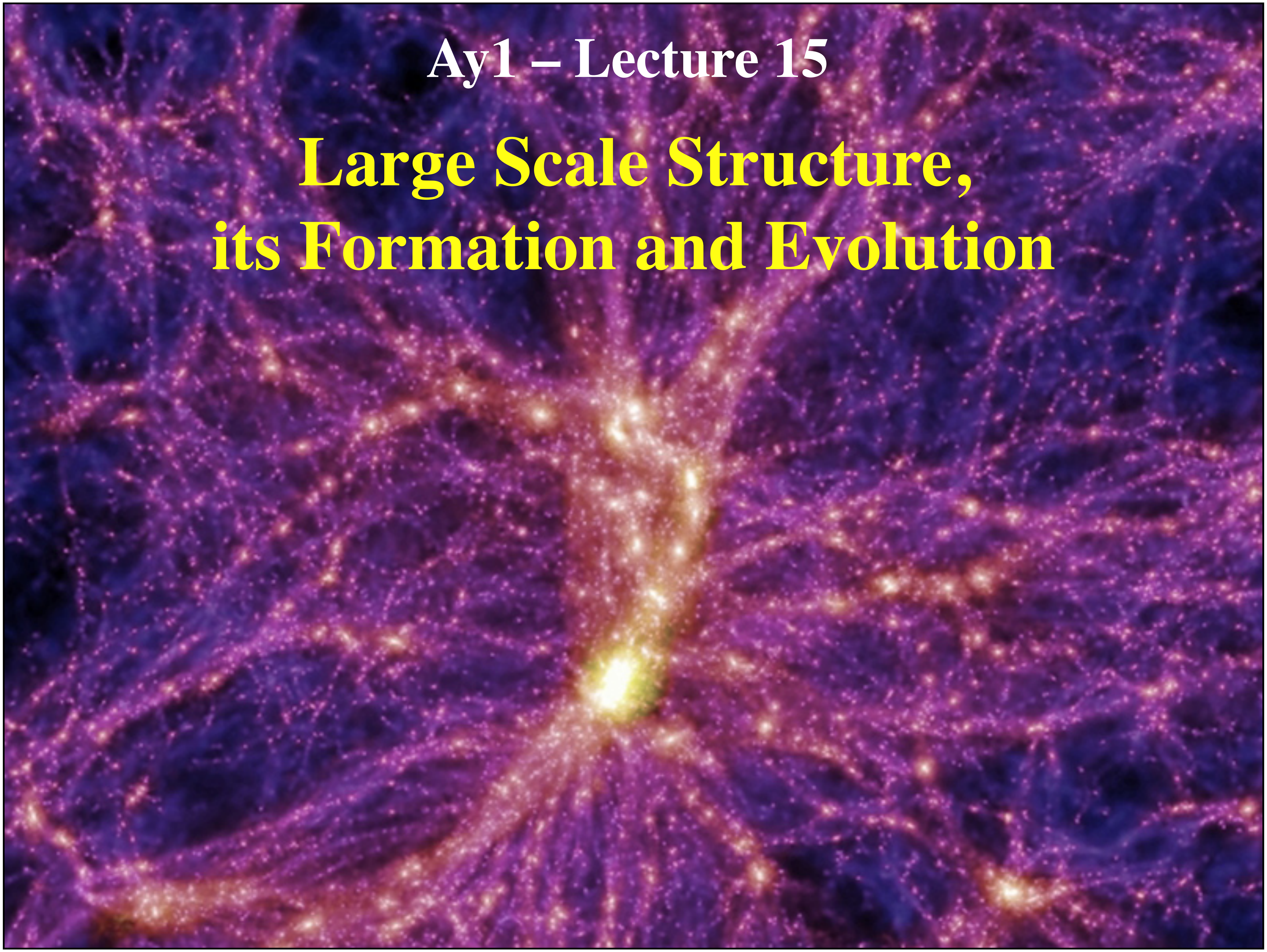
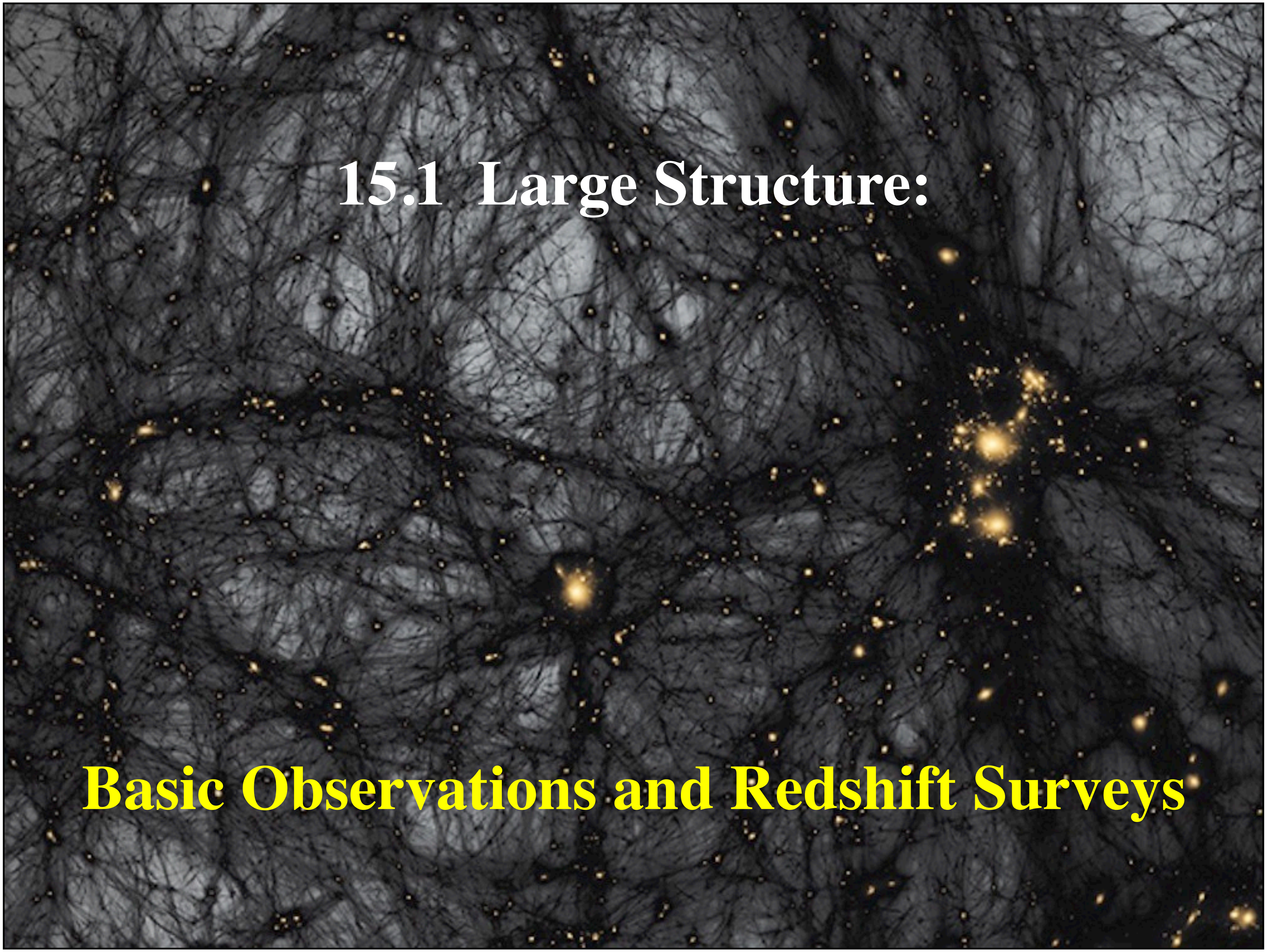
Ay1 – Lecture 15

Large Scale Structure, its Formation and Evolution

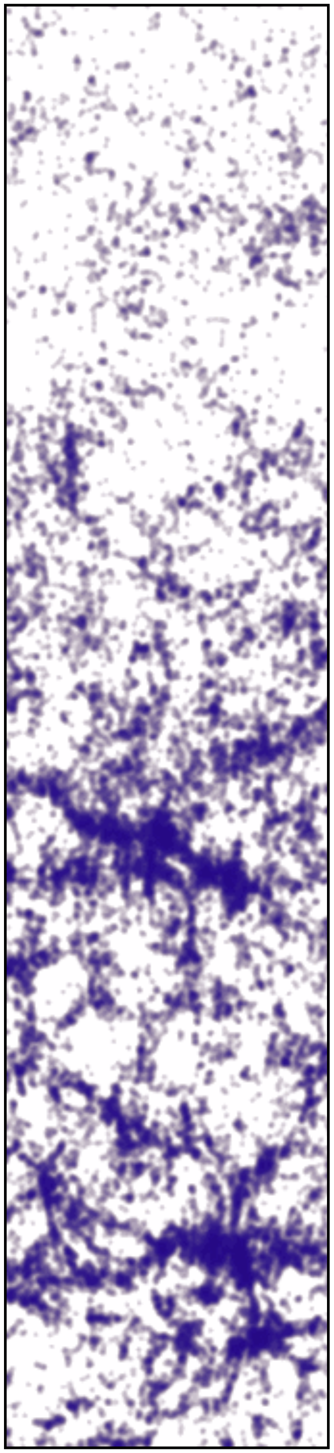


15.1 Large Structure:

Basic Observations and Redshift Surveys

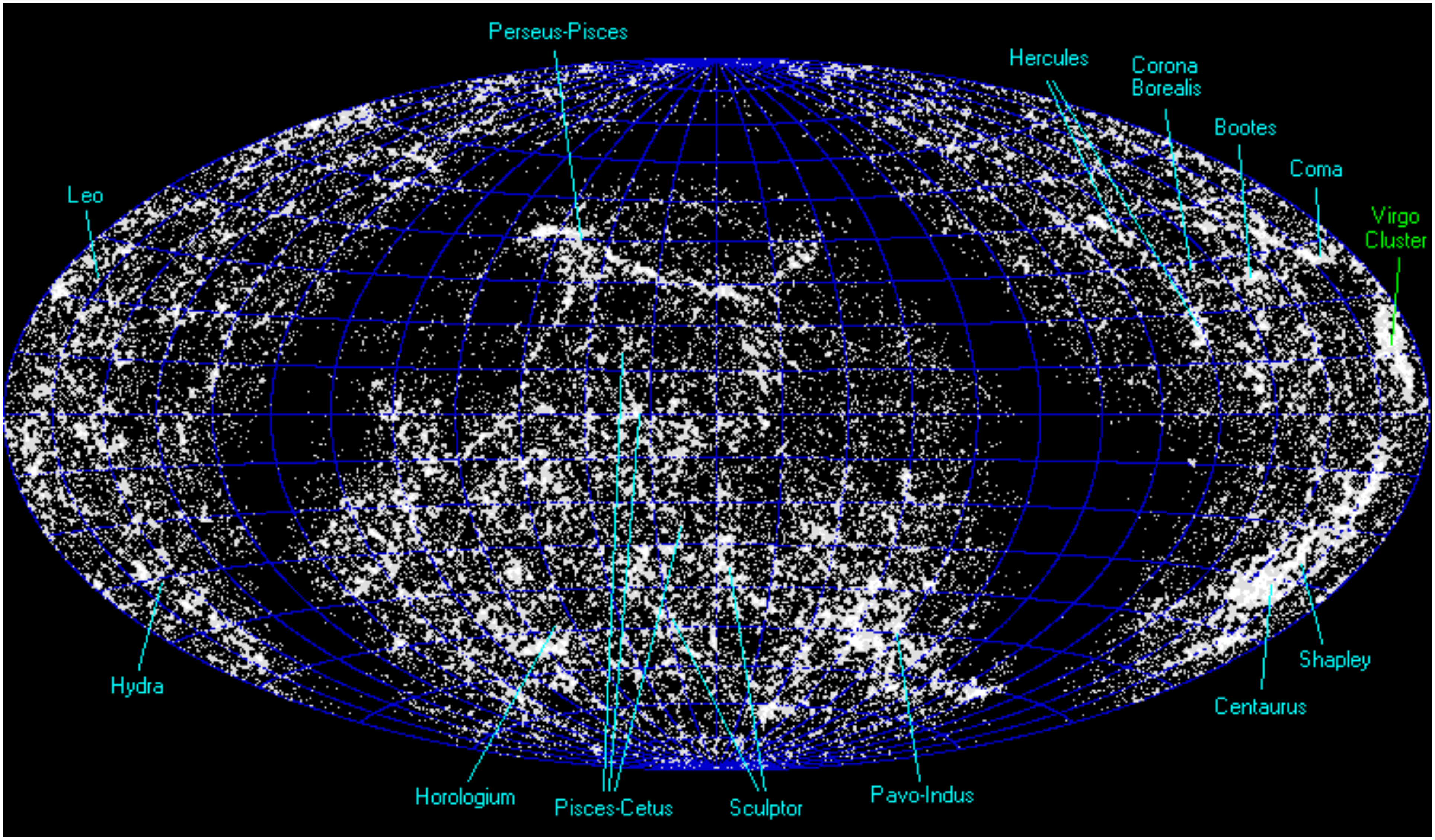


Large-Scale Structure



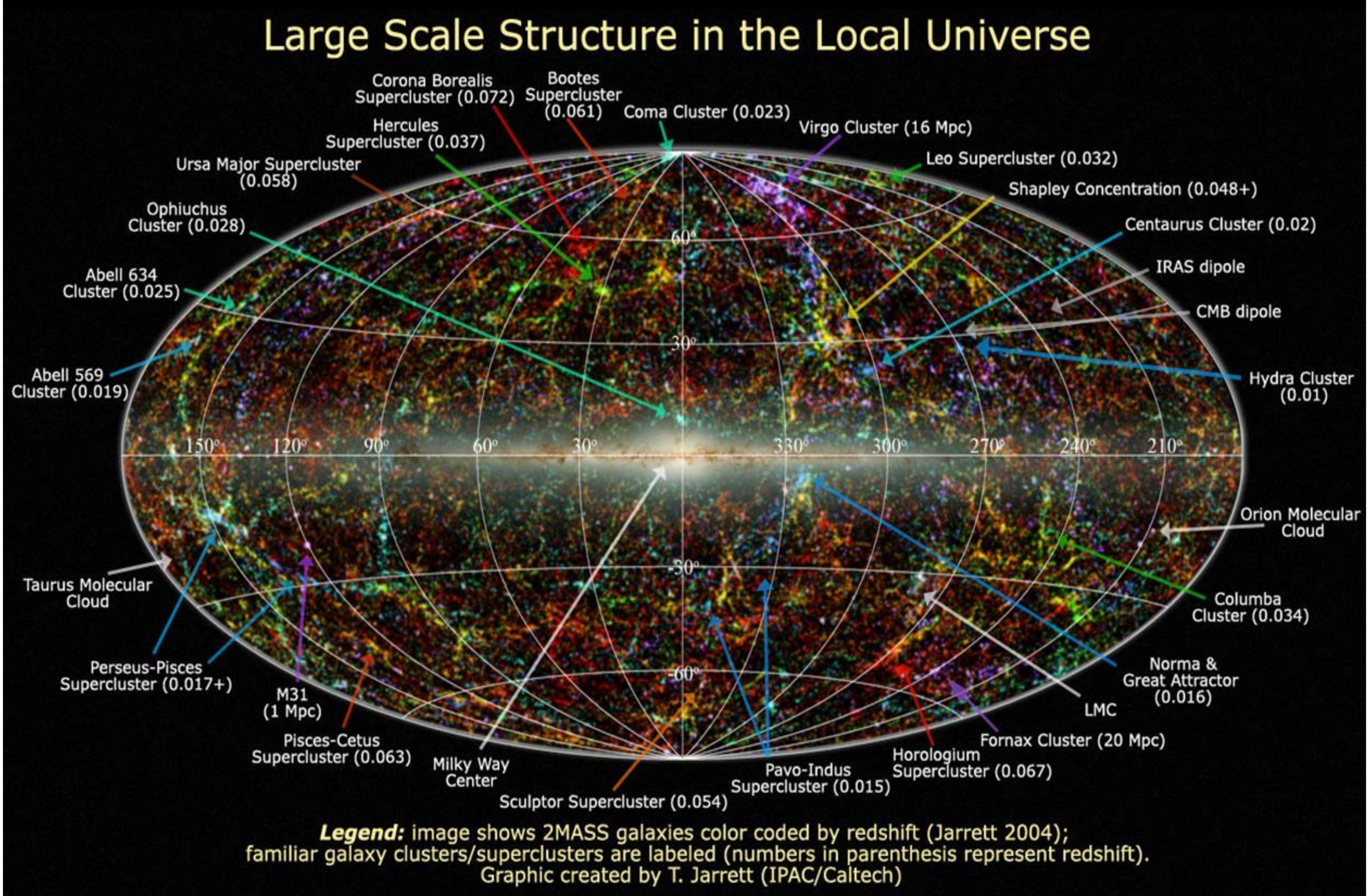
- Density fluctuations in the early universe evolve into structures we observe: galaxies, clusters, etc.
- On scales > galaxies, we talk about the **Large Scale Structure (LSS);** groups, clusters, filaments, walls, voids, superclusters are the elements of it
- To map and quantify the LSS (and compare with the theoretical predictions), we need **redshift surveys**: mapping the 3-D distribution of galaxies in the space
  - Redshifts are a measure of distance in cosmology
  - We now have redshifts measured for ~ 2 million galaxies
- The existence of clusters was recognized early on, but it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures

6000 Brightest Galaxies on the Sky

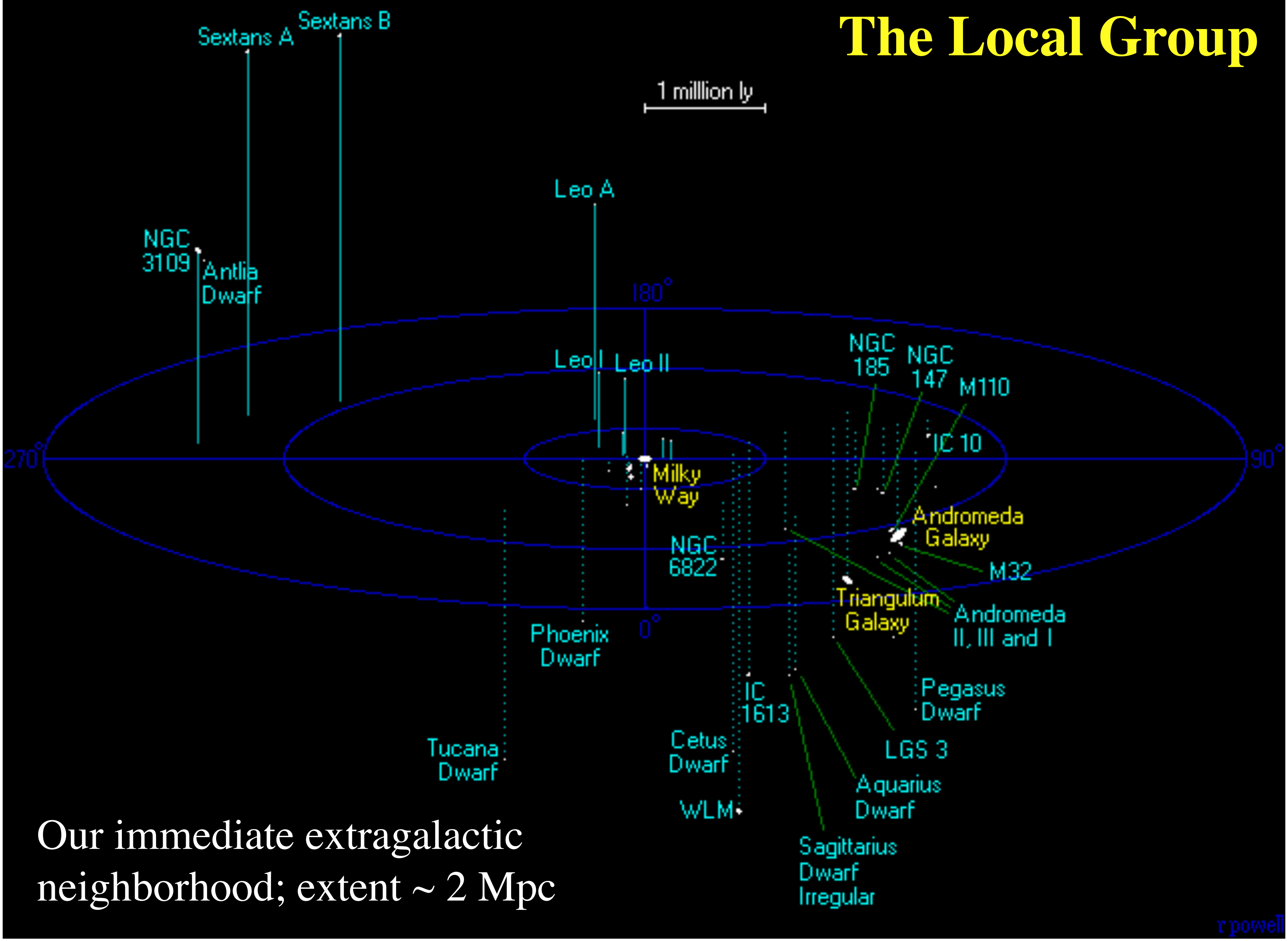


How would the picture of the 6000 brightest stars on the sky look?

A View From Our Galaxy in the Near-IR



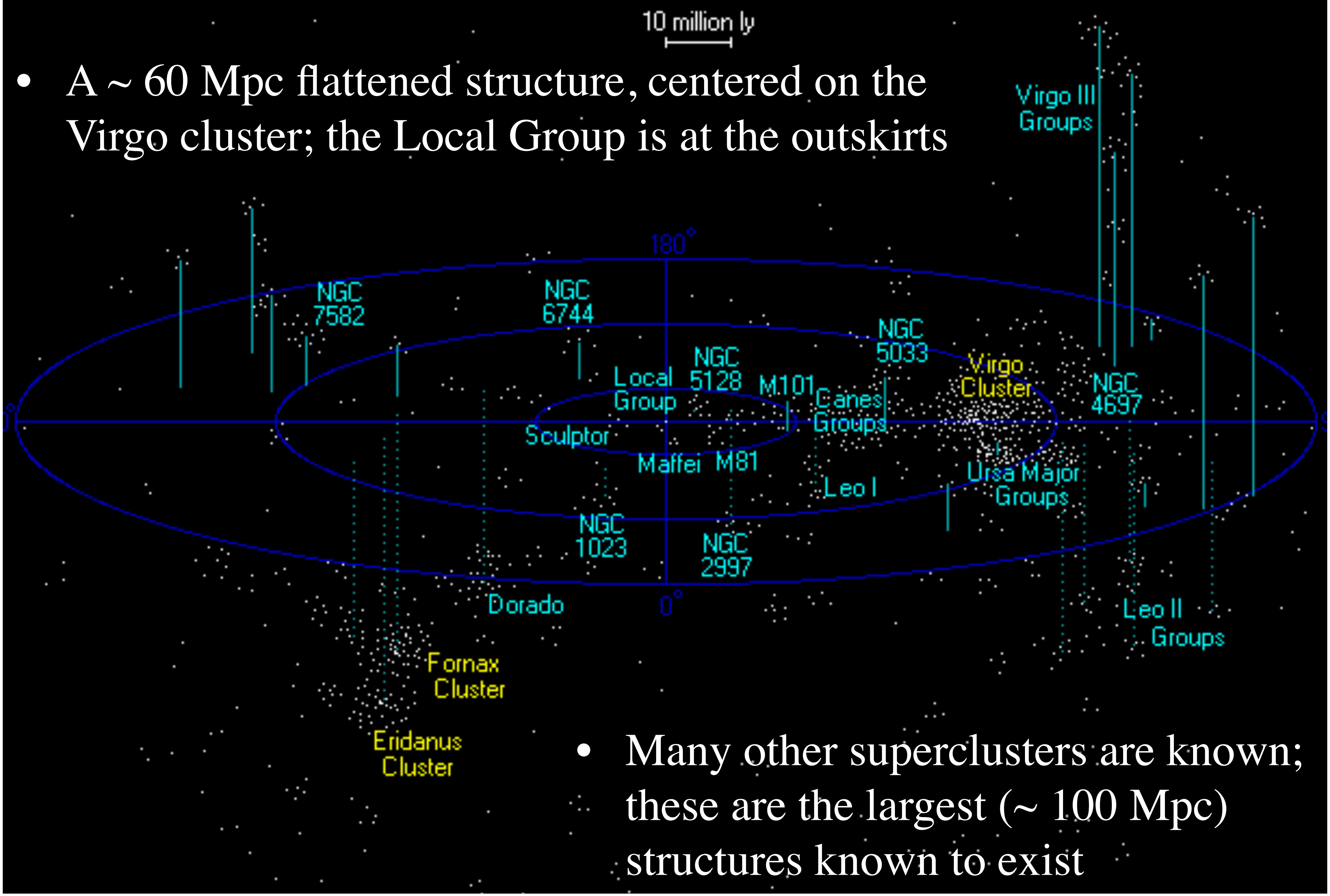
The Local Group



Our immediate extragalactic neighborhood; extent ~ 2 Mpc

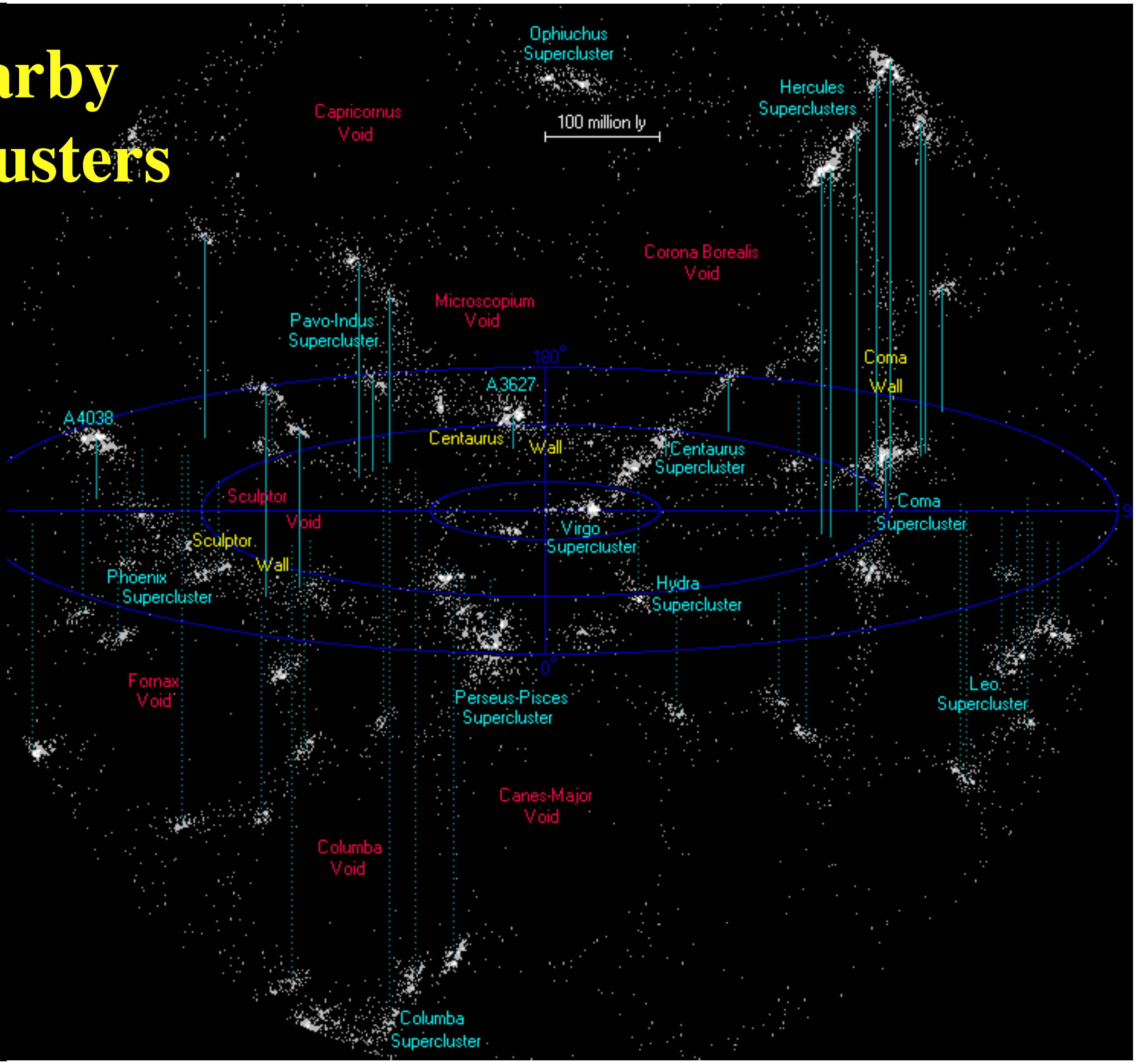
The Local Supercluster

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



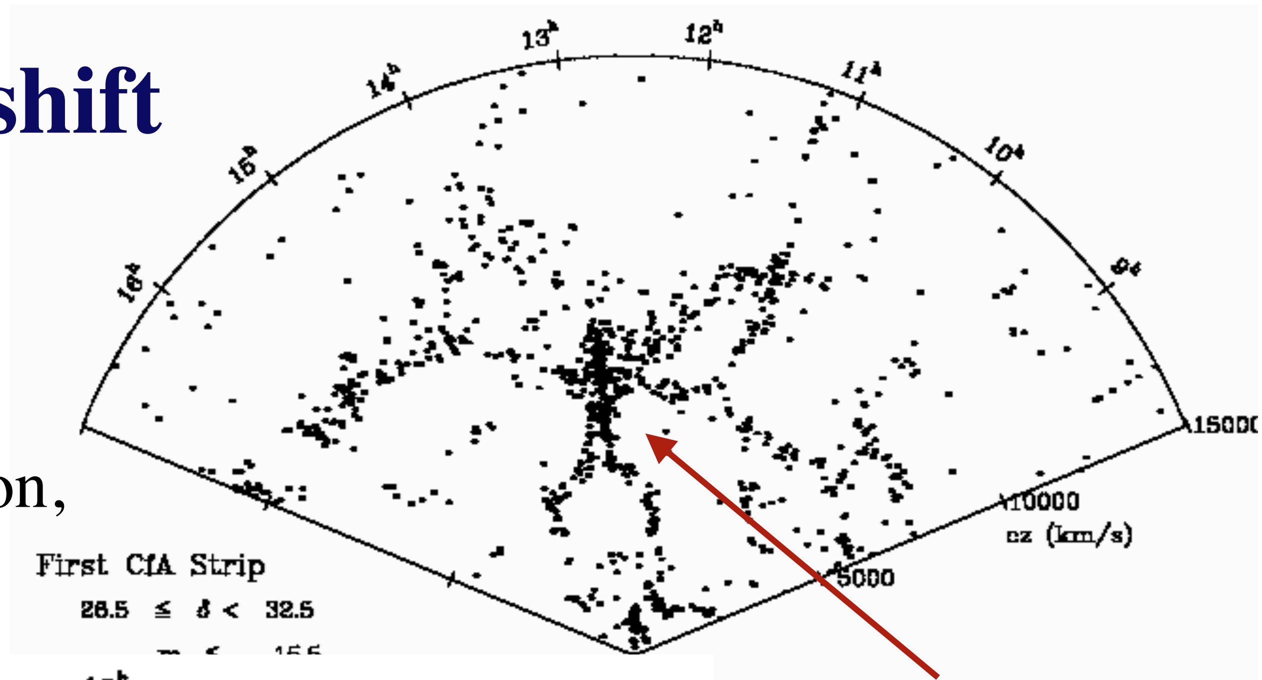
- Many other superclusters are known; these are the largest (~ 100 Mpc) structures known to exist

The Nearby Superclusters

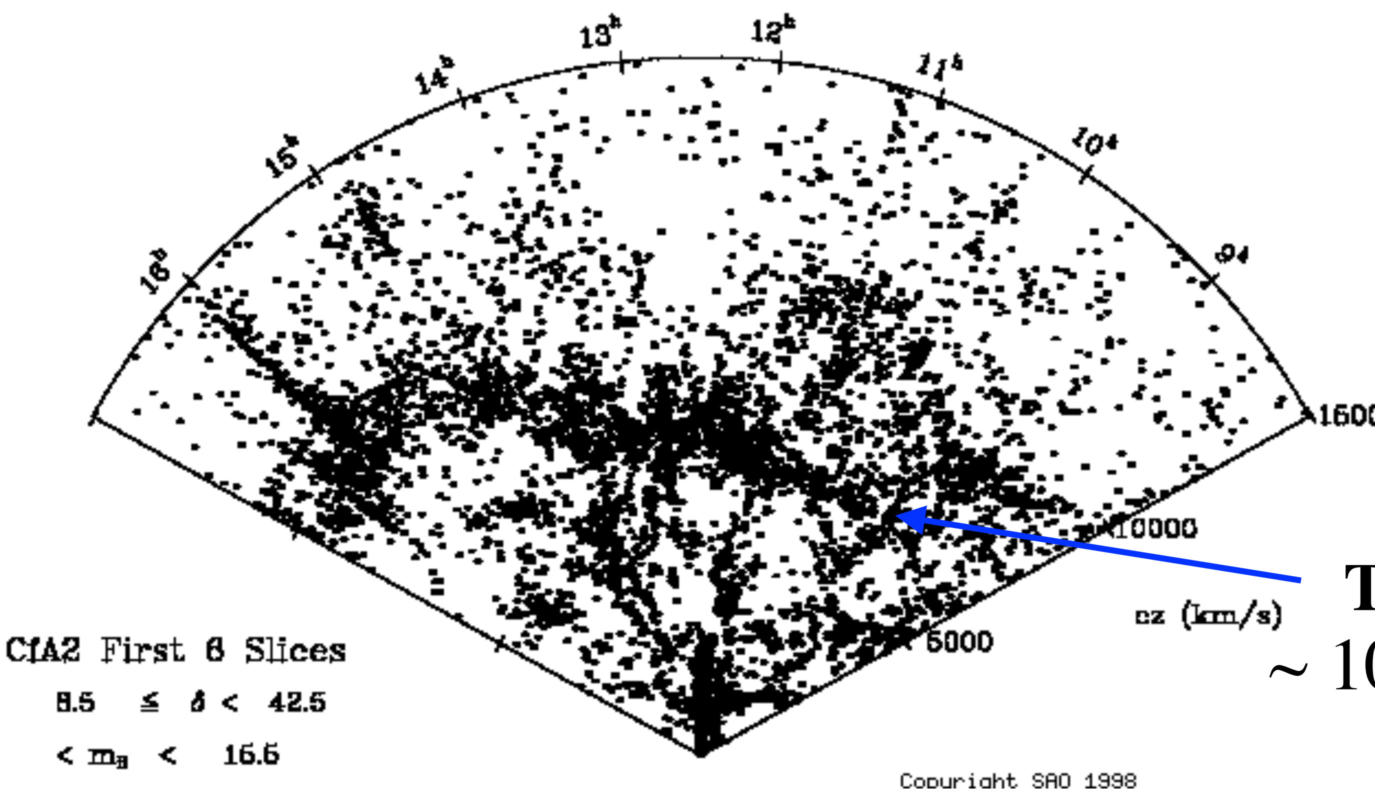


The CfA2 Redshift Survey

Slices on the sky:
long in Right Ascension,
thin in Declination

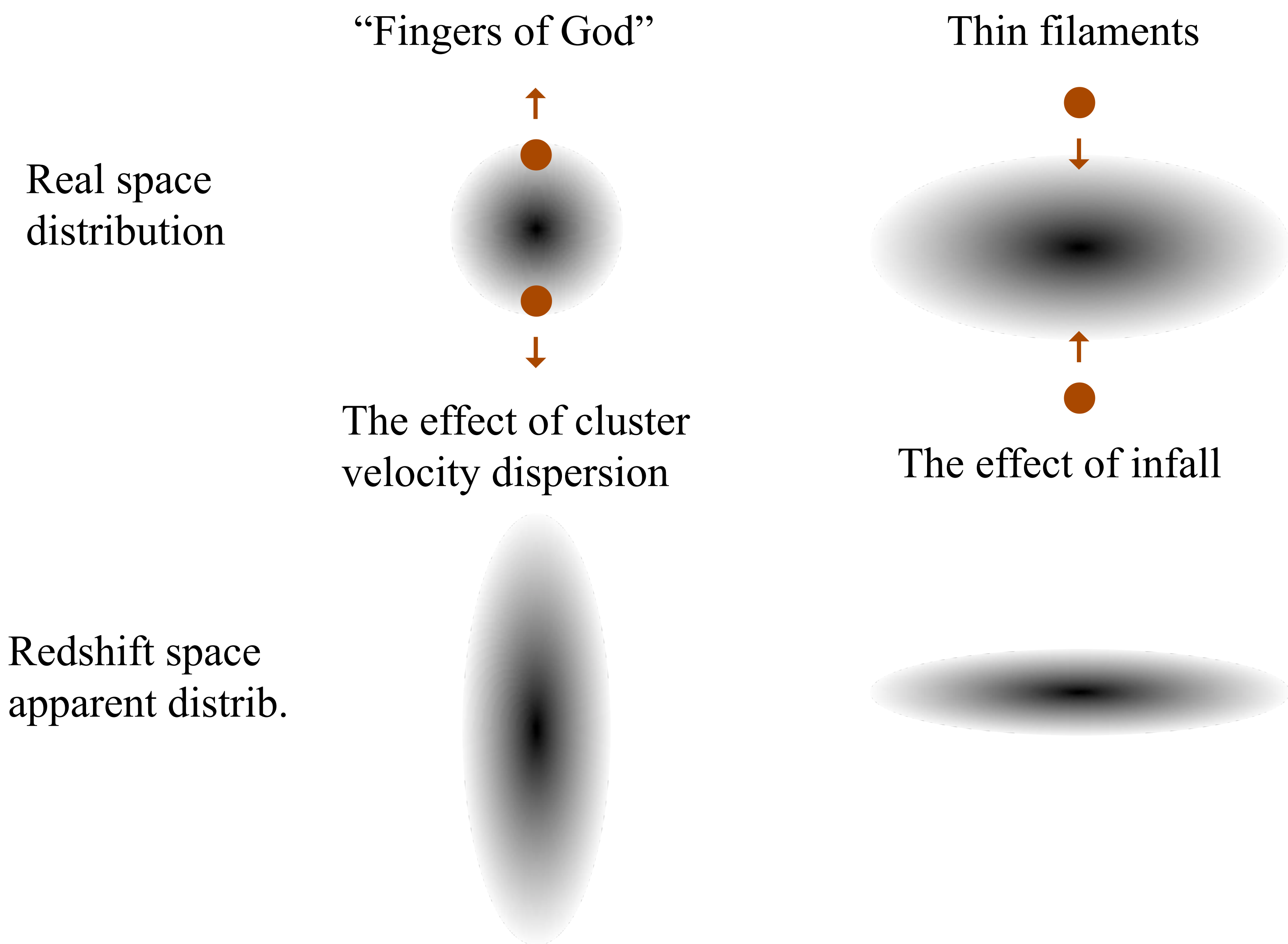


Coma cluster:
Note the "finger of God" effect, due to the velocity disp. in the cluster



The "Great Wall":
~ 100 Mpc structure

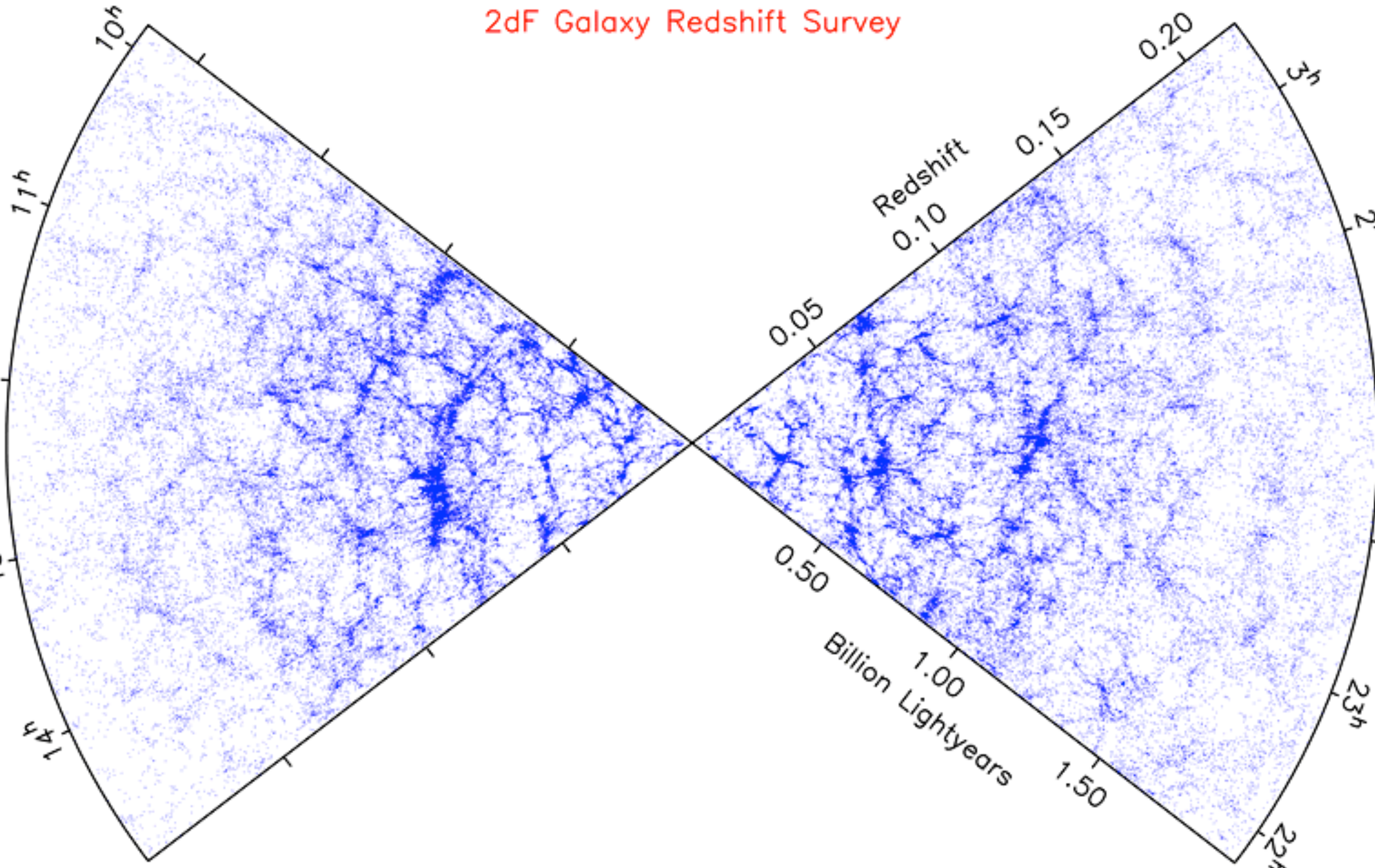
Redshift Space vs. Real Space



Huge Redshift Surveys

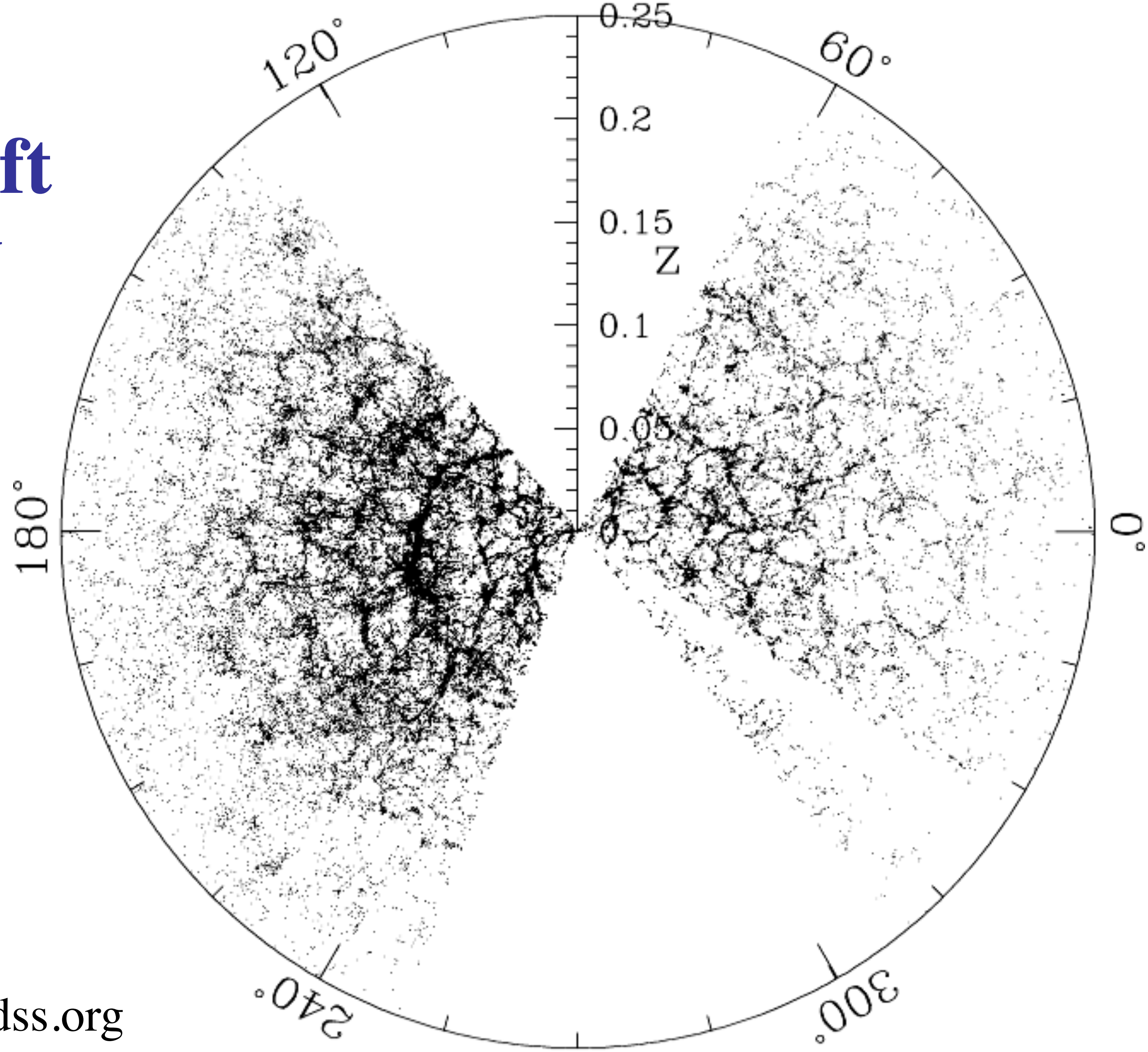
- **The 2dF (2 degree Field) redshift survey** done with the 3.9-m Anglo-Australian telescope by a UK/Aus consortium
  - Redshifts of ~ 250,000 galaxies with $B < 19.5$ mag, covering 5% of the sky reaching to $z \sim 0.3$
  - Spectrograph can measure 400 redshifts at a time
  - Also spectra of ~ 25,000 QSOs out to z ~ 2.3
- **The Sloan Digital Sky Survey (SDSS)** done with a dedicated 2.5-m telescope at Apache Point Observatory in New Mexico
  - Multicolor imaging to $r \sim 23$ mag, and spectra of galaxies down to $r < 17.5$ mag, reaching to $z \sim 0.4$, obtaining ~ 600 (now ~ 1,000) spectra at a time, covering ~ 14,000 deg^2
  - As of 2012 (SDSS III, DR 9): > 900 *million* detected sources, ~ 1.5 *million* galaxy spectra, ~ 670,000 stellar spectra, ~ 230,000 quasar spectra (reaching out to $z \sim 6.4$)

2dF Galaxy Redshift Survey



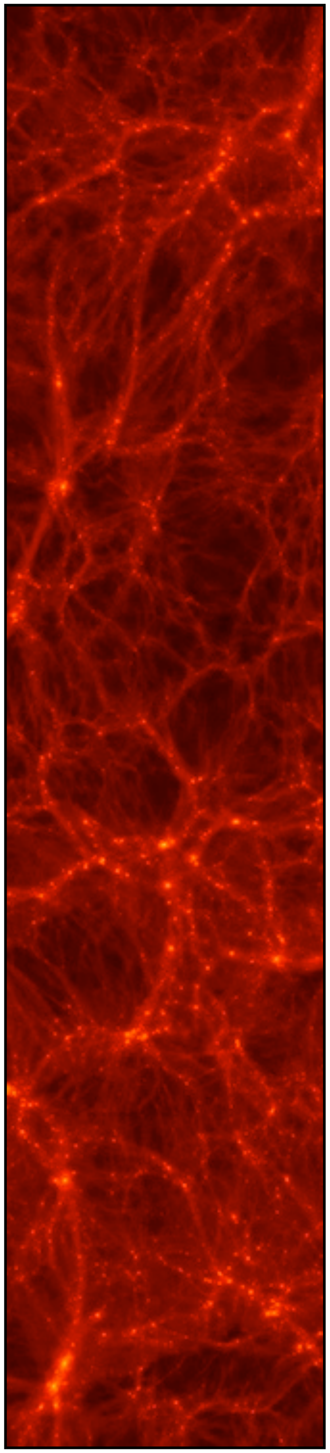
http://www.mso.anu.edu.au/2dFGRS/

SDSS Redshift Survey



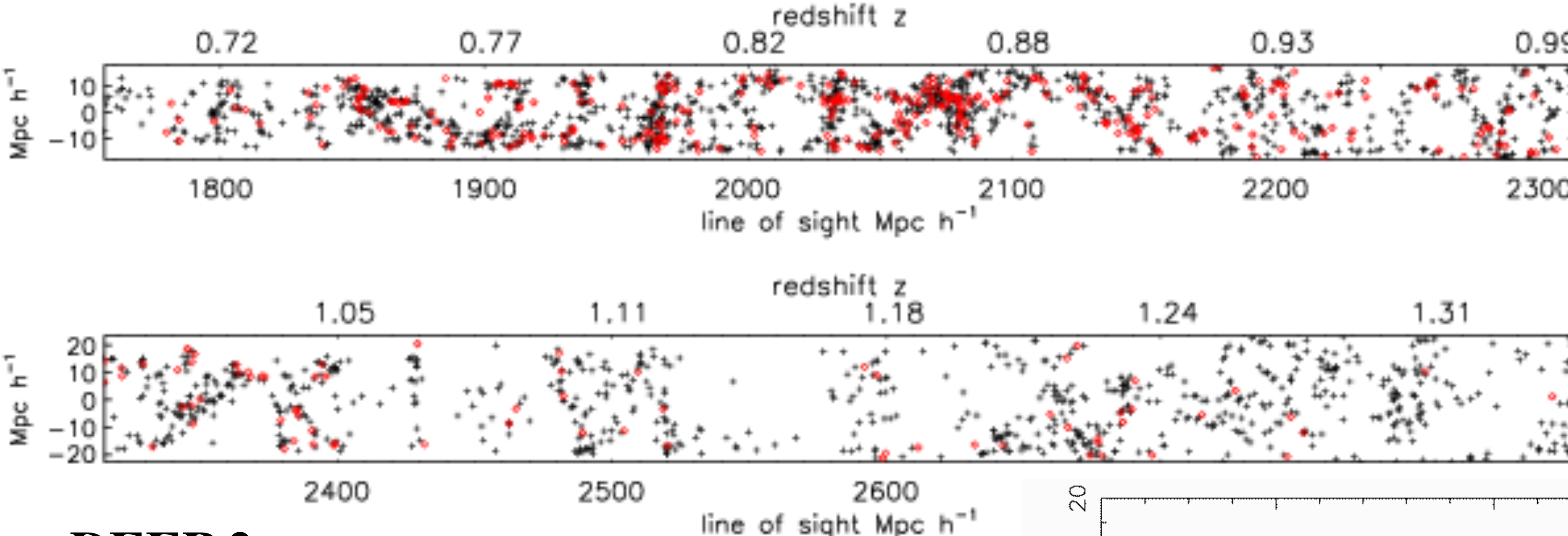
http://www.sdss.org

"Pencil Beam" Surveys



- To probe structure at higher redshifts is generally done with deep "pencil beam" surveys in small patches of the sky, but going very deep, using big telescopes
- Original pencil beam surveys done by D. Koo, R. Kron, & collaborators in early 1990's showed walls showing up at large redshifts
  - The same structure and scale of voids and walls we see locally seems to continue out to $z \sim 1$
- Even deeper surveys done with Keck and VLT of the Hubble Deep Field and several other deep surveys show the same effects
- These surveys map out evolution of field galaxies and LSS out to z ~ 1 - 2

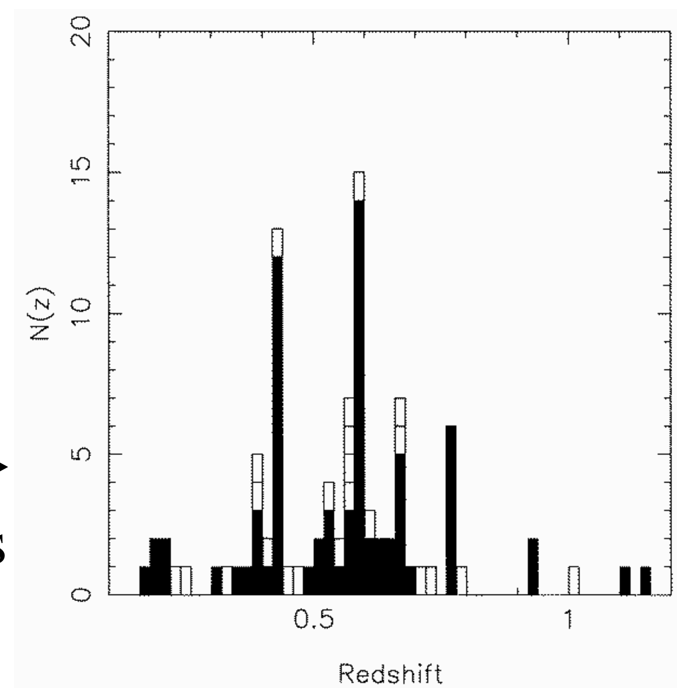
Structures in Deep Redshift Surveys



DEEP 2
02 hr field

red=emission-line
black=absorption

Spikes in the redshift histogram →
as line of sight intersects walls or filaments



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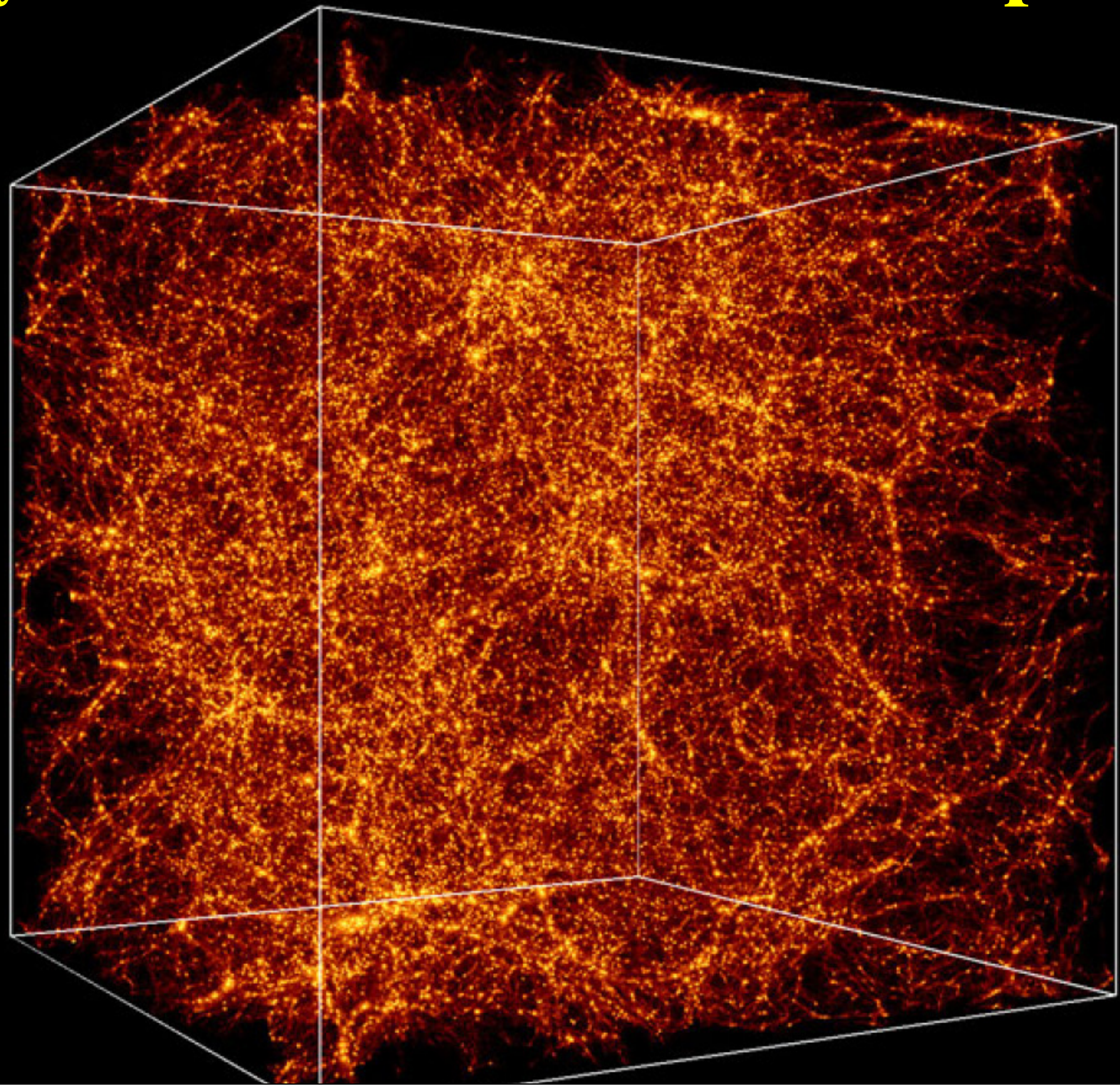
15.2 Quantifying Large scale Structure:
Galaxy Correlations and Power Spectrum



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:

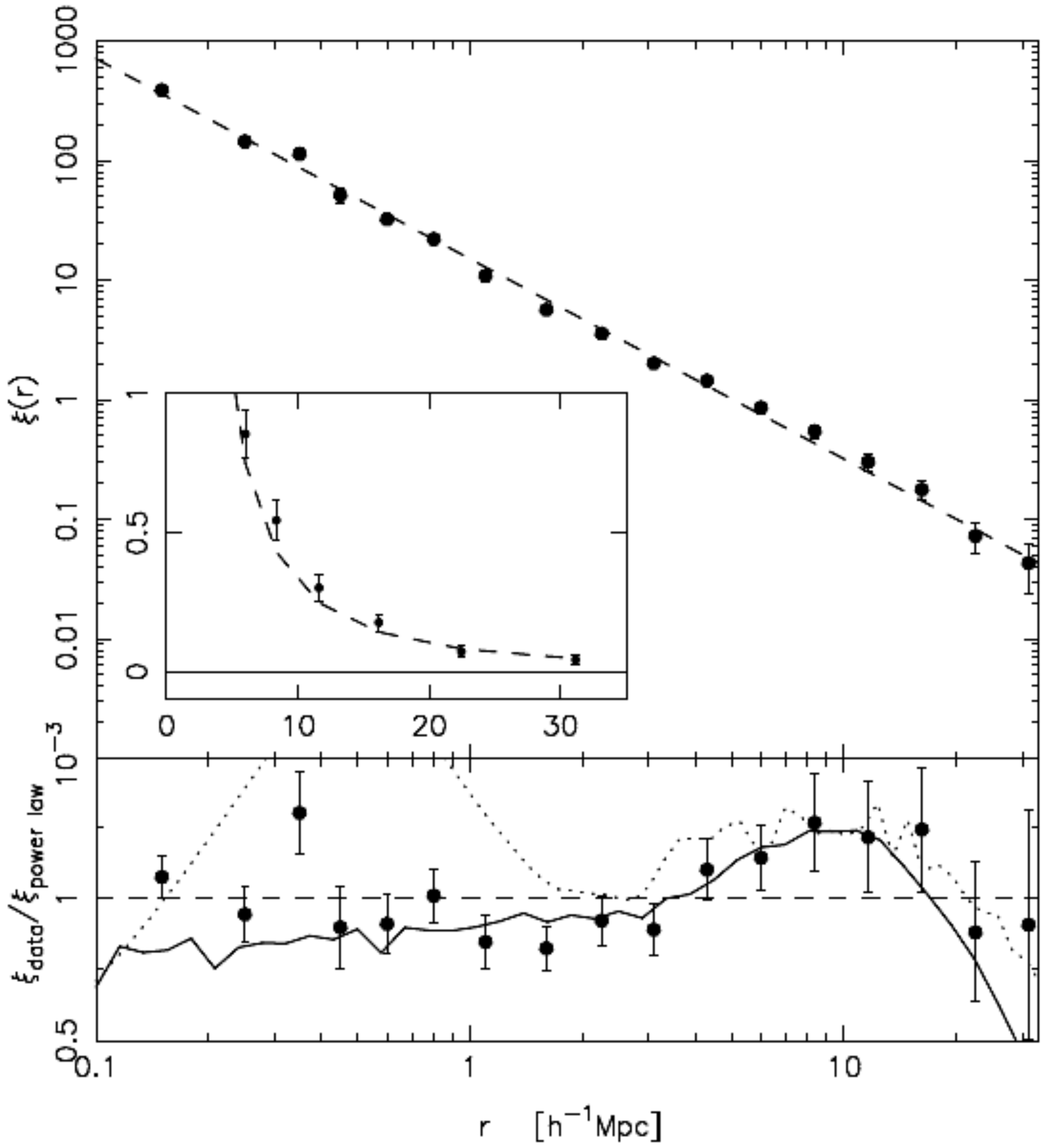
$$\xi(r) = \left(r / r_0\right)^{-\gamma}$$

- For galaxies, typical *correlation or clustering length* is $\boldsymbol{r_0}$ ~ 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

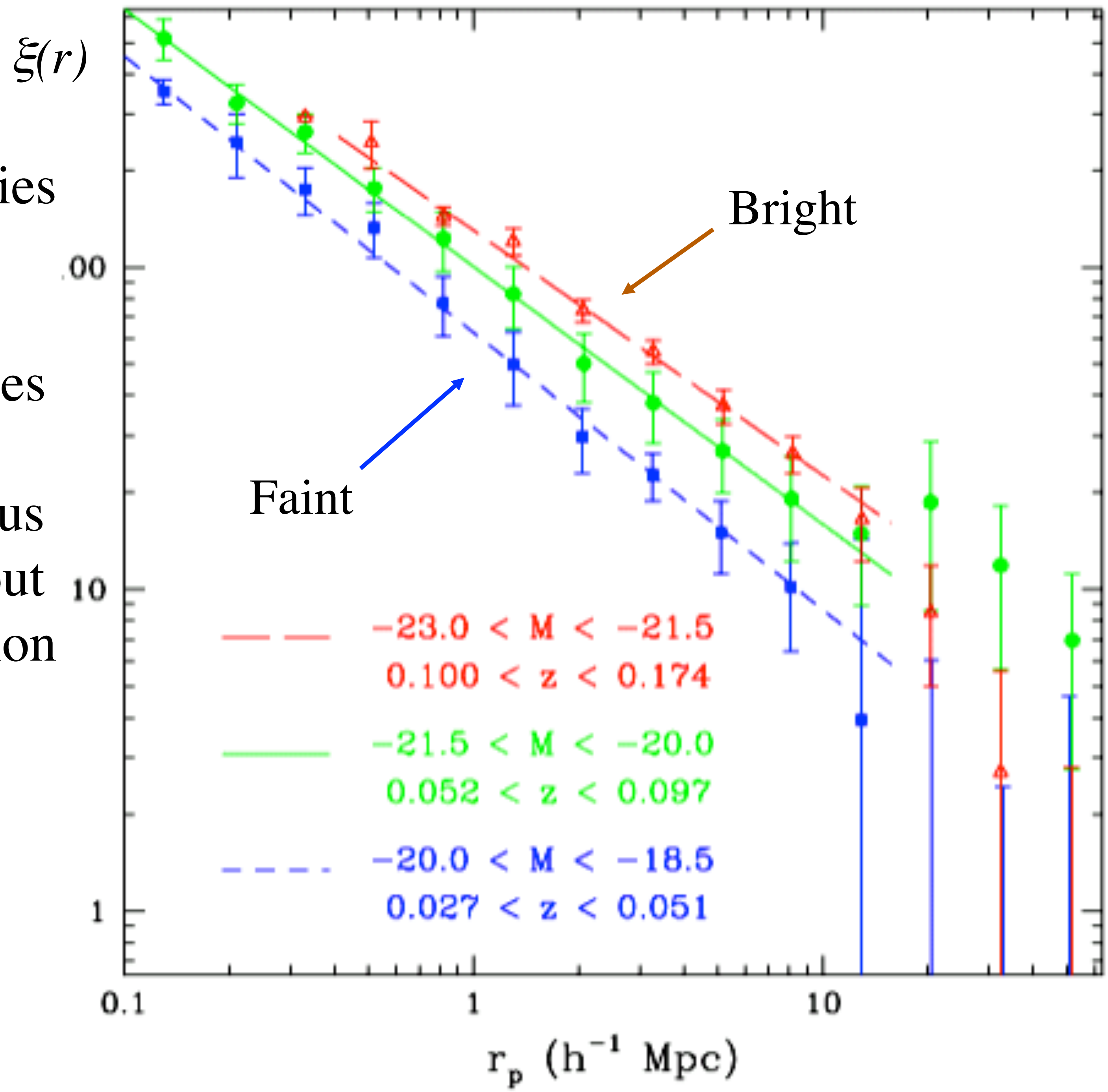
As measured by the 2dF redshift survey

Deviations from the power law:



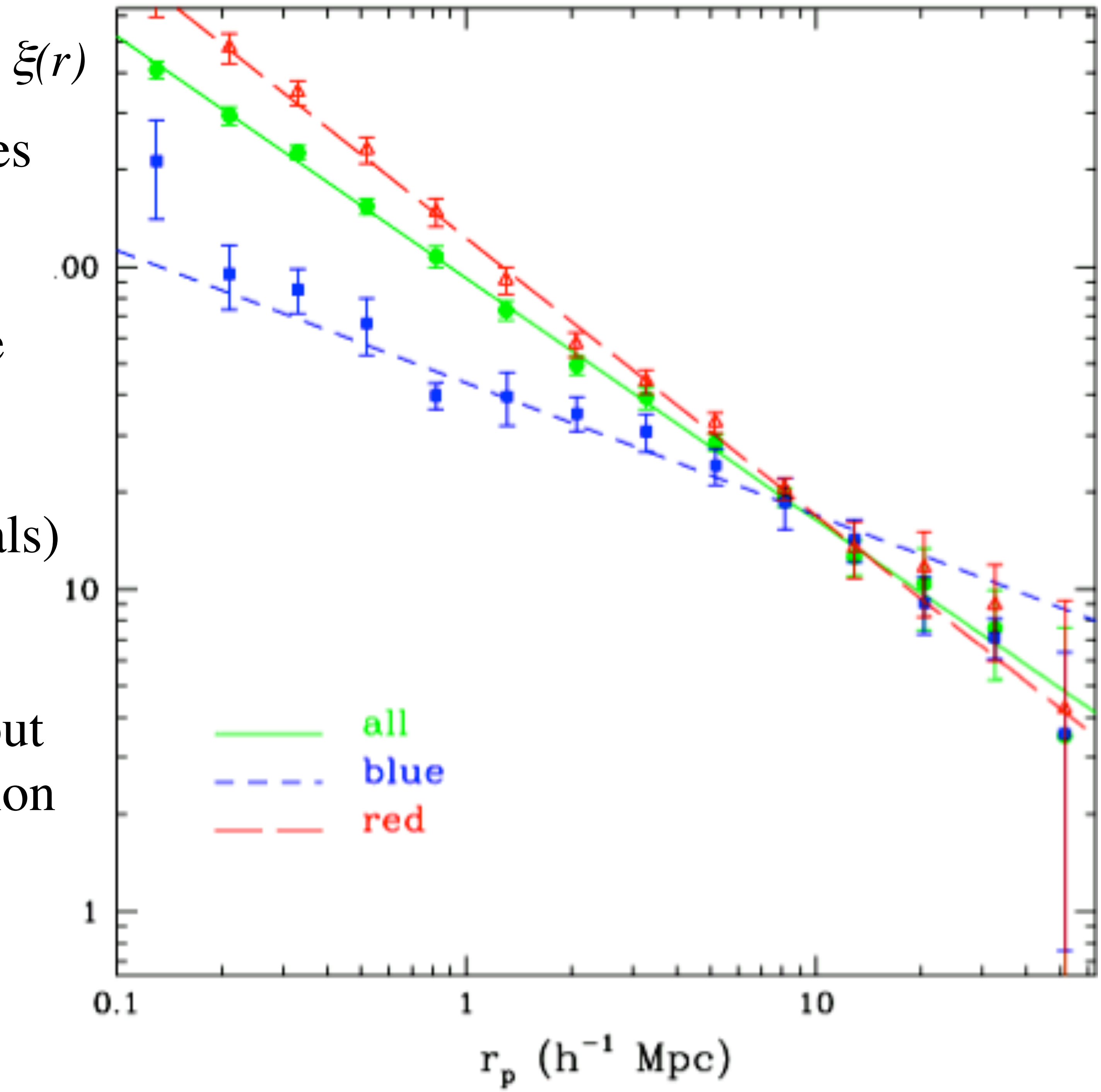
Brighter galaxies are clustered more strongly than fainter ones

This is telling us something about galaxy formation



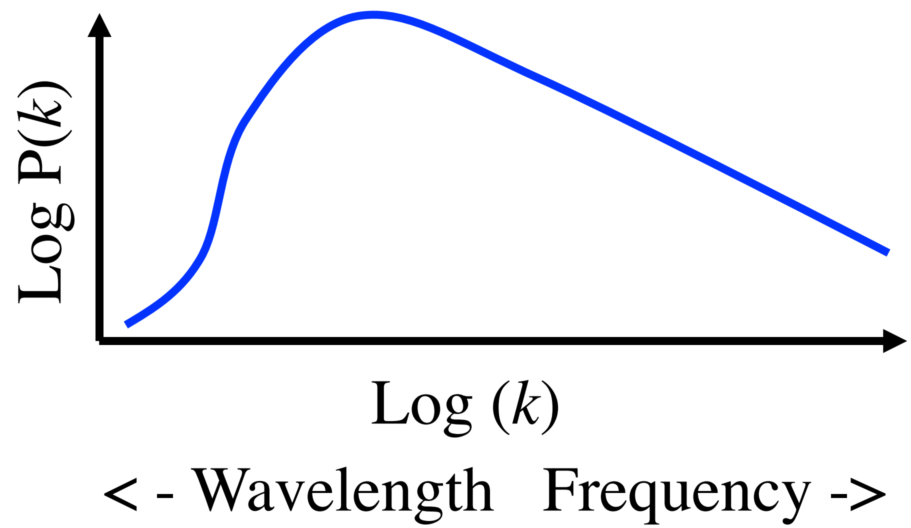
Redder galaxies (or early-type, ellipticals) are clustered more strongly than bluer ones (or late-type, spirals)

That, too, says something about galaxy formation



Power Spectrum of Galaxy Clustering

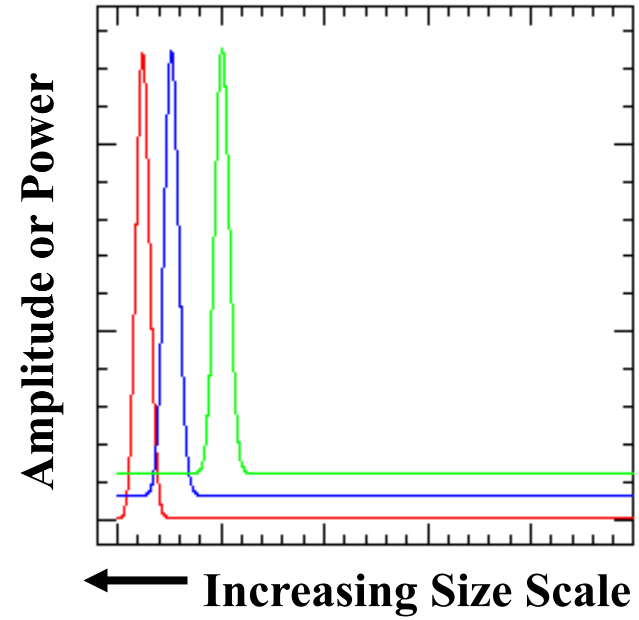
- A more modern alternative to the 2-point correlation function is the Fourier Power Spectrum of the galaxy density field
- The overall density is expressed as a sum of density waves with varying spatial frequencies and amplitudes
- The power spectrum tells us how much mass is clumped on what spatial scale
- It can be directly connected to theoretical predictions
- Power spectrum and the correlation function are a Fourier pair

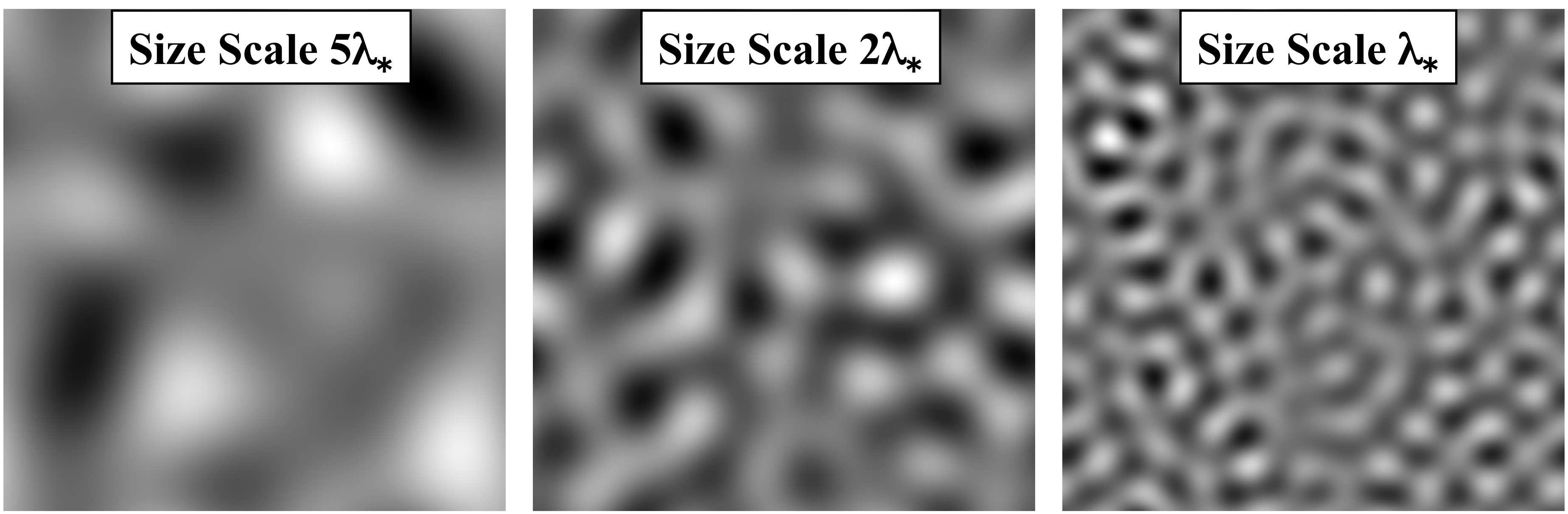


Images of Structure on Specific Scales

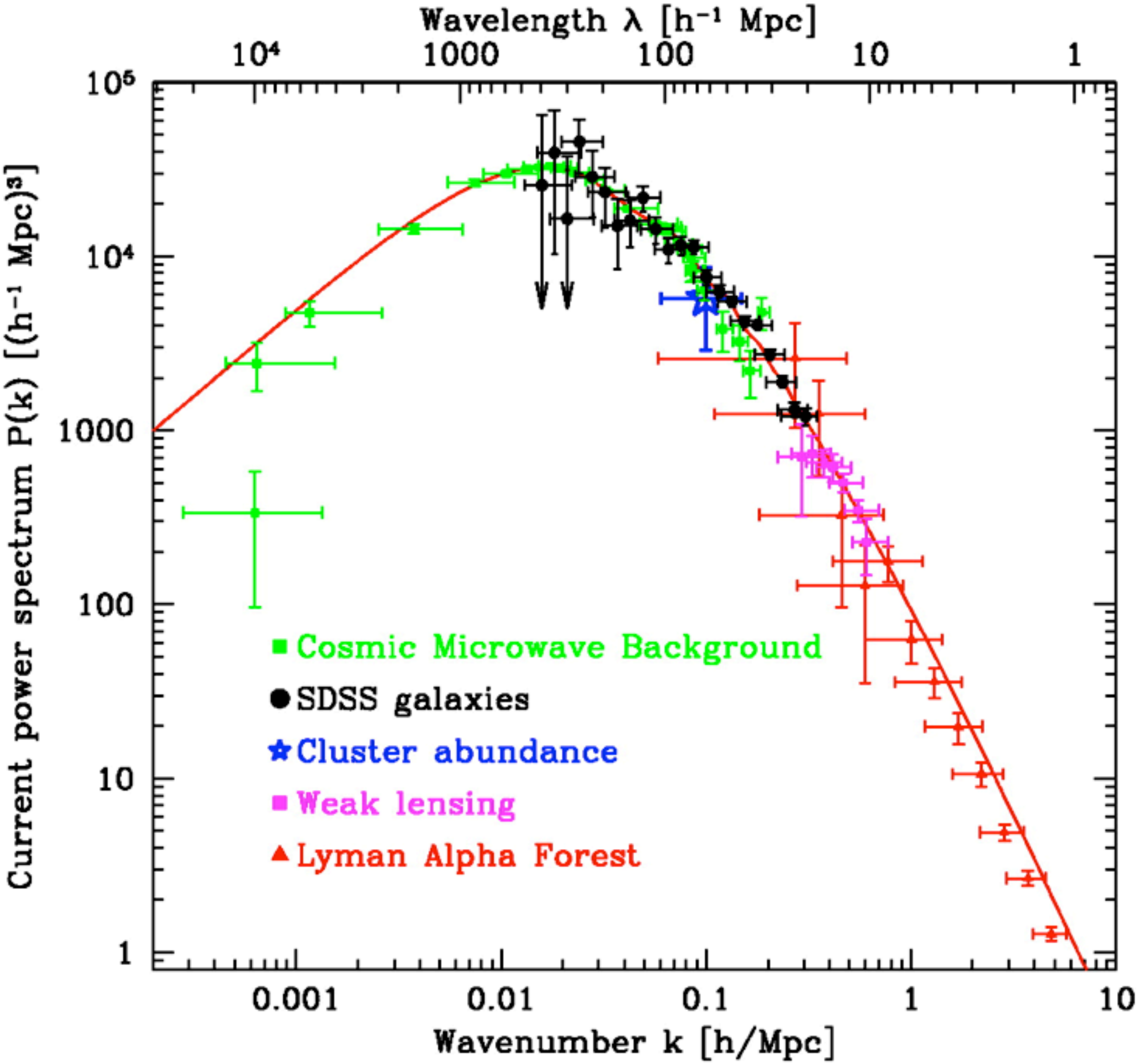
Consider a hypothetical case where the density field has fluctuations on some preferred scale, i.e., with a narrow range of frequencies

Power Spectra of fluctuations represented in images below:





The Observed Power Spectrum

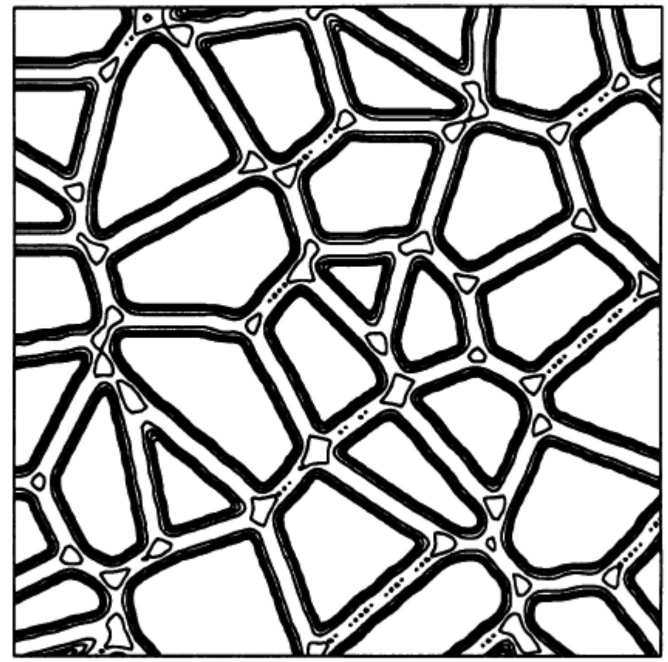


(Tegmark et al.)

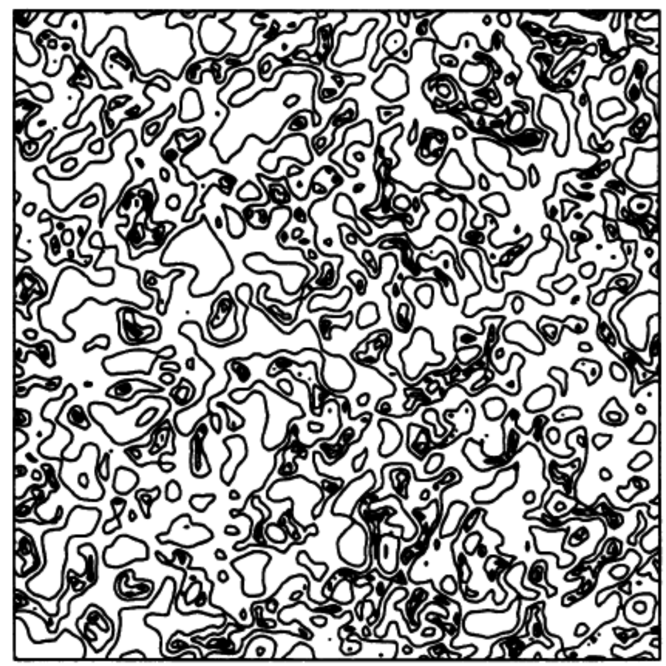
Is the Power Spectrum Enough?

These two images have ***identical power spectra*** (by construction)

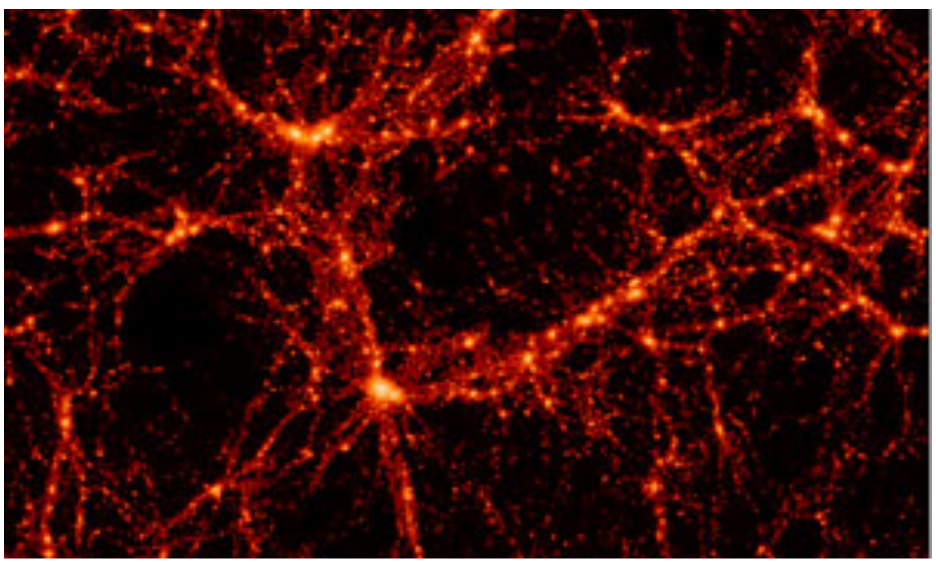
Voronoi foam, R=1.6, smoothed original



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 …)



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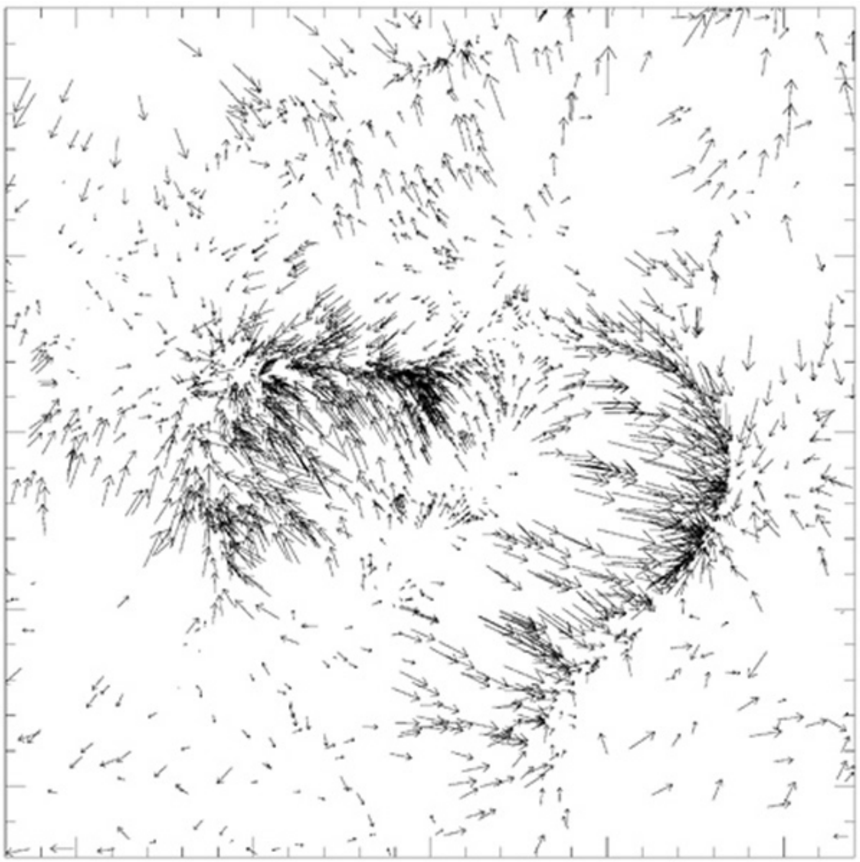
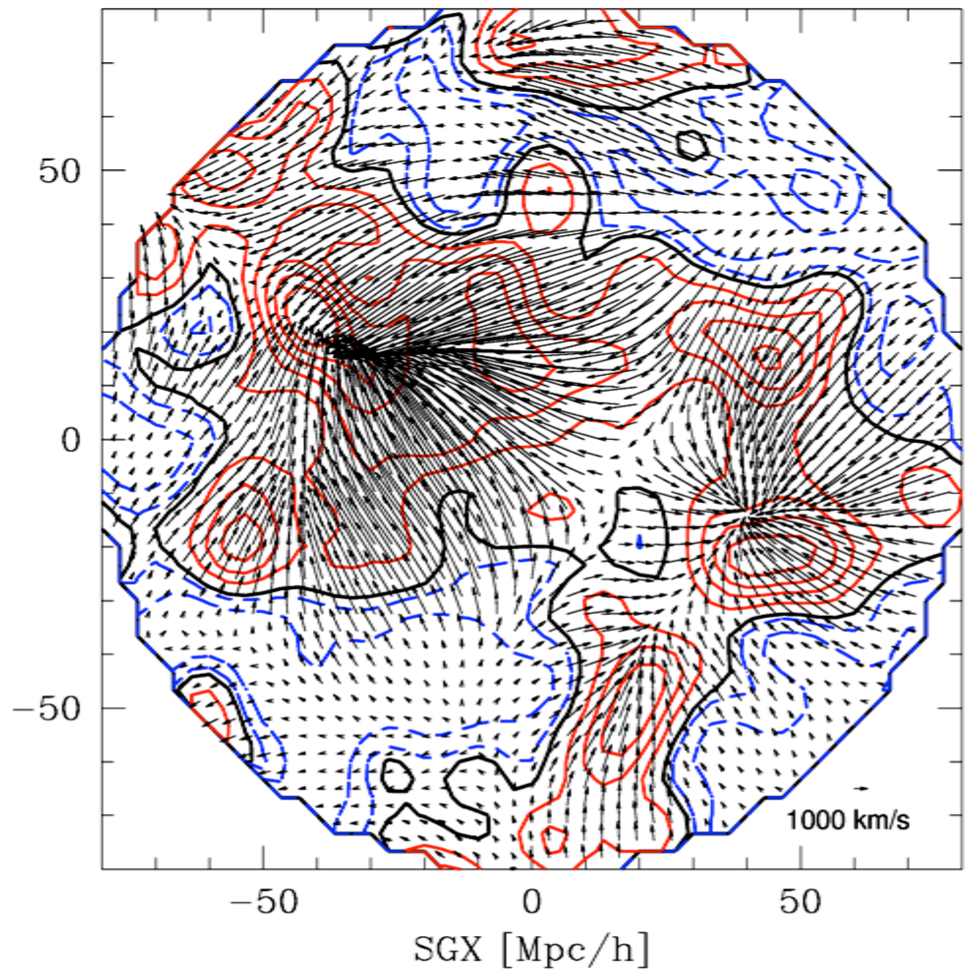
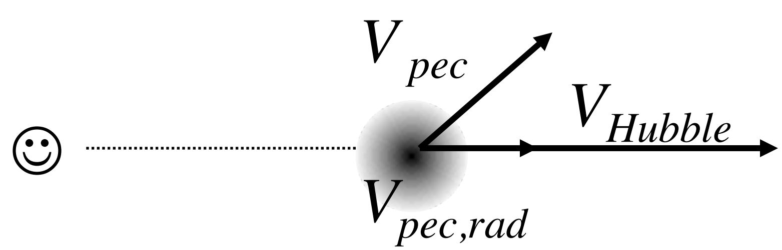
15.3 The Large Scale Velocity Field



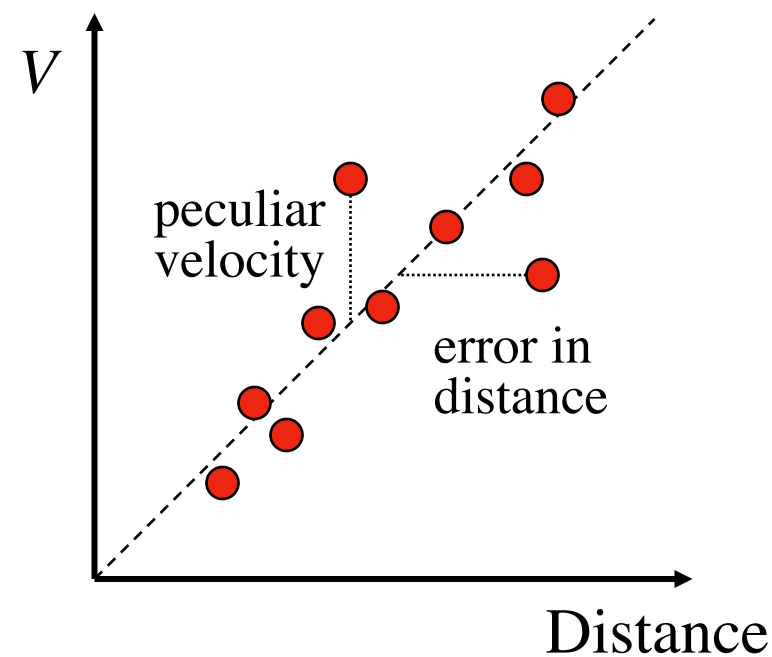


Peculiar Velocities

- It means velocities of galaxies in addition to their Hubble flow velocities, i.e., relative to their comoving coordinates restframe
- Note that we can in practice only observe the radial component
- They act as a noise (on the $V = cz$ axis, and in addition to errors of distances) in the Hubble diagram (velocity vs. distance), and could thus bias the measurements of the cosmological expansion rate

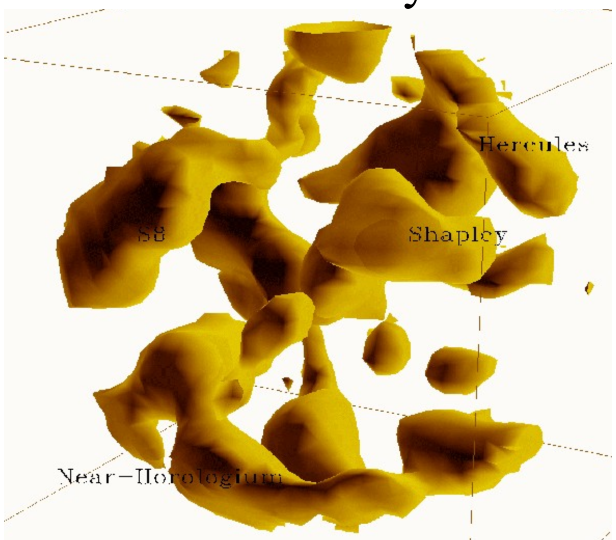


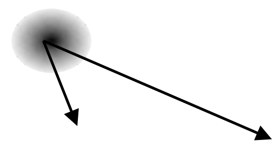
$$V_{total} = V_{Hubble} + V_{pec,rad}$$



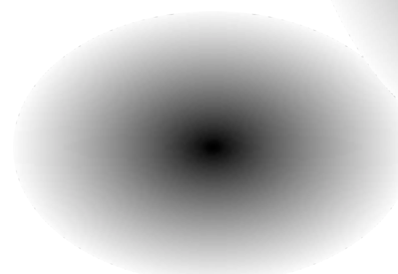
Large-Scale Density Field Inevitably Generates a Peculiar Velocity Field

The PSCz survey
local 3-D density field





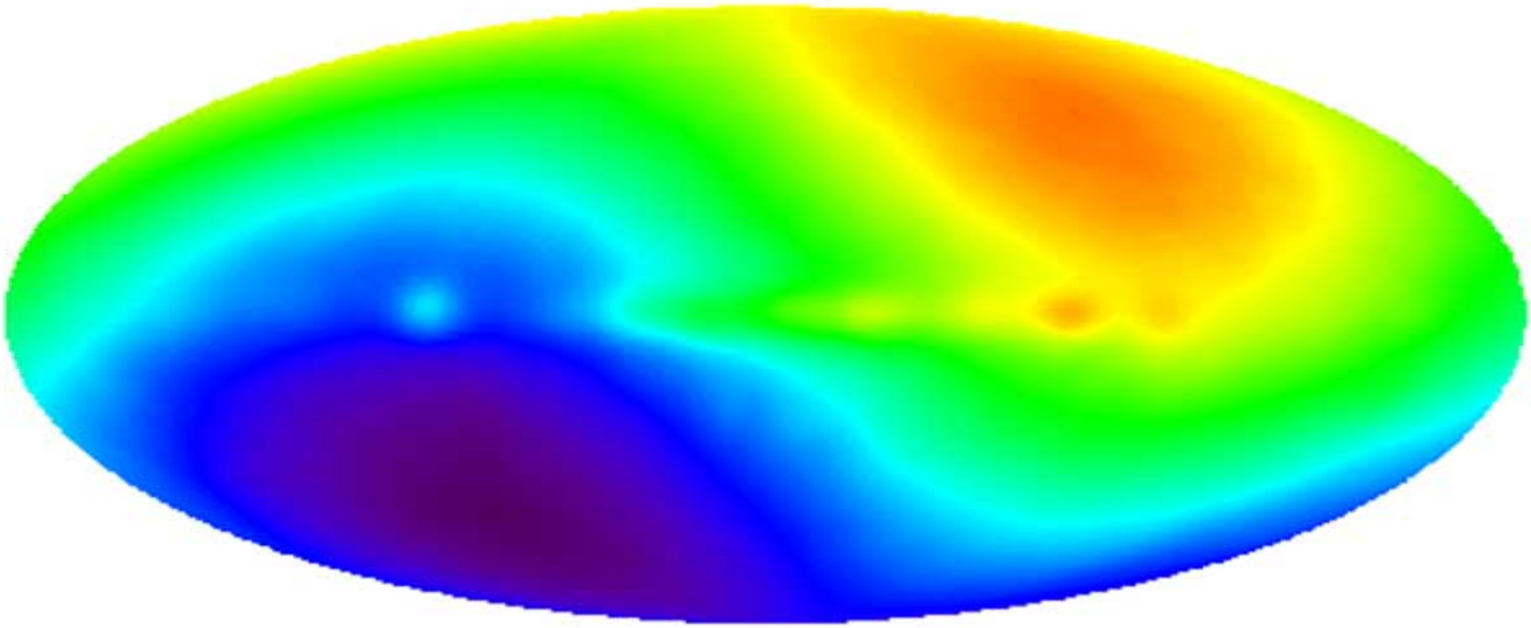
A galaxy is accelerated towards the nearby large mass concentrations



Integrated over the Hubble time, this results in a peculiar velocity

The pattern of peculiar velocities should thus reflect the underlying mass density field

CMBR Dipole:
The One Peculiar Velocity We Know Very Well



We are moving wrt. to the CMB at ~ 620 km/s towards *b=27°, l=268°*
This gives us an idea of the probable magnitude of peculiar velocities in the local universe. Note that at the distance to Virgo (LSC), this corresponds to a ~ 50% error in Hubble velocity, and a ~ 10% error at the distance to Coma cluster.

How to Measure Peculiar Velocities?

1. Using distances and residuals from the Hubble flow:

$$V_{total} = V_{Hubble} + V_{pec} = H_0 D + V_{pec}$$

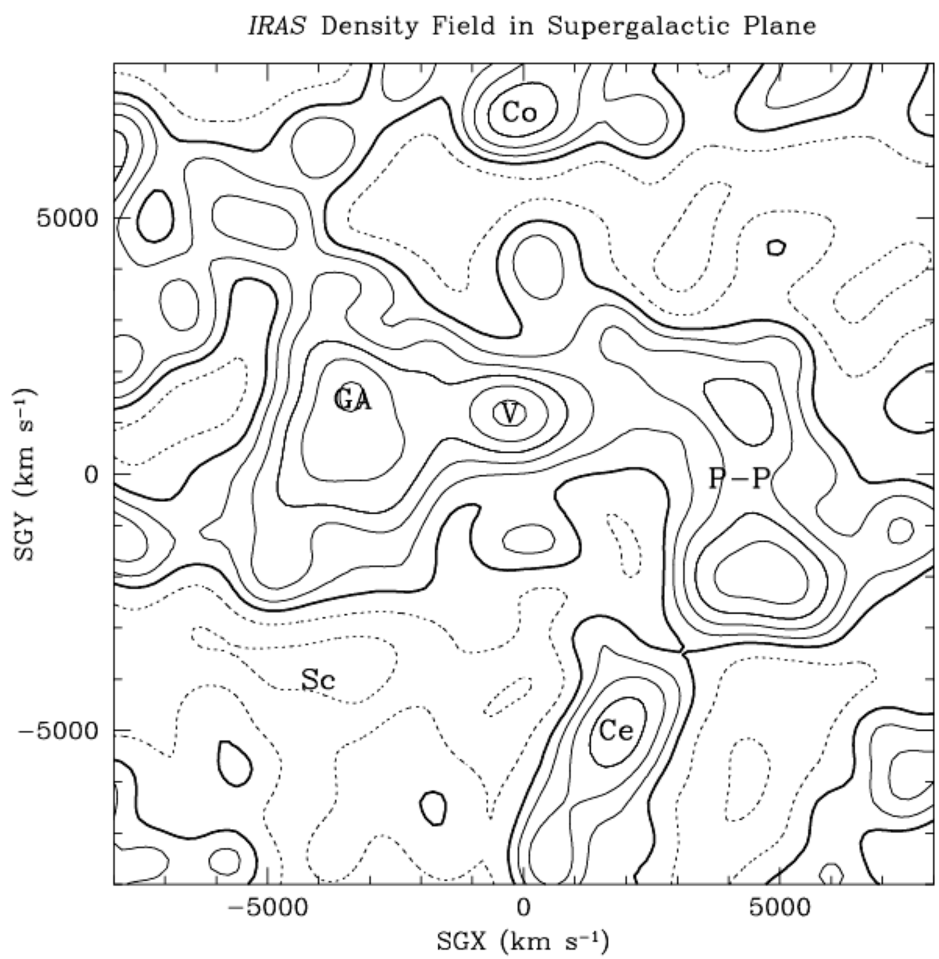
- So, if you know relative distances, e.g., from Tully-Fisher, or D_n-σ relation, SBF, SNe, …you could derive peculiar velocities
- A problem: distances are seldom known to better than ~10% (or even 20%), multiply that by V_{Hubble} to get the error of V_{pec}
- Often done for clusters, to average out the errors, but there could be systematic errors - distance indicators may vary in different environments

2. Statistically from a redshift survey

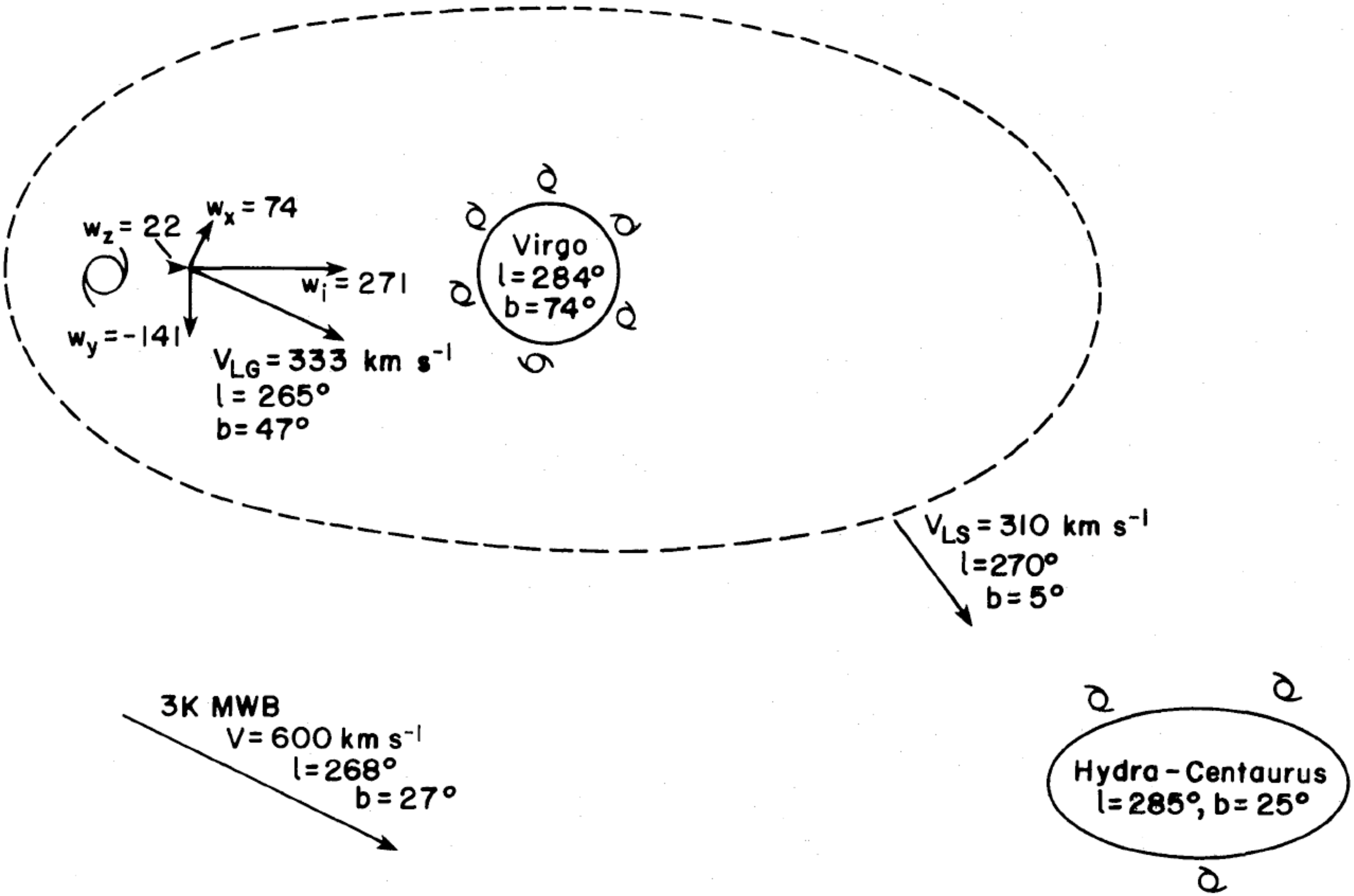
- Model-dependent

Measuring Peculiar Velocity Field Using a Redshift Survey

- Assume that galaxies are where their redshifts imply; this gives you a density field
- You need a model on how the light traces the mass
- Evaluate the accelerations for all galaxies, and their esimated peculiar velocities
- Update the positions according to new Hubble velocities
- Iterate until the convergence
- You get a consistent density and velocity field

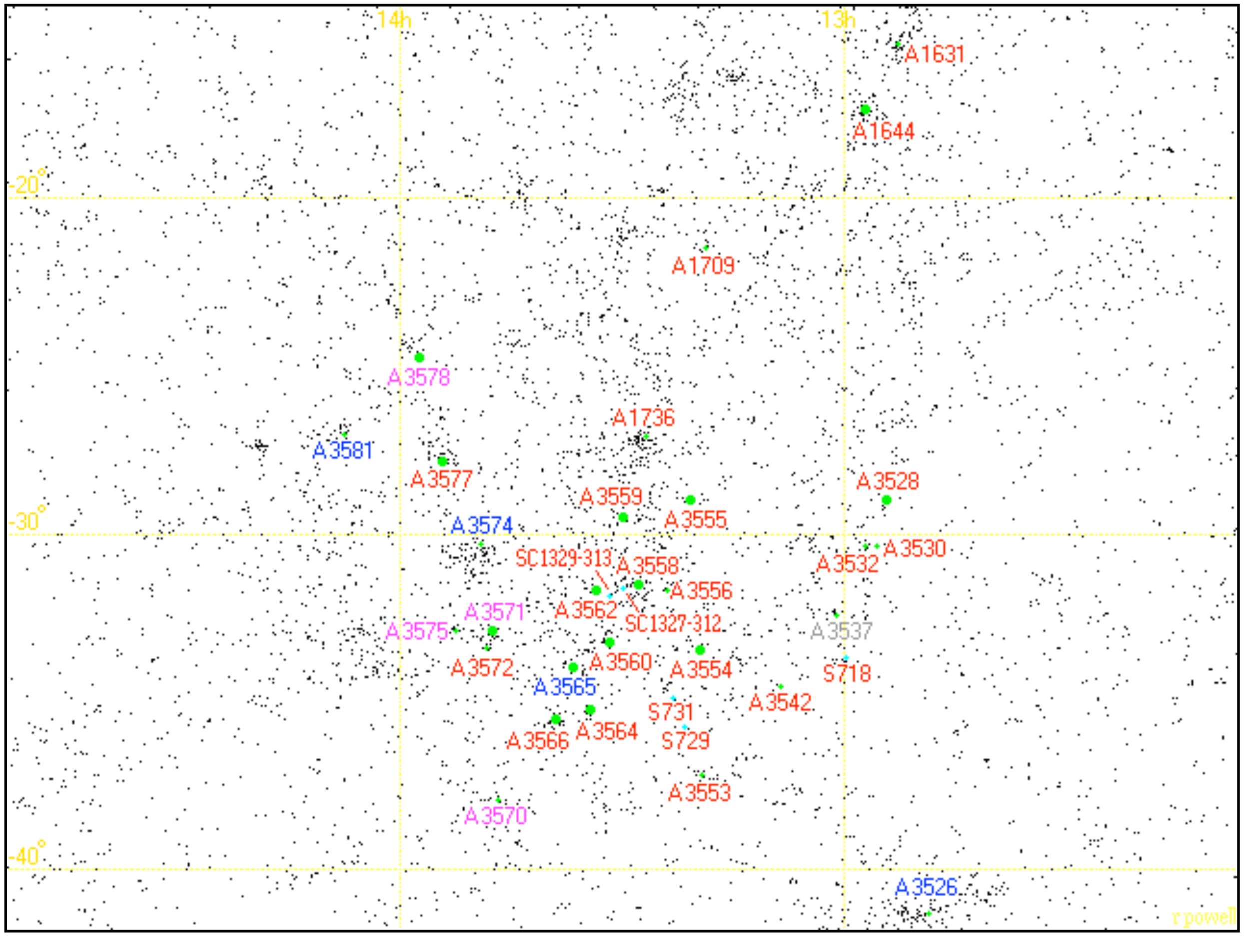


Virgo Infall, and the Motion Towards the Hydra-Centaurus Supercluster



The Flow Continues?

The Shapley Concentration of clusters at ~ 200 Mpc, beyond the Hydra-Centaurus may be responsible for at least some of the large-scale bulk flow



Peculiar Velocities: Summary

- Measurements of peculiar velocities are very, very tricky
  - Use (relative) distances to galaxies + Hubble flow
  - Use a redshift survey + numerical modeling
- **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)

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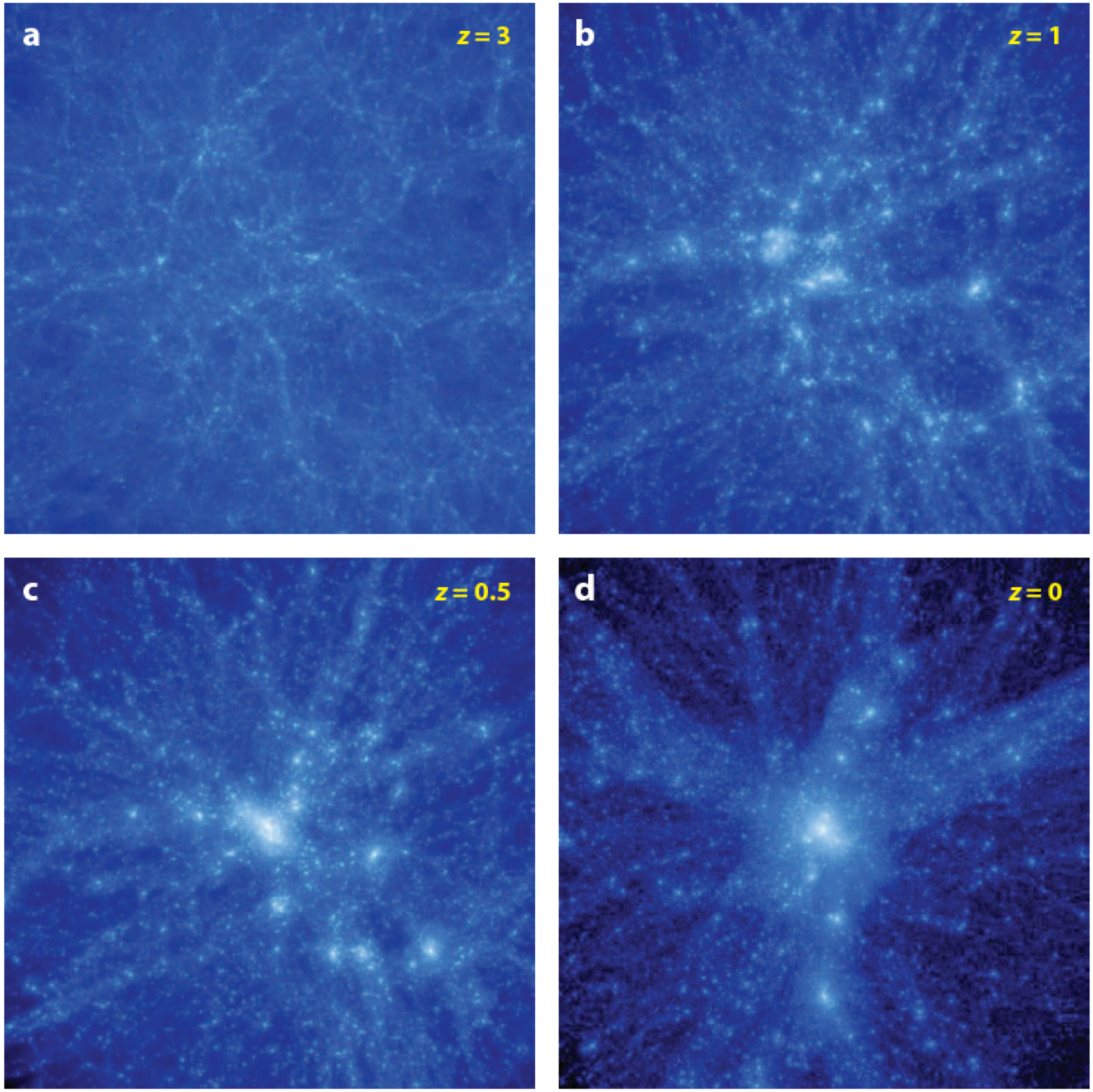
15. 4 Galaxy Bias and the Evolution of Clustering



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:

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

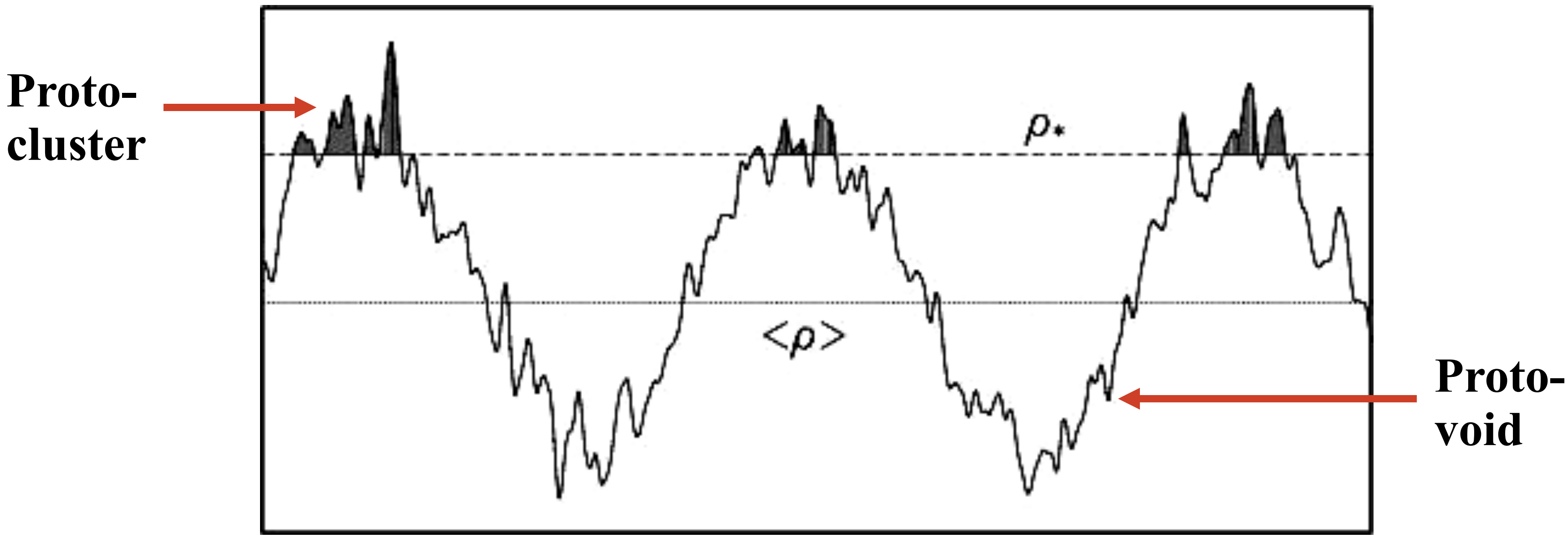
Here ***b*** is the *bias factor*.

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.

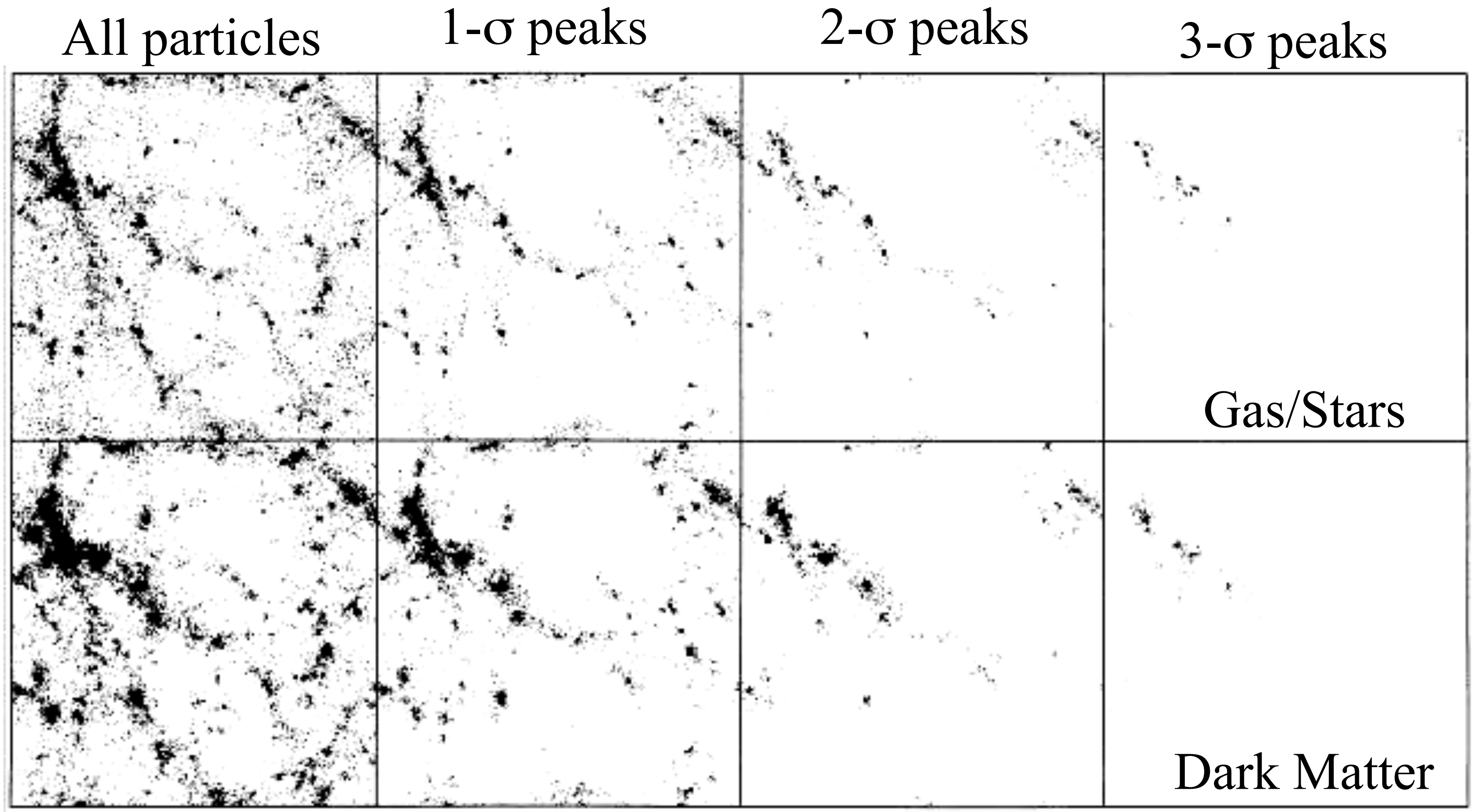
High Density Peaks as Biased Tracers

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

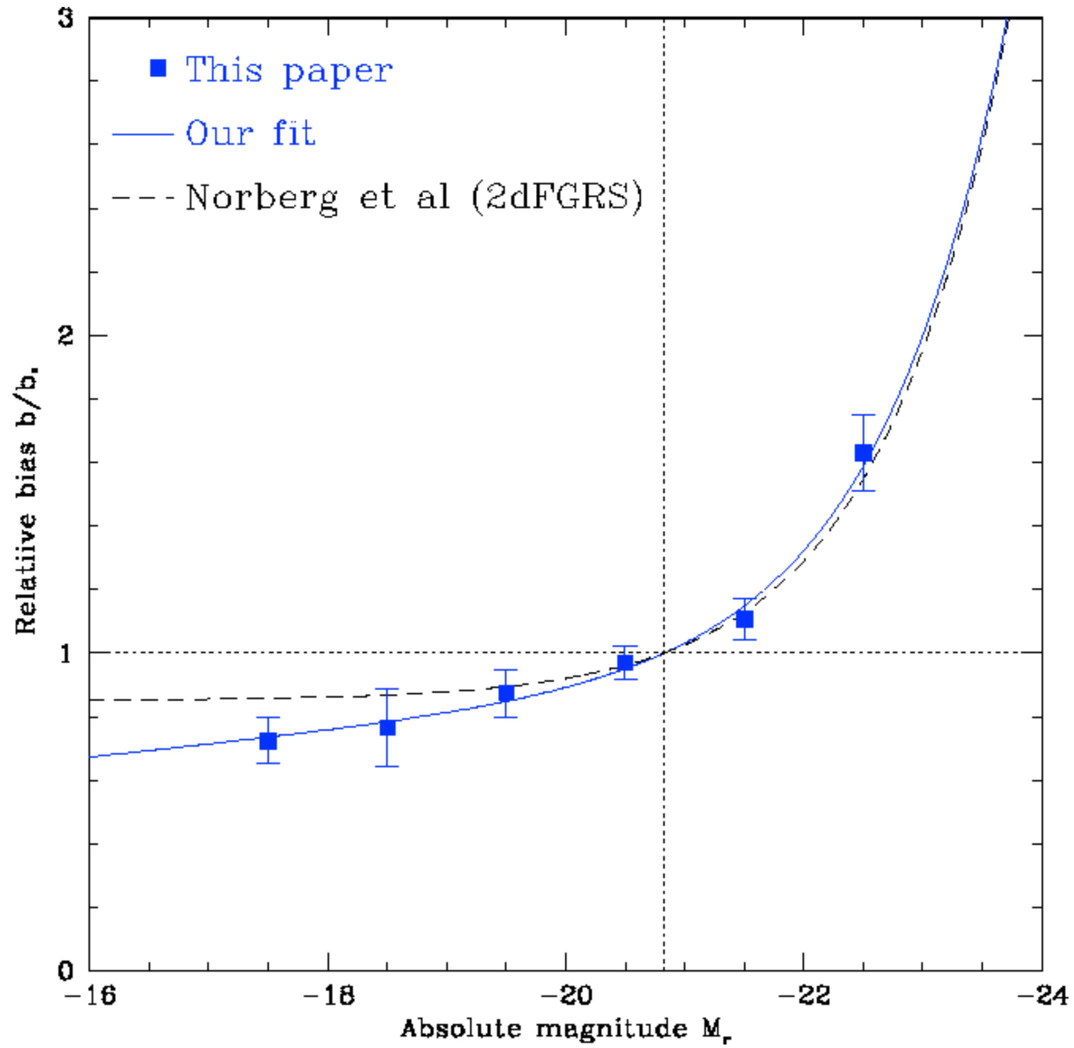


(From an N-body simulation by R. Carlberg)

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.

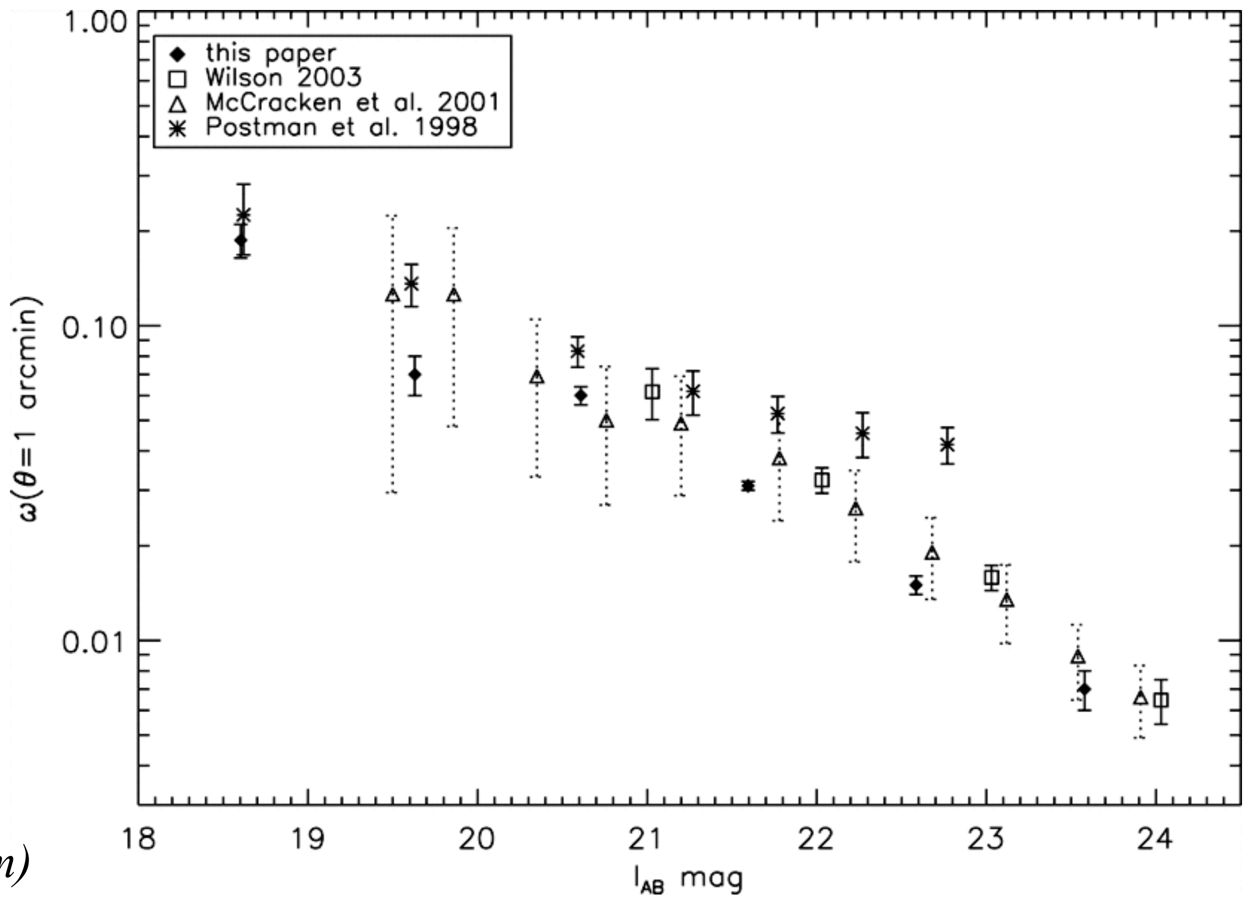


Biasing in the SDSS, Tegmark et al (2004)

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

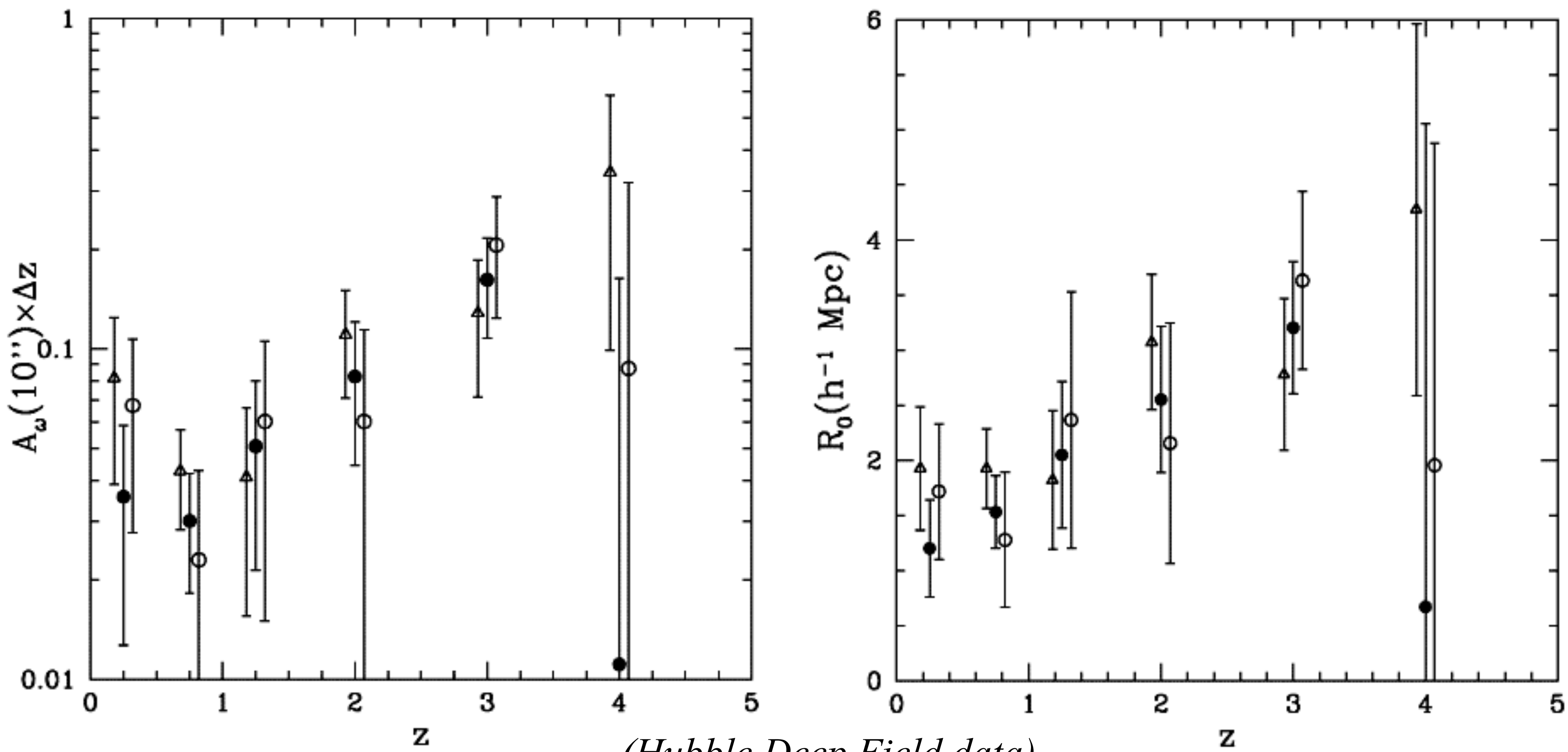
Amplitude of the angular correlation function on the scale of 1 arcmin, as a function of the survey depth



(Coil et al., DEEP survey team)

Evolution of Clustering

- But at higher redshifts (and fainter/deeper galaxy samples), *the trend reverses*: **stronger** clustering at higher redshifts = earlier times! How can that be?
- The answer is in **the evolution of bias**



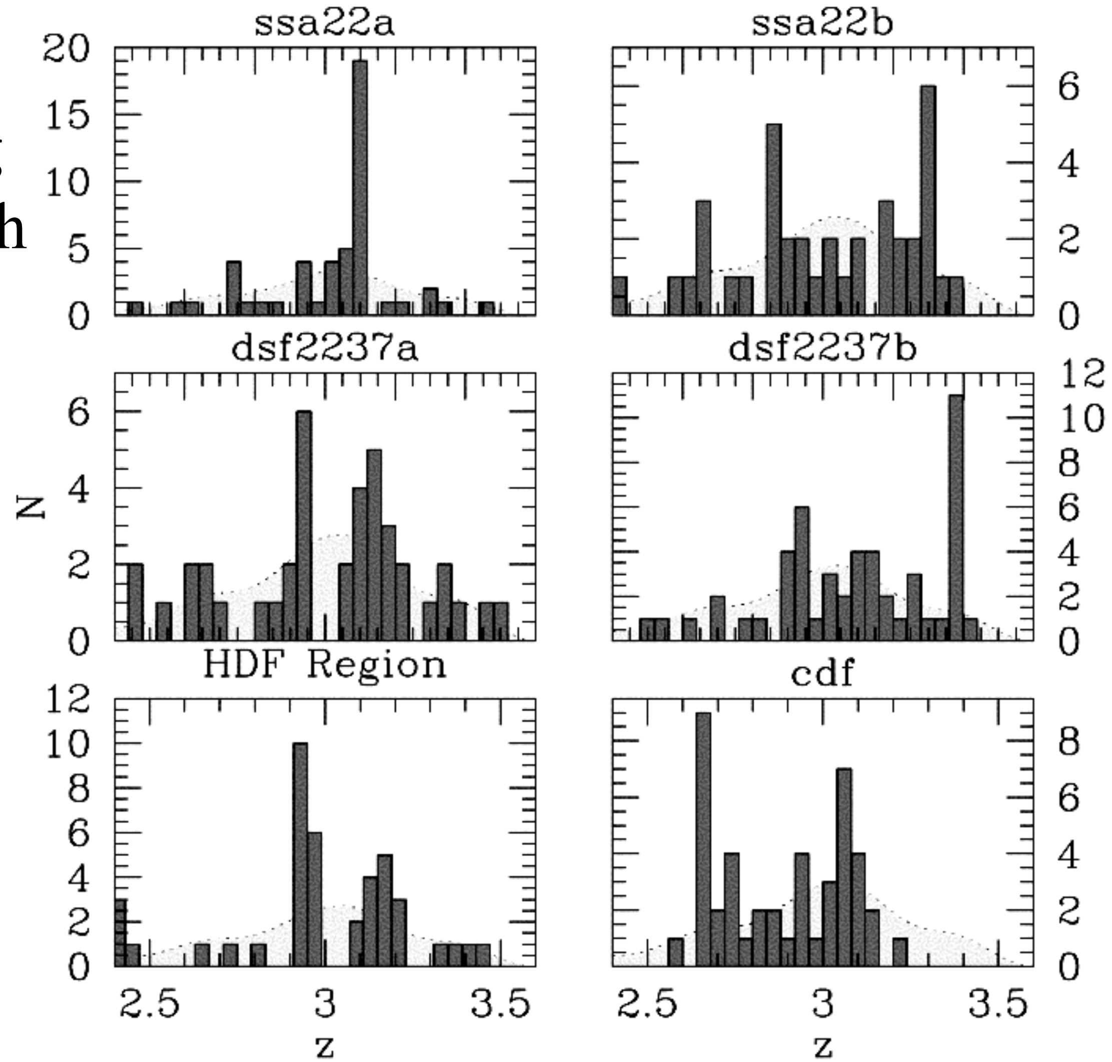
(Hubble Deep Field data)

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

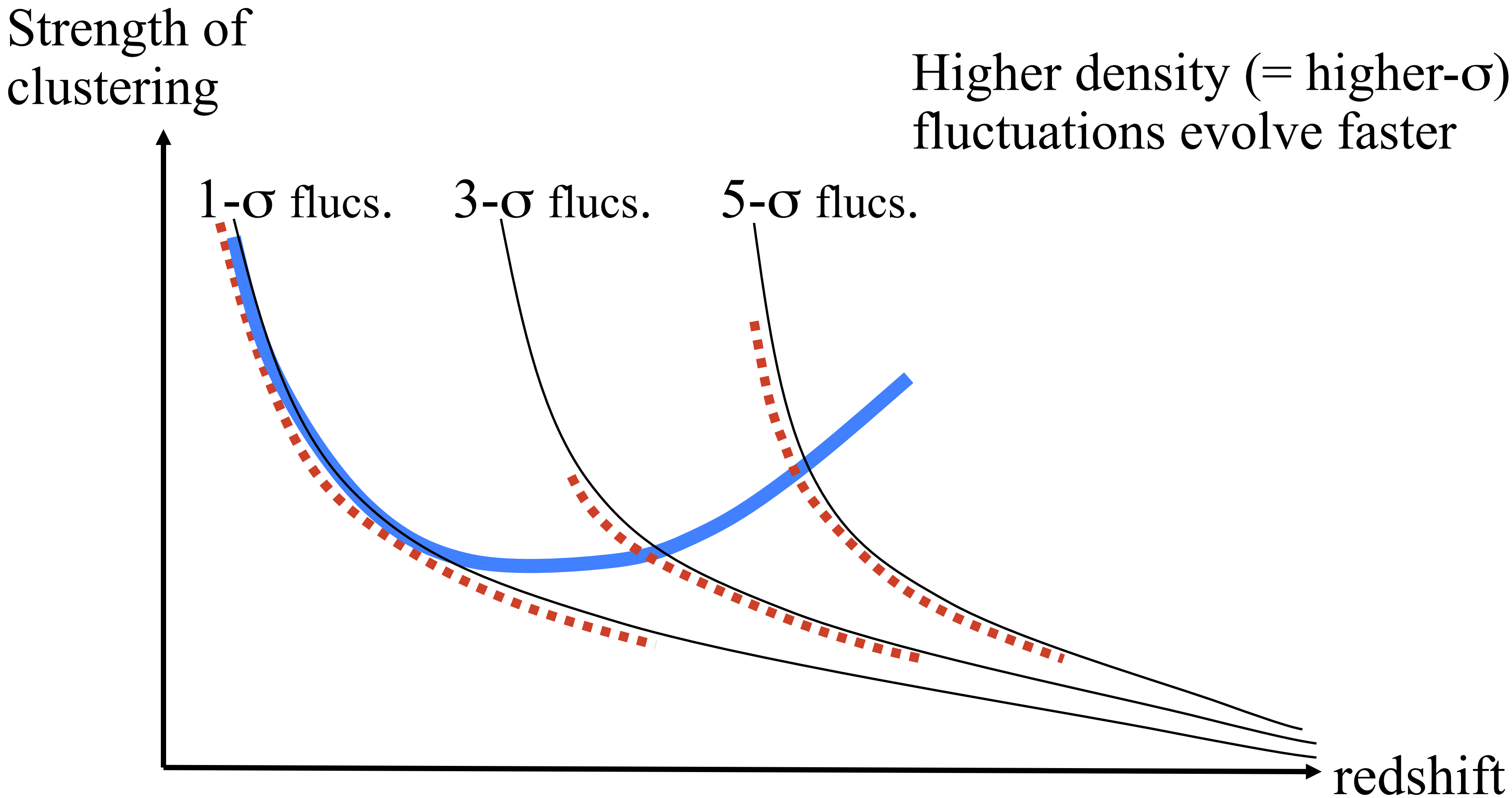
Strong clustering of young galaxies is observed at high redshifts (up to *z* ~ 3 - 4), apparently as strong as galaxies today

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

(Steidel, Adelberger, et al.)



Biasing and Clustering Evolution

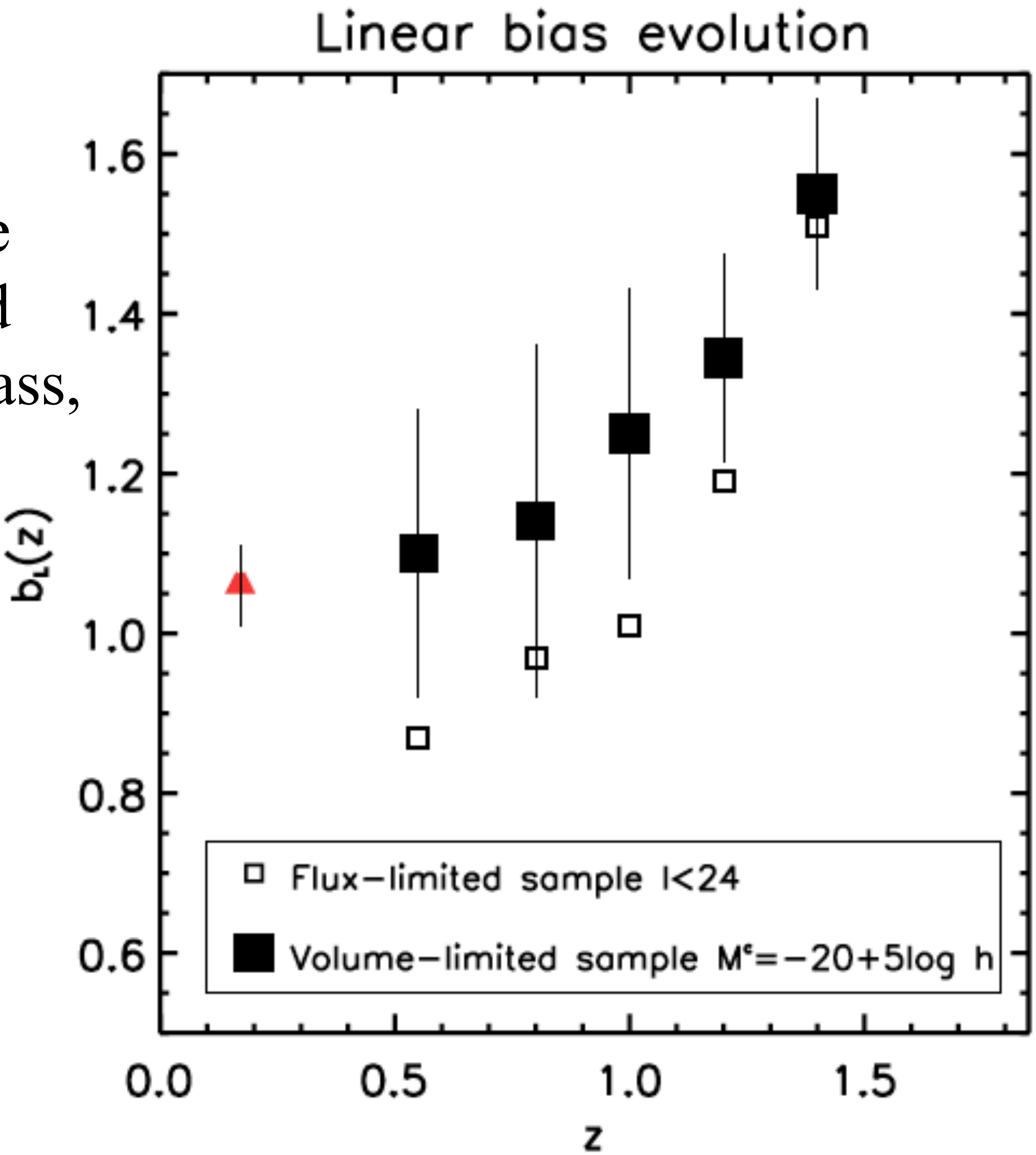


At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly …

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)

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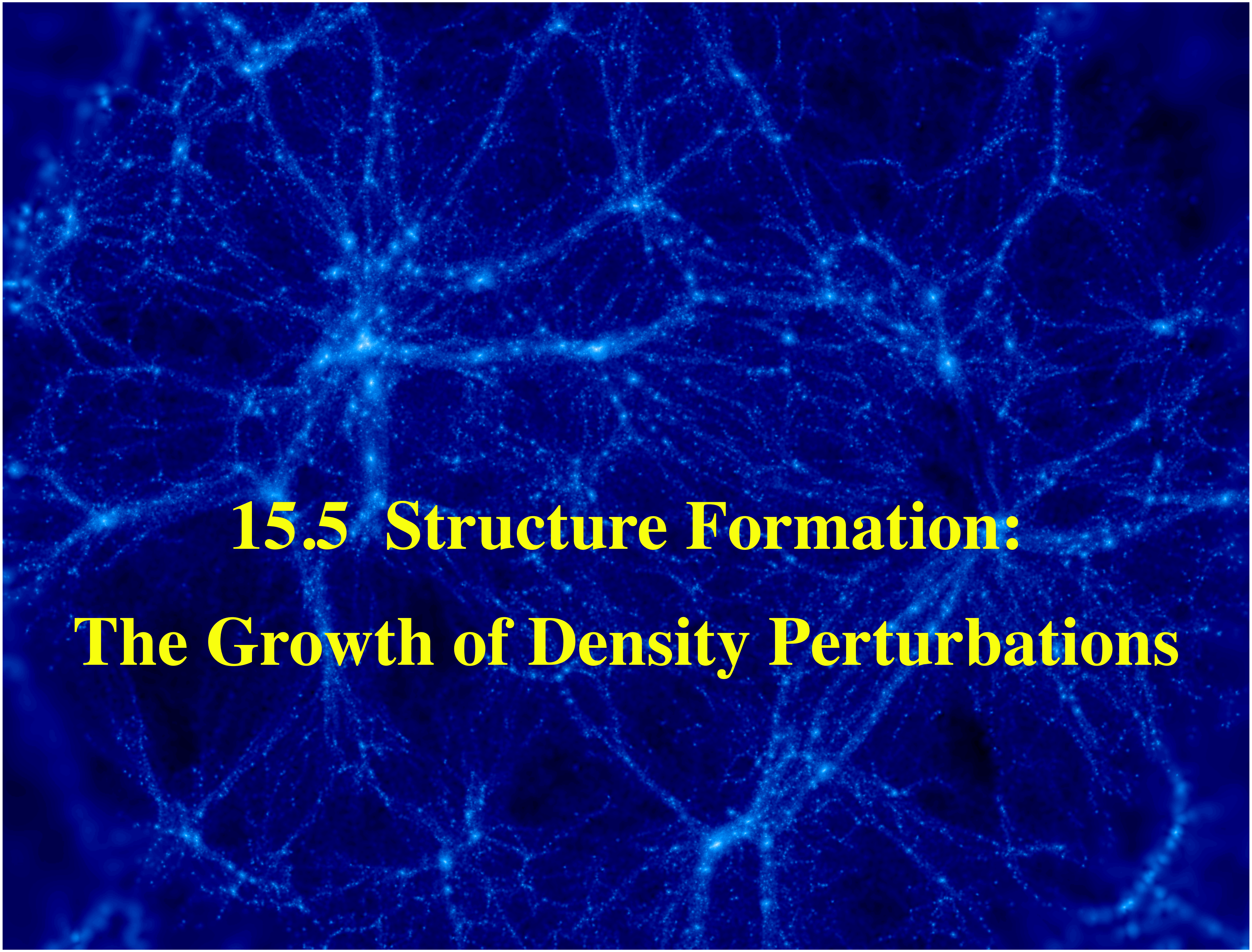
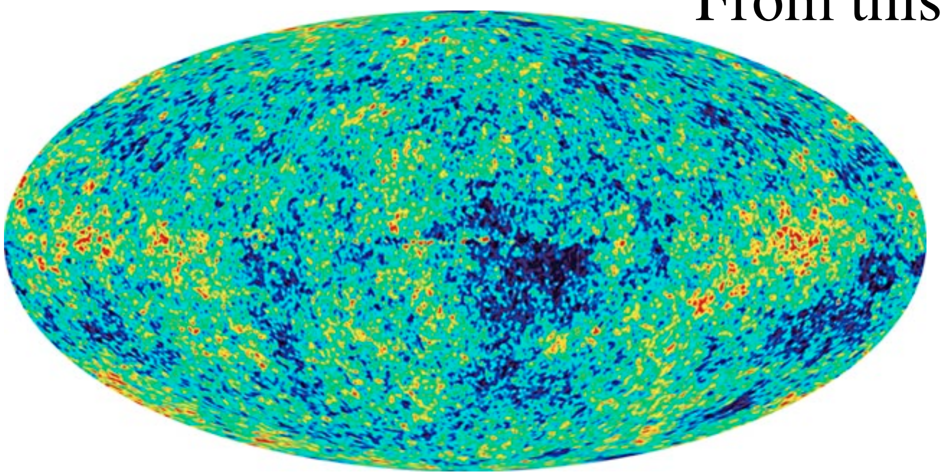


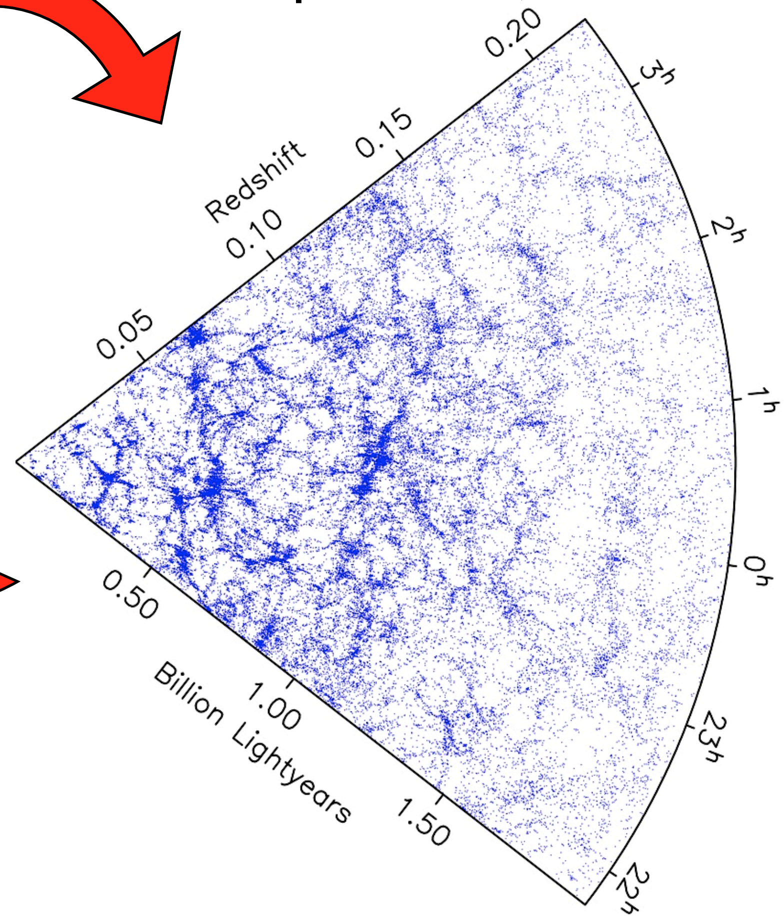
15.5 Structure Formation:
The Growth of Density Perturbations

Structure Formation and Evolution

From this ($\Delta\rho/\rho \sim 10^{-6}$)



to this
($\Delta\rho/\rho \sim 10^{+2}$)

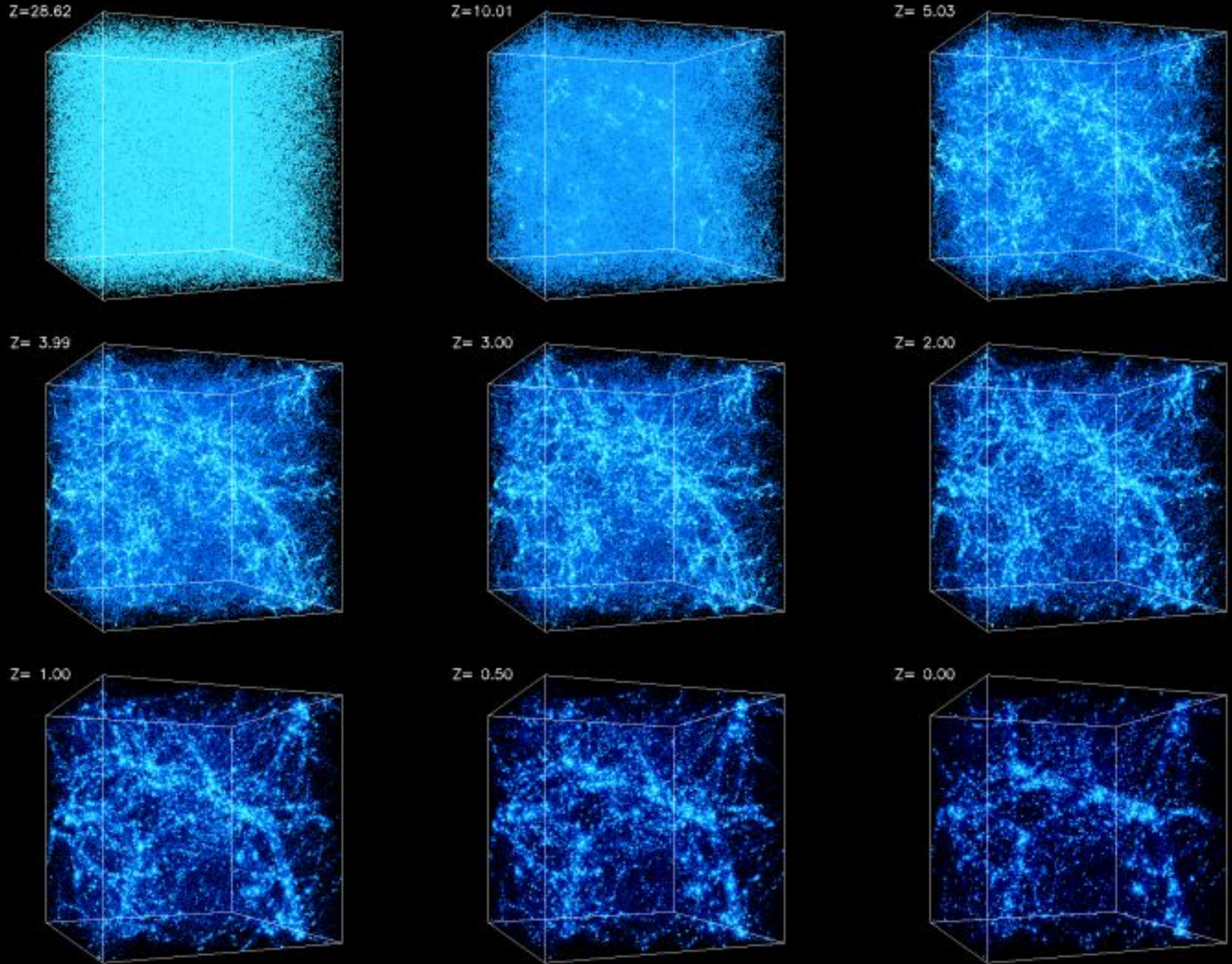


to this
($\Delta\rho/\rho \sim 10^{+6}$)

Origin of Structure in the Universe

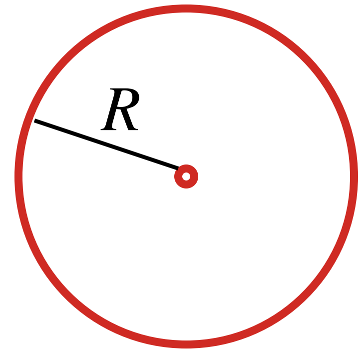
- Origin and evolution of the structure in the universe (galaxies, large-scale structures) is a central problem in cosmology
- Structure is generally thought to arise through a growth of density perturbations which originate in the early universe
  - We think they came from quantum fluctuations in the scalar field that caused inflation, and were then amplified by the exponential inflation of the universe
- What do we know about the early structure formation?
  - We see CMB fluctuations with $\delta T/T \sim 10^{-6} \sim \Delta\rho/\rho$, since radiation and baryons are coupled before recombination
  - High-z objects: We observe galaxies and quasars at $z > 6$. A galaxy requires an overdensity of $\sim 10^6$ relative to the mean

A “Cosmic Cube” Simulation by A. Kravtsov



How Long Does It Take?

The (dissipationless) gravitational collapse timescale is on the order of the free-fall time, t_{ff}:



The outermost shell has acceleration $g = GM/R^2$

It falls to the center in:

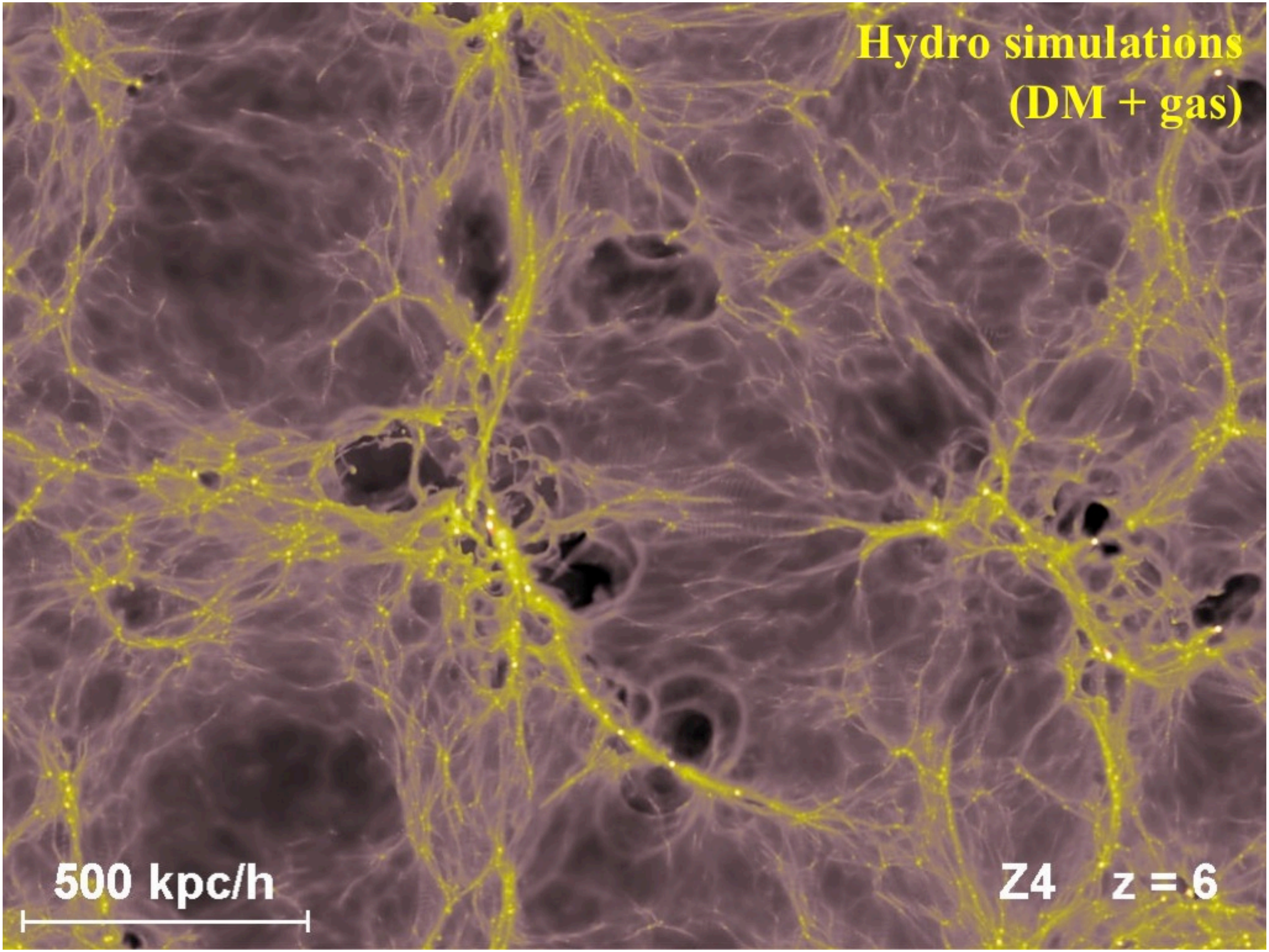
$$t_{ff} = (2R/g)^{1/2} = (2R^3/GM)^{1/2} \approx (2/G\rho)^{1/2}$$

Thus, low density lumps collapse more slowly than high density ones. More massive structures are generally less dense, take longer to collapse. For example:

For a galaxy: $t_{ff} \sim 600$ Myr $(R/50\text{kpc})^{3/2}$ $(M/10^{12}M_\odot)^{-1/2}$

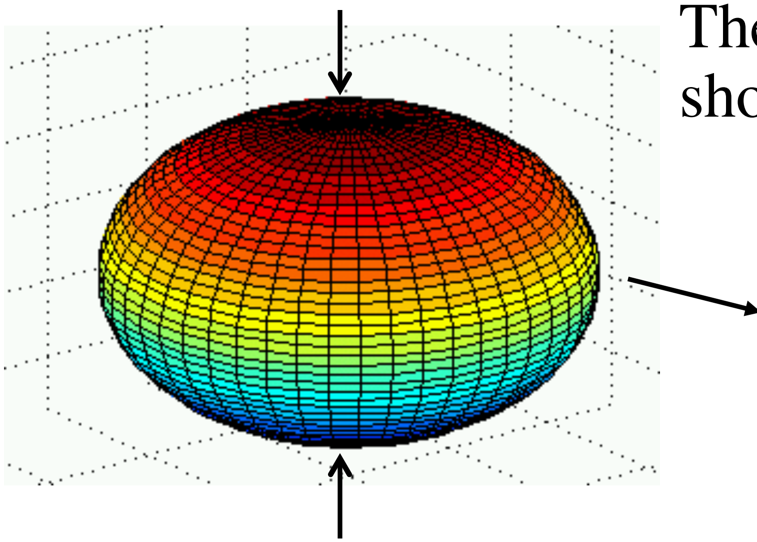
For a cluster: $t_{ff} \sim 9$ Gyr $(R/3\text{Mpc})^{3/2}$ $(M/10^{15}M_\odot)^{-1/2}$

So, we expect that galaxies collapsed early (at high redshifts), and that clusters are still forming now. This is as observed!


Hydro simulations
(DM + gas)
500 kpc/h
Z4
z = 6

Non-Spherical Collapse

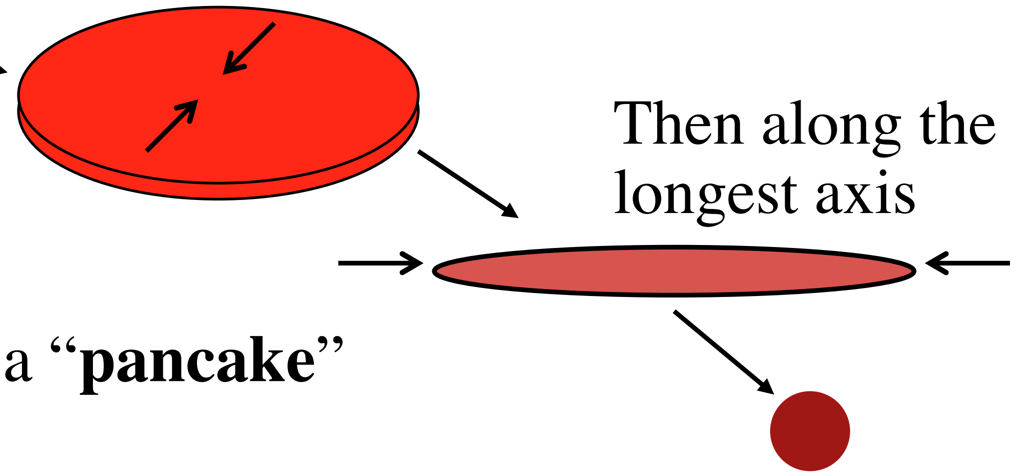
Real perturbations will not be spherical. Consider a collapse of an ellipsoidal overdensity:



The expansion turns into collapse along the shortest axis first …

Then along the intermediate axis

Then along the longest axis



- Perturbation first forms a "**pancake**"
- Then forms **filaments**
- Then forms **clusters**

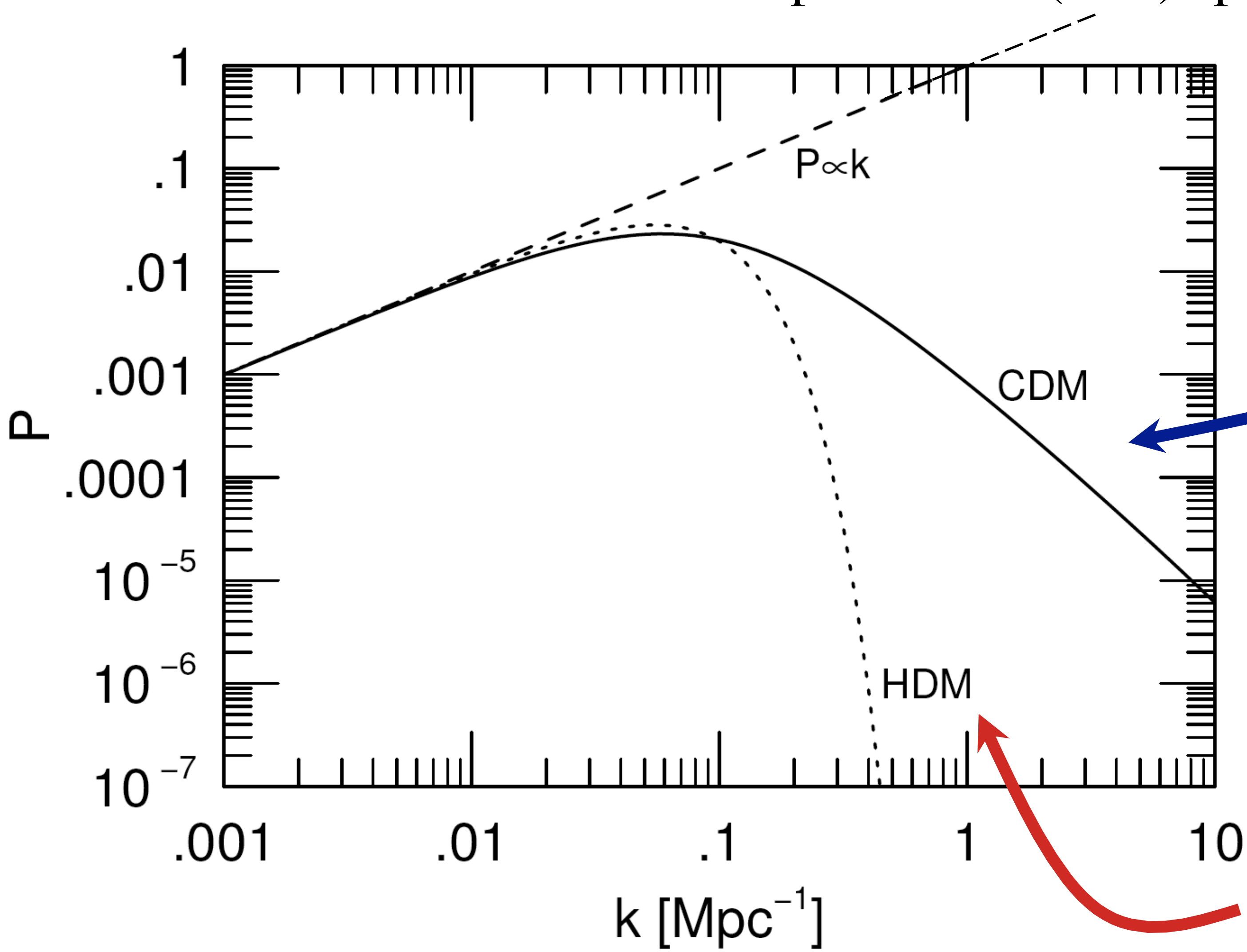
This kinds of structures are seen both in numerical simulations of structure formation and in galaxy redshift surveys

Dark Matter and Damping of Fluctuations

- Different types of dark matter form structure differently
- Baryonic dark matter is coupled to radiation, so it does not help in forming structure prior to the recombination
- Fluctuations can be erased or damped by sound waves (this is also called the Meszaros effect). This is important for slowly moving DM particles, i.e., cold dark matter (CDM)
- They can be erased by free streaming of relativistic particles, i.e., hot dark matter (HDM); diffusion of photons, which then "drag along" the baryons in the radiation-dominated era, does the same thing (this is also called the Silk damping)
- Thus HDM vs. CDM make very different predictions for the evolution of structure in the universe!
- In any case, the smaller fluctuations are always erased first

Damping of Fluctuations

The primordial (H-Z) spectrum

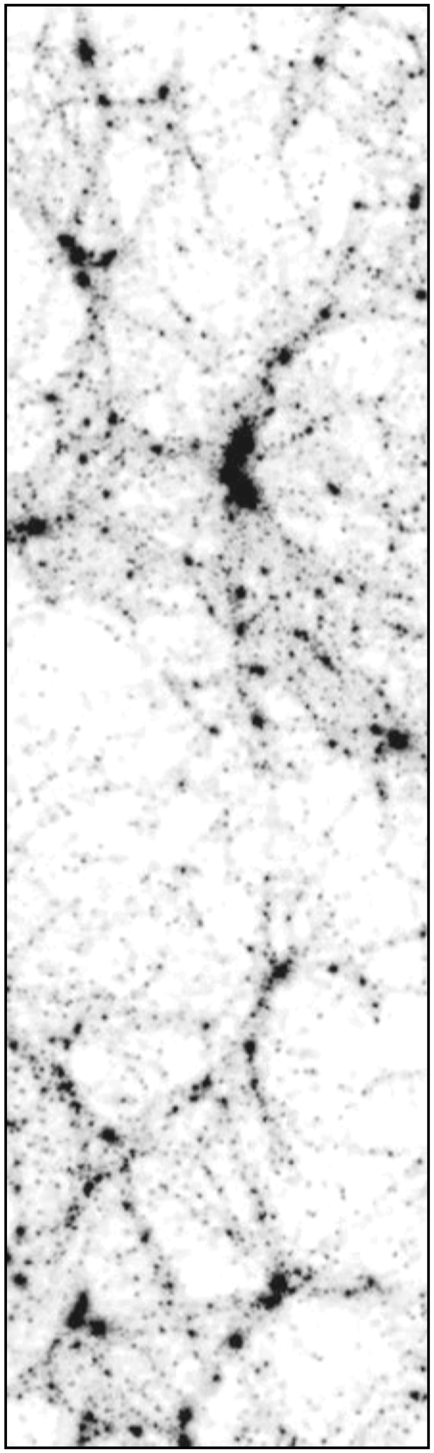


Sound waves diminish the strength of small scale fluc's for the CDM case

Relativistic streaming and photon diffusion erase them completely for the HDM case

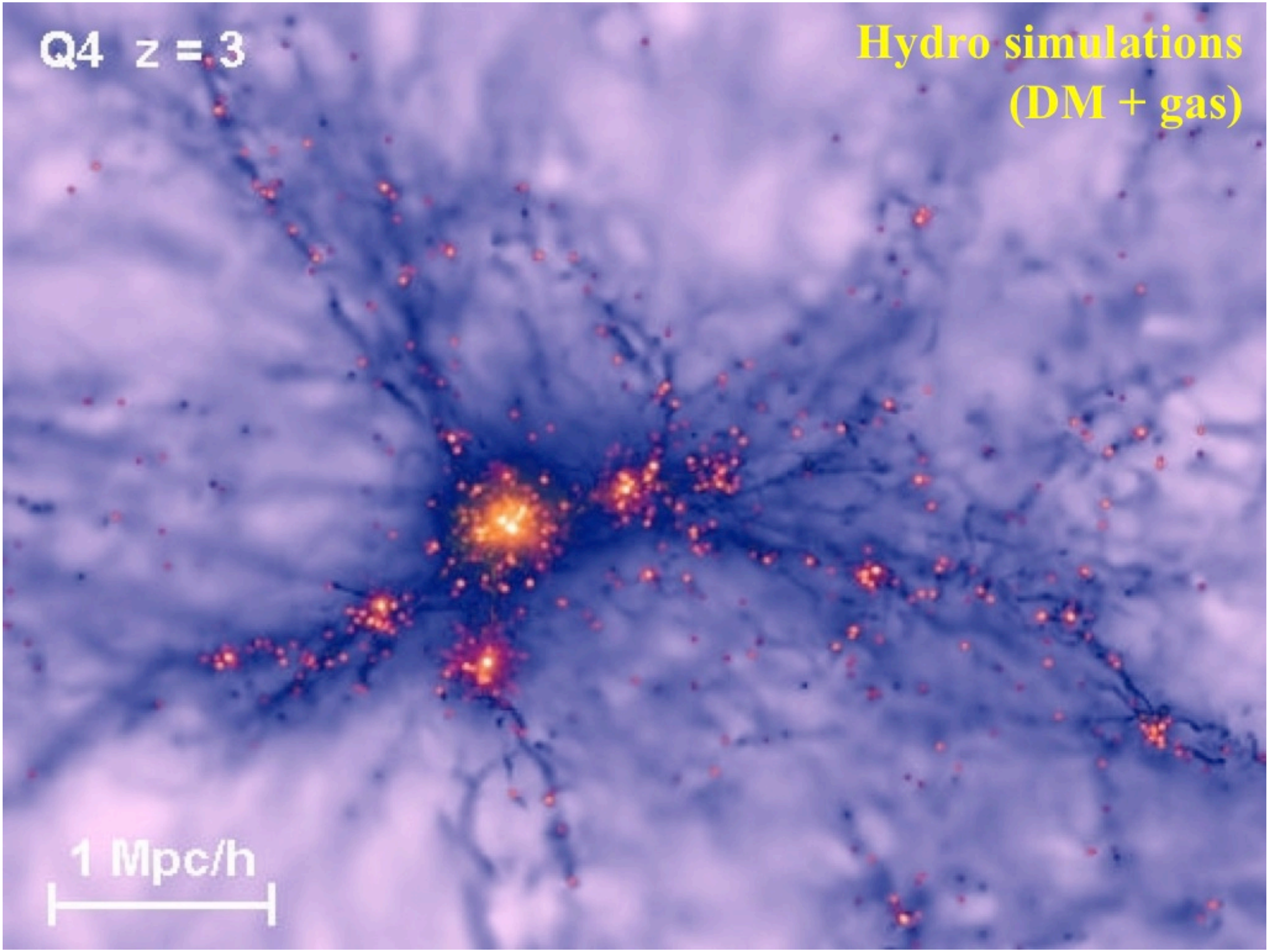
Structure Formation in the Cold Dark Matter Scenario

- CDM particles don't diffuse out of small lumps. So lumps exist on all scales, both large and small
- Small lumps collapse first, big things collapse later. The larger overdensities will incorporate smaller things as they collapse, via merging
- Structure forms early, and it forms **"bottom-up"** Galaxies form early, before clusters, and clusters are still forming now
- This picture is known as **"hierarchical structure formation"**
- This closely matches what we observe, and also produces the right kind of CMB fluctuations



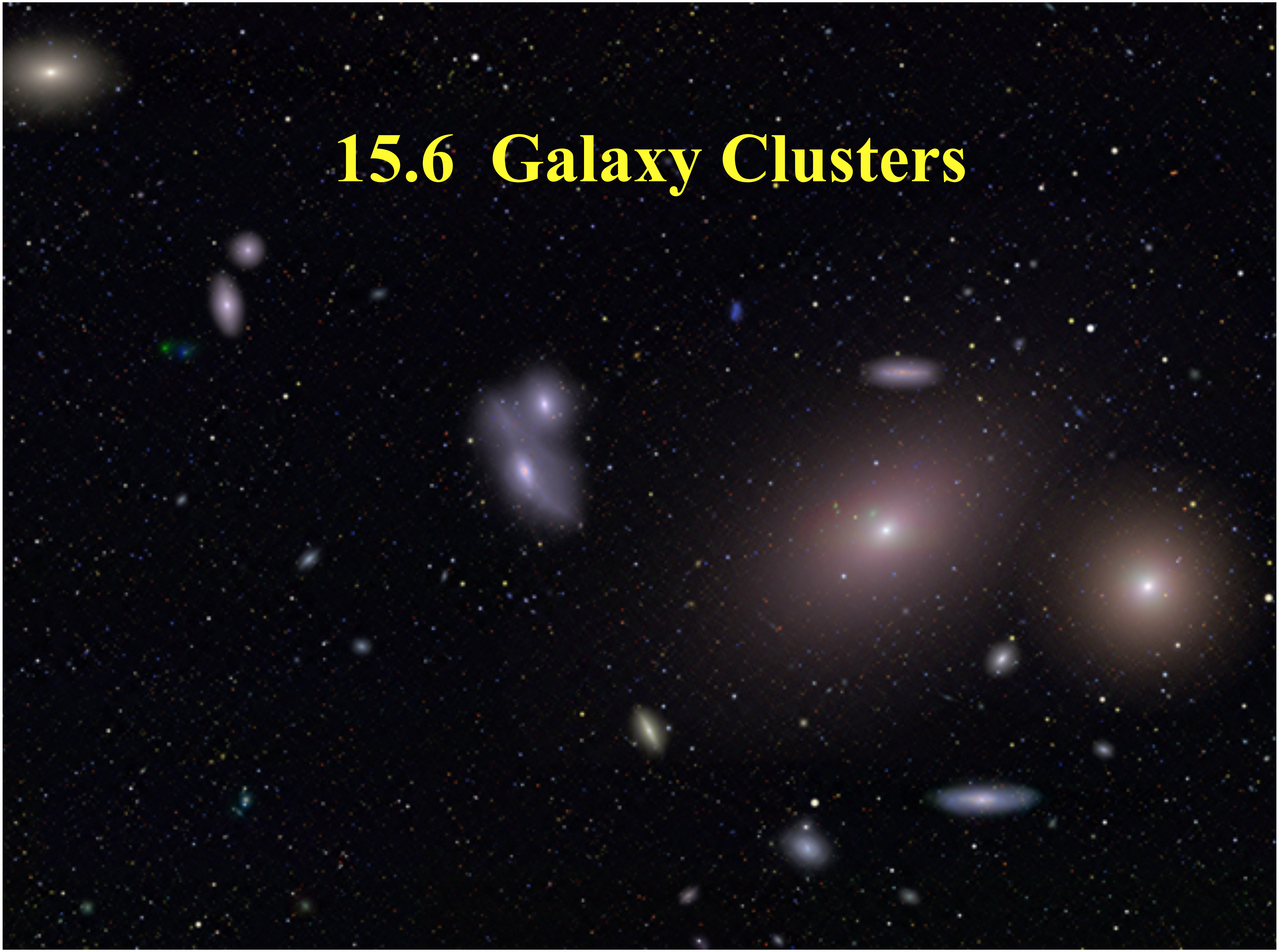
Cooling and Dissipative Galaxy Formation

- Pure gravitational infall leads to overdensities of ~ 200 when the virialization is complete
- That is about right for the clusters of galaxies
- But galaxies are ~ 10^6 times denser than the mean; that means that they had to collapse by an additional factor of 10+
- Therefore, they had to release (dissipate) this excess binding energy. This process is called cooling, and it is what separates galaxies from the large scale structure


Q4 z = 3
Hydro simulations
(DM + gas)
1 Mpc/h

?

15.6 Galaxy Clusters

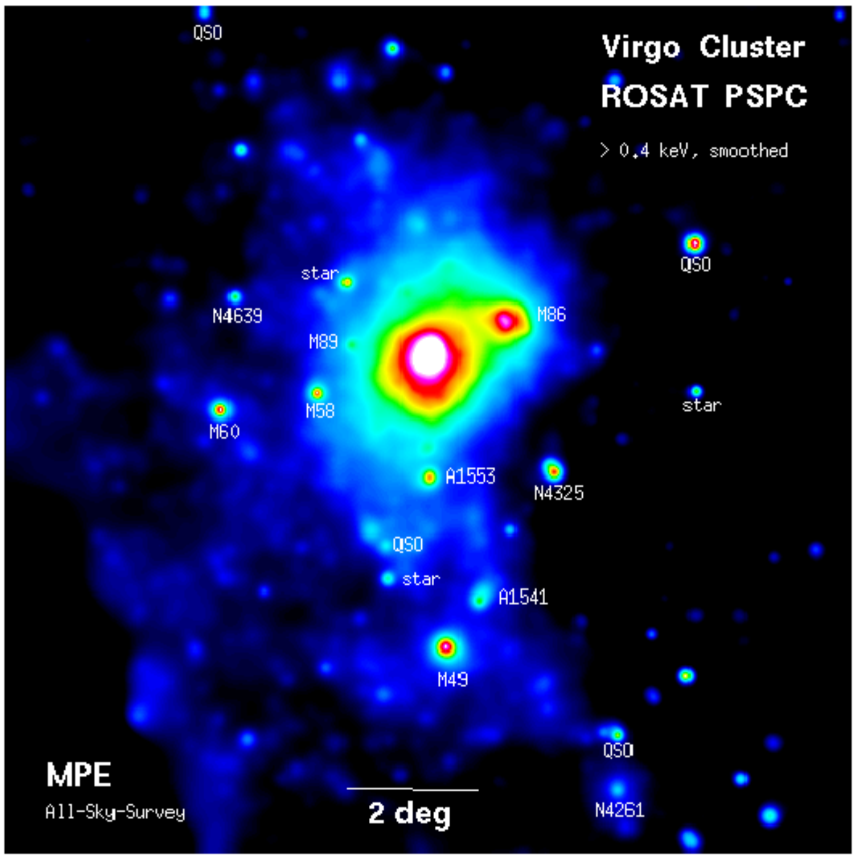


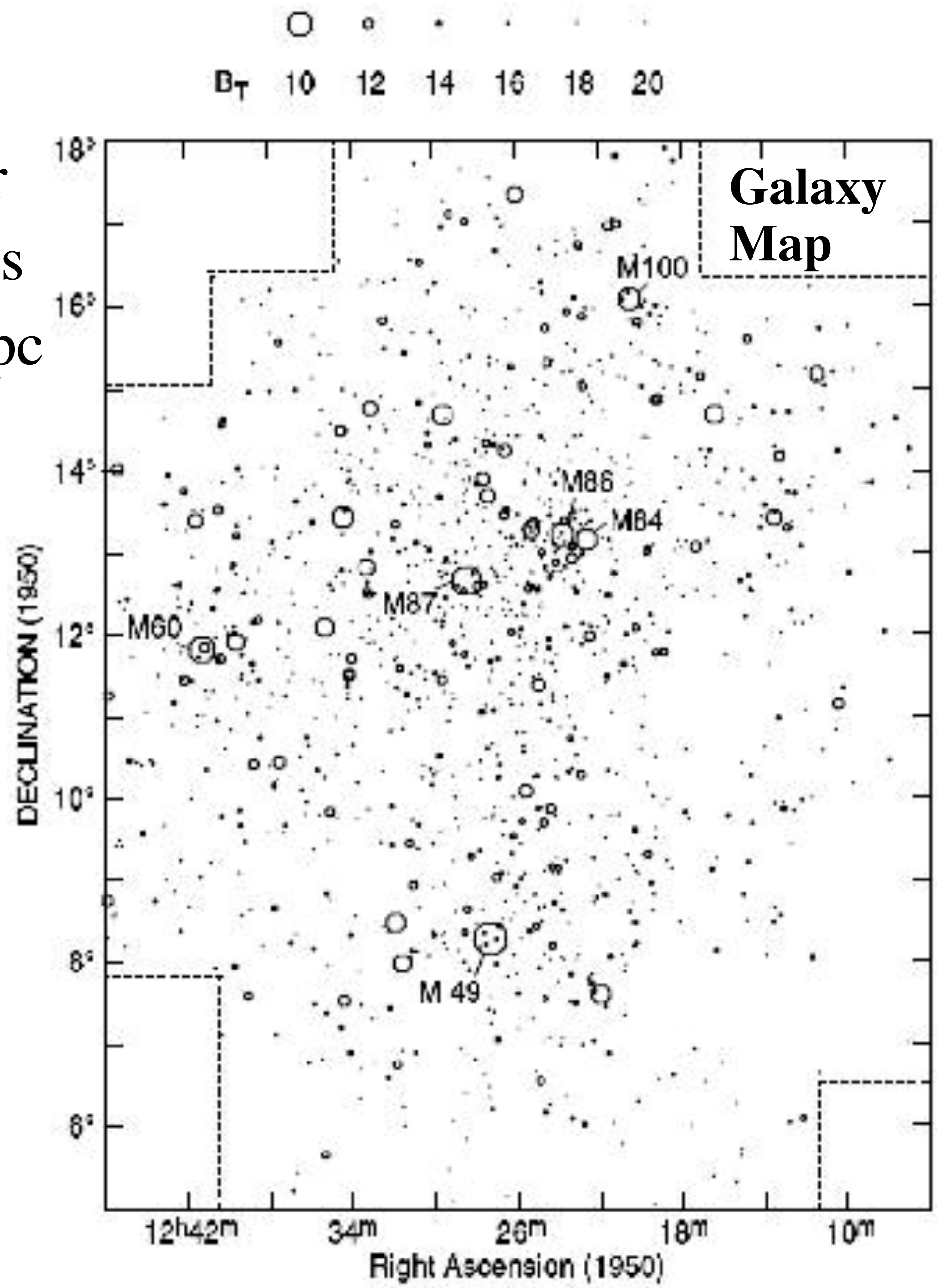
Clusters of Galaxies:

- 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:

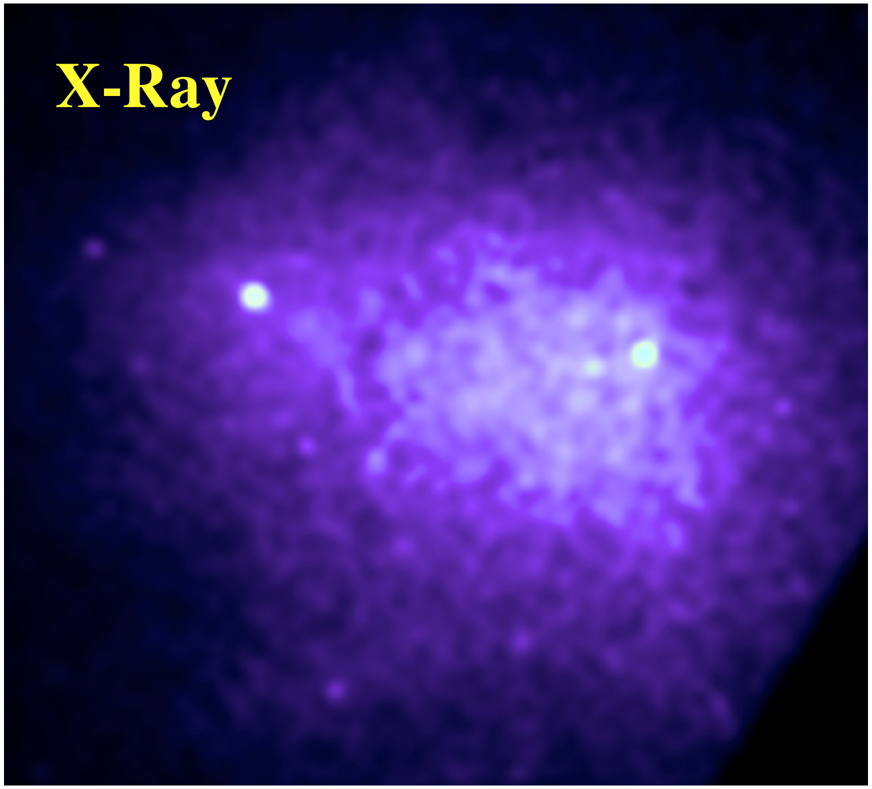
- Irregular, relatively poor cluster
- Distance ~ 16 Mpc, closest to us
- Diameter ~ 10° on the sky, 3 Mpc
- ~ 2000 galaxies, mostly dwarfs

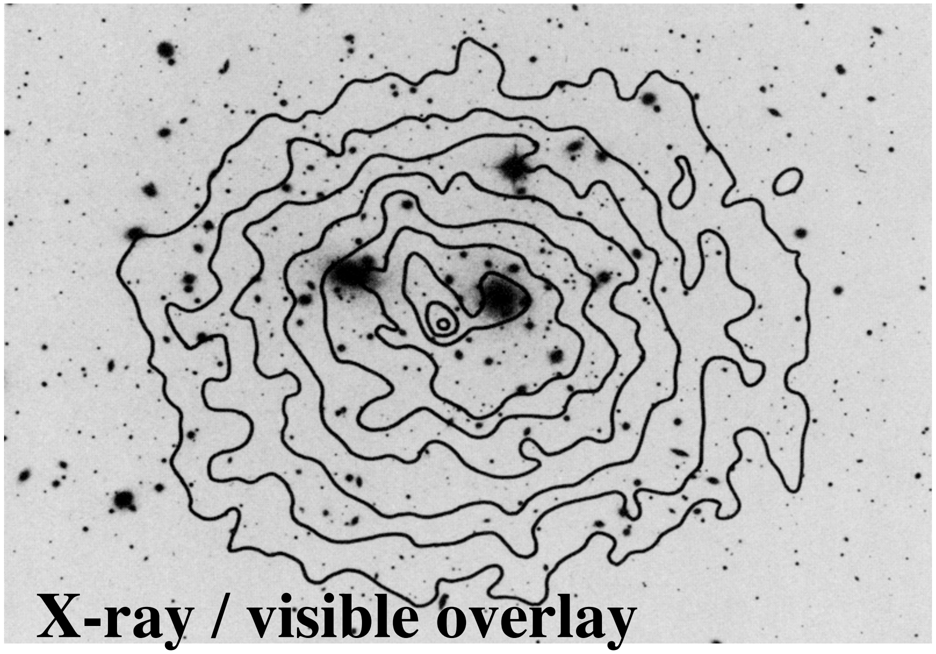


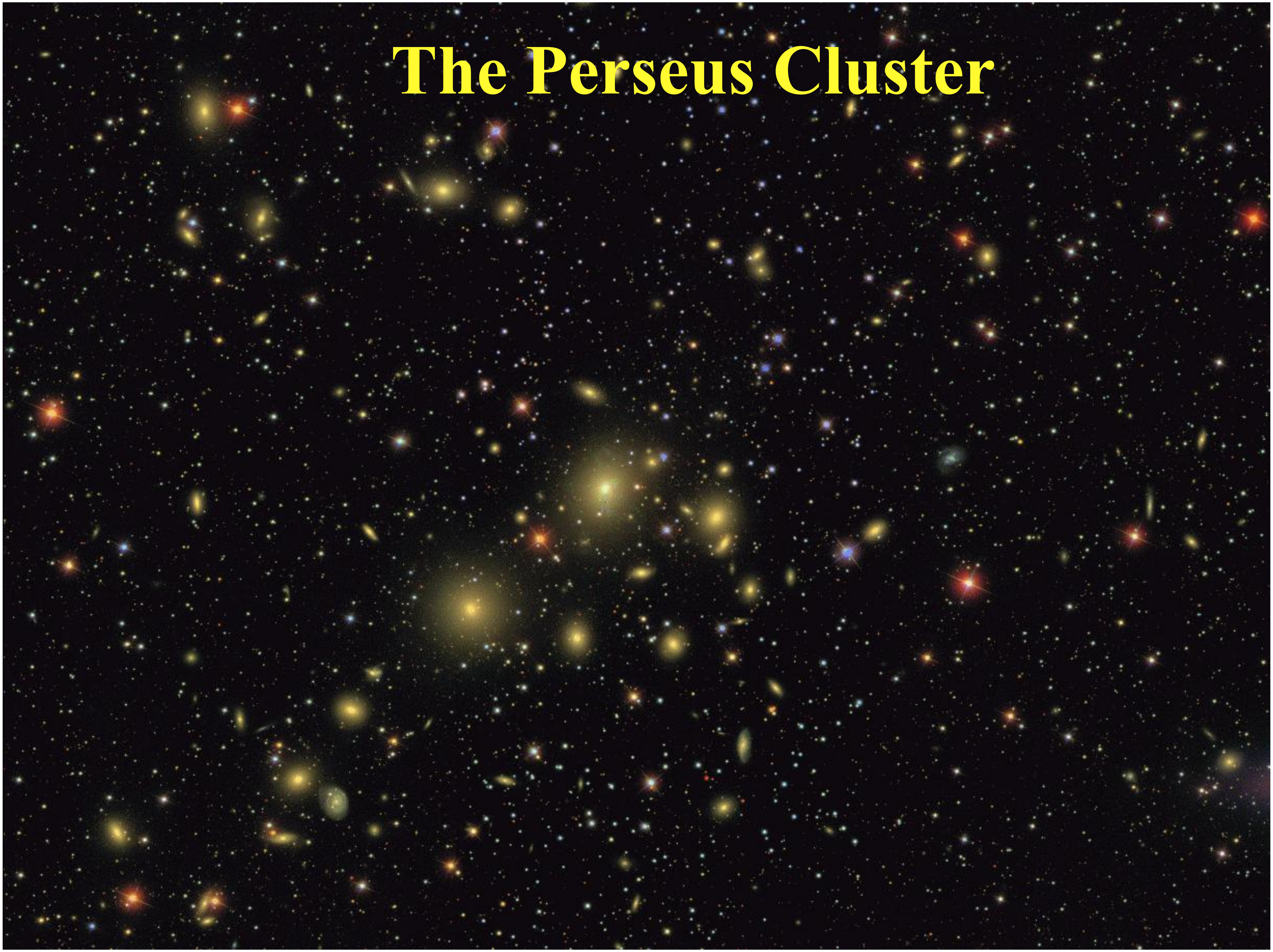


The Coma Cluster

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

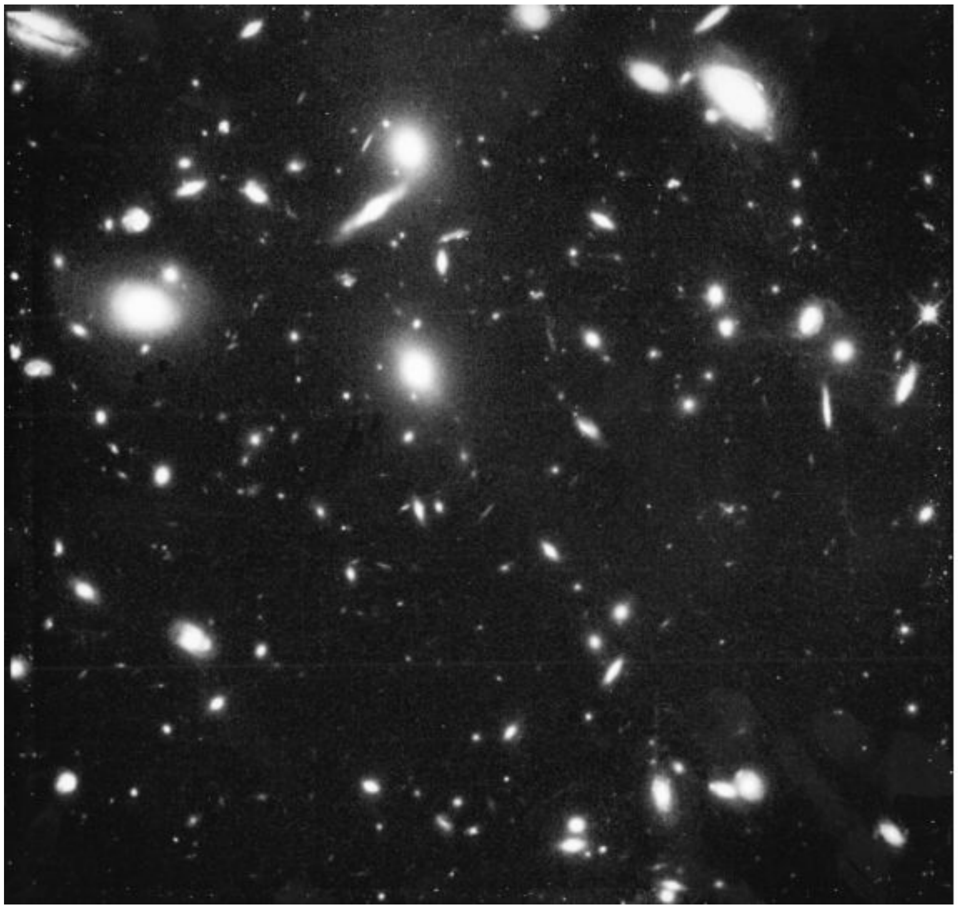




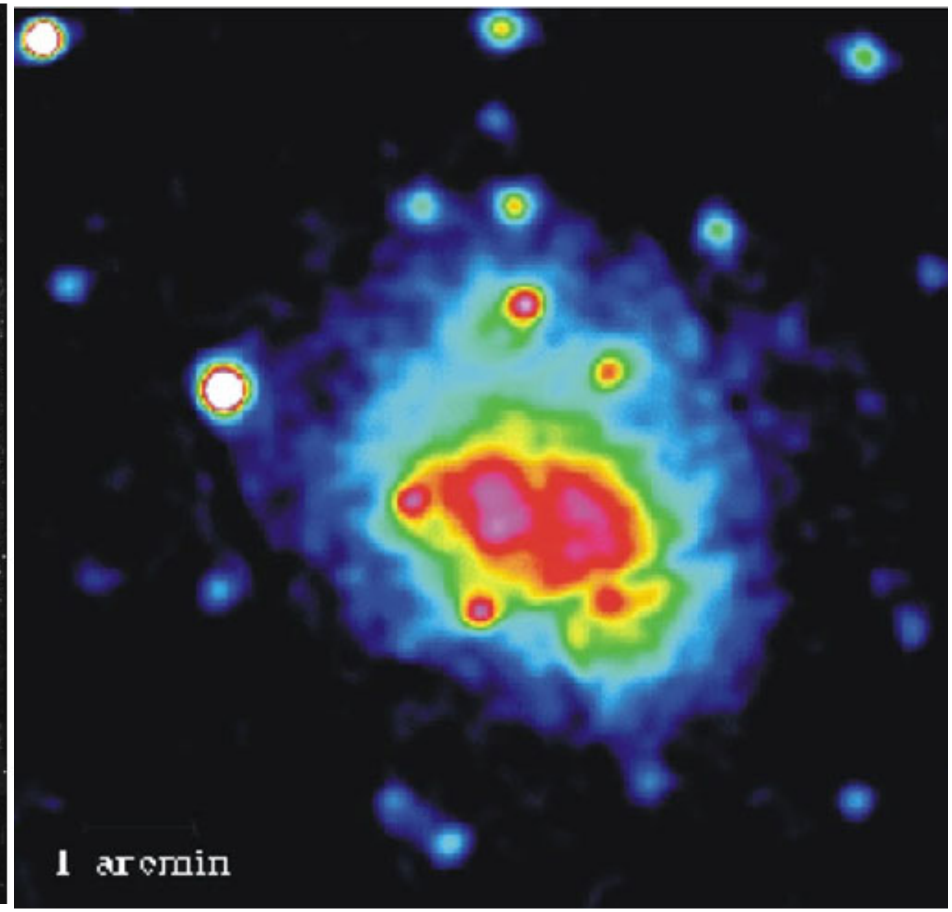

The Perseus Cluster

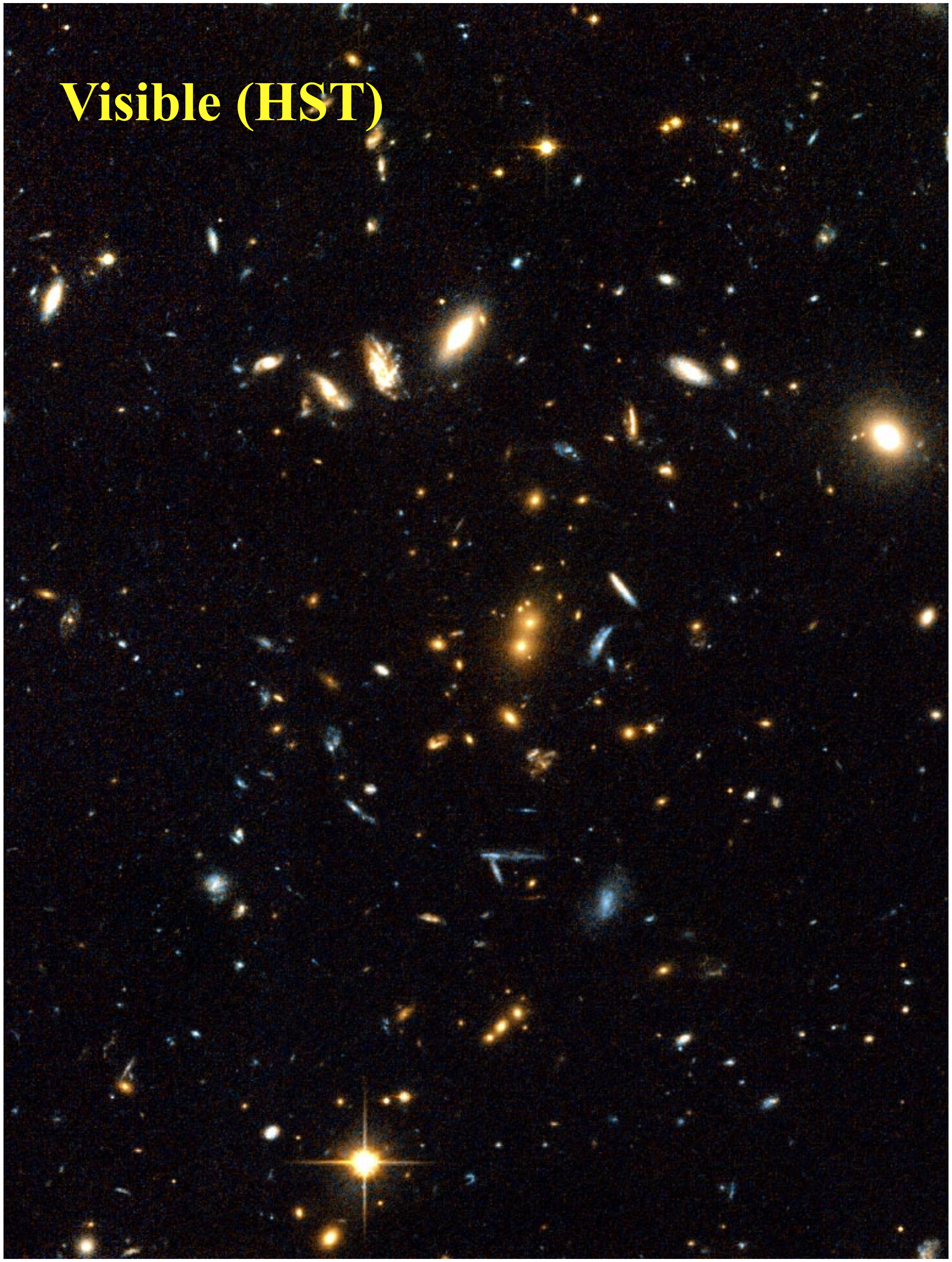
A Very Distant Cluster 0939+4713 (z = 0.41)

Visible (HST)

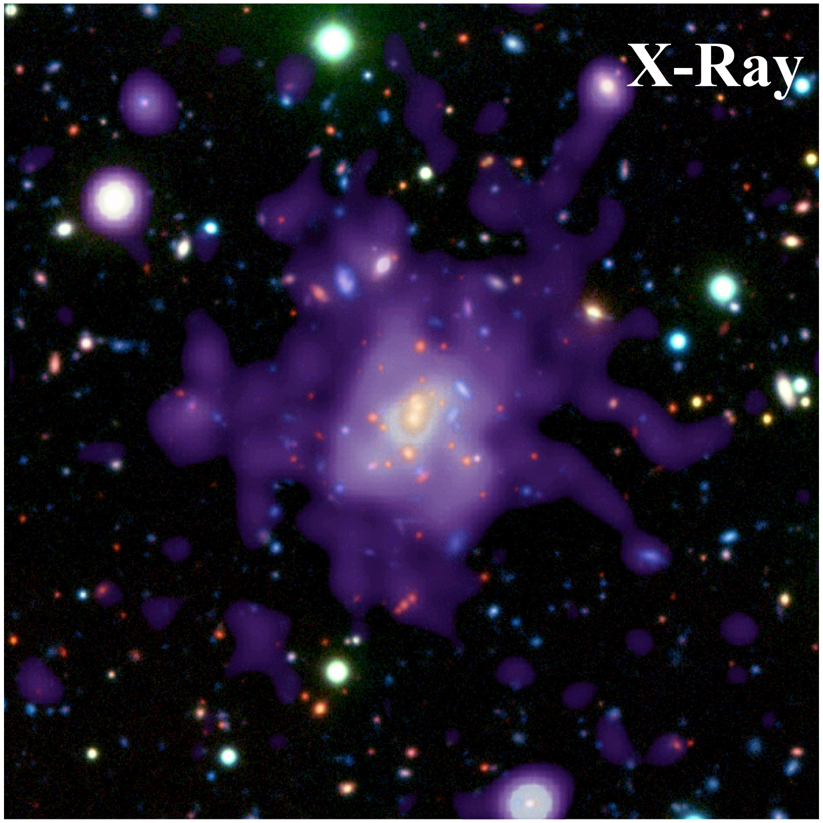


X-Ray (Rosat)





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, and we can search for them through each of these components

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. **Weak Gravitational Lensing**: look for systematic distortions in background galaxy images
   - Selection based on mass. Difficult observationally

Some important trends:

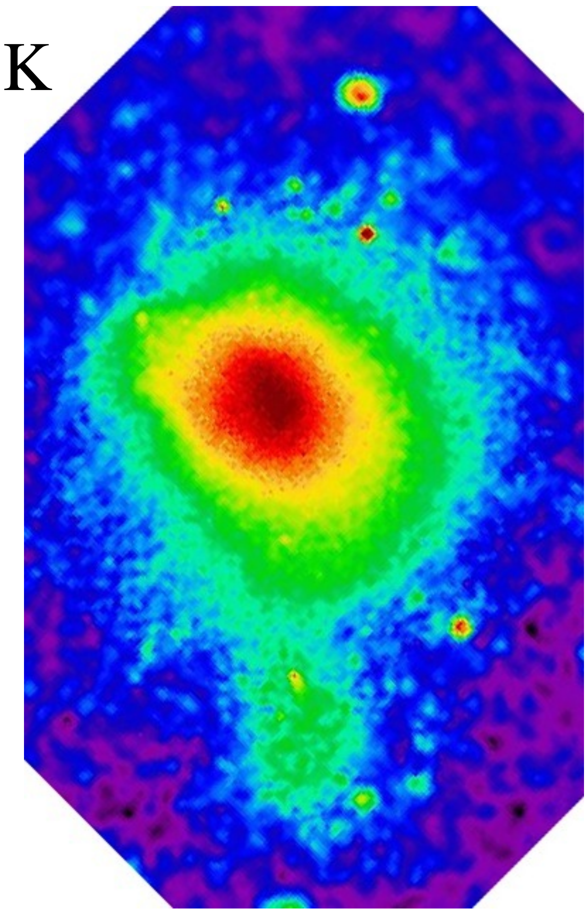
- Spatial distribution of galaxies:
  - Elliptical-rich and regular clusters: spatial distribution is smooth and symmetric, density increases rapidly towards cluster center
  - Spiral-rich and irregular clusters are not symmetric, little central concentration. Spatial density is ~ uniform
- Morphological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

What does it all mean?

- Regular, Elliptical-rich 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

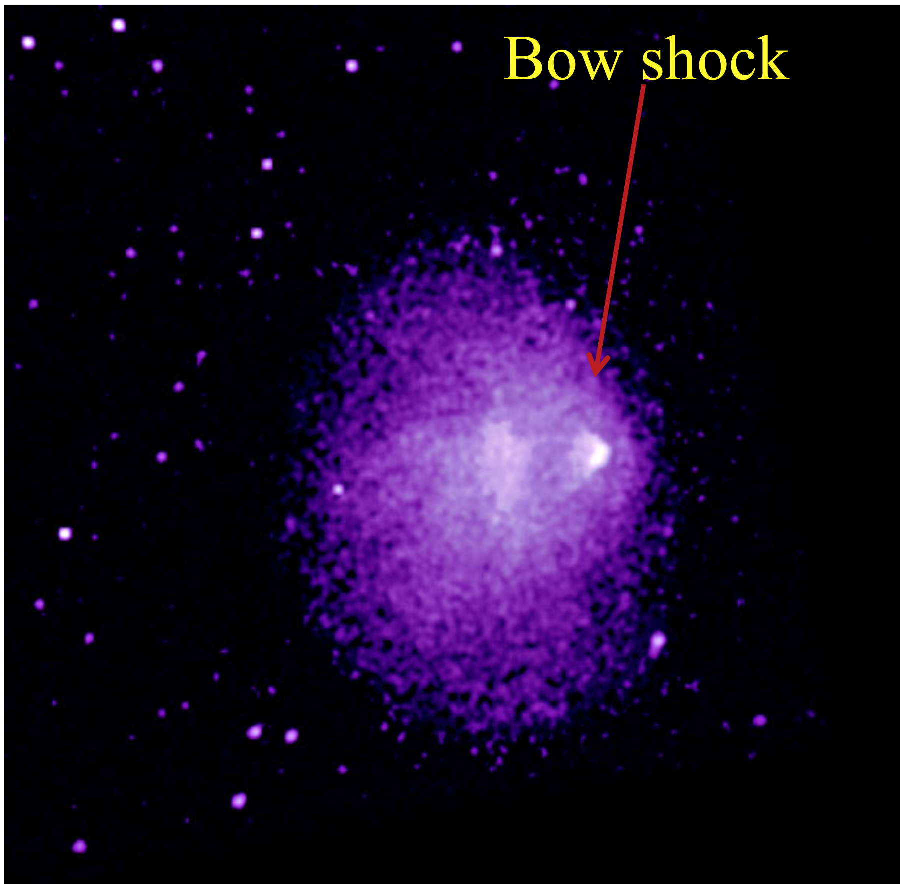
Hot X-ray Gas in Clusters

- Some of the gas is primordial, never condensed into galaxies, and heated via shocks as the gas falls into the cluster potential
- But some must have come from galaxies, expelled by galactic winds, since metallicity is ~ 1/3 Solar
- Virial equilibrium temperature T ~ $10^7 – 10^8$ K
- Excellent probe of the cluster gravitational potential, used to measure cluster masses
- Temperatures are not uniform: “hot spots” may be due to mergers as clumps of galaxies fell into the cluster, or to energy input by active galactic nuclei
- There are good correlations between the cluster mass, X-ray luminosity, and temperature

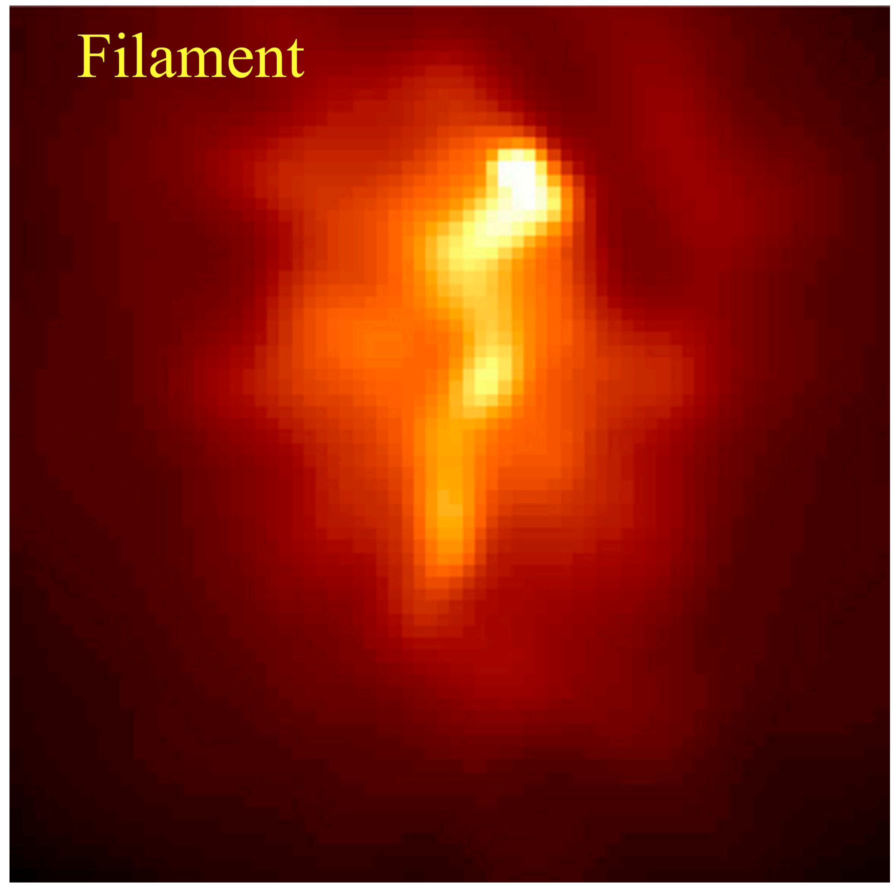


Substructure in the X-Ray Gas

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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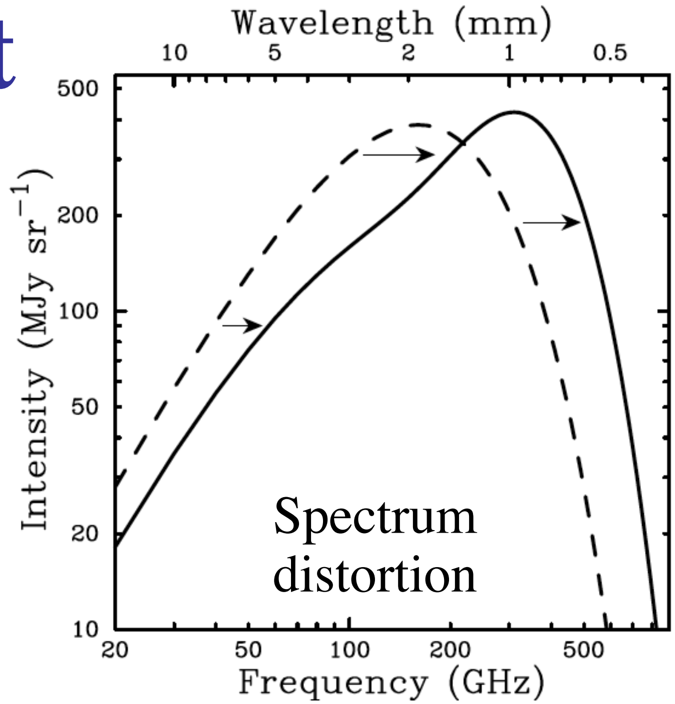
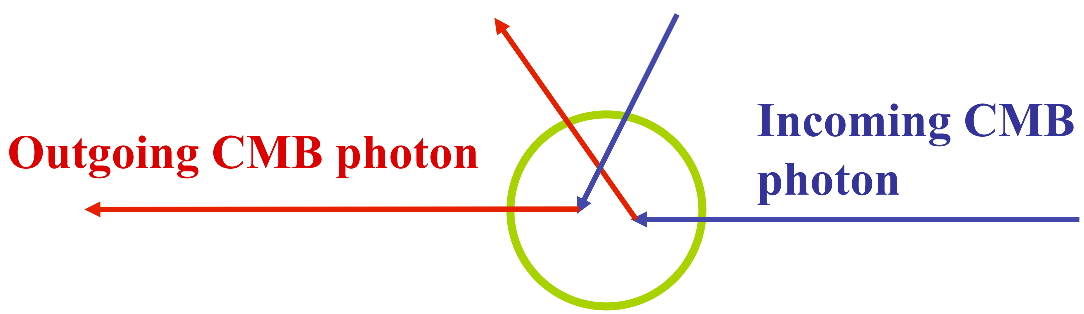
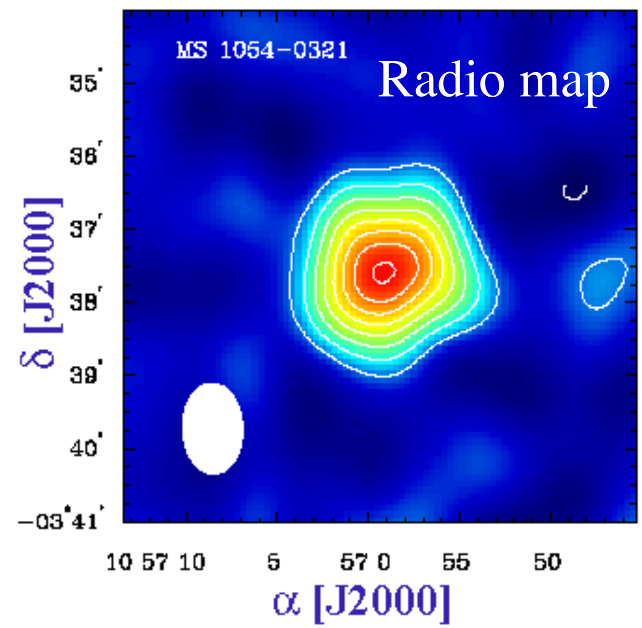
Synyaev-Zeldovich Effect

- Clusters of galaxies are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons 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







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

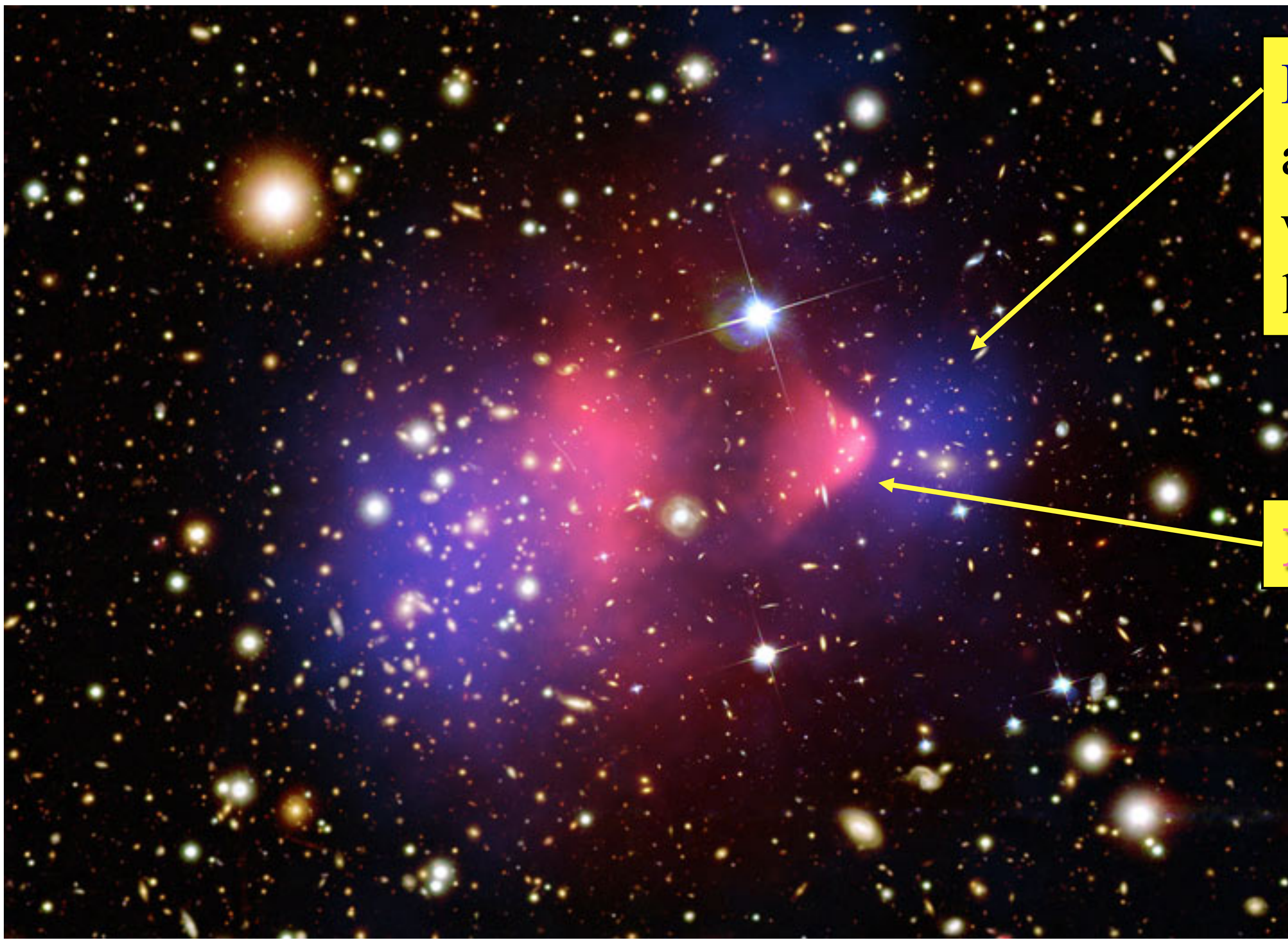
Thus, typical cluster masses are $\boldsymbol{M_{cl} \sim 10^{14} - 10^{15} M_\odot}$

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!***

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

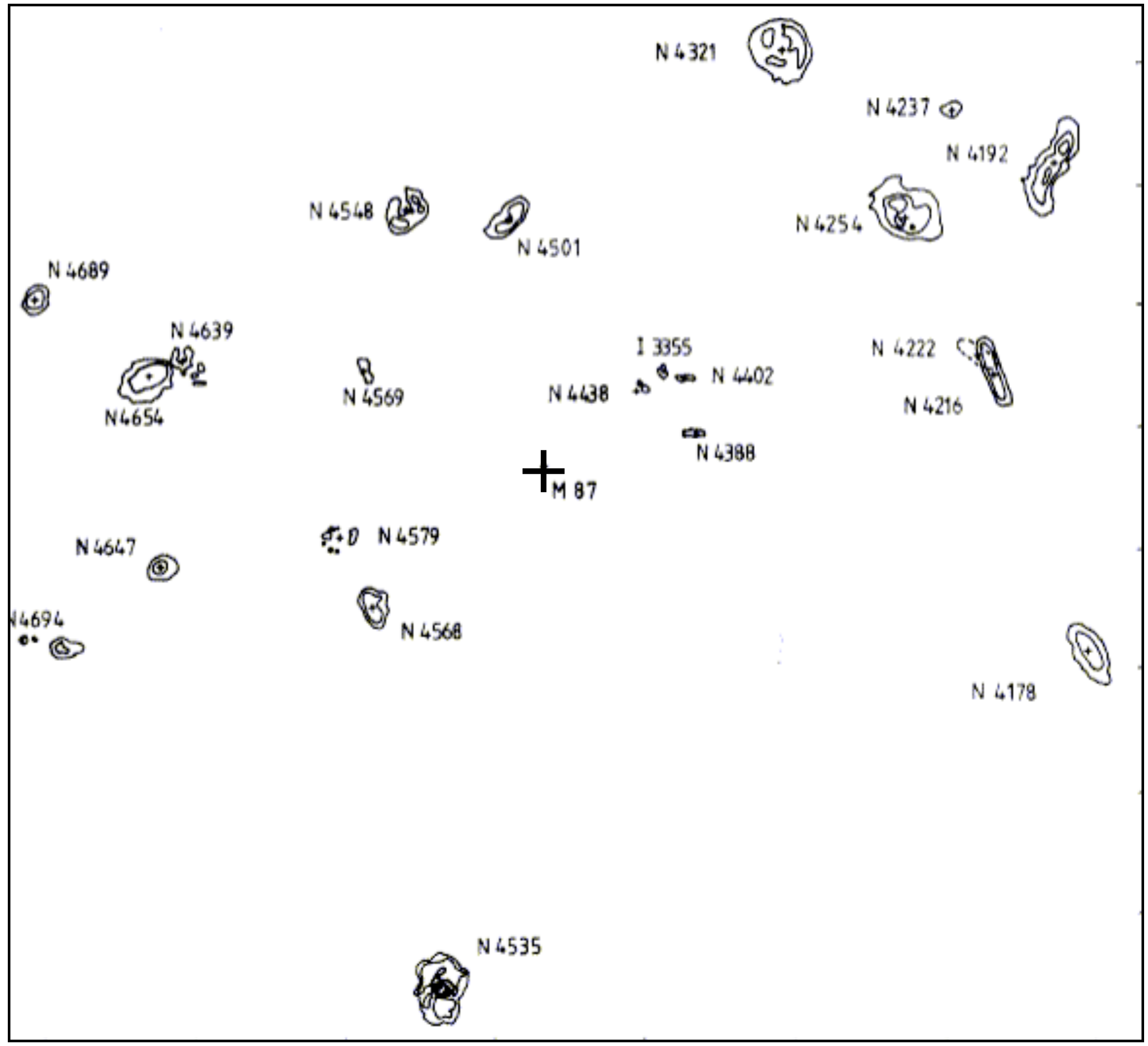
(Bradac et al.)

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

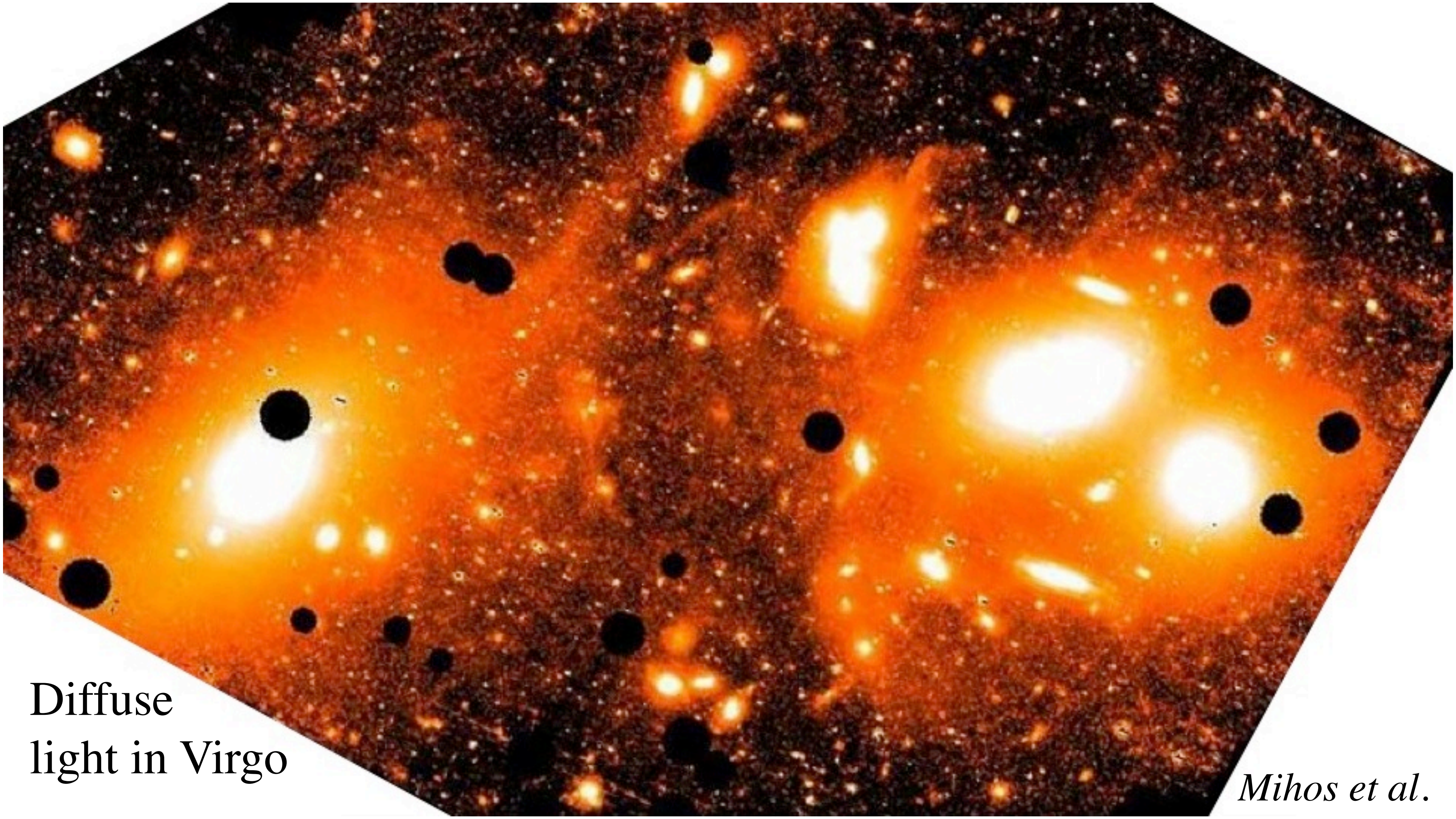
- Thus, evolution of disk galaxies can be greatly affected by their large-scale environment

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



Intracluster Light

- Probably caused by galaxy-galaxy or galaxy-cluster potential tidal interactions, which do not result in outright mergers



Diffuse light in Virgo

Mihos et al.

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