Chapter 12
Welcome to Your New Universe(s)

This chapter and the following extend our discussion of cosmology, including new (as of 2016) discoveries made possible by higher resolution studies of the cosmic microwave background and by advances in theoretical physics. In this chapter, we update the evidence that our universe began with an episode of inflation 13.7 billion years ago and that its composition includes significant portions of dark matter, contributing especially to galactic structure, and dark energy, accelerating the expansion of the universe. In the next chapter, we argue that the process of inflation leads inevitably to a multitude universes bubbling out of the vacuum, and that our universe is just one of an infinitude in a multiverse.

Twenty years ago we thought we knew pretty much everything about the structure and the history of the universe. The standard model of particle physics was complete, with only a few loose ends, and big bang cosmology seemed well established.

Then some astronomers, trying to tie up those loose ends, unraveled the whole thing. The universe isn't behaving like it was supposed to. It is not only expanding (we already knew that), but it is accelerating. Galaxies are flying apart faster today than they were yesterday.
Turns out the standard model of particle physics only includes about 5% what the universe is made of. We have clues as to the rest, and it's remarkable that we can measure how much we don't know. Evidence indicates about 25% of the universe is in the form of matter that we can't see directly, so-called "dark matter." And about 70% of the stuff of the universe, whatever it is pushing the expansion, is in the form of "dark energy." In this chapter, we present recent evidence (as of 2016) supporting the hypothesis that our universe began with a period of rapid, exponential inflation. We review the evidence for the existence of dark matter and dark energy, and we consider what they might be. And we discuss the mind-boggling possibility that our universe is just one among an infinitude in a multiverse. Curiouser and curiouser.

Clues from the cosmic microwave background

The cosmic microwave background radiation (CMB) fills our universe. It is remnant energy left over from the origin. As we will see, its characteristics imply that our universe originated in a brief period of rapid inflation followed by energy transformations at extreme temperature. The universe has been cooling ever since, over a period of about 13.7 billion years, as it expands. Today the CMB is in the form of microwave radiation at an effective temperature of about 2.7 K, i.e. 2.7 degrees C above absolute zero. It's as if a steam piston exploded into a vacuum, and all that heat has been distributed over the enormous volume of the universe, cooling all the while. (We have to be careful with analogies here. Our universe did not explode "into" some larger space. All that space, and time itself, originated at that event. More on that later.)

The CMB has been studied in increasingly finer detail over the past several years by satellite and ground-based observatories. The latest data from the Planck satellite allow us to measure its properties to a resolution within fractions of a degree, both temperature and angular measure, across the entire sky.

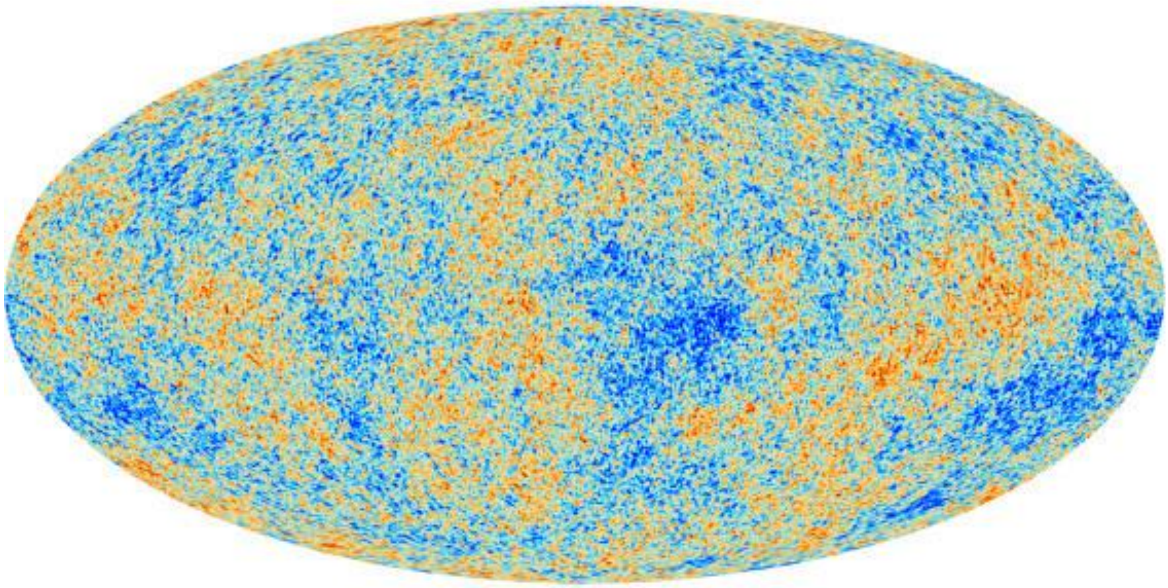

Figure 12.1. Planck satellite image of the cosmic microwave radiation. Reds show slightly warmer regions of the sky, blues slightly cooler. Temperature differences are on the order $1/100{,}000^{th}$ of a degree.

Planck has confirmed previous observations that the CMB is remarkably uniform. Its temperature varies only by about one part in 100,000 from point to point across the entire sky. But it does vary slightly, and those variations carry information about the composition of the universe and conditions at its origin.

From Planck data, scientists analyze the "power spectrum" of the CMB. The temperature varies across the sky on spatial scales similar to the harmonics of a musical instrument. It's as if we are looking at the surface of a pond with smaller ripples on top of larger waves. On the CMB we see ripples of temperature variation superimposed on larger temperature fluctuations.

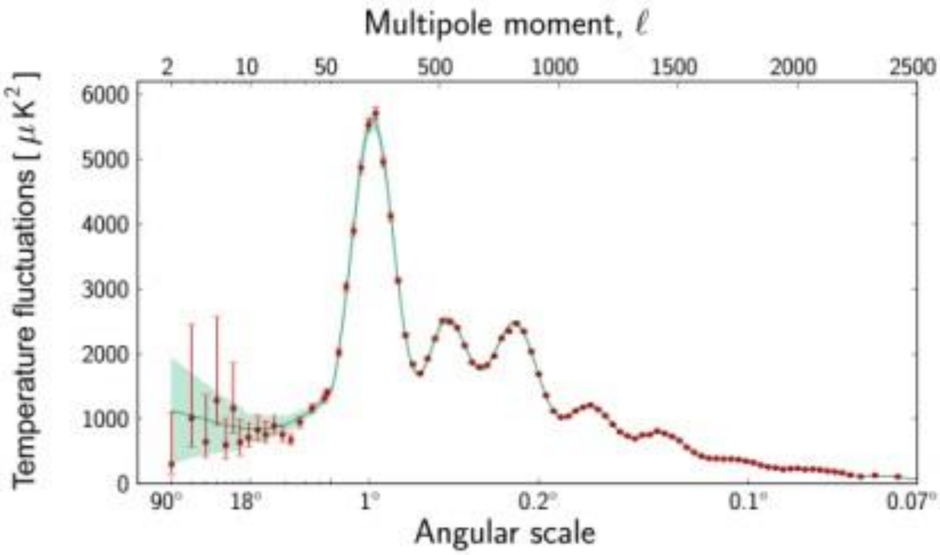

Figure 12.2. Power spectrum of the cosmic microwave background showing temperature variation from point to point across the sky as a function of angular separation of points. Red dots represent Planck data. Green curve is the theoretical prediction for the power spectrum including inflation, dark matter, and dark energy.

The size of the peaks in the power spectrum provides information about the mass density of the early universe. Just as stiffer materials oscillate at higher frequencies (think of the oscillations of a stiff spring compared to a slinky), so the frequencies in the power spectrum provide information about the "stiffness" of the early universe. The best match for the observed power spectrum is a universe containing about 70% dark energy, 25% dark matter, and only 5% baryonic matter, the stuff we experience in our daily lives.

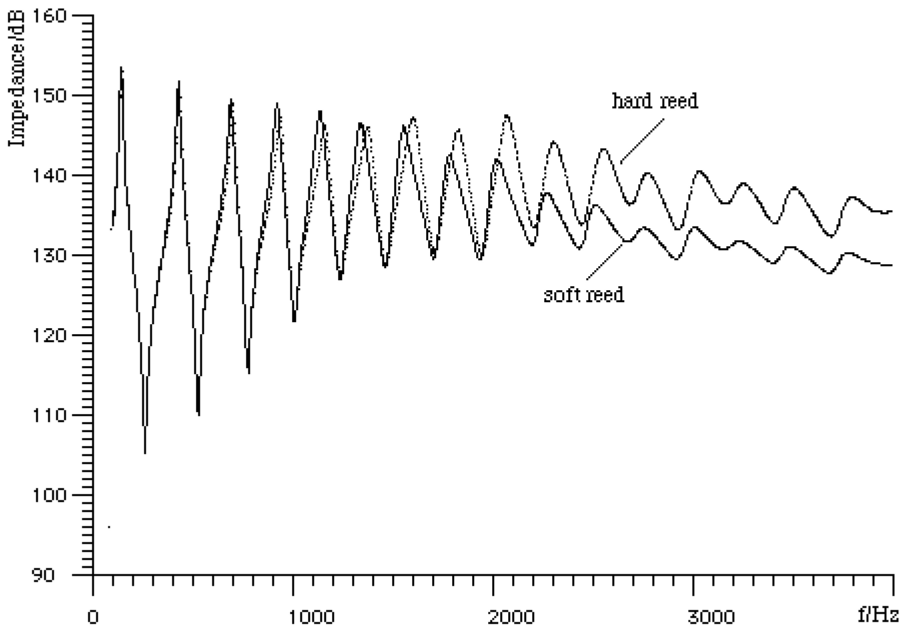

Figure 12.3. Acoustic spectra for a clarinet played with different reeds, one stiff and the other soft, for comparison with Figure 7.2. If the composition of the early universe had been "softer" (less dense), the peaks at higher angular frequency would be smaller. The CMB spectrum provides evidence for an energy-dense universe including dark matter and dark energy.

The CMB provides a treasure trove of information, with more yet to be extracted. Taken together, the CMB and its power spectrum provide evidence supporting the hypothesis that the universe originated from a fluctuation in a quantum field and underwent a brief period of rapid inflation, from quantum scale to macroscopic size. It has been expanding and cooling ever since. Onward to the question how that might have occurred.

Evidence for dark matter

First the dark matter. We can't see it, but we can detect its presence by its gravitational imprint.

The baryonic matter 5% of our universe interacts with the electromagnetic force, i.e. it can absorb and emit electromagnetic radiation. We can see it. Dark matter does not interact with the electromagnetic force, but it does interact with gravity just like ordinary matter. So even though we can't see it directly, we can see other objects – stars and galaxies and even light itself – pulled responding to its gravity.

The first evidence for dark matter came from studies of galaxy clusters. Fritz Zwicky, 'way back in the 1950's, found that clusters of galaxies, hundreds or thousands of them orbiting a common center of mass, didn't have enough visible mass to keep the cluster from evaporating. Taking into account only the mass he could see, Zwicky calculated that the galaxy clusters should have dispersed like a swarm of bees flying off into the fields. Some invisible mass must be holding the cluster together.

Later, Vera Rubin and her colleagues found a similar story inside of individual galaxies. Rubin measured the velocities of stars at increasing distance from the galactic center. If most of the mass was concentrated in the nucleus of the galaxy, as they appeared seen through telescopes, then velocities should decrease out toward the edge of the galaxy. That turned out not to be the case. Velocities continued to increase out toward the edge. The conclusion: galaxies contain invisible matter, dark matter, extending outward to the visible edge and beyond.

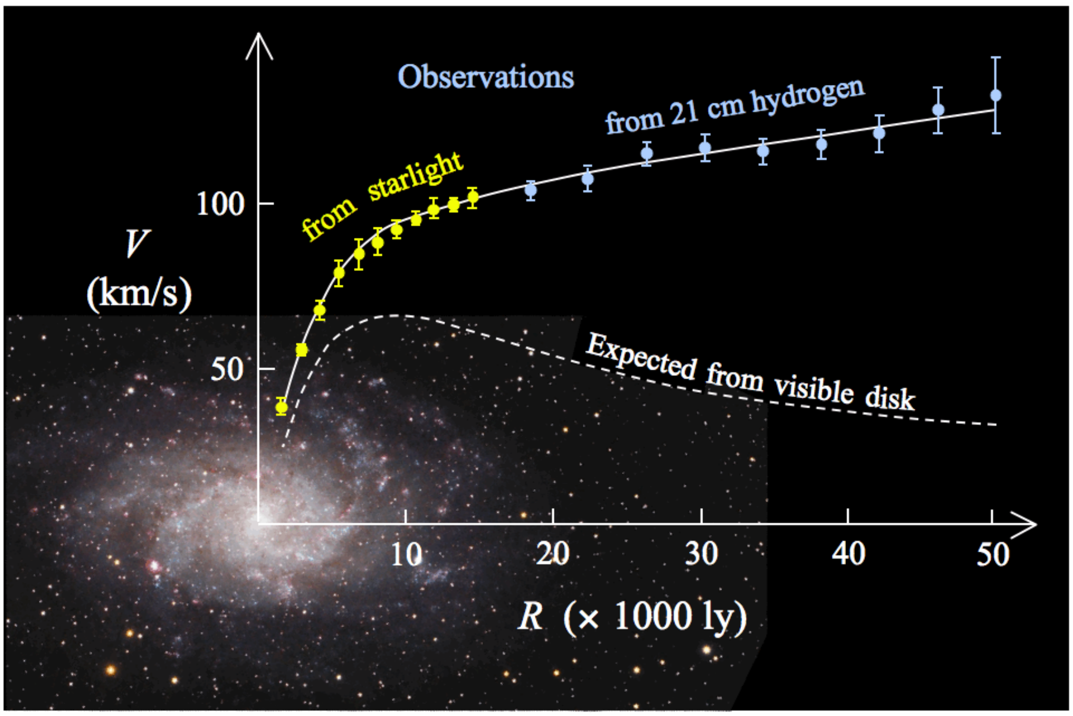

Figure 12.4. Orbital velocity of stars in the galaxy M33 as a function of distance from the nucleus. Measured velocities, upper curve, are greater than expected, and velocities continue to increase out to the visible edge of the galactic disk. This result is best explained by the presence of dark matter distributed throughout the visible galaxy and extending beyond the visible disk.

One of the coolest advances in modern astronomy allows us to "see" the distribution of dark matter by its effects as a gravitational lens. The gravitational field of nearby objects deflects light from objects that are farther away. The nearer objects act as a lens. The greater the gravitational field, the greater the deflection, the stronger the lens. So if we look through a cluster of galaxies, A, for example, at a more distant cluster, B, we can tell how much mass there is in A by how much the light from B is bent. Dark matter contributes to the gravitational lensing in A, so we can tell how much dark matter there is. Just subtract the lensing due to A's visible matter from the actual lensing.

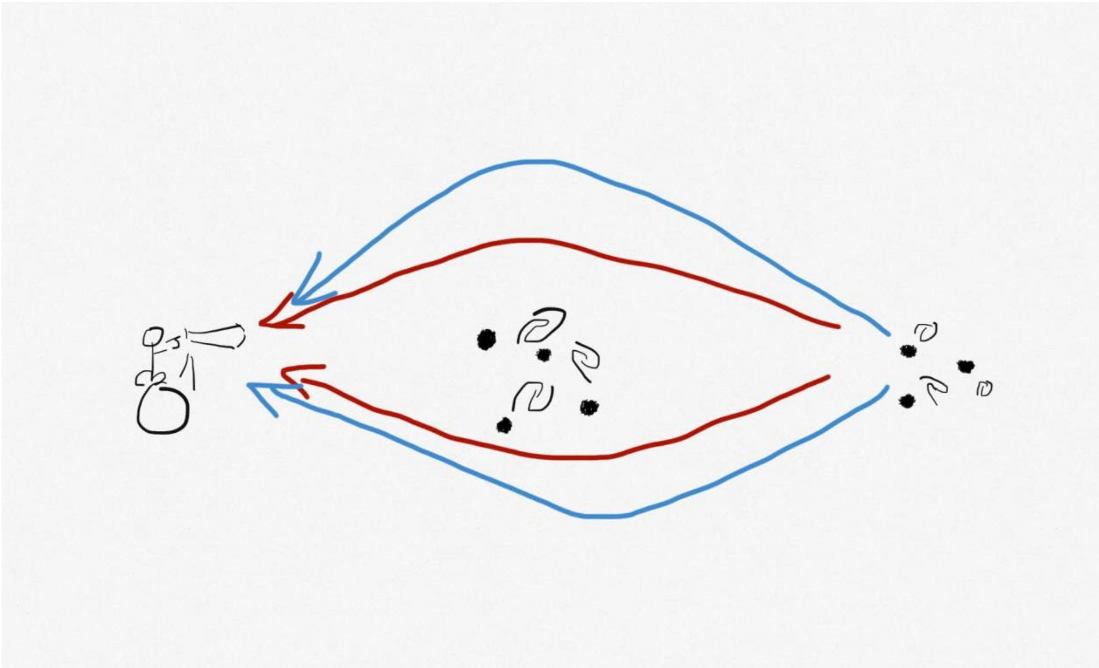

Figure 12.5. Gravitational lensing. Light from a distant galaxy cluster, right, is bent by the gravitational field of a nearer cluster, center. The presence of dark matter bends light more, blue paths, than would the gravitational field of visible matter alone, red paths. We can measure the amount of dark matter by the amount of deflection.

Images of the Bullet Cluster demonstrate these capabilities and more. The picture below shows two clusters of galaxies that have recently crossed paths. (It seems strange, but even if two galaxies "collide," it is rare for stars from one to crash into stars in the other. Space is mostly empty. Space in between galaxies in a cluster is even emptier.) The image is color enhanced to reveal galactic dust (red), a component baryonic matter associated with the clusters, and the distribution of dark matter (blue) calculated by lensing. As evident in the picture, gas from the clusters interacts; like a bulldozer blade piling up dirt, gas from one cluster piles into gas from the other, and the gas clouds fall behind the stars in the clusters. Dark matter, on the other hand, travels along merrily with the clusters. Dark matter in one cluster does not interact with material in the other cluster.

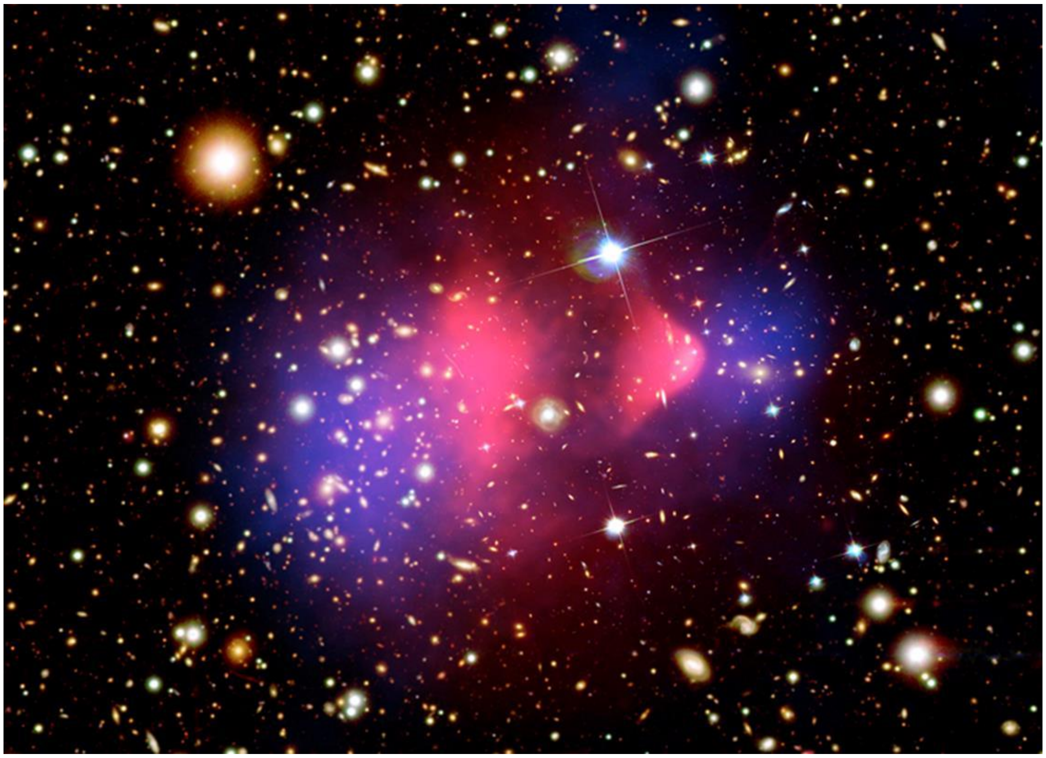

Figure 12.6. The Bullet Cluster. Cluster of galaxies in the blue halo on the right has passed through the larger cluster on the left. Electromagnetic interactions produced a viscous drag on dust in the clusters, red, leaving it piled up behind the clusters. Dark matter, blue, surrounding the clusters is not affected by electromagnetic interactions. Its distribution was mapped by its effect on gravitational lensing of light from more distant galaxies.

Accelerated expansion: the 1998 surprise

In the 1920's, Edwin Hubble and Milton Humason discovered that the universe is expanding, and they measured the rate of expansion, the Hubble constant. Their discoveries not only expanded our appreciation for the size of the universe but allowed astronomers to trace its evolution. If the galaxies are flying away from each other, then at some time in the distant past all that material must have been jam-packed in some cosmic egg. A giant explosion, the big bang, sent them flying.

With refinements from improved observations, big bang theory became established as our best model for the origin of the universe. As of the 1990's, only a few questions remained. What, for example, was the value of Ω (omega), the ratio of actual mass density to the critical mass density of the universe?

With the discovery of dark matter, astronomers had pegged omega somewhere between 0.2 and 0.3, not enough to stop the expansion. On the other hand, data from CMB observations, which supported inflation theory, gave an omega of 1.0, just right to slow the universal expansion asymptotically to zero. What was going on?

Came 1998, and two teams of astronomers independently found evidence for the critical ingredient. Saul Perlmutter's team at U.C. Berkeley / LLNL, Adam Reiss's team at Johns Hopkins / HSTSI, and Brian Schmidt at the Australian National University found that our universe is not just expanding. The expansion is accelerating. Something out there in the fabric of spacetime is pushing entire clusters of galaxies. The clusters are not just coasting along on momentum from the big bang. Something out there in the emptiness of intergalactic space, something in the stuff of spacetime itself, is pushing them. Or, more accurately, the clusters are carried along, embedded in the accelerated stretching of spacetime.

Perlmutter, Schmidt, and Reiss studied type Ia supernovas (SN Ia) in distant galaxies. SN Ia are good standard candles. A white dwarf star in a binary star system pulls gas off its companion star. The mass of the white dwarf crosses a critical threshold, and the star collapses, igniting the supernova. Because SN Ia have a common origin, they emit the same amount of light. By measuring how bright they appear, astronomers can determine how far away they are.

OK, we can measure distance to the SN Ia. How do we know how fast it is moving?

The speed of recession is related to the z factor. z measures how much the wavelength of light has stretched as it crosses the universe, from its origin in a distant galaxy to our telescopes. As such, it is a measure of the scale factor of the universe, i.e. by how much has spacetime itself been stretched. If we plot distances to SN Ia's vs. their z's, we can determine whether or not the rate of expansion is constant over time.

Figure 12.7 shows how astronomers can determine the rate of expansion of the universe. Galaxy G_1 is twice as far from the observer as G_2 as determined by their relative brightness. (An SN Ia in G_1 would appear one-quarter as bright as an SN Ia in G_2. Brightness decreases as the inverse square of the distance.) We measure light produced by the same process in both galaxies, say the hydrogen alpha line. In all three scenarios, light leaves G_1 at time t_1, passes G_2 at t_2, and light waves from both sources arrive at the observer at the same time. Scenario A represents a static universe, neither expanding nor contracting. Light from G_1 arrives at our telescope at the same wavelength as the light from G_2. Scenario B represents a universe expanding at a constant rate over time. The wavelength of light from G_1 is stretched by twice the factor, z, relative to light from G_2. Scenario C illustrates conditions in an accelerating expansion. It assumes the extreme case where the acceleration begins at t_2. In this instance, light from both sources is stretched by the same factor; z_2 is the same as z_1 even though G_1 is twice as far away. Accelerated expansion produces a "z-deficit" for distant objects.

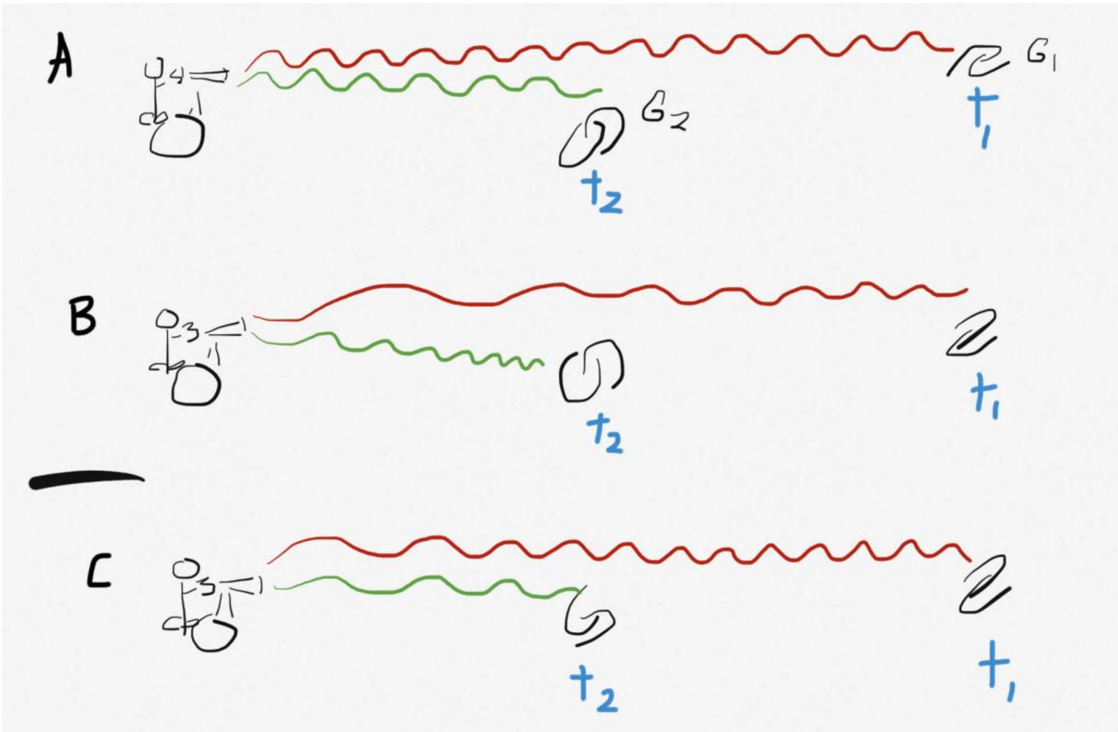

Figure 12.7. Accelerated expansion results in a *z*-deficit. As explained in the text, light arriving from a distant galaxy is not stretched as much as expected if the expansion rate has increased during the time the light has been traveling across the universe. Scenario A: static universe. Scenario B: constant rate of expansion. Scenario C: increased rate of expansion beginning at t_2.

The actual observational findings are more subtle than the illustrations above, but they are compelling. They show a *z*-deficit relative to brightness. The SN Ia data imply that our universe entered an epoch of accelerated expansion about 5 billion years ago. That acceleration, we believe, is driven by dark energy.

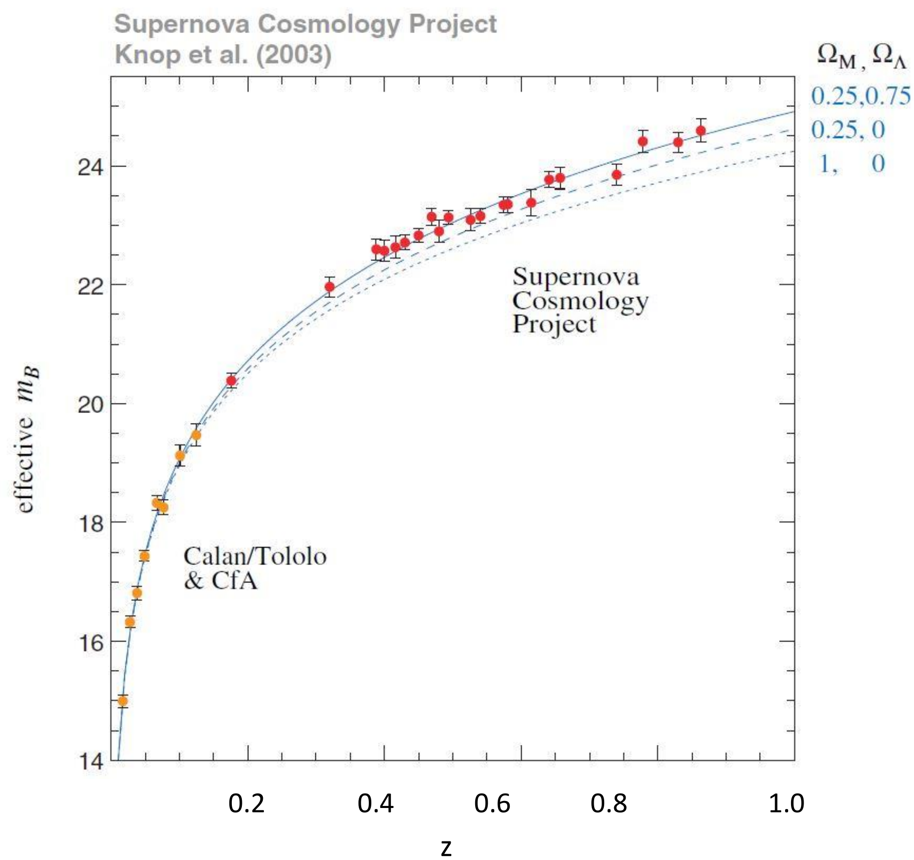

Figure 12.8. SN Ia data, magnitude vs z. Red are data points with error bars. Blue curves are models based on relative proportions of matter density, Ω_M, and dark energy, Ω_Λ. Note that increasing magnitude corresponds to decreasing brightness, e.g. a 1st magnitude star is brighter than a 5th magnitude star. These data show a *z*-deficit (data points lie to the left of the $\Omega_\Lambda = 0$ curves), implying that the universe is undergoing an accelerated expansion. The best fit model is a universe with about 25% ordinary + dark matter and about 75% dark energy.

Vacuum energy and repulsive gravity

As with dark matter, we can measure the effects of dark energy but we don't know (yet) what it is. Dark energy accelerates the universal expansion, so it acts as a gravitational repulsion. It's as if you threw a baseball upward and it continued to accelerate into the sky. What would do that?

The good news is that repulsive gravity is built into Einstein's equations. It is a familiar ingredient in general relativity – not familiar in our everyday lives, but an accepted outcome to the laws of nature. Einstein's field equation allows solutions for which the force of gravity is negative.

$$G^{\mu\nu} = 8\pi T^{\mu\nu}$$

Left side of the equation, the Einstein tensor $G^{\mu\nu}$, is gravitational curvature. It's a four-dimensional matrix measuring curvature in a region of spacetime along each of the four dimensions, three of space and one of time. It measures how clocks and rulers change as you move radially away from a black hole. How clocks and rulers change as you move in orbit around a star. How they change as you cross space in between the galaxies.

The right side of the equation contains the ingredients that cause curvature. Included in the energy-momentum tensor, $T^{\mu\nu}$, is the familiar source of gravity, plain old mass. But Einstein realized there are other sources of gravity, as well. Energy, of course, is related to mass by $E = mc^2$, so energy in any form generates a gravitational field. Not quite so intuitively, the flow of momentum between regions of spacetime also acts as a source of gravity. Flow of momentum is pressure. In a region of negative pressure, there's negative gravity.

Out there in the void between the galaxies, everywhere in our universe really, there is a very slight negative pressure. Here's the simple thinking. As the universe expands, the void fills to maintain a uniform mass / energy density. It's as if some kind of suction, negative pressure, pulls in energy to fill the void. Negative pressure, negative gravity, and that pushes further expansion.

Whoa! If that's the case, won't the universe blow itself apart? We'll get to that in the next chapter. The simple answer is that the negative pressure is extraordinarily tiny. Over large scales in the universe we can observe its effects, but only over large scales and long time.

What is the source of this negative pressure? Physicists give it various names – dark energy, the cosmological constant lambda (Λ), vacuum energy. Einstein added a cosmological constant term, representing a repulsive gravity, to his equations in order to stabilize the universe. He realized that, without such a term, the universe would collapse on itself.

The current favorite candidate for dark energy / cosmological constant is vacuum energy. Vacuum energy was discovered in the early days of quantum physics. The uncertainty principle does not allow an energy state of exactly zero. There are always fluctuations in the vacuum around zero – particles that pop briefly into existence, fluctuations in the fields. These have been measured experimentally, as in the Casimir effect.

Out there in the vacuum, spacetime is seething with field fluctuations and virtual particles. But quantum calculations predict the vacuum energy associated with those fluctuations should be about 120 orders of magnitude greater than the observed dark energy. That's a problem. Why is lambda tuned so precisely that our universe has not blown itself apart, or vice versa, not already collapsed?

That's the work in progress and as of this writing (2016) the great problem in physics yet to be solved.

Putting it all together: the inflation model

Here are the pieces of the puzzle, the bits of evidence from observations. The CMB reveals a universe that is extraordinarily homogeneous and isotropic – same large-scale structure everywhere, and the same in all directions. The power spectrum matches a model universe with exactly the critical density, i.e. a universe precisely tuned such that attractive gravitational mass / energy exactly balances repulsive dark energy. Other observations, such as gravitational lensing and the supernova type Ia data, confirm the presence of dark matter and dark energy necessary to provide the critical density.

These observations raise two questions. How can it be that the structure of universe is so extraordinarily uniform on large scales (the CMB), but with fluctuations in mass / energy density at smaller scales (galaxy clusters and voids in between)? CMB photons reaching us from the east have been traveling for the same time, since shortly after the big bang, as photons reaching us from the west. It would seem that those two cosmic horizons, east and west, could not have been in contact with each other. Yet the temperature at those horizons is the same, so they must have been in contact. This is the "horizon problem."

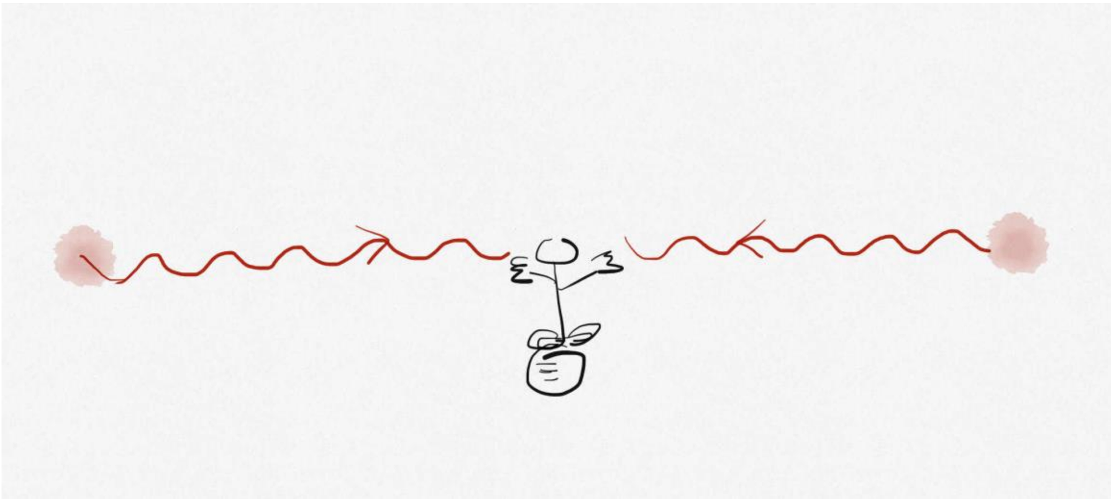

Figure 12.9. The horizon problem. Microwave photons arriving from the western CMB horizon have the same temperature as photons arriving from the eastern horizon. But those photons have been traveling to us since the origin of the universe, so, at first glance, the horizons could not have been in contact, as required to reach thermal equilibrium. Inflation solves the problem – the horizons were in contact before inflation.

The second question, the “flatness problem,” has to do with $\Omega = 1$. The mix of ordinary matter, dark matter, and dark energy gives the universe exactly critical mass. It is geometrically “flat” on large scales. Parallel light rays travel forever parallel.

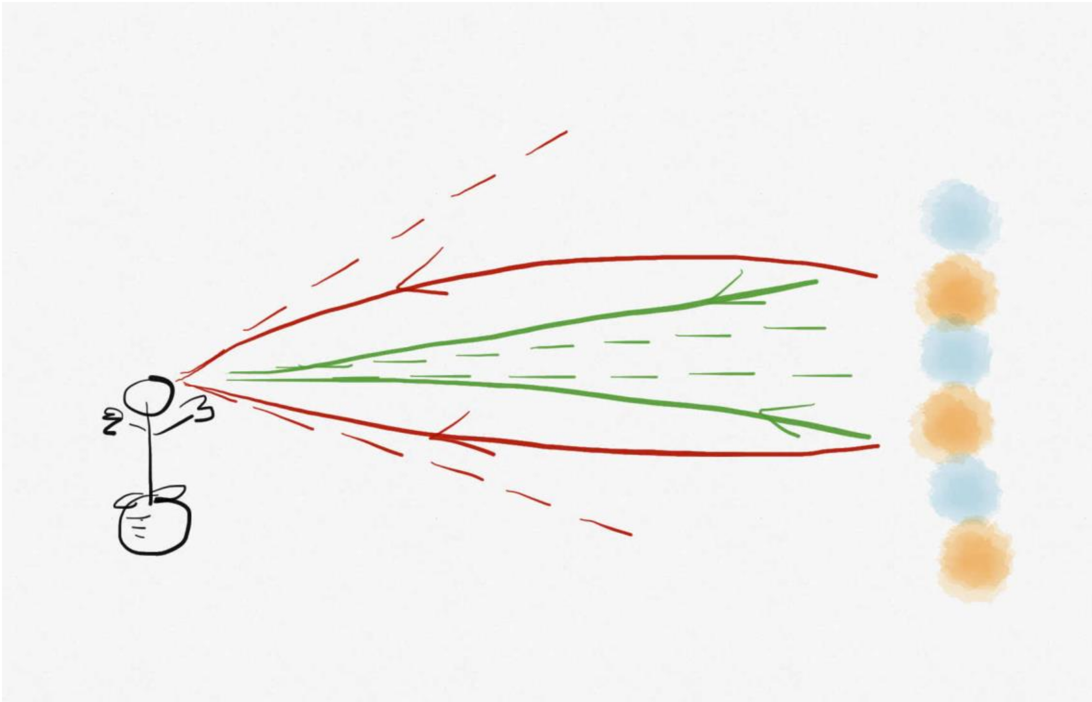

Figure 12.10. How to detect curvature and, thereby, measure the mass of the universe. One way to measure curvature is to measure angular separation of distant objects. For example, we can calculate the angular separation expected between hot and cold patches on the CMB (colored patches to the right in the figure). Then we measure the observed angular separation. If the universe has a positive curvature ($\Omega > 1$), light rays from different patches will curve toward each other as they travel across spacetime (solid red trajectories). As a result, we will observe the patches more widely separated than they actually are (red dashed lines). On the other hand, if $\Omega < 1$ and the universe has a negative curvature, light rays from the patches will diverge (sold green), and the patches will appear closer together (green dashed lines).

How resolve the horizon and flatness problems? How did the universe get that way? Alan Guth in 1981 proposed a possible answer: inflation. The idea has been refined since, but the key notion is that the universe, at its origin, underwent a period of rapid inflation, from quantum scale to macroscopic scale in a fraction of a fraction of a second. The universe originated as a quantum fluctuation from a zero energy state, the vacuum.

Problems solved. The temperature of the cosmic horizon is uniform in all directions because all the universe was in thermal contact before inflation. Bonus prize is an explanation for the fluctuations at smaller scales. They represent quantum fluctuations now blown up to cosmic proportions by inflation. And mass / energy density is exactly critical because the net energy of the universe at the origin was, and still is, exactly zero. The universe is flat for reasons similar, by analogy, to the surface of an expanding balloon. The larger the balloon, the flatter the surface.

The models

Measurements from the Planck satellite not only confirm the general idea of inflation but they weed out the garden of inflationary models. Models are the mathematical equations that physicists invent to describe nature, and various models have been proposed to describe the origin of the universe.

As of this writing (2016) the latest analysis of Planck data appears to have eliminated the simplest cosmological model, first proposed by Andrei Linde in 1983 (Linde, 1983). That model hypothesizes a vacuum energy density proportional to the square of the inflaton field.

$$V = \frac{m^2}{2}\varphi^2$$

Predictions about the pattern of density fluctuations and polarization of the CMB based on that model fall just on the edge of the Planck measurements. See Linde's excellent 2015 Oppenheimer lecture for a full discussion. We've seen the CMB image and power spectrum. Let's take a final look at one more Planck data set, the r vs n plot, which sets the strictest limits on viable models.

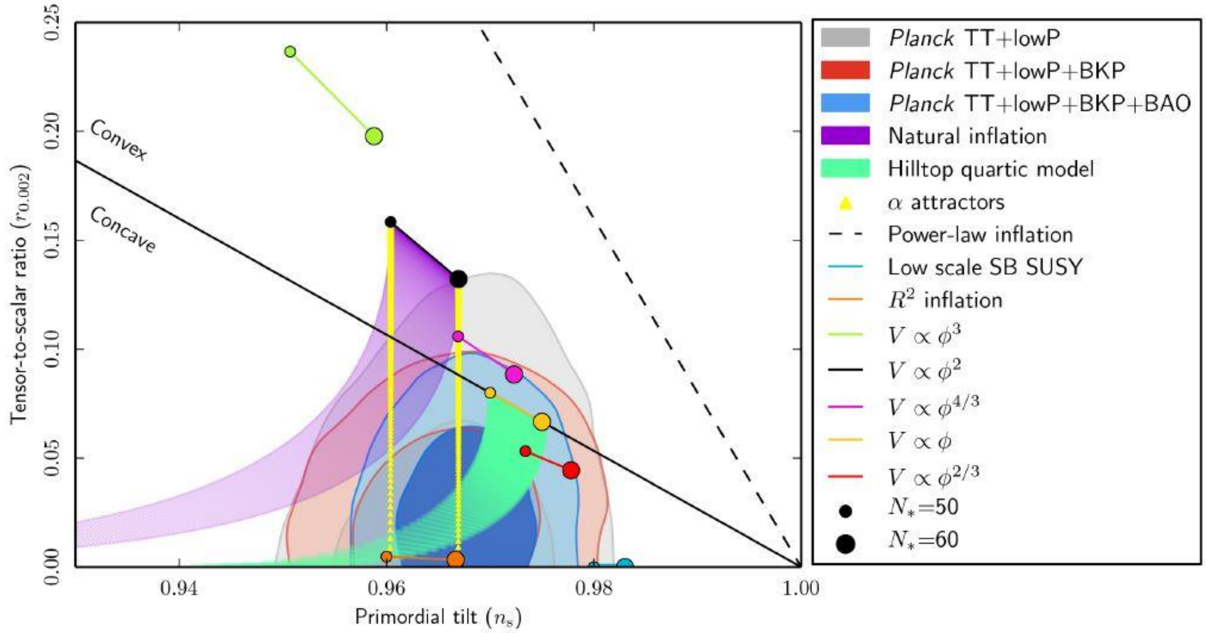

Figure 12.11. Data from Planck Collaboration, 2015. Constraints on various inflation models, plotted on Planck satellite data. Tensor-to-scalar ratio is, roughly, a measure of how much amplitude gravity waves contributed to the temperature variation on the CMB compared to the contribution by fluctuations in the scalar (inflaton) field. Primordial tilt measures the smoothness of the CMB power spectrum. A tilt of 1.0 is adiabatic, that is all frequencies contribute equal power.

Figure 12.11 illustrates two sets of constraints on cosmological models. The tensor-to-scalar ratio, r, obtained from measuring polarization in the CMB, compares the contribution of gravitational waves to fluctuations in the scalar field as imprinted on the CMB. Note its dependence on N, the number of "e-foldings" during inflation. e-foldings, to a good approximation, count how many times the universe doubled in scale. Inflation was driven by the scalar field, so more e-foldings correlate to a greater contribution in CMB structure from the scalar field and a smaller r. On the other hand, gravitational waves, generated mainly during decay of the scalar field, would dominate under conditions of slower inflation and fewer e-foldings, giving regions more time to expand after the decay of the field.

The "primordial tilt," n_s, measures the smoothness of the CMB power spectrum. For adiabatic expansion, i.e. expansion in which all wavelengths are equally represented up to the cutoffs at beginning and end of inflation, $n_s = 1$. This is a perfectly fractal universe: zoom in at any magnification on the CMB and it still looks the same. Deviation from 1 might be due to change in the rate of expansion at different times during inflation. For example, as the scalar field approached its new equilibrium, inflation might have slowed, giving more time for decay / phase transition out of the vacuum and skewing n_s away from 1.

As more data accumulates from Planck and its successors, the constraints will grow tighter and physicists will find which equations best model our universe. The most remarkable conclusion is that detailed observations support the theory of cosmic inflation, that the data eliminate other hypotheses about the origin of the universe, and that fairly simple models match the data. It is an exciting time in cosmology.

Summary:

Evidence from the cosmic microwave background and its power spectrum support the hypothesis that our universe originated in a brief period of rapid inflation and that its composition includes about 5% baryonic matter, the familiar particles and forces, about 25% dark matter, and about 70% dark energy. Inflation naturally explains the uniform CMB and its fluctuations. It also solves the cosmological flatness and horizon problems.

Astronomers have found further evidence for dark matter. Galaxy rotation curves and the gravitational binding of galaxy clusters requires the presence of dark matter. Gravitational lensing confirms the presence of hidden mass in galaxy clusters. Dark matter probably includes massive particles interacting via the weak force and not the electromagnetic force. The identity of the dark matter is unknown as of this writing, and the search for dark matter is an active realm of research.

Evidence for dark energy comes from magnitude vs. redshift of distant SN Ia supernovae. There is a “z-deficit” in distant SN Ia best explained by acceleration of the universal rate of expansion. Theory predicts that the dark energy probably represents quantum fluctuations in the vacuum, but the identity of the dark energy is not yet known. Understanding dark energy almost certainly will help us understand the origin or our universe and our place in it.

In the next chapter, we’ll probe further beyond the frontier. Why is our universe “fine-tuned” for the existence of life? Change the value of the cosmological constant – or the fine structure constant or any number of other parameters – by even a tiny amount, and we wouldn’t be here to observe our universe. How did it get that way?

References:

Linde, Andrei D. 1983. Chaotic inflation. Physical Letters B 129: 177-181.

Planck Collaboration. 2015. Planck 2015 results. XX. Constraints on inflation. arXiv:1502.02114v1