Homework #8

- Due Thursday, April 18, 11:59PM
- Covers Chapters 15 and 16
- Read chapters, review notes before starting

Reminder: You can still complete old homeworks for up to 50% credit.
Chapter 16
A Universe of Galaxies
The Cosmic Distance Ladder
The expansion rate appears to be the same everywhere in space.

The universe has no center and no edge (as far as we can tell).

Space *itself* is expanding.

Our space might be infinite, or not, but the Universe is expanding nonetheless.
One example of something that **expands** but has **no center or edge** is the surface of a balloon (2-dimensional example).
Every point on the balloon is moving away from every other point. **Point D** moved away from **Point A** faster than **Point B** moved away from **Point A**. ← Hubble’s Law!
The galaxies themselves are not receding from each other at a high velocity, but **space itself is expanding**, carrying the galaxies along for the ride.
Cosmological Principle

The universe looks about the same no matter where you are within it.

- Matter is evenly distributed on very large scales in the universe.
- Universe has no center and no edges
- Not proven but consistent with all observations to date
Suppose you are an alien in a galaxy far, far away looking at the galaxies in your night sky. What do you see?

A) More galaxies on one side of your Universe than the other.
B) The Universe looks much younger than what we on Earth see.
C) Pretty much the same Universe as we on Earth see.
D) In one direction a location devoid of galaxies that appears to be an edge beyond which there are no galaxies.
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The cosmological principle says the Universe looks about the same no matter where you are in the Universe.
How do we observe the life histories of galaxies?
Deep observations show us very distant galaxies as they were much earlier in time (old light from young galaxies).

Almost like a time machine…
Just a billion years after the Big Bang, galaxies were already full of stars – their evolution had already begun.
Our best models for galaxy formation assume:

- Matter originally filled all of space *almost* (but not quite!) uniformly
- Gravity of denser regions pulled is surrounding matter
At early times (large value of $z$) matter was very uniformly (but not perfectly!) distributed. Slightly over-dense regions condensed into galaxies and clusters of galaxies.

$z=0$ represents today

Larger and larger $z$ represents earlier and earlier times.

A very large, fixed volume cube
Denser regions contracted, forming *protogalactic clouds*.

Hydrogen and Helium gas in these clouds formed the first stars (no heavy elements yet).

Unused gas begins to collapse into a disk (as we have seen before).

Leftover gas (if any) settled into spinning disk.

*Conservation of angular momentum*
Seems like a simple picture.....
But why do some galaxies end up looking so different? Why don’t all galaxies look like the Milky Way and have a disk?

Let’s consider both hereditary (how the galaxy formed) and environmental (how it interacted later) effects.
Spin: Initial angular momentum of protogalactic cloud could determine the size of the resulting disk. ← hereditary

Ellipticals: protogalactic cloud had little angular momentum

Spirals: protogalactic cloud had much angular momentum
Elliptical galaxies could come from dense protogalactic clouds that were able to cool and form stars before gas settled into a disk. More dense cloud → elliptical galaxy (no disk). Less dense cloud → spiral galaxy (disk).
Which type of protogalactic cloud is most likely to form an elliptical galaxy?

A) one that is dense and rotates slowly
B) one that is dense and rotates rapidly
C) one that is diffuse and rotates slowly
D) one that is diffuse and rotates rapidly
Which type of protogalactic cloud is most likely to form an elliptical galaxy?

A) one that is dense and rotates slowly
B) one that is dense and rotates rapidly
C) one that is diffuse and rotates slowly
D) one that is diffuse and rotates rapidly.

The denser it is, the faster it forms stars \(\rightarrow\) no gas left over to form a disk.

The less it rotates, the less chance it spins out a disk.
We must also consider the effects of collisions (environmental).
Collisions were much more likely early in time, because galaxies were closer together (Universe was smaller).

Many of the galaxies we see at great distances (and early times) do indeed look violently disturbed.
The collisions we observe nearby trigger bursts of star formation – some are called **starburst galaxies**.
Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical.

This is an environmental way to make an elliptical.
Collisions probably explain why elliptical galaxies tend to be found where galaxies are closer together (at the centers of rich clusters of galaxies).
What are quasars/active galactic nuclei?
If the very center of a galaxy is unusually bright, we call it an **active galactic nucleus (AGN)**.

Quasars are the most luminous examples of AGN.

AGN are rare (1% of all galaxies).
From brightness and distance, we find that luminosities of some quasars are $1 \text{ trillion } L_{\text{sun}}$ -- most luminous individual objects in the Universe!

Time variability shows that all this energy comes from a region the size of our Solar System or smaller $\Leftarrow$ what can generate such energy?
An active galactic nucleus can shoot out massive **blobs of plasma** moving at nearly the speed of light.

The speed of ejection again suggests that a **powerful mechanism** is present. What is it?
What is the power source for quasars and other active galactic nuclei?

The accretion (eating) of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars/AGN.
Orbits of stars at center of Milky Way indicate a black hole with mass of 4 million $M_{\text{Sun}}$.

But our black hole is quiet – not eating gas (not an AGN/quasar)

What about other galaxies?
Orbital speed and distance of gas orbiting center of M87 galaxy indicate a black hole with mass of 6.5 billion $M_{\text{Sun}}$ (utilizing Newton’s gravity laws). This sounds large, but is still a small fraction of the mass of the galaxy (think mass of your hair vs. mass of your body).
We can actually see black holes now!

In 2019, the Event Horizon Telescope imaged a black hole for the first time ever in M87 (left), compared to Milky Way’s black hole (right).
If supermassive black holes did not exist, which of the following would be true?

A) Stars/gas at the very centers of galaxies would not orbit so fast.
B) AGN/quasars would not exist.
C) Galaxies would become "unglued" since the decreased gravity wouldn’t be able to hold the galaxy together.
D) Both A) and B) are correct.
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D) Both A) and B) are correct.

AGN/quasars are powered by black holes, but black holes are not responsible for the vast majority of the self-gravity of a galaxy.
Most galaxies—perhaps all of them—have supermassive black holes at their centers.

These black holes seem to be dormant active galactic nuclei in most galaxies. Most black holes are not being fed enough gas to trigger an AGN phase.

All galaxies may have passed through an AGN/quasar-like stage earlier in time.

Most galaxies are not currently in their “active” AGN phase (only ~1% are active now). Did the Milky Way have an AGN in the past? Possibly! It just does not currently have one since its massive black hole is not being fed.
Chapter 16 Study Guide

1) Galaxies help us investigate cosmology, or the study of the structure and evolution of the Universe.

2) Three main types of galaxies: spirals (ongoing star formation, young+old stars, gas/dust), ellipticals (no recent star formation, only old stars, no gas/dust), and irregulars (ongoing star formation, young+old stars, gas/dust).

3) Spirals: disk component (star formation) + spheroidal component (bulge+halo+globular clusters - no star formation).

4) Ellipticals: only a spheroidal component (no star formation) – “red and dead”.

5) Spirals generally reside in sparse groups, ellipticals reside in rich clusters.
Chapter 16 Study Guide

6) We get the distance of all astronomical objects from the cosmic distance ladder: radar (to get AU) \(\rightarrow\) parallax \(\rightarrow\) star cluster main sequence fitting \(\rightarrow\) Cepheids (gets us out to other galaxies) \(\rightarrow\) white dwarf supernova, Hubble’s Law (gets us to other side of Universe)

7) Each step of the cosmic distance ladder is dependent on the correct calibration of the step preceding it

8) Edwin Hubble discovered that nearly all galaxies are moving away from our Milky Way galaxy at a velocity that increases with how far away the galaxy is: Hubble’s Law:

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\text{velocity} = H_0 \times \text{distance } \quad (H_0 \text{ is Hubble’s constant})
\]

9) If you can measure the recessional velocity of a galaxy from the redshift of its spectral features, you can get its distance from Hubble’s Law.
10) The Universe is about 14 billion years old.

11) Space itself is expanding, taking the galaxies along for the ride, so it appears the galaxies are moving away from us (think of flat stickers on an expanding balloon – 2-d example)

12) Cosmological Principle: (1) Matter (galaxies) are evenly distributed throughout the Universe; (2) Universe has no center or edge → no special place in the Universe

13) Galaxies formed from very slight over-densities of gas in the very early Universe → gravity magnified these over-densities, leading to collapse of protogalactic clouds

14) Spirals formed from more diffuse, faster spinning clouds, while ellipticals formed from dense, slower spinning clouds (hereditary)
15) Colliding spirals can form an elliptical (particularly in small, early Universe and in centers of rich galaxy clusters) – environmental – form central dominant elliptical galaxies in clusters by galactic cannibalism

16) Active galactic nuclei (AGN) and quasars generate a tremendous amount of energy at the centers of a small percentage of galaxies.

17) 1 trillion Suns energy generated in a region the size of a solar system in a quasar, also blobs of gas can be ejected at very high velocities → must be powered from accretion onto a supermassive black hole

18) All galaxies have central black holes, but only 1% are active AGN/quasars → needs a trigger