Beyond Einstein: From the Big Bang to Black Holes

How did the Universe begin? Does time have a beginning and an end? Does space have edges? Einstein's theory of relativity addresses these ancient questions with three startling predictions: that the Universe is expanding from a Big Bang; that black holes so distort space and time that time stops at their edges; and that a dark energy could be pulling space apart, sending galaxies forever beyond the edge of the visible Universe. Observations confirm these remarkable predictions, the last finding only four years ago. Yet Einstein's legacy is incomplete. His theory raises—but cannot answer—three profound questions:

- What powered the Big Bang?
- What happens to space, time, and matter at the edge of a black hole?
- What is the mysterious dark energy pulling the Universe apart?

NASA's Beyond Einstein program aims to answer these questions. Beyond Einstein is the name of the umbrella program for a series of missions utilizing innovative new technologies to obtain the data needed to address these very important questions. Just as Einstein revolutionized physics a century ago, the answers to these questions could revolutionize physics as we know it today.

What powered the Big Bang?

If the Universe is expanding, as countless observations have shown, it is only logical to assume that the Universe was more compact yesterday, even more compact the day before, and so on. At some point in the distant past, all the matter and energy we see today must have been confined to a microscopic region of unimaginably high density. This would be the moment of the Big Bang.

We know a great deal about the history of the Universe, from its hot, formless beginnings to the glorious hierarchal structure of stars and galaxies in the modern era. Clues to the past are all around us. In the 1960s scientists identified a pervasive microwave radiation emanating from all points in the sky. This radiation, called the cosmic microwave background, is the afterglow of the Big Bang itself. Embedded in this afterglow are slight temperature fluctuations—a little warmer here, a little cooler there—that point back to slight density differences in the infant Universe—a little more matter here, a little less there. These fluctuations are the seeds of all the structure we see today.

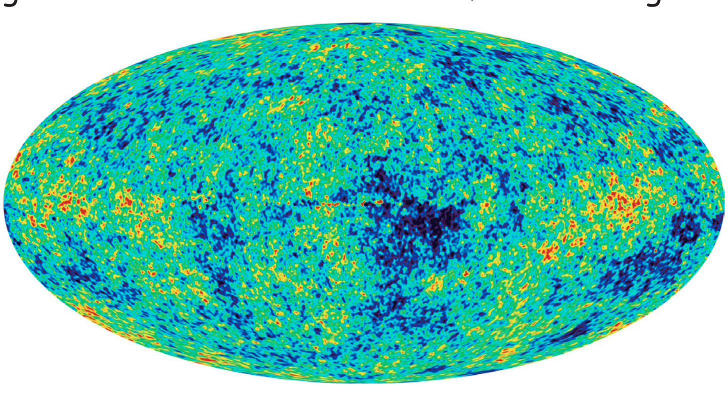


Image from WMAP showing the tiny fluctuations in the Cosmic Microwave Background (CMB) that grew to become galaxies. Credit: NASA/WMAP Science Team.

NASA's Cosmic Background Explorer (COBE) satellite discovered the fluctuations and, most recently, NASA's Wilkinson Microwave Anisotropy Probe (WMAP) has refined the measurement. We see how gravity has pulled these wrinkles into stars and planets. We can even determine the ratio of matter to energy, the era of first starlight, and the age of the Universe, 13.8 billion years.

What we don't know is the most basic fact of them all: What started it all? Modern theoretical ideas that try to answer this question predict that the wrinkles COBE discovered arose from two kinds of primordial entities: the energy field that powered the Big Bang; and gravitons, fundamental particles of space and time.

Clues to the nature of these particles exist in the Big Bang afterglow. We need to coax more detailed information from this ancient light, which has held its secrets for so long. This would enable us to piece together the story of how time, space, and energy worked together to power the Big Bang.

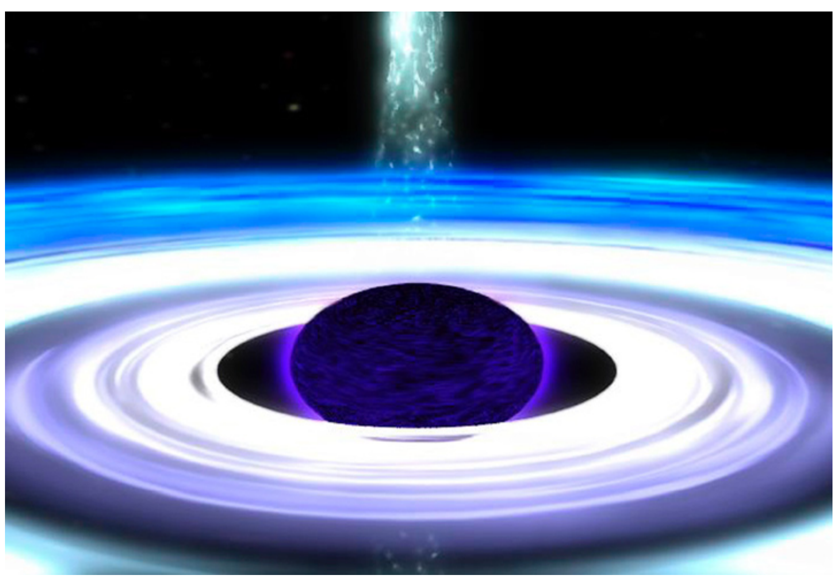
What happens to space, time, and matter at the edge of a black hole?

The greatest extremes of gravity in the Universe are the black holes formed at the centers of galaxies and by the collapse of stars. Gravity is so overpowering here that nothing, not even light, can escape its grasp. By definition black holes are invisible. Yet these invisible bodies disturb space considerably, offering us two ways to study them: by observing matter swirling into them, and by observing the waves of distortion they make in spacetime.

Data from X-ray satellites, such as NASA's Chandra X-ray Observatory and ESA's X-ray Multi Mirror (XMM) Newton Observatory, 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 escape is impossible. However, we need to get more detailed information

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 gravitational pits.

One key mission will create movies from the X-ray light emitted from multimillion-degree gas as it approaches a black hole's border, called the event horizon. Another mission will listen for gravitational waves, which are ripples in spacetime predicted by Einstein. These waves are created by black hole mergers; they move across the "sea" of space at light speed, undisturbed, and offer an unobstructed view of these powerful collisions.



Black holes are surrounded by accretion disks and power very strong jets. Credit: NASA/GSFC/Dana Berry.

Einstein himself never dreamed that it would be possible to detect gravitational waves—they are so subtle that they only distort the distance between objects as far apart as the Earth and Moon by less than the width of an atom. Yet the technology is now being developed to do so.

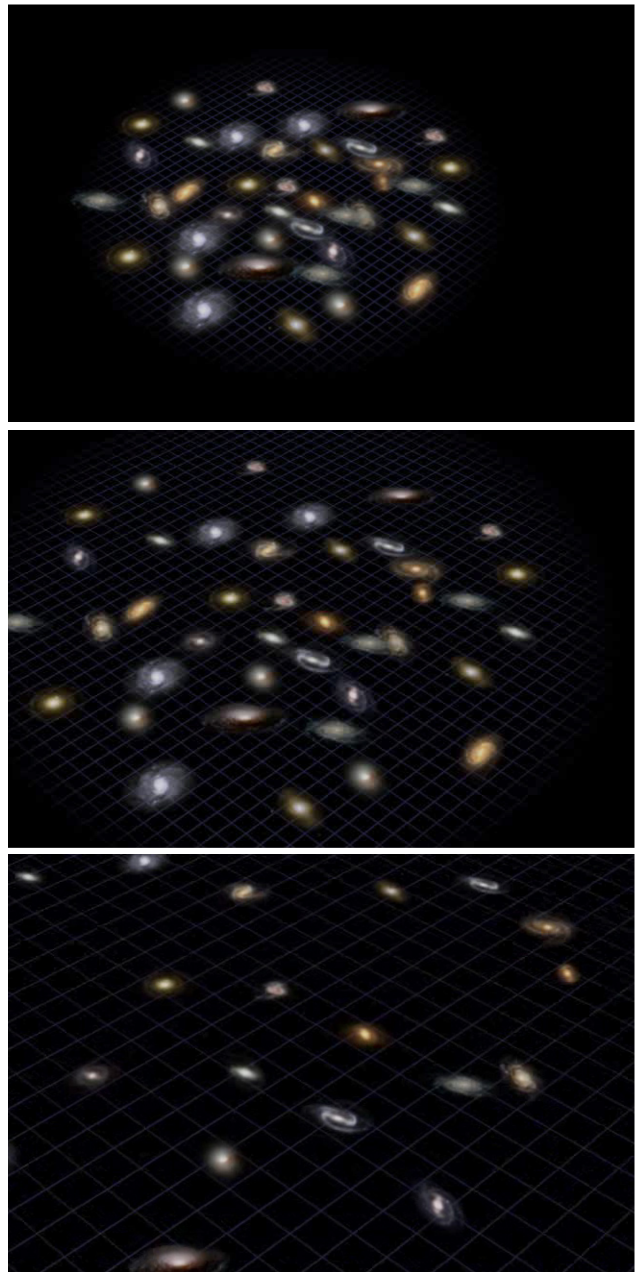
What is the mysterious dark energy pulling the Universe apart?

The landmark discovery of the 1990s was that the expansion of the Universe is accelerating. The greatest mystery in astronomy today is the nature of this force opposing gravity, which we call "dark energy."

Because Einstein originally thought the Universe was static, he conjectured that even the emptiest possible space, devoid of matter and radiation, might still have an energy countering gravity, 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.

But the Universe isn't just expanding; the expansion rate, which appears to have slowed several billion years ago, is revving up. We live in a runaway Universe, in which the most distant galaxies visible today will eventually fly off forever beyond the horizon. This acceleration could be due to the concept that "empty space" isn't empty. Richard Feynman and others who developed the quantum theory of matter realized that empty space is filled with "virtual" particles continually forming and destroying themselves. These particles create negative pressure, like a vacuum energy, that pulls space outward. No one, however, could predict this energy's magnitude.

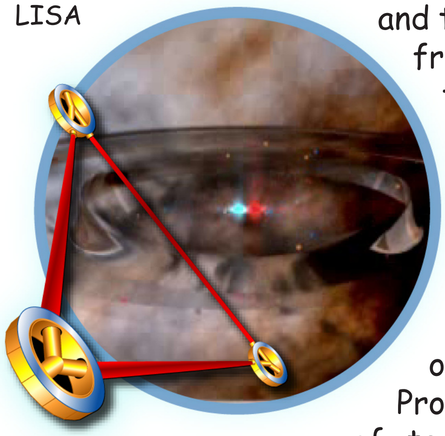
Independent measurements reveal that dark energy comprises about 70% of the total mass-energy budget of the Universe. We still do not know whether or how the highly accelerated expansion in the early Universe, called inflation, and the current accelerated expansion, due to dark energy, are related. A 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 its strength varies over time, a property predicted by modern theories of the forces of nature.



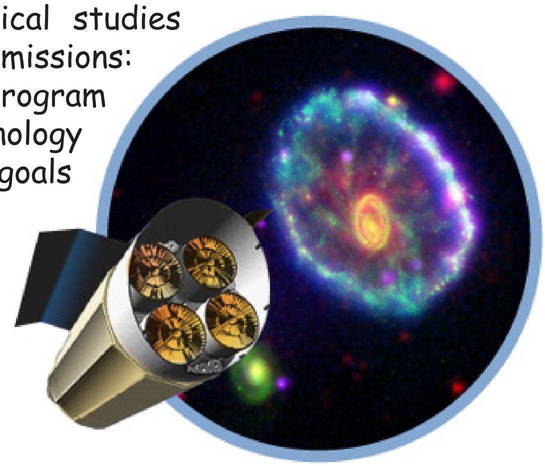
This sequence of images shows a possible future for the Universe by modeling the Universe as a two dimensional grid of galaxies. If dark energy is constant, consistent with Albert Einstein's suggestion, then the expansion of the Universe should continue accelerating until in a hundred billion years or so, only a tiny fraction of the known galaxies in the Universe will be observable. Credit: NASA/STScI/G.Bacon.

The Beyond Einstein Program

LISA



The Beyond Einstein program has three linked elements that advance science and technology towards two visions: to detect 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 (the Laser Interferometer Space Antenna). 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. The second element is a series of competitively selected Einstein Probes, each focused on one of the science questions: the Inflation Probe, the Dark Hole Finder Probe, and the Dark Energy Probe. 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.



Constellation-X

Useful Websites for more information:

- Beyond Einstein website:
  http://beyondeinstein.gsfc.nasa.gov/
- Cosmology 101 from the WMAP mission:
  http://map.gsfc.nasa.gov/m_uni.html
- Explanation of science topics from NASA's Imagine the Universe:
  http://imagine.gsfc.nasa.gov/docs/science/science.html
- Answers to commonly asked questions are available at the Ask-an-Astrophysicist site:
  http://imagine.gsfc.nasa.gov/docs/ask_astro/ask_an_astronomer.html