## 14. Cosmological Frontiers

We now have a "standard model" of cosmology, that goes beyond the Big Bang theory to specify the matter and energy contents of the universe and the origin of CMB anisotropies and structure.

This model is usually referred to as ΛCDM, shorthand for cold dark matter plus a cosmological constant.

The other ingredients of the model are a flat universe and primordial fluctuations from inflation.

### The "ΛCDM" Model: Key Observations

This list can be read consecutively with key observations for the big bang theory, from Lecture 1.

9. The present day universe is structured: galaxies, clusters, superclusters, etc.
10. Dynamical studies imply that most of the mass in the universe is dark. The dark matter around galaxies is much more extended than the luminous components.
11. Dynamical estimates of the average density of dark matter imply that (a) it is $\sim 25\%$ of the "critical density" required to make space flat, (b) it is more than the average baryon density allowed by the observed light element abundances and the theory of big bang nucleosynthesis.
12. Star-forming galaxies and quasars are observed out to redshifts $z \sim 6$ and beyond.
13. The cosmic microwave background (CMB) has fluctuations, $\left(\frac{\Delta T}{T}\right)_{\rm rms} \sim 10^{-5}$.
14. Best estimates of the Hubble constant are
$$H_0 \approx 70 \text{km s}^{-1}\ \text{Mpc}^{-1} = (4.4 \times 10^{-17}\,\text{s})^{-1} = (14.0\,\text{Gyr})^{-1},$$
with $1/H_0 \sim 14$ Gyr. Inferred ages of oldest globular clusters are $\sim 1/H_0$, significantly older than $2/(3H_0)$.
15. Studies of redshifts of distant supernovae, assumed to be "standard candles" as they are in the local universe, imply that the cosmic expansion has accelerated over the last $\sim 5$ Gyr.
16. The power spectrum of CMB anisotropies is approximately flat at large angle, and shows a series of alternating peaks and troughs at smaller angles. The first of these peaks is at multipole $l \sim 200$, angle $\theta \sim 0.5$ degrees. CMB fluctuations are Gaussian to high precision.
17. The amplitude of matter fluctuations at lower redshifts over a wide range of scales, inferred from galaxy clustering, weak gravitational lensing, and the Ly$\alpha$ forest, is consistent with ΛCDM predictions (normalized to the CMB) at the $\sim 20\%$ level.

### Implications and connections

(9) implies that the homogeneous model of the standard big bang theory is only an approximation that holds on large scales.

(10)-(12) imply the existence of non-baryonic, non-dissipative dark matter that had a low velocity dispersion in the early universe, a.k.a. "cold dark matter (CDM)."

The leading idea for CDM is some kind of not-yet-discovered, stable fundamental particle, such as the lightest supersymmetric partner or the axion.

(13) Shows that the fluctuations that seeded the growth of galaxies and present-day structure were present at recombination, $z \sim 1100$. Structure formed by gravitational instability.

(15) implies that the present energy budget of the universe is dominated by some component with an exotic equation of state that produces (in GR) repulsive gravity.

This component could be a "cosmological constant" (denoted $\Lambda$), whose energy density is constant in space and time, or it could be something else.

The angular scale ($l \sim 200$) in (16) implies that space is approximately flat, and thus that the total energy density is close to the critical density.

Combination with (11) implies that there is an additional component to the energy budget beyond baryonic matter and dark matter.

Combination with (14) implies that this additional component has an exotic equation of state (repulsive gravity), since otherwise the age of the universe would be $\lesssim 2/(3H_0)$.

Given parameters $\rho_{\rm CDM} \sim 0.2\rho_{\rm crit}$, $\rho_{\rm bar} \sim 0.05\rho_{\rm crit}$, and $\rho_\Lambda \sim 0.75\rho_{\rm crit}$, the detailed statistical properties of CMB anisotropies and other measurements of structure (16, 17) are consistent with the predictions of *inflation*, which posits that the primordial fluctuations originated as quantum fluctuations during a period of rapid accelerated expansion in the very early universe.

Thus, $\Lambda$CDM is shorthand for "inflationary cosmology with cold dark matter and a cosmological constant."

It is possible that the evidence for cosmic acceleration reflects a breakdown of GR on cosmological scales rather than a new constituent of the universe. The predictions of a modified gravity model must be fairly similar to those of $\Lambda$CDM. However, given the absence of good candidates for the exotic component, and the limited observational constraints on cosmic expansion, this kind of solution to the "dark energy problem" seems plausible.

In a similar vein, it is possible that the evidence for "dark matter' is really evidence for a breakdown of GR on galactic and larger scales. Again, the predictions of a modified gravity model must be fairly similar to those of $\Lambda$CDM. Given the presence of several plausible candidates for dark matter and the rich phenomenology of structure formation that any alternative model must reproduce, this kind of solution to the "dark matter problem" seems unlikely.

### Big cosmological questions for the next decade (or more)

What is dark matter?

Why is the universe accelerating?

How did the universe begin?

How did galaxies form?

### What is dark matter?

Lots of evidence now points to "cold dark matter," a weakly interacting particle that moved too slowly to erase structure in the early universe.

If the CDM particle has conventional weak interactions, there are reasonable prospects for detecting it in the next 10-15 years, via

- Production in accelerators (LHC)
- Direct detection in underground experiments
- Indirect detection of gamma-rays or other particles produced by dark matter annihilation

### Why is the universe accelerating?

Is acceleration caused by a new energy component or by a breakdown of General Relativity on cosmological scales?

If it is a new energy component, is its energy density constant in time (a cosmological constant), or does the energy density change as the universe expands?

Methods for investigation:

Improved measurements of the distance-redshift relation and the growth of structure.

- Bigger, deeper, and better supernova surveys.
- Big large scale structure surveys for baryon acoustic oscillations (standard ruler instead of standard candle).
- Large area imaging surveys for weak gravitational lensing measurements of the growth of matter clustering.

Hope for insight from unexpected directions:

- Test GR on small scales at high precision.
- Other observational "surprises," like time-variation of the gravitational constant.
- Theoretical breakthrough, maybe from quantum gravity or string theory.

**How did the universe begin?**

Did inflation happen?

If so, what was the physics of inflation (energy scale, shape of potential, initial conditions, identity of $\phi$)?

What is the "larger scale" setting for inflation (or alternatives)?

- Universe or multiverse?
- Initial time, infinite age, cyclic?

Methods for investigation:

- Improved maps of cosmic microwave background and CMB polarization. Hope to find signature of primordial gravity waves and/or departures from the most generic predictions of the simplest inflation models.
- Large scale structure surveys to map fluctuations at later times and smaller scales.
- Hope for stronger theoretical connection to a compelling physics model, ideally one that *predicts* $\Delta T/T \sim 10^{-5}$.

**How did galaxies form?**

Basic unit of cosmic structure. We have a basic picture of how they formed, but it's a complicated process, and there are many aspects we don't understand.

Methods for investigation:

- Surveys of galaxy properties and galaxy clustering over a wide range of redshifts.
- Computer simulations and other theoretical models of the galaxy formation process, tested against observations.