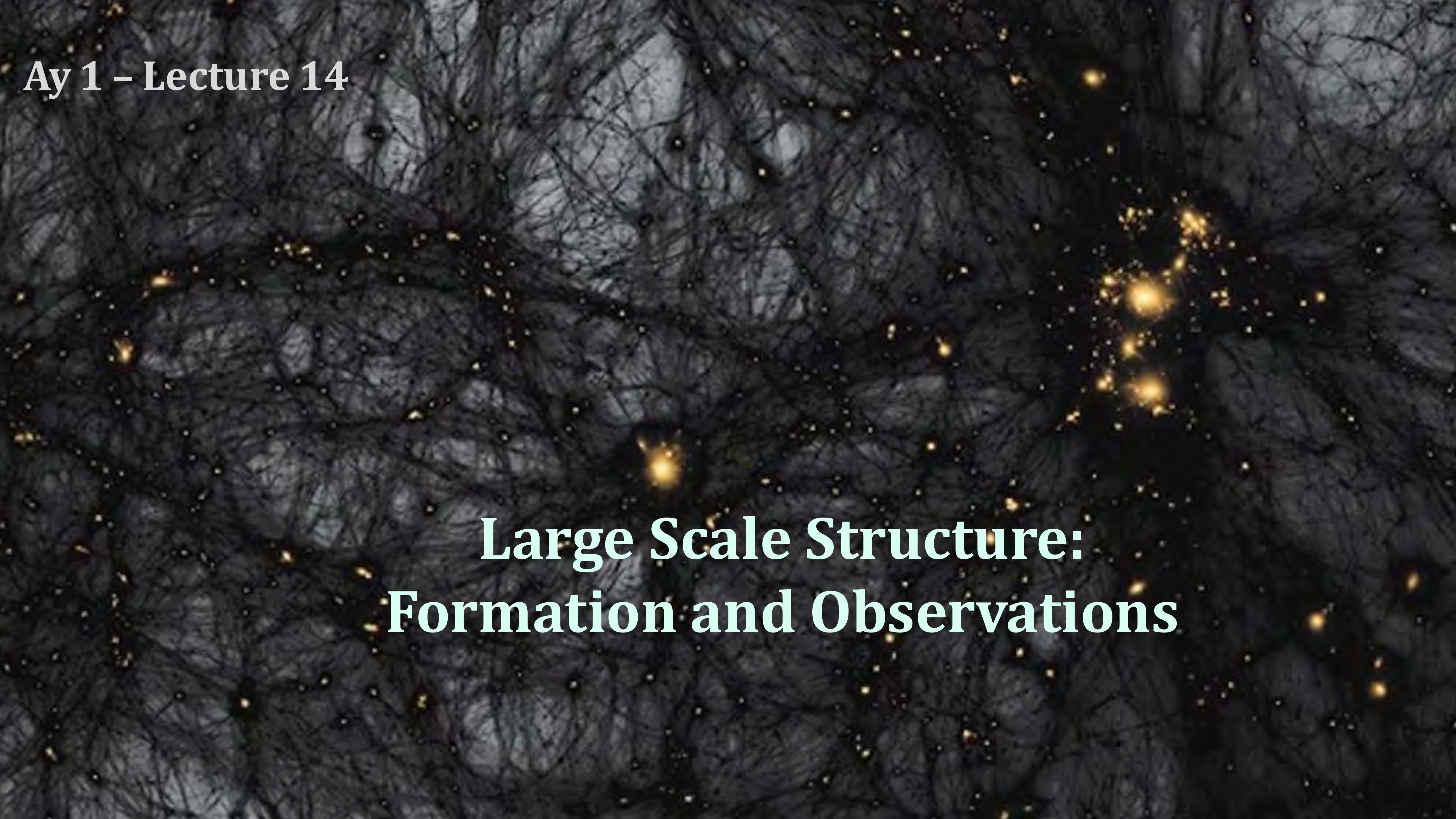


Ay 1 – Lecture 14

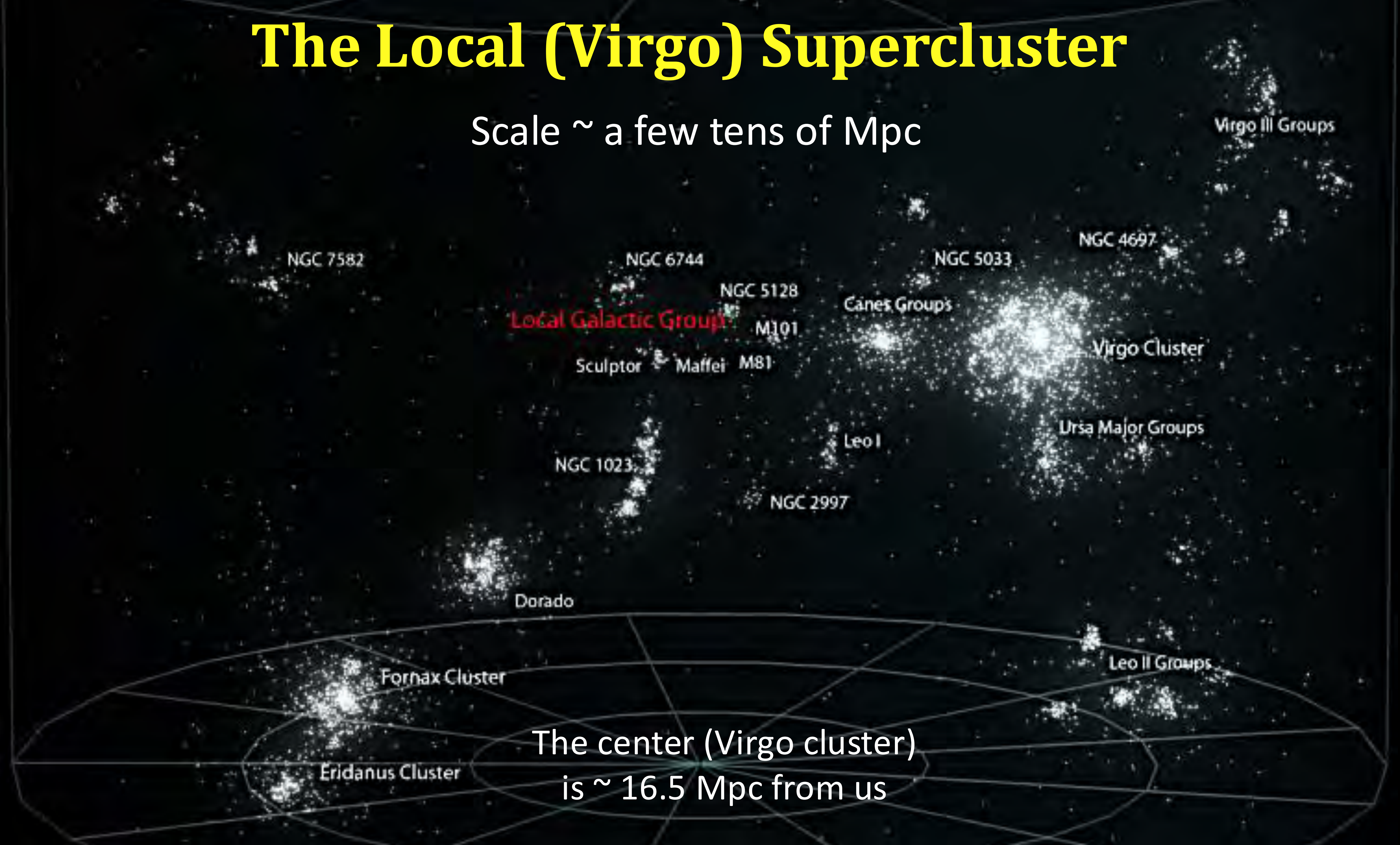
Large Scale Structure: Formation and Observations

Large-Scale Structure

- ***Density fluctuations*** in the early universe evolve into structures we observe: galaxies, clusters, filaments, etc., mainly through gravity, and driven by ***dark matter***
- On scales > galaxies ($\gtrsim$ Mpc), we talk about the **Large Scale Structure (LSS)**; groups, clusters, filaments, walls, voids, superclusters are the elements of it
- ***Theoretical modeling*** of LSS and its evolution requires large ***numerical simulations***
- To ***map and quantify the LSS*** (i.e., the large-scale density field) and compare it 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 or estimated for ~ 140 million galaxies
  - Galaxies are used as a tracer of the LSS, but the distribution of light need not be the same as the distribution of mass; they can be biased tracers
- 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

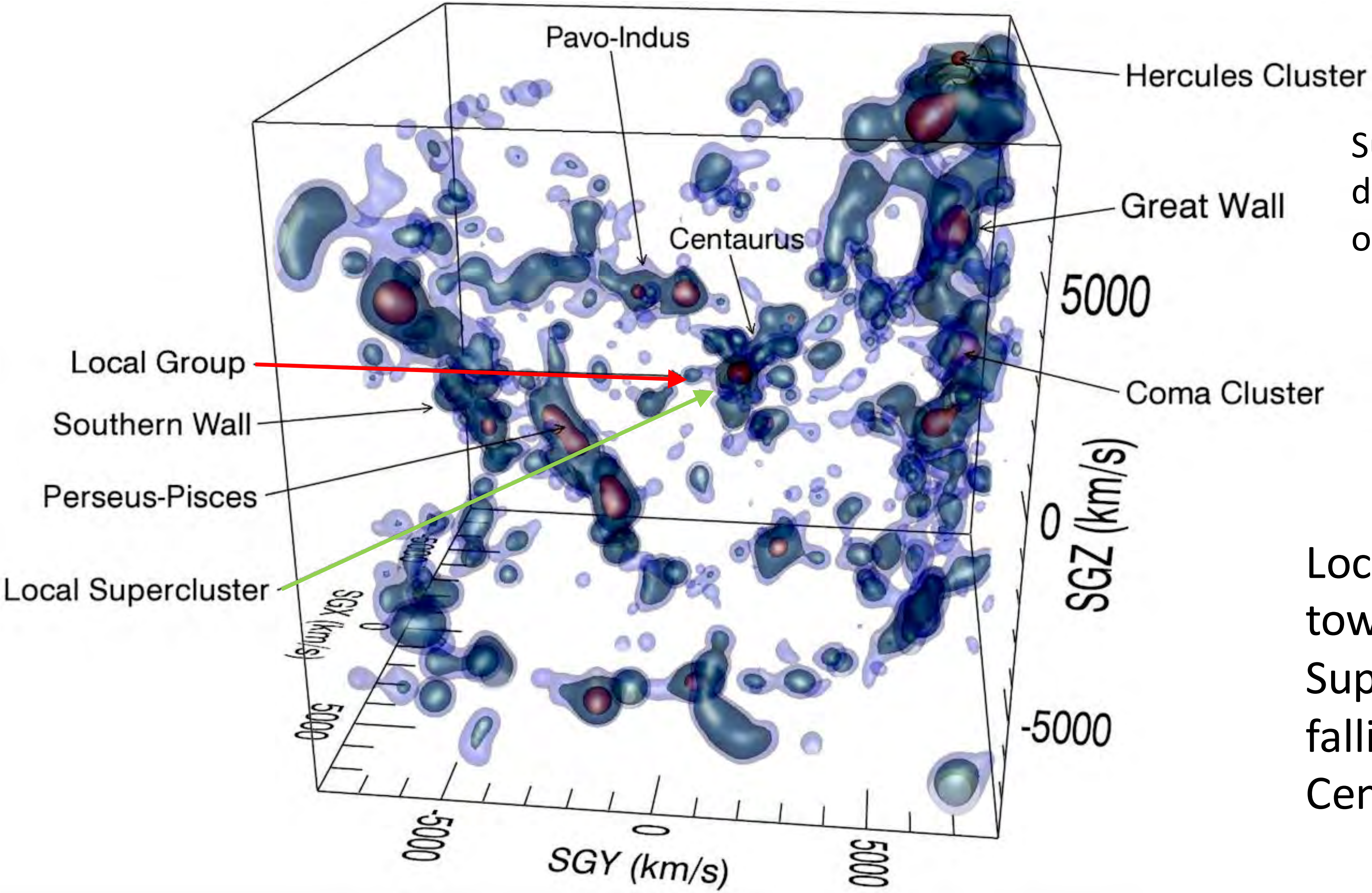
The Local (Virgo) Supercluster

Scale ~ a few tens of Mpc



The center (Virgo cluster)
is ~ 16.5 Mpc from us

3D View in the Supergalactic Coordinates



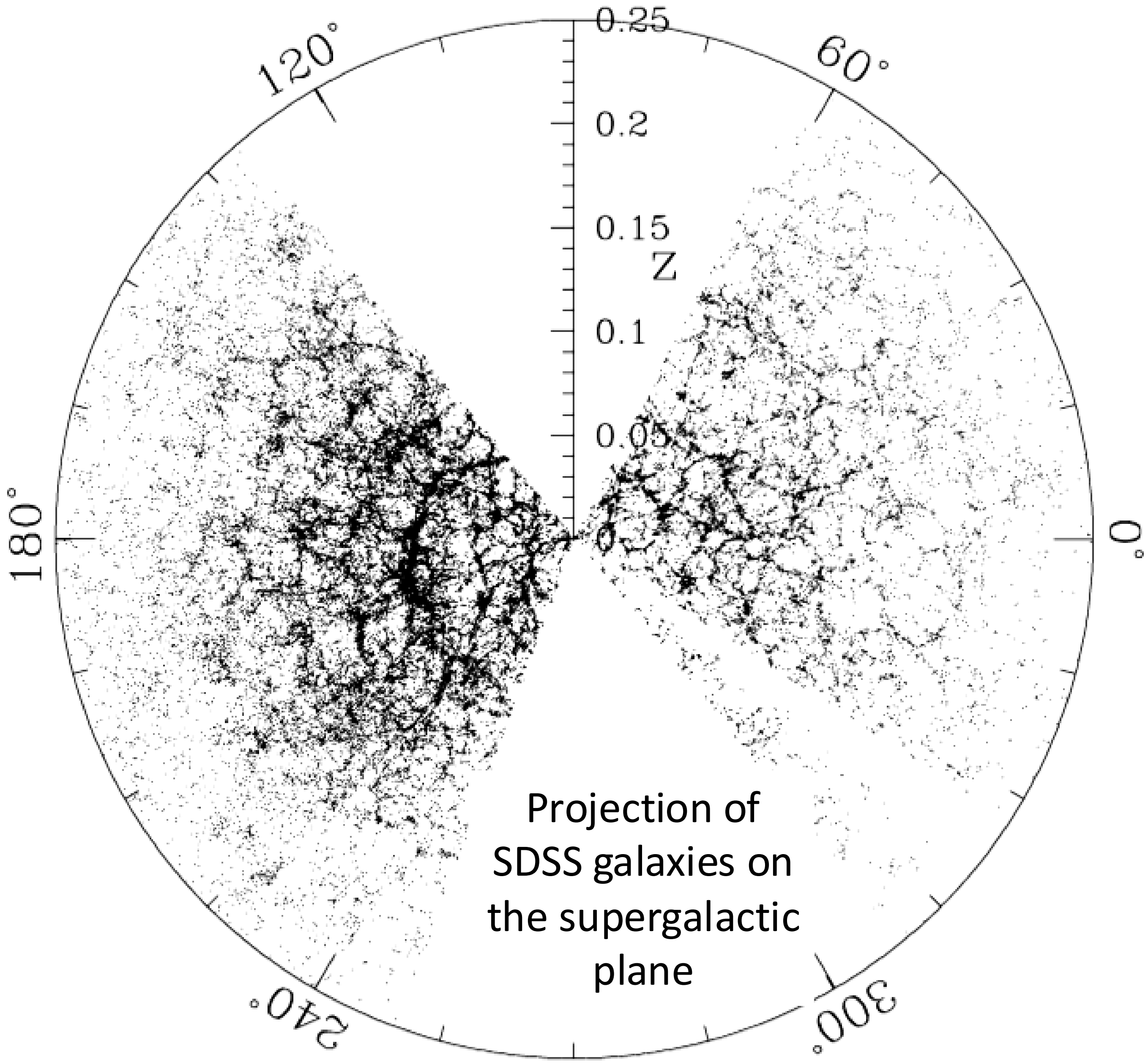
Supergalactic coordinates: defined by the principal plane of the Local Supercluster

Local Group is falling towards the Local Supercluster, which is falling towards the Centaurus Supercluster

The Sloan Digital Sky Survey (SDSS)

Actually a series of sky surveys done with a 2.5-m telescope at Apache Point Observatory in NM, started in 2000 and still going on

- Covered ~ 8000 square degrees, mostly in the Northern sky
- Multicolor imaging to *r* ~ 23 mag for ~ 1 billion objects
- Catalogs of ~ 350 million galaxies, with redshifts for ~ 3 million
- Catalogs and spectra for ~ 1 million quasars out to z ~ 6.5
- Spectra of ~0.8 million stars



Projection of SDSS galaxies on the supergalactic plane

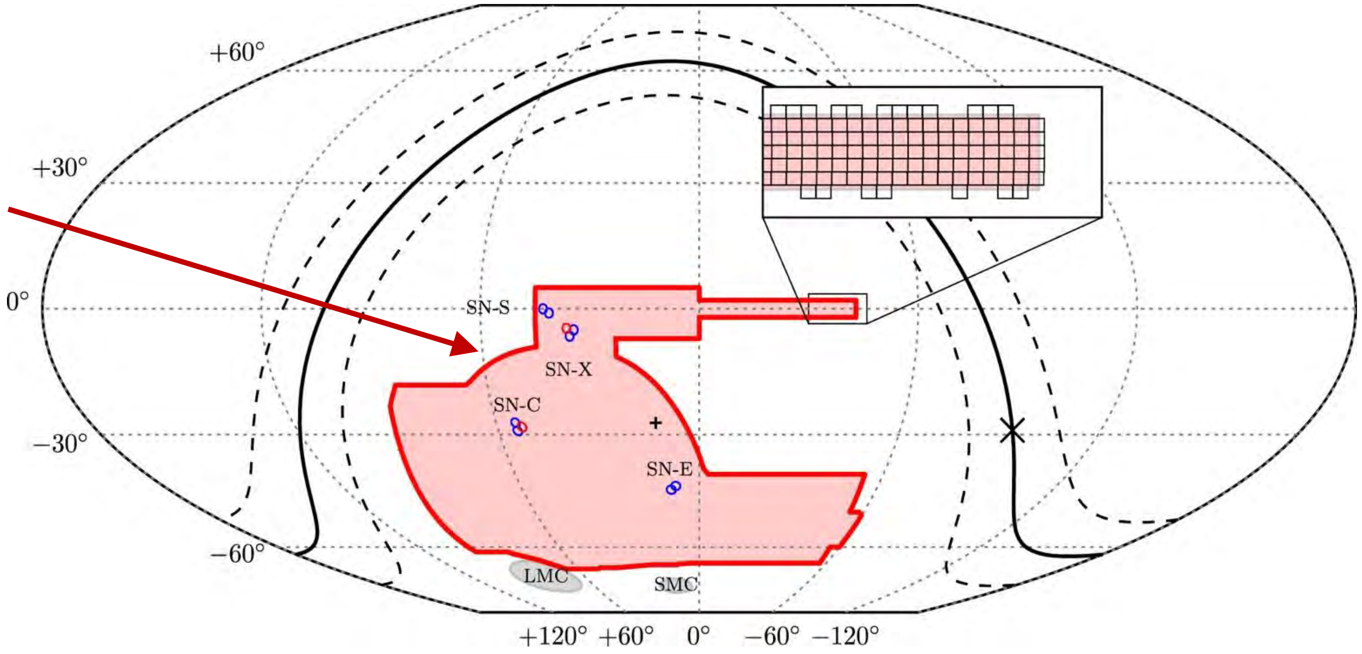
The Dark Energy Survey (DES)

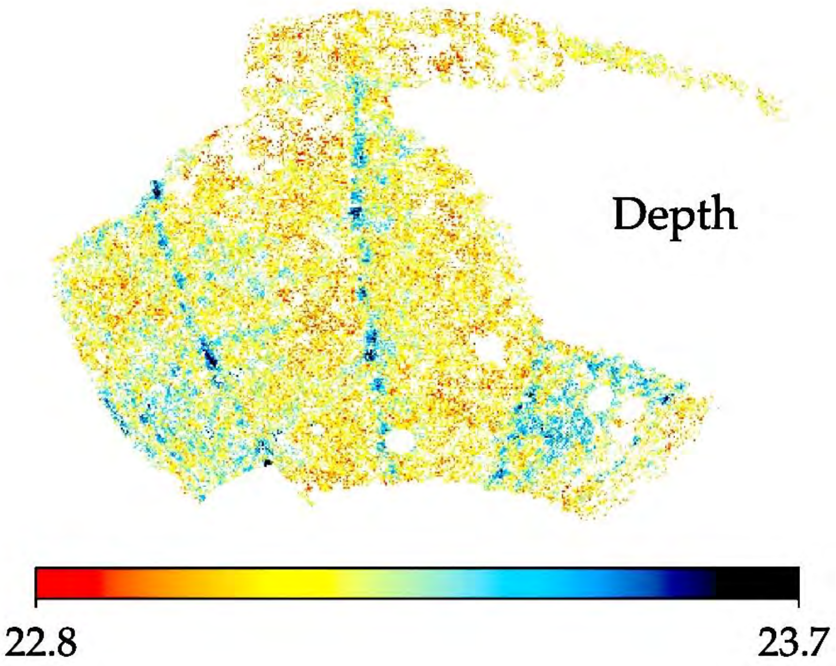
The largest galaxy survey to date

Covers ~ 5000 *deg*^{2} in the Southern sky

Catalogs of > 300 million galaxies

Spectra of > 50 million galaxies, some reaching to $z > 1$, plus many quasars

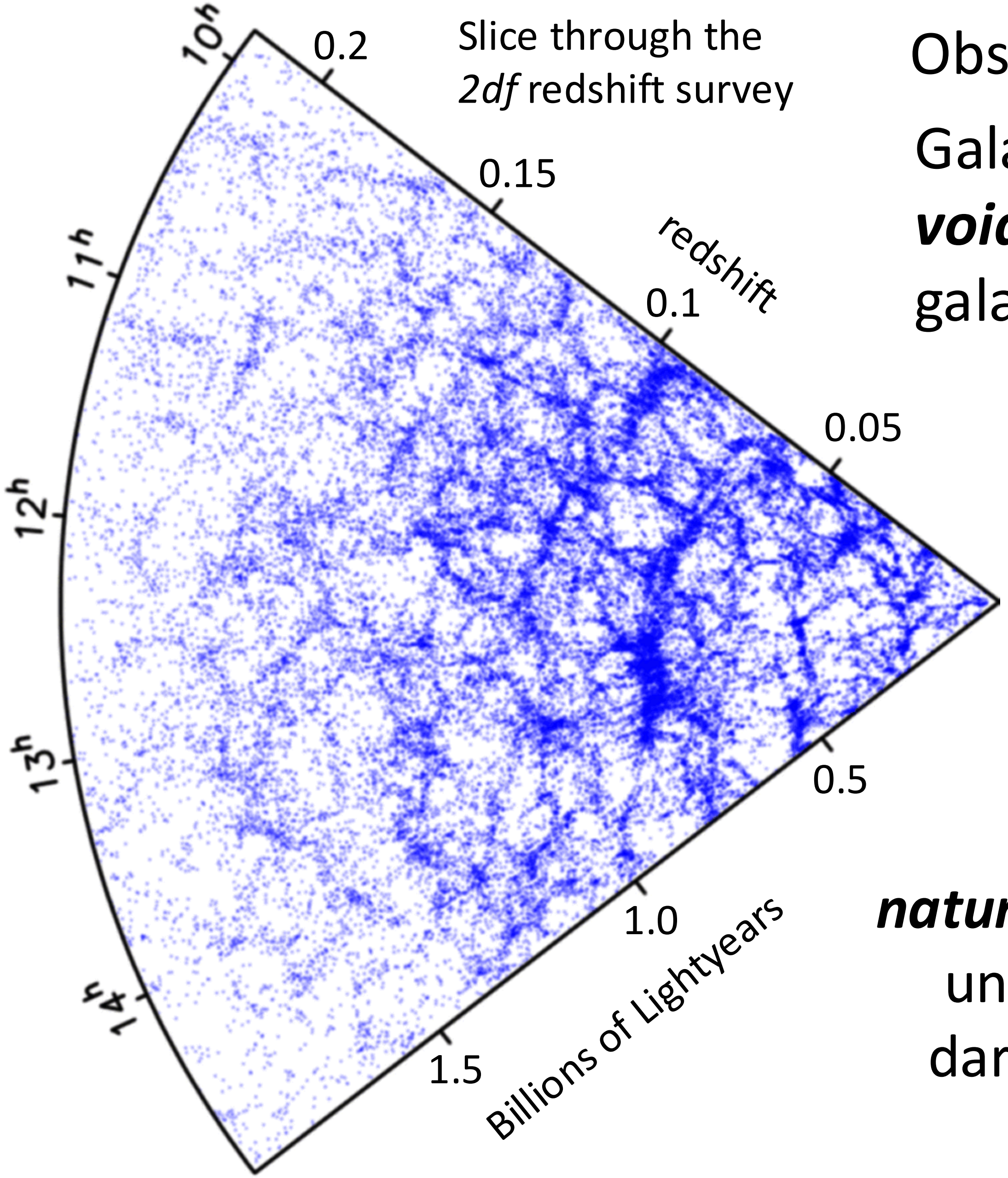




Combines measurements of the LSS and its evolution over the cosmic time, plus the cosmological parameters, with a focus on dark energy

Uses weak gravitational lensing to measure the distribution of mass as a function of time

The Cosmic Web

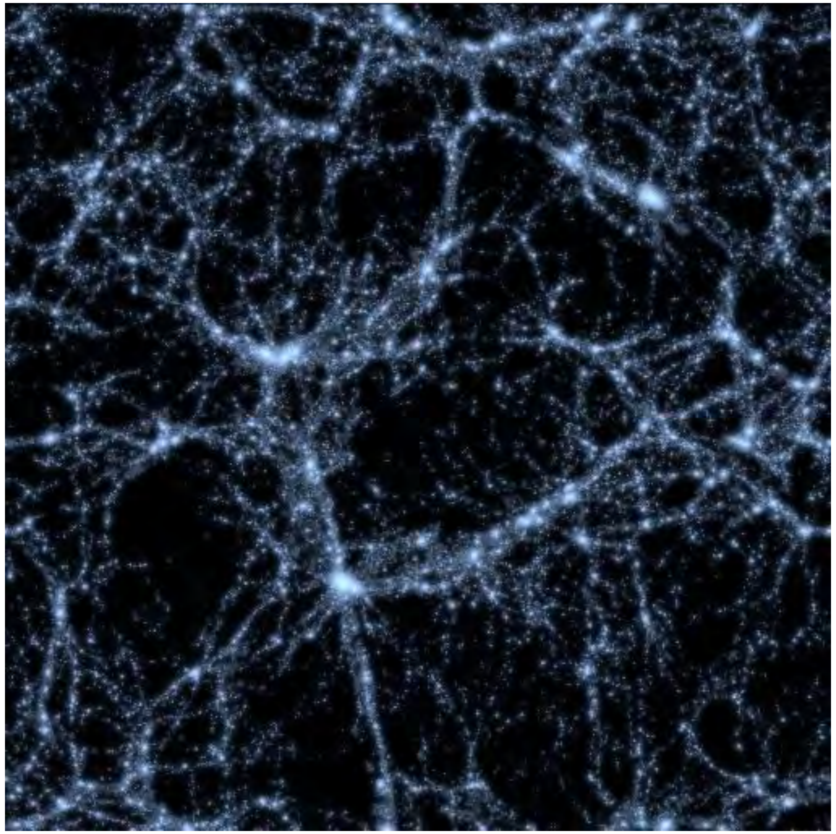


Observations have revealed the ***topology*** of the LSS:

Galaxies lie on the ***sheets or filaments***, separated by ***voids*** (typical size a few tens of Mpc). Clusters of galaxies are found on the intersections of filaments

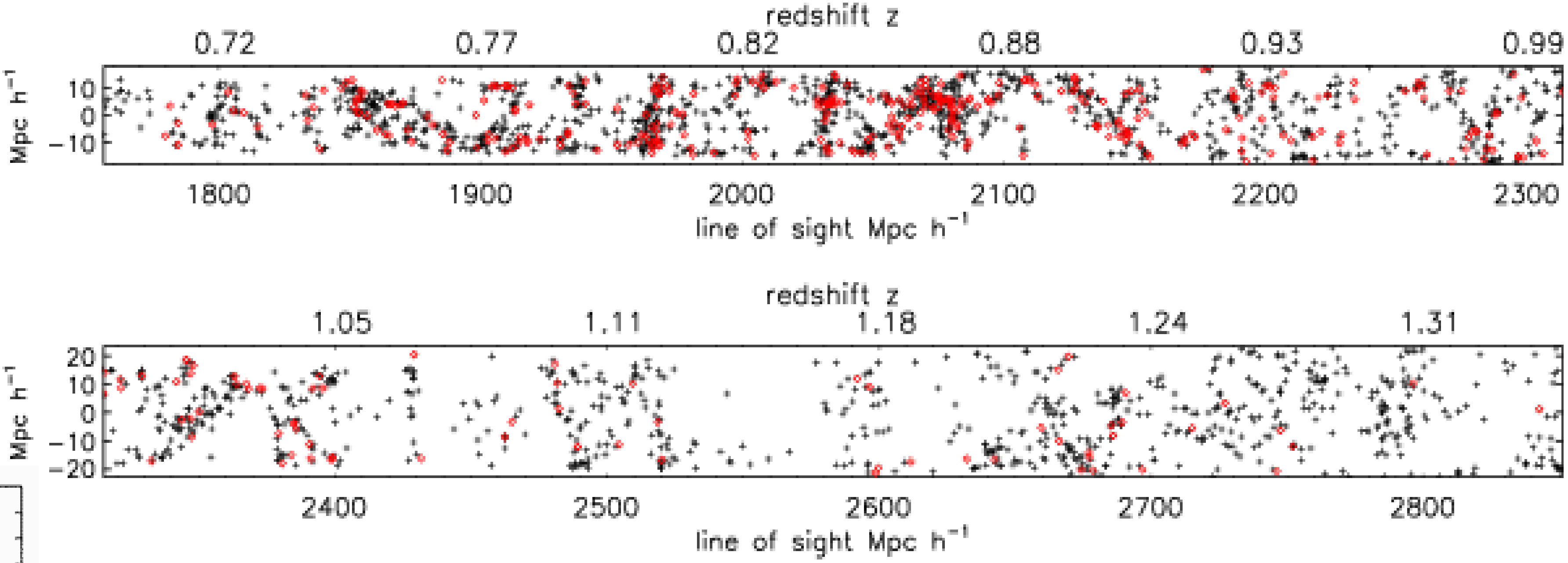
This is ***reproduced by the numerical simulations*** of the LSS formation and evolution

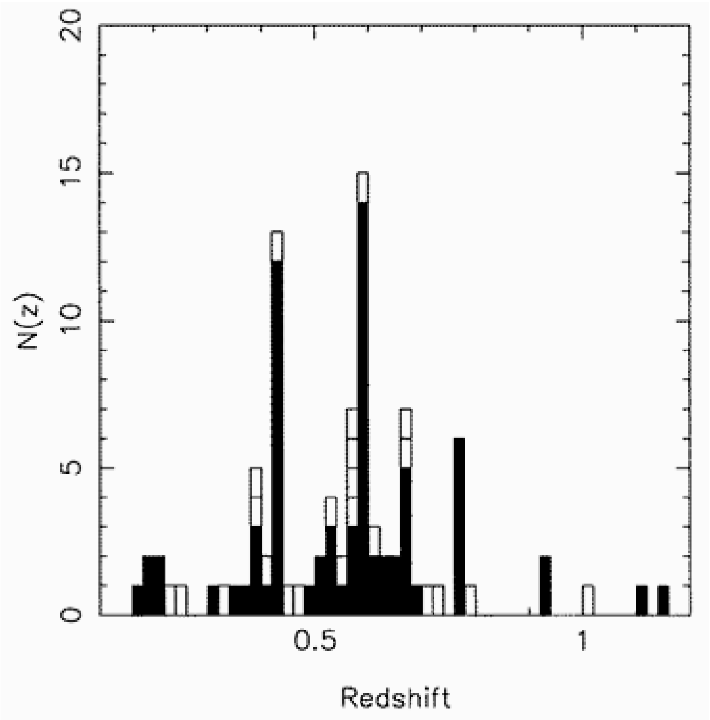
This ***pattern arises naturally*** in an expanding universe dominated by dark matter, interacting gravitationally



Structures in Deep Redshift Surveys

Deep redshift surveys (over a small area, but going deep) find *similar structures* intersected by the survey beam





⟵ This is also shown by the spikes in the redshift histogram as the line of sight intersects walls or filaments

Since galaxy clustering should be growing in time, this was surprising: such structure should not have had enough time to form. It is now understood as a consequence of ***biasing***

Quantifying Galaxy Clustering

Galaxies like company – the best place to look for a galaxy is next to another galaxy

This is quantified through the two-point correlation function, $\xi(r)$, an "excess" probability over a purely random distribution that a galaxy will be found at some distance r from another galaxy:

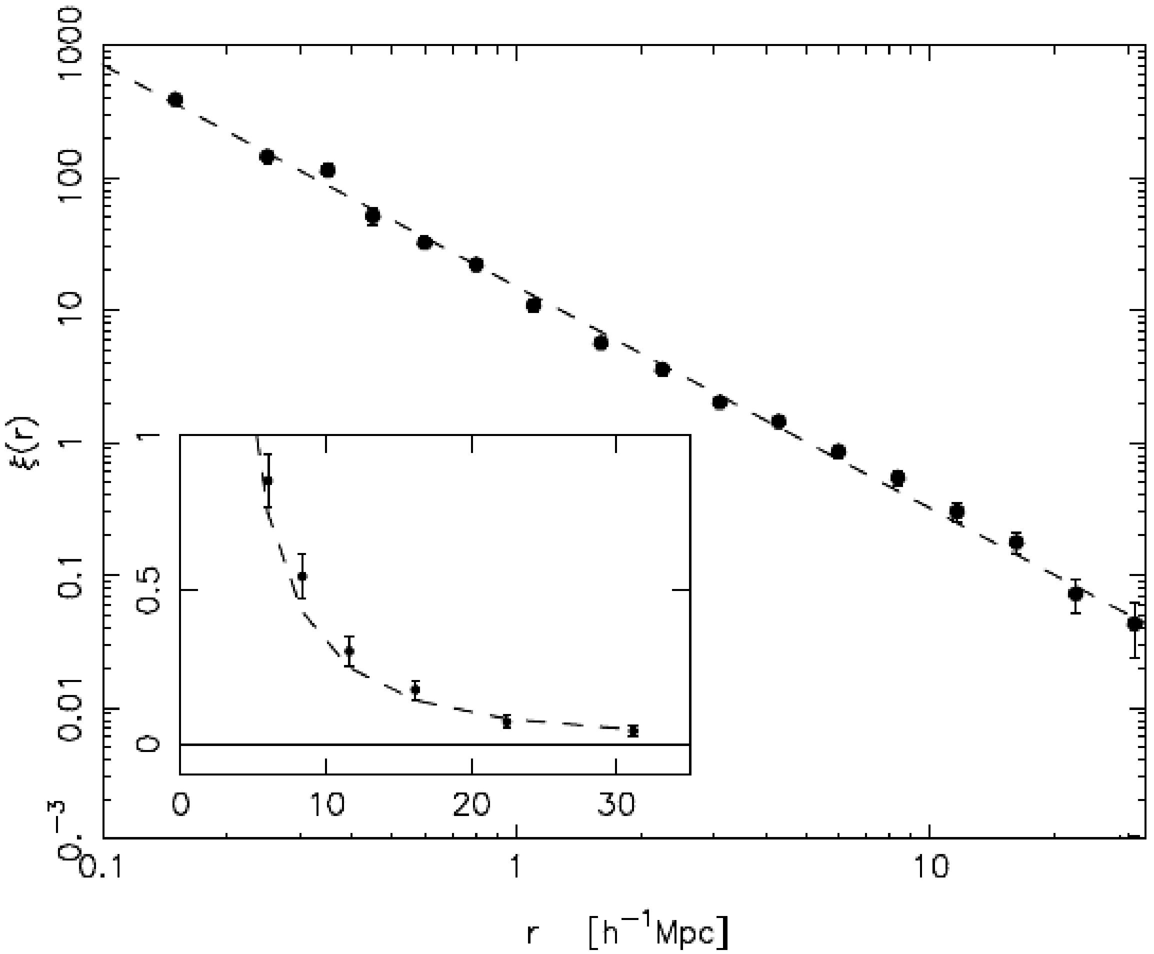
$$\xi(r) = P(r) / P_{random} - 1$$

For an unclustered distribution, $P(r) = P_{random}$ so $\xi(r) = 0$. The more clustered galaxies are, the higher value of $\xi(r)$

$\xi(r)$ is well fit by a power law,

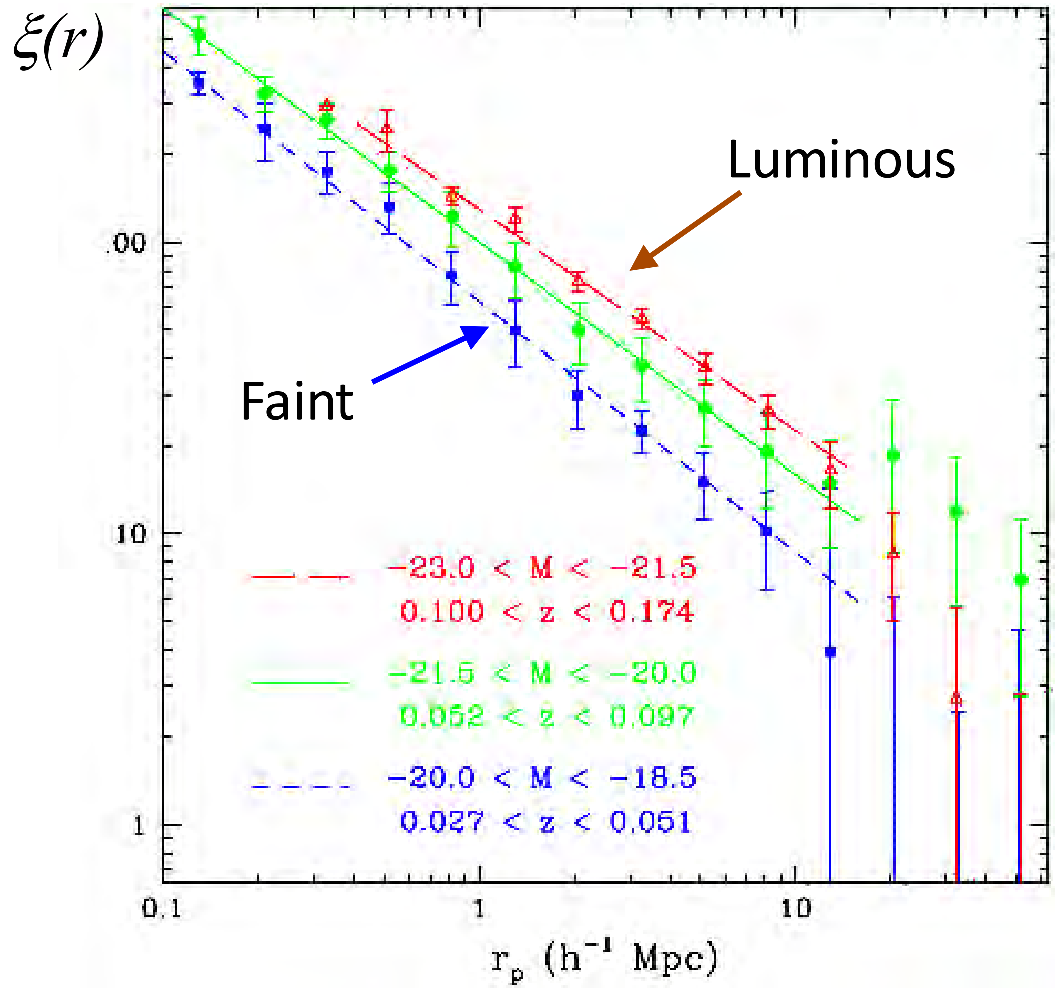
$$\xi(r) = (r/r_0)^{-\gamma}$$

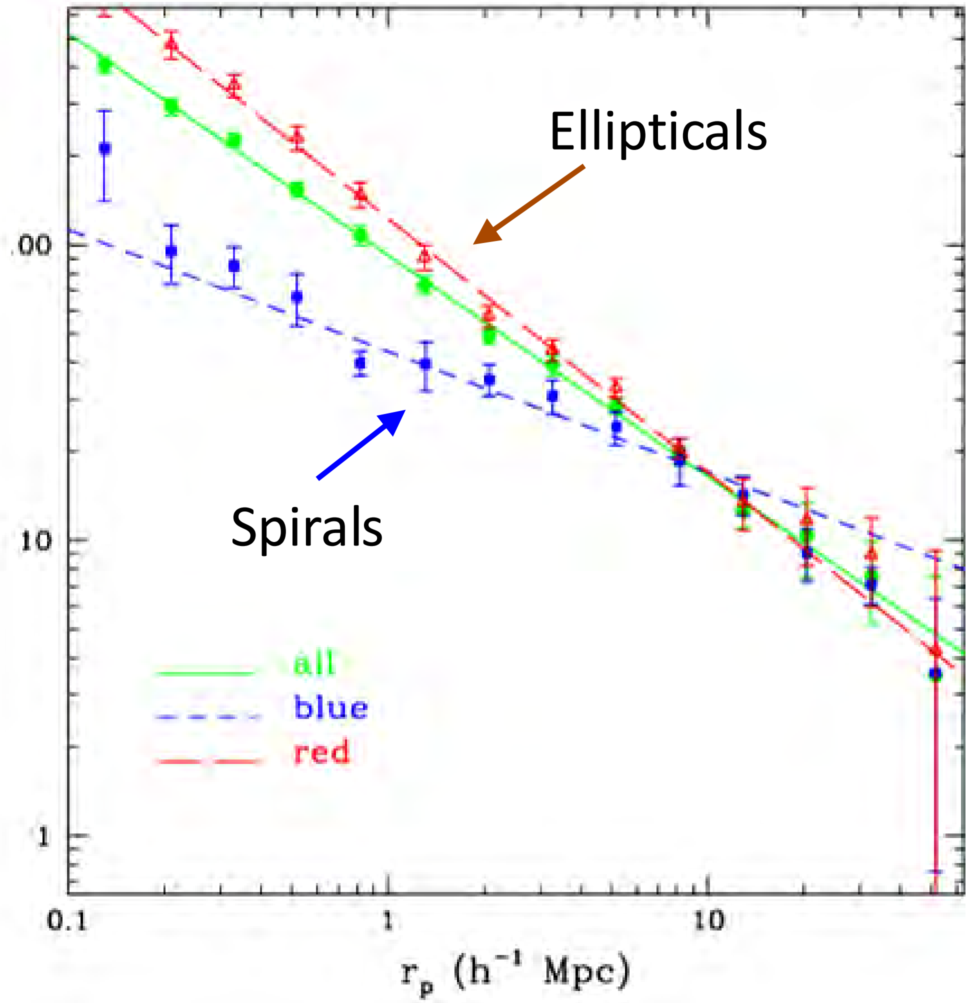
where r_0 is the clustering length, typically ~ 5 Mpc today, and power law index $\gamma \approx 1.8$



Clustering of Different Types of Objects

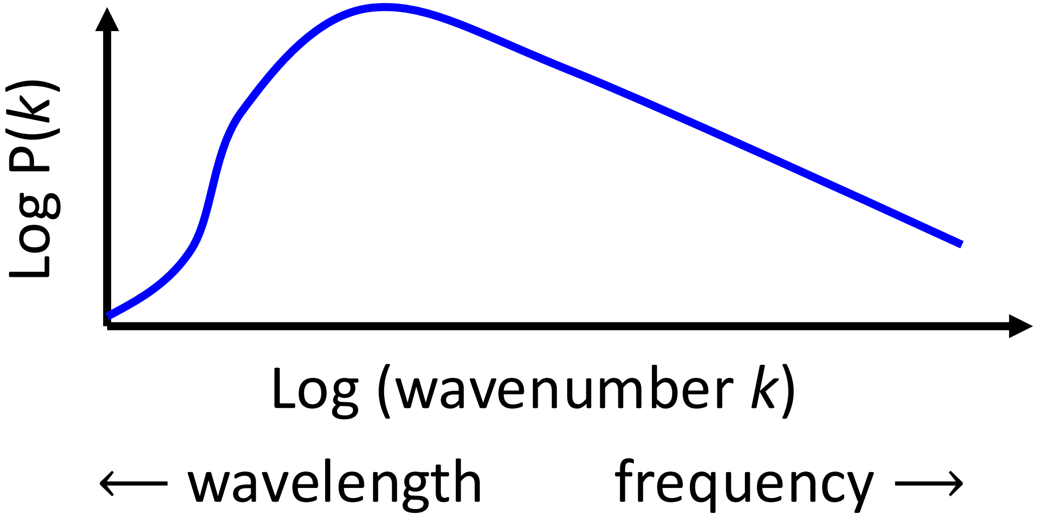
More luminous, more massive, older, and redder galaxies (typically ellipticals) are clustered more strongly, i.e., ***galaxy properties and formation histories depend on their large scale environments***. The more massive ones formed earlier, and stopped making stars earlier





Power Spectrum of Galaxy Clustering

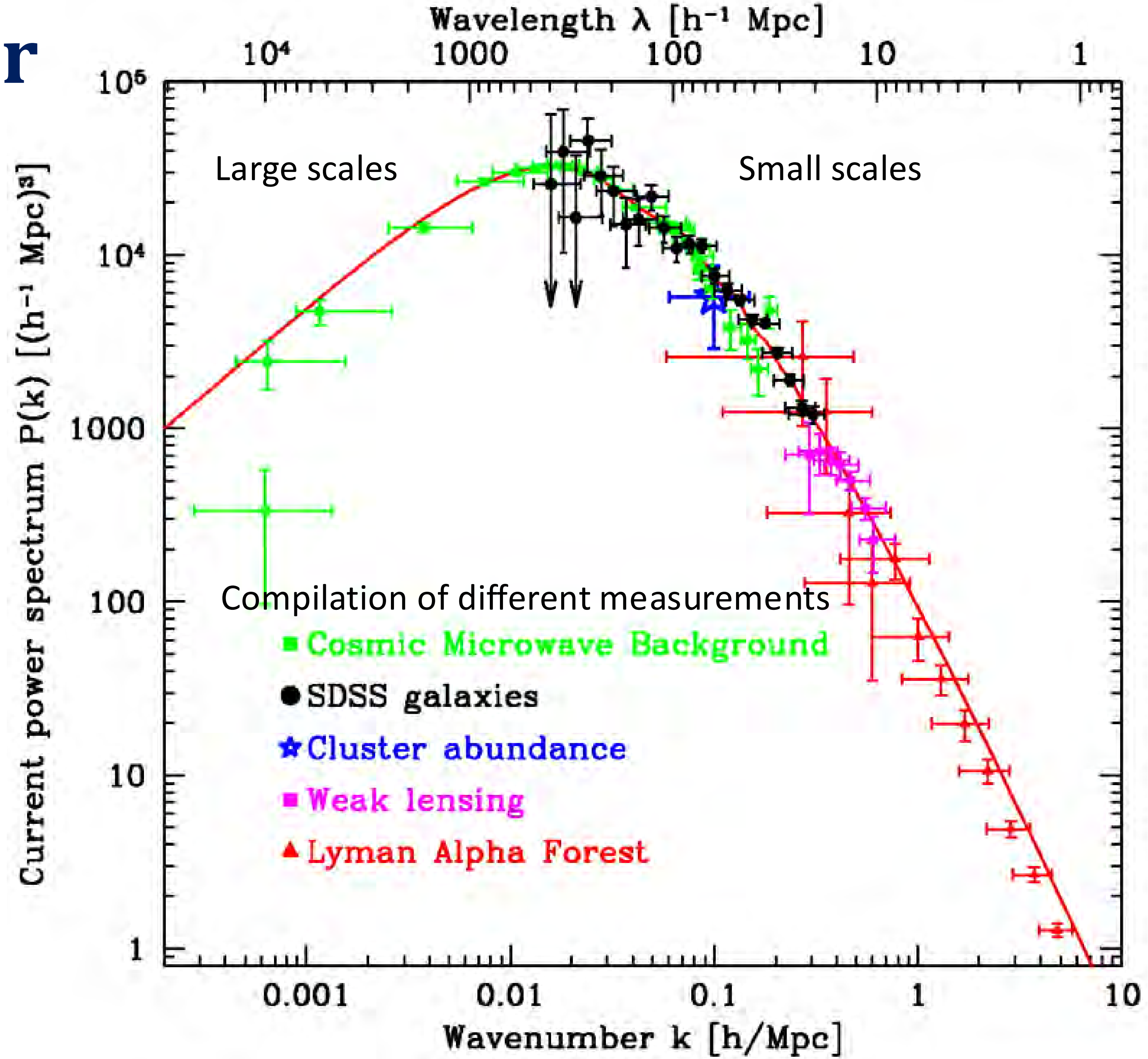
- A more modern alternative to the 2-point correlation function is the ***Fourier Power Spectrum of the galaxy density field***
- The overall density is expressed as a sum of density waves with varying spatial frequencies and amplitudes
- The power spectrum tells us ***how much mass is clumped on what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



More power at large scales

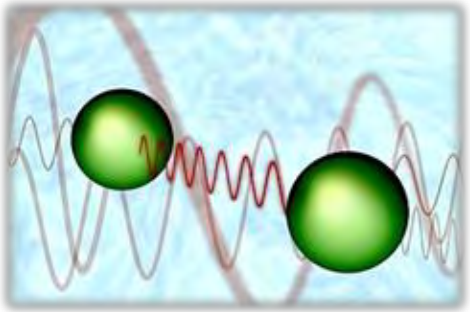
More power at small scales

The Observed Power Spectrum of LSS

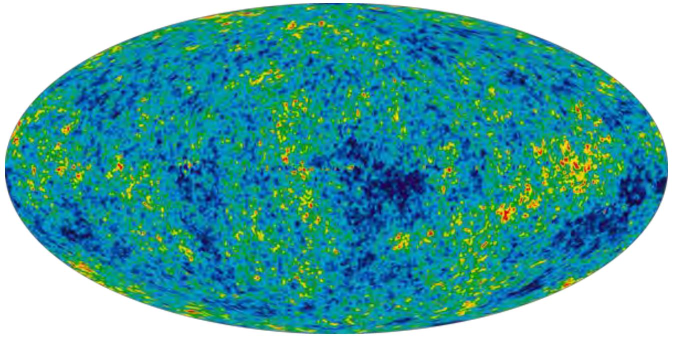


How Large Scale Structure Formed

From density fluctuations in the early universe that collapse under their own gravity and merge into ever larger structures

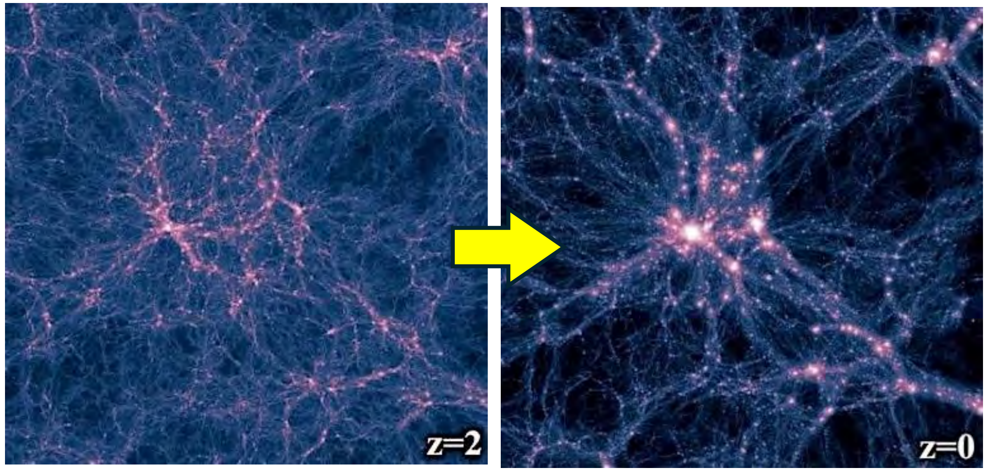


Their seeds are ***quantum fluctuations*** in the very early universe (age << 1 sec) , which get inflated by many orders of magnitude



We observe them as the fluctuations in the ***Cosmic Microwave Background,*** on scales ~ 100 Mpc, when the universe transitions from ionized plasma to neutral gas (age = 380,000 years)

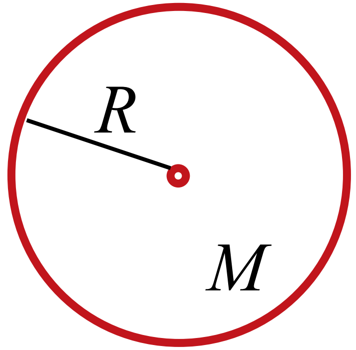
Dark matter (DM) drives the evolution of structure. Density fluctuations grow through their self-gravity and hierarchical merging of smaller dark halos into larger ones. This can be modeled only through large numerical simulations



Baryons follow the DM, and star formation ignites in the deep potential wells of DM halos

How Long Does It Take? Free-Fall Time Scale

Consider a mass overdensity with the mass M and the initial radius R :



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

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

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

Dissipationless vs. Dissipative Collapse

Consider a mass overdensity with the mass M and the initial radius R_{init}

It is just bound, so that:

$$E_{kin} = MV^2/2 = E_{pot} = GM^2/R_{init}$$

$$V^2 = 2\,GM/R_{init}$$

If there is no dissipation (just mass particles moving in a gravitational potential well), then the kinetic energy per unit mass, V^2, is constant

The overdensity collapses disspationlessly, and the Virial Theorem tells us that a for a gravitationally bound system in an equilibrium, $E_{kin} = ½\,E_{pot}$ within a sign, so that now:

$$E_{kin} = MV^2/2 = ½\,E_{pot} = ½\,GM^2/R_{final}$$

$$V^2 = GM/R_{final}$$

Therefore, $R_{final} = ½\,R_{init}$, and since the density $\sim R^{-3}$, the collapse by a factor of 2, leads to **an increase of density by a factor of 8**

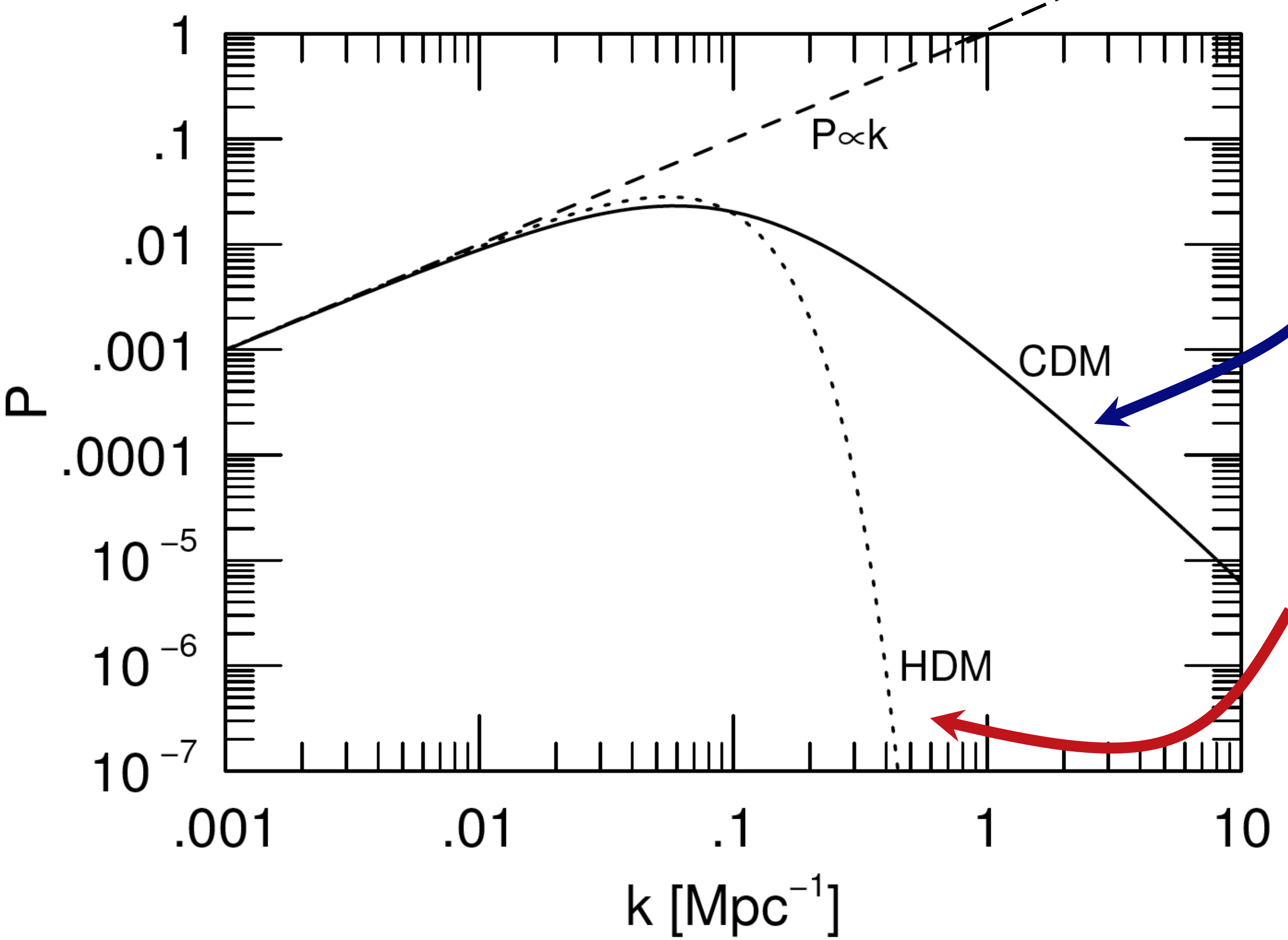
For galaxies to increase their density by another factor of 10^3, **they must dissipate energy**

Dark Matter and Damping of Fluctuations

- ***Different types of dark matter form structure differently***
- Baryonic matter is coupled to radiation, so it does not help in forming structure prior to the recombination. It then follows the structures formed by the dark matter
- Primordial ***density fluctuations can be erased*** or damped by ***sound waves***. This is important for slowly moving, more massive DM particles, i.e., ***cold dark matter*** (CDM)
- They can be also erased by ***free streaming*** of low mass relativistic particles, i.e., ***hot dark matter*** (HDM). Since they move faster, they can erase larger fluctuations
- Thus ***HDM vs. CDM make very different predictions*** for the evolution of structure in the universe: with HDM, only the largest density fluctuations would survive
- In any case, ***the smaller fluctuations are always erased first***
- Observations and simulations ***exclude a pure HDM***. Thus we believe that CDM dominates (small quantities of HDM, like neutrinos, are allowed)

Damping of Density Fluctuations

The expected primordial power spectrum

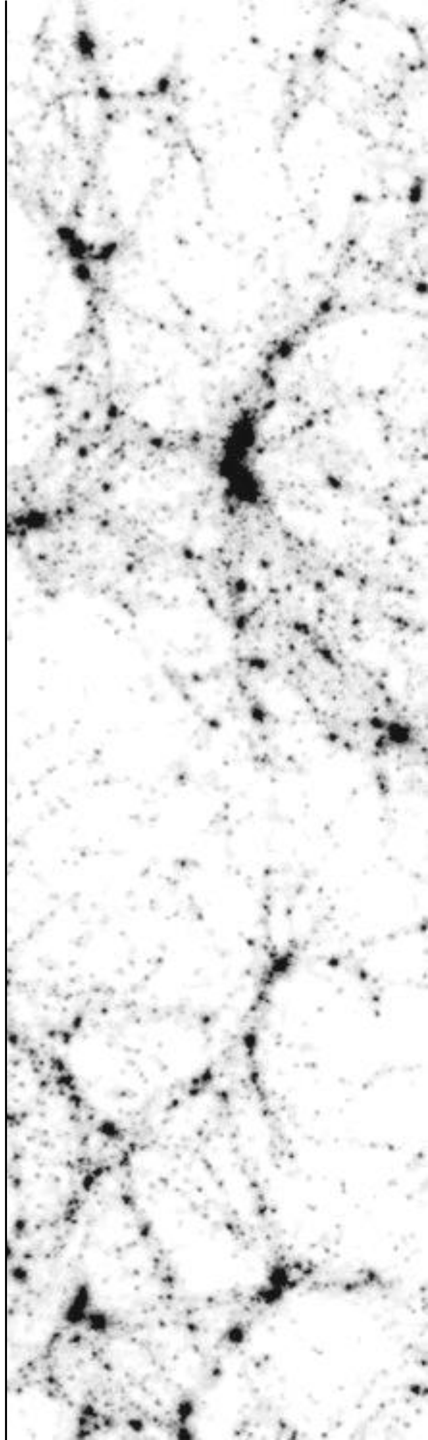


Sound waves diminish the strength of small scale fluc's for the CDM case

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

We observe a lot of power at small scales (~ galaxies), so CDM must be right

Structure Formation in the Cold Dark Matter Scenario



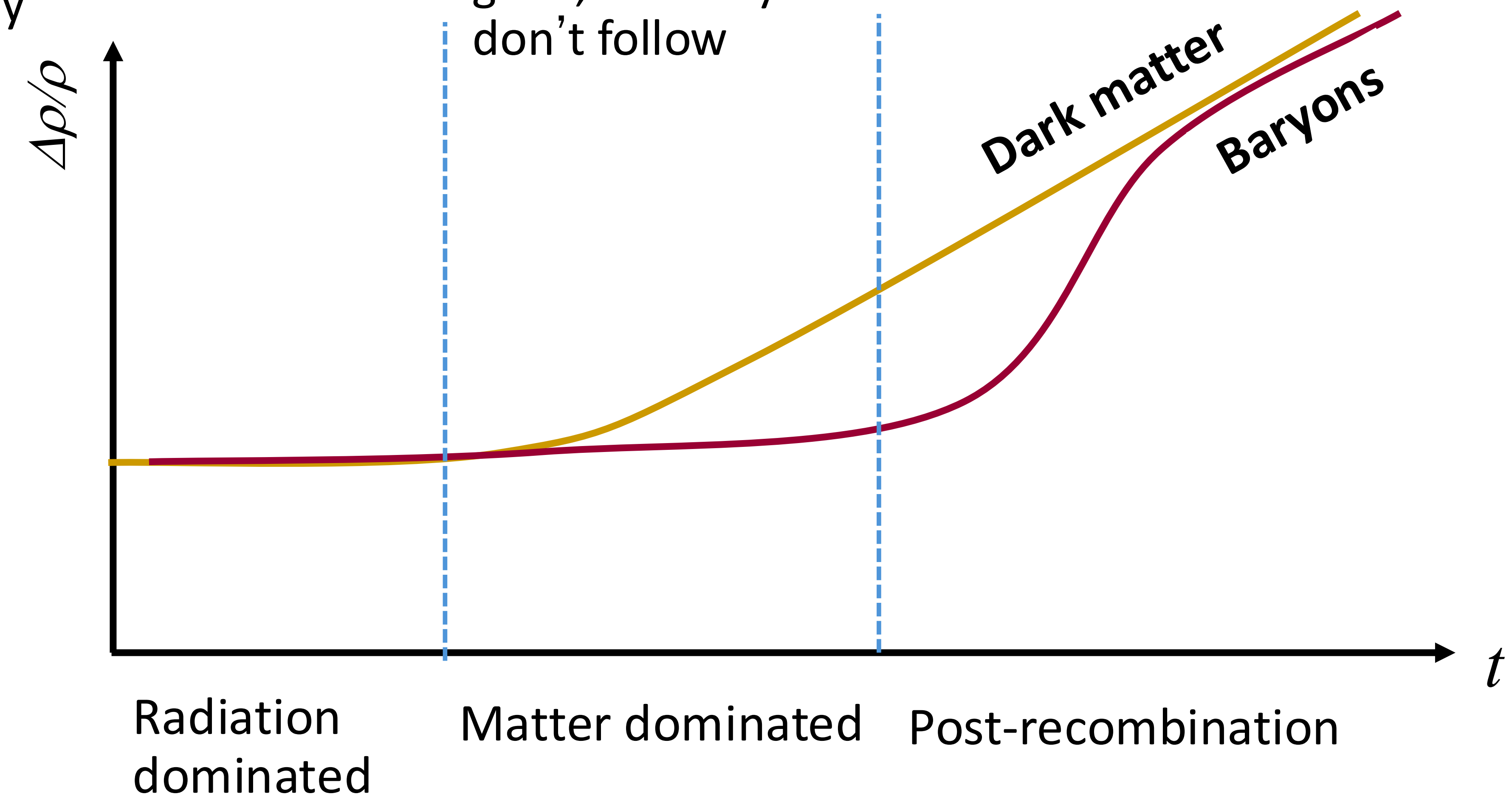
- CDM particles don't diffuse out of small density fluctuations. So overdensities exist on all scales, both large and small
- Small overdensities collapse first, big ones collapse later. The larger overdensities will incorporate smaller ones as they collapse, via merging
- Structure forms early, and 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 Cosmic Microwave Background fluctuations
  - While some challenges remain, the overall big picture is probably right

The Evolution of Fluctuations

In the early universe, radiation (not DM) dominates the energy density

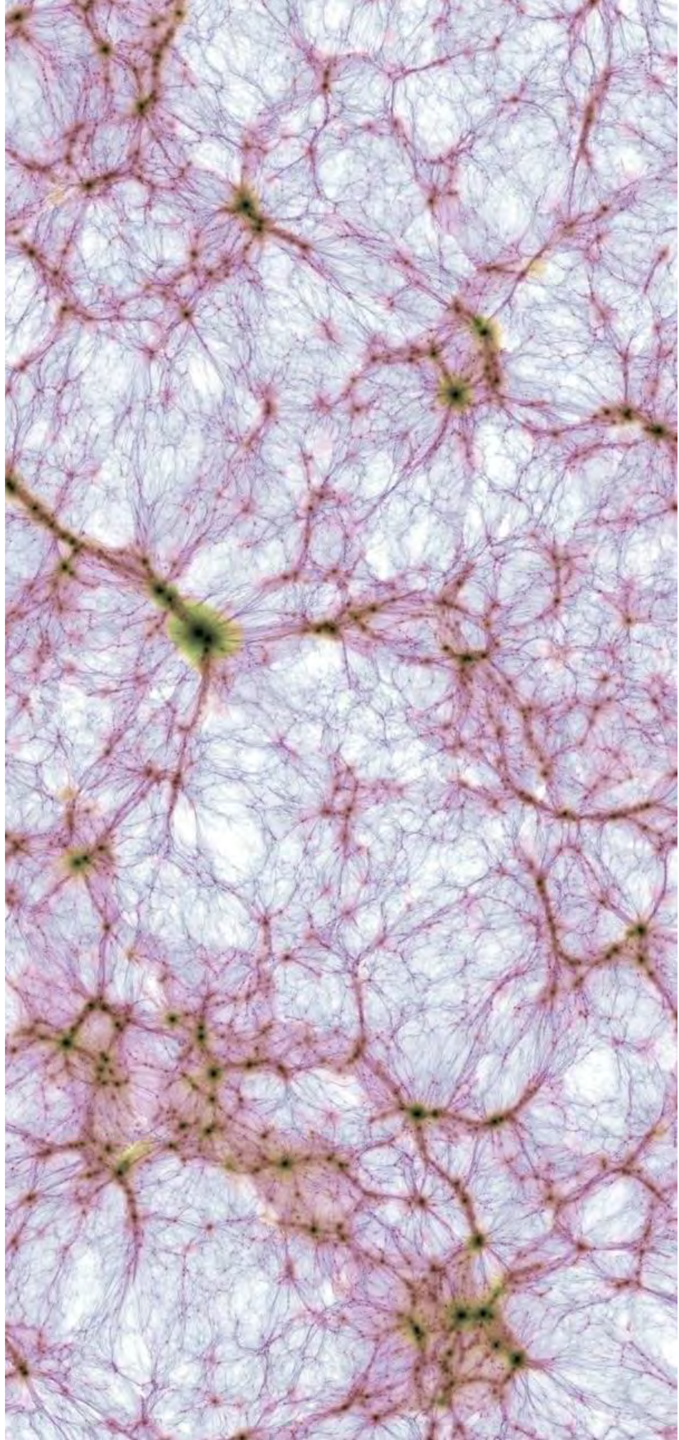
When matter becomes dominant, DM fluctuations grow, but baryons don’t follow

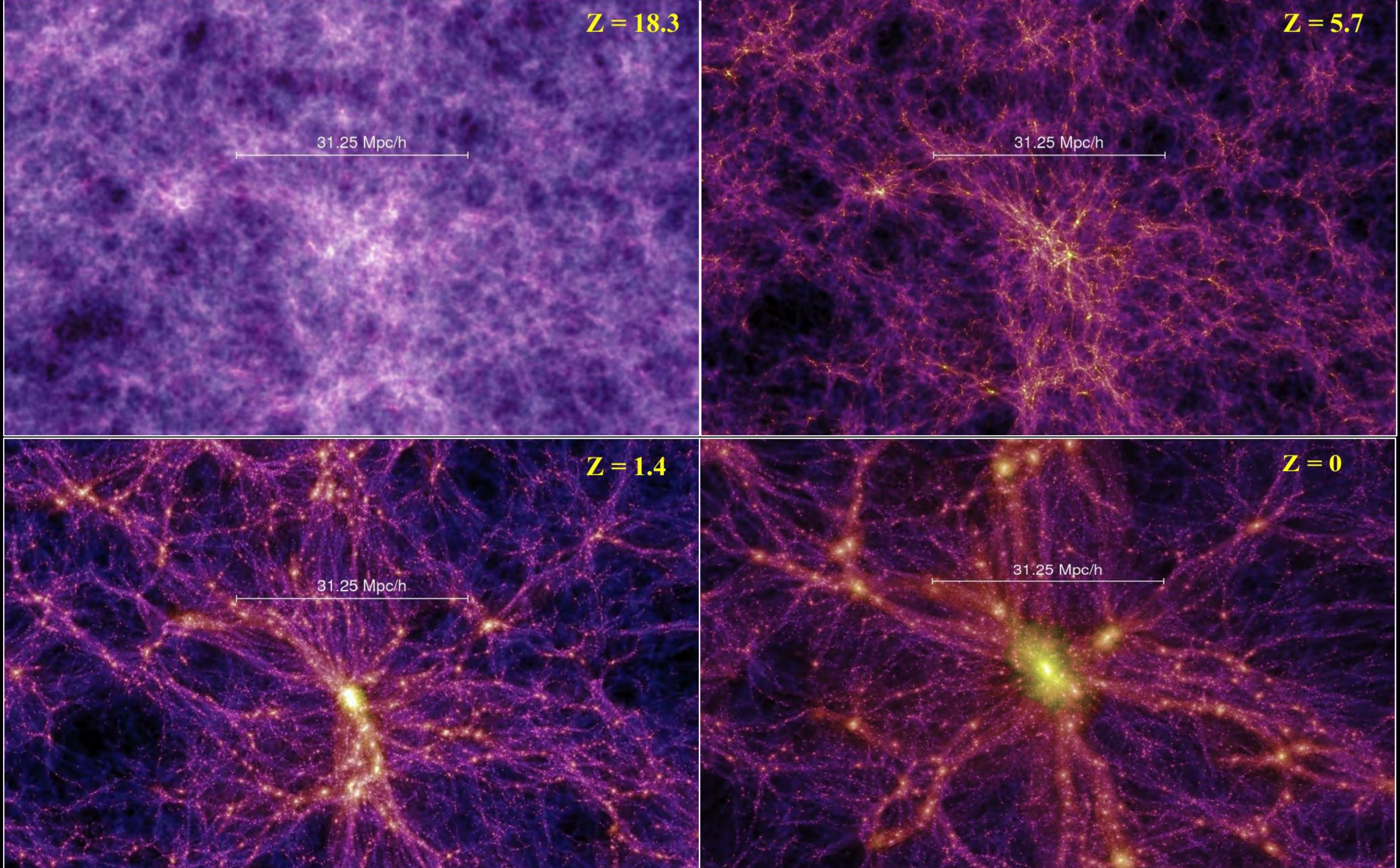
After the recombination, baryons collapse into the potential wells of DM halos



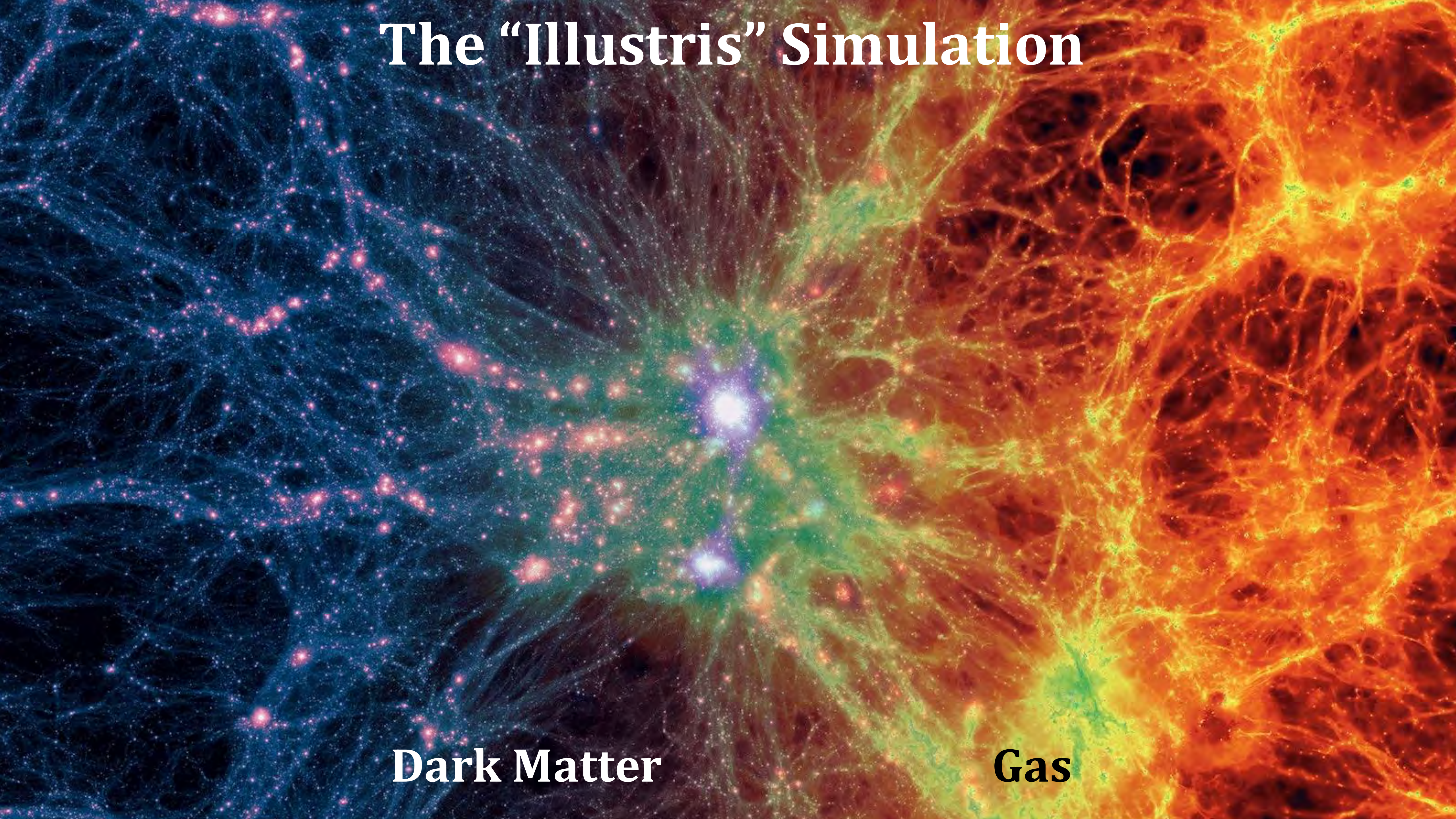
Numerical Simulations in Cosmology

- Many problems in astrophysics generally *do not allow analytic solution*. A full 3D numerical treatment is required
- For the Newtonian gravity, there are no exact analytical solutions beyond the 2-body (Kepler) problem
- *Numerical simulations thus play a key role in cosmology*
- In cosmology know both the governing equations (Newtonian gravity, cosmological expansion) *and* can assume the initial conditions (primordial density field)
- Pure gravity simulations are *dissipationless;* adding gas and radiation makes the problem much harder, due to dissipation, hydrodynamical effects, radiation transfer…
- The output of simulations can be compared to observations





The "Millenium" Simulaton (Dark Matter Only)



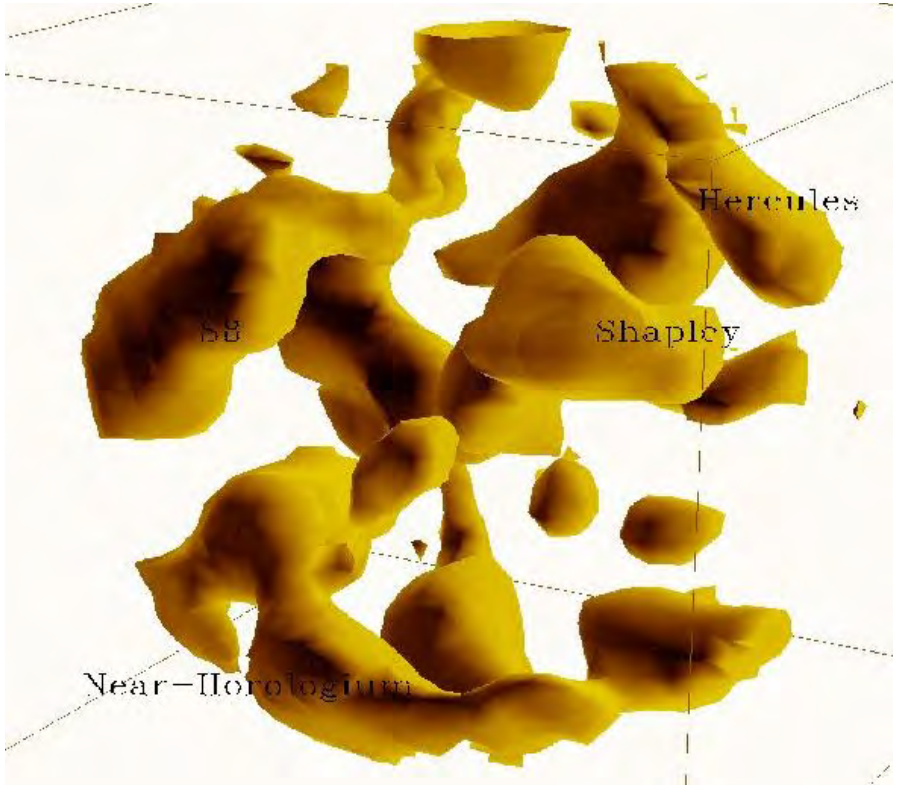
The “Illustris” Simulation
Dark Matter
Gas

Dark Matter vs. Gas and Radiation from Young Stars

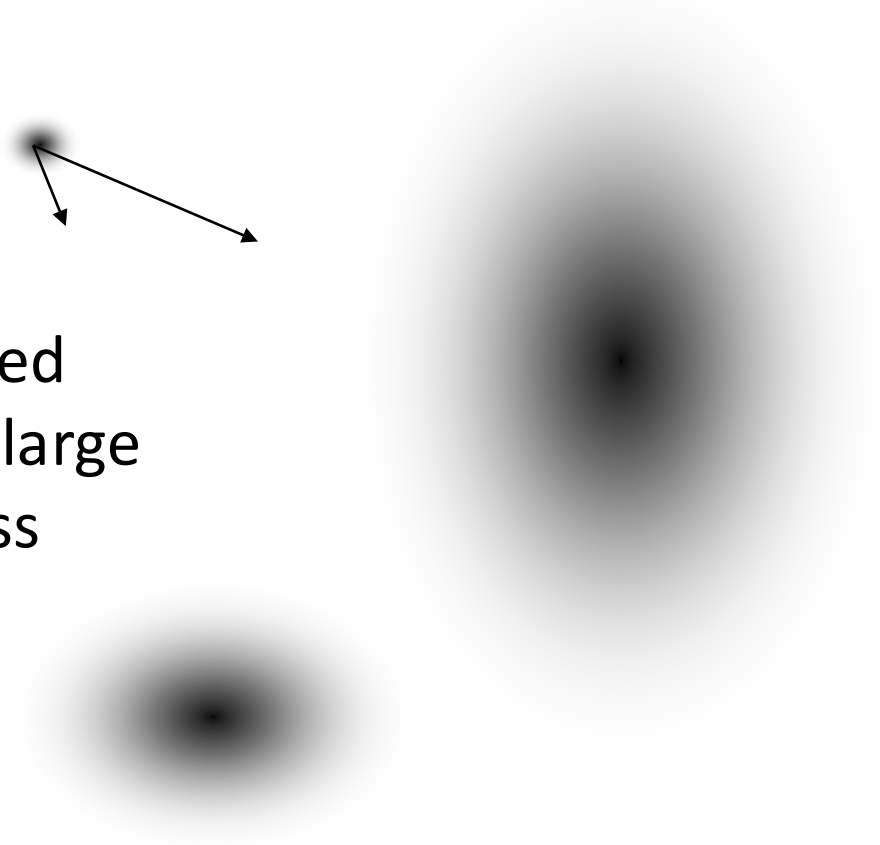
The “Illustris” Simulation:
gas velocities overlaid on
dark matter density

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 concentrationss

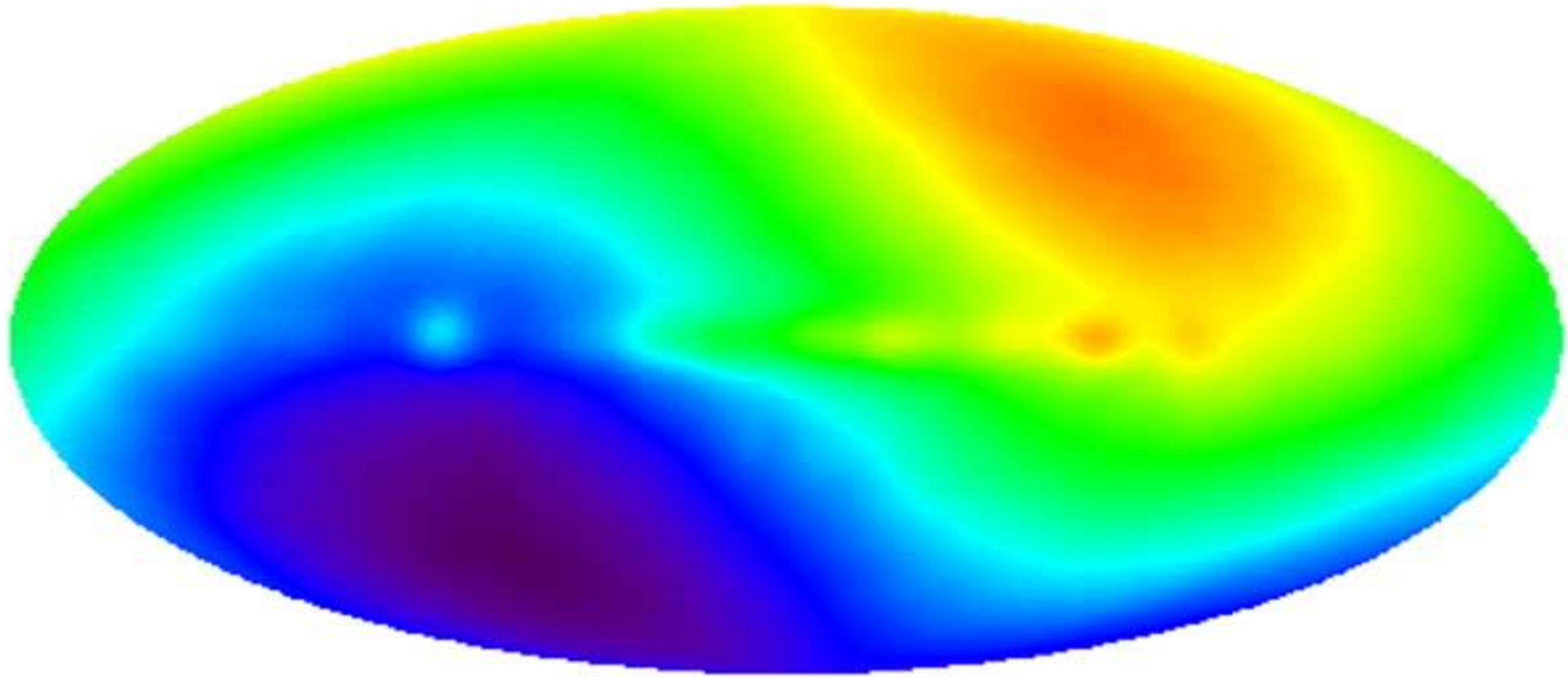


Integrated over the Hubble time, this results in a peculiar velocity

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°*

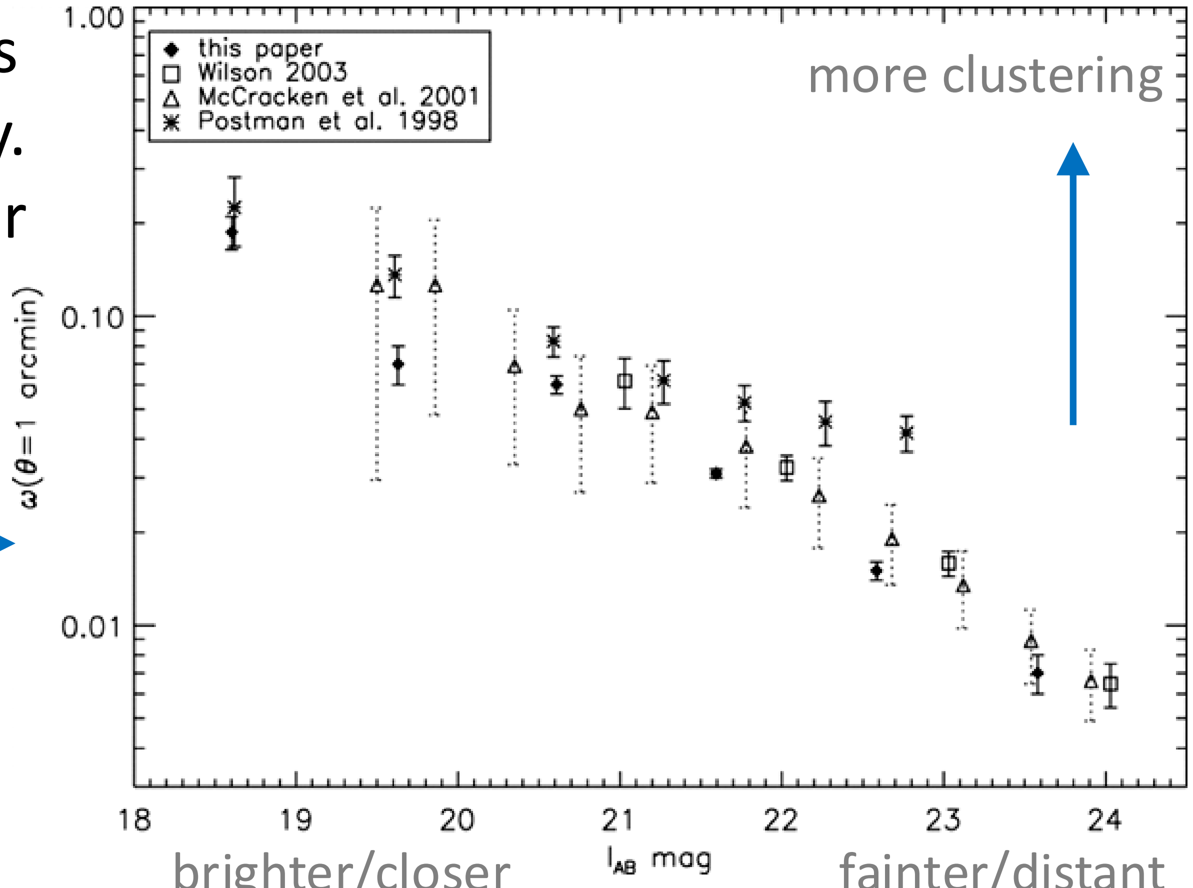
This gives us an idea of the probable magnitude of peculiar velocities in the local universe. Note that at the distance to Virgo (LSC), this corresponds to a ~ 50% error in Hubble velocity, and a ~ 10% error at the distance to Coma cluster.

Peculiar Velocities

- Measurements of peculiar velocities are very, very tricky
  - Use (relative) distances to galaxies + Hubble flow
  - Use a redshift survey + numerical modeling $V_{total} = V_{Hubble} + V_{pec} = H_0 D + V_{pecx}$
- **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)

Evolution of Clustering

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

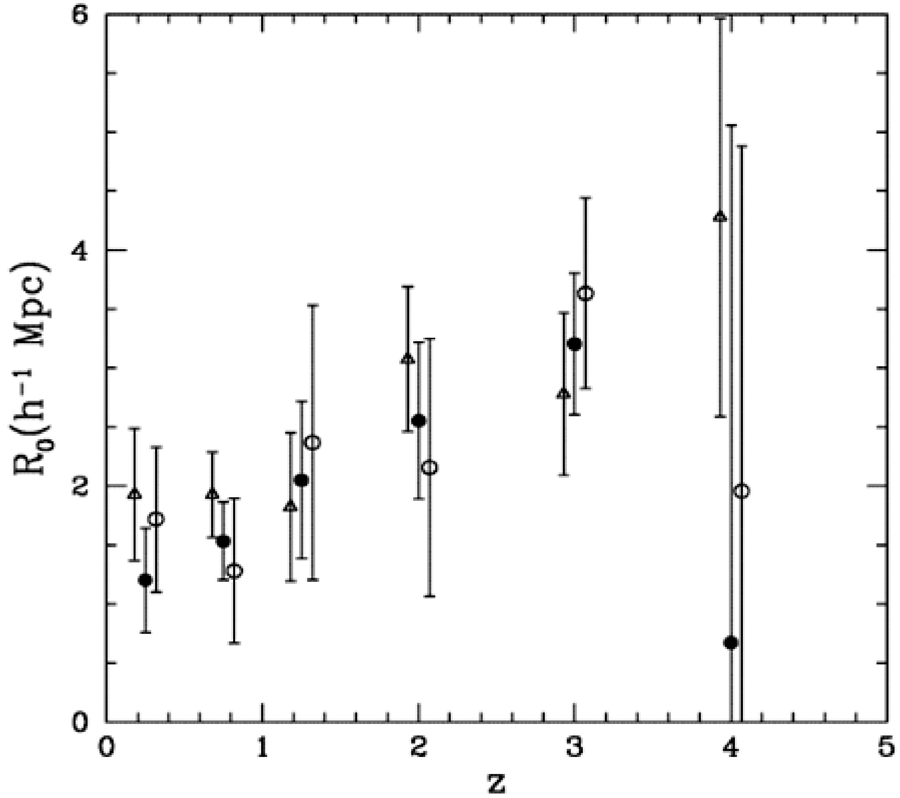


more clustering

brighter/closer

fainter/distant

This is as observed



But at higher redshifts, the trend reverses: the clustering grows in the past. Why?

The answer is ***galaxy biasing***

Galaxy Biasing

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

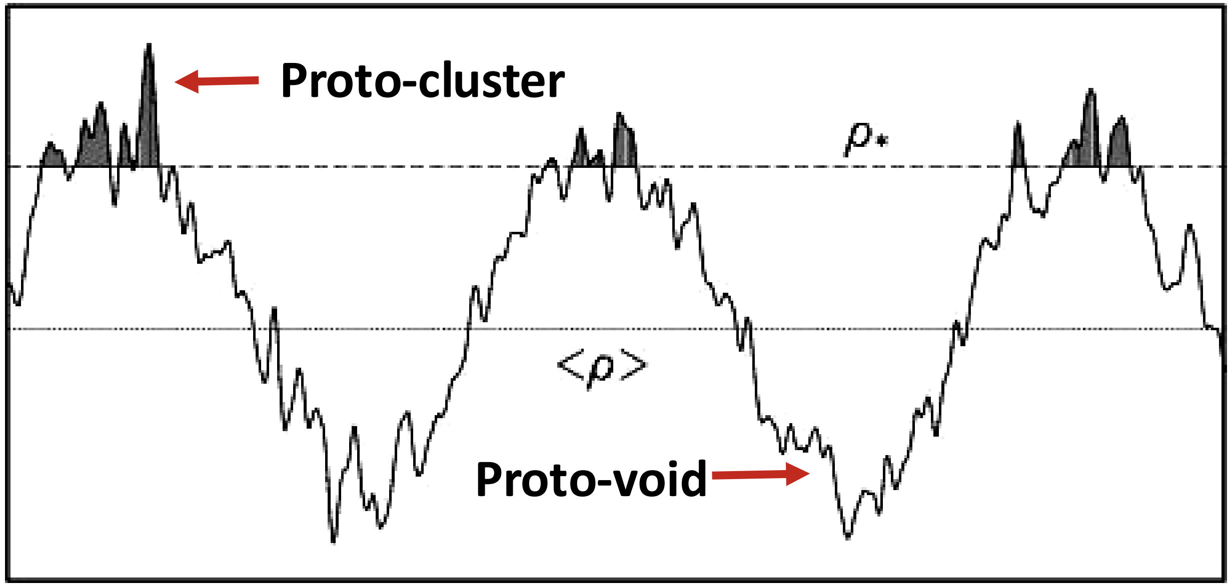
$$(\Delta\rho/\rho)_{light} = b\ (\Delta\rho/\rho)_{mass}$$

Or:

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

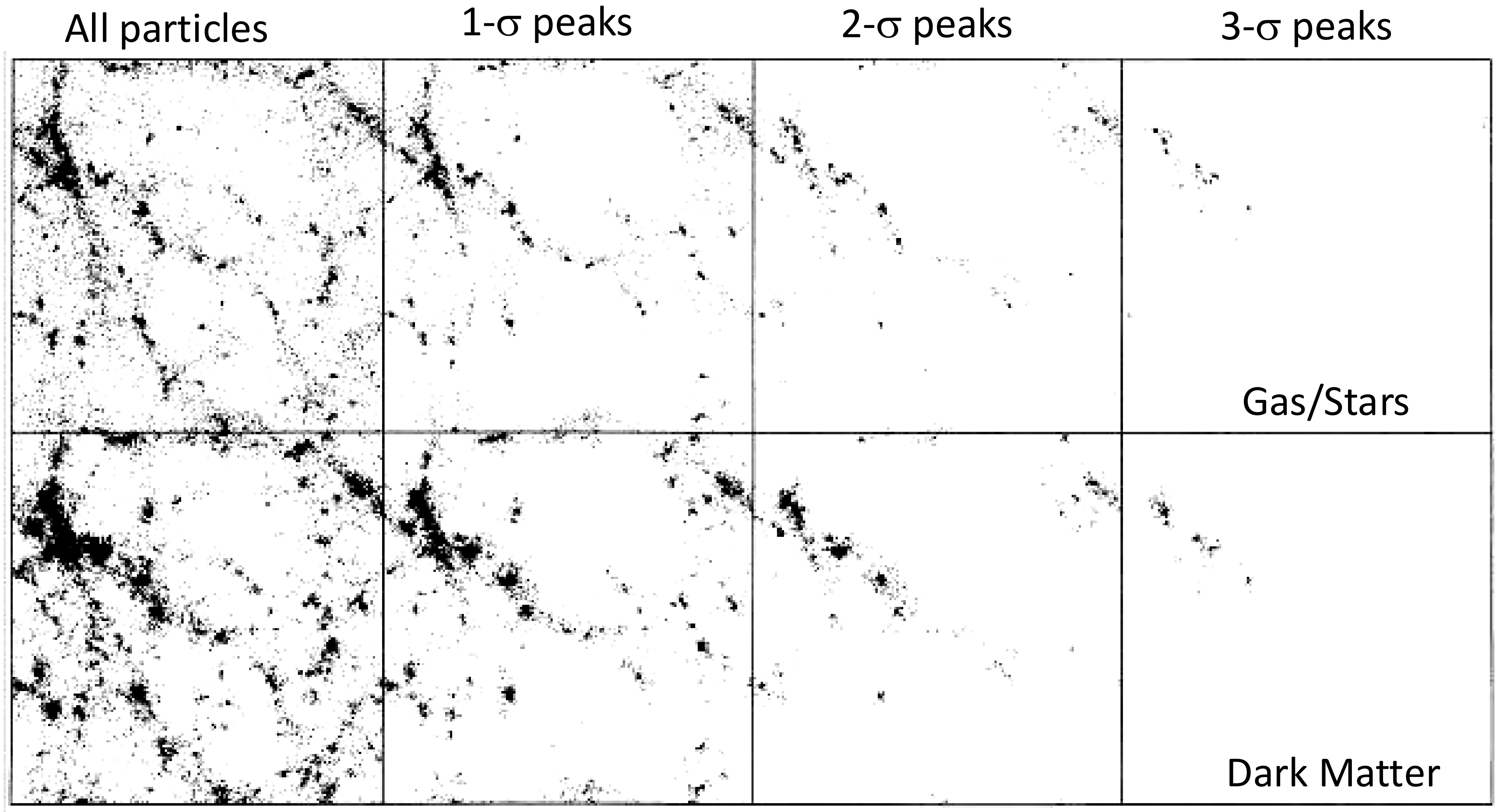
Here ***b*** is the *bias factor*. If $b = 1$, light traces mass exactly (this is indeed the case at $z \sim 0$, at scales larger than the individual galaxy halos). If $b > 1$, light is a *biased tracer* of mass.

One possible mechanism for this is if the galaxies form at the densest spots, i.e., the highest peaks of the density field, , which lift them up; 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 a **highly biased tracer** of mass

Biasing: An Example From a Numerical Simulation

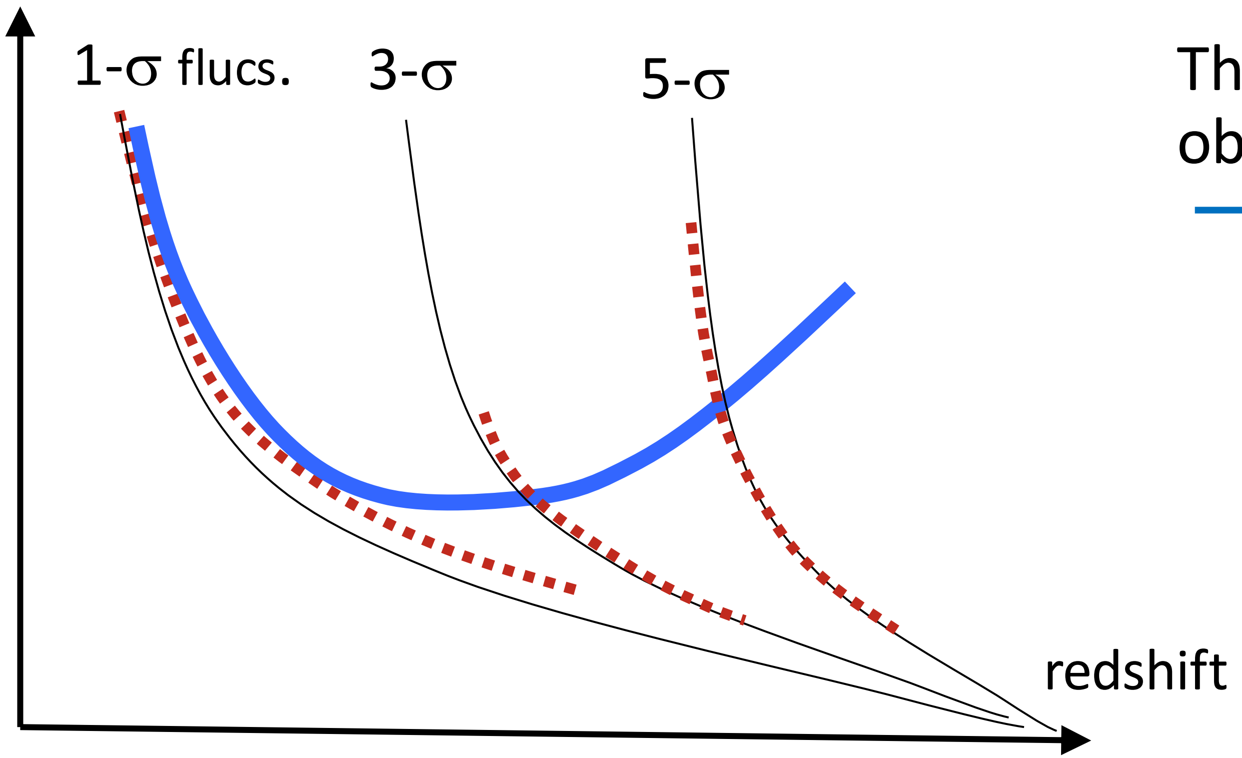


(From an N-body simulation by R. Carlberg)

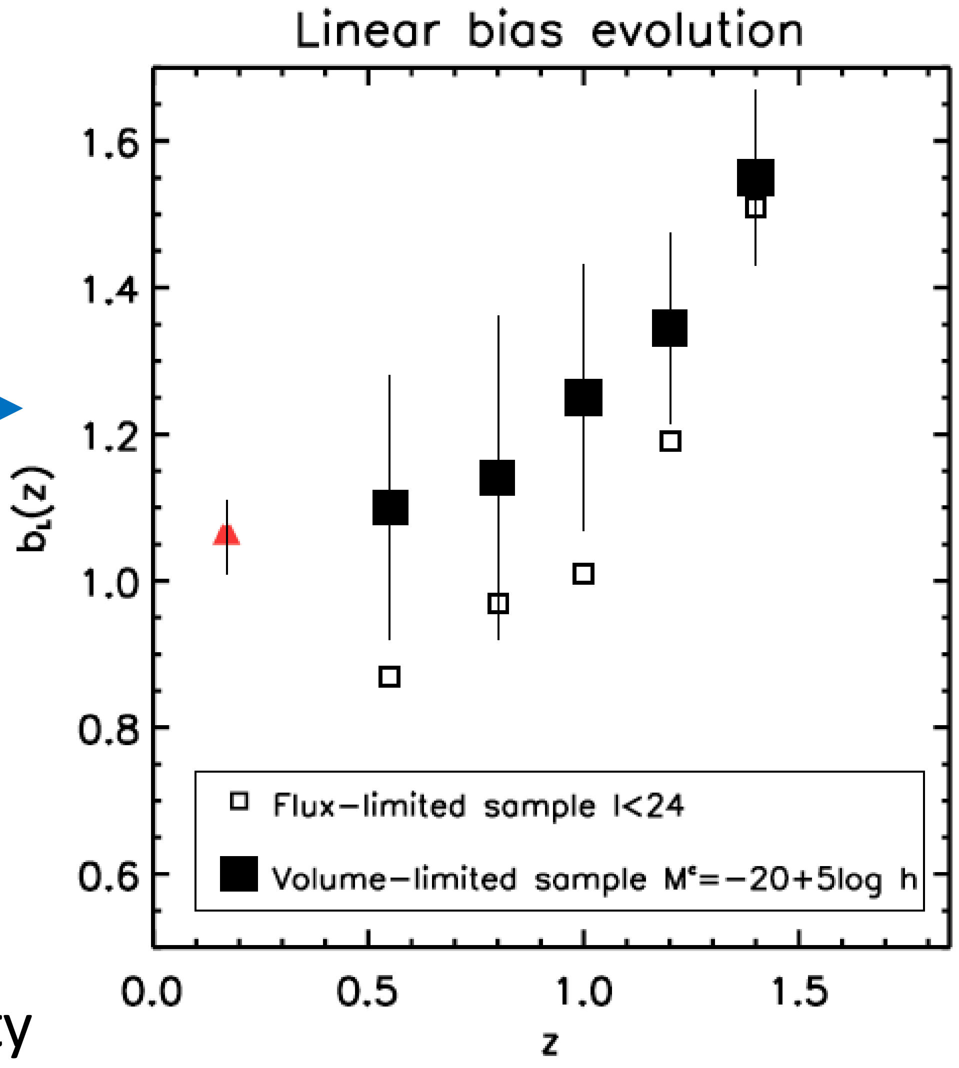
Biasing and Clustering Evolution

Strength of clustering

Higher density (= higher-σ) fluctuations evolve faster



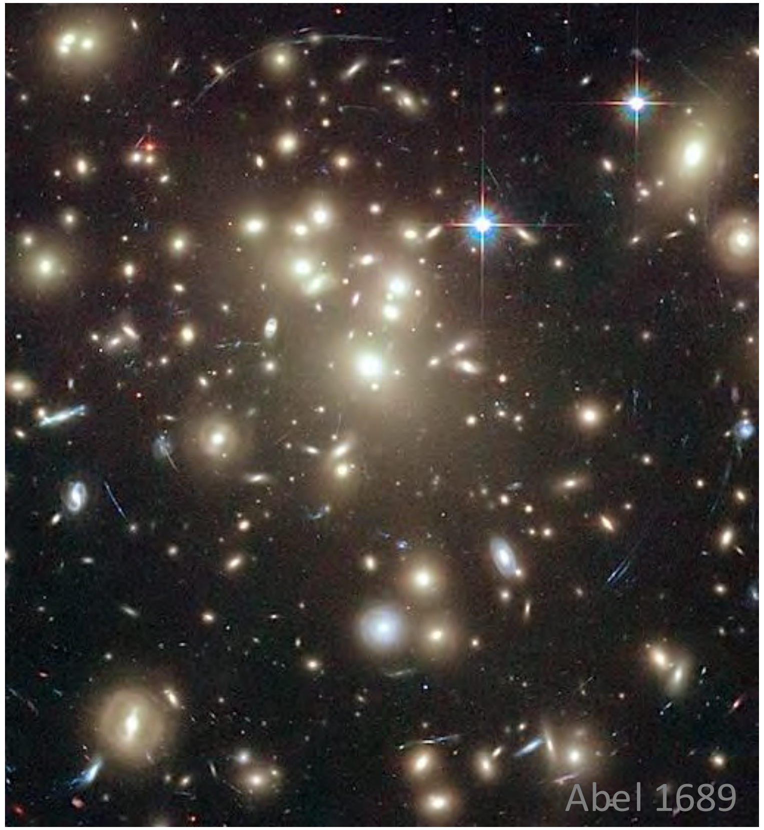
This is as observed



At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly … they are a ***biased sample***

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

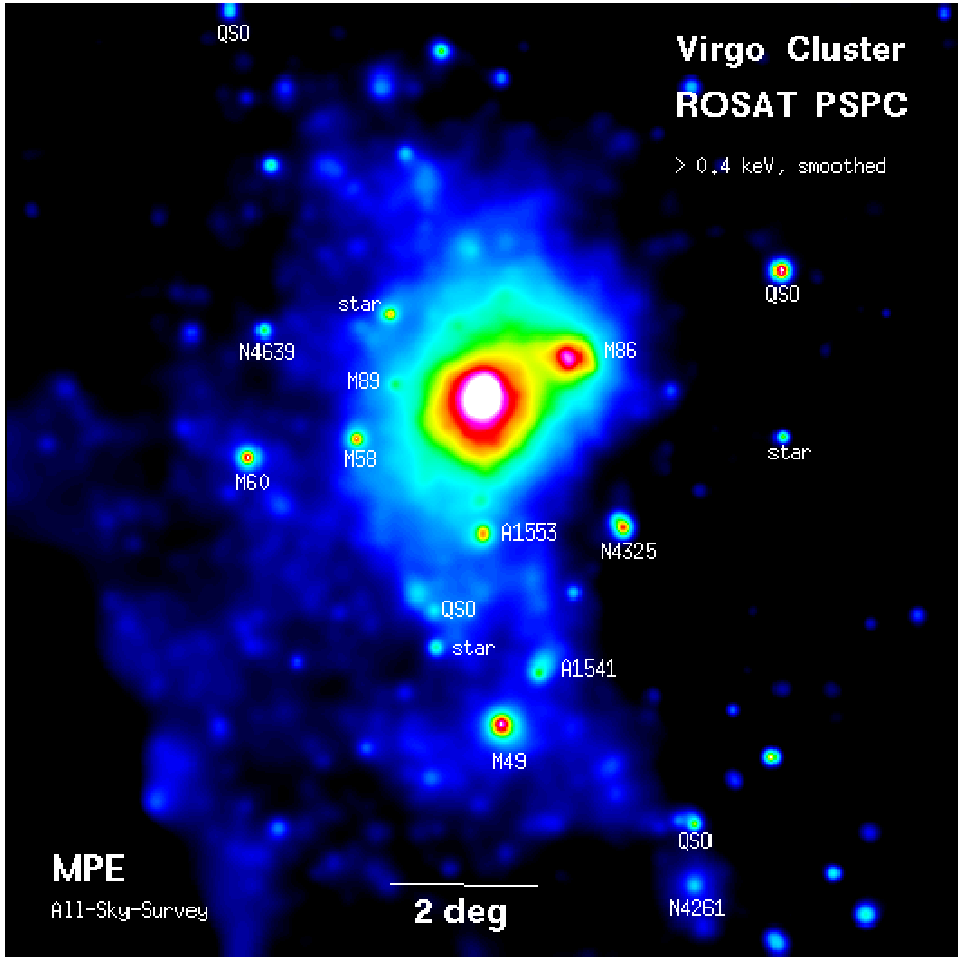
Clusters of Galaxies



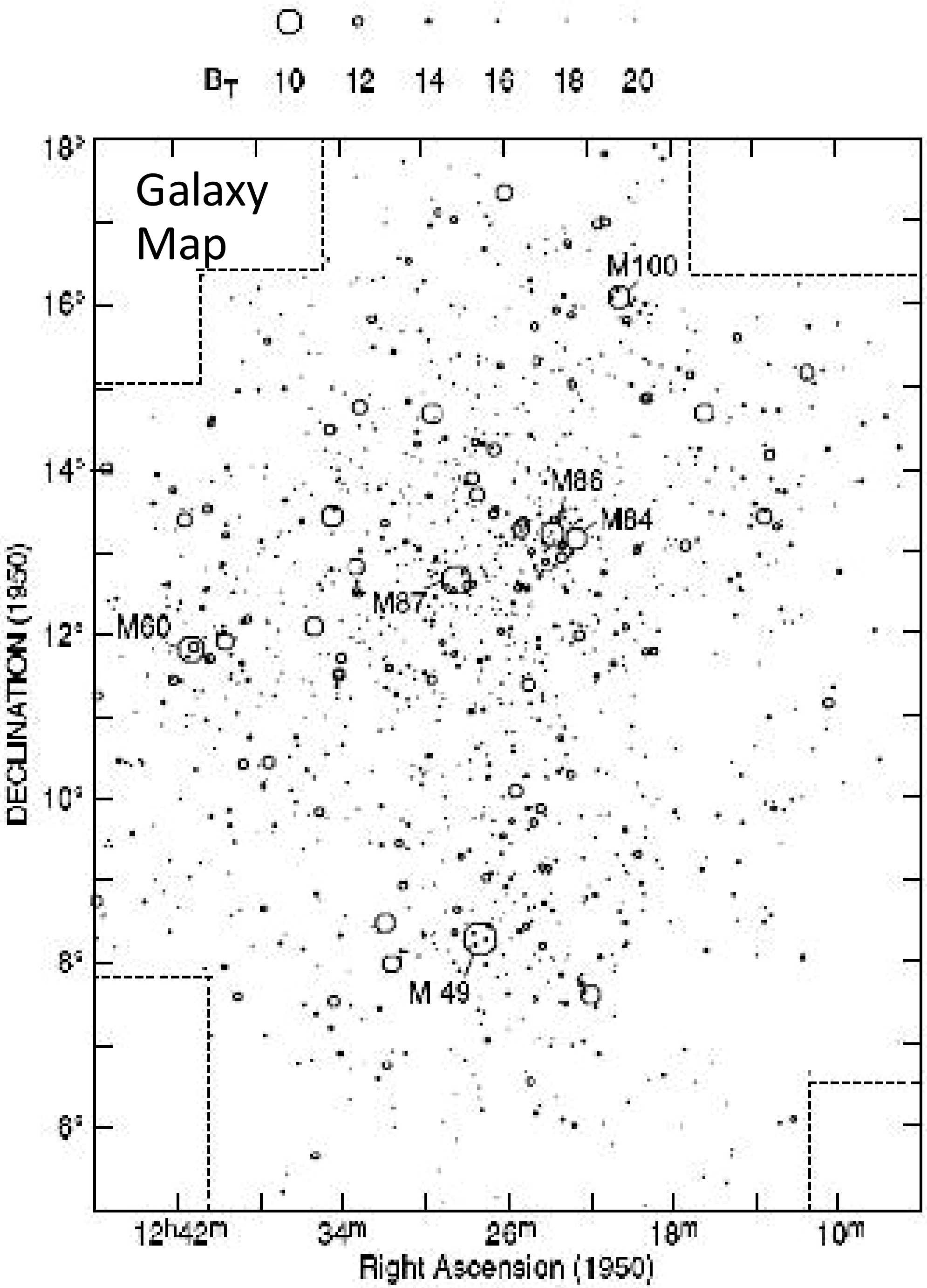
- Clusters are perhaps the most striking elements of the LSS
- Typically a few Mpc across, contain ~ 100 - 1000 luminous galaxies and many more dwarfs, masses ~ 10^{14} - 10^{15} $M_{\odot}$
- **Gravitationally bound, but may not be fully virialized**: clusters are **still forming**
- **Filled with hot 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 are in clusters, most galaxies are in groups or field
- **Galaxy populations and evolution in clusters differ from the general field**: clusters 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, still forming, relatively poor cluster, but the center of the Local Supercluster
- Distance ~ 16.5 Mpc, closest cluster to us

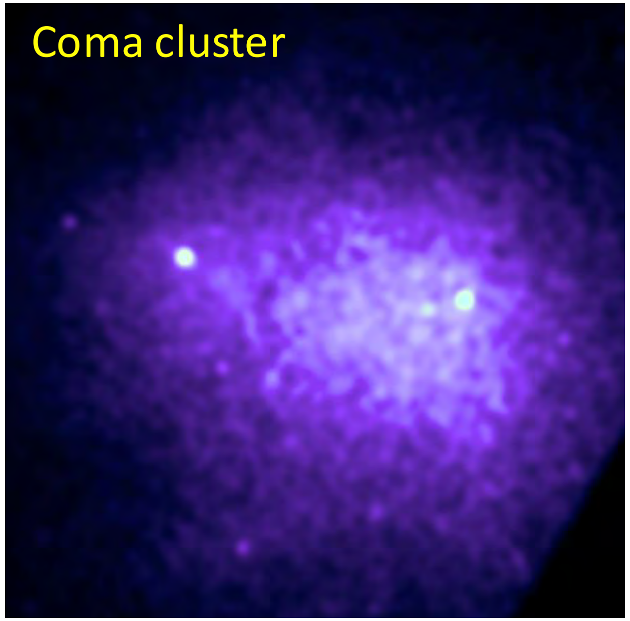


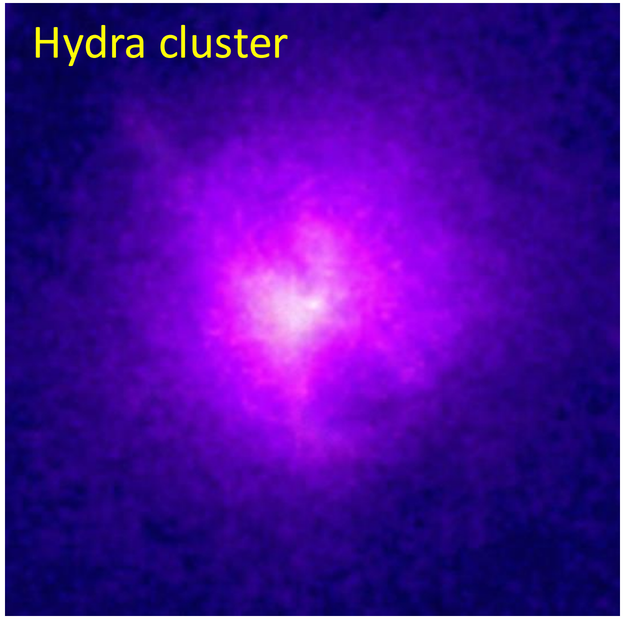
- Diameter ~ 10° on the sky, or ~ 3 Mpc
- Contains about 2000 galaxies, mostly dwarfs
- Giant elliptical M87 is at its center



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 gas must have come from galaxies, expelled by galactic winds, since metallicity is ~ 1/3 Solar
- Virial equilibrium temperature T ~ $10^7 – 10^8$ K
- An 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





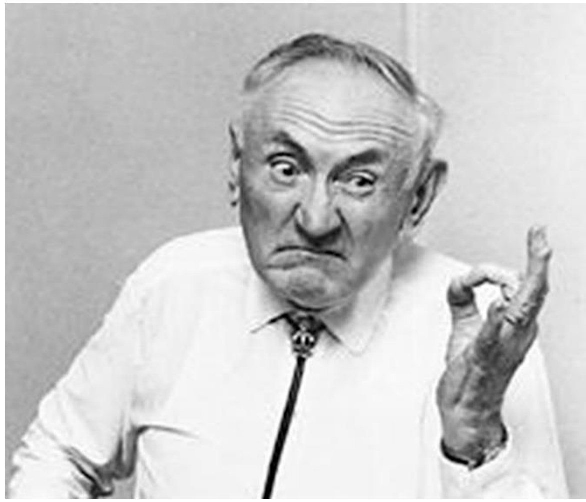
Virial Masses of Clusters

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

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

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 $\boldsymbol{M_{cl} \sim 10^{14} - 10^{15} M_\odot}$

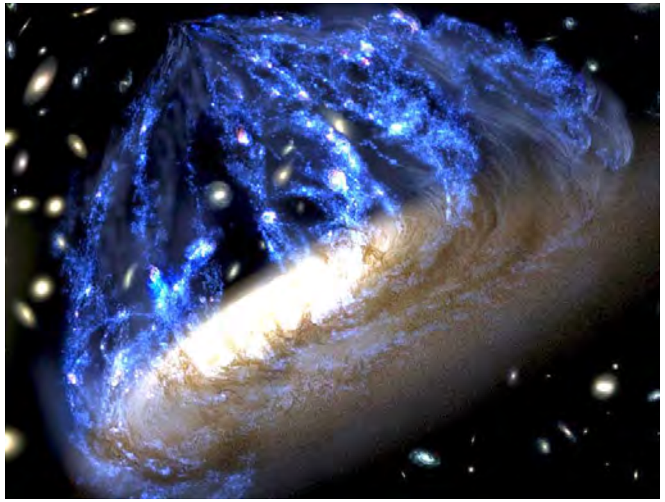
That is how Fritz Zwicky discovered DM in 1937

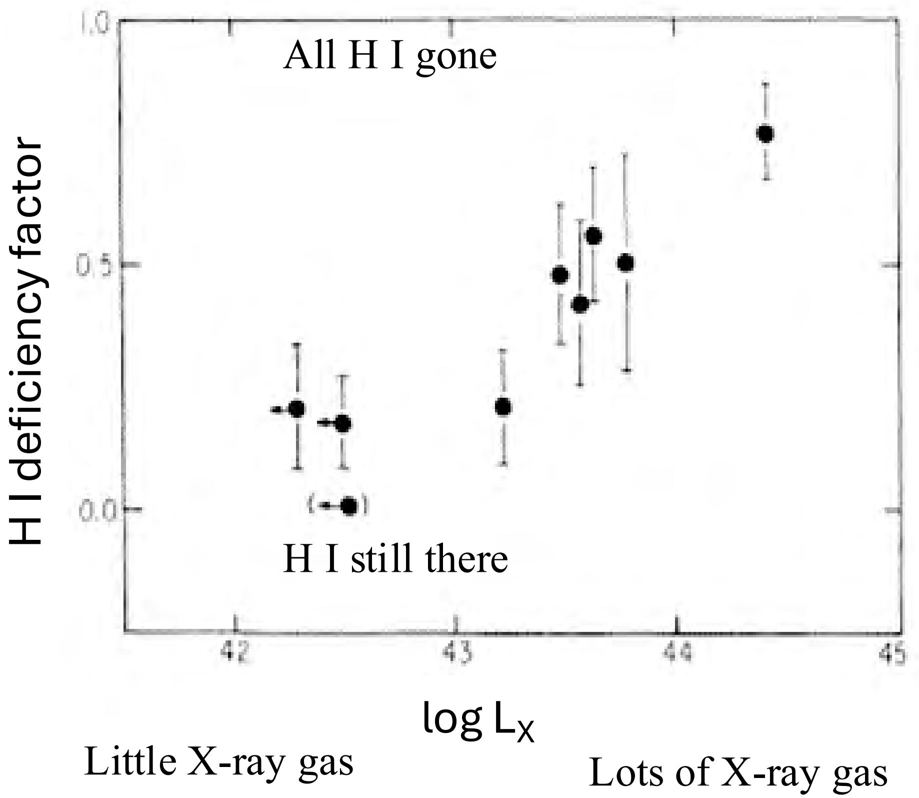
The result is the same, whether you use kinetic energy of galaxies ($E_k = m_g \sigma^2 / 2$), or protons ($E_k = 3/2 \, k_B \, T$), and also from gravitational lensing

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!***

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





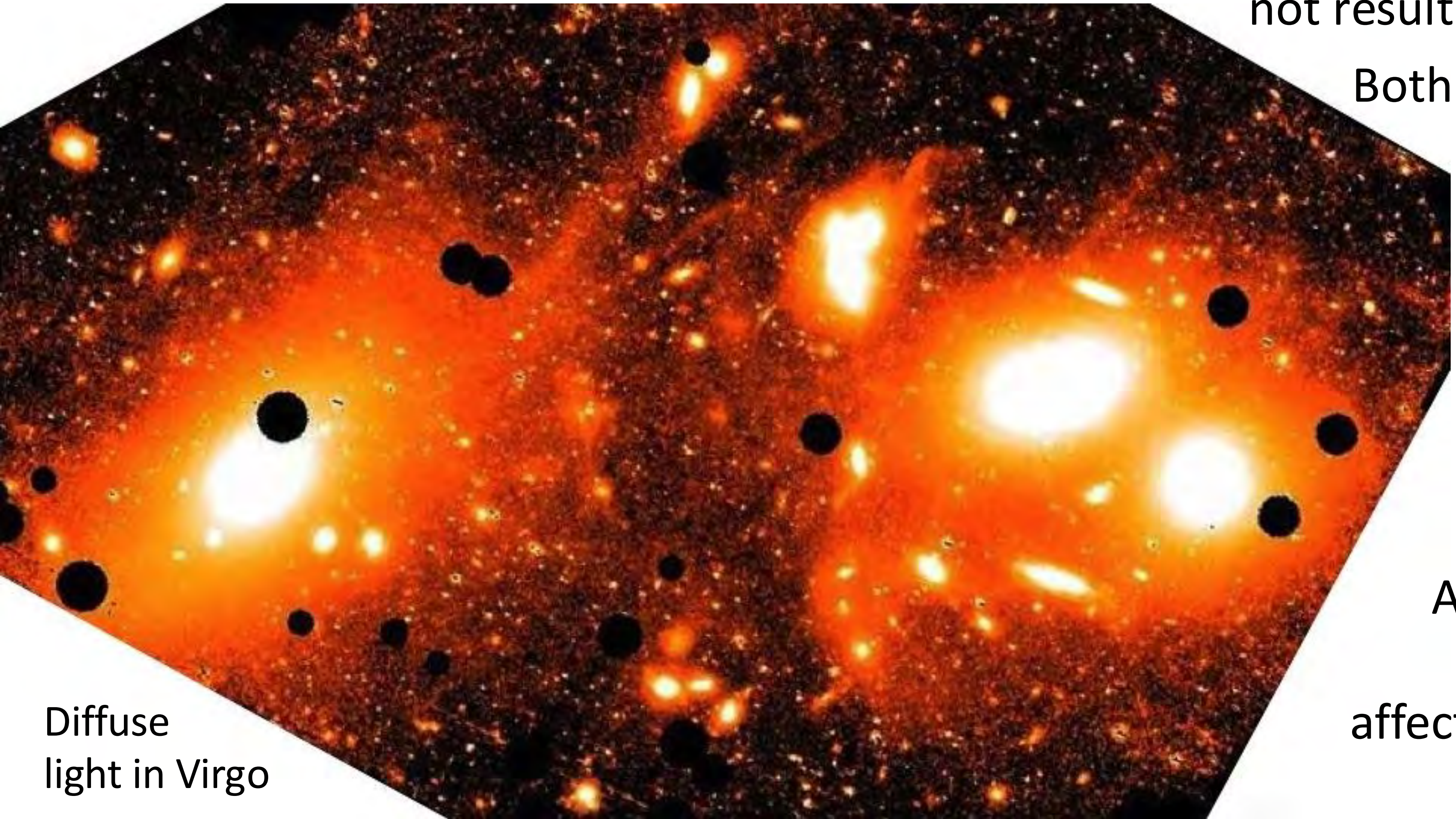
- HI deficiency correlates with X-ray luminosity (which correlates with cluster richness)
- It is the outer disks of the spirals that are missing
- Thus, ***evolution of disk galaxies can be greatly affected by their large-scale environment***

Intracluster Light

Shows as **very low surface brightness** envelopes of ellipticals in high-contrast images

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

Both gas and stars can be stripped away



Diffuse light in Virgo

Another environment dependent process affecting galaxy evolution

Key Concepts in This Lecture

- **Large Scale Structure (LSS)** is on scales > galaxies; groups, clusters, filaments, walls, voids, superclusters are the elements of it
- It originates from **density fluctuations** in the early universe that **evolve through self-gravity and hierarchical merging**, driven by dark matter. **Free-fall time** scale characterizes the dissipationless structure formation
- **Theoretical modeling** of LSS and its evolution requires **large numerical simulations**
- To **map and quantify the LSS** (the large-scale 3-D density field) and compare it with the theoretical predictions), we need **redshift surveys.** It is quantified through **two-point correlation function** and the **power spectrum** of the LSS density field
- Primordial **density fluctuations** are damped/erased on the small scales first, and depend on the nature of the dark matter: **cold dark matter** fits all the data
- **Dark halos form first**, and the baryons flow into them, and make stars later
- **Galaxy biasing** implies that galaxies form first in the highest peaks of the density field
- **Galaxy clusters** are the largest bound structures known. Interactions in them can alter galaxy evolution

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