The Story of Galaxy Formation in Our Universe:

The Onset of Galaxy Formation

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Lecture Plan

- Evidence for the Expanding Universe (4/16)
- What is the Universe made of? (4/23)
- Seeds of Galaxy Formation and the Development of Structure (4/30)
- The Age, Shape and Expansion History of the Universe (5/7)
- The Onset of Galaxy Formation (Today)
- Creating the Galactic Zoo: Galaxy Interactions and the Hubble Sequence (5/21)
- Research Frontiers in Galaxy Formation (5/28)
- Beginning to End (6/4)

The Universe at 400,000 years

Dark Matter in the Universe today

The Universe at 400,000 years

Galaxy Light in the Universe today
Galaxies change with environment

Galaxies change with wavelength

Galaxies change with time

Galaxy Evolution
Why are there galaxies at all?
Groups of ~100 billion stars, separated by large distances

Questions about the onset of Galaxy Formation
- How did dark matter and gas separate?
- How did the first stars form?
- How did the process of galaxy formation begin, and how does it change with time?

Questions about Galaxy Formation and Evolution
- How do galaxies form, and how do they change over time?
- Why do we see so many different kinds of galaxies? Are their differences a result of ‘nature’ or ‘nurture’?
- How do the properties of galaxies depend on their environment?
- How do galaxies observed at different epochs relate to one another?

The prevalence of Dark Matter
- ~85% of the matter in the universe is dark
- ~spherical dark matter “halo” surrounding each galaxy
- What caused this configuration?

In the beginning...
- The Universe started out very hot and dense, and very smooth
- Most of the mass was in the form of invisible dark matter, and the rest was hydrogen and helium gas.
- Initially, the dark matter and gas were distributed in the same way throughout space.

The Force of Gravity
- Small lumps (inhomogeneities): some regions of the Universe were slightly denser than others
- At ~100,000 years after the big bang, these lumps were one part in 10,000
- As the Universe expanded, these lumps grew larger and denser because of the force of gravity
collapse of density perturbations

Cosmological Expansion

Gravity

over-densities grow into gravitationally bound structures.
regions where space & mass are no longer moving with the “hubble flow” ...

small initial lumps are amplified by gravity

How do dark matter and normal matter separate?

The “normal” stuff (hydrogen and helium gas) can cool!

These gravitationally bound structures occur at the peaks in the density distribution

Clumps gain angular momentum from interactions and “tidal torques”
gas collapses to form a disk

As the gas cools and forms a disk, it eventually gets dense enough to form stars

Conditions for the formation of the first stars
- The conditions for first star formation are very different than those of today.
- Remember that the Universe has only H and He at this time. In addition, the density contrasts are much smaller and dark matter and baryons are extremely well mixed.
- The first star is likely to be very massive: 100-1000 times more massive than the sun

The life and death of the first stars
- The first star in a region will be very massive (very short lifetime) and will probably explode in a gigantic supernova explosion
- During its brief life (a few million years) and violent death, it will create heavier elements, that will get blown out in the supernova and will polute the surrounding gas
- The supernova remnant may collapse to become a black hole, providing the seeds for supermassive black holes at the centers of today’s galaxies

Supernovae heat the surrounding gas

no SN with SN
Risa H! Wechsler Spring Compton Lectures

supernovae “feedback”
an important process in galaxy formation: more on this next time!

What about the second generation of stars?

- Since the first star has no metals, it burns at very hot temperatures. This very hot star produces energetic ionizing photons, which ionize the surrounding gas
- The supernova from the first star has polluted the surrounding gas with metals
- Metals lead to more efficient cooling, and may accelerate this early star formation

Reionization

- star or quasar
- gas is neutral before the stars start forming (no free electrons)
- energetic photons produced by young, hot stars or quasars ionize the surrounding hydrogen gas
- first stars and/or quasars ionize bubbles
- larger objects become common
- ionized regions begin to overlap
The end of the "dark ages"

When did this reionization occur?
Various ways to probe the history of the Universe

- direct imaging of distant galaxies, quasars, supernovae, etc.
- probing the gas between galaxies via quasar spectra
- observations of the Cosmic Microwave Background (CMB)

The Lyman-α Transition

The 'Lyman alpha forest' tells us that most of the gas in the universe was re-ionized sometime before $z \sim 6$. ...
Probing reionization with the CMB!

Can we really get more information from this picture???

Polarization of light from the Big Bang

- a preferred direction of "wiggle" for photons
- sunlight can become polarized by scattering from dust or water – polarizing sunglasses reduce the glare
- about 15% of the light detected by WMAP is polarized
- CMB photons can become polarized by scattering on free electrons (i.e. ionized gas)

The longer the distance traveled by CMB photons through ionized gas, the more likely they are to have scattered off of free electrons

This scattering polarizes the CMB photons, so the earlier reionization happened, the higher the polarization signal will be

the WMAP polarization results suggest that reionization took place at z~17 (but still uncertain!)
Big Surprise!

- SDSS quasar observations were interpreted as showing that the Universe was neutral at $z>6$
- Early theoretical simulations had predicted that reionization should happen between about $z=13$ and $z=8$
- If these results are correct, it indicates that the reionization history of the Universe must be complicated

Still to come:

- Galaxy merging
- How do galaxies consume their gas and form stars over time?
- What is the role of supernovae and black holes in galaxy formation

Next Week:
Creating the Galactic Zoo:
Galaxy Interactions
and the Hubble Sequence