Lecture 4: The Age, Shape, and Expansion History of the Universe

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1 Key Concepts

1.1 Expansion history, density, and geometry

- The expansion history of the Universe is determined by the combination of the matter density and the curvature
- A universe with less than the critical density is “open”, it will expand forever
- A universe with more than the critical density is “closed”, it will eventually recollapse
- A universe with exactly the critical density is “flat”, will expand forever, but is asymptotically approaching a zero expansion rate. Inflation predicts a flat Universe.

1.2 Measuring the matter density

- In clusters, expect the baryon fraction to be the universal value. Can measure this number, get a limit that $\Omega_m < 0.3$.
- Can use clustering to measure this: more matter results in faster evolving structure, more clustered today.

1.3 Measuring the expansion rate

- Need a standard candle: can measure the distance by how much the brightness changes.
- The apparent brightness of a standard candle will fall off as distance squared.
- Nearby, can use Cepheid variable stars, whose luminosity is related to their period
- Farther away, can observe bright Supernovae. Type Ia Supernovae are an excellent standard candle, and can be observed over more than half of the Universe.

1.4 The accelerating Universe

- Measurements of distant supernovae over half of the history of the Universe show that the Universe is currently accelerating
- This implies some repulsive force of space, which we now call “dark energy”
• Measurements of a flat Universe from the CMB + a matter density which is much less than 1 also imply this extra energy
• This is fully consistent with general relativity; a term with constant “dark energy” was originally introduced by Einstein to maintain a static Universe.

1.5 The nature of dark energy
• The existence of dark energy implies that the vacuum (empty space) has energy
• This energy is repulsive: it counteracts the affects of gravity
• Dark energy is smoothly distributed through space
• Dark energy is either constant or slowly changing.

1.6 A consistent picture
• The cosmic microwave background shows that the Universe is flat
• Measurements of clusters and structure show that the matter density is \( \sim 0.3 \).
• Measurements of supernovae show that the dark energy component is \( \sim 0.7 \).
• Provides a consistent picture where \( \Omega_{\text{tot}} = \Omega_m + \Omega_\Lambda = 0.3 + 0.7 = 1.0 \), and the expansion rate is \( H_0 = 70 \text{ km/s/Mpc} \).
• The age of the Universe is 13.7 billion years.

1.7 But with puzzles...
• What is the dark matter?
• What is the dark energy?
• Why are their densities comparable?

2 Further Reading

See the Further Reading link at http://kicp.uchicago.edu/~risa/compton

• WMAP Cosmology 101 http://map.gsfc.nasa.gov/m_uni/
• Science Magazine, Breakthrough of the Year 1998
  (see also http://www.lbl.gov/supernova/)
• Supernovae, Dark Energy, and The Accelerating Universe, Saul Perlmutter, Physics Today, 2003
• The Preposterous Universe, Sean Carroll
• Adam Riess and Mike Turner Science Magazine Special Issue: The Dark Side, July 2003 http://www.sciencemag.org/feature/data/darkside/index.shtml