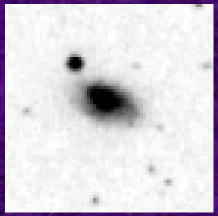
Astronomy 540: Structure & Dynamics of Galaxies

Look at http://ircamera .as.arizona.edu/Astr_540
for announcements and updates.

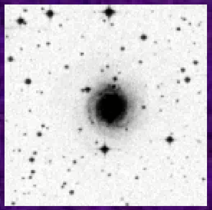
August 21: Galaxy Classification, The Milky Way as a Galaxy,
Aug 23: Components of Galaxies: disks, bulges, interstellar medium, kinematic properties
Aug 28: Disk Dynamics: disk formation, disk heating, spiral arm formation, dark matter
Aug 30: Disk & Spiral arms, cont'd

Marcia Rieke
Rm 262 621-2731

Romeel Davé
Rm 314 621-4681



NGC2731



NGC4681

Why Begin with Classification?

- The Hubble system forms the basic vocabulary of the subject.
- The Hubble sequence of galaxy types reflects an underlying physical and evolutionary sequence.
  - provides an overview of integrated properties
  - reproducing the variation in these properties along the Hubble sequence is a major (unsolved) challenge for galaxy formation/evolution theory
  - One of JWST's four themes is to unravel the evolutionary causes of the Hubble sequence

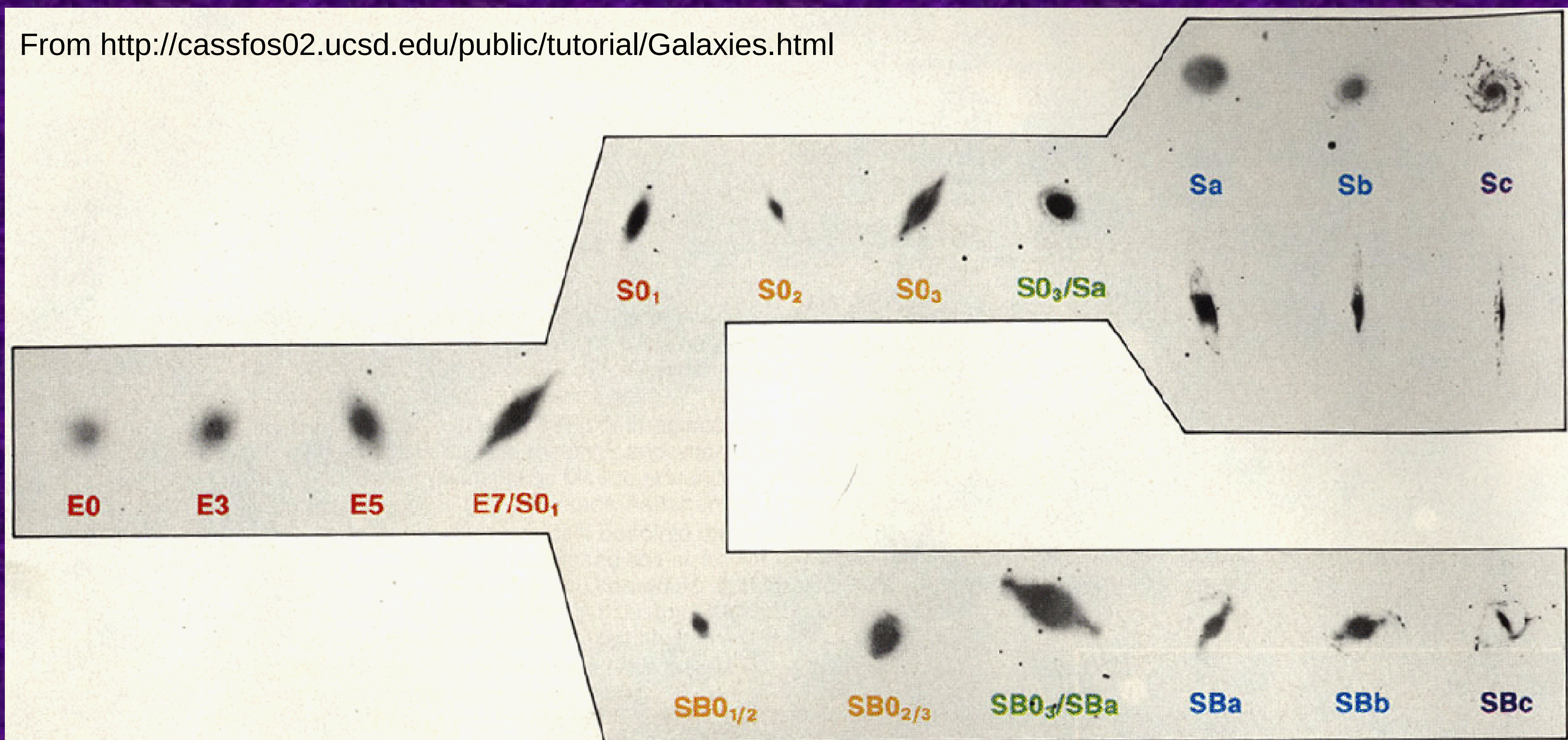
Galaxy Classification Depends on How You Observe

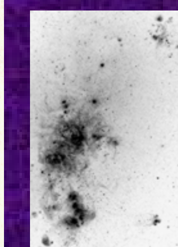
Centaurus A in Visible Light

Centaurus A in Mid-Infrared Light

Hubble Classification System

System based on blue photographic plates.
Hubble 1926, ApJ, 64, 321
Hubble 1936, Realm of the Nebulae





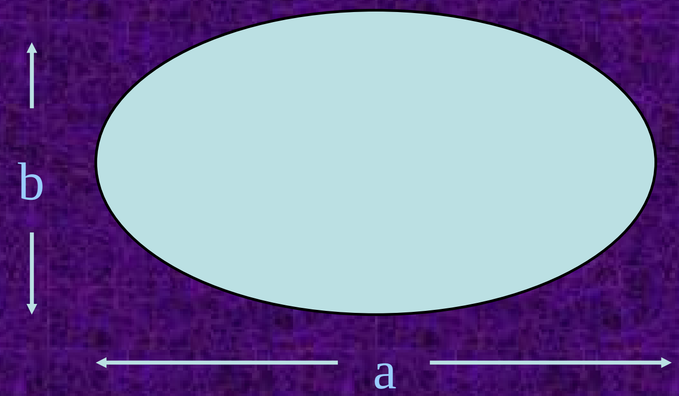
Irr

"Early" "Late"

Hubble cautioned against using early and late in a temporal sense!

- Elliptical galaxies
  - smooth structure, elliptical light distribution
  - *relatively* little evidence of gas, dust
  - subtypes defined by projected flattening

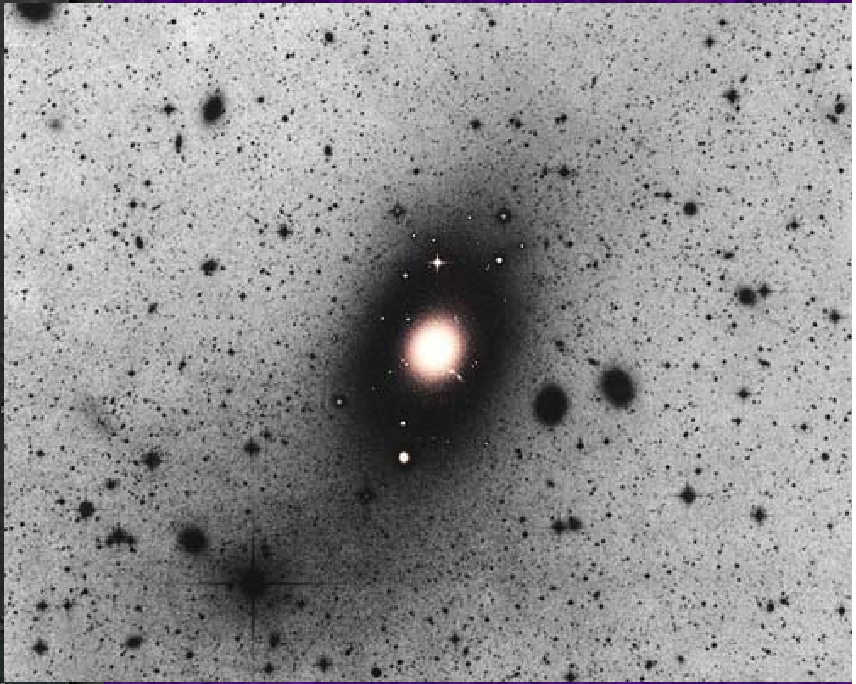
    E0 - E7 where $n = 10(a-b)/a$



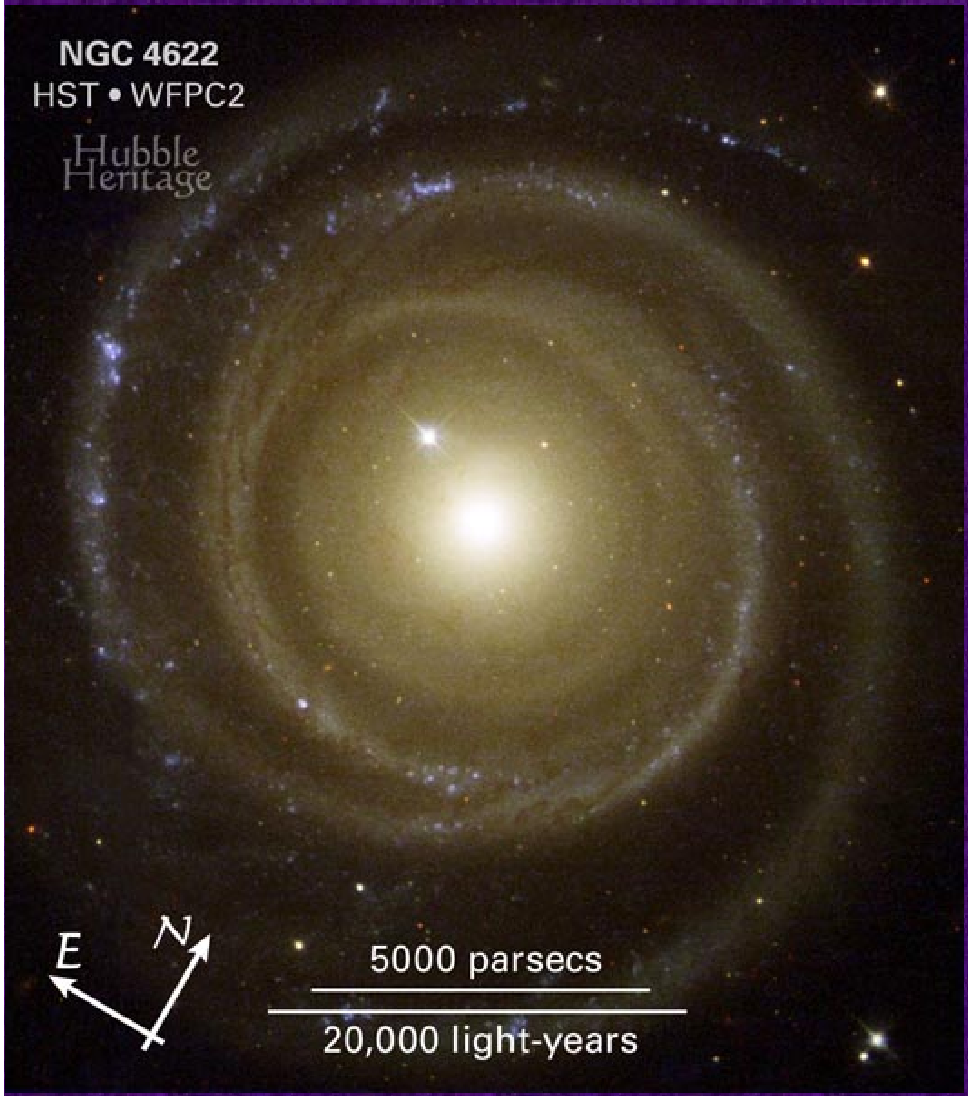
- S0 (lenticular) galaxies
  - introduced in 1936 revision of system
  - disk and bulge but no spiral structure

NGC 4486
M87

E0 - E1
(Virgo)



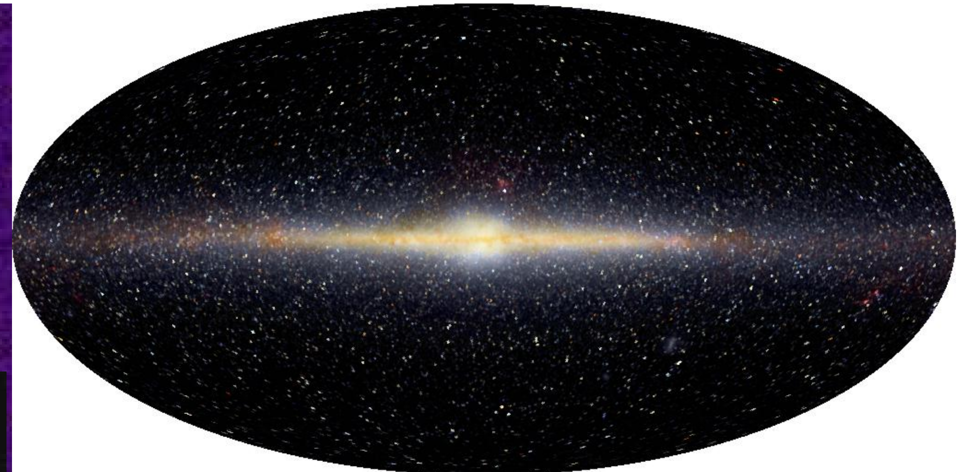
- Spiral galaxies
  - flattened disk + central bulge (usually)
  - two major subclasses: normal and barred
  - subtypes Sa, Sb, Sc distinguished by 3 criteria
    - bulge/disk luminosity ratio
      - B/D ranges from >1 (Sa) to <0.2 (Sc)
    - spiral arm pitch angle
      - ranges from 1-7^{o} (Sa) to 10-35^{o} (Sc)
    - "resolution" of disk into knots, HII regions, stars
  - these three criteria are not necessarily consistent!
  - each reflects an underlying physical variable
    - B/D ratio ---> spheroid/disk mass fractions
    - pitch angle ---> rotation curve of disk, mass concentration
    - resolution ---> star formation rate


NGC 4622
HST • WFPC2
Hubble Heritage
E
N
5000 parsecs
20,000 light-years

Sab


Spiral Galaxy Messier 83 (VLT ANTU + FORS1)
ESO PR Photo 41/99 (29 November 1999)
© European Southern Observatory

Sc

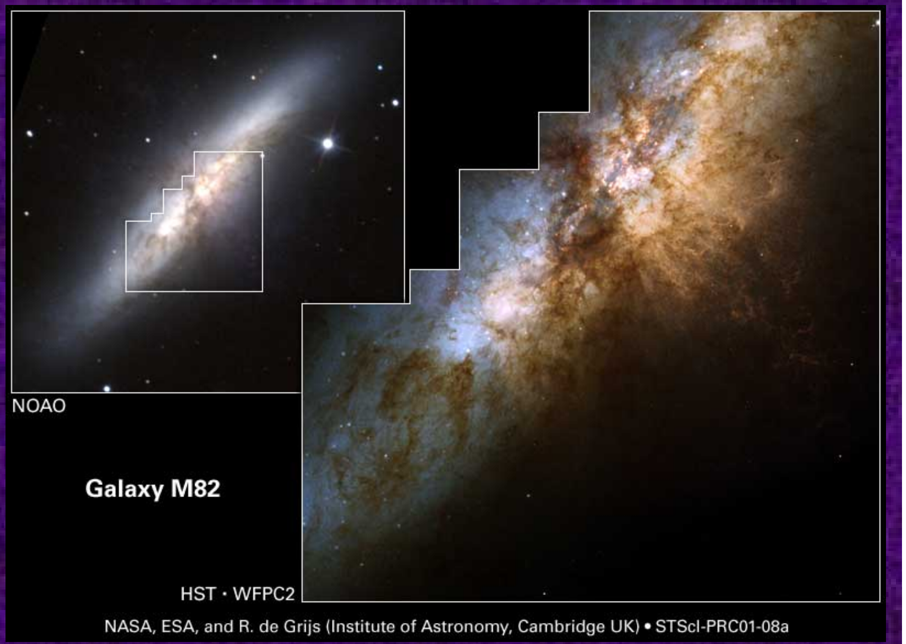


The Sombrero Galaxy (VLT ANTU + FORS1)

ESO PR Photo 07a/00 (22 February 2000)

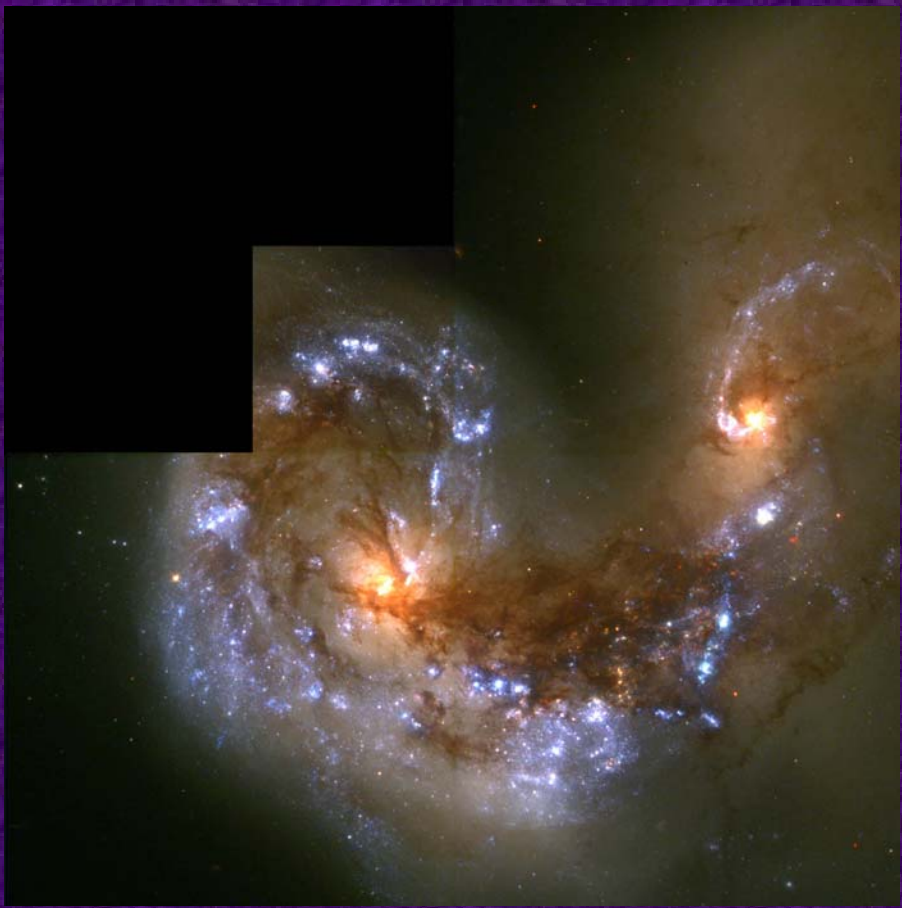
Spiral Galaxy NGC 4945
(MPG/ESO 2.2-m + WFI)

- Irregular galaxies
  - little or no spatial symmetry
  - two major subtypes
    - Irr I: highly resolved (e.g., Magellanic Clouds)
    - Irr II: smooth but chaotic, disturbed (e.g., M82)



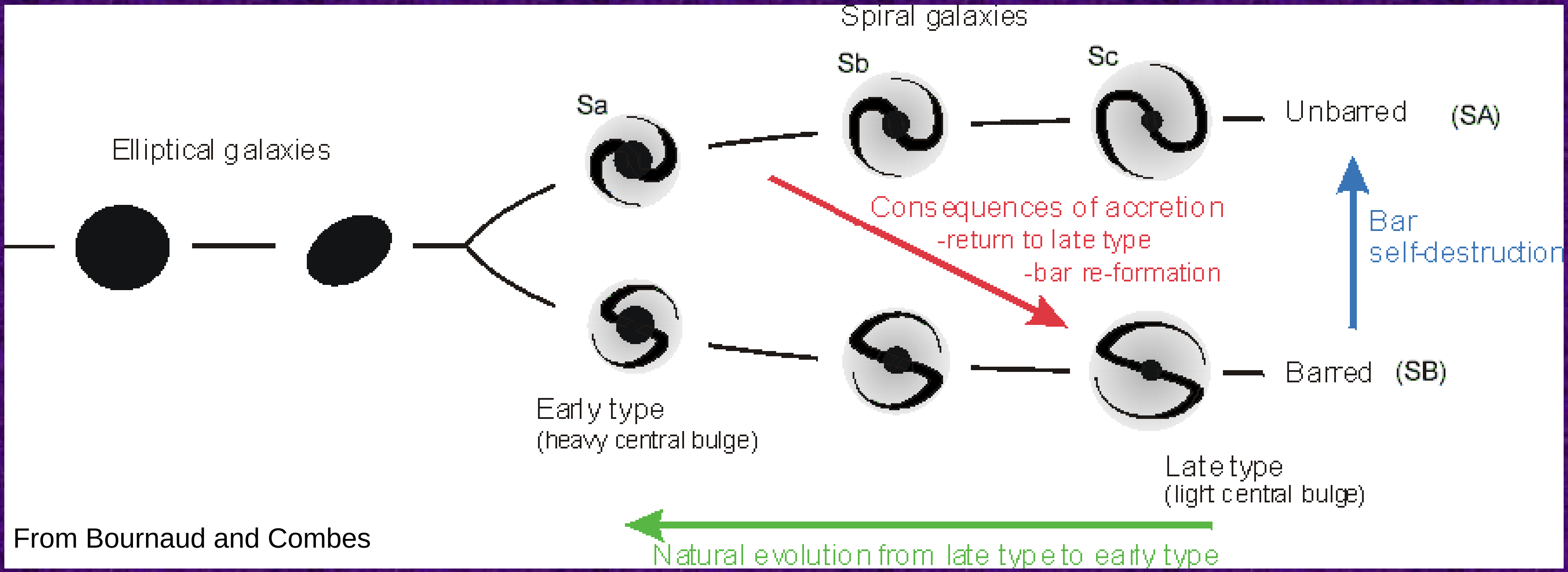
- Unclassifiable galaxies?
  - ~2% of galaxies cannot be classified as E, S, Irr
  - predominantly disturbed or interacting systems

NGC 5128 = Cen A



NGC 4038/9 = "Antennae"

Connection between Evolution and Morphology



- Bars are a transient structure and spirals may alternate between barred and not
- Some spiral mergers appear to result in elliptical galaxies
- Spirals have much higher angular momentum than ellipticals which suggests differences at the formation epoch (but look at what happens in some mergers)

Other Classification Systems

- Revised Hubble system

  de Vaucouleurs 1958, Handbuch der Phys, 53, 275

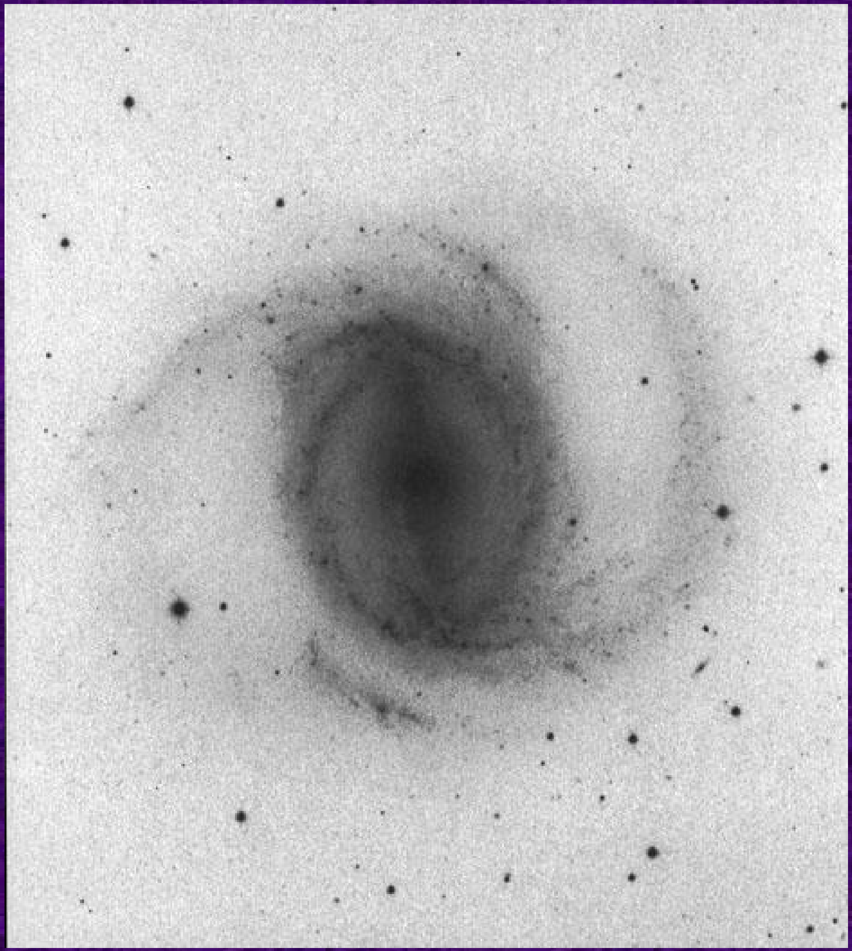
  de Vaucouleurs 1964, Reference Catalog of Bright Galaxies (RC1)

  – goal: retain basic system, add more information
    - mixed types: E/S0, Sab, Sbc, etc
    - intermediate barred: SA, SAB, SB
    - extended types: Sd, Sm, Sdm
    - inner rings: S(r) , S(s)
    - outer rings: (R) S
    - Magellanic spirals, irregulars: Sm, Im
    - t-type numerical scale: E0 -- S0 -- Sa -- Sb -- Sc -- Im

      -5 -- -1 --- 1 --- 3 --- 5 --- 9

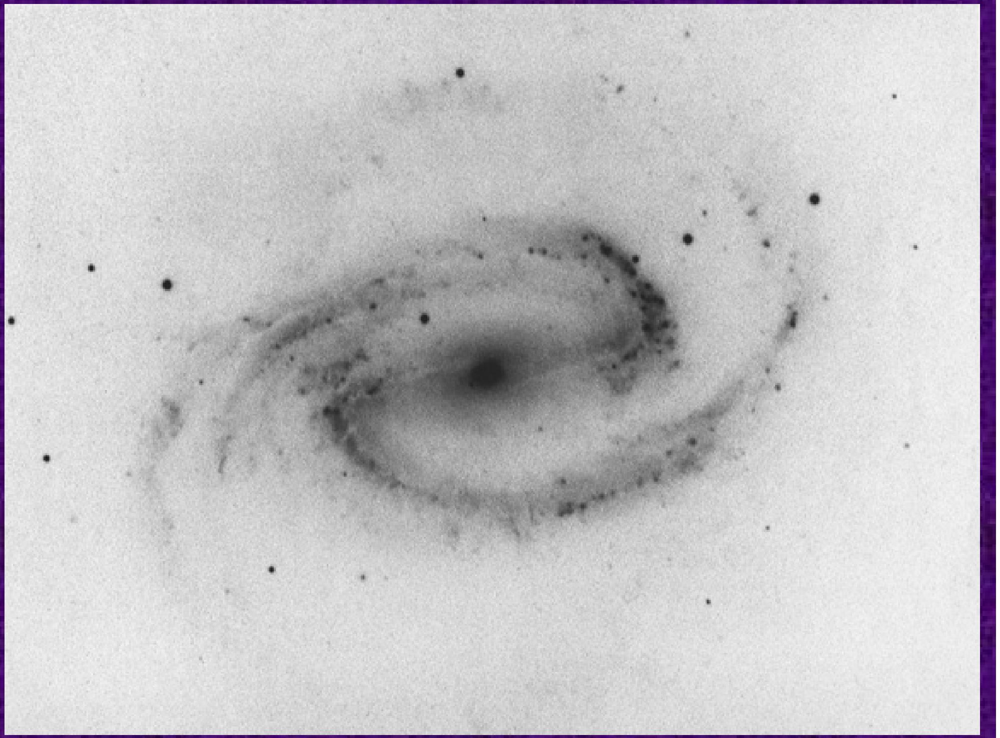
NGC 1433

(R)SB(r)ab



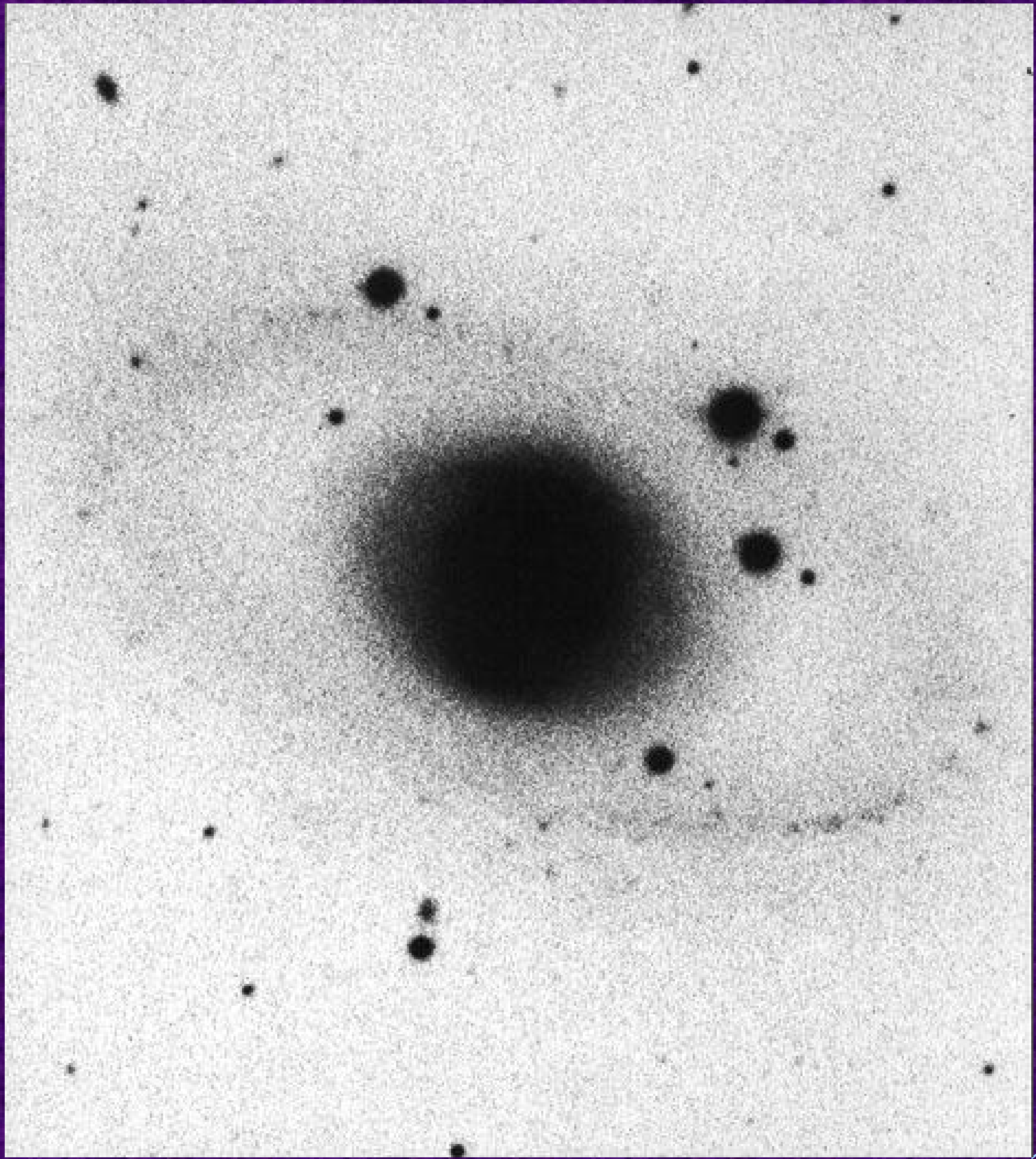
NGC 1300

SB(rs)bc



NGC 3945

RSB(rs)0+



Other Classification Systems

- Luminosity classification (DDO system)

  van den Bergh 1960, ApJ, 131, 215

  - goal: use morphology to subdivide galaxies by absolute luminosity and mass
  - basic criterion is spiral arm "development" (arm length, continuity, relative width)
  - secondary criterion surface brightness (dwarfs)
  - roman numeral designation after Hubble type (indicates luminosity class)
    - Sc I, I-II, II, II-III, III, III-IV, IV
    - Sb I, I-II, II, II-III
    - Ir IV-V, V
  - mean M_B ranges from -21 (I) to -16 (V)

NGC 1232: SBc I

NGC 598 = M33 Sc II-III

NGC 1232: SBc I

NGC 598 = M33 Sc II-III

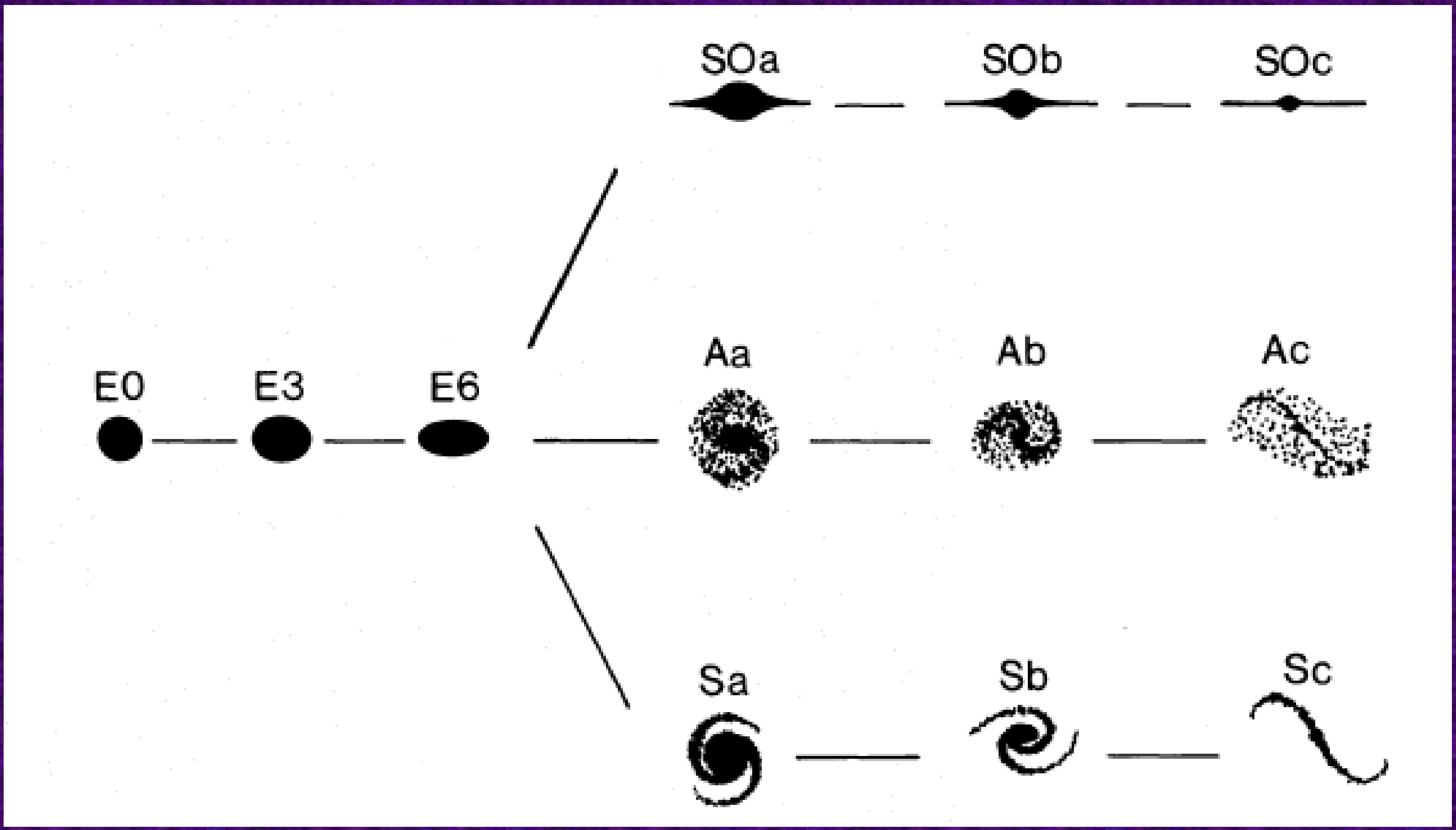
Other Classification Systems

- Revised DDO (RDDO) system

  van den Bergh 1976, ApJ, 206, 883

  – premise: the evolutionary axis along the "tuning fork" is actually a two-parameter sequence:
    - bulge/disk ratio: a --> b --> c
    - disk resolution, star formation rate: S0 --> A --> S

  – van den Bergh hypothesizes that all disk galaxies are formed as normal spirals, but gradually consume gas (or lose gas) and evolve to anemic and eventually S0 galaxies, while retaining roughly constant bulge/disk ratio


SOa
SOb
SOc
E0
E3
E6
Aa
Ab
Ac
Sa
Sb
Sc

Quantitative Classification

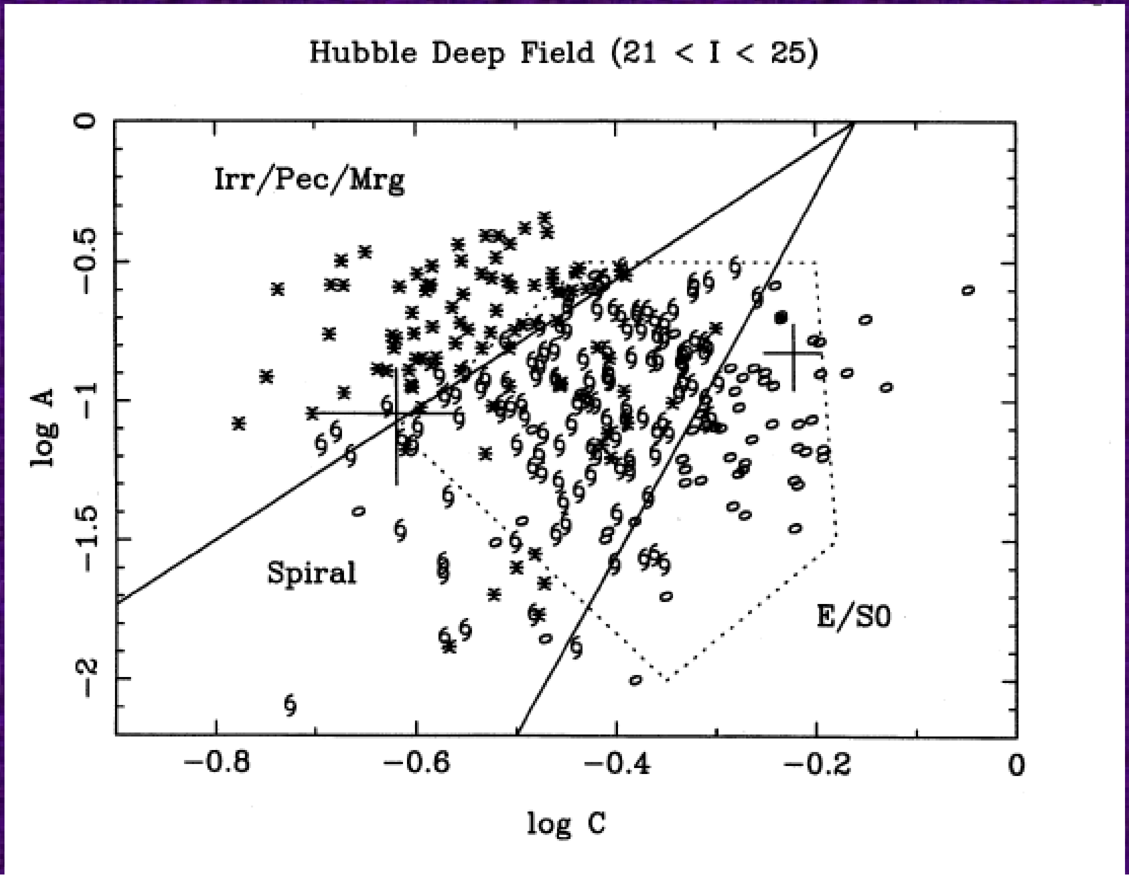
- Motivation
  - automated classification is needed for very large imaging or spectroscopic surveys (e.g., Sloan Digital Sky Survey = SDSS)
  - can obtain objective measures, that are less susceptible to systematic or subjective effects
  - the current morphological sequence may not be representative of galaxies at earlier cosmic epochs
  - since many physical and spectral properties of galaxies correlate with type, a physical classification system can be created
  - parametric classifications provide information on the dimensionality of the galaxy parameter space

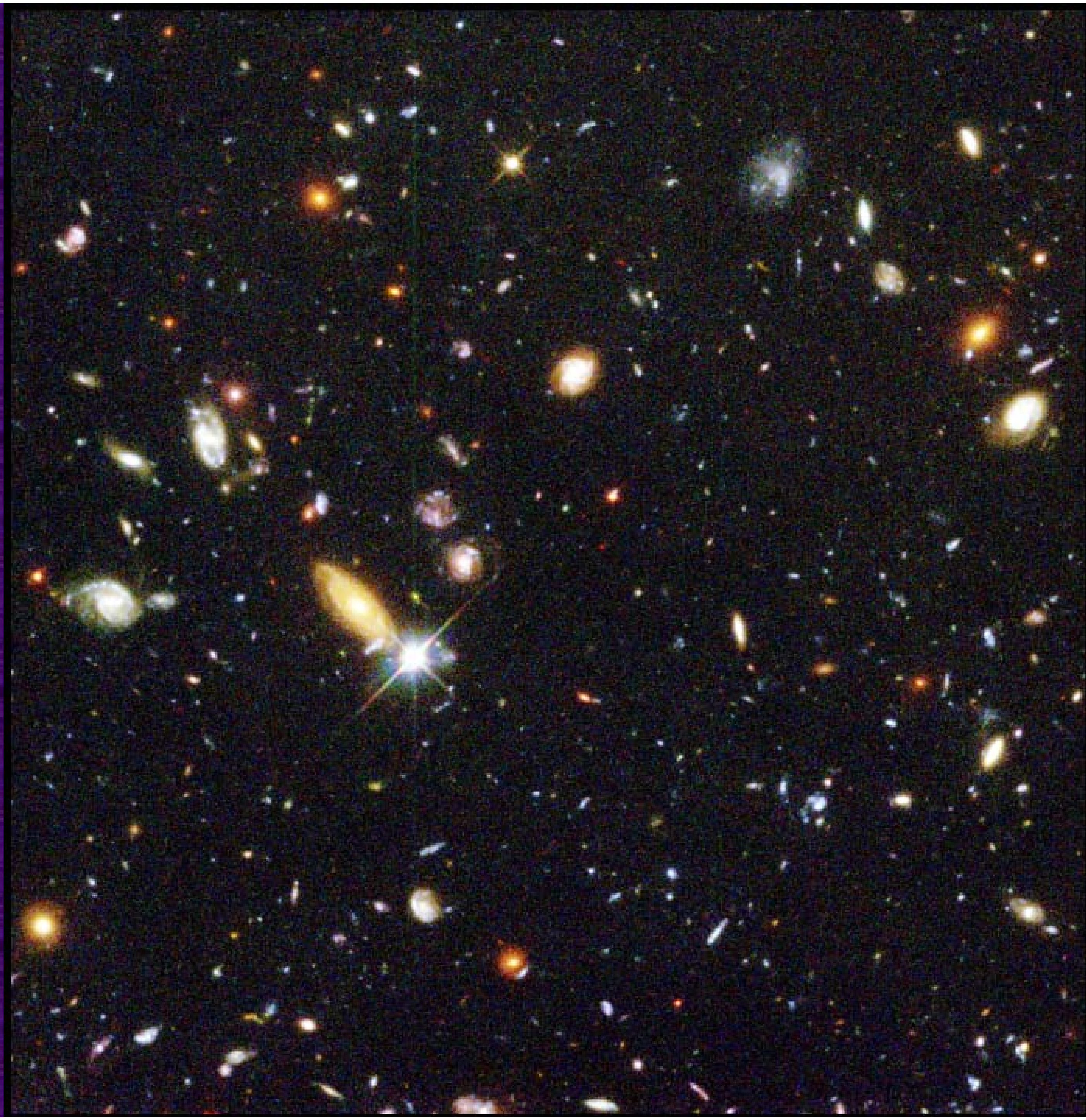
- Example 1: Quantitative image classification

Abraham et al. 1994, ApJ, 432, 75

Abraham et al. 1996, MNRAS, 279, L49

- simple 2-parameter system
  - concentration index C --> ratio of fluxes in two isophotal regions
  - asymmetry index A --> flip image, subtract from initial image, measure fraction of residual flux



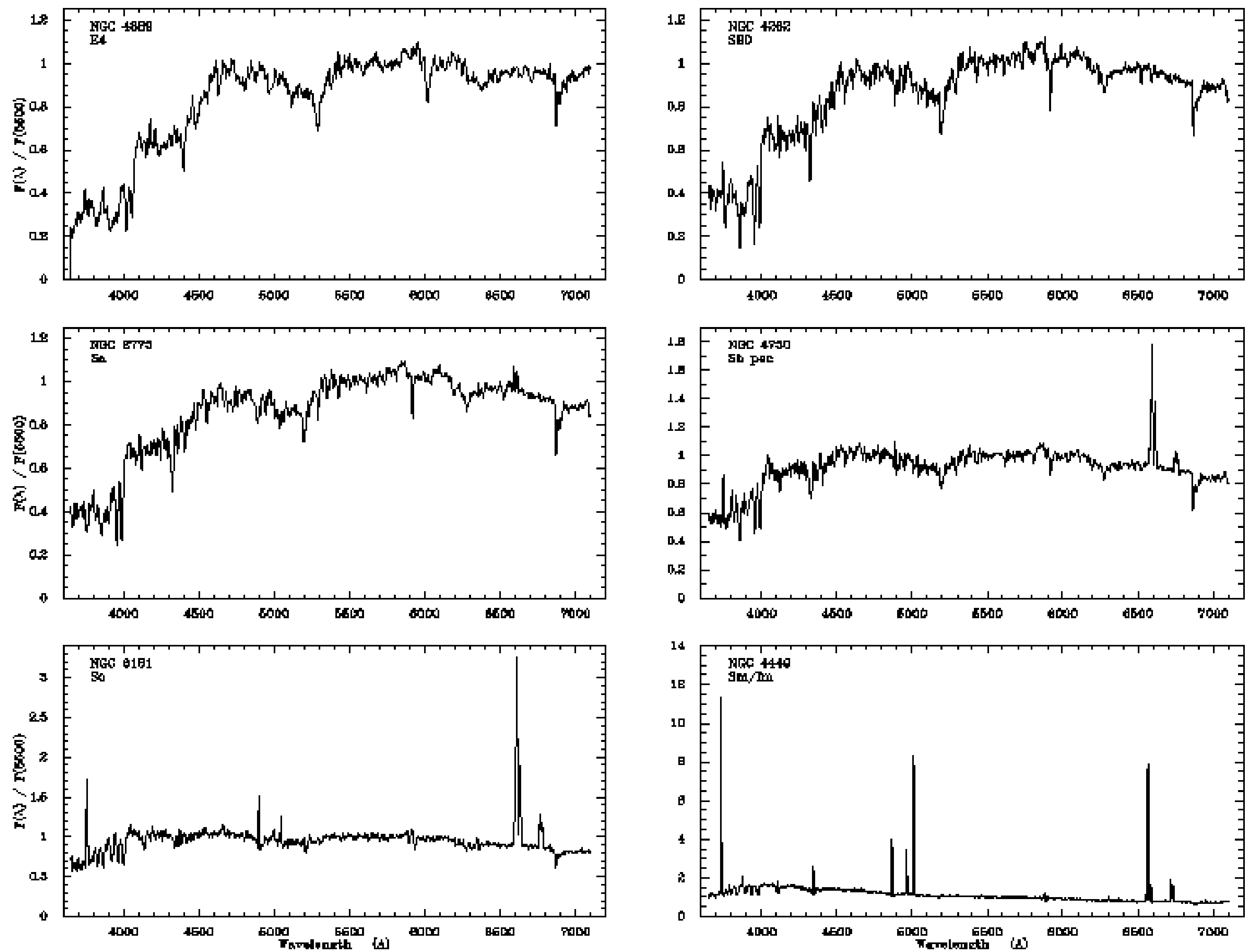


- Example 2: <u>Quantitative spectral classification</u>

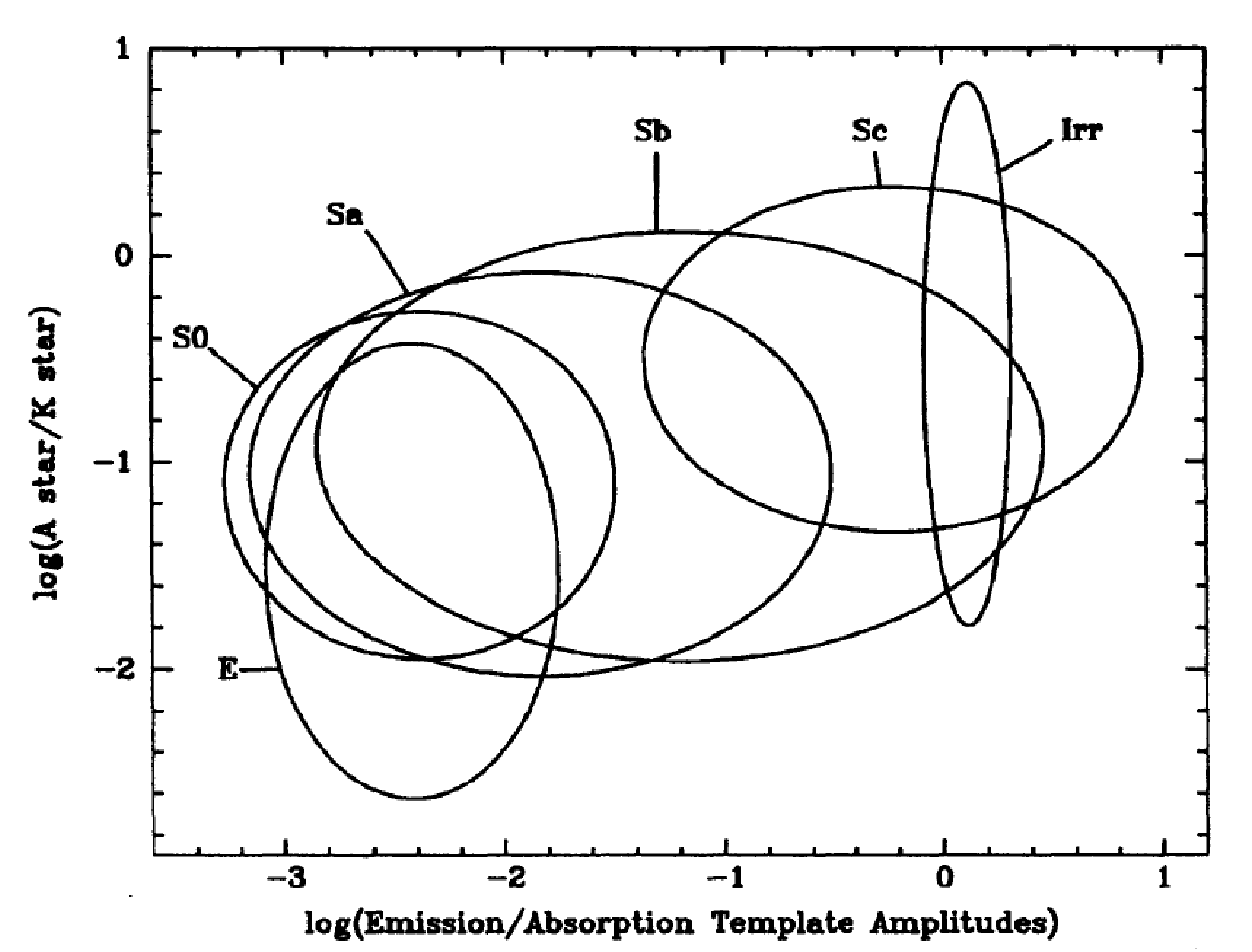
  Kennicutt 1992, ApJS, 79, 255

  Zaritsky, Zabludoff, Willick 1995, AJ, 110, 1602

  - galaxy spectra correlate strongly with Hubble type
    - Morgan & Mayall (1957) developed a morphological classification system (Yerkes system) based on galaxy spectra (PASP, 69, 291)
  - principal component analysis shows that most of the variation is due to 2 parameters (eigenfunctions)
    - change in absorption spectrum: A stars vs K stars
    - change in emission line strength vs continuum + absorption
  - fit each galaxy spectrum to these eigenspectra (maximum likelihood), measure spectral indices
  - classifications are independent of morphology, but one can correlate spectral vs morphological types



Kennicutt 1992, ApJS, 79, 255



Zaritsky et al. 1995, AJ, 110, 1602

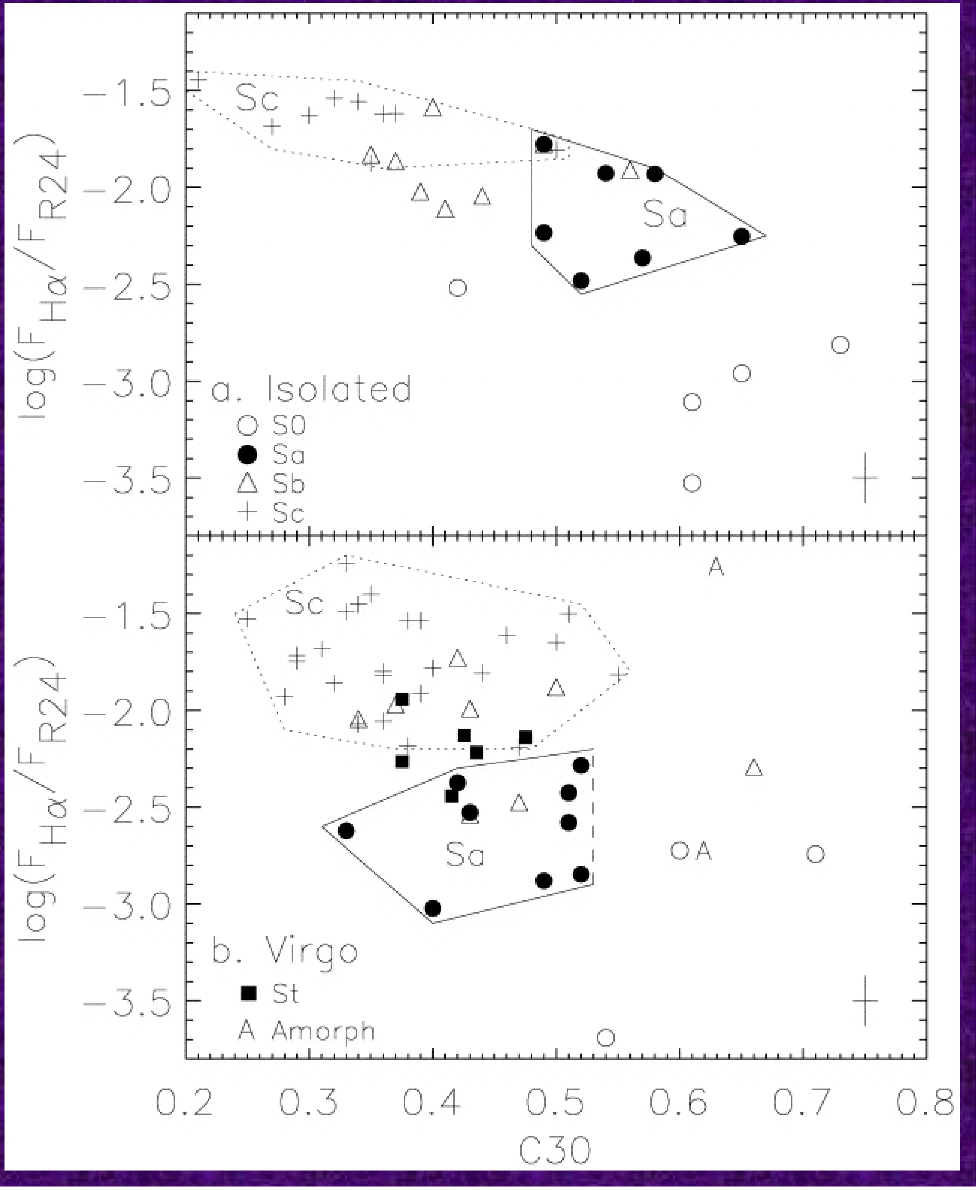
• Example 3: morphology/spectral classification

Koopman & Kenney 1998, ApJ, 497, L75 (Virgo S0-Scd galaxies)

- question: Does galaxy cluster environment (Virgo) affect spiral galaxy evolution?

- hybrid system
  - define emission-line spectral index (scales as SFR per unit red luminosity)
  - correlate with concentration index, to remove subjectivity of morphological types

- result: Virgo cluster contains galaxy population not found elsewhere



F_{R24} = R flux within μ_R=24, C=fraction within 0.3 of r_{24}

Parametric Classification

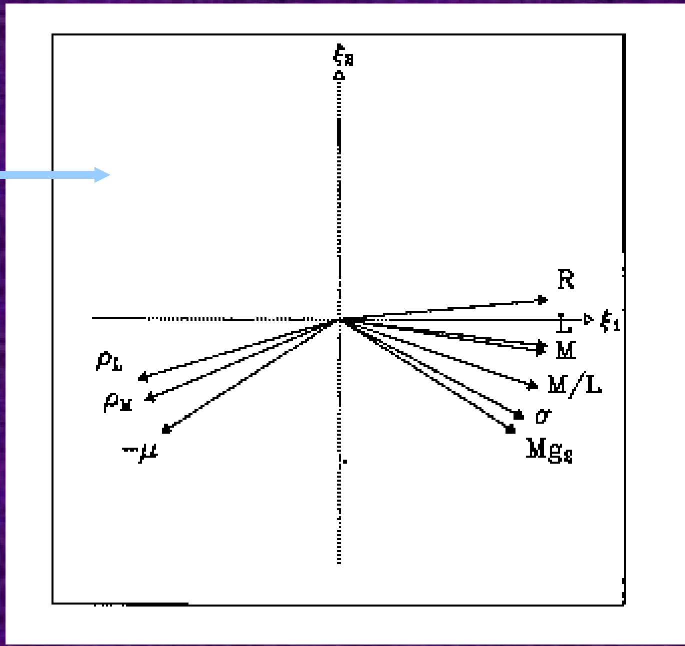
- Basic Idea: Hubble type correlates with several integrated properties of galaxies (e.g., bulge fraction, gas fraction, color, star formation rate, angular momentum…
- Goal: define a physical classification in an n-space of galaxy properties
- Use correlations between these parameters to analyze the number of independent variables that define galaxy properties

- Example: <u>principal component analysis (PCA)</u>

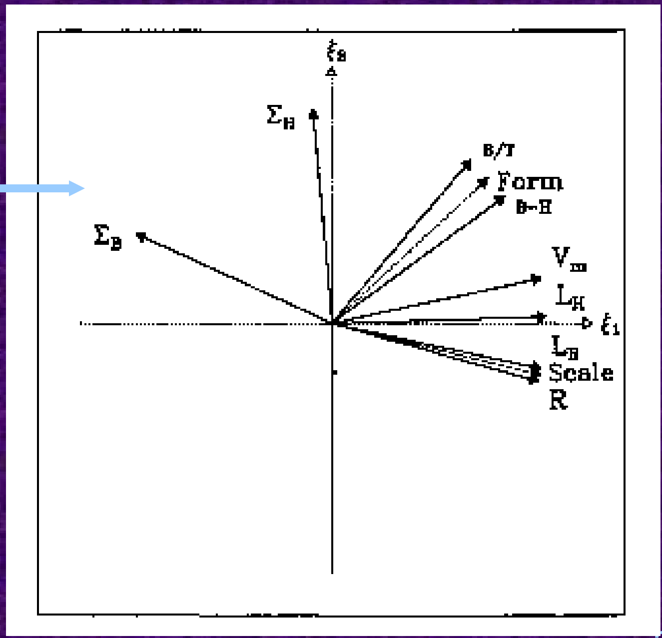
  Djorgovski 1992, in Cosmology and Large Scale Structure of the Universe, ASP Conf Ser, 24, 19

  - for a series of measured galaxy properties, calculate the correlation coefficient for each pair of parameters
  - construct a correlation matrix of these coefficients
  - diagonalize the correlation matrix and solve for its eigenvalues and eigenfunctions
    - each eigenfunction is a linear combination of galaxy properties, representing an independent degree of variability (or noise)
    - the corresponding eigenvalues represent the fraction of observed variation of galaxy properties in each degree of freedom

- when applied to elliptical galaxies:
  - most (~80%) of the variance is in a single parameter (mass/luminosity/ radius/velocity dispersion/color/line strength)
  - virtually all of the remaining variance is in a second parameter (ellipticity, rotation…) --> the fundamental plane



- when applied to spiral galaxies:
  - two parameters needed (Hubble type, luminosity/mass)



Djorgovski 1992

Summary of Trends in Physical Properties w/ Morphological Type

Angular Momentum:	Low in ellipticals
	High in spirals
Interstellar Medium:	Zero to v. low in ellipitcals
(star formation rate follows	High in spirals
same pattern)	v. high in some Irrs
Stars:	Only old in ellipticals
	Mixture of old & young in spirals
Metallicity:	High in ellipticals
	Mixture in spirals
	v. low in some Irrs

Galaxy Classification at other Wavelengths

Systems at other wavelengths typically describe some characteristic of a galaxy's non-stellar activity. Another example is Seyfert 1s and 2s.

Example:

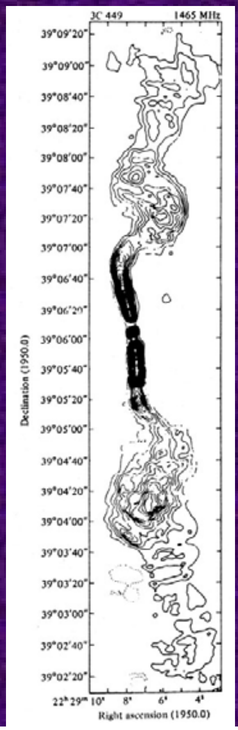
Radio galaxies are divided into two classes.

Fanaroff-Riley I (FRI)

Radio surface brightness declines center from to edge. Core and jets are most prominent.

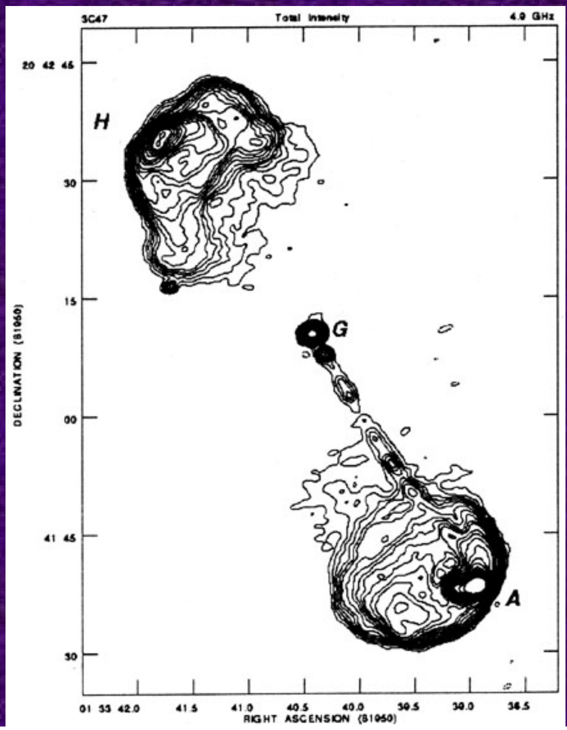
Fanaroff-Riley II (FRII)

Outer edges of radio lobes are brightest. More luminous than FRIs.

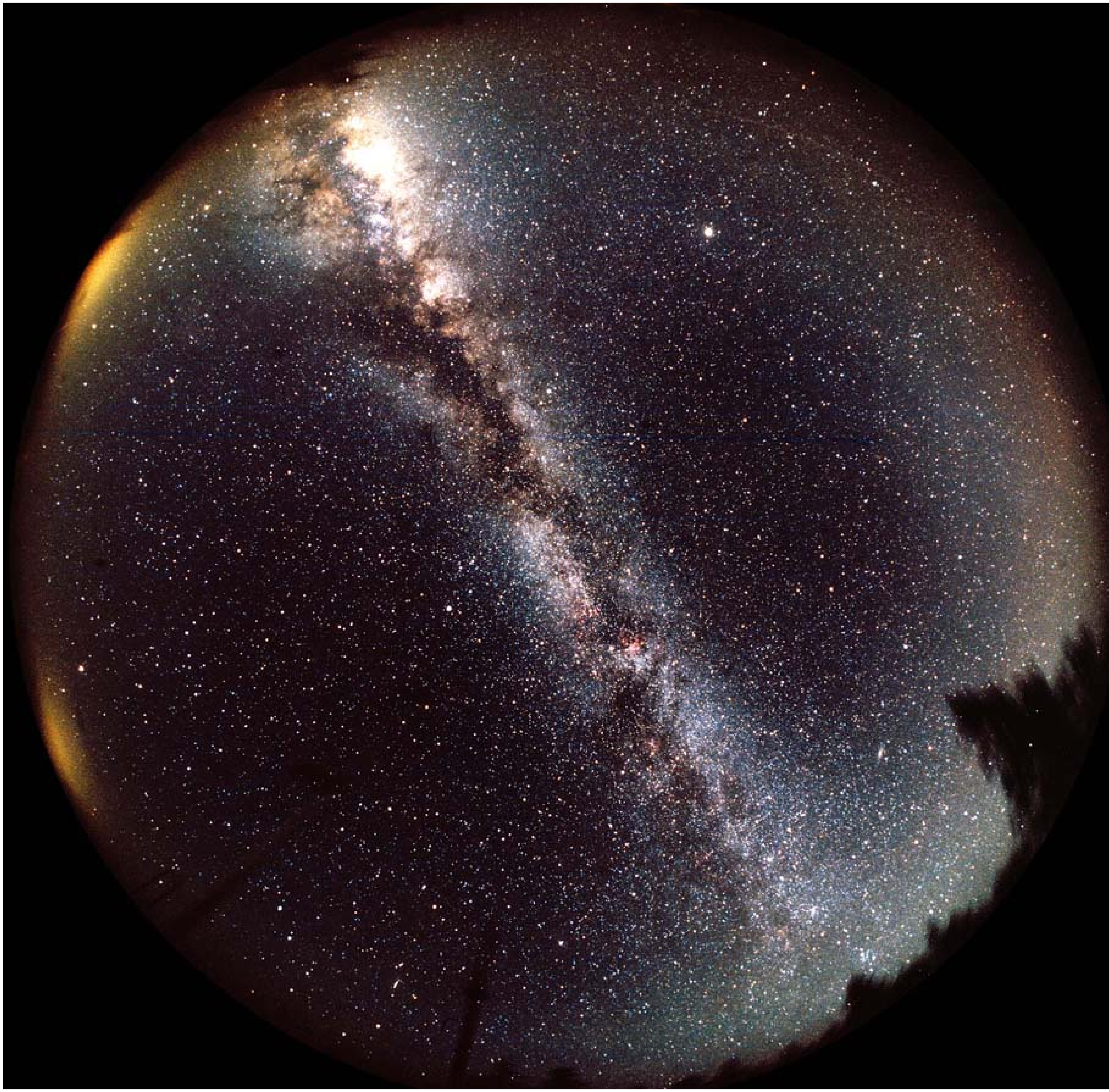


3C449

These galaxies are ellipticals in stellar light.



3C47

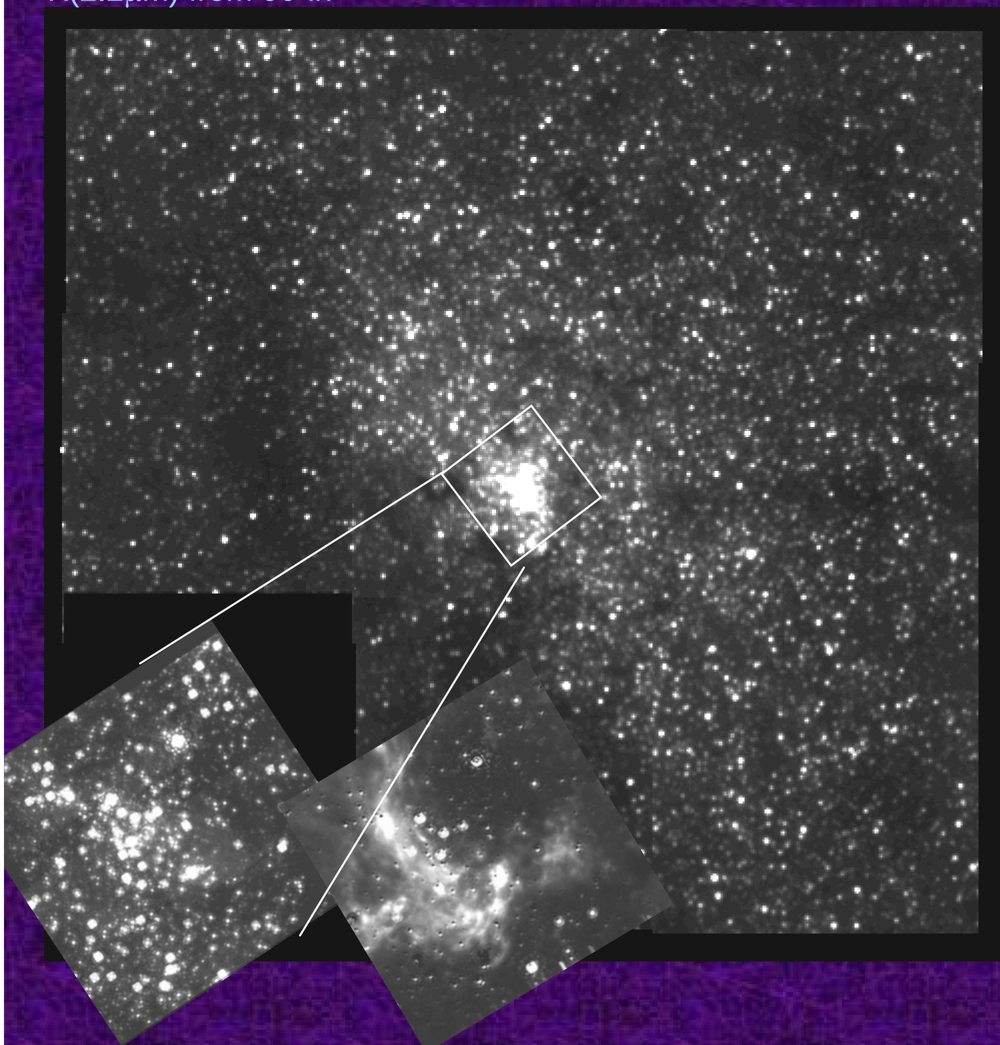


The Milky Way from Mt. Graham

Many Different Types of Data Available for the Milky Way

Nucleus of the Milky Way

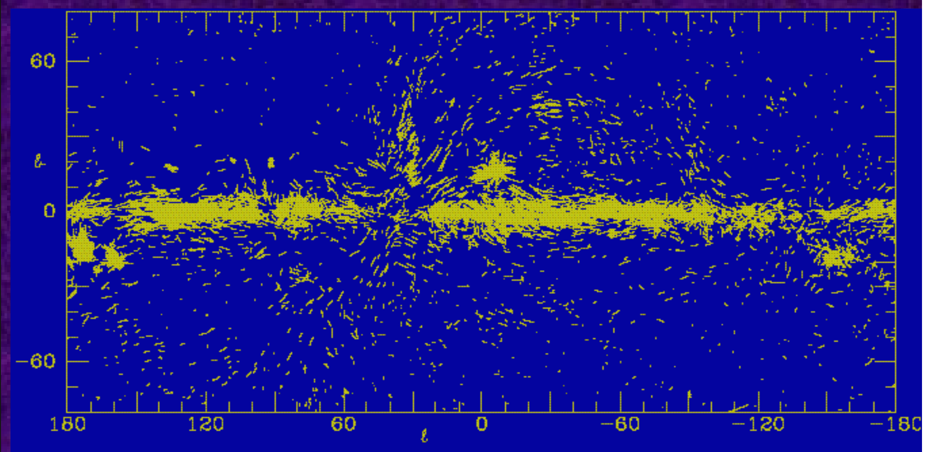
K(2.2μm) from 90-in

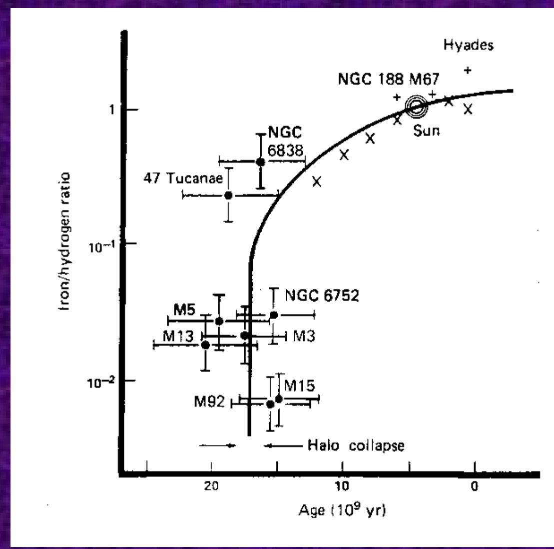


1.6μm

Pα (1.87μm) from NICMOS on HST

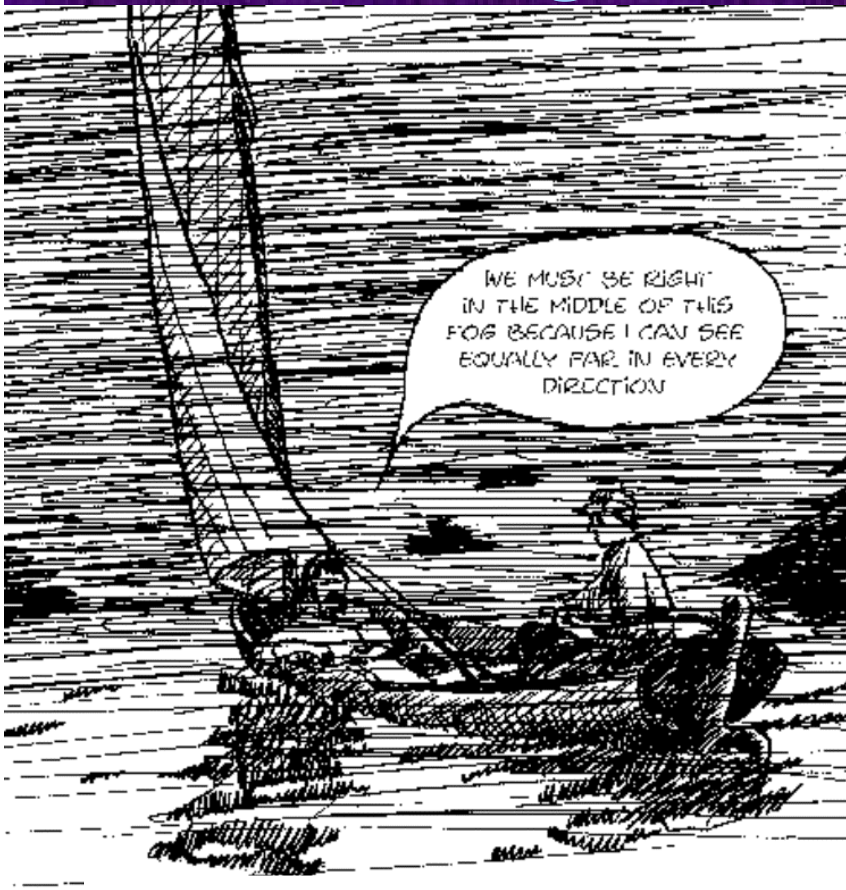
Milky Way Polarization from Mathewson & Ford (1970).



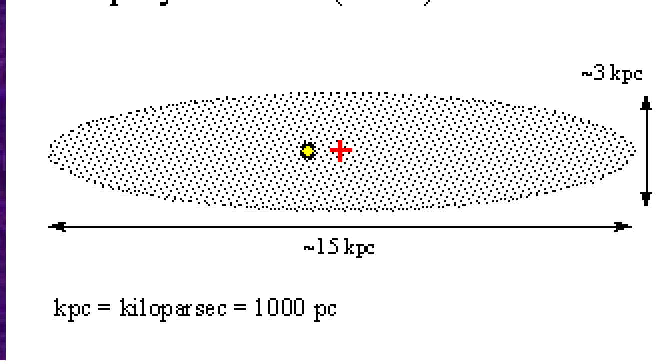


Age-metallicity relation after Sandage 1982

Looking at a Galaxy from the Inside



Kapteyn Model (1922)



Milky Way is the nearest galaxy so its constituents can be discerned with exquisite precision:

stellar populations and their motions

detailed compositions as a function of location within the galaxy

types of gas and dust (even a few samples have been collected!)

But being inside has disadvantages:

some interstellar material restricts our view

difficult to discern overall patterns (only realized that the Milky Way has a bar a dozen years ago!)

We must also keep in mind that the Milky Way is a sample of one – there are many other types of galaxies.

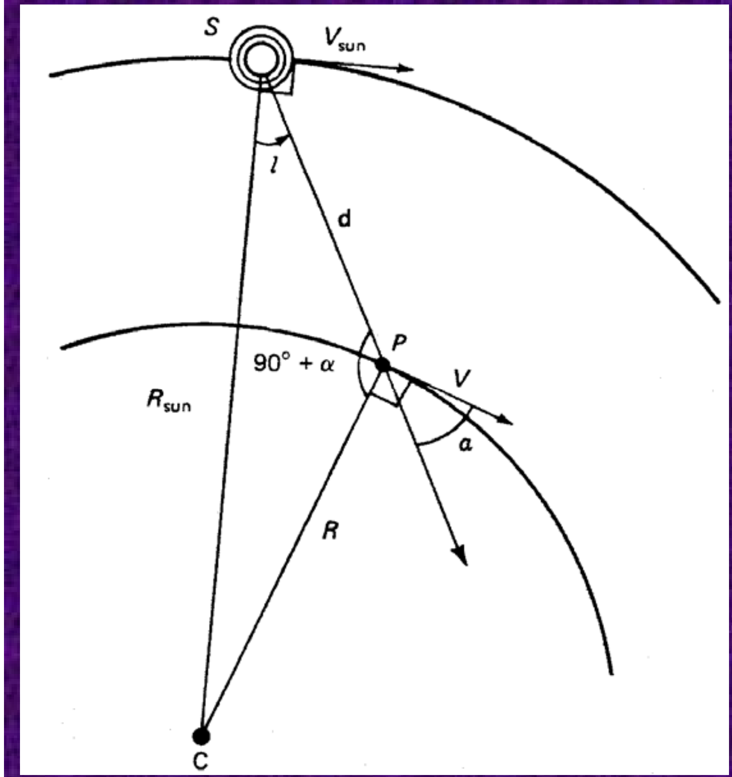
Structure of the Milky Way

Table 1. The Galaxy: Some Vital Statistics

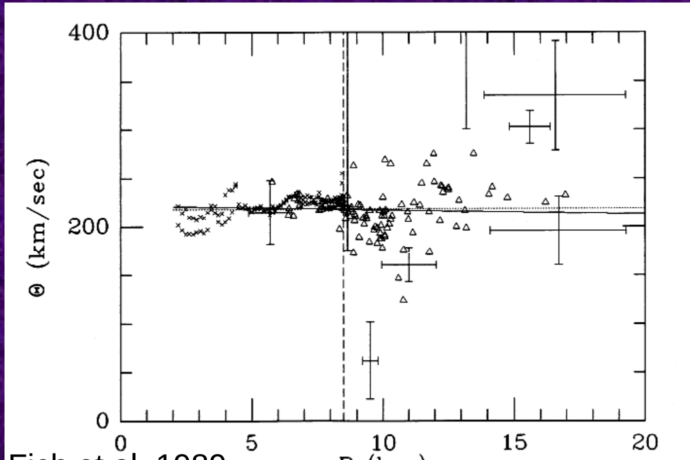
Solar Orbit	$V_0/R_0 = 29 \pm 1$ km s^{-1} kpc^{-1} $V_0 = 220 \pm 10$ (R_0/8 kpc) km s^{-1} $R_0 = 8.0^{+0.5}_{-1.0}$ kpc
Mass	M (<10 kpc) $= (1.0 \pm 0.2) \times 10^{11}$ $M_\odot$ M (<100 kpc) $= (7 \pm 2.5) \times 10^{11}$ $M_\odot$
Luminosity (bol)	$L = 3\ ^{+2}_{-1} \times 10^{10}$ $L_\odot$ $M_V \sim -20.5 \pm 1.0$ $\quad M_H \sim -23 \pm 1$
Stellar Mass	$M_* \sim (4 \pm 2) \times 10^{10}$ $M_\odot$
Interstellar Mass	$M_{ISM} \sim (7 \pm 3) \times 10^9$ $M_\odot$ $M_{ISM}/M_* \simeq 0.2$
Total Visible Mass	$M_{vis}/M_{tot} \sim 0.5$ $\quad (R \leq 10$ kpc) ~ 0.07 $\quad (R \leq 100$ kpc)
Star Formation Rate	$SFR = 2 \pm 1$ $M_\odot$ yr^{-1} $SFR/\langle SFR \rangle_{past} \sim 0.7 \pm 0.3$ $M_{ISM}/SFR \sim 3.5$ Gyr
Revised Hubble Type	SB(r)bc pec

Kennicutt 2001, Tetons 4, ASP Conf Ser, 231, p2

Measuring the MW's Spiral Structure



- Delineating a galaxy's spiral pattern requires using young stars or interstellar material.
- First measurements used HI
- Scheme requires a model for the rotation of the Milky Way's disk – made easier by the nearly flat rotation curve for the MW
- Measure radial velocity and derive a distance



Fich et al. 1989

$$V_r = V\cos\alpha - V_{sun}\sin l$$

$$\frac{\sin(90+\alpha)}{R_{Sun}} = \frac{\sin l}{R}$$

so

$$\cos\alpha = \frac{R_{Sun}}{R}\sin l$$

$$V_r = V\frac{R_{Sun}}{R}\sin l - V_{Sun}\sin l$$

$$= R_{Sun}\sin l\cdot\left(\frac{V}{R} - \frac{V_{Sun}}{R_{Sun}}\right)$$

Because of the flat rotation curve, know V and V_{Sun} =220 km/sec easily!

$$R^2 = R_{sun}^2 + d^2 - 2R_{Sun}d\cos l$$

Can solve for R or d.

l=Galactic longitude
V=rotational velocity
R = distance from Galactic Center
V_{Sun}=Sun's velocity around the Galactic Center
R_{Sun}=Sun's distance from center
d=distance to HI cloud
V_r=radial velocity of cloud

MONTHLY NOTICES OF R.A.S. VOL. 118, PLATE 6

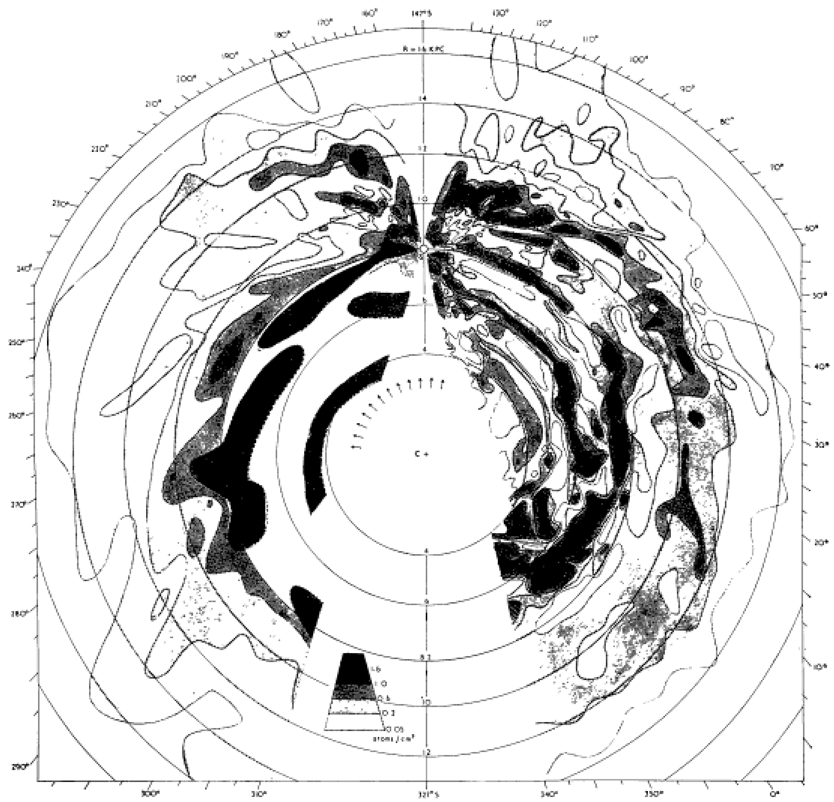
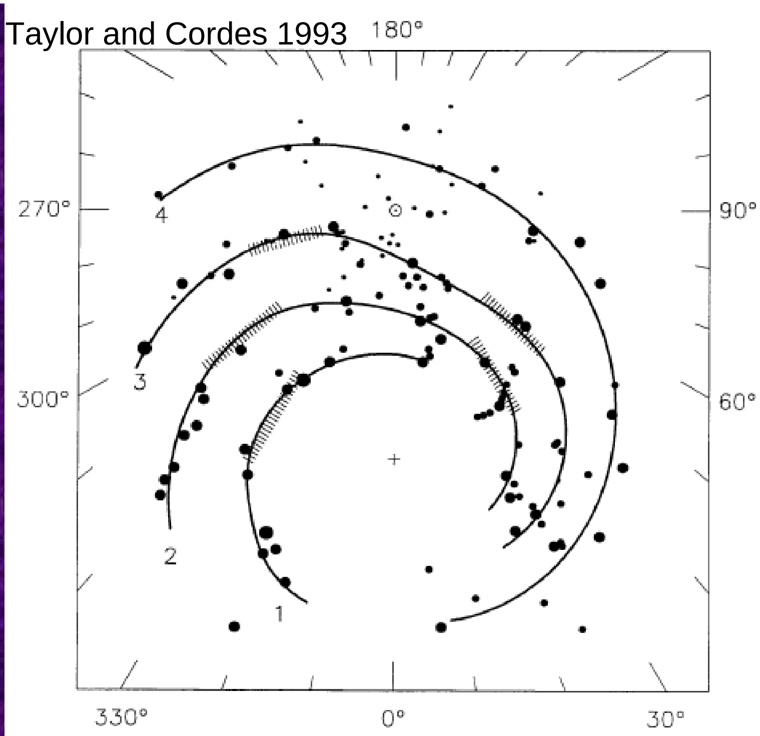


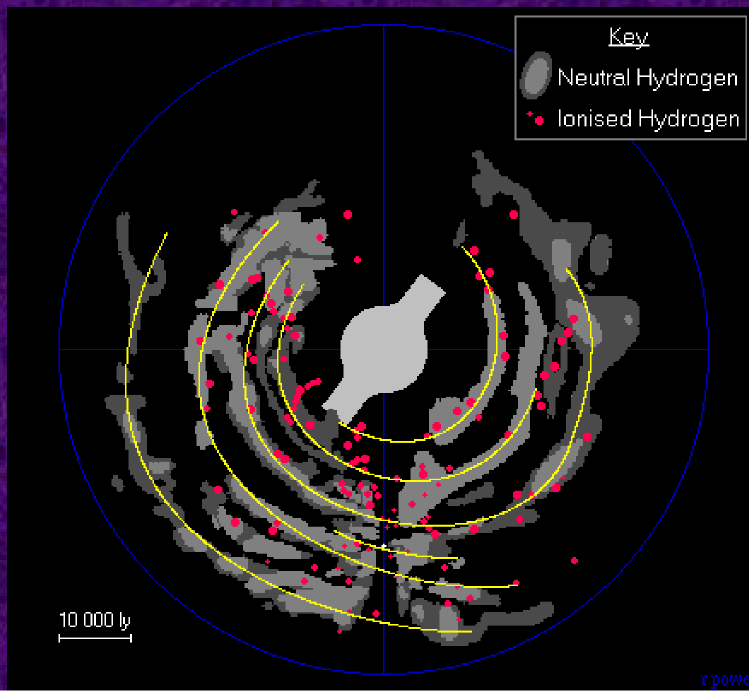
FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

Oort, Kerr, and Westerhout 1958

The Galactic System as a Spiral Nebula

Taylor and Cordes 1993

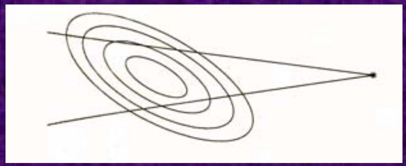




- Best constraints on other shape parameters come from modeling of near-IR all-sky data (DIRBE instrument on COBE)

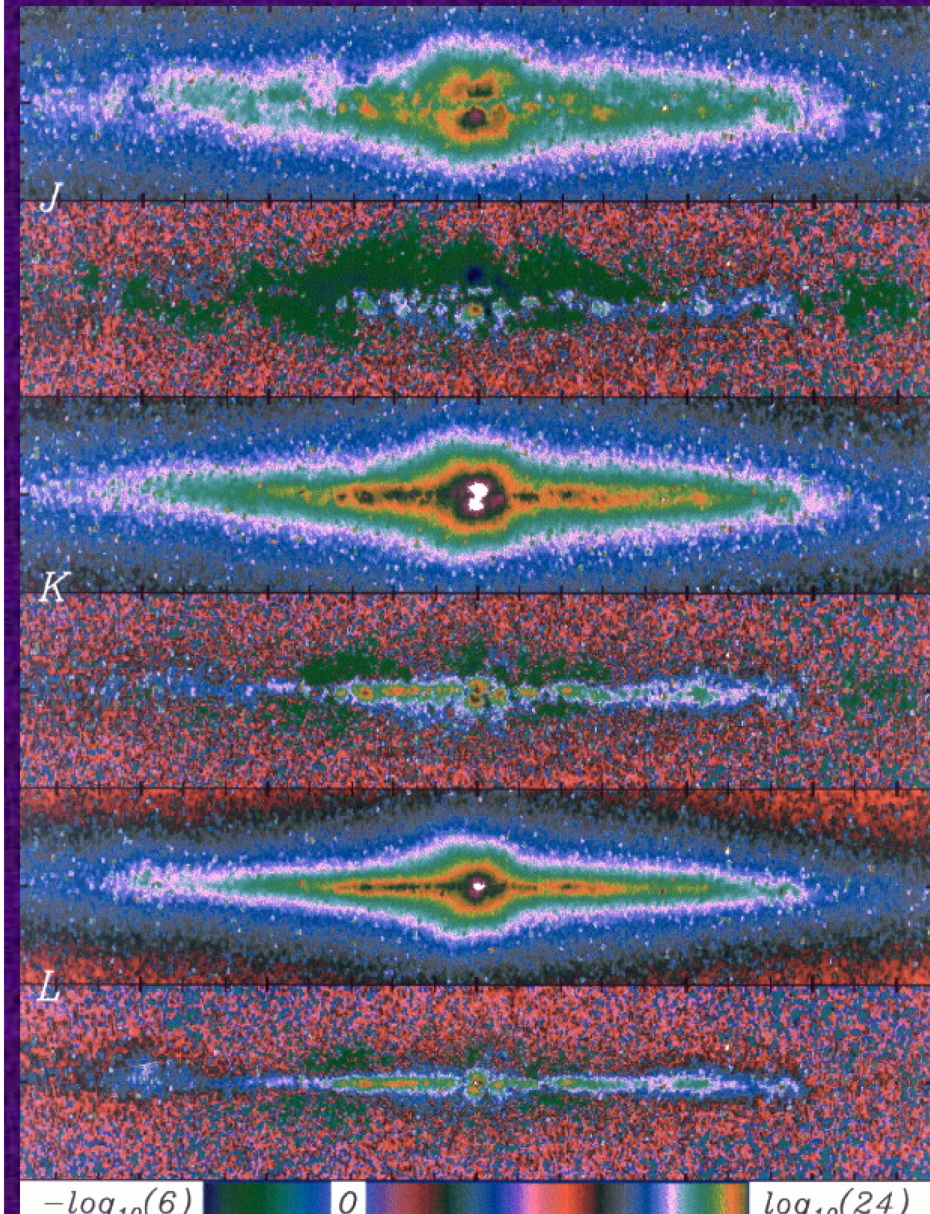
Freudenreich 1998, ApJ, 492, 495

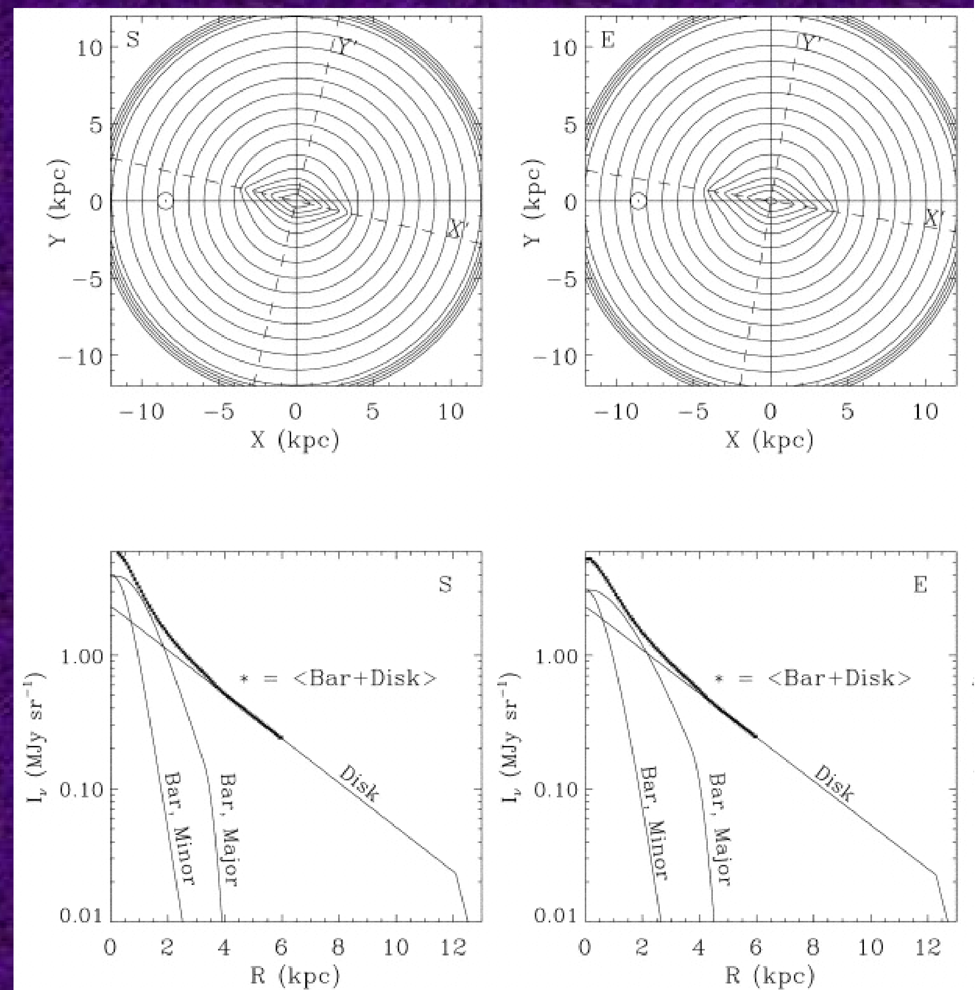
- Method
  - measure projected light distribution at 2 - 5 μm
  - correct for dust extinction and emission
  - deproject to 3D
    - fit multi-parameter model, minimize residuals with data
    - use physical, dynamical constraints to remove model degeneracies
    - best measurements for Milky Way, from star counts
- Results
  - strong evidence for a bar (+ bulge, disk)
    - bulge/bar light fraction ~ 20% (+-10%)
    - bar radius 3-5 kpc
    - bar axis 15-40^{o} from line of sight to Galactic center
    - shape of bar/bulge strongly triaxial
    - strong molecular/HII ring in disk may coincide with end of bar
  - Sun is ~15 pc above Galactic midplane
  - DIRBE confirms presence of thick disk (primary evidence from star counts)
  - spiral arms detected, with pitch angle ~10-15^{o}



Bar can be deduced from surface brightness and shape variations.

These models use ~40(!) free parameters.





- Disk: vertical structure
  - best measurements for Milky Way, from star counts
  - counts near Galactic plane well fitted with exponential function

$$\rho(z) = \rho_0 \, e^{-z/z0}$$

  - scale height z_0 is a strong function of stellar type and age, reflecting dynamical heating of stars
    - $z_0 \sim 100$ pc for youngest stars
    - ~ 400 pc for old disk population
  - counts at high z-height show a significant excess, attributed to a second "thick disk"

Kuijken & Gilmore 1989, MNRAS, 239, 605

good fit to double exponential:

$$\rho(z) = \rho_0 \, e^{-z/z0} + \rho_1 \, e^{-z/z1}$$

$\rho_0 = 0.96 \quad z0 = 250$ pc
$\rho_1 = 0.04 \quad z0 = 1000$ pc