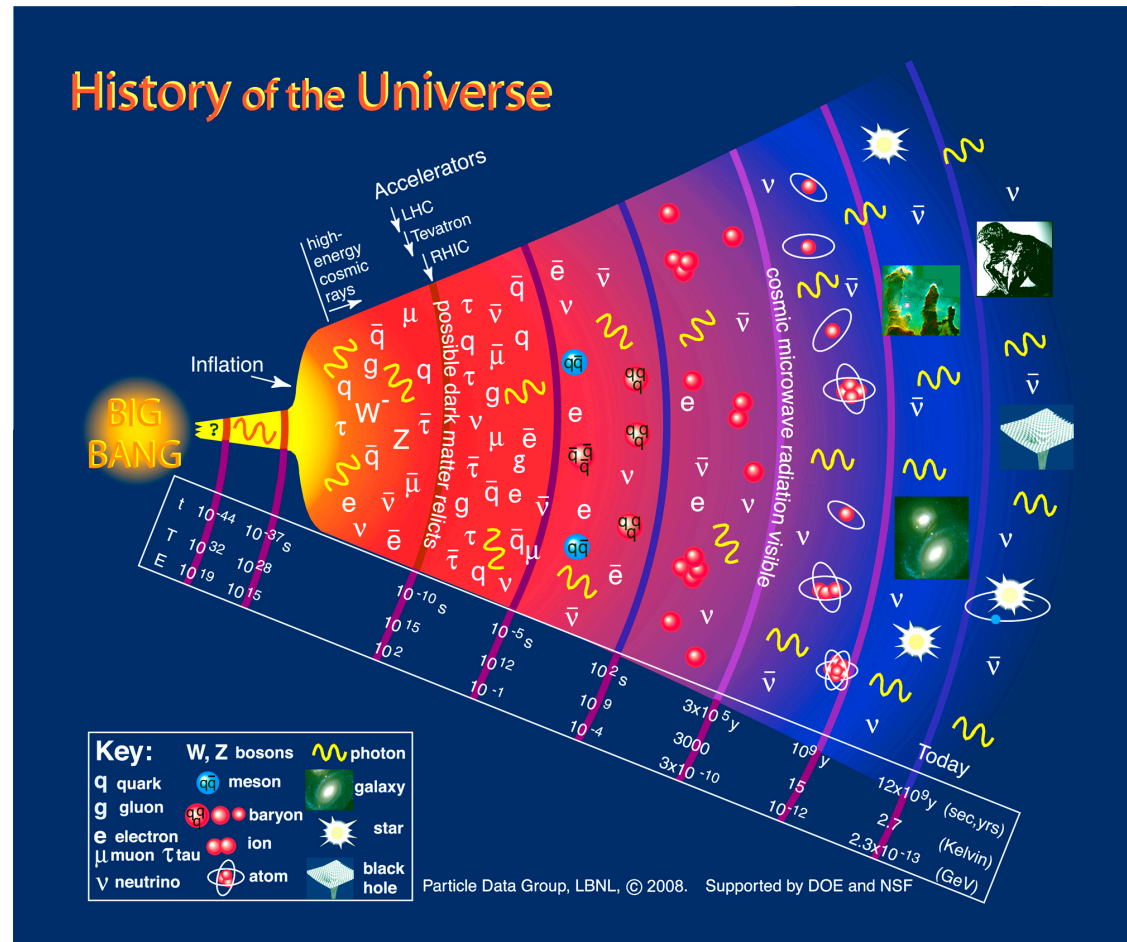


# Particle Physics and Cosmology in the Age of the Large Hadron Collider (LHC)

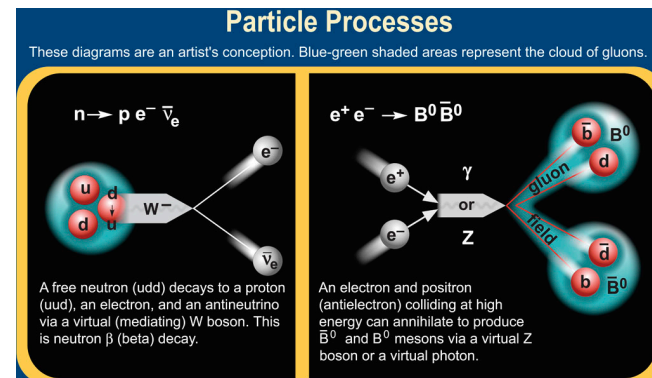


"The Universe is not made of Atoms it is made of Stories"  
 Muriel Rukeyser

# Solved and Unsolved

The Standard Model answers many of the questions about the structure and stability of matter, but???

- Are quarks and leptons actually fundamental, or are they made up of even more fundamental particles?
- Why can't the Standard Model predict a particle's mass?
- How does gravity fit into all of this?
- Why is there more matter than antimatter in the universe
- What is this "dark matter"?



# Standard Model

## Particle Physics Review

**"If I could remember the names of all these particles... I'd be a botanist!" Enrico Fermi**

- Fundamental particles
  - Quark
  - Electron
- Hadron-Two types, experience strong interaction
  - Baryon-made of three quark, *fermions*
    - Proton
    - Neutron
  - Meson-made of quark and antiquark, *bosons*
    - Pion
    - Kaon
- Lepton-Three flavors, spin  $\frac{1}{2}$  does, does not experience strong interaction
  - Electron
  - Muon
  - Tau
- Neutrino-Three flavors, lepton
- Fermion-Obey Pauli exclusion principle odd  $\frac{1}{2}$  integer spin
  - Lepton, quarks
  - Baryon
- Boson-Do not obey Pauli exclusion integer spin
  - Force carrier-Photon, W and Z particles, and Gluons
  - Meson

# Standard Model

## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

**FERMIONS** matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino*	(0-0.13) $\times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_\mu$ middle neutrino*	(0.009-0.13) $\times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ heaviest neutrino*	(0.04-0.14) $\times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

\*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$ .

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$ . The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

### Neutrinos

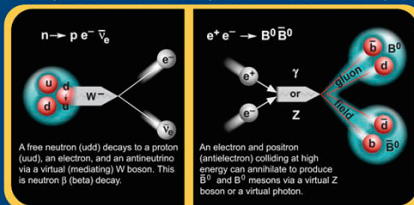
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$  labeled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

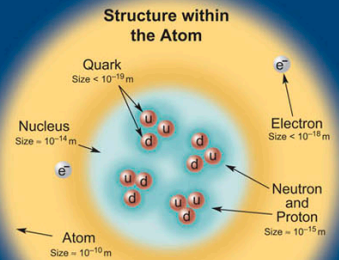
### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



A free neutron ( $udd$ ) decays to a proton ( $uud$ ), an electron, and an antineutrino via a virtual (mediating)  $W$  boson. This is a neutron  $\beta$  (beta) decay.

An electron and positron (antielec)ron) colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual  $Z$  boson or a virtual photon.



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### Properties of the Interactions

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

Property	Gravitational Interaction	Weak Interaction	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-19} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$	0.8 $10^{-4}$	1	25 60

**BOSONS** force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
$W^-$	80.39	-1			
$W^+$	80.39	+1			
$Z^0$ Z boson	91.188	0			

### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light, just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton ( $uud$ ), antiproton ( $\bar{u}\bar{d}\bar{d}$ ), neutron ( $udd$ ), lambda  $\Lambda$  ( $uds$ ), and omega  $\Omega^-$  ( $sss$ ). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  ( $u\bar{d}$ ), kaon  $K^+$  ( $u\bar{s}$ ),  $B^0$  ( $d\bar{s}$ ), and  $\eta_c$  ( $c\bar{c}$ ). Their charges are +1, -1, 0, 0 respectively.

Visit the award-winning web feature *The Particle Adventure* at [ParticleAdventure.org](http://ParticleAdventure.org)

This chart has been made possible by the generous support of:  
U.S. Department of Energy  
U.S. National Science Foundation  
Lawrence Berkeley National Laboratory  
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### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

#### Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Origin of Mass?

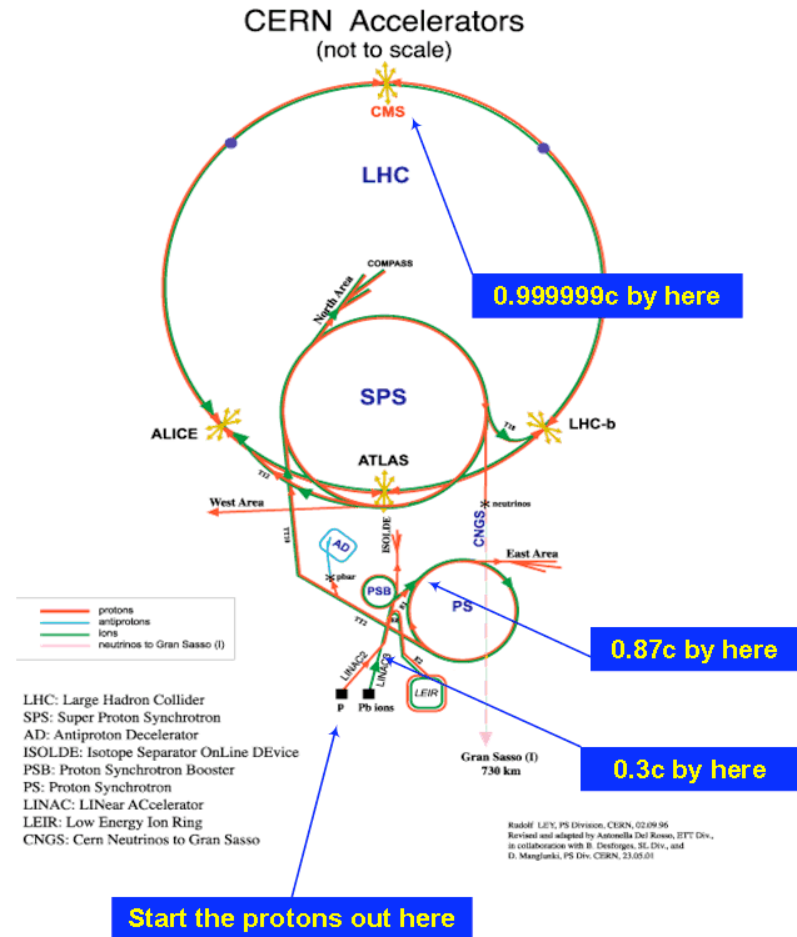
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

# Large Hadron Collider (LHC) Solving the Unsolved???



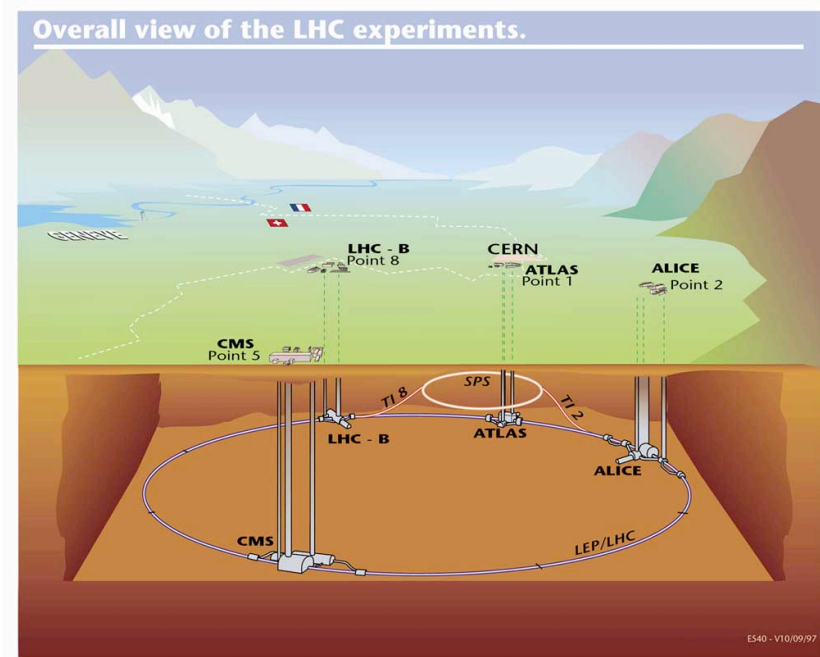
# Overview of LHC

- Linear Accelerator-0.31c
- Booster-0.87c -0.92c
- Proton Synchrotron PS-.996c
- Super Proton Synchrotron SPS-450 GeV
- LHC-2, 7 TeV beams of protons

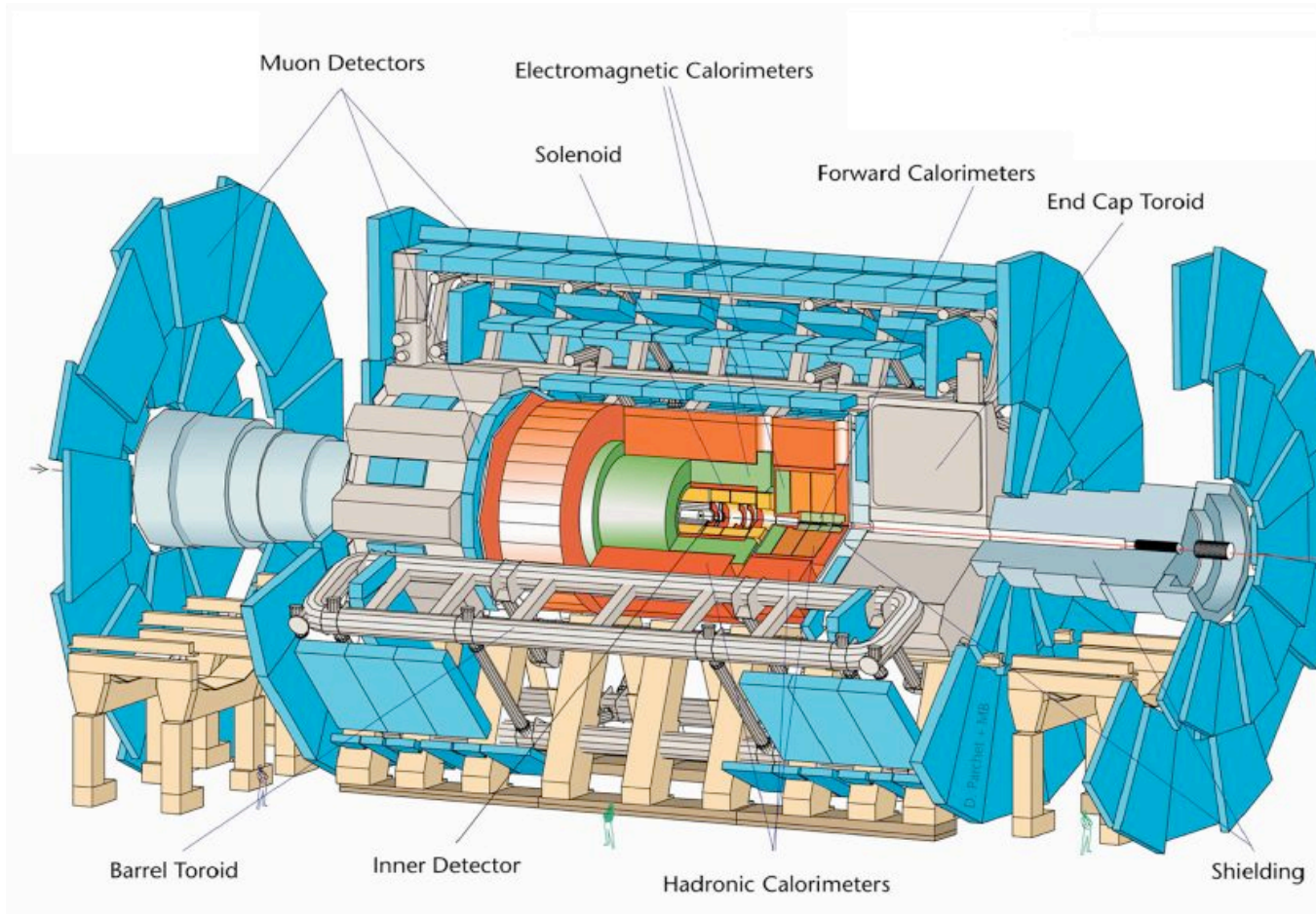


# Four main detectors at LHC

- Four main experiments
  - LHCb-designed to measure CP violation of heavy particles containing bottom quarks (why is there more matter than antimatter)
  - Alice-Pb Pb collision study quark-gluon plasma
  - Atlas-general purpose detector
  - CMS-general purpose detector










# Atlas

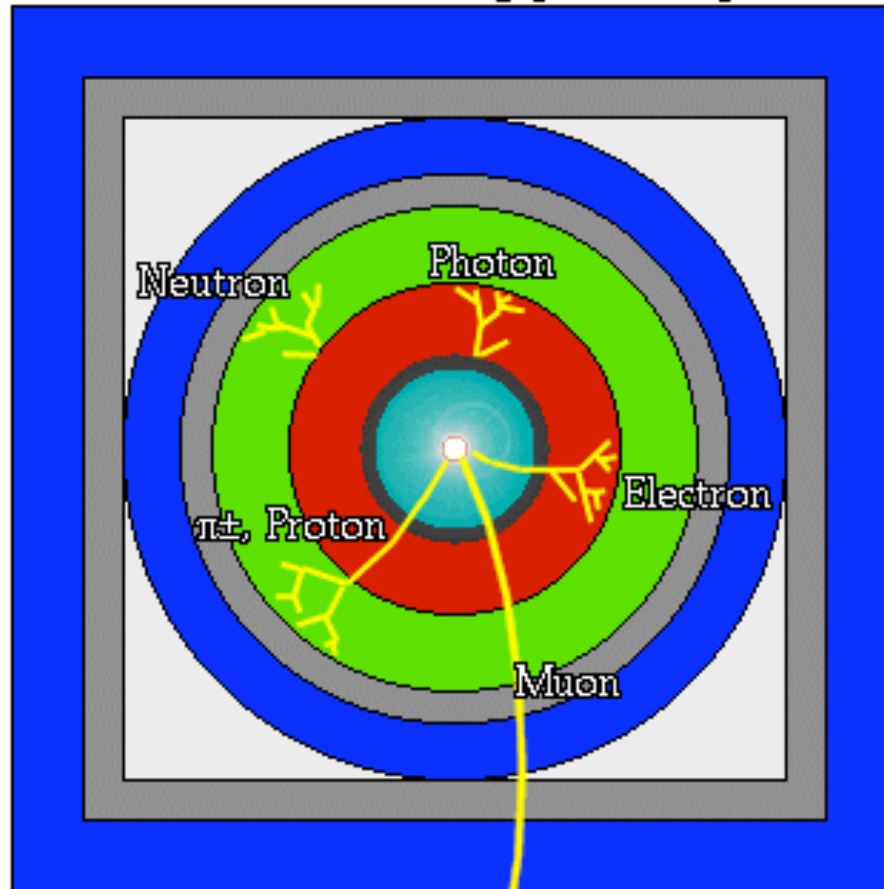




# Detector

A detector cross-section, showing particle paths

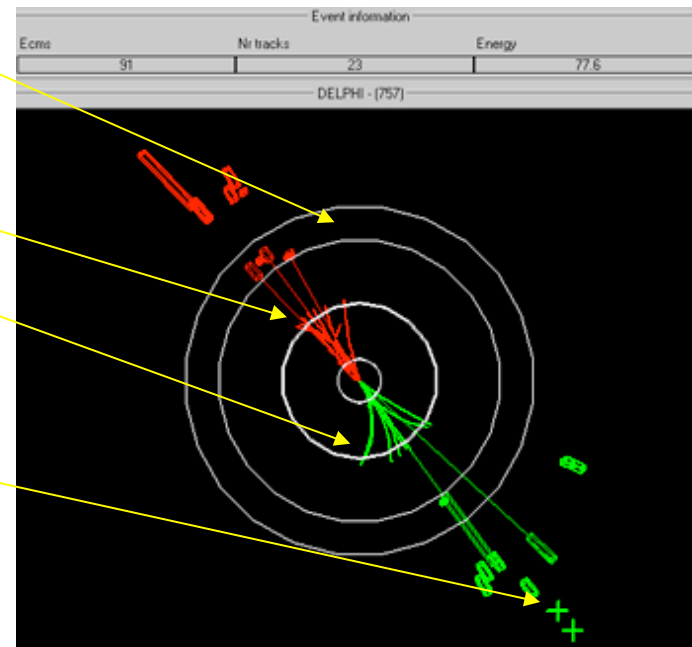
-  Beam Pipe (center)
-  Tracking Chamber
-  Magnet Coil
-  E-M Calorimeter
-  Hadron Calorimeter
-  Magnetized Iron
-  Muon Chambers



# Delphi Detector at CERN

## Z particle decay

- E & M detector
- Quark jets (red and green spaghetti lines)
- Muons (green ++)



# How particles acquire mass...

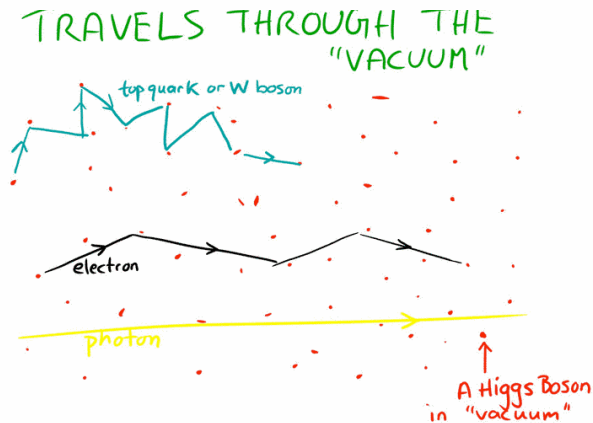
## Higgs Boson?

- Standard theory tells us all particles have a zero rest mass
- Particles interacting with the Higgs field gives mass to a particle!
- Particles moving through a Higgs field can be modeled like resistance in a conductor.
- [What is the Higgs particle](#) (first 8 min.)

### "STANDARD MODEL"

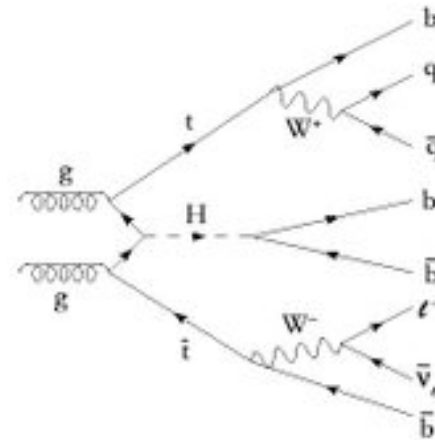
⇒ Elementary particles are fundamentally all massless, but "vacuum" is a rich bath ("condensate") of Higgs Bosons that

- (a) is extremely difficult to detect, evading all tests for an aether etc.
- (b) slow down elementary particles below light speed (so they acquire mass)

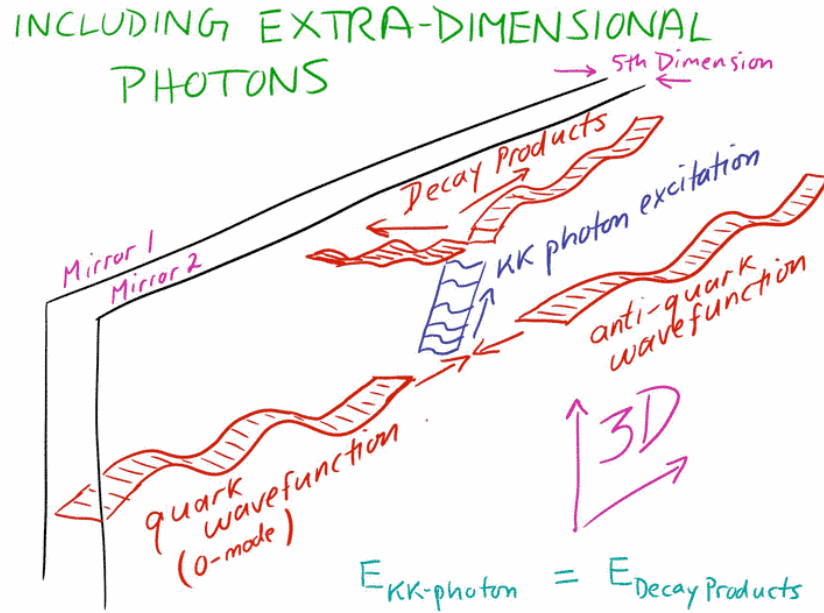


# How to detect a Higgs particle at the LHC

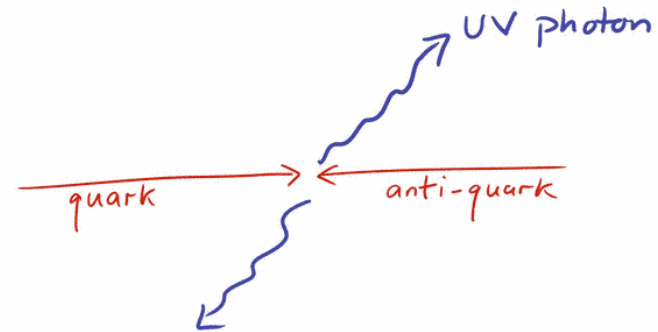
- This point in history should see a merger of radioactivity and E&M. (symmetry breaking) which leads to the Higgs mechanism. The LHC is poised to see this.
- One way the **Higgs boson** may be produced at the LHC.
  - Two gluons decay into a top/anti-top quark pair
  - The quark pair then combine to make a neutral Higgs



# Could a hidden dimension be seen at LHC?



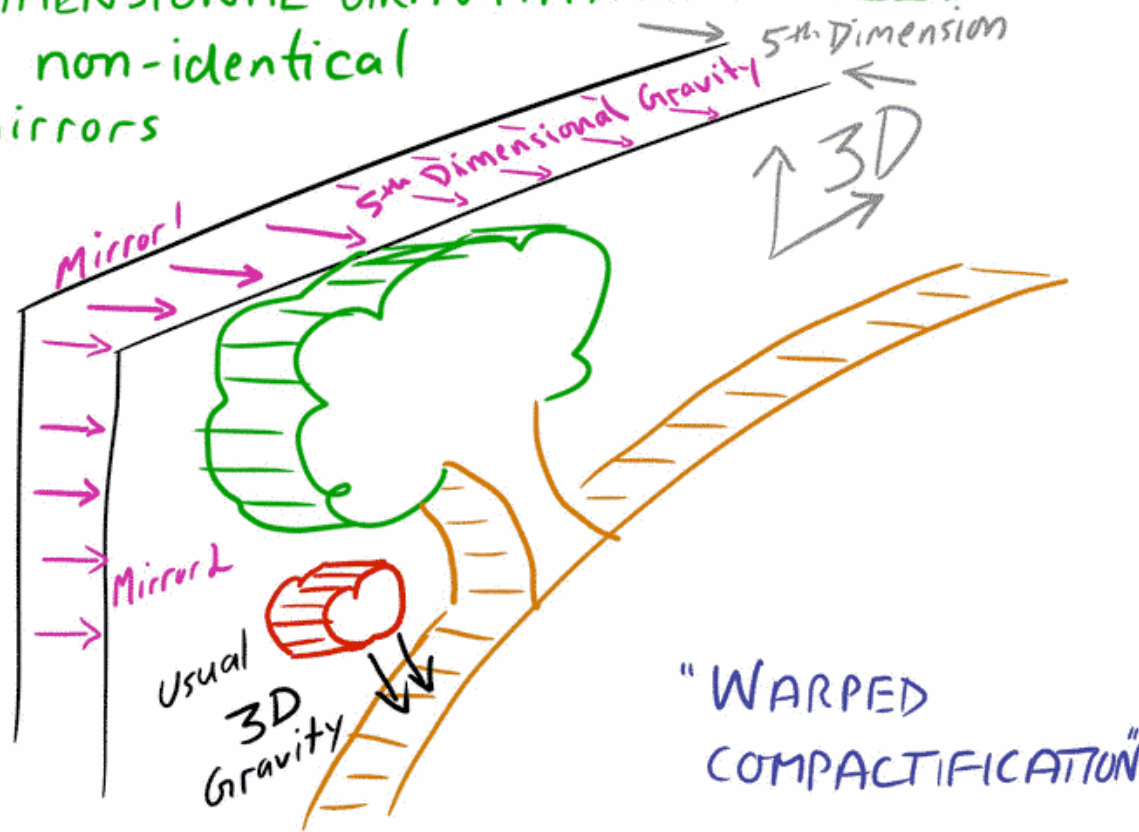
FAR ULTRAVIOLET PHOTONS CAN BE CREATED IN PARTICLE COLLIDERS



from energy of colliding particles.

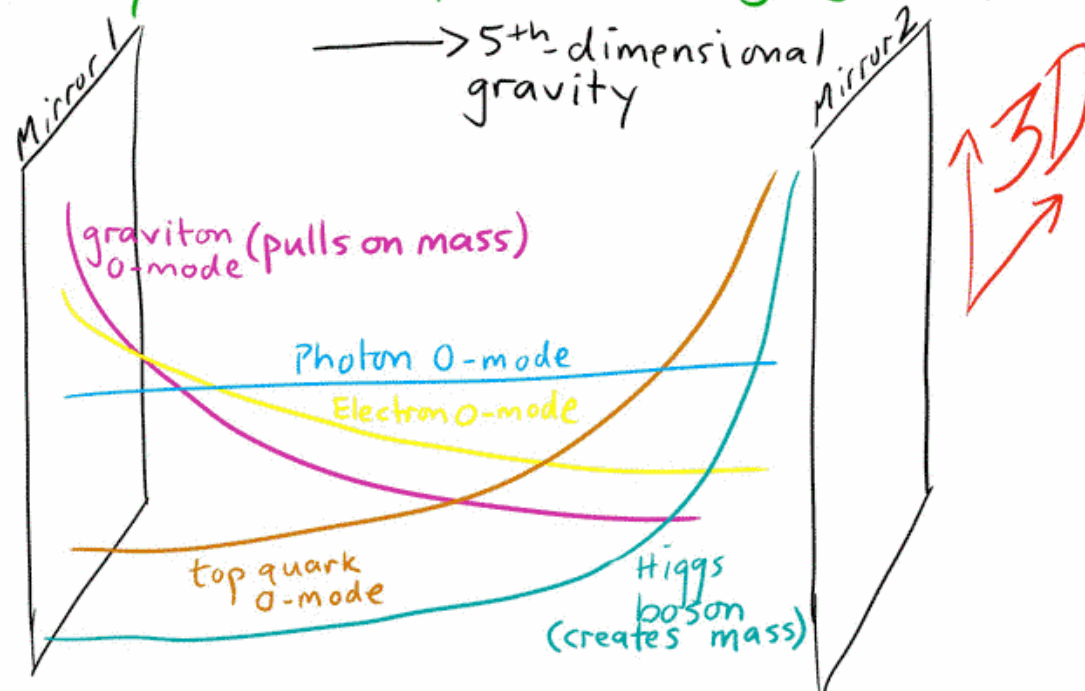
# Warped compactification and the hierarchy problem...

HIDDEN 5<sup>th</sup> DIMENSION CAN HIDE A 5<sup>th</sup> DIMENSIONAL GRAVITATIONAL FIELD For non-identical mirrors



# Hierarchy Problem Solved?

**WARPED EXTRADIMENSION**  
naturally separates graviton from Higgs,  
thereby drastically weakening gravity.

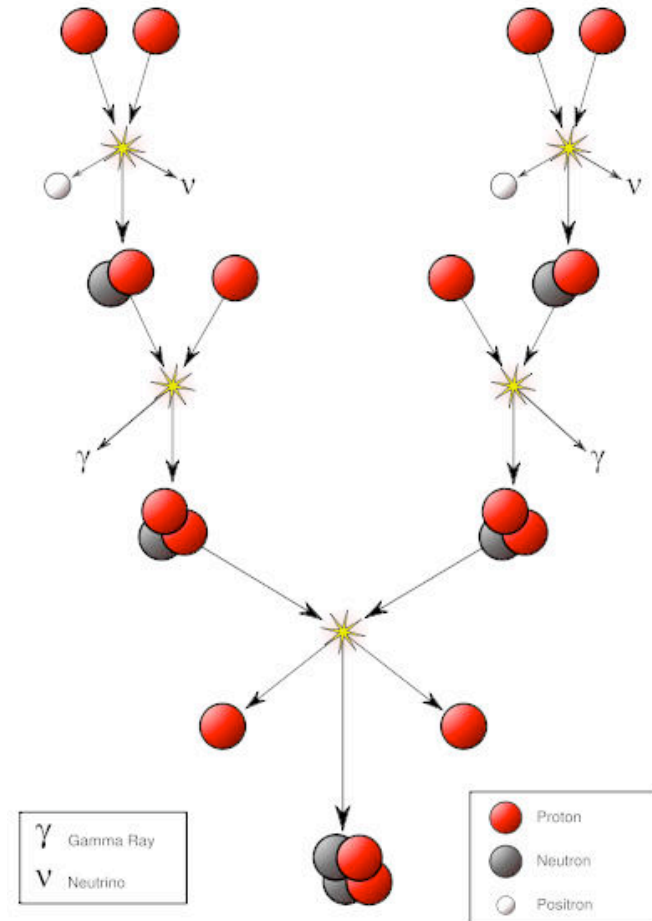


ONE OF FEW KNOWN SOLUTIONS TO HIERARCHY PROBLEM!

# Neutrinos Physics

## ‘You don’t work at the LHC’?

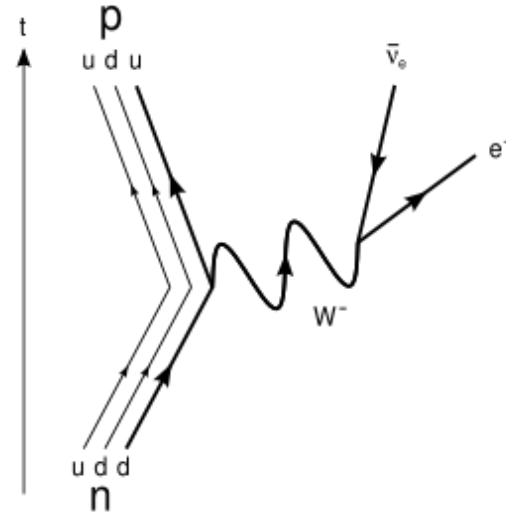
- Produced in nuclear fusion (Sun)
- Product of radioactive decay ( $\beta$  decay)
- Produced by cosmic rays (protons) interacting with the atmosphere
- There are 3 flavors of neutrinos





# Weak Force Beta Decay and the Neutrino

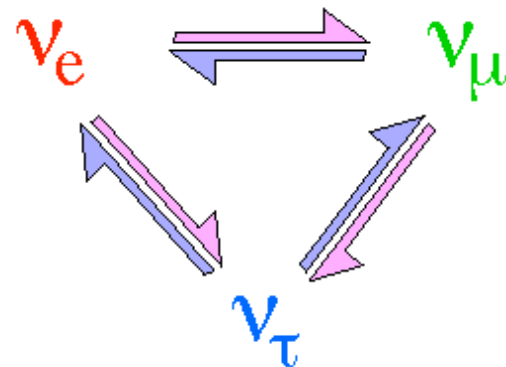
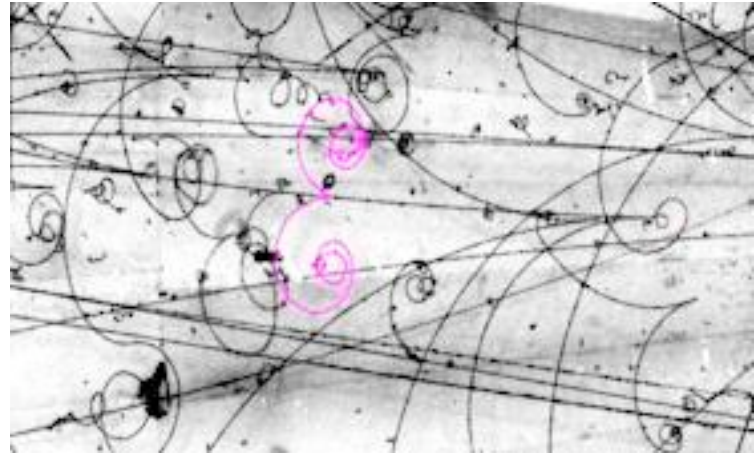
- Weak force
  - $10^{13}$  times less than strong force (hence name)
  - Range of weak interaction  $10^{-18}$  m
  - Only weak force affects neutrinos (gravity has a very small affect)
  - Weak force is the only interaction capable changing flavors (up quark to down)



# Why study neutrinos?

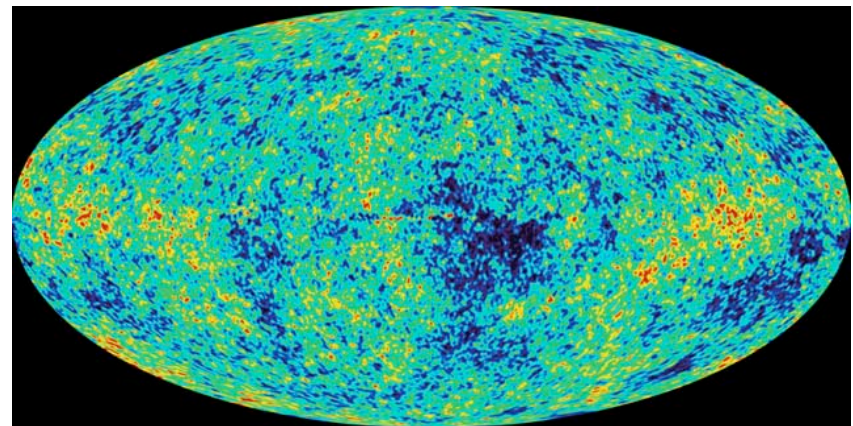
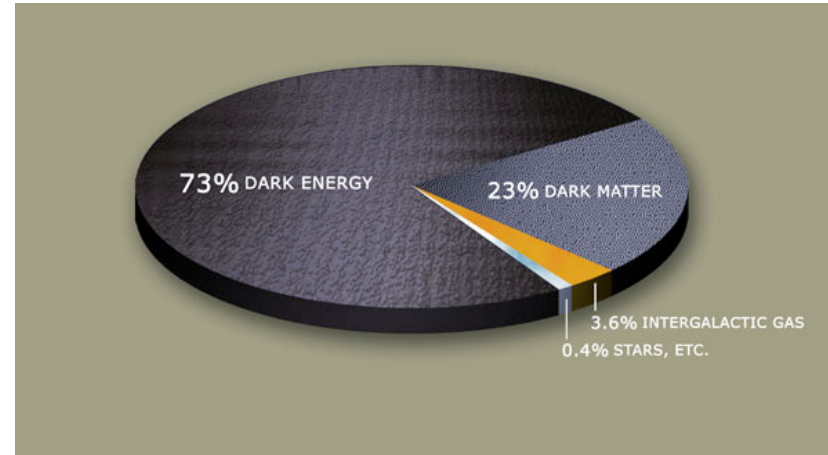
## Matter Antimatter Asymmetry

- Neutrinos may oscillate between the three flavors. Will this show why we see a large matter antimatter asymmetry in the universe?



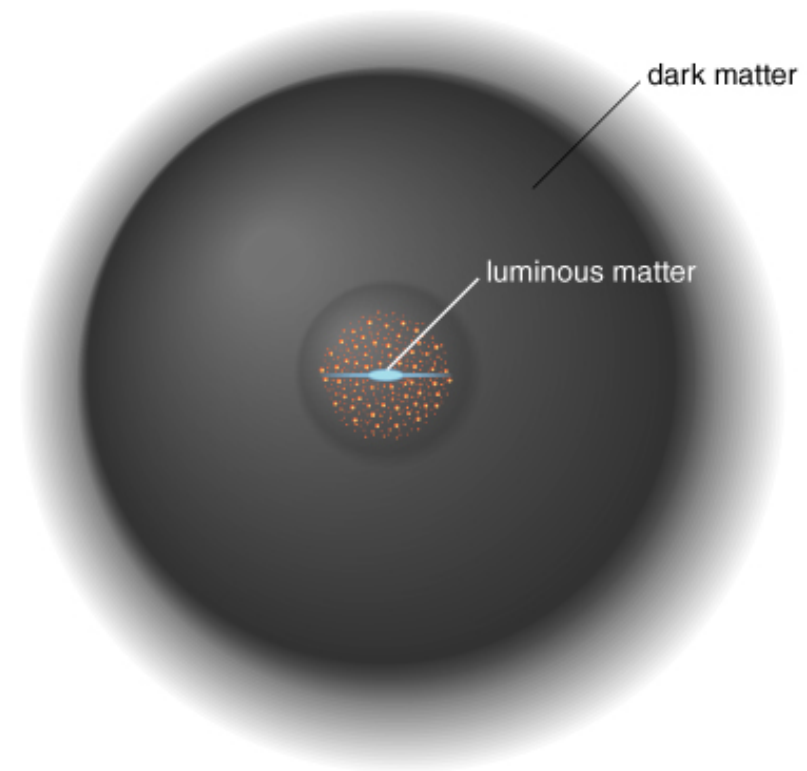
# The search for Dark Matter

- Cosmology requires the existence of dark matter
- How do we know this?
  - Galactic rotation curves
  - Collision of cluster galaxies
  - Cosmic microwave background temperature fluctuations

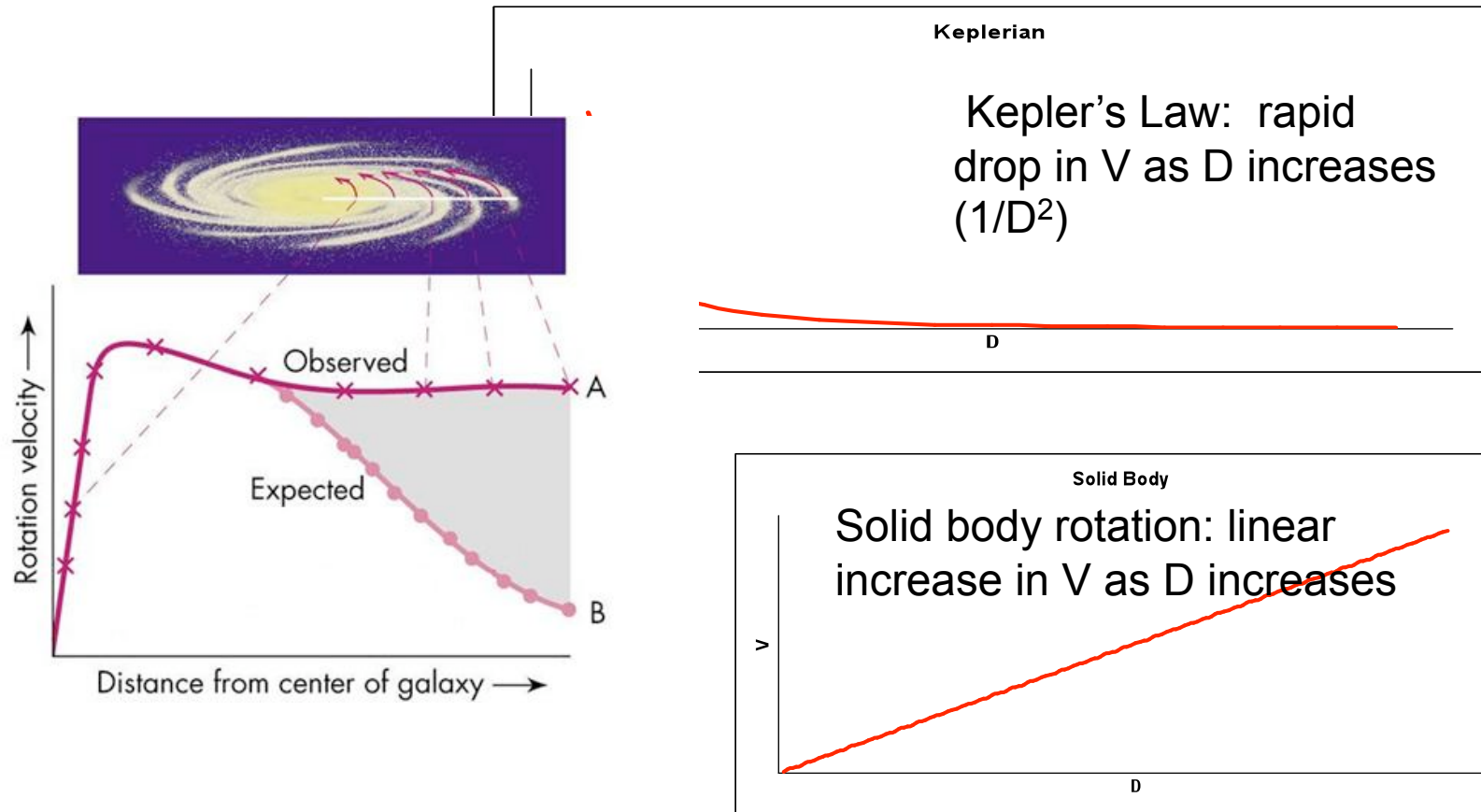


# What is Dark Matter?

- Properties of simplest Dark Matter
  - Must be stable (have immutable qualities)
  - Density 1 particle per hand
  - $Z_2$  charge invariance with an odd charge
  - R-parity
- Possible Candidates
  - Lightest Supersymmetric Particle (LSP)
  - Lightest Kaluza-Klein
  - Technibaryons
  - Singlet Fermion
  - Gravitons
  - WIMP



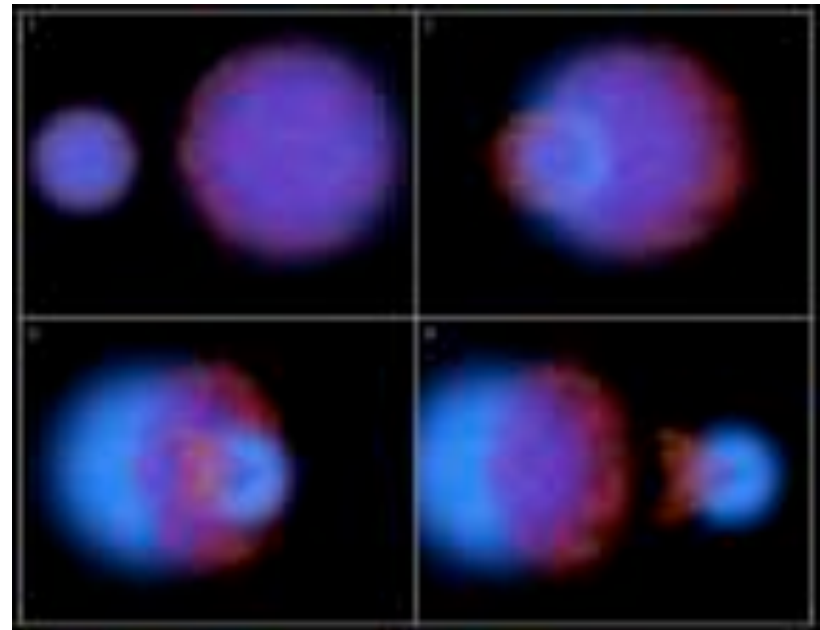
# Existence of Dark Matter Galactic Rotation Curves



# Existence of Dark Matter

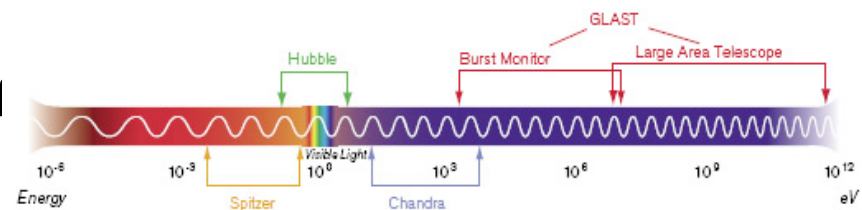
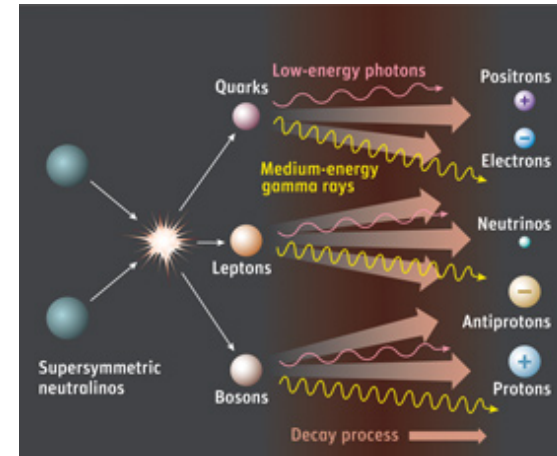
## Collision of Galactic Clusters

- Artist's representation of the collision between two clusters in the Bullet Cluster
- **Normal matter in the cluster, is shown in red and dark matter is shown in blue.**
- The last image is showing the hot gas seen with the Chandra X-ray Observatory (pink) and the cluster mass as inferred by gravitational lensing (blue), which is mostly dark matter.
- Best evidence for dark matter to date



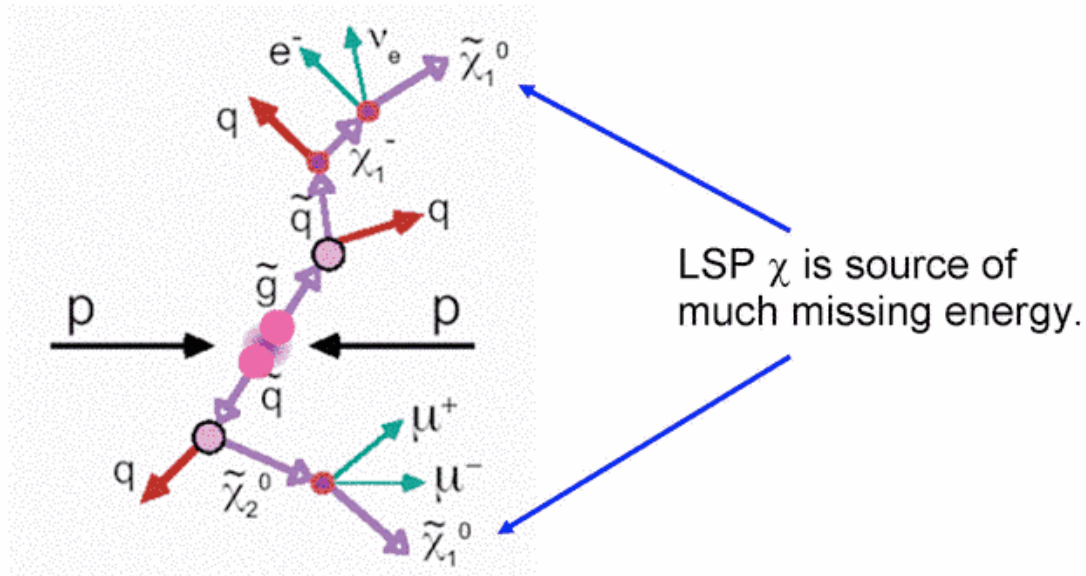
# Search for Dark Matter NASA GLAST

- Glast (NASA)Gamma-ray Large Area Space Telescope
- The GLAST space telescope, launched June 11, 2008, searching for gamma wave events, may also detect WIMPs.
- Supersymmetric particle and antiparticle collisions should release a pair of detectable gamma waves. The number of events detected will show to what extent WIMPs comprise dark matter.



# Search for Dark Matter at the LHC

## Example SUSY Event at LHC



<http://www.icepp.s.u-tokyo.ac.jp/~kenta/analysis.html>



# Summary

- LHC looks at  $<10^{-10}$  s after the Big Bang
- LHC will produce energies near 14 TeV
- Atlas is one of the main detectors at the LHC
- Some unsolved physics problems that may be solved at the LHC
  - Why is gravity so much weaker than the 3 other forces? Can the hierarchy principle solve this?
  - What is mass? Will the Higgs particle be found?
  - Why is there more matter than antimatter? Does this have to do with neutrino oscillation?
  - What is dark matter and will we find any? GLAST and the LCH just might!

# The next couple years in particle physics will be exciting!



Before the linear accelerator



# Homework

- <http://hands-on-cern.physto.se/> (If this doesn't work, try the link below)
- [http://www.physicsmasterclasses.org/exercises/hands-on-cern/hoc\\_v21en/](http://www.physicsmasterclasses.org/exercises/hands-on-cern/hoc_v21en/)

(hands on CERN WIRED)

- <http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotation.html>

Galactic Rotation Lab (Great experience!)

- <http://www.particleadventure.org/>

Particle Adventure

- <http://www.particleadventure.org/other/education/index.html>

Education material

# References

- [http://online.kitp.ucsb.edu/online/lhct\\_c08/](http://online.kitp.ucsb.edu/online/lhct_c08/)

Lesson based on talks for 2008 Teachers Conference Kavli Institute UCSB

- <http://www.youtube.com/watch?v=AM7SnUlw-DU&feature=related>

Dr. David Gross's overview of the Future of particle physics and what can be expected from the LHC.

- <http://www.youtube.com/watch?v=1sVPCT5qHM>

(Start at 22min.) Richard Muller Quarks, exchange forces and confinement

- [http://www.youtube.com/watch?v=Xcww72\\_6gCI&feature=related](http://www.youtube.com/watch?v=Xcww72_6gCI&feature=related)

You Tube video on quarks and leptons

- <http://www.youtube.com/watch?v=AHT9RTICqjQ>

Good collision You Tube video

- <http://www.youtube.com/user/TheATLASExperiment>

Good You Tube video of Atlas

- <http://www.youtube.com/watch?v=FNCS1c9A-Vs>

Physics for future Presidents Richard Muller talks about the Higgs particle

What is the Higgs particle? What first 8 min.

- <http://www.youtube.com/watch?v=kw0iRW2hoC4>

Peter Higgs-Interviewed (11 min.)

- <http://www.pbs.org/wgbh/nova/sciencenow/3410/02.html>

PBS 12 min video on CERN

- <http://www.pbs.org/wgbh/nova/sciencenow/dispatches/080111.html>

Science Now dark matter and the Bullet Cluster

# References

- **Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions (Paperback)** by Lisa Randall **Paperback:** 512 pages  
**Publisher:** Harper Perennial (September 19, 2006) **ISBN-10:** 0060531096 **ISBN-13:** 978-0060531096
- **Particle Physics A very short Introduction** by Frank Close Oxford Press
- [http://www.nasa.gov/mission\\_pages/chandra/main/index.html](http://www.nasa.gov/mission_pages/chandra/main/index.html)  
Chandra x-ray telescope
- <http://www.nasa.gov/multimedia/podcasting/index.html>  
Nasa Video/Audio podcast Dark Energy/Matter
- <http://glast.gsfc.nasa.gov/>  
Search for composition of dark Matter
- <http://www.pbs.org/wgbh/nova/sciencenow/3410/02.html>  
PBS show Dark Matter