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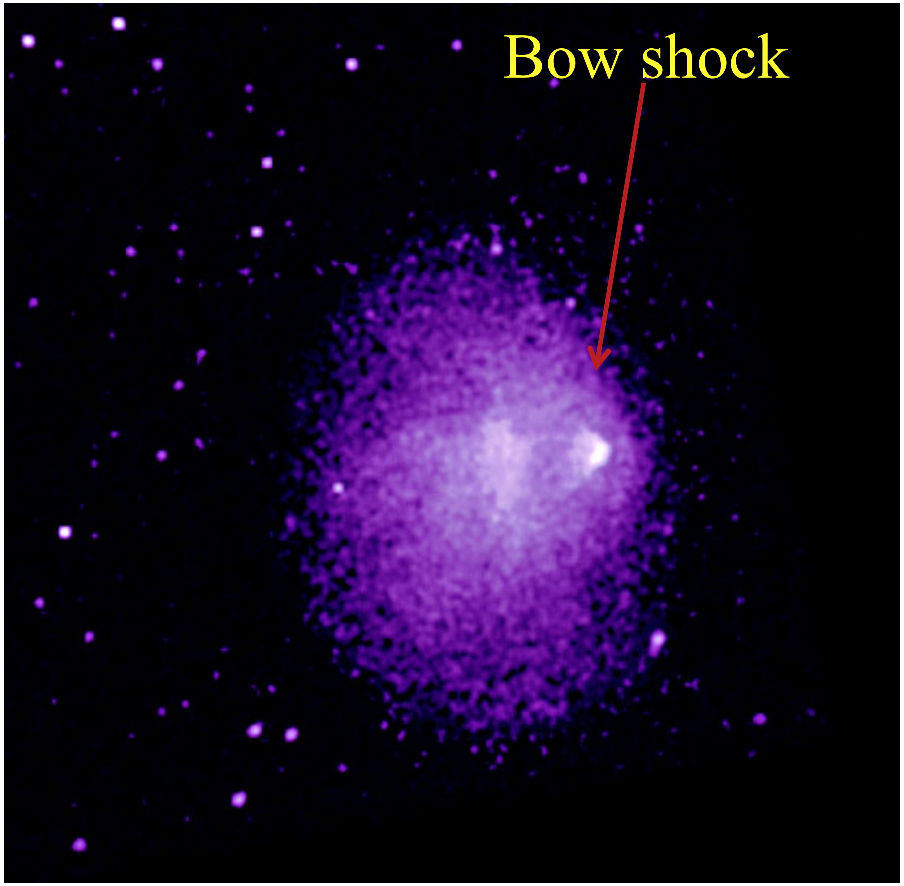
Galaxy Clusters: Contents

Hot X-ray Gas in Clusters

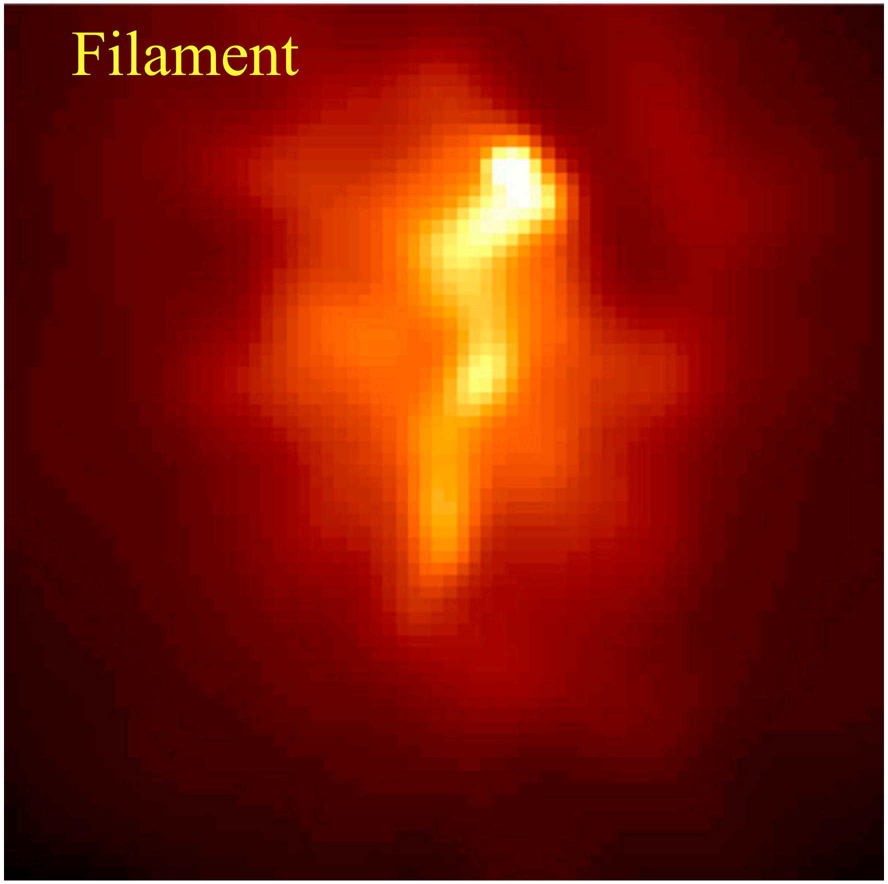
- Virial equilibrium temperature $T \sim 10^7 - 10^8$ K, so emission is from free-free emission
- Many distant clusters are now being discovered via x-ray surveys
- Temperatures are not uniform, we see patches of "hot spots" which are not obviously associated with galaxies. May have been heated as smaller galaxies (or clumps of galaxies) fell into the cluster
- In densest regions, gas may cool and sink toward the cluster center as a "cooling flow"
- Unlikely that all of it has escaped from galaxies, some must be around from cluster formation process. It is heated via shocks as the gas falls into the cluster potential
- But some metals, metallicity ~ 1/3 Solar, must be from stars in galaxies
- X-ray luminosity correlates with cluster classification, regular clusters have high x-ray luminosity, irregular clusters have low x-ray luminosity

Substructure in the X-Ray Gas

High resolution observations with *Chandra* show that many clusters have substructure in the X-ray surface brightness: hydrodynamical equilibrium is not a great approximation, clusters are still forming



1E 0657-56



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Virial Masses of Clusters:

Virial Theorem for a test particle (a galaxy, or a proton), moving in a cluster potential well:

$$E_k = E_p / 2 \quad \rightarrow \quad m_g \, \sigma^2 / 2 = G \, m_g \, M_{cl} / (2 \, R_{cl})$$

where σ is the velocity dispersion

Thus the cluster mass is: $M_{cl} = \sigma^2 \, R_{cl} / G$

Typical values for clusters:

$\sigma \sim 500$ - 1500 km/s

$R_{cl} \sim 3$ - 5 Mpc

Thus, typical cluster masses are $\boldsymbol{M_{cl} \sim 10^{14}}$ **-** $\boldsymbol{10^{15} \, M_\odot}$

The typical cluster luminosities (~ 100 - 1000 galaxies) are $L_{cl} \sim 10^{12} \, L_\odot$, and thus $(M/L) \sim 200$ - 500 in solar units

➞ ***Lots of dark matter!***

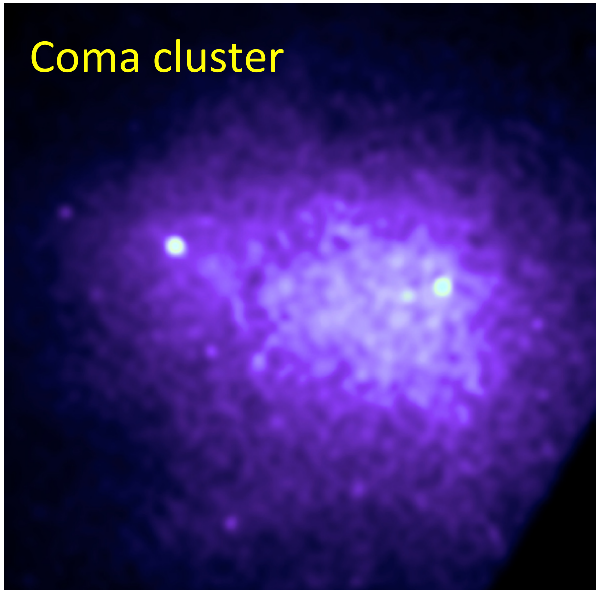
Masses of Clusters From X-ray Gas

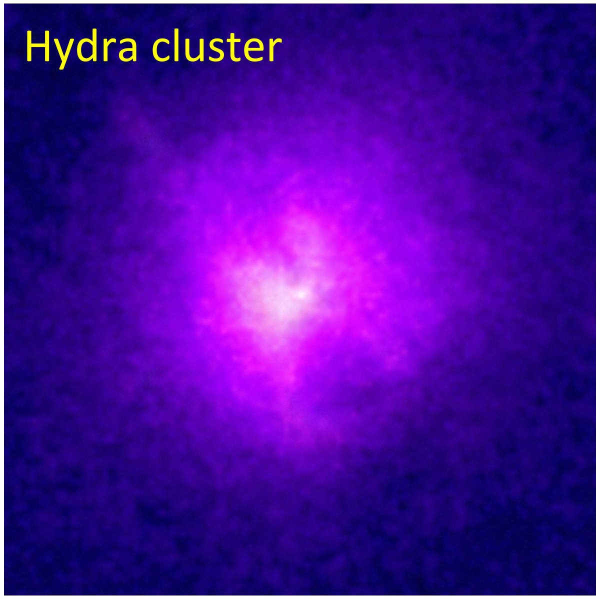
- Note that for a proton moving in the cluster potential well with a $\sigma \sim 10^3$ km/s, $E_k = m_p \sigma^2 / 2 = 5\, k\, T / 2 \sim$ few keV, and $T \sim$ few 10^7 °K ➔ **X-ray gas**
- Hydrostatic equilibrium requires:

$$M(r) = - kT/\mu m_H G\ (d \ln \rho / d \ln r)\ r$$

- If the cluster is ~ spherically symmetric this can be derived from X-ray intensity and spectral observations
- Typical cluster mass components from X-rays:

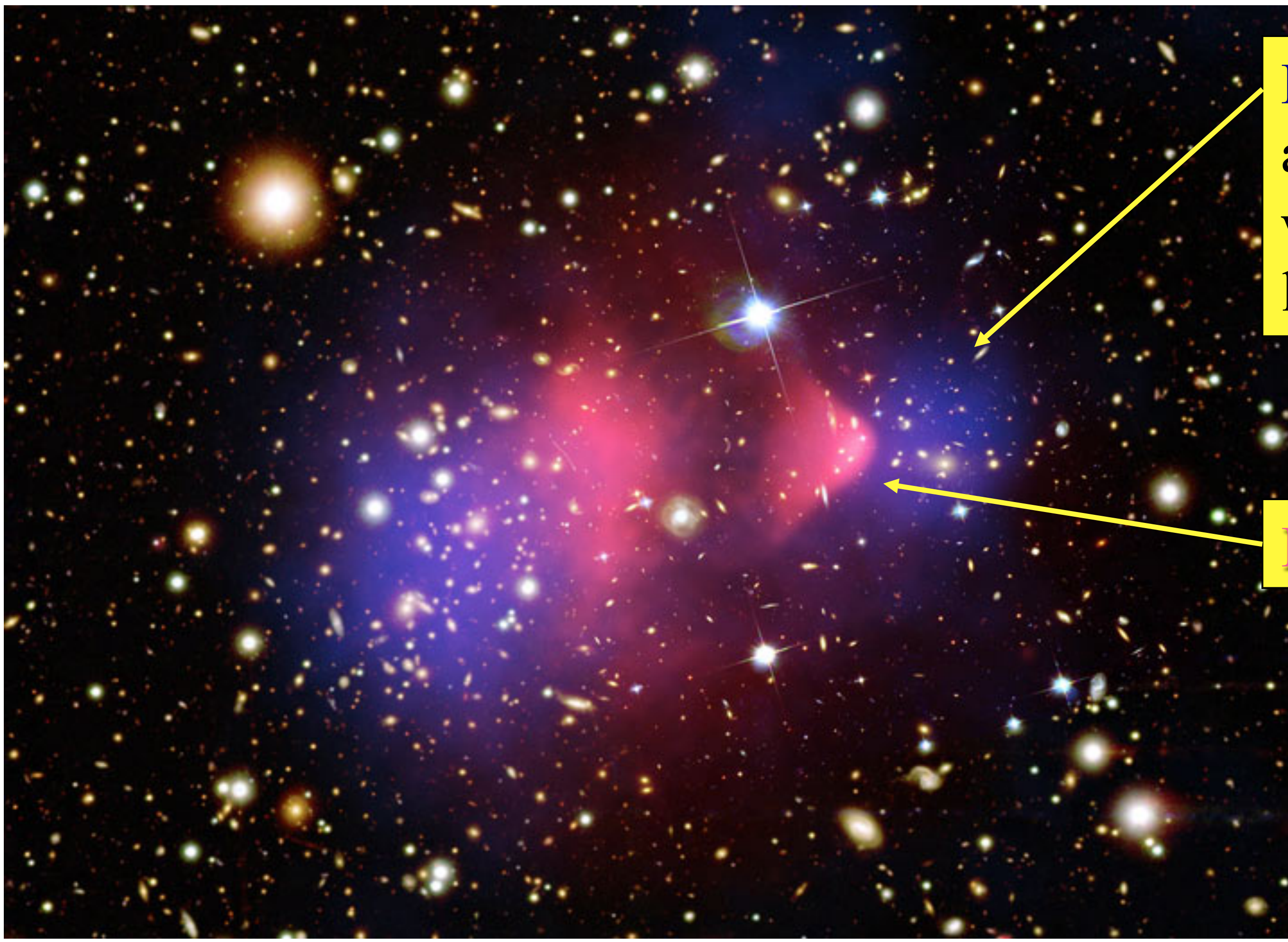
  Total mass: 10^{14} to 10^{15} $M_\odot$
  Luminous mass: ~5%
  Gaseous mass: ~ 10%
  Dark matter: ~85%





Dark Matter and X-Ray Gas in Cluster Mergers: The "Bullet Cluster" (1E 0657-56)

The dark matter clouds largely pass through each other, whereas the gas clouds collide and get shocked, and lag behind

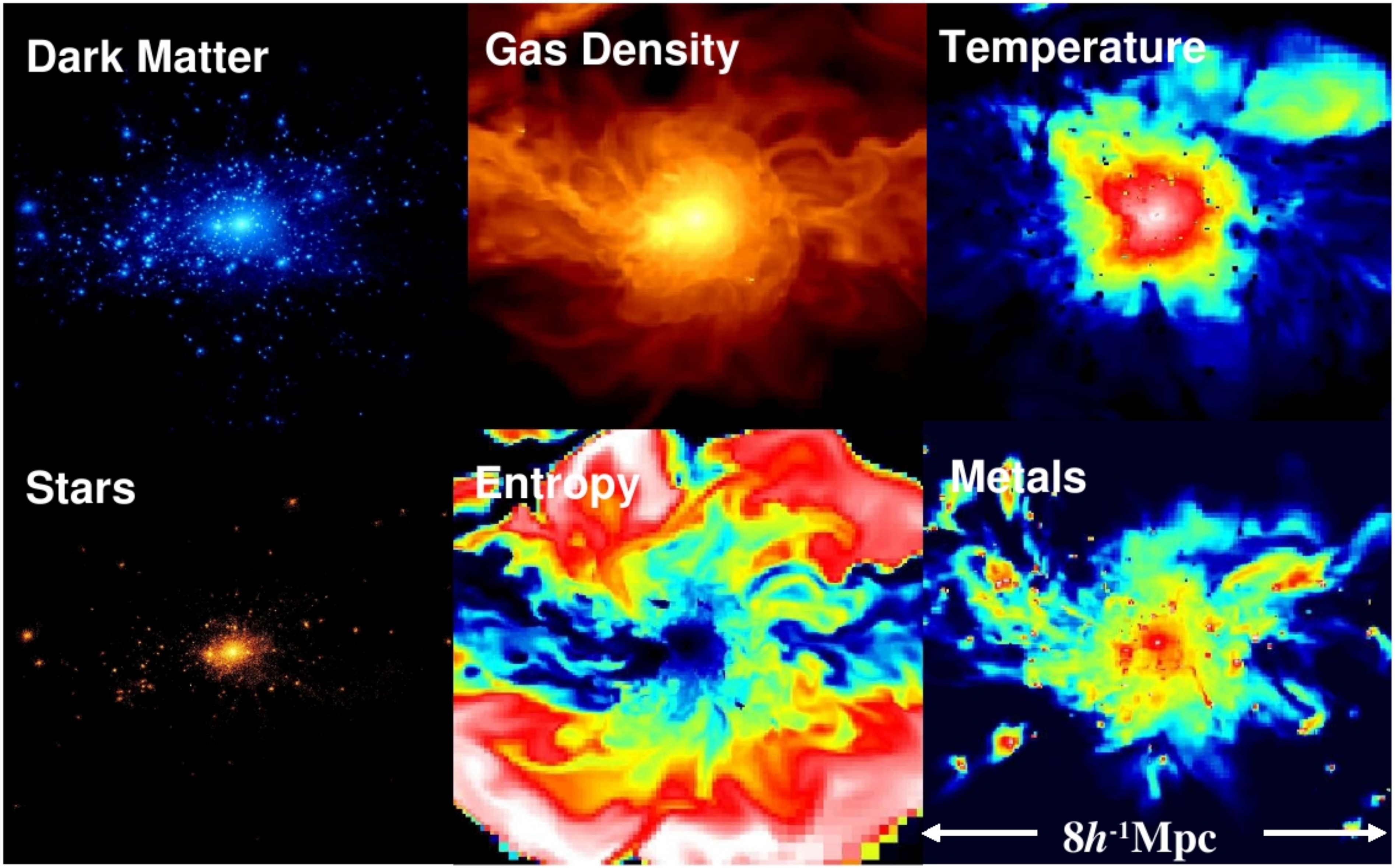


Blue: dark matter, as inferred from weak gravitational lensing

Pink: X-ray gas

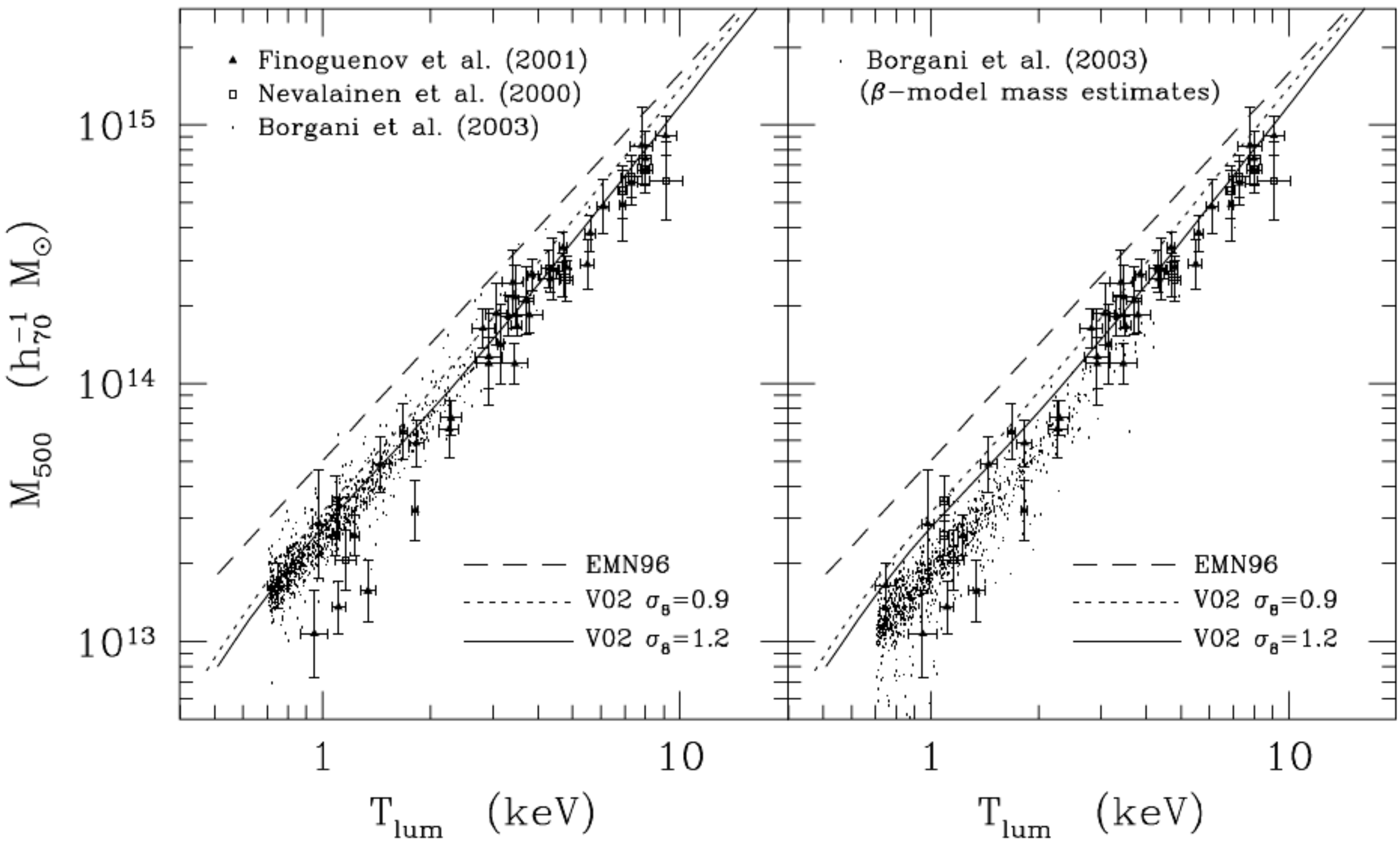
(Bradac et al.)

Numerical Simulations of Cluster Formation

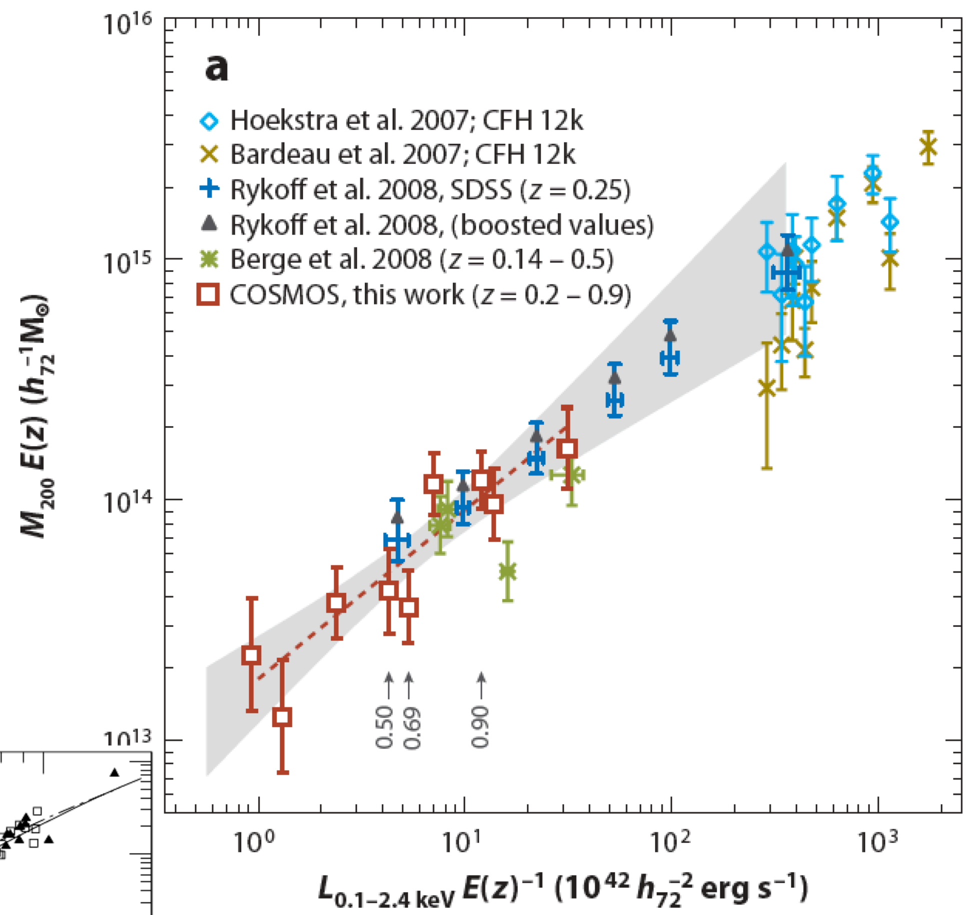


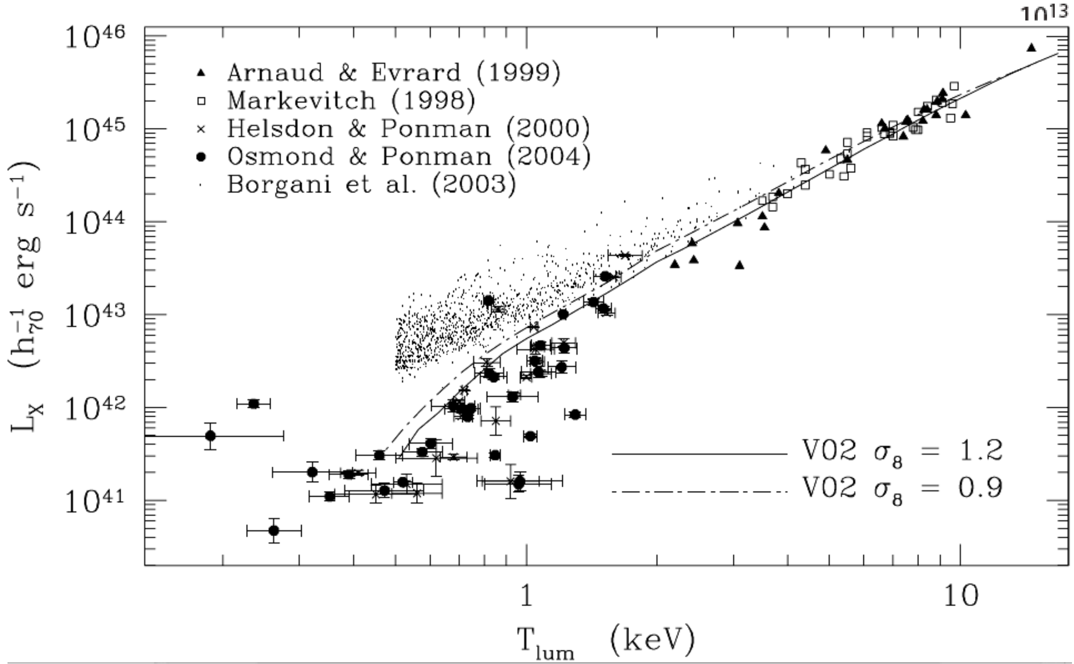
(D. Nagai & A. Kravtsov)

Cluster Masses Correlate With Temperature



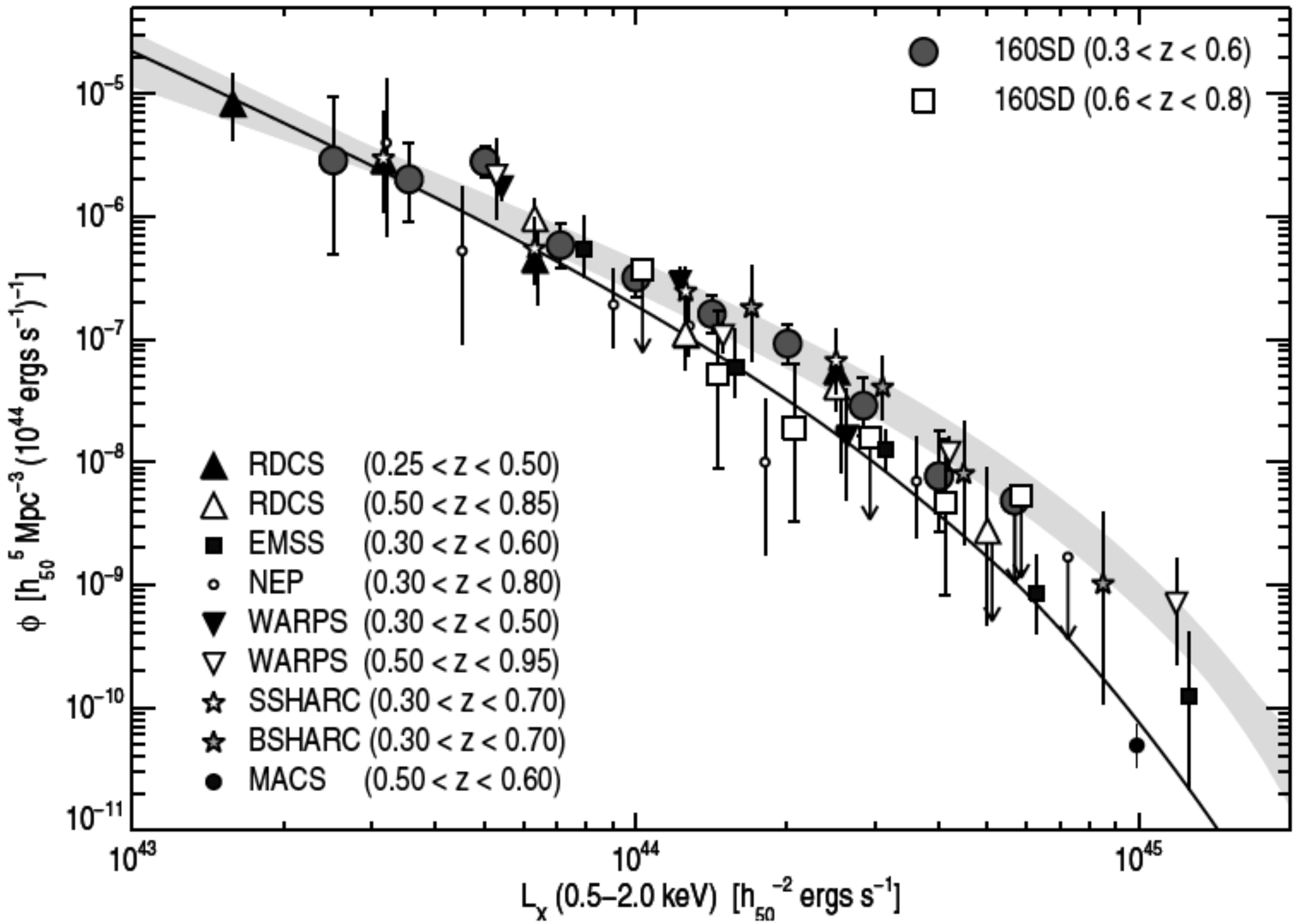
Cluster X-Ray Luminosities Correlate With Mass





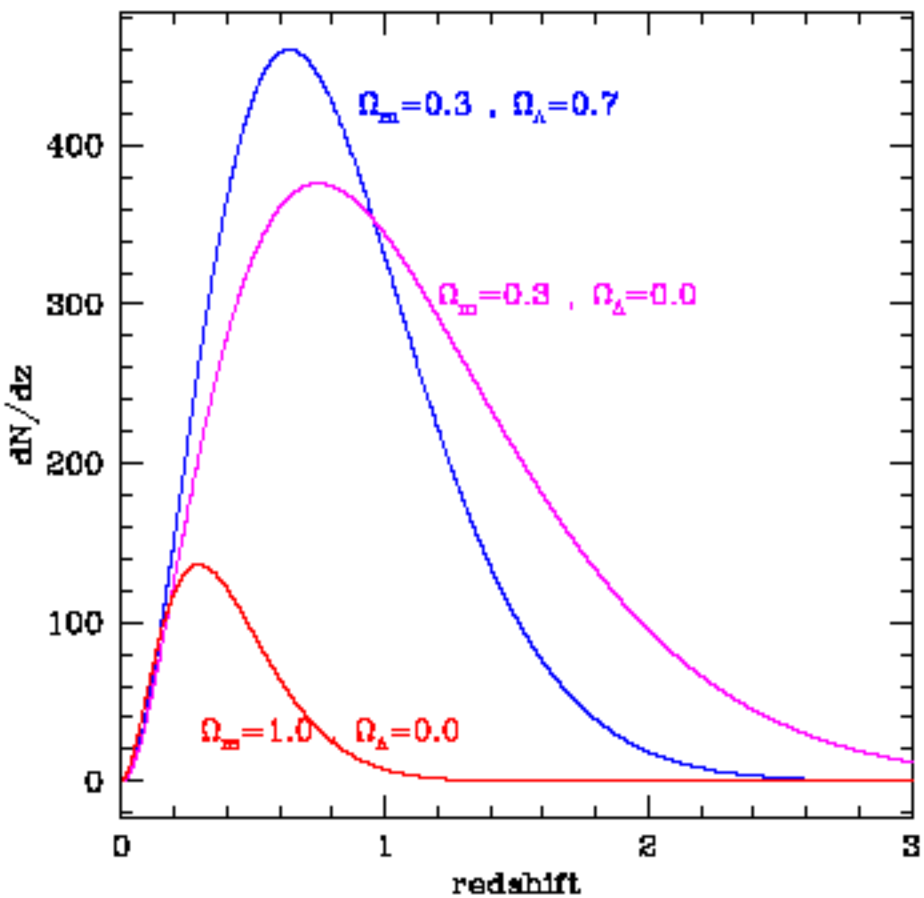
… and Temperature

Evolution of the Cluster X-Ray Luminosity Function



Clusters as Cosmological Probes

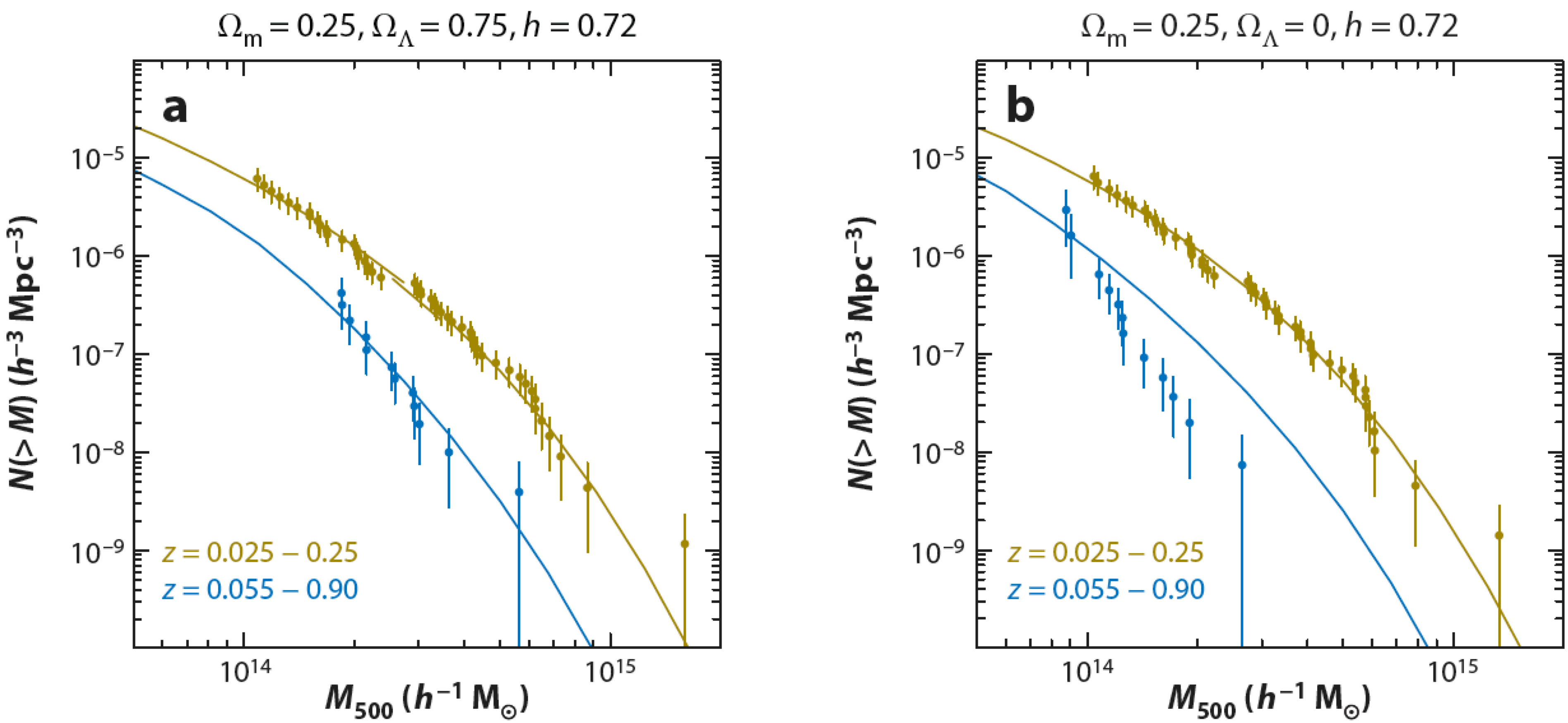
- Given the number density of nearby clusters, we can calculate how many distant clusters we expect to see
- In a high density universe, clusters are just forming now, and we don't expect to find any distant ones
- In a low density universe, clusters began forming long ago, and we expect to find many distant ones



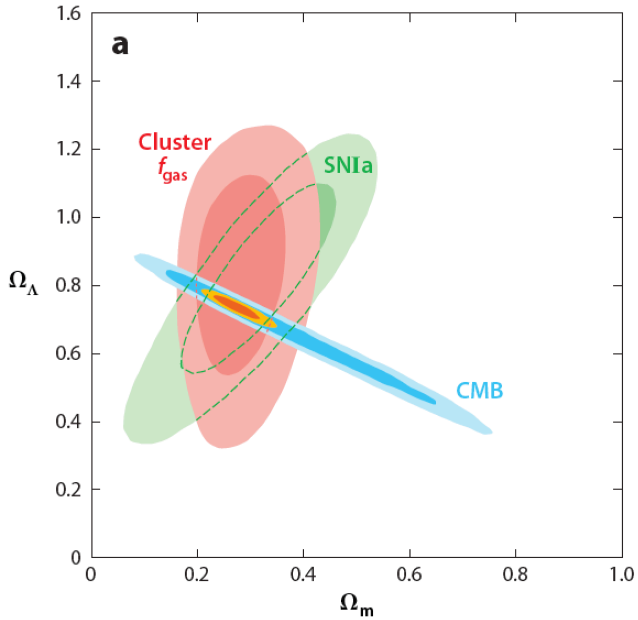
- Evolution of cluster abundances:
  - Structures grow more slowly in a low density universe, so we expect to see less evolution when we probe to large distances

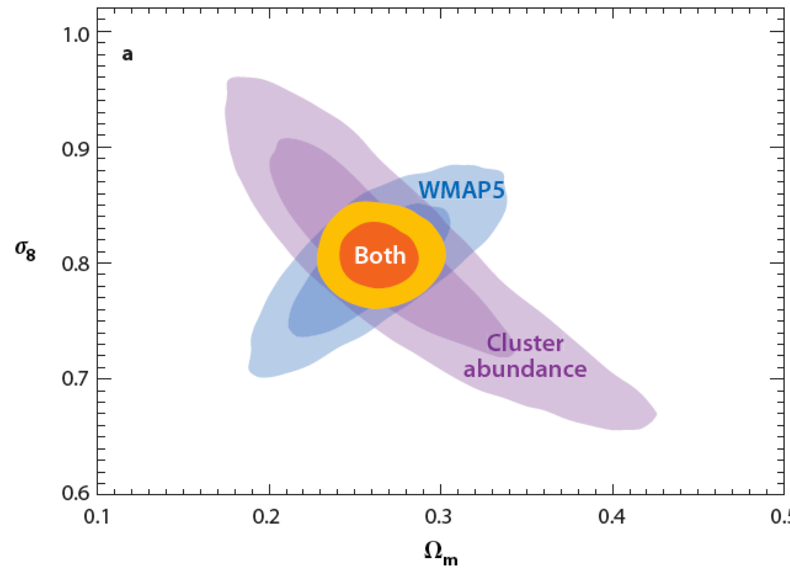
Clusters as Cosmological Probes

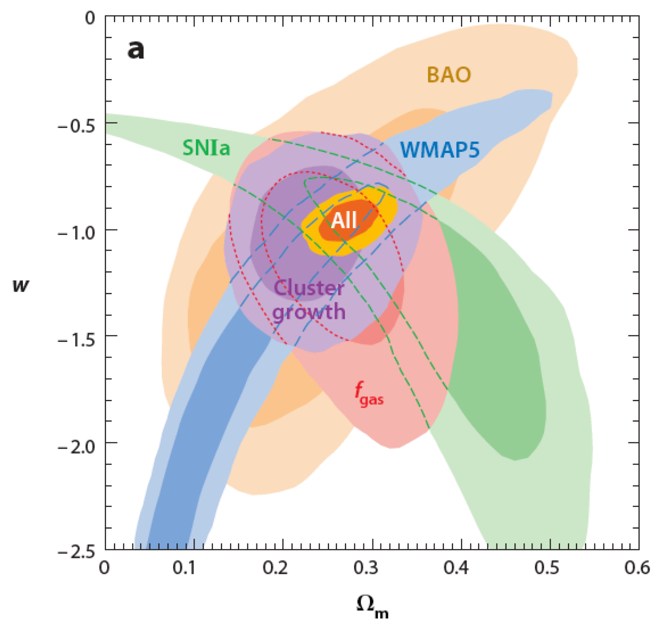
From the evolution of cluster abundance, expressed through their mass function:

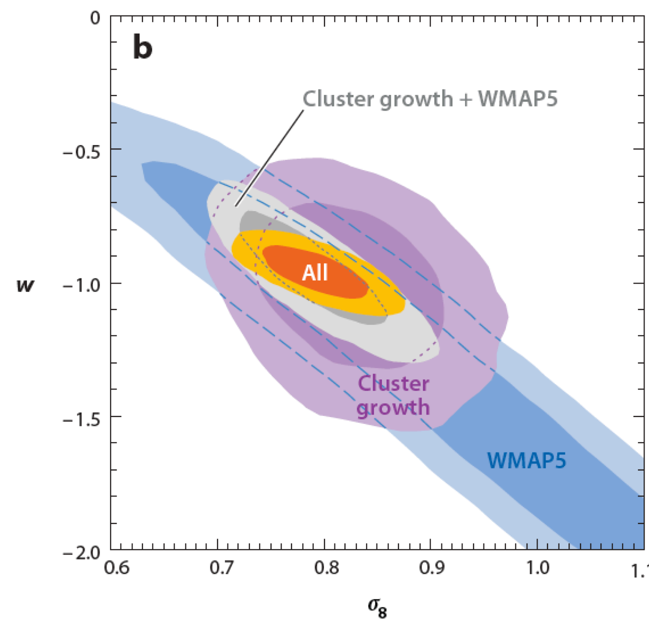


Clusters as Cosmological Probes









Hydrogen Gas Deficiency

- As gas-rich galaxies (i.e., spirals) fall into clusters, their cold ISM is ram-pressure stripped by the cluster X-ray gas
- Evidence for stripping of gas in cluster spirals has been found from HI measurements
- Most deficient spirals are found in cluster cores, where the X-ray gas is densest
- HI deficiency also correlates with X-ray luminosity (which correlates with cluster richness)
- It is the outer disks of the spirals that are missing
- Thus, evolution of disk galaxies can be greatly affected by their large-scale environment

HI Deficiency vs. X-ray Luminosity

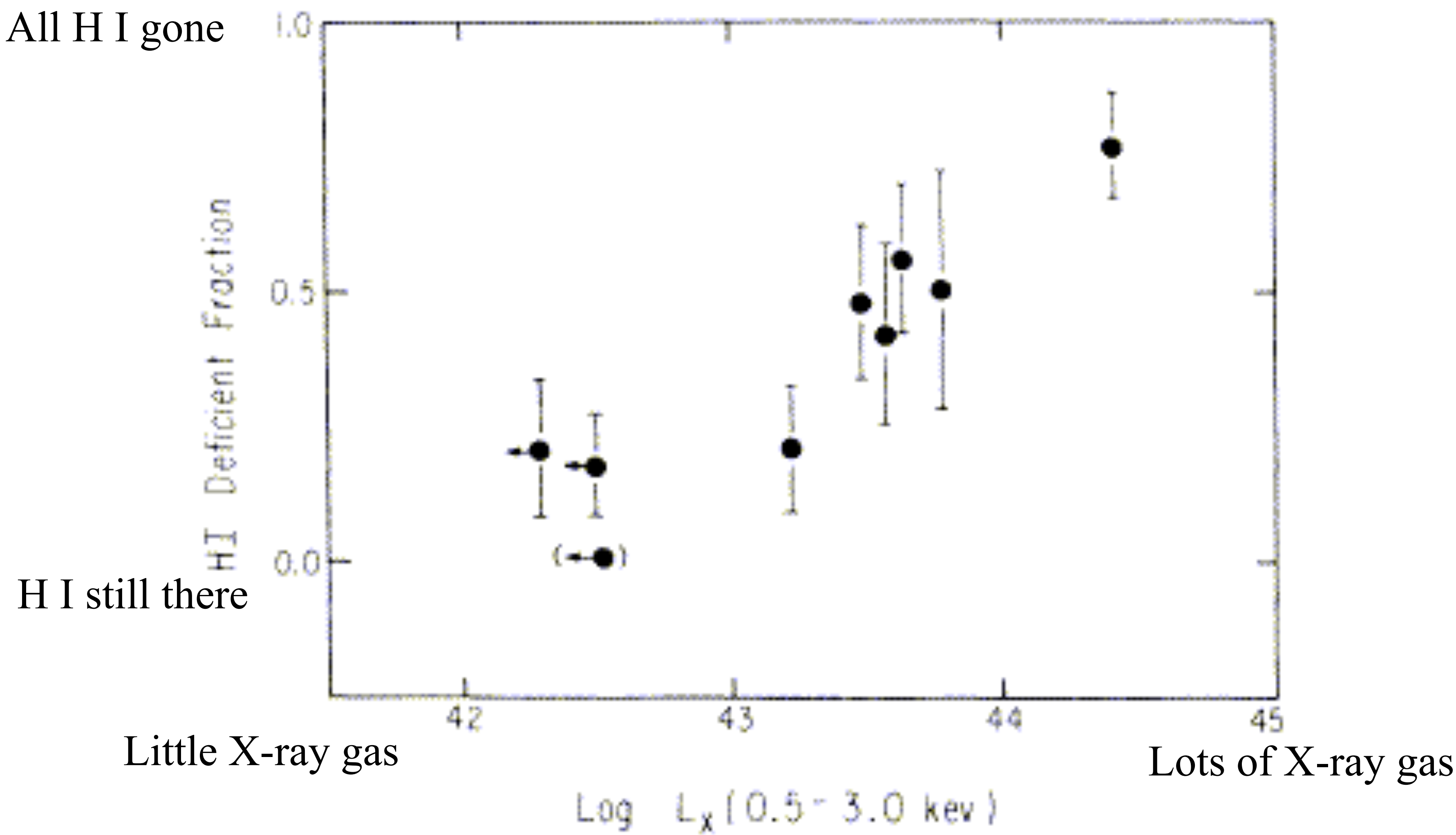
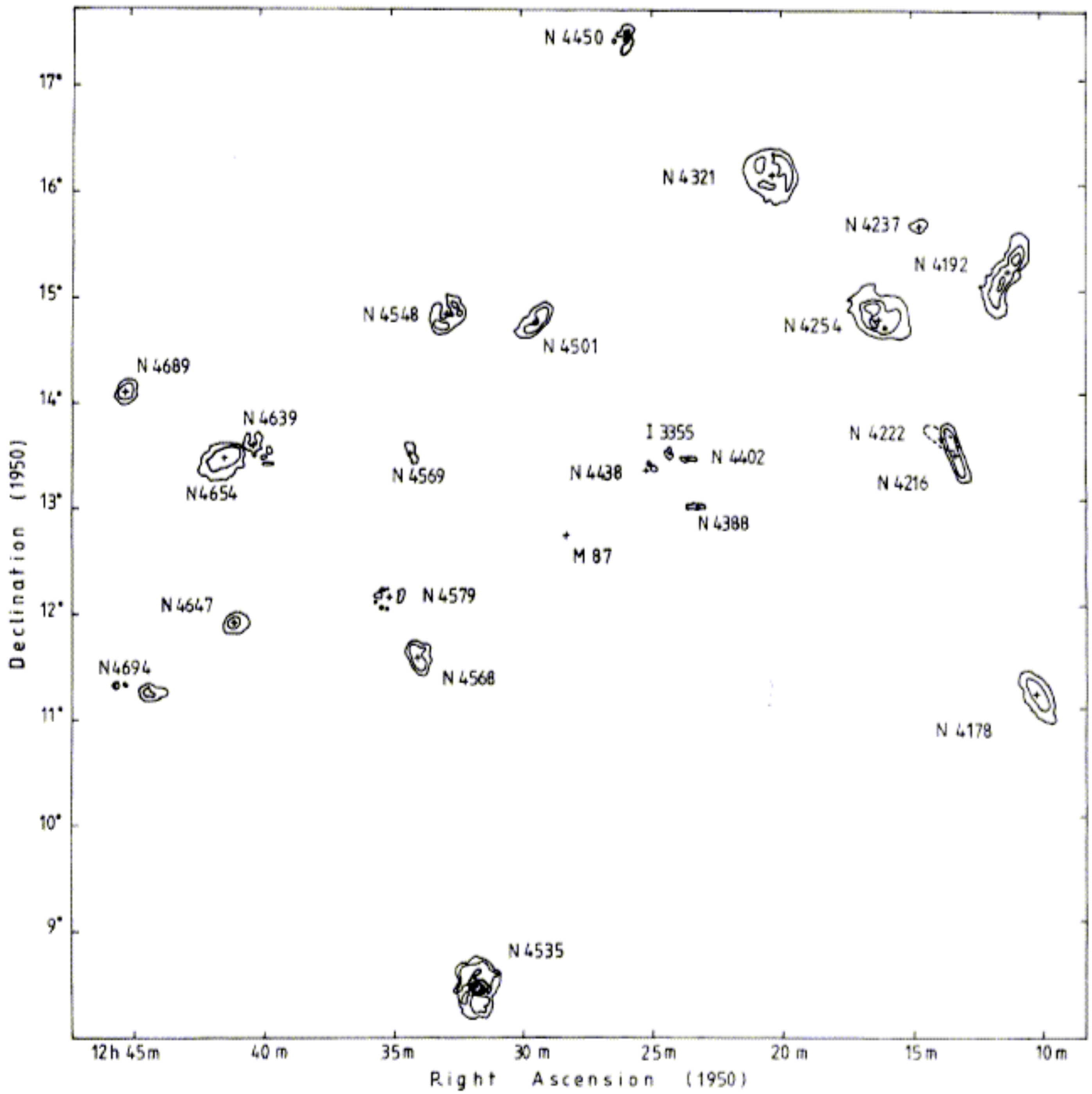


FIG. 9.—Suggested relationship between the deficient fraction *f*, defined in the text, and the cluster X-ray luminosity in the 0.5–3.0 keV range.

HI Map of the Virgo Cluster

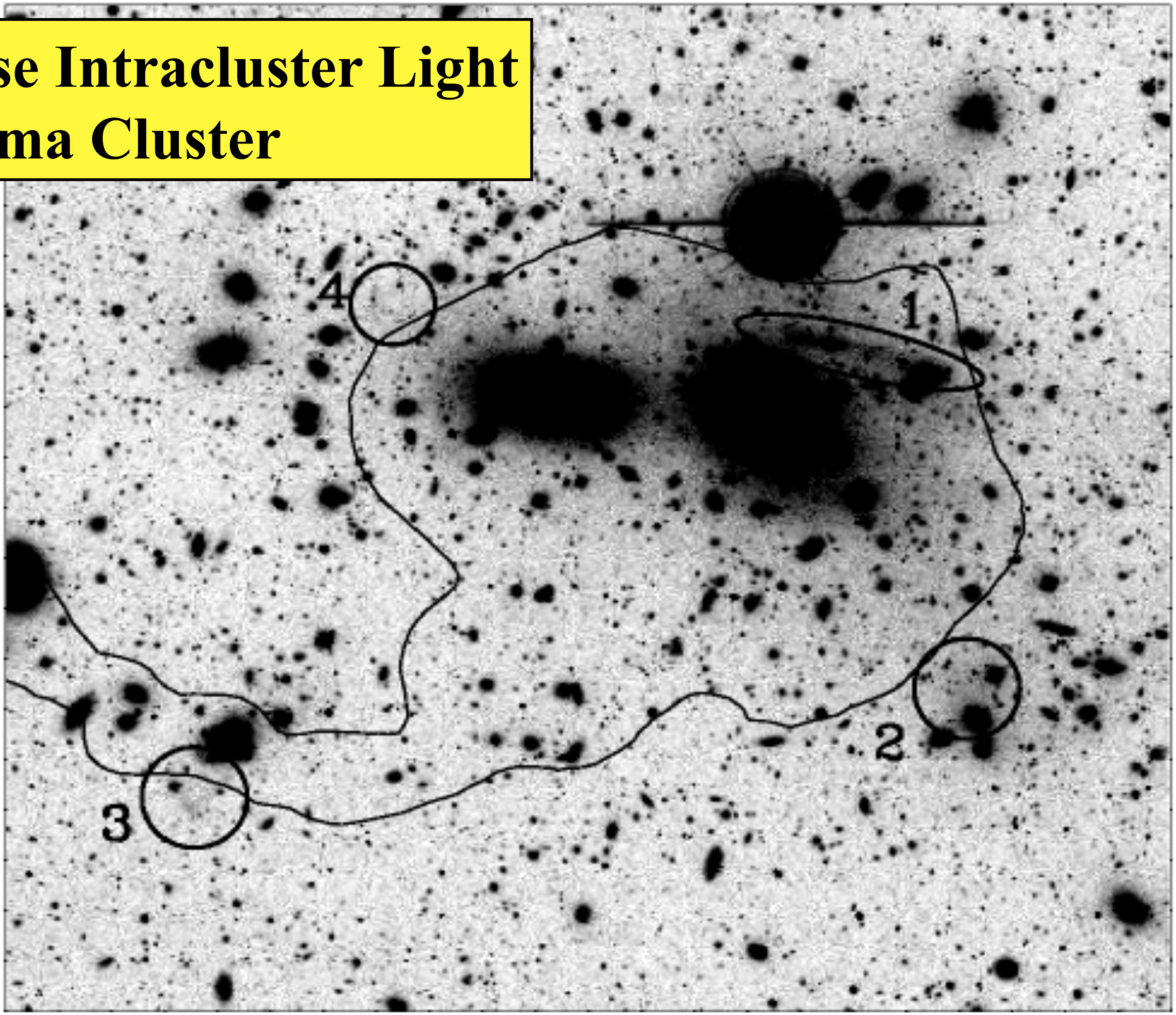


Gaseous disks of spirals are much smaller closer to the cluster center

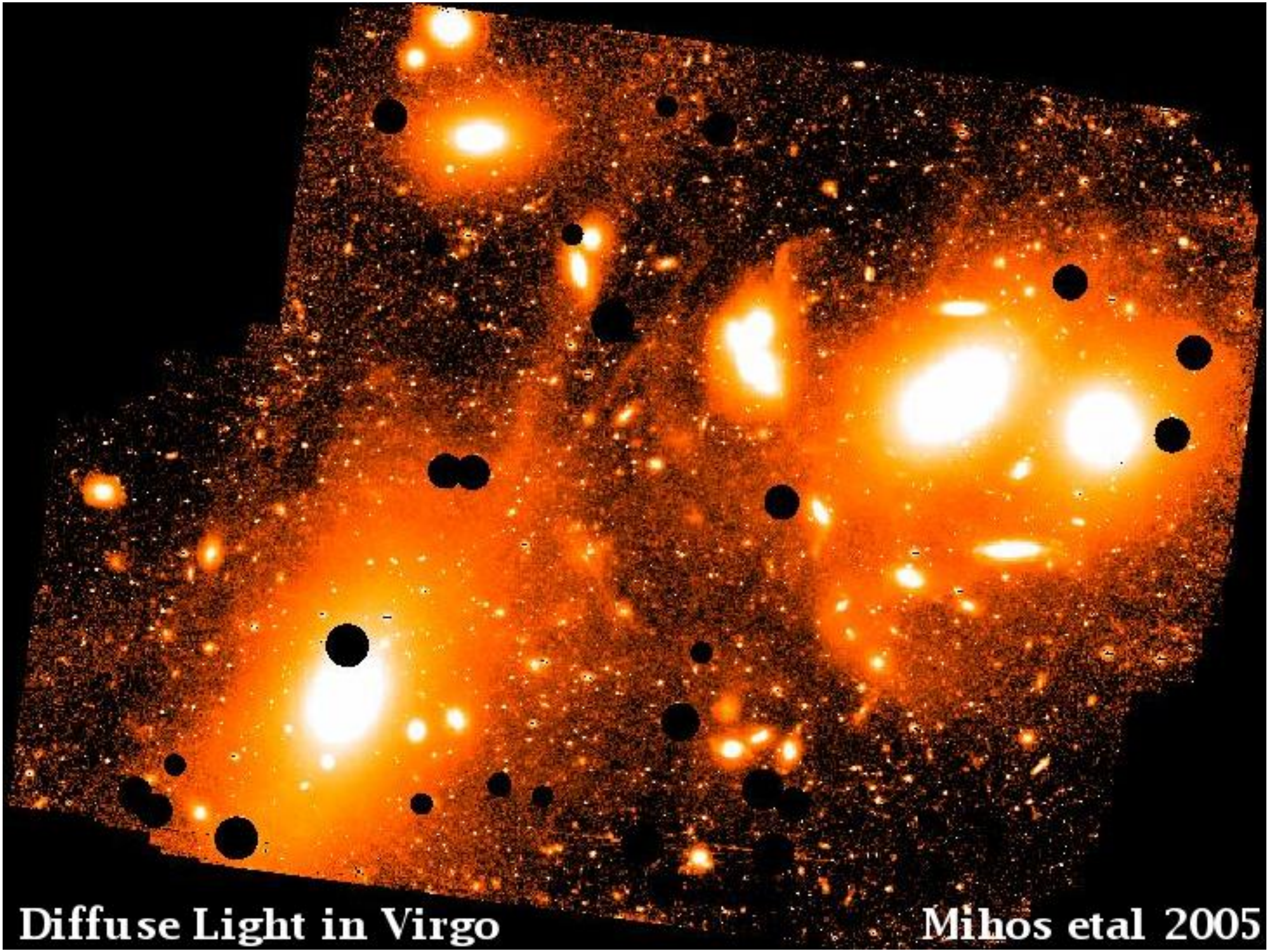
Intracluster Light

- Zwicky (yes, him again!) in 1951 first noted "an extended mass of luminous intergalactic matter of very low surface brightness" in Coma cluster
- Confirmed in 1998 by Gregg & West, features are extremely low surface brightness >27 mag per arcsec^2 in *R* band
- Also discoveries of intracluster red giant stars and intracluster planetary nebulae in Virgo & Fornax, up to ~ 10-30% of the total cluster light
- Probably caused by galaxy-galaxy or galaxy-cluster potential tidal interactions, which do not result in outright mergers
  - This is called "galaxy harassment"
  - Another environment-dependent process affecting galaxy evolution

Diffuse Intracluster Light in Coma Cluster



Gregg & West 1998


Diffuse Light in Virgo
Mihos etal 2005

Clusters of Galaxies: Summary

- Clusters are the largest bound (sometimes/partly virialized) elements of the LSS
  - A few Mpc across, contain ~ 10^2 - 10^3 galaxies, $M_{cl} \sim 10^{14}$ - 10^{15} $M_{\odot}$
  - Contain dark matter (~80%), hot X-ray gas (~10%), galaxies (~10%)
  - This maps into discovery methods for clusters: galaxy overdensities, X-ray sources (via emission of SZ effect), weak lensing, etc.
- Clusters are still forming, via infall and merging
  - Studied using numerical simulations, with galaxies, gas, and DM
- Galaxy populations and evolution in clusters differ from the general field
  - While only ~ 10 - 20% of galaxies are in clusters today, > 50% of all galaxies are in clusters or groups
  - Clusters have higher fractions of E's and S0's relative to spirals
  - Interesting galaxy evolution processes happen in clusters


Next:
Galaxies