The Evolution of the Universe

edited by

David L. Alles

Western Washington University

e-mail: alles@biol.wwu.edu

This web paper was last updated 1/22/05.

"If being educated means having an informed sense of time and place, then it is essential for a person to be familiar with the scientific aspects of the universe and know something of its origin and structure."

Project 2061, American Association for the Advancement of Science

Introduction

Science at the beginning of the twenty-first century can make some bold, yet simple observations:

1) the universe has evolved

2) we are a result of that evolution.

> "We are the first generation of human beings to glimpse the full sweep of cosmic history, from the universe's fiery origin in the Big Bang to the silent, stately flight of galaxies through the intergalactic night." (National Research Council)

Order in the Universe

Cosmology is the study of the evolution of the universe from its first moments to the present. In cosmology the most fundamental question we can ask is: Does our universe have intelligible regularities that we can understand—is it ordered? This question lies at the heart of the scientific revolution beginning in the sixteenth century. That revolution began with the discoveries by Copernicus, Galileo, and Newton of order in our world. Today our scientific understanding of nature's order has reached a critical threshold. Only now can we begin to piece together a coherent picture of the whole. Only now can we begin to see the deep order of our universe.

Web Reference
http://www.tufts.edu/as/wright_center/cosmic_evolution/index.html

"The evolution of the world can be compared to a display of fireworks that has just ended; some few red wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanishing brilliance of the origin of the worlds."
—Abbé Georges Lemaître

We now understand the order in our world by using the standard Hot Big Bang model of the evolution of the universe. The four key observational successes of the model are:

The Expansion of the Universe

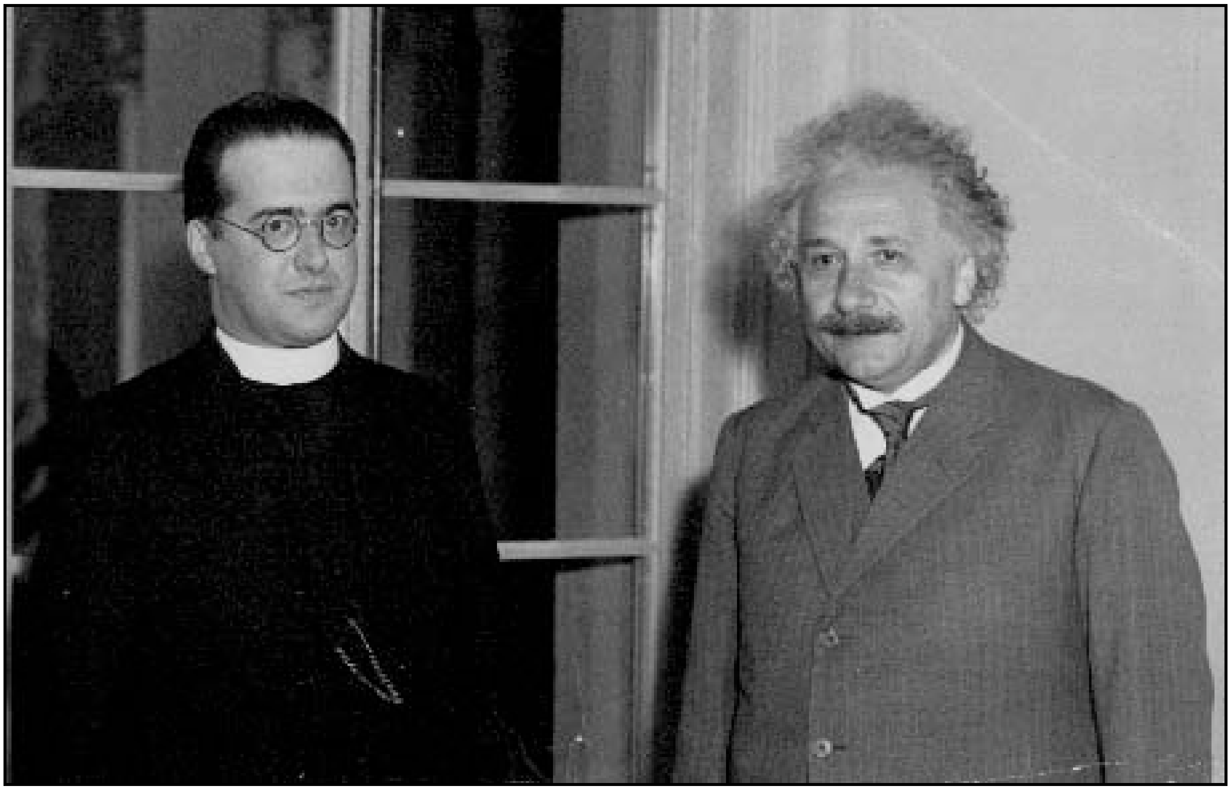
Nucleosynthesis of the light elements

Origin of the cosmic background radiation

Formation of galaxies and large-scale structure

The Big Bang model makes accurate and scientifically testable hypotheses in each of these areas, and the remarkable agreement with the observational data gives us considerable confidence in the model.

Web Reference
http://www.damtp.cam.ac.uk/user/gr/public/cos_home.html



Lemaître with Einstein

Abbé Georges Edouard Lemaître (1894-1966) was a Belgian astrophysicist and Priest who developed an evolving cosmological model which indicated that the universe had begun in a "Big Bang."

Einstein's theory of general relativity, announced in 1916, had led to various cosmological models, including Einstein's own model of a static universe. Lemaître in 1927 (and, independently, Alexander Friedmann in 1922) discovered a family of solutions to Einstein's field equations of relativity that described not a static but an expanding universe. This idea of an expanding universe was demonstrated experimentally in 1929 by Edwin Hubble who was unaware of the work of Lemaître and Friedmann. Lemaître's model of the universe received little notice until Eddington arranged for it to be translated and reprinted in 1931. It was not only the idea of an expanding universe which was so important in Lemaître's work, on which others were soon working, but also his attempt to think of the cause and beginning of the expansion.

If matter is everywhere receding, it would seem natural to suppose that in the distant past it was closer together. If we go far enough back, argued Lemaître, we reach the 'primal atom', a time at which the entire universe was in an extremely compact and compressed state. He spoke of some instability being produced by radioactive decay of the primal atom that was sufficient to cause an immense explosion that initiated the expansion.

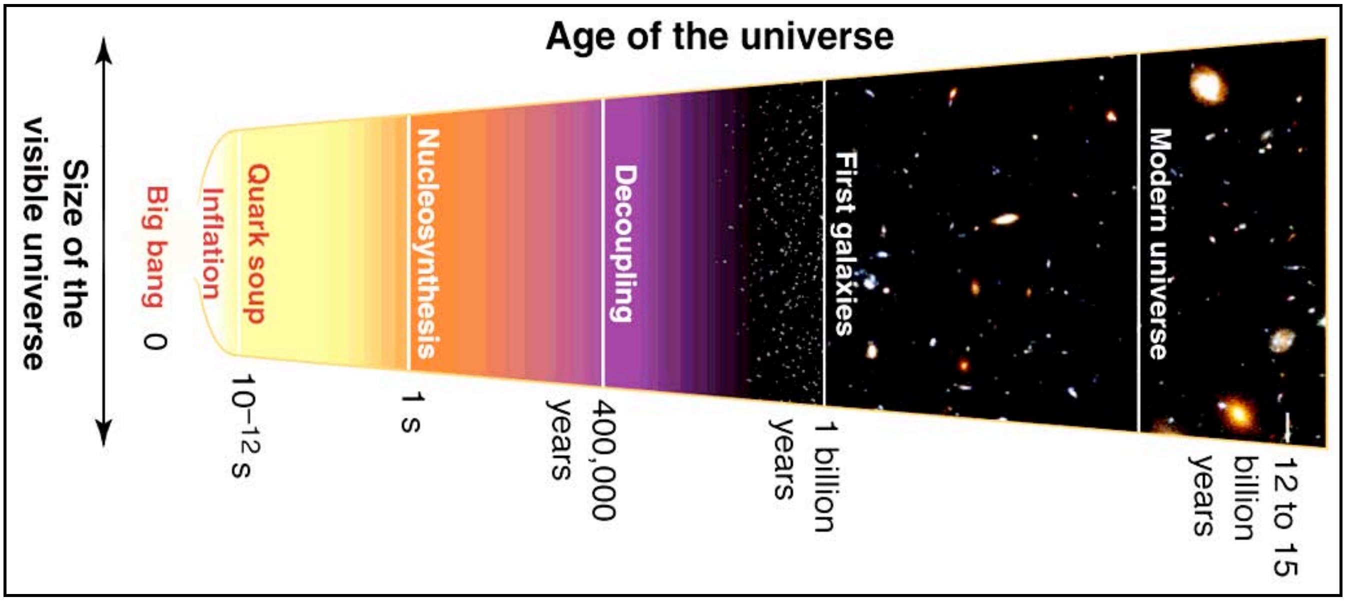
This Big-Bang model did not fit well with the available time scales of the 1930s. Nor did Lemaître provide enough mathematical detail to attract serious cosmologists. Its importance today is due more to the revival and revision it received at the hands of George Gamow in 1946.

George Gamow (1904-1968)

Web References

http://school.discovery.com/schooladventures/universe/stargazers/einstein.html

http://scienceworld.wolfram.com/biography/Gamow.html



The Expansion of the Universe

As bizarre as it may seem, space itself is expanding—specifically, the vast regions of space between galaxies. According to Einstein, space is not simply emptiness; it's a real, stretchable, flexible thing. The notion that space is expanding is a prediction of Einstein's theory of gravity, which describes a simple but universal relationship between space, time, and matter.

In the late 1920's, the astronomer Edwin Hubble first observed that distant galaxies are moving away from us, just as would be expected if the space between galaxies were growing in volume and just as predicted by Einstein's theory of gravity. Since then, astronomers have measured this recession for millions of galaxies.

Web Reference
http://www.pbs.org/deepspace/timeline/

Galaxy NGC 4414, a spiral galaxy like our own Milky Way

The galaxies sit more or less passively in the space around them. As the space between galaxies expands, it carries the galaxies further apart—like raisins in an expanding dough. However, the universe is a chaotic place and the gravity from one galaxy, or from a group of galaxies, may disturb the motion of its near neighbors, causing them to collide. But on average, when you compare two large enough chunks of space, the galaxies in one are moving away from the galaxies in the other. Amazingly, space is not actually expanding "into" anything. Put another way, a given region of space doesn't actually "push" the rest of the universe out of the way as it expands.

(Image courtesy of the Hubble Space Telescope / NASA)

The Big Bang “Theory”

The Big Bang is actually not a "theory" at all, but rather a scenario or model about the early moments of our universe, for which the evidence is overwhelming.

It is a common misconception that the Big Bang was the origin of the universe. In reality, the Big Bang scenario is completely silent about how the universe came into existence in the first place. In fact, the closer we look to time "zero," the less certain we are about what actually happened, because our current description of physical laws do not yet apply to such extremes of nature. The Big Bang scenario simply assumes that space, time, and energy already existed. But it tells us nothing about where they came from or why the universe was born hot and dense to begin with.

But if space and everything with it is expanding now, then the universe must have been much denser in the past. That is, all the matter and energy (such as light) that we observe in the universe would have been compressed into a much smaller space in the past. Einstein's theory of gravity enables us to run the "movie" of the universe backwards—i.e., to calculate the density that the universe must have had in the past. The result: any chunk of the universe we can observe—no matter how large—must have expanded from an infinitesimally small volume of space.

By determining how fast the universe is expanding now, and then "running the movie of the universe" backwards in time, we can determine the age of the universe. The result is that space started expanding 13.7 billion years ago. This number has now been experimentally determined to within 1% accuracy.

It's a common misconception that the entire universe began from a point. If the whole universe is infinitely large today (and we don't know yet), then it would have been infinitely large in the past, including during the Big Bang. But any finite chunk of the universe—such as the part of the universe we can observe today—is predicted to have started from an extremely small volume.

Part of the confusion is that scientists sometimes use the term "universe" when they're referring to just the part we can see ("the observable universe"). And sometimes they use the term universe to refer to everything, including the part of the universe beyond what we can see.

It's also a common misconception that the Big Bang was an "explosion" that took place somewhere in space. But the Big Bang was an expansion of space itself. Every part of space participated in it. For example, the part of space occupied by the Earth, the Sun, and our Milky Way galaxy was once, during the Big Bang, incredibly hot and dense. The same holds true of every other part of the universe we can see.

We observe that galaxies are rushing apart in just the way predicted by the Big Bang model. But there are other important observations that support the Big Bang.

Astronomers have detected, throughout the universe, two chemical elements that could only have been created during the Big Bang: hydrogen and helium. Furthermore, these elements are observed in just the proportions (roughly 75% hydrogen, 25% helium) predicted to have been produced during the Big Bang. This is the nucleosynthesis of the light elements. This prediction is based on our well-established understanding of nuclear reactions—independent of Einstein's theory of gravity.

Second, we can actually detect the light left over from the era of the Big Bang. This is the origin of the cosmic microwave background radiation. The blinding light that was present in our region of space has long since traveled off to the far reaches of the universe. But light from distant parts of the universe is just now arriving here at Earth, billions of years after the Big Bang. This light is observed to have all the characteristics expected from the Big Bang scenario and from our understanding of heat and light.

The standard Hot Big Bang model also provides a framework in which to understand the collapse of matter to form galaxies and other large-scale structures observed in the Universe today. At about 10,000 years after the Big Bang, the temperature had fallen to such an extent that the energy density of the Universe began to be dominated by massive particles, rather than the light and other radiation which had predominated earlier. This change in the form of matter density meant that the gravitational forces between the massive particles could begin to take effect, so that any small perturbations in their density would grow. Thirteen point seven billion years later we see the results of this collapse in the structure and distribution of the galaxies.

For further reading about cosmology and the Big Bang, see Silk (2001).

Web Reference
http://cfa-www.harvard.edu/seuforum/

Before the Bang

An Interview with two University of Washington Astronomy Professors

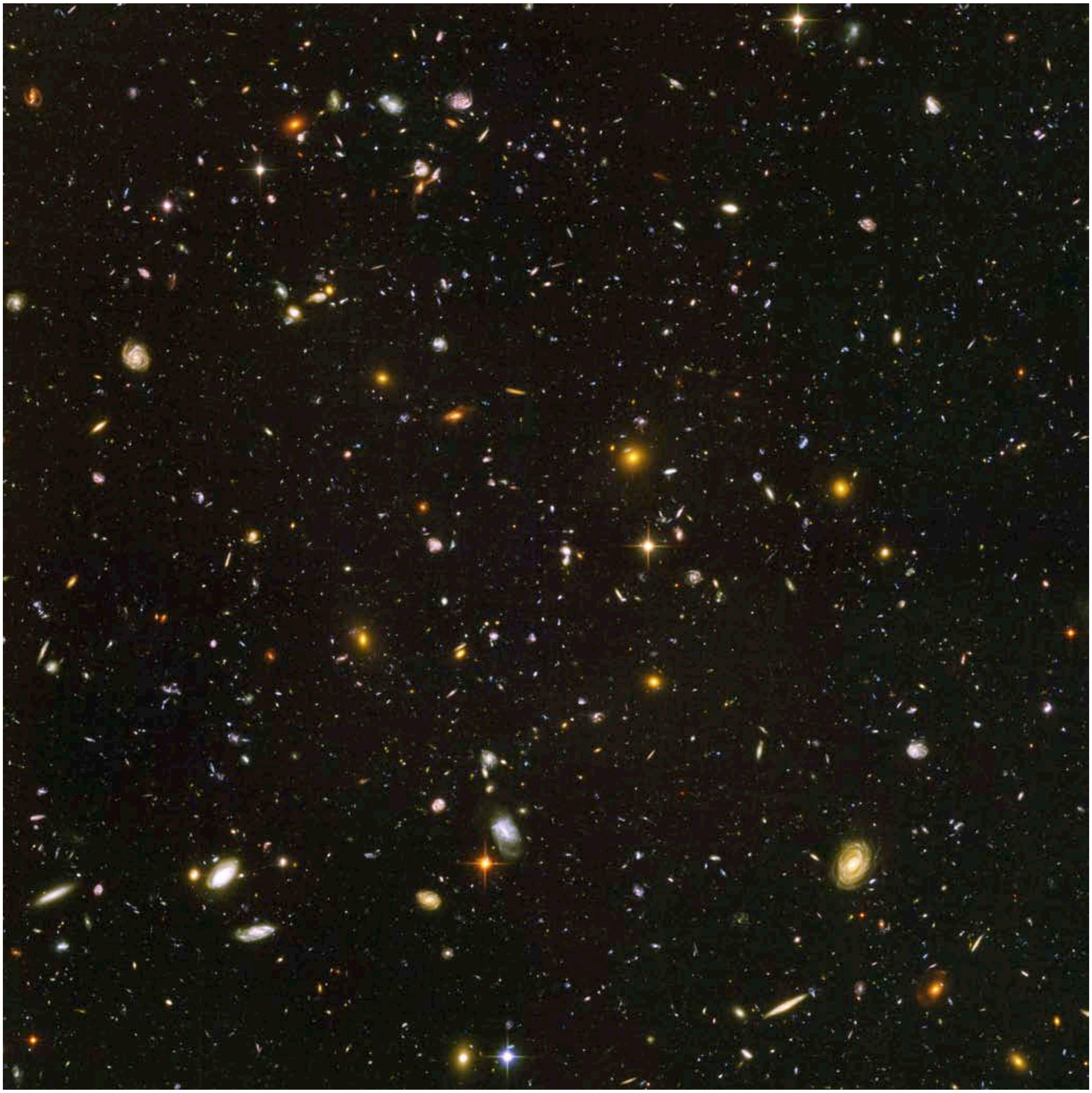
Modern physics enables astrophysicists to calculate the size and density of the universe at any time in its 13.7-billion year history—right back to the Big Bang. Scientists are very proud of this accomplishment. "Only the first 10^{-43} seconds remain obscure," notes a self-confident UW Astronomy Professor Bruce Margon.

But what happened before the Big Bang? That stops Astronomy Chair Craig Hogan dead in his tracks. "What, you're not greedy or anything, are you?," he asks with incredulity that anyone would not be satisfied to know what happened over 13.7 billion years after the Big Bang.

And then he pauses, thoughtfully: "What happened before?," he muses. "No one could really know. All memory of that time is lost, everything from then is forgotten. That was a period of such catastrophic instability that it just doesn't remember what came before it. We probably could never find out, either. There just isn't any information left over from it."

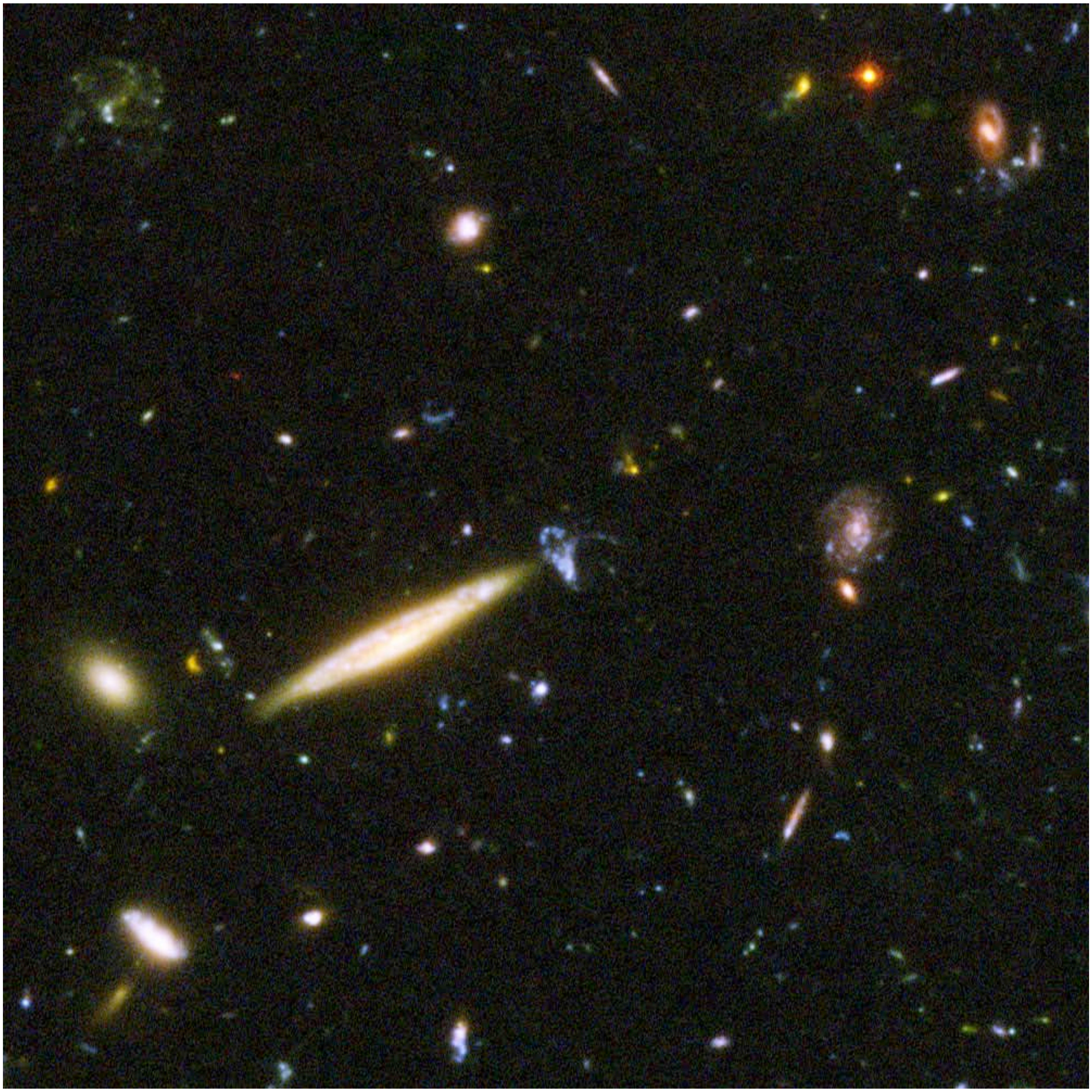
Margon has addressed this question, too. As he told the Washington Post last year, "One would think that if someone has trouble reconciling religion with physics, they would like the Big Bang. It has beautiful elements of ultimate mystery."

What happened before the Big Bang is a very good question, even an important question. But because there's no possibility of physical evidence from this period, it's not a question that science can address.



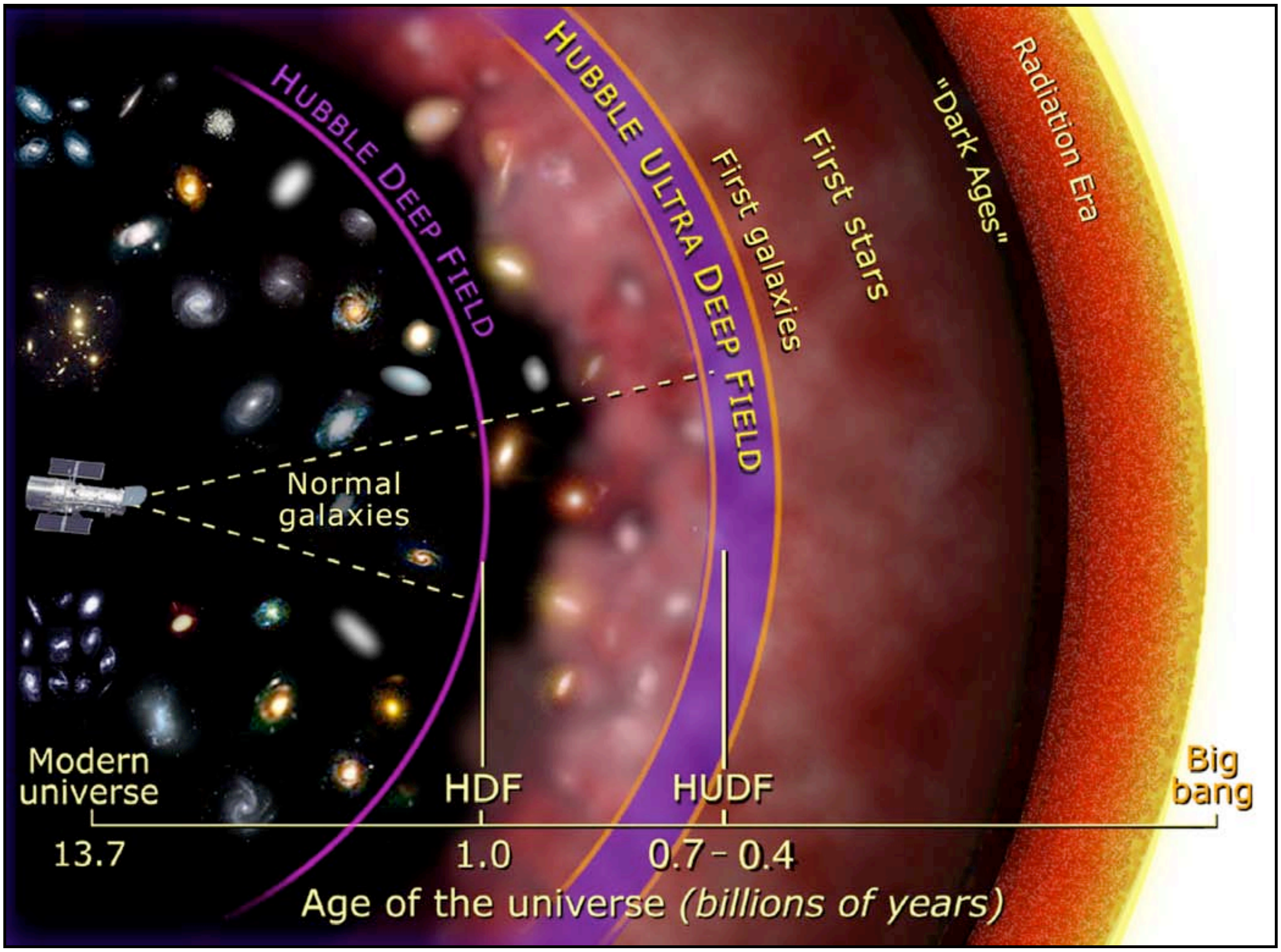
This view of nearly 10,000 galaxies is the deepest visible-light image of the cosmos. Called the Hubble Ultra Deep Field, this galaxy-studded view represents a "deep" core sample of the universe, cutting across billions of light-years.

The snapshot includes galaxies of various ages, sizes, shapes, and colors. The smallest, reddest galaxies, about 100, may be among the most distant known, existing when the universe was just 700 million years old. The nearest galaxies—the larger, brighter, well-defined spirals and ellipticals—thrived about 1 billion years ago, when the cosmos was 13 billion years old.



In vibrant contrast to the rich harvest of classic spiral and elliptical galaxies, there is a zoo of oddball galaxies littering the field, as shown in this close-up view. Some look like toothpicks; others like links on a bracelet. A few appear to be interacting. These oddball galaxies chronicle a period when the universe was younger and more chaotic. Order and structure were just beginning to emerge.

Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap040929.html



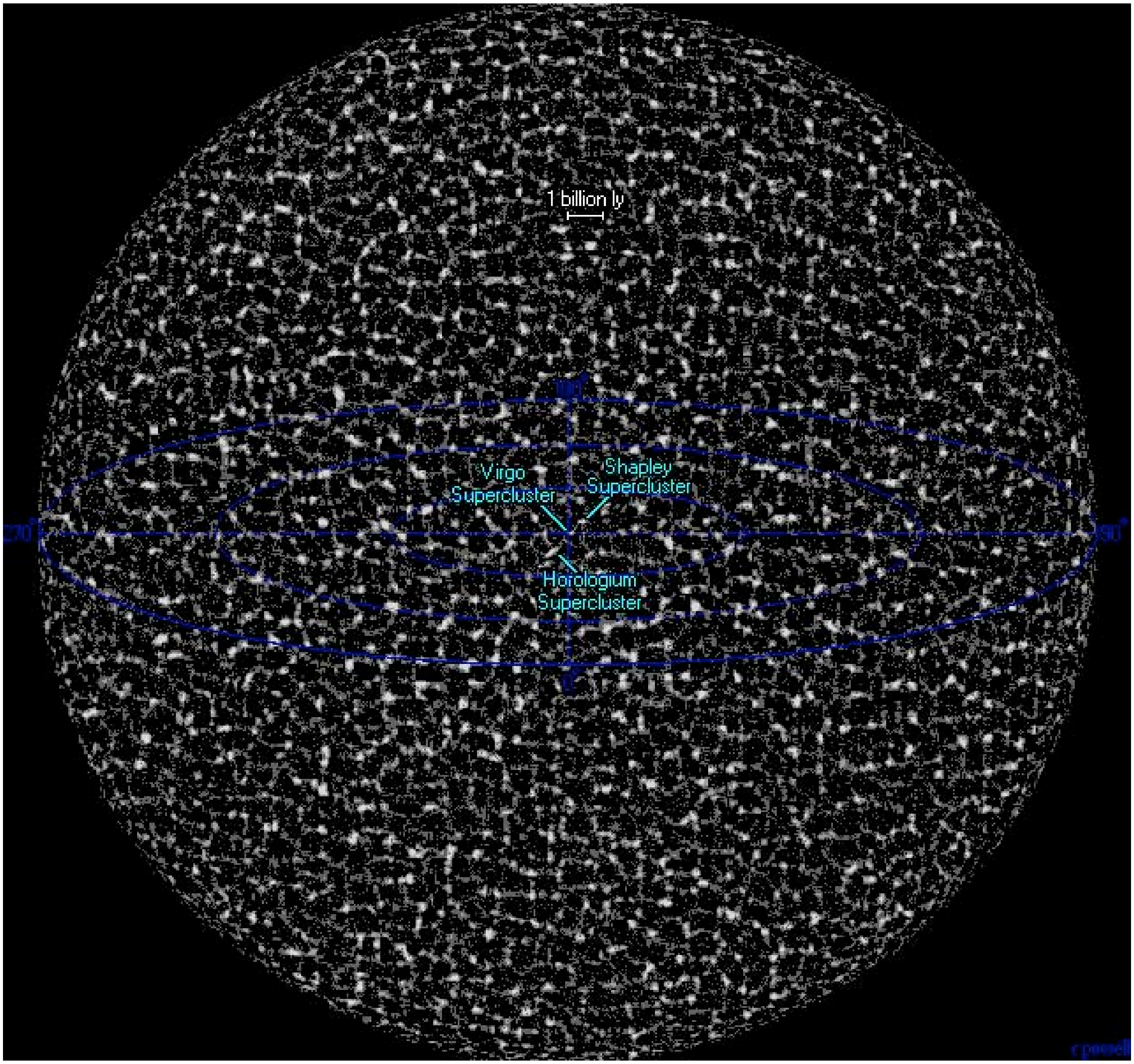
The Hubble Deep Field (HDF), released June of 2003, looked back to within a million years after the Big Bang. The Hubble Ultra Deep Field (HUDF), released March 2004, looks back even further to a time only 700 million years after the Big Bang, close to the period when the first galaxies formed.

HUDF Image Credits: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

Web References

HDF http://hubblesite.org/newscenter/archive/2003/18/

HUDF http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/07/



Above is a representation by Richard Powell of the “observable universe” with an uncorrected diameter of 27.4 billion light years (current estimates that correct for the expansion of the universe put the diameter at least 156 billion light years wide).

When speaking of the visible or observable universe, since by definition it is what is visible from Earth, the Earth is at the center. Note that the filaments (light gray areas above) of superclusters of galaxies, on the largest scale of the universe, are homogenous.

Web Reference

http://www.anzwers.org/free/universe/index.html

The Observable Universe

The estimate that the observable universe is 156 billion light years wide comes from data obtained by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) that examined the cosmic microwave background radiation—often called the echo of the Big Bang. The echo contains information of what the cosmos was like when it was young and how it might develop.

The cosmos is 13.7 billion years old but the stretching of space with its expansion after the Big Bang means that simple distance measurements do not apply. This means that radiation reaching us from the earliest universe has been traveling for more than 13 billion years. But the assumption that flows from this—that the radius of the observable universe is 13.7 billion light years, and that it is 27.4 billion light years wide does not follow. Astronomers realize the universe is more complex. It has been expanding ever since the Big Bang when energy, space and time itself began. According to Neil Cornish of Montana State University and colleagues writing in the journal *Physics Review Letters*, the distance covered by the light in the early universe gets increased by its overall expansion.

To get the picture try to imagine the universe a million years after the Big Bang. Light travels for a year, covering one light year. But at that time, the universe was about a thousand times smaller than it is today meaning that one light year has now become stretched to about a thousand light years. When this expansion is taken into account the observable universe is bigger than it would appear to be. Because of this stretching, radiation from the early universe cannot be said to have traveled 78 billion light years. What it means is that the starting point of a particle of light, a photon, reaching us today after traveling for 13.7 billion years is now 78 billion light years away (Whitehouse, 2004).

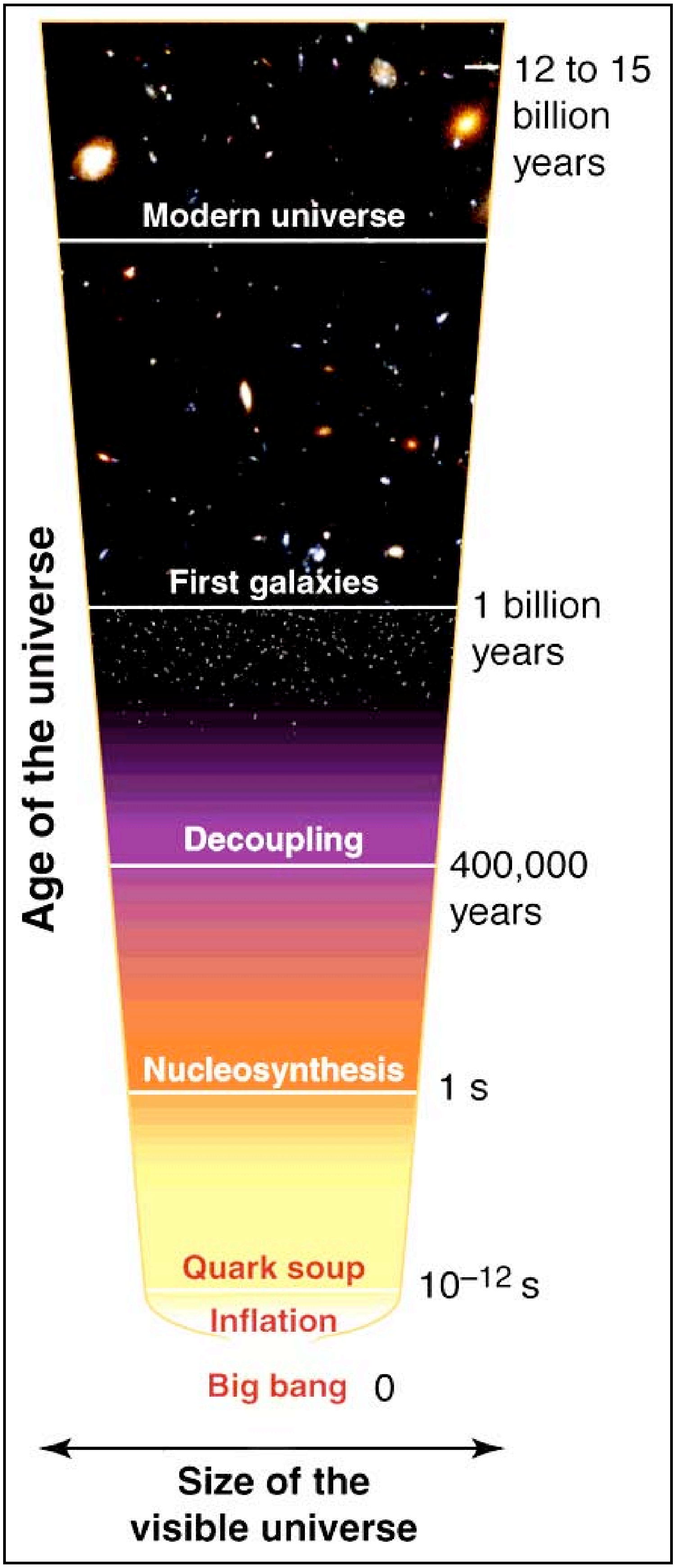
The Early Cosmos: Out of the Darkness

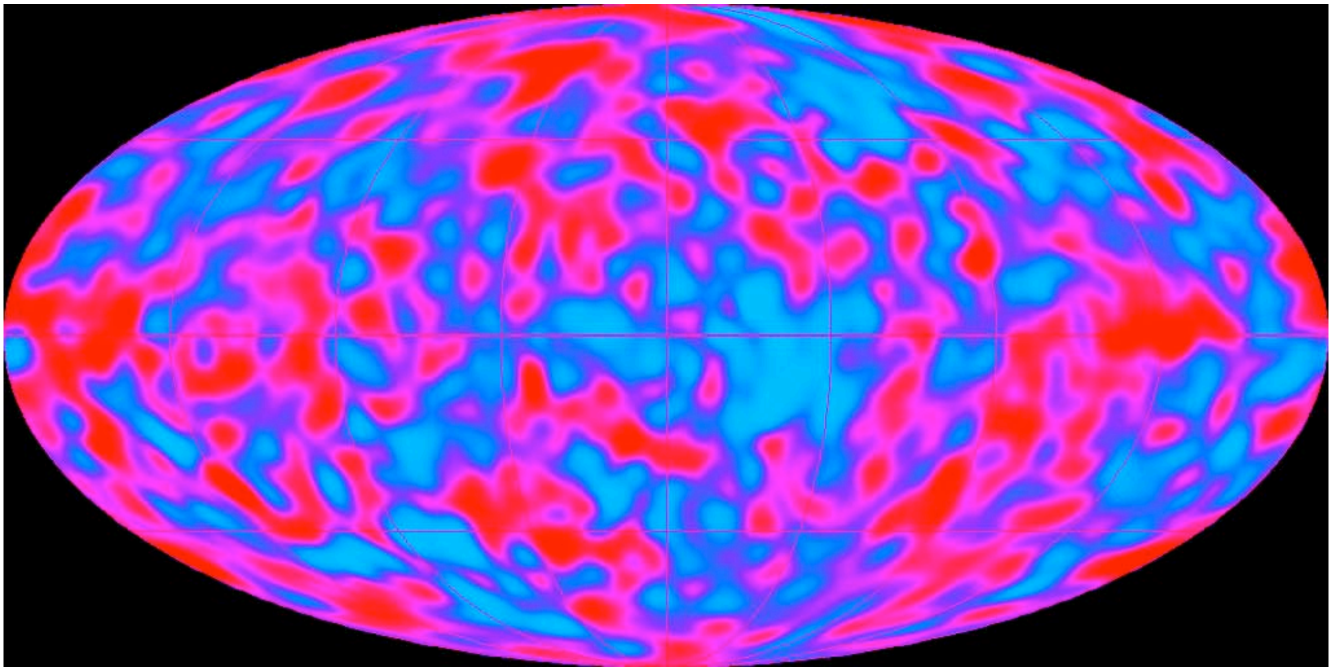
Although no stars and galaxies existed just after the Big Bang, the young cosmos was anything but dull. It was humming with activity. In the beginning, physical conditions were so extreme that matter as we know it today did not exist.

During the early part of its existence, after one times ten to the minus 12th of a second, our universe was so small and dense that light and matter intertwined; space was hot, dark, and ionized—filled with a plasma of charged particles. By the time the universe was one second old, the temperatures and densities had dropped enough for protons and neutrons to form from quarks. Within the next few minutes, the nuclei of the light elements, hydrogen, helium, and lithium, were created in a process called primal or Big Bang nucleosynthesis. The universe at this point was cooling rapidly enough to shut off the process of nucleosynthesis before elements heavier than boron could form.

About four hundred thousand years after the Big Bang the cosmos had grown large enough for matter and energy to move through space without immediately colliding—ending the plasma state of the early universe. The universe had cooled to about 3,000 degrees Celsius (5,400 degrees Fahrenheit) allowing electrons, protons, and neutrons to come together to form neutral atoms—the basic building blocks of all visible matter in the universe. This marked the “Decoupling” of matter and energy that we detect today as the cosmic microwave background radiation. This radiation has been stretched and cooled by the expansion of the universe from three thousand degrees to minus 270.42 degrees Celsius, or just three degrees above absolute zero.

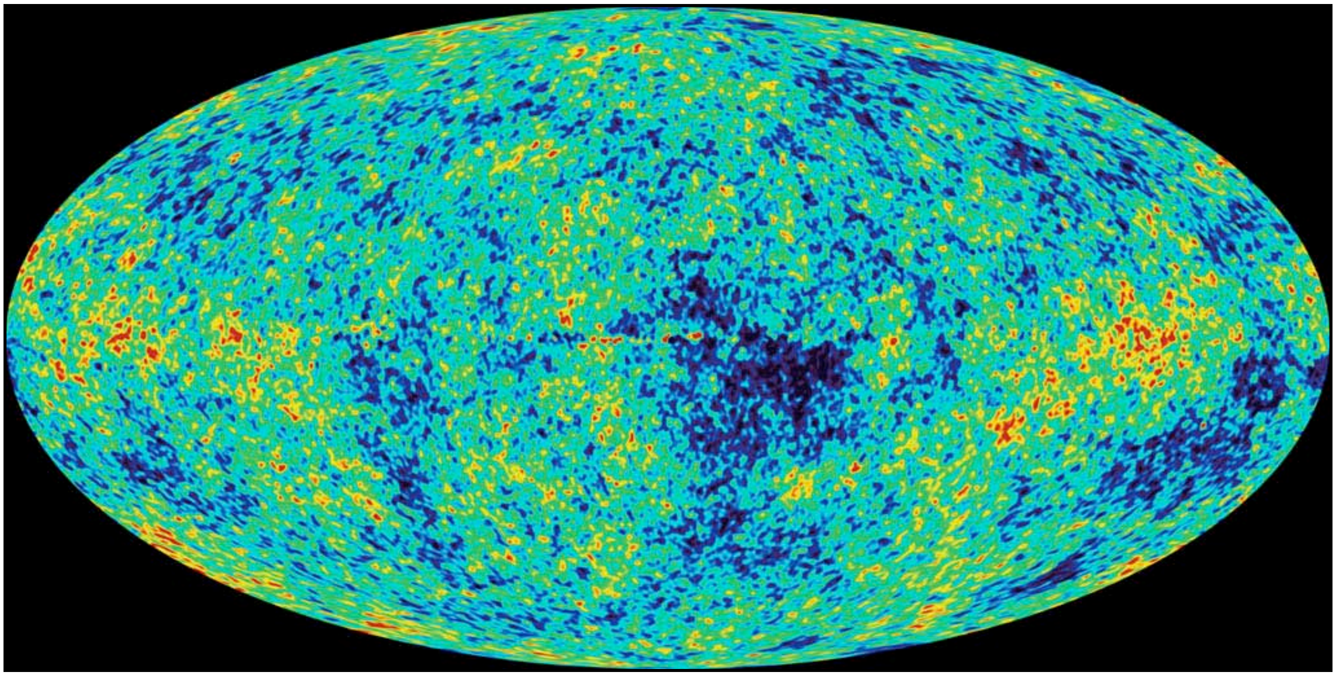
At this point the universe was made up mostly of clouds of hydrogen and helium atoms. As the universe expanded and cooled, some regions of space amassed slightly higher densities of hydrogen. As millions of years passed, the slight differences grew large, as dense areas drew in material because they had more gravity. Researchers have dubbed this period of coalescing the "Dark Ages."


12 to 15 billion years
Modern universe
First galaxies
1 billion years
Decoupling
400,000 years
Nucleosynthesis
1 s
Quark soup
10^{-12} s
Inflation
Big bang
0
Age of the universe
Size of the visible universe



COBE All-Sky Map of variations in the Cosmic Microwave Background Radiation

The Cosmic Background Explorer (COBE) satellite was launched in 1989, twenty five years after the discovery of the microwave background radiation in 1964. In spectacular fashion in 1992, the COBE team announced that they had discovered "ripples at the edge of the universe", that is, the first sign of primordial fluctuations at 380,000 years after the Big Bang. These are the imprint of the seeds of galaxy formation. These appear as temperature variations on the full sky map that COBE obtained (shown above). Red areas represent areas with slightly higher temperatures and blue areas a slightly lower temperature than the mean.

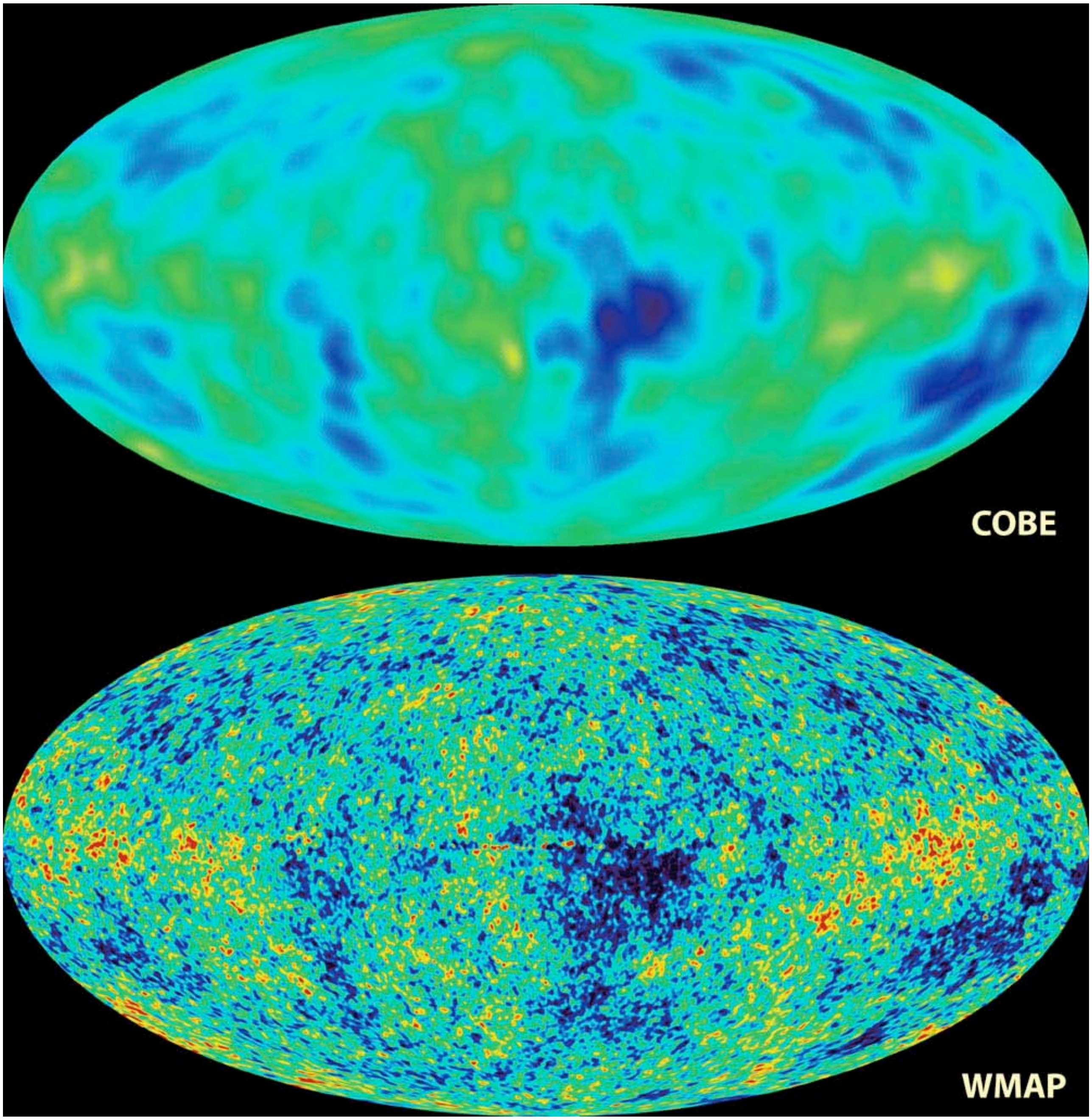


Wilkinson Microwave Anisotropy Probe (WMAP) All-Sky Map

Analyses of a new high-resolution map of microwave light emitted only 380,000 years after the Big Bang (pictured above) appear to define our universe more precisely than ever before. The results from the orbiting Wilkinson Microwave Anisotropy Probe resolve several long-standing disagreements in cosmology rooted in less precise data. Specifically, present analyses of the WMAP all-sky map indicate that the universe is 13.7 billion years old (accurate to 1 percent), composed of 73 percent "dark energy", 23 percent cold dark matter, and only 4 percent atoms, is currently expanding at the rate of 71 km/sec/Mpc (accurate to 5 percent), underwent episodes of rapid expansion called inflation, and will expand forever. This new experimental data provides a dramatic and direct confirmation of the Hot Big Bang model.

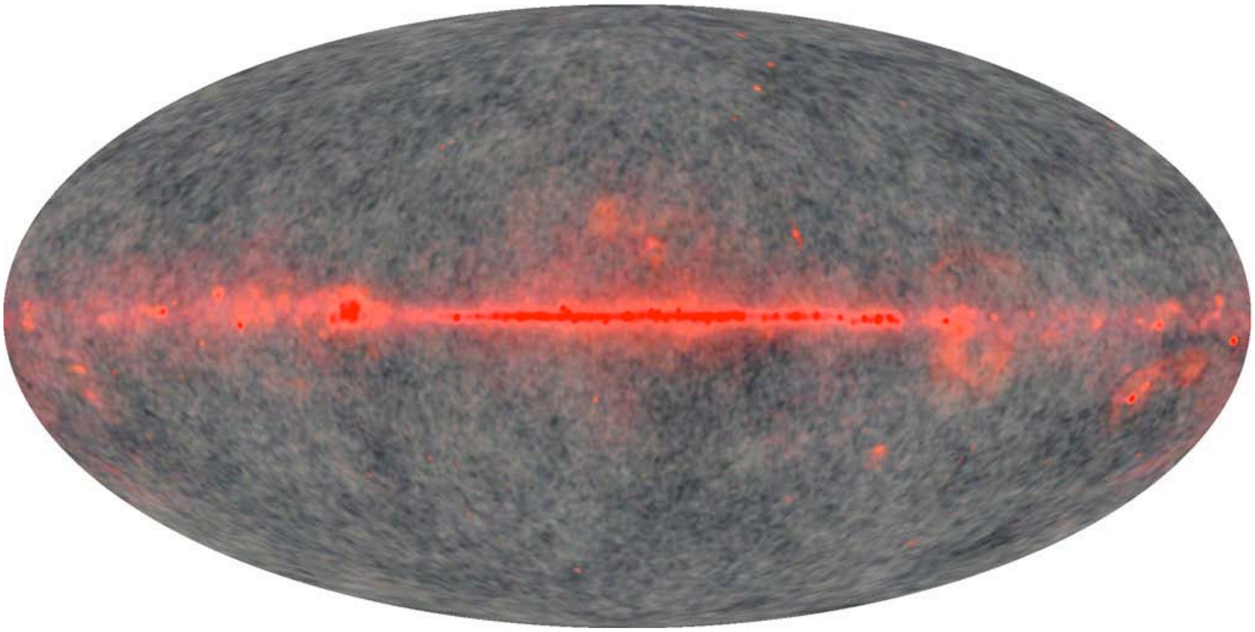
(Image courtesy of NASA/WMAP Science Team)

Web Reference
http://map.gsfc.nasa.gov/m_mm.html



Comparison of the COBE sky map with that obtained from the WMAP satellite shows the increase in resolution of the new data. It is analogous to replacing a small telescope (COBE) with a very large telescope (WMAP).

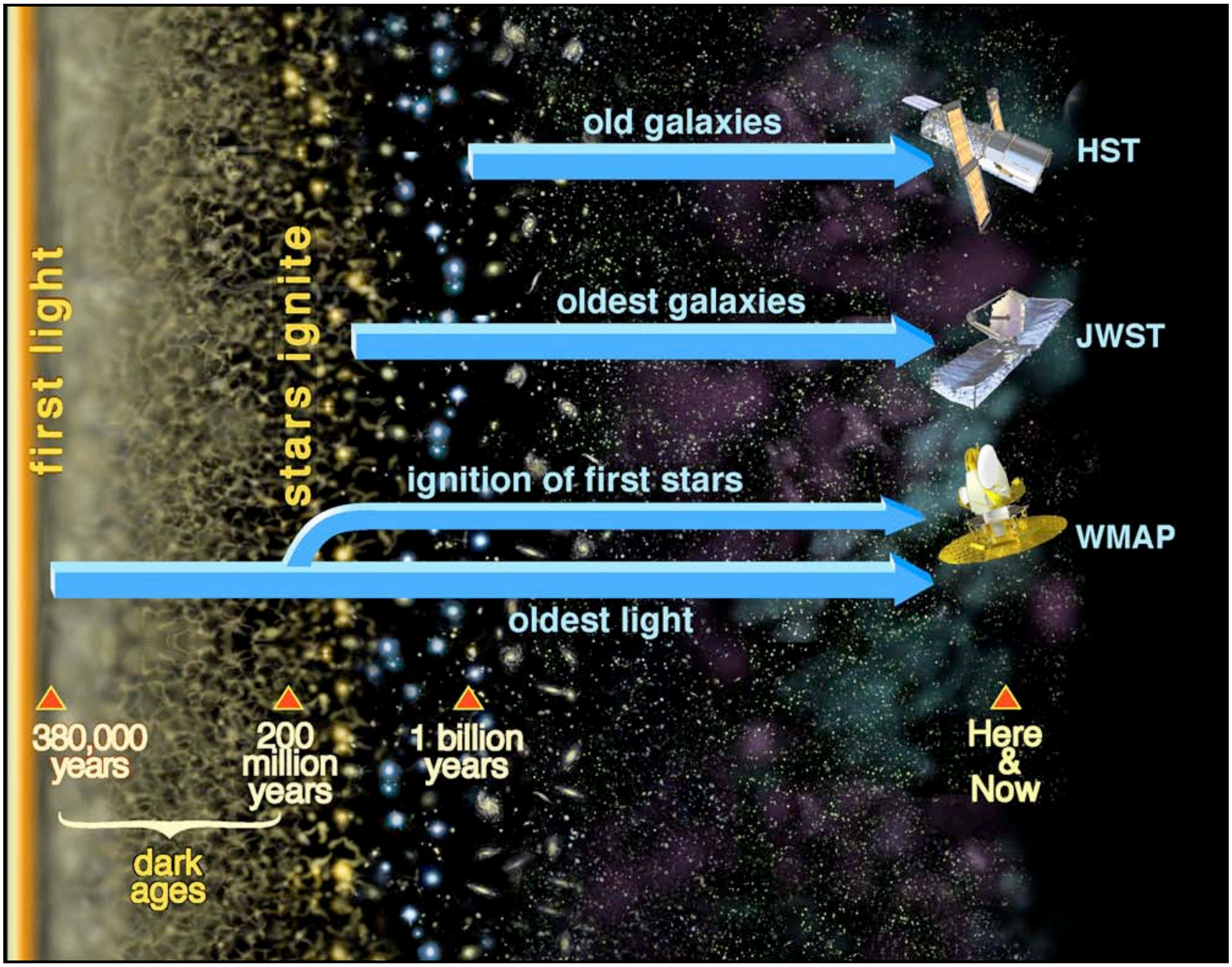
(Images courtesy of NASA/WMAP Science Team)



The sky map above, taken by the WMAP satellite, tells us the universe is 13.7 billion years old—but how? At first look, one only sees the microwave glow of gas from our Milky Way Galaxy, coded red, and a spotty pattern of microwaves emitted from the early universe, coded in gray. The gray cosmic microwave background is light that used to bounce around randomly but came directly to us when the expanding universe became cool enough for nearly transparent atoms to form. A close inspection of the spots reveals a slightly preferred angular distance between them. One expects such a pattern to be generated by sound emanating from slightly over-dense regions of the early universe. Sound waves will take time to generate such a pattern, and the present age of the universe can be directly extrapolated from this pattern. Using this method the age of the universe can be estimated to an accuracy of 1%.

(Image courtesy of NASA/WMAP Science Team)

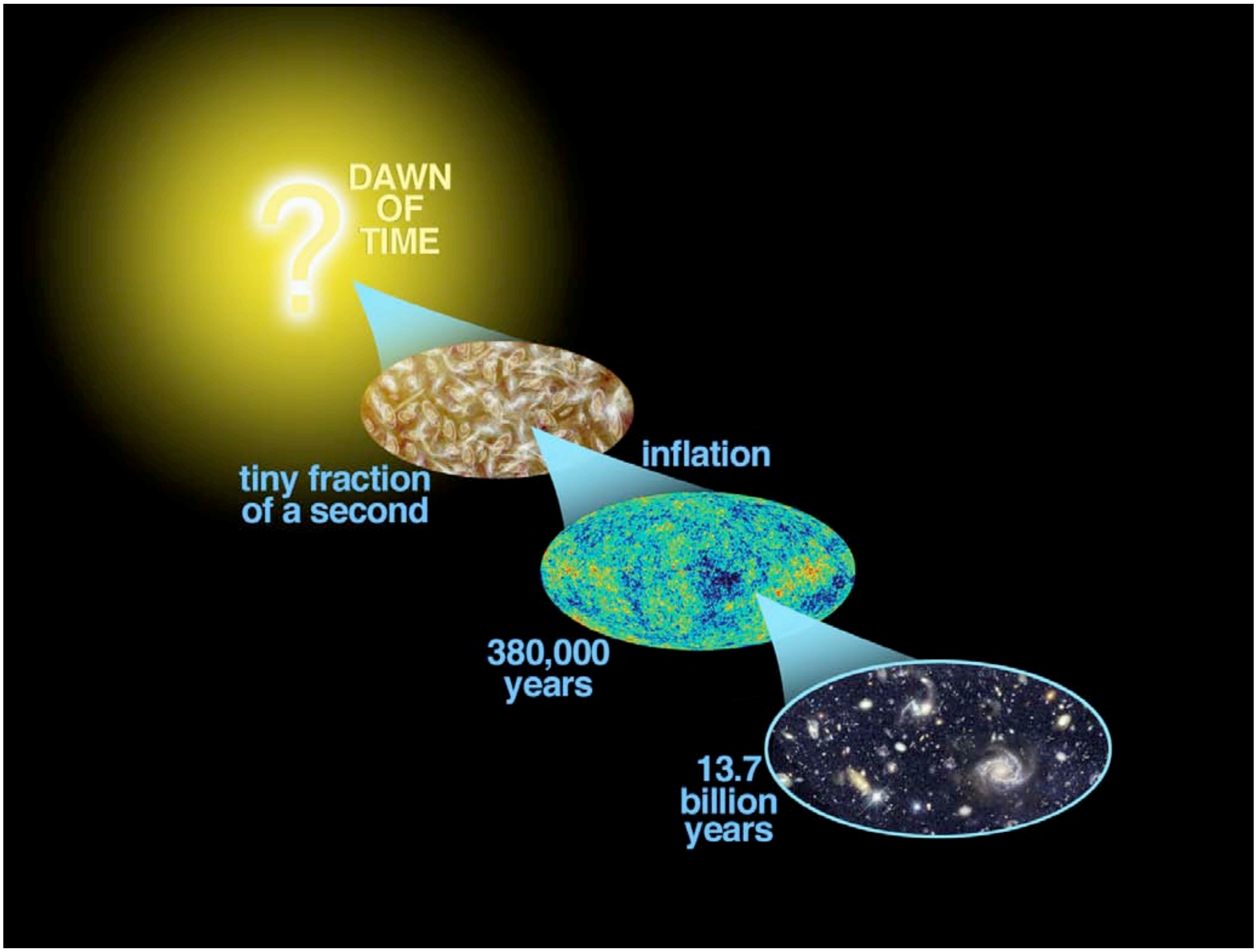
Web Reference
http://antwrp.gsfc.nasa.gov/apod/ap030217.html



Looking Back In Time

This image illustrates the ages of light detected by three NASA missions: the Hubble Space Telescope (HST), the Wilkinson Microwave Anisotropy Probe (WMAP), and JWST. The James Webb Space Telescope (JWST) is an orbiting infrared observatory that will take the place of the Hubble Space Telescope at the end of this decade.

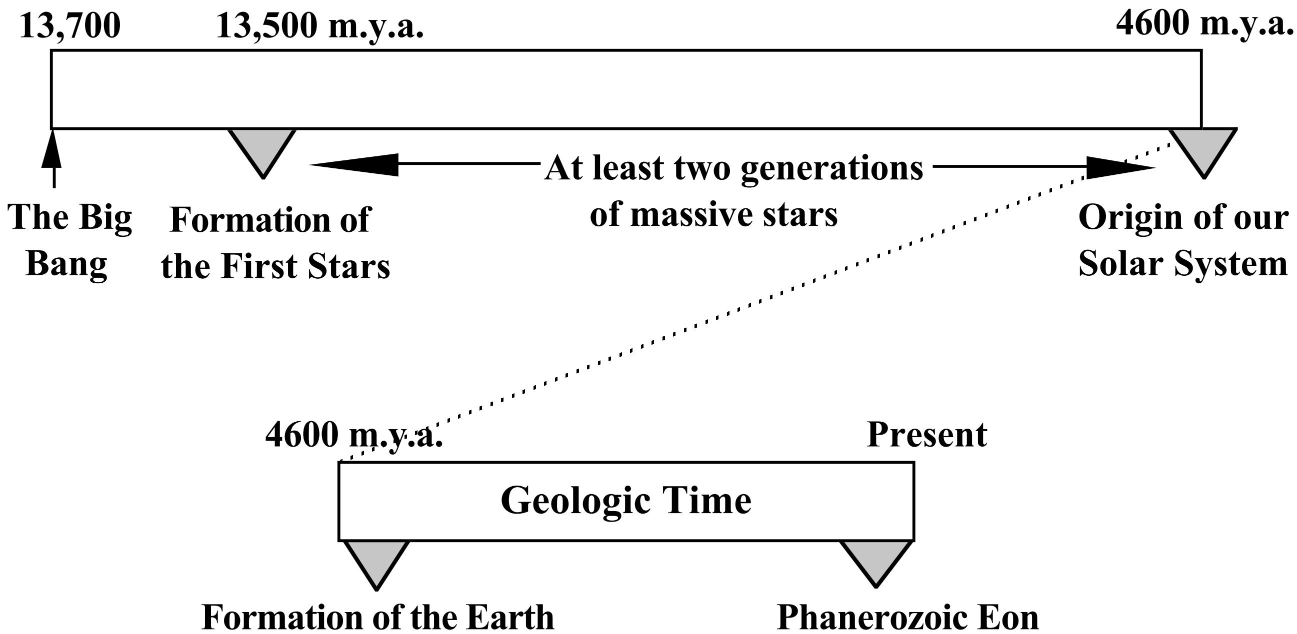
(Image courtesy of NASA/WMAP Science Team)



A New Timeline for the Evolution of the Universe

(Image courtesy of NASA/WMAP Science Team)

Cosmological Timeline



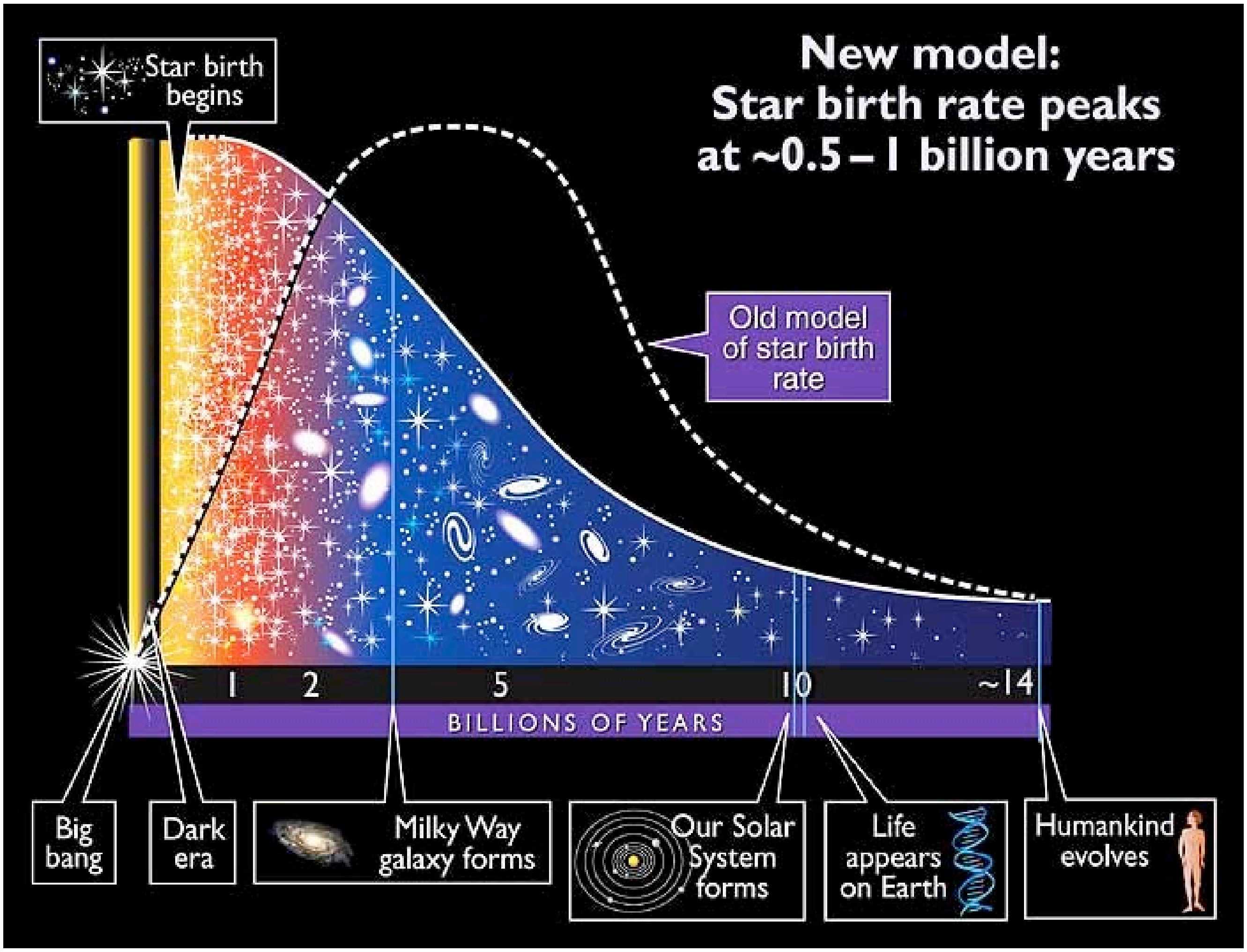
All dates are in millions of years ago (m.y.a.).

The dawn of light, called the "cosmic renaissance," began as hydrogen collapsed into small areas, eventually reaching the point at which the effect of gravity became great enough to trigger nuclear fusion reactions and form the first stars. These first-generation stars were probably born 200 million years after the Big Bang.

Today, astronomers who study distant galaxies are beginning to probe the cosmic renaissance. Roughly a thousand galaxies have been identified whose light left them when the universe was about one billion years old. At that epoch stars were forming at a rate about 10 times higher than in the present-day universe. Stars in that early epoch were making heavier elements, such as carbon and oxygen, which mixed with pristine gas from the Big Bang to create successive generations of stars.

Artist's View of Star Formation in the Early Universe
Painting by Adolf Schaller • STScI-PRC02-02

This is an artist's impression of how the very early universe might have looked when it went through a voracious onset of star formation, converting primordial hydrogen into myriad stars at an unprecedented rate. Back then the sky would have looked markedly different from the sea of quiescent galaxies around us today. This sky is ablaze with primeval starburst galaxies; giant elliptical and spiral galaxies have yet to form. Within the starburst galaxies, bright knots of hot blue stars come and go like bursting fireworks shells. The most massive stars self-detonate as supernovas, which explode across the sky like a string of firecrackers. The foreground starburst galaxies at the lower right are sculpted with hot bubbles from supernova explosions and torrential stellar winds.



Recent analysis of Hubble Space Telescope deep sky images supports the theory that the first stars in the universe appeared in an abrupt eruption of star formation, rather than at a gradual pace. The universe could go on making stars for trillions of years to come, before all the hydrogen is used up, or is too diffuse to coalesce. But the universe will never again resemble the star-studded tapestry that brought light to the darkness.

Web References

http://oposite.stsci.edu/pubinfo/pr/2002/02/pr.html

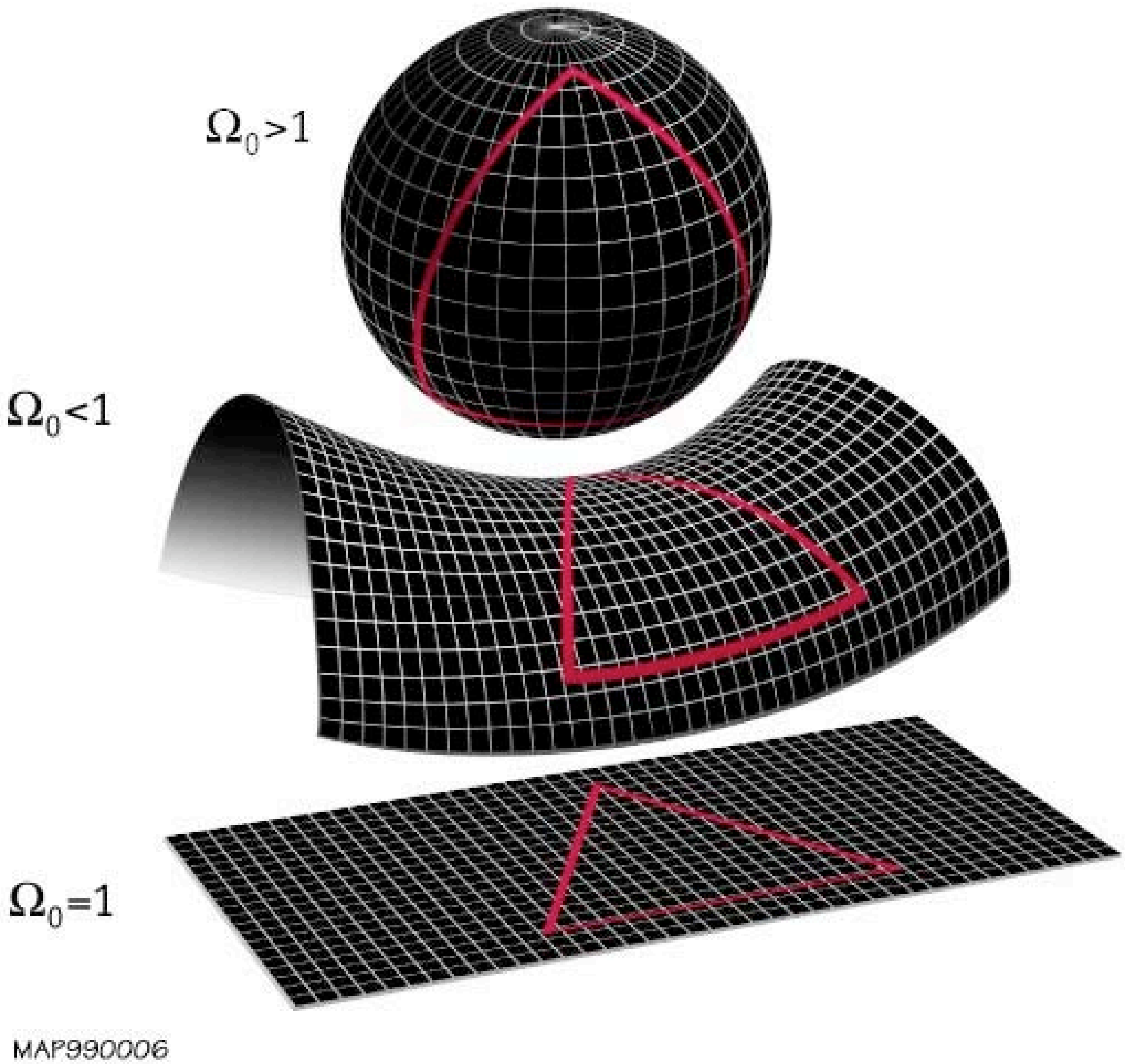
http://antwrp.gsfc.nasa.gov/apod/ap030610.html

The Fate of the Universe

Dr. Allan Sandage, the Carnegie Observatories astronomer, once called cosmology "the search for two numbers" The first number is the Hubble constant, which tells how fast the universe is expanding. Together with the other number telling how fast the expansion is slowing, they determine whether the universe will expand forever or not.

The second number, known as the deceleration parameter, indicates how much the cosmos had been warped by the density of its contents. In a high-density universe, space would be curved around on itself like a ball. Such a universe would eventually stop expanding and fall back together in a big crunch that would extinguish space and time, as well as the galaxies and stars that inhabit them. A low-density universe, on the other hand, would have an opposite or "open" curvature like a saddle, harder to envision, and would expand forever.

In between with no overall warpage at all was a "Goldilocks" universe with just the right density to expand forever but more and more slowly, so that after an infinite time it would coast to a stop. This was a "flat" universe in the cosmological parlance, and to many theorists the simplest and most mathematically beautiful solution of all. This solution has now been confirmed by the Wilkinson Microwave Anisotropy Probe.



It is now thought that Omega (Ω), the ratio of the density of matter in the universe to the density of matter required for a flat universe, is equal to one. That is, the universe is flat so it will expand forever but more and more slowly, so that after an infinite time it will coast to a stop.

Web Reference
http://map.gsfc.nasa.gov/m_uni/uni_101bb2.html

An Accelerating Universe

Excerpts from *A Cosmic Conundrum* by Krauss & Turner (2004)

Beginning in 1998, the cozy picture of a flat, ever expanding universe began to unravel. In 1998, two research groups, working independently, one led by Saul Perimutter, the other by Brian Schmidt, both made the same startling discovery. Over the past five billion years the expansion of the universe has been speeding up, not slowing down as it would under the influence of gravity alone. Since then the evidence for a cosmic speedup has gotten much stronger and has revealed not only a current accelerating phase but an earlier epoch of deceleration dominated by gravity. Added to the question of what is causing the acceleration, a flat universe requires a critical energy density, but ordinary matter even combined with cold dark matter together comprise only 27 present of the needed mass, leaving the balance of 73 percent to be in the form of a mysterious "dark energy".

Vacuum or Dark Energy—a new form of energy driving the cosmic expansion

One proposal for what is driving the current accelerating phase of the universe is the energy of space itself. In quantum mechanics even empty space has an energy density in the form of virtual particles that appear and then disappear almost instantaneously. On the very small scales where quantum effects become important, even empty space is not really empty. Instead virtual particle-antiparticle pairs pop out of the vacuum travel for a short distance and then disappear again on timescales so fleeting that one cannot observe them directly. Yet their indirect effects are very important and can be measured. This vacuum energy is now thought of as Einstein's cosmological term. This new concept of the cosmological term, however, is quite different from the one Einstein introduced into his equations. The problem with this picture, however, is that all calculations and estimates of the magnitude of the empty-space energy so far, lead to absurdly large values.

It is also possible that the explanation of cosmic acceleration will have nothing to do with resolving the mystery of why the cosmological term is so small or how Einstein's theory can be extended to include quantum mechanics. General relativity stipulates that an object's gravity is proportional to its energy density plus three times its internal pressure. Any energy form with a large, negative pressure—which pulls inward like a rubber sheet instead of pushing outward like a ball of gas—will therefore have repulsive gravity. So cosmic acceleration may simply have revealed the existence of an unusual energy form, dubbed "dark energy", that is not predicted by either quantum mechanics or string theory.

The Fate of the Universe—Updated

The discovery of cosmic acceleration has forever altered our thinking about the future of the universe. Einstein's cosmological model was a universe finite in space but infinite in time, remaining the same fixed size for eternity—a static universe. This universe has no spatial boundaries; it curves back on itself like a circle. After the discovery of cosmic expansion by Edwin Hubble in 1929, cosmologists constructed a model of an infinite universe in which the rate of expansion continuously slowed because of gravity, possibly leading to collapse. In the 1980s theorists added an early phase of rapid growth called inflation, for which there is now good evidence. In the past six years observations have shown that the cosmic expansion began to accelerate about five billion years ago. The ultimate fate of the universe—continued expansion, collapse or a hyper-speedup called the big rip—depends on the nature of the mysterious dark energy driving the accelerated expansion. Given this, we won't be able to predict what the fate of the universe will be until we understand the nature of "dark energy".

For an excellent review of modern cosmology see *The state of the Universe* by Peter Coles (2005).

References

Coles, Peter (2005). The state of the Universe. *Nature*, 433(Jan 20), 248-256.

Krauss, L. M. & Turner, M. S. (2004). A Cosmic Conundrum. *Scientific American*, (Sept), 71-77.

Silk, J. (2001). *The Big Bang (3rd Edition)*. New York: Freeman

Tyson, N. D. & Goldsmith, D. (2004). *Origins: Fourteen Billion Years of Cosmic Evolution*. New York: Norton.

Whitehouse, D. (2004). Astronomers size up the Universe. Story from BBC News http://news.bbc.co.uk/2/hi/science/nature/3753115.stm Retrieved 9/25/04.

For more about cosmology on the web go to:

Introduction to Cosmology by the Microwave Anisotropy Probe (MAP) project http://map.gsfc.nasa.gov/m_uni.html

Cosmology: A Research Briefing by the National Research Council (NRC) http://www.nap.edu/readingroom/books/cosmology/

Foundations of Modern Cosmology by John F. Hawley and Katherine A. Holcomb http://astsun.astro.virginia.edu/~jh8h/Foundations/contents.html

----

For further information on related topics go to:

Cosmological Evolution
http://fire.biol.wwu.edu/trent/alles/Cosmic_Evolution_index.html

Alles Introductory Biology Lecture: *Cosmological Evolution*
http://fire.biol.wwu.edu/trent/alles/101Lectures_Index.html

David L. Alles Biology Home Page
http://fire.biol.wwu.edu/trent/alles/index.html