XXXII Canary Islands Winter School of Astrophysics

Galaxy clusters in the local Universe

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Introduction

What do we mean by ‘local Universe’?

Introduction

What do we mean by ‘local Universe’: $\mathbf{0 \leq z \leq 1}$

z~0 and z~1 clusters have similar internal structure and dynamics (AB+21).
If clusters form at z~2.5, they are already mature (dynamically speaking) when they are 1/5 of their present age, even if they will grow in mass by x4.

(Figure: young elephants look similar to old elephants, even if their tusks still have to grow)

...higher-z: Giulia and Nina!

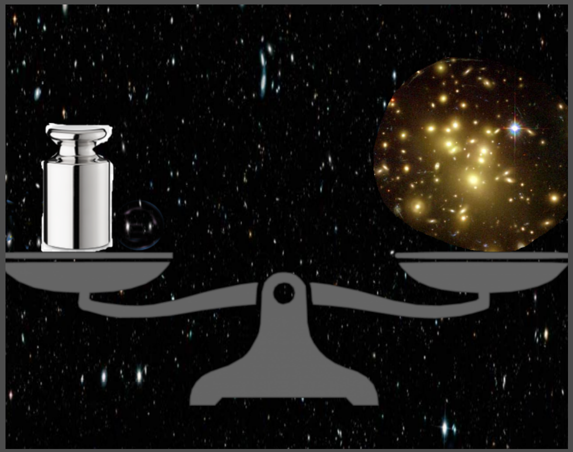
Introduction

What do we need to do cosmology with clusters?

Introduction

What do we need to do cosmology with clusters:

counts, distribution, and **masses**



...cluster counts, distribution: ask Giulia

Masses: using cluster galaxies or ICM as tracers, or via gravitational lensing

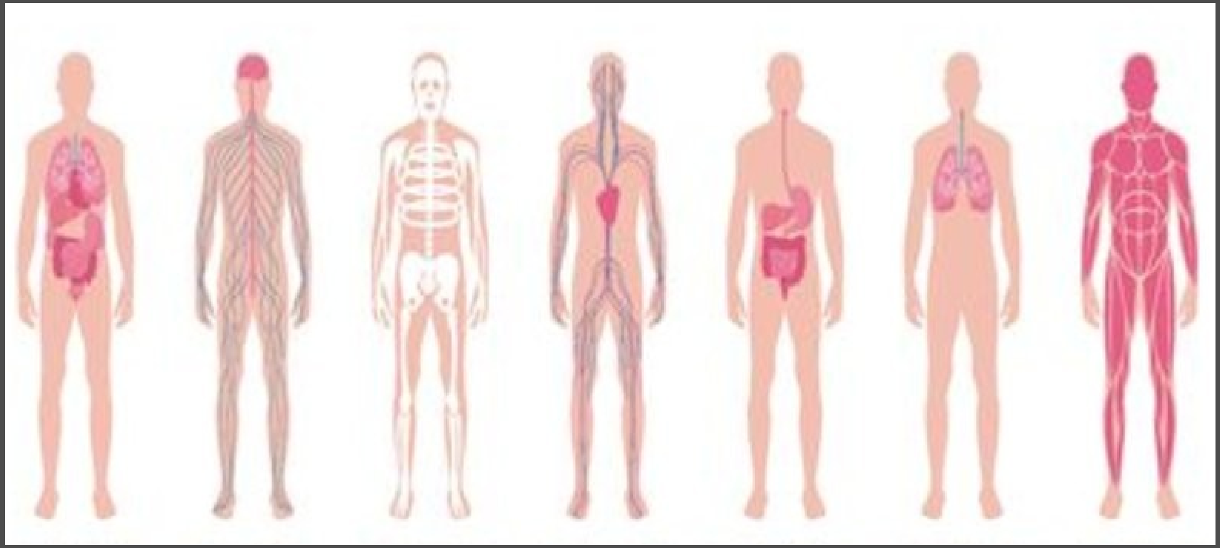
Introduction

What do we need to constrain Dark Matter and gravity?

Introduction

What do we need to constrain Dark Matter and gravity:

internal cluster structure



By comparing the mass distribution of different cluster components we can get insight on the nature of DM (e.g. self-interacting?) and gravity (e.g. MOND?)

Introduction

How do galaxies evolve in clusters?

Introduction

How do galaxies evolve in clusters:

ask *Rhea Silvia, Alessandro, and Emanuele*

...but let us talk about orbits!

Introduction

Structure of my course (*6 hours*):

- Historical notes

- Internal structure (optical, X-ray, radio)

- Probing DM and theories of gravitation with clusters

- Mass and mass profile:

  - ➔ gravitational lensing (GL)
  - ➔ intra-cluster (IC) plasma as tracer
  - ➔ galaxies as tracer
  - ➔ the orbits of galaxies in clusters
  - ➔ comparing mass determinations from GL, IC plasma and galaxies

- The evolution of cluster internal structure from z~0 to z~1

Lecture 1:

Historical notes

Based on:

FROM MESSIER TO ABELL:
200 YEARS OF SCIENCE WITH GALAXY CLUSTERS

Andrea Biviano

available at: http://ned.ipac.caltech.edu/level5/Biviano2/frames.html

Historical notes

When was the first evidence of clusters of galaxies provided?

Historical notes

When was the first evidence of clusters of galaxies provided:

1784

by ***Charles Messier*** in his
“Catalogue des nébuleuses et des amas d'étoiles que l'on découvre parmi les étoiles fixes, sur l'horizon de Paris”

He described an exceptional concentration of nebulæ in the constellation of Virgo.

The discovery of the Coma cluster of galaxies (nebulæ) by ***William Herschel*** was described in 1785, in his *“On the Construction of the Heavens”*, followed by other discoveries (Leo, Ursa Major, Hydra). His son, *John Herschel*, discovered the Fornax cluster in the southern emisphere and hinted at the existence of the Local Supercluster.

In 1927 *Knut Lundmark* wrote: *“The most characteristic feature in the charts of the nebular distribution is the clustering tendency”*.

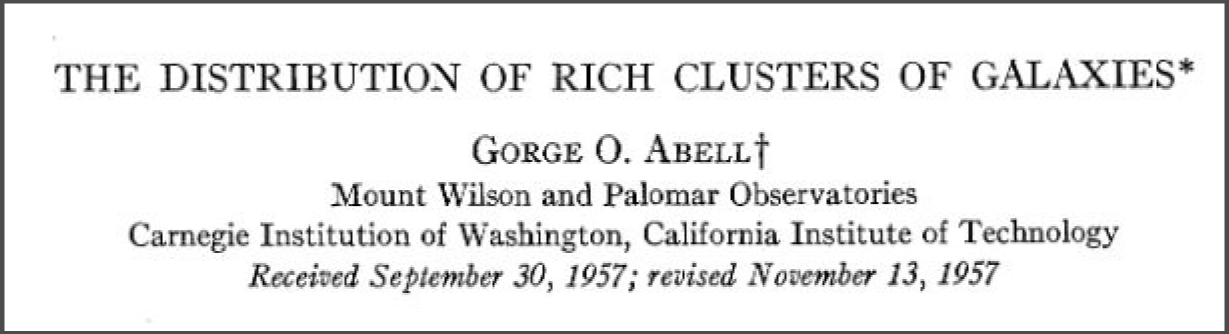
Historical notes

Who is this guy?

Historical notes

Who is this guy: *George O. Abell*

He published the first catalog of clusters of galaxies in 1958



THE DISTRIBUTION OF RICH CLUSTERS OF GALAXIES*

GORGE O. ABELL†

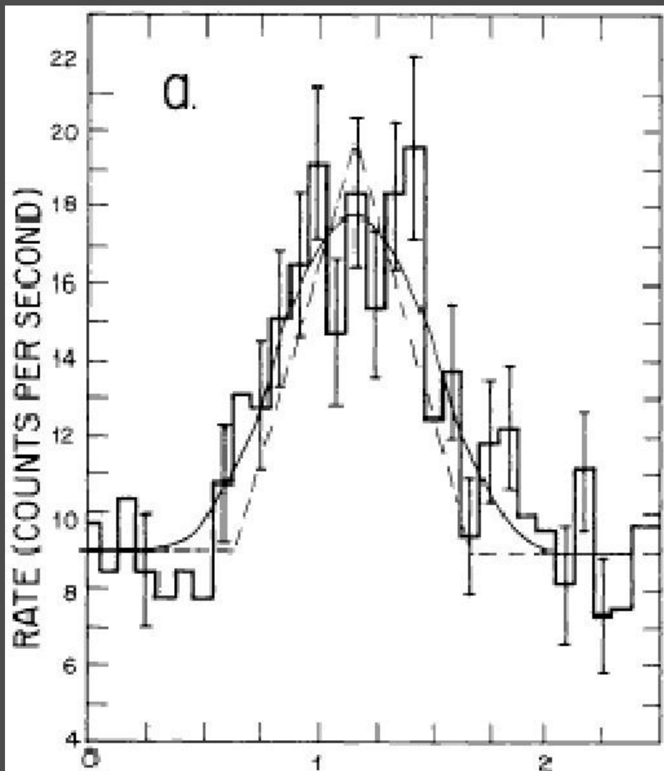
Mount Wilson and Palomar Observatories

Carnegie Institution of Washington, California Institute of Technology

Received September 30, 1957; revised November 13, 1957

Where he also defined a characteristic cluster radius, now known as the Abell's radius, 2.14/h_{70} Mpc, he introduced the concept of cluster richness (the number of galaxies per cluster down to a given magnitude and within a given radius), and the concept of completeness of a cluster catalog as a function of richness, paving the way to the use of clusters in cosmology.

Historical notes



Gursky+71: counts as a f(position), solid curve
fits the data, dashed curve as expected for a pt sce

1971: *Gursky et al.* and *Meekins et al.* detect X-ray extended emission from the Coma cluster

Starting the era of X-ray surveys of clusters of galaxies

Session 68: Clusters of Galaxies
2:50–4:20 (Room C-112)

68.01
Giant Luminous Arcs in Galaxy Clusters

R. Lynds (KPNO/NOAO), V. Petrosian (Stanford U.)

We announce the existence of a hitherto unknown type of spatially coherent extragalactic structure having, in the two most compelling known examples, the common properties: location in clusters of galaxies, narrow arc-like shape, enormous length, and situation of center of curvature toward both a cD galaxy and the apparent center of gravity of the cluster. The arcs are in excess of 100 Kpc in length, have luminosities roughly comparable with those of giant E galaxies, and are distinctly bluer than E galaxies - especially so in one case. Interpretations of the nature of the arcs are discussed within the framework of available data.

1985: *Lynds & Petrosian* detect gravitational arcs in two clusters

Starting the era of gravitational lensing studies of clusters of galaxies

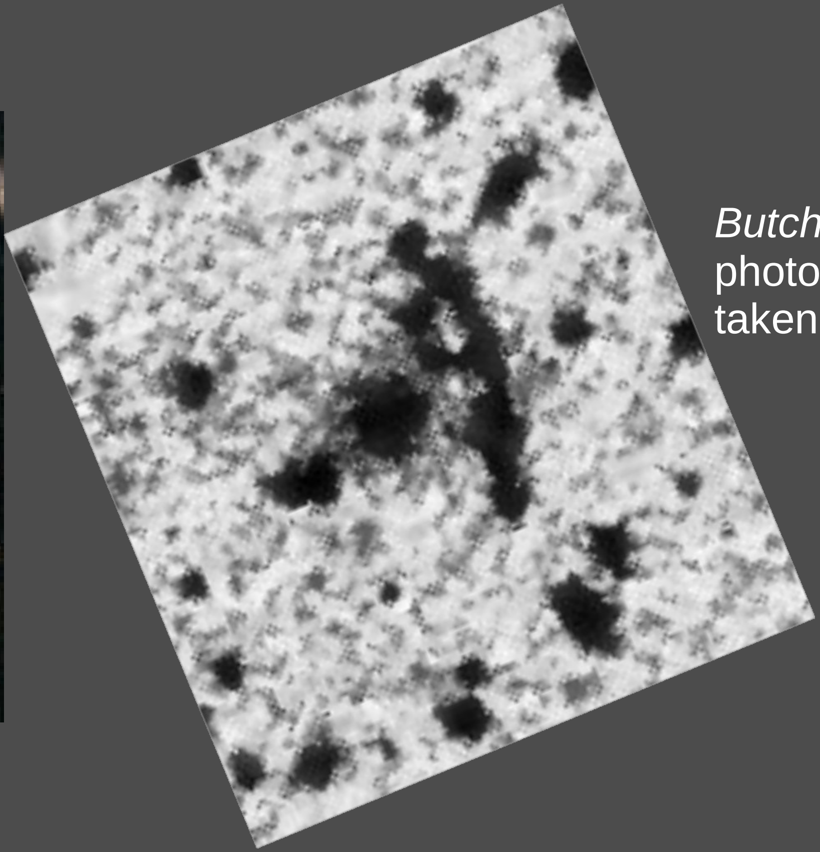
Historical notes

1985: *Lynds+Petrosian* detect gravitational arcs in two clusters

Starting the era of gravitational lensing studies of clusters of galaxies

...but the discovery could have been made earlier:

A370: HST



Butcher+Omler (1983):
photographic plate
taken at 4 m telescope

Historical notes

The content of clusters of galaxies: galaxies

"The predominance of early types is a conspicuous feature of clusters in general"

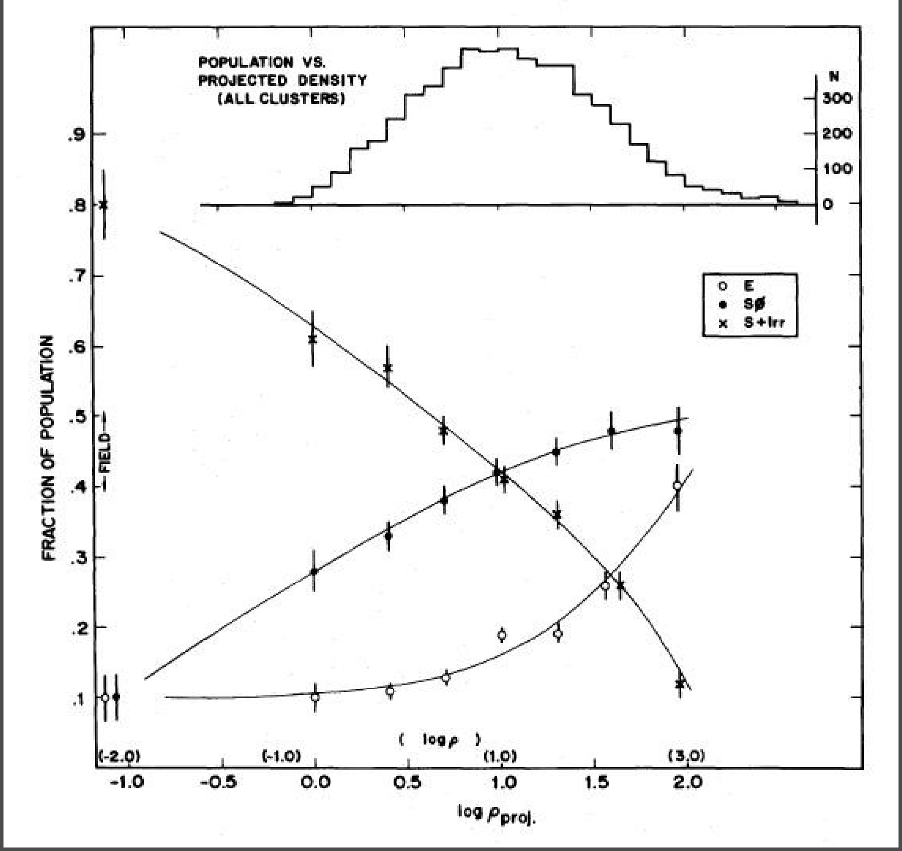
Who wrote this sentence and when?

Historical notes

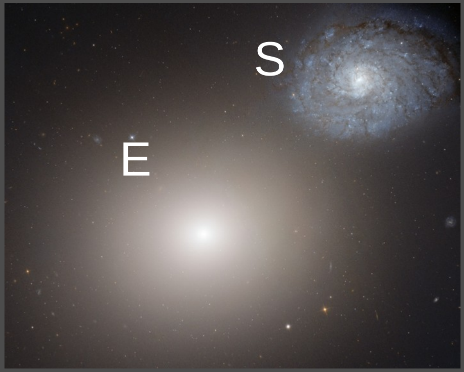
The content of clusters of galaxies: galaxies

Hubble & Humason 1931:
"The predominance of early types is a conspicuous feature of clusters in general"

The prevalence of early-type galaxies in clusters was already noted before
(e.g. by *H. Shapley, 1926*)



The density dependence of the morphological type of population was put on a quantitative solid basis by ***Dressler*** *(1980)*:



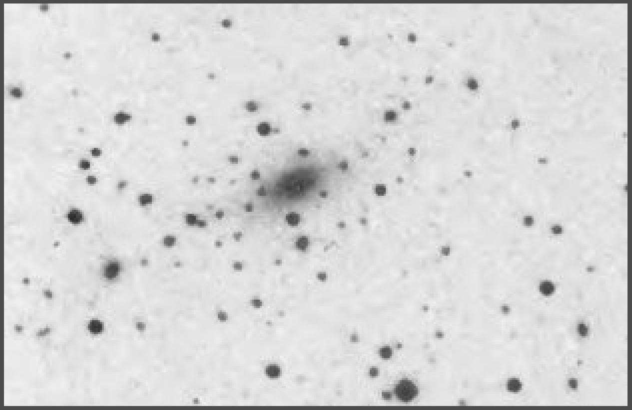
Historical notes

The content of clusters of galaxies: galaxies

Early- and late-type galaxies in clusters not only have ≠ spatial distributions but also **≠ velocity distributions**: the first evidence dates back to *Holmberg (1940)*

The **red sequence** of cluster galaxies was discovered by *Baum (1959)*.

The **cD galaxies** (or Brightest Cluster Galaxies, **BCG**s) were first identified as optical counterparts of radio-galaxies (*Matthews, Morgan & Schmidt 1965*): an extreme example of the morphology-density relation (they are located at the cluster centers)



A2029: Palomar Observatory Sky Survey,

Sloan Digital Sky Survey

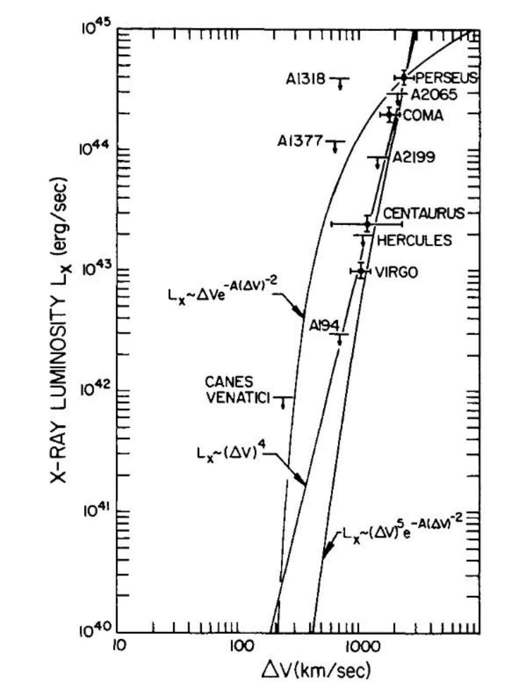
Cluster spirals differ from the general population of field spirals:
Holmberg (1958): **redder spirals;** *Davies & Lewis (1973)*: **HI-deficient spirals**)

Historical notes

The content of clusters of galaxies: the intra-cluster medium

Large et al. (1959): first cluster radio halo detected (at 408 MHz)

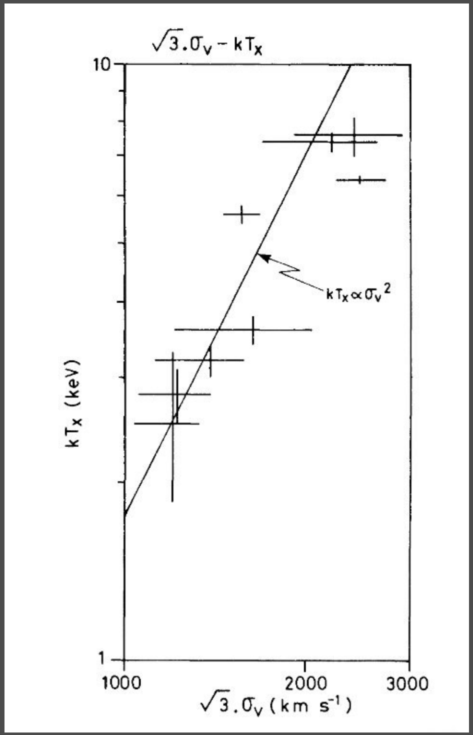
Gursky et al. (1972): *“most, if not all, rich clusters include an X-ray emission region of large size”*



Solinger & Tucker (1972):
L_x – velocity dispersion correlation

Mitchell et al. (1977):
T_x – velocity dispersion correlation

starting the era of X-ray determination of cluster masses



The intra-cluster gas detection by the Sunyaev-Zel’dovich effect will have to await until 1984 (*Birkinshaw et al.*), after many spurious claims

Historical notes

The structure of clusters of galaxies

- *Zwicky (1937)*: the distribution of galaxies in the Coma cluster is similar to the distribution of stars in elliptical galaxies. ***de Vaucouleurs**’ (1948)* showed his model for the elliptical galaxy surface brightness profile also fits cluster galaxy number density profiles:

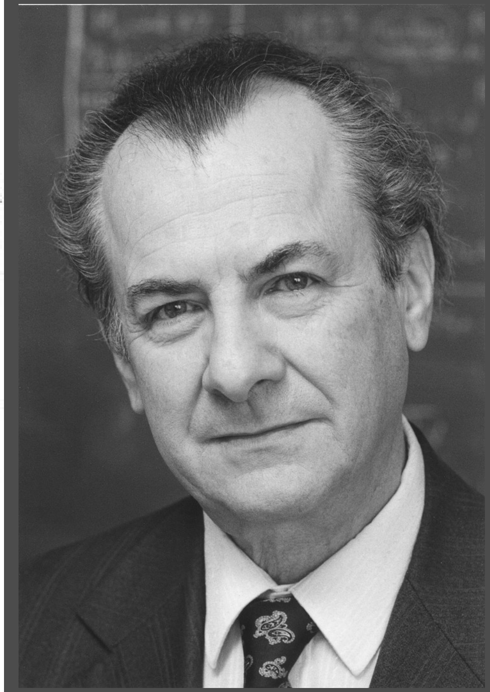
ASTROPHYSIQUE. — *Sur une analogie de structure remarquable entre les nébuleuses elliptiques et les amas de nébuleuses extragalactiques.* Note (*) de M. Gérard de Vaucouleurs, présentée par M. André Danjon.

J’ai précédemment (1) indiqué que la distribution de la luminosité dans les nébuleuses elliptiques est très bien représentée par une relation de la forme

(1) $$\log \mathcal{B} = -A(\alpha^{1/4} - 1),$$

avec $A = 3{,}25$, si l’on pose $\mathcal{B} = B/B_e$ et $\alpha = a/a_e$, B_e étant la brillance correspondant au demi-grand axe *effectif* a_e.

La même formule représente également bien, et avec un coefficient A très voisin, la distribution des nébuleuses dans les amas sphéroïdaux de nébuleuses extragalactiques, si l’on pose de même $\mathcal{N} = n/n_e$, n_e étant la densité nébulaire superficielle dans l’amas à la distance a_e du centre, (rayon du cercle englobant 50 % de la population totale de l’amas), déterminée comme il a été indiqué antérieurement (2).



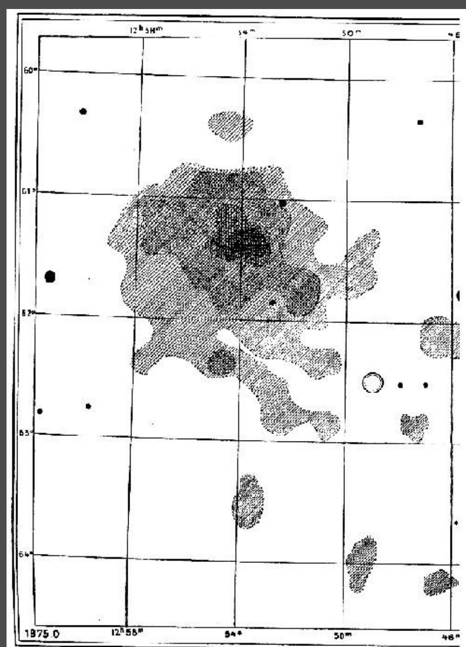
somehow anticipating by half a century the discovery of the universality of halo density profiles by Navarro, Frenk & White (1996, 1997)

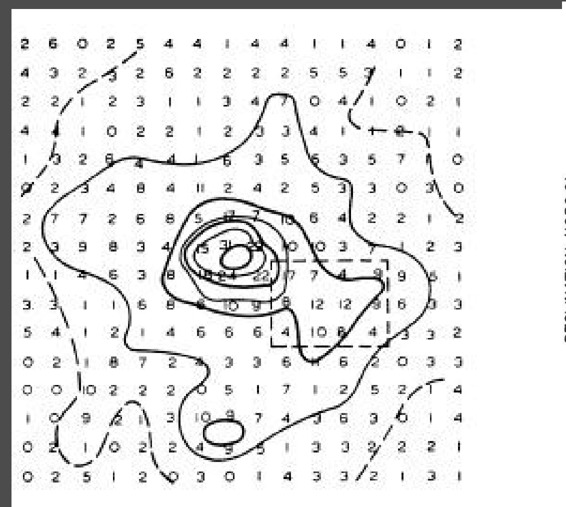
- *Lea et al. (1973)*: the intra-cluster gas is more extended than the galaxies distribution

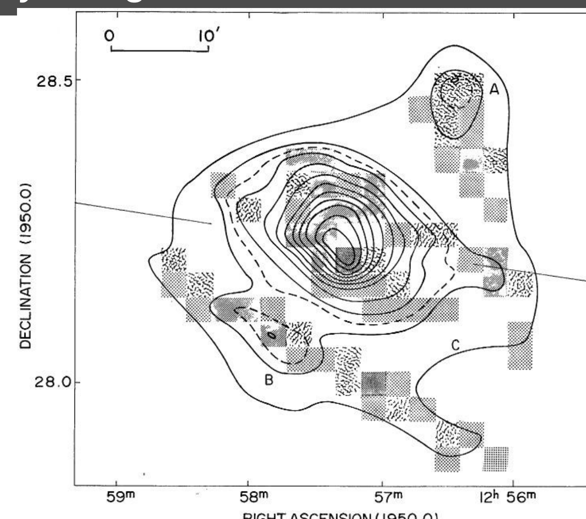
Historical notes

The structure of clusters of galaxies

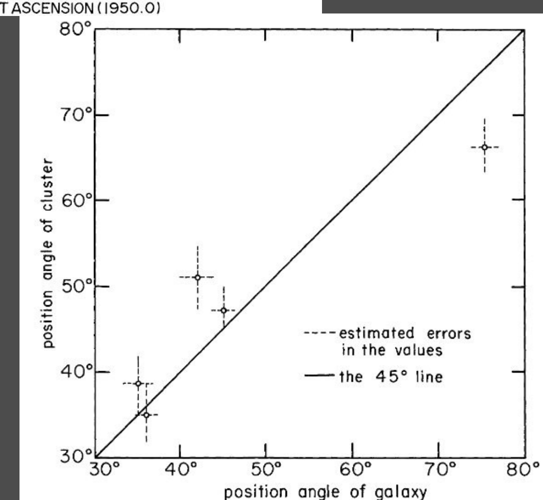
Clusters are not spherical; the elongation of the Coma cluster was already visible in the map of ***Wolf*** *(1901)*, and became more evident in the galaxy maps of ***Shane & Wirtananen*** *(1954)* and, much later on, in the X-ray maps of *Gorenstein et al. (1979)* and ***Johnson et al.*** *(1979)*: the intra-cluster gas shape ≈ cluster shape as traced by the galaxies.







Sastry *(1968)* measured the position angles of 5 clusters and found them to correlate with the position angles of their cD galaxies

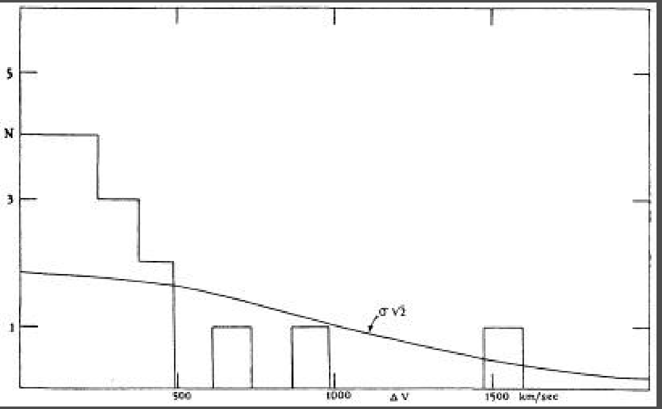


Historical notes

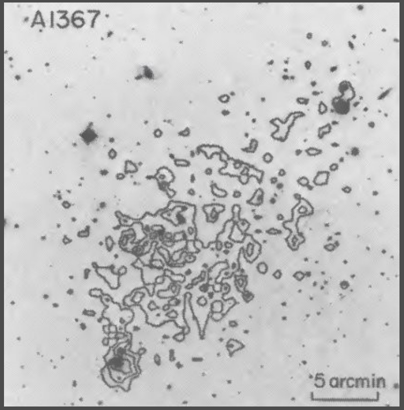
The *sub*-structure of clusters of galaxies

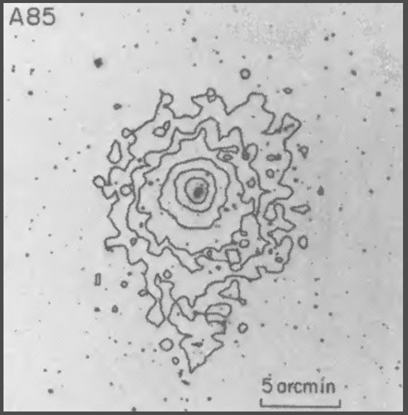
Substructure in the distribution of cluster galaxies was observed early on (*Wolf 1901, Zwicky 1937*), but generally attributed to projection effects (*Shane & Wirtanen 1954*).

Kinematical evidence for sub-clustering in clusters was provided by ***van den Bergh*** *(1960)*, as an excess of small-velocity difference among pairs of galaxies in Virgo and Coma, with respect to that obtained by azimuthal scrambling of the galaxy positions.
His technique anticipated by ~30 years the widely used and still very popular Dressler & Shectman's technique of subclusters identification.



Subclusters became theoretically appealing when *White's (1976)* numerical simulations showed that "clusters form by the progressive amalgamation of an inhomogeneous system of subclusters".





In 1979, X-ray cluster images from the *Einstein* Observatory clearly showed the variety of shapes of different clusters (***Jones et al.***).

That clusters hosting radio-halos were rather peculiar was recognized by *Hanisch (1982)*, but it took 10 years to make the physical association to (sub)clusters mergers (*Tribble 1993*)

Historical notes

Who discovered Dark Matter
(in the modern sense) and when?

Historical notes

Fritz Zwicky discovered Dark Matter in the Coma cluster in 1933

Die Rotverschiebung von extragalaktischen Nebeln
von **F. Zwicky.**
(16. II. 33.)

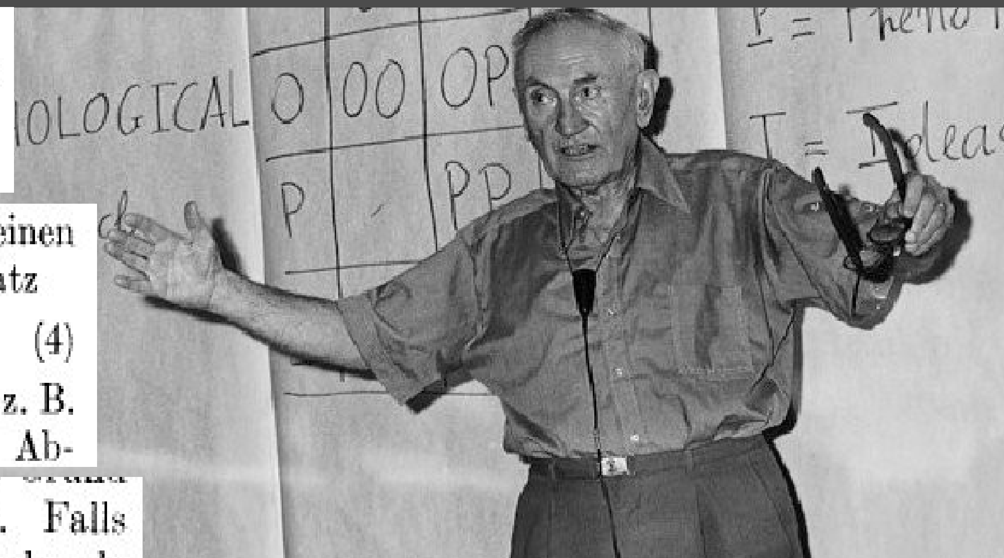
1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

Virial theorem $$\bar{\varepsilon}_k = -\tfrac{1}{2}\,\bar{\varepsilon}_p\,, \qquad (4)$$

wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Ab-

von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Dark matter



Cluster masses are large!

Zwicky applied the virial theorem to the projected phase-space distribution of galaxies in Coma, using the recent observations by Hubble & Humason, finding luminous-virial mass discrepancy. *Smith (1936)* found the same in the Virgo cluster. The first evidence from galaxy rotation curves came later (*Babcock 1939; Roberts 1969*). But it took decades for the Dark Matter hypothesis to become the leading paradigm: *"observations now leaves little doubt of its presence"* (*Gunn 1980*). The "*simplest and most accurate mass determination*" of a cluster would later come from gravitational lensing, as originally suggested by *Zwicky* himself in *1937*!

Historical notes

What is Dark Matter?

- ✗ *Zwicky (1937)*: A failure of Newton's law (and GR … → MOND, *Milgrom 1983*)
- ✗ *Holmberg (1950)*: dwarf galaxies (not enough, Rood et al. 1972)
- ✗ *Zwicky (1952)*: light obscuration by DM explains the inhomogeneity of galaxy distribution
- ✗ *Limber (1959)*: intra-cluster gas; since it is not seen in HI, it could be ionized
- ✗ *Penzias (1961)*: cluster HI mass not enough
- ✗ *Rood (1965)*: DM cannot be entirely in galaxy halos, dynamical friction would be too strong
- ✗ *van den Bergh (1969)*: massive collapsed objects ruled out by limited tidal effects observed
- ✗ *Gursky et al. (1971)*: intra-cluster gas detected in X-ray, not enough
- ✗ *Peebles (1971)*: frozen HI snowballs
- ✗ *Napier & Guthrie (1975)*: 10^{-2} $M_\odot$ black dwarfs (rejected by microlensing surveys MACHOS, EROS)
- ✗ *Thuan & Kormendy (1977)*: diffuse intra-cluster light not enough
- ✗ *Bond et al. (1982)*: Cold Dark Matter

Alan Dressler (1978): "The answer to the mass discrepancy problem awaits more data and more inspiration, not necessarily in that order"