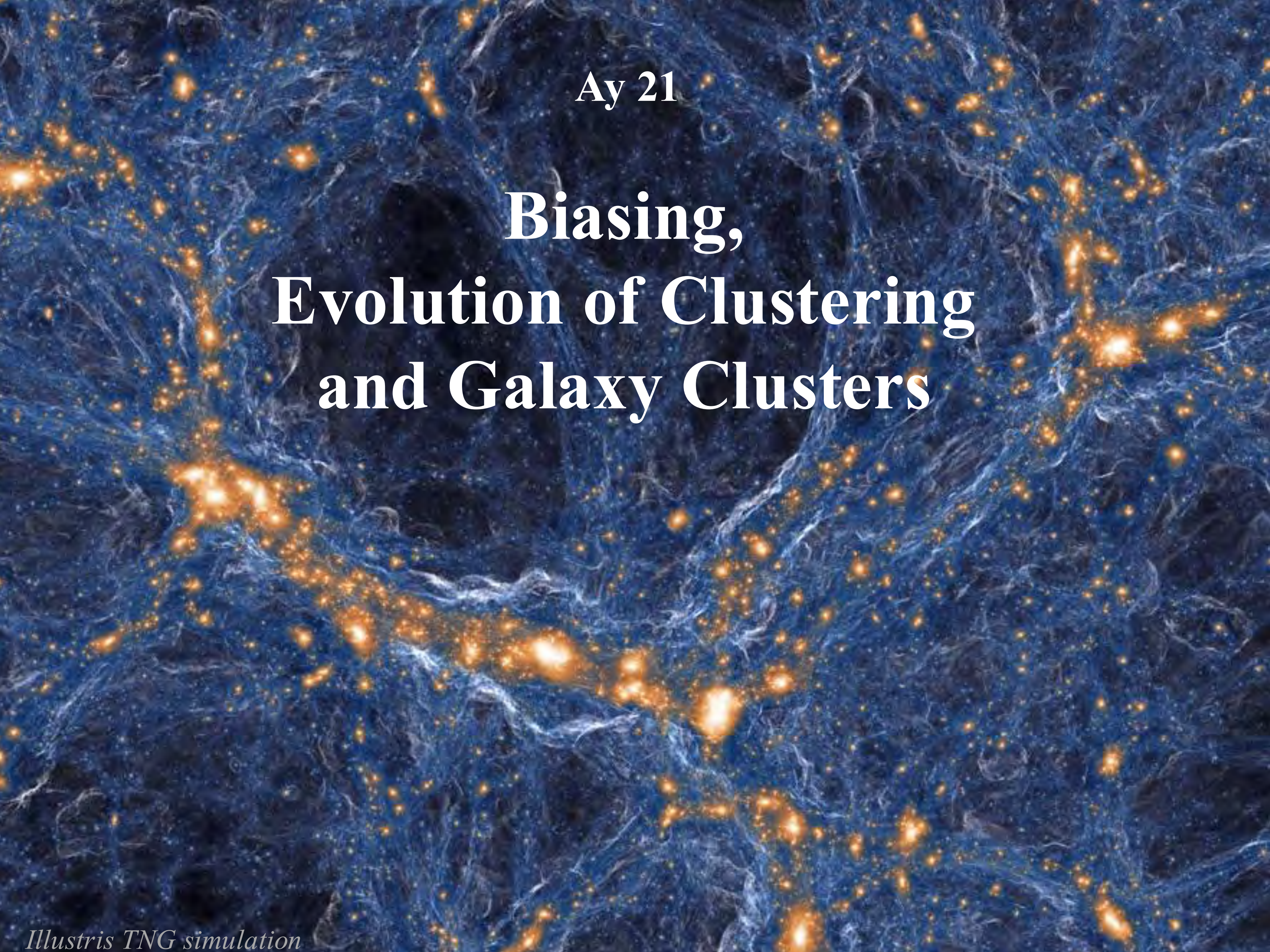
Ay 21

Biasing, Evolution of Clustering and Galaxy Clusters



Illustris TNG simulation

Galaxy Biasing

Suppose that the density fluctuations in mass and in light are not the same, but

$$(\Delta\rho/\rho)_{\mathrm{light}} = b\,(\Delta\rho/\rho)_{\mathrm{mass}}$$

Or:

$$\xi(r)_{\mathrm{light}} = b^2\,\xi(r)_{\mathrm{mass}}$$

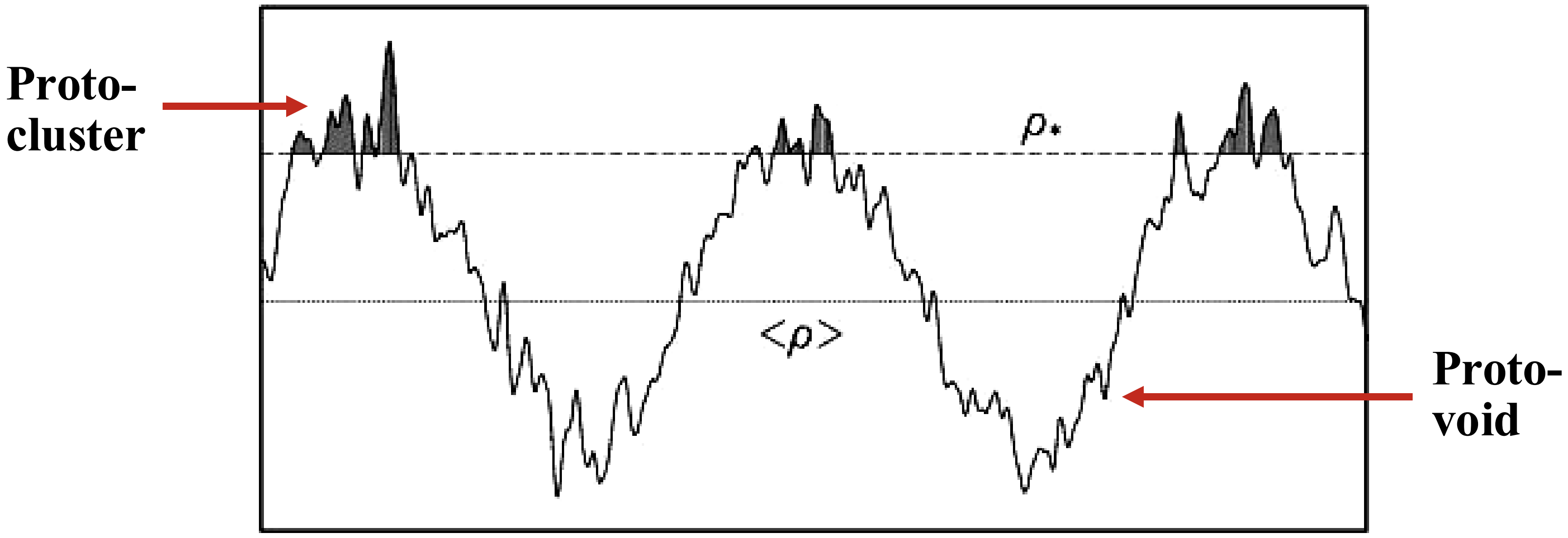
Here ***b*** is the *bias factor*.

If $b = 1$, light traces mass exactly (this is indeed the case at $z \sim 0$, at scales larger than the individual galaxy halos). If $b > 1$, light is a *biased tracer* of mass.

One possible mechanism for this is if the galaxies form at the densest spots, i.e., the highest peaks of the density field. Then, density fluctuations containing galaxies would not be typical, but rather a biased representation of the underlying mass density field; if 1-σ fluctuations are typical, 5-σ ones certainly are not.

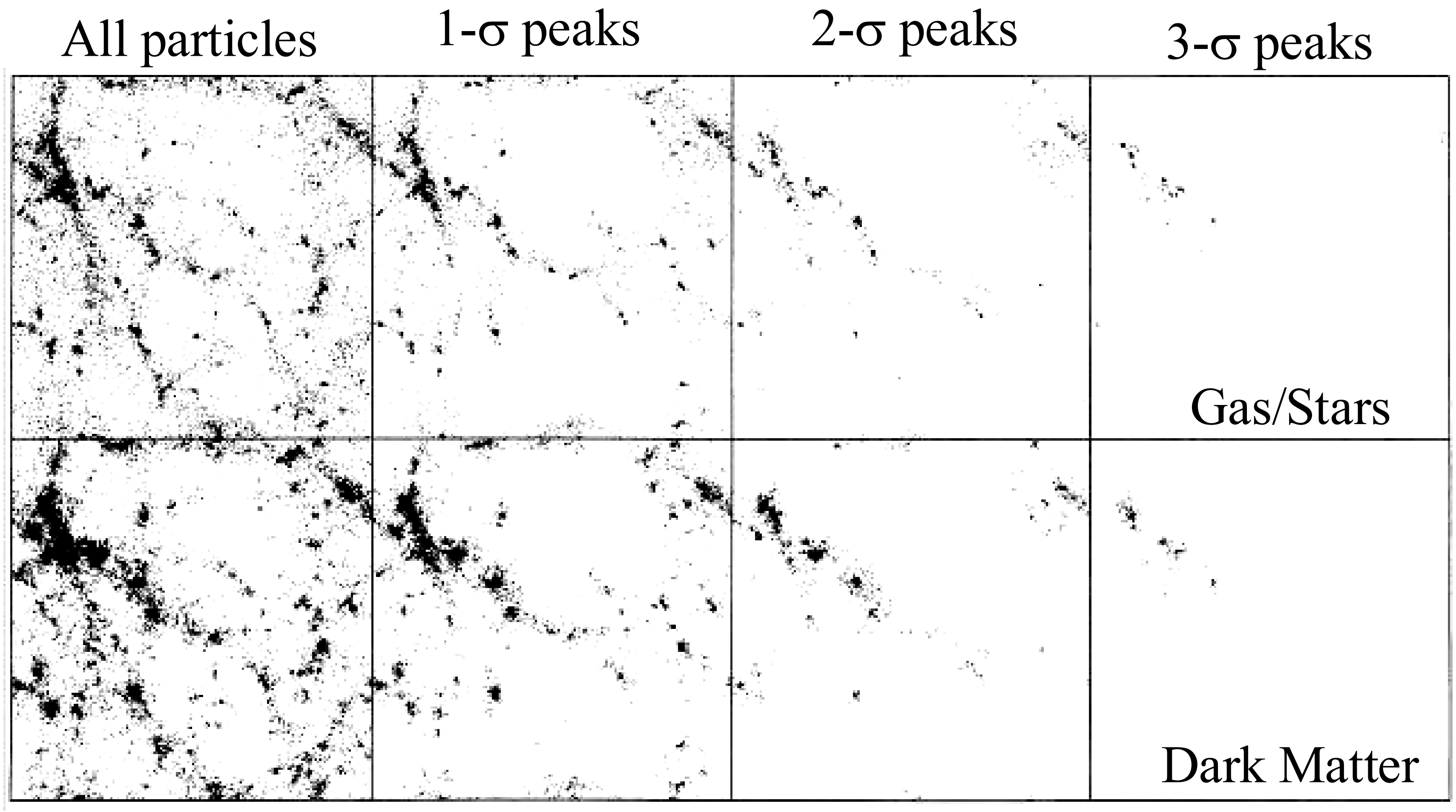
High Density Peaks as Biased Tracers

Take a cut through a density field. Smaller fluctuations ride atop of the larger density waves, which lift them up in bunches; thus the highest peaks (densest fluctuations) are a priori clustered more strongly than the average ones:



Thus, if the first galaxies form in the densest spots, they will be strongly clustered, but these will be very special regions.

An Example From a Numerical Simulation

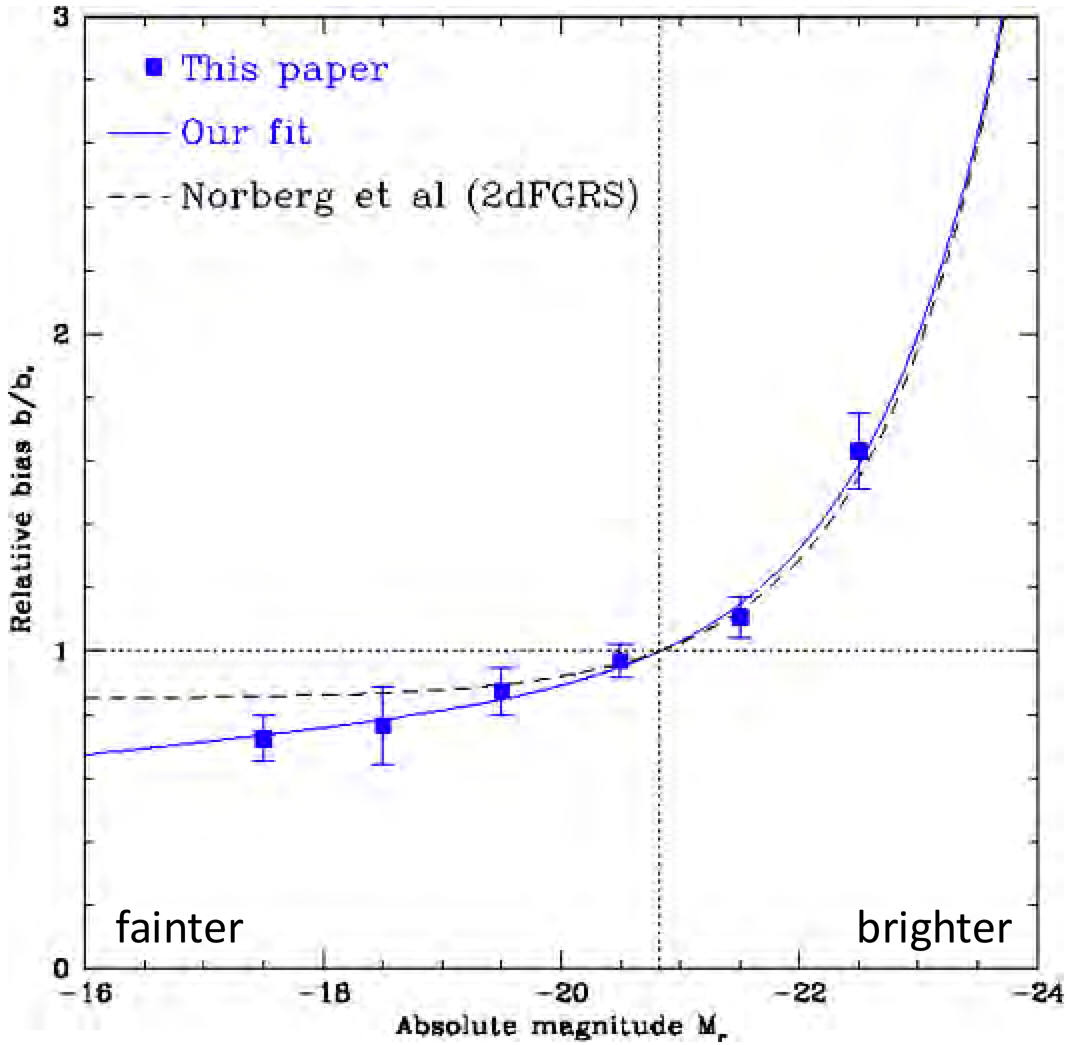


(From an N-body simulation by R. Carlberg)

Galaxy Biasing at Low Redshifts

While on average galaxies at $z \sim 0$ are not biased tracers, there is a dependence on luminosity: the more luminous ones are clustered more strongly, corresponding to higher peaks of the density field.

This effect is stronger at higher redshifts.



Biasing in the SDSS, Tegmark et al (2004)

Evolution of Clustering

- Generally, density contrast grows in time, as fluctuations collapse under their own gravity
- Thus, one generically expects that clustering was weaker in the past (at higher redshifts), and for fainter galaxy samples
- A simple model for the evolution of the correlation function:

$$\xi(r, z) = \xi(r, 0) \times (1 + z)^{-(3+\epsilon)}$$

and the clustering length (in proper coordinates):

$$r_0(z) = r_0(0) \times (1 + z)^{-(3+\epsilon)/\gamma}$$

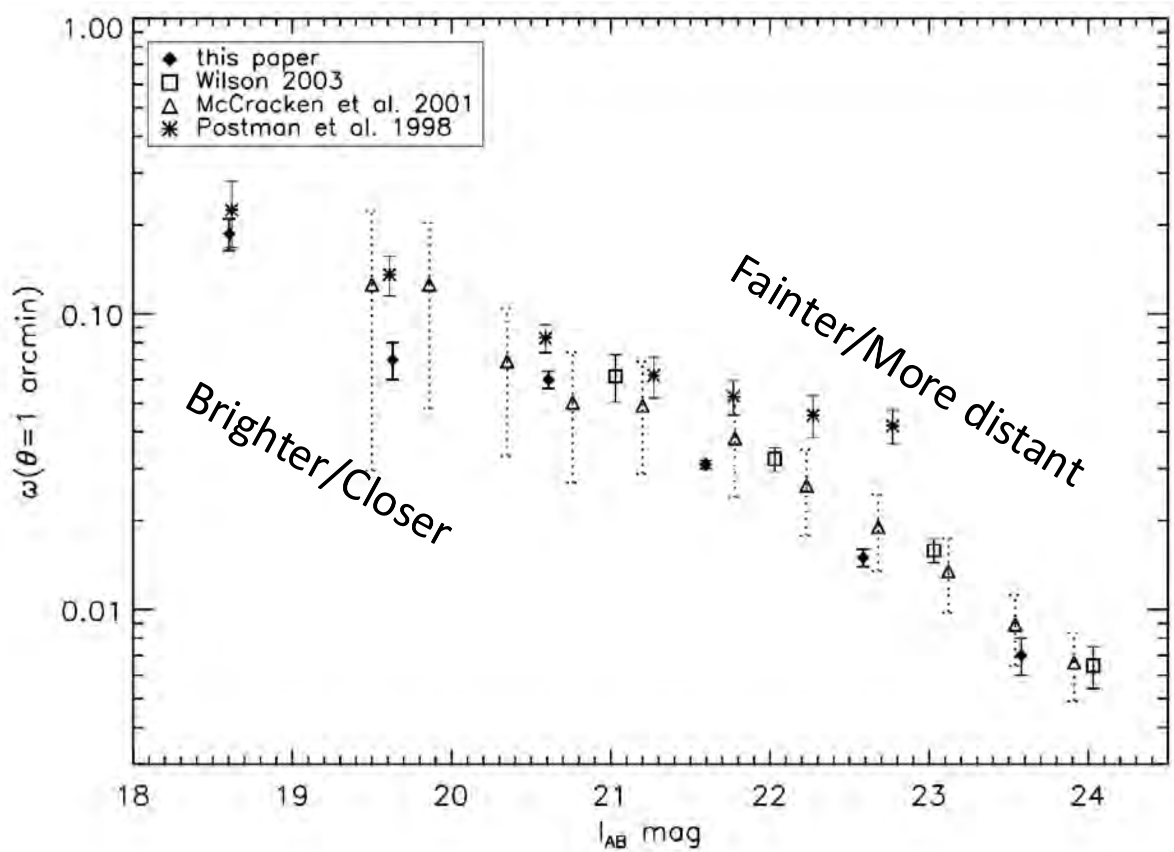
If $\varepsilon = -1.2$, clustering is fixed in comoving coords.
If $\varepsilon = 0$, clustering is fixed in proper coords.
If $\varepsilon > 0$, clustering grows in proper coords.

- Observations indicate $\varepsilon > 0$, but not one single value fits all data

Evolution of Clustering

- Generally, density contrast grows in time, as fluctuations collapse under their own gravity
- Thus, one generically expects that clustering was weaker in the past (at higher redshifts), and for fainter galaxy samples

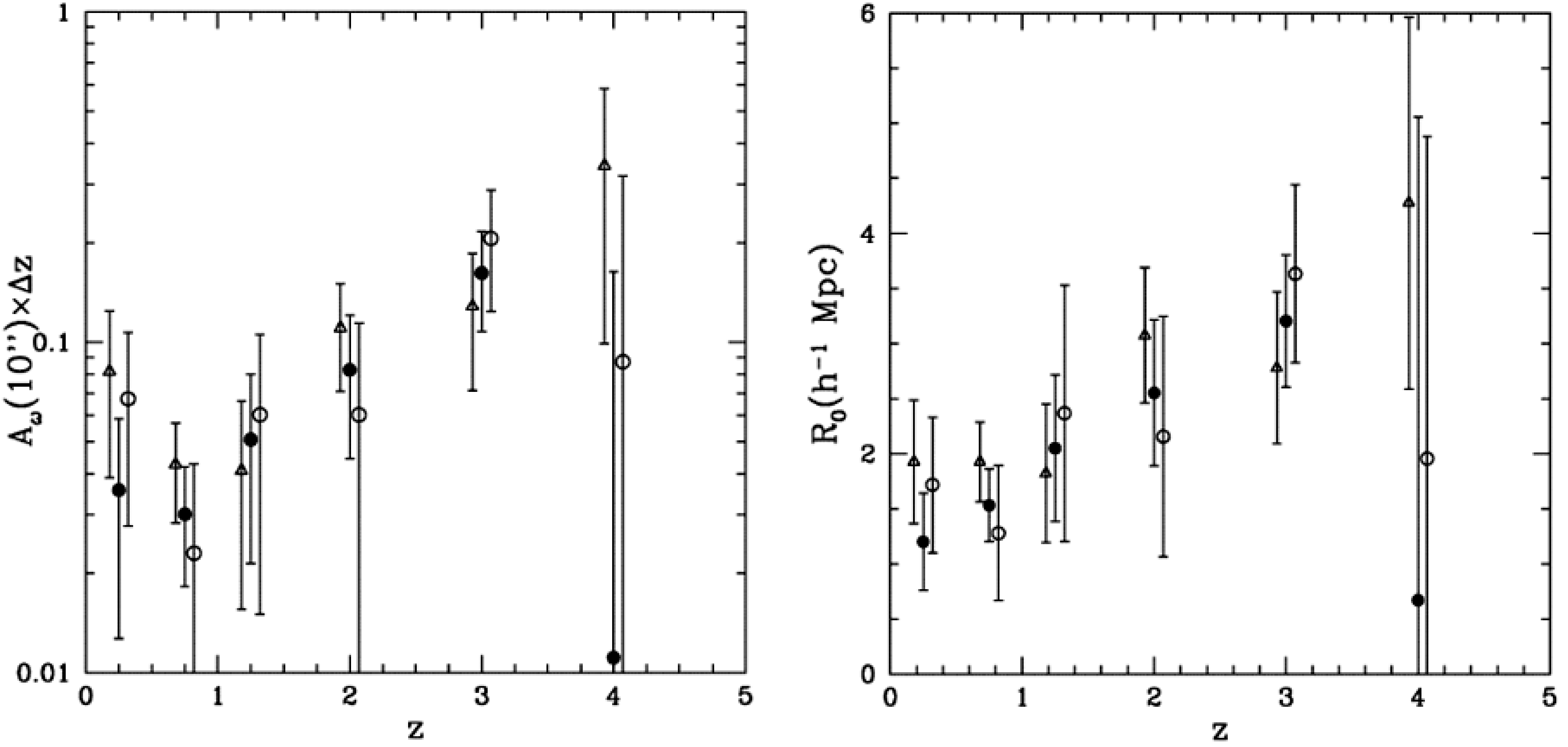
- Deep redshift surveys indicate that the strength of the clustering decreases at higher redshifts, at least out to $z \sim 1$, as expected:



(Coil et al., DEEP survey team)

Evolution of Clustering

- But at higher redshifts (and fainter/deeper galaxy samples), the trend reverses: stronger clustering at higher redshifts = earlier times!

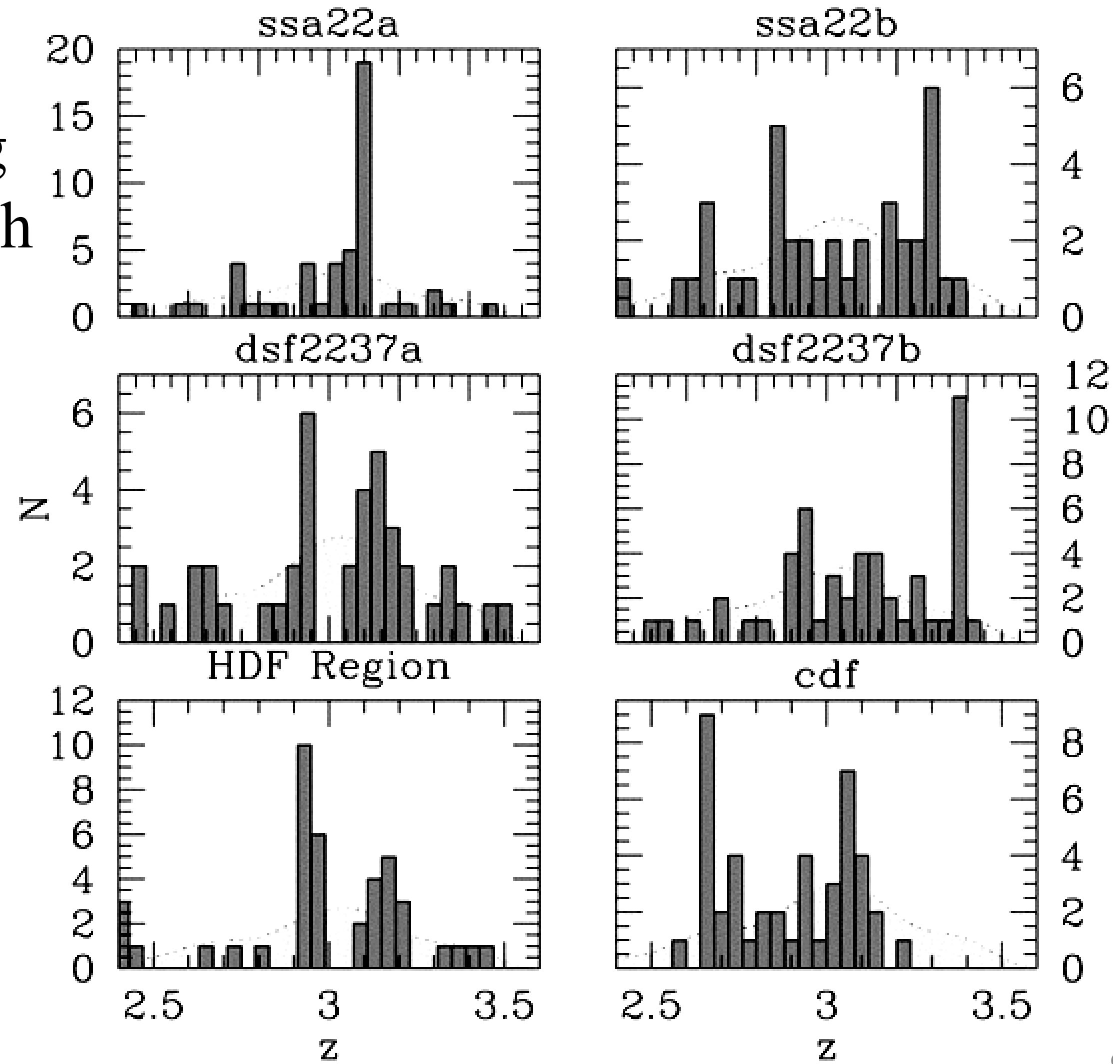


(Hubble Deep Field data)

Early Large-Scale Structure: Redshift Spikes in Very Deep Surveys

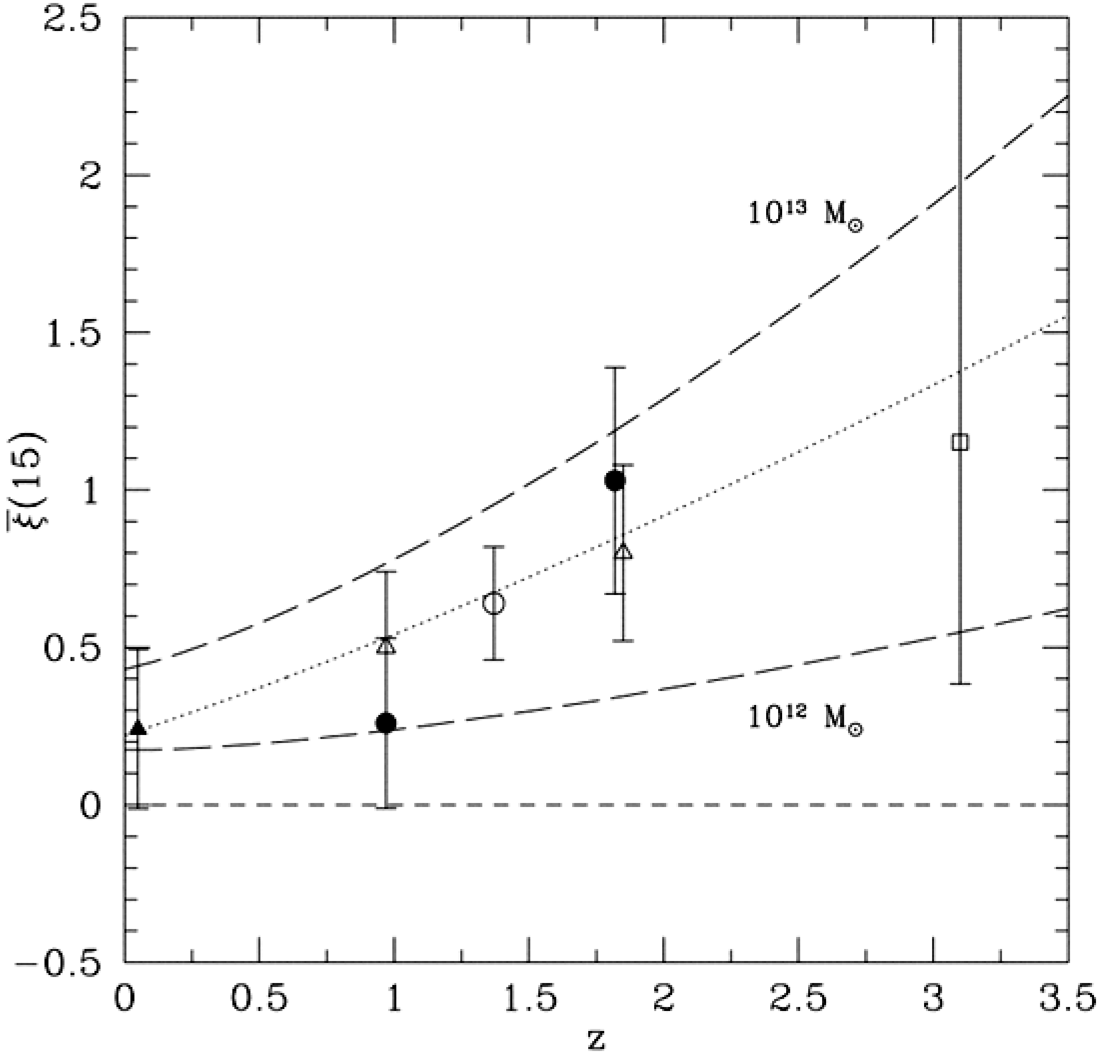
Strong clustering of young galaxies is observed at high redshifts (up to $z \sim 3$ - 4), apparently as strong as galaxies today

This is only possible if these distant galaxies are highly biased - they are high-sigma fluctuations



(Steidel, Adelberger, et al.)

Clustering of Quasars is Also Stronger at Higher Redshifts

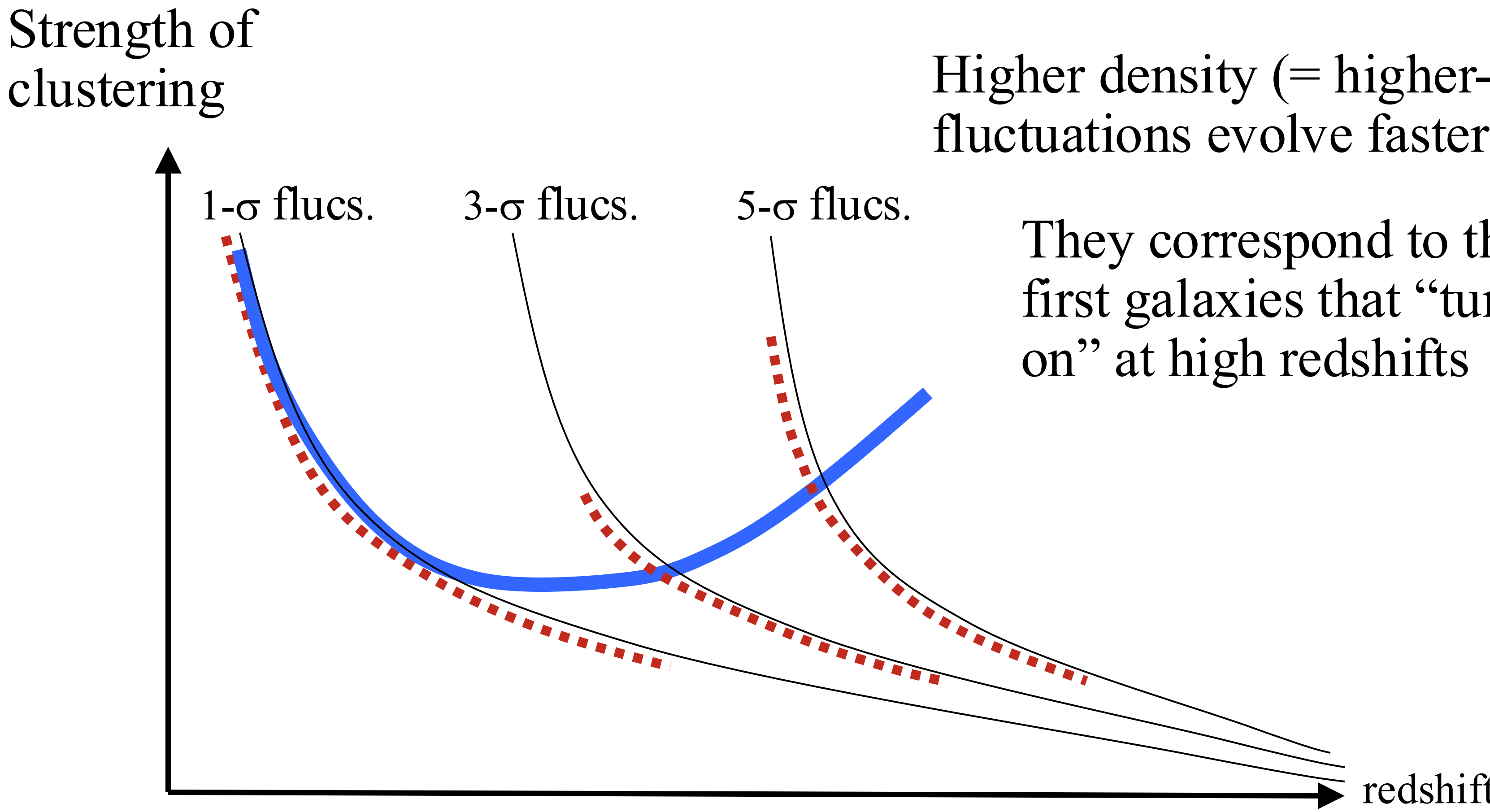


How is this possible?

Clustering is supposed to be ***weaker*** at higher z's as the structure grows in time.

Evolution of bias provides the answer

Biasing and Clustering Evolution



Higher density (= higher-σ) fluctuations evolve faster

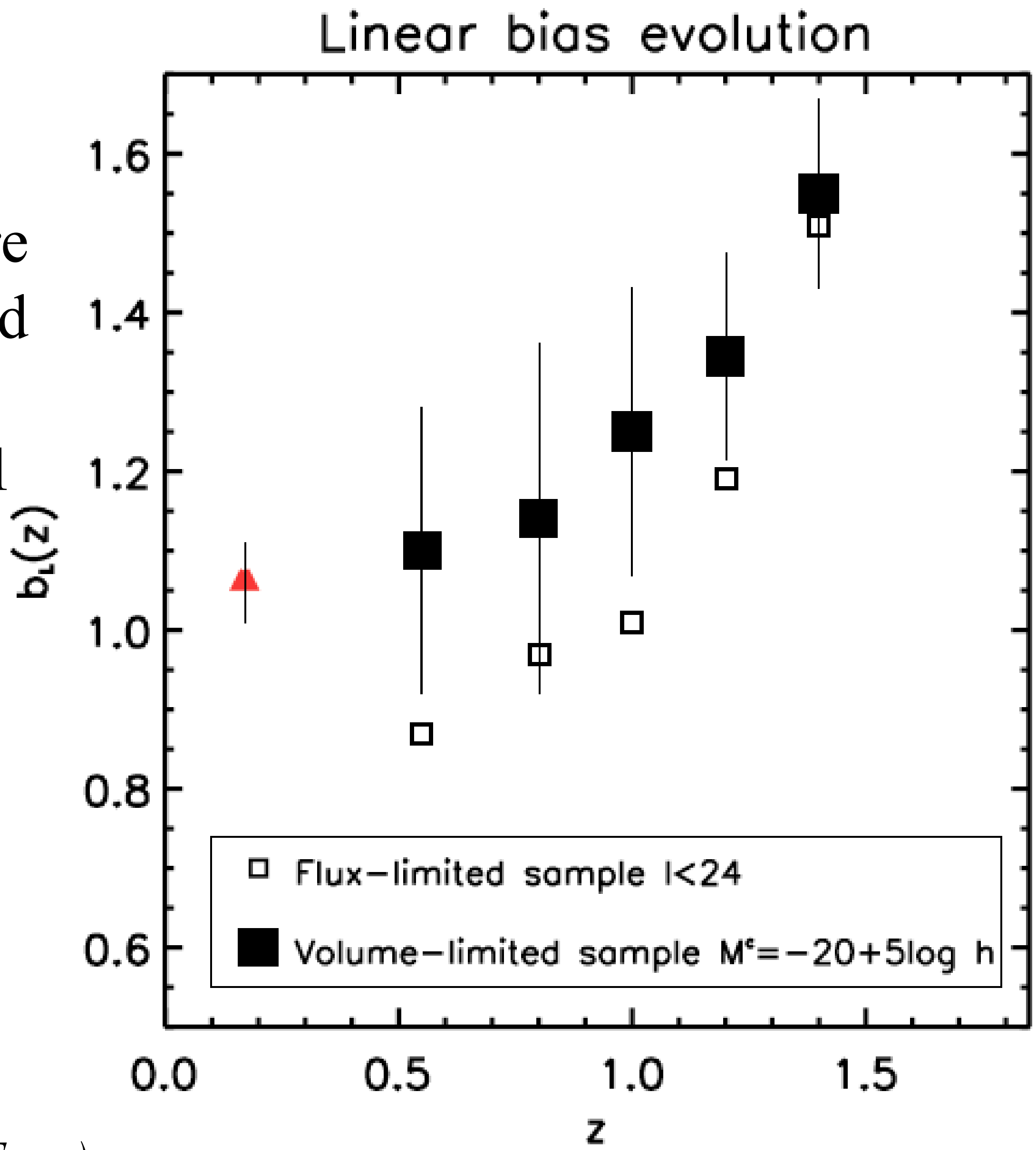
They correspond to the first galaxies that "turn on" at high redshifts

At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly …

Thus the net strength of clustering seems to increase at higher z's

The Evolution of Bias

At $z \sim 0$, galaxies are an unbiased tracer of mass, $b \sim 1$



But at higher *z's*, they are progressively ever more biased

(Le Fevre et al. VIMOS Survey Team)

Evolution of Clustering and Biasing

- The strength of clustering (of mass) grows in time, as the gravitational infall and hierarchical assembly continue
  - However, the rate of growth and the strength of clustering at any given time depend on the mass and nature of objects studied
  - This is generally expressed as the evolution of the 2-point correlation function, $\xi(r,z) = \xi(r,0)\ (1+z)^{-(3+\varepsilon)}$
  - Clustering/LSS is observed out to the highest redshifts ($z \sim 4$ - 6) now probed, and it is surprisingly strong
- What we really observe is *light*, which is not necessarily distributed in the same way as *mass*; this is quantified as ***bias:***

$$(\Delta\rho/\rho)_{light} = b\ (\Delta\rho/\rho)_{mass},\quad \xi(r)_{light} = b^2\ \xi(r)_{mass}$$

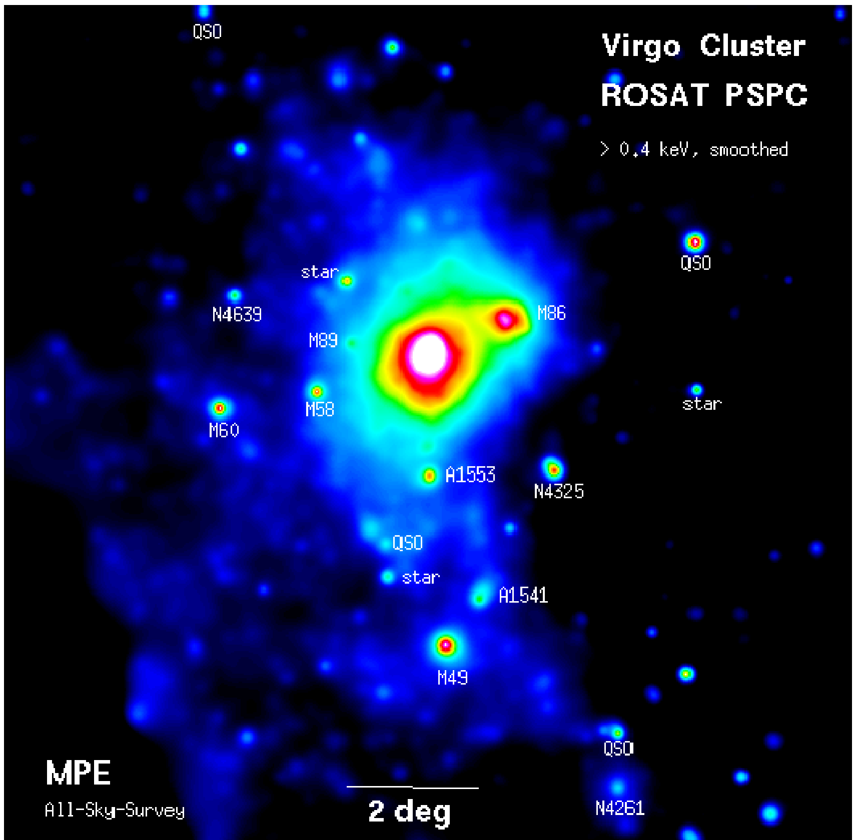
  - Bias is a function of time and mass/size scale
  - ***Galaxies (especially at high redshifts) are biased tracers of LSS***, as the first objects form at the highest peaks of the density field
  - Today, $b \sim 1$ at scales > galaxies

Clusters of Galaxies

- Clusters are perhaps the most striking elements of the LSS
- Typically a few Mpc across, contain ~ 100 - 1000 luminous galaxies and many more dwarfs, masses ~ 10^{14} - 10^{15} $M_{\odot}$
- Gravitationally bound, but may not be fully virialized
- Filled with hot X-ray gas, mass of the gas may exceed the mass of stars in cluster galaxies
- Dark matter is the dominant mass component (~ 80 - 85%)
- Only ~ 10 - 20% of galaxies live in clusters, but it is hard to draw the line between groups and clusters, and at least ~50% of all galaxies are in clusters or groups
- Clusters have higher densities than groups, contain a majority of E's and S0's while groups are dominated by spirals
- Interesting galaxy evolution processes happen in clusters

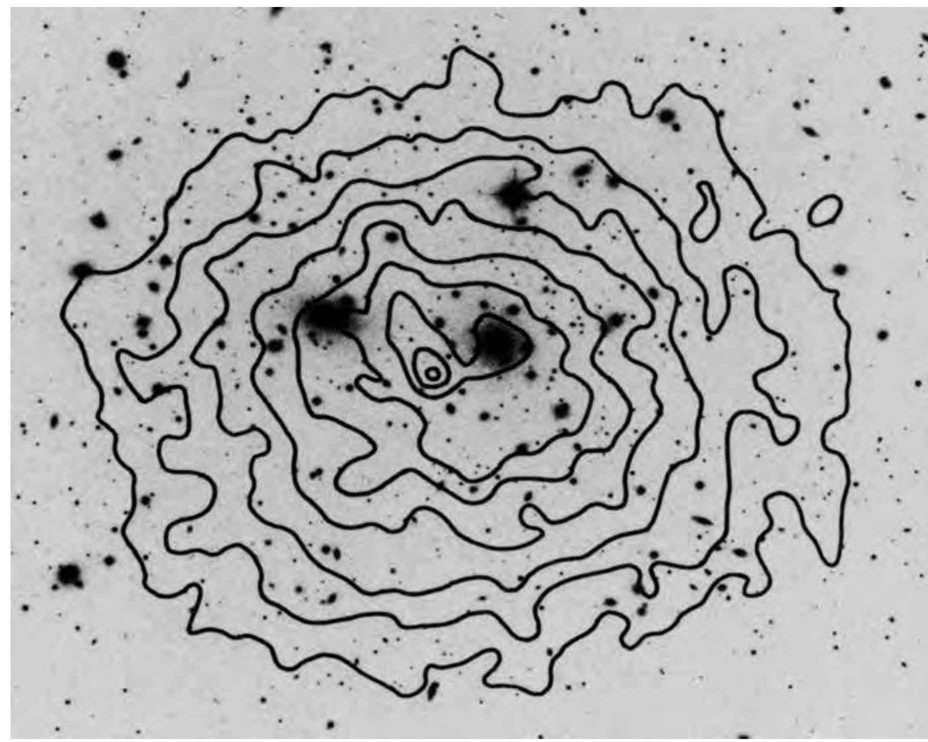
The Virgo Cluster

- Irregular, relatively poor cluster
- Distance ~ 16 Mpc, closest to us
- Diameter ~ 10° on the sky, 3 Mpc
- ~ 2000 galaxies, mostly dwarfs

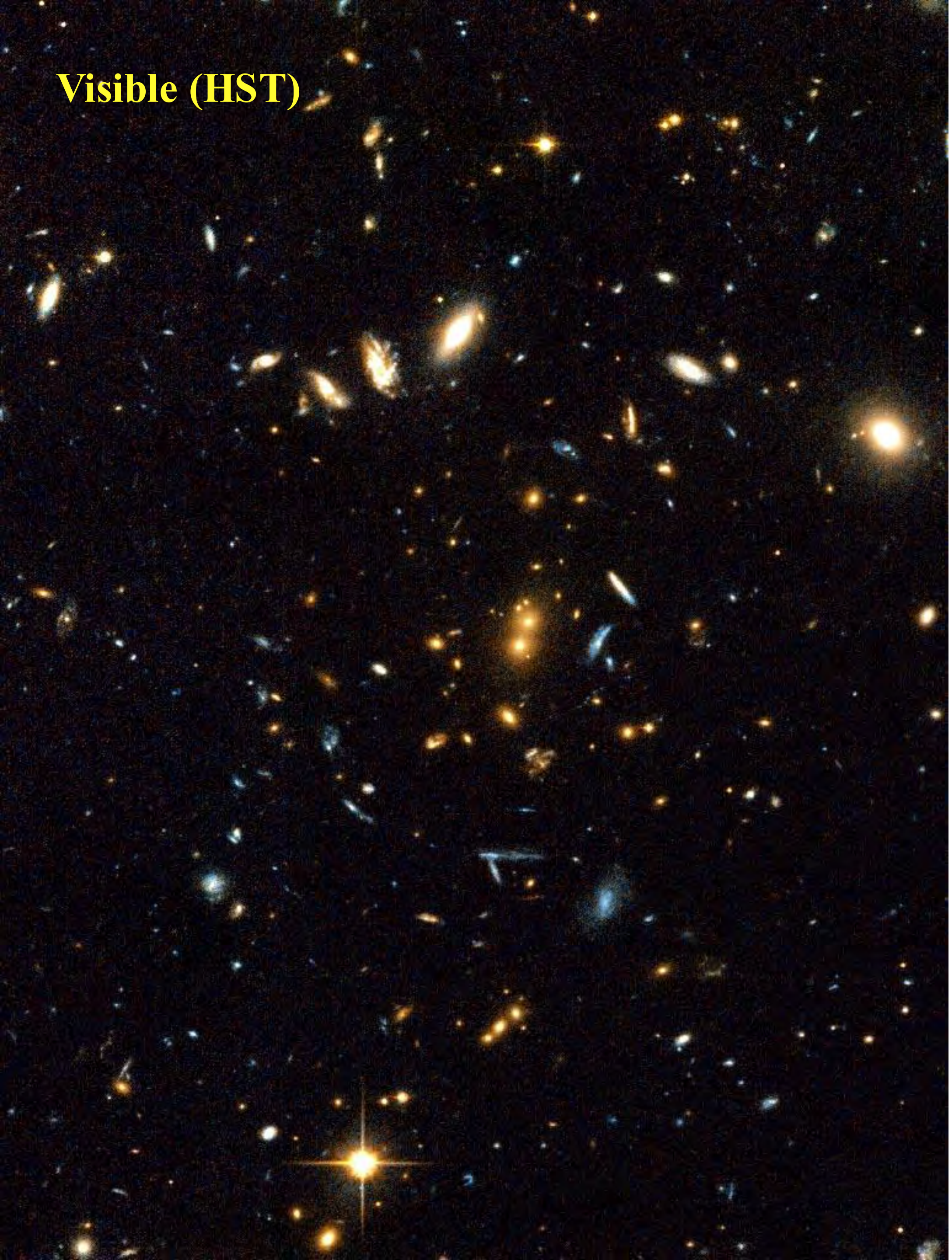


The Coma Cluster

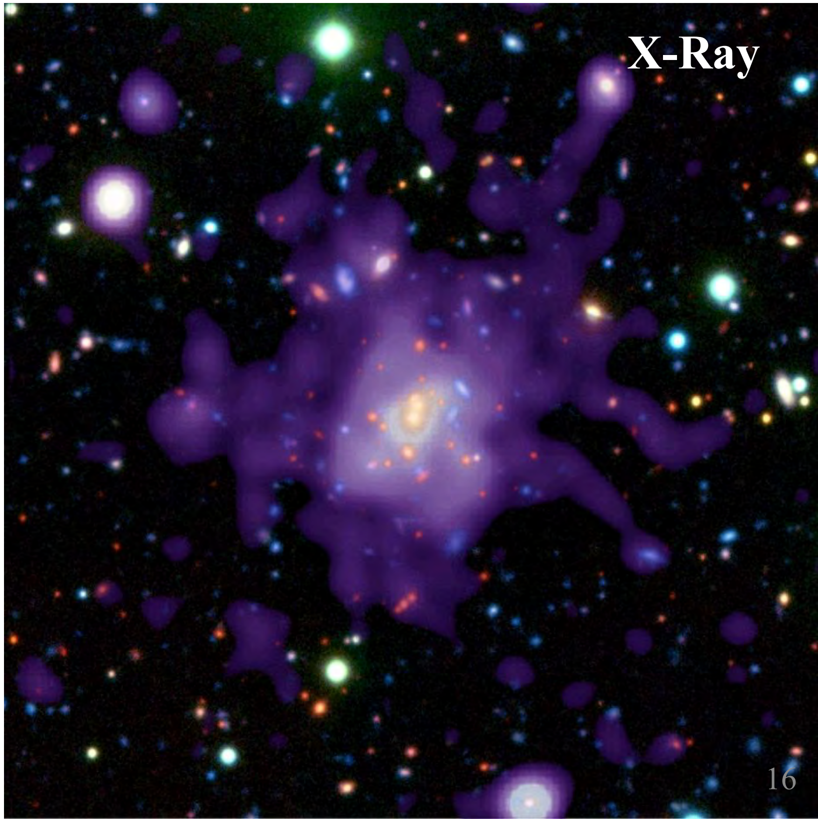
- Nearest rich cluster, with >10,000 galaxies
- Distance ~ 90 Mpc
- Diameter ~ 4-5° on the sky, 6-8 Mpc



X-ray / visible overlay



One of the most distant clusters now known, 1252-2927 (z = 1.24)



Surveys for Galaxy Clusters

Galaxy clusters contain galaxies, hot gas, and dark matter

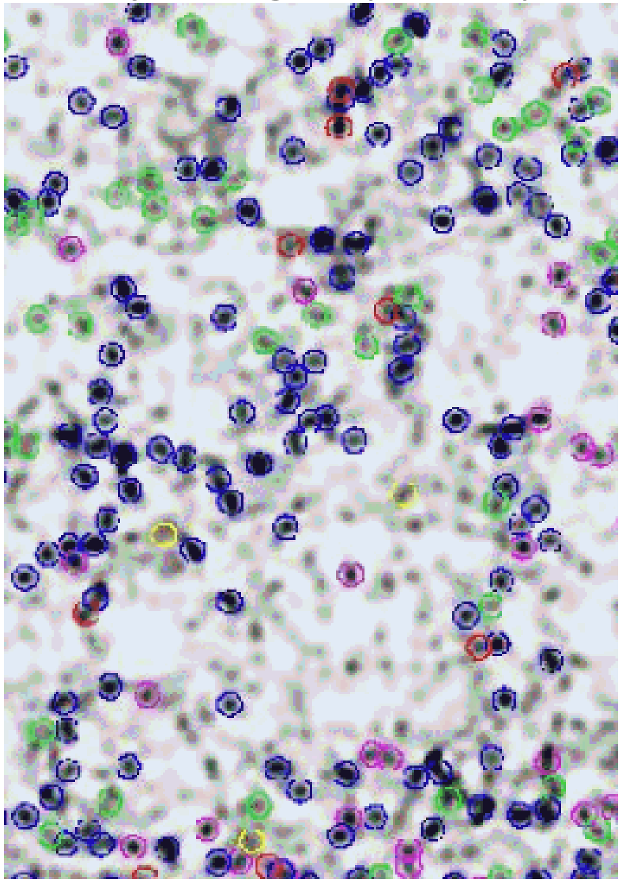
Can survey for each of these components using observations in different wavebands:

1. Optical

- Look for an overdensity of galaxies in patches on the sky
- Can use color information (clusters contain many red elliptical galaxies)
- At higher redshifts, use redder bands

Disadvantages: vulnerable to the *projection effects*, and rich clusters in the optical may not have especially high mass

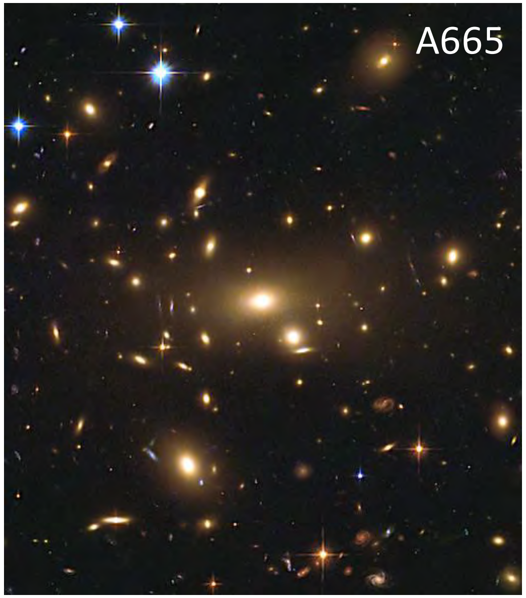
Projected galaxy density

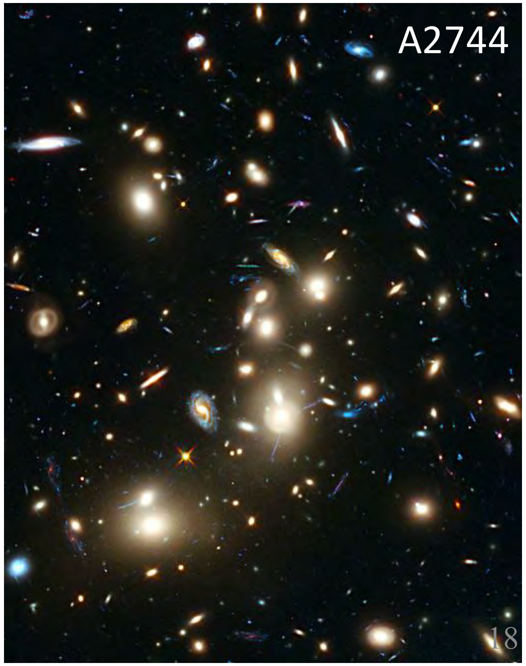


(Gal et al., DPOSS)

Abell Cluster Catalog

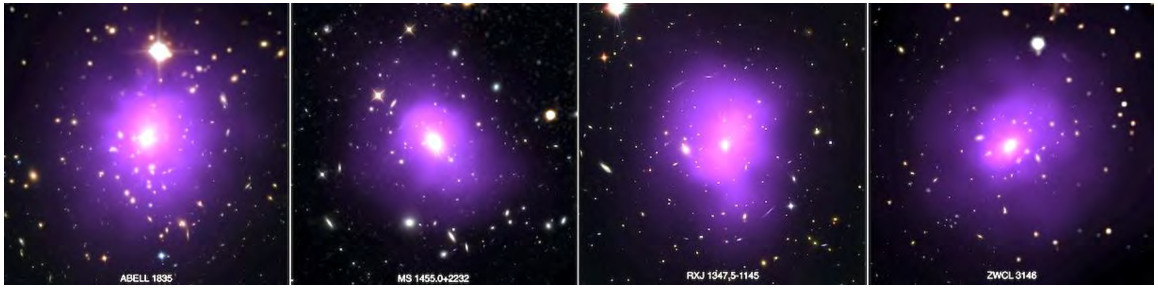
- Nearby clusters cataloged by Abell (1958), extended to the south by Abell et al. (1989)
  - Found by visual inspection of the sky survey plates
  - Define a region of radius $R_A = 1.5h^{-1}$ (Abell radius)
  - Count galaxies within R_A with an apparent magnitude $m_3 < m < m_3 + 2$ (m_3 is the magnitude of the 3rd brightest cluster member)
  - A total of 4073 rich clusters (2712 in the north)
- Richness class is defined by the number of galaxies with $m < m_3 + 2$ over the background
  - Richness class 1-2-3-4 correspond to N = 50-80-130-200 galaxies
  - Most clusters are poor (richness class 0), the catalog is incomplete here
- Extended by more modern work using an automated, objective selection, e.g., ~ 20,000 clusters from DPOSS (Gal et al.)





Surveys for Galaxy Clusters

2. X-Rays



- Clusters contain hot ($\sim 10^7$ K) X-ray gas
- **Advantage:** emissivity scales with density and temperature as $n^2 T^{1/2}$ - i.e., *quadratically* in the density. ***Much less*** vulnerable to accidental line-of-sight projection effects
- **Disadvantage:** still not detecting clusters based on mass

3. Sunyaev-Zeldovich effect

- Distortion of the CMB due to photons scattering off electrons in the cluster. Mass weighted measure, but really detects hot gas, not dark matter, and subject to messy hydrodynamics

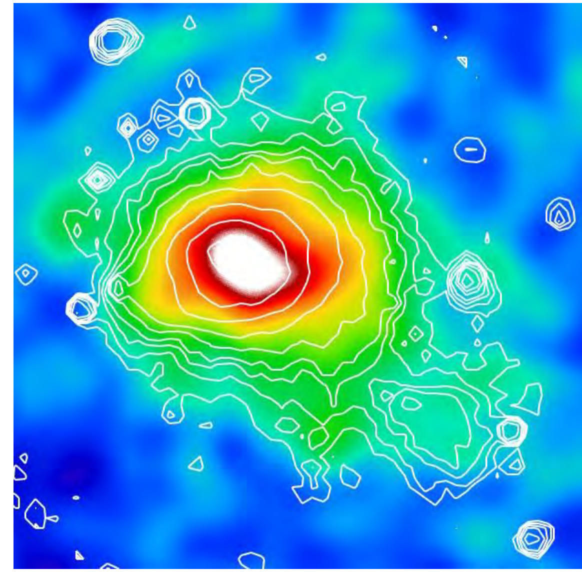
4. Weak Gravitational Lensing

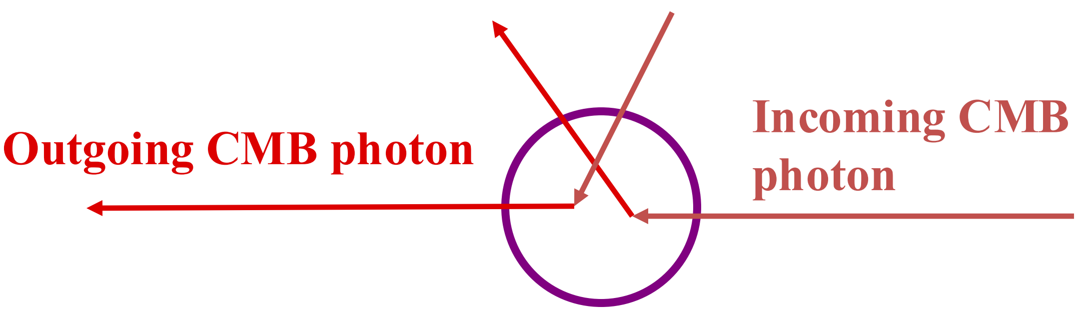
- Selection based on mass. Difficult observationally

Synyaev-Zeldovich Effect

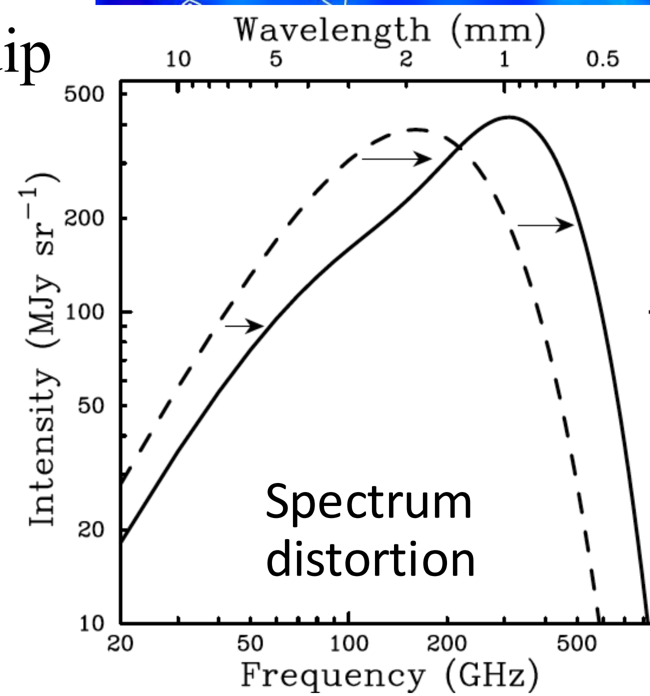
- Clusters are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons (inverse Compton scattering) from the CMBR to higher energies and distort the blackbody spectrum
- This is detectable as a slight temperature dip or bump in the radio map of the cluster, against the uniform CMBR background

Color =CMB intensity (*Planck*)
Contours = X-ray emission



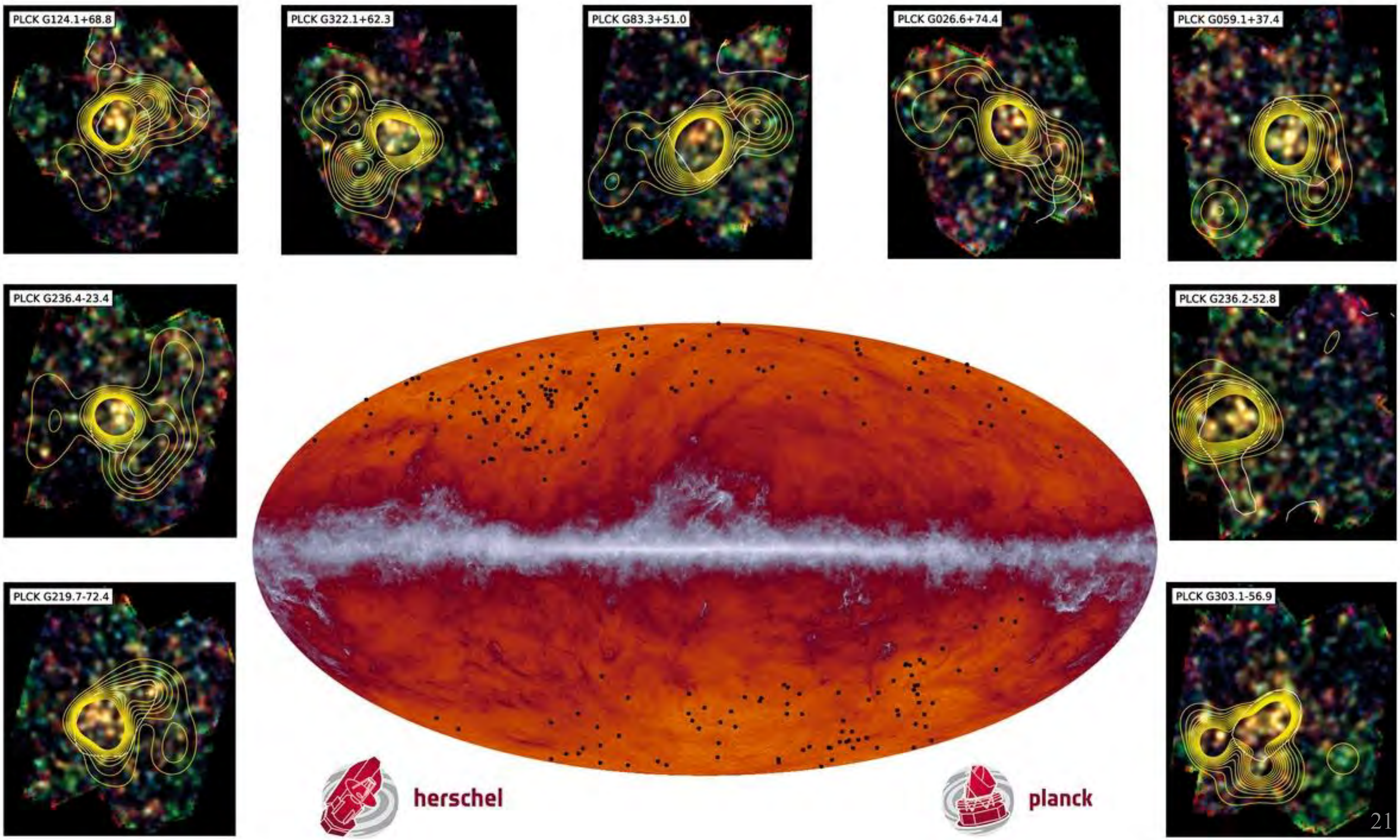


Galaxy Cluster with hot gas



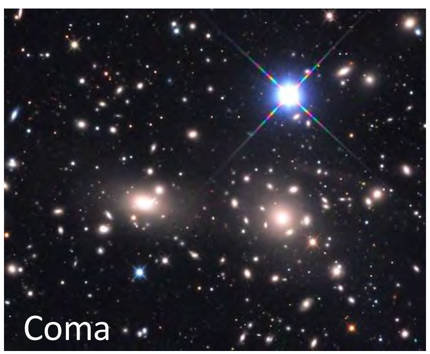
S-Z Cluster Selection

→ Herschel and Planck proto-cluster candidates



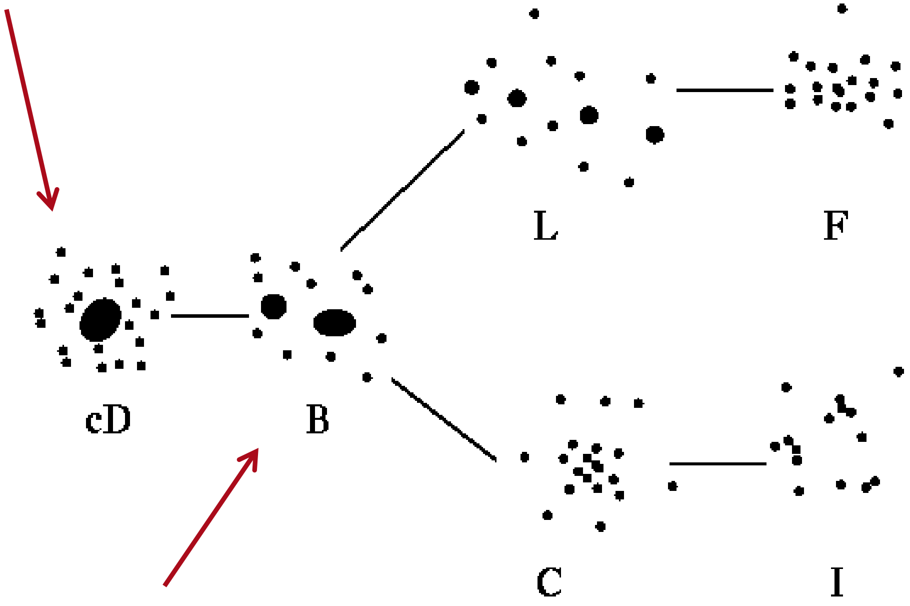
Morphological Classification of Clusters

An example is the **Rood and Sastry classification:**



Dominant central galaxy

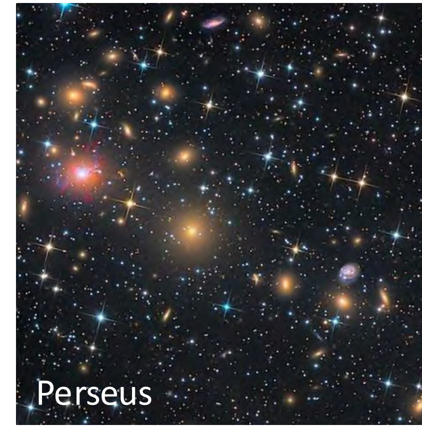
Linear or Flattened

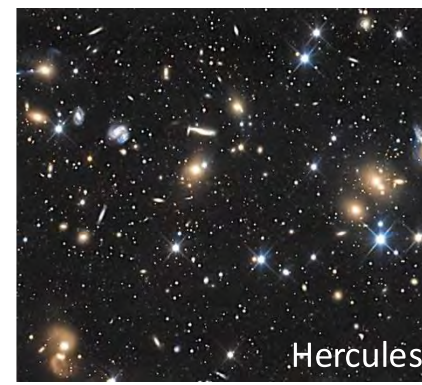


Central binary

Irregular

Evolution

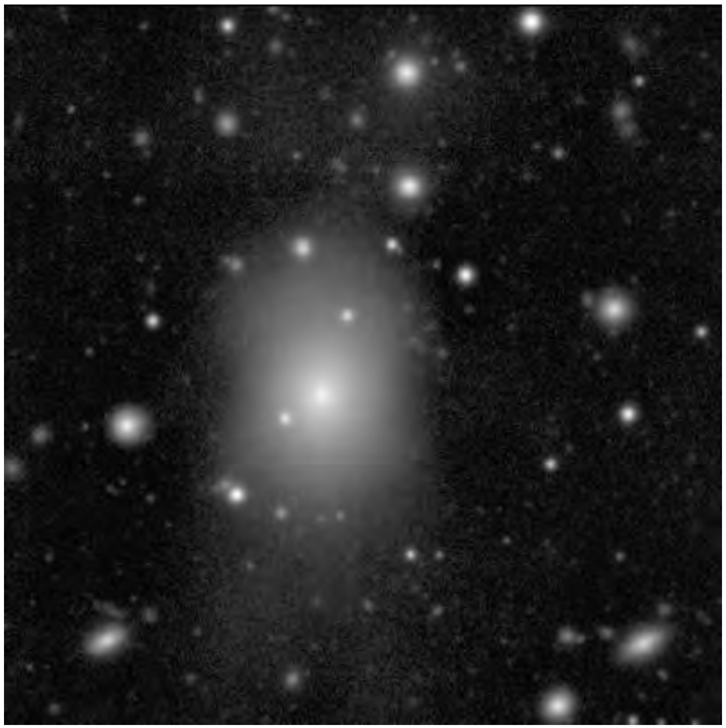


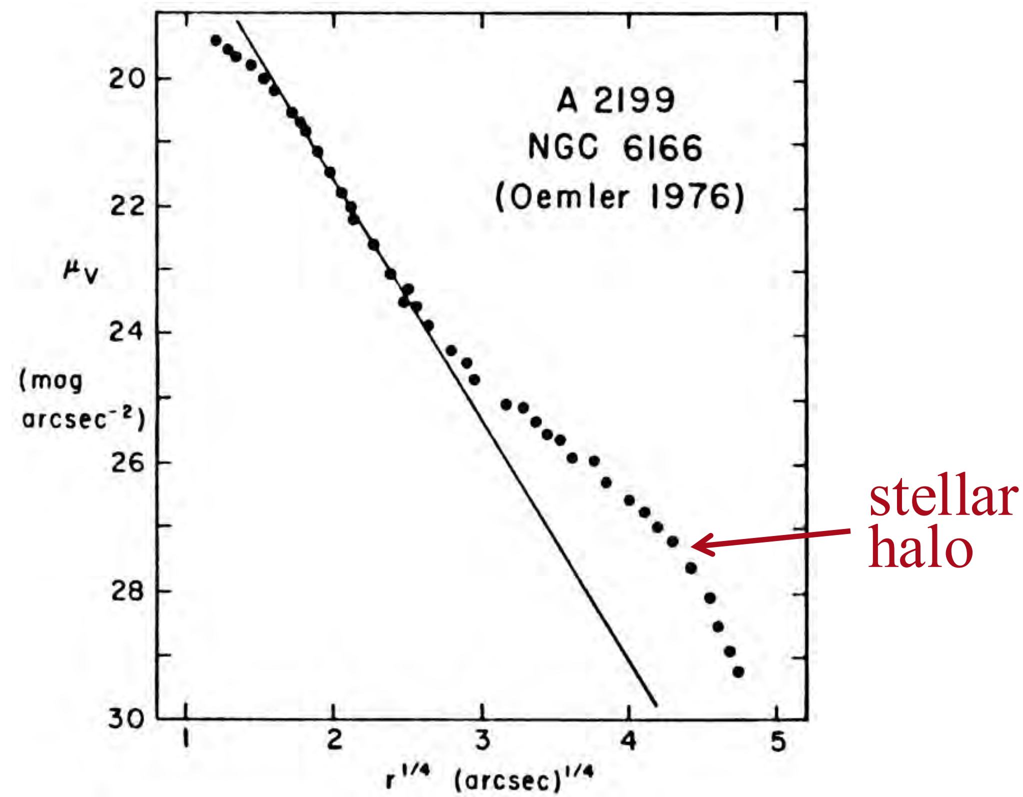


They reflect different stages of cluster assembly and dynamical evolution, which are still forming: more regular, symmetric clusters are dynamically older

Central Dominant (cD) Galaxies in Clusters

Many clusters have a single, dominant central galaxy. These are always giant ellipticals (gE), but some have extra-large, diffuse envelopes - these are called cD galaxies





These envelopes are probably just “star piles”, a remainder of many tidal interactions of cluster galaxies, sharing the bottom of the potential well with the gE galaxy

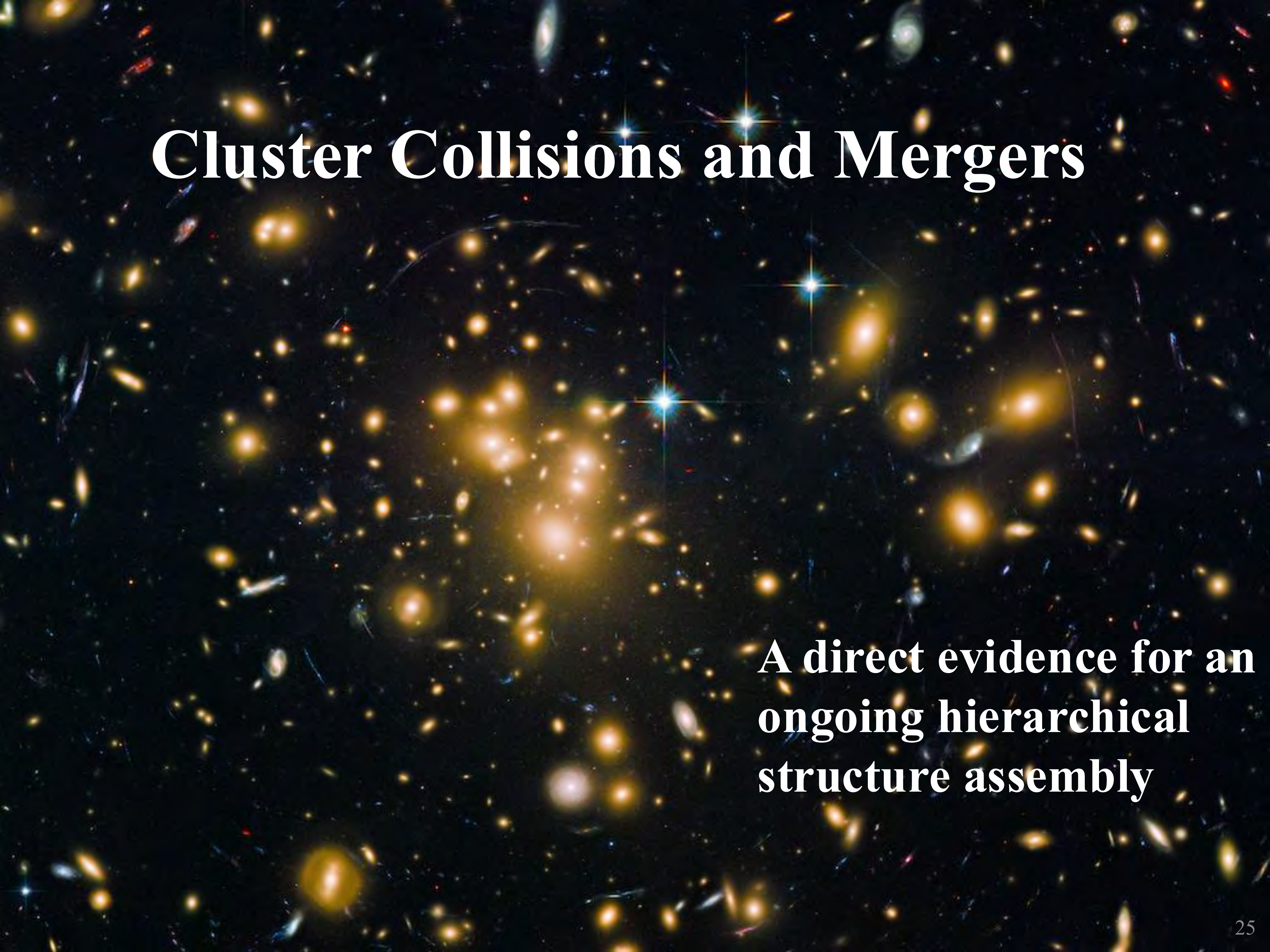
Some important trends:

- Spatial distribution of galaxies:
  - cD and regular clusters: spatial distribution is smooth and circularly symmetric, space density increases rapidly towards the cluster center
  - Spiral-rich and irregular clusters are not symmetric, with little central concentration. Spatial density is ~ uniform
- Morphological segregation:
  - In spiral-rich clusters, the distribution of E, SO, and Sp galaxies is about the same
  - In cD and spiral-poor clusters, the relative space density of spirals decreases rapidly to cluster core (morphology-density relation)

What does it all mean?

- Regular, cD clusters had time to relax and reach dynamic equilibrium
- Intermediate and Irregular clusters are still forming, and have not yet reached dynamic equilibrium
- cD galaxies are probably formed by merging in the central regions

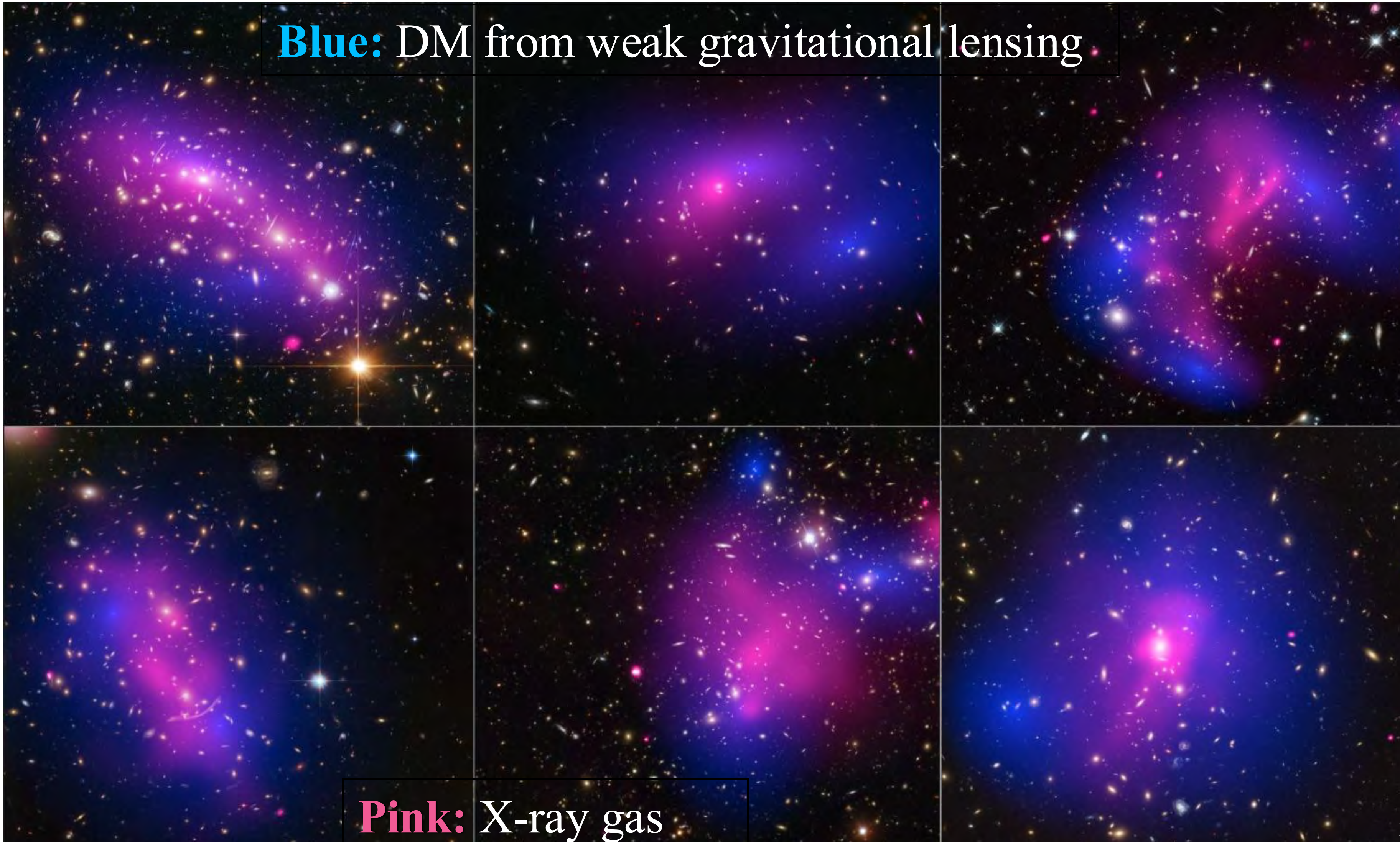
Cluster Collisions and Mergers



A direct evidence for an ongoing hierarchical structure assembly

Cluster Collisions and the "Bullet Clusters"

The dark matter halos largely pass through each other, whereas the X-ray gas collides and get shocked, and lags behind

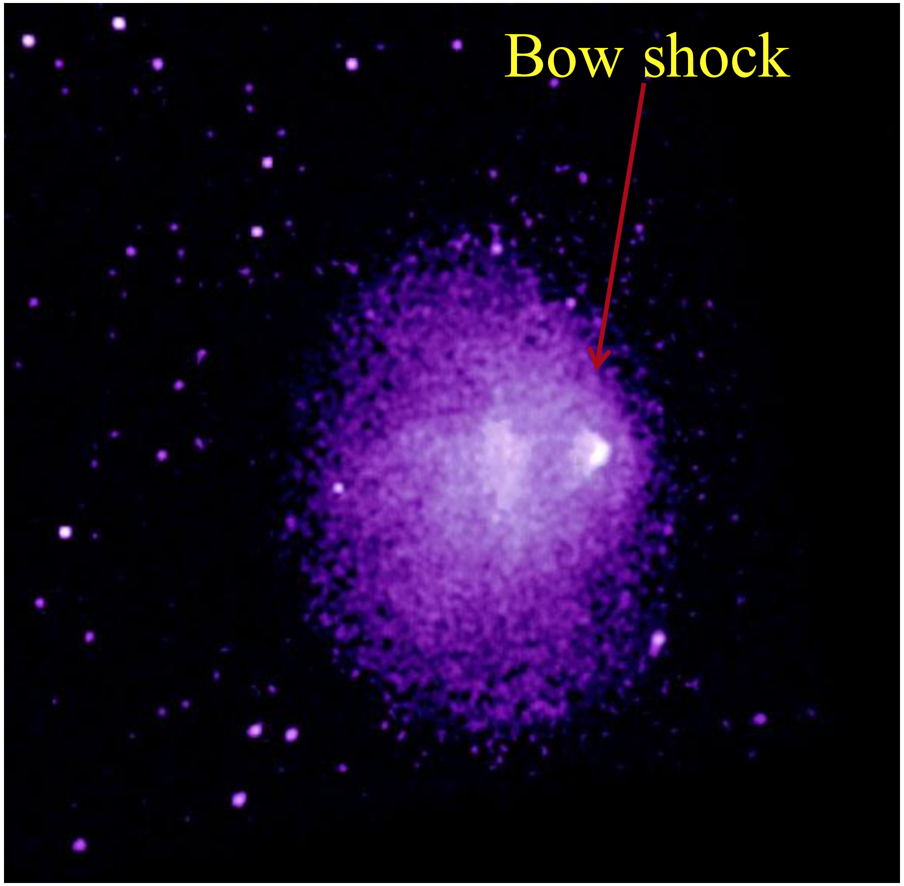


Hot X-ray Gas in Clusters

- Virial equilibrium temperature $T \sim 10^7 - 10^8$ K, the mechanism. Is free-free emission (Bremsstrahlung or "braking radiation")
- Many distant clusters are now being discovered via X-ray surveys
- Temperatures are not uniform, and such features may be due to the active galactic nuclei or to mergers with groups of galaxies
- X-ray gas has metallicity ~ 1/3 Solar, indicating that some of it was enriched ISM from galaxies, expelled by supernova winds
- But some gas must be around from the cluster formation process. It is heated via shocks as the gas falls into the cluster potential
- X-ray luminosity correlates with cluster classification: more regular clusters have higher X-ray luminosities

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



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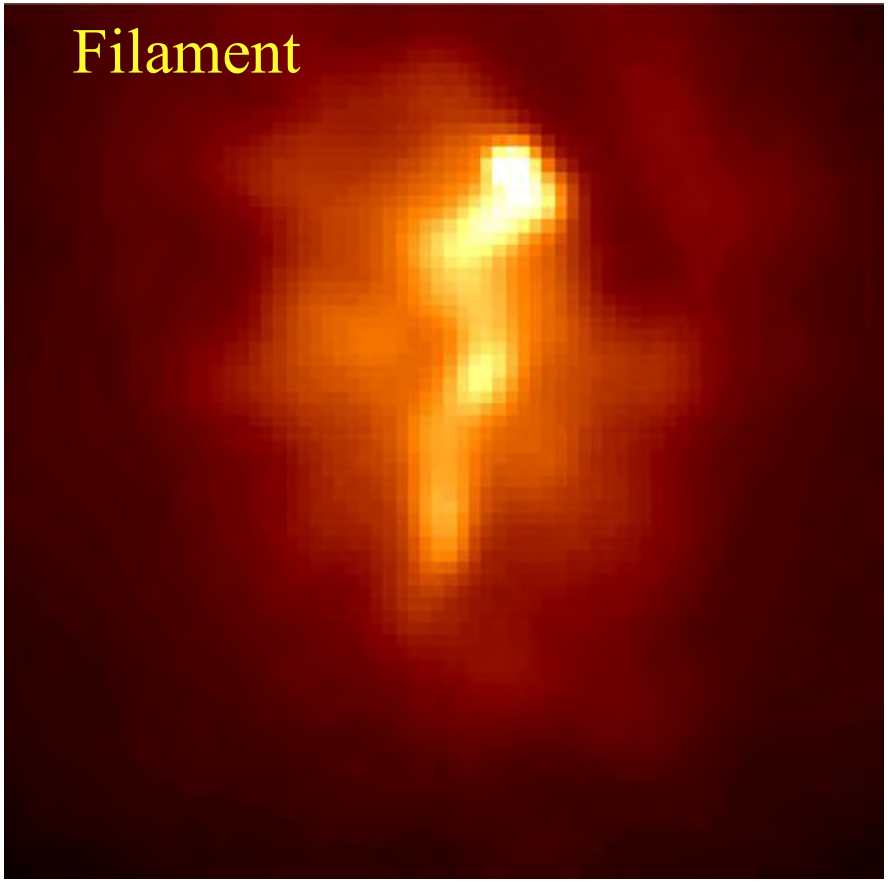

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Masses of Clusters From X-ray Gas

- 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

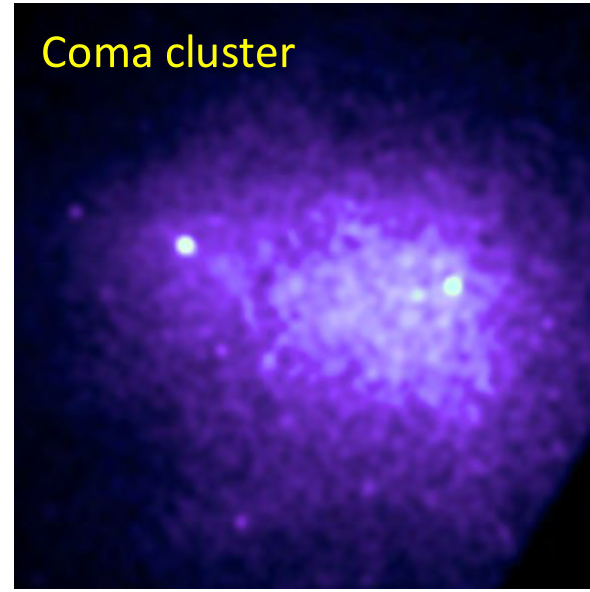
- Typical cluster mass components from X-rays:

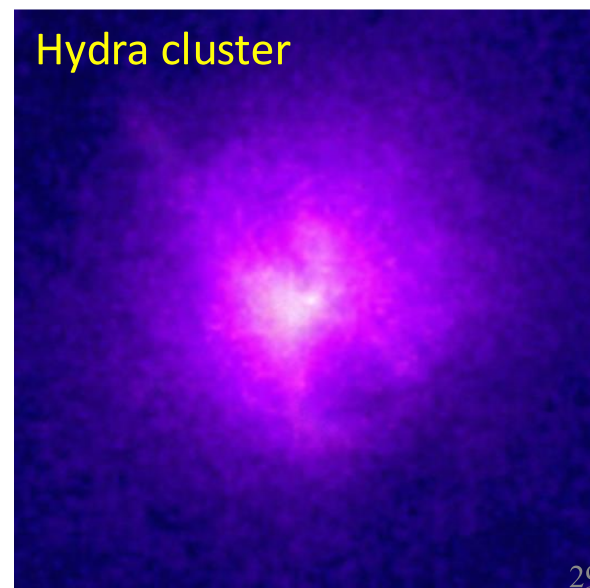
  Total mass: 10^{14} to 10^{15} $M_\odot$

  Luminous mass: ~5%

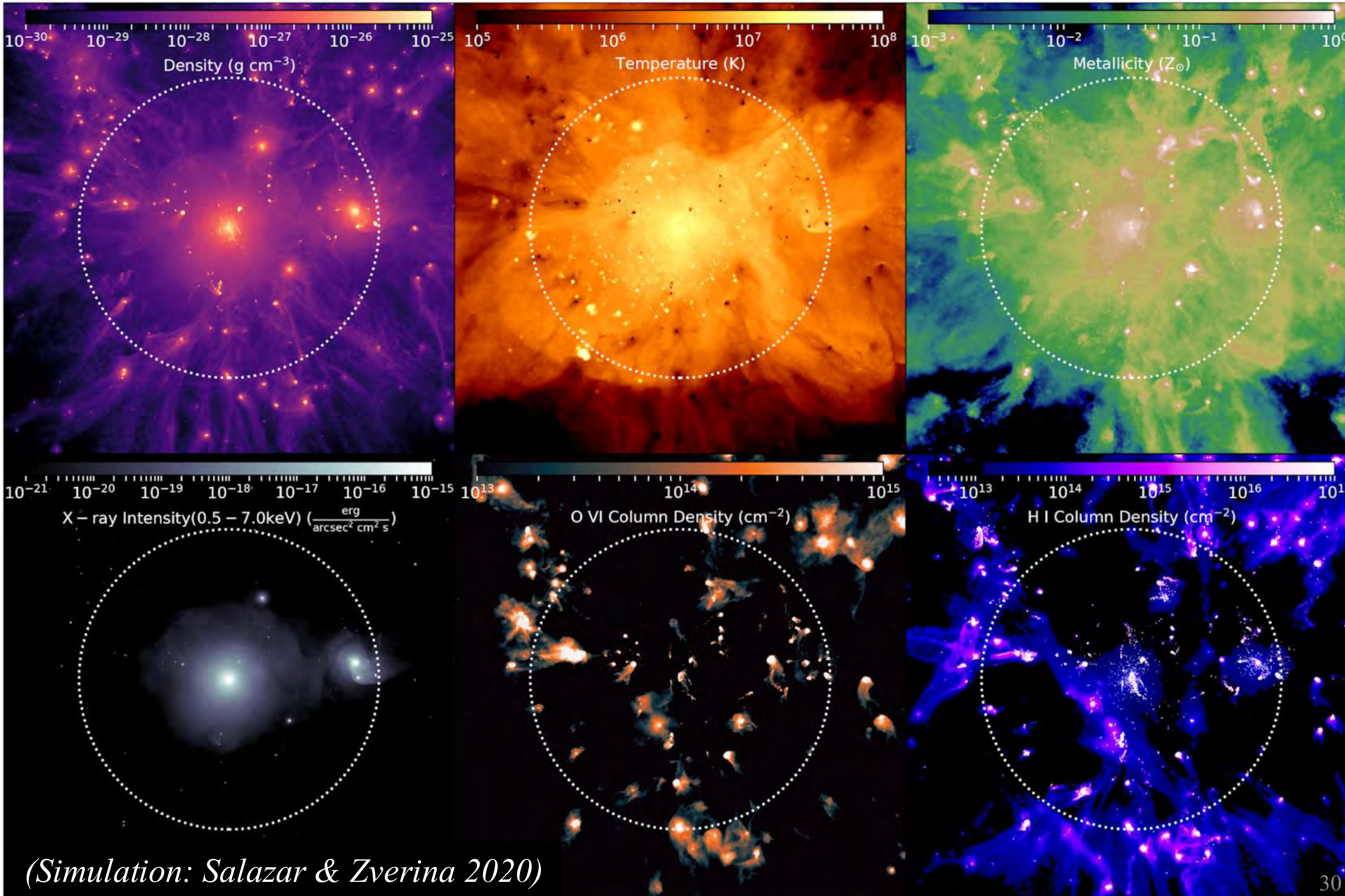
  Gaseous mass: ~ 10%

  Dark matter: ~85%



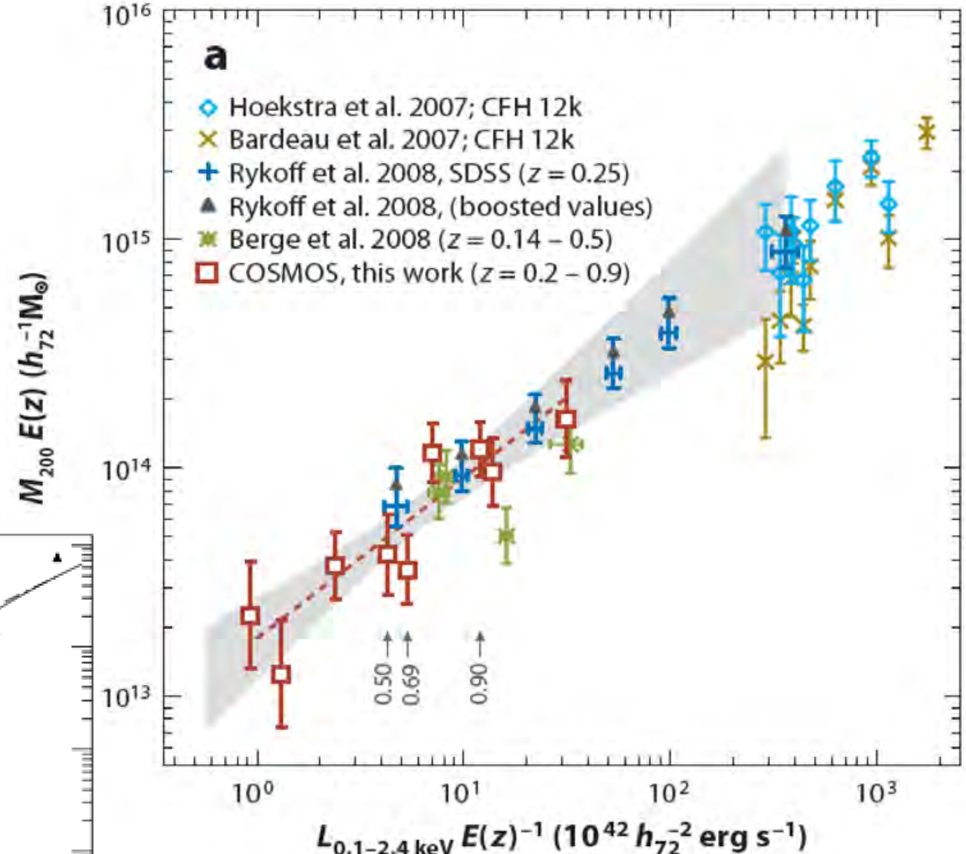


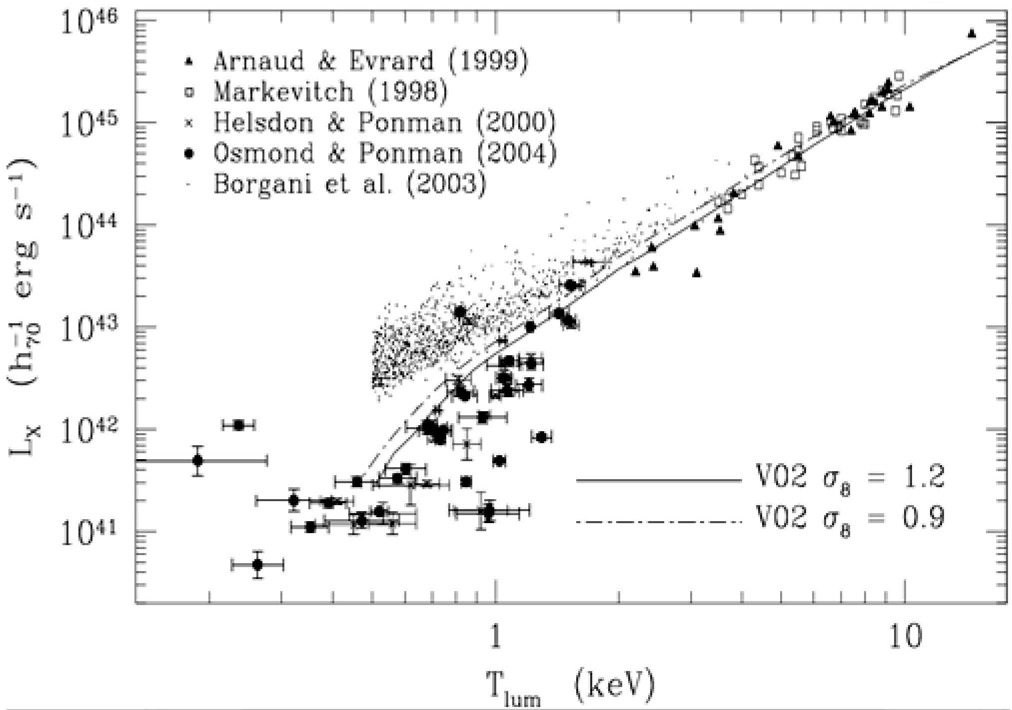
Numerical Simulations of Cluster Formation



(Simulation: Salazar & Zverina 2020)

Cluster X-Ray Luminosities Correlate With Mass and Temperature



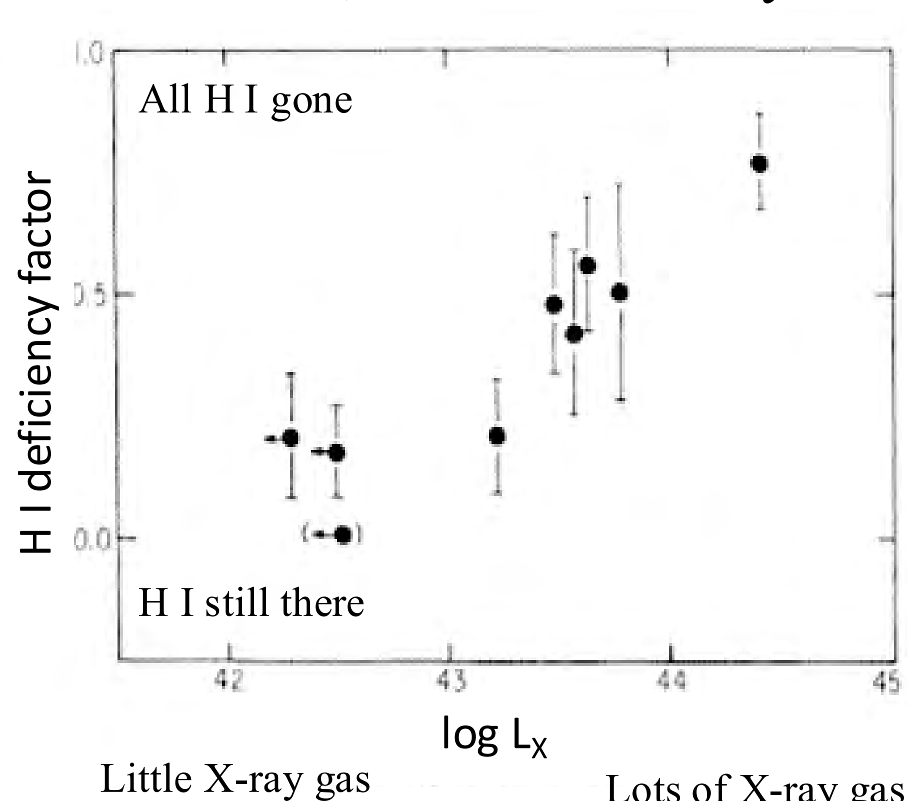


The gas temperature reflects the kinetic energy ($\sim kT$) needed to balance the gravitational potential

This implies that the X-ray luminous clusters are close to the dynamical equilibrium

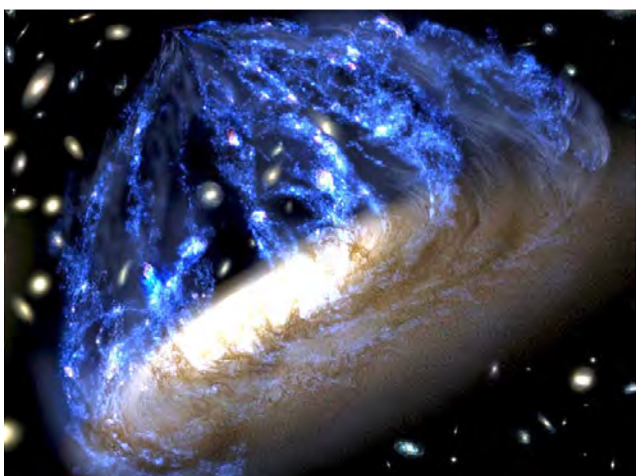
Hydrogen Gas Deficiency

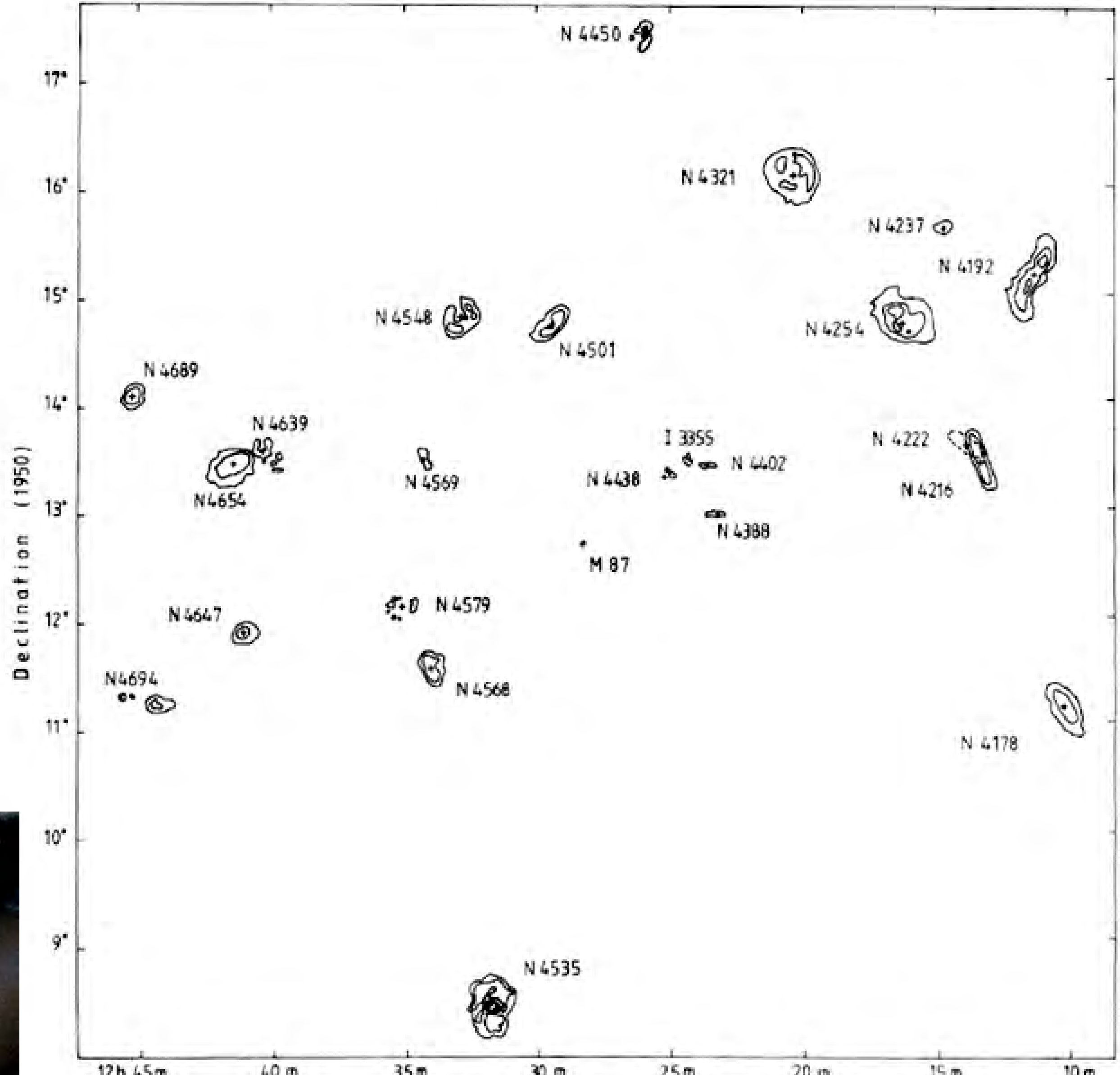
- As gas-rich galaxies (i.e., spirals) fall into clusters, their cold ISM is ram-pressure stripped by the cluster X-ray gas
- Evidence for stripping of gas in cluster spirals has been found from HI measurements
- Most deficient spirals are found in cluster cores, where the X-ray gas is densest
- HI deficiency 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 Map of the Virgo Cluster

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

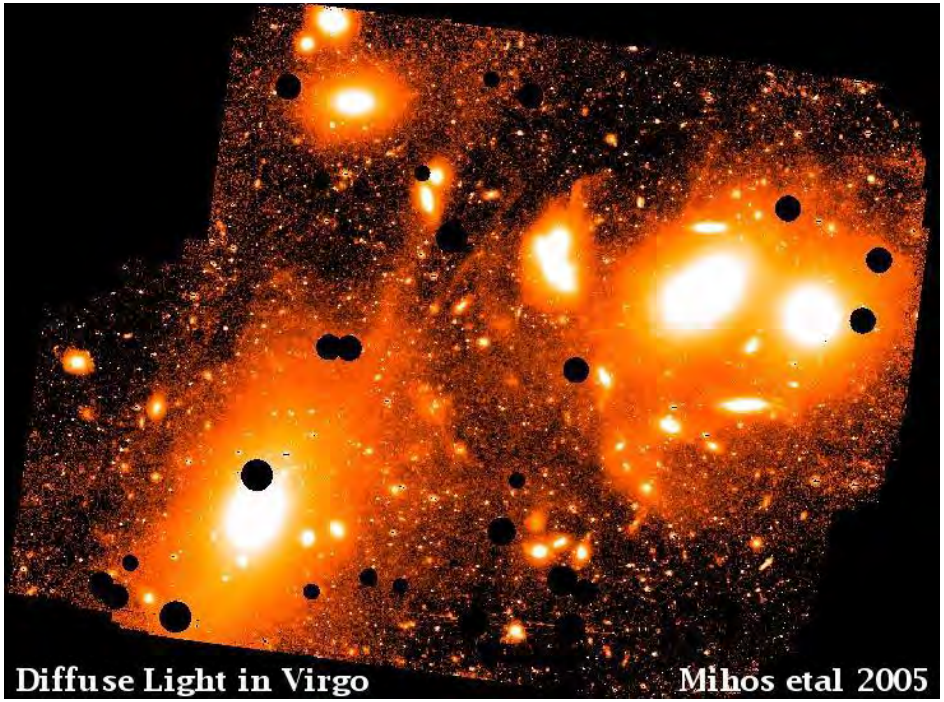




A direct evidence for the ram pressure stripping by the cluster X-ray gas

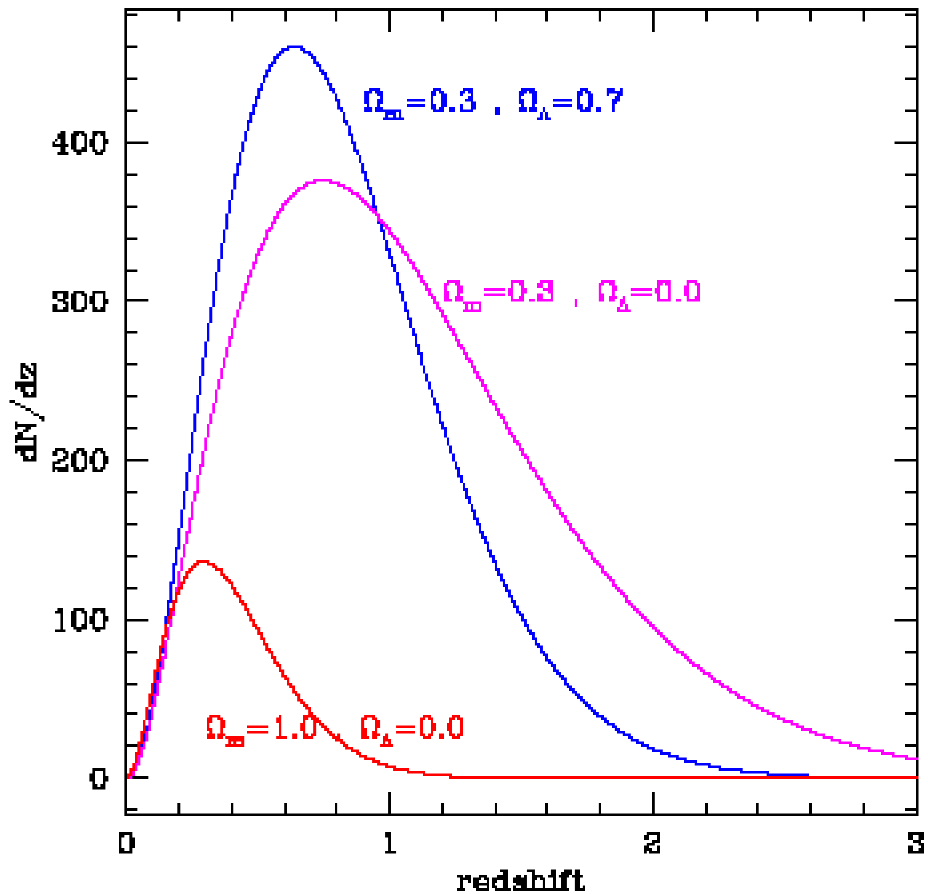
Intracluster Light

- Zwicky 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



Clusters as Cosmological Probes

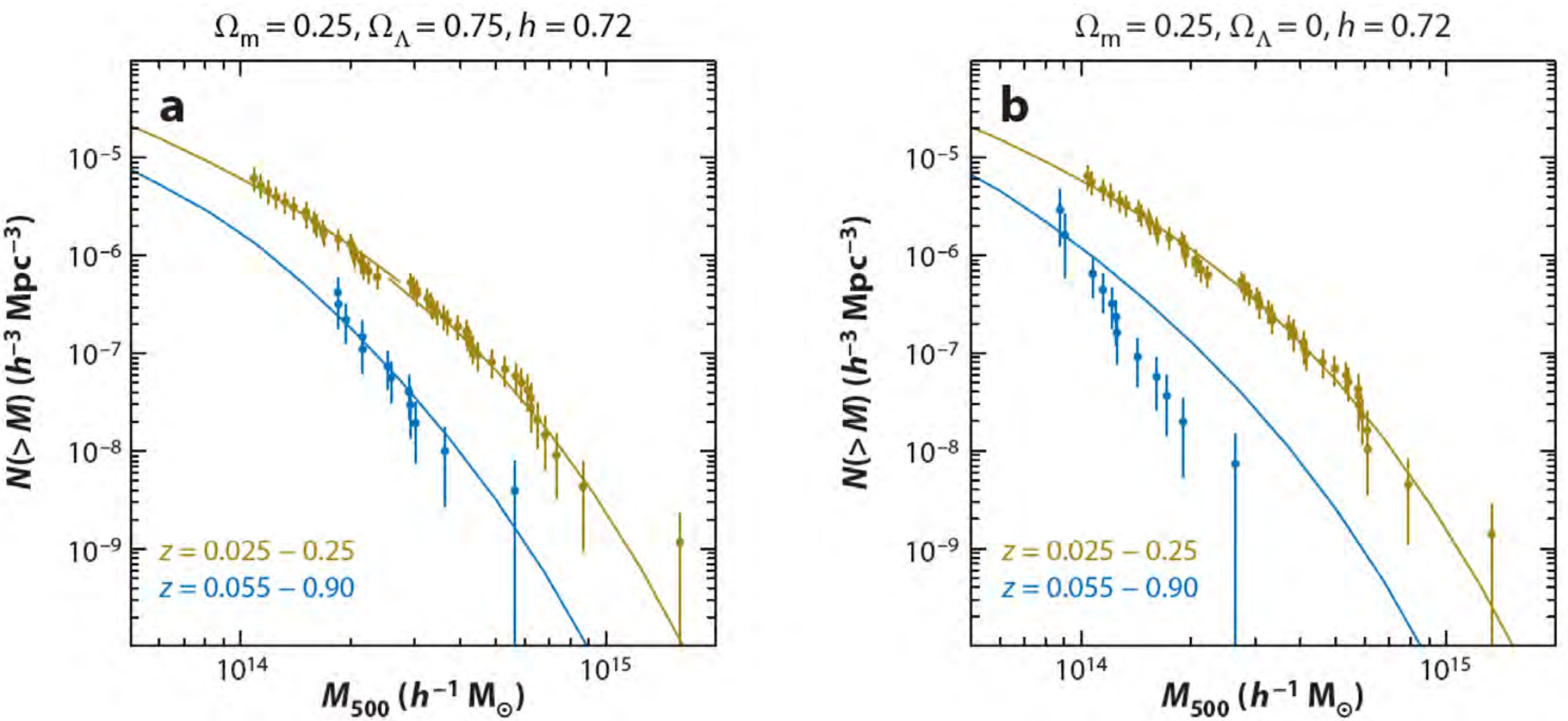
- Given the number density of nearby clusters, we can calculate how many distant clusters we expect to see
- In a high density universe, clusters are just forming now, and we don't expect to find any distant ones
- In a low density universe, clusters began forming long ago, and we expect to find many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



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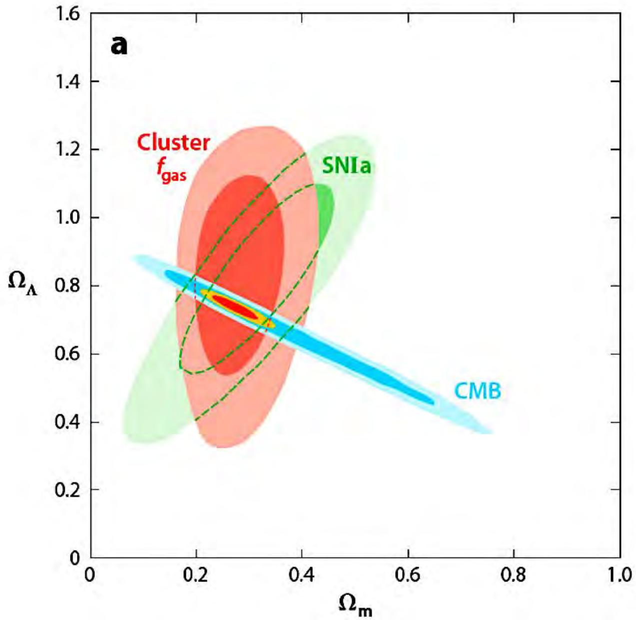

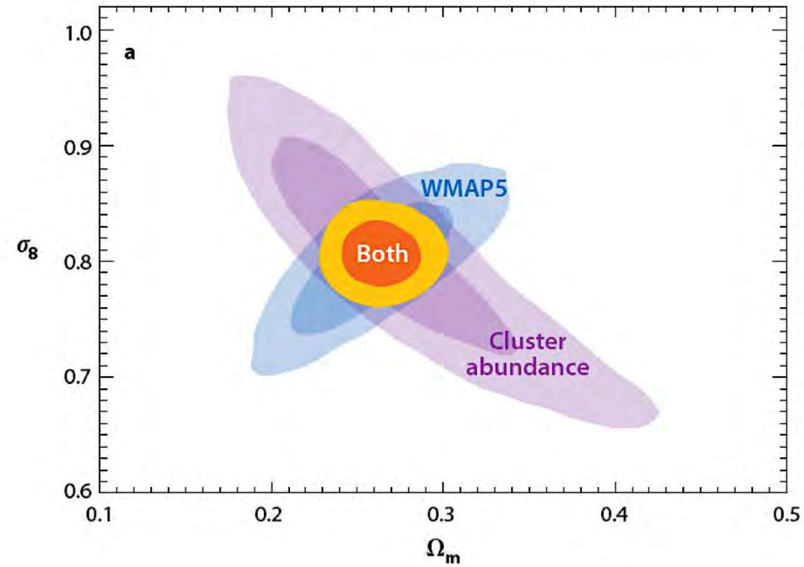

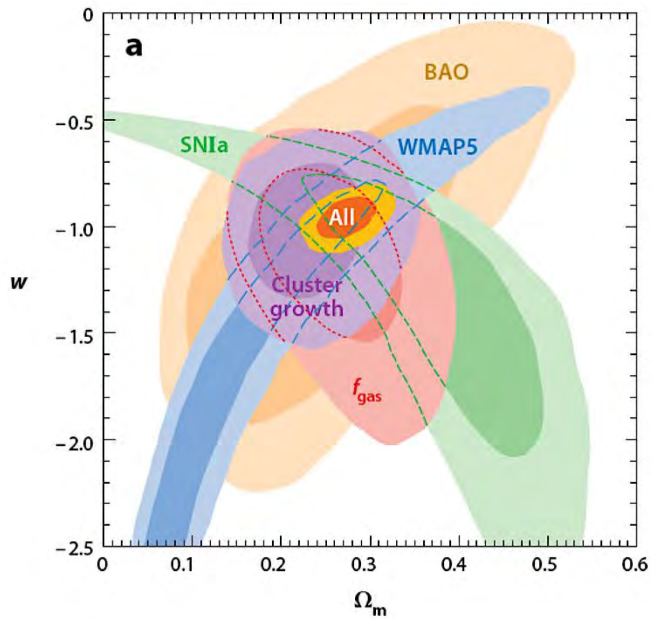

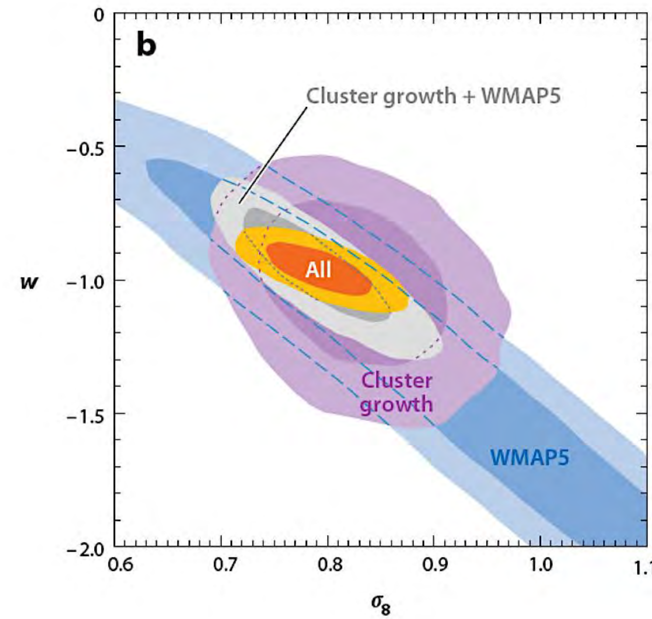

Clusters of Galaxies: Summary

- 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