Astro 358/Spring 2008 (49520)

Galaxies and the Universe

Figures + Tables for Lecture 7 on Th Feb 14
Lecture 8 on Tu Feb 19
Lecture 9 on Th Feb 21
Dark Matter in Galaxies, Group, and Clusters
Flat rotation curve of Milky Way at large radii $r$, with a circular speed of 220 km/s cannot be accounted for if the total enclosed mass $M(r)$ is made up of only visible mass. It requires a large fraction of $M(r)$ to be dark matter.
Fig. 3.15. Examples of rotation curves of spiral galaxies. They are all flat in the outer region and do not behave as expected from Kepler's law if the galaxy consisted only of luminous matter. Also striking is the fact that the amplitude of the rotation curve is higher for early types than for late types.

Fig. 3.16. The flat rotation curves of spiral galaxies cannot be explained by visible matter alone. The example of NGC 3198 demonstrates the rotation curve which would be expected from the visible matter alone (curve labeled "disk"). To explain the observed rotation curve, a dark matter component has to be present (curve labeled "halo"). However, the decomposition into disk and halo mass is not unambiguous because for it to be so it would be necessary to know the mass-to-light ratio of the disk. In the case considered here, a "maximum disk" was assumed, i.e., it was assumed that the innermost part of the rotation curve is produced solely by the visible matter in the disk.
Figure 5.21 Rotation curves for disk galaxies of various types. Open circles show scale length $h_R$ of the stellar disk, and peak rotation speed $V_{\text{max}}$ for each galaxy. Curves are plotted in units of $R/h_R$, to the same horizontal scale as the inset, showing $V(R)$ for the exponential disk (Equation 5.1). LSB denotes a low-surface-brightness galaxy. The measured rotation does not fall as it should if the stellar disk contained most of the mass – A. Broeils, E. de Blok.
Using gravitational lensing to trace the total (dark+visible) mass of a galaxy cluster

Bottom image: the cluster of galaxies Cl0024+17 ($z = 0.39$) contains a rich system of arcs. The arcs appear bluish, stretched in a direction which is tangential to the cluster center. The three arcs to the left of the cluster center, and the arc to the right of it and closer to the center, are images of the same background galaxy which has a redshift of $z = 1.62$. Another image of the same source was found close to the cluster center. Also note the identical ("pretzel"-shaped) morphology of the images.
Fig. 6.31. The cluster of galaxies Cl2244—02 at redshift $z = 0.33$ is the second cluster in which an arc was discovered. Spectroscopic analysis of this arc revealed the redshift of the corresponding source to be $z_s = 2.24$ - at the time of discovery in 1987, it was the first normal galaxy detected at a redshift $> 2$. This image was observed with the near-IR camera ISAAC at the VLT. Above the arc, one can see another strongly elongated source which is probably associated with a galaxy at very high redshift as well.

Fig. 6.33. Top image: the cluster of galaxies A2218 ($z_d = 0.175$) contains one of the most spectacular arc systems. The majority of the galaxies visible in the image are associated with the cluster and the redshifts of many of the strongly distorted arcs have now been measured. Bottom image: the
• Mass of galaxy cluster
  = 3% stars in galaxies
  = 15% in hot gas \((T>=10^7 \text{ K})\)
  located BETWEEN galaxies, and seen in X-ray. Called the intra-cluster medium or ICM
  = 80% dark matter
• \(\frac{M}{L}\) of cluster  = 300/h Mo/Lo !!
Candidates for Dark Matter
Candidates for Dark Matter

Can rule OUT options below for dark matter candidates:

- high and intermediate mass stars: emits UV, optical light
- low mass stars: emit near-IR light
- hot gas: emits X-ray light
- warm gas and dust: emit mid-IR light
- cold gas: emits radio light
**Candidates for Dark Matter**

**Dark Matter**

- **Baryonic dark matter** (made of n and p)
  - MACHOS (Massive Compact Halo Objects)
    - a. Brown dwarfs or failed stars, planetary bodies
    - b. Dead white dwarfs
    - c. Black holes, neutron stars
    - d. Extremely low-mass stars
- **Non-baryonic dark matter** (contains no n or p)
  - **Cold Dark matter**
    - Massive, slow-moving.
    - Predictions of bottom up or hierarchical formation of structure mostly agrees with observations
  - **WIMPS** (Weakly Interacting Massive Particles)
    - Likely produced right after Big Bang when Universe was very hot and protons had extreme energies
  - **Hot dark matter**
    - Fast-moving \( v \approx c \)
    - Predicts top-down structure formation that disagrees strongly with observations of galaxies, clusters, and superclusters
  - **Neutrinos**
    - Produced
    - when Universe was very hot soon after Big Bang
    - in nuclear reaction of stars

**Leading candidate = Cold dark matter = WIMPS**
Detecting MACHOS in our Galaxy via Microlensing

As light from a bulge star or halo star travels to us, it can be bent by the force of gravity from a passing MACHO if the latter crosses the light's path.

The light gets focused and the apparent brightness of the star increases for a short period until the MACHO moves away.

Results to date: MACHOS make up only a small fraction of the dark matter in Milky Way.
Large Hadron Collider (LHC) will be online in 2008 at CERN, at Franco-Swiss border.

LHC is an accelerator that will collide protons and ions head-on at energies \(E=10^{12} \text{ eV}\) and temperatures \(T = 10^{16-17} \text{ K}\) higher than ever achieved before. These conditions recreate the conditions just after the "Big Bang".

It will characterize WIMPS (WIMPS) are leading candidates for dark matter.
Bottom-Up or Hierarchical Mode of Structure Formation in CDM models
Cold DM models: structure on small scales form first

Matter particles (p,n,e) have emerged over $t=10^{-6}$-1s due to symmetry breaking or the excess of matter over antimatter particles.

Recombination era ($t=3\times10^5$ yr)
Electrons and H+ recombine to form neutral H. The photons no longer trapped by e-, travel freely, causing the Universe to change from opaque to transparent. The photons get redshifted to form the present CMB at $\lambda\sim1.2$ mm and $T=2.7$ K.

Formation of He Li ($t=3$ min): 90% of the He and 10% of the Li nuclei present today form by 3rd min.

Universe transitions from radiation-dominated to matter-dominated. ($t=3\times10^4$ yr)
Matter over-densities collapse on small scales first.

Formation sequence: stars at $t=0.05$-0.1 Gyr, then proto-galaxies ($t=0.3$-0.7 Gyr), then clusters and super-clusters form at $t>5$ Gyr.
Observed structures compared to HDM & CDM models

Structures on small spatial and mass scales (e.g., dwarf galaxies) are seen at early epochs (z~6, age of Universe ~0.9 Gyr)

Hubble Ultra Deep Field imaged in 2004 (Credit: NASA/STScI/HUDF home team)
Observed structures compared to HDM & CDM models

Structures on large scales, such as galaxy clusters (R~few Mpc) and galaxy superclusters (R~10 Mpc) are frequent at late epochs (z<1, age of Univ >5.7 Gyr)

Galaxy cluster with radius ~1.5 Mpc, seen at z=0.33 (age of Universe =9.9 Gyr)

Abell 901/902 supercluster with R~10 Mpc (Xray map) Made of 3 galaxy clusters in the process of assembling Seen at z=0.17 (age of Univ =11.4 Gyr)
(Visible + Dark Matter) vs Dark Energy

1) Matter (dark + luminous) exerts an attractive force of gravity that tries to make the Universe contract.

2) Dark energy is a repulsive force or pressure that acts on large scales, is associated with a vacuum energy and tries to make the Universe expand.

3) The competition between matter (both dark and luminous) versus dark energy determines:
   - the geometry of space (close, flat, open)
   - the ultimate fate of the Universe: whether it expands forever or eventually re-collapse

4) Observations show (dark matter + visible matter + radiation) make up only 30% of the total energy density while dark energy makes up a whopping 70%.

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation like CMB</td>
<td>0.005%</td>
</tr>
<tr>
<td>Visible matter</td>
<td>0.5%</td>
</tr>
<tr>
<td>Baryonic dark matter (e.g., MACHOS)</td>
<td>3.5%</td>
</tr>
<tr>
<td>Non-baryonic cold dark matter (e.g., WIMPS)</td>
<td>26.5%</td>
</tr>
</tbody>
</table>

Total energy density in
(dark matter + luminous matter + radiation) 30.0%
Total energy density in dark energy 70.0%
Before $t=30,000$ yrs, the Universe was radiation-dominated.

At $t=30,000$ yrs, the Universe became matter-dominated and structures (density enhancements, stars, galaxies, clusters) started to grow.

At present times, the Universe is dominated by dark energy.