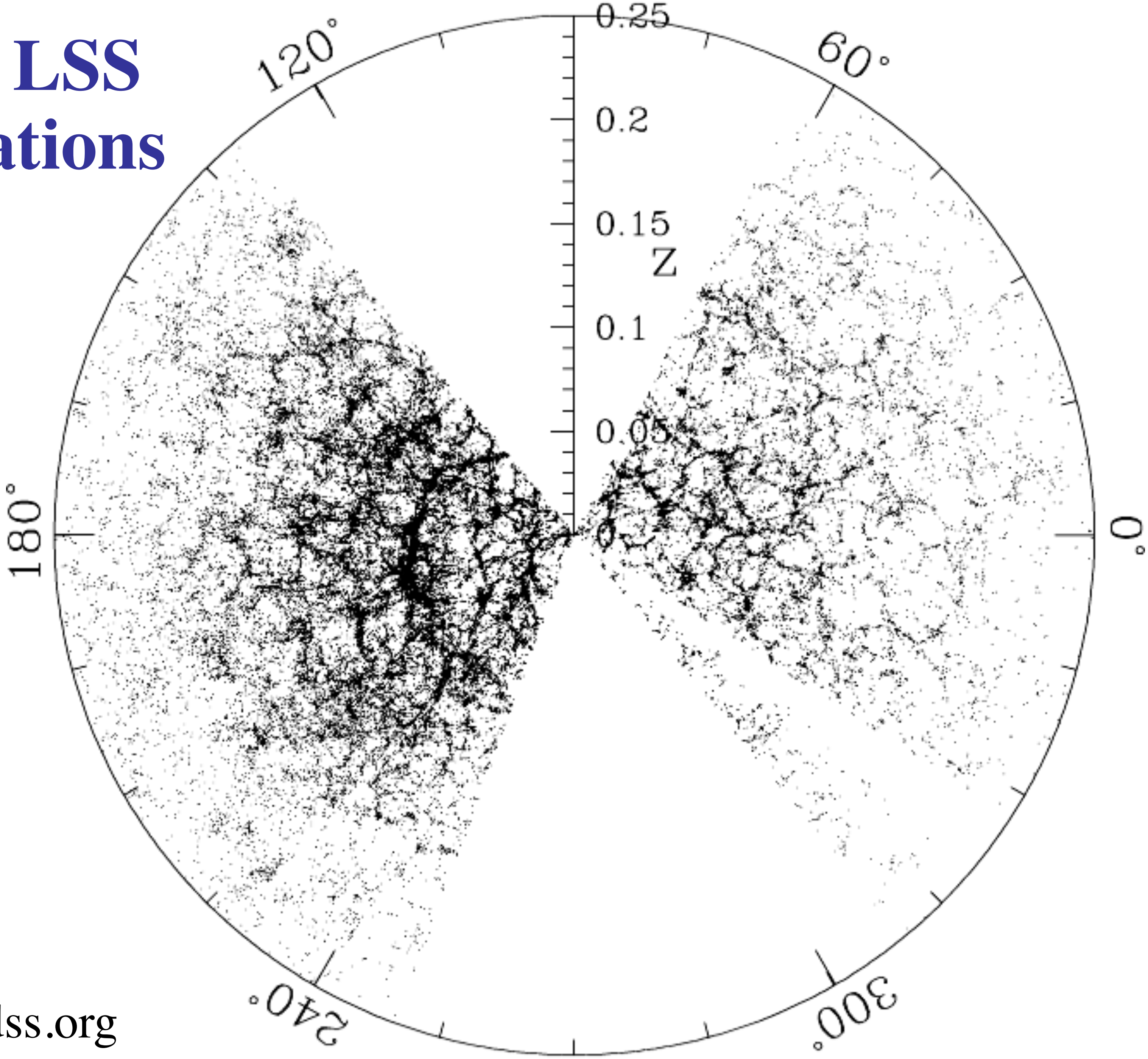
Ay 127: LSS Observations



http://www.sdss.org

Large-Scale Structure

- Density fluctuations evolve into structures we observe: galaxies, clusters, etc.
- On scales > galaxies, we talk about the **Large Scale Structure (LSS);** groups, clusters, filaments, walls, voids, superclusters are the elements of it
- To map and quantify the LSS (and compare with the theoretical predictions), we need **redshift surveys**: mapping the 3-D distribution of galaxies in the space
  - Today we have redshifts measured for ~ a million galaxies
- While the existence of clusters was recognized early on, it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures

Galaxy Distribution and Correlations

- If galaxies are clustered, they are "correlated"
- This is usually quantified using the ***2-point correlation function***, $\boldsymbol{\xi(r)}$**,** defined as an "excess probability" of finding another galaxy at a distance ***r*** from some galaxy, relative to a uniform random distribution; averaged over the entire set:

$$dN(r) = \rho_0 \left(1 + \xi(r)\right) dV_1 dV_2$$

- Usually represented as a power-law:

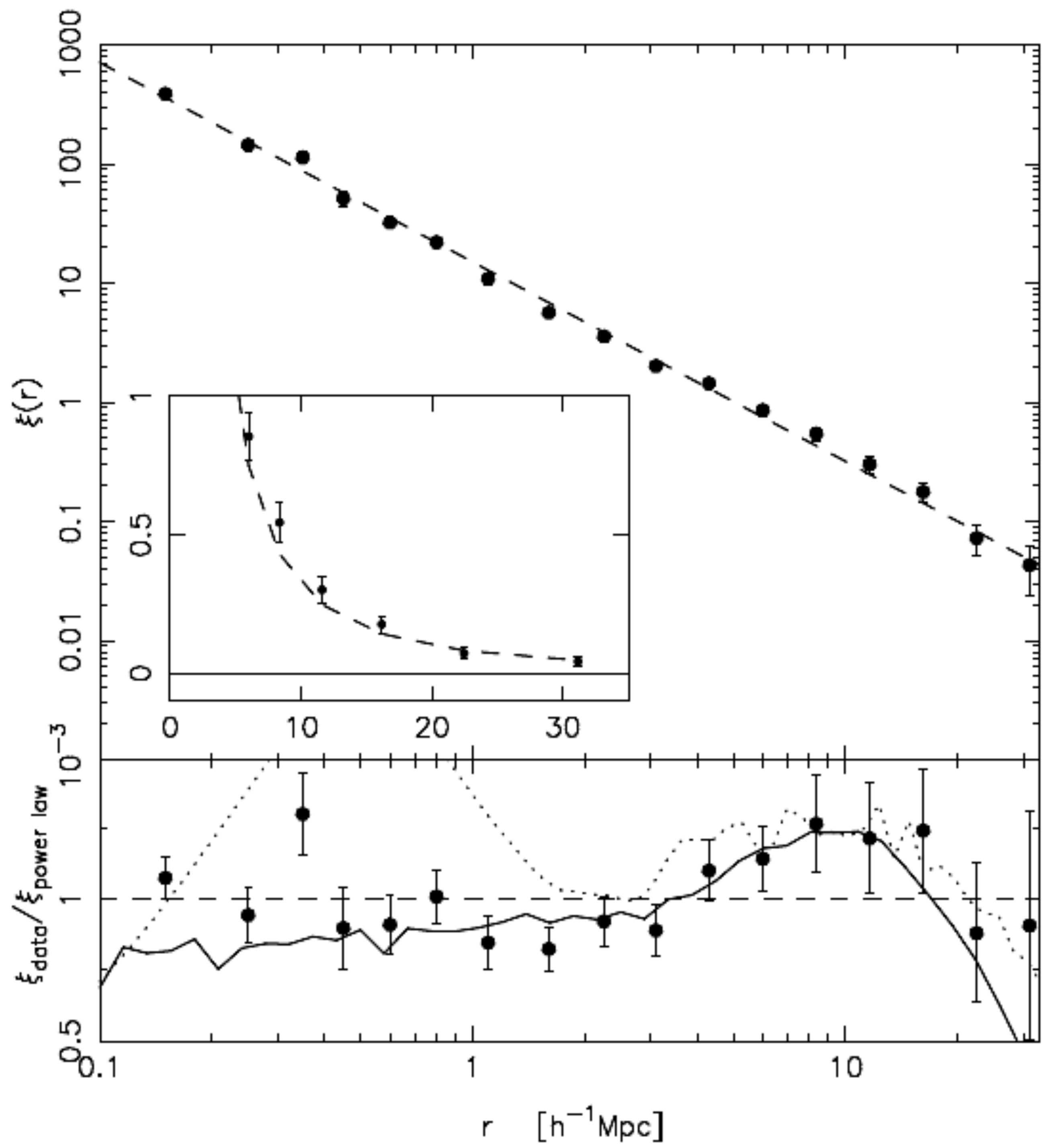
$$\xi(r) = \left(r / r_0\right)^{-\gamma}$$

- For galaxies, typical *correlation or clustering length* is $\boldsymbol{r_0} \sim 5$ h^{-1} Mpc, and typical slope is $\gamma \approx 1.8$, but these are functions of various galaxy properties; clustering of clusters is stronger

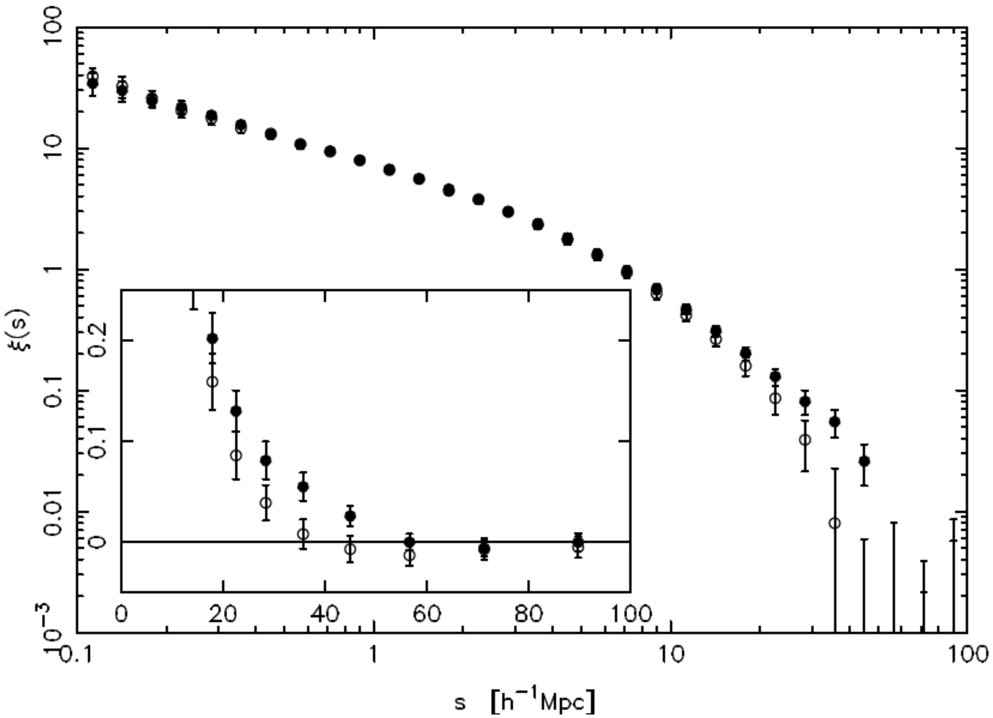
Galaxy Correlation Function

As measured by the 2dF redshift survey

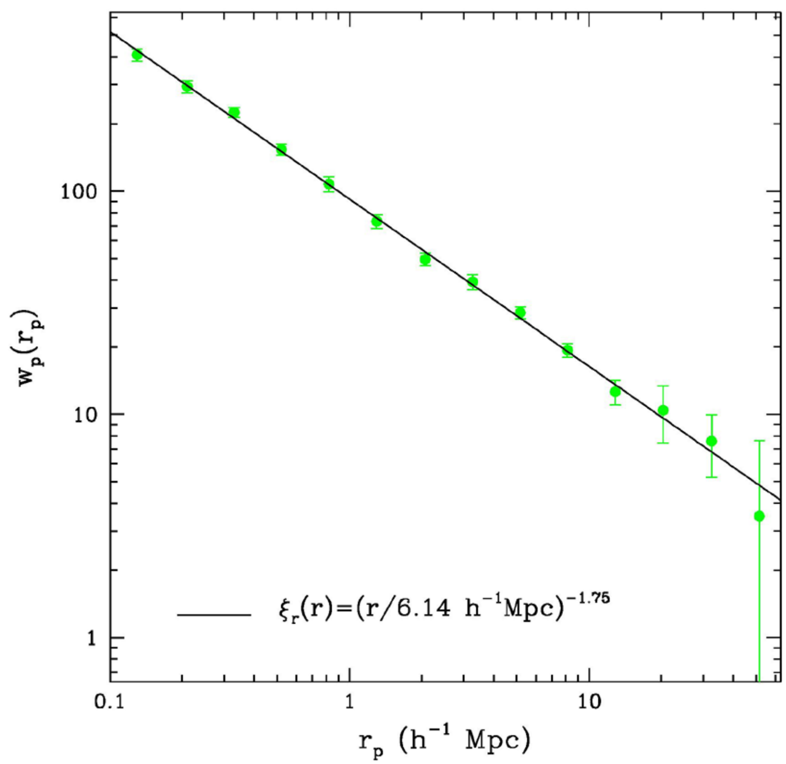
Deviations from the power law:



Galaxy Correlation Function



At sufficiently large scales, e.g., voids, $\boldsymbol{\xi(r)}$ must turn negative



- If only 2-D positions on the sky are known, then use angular separation $\boldsymbol{\theta}$ instead of distance $\boldsymbol{r}$:
  $\boldsymbol{w(\theta) = (\theta/\theta_0)^{-\beta},\ \ \beta = \gamma - 1}$

How to Measure ξ(r)

- Simplest estimator: count the number of data-data pairs, $\langle DD \rangle$, and the equivalent number in a randomly generated (Poissonian) catalog, $\langle RR \rangle$:

$$\xi(r)_{est} = \frac{\langle DD \rangle}{\langle RR \rangle} - 1$$

- A better (Landy-Szalay) estimator is:

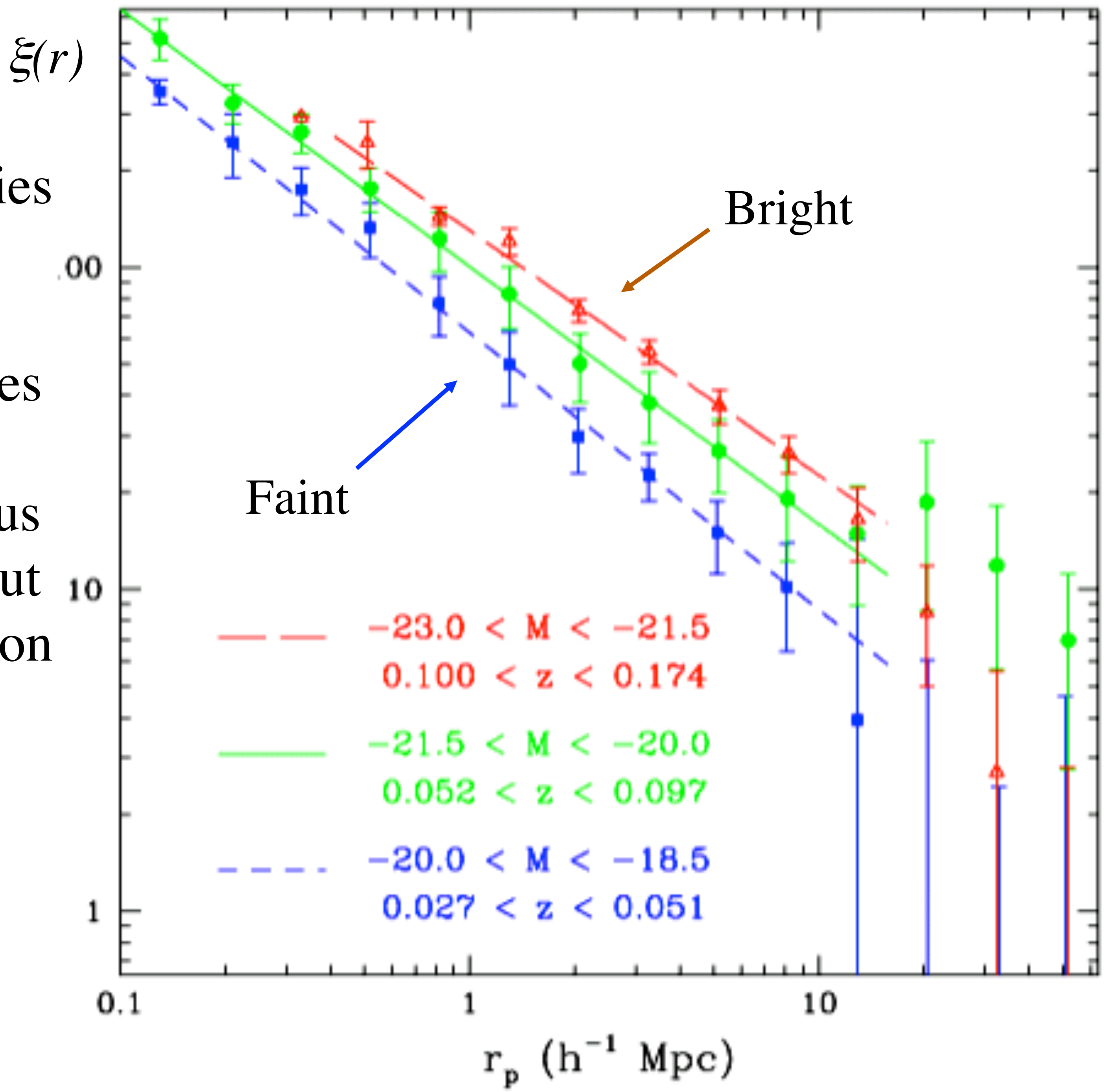
$$\xi(r)_{est} = \frac{\langle DD \rangle - 2\langle RD \rangle + \langle RR \rangle}{\langle RR \rangle}$$

where $\langle RD \rangle$ is the number of data-random pairs

- This takes care of the edge effects, where one has to account for the missing data outside the region sampled, which can have fairly irregular boundaries

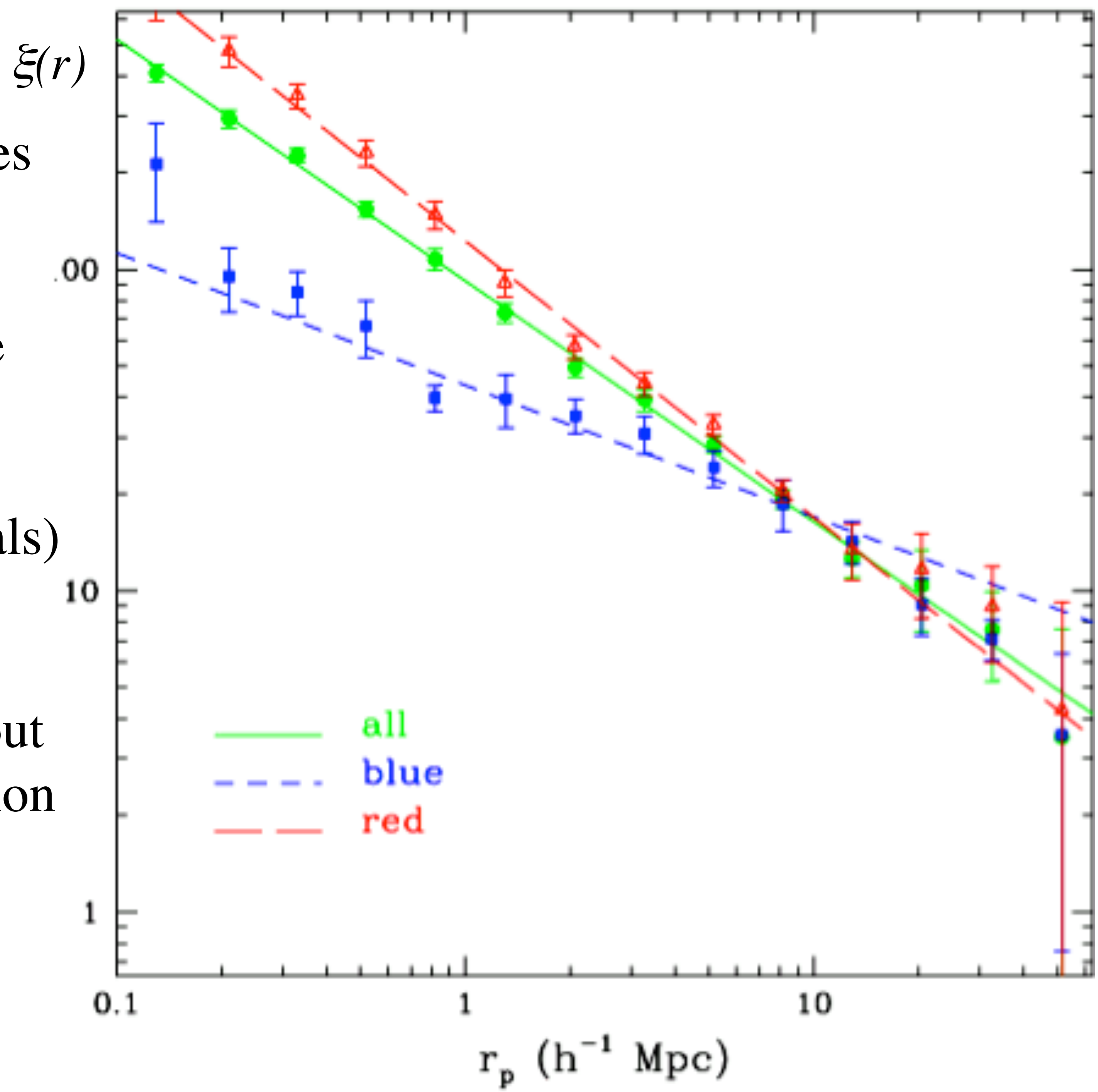
Brighter galaxies are clustered more strongly than fainter ones

This is telling us something about galaxy formation

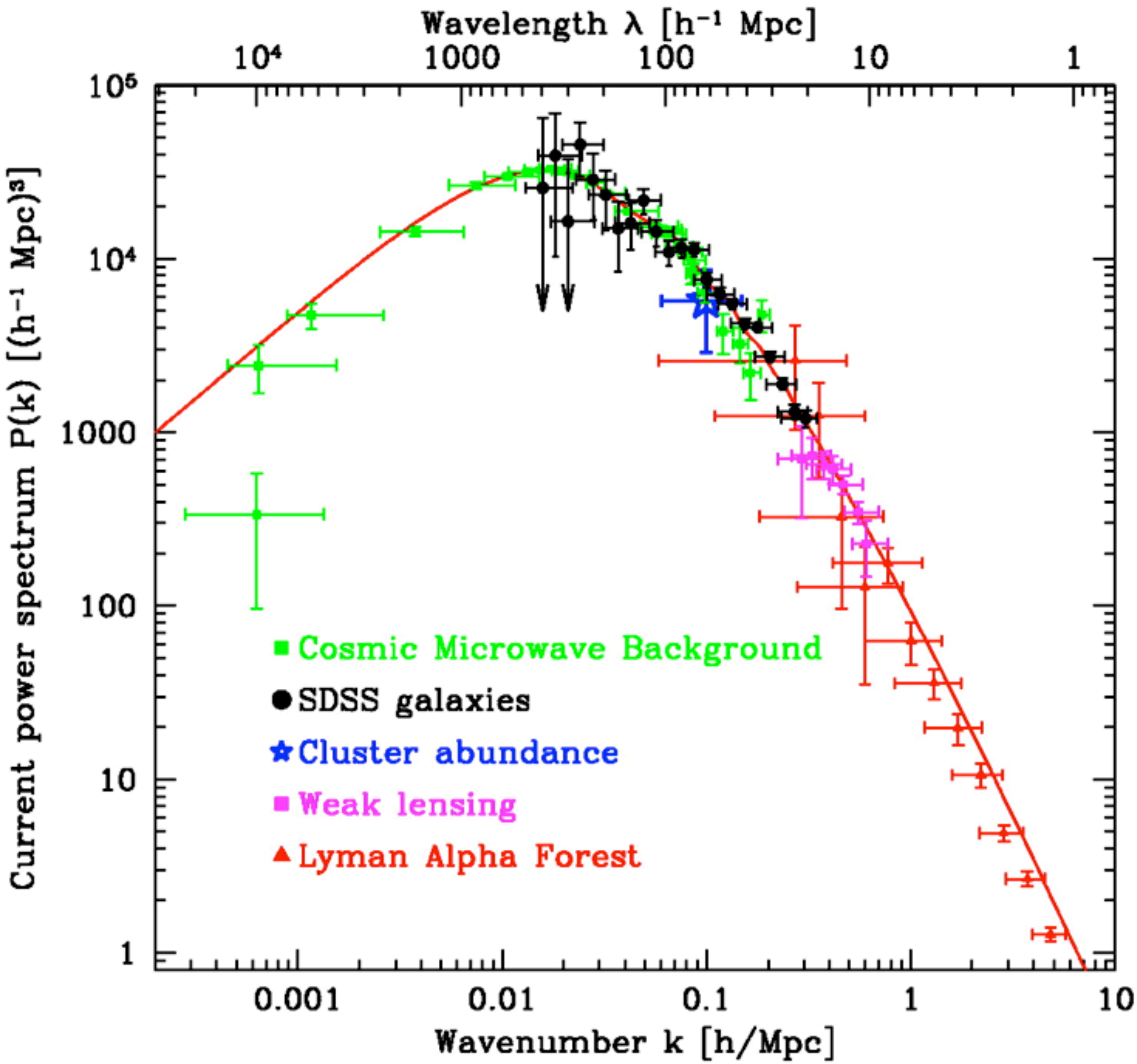


Redder galaxies (or early-type, ellipticals) are clustered more strongly than bluer ones (or late-type, spirals)

That, too, says something about galaxy formation



The Observed Power Spectrum



(Tegmark et al.)

Normalizing the Power Spectrum

- Define σ_R as the r.m.s. of mass fluctuations on the scale R
- Typically a sphere with a radius $R = 8\ h^{-1}$ Mpc is used, as it gives $\sigma \approx 1$
- So, the amplitude of $P(k)$ is ~ 1 at k = 2π / (8 h^{-1} Mpc)
- This is often used to normalize the spectrum of the PDF
- Mathematically, where K_R is a convolving kernel, a spherical top-hat with a radius R:

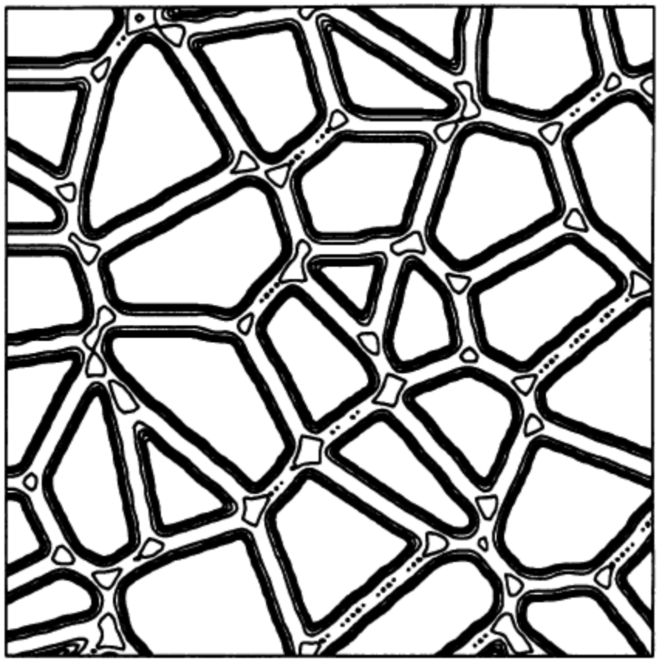
$$\sigma_R{}^2 = \frac{1}{4\pi^2}\int d\ln k\left[k^3 P(k)\left|K_R(k)\right|^2\right]$$

$$K_R(r) = \begin{cases} 1, & \text{if } r < R \\ 0, & \text{if } r \geq R \end{cases} \qquad K_R(k) = \left[\frac{j_1(kr)}{kr}\right]$$

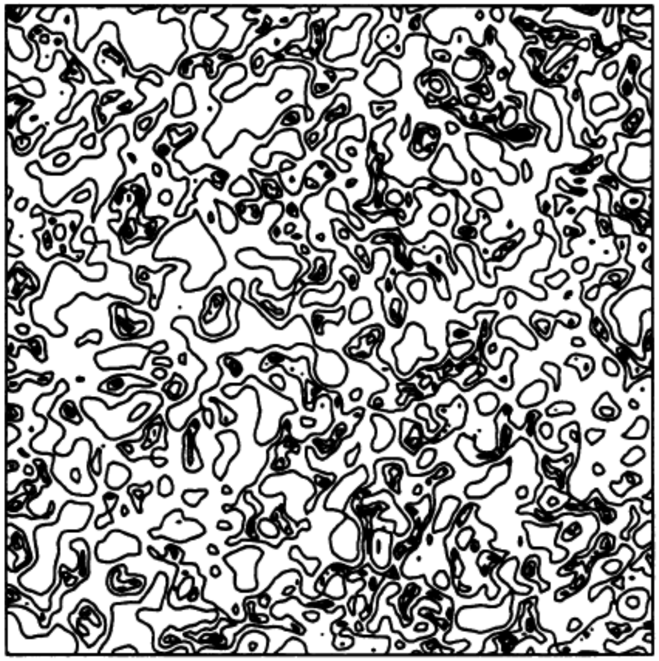
Is the Power Spectrum Enough?

These two images have
identical power spectra
(by construction)

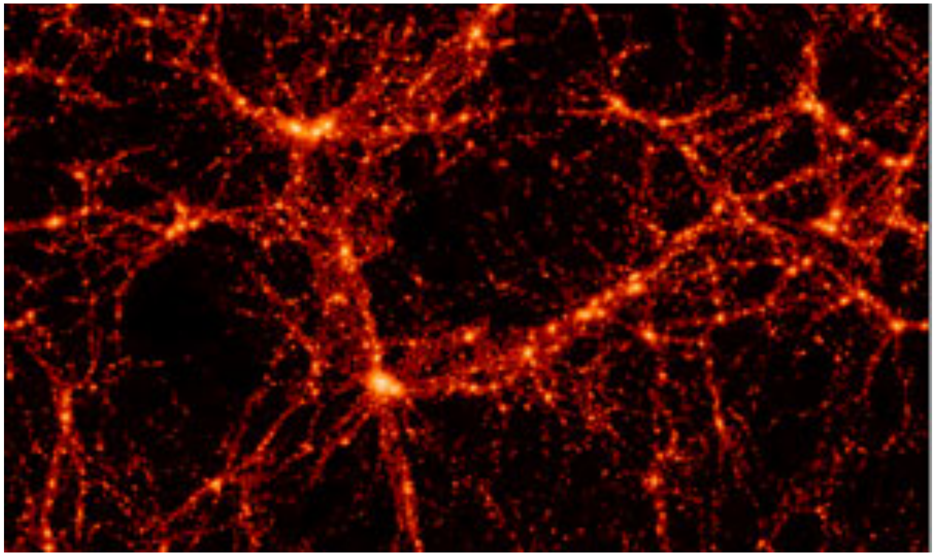
Voronoi foam, R=1.6, smoothed original



Voronoi foam, R=1.6, random phases



The power spectrum alone does not capture the phase information: the coherence of cosmic structures (voids, walls, filaments …)



LSS Observations Summary

- A range of structures: galaxies (~10 kpc), groups (~ 0.3 - 1 Mpc), clusters (~ few Mpc), superclusters (~ 10 - 100 Mpc)
- Redshift surveys are used to map LSS; ~ 10^6 galaxies now
- LSS topology is prominent: voids, sheets, filaments…
- LSS quantified through 2-point (and higher) correlation function(s), well fit by a power-law:

  $$\xi(r) = (r / r_0)^{-\gamma}$$

  typical $\gamma \sim 1.8$, $r_0 \sim$ few Mpc
- Equivalent description: power spectrum *P(k)* - useful for comparisons with the theory
- CDM model fits the data over a very broad range of scales
- Objects of different types have different clustering strengths
- Generally more massive structure cluster more strongly

Peculiar Velocities: Summary

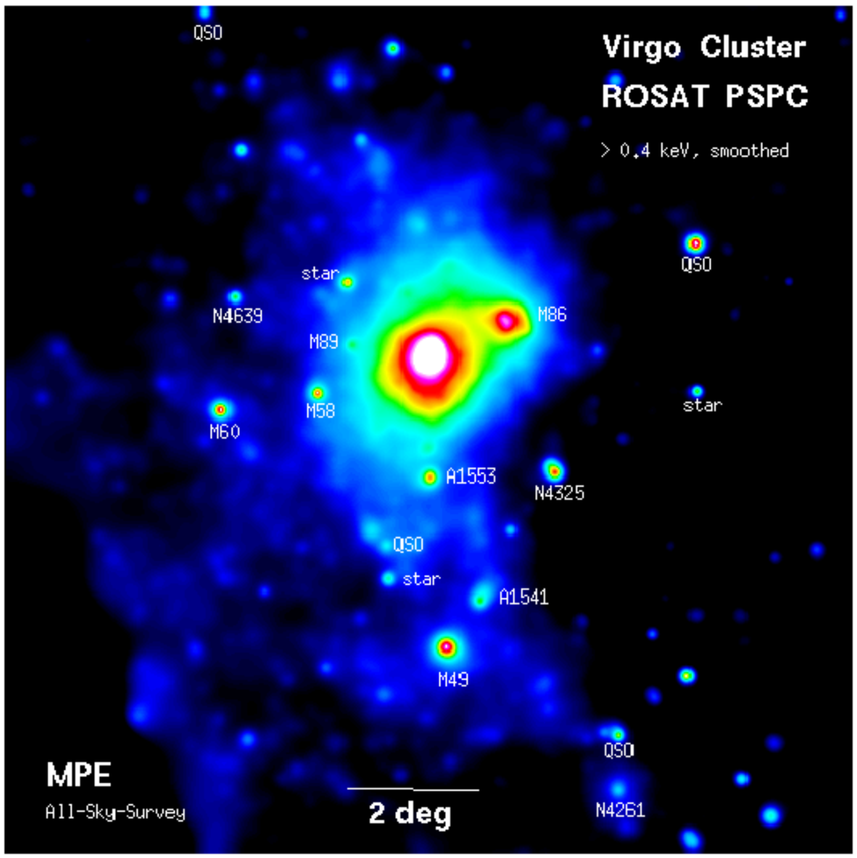
- Measurements of peculiar velocities are very, very tricky
  - Use (relative) distances to galaxies + Hubble flow, to infer the peculiar velocities of individual galaxies. Systematic errors?
  - Use a redshift survey + numerical modeling to infer the mass density distribution and the consistent peculiar velocity field
- Several general results:
  - We are falling towards Virgo with ~ 300 km/s, and will get there in about 10 - 15 Gyr
  - Our peculiar velocity dipole relative to CMB originates from within ~ 50 Mpc
  - The LSC is falling towards the Hydra-Centaurus Supercluster, with a speed of up to 500 km/s
  - The whole local ~ 100 Mpc volume may be falling towards a larger, more distant Shappley Concentration (of clusters)
- The mass and the light seem to be distributed in the same way on large scales (here and now)

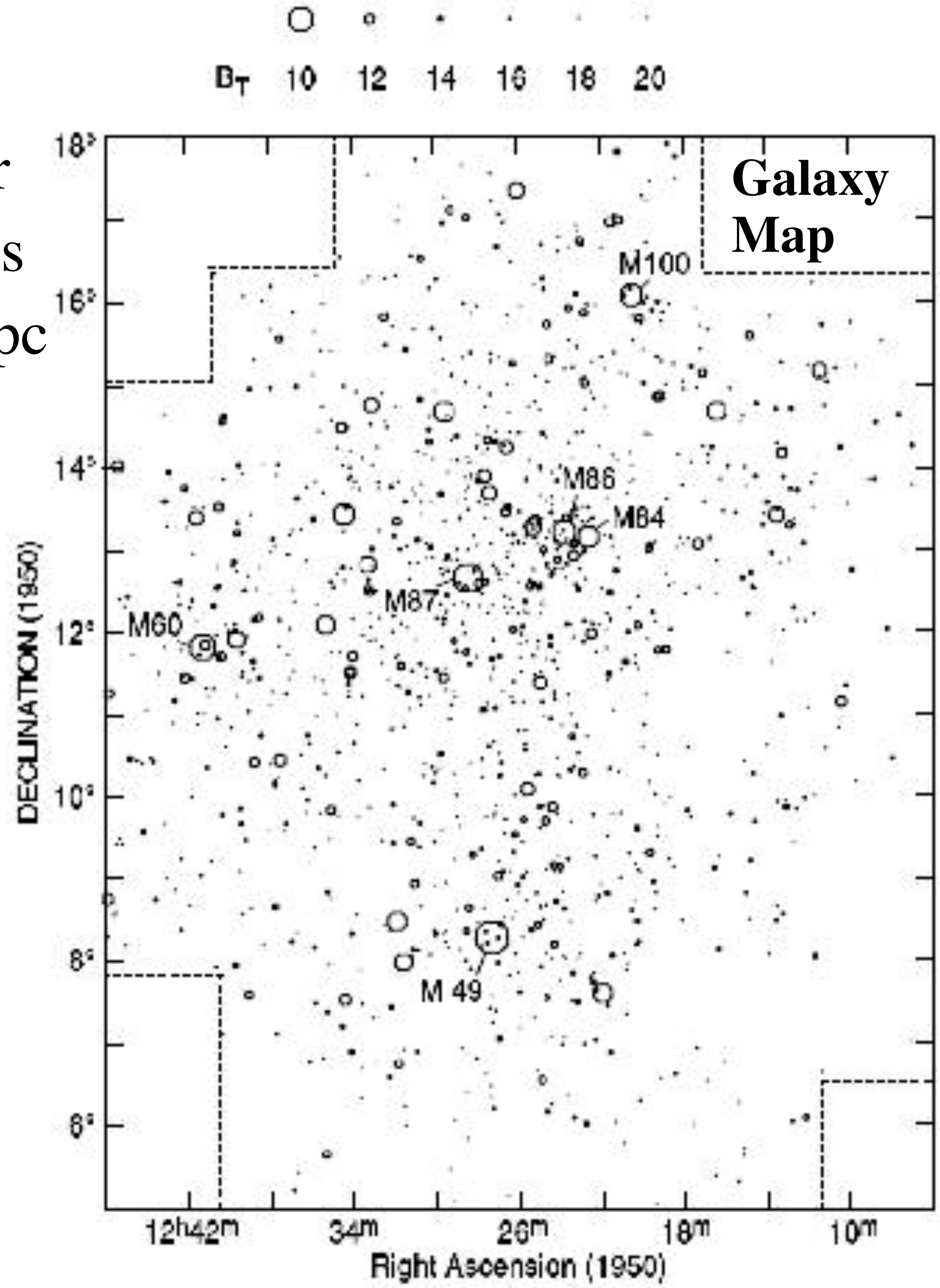
Clusters of Galaxies:

- 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:

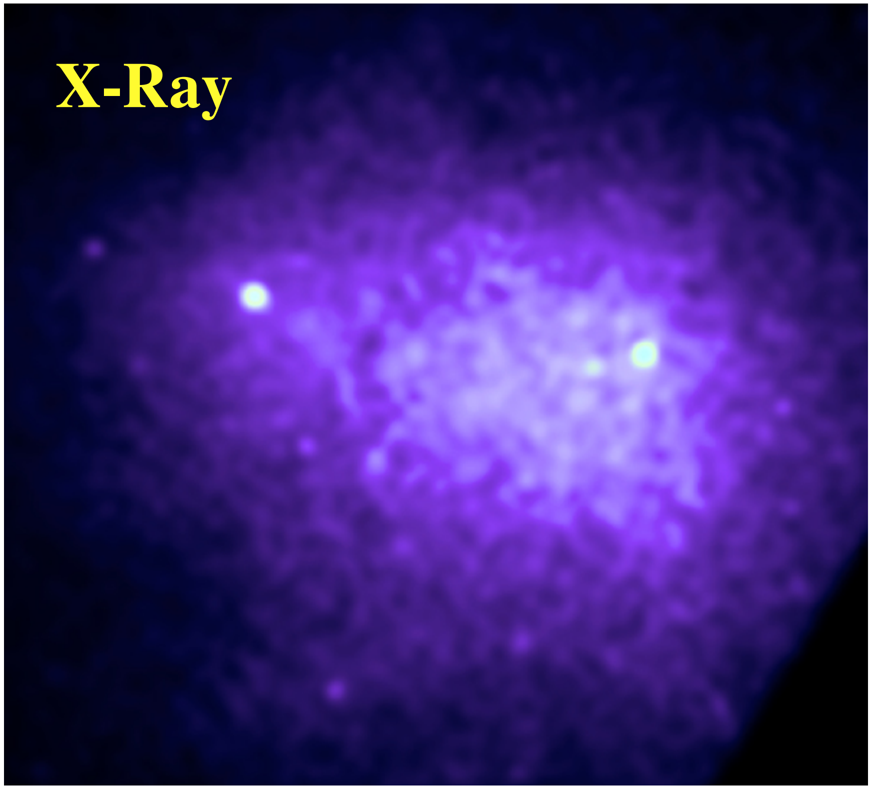
- Irregular, relatively poor cluster
- Distance ~ 16 Mpc, closest to us
- Diameter ~ 10° on the sky, 3 Mpc
- ~ 2000 galaxies, mostly dwarfs

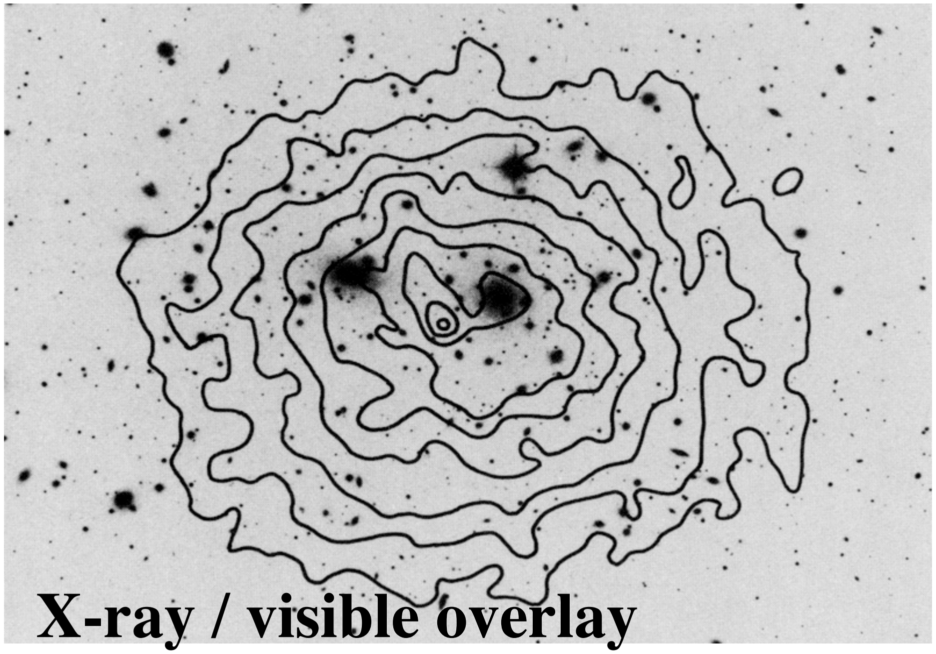




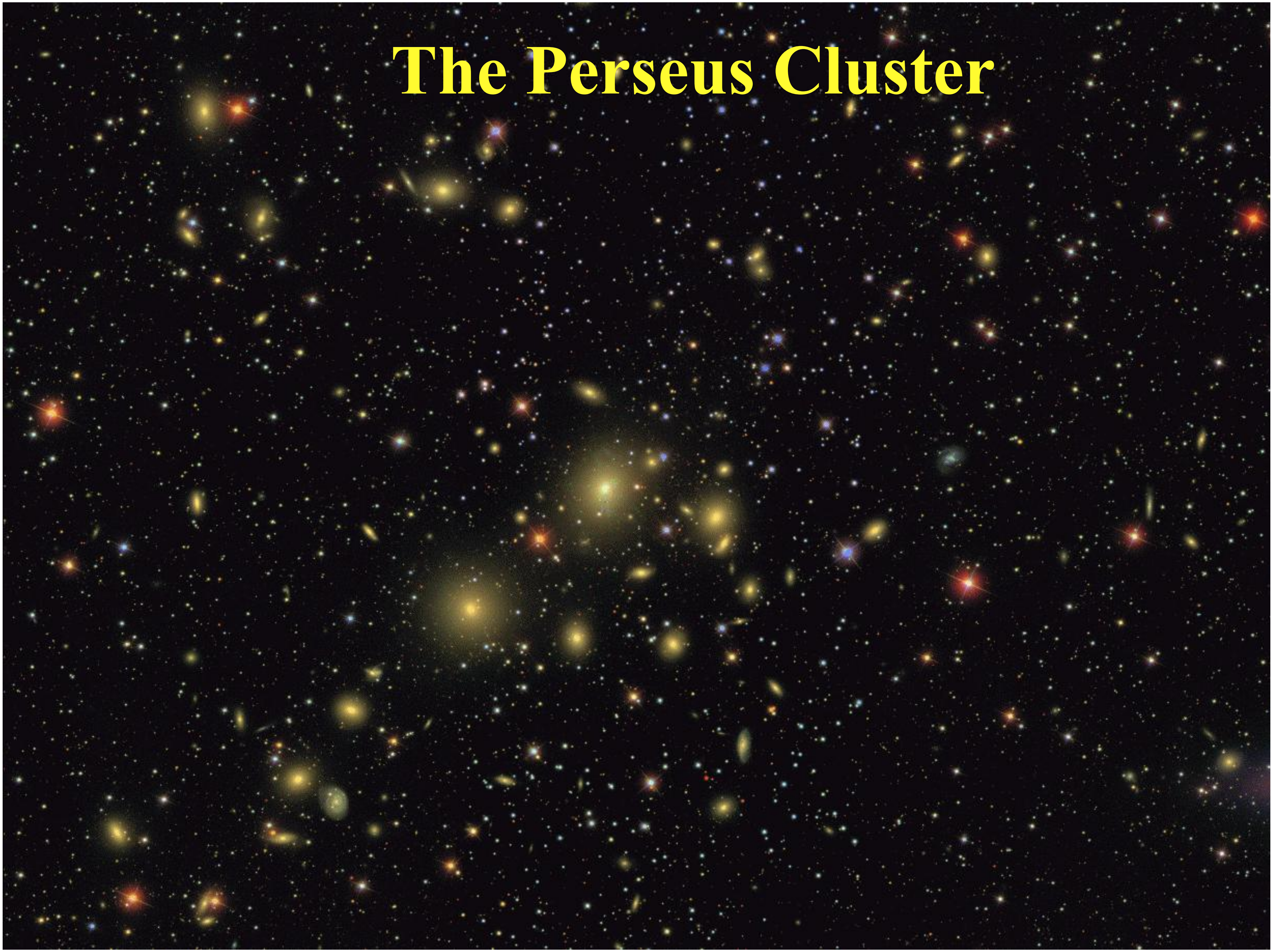
The Coma Cluster

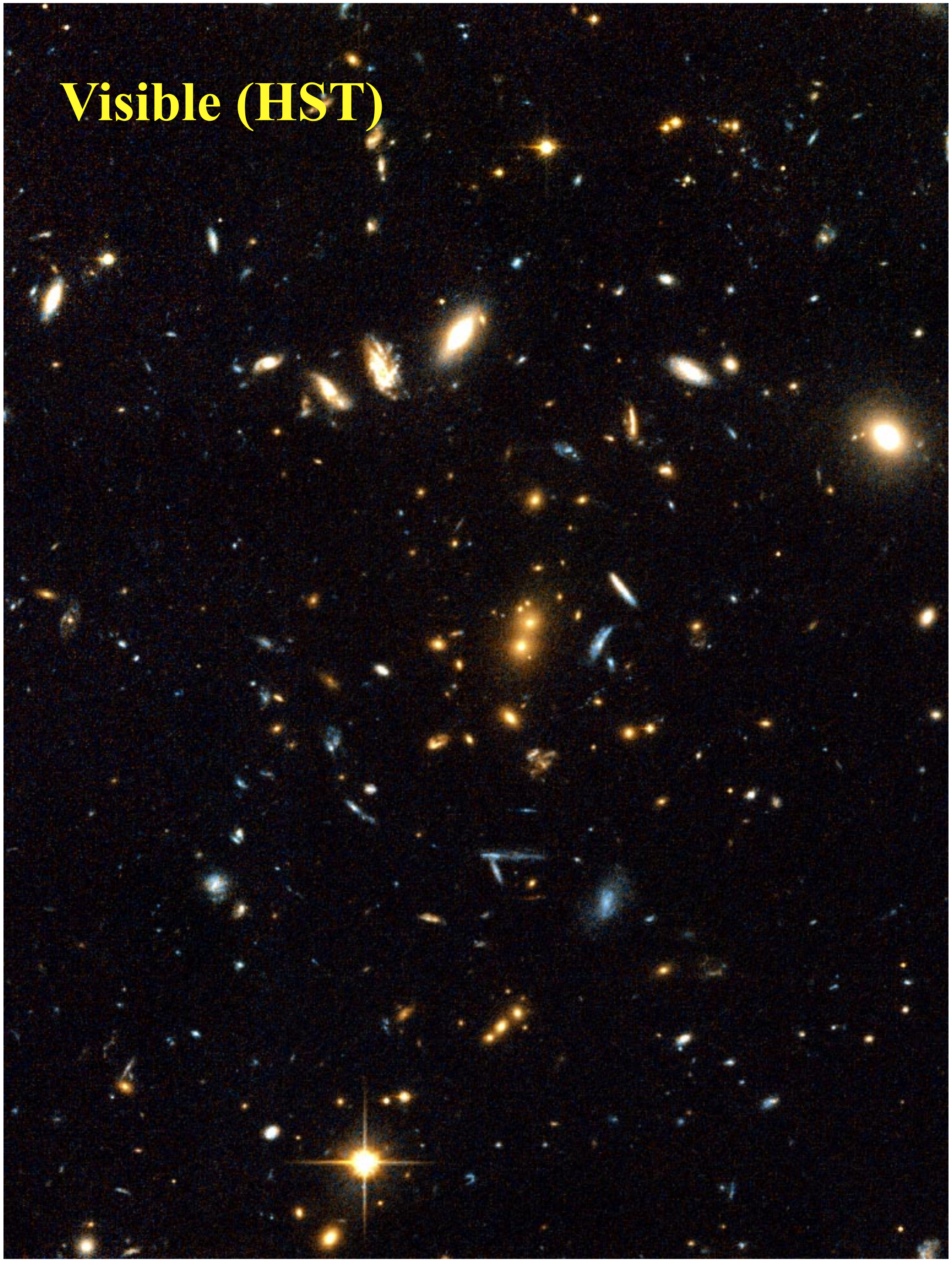
- Nearest rich cluster, with >10,000 galaxies
- Distance ~ 90 Mpc
- Diameter ~ 4-5° on the sky, 6-8 Mpc



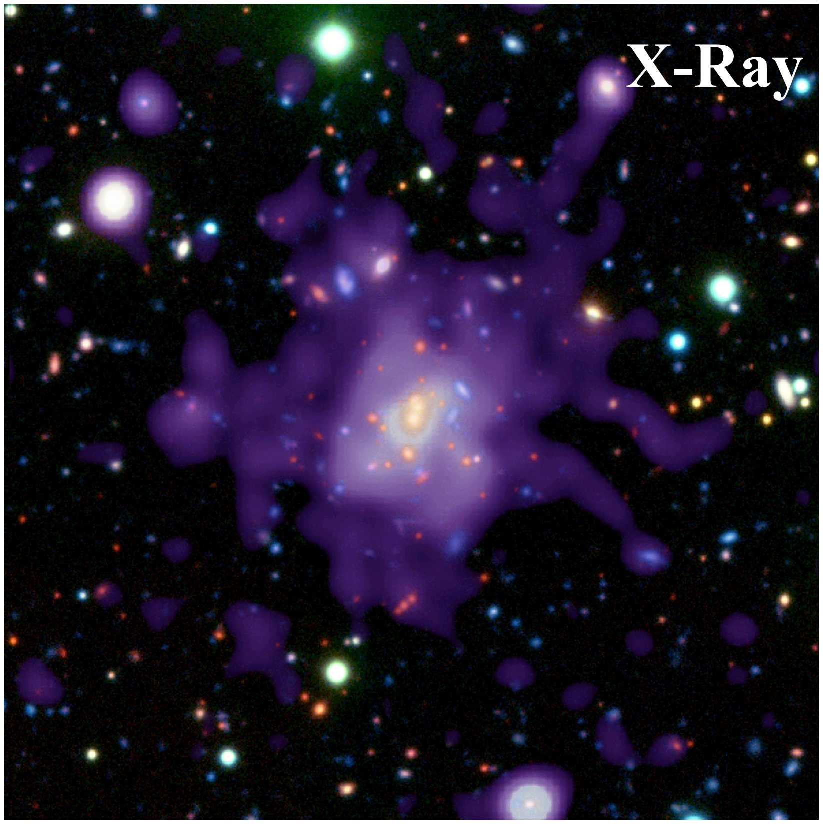


The Perseus Cluster





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



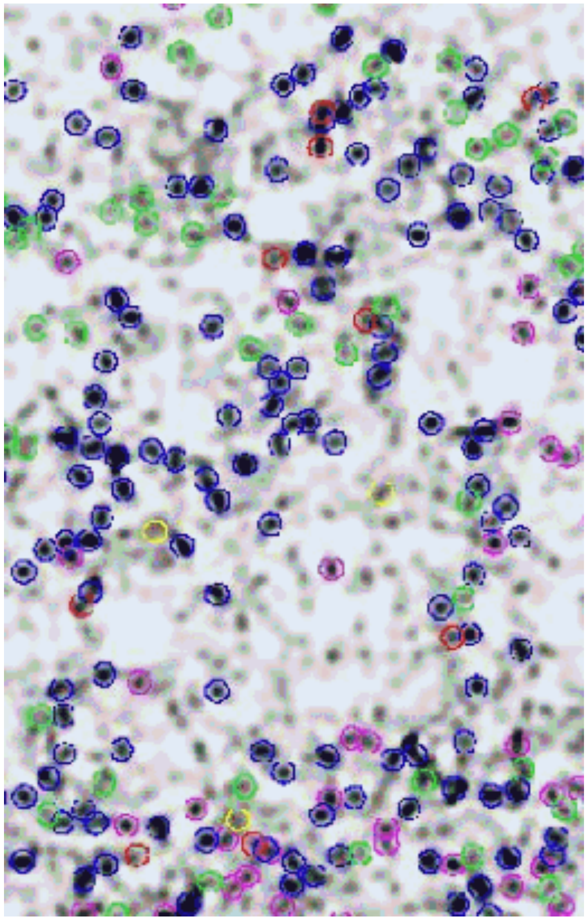
Surveys for Galaxy Clusters

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 (IR)
- **Disadvantages:** vulnerable to projection effects, rich cluster in the optical may not have especially high mass



Abell Cluster Catalog

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

Clusters From Photographic Digital Sky Surveys

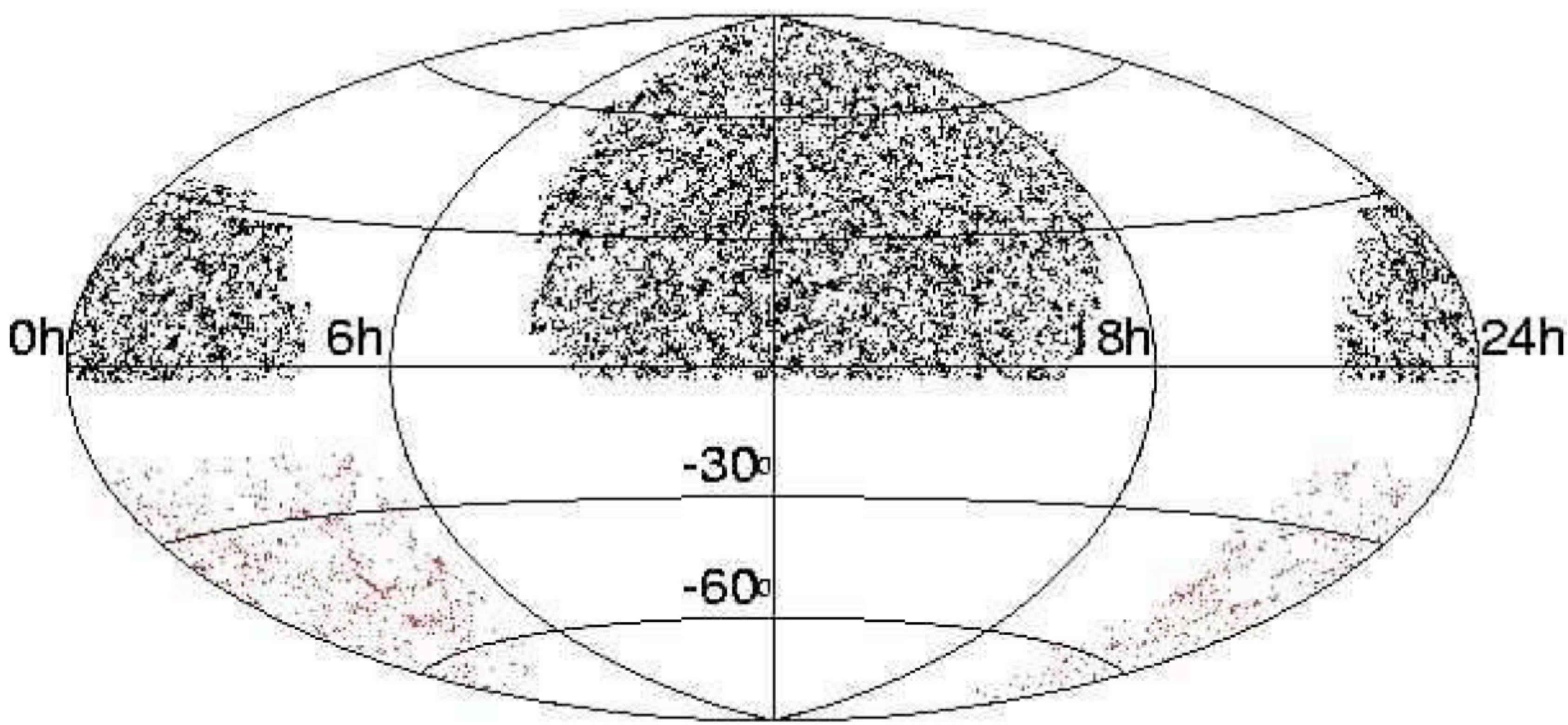
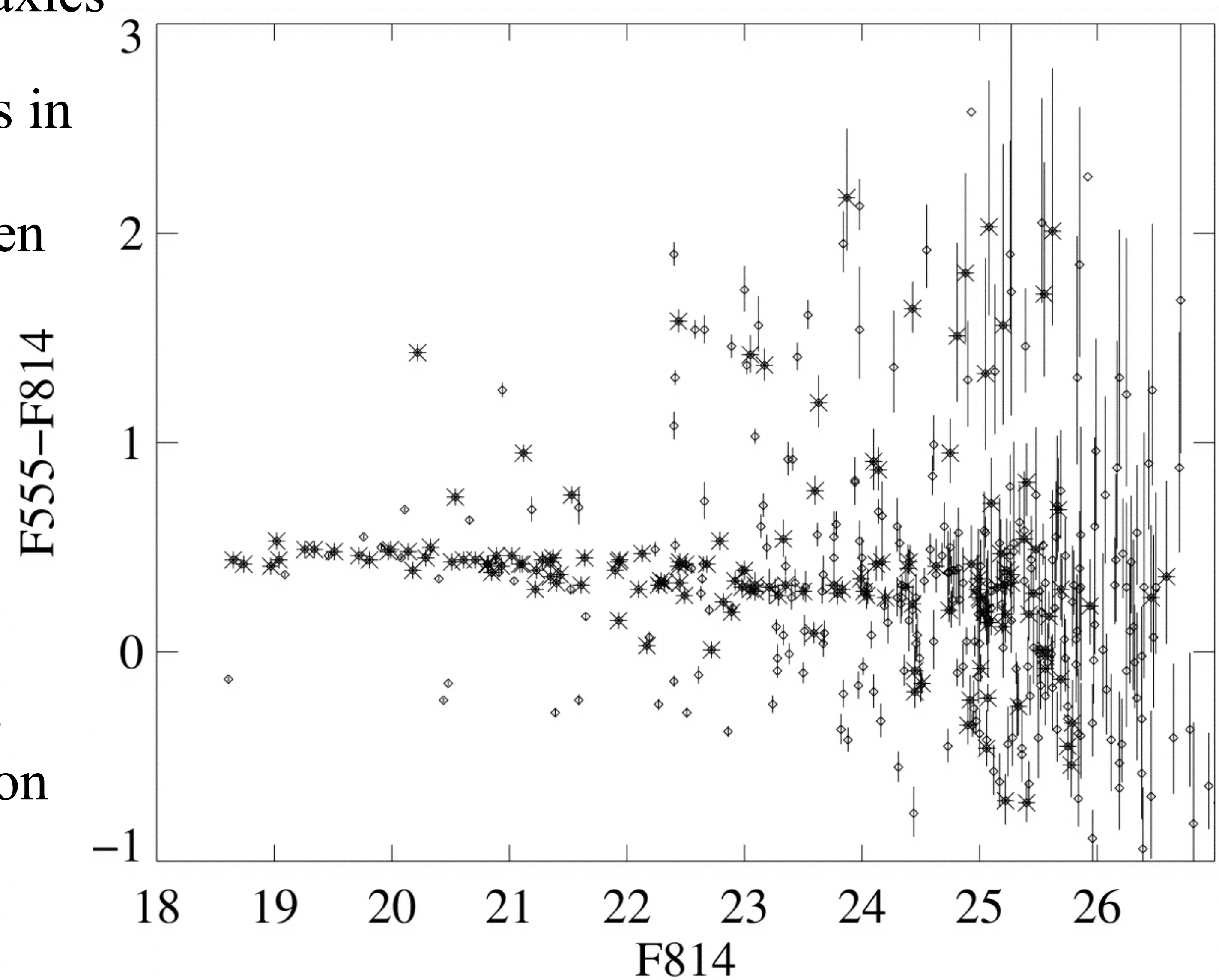


Fig. 2. The sky distribution of NoSOCS (northern sky) and APM (southern sky) candidate clusters in equatorial coordinates. The much higher density of NoSOCS is due to its deeper photometry and lower richness limit.

The Red Sequence Technique

- Exploit the color-magnitude (i.e., ~ mass-metallicity) relation for early-type galaxies
- Select galaxies in the right color band for a given redshift
- The sequence changes in redshift due to the K-correction



The "Cut and Enhance" Technique

Use the color cut to select likely early-type galaxies, then smooth

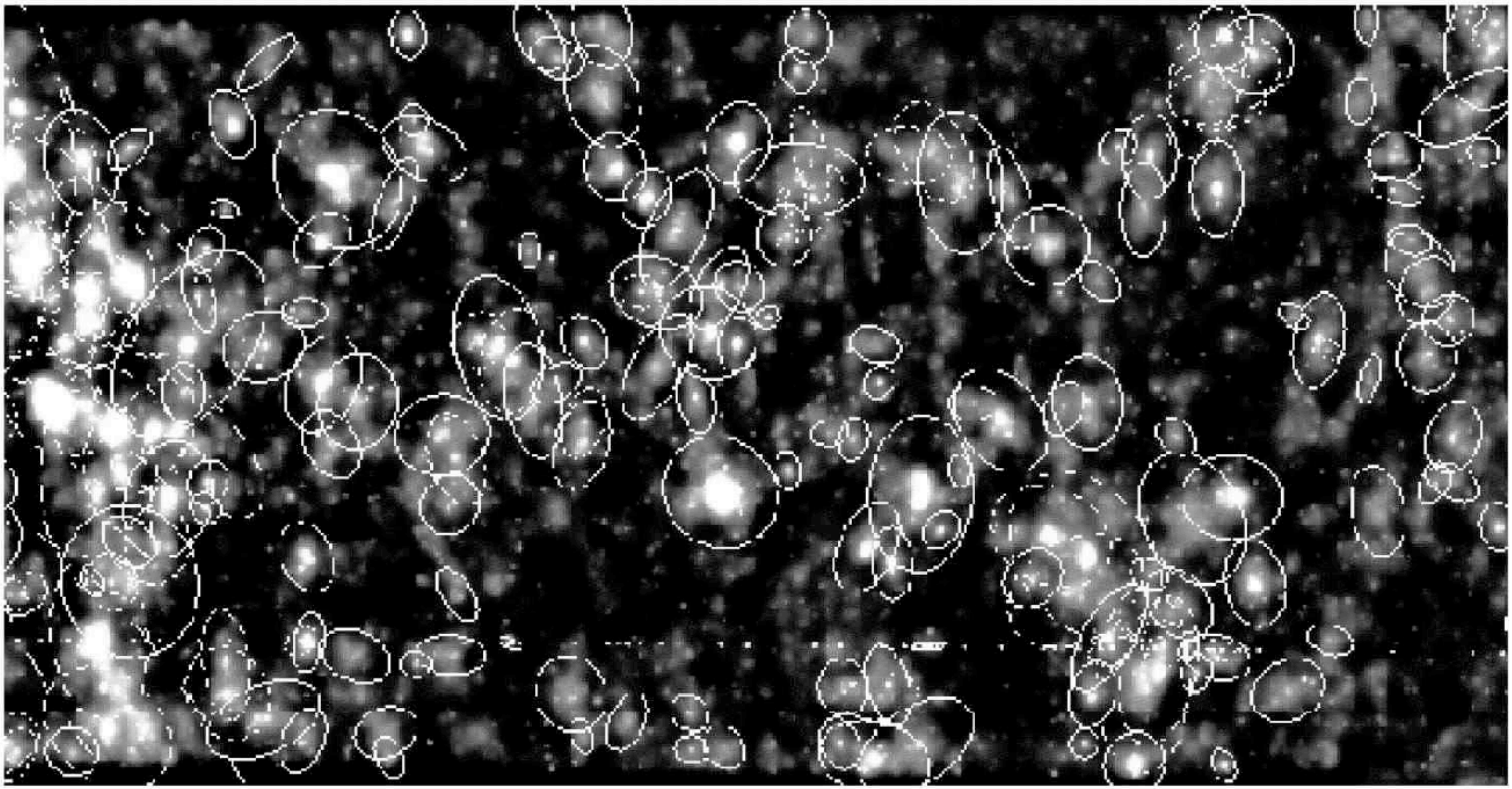
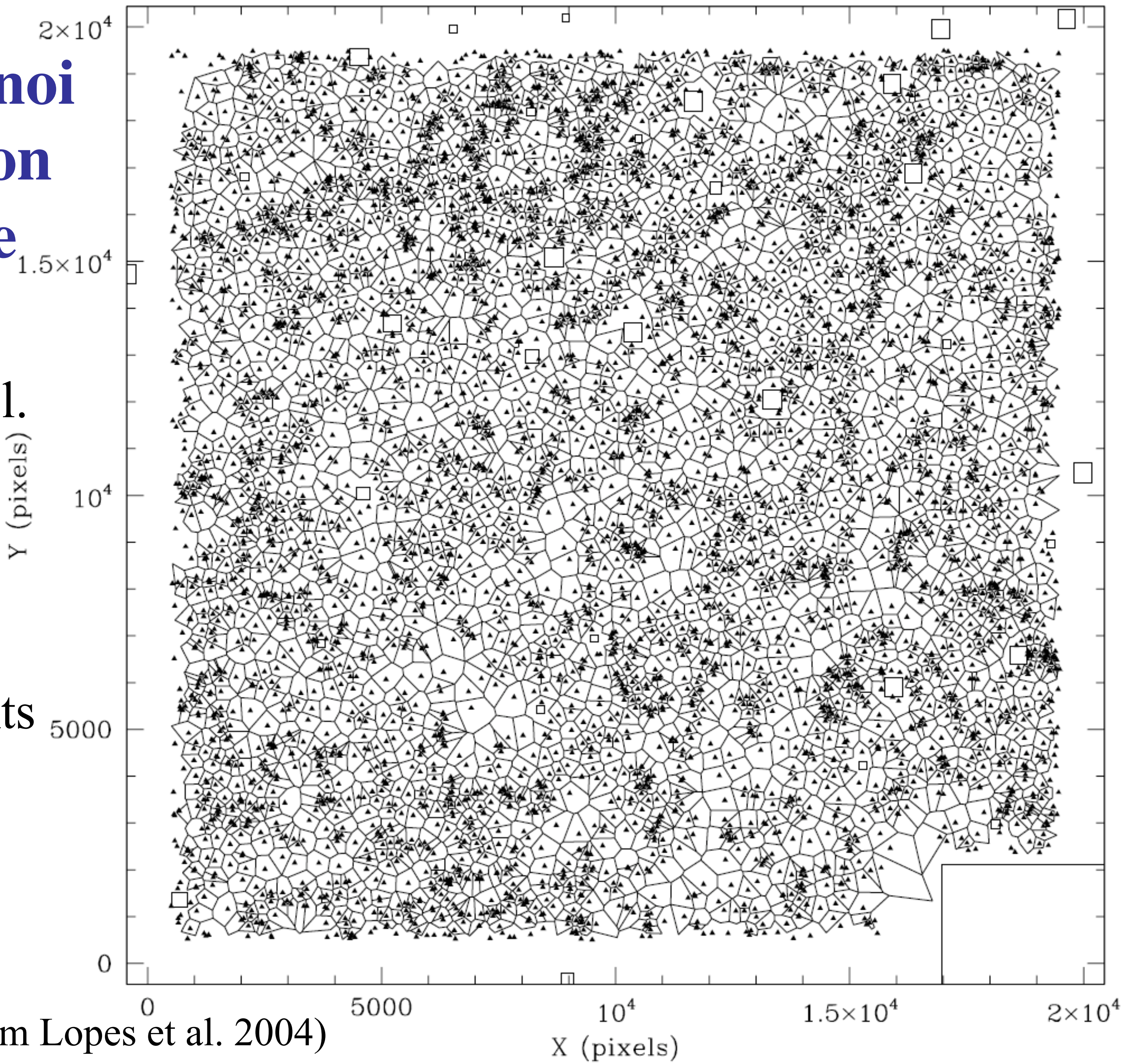


Fig. 4. An enhanced map of the galaxy distribution in the SDSS Early Data Release, after applying the $g* - r* - i*$ color-color cut. Detected clusters are circled. Taken from Goto *et al.* (2002).

The Voronoi Tessellation Technique

Each galaxy defines a cell. Cell area ~ 1/density; look for density enhancements



(DPOSS data, from Lopes et al. 2004)

Cluster Classifications

- Abell classified clusters as:
  - Regular: ~ circularly symmetrical w/ a central concentration, members are predominantly E/S0's (e.g., Coma)
  - Irregular: ~ less well defined structure, more spirals (e.g., Hercules, Virgo)
- Bautz-Morgan classification scheme (1970), based on brightest galaxy in cluster:
  - I: Cluster has centrally located cD galaxy
  - II: central galaxy is somewhere between a cD and a giant elliptical galaxy (e.g., Coma)
  - III: cluster has no dominant central galaxy
- Oemler (1974) classified clusters by galaxy content:
  - cD clusters: 1 or two dominant cD galaixes, E:S0:S ~3:4:2
  - Spiral rich: E:SO:S~1:2:3 (similar to the field)
  - Spiral poor: no dominant cD, E:S0:S~1:2:1

Some important trends:

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

What does it all mean?

- Regular, cD clusters have had time to "relax" and reach dynamic equilibrium
- Intermediate and Irregular clusters are still in the process of coming together, have not yet reached dynamic equilibrium
- cD galaxies probably formed by merging in the central regions
  - Many show multiple nuclei, and have extended outer envelopes compared to luminous ellipticals, accrete additional material due to tidal stripping of other galaxies

Surveys for Galaxy Clusters

2. X-Ray

- Galaxy clusters contain hot gas, which radiates X-ray radiation due to bremsstrahlung
- Advantage: bremsstrahlung scales with density and temperature as $n^2T^{1/2}$ - 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

Hot X-ray Gas in Clusters

- Virial equilibrium temperature T ~ $10^7 - 10^8$ 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

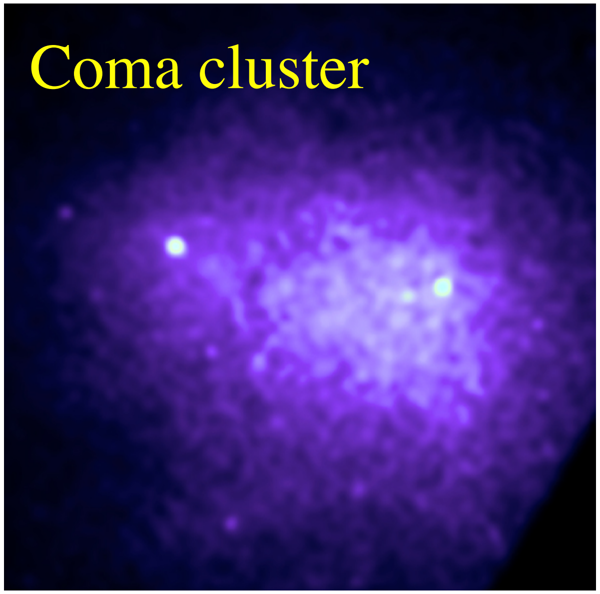
Masses of Clusters From X-ray Gas

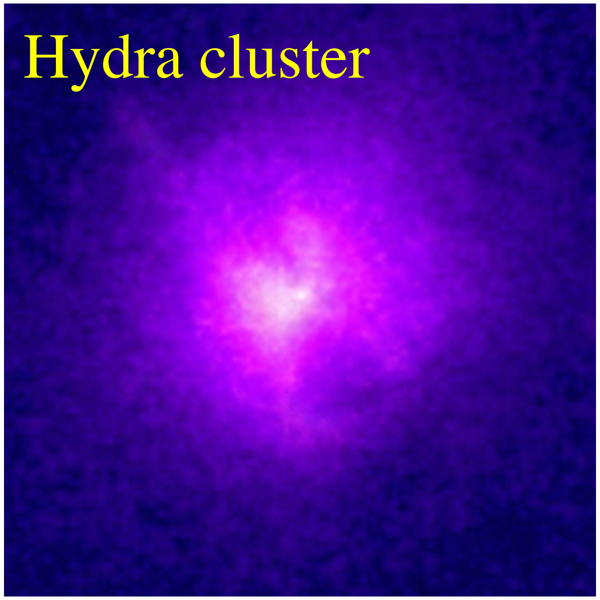
- Note that for a proton moving in the cluster potential well with a $\sigma \sim 10^3$ km/s, $E_k = m_p \sigma^2 / 2 = 5\, k\, T / 2 \sim$ few keV, and $T \sim$ few 10^7 °K ➞ **X-ray gas**
- Hydrostatic equilibrium requires:

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

- 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%





SZ Clusters from *Planck*

Keep an eye on the South Pole Telescope (SPT) as well

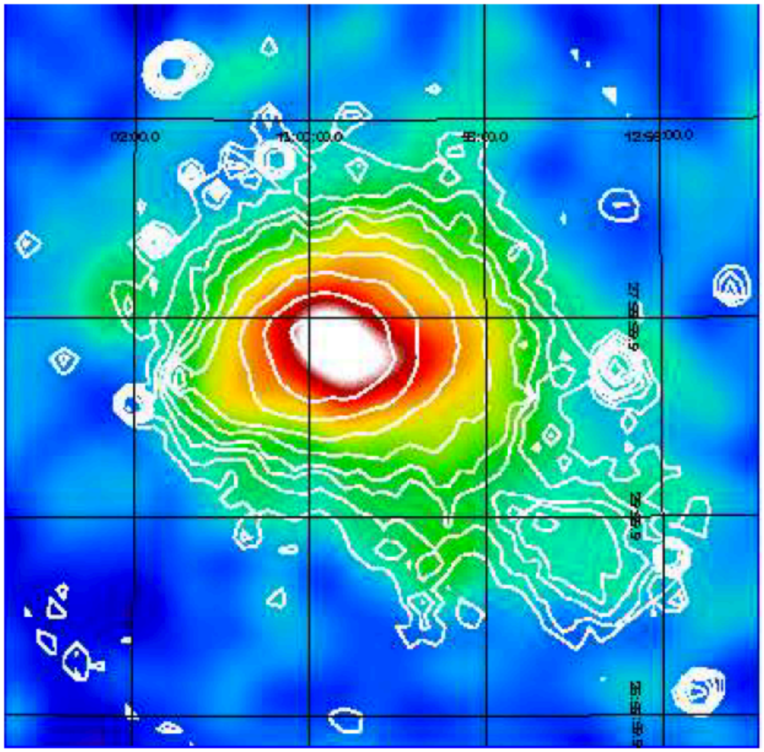
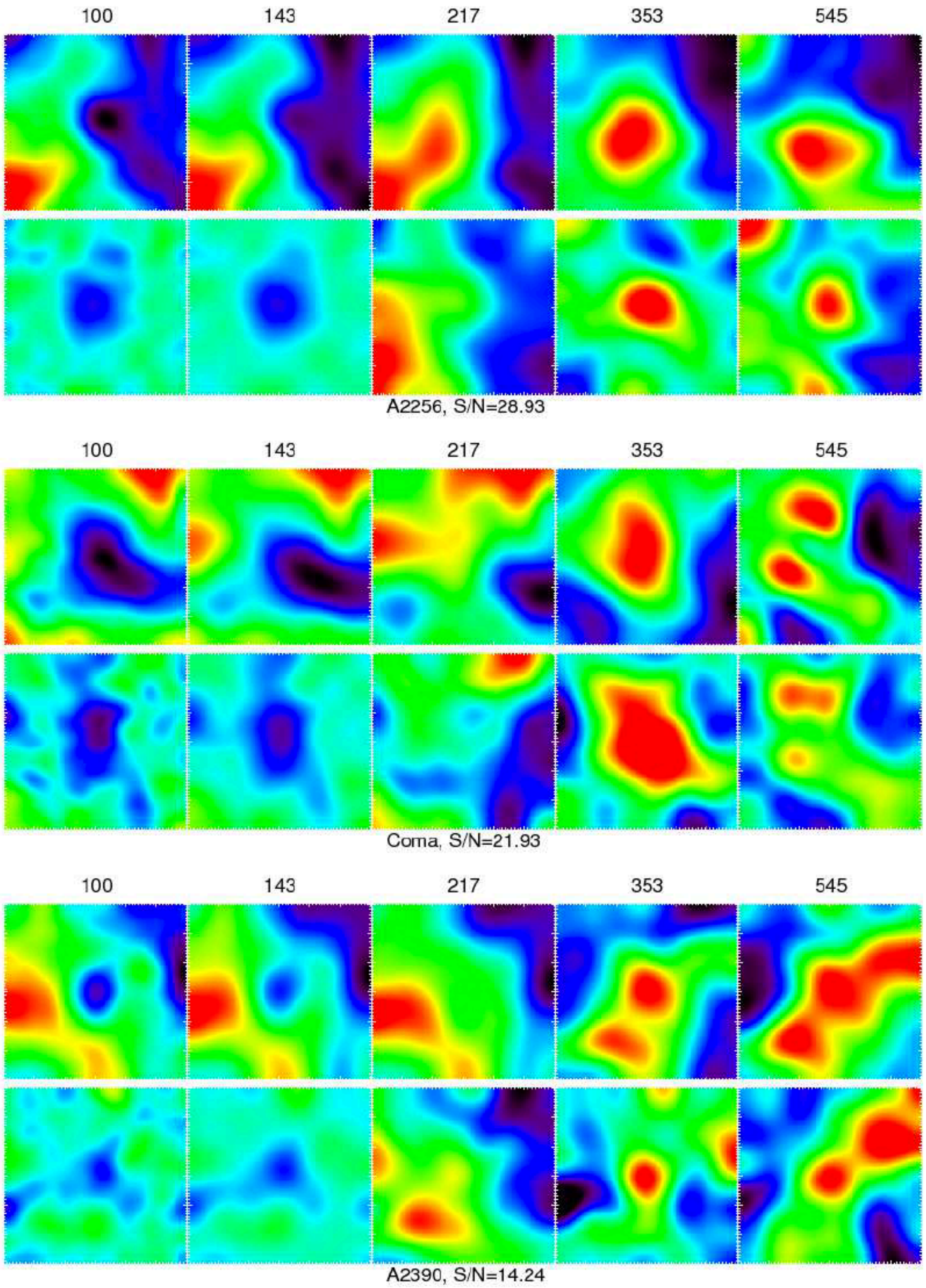


Fig. 1. *Planck* *y*-map of Coma on a ∼ 3° × 3° patch with the *ROSAT-PSPC* iso-luminosity contours overlaid.



SZ Clusters from *Planck*

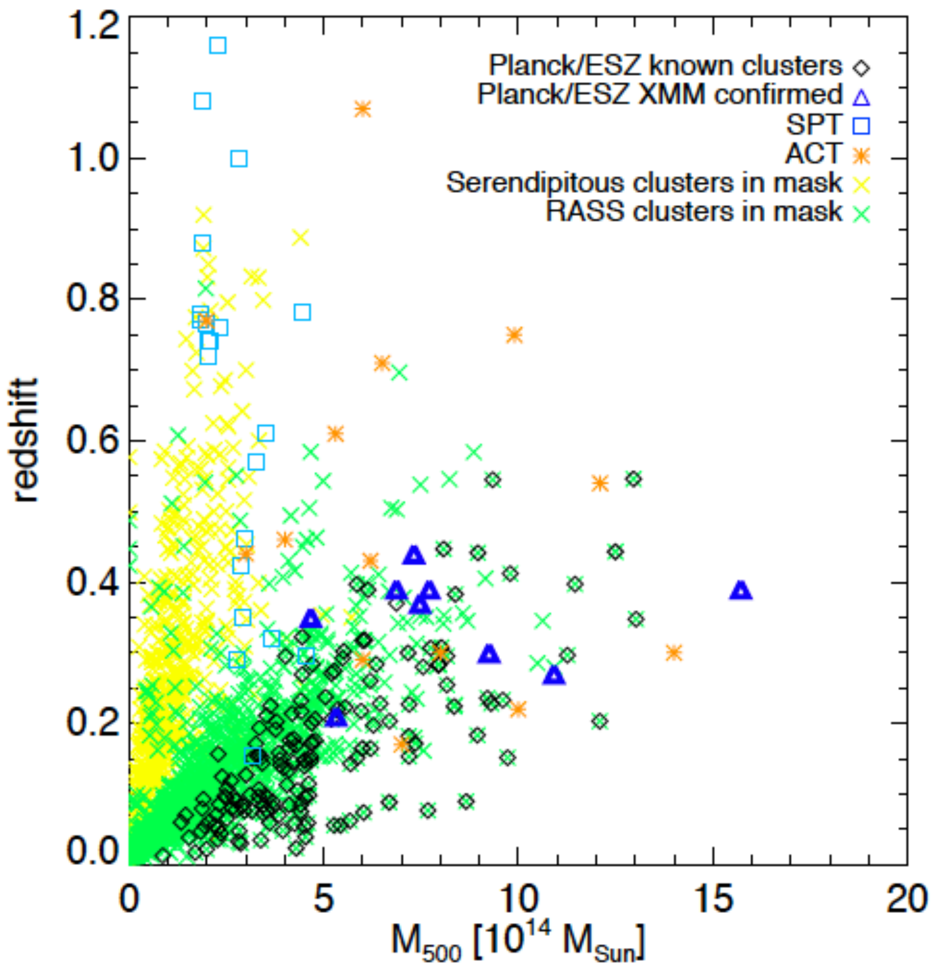


Fig. 20. The 158 clusters from the *Planck* ESZ sample identified with known X-ray clusters in redshift–mass space, compared with SPT and ACT samples from Menanteau et al. (2010); Vanderlinde et al. (2010), as well as serendipitous and RASS clusters

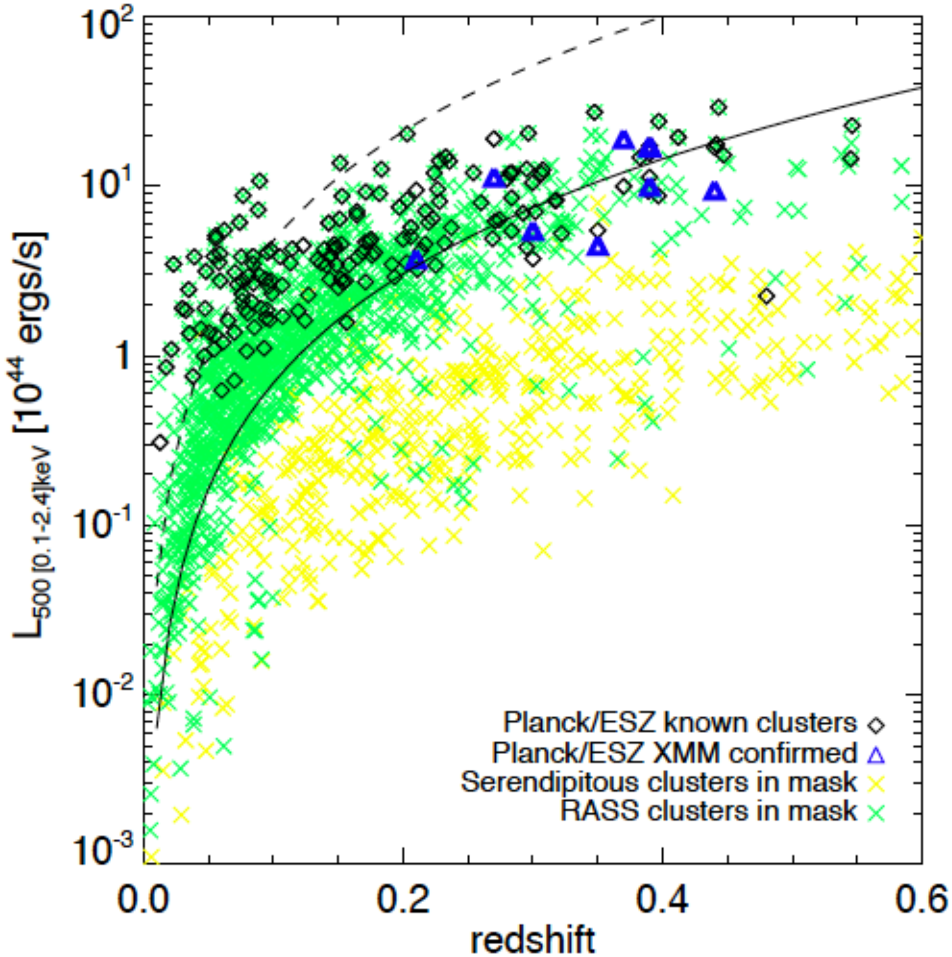
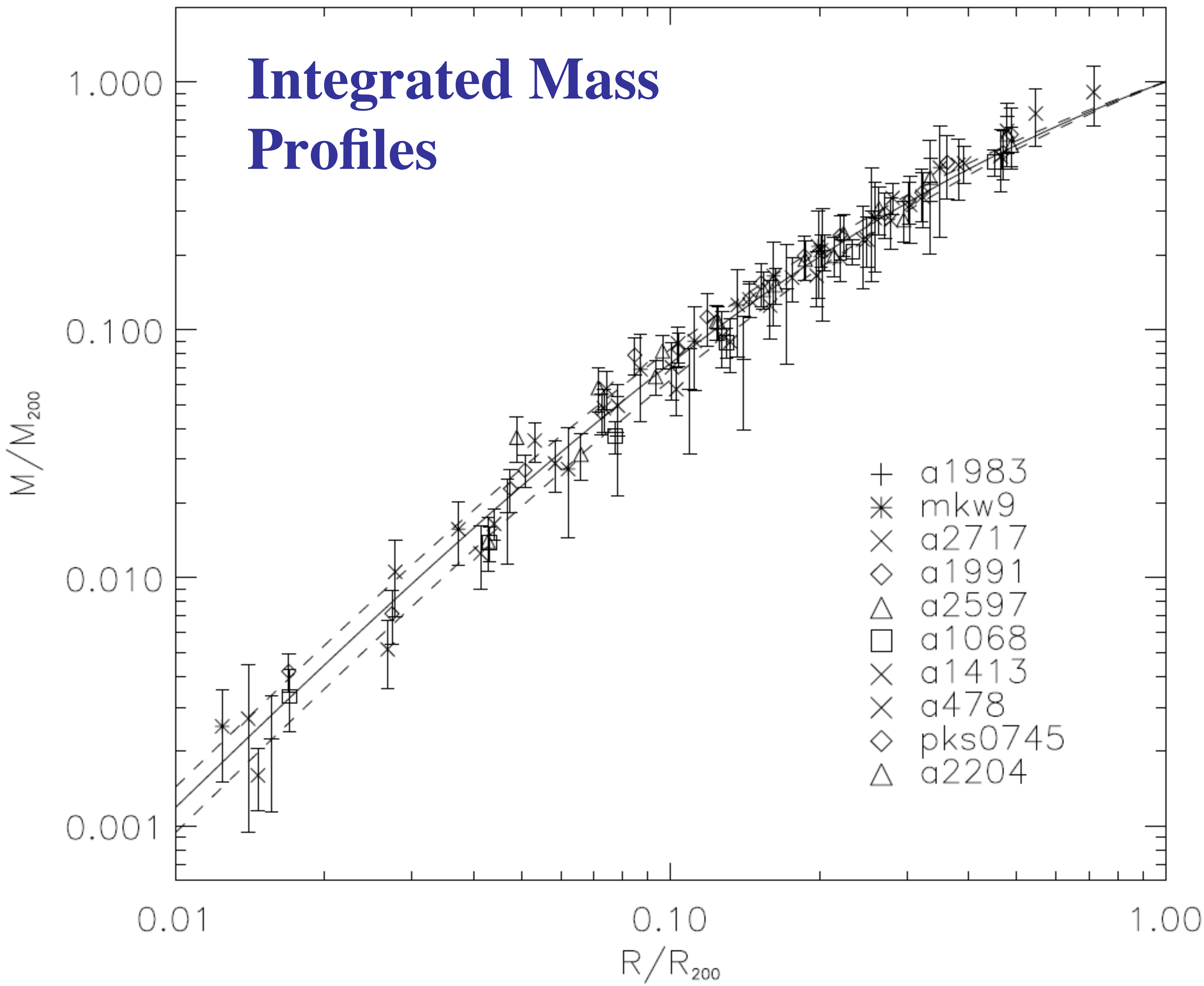


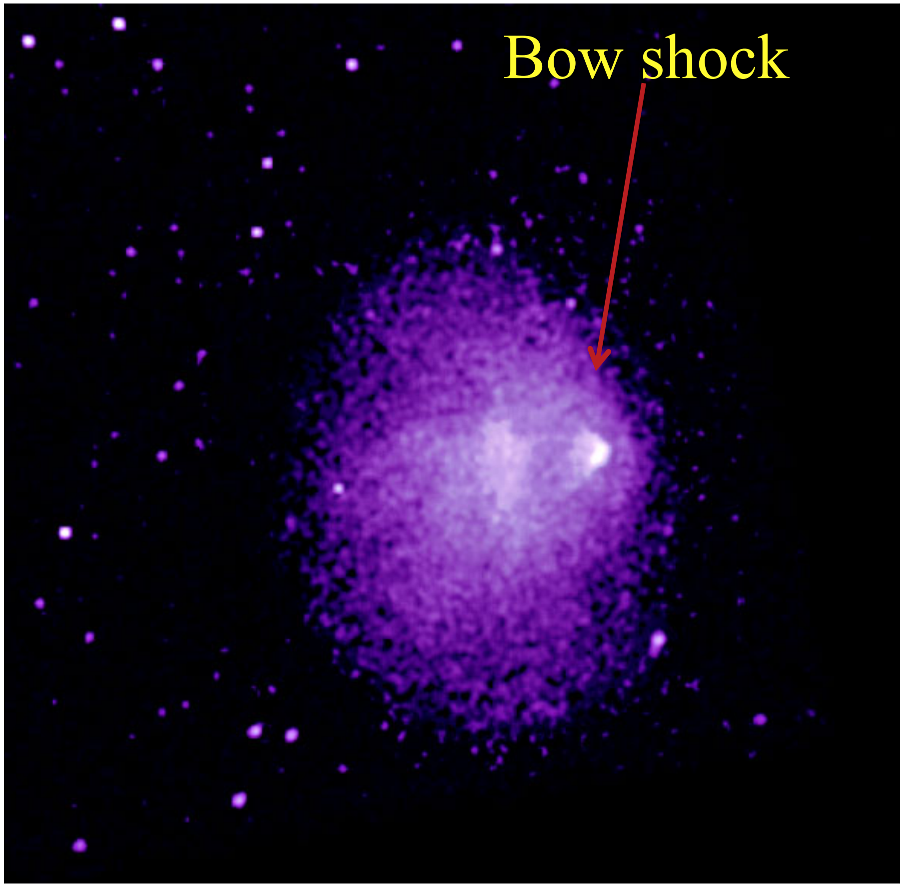
Fig. 21. The 158 clusters from the *Planck* ESZ sample identified with known X-ray clusters in redshift–luminosity space, compared with serendipiti and RASS clusters

Integrated Mass Profiles

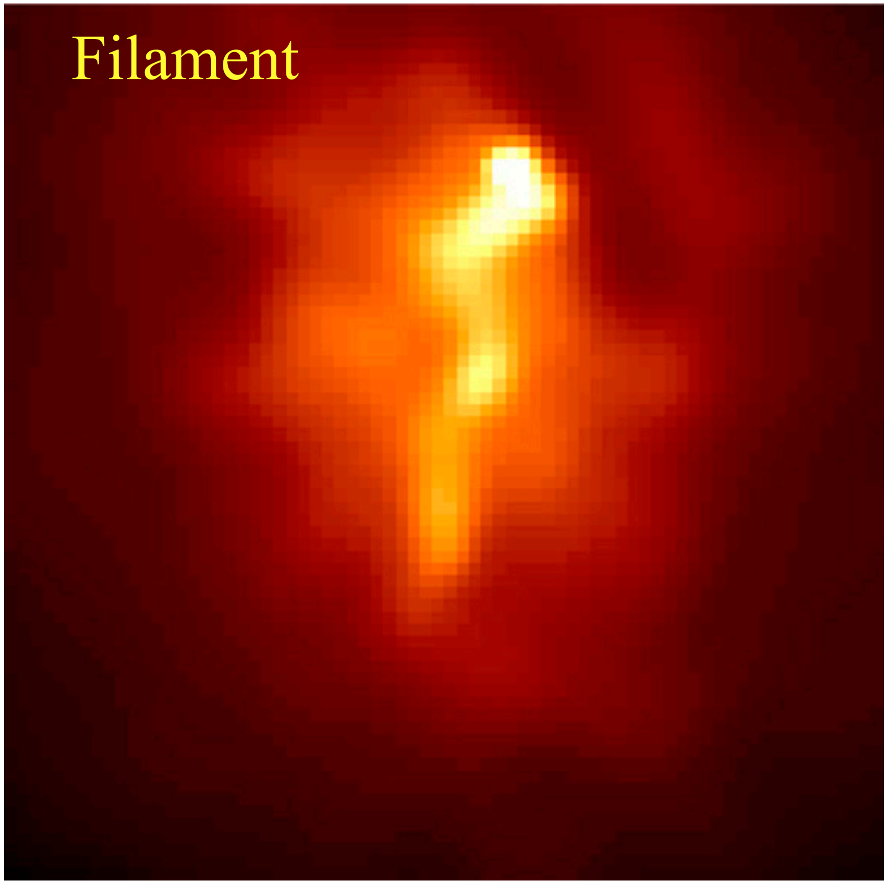


Substructure in the X-Ray Gas

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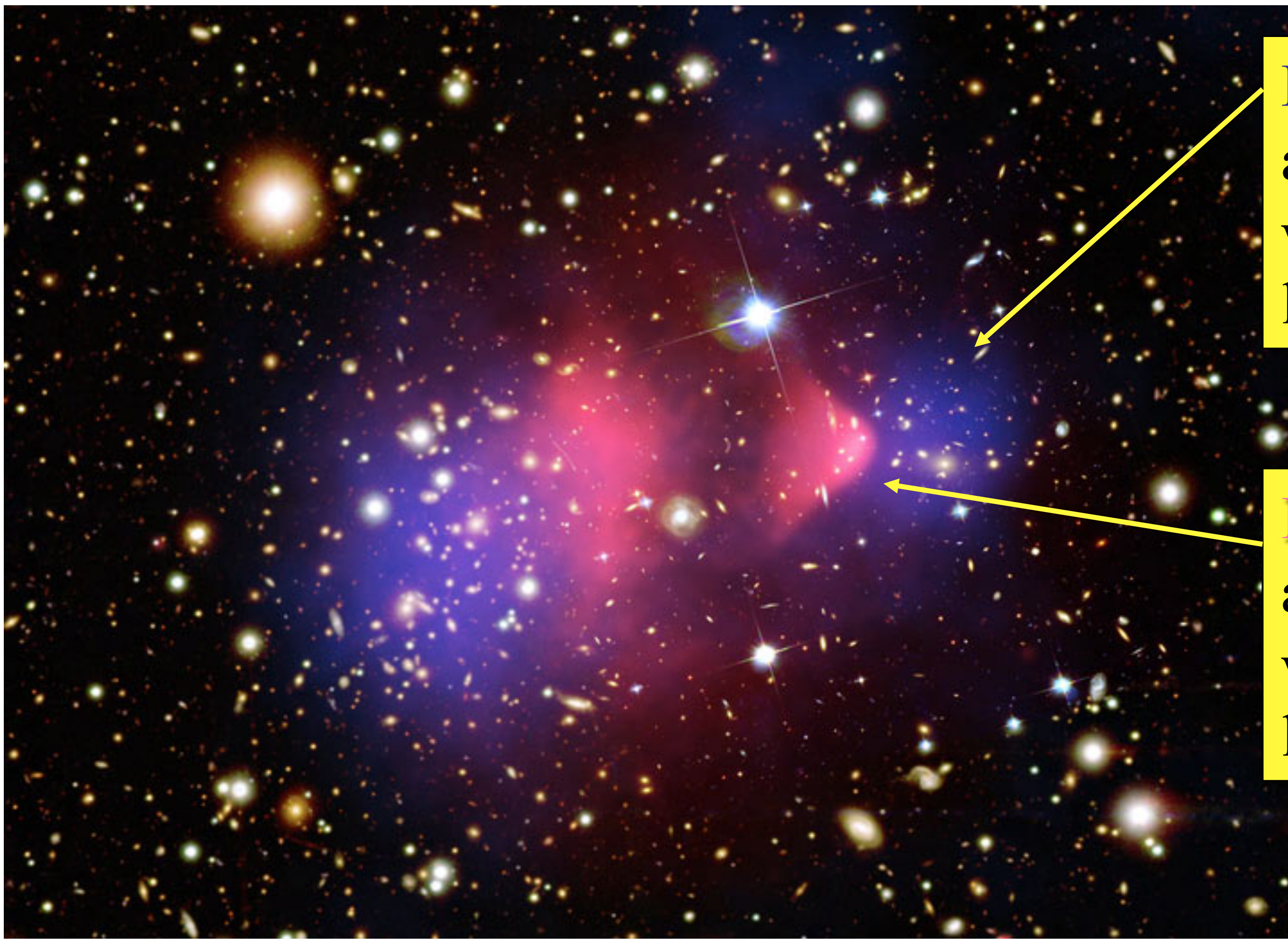
Dark Matter and X-Ray Gas in Cluster Mergers: The "Bullet Cluster" (1E 0657-56)

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: dark matter, as inferred from weak gravitational lensing

(Bradac et al.)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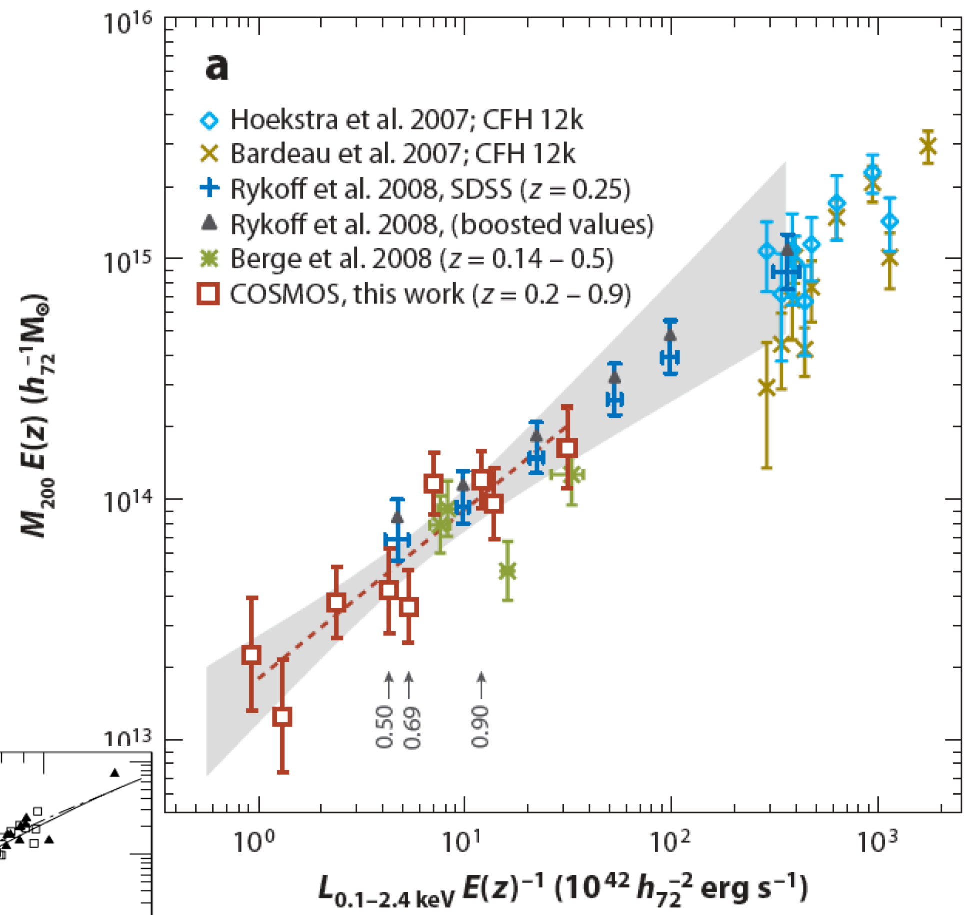
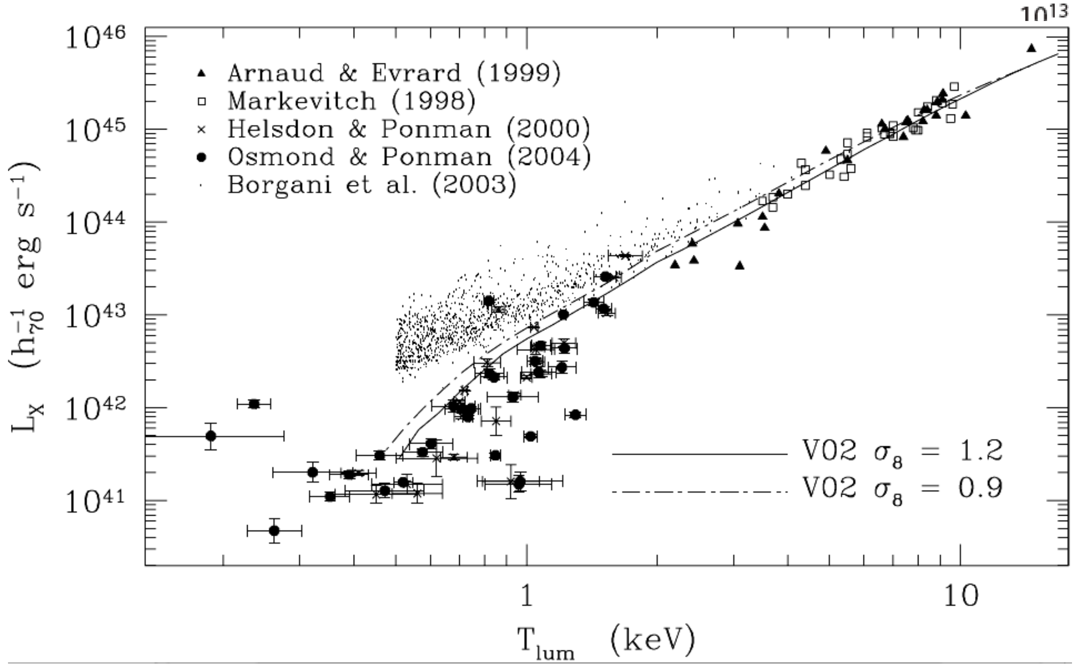
Cluster X-Ray Luminosities Correlate With Mass

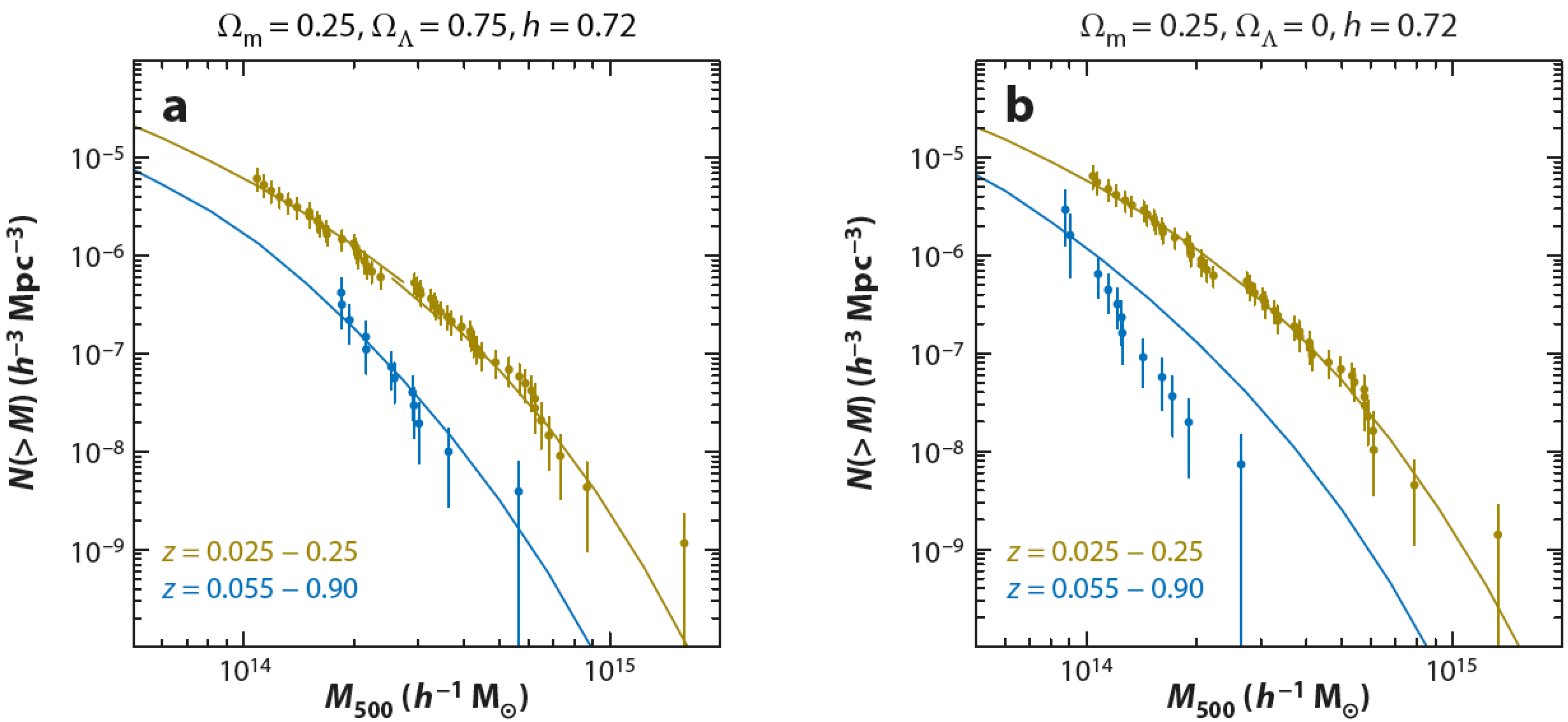




… and Temperature

Clusters as Cosmological Probes

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

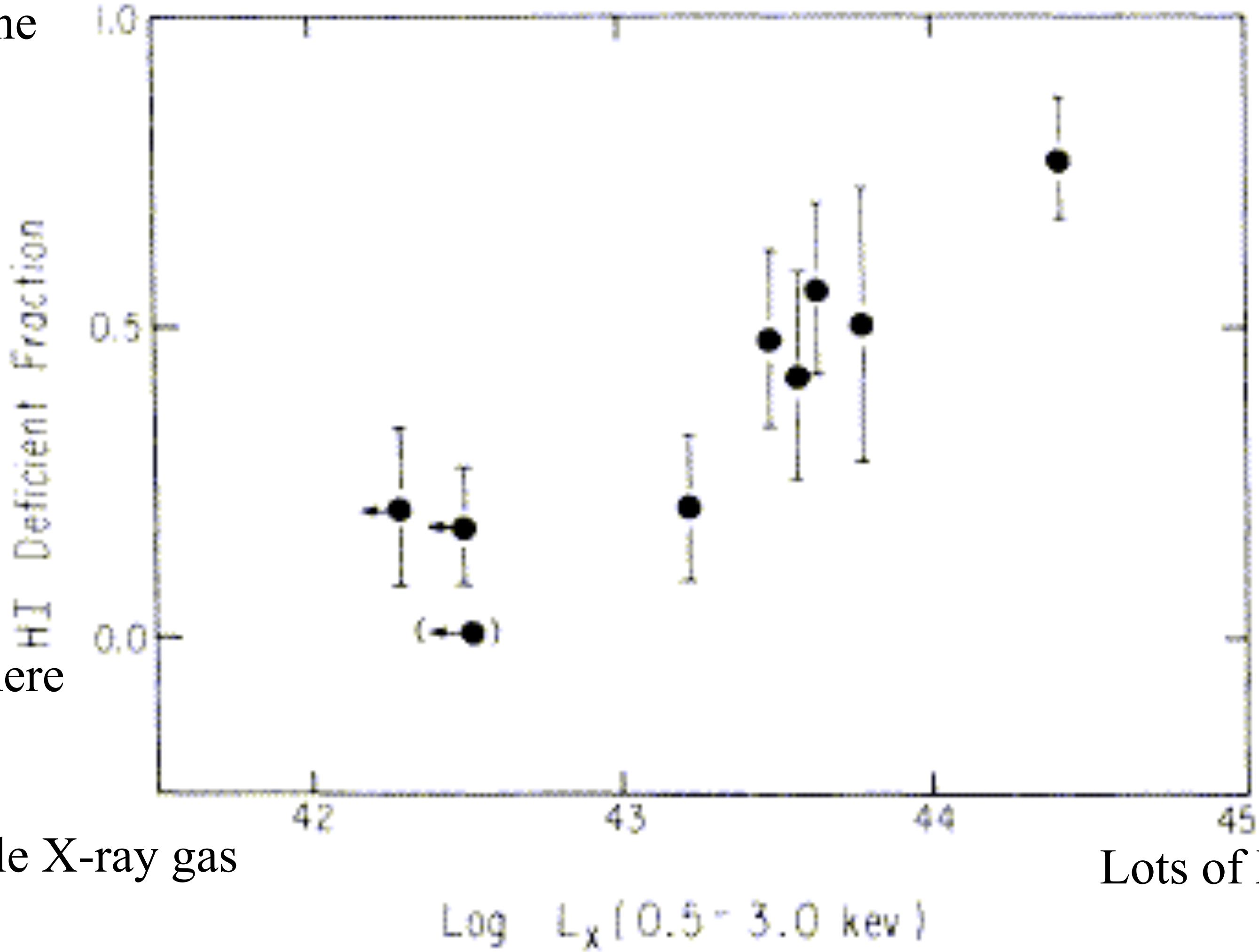


Hydrogen Gas Deficiency

- 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

All H I gone



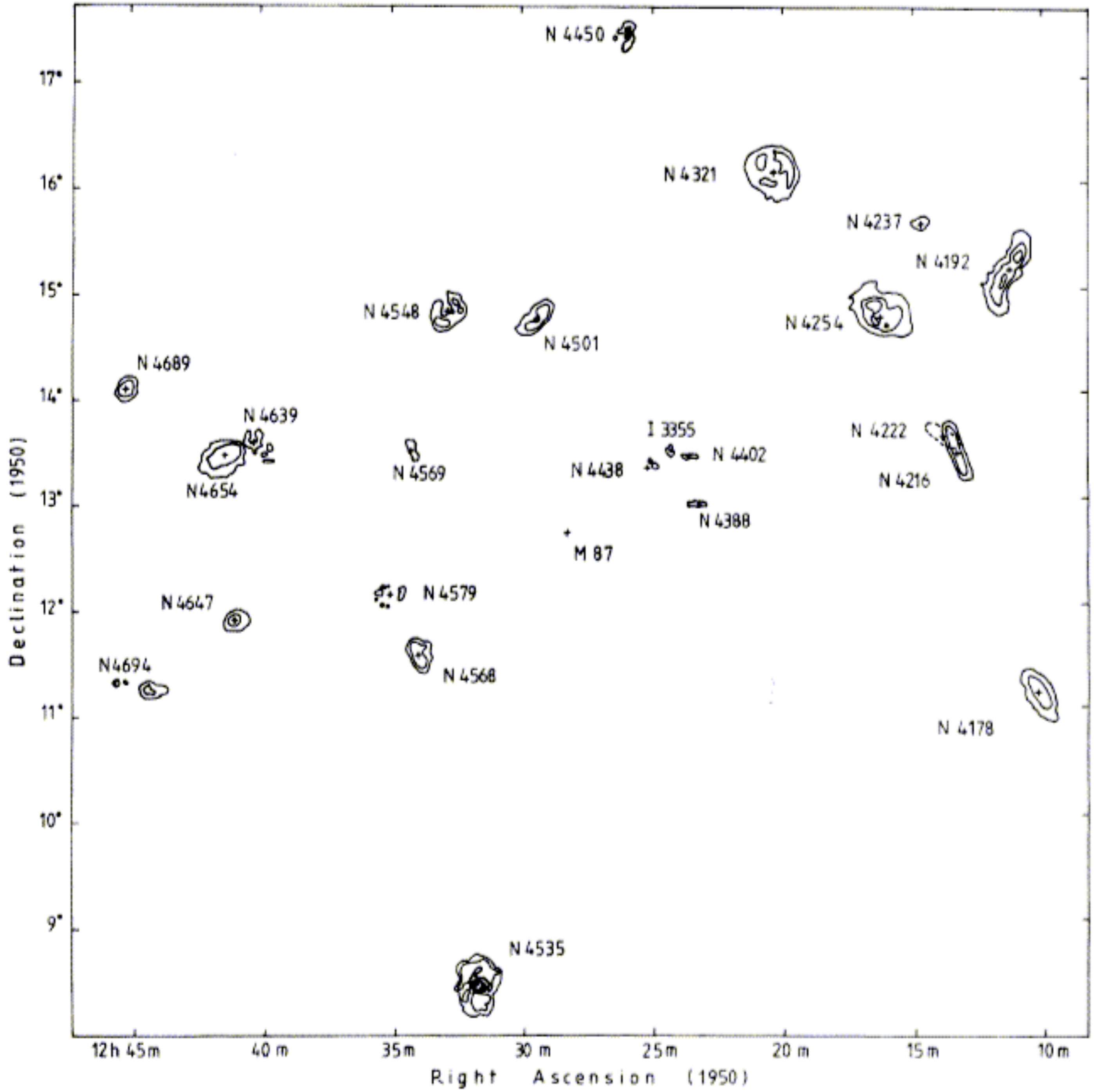
H I still there

Little X-ray gas

Lots of X-ray gas

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.

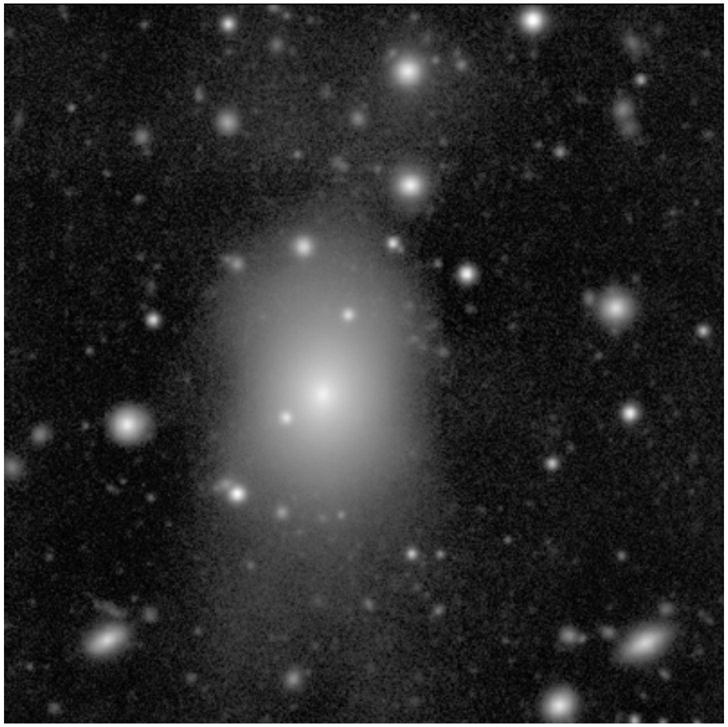
HI Map of the Virgo Cluster

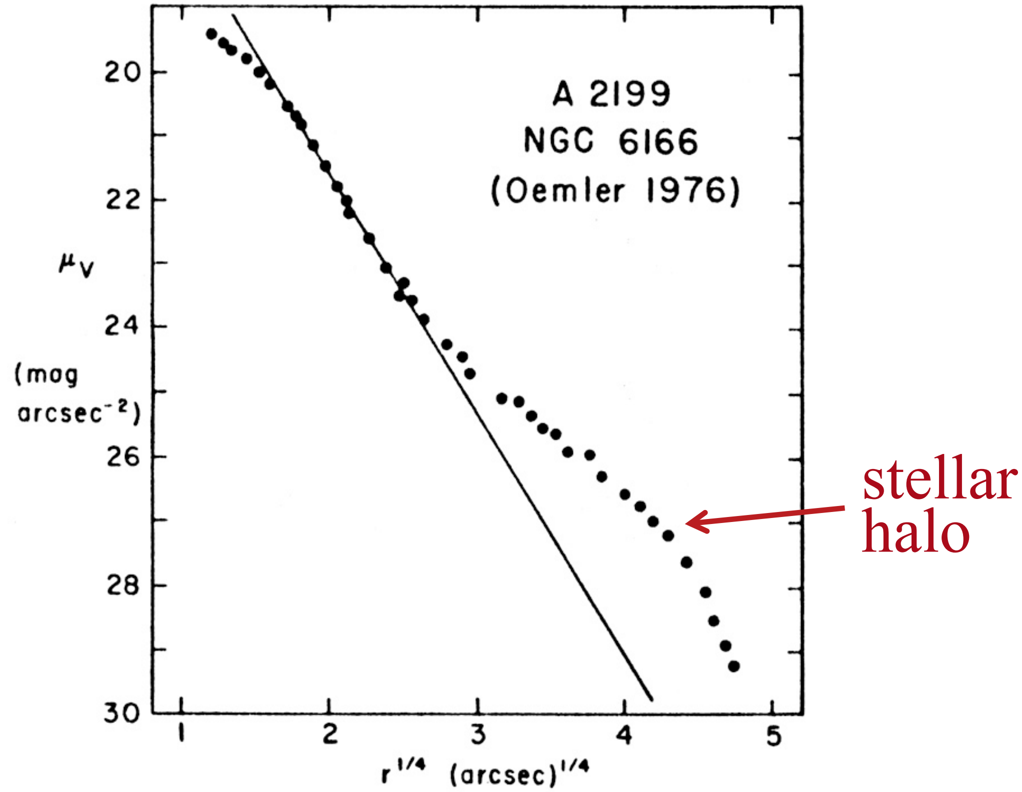


Gaseous disks of spirals are much smaller closer to the cluster center

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



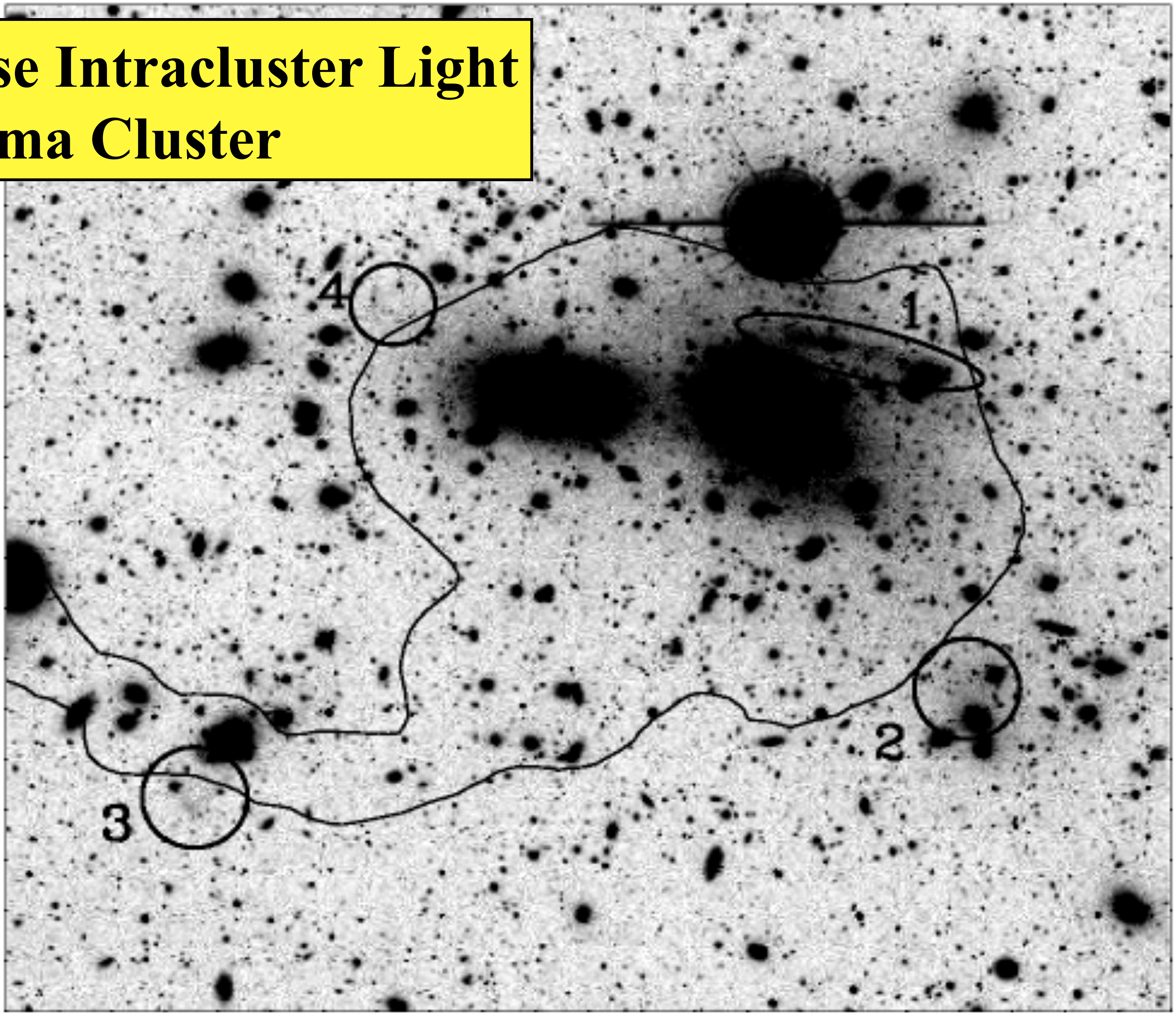


These envelopes are probably just "star piles", a remainder of many tidal interactions of cluster galaxies, sharing the bottom of the potential well with the gE galaxy

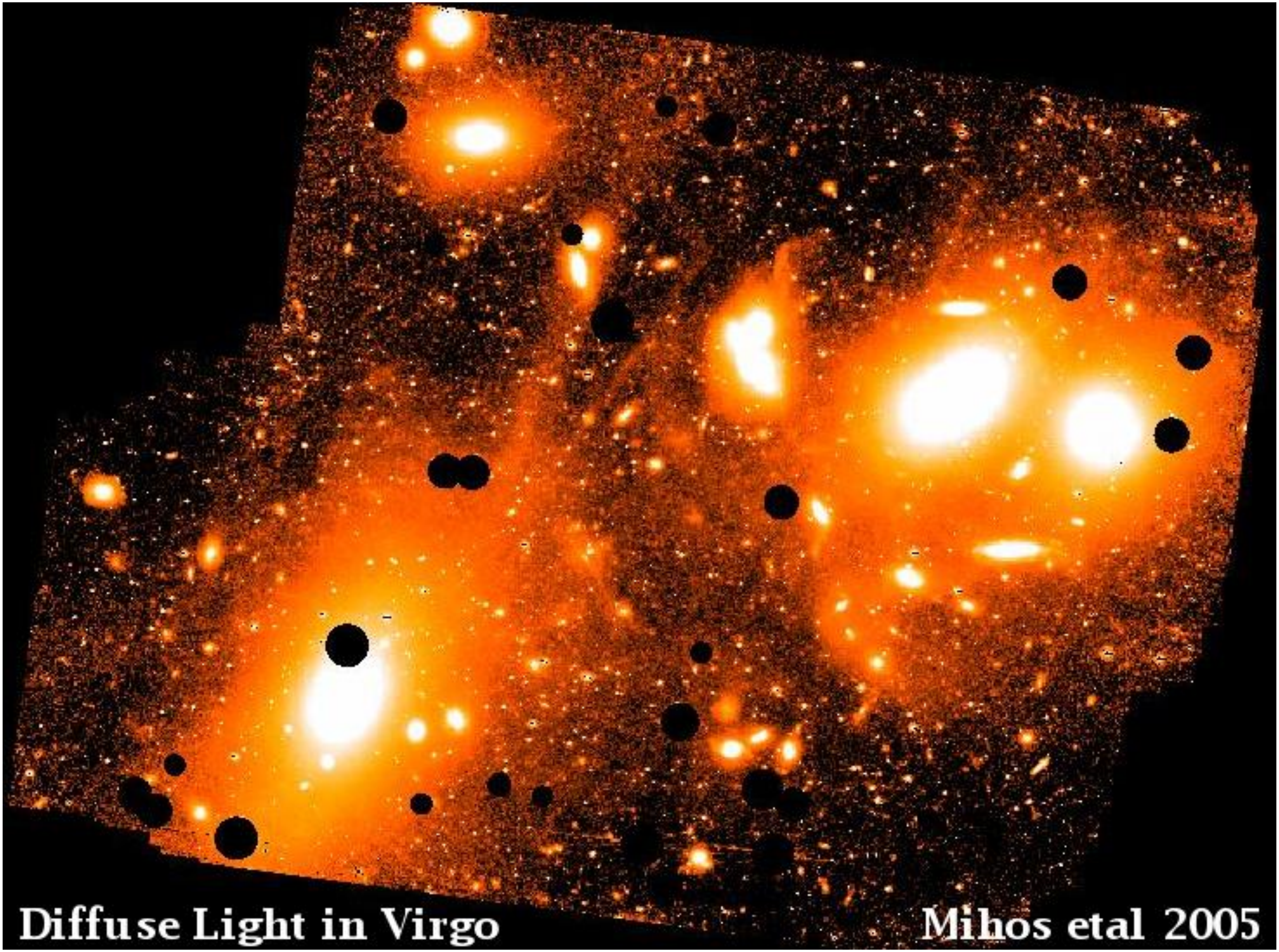
Intracluster Light

- 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

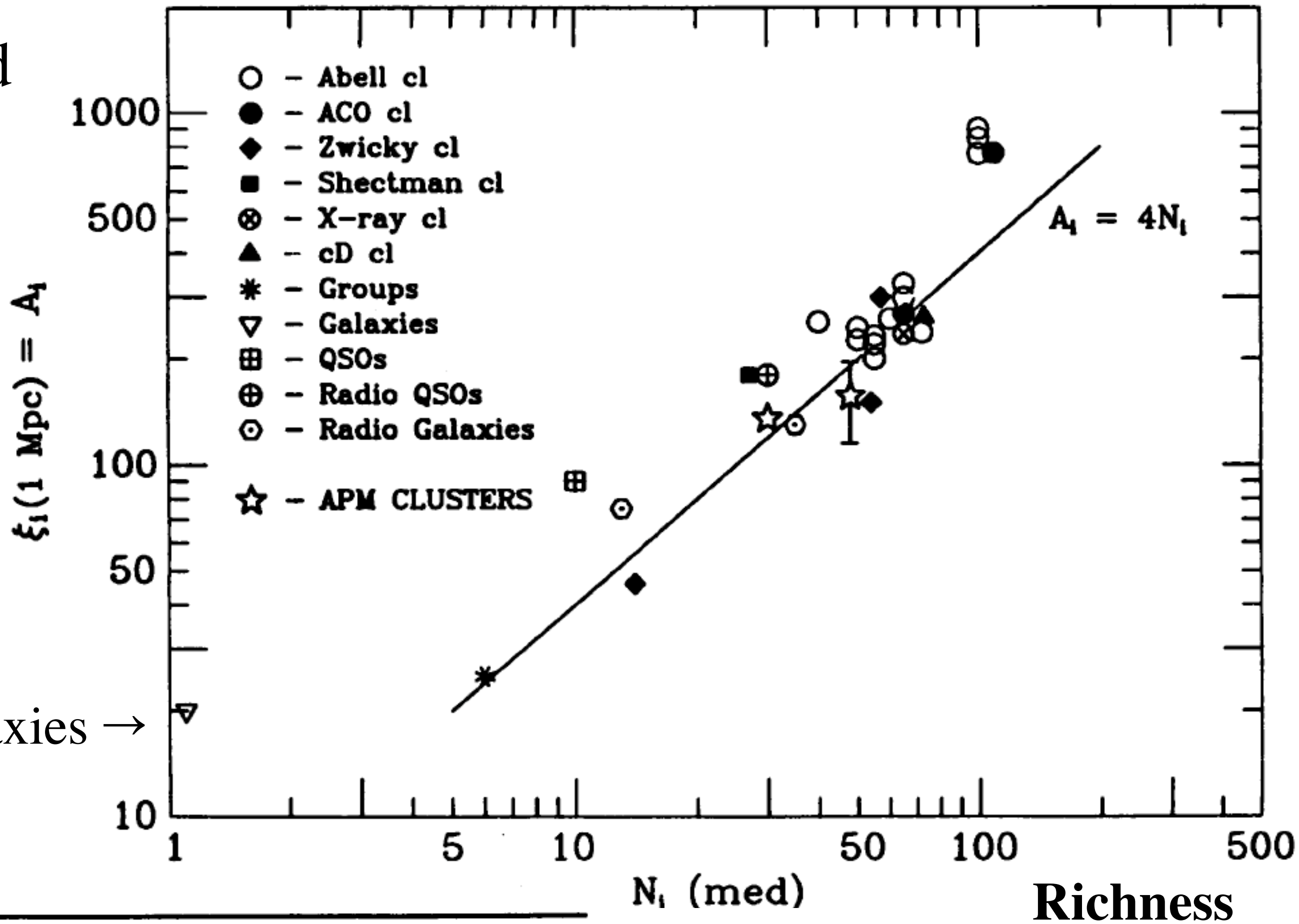
Clusters of Galaxies: Summary

- 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

Cluster-Cluster Clustering

Clusters are clustered more strongly than individual galaxies, and rich ones more than the poor ones

Field galaxies →



Richness

Table 1. Cluster correlations

Catalog	n_c, h^3 Mpc^{-3}	d, h^{-1} Mpc	r_o(obs)	$r_o = 0.4d$
Abell, $R \geq 2$	1.2×10^{-6}	94	42 ± 10	37.6
Abell, $R \geq 1$	6×10^{-6}	55	22 ± 3	22.0
EDCC	15×10^{-6}	40.5	16 ± 4	16.2
APM	24×10^{-6}	34.7	13 ± 2	13.9

(from N. Bahcall)

Galaxy Biasing

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

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

Or:

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

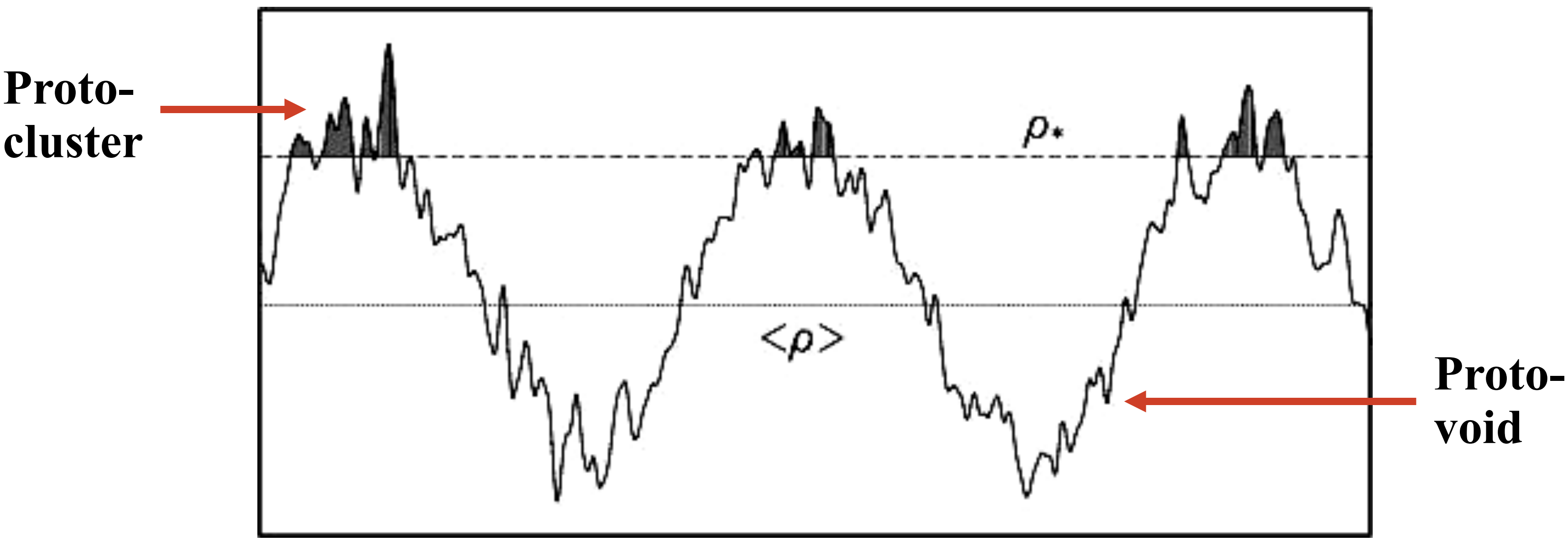
Here ***b*** is the *bias factor*.

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.

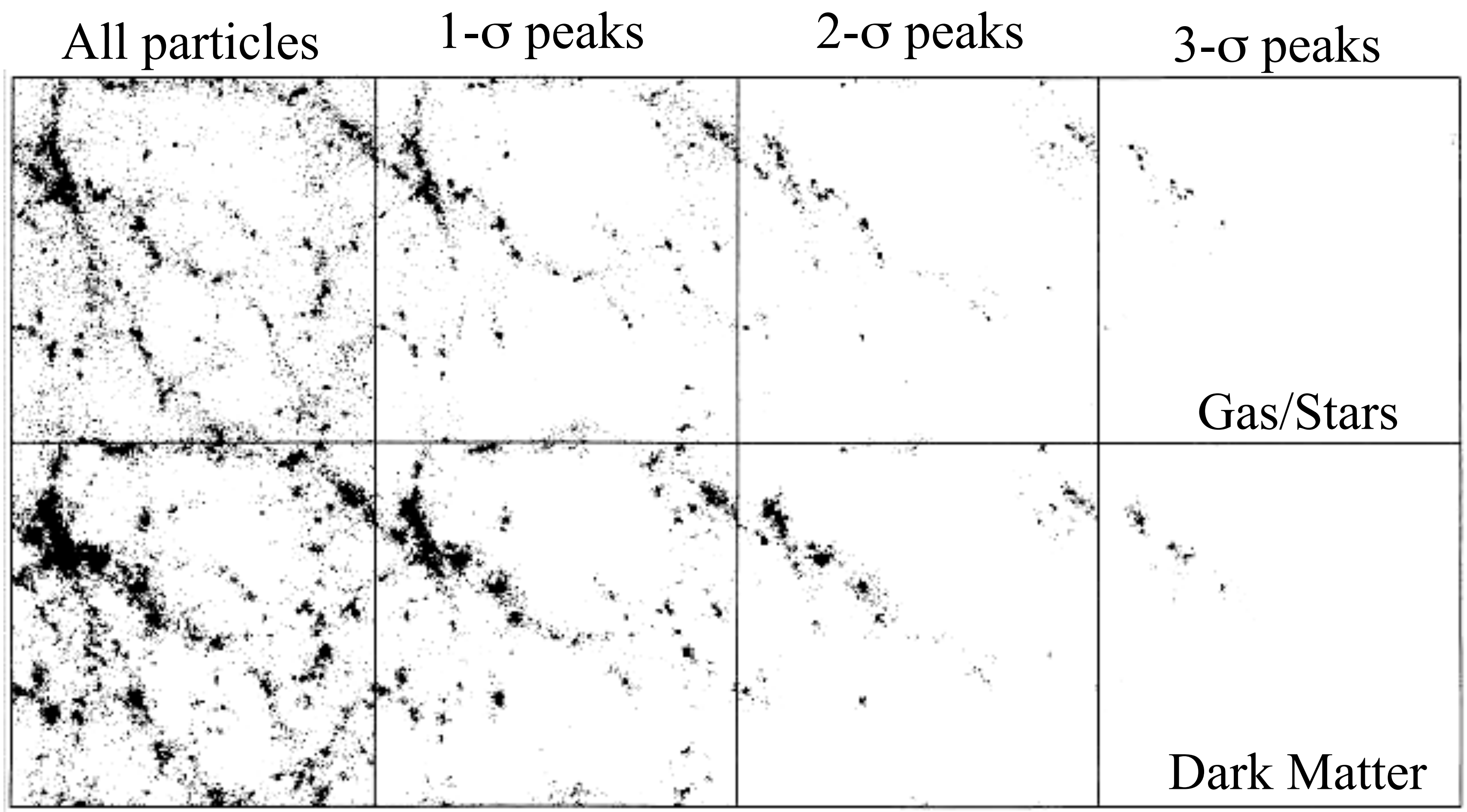
High Density Peaks as Biased Tracers

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

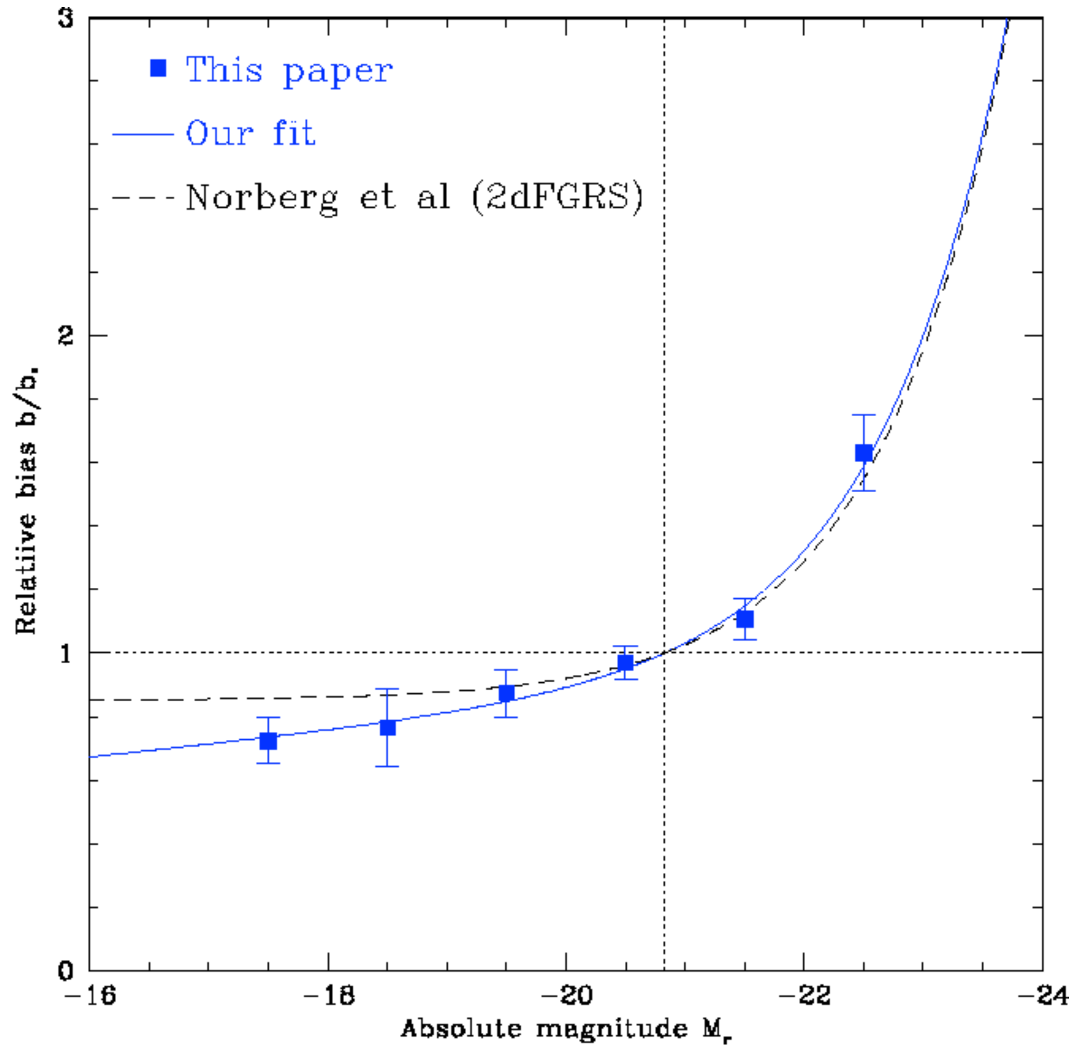


(From an N-body simulation by R. Carlberg)

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):

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

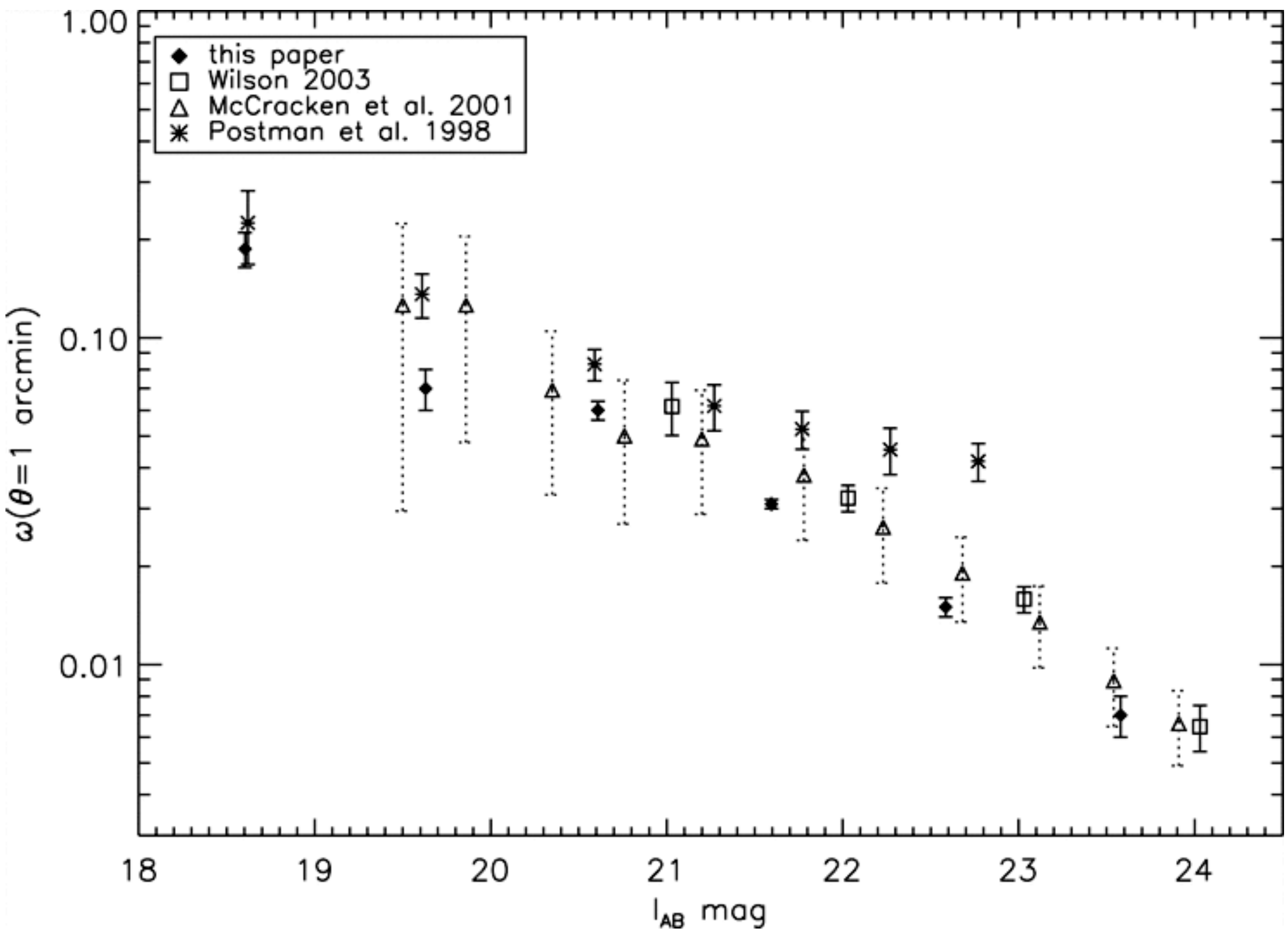
If $\varepsilon = -1.2$, clustering is fixed in comoving coords.
If $\varepsilon = 0$, clustering is fixed in proper coords.
If $\varepsilon > 0$, clustering grows in proper coords.

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

Evolution of Clustering

- Indeed, the strength of the angular clustering is observed to be weaker at fainter magnidudes (~ more distant samples)

Amplitude of the angular correlation function on the scale of 1 arcmin, as a function of the survey depth

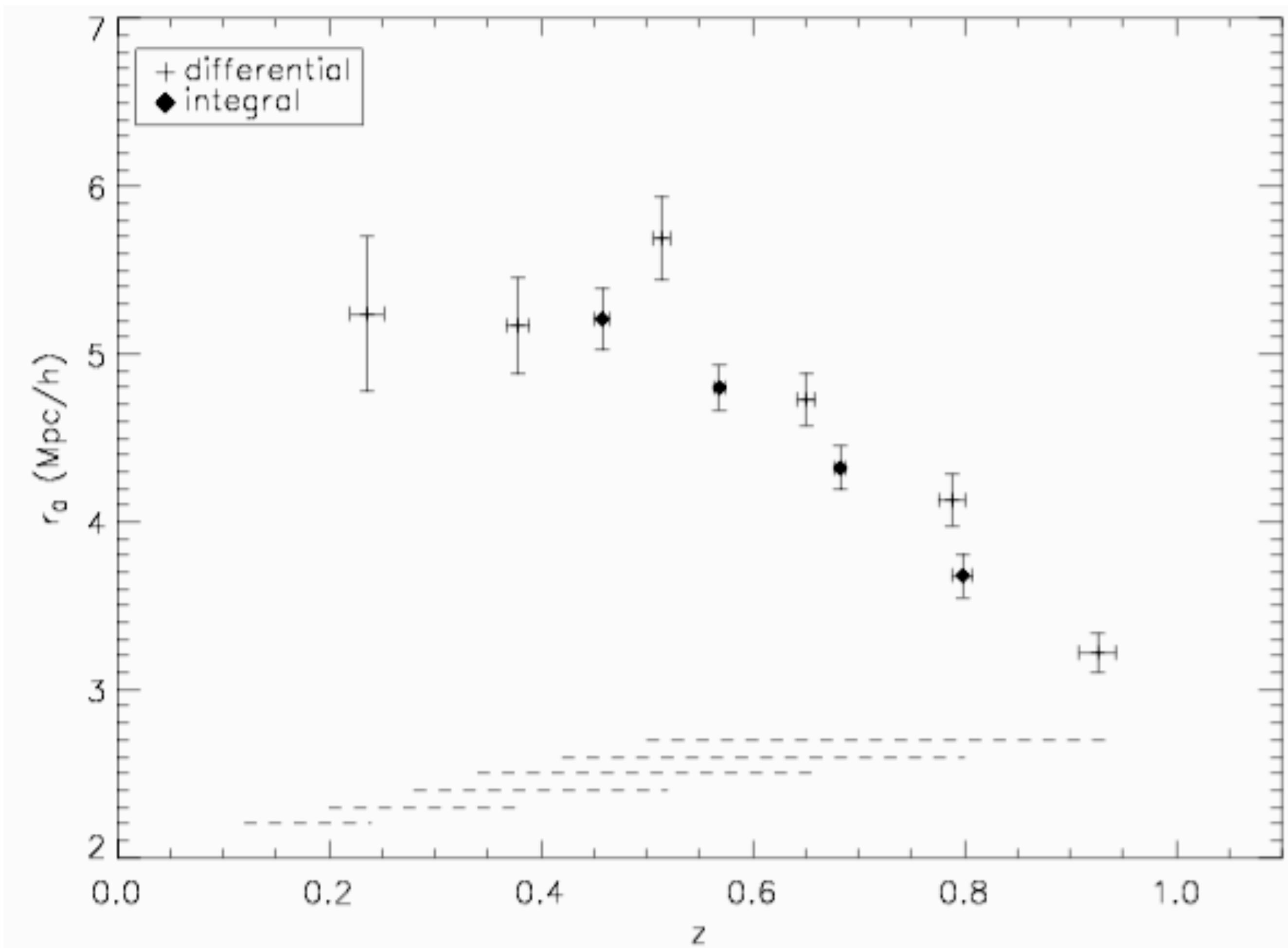


(Coil et al., DEEP survey team)

Evolution of Clustering

- Deep redshift surveys give the same result for the spatial clustering, at least out to $z \sim 1$:

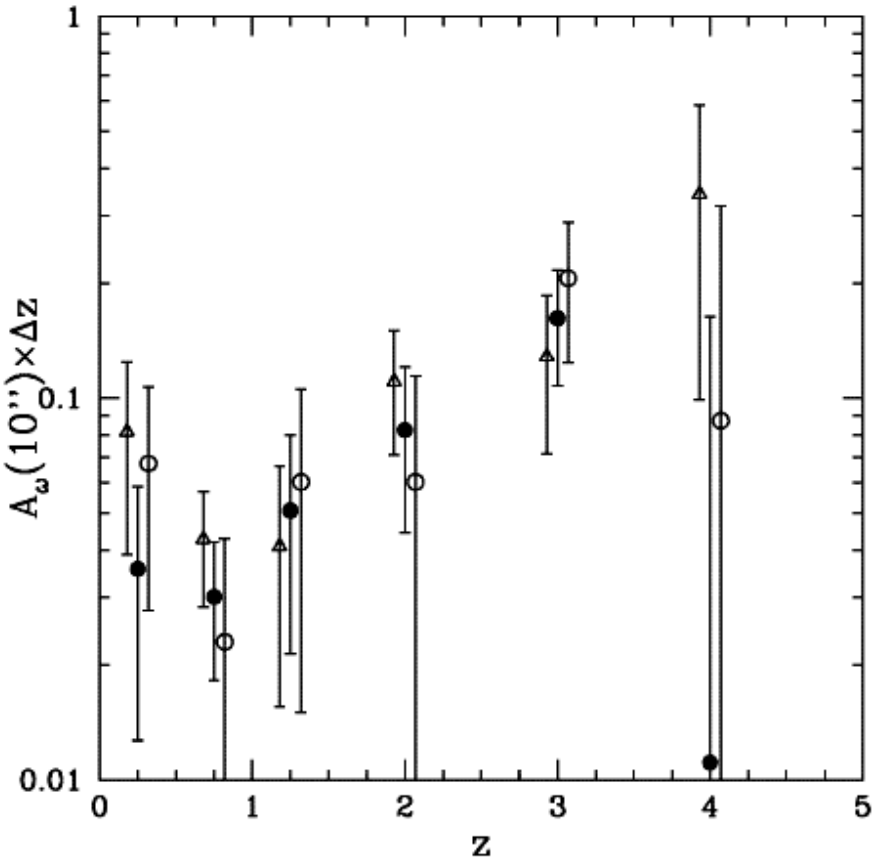
Clustering length as a function of redshift

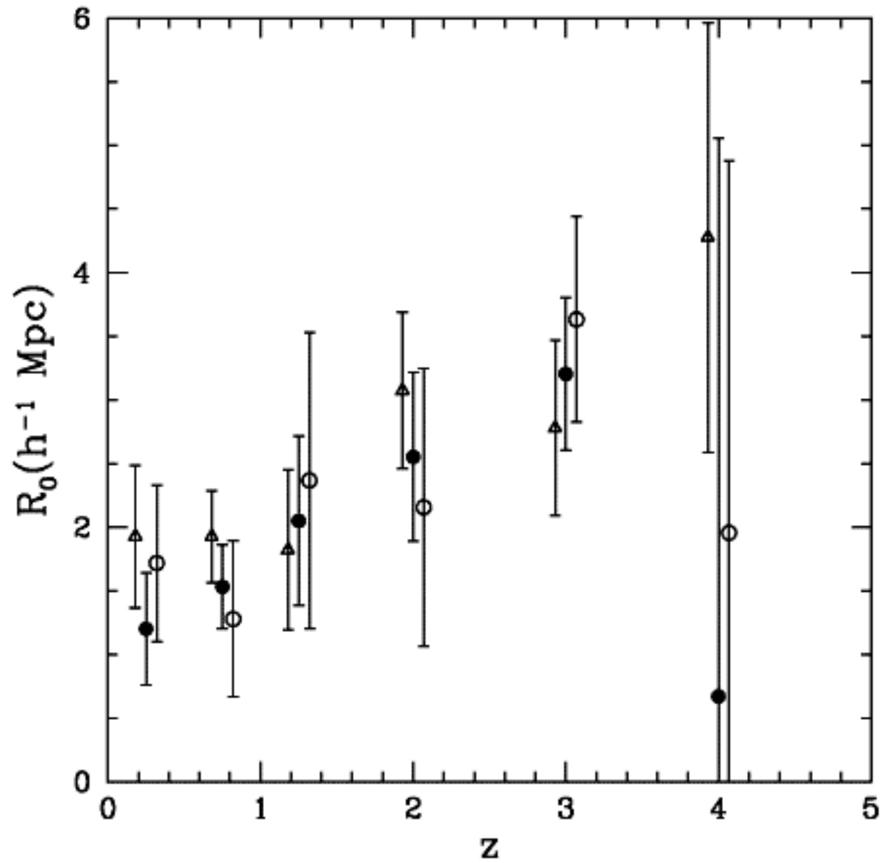


(Coil et al., DEEP survey team)

Evolution of Clustering

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

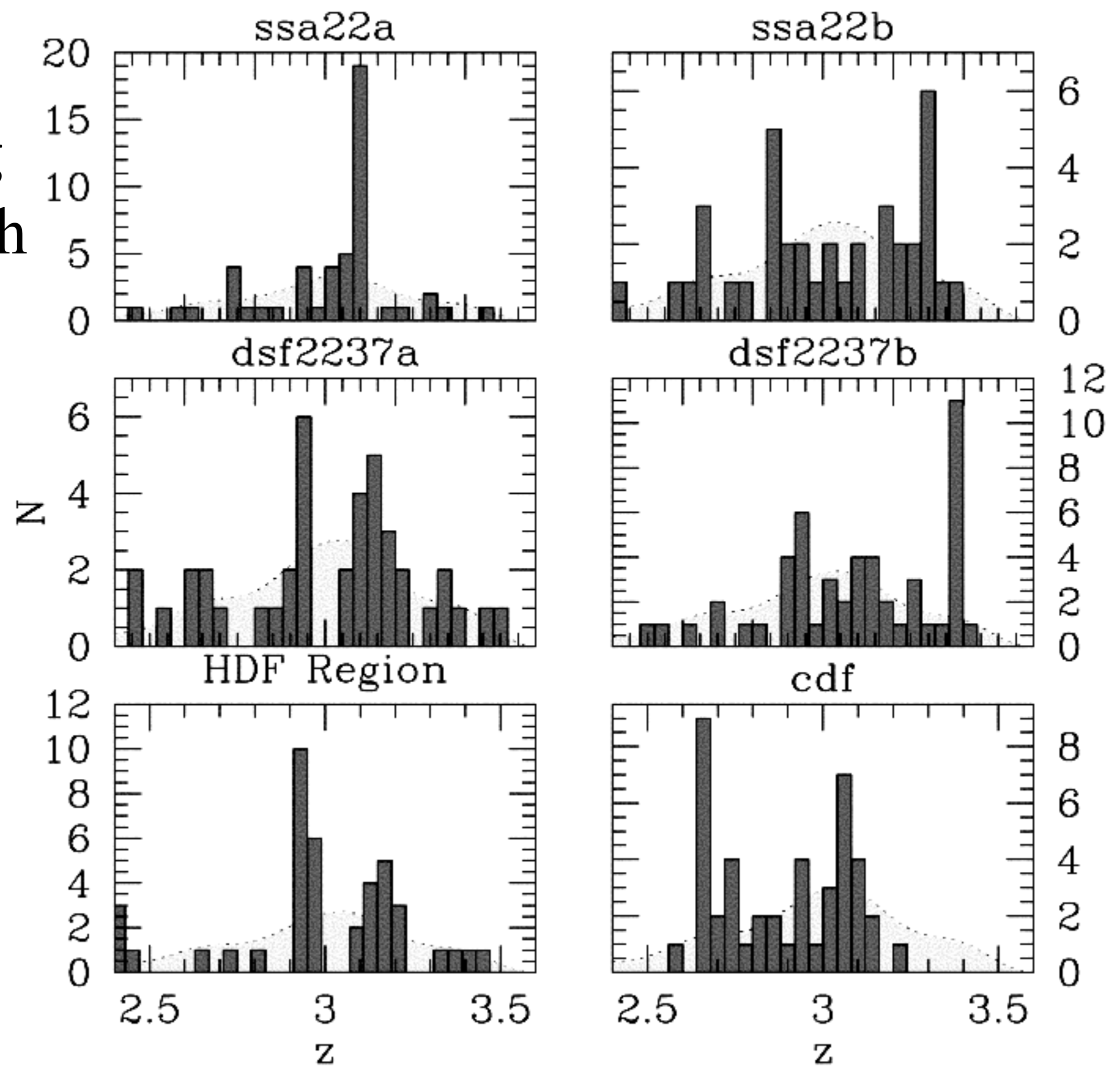




(Hubble Deep Field data)

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

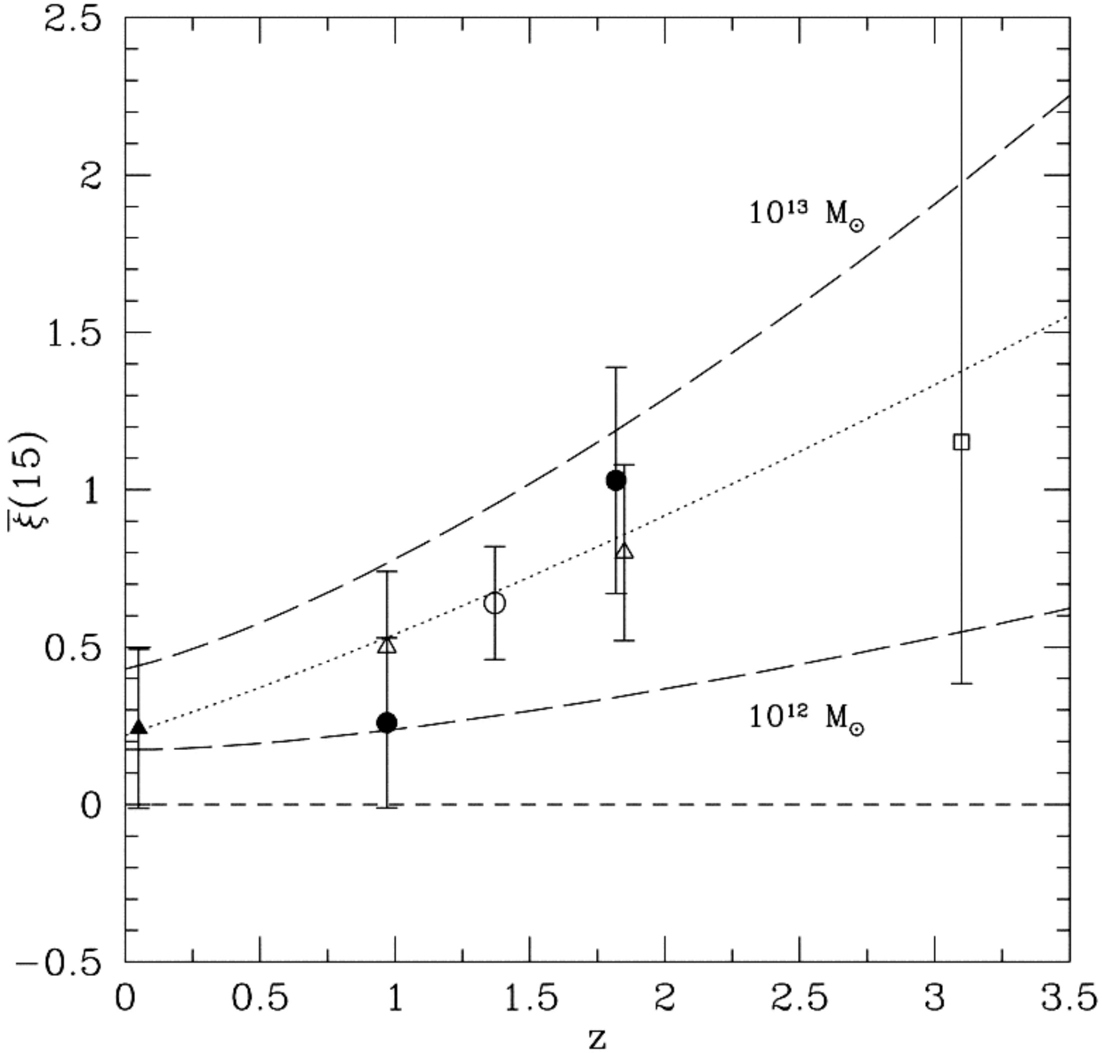
Strong clustering of young galaxies is observed at high redshifts (up to $z \sim 3$ - 4), apparently as strong as galaxies today



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

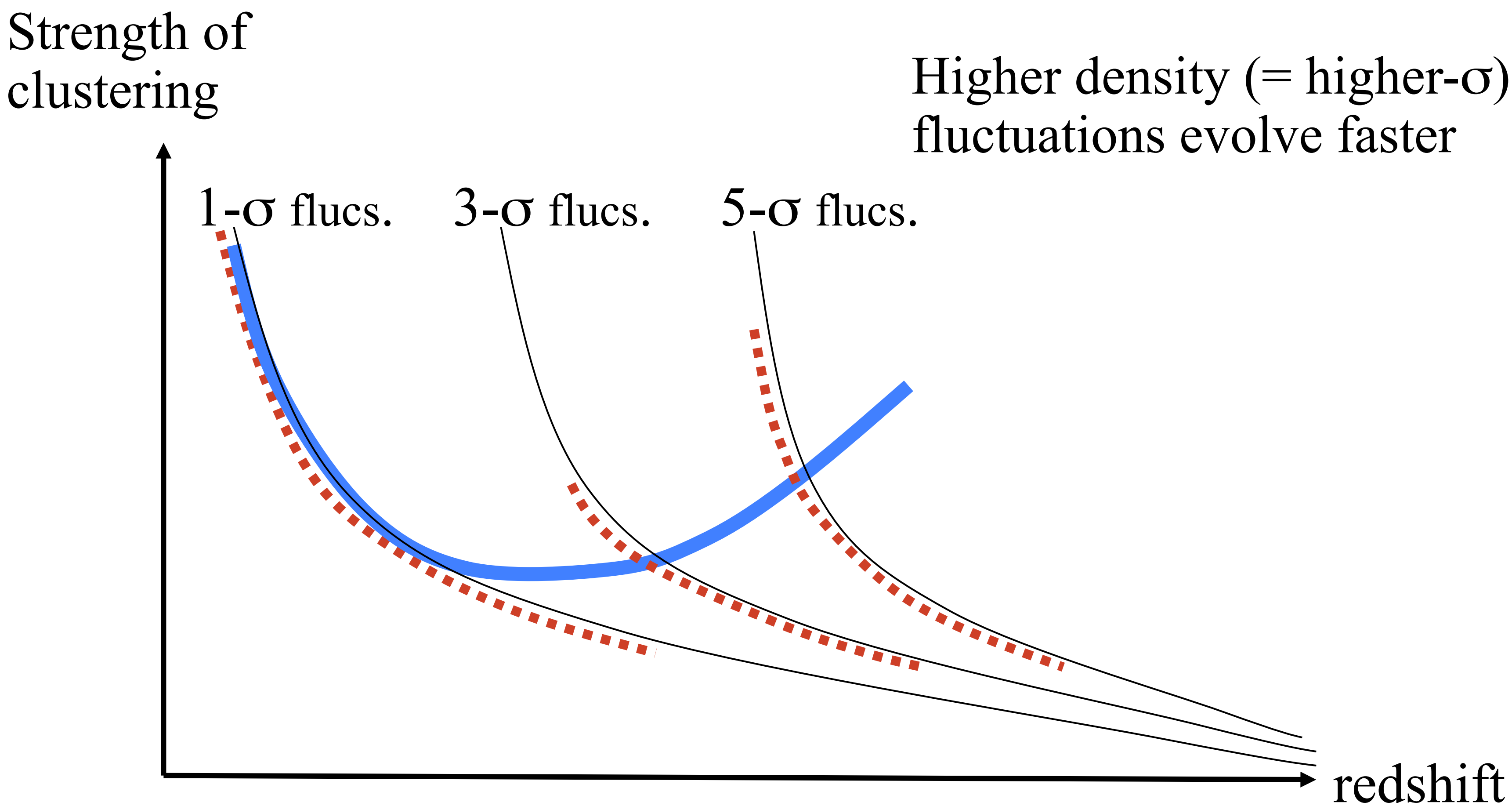


How is this possible?

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

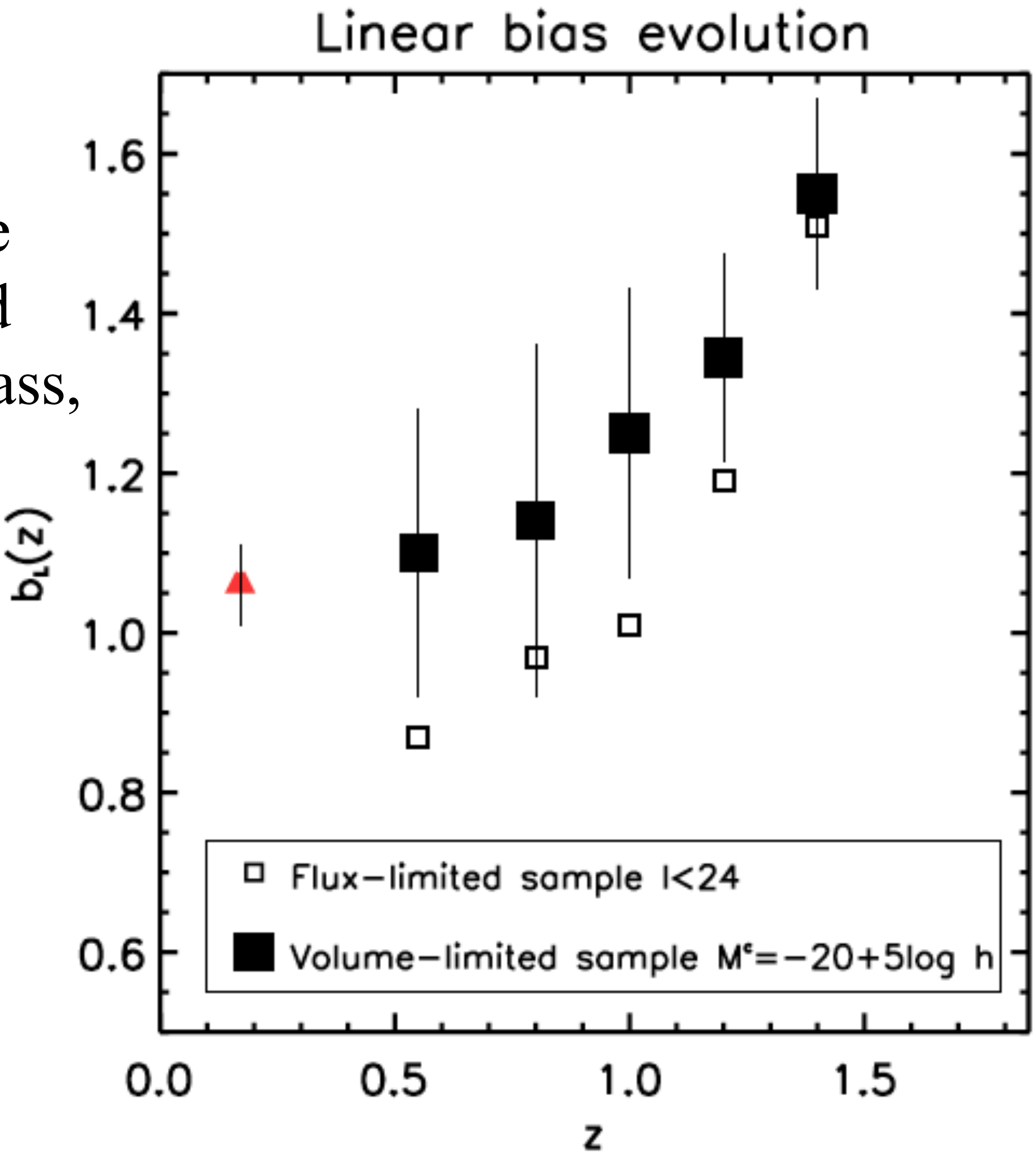


At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly …

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