Large-Scale Structure and Galaxy Environment

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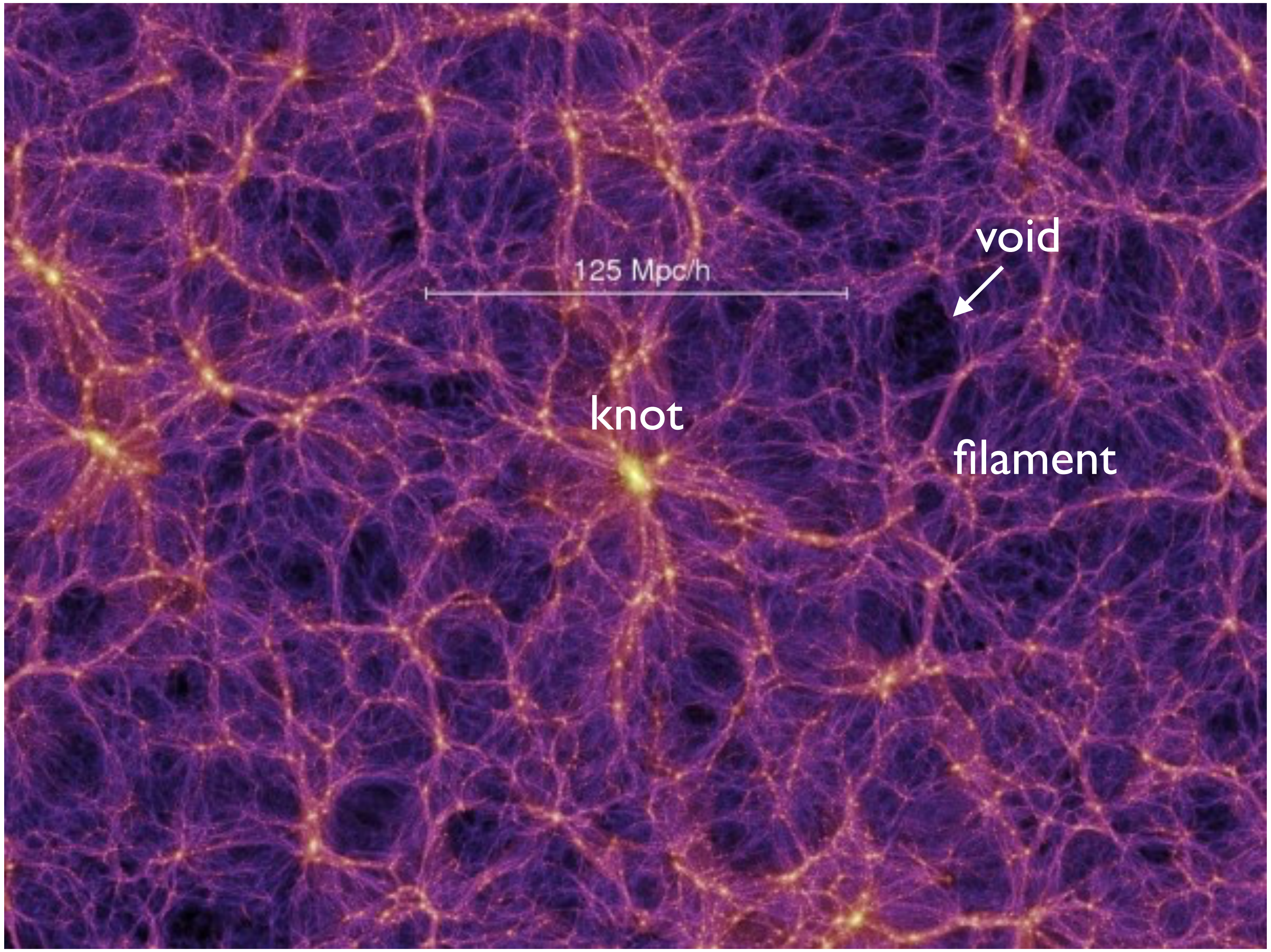
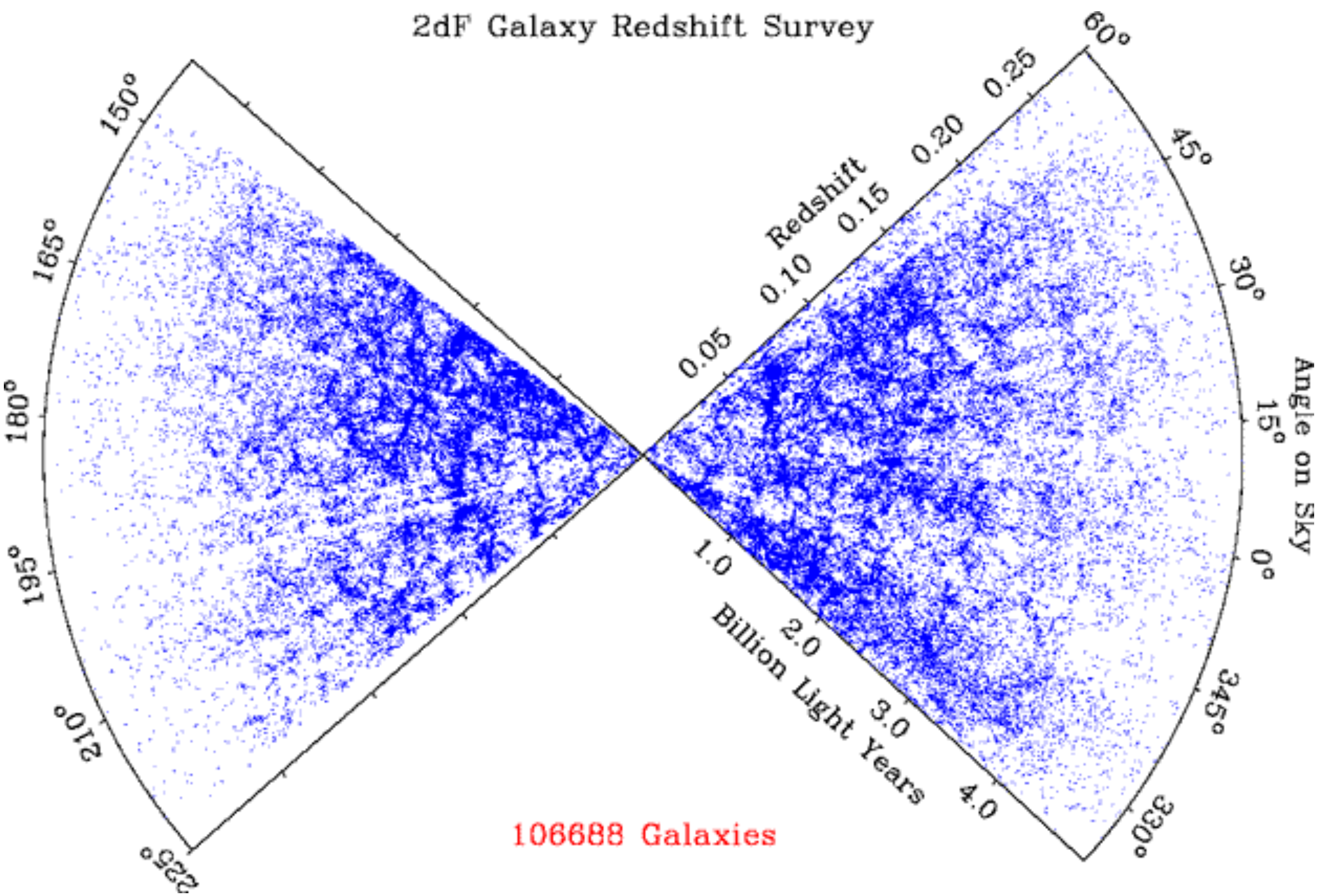
The Cosmic Web

Large-scale distribution of dark matter



Volker Springel and the VIRGO Consortium

Probing large-scale structure with galaxy surveys



Galaxy spatial distribution

Question: what kind of clustering do you expect in a perfectly homogeneous and isotropic Universe?

NONE!

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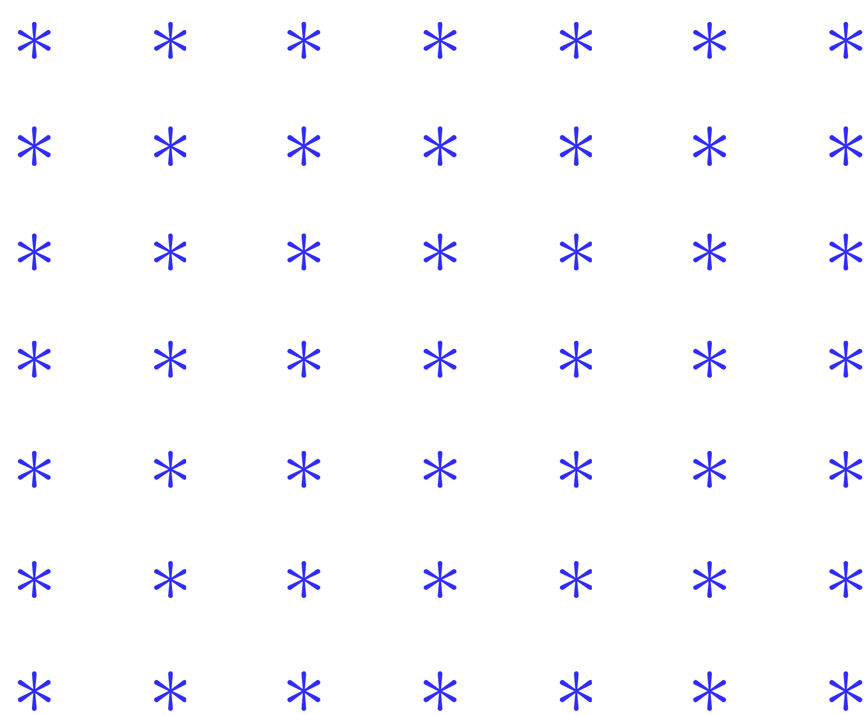
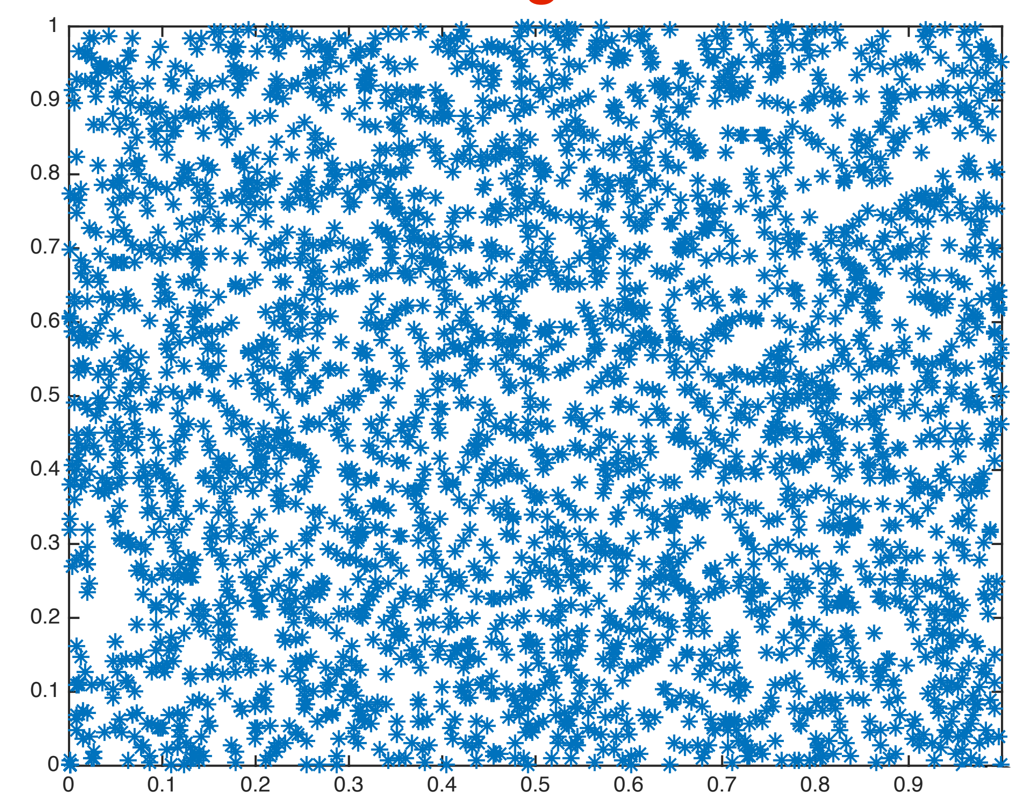


NONE!

The real Universe has structure precisely because it is not perfectly homogeneous



Quantifying the galaxy spatial distribution

- If galaxies are clustered, they are "correlated"
- This is usually quantified using the ***2-point correlation function,* $\xi(r)$,** 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

The 2-point correlation function

Joint probability $\delta^2 P_{12}$ of finding a galaxy in some volume δV_1 at $\underline{r}_1$ and another in δV_2 at $\underline{r}_2$ is

$$\delta^2 P_{12} = \bar{n}^2 \left[1 + \xi(r_{12})\right] \delta V_1 \, \delta V_2$$

$\xi(r)$ is the two-point galaxy-galaxy correlation function
$\bar{n}$ is mean number density of galaxies
$r_{12} = |\underline{r}_1 - \underline{r}_2|$ (statistical homogeneity and isotropy)

$\xi(r) > 0 \implies$ galaxies are clustered
$\xi(r) = 0 \implies$ galaxies are randomly distributed
$\xi(r) < 0 \implies$ galaxies tend to avoid each other

NB: Integral constraint $\left(4\pi \int \xi(r) r^2 \mathrm{d}r \text{ must not diverge}\right)$

Computing ξ(r)

A simple ‘estimator’ used to compute $\xi(r)$ is

$$\hat{\xi}(r) = \frac{DD(r)}{RR(r)} - 1$$

$DD(r)$ are ‘data-data’ pair counts, number of galaxy pairs in bin of separation $r \pm \Delta r/2$
$RR(r)$ are ‘random-random’ pair counts

Can be computationally ‘expensive’ as for N_d galaxies there are $N_\mathrm{d}(N_\mathrm{d} - 1)/2$ pairs!

NB: Randomly generated points must have same ‘selection function’ as data

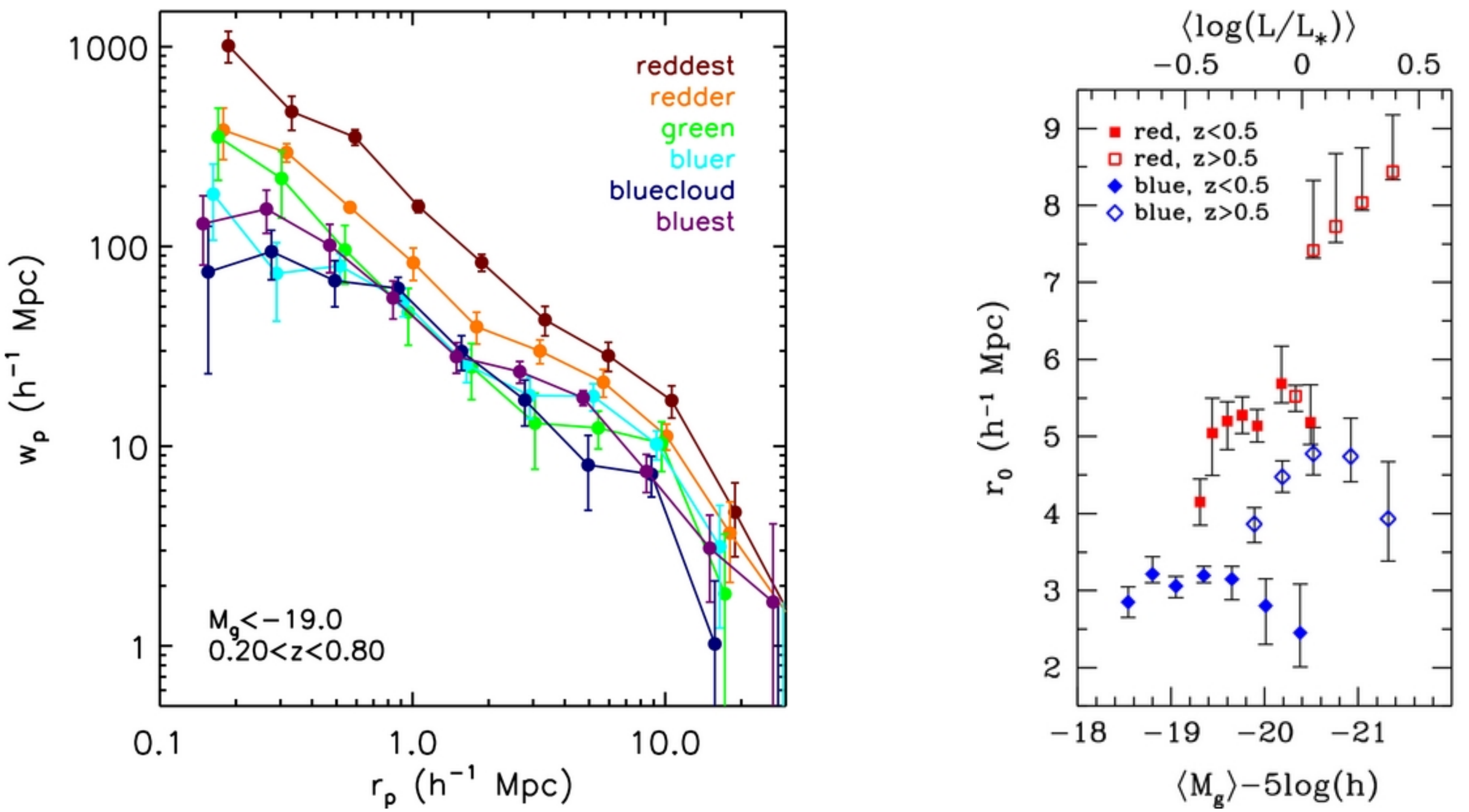
Galaxy clustering by colour

A good description of $\xi(r)$ is (sometimes!) a powerlaw

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

r_0 is correlation length

'Red' galaxies are more strongly clustered than 'blue' galaxies (have larger r_0)

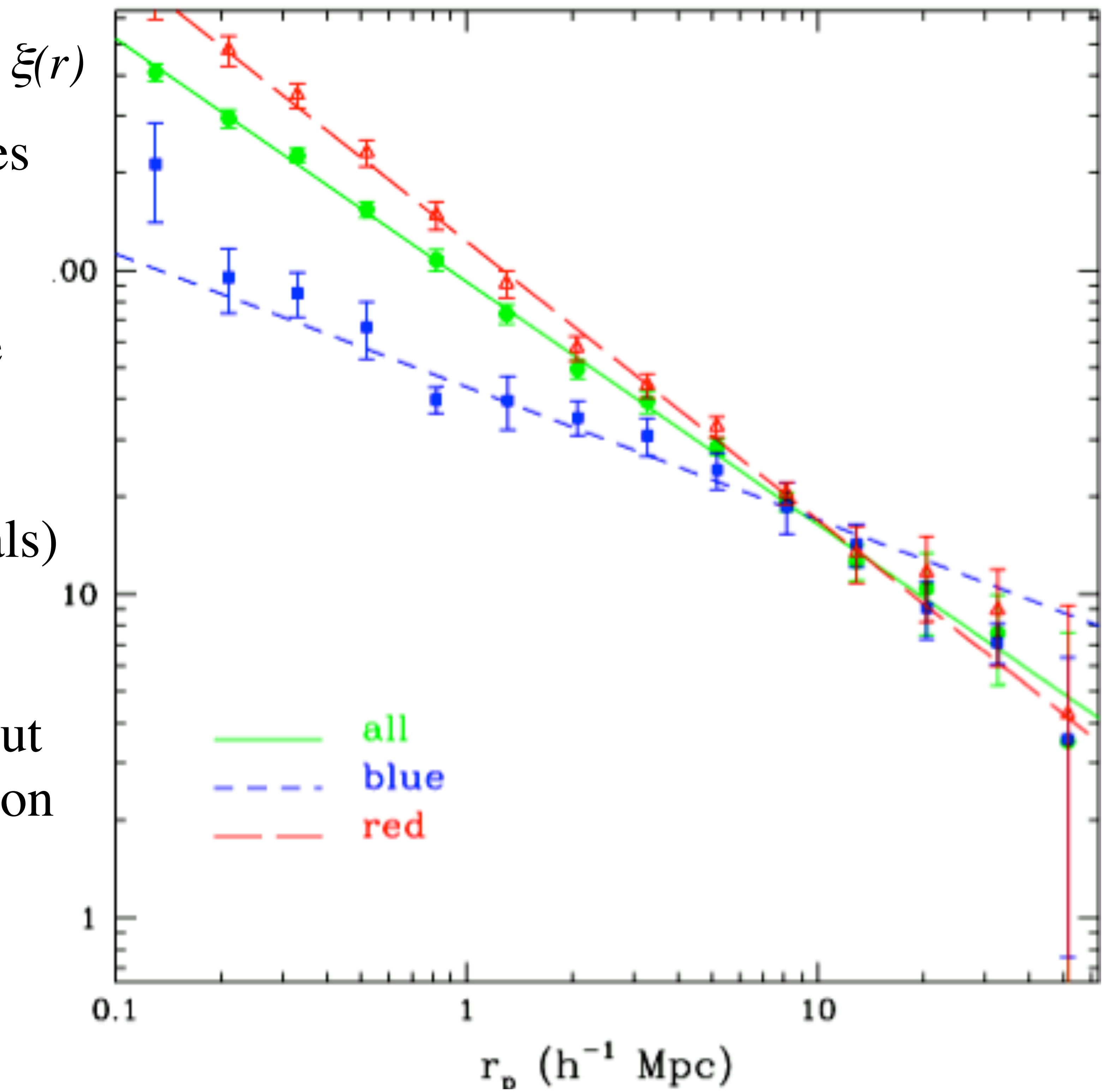


Skibba+ 13

Clustering dependence on galaxy type

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

That, too, says something about galaxy formation



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:

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

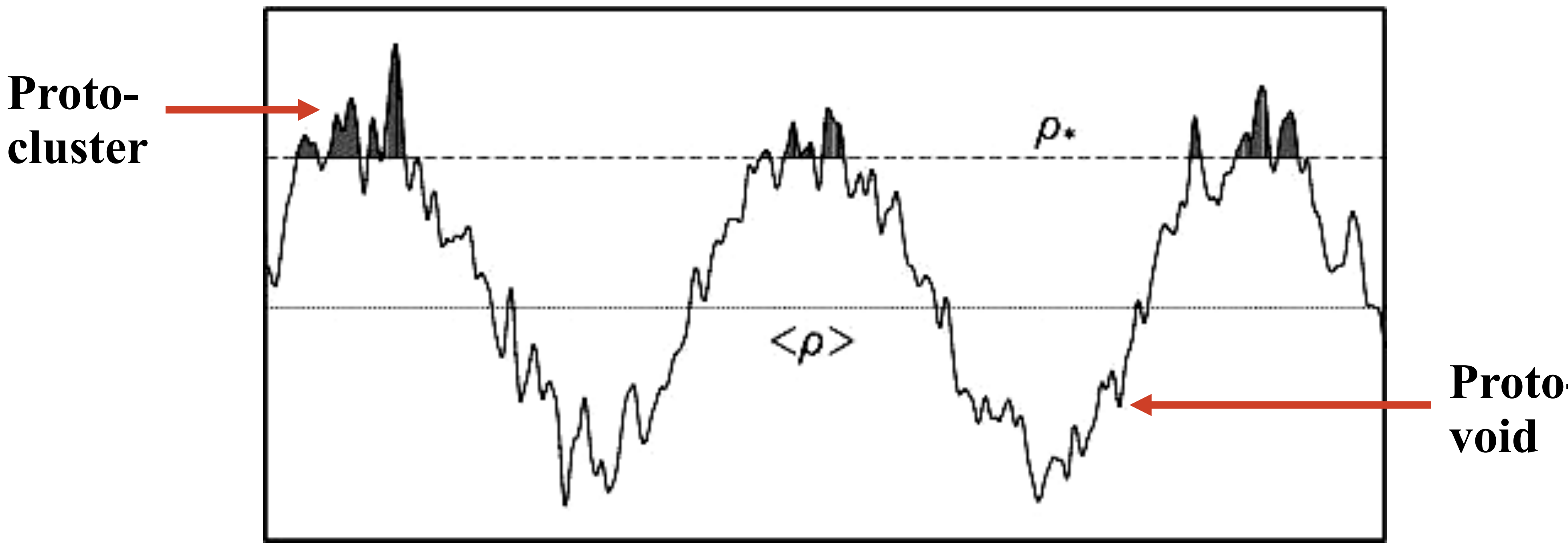
Here ***b*** is the *bias factor*.

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

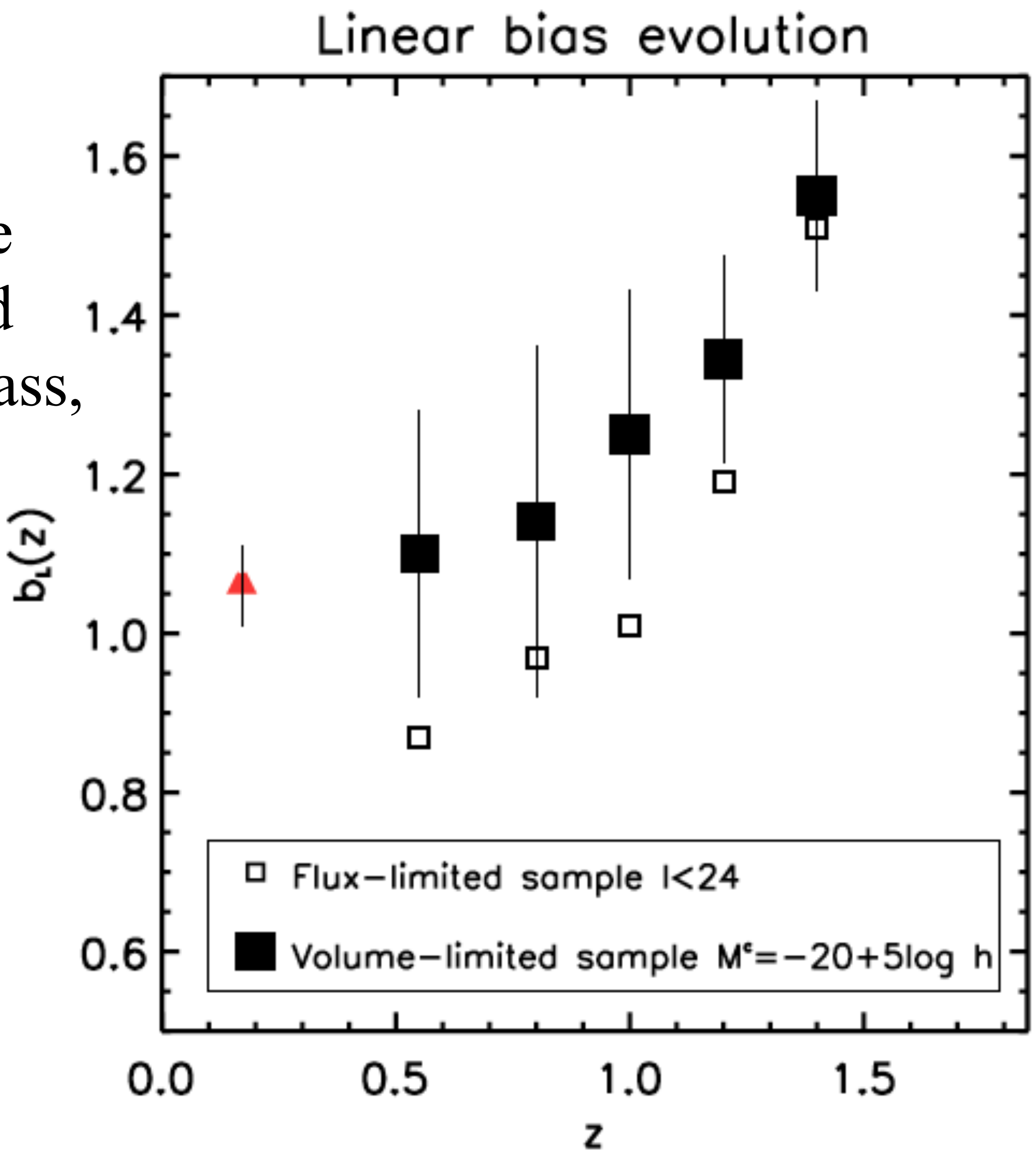
Take a cut through a density field. Smaller fluctuations ride atop of the larger density waves, which lift them up in bunches; thus the highest peaks (densest fluctuations) are a priori clustered more strongly than the average ones:



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

The Evolution of Bias

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

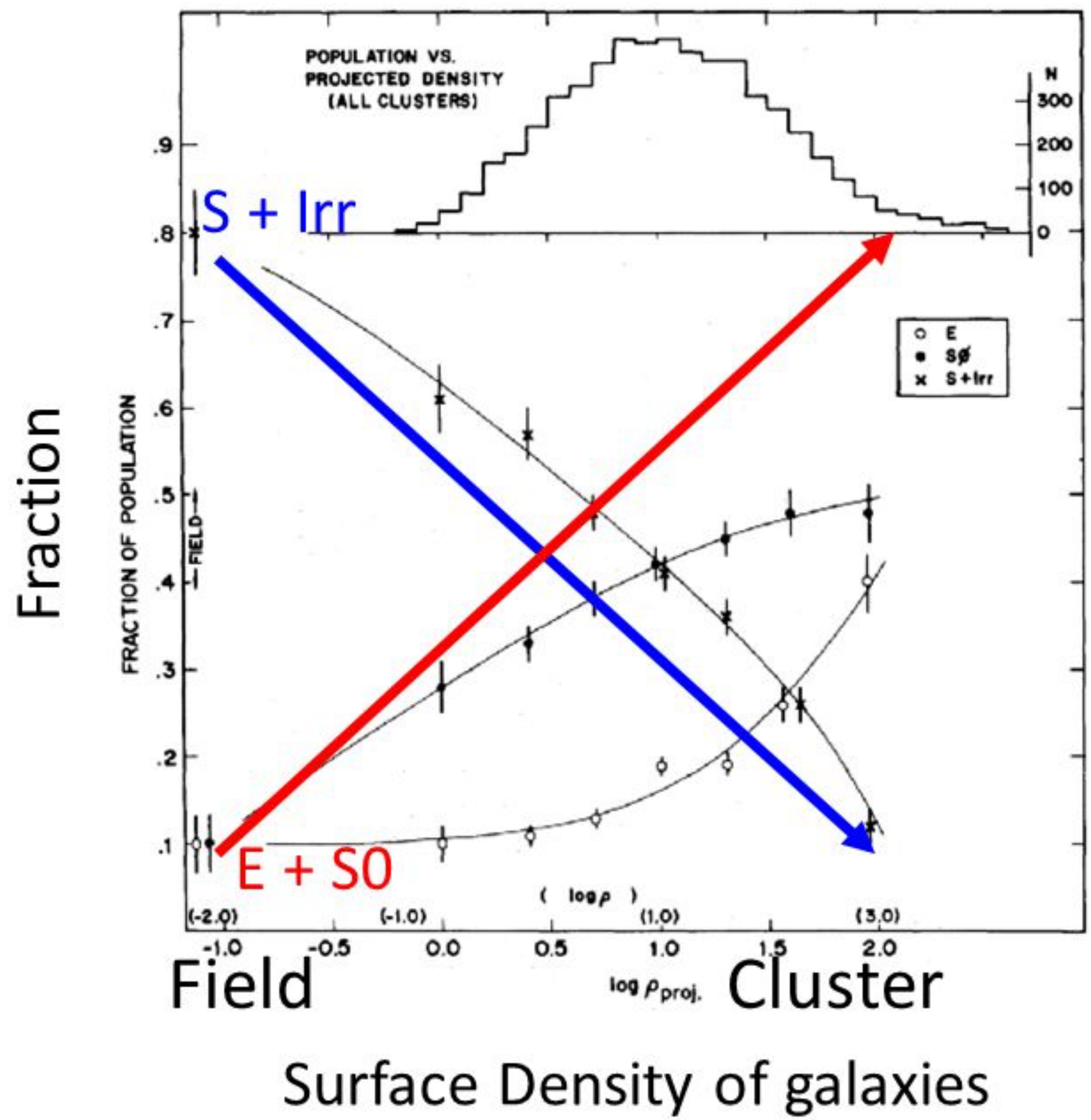


But at higher z's, they are progressively ever more biased

(Le Fevre et al., VIMOS Survey Team)

Environment and Galaxy Properties

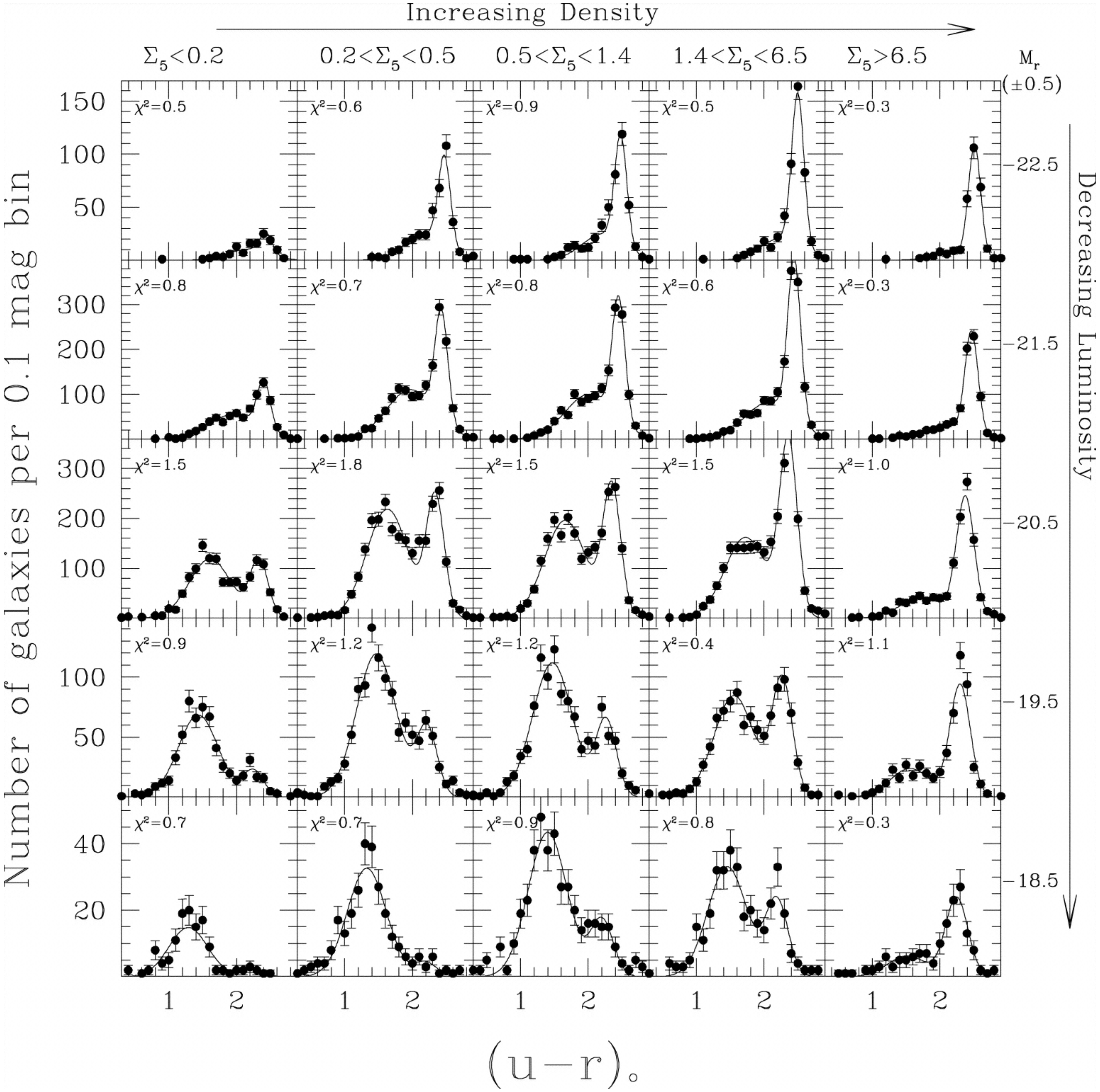
Local Morphology Density Relation



Dressler 80

Y. Matsuda based on Dressler (1980)

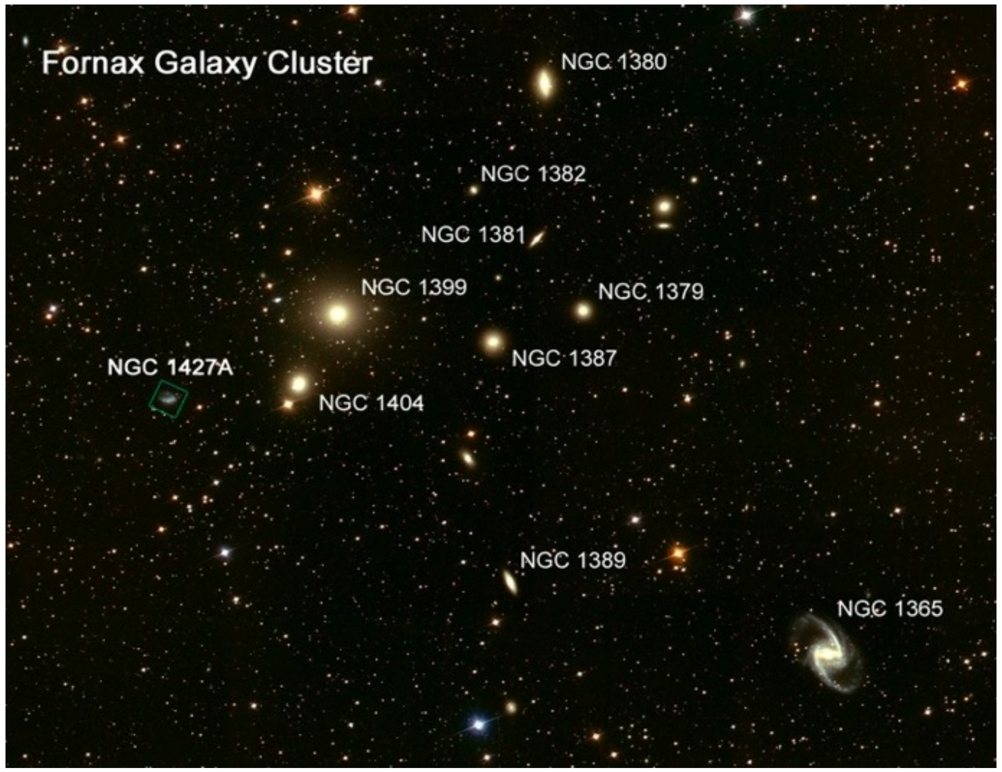
Colour-density relation



Balogh et al. (2004)

Galaxy Groups and Clusters

Galaxy clusters V/s galaxy clustering

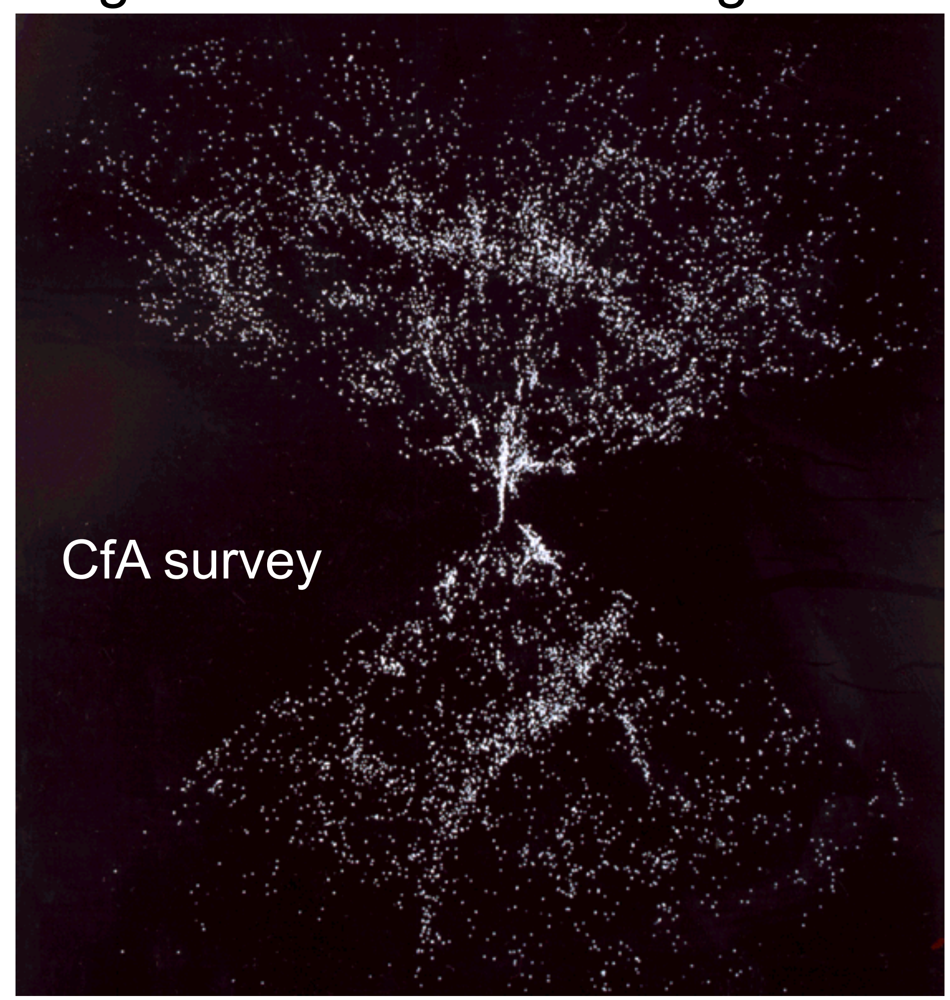


Galaxy clusters: conglomeration of galaxies

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

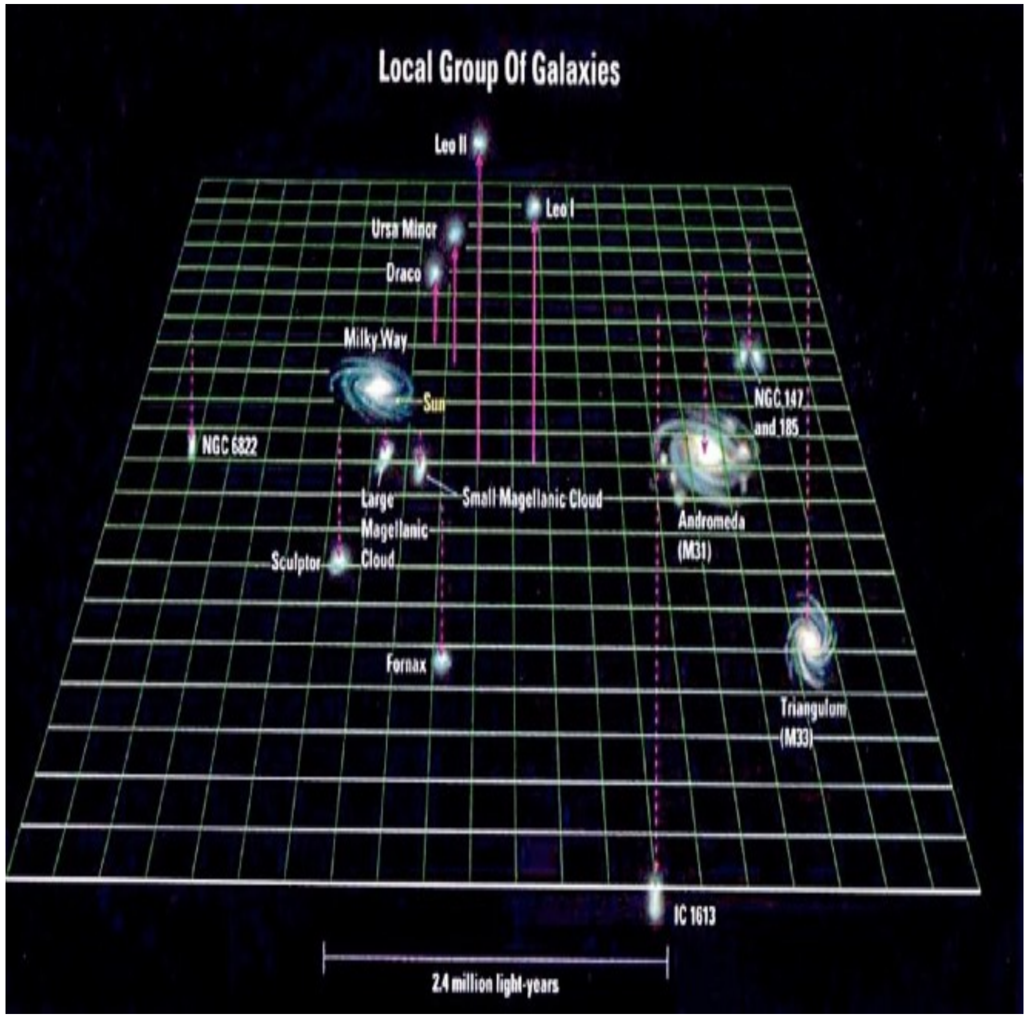
typical cluster luminosities (~ 100 - 1000 galaxies) are $L_{cl} \sim 10^{12}\, L_{\odot}$

Galaxy clustering: describes the large-scale distribution of galaxies



Galaxy groups and clusters

Galaxies are preferentially found in groups or larger conglomerations called clusters.



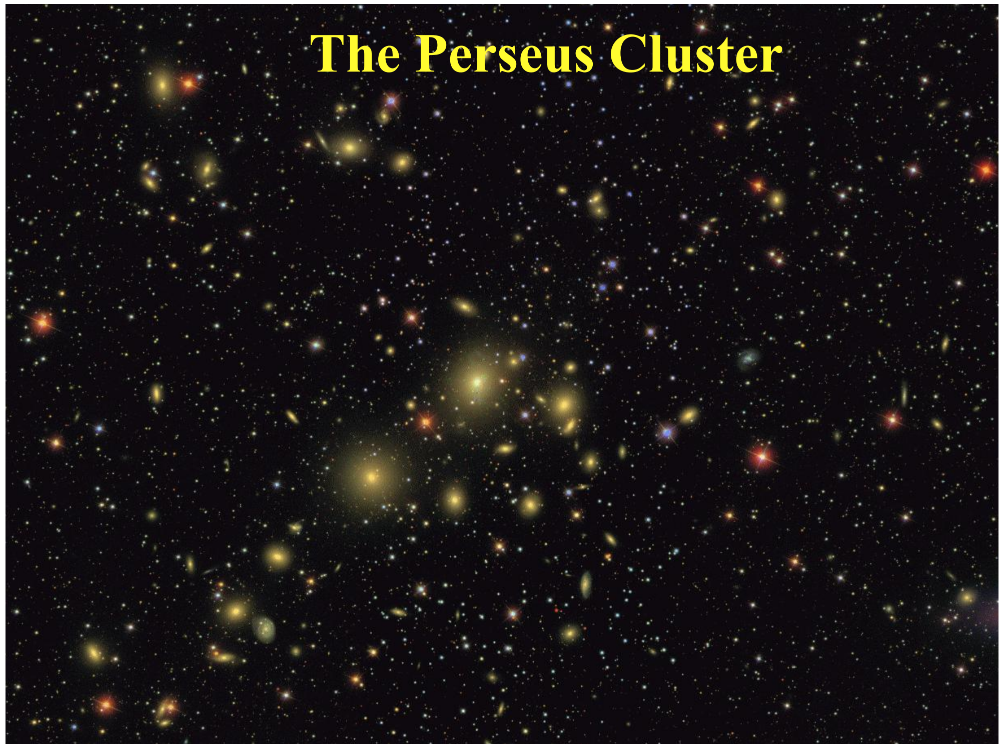
Group/Poor cluster

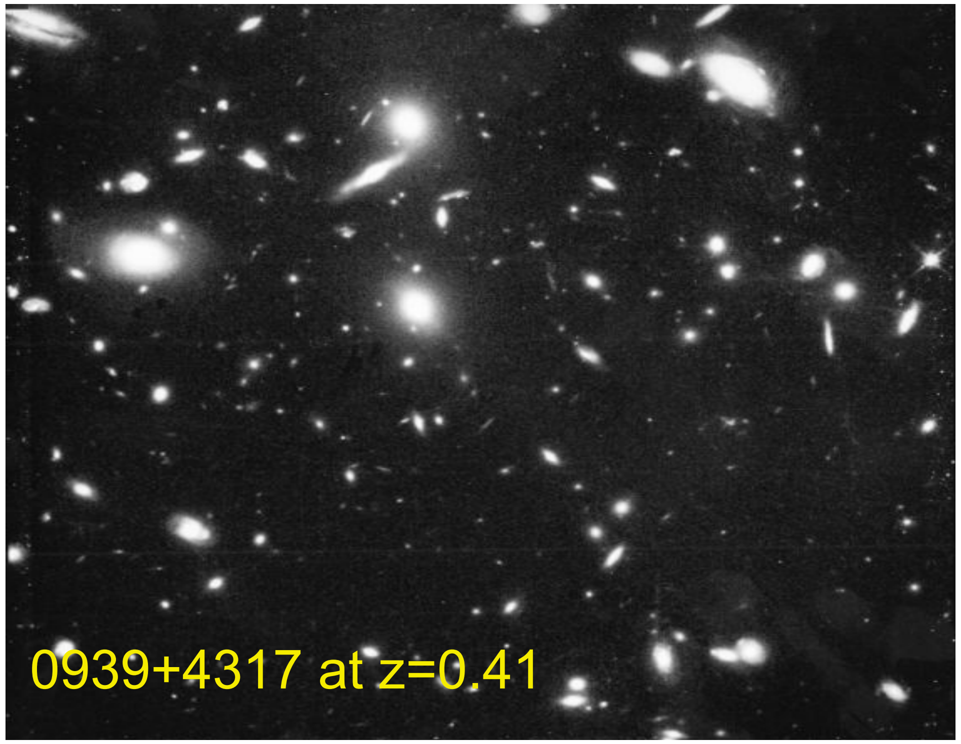
- a few to tens of bright galaxies
- classic example is our "Local Group"
- median radius ~ 1 Mpc

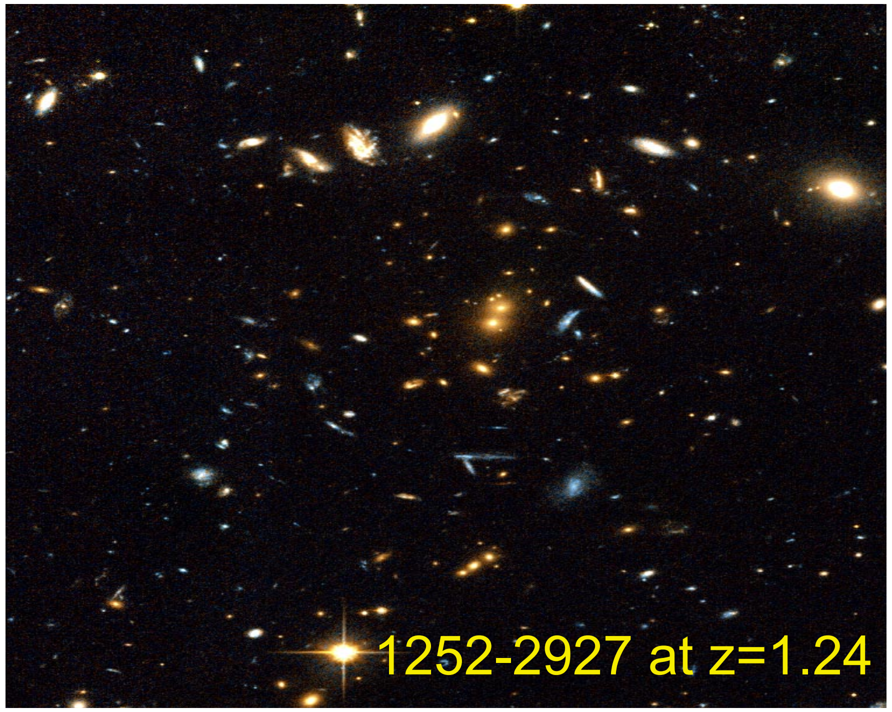
(Rich) Cluster

- tens to hundreds of bright galaxies
- classic example is Abell 1689
- median radius ~ 4-5 Mpc

Clusters come in all shapes & forms at all z

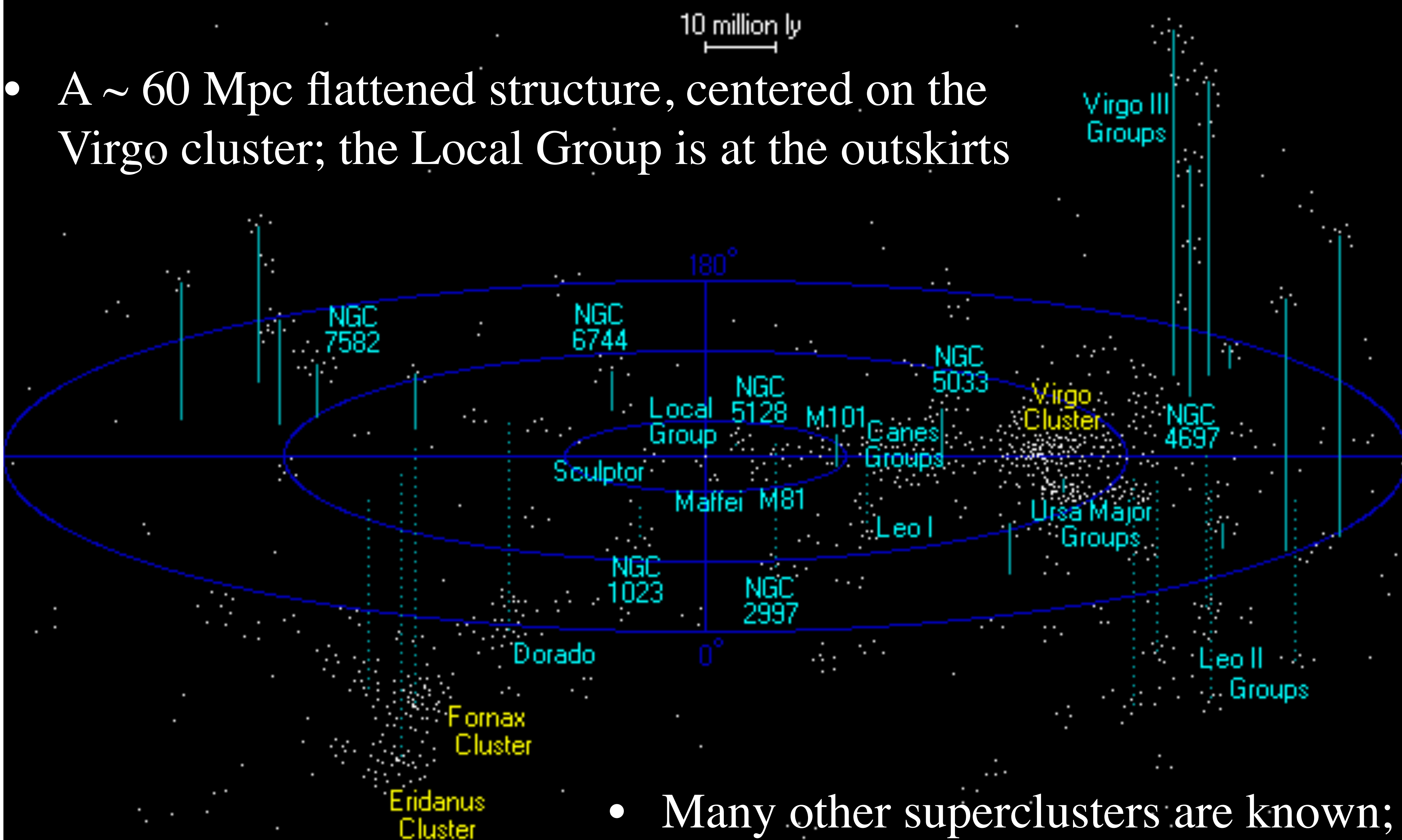






The Local Supercluster

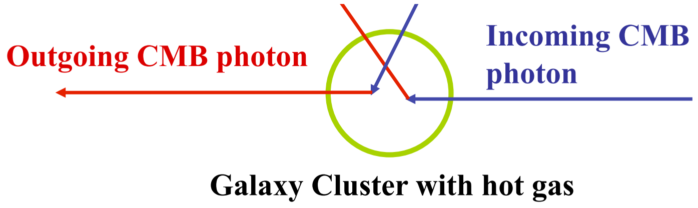
- A ~ 60 Mpc flattened structure, centered on the Virgo cluster; the Local Group is at the outskirts



- Many other superclusters are known; these are the largest (~ 100 Mpc) structures known to exist

Galaxy cluster surveys

1. **Optical:** Look for overdensities of galaxies on the sky
   - Could use colors for an additional selection
   - **Disadvantage:** vulnerable to projection effects
2. **X-Ray**: Clusters contain hot gas, and are prominent X-ray sources
   - ***Much less*** vulnerable to accidental projection effects
3. **Sunyaev-Zeldovich effect**: Distortion of the CMB due to photons scattering off electrons in the cluster
   - **Advantage:** redshift independent, can see clusters far away

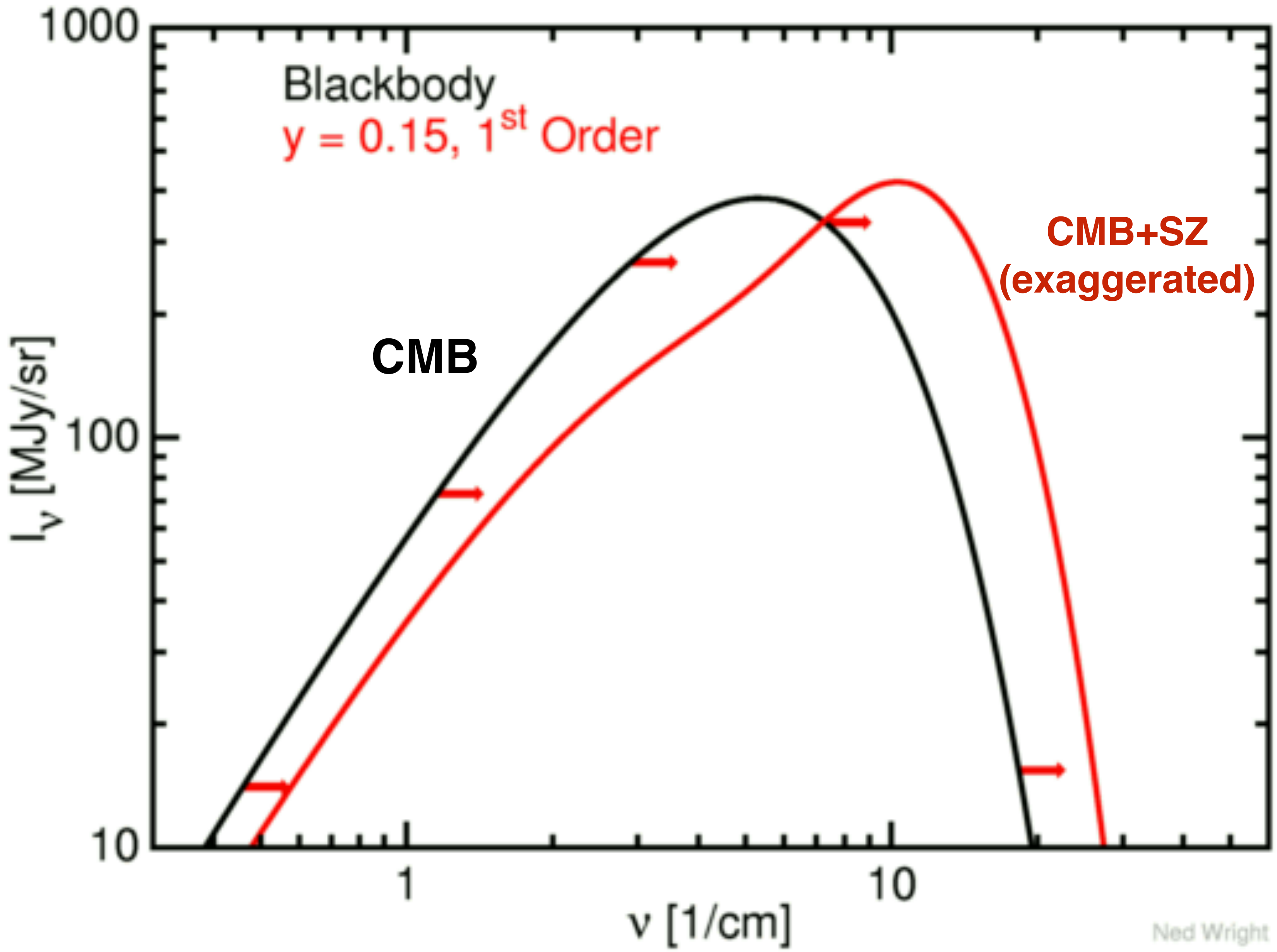


4. **Strong Gravitational Lensing**: look for systematic distortions in background galaxy images

The SZ effect on the CMB spectrum

Interaction of CMB photons with high-energy electrons in ICM

The SZ effect has been used to discover new galaxy clusters



<u>Figure credit:</u> Ned Wright

The SZ effect in combination with X-ray images allows us to determine the thermal profile and mass profile of the galaxy cluster

Why are clusters interesting?

Observationally:

- Large number of galaxies at same distance
- Best place to look for environmental effects on galaxy formation and evolution

Theoretically:

- Largest bound structures in the Universe. Indeed, time for a galaxy to cross a cluster is:

$$t_{cross} \approx 10^{10}\left(\frac{d}{10\ \mathrm{Mpc}}\right)\left(\frac{v}{1000\ \mathrm{km\ s^{-1}}}\right)^{-1}\ \mathrm{yr}$$

where d is the cluster radius and v is the velocity dispersion.

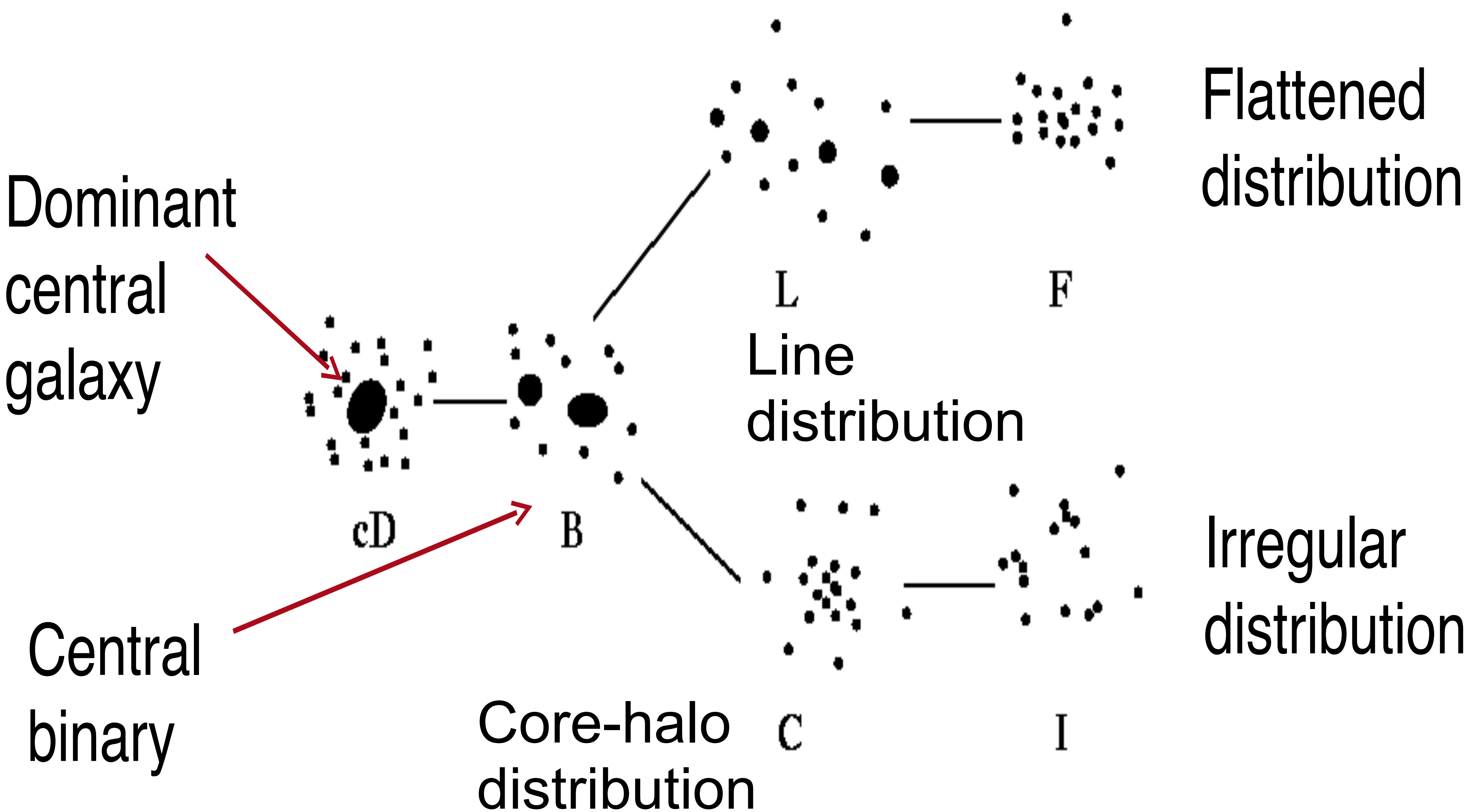
- Extremely rare objects that formed in the most over-dense peaks of the initial density fluctuations. This implies that their number density (number per comoving volume) is a sensitive function of the amplitude of the initial perturbations.

Morphological classification of clusters: the Rood & Sastry scheme

cD (supergiant)	A cluster which contains an outstandingly brightest member, a cD galaxy (defined originally by Morgan and Lesh 1965). For an operational definition, the size (semimajor axis plus semiminor axis) is $\geqslant 3$ times that of any other galaxy in the cluster. If the main body is multiple or shows any other peculiarity, a subscript p is added to the type designation.
B (binary)	Two supergiant galaxies separated by $\leqslant 10$ diameters of the larger galaxy, and with combined size $\geqslant 3$ times that of any other cluster member. A subscript b indicates a connecting bridge between the supergiant binary, or the components of one or both of its members.
L (line)	Three or more brightest galaxies among the top ten members arranged with comparable separations in a line, and numerous fainter members distributed around them.
C (core-halo)	Four or more of the top ten brightest members with comparable separations located near the center, and numerous fainter members distributed around them.
F (flat)	Several of the top ten brightest members and a large fraction of fainter galaxies are distributed in a flattened configuration.
I (irregular)	The galaxies are distributed irregularly, or without a well-defined center.

This classification is not as clean as the Hubble sequence because clusters are young, merging systems

Classification of clusters: morphology



A tuning fork for clusters: Rood & Sastry (1971)

Question: baryon fraction in clusters V/s that in normal galaxies - higher or lower?

$$f_b = \frac{M_{baryons}}{M_{total}}$$

$M_{baryons}$ → stars + gas

M_{total} → stars + gas + Dark Matter

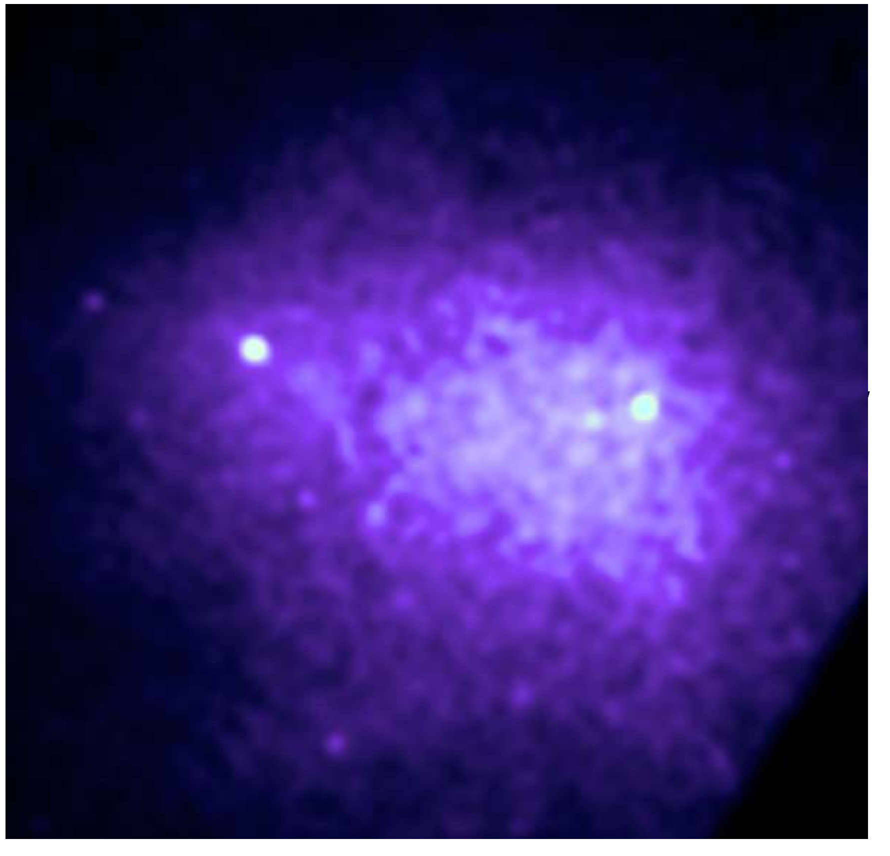
Deeper cluster potential wells (i.e. stronger gravity) ensure that the cluster holds on to its gas mass. The baryon fraction is very close to the cosmological ratio.

Question: temperature of gas in a cluster

$$kT \simeq \frac{1}{2} m_p v^2$$

where k is Boltzmann constant, T is gas temperature, m_p is proton mass and v is velocity dispersion (assume ~ 1000Km/s). This yields T ~ 10^8 K.

Coma in the optical



Coma in X-rays

Cool-core and non-cool-core galaxy clusters

Cool-core:

* central temperature increases outwards
* more regular and symmetric
* central dominant galaxy / little substructure
* not recent merger

Non-cool-core:

* central temperature has flatter profile
* irregular
* no central dominant galaxy / multiple substructures
* recent merger