



7-1

Galaxy Groups and Clusters



Stephan's quintet: compact group of galaxies; Credit: ESO



7-2

Observations, I

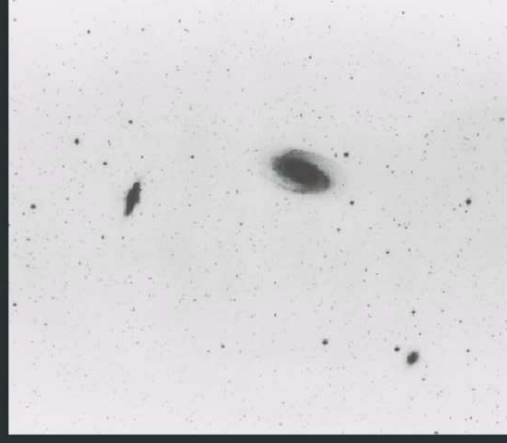
~ 50 % of all galaxies are found in groups and clusters!

Rule of thumb characteristics of groups and clusters:

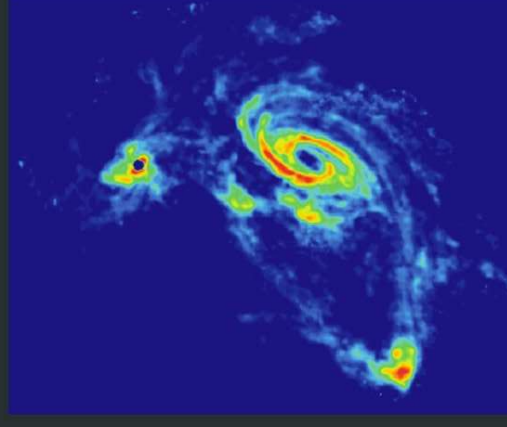
- Ensemble of galaxies packed into $\lesssim 1$ Mpc
- Gravitationally bound
- $M \gtrsim 10^{13} M_{\odot}$ (groups); up to $M \sim 10^{15} M_{\odot}$ for largest clusters
- *Galaxy Groups*: $\lesssim 50$ members, $M \lesssim 10^{14} M_{\odot}$, mostly spirals and irreg. galaxies, about 50 % of all groups contain hot gas ($T > 10^6$ K) that shines at X-rays
- *Galaxy Cluster*: $\gtrsim 50$ members, $M \gtrsim 10^{14} M_{\odot}$, mostly ellipticals and S0 galaxies, most mass in a hot intracluster gas (X-ray emission)
- Cosmologically young structures (see structure formation)

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution



21 cm HI Distribution



Optical DSS image (left), HI VLA image (right); Credit: NRAO/AUI



Classification of Groups and Clusters

First catalog of galaxy clusters: Abell (1958)

- Palomar Observatory Sky Survey (POSS): visual identification; northern sky
- Criteria: > 50 galaxies in brightness range $m_3 < m < m_3 + 2 \text{ mag}$ within 1.5 Mpc of cluster center (m_3 : magnitude of 3rd brightest galaxy)
- Distance estimate based on brightness of 10th-brightest member; $z \lesssim 0.2$
- ~ 4000 Clusters (including southern extension of catalogue, "Abell-Clusters", e.g., A1656=Coma)

Any catalog based on galaxy counts and 2D-density determination, will be incomplete and will contain both foreground and background objects.

Richness classes 1-5: number of galaxies $> 50, > 80, > 130, > 200, > 300$.

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Classification of Groups and Clusters

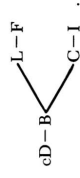
PUB. ASTRON. SOC. PACIFIC, Volume 83, June 1971

"TUNING FORK" CLASSIFICATION OF RICH CLUSTERS OF GALAXIES

HERBERT J. ROOD AND GUMMULURU N. SASTRY
Van Vleck Observatory, Wesleyan University, Middletown, Connecticut

Received 28 December 1970

A classification scheme of rich clusters of galaxies based on the distribution of the ten brightest member galaxies is described. The cluster types, which fall naturally into an ordered sequence with criteria varying systematically from one end to the other, can be represented by a "tuning fork" diagram:



Preliminary types are listed for the 111 Abell clusters with distance classes less than four.
Key words: clusters of galaxies — galaxies

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Coma cluster: prototype for rich clusters; courtesy Jim Misti



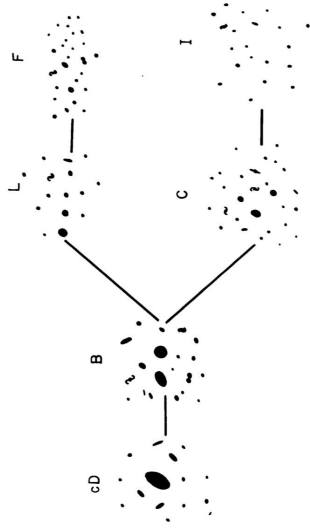
Virgo, A Laboratory for Studying Galaxy Evolution

HI images (VLA) of 47 spiral galaxies in Virgo, overlaid on X-ray image (ROSAT). Galaxy sizes upscaled by a factor of 10.

Most central cluster galaxies have been stripped of their cool HI gas. Interaction with the hot intracluster gas.

Image courtesy of NRAO/AUI and Chung et al., Columbia University

Classification of Groups and Clusters



Rood & Sastry (1971)

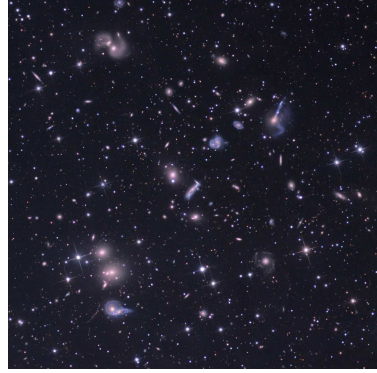
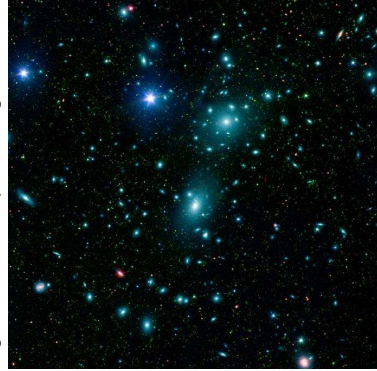
- *cD*: dominated by a central cD galaxy
- *B*: central pair of bright galaxies
- *L*: linear configuration of the dominant galaxies
- *C*: multiple galaxies in one core region
- *F*: flattened configuration of brightest galaxies
- *I*: irregular configuration

Observations and Classification

Classification of Groups and Clusters

Simplified classification:

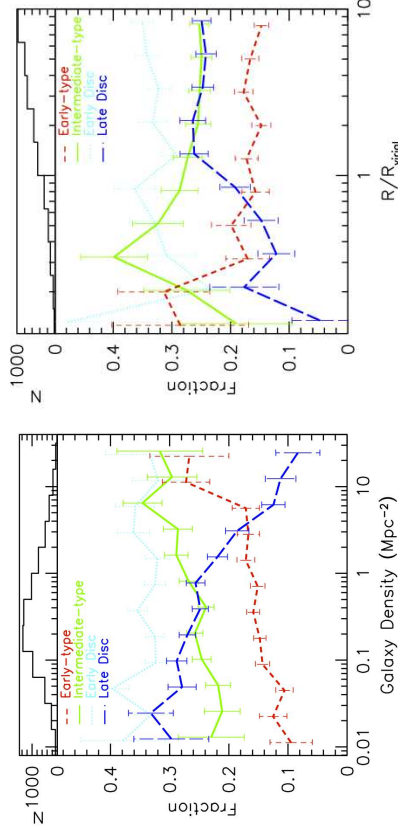
- Regular clusters: compact configuration, mainly elliptical and S0, large richness
- Irregular clusters: open configuration, more spirals, low richness



Coma cluster (left): NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.; Hercules cluster (right): Tony Hallas

Observations and Classification

Classification of Groups and Clusters



Goto et al. (2003)

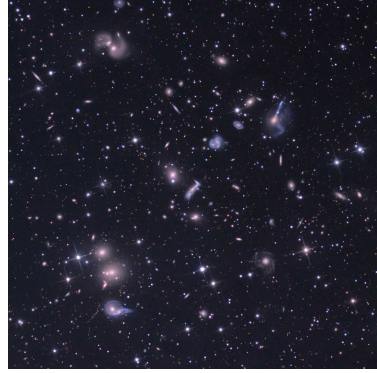
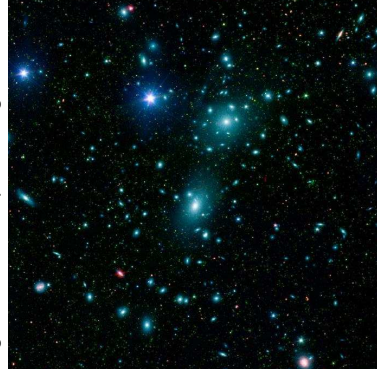
Local galaxy density determines morphological galaxy mixture!

Observations and Classification

Classification of Groups and Clusters

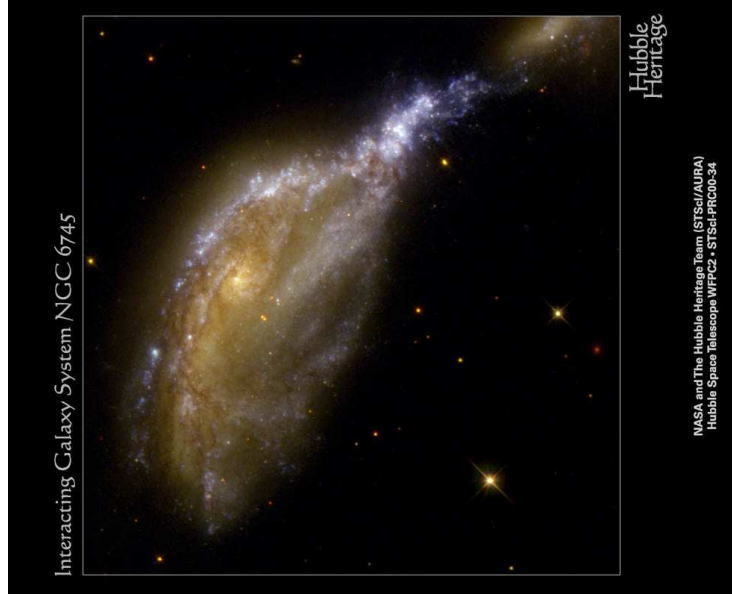
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Observations and Classification



Interacting Galaxy System NGC 6745

Hubble Heritage

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFP02 - STScI-PRC00-34

**Dynamical Friction, IV**

$$\Delta v_{\perp} = \int \frac{Gmb}{(b^2 + v^2 t^2)^{3/2}} dt = \frac{2Gm}{bv} \quad (7.3)$$

The faster the galaxies move, the smaller the velocity change.

This calculation assumes that the galaxies are much smaller than b and that we have a rapid flyby, i.e., M and m do not move during the encounter.

The star m gains an equal and opposite momentum, so the total energy transferred into perpendicular motion is:

$$\Delta E_{\text{kin},\perp} = \frac{M}{2} \left(\frac{2Gm}{bv} \right)^2 + \frac{m}{2} \left(\frac{2GM}{bv} \right)^2 = \frac{2G^2 m M (M + m)}{b^2 v^2} \quad (7.4)$$

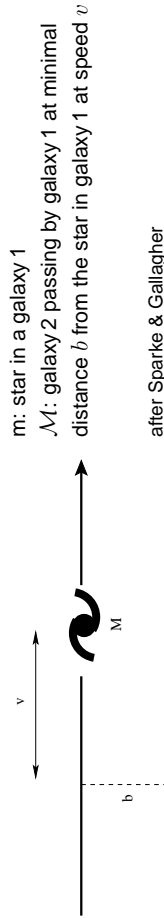
The object of the smaller mass (here: the star) acquires most of the energy. The object with the higher mass (the galaxy) is slowed down in v_{\parallel} .

Galaxy Interactions and Mergers

**Dynamical Friction, III**

What happens when two galaxies in a group or cluster pass close to one another?

Part of their energy of motion is transferred to motion of individual stars. The interacting galaxies are slowed down and may eventually merge.



Perpendicular force:

$$\mathbf{F}_{\perp} = \frac{GmM}{(b^2 + v^2 t^2)^{3/2}} = M \frac{dv_{\perp}}{dt} \quad (7.1)$$

Integrating over time gives:

$$\Delta v_{\perp} = M^{-1} \int \mathbf{F}_{\perp}(t) dt \quad (7.2)$$

Galaxy Interactions and Mergers



The Mice (NGC 4676); Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA

**Dynamical Friction, V**

Long before and long after the encounter, the potential energy is small and the energy equation can be expressed solely with the various terms of the kinetic energies:

$$\frac{M}{2} v^2 = \Delta E_{\text{kin},\perp} + \frac{M}{2} (v + \Delta v_{\parallel})^2 + \frac{m}{2} \left(\frac{M}{m} \Delta v_{\parallel} \right)^2 \quad (7.5)$$

If $\Delta v_{\parallel} \ll v$, the quadratic terms can be dropped:

$$\Delta v_{\parallel} \approx - \frac{\Delta E_{\text{kin},\perp}}{Mv} = - \frac{2G^2 m (M + m)}{b^2 v^3} \quad (7.6)$$

Finally, integrate over all stars in galaxy 2 (n stars of mass m):

$$\frac{dv}{dt} = - \int n v \frac{2G^2 m (M + m)}{b^2 v^3} 2\pi b db = - \frac{4\pi G^2 (M + m)}{v^2} n m \ln \Lambda \quad (7.7)$$

with $\Lambda = b_{\text{max}}/b_{\text{min}}$.

Deceleration of galaxy 2 by the stars of galaxy 1: dynamical friction.

Galaxy Interactions and Mergers

Dynamical Friction, VI

Eq.7.7 shows that the slower M moves, the larger is its deceleration.

- Once v falls below the velocity dispersion of stars, $dv/dt \propto -v$ (Stokes' law). According to Eq.7.7, massive galaxies are slowed more quickly than small ones \Rightarrow the LMC is likely to merge with the Milky Way in a few gigayears, while most globular clusters are in no danger.
- Galaxy encounters transfer bulk kinetic energy into internal kinetic energy \Rightarrow the system is less strongly bound and expands. Stars can escape from their galaxy and in disk systems, the stellar disks are thickened.
 - High velocities in clusters prevent the galaxies from merging. Almost all mergers are observed in groups.
 - As we saw before, close encounters can trigger bar formation and force gas towards the galaxy center to fuel an active nucleus. Both NGC 7319 in Stephan's Quintet and M81 are Seyfert galaxies.

Galaxy Interactions and Mergers

Dynamical Friction, VII

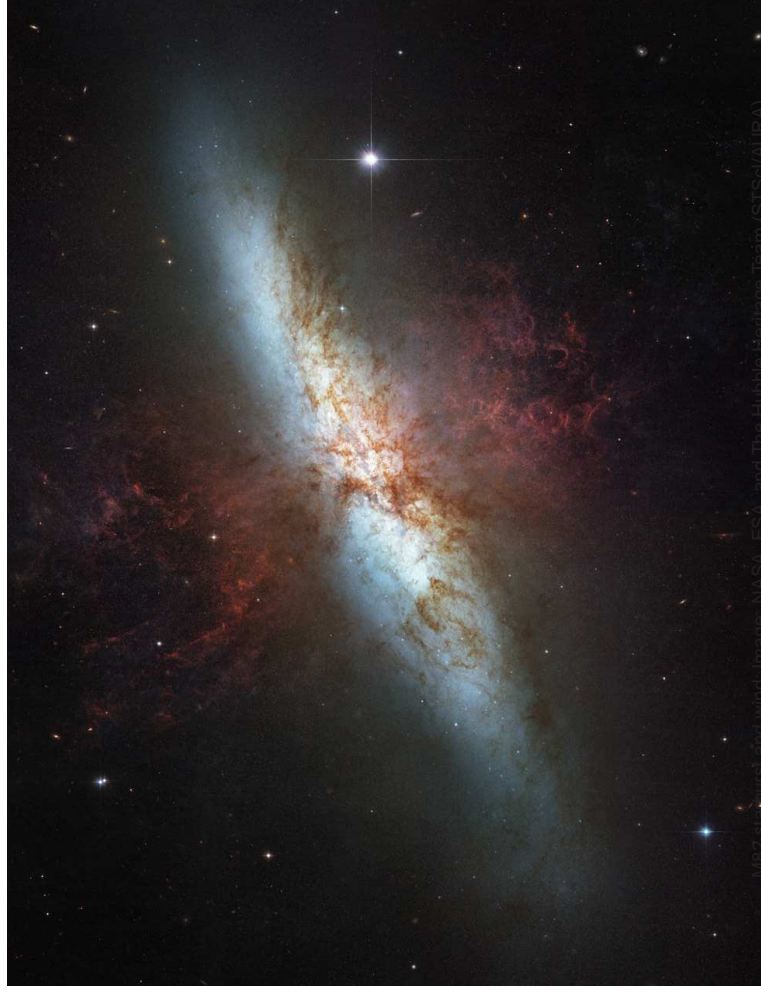


Movie time: http://www.nicolascrutton.ch/Astronomy/Galaxies/Galaxy_mergers/Mice_long.mpg

Galaxy Interactions and Mergers



M81 and M82; Image: Johannes Schedler (Panther Observatory)



M82; Images and World Image NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



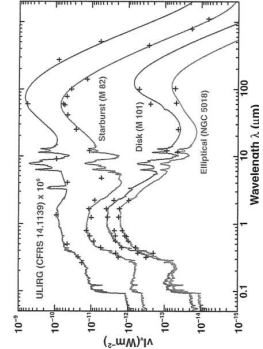
Observations, I

- 1965: M87 is first extragalactic source detected in X-rays
- 1969: Perseus clusters detected
- 1973-1975: UHURU detects emission from many clusters
- 1979: HEAO-1: Spectra: optically thin radiation
- 1984: Einstein: imaging and high resolution spectra
- 1990: ROSAT: Emission from essentially all clusters
- 1990: ASCA: high resolution spectra
- 2000: XMM-Newton/Chandra: high resolution spectra, imaging,...



Starbursts

Starbursts: Stars form so rapidly as to exhaust the gas supply within a few hundred million years.



Sparke & Gallagher Fig 7.7

- Primary (blue) light of newborn stars largely absorbed by dust
- Re-emitted in the IR
- Even more extreme: Ultraluminous infrared galaxies (ULIRGs)
- In almost all cases triggered by interactions of gas-rich galaxies
- Star formation rate: $\frac{SFR}{M_{\odot}/yr} \approx \frac{L_{IR}}{6 \times 10^9 L_{\odot}}$
 \Rightarrow up to $1000 M_{\odot}/yr$



Observations, II

X-ray astronomy has shown that galaxy clusters are the brightest X-ray sources in the sky (next to AGN). In contrast to AGN, the emission is resolved by modern X-ray telescopes and may be difficult to detect in small field-of-view observations.

In the richest systems, there is 10 times more mass in hot gas than in stars!

- The hot gas fills the whole cluster and can be traced to larger radii than the stellar light.
- Possible ways to add energy to the intracluster gas:
 - Starbursts (see, e.g., Chandra image of M82.)
 - AGN and jets



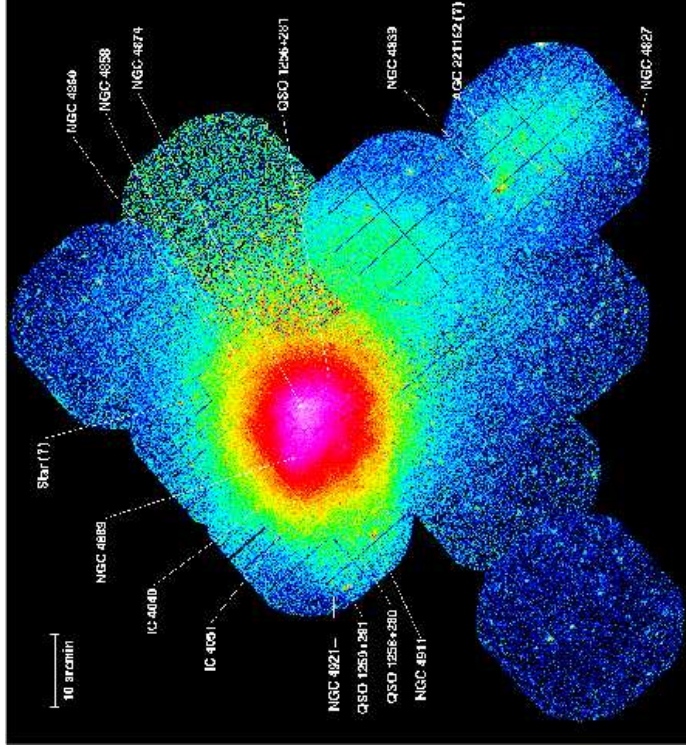
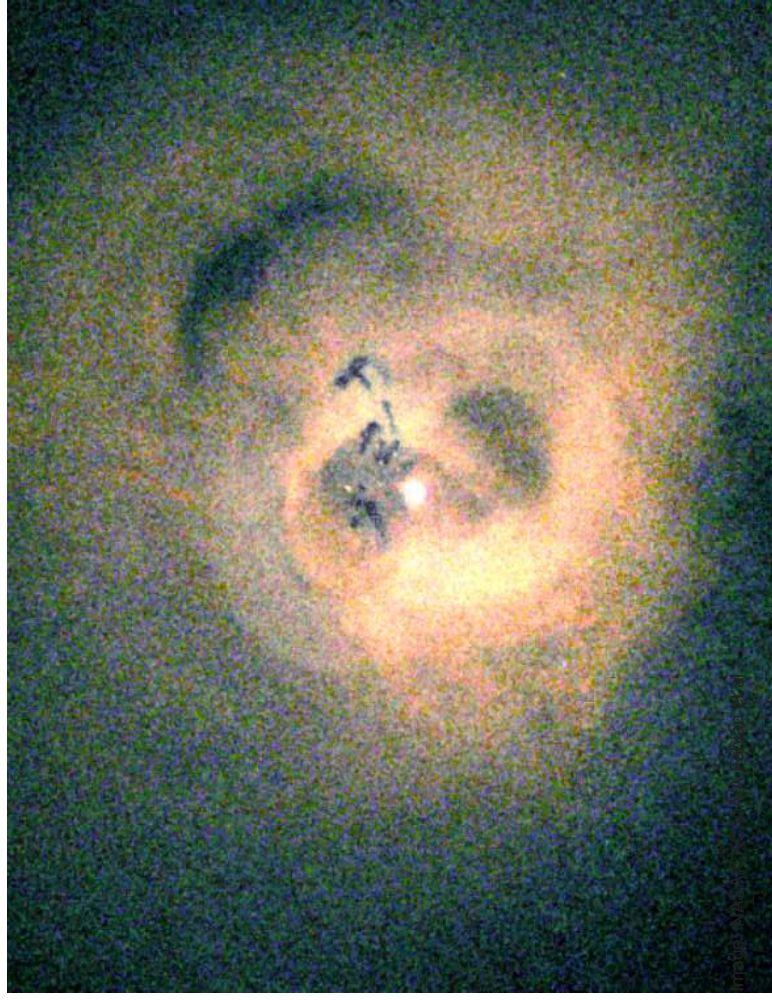
Cooling Flows

X-ray emission is a very efficient way of cooling the intracluster gas (radiate away its energy). This effect should be strongest at the cluster centers. Pressure of the outer (hotter) regions should drive material inward \Rightarrow Cooling Flow.
 Cool gas should trigger massive star formation.

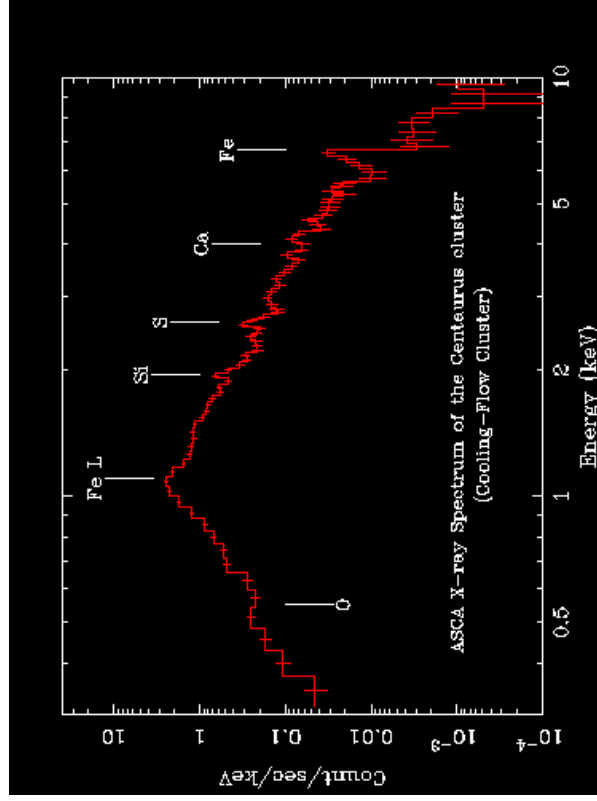
There is little evidence for cool X-ray emitting gas nor for massive starbursts in cluster centers \Rightarrow Cooling Flow Problem \Rightarrow Gas must be re-heated.

The currently favored model for the heating involves AGN feedback (Example: Perseus cluster).

Hot Gas in Galaxy Clusters



XMM-Newton mosaic of the Coma cluster



First seen with Einstein: Cluster gas emits $K\alpha$ lines from highly ionized Mg, Si, S, Fe, etc.
 No primordial gas!

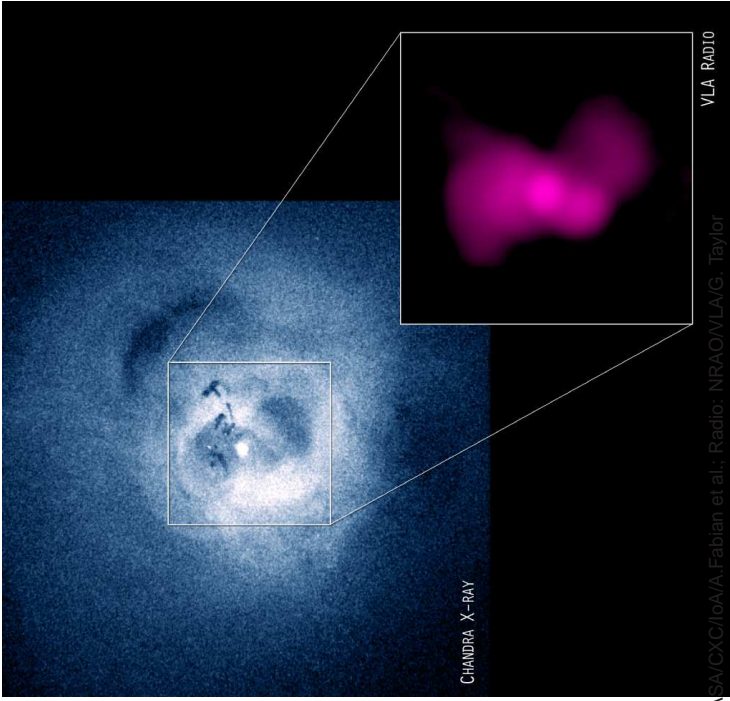


Image: X-ray: NASA/CXC/Ia/A.Fabian et al.; Radio: NRAO/VLA/G. Taylor