Galaxies, Cosmology and Dark Matter

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Chapter 12

Clusters and Groups of Galaxies

12.1 Selection Criteria for Clusters and Groups

12.1.1 Abell's Catalog of Rich Clusters (1958)

Abell's criteria:

- > 50 cluster members in the magnitude range $[m_3, m_3 + 2]$ (with the magnitude m_3 of the 3rd brightest galaxy) and within the radius $R_{\text{Abell}} = \frac{1.7}{(1+z)} \hat{\simeq} 3h_{50}^{-1} Mpc$.
- Redshift range: $0.02 < z < 0.20$
- Sorted into 'richness classes' according to number of galaxies N and density.
- The redshift was usually not measured, but determined from the apparent magnitude of the brightest cluster galaxies.
- The clusters were found using the Palomar Sky Survey

Richness class R	N	Number of clusters in the complete northern sample
0	$30-49$	$\geq 10^3$
1	$50-79$	1224
2	$80-129$	383
3	$130-199$	68
4	$200-299$	6
5	≥ 300	1

12.1.2 Tully's Nearby-Galaxy-Catalog

This catalog uses the following group definitions:

- Obtain the galaxy density around a given galaxy, add the luminosities up to the limiting magnitude, and extrapolate to the standard luminosity function
- A **group of galaxies** (gravitationally bound) is found if:

  luminosity density: $j_G > 2.5 \cdot 10^9 \frac{L_\odot}{Mpc^3}$

- An **association of galaxies** (not gravitationally bound) is found if:

  $$j_A > 2.5 \cdot 10^8 \frac{L_\odot}{Mpc^3}$$

- mean luminosity density obtained from a large volume (using the APM survey):

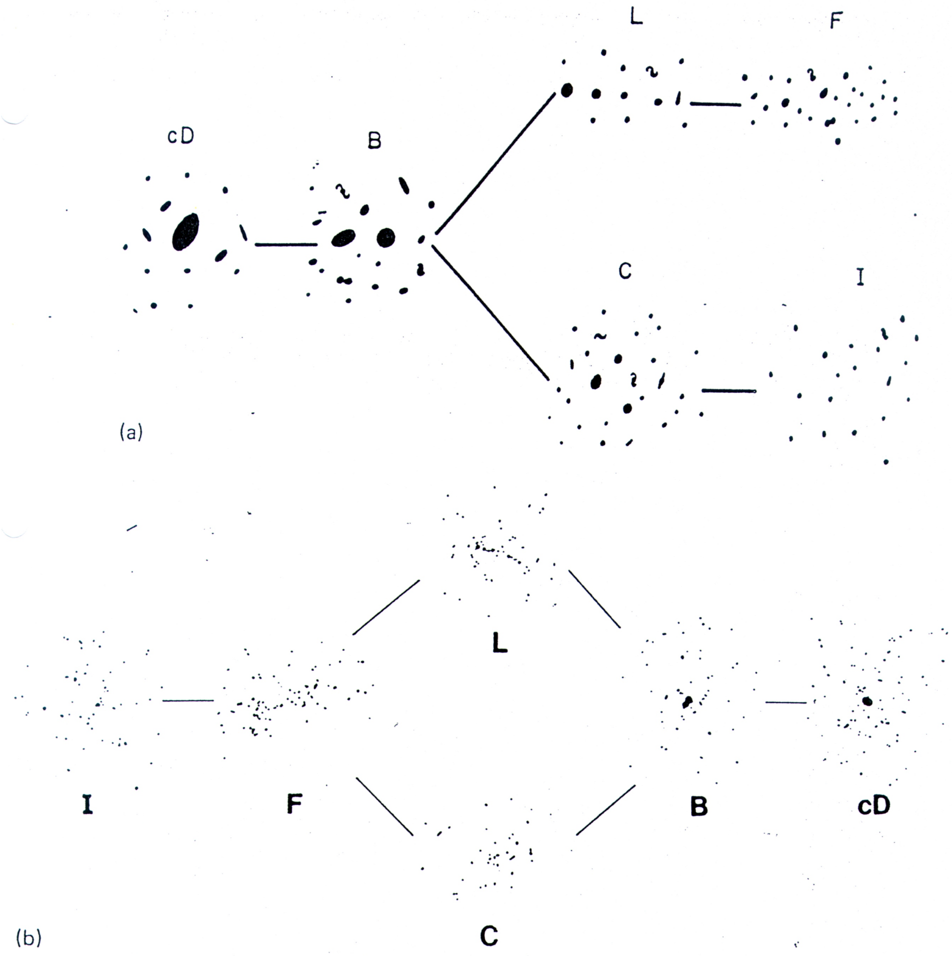
  $$\bar{j} \simeq 10^8 \frac{L_\odot}{Mpc^3}$$

12.1.3 The Rood-Sastry Classification System

The original Rood-Sastry (1971) classification system is based on the nature and distribution of the ten brightest cluster galaxies. Basically, the six Rood-Sastry (RS) classes are defined as follows:

- cD : the cluster is dominated by a central cD galaxy (e.g. A2199).
- B : binary - the cluster is dominated by a pair of luminous galaxies (e.g. A1656 (Coma))
- L : line - at least three of the brightest galaxies appear to be in a straight line (e.g. A426 (Perseus))
- C : core - four or more of the ten brightest galaxies form a cluster core with comparable galaxy separations (e.g. A2065 (Corona Borealis))
- F : flat - the brightest galaxies form a flattened distribution on the sky (e.g. A2152 (Hercules))
- I : irregular - the distribution of brightest galaxies is irregular, with no obvious center or core (e.g. A400)

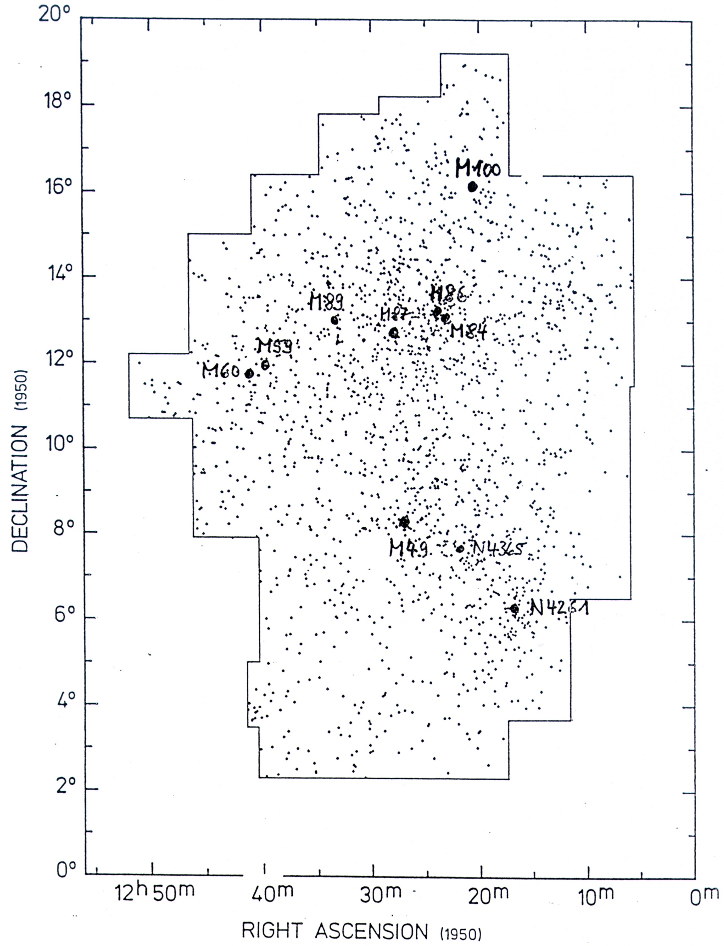
Fig. 3. (a) The Rood–Sastry (1971) cluster classification scheme. (b) The revised Rood–Sastry classes from Struble and Rood (1982).



12.2 Nearby Galaxy Clusters

12.2.1 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 $\sim 15 - 20\ Mpc$ (dependent on H_0)
- Extend $\sim 10^\circ \hat{=} 3\ Mpc \times 3\ Mpc$
- Irregular cluster, densest regions dominated by ellipticals
- Velocity Dispersion of Galaxies about 600 km/s



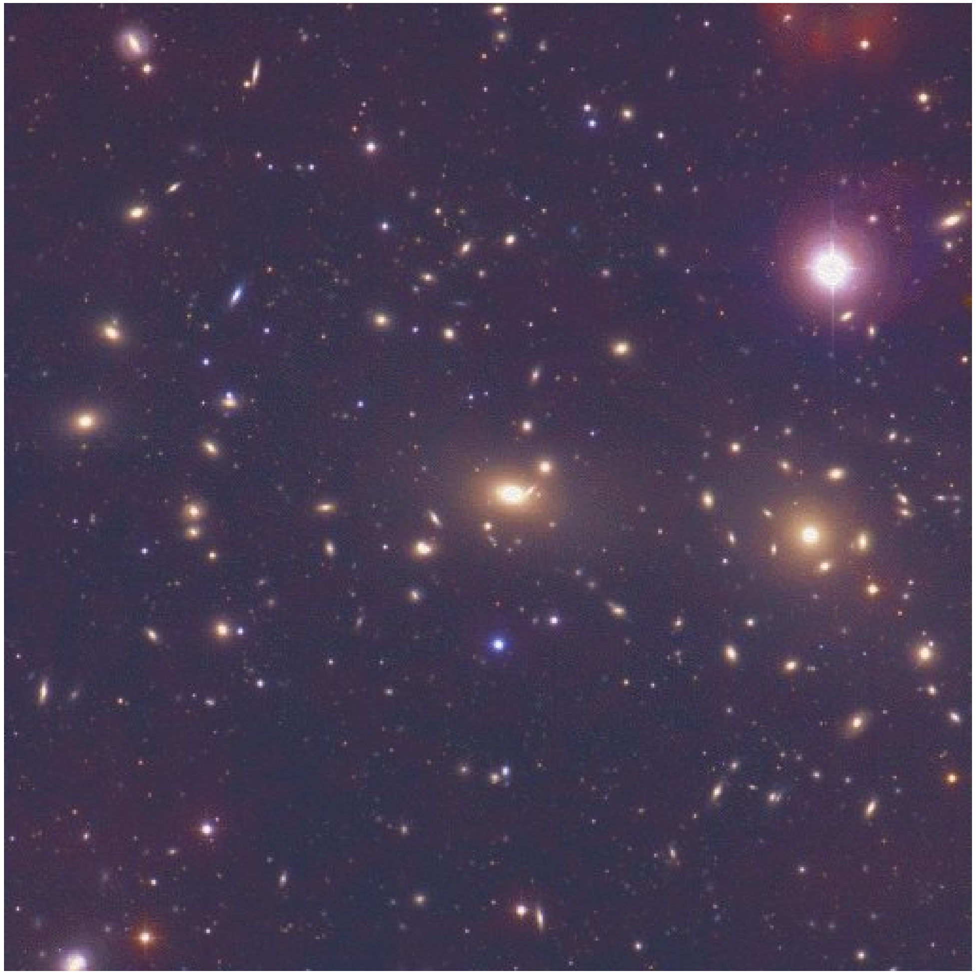
Overview of the Virgo Cluster

Virgo Cluster

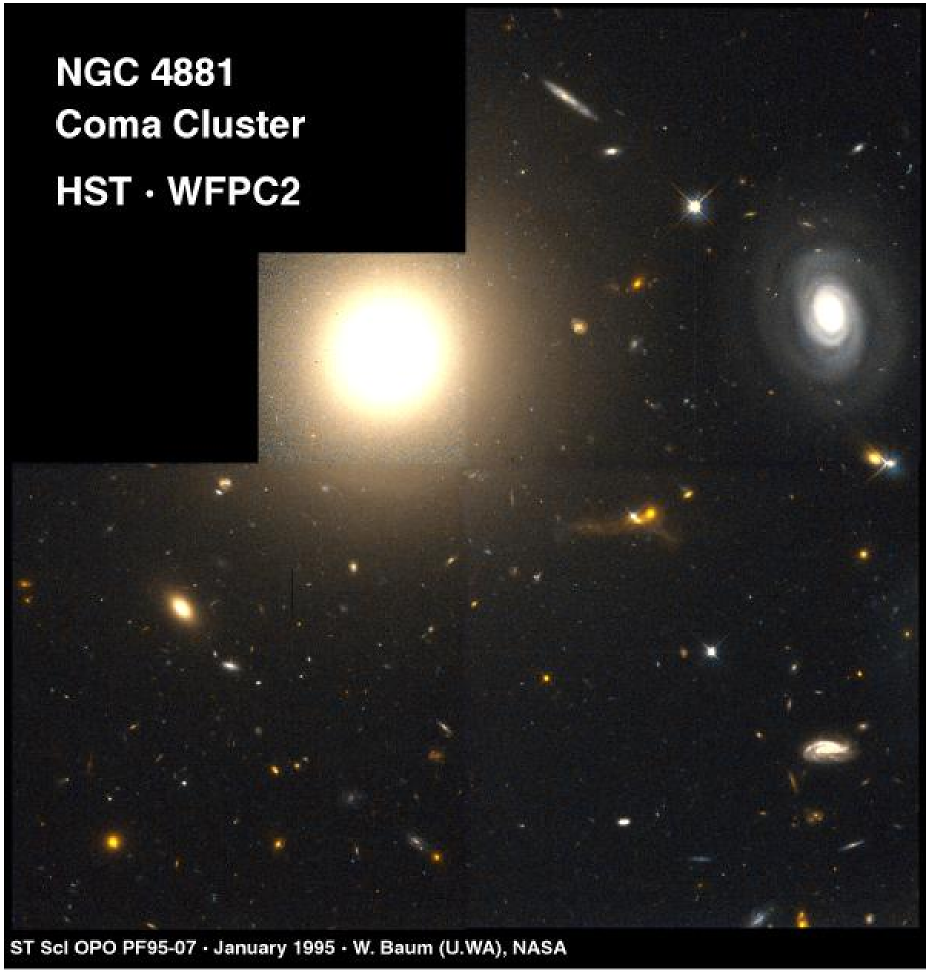
Virgo Cluster

12.2.2 Coma Cluster

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



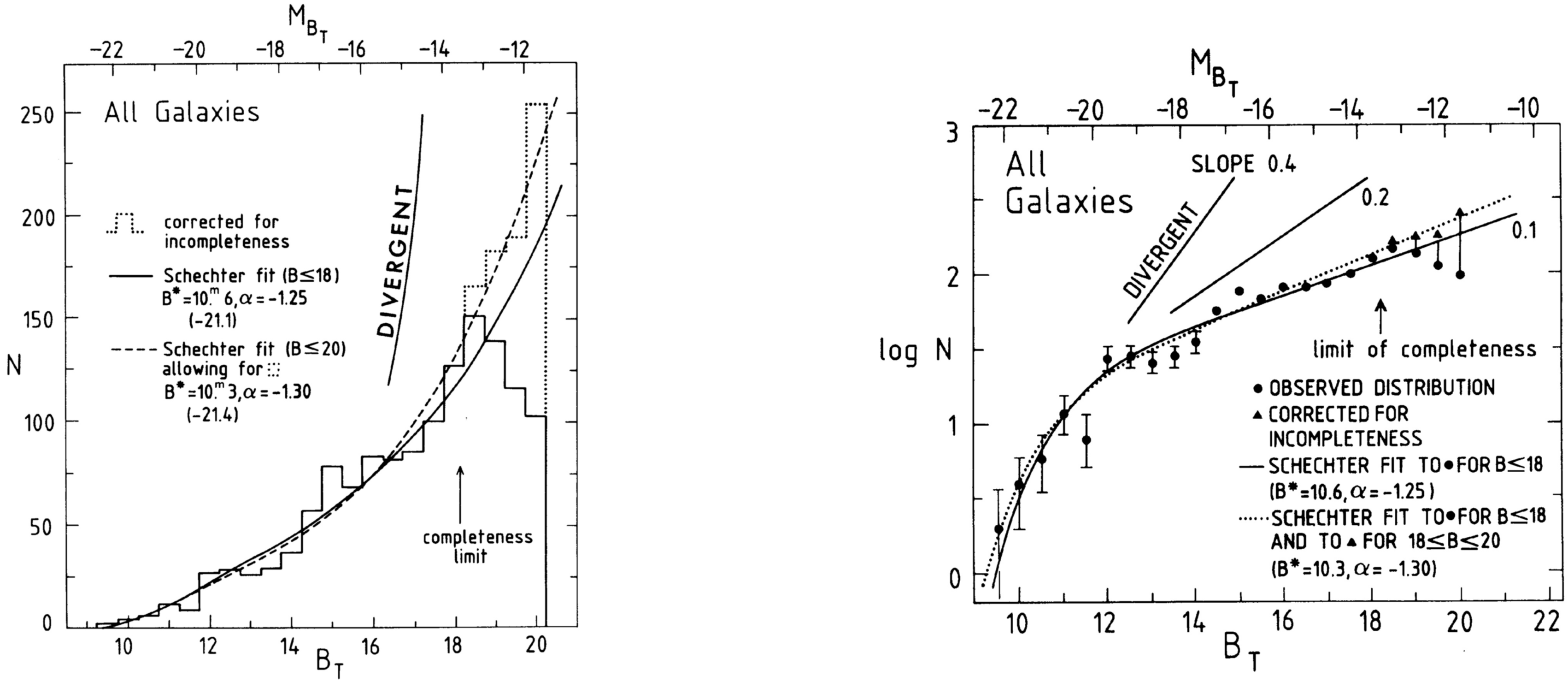
Coma Cluster



Coma Cluster

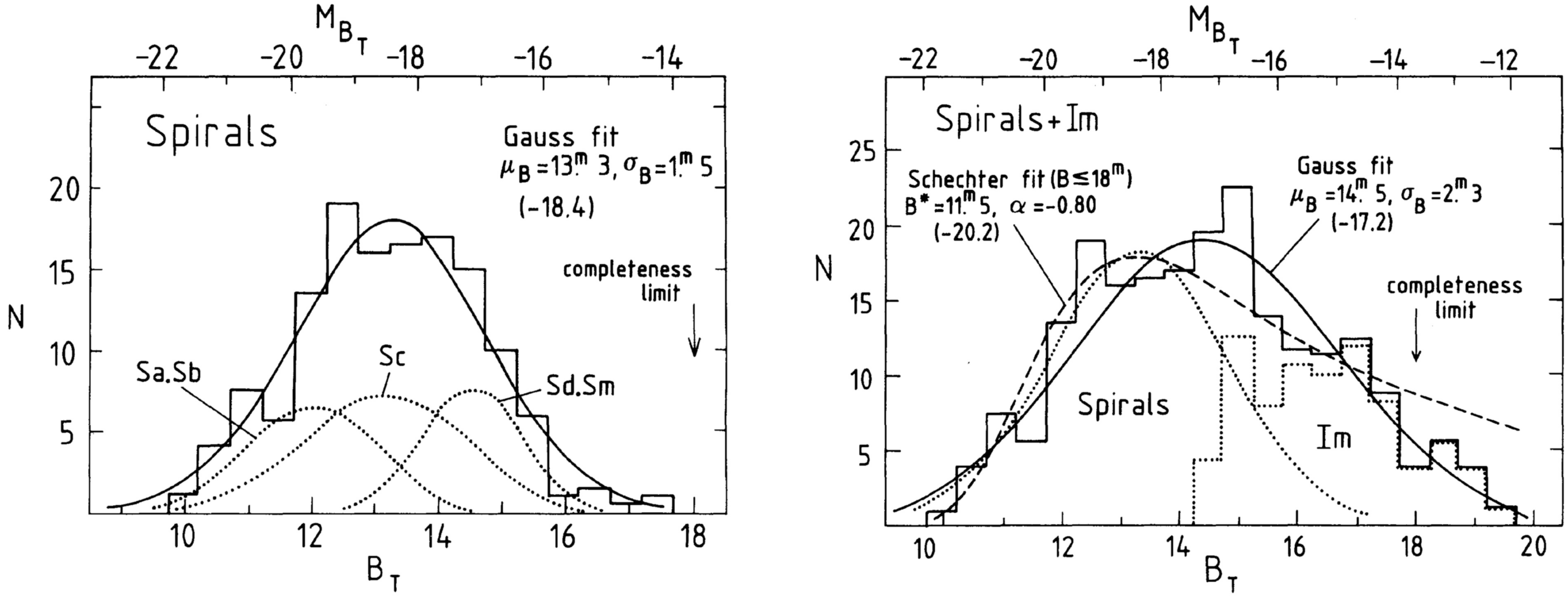
12.3 Luminosity Functions

Luminosity Function for Virgo Galaxies:



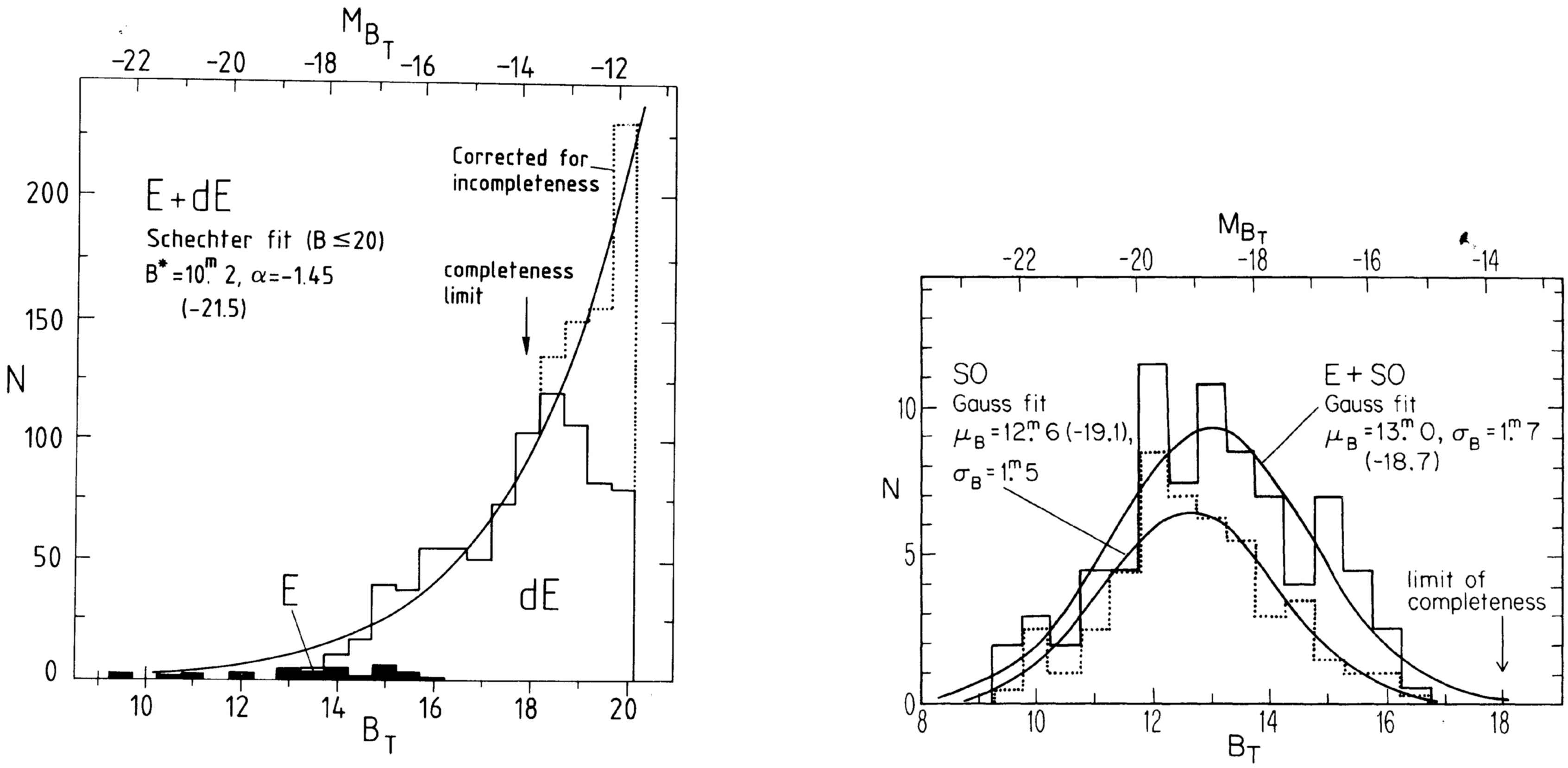
see: Sandage et al. (1985) *AJ*, **90**, 1759

Luminosity Function for Virgo Galaxies:



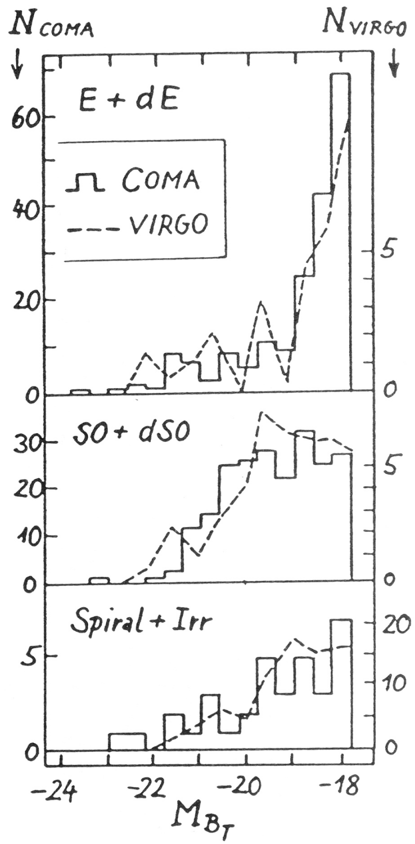
see: Sandage et al. (1985) *AJ*, **90**, 1759

Luminosity Function for Virgo Galaxies:

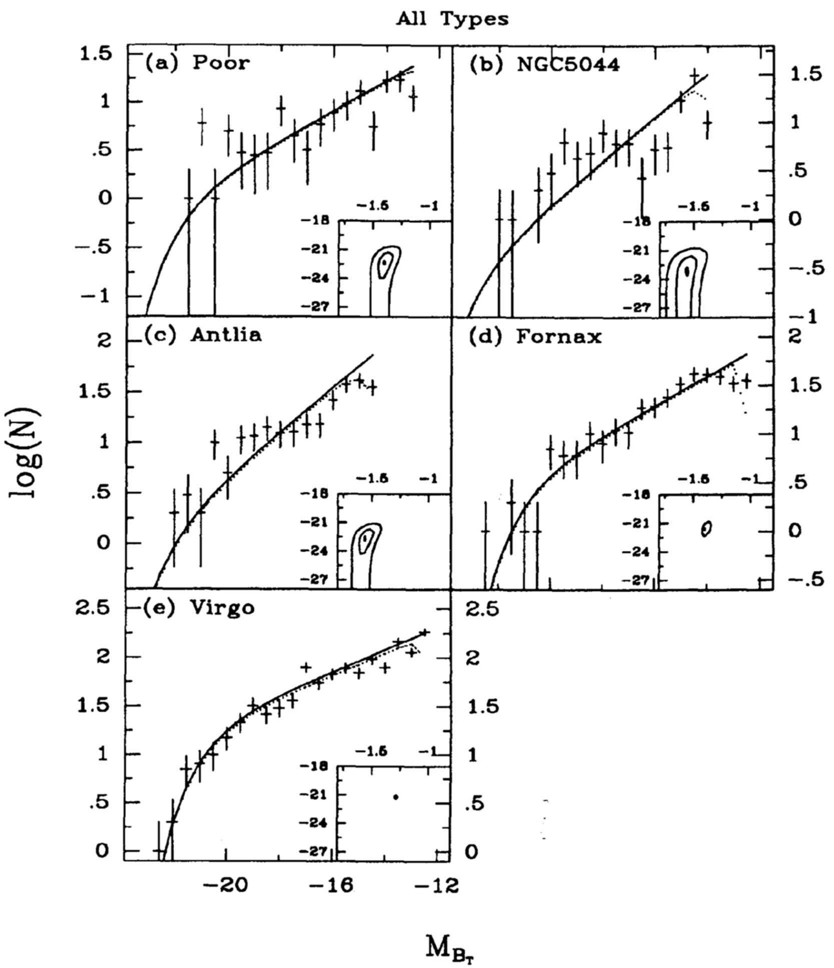


see: Sandage et al. (1985) *AJ*, **90**, 1759

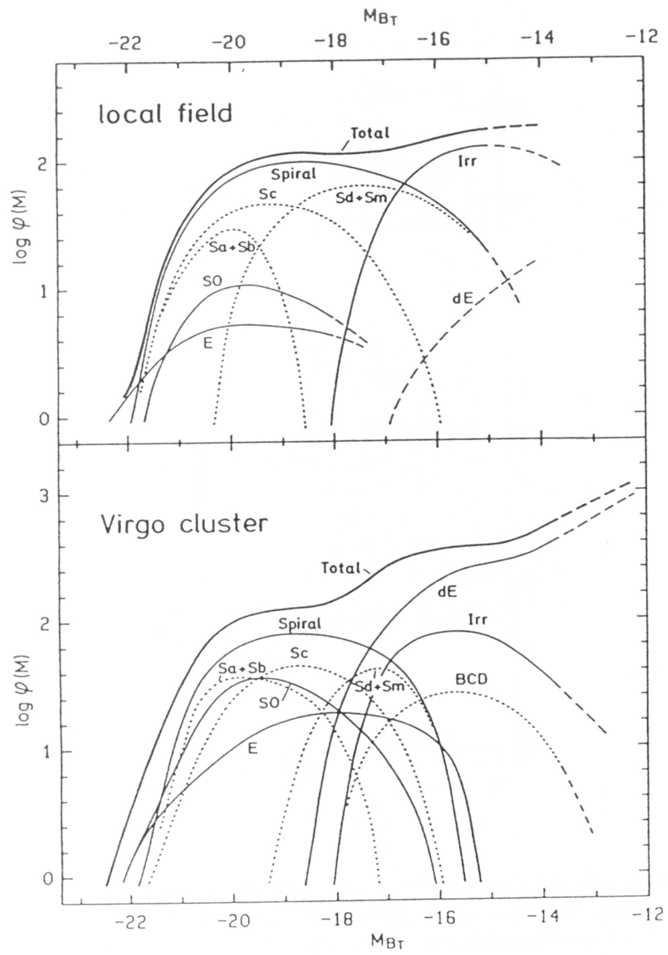
Virgo vs Coma Luminosity Functions:



see: Sandage (1990) in *Clusters of Galaxies* Cambridge University Press

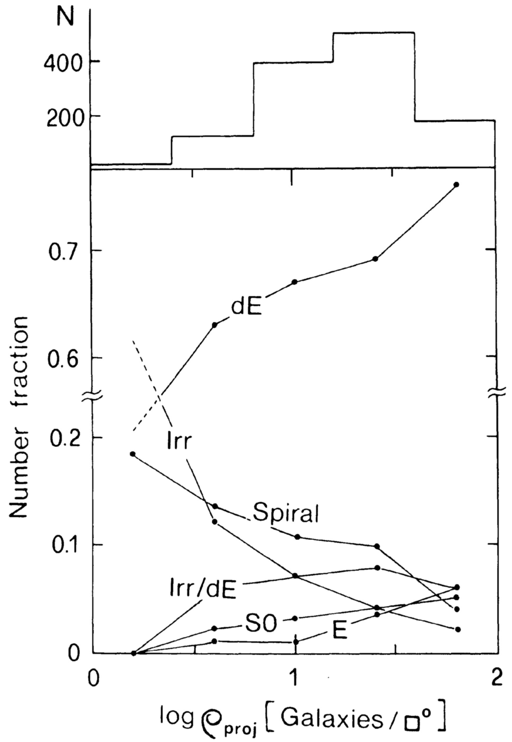


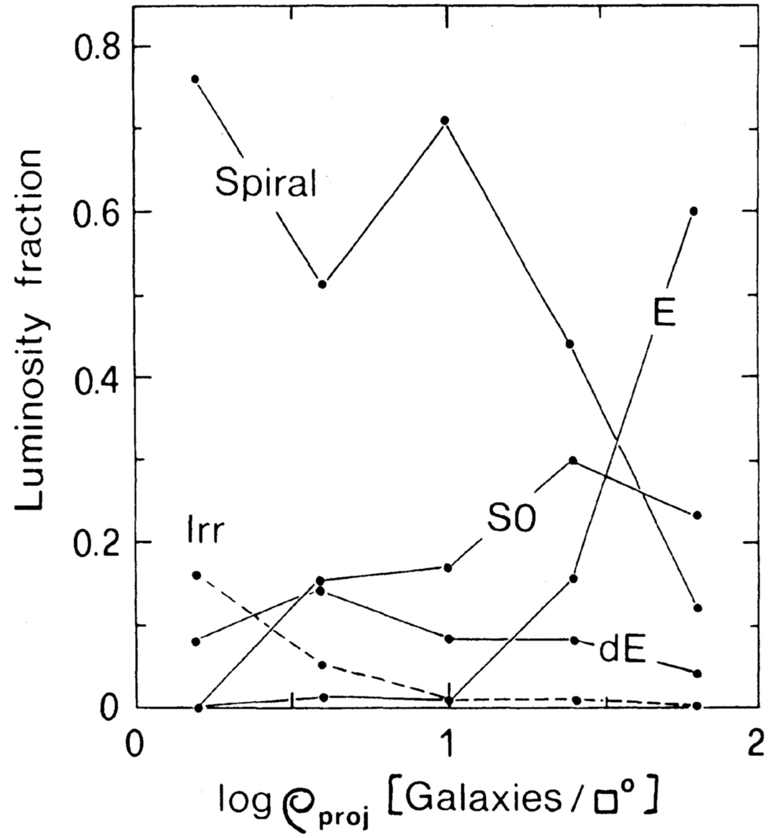
Nearby galaxy groups from Ferguson, Sandage (1991) *AJ*, **101**, 765



see: Sandage (1990) in *Clusters of Galaxies* Cambridge University Press

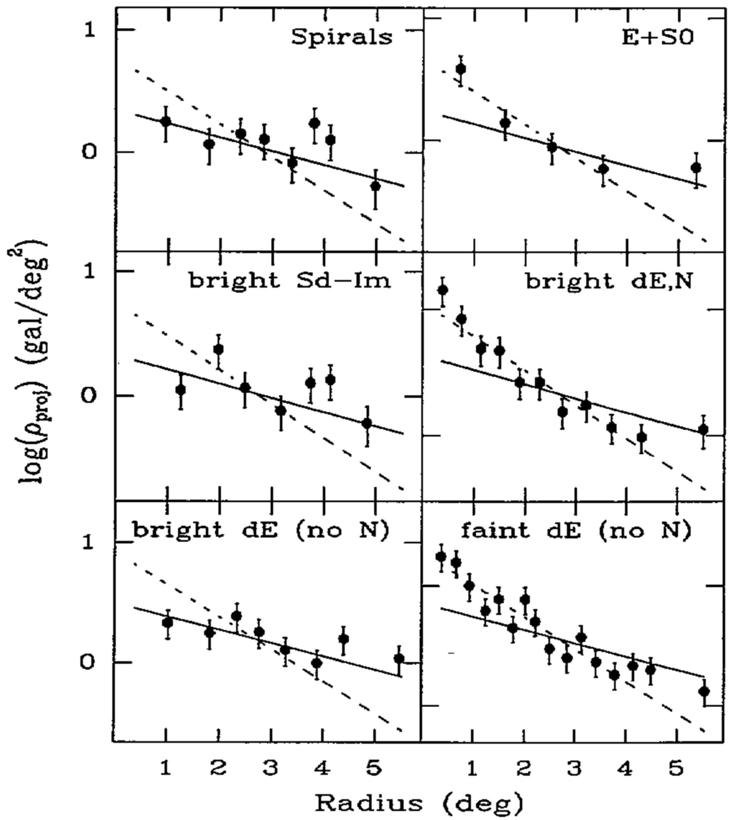
Morphology-Density Relation:

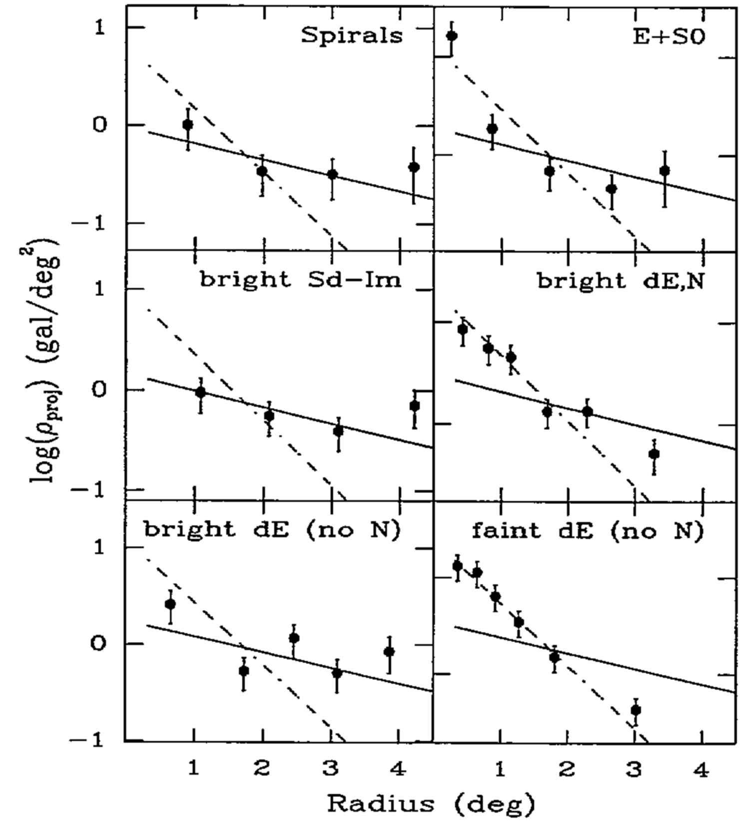




see: Binggeli et al. (1987) *AJ*, **94**, 251

Morphology-Radius Relation:





see: Ferguson, Sandage (1989) *ApJ*, **346**, L53

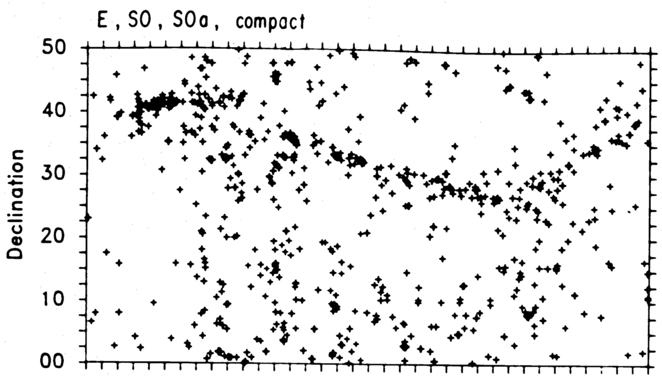


FIG. 6*b*

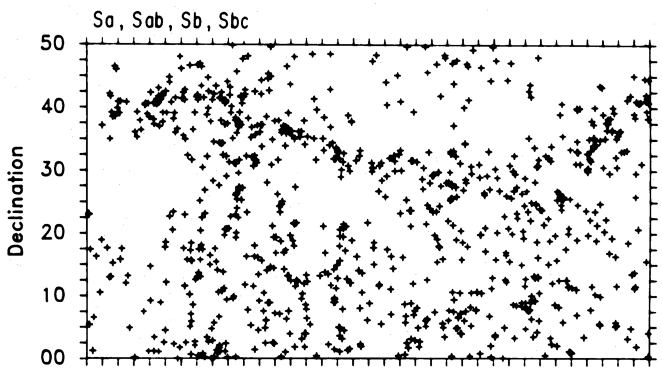


FIG. 6*c*

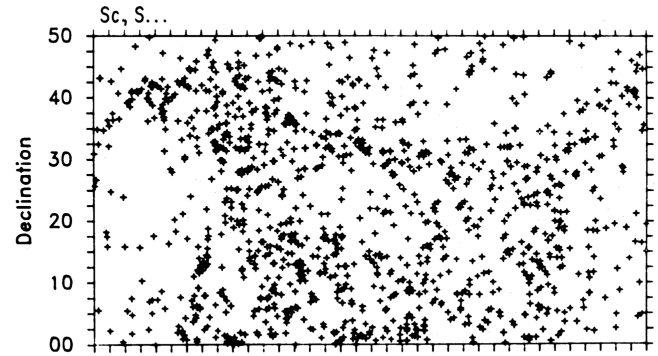
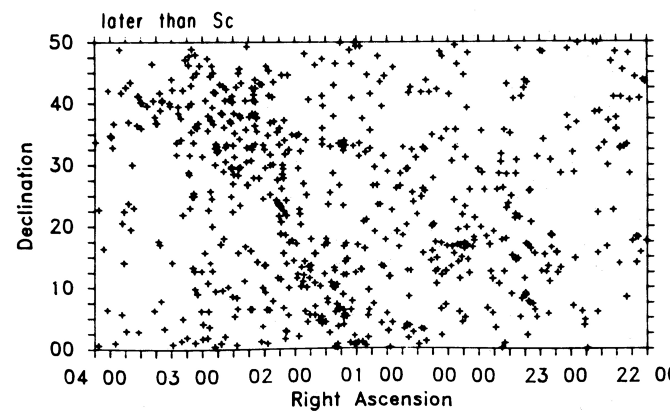


FIG. 6*d*



see: Giovanelli et al. (1986) *ApJ*, **300**, 77

12.4 Characteristic Time Scales for Groups and Cluster

- **Crossing time:**

$$t_{cr} \simeq \frac{R}{\sigma_{cl}} \simeq 10^9 yrs \frac{(R/Mpc)}{\sigma_{cl}/1000 km/s}$$

- **Relaxation time:**

Two body relaxation:

$$t_{relax} \simeq \frac{0.1 N t_{cr}}{f^2 \ln \Lambda} \quad \text{(see: Binney/Tremaine)}$$

$$f = \frac{N \cdot m}{M_{tot}} \simeq 0.1 \quad \text{(90\% dark matter)}$$

$$\ln \Lambda \simeq 3 \quad \text{(Coulomb-Logarithm)}$$

Relaxation of the galaxies: $N \simeq 300 \ldots 3000$

$$\Rightarrow t_{relax} \simeq 10^{12} \ldots 10^{13} yrs$$

Relaxation of sub-clumps: $N \simeq 3 \ldots 30$

$$t_{relax} \simeq 10^{10} \ldots 10^{12} yrs$$

Violent Relaxation (e.g. merging of galaxy clusters of similar size)

$$t_{violent} \simeq 5t_{cr} \simeq 5 \cdot 10^9 yrs \frac{(R/Mpc)}{(\sigma_{cl}/1000km/s)}$$

- **Dynamical friction scale:**

Assume a massive object moving between numerous less massive objects.
$\Rightarrow$ The lighter objects are focused in the wake of the massive object and cause its deceleration.

For a spherical system of background particles with a radially constant velocity dispersion and a massive body moving with $v \sim 2\sigma$ the deceleration is:

$$\frac{dv}{dt} \simeq 2\frac{GM}{r^2}$$

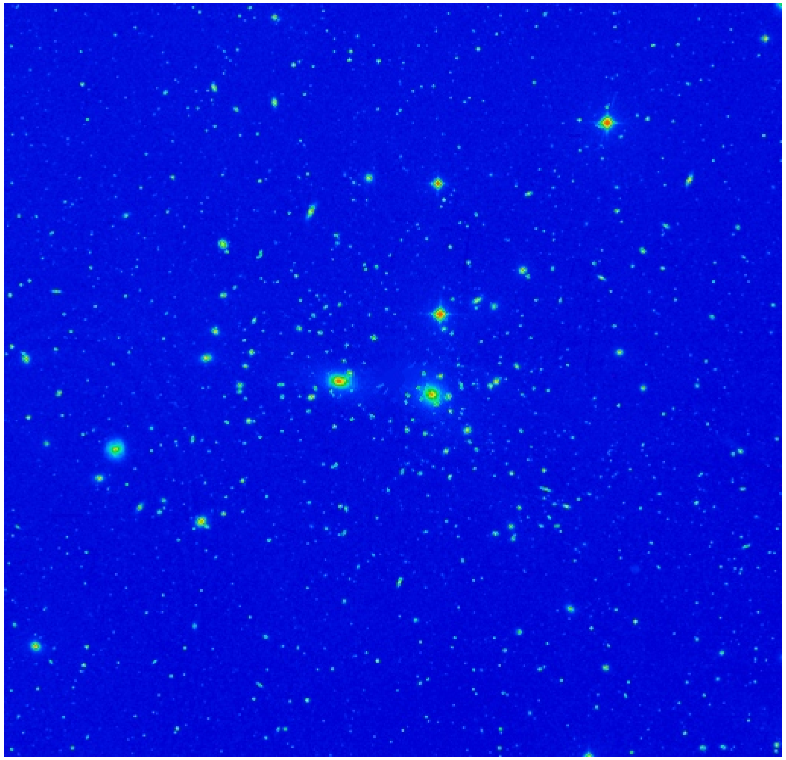
with the mass of the body M and the distance from the center r.

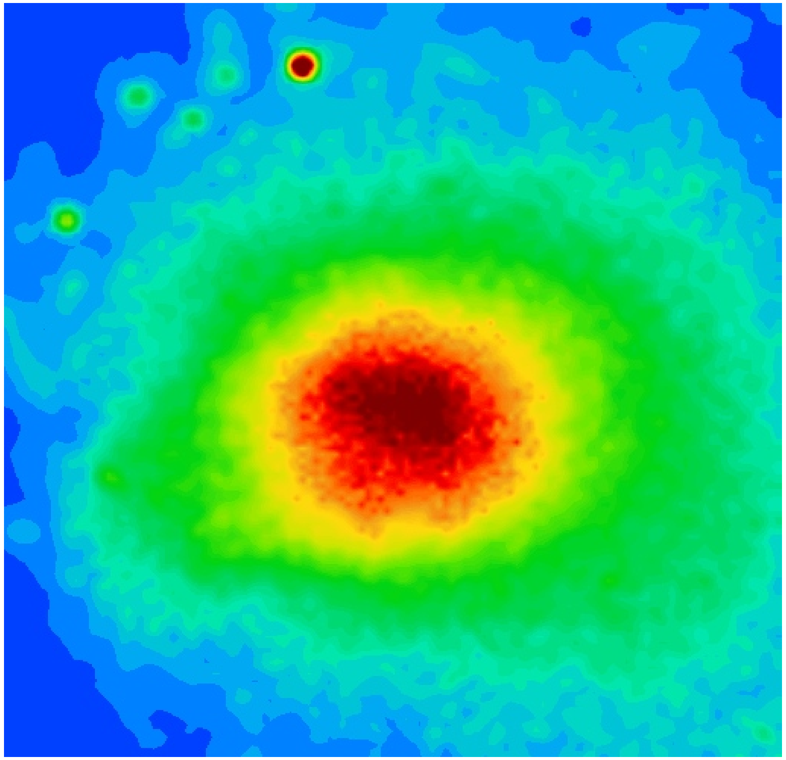
Defining $t_{friction}$: $\frac{v}{t_{friction}} = \frac{dv}{dt}$ yields:

$$t_{friction} \simeq 5 \cdot 10^{13} yrs \frac{(v/(1000km/s)) \cdot (r/Mpc)^2}{M/(10^{10}M_\odot)}$$

$\Rightarrow$ irrelevant for galaxies (maybe except the most massive ones), but not for sub-clumps in clusters.

12.5 X-Ray Gas in Galaxy Clusters





Coma cluster

12.5.1 Properties of the X-Ray Gas

- The first complete sky survey in X-Rays with the Uhuru satellite showed that numerous galaxy clusters have an $L_X \sim 10^{43} - 10^{45} \frac{erg}{s}$.
- The spectra are characteristic of the Bremsstrahlung of a $\sim 10^8 K$ hot gas.

$$\frac{dP}{dV\,dE} = 10^{-11} T^{-1/2} e^{\frac{-E}{kT}} N_e N_Z Z^2 \overline{g} \left[\frac{erg}{cm^3\ s\ erg} \right]$$

$$\overline{g} \sim \ln \frac{T}{E} \quad \text{for } E \ll kT$$

$$\overline{g} \sim \left(\frac{E}{kT} \right)^{-0.4} \quad \text{for } E \simeq kT$$

for several ions $N_e N_Z Z^2$ is replaced by $\sum N_e N_Z Z^2$.
For cosmical abundances applies, integrated over the energy:

$$\frac{dP}{dV} = 2.410^{-27} T^{-1/2} N_e^2 \left[\frac{erg}{cm^3\ s} \right]$$

Cooling time of the plasma:

$$t_{cool} = \frac{3N_e kT}{\frac{dP}{dV}} \simeq \frac{10^{11}}{N_e} T^{1/2}\ [s]$$

Total luminosity for $T \simeq 5 \cdot 10^7$ K ($\simeq 5$ keV):

$$L = \int \frac{dP}{dV} dV \simeq 10^{-23} \int N_e^2 dV \ \left[\frac{erg}{s}\right]$$

E.g. the Coma cluster:

$$L \simeq 10^{44} erg/s \quad (12.1)$$

$$V \simeq (1Mpc)^3 \quad (12.2)$$

$$\Rightarrow \overline{n_e} \simeq 10^{-3} cm^{-3} \quad (12.3)$$

$$\overline{\tau_{cool}} \simeq 10^{10} yrs \quad \text{(smaller at center)} \quad (12.4)$$

$$M_{gas} \simeq 10^{13} M_\odot \quad (12.5)$$

The following correlations are known:

- Central galaxy density higher with higher L_X
- Fraction of spirals lower with higher L_X
- Temperature $\sim L_X$ and of order 10^8K
- Gas metallicity lower with higher T and typically 1/3 of solar or lower
- Gas mass to galaxy mass ratio increases with T up to 5 or more

12.5.2 Cooling Flows

- The cooling time in the cluster is longer than the Hubble time, this does *not* apply in the centers, where $n_e \sim 10^{-2} cm^{-3}$

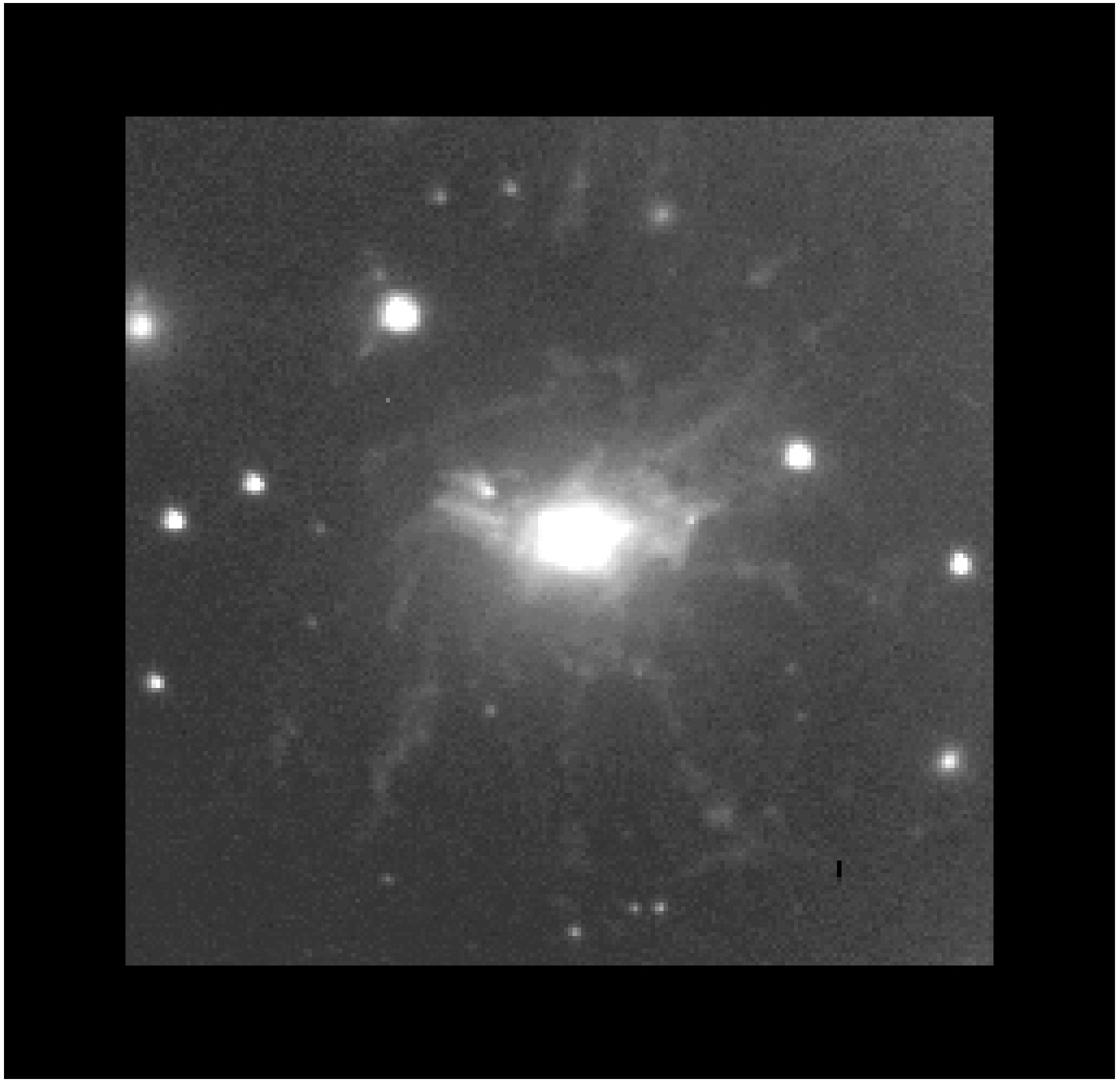
$$\Rightarrow \; t_{cool} \sim 10^9 yrs$$

- Approximations showed that up to

$$\dot{M} = 1000 \frac{M_\odot}{yr}$$

  of gas can cool out of the X-ray halo. This gas can form stars, and indeed many cD galaxies show filaments of gas emission and blue colours in the central region (i.e. young massive stars).

- During the Hubble time a complete cD galaxy could be formed by cooling flows, $\rightarrow$ possible formation scenario for the cD galaxies.
  (Alternatively: Formation by merging of cluster galaxies).



12.6 Masses of Galaxy Clusters

12.6.1 Masses from X-Ray Halo Equilibrium

Similar to the approach used for elliptical galaxies, temperature and density profiles can be used to determine the gravitational acceleration and so thus the mass of the galaxy cluster:

Assuming hydrostatic equilibrium and spherical symmetry:

$$\frac{dP_{gas}}{dr} = -G\frac{M_{tot}(< r)\rho_{gas}(r)}{r^2}$$

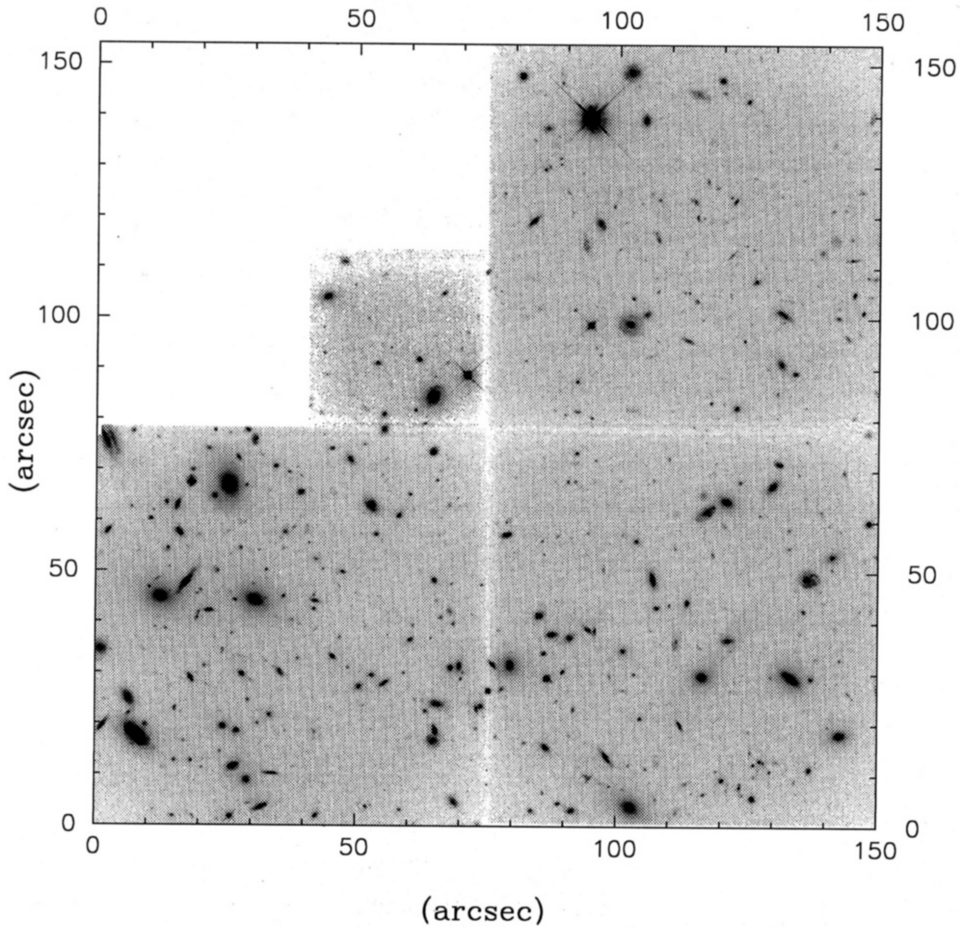
and using the ideal gas equation: $P = \frac{\rho}{\mu m_H}kT$ yields:

$$\frac{GM_{tot}(< r)}{r} = -\frac{kT}{\mu m_H}\underbrace{\left(\frac{d\ln\rho_{gas}}{d\ln r} + \frac{d\ln T}{d\ln r}\right)}_{\simeq\, const\, \simeq\, -2...-1}$$

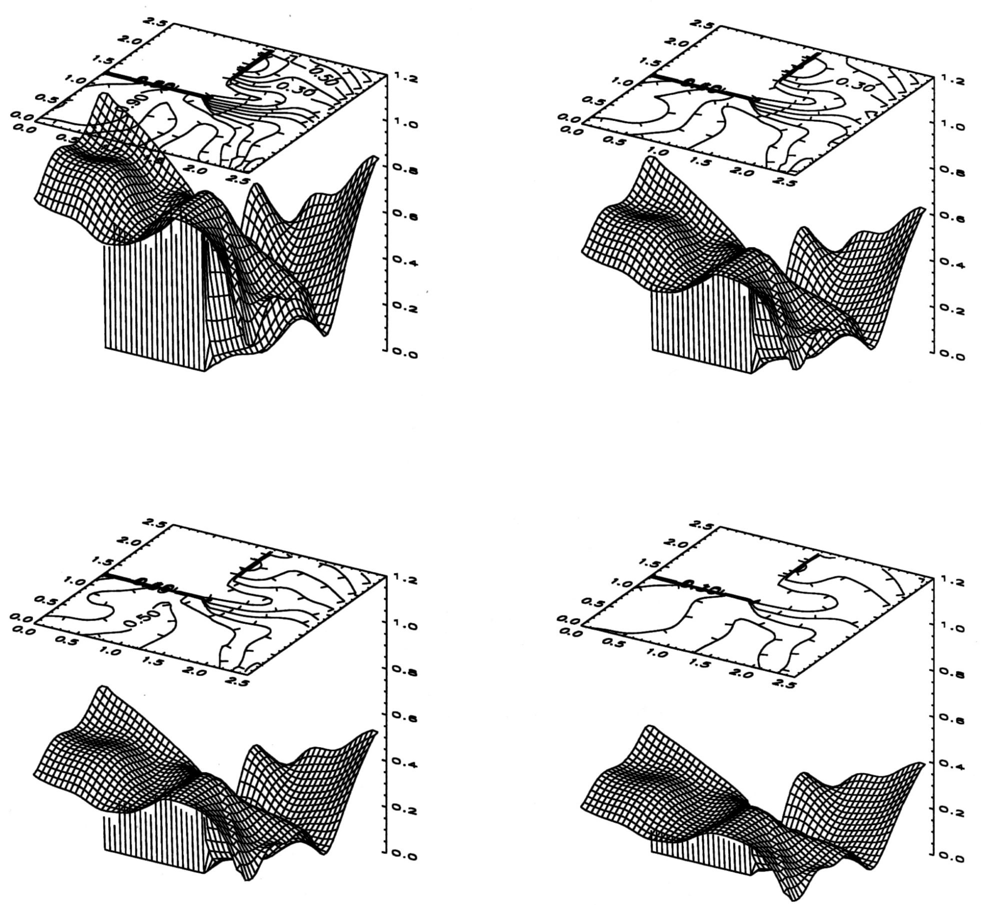
$\Rightarrow$ allows in principal a good determination of the mass (gas has no anisotropy like galaxies but problems may be substructures and nonuniform temperatures).

12.6.2 Masses from Gravitational Lensing

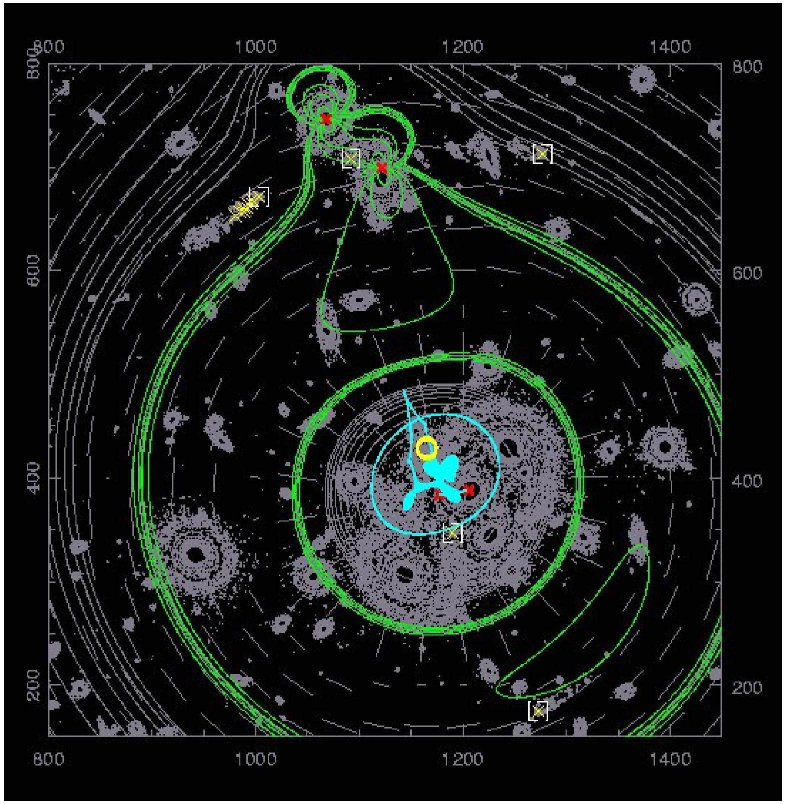
- Galaxy clusters act as gravitational lenses on even more distant background galaxies.
- Shape and radial trend of the weak shear and strong lensing effects yield the cluster mass distribution independent of the nature of the mass and therefore allow reliable total mass estimates including the dark matter.
- Hubble Space Telescope images provide excellent shear maps, though only for small fields. Ground-based results get better and better but require very good observing conditions.
- This technique has become one of the most important methods for the mass determination of galaxy clusters.

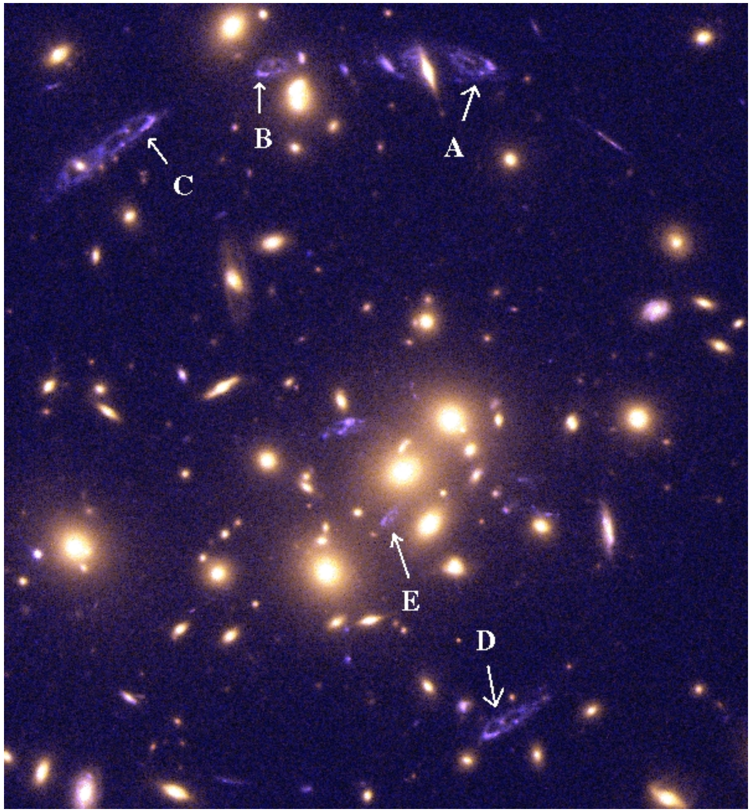


HST image of CL0939+4713, C. Seitz (1996) *PhD Thesis*

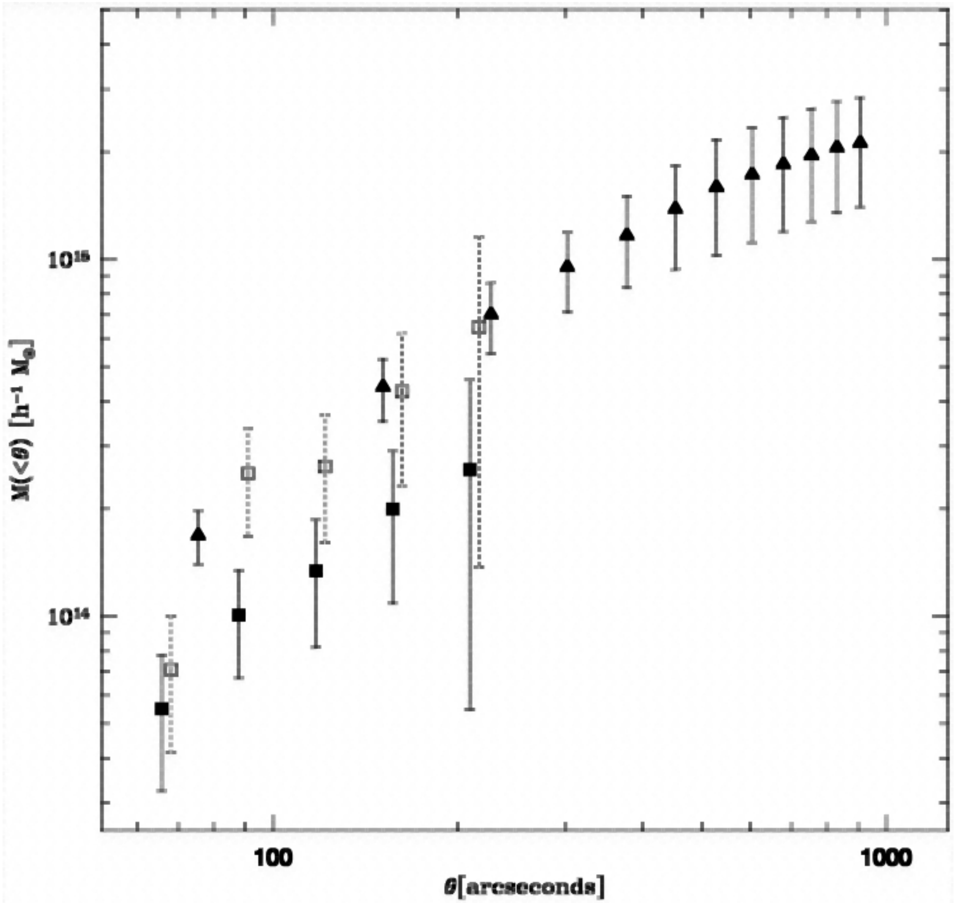


Reconstruction of the projected mass density of CL0939+4713 with weak shear analysis, see: C. Seitz (1996) *PhD Thesis*





Galaxy Cluster Cl0024+1645, strong lensing reconstruction (left, courtesy S. Seitz) of HST image (right, Colless et al.); light blue = caustic structure, bold green = critical lines of 'infinite' amplification, squares = observed positions of multiple imaged source (A,B,C,D,E in color image), yellow crosses = predicted position of the lens model, yellow circle = position of source in source plane, red crosses = mass centers used for the lens model. The caustics are obtained by mapping the critical lines into the source plane.



The radial mass profiles of the galaxy cluster Abell 2163 determined from the X-ray and lensing analysis. The triangles display the total mass profile determined from the X-ray observations. The solid squares are the weak lensing estimates. The open squares are the lensing estimates corrected for the mean surface density in the control annulus determined from the X-ray data.

see: Squires et al. (1997) *ApJ*, **482**, 648

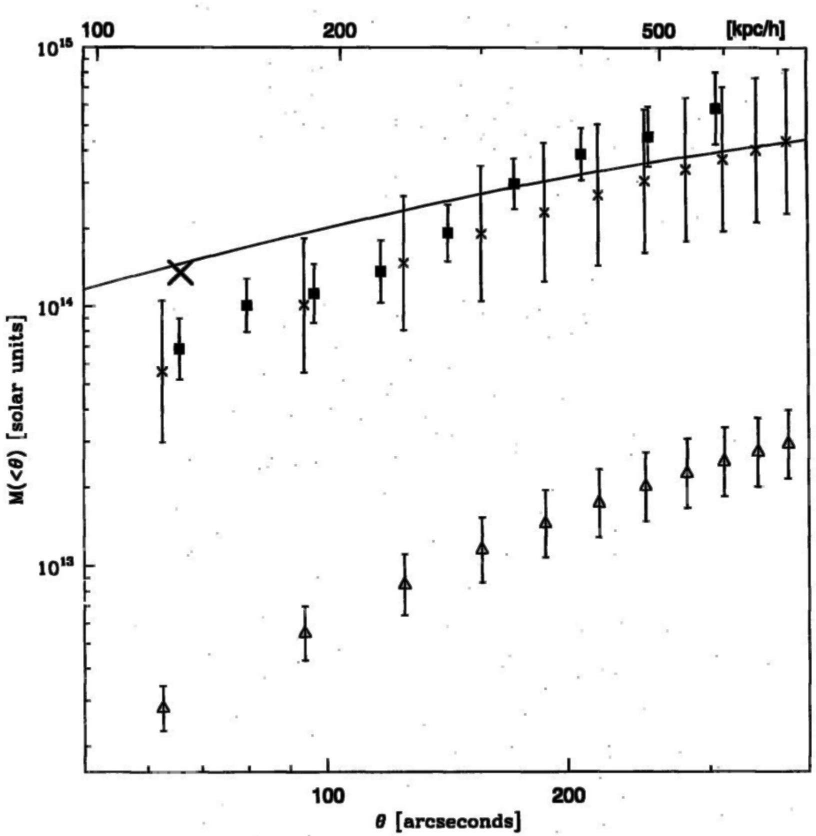


FIG. 18.—The two-dimensional mass profile of the cluster. The filled squares are estimates from the weak lensing. The crosses are total mass determined from the X-ray gas, with the error bars being the 2 σ dispersion calculated from the 10^5 simulations. The open triangles are the corresponding estimates of the projected gas mass. The solid line is the isothermal model with a velocity dispersion of 1370 km s^{-1}, and the large "X" represents the mass computed by Kneib et al. (1995) by modeling the giant arcs.

The two-dimensional mass profile of the cluster Abell 2218

see: Squires et al. (1996) *ApJ*, **461**, 572

12.6.3 Typical Masses of Rich Clusters

	total mass $< 0.5 Mpc$	gas mass $< 0.5 Mpc$
Abell 85	$2 \cdot 10^{14} M_\odot$	$3.4 \cdot 10^{13} M_\odot$
Abell 1795	$2.3 \cdot 10^{14} M_\odot$	$3.6 \cdot 10^{13} M_\odot$
Abell 2255	$3.3 \cdot 10^{14} M_\odot$	$3.5 \cdot 10^{13} M_\odot$
Abell 2256	$6.3 \cdot 10^{14} M_\odot$	$4.1 \cdot 10^{13} M_\odot$

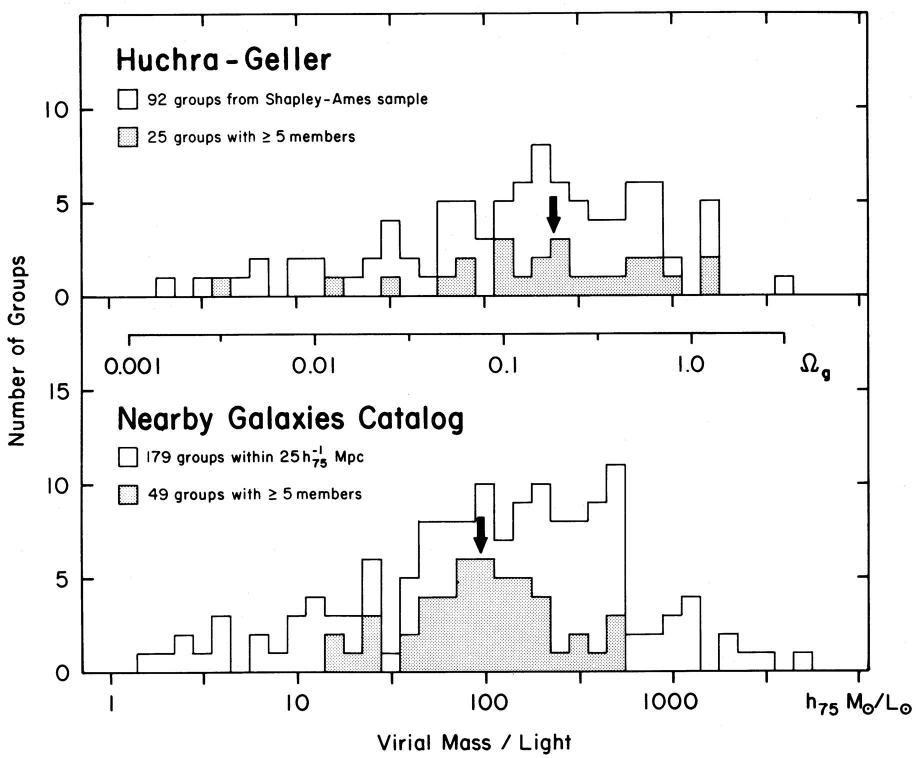
The mass of the gas can be up to five times the mass of the galaxies. However galaxies and gas together only contribute about 20% of the total mass.
$\Rightarrow$ dark matter

$$\frac{M}{L} \text{ of the clusters: } 100 \ldots 500 \frac{M_\odot}{L_\odot}$$

To reach the critical density needed for a flat universe $\frac{M}{L} \sim 1500 \frac{M_\odot}{L_{\odot,B}}$ would be needed.

$\Rightarrow$ If clusters are representative, then the universe is open!
$\Rightarrow \Omega \lesssim 0.25$

12.6.4 Typical Masses of Galaxy Groups



see: Tully (1987) *ApJ*, **321**, 280