Week 2 Review

Intro to Monte Carlo:

The Monte Carlo method was developed by Stanislaw Ulam while he was working on nuclear weapons at Los Alamos National Lab (during WWII possibly, since "Monte Carlo methods were central to the simulations required for the Manhattan Project, though severely limited by the computational tools at the time" http://en.wikipedia.org/wiki/Monte_Carlo_method). Supposedly he thought of the approach while playing a version of Solitaire, known as Canfield Solitaire, in order to determine the probability of winning if all 52 cards were laid out. So at heart, the Monte Carlo method was created to solve a counting problem. But instead of using Combinatorics to solve it, he had the idea to manually observe and count the probability.

Monte Carlo Computations Method:

Monte Carlo is a generic name that describes a wide variety of different computational algorithms. Monte Carlo is a method that determines a numerical result; The Monte Carlo method keeps running a simulation over and over to obtain that numerical result (which is the distribution of an unknown probabilistic entity). Monte Carlo means using random numbers in scientific computing. More precisely, it means using random numbers as a tool to compute something that is not random. The general rule is that deterministic methods are better than Monte Carlo in any situation where the deterministic method is practical.

Solving equations which describe the interactions between two atoms is fairly simple; solving the same equations for hundreds or thousands of atoms is impossible. With MC methods, a large system can be sampled in a number of random configurations, and that data can be used to describe the system as a whole. http://www.chem.unl.edu/zeng/joy/mclab/mcintro.html

A popular example is using the Monte Carlo method to estimate the value of pi. If you actually do this experiment, you'll soon realize that it takes a very large number of throws to get a decent value of pi...well over 1,000 (using a dartboard and counting the number of darts within the circle and the number of darts outside the circle inscribed within a square).

Instead of throwing a dart 1,000 times to estimate the value of pi, we can generate random numbers that act as if we have in fact thrown the dart 1,000 times. If we say our circle's radius is 1.0, for each throw we can generate two random numbers, an x and a y coordinate, which we can then use to calculate the distance from the origin (0,0) using the Pythagorean theorem. If the distance from the origin is less than or equal to 1.0, it is within the shaded area and counts as a hit. Do this thousands (or millions) of times, and you will wind up with an estimate of the value of pi.
How good the estimate is depends on how many iterations are done, and to a lesser extent on the quality of the random number generator (however, computer-generated numbers aren't really random, since computers are deterministic). Simple computer code for a single iteration (or throw) might be:

```
x=(random#)
y=(random#)
dist=sqrt(x^2 + y^2)
if dist.from.origin (less.than.or.equal.to) 1.0
let hits=hits+1.0
```

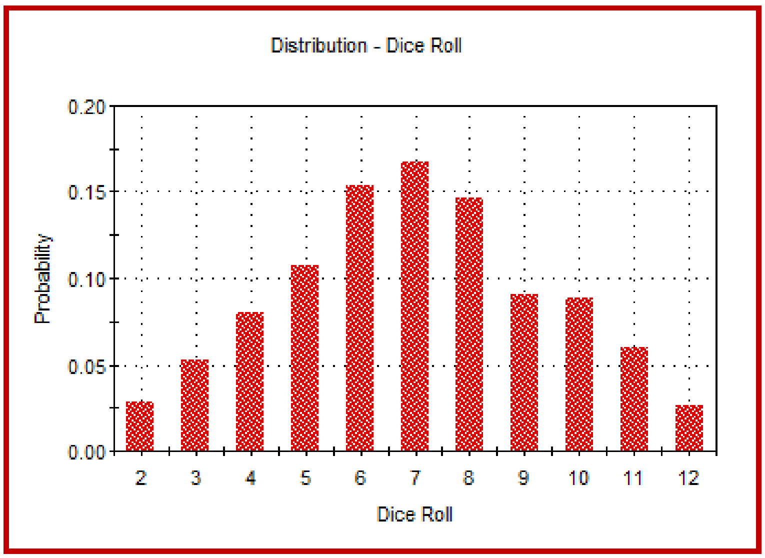
If the inputs describing a system are uncertain, the prediction of future performance is necessarily uncertain. In order to compute the probability distribution of predicted performance, it is necessary to *propagate* (translate) the input uncertainties into uncertainties in the results. A variety of methods exist for propagating uncertainty. Monte Carlo simulation is perhaps the most common technique for propagating the uncertainty in the various aspects of a system to the predicted performance.

Quantification of Uncertainty:

Whereas the result of a single simulation of an uncertain system is a *qualified statement* ("if we build the dam, the salmon population could go extinct"), the result of a probabilistic (Monte Carlo) simulation is a *quantified probability* ("if we build the dam, there is a 20% chance that the salmon population will go extinct"). http://www.goldsim.com/Web/Introduction/Probabilistic/MonteCarlo/

In Monte Carlo simulation, the entire system is simulated a large number (e.g., 1000) of times. Each simulation is equally likely (according to the Principle of Statistical Physics 1.1.2 http://dao.mit.edu/8.08/micro.pdf)

This is the output of rolling two six-sided die 10,000 times, generated using MC simulation:



The accuracy of a Monte Carlo simulation is a function of the number of iterations (called “realizations”).

We are driven to resort to Monte Carlo by the “curse of dimensionality”. The curse is that the work to solve a problem in many dimensions may grow exponentially with the dimension. http://www.cs.nyu.edu/courses/fall06/G22.2112-001/MonteCarlo.pdf

One favorable feature of Monte Carlo is that it is possible to estimate the order of magnitude of statistical error, which is the dominant error in most Monte Carlo computations, called error bars. They are essentially statistical confidence intervals.

The density is constant, which means that U is equally likely to be anywhere inside the interval [0,1]. The two important theorems for simple Monte Carlo are the law of large numbers and the central limit theorem.

The native C/C++ procedure random ( ) is good enough for most Monte Carlo. Bad ones, such as the native rand ( ) in C/C++ can give incorrect results.

The High Energy Universe

The presence of what will later become known as the neutrino became increasingly obvious due to the fact that in the nuclear reactions, when measuring the energy and the momentum of the initial and final particles (which are thought to be subject to an overall conservation law) the accounting fell short, unless one postulated the existence of an unknown and undetected particle. Experimental observations indicated these unknown particles have zero electric charge (since they would have been detected), and they are either mass-less or have extremely small masses.

Anti-matter was found to be extremely short-lived in the presence of ordinary matter, since the anti-particle quickly annihilates itself with one of its ubiquitous (ordinary matter) partners, emitting two photons.

The MeV is a natural energy unit in nuclear physics, but it is extremely small compared to everyday quantities. For example, one calorie is equivalent to 26 trillion MeV.

Average lifetime of a neutral pion is less than a femtosecond ---> 10^(-17) seconds
Average lifetime of a charged pion is a little more than a nanosecond ---> 10^(-8) seconds
Average lifetime of protons and neutrons is 10^(32) years
Average lifetime of electrons and positrons is forever (they never decay)
Average lifetime of a muon is a micosecond ---> 10^(-6) seconds

The problem was that there were so many particles **that any sort of classification and categorization of properties which could lead to a comprehensive theory** was extremely difficult.

The 2 most common quarks are the up and down quarks.
Electrons, positrons and photons are considered elementary particles (having no sub structure)
A proton is an up,up,down quark such that the sum of all charges equals 1
A neutron is an up, down, down quark such that the sum of all charges equals zero
Up and down quarks are the lightest of the 6 quarks
Strange and charm quarks are heavier than the up and down
Top and bottom are the heaviest of all 6 quarks

These particles interact through various types of forces, the interaction occurring through the exchange of an intermediary particle which is a boson, more technically called a gauge boson. Four basic types of forces, or types of interactions, are known **so far** in Nature.

The latter two can only be described adequately by means of a new type of description, quantum mechanics, which as mentioned is based on the postulate that all physical quantities associated with elementary particles come in small discrete chunks, or quanta. There has been no evidence to date that gravity behaves on a quantum level. There are many theories that say it does, and researchers are actively searching for this evidence.

The electromagnetic force is the only force of the 4 that has been observed to exist in both the macroscopic and microscopic realms. Gravity has only been observed on the macroscopic level. And the weak and strong forces have only been observed on the microscopic scale.

The particles that interact are the fermions. The interactions are classified as an exchange of gauge bosons. Every force has at least one postulated gauge boson. According to gauge theory, a branch of the Standard Model, all force-carrying particles should be massless (W and Z bosons are not massless).

1. Electromagnetic force gauge boson is the photon.

The electromagnetic force is the best understood force in nature, and its most defining features are that it is long range and has two different types of charges. The photons mediate the electromagnetic interactions between charged elementary particles. Electromagnetic theory has been fantastically successful, allowing incredibly precise calculations which agree with experiment to within 10 digits and more accuracy. The electromagnetic waves, consisting of many photons traveling together and behaving similarly, can be described through Maxwell's equations as a traveling set of forces exerted in a direction perpendicular to the direction of travel. Photons or electromagnetic waves whose wavelengths are of order 400-700 nm are called optical photons (or light), these being the photons to which our eye is sensitive. At longer wavelengths, the electromagnetic radiation consists of, successively, infrared, sub-millimeter and radio photons, while at shorter wavelengths we have ultraviolet, X-ray and gamma-ray photons.

The Sun emits most of its electromagnetic energy in the form of optical photons (that is why our eyes developed to be sensitive to optical photons), but it also emits smaller fractions of energy at practically all other wavelengths. It plays a major role in everyday life, from controlling molecular structures in our and in other bodies, animate and inanimate, to being the basis of countless industrial applications such as motors, lighting, radio, television, telephony, wireless, etc. The fact the force is proportional to 1/r^2 is what makes radio and other electromagnetic signals, consisting of individual photons, propagate not just from some station to our home, but also over astronomical distances. It is thanks to this long-range property that almost all of what we know about the Universe has been learned through analyzing the photons emitted by various astronomical objects.

2. Strong force gauge boson is the gluon.

In contrast to the electromagnetic and the gravitational forces, the weak and the strong forces are felt only at short range, over dimensions comparable to the sizes of nuclei and elementary particles. This is unique to the strong force: none of the other three interactions have messengers carrying the charge corresponding to the interaction, only the sources do. This means that quantum chromodynamics is a more complicated theory. The fact that the gluons are massless might suggest that the range of the interaction is infinite, as in the case of the photons. However, since there are three types of color charges and since the particles must be color neutral, this leads to a cancellation of the color forces beyond nuclear distances, making the strong force essentially short range. Quantum chromodynamics is a very successful theory, which has allowed much progress to be made in the understanding of the strong interactions and particle physics in general.

3. Weak force gauge bosons are the W and Z bosons

HIGGS NOTE: the Higgs boson is a gauge boson, but not for the weak force. The Higgs is believed to interact with the Higgs field, which is still a theory since no evidence discovered as of yet. Scientifically, the Higgs Effect (which has been observed) breaks SU(2) symmetry. The way that the SU(2) symmetry is broken is known scientifically as "Spontaneous symmetry breaking". Spontaneous implies random or unexpected, the symmetries are the rules that are being changed, and breaking refers to the fact that the symmetries are no longer the same. The result of spontaneously breaking the SU(2) symmetry can be a Higgs boson.

The weak interaction has, after electromagnetism, the next best developed quantum theory, although the level of complexity is significantly higher and the level of understanding is much more approximate. In its modern form the weak interactions have in fact come to be described in a completely similar manner as electromagnetism, in a joint quantum formulation called the electroweak theory. In this joint theory, these two interactions and their experimental phenomenology differ substantially from each other at energies below the so-called electroweak energy scale, which is about 100GeV, but above this energy the two sets of phenomena start to become increasingly similar. The electroweak energy is roughly the energy of either the Z or W boson.

The W and Z bosons mediate between particles carrying a weak charge, just as the photons mediate between particles carrying electrical charges. The fact that the messenger particles are so heavy is the basic reason why the interaction is of short range. The messengers are so heavy and sluggish that they can't travel very far, unlike the massless, infinitely nimble photons.

4. Gravity gauge boson is the graviton (still just a theory – no evidence).

According to the Standard Model of particle physics, neutrinos would actually be massless, and consequently they would be expected to travel at the speed of light in vacuum. But one of the reasons why we know that physics beyond the Standard Model is needed is that now we know that neutrinos do have a very small mass. 50 trillion neutrinos emitted form the sun pass through our bodies every second. This is that, unlike the electromagnetic interaction, it has only one type, or sign, of gravitational "charge", namely the mass. There are no negative or positive masses, just masses. All masses produce attractive forces proportional to their mass, falling off with distance as 1/r2, no matter what other matter is between the source and the point of observation. The other three forces, although microscopically stronger than gravity, have their effects wiped out by virtue of their effective ranges being much smaller than our body size.

Table 2.3. *Approximate comparison of the relative strengths of the four basic interactions*

Strong	Electromagnetic	Weak	Gravitational
1	10^{-2}	10^{-7}	10^{-39}

For instance, the larger mass of the Earth distorts the structure of the space-time around it, and the Moon simply follows, or freely falls along, the natural curvature of this space-time in which it finds itself, resulting in its motion around the Earth. General relativity even describes the large scale gravitational equivalent of Maxwell's electromagnetic waves, namely gravitational waves. These are ripples in space-time, which travel at the speed of light, and which are being searched for currently. The chamber concert of modern physics consists, at the moment, of three somewhat easier pieces, and a fourth one which apparently is simpler but upon closer inspection turns out to be more puzzling than the other three.

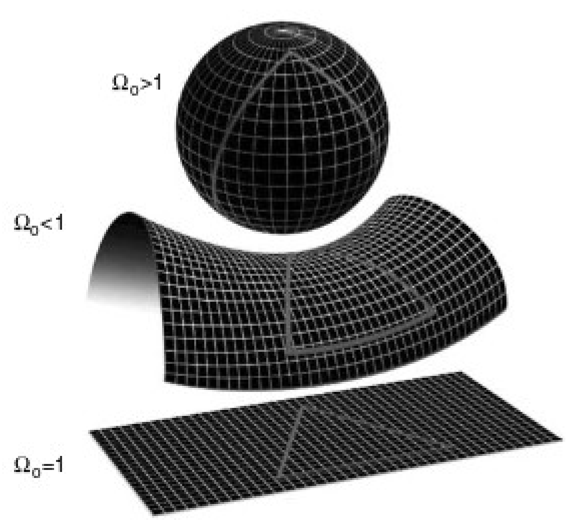
Thus, despite being the oldest and perhaps the best understood force in its macroscopic form, in its wished-for microscopic quantum formulation gravity remains the most recalcitrant among the four forces.

The present-day Universe appears to be expanding in all directions, as shown by the fact that all distant galaxies and clusters of galaxies appear to be receding from us. This was the first and most obvious piece of evidence indicating that our Universe was initially much denser, leading to the hypothesis of an origin in an initial “Big Bang”. That is, the Universe is homogeneous and isotropically expanding. If we naively extrapolate the expansion backwards in time, we would reach the conclusion that at some instant around 14 billion years before the present time the Universe should have had an essentially infinite density. This instant of time at which the expansion started is called the Big Bang.

This is the same kind of thing which happens with a rock thrown up in the air: even though initially it moves up, it will slow down and eventually it falls back. However, if one threw it fast enough, it could escape the Earth and fly “forever”. In the same way, a rocket equipped with a strong enough booster can achieve a velocity large enough to escape the gravitational attraction of the Earth, and never come back. If the gravitational energy just equals the kinetic energy, the rocket can continue moving away forever (Newton's first law – an object in motion stays in motion). In General Relativity, as discussed in Chapter 2, gravity is described as a distortion of space-time caused by the masses, such that all massive bodies or particles naturally move in it following the curvature of space-time. The total amount of mass in the Universe is what determines the curvature of space-time. In Einstein’s equations for a homogeneous isotropically expanding Universe, also called a Friedman model of the Universe, there is a critical mass density that depends on just a few variables, two of them including the Hubble constant (H_0) and Newton's universal gravitation constant (G). It's actually 3(H_0)^2/(8*pi*G),which is 3/8*(H_0)^2/(pi*G).

The critical mass density is equivalent to 1/50th the mass of an aspirin. What does it mean? It means the distribution of mass throughout the volume of the Universe results in a density so minute that the “vacuums” the best laboratories in the world achieve are still terribly dense compared to the actual density of the universe. 6/7 of this mass is dark matter. There are roughly 60 sextillion stars in the entire universe. The number of kilograms of normal matter and dark matter is estimated at 1 followed by 54 zeros. The number of cubic meters in the Universe is estimated at 1 followed by 80 zeros. The geometry of space time is governed by this critical density. If the density is the same as this critical density, if the density is above or below this critical density, the geometry will change. Similar to monitoring the nuclear reaction. K effective has to be exactly equal to 1. If it deviates by 0.00005, the reaction can die out of explode. If the density of the Universe is exactly equal to the critical density omega, then omega equals 1. In this situation, the Earth is completely flat (infinite Euclidean plane). Such a Universe extends infinitely in all directions.

Chernobyl: The reactor lid had a mass of 1.8 million kilograms (4 million pounds)... which is 17.65 million newtons. Reactor lid was blown clear off by the pressure of the steam, and launched it through the roof.



The amount of dark energy plus that of dark matter and baryonic matter just about equals the critical density, making the Universe flat, as indicated by current observations. So right now, scientists believe we are at 1, which is why 3 out of the 5 models for the universe have omega equal to 1. Most of the models have a vacuum energy of zero. The most abundant type of photons in the Universe have a wavelength
in the millimeter range, between the radio and the far infrared wavelengths: these are the so-called cosmic microwave background (CMB) photons. Their density exceeds that of any other type of photons: there are around 430 of them per cubic centimeter. Their frequency spectrum is thermal, which means that it is a continuous spectrum such as would be emitted by a black body heated to a certain temperature.

The modest millimeter photons of today's CMB must have earlier been optical photons, and even earlier UV photons, X-ray photons, and so on, since the faster they oscillate up and down, the more energy is involved. The matter, such as hydrogen, heavier elements, dark matter, etc. must also have been hotter earlier on. This means that the collisions among baryonic matter and photons must have been more frequent, since they had less distance to travel to encounter each other. The photons were also more energetic earlier on, and if we consider an epoch when the scale of the Universe was about 1000 times smaller than at present, the energy of the photons would have corresponded to a temperature of T proportional to 2700K. Photons of such energy are capable of stripping electrons out of neutral atoms, a process called ionization. An atom stripped of one or more of its electrons is called an ion. The hydrogen atom has only one electron, so at earlier times or smaller R, hydrogen would be fully ionized.

One common feature of many GUTs is that they appear to lead to a phenomenon called inflation, which has a huge impact on cosmology. Inflation is a period of extremely rapid expansion, where the scale R of the Universe grows exponentially with time over a brief period of time.

Our Universe is at present in the midst of a smooth and uniform expansion in all directions.
Gravity depends on position. As the positions of two orbiting bodies change with respect to a certain reference point, the magnitude of the gravitational field will weaken or strengthen.

Planck Epoch

After four minutes, the universe was no longer hot nor dense enough to create atomic nuclei, and the primordial ratios were frozen until the first stars. The universe continued to expand and cool, but if we were to have existed back then (baring the fact that our atoms would not have yet been formed), we would not have been able to "see" anything. The universe was opaque to light and radiation.
This is because all of the electrons were still too energetic - too hot - to be bound to nuclei, and therefore were able to roam freely about. This means that photons could not move about freely, for they kept being absorbed and re-emitted by the electrons.

When the universe had aged to 380,000 years, it had cooled to approximately 3000 K (5000 °F). Electrons no longer had enough energy to overcome the attractive force of atomic nuclei, and became bound to atoms. Light could now stream forth unimpeded. This process is called "recombination," and this "first light" is what we now see as Cosmic Microwave Background (CMB) Radiation.

When the universe formed with the Big Bang, it was very hot. In order to understand what occurred during the first few hundred-thousand years of the universe's history, you must first understand what heat really is at a microscopic level: Heat is a form of energy, just as light and momentum are forms of energy. On very small scales, this heat energy is represented in the momentum of particles. For example, take an atom of hydrogen: If it is very cold, then it does not move very quickly. If, however, you were to take an atom of hydrogen from the core of the sun (10,000,000 K; 18,000,000 °F), it would be moving very quickly.

Cosmic Microwave Background (CMB)

Radiation that fills the universe and can be detected in every direction. They cannot be seen without instrumentation since microwave frequency is outside the visible spectrum. The cosmic radiation background was generated 380,000 years after the Big Bang.

HAWC Shower spread

A cosmic ray shower has a spread of about 100 meters in diameter when it reaches the detectors.
A gamma ray shower has a spread of (perhaps) less than 40 meters in diameter.
HAWC detectors cover roughly a 20,000 square meter area in a hexagon shape. (There is a distinct middle, nicknamed 10th Avenue, since there are exactly 10 rows of tanks above it and 10 rows of tanks below it).
A cosmic ray shower has an area of around 7,000-8,000 square meters (?) Would cover about 100-110 detectors out of 300
A gamma ray shower has an area of around 1,000-1,500 square meters (?) Would cover about 20–25 detectors.

Facts and Mysteries in Elementary Particle Physics

An atom is largely empty space. If a nucleus were the size of a tennis ball, the first electron would orbit at a distance of 4 miles. The atomic binding is a result of the electromagnetic force between electrons and the nucleus via photons (the mediators of the force). “Great physics does not automatically imply complicated mathematics!” The photoelectric effect contains barely any mathematics. Law of nature that to each particle there exist an antiparticle. The antiparticle for a particle with zero net charge is itself. Measure the energy and the velocity of the particle, and then its mass can be determined from those.

Problems with the Standard Model

- Does not account for gravity. In fact, the Standard Model is widely considered to be incompatible with the most successful theory of gravity to date, general relativity.
- The above-mentioned incompleteness of the gravitational theory is just one of the signs that some important pieces are missing.
- Does not account for Dark Matter, which is estimated to include around 27% of the entire mass of the Universe.

- Does not account for dark energy. More is unknown than is known (NASA). In 1998 the Hubble Space Telescope ($2.5 billion, launched in 1990) observations of very distant supernovae showed that, a long time ago, the Universe was actually expanding more slowly than it is today.
- Another indication that skeletons remain lurking in the closet is that the electroweak theory can explain the masses of fermions and bosons, but it requires a large number of ad-hoc parameters to do so. (for the particular end or case at hand without consideration of wider application).
- Another sign is that neutrinos, which are key participants in the weak interactions, were for a long time happily considered to be massless, even in the unified electroweak theory. However, according to experiments in the last one and a half decades, it appears that neutrinos, unlike what is postulated in the Standard Model of particle physics, have mass.

Dark Energy

Scientists using NASA's Hubble Space Telescope have discovered that dark energy is not a new constituent of space, but rather has been present for most of the universe's history. Dark energy is a mysterious repulsive force that causes the universe to expand at an increasing rate.
"Although dark energy accounts for more than 70 percent of the energy of the universe, we know very little about it." Riess led one of the first studies to reveal the presence of dark energy in 1998. "Our latest clue is that the stuff we call dark energy was relatively weak, but starting to make its presence felt nine billion years ago." Supernovae can be used to trace the universe's expansion. Einstein first conceived of the notion of a repulsive force in space in his attempt to balance the universe against the inward pull of its own gravity, which he thought would ultimately cause the universe to implode. His "cosmological constant" remained a curious hypothesis until 1998, when Riess and the members of the High-z Supernova Team and the Supernova Cosmology Project used ground-based telescopes and Hubble to detect the acceleration of the expansion of space from observations of distant supernovae.

Astrophysicists came to the realization that Einstein may have been right after all: there really was a repulsive form of gravity in space that was soon after dubbed "dark energy."

The observations also confirmed that the expansion rate of the cosmos began speeding up about five to six billion years ago. That is when astronomers believe that dark energy's repulsive force overtook gravity's attractive grip. Every bit of matter in the universe exerts a gravitational pull on every other bit. This creates a drag that should be slowing the universe down.

The other mystery is why dark matter, which also appears to involve BSM physics, provides an energy density which at the present time is so close to the apparently unrelated dark energy density. Dark matter seems to be a pressure-less gas of massive, non-relativistic particles (see Chapter 4), while dark energy appears to be due to the vacuum quantum fluctuations of an unknown scalar field, leading to a negative pressure.

Scalar field: A scalar field is a field which depends on only a single quantity at each position in space-time to denote its strength, unlike a vector field which requires three quantities, one
for the strength and two angles for its direction.

So what is dark energy? Well, the simple answer is that we don't know. It seems to contradict many of our understandings about the way the universe works. The Sun is powered by the conversion of mass to energy. But energy is supposed to have a source — either matter or radiation. The notion here is that space, even when devoid of all matter and radiation, has a residual energy. Perhaps dark energy results from weird behavior on scales smaller than atoms. The physics of the very small, called quantum mechanics, allows energy and matter to appear out of nothingness, although only for the tiniest instant. The constant brief appearance and disappearance of matter could be giving energy to otherwise empty space. Or perhaps the answer lies within another long-standing unsolved problem, how to reconcile the physics of the large with the physics of the very small. Einstein's theory of gravity, called general relativity, can explain everything from the movements of planets to the physics of black holes, but it simply doesn't seem to apply on the scale of the particles that make up atoms. To predict how particles will behave, we need the theory of quantum mechanics. Quantum mechanics explains the way particles function, but it simply doesn't apply on any scale larger than an atom. The elusive solution for combining the two theories might yield a natural explanation for dark energy.

1917: Einstein was working on special relativity, He found that his equations didn't quite work for a static universe, so he threw in a hypothetical repulsive force that would fix the problem by balancing things out, an extra part that he called the "cosmological constant." His fame was due to his original and creative theories that at first seemed crazy, but that later turned out to represent the actual physical world. His theory was confirmed when he predicted that even starlight would bend when passing near the sun during a solar eclipse.

Saul Perlmutter (LLNL), Brian Schmidt & Adam Reiss (AUST), 2011 Nobel laureates

Two competing groups of astronomers that set out to determine the difference between the speed of the universe now compared to the speed of the expansion in the past. Everyone expected that the expansion now would be less than the expansion speed in the past, but that is not the case. After a few years of gathering data (searching for supernovae is a slow process), they had enough to start combing through it. It wasn't long until they got some odd results: the supernovae were dimmer than expected...meaning they must be further away than they should be. If they really were that far away, then the universe's expansion must be speeding up, not slowing down. But what could cause this acceleration? Gravity is an attractive force, not a repulsive one. Some force that we have never known before must be causing this acceleration. When the results were announced, they were met with skepticism, since it would contradict the established understanding of how the universe worked. Then Hubble was sent to double check. In 2002, Hubble's results were consistent only with the theory of an accelerating expansion. Both groups arrived at the same result. Therefore the findings of the 2011 Nobel Laureates in Physics have helped to unveil a Universe that to a large extent is unknown to science. And everything is possible again.