheids in these objects and determines their distance (then: 300kpc, modern value: 770kpc).

- 1926/27:

  B.Lindblad and J.Oort derive the first realistic model of the Galaxy. They determine ist rotation velocity to 200km/s to 300km/s (modern value 220km/s) and estimate its mass.

- 1929:
  Hubble discovers the expansion of the Universe and determines the Hubble constant to 530 km/s/Mpc (today: 70±10km/s/Mpc).

- 1930:
  Trumpler demonstrates the existence of an absorbing interstellar material.

- Thirties:
  Fritz Zwicky observes the redshifts of individual galaxies in the Coma cluster and finds first evidence for ‘dark matter’. (Nobody believes him...)

- 1944:
  During the wartime blackout of Los Angeles, Walter Baade discovers the differences in the stellar populations between the center of M31, its companions and the solar neighborhood (Population I and II, i.e. young and old).

- 1944:
  van der Hulst predicts the HI-Emission of neutral atomic hydrogen (hyperfine structure transition at 21cm wavelength). This emission is discovered in 1951 using the newly developed radar technology.

- 1962:
  Maarten Schmidt discovers Quasars as first objects of significant redshift.

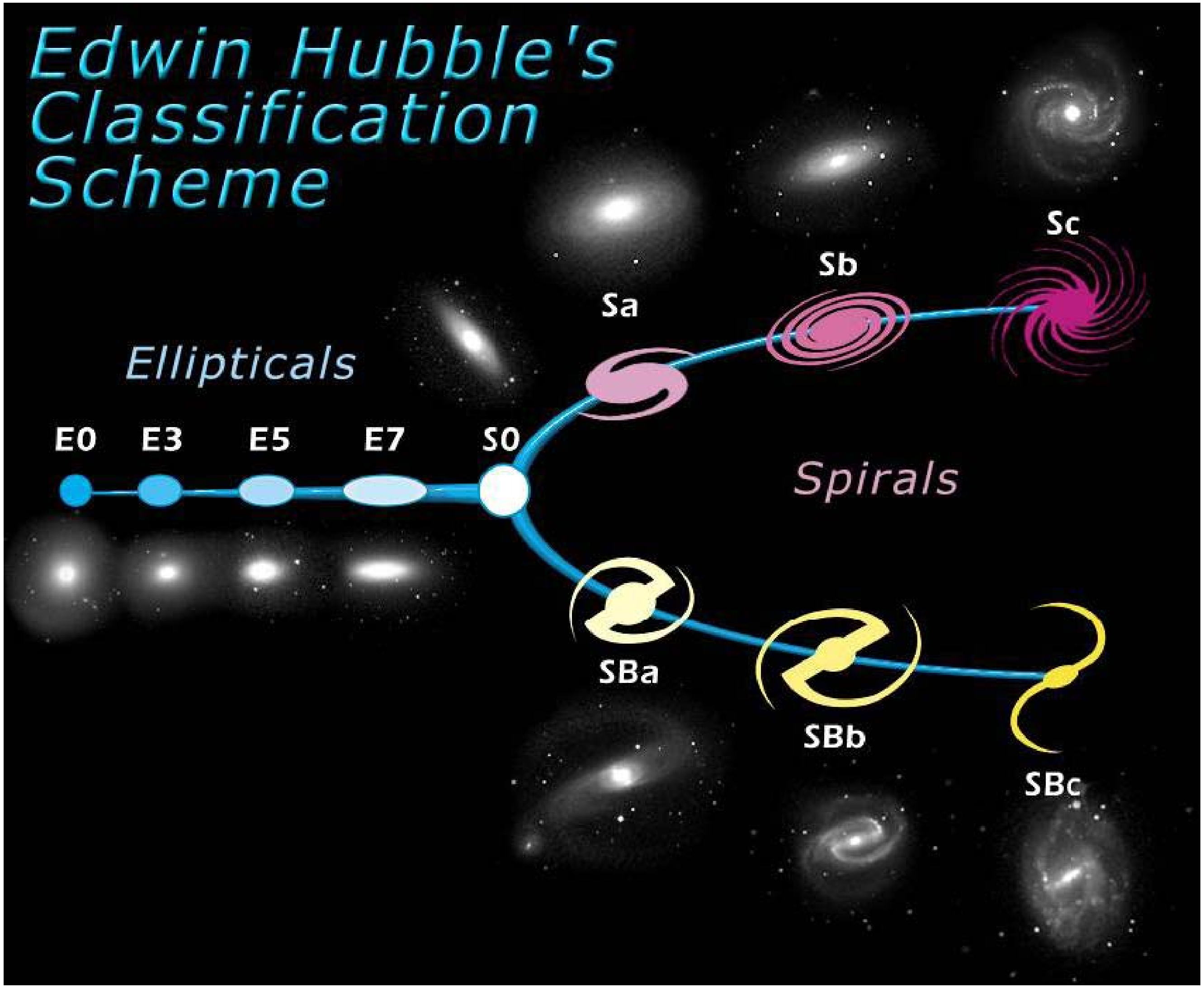
- 1965:
  Penzias and Wilson discover the 3K microwave background (as predicted by Gamov et al. 1940).

- Seventies:
  Evidence for dark matter becomes stronger, mostly due to flat rotation curves of spiral galaxies. (This leads to the standard cold-dark-matter model of the eighties).

- Eighties:
  Second revolution in astronomical observing techniques: In the optical wavelength region, Charge Coupled Devices (CCDs) improve the detection sensitivities by a factor 10 to 100 relative to photographic plates. Satellites provide new observing windows in the infrared and X-rays. It is now possible to study the structure, dynamics, stellar populations and interstellar medium of external galaxies in detail. The systematic study of the large-scale-structure of the Universe begins.

- Nineties:
  A quantum jump in spatial resolution is provided by the Hubble-Space-Telescope. 10m class telescopes are being built. Both lead to a boom in extragalactic studies and cosmology. Fluctuations in the cosmic microwave background are detected at a level of 10^{-5}. Galaxies and Quasars are now found at redshifts of 5 and beyond.

6.2 The major types of galaxies: Hubble-Sandage system



an alternative: de Vaucouleurs' Classification Scheme:

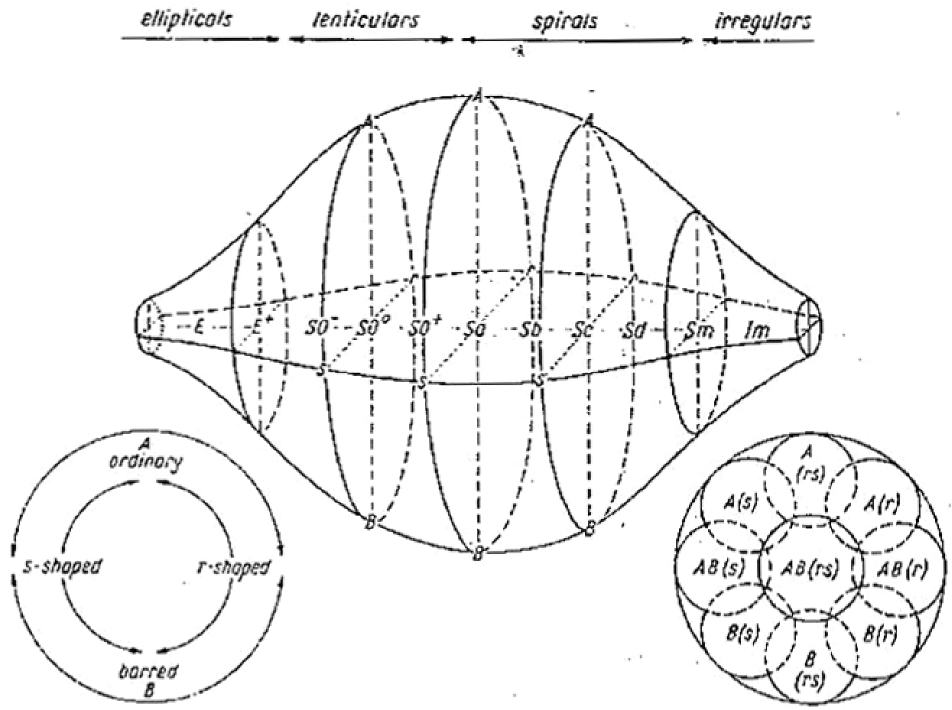


Figure 1. - The basic Hubble-Sandage-de Vaucouleurs classification scheme. Hubble's (1936) well known tuning-fork diagram (upper panel) was a two-dimensional classification. The lower panel shows the three-dimensional classification volume envisaged by de Vaucouleurs (1959a). There is a continuous sequence 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, Saas Fee 1982

Basic Components of Galaxies

Spheroid (bulge): metal poor to super metal rich, generally old stars; surface brighness profile I(r) follows roughly a de Vaucouleurs law:

$$I = I_e 10^{-3.33((r/r_e)^{0.25}-1)} \qquad r_e = \text{half - light radius}$$

Disk: metal rich stars, strong rotation, stars show a wide range of ages, Sa and later types show star formation,
HI, H2-gas, molecular clouds, dust, hot gas (heating by star formation and supernovae); surface brighness profile I(r) follows exponential law:

$$I = I_0 e^{-r/r_0} \qquad r_e = \text{disk scale - length}$$

Baryonic halo: metal poor stars with little/no rotation and a wide variety of orbits (only detected in MilkyWay); globular clusters, X-ray gas (prominent in ellipticals), low density HI/HII-gas

Dark halo: dominating mass outside of 10kpc, total mass in dark matter 5 to 10 times larger than baryonic mass, dark halo (maybe) slightly flattened

Luminosities of Bulges and Disks

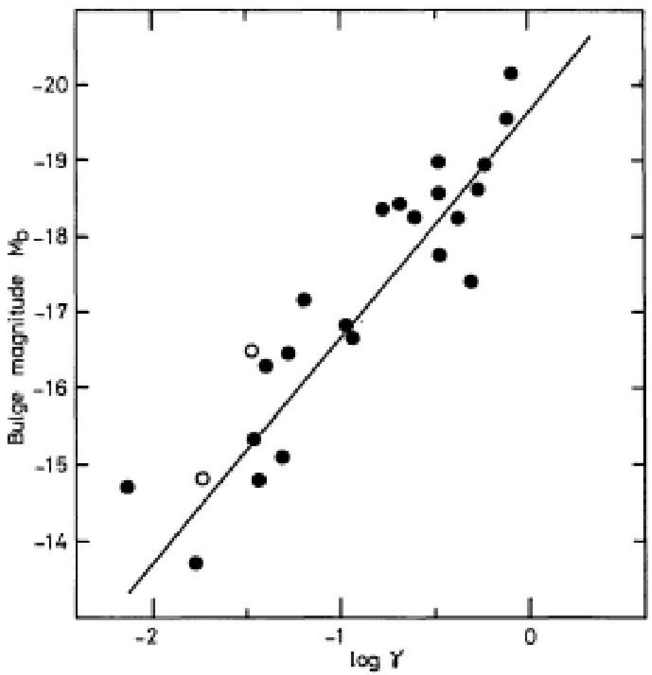


Fig. 3. Absorption-free, absolute magnitude of the bulge, M_b, plotted against $\log\gamma$. Straight line represents the least squares fit [Eq. (3)]. Open circles are of the same meaning as in Fig. 1 and are omitted in the least squares fit

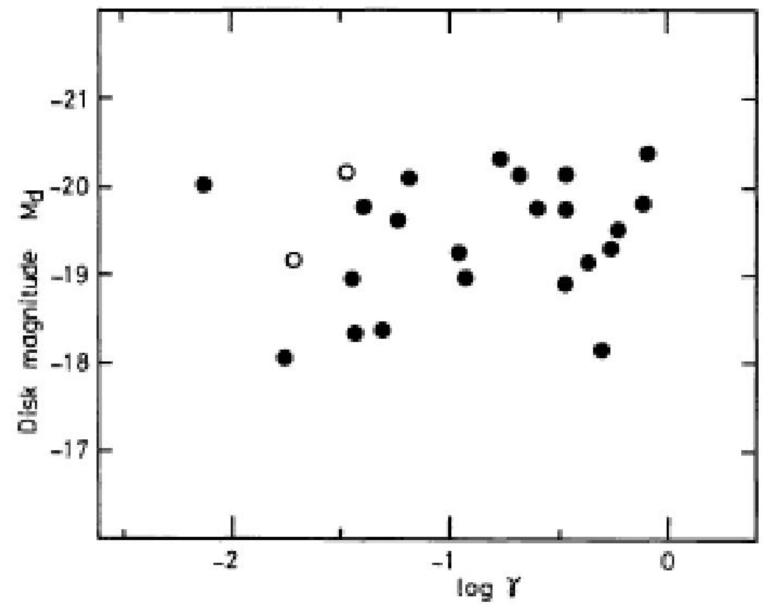


Fig. 4. Absorption-free, absolute magnitude of the disk, M_d, plotted against $\log\gamma$. Open circles are of the same meaning as in Fig. 1. Note that no correlation can be seen in contrast to in Fig. 3

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

Yoshizawa, Wakamatsu A&A 44, 363 (1975)

→ the Hubble sequence is primarily a bulge sequence

Overview of classification systems:

System	Principal criteria	Symbols	Examples
Hubble-Sandage (Sandage (1961-1995))	barrishness; openess 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; openess 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

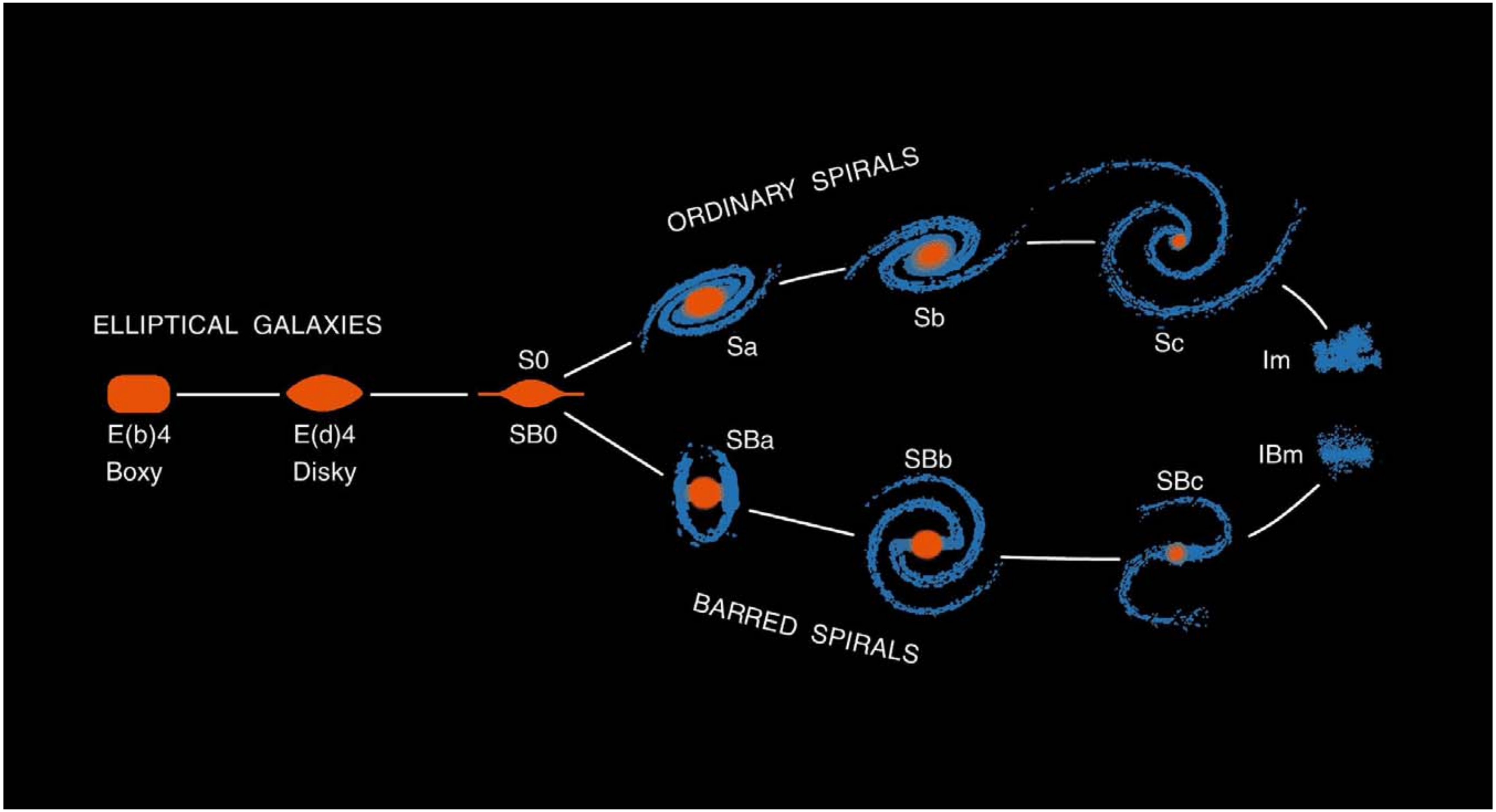
de Vaucouleurs' Numeric Types:

Type T	Type T	b/a	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^+	. . .	Compact Im

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

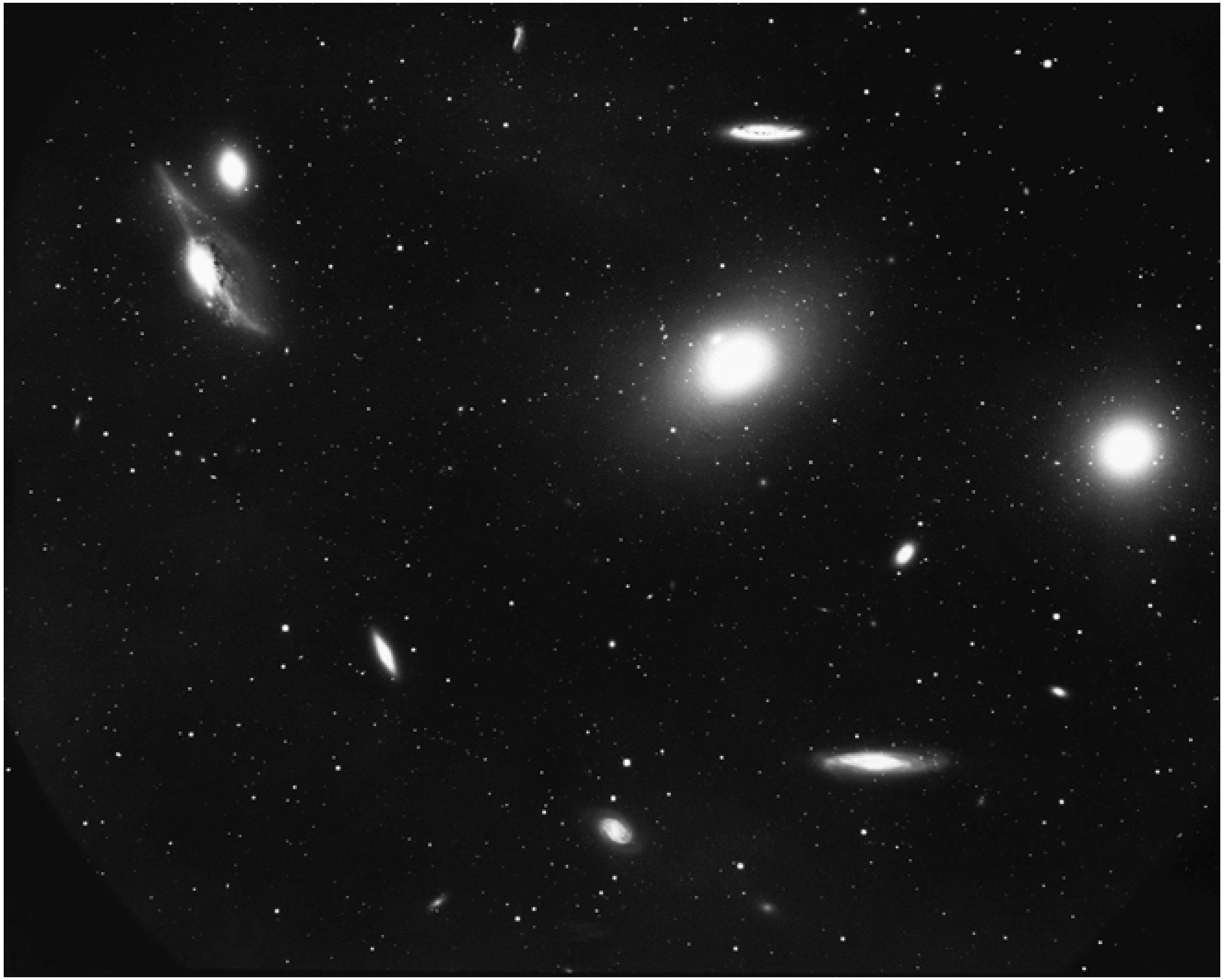
- Primary classification criteria of commonly used Hubble-Sandage system:
  - Bulge-to-disk ratio (S0/Sa: 5 to 0.3, Sb: 1 to 0.1, Sc/Irr: 0.2 to 0)
  - Opening angle of spiral arms (Sa: 0 to 10, Sb: 5 to 20, Sc: 10 to 30 degrees)
  - Bars

- Physical parameters varying along the Hubble-Sandage system:
  - Stellar mass M increases from irregulars ($10^8 M_\odot$) to ellipticals ($10^{12} M_\odot$)
  - Specific Angular Momentum J/M of baryons increases from ellipticals to spirals
  - Mean age increases from irregulars through spirals to ellipticals (B-V increases from 0.3 to 1.0, mass-to-light M/L_B ratio increases from about 2 to 10)
  - Mean stellar density of spheroids increases with decreasing spheroid luminosity
  - Mean surface brightness of disks increases with luminosity
  - cold gas content increases along Hubble sequence (fraction of baryonic mass: 0 in E/S0, 0.1 to 0.3 in Sa to Sc, up to 0.9 in Irr)
  - hot gas content only significant in massive E (few percent of baryonic mass)



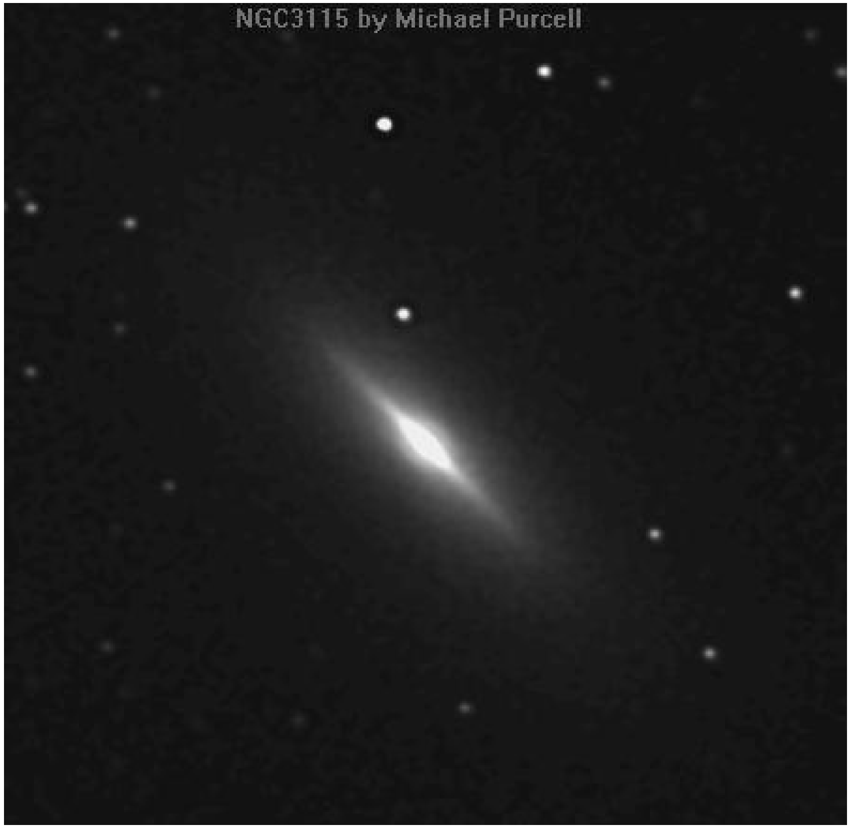
Kormendy & Bender (1996): Hubble Sequence revised for ellipticals,
for justification see chapter on ellipticals

Examples for Normal Galaxies: Elliptical (E) Galaxies:

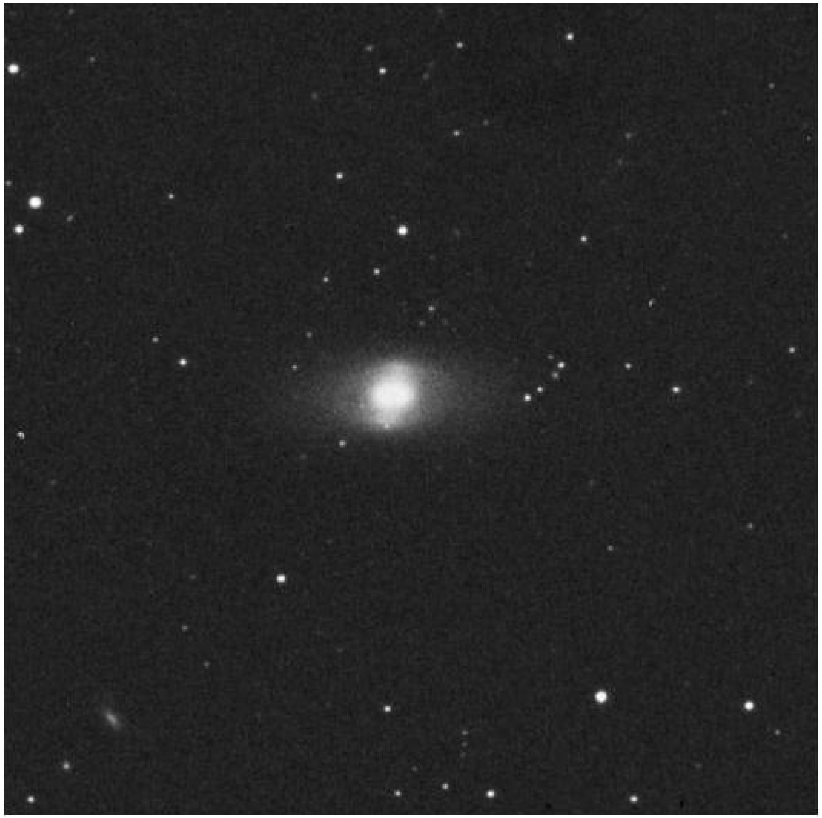


The ellipticals M 84 (right) and M 86 (middle) in the Virgo cluster (NOAO).

Lenticular (S0) Galaxies:



NGC 3115: S0-galaxy



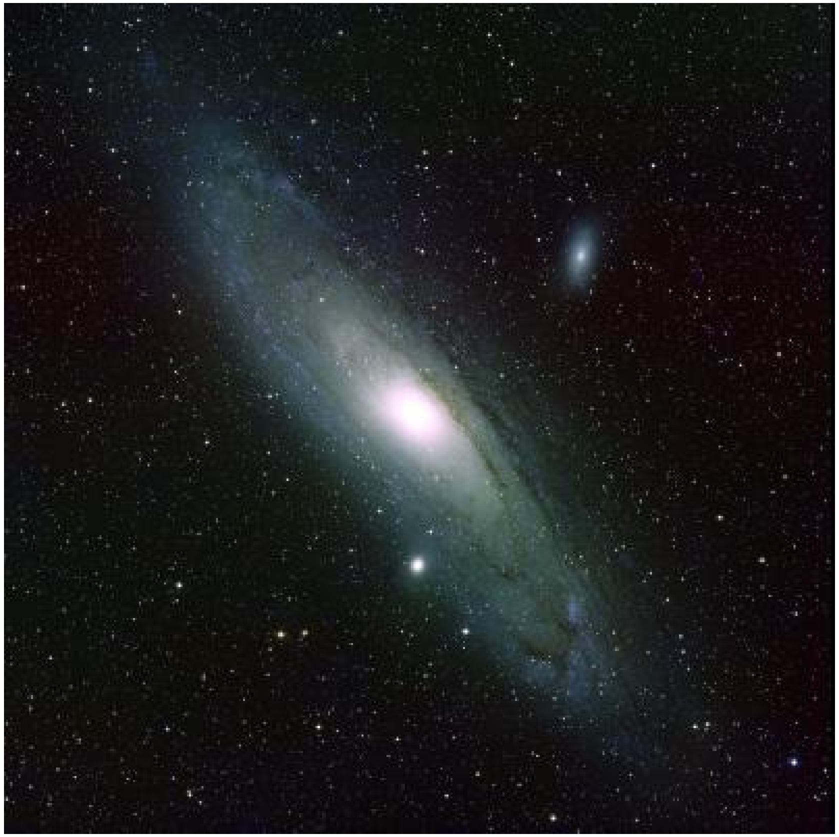
NGC 4371: SB0-galaxy

Spiral (Sa) Galaxies:

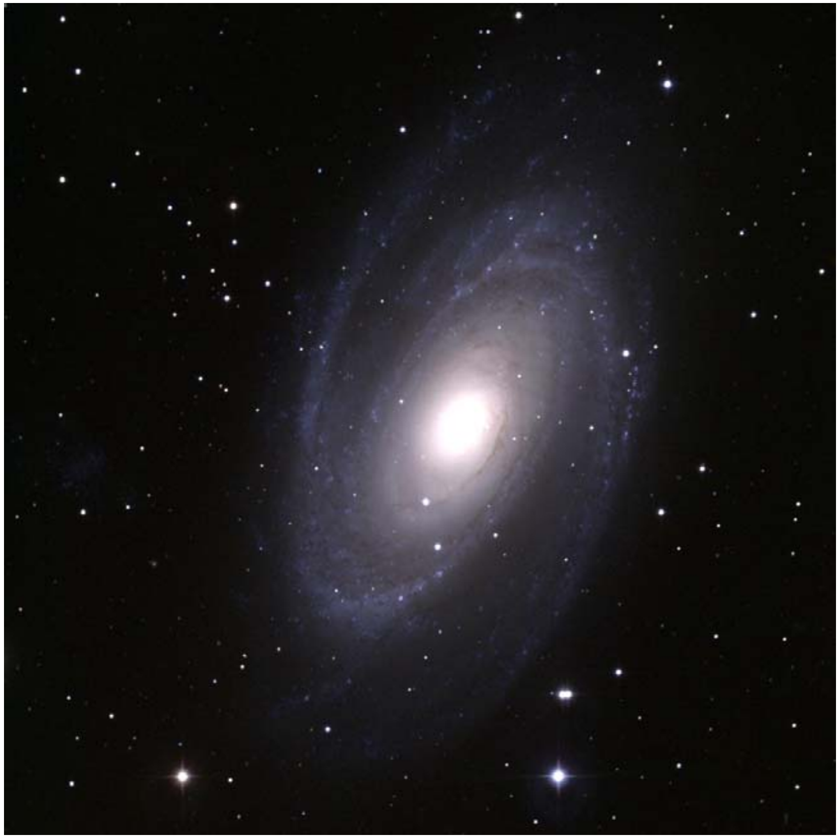
NGC 3223: Sa-galaxy

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

Spiral (Sb) Galaxies:



M 31 (Andromeda): Sb-galaxy



M 81: Sb-galaxy

Spiral (Sc) Galaxies:

M 51: Sc-galaxy
courtesy: C. Gössl, Wendelstein Observatory, USM

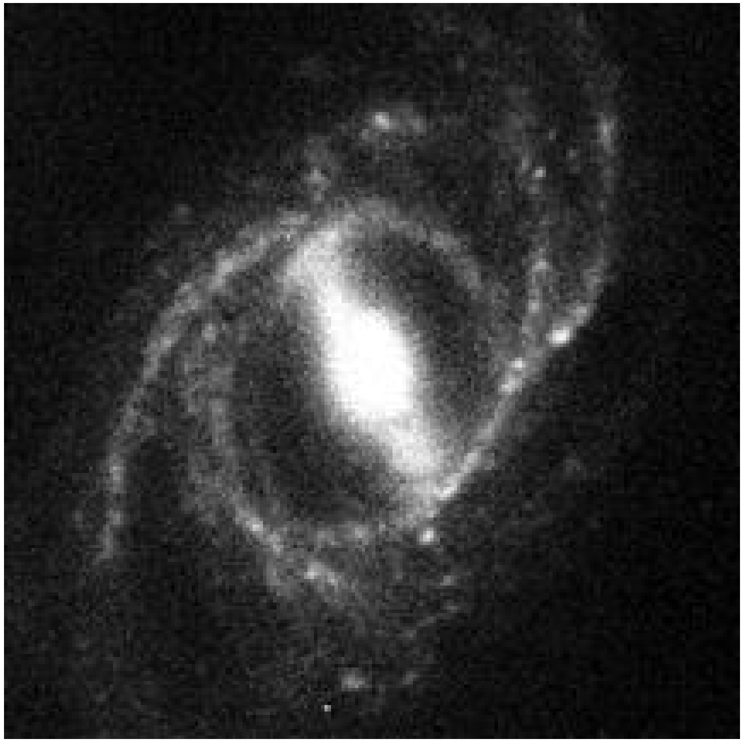
M 101: Sc-galaxy
courtesy: C. Gössl, Wendelstein Observatory, USM

Barred-Spiral (SB) Galaxies:

M 83 (Southern Pinwheel): SBa-galaxy

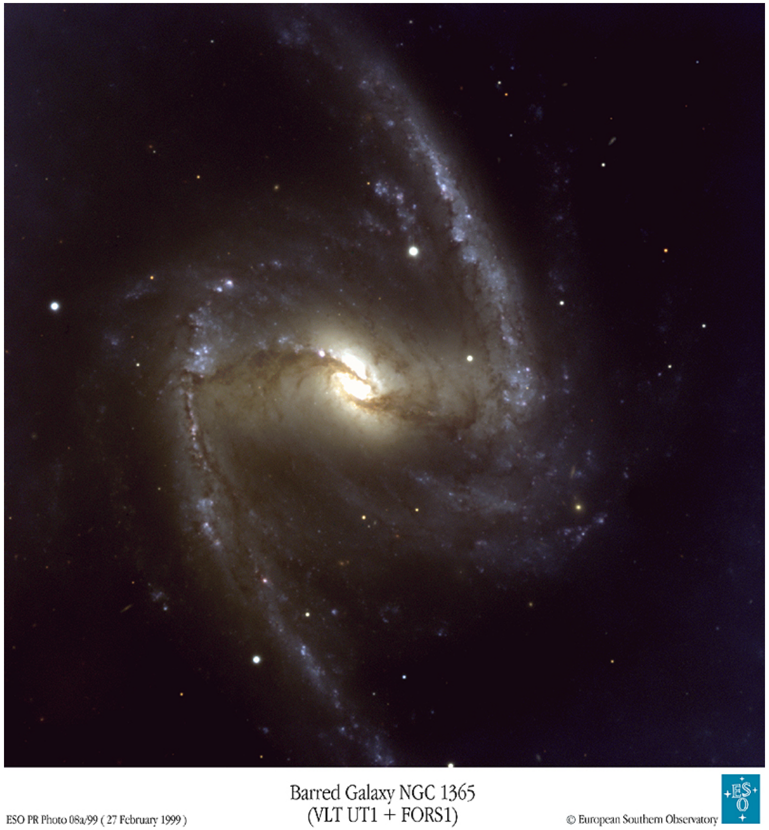
Barred-Spiral (SBb) Galaxies:

M 95: SBb-galaxy

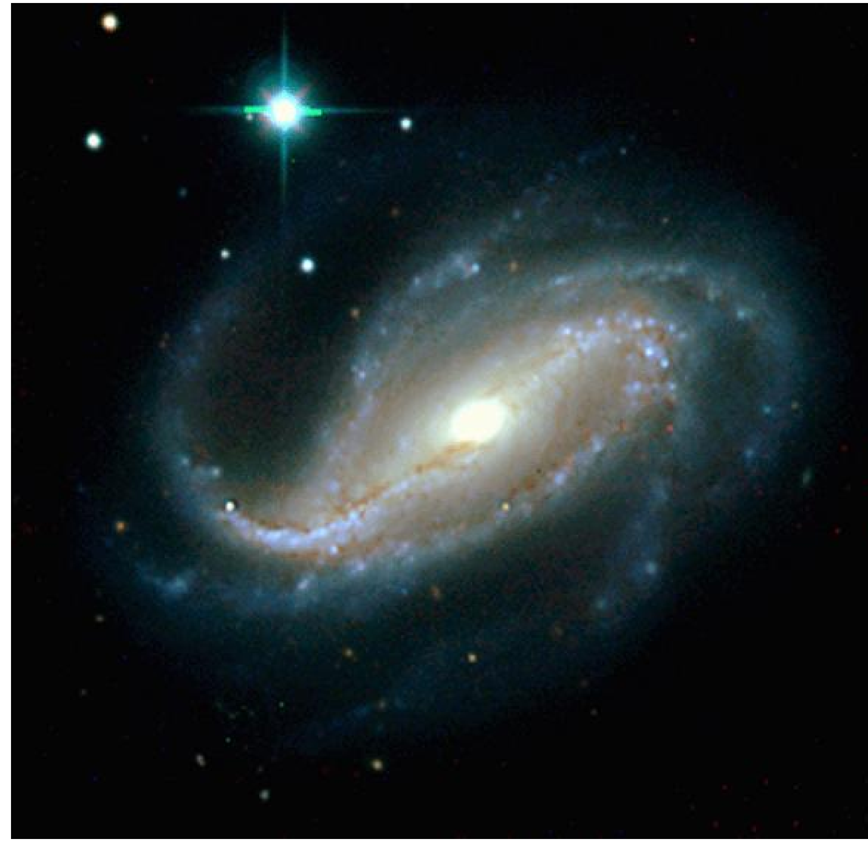


NGC 2523: SBb-galaxy

Barred-Spiral (SBc) Galaxies:



NGC 1365: SBc-galaxy

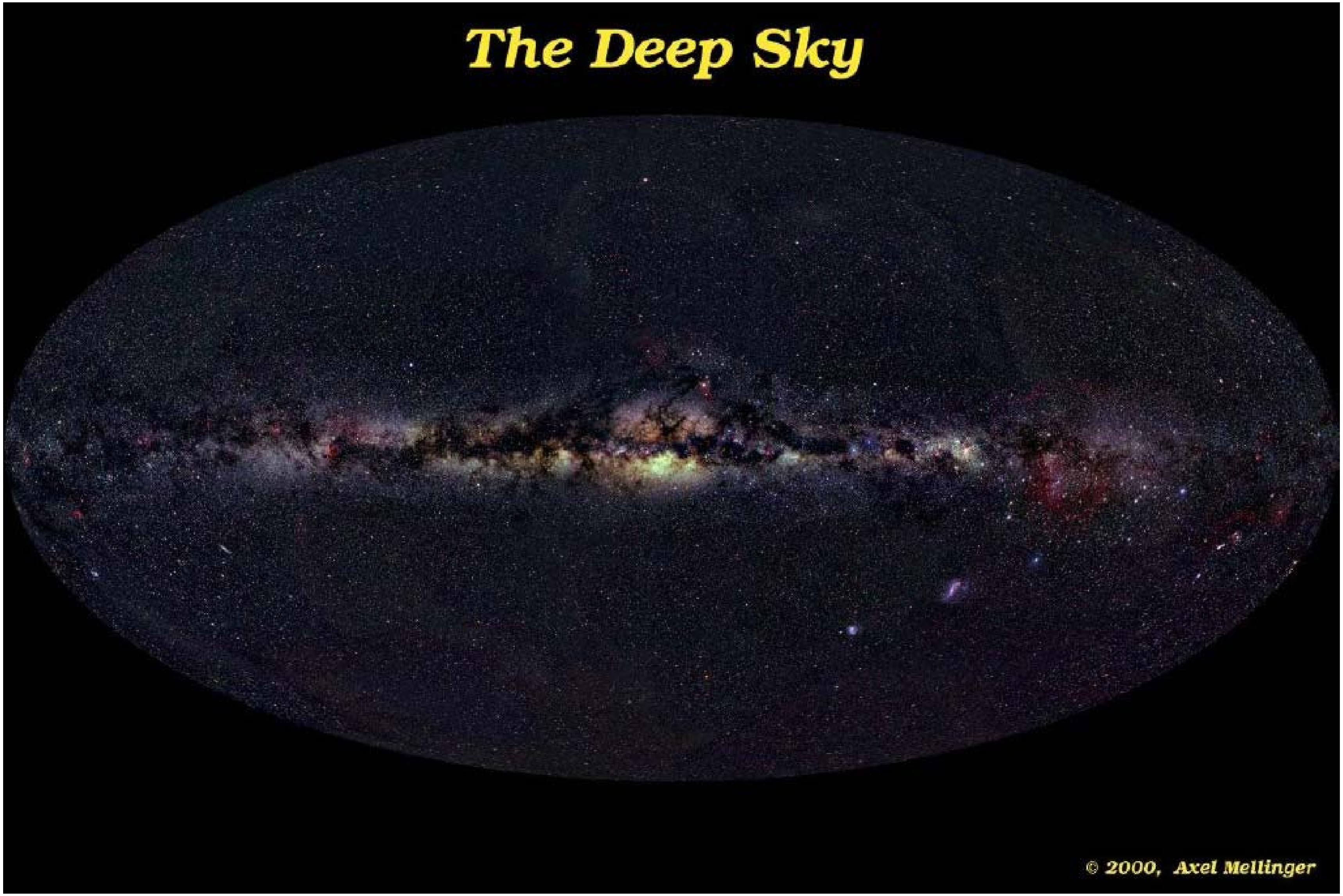


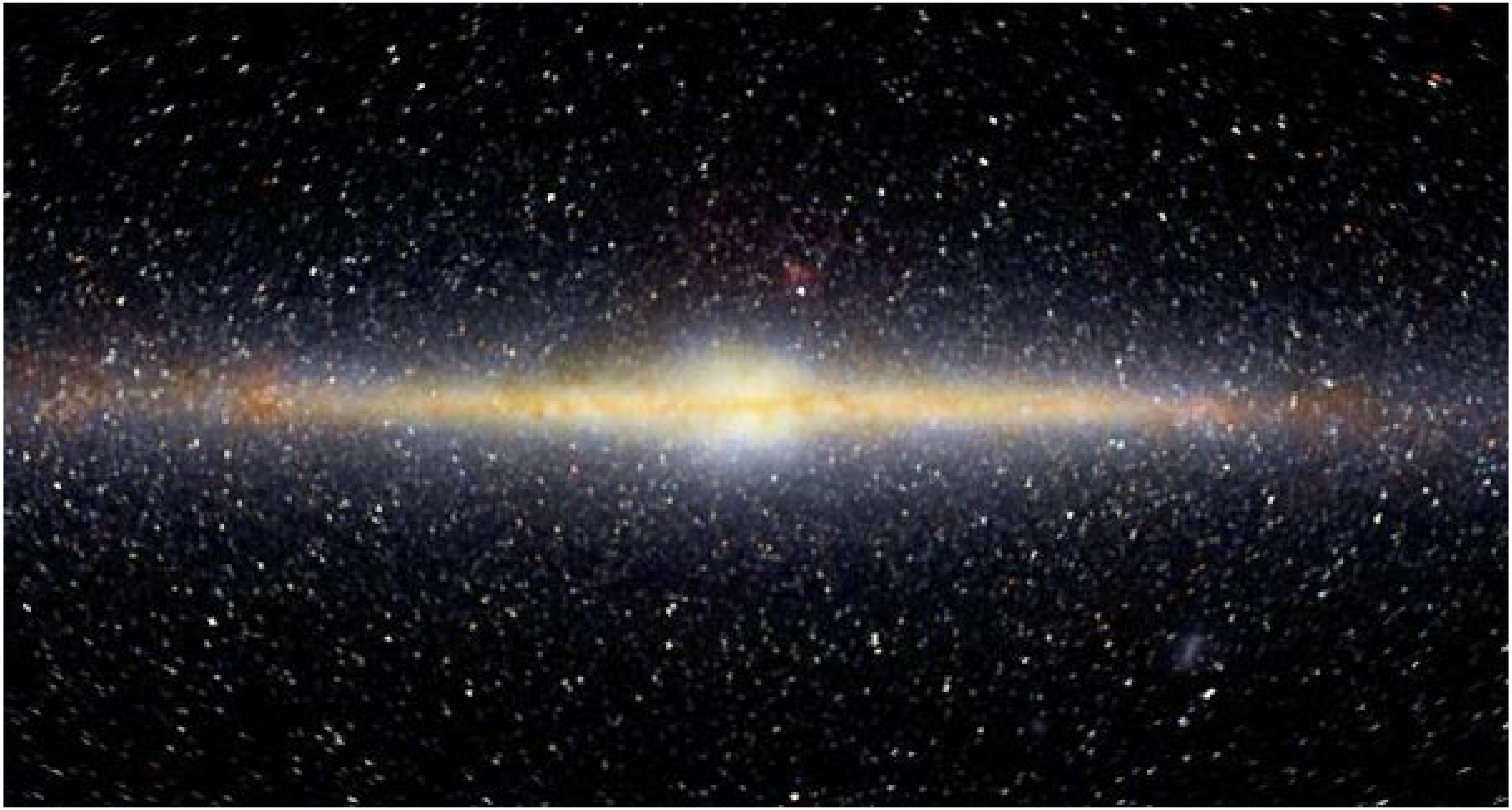
NGC 613: SBc-galaxy

Irregular (Irr) Galaxies:

LMC: Irr-galaxy

SMC: Irr-galaxy


The Deep Sky
© 2000, Axel Mellinger



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

6.3 Important other galaxy types not contained in the Hubble-Sandage system:

- dwarf galaxies:
  dE: dwarf ellipticals or dwarf spheroidals, similar to E but of low luminosity and low surface brightness
  BCD: Blue Compact Dwarfs, concentrated starburst, faint old stellar components

- 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: mostly luminous but very low surface brightness disk galaxies

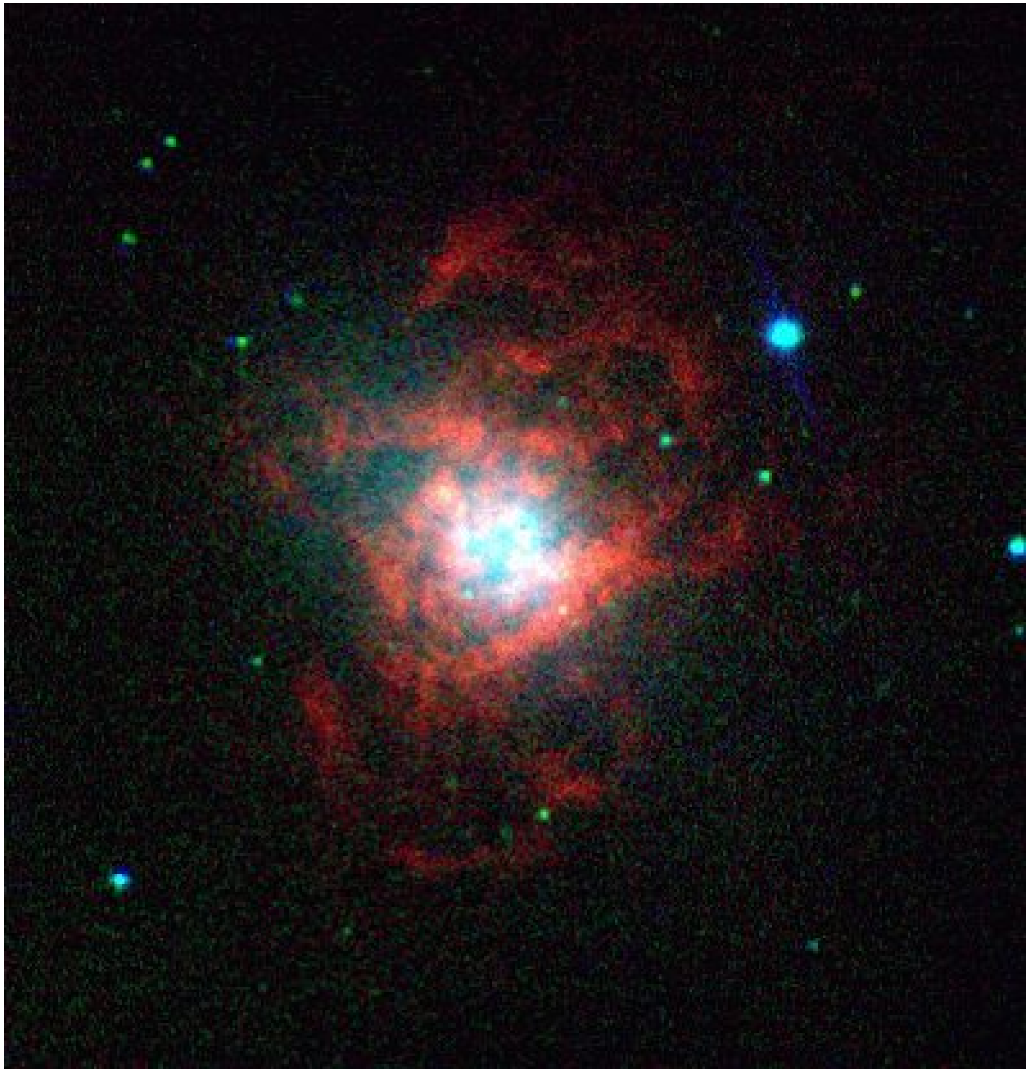
- active galaxies: radio galaxies; galaxies with unusual nuclear emission lines and/or extreme nuclear luminosity (QuasiStellarObjects-QSOs, Seyfert galaxies) and/or with powerful non-thermal radio emission (radio galaxies, quasars)

- interacting, merging and starbursting galaxies (IRAS mergers, ULIRGs, i.e. Ultra-Luminous Infra-Red Galaxies)

Dwarf galaxies

Leo 1 ($M_V = -12$), dwarf elliptical (dwarf spheroidal) companion of Milky Way

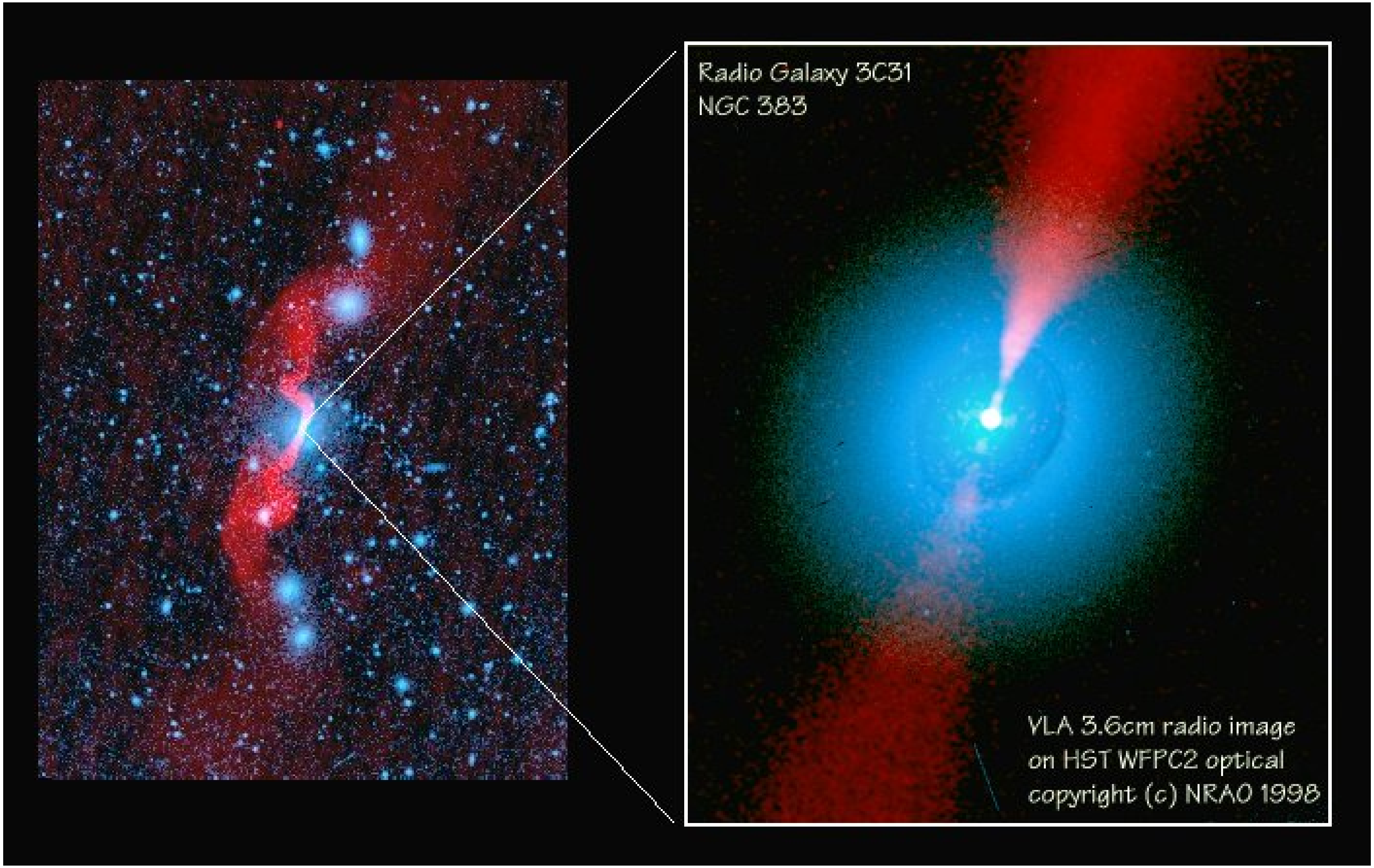
NGC 205 ($M_V = -16.3$), dwarf elliptical companion of M31 (NOAO)



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

Active galaxies

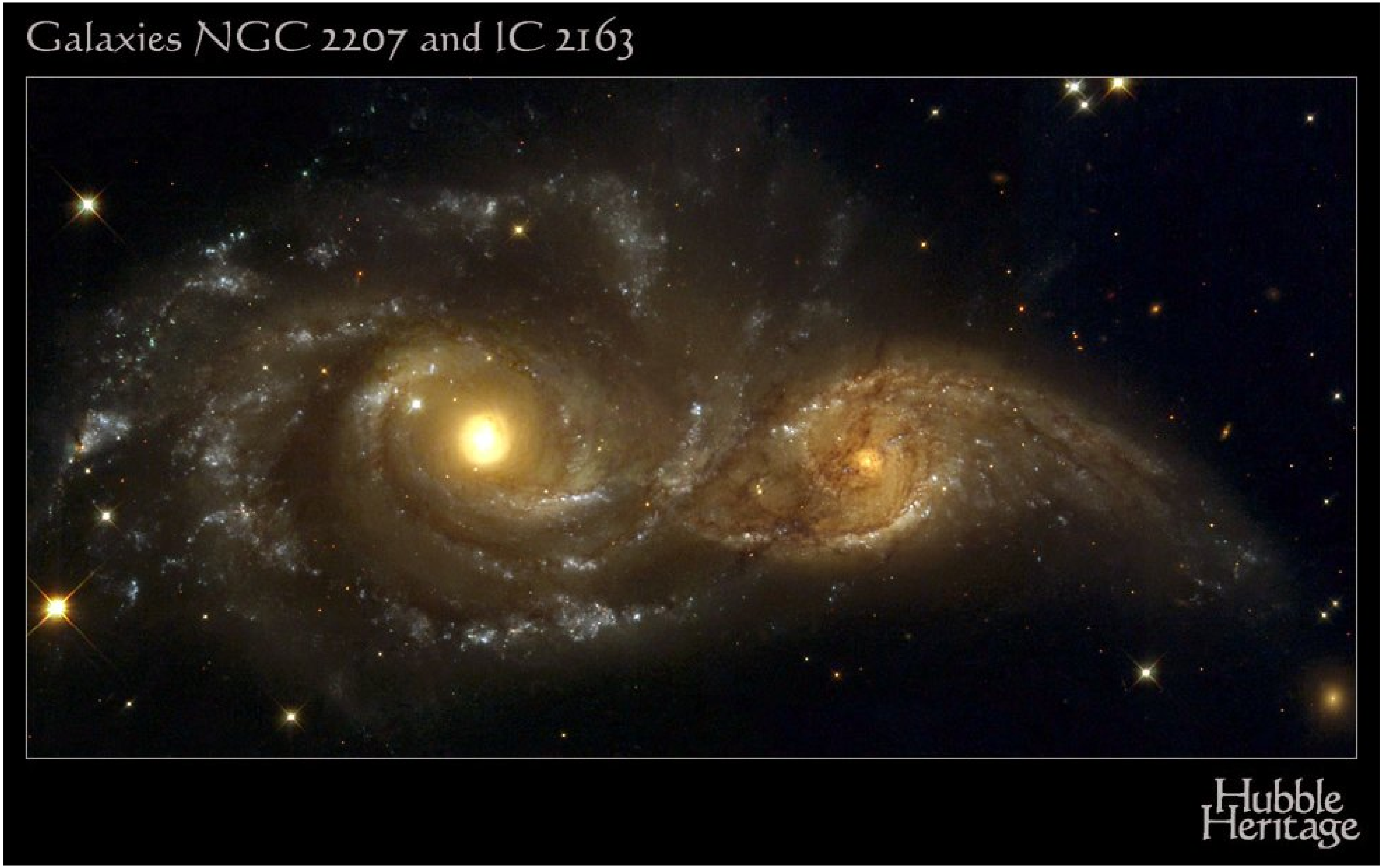
NGC 7742, a Seyfert galaxy



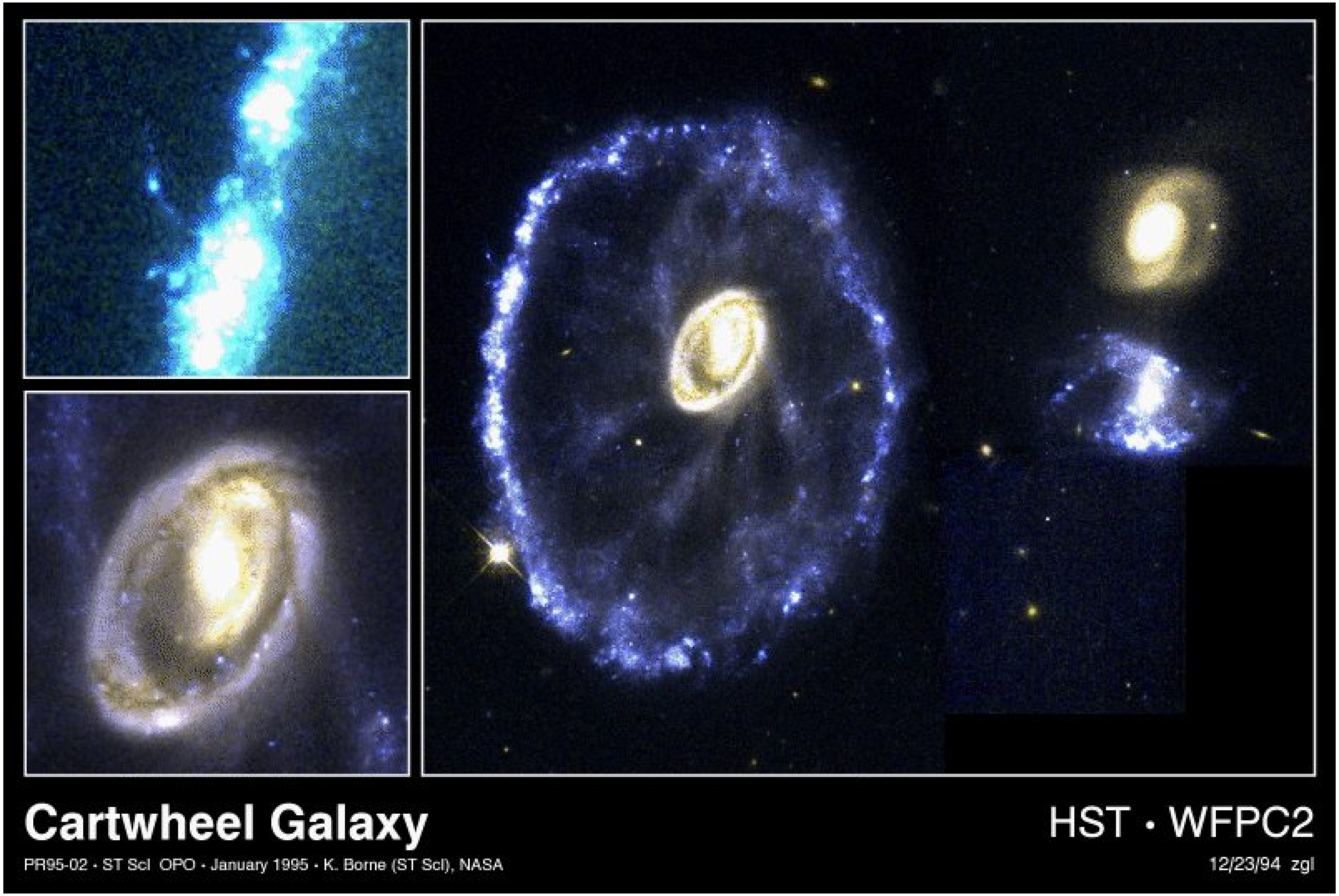
NGC 383 (= 3C31), a radio galaxy, blue: optical, red: radio (A. Bridle)

One of the currently most distant objects known,
a quasar at redshift 5.8 (April 2000, Sloan Digitial Sky Survey)

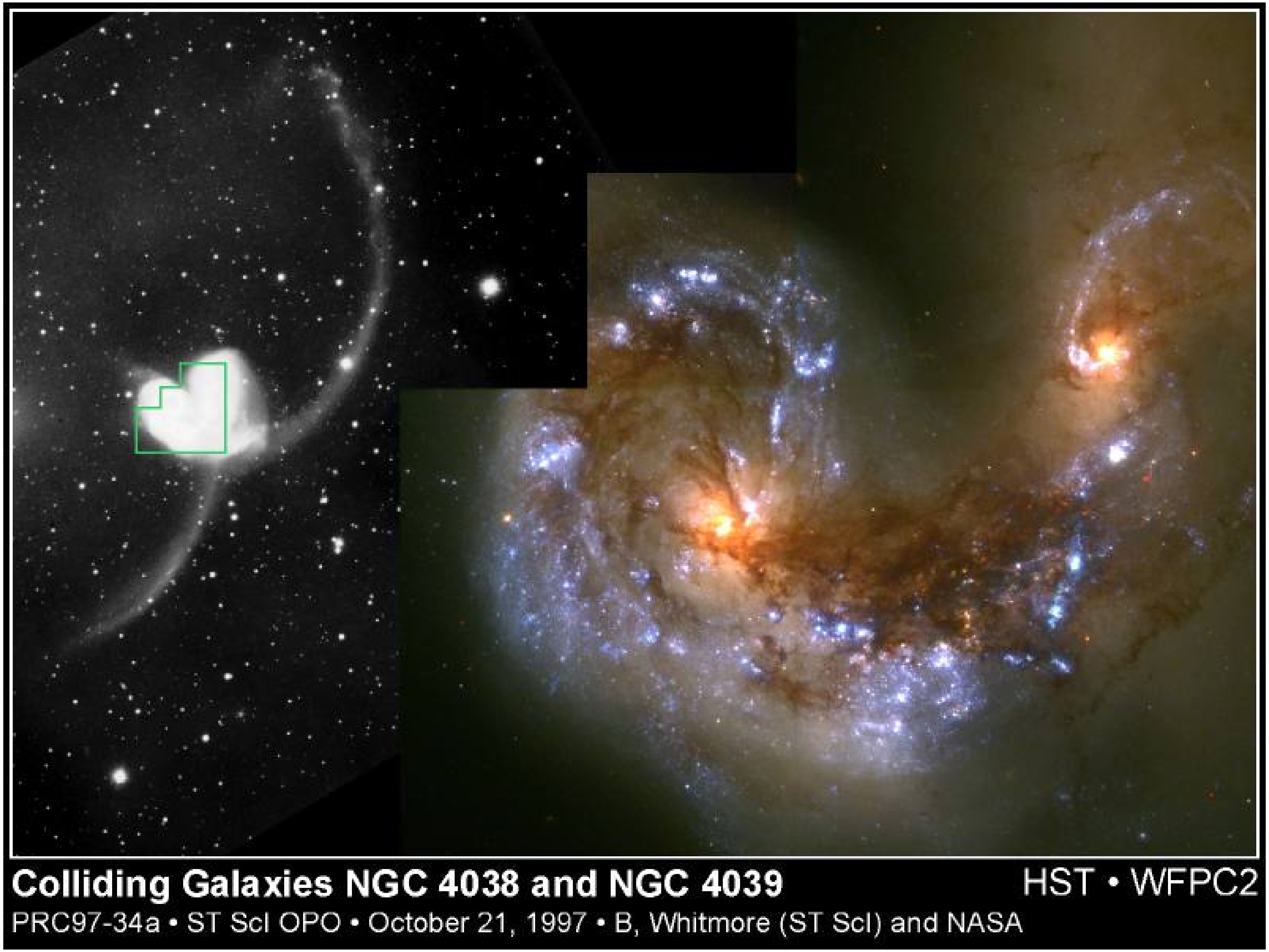
Interacting, merging and starbursting galaxies



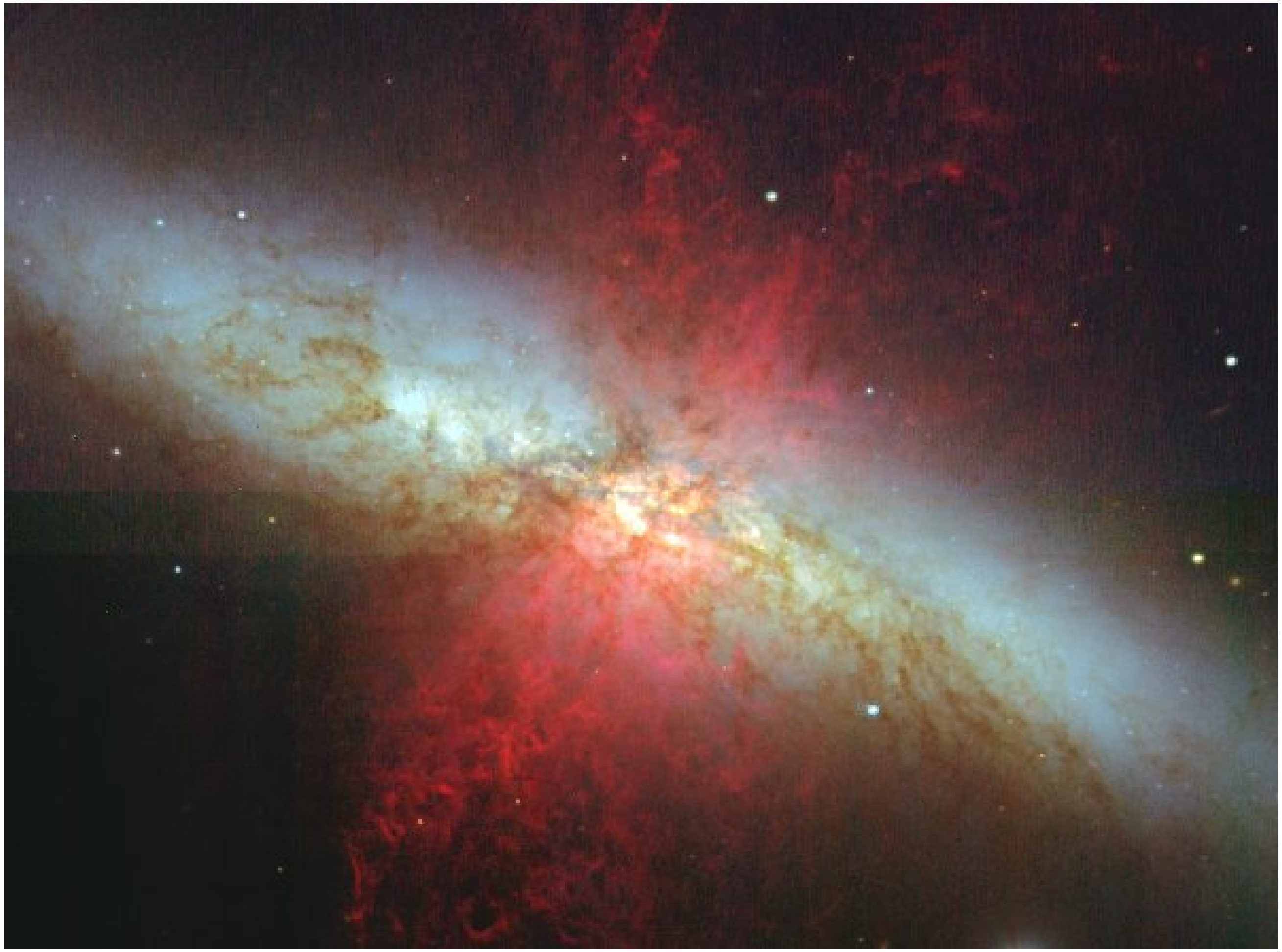
Interacting galaxy pair. Note that spiral disks are not optically thick!



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

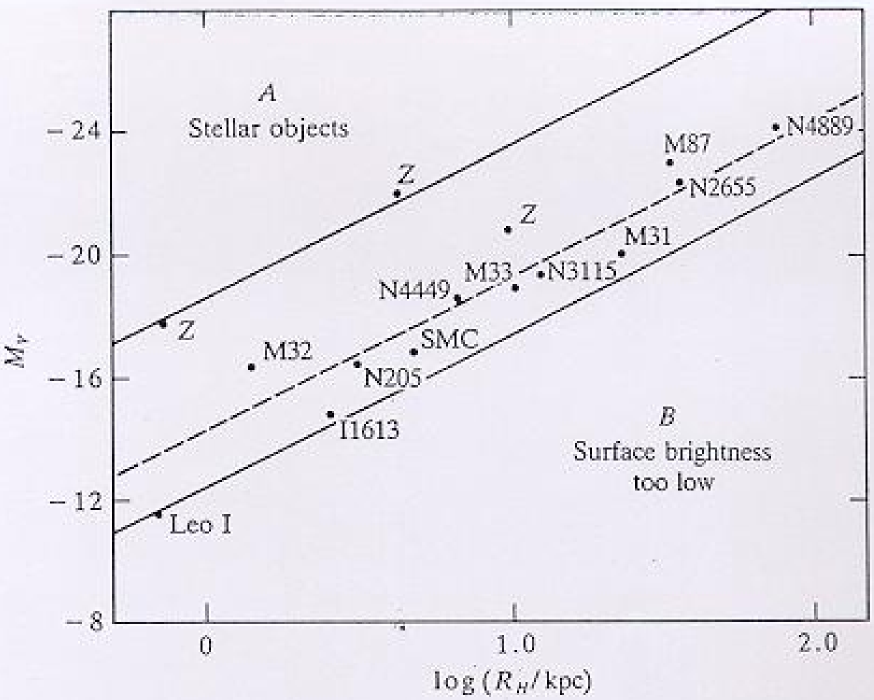
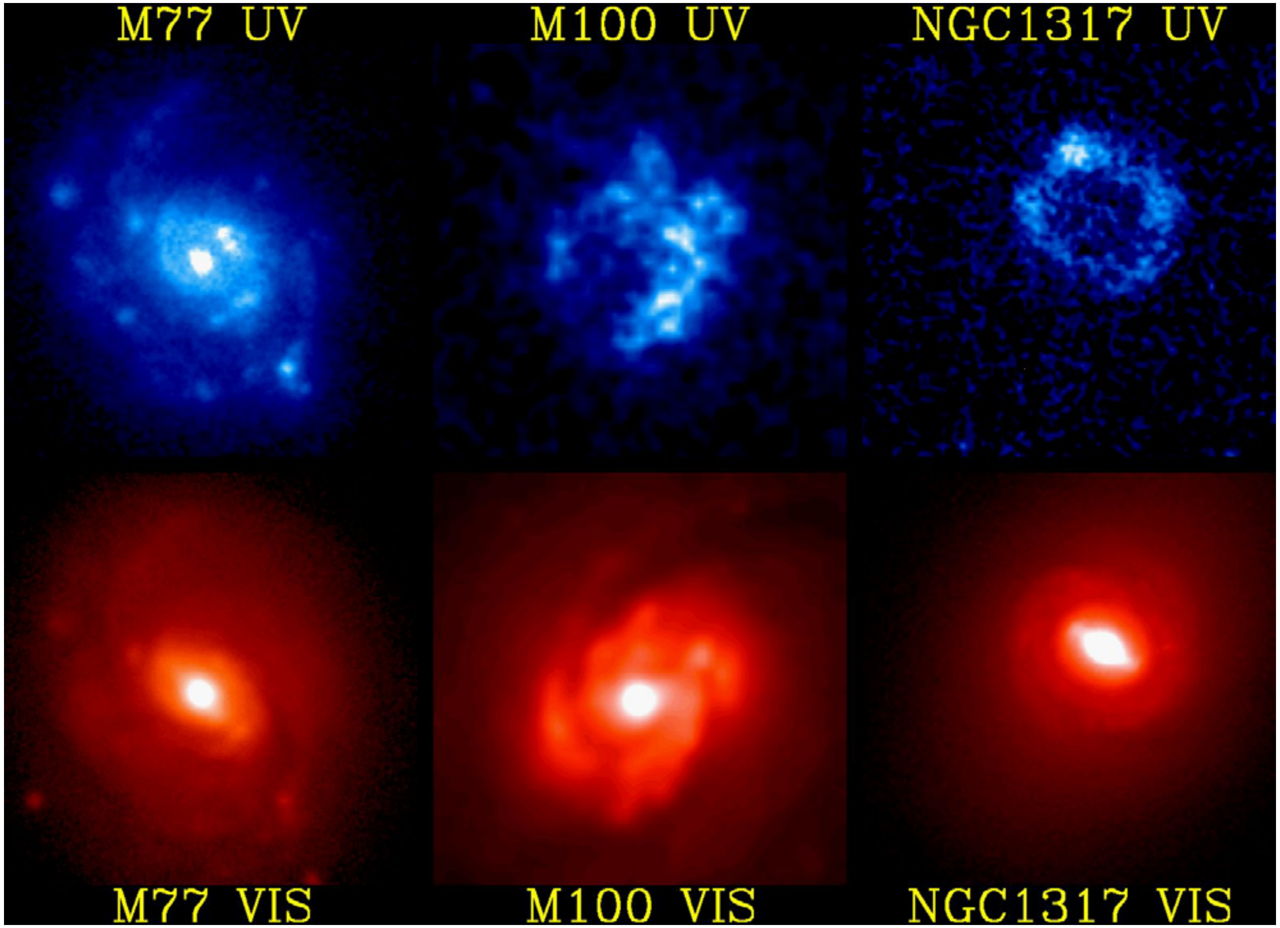


Figure 5-47. Observed galaxies might not be typical of all extragalactic objects. Here we plot the absolute magnitude of a number of galaxies against their Holmberg radii (both based on a Hubble constant $H = 50$ km s^{-1} Mpc^{-1}). Most objects whose representative points fell in region *A* would be 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).]

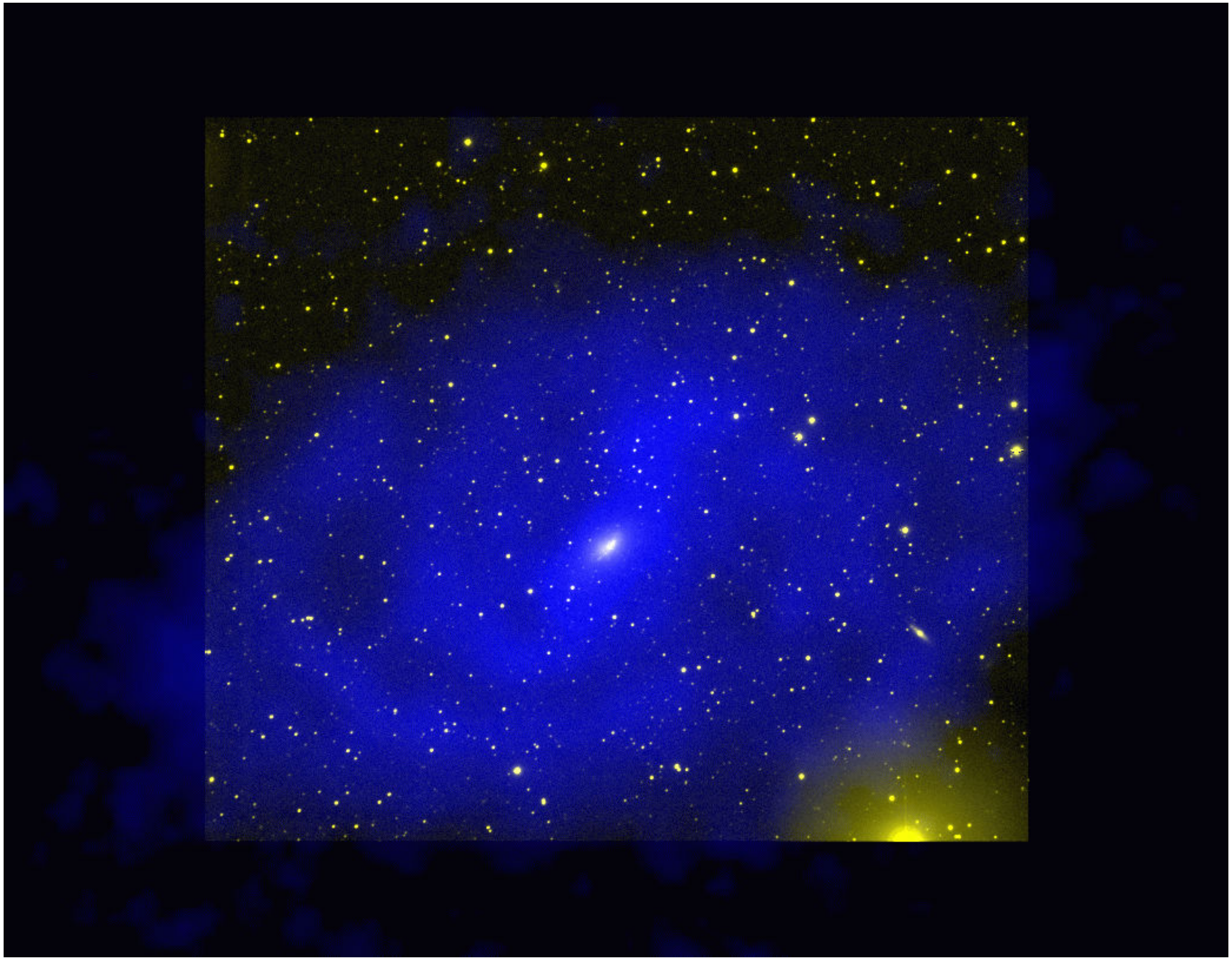
see: Mihalas / Binney: Galactic Astronomy

Galaxies at non-optical wavelengths

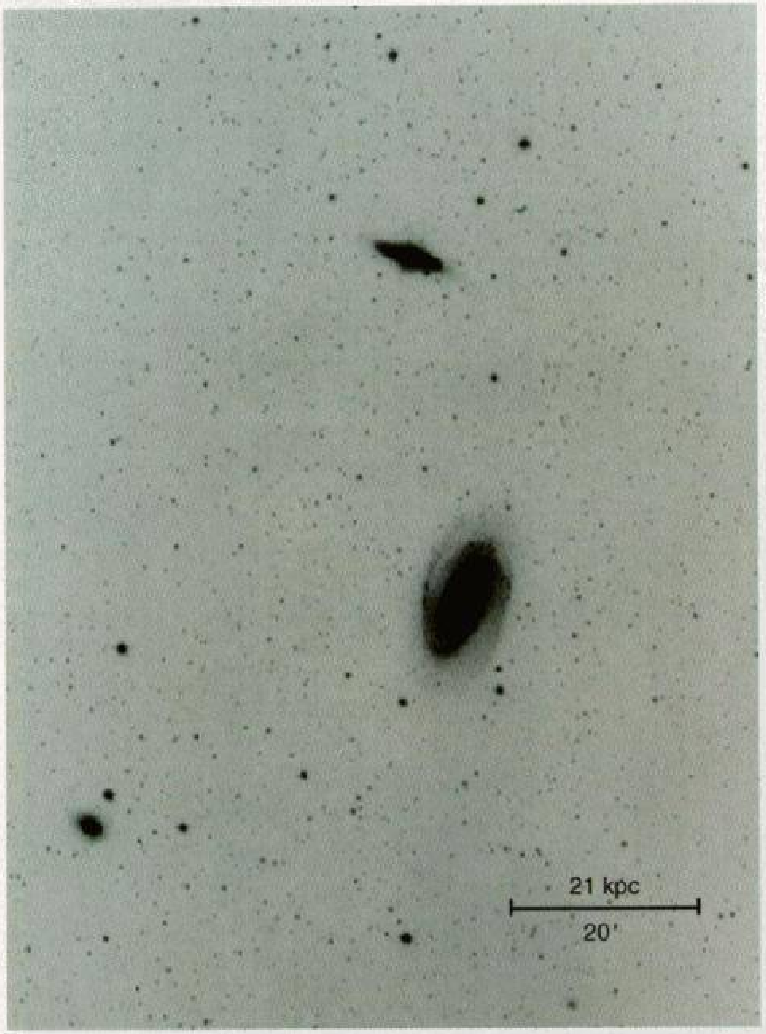


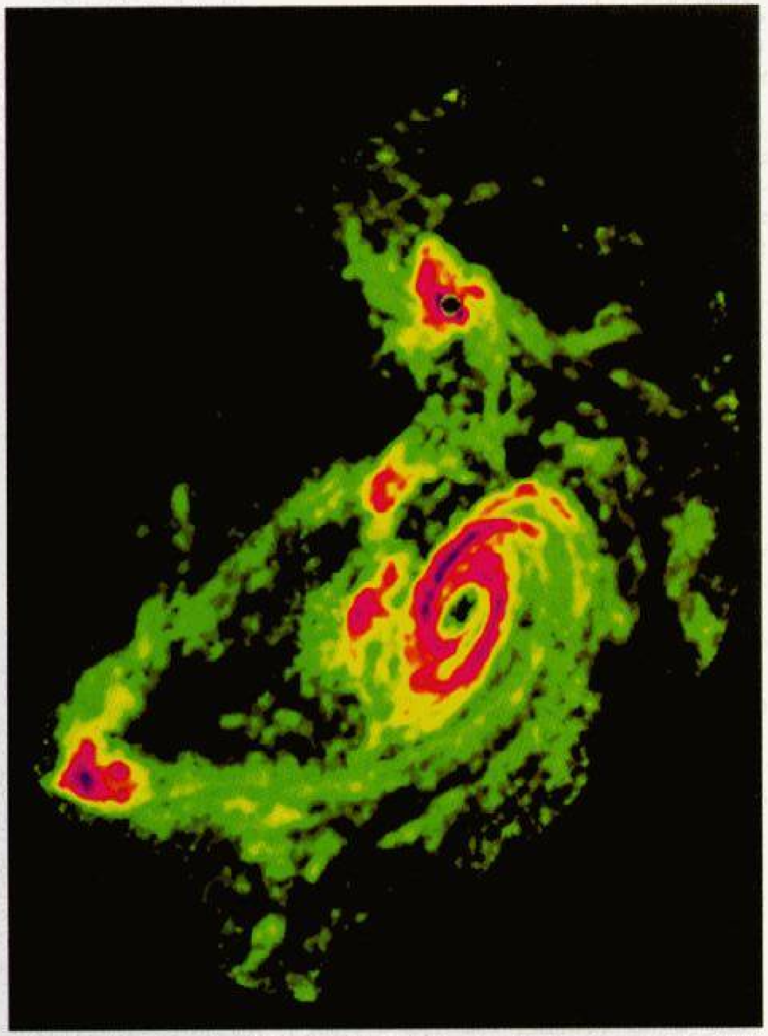
Spirals in ultraviolett (dominated by massive stars) and visual (average population),
Ultraviolet Imaging Telescope, Astro mission.

Note: Redshifted spirals observed in the optical will show rest-frame UV morphology!

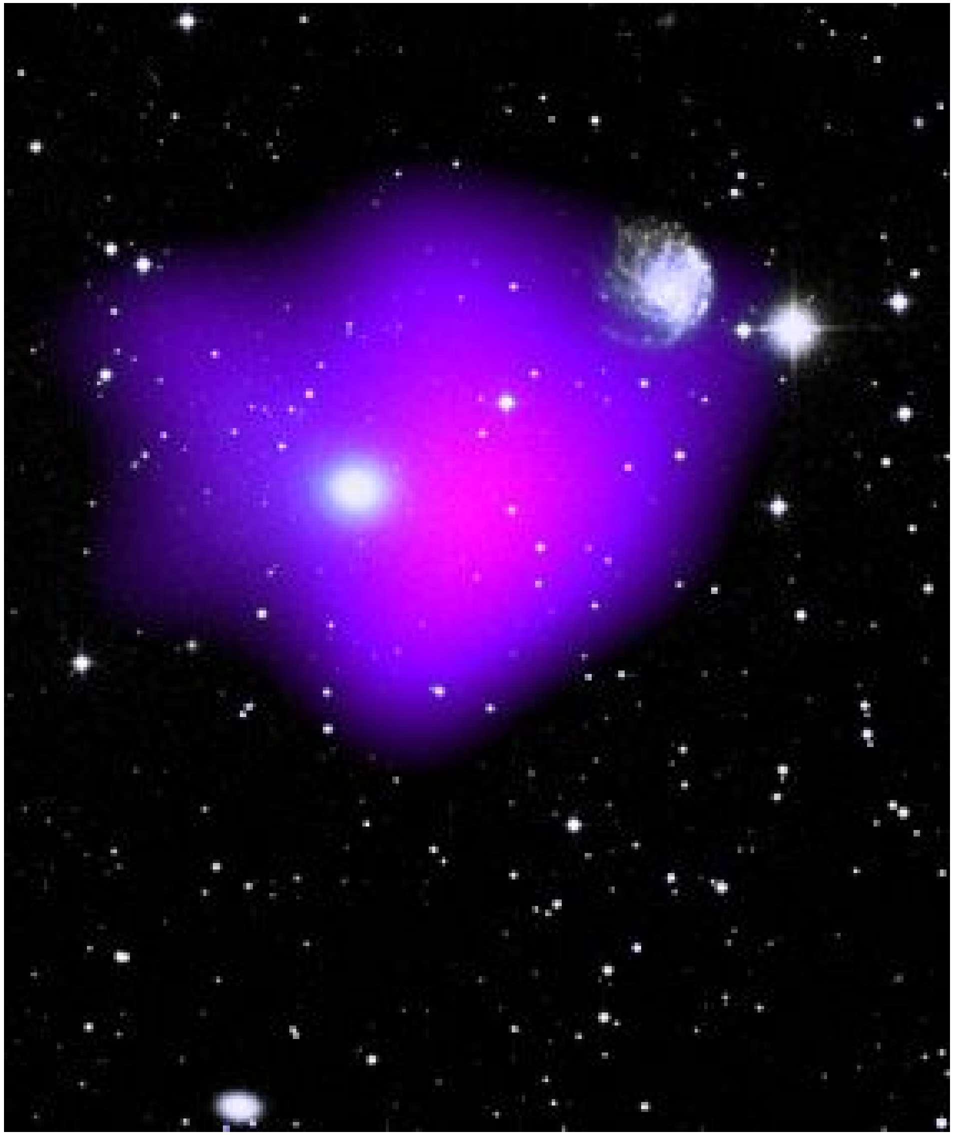


Dwarf irregular NGC 2915 yellow: optical blue: HI

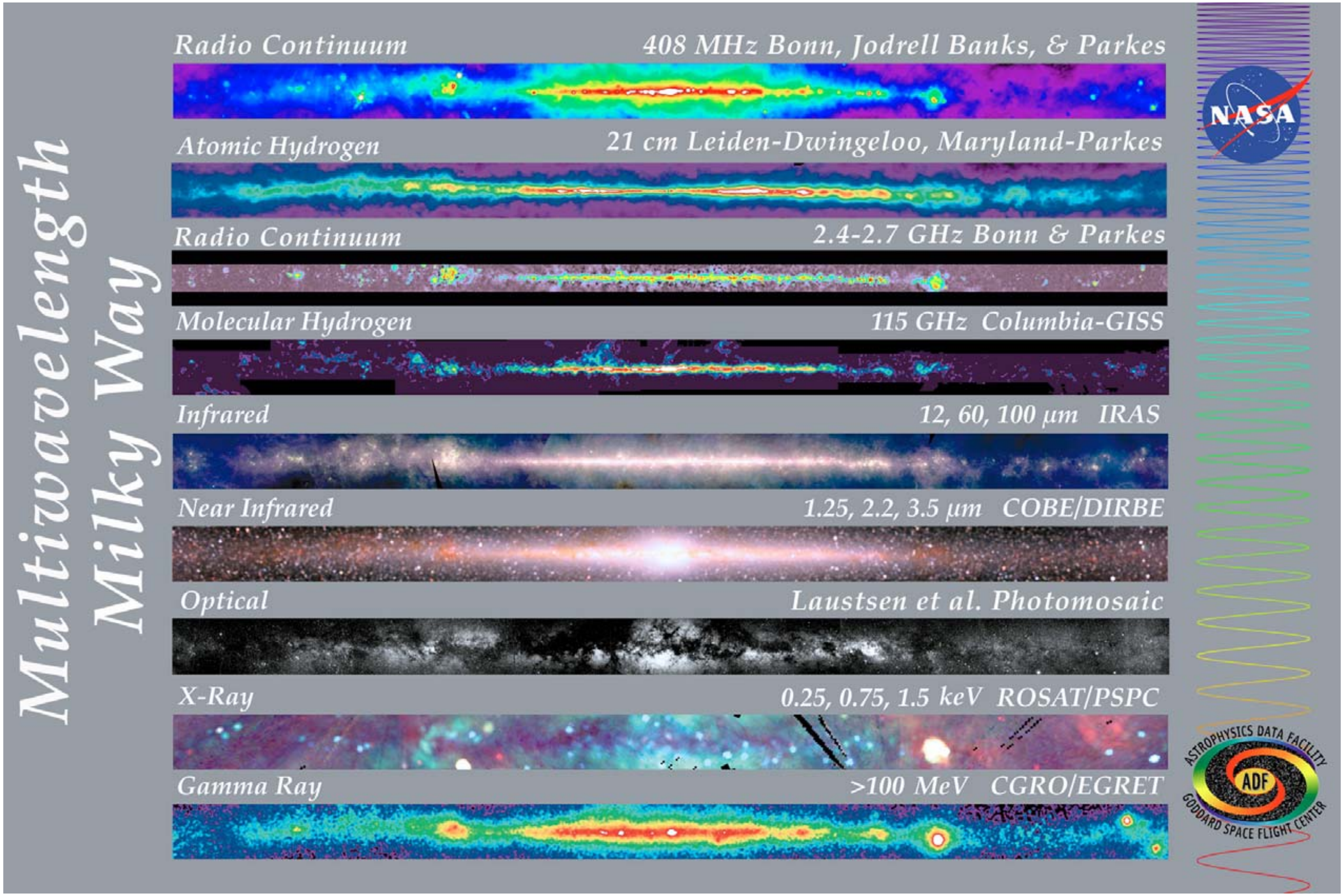




optical M81-group HI



NGC 2300 group (black&white = optical, blue/pink = X-rays)



Milkyway (Sbc-galaxy) in different wavebands

6.4 Luminosity Functions of Galaxies

- Schechter (ApJ 203, p297, 1976) proposed a 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)

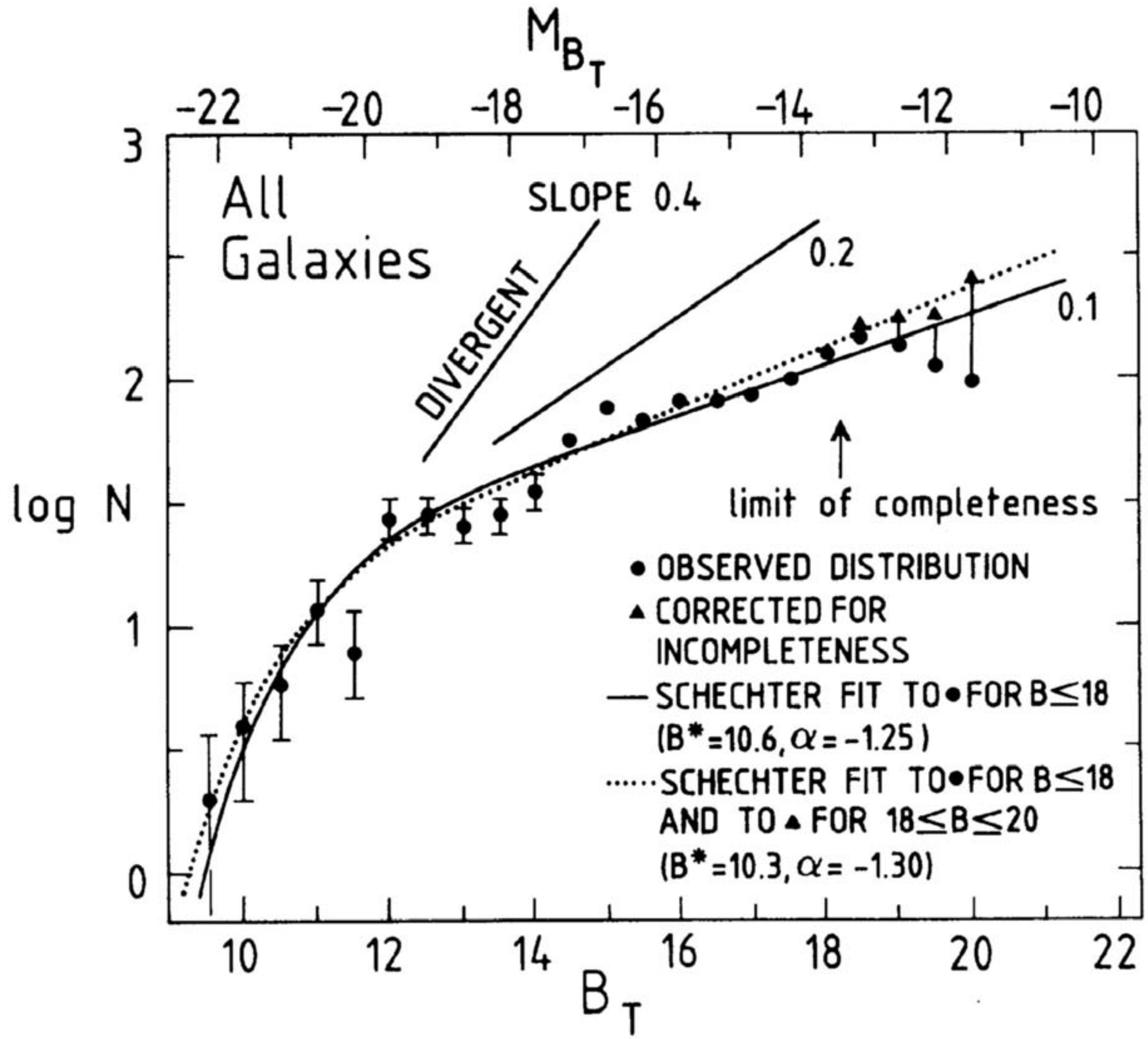
$$L_{B,*} \simeq 10^{10} L_{B,\odot} h^{-2}$$

$$\text{or} \qquad M_{B,*} \simeq -19.5 + 5\log h$$

$$\Phi_* \simeq 0.01 Mpc^{-3} h^3$$

$$\alpha \simeq -1 \ldots -1.3 \qquad \text{(see Peebles 1993)}$$

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



Galaxy luminosity function in the Virgo cluster (Binggeli et al. (1985), AJ 90, 1759

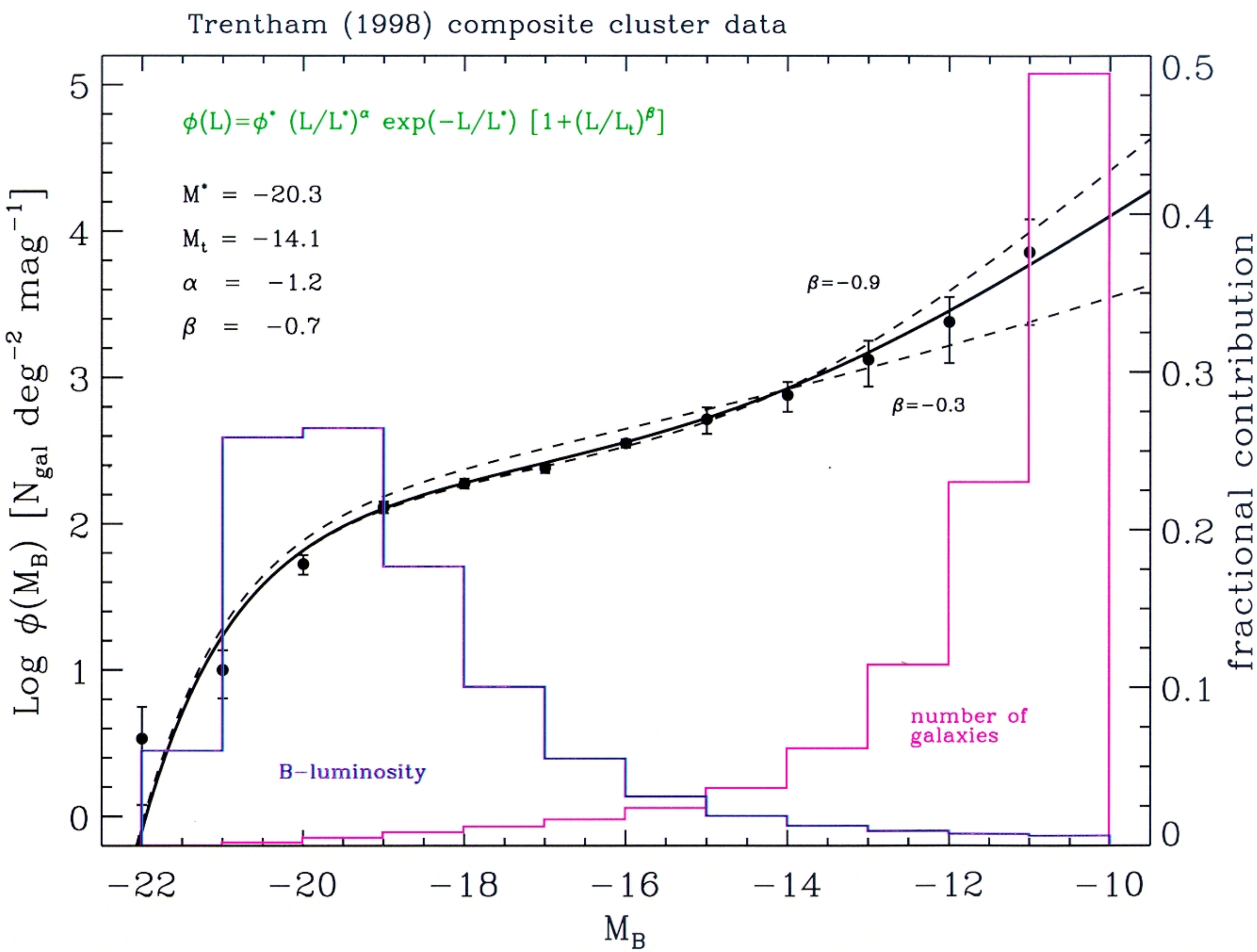
- $\Phi(L/L_*)dL$ is the number density of galaxies with luminosities in the range (L, L+dL) (strong variation of Φ_* depending on environment)

- averaged luminosity per volume:

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

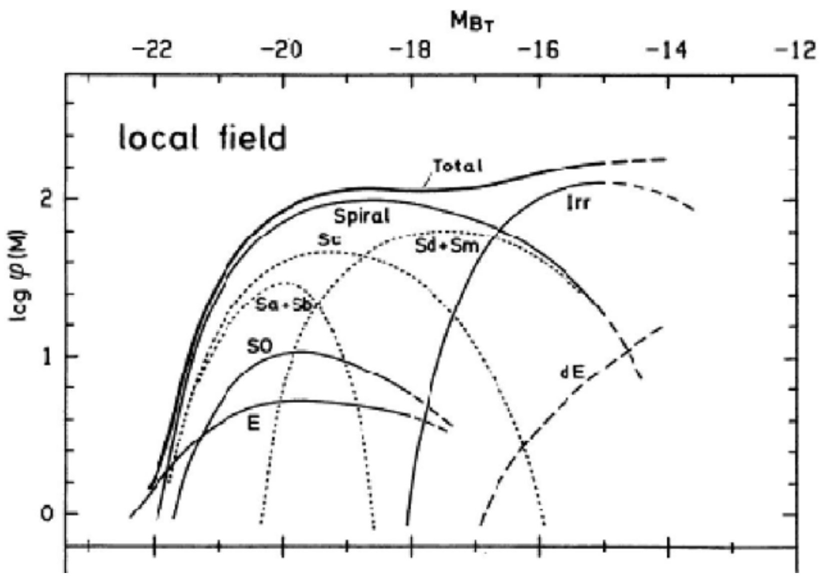
$$\Rightarrow j \simeq 10^8 \frac{L_\odot}{Mpc^3}$$

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



see: Thomas: ESO Astrophysics Symposia (1999)

Luminosity Function Φ(M) versus Absolute Blue Magnitude M_{B_T}



Binggeli, Sandage, Tammann:
ARAA 26 (1988)

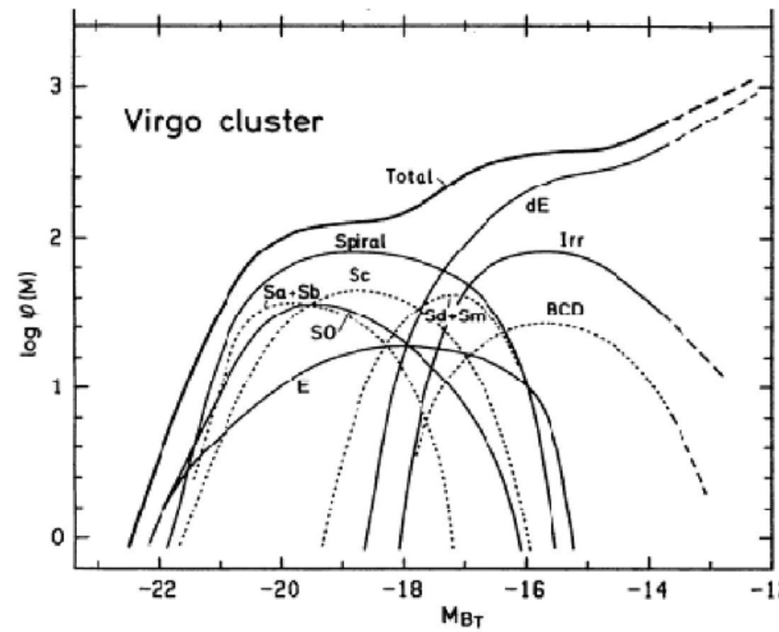


Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa+Sb, Sc, and Sd+Sm are 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).