Lecture 33: Einstein’s Universe
Readings: Sections 28-1 and 28-2

Key Ideas:
Cosmological Principle:
  The Universe is *Homogeneous* and *Isotropic* on Large Scales
  No special places or directions
General Relativity predicts an expanding Universe
Einstein’s Greatest Mistake (?)

Cosmology

*Cosmology* is the study of the Universe
  Physics of the Universe
  Distribution of objects on all scales
  Motions of objects in the Universe
  Evolution of the Universe
  Age, Origin, and Fate of the Universe

The Universe in 1917

Einstein explored the cosmological implications of General Relativity

Observational State in 1917
  Kapteyn model of the Milky Way was favored by some (but not all) astronomers.
  No agreement on the “spiral nebulae”
  First good calibrations of the P-L relations for Cepheids and RR Lyrae variables

The Cosmological Principle

*The Universe is Homogeneous and Isotropic on the Largest Scales*
Critical assumption underlying Cosmology.

*Homogeneous*
  No special places in the Universe
*Isotropic*
No special directions

Largest Scales
Average out small-scale details

Homogeneity

When viewed on the largest scales:
  The average density of matter is about the same in all places in the Universe
  The Universe is fairly smooth on large scales
Does not apply locally:
  We see planets, stars, galaxies in regions nearby in space
  The Universe is locally rather “lumpy”

Example from the Distribution of Galaxies about the scales we are talking about (~100 Mpc)

Isotropy

When viewed on the largest scales:
  The Universe looks the same to all observers
  The Universe looks the same in all directions as viewed by a particular observer
Does not apply locally
  We see different numbers of local objects in different directions.

The Dynamic Universe

Einstein applied the Cosmological Principle to General Relativity and got a surprise:

  The spacetime of the Universe could not be static and unchanging
  The Universe must either expand or contract!

In 1917, astronomers assured him that no such general motion was observed

The Cosmological Constant

To make the Universe static, Einstein added a new term to his equations:
The Cosmological Constant, \( \Lambda \):
  Repulsive gravitation-like force term
Arises from empty space
Balances the effects of gravity
At this time, there was no physical reason to introduce a Cosmological Constant

**Cosmic Expansion**

1914-22: Vesto Slipher, Lowell Observatory measured the radial velocities of the brightest “spiral nebulae”

Results:
21 out of 25 spirals showed a systematic redshift
   Systematic motion away from us
   Some velocities are large: > 2000 km/sec

**Einstein’s Greatest Blunder…**

1920s:
   DeSitter corrects an error in Einstein’s math, showing that the \( \Lambda \) Universe was unstable

   Friedmann & Lemaitre showed that without \( \Lambda \), GR predicts that the Universe expands.

Edwin Hubble firmly established cosmic expansion observationally in 1929.

**State of the Art**

Einstein’s guess about the homogeneity and isotropy of the Universe was brilliant and far ahead of the scanty empirical data of his time.

Modern observations bear out large-scale homogeneity & isotropy on average
   Large-scale galaxy surveys
   Cosmic Microwave Background

**Modern Cosmological Constant**

In modern cosmology, \( \Lambda \) reappears in modified form as the “vacuum energy” of space:

   Quantum ground-state of empty space
Acts as an extra pressure on the Universe

**Distinction**
Actually accelerates the expansion!
Increasing observational evidence that $\Lambda$, or something very like it, may be real