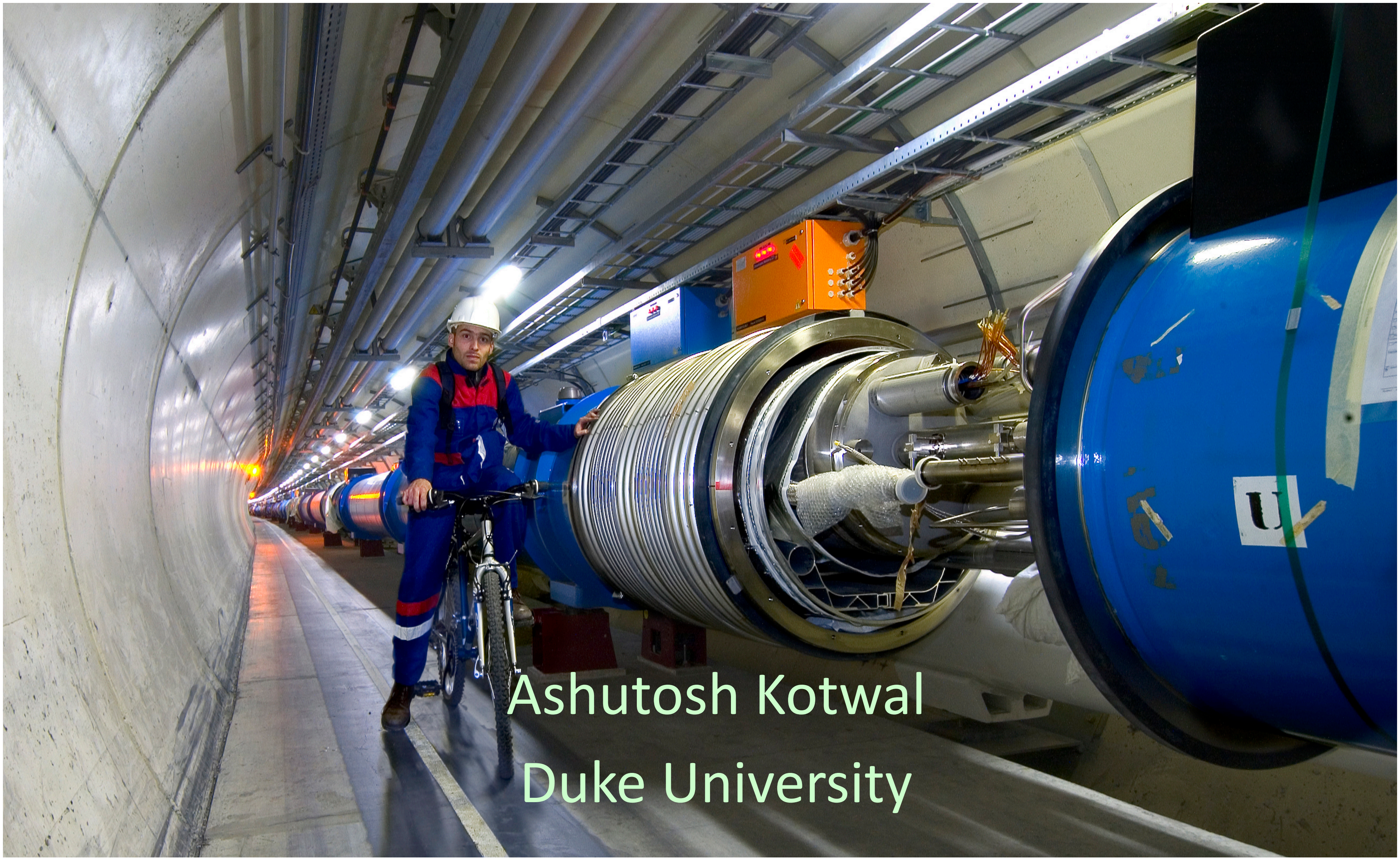
The Higgs Boson, Dark Matter and all that:

Revolutionizing the Laws of the Universe with the LHC



Ashutosh Kotwal
Duke University

Egyptian Pyramids: Monument for Glory

Great Wall of China: Monument for Defense

Monument for Knowledge:
The Large Hadron Collider

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

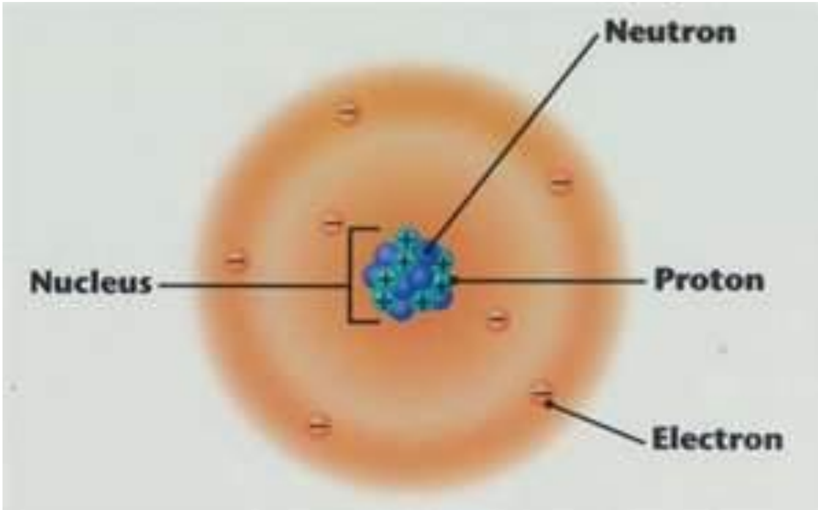
Why have we been hunting for the Higgs for more than half a century?

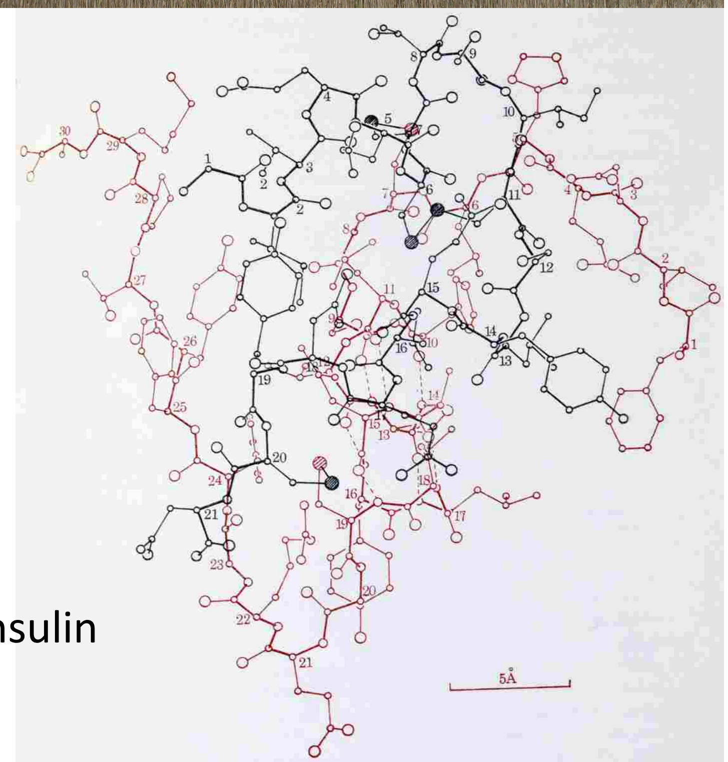
To solve a deep riddle in Quantum Mechanics, the proven theory of the microscopic world

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

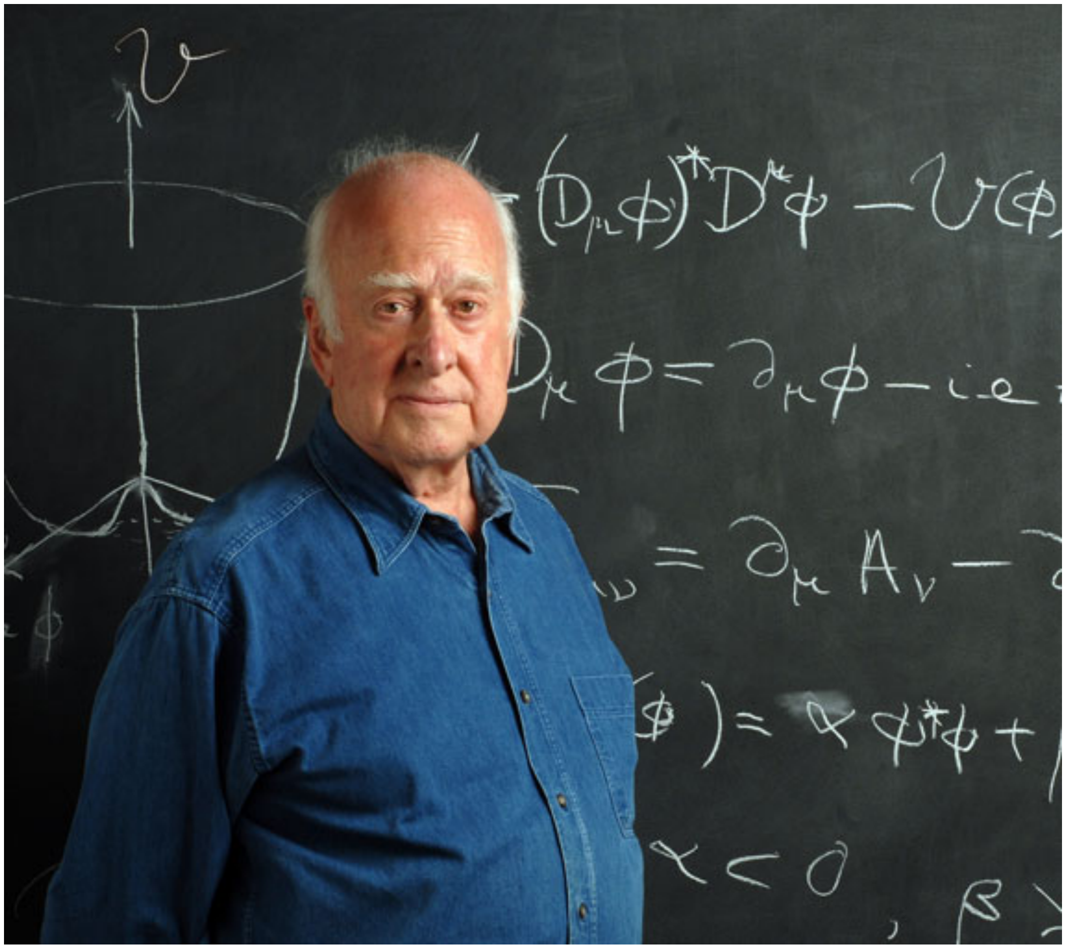
- In spite of its success, a self-consistent quantum mechanical theory of matter and forces has a huge missing link – the theory requires all fundamental particles to have exactly zero mass
- The non-zero electron mass cannot be understood – and yet the electron mass defines the size of the atom and 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?

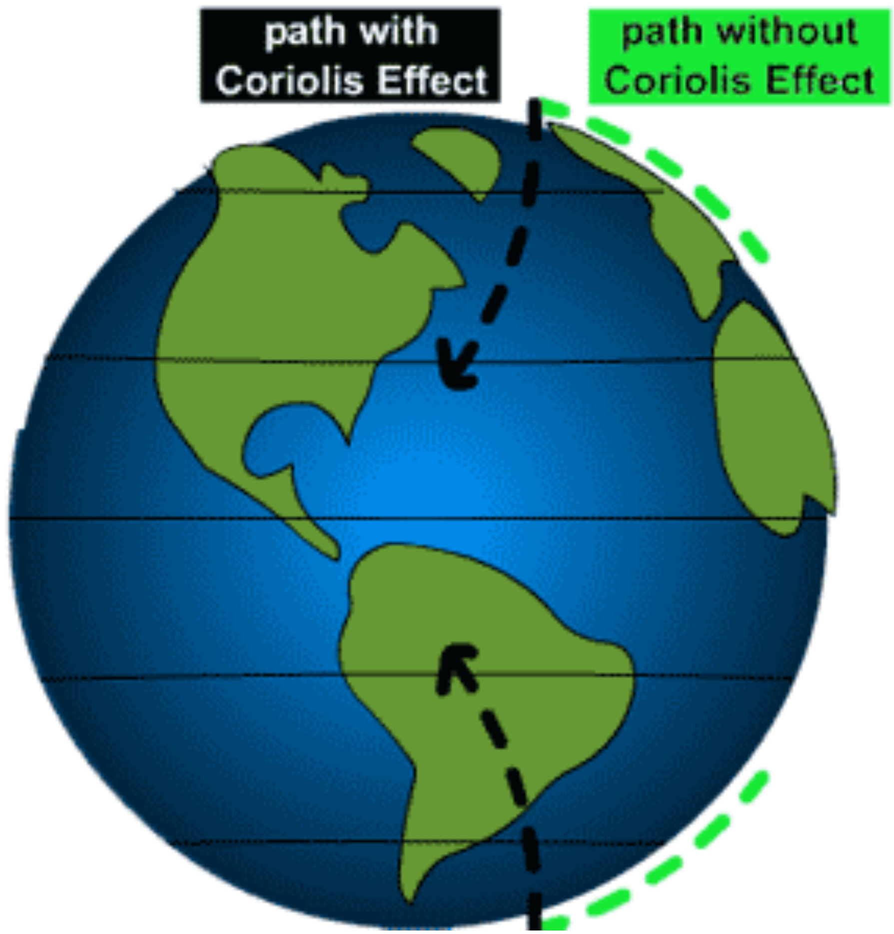
The Higgs Boson



Peter Higgs

Satyendra Nath Bose in 1920's

How to Predict Fundamental Forces



“fictitious” forces observed in accelerating frame of reference

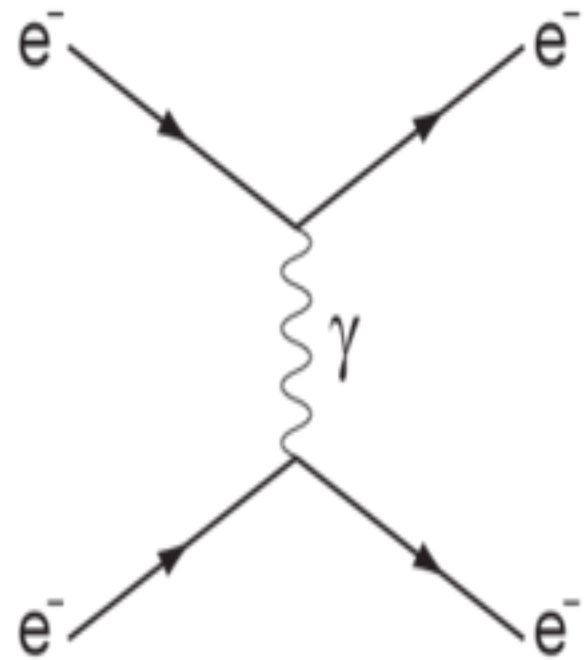
Manifestation of Coriolis Force

Hurricanes appear to rotate in Earth's frame of reference

Quantum Mechanics
force $\Leftrightarrow$ particle exchange

Feynman Diagram: Force by Particle Exchange

Richard Feynman



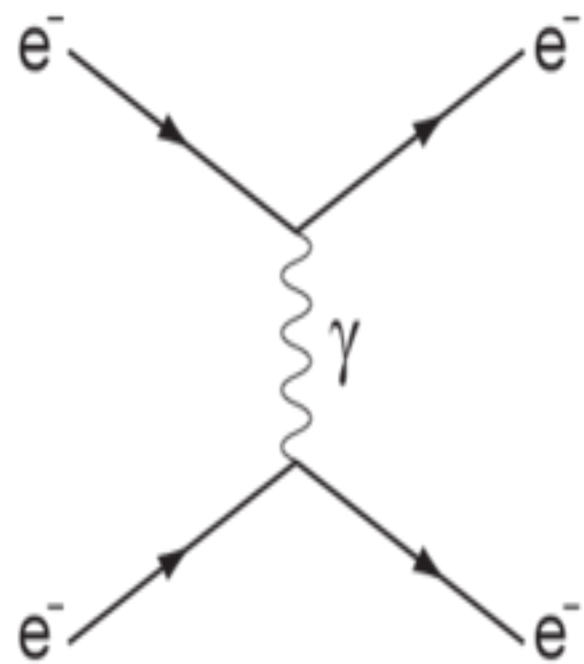
Electromagnetic force between two electrons mediated by "photon" exchange

Feynman Diagram: Force by Particle Exchange

The most precisely tested theory, ever:

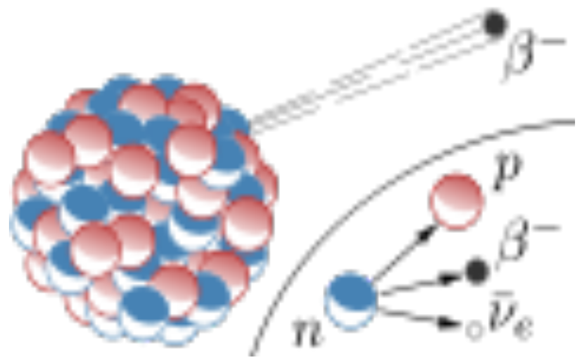
The quantum theory of the electric and magnetic forces, radio waves, light and X-rays:

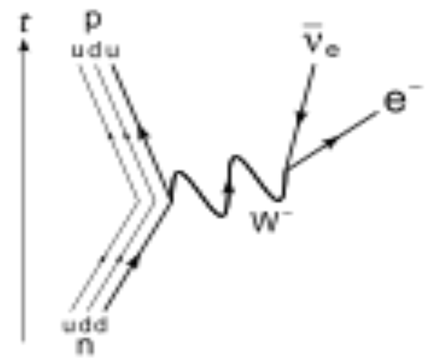
Measured and predicted magnetic moment of an electron agree within 0.3 parts per trillion accuracy

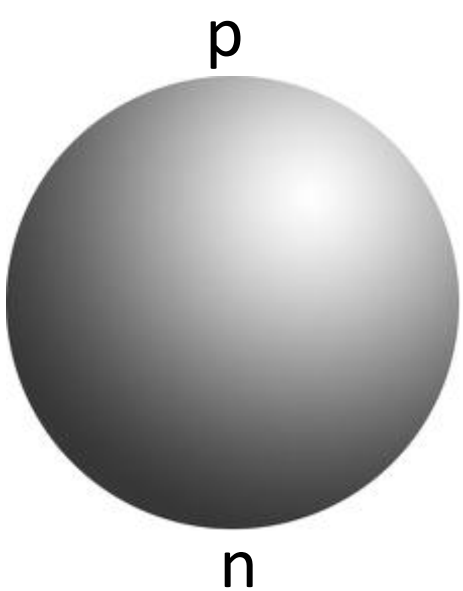


Electromagnetic force between two electrons mediated by "photon" exchange

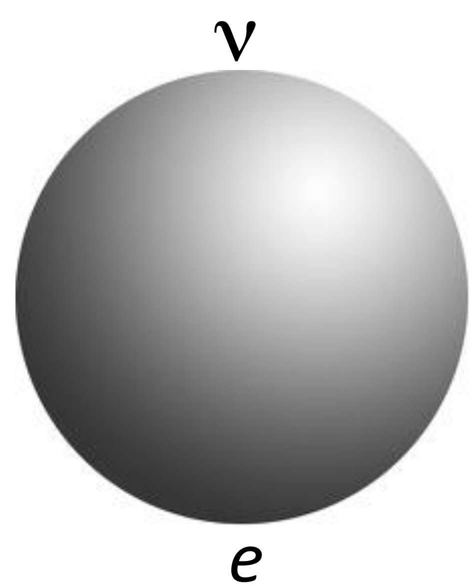
Weak Nuclear Decay







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?

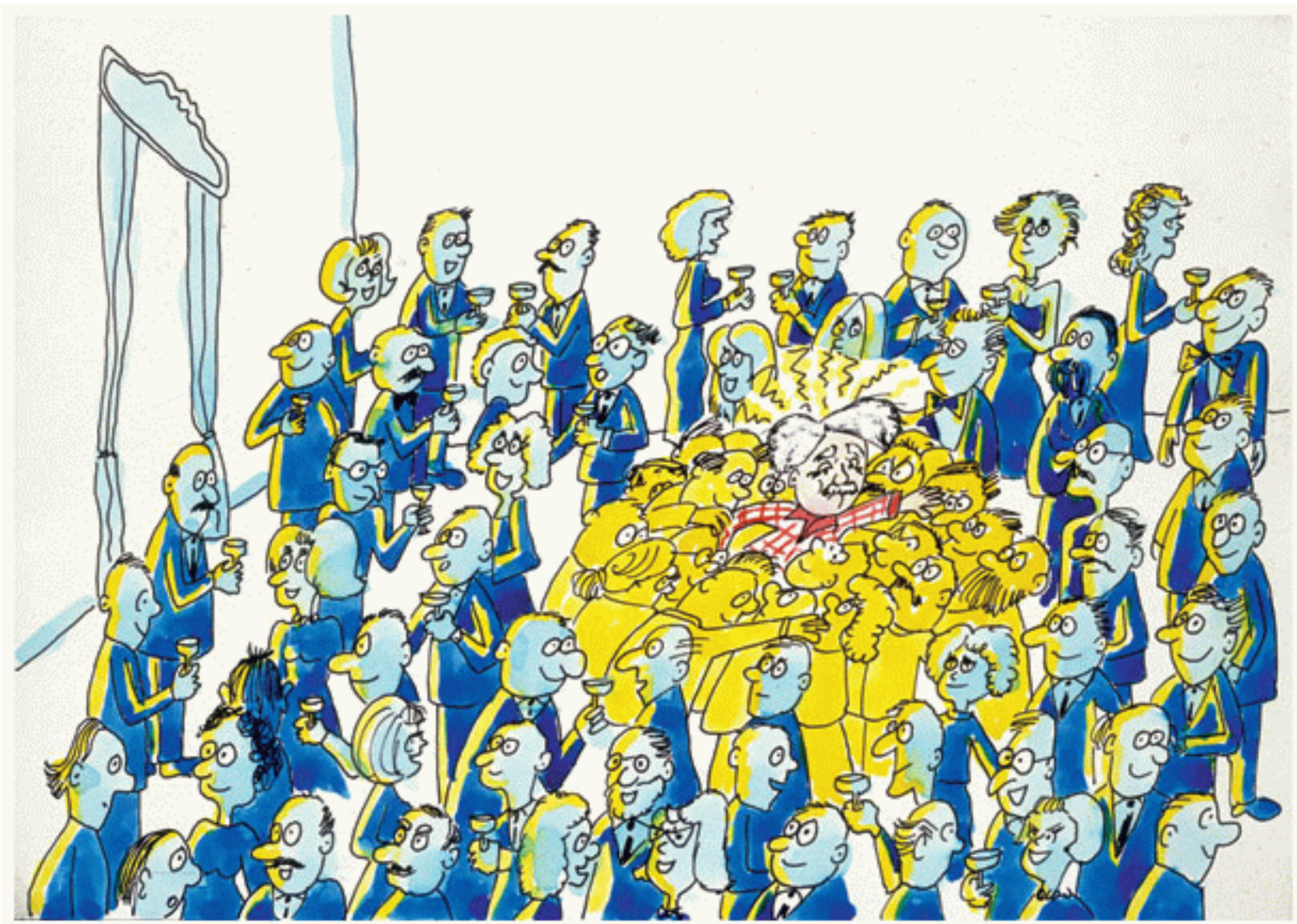
Solution to the Problem of W Boson Mass

- Fill all of space with "Higgs" field

- W boson propagating through "empty space" actually propagating though Higgs field

- Interaction of W boson with Higgs field slows down the W boson ⬄ imparting the property of mass to it

The “Sticky” Higgs Field



Implications of Higgs Hypothesis

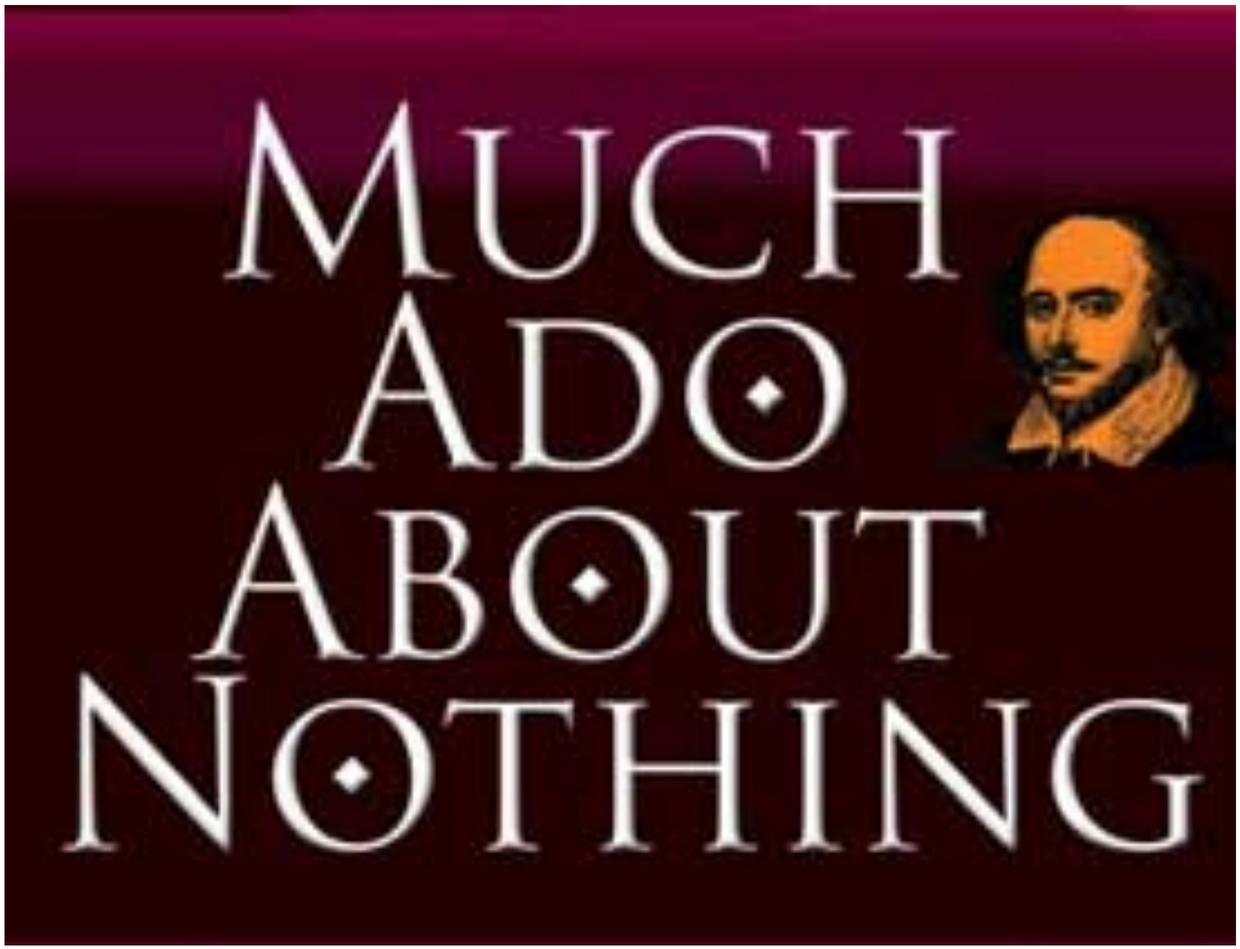
- Empty space is not really empty
- Filled with the Higgs
- All fundamental particles interacting with the Higgs field “slow down”
  - appear to be massive

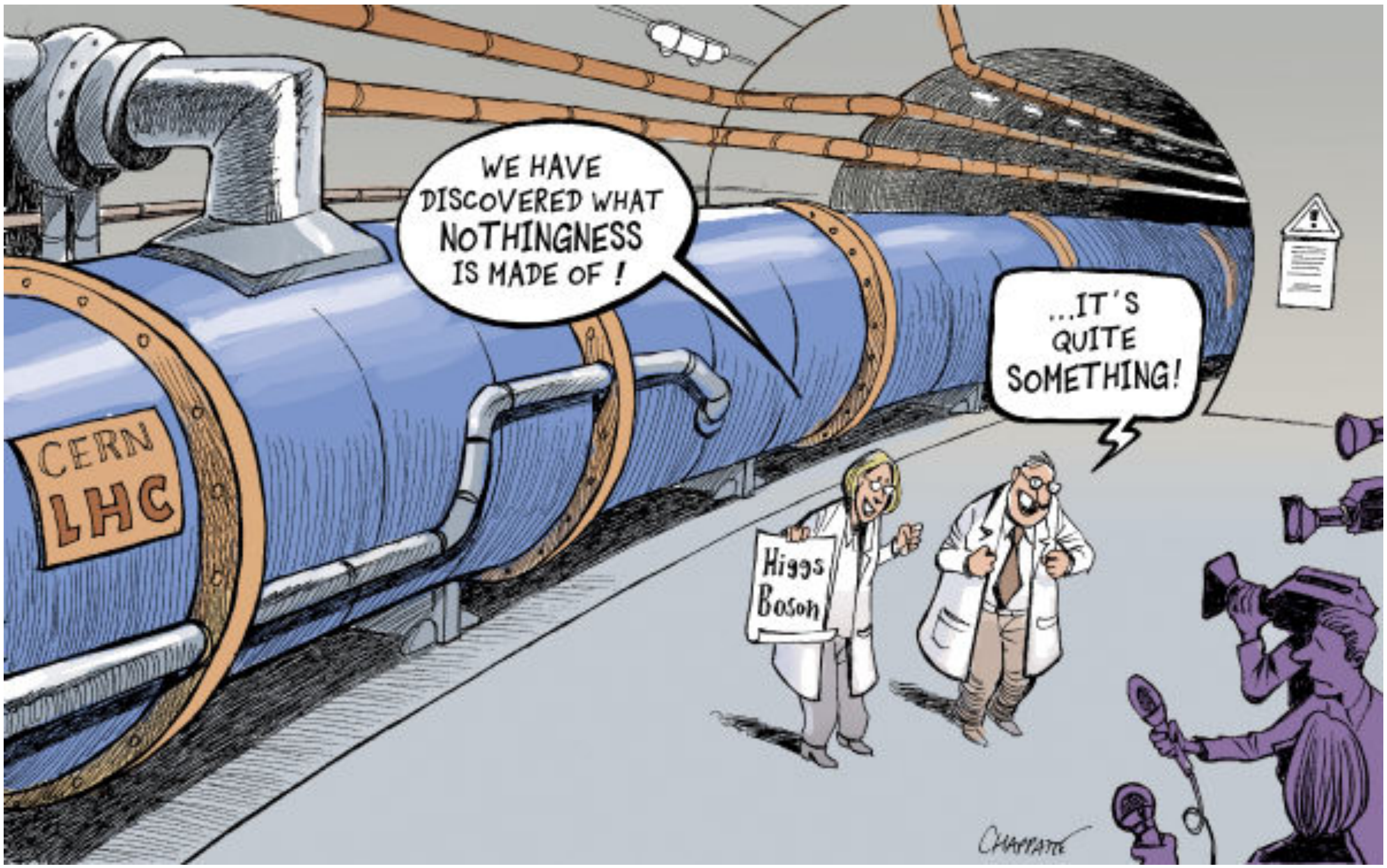
Light versus Heavy Particles – like moving through water

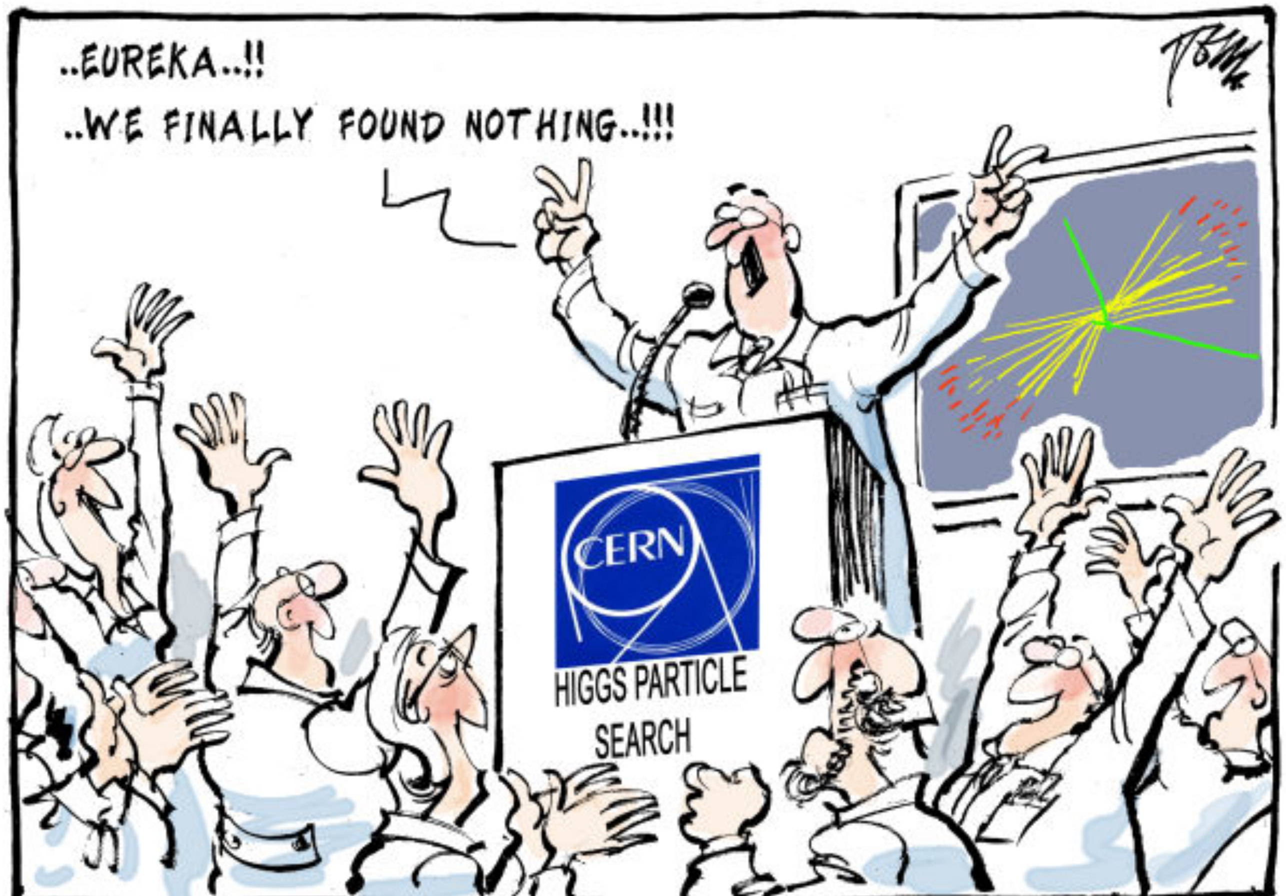
Streamlined
⇒ Moves fast through water
⇒ analogous to light particle

Not streamlined
⇒ Moves slowly through water
⇒ analogous to heavy particle

Alternate title of my talk:




WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson
CHAPPATTE


..EUREKA..!!
..WE FINALLY FOUND NOTHING..!!!
CERN
HIGGS PARTICLE
SEARCH

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!

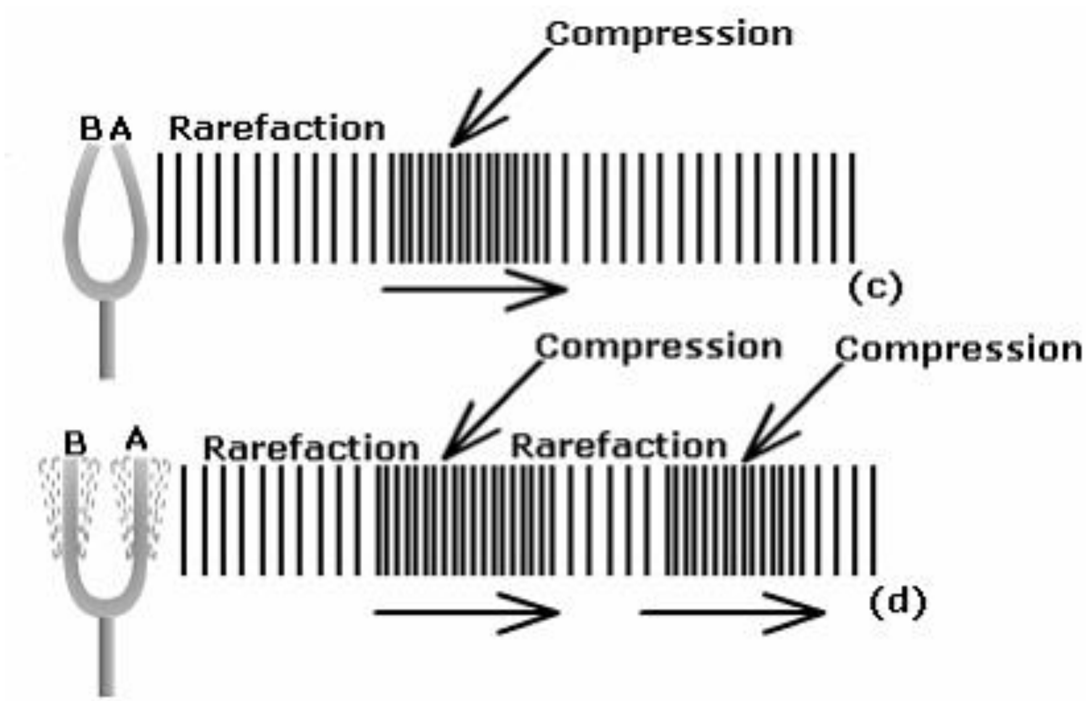
How can we confirm the existence of the Higgs?

- Create ripples in the Higgs field

Ripples ⇔ Higgs boson

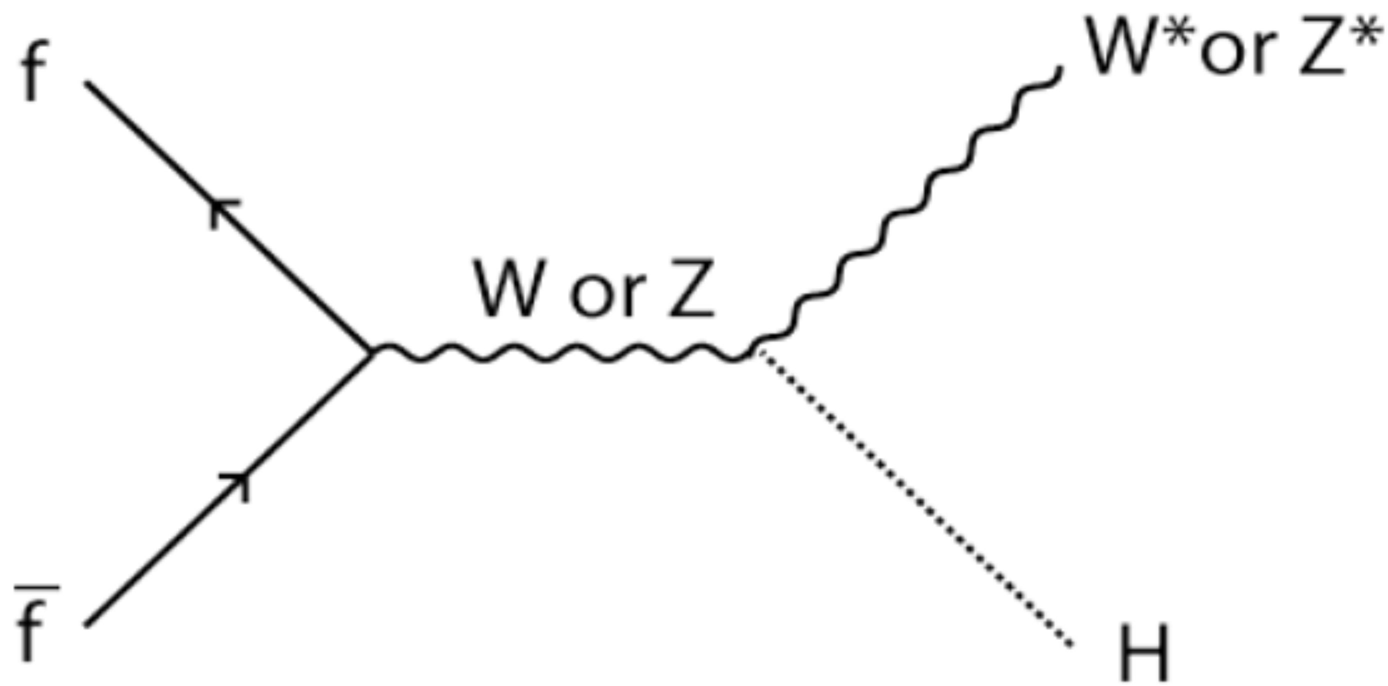
How can we confirm the existence of the Higgs?

- Create ripples in the Higgs field

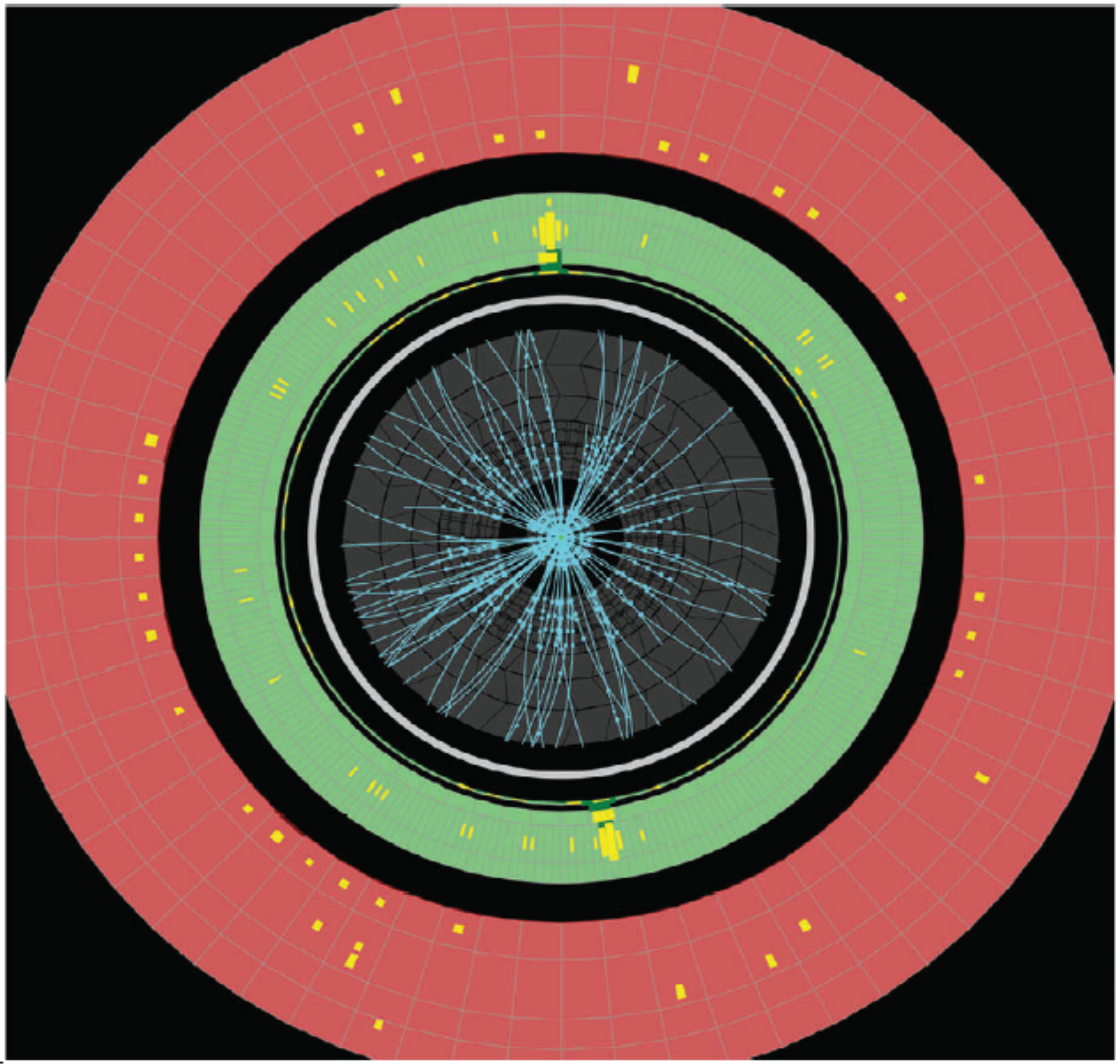


Ripples ⇔ phonons ⇔ Higgs boson

How to Create the Higgs Boson



Observation of Higgs Boson Production



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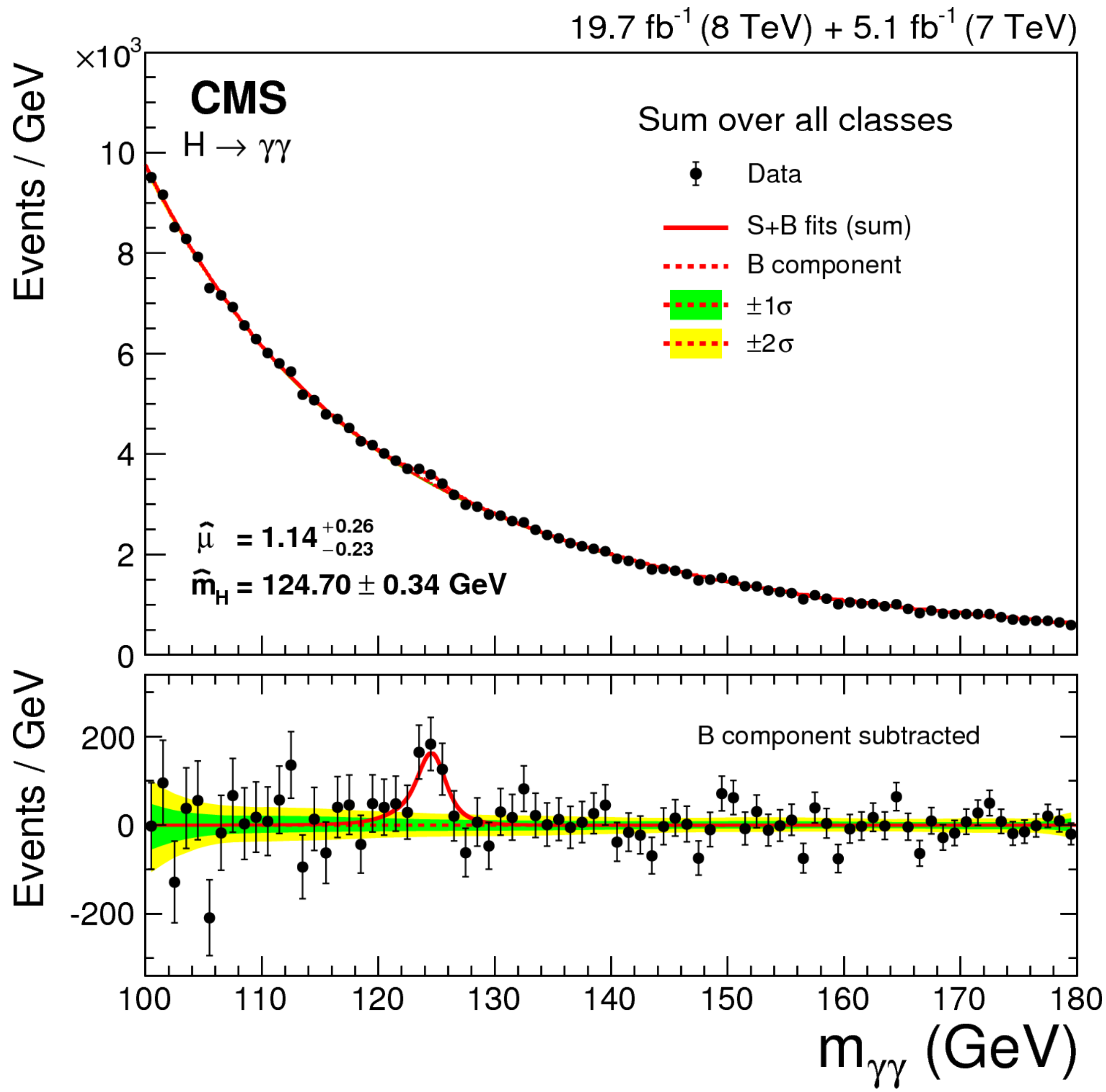

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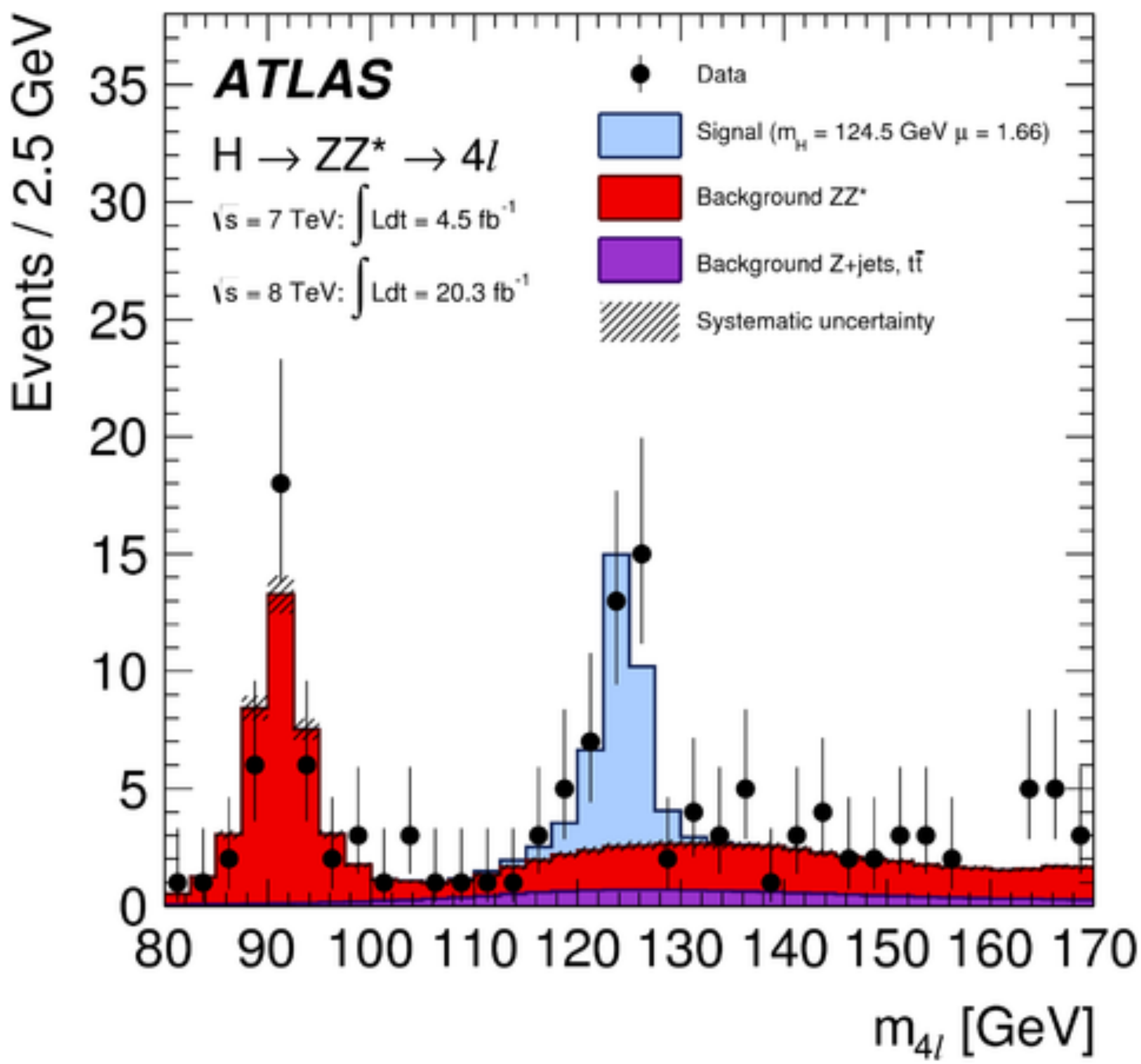
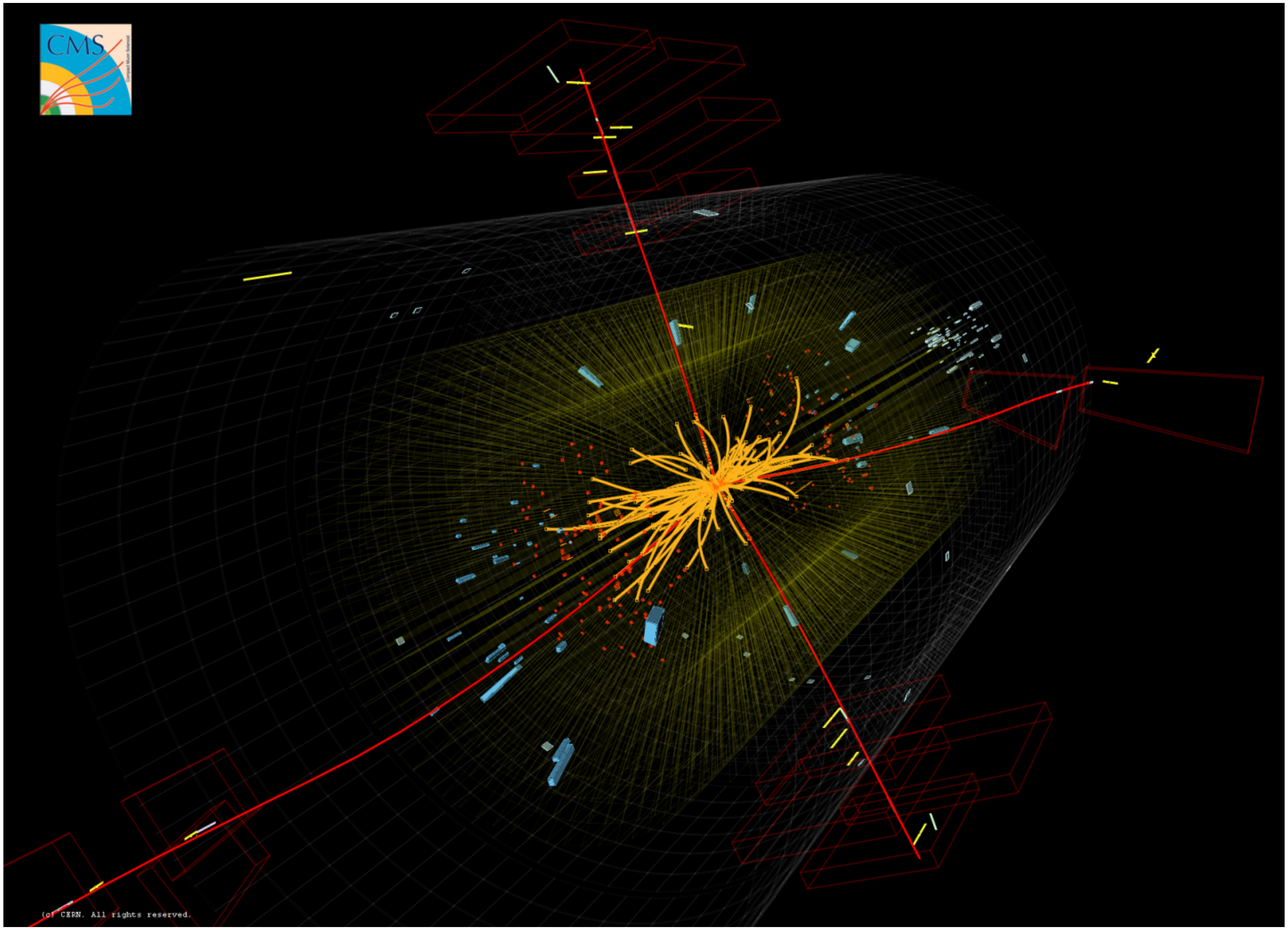


Higgs Boson Production and Detection at CMS

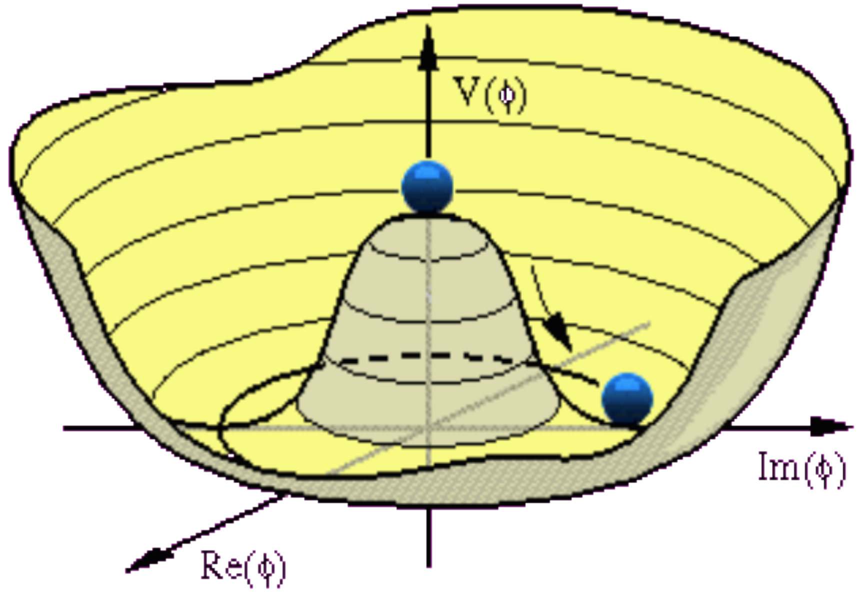


Higgs Discovery Implications

- 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…

Spontaneous Symmetry Breaking of Gauge Symmetry

- The Higgs potential in the SM is a parameterization that respects certain rules of QFT

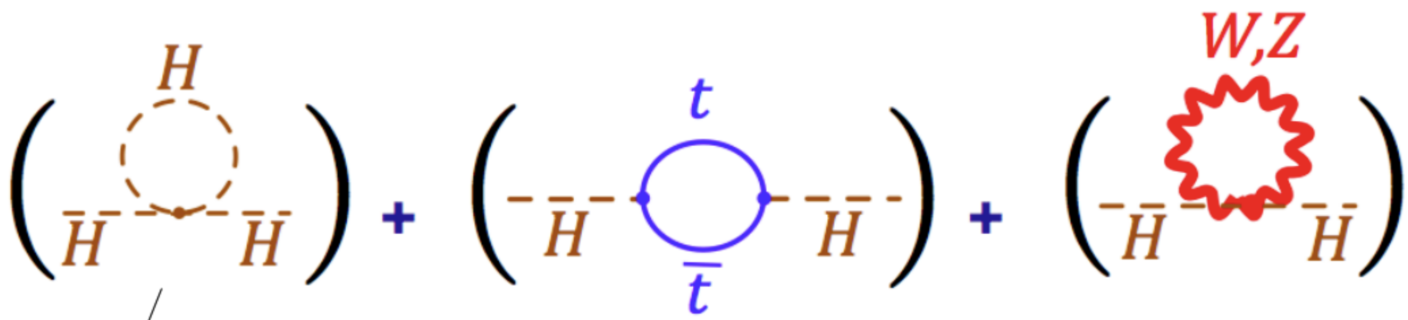


- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- Discovery of the "radial excitation" a.k.a the Higgs boson means that we have taken the first, big step in establishing the properties of this potential

Next Big Question: Why is the Higgs Boson so Light?

$$m_H^2 - m_{\text{bare}}^2 =$$



$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H^2)^{-1} \sim \Lambda^2 \lambda$$

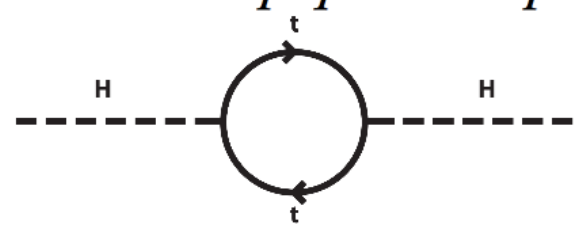
The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, **Λ**, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



- physical Higgs boson mass ~ 125 GeV
- Therefore need extreme "fine-tuning" through renormalization

SuperSymmetry

- SuperSymmetry is a space-time symmetry introduced in particle physics in the 1970's

  A SuperSymmetry (SUSY) operator Q is defined by

  $$Q\,|\,j > \;=\; |\,j \pm ½ >$$

  ie. angular momentum of a quantum state is changed by ½ unit

  - A (symmetry) operator linking fermions and bosons

- A minimal supersymmetric extension of the Standard Model (MSSM) has been constructed some time ago

SUSY to the Rescue

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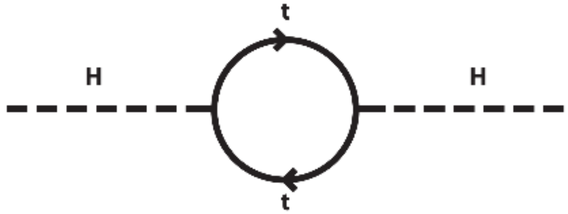
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



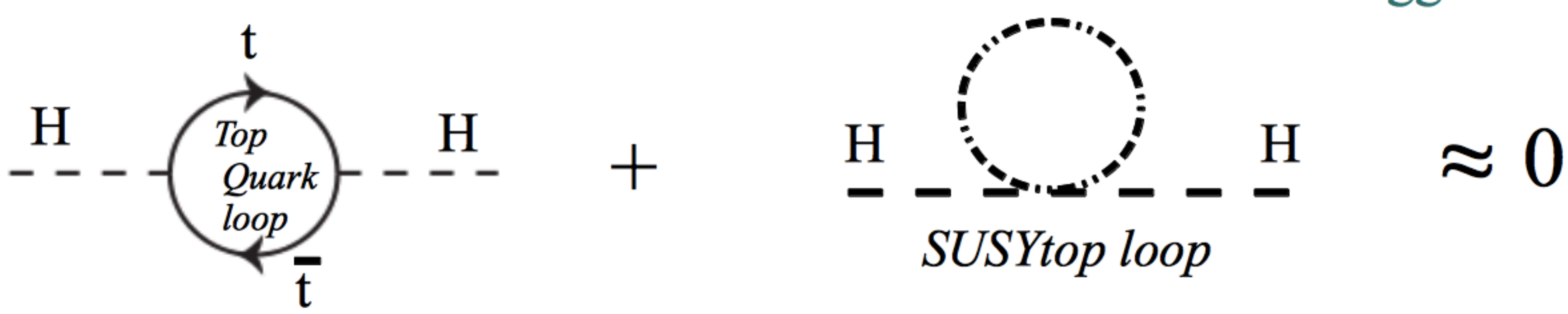
- physical Higgs boson mass $\sim$ 125 GeV
- Therefore need extreme "fine-tuning" through renormalization

SUSY top loop

- SUSY vastly reduces fine-tuning requirement by introducing additional amplitudes containing fermion → boson loops and boson → fermion loops

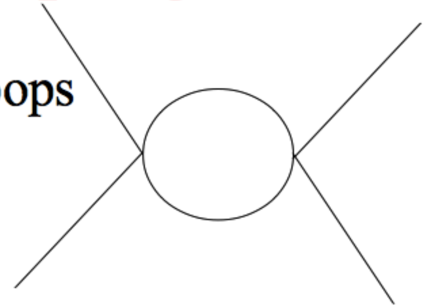
SUSY to the Rescue

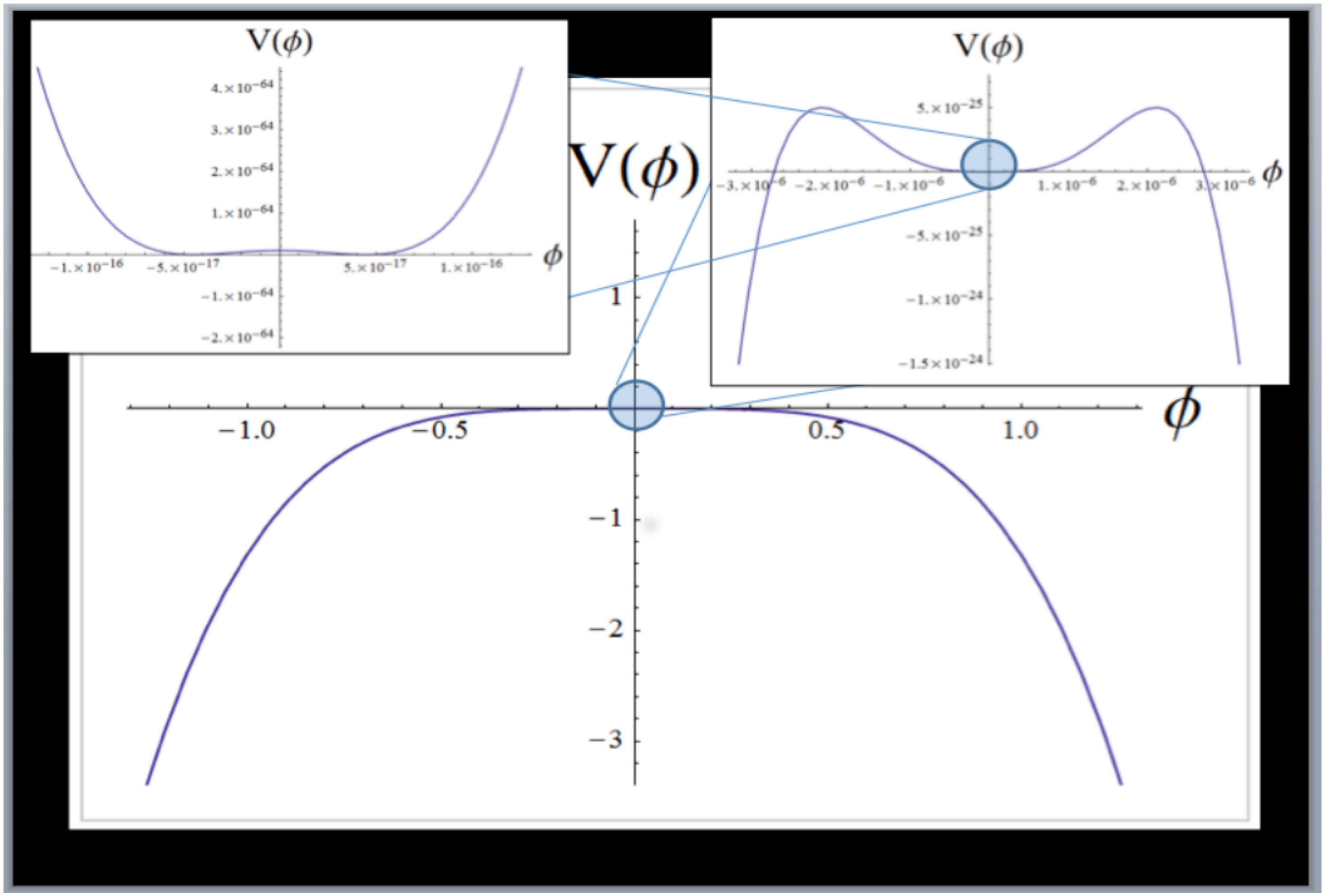
- SUSY adds bosonic (scalar) partners to fermions and fermionic partners to scalar and vector bosons
  - Higgs bosons ↔ Higgsino fermions
  - Top quark fermions ↔ supersymmetric top bosons
  - *W* and *Z* bosons ↔ Wino and Zino fermions
- By construction, all properties other than spin identical between super-partners
- Fermion loop with negative sign relative to boson loop, cancels exactly if SUSY was a exact symmetry
  - Eliminates uncontrolled radiative corrections in the Higgs sector



Radiative Corrections to Higgs Self-Coupling

- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top loops





Paul Steinhardt's talk on 7/15/2013 at Argonne USATLAS Workshop

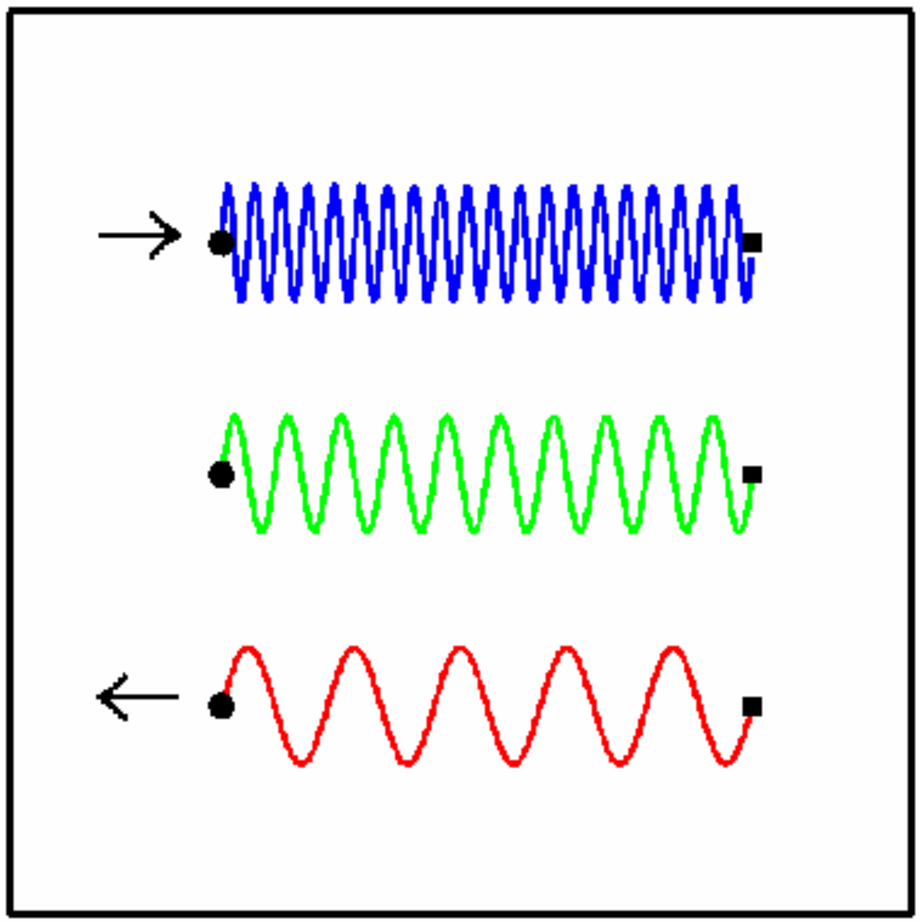
The Mystery of Dark Matter

Centripetal Force

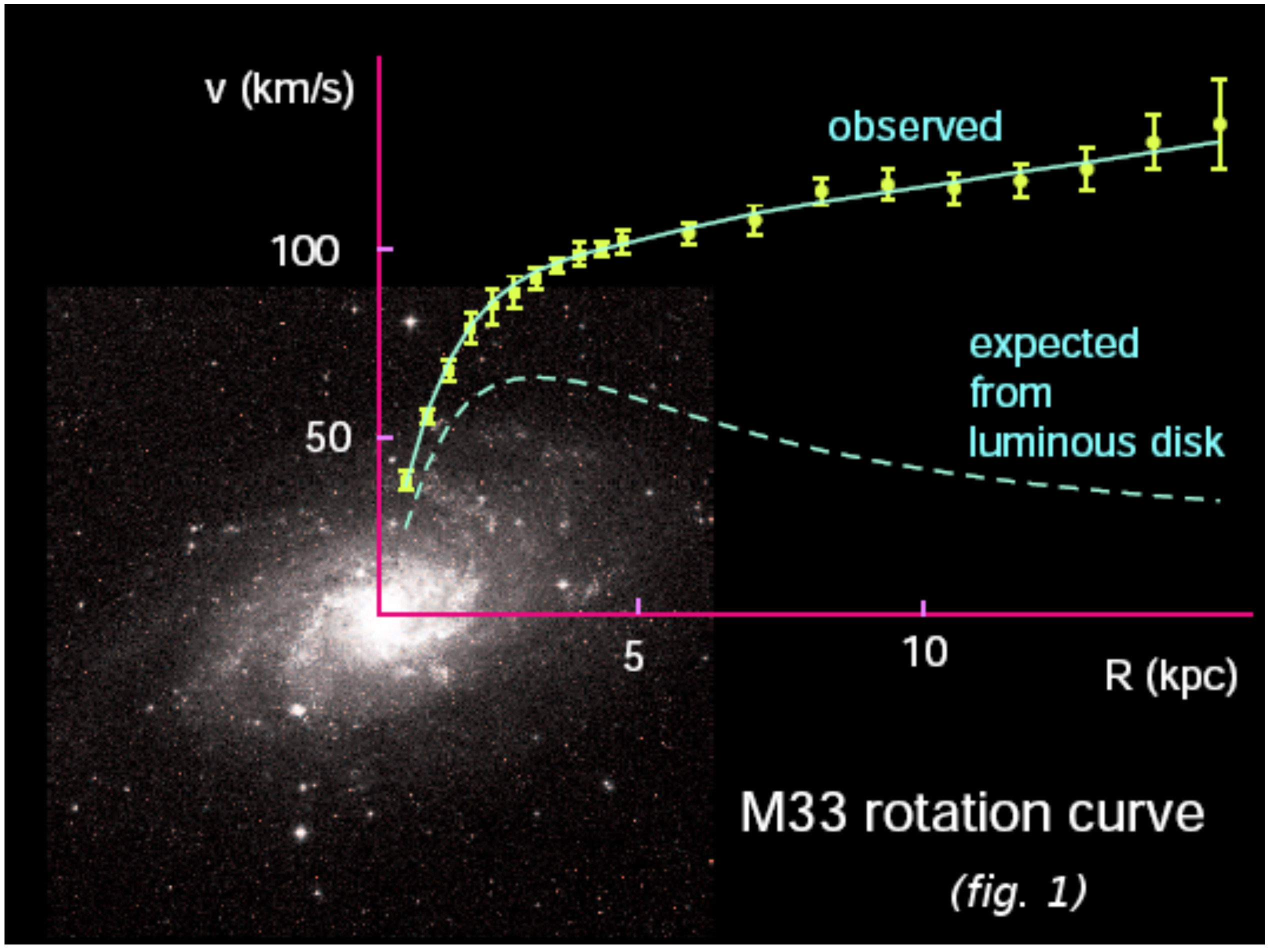
Stars Orbiting a Galaxy

Gravity provides the centripetal force

Measuring Velocity with Doppler Shift of Starlight

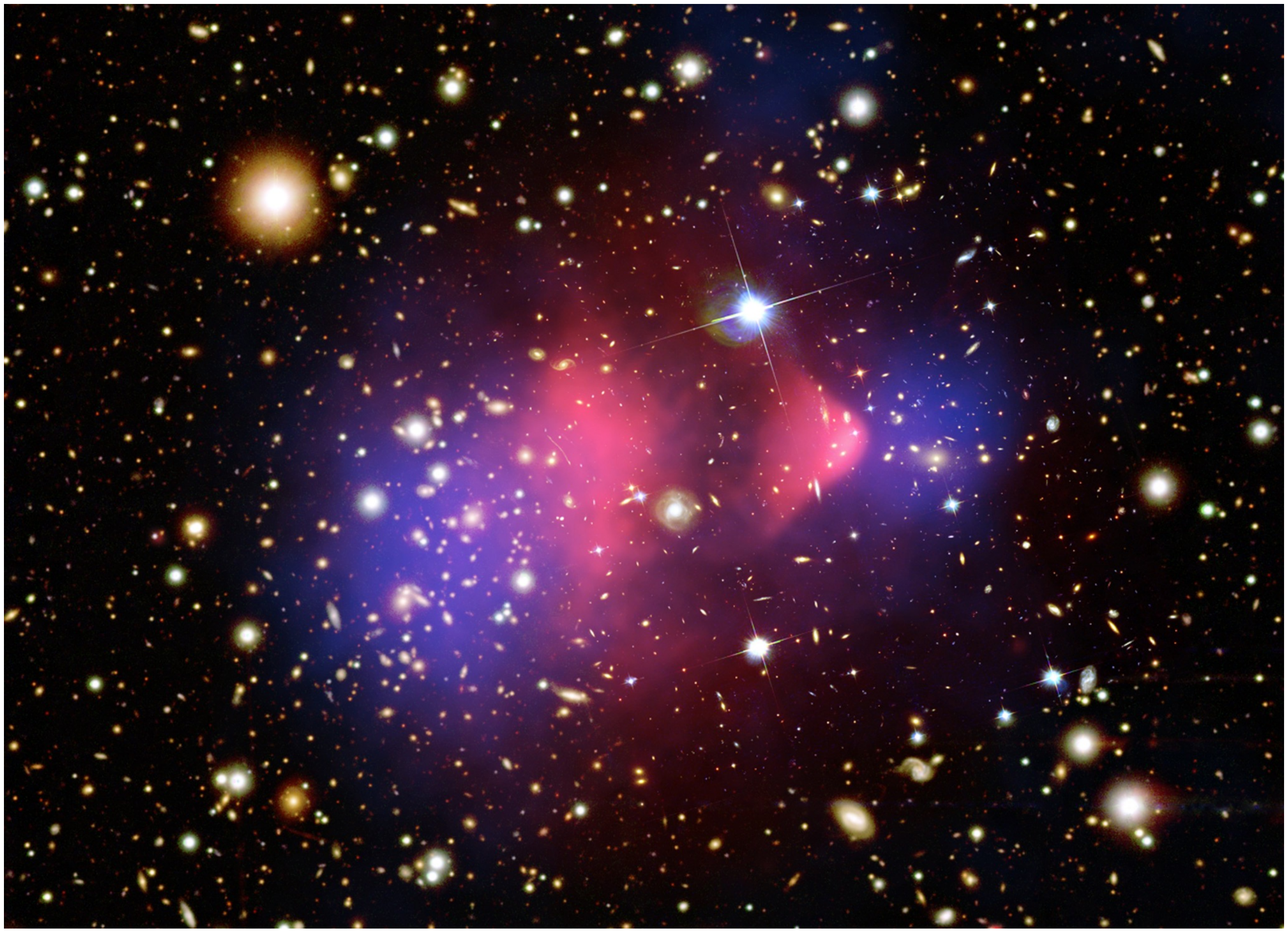


Galactic Rotation Curve



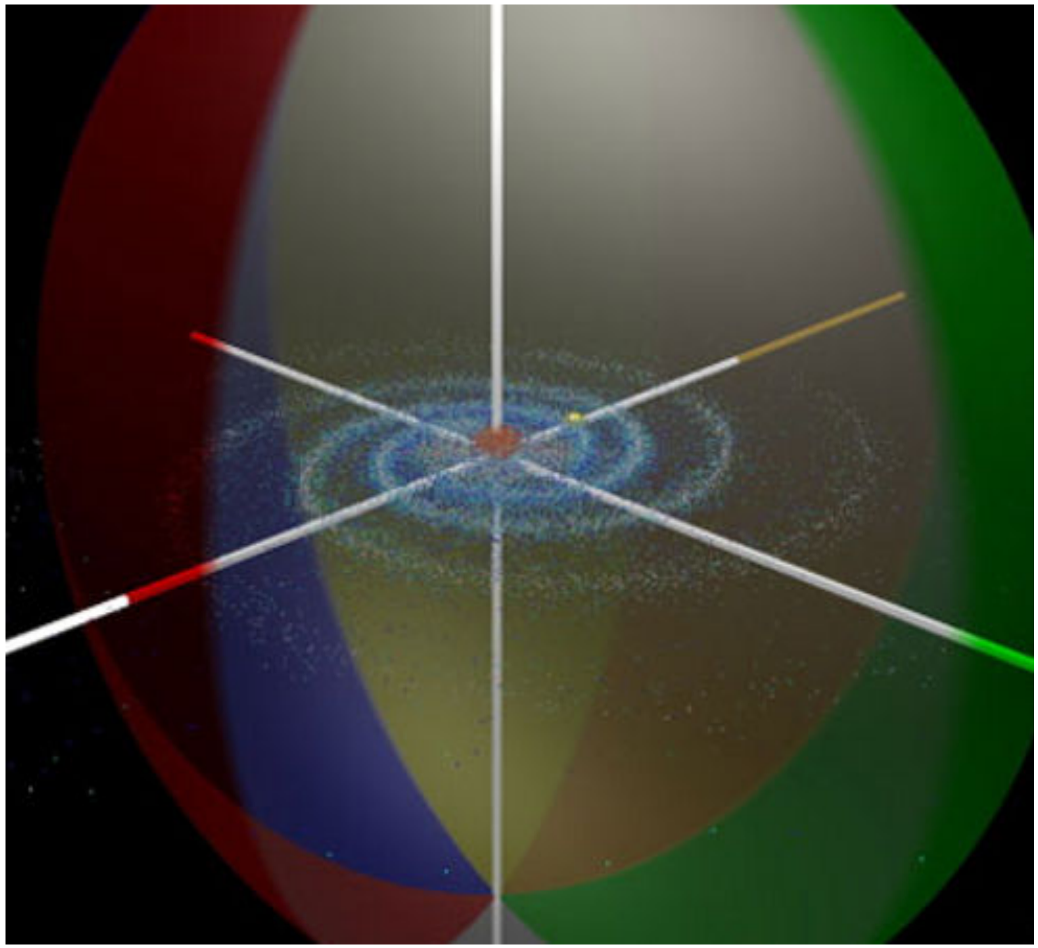
Stars' orbit speed too high ⇔ too much centripetal force

Collision of Galaxy Clusters



Luminous Matter (emitting X-rays) separated from total Mass ⇔ confirms Dark Matter hypothesis

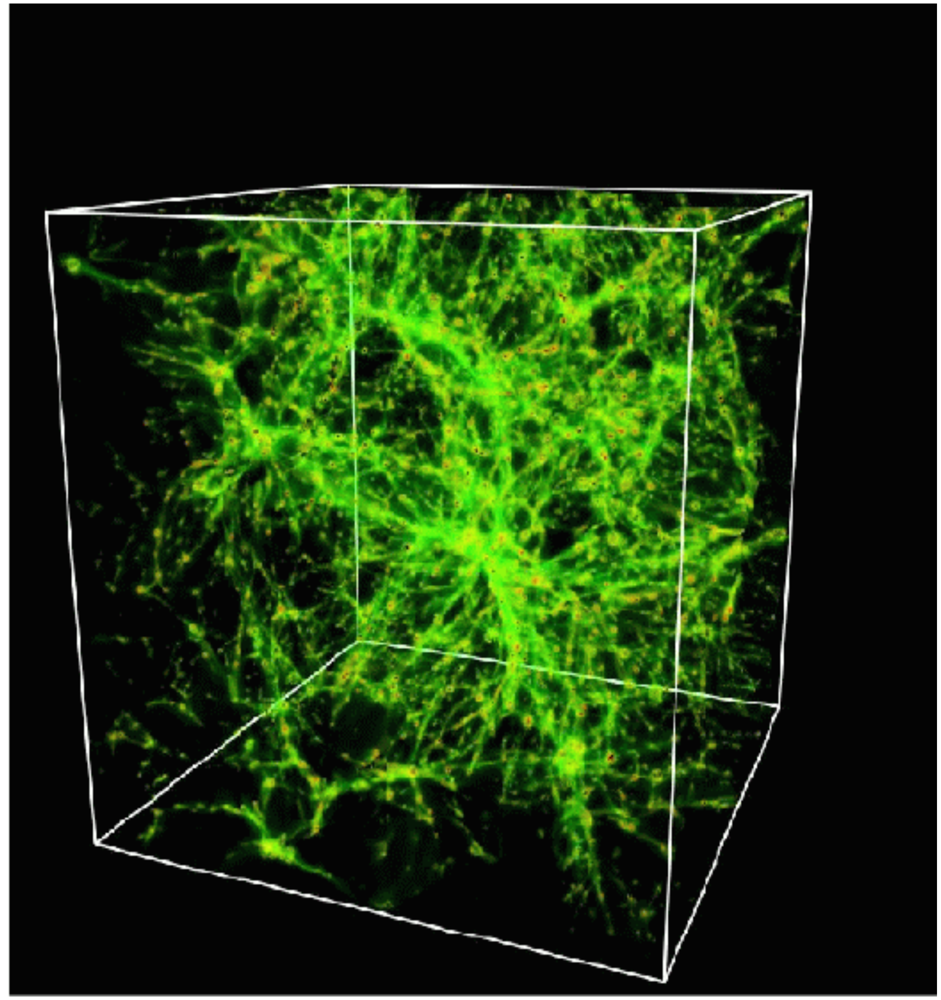
Halo of Invisible Dark Matter around Galaxies



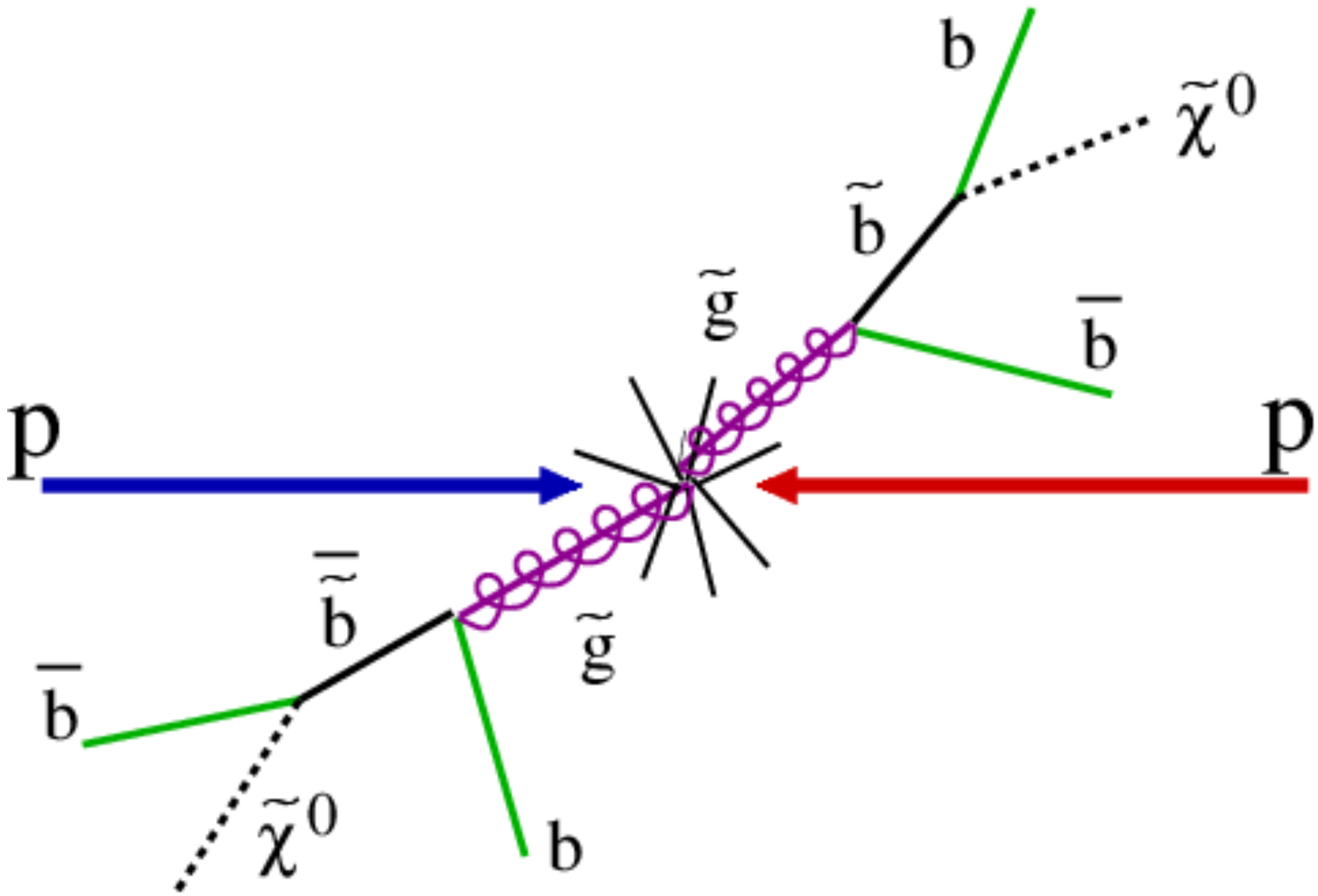
Four times as much dark matter as visible matter

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 SUSY Dark Matter Particles at LHC



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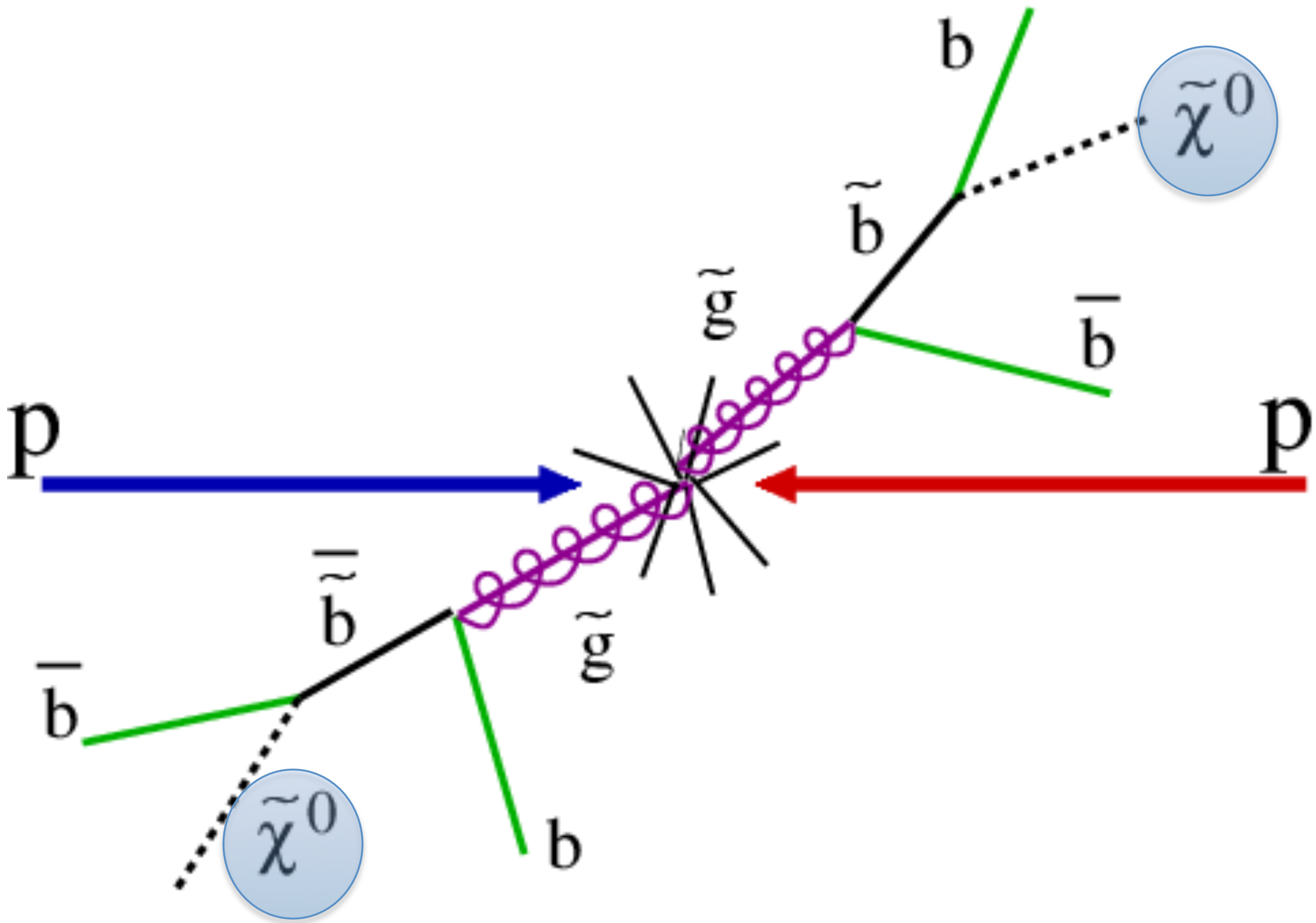
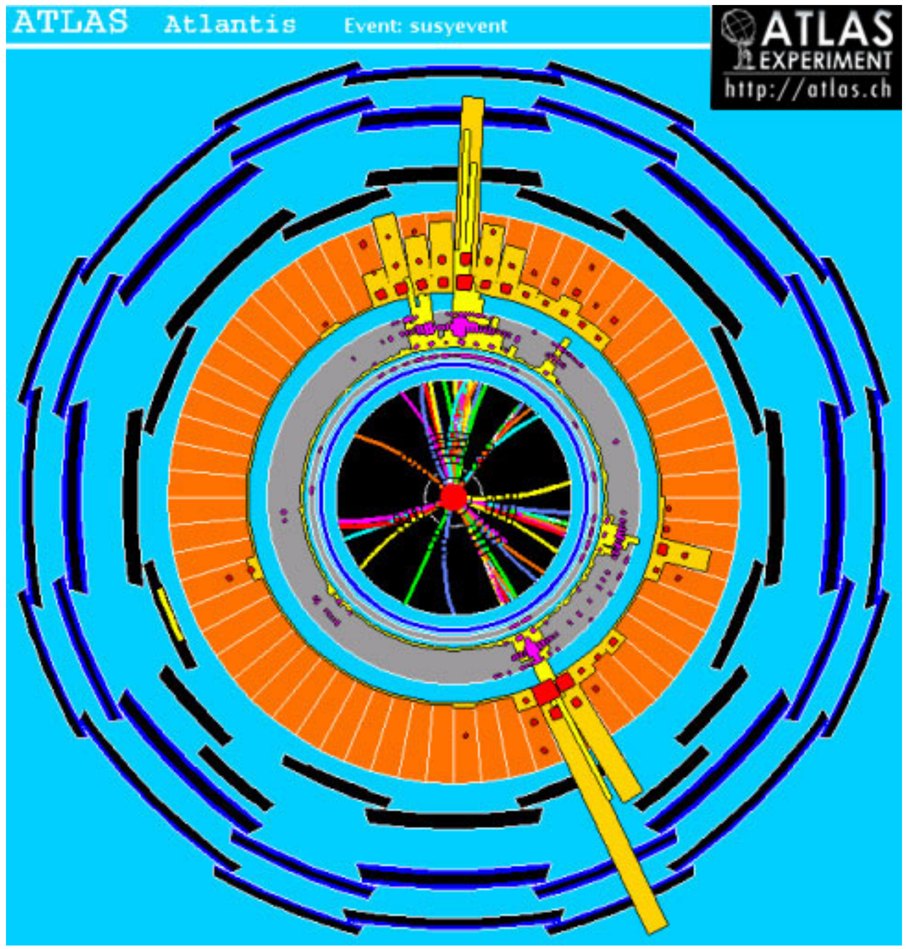


Simulated SUSY Dark Matter Particle Production at LHC



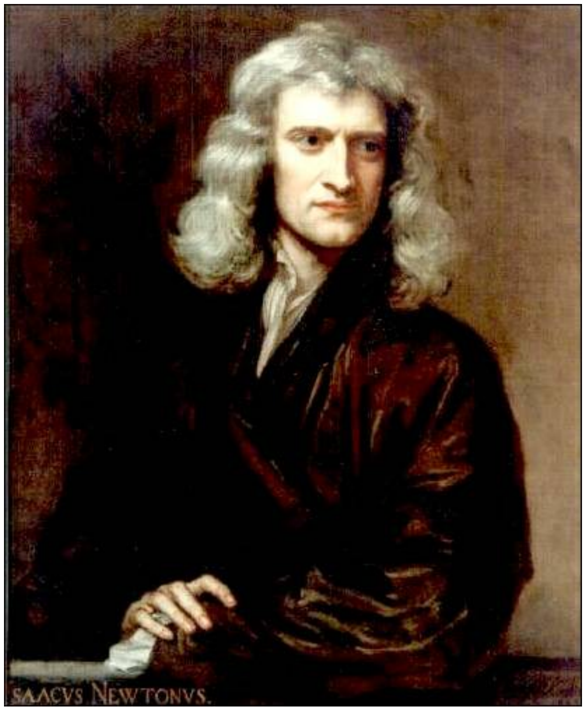
Dark Matter Particles

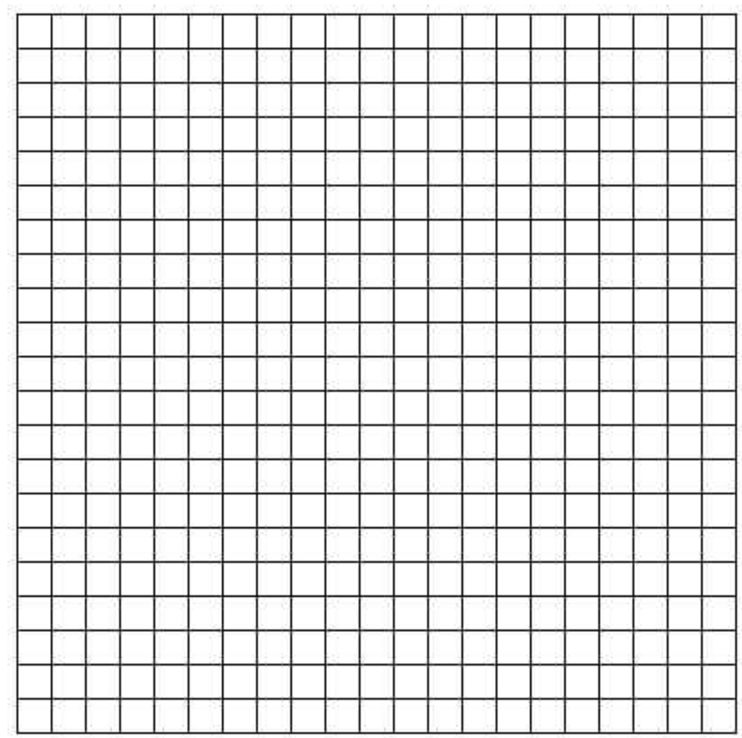
- Bridge between cosmology, astrophysics and particle physics
- "Supersymmetry" theory predicts dark matter particles
- Supersymmetry ⇔ quantum properties of space ⇔ dawn of a "new quantum mechanics"

Black Holes at the LHC

The Possibility and the Myth

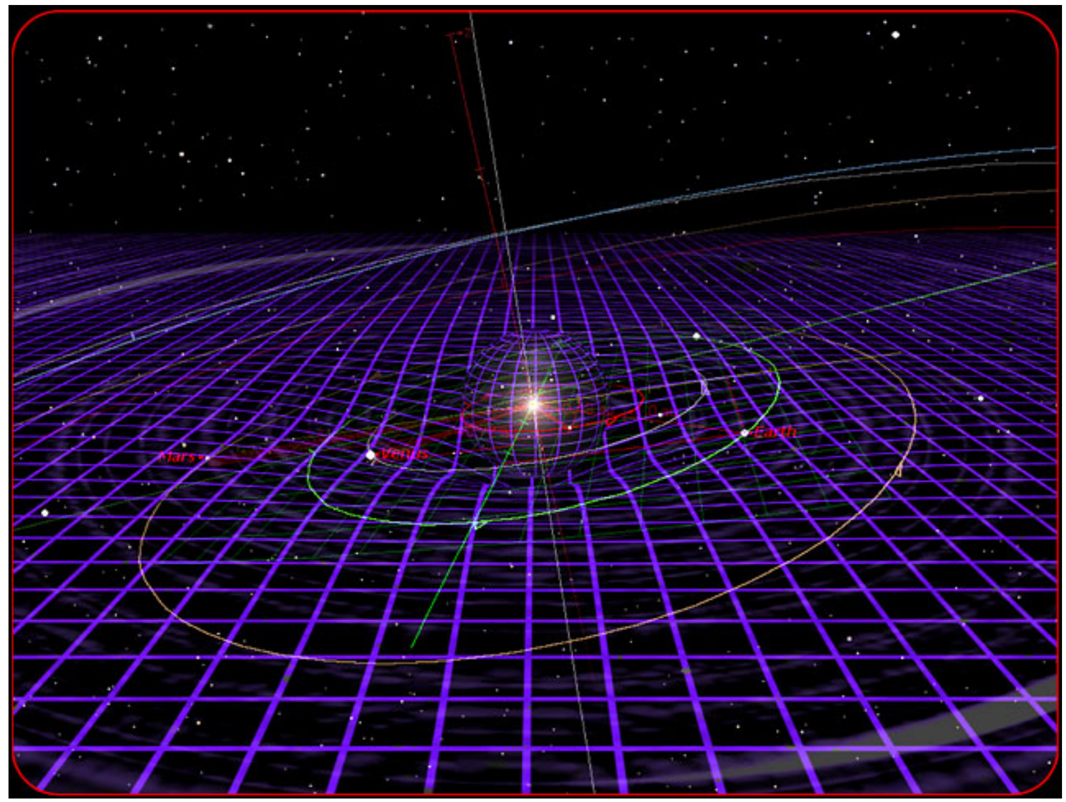
Isaac Newton





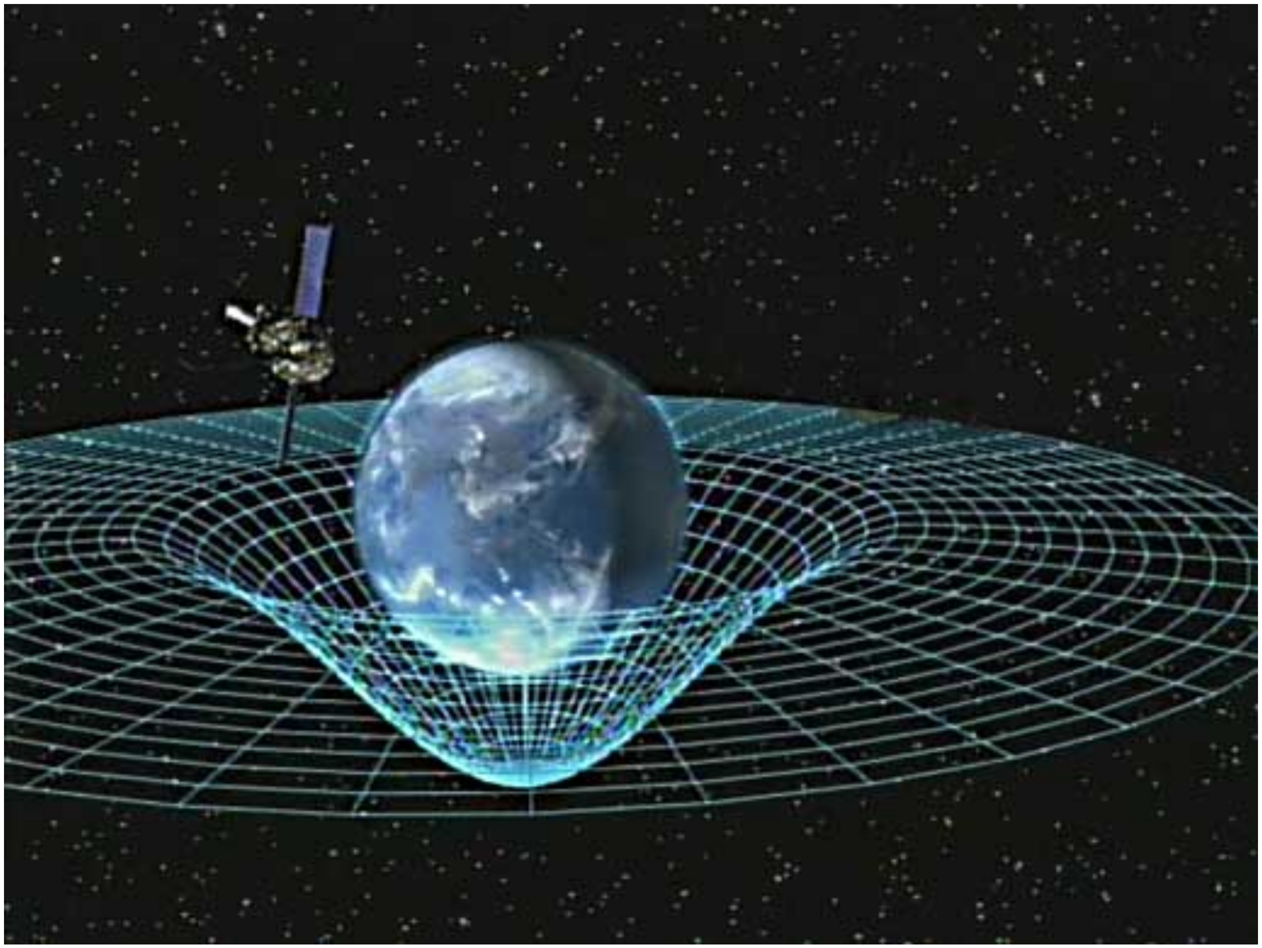
1687: Space and time are the static stage
on which physical processes act

Albert Einsten

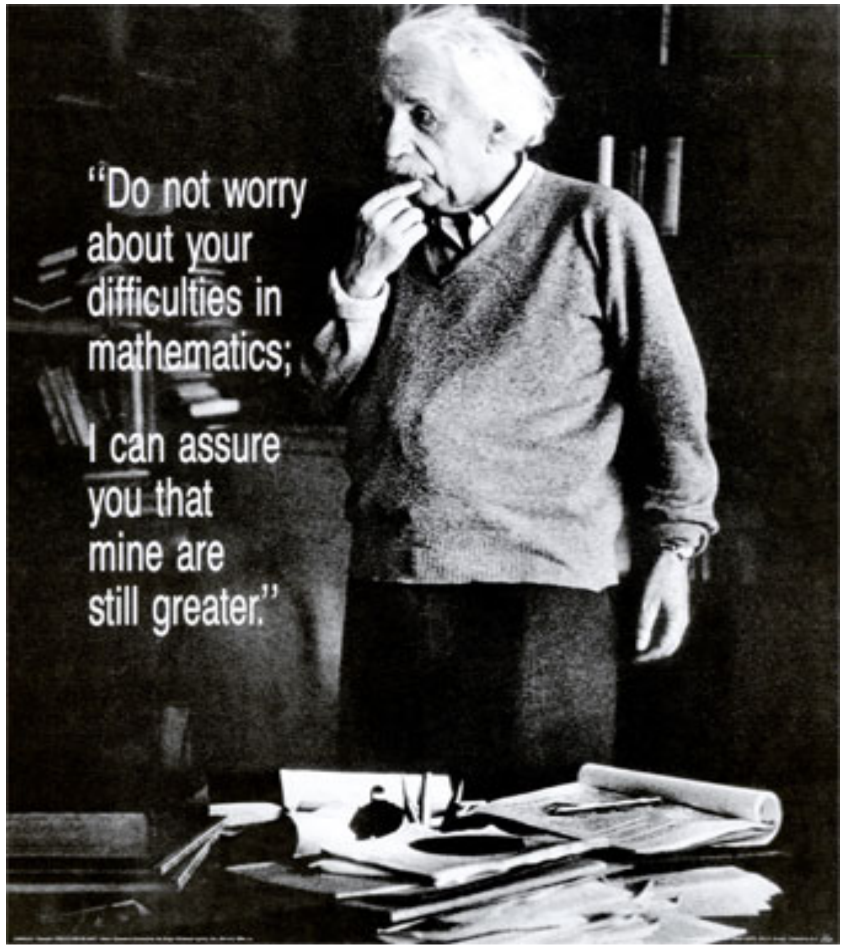


1915: Spacetime is an active player:
curves, expands, shrinks, …

Matter and Energy Curves Space



Einstein's Attempt to Unify Electromagnetism and Gravity



The problem with gravity

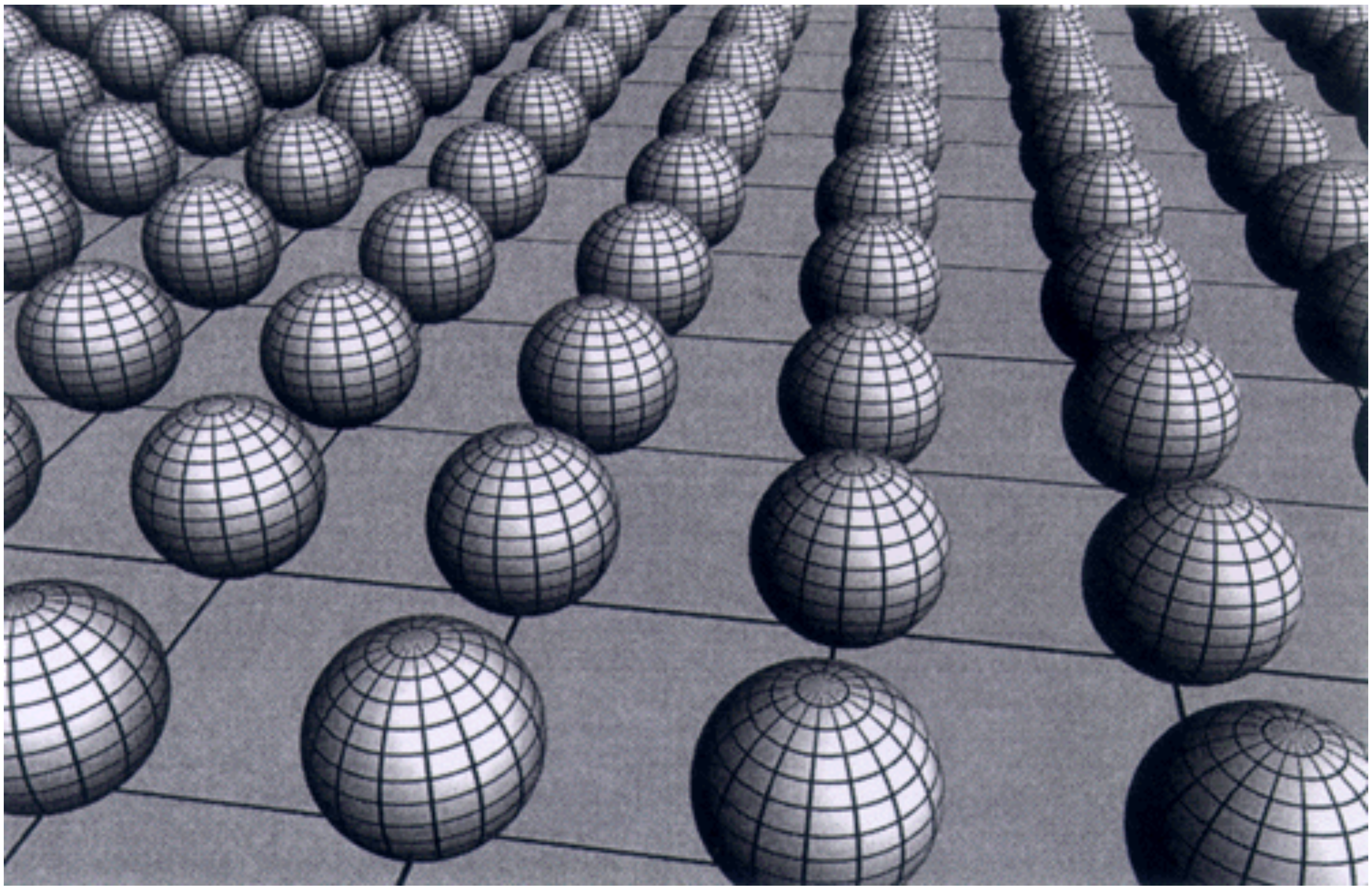
Gravity is a *very* weak force

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

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

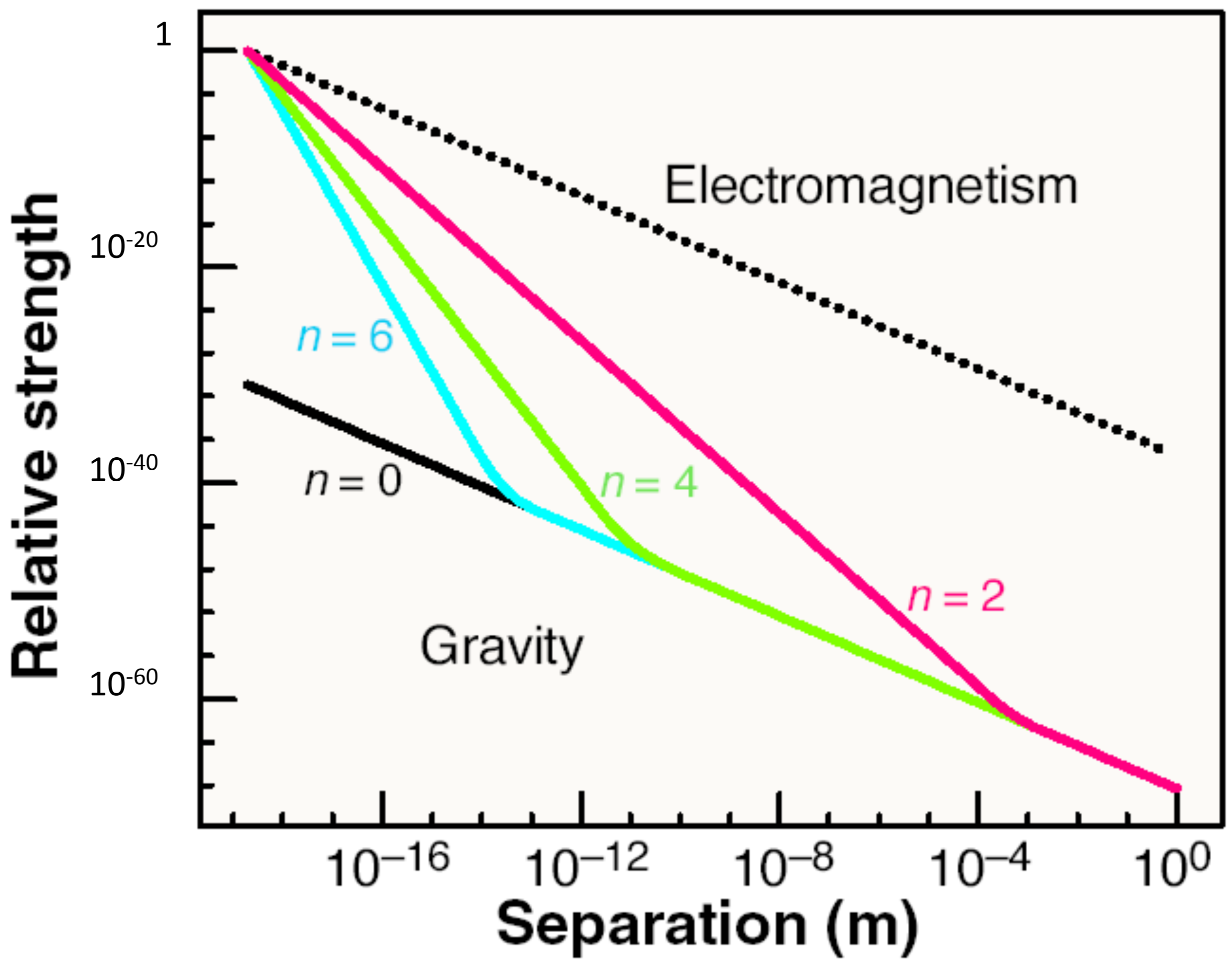


Newton's Law

- In this case, gravity may be strong but appear weak only because its strength is diluted by extra dimensions.

- $F_{gravity} \sim 1/r^{2+n}$

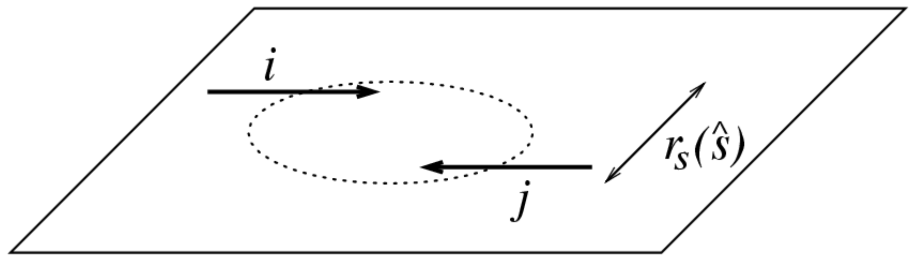
  for small lengths *r*, where *n* is the number of extra dimensions



Feng, *Science* (2003)

Microscopic Black Holes at LHC

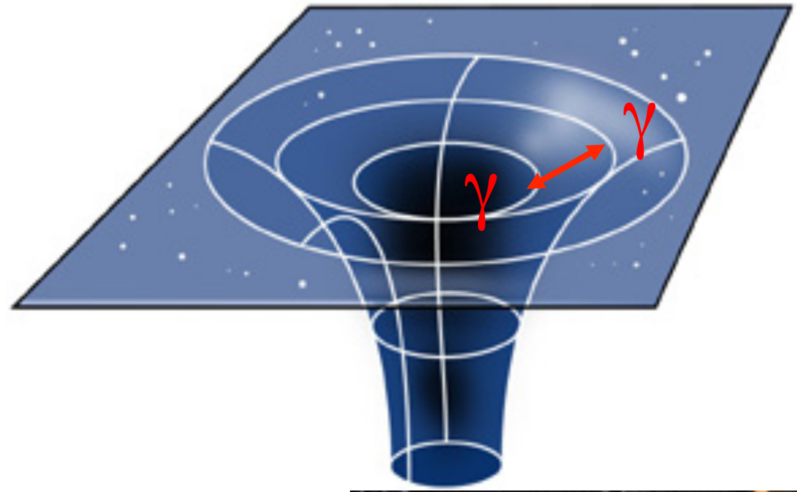
- If two particles pass close enough with enough energy, they will form a microscopic black hole

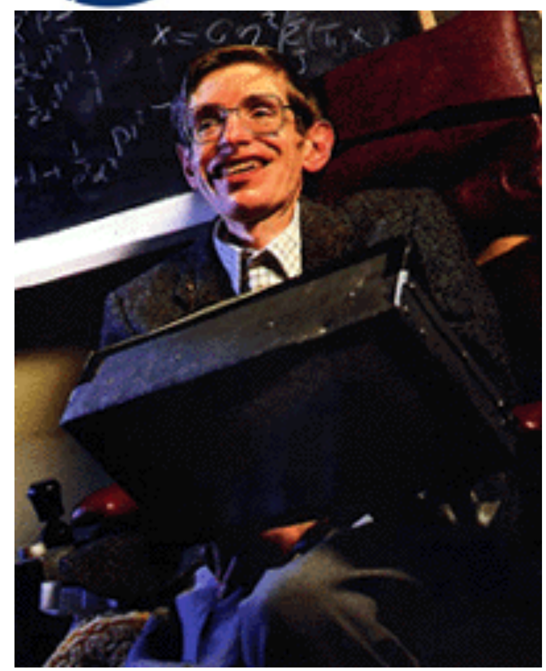


- For 3 spatial dimensions, gravity is too weak for this to happen. But with extra dimensions, gravity becomes stronger, micro black holes can be created in particle collisions!

Microscopic Black Holes

- In Einstein's theory, light and other particles do not escape; black holes are black.

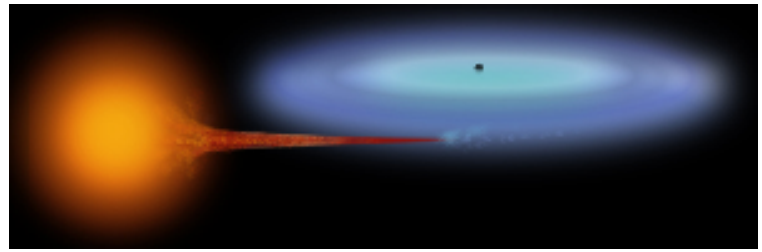




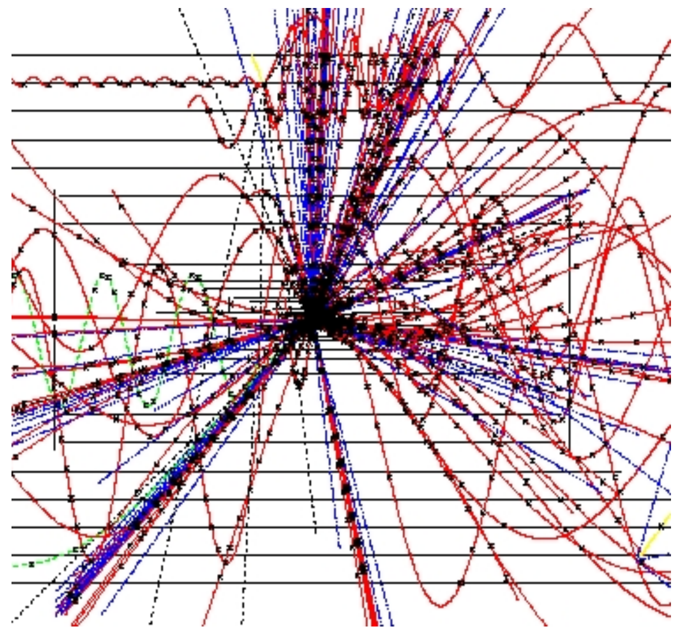
- But quantum mechanically, black holes radiate according to Stephen Hawking; black holes emit light!

Black Hole Evaporation

- "Normal" black holes:
  Mass: M_{BH} ~ M_{sun}
  Size: kilometer
  Temperature: 0.01 K
  Lifetime: ~ forever



- Micro black holes:
  Mass: M_{BH} ~ 1000 M_{proton}
  Size: 10^{-18} m
  Temperature: 10^{16} K
  Lifetime: 10^{-27} seconds



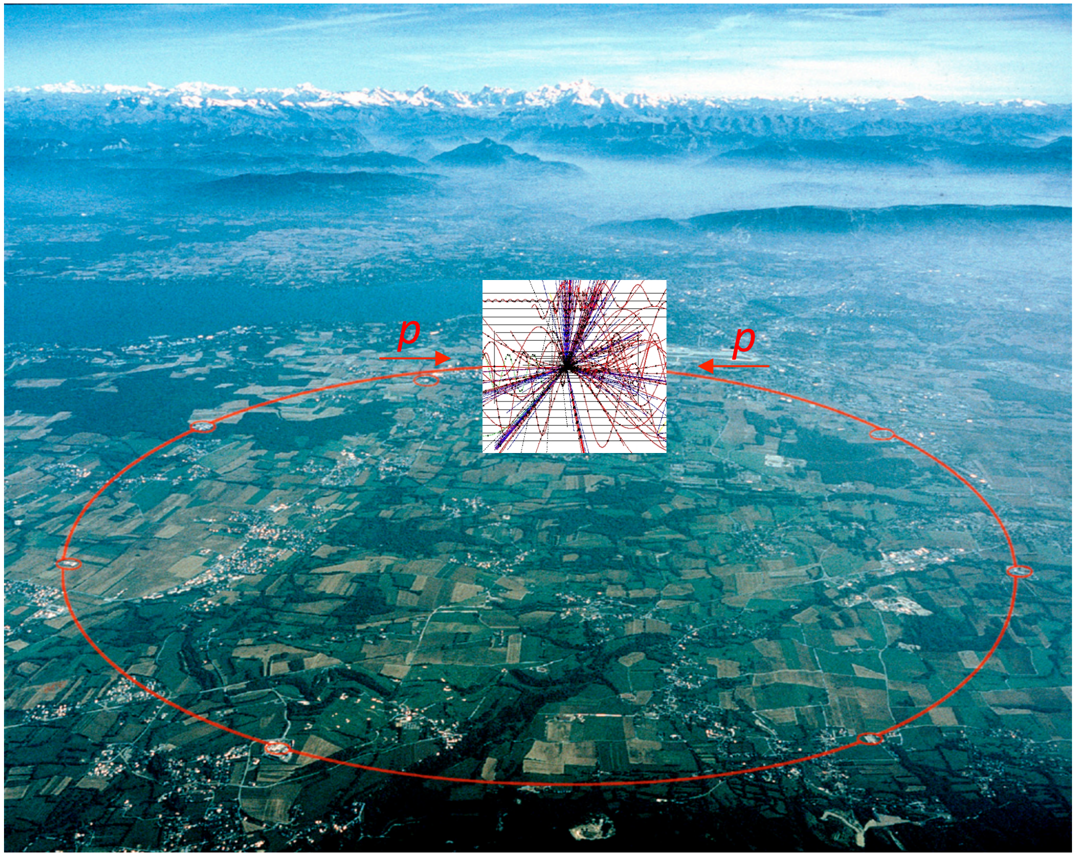
Microscopic black holes explode!

Black Holes at LHC

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

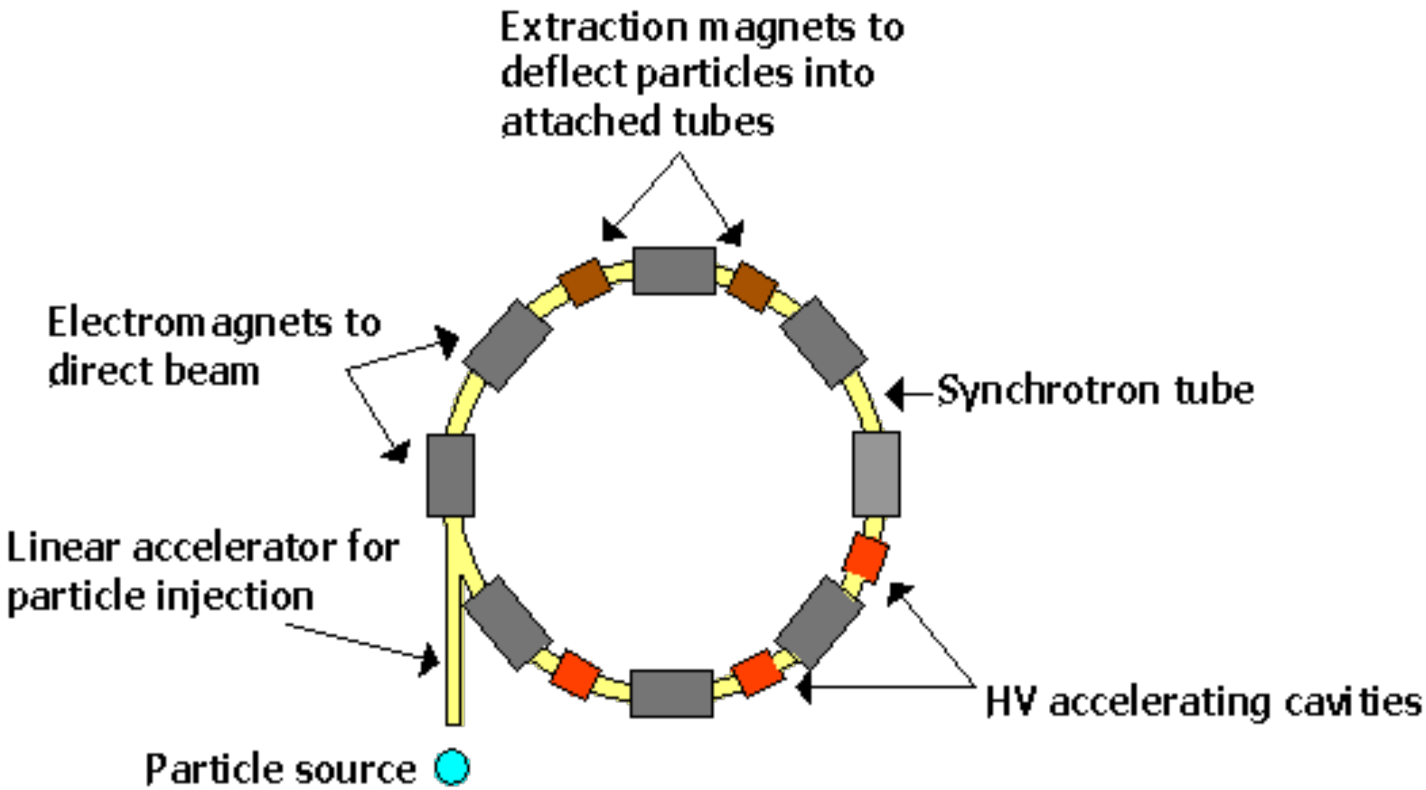
Closer to Einstein's last dream

Closer to a quantum theory
of Gravity



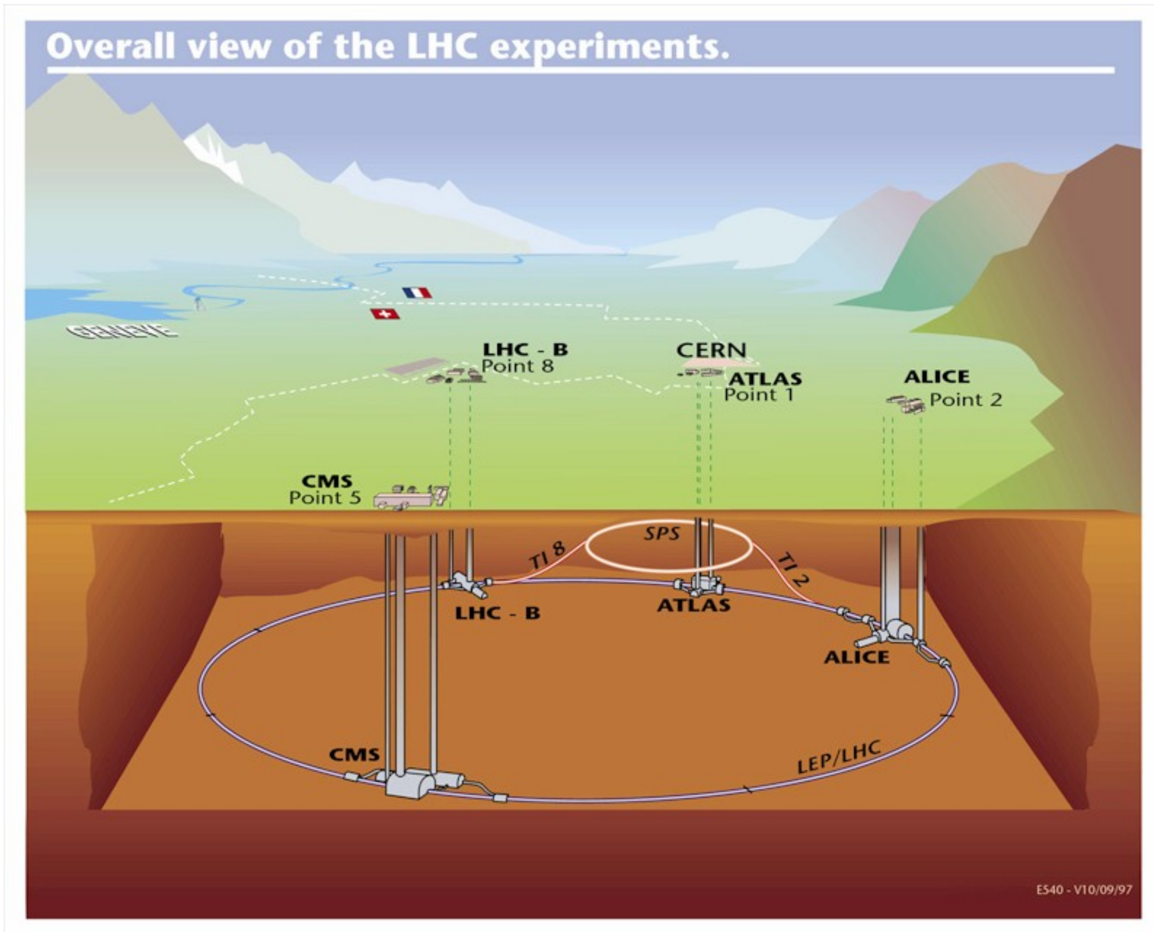
How does LHC work?

How does a particle accelerator work?



Synchrotron Accelerator

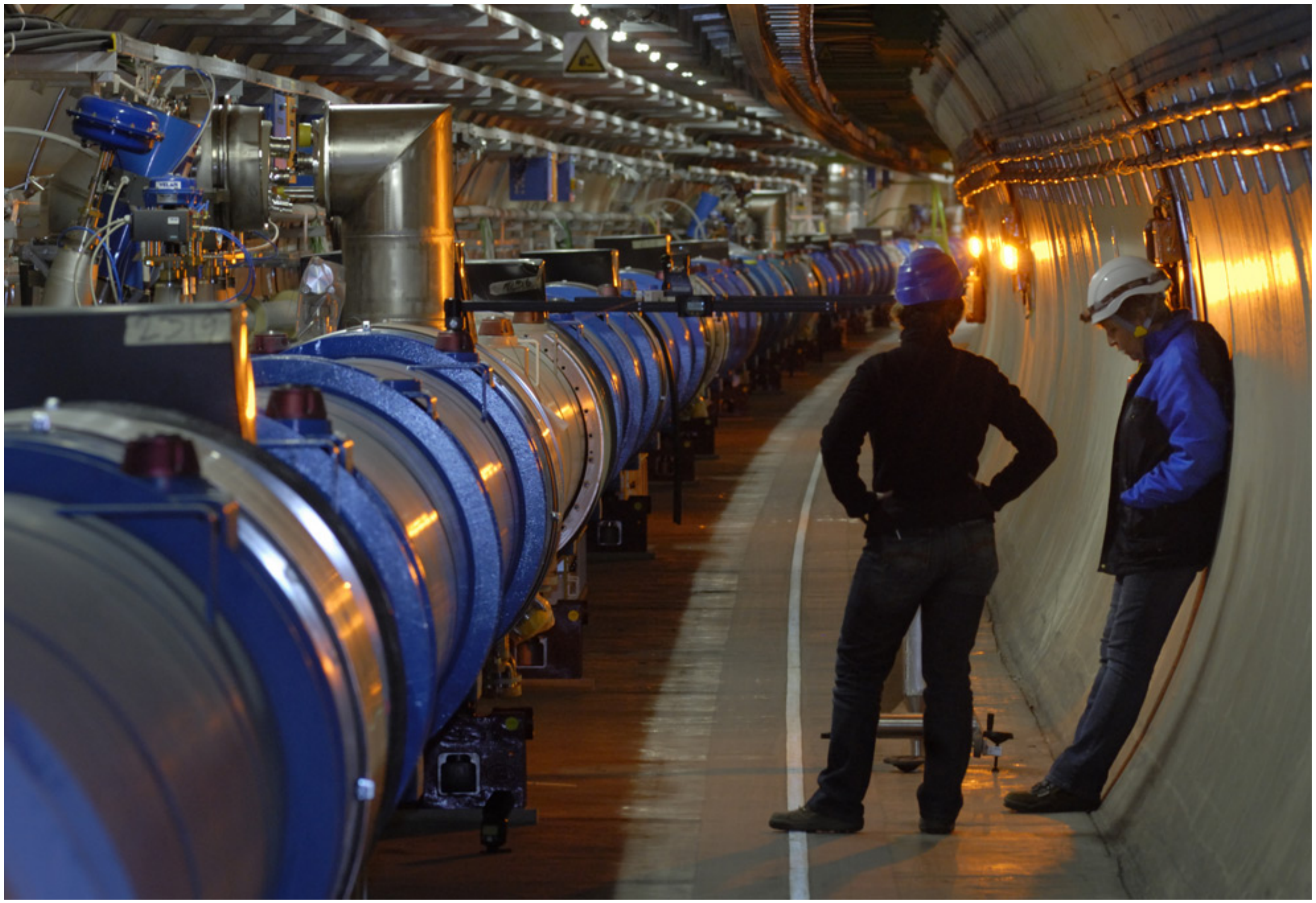
LHC below Geneva, Switzerland



LHC below Geneva, Switzerland

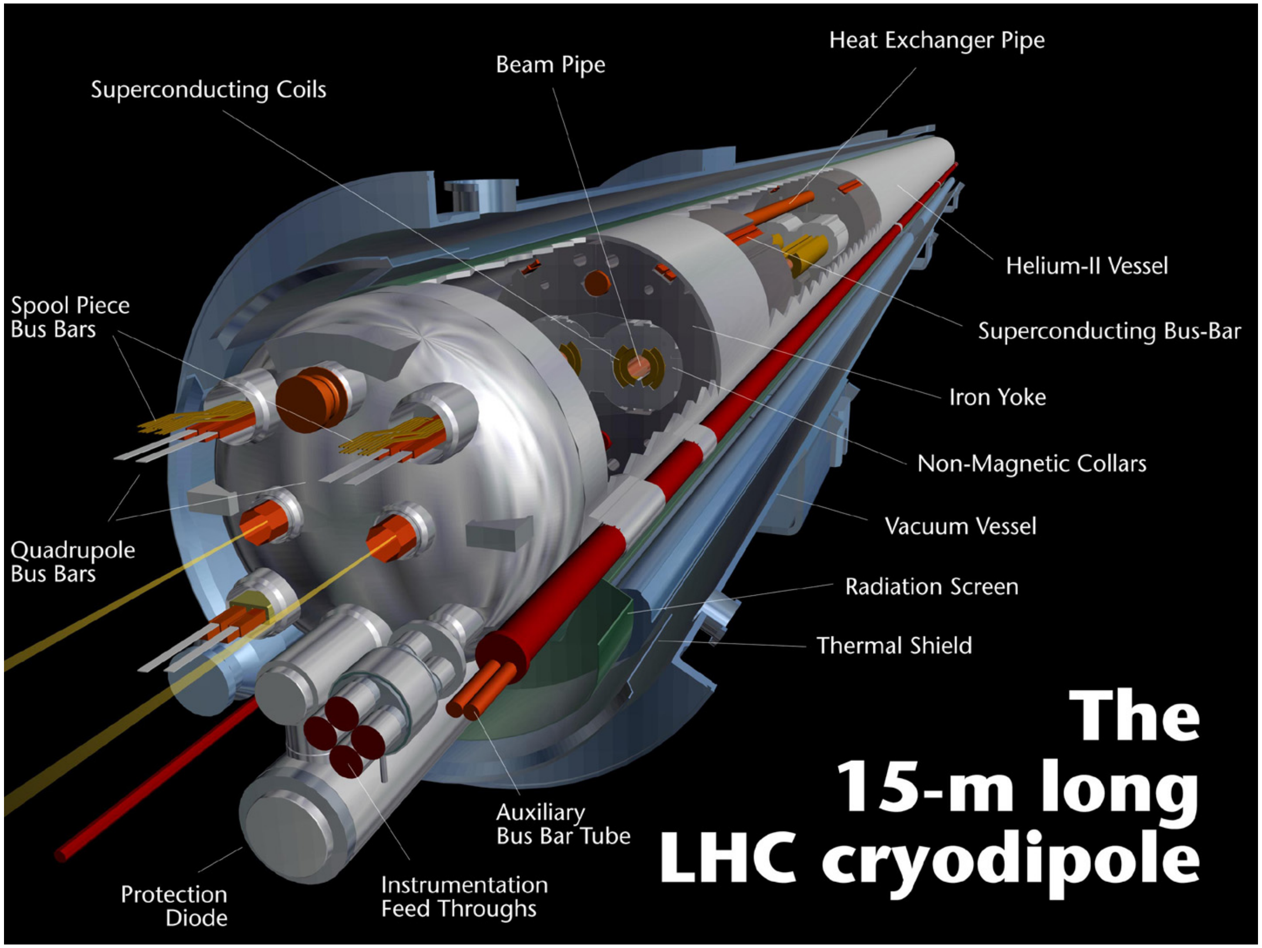
Accelerates and collides proton beams, each 4 micrometers wide

LHC Accelerator in Tunnel



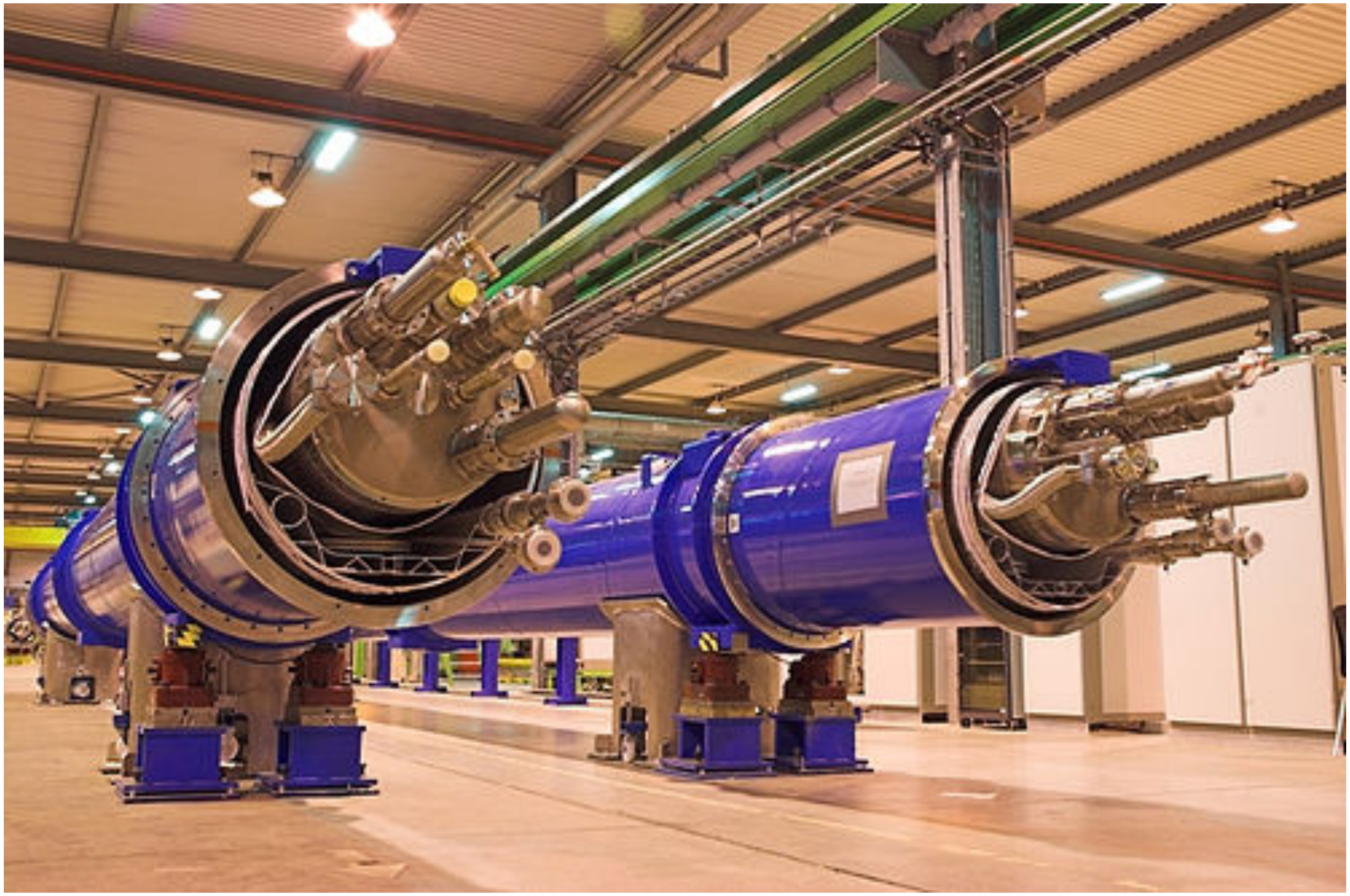
Vacuum in the beampipe is better than vacuum in outer space

LHC Superconducting Magnet



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

LHC Superconducting Magnet



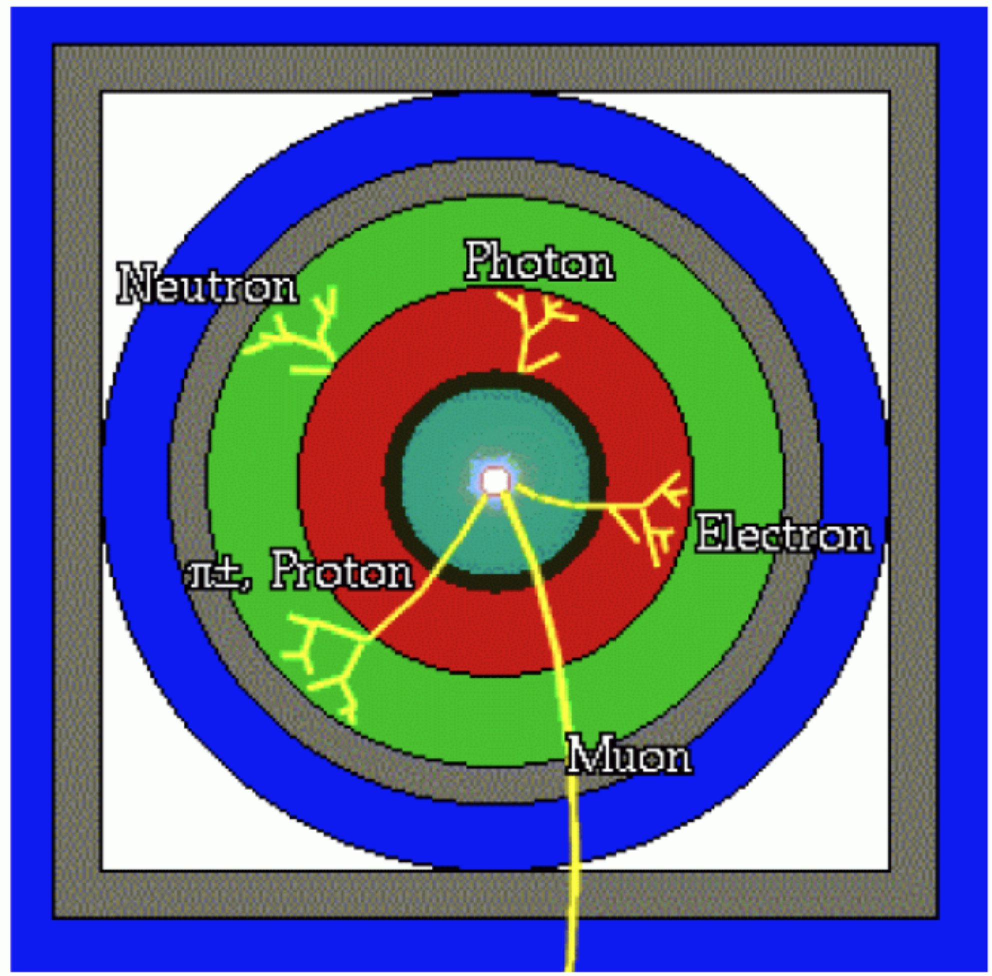
Similar magnet design used in MRI machines

LHC Superconducting Magnet

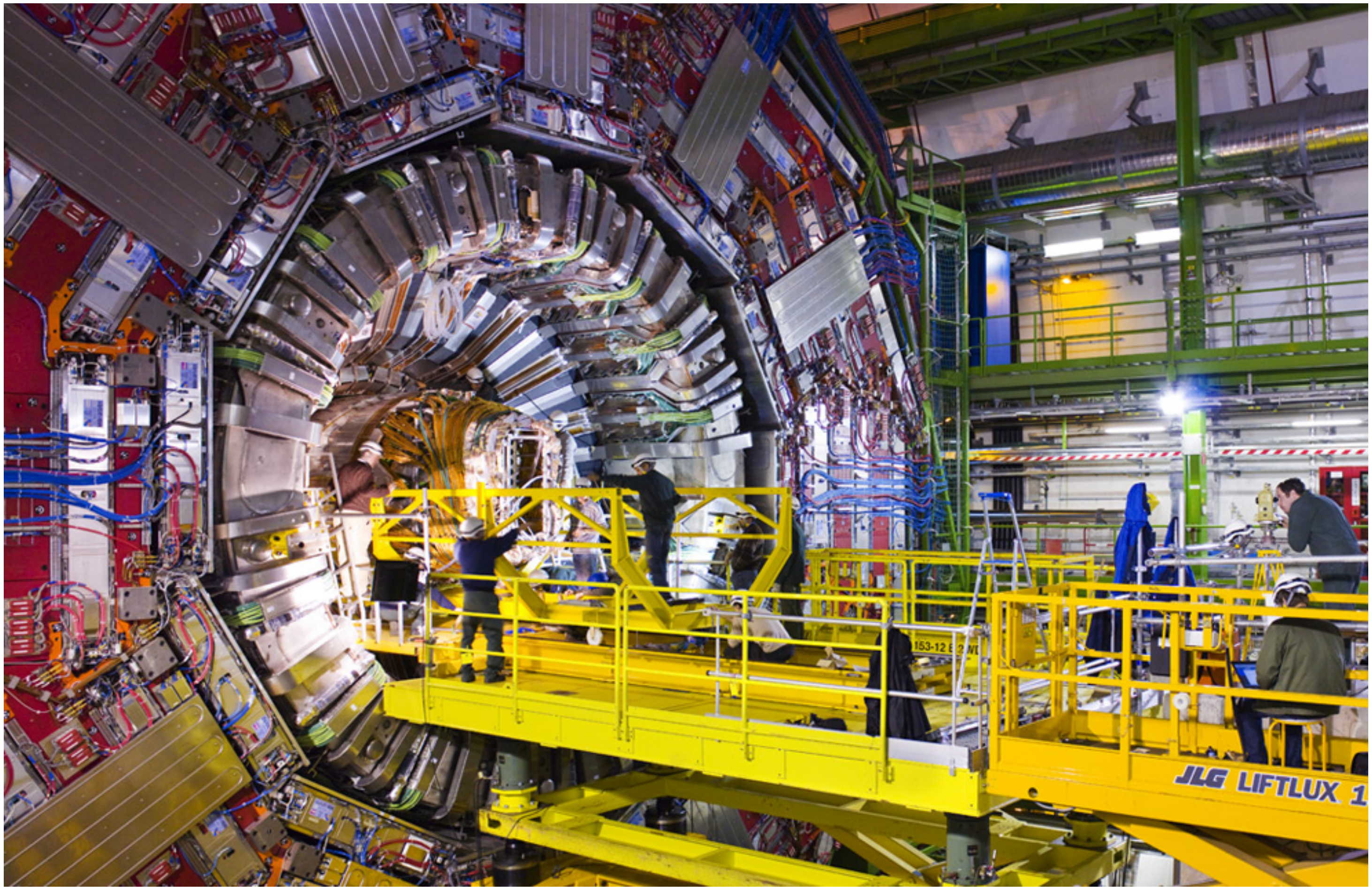
1200 magnets lowered 100 meters down into tunnel, distributed over 27 kilometers

Particle Detector Design

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

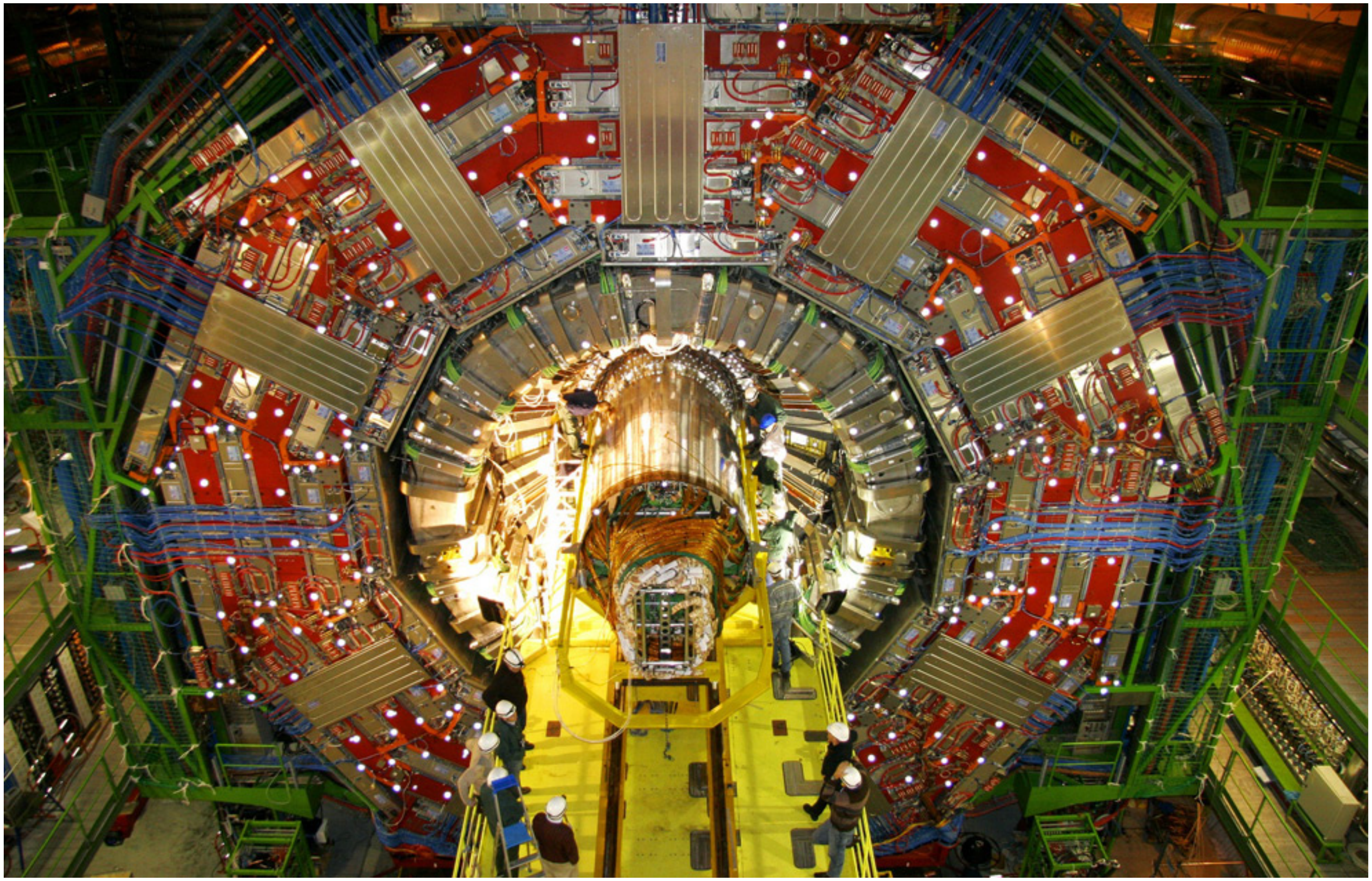


LHC Particle Detector – CMS Experiment



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 China, Europe, and USA to build higher-energy colliders
  - Need a bigger tunnel !
  - Need more powerful magnets !!

Life after LHC?

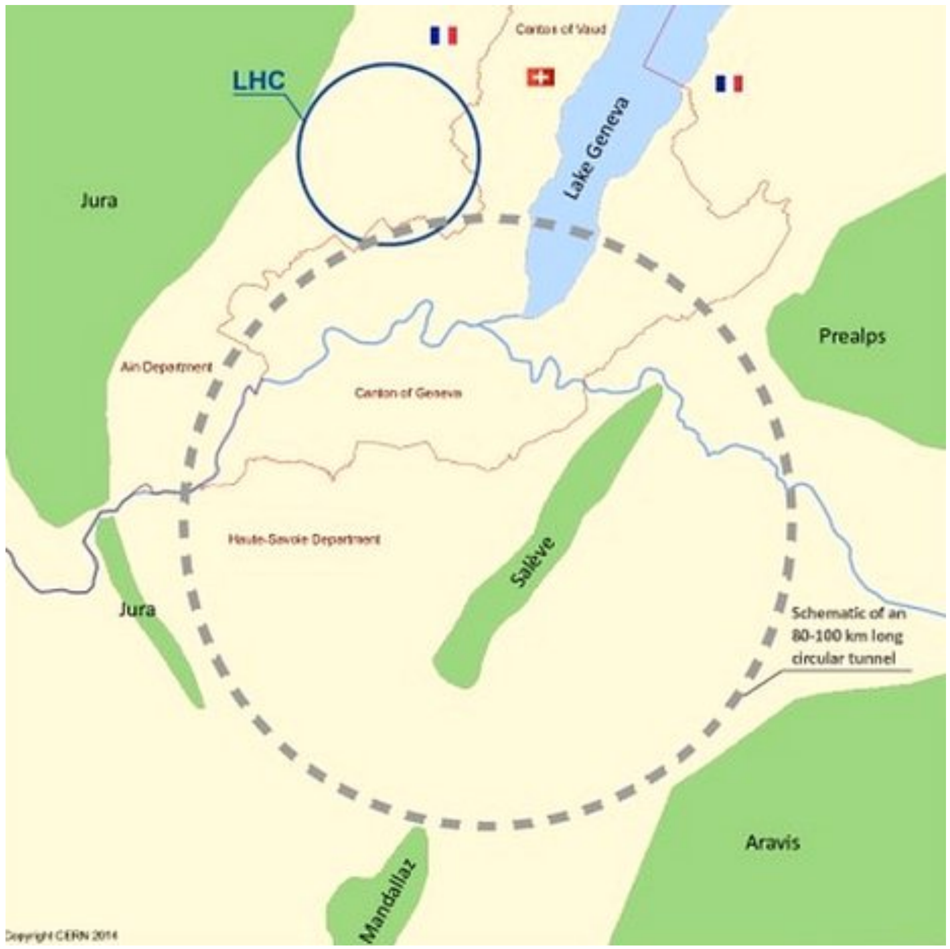
Site

- Preliminary selected: Qinhuangdao (秦皇岛）
- Strong support by the local government

A possible big tunnel east of Beijing

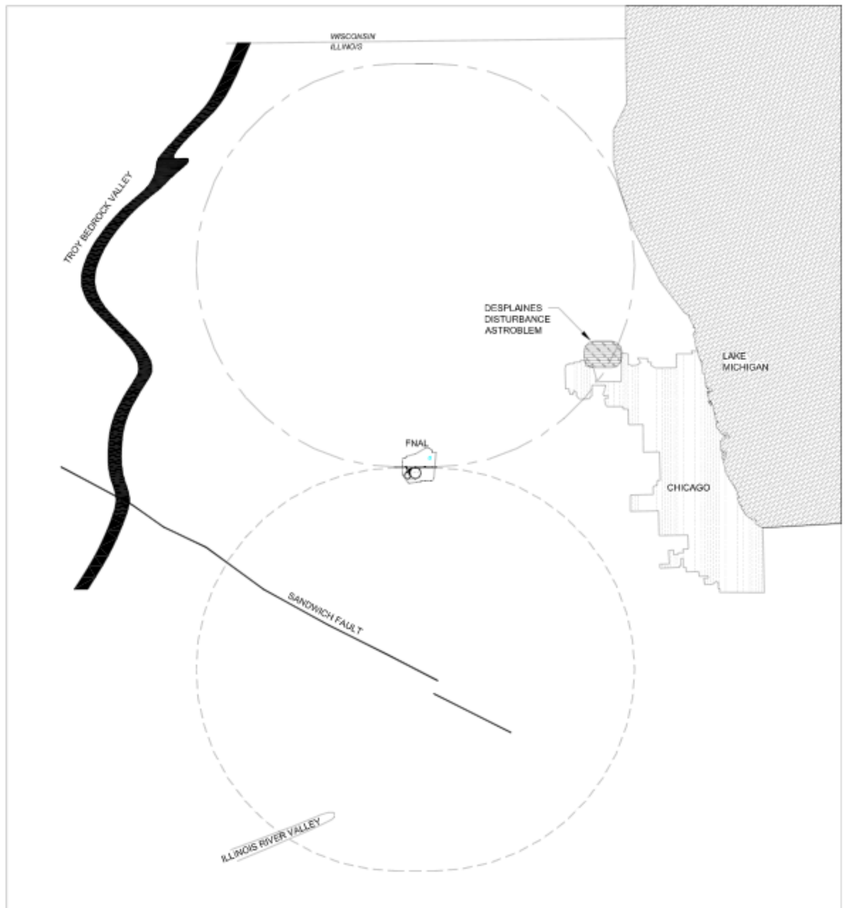
(from presentation by Prof. Yifang Wang, Director of IHEP Beijing, on 13 February 2014, Geneva)

Life after LHC?



A possible big tunnel close to CERN, Geneva, Switzerland

Life after LHC?



A possible even bigger tunnel close to Chicago, USA

Conclusion

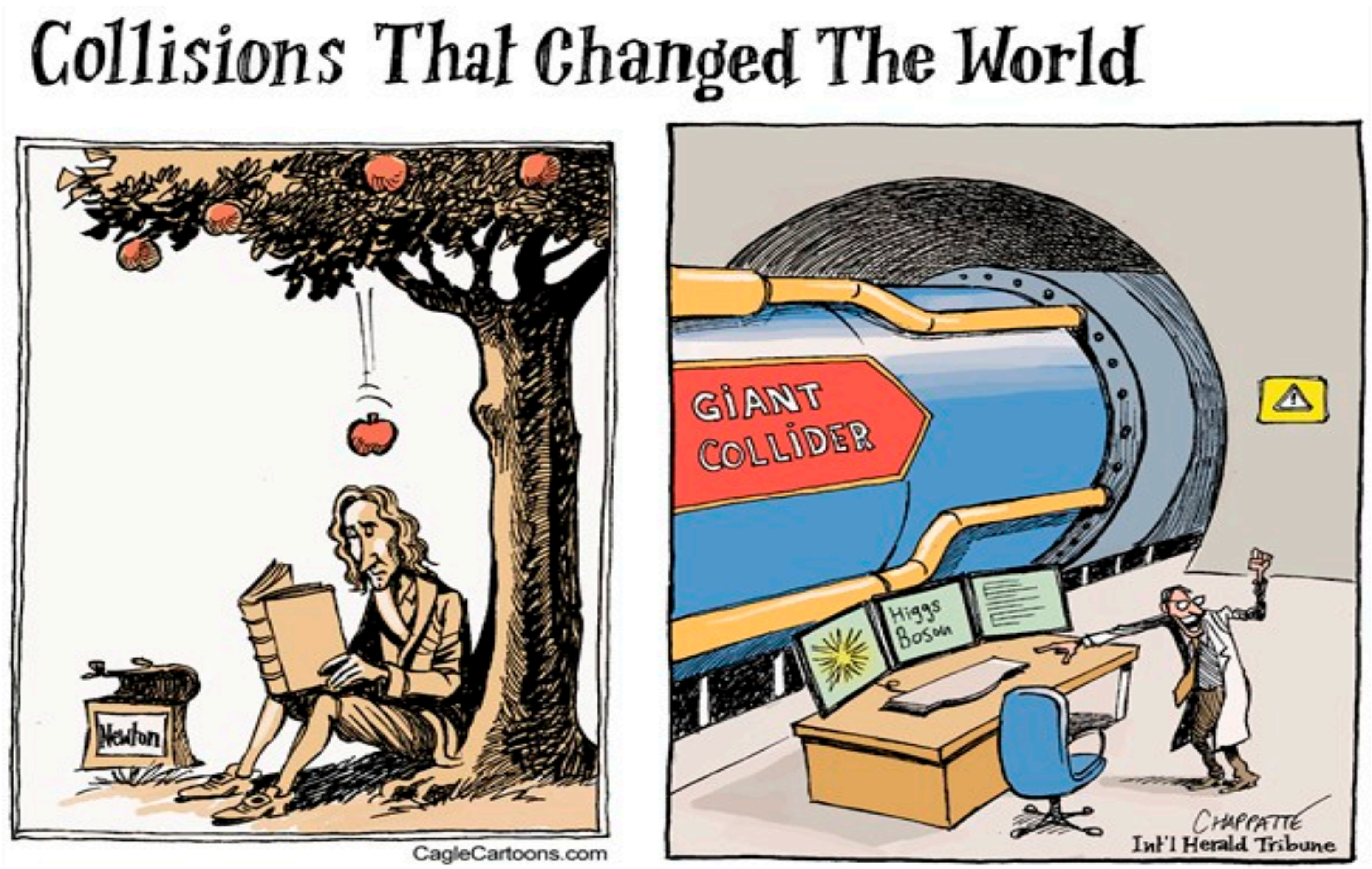
- LHC is operating successfully – a great achievement of science and engineering and of international cooperation

- 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
Newton
GIANT COLLIDER
Higgs Boson
CagleCartoons.com
CHAPPATTE
Int'l Herald Tribune

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 get 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.
Higgs boson
LIGHT
HEAVY
$9.75
PLUS SHIPPING
HIGGS BOSON
The PARTICLE ZOO