The Universe
What Are the Questions Today?

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Today the frontier of our understanding of the structure of matter is in the area of particle physics – the study of basic elements that make-up ourselves, our world, and our universe.

There are existential questions that have been asked since antiquity:

- *How does the Universe work?*
- *What is it made of?*
- *What are the basic components and rules governing our world?*

Over the past few hundred years we came to the conclusion that the rules governing the Universe are the same as the rules that describe what happens on Earth.

Today, to understand the "big picture" we not only look at the sky...

Illustration by Dorota Mann

... but we also study the smallest components of matter.

Illustration by Dorota Mann

The science that operates at the frontier of our understanding of the structure of matter is the study of *elementary particle physics*.

What is "elementary" varied with time and with the level of our knowledge.

The smallest size is limited by the status of our technology and at this time we think that the basic components of matter are quarks. It is interesting to compare the sizes of the element making up what may seem as a solid matter...

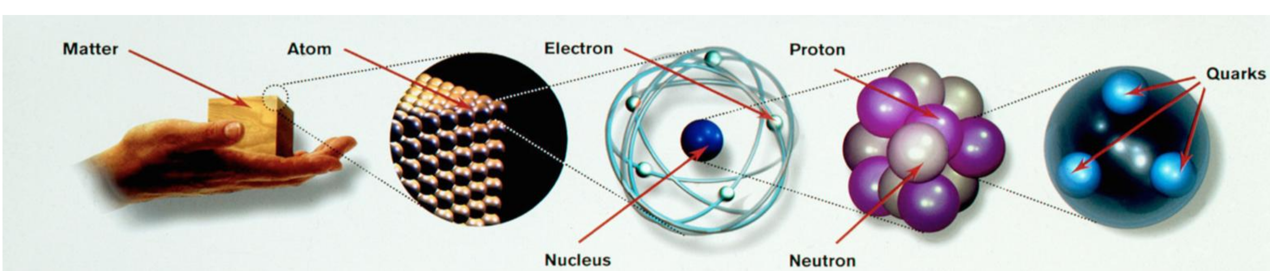


Image courtesy of CERN

An atom, very small by itself, has at its center a nucleus that is about 10,000 times smaller than the atom. Inside the nucleus there are protons and neutrons and inside those are quarks. We do not know how small quarks are. 25 years ago we thought that they were at least 1000 times smaller then the proton but now that limit may have been pushed down by at least another factor of 10. Thus the picture that we have today is that our everyday matter is mostly empty space with tiny quarks making up protons, neutrons, atoms and - most importantly - us.

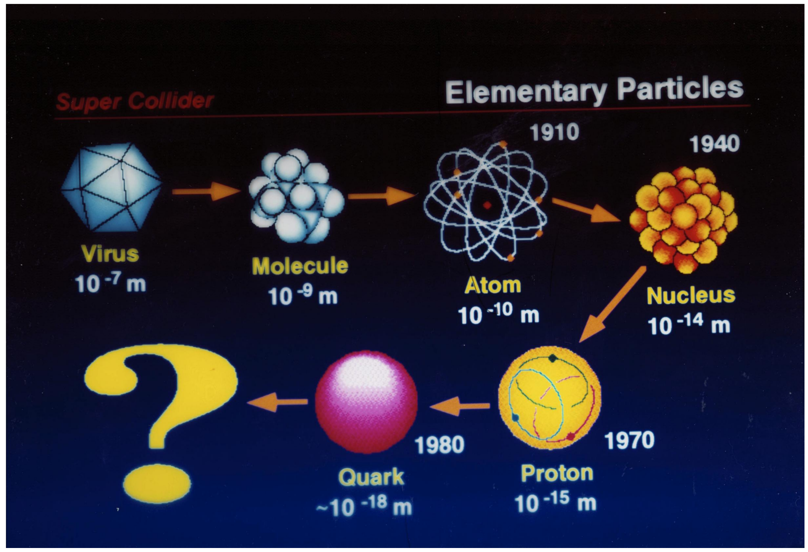


Image courtesy of the Superconducting Super Collider

All matter that surrounds us and that we can touch is made up from various combinations of just two quarks, which we named "up" and "down", and some number of electrons. But we have also discovered that there are other, very short-lived, heavy "siblings" of these quarks and electrons than can be produced under special conditions but quickly decay to their lightest siblings.

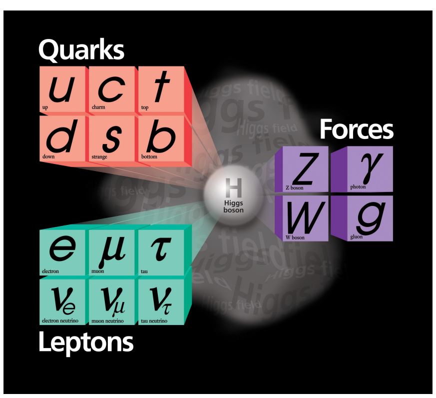


Image courtesy of Fermilab Visual Media Services

Our "periodic table of basic elements" looks today as follows.

We have three families of quarks and leptons with fancy names like "charm", "strange", "top", "bottom", "muon", "tau" and "neutrino" that have similar characteristics and differ amongst themselves only by their masses.

We also have established the four different ways that all these particles interact with each other. These are four types of "forces" or "interactions":

- **Strong** – that keep the quarks together to make up protons and neutrons.
- **Electromagnetic** – the interactions between the charges of material objects.
- **Weak** – that is responsible for radioactive decays, driving the fusion making all stars, including our own sun, shine. This makes heavy quarks and leptons decay into light ones.
- **Gravity** – the interaction between masses of the objects that has been known for many centuries. It is the least well-understood of the four forces, believe it or not!

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Image courtesy of CPEPweb.org

We also developed a mathematical description of these forces and it appears that their strength varies dramatically. For example, the interaction between masses of the objects is 1 with 41 zeros (41 orders of magnitude) weaker than the interactions between the charges. The only reason why we feel it at all is that it is always attractive and there are many particles of matter while there is equal number of positive and negative charges and the forces are either attractive or repulsive providing very precise cancellation.

The mathematical description of these interactions was made in several stages in the framework of quantum theory. We do not have yet the quantum theory of gravity but some progress has been made in the last 50 years. The three forces that have been so far well-described - weak, electromagnetic and strong - are mediated by exchanges of another type of particles that can be considered as carriers of the force. These carriers are the photon (γ) for electromagnetic interactions, eight gluons (g) for strong interactions, and heavy W and Z particles for the weak interaction. The discovery of W and Z particles about 30 years ago was what made us think that we are on the right track and that some day we will be able to describe all of our material world by a general "Theory of Everything" based on quantum mechanics. Weinberg, Glashow and Salam formulated the Standard Model this way, and in doing so provided a unified mathematical description of the three forces.

Until a couple of years ago, the Standard Model had a problem. The basic premise of the theory was (and still is today) that all interactions behave in the same way at high energy. They are distinct only at low energy. The simple analogy is that of air in Earth's atmosphere. When the air is warm all molecules behave in the same way – air seems to be only one thing. But when the temperature drops down (the kinetic energy of each molecule get smaller) the water vapor in air condenses and we get rain, snow or ice. Suddenly, air is separated into distinct components. A further temperature drop will liquefy the nitrogen, then the oxygen, and so on. Mathematically this is called "symmetry breaking" between different types of molecules. In the Standard Model, the symmetry at high energy required that the masses associated with the carriers of the electromagnetic and weak forces should be the same. What we observed was that the photon – the carrier of the electromagnetic force - has no mass, while in contrast the W and Z – the carriers of weak force - have masses almost 100 times larger than that of the proton! Thus the symmetry is broken and required a mathematical explanation. In addition we also do not understand where the masses of all quarks and leptons came from. The initial mathematics was suggesting all of these to be massless and that is, of course, contrary to the observation. Among many proposed solutions there was one made about 50 years ago by Peter Higgs and several of his colleagues. It invoked the existence of a new type of elementary particle with unusual properties. All of these properties were predicted by the theory except for its mass. It took 50 years and about 100,000 person-years of work but the predicted Higgs boson was discovered in 2012 at the Large Hadron Collider.

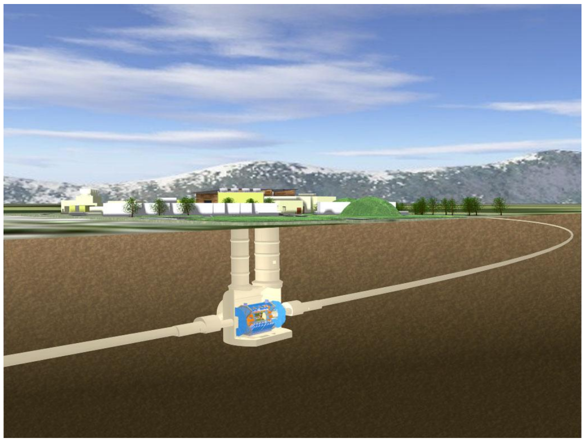
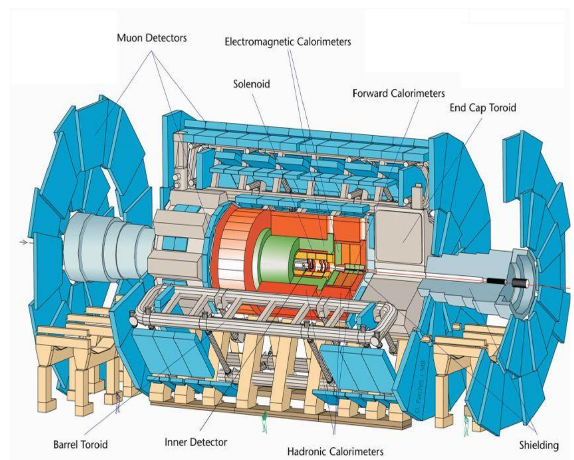


Image courtesy of the ATLAS Collaboration

Since we are firing the LHC accelerator again I cannot resist flashing of a few pictures as an advertisement of our experiment.

The LHC is a 27 km ring of magnets and accelerating structures in an underground tunnel about 300 feet below ground level. The protons circulate in these rings in opposite directions and collide at the center of the detector. The collisions release all the energy stored in the protons and that energy is transformed



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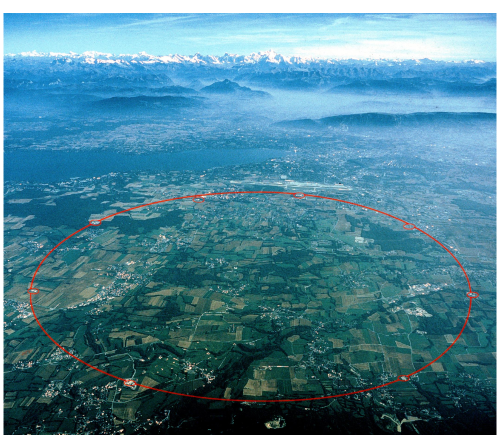

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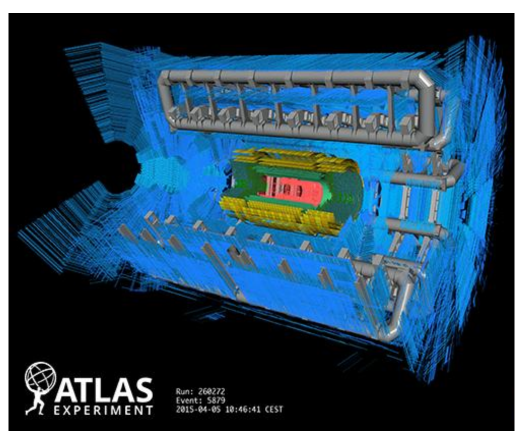

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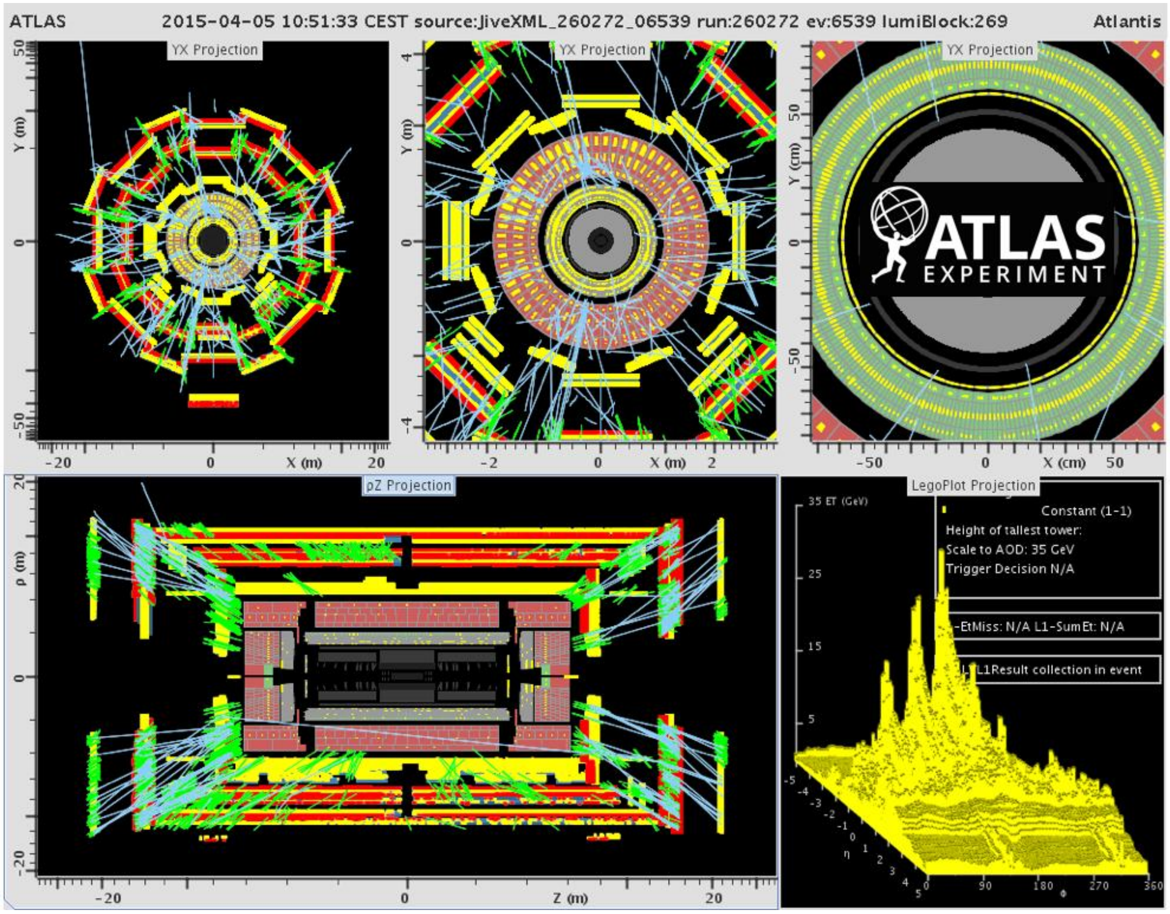


Image courtesy of the ATLAS Collaboration

via the famous equation, $E=mc^2$, into the production of many new particles. We sieve through the debris looking for rare, new objects ... like a Higgs boson.

The detector is huge; it is almost eight stories high and has a footprint of a half of a football field. It looks solid, but when you peel the layers it contains a gossamer of millions of tiny sensor wires and pixels that tell us where particles traveled and what kind of particles they were. In the previous data run of 2011-2013 we had about 40 million collisions every second and ended up with just a few hundred precious Higgs bosons. You can see that the technological and operational requirements are very challenging.

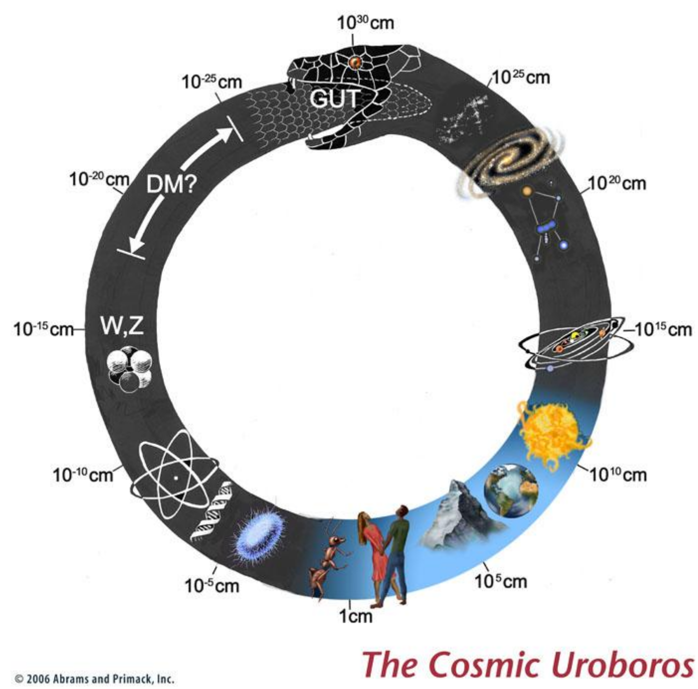
The hoopla and enthusiastic articles and TV programs generated by the discovery of the Higgs boson left an impression among many people that we have succeeded, that particle physics is done. Of course we need to make sure that there is no mistake and re-measure Higgs properties with better precision; but there is a false impression that we understand everything and can now concentrate on drinking beer and tending the flower beds.

Some news items sounded especially like tent revival meetings.

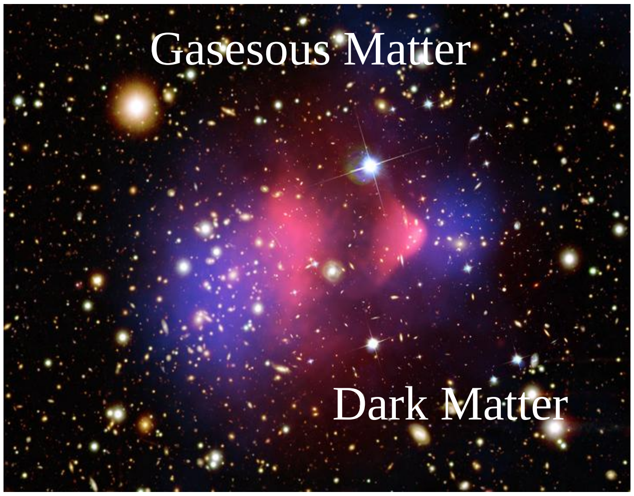
Illustration by S. Harris

The reality is far from this. The only thing that we have discovered is that Higgs exists and therefore that the Higgs mechanism of generating the mass of fundamental particles is possible. But our knowledge of the universe is incomplete, and we still think that by understanding the laws governing the smallest things we can describe the whole cosmos ... sort of like the ancient *Uroboros snake*.

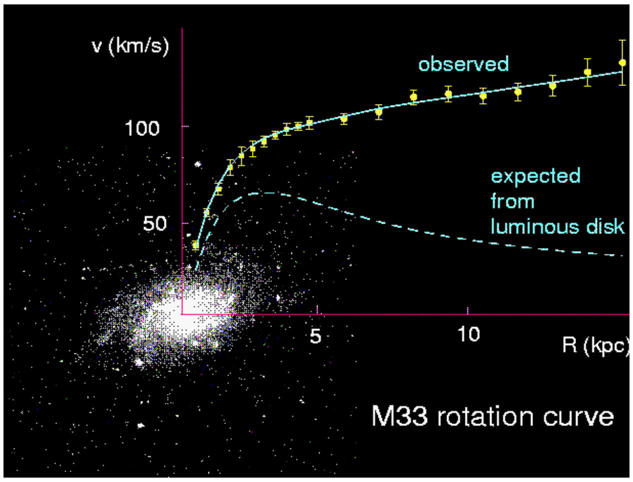
The importance of the study of structure of matter at its most elementary level has become evident due to several troubling astrophysical observations. For the past 20 years astronomers, armed with increasingly more precise technology (especially satellites), definitively observed new, strange features of our universe. Many once-annoying and easily dismissed observations have been either confirmed, and some are newly discovered. Several have no good astronomical explanation and it is up to particle physics to try to discern possible answers.



The Cosmic Uroboros



Among those is the issue of "dark matter." The astronomers knew for many years that galaxies and clusters of galaxies rotate at speeds that should tear these structures apart. This was reinforced by discovery of gravitational lensing – the bending of light due to massive invisible objects between us and the source of light. This phenomenon was predicted by Einstein's theory of relativity and yields multiple images of the same object otherwise hidden behind a large mass.



These observations led to the postulation of "dark matter." It is "dark" because it does not shine in the sky; it consists of something that interacts very weakly with us (so we do not see it) and at the same time provides a lot of gravitational force to keep galaxies together. There should be five times more of the dark matter than regular matter to provide an explanation of the current observations. Astronomers did not find anything suitable known explanation in the sky, but particle physics have a candidate mathematical framework called "Supersymmetry" predicting WIMPs – Weakly Interacting Massive Particles - that would fit the bill. These would be a new type of elementary particles – something beyond our Standard Model.

Even more unsettling is the observation that not only the universe is expanding in all directions, - that is, the distances between all galaxies increase with time - but also that this expansion is *accelerating*. Why? A possible explanation is called "dark energy" - a kind of negative pressure inherent in space and time - but there is no real understanding of what dark energy is and how it fits together with our Standard Model.

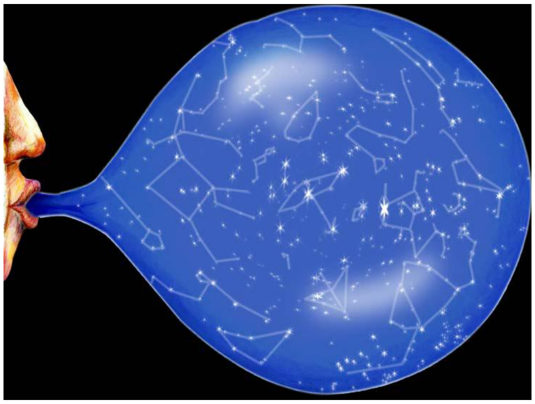


Image courtesy of Courtesy of SLAC and Nicolle Rager

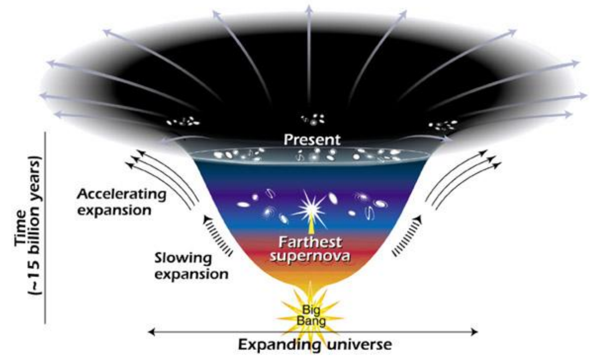


Image courtesy of NASA/STSci/Ann Feild

You can find many pundits proposing colorful pictures and outrageous ideas ranging from the concepts of "multiverses" - multiple parallel universes with different physical laws - to modifications of basic postulates of our science as we know it today. Most of these are impossible to test and remain in the realm of science fiction but some elements of various proposals may be searched for in our experiments.

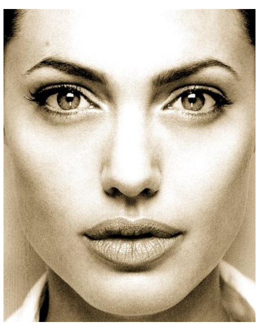


Image source unknown

Our physical laws seem to be well-described by mathematics and we expect that future new discoveries will be described by an expanded mathematical picture. However, there are many mathematical approaches that one can take. Most of them have little to do with the natural world. The hidden assumption behind theoretical physics is that the mathematical description should be simple and elegant. Elegance and beauty are usually associated with "symmetry."

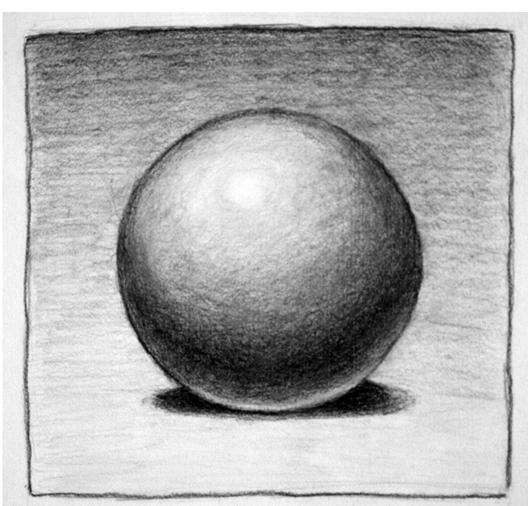


Illustration "Shaded Sphere" by PMucks

"Vitruvian Man" by Leonardo Da Vinci

Image courtesy of iStockPhoto.com/Floortje

However, what we see in real life is rarely symmetric. The universe is quite lumpy with stars, galaxies and their clusters, and the masses of elementary particles differ from each other in irregular manners. The ideal symmetry must be broken in some manner.

One somewhat outlandish way to restore symmetry to the universe of elementary particles is to introduce extra dimensions. In this picture, we live in the regular three-dimensional space and are oblivious to the other dimensions – perhaps as many as eight additional dimensions! In one version of such picture particles are in all dimensions but stick out into our dimensions in slightly different way and we see only part of them and think that they have different masses. In another version, they all have supersymmetric shadow particles.

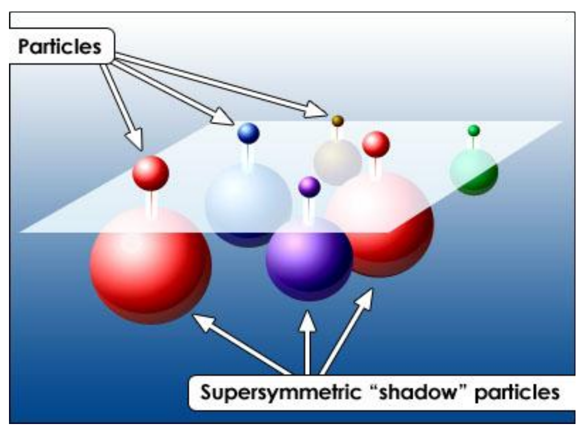


Image courtesy of particleadventure.org

As you can see the answer to the question "How does the Universe work?" is "We do not know yet." We seem to know only a small fraction of what makes up our universe and like an iceberg in the ocean we do not know what is yet below the surface of our knowledge.

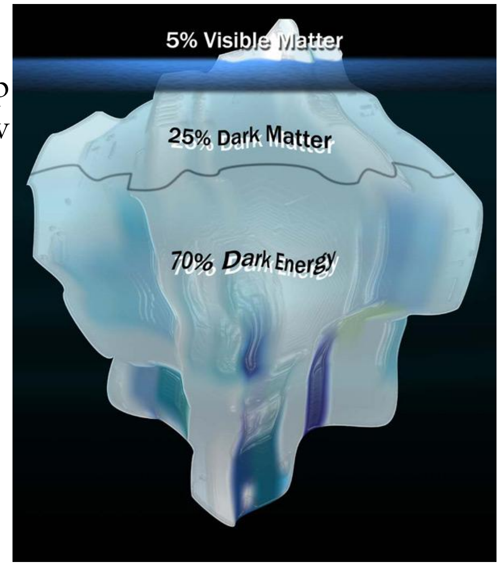


Image courtesy of SLAC and Nicolle Rager

There are many unanswered questions that will need answering. I will leave you with my personal list of the six most important questions that can be addressed in the next 20 years.

1. What is "dark matter"?
2. What is the "dark energy"?
3. Why there is very little (if any) antimatter in the universe, while our cosmology tells us that the creation of particles in the Big Bang was due to symmetric interactions that should produce equal number of particles and antiparticles?
4. Why do different quarks and leptons have different masses and how exactly do the neutrinos fit into the scheme of the Standard Model? Where does the proton mass comes from? (A proton is composed of two up and one down quarks, whose masses are over 100 times smaller than actual mass of the proton.)
5. Can gravitational interactions be described by a quantum theory?
6. Is there an explanation for the accelerating expansion of the Universe?

Somewhat like Columbus (motivated by money) initiated a search for the east coast of India, so are the scientists (motivated by fame) setting up the newest state-of-the-art technology to study the unknown. And like Columbus (and a number of previous unsuccessful adventurers) the voyage is expensive, risky, tedious and dreary. Every so often on the voyage one discovers something completely new and then the race is on to understand what it means, how it works, and how to optimize the route of getting there.

Medieval celestial woodcut.

Many of the ideas that we have require reproducible experiments to narrow the number of possible answers. Large Hadron Collider experiments will search for new physics effects at very high energy. In the coming run we will sieve through more data than in all particle physics experiments in the world together for the past 50 years. Nature would be really strange if we do not find something new. The neutrino program at Fermilab will seek answers to the matter-antimatter problem, astronomical observations and astrophysics experiments will look for clues to the nature of the dark matter and dark energy, and theoretical physicists need a lot of data to start rearranging the pieces of the puzzle to find exactly how the universe fits together.