Today’s Events

- How do we see really far back in time? Quasars and gravitational lensing both help.
- Begin looking at evidence for dark matter in galaxies, and within galaxy clusters.
- Gravitational lensing helps us get information from very distant galaxies – thus look very far back in time.
- Implications for models for our universe.
- Complete reading Chap 22: Dark Matter and Fate of Universe.
- New (and final) Homework Set #12 today.

Thinking clicker – looking back in time

- If we can detect light from a quasar and decide that its emission line spectrum is at redshift $Z = 4$, how much bigger has the universe grown since that light left?
  
  - A. 2 times bigger
  - B. 3 times bigger
  - C. 5 times bigger
  - D. 16 times bigger

Redshift is “expansion factor”

- $1 + Z$ also measures how much universe has expanded.
- $1 + Z$ = \[
\frac{\text{distance between galaxies now}}{\text{distance between galaxies then}}
\]

Cosmological Redshifts (from expansion of universe)

**Definition of redshift:**

\[ Z = \frac{\text{change in wavelength}}{\text{"normal" wavelength}} \]

**Remind:**

- $Z = \frac{\text{observed wavelength}}{\text{"normal" wavelength}}$
- Redshifts always have $Z > 0$ (redder light has larger wavelengths).

Relativistic redshifts

- If $Z$ is big (~2+), use relativistic formula to get velocity $v$ (e.g. $v = \frac{c}{\sqrt{1 - \beta}} - c$ with $\beta = 1/(\sqrt{1 + Z})$).
Quasars reveal: Protogalactic Clouds

- Looking for gas between the galaxies
- Cold, invisible, too dim even at 21 cm
- But quasars provide the way to detect them!

Use quasars as bright beacons — see absorption lines from intergalactic gas

Now to Case for Dark Matter

- > 90% of mass of universe is dark matter (invisible, missing matter)
- Detectable ONLY via its gravitational forces on "light" matter (gas and stars)
  - Note -- this dark matter is NOT the same as black holes, brown/black dwarfs, or dust

REVISIT

Quasar spectra

Redshifts from emission lines + Many absorption lines (forest)

Individual galaxies show it

- Rotation curves: motions of stars in the galaxy
- Reveal that dark matter extends beyond visible part of the galaxy, mass is 10x stars and gas

Flat rotation curve of galaxy

High speeds far from luminous center; means there is dark matter in the outer regions
Spiral galaxy ROTATION CURVES

- Discovered by Vera Rubin in the 1970s
- Highly controversial until many rotation curves confirmed

Galaxy Clusters: reveal dark matter in three ways

- #1: Galaxy velocities too large to be explained by gravity of visible galaxies
- Expected ~100 km/sec for a typical cluster, found 1000 km/sec!
- Discovered in 1930's by Fritz Zwicky (they didn't believe him, either)

# 2: Hot x-ray emitting gas in cluster

- Gas between galaxies is also moving because of gravity of dark matter: gets very hot
- 1000 km/sec → 100 million K: emits x-rays!

# 3: Gravitational Lenses

- Dark (& visible) matter warps space → acts like a lens and distorts and magnifies the view of more distant galaxies
- Can form circular arc segments

Gravitational lensing: how it works

Medley of best HST gravitational lensing
Gravitational lens drifts across your harbor view

Effects of gravitational lensing on background galaxies

Bending of light by cluster Abell 2218

Lensing by massive galaxy cluster Abell 1689

“The Beast”

4 or 5 different galaxies!

Red arc at the bottom: Z = 4.8

Have not gotten the other Z’s yet

Erica Ellingson -- HST
Clicker on galaxy clusters

- Two galaxy clusters are studied. Cluster A has typical velocities for its galaxies of 300 km/sec. Cluster B has 1000 km/sec. Which is most likely?
  - A. Cluster A has more galaxies than cluster B
  - B. Cluster A is more massive than cluster B
  - C. Gas between galaxies in cluster A will have lower temperature than gas in cluster B
  - D. Cluster B galaxies are more likely to be spirals

How much dark matter overall?

- All cluster methods generally agree
- About 10 times as much dark matter as “normal” matter overall in the universe
- Note: Our solar system has much more light matter than dark matter here! (DM probably immeasurable)

What is Dark Matter?

- Two flavors for Dark Matter:
  - Possibility 1. MACHOs
    - Massive Compact Halo Objects
    - Stuff we’ve studied already: very faint, actual things; baryonic matter
    - Brown dwarfs, black holes, black dwarfs … etc.
    - May be floating through the galaxy halo unnoticed
  - Possibility 2. WIMPs
    - Weakly Interacting Massive Particles
    - Non-baryonic $\rightarrow$ subatomic particle
    - Neutrinos? probably not …. they move too fast and cannot be collected into stable galaxy halos
    - Other unknown particles ???
    - Slower particles: “Cold Dark Matter”

MACHO Searches

- Use gravitational lensing
- When a MACHO floats in front of a star, the star suddenly brightens
- Focusing effect of compact massive object
MACHO hunt results: 2005

- MACHOs are detected
- But not enough to explain all dark matter

Models of our universe

Dark matter has big influence on "open" vs "closed"

If enough mass, gravity eventually wins!