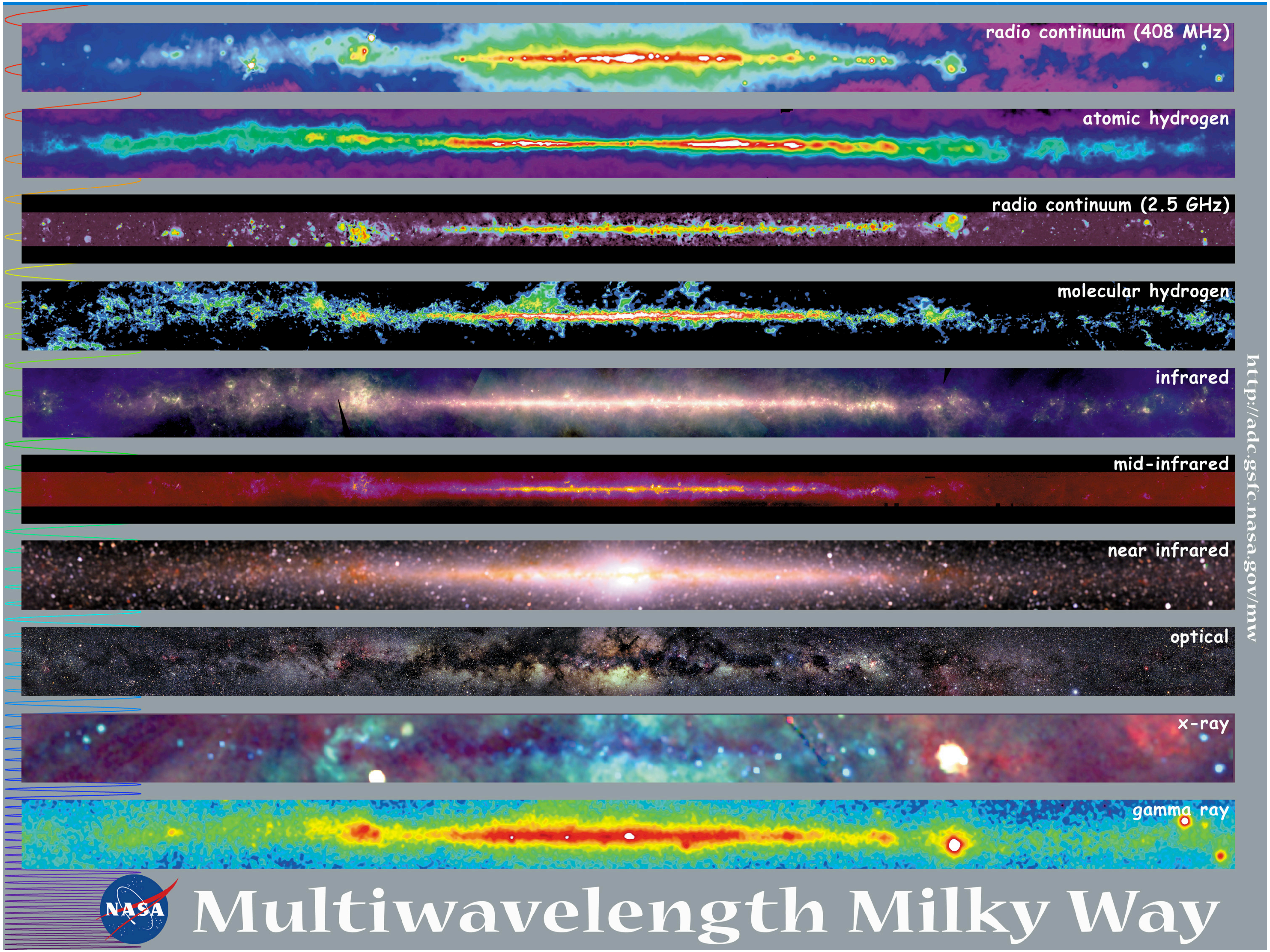
The Basic Structure of Present-Day Galaxies

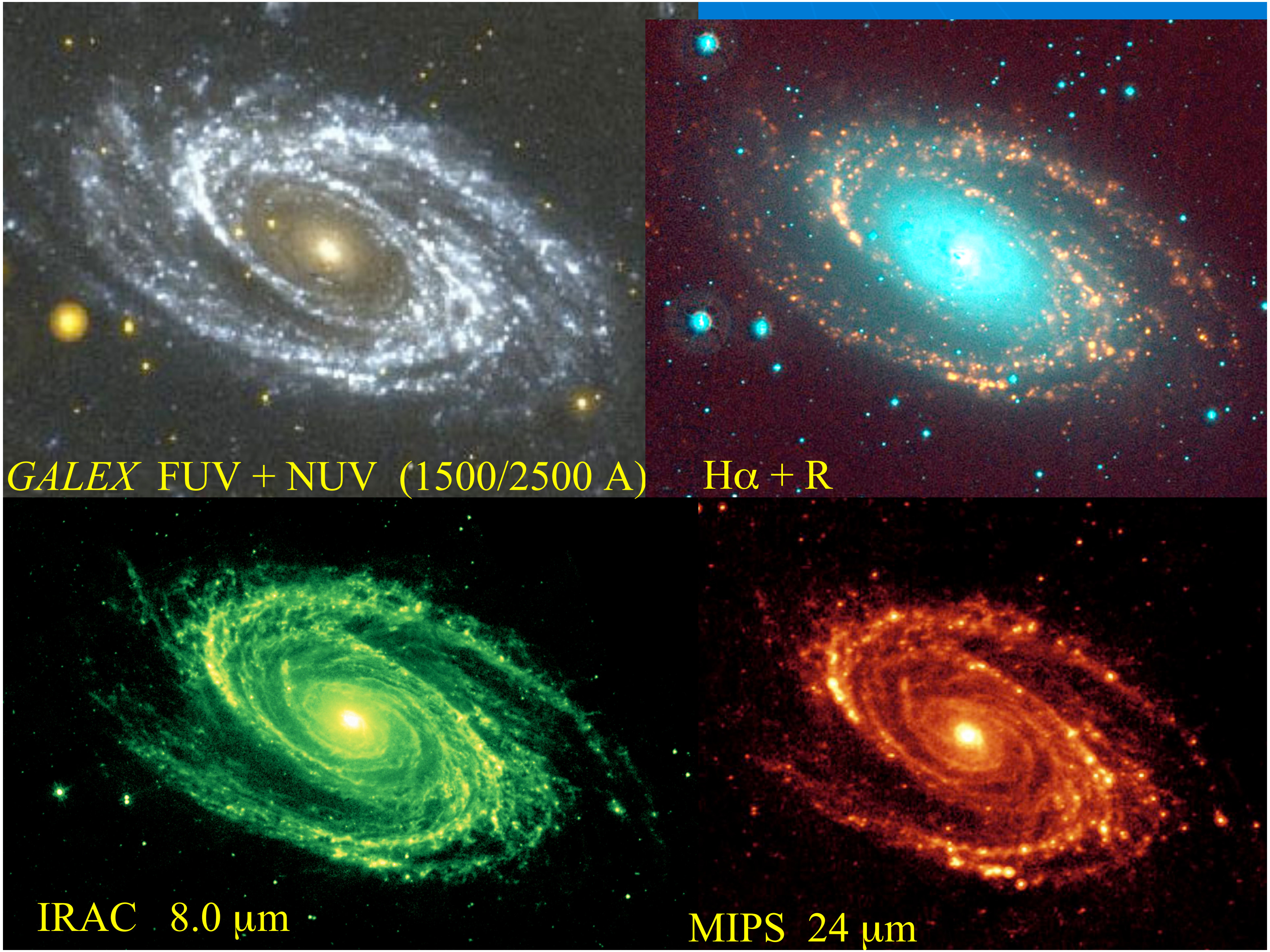
1) Basic description of galaxy 'components'
- Stellar distribution: bulge, disk, bars,
- Distribution of gas (and dust)
- Dark matter halo

2) Parameter Relations in Galaxies
- Tully-Fisher, the 'Fundamental Plane' and the Kormendy relations
- Morphology, mass vs. kinematics
- Stellar mass vs. halo mass

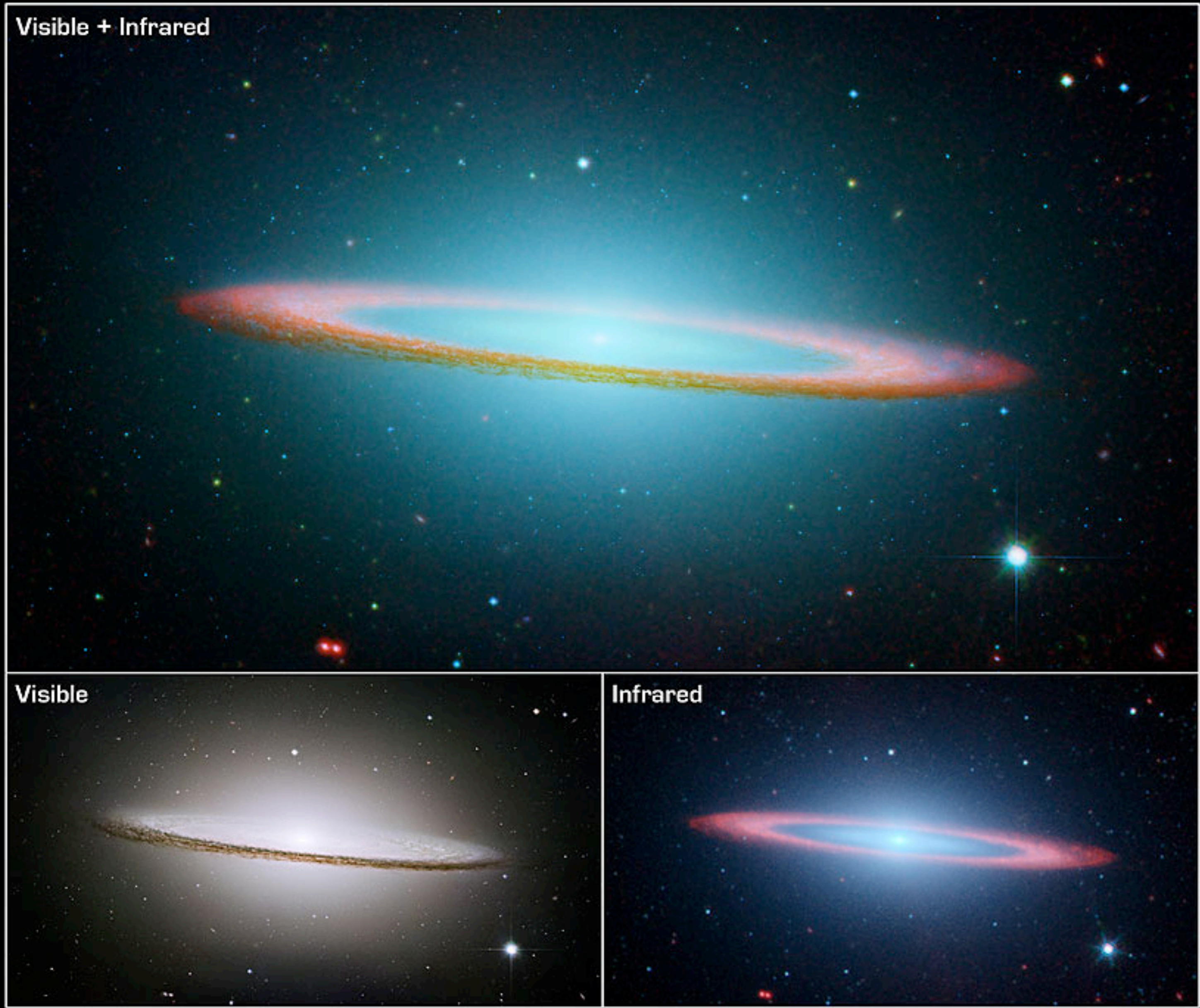
3) Morphology and structure vs. formation history
- the sizes of disk galaxies
- the shapes of massive galaxies

4) Extreme ends of the galaxy property spectrum
- the smallest galaxies
- the most massive galaxies and galaxy clusters


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way



GALEX FUV + NUV (1500/2500 A)
Hα + R
IRAC 8.0 μm
MIPS 24 μm



Sombrero Galaxy/Messier 104

Spitzer Space Telescope • IRAC

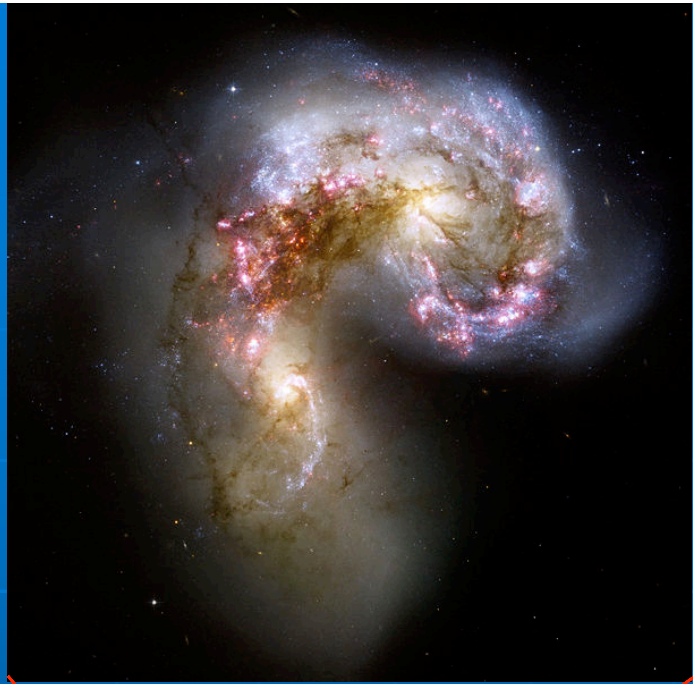
Visible: Hubble Space Telescope/Hubble Heritage Team

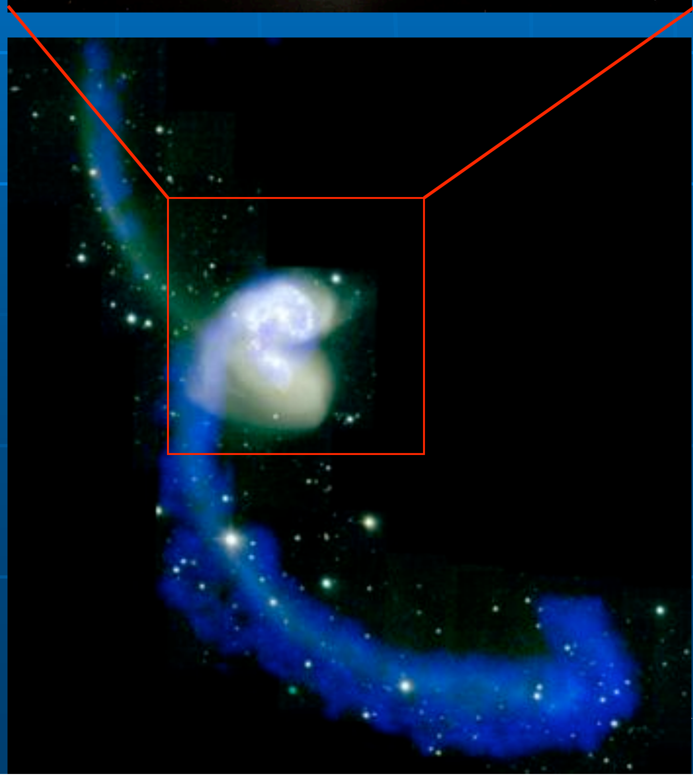
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team

ssc2005-11a

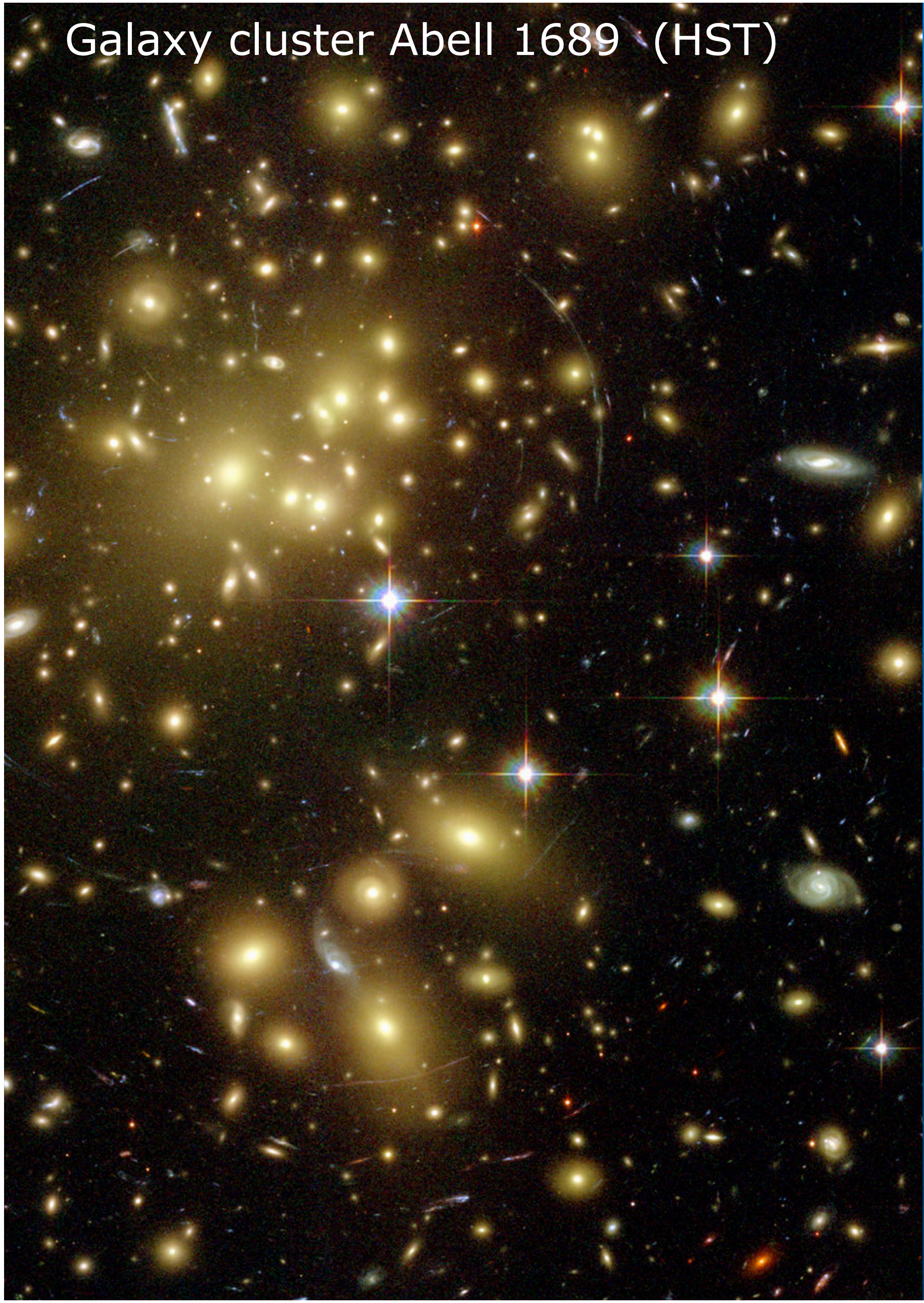

M87 with HST

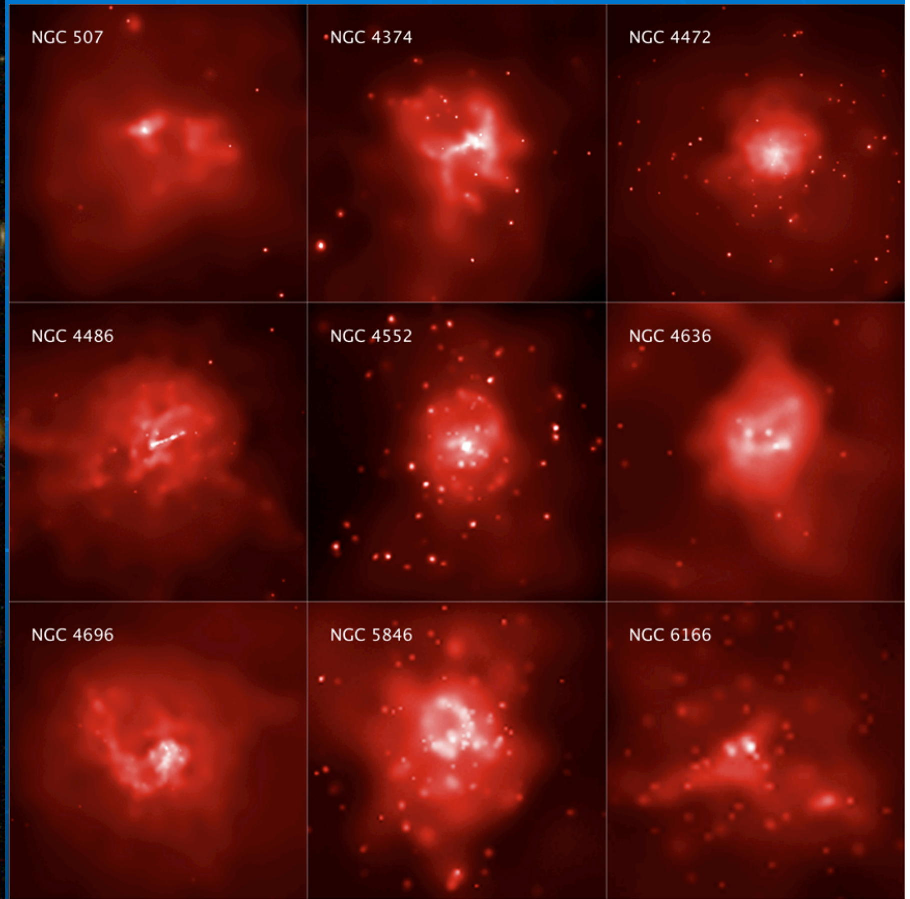
Interacting/merging galaxies





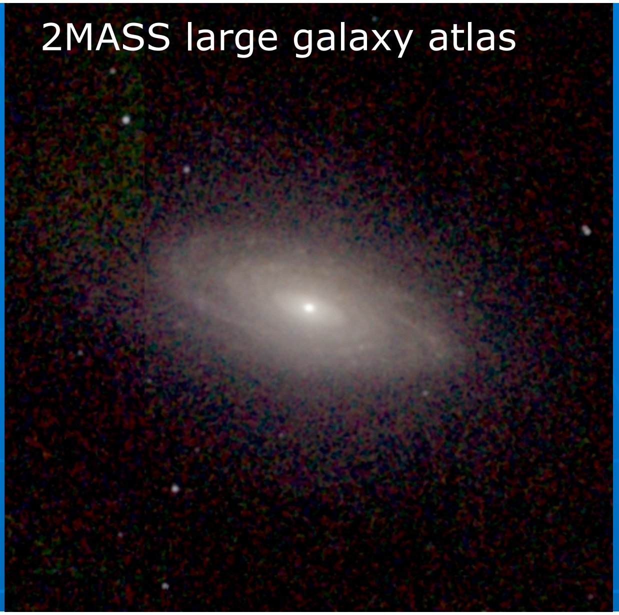
, 2008





X-ray (hot gas) in nearby Elliptical galaxies with Chandra satellite

Basic Description of the Stellar Distribution



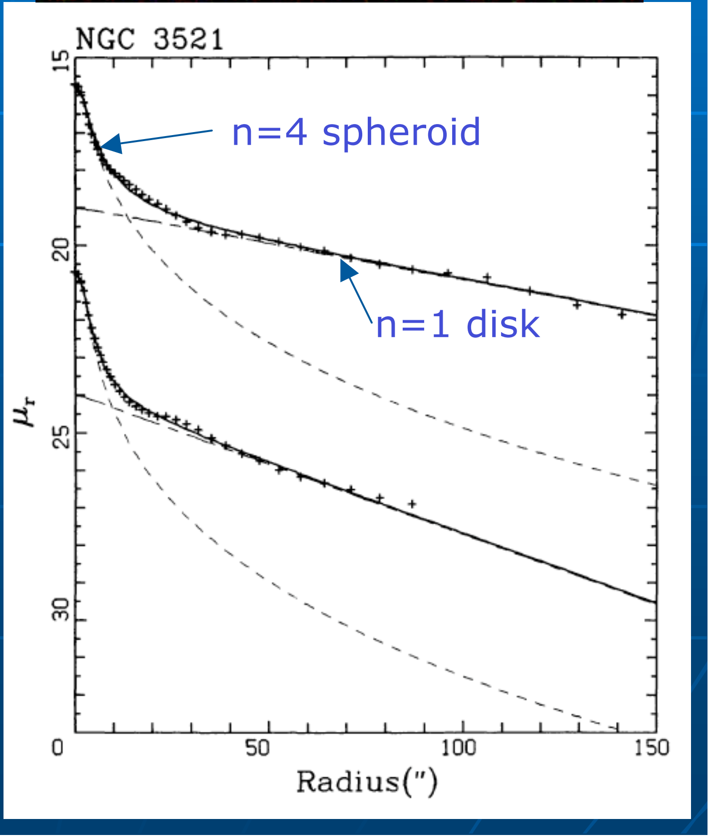
- For fairly massive galaxies a basic two-component description of the stellar distribution proves useful:
  - **Bulges/spheroids**
  - **Disks**
- Radial profile description

  Sersic (1968) profile

$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n}-1]}$$
$$\kappa \approx 2n - 0.331$$

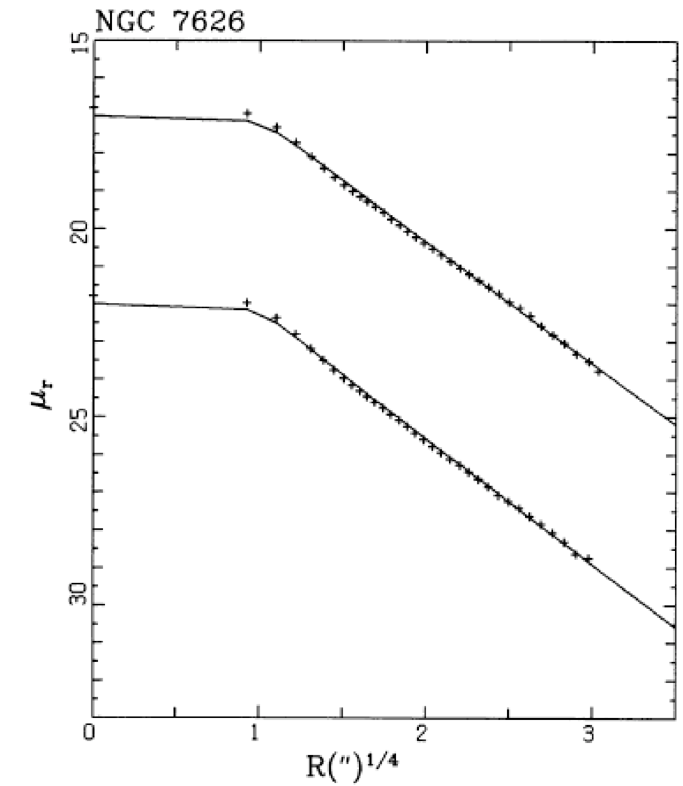
Disks: n~1: 'exponential profile'
Spheroids: n~2-5 (n=4: deVaucouleur)
NB: $n_{spheroid} = f(L_{spheroid})$

Note: bulge/disk approach (3D shape ←→ profile) not sensible for low-mass galaxies



Radial profiles: Comments

- Many (massive) ellipticals fit the de Vaucouleur's profile beautifully
- Bulge-disk decompositions on the basis of radial profles alone are terribly prone to fitting degeneracies



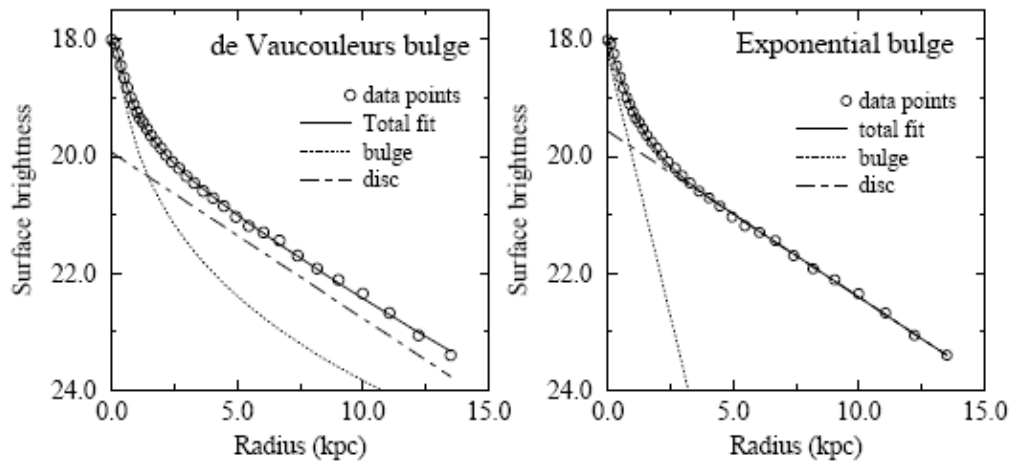
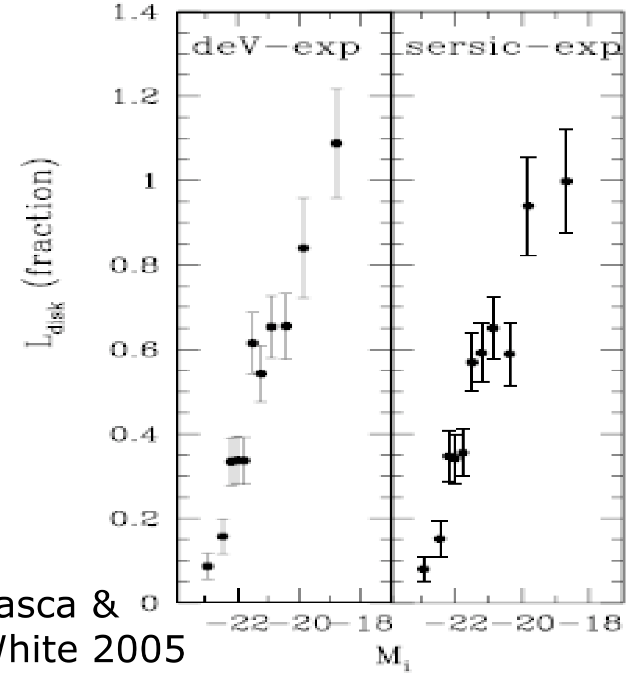


Figure 2: Decomposition of NGC2708 with both models. **(a)** *(Left panel):* $r^{1/4}$ bulge. **(b)** *(Right panel):* Exponential bulge.

Bulge-to-Disk Ratios in the Present-Day Universe

(e.g. Tasca and White 2005 and Benson et al 2007 based on SDSS)

- Bulge-disk decomposition is interesting, because
  a) disk-stars: no violent relaxation
  b) Spheroid stars: post-violent relax
  c) $M_{BH} \sim M_{Spheroid}$



Tasca & White 2005

Globally:

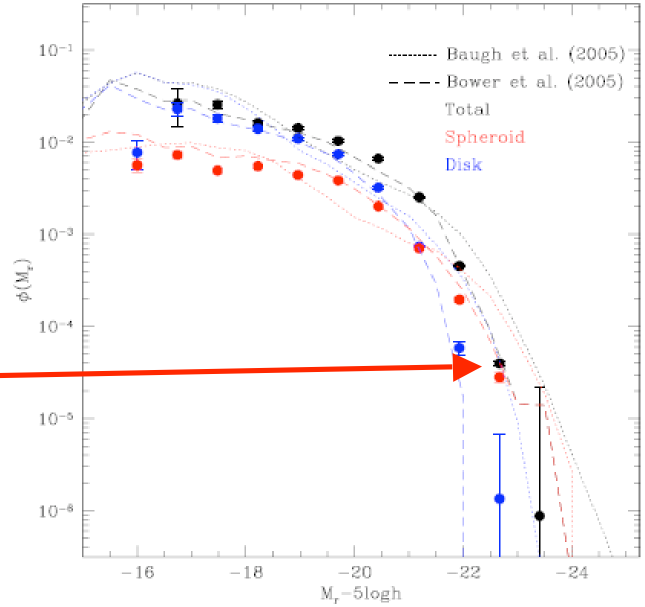
60% of r-band light from disks

40% from spheroids

In stellar mass:

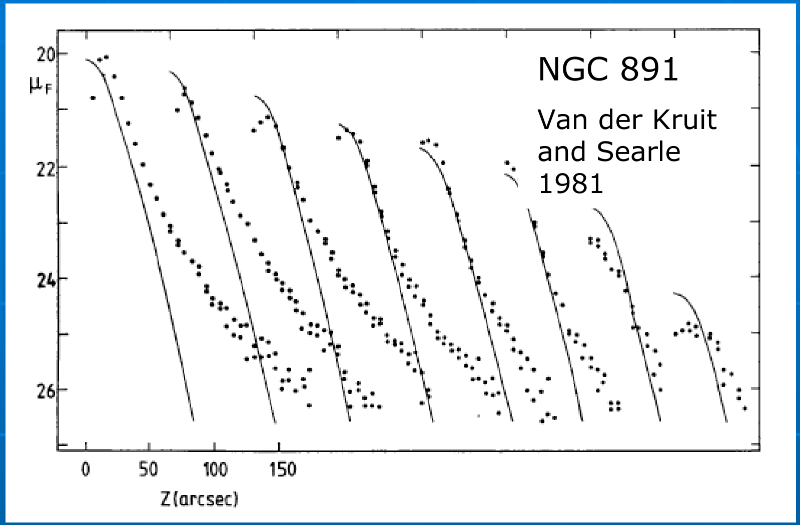
40%/60% disk/spheroid mass fraction

Spheroids dominate the massive end

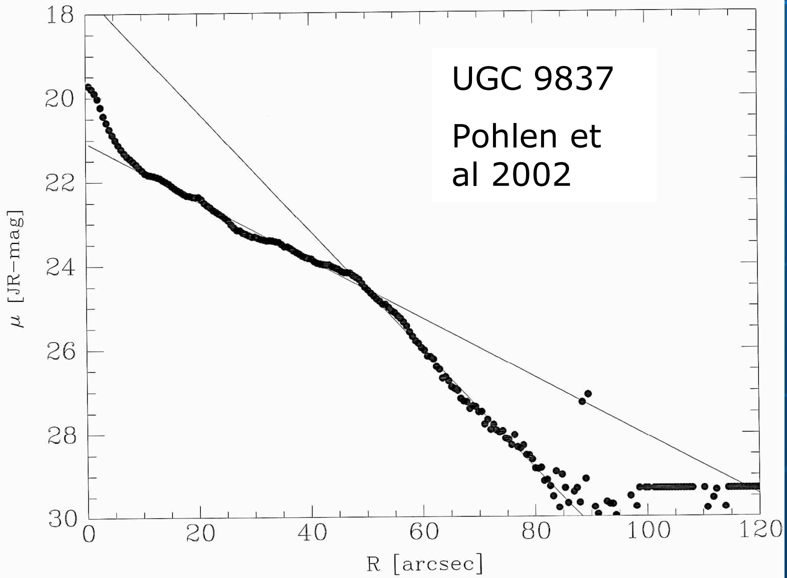


Structure of Galaxy Disks I

- Vertical stellar profile can often be described by $f(z) = \mathrm{sech}^{2/N}(Nz/z_0),$
- In most galaxy disks a description by two vertical components is suggested (incl. Milky Way)
  - Thicker → more (vertical) kinetic energy → Why?

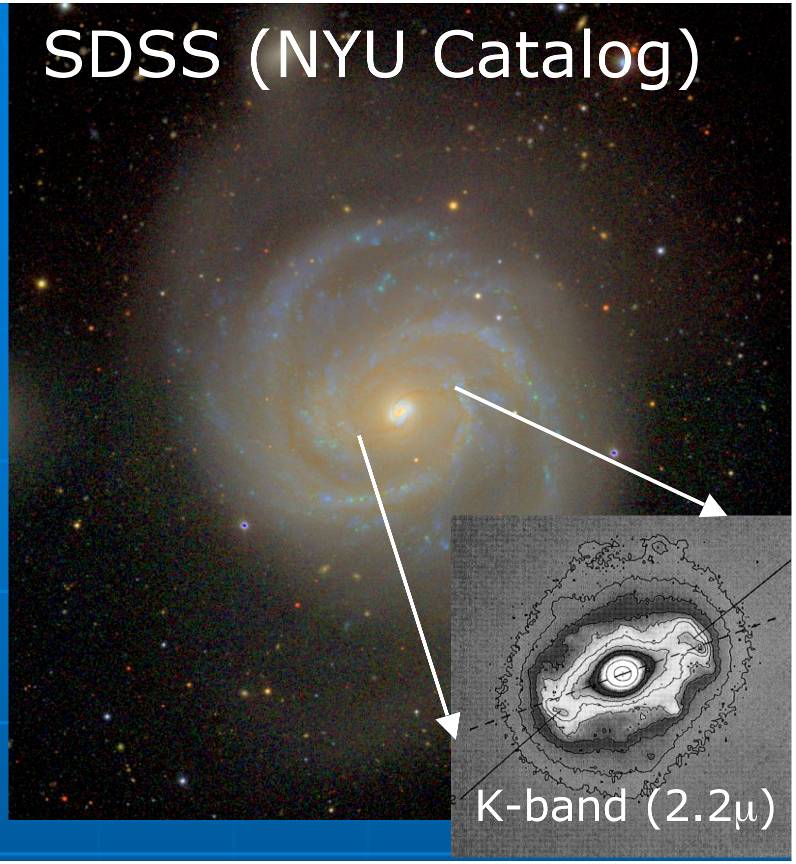


- (Some) stellar disks are 'truncated' in radius
  - Max. angular momentum, or
  - Threshold in star-formation efficiency?

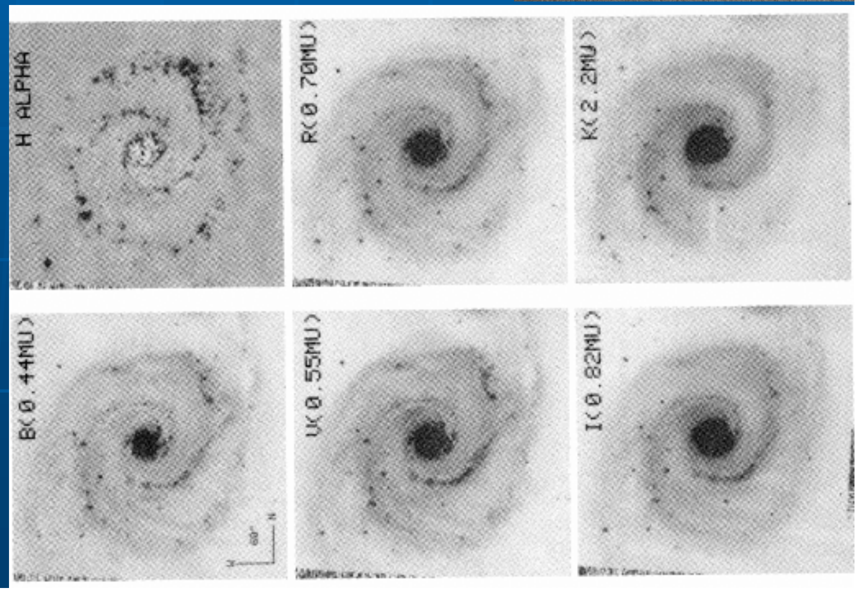


Structure of Galaxy Disks II

- Stellar bars are common in disk galaxies
  - Often only recognized in near-IR images (less dust)
  - Consequence of disk instability
  - Effective means of angular momentum transport



- Spiral arms are common and coherent features
  - even after accounting for young stars



- e.g. M51, Rix and Rieke 1995

The 3D Shapes of Spheroidal Galaxies

- What is the relation between intrinsic shape and projected ellipticity

axially symmetric case (oblate or prolate, see Binney/Merrifield):

$$q^2_{\text{internal}} \sin^2 i + \cos^2 i = \begin{cases} q^2_{projected} & \text{(oblate)} \\ 1/q^2_{projected} & \text{(prolate)} \end{cases}$$

- If we view a sample from random angles, then cos(i) is uniform →

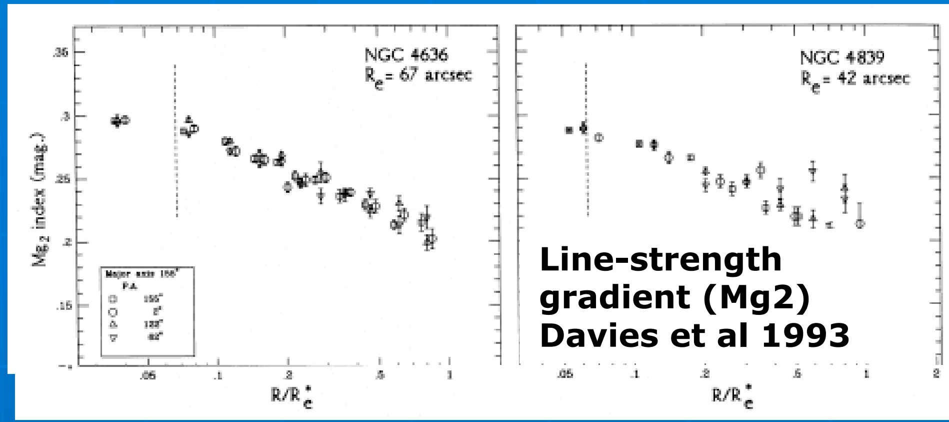
$$a : b : c \approx 1 : 0.95 : 0.7$$

- Massive spheroidal galaxies are nearly oblate and only somewhat flat

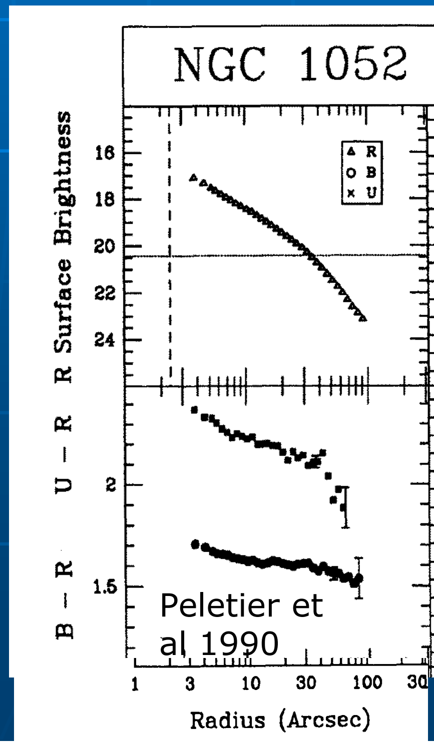
Color-gradients in Galaxies

- Almost all galaxies become bluer outward
- Combination of
  - Decreasing dust
  - Decreasing age(?)
  - Decreasing metallicity

- Sheroids are redder/older than disks

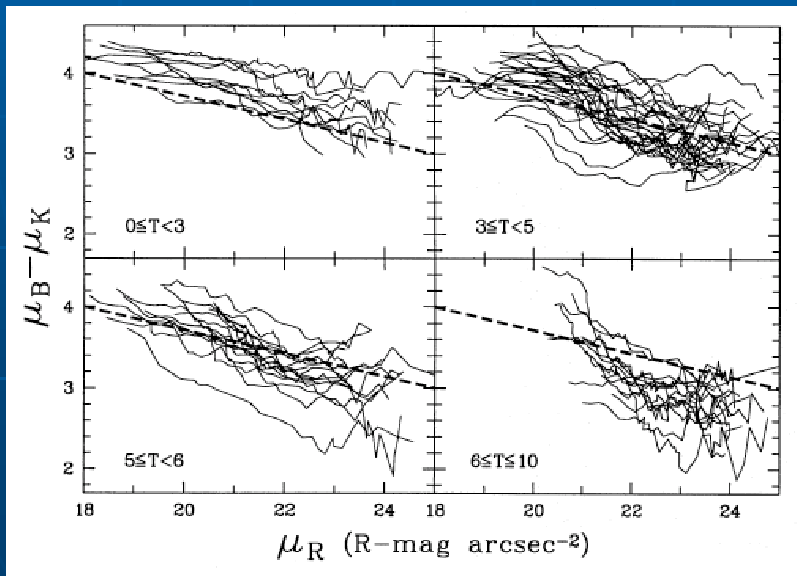


(dust-free) massive spheroids



Ensemble of spiral galaxies with dust and red bulges at the center →

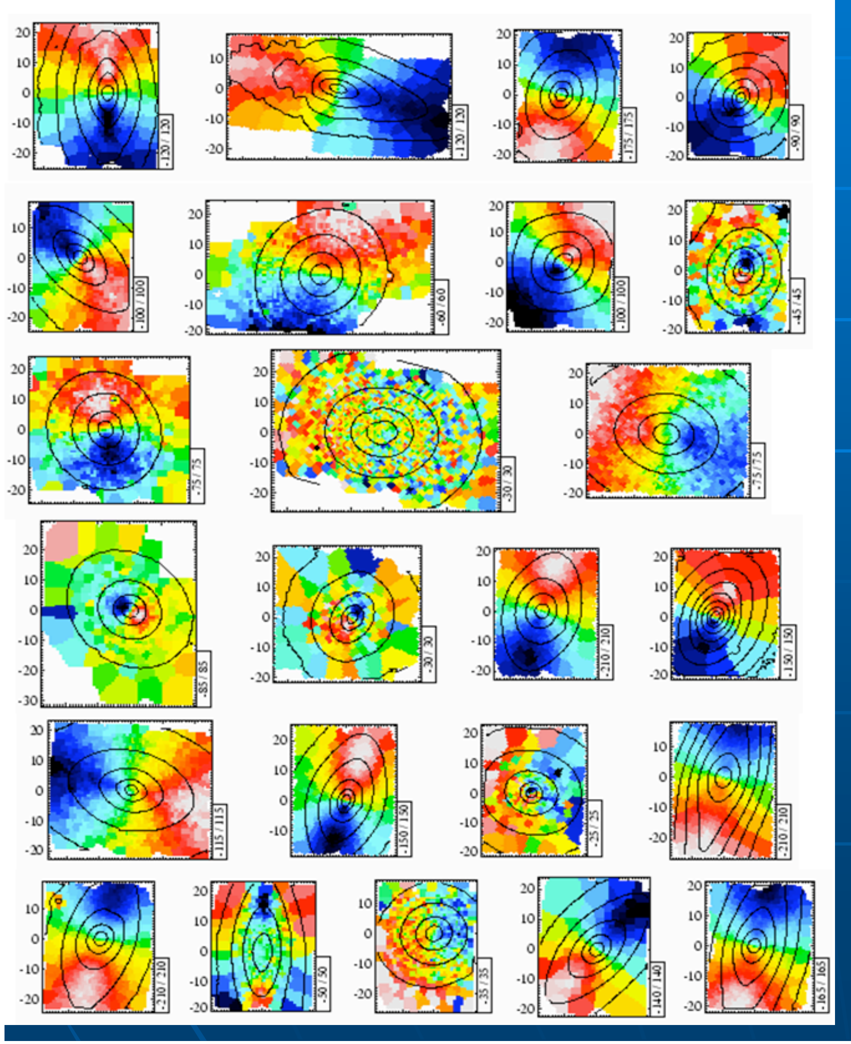
(de Jong 1996)

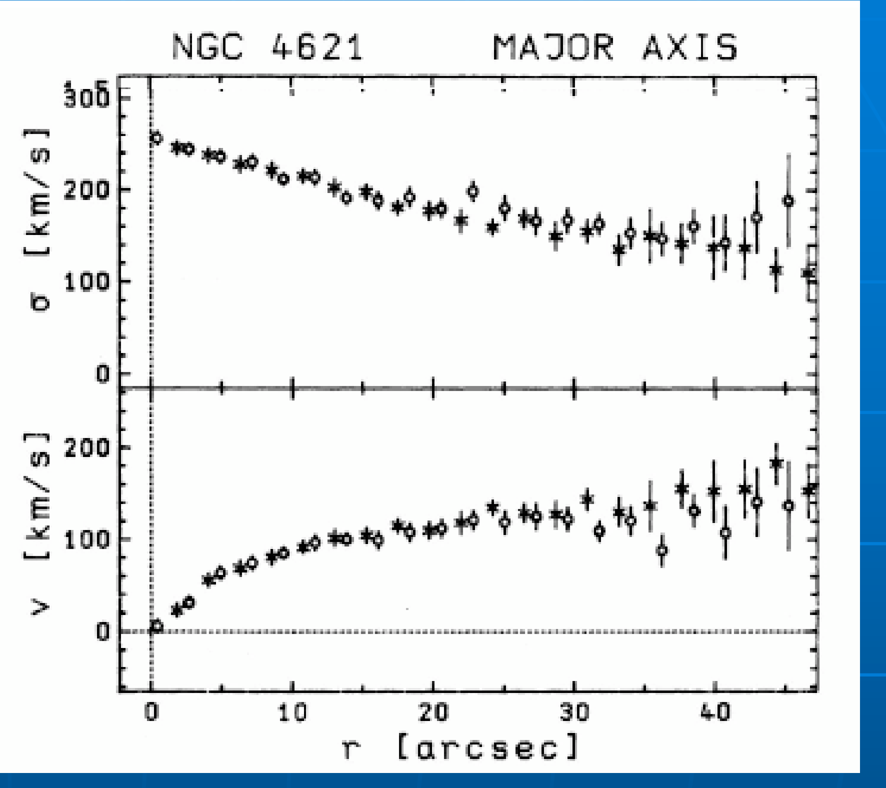


Basic Kinematics of Spheroidal Galaxies

Stellar velocity fields for nearby spheroidal galaxies

(Capellari, deZeeuw, Bacon, et al 2005)





- Generically:
  - Rotation rises slowly outwards
  - Dispersion falls gently outward
- $0 < v/\sigma < 1.5$

„Interstellar Gas“ in Galaxies

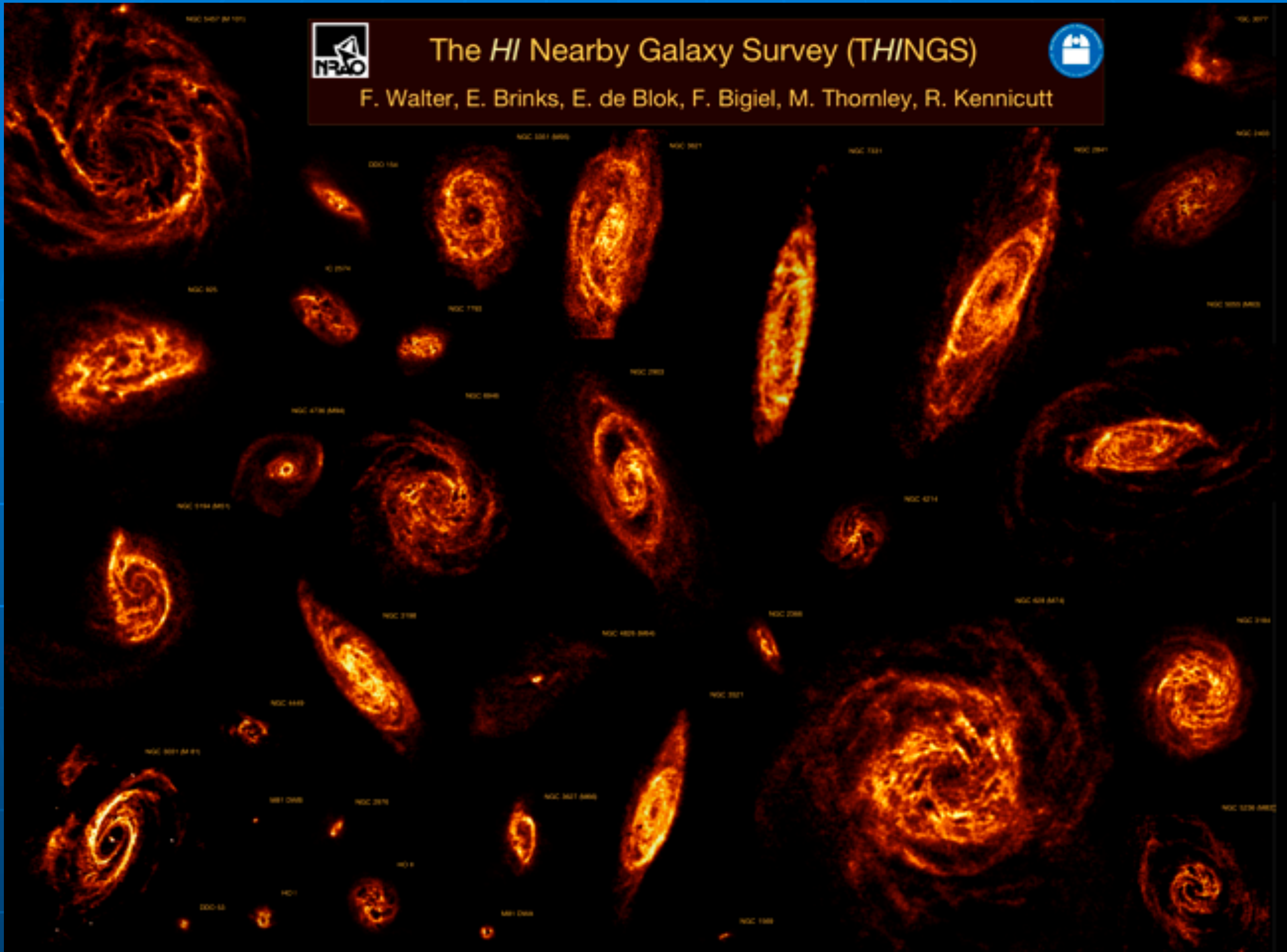
Interstellar gas occurs in a wide range of physical conditions

Name	**State**	**Density**	**Temperature**	**Main diagnostics**
„hot“	fully ionized	10^{-2} cm^{-3}	10^{6} K	X-rays UV absorption
warm (H II)	fully ionized	1cm^{-3}	10^{4} K	Optical emission lines
neutral (H I)	neutral atomic	1 cm^{-3}	10^{2} K	21cm line
„cold“ molecular gas	molecular	100	20 K	CO lines (radio, sub-mm)

What sets the temperature and the physical state of the gas?

Heating processes
- photo-ionization
- mechanical (shock) heating

Cooling processes
- Bremsstrahlung
- line cooling


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt

Galaxies and their Dark Matter Halos

- **All evidence for dark matter halos on galaxy scales comes from the comparison/modeling of kinematic tracers with identified mass components.**
- *Kinematic tracers:* stars, cold gas (HI and Ha), hot gas (X-ray), satellites (GCs and galaxies) and photons (gravitational lensing)
- *Identified (baryonic) mass components:* stars, hot gas (in clusters), cold gas (~10% of stars)

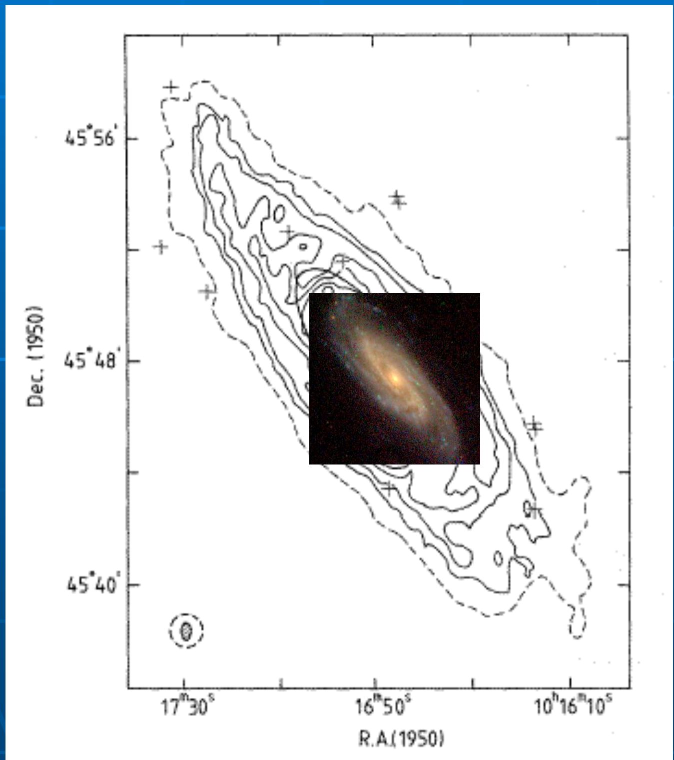
- *Historically:*
  - Need for dark matter from dynamics on scales of galaxies played an enormous role in establishing its (dynamical) existence
- *Current Paradigm:*
  - Dark matter is a indispensible ingredient in structure formation; galaxies are the places where DM is least dominant → DM studies on galaxy scales can be tricky

Observational Constraints on Dark Matter Halos around Big Galaxies

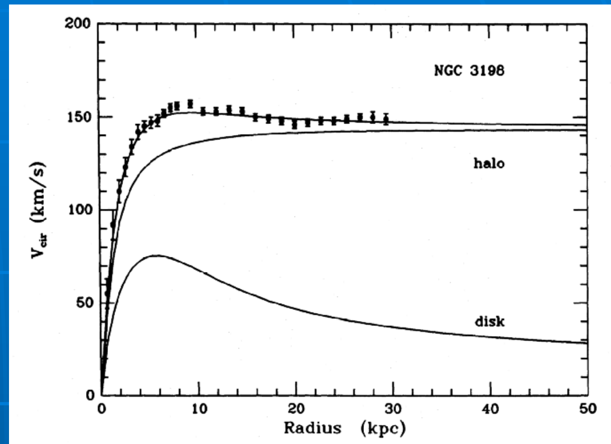
a) HI rotation curves

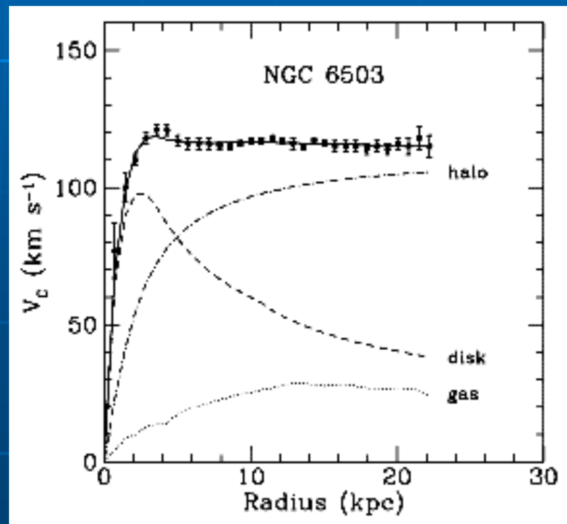
„flat" to ~ 30 kpc (» R_{opt})

$$V_c^2(R) = -R\,\frac{d\,\Phi(\vec{r})}{d\,R} \approx -g\,M(<R)/R$$

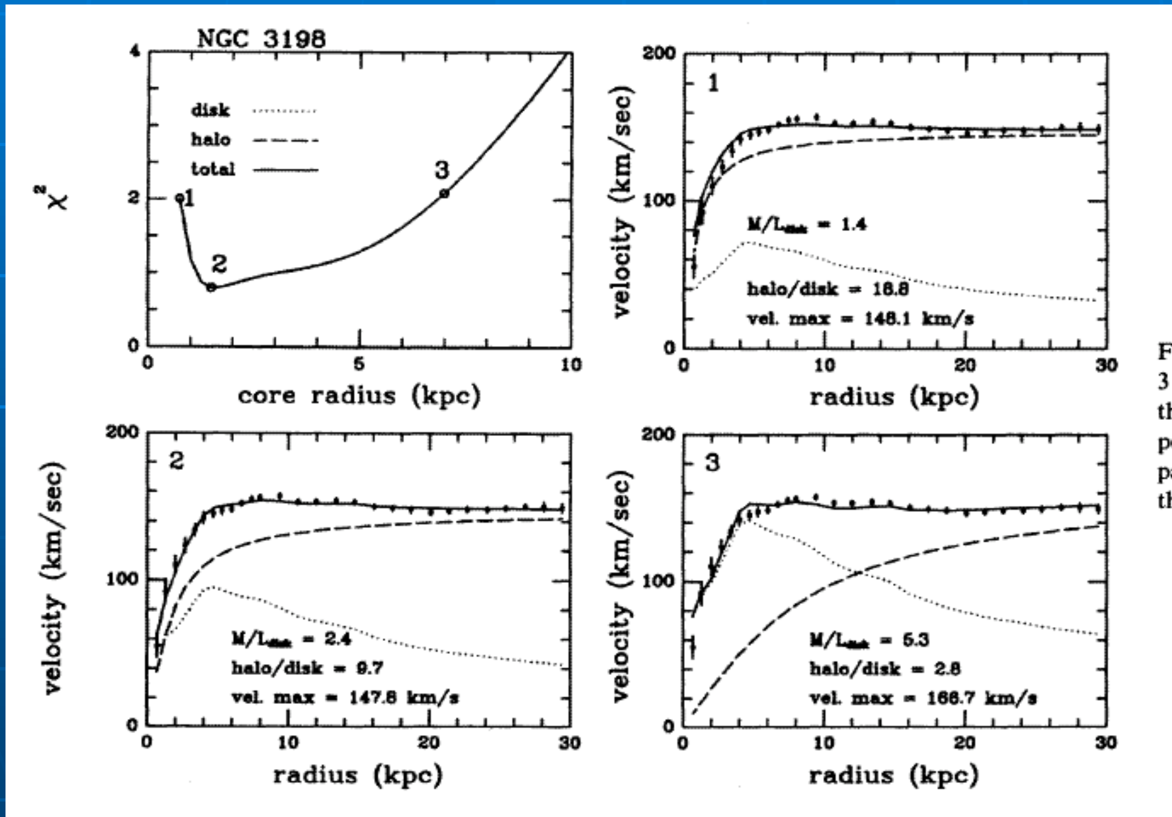


Model fits to HI rotation curves





Note:
can‘t constrain 2 functions, $\rho_*(r)$ and $\rho_{DM}(r)$,
by only one observable function $V_c(r)$ → degeneracies



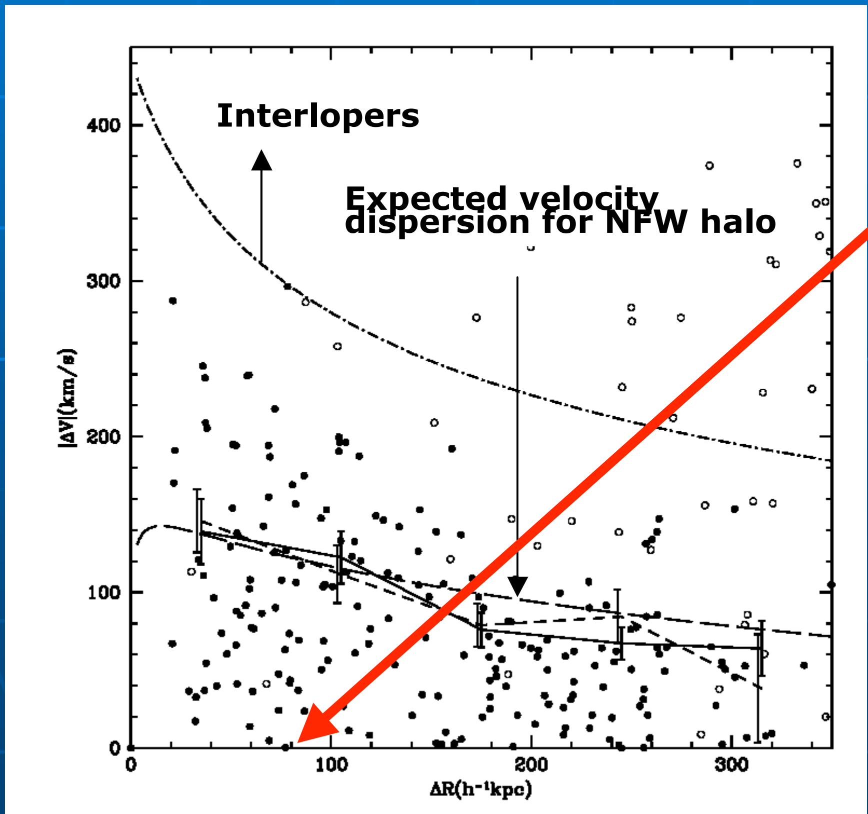
b) Satellite galaxies

e.g. Zaritsky 1994, Prada et al 2002 by stacking images

→ DM halos around MW-like galaxies extend to >200kpc

NFW profile:

$$\rho(r) = \delta_s / [(r/r_s)\ (I + r/r_s)^2]$$



Present-Day knowledge about Dark Matter Halos

Correlation function between

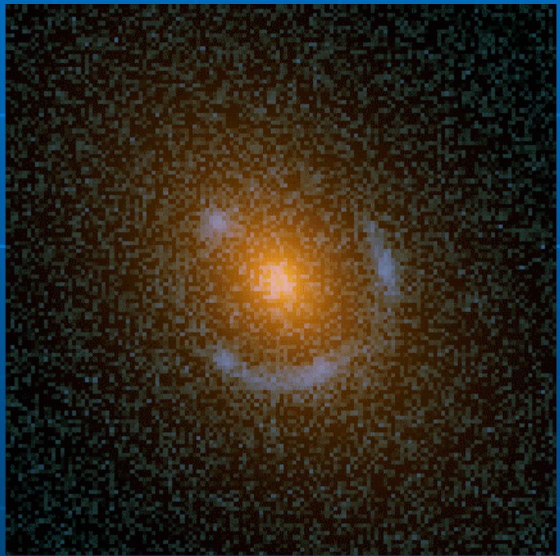
c) Strong and weak gravitational lensing

a) Shear (from gravitational lensing seen in background images

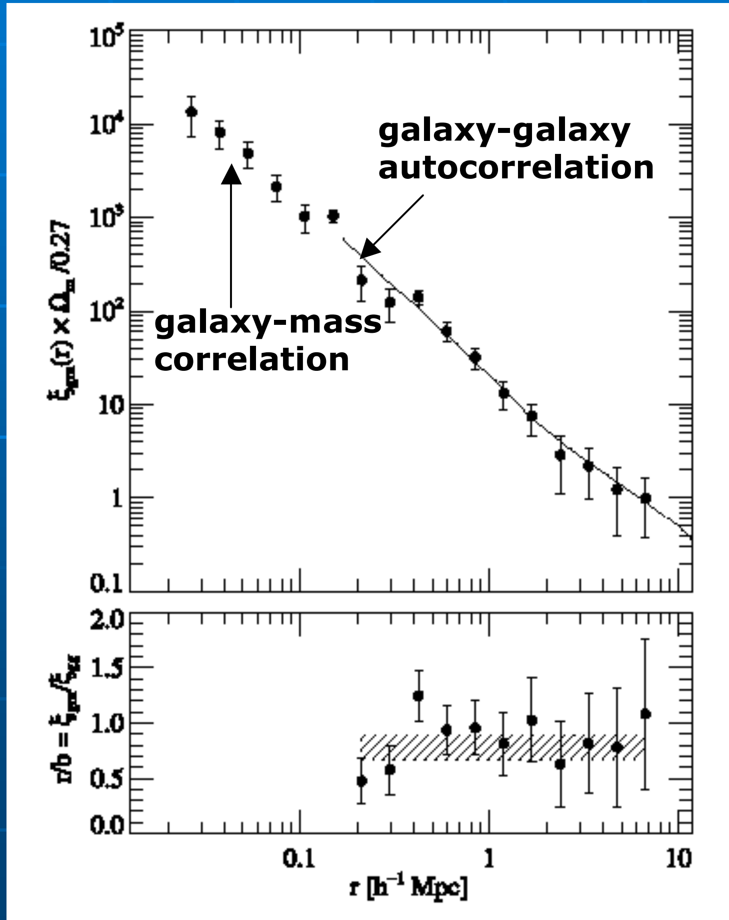
b) Position of foreground galaxies

(Maoz and Rix 1993; Brainerd et al 1988; McKay et al 2001)

Background galaxy lensed into arcs by lens



(Sheldon et al. 2004; SDSS)



d) X-ray gas around massive galaxies

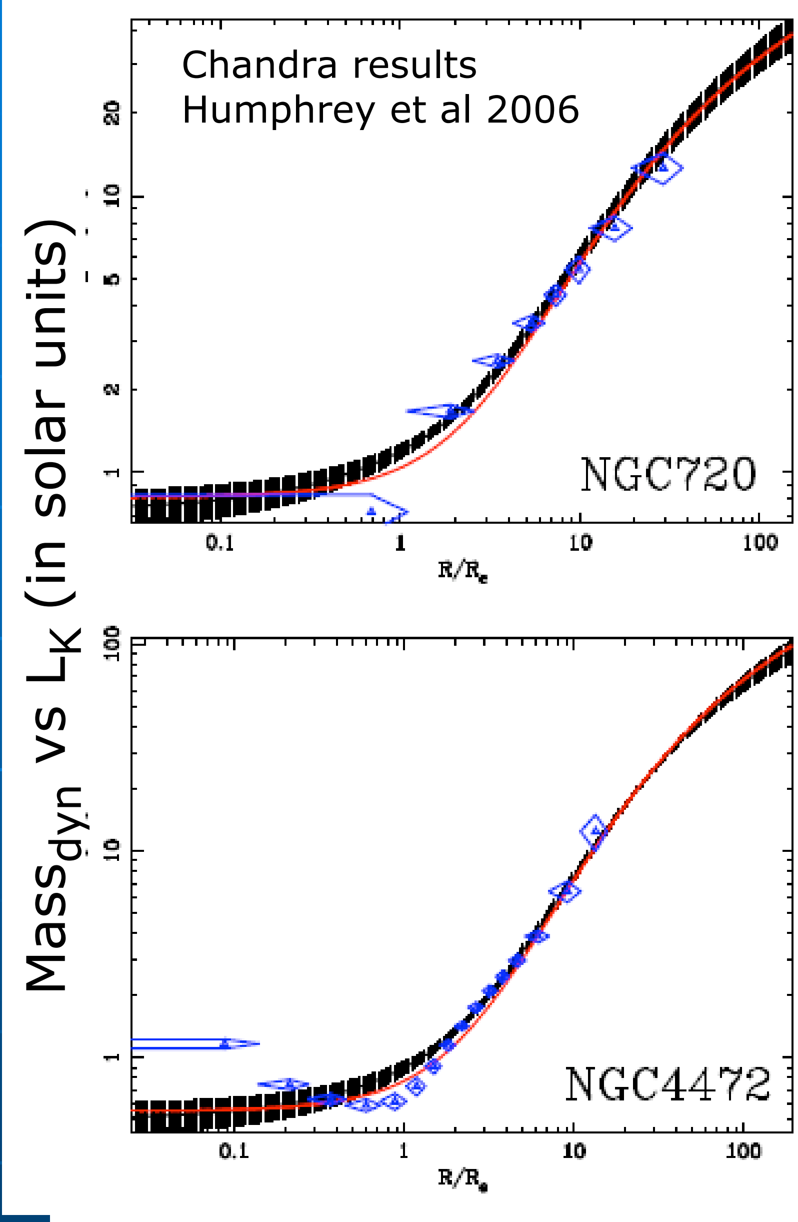
- Only in massive galaxies (and galaxy clusters) is the 'hot' phase hot enough to be detected by current X-ray satellites

- Assume gas is in (approximate) hydrostatic equilibrium

$$\ln\left(\frac{\rho_g}{\rho_{g0}}\right) = -\ln\left(\frac{T}{T_0}\right) - G\mu m_p \int_{R_0}^{R} \frac{M_{grav}(<R)}{kTR^2} dR$$

- In all massive galaxies with good measurements:

DM halo with properties expected from ΛCDM (NFW halo)



2) ‘Parameter Relations’ in (Present-Day) Galaxies

Many parameters with which to describe the stellar component of galaxies are tightly correlated

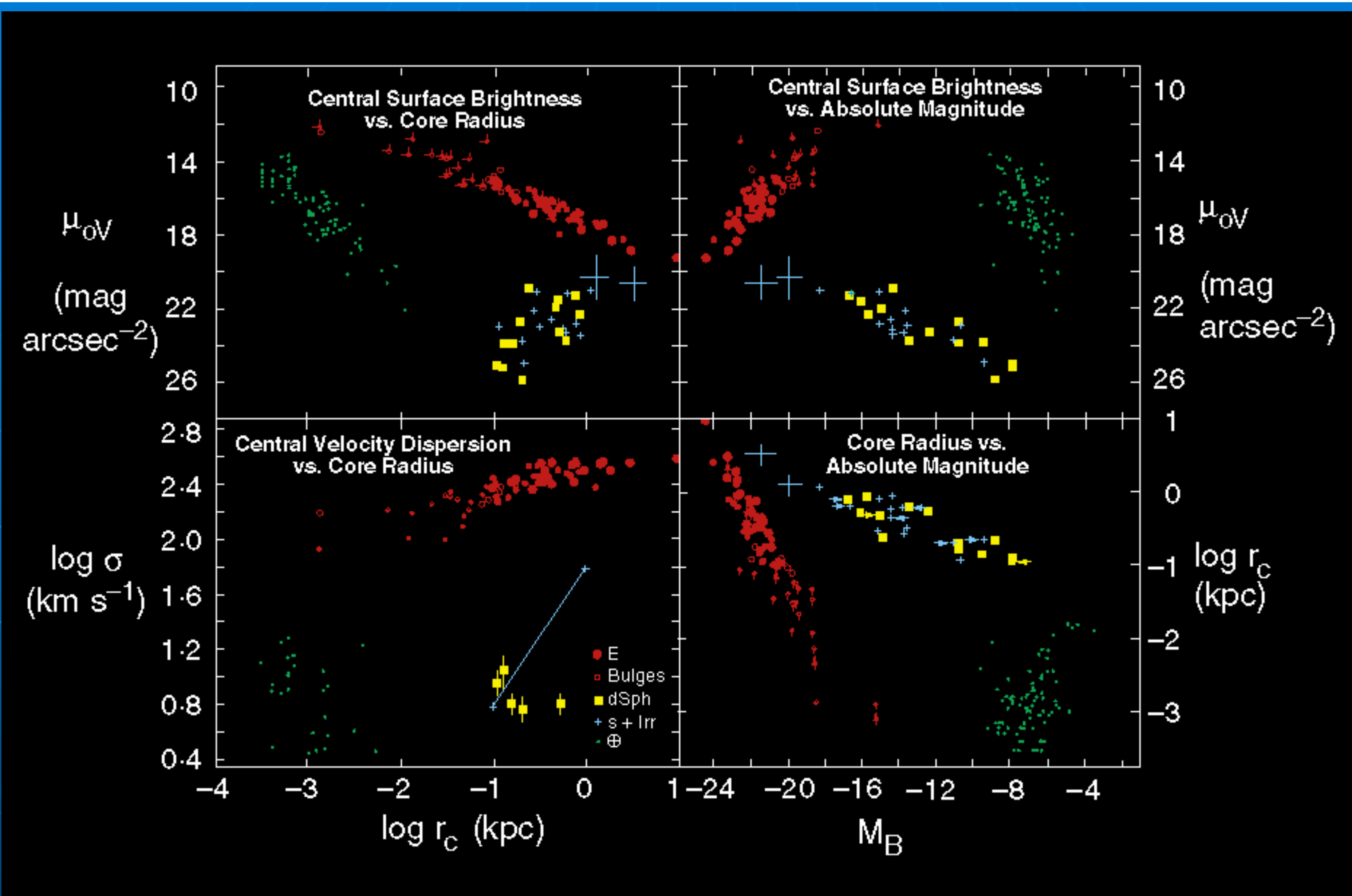
(though such correlations are/were not ‘expected’)

Most of them can be cast as

(stellar) luminosity/mass vs

- size
- characteristic velocity (Tully-Fisher; Faber-Jackson)
- 3D - shape
- (radial) concentration, black hole mass

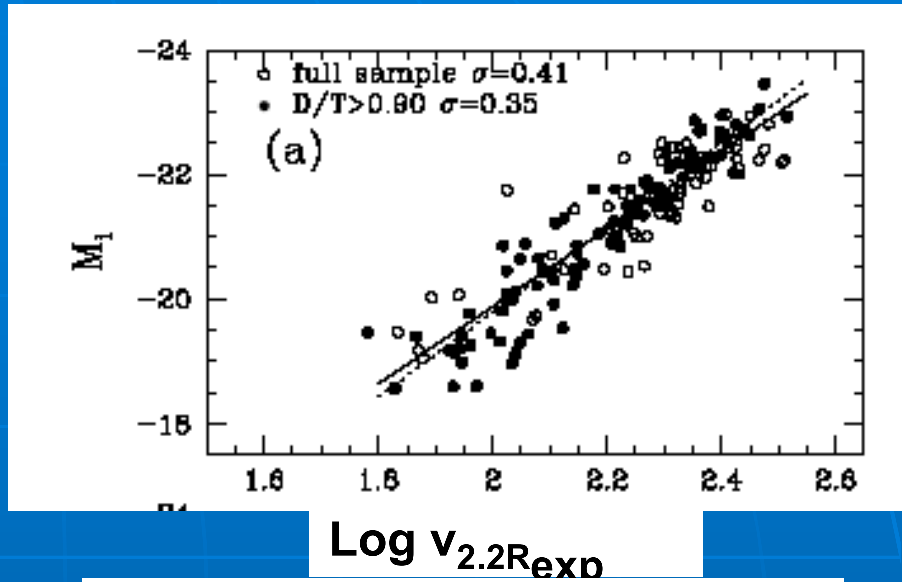
These correlations are important constraints on galaxy formation mechanisms

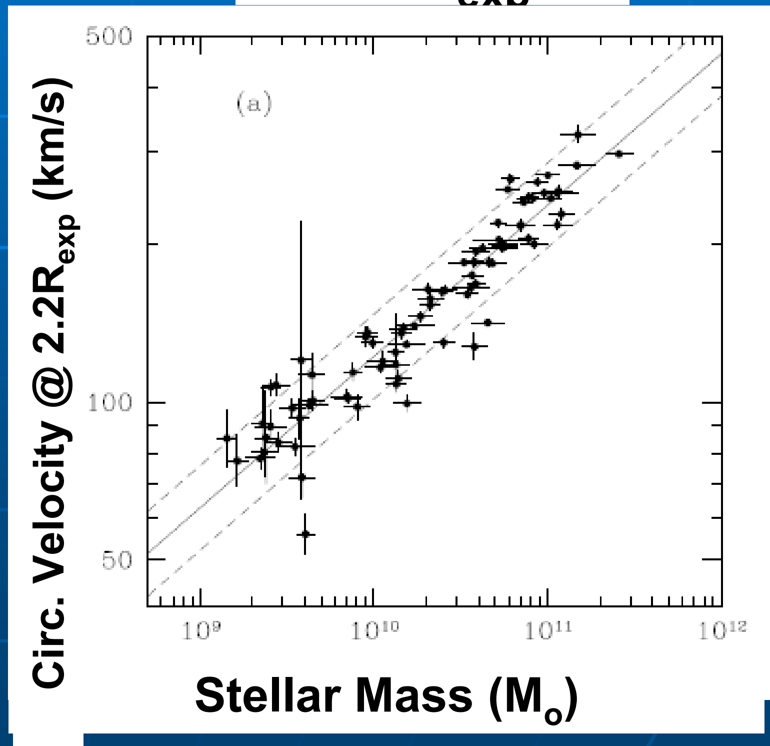


John Kormendy has been a pioneer in pointing out that the photometric descriptions are correlated

The 'Tully-Fisher' Relation for Disk Galaxies

- Tully&Fisher 1977
  - HI linewidth correlates well with absolute magnitude of spiral galaxy.
- In general:
  - Correlation between circular velocity and stellar luminosity
  - L_{opt} can predict v_{circ} to ~5-8%
    - $M_*, L_{opt} \sim v_c^{3-4}$
- Historically: extremely important distance indicator
- Now: also constraint on galaxy formation





Stellar Mass (SED + Kroupa IMF)

Explanations for a Tully-Fisher-like relation

- Let's consider the self-gravitating case

$$v^2_{max} \sim G\Sigma_0 R_d \quad \text{with } \Sigma_0 \text{ central mass density and } R_d \text{ scale length}$$

$$\Rightarrow L \sim v^4_{max} I_0^{-1} \Gamma_{disk}^{-2} \qquad \text{with } I_0 = \Sigma_0 / \Gamma_{disk}$$

Right slope, but central surface brightness/mass density should be a 3rd parameter

- Let's presume the disk is a small fraction assembled from a DM halo

For the halo (also Mo, Mao and White 1993)

$$r_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}} \frac{V_{vir}}{H(z)} \quad \text{and} \quad M_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}} \frac{V^3_{vir}}{GH(z)}$$

$$\rho_{crit} = 3H^2(z)/(8\pi G)$$

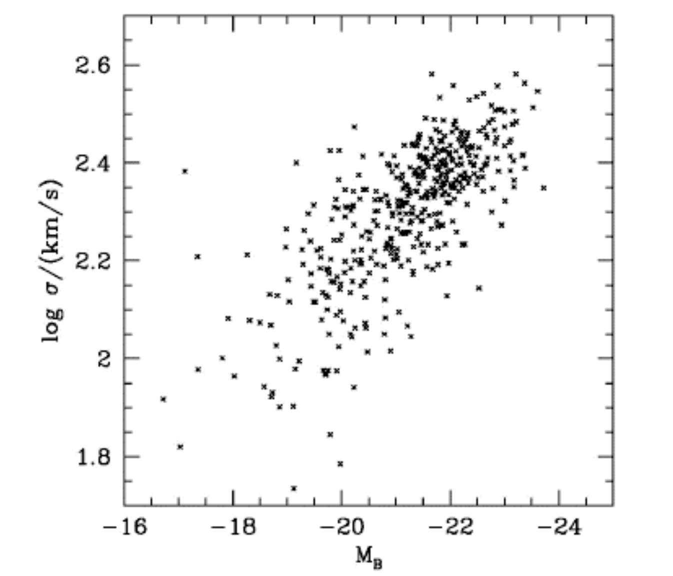
$\Delta_{vir}(z)$

Factor by which density within virial radius exceeds mean density of the universe

$$M_d \approx 1.3 \times 10^{11} h^{-1} M_\odot \left(\frac{m_d}{0.05}\right) \left(\frac{V_{vir}}{200\,\mathrm{km\,s^{-1}}}\right)^3$$

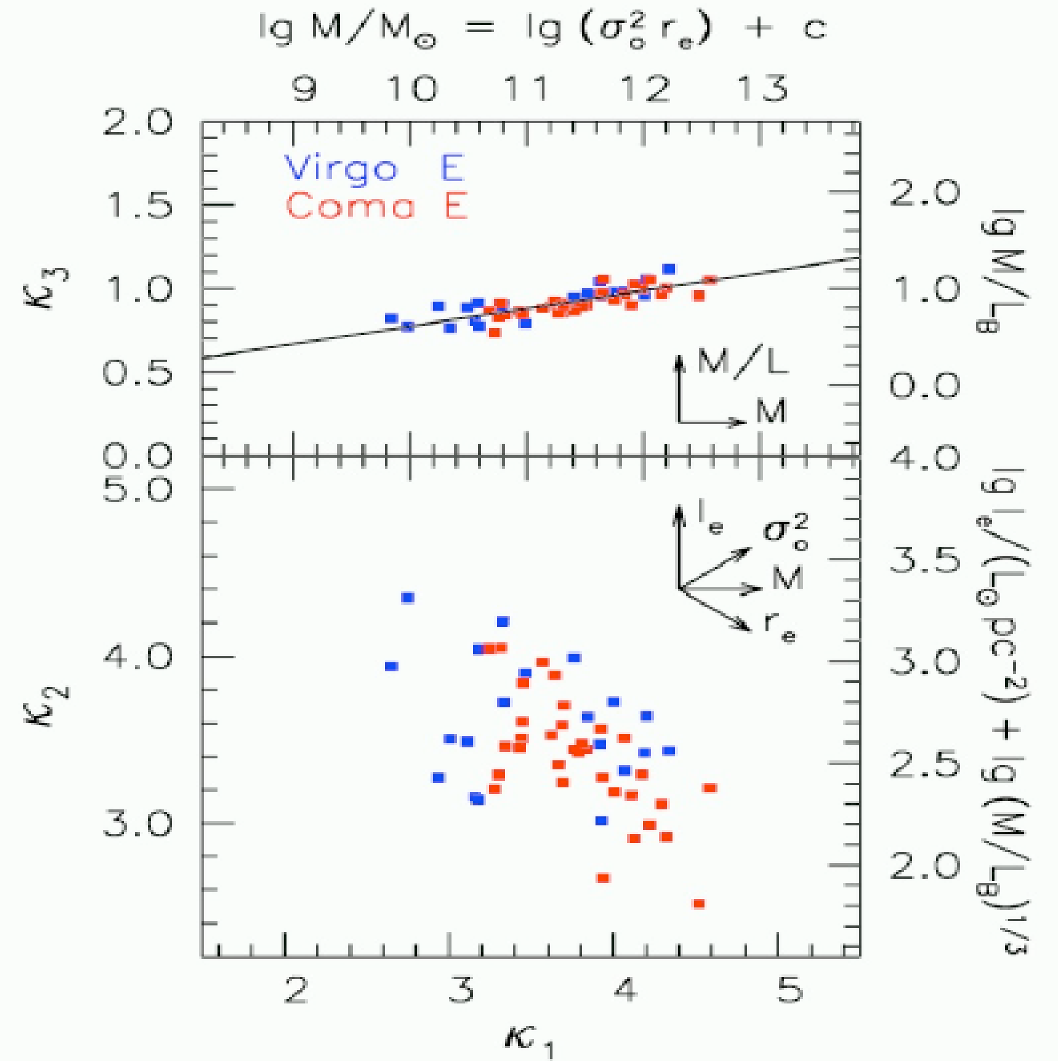
with NO surface brighness/mass dependence!

Parameter relations for (massive) spheroids: Faber-Jackson and the 'fundamental plane'



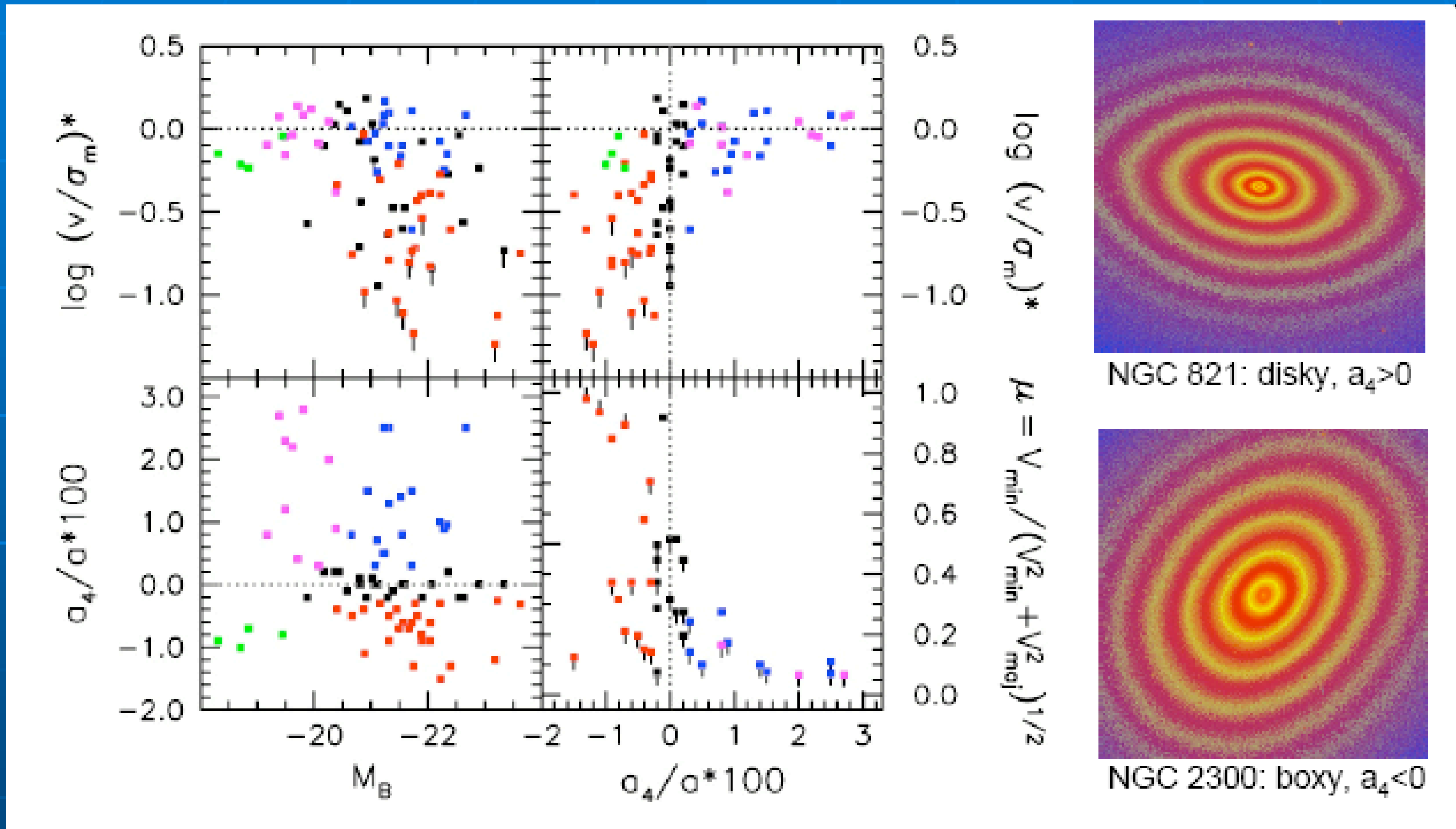
Faber-Jackson relation between central velocity dispersion and total magnitude of elliptical galaxies ($L_B \sim \sigma^4$).

One version of the 'fundamental plane', involving L, R_e, σ_*



- **For spheroids: → 3-parameter relation!!**
- M/L = f(M)

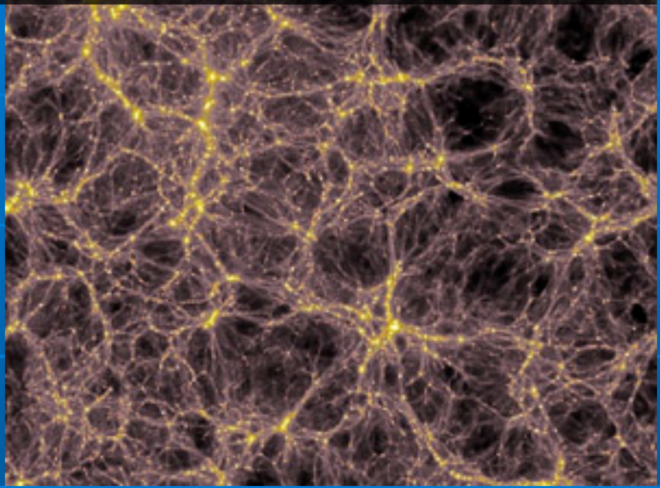
Rotation support and isophote shape = f(L)

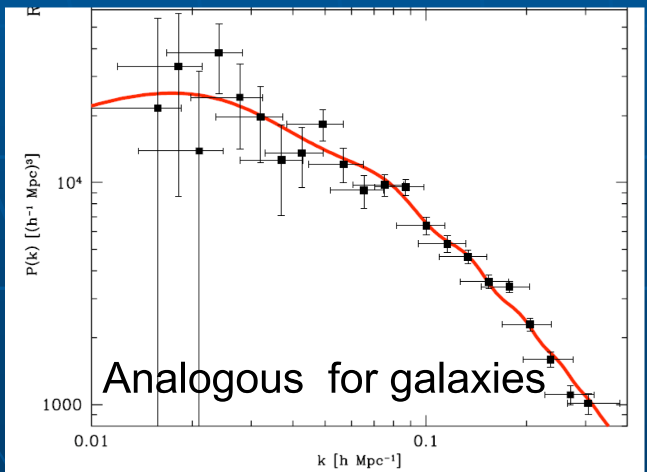


Stellar mass vs. Halo Mass

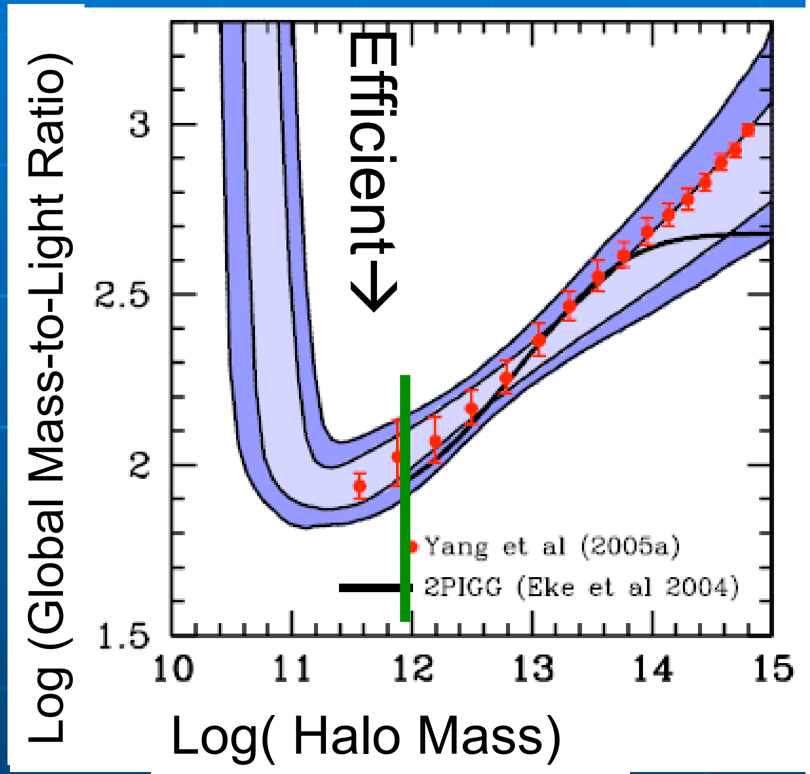
How efficient is galaxy formation?

Dark matter halos cluster …
more massive→more clustered





Identify (observed) galaxy populations with (simulated) halos that have the same clustering properties



M/L strong function of M!

Van den Bosch et al 2006

3) Galaxy Structure vs Formation Mechanisms

a) (Disk) Galaxy Sizes and Angular Momentum

- In disk galaxies the stellar body is centrifugally supported (stars move on near-circular orbits), with at "spin parameter",

$$\lambda \equiv \frac{J}{G}\sqrt{\frac{E}{M^5}}$$

where J is the angular momentum and E is the binding energy of the system.

$\lambda_{*,observed} \approx$ **0.5 - 1** for disks ($\lambda_* \approx 0.005$ for spheroids)

→ Disk size is given by the angular momentum of the material

Angular momentum comes from torques of (adjacent) mass distribution (Hoyle 1949, Ryden and Gunn 1987)

Linear theory: $\lambda_{total} = \lambda_{DM} = \lambda_{gas}(init) \sim 1/20$

Why galaxies are disks of a characteristic size

- Torques before the collapse induce spin $\lambda \sim 0.07$

- **Gas dissipates (by radiation) all the energy it can without violating angular momentum conservation → circular orbit**

- Fall and Efstathion (1980) showed that observed galaxy disks ($\lambda \sim 0.5$) can form only in DM halos through dissipation
 → central concentration (J conserved) → spin-up.

a) Presume there is no DM:

$$\lambda_{obs} \equiv \frac{J \cdot E^{1/2}}{GM^{5/2}} = \lambda_{init} \sqrt{\frac{R_{init}}{R}} \quad \Rightarrow \quad \frac{R_{init}}{R} \approx 50$$

We observe $M_{disk} \approx 5\text{x}10^{10}\ M_{sun}$, $R_{disk} \approx 8\ kpc \Rightarrow R_{init} \approx 400\ kpc$
$\Rightarrow R_{turn\text{-}around} \approx 2\ R_{init} \approx 800\ kpc$
$\Rightarrow t_{collapse} \sim 50 \cdot 10^9\ years$ for $M \sim 5\text{x}10^{10}\ M_{sun}$

b) If the gas is only a small fraction of the total mass:

⇒ $v_c(r)$ remains unchanged

⇒ $R_{init} / R \sim \frac{\lambda_{obs}}{\lambda_{init}}$ ⇒ $R_{init} \sim 80\ kpc$

⇒ $t_{dyn} \sim 10^9$ *years*

and there is enough time to form disks.

It turns out that the assumption of angular momentum conservation during the gas dissipation yield disk sizes as observed (assuming $\lambda \sim 0.07$)

However: in (numerical) simulations much of the angular momentum is lost → modelled disks too small (unsolved)

Luminosity/Mass vs. Size

[state of the art incarnation: Shen et al 2004 based on SDSS]

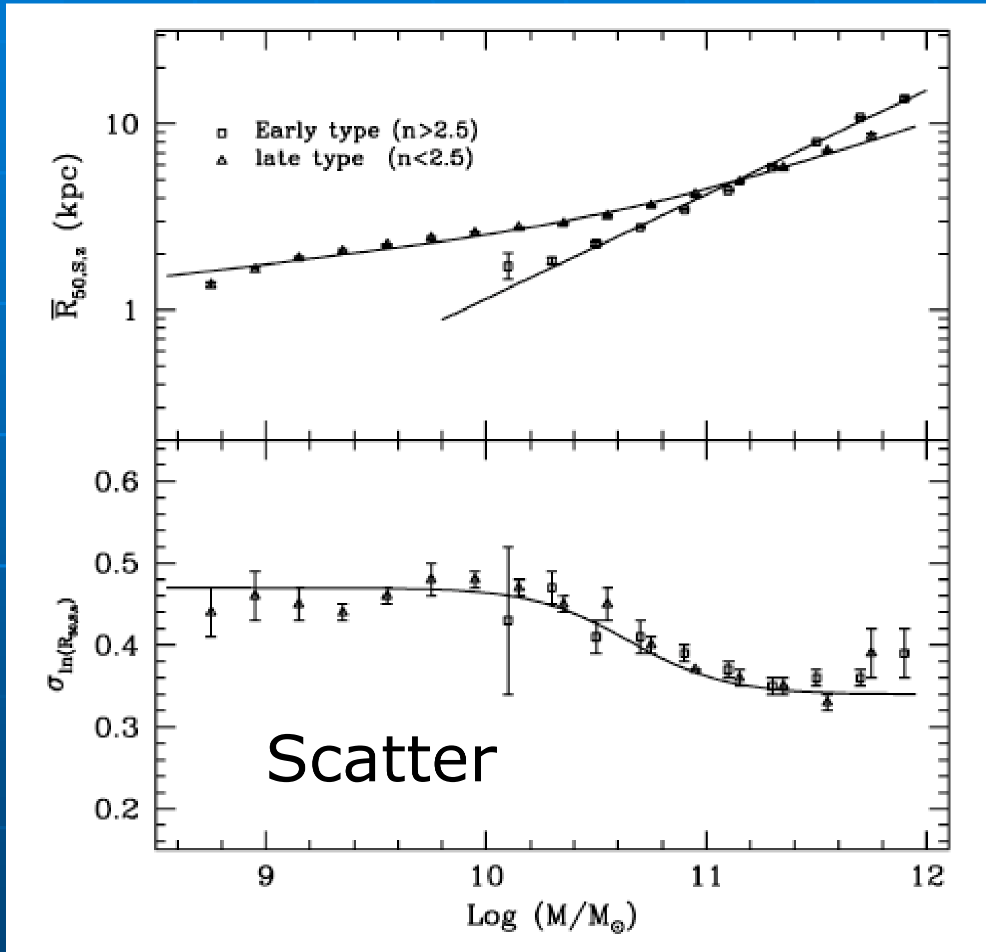
- Well defined size relations with ~2.5 scatter

  $R \sim M^{0.5}$

  at $M > 3 \times 10^{10}\ M_{Sun}$

- Galaxy (stellar) sizes are related to the characteristic angular momentum of the stars

  (see below)



Why are massive galaxies spheroids?

1. Stars form from dense, cold gas
   - either in disks
   - or from gas that is (violently) shock compressed
2. In the established cosmological paradigm larger (halos) form from the coalescence of smaller units

→ Stars in an (near) equilibrium system form from a disk and stay disk-like

→ 'Violent relaxation' shaking up stars (or stars formed during such an event) end up in spheroids

Is it plausible that in nearly all massive galaxies a (major) merger occurred after star-formation was largely complete?

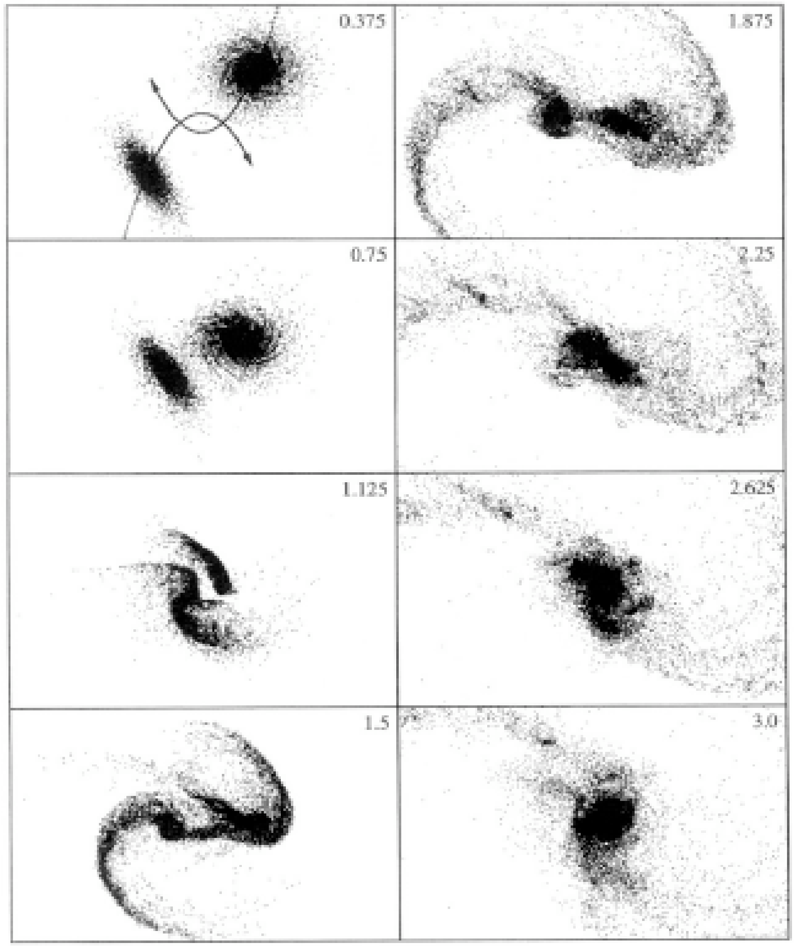
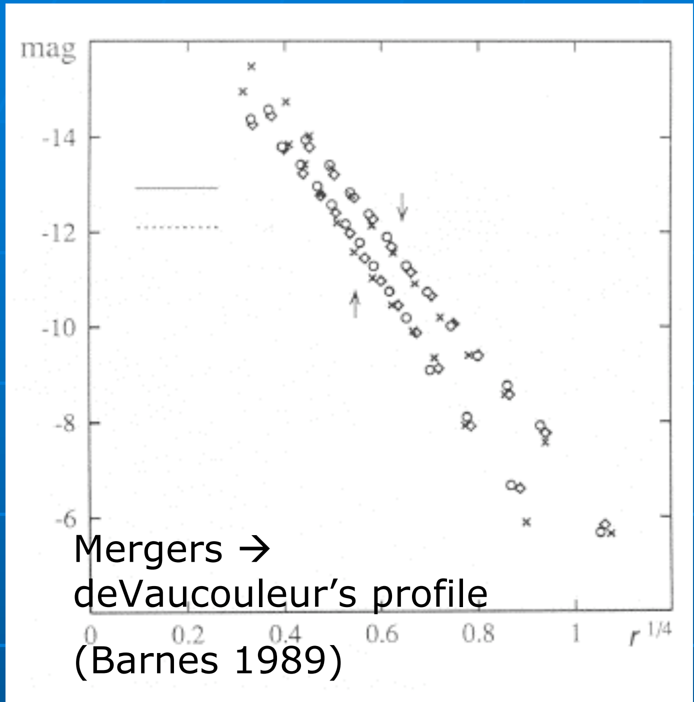


FIG. 4.—Evolution of the stellar distribution in encounter A, projected onto the orbital plane. The scale is the same as in Fig. 3.

Some physics of mergers

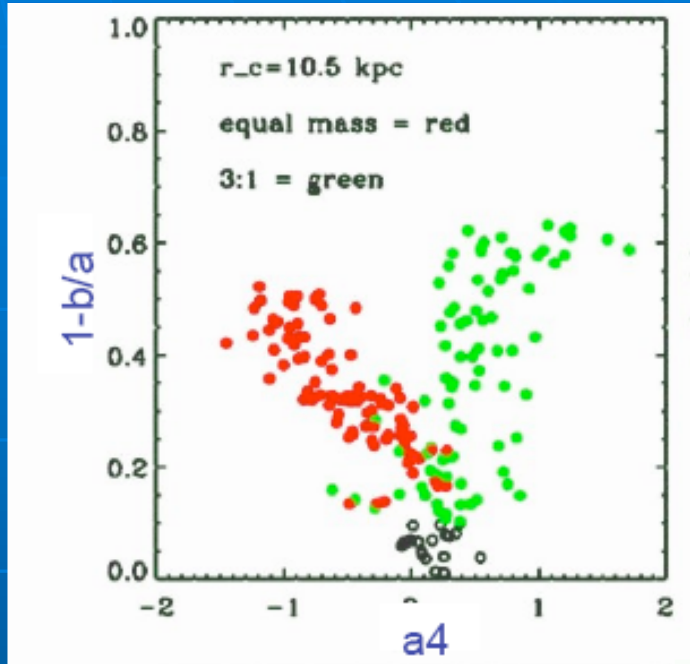


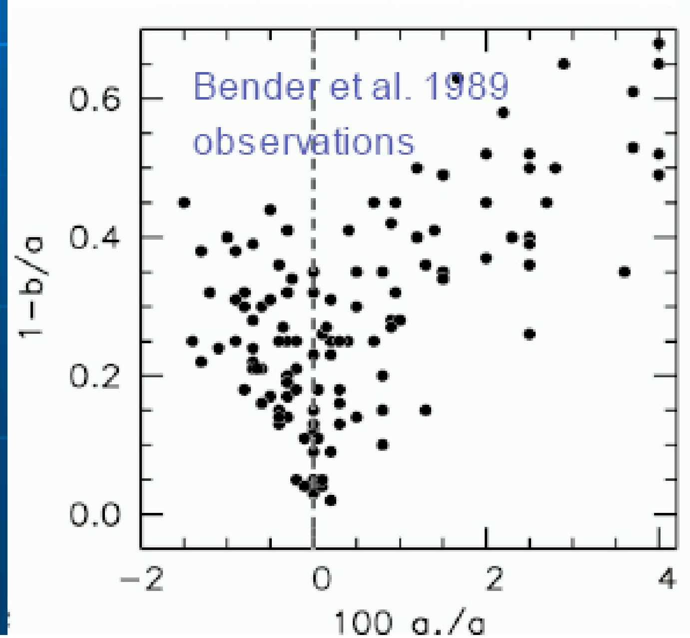
Mergers → deVaucouleur's profile

(Barnes 1989)

Isophote shapes

Naab&Burkert simulations





+ Some gas dissipation is needed to get the (central) densities of ellipticals 'right'

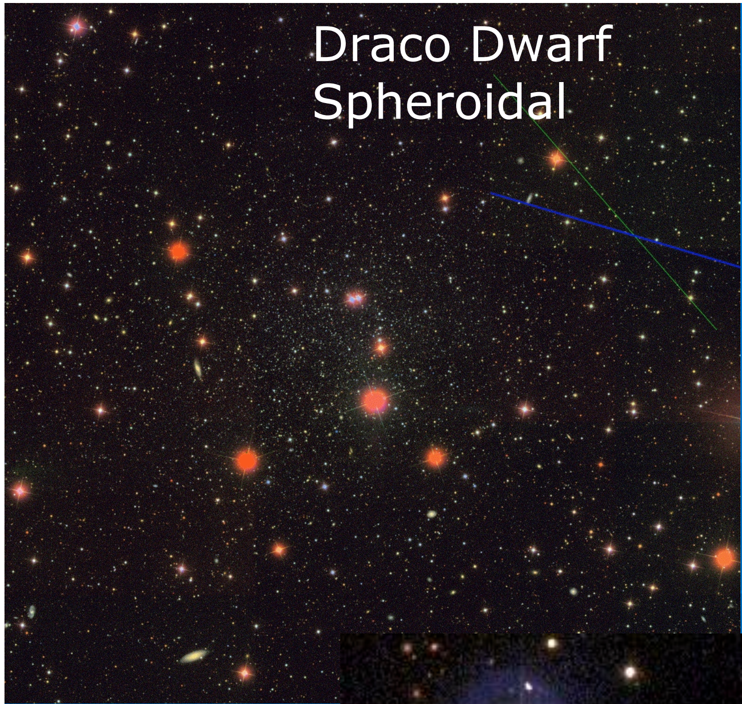
Merging moves objects 'within' the fundamental plane!

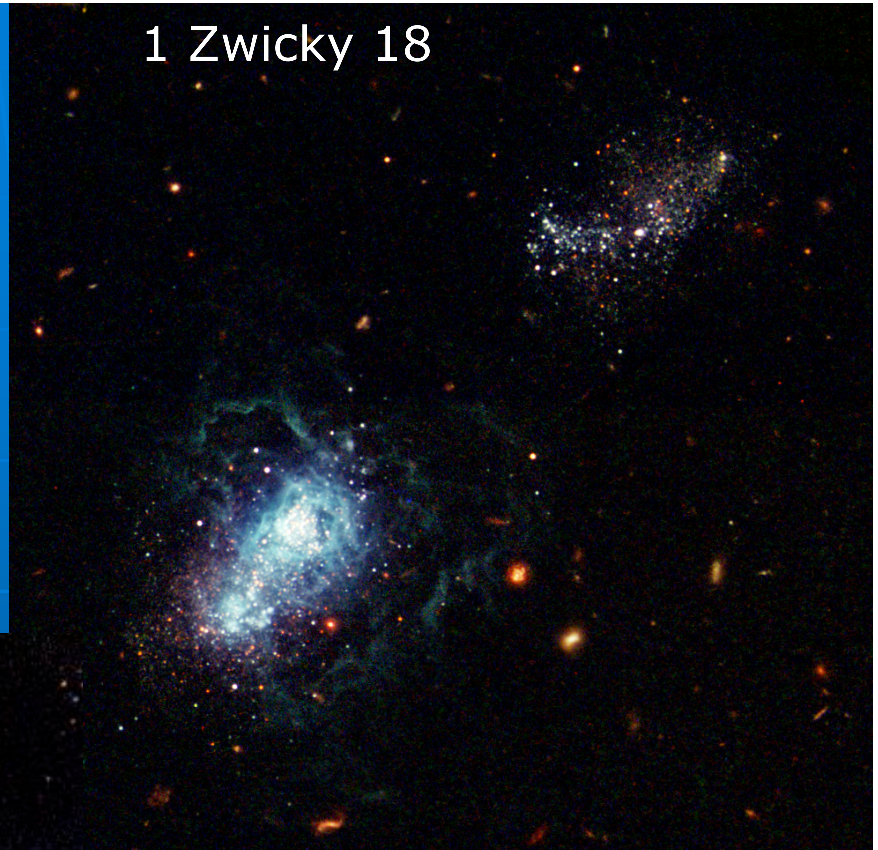
The Smallest and the Largest Galaxies

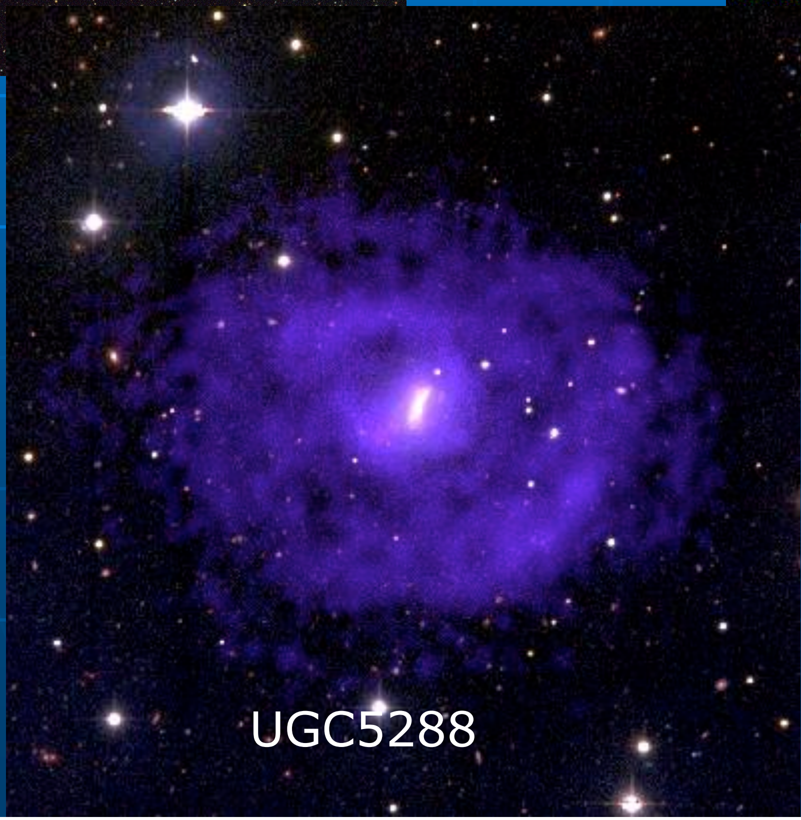
- Questions:
  – Is there an empirical (upper/lower) limit to 'galaxies'?

1) 'Dwarf' Galaxies

- Definition (not universally established):
  - galaxy that has < 1/10th of L_* (or M_*)Milky_Way
  - or v_circ < 100km/s
- Most abundant type of galaxies; contributes negligibly to the total stellar mass budget.
- Structure and morphologies
  - Often 'irregular' (highly asymmetric)
  - Often of very low surface brightness
- Stellar populations
  - Inevitably low metallicity (<1/10 solar)
  - Some have very young pops. (most stars after z<0.5)
  - Some have only old (>10Gyrs) stars, many are mixed populations
- Dwarfs are interesing regime to test gravity ← → 'feed-back'

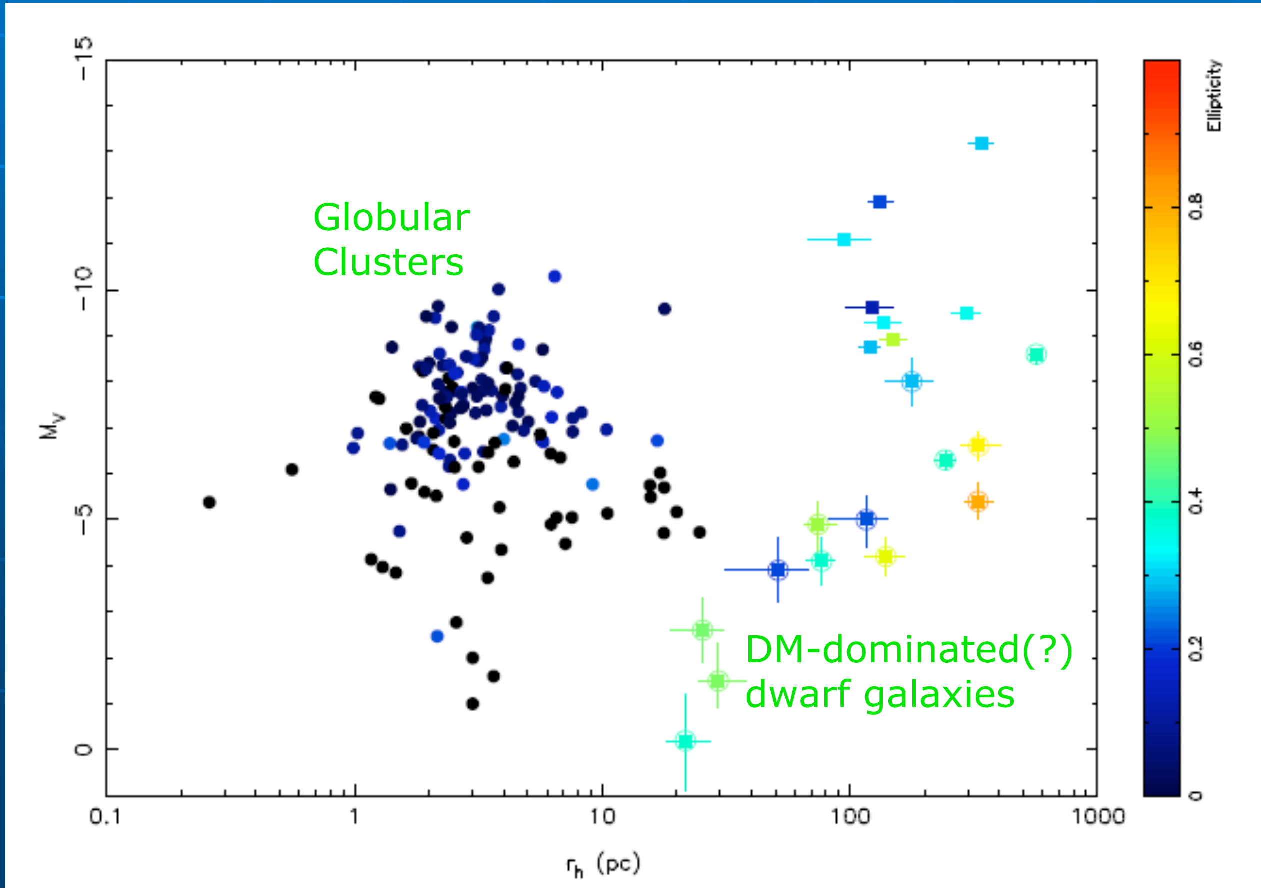

Draco Dwarf
Spheroidal


1 Zwicky 18


UGC5288

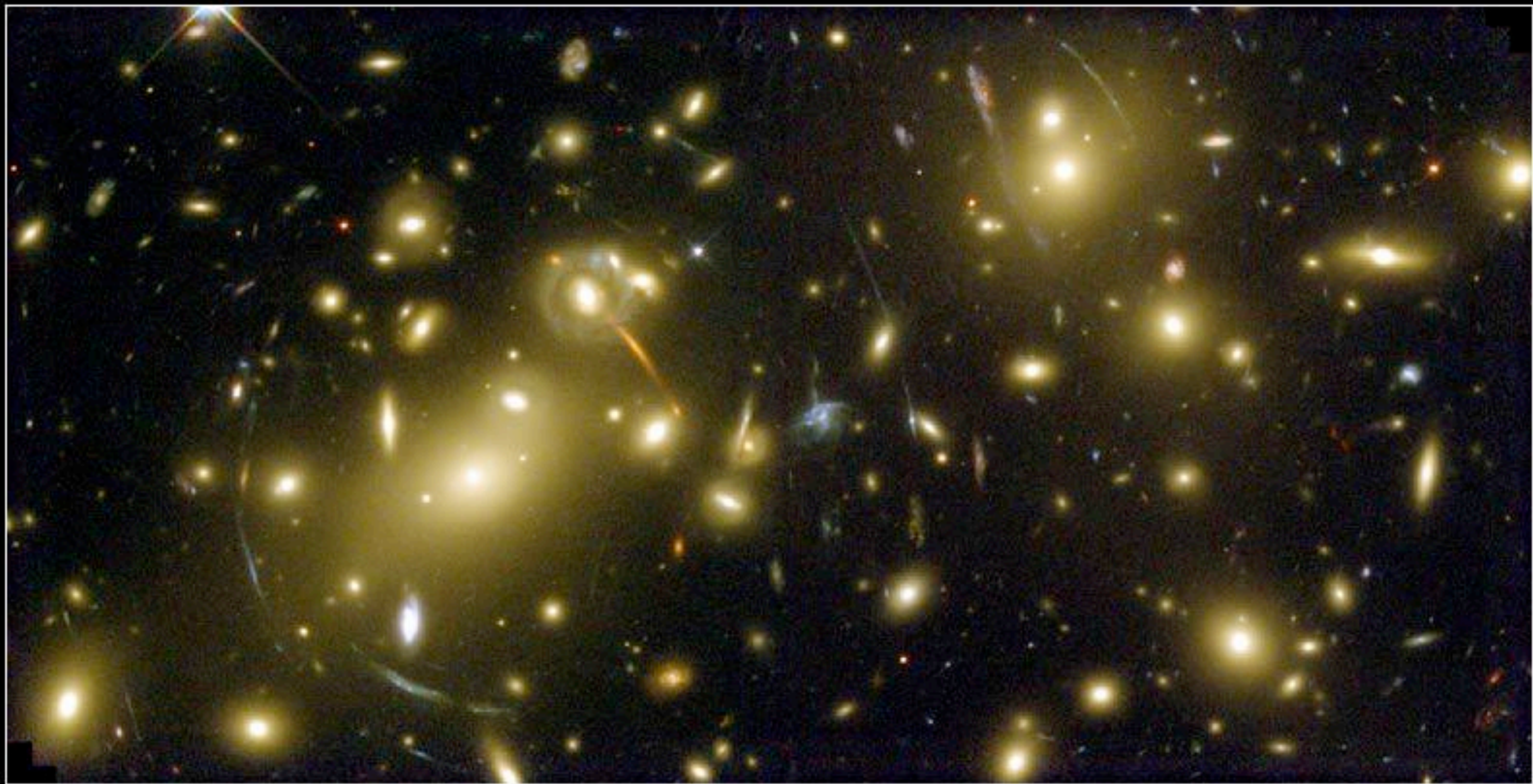
The Faintest Galaxies Known to Date
Milky Way Satellites

- Most found recently by SDSS (e.g. Belokurov et al 2006)
- Seem to be dark matter dominated
- Same luminosity as globular clusters, but 1000x lower stellar surface mass density



The Extreme Limit of “Galaxy Clustering”

Galaxy Clusters



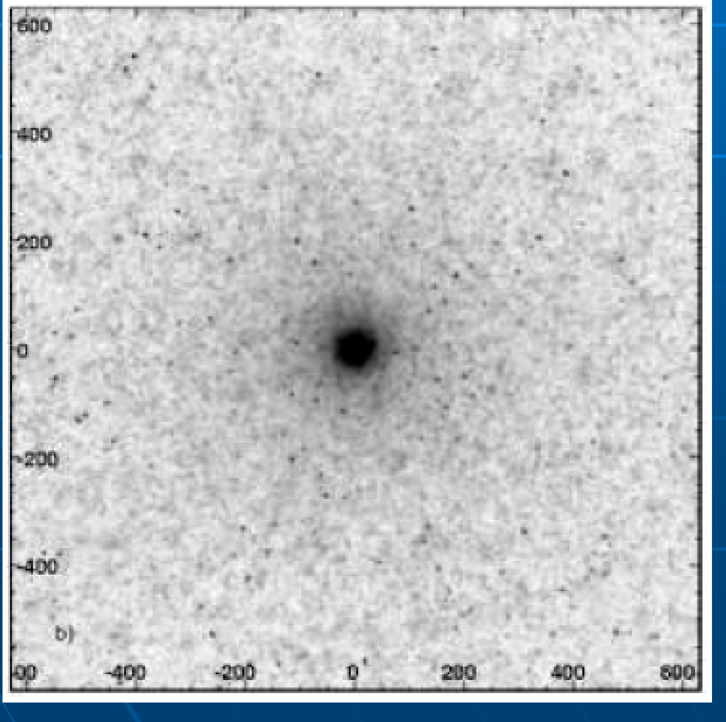
Galaxy Cluster Abell 2218 **HST • WFPC2**

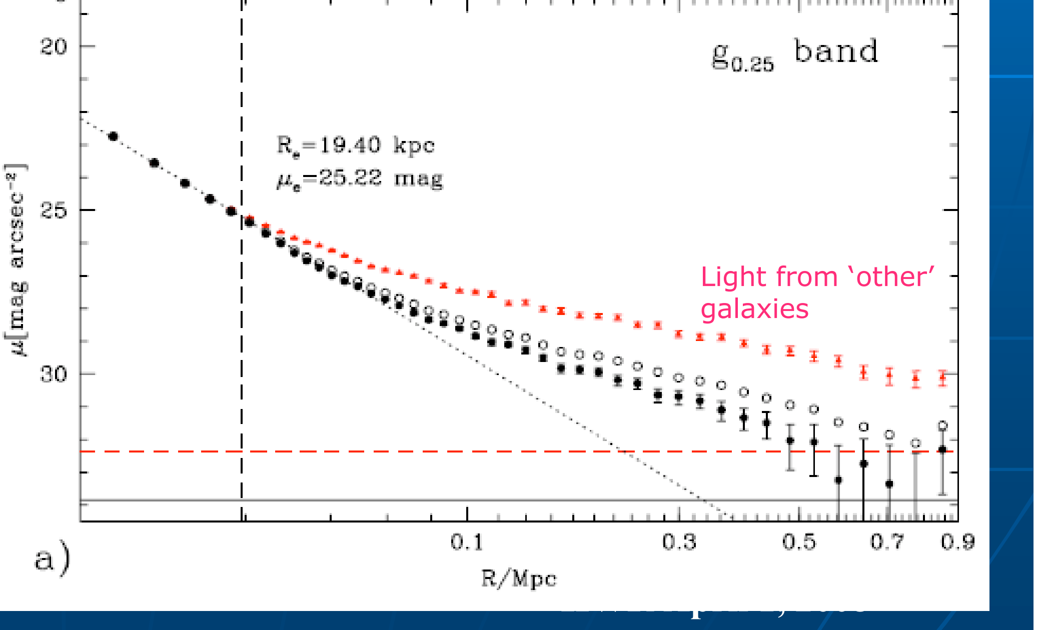
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

cD galaxies: the most massive galaxies

- Galaxies with >= 5 L_{MW} are only found at the centers of galaxy clusters
- They are without exception spheroidal
- They have extended light profiles that blend into 'intra-cluster' light

'stacked' image of 700 cluster centers (Zibetti et al 2005)



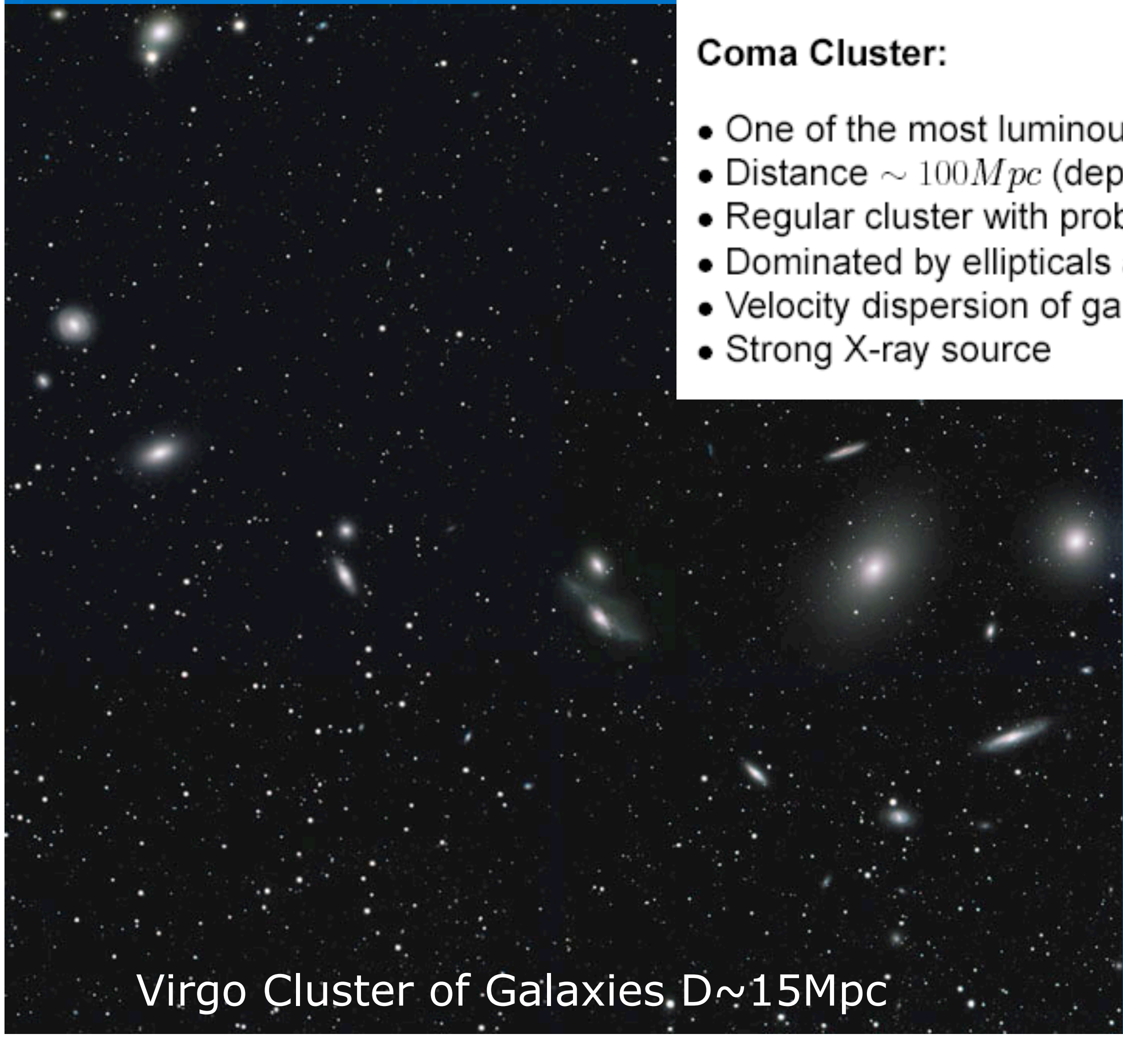


Virgo Cluster:

- Nearest large galaxy cluster with more than 2000 galaxies brighter than $M_B \simeq -14$ ($L_B \sim 10^{7.8} L_\odot$)
- Distance $\sim 17 Mpc$ (dependent on H_0)
- Extend $\sim 10^\circ \triangleq 3Mpc \times 3Mpc$
- Irregular cluster, densest regions dominated by ellipticals
- Velocity dispersion of galaxies about 600km/s

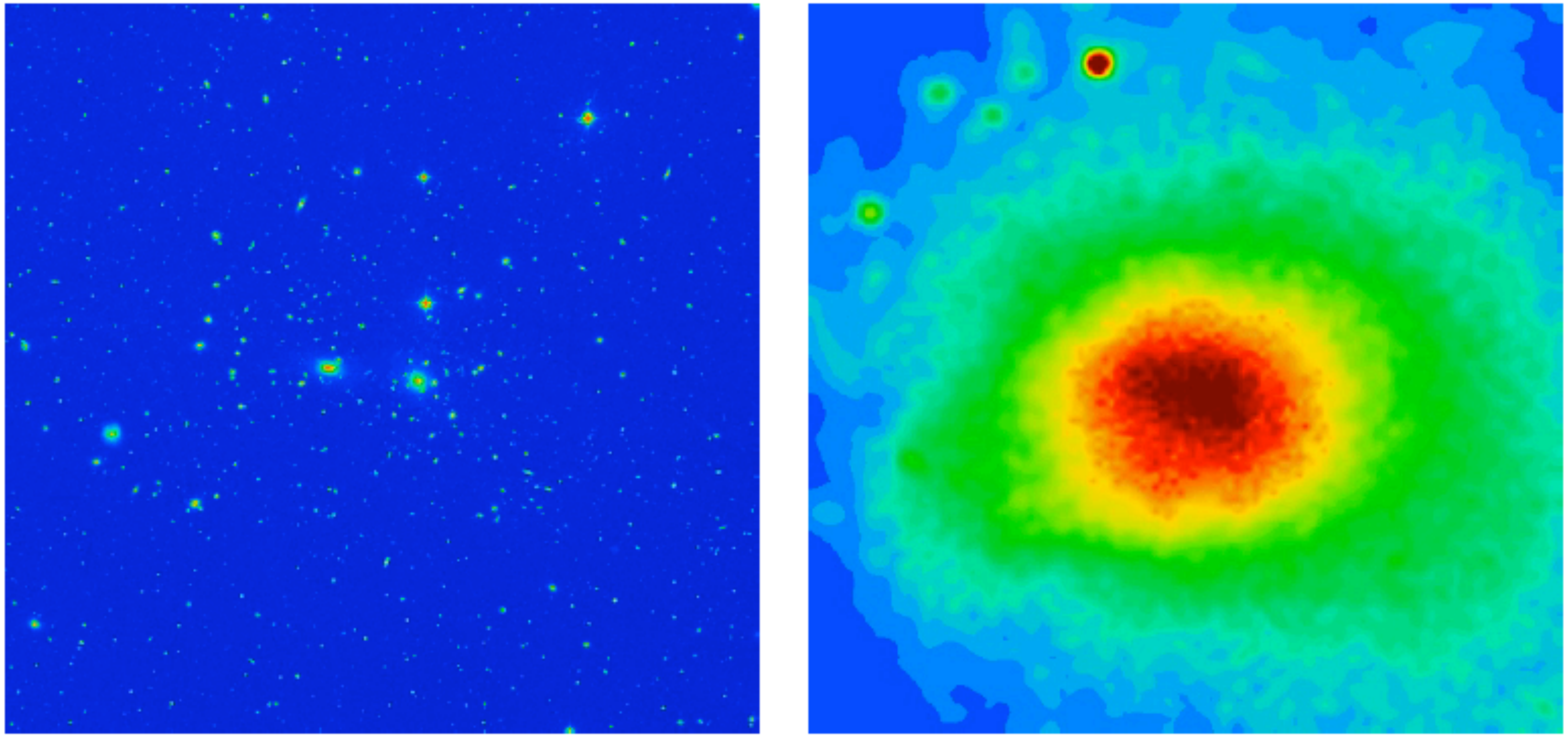
Coma Cluster:

- One of the most luminous clusters known
- Distance $\sim 100 Mpc$ (dependent on H_0)
- Regular cluster with probably subcluster merging from SW
- Dominated by ellipticals and S0s, two central cDs and one in subcluster
- Velocity dispersion of galaxies about 1000km/s
- Strong X-ray source



Virgo Cluster of Galaxies D~15Mpc

Galaxy Clusters are filled with Hot Gas



Coma cluster (left: optical image, right: X-ray image)

The X-ray spectra show the characteristics of Bremsstrahlung of a $\sim 10^8 K$ hot gas.
The volume emissivity is: $\frac{dP}{dV} = 2.410^{-27} T^{-1/2} N_e^2 \left[\frac{erg}{cm^3\, s}\right]$
The cooling time of the plasma is: $t_{cool} = \frac{3N_e kT}{\frac{dP}{dV}} \simeq \frac{10^{11}}{N_e} T^{1/2}\ [s]$
For the center of the Coma cluster we have:

$$L \simeq 10^{44} erg/s$$
$$\overline{n_e} \simeq 10^{-3} cm^{-3}$$
$$\overline{\tau_{cool}} \simeq 10^{10} yrs$$
$$M_{gas} \simeq 10^{13} M_\odot$$

The following correlations exist between the different components of galaxy clusters:

- The central galaxy density is higher for higher L_X.
- The fraction of spirals is lower for higher L_X.
- The temperature T is proportional to L_X and typically 10^8K.
- The gas metallicity is lower for higher T and typically 1/3 of solar.
- The ratio of gas-mass to galaxy-mass increases with T up to 5 or more.
- The dominant component in all clusters is dark matter. This follows consistently from the dynamics of galaxies, the hydrostatic equilibrium of the X-ray gas and from gravitational lensing. The typical mass ratios are:

galaxies : X-ray-gas : dark-matter $\simeq$ 1 : 5 : 25

From R. Bender

Galaxy Properties: Summary

- Description of the stellar body of galaxies
  - Spheroid : post-violent relaxation/merger stars
  - Disks: not shook-up since formation
  - In the present-day universe ~50%/50
- The variety of galaxies in
  - Morphology, shape, structure, …
  - Stellar content and metallicity….

  is very restricted (many parameter relations).
- The stellar mass range of galaxies
  - Clearly limited at upper end: 'brightest cluster galaxies'
  - No end in sight (<1000 M*) at the lower end?
- Milky Way
  - Typical galaxies in many ways
  - Central in shaping our thinking about galaxies
    - (historically, but also in future)