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13 THINGS THAT DON'T MAKE SENSE

MICHAEL BROOKS

The Most Intriguing Scientific Mysteries of Our Times

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CONTENTS

13 THINGS THAT DON'T MAKE SENSE

PROLOGUE

I am standing in the magnificent lobby of the Hotel Metropole in Brussels, watching three Nobel laureates struggle with the elevator.

It's certainly not an easy elevator to deal with; it's an open mesh cage, with a winch system that looks like something Isambard Kingdom Brunel might have built. When I first got into it three days ago, I felt like I was traveling back in time. But at least I got it to work.

Embarrassed for the scientists, I look away for a moment and distract myself with the grandeur of my surroundings. The Metropole was built at the end of the nineteenth century and is almost ridiculously ornate. The walls are paneled with vast slabs of marble, the ceilings decorated in subtle but beautiful gold and sage green geometric patterns. The glittering crystal chandeliers radiate a warmth that makes me want to curl up and go to sleep beneath their light. In fact, there are glowing, comforting lights everywhere. Outside, in the Place de Brouckère, the wind is blowing a bitter cold across the city; faced with the bleak December beyond those revolving doors, I feel like I could stand here forever.

The Nobel laureates are still struggling. No one else seems to have noticed their plight, and I'm wondering whether to walk across the lobby and offer help. When I had my long fight with the door, I discovered there's something about the shutter mechanism that defies logic—when you think it must be locked, it isn't; it needs a final pull. But it occurs to me that people who have attached Nobel Academy pins to their lapels ought to be able to work that out for themselves.

I like to think of scientists as being on top of things, able to explain the world we live in, masters of their universe. But maybe that's just a comforting delusion. When I can tear myself away from the farce playing out in the elevator, I will be getting into a cab and leaving behind perhaps the most fascinating conference I have ever attended. Not because there was new scientific insight—quite the contrary. It was the fact that there was no insight, seemingly no way forward for these scientists, that made the discussions so interesting. In science, being completely and utterly stuck can be a good thing; it often means a revolution is coming.

The discussion at the conference was focused on string theory, the attempt to tie quantum theory together with Einstein's theory of relativity. The two are incompatible; we need to rework them to describe the universe properly, and string theory may be our best bet. Or maybe not. I have spent the last three days listening to some of today's greatest minds discuss how we might combine relativity and quantum theory. And their conclusion was that, more than three decades after the birth of string theory, we still don't really know where to start.

This was a Solvay physics conference, a meeting with the richest of histories. At the first Solvay conference in 1911—the world's first physics conference—the delegates debated what was to be made of the newly discovered phenomenon of radioactivity. Here in this hotel Marie Curie, Hendrik Lorentz, and the young Albert Einstein debated how it was that radioactive materials could apparently defy the laws of conservation of energy and momentum. Radioactivity was an anomaly; it didn't make sense. The problem was eventually solved by the birth of quantum theory. At the 1927 Solvay conference, though, the strange nature of quantum theory caused its own problems, provoking Einstein and Niels Bohr, Lorentz and Erwin Schrödinger, Ernest Rutherford and John von Neumann to sit discussing these new laws of physics with the same degree of confusion as they had shown toward radioactivity.

can affect the body's biochemistry in ways that banish pain and produce startling medical effects. Except that, like dark matter, no one is quite sure that the placebo effect really exists. Cold fusion experiments, where nuclear reactions inside metal atoms safely release more energy than they consume, have also survived nearly two decades of skepticism, and the U.S. Department of Energy recently declared that the laboratory evidence is strong enough to merit funding of a new round of experimental research. The thing is, cold fusion goes against all the received wisdom in physics; there is no good explanation for why it should work—or even strong evidence that it does. But it is still worth investigating: the hints that we do have suggest that it could expose a new, deeper theory of physics that could have an enormous impact on many aspects of science. Then there is the "intelligent" signal from outer space that has defied explanation for thirty years; the enigma of our sense of free will despite all scientific evidence to the contrary; the spacecraft that are being pushed off course by an unknown force; the trouble we have explaining the origin of both sex and death using our best biological theories . . . the list goes on.

The philosopher Karl Popper once said, rather cruelly perhaps, that "science may be described as the art of systematic oversimplification." Though that is an oversimplification in itself, it is clear that science still has plenty to be humble about. But here is the point that is often missed by scientists eager to look as if nothing is beyond their abilities. Dark energy has been described as the most embarrassing problem in physics. But it is not; it is surely the greatest opportunity in physics—it gives us reason to examine our oversimplifications and correct them, bringing us to a new state of knowledge. The future of science depends on identifying the things that don't make sense; our attempts to explain anomalies are exactly what drives science forward.

In the 1500s, a set of celestial anomalies led the astronomer Nicolaus Copernicus to the realization that the Earth goes around the Sun—not the other way around. In the 1770s, the chemists Antoine Lavoisier and Joseph Priestley inferred the existence of oxygen through experimental results that defied all the theories of the time. Through several decades, plenty of people noticed the strange jigsaw-piece similarity between the east coast of South America and the west coast of Africa, but it wasn't until 1915 that someone pointed out it could be more than a coincidence. Alfred Wegener's insightful observation led to our theory of plate tectonics and continental drift; it is an observation that, at a stroke, did away with the "stamp-collecting" nature of geologic science and gave it a unifying theory that opened up billions of years of Earth's history for inspection. Charles Darwin performed a similar feat for biology with his theory of evolution by natural selection; the days of remarking on the wide variety of life on Earth without being able to tie them all together were suddenly over. It is not just an issue of experiments and observations either; there are intellectual anomalies. The incompatibility of two theories, for example, led Albert Einstein to devise relativity, a revolutionary theory that has forever changed our view of space, time, and the vast reaches of the universe.

Einstein didn't win his Nobel Prize for relativity. It was another anomaly—the strange nature of heat radiation—that brought him science's ultimate accolade. Observations of heat had led Max Planck to suggest that radiation could be considered as existing in lumps, or quanta. For Planck, this quantum theory was little more than a neat mathematical trick, but Einstein used it to show it was much more. Inspired by Planck's work, Einstein proved that light was quantized—and that experiments could reveal each quantum packet of energy. It was this discovery, that the stuff of the universe was built from blocks, that won him the 1922 Nobel Prize for Physics.

Not that a Nobel Prize for Physics is the answer to everything—my view across the Metropole's lobby makes that abundantly clear. Why can't these three men, three of the brightest minds of their generation, see the obvious solution? I can't help wondering if Einstein struggled with that elevator; if he did, by now even he, shaking his fist at the Almighty, would have called out for help.

Admitting that you're stuck doesn't come easy to scientists; they have lost the habit of recognizing it as the first step on a new and exciting path. But once you've done it, and enrolled your colleagues in helping resolve the sticky issue rather than proudly having them ignore it, you can continue with your journey. In science, being stuck can be a sign that you are about to make a great leap forward. The things that don't make sense are, in some ways, the only things that matter.

1

THE MISSING UNIVERSE

We can only account for 4 percent of the cosmos

The Indian tribes around the sleepy Arizona city of Flagstaff have an interesting take on the human struggle for peace and harmony. According to their traditions, the difficulties and confusions of life have their roots in the arrangement of the stars in the heavens—or rather the lack of it. Those jewels in the sky were meant to help us find a tranquil, contented existence, but when First Woman was using the stars to write the moral laws into the blackness, Coyote ran out of patience and flung them out of her bowl, spattering them across the skies. From Coyote's primal impatience came the mess of constellations in the heavens and the chaos of human existence.

The astronomers who spend their nights gazing at the skies over Flagstaff may find some comfort in this tale. On top of the hill above the city sits a telescope whose observations of the heavens, of the mess of stars and the way they move, have led us into a deep confusion. At the beginning of the twentieth century, starlight passing through the Clark telescope at Flagstaff's Lowell Observatory began a chain of observations that led us to one of the strangest discoveries in science: that most of the universe is missing.

If the future of science depends on identifying the things that don't make sense, the cosmos has a lot to offer. We long to know what the universe is made of, how it really works: in other words, its constituent particles and the forces that guide their interactions. This is the essence of the "final theory" that physicists dream of: a pithy summation of the cosmos and its rules of engagement. Sometimes newspaper, magazine, and TV reports give the impression that we're almost there. But we're not. It is going to be hard to find that final theory until we have dealt with the fact that the majority of the particles and forces it is supposed to describe are entirely unknown to science. We are privileged enough to be living in the golden age of cosmology; we know an enormous amount about how the cosmos came to be, how it evolved into its current state, and yet we don't actually know what most of it *is*. Almost all of the universe is missing: 96 percent, to put a number on it.

The stars we see at the edges of distant galaxies seem to be moving under the guidance of invisible hands that hold the stars in place and stop them from flying off into empty space. According to our best calculations, the substance of those invisible guiding hands—known to scientists as *dark matter*—is nearly a quarter of the total amount of mass in the cosmos. Dark matter is just a name, though. We don't have a clue what it is.

And then there is the *dark energy*. When Albert Einstein showed that mass and energy were like two sides of the same coin, that one could be converted into the other using the recipe $E = mc^2$, he unwittingly laid the foundations for what is now widely regarded as the most embarrassing problem in physics. Dark energy is scientists' name for the ghostly essence that is making the fabric of the universe expand ever faster, creating ever more empty space between galaxies. Use Einstein's equation for converting energy to mass, and you'll discover that dark energy is actually 70 percent of the mass (after Einstein, we should really call it mass-energy) in the cosmos. No one knows where this energy comes from, what it is, whether it will keep on accelerating the universe's expansion forever, or whether it will run out of steam eventually. When it comes to the major constituents of the universe, it seems no one knows anything much. The familiar world of atoms—the stuff that makes us up—accounts for only a tiny fraction of the mass and energy in the universe. The rest is a puzzle that has yet to be solved.

HOW did we get here? Via one man's obsession with life on Mars. In 1894 Percival Lowell, a wealthy Massachusetts industrialist, had become fixated on the idea that there was an alien civilization on the red planet. Despite merciless mocking from many astronomers of the time, Lowell decided to search for irrefutable astronomical evidence in support of his conviction. He sent a scout to various locations around the United States; in the end, it was decided that the clear Arizona skies above Flagstaff were perfect for the task. After a couple of years of observing with small telescopes, Lowell bought a huge (for the time) 24-inch refractor from a Boston manufacturer and had it shipped to Flagstaff along the Santa Fe railroad.

Thus began the era of big astronomy. The Clark telescope cost Lowell twenty thousand dollars and is housed in a magnificent pine-clad dome on top of Mars Hill, a steep, switchbacked track named in honor of Lowell's great obsession. The telescope has an assured place in history: in the 1960s the Apollo astronauts used it to get their first proper look at their lunar landing sites. And decades earlier an earnest and reserved young man called Vesto Melvin Slipher used it to kick-start modern cosmology.

Slipher was born an Indiana farm boy in 1875. He came to Flagstaff as Percival Lowell's assistant in 1901, just after receiving his degree in mechanics and astronomy. Lowell took Slipher on for a short, fixed term; he employed Slipher reluctantly, as a grudging favor to one of his old professors. It didn't work out quite as Lowell planned, however. Slipher left fifty-three years later when he retired from the position of observatory director.

Though sympathetic to his boss's obsession, Slipher was not terribly interested in the hunt for Martian civilization. He was more captivated by the way that inanimate balls of gas and dust—the stars and planets—moved through the universe. One of the biggest puzzles facing astronomers of the time was the enigma of the spiral nebulae. These faint glows in the night sky were thought by some to be vast aggregations of stars—"Island Universes," as the philosopher Immanuel Kant had described them. Others believed seems. But it was one that set an English astronomer called Edwin Powell Hubble on the path to fame.

The Cambridge University cosmologist Stephen Hawking makes a wry observation in his book *The Universe in a Nutshell.* Comparing the chronology of Slipher's and Hubble's careers, and noting how Hubble is credited with the discovery, in 1929, that the universe is expanding, Hawking makes a pointed reference to the first time Slipher publicly discussed his results. When the audience stood to applaud Slipher's discoveries at that American Astronomical Society meeting of August 1914, Hawking notes, "Hubble heard the presentation."

By 1917, when Einstein was petitioning astronomers for their view of the universe, Slipher's spectrographic observations had shown that, of twenty-five nebulae, twenty-one were hurtling away from Earth, with just four getting closer. They were all moving at startling speeds—on average, at more than 2 million kilometers per hour. It was a shock because most of the stars in the sky were doing no such thing; at the time, the Milky Way was thought to be the whole universe, and the stars were almost static relative to Earth. Slipher changed that, blowing our universe apart. The nebulae, he suggested, are "stellar systems seen at great distances." Slipher had quietly discovered that space was dotted with myriad galaxies that were heading off into the distance.

When these velocity measurements were published in the *Proceedings of the American Philosophical Society*, no one made much of them, and Slipher certainly wouldn't be so vulgar as to seek attention for his work. Hubble, though, had obviously not forgotten about it. He asked Slipher for the data so as to include them in a book on relativity, and, in 1922, Slipher sent him a table of nebular velocities. By 1929 Hubble had pulled Slipher's observations together with those of a few other astronomers (and his own) and come to a remarkable conclusion.

If you take the galaxies moving away from Earth, and plot their speeds against their distance from Earth, you find that the farther away a galaxy is, the faster it is moving. If one receding galaxy is twice as far from Earth as another, it will be moving twice as fast. If it is three times more distant, its speed is three times greater. To Hubble, there was only one possible explanation. The galaxies were like paper dots stuck onto a balloon; blow it up, and the dots don't grow, but they do move apart. The very space in between the galaxies was growing. Hubble had discovered that the universe is expanding.

It was a heady time. With this expansion, the idea of a big bang, first suggested in the 1920s, bubbled to the surface of cosmology. If the universe was expanding, it must once have been smaller and denser; astronomers began to wonder if this was the state in which the cosmos had begun. Vesto Slipher's work had led to the first evidence of our ultimate origins. The same evidence would eventually bring us the revelation that most of our universe is a mystery.

TO understand how we know a significant chunk of the cosmos is missing, tie a weight to a long piece of string. Let the string out, and swing the weight around in a circle. At the end of a long string, the weight moves pretty slowly—you can watch it without getting dizzy. Now pull the string in, so the weight is doing tiny orbits of your head. To keep it spinning around in the air, rather than falling down and strangling you, you have to keep it moving much faster—so fast you can hardly see it.

The same principle is at work in the motions of the planets. The Earth, in its position close to the Sun, moves much faster in its orbit than Neptune, which is farther out. The reason is simple: it's about balancing forces. The gravitational pull of the Sun is stronger at Earth's radial distance out from the Sun than at Neptune's. Something with Earth's mass has to be moving relatively fast to maintain its orbit. For Neptune to hold its orbit, with less pull from the distant Sun, it goes slower to keep in equilibrium. If it moved at the same speed as Earth, it would fly off and out of our solar system.

Any orbiting system ought to follow this rule: balancing a gravitational pull and the centrifugal forces means that, the farther something is from whatever is holding it in orbit, the slower it will move. And, in 1933, that is exactly what a Swiss astronomer called Fritz Zwicky didn't see.

As construction began on the Golden Gate Bridge and a forty-three-year-old Adolf Hitler was appointed chancellor of Germany, Zwicky noticed something odd about the Coma cluster of galaxies. Roughly speaking, stars emit a certain amount of light per kilo, so, looking at the amount of light coming out of the Coma cluster, Zwicky could estimate how much stuff it contained. Zwicky's problem was that the stars on the edges of the galaxies were moving far too fast to be constrained by the gravitational pull of that amount of material. According to his calculations, the only explanation was that there was about four hundred times more mass in the Coma cluster than could be accounted for by the cluster's visible matter.

It should have been enough to launch the dark matter hunt, but it wasn't—for the worst of scientific reasons. Comb the Internet for references to Zwicky, and you'll find *brilliant* next to *maverick*, *genius* next to *insufferable*. Like Slipher, he doesn't figure large in the astronomy textbooks, despite his many important discoveries. He was the first to see that galaxies form clusters. He coined the term *supernova*. He was certainly one of a kind. He built a ski ramp next to the Mount Wilson Observatory in the San Gabriel Mountains of California, for example; in the winter Zwicky would haul his skis to work so he could keep his ski-jumping skills honed. But it was his interpersonal skills that needed most attention. He was a prickly, difficult man, convinced of his own genius, and convinced that he never got the recognition he deserved. He had a tendency to refer to all his colleagues as "spherical bastards": bastards whichever way you looked at them. Small wonder, then, that his colleagues turned a blind eye to his discovery of the Coma cluster's missing mass.

But he was right. Something about the mass of galaxies just doesn't add up—unless, that is, the universe is heavily sprinkled with dark matter. In 1939, at the dedication of the McDonald Observatory in Texas, the Dutch astronomer Jan Oort added to the evidence. Oort gave a lecture in which he showed the distribution of the mass in a certain elliptical galaxy had to be very different from the distribution of the light. He published the data three years later, making this very point clear in the abstract. Again, in a classic Kuhnian response, no one reacted. This spectacular ability to ignore such anomalous results continued for decades until, for some reason, people finally listened to Vera Rubin.

Rubin, who is now in her late seventies, made her first big mark on cosmology at the age of twenty-two. The New Year's Eve, 1950, edition of the *Washington Post* reported on a talk she gave at the American Astronomical Society, hailing her achievements under the headline "Young Mother Figures Center of Creation by Star Motions." The accompanying piece described how Rubin's work was "so daring . . . that most astronomers think her theories are not yet possible." But her most daring work, the fight to get dark matter taken seriously, was still to come.

Not that she even took herself seriously to start with. The story, she says, is a lesson in how dumb a scientist can be. In 1962 Rubin was teaching at Georgetown University in Washington, D.C. Most of her students were from the U.S. Naval Observatory down the road, and they were very good astronomers, she recalls. Together they were able to map out the *rotation curve* of a galaxy. This is a graph that shows how the velocity of the stars changes as you move out from the center of the galaxy. As with that weighted string twirling around your head, the velocities should fall as you get farther out. For Rubin and her naval researchers, though, they didn't; once they got away from the center, the curve was flat. They presented the results in a series of three papers, and Rubin made nothing of it.

Three years later, in 1965, she took a job at the Carnegie Institution of Washington. After a year in the cutthroat business of looking for quasars, the most distant objects known, she wanted to do something a little less competitive, something she could make her own. She decided to look at the outside of galaxies because no one had studied them—everyone concentrated on the centers. Not only had Rubin completely forgotten about her work with the Naval Observatory students, she also didn't believe her own results as she was gathering them. She measured the speeds by looking at how the motion had changed the spectrum of light coming from a star. Rubin was gathering about four spectra each night, gradually going farther and farther out from the center of the galaxy. Even though she developed the spectra as she went along, and they all looked the same, the penny didn't drop.

"You always thought the next point would fall," she says. "And it just didn't."

Eventually, though, she got it. By 1970 Rubin had mapped out the rotation curve for Andromeda; the star velocities remained the same however far out she looked. With the velocities of the stars remaining high at the edge, centrifugal forces should be throwing Andromeda's outer stars off into deep space. By rights, Andromeda should be falling apart. Unless, that is, it is surrounded by a halo of dark matter.

* * *

NO one knows what the dark matter actually is. When the Cambridge professor Malcolm Longair wrote his cosmology primer *Our Evolving Universe*, he listed some of the things it might turn out to be. At the top of the list were things like interstellar planets and low mass stars. Toward the bottom of the list were house bricks and copies of the *Astrophysical Journal*. This last candidate seems most appropriate; if it were discovered to be the answer, it would add a pleasing irony to the dark matter story. The *Astrophysical Journal* is where, in 1970, Rubin published her results and brought dark matter in from the cold.

Not that you'd necessarily get that from the paper. The title seems innocuous: "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions." The abstract, the summary of the paper, seems to say nothing controversial. The conclusions of the paper are similarly disappointing. It presents the data—measurements of the rotation speeds of the stars in Andromeda—and says nothing more. The graph from page 12 is still on the wall of Rubin's office at the Carnegie Institution's Department of Terrestrial Magnetism in Washington, D.C., however. And today it remains just as relevant, and just as mysterious, as it was on publication.

The idea of a clutch of invisible matter holding on to Andromeda's outer stars didn't catch on straightaway, but at least this time it wasn't ignored. First, astronomers justified the blind eye they had turned for thirty-seven years. They started constructing their own rotation curves, for example, by coming up with exotic explanations for how the mass might be distributed through the galaxies. None of these efforts ever convinced Rubin, she says; somehow, a couple of the points were always so far off the curve—and ignored—as to make the ideas laughable.

By the 1980s astronomers had given up trying to fudge the data. Something about the gravitation of galaxies didn't fit, and the best explanation was the existence of some matter that didn't shine like the stars, or reflect light, or give off detectable radiation, or behave in any way that would make its presence known—except by its gravitational pull. The quest was now on to find out what this strange stuff was.

The first meeting on the subject of the new dark matter was held at Harvard University in 1980. Rubin then confidently proclaimed to the audience

IF the universe is expanding, as Hubble showed it is, two questions spring immediately to mind. First, how fast is it expanding? Second, will it keep expanding forever?

The answer to the first question comes from measuring the velocities of the receding galaxies, and knowing how far away they are. You can't just measure how fast a galaxy is moving away from us and call that the expansion rate of the universe; the way space expands messes with your common sense. The farther away from us a galaxy lies, the faster it is moving away from us because the space in between Earth and the galaxy is also expanding. The result, known as *Hubble's constant*, gives a measure of the expansion rate; currently, we think it is about seventy kilometers per second per (roughly) 3 million light-years. The accuracy shouldn't be taken too seriously; that value is always subject to change when a better set of measurements come in.

Answering the second question is, in many ways, much more interesting. If the universe is still expanding after the big bang, that expansion should be slowing down; the mutual pull of all the matter in the universe works against any further expansion. So our cosmic future depends on how much stuff there is out there, and how it is arranged.

Cosmologists already know something about those questions from one very easy scientific observation: the fact that we exist. For that to be the case, the universe must have expanded from its hot, dense beginnings with a particular amount of energy. If there had been too much, any matter that was created would have been spread so thinly that gravity couldn't have pulled atoms together into stars, galaxies, and—eventually—humans. As the matter spread farther, its gravitational pull would have become even weaker and the expansion energy ever more dominant. The universe would have blown itself apart before anything interesting—humans, for example—happened.

If there had been too little expansion energy, on the other hand, gravity would have pulled all the matter together in a similar feedback cycle: once things got closer together, their gravitational pull would have become stronger, pulling them even more. Eventually, the fabric of the universe would have shrunk back to implode in a scenario astronomers call the *big crunch*.

Given a certain amount of expansion energy, producing a Goldilocks universe like ours—one that's "just right"—involves a precise distribution of matter. As a shorthand for talking about the density of gravitating matter, astronomers refer to the *Omega* value of the universe. An Omega of 1, which corresponds to a measly six hydrogen atoms per cubic meter of universe (a cubic meter of the air around you has something like 10 million billion billion atoms), is where the matter density more or less balances out the expansion.

According to theory, the existence of stars and galaxies relies on Omega starting out within one part in a million billion of 1. And, because of the nature of the feedback cycle with Omega, starting out in balance means remaining in balance. Today, if the theorists are right, Omega should still be near 1. The trouble is, we know that there's not nearly enough matter—dark or otherwise—to make Omega 1.

It is this problem that led to the return of Einstein's cosmological constant, something that no one saw coming. Hubble's triumphant discovery of the universe's expansion had meant the cosmological constant could be ditched. The equations of general relativity simply didn't need the fudge factor that produced a steady-state universe, and by 1930 Einstein's antigravity lay embarrassingly redundant. Who could have imagined that, nearly seventy years later, it would be back, reincarnated in the ghostly form of dark energy?

ASTRONOMERS first started investigating Omega in the 1930s as a means of predicting the fate of the universe. If Omega is indeed 1, the expansion will continue at its present rate. If the theorists are wrong, and Omega is less than 1, the power behind the expansion will increase as the matter thins out. If Omega turns out to be greater than 1, gravity will eventually win out, and our future lies in a big crunch.

Initially, the astronomers investigated Omega by continuing Slipher and Hubble's methods: measuring the properties of the light from galaxies. The vast number of light sources in a galaxy meant that this never produced anything reliable, however; it is rather like trying to measure the properties of human speech by listening to the noise of a soccer crowd. What they needed was a single object, something whose properties you could measure and draw inferences from. In 1987 they found one. If you want to understand the fate of the universe, it turns out you're going to have to get to grips with exploding stars: supernovae.

We've been seeing supernovae in the skies for centuries; the Danish astronomer Tycho Brahe reported seeing one in 1572, more than thirty years before the invention of the telescope. They occur when a star gets too big and collapses under its own gravity. During the few weeks or months over which this collapse takes place, transforming the star into a neutron star or even a black hole, it shines with the power of 10 billion suns. On Monday, February 23, 1987, we saw such a sight. The explosion of Sanduleak-69 202, a blue giant star in the Large Magellanic Cloud galaxy, was notable for two reasons. First, because it turned the star into the brightest supernova seen since 1604. Second, because its light was the first to give a standard for measuring cosmic distances.

The way certain supernovae—they are known as Type 1a Supernovae—emit their light has a peculiar characteristic that makes them supremely appealing to astronomers. Type 1a explode because they have sucked too much material from a nearby star. Analyze the spectrum of the light from this kind of explosion, and how fast its brightness fades away, and it will tell you how far the light traveled to Earth, and how the expansion of space stretched the light on its journey.

The only drawback is that you have a limited window of opportunity. With supernovae, timing is everything. If you want to get useful information, you have to find it within a couple of weeks of the light first reaching Earth. Since an explosion happens about once per century in each galaxy, that means scanning a lot of galaxies with your telescope.

This kind of drudge work is a long-standing problem for astronomers. Inside Flagstaff's Lowell Observatory, for example, you can experience the agonizing nature of astronomy in Slipher's day. When he led the search for Pluto, the technique used was a celestial Spot-the-Difference. Put two photographic plates of the same region of the sky, taken on different nights, into a machine called a blink comparator, and you can shuttle between the two almost entirely similar views. The winner is the first to spot the one white dot—in the mess of white dots—that has moved. That shifting white dot is the planet you are looking for.

Fortunately, in the Lowell exhibition, someone marked the displaced dot with a big white arrow. Modern image-reading technology has made spotting the appearance of a supernova even easier; today, we have computers to provide the big white arrow. They can compare two different photographs of the sky, then highlight the differences. Some of those will be asteroids; some will be the varying brightness associated with the black holes at the center of galaxies; some will be false signals—bright flashes from subatomic particles hitting Earth's atmosphere. And, just occasionally, one will be a distant supernova.

The first strong interpretations of supernova data came in June 1996 from a team based at California's Lawrence Berkeley National Laboratory (LBNL). This announcement was made at a cosmology meeting convened to celebrate the 250th birthday of Princeton University, the adopted intellectual home of Albert Einstein. A perfect place to begin the resurrection of his cosmological constant, as it turned out.

When astronomers first got close to using supernovae to chart the universe's expansion, they were convinced they were going to find a deceleration. After all, the power of the big bang should be running out; gravity had taken over, and the brakes were firmly on. It turns out, though, that the universe is not so simple.

At first glance, the LBNL results confirmed suspicions. The supernova light suggested that the universe's expansion was slowing down: the gravitational pull of the universe's contents was decelerating the cosmos and setting Omega to somewhere around 1.

But it was a controversial finding. All the known gravitating matter in the universe—including the dark matter—gave an Omega of only 0.3. Had everyone underestimated the amount of dark matter? It seemed unlikely; by this time various different methods for determining the mass of galaxies were in use, and each showed there was significantly more gravitating matter than we could see, and each gave approximately the same numbers.

If dark matter was on a fairly solid footing, what was going on? The cosmologists Michael Turner and Lawrence Krauss were at the Princeton meeting, and they had an answer ready. Why not keep the dark matter at 0.3 but let something else make up the missing 0.7? Instead of looking for some extra matter, why not assume it is actually extra energy? Bring back Einstein's cosmological constant, they said.

As is proper, experiment won out over the theorists' speculations. When Saul Perlmutter published his LBNL group's results, the supernova data indicated that gravitating matter could account for pretty much all of Omega. No one needed to bring back the cosmological constant; someone just needed to sort out the dark matter discrepancy. There must be more out there.

The trouble was, Perlmutter's results raised problems of their own. If you know the matter density in the universe, the current expansion rate (Hubble's constant), and how much the universe's expansion is slowing down, you can work out how long it is since the expansion started; the age of the universe, in other words. With an Omega of 1 that is entirely due to matter, the deceleration from the Lawrence Berkeley data put the universe's age at not more than 8 billion years old. Unfortunately, astronomers who had analyzed the light from the universe's oldest stars set *their* age at around 15 billion years old. It doesn't take a Harvard-trained mind to work out that the universe simply can't be 8 billion years old if the stars are nearly twice that age. If there was a problem with the cosmological constant making up Omega, there was also a problem with having a matter-induced Omega of 1. The only reliable fact, it seemed, was that dark matter made up 0.3 of Omega; everything else was up for grabs.

Not everyone was disappointed by this impasse; Robert Kirshner, for one, was rather pleased. The Harvard astronomer was worried that his own supernova results were coming too slowly to compete with the LBNL team; that his team had been beaten to the punch. But it seemed the race to understand the fate of the universe was still wide-open.

In his book *The Extravagant Universe* Kirshner tells the story behind the supernova searches and the reinstatement of Einstein's cosmological constant with great clarity and wit. In the end, he turned the tables and came out first with the result that defined a new era in cosmology. But only after he had defeated his own prejudices.

Kirshner's team, composed of a handful of researchers from all over the world, was using supernova observations from telescopes on mountaintops how nature behaves at the scale of atoms and subatomic particles, the British physicist Paul Dirac used it to produce a quantum version of the theory behind the characteristics of electric and magnetic fields. Dirac's *quantum field theory* eventually led to the prediction that empty space has energy. Since physicists refer to empty space as *the vacuum*, Dirac's energy has come to be known as the *vacuum energy.*

According to our best guess, this vacuum energy must be what powers the "antigravity" acceleration uncovered by the supernovae; the vacuum energy is the cosmological constant. The trouble is, the measurements from the supernovae tell us the vacuum energy is tiny. It is usually measured in grams. (Remember, according to Einstein's famous equation $E = mc^2$, mass and energy are interconvertible.) The amount of vacuum displaced by the Earth's volume in space would contain about one hundredth of a gram's worth of vacuum energy. That's how small it is.

When, however, theorists work out the vacuum energy from quantum field theory, they get a number that is too big. Massively too big. Their theory suggests that the vacuum energy is so big, it should have ripped the universe apart already in one massive hyperacceleration. This is known as the cosmological constant problem and is widely accepted—even by the physicists involved—as *the* most embarrassing mismatch between theory and experiment ever. A million is a big number: a 1 followed by 6 zeroes. A trillion has 12 zeroes. The mismatch between the measured and the theoretical value for the cosmological constant has 120 zeroes. One hundred and twenty.

Faced with this failure, many physicists have adopted an idea first raised by the Nobel laureate Steven Weinberg in 1987. In his book *Dreams of a Final Theory*, Weinberg suggested that a cosmological constant might exist in our universe without us ever being able to explain its value. If ours was just one universe among many, each might have different values for its constants. Some of these universes would no doubt be sterile, but some would lead to the production of life; there would probably be at least one where things like humans evolved. This is the *anthropic landscape* approach to explaining the nature of the universe. (*Anthropic* means "of humans.") The approach, when you boil it down, essentially says that our universe is the way it is because otherwise we couldn't be here to observe it. It doesn't necessarily invoke a designer or any intention; it simply means if conditions were different, no one would be around to observe them. Essentially, it says the very fact that we observe the universe limits the range of forms it can take. The landscape bit comes from the physicists' assertion that our universe is composed of a hugely varied terrain, a patchwork quilt of subuniverses, each with its own unique and randomly assigned properties. There need be no explanation for the values of the constants in each one.

As an "explanation" for the value of the cosmological constant, this is, to many physicists, abhorrent. Weinberg's suggestion is, says the Stanford University physicist Leonard Susskind, "unthinkable, possibly the most shocking admission that a modern scientist could make."

The idea is so distasteful because it turns science on its head. The philosopher Karl Popper said that science progresses only by falsification: Someone throws up a hypothesis, and then anyone can use experimental data to attempt to shoot it down. If the data falsify the hypothesis, you move on to the next one. Only when you have a hypothesis that has survived many shots can you start to place some faith in what it's saying.

With the anthropic landscape, this approach doesn't work because the other universes are out of reach. You can't falsify the notion because you can never test it with experimental data. No longer do we explain why the universe is as it is; instead, the universe is as it is because that makes it the kind of universe we can inhabit. Is this science? It might just be, Susskind says; he thinks Weinberg is probably right. If we are to make progress toward understanding the universe, we may now have to ditch Karl Popper and his adherents—Susskind calls them the *Popperazzi*—as the ultimate arbiters of what science is and isn't. Perhaps we should just accept that, however much it makes the Popperazzi fume, the laws of our universe may be as they are because of our own existence.

Difficult as this notion is to swallow, there is reason to take it seriously. Quantum field theory suggests that, if we must use a cosmological constant to complete our description of the universe, our universe really ought to be one of very many. It may be that, as E. E. Cummings once wrote, "there's a hell of a good universe next door."

At the root of this argument is the *uncertainty principle* of quantum theory, which says the fundamental properties of any system are never exactly defined but have an intrinsic fuzziness. The uncertainty principle, when applied to quantum field theory, produces natural fluctuations in the properties of certain regions of the universe. It is rather like having a balloon that is peppered with weak spots; as the universe inflates, these fluctuations can grow, producing a new region of space and time. In other words, a universe containing a cosmological constant that arises from the vacuum energy will produce new bubble universes all the time. Those bubbles will produce their own new baby universes in turn—and so on, ad infinitum. What we think of as the universe is only one region of space-time in a frothing sea of mini-universes.

The anthropic landscape idea has many supporters now, especially among theorists; that is why Steinhardt puts himself in the minority. But if we can't access these bubble universes to see whether they have different constants, aren't we effectively giving up on physics?

This was the root of the discussion in Brussels, the ghost of Albert Einstein looking over every shoulder. Should we be shrugging our shoulders and putting the value of the cosmological constant down to the particular kind of universe we live in? Can we face the idea that we may never understand what most of the universe is, that we may never get to the root of dark energy? The answer was both yes and no: yes, it is a possibility we have to face; no, it doesn't mean giving up hope of an explanation. David Gross, who chaired the conference, was quick to make the point that at the first Solvay conference in 1911, the physicists were similarly puzzled. Some materials had been shown to be emitting particles and radiation in a way that seemed to violate the laws of conservation of mass and energy. The explanation came a few years later, when quantum theory was developed. "They were missing something absolutely fundamental," Gross told the 2005 Solvay assembly. "We are missing perhaps something as profound as they were back then."

So what is that "something fundamental"? Do we have any clues? The answer depends on whom you ask. Adam Riess, the man whose radical, Shakespearean rhetoric pulled us into the dark energy era, offers a provocative suggestion. What if, he says, we just don't know enough about how gravity works? Maybe there isn't any dark matter, and maybe there isn't any dark energy. Maybe for the last four centuries we've all been blind to tiny inaccuracies in Newton's law of gravity, and these inaccuracies hold the key to restoring the lost universe.

Riess isn't the first to raise the idea, and he's not saying it necessarily has any merit. His point is that it is a possibility, and it has yet to be ruled out. Vera Rubin feels the same. She reckons that ninety-nine physicists out of a hundred still believe in the existence of some dark stuff that fills the universe, its gravitational influence holding galaxies together. But, to her eyes, changing the fundamentals of physics is starting to look like a better option.

On the face of it, the fix can be a relatively simple one. It was first suggested in 1981 by an Israeli physicist called Mordehai Milgrom. Basically, you tweak Newton's law of gravity so that at large distances, the kinds of distances that stretch across galaxies and even clusters of galaxies, gravity is a little bit stronger than you'd otherwise expect. The idea is known as *Modified Newtonian Dynamics*, or *MOND,* and—despite its apparently innocuous nature—it has caused a lot of trouble.

Taking something that has worked perfectly well for four hundred years, something that was created by a man widely considered to be the greatest scientist of all time, and suggesting it needs a little tweak is a brave move. Milgrom was not taken seriously when he first suggested it. But he did gain a few supporters. Most notable among them was a young astronomer named Stacy McGaugh.

MCGAUGH has taken so much flak in defense of MOND, he should be issued with a Kevlar jacket. If the way the dark matter problem was overlooked for forty years taught Vera Rubin how dumb scientists could be, McGaugh, who used to be one of her graduate students, taught her something else: just how resistant science is to change.

In March 1999 McGaugh gave a talk on MOND at the Max Planck Institute in Germany. No one there was willing to embrace the idea. If you want us to take you seriously, they said, predict something; when it is borne out by experiment, we'll listen.

A few months later McGaugh published a paper in the *Astrophysical Journal* that asked the cheeky question "What if there is no dark matter?" The result, he said, would be that a characteristic feature in the cosmic microwave background radiation, the echo of the big bang, would be different from what the dark matter advocates expected. The *power spectrum*, a kind of breakdown of the radiation, would show it up. Both MOND and dark matter models predicted that the power spectrum would take the form of a series of peaks and troughs. Dark matter theory said the second peak would be slightly lower than the first, but not significantly. Without dark matter, that second peak would be tiny, McGaugh pointed out; let's see what happens when the data come in.

McGaugh's paper was published in late 1999. In the summer of 2000 Rubin was at a conference in Rome, watching him give a presentation based on his paper to an audience of astronomers. Now there were data. And there was no second peak. None at all.

McGaugh had been granted a ten-minute slot. Rubin watched in shock as, when McGaugh ended his talk, nothing happened. "There was not a single question afterwards," she recalls. What's more, she adds, the next morning some eminent cosmologist started the discussion of the new results with not a single mention of the fact that they were different from the accepted dark matter model.

Rubin has been impressed by MOND from that time on. Partly because she doesn't like the idea of invoking exotic new particles to explain a straightforward observation, and partly because mainstream astronomy has gotten too good at public relations, and good PR, she says, suppresses proper scientific debate. Rubin has always been a fan of the underdog in science.

For a long time, MOND wasn't even an underdog. As McGaugh will testify, it was more like a mangy dog sitting outside the conference hall: an ad hoc idea cobbled together by an Israeli physicist with no better rationale for modifying gravity than the majority had for invoking dark matter. But then, in 2004, Jacob Bekenstein got involved.

Bekenstein was born in Mexico City, studied physics at the Polytechnic Institute of Brooklyn and Princeton University, and is now a professor at the Hebrew University of Jerusalem. As a young man he got up Stephen Hawking's nose by making various controversial proposals about black holes (which all turned out to be correct); now he is simply seen as one of our most formidable minds. As soon as Bekenstein developed a version of Einstein's relativity specifically tailored to show why MOND should be taken seriously, the physics world had no choice but to sit up and listen. When Bekenstein's relativistic MOND started fitting rather nicely with other obfrom Trinity College, Cambridge—without ever earning an undergraduate degree.

Not that luck has always been on Moffat's side. His unconventional genius led him to work on unfashionable ideas, and in science fashion matters. He had his biggest idea—that the speed of light might have been different in the past—around a decade too early. Though Moffat only managed to publish it in an obscure journal in the early 1990s, the idea came to the forefront of physics ten years later. Even then, Moffat had to kick up a fuss before he got any proper recognition.

And he is still kicking up a fuss—but now in the realm of dark matter. Moffat's explanation for the flat rotation curves of galaxies is called, rather inelegantly but at least unpretentiously, *MOG. Modified Gravity*—that's it. But according to Moffat, MOG's slight adjustment to Newtonian gravity, making it a little stronger than normal at large distances, explains the Chandra observations.

Maybe dark matter is there; maybe it is not. There are alternatives, and any neutral observer has to say the dark matter issue has not yet been resolved. So far, we've waited more than sixty years to find out what is causing those strange galactic rotations, and it is possible that none of us alive today will ever find out the truth about dark matter. Maybe we'll know tomorrow. Until we do, though, as Adam Riess pointed out, we can't be sure about dark energy.

NOT that the dark energy researchers are twiddling their thumbs. NASA, the National Science Foundation, and the U.S. Department of Energy have commissioned a group of physicists to find the best way forward for exploring the dark energy enigma, and in September 2006 the Dark Energy Task Force issued their report. Most of their conclusions recommended an "aggressive program" of experiments and astronomical observations that will help us make sense of it all. What is most intriguing, though, is that, besides all the program recommendations, the chair of the task force quietly recommended another way to approach the dark energy issue. What we really need, says Edward "Rocky" Kolb, is another Einstein.