23.3 Dark Matter and Galaxy Formation

- Our goals for learning:
  - What is the role of dark matter in galaxy formation?
  - What are the largest structures in the universe?
What is the role of dark matter in galaxy formation?
Gravity of dark matter is what caused protogalactic clouds to contract early in time.
WIMPs can't collapse to the center because they don't radiate away their orbital energy.
Dark matter is still pulling things together.

After correcting for Hubble's law, we can see that galaxies are flowing toward the densest regions of space.
What are the largest structures in the universe?
Maps of galaxy positions reveal extremely large structures: **superclusters** and **voids**.
As the universe expands over time, denser regions draw in more and more matter, creating a “lumpy” distribution.

Models show that gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.
Models show that gravity of dark matter pulls mass into denser regions—universe grows lumpier with time.
Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.
23.4 Dark Energy and the Fate of the Universe

Our goals for learning:

- Why is accelerating expansion evidence for dark energy?
- Why is flat geometry evidence for dark energy?
- What is the fate of the universe?
Why is accelerating expansion evidence for dark energy?
Does the universe have enough kinetic energy to escape its own gravitational pull?
The fate of the universe depends on the amount of dark matter.
Since the amount of dark matter is ~25% of the critical density, we expect the expansion of the universe to overcome its gravitational pull.
In fact, the expansion appears to be speeding up!

Dark energy?
Estimated age depends on the amount of both dark matter and dark energy.
Thought Question

Suppose that the universe has more dark matter than we think there is today. How would this change the age we estimate from the expansion rate?

A. The estimated age would be larger.
B. The estimated age would be the same.
C. The estimated age would be smaller.
Thought Question

Suppose that the universe has more dark matter than we think there is today. How would this change the age we estimate from the expansion rate?

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B. The estimated age would be the same.
C. The estimated age would be smaller.
The brightness of distant white dwarf supernovae tells us how much the universe has expanded since they exploded.
• An accelerating universe best fits the supernova data.

The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.

Plotting actual supernova data on this graph shows that the data fit the accelerating model best.

If the accelerating model is correct, then the universe must be nearly 14 billion years old.

time in billions of years

(lookback times for supernovae based on apparent brightness)
Why is flat geometry evidence for dark energy?
Measurements of the cosmic microwave background indicate that the universe has a flat geometry, thus dark energy is needed to fill out the remaining mass-energy.
What is the fate of the universe?

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The average distance between galaxies (based on redshift)

Time in billions of years

Past

Now

Future

10

0

-4.4

-8.8

-13.0

14

past

future

looking back for supernovae based on apparent brightness
The eventual fate of the universe depends upon the rate of the acceleration of the expansion.

If the universe does not end in a Big Rip, it should keep expanding for a very long time. (Forever?)

All matter will eventually end up as part of black holes, which will, if Stephen Hawking is right, will eventually evaporate.
What have we learned?

- **Why is accelerating expansion evidence for dark energy?**
  - In the absence of the repulsive force of dark energy the expansion of the universe not be accelerating.

- **Why is flat geometry evidence for dark energy?**
  - Evidence from the CMB indicates that the universe is very near critical density, requiring an additional contribution to the mass-energy of the universe.
What have we learned?

- What is the fate of the universe?
  - The universe should keep expanding indefinitely, the universe eventually consisting of a dilute sea of fundamental particles.