COSMOLOGY: SOME DEFINITIONS & PRINCIPLES

The density parameter:

In cosmology, we are interested in the large scale structure of the Universe (how clusters and superclusters are "laid out"), but also in the dynamics of the whole Universe (its overall expansion). To address that, we ignore the "fine grain structure" (stars, galaxies, etc.) and imagine that the material is spread out smoothly so that the Universe has some average density of matter within it; it's like ignoring the grains of sand that make up a beach, and seeing the beach as a smooth but changing sea of material. Then the key number is

$$\Omega_0 = \frac{\text{Actual density of the Universe}}{\text{Critical density of the Universe}}$$

where the critical density is that needed to *just* halt the expansion after infinite time, in our simplest scenario – the Universe has some expansion rate, and is decelerated to a greater or lesser degree because of the mass within it.

There is a fundamental relationship between the value of Ω_0, whether space is flat or curved, and whether the Universe is finite (closed) or infinite (open): check out Table 26-1 and Figure 26-15 in the text.

Mass-to-light ratio:

M/L is the mass of something in solar masses, divided by its luminosity in solar luminosities. Thus for the Sun, $M/L = 1$. Think of it as a conversion factor. We want to know the mass of a galaxy, and it's no more than a smudge on a photograph, so you can barely see it, let alone the individual stars, gas, etc. But galaxies are approximately transparent, so we do see all the light. If by exploring the neighborhood of our Sun we establish that for every 1 Sun's worth of light, there are 5 Sun's worth of mass ($M/L = 5$), and assume that is representative of the Universe as a whole, a galaxy emitting 10^{11} Sun's worth of light, should have 5×10^{11} Sun's worth of mass.

Location explored	*Estimated M/L*	*Inferred Ω_0*
Naive value	1	1/1350
Solar neighborhood	5-10	1/270
Galaxy rotation	50-100	1/27
Galaxy clusters	< 500	$< 1/3$
Superclusters	< 500	$< 1/3$

The particle families:

Leptons (a family of 6 light particles)

e (electron)	ν_e (electron neutrino)
μ (muon)	ν_μ (muon neutrino)
τ (tau)	ν_τ (tau neutrino)

Hadrons (a family of 6 heavy particles)

d (down quark)	u (up quark)
s (strange quark)	c (charmed quark)
b (bottom quark)	t (top quark)

This is our "standard model" of the particles that make up the world. We never see quarks, only them in combination. Combine 2 quarks and you get particles called mesons, add 3 together and you get particles called **baryons**; think of baryons as the particles that give the day-to-day world most of its mass – things like protons and neutrons. Thus the three possible constituents of the Universe are a) baryons; b) light particles like electrons and neutrinos; c) exotic, yet-to-be discovered particles (like axions and WIMPS) that don't fit into the "standard model", but need an extension of it.

Hot & Cold:

The terms "hot" and "cold" applied to dark matter do *not* refer to the nature of the individual components of dark matter; in a hot gas the particles move quickly, in a cold gas slowly; by analogy, hot dark matter means that the components (neutrinos, perhaps) are moving around quickly; cold dark matter means that the components (white dwarfs, perhaps) are moving around slowly. As a good (but imperfect: axions are light but cold) rule of thumb, baryonic material (which is heavy) is cold, while light particles like neutrinos, are hot.

COSMOLOGY: KEY POINTS & RELATIONSHIPS

Observations of

$$\left\{\begin{array}{l}\text{Expansion of Universe}\\ \text{Background Radiation (CMBR)}\\ \text{Abundance of He}\end{array}\right\} \quad \Longrightarrow \quad \text{Big Bang}$$

Theory:
Big Bang + Flatness and Horizon problems $\Longrightarrow$ Inflation $\Longrightarrow \Omega_0 = 1$

Observation:
BOOMERANG/WMAP observations of the CMBR suggest space is indeed flat, i.e., $\Omega_0 = 1$

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Observations of

$$\left\{\begin{array}{l}\text{Galaxies (rotation curves)}\\ \text{Clusters of galaxies (galaxy motions, X-ray emitting gas, lensing)}\\ \text{Superclusters (cosmic flows)}\end{array}\right\} \quad \Longrightarrow \quad \Omega_0 \sim 1/3$$

Theory:
So where is the remaining 2/3?! Perhaps there is a "cosmological constant" (Λ): space itself provides the energy/mass to make $\Omega_0 = 1$ in total. (In other words $\Omega_0 = \Omega_M + \Omega_\Lambda = 1/3 + 2/3$.)

Observation:
Observations of distant Type Ia supernovae support this, through evidence for an acceleration of the expansion, and in particular suggest that $\Omega_\Lambda \sim 2/3$. (Note that this fits in nicely with the evidence for $\Omega_\Lambda \sim 2/3$ from structure formation discussed below.)

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That still leaves a lot of matter – 1/3 of that needed to close the Universe – **unseen**, i.e., dark. What is it?

Nucleosynthesis (the formation of He 100s after the Big Bang) and observations of the CMBR tell us the density in **baryons** now. The density in baryons now is a good deal more than seen in luminous matter, but far less than needed to explain $\Omega_M \sim 1/3$. X-ray emitting cluster gas and intermediate temperature filaments may make up the difference between baryons "seen" and baryons inferred. But most dark matter must be **nonbaryonic**.

Computer simulations of **structure formation** with different assumptions about the nature of the dark matter, have very different success in explaining the structure we observe. Researchers have tried Hot Dark Matter, Cold Dark Matter, Cold Dark Matter plus trace of Hot Dark Matter, and Cold Dark Matter plus a "cosmological constant" – and only the latter produces results in good agreement with observation. The implication is that dark matter is **cold**.

Thus... dark matter is (at least mostly) **nonbaryonic** and **cold**. What do we know that "fits the bill"? **Nothing!** Most of the Universe's matter must be yet to be discovered material: WIMPS, axions, or whatever.

PAH June 2008