Dark Energy and Dark Matter
Attendance Quiz

Are you here today?
(a) yes
(b) no
(c) The Dark Lord wants his ring back!

Here!
Final Exam

• The final exam is **Thursday, 6/8**, from 11:30am to 1:30pm (2 hours), in this room; please arrive early!
• The final exam will be comprehensive, i.e., it will cover all the material you have studied this quarter
• It will be multiple choice, so make sure to bring a 100-question (2-sided) scantron to class!
Today’s Topics

- Hubble’s Law
  - The Age of the Universe
  - Dark Energy and the Fate of the Universe
- Dark Matter
- Composition of the Universe
- The Growth of Structure in the Universe
Hubble’s Law and the Age of the Universe

- Hubble’s Law tells us that all galaxies are moving apart at a rate proportional to their separation distance.
- The slope of this relationship is called Hubble’s Constant, or $H_0$.
- If that rate stayed the same throughout the history of the universe, we could run a “movie” of the universe backwards to find out when all the galaxies were on top of each other.
- The faster the galaxies are receding now (the larger $H_0$), the shorter the time until the “movie” reaches its beginning.
- Thus, the age of the universe is proportional to $1/H_0$.
- This simple calculation gives an age of the universe of 13.6 billion years.

Interactive Figure 1: Estimating Age of the Universe
Interactive Figure 2: Dependence of Age on $H_0$
Cosmology Quiz III

Astronomers currently believe that the Hubble constant has a value of about 22 km/s/Mly. If some new measurement revealed that instead the Hubble constant is closer to 5 km/s/Mly, what would this imply about the age of the universe?

a) It is much younger than current estimates
b) It is much older than current estimates
c) This change would have no effect on estimates of the age of the universe
Hubble’s Law and the Age of the Universe

• However, it is not true that the rate of expansion hasn’t changed
• Gravity has slowed the rate of expansion (like a ball thrown in the air), so the expansion would have been faster in the past, suggesting the universe is younger than 13.6 billion years; the more matter, the younger the universe
• If something were able to speed up the expansion, then the expansion would have been slower in the past, meaning the universe is older than 13.6 billion years
Acceleration of the Universe and Dark Energy

- White dwarf (Type I) supernovae now provide evidence that the universe \textit{did} expand slower in the past, meaning \textit{something} accelerated the expansion rate - and implying an age of \textbf{\~14 billion years} for the universe. What is this \textit{something}?
- No \textit{known} force could push the galaxies apart so they move faster with time
- Because this acceleration implies large amounts of energy, but the material responsible is not seen (by EM waves), astronomers have dubbed it \textbf{dark energy}
Cosmic tug of war

The force of dark energy surpasses that of dark matter as time progresses.
Dark Energy and the Cosmological Constant

- When Einstein developed General Relativity, he applied it to the universe as a whole and found that the universe would start contracting, due to gravity’s distortion of spacetime.
- He was troubled by this, and introduced a *repulsive* term into his equations, dubbed the *cosmological constant*.
- This is a constant density of energy in the universe that exerts a negative pressure, counteracting gravity.
- When Hubble showed the universe was expanding, Einstein realized his arbitrary term wasn’t needed, calling it his “greatest blunder.”
Dark Energy and the Cosmological Constant

- Theorists have now reintroduced this term into the equations to explain the acceleration seen in the supernova data.
- Some theorists have introduced another term to describe what might cause the acceleration, *quintessence*.
- This is the name for a quantum field whose effects (unlike the cosmological constant) can vary in space and time, and which has a slightly smaller effect.
- However, it is still unknown what causes this acceleration, or its nature (e.g., does it change in time) and *dark energy* is simply a name for a mystery still to be solved as we learn more.
Composition of the Universe

- **Dark energy** accounts for 70% of the substance of the universe!
- However, although we are confident it exists, this is just a *name* for something whose nature we still don’t understand.
- Does dark energy fill all space uniformly? Do its affects vary with space and time?
Dark Matter

- Even before astronomers discovered dark energy, there was evidence for another mysterious substance known as **dark matter**
- This material makes up another 25% of the universe
Galaxy Rotation Curves and Dark Matter

- Evidence for **dark matter** comes from measured rotation rates (using Doppler shifts) of galaxies as a function of distance from the center.

Active figures (Ch. 22 MGR, SS, SG)

- Astronomers discovered something surprising, namely that the speed of stars and gas in the outer parts of all galaxies remains constant or flat as far as could be measured.
- This differs from the solar system, where speed decreases with distance.
- This implies that, unlike the solar system, where most of the mass is in the Sun, galaxy mass is more distributed.
- In fact, the speed is so high that it can’t be accounted for by all the visible mass in the galaxy.
Lecture Tutorial:  
*Dark Matter*, pp. 143-147

- Work with one or more partners - not alone!
- Get right to work - you have 15 minutes
- Read the instructions and questions carefully.
- Discuss the concepts and your answers with one another. Take time to understand it now!!!!
- Come to a consensus answer you all agree on.
- Write clear explanations for your answers.
- If you get stuck or are not sure of your answer, ask another group.
- If you get really stuck or don’t understand what the Lecture Tutorial is asking, ask me for help.
Galaxy Clusters and Dark Matter

- Similar evidence from speeds of galaxies in clusters suggests that there is 5 times as much dark matter in clusters as in a single galaxy.
- Thus, there is 50 times as much dark matter in galaxy clusters as is seen in stars, gas, and dust.
- Further evidence for dark matter in galaxy clusters comes from hot gas surrounding these clusters, and from gravitational lensing around clusters.

Active Figure 22.9

- All of these measures suggest equal amounts of dark matter, lending great credence to dark matter's existence, in spite of the mystery as to its nature.
What is Dark Matter?

- Could dark matter be burned out WDs, NSs, BHs, brown dwarfs, asteroids and other objects made of ordinary matter too cold to emit light?
- There *is* evidence for such Massive Compact Halo Objects (MACHOs), but not enough to explain more than 20% of the total amount of dark matter.
- The likeliest candidate for the remaining dark matter is Weakly Interacting Massive Particles (WIMPs).
- These particles are electrically neutral (hence no EM radiation), but massive enough to make stars and galaxies move faster than expected.
- These are subatomic particles, massive only compared to their very light or massless cousins, neutrinos.
• Together, dark energy and dark matter account for 95% of the substance of the universe
• Less than 5% of the universe (the entire part we can see) is in the form of “ordinary matter”, stars, gas and dust, plus a tiny fraction of the heavy elements that make up the Earth and those who live on it
Gravity binds all systems together in the Universe (stars, solar system, galaxies, clusters of galaxies, …)
All these objects started as small density enhancements in gas clouds (on different scales) that grew by self-gravity to become a (star, galaxy,…)
As the Universe expands, small density enhancements pull matter together locally, even as the overall space gets larger (like the balloon)
These deviations from the “Hubble flow” appear as peculiar velocities
Note that locally (~600 Mly), galaxies tend to flow towards regions of already high density - superclusters!
Dark Matter and Structure in the Universe

- On even larger scales we also see structure
- Note the CfA Great Wall approximately 500 Mly long, and the Sloan Great Wall approximately a billion light years long!
The Sloan Digital Sky Survey is the largest astronomical survey in history. It uses a 2.5-m dedicated telescope in New Mexico to survey a quarter of the entire sky using two instruments. A 120-megapixel camera can image 1.5 square degrees of sky at a time, about eight times the area of the full moon. A pair of spectrographs fed by optical fibers can measure spectra of (and hence distances to) more than 600 galaxies and quasars in a single observation. For each patch of sky observed with the spectrograph, a custom plate is made with holes drilled at the positions of each galaxy. Fiber optics are fed from each hole to the spectrograph, allowing multiple spectra to be observed simultaneously. The survey will measure the spectra, and therefore redshift and distances to over a million galaxies!
Growth of Large Scale Structure

- Computer models can show how gravity leads to the growth of such structures over time
- However, such models need dark matter (~90% of the matter that “feels” gravity) to work

- 0.5 billion years
  - 13 million light-years

- 2.2 billion years
  - 35 million light-years

- 5.9 billion years
  - 70 million light-years

- 8.6 billion years
  - 93 million light-years

- 13.7 billion years
  - 140 million light-years

*Not to scale*
Growth of Large Scale Structure

$Z = 28.62$
Hubble Ultra Deep Field (10,000 galaxies)
The Beginning of Time

- As we look at distant galaxies, we are looking back in time, due to the finite speed of light.
- Thus, when we see a galaxy 13 billion light years away, we are seeing it as it was 13 billion years ago.
- Since the expansion rate of the universe tells us the universe is about 14 billion years old, we are seeing these galaxies very early in the history of the universe.
Lookback Time Quiz I

Fourteen years ago, a quasar was observed that was found to be located 8 billion light years away. If our universe is approximately 14 billion years old, when did the quasar emit the light that we observed?

a) 14 years ago  
b) 6 billion years ago  
c) 8 billion years ago  
d) 14 billion years ago
Lecture Tutorial:
*Looking at Distant Objects*, pp. 149-150

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Homework

- For homework, complete the ranking task “Stellar Evolution and Lookback Time” on course website
Dark Matters video