L20 - Large-Scale Structure

Galaxy Clusters

Galaxies are "dynamically young".
The Local Group is even now falling in toward itself.
Even the densest groups have $\langle n \rangle_{gal}$ only ~100 times the Universe as a whole.

Contrast this with the MW: The central n_*, density in stars, is $\underline{10^6}$ times the mean density of stars in the Universe.

little groups and voids

There are about 20 small groups of galaxies between us and the 1st substantial cluster, Virgo ($D \simeq 16$ Mpc).
Within these small groups, there are many more dwarf galaxies than large galaxies, + the latter are <u>spirals</u>.
Even out to $D \sim 10$ Mpc, we begin to see regions that are empty, called "voids."

$\boxed{\text{Virgo}}$, the nearest true cluster, covers a big region in the sky - $10° \times 10°$!
It is a rich ($N \gtrsim 1000$) irregular cluster (not spherical)

The 4 brightest galaxies are ellipticals, each of which is the size of the entire Local Group!
Toward the center $\langle n \rangle_{gal} = 10^3 \times$ density in Universe.

brightest galaxy in Virgo

$\boxed{\text{M87}}$, has the huge, X-ray emitting halo. This gas is from stellar winds.
It emits X-rays through <u>brehmsstrahlung</u> ("braking radiation")

Nucleus of M87 is firing off a huge (2 Mpc) radio jet.
So this is a <u>radio galaxy</u> (AGN). NB: Most ellipticals are <u>not</u> AGNs.

$\boxed{\text{Coma}}$ covers a smaller area in the sky - $4° \times 4°$, but physically larger.
$D = 90$ Mpc, diameter = 6 Mpc
It is a rich ($N \simeq 10^4$) <u>regular</u> cluster: spherical

The vast majority of galaxies in Coma are ellipticals and S0 galaxies. At the center are two cD galaxies.

More distant clusters

These contain more spirals and other smaller galaxies toward their centers than nearby clusters of galaxies.

The galaxies also tend to be bluer in color [Butcher-Oemler effect]
There are also a lot more irregular galaxies

Possible interpretation! Ancient galaxies in clusters were active forming stars and merged to form today's elliptical galaxies.

Intracluster Gas

Many clusters emit X-ray gas from the volume in between galaxies. This gas, like that in M87, appears to be in hydrostatic balance in the larger gravitational potential well.

The mass of X-ray emitting gas $\gtrsim$ mass in luminous stars

$\boxed{\text{BUT}}$

" " $\ll$ mass in dark matter

Coma:

$$M_{gas} = 3 \times 10^{13}\ M_\odot$$
$$M_{stars} = 2 \times 10^{13}\ M_\odot$$
$$M_{DM} = 3 \times 10^{15}\ M_\odot$$

Superclusters

This is a cluster of clusters, with a size of 100 Mpc.

→ $\boxed{\text{Every known rich cluster is found in a supercluster.}}$

Virgo is a center of "local supercluster" – a flattened ellipsoid with diameter 40 Mpc

The Local Group is at the edge of the local Supercluster.

Total mass of local supercluster = $8 \times 10^{14} M_\odot$ $\left\langle \frac{M}{L} \right\rangle = 400 \frac{M_\odot}{L_\odot}$

Bubbles and Voids

Photographic mosaics have imaged millions of galaxies, covering several 1000 square degrees on the sky.*

Clusters show up as bright spots, superclusters as filaments (edge-on sheets).

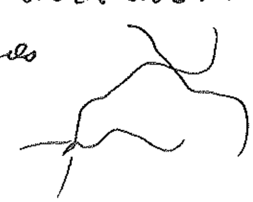
However, this is just a 2D projection onto the sky.
Redshift surveys give the distances to the galaxies & thus full, 3D maps
[recently, SDSS got z for over 10^6 galaxies.]
In the 1980's, these first revealed the existence of huge voids.

$\boxed{\text{Voids have diameters of} \sim 100 \text{ Mpc and are roughly spherical.}}$

That is, they are not flattened, like sheets of superclusters.

The interior of a void has no spiral or elliptical galaxies, but may contain a few dwarf ellipticals.

Redshift surveys observed narrow slices (in declination) & broad swaths in RA (9 hours = $\frac{9}{24} \times 360°$). Observed filaments & spaces



soap bubble model

Galaxies are NOT located on tangled tubes, since then the slices would show small, cross-sectional areas.
They are 2D sheets that are the intersections of bubbles. Voids are the interiors of the bubbles.

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* The full hemisphere contains 2π sr. Each sr = $\left(\frac{180}{\pi}\right)^2$ square degrees.
So hemisphere has $2\pi \times \frac{180^2}{\pi^2} = \frac{2 \times 180^2}{\pi} = 20{,}626$ square degrees

Correlation Function

If galaxies were uniformly distributed in space, the probability of finding one in a volume dV would be

$$dP = n_0\, dV$$

Here n_0 = constant is the average number density of galaxies.
NB: dP can only be interpreted as a probability if $n_0 dV < 1$. If $n_0 dV > 1$, then "dP" is the <u>average number</u> of galaxies in dV.

In fact, galaxies are <u>not</u> uniformly distributed, as we have seen. So we write

$$dP = n_0[1 + \xi(r)]\, dV$$

where r is the distance to the dV being sampled.

Note that $\xi(r)$ can be (+) or (−). In some sense, it must average to zero. Take dV to be very large. (or do $\int dV$). Then "P" $= \int dP$ is the total no. of galaxies in the huge volume. This must be $n_0 \int dV$. So

$$n_0 \int dV = n_0 \int [1 + \xi(r)]\, dV = n_0 \int dV + n_0 \int_0^\infty \xi(r)\, 4\pi r^2 dr$$

Thus $\boxed{\int_0^\infty \xi(r)\, 4\pi r^2 dr = 0}$

$\xi(r)$ is called the "two-point correlation function". Why? The probability of finding one galaxy in dV_1 <u>and</u> another in dV_2 is

$$d^2P = n_0^2 [1 + \xi(r_{12})]\, dV_1\, dV_2$$

In the figure, taken from a large redshift survey,

Show Fig. 7.7 of Sparke & Gallagher

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

$\gamma \approx 1.5$, $r_0 = 6$ Mpc for $2 \lesssim r \lesssim 16$ Mpc

That is, there is less deviation from smoothness as r increases.

Results of many surveys: $\gamma \approx 1.8$, $r_0 = 5$ Mpc

Smoothness Scale

For large enough r, $\xi(r)$ must fall negative and then oscillate (in a decaying manner) around 0.

The r-value where $\xi(r)$ first reaches 0 is r_{max}. For distances $r \gtrsim r_{max}$, the Universe can be considered smooth and homogeneous. $\boxed{\text{What is } r_{max}?}$

From the left panel of the figure, $r_{max} \simeq 30$ Mpc. There is another way of seeing this.

Power Spectrum [advanced]

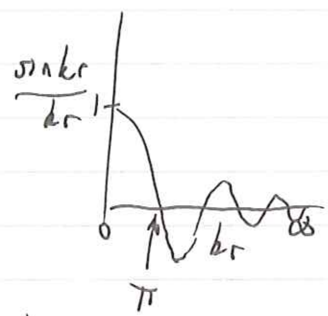
Take 3D Fourier transform:

$$\underbrace{P(\vec{k})}_{\text{power spectrum}} = \int_0^\infty \xi(\vec{r}) \exp(i\vec{k}\cdot\vec{r})\, d^3r$$

$$= 4\pi \int_0^\infty \xi(r)\, r^2 \left(\frac{\sin kr}{kr}\right) dr \quad *$$

$\frac{\sin kr}{kr}$ is a "window function"; it is ≈ 0 for $kr \gtrsim \pi$. So

$$P(k) \approx 4\pi \int_0^{\frac{\pi}{k}} \xi\, r^2 \left(\frac{\sin kr}{kr}\right) dr$$



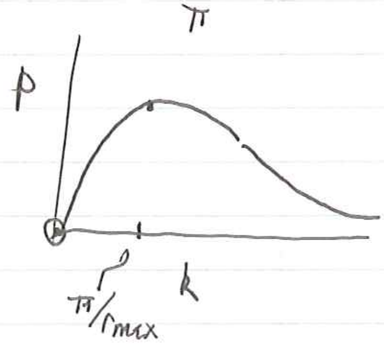
What does $P(k)$ look like?

① If $k=0$, $P(k) = 4\pi \int_0^\infty \xi r^2 dr = 0$

② If $k=\infty$, $P(k) = 4\pi \int_0^0 \xi r^2 dr = 0$

③ As k decreases from ∞, π/k increases, so $P(k)$ increases

④ But if k decreases so much that π/k increases to r_{max} [where $\xi \doteq 0$], $P(k)$ does not increase any more.



$$\boxed{\text{Thus } P(k) \text{ should peak at } k \simeq \frac{\pi}{r_{max}}}$$

In the figure, $P(k)$ does peak at $k \simeq 0.1\ \text{Mpc}^{-1} \rightarrow 0.1 \simeq \frac{\pi}{r_{max}}$

Thus, $r_{max} \simeq 10\pi$ Mpc $= 30$ Mpc ✓

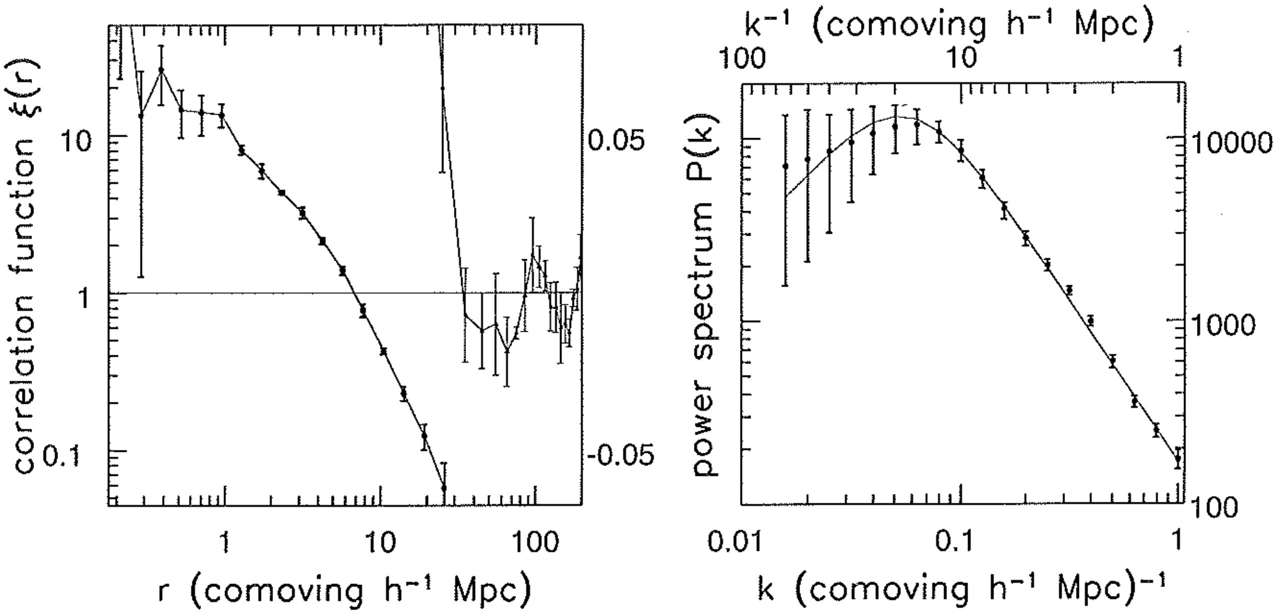


Figure 7.7 Left, correlation function $\xi(r)$ for the Las Campanas galaxy survey, at small separation (left logarithmic scale) and large (right linear scale). Vertical bars show uncertainties; redshifts were converted to distances assuming $\Omega_0 = 1$. Right, power spectrum $P(k)$; the smooth curve shows a fitting function that joins smoothly to constraints from COBE at small k – H. Lin, D. Tucker.