Chapter 1. Executive Summary

How did the Universe begin? Does time have a beginning and an end? Does space have edges? The questions are clear and simple. They are as old as human curiosity. But the answers have always seemed beyond the reach of science. Until now.

In their attempts to understand how space, time, and matter are connected, Einstein and his successors made three predictions. First, space is expanding from a Big Bang; second, space and time can tie themselves into contorted knots called "black holes" where time actually comes to a halt; third, space itself contains some kind of energy that is pulling the Universe apart. Each of these three predictions seemed so fantastic when it was made that everyone, including Einstein himself, regarded them as unlikely. Incredibly, all three have turned out to be true. Yet Einstein's legacy is one of deep mystery, because his theory is silent on three questions raised by his fantastic predictions: (1) What powered the Big Bang? (2) What happens to space, time, and matter at the edge of a black hole? (3) What is the mysterious dark energy pulling the Universe apart?

To find answers, we must venture beyond Einstein. The answers require new theories, such as the inflationary universe and new insights in high-energy particle theory. Like Einstein's theory, these make fantastic predictions that seem hard to believe: new unseen dimensions and entire universes beyond our own. We must find facts to confront and guide these new theories. Powerful new technologies now make this possible.

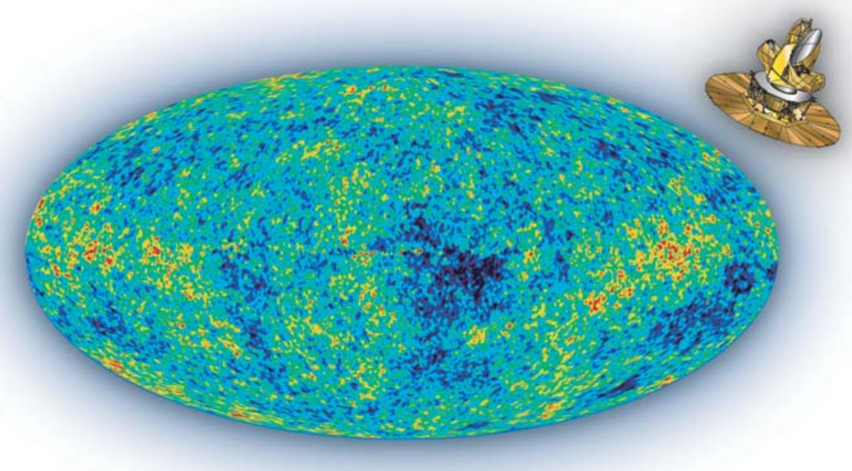
Here is where the *Beyond Einstein* story starts. By exploring the three questions that are Einstein's legacy, we begin the next revolution in understanding our Universe. We chart our way forward using clues from observations and from new ideas connecting the worlds of the very small and the very large.

What powered the Big Bang?

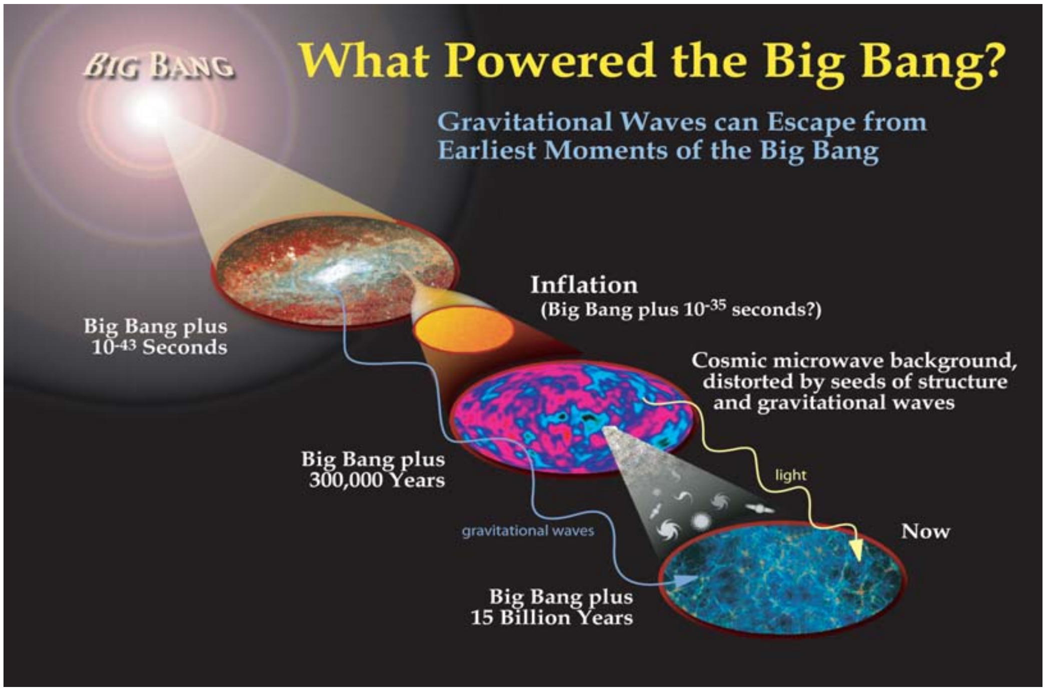
The wrinkles imprinted on the Universe in its first moments have been revealed in sky maps of the radiation relic of the Big Bang ---first a decade ago by NASA's Cosmic Background Explorer (COBE) satellite and more recently in greater detail by other experiments, including Antarctic balloon flights and NASA's Wilkinson Microwave Anisotropy Probe (WMAP). Gravity has pulled these wrinkles into the lumpy Universe of galaxies

The WMAP Explorer mission provides the clearest view yet of the cosmic microwave background, using the wrinkles imprinted upon it from the earliest moments of the big bang to provide precision measurements on the expansion and contents of the Universe.

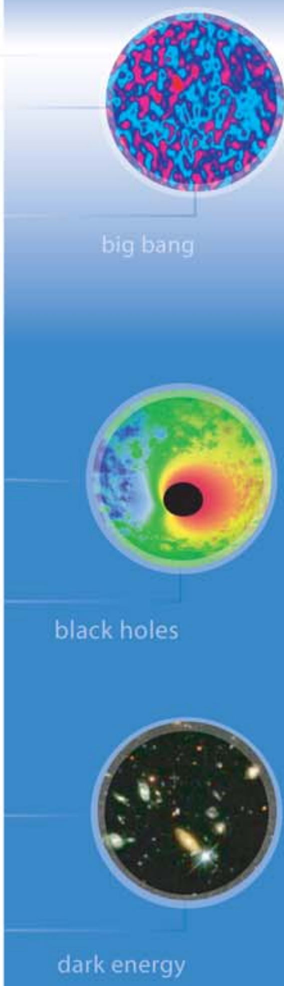
MAPping the Cosmic Background



The initial map of the cosmic microwave background obtained by NASA's Wilkinson Microwave Anisotropy Probe (WMAP).



Quantum fluctuations during the Big Bang are imprinted in gravitational waves, the cosmic microwave background, and in the structure of today's Universe. Studying the Big Bang means detecting those imprints.



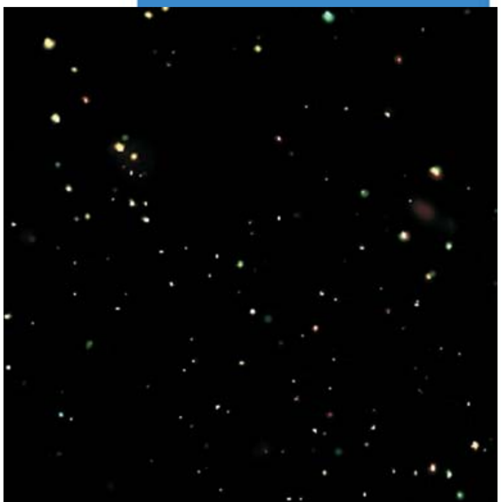
and planets we see today. Yet still unanswered are the questions: why was the Universe so smooth before, and what made the tiny but all-important wrinkles in the first place?

Einstein's theories led to the Big Bang model, but they are silent on these questions as well as the simplest: "What powered the Big Bang?" Modern theoretical ideas that try to answer these questions predict that the wrinkles COBE discovered arose from two kinds of primordial particles: of the energy field that powered the Big Bang; and gravitons, fundamental particles of space and time.

Measurements by missions of the *Beyond Einstein* program could separate these different contributions, allowing us to piece together the story of how time, space, and energy worked together to power the Big Bang.

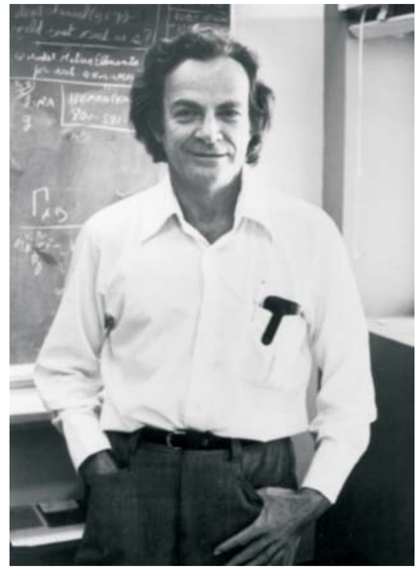
What happens to space, time, and matter at the edge of a black hole?

The greatest extremes of gravity in the Universe today are the black holes formed at the centers of galaxies and by the collapse of stars. These invisible bodies can be studied by examining matter swirling into them, and by listening to the waves of distortion they make in spacetime. New data from X-ray satellites, such as NASA's Chandra X-ray Observatory and ESA's XMM-Newton, show signs of gas whizzing about black holes at close to the speed of light and hint that time is slowing as the gas plunges into the zone from which



Most of the X-ray sources seen in this 12-day exposure by the Chandra X-ray Observatory are active galaxies and quasars powered by massive black holes. Ground-based observations show that many of them are shrouded by dust; many others remain unidentified, invisible except in X-rays.

Richard Feynman [Nobel Prize, 1965] showed that "empty" space was filled with virtual particles.



"In modern physics, the vacuum is simply the lowest energy state of the system. It need not be empty nor uninteresting, and its energy is not necessarily zero."
—From Quarks to Cosmos, *Report of the Committee on the Physics of the Universe*

escape is impossible. *Beyond Einstein* missions will take a census of black holes in the Universe and give detailed pictures of what happens to space and time at the edges of these roiling vortices.

Beyond Einstein missions will listen to the sounds of spacetime carried by a new form of energy, predicted by Einstein, called gravitational waves. We will hear the booming, hissing, and humming of colliding and merging black holes and other extreme flows of matter throughout the Universe. These sounds will detail the conversion of matter and energy into warps in space and time. The measurements of gravitational waves will provide a new way of understanding the behavior of space and time near black holes and take us beyond to a new understanding of spacetime singularities.

Einstein himself never dreamed that it would be possible to detect these waves, which only vary the distance between objects as far apart as the Earth and Moon by less than the width of an atom. Yet the technology now exists to do so.

What is the mysterious dark energy pulling the Universe apart?

A landmark discovery of the 1990s was that the expansion of the Universe is accelerating. The source of this mysterious force opposing gravity we call "dark energy."

Because he originally thought the Universe was static, Einstein conjectured that even the emptiest possible space, devoid of matter and radiation, might still have a dark energy, which he called a "Cosmological Constant." When Edwin Hubble discovered the expansion of the Universe, Einstein rejected his own idea, calling it his greatest blunder.

As Richard Feynman and others developed the quantum theory of matter, they realized that "empty space" was full of temporary ("virtual") particles continually forming and destroying themselves. Physicists began to suspect that indeed the vacuum ought to have a dark form of energy, but they could not predict its magnitude.

Through recent measurements of the expansion of the Universe, astronomers have discovered that Einstein's "blunder" was not a blunder: some form of dark energy does indeed appear to dominate the total mass-energy content of the Universe, and its weird repulsive gravity is pulling the Universe apart.

"I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms which are connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe that such an ugly thing should be realized in nature."
—*Albert Einstein,* in a Sept. 26, 1947, letter to Georges Lemaître

We still do not know whether or how the highly accelerated expansion in the early Universe (inflation) and the current accelerated expansion (due to dark energy) are related.

A *Beyond Einstein* mission will measure the expansion accurately enough to learn whether this energy is a constant property of empty space (as Einstein conjectured), or whether it shows signs of the richer structure that is possible in modern unified theories of the forces of nature.

The Beyond Einstein Program

The *Beyond Einstein* program has three linked elements which advance science and technology towards two visions: to detect directly gravitational wave signals from the earliest possible moments of the Big Bang, and to image the event horizon of a black hole. The central element is a pair of Einstein Great Observatories, Constellation-X and LISA. These powerful facilities will blaze new paths to the questions about black holes, the Big Bang, and dark energy. They will also address other central goals of contemporary astrophysics (discussed in Part II of this roadmap). The second element is a series of competitively selected Einstein Probes, each focused on one of the science questions. The third element is a program of technology development, theoretical studies, and education, to support the Probes and the vision missions: the Big Bang Observer and the Black Hole Imager. The program offers competitive opportunities for mission leadership, technology development, and groundbreaking scientific research, with goals that excite the public.

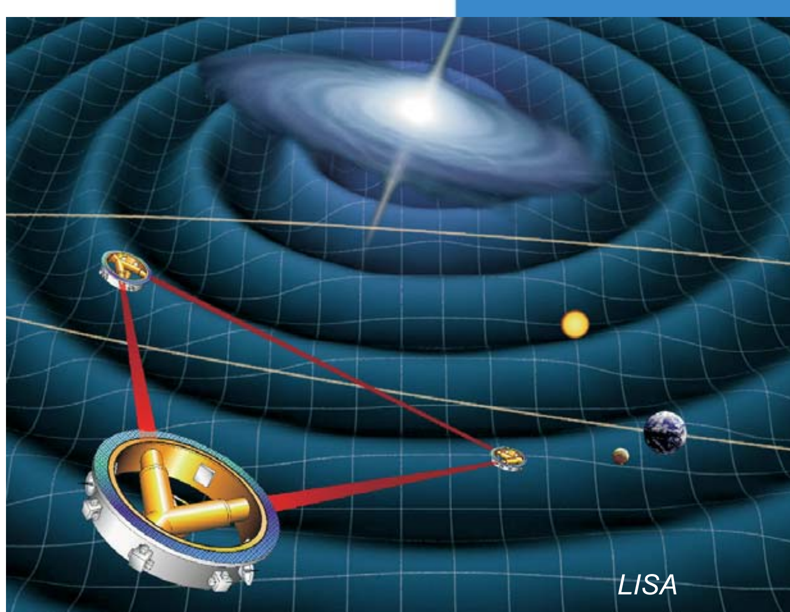
Einstein Great Observatories

While these two missions are focused on specific observational goals, the capabilities they provide are so dramatically new that they will also provide a broad science return that will impact all areas of astrophysics, as have Hubble Space Telescope and the Chandra X-ray Observatory before them.

The Laser Interferometer Space Antenna (LISA) will deploy three spacecraft orbiting the Sun, separated from each other by five million kilometers (17 light seconds). Each spacecraft will contain freely falling "proof masses" protected from all forces other than gravity. The relative motion of the masses can be measured to sub-nanometer accuracy by combining laser beams shining between the spacecraft. Passing gravitational waves will ripple space and time, revealing their presence by altering the motion of the proof masses.

LISA will probe space and time at the forming edges of black holes by listening to the sounds of vibrating spacetime: the booming roar of supermassive black holes merging, the chorus of death cries from stars on close orbits around black holes, and the ripping noise of zipping singularities. It may even hear whispers from the time in the early Universe when our three-dimensional space formed within the now unseen space of six or seven dimensions. LISA will plot the orbits of stars around black holes to test Einstein's theory under extreme conditions.

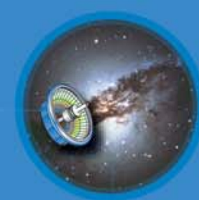
LISA measurements of merging black holes will provide a new yardstick with which to mea-



LISA

laser interferometer space antenna

constellation-x

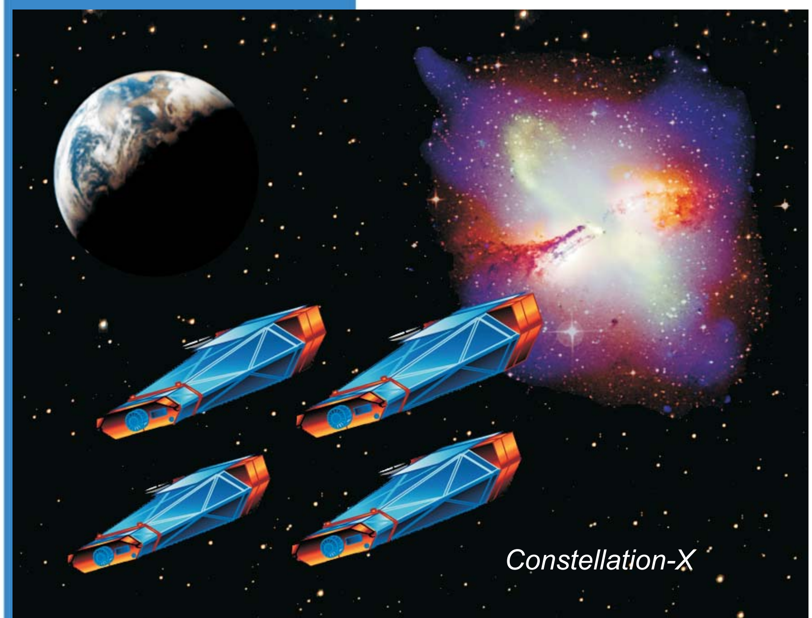


einstein probes

sure the Universe and constrain the nature of dark energy. LISA will also measure waves from black holes in the first structures of the Universe to collapse. It will measure gravitational waves from thousands of binary star systems in our Galaxy, yielding new insights into the formation and evolution of binary stars.

The Constellation-X mission will consist of four 1.6-meter X-ray telescopes orbiting the Earth/Sun system, providing nearly 100 times the sensitivity of the Chandra X-ray Observatory and other planned missions for X-ray spectroscopy. They will be instrumented to cover a range of more than a factor of 100 in X-ray energy with unprecedented energy resolution.

Constellation-X will address the question, "What happens to matter at the edge of a black hole?" When plasma streams collide at nearly the speed of light, they become hot enough to emit X rays. The vibrations of the X-ray light act as clocks that we can use to track the motions of the plasma and the distortions of space and time near the black hole. The great sensitivity of Constellation-X will allow us to make "slow-motion movies" of the gas at a high frame rate. Current instruments are not sensitive enough for the short exposures needed to freeze the motion.



Constellation-X

Constellation-X will dramatically increase our ability to obtain high resolution X-ray spectroscopy of faint X-ray sources. This will enable us to constrain the nature of dark matter and dark energy by observing their effects on the formation of clusters of galaxies. These measurements, and those by the Dark Energy Probe, LISA, and the Inflation Probe, will each constrain different possible properties of dark energy and together lead to its understanding. Constellation-X's high resolution spectra will provide fresh diagnostics of the speed, density, temperature, and composition of plasma in galaxies and exotic stars throughout the Universe, allowing new studies of their nature and evolution.

Black holes grow both by accreting gas and by accreting stars. They change both by ejecting gas and by merging with other black holes. To understand the origin and nature of the giant black holes in the centers of galaxies requires both LISA and Constellation-X, working together to cover all four of these processes.

Einstein Probes

Complementing the facility-class Einstein Great Observatories, a series of sharply focused missions will address those critical science goals that do not require facility-class missions. For these missions, the science question is defined strategically but the science approach and mission concept will be determined through peer review. We identify three compelling questions whose answers can take us beyond Einstein.

"How did the Universe begin?" Scientists believe the Universe began with a period of "inflation," when the Universe expanded so rapidly that parts of it separated from other parts faster than the speed of light. Inflation theory predicts that this expansion was propelled by a quantum-mechanical energy of the vacuum similar to the dark energy today. It may hold the answer to the question, *"What powered the Big Bang?"* One way to test this

Many NASA missions have laid the groundwork for the *Beyond Einstein* program, and will complement it. NASA's *COBE* discovered the first evidence for primordial density fluctuations in the CMB. NASA's balloon program (e.g., the NASA/NSF/Italian/UK *BOOMERanG*) has supported the discovery of the interaction of those fluctuations with matter in the Universe. NASA's *WMAP* satellite and the ESA's planned *Planck* satellite will extend these discoveries and are vital precursors to the proposed Inflation Probe.

The Hubble Space Telescope has helped to find and measure the distant supernovae that have forced us to accept the reality of dark energy.

X-ray missions, including NASA's *Chandra X-ray Observatory* and *RXTE,* ESA's *XMM-Newton,* and Japan's *ASCA,* have discovered X rays from matter spiraling into black holes, illustrating the potential of Constellation-X.

GP-B will test one of Einstein's exotic predictions: that the rotation of the Earth drags space and time around the Earth into a mild version of the tremendous vortical spin near a spinning black hole.

Swift will study gamma-ray bursts, believed to be a result of the stellar explosions and mergers which create black holes. Swift will also test technology for the Black Hole Finder Probe.

GLAST will provide more sensitivity and energy coverage than ever before for the study of high-energy emissions from particles accelerated in gamma-ray bursts and in the jets from spinning black holes in galactic nuclei.

Japan/NASA's *Astro-E2* will be the first to use NASA-provided microcalorimeters that are prototypes for Constellation-X detectors.

ST-7 and ESA's *SMART-2* will provide a flight comparison of two disturbance reduction technologies competing for use on LISA.

idea is to look for relics of quantum fluctuations. Gravitational waves are the most direct relics since they penetrate the heat and density of those early days.

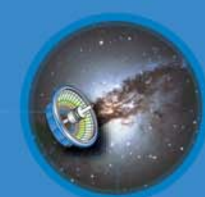
It is technically feasible to look for the quantum effect of gravitational waves and distinguish them from the quantum effects of the primordial energy, by examining their distinctive effects on the polarization of the cosmic microwave background. An "*Inflation Probe"* with this capability will help define the nature of the vacuum that drove inflation.

"How did black holes form and grow?" Most astronomers believe that the black holes in the centers of galaxies grew by swallowing stars and gas, emitting light in the process. But there is an accounting problem: not enough light is coming from black holes in active galaxies to explain their growth. There are hints that much of the growth occurred behind a veil of dust. One way to see into these dark corners is to use the most penetrating of X rays. The *"Black Hole Finder Probe"* will perform a census of hidden black holes, revealing the demographics and life cycles of black holes and identifying black holes for study with Constellation-X. Combining these data with studies of accretion by Constellation-X and of black hole mergers by LISA will reveal how giant black holes formed.

"What is the mysterious energy pulling the Universe apart?" is a question that would not have been asked five years ago, before there was evidence that the Universe was being pulled apart. To understand this energy, we must measure the expansion of the Universe with high precision. This will require the most precise cosmic yardsticks we can find.

laser interferometer space antenna

constellation-x



einstein probes

Gravitational waves are vibrations in the fabric of space and time. Gravitons are their quanta. Unlike photons (the quanta of light), gravitons hardly interact at all with matter, so our senses have never before detected them. The light we see from the Big Bang, the Cosmic Microwave Background, last bounced off matter when the Universe was 300,000 years old. Gravitons from the Big Bang have been hurtling toward us unchanged since the Universe was 10^{-35} seconds old!

The dark energy filling your house has just enough energy for a flea to make one jump. Yet across the immense volume of the Universe, this energy can overcome the gravitational attraction of all the billions of galaxies.

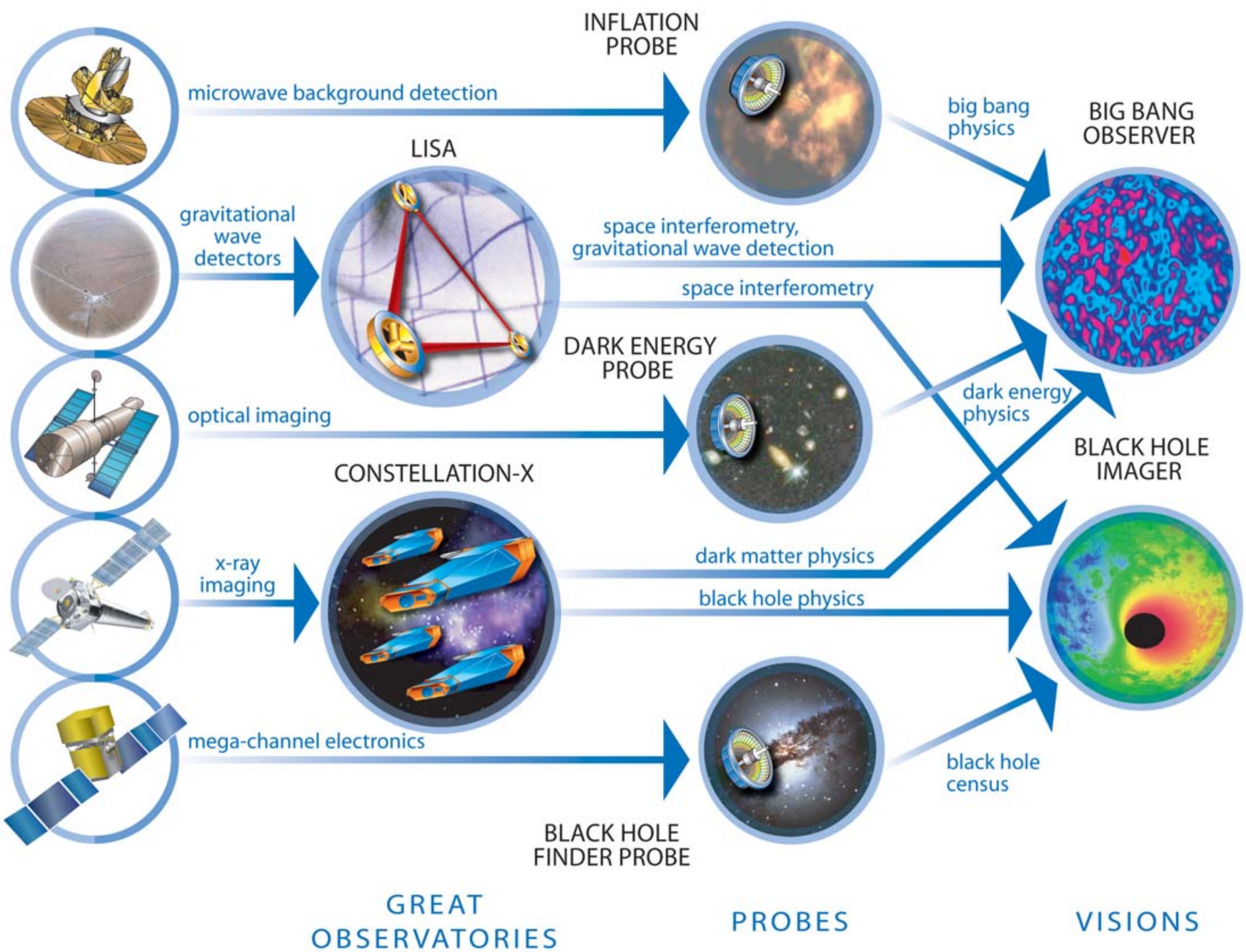
Several ideas for such "*Dark Energy Probes"* have been proposed—for example, precision measurement of distant supernovae by a wide-field space telescope.

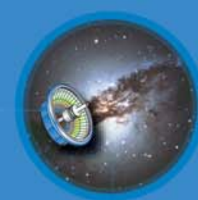
Independent diagnostics of the dark energy will be crucial to verify the validity of results and to increase the precision of the measurements. The Inflation Probe and LISA will provide completely independent cosmic yardsticks with which to measure the effects of dark energy, and Constellation-X will observe the first clusters of galaxies whose evolution depends critically on dark matter and dark energy.

The Ultimate Vision

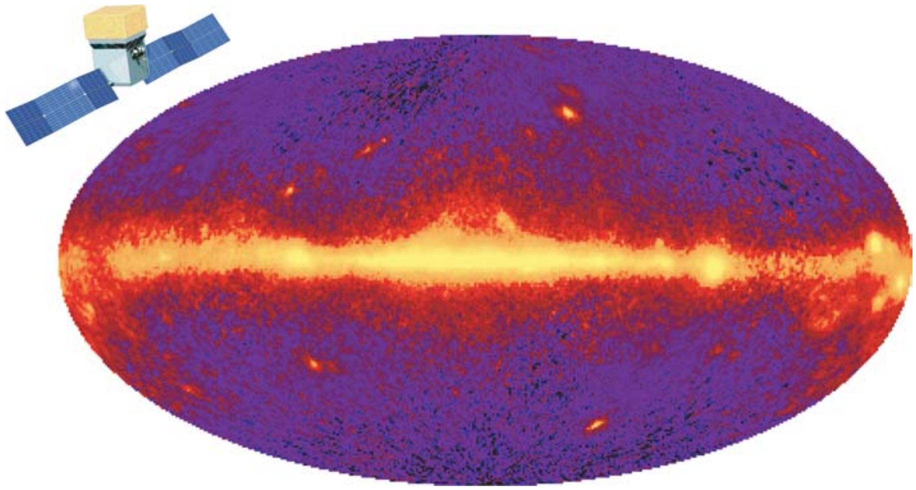
The technology to go far beyond Einstein is within our reach if we approach the grand goals systematically, mission building upon mission, proving and refining the required technology. Strategic investments in hardware, software, and astrophysical theory will lead the way forward to two visions:

To explore the beginning of time, a "Big Bang Observer" will build upon LISA to *directly* measure gravitons from the early Universe still present today. In contrast to the Inflation Probe's measurement of frozen imprints of much longer waves on the microwave background, the Big Bang Observer will observe gravitational waves in their origi-





The Gamma-Ray Large Area Space Telescope (GLAST) is the highest priority mission already under development in the Structure and Evolution of the Universe theme. This roadmap assumes its completion and scheduled launch in 2006. GLAST is an international and multi-agency (NASA and DOE) project.



GLAST builds upon the success of the EGRET high-energy telescope on the Compton Gamma Ray Observatory. The Large Area Telescope on GLAST will map the sky in one day at the same flux level that EGRET could achieve in one year, shown in the EGRET all-sky map above.

With more than 30 times the sensitivity of EGRET and broader energy coverage, GLAST will study the processes that expel relativistic plasma and accelerate particles near the black holes believed to lurk in Active Galactic Nuclei and Gamma-Ray Bursts. It will elucidate the origin of energetic gamma-radiation from pulsars and the acceleration of cosmic rays in supernova remnants. It will help identify the many EGRET sources whose nature remains a mystery and search the Universe for gamma-ray signatures of hypothesized decaying particles of Dark Matter.

nal form, from still earlier in the Big Bang. The Big Bang Observer would give us a direct view of the creation of spacetime, a truly profound achievement.

To explore the end of time and the edges of space, Constellation-X will measure the spectral signatures of gas swirling into black holes, and LISA will record the tune to which stars dance around it. But there is no substitute for a direct image. A “Black Hole Imager” based on X-ray interferometry could take this epochal picture, revealing directly the fate of matter near a black hole.

Technology

While the enabling foundations are well in hand, the *Beyond Einstein* program demands many refinements in technology. Constellation-X will need lightweight optics and cryogenic X-ray calorimeters. LISA will need sensitive monitoring units coupled to micronewton thrusters to keep its test masses free of non-gravitational forces. It will also require very stable laser measurement systems. The Einstein Probes require study of a broad range of technologies so that the most effective approach to their science goals can be chosen. The vision missions, Black Hole Imager and Big Bang Observer, need still greater precision in spacecraft pointing and control.

Research and Analysis

The R&A program is the cradle this necessary technology, and for the theoretical underpinnings of NASA space science missions. It is the first step in a process that turns ideas into missions, as well as the final step in turning missions into scientific advances. NASA's R&A program draws heavily on the resources of our universities, providing an additional benefit: the training of students who become the architects and builders of future missions. The Einstein Probes require new detectors for which ground-based and balloon tests will be essential. Laboratory measurements of atomic data are necessary to link observations to scientific conclusions.

Theory provides the intellectual context for any scientific effort. Theoretical work is essential to the conception and design of missions and to the interpretation of the data they provide—especially for the *Beyond Einstein* missions, which are designed to test predictions that challenge our beliefs.

Public interest in the Chandra X-ray Observatory has led to more than 850 newspaper articles and wire stories in its first three years of operation—including 27 in the NY Times, Washington Post, and USA Today—and more than 10 newscasts, including CNN, ABC, CBS, and NPR.

Education and Public Outreach

Beyond Einstein offers an unparalleled opportunity to involve the public in the excitement of cosmic exploration, and to inspire and cultivate the next generation of scientists and engineers. The public's eagerness to share this adventure is reflected in part by the many Hollywood movies, television series, bestselling books, and popular articles that draw on

Beyond Einstein themes. The origin of the Universe and black holes are central to K-12 science literacy standards and curricula. The television shows and educational materials for "Live from a Black Hole" and "Live from the Edge of Space" reached an estimated five million students. Public television's NOVA program on dark energy (*Runaway Universe*) was seen initially by more than two million Americans. The *Beyond Einstein* themes will soon provide the *majority* of materials on these subjects in our nation's schools and the missions will weave an ongoing story that is one of the most compelling in all science.

Einstein's Legacy

Einstein sought, but never achieved, an understanding of how nature works at its deepest level. We now seek the next level of Einstein's quest through a program of missions we can conceive and design today and carry out over the next decade. In the future, the "vision missions" of this roadmap will extend these ventures even closer to the edges of space and time. We will follow matter to the very brink of black holes and detect quanta or particles of time left over from the beginning of the Universe. We will use breakthrough technologies to see beyond the vision of Einstein—to the uttermost extremities of existence.

"Each one has the right to share in the knowledge and understanding which society provides"
—Albert Einstein