Universe Exploration:
From the Big Bang to Life

A strategic roadmap of universe exploration to understand its origin, structure, evolution and destiny.

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Universe Exploration

1. **Agency Objective Statement:** Explore the universe to understand its origin, structure, evolution, and destiny.

2. **Flow-down to roadmap objectives**

Universe Exploration: From the Big Bang to Life

Science is now poised to answer some of humanity's deepest questions, such as how the universe came into being; how it formed the galaxies, stars, and planets that set the stage for life; and whether there is life on other worlds. The scientific pursuit of our origin, structure, evolution and destiny requires deep and detailed explorations into space and time, and challenges the limits of America's technical capabilities in space. This roadmap articulates a long-term plan for scientific exploration of the universe, from the Big Bang to life. It is composed of two program elements, the Beyond Einstein Program and the Pathways to Life Program.

The **Beyond Einstein Program** explores the ultimate extremes of nature: the birth of the universe, the edges of space and time near black holes, and the darkest and emptiest space between the galaxies. It will determine the initial conditions and natural laws that govern everything that happens in the universe, from beginning to end. This program takes up the challenge to explore the origin and destiny of the universe through three roadmap objectives:

1. Find out what powered the Big Bang.
2. Observe how black holes manipulate space, time and matter.
3. Uncover the nature of the mysterious dark energy pulling the universe apart.

The Beyond Einstein program's cornerstone missions are the Laser Interferometer Space Antenna (LISA), the first instrument in space to measure spacetime ripples called gravitational waves, and Constellation-X (Con-X), a path-breaking X-ray telescope that can study matter near black holes. A focused line of more specialized Einstein Probe missions is dedicated to specific studies of black hole discovery, the cosmic inflation that powered the Big Bang, and the dark energy propelling the cosmic expansion today. Forward-looking technology development, as well as foundational and exploratory studies in theory, modeling, and predictive simulation, aim ultimately toward two Vision missions: the Big Bang Observer, an ultrasensitive gravitational wave observatory, and the Black Hole Imager, an X-ray interferometer.

The simple Big Bang ultimately created a rich structure, giving rise to galaxies, stars and planets. Peering back nearly 14 billion years, this global history — from epoch to epoch, from the formless infant universe through nascent galaxy building to the formation of solar systems — can be traced by direct observations of distant space. For example, all-sky images from the Wilkinson Microwave Anisotropy Probe (WMAP) reveal the afterglow of the Big Bang, a remnant primordial radiation created by faint vibrations in matter and light half a million years after the Big Bang, triggered by the event itself. The more advanced ESA-NASA Planck Surveyor mission and eventually the Beyond Einstein Inflation Probe will measure these vibrations in exquisite detail. The weak ripples in gas and dark matter — a little more matter here, a little less there — later created the first stars, then the quasars powered by supermassive black holes, and finally the great cosmic web of galaxies linked by invisible rivers of dark matter and hot, tenuous gas. Con-X and LISA explore the era when massive black holes dominated; other Beyond Einstein missions will probe the era when dark energy became the dominant force in the universe.

As the universe evolved to the present day, stars played increasingly dominant roles in the evolution of matter and complex structure. Stars are the sources of the energy, light, and chemical elements that drive the cosmic cycling of matter into new generations of stars, planets, and eventually life. From hydrogen and helium created in the Big Bang comes carbon, oxygen, nitrogen and life itself. The **Pathways to Life Program** explores the formation and evolution of all of this grand system. It takes up the challenge to explore the structure and evolution of the universe through one overarching objective:

4. Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

This objective has three key components:

- Map directly the structure and evolution of the Cosmic Web.
- Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars and planets.
- Trace the evolution of nuclei, atoms, and molecules that became life.

The Pathways to Life program builds on the historic legacy of the Hubble Space Telescope, and includes the airborne Stratospheric Observatory For Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), the Gamma-ray Large-Area Space Telescope (GLAST), competed Probes, and the Pathways to Life Observatories. Con-X, LISA, and the Einstein Probes will contribute significantly.

All of these explorations require the development of complex space missions with unprecedented capabilities, from new ultrasensitive detectors and precision optics, to multiple spacecraft flying in formation to subatomic accuracy. New technology development is systematically incorporated into the multiple stages of the Beyond Einstein and Pathways to Life programs. The overall plan maximizes investment return by focusing on strategic technologies, where each development pays off multiple times.

Beyond the strategic space missions, NASA's scientific success depends on rapid and flexible response to new discoveries, inventing new ideas and theoretical tools supporting space science initiatives, converting hard-won data into scientific understanding, and developing promising technologies that are later incorporated into major missions. These activities are supported through a balanced portfolio of competed Research and Analysis (R&A), Probe, Discovery, Explorer, and sub-orbital programs, which collectively are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and manpower investments. Importantly, NASA, through its Education and Public Outreach programs and through the R&A program's support of student and postdoctoral researchers at America's universities, plays a critical role in educating the nation and training the next generation of explorers.

This roadmap describes a framework for exploration on the grandest scale. It lays out a scientific and technological agenda to discover the origin, evolution, structure and destiny of space and time, matter and energy, atoms and molecules, stars and galaxies, and ultimately life itself.

3. Implementation framework

Origin and Destiny of the Universe: Beyond Einstein

Our "common sense" about how things move works well on a human scale: a light beam travels a straight path; clocks tick at the same speed, whether in New York or London; an inch is an inch. But experiments have shown that our "common sense" fails spectacularly when we start to explore the extremes of Nature: the very small, the very fast and the very large — especially at the beginning and end of time, and the edges of space. Light bends, time slows, distances alter. Theories describing this non-intuitive natural world have been remarkably successful.

- Quantum mechanics describes the very small. Its weird predictions govern the operation of microcomputers, lasers and nuclear reactors. We know therefore that our theories of quantum mechanics are very precisely "right" on the scales of atoms and their components.
- Special relativity, Einstein's first unification of space and time, describes the very fast. Its predictions (such as $E=mc^2$ and the slowing of time at high velocities) have been tested to fantastic precision in particle accelerators, where small things move close the speed of light.
- General relativity, Einstein's great theory unifying space, time and gravity, also describes the behavior of very large and massive things: stars, black holes and the universe as a whole. The giant scale on which it works means that we need to go to space to explore nature's most outlandish violations of common sense. This is NASA's domain.

Einstein's general theory of relativity reveals the familiar "force of gravity" as an illusion. Instead, it views the whole world differently: Space and time are curved by matter, and the curvature of space and time determines how matter moves. An ant, walking in a straight line on a flat floor, will not return to his starting place. But an ant walking in a straight line on the curved surface of an orange will end up going around in circles. In Einstein's view, the Space Shuttle and the astronauts in it, like the ant on the orange, all move in the straightest lines they can on a four-dimensional spacetime curved by the matter of the earth. Experiments show that Einstein's description works better than Newton's more common-sense "force of gravity" description: for example, Einstein's theory predicts that identical clocks at different heights above the earth run at different rates, because time itself is distorted. Although the effect once seemed exotic, nowadays our global positioning system (GPS) satellites, which are used in all forms of navigation, must correct for this effect or their position errors would increase at about 8 miles every day!

Most checks of Einstein's general theory of relativity have been done in the Solar System, where gravity is weak, the curvatures of spacetime are small and everything moves much more slowly than light. These experiments include laser ranging from Earth to the Apollo astronauts' reflectors on the moon, radio ranging to the Viking and Cassini spacecraft, and the precession of LAGEOS orbits and Gravity-Probe B's gyroscopes. These have all so far confirmed that Einstein's theory works as perfectly as they can measure.

But in environments far more extreme than our solar system, Einstein's theory departs even more from common sense: not only can matter curve spacetime, but curved spacetime can curve itself. This leads to two breathtaking predictions: 1) there should exist vibrations in space and time, called gravitational waves, and 2) dense concentrations of matter or curvature should close off curved knots in space and time called black holes. So far, we have only indirect evidence that these two astonishing predictions are true. NASA's Beyond Einstein missions will obtain direct evidence by exploring the most extreme places in the universe, in ways never before attempted. Their quest will also explore the origin and destiny of the universe itself.

The Sound of Spacetime: Gravitational Waves

Since ancient times, astronomers have used one form of energy to study the universe. Called simply "light," it includes X-rays and radio waves and all the colors of the rainbow in between which humans have always seen with their own eyes. Light is made of vibrating waves of electric and magnetic fields traveling through space and time. In Einstein's theory of gravity, vibrating waves of space and time, which also travel at light speed, can carry energy. In the same way that black holes are made just of space and time, gravitational waves are also "pure" space and time, but behaving in a way that has not yet been detected. The new technology of Beyond Einstein will open up to science a whole new sense of the cosmos; suddenly, after centuries of silence, science will no longer be deaf to the sounds of spacetime.

Of all the outflows of energy in the universe, the most powerful are carried not by light but by the gravitational waves emitted when two black holes orbit, collide, and merge into a single black hole. In the final minutes or hours before the merging of just a single pair of supermassive black holes, a million times more power is radiated in gravitational waves than all the light from all the stars in all the galaxies in the entire visible universe put together. It is possible that the universe contains more of this gravitational radiation than it does light.

In spite of carrying enormous amounts of energy, gravitational waves interact very weakly with matter and penetrate anything without losing strength. While this makes them powerful probes of extreme conditions, it also makes them hard to detect — so hard that they have not yet been directly detected. They interact so weakly with any measuring apparatus that only in the past few years has technology advanced to the point that we are confident we can build equipment to detect them.

Detecting gravitational waves will give Einstein's theory a workout it has never had before. Through gravitational wave detection we will listen to collisions and mergers between black holes, the most violent events in the universe. The sounds of the universe will tell us how well Einstein's ideas still work in these extreme conditions, and yield detailed maps of the structure of space and time around both old and newly merging black holes. They will also allow us to penetrate times and places impossible to see with light, such as the birth of our universe, perhaps revealing startlingly violent events, such as the formation of our three-dimensional space from an original space with more dimensions.

Gravitational waves produce tiny jiggles in the distance between masses that are floating freely in space, isolated from all forces other than gravity. The distances between the masses can be monitored using laser interferometry. An early generation of such detectors has now been deployed on the ground—the NSF-funded Laser Interferometer Gravity-wave Observatory (LIGO) in the United States, and similar systems worldwide. It is hoped that these systems will make the first detection of gravitational waves from some sources of high-frequency waves. Beyond Einstein's LISA will operate in a broad band at much lower frequency. It will detect entirely different sources in great numbers and with exquisite precision.

The most powerful gravitational waves come from quickly changing systems with very strong gravity, so LISA's strongest signals will probably come from black holes spiraling into other supermassive black holes. In addition to detecting sources like these, which cannot be detected in any other way, LISA will break new ground in yet another way. By detecting for the first time gravitational waves from sources (such as orbiting pairs of white dwarf stars) that can be studied by optical telescopes, LISA will introduce gravitational waves as an entirely new way to study a wide range of astronomical objects.

The vision mission Big Bang Observer will study with unprecedented sensitivity the spectrum of gravitational waves at frequencies of 0.03Hz to 10Hz, in between those studied by LISA (0.0001 Hz to 0.03 Hz) and those studied by LIGO (30Hz-1000Hz), and extend the reach of gravitational wave astronomy towards its ultimate limit: detecting the quantum noise from the inflationary universe. In doing so it will enable detection of a vast range of astronomical sources.

Beyond Einstein: Exploring the largest and smallest scales

Two roadmap objectives explore relativity to the very largest scales and the very smallest scales possible: the size of the universe today, and the scale of the tiny point from which the Big Bang began.

The evolution of the universe predicted by the equations of the general theory of relativity has been spectacularly confirmed by measurements of the cosmic radiation background, the abundances of light elements, and the growth of structure in our universe. But theoretical inconsistencies, and disagreements with observation, arise if we try to use standard relativity to extrapolate back earlier in time `to the beginning', or to the physics of the emptiest space today. Physicists suspect that the general theory of relativity is not a reliable guide to exploration of space and time at these extremes. *To understand where we came from, or where we are going, we may need a theory beyond Einstein's.*

To fix the problem of cosmic expansion on the largest scales seems to require re-introducing to relativity something similar to Einstein's cosmological constant, a new form of `dark energy' permeating so-called empty space. Because measurements of the effect of dark energy on the universe are so difficult and fraught with possible systematic errors, it will be important to make several independent measurements of it. For example, LISA will use self-calibrating sources of gravitational waves to measure the universe, Constellation-X will use clusters of galaxies and growing structures to measure it, and the Dark Energy Probe may use supernovae or the deflections of light by growing structures as the measuring rods.

A theory describing something that is at once both very small and very massive — like the universe at the beginning of the Big Bang — has to include quantum mechanics and general relativity in one package. Many ideas of string theory and inflation models have been proposed, but only real data can tell us how nature actually works. Gravitational waves are the only signals that can escape the dense early universe to inform us directly about conditions at the earliest times.

Objective 1: Find out what powered the Big Bang.

Since ancient times, humans have sought to explain how the universe began. While a true scientific determination of our origins once seemed impossible, astounding recent discoveries have already started to a lead us to deep and mathematically rigorous understanding. Even more remarkable, we are not at a dead end; we know what measurements are needed to make further progress, and how to make them with the tools of space science.

In 1929 the great American astronomer Edwin Hubble made the surprising discovery that our universe is expanding. This discovery, and other abundant and compelling evidence, tied with Einstein's theory of space and time, now shows that our universe began in an unimaginably hot and dense condition and has been expanding and cooling ever since. This framework is known as the Big Bang theory. But what powered the Big Bang in the first place?

We are lucky to have an intact fossil of the beginning we can study directly: a faint glow of light left over from the Big Bang, which carries with it detailed evidence we can use to unravel the mysteries of our origins. This relic light from the earliest moments of the Big Bang, called the cosmic microwave background (CMB), has been traveling freely through space for over 13 billion years. Observations of the CMB reveal slight variations in the brightness of the otherwise remarkably smooth relic heat. These tiny deviations are thought to be direct imprints in the fabric of spacetime, dating to the moment of its creation.

They also mark congregations of matter and energy that have now grown into galaxies, stars, planets and life. Tracing the evolution of those small deviations into galaxies, stars and the complex living universe of today – driven first by the gravity of cosmic "dark matter", and later by the gas that eventually became stars, planets and life – is an exciting frontier of exploration addressed in the Pathways to Life Program.

We already have a definite model of how the Big Bang began. Many key facts can be explained if the universe started with a new form of energy whose gravity is repulsive. This "inflaton" field caused the infant universe to expand at a fantastic rate, made space large and nearly uniform, and gave the impetus to the expansion still seen among the galaxies. The inflaton energy then converted into the light energy, dark matter and atoms of the hot Big Bang that we see. This theory is called "inflation" because it describes a sudden dramatic growth of the infant universe.

The energy driving inflation had tiny imperfections due to the fact that all energy is quantized. As a result, during the dramatic cosmic inflation some parts of the universe got slightly bigger and faster than others. The effect of a single quantum fluctuation was inflated to an enormous size along with the universe itself. Sky maps of the CMB, such as from NASA's Cosmic Background Explorer (COBE) and WMAP missions, show a pattern of fluctuations very much like that predicted by inflation. They show the detailed ringing effect of primordial fluctuations resulting from the interaction of light and matter in the early universe – a "cosmic ultrasound" that images the infant universe. In much the same way that seismology on the Earth or the Sun reveals details of hidden composition and structure of those bodies, the primordial sound waves in light and matter visible on the sky reveal details of the composition of the universe as a whole, including the invisible dark matter.

As described below, cosmic evolution is studied in other very different ways, such as with supernova measurements of the cosmic expansion history, and three-dimensional maps of the galaxy distribution showing large scale structure of the cosmic web. One of the great scientific accomplishments of our time is that these experiments now all agree, with considerable precision, on a set of basic parameters describing the behavior of the universe on large scales: how old it is, how fast it is expanding, its composition (the amount of atoms and stars, dark matter and dark energy it contains), how close it is to being geometrically flat, and what kind of perturbations inflation left behind. This scientific accomplishment – the establishment of a precise ``concordance model'' of the universe – was recognized in 2003 by Science Magazine as the "Breakthrough of the Year," chosen over all fields of scientific study (as the discovery of the acceleration of the cosmic expansion was in 1998). The complete data set from WMAP, and the even more detailed maps to be made by the Planck Surveyor mission, will make our universe as a whole one of the most precisely measured of all physical systems.

While the Big Bang framework is well established, we are far from certain that the inflationary scenario is correct, or how it connects with new physics unifying gravity and quantum mechanics. Even if inflation is generally the right story, the details of the plot, and even the main characters, remain a mystery. We need new data to determine whether the early universe underwent a period of rapid inflation, and if so, to determine the mechanism responsible for driving it. Real data will teach us both about how the universe began, and about the new physics we need to understand it: the behavior and parameters governing new inflaton energy fields, and their relationship with the fundamental characteristics of space and time at the deepest level. That data will come from the Inflation Probe.

We already know a way to uncover these secrets. Calculations predict that in addition to tiny inflaton fluctuations already detected, inflation also generates gravitational waves. Since they originate as ``gravitons'' or quanta of spacetime itself, these waves deeply probe the new physics controlling the quantum beginnings of space and time. For this reason, detecting the signature of primordial gravitational radiation is one of the main strategic goals of Beyond Einstein. Primordial gravitons do not affect the formation of galaxies, but they do leave a subtle, distinctive pattern in the polarization of the light of the CMB that might be measured.

One candidate concept for an "Inflation Probe" is an ultrasensitive sky-mapping mission designed to discover this subtle pattern. The existence, strength, and details of the pattern will tell us whether inflation powered the Big Bang, and how it worked. It should tell us, for example, how fast the universe was expanding during inflation, and other details of the fields that controlled inflation. The data from WMAP is providing information about the levels and sources of contamination signals. Data from Planck, and from balloon polarization experiments, will help to refine these estimates. Thus, the tools are in hand to assess the feasibility and guide the design of an Einstein Inflation probe that uses the polarization of the microwave background to constrain the nature of inflation

While Inflation Probe may detect gravitational waves from inflation via their imprint on the CMB sky, LISA and the Big Bang Observer can directly detect many different kinds of cosmic backgrounds. Since gravitational waves are produced from motions of all kinds of mass and energy, and penetrate everything with almost no absorption, these experiments are a uniquely powerful exploration tool: they hear everything that has happened in the observable universe since inflation.

For example, it is possible that the early universe, after inflation but still in the first microsecond, has periods of roiling turbulence and chaos on small scales, perhaps associated with the formation of baryons during a phase transition, or with collapse of extra dimensions of space. These events generate high-frequency gravitational waves that would not affect the CMB (they are many orders of magnitude smaller wavelength), but may be strong enough to be detected by LISA in the millihertz band. If so, LISA will open a new window into a new episode of previously unknowable cosmic history.

Of course, such events, or other activity much later, may also create so much spacetime noise that it overwhelms fainter signals. Data from LISA, and its ground-based counterparts such as LIGO extending to higher frequencies, will directly measure the gravitational wave activity of the universe. This will help us evaluate the feasibility of the Big Bang Observer and guide its design. If the universe has been relatively quiet over much of its history at the relevant frequencies, its irreducible quanta of space-time – of the same kind as measured by Inflation Probe but at later stages of inflation – may be measured directly some day by the Big Bang Observer. Gravitational waves would then trace the origin of spacetime over eighteen orders of magnitude in length, spanning scales extending from the size of the observable universe right down to the size of our solar system.

It could be that the universe at all epochs is quiet enough to allow Big Bang Observer to make direct measurements of signals from as close to the beginning of time that we can ever, in principle, observe. This program carries human exploration to the most extreme science frontier that humans can currently imagine: a frontier that only NASA can explore.

Expected Achievements for Objective 1: Find out what powered the Big Bang.

In the 2005-2015 timeframe:

Assess astrophysical CMB foregrounds. The analysis of the complete WMAP dataset provides an understanding of astrophysical "foregrounds" sufficient to assess the feasibility of an Einstein Inflation probe that uses the polarization of the microwave background to constrain the nature of inflation. Results from the Planck Surveyor mission will add to that understanding with higher frequency studies.

Tighten constraints on inflationary models. Both WMAP and Planck Surveyor provide detailed images of fluctuations from inflation, revealing some details of the basic inflationary process.

In the 2015-2025 timeframe:

Detect gravitational waves. LISA reaches unprecedented levels of sensitivity for direct detection of gravitational waves. It may detect gravitational radiation generated around the first picosecond, when strong cosmic phase transitions are believed to have generated a slight excess of matter over antimatter in the Universe. (Later, all the antimatter disappeared after annihilating with matter, leaving behind this slight excess of matter, of which we and all the stars and galaxies are made.)

Observe the signature of gravitational waves from inflation. Informed by the WMAP polarization studies, the Inflation Probe finds correlations that indicate a unique signature of gravitational waves (tensor modes) from inflation. This data reveals details of which specific process powered the big bang.

In the 2025 and beyond timeframe:

Directly detect gravitational waves from inflation. The Big Bang Observer (BBO), building on LISA technologies, detects signals from all important sources of gravitational waves since the Big Bang, and directly detects gravitational waves from quantum effects during inflation. This data tests inflationary predictions at frequencies spanning 18 orders of magnitude and gives the first detailed spectral test of unified quantum gravity/string theory: BBO hears directly the beginning of time.

Objective 2: Observe how black holes manipulate space, time and matter.

Einstein's theory tells us that a black hole is made of pure gravitational energy. It tells us that a black hole should contain no actual surviving matter of the kind we are familiar with; anything whatsoever that falls into a black hole is quickly converted to pure gravity. The black hole should quickly radiate away as gravitational waves any bumps or mountains on its surface, leaving it smooth and simple, described only by a mass and a spin. Though we infer that the universe contains many black holes, we have yet to see one in detail. Einstein's general theory of relativity provides a mathematical picture of what one should be like: At a black hole's heart is a singularity, where space and time are infinitely curved and energy is infinitely concentrated. Surrounding the singularity is a region from which nothing can escape. The edge of this region is called the event horizon. There, time is so warped that it seems, from outside, to have stopped. How could we find out if such objects really exist, and if they do, behave in this weird way?

We could shake the black holes, and listen to the gravitational waves that Einstein's theory predicts should radiate away all the perturbations to the black hole. Fortunately we do not have to send astronauts to do the shaking: the giant black holes at the centers of galaxies are predicted to capture large numbers of stars and stellar mass black holes, and smaller numbers of their own relatives. As these orbit the giant black holes, they shake them and perturb their spacetime. LISA will observe the patterns of the resulting gravitational waves, and compare the wave patterns to those predicted, thus measuring precisely the properties of black hole and spacetime around it.

A second way to study black holes is to map the motions of clocks orbiting and falling into black holes. Again, nature provides a way to do this. We can observe the radiation from atoms of gas that falls into black holes. The frequency of the light they emit is like the ticks of a clock. Changes in that frequency are caused by the motion of the gas—the familiar "Doppler effect" change in tone you hear as an ambulance races past—and by the gravitational redshift due to spacetime curvature. Because the matter near the black hole is so hot, the atoms emit mainly X-rays. Constellation-X will measure the changes in brightness and frequency of these atoms as they orbit the black hole. Watching the spectra of these flows can reveal many details of how accretion of matter occurs, and the spacetime environment in which it orbits. If the things we call black holes are not actually the black holes of relativity, we may be so mystified by the results of LISA and Constellation-X that orbits and spectra alone may not be enough to understand them. In other cases the motions observed by Constellation-X may be so complicated (due to shock waves, ejected jets, instabilities) that more information is needed. The vision mission Black Hole Imager will address these problems by directly imaging the moving matter and its inward radial motion right down to the edge of the event horizon.

In addition to understanding the fundamental nature of black holes, and whether they exist as described by Einstein's theory, we would like to understand how they are made, how numerous they are, where they are located, how they grow, what properties they have, and how the matter and radiation they eject affect their host galaxies and their surrounding environment.

Black holes grow in two ways. One way black holes grow is by merging with each other. As two black holes approach each other, the two spacetime vortices spiral together faster and closer until they form just one rapidly spinning and pulsating hole, in the process broadcasting much of their mass into distant space as gravitational radiation. These events — the most powerful transformations of energy allowed by the laws of physics — can only be studied by their gravitational radiation, requiring the revolutionary capability of LISA.

The other way black holes grow is by swallowing gas. Matter falls into black holes in many ways. Whole stars can fall in, ripping apart as they approach. Streams of infalling gas can form bright hot torrents or delicate cool rivulets; sometimes, hot matter is splashed back out into space, or spewed at almost the speed of light in jets powered by the black hole's spin and magnetism. X-rays, such as those studied by Constellation-X, generally provide the best way to measure the motions of gas near black holes. Sometimes there is so much obscuring matter that even X-rays cannot get out, which is why the Black Hole Finder Probe observes in the more penetrating gamma-ray band.

The Beyond Einstein program will systematically explore this spectacular interplay of matter and gravity. The Black Hole Finder Probe will survey the universe seeking radiation from matter falling into black holes and mapping their locations; Constellation-X will study the spectrum of light coming from atoms as they fall in, collecting clues to the structure of spacetime in the neighborhood of the horizon; and in the distant future, the Black Hole Imager will create moving images of the swirling matter right down to the edge of the event horizon. The many forms of energy ejection from these events can even affect the evolution of a whole galaxy, including the formation of stars, planets, and life; these effects will be explored by GLAST, Constellation-X, and the Pathways to Life Observatories.

Expected Achievements for Objective 2: Observe how black holes manipulate space, time and matter.

In the 2005-2015 timeframe:

Observe the acceleration processes of relativistic jets emerging from black holes.
Many black holes accreting matter spew some of it out in vast jets moving at relativistic speed. These affect the environment and the properties of the host galaxies, but we do not know how the jets are formed, nor even what they are made of. GLAST will measure the radiation from regions near the black hole where these jets are formed and accelerated.

Observe the merging and growth of the first black holes to form in the universe.
The cosmological models that best describe current data predict that the first stars and black holes formed at a redshift of about 20, when the universe was about 100 million years old. The farthest we can now see black holes is to a redshift of about 6, when the universe was about 600 million years old, and by then they have already grown to enormous size. JWST will see the first black holes growing by swallowing gas in the intervening period. LISA will be lunched in this time frame; it will detect mergers between these first black holes at redshifts of 6-30 as their host galaxies coalesce into larger galaxies, and measure the properties of the black holes.

In the 2015-2025 timeframe:

Determine if the dense objects at the centers of galaxies, which we call "black holes," are truly the black holes predicted by Einstein's general relativity. LISA will measure the gravitational waves from stars and black holes shaking the spacetimes of the "black holes" they orbit. These waves encode a complete description of the spacetime and horizon properties. Comparing these properties measured by LISA with those predicted by Einstein's theory of relativity will tell us if these objects are the "black holes" of relativity.

Determine the precise masses and spins of a large sample of nearby galactic black holes. If the "black holes" at the centers of galaxies are the black holes of Einstein's general theory of relativity, all the properties measured by LISA for a given black hole will be determined by just two numbers: its mass and spin. LISA should measure these for about 100 supermassive black holes at redshifts greater than 0.2, using the gravitational waves from stars and stellar-mass black holes orbiting them.

Determine the spin and mass of black holes over a range of redshifts to constrain how black holes evolve. If the motions of the atoms observed by Constellation-X can be well modeled, we can infer from them the masses and spins of the black holes themselves, and do so for black holes in a wide variety of environments and redshift.

Measure the motions of matter orbiting close to black hole event horizons. Constellation-X will measure, through time-resolved spectroscopy, the speeds and changing brightness of iron and other atoms spiraling into black holes in galactic nuclei, from which we can infer how fast the black holes are growing, how they are ejecting matter and radiation, and perhaps also the mass and spins of the black holes themselves.

Determine how black holes grow by accretion in the local universe. There is evidence that a large fraction of the growth of black holes occurs while they are hidden behind dense clouds of gas and dust, and behind the glare of vast numbers of young stars. The Black Hole Finder probe will reveal these currently hidden black holes, and quantify their importance.

In the 2025 and beyond timeframe:

Directly image matter falling into a black hole. The Black Hole Imager will have the resolution to actually make a picture of the matter falling into the black holes identified by Constellation-X and the Black Hole Finder Probe. It will show us exactly where it is and what it is doing, and how fast it is moving at each point. This will enable us to investigate the nature of the black holes, the mechanisms of energy release in accretion disks, and the formation of jets.

Determine the cosmic history of formation of stellar-mass black holes. The Big Bang Observer will observe the mergers of tens to hundreds of thousands of intermediate mass (100-10,000 times the mass of the sun) and stellar-mass black holes (1-100 times the mass of the sun), and neutron stars, from redshifts of 0 to 5 and beyond.

Objective 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

Deep as Einstein's general theory of relativity may be, it remains silent on a profound question: Is empty space really empty? Inflation models predict that it was not so in the past, and suggest that it may not be so today either. Einstein introduced a "cosmological constant" into his equations, to represent the possibility that even empty space has energy and couples to gravity. The unknown magnitude of the cosmological constant is set by parts of physics beyond Einstein's understanding – and, at present, our own. The recent discovery that the expansion of the universe appears to be accelerating suggests the presence of something dubbed "dark energy" that drives space apart. It seems likely that we have measured the value of a cosmological constant, or something like it.

The presence of dark energy is already widely accepted because it explains many observations. The first indication that the rate of expansion of the universe is increasing was revealed by observations of Type Ia supernovae and was confirmed in detail by WMAP. Supporting evidence for the increasing rate of expansion also comes from studies of global geometry, structure formation, cosmic age, galaxy clustering, and X-ray emitting galaxy clusters. All these observations leave little doubt that in some sense Einstein's "cosmological constant" is a reality: the energy of the universe is dominated by "empty" space whose gravitational effect is to pull the universe apart.

Given the crude state of our preliminary data on dark energy, a wealth of potential theories have been suggested which have very different implications for physics and for the future of the universe. Further more accurate measurements are essential for distinguishing this plethora of possibilities. Anything new we learn about dark energy would be an unexpected discovery. A simplistic unification of quantum mechanics and gravity predicts an amount of dark energy larger than that observed by a factor of 10^{120}. Some modern scenarios predict that the amount of dark energy decreases with time, instead of staying constant as in Einstein's conception. For these reasons dark energy is among the most exciting new developments in fundamental physics. *Because dark energy seems to control the expansion of the universe, we cannot predict the fate of the* *universe without understanding the physical nature of dark energy*. As we develop this understanding, we will be poised to answer the profound question: will the universe last forever?

We estimate that our universe today consists of about four percent ordinary matter, made of the familiar elements from the periodic table (in the form of stars, planets, gas, and dust); twenty-six percent "nonbaryonic dark matter", thought to be a new kind of particle left over from the early universe; and seventy percent dark energy (which can be considered to have mass, too, because energy $E = mc^2$). To learn how dark energy really works, we need to measure its properties in more detail. It is spread so thin that it can only be studied in the enormous volumes of deepest space, where its cumulative effects make its presence evident. The first step in the exploration of dark energy will be to measure its density and pressure and how they change with time.

Initial and on-going observations from ground-based observatories and from the Hubble Space Telescope (HST) point the way toward a dedicated, special-purpose instrument that could provide much more accurate constraints on the expansion history of the universe. Such measurements could determine whether the dark energy is really constant, as Einstein conjectured, or whether it evolves over cosmic time, as suggested by some more modern theories. Real data on that question would help us discover where dark energy comes from, and what the future of our universe will be.

The Dark Energy Probe, which will be executed jointly with the Department of Energy as the Joint Dark Energy Mission (JDEM), will deploy the best available technology to study this effect. But other constraints will come from Constellation-X, LISA, Planck and the Inflation Probe. Constellation-X will make precision measurements of the matter and dark matter content of clusters of galaxies and constrain their abundance with cosmic time. These data can be used to determine distance/redshift relations and to chart the growth of structure in the universe, which depends on its expansion history. LISA, and later the Big Bang Observer with a much larger sample, will measure the rates at which binary black holes spiral together, because they lose energy to gravitational waves (i.e. it measures directly the wattage of the `wavebulb'). It also measures the amplitudes of those same gravitational waves. The ratio directly gives precise distances to the inspiralling binaries, from which one can measure the effect of dark energy on the expansion history of the universe. Planck and the Inflation Probe will refine our measurements of fluctuations in the CMB and the precision determination of the cosmological parameters.

Given the importance of this problem, it is essential that we invoke this wide variety of techniques to ensure that our inferences about the properties of dark energy are free from systematic uncertainties associated with specific measurements. On a longer timescale, the nature of future missions studying dark energy will depend on what we learn from these earlier experiments.

Expected Achievements for Objective 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

In the 2005-2015 timeframe:

Measure cosmological parameters. The continued analysis of the WMAP dataset and the first analyses of the datasets acquired by Planck will yield improvements in the precision determinations of the global cosmological parameters like the global curvature, the Hubble constant, and the fractions of the energy density due to baryons, dark matter, and dark energy. Measurements of dark energy require knowing these parameters.

Constrain the nature of dark energy. Measurements with Chandra and XMM-Newton will benchmark the use of massive clusters of galaxies for cosmology. HST and ground-based observatories will increase our sampling of Type 1a supernovae, further refining our measurements of the acceleration of the cosmic expansion.

In the 2015-2025 timeframe:

Determine the cosmic evolution of dark energy. The launches of Con-X, LISA, and JDEM will allow a large number of complementary measurements of the dark energy equation of state. These will be cross-compared to improve precision and to search for possible systematic effects that could bias the results. Con-X will enable a large sample of massive clusters to be analyzed in detail, yielding accurate measurements of their number density as a function of redshift as well as the apparent variation of their baryon to dark matter content as a function of redshift. LISA will enable precision absolute luminosity-distance measurements to cosmologically distant black holes. Although the design of the JDEM mission has not been finalized, one possibility is that it involves a capability to acquire a large sample of well-calibrated Type 1a supernovae out to redshifts of about 1.5. Such a large data sample will test the use of these sources as calibratable standard candles and enable a precision measurement of the cosmic expansion. All dark energy measurement techniques (including supernovae, baryon acoustic oscillations, cluster counting, weak lensing, and galaxy correlations) will be extensively pursued by ground-based measurements as well.

In the 2025 and beyond timeframe:

Constrain the geometry and kinematics of the universe. The Big Bang Observer will measure precise absolute distances to over one million cosmological binaries containing neutron stars and black holes, simultaneously constraining both the geometry and kinematics of the universe.

Structure and Evolution of the Universe: Pathways to Life

The "Beyond Einstein" missions are designed to determine the initial conditions for the large-scale structure of the universe. They will also test the fundamental physics of Einstein's theories of gravity, and the exotic new ideas of cosmic inflation. From these fundamental starting points, astronomers can progress to a deeper understanding of how the modern universe develops the complex and rich structures we see today — clusters, galaxies, stars, and planets, at least one of which has produced life.

The early universe began as a nearly perfectly smooth ocean of matter and radiation, and has since developed into our complex modern universe, with clusters, galaxies, stars, and planets. Somehow the tiny primordial wrinkles grew into the structures and roiling activity that we observe today: a "cosmic web" of dark and ordinary matter, punctuated by galaxies and clusters, energized by successive generations of stars, supernovae, black holes, and quasars, and enriched by heavy chemical elements necessary for the formation of planets and life. How did the simple Big Bang develop such a rich structure?

The first stages of the structure formation in the cosmos were dominated by just one force, gravity. The gravitational pull of invisible cold dark matter (CDM) collected matter and atoms together, reversing the expansion in places and creating a cosmic web of clustered matter, distributed in knots connected by filamentary clouds. Atoms falling into the knots of this web produced the first stars and galaxies. The accompanying formation of stars and black holes transformed matter and released energy in many forms, creating a complex system structured by many interrelated components spanning a great range of scales. One byproduct of special importance to us was the synthesis inside stars of many elements of the periodic table not present in the simple Big Bang; those heavy atoms coalesced into earthlike planets, and were able to chemically combine in reactions that eventually gave rise to life. These processes have taken billions of years, much of it observable in the last 11-12 billion years. This critical epoch in the history of the modern universe is observable through optical, ultraviolet, and X-ray telescopes.

Objective 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

The Pathways to Life program explores the interconnected evolution of systems on many scales: gas and galaxies (and their nuclei), stars and planets, atoms and molecules, from the pregalactic era to the present time. By looking deep into space, we can see back in time and study this cosmic evolution directly; we can also study modern fossils of past events. Because these systems cover a large dynamic range in many physical parameters, a comprehensive view of the transformation and flows of matter and energy demands high-resolution imagers and spectrometers on large telescopes extending from submillimeter to ultraviolet, X-ray and gamma-ray bands. For example, NASA is now building the James Webb Space Telescope (JWST), focusing on early stars in the first galaxies. The ultraviolet and optical radiation from these early stars is redshifted to near-infrared JWST wavelengths. However, comprehensive studies of stars extending from high redshift to the present will require access to large-aperture telescopes in the optical and ultraviolet; penetrating into their obscured star/planet formation regions requires far-infrared and sub-millimeter; and probing nuclear activity requires X and gamma rays. Access to the whole range of wavebands will bring detailed information about the entire cosmic ecosystem of matter, as it evolves from the relatively calm filaments of diffuse gas in the cosmic web and then cycles into galaxies, stars, planets, molecules and life. These deep, multi-band observations can only be carried out from space.

There are many unanswered questions about the complex pathways from the early universe to the present-day stars, planets, and life. For example, how did successive generations of stars and black holes form and coevolve with galaxies? What determines the mass distributions of stars and galaxies, how are they assembled, and how did they evolve with time? Why is cosmic star formation inherently episodic? What role is played by the vast reservoirs of matter in intergalactic space, and how is its distribution affected by the first stars, quasars, and chemical elements? In the local universe and within our own Milky Way galaxy, how does chemical enrichment affect the development of stars and planets? How do the radiation and magnetic activity of young stars impact the environment of newly forming stars, planets, and life?

Because of the great reach in scales and diversity of phenomena, it is natural to break down objective 4 into three key components, described in the following sections. Carrying out these investigations requires an implementation approach that is equally broad, involving competed probes and strategic missions called **Pathways to Life Observatories.** They will explore the history of star formation, both the visible stars at redshifts greater than 3 and those obscured by dust. They will chart the assembly and growth of galaxies and large black holes and gauge the impact these objects have on their host galaxies and surrounding gas. The Pathways to Life Observatories will allow astronomers to connect the observations of the early universe and first objects down to the present — a roadmap that leads from the Big Bang to the "Emergence of the Modern Universe".

The Pathways to Life Observatories encompass several possible approaches:

- A Far Infrared/ Submillimeter Interferometer (FIRSI), of which SPECS is an example
- A Large UV/Optical Telescope (LUVO)
- A UV/Optical Interferometer (UVOI), of which Stellar Imager is an example
- A large area, high spatial resolution X-Ray Observatory generically titled “Early Universe X-ray Observer” (EUXO), of which Gen-X is an example
- An advanced Compton gamma-ray telescope generically titled “Nuclear Astrophysics Compton Telescope” (NACT), of which ACT is an example
- The Single Aperture Far-Infrared Telescope (SAFIR)

Key Components of Objective 4:

4A. Map directly the structure and evolution of the Cosmic Web.

The CDM model, which succeeds very well in connecting inflationary cosmology with the modern distribution of galaxies, also makes predictions for the distribution of dark matter and atoms, or baryons, in the evolving universe as a function of time. Some baryons eventually form stars and other compact objects, but most of them are distributed on the largest scales in a cosmic web of diffuse filamentary clouds that grows steadily hotter and larger with time. The formation of the cosmic baryon web is the first step in the conversion from simple expanding behavior to rich and intricate complexity. Theorists have guessed at its structure, but only parts of it have as yet been detected directly.

Computer simulations predict that intergalactic matter is distributed over a range of different temperatures: warm photoionized gas (10^4 K), warm/hot shocked gas (10^5 - 10^7K), and much hotter gas ($T > 10^7$ K), the latter mostly associated with clusters of galaxies at the knots of the cosmic web. The warm and hot gas has stripped its atoms of most electrons, so those that remain bound have transitions visible only at high energies. In dense places, the hot phase is sometimes visible in X-ray emission; its composition and other properties will be studied in great detail with Constellation-X. Until recently, the warm/hot phase, containing most of the atoms in the universe, has been practically invisible, but is now starting to be observed through absorption lines in far ultraviolet and soft X-rays. The UV absorption lines are much more sensitive than their X-ray counterparts; however, only the X-ray features can probe the hottest gas at temperatures over a million degrees.

Theory tells us that the warm/hot medium is produced by shocks as gas falls into dark matter filaments. The medium is also affected by outflows: heavy elements are expelled from galaxies by winds and jets, whose shocks also contribute to the heating. To study this gas and the rich details of its behavior and composition, and its relationship to the surrounding environment of galaxies, we need large-aperture telescopes to deliver spectra of background quasars. These studies will determine the physical conditions and evolution of the intergalactic absorbers, and dissect galactic halos and outflows from galaxies. Both LUVO and EUXO will be needed to observe the faint quasars behind these structures.

4B. Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars to planets.

Once stars form, energy feedback connects small systems with the larger ones they inhabit: galaxies and quasars energize the intergalactic gas, and stars energize the gaseous environment within galaxies. Outflows of radiation and matter from stars and black holes have powerful influences on subsequent generations of stars, and outflows from galaxies shape larger-scale structures. Energy flows, mediated by gas motions, magnetic fields, cosmic rays, and light, add to gravity to influence the formation of stars and galaxies and control the production of energy, radiation, and chemical elements. All of these processes create the cosmic weather systems that structure the living baryonic universe. Like weather on Earth, they display “butterfly effects”, where a tiny influence in one place can lead to huge effects, often millions of light years away. Since they directly connect phenomena spanning more than ten orders of magnitude in length, they can, like the atmosphere and oceans of our planet, only be understood by synthesizing results from a wide range of techniques. Studying the cosmic history of star formation and the role of feedback on the formation of stars and galaxies will require exquisite imagers at many wavebands (JWST, LUVO, SAFIR, EUXO), as well as powerful spectrographs (JWST, Con-X, LUVO, EUXO) to connect the transport of matter and energy with the larger-scale galactic and intergalactic environments.

Because stars are so important for cosmic transformations of matter and energy, a central strategy is to make observations of star formation everywhere: in nearby galaxies, over time in the past, and in diverse environments. This can be accomplished with high-resolution, sensitive imagers and spectrographs (JWST, LUVO, Con-X, SAFIR, FIRSI), from X-ray to far-infrared bands, that can probe dense and complicated star-forming regions containing both high-energy sources and cold molecular gas. Sensitive observations all the way to the sub-millimeter band will explore the substantial amount (perhaps half) of star formation that occurs in extremely dust-enshrouded environments. Even within our local neighborhood, normal galaxies reveal a bewildering variety of star formation and chemical enrichment histories. They can be addressed empirically by observations of a large sample of galactic populations in the full range of evolutionary states. To reconstruct the evolution of star formation, chemical abundances, and dynamics for a large sample of galaxies requires a large-aperture optical and ultraviolet telescope (LUVO).

Many stars are born in associations near massive stars, which rapidly erode the dusty molecular clouds that shroud the earliest phases of star birth. When shrouded, these regions are best penetrated by far infrared and sub-millimeter radiation. However, less than a million years after birth, the majority of young stars and their protoplanetary disks become accessible to high-resolution studies at optical wavelengths, allowing an investigation of early phases of planet formation, cluster evolution, and stellar youth. Infrared studies with JWST and SAFIR probe the earliest, dusty phases, while optical/UV observations with LUVO provide the combination of sensitivity and high spectral resolution necessary to deconstruct these objects. Through high-precision radial velocity studies of the fainter stars, astronomers will soon discover a vastly increased population of extrasolar planets. This population will improve statistical analysis of planetary and host-star characteristics, in the context of the many environments within the Galaxy, as well as their chemical history. This will give us much better idea of the possibilities for life in the universe as a whole.

Cosmic influences from outside the solar system extend right down to life on Earth. Galactic tides trigger comet storms that may cause extinction events; massive black holes can create hostile, sterilizing radiation reaching across an entire galaxy. Planetary atmospheres, including Earth's, are profoundly influenced by effects of high-energy radiation (UV, X-ray and paarticles) upon atmospheric photochemistry and photoionization. With the advent of space observatories, it has become clear that the ionizing radiation output of even normal, solar-like stars decreases by orders of magnitude over their lifetimes. As a result, the effects of stellar variations on climate are of great significance to the emergence and evolution of life forms on Earth-like planets. The details are still lacking, especially a comprehensive picture of magnetic evolution in stars. Observations of stellar magnetic activity with Con-X, LUVO, EUXO and UVOI will lead to an improved understanding of these phenomena and how they influence biological evolution in the nascent Earth and extrasolar planets.

4C. Trace the evolution of the nuclei, atoms, and molecules that become life.

In addition to energy flows, nuclear matter itself is transformed by stars into new elements, and then recycled into the interstellar and intergalactic gas. Galaxies and quasars in turn expel their interstellar gas, chemically enriching pristine intergalactic space with heavy nuclei. This enrichment with a variety of chemically active elements creates dust and molecules that strongly affect the cooling and collapse of gas into new stars, control the formation of planets, and ultimately form the basis of life.

The global natural history of nuclei will be traced on many levels. The production sites of heavy elements, hot young stars and supernovae, and their surrounding emission nebulae, as well as the acceleration sites of nuclei into cosmic rays, can be studied via X-rays and gamma rays (Con-X, GLAST, NACT, EUXO). Similar techniques can follow these chemical elements as they are transported into the interstellar medium and widely spread throughout our Galaxy and others. On the grandest stage of all, the flows of material from various types of galaxies out into the IGM and back into galaxies will be visible to a wide range of instruments, including UV and X-ray spectrographs (LUVO, Con-X, EUXO), probing interstellar and intergalactic gas via absorption of light from background sources. They will be diverse enough to capture a broad set of elements and ionization stages to provide nucleosynthetic signatures of the stellar sources, and sensitive enough to provide a densely sampled spatial and velocity map. Experiments will eventually comprehensively map chemical composition throughout galaxies, up into galactic halos, and out into the IGM. At the other extreme, as atoms combine with each other in cold and dense molecular phases, they become visible in the infrared to submillimeter bands, and start to reveal the development of the molecular complexity that presages true living molecules.

Expected Achievements for Objective 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

In the 2005-2015 timeframe:

Determine the early history of stars and their environment. HST, Chandra, Spitzer, SOFIA, and JWST will provide comprehensive infrared through X-ray imaging and spectroscopy of protostars and their disks. This will allow us to develop a cohesive picture of stellar birth and youth, thus setting the stage for planetary formation.

Characterize evolution of surface activity of solar-type stars. HST and Chandra high resolution spectroscopy in the UV and X-ray will provide a survey of the ionizing radiation output and variability of aging solar-type stars. This will lead to a much better understanding of how the time history of such radiation influences biological evolution on the Earth and extrasolar planets.

Detect the hot intergalactic medium. Chandra and HST will provide early detection of the hot phase of the intergalactic medium. This will improve current models that predict that intergalactic matter exists at a range of different temperatures, including temperatures > 10 million degrees.

In the 2015-2025 timeframe:

Observe the formation of the first generation of stars. JWST will provide infrared imaging and spectroscopy that will allow studies of the history of star formation at high redshift. This information, combined with current UV measurements of start formation rates will provide an improved understanding of the evolution of star formation.

Confirm dispersion of heavy elements in the IGM. Constellation-X will build on the early results from Chandra and HST to measure the properties and composition of the hot intergalactic matter, providing the extent of dispersion of heavy elements in the IGM.

In the 2025 and beyond timeframe:

Map the missing baryons in the IGM. Some of the concepts for the Pathways to Life Observatories will be able to study the composition of the IGM through high energy spectroscopy of the radiation from background quasars.

Study the cosmic transformation of matter and energy. Star formation is key to the distribution of matter and energy in the Universe. The Pathways to Life Observatories will provide observations from X-ray to submillimeter, allowing the study of star formation in dense regions containing both high energy sources and cold molecular gas.

Trace the evolution of the nuclei, atoms, and molecules that become life. The Pathways to Life Observatories will provide imaging and spectroscopy in the infrared and sub-millimeter part of the spectrum, allowing the study of those spectral features that indicate the molecular complexity associated with life.

Universe Exploration Targeted Research and Analysis Needs

Without Research and Analysis (R&A) programs there would be no space science missions. R&A programs support the ground-breaking technology developments needed to enhance our ability to observe the universe, leading to new mission concepts. R&A programs support the analysis of mission data from which all discoveries are made. R&A programs support theoretical work that both explains what we see and predicts what we have yet to see; theory establishes the framework within which we understand the phenomena that we observe. R&A programs also support additional research needed for the success of space missions, such as laboratory measurements of physical parameters that must be known for space experiments (an example being the detailed X-ray spectra of iron-group isotopes). R&A programs, although costing a small fraction of the funds going to space missions, are an essential component of this roadmap.

Theory

Theoretical studies — here taken to include conceptual and analytical theory, development of software technologies supporting data exploration, astrophysical simulations, and combinations of these — were recognized by the National Academy's AASC decadal report as a central component of modern mission technology development. That survey recommended that supporting theory be explicitly funded as part of each mission funding line, because detailed modeling connecting the elements of a mission to the system under investigation is critical to design and even to conceive successful and cost-effective missions. Rigorous modeling is an important factor in reducing mission risk and evaluating competing mission strategies, and simulations can vividly demonstrate mission goals.

Beyond Einstein Theory Needs

Beyond Einstein explores to the boundaries of foundational knowledge as well as the boundaries of spacetime, so detailed and quantitative theoretical studies are indispensable, starting with the earliest design phases. To this end the Beyond Einstein Foundation Science (BEFS) program has been created to provide ancillary theoretical (and experimental) support for NASA's Beyond Einstein missions. In accordance with the AASC decadal report, a significant fraction of Beyond Einstein line funds are used for the BEFS program. Examples of the theoretical studies required by Beyond Einstein missions that are now being supported include:

• *Constellation-X*. Models of relativistic hydrodynamic flows in accretion disks, including radiative transfer models, leading to simulated, time-dependent spectra.

• *LISA*. Studies and simulations of signal extraction in the presence of multiple, overlapping signals; numerical relativity, aimed at accurate calculation of predicted gravitational waveforms for the whole range of merging and orbiting systems;

astrophysical modeling and simulations to connect binary population predictions with other data sets.

• *Inflation Probe*. Theoretical studies of early universe cosmology, including tensor and scalar mode predictions and their connection with fundamental theory; simulations of polarization effects, including the contamination effects of astrophysical foregrounds and gravitational lensing; development of optimal statistical signal extraction techniques.

• *Dark Energy Probe*. Theoretical studies of Type Ia supernovae and other candidate systems for calibrating cosmic distances, including realistic simulations of competing techniques for constraining dark energy models, with a view toward the development of a better understanding of the principal sources of systematic error and contamination in each case. This work will benefit greatly from an expanded program of precursory ground-based observations.

• *Big Bang Observer*. Early universe cosmology and phenomenology of quantum gravity, string theory, and brane world models; models of coalescing white dwarf and neutron star binaries and populations in the 0.1 to 1 Hz range.

• *Black Hole Imager*. Comprehensive simulation of black hole environments, including electromagnetic field interactions with flows and the spacetime metric, and radiative transfer over many decades of dynamic range.

Pathways to Life Theory Needs

The Pathways to Life Observatories encompass several approaches, and the associated objective is both challenging and broad. The theory areas defined below represent a portion of the theory challenges for the Pathways to Life Program:

• *JWST*. Calculations of the formation of the first stars; multi-dimensional magneto/radiation/hydrodynamical simulation of the formation, evolution, and spectra of stars and protostellar disks; models of the magnetic interstellar medium and the origin of the initial mass function of stars; studies of reionization; simulations of galaxy formation, large-scale structure, and Lyman-alpha clouds; models of the chemical and “metallicity” evolution of the universe and the history of star formation; studies of the formation of planetary systems; models of the zodiacal dust around nearby stars; MHD simulations of bipolar outflows.

• *Spitzer*, *SOFIA*, *SAFIR*. Simulations of particle and gas disks around protostars; chemical models of molecular clouds and protostellar disks; detailed spectral, kinetic, evolutionary, and growth models of debris disks; models of chondrule and planetesimal growth; spectral models of protoplanetary disks and brown dwarfs; studies of what distinguishes a giant planet from a brown dwarf; models of ultra-luminous infrared galaxies; studies of the formation of the Kuiper belt and Oort cloud; studies of star formation at high redshifts; models of chemical enrichment at the earliest epochs; simulations of the assembly of rocky planets from debris disks; models of the spectra of high-z and dust-enshrouded galaxies; calculations of the fine structure lines of molecules in protostellar and protoplanetary nebulae; spectral models of the molecular tracers of the multi-dimensional collapse of molecular cloud cores to stars; simulations of bipolar outflows from protostars.

• *Large UV/Optical Mission, EUXO.* Models of the IGM on small scales; high-precision calculations of big-bang nucleosynthesis, in particluar the D/H ratio; detailed models of AGN and AGN disks; models of star formation at high redshift and in various galaxy types; models of the role of supernovae and winds in galaxy formation; simulations of absorption features through the early warm- and hot-ISM/IGM; studies of the early structures of the universe and galaxy-galaxy interactions; simulations of the possible roles of supermassive black holes in galaxy formation and evolution.

Supporting Ground-Based Research and Analysis

Universe Exploration missions also require specialized supporting ground-based programs. As in the case of theory, these studies should start early in the program since they will influence the optimization of the mission design parameters. In the case of the Einstein Probes, a broad effort is needed since even the mission concept will be competed. Here, again, the BEFS program supports a modest experimental effort.

The Inflation Probe, if it is based on microwave background anisotropy polarization, will require new generations of polarization-sensitive detectors, excellent control of systematic effects and a thorough understanding of astrophysical foregrounds. Ground-based Cosmic Microwave Background polarization experiments will be essential preparation for this candidate Inflation Probe, both for testing of new technology, investigation of observing strategies and systematics, and for providing data to test new analysis techniques. (These needs are laid out in detail in the soon-to-be-released Report of the Task Force for Cosmic Microwave Background Research, which will act as the CMB technology roadmap document for the foreseeable future.) Detector technology for COBE, MAP and Planck was a direct product of ground-based and sub-orbital programs. In the same way, a strong ground-based program is an essential precursor to the Inflation Probe.

Whatever technique is adopted, the Dark Energy Probe will require ground-based data of unusual uniformity, quality and completeness. If Type Ia supernovae are employed, space studies must be supported by detailed and precise ground-based spectra and photometry of a large, uniformly selected sample of relatively nearby supernovae. This is required both as a calibrating set for the high-redshift Hubble diagram, and as a statistical control sample to study the systematic correlations of supernova properties--- the generalization of the one-parameter fits to light curve shape currently being used. Similar foundational studies are needed for other candidate techniques for the Dark Energy Probe. Programs supporting ground-based studies of this type are already underway with funding from the National Science Foundation.

Mission Priorities

The highest priority missions are the Beyond Einstein Great Observatories LISA and Constellation-X. These were both highly ranked by the National Academy of Sciences Decadal Survey and their science has also been highly ranked in several other reports. The science questions these missions address will provide crucial information necessary to make key decisions by the middle of phase 2, in order to prioritize and begin the Visions Missions at the start of phase 3. The next priority is the competed line of Probes to address focused science questions, central to the Beyond Einstein program. These competed missions will begin with the Joint Dark Energy Mission, and then continue at 3 to 4 yr intervals with the Black Hole Finder Probe and the Inflation Probe (with the mission order determined by technology readiness).

Mission Summary for Universe Exploration

Strategic Observatories providing breakthrough capabilities

•GLAST (Phase 1): Jets from black holes and dark matter decay signatures

•Pathways to Life: JWST (Phase 1): First galaxies and stars

•Beyond Einstein: LISA (Phase 1): Gravitational waves from many sources, how space and time behave around black holes and constrain dark energy

•Beyond Einstein: Constellation-X (Phase 2): Observe matter falling into black holes & address the mysteries of dark matter and dark energy

Competed Missions that address focused science questions through scientist-led investigations with a range of sizes, up to a strict cost cap of $600M

•Explorers: Missions linked to Universe Exploration strategic goals (all phases)

•Einstein Probe: Joint Dark Energy Mission (JDEM) (first prioritized probe) (Phase 2)

•Einstein Probe: Black Hole Finder Probe (BHFP) (Phase 2)

•Einstein Probe: Inflation Probe (IP) (Phase 2)

•Pathways to Life (Probe): What is the nature of the Cosmic Web?

Vision Missions that result from long term objectives (late Phase 2, Phase 3)

•Beyond Einstein: Big Bang Observer (BBO)

•Beyond Einstein: Black Hole Imager (BHI)

•Pathways to Life Observatories

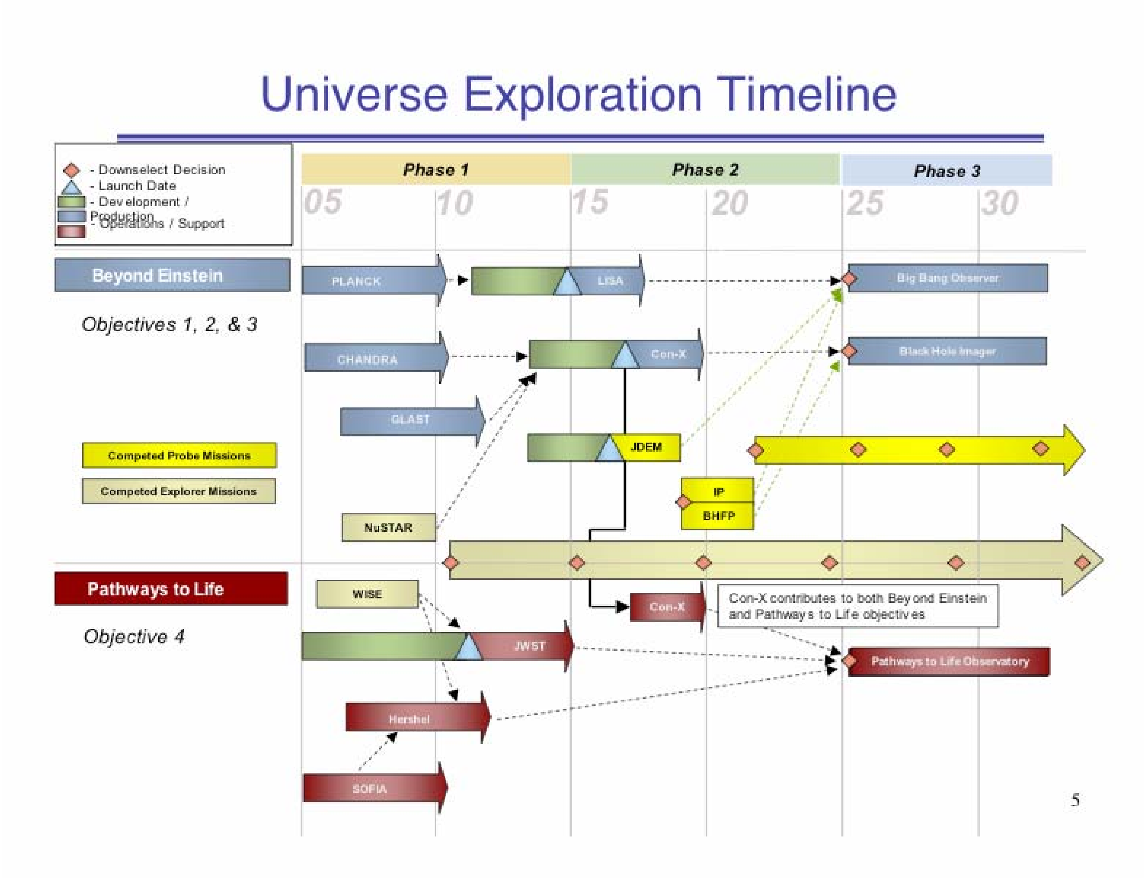

Figure 1 Roadmap timeline for Universe Exploration.

4. **Milestones and Options, with decision points and criteria**

OBJECTIVE 1: Find out what powered the Big Bang.

LISA, and its ground-based counterparts at higher frequencies such as LIGO, will for the first time measure directly the gravitational wave activity of the universe. We anticipate surprises. For example, LISA might unexpectedly detect a cosmic gravitational wave background originating from the early moments of the Big Bang. These first observations of the gravitational wave sky, combined with results from Planck and the Inflation Probe, will provide information on the priority of the Big Bang Observer and guide its final design.

OBJECTIVE 2: Observe how black holes manipulate space, time and matter.

If the things we call black holes are not actually the black holes of relativity, we may be so mystified by the results of LISA and Constellation-X that orbits and spectra alone may not be enough to understand them. In other cases the motions observed by Constellation-X may be so complicated (due to shock waves, ejected jets, instabilities) that more information is needed. These observations may point to fundamental flaws with General Relativity that change the priority of the next phase missions such that a direct image of a

Black Hole becomes the highest priority. The vision mission Black Hole Imager will address these problems by directly imaging the moving matter and its radial motion right down to the edge of the event horizon.

OBJECTIVE 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

The combination of Constellation-X, LISA and the Joint Dark Energy Mission (JDEM) provide independent measurements of the acceleration of the universe. The most exciting result would be if the different techniques disagree. This would point to a fundamental problem with our view of the universe and would require a major reassessment of the priorities for the missions that follow in phase 3.

OBJECTIVE 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

The creation of the conditions for life to emerge on the Earth is the result of a combination of events that start with the formation of the first elements, and ends with the emergence of the first life forms. The exact sequence of events and the ingredients necessary to produce a "Planet Earth" are not known. It may be that the correct sequence is highly improbable, a rare event; or it may be commonly found in our Galaxy. JWST, Constellation-X, and GLAST will investigate the various pathways that are necessary to set the scene for life. These missions might discover that the favorable conditions found in our own solar system are relatively rare, for example, that the relative inactivity of our Sun is rare and that this is essential for the emergence of life. Such a discovery will change the priority of the Pathways to Life Observatories so as to better define where to seek out habitable planets. The observations made by HST, Chandra, GLAST, JWST, Constellation-X, and LISA may find unusual objects. These may be new types of galaxies in the early universe, or massive nearby stars with unusual properties. These observations will determine the priority for the wavelength and capabilities of the first Pathway to Life Observatories, which currently encompass several possible approaches.

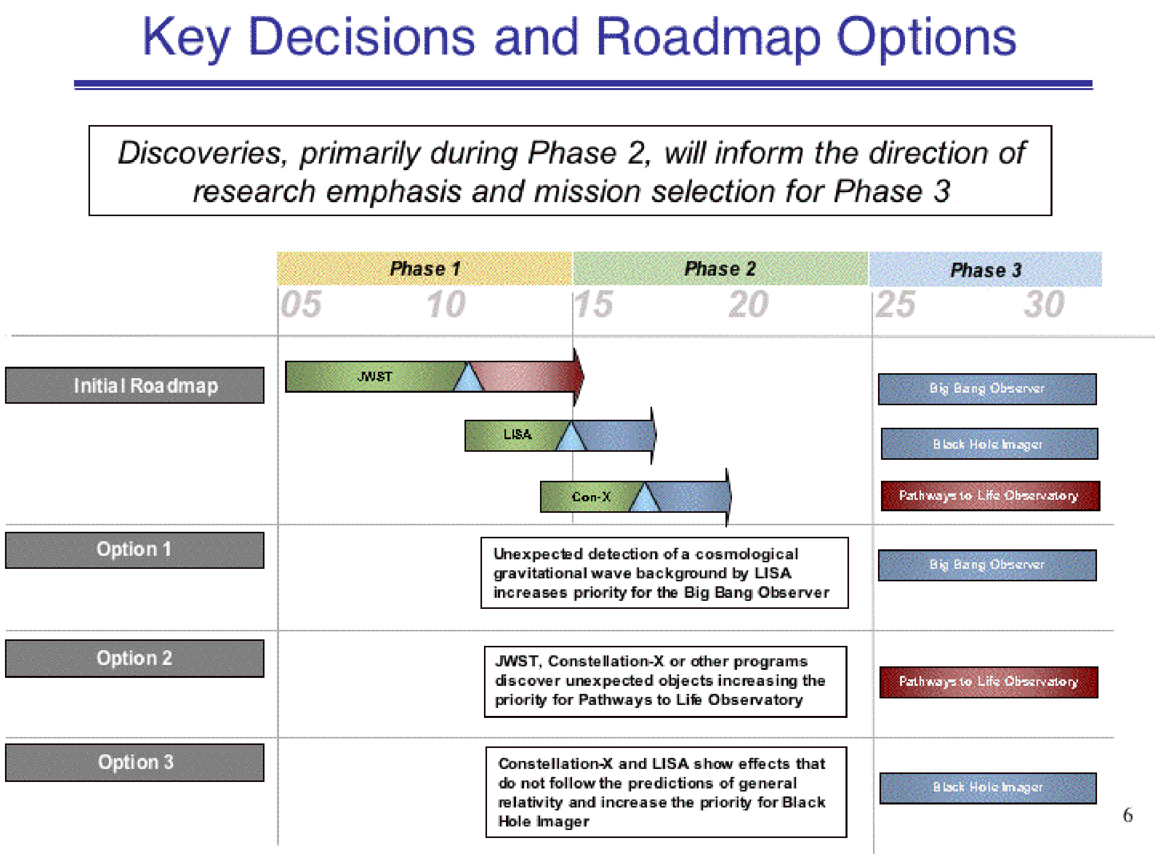

Figure 2 Milestones and Options.

5. Inter-roadmap Dependencies

Any decomposition of NASA's overall science goals into a finite set of strategic objectives will necessarily have linkages, or dependencies, between the individual strategic roadmaps. The Universe Exploration Roadmap (Strategic Roadmap 8) has linkages of several types to other roadmaps, ranging from weakly coupled "opportunistic" linkages to strongly coupled "synergistic" linkages.

Our strongest link by far is with Strategic Roadmap 4 (Search for Earth-like Planets). Sharing its home in the same Universe Division as our roadmap, several Universe Division missions address science goals of both roadmaps, and are of major importance in the achievement of both roadmaps' goals. These missions include JWST, SAFIR, SOFIA, and the Pathways-to-Life Observatories. In addition, the science goals of SR 8 flow naturally into those of SR4; SR 8 is devoted to understanding the origin, evolution, structure and destiny of the Universe, in which the stage is set for the emergence of life. SR 4 continues with this theme by searching for Earth-like planets which could harbor life as we know it. Finally, many of the technologies are shared as well: Light-weight and large optics, detectors, electronics, even novel materials (such as may be provided by nanotechnology) are technologies that enhance the capabilities for both roadmaps.

Strategic Roadmaps 1 (Robotic and Human Lunar Exploration) and 2 (Robotic and

Human Exploration of Mars) present an opportunity for furthering Beyond Einstein science. Specifically, the placement of laser ranging transponders on either the Moon or on Mars would allow much more sensitive solar system tests of Einstein's General Relativity than have been currently achieved. Similarly, radar timing studies with outer planetary probes (Strategic Roadmap 3, "Solar System Exploration") in the manner of Cassini would also enable more sensitive tests of the weak-field regime of Einstein's gravity.

SR 5 (Exploration Transportation) may impact SR 8 by providing launch capability for larger payloads, in particular for larger optics. A weaker synergistic link exists with SR 10, (Sun-Solar System Connection). Both roadmaps require improved understanding of astrophysical magnetic fields and plasmas, and stellar physics.

There are also substantial and important connections with Strategic Goal 12: (Identify and pursue opportunities to educate students and the public and to expand the nation's base of technical skills and capabilities). These education and public outreach activities are built into all of the Universe Division's science missions. Moreover, the scientific topics of the origin and fate of the universe, and black holes, are natural interests of the public and students so the Strategic Goals in Roadmap 8 are of particular importance to Roadmap 12.

SR8 also requires development of technologies that are called out in several capability roadmaps, specifically, CR4 (Advanced Telescopes and Observatories), CR10 (Autonomous Systems, Robotics and Computing Systems), CR12 (Scientific Instruments and Sensors), CR14 (Advanced Modeling, Simulation and Analysis), and CR15 (Nanotechnology and Advanced Concepts). Details are presented in the next section.

6.0 Required Capabilities

NASA missions require technologies usually well beyond the commercial state-of-the art in order to explore the universe with unprecedented clarity and sensitivity. The Hubble primary mirror is so smooth that if the mirror were expanded to the size of the Pacific Ocean, the highest waves would be five centimeters high. The Spitzer Space Telescope operates at temperatures just a few degrees above absolute zero, and this cold operating temperature gives it the sensitivity to detect infant stars buried in clouds of obscuring dust, thousands of light years away. X-rays glancing off Chandra's extremely smooth grazing incidence mirrors are focused so accurately that they could hit the bull's-eye of a dartboard placed six kilometers away. The high reflectivity and sharp images of these superb optics have allowed Chandra to identify, one-by-one, the accreting black holes at cosmic distances that collectively make up the diffuse X-ray background.

Future Universe Missions require even more demanding technologies. The James Webb Space Telescope (JWST) will carry a mirror with a collecting area nearly ten times larger than Hubble's, and will unfold on the way to its distant orbit. The light gathering power of this gigantic mirror will enable JWST to detect the first galaxies and quasars. Con-X will operate new-technology array detectors, cooled to just one-twentieth of a degree above absolute zero, in order to track X-ray-emitting plasma falling into the event horizon of a black hole. The LISA mission will sense the relative positions of its components, measuring changes in their five million kilometer separations with phenomenal accuracy — to within a small fraction of an atomic diameter – in order to detect the ghostly signal of a passing gravitational wave as it ripples the space-time between them.

"Vision" Missions such as Big Bang Observer (BBO), Black Hole Imager (BHI), and the Pathways to Life Observatories push the development of new technologies to achieve their extraordinary science goals. BBO will seek to observe relic gravitational waves that are a key signature of inflation at a level that is orders of magnitude fainter than LISA. BHI will perform X-ray imaging of the structure of a black hole's accretion disk at the microarcsecond level. The technologies such missions require are only now just being conceived. The various Pathways to Life Observatories require large, precise, lightweight optics and high-sensitivity sensors across a wide range in wavelength.

6.1 Technology Implementation

To succeed in such an ambitious program of outstanding science, aggressive technology development is required. Developing these new technologies brings new missions and science to NASA, and new economic benefits for the country. Focused and efficient management of this technology development, with leadership of experienced and capable scientists and engineers in academia and industry, will reduce mission risk and cost. This technology program is an investment in NASA's future, and must be managed in a similar way to that of an investment portfolio, with one eye on short-term needs and another on long-term goals. *Enabling technologies* provide identified capabilities that are essential for nearer-term missions. These technologies have demonstrated feasibility, but must require significant further development and testing before they can be flown reliably on a major mission. These technologies are key to securing the most immediate and reachable science goals in this roadmap, so their development must be given high priority. The future vision missions needs are met with investment in more *exploratory technologies*, those based on new concepts with high potential, which can create new capabilities that address previously inaccessible science goals or address existing goals much more powerfully or less expensively. Advanced technologies can greatly improve the performance and reduce the cost of a mission, but no matter how attractive they seem in principle, we must first validate the new technologies in a space environment well before committing to build a strategic mission.

Maintaining a steady development program to bring forward both enabling and exploratory technologies to maturity is vital for the success of the Universe Exploration Roadmap. The Research & Analysis (R&A) technology incubation program takes the most innovative exploratory technologies through the initial development and testing phase. The R&A program also serves as a useful bridge by providing platforms such as balloons and sounding rockets for gaining confidence in new technologies before they are flown in space. The latter phases of guiding an enabling technology to full space readiness are traditionally carried out in the context of a specific mission, under the auspices of mission project funding. However, a systematic program supporting the early and mid-phases of enabling technology development has often been absent in the past. Such a program must support the development of technologies for missions in this roadmap that do not yet have their own funding lines; so once these missions are selected they can take advantage of the most powerful and appropriate technological tools. It also enables better decisions on mission timing: A new mission starts once the most appropriate technologies are mature enough to be incorporated.

6.2 Strategic Technologies

The Universe science missions described in this Roadmap require advances in four main strategic technology areas: *Optical Systems* — the optics, such as grazing and normal incidence, precision, high stability structures, and the wavefront sensing and control needed to focus electromagnetic radiation with superb accuracy and minimum mass; *Detector Systems* — the devices that convert electromagnetic or gravitational radiation to countable units; *Cryogenic Coolers and Thermal Control* — the methods for cooling telescopes and detectors so that they achieve very low noise and correspondingly high sensitivity and the capability to maintain extremely stable thermal environments; and *Distributed and Advanced Spacecraft Systems* – the critical technology required to support the science payloads including precision attitude control systems and the ability to fly spacecraft in coupled formations, measuring and maintaining their relative positions to extraordinary precision. Table 1 summarizes the technology needs for Universe missions.

For many of the Universe Exploration Probes and Vision Missions there exists multiple implementation approaches with different technology needs that can be used to achieve the desired science. For example, determining the nature of dark energy can be done through optical/infrared measurements or through X-ray measurements, with appropriately different technology needs. In many cases critical technology development progress and performance may be a factor in deciding the approach. So in the following discussion technology needs of multiple implementation approaches (where they exist) have been considered.

The increasing technical complexity and scope of major space science missions should also encourage NASA to explore new approaches for partnering in technology development with academic institutions and with U.S. industry. Besides supporting NASA missions this new technology partnership will help stimulate and advance U.S. technology leadership.

6.2.1 Optical Systems

Advanced telescopes are a critical capability to the Universe Exploration science goals for imaging the horizons of black holes, and galaxies near the edge of the universe, and exploring pathways to life. These telescopes must be larger and have better angular resolution than ever before. This requires that the optical systems be more stable than ever before, with unprecedented wavefront sensing and control, disturbance (mechanical and thermal) stability and control, and pointing and tracking stability. For example the lightweight, grazing incidence X-ray optics required for Constellation-X requires an increase in the effective area-to-mass ratio of X-ray mirrors by a factor of 10 over previous missions.

Lightweight, affordable, *optical systems* are an enabling capability for all future large-aperture space telescopes. They are systems of optical elements, substrates and support structures. Associated capabilities include wavefront sensing and control to compensate for unwanted surface irregularities, metrology, deployment and assembly of large telescope structures in space, and manufacturing and test processes. Key metrics for these systems are the mirror size, the mirror surface figure error or resolution for X-ray mirrors, the areal density, areal cost, and the performance requirements for the wavefront control, metrology and stability needed to meet science requirements.

The greatest technical challenge for optics is the ability to make large-aperture low-areal density mirrors of sufficient surface figure precision and mechanical stiffness. Current observatories are mass and volume limited by the launch vehicle, in turn limiting their maximum aperture. Developing a capability to produce lower areal density mirrors coupled with efficient launch packaging concepts will enable future large aperture observatories. Furthermore, lightweight optics must be very stiff and thermally stable to retain the required optical figure and line-of-sight pointing. The greatest programmatic challenge is to rapidly manufacture affordable mirrors. Reducing the areal-cost of mirrors enables missions to afford larger apertures within the constraint of launch mass/volume limits.

Constellation-X and other future X-ray telescopes such as the Early Universe X-ray Observer (EUXO) or the Black Hole Imager (BHI) require large-aperture precision-quality grazing incidence mirrors. The technology required to produce these mirrors is revolutionary compared to Chandra optics. Technology investment is needed to manufacture 1- to 2-meter class mirrors with two orders of magnitude (100X) reduction in both areal density and areal cost. This will require developing new materials and new fabrication processes, and the mechanical support, alignment and stability of such optics are an additional significant challenge. Both these X-ray mirrors and the normal incidence mirrors for future ultraviolet and visible wavelength missions such as Large Ultraviolet-Visible Observatory (LUVO) also require extremely smooth, extremely stable, ambient temperature mirrors — particularly as telescope apertures increase.

Future infrared/far-infrared/sub-millimeter and millimeter wavelength missions such as JWST, Single Aperture Far-Infrared Telescope (SAFIR), Far Infrared/ Submillimeter Interferometer (FIRSI), and one of the implementation approaches for the Inflation Probe (IP), require large-aperture modest-quality mirrors operating at temperatures from 4 to 40K. Current state of the art cryogenic mirrors can satisfy most of the technical requirements for such missions, but their areal cost is too great. The most important enabling capability is to reduce the areal cost of cryogenic mirrors by an order of magnitude. Approaches to achieve this goal include replication, nanolaminates, near-net shaping and advanced polishing techniques.

6.2.2 Detector Systems

Virtually all NASA Universe Exploration missions require detectors with exquisite sensitivity, extraordinary spectral resolution, spectacular imaging capabilities, and sometimes all of these. In addition, the Universe Exploration Strategic Roadmap cuts across the electromagnetic spectrum from the submillimeter to the gamma ray. Large-area, low-power gamma-ray and hard X-ray detector systems are required for Constellation-X, the Black Hole Finder Probe, Black Hole Imager and the Nuclear Astrophysics Compton Telescope. Multiplexed microcalorimeter and bolometer arrays are needed by Constellation-X, EUXO and the Black Hole Imager in order to meet the energy resolution and sensitivity requirements in the soft X-ray band. These are also required by one of the candidate Inflation Probe architectures to realize large-format high sensitivity mm polarimeters. The development of the Constellation-X and Inflation Probe detector arrays dovetails into the large-format, ultrahigh-sensitivity arrays also needed for SAFIR. Very large format (billion-pixel or greater) optical/infrared focal planes are needed for JDEM and LUVO, which also need high quantum efficiency, solar blind photon counting UV arrays.

The detector systems investment program should nurture the natural synergy between X-ray and far-infrared/millimeter-wave core detector technologies. For example, both wavelength regimes are rapidly developing transition-edge superconducting (TES) sensors and superconducting quantum interference device (SQUID) multiplexers. Newer technologies such as Kinetic Inductance Detectors (KIDs) or magnetic microcalorimeters hold substantial promise.

LISA and the Big Bang Observatory require gravitational reference sensors to perform drag-free flight. The sensors must minimize disturbance to the freely falling proof masses in addition to monitoring and controlling the position of the proof masses relative to the spacecraft. Precision micro-thrusters are required to maintain spacecraft attitude and position relative to the proof masses. Stabilized laser technology is required to monitor the position of the proof masses relative to the proof masses in the distant spacecraft.

6.2.3 Cryogenic Coolers and Thermal Control

Cryogenic coolers are required for Universe Exploration instruments and telescopes to produce much of the desired science. The advanced calorimeter and bolometer detectors that enable Constellation-X and other missions require cooling to 0.05 degree above absolute zero. Passive cooling techniques enable the Spitzer telescope to fully exploit the natural space environment, requiring no power, stored cryogens, or moving parts. Passive cooling allows space missions to achieve temperatures several tens of degrees above absolute zero, sufficient for near/mid-infrared telescopes such as JWST, and serves as a valuable first temperature stage towards reaching lower temperatures. But future applications, such as cooling very large telescopes as well as the detector system for some of the architectures for the Inflation Probe, SAFIR, and FIRSI require new technology. Active cooling technologies offer the potential of high efficiency and high reliability cooling to 4-6 K. New sub-Kelvin coolers, operating from this base temperature, will reach the ultra-low temperatures required for calorimeter and bolometer focal planes, providing more heat lift, continuous operation, and high temperature stability. Adiabatic Demagnetization Refrigerators (ADRs), ^{3}He sorption coolers, and open-cycle dilution refrigerator precursor technologies show many of the attributes needed to meet these requirements. In addition, cryogenic and non-cryogenic missions will require advances in thermal stability and control technology (heat pipes and other heat transport systems) that exceed current state of the art performance by an order of magnitude or more.

6.2.4 Distributed and Advanced Spacecraft Systems

Distributed Spacecraft Systems

In order to achieve the science goals described in this roadmap, NASA will require a precision formation flying capability (for LISA, BHI, BBO, FIRSI, and others). Carrying out this type of spacecraft coordination requires technologies such as extremely stable gyros, disturbance (thermal/mechanical) control, clock synchronization systems, precise star trackers, laser ranging systems between spacecraft, and micro-Newton thrusters to perform minute adjustments. In addition, spacecraft control algorithms need to be developed for continuous monitoring, formation flying, reconfiguration and reorientation and autonomous recovery. LISA will provide the initial demonstration of advanced formation-flying techniques by measuring the relative displacements of inertial test masses contained in each spacecraft separated by millions of kilometers to picometer accuracy.

These mission ensembles are a set of more than one spacecraft whose dynamics are coupled through a cooperative sensing and control architecture. This enables many satellites sometimes separated by millions of miles to act as one giant observatory. A key challenge is the need to build multiple spacecraft, requiring a reduction of development and test costs for replicated spacecraft to enable competitive formation flying systems. Current formation flying systems rely upon propulsion to maneuver and maintain formation, thereby limiting mission lifetime and contaminating their environment (deposition on optical surfaces, plume impingement, thermal emission). Propellant-less formation flight should be investigated, including the use of natural orbits, tethers, natural fields (magnetic, solar pressure), as well as potential fields generated by the spacecraft themselves (electro-magnetic, electrostatic).

Advanced Spacecraft Systems

Universe Exploration missions require improvement over the current state of the art in a number of fundamental spacecraft elements, i.e., more accurate and more stable gyros, star trackers and other attitude control sensors and algorithms. Also critically important are electronics and processors with better radiation tolerance and lower cost; lower cost, more efficient power systems; larger launch vehicle fairings; and launch load alleviation systems. Investments in these areas should not be neglected.

Industrial and Academic Capacities, Agency Human Capital and Infrastructure

As Universe Missions become more complex and technologically demanding, strong cooperation among NASA, universities, national labs, and industry is essential to meeting critical science objectives within cost and schedule constraints. For example, bolometer and microcalorimeter technologies for Con-X are developed through a collaboration including Goddard Space Flight Center (GSFC), the University of Wisconsin, Smithsonian Astrophysical Observatory (SAO), and National Institute of Standards and Technology (NIST). While NASA manages LISA, major technological components come from Stanford, the University of Colorado, the Jet Propulsion Laboratory, and Busek Technologies Corporation. Because the technologies for astronomy are driven by science objectives, scientists must be involved at all phases of development, working with the technologists who make these capabilities possible. In some areas, experimental scientists *are* the technologists, pushing the boundaries of performance to meet their scientific goals. Whenever NASA's technology goals align with commercial interests, NASA can leverage capabilities in industry to the fullest extent possible. On the other hand, whenever NASA is the sole customer, NASA must vigorously support research and development at universities, government research centers, and industrial research laboratories to realize its goals. NASA must also identify new ways to aggressively team with industry in areas of technology development, new facilities and test capabilities, and workforce development.

The availability of human capital, infrastructure, and institutional support at any or all of these types of institutions can make or break a NASA mission. At universities, the training of the next generation of instrumentalists for space missions is a key capability that must be encouraged and maintained. NASA contributes to this through funding R&A, sub-orbital payloads, and P.I.-led competed missions such as Explorers and Probes. Aerospace corporations provide the infrastructure for launch vehicles, management of large space hardware programs, spacecraft and instrument construction, and test facilities. Where industry cannot supply such facilities, NASA often develops unique infrastructures of its own: for example, the Marshall Space Flight Center X-ray Calibration Facility, which was used to calibrate the Chandra X-ray instruments and may be used for Con-X as well. A NASA facility will also be used for JWST testing. The development of microfabrication capabilities at NIST and NASA/GSFC were key to making prototype microcalorimeter arrays.

There are, however, significant concerns about the ability to maintain some of these capabilities for future Universe Exploration missions. The R&A and Explorer programs, while very cost effective in solving technology problems at an early stage of development, are under intense financial pressure in the current NASA budget environment. For many missions there are only a few suppliers of key detector, optics or filter technology. These are often small concerns which, if they cannot attract a steady stream of business, will lose key personnel or even go out of business. The Universe Division and Science Mission Directorate should undertake a comprehensive review of these issues to ensure that mission critical capabilities are preserved in the vendor community. In addition, it is essential that the most efficient methods be invoked to ensure mission reliability, so that excessively burdensome review processes do not significantly drive up mission costs.

Unique Requirements

Investments in infrastructure that enable researchers to communicate, organize and share information are crucial to ensure the widest participation in the research effort. These assets include NASA's Deep Space Network (DSN), TDRSS, and other supporting orbital and ground networks, data archival and distribution networks, and high-speed ground links.

It is anticipated that the rates and volume of scientific data in the future missions, especially those involving wide-field imaging and orbits at L2 and beyond, will far exceed existing downlink and storage capabilities. An upgraded DSN and wider bandwidth space communication systems will be vital. The large data volumes may be accommodated in part by distributing data sets and analysis. However, the software tools as well as the connectivity for such data systems will require new approaches and architectures for synthesizing these data streams (e.g., National Virtual Observatory (NVO). Continual investment in information technology tools will be required to address the spatial, temporal, and spectral data needed to understand the cosmos. Furthermore, information technology investments to
support on-board control strategies of more capable spacecraft will be essential as we move to an era of constellation or formation flying.

***Critical* Technology Needs for Univere Exploration Science**	Mission	Strategic Missions		Probes			Vision Missions							
							Beyond Einstein		Pathways to Life Observatories					
Technology Area & Sub-Areas		LISA	Con-X	JDEM	IP	BHFP	BHI	BBO	NACT	LUVO	SAFIR	EUXO	FIRSI	UVOI
Optical Systems														
Light Weight Grazing Incidence Mirror Systems			Enabling			Enabling	Enabling					Exploratory		
Light Weight Normal Incidence Mirror Systems				Enabling				Enabling		Exploratory				Enabling
Light Weight Cryogenic Mirror Systems					Enabling						Exploratory		Exploratory	
Wavefront Sensing and Control and Interferometry				Enabling						Enabling			Exploratory	Exploratory
Precision Structure Disturbance Sensing and Control							Exploratory			Exploratory	Enabling	Exploratory	Exploratory	Exploratory
Detector Systems														
γ-Ray and Hard X-ray Detector Systems			Enabling			Enabling	Exploratory		Enabling			Enabling		
X-ray Detector Systems (calorimeters, CCDs, etc)			Enabling				Exploratory					Exploratory		
UV, Optical, Near-IR Detector Systems, including Large Focal Plane Technology				Exploratory						Exploratory				Enabling
Mid- and Far-IR Detector Systems					Exploratory						Exploratory		Exploratory	
Gravitational Wave Detector Systems		Enabling						Exploratory						
Cryogenic Coolers and Thermal Control														
Passive Thermal Systems for Cooling and/or Control (sunshades, radiators, etc)		Enabling		Enabling				Enabling		Enabling	Enabling		Enabling	
Low Power, Low Vibration, Active Instrument Cooling Systems			Enabling	Enabling	Exploratory				Exploratory		Enabling	Exploratory	Enabling	
Low Power, Low Vibration, Active Telescope Cooling Systems					Exploratory						Exploratory		Exploratory	
High Precision Thermal Sensing and Active Control (> 0.01 K stability)							Exploratory			Exploratory	Exploratory		Exploratory	
Distributed & Advanced Spacecraft Systems														
Micro-Newton Thrusters		Enabling					Enabling	Enabling						Enabling
Propellant-less Formation Flight							Exploratory	Exploratory					Exploratory	Exploratory
Precision Formation Flying Algorithms							Exploratory	Exploratory				Exploratory	Exploratory	Exploratory
Precision Formation Flying Metrology and Navigation Sensors & Systems							Exploratory	Exploratory				Exploratory	Exploratory	Exploratory
Precision Attitude Control Sensors & Systems (sensors, gyros, momentum wheels, etc)		Enabling	Enabling	Enabling			Enabling	Enabling		Enhancing	Enhancing	Enhancing	Enhancing	Enhancing

Key	
Enabling Technology	Technology Currently at TRL 3-6
Exploratory Technology	Technology Currently at TRL 1-3

Table 1 Capabilities needed to reach roadmap science goals.

APPENDICES

A. National Policy Framework

The Universe Roadmap is a framework for Exploration on the grandest scale. It lays out a scientific and technological agenda to discover the origin, structure, evolution, and destiny of space and time, matter and energy, atoms and molecules, the stars and galaxies that animate and enrich the cosmos, and ultimately life itself. It leverages NASA's considerable experience to achieve what only NASA can. It is a response to NASA's Mission statement "…To explore the Universe and Search for Life" and "…To Inspire the Next Generation of Explorers." If fully implemented, it would realize a critical component of the Space Exploration Vision, as described in the "President's Commission on Implementation of United States Space Exploration Policy." This Vision calls for the exploration of the beginnings of the universe, planetary systems, and life. This roadmap advocates a scientific agenda that would reveal the origin, structure, evolution, and fate of the elements, the stars, the galaxies, and the cosmic web that comprise the known Cosmos. The Vision also challenges NASA to conduct a comprehensive program to explore the origin, evolution, and destiny of the universe. Space astronomy has been a powerful development driver of American high technology, and is a credible source of national pride.

The NASA Strategic Roadmapping process does not operate in isolation. It has benefited from guidance provided by a number of other national advisory committees that have been commissioned in recent years to chart the future of multi-agency research in astronomy, astrophysics, cosmology, and planetary science. Of particular importance is the decadal survey in astronomy and astrophysics conducted by the National Academy of Sciences (NAS), which resulted in the report "Astronomy and Astrophysics in the New Millenium." Many of the missions identified in this Universe Roadmap were highly ranked in that report. The NAS also subsequently commissioned "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century," which recommended a multi-agency coordinated program of research at the frontiers between physics and astronomy. The Beyond Einstein program included here has been formulated largely along the lines recommended by that study. Finally, in 2004, the Office of Science and Technology Policy (OSTP) issued the report "A 21st Century Frontier for Discovery: The Physics of the Universe, A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy," which responded to these NAS recommendations with a prioritized program of research on the physics of the universe. The NASA Universe Exploration roadmap is fully consistent with the OSTP recommendations.

As the arena of space has become increasingly vital in the scientific investigations of various research communities, the programmatic goals of other Federal funding agencies, such as the NSF and DOE, intersect with those of the Universe Division within NASA. The Gamma-Ray Large Area Telescope (GLAST) is being developed in partnership with the DOE, and a similar arrangement has been envisioned for the Joint Dark Energy Mission (JDEM), which will be the first of the Einstein Probes. Given these collaborations, it is essential that the strategic planning efforts at NASA be coordinated with those at these other agencies. The membership of the Universe Exploration Startegic Roadmap committee has been constructed to enable this coordination: Senior NSF and DOE personnel have been included, as well as a representative of the Astronomy and Astrophysics Advisory Committee and High Energy Physics Advisory Panel.

The intense multi-agency interest in the topics discussed here reflect the expectation that the *discoveries likely to emerge from the Beyond Einstein and Pathways to Life missions will fundamentally change our understanding of our place in the universe.* The implications could be as profound and paradigm-breaking as those that resulted from the revolutions due to Copernicus, Galileo, Newton, and Einstein. The Universe Exploration Program will ignite the public imagination, while fulfilling its obligation to inspire the students of the future who will carry out its programs of discovery. It will play a major role in helping to maintain the U.S. presence at the forefront of fundamental research in the physical sciences.

External Constituencies

Space-based astronomical research is not an isolated discipline, but rather has important and direct links to other research areas and to other constituent groups. Research fields in fundamental physics (in particular particle physics, nuclear physics, cosmology and gravitational physics) are asking questions which in many cases can only be answered by space missions using the universe as a laboratory. Two specific examples — understanding the nature of dark energy and of the quantum gravity of the early universe — could well have enormous repercussions on our picture of particle physics, but, as yet, there is no currently known way to directly probe these issues using ground-based accelerators and laboratories. Another research field that links to the Universe Exploration theme is biology. With the search for habitable solar systems and with the increasingly detailed understanding of the chemical and environmental makeup of the universe, astronomers are providing important clues towards unraveling the mystery of the origin of life. Indeed, the field of astrobiology has emerged as an exciting discipline both at NASA and at research institutions across the country.

There are other important constituencies that go beyond the broader scientific research community. Educators and students at K-12 schools and universities make heavy use of the results from astronomical research in classrooms and in extracurricular activities (for example, museum visits). Information gathered from NASA web sites serves, in many cases, as the primary scientific archive for students of all ages. Another key constituency is represented by our industrial and commercial partners. These groups work with researchers at universities and NASA centers to design and carry out space missions and to develop forefront technologies for future missions. Finally, the general public, as our ultimate customer, is a crucial external constituency. Results from NASA space missions, as covered by popular media, have the demonstrated ability to inspire citizens of all ages, and they engender good will in support of the overall vision and goals of the agency.

B. **Unique Education and Outreach Opportunities**

The Universe Exploration missions and related activities are key to achieving NASA's strategic objective #13:

> "Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation."

The Universe Roadmap Committee affirms the importance of aiding the nation's efforts in science, technology, engineering, and mathematics (STEM) education—both in higher education and at the pre-college level. Maintaining and nurturing an adequate workforce is especially critical in view of the long lead-time for missions and the increasing restrictions on foreign nationals at NASA's corporate partners. A strong public engagement effort is also key to achieving sustained public support for NASA's space effort.

Demand is high, need is great

The public's interest in Universe Exploration is evident from the great popularity of museum exhibits, planetarium shows, and television shows in the Universe Exploration theme. For example, recent and forthcoming television documentaries on black holes have already garnered millions of viewers. More than a million people have visited the *Cosmic Questions* traveling exhibition. *Inside Einstein's Universe*, a collaborative effort of missions in Universe Exploration, has attracted the active participation of 114 science museums nationally. Research on our cosmic origins has led to extensive coverage in major newspapers such as *The New York Times* and *The Washington Post*.

In the nation's schools, black holes remain one of the two most asked-about topics in astronomy. More importantly, the topics of Universe Exploration are firmly rooted in the *National Science Education Standards* (issued by the National Academy of Sciences), which together with the AAAS' *Benchmarks for Science Literacy* form the basis for most frameworks for education at the state level. The national standards mandate an understanding of the Big Bang and the life cycles of stars, while the benchmarks cite black holes as "an excellent" way to explore the nature of science.

The Universe Exploration missions have an important role: Recent surveys confirm that, despite the standards, students and teachers are generally unfamiliar with the universe beyond the solar system. In a recent assessment of 7,000 students in 37 states, *most* students had trouble with such basic concepts as where the stars are in relation to the solar system and the space shuttle, or with concepts such as the nature of gravity. This situation is unlikely to improve without NASA's presence in the classroom.

Universe Exploration missions offer unique opportunities

NASA's goal to "Explore. Discover. Understand." is well-served by the Universe Exploration Program. Missions such as Constellation-X, LISA, the Black Hole Finder Probe and, ultimately, the Black Hole Imager, will take the public on a great voyage of exploration culminating at the very edge of a black hole. Like any great exploration, the ultimate goal is preceded by scouting and reconnaissance — making sense of the ultimate target. Similarly, LISA, the Inflation Probe, and the Big Bang Observer will engage the public in a form of time travel, exploring the universe's distant past back to its origins, and the Joint Dark Energy Mission will help predict the universe's eventual destiny. In addition, missions exploring the "ecology" of our universe will paint an extraordinary story of why our physical universe appears to be so hospitable to life, setting the stage for the search for life beyond Earth. Finally, one of the great stories of our time is the emerging revolution in fundamental physics, a story that will likely blossom in the public's attention shortly after the world's most powerful collider goes on line at CERN in 2007. Many of the missions presented here—especially LISA, JDEM, the Inflation Probe, Planck and GLAST—are likely to play key roles in testing the new physics and will be an important part of the narrative. These great stories of exploration, discovery, and understanding are an indispensable vehicle for engaging the public's interest.

Furthermore, the Universe Exploration missions offer unprecedented opportunities in the classroom for helping students and teachers with such fundamental STEM concepts as the structure of the universe, gravity, the interaction of light and matter, and the formation of elements. These are not mere facts, but rather core concepts that leverage future learning in STEM. For example, the Universe Exploration missions offer an unmatched opportunity for students to learn about (and to visualize) all regions of the electromagnetic spectrum, a concept that is fundamental to every branch of science. Missions such as LISA, which push the bounds of technology, will also provide unmatched learning opportunities for technology education.

Elements of the Public Engagement Plan

Identifying the Needs of Stakeholders. Basic to our approach is to research and identify the needs of our audiences and stakeholders. The Universe public engagement programs seek to harness NASA's unique resources to help address the needs of three major audiences:

> *Formal education*. These are classroom teachers (K-12 and college level), curriculum developers, textbook publishers, and other educators who are tasked with teaching the national science education standards and who need compelling examples, activities, and scientific visualizations, as well as professional development to make optimum use of these materials. Formal education can include the use of real research data and learning tools such as online telescopes.
>
> *Informal education*. These organizations include science museums, planetariums, and other institutions of informal learning which bring the public along on the exploration of space, and which require compelling stories to tell as well as the

raw resources such as scientific visualizations and artifacts with which to construct these stories. Informal learning also takes place in after-school programs, and with organizations such as the Girl Scouts, amateur astronomers' clubs, and national parks, which engage the public with demonstrations, activities, and other educational resources.

General public. Young and old alike participate in the excitement of NASA's space exploration through news, radio and television programs and Web access to information.

Focus on High-Priority Areas.

Several areas have been identified for which NASA's educational assets can make a particularly important contribution. Among these are:

- Professional development for pre-service and in-service teachers and college instructors.
- Flexible learning tools and experiences that support the learning of scientific inquiry, fundamental concepts in STEM (science, technology, engineering and math), and / or language arts.
- National partnerships with informal education organizations.
- Scientific visualizations, including multimedia and interactive experiences.
- Distance and e-learning.

Guiding Principles.

Universe public engagement programs incorporate several principles that will guide all future work:

Coherence. Achieve a coherent and coordinated set of programs and products that meet the needs of varied audiences and stakeholders, and that mesh seamlessly with NASA's other science themes and education initiatives.

Leverage. Expand public engagement on a large scale by creating sustainable national programs through effective and flexible partnerships with existing organizations.

Scientist participation. Maximize the impact of NASA's programs by fostering the participation of scientists and engineers.

Authentic experiences. Involve students and teachers in real research and expand access to real data.

Diversity. Engage underserved and underutilized groups in ways that genuinely meet mutual needs and interests and that contribute to the pipeline.

Training of students. Provide continuing support for STEM students in higher education, including programs providing research experiences for undergraduates.

Pathways to the Future for Public Engagement

Universe public engagement programs build on and extend an existing educational network of scientists, educators, brokers, and forums that is unprecedented in scope and reach. This network ensures that future efforts will be both cost-effective and highly leveraged.

One key component is the active participation of research scientists and engineers who provide visualizations, data, artifacts, public lectures, reviews for accuracy and, most important, serve as role models and mentors for the next generation of explorers. Another important element is the active involvement of education organizations nationwide, such as the Girl Scouts USA, the Night Sky Network of astronomy clubs, the Great Lakes Planetarium Association, and many more. Finally, the network is coordinated by a small number of education forums who work with mission scientists and mission educators to develop educational strategies and products—and by regional brokers, who partner with educational institutions and regional audiences to ascertain their needs.

The connectivity of this network of scientists, missions, and educational institutions allows NASA's educational assets to enjoy maximum reach and impact. When high-resolution images from the Chandra X-ray Observatory are quickly distributed to a large number of planetariums; when world-class scientists give public presentations about black holes; or when amateur astronomers hold hundreds of NASA-sponsored events around the country, it is clear that the network insures that programs achieve the broadest possible reach and impact.

Strategic leadership.

The Universe public engagement program is coordinated by a team at the Space Telescope Science Institute and the Harvard-Smithsonian Center for Astrophysics. The team helps provide continuity and direction for the education programs of missions and research scientists, and provides core services such as evaluation of products, entree to the education research literature, and coordination of effort. Future missions will be able to take advantage of existing partnerships and programs, and it is expected that new programs will relate to the overall goals, program areas, and customer needs identified in this roadmap.

C. **External Partnerships**

Other Federal Agencies. Understanding the origin, evolution, structure and destiny of the universe is an inherently interdisciplinary enterprise, and it is becoming increasingly clear that a broad-based multi-agency attack on the key problems is warranted. The National Academy of Sciences report “Connecting Quarks with the Cosmos” highlighted the need for inter-agency coordination of overlapping science areas. In response to this report, a Physics of the Universe Interagency Working Group (IWG) was formed by OSTP. This IWG reports to the National Science and Technology Council (NSTC) Committee on Science (COS). The IWG delivered a strategic plan to respond to the

"Connecting Quarks with the Cosmos" recommendations, identified priorities for immediate investments, and the appropriate agency roles and responsibilities. The IWG gave high priority to studies of dark energy and a future Joint Dark Energy Mission (JDEM) to be implemented by NASA, in partnership with DOE. This will build on the successful NASA/DOE partnership for the Gamma Ray Large Array Telescope (GLAST). The IWG also recommended a Task Force for Cosmic Microwave Background Research that has delivered a technology roadmap (including a candidate Inflation Probe based on CMB polarization measurements) that will inform not just NASA, but also the NSF and the DOE, so that the funding strategies of each agency may be combined into a comprehensive program of support to achieve the collective aims of these agencies. Interagency cooperation continues to be exemplified by the participation of NSF and DOE personnel in our roadmap efforts, with reciprocation on NASA's part.

International Partners. With the increasing complexity and cost of major space science missions, international partnerships provide a lower-cost-to-NASA option for carrying out its space missions. The European Space Agency (ESA) and several of the European national space institutes are major partners in LISA and JWST. Substantial ESA and Japanese (JAXA) participation in the Constellation-X mission also appears to be likely. There is also considerable international interest in the Einstein Probes for Dark Energy and Inflation, the Pathways to Life Missions and Big Bang Observer.

D. **Bibliography**

Key Agency Documents

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E. Inputs to Roadmap Committee

This roadmap was prioritized on the basis of science priorities and programmatic considerations. The committee gave careful consideration to a wide variety of inputs from the public and the astronomy and physics communities during three open meetings. These inputs included direct presentations by Vision Missions Concept Study teams, white papers submitted in response to a call for community input by NASA's Advanced Planning and Integration Office, review of power point presentations prepared by Origins Probes Concept Study teams, and drafts of the Universe Division's Legacy Roadmap which itself incorporates substantial additional input from the community.

F. Universe Exploration Strategic Roadmap Committee

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Nick White, Goddard Space Flight Center, *co-chair*
Kathryn Flanagan, Massachusetts Institute of Technology, *co-chair*
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Staff

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G. Acronyms

BBO	Big Bang Observer
BHFP	Black Hole Finder Probe
BHI	Black Hole Imager
CMB	Cosmic Microwave Background
COBE	Cosmic Background Explorer
Con-X	Constellation-X
DEP	Dark Energy Probe
ESA	European Space Agency
EUXO	Early Universe X-ray Observer
FIRSI	Far Infrared/ Submillimeter Interferometer
GLAST	Gamma Ray Large Area Telescope
GPB	Gravity Probe B
Herschel	ESA/NASA far infrared mission
HST	Hubble Space Telescope
IP	Inflation Probe
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
LIGO	Laser Interferometer Gravity Wave Observatory
LISA	Laser Interferometer Space Antenna
LUVO	Large Ultarviolet/Optical Telescope
NACT	Nuclear Astrophysics Compton Telescope
NuSTAR	Nuclear Spectroscope Telescope Array
P.I.	Principal Investigator
Planck	ESA/NASA cosmic microwave background mission
SAFIR	Single Aperture Far-InfaRed Telescope
SOFIA	Stratospheric Observatory For Infrared Astronomy
UVOI	UV/Optical Interferometer
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
XMM	X-ray Multimorror Mission