Observational Overview

In this lecture we will discuss some of the observational handles we have on the universe and a few of the inferences that can be drawn from them. We will largely follow Chapter 2 from Liddle.

For the overwhelming majority of history our only probe of the universe has been via visible light. Even now it is our primary tool, thanks to our atmosphere being transparent in only a couple of narrow windows and also thanks to typical stars and hence galaxies emitting most of their radiation in visible light or thereabouts. What, then, do we see as we look farther and farther out?

The first obvious component of the universe is stars, and looking at greater distances we see that stars tend to be collected in groups of hundreds of millions to (rarely) trillions, which are called galaxies. In our galaxy we have all types of stars: young and old, large and small, but this is not the case for all galaxies. In fact, whereas stars can be described with comparative simplicity (balls of gas with hydrogen fusion operating in their cores for most of their lifetimes), galaxies are more complex entities. To take a very broad view, most galaxies can be shoehorned into two basic types. Spiral galaxies tend to be relatively disklike (often with a bulge in the middle, like the Milky Way has), rotationally supported (stars orbit the center in the same direction for the most part), have a lot of interstellar gas, and contain young, hot, blue stars as well as old, cool, red stars. Elliptical galaxies tend to be thick in all three dimensions (e.g., as a triaxial ellipsoid), their stars move every which way, they are gas-poor, and young stars are rare. Naturally there are galaxies that don't fit into this simple classification (e.g., irregular galaxies such as our Magellanic Clouds). The evolution of galaxies and the relationship between different types is an important focus of cosmology and will become progressively more important as observations improve.

Moving to still larger scales we see that galaxies tend to cluster together over scales of roughly a megaparsec. The terminology typically used is that if there are just tens of galaxies together this constitutes a "group", but if there are hundreds to thousands together this is a "cluster". Our Milky Way is in the Local Group, which has two significant galaxies (the Milky Way and Andromeda, called M31) and a whole bunch of little guys like our Magellanic Clouds, M33, and M32, making possibly 50ish galaxies total (for reasons we will discuss more when we come to structure formation, a number of galaxies in our Local Group have been discovered recently and were previously very difficult to detect). The nearest cluster is the Virgo Cluster, about 50-60 million light years away, and it contains about 1000 galaxies, most of which are smaller than the Milky Way but a few of which are much larger. About 10% of galaxies are in clusters, with the rest being in the "field". An interesting hint about the origin of galaxy types is that the fraction of ellipticals is much higher in clusters (especially "rich" [dense] clusters) than in the field.

Moving still farther out, clusters themselves tend not to be randomly distributed, instead forming beautiful filaments and sheets called "superclusters", which can extend for a hundred megaparsecs in extreme cases. Another interesting hint about the evolution of these systems is that whereas clusters tend to be roughly spherical, superclusters are not. Between the superclusters are regions of very few galaxies called "voids", which can also be a hundred megaparsecs across. See Figure 1, which shows a mapping of galaxies in one slice of data from the Sloan Digital Sky Survey (note that at the far side, incompleteness begins to come in).

At even larger scales, however, we do not find a continued hierarchy of structure. Instead, at increasing scales the universe looks more and more uniform. On average, one finds a galaxy with the mass of the Milky Way or Andromeda every few hundred cubic megaparsecs, so most of space is pretty much bereft of matter.

This observation, however, was not secure by any means in 1917 when Einstein proposed his cosmological principle to aid in mathematical treatments of the universe as a whole. This principle says that to lowest order, and on large scales, the universe is homogeneous and isotropic. This was an extremely bold hypothesis not supported by data at the time (in 1917 people didn't really even know about other galaxies!), and it smacks of the aesthetic motivations that drove the Greeks to think about a geocentric universe ruled by circles. We therefore need to define what we mean, and think about how current observations do or do not match these principles.

The universe is *homogeneous* if every part looks the same locally. That is, if you were to go to any place in the universe and measure the properties of some local volume, you would not be able to tell where you were.

The universe is *isotropic* if it looks the same in all directions. This might seem equivalent to homogeneity, but we can think of counterexamples. A smooth universe with a uniform magnetic field is homogeneous, but not isotropic (looking along the field is different from looking across it). A spherically symmetric universe with a density that drops off as r^{-2} (say) from the center looks isotropic from the center, but is not homogeneous. If the universe appears isotropic from more than one location, though, it is homogeneous.

The only problem with these hypotheses is that they are obviously wrong! To drive that home, consider our everyday experience. Looking at the Sun is rather different from looking away, so clearly we do not see isotropy. Your average density or mine is about a thousand times the density of the air we breathe, so homogeneity doesn't hold either. If we consider the space between stars, the density is yet another factor of 10^{21} less! Indeed, in the first few years after Einstein proposed his theory, astronomical observations also seemed to show major differences; telescopes of that time showed many galaxies in some directions and few in others.

However, in the modern case there was a prediction that could be tested. The physicists who derived properties of the universe from these assumptions did not require that homogeneity and isotropy hold at all scales. They only needed that this be a good approximation on very large scales. Therefore, the prediction was that as larger and larger parts of the universe were sampled, it would appear smoother and more uniform.

Put another way, suppose that we have a box a kilometer on a side, and we use it to sample various cubic kilometers' worth of the universe. If we did this, we would usually find almost nothing;

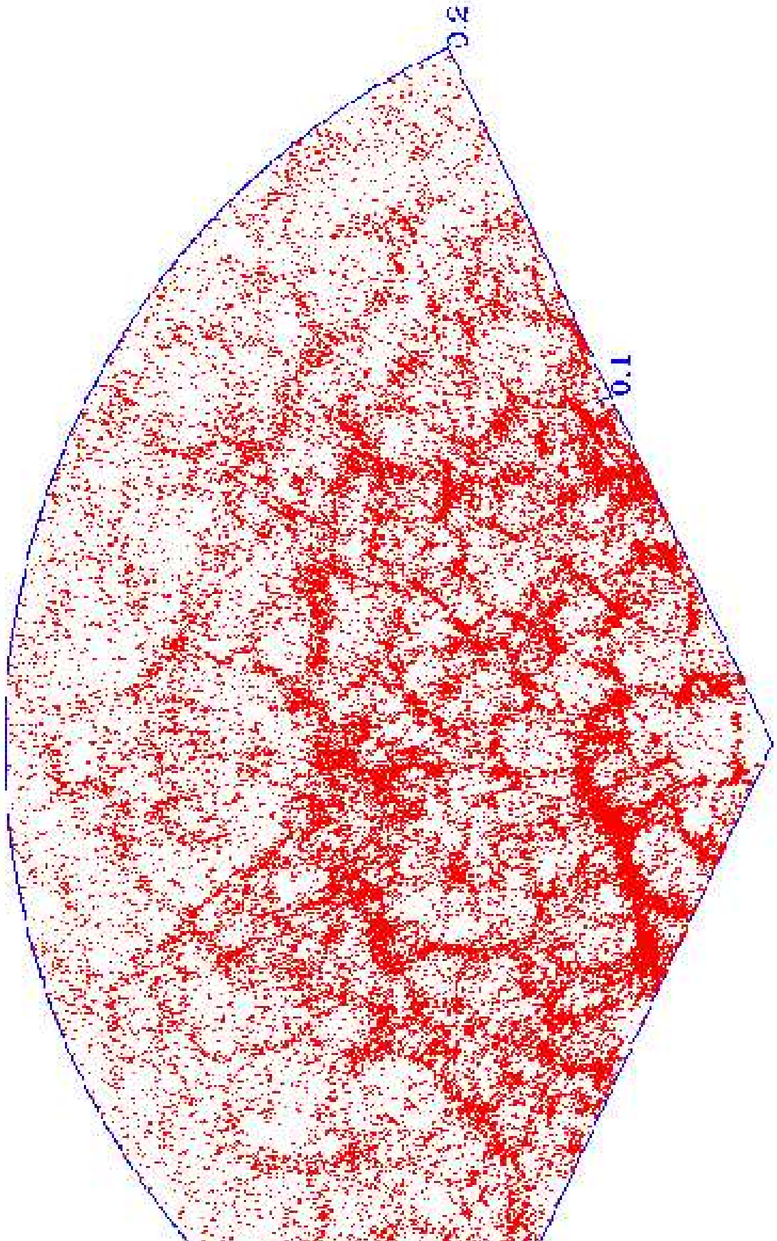

Fig. 1.— A slice of data from the Sloan Digital Sky Survey, showing locations of galaxies as determined by angle and redshift. Note the filamentary structure, but also note that as a whole this is a fairly uniform distribution. The apparent decrease in galaxies at high redshifts is due to incompleteness of the survey.

maybe a few stray particles. On occasion we would get a cubic kilometer of a gas cloud or a star, which has vastly greater density. Therefore, on this scale the universe is not even remotely uniform. The difference between the highest density you could get and the lowest density you could get is phenomenal; roughly a factor of 10^{45}!

Suppose that we increase the size of our box, to a light year on a side. Now we can still get a part of the almost empty region between galaxies, or a gas cloud, but our box is much larger than any star and therefore it is not possible that the average density is that large. There are thus still variations in density (e.g., in one case you might put your box in a galaxy, with a comparative wealth of matter, and in another your box would be outside a galaxy, with a paucity of particles). However, there is more averaging out than in the first case. At this scale, the density range is less but still large, more than a factor of 10^{10}.

Now suppose that the box is ten million light years on a side. This is bigger than any galaxy, so even if there is a galaxy there, its density will be largely compensated by the emptier regions that you are guaranteed to include. At this scale, the range in density is a factor of a few hundred.

If your box is a billion light years on a side, however, the density is constant to within 10% or less. The observable universe is some 14 billion light years in radius, so in fact the universe is homogeneous and isotropic to reasonable accuracy at the largest scales. This is a very non-trivial confirmation of a prediction! When the assumptions were made originally, telescopes could not see far enough to verify the prediction, and we could have imagined a universe that didn't work like that. Therefore, the assumptions were justified, albeit after the fact.

Other Wavebands

In the last several decades many other observing windows have opened up, and these yield essential new insights about the universe. We will encounter these in more detail throughout the course, but here is a quick summary:

- X-rays. My favorite, as a high-energy astrophysicist, these are somewhat neglected by cosmologists because of the information that exists in other wavebands. One reason these are important is that clusters of galaxies actually have most of their mass in other forms. The dominant form turns out to be dark matter, which we will discuss in much greater detail later, but of the ordinary matter by far the majority is in a tenuous hot gas at $10^7 - 10^8$ K, which is only visible in X-rays. It turns out that observations of such clusters in X-rays at different redshifts give critical clues to the development of structure and also information about the evolution of dark energy, one of the most important topics in cosmology.

- Infrared. Galaxies with a lot of dust and gas have much or most of their radiation scattered, absorbed, and re-radiated in the infrared. Indeed, some of the most luminous galaxies in the universe are in this state. In addition, galaxies at high redshifts have their emission shifted into the infrared, hence direct observation of the earliest galaxies requires infrared. This is the reason that the James Webb Space Telescope is an IR-focused mission.

- Radio waves. The types of emission discussed above are "thermal", meaning that they are characteristic of the temperature of the emitting object. Long wavelength radio emission, however, is produced by nonthermal processes often involving the spiraling of electrons around magnetic fields. Remarkably, it turns out that active galaxies (which have a far greater luminosity than normal galaxies such as the Milky Way) emit copious amounts of radio waves. Our atmosphere is transparent to radio, meaning that ground-based radio astronomy is feasible and large collecting areas are possible. The observations of distant radio sources led to an important clue that the early universe was distinct from the current universe, thus ruling out some models for the cosmos.

- Microwaves. For modern cosmologists interested in the relatively early universe (before stars and galaxies formed), this is the biggie. As first discovered by Arno Penzias and Robert Wilson (and Robert Dicke) in 1965, there is a cosmic microwave background (CMB) that comes from everywhere in the universe. In the last 15 years, it has been shown that there are very small fluctuations in the CMB, which have now been characterized very precisely by missions such as WMAP. These fluctuations are profoundly informative about the early universe and have the advantage that the physics is relatively simple and thus confident inferences can be drawn from their properties. We will have a lot more to say about the CMB in future lectures.

The Expansion of the Universe

The last stop on our brief tour of the universe involves its expansion. As you know, a number of observational developments culminated in Edwin Hubble's 1929 announcement that the apparent recession speed of galaxies from us was linearly related to the distance of the galaxies. This could be interpreted as social ostracism of us in particular, but the Copernican principle suggests otherwise. In fact, this would be observed from any galaxy. How is this possible?

You've probably seen the standard analogies for this. For example, if you affix pennies to a balloon and blow up the balloon, you find that from the standpoint of any one penny all others move away, and the farther they are the faster they appear to move. As a three-dimensional analogy, if you bake raisin bread, then as the bread rises all the raisins move away from each other.

The rate of expansion is denoted by the unfortunately named "Hubble constant" H_0; unfortunate, because it changes with time (the "constant" means it is the same everywhere in space at a given time). The current value is

$$H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \,. \tag{1}$$

For example, two galaxies 100 Mpc from each other will typically measure a relative redshift corresponding to 7200 km s^{-1}. The actual redshift will differ some from this because of "peculiar velocities" relative to the overall Hubble flow.

It is natural to "run the clock backward" and conclude that the universe was much smaller at one point and thus had a beginning. This, however, requires additional empirical support. For example, a viable model until the discovery of the CMB was the "steady-state" hypothesis, in which there is very slow creation of matter from nothing, which gradually accumulates into new galaxies and means that the universe is infinite and eternal (but distant parts are beyond our visible horizon, thus avoiding Olbers' paradox). Disproof of this model required a demonstration that the early universe was different from the current universe. We will explore various aspects of this in subsequent classes.

Intuition Builder

Convince yourself that if the universe appears isotropic from more than one point, it must be homogeneous.