tending versions of cosmic genesis was the notion that galaxies had grown gravitationally from slight density enhancements in the stew of energy and mystery particles that comprised the early universe. According to inflation, the quantum burp theory of the big bang, these primordial seeds were quantum fluctuations; in the case of string theory they resulted from discontinuities in the pattern of primordial symmetry breaking. Whatever their source, these progenitors of cosmic structure should have shown up as hot and cold blotches in the cosmic radiation. Yet since its discovery eighteen years before, the cosmic background, the electromagnetic imprint of the big bang circa a million years old, had been famously and frustratingly bland.

By 1989 when COBE was launched, the temperature of the cosmic background was known to be uniform to within one part in ten thousand, about 300 millionths of a degree Kelvin. The ever more stringent limits on any possible variations were tightening like a noose around the necks of theorists. Inflation predicted temperature variations of about 30 millionths of a degree. Among COBE's other instruments were a pair of horn antennas that could measure the difference in temperature between two spots on the sky. For the next two years, as the satellite wheeled around the Earth, the horns crossed and recrossed the heavens, building up a portrait of the primordial sky while down below cosmologists fretted.

Smoot, a tall amiable workaholic with a taste for fine suits and wild ties, had spent his entire career on the microwave background, and on COBE he ran a tight ship. No hint of his results had leaked into the wider world until he stood up at the American Physical Society meeting in Washington in 1992 and showed off the first year's data in the form of a map of the universe—a splotchy oval of blue and red spots representing mostly random noise. No one patch on that first map, he explained, could be reliably identified with an actual hot or cold spot in the big bang, but within the noise, where only the powerful statistics of correlation functions could root it out, was a pattern of real variations at last. These patches, moreover, were too large in spatial extent to be the precursors of galaxies. COBE's horns could not resolve anything smaller than about 10 degrees across. Galaxies, according to the standard theory, arose from finer-grained fluctuations about a degree in width. Thus, Smoot's hot spots would have grown into enormous structures in today's universe.

It was partly to emphasize the gigantic scale of these fluctuations, as well as their importance, Smoot later admitted, that he had compared the discovery to "seeing God," a phrase he soon regretted. Cosmologists had never doubted the big bang, despite the headlines of the year before, but its putative demise and the attendant public confusion probably helps explain the enthusiasm that greeted Smoot's announcement. Here was a testament that the big bang worked after all; cosmologists had not been selling snake oil all these years. Was this also proof of inflation? Not yet. Still, it was a promising first step. In their relief, theorists said it would have been bigger news if COBE had *failed* to find fluctuations.

The COBE results were only one data point, a glimpse into the physics of the first trillionth of a trillionth of a second of time. They were a reassurance perhaps that such physics, the stuff of twenty-first-century dreams, existed—just as the discovery of the cosmic background had once reminded astronomers that the early universe itself existed. Only when more observations* at higher resolution had filled in the finer features on the face of the early universe could cosmologists know whether inflation or some other as-yet-undreamt idea was the correct story about the way the world began.

It was a race to find out how the world would end that led six years later to one the most dramatic and surprising discoveries in the recent history of astronomy. Ever since Edwin Hubble's discovery that the universe was expanding, astronomers had been obsessed with discerning the fate of that expansion: Would the collective gravity of the cosmos eventually halt it and bring about a so-called big crunch, or would the universe expand forever? Early in 1998 two rival teams of astronomers announced not only that gravity had failed to slow the expansion, but that the universe actually seemed to be speeding up. Astronomers were wondering whether they had discovered a new force of nature or even had detected Einstein's cosmological constant—the fudge factor he had introduced into his equations as a repulsive force to keep the universe from collapsing and then famously rejected as a blunder—alive and at work in the universe after all.

Neither Saul Perlmutter, a Lawrence Berkeley Laboratory physicist who headed one of the teams, nor Bob Kirschner, the voluble Harvard astronomer who was a prominent and outspoken member of the other team, had originally set out to resurrect Einstein's blunder. Instead, both teams were engaged in a throwback to the classical cosmology of Hubble and Sandage: They were trying to determine the fate of universe by measuring q_0, the deceleration parameter.

That parameter, recall, was a measure of how much the universe is slowing down with time. In a universe with negligible mass or gravity, space would expand forever at the same rate, and a plot of the redshifts of objects against their distances would produce a straight line. In the real universe, however, if one looked far enough out and into the past, when

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*Two satellites, NASA's MAP and the European Space Agency's Planck, should achieve this goal of measuring the background fluctuations on angular scales down to a fraction of a degree early in the next century, if clever balloon experiments do not beat them to it.

it was presumably expanding faster than it is today, the line would bend, and the amount of bending would betray the nature of the cosmos we actually live in. The problem with chasing q_0 was that it required a standard candle, an object whose distance could be gauged accurately over cosmic distances from its apparent brightness in a telescope. Sandage had spent half his life trying to measure the deceleration parameter using giant elliptical galaxies as his standard candles but in the end decided that they could not be trusted to remain constant over time.

In 1986 Perlmutter, a wiry, sandy-haired, fast-talking man, had just finished his Ph.D. in physics at Berkeley and was looking for an alternative to being a cog in a gigantic particle-physics experiment. Astronomy was the answer he came up with. "Astronomers ought to be able to ask fundamental questions without particle accelerators," he would say. Perlmutter and Carl Pennypacker, a fellow University of California astronomer who had built a robotic telescope to search for supernovae, hit upon the idea of using supernovae to measure the deceleration of the universe.

Supernovae were obviously bright enough to be seen across the entire universe. Moreover, recent work suggested that a particular subtype was uniform enough to serve as standard candles. The trick was finding enough of these rare celestial bombs in the glittery coal bin of the sky.

The scheme that Perlmutter and Pennypacker eventually proposed came to be known as the Supernova Cosmology Project. It called for an elaborate international orchestration of telescopes, starting with an electronic camera in Chile that could photograph a wide-enough swath of galaxies to ensure that a few supernovae could be detected going off in any given month. The Hubble Space Telescope would then monitor each supernova and measure its brightness once it had been discovered, and the Keck or some other monster mirror would make detailed spectral studies and measure the all-important redshift.

Not everyone thought that Perlmutter could do it. The proposal endured prolonged criticism from more experienced astronomers, particularly Kirschner, a longtime supernova expert who was on the visiting committee that reviewed work at Berkeley's new Center for Particle Astrophysics, where the project was based. "We were getting reviewed three or four times a year," Perlmutter complained.

In fact, Perlmutter admits, they made a lot of mistakes in the beginning. Not until 1995, seven years into the project, did his group start discovering supernovae in the numbers they'd envisioned. At that point Kirschner and few other astronomers formed their own team, the High-Z Supernova Search, to do the same work. It was a rude shock to Perlmutter's group, who resented the notion that they might be elbowed aside by someone who had been pooh-poohing their idea all along, after investing nearly a decade of their careers in developing the new technique.

Kirschner responded that his criticism and that of others over the years had strengthened Perlmutter's supernova program and made it more feasible. Moreover, he added, the detailed nitty-gritty techniques for observing and analyzing the light from supernova explosions had been largely invented by him and his friends. Who better to apply them to cosmological ends?

The stage had been set for a tense rivalry. In the ensuing months, Kirschner and Perlmutter were not to be found on the same stage at various conferences. At least one astronomer, Alexei Filippenko, of the University of California, Berkeley, switched sides amid rumors he was dissatisfied with his role on Perlmutter's team. But at the lower levels, members of the two teams collaborated on technical papers and often shared telescope time.

The two groups mirrored their founding cultures perfectly. Perlmutter's team of physicists was highly organized and tightly controlled, not unlike those at the big particle accelerators, in which he had resisted becoming a cog. The upstart group, whose titular leader was Brian Schmidt of the Mount Stromlo and Siding Spring Observatory in Australia, was anarchic and loose knit, meeting only once a year. Though behind in the supernova count, their superior astronomical expertise made them more willing to push the data they had. Both programs flourished and the two groups began to leapfrog each other. "Hey, what's the most powerful force in the universe? It's not gravity, it's jealousy," Kirschner told the *New York Times.*

Only a year later in 1996, with seven supernovae in hand, Perlmutter thought he could see the first hint that the universe was slowing. At a conference in Santa Monica sponsored by UCLA, he was too cagey to venture a value for the deceleration parameter or a decision on whether the universe had a big crunch in its future, but he did announce to a cheering crowd, "We do want to say it is very difficult to have an accelerating universe. We live in a decelerating universe."

Those were historic words, but they were wrong. Perlmutter had been misled by one anomalous supernova, and as more points were added to the redshift-distance graph, the evidence for deceleration vanished. The continued future expansion of the universe seemed assured. The brass ring of cosmology was at hand.

Both teams arrived at the Final Answer simultaneously. At the January 1998 meeting of the American Astronomical Society in Washington, D.C., Perlmutter and Peter Garnavich of the Harvard-Smithsonian Center for Astrophysics, representing the other team, shared a stage and announced that the universe would expand forever and ever. There was, it seemed, not enough mass in the universe to reclaim the galaxies, nor even existence itself, from their heedless flight. "If q-nought was a fuel gauge, the needle would be pointing to empty," Garnavich said.

That would have been news enough for the year. "New Data Suggest Universe Will Expand Forever," read the headline on the front page of the January 9, 1998, *New York Times,* where a future archivist could now find Perlmutter and Garnavich rubbing shoulders with Sandage and Hubble across the ages. Outside the press conferences and formal presentations, however, the buzz was about something else. In the data of 40 supernovae collected by Perlmutter's team and another 17 (including the most distant supernova yet) garnered by Schmidt's ensemble was a suggestion that the expansion of the universe was *accelerating*. The words "cosmological constant" were suddenly on everybody's lips, not as a fudge factor, but as an experimental possibility.

In fact the cosmological constant had already been on the lips of a few brave souls, including the expressive Turner, laying a fortuitous groundwork for what might otherwise have been an outlandish notion. Despite Einstein's abandonment of his creation, the cosmological constant had refused to die, instead being resurrected time and again over the years. In the 1990s the cosmological constant—lambda, as Einstein had denoted it—was back in vogue for a variety of reasons. First of all, modern quantum physics had supplied a basis for the repulsive force by predicting that empty space was teeming with energy. The original dancing genius of inner and outer space, Yakov Zeldovich, had pointed out in 1967 that this energy would mimic Einstein's cosmological constant, exerting a universal repulsive force on the cosmos.

Second, the boost that this repulsive force would impart to the cosmic expansion would allow the universe to be older than it appeared from the present expansion rate alone, opening up a way to resolve conflicts between the age of the universe as given by the Hubble constant and the ages of the oldest stars. Such a conflict was brewing in 1995, when proponents of a high Hubble constant seemed to be getting the upper hand. At a widely publicized press conference at the end of that year, Wendy Freedman announced that preliminary results from a major project to measure the Hubble constant with the space telescope implied an age of only 8 to 12 billion years for the universe. The oldest stars, however, topped out at around 15 billion years. Freedman's declaration inspired a *Time* magazine cover story entitled "Unraveling Universe."

Finally, by the rules of general relativity, just like any other form of mass or energy, the cosmological constant would add to the overall density of the cosmos and thus help fatten up a distressingly underweight universe. The grandest prediction of inflation theory was that space on the largest scales should be geometrically flat. In the case of the simplest and most favored universe, the so-called Einstein–de Sitter model, flat space meant that omega—the ratio of the universe's actual mass density to the borderline density between big crunch and eternal expansion—should be exactly 1.0. Inventories of starlight and the famous big bang nucleosynthesis calculations had long since concluded that ordinary matter in the universe at most amounted to only 10 percent or so of the critical density, but many cosmologists hoped that they would eventually find enough exotic dark matter floating out between the galaxies to make up the deficit.

Indeed, as the 1990s wore on, astronomers glorying in their new data flow devised techniques for weighing larger and larger chunks of the cosmos—including the entire local slab, some 300 million light-years across, that the Seven Samurai had discovered was falling toward the so-called Great Attractor. More dark matter was found and estimates of omega inched up to as much as 30 or 40 percent of the critical density. But that still left the universe less than half full, and a growing number of cosmologists suspected it was going to stay that way. "Maybe we should stop insisting that the universe is a higher density when there is no evidence for it," admitted Marc Davis. While some theorists began to pursue versions of inflation that did not produce flat universes, others wondered if the shortfall could be made up with the energy of nothing, that is to say, the cosmological constant.

Mike Turner, middle-aged and a father by now but still a young Turk at heart, was among those who began to take lambda seriously as a solution to the problems of the universe. In 1990 he pointed out that the "best fit" was a universe composed of one-third matter and two-thirds vacuum energy. It was a heretical notion, and he recalled that in his first talk about the subject he felt compelled to apologize "up one wall and down the other."

But he kept talking and defending that model, most notably at a large 1996 Princeton conference that was billed as a showdown about cosmological issues. By then he was not apologizing. It was, he said, the theory to watch. This time, "nobody said it was a dumb idea."

A year and a half later Turner was standing in a corridor at the January astronomical society meeting, staring at a graph of Perlmutter's unpublished data suggesting that the universe was indeed under the influence of some strange force, and basking in his prediction. "It would be a magical discovery," he said softly. "What it means is that there is some form of energy we don't understand. And the astronomers discovered it first."

A month later, Schmidt's team beat Perlmutter's to the punch and went public with the new information. At the same yearly meeting in Los Angeles at which, two years before, Perlmutter had said the universe was decelerating, Alexei Filippenko announced that the universe was instead accelerating under the influence of a mysterious force, a sort of cosmic repulsion or antigravity. The announcement predictably riled Perlmutter's group, who were quick to point out they had far more data but had been proceeding more cautiously. "Basically, they have confirmed our result," grumbled one of Perlmutter's associates.

To a man, members of both teams professed awe at what their own work had wrought: "My own reaction is somewhere between amazement and horror," said Schmidt.

In the aftermath even Perlmutter admitted that the competition had been salubrious in its effect. The fact that two different and disputatious teams had simultaneously reached the same startling conclusion made it hard for other astronomers to dismiss the discovery, even as they reserved judgment on the final outcome. "With only one group," he explained, "it would have been a lot harder to get the community to buy into such a surprising result."

Exactly what the community was buying into was not likely to be clear for some time. Was this "dark energy," as the repulsive force was dubbed, really Einstein's cosmological constant and a permanent feature of the universe, or was it a more ephemeral phenomena, some temporary field that had arisen as a result of some unknown facet of elementary particle physics? Perhaps the universe, some people even suggested, was entering a period of mild inflation.

At a meeting called to ponder these issues Turner argued that the cosmological constant should be the default explanation. "What was good enough for Einstein, should be good enough for us," he declared. Many physicists, however, were inclined to favor the idea of a more ephemeral field, which Paul Steinhardt dubbed "quintessence," after Aristotle's fifth essence. After all, the physics literature was alive every month with new theories, or wrinkles on old ones, that posited novel particles and fields whose existence could alter the universe in ways large and small. What physics did not have was a plausible explanation for the cosmological constant—at least as it appeared from astronomical observations.

Unfortunately for the theorists, the same quantum calculations that suggested that empty space was teeming with repulsive energy also suggested the density of this strange energy should be about 10^{120} times the density of matter. Yet if that were the case, the universe would have blown apart in its first millisecond before even an atom had had time to form. The fact that the universe has been expanding more or less peacefully for some 15 billion years suggested that any cosmological constant, if it existed, was modest, if not zero. That left physics with a rather, well . . . cosmic discrepancy. In a 1989 paper reviewing the whole baffling history of this subject, the renowned theorist Steven Weinberg referred to the cosmological constant as "a veritable crisis," whose solution probably awaits the marriage of quantum theory and gravity. In the meantime many theorists have simply assumed that for as-yet-unknown reasons the cosmological constant is precisely zero. If the cosmological constant is not zero, then the physicists will have to explain why.

Asked to discuss the cosmological constant at a conference once, the theorist Frank Wilczek confined himself to quoting a single line from Wittgenstein. "Whereof one cannot speak," he said, "thereof one must be silent."

In the wings the cosmologists could be heard clearing their throats.

In the fall of 1998 Mike Turner and Jim Peebles appeared together at the auditorium of the Smithsonian Institution's Museum of Natural History in Washington, D.C., to debate the fate of cosmology. It was one in a now-annual series of astronomical debates conducted in the style and setting of the historic Curtis-Shapley debate in 1920 on the nature of the spiral nebulae. This one had been postponed for several months after David Schramm, who had originally been scheduled to debate Peebles on the fate of the universe, was killed in a plane crash, shortly before Christmas 1997.

The evening was dedicated to Schramm's memory. That was fitting, Turner told the audience, because Schramm had been speaking for years about a coming Golden Age in cosmology, when a flood of astronomical data would finally test the heroic ideas that had been born of the inner space/outer space connection between particle physics and astronomy. No one had promoted that connection more vigorously or consistently than Schramm.

Egged on by the nature of the occasion, Turner argued that this Golden Age was now upon us. "For the first time we have a complete and plausible accounting of the matter and energy in the universe," he said. For the record, the elements of that accounting were as follows: The universe was flat, with ordinary and cold dark matter making up 40 percent of the cosmic density and "dark energy" making up the other 60 percent; inflation was the engine of the big bang; the Hubble constant was 65; galaxies were born from quantum fluctuations.

If these results held up under the avalanche of data to come, future generations, he said, might well remember 1998 as the year that cosmology was solved. "Big surprises could still be in store for us. Still, I think I can see the top of the mountain emerging through the haze."

Peebles responded by recalling a statement that Willem de Sitter, Einstein's old debating partner, had made back in 1931. "It should not be forgotten that all this talk about the universe involves a tremendous extrapolation, which is a very dangerous operation."

Cosmologists would do well, he went on, to imitate de Sitter's wonder at the success of science as well as his caution in deciding just how well they understood the world. Peebles was willing to concede that the future looked promising, but on his scorecard, as usual, there were more question marks than answers.

Peebles had told me once that if someone offered him the cosmological answers inscribed on a clay tablet he would throw it away, because the real discovery was always *how* you got the answer, not the answer itself. Nor was he ready to accept them on a viewgraph from Turner that afternoon. For example, he pointed out, lacking any believable theory of the cosmological constant, cosmologists could not be sure that a slight shift of the supernova data in the future would reverse the direction of its effect, meaning that space would exert an attractive force rather than a repulsive one. In that case the universe would recollapse someday regardless of how little matter it contained. "This may be of some comfort if the big crunch is more to your taste," he said.

"The main lesson," he concluded, "is that we should stop all this talk about how the world ends until we can think of some scientific meaning to attach to the answer."

In the end, as always in cosmology, the answers to questions of profound import would be sought among shadows and ghostly errors, electronic noise and photographic grains, that is to say, in gritty details retrieved from mountaintops and lonely orbits. The cosmological constant and the accelerating universe in 1999 are at the same stage as the expanding universe and the big bang were in 1929 when Edwin Hubble first divined a law, the mortality marks on the door, from a few dozen dots on a graph of galaxy distances and redshifts. On the basis of those few hints an army of astronomers had fanned out into the night. Seventy years and several hundred thousand redshifts later, it seemed that Hubble's work was receiving its first major correction, by methods he would have well understood.

The conclusion that the universe is accelerating was based on the fact that a few dozen dots, representing distant supernovae, appeared 10 or 15 percent fainter than they should have been. A subtle shift in the properties of supernovae over the ages or in the composition of interstellar dust, for example, could rearrange those dots and wipe out that finding, or even reverse it, as Peebles suggested. Already there is talk of a dedicated telescope in space to discover and track the flight of these supernovae in every direction and in every epoch. Data is harvested faster now, but imagination and understanding run at their own pace. It is not unreasonable to presume that another army scouring the sky, thousands of telescope hours, and virtuosic manipulations of data will be required before there is an answer to dark energy, the accelerating stars, and the other questions that the new observations have dragged in from the sky—nor that the answer when it comes will be different and richer than we now suspect. Only time will tell if Perlmutter and Kirschner and their colleagues have discovered another fact as fundamental and inescapable as Hubble's expansion. Only time will tell if a new mythology is being born. Only time and the sweat and genius of a new generation.