10.1 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 - and could thus bias the measurements of the $H_0$ (which is why we want “far field” measurements)

\[ V_{\text{total}} = V_{\text{Hubble}} + V_{\text{pec,rad}} \]
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
We are moving wrt. to the CMB at ~ 620 km/s  towards $b=27^\circ$, $l=268^\circ$

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 $\sim 50\%$ error in Hubble velocity, and a $\sim 10\%$ error at the distance to Coma cluster.
How to Measure Peculiar Velocities?

1. Using distances and residuals from the Hubble flow:

\[ V_{\text{total}} = V_{Hubble} + V_{pec} = H_0 D + V_{pec} \]

- So, if you know relative distances, e.g., from Tully-Fisher, or \( D_n - \sigma \) relation, SBF, SNe, …you could derive peculiar velocities
- A problem: distances are seldom known to better than \( \sim 10\% \) (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
Redshift Space vs. Real Space

Real space distribution

“Fingers of God”

The effect of cluster velocity dispersion

Spatial depth

Redshift space apparent distrib.

Thin filaments

The effect of infall

Observe d redshift

Position on the sky
Redshift-Space Correlation Function

- Small $\sigma \Rightarrow$ non-linear ‘Finger-of-God’ effect
- Large $\sigma \Rightarrow$ flattening due to coherent infall
- Fit to $r = 8-30 \, h^{-1} \, \text{Mpc}$; (nb: $\langle z \rangle = 0.15$, $\langle L \rangle = 1.4L^*$)
- Distortion parameter
  $\beta = \Omega^{0.6} / b = 0.47 \pm 0.09$
- Pair-wise vel. dispersion
  $\sigma_p = 495 \pm 52 \, \text{km/s}$
- If $b \approx 1 \Rightarrow \Omega \approx 0.21$
- If $\Omega \approx 0.3 \Rightarrow b \approx 12$
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 estimated 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

\[ \begin{align*}
  w_x &= 74 \\
  w_y &= -141 \\
  w_z &= 22 \\
  V_{LG} &= 333 \text{ km s}^{-1} \\
  l &= 265^\circ \\
  b &= 47^\circ \\
  V_{LS} &= 310 \text{ km s}^{-1} \\
  l &= 270^\circ \\
  b &= 5^\circ \\
  V &= 600 \text{ km s}^{-1} \\
  l &= 268^\circ \\
  b &= 27^\circ \\
\end{align*} \]
The “Great Attractor” aka the Hydra-Centaurus Supercluster

30,000 GALAXIES, culled from three standard astronomical catalogues, are shown as dots on this map. The galaxies appear all over the sky except in the so-called zone of avoidance, which corresponds to the plane of our Milky Way galaxy (green horizontal center line). Outside the zone, the galaxies tend to clump near a line that traces out the Supergalactic Plane (purple line).
Local Density and Velocity Fields From Peculiar Velocities of Galaxies
PSCz: The corresponding velocity field
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.
Kaslinsky et al. measured peculiar velocities of clusters, and find that the flow extends to even larger scales, approaching a Gpc – and maybe beyond.

“Dark flow” galaxy clusters and flow direction by distance.
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)
10.2 Bias and the Evolution of Clustering

![Diagrams showing the evolution of clustering at different redshifts (z): (a) z = 3, (b) z = 1, (c) z = 0.5, (d) z = 0.](image-url)
Galaxy Biasing

Suppose that the density fluctuations in mass and in light are not the same, but
\[
\left(\frac{\Delta \rho}{\rho}\right)_{\text{light}} = b \left(\frac{\Delta \rho}{\rho}\right)_{\text{mass}}
\]
Or:
\[
\xi(r)_{\text{light}} = b^2 \xi(r)_{\text{mass}}
\]

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-\(\sigma\) fluctuations are typical, 5-\(\sigma\) 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

<table>
<thead>
<tr>
<th>All particles</th>
<th>1-σ peaks</th>
<th>2-σ peaks</th>
<th>3-σ peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="All particles" /></td>
<td><img src="image2" alt="1-σ peaks" /></td>
<td><img src="image3" alt="2-σ peaks" /></td>
<td><img src="image4" alt="3-σ peaks" /></td>
</tr>
<tr>
<td><img src="image5" alt="Gas/Stars" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image6" alt="Dark Matter" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*(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.
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 \( \epsilon = -1.2 \), clustering is fixed in comoving coords.
If \( \epsilon = 0 \), clustering is fixed in proper coords.
If \( \epsilon > 0 \), clustering grows in proper coords.

• Observations indicate \( \epsilon > 0 \), but not one single value fits all data.
Evolution of Clustering

- Deep redshift surveys indicate that the strength of the clustering decreases at higher redshifts, 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)
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.
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*
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:
  \[
  (\Delta \rho/\rho)_{\text{light}} = b (\Delta \rho/\rho)_{\text{mass}}, \quad \xi(r)_{\text{light}} = b^2 \xi(r)_{\text{mass}}
  \]
  – 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
10.3 Galaxy Clusters: Morphology
Clusters of Galaxies:

• Clusters are perhaps the most striking elements of the LSS
• Typically a few Mpc across, contain \( \sim 100 \) - \( 1000 \) luminous galaxies and many more dwarfs, masses \( \sim 10^{14} \) - \( 10^{15} M_\odot \)
• 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 (\( \sim 80 \) - 85%)
• Only \( \sim 10 \) - \( 20\% \) of galaxies live in clusters, but it is hard to draw the line between groups and clusters, and at least \( \sim 50\% \) 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 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

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.)
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. \textit{quadratically} in the density. \textit{Much less} vulnerable to accidental line-of-sight projection effects
   • \textbf{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
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
Classification of Clusters

Can classify clusters of galaxies according to (i) **richness**, or (ii) **morphology**. No morphological scheme enjoys same support as Hubble’s tuning fork diagram for galaxies. Example:

**Rood and Sastry scheme**

- Dominant central galaxy
- Central binary
- cD
- B
- L
- F
- Flattened distribution
- Irregular distribution
- C
- I

Importance: some clusters have cD galaxies. Expect a range of morphologies because clusters are young, merging systems…
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.
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, relative 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
10.4 Galaxy Clusters: Contents
Hot X-ray Gas in Clusters

- Virial equilibrium temperature $T \sim 10^7 - 10^8$ 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 $\sim 1/3$ 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
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.
Virial Masses of Clusters:

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

\[ E_k = E_p / 2 \rightarrow m_g \sigma^2 / 2 = G m_g M_{cl} / (2 R_{cl}) \]

where \( \sigma \) 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 \( M_{cl} \sim 10^{14} - 10^{15} M_\odot \)

The typical cluster luminosities (\( \sim 100 - 1000 \) galaxies) are \( L_{cl} \sim 10^{12} L_\odot \), and thus \( (M/L) \sim 200 - 500 \) in solar units

\( \rightarrow \text{Lots of dark matter!} \)
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 $10^7 \, ^\circ$K $\Rightarrow$ X-ray gas

- Hydrostatic equilibrium requires:
  $$M(r) = - k T/\mu m_H G \left( \frac{d \ln \rho}{d \ln r} \right) r$$

- If the cluster is $\sim$ 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: $\sim 5\%$
  - Gaseous mass: $\sim 10\%$
  - Dark matter: $\sim 85\%$
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.)
Numerical Simulations of Cluster Formation

Dark Matter

Gas Density

Temperature

Stars

Entropy

Metals

$8h^{-1}\text{Mpc}$

(D. Nagai & A. Kravtsov)
Cluster X-Ray Luminosities Correlate With Mass

... and Temperature
Clusters as Cosmological Probes

• Given the number density of nearby clusters, we can calculate how many distant clusters we expect to see.
• In a high density universe, clusters are just forming now, and we don’t expect to find any distant ones.
• In a low density universe, clusters began forming long ago, and we expect to find many distant ones.

• Evolution of cluster abundances:
  – Structures grow more slowly in a low density universe, so we expect to see less evolution when we probe to large distances.
Clusters as Cosmological Probes

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

\[ \Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.72 \]

\[ \Omega_m = 0.25, \Omega_\Lambda = 0, h = 0.72 \]

\[ N(\Delta M) (h^{-3} \text{Mpc}^{-3}) \]

\[ M_{500} (h^{-1} M_\odot) \]

\[ z = 0.025 - 0.25 \]
\[ z = 0.055 - 0.90 \]
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
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
Clusters of Galaxies: Summary

- Clusters are the largest bound (sometimes/partly virialized) elements of the LSS
  - A few Mpc across, contain $\sim 10^2 - 10^3$ galaxies, $M_{cl} \sim 10^{14} - 10^{15} M_{\odot}$
  - Contain dark matter (\sim 80\%), hot X-ray gas (\sim 10\%), galaxies (\sim 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 $\sim 10 - 20\%$ 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