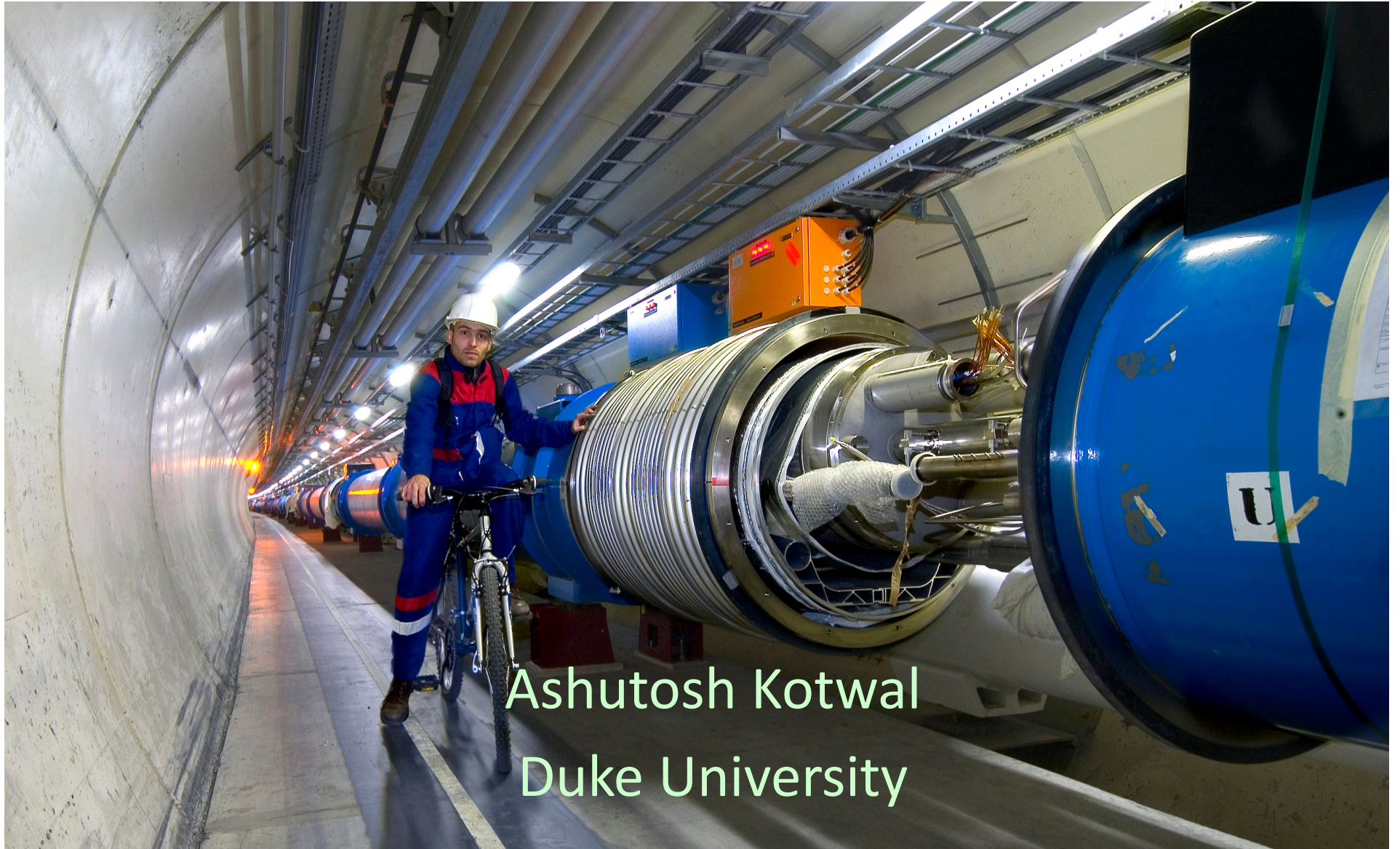


The Higgs Boson, Dark Matter and all that: Revolutionizing the Laws of the Universe with the LHC



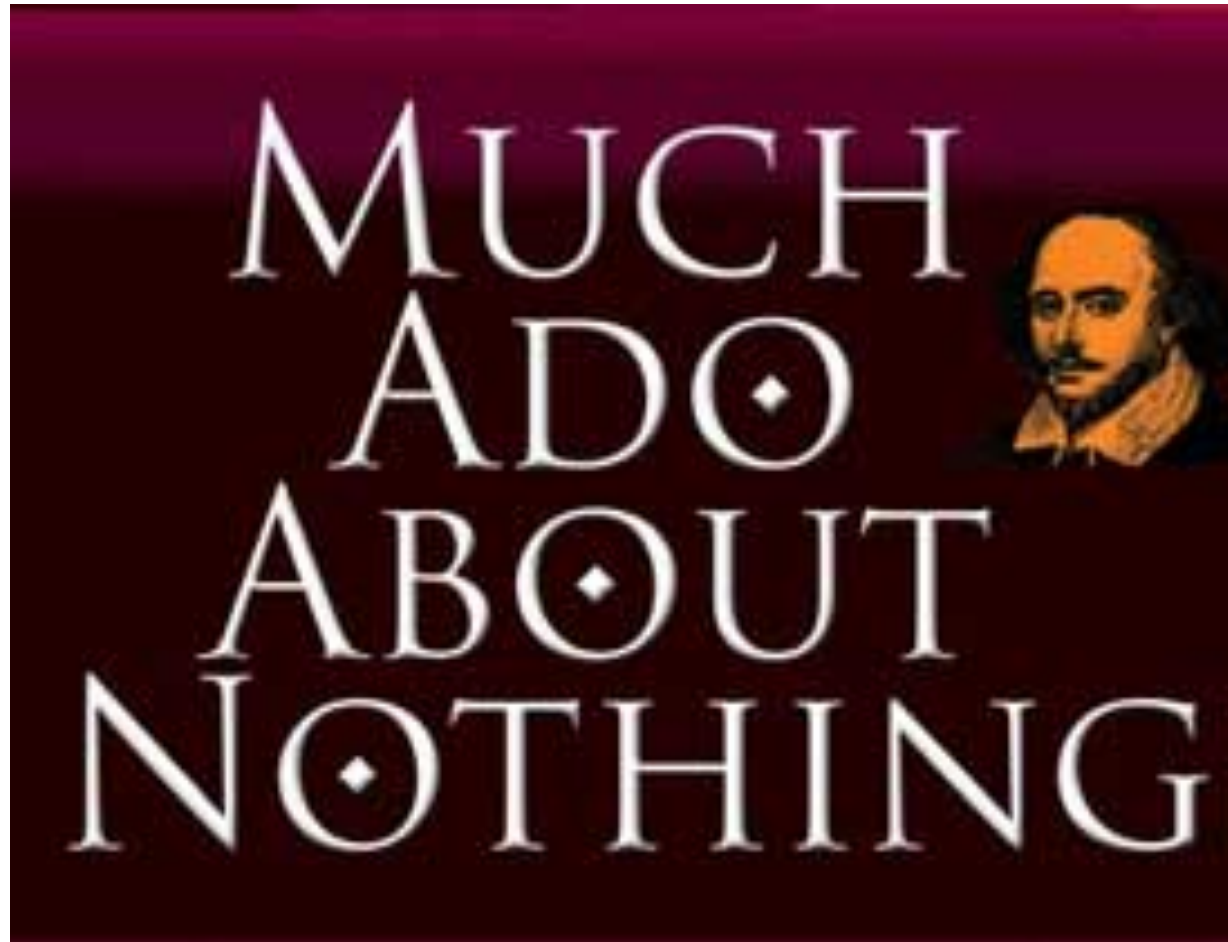
Ashutosh Kotwal
Duke University

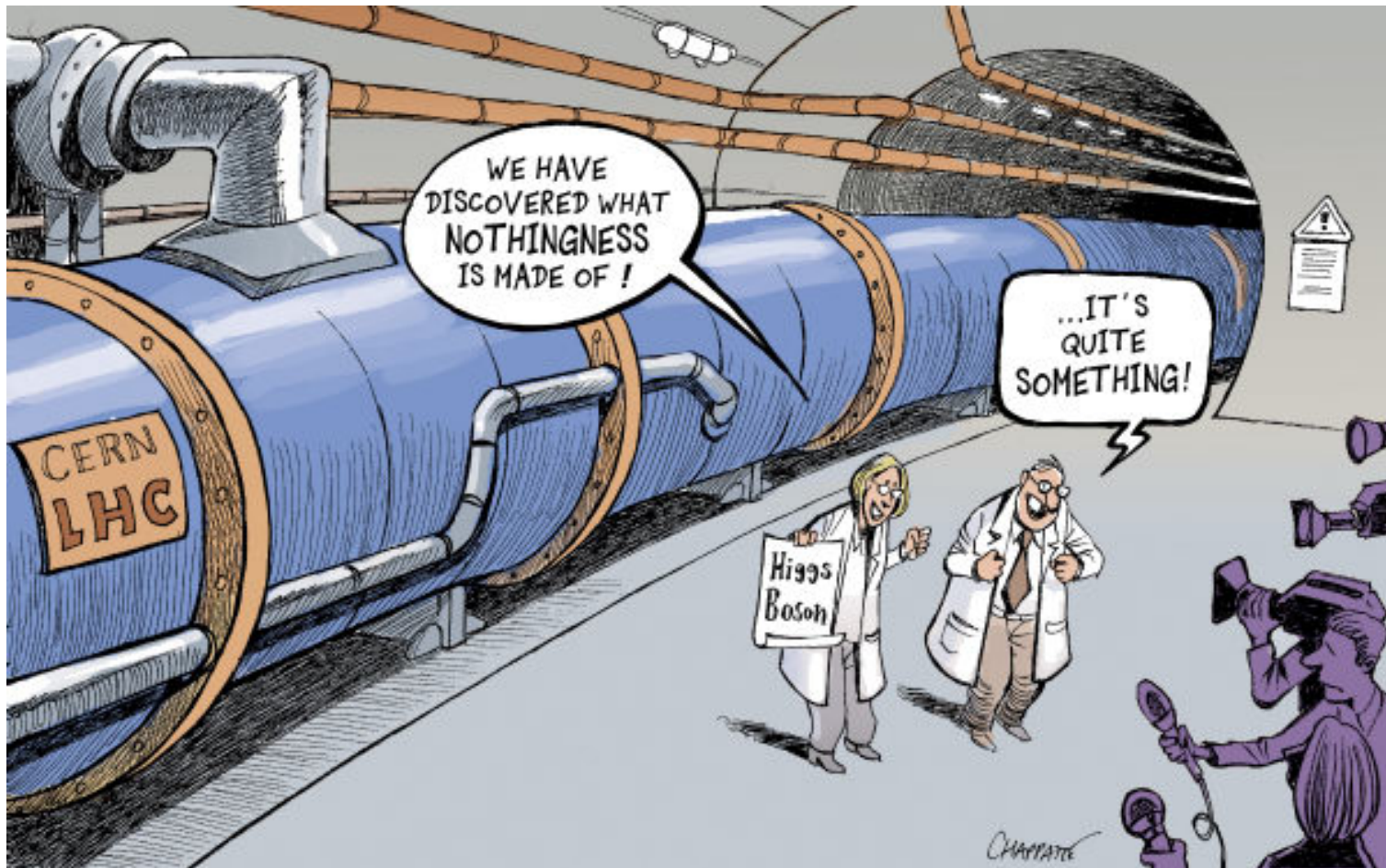
SO, WHAT DOES THE LITTLE HADRON COLLIDER SCIENTIST WANT?

can OTTAWA CITIZEN
Cartoonists.com
Syndicated.com



Alternate title of my talk:







The Higgs boson and Dark Matter are both
intimately connected with properties of empty
space...

(or what we thought was “empty space”)

...Making these phenomena unlike any other we
have observed in the past

Why have we been hunting for the Higgs for more than half a century?



Search culminating in the construction of the
Large Hadron Collider at the CERN Laboratory of Particle
Physics in Geneva, Switzerland

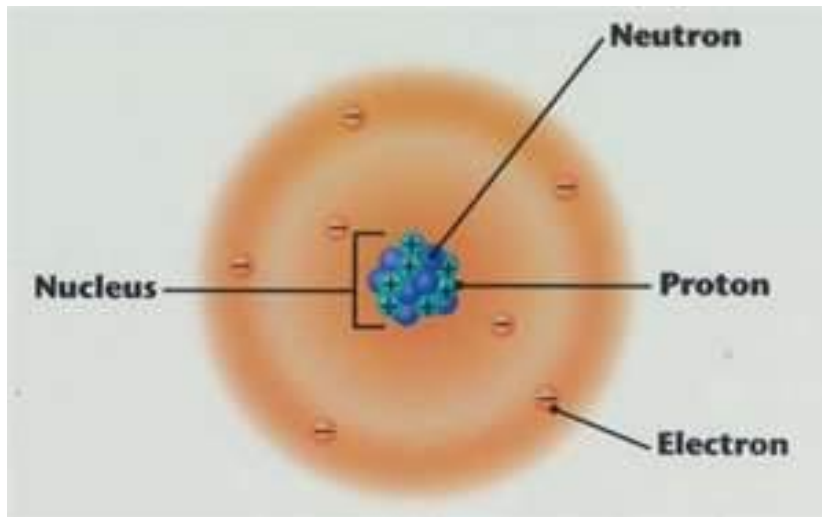
Why have we been hunting for the Higgs for more than half a century?



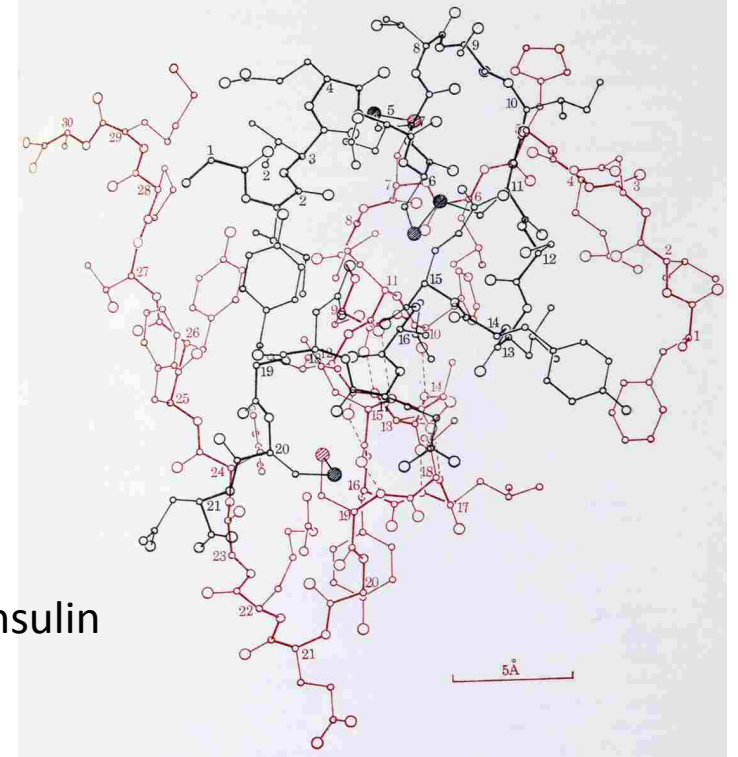
To solve a deep riddle in Quantum Mechanics, the
proven theory of the microscopic world

20th Century Built on Quantum Mechanics

- The scientific advances of the 20th century have transformed our lifestyle
- Impact of Quantum Mechanics
 - All electronics devices, computers and communication
 - Nuclear power
 - Atomic and molecular manipulation of materials for chemical and biological applications



Molecule of Insulin



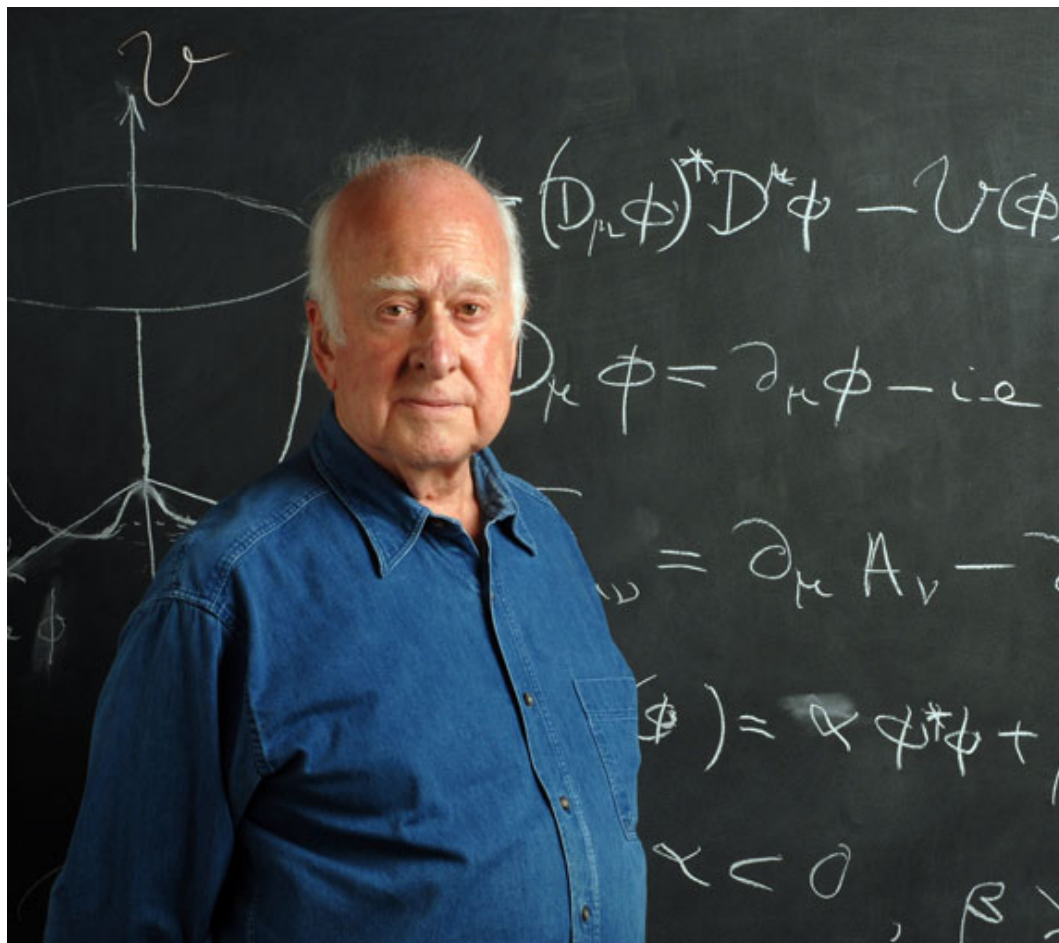
Conceptual Problem in Quantum Mechanics

- In spite of its success, a self-consistent quantum mechanical theory of matter and forces has a huge missing link – **the theory requires all fundamental particles to have exactly zero mass**
- The non-zero electron mass cannot be understood – **and yet the electron mass defines the size of the atom and physical and chemical properties of all substances**
- If the electron's mass were zero, the atom would not exist

Knowledge from the LHC

- Why do fundamental particles have mass?
 - the Higgs hypothesis
- The mystery of Dark Matter –
 - Could Dark Matter particles be produced at the LHC?

The Higgs Boson

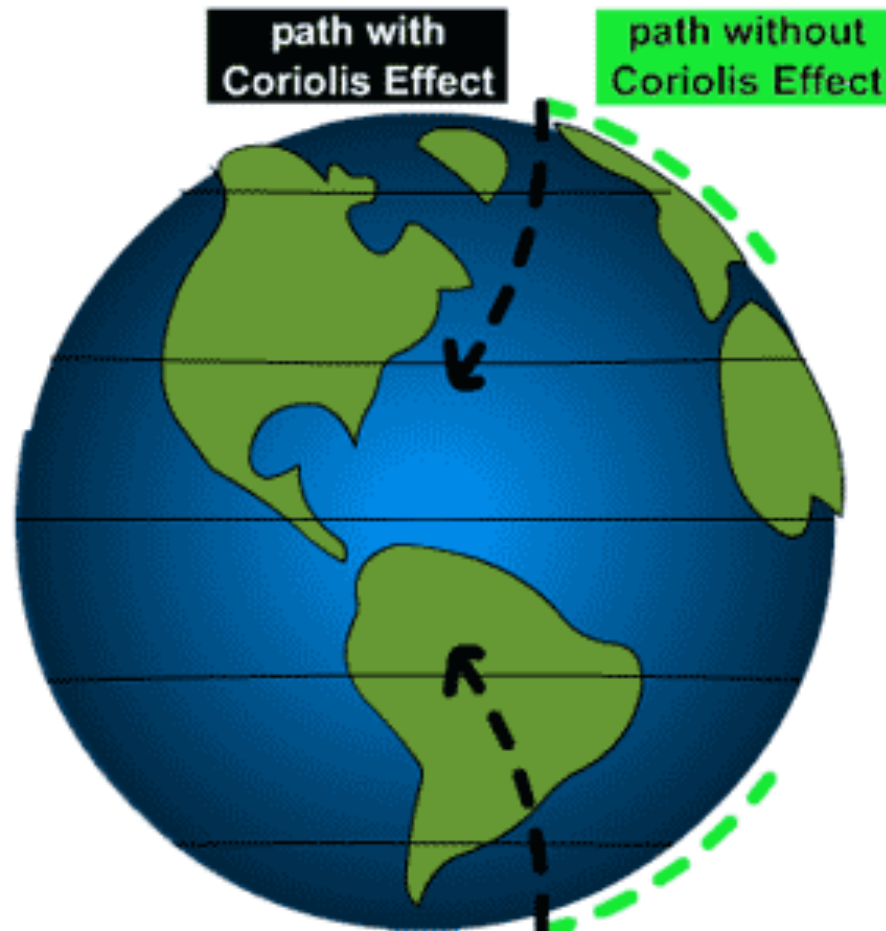


Peter Higgs



Satyendra Nath Bose in 1920's

How to Predict Fundamental Forces



“fictitious” forces observed in accelerating frame of reference

Manifestation of Coriolis Force



Hurricanes appear to rotate in Earth's frame of reference

Quantum Mechanics

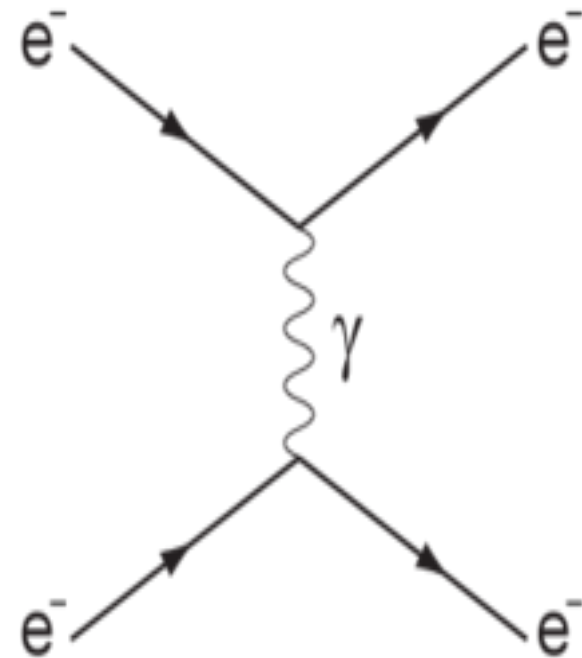
force $\Leftrightarrow$ particle exchange



Feynman Diagram: Force by Particle Exchange



Richard Feynman



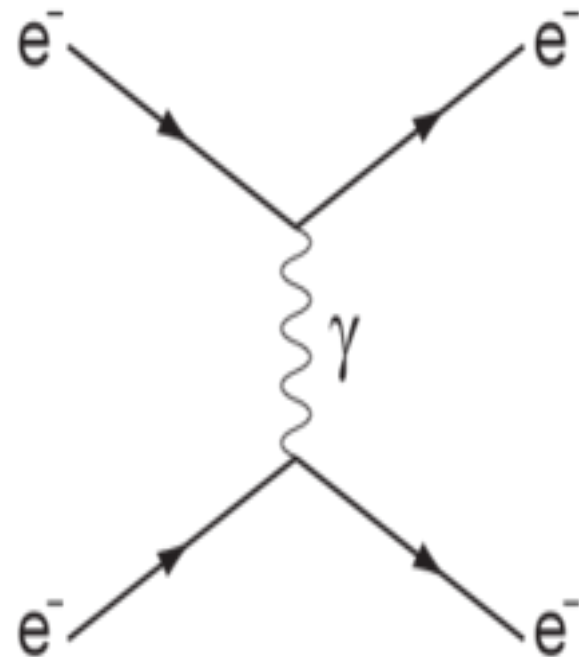
Electromagnetic force between two electrons mediated by “photon” exchange

Feynman Diagram: Force by Particle Exchange

The most precisely tested theory,
ever:

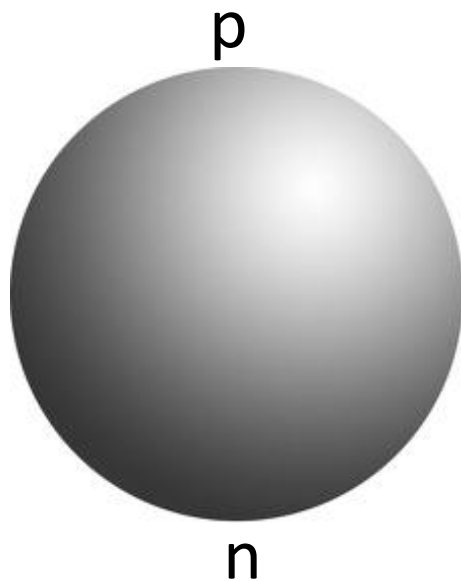
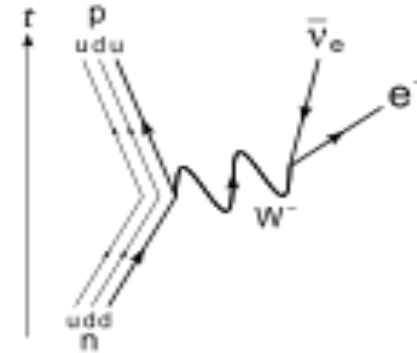
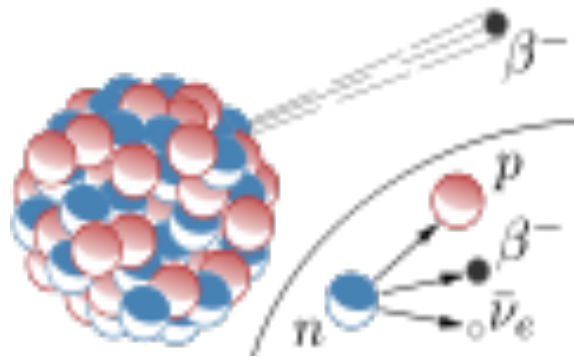
The quantum theory of the electric
and magnetic forces, radio waves,
light and X-rays:

Measured and predicted magnetic
moment of an electron agree within
0.3 parts per trillion accuracy

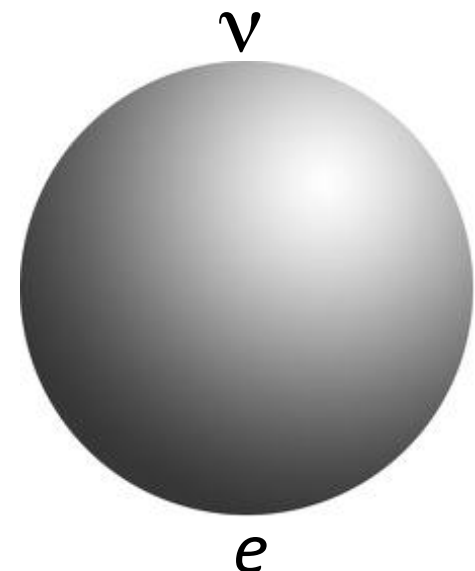


Electromagnetic force between
two electrons mediated by
“photon” exchange

Weak Nuclear Decay



The force causing this interaction is described by particles making transitions on a “mathematical sphere”



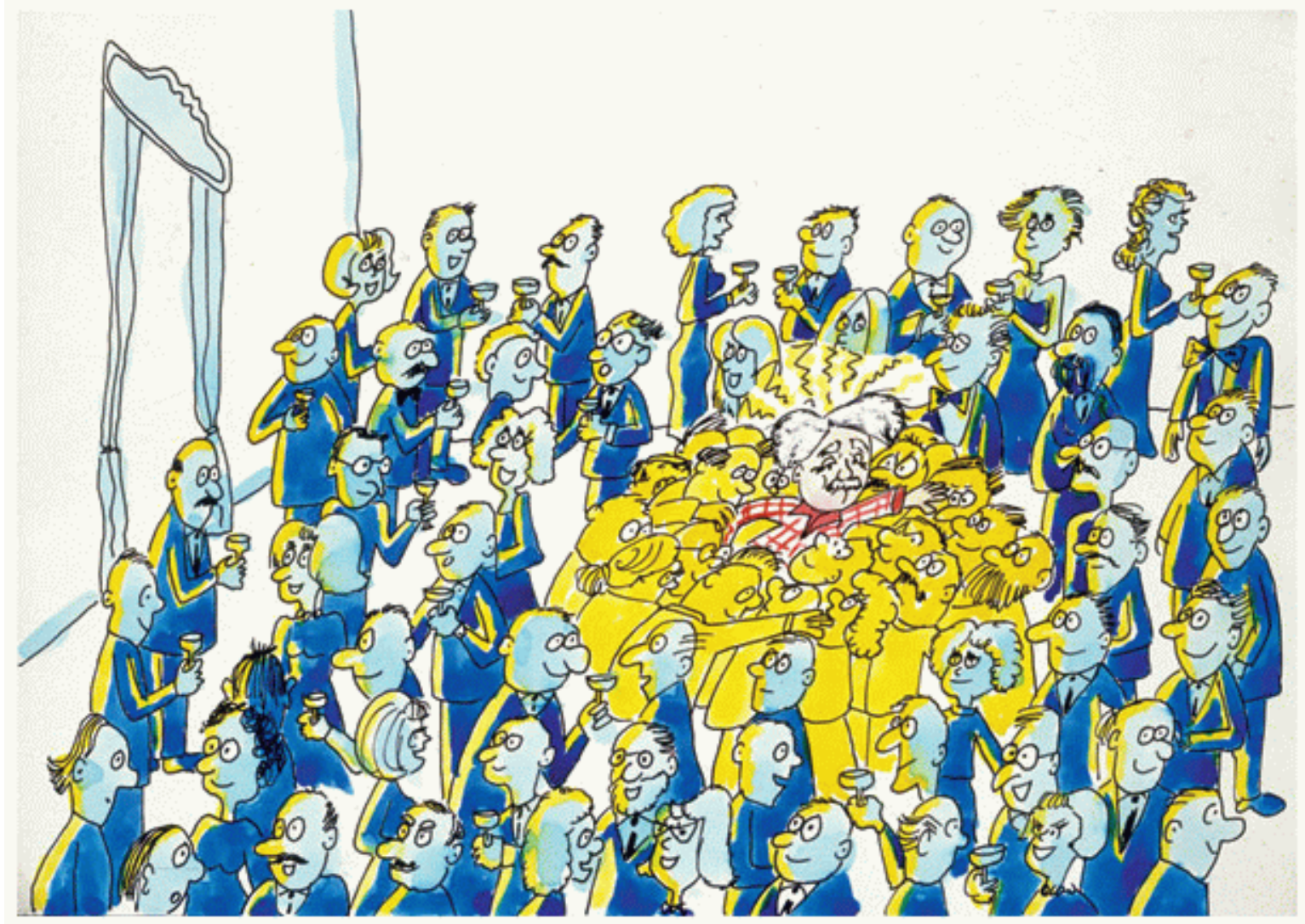
Success and Problem of Quantum Mechanics

- **Success:** correct mathematical description of all properties of electromagnetic force and the weak nuclear force
- **Another prediction:** force-mediating particles must be massless
- **Correct prediction for photon** – mediator particle of electric and magnetic forces and all electromagnetic waves: radio, light, microwave, x-rays described by massless photons
- **Problem:** for the weak nuclear force causing nuclear beta-decay, the mediator particle, “W boson” is very heavy
- **Question:** How can we preserve the original theory and simultaneously impart mass to the W boson?

Solution to the Problem of W Boson Mass

- Fill all of space with “Higgs” field
- W boson propagating through “empty space” actually propagating through Higgs field
- Interaction of W boson with Higgs field slows down the W boson $\Leftrightarrow$ imparting the property of mass to it

The “Sticky” Higgs Field



Implications of Higgs Hypothesis

- Empty space is not really empty
- Filled with the Higgs
- All fundamental particles interacting with the Higgs field “slow down”
 - appear to be massive

Light versus Heavy Particles – like moving through water



Streamlined

⇒ Moves fast through water

⇒ analogous to light particle

Not streamlined

⇒ Moves slowly through water

⇒ analogous to heavy particle



Detecting the Higgs

- Why don't we see and feel the Higgs?
- Our senses and instruments detect electrical charge
- Higgs is electrically neutral – has no electric and magnetic interaction!

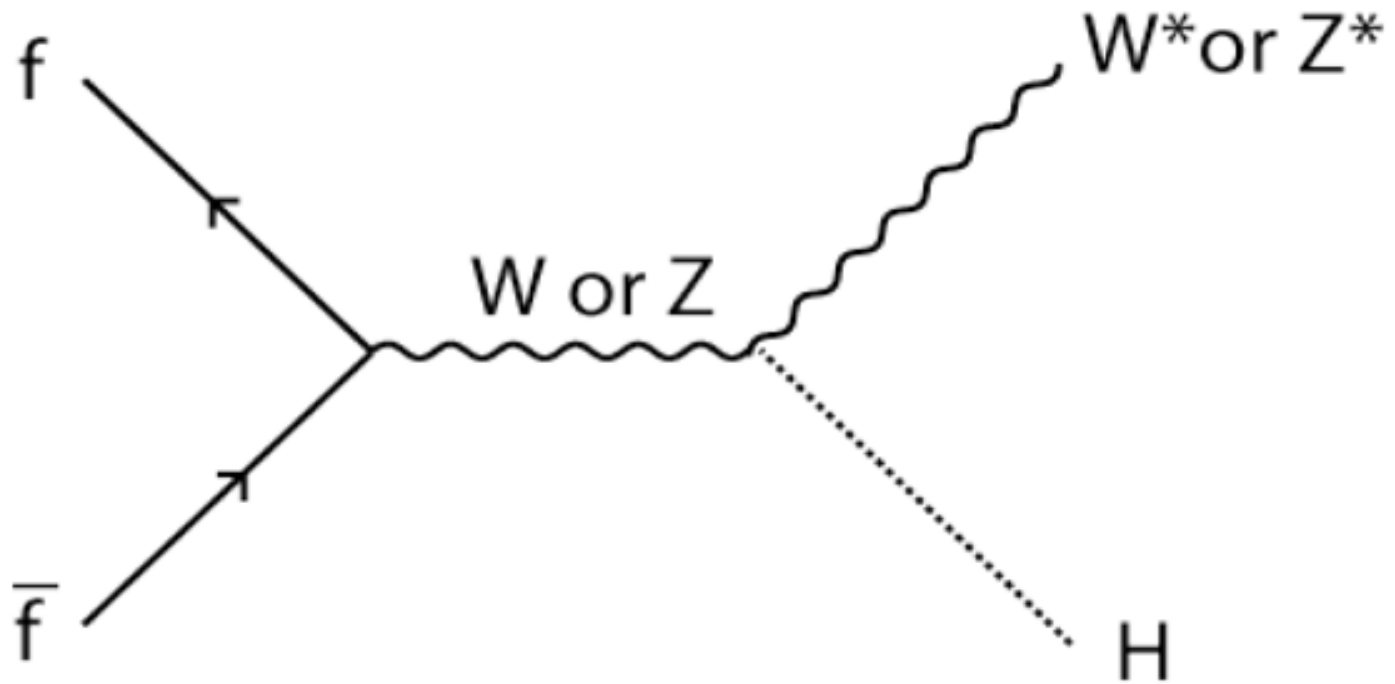
How can we confirm the existence of the Higgs?

- Create ripples in the Higgs field

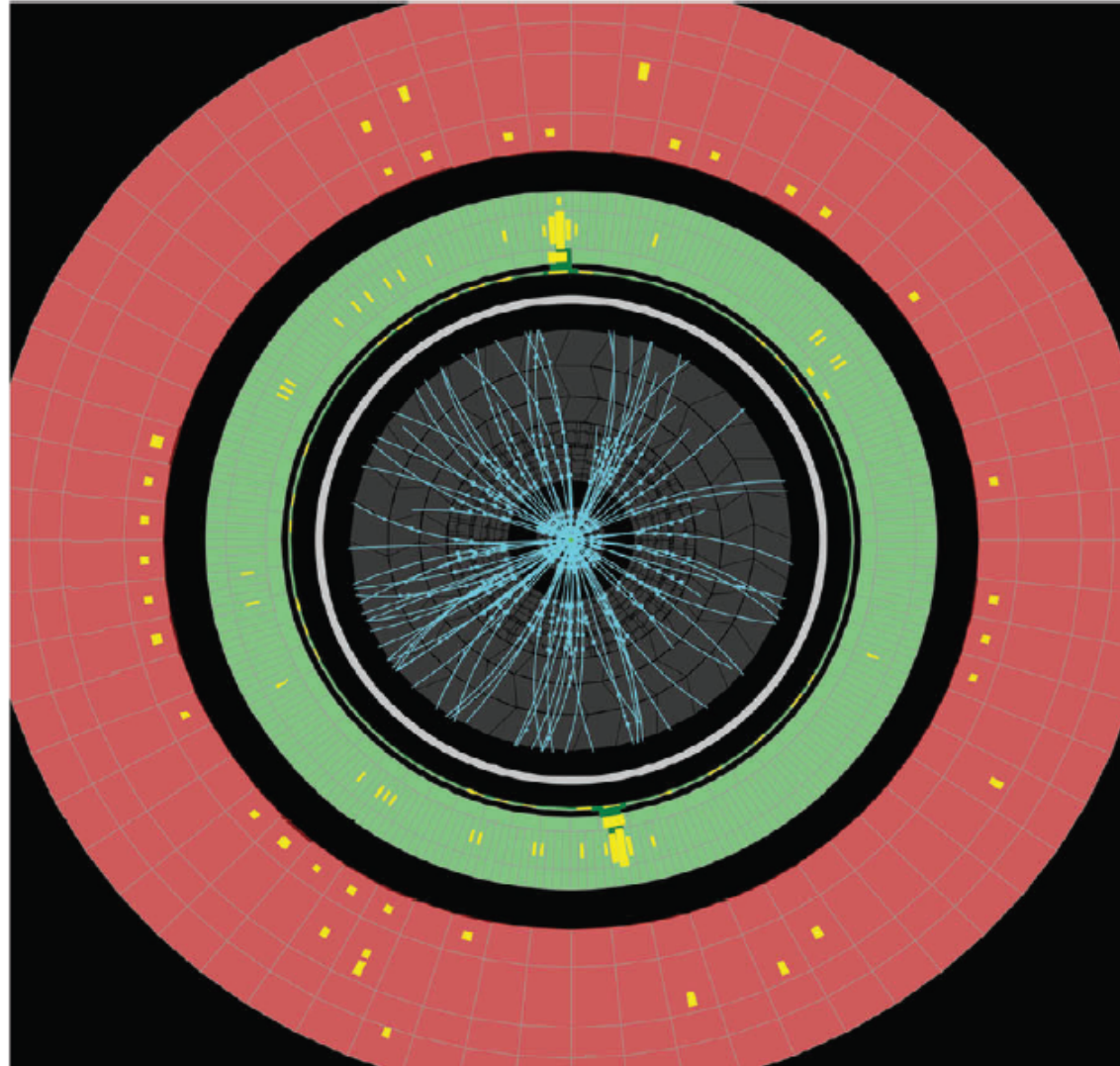


Ripples $\Leftrightarrow$ Higgs boson

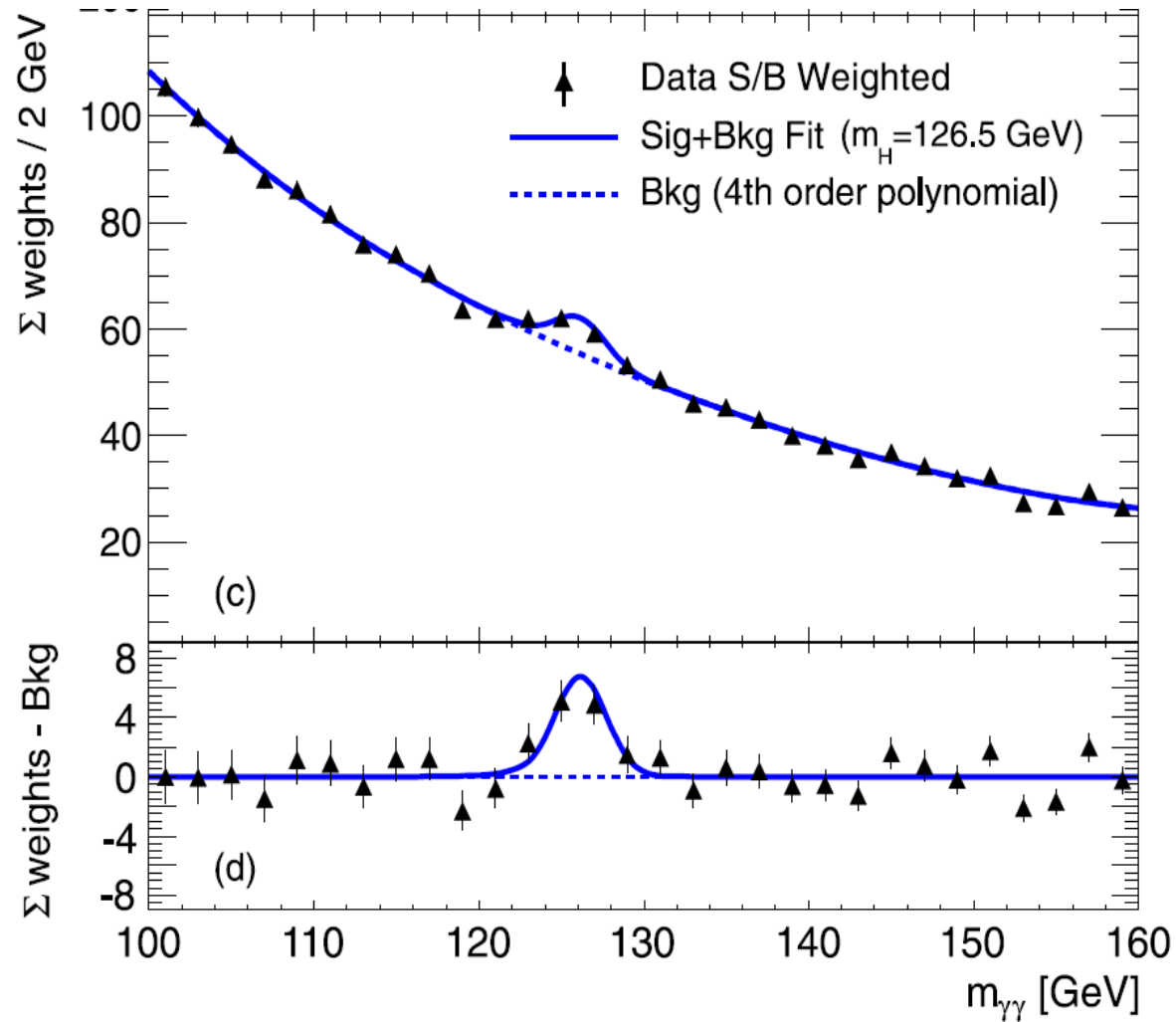
How to Create the Higgs Boson



Evidence of Higgs Boson Production



Evidence of Higgs Boson Production



Higgs Discovery Implications

- Provide an understanding of all masses of fundamental particles
- Revolutionizes our understanding of empty space
⇔ filled with Higgs
- Further studies of the properties of the Higgs are of tremendous importance
 - Where did this “Higgs field” stuff come from?
 - Why do different particles interact differently with it?
- We are going to be busy studying the Higgs for a while...

The Mystery of Dark Matter

Centripetal Force

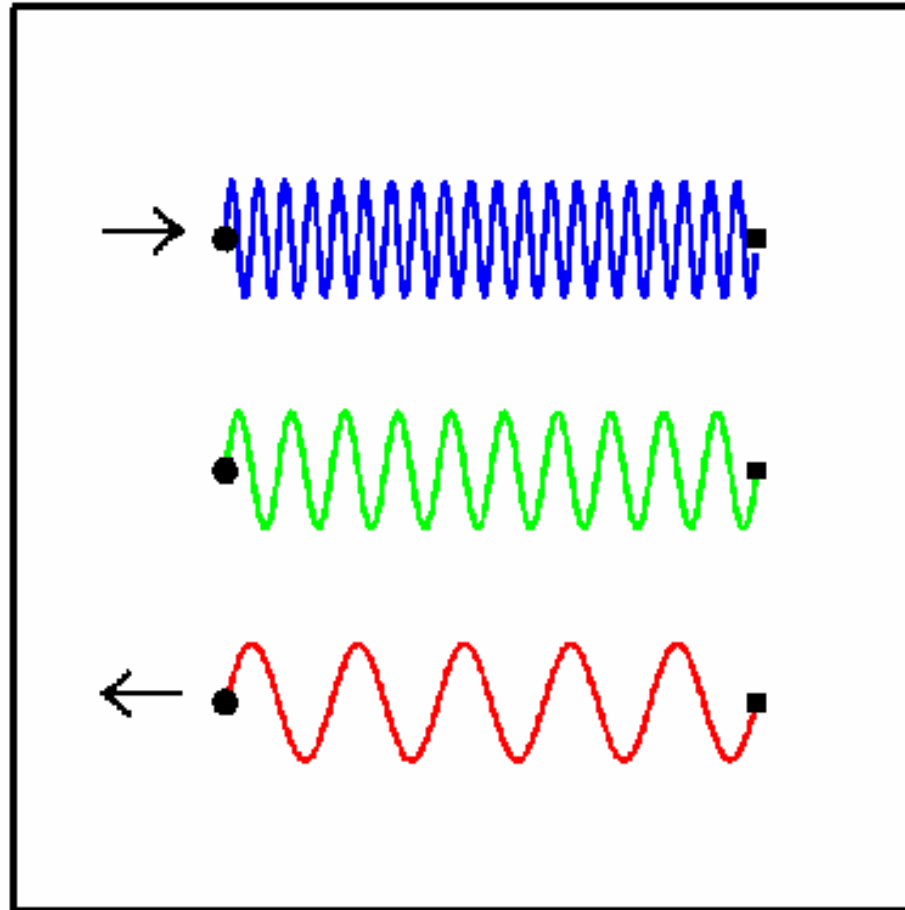


Stars Orbiting a Galaxy

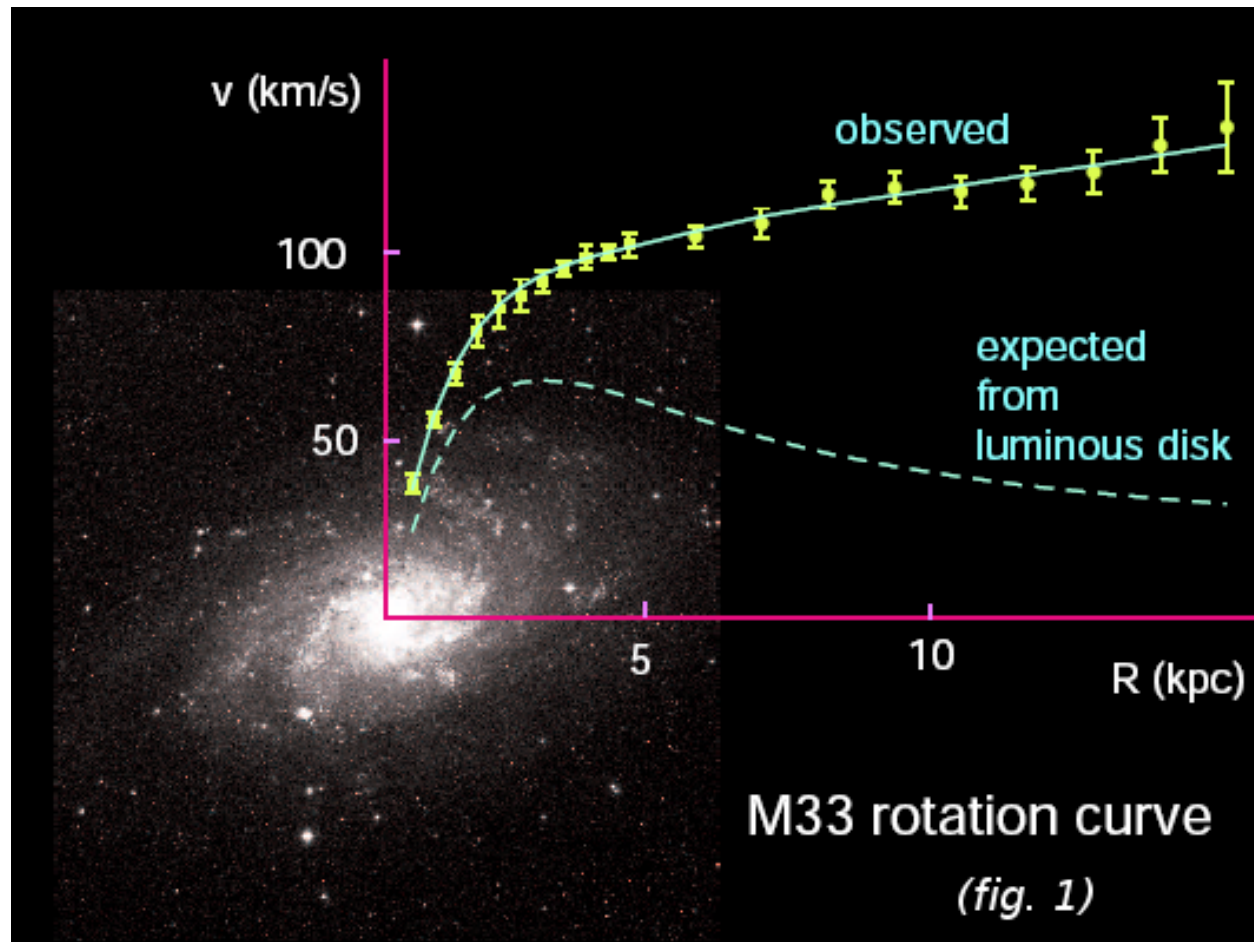


Gravity provides the centripetal force

Measuring Velocity with Doppler Shift of Starlight

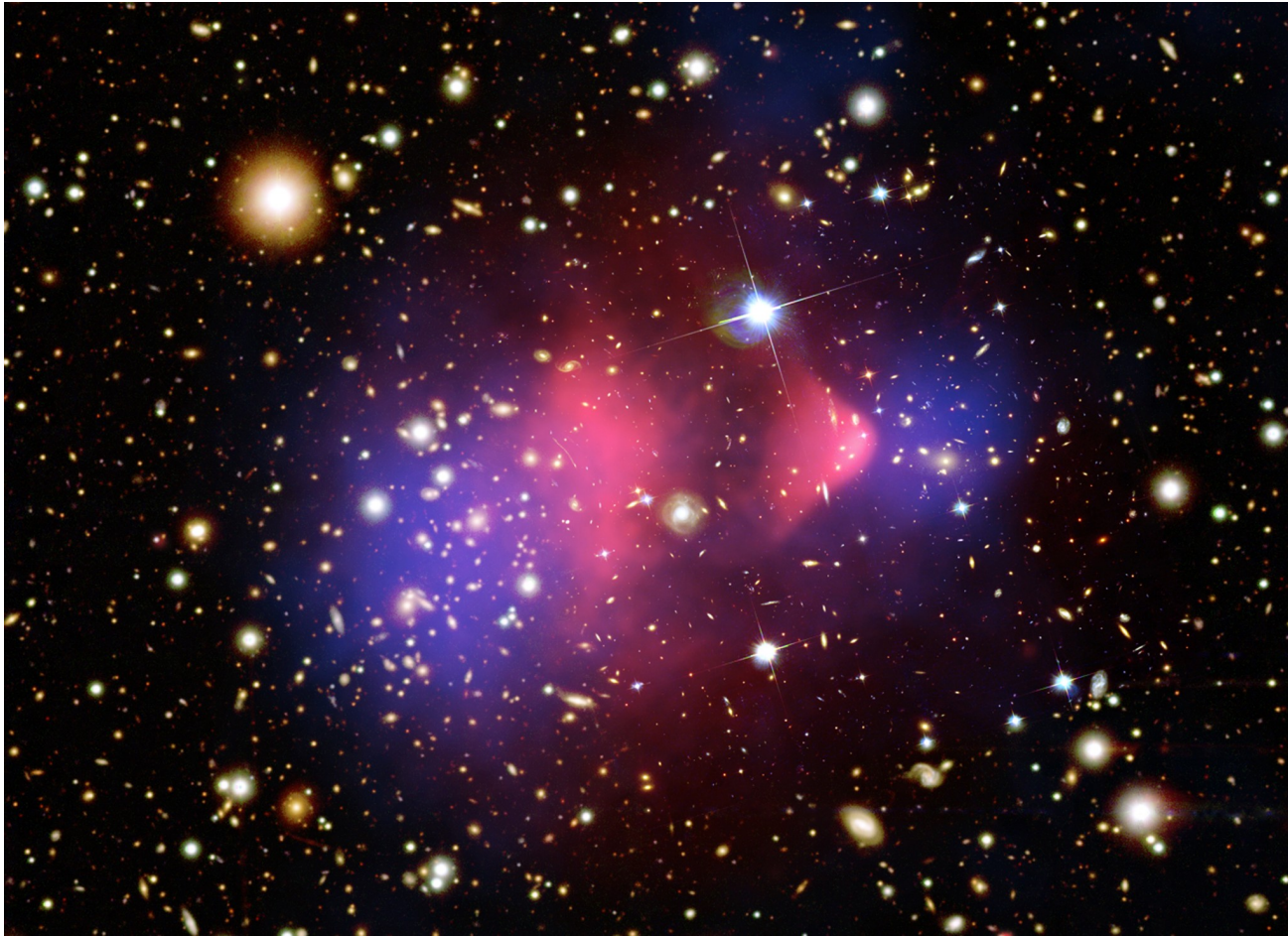


Galactic Rotation Curve



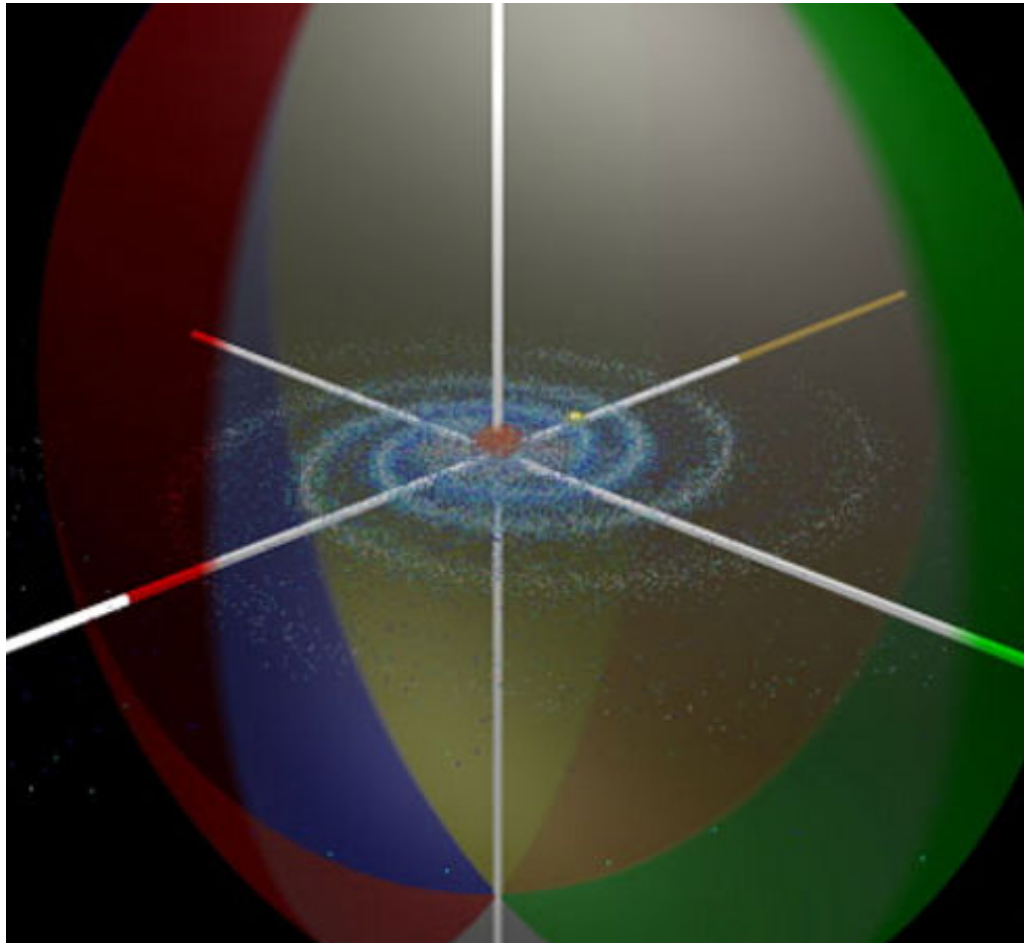
Stars' orbit speed too high $\Leftrightarrow$ too much centripetal force

Collision of Galaxy Clusters



Luminous Matter (emitting X-rays) separated from total Mass $\Leftrightarrow$ confirms Dark Matter hypothesis

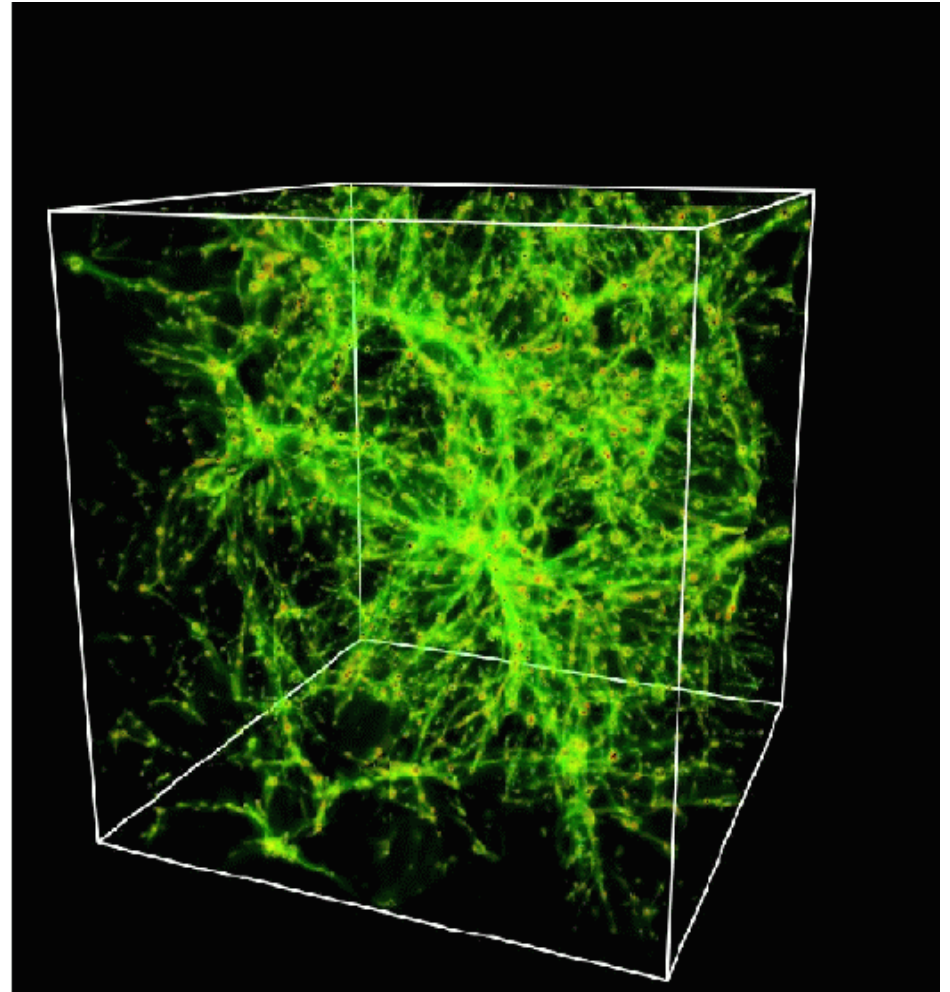
Halo of Invisible Dark Matter around Galaxies



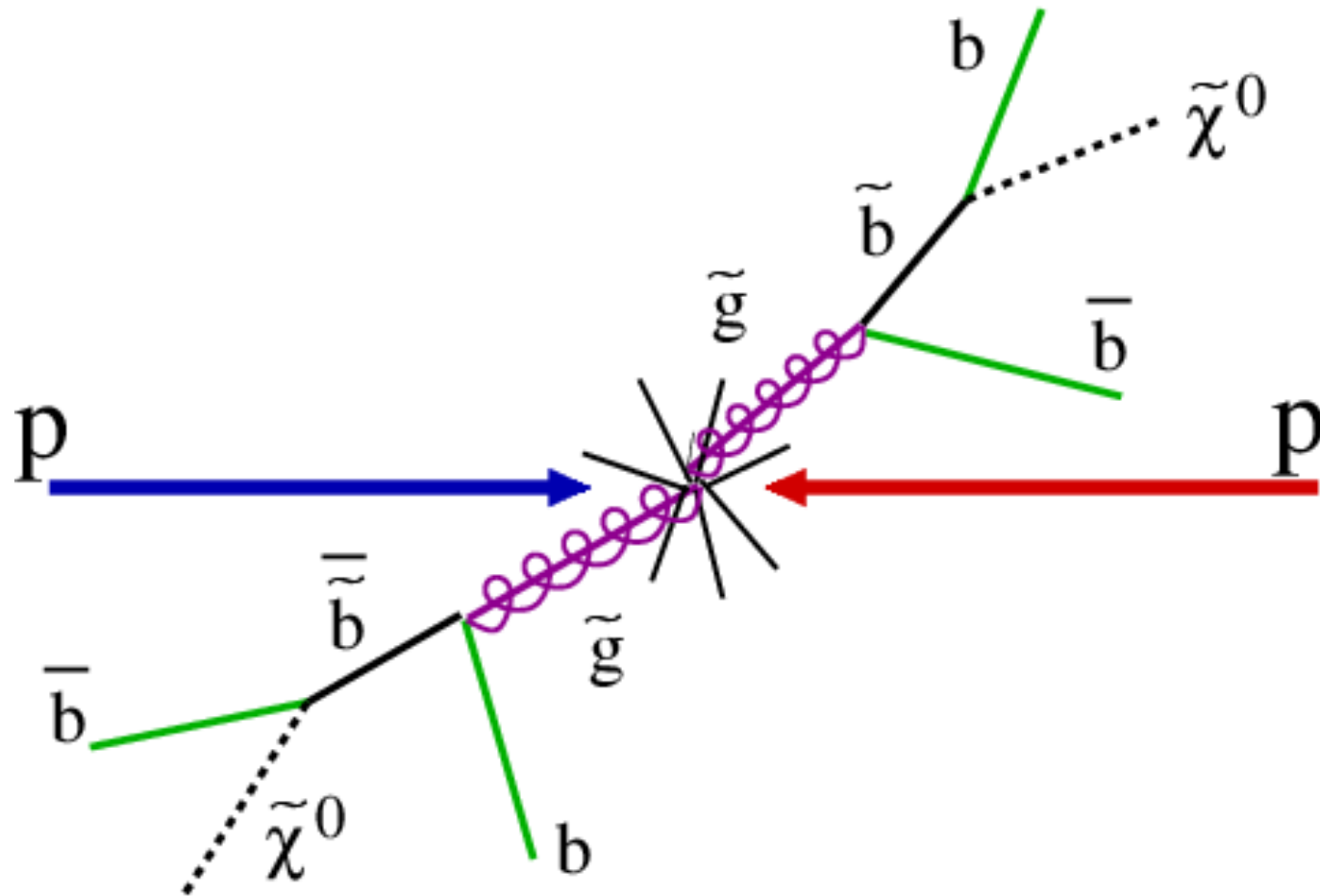
Four times as much dark matter as visible matter

Mapping out the Dark Matter

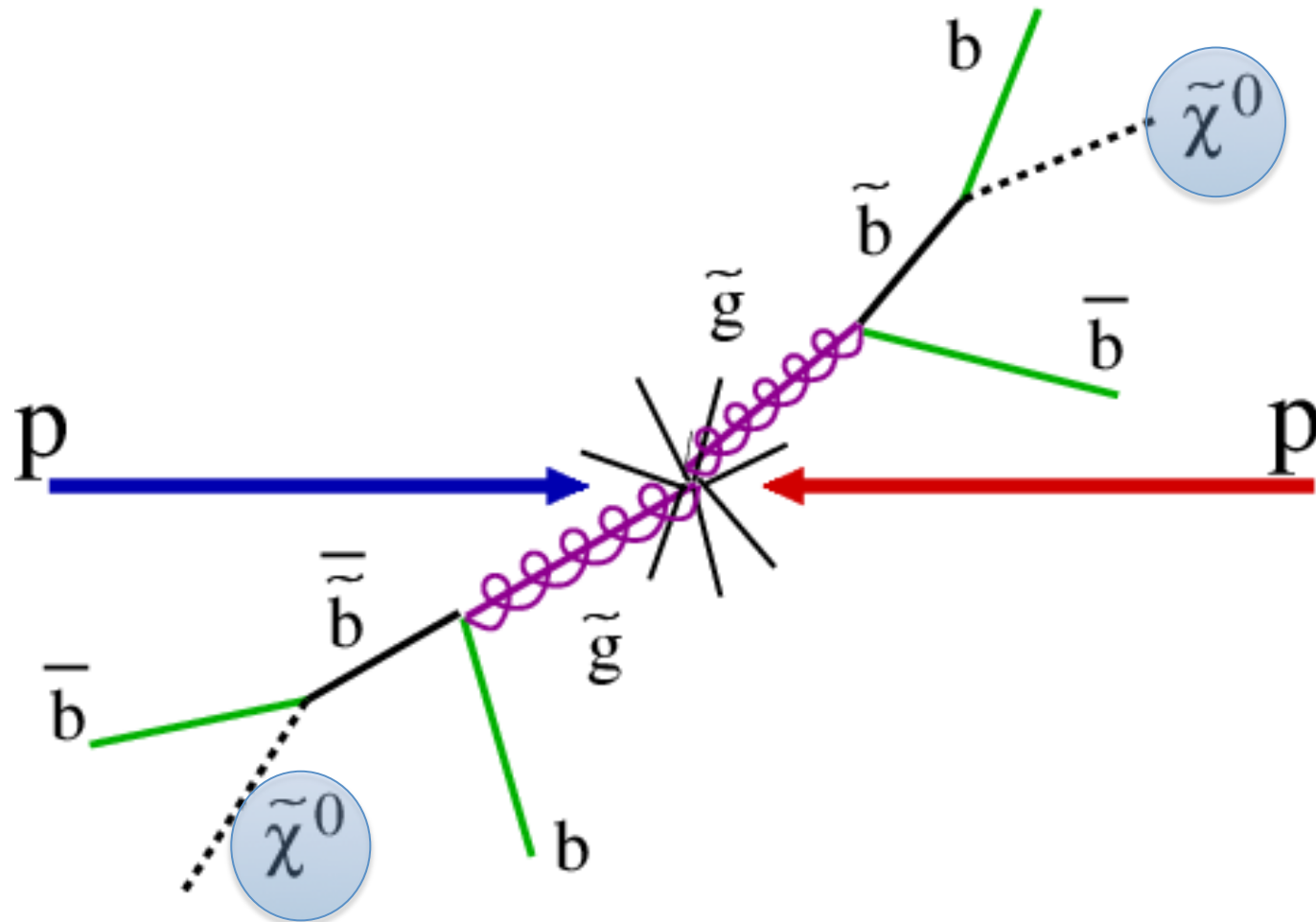
- *A lot* of dark matter is required to hold galaxies together
- It cannot all be made of protons
- It must be neutral, stable, heavy
- It must be some new form of matter – new fundamental particles



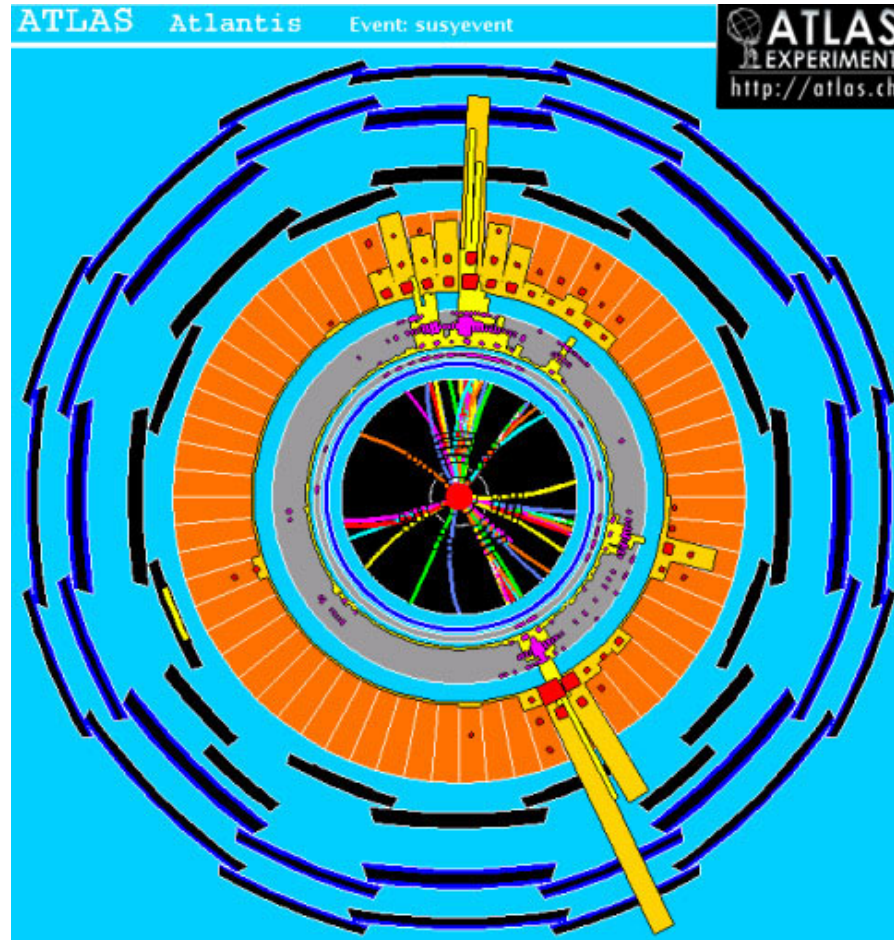
Feynman Diagram depicting Production of Dark Matter Particles at LHC



Feynman Diagram depicting Production of Dark Matter Particles at LHC



Simulated Dark Matter Particle Production at LHC



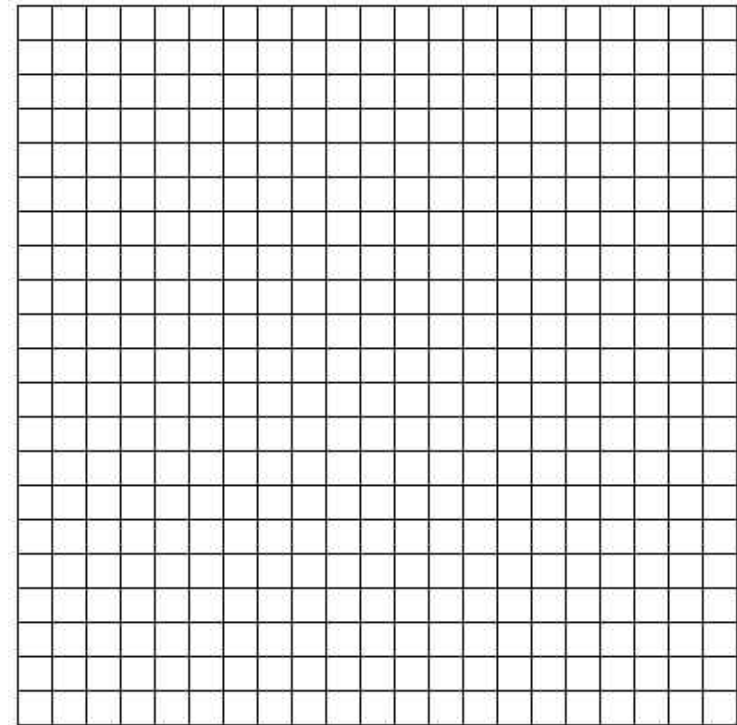
Dark Matter Particles

- Bridge between cosmology, astrophysics and particle physics
- “Supersymmetry” theory predicts dark matter particles
- Supersymmetry $\Leftrightarrow$ quantum properties of space $\Leftrightarrow$ dawn of a “new quantum mechanics”

Black Holes at the LHC

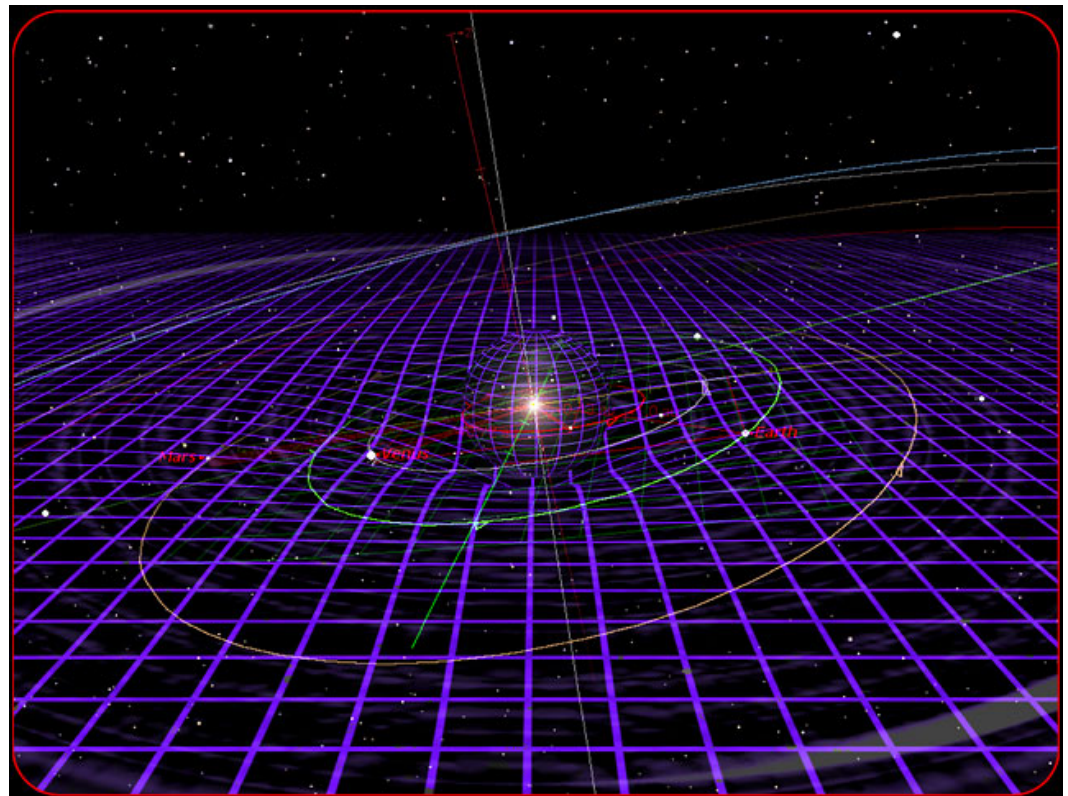
The Possibility and the Myth

Isaac Newton



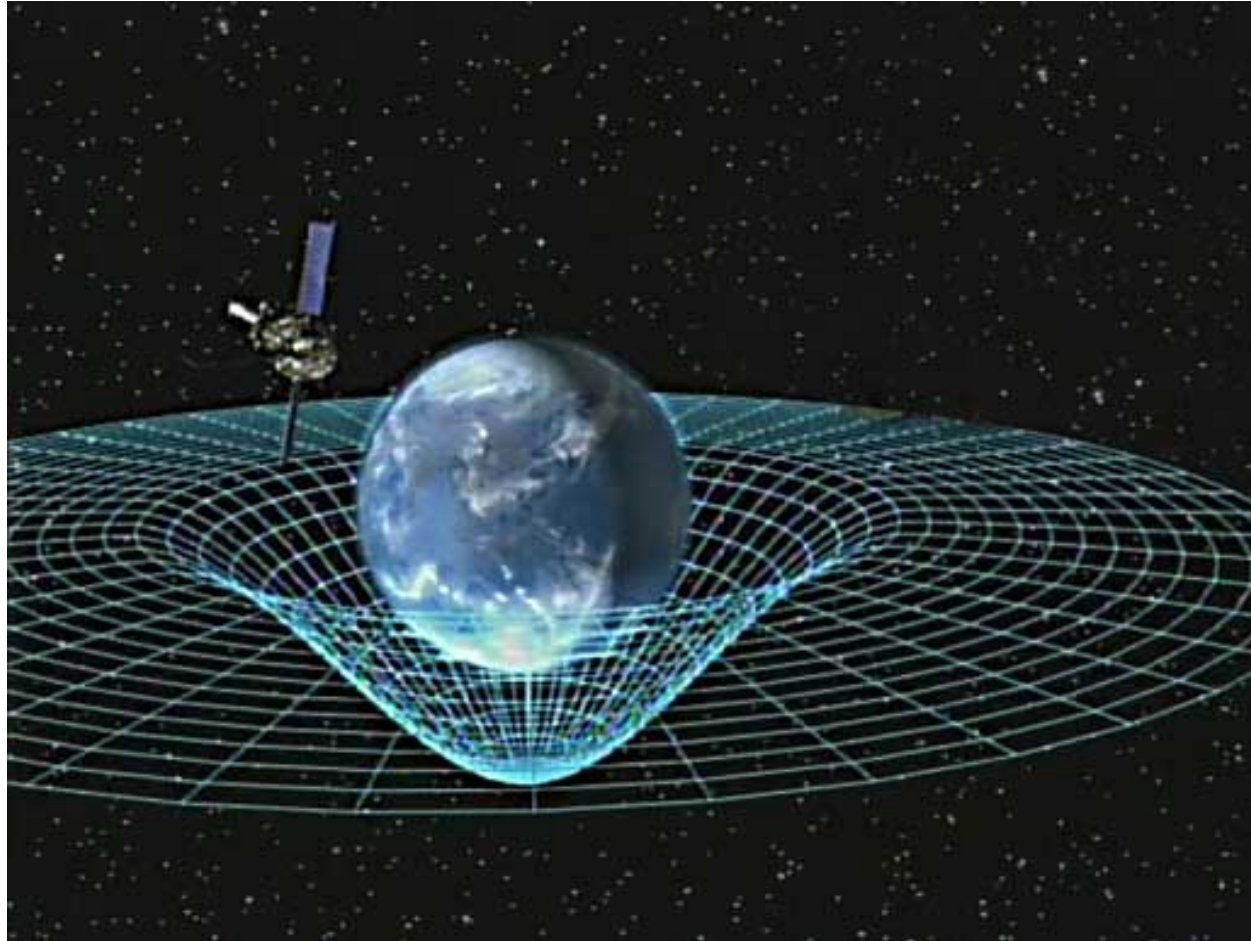
1687: Space and time are the static stage
on which physical processes act

Albert Einstein

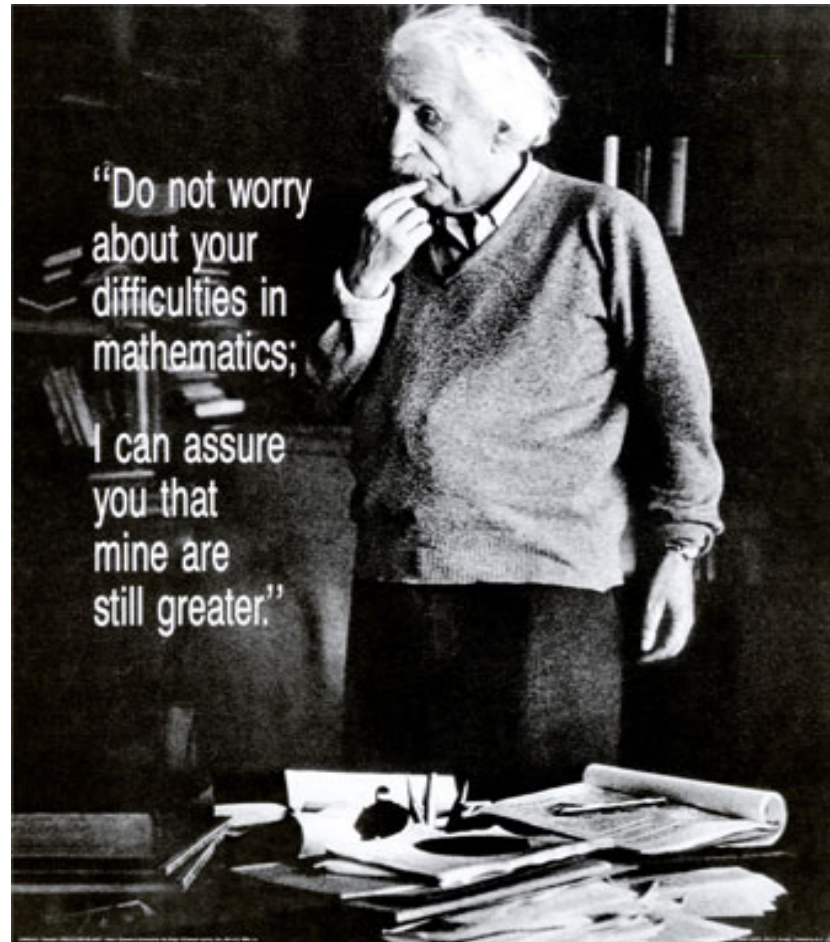


1915: Spacetime is an active player:
curves, expands, shrinks, ...

Matter and Energy Curves Space



Einstein's Attempt to Unify Electromagnetism and Gravity



The problem with gravity

Gravity is a *very* weak force

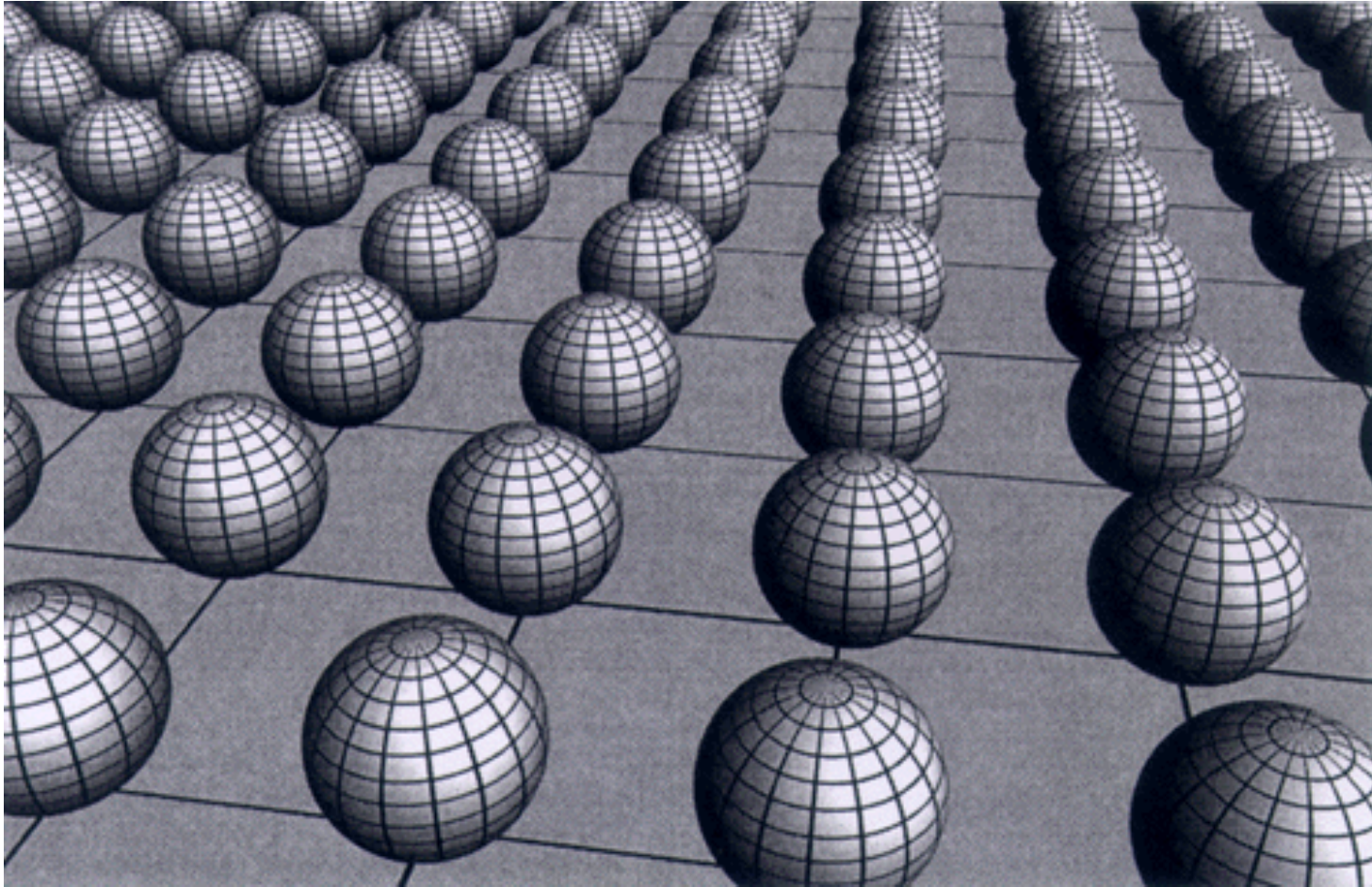
$$F_{\text{gravity}} \sim 10^{-36} F_{\text{EM}}$$

Very likely, we are missing something important. Why is gravity so weak compared to other forces?

Maybe it isn't...

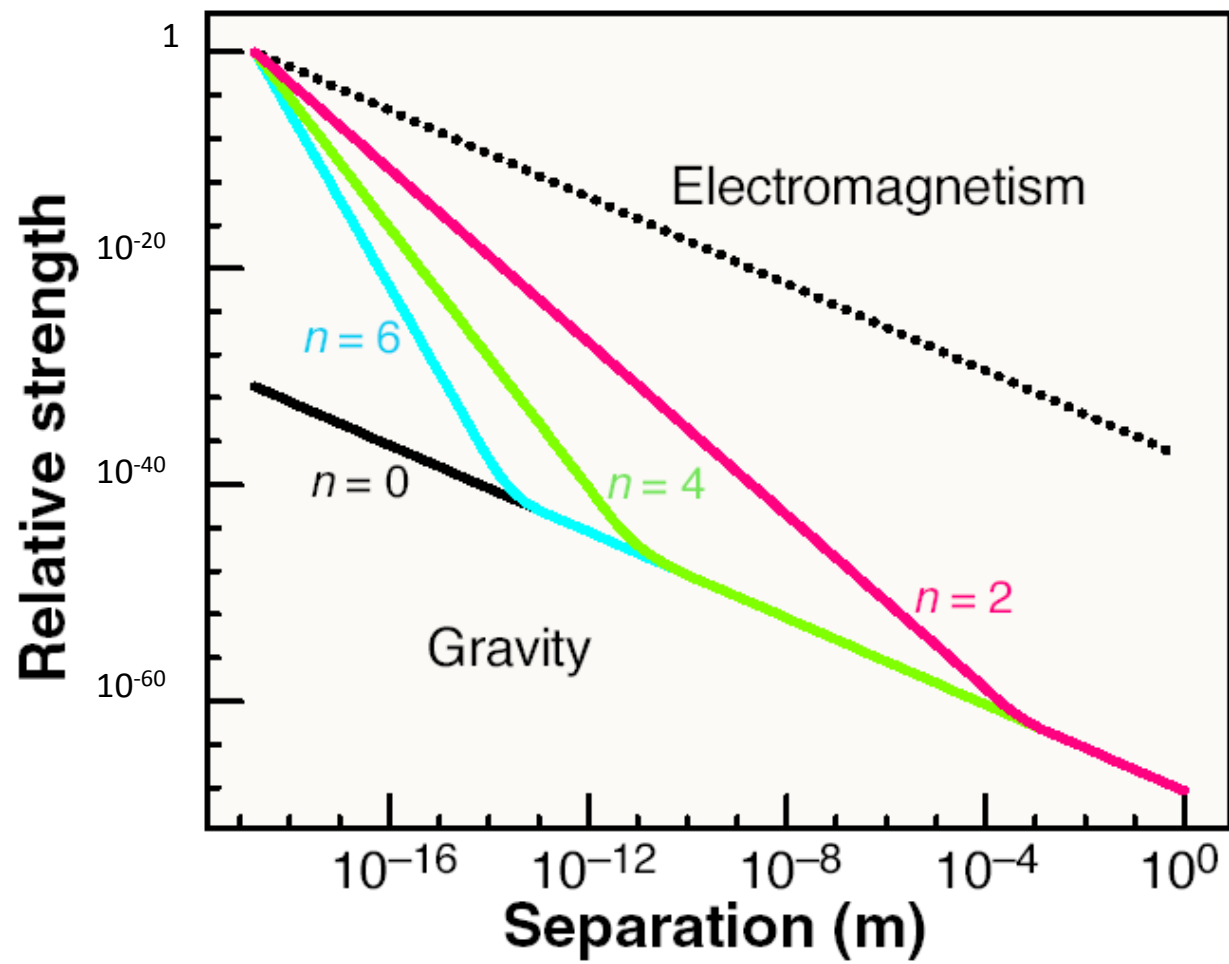


Curled-up Extra Dimensions of Space



Newton's Law

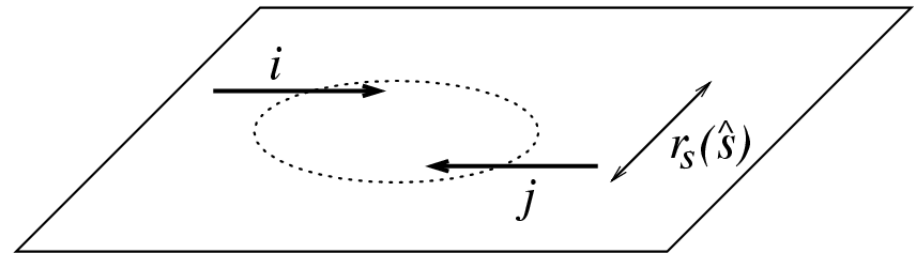
- In this case, gravity may be strong but appear weak only because its strength is diluted by extra dimensions.
- $F_{gravity} \sim 1/r^{2+n}$
for small lengths r , where n is the number of extra dimensions



Feng, Science (2003)

Microscopic Black Holes at LHC

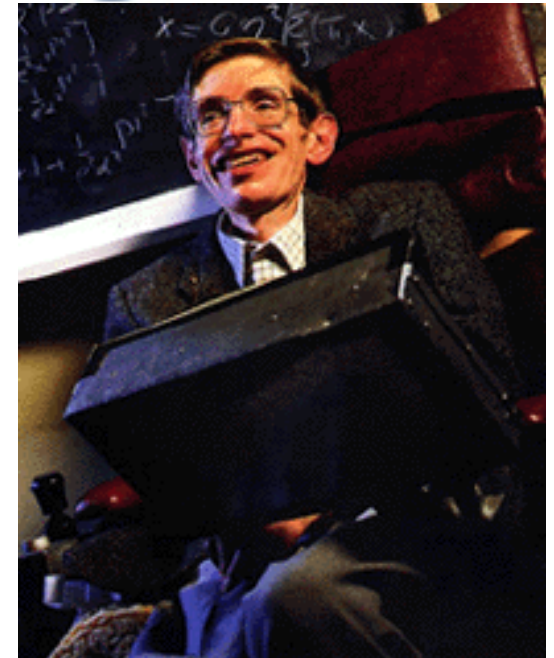
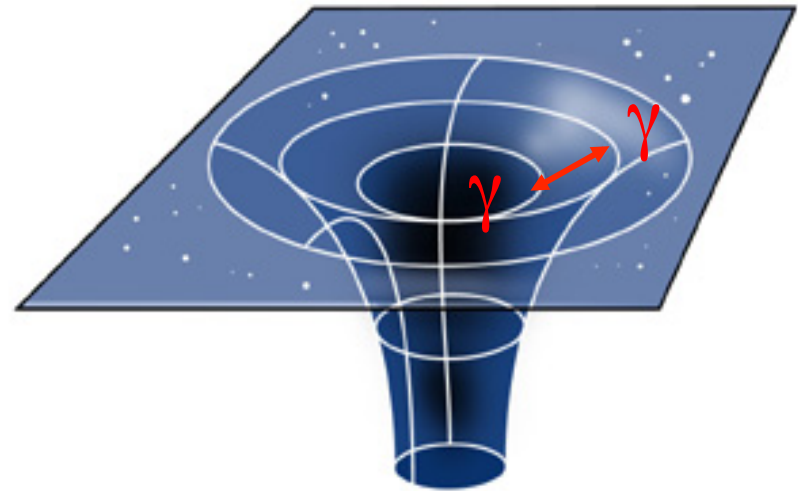
- If two particles pass close enough with enough energy, they will form a microscopic black hole



- For 3 spatial dimensions, gravity is too weak for this to happen. But with extra dimensions, gravity becomes stronger, micro black holes can be created in particle collisions!

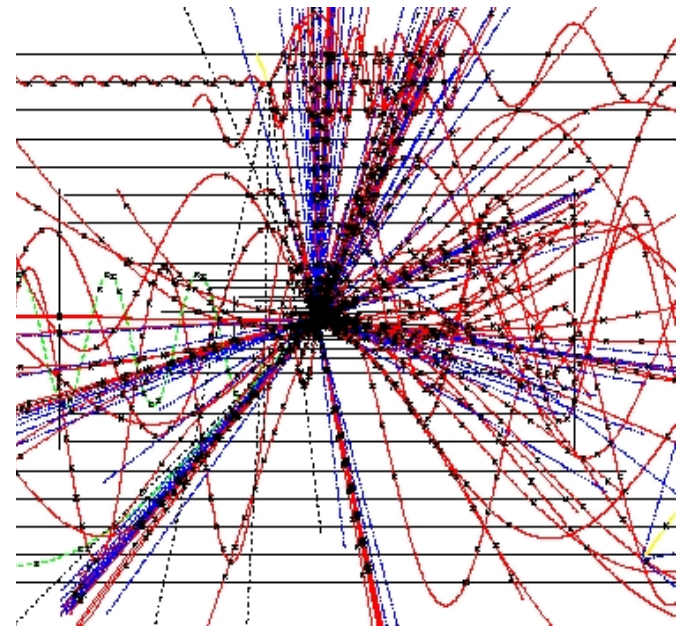
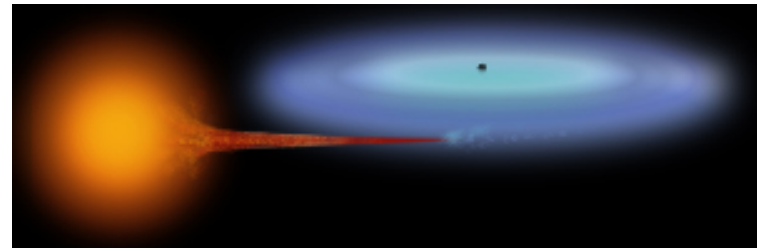
Microscopic Black Holes

- In Einstein's theory, light and other particles do not escape; black holes are black.
- But quantum mechanically, black holes radiate according to Stephen Hawking; black holes emit light!



Black Hole Evaporation

- “Normal” black holes:
Mass: $M_{\text{BH}} \sim M_{\text{sun}}$
Size: kilometer
Temperature: 0.01 K
Lifetime: $\sim$ forever
- Micro black holes:
Mass: $M_{\text{BH}} \sim 1000 M_{\text{proton}}$
Size: 10^{-18} m
Temperature: 10^{16} K
Lifetime: 10^{-27} seconds



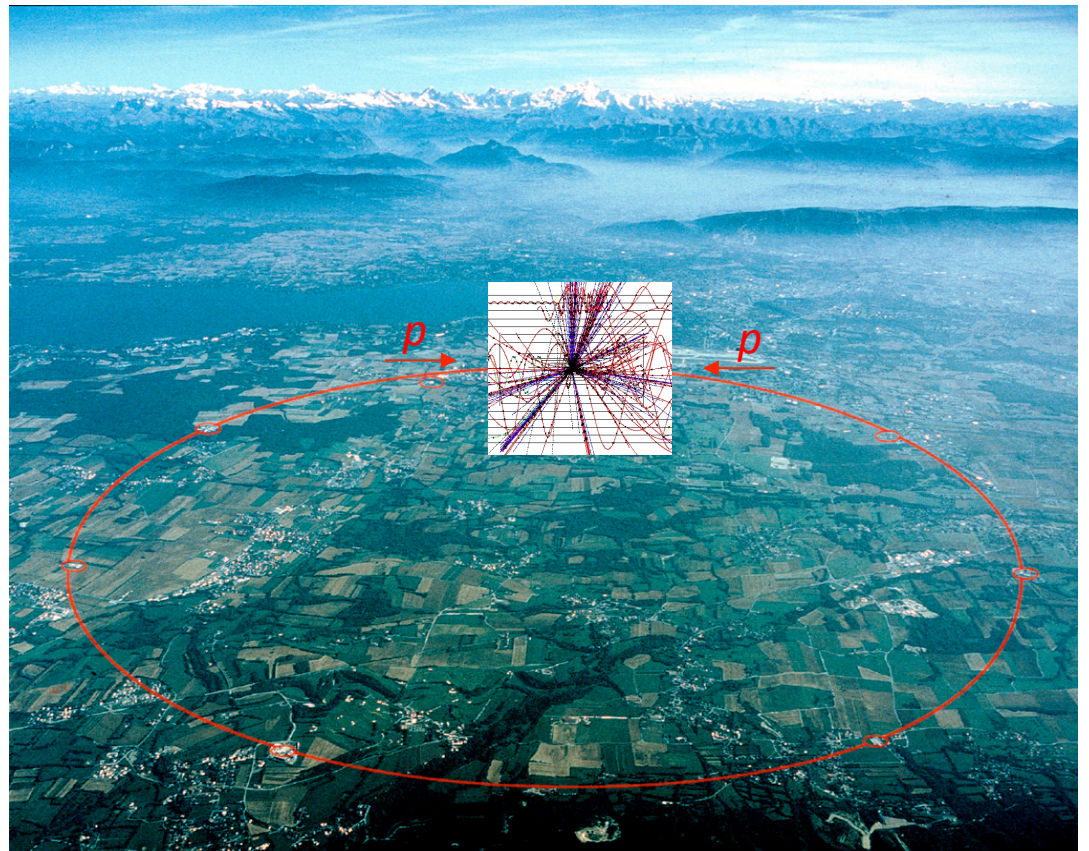
Microscopic black holes explode!

Black Holes at LHC

If effects of strong gravity, for example black holes, are observed $\Leftrightarrow$
revolutionize our understanding of space itself

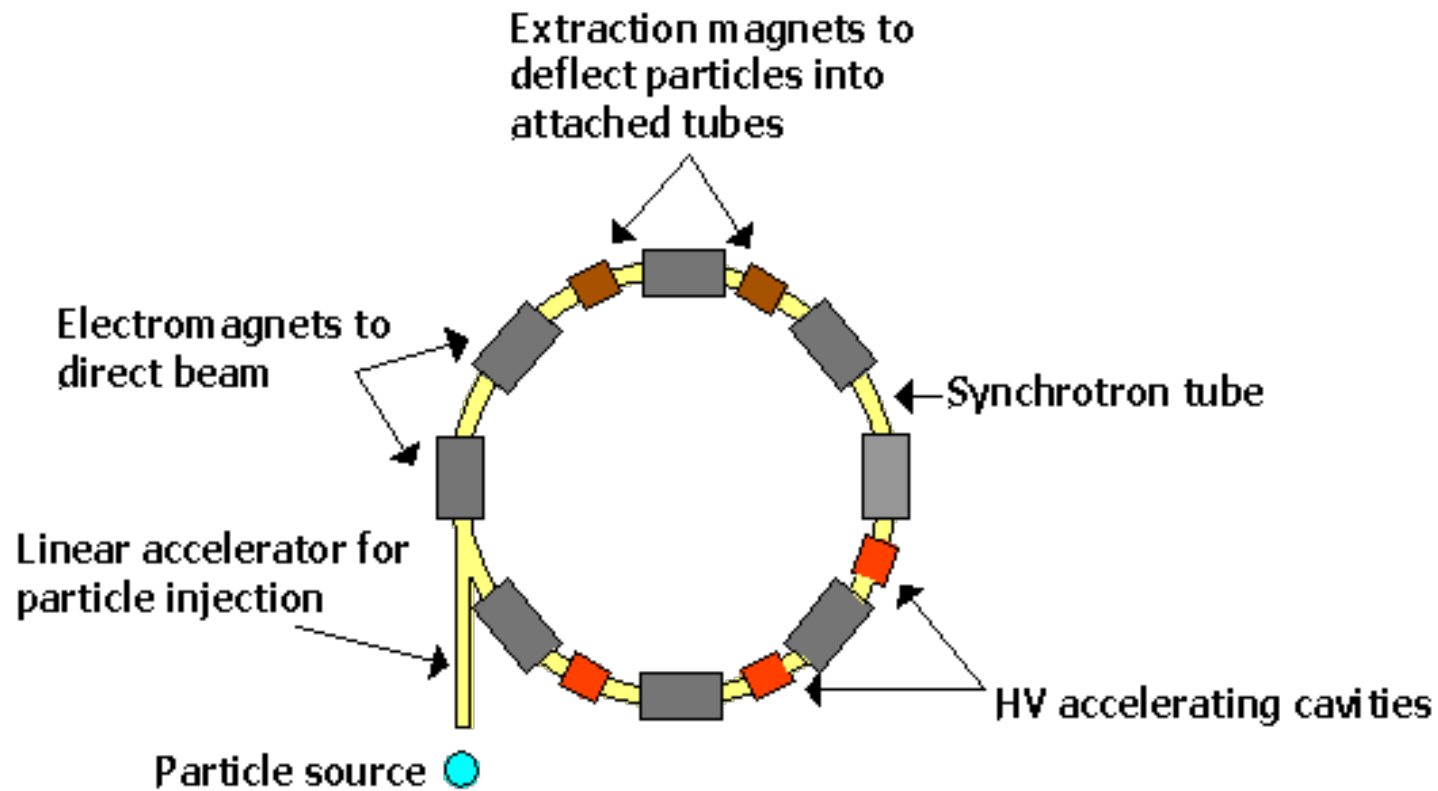
Closer to Einstein's last dream

Closer to a quantum theory
of Gravity



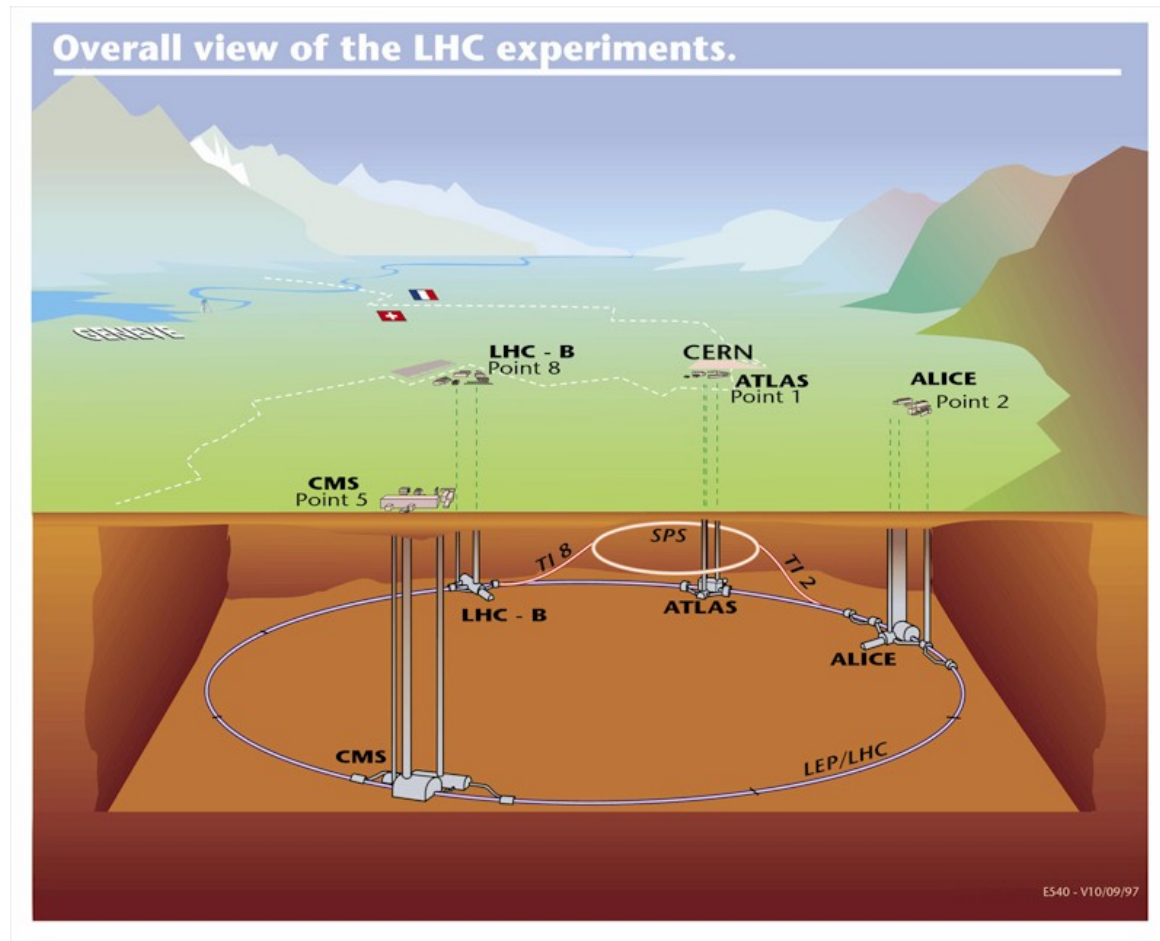
How does LHC work?

How does a particle accelerator work?



Synchrotron Accelerator

LHC below Geneva, Switzerland



LHC below Geneva, Switzerland



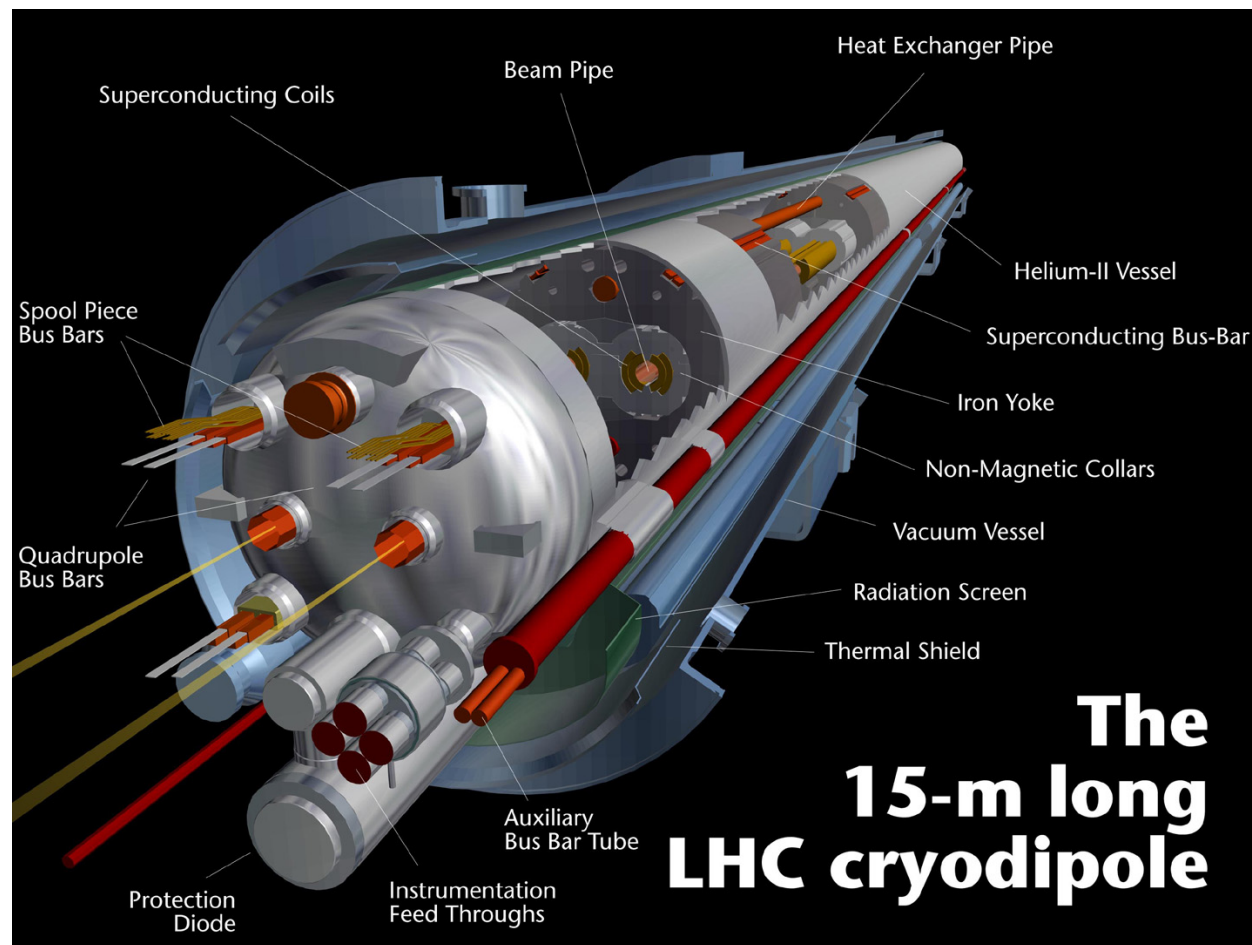
Accelerates and collides proton beams, each 4 micrometers wide

LHC Accelerator in Tunnel



Vacuum in the beampipe is better than vacuum in outer space

LHC Superconducting Magnet



Weight 35 tons, magnetic field 100,000 times Earth's magnetic field
Magnetic force is thousands of tons

LHC Superconducting Magnet



Similar magnet design used in MRI machines

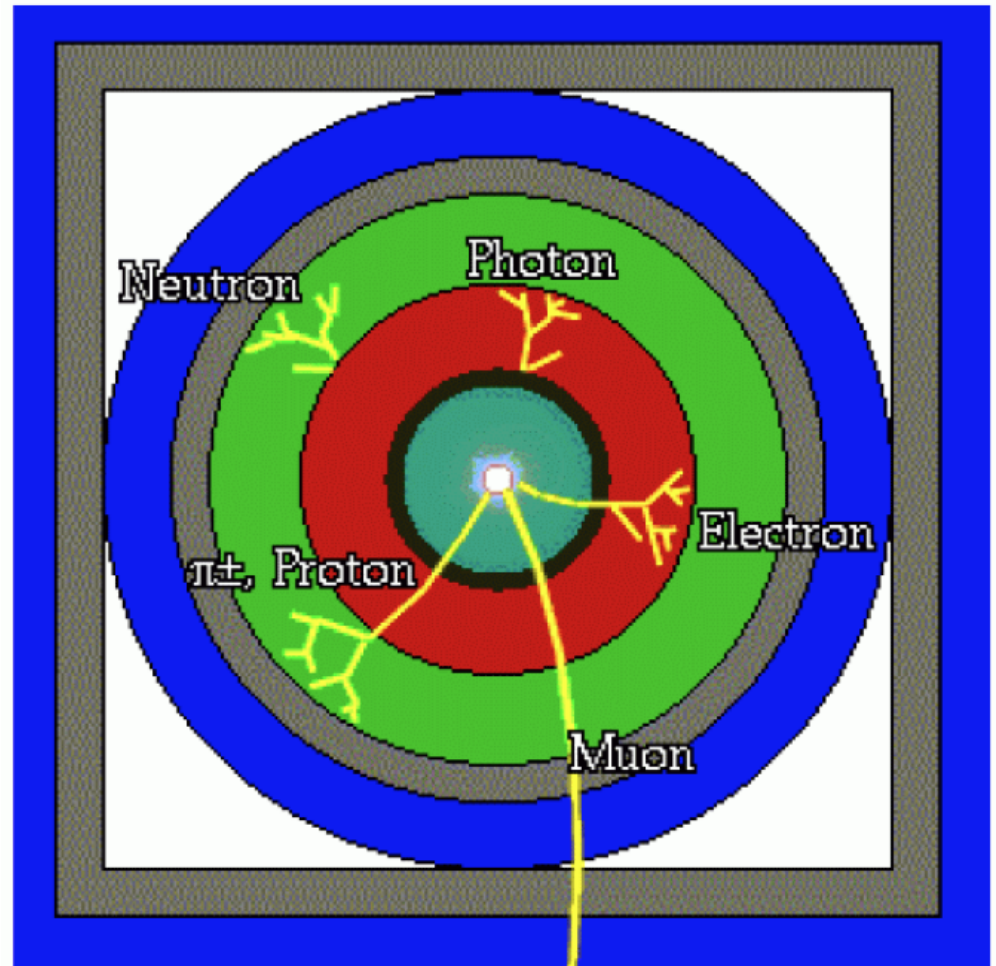
LHC Superconducting Magnet



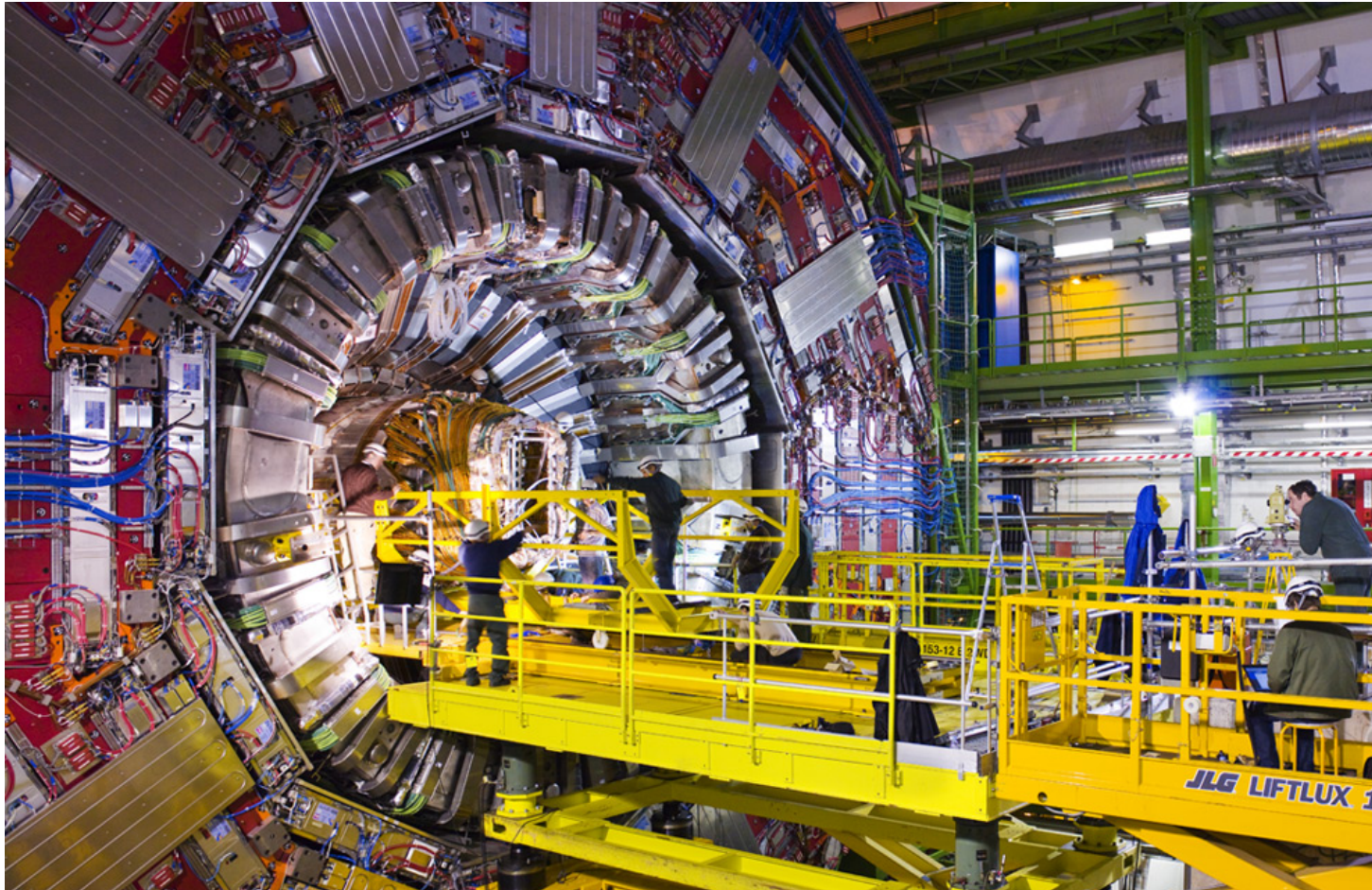
1200 magnets lowered 100 meters down into tunnel,
distributed over 27 kilometers

Particle Detector Design

- Concentric cylinders of different kinds of detector technologies
- Decay products of unstable particles identified



LHC Particle Detector – CMS Experiment



size about 20 meters

weight 12,000 tons (more than Eiffel Tower)

CMS (Compact Muon Solenoid) Experiment



Very large, very fast “digital camera”
60 million pixels, can take 40 million snapshots per second

Physicists in the Control Room



24 hours x 7 days x 365 days x 10 years operation

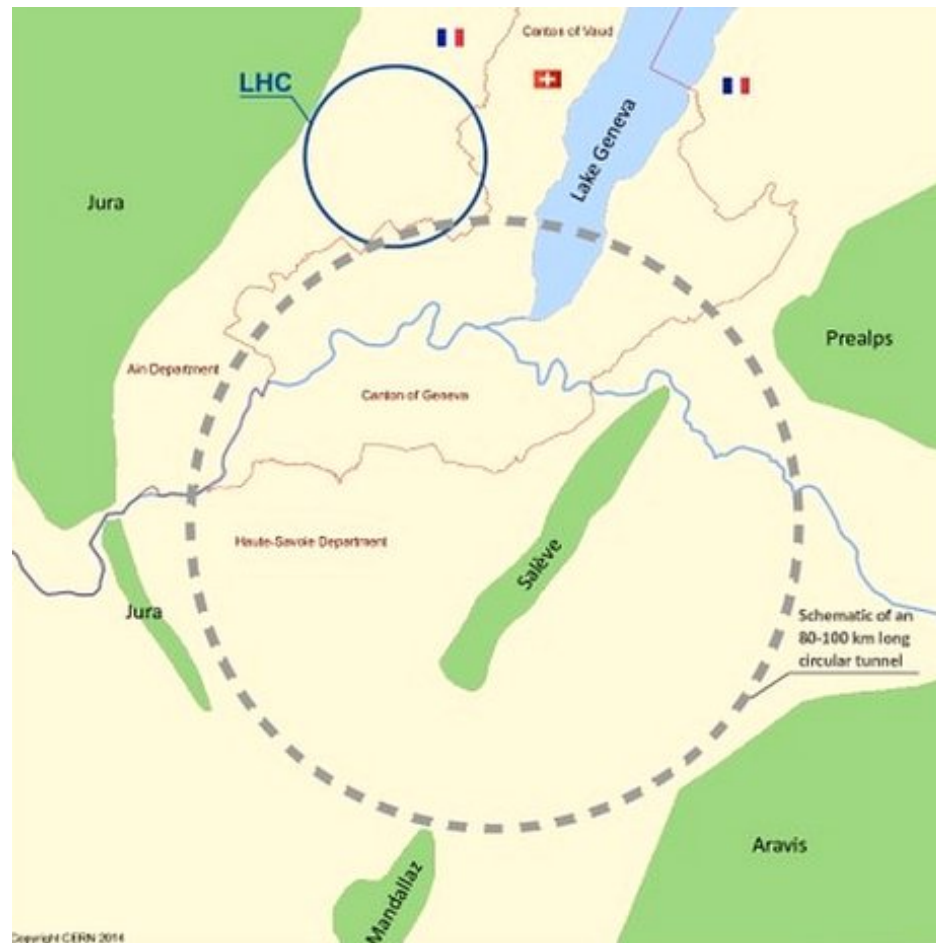
Why LHC Works



Life after LHC?

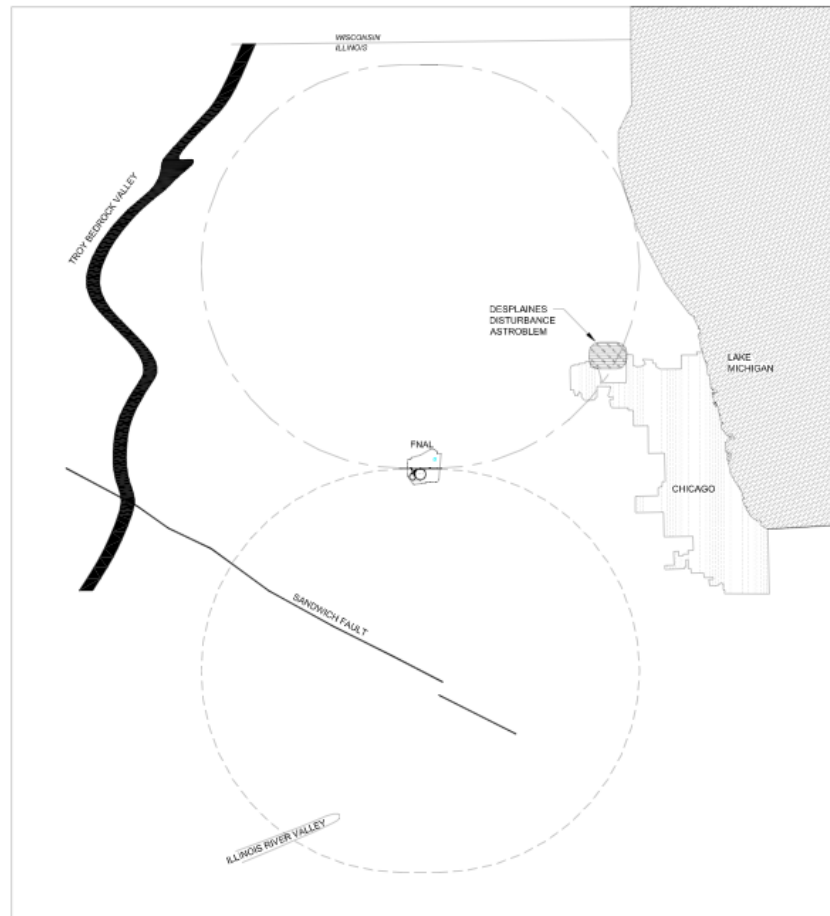
- Interest in Europe, USA and China to build a higher-energy proton-proton collider
 - Need a bigger tunnel !
 - Need more powerful magnets !!

Life after LHC?



A possible big tunnel close to CERN, Geneva, Switzerland

Life after LHC?



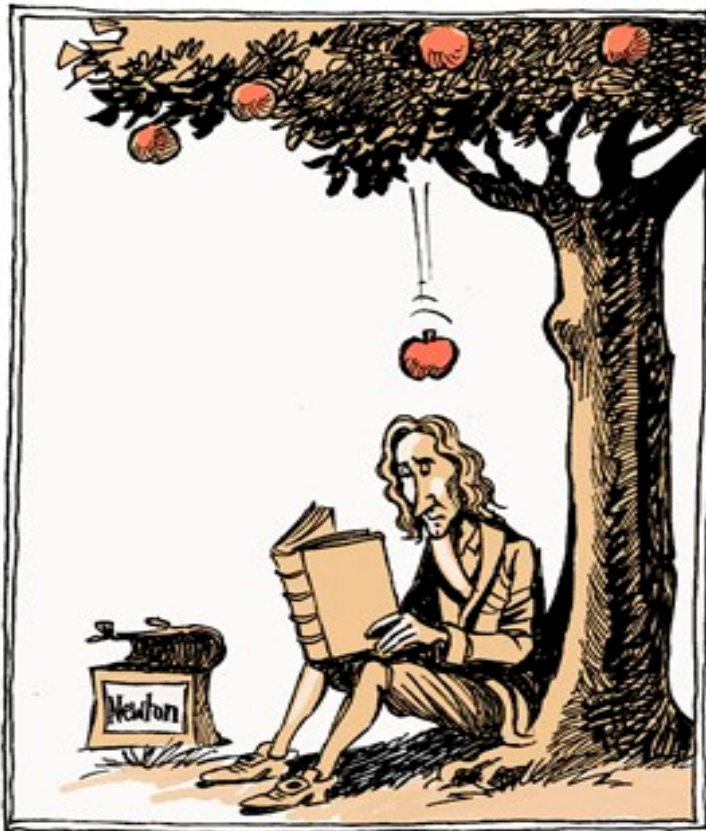
A possible even bigger tunnel close to Chicago !!

Conclusion

- LHC is operating successfully – a great achievement of science and engineering and of international cooperation
- Higgs boson discovery confirms theory of massive particles
 - Vacuum is actually permeated with the Higgs field
- Discovering other Higgs properties could start a new revolution in physics
 - As grand as the revolution started by quantum mechanics and theories of relativity a century ago
- Phenomena still not understood
 - What causes the Higgs field to condense?
 - What is Dark Matter ?
 - Can we understand the force of gravity from the Quantum perspective?

Thank You!

Collisions That Changed The World



Thank You!

HIGGS BOSON

H



The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

Wool felt with
gravel fill for
maximum mass.

LIGHT HEAVY

\$9.75 PLUS SHIPPING

The PARTICLE ZOO