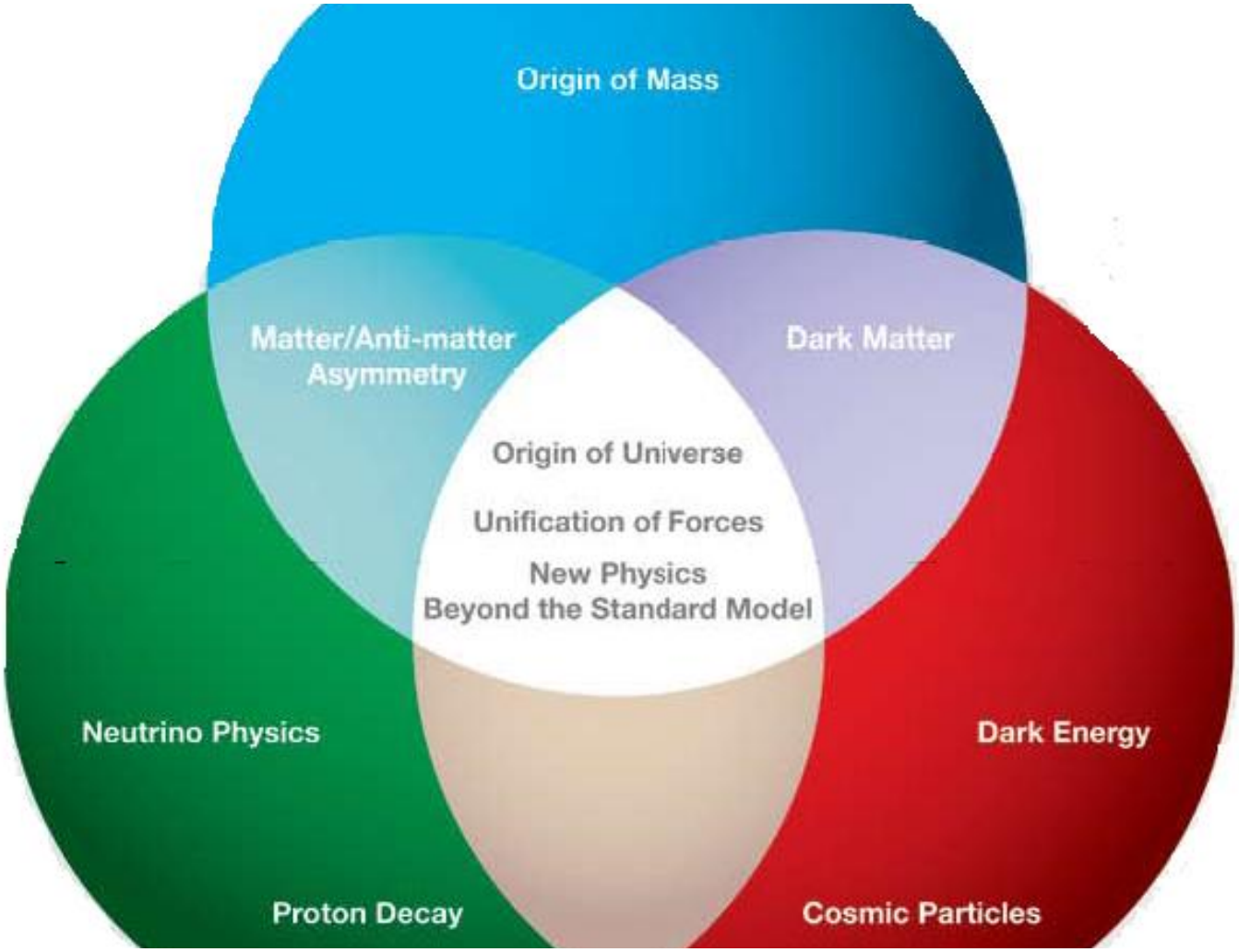
A Theory of Everything?



Shabnam Jabeen
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What is the nature and origin of this universe?

How it all started and how it will end?

What is everything around us made of?

……?
……..?
….?

A final Theory?

Will it answer even questions like

where are my socks?

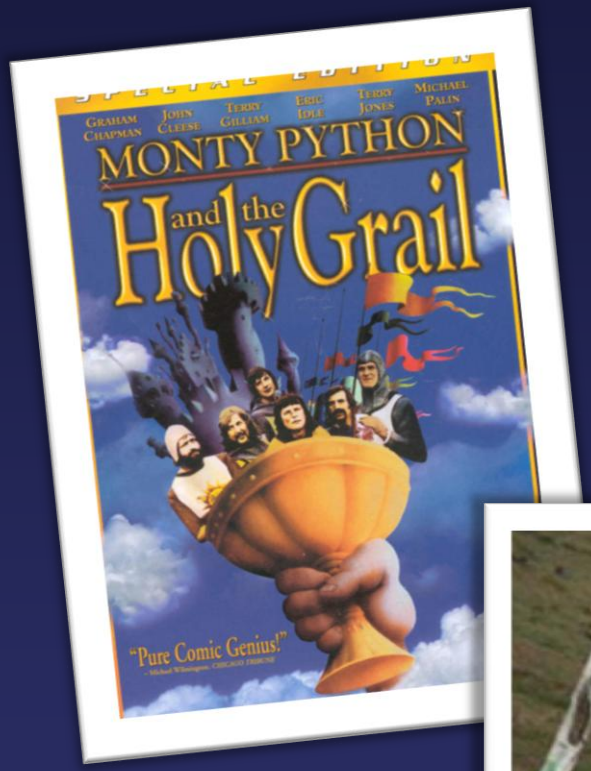
or

what is coming on the test?

or

Does s/he like me?

Well, its not a crystal ball!


Graham Chapman
John Cleese
Terry Gilliam
Eric Idle
Terry Jones
Michael Palin
MONTY PYTHON
and the Holy Grail
"Pure Comic Genius!"

It’s a theory that will

combine all known forces and particles

and

explain all phenomenon we observe in nature

and

will predict many more that we may not have even thought about

It is a theory we still have to discover!

But before we talk about the final theory

let us take a brief look at

the picture of this universe

the way we understand it today

and

why we think there should be a” final theory” at all?

Forces we Know Exist!

Standard Model

General Relativity

Holds atoms and molecules together

Converts neutron in to an electron and proton

Strong enough to hold same charge particles in a nucleus

Makes apples fall on the ground

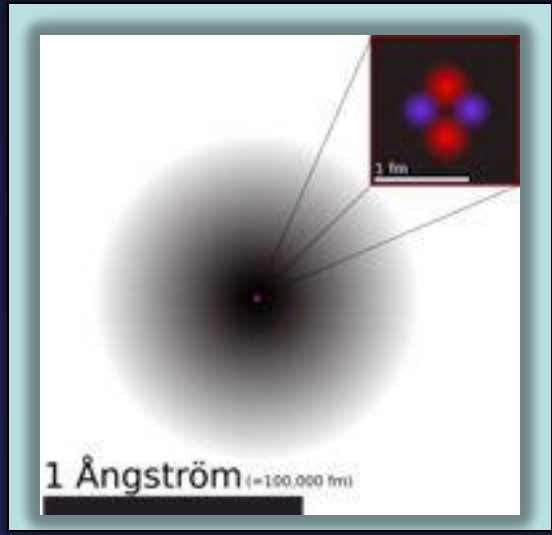
Two Different Worlds

The smallest:

The world of molecules, atoms, quarks and leptons

Where one can ignore effects of gravity

A world explained by quantum mechanics!

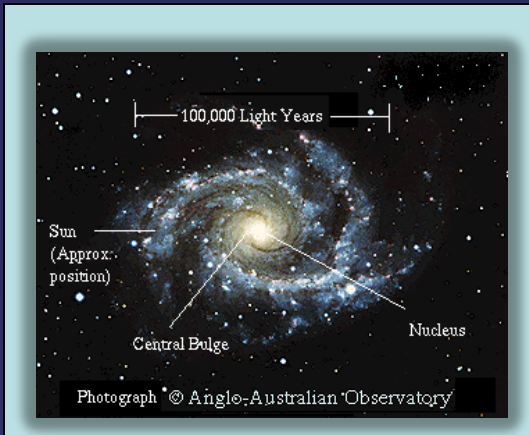


The largest:

World of stars, galaxies and beyond

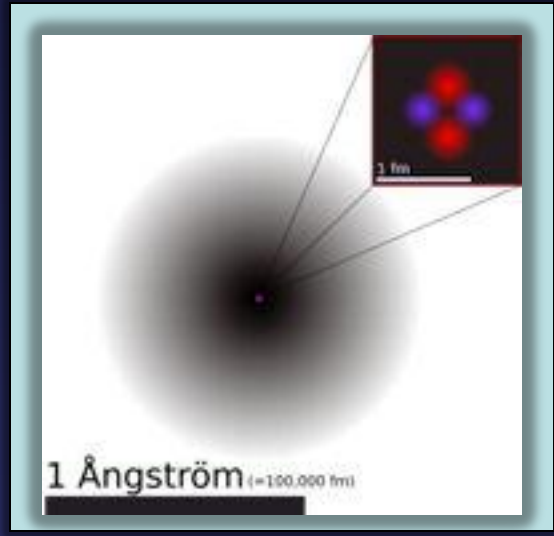
Where one can ignore quantum mechanics.

A world explained by cosmology and general relativity

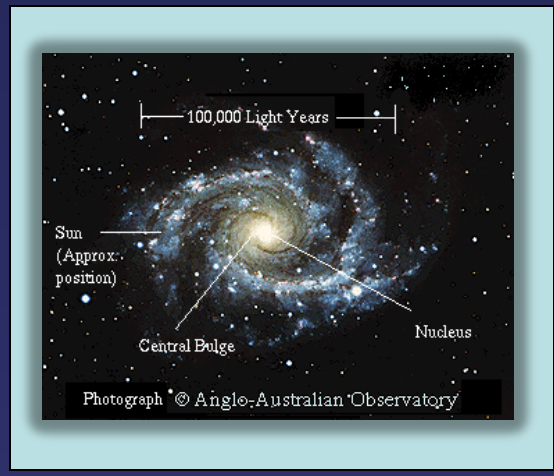


Two Different Worlds

- Standard Model of particle physics:
  - A quantum theory that explains, with breathtaking accuracy, the world of molecules, atoms, quarks and leptons.
  - A theory that describes phenomena involving 3 out of 4 known forces: electromagnetic, weak and strong.
  - It doesn't talk about is gravity.
  - It doesn't explain everything: e.g. origin of masses, dark matter,..)



- General Relativity:
  - Theory of gravity that relates curvature of spacetime and the energy and momentum within the spacetime.
  - Successfully explains many cosmological phenomena.

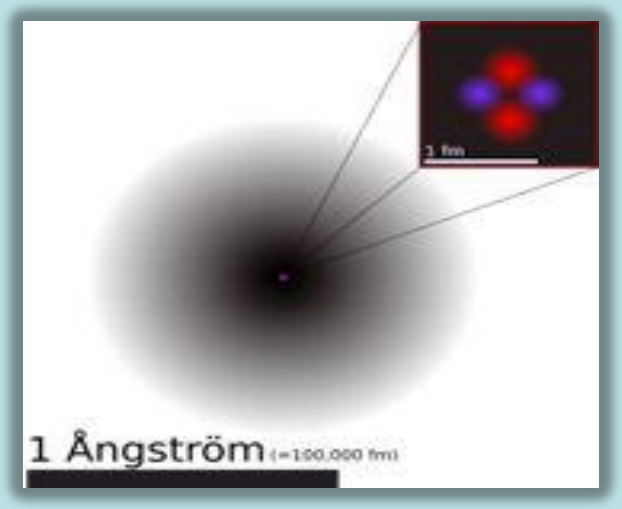


Question: How would you explain what is happening in the center of a black hole where huge mass (huge gravitational pull) is enclosed in a volume of quantum scale?

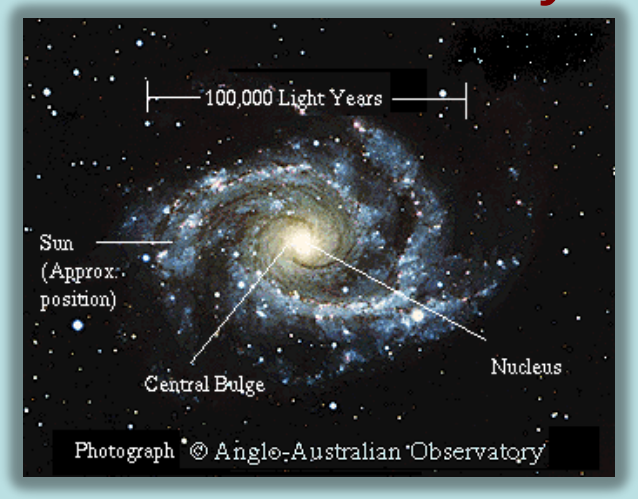
Homework Problem 1:

Two Different Worlds

Standard Model



General relativity



We have yet to discover something that contradicts either of these theories – but they are both incomplete and incompatible

Can we combine them to get a theory that explains smallest to the largest?

Before answering these questions

lets see how we ended up having

two different worlds!

Little Bit of History (1)

19th century physics was divided in different subfields

Dynamics →	Laws of motion and gravitation
Thermodynamics →	Laws of temperature and heat energy, behavior of solids and liquids
Waves →	Study of oscillations of continuous media and Sound waves
Optics →	Study of light
Electricity →	Where does lightening comes from? How a battery works?
Magnetism →	Why does compass always point north?

Little Bit of History (2)

By the beginning of 20th century we were left with two major branches of physics

Described by atomic theory

- Dynamics — Laws of motion and gravitation
- Thermodynamics — Laws of temperature and heat energy, behavior of solids and liquids
- Waves — Study of oscillations of continuous media. Sound waves

Described by theory of electromagnetic fields

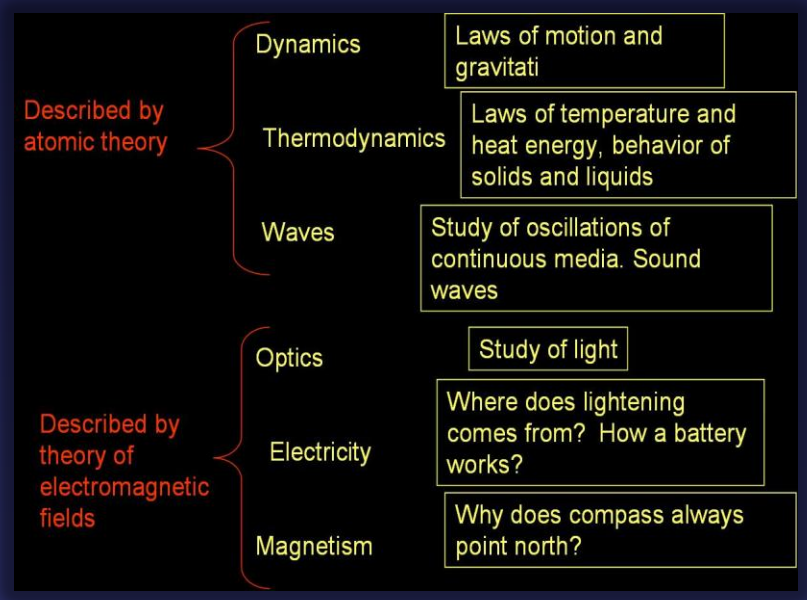
- Optics — Study of light
- Electricity — Where does lightening comes from? How a battery works?
- Magnetism — Why does compass always point north?

Everything in the world is either particles or waves

Little Bit of History (3)

Such successful a picture it was that a leading physicist (A. Michelson) said this in 1894

"It seems probable that most of the grand underlying principles have been firmly established and …….The future truths of Physics are to be looked for in the sixth place of decimals"



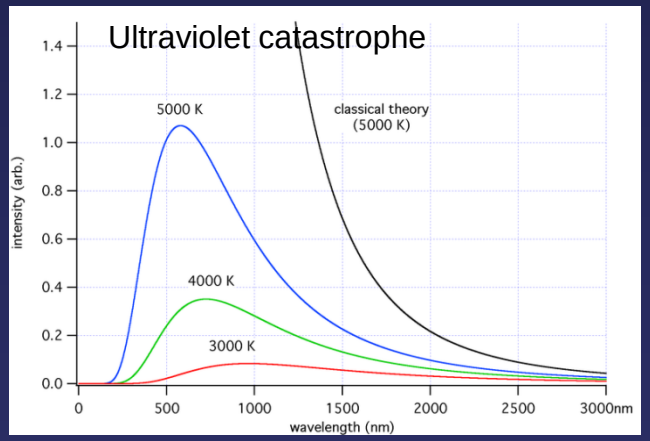
This announcement came at a time when there were only a few problems left unsolved

But what he didn't know was that we were about to witness two revolutions in physics

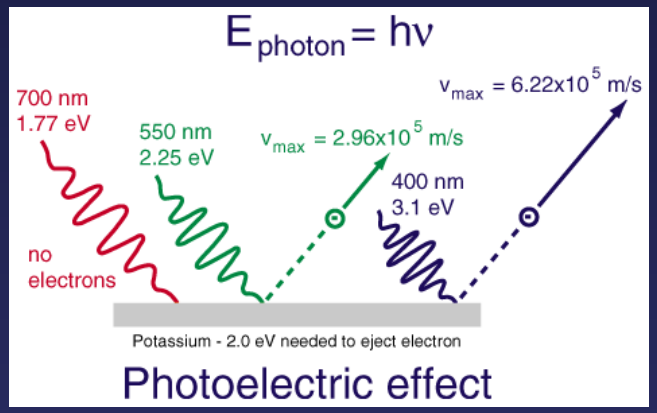
Revolutions which will change existing concepts of particles and fields beyond recognition!

Problems Left Unsolved

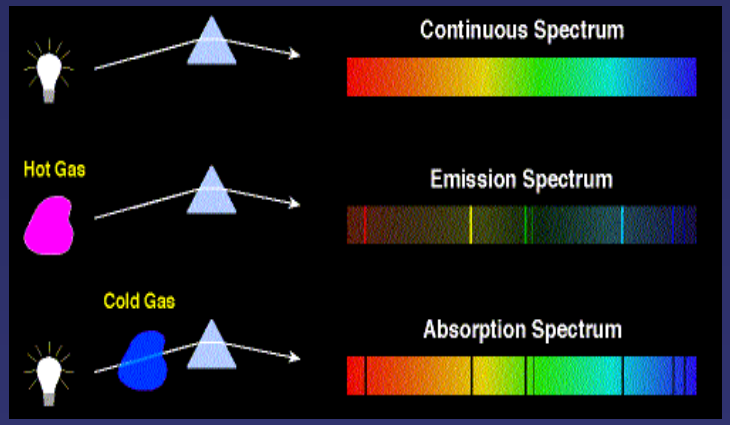
1. Blackbody Radiation



2. Photoelectric Effect



3. Atomic Line Spectra



Finding solution to these problems led to …

The Birth of Quantum Mechanics

Quantum Mechanics

- In 1925-26 Werner Heisenberg, Erwin Schrödinger proposed a new theory called quantum mechanics

1) Wave particle duality
2) For the outcome of an experiment, only probabilities can be determined
3) Schrödinger's equation gives that state of particle

(something like equations of motion in classical physics)

what exactly is quantum mechanics (in simple words)??

A Quantum Mechanical System

- In general, quantum systems exist in superposition of all possible states.

- When not being measured or observed, this system evolves according to the time dependent QM equation of motion

  (Schrödinger equation, relativistic quantum field theory or some form of quantum gravity or string theory).

- However, when this system interacts with experimental apparatus, the wave function collapses and (from an observer's perspective) the state seems to "leap" to just one of the basis states and uniquely acquire the value of the property being measured

- Not all the properties of a system can be measured with full certainty

"I can safely say that nobody understands quantum mechanics"

(Richard Feynman)

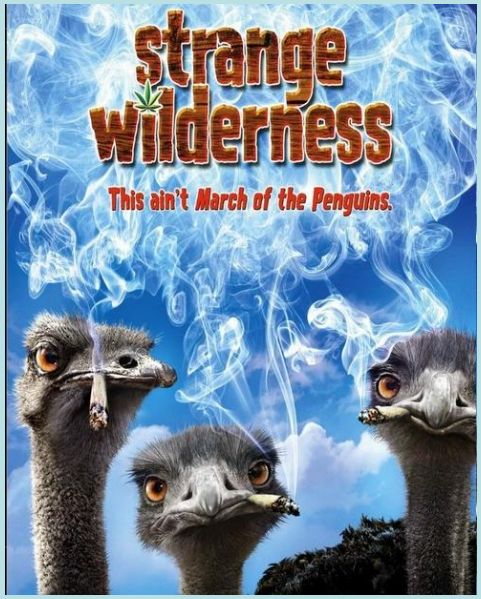
"Those who are not shocked when they first come across quantum theory cannot possibly have understood it"

(Niels Bohr)

"Nobody feels perfectly comfortable with it"

(Murray Gell-Mann)

Welcome to the world of Quantum Mechanics!



Question: why we abandoned classical physics with full predictive power with something that describes everything in terms of probabilities and uncertainties?

Answer: we were forced by nature because quantum mechanics explained puzzles of the time.

What is the correct interpretation of Quantum Mechanics? - this is a hot topic even today

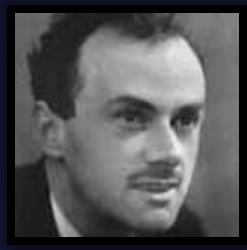
There are still open questions – including whether QM is at odds with theory of relativity

But QM Didn't Solve Everything Either

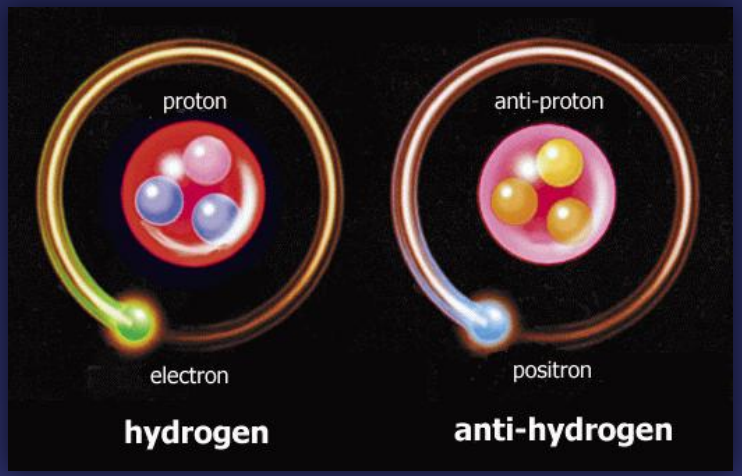
- There were still problems:
  - Theoretical : QM (with Newtonian description of space and time) was in conflict wit Special Relativity although, by that time, special relativity was believed to be the correct description of space and time.
  - Experimental: QM explained line spectra but not completely.

Relativistic QM (QM+Special Relativity)

- In 1928 P. A. M. Dirac came up with the first theory of QM which was compatible with special relativity



– As a bonus, theory predicted "anti electron"

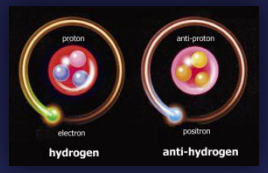


- A particle which has same mass and spin as electron but opposite charge which we call positron
- 1932, positrons were discovered (C.D. Anderson)
- First (but not last) particle discovered which was predicted by a theory first

Dirac and Anderson both were awarded Nobel Prize

Antimatter – Where is it Anyway?

- So far we haven't found any evidence of anti-matter region in the universe



but

- Laws of physics treat matter and antimatter <u>almost</u> symmetrically.
- There are some cases in which, it seems like, some processes prefer particle interactions than anti-particle interactions – referred to as CP-violation

- But observed CP violation is not enough to account for the matter-antimatter asymmetry observed in the universe

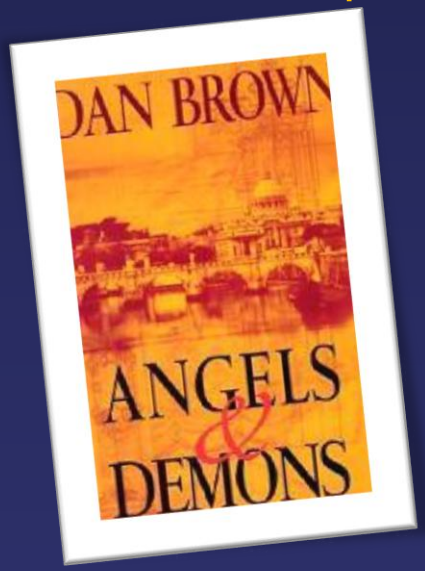
  - Intriguing Puzzle: Why we see more matter than antimatter?

    This is still a mystery we haven't solved yet!

  - No experimentally evidence of annihilation radiation from outer space
  - A rich program of searches for antimatter in cosmic radiation exists

Antimatter – Weapon / Fuel in the Future?

- When a particle and its anti-particle collide, they annihilate into energy
  - Antimatter used as fuel for the fictional starship Enterprise in Star Trek
  - Used as a weapon in Angels and Demons

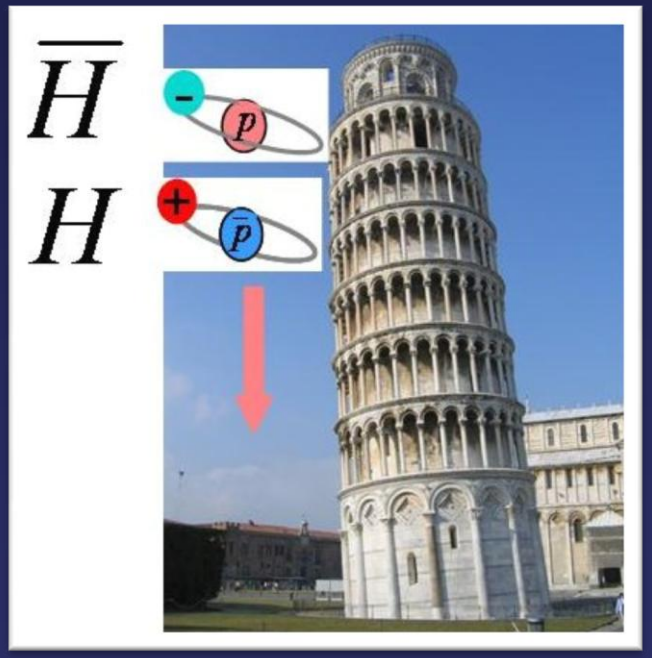


- NASA is paying attention to antimatter as a possible fuel for interstellar propulsion

See you on the Mars?

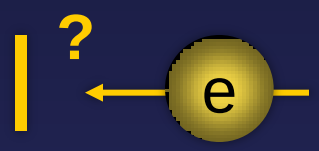
Antimatter and Gravity

- General Relativity predicts that the gravitational forces on matter and antimatter should be identical,
- But no direct experimental test of this prediction has yet been made.
- There are models which predict opposite behavior of antiparticles in gravity
- Could opposite behavior of matter and antimatter to gravity explain Dark Energy?



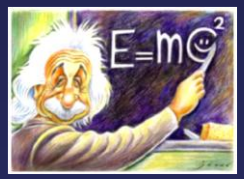
Does matter and antimatter fall similarly?

QM + Special Relativity + Fields



- Another Puzzle:

What happens if an electron collides with another electron?



  - According to relativity, when sufficiently high energy particles collide, could convert their energy to mass, producing new particles.
  - What we need is a theory that can explain electron-electron interaction and interaction of electrons with photons of the electromagnetic field

This means a complete theory must include QM, relativity and electromagnetic field theory

We call it

<u>"Relativistic Quantum Field Theory"</u>

Forces we Know Exist!

Standard Model

General Relativity

Field Theory of Electrons and Photons

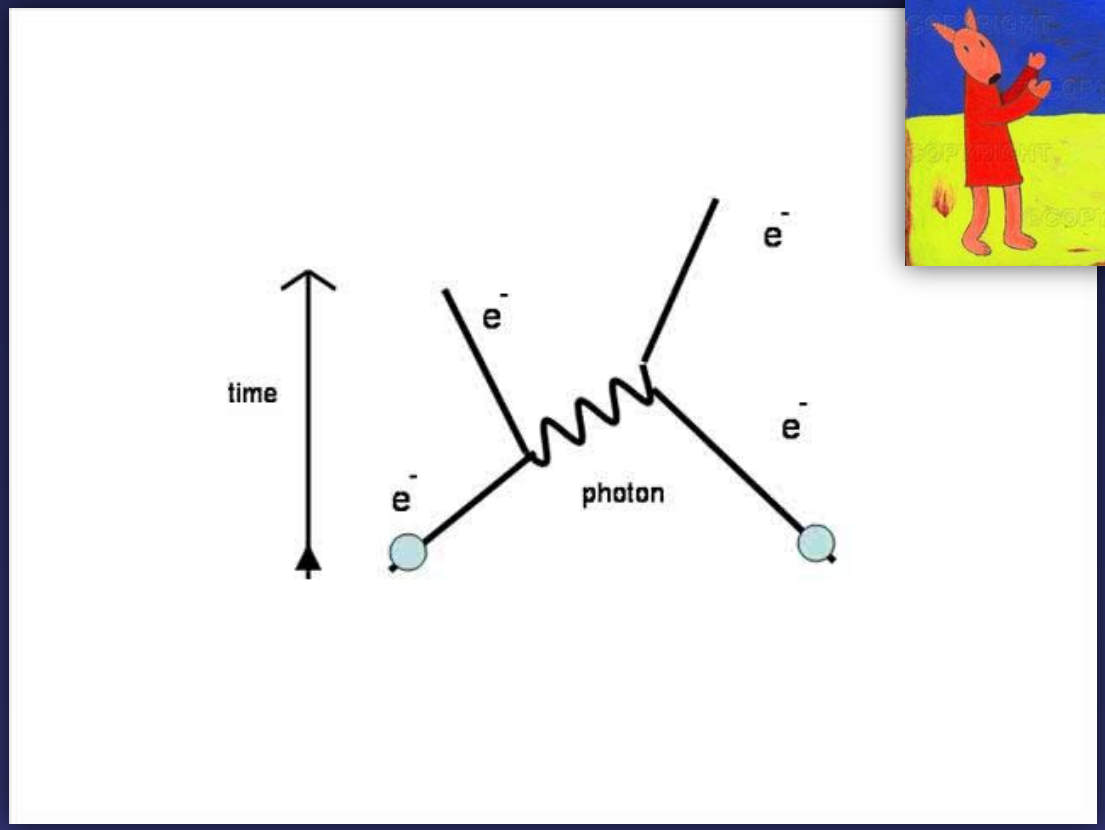
Quantum ElectroDynamics (QED)

- In 1940s, Feynman, Schwinger and Tomonaga independently proposed a quantum field theory to explain interactions of electron and photons.

- In 1965 Feynman, Schwinger and Tomonaga all received a Nobel prize for their different but consistent approaches to QED

What does “Interaction” Mean?

Forces between particles arise from a continual exchange of force-carrying particles (also called, quanta of the field)

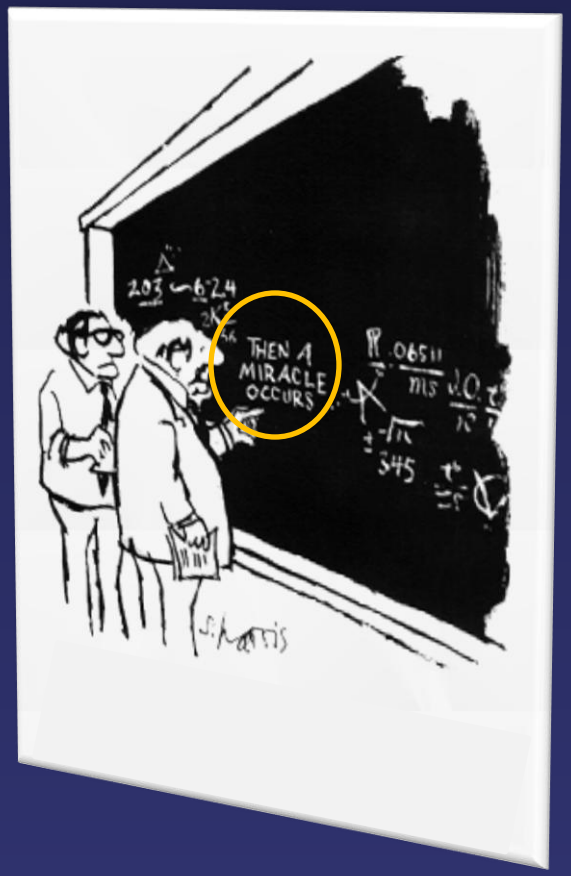


Triumph of QED

- In 1948 Schwinger published his approach to QED and along with first experimentally verifiable calculation of magnetic moment of electron

- This has been called the most accurate prediction of any scientific theory ever

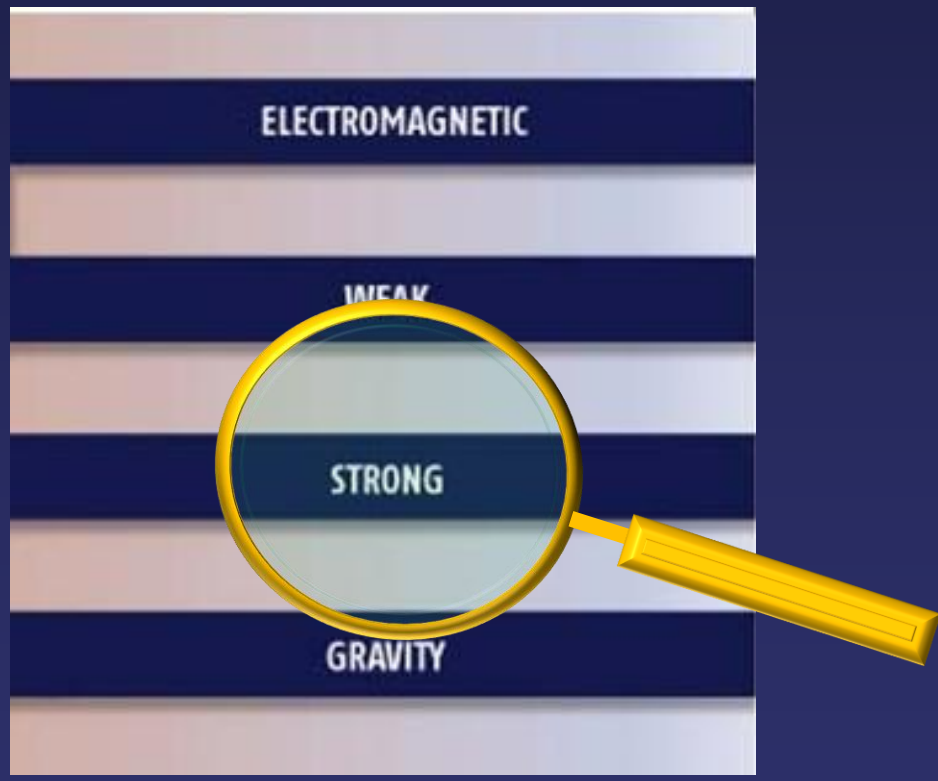
The current value is 2.0023193044 with an uncertainty of 2 in the last digit with an experimental value with agrees with this prediction with even a smaller uncertainty



Forces we Know Exist!

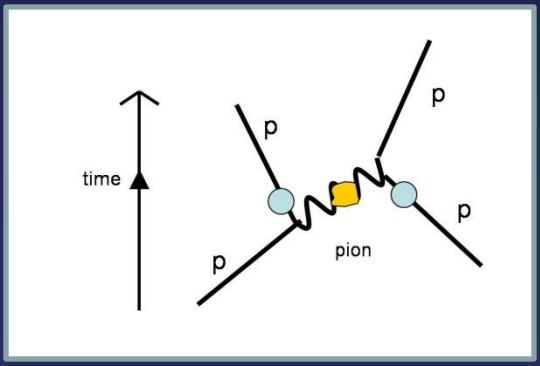
Standard Model

General Relativity



Strong Force

- In 1935, Yukawa suggested that protons and neutrons were held together in a nucleus by exchange of a particle between proton and neutron, like photon exchange between electrons.

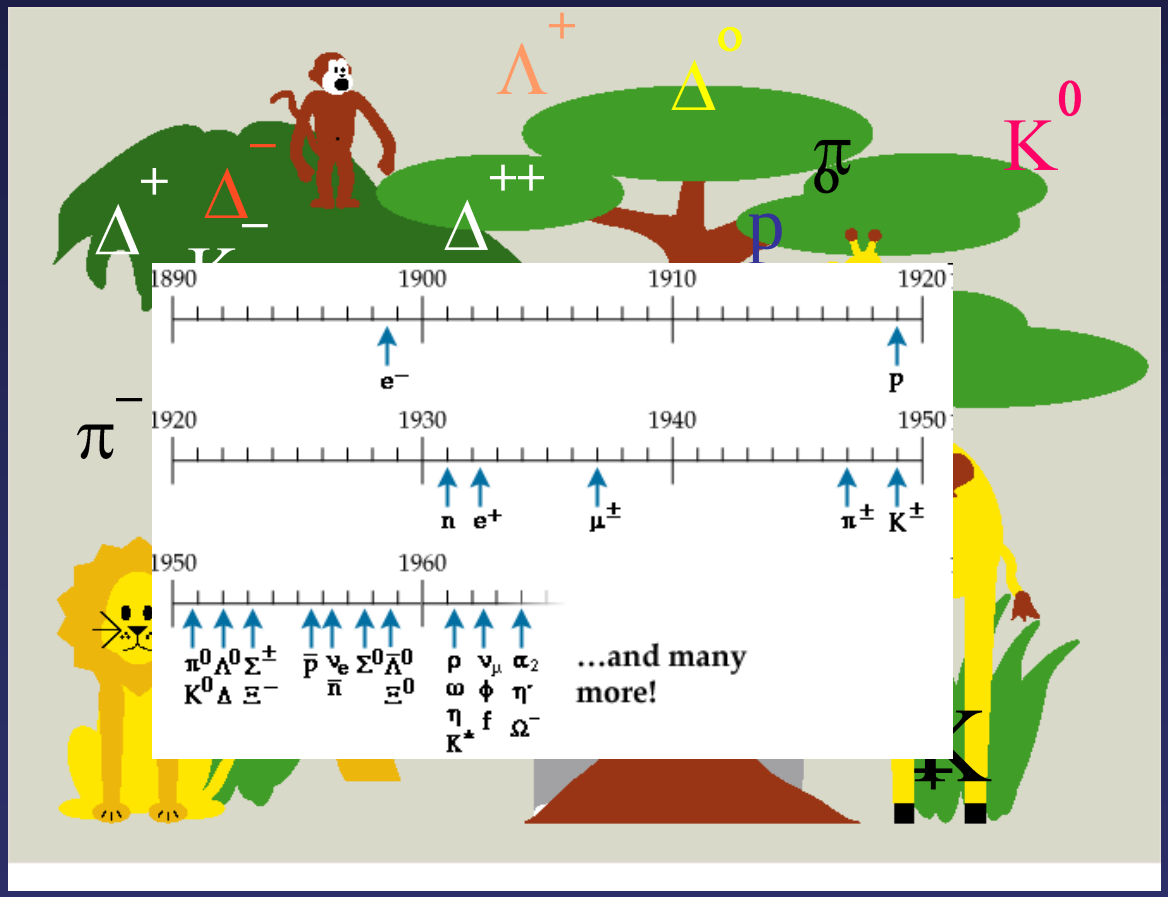


In 1937 Carl Anderson discovered another charged particle

This particle was named muon – in all respects it was another electron, just more heavier. Muon's discovery prompted the famous comment from I.I. Rabi

During 1940s -1950s, with improved experimental techniques, many more particles were discovered, including Yukawa's pion.

It's a Jungle Out there!



Subatomic Zoo! Question is why are these particles necessary?

and

what is their relationship with one another?

(we had gone from 3 in 1932 to 18 in 1960)

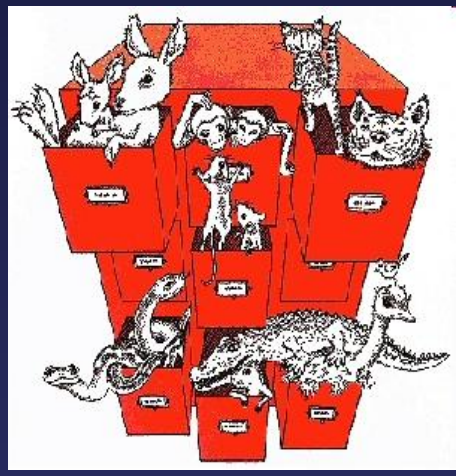
Arranging the Animals?

- Until 1960s experiments had found a large number of new particles but no one had any understanding of fundamental principles requiring all these particles.

How to classify these particles?

- What's their mass?
- What's their spin?
- How they interact?

Arranging the Animals?



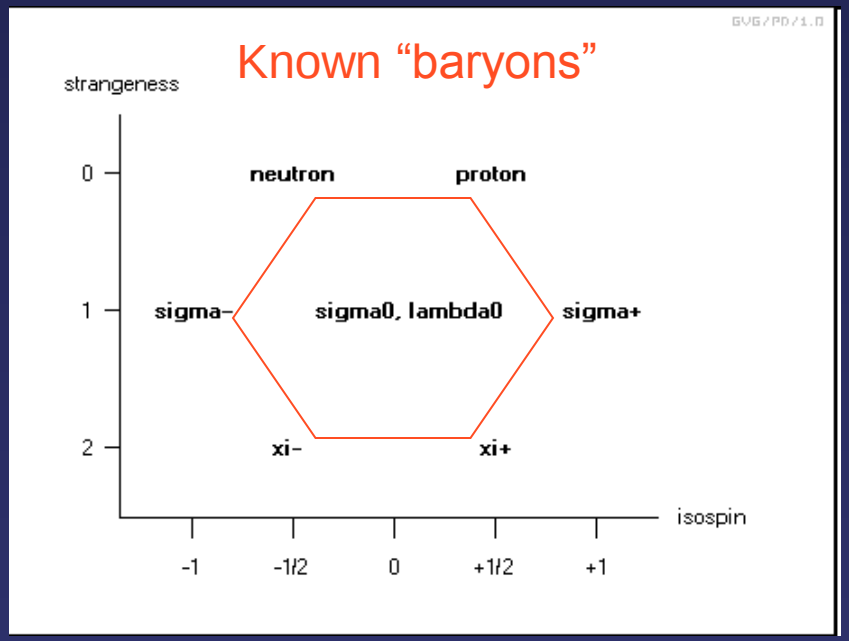
How to classify these particles?

- What's their mass
  - Low mass (neutrino,electron), called leptons
  - Middle mass (pion,muon) called mesons
  - High mass range (proton, neutron,…) called baryons
- What's their spin
  - Half integer spins (1/2,3/2…) called fermions
  - Integer spins (0,1…) called bosons
- How they interact? (or what kind of force they respond to)
  - Electromagnetic – force between charged particles
  - Strong – force which holds a nucleus with positively charged protons together
  - Weak – force that converts a Neutron into a proton and gives off radiation

  - Gravity: we are not even thinking about gravity at this point

Symmetry to the Rescue?

- In 1961, Murray Gell-Mann and Yeval Ne'eman independently came up with first “periodic table” for subatomic particles by using symmetry

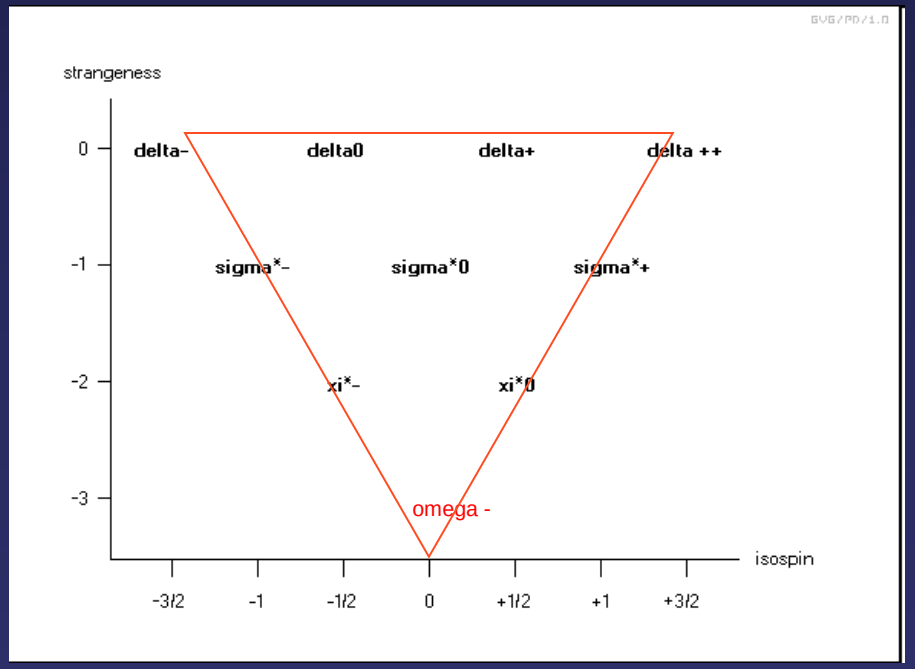


These "octoplets" followed a symmetry group "special unitary group 3" or SU(3).

It Has to be Symmetry!

- In1962, Gell-Mann claimed that a particle should be found with a triple strangeness value, mass of about 1680 MeV, and gave it the name: "omega minus".

- A Brookhaven team found the particle in February 1964; CERN confirmed the discovery a few weeks later.



The SU(3) symmetry is what was needed to arrange our subatomic zoo

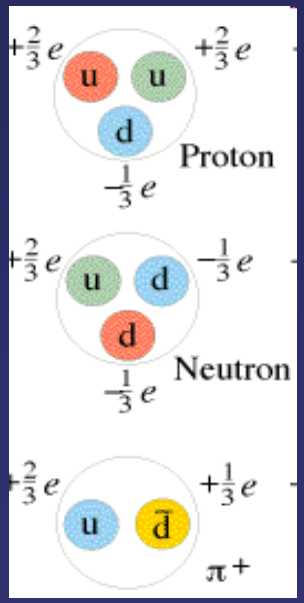
If it's SU(3), Where are the Quarks?

- Gell-Mann noticed that he has found 8,8, and 10 particle representations of SU(3) symmetry group but where was the simplest multiple - the triplet

- Gell-Mann and Zweig independently suggested that the simplest solution in fact corresponds to 3 fundamental particles – smallest particles which make up all other particles

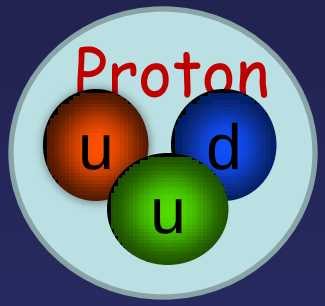
Question is:

Why we haven't seen any such particles with fractional charges?

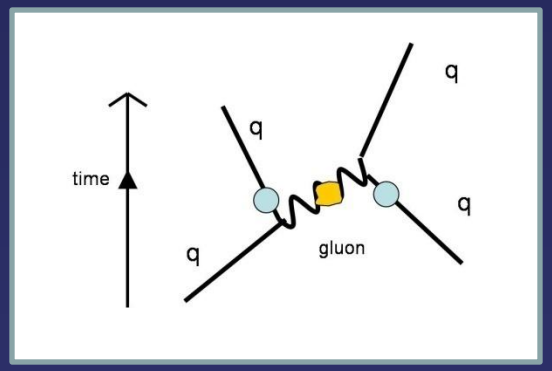


Color Theory of Quarks

- In 1972, Gell-Mann and two of his collaborators proposed that quarks have another property "color" and each flavor (up, down strange) come in three colors which they named "red", "blue" and "green"



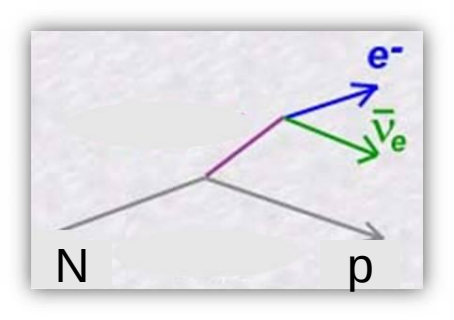
- Only "color-less" particles can be seen in nature
- And the force that "glues" quarks together in a proton is carried by a new type of particles called "gluons"



Complete theory of interactions of quarks and gluons is called Quantum ChromoDynamics (QCD)

Weak Force

- In contrast to electromagnetic and strong forces, the strength of the weak force is different for particles and anti-particles

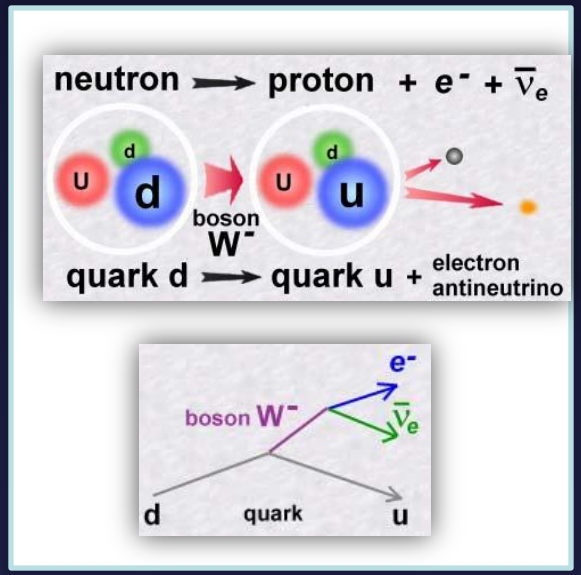


This may partially explain observed dominance of matter over antimatter

- The nuclear fusion reaction taking place in sun is one example of this force

Theory for Weak Interactions

- We can use the similar approach we used for QED and make a theory for weak interactions as well
  - For our theory to work there should be three force carrying particles



- There is only one problem now:
  - Our theories, so far, predicted mass-less force Carrier (photons and gluons)

In fact, now that we are talking about mass, our beautiful, symmetric theories do not give masses to any leptons or quarks either.

Electroweak Theory

- It turns out that:
  1) Electromagnetic and weak forces seem to be a single force at higher energies
  2) Symmetry describing this force is broken at everyday energies
  3) The mechanism to break this symmetry introduces a new field and a new particle of that field

     This new particle is called Higgs and the field is called Higgs Field

- Peter Higgs suggested:
  1) This new field fills up all the space
  2) A particles acquire mass by interacting with this new field
  3) Heavier particles interact more strongly, whereas mass-less photons don't interact at all

The Higgs particle - still undiscovered

Higgs Mechanism

space filled only with the Higgs field....

... a well known scientist walks in, attracting a cluster of admirers with each step ...

... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field ...

... if a rumor crosses the room ...

... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.

Higgs – The God Particle?

- Higgs mechanism explains these masses but this is only one of the ways in which particles can get mass
- There could be different types of Higgs particles or a very different type of symmetry breaking

And Higgs is not what accounts for most of the visible mass anyway

- The quark pairs are responsible for the proton's mass
- Interaction energy provides proton mass

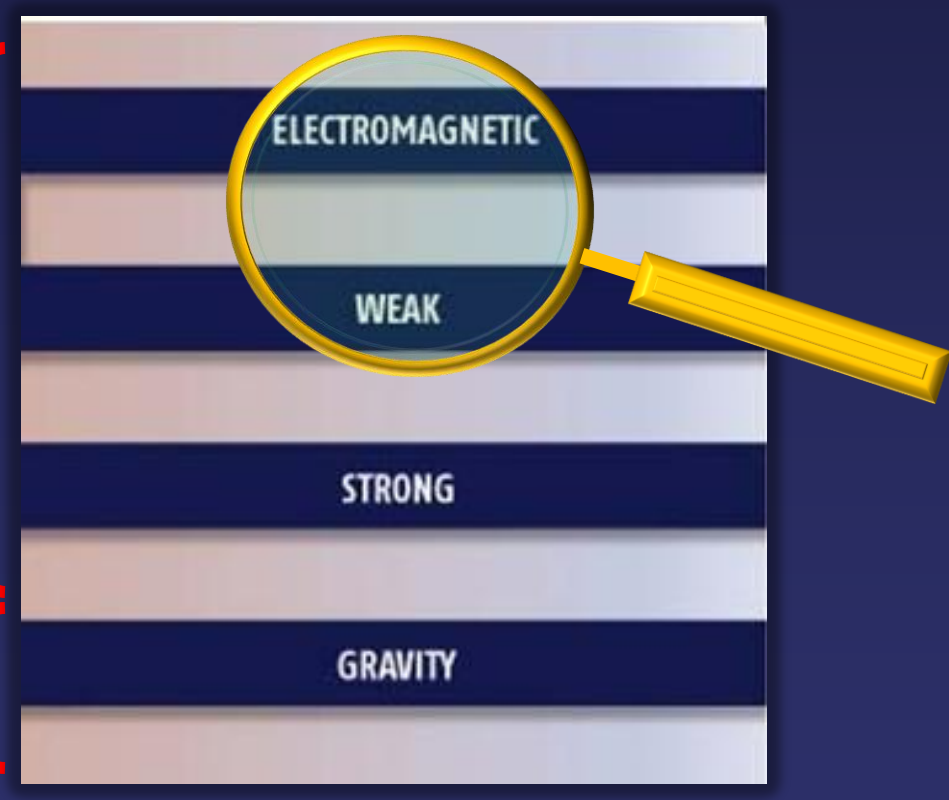
We don't really know what exactly is the origin of masses for existing particles

And Don't take this question lightly

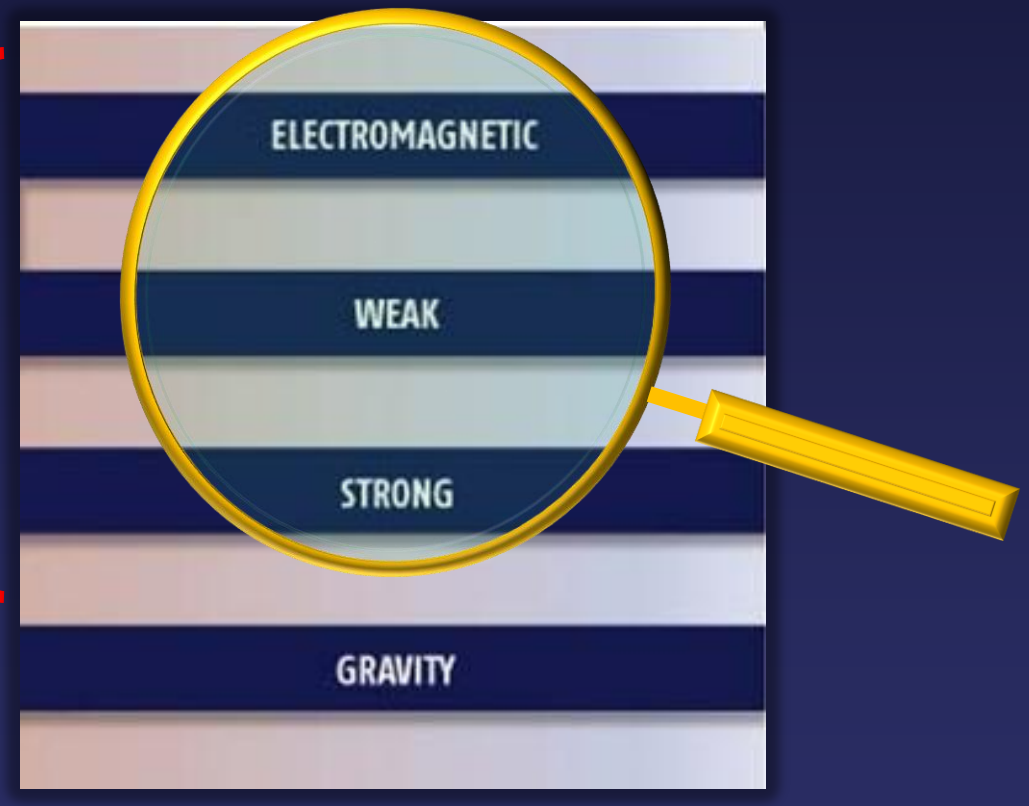
Forces we Know Exist!

Standard Model

General Relativity



Standard Model

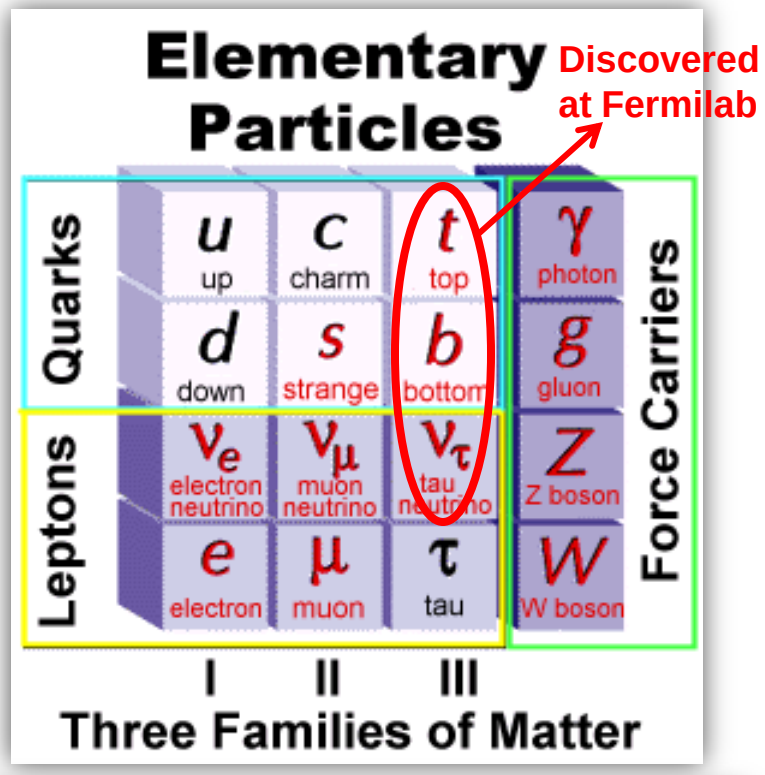


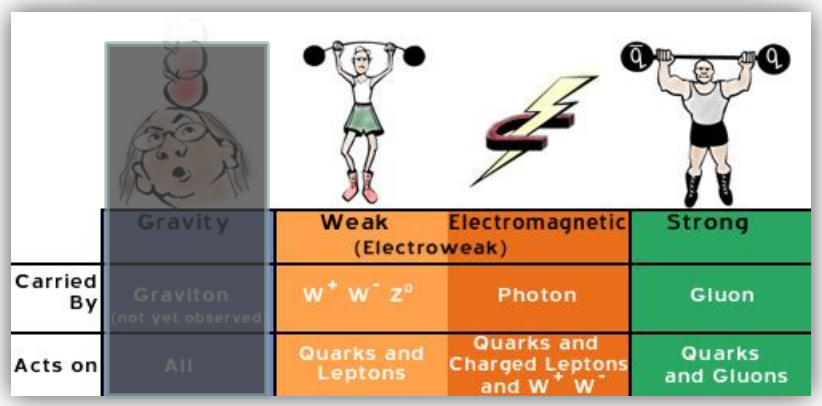
Electroweak together with QCD, explains the world around us in terms of a single theory called… The Standard Model

The Standard Model of Particle Physics

- Quarks and leptons are the most fundamental particles of nature that we know about
- Up & down quarks and electrons are the constituents of ordinary matter
- The other quarks and leptons can be produced in cosmic ray showers or in high energy particle accelerators
- Each particle has a corresponding antiparticle.

Note – we didn't have to worry about gravity so far





SM: Theory of (Almost) Everything

(everything we encounter in everyday life, that is)

…..(Standard Model) surpasses in precision, in universality, in its range of applicability, from the very small to the astronomically large, every scientific theory that has ever existed …

Robert Oerter

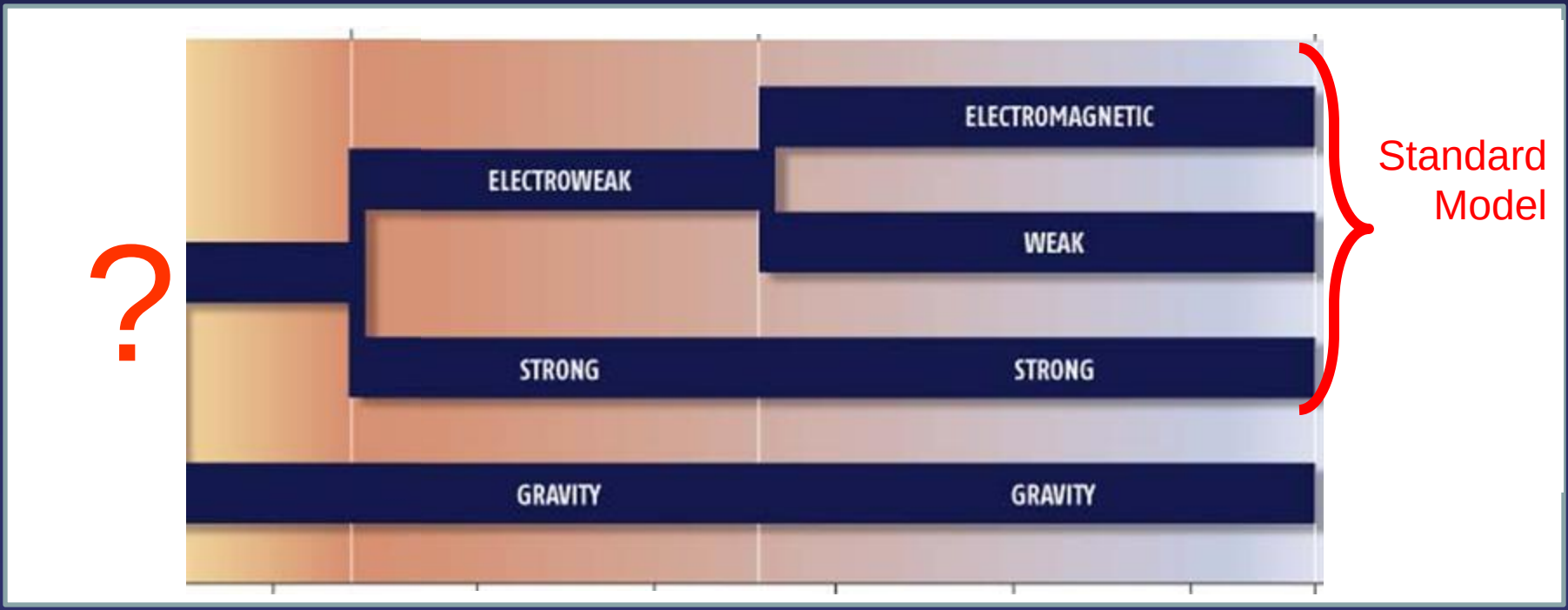
But Standard Model is not theory of everything

It does not explain origin of mass

It does not include gravity

What do we have so far?

- All interactions are fundamentally exchange of particles
- These exchanges are completely random and unpredictable
- We can only discover the probability of any process



What is beyond Standard Model?

Could it be GUTs?

- Symmetries worked so well so far
  - What if electromagnetism, the weak force and the color force all derive from a single force, described by theories based on a bigger symmetry
    - The Grand Unified Theories or GUTs

- They have their own problems, e.g. prediction of proton decay
- Experimental limit on the proton's lifetime has ruled some of them out

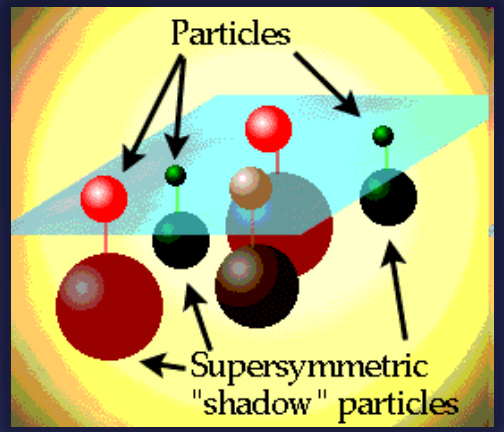
There is still no hard evidence that nature is described by a Grand Unified Theory

Or May be its SUSY?

(Suersymmetry)

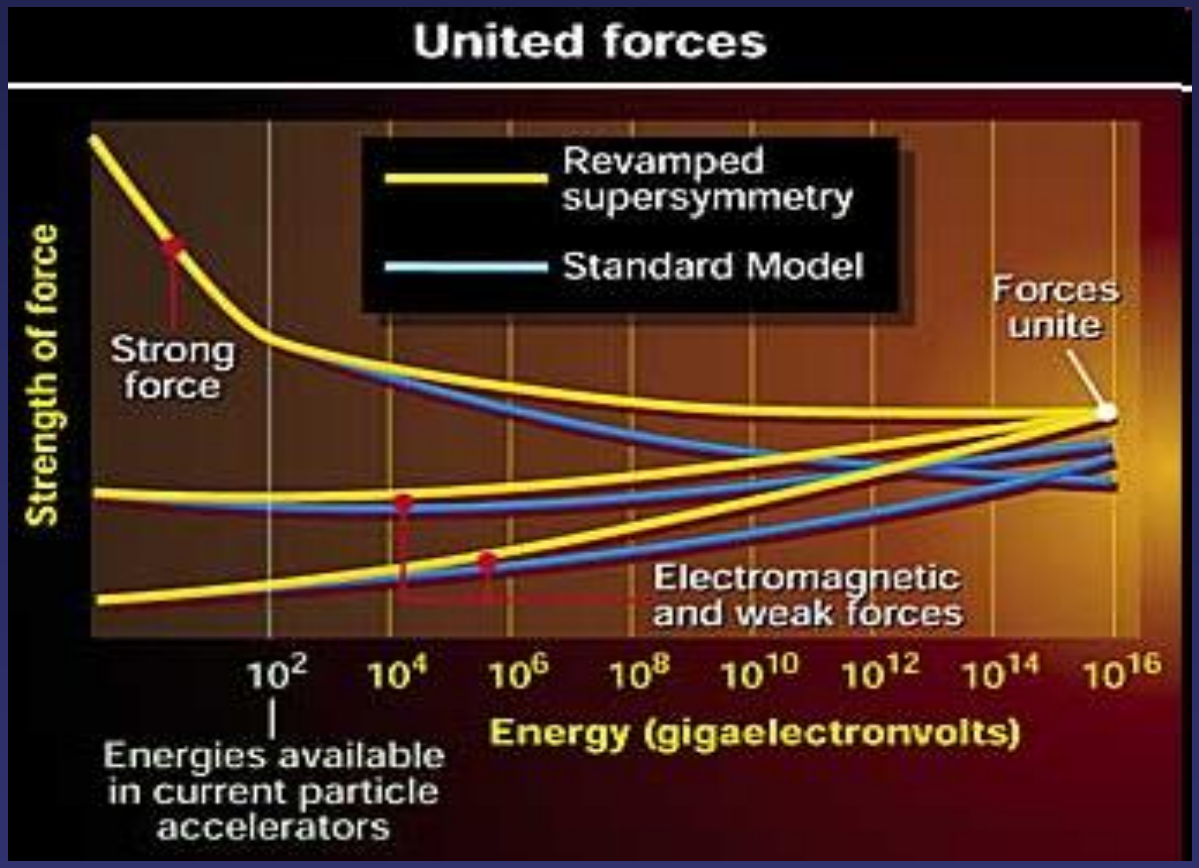
(Supertechnifragilisticexpialidocious?)

- One leading approach, called SuperSymmetry (SUSY), predicts the existence of a new Supersymmetric particles for every known particle.
- This increases parameters of the theory to at least 105 (compared to 19 for SM)
- But none of these supersymmetric particles, or **sparticles**, has yet been detected.

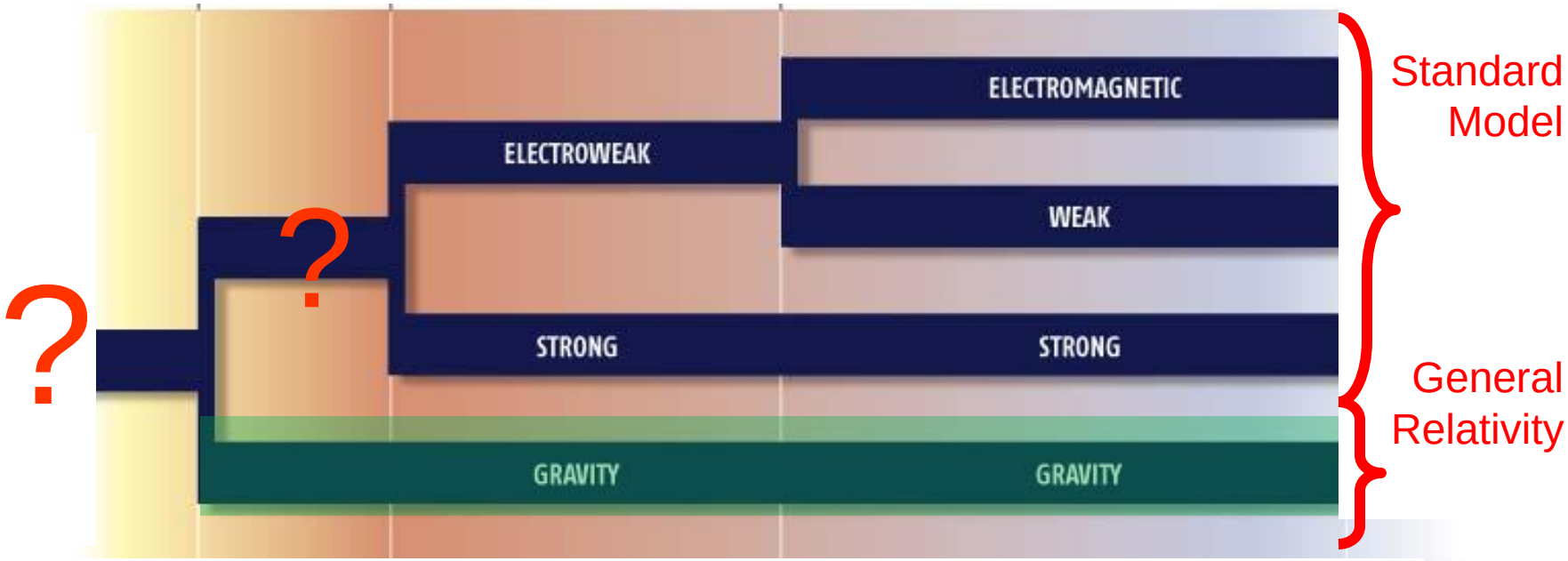


- The lowest mass supersymmetric particle, neutralino, is one of the favorite candidates for dark matter
- An essential ingredient for string theory

A Hint of Unification



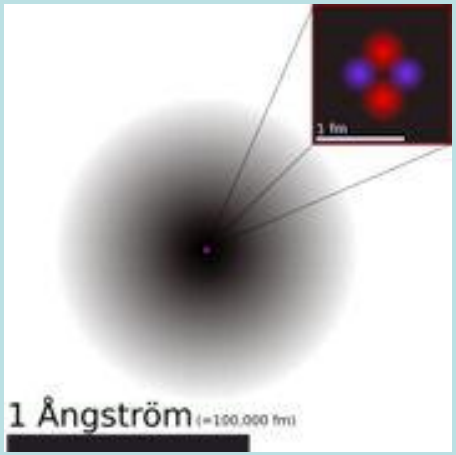
UNIFYING THE FORCES



Main Idea: Two Different Worlds

The smallest:

where one can ignore effects of gravity. The world of molecules, atoms, quarks and leptons. A world explained by quantum mechanics!

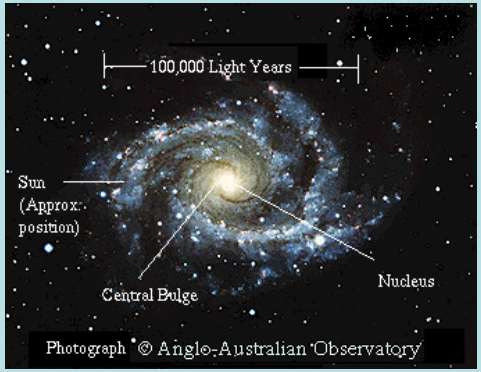


The largest:

where one can ignore quantum mechanics.

World of stars, galaxies and beyond.

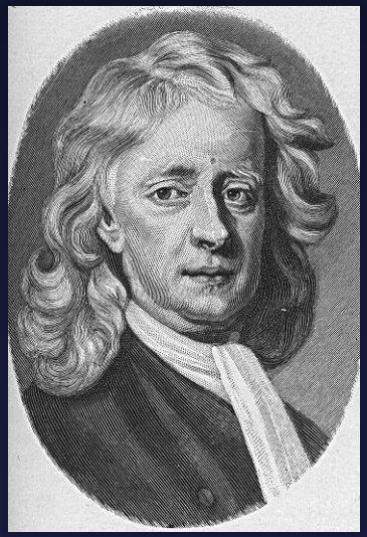
A world explained by cosmology and general relativity



Classical Mechanics vs. Relativity

- Absolute space, in its own nature, without relation to anything external, remains always similar and immovable.

  Isaac Newton 1686 Principia



- Space and time are related.

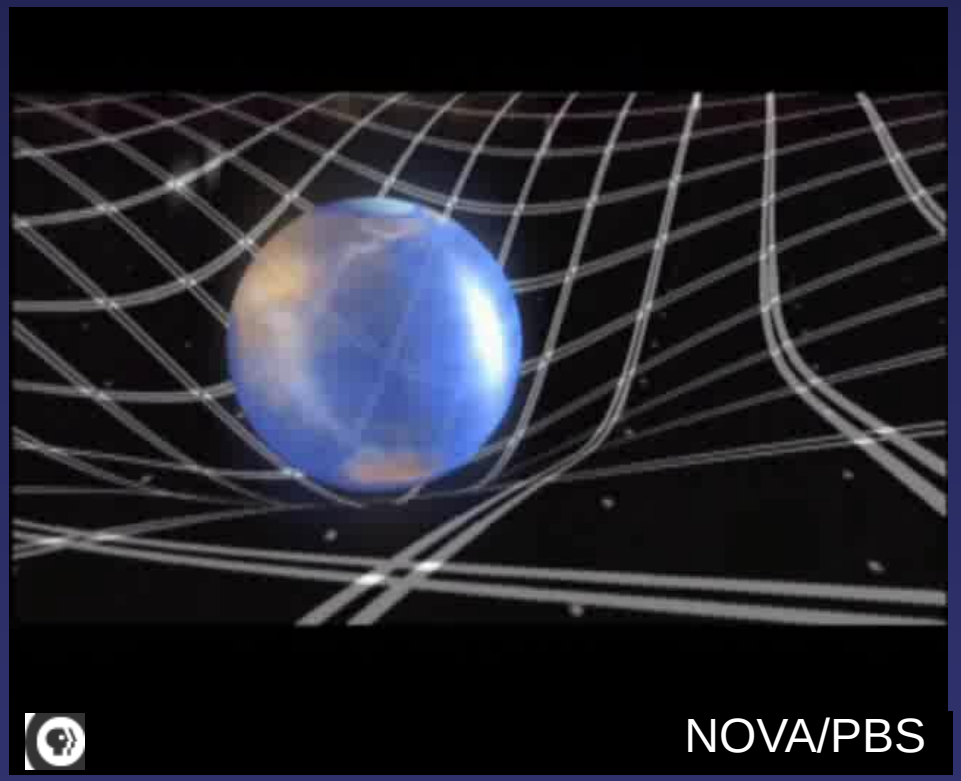
  Albert Einstein 1905

- Space is dynamical.

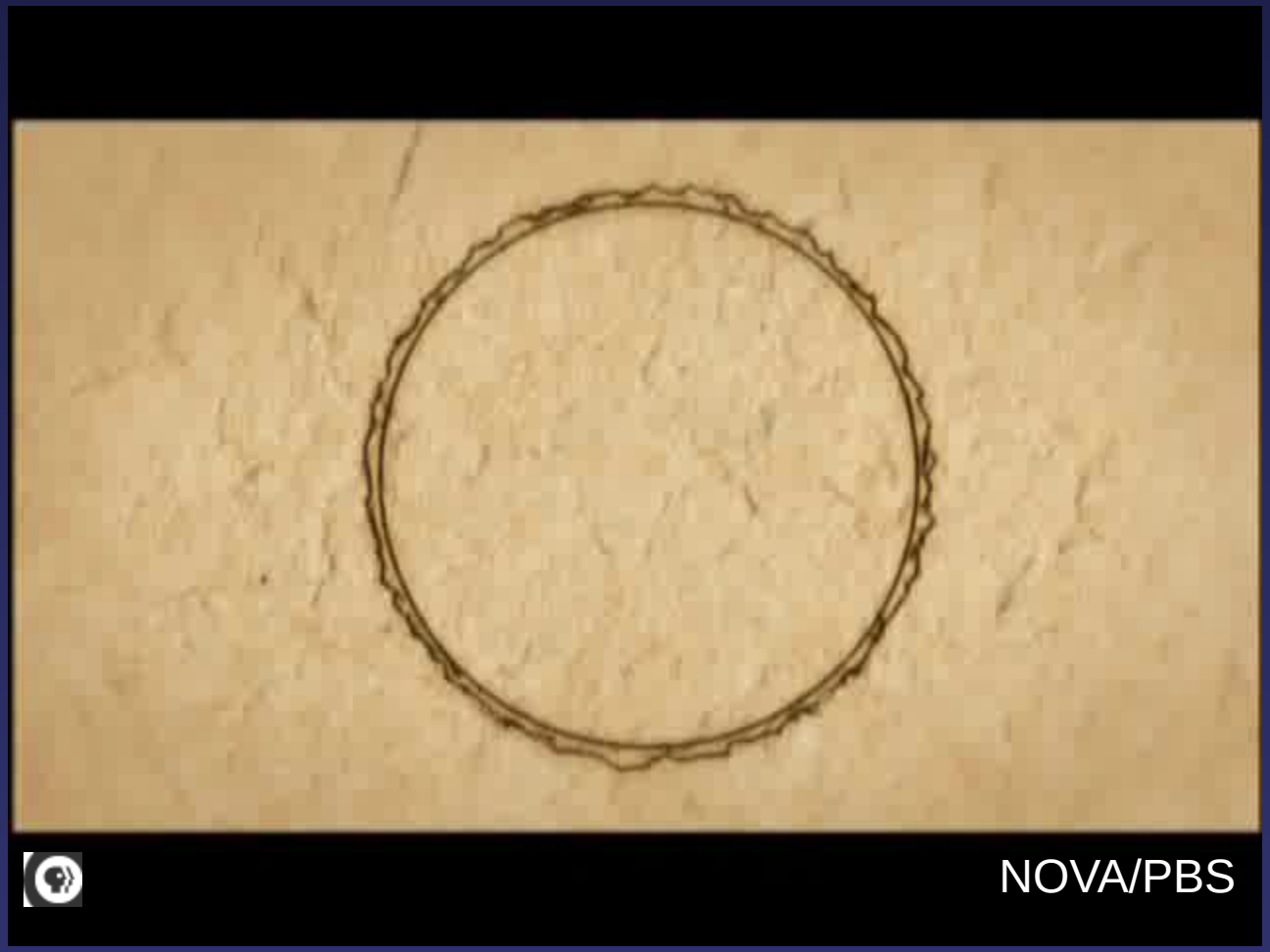
  Albert Einstein 1915

General Relativity

Mass (energy) in space-time can bend (curve) space-time around that mass



GR Predicts Black Holes



But does not explain what happens inside a black hole

Cosmological Constant

(Einstein's biggest blunder?)

In general relativity:

Curvature in space-time + Λ = Energy-momentum in (that) space-time

Einstein added a constant Λ by hand (he didn't like that solution to his original equations pointed towards a dynamic universe)

- In 1929, Hubble discovered universe is actually expanding

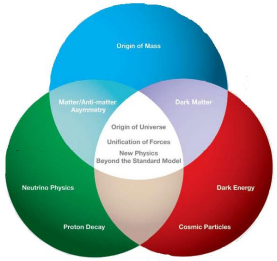
Einstein said cosmological constant Λ was his biggest blunder and cosmological constant became redundant

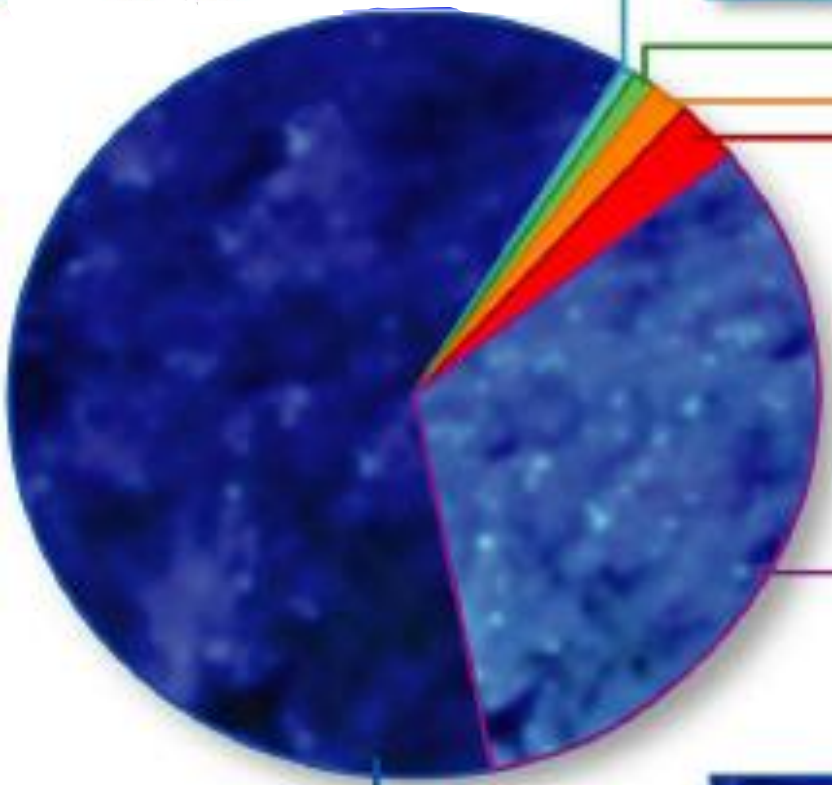
- In 1998, using Hubbel telescope, scientists measured the rate of expansion - It was increasing!

There exists some sort of energy that makes this rate increase → Dark Energy

Cosmological constant in equation of GR is necessary to explain this energy

Our best theories predict a value for the amount of dark energy that is too large by a factor of 10^{120}



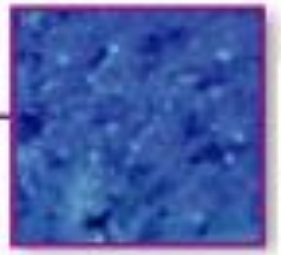


Chemical Elements:
(other than H & He) 0.03%

Neutrinos:
0.47%

Stars:
0.5%

Free H
& He:
4%



Dark Matter:
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Mystery

"The Universe is not only queerer then we suppose, it is queerer than we can suppose."
-Mark Twain

Outstanding Questions

- Interpretation of QM – deterministic or nondeterministic

- Within Standard Model, among others,
  - origin of mass?
  - what about gravity?

- General relativity: Cosmological constant and values of other parameters in the cosmological model?
- What happened at and before the Big Bang
- What is dark matter and dark energy?

- Combining all known forces and particles into one fundamental entity (should we expect such an entity to exist in the first place?)

Can we combine relativity and QM in a single theory?

Any theory that claims to be a fundamental theory must answer these questions

You can also add to this list:

Why do we want to know?

(we don't expect final theory to answer this one)

String Theory

- Fundamental particles are string-like at a length scale of 10^{-33} m.

- Infinite number of possible vibration modes → infinite number of possible particles
  – one of these vibrations correspond to graviton.

- It actually predicts the equations of general relativity.

- At low energies, string theory behaves like the supersymmetry (hence the name **superstring**

How Many String Theories?

- There are 5 distinct string theories
- They all involve strings but details are quite different
- Edward Witten, in 1995, proposed that these theories were 5 different ways of looking at the same theory
  - called M theory

How Many Dimensions?

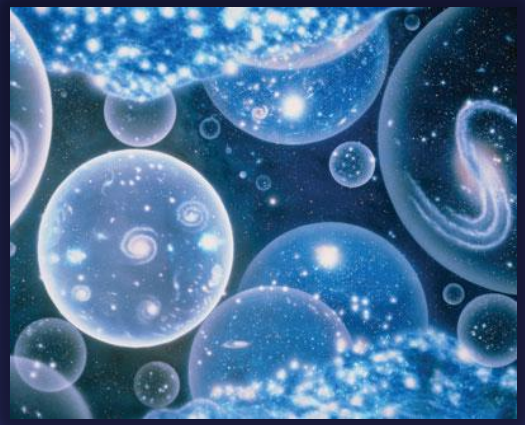
- Strings need to move in more than 3 dimensions.

- Before M theory, strings seem to exist in 10 dimensions.
  Time +space + 6 curled up dimensions (compactified).
  but M theory needs another extra space.

- There weren't only strings in these theories but larger objects that looked like membranes and can have 3 or more dimensions and with enough energy could grow as large as universe.
- String theory explains why gravity is so weak

- Fermilab is and LHC will look for extra dimensions

How Many Universes?



- Multiverse (or "many worlds") interpretation of quantum theory
  - QM is not uncertain
    every possible outcome actually happens just in a different universe

- This idea has been given mathematical form by string theory and leads to at least 10^{500} potential universes.

String Theory and Big Bang

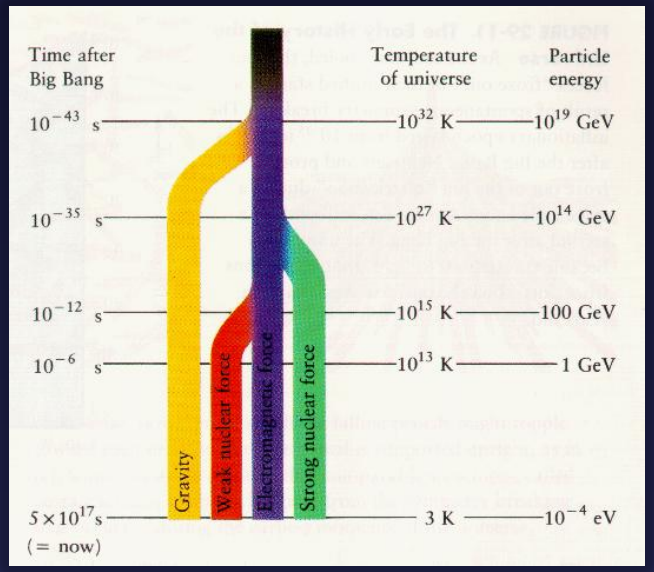
- According to Standard Model of Cosmology our universe (matter, energy, space, time) started from a big bang
- we don't know what happened before, or at the big bang?

- The idea of branes provides a solution - it could have happened when two branes collide and all that energy caused our universe.

- Problem is we don't know what happens when two branes collide because equations break down at that point as well.

String Theories

- It is a theory that:
  - Avoids all the infinities of GUTs
  - It is a theory that constrains the number of dimensions
  - It is a theory in which gravity is not left out
  - And it is a theory that combines quantum theory with General Relativity

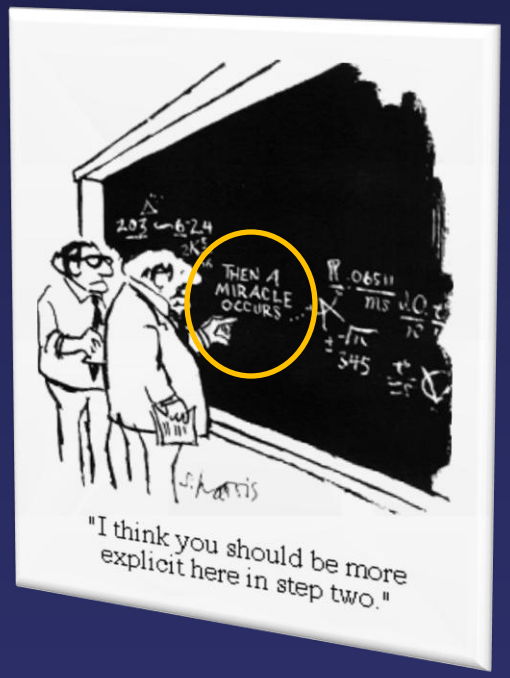


- One of the central prediction of string theory is existence of supersymmetry at lower energies
  - Finding sparticles will not prove string theory but will provide circumstantial evidence.

Is String Theory the “Chosen One”

- String theory is the most widely known candidate for a theory of everything

- But string theory also has a fundamental problem:
  - Experimentally:
    - No experimental proof so far – many of the predictions almost impossible to check at the present colliders
  - Theoretically :
    - Fails to explain the nature of space and time
    - It is not “background independent”

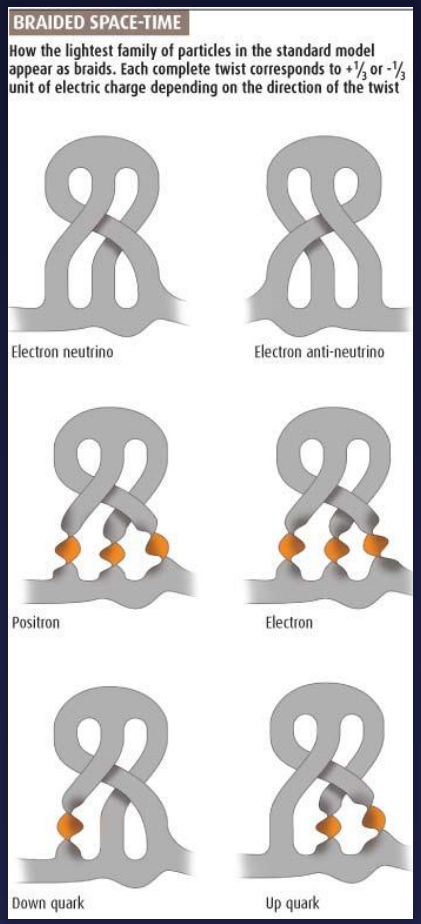


so over the years physicists have proposed several alternatives to string theory

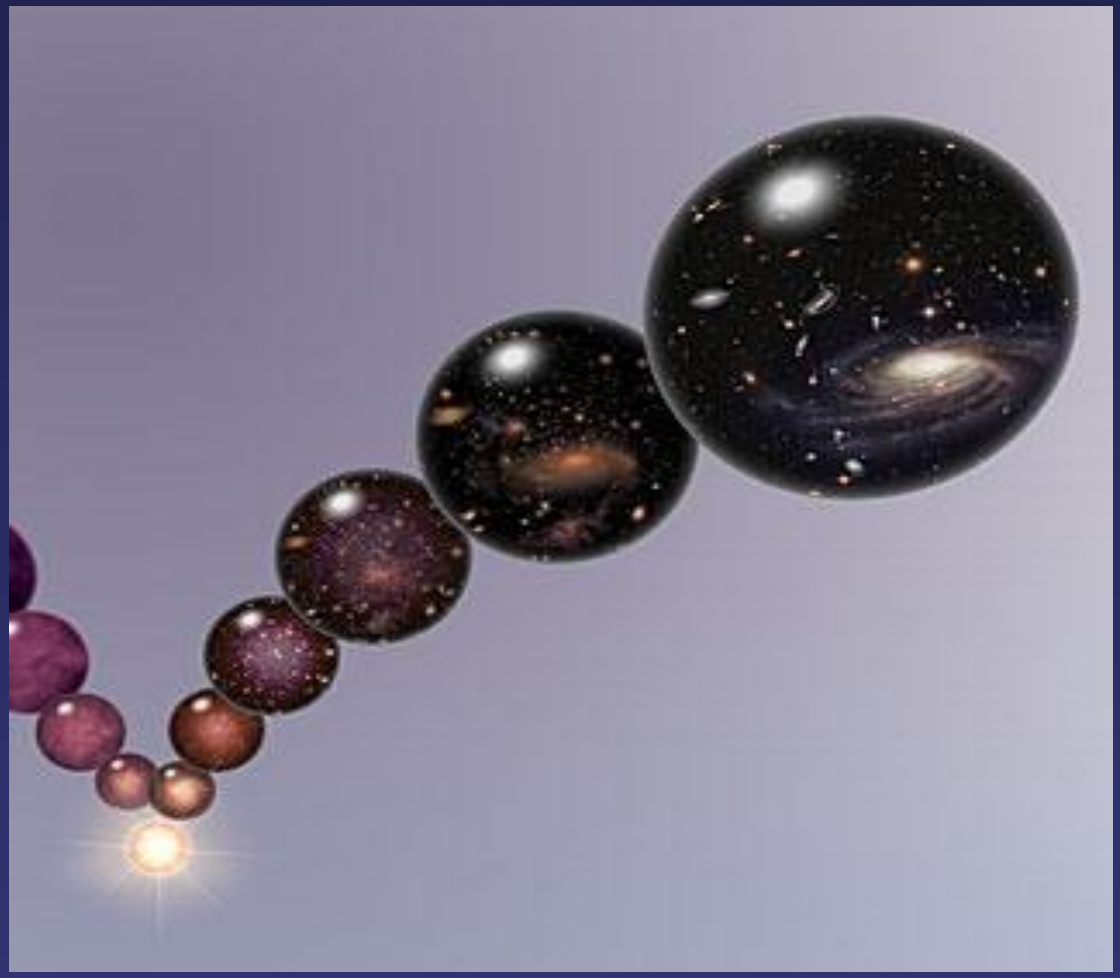
Though, all of them have their share of problems as well

Loop Gravity

- Attempt to merge general relativity and quantum mechanics into a single consistent theory – quantization of space
  - space is not smooth and continuous but instead comprises indivisible chunks just 10^{-35} meters in diameter.
- No black hole singularity – may lead to baby universes
- Loop quantum gravity is "background independent" theory – infact it is supposed to give rise to space-time at distances larger compared to Planck's scale
- As with string theory, devising experiments to test for the new theory will also be difficult.
  - No conceivable experiment can probe space down to 10^{-35} meters



Loop Gravity and Big Bang (or Big Bounce?)



Theories of Everything
Alternatives to String Theory

THEORIES OF EVERYTHING

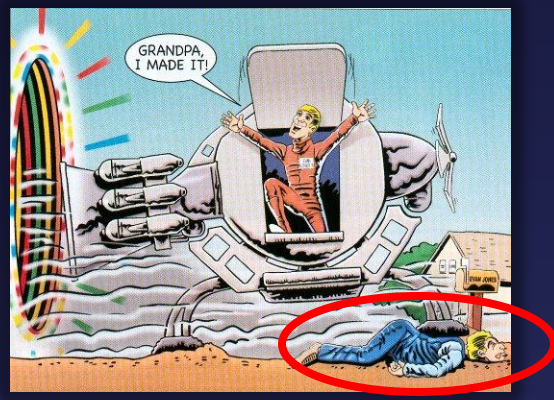
In the quest for an ultimate theory of the universe, there is now a bevy of alternatives to string theory. These seek to develop models of space-time and gravity on a quantum scale

New Scientist

ALTERNATIVE THEORY	LOOP QUANTUM GRAVITY	CAUSAL DYNAMICAL TRIANGULATIONS	QUANTUM EINSTEIN GRAVITY	QUANTUM GRAPHITY	INTERNAL RELATIVITY
KEY POINT	Space-time has a discrete, loopy structure at the quantum scale	Space-time is divided into tiny building blocks joined according to quantum mechanics	At the quantum scale, gravity attains a fixed strength and space-time is fractal	Space-time emerges when a network of nodes undergoes a phase transition	General relativity may emerge from a quantum phase transition
WHY IT'S INTERESTING	Might tell us what happened before the big bang	Enforcing causality yields three dimensions of space and one of time at large scales	Unlike in relativity, gravity does not blow up at small scales	May provide an alternative to the inflationary model of the early universe	May eliminate the need for Einstein's cosmological constant
REMAINING PROBLEM	Doesn't replicate our own space-time at large scales	Needs to make testable predictions	Proving that gravity's strength becomes fixed	Details of how space-time emerges remain unclear	Theory still needs to be fleshed out

Physicists' imagination is expanding as fast as the universe is….

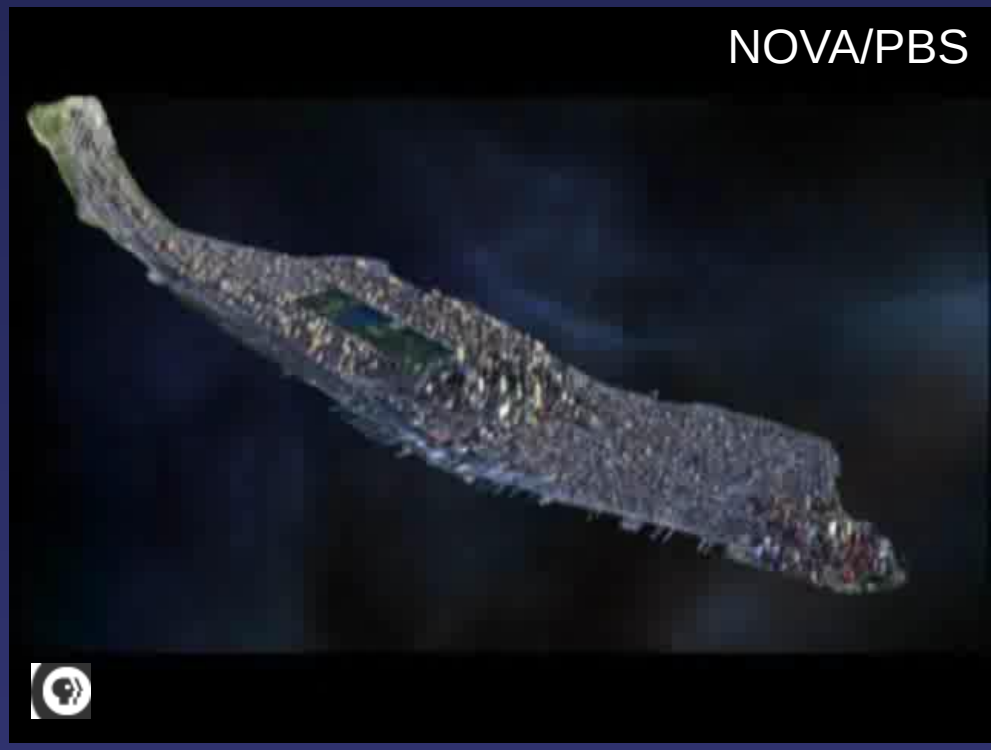
Time Travel



- Travel to future:
  - More speed → less time in your frame
    → travel to future
- Travel to Past:
  - Grand father paradox?

  Parallel universes already take into account all possibilities
  – so what does it matter anyway?

- The best hypothetical time machine (so far) is a wormhole



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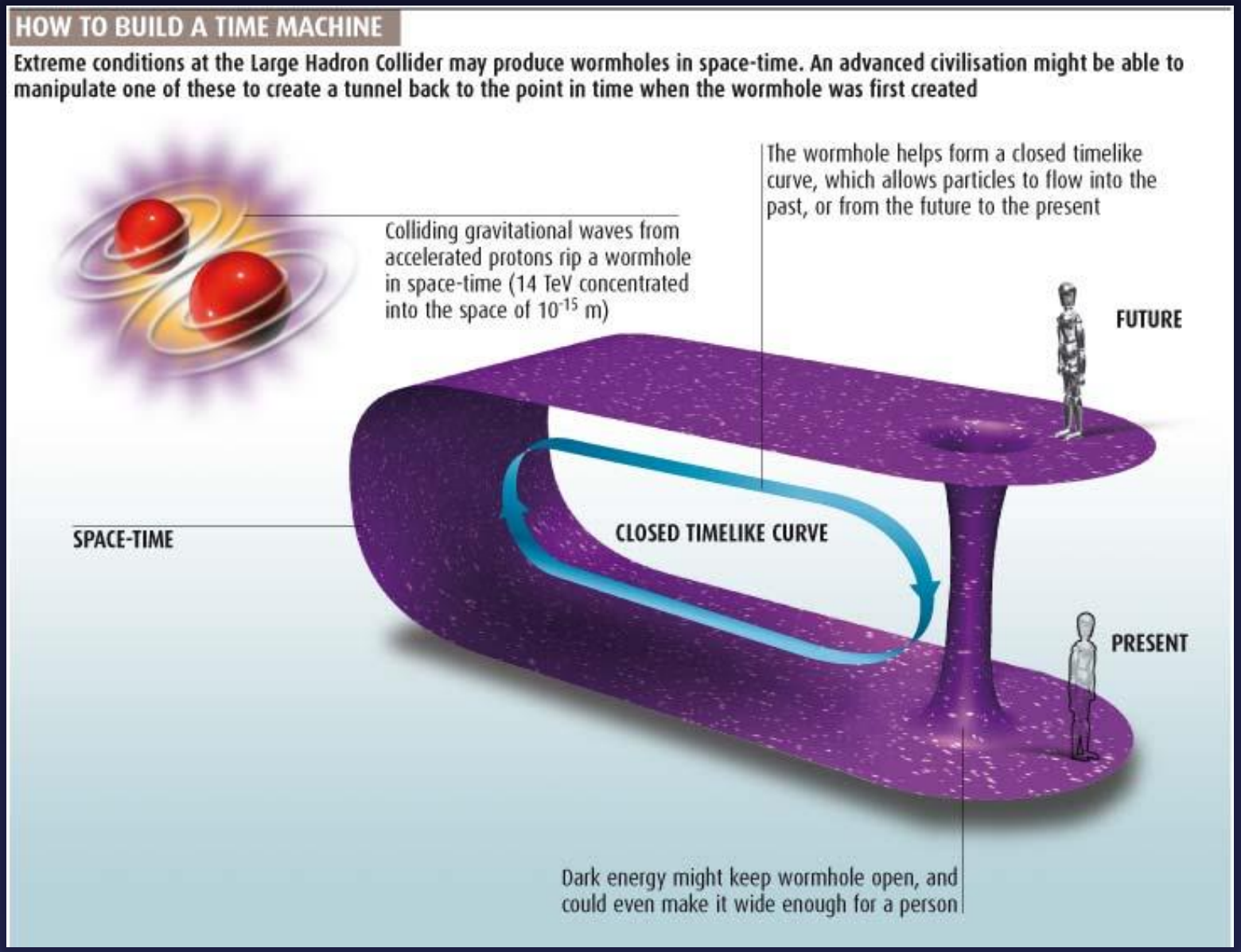
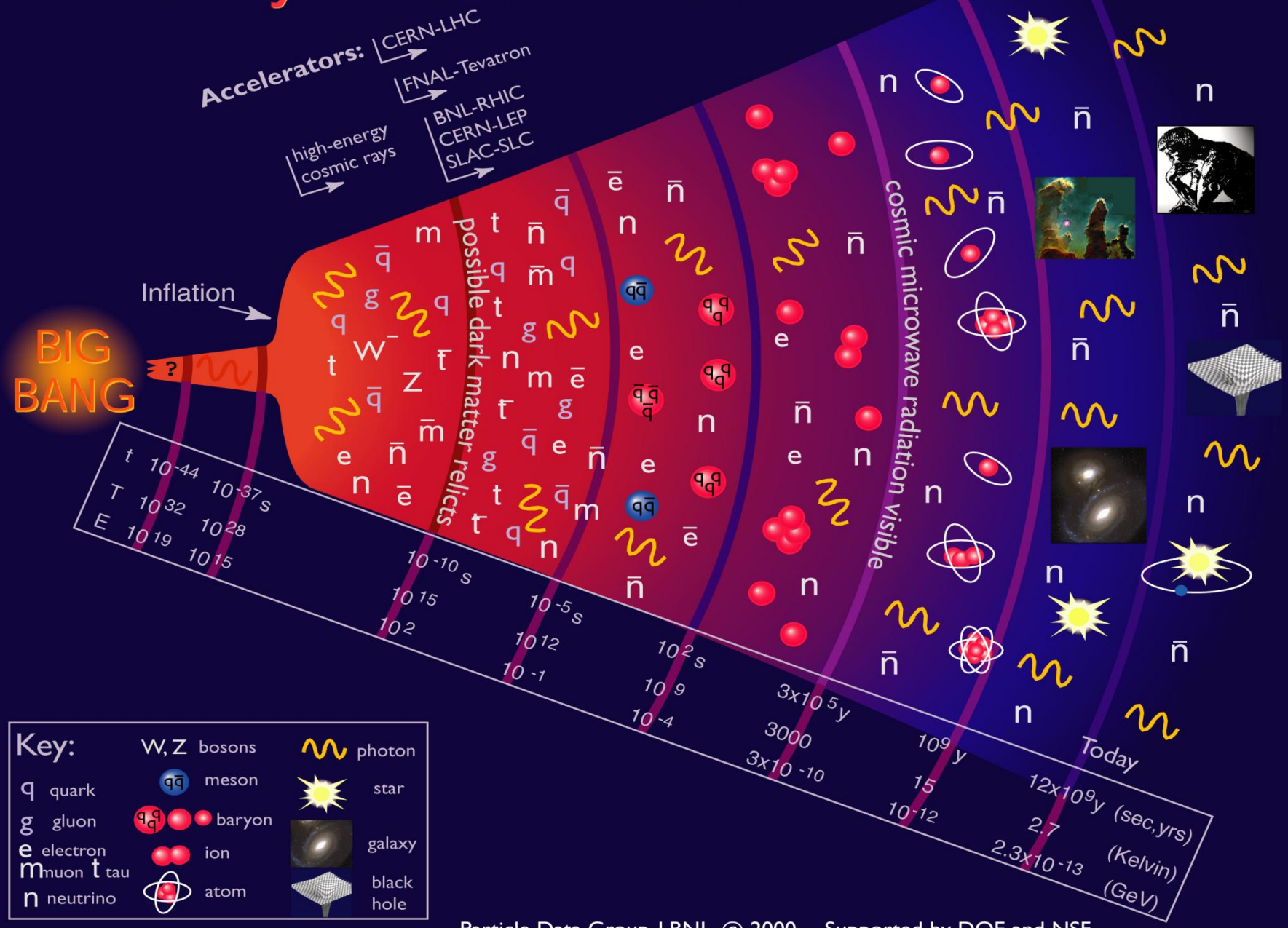
Could LHC be a Time Machine?



Arrow of Time

- A direction of time on a four-dimensional relativistic map of the universe
- Laws of physics are symmetric in time but nature is not --- why?
- As far as the physics is concerned (so far), time's arrow is a property of entropy alone

History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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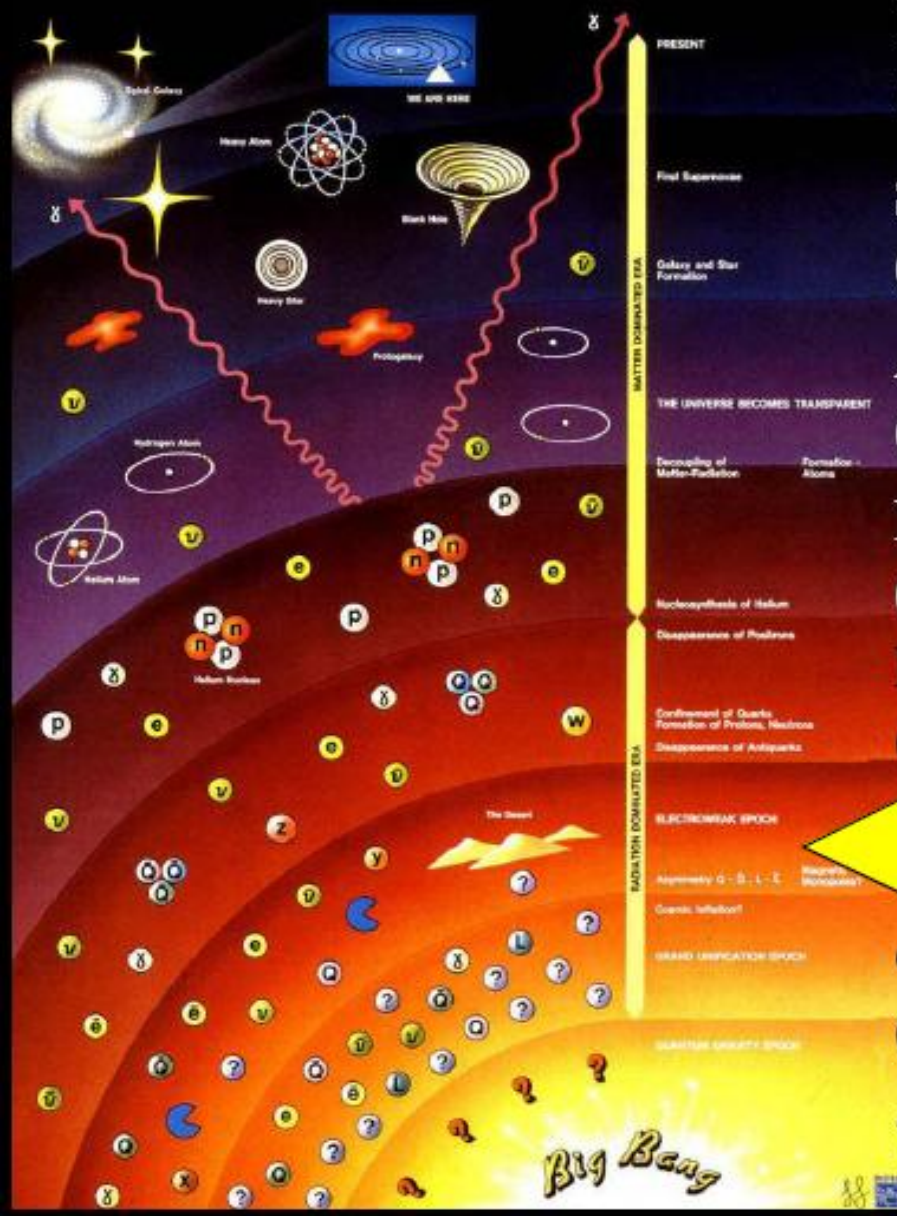


Now
(15 billion years)

Stars form
(1 billion years)

Atoms form
(300,000 years)

Nuclei form
(180 seconds)

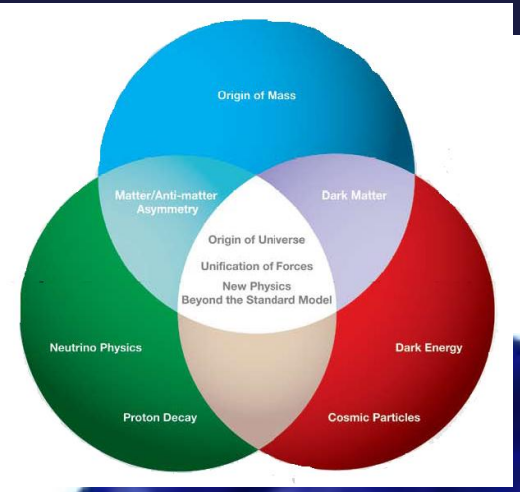
Nucleons form
(10^{-10} seconds)

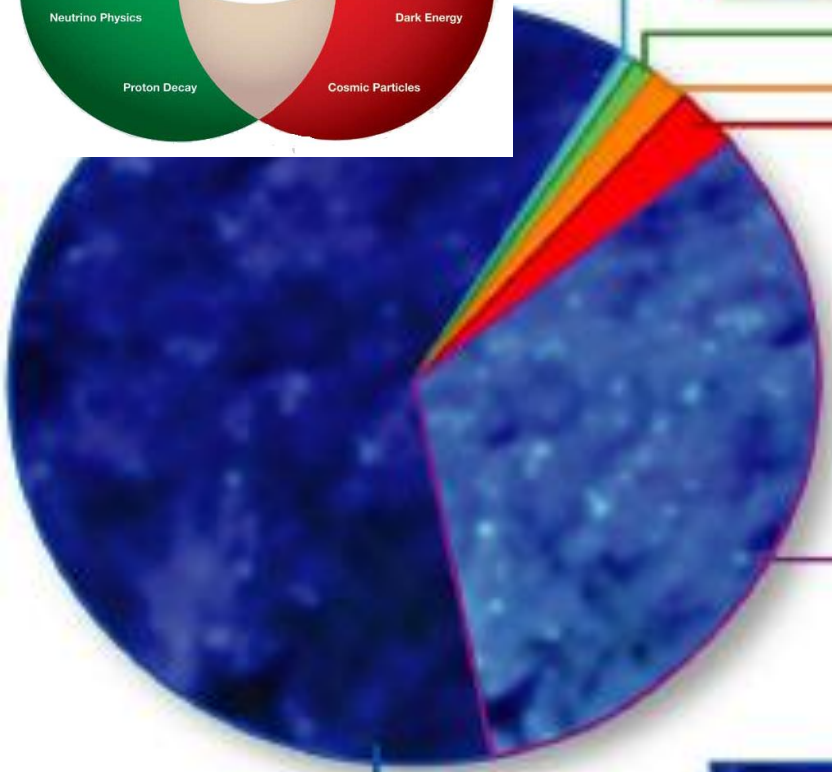
Fermilab

4×10^{-12} seconds

Quarks differentiate
(10^{-34} seconds?)

??? (Before that)





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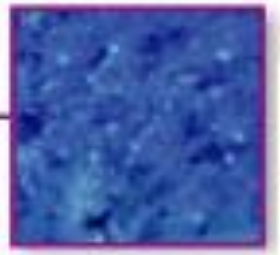

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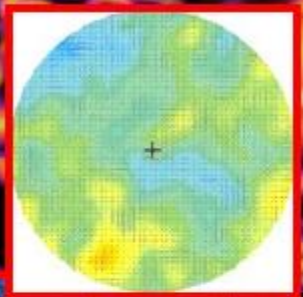
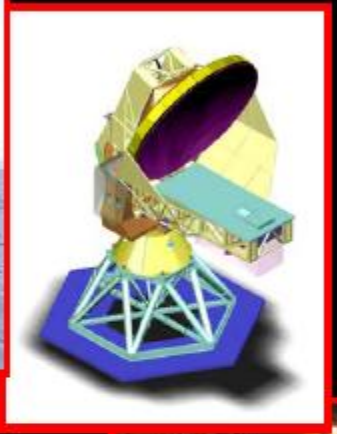
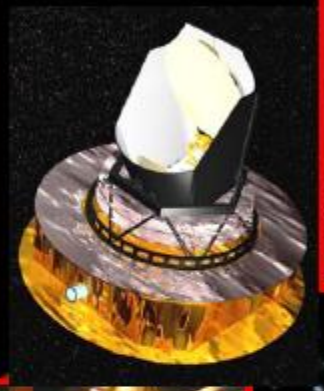
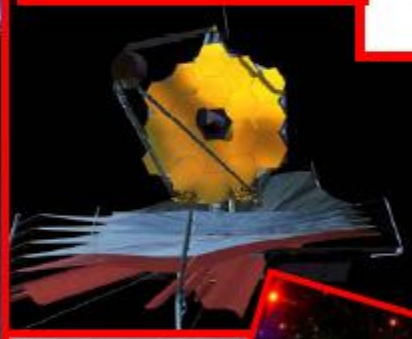
Why do we want to know?

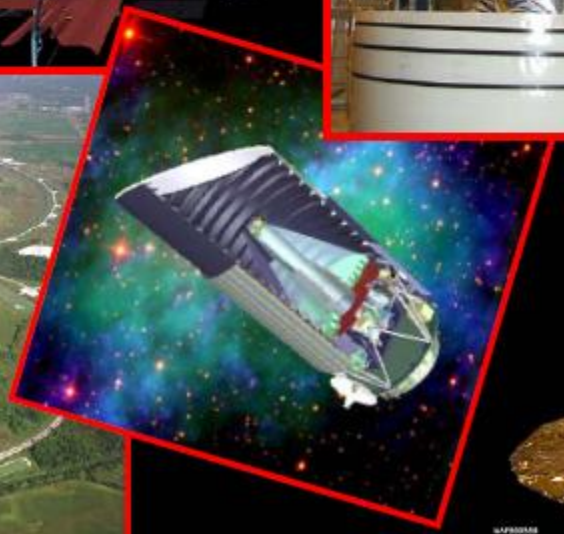
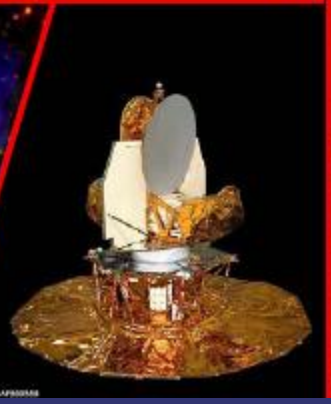
(we don't expect final theory to answer this one)

Poised to Answer the Big Questions





Should We Expect Final Theory to Exist?

The history of evolution of physics and of unification starts from very early times:

- Bruno Unification of sun with other stars
- Copernicus Unification of earth with other planets
- Newton Unification of gravity on earth with motion of planets
- Maxwell Unification of centricity and magnetism
- Einstein Unification space and time, mass and energy, and gravity and acceleration
- Standard Model An “almost” unification of three of the known forces

Yes, Why Not!

But when we think about any new theory (string theory or loop gravity or dark energy), we should not forget that final word should come form the scientific proof

because this is what real physics and real science is about

Acknowledgments

Douglas McKay
Darien Wood
Horst Whal
Erik Ramberg
Roger Dixon

Books

There are many books on all or some of these topics and not hard to find.

- The Theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics *by Robert Oerter*
- Three Roads to Quantum Gravity by Lee Smolin Oerter
- The Trouble with Physics: The Rise of String Theory, the Fall of a Science by Lee Smolin
- Programs made by PBS/NOVA and, of course, Wikipedia and Google
- Fiction: Final Theory: A Novel (Hardcover)by Mark Alpert