Some FAQs and Answers for the Big Bang, Dark Matter, and Dark Energy

Ganpathy Murthy

Department of Physics and Astronomy, University of Kentucky

Abstract

There are three main topics connected to the three parts of the title, and I will consider some common questions in turn for each of them.

I. TABLE OF CONTENTS

II. THE BIG BANG

A. How do we know it happened?

There are two solid pieces of evidence for the Big Bang. One is the fact that the galaxy clusters are moving away from each other right now. If we extrapolate back in time, using physics that we know quite well, we realize that about 13.7 billion years ago the universe must have been very hot and dense. The second signature of the Big Bang is the Cosmic Microwave Background (CMB). As we extrapolate back in time, we reach a point where the temperature exceeds 3000 Kelvin. Atomic Hydrogen is ionized at this temperature, so before this time, there were very few atoms. Rather, the Universe was a plasma of protons and electrons, and perhaps other particles. Light does not propagate through a plasma, so the Universe was opaque. As the Universe cooled through 3000 Kelvin, it became transparent, and the glow from the $3000K$ gas has been streaming freely ever since. In the meantime, the Universe has stretched by an enormous factor (roughly 1000), which also stretches the wavelength of the light. The glow, which is the CMB, now looks like radiation from a much cooler gas at a temperature 3 Kelvin. This is an actual decrease of the temperature of the Universe by a factor or roughly 1000. To understand this, imagine the Universe as a gas expanding in a cylinder. As the gas expands, it cools, and that is what has happened to the Universe, though, of course, there is no "wall" as there would be in a cylinder.

Another important fact about the observable Universe is that on very large scales (10^8 light yrs) it is homogeneous and isotropic. Homogeneous means that one place looks pretty much like any other place, and isotropic means one direction looks like any other direction. On smaller scales (10^6 to 10^7 light yrs) we have inhomogenieties such as Galaxy clusters, etc. The homogeneity and isotropy is reflected in the fact that the CMB is amazingly uniform. No matter which direction in the sky you look at, the temperature of the radiation is $3K$.

B. What exactly is expanding in an expanding Universe?

It gets very confusing to think of *everything* expanding, because then your meter sticks, which you use to measure distances, would also expand, and all distances would appear to be the same!!! In fact, meter sticks and material objects do not expand in an expanding Universe. Only the space between galaxy clusters expands. Within a galaxy cluster, the space is expanding but gravity is strong enough to keep the galaxies together, so the size of the cluster remains the same as the Universe expands. Similarly, the space between the atoms of your body is expanding but the forces between the atoms are strong enough to keep those atoms at the same distances from each other.

C. Are there alternative theories without a Big Bang?

Various very creative people have tried to construct alternative explanations for these two pieces of evidence. For example, in the 30s and 40s the Steady State theory of Fred Hoyle was a popular alternative, but it could not explain the CMB (seen first in 1965 and by now extremely well-characterized) in a simple way. The Big Bang remains the simplest explanation.

D. What we do not know about the Big Bang?

Temperature is a measure of the average kinetic energy of a system (in fact it is proportional to the average kinetic energy of a molecule). As we go back in time towards the Big Bang, we encounter higher and higher temperatures. Currently our physics is valid to energies of 10^9 electron Volts (denoted eV), which corresponds to a temperature of 10^{13} K. Most of our knowledge of this physics comes from particle accelerators such as Fermilab in Chicago and CERN in Switzerland. When we extrapolate to a time which corresponds to a temperature higher than 10^{13} K, we have to start guessing about the physics. This is presumably controlled by a Grand Unified Theory (GUT) of particle physics, which would treat the electromagnetic, strong, and weak forces on the same footing. While there are many candidates for the GUT, we don't know which one, if any, is correct. When the energy reaches the Planck energy $E_{Pl} \simeq 10^{28} eV$, gravity becomes quantum mechanical.

E. What does quantum gravity mean?

In the Quantum Mechanics of a particle such as an electron, the Heisenberg Uncertainty Principle plays a crucial role. It says that the product of the uncertainties of position x and momentum $p = mv$ must be larger than Planck's constant

$$\Delta x \Delta p \geq \hbar \simeq 10^{-34} Joule \cdot sec \tag{1}$$

So trying to confine an electron into a tiny box makes its momentum uncertainty large and measuring its momentum precisely means we don't know where it is! *In Quantum Mechanics, there is an intrinsic fuzziness about the position or momentum.* So why do we never see fuzziness in, say, a baseball's position? Say the baseball has a mass of $0.5 kg$ and a speed of $v = 1 meter/sec$. Its momentum is $p = 0.5 kgm/s$. Assume that we know the speed to 1% so the uncertainty of the momentum is 1% of p.

$$\Delta p = 0.005 kg \cdot meter/sec \tag{2}$$

The Heisenberg Uncertainty principle then says we cannot know the baseball's position to better than

$$\Delta x = \frac{\hbar}{\Delta p} \simeq 2 \times 10^{-30} meter \tag{3}$$

This is a ridiculously small uncertainty! For comparison, the size of an atom is $10^{-10} meter$ and the size of a nucleus is $10^{-14} meter$. In fact, a key and extremely counterintuitive notion of Quantum Mechanics is that until you measure the position of an electron, it does not have a definite position! Instead it has a wave function which tells you the probability for the electron to have various positions.

For many purposes, electrons behave more like waves, and we know that waves are spread out and don't have a definite position. In fact, one can assign a wavelength λ to a particle of momentum p by de Broglie's rule

$$\lambda = \frac{2\pi\hbar}{p} \tag{4}$$

Experimentally, electrons have been seen acting like waves, exhibiting interference. In fact, the electron microscope uses electron waves instead of light to look at very tiny objects.

If one wants to treat many particles at the same time, and allow for particles and anti particles to annihilate, it turns out to be necessary to introduce quantum fields. One then thinks of the observed particles as the smallest observable unit of the quantum fields. One example is the photon, which is the smallest observable unit of the electromagnetic field.

Now, we know classically about the gravitational field, which according to Einstein's General Theory of Relativity is the curvature of spacetime. Quantum Gravity is relevant when the curvature becomes fuzzy, and so spacetime itself becomes fuzzy. This becomes important at the Planck scale, which I will now describe.

By dimensional analysis, out of Newton's constant $G = 6.67 \times 10^{-11} Newton \cdot meter^2/kg^2$, Planck's constant $\hbar = 10^{-34} Joule \cdot sec$, and the speed of light $c = 3 \times 10^8 meter/sec$, one can construct one (and only one) energy, the Planck energy

$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \simeq 10^{28} eV = 10^9 Joules \tag{5}$$

This is related to the Planck mass by $E = mc^2$

$$M_{Pl} = \frac{E_{Pl}}{c^2} \simeq 10^{-8} kg \tag{6}$$

and by Heisenberg's Uncertainty principle to the Planck time

$$t_{Pl} = \frac{\hbar}{E_{Pl}} \simeq 10^{-43} sec \tag{7}$$

The Planck time is related by the speed of light to the Planck length

$$l_{Pl} = ct_{Pl} \simeq 10^{-34} meter \tag{8}$$

At these length and time scales gravity is quantum mechanical. One way of understanding the Planck energy better is to think of it as the Black Hole of the smallest energy allowed by Quantum Mechanics. Consider a Black Hole of mass M. According to General Relativity, it has a horizon beyond which even light cannot escape and the radius of this horizon is

$$R = \frac{GM}{c^2} = \frac{GE}{c^4} \tag{9}$$

The quantum mechanical wavelength of such a particle by de Broglies rule is

$$\lambda \simeq \frac{\hbar}{Mc} = \frac{\hbar c}{E} \tag{10}$$

If $\lambda > R$, quantum uncertainty will prevent the Black Hole from forming, but if $\lambda < R$ the Black Hole can form. The threshold is

$$\lambda = R \Rightarrow \frac{GE}{c^4} = \frac{\hbar c}{E} \Rightarrow E = \sqrt{\frac{\hbar c^5}{G}} \tag{11}$$

In order to deal with this energy scale, we need to know the quantum theory of gravity. We have a potential candidate, String Theory, but so far it has not been possible to make experimental tests to see if it is correct.

Bottom line: We don't know enough physics to understand what happened very close to the Big Bang. In particular, we don't know if the Big Bang is a genuine singularity in the sense of having infinite energy density, and in General Relativity, an infinite curvature for spacetime. Perhaps quantum effects make everything fuzzy, so that the energy density never really becomes infinite and the singularity does not really occur. We just don't know.

Another FAQ is **What was there before the Big Bang?** Again, we just don't know because we don't know the correct physics at extremely high energy densities.

F. Is the Universe finite or infinite?

It is possible to have a Big Bang in both cases, because a Big Bang postulates infinite energy *density*, not infinite energy. The common picture used to describe an expanding Universe, that of an expanding balloon, describes a finite Universe. In such a Universe, if one looked far enough, one would see the back of ones head (assuming you lived long enough for light to circumnavigate the Universe!) The corresponding picture for an infinite Universe has an infinite rubber sheet being expanded.

At the moment, we don't know whether the Universe is finite or infinite but the consensus is that it is effectively infinite due to cosmic inflation. Inflation is a process believed to have occurred at the energy density just beyond where our physics begins to break down. Driven by a supercooled quantum field (in a state very similar to a supercooled liquid which ought to freeze, but is not yet frozen due to fast cooling), a part of the Universe expands exponentially for a brief time.

The key point is that the expansion of space can happen faster than the speed of light. The whole idea of faster-than-light expansion of space is very confusing, and I will exlain it some more shortly. If you lived in a Universe undergoing inflation, you would see the most distant galaxies becoming redder and ultimately dropping out of view. If inflation is correct, what we live in used to be a very tiny patch of the Universe soon after the Big Bang, so we may never find out if the entire Universe if finite or not.

G. Doesn't Special Relativity rule out the faster-than-light expansion of space?

This is one of the most confusing issues that I have encountered. The surprising answer is NO, special relativity does not rule out the superliminal expansion of space predicted by inflation. Without going into too much detail, the assumptions behind special relativity are that spacetime is flat (no curvature) and infinite. While this is always locally true (in a small enough region of space), it is certainly not true in an inflating Universe. Because it is locally correct, you will never see any object whizzing past you faster than c. However, because special relativity does not apply globally, distant galaxies can move apart faster than c. Consider the light emitted from a distant galaxy. Each observer it goes past will agree that it is travelling at c, but if the galaxy is distant enough, in an inflating universe

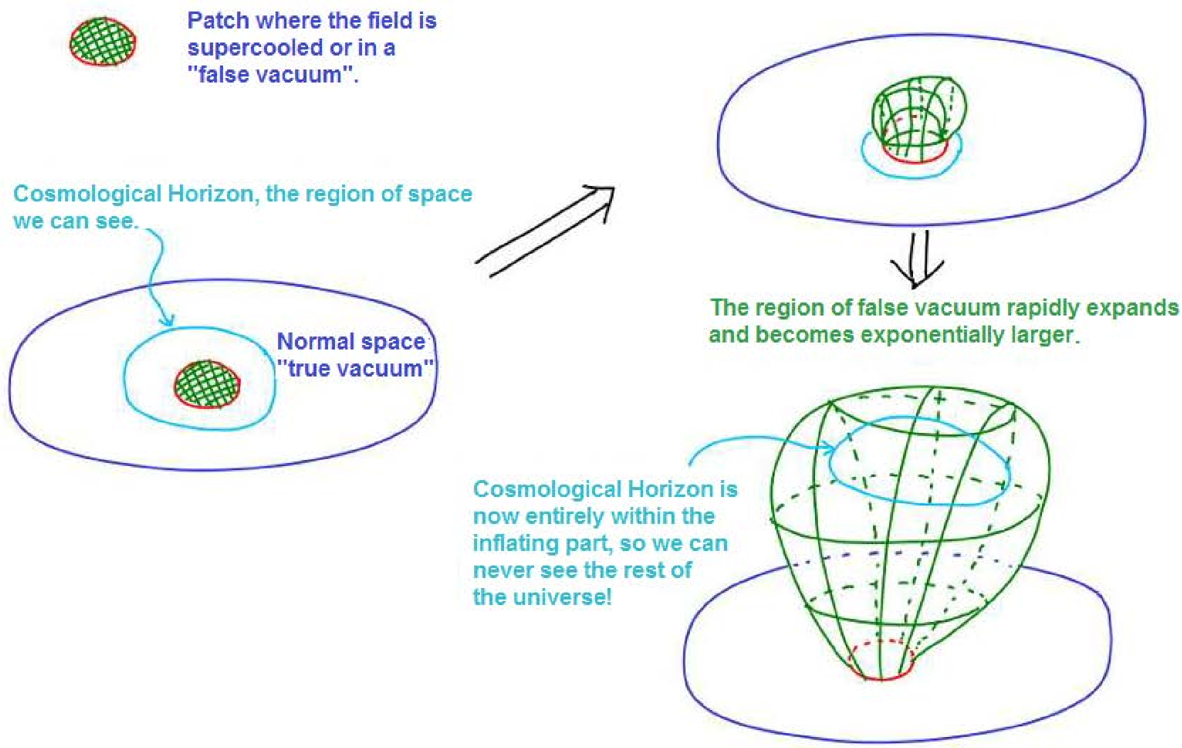

FIG. 1: A Cartoon of Cosmic Inflation. A quantum field in a patch of the past universe (labelled by green hatching) becomes supercooled and produces a cosmological constant with accelerating expansion for that region. At that inital time, the region of space that an observer can see, called the cosmological horizon, is dipicted by the light blue circle. The patch starts expanding exponentially fast, with apparent velocities of distant galaxies greater than the speed of light. Eventually the cosmological horizon is entirely within the inflating patch. We will never be able to see outside it as long as the universe continues inflating.

the light from it will never reach us. *There are parts of the Universe we will never see in an inflating Universe, no matter how long we wait*!! What would we see if the Universe started inflating today? We would initially see the distant galaxies becoming redder. Then as their relative velocity with us exceeded c, they would disappear into a cosmological horizon, in much the same way as objects dropped into a Black Hole disappear into its horizon.

III. DARK MATTER

A. What do we know about Dark Matter?

There are many things we don't know about Dark Matter, but here are a few things we are sure about. We know that it is matter of some kind, and has mass. So it is not a massless form of energy like light or gravitational waves. It must be stable (not like radioactive nuclei, which decay) because it has been around since the Big Bang. It must interact extremely weakly (if at all) with light and ordinary matter, because ordinary matter seems to pass right through Dark Matter and it does not absorb light.

B. How do we know Dark Matter exists?

Because we can detect its gravitational effects on ordinary matter by two methods. First, we can measure the speed v of a stars rotation around its galactic core as a function of r, the distance from the core. If the mass of the Galactic core within a radius r is $M(r)$, then Newtons law of Universal Gravitation says the force on the star is

$$F = \frac{GM(r)m_{star}}{r^2} \tag{12}$$

where m_{star} is the mass of the star we are looking at. The centripetal force (needed to keep the star moving in a circle) is

$$F_c = \frac{m_{star}v^2}{r} \tag{13}$$

Since the only force acting on the star is gravity the two must be equal and we get

$$v = \sqrt{\frac{GM(r)}{r}} \tag{14}$$

So the more mass of the galaxy $M(r)$ within the radius r, the faster the star revolves around it. By looking at nearby galaxies (up to 100 million lightyears) we can estimate $M(r)$ by looking at luminous matter (stars, and dust illuminated by stars). It turns out this is WAY too small to account for the speed $v(r)$. So there must be some non-luminous matter there as well. There are several kinds of ordinary non-luminous matter, such as interstellar dust and interstellar gas, but we can detect them by how they absorb light. Including all this ordinary non-luminous matter still leaves $M(r)$ about five times too small to account for the $v(r)$. Hence, we are forced to postulate the existence of Dark Matter. Now this cannot be ordinary matter, because it does not absorb light the way ordinary matter does.

The second way of detecting Dark Matter is by Gravitational Lensing. General Relativity predicts that matter should curve space time, and light travelling in such a curved spacetime should bend. This was detected in 1918, and is one of the best-verified results of General Relativity. Using this we can find the total mass (ordinary matter + Dark Matter) in a galaxy or galaxy cluster. Once again, we find about 5 times as much Dark Matter as ordinary matter. What else do we know about Dark Matter? It seems to have no (or extremely extremely weak) interactions with ordinary matter. This inference comes from looking at galaxies in collision, and imaging the Dark Matter distribution by Gravitational Lensing, and ordinary matter by light and X-ray emission. While the ordinary matter has a lot of friction with itself, the Dark Matter simply goes through!

C. Is Dark Matter antimatter?

Dark Matter is definitely not antimatter. We know antimatter very well because we have created it in the lab! An antielectron in just like an electron, except with a positive charge. In fact, it is called a positron and is emitted in some radioactive nuclear decays. The mass and spin of a positron are identical to that of an electron. When an electron and positron collide, they annihilate each other in a burst of electromagnetic radiation ($E = mc^2$). Similarly, an antiproton has the same mass and spin as a proton, but a negative charge. Antimatter absorbs and emits light in exactly the same way as matter, so we know that Dark Matter is not antimatter.

D. Is Dark Matter related to Dark Energy?

Most probably not, but we don't know for sure. The reason I say probably not is that most guesses for Dark Energy seem to hinge on it being a property of space itself, rather than matter.

E. Can we have an alternative explanation without invoking Dark Matter?

There is a proposed modification of Newtonian Gravity that can be tweaked to produce the $v(r)$ that is observed, but it does not explain the Gravitational Lensing. *The point is not to explain a particular observation (like $v(r)$) but to explain all observations with the same theory.* Dark Matter does explain all current observations.

F. What is Dark Matter, really?

The constraints on it are that it must be extremely weakly interacting, sufficiently massive, and stable. The best guess right now is that it is a particle like the neutrino that has no charge (so it wouldnt absorb or emit light) but much more massive. Most massive particles are unstable, so we need some symmetry to stabilize it. The current favourite among particle physicists in Supersymmetry, which postulates a new kind of symmetry between bosons and fermions. If Supersymmetry is correct, we should see some new particles at CERN (other than the Higgs particle). We just have to wait and see!

IV. DARK ENERGY

A. Why do we need Dark Energy?

Recall that we looked at the galaxies receding from each other and played the movie backward to conclude that 13.7 billion years ago the Universe was hot and dense. Given that initial condition, now play the movie forward. There are a bunch of galaxies moving away from each other. As they move away, we expect gravity to slow their speeds the same way that a ball thrown upward slows as it climbs the gravity well. Of course, the galaxies may have been moving so fast in the beginning that they will escape each other's gravity eventually, but they should still be slowing down as they move apart.

In the last 10-15 years evidence has built up that the galaxies are slowing down less than they should based on known physics. Something seems to be counteracting gravity. It seems to be acting like an extra repulsive force. This is something given the name Dark Energy. One candidate for Dark Energy is Einstein's Cosmological constant Λ. Einstein added this term to General Relativity to obtain a static Universe, because this was before Hubble discovered the expansion of the Universe. After Hubble, Λ was thrown away (Einstein called it the greatest blunder of his life!). Now it is making a comeback as Dark Energy.

B. What is the physical origin of Dark Energy?

One possibility is zero-point or vacuum energy. Quantum mechanics says that a system in its lowest energy state need not have zero energy. Energy curves spacetime just like mass does. So one conjecture is that Λ is just the vacuum energy of quantum fields. There is one huge problem. The natural size of Λ that comes out of quantum field theory is 10^{120} (yes, this is right, ten to the power 120!!) times what is observed. We will almost certainly need new physics to explain Dark Energy. Stay tuned!

C. How is the ratio of ordinary matter, Dark Matter, and Dark Energy determined?

Remember that we know the total amount of ordinary matter because it either shines (stars) or blocks light (dust and gas). We can use either galactic rotation curves ($v(r)$) or Gravitational Lensing to infer the amount of Dark Matter. The ratio between ordinary and Dark matter has stayed constant since the Big Bang. Dark Energy is more difficult to pin down, since the only way we infer its existence is by cosmic acceleration, a very mild form of inflation. The current proportion of Dark Energy is estimated by assuming a cosmological constant that is truly constant, that is, independent of time. In this case, there is Λ of energy per cubic meter of space. As the Universe expands, there is more space and the proportion of Dark Energy grows. This is why the proportion of Dark Energy was negligible soon after the Big Bang, but will increase in the future. Can Dark Energy be converted to other energy or matter? If Dark energy has the same origin as Inflation (the energy of some field in the false vacuum) then yes, the Universe will eventually decay to the true vacuum, which presumably has zero energy. This decay is indeed associated with the release of ordinary energy and matter. At the moment we know too little about Dark Energy to say anything concrete.