Previously: **Dark Matter and Large Scale Structure**

- Galaxies are mostly found in groups and clusters
- Clusters are further organized into superclusters
- Dark matter is needed to hold clusters together
- The large-scale structure of the visible Universe shows large voids threaded by filamentary superclusters

Today: **Cosmology I - The Age of the Universe and the Big Bang**

- Cosmology - answering questions about the origin of the Universe and answering them using observations
- Independent measurements all yield an age of the Universe of about 13.5 billion years
- Time began with a hot Big Bang - expansion and cooling until today
- The Big Bang makes several predictions that can be tested
Cosmology

• The study of the overall structure and history of the Universe

• What caused the Large Scale Structure
  • How did the first galaxies form?
  • When did the first galaxy clusters form?
  • What happened before there were galaxies?

• We live in an expanding universe
  • How long has it been expanding?
  • What caused the expansion?
  • Will it expand forever?

• The Universe is VERY big
  • Is it truly infinite or is there an “edge”?
  • Are there other universes?
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Addressed (most of) this last time!
Gravity is the key to explaining large scale structure

$t = 0.1 \text{ Gyr}$
Cosmology

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Gravity says that the Universe should collapse in on itself!
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Einstein did not like this and proposed a “cosmological constant”
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Instead, expansion is overpowering gravity

• When it was discovered that the Universe is expanding, Einstein was forced to concede his notion
• An example of how science works!
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Hubble expansion
But *why* is the Universe expanding?
A simpler picture of the Big Bang (for now)
How long did it take for the Universe to expand to its current size?

Now

Big Bang

$t = ?$
How long did it take for the Universe to expand to its current size?

\[ t = \frac{d}{v} \]

- \( t \) is the time taken
- \( d \) is the distance to a galaxy
- \( v \) is the velocity of expansion
How long did it take for the Universe to expand to its current size?

$H$ is the Hubble constant (this is just the Hubble expansion)

$t = \frac{d}{v}$

$v = H \times d$
How long did it take for the Universe to expand to its current size?

\[ t = \frac{d}{v} \]

\[ v = H \times d \]

\[ t = \frac{d}{H \times d} \]
How long did it take for the Universe to expand to its current size?

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$t = \frac{d}{H \times d}$
How long did it take for the Universe to expand to its current size?

\[ t = \frac{d}{v} \]

\[ v = H \times d \]

\[ t = \frac{d}{H \times d} = \frac{1}{H} \]
The age of the Universe (aka the Hubble time)

Big Bang

Now

\[ t = \frac{1}{H} \]

The Hubble Time

\[ H = 70 \text{ km/s/Mpc} \]

\[ t \approx 13 \text{ billion years!} \]
But this only applies for a constant rate of expansion.
Universe’s expansion is actually **accelerating!!!**

(more on this in Lecture 26)

- Expansion started to slow down
- But “dark energy” eventually starts speeding things up
- As a happy coincidence, these factors sort of cancel
- Age of the Universe is **13.8 billion years**
The age of the Universe
(by looking at the oldest objects)

Age of globular clusters: ~13 billion years — consistent!
Looking for hints of the Big Bang (and a review of look back time)

- More distant galaxies - longer time for light to reach us
- We see distant galaxies as they were when light left them
Hubble Deep Fields

Hubble Deep Field
(500 million years after the Big Bang)

Hubble Ultra Deep Field
The furthest one can see in visible light
Hubble Ultra Deep Field in the IR
No galaxies beyond this point
We can’t see all of the way back to the Big Bang, but we can get close!

• The universe is only 380,000 years old (a baby!)
• Redshifted into the microwave part of the spectrum by expansion
• Called Cosmic Microwave Background (CMB)
Is there an “edge” to the Universe?

- **Olbers’ Paradox**
  - assume: infinite Universe
  - assume: uniform distribution of matter (on large scales)
  - consequence: all lines of sight end on a star
  - consequence: whole sky should be as bright as the Sun
  - Dark night sky $\rightarrow$ Universe has an “edge”

- **The Edge (or Horizon)**
  - back in space = back in time
  - beyond $\sim$14 billion light years $\rightarrow$ no stars
  - is this a physical edge? No
  - viewed from anywhere, $R_{univ} = 14$ billion ly
The Universe was hotter in the past
The Universe was hotter in the past
The very hot very early Universe

Energy (radiation) and mass were in equilibrium
Testing the Big Bang Idea

• Big Bang Nucleosynthesis
  • production of light elements in the early Universe

• Remnant radiation from primeval fireball
  • universal background radiation

• Origin of Cosmic Structures
  • formation of galaxies and huge superclusters in an expanding Universe
Big Bang Nucleosynthesis

- **Earliest minutes**
  - H, deuterium
  - $\text{He}^3$, $\text{He}^4$

- **Expansion and cooling**
  - halts further fusion

- **net Big Bang production**
  - $\sim 75\%$ Hydrogen
  - $\sim 25\%$ Helium
  - $< 0.1\%$ lithium, beryllium, etc.

- **Matches composition of the oldest stars!**
Testing the Big Bang Idea

Big Bang Nucleosynthesis
- production of light elements in the early Universe

Remnant radiation from primeval fireball
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Origin of Cosmic Structures
- formation of galaxies and huge superclusters in an expanding Universe