XIII. Dark Matter and Dark Energy

We have been discussing dark matter and dark energy throughout the course, but since they are the two biggest open questions in cosmology we'll wrap up with some review and prospects on these topics.

Readings

Huterer's chapters 11 and 12 give good introductions to these topics.

Davis, Efstathiou, Frenk, & White (1985, ApJ 292, 371) is an excellent and historically important article on structure formation with CDM.

For particle physics discussions of dark matter candidates, Feng (2010ARA&A 48, 495) is a highly referenced review; I concede that I haven't read it, but I have always found Feng's writing and presenations to be very clear.

A brief introduction to astrophysical probes of dark matter properties is Weinberg, Bullock, Governato, Kuzio de Naray, & Peter (2015, PNAS, 112, 12249), which was based on a panel discussion at a 2012 dark matter symposium.

The review article *Observational probes of cosmic acceleration* (Weinberg, Mortonson, Eisenstein, Hirata, Riess, and Rozo 2013, Physics Reports 530, 87) is long but designed so that you can read the parts you are most interested in. The introduction gives a concise history and overview, and section 2 will be familiar to you from this course.

I consider myself to be a good scientific writer and this article to be the best scientific writing I have done.

Dark matter: brief history

First evidence from velocity dispersion of galaxies in the Coma cluster (Zwicky 1933, 1937).

Evidence continued in studies of groups and clusters, rotation curve of Andromeda galaxy.

DM becomes a central issue in the 1970s, with a combination of (a) extended rotation curves in the optical (Hα) and radio (21cm HI), and (b) theoretical arguments that dark halos are needed to stabilize galactic disks.

Many ideas for baryonic dark matter, each with its own problems.

Neutrinos with $\sim 10-30$ eV mass briefly popular, in part because of (incorrect) experimental detection of neutrino mass. Implies top-down structure formation, "hot dark matter" or "pancake" scenario.

Idea that DM is a new fundamental particle, "warm" or "cold" dark matter, emerges in late 1970s/early 1980s.

Papers in 1982 and 1983 (Starobinsky; Guth & Pi; Hawking; Bardeen, Steinhardt, & Turner) show that inflation can produce primordial fluctuations that are adiabatic and scale-invariant.

Peebles (1982) and Blumenthal, Faber, Primack, & Rees (1984) are often taken as the "foundational" papers of the inflation+CDM structure scenario, followed shortly by the N-body simulation paper of Davis, Efstathiou, Frenk, & White (1985).

Inflation+CDM with $\Omega_m = 1$ was a theoretically attractive scenario, but mass-to-light estimates of Ω_m closer to 0.2. Biased galaxy formation as a way out for high Ω_m?

Several key developments in 1990s: "Excess large scale power" strengthened evidence for low Ω_m; COBE detection of CMB anisotropies showed a scenario like inflation+CDM was on the right track; microlensing searches for compact dark objects failed to detect baryonic DM; improved BBN constraints provided general arguments against baryonic DM.

Many scenarios still in play: $\Omega_m = 1$ with tilted initial spectrum ($n \approx 0.7$ instead of $n \approx 1$) or mix of cold and hot dark matter, $\Omega_m \sim 0.2$ models with open universe or cosmological constant.

Alternative gravity theories are a long-standing alternative to DM, most popularly the "Modification of Newtonian Dynamics" (MOND) scenario proposed by Milgrom.

This idea is not ridiculous, but over time alternative gravity models have had to become more and more contrived to explain the rich and precise phenomenology successfully predicted by inflation+CDM.

Dark energy: brief history

Cosmological constant introduced by Einstein (1917) as a way of enabling a static, homogeneous cosmology.

It remains an element of expanding cosmological models developed by de Sitter, Lemaitre, Friedmann, others.

A large cosmological constant seems like a natural prediction of quantum field theory. By 1980s, the "cosmological constant problem" is the puzzle of how to explain the low value of Λ, usually presumed to be effectively zero. Famous review article of S. Weinberg (1989, Rev Mod Phys, 61, 1).

Success of low-Ω_m models of large scale structure in explaining matching CMB + large scale structure highlighted "OCDM" (open universe) vs. "ΛCDM," with the latter being the most empirically successful.

In late 1990s, direct evidence for acceleration from distance-redshift relation in two high-z supernova experiments, enabled by large format CCD cameras on 4-m telescopes. Riess et al. (1998) and Perlmutter et al. (1999).

Quickly followed by two CMB balloon experiments detecting first acoustic peak and providing strong evidence for flat space (de Bernardis et al. 2000; Hanany et al. 2000).

Rapid acceptance of a cosmological constant or some more general "dark energy" component producing acceleration and making up the difference between $\Omega_m \sim 0.3$ and $\Omega_{\rm tot} = 1$.

Dark matter: current status and prospects

Leading candidates: WIMPs or axions, both motivated by other physics.

Can search for WIMPS through
• Collider production
• Direct detection in underground experiments — xenon, germanium
• Indirect detection from annihilation or decay — gamma rays most likely signal, but depends on annihilation/decay channels

Can also search for axions with direct and indirect experiments.

ΛCDM is remarkably successful, but challenges on small scales with central densities of galaxies and satellites.

Can it be explained by baryonic physics, or does it imply more complex dark matter physics: warm, self-interacting, fuzzy, decaying, dark sector?

Failure to detect WIMPs so far has made community more open to more exotic models.

Astrophysical tests from dwarf satellite counts and properties, Lyman-alpha forest.

Key CDM prediction to test is the existence of a spectrum of halos continuing to low masses. Strong lens anomalies and disturbance of tidal streams are the most promising.

Dark matter is a problem with many "good" solutions, though maybe none of the current ones is right.

Dark energy: current status and prospects

The big empirical questions:

1. Is cosmic acceleration caused by deviation from GR or by form of energy that produces acceleration within GR?

2. If the latter, is the energy density constant in space and time (Λ or not)?

Alternative dark energy frequently parameterized by

$$w(a) = w_0 + w_a(1 - a) = w_p + w_a(a_p - a). \tag{13.1}$$

But this is mathematical convenience to approximate a physical model.

Viable alternatives to GR are hard to construct. They generically predict that effective strength of gravity can change with environment, scale, redshift.

Basic approach is to measure expansion history $a(t)$ and growth history $D(t)$ with as much precision as possible over as wide a redshift range as possible.

Expansion history: Type Ia supernovae, BAO

Growth history: Weak gravitational lensing, redshift-space distortions, galaxy clusters

Inconsistency between these two could point to modified gravity.

Dark Energy Task Force (Albrecht et al. 2006) defined terminology of Stage I discovery experiments, Stage II then ongoing, Stage III and Stage IV defined by quantitative goals in parameter precision.

Stage III includes: Dark Energy Survey (DES), Baryon Oscillation Spectroscopic Survey (BOSS).

Prominent Stage IV experiments: Dark Energy Spectroscopic Instrument (DESI), Euclid mission, Legacy Survey of Space and Time (LSST) from Vera Rubin Observatory, Nancy Grace Roman Space Telescope.

Other probes: Hubble constant, Lyman-alpha forest, CMB lensing, other CMB, standard sirens, surprises

Two current tensions, both at 5-10% level.

Cepheid-based H_0 higher than ΛCDM predictions based on CMB+BAO.

Weak lensing based $S_8 \equiv \sigma_8 \Omega_m^{0.5}$ lower than CMB-based predictions.

Neither is easily explained by $w_0 - w_a$ dark energy, or non-zero Ω_k.

Non-standard neutrino physics or decaying dark matter could help.

The S_8 discrepancy could point towards modified gravity, which would have a rich phenomenology to explore.

Dark energy is a problem with several "bad" solutions, though one of them could be correct.