Previously: **Quasars, Active Galaxies, and Monster Black Holes**

- Discovery of quasars — distant objects that are very bright (Hubble Law and redshift — receding very fast and very far away)
- “Active Galaxies” show evidence for high-energy phenomena in and around a small central engine that drives enormous structures
- Supermassive black holes as the engine for AGN phenomena

Today: **Dark Matter and Large Scale Structure**

- Galaxies are mostly found in groups and clusters
- Clusters are further organized into superclusters
- Dark matter is needed to hold clusters together
- The large-scale structure of the visible Universe shows large voids threaded by filamentary superclusters
The Cosmological Principle

Hubble observed approximately the same distribution of galaxies no matter where he looked.

But this is only part of the picture — if we look more closely, we see something different altogether.
Large Scale Structure

- At smallest scales, there are groups
- Larger scales: galaxy clusters
- Even larger scales: galaxy superclusters
The Local Group

- 3 million light years across (~1 Mpc)
- ~60 members
- Three large spirals (MW, Andromeda, M33)
- Two intermediate ellipticals
- Many dwarf galaxies
- At least 50% mass in MW and Andromeda
Andromeda Galaxy
M33 (Triangulum Galaxy)
Magellanic Clouds (Dwarf Galaxies)
Local Group galaxies are moving toward/around each other

- But how can this be if the Universe is expanding?
- Locally, gravity is stronger than expansion
Local Group galaxies are moving toward/around each other

• But how can this be if the Universe is expanding?
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Hubble expansion
Local Group galaxies are moving toward/around each other

- But how can this be if the Universe is expanding?
- Locally, gravity is stronger than expansion
Gravity is the key to explaining large scale structure

\[ t = 0.1 \text{ Gyr} \]
Galaxy clusters

- Much larger than galactic groups
- 1000s - 10,000s of galaxies!!!
- Typically 5-10 Mpc across (~300 MW’s lined up!)
- Components:
  - cD (central dominant) “cannibal” galaxy
  - other ellipticals closer together - “social ellipticals”
  - few spirals (these are further way) - “shy spirals”
  - lots of interacting galaxies
Ellipticals near center are the result of mergers

“Social ellipticals”

“Shy spirals”
Virgo cluster

- 50 million light years away
- 1000s of members
- M87 (which we’ve seen previously) is at the center
Coma cluster

- 300 million light years away
- Maybe as many as 30,000 galaxies!
- Total mass: $4 \times 10^{15} \, M_{\text{Sun}}$
Galaxy superclusters

• Even larger scales! (~100 Mpc or more)
• Largest structures known in the Universe
• Demonstrated by the “cosmic web”
  • Filaments of galaxies
  • Voids as large as 150 million light years (46 Mpcs)!
  • 90% of galaxies occupy < 10% of volume of space
Galaxy superclusters

$t = 0.1 \text{ Gyr}$
But the mass that we “see” is not enough to account for this gravitational collapse!!!

Dark Matter!
Astro 150 Fall 2020: Lecture 23 page 17

Dark Matter I (brief review)

In spiral galaxies, matter extends well beyond visible disks

90% of all mass in galaxies is DARK
In spiral galaxies, matter extends well beyond visible disks

90% of all mass in galaxies is DARK
Dark Matter Halos
Dark Matter Halos

3 x the size of the MW
Dark Matter II (in galaxy clusters)

• Evidence line #1: Galaxy velocities within clusters
  • typical radial velocities $\sim 1000$ km/s in a big cluster
  • escape velocity (counting galaxies alone) $\sim 300$ km/s

• Evidence line #2: Hot gas between cluster members

• Evidence line #3: Gravitational lensing
Dark Matter II (in galaxy clusters)

• Evidence line #1:
  Galaxy velocities within clusters
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Dark Matter II (in galaxy clusters)

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Dark Matter II (in galaxy clusters)

• Evidence line #1:
  
  Galaxy velocities within clusters
  
  • typical radial velocities ~ 1000 km/s in a big cluster
  • escape velocity (counting galaxies alone) ~ 300 km/s
**Dark Matter II (in galaxy clusters)**

- **Evidence line #1:**
  - Galaxy *velocities* within clusters
  - typical radial velocities \( \sim 1000 \text{ km/s} \) in a big cluster
  - escape velocity (counting galaxies alone) \( \sim 300 \text{ km/s} \)
Dark Matter II (in galaxy clusters)

• Evidence line #1: 
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Dark Matter II (in galaxy clusters)

- Evidence line #1:
  - **Galaxy velocities within clusters**
  - typical radial velocities $\sim 1000$ km/s in a big cluster
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Dark Matter II (in galaxy clusters)

Evidence line #2: Hot gas in galaxy clusters

- $10^8$ K, concentrated at center-of-mass
- Cluster must contain a lot of mass to confine this hot gas - requires more mass than in galaxies alone
- Thermal velocity $\sim 1200$ km/s must be $< v_{\text{esc}}$
Dark Matter II (in galaxy clusters)

Evidence line #3: Gravitational lensing
Gravitational Lensing
Gravitational Lensing
The Bullet Cluster
How much mass is there in dark matter?

<table>
<thead>
<tr>
<th>Type of Object</th>
<th>Mass-to-Light Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1</td>
</tr>
<tr>
<td>Matter in vicinity of Sun</td>
<td>2</td>
</tr>
<tr>
<td>Mass in Milky Way within 80,000 light-years of the center</td>
<td>10</td>
</tr>
<tr>
<td>Small groups of galaxies</td>
<td>50–150</td>
</tr>
<tr>
<td>Rich clusters of galaxies</td>
<td>250–300</td>
</tr>
</tbody>
</table>

*If M/L > 100, then dark matter is present*
The Big Picture

1. Universe started off mostly smooth, with some regions denser than others
2. Regions of higher density (both luminous and dark matter) begin to collapse
3. Collapse proceeds along filaments
4. Smaller objects form first (e.g., dwarf galaxies, globular clusters)
5. Smaller objects merge together to form bigger objects
6. Groups form
7. Clusters form
8. Superclusters form
Before we wrap up, there is one important question to address

What is dark matter?!
Short answer: we don’t know

1. MACHOs (Massive Compact Halo Objects); e.g., black holes without an accretion disk
2. WIMPs (Weakly Interacting Massive Particles)
   (a) Hot dark matter (hot means fast moving)
   (b) Cold dark matter (cold as in slow moving)

Not enough mass in MACHOs

Hot WIMPs would smear out structures -> fewer small galaxies

Cold WIMPs seem to fit best with the observations