CHAPTER 2

A COSMIC MYSTERY STORY: WEIGHING THE UNIVERSE

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

—DONALD RUMSFELD

Having established that the universe had a beginning, and that that beginning was a finite and measurable time in the past, a natural next question to ask is, "How will it end?"

In fact, this was the very question that led me to move from my home territory, particle physics, into cosmology. During the 1970s and 1980s, it became increasingly clear from detailed measurements of the motion of stars and gas in our galaxy, as well as from the motion of galaxies in large groups of galaxies called clusters, that there was much more to the universe than meets either the eye or the telescope.

Gravity is the chief force operating on the enormous scale of galaxies, so measuring the motion of objects on these scales allows us to probe the gravitational attraction that drives this motion. Such measurements took off with the pioneering work of the American astronomer Vera Rubin and her colleagues in the early 1970s. Rubin had graduated with her doctorate from Georgetown after taking night classes while her husband waited in the car because she didn't know how to drive. She had applied to

Princeton, but that university didn't accept women into their graduate astronomy program until 1975. Rubin rose to become only the second woman ever to be awarded the Gold Medal of the Royal Astronomical Society. That prize and her many other well-deserved honors stemmed from her groundbreaking measurements of the rotation rate of our galaxy. By observing stars and hot gas that were ever-farther from the center of our galaxy, Rubin determined that these regions were moving much faster than they should have been if the gravitational force driving their movement was due to the mass of all the observed objects within the galaxy. Due to her work, it eventually became clear to cosmologists that the only way to explain this motion was to posit the existence of significantly more mass in our galaxy than one could account for by adding up the mass of *all* of this hot gas and stars.

There was a problem, however, with this view. The very same calculations that so beautifully explain the observed abundance of the light elements (hydrogen, helium, and lithium) in the universe also tell us more or less how many protons and neutrons, the stuff of normal matter, must exist in the universe. This is because, like any cooking recipe—in this case nuclear cooking—the amount of your final product depends upon how much of each ingredient you start out with. If you double the recipe—four eggs instead of two, for example—you get more of the end product, in this case an omelet. Yet the initial density of protons and neutrons in the universe arising out of the Big Bang, as determined by fitting to the observed abundance of hydrogen, helium, and lithium, accounts for about twice the amount of material we can see in stars and hot gas. Where are those particles?

It is easy to imagine ways to hide protons and neutrons (snowballs, planets, cosmologists . . . none of them shines), so many physicists predicted that as many protons and neutrons lie in dark objects as visible objects. However, when we add up how much "dark matter" has to exist to explain the motion of material in our galaxy, we find that the ratio of total matter to visible matter is not 2 to 1, but closer to 10 to 1. If this is not a mistake, then the dark matter cannot be made of protons and neutrons. There are just not enough of them.

As a young elementary particle physicist in the early 1980s, learning of this possibility of the existence of exotic dark matter was extremely exciting to me. It implied, literally, that the dominant particles in the universe were not good old-fashioned garden-variety neutrons and protons, but possibly some new kind of elementary particle, something that didn't exist on Earth today, but something mysterious that flowed between and amidst the stars and silently ran the whole gravitational show we call a galaxy.

Even more exciting, at least for me, this implied three new lines of research that could fundamentally reilluminate the nature of reality.

1. If these particles were created in the Big Bang, like the light elements I have described, then we should be able to use ideas about the forces that govern the interactions of elementary particles (instead of the interactions of nuclei relevant to determine elemental abundance) to estimate the abundance of possible exotic new particles in the universe today.
2. It might be possible to derive the total abundance of dark matter in the universe on the basis of theoretical ideas in particle physics, or it might be possible to propose new experiments to detect dark matter—either of which could tell us how much total matter there is and hence what the geometry of our universe is. The job of physics is not to invent things we cannot see to explain things we can see, but to figure out how to see what we cannot see—to see what was previously invisible, the known unknowns. Each new elementary particle candidate for dark matter suggests new possibilities for experiments to detect directly the dark matter particles parading throughout the galaxy by building devices on Earth to detect them as the Earth intercepts their motion through space. Instead of using telescopes to search for faraway objects, if the dark matter particles are in diffuse bunches permeating the entire

galaxy, they are here with us now, and terrestrial detectors might reveal their presence.

3. If we could determine the nature of the dark matter, and its abundance, we might be able to determine how the universe will end.

This last possibility seemed the most exciting of all, so I will begin with it. Indeed, I got involved in cosmology because I wanted to be the first person to know how the universe would end.

It seemed like a good idea at the time.

When Einstein developed his theory of general relativity, at its heart was the possibility that space could curve in the presence of matter or energy. This theoretical idea became more than mere speculation in 1919 when two expeditions observed starlight curving around the Sun during a solar eclipse in precisely the degree to which Einstein had predicted should happen if the presence of the Sun curved the space around it. Einstein almost instantly became famous and a household name. (Most people today think it was the equation $E = mc^2$, which came fifteen years earlier, that did it, but it wasn't.)

Now, if space is potentially curved, then the geometry of our whole universe suddenly becomes a lot more interesting. Depending upon the total amount of matter in our universe, it could exist in one of three different types of geometries, so-called *open, closed,* or *flat.*

It is hard to envisage what a curved three-dimensional space might actually look like. Since we are three-dimensional beings, we can no more easily intuitively picture a curved three-dimensional space than the two-dimensional beings in the famous book *Flatland* could imagine what their world would look like to a three-dimensional observer if it were curved like the surface of a sphere. Moreover, if the curvature is very small, then it is hard to imagine how one might actually detect it in everyday life, just as, during the Middle Ages at least, many people felt the Earth must be flat because from their perspective it looked flat.

Curved three-dimensional universes are difficult to picture—a closed universe is like a three-dimensional sphere, which sounds pretty intimidating—but some aspects are easy to describe. If you looked far enough in one direction in a closed universe, you would see the back of your head.

While these exotic geometries may seem amusing or impressive to talk about, operationally there is a much more important consequence of their existence. General relativity tells us unambiguously that a closed universe whose energy density is dominated by matter like stars and galaxies, and even more exotic dark matter, *must* one day recollapse in a process like the reverse of a Big Bang—a Big *Crunch,* if you will. An open universe will continue to expand forever at a finite rate, and a flat universe is just at the boundary, slowing down, but never quite stopping.

Determining the amount of dark matter, and thus the total density of mass in the universe, therefore promised to reveal the answer to the age-old question (at least as old as T. S. Eliot anyway): Will the universe end with a bang or a whimper? The saga of determining the total abundance of dark matter goes back at least a half century, and one could write a whole book about it, which in fact I have already done, in my book *Quintessence*. However, in this case, as I shall now demonstrate (with both words *and* then a picture), it is true that a single picture is worth at least a thousand (or perhaps a hundred thousand) words.

The largest gravitationally bound objects in the universe are called *superclusters* of galaxies. Such objects can contain thousands of individual galaxies or more and can stretch across tens of millions of light-years. Most galaxies exist in such superclusters, and indeed our own galaxy is located within the Virgo supercluster of galaxies, whose center is almost 60 million light-years away from us.

Since superclusters are so large and so massive, basically anything that falls into anything will fall into clusters. So if we could weigh superclusters of galaxies and then estimate the total density of such superclusters in the universe, we could then "weigh the universe," including all the dark matter. Then, using the equations of general relativity, we could determine whether there is enough matter to close the universe or not.

So far so good, but how can we weigh objects that are tens of millions of light-years across? Simple. Use gravity.

In 1936, Albert Einstein, following the urgings of an amateur astronomer, Rudi Mandl, published a short paper in the magazine *Science* titled "Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field." In this brief note Einstein demonstrated the remarkable fact that space itself could act like a lens, bending light and magnifying it, just like the lenses in my own reading glasses.

It was a kindlier, gentler time in 1936, and it is interesting to read the informal beginning of Einstein's paper, which after all was published in a distinguished scientific journal: "Some time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish." Perhaps this informality was accorded to him because he was Einstein, but I prefer to suppose that it was a product of the era, when scientific results were not yet always couched in language removed from common parlance.

In any case, the fact that light followed curved trajectories if space itself curved in the presence of matter was the first significant new prediction of general relativity and the discovery that led to Einstein's international fame, as I have mentioned. So it is perhaps not that surprising (as was recently discovered) that in 1912, well before Einstein had in fact even completed his general relativity theory, he had performed calculations—as he tried to find some observable phenomenon that would convince astronomers to test his ideas—that were essentially identical to those he published in 1936 at the request of Mr. Mandl. Perhaps because he reached the same conclusion in 1912 that he stated in his 1936 paper, namely "there is no great chance of observing this phenomenon," he never bothered to publish his earlier work. In fact, after examining his notebooks for both periods, we can't say for sure that he later even remembered having done the original calculations twenty-four years before.

What Einstein did recognize on both occasions is that the bending of light in a gravitational field could mean that, if a bright object was located well behind an intervening distribution of mass, light rays going out in various directions could bend around the intervening distribution and converge again, just as they do when they traverse a normal lens, producing either a magnification of the original object or the production of numerous image copies of the original object, some of which might be distorted (see figure below).

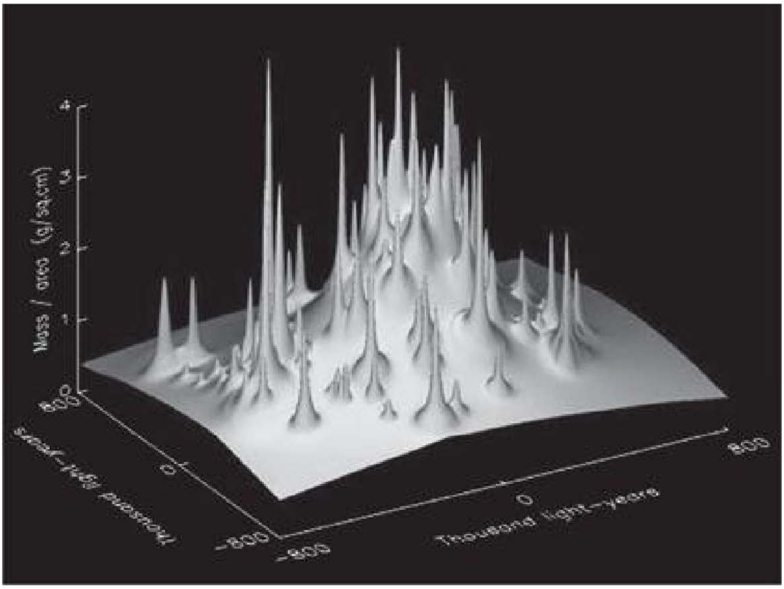
When he calculated the predicted effects for lensing of a distant star by an intervening star in the foreground, the effect was so small that it appeared absolutely unmeasurable, which led him to make the remark mentioned above—that it was unlikely that such a phenomenon could ever be observed. As a result, Einstein figured that his paper had little practical value. As he put it in his covering letter to the editor of *Science* at the time: "Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."

Einstein was not an astronomer, however, and it would take one to realize that the effect Einstein had predicted might be not only measurable, but also useful. Its usefulness came from applying it to the lensing of distant objects by much larger systems such as galaxies or even clusters of galaxies, not to the lensing of stars by stars. Within months of Einstein's publication, the brilliant Caltech astronomer Fritz Zwicky submitted a paper to the *Physical Review* in which he demonstrated the practicality of precisely this possibility (and also indirectly put down Einstein for his ignorance regarding the possible effect of lensing by galaxies rather than stars).

Zwicky was an irascible character and way ahead of his time. As early as 1933 he had analyzed the relative motion of galaxies in the Coma cluster and determined, using Newton's laws of motion, that the galaxies were moving so fast that they should have flown apart, destroying the cluster, unless there was far more mass in the cluster, by a factor more than 100, than could be accounted for by the stars alone. He thus should properly be considered as having discovered dark matter, though at the time his inference was so remarkable that most astronomers probably felt there might be some other less exotic explanation for the result he got.

Zwicky's one-page paper in 1937 was equally remarkable. He proposed three different uses for gravitational lensing: (1) testing general relativity, (2) using intervening galaxies as a kind of telescope to magnify more distant objects that would otherwise be invisible to telescopes on earth, and, most important, (3) resolving the mystery of why clusters appear to weigh more than can be accounted for by visible matter: *"Observations on the deflection of light around nebulae may provide the most direct determination of nebular masses and clear up the above-mentioned discrepancy."*

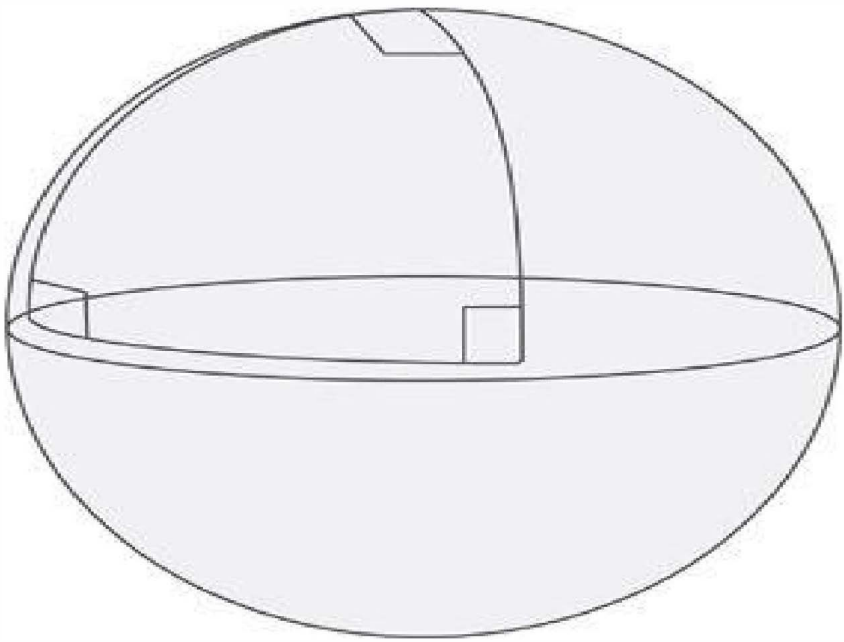
Zwicky's paper is now seventy-four years old but reads instead like a modern proposal for using gravitational lensing to probe the universe. Indeed, each and every suggestion he made has come to pass, and the final one is the most significant of all. Gravitational lensing of distant quasars by intervening galaxies was first observed in 1987, and in 1998, sixty-one years after Zwicky proposed weighing nebulae using gravitational lensing, the mass of a large cluster was determined by using gravitational lensing.



In that year, physicist Tony Tyson and colleagues at the now defunct Bell Laboratories (which had such a noble and Nobel tradition of great science, from the invention of the transistor to the discovery of the cosmic microwave background radiation) observed a distant large cluster, colorfully labeled CL 0024 + 1654, located about 5 billion light-years away. In this beautiful image from the Hubble Space Telescope, a spectacular example of the multiple image of a distant galaxy located another 5 billion light-years behind the cluster can be seen as highly distorted and elongated images amidst the otherwise generally rounder galaxies.

Looking at this image provides fuel for the imagination. First, every spot in the photo is a galaxy, not a star. Each galaxy contains perhaps 100 billion stars, along with them probably hundreds of billions of planets, and perhaps long-lost civilizations. I say long-lost because the image is 5 billion years old. The light was emitted 500 million years before our own Sun and Earth formed. Many of the stars in the photo no longer exist, having exhausted their nuclear fuel billions of years ago. Beyond that, the distorted images show precisely what Zwicky argued would be possible. The large distorted images to the left of the center of the image are highly magnified (and elongated) versions of this distant galaxy, which otherwise would probably not be visible at all.

Working backward from this image to determine the underlying mass distribution in the cluster is a complicated and complex mathematical challenge. To do so, Tyson had to build a computer model of the cluster and trace the rays from the source through the cluster in all possible different ways, using the laws of general relativity to determine the appropriate paths, until the fit they produced best matched the researchers' observations. When the dust settled, Tyson and collaborators obtained a graphical image that displayed precisely where the mass was located in this system pictured in the original photograph:



Something strange is going on in this image. The spikes in the graph represent the location of the visible galaxies in the original image, but most of the mass of the system is located *between* the galaxies, in a smooth, dark distribution. In fact, more than 40 times as much mass is between the galaxies as is contained in the visible matter in the system (300 times as much mass as contained in the stars alone with the rest of visible matter in hot gas around them). Dark matter is clearly not confined to galaxies, but also dominates the density of clusters of galaxies.

Particle physicists like myself were not surprised to find that dark matter also dominates clusters. Even though we didn't have a shred of direct evidence, we all hoped that the amount of dark matter was sufficient to result in a flat universe, which meant that there had to be more than 100 times as much dark matter as visible matter in the universe.

The reason was simple: a flat universe is the only mathematically beautiful universe. Why? Stay tuned.

Whether or not the total amount of dark matter was sufficient to produce a flat universe, observations such as these obtained by gravitational lensing (I remind you that gravitational lensing results from the local curvature of space around massive objects; the flatness of the universe relates to the global average curvature of space, ignoring the local ripples around massive objects) and more recent observations from other areas of astronomy have confirmed that the total amount of dark matter in galaxies and clusters is far in excess of that allowed by the calculations of Big Bang nucleosynthesis. We are now virtually certain that the dark matter—which, I reiterate, has been independently corroborated in a host of different astrophysical contexts, from galaxies to clusters of galaxies—must be made of something entirely new, something that doesn't exist normally on Earth. This kind of stuff, which isn't star stuff, isn't Earth stuff either. But it *is* something!

These earliest inferences of dark matter in our galaxy have spawned a whole new field of experimental physics, and I am happy to say that I have played a role in its development. As I have mentioned above, dark matter particles are all around us—in the room in which I am typing, as well as "out there" in space. Hence we can perform experiments to look for dark matter and for the new type of elementary particle or particles of which it is comprised.

The experiments are being performed in mines and tunnels deep underground. Why underground? Because on the surface of the Earth we are regularly bombarded by all manner of cosmic rays, from the Sun and from objects much farther away. Since dark matter, by its very nature, doesn't interact electromagnetically to produce light, we assume that its interactions with normal material are extremely weak, so it will be extremely difficult to detect. Even if we are bombarded every day by millions of dark matter particles, most will go through us and the Earth, without even "knowing" we are here—and without our noticing. Thus, if you want to detect the effects of the very rare exceptions to this rule, dark matter particles that actually bounce off atoms of matter, you had better be prepared to detect very rare and infrequent events. Only underground are you sufficiently shielded from cosmic rays for this to be possible even in principle.

As I write this, however, an equally exciting possibility is arising. The Large Hadron Collider, outside of Geneva, Switzerland, the world's largest and most powerful particle accelerator, has just begun running. But we have many reasons to believe that, at the very high energies at which protons are smashed together in the device, conditions similar to those in the very early universe will be re-created, albeit over only microscopically small regions. In such regions the same interactions that may have first produced what are now dark matter particles during the very early universe may now produce similar particles in the laboratory! There is thus a great race going on. Who will detect dark matter particles first: the experimenters deep underground or the experimentalists at the Large Hadron Collider? The good news is that, if either group wins the race, no one loses. We all win, by learning what the ultimate stuff of matter really is.

Even though the astrophysical measurements I described don't reveal the identity of dark matter, they do tell us how much of it exists. A final, direct determination of the total amount of matter in the universe came from the beautiful inferences of gravitational lensing measurements like the one I have described combined with other observations of X-ray emissions from clusters. Independent estimates of the clusters' total mass is possible because the temperature of the gas in clusters that are producing the X-rays is related to the total mass of the system in which they are emitted. The results were surprising, and as I have alluded, disappointing to many of us scientists. For when the dust had settled, literally and metaphorically, the total mass in and around galaxies and clusters was determined to be only about 30 percent of the total amount of mass needed to result in a flat universe today. (Note that this is more than 40 times as much mass as can be accounted for by visible matter, which therefore makes up less than 1 percent of the mass needed to make up a flat universe.)

Einstein would have been amazed that his “little publication” ultimately was far from useless. Supplemented by remarkable new experimental and observational tools that opened new windows on the cosmos, new theoretical developments that would have amazed and delighted him, and the discovery of dark matter that probably would have raised his blood pressure, Einstein’s small step into the world of curved space had ultimately turned into to a giant leap. By the early 1990s, the holy grail of cosmology had apparently been achieved. Observations had determined that we live in an open universe, one that would therefore expand forever. Or had they?