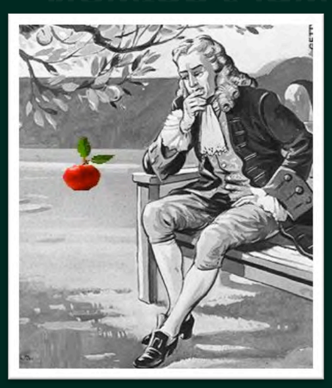
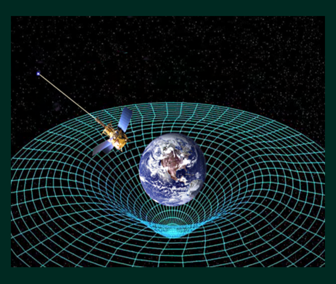
QUANTUM GRAVITY

Newton's law of Universal Gravitation



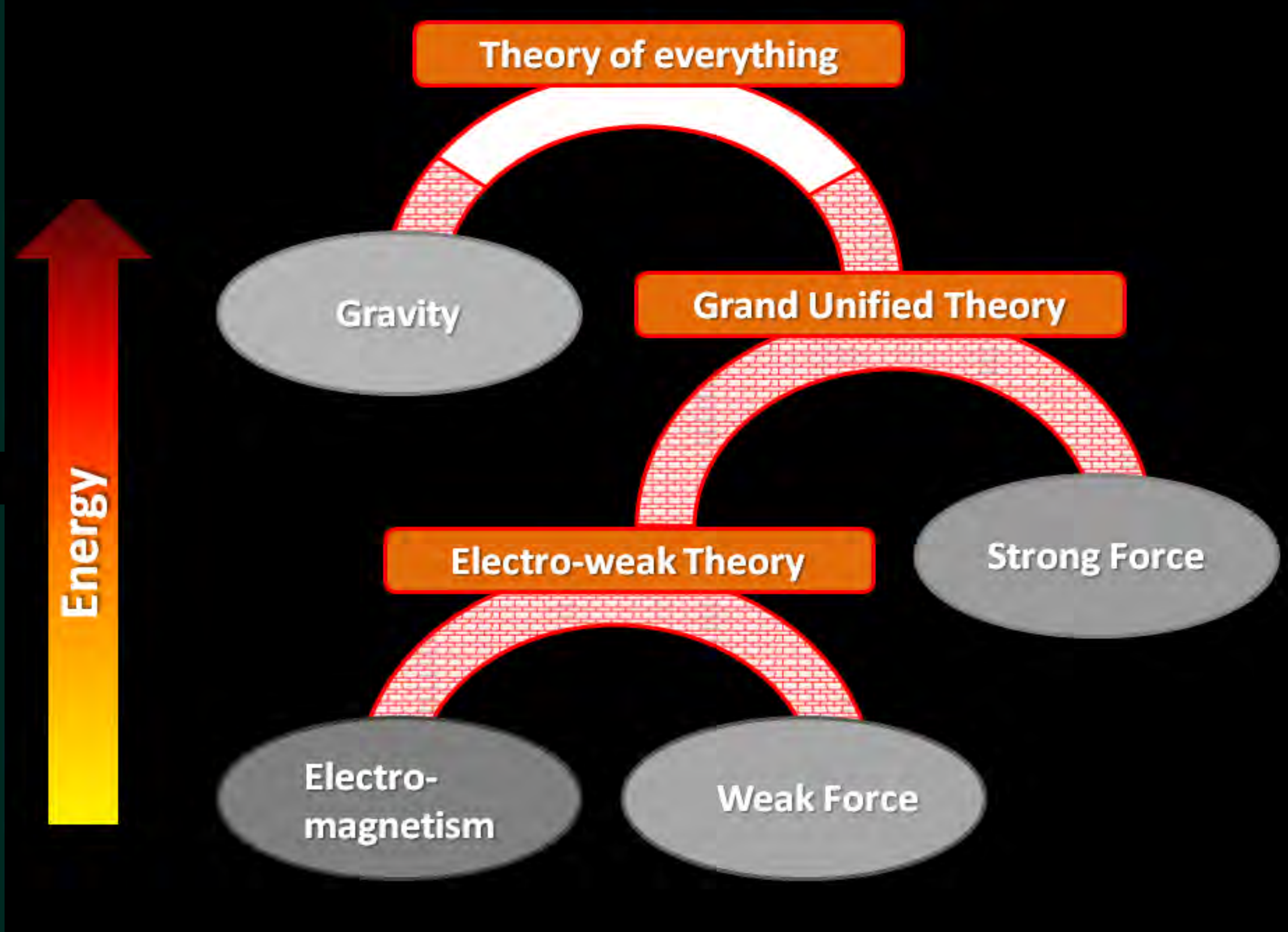
Newton's law of gravitation states that every massive particle in the universe attracts every other massive particle with a force. The force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. This force is known as Gravity.

Einstein's General theory of Relativity



General Relativity (GR) is a theory of gravity. It describes the workings of the universe on the large scales of solar systems, galaxies, clusters etc. Newton believed gravity to be a long range force that acts between bodies instantaneously. But in 1905, Einstein put forward the Special theory of Relativity, which forbids the idea of anything, including gravity, moving faster than light. This contradiction ultimately led Einstein to formulate the General theory of Relativity (GR). In this picture, gravity is not really a force, but rather a manifestation of the curvature (or warping) of space time.

A massive body distorts the fabric of space time, and the motion of any nearby object in this curved geometry appears as if there is a force of attraction on it. In other words, matter tells space time how to curve and space time tells matter how to move. Several predictions of GR like the bending of light by a massive object, precession of the perihelion of Mercury and gravitational red-shift have been successfully verified.



Strong Interaction	Force which holds nucleus togeher	1	10^{-15}(m) (diameter of a medium size nucleus)	Gluons
Electro – megnetism		1/137	Infinite	Photon mass = 0 spin = 1
Weak Interaction	neutrino interaction induces beta decay	10^{-6}	10^{-18}(m) (0.1% of the diameter of a proton)	Intermidiate vector bosons W+,W-,Z0 Mass>80GeV spin =1
Gravity		6×10^{-39}	Infinite	Graviton? mass = 0 Spin = 2

Electromagnetic force

The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as magnetism, is caused by the E-M force. For instance, the force that keeps you from falling through the floor is the electromagnetic force which causes the atoms making up the matter in your feet and the floor to resist being displaced. The carrier particle of the electromagnetic force is the photon (γ)

Strong Force

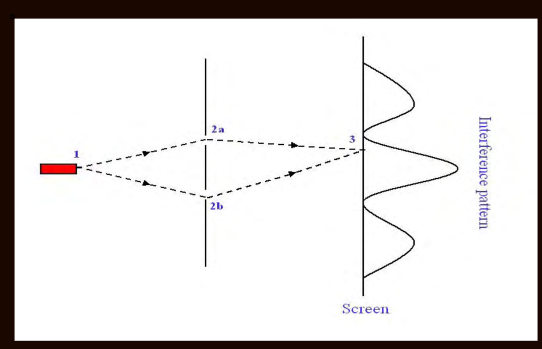
Strong interaction is a short range attractive force which holds the nucleons together inside the nucleus. It is a little stronger then EM force. Force carriers are gluons.

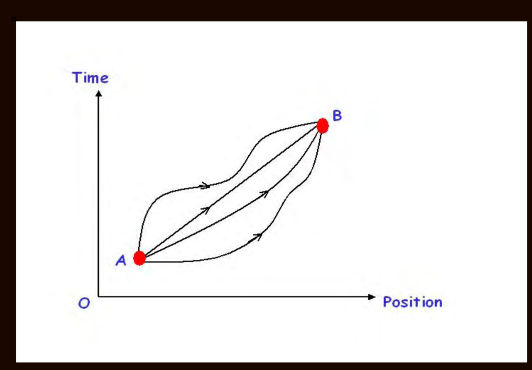
Weak Force

The force responsible for the nuclear beta decay. It is weaker then EM force. Here the force carriers are W and Z bosons.

Quantum Mechanics

Quantum theory describes the universe on the microscopic scales of molecules, atoms and elementary particles. In this framework, nature is inherently probabilistic. It is based on the fundamental principles of uncertainty and superposition. The former implies that it is impossible to determine the complete state of any system with arbitrary accuracy and imposes a fundamental limit on our knowledge about it. For example, the position and speed of any microscopic particle both cannot be simultaneously measured with absolute precision. The principle of superposition, on the other hand, says that any quantum system can exist in several different states at the same time, and when a measurement is performed on it, the state of the system "collapses" into one of the alternatives with appropriate probability.

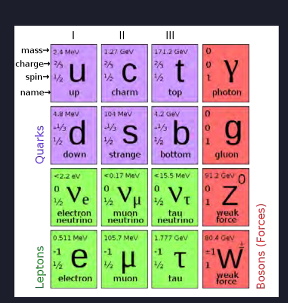




As an example, if a particle emitted at point 1 in a double slit experiment (Fig. 1) is to reach point 3 on the screen S, it can do so via either of the slits 2a or 2b. Quantum mechanics associates a complex number called amplitude (K) with each path, and the total amplitude is the sum over all possible paths, i.e. $K_{1\to3} = K_{1\to2a\to3} + K_{1\to2b\to3}$. The corresponding probability for the particle to get from 1 to 3 is then given by the square of the amplitude and depicts the interference term producing the wavy pattern on the screen. This can be generalized by saying that if a particle has to get from point A to point B (see Fig. 2), the total amplitude will be a sum over all the infinitely many possible paths. This is totally contradictory to everyday experience; this is because on scales of ordinary objects like cricket balls, quantum effects are negligible, and we see things moving along well defined trajectories.

This theory has been immensely successful in explaining the structure and properties of matter, as well as three of the four basic interactions (excluding gravity), namely the electromagnetic, strong & weak forces.

Why do we need Unification?



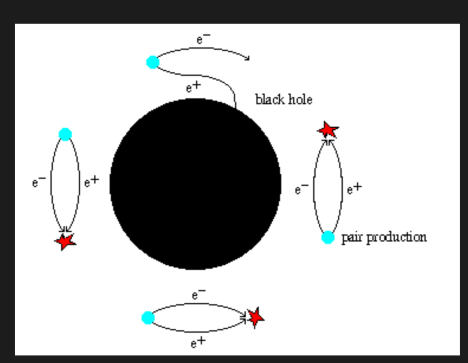
The standard model of particle physics is a theory concerning the electromagnetic, weak, and strong interactions, which mediate the dynamics of the known subatomic particles. It is successful in explaining a wide variety of collider experimental results. However, the standard model has its own drawbacks such as it does not incorporate the theory of gravity. Further, it does not correctly account for neutrino oscillations (and their non-zero masses). Also it requires the values of 20 constants to be put in by hand; parameters such as the masses of the particles, etc. Further, when one is calculating the physical parameters involved in a collision process in the theory then inevitably one encounters infinities which have to subtracted by hand in a process called as renormalization.

The general theory of gravitation predicts the existence of a naked singularity widely known as the big Bang singularity in the earliest epoch of our universe when the physical size of our universe was zero! However, at very small length scales, one expects quantum effects along with gravity to govern the evolution of our universe. Further it is known now for quite sometime, that Black hole horizons have properties similar to a heated gas in equilibrium like temperature, entropy, pressure, etc. These peculiar behavior have no explanation in the conventional theory of gravity and needs further investigation.

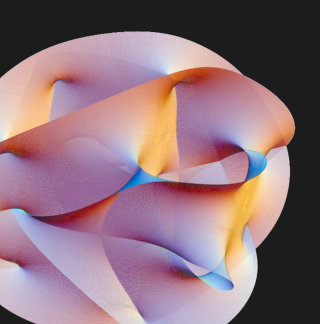
In most situations, physicists study things that are either very large & massive or very small & light, but not both. In such cases, one needs to apply only one of the two theories in order to have an accurate description, and the effect of the other, being very weak, can be happily ignored. But there are places, like black hole horizon or the very early phase in the evolution of the universe, which require both quantum laws *and* general relativity to be applied simultaneously. However, all straightforward attempts to do so lead to nonsensical results, and this seems to suggest a fundamental incompatibility of these two theories as we understand them today. It is believed that a future unified quantum gravity theory will resolve this conflict and provide an accurate and sensible picture of the workings of nature on all scales and under all possible conditions.

Works @ IUCAA

One possible explanation of the hawking radiation from black holes is provided by the tunneling mechanism across the horizon surface. In this picture the space time is assumed to be filled by virtual particle anti-particle pairs created due to quantum fluctuations. If such a process occurs near the horizon, the antiparticle can tunnel into the black hole and the particle escapes leading to a net decrease in black hole mass. An observer far from the black hole will interpret these particles as the outgoing radiation.

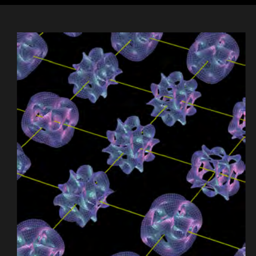


Researchers in IUCAA provided a consistent mathematical description of this broad picture and have discovered a correction to the particle spectrum that Hawking found. It turns out that the tunneling mechanism for black holes radiation is also intimately connected with the first law of thermodynamics of the form TdS = dE + PdV applied to black hole horizons.



Scientists at IUCAA are also working on holography, a remarkable idea that the world may have, in some sense, fewer dimensions than we see, like a hologram that looks three dimensional but is actually flat. Another research topic is string theory, a candidate theory of quantum gravity that unifies all the known forces. Currently, researchers in IUCAA are applying string theory as well as holography to cosmology, the study of the entire universe.

Einstein's gravity lives in four dimensional space time, but it can be argued that four dimensions are not sufficient to fully encompass gravitational dynamics. Attempts are also being made by researchers in IUCAA to study gravity in higher dimensions with a view to explore its rich quantum structure.



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Scientists in IUCAA are actively involved in efforts to understand the dynamical interplay between quantum theory and gravity along the following lines. If we take the continuum space-time to be analogous to a smooth solid, then Einstein's theory, which describes the space time dynamics, will be similar to the theory of elasticity. Just as the microscopic description of the solid should start from identifying the atomic structure, the quantum theory of the space time will require understanding the 'atoms of space time'. A bridge across these two levels of description is provided by thermodynamics. In this novel prescription, Einstein's field equations can be expressed in the form TdS = dE + PdV, where T is the temperature, S is the entropy associated with any horizon and the term PdV represents the work done under a virtual displacement of the horizon. The horizons themselves act like holograms capturing the physics of the bulk region in a terms of two dimensional surfaces. This seems to show that the true degrees of freedom describing gravity may not live in the bulk of the space time, but only on the surface bounding it. IUCAA scientists have shown that such interpretation remains also valid for complicated space times which involve time dependence or rotation. These concepts have also been extended to general gravity theories in higher dimensions. The crucial input to this approach is the existence of null surfaces in space time which allows a kind of thermodynamic interpretation of the field equations governing the dynamics of gravity. As a result one can expect gravity as an emergent phenomenon from the underlying statistical mechanics of space time.

Another added feature of this approach is the possibility that gravity may be immune to the bulk vacuum energy. This may lead to very important consequences for the understanding of late time acceleration of our universe and related issue of the magnitude of cosmological constant.

Spherically symmetric space time: $ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$

Horizon is at $r = a$ such that: $f(a) = 0$

Einstein equations on the horizon: $\frac{af'(a)}{2} - \frac{1}{2} = 4\pi T_r^r(a)a^2$

Under a displacement 'da', this can be written as:

$$\frac{f'(a)}{4\pi}\mathrm{d}(\pi a^2) = \mathrm{d}\left(\frac{a}{2}\right) + T_r^r\,\mathrm{d}\left(\frac{4\pi}{3}a^3\right)$$

$$TdS = dE + PdV$$