PHYSICS 419 - Spring 2021

Lecture 24: April 20, 2021

1 Big Bang Cosmology

Evidence for the standard cosmology

Recall that we solved Olber's paradox by appealing to the experimental finding of Hubble that the universe is in fact expanding. The paradox arose by assuming that the universe was in equilibrium and static. Hubble's observation changed all of this. The fundamental observation of Hubble's in 1929 was that the "red shift" of galaxies is proportional to their distance. If the red shift is a Doppler shift, this means that galaxies are receding from us at speeds which are proportional to distance: $v = H_o d$. It is worth making a few comments.

1.) The idea that galaxies existed outside the Milky Way, and that the MW is a galaxy, was only developed in the 1920's (by Hubble and others). This changed the view of the large-scale structure of the universe. It is "lumpy." We are still trying to understand the nature and origin of this lumpiness.

2.) A key opponent of the expanding universe theory is Arp. Consider firing a cannon ball from the moon. If the cannon ball were emitting gases of some type, then we would observe that the spectra of the gases was in fact red-shifted from us. Arp maintains that very massive objects far away from us spew out lots of stuff that moves away from us. Hence, the apparent red shift is not of fundamental cosmological importance. That is, it has nothing to do with the origin of the universe. The problem with this is that we would expect objects to be coming towards us as well. Hence, we should see blue shifts as well. This is not seen. Hence, it is hard to take this scenario seriously. We now survey the key evidence in support of the expanding universe scenario.

The Cosmic microwave background (CMB)

When the universe was small, it must have been hot. It should be possible to see the afterglow from this period. When the universe was about 10^5 years old, it had a temperature of approximately $3000K$. Below this temperature, atoms are not ionized, and the universe becomes transparent. The "relic photons" will have been red shifted to an effective temperature of only 2.7K. This radiation was observed in 1965.

The CMB is a nearly perfect "black body" spectrum. The only distortion larger than 10^{-5} is an anisotropy that indicates that our galaxy is moving a few hundred km/s with respect to the matter that emitted the radiation.

Comments:

1.) At 10^5 years the radius of causal connection corresponds to a 1^o circle in the sky. So, why is the CMB the same in every direction? There appears to be a deeper connection (more later). (remember we also asked why entropy was low everywhere in the past)

2.) The fluctuations are interesting, and tell us something about how lumpy the matter distribution was at that epoch. More on this later as well.

3.) Theories without a "hot big bang" need to propose alternative mechanisms for the CMB. None are able to reproduce the spectrum.

Nucleosynthesis

The universe is mostly hydrogen and helium (about 24% of the mass is helium). Can we understand the abundance of these and the heavier elements?

I won't go through this in any detail. The idea is that as the universe cooled down, at some point (when $T \sim 10^7 K$, about 1 minute after the bang) the neutrons and protons began to combine to form nuclei. Nuclear abundance is the result of the competition between the combination rate and neutron decay. The theory allows the isotopic abundances of H, He, Li, and Be to have their actual values with only one or two adjustable parameters, to the accuracy that they are known. No significant heavy elements are made in that epoch.

The heavier elements (oxygen, iron, etc.) were made in supernovas. I won't discuss this at all, except to note that this implies that stars which support life as we know it must be at least "second generation." The Sun is only 5 billion years old.

Mass distribution (structure)

The universe is lumpy. It contains planets, stars, galaxies, clusters, and even larger objects. Can we understand this structure, especially the hierarchy of scales?

In a universe where gravity is the dominant force, small fluctuations in the mass density will grow, due to the unbalanced forces. How they grow depends on the initial distribution of matter and on what kind of matter there is. (By kind, I mean generically whether it is heavy and slow moving, like protons, or light and fast, like neutrinos).

Measuring the lumpiness of the universe as a function of time, to infer the growth of structure, is currently a very active field. Large-scale structure appeared very quickly, from almost nothing at 10^5 years, to galaxies only a billion years later.

Study of the mass distribution can answer three questions:

What was the nature of the very early big bang, where the fluctuations originated?

What kind of stuff is in the universe?

How much stuff is there?

How much stuff was required to form the universe?

These are very much open questions. There are many viable theories, which will be tested over the next decade.

We'll take up these points in (more-or less) reverse order. There will be several side trips along the way.

Time has a beginning. Does it have an end?

It appears that the universe began in a "big bang" about 17 billion years ago ($t_0 \approx 1/H_0$). Will it end in a "big crunch?" This depends on the mass density and the cosmological constant. Recall that Einstein added the cosmological constant to the equations of general relativity to generate a static universe. Gravity alone yields either a shrinking or an expanding universe. There is a critical density below which the expansion will continue forever. But this is too simplistic. Depending on the sign of the cosmological constant there are many possibilities. The fundamental equation that governs all of this is as follows: $\Omega + \Lambda + k/H_0 * H_0 * R * R = 1$, where Ω is proportional to the mass density in the universe, Λ is proportional to the cosmological constant and the k a constant that depends on the curvature of the universe. $k = 1, 0, -1$ correspond to a closed, flat, or an open universe respectively. From the fact that the universe is expanding, we deduce that the cosmological constant is positive. The point of this is now that the fate of the universe is not governed solely by the critical mass density. Even if the universe is closed, it can still expand forever if the cosmological constant, Λ, is large enough. This extra degree of freedom has added to the richness of cosmology. Many believe that $\Omega + \Lambda = 1$. Hence, either the radius of curvature of the universe is infinite or $k = 0$ (that is, the universe is flat). If $\Omega + \Lambda = 1$, then the universe will expand forever.

Copernican Principle

It is a given in modern cosmology that the universe is the same pretty much everywhere. There are some density fluctuations in the CMB but those are only on the order of 10^{-5} or so. The two postulates that underlie the Copernican principle are 1) isotropy and 2) homogeneity. Isotropy applies to specific points in a manifold and implies that from any point, space looks the same. Homogeneity is a statement about the metric, namely it is the same throughout the manifold. Consider any two points in a manifold.

Homogeneity implies that there is an isometry that takes p into q for any p and q. A corollary is that if space is isotropic everywhere then it must be homogeneous. We seem to live in a universe which is both isotropic and homogeneous. So what does this say about the possible geometries of the universe? There are three sorts of non-time dependent metrics that come out of solving Einstein's equations that satisfy both requirements. 1) flat Minkowski space, 2) de Sitter space which has a positive crvature, $k = 1$, and 3) anti-de Sitter space, negative curvature $k = -1$. We seem to be living in a universe in which the visible matter is moving apart. This means that in the past the density was higher. All of these solutions above are derived for fixed density. Hence, none of these are realistic models of the real world. They simply represent unique solutions to Einstein's equations in the absence of ordinary matter and gravitational radiation. Our current universe can be viewed as some sort of excited state of these constant density solutions. The more realistic metrics that describe the current universe all have time dependent matter composition and are termed Robertson-Walker metrics. A good reference to read about this is Sean Carroll's book entitled, "Spacetime and Geometry."

What is "dark" matter?

25% of the universe is made of dark matter. 70% is dark energy (vacuum) energy and only 5% matter. Dark matter is some kind of particle that we have not yet detected in experiments here on Earth, but nevertheless comprises most of the matter in the universe. The first evidence for its existence came from studying the dynamics of galaxies and clusters of galaxies. The basic point is that something in orbit around a massive object moves more rapidly, the more mass the object has. Fritz Zwicky was the first to put this idea into action, studying the motion of galaxies in the Coma cluster; their motions were too rapid to be accounted for by the visible matter in the galaxies. Later, Vera Rubin looked at matter orbiting at the edges of individual galaxies, and noticed a similar effect – the rotation speeds of the galaxies did not fall off with distance as they should if the gravitational fields were being caused by the visible matter alone. What we know about dark matter, then, is that it is a new kind of unseen particle that falls readily into galaxies and clusters. The fact that it is dark means that it is neutral, rather than electrically charged; in general, charged particles interact readily with light, and would not be dark. The fact that the dark matter is concentrated in galaxies and clusters indicates that it is slowly moving; particles of this form are referred to as "cold." What could the cold dark matter be made of? We are not at all sure, although numerous theories have been proposed. Two ideas are especially popular: neutralinos and axions. "Neutralinos" are a kind of particle predicted by supersymmetry, a popular (but as yet purely conjectural) theory in particle physics. According to supersymmetry, each kind of known particle has a "superpartner" with a different intrinsic spin; the neutralino is simply a massive, neutral, stable superpartner of one of the known particles, and is a natural dark matter candidate. (Such a particle would interact predominantly through the weak nuclear force, and is therefore an example of a Weakly Interacting Massive Particle, or WIMP.) Axions, on the other hand, are another kind of hypothetical particle, originally postulated to explain certain symmetries of the strong nuclear force. In the case of both neutralinos and axions, active experimental programs are underway to detect these dark matter candidates in the laboratory, either by producing them directly or by observing the effects of ambient particles floating through the Solar System. Finally, it may be possible to detect dark matter particles indirectly, if they annihilate into photons in high-density regions of the universe; the resulting radiation would have a characteristic form that would signal the existence of a new kind of particle.

What was it like "way back then"?

Let's extrapolate back from the present. Suppose t_o is 17 billion years ago.

For the last 15 billion years or so, the universe has looked pretty much the same as now. Second generation stars, with heavy elements, planets, and (maybe) life, arose 5-10 billion years ago. Some unusual objects (e.g., quasars) existed only near the beginning of this epoch. They were probably galaxies with gigantic black holes in the center. (Black holes might be a significant part of the "dark matter.") The temperature of the cosmic microwave background (CMB) was about 12K then.

Between 10^5 and 2×10^9 years after t_o, we aren't sure what was happening. Galaxies formed during this period, but we can't yet see them (too far away and dim). At 10^5 years, the temperature was about $3000K$, and the atoms were just cool enough to cease being ionized. The density fluctuations were small (about 10^{-5}).

At about 1 minute, the temperature was about $10^9 K$, and the nuclei were being made. Protons and neutrons could stick together without being knocked apart by the heat.

At about 1 ms, the temperature was about $10^{13} K$, and the quarks were becoming confined inside nucleons. This was the end of the period of the "quark-gluon plasma." Experiments at Brookhaven Lab will try to reproduce this plasma.

Prior to this is purely speculation. (As if the preceding wasn't!)

The main features of hot big bang cosmology

1.) As the universe expands, it cools. The very early universe was very hot, and massive objects could be produced by the heat. Objects that are bound today were liberated then.

2.) Density fluctuations increase with time. Way back then, the universe was very homogeneous, as shown by the CMB.

3.) The overall density of the universe evolves away from Ω_0. As we look closer to t_0, the density becomes closer to this critical value. One can't extrapolate all the way back to $t = 0$. When the temperature rises to about $10^{32}K$, one needs to be able to unify QM and gravity. Actually, it is thought that new phenomena might appear, because there are three conceptual issues:

a.) Why is the universe so homogenous at early times? Remember that there hadn't been enough time for the various regions that we can see to have communicated, so why do they look the same?

b.) Why did the density of the universe start out so close to Ω_0? If it was so close to the critical value then (differing by about one part in 10^{-42} at the earliest times) why not exactly 1?

c.) Entropy only increases with time. This implies that the universe was in a very low entropy state at early times. How is that consistent with high temperatures? .

Entropy in the Big Bang

The issue here is this: If the universe was very hot at early times, one would guess that the entropy was very high then. If so, how do we explain the low entropy at the present time?

We exist only because the universe does not have the highest possible entropy. Life exists by taking advantage of this. One indicator of low entropy is that there are hot objects and cold ones. The universe is not in thermal equilibrium.

The answer is that gravitationally condensed objects like the Sun, neutron stars, and black holes, have very large entropy. So, as long as stuff can keep falling into gravity wells, there will continue to be regions of high and low entropy.

In the early universe, the matter was very hot and in a high entropy state (thermal equilibrium), but that gravity was in a low entropy state (i.e., the curvature of spacetime was not "wrinkled"). Geometry has entropy. It is a physical entity. The processes that we see happening now are made possible by a transfer of entropy from the former to the latter.

Why did spacetime start out in this special, orderly state? This seems to be very unlikely. If there is to be a big crunch, the universe will collapse back to a singularity, but it will have high entropy. Without some further constraint, there is no known reason why a very dense universe would have to be low-entropy.

2 Quantum Mechanics and Special Relativity

In 1928-1930, Dirac wrote QM in a form that satisfied SR. He found that it predicted the existence of a new form of matter, antimatter. Antimatter's properties are the "mirror" of matter; each particle has an associated antiparticle with the same mass and opposite charges (e.g., the positron). Dirac was so surprised by this that at first he didn't believe it and thought the theory was somehow relating the proton and electron. The positron was found in cosmic rays by C. Anderson in 1932. One important consequence of the existence of antimatter is that matter and antimatter can annihilate each other, and new forms of matter can be produced. The easiest way to visualize this is with a graphical method invented by Feynman. For example, electrons and positrons can annihilate and produce muons and antimuons: We will discuss later what the term "virtual photon" means. For now, just think of it as the intermediate state that contains the energy and momentum for the short time between the electron annihilation and the muon production. There is nothing special about muons. Any particle-antiparticle pair can be produced as long as there is enough energy for $E = mc^2$.

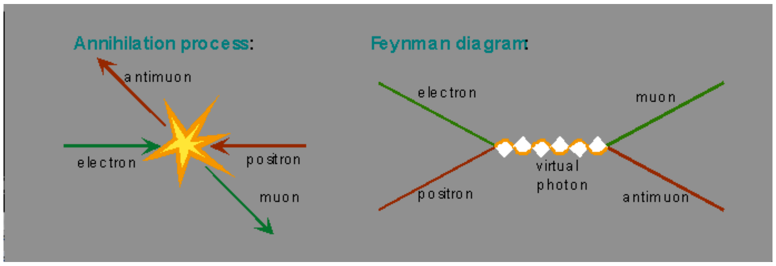

Figure 1: Feynman diagram illustrating particle-antiparticle annihilation

The uncertainty principle revisited

We need to consider the uncertainty principle in light of the existence of matter-antimatter creation and annihilation. In particular, we will be forced to rethink our concept of the vacuum.

In Newton's physics, the vacuum consists of empty space. We are not interested for now in the Newton-Leibniz debate. We are also not concerned with the possible existence of gravitational waves. Just imagine the stuff (or lack thereof) between here and the Moon.

The question is, what is the least amount of stuff that we can have? To put it differently, what is the QM state with the lowest energy? That state is the vacuum, because as energy is dissipated that's where things end up. Think of a marble rolling around in a bowl.

The uncertainty principle makes the vacuum more complicated.

The lowest energy state is not the one in which we can say with certainty that nothing is there. Rather, it is a superposition such that when we look we usually see nothing, but there is a nonzero probability of finding stuff there. (The exact probability depends on how we look - i.e., what we measure.) The reason for this is that the quantities that describe electron-positron pairs are not all simultaneously measurable. If we were to know definitely that there were zero particles, then we would know the values of all these quantities, in violation of the uncertainty principle.

Something weird is happening...

This picture doesn't seem to make sense. How can the nonzero probability of the existence of an electron-positron pair (with $E = 2m_0c^2$) possibly be lower energy than its nonexistence? The stuff that fills the vacuum doesn't satisfy $E = mc^2$.

In SR, space and time behave similarly. The uncertainty principle has a time component that is similar to the space component:

$$\Delta p \Delta x \geq \hbar/2 \tag{1}$$

$$\Delta E \Delta t \geq \hbar/2 \tag{2}$$

This means that although particles can't really exist in the vacuum, they can have a virtual existence. The stuff in the vacuum must (by conservation of E and p) have $E = 0$ and $p = 0$, and therefore, $E^2 - p^2 \neq m^2$. This is allowed to happen for a time that depends on how badly the equality is violated. More massive particles can only exist for shorter times and are thus much more rare than less massive ones.

It is tempting to think of the vacuum as being filled with particle-antiparticle pairs, blinking in and out of existence, vacuum "bubbles":

Does this view of the vacuum make sense?

Many experiments confirm it. I'll discuss some ideas:

a.) Sparking of the vacuum.

Consider a region of extremely strong electric field. If there is any residual gas in the gap, one is likely to get a spark. Suppose we have a perfect vacuum. The vacuum isn't empty, so if there is enough energy stored in the field, that energy can be transferred to the virtual pairs, making them real. The required electric field is enormous, and this effect has only been seen in the electric field near super-heavy nuclei (Z 180).

b.) Hawking radiation. (no experiments yet) Near black holes, the gravitational field is very strong, and

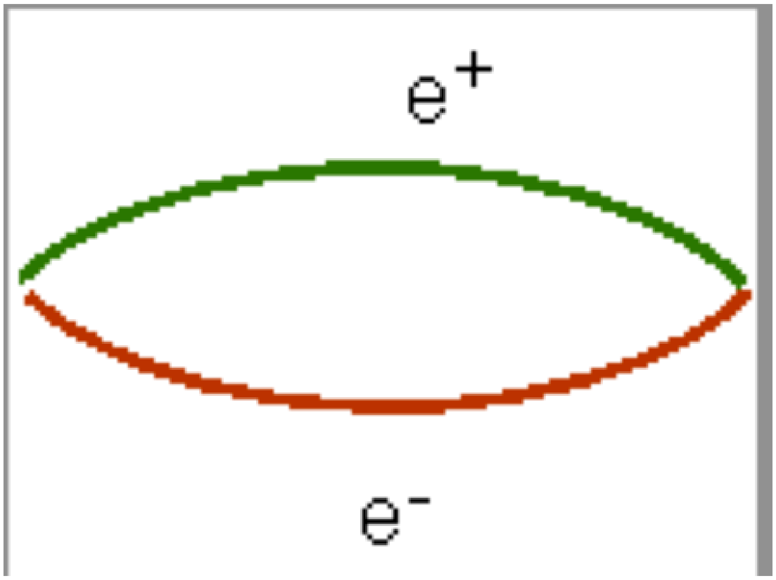

Figure 2: Quintessence: electron-hole pair.

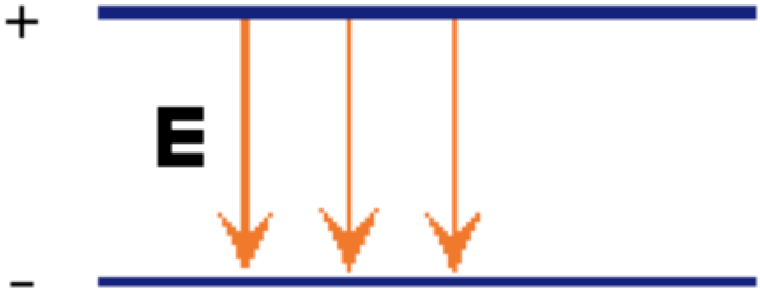

Figure 3: Vacuum energy exists even between two charged plates.

the energy stored in the field can be converted into particle pairs in a similar way. By this mechanism, black holes are predicted to "evaporate." (The evaporation time for a solar mass BH is longer than the age of the universe.)

c.) Virtual particles in other situations. The virtual photon I drew in the e^+e^- process did not come from the vacuum, but it has similar properties ($E^2 - p^2 \neq m^2$). This means that it cannot exist very long and must re-appear as a real pair of particles.