Astronomy 114

Lecture 32: Large-Scale Structure and Dark Matter

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UMass/Astronomy Department
Announcements

- PS#7: due Today
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- No class this Wednesday 2 May!
- Class evaluations at (about) 2pm
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- Distances to galaxies...
  - Galaxies, Chap. 26
- By the end of next week...
  - Quasars and “Active” Galaxies, Chap. 27
Hubble Law: review

- Redshift of spectral lines: \( z = \frac{v}{c} = \frac{\Delta \lambda}{\lambda_0} \)

- \( v = H_0d \quad H_0 = 70 \text{ km/s/Mpc} \)

- New distance indicator: \( d = zc/H_0 \)
Hubble Law: review

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- Example:
  - Redshift of a galaxy is \( z = 0.1 \)
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- Example:
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  - Recession velocity: \( v = zc = 30,000 \text{ km/s} \)
  - Distance:
    \[
    d = \frac{zc}{H_0} = \frac{30,000 \text{ km/s}}{70 \text{ km/s/Mpc}} = 429 \text{ Mpc}
    \]
CfA redshift diagram
- Sun at center
- Angular position of galaxy determines a ray
- Redshift determines distance along the ray
Superclusters and beyond

- Clusters of clusters
- The Local Group is part of the Virgo Supercluster
- Large-scale structures containing many clusters have been found
Q: Does clustering continue to the scale of the Universe?
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Large Scale Structure
Dark matter again!

- Recall dark matter *problem* in the Milky Way
- Orbital speed of an object around a central mass depends on
  - Its distance from the central mass
  - The total mass enclosed within its orbit
- Found for Milky Way: Mass/Light = 10
  - *Mass-to-light ratio*
  - For each solar luminosity of light detected we find 10 solar masses
- Problem is even worse for clusters of galaxies
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*Dispersion*: variation between the individual and mean speed of galaxies in the cluster.
Mass-to-light ratio (1/2)

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Dispersion: variation between the individual and mean speed of galaxies in the cluster.

Mean or average: \[ \mu = \frac{1}{N} \sum_{i=1}^{N} x_i \]

Variance: \[ \sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^2 \]

Dispersion = \sigma
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Assuming that the galaxies in clusters are gravitationally bound:
- Orbital motions will appear random.
- Speed must be less than the escape speed from the cluster.
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- Fritz Zwicky (1930) measured the dispersion of speeds of galaxies in clusters by measuring their Doppler shifts.

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- The velocity dispersion, then, depends on the mass of the cluster.
Turn the argument around: **maximum speed of the galaxies measures the total mass of the cluster**

- Measure the total luminosity of the cluster
- Compare luminosity to the total mass of the cluster inferred from the dispersion of speeds
- Find: far more mass than would be indicated by the luminosity

**Mass-to-light ratios of clusters generally exceed** $100 M_\odot/L_\odot$
Gravitational Lensing (1/3)

- Most of our methods depend on Newton’s laws
- Independent approach: user General Relativity
- Mass curves space: light is affected
Use this bending to determine the mass of the cluster:

- Find multiple images of a single galaxy created by the gravitational lensing
- Determine the angular distance to the multiple images
- Determine the distance to the distorted galaxy from its recession velocity
- Hubble’s Law determine the distance to the cluster
- Use Einstein’s theory of general relativity to relate the angular separation to the mass of the cluster
Gravitational Lensing (3/3)

Same result!

Clusters contains as much as 10-100 times more dark matter than ordinary luminous matter!
X-ray emission from clusters

- The dark matter halo of galaxy clusters collects hot gas
- Temperature: of 10-100 million K
- Map with X-ray telescopes
- Temperature and extent depends on mass
- Consistent with lensing and dynamical measurements

Cyg A cluster