Revised version of essay for volume edited by Bill Stoeger on philosophical issues in cosmology, in Pachart Press *Philosophy in Science* series

Scientific Revolutions in Cosmology: Overthrowing vs. Encompassing

Nancy Ellen Abrams and Joel R. Primack
Physics Department, University of California, Santa Cruz, CA 95064

Abstract: The claim of Thomas Kuhn that scientific revolutions overthrow preceding theories is only true in the early stages of a science, as illustrated by the Copernican revolution. Once a field has established a fundamental theory, for example Newtonian mechanics, that theory is usually encompassed rather than overthrown by a broader theory that reduces to (i.e., makes the same predictions as) the older theory in appropriate circumstances. The old, encompassed theory then represents the highest grade of truth possible in science, within the limited arena in which its predictions agree with those of the encompassing theory. Physics is searching for a theory that can encompass relativity and quantum theory, not overthrow them. The Big Bang cosmology has encompassed the Newtonian solar system. Inflationary Cold Dark Matter cosmology, our most promising theory today to encompass the Big Bang, challenges us to reassess our human role in light of the new metaphors and visions of our highly counter-intuitive universe. Religions might make moral progress by adopting the scientific model of "encompassing revolutions" and opening to the realization that a larger picture of reality could respectfully encompass the wisdom of their tradition without threatening it.

Many people believe, based on their reading of Thomas Kuhn's book *The Structure of Scientific Revolutions* [1], that when a scientific theory is replaced by a newer and broader theory that makes better predictions, the old theory has simply been overthrown. The newer theory requires new concepts that would have no meaning, or at least a different meaning, in the old theory. As a consequence, although the newer theory is certainly more useful for prediction, the conceptual basis of the newer theory can't be directly compared to that of the older one – Kuhn said that they are "incommensurable." Kuhn therefore denied that the new theory is closer to a "true" representation of the natural world, since there is no convergence in the conceptual frameworks of theories, and eventually the new theory will presumably be overthrown in turn.

This kind of overthrowing revolution has certainly happened – for example, when the Copernican/Newtonian cosmology replaced that of Ptolemy. But we argue here that once a scientific field achieves a well-tested foundational theory, further revolutions may be of a different, encompassing kind, in which the newer theory reduces to the old one in appropriate limits. Moreover, an encompassing relationship between theories defines a special kind of truth – the highest grade of truth available in science. This idea of encompassing theories may also have interesting implications beyond science, for example in ethics and religion.

In physics, we say that there is a "correspondence principle" when one theory makes the same predictions as another theory in an appropriate limiting case. For example, there is a correspondence between Einstein's relativity and Newton's mechanics when speeds are slow (compared to the speed of light) and gravitational fields are weak [2]. Another example is the correspondence between quantum theory and Newtonian

mechanics when the action (mass × speed × distance) is large compared to Planck's constant h, which is typically true in the macroscopic world but not at the atomic scale.

Are there correspondence principles in cosmology? The three cosmologies that we will consider in answering this are the Medieval, the Newtonian, and the modern expanding universe cosmologies. Of course, many people continued to hold a Medieval view of the cosmos long after the end of the Middle Ages, and some still do today. Most educated people today appear to subscribe to an essentially Newtonian conception of the universe beyond the solar system, in which stars are scattered more or less at random in the unchanging arena of infinite space.

The Medieval picture [3] is based on the Ptolemaic and even earlier Platonic and Aristotelian conceptions. The earth was understood to be round and at the center of the universe. Around it nested crystalline spheres, with all the spheres revolving around the earth every day. The spheres also revolved slowly against each other, creating vibrations called the "music of the spheres." The innermost sphere carried the moon, the next carried Mercury, then Venus, then the sun (with Mercury and Venus closely linked to the sun, as we will discuss further below). Beyond the sun were Mars, Jupiter, and Saturn (the Seventh Heaven), the fixed stars, and then the angelic spheres with God surrounding all. This basic hierarchical picture reflected Medieval culture in many ways, including the hierarchies of the Church and of the feudal system. Medieval Jews who had a mystical Kabbalistic picture of the universe represented it also as ten concentric spheres, but although the image is similar, the explanation is different. In Lurianic Kabbalah God creates the universe by withdrawing from a point within Himself, creating a spherical space that is not God for the universe to grow in, a process called *Tzimtzum* in Hebrew. The ten spheres (or *sephirot*, the numbers) represent the emanations of God into the universe. *Ein Sof* – the infinite God – surrounds all [4].

The Medieval cosmos is of finite size, it is geocentric, and it began a finite length of time ago – which later scholars such as Archbishop James Ussher (1581-1656) calculated by adding up the generations in *Genesis*. In the Middle Ages, when one went out at night and looked up, the spheres were majestically high, like the ceiling of a cathedral, but certainly not infinite, since all the spheres revolved around the earth each day. The Medieval picture distinguishes between the material contents of the sublunar world and the perfect, unchanging heavens. The unifying ideas are constant circular motion and the Great Chain of Being [5]: hierarchy, continuity, plenitude. God pervades the entire structure – or gods: pagan planetology coexisted with Christian cosmology.

Galileo's observations with the telescope provided the first convincing evidence that the Ptolemaic picture was wrong. This toppled the entire hierarchical structure of the Medieval universe – including the human universe, whose hierarchies were always assumed to reflect God's cosmic design and had been unquestionable for that reason. Galileo's work, published in Italy in 1610, spread quickly throughout Europe. By 1611 John Donne in England had written [6,7]:

The new Philosophy calls all in doubt,
The Element of fire is quite put out [8];
The Sun is lost, and th'earth, and no man's wit
Can well direct him where to look for it...
'Tis all in pieces, all coherence gone;
All just supply, and all Relation;
Prince, Subject, Father, Son, are things forgot...

Charles I of England was deposed and executed in 1649. Even when the British Monarchy was restored in 1660, the divine right of kings had all but vanished.

The Newtonian cosmos replaced the Medieval picture. In the Newtonian cosmology there is simply empty space, stretching on indefinitely in all directions. The statement in Pascal's *Pensees* [9], "the eternal silence of these infinite spaces alarms me," is an expression of a fear that one simply never encounters in Medieval writings [3]. But it is a common experience in the Newtonian universe.

Newton argued that if the cosmos were finite, then everything would fall to the center [10], so it was probably infinite. But there were paradoxes associated with this: Kepler had already pointed out that the night sky would be bright as day in an everlasting infinite universe ("Olber's paradox" [11]). It also wasn't clear whether the Newtonian universe was created a finite length of time ago. The unifying ideas of the Newtonian picture are deterministic local mechanics and universal gravitation: the laws of motion are the same on earth as throughout the universe. God's role is to create this clockwork universe at the beginning. For Newton at least, God also kept setting the clock right again every so often.

Our modern conception of the universe contains some elements of both Medieval and Newtonian pictures, but it is also very different from them. In the modern cosmos, we know how big the visible universe is, about 10^{28} centimeters (cm). This distance is called the "cosmic horizon." We know how long ago the universe started – about 13 billion years ago. We know that on large scales, it is homogeneous and isotropic (the same in all directions). The contents of the universe are atoms, dark matter, and radiation – but most of the energy density in the universe appears to be associated with "dark energy," related to Einstein's cosmological constant. Dark energy is causing the expansion of the universe to accelerate. Gravity is curvature of spacetime and can create horizons, including the horizons that hide black holes. Nondeterministic quantum mechanics and evolution are the key ideas. It's not clear whether there is a role for God. But if the parameters describing the laws of physics and the structure of the universe were even a little different from their measured values, carbon-based life would be impossible – a situation known as the anthropic principle [12]. Why it is true is a deep mystery. The logical possibilities are (a) that God designed the universe with us in mind; (b) that there are many universes, as suggested by the idea of cosmic inflation (discussed further below), and we naturally live in one suited for our sort of life; or (c) that only one set of values for the physical parameters is mathematically possible, which might in turn follow from a fundamental "theory of everything." Polkinghorne [13] has argued that (a)

is the most economical assumption. But physicists generally try to answer physical questions with physical theories, so naturally most physicists are working on (b) and (c).

Table 1. Three Cosmologies: Medieval, Newtonian, and Modern.

Size R Age T Center	Composition	Unifying Ideas	God's Role?
Medieval Cosmos			
Finite R Finite T Geocentric	Sublunary: **Earth, Water, Air, Fire** Heavens: **Ether**	Circular motion Great Chain of Being	Prime mover Hierarch Saviour
Newtonian Cosmos			
Infinite R? Infinite T? No center	Atoms, Void Ether?	Deterministic mechanics Universal gravitation	Clockmaker
Modern Cosmos			
R = 10^{28} cm T = 10^{10} yr Homogeneous & Isotropic	Atoms **quarks, electrons** Radiation Dark Matter Vacuum	Gravity = space curvature Nondeterministic quantum theory Evolution	Before the Big Bang? Immanent?

Now, what is the relationship among these three cosmologies? It's clear that the Copernican-Galilean-Keplerian-Newtonian revolution overthrew the Ptolemaic system, just as Kuhn explained. Ptolemy is only taught as history and never as science. But the Newtonian picture has not been overthrown. Newtonian cosmology will always be taught as science, because Newton's picture is basically right – *on the scale of the solar system*. The scientific revolution that led to the modern cosmos, including the early 20th century contributions of relativity and quantum mechanics, has encompassed the Newtonian cosmology with an explanation of the universe that works from sub-atomic to astronomical scales and velocities. However, it reduces to the Newtonian treatment for the solar system, for normal sized things on Earth, and generally for macroscopic situations where speeds aren't too high and gravitational forces aren't too great [2].

Thus, modern cosmology represents an encompassing revolution as opposed to an overthrowing revolution. The expanding universe has encompassed the Newtonian solar system.

The Ptolemaic picture was not overthrown by the heliocentric theory of Copernicus, whose main argument for it was aesthetic. It was overthrown by observational data. Galileo's discovery that the four bright moons of Jupiter formed a miniature planetary system was strong evidence, but what absolutely disproved the Ptolemaic scheme was Galileo's observations of the phases of Venus, announced in late 1610. In the Ptolemaic system, Mercury and Venus were treated in a special way, since it was well known that they were never seen far from the sun. These two planets with the shortest periods moved on epicycles centered on a line between the earth and the sun. Since they always lay between the earth and sun, these planets could only be partially illuminated by the sun, and if we could see them sharply they would always appear as crescents. But Galileo found that Venus had a circular shape when it was small, and an increasingly narrow crescent shape as it became larger. This is exactly as expected in the Copernican theory, in which Venus appears small and circular when it is on the opposite side of the sun from the earth, and larger and more crescent-shaped when its orbit around the sun brings it closer to the earth [7]. Moreover, Kepler's nearly contemporaneous calculations, based on Tycho Brahe's accurate observations, showed that the planets move on ellipses with the sun at one focus, with a simple relationship between the speed of the planet and its distance from the sun, and with another simple relationship between the period of the planet and the size of the long axis of its elliptical orbit. Later in the 17^{th} century, Newton showed that all these facts could be explained if the sun attracted the planets with a gravitational force that falls off as the inverse square of the distance. Newton also showed that many other things could then be understood with his new mechanics, including the tides and other phenomena on earth. Indeed, the great power of Newtonian mechanics is its unified treatment of heavenly and earthly phenomena.

The important point here is that there is no limiting case in which the Newtonian scheme reduces to the Ptolemaic one in its predictions for the kinds of observations just mentioned. Moreover the Newtonian scheme is far simpler once its basic ideas are grasped. After the success of the Newtonian synthesis, the Ptolemaic system would never again be taught as science, only as history. The Newtonian system had completely overthrown the Ptolemaic one. However, since the Newtonian scheme accurately predicts the planetary motions, with only tiny errors even for the innermost planets Mercury and Venus (which feel the strongest gravitational force and move the fastest), any subsequent theory must obey a correspondence principle. Relativity and quantum theory do indeed reduce to Newtonian mechanics in the limits appropriate for describing the planetary motions, although the tiny deviations predicted by general relativity provided the first observational tests of that theory.

Charles Misner has pointed out a deep insight about scientific truth arising from this correspondence [14]: the only sort of theory we can know to be "true" is one which has been shown to be false – in the sense that its limitations are known. As philosophers of science from Hume to Popper have emphasized, we can never prove that a scientific

theory is true, since there is always the possibility that new data will be discovered that disprove it. But when a scientific theory has been encompassed by a more comprehensive theory that itself has been well tested, we can have considerable confidence that the encompassed theory is "true" within its known limits. This is the highest grade of scientific truth that is available.

Of course, an encompassing theory "reduces to" the encompassed theory only in its predictions, not in its conceptual framework. In other words, correspondence does not apply to the underlying concepts but rather to the description of observations or measurements. For example, as far as the description of naked eye observations is concerned, the Ptolemaic, Newtonian, and modern cosmologies are equally good. The earth-centered perspective is almost inevitable when viewing the sky with the unaided eye.

> Meeting a friend in a corridor, Wittgenstein said: "Tell me, why do people always say it was *natural* for men to assume that the sun went round the earth rather than that the earth was rotating?" His friend said, "Well, obviously, because it just *looks* as if the sun is going round the earth." To which the philosopher replied, "Well, what would it have looked like if it had looked as if the earth was rotating?" [15]

An illustration that the relationship between the corresponding theories is merely instrumental, not conceptual, is the fact that the term "mass" has a somewhat different meaning in relativity than it does in Newtonian mechanics. This kind of difference underlay Thomas Kuhn's claim [1] that the differences between one scientific theory and the one that replaces it after a scientific revolution are so profound that the theories are "incommensurable". However, much subsequent work by philosophers of science has not succeeded in clarifying this slippery term [16], and it would be a profound mistake to suppose, because translations between successive theories cannot be exact, that science does not make progress but rather merely embraces succeeding fads.

"Conceived as a set of instruments for solving technical puzzles in selected areas," Kuhn wrote, "science clearly gains in precision and scope with the passage of time. As an instrument, science undoubtedly does progress" [17]. But conceptually, he argued, the new theory is really no closer to truth than the one before. However, this argument about conceptual evolution of theories may not be very meaningful. As every physicist learns, one should not get too attached to any particular way of formulating a theory. Not only can there be different verbal formulations, there can be completely different mathematical formulations that nevertheless are related mathematically and lead to identical predictions – for example, a "least action" vs. a "differential equations" formulation. These equivalent formulations may not be of equal value conceptually, however. One version can be more fertile than another, pointing much more clearly toward a larger encompassing theory, or having greater metaphorical value outside science.

Misner's insight emphasizes the importance of a kind of truth that can only be reached by theories that have been shown to be false by having been encompassed.

While no scientist would claim to have reached the kind of Absolute Truth that religious people often demand, an encompassed theory represents a genuine sort of epistemological progress.

Although one or more overthrowing revolutions may occur in the early development of a science, subsequent scientific revolutions are mostly of the encompassing rather than the overthrowing variety. Overthrowing revolutions happen when theories are not based on sufficiently careful experiment and observation. In physics there have been several scientific revolutions since Newtonian mechanics was created, but all of these have been encompassing revolutions. The great achievements in physics in the 19th century were the development of thermodynamics and field theory, and then in the first half of the 20th century the triumph of statistical thermodynamics, relativity, and quantum theory. The successes of these theories can be symbolized by their introduction of new constants of nature that relate concepts previously thought to be independent: electrical and magnetic properties of space, temperature and energy, space and time, time and energy. But in none of these scientific revolutions were the old Newtonian ideas relegated to the dustbin of history, as Ptolemy's theory had been by the Newtonian revolution. In some sense, the search for progress in fundamental physics today is a search for a theory – perhaps superstring theory – that will encompass general relativity and quantum theory, and lead to a deeper understanding of the nature of matter and energy.

In cosmology, a series of major discoveries has occurred in the 20th century. Einstein's general relativity (1916) provided the conceptual foundation for the modern picture. Then Hubble discovered that “spiral nebulae” are large galaxies like our own Milky Way (1922), and that distant galaxies are receding from the Milky Way with a speed proportional to their distance (1929), which meant that we live in an expanding universe. The discovery of the cosmic background radiation by Penzias and Wilson (1966) made scientists take seriously the possibility that the universe began in a very dense, hot, and homogeneous state: the Big Bang. This has been further reinforced by confirmation that the cosmic background radiation has exactly the same spectrum as heat radiation, and the measured abundances of the light elements agree with the predictions of Big Bang theory if the total quantity of ordinary matter (i.e., atoms) is about 5% of the “critical density” [18,19].

The Big Bang theory thus appears to be right, as far as it goes. But it is regarded by cosmologists as unsatisfactory, because it does not explain why the universe started in such a special state of uniform expansion. The startling uniformity of these initial conditions is illustrated by the fact that the temperature of the cosmic background radiation is the same in all directions to an accuracy of about 0.001%, even though according to the Big Bang theory there was no way for the material in these different regions to have come to thermal equilibrium before the radiation was emitted. Nor does the Big Bang explain why, since the temperature is extremely uniform, it is not perfectly uniform. But tiny fluctuations in the temperature and other properties are essential, since if the conditions were everywhere the same there would be no reason for galaxies to form in one place rather than another.

The theory of Cosmic Inflation has been proposed to account for these otherwise puzzling initial conditions of the Big Bang [20]. According to this theory, the universe started by expanding for a brief moment at ever increasing speed. Physical explanations for this initial burst of Cosmic Inflation are readily provided within the context of modern theories of particle physics. Inflationary Cosmology predicts that the total density of matter plus energy of the universe is exactly equal to critical density. This prediction has been confirmed by the latest observations of the cosmic background radiation. Details of the formation and distribution of galaxies, and also of the fluctuations in the temperature of the cosmic background radiation, agree with observations if two key assumptions are right: that most of the matter in the universe is invisible and has properties of the sort predicted by the "Cold Dark Matter" theory [21]; and that the total density of matter is about 1/3 of critical density, with a cosmological constant (or "dark energy") making up the remaining 2/3. Further confirmation of the Inflationary Cold Dark Matter theory was provided by the recent measurements of the brightness of the brightest supernovae as a function of their redshifts, which indicate how much the universe has expanded since they exploded.

People have speculated about the origin of the universe for thousands of years, but only in the last few years have we actually had any reliable data about it. New data has ruled out large classes of theories, such as the alternative cosmological theories known as Cosmic Defects (which includes Cosmic Strings). Inflationary Cold Dark Matter Cosmology is now the only theory that is in excellent agreement with all the data currently available. This is a truly remarkable achievement, given the quality and quantity of data now being provided by the latest generation of ground- and space-based telescopes. But the theory is itself still seriously incomplete, since it does not explain what the mysterious dark matter is [22], nor the nature of the even more mysterious dark energy, nor why the temperature fluctuations are 0.001%. Nor does it explain what came before Cosmic Inflation. However, according to a plausible extrapolation called "Eternal Inflation" [23], the part of the universe that we can see (the part within our cosmic horizon) and a large region of space-time surrounding it are not representative of the vast majority of the volume of the universe. Instead, in most of the universe beyond our region of space-time, inflation reigns forever.

The situation in particle physics is similar: we have a "Standard Model" (the $SU(3)\times SU(2)\times U(1)$ gauge theory of the strong and electroweak interactions), which correctly predicts the results of all the experiments conducted at particle accelerators, but which does not explain why the elementary particles have the properties that they do, such as their masses and charges. The first hints of physics beyond the Standard Model are the discovery of neutrino mass from studies of cosmic rays at the Super-Kamiokande underground laboratory, and the discovery that most of the matter in the universe is dark matter, made of some sort of particle not included in the Standard Model. Thus the search is on for an encompassing theory. Perhaps a superstring "theory of everything" will eventually play that role, although the present version of this theory describes a higher-dimensional space-time whose relationship to our own three+one dimensional space-time remains mysterious. However the search for an encompassing cosmological

theory turns out, it is likely that the current Big Bang theory will remain correct, in the same sense in which Newtonian physics is correct as a limit of several encompassing theories.

Eternal Inflation is the first theory proposed to encompass Cosmic Inflation that could perhaps be true. But unless it can be tested – and at least for now, no one knows how that could be done – it can never really confer upon Cosmic Inflation the truth status of an encompassed theory, let alone itself ever be deemed true. Unless Eternal Inflation can be tested, we may have reached a limit to Misner's kind of scientific truth. Rather than as an encompassing theory, it may be better to think of Eternal Inflation as a grand metaphor whose purpose is to suggest, to open the mind, not yet as something to be regarded even potentially as a scientific truth.

What is the broader significance of correspondence principles in cosmology? Since encompassing theories have different conceptual frameworks from the theories encompassed, the cultural implications of using a new theory's metaphors could be substantial even though the scientific predictions may satisfy a correspondence principle.

Ever since Descartes recommended splitting the study of human meaning from the study of the material world in order to protect science and religion from each other, it has been traditional in Western thought to ignore cosmology in thinking about the cultural universe. To some extent this was also a reaction to the uncertainty of cosmology, which, in the absence of reliable data, had long been the most speculative of sciences. This is no longer the case. Big Bang cosmology is one of the great discoveries of the twentieth century, and it is high time to rethink the human role in terms of it. At the very least, cosmology and the other historical sciences – including geology, evolutionary biology [24], archaeology, and anthropology – provide a increasingly reliable framework for understanding the evolution of the universe, our planet, life, our species, and the rich diversity of human cultures.

An encompassing revolution in science does not behead its predecessors or even depose them. The scientific revolution underway in cosmology illuminates a potentially boundless unknown country, in which formerly great potentates like the Big Bang are revealed as minor princes of now better defined realms. Encompassing is intellectually respectful, and a worldwide community of creativity underlies it. It has decoded something fundamental about nature – that truths need not threaten each other. As our understanding expands, a "true" theory's place becomes secure with the discovery of its limits. Perhaps this has something to teach religion, political ideology, and other human pursuits that demand to be right and cannot imagine that other views could also be. As a model of intellectual progress, the current revolution in cosmology may be able to help religions make moral progress. The first moral improvement will be humility: religions do not possess absolute truth about reality. The only thing about which humans can, but rarely do, know the absolute truth is our own feelings, but even there uncertainty takes over the moment we try to express them. The value of a religious myth can only become secure when it accepts its own limits and allows for the possibility that a larger picture of reality might respectfully encompass it.

Sixteen years ago, Józef _yci_ski, the current Archbishop of Lublin, came to visit our house. (He and Joel had earlier met by chance in an airport in Poland, discovered their mutual passion for astrophysics, and became friends.) Nancy and Józef had a conversation that she relates in the following song. Recently, Nancy performed the song while Charles Misner was in the audience. He came up to her afterward and said, "When did you have that conversation with Józef?" She told him. "Well," Misner replied, "I met with Józef just a month or two before that, and I believe he may have gotten that idea from me." Misner may have provided the idea that an encompassing theory establishes a special kind of truth, but it seems that Józef _yci_ski went beyond. He saw that the concept of encompassing theories opens the possibility of progress in morality without any necessity of abandoning wise aspects of religious tradition.

ALIEN WISDOM

words and music © 1989 Nancy Ellen Abrams

Joseph is an astrophysicist; he knows how stars evolve
How space expands with the Big Bang, what problems remain unsolved
But at any moment he is liable
To put down his pencil and open the Bible

And I said, "Joseph, Joseph
Tell me what is real
With all the science that you know
Tell me what you feel"

Joseph is a Catholic Archbishop. He's a complicated man
He looked at me with a peaceful smile, said, "I'll tell you if I can
The Bible is the word of God
It's universal truth, though it may seem odd"

And I said, "Joseph, Joseph
Somewhere out in space
Don't you think there may be some other
Intelligent race?"

"Yes," he said, "I think it's likely, for it would be a cosmic waste
Of billions of billions of planets if there were no other place
That conscious beings could call home
Where God in His glory could be known"

And I said, “Joseph, Joseph
How can that book you hold
Speak the truth for beings
Of whom nothing can be told?”

Joseph leaned back in his chair
For a moment he was not there
He raised the Bible to his lips
And planted there a kiss
Then he spoke these words as if in prayer

“The Bible is the word of God, but God speaks as we can hear
Universal does not mean ultimate. It may not even come near
We are merely children who've never dreamed
Of the wonders of this universe God may mean
“For hundreds of years Newton's laws
Certainly were true
In the narrow range of experience
That was all humans knew

“Till Einstein helped us see
With the theory of relativity
That things are not as they seem
So yes, alien beings
May have found deeper morality

“But as Einstein's laws reduce
At slow speeds to Newton's simpler truths
Alien wisdom must enfold
This Bible that I hold
For age can only come from youth”

NOTES and REFERENCES

1. T. S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago Press, 1962; 2nd ed. 1970).

2. The gravitational potential at a distance r from a mass M is $\varphi(r) = GM/r$, where G is Newton's constant of gravitation. Writing the speed of light as c, the quantity φ/c^2 is dimensionless – that is, it is a pure number, independent of the choice of physical units of length, time, or mass. The condition that the gravitational potential is small is simply that this number be much smaller than 1. For example, on the surface of the earth, this quantity is $g R_E /c^2 = (9.8 \text{ m/s}^2) \times (6.4 \times 10^6 \text{ m}) / (9 \times 10^{16} \text{ m}^2 / \text{s}^2) = 7.0 \times$

10^{-10}, which is certainly much less than 1. At the earth's distance from the sun, the sun's gravitational potential is also very weak: its dimensionless value is 10^{-8}. Thus Newtonian physics is extremely accurate in these regions for speeds $v << c$. On the other hand, the dimensionless value of the gravitational potential is _ at the Schwarzschild radius, or horizon, around a black hole. Newtonian physics breaks down completely near a black hole, and it is essential to use Einstein's theory of space, time, and gravity, which is known as general relativity.

3. C. S. Lewis, "The Heavens," *The Discarded Image* (Cambridge University Press, 1967), pp. 92-121, is a good summary of the Medieval cosmology.

4. Cf. D. S. Ariel, *The Mystic Quest* (Schocken, 1988), especially pp.169ff; D. C. Matt, *God & the Big Bang* (Jewish Lights, 1996). See also J. R. Primack and N. E. Abrams, " 'In a Beginning': Quantum Cosmology and Kabbalah," *Tikkun* 10 (1), 66-73 (Jan-Feb, 1995).

5. A. O. Lovejoy, *The Great Chain of Being; a Study of the History of an Idea* (Harvard University Press, 1936).

6. J. Donne, "An Anatomie of the World: First Anniversary," in *John Donne's Poetry*, A. L. Clements, ed. (W.W. Norton & Co., 1992), p. 102. Cf. [7], esp. pp. 193ff.

7. T. S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Harvard University Press, 1957).

8. I.e., the sphere of fire, created by the earthly element of fire rising to just below the lunar sphere, no longer exists in the new cosmology.

9. B. Pascal, *Pensees*, Sec. III, no. 206.

10. I. Newton letter to R. Bentley, in *Space, Time and Creation*, M. K. Munitz, ed. (Free Press, 1957).

11. E. R. Harrison, *Darkness at Night: a Riddle of the Universe* (Harvard University Press, 1987).

12. A recent introduction to these anthropic ideas is M. J. Rees, *Just Six Numbers: The Deep Forces that Shape the Universe* (Basic Books, 1999).

13. J. Polkinghorne, *Science and Creation the Search for Understanding* (Books Britain, 1988).

14. C. W. Misner, "Cosmology and Theology", in *Cosmology, History, and Theology*, W. Yourgrau and A. D. Breck, eds. (Plenum Press, 1977), pp. 75-100.

15. T. Stoppard, *Jumpers* (Faber and Faber, 1972), p.66.

16. See H. Sankey, *The Incommensurability Thesis* (Avebury, 1994) for a review of this literature, and P. Hoyningen-Huene, *Reconstructing Scientific Revolutions* (University of Chicago Press, 1993) for a comprehensive study of Kuhn's philosophy of science. *Note added in proof:* After writing the present paper, we became aware of Paul Thagard, *Conceptual Revolutions* (Princeton University Press, 1992). In addition to criticizing Kuhn's writings on incommensurability, Thagard shows that the relativity and quantum mechanics revolutions "sublated" Newtonian mechanics (from Hegel's German term *aufheben*, to both annul and preserve) rather than supplanting it; this is in agreement with our claim that these were encompassing revolutions.

17. T. H. Kuhn, "Metaphor in Science," in *Metaphor and Thought*, A. Ortony, ed. (Cambridge University Press, 1979), pp. 409-419; cf. [1], 2nd ed., p. 206.

18. The cosmological mass density ρ_m is the mass of matter in a very large volume of space, divided by the volume. In general relativity, the critical density can be expressed in terms of G (Newton's constant of gravitation) and the rate of expansion of the universe H (Hubble's constant) as $\rho_c = 3\ H^2 / 8\pi G$. The density is written as Ω when it is expressed in units of critical density: $\Omega_m = \rho_m / \rho_c$. In the absence of a cosmological constant, critical density is the dividing line between a universe that will expand forever ($\Omega_m \leq 1$) or eventually collapse ($\Omega_m > 1$). The total cosmological energy density Ω_{tot} includes the cosmological constant or "dark energy" Ω_Λ. If $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$, as appears to be the case based on the latest observations, then the universe on large scales is "flat" (i.e., parallel light beams neither converge nor diverge).

19. A recent review of the observational evidence with references to the relevant papers is J. R. Primack, "Cosmological Parameters," in *Dark Matter 2000*, D. Cline, ed. (Springer, 2001, in press), available at http://xxx.lanl.gov/astro-ph/0007187.

20. Cosmic Inflation was first proposed by A. Guth, Phys. Rev. D **23**, 347 (1981), although closely related ideas were suggested by several others. A popular account is provided by A. Guth and A. P. Lightman, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins* (Perseus Press, 1998).

21. The cold dark matter (CDM) theory of galaxy and structure formation was presented in G. R. Blumenthal, S. M. Faber, J. R. Primack, M. J. Rees, Nature **311**, 517 (1984). All the presently available data is consistent with the predictions of CDM with $\Omega_m \approx 1/3$ and $\Omega_\Lambda \approx 2/3$ [19]. Detailed comparison of galaxy formation theory in this ΛCDM cosmology with a great deal of data on galaxies is presented in R. S. Somerville and J. R. Primack, Monthly Notices of the Royal Astronomical Society **310**, 1087 (1999).

22. H. Pagels and J. R. Primack, Phys. Rev. Letters **48**, 223 (1982) first proposed that the dark matter particle is the lightest supersymmetric partner particle, which remains perhaps the most popular theory.

23. Eternal Inflation was first worked out by A. Linde, Phys. Lett. **175**, 395 (1986), although similar ideas were put forward earlier by A. Vilenkin, Phys. Rev. D **27**, 2848 (1983). A brief popular account by the present authors is in [4]. See also T. Ferris, *The Whole Shebang: A State-of-the-Universe(s) Report* (Simon & Schuster, 1997), M. J. Rees, *Before the Beginning: Our Universe and Others* (Helix Books, 1998), and the book by Guth [20].

24. Evolutionary biology provides another example of an encompassing scientific revolution. J. M. Smith, "Science and Myth," in *The Natural History Reader*, ed. N. Eldredge (Columbia University Press, 1987), p. 228, says "[Kuhn's] insistence on a distinction between normal and revolutionary science, and on the incommensurability of paradigms, has been exaggerated. The major scientific revolution during my working life has been the rise of molecular biology, which has all the characteristics of a new 'disciplinary matrix' in Kuhn's sense – new scientists, new problems, new experimental methods, new journals, new textbooks, and new culture heroes. But where was the incommensurability? … Those of us trained in classical genetics sometimes had difficulty in learning the new techniques, but there were few conceptual difficulties and no paradigm debate."