Particle Physics in the Age of the Large Hadron Collider

The following presentation is based upon talks presented at a Teachers' Conference at the

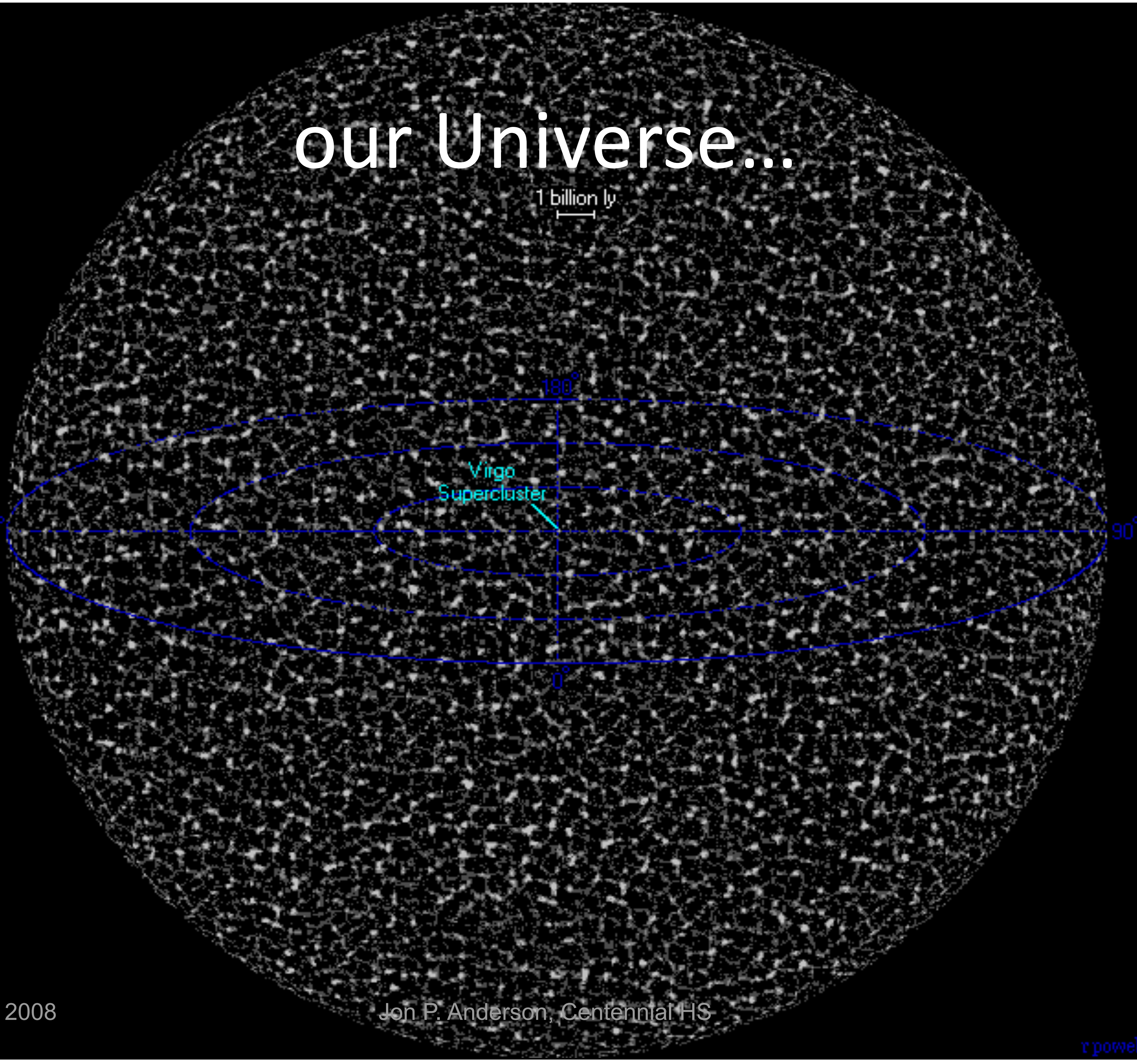
Kavli Institute for Theoretical Physics

on May 31, 2008.

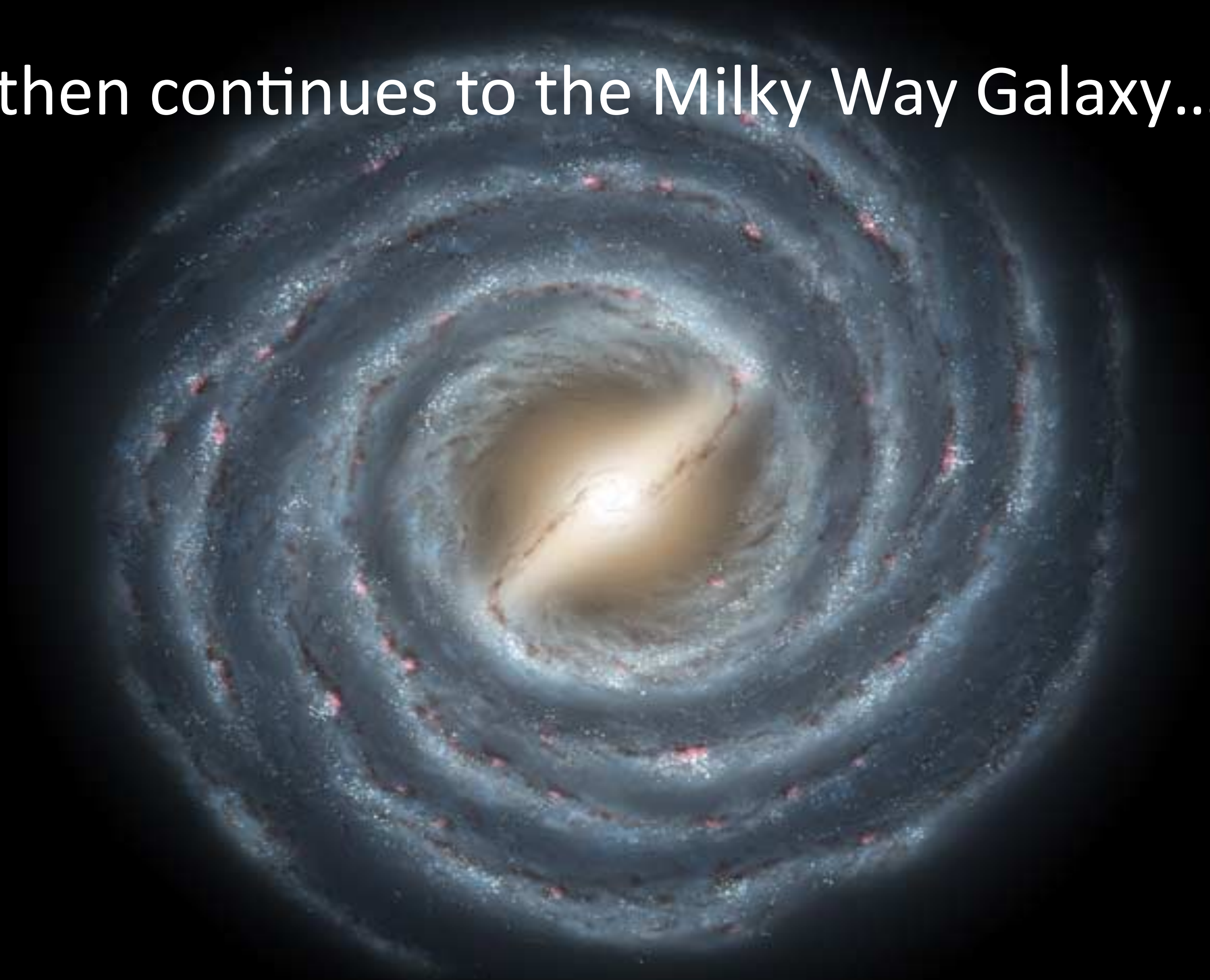
We are about to take a journey into the world of particle physics

A trip that begins at the far edges of…

our Universe…



then continues to the Milky Way Galaxy….

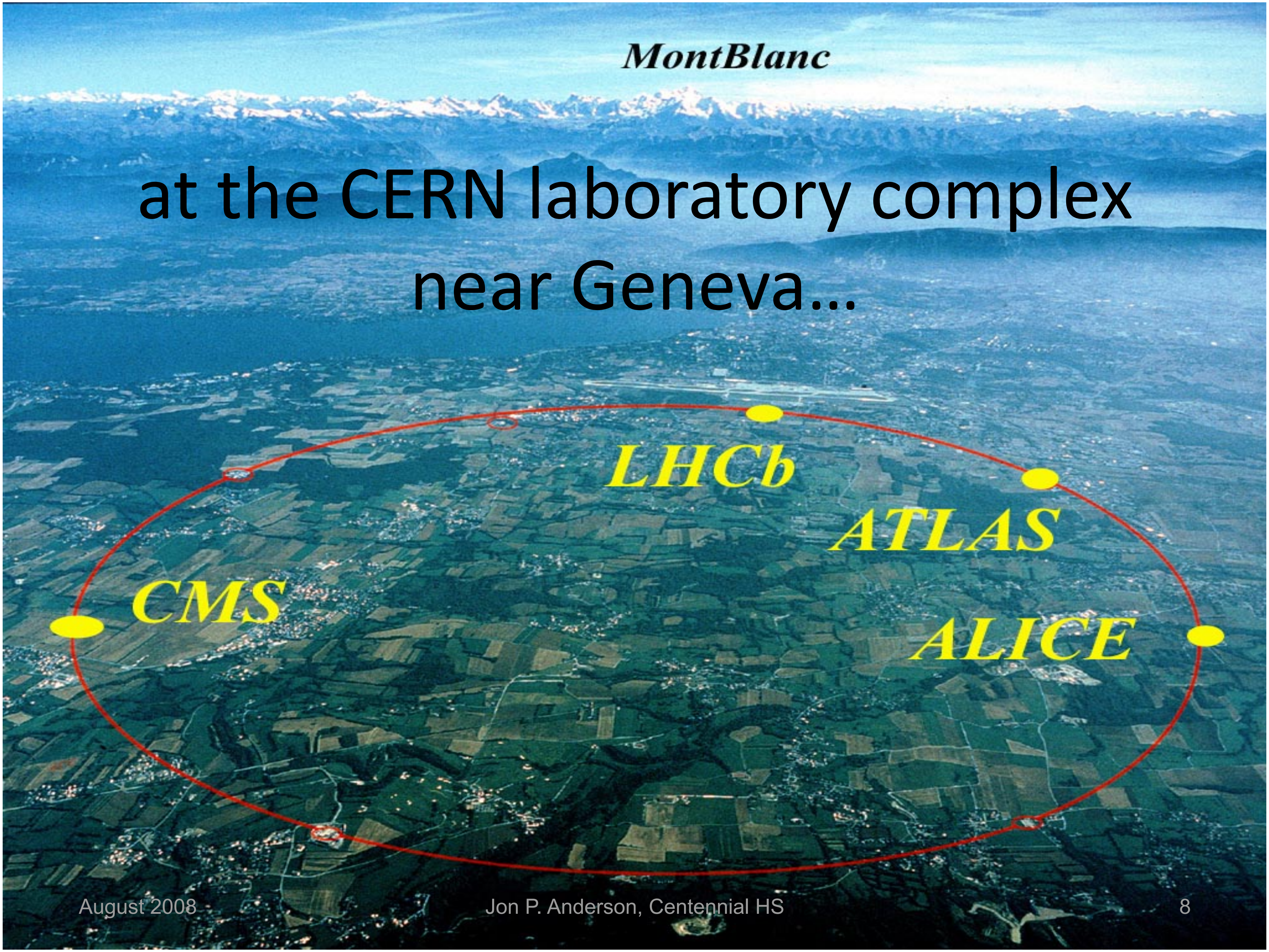


enters the Solar System…

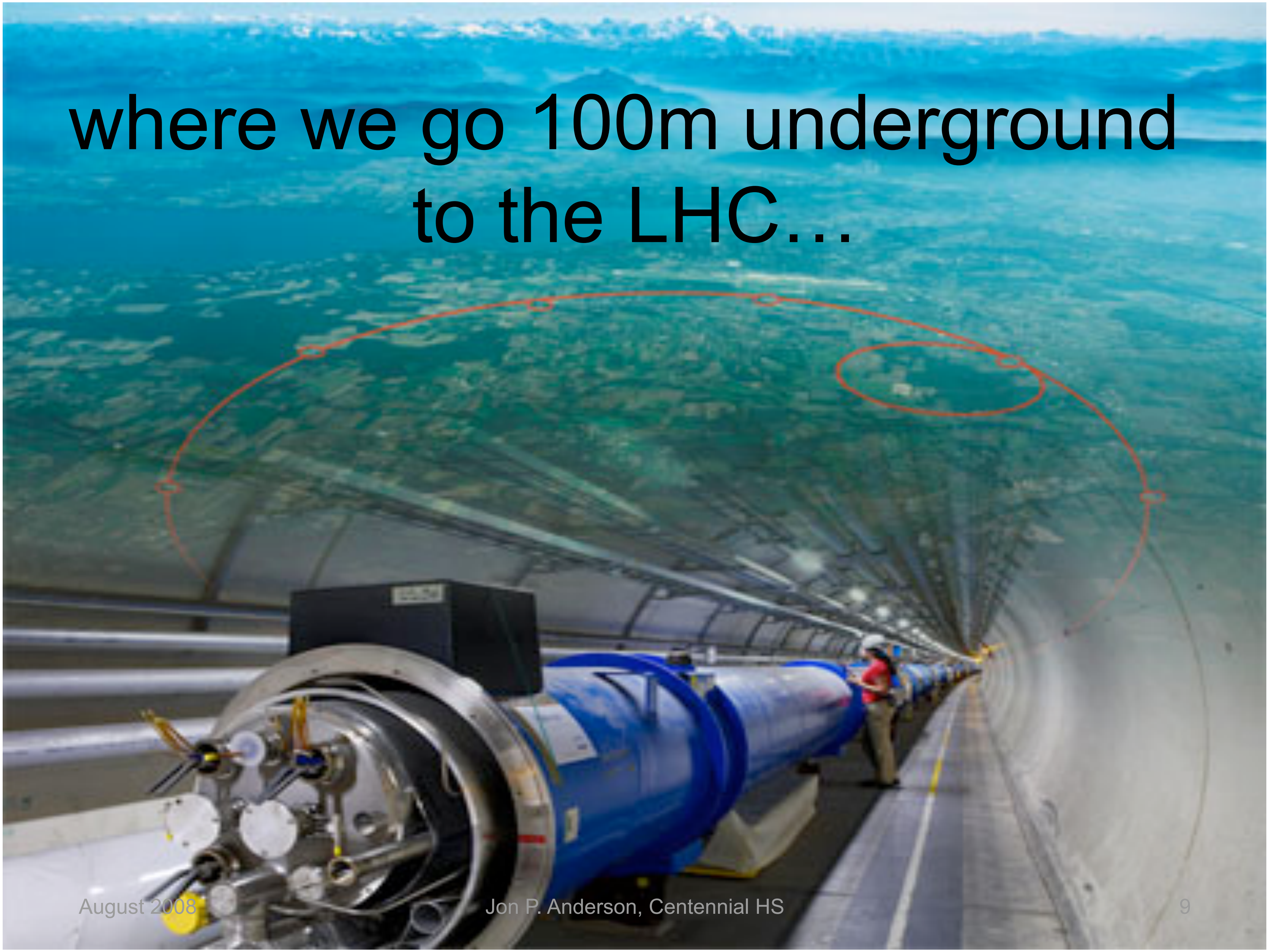
continues to the Earth…

and arrives in Switzerland…

at the CERN laboratory complex near Geneva…



where we go 100m underground to the LHC…



where the journey is far from over!

- It is actually here that the **REAL** journey begins.
- Every good journey needs a map and ours will follow this path and address these questions

1. How does the LHC work?→ 2. What can we learn about our world from the LHC?→ 3. How can the LHC help us learn about other physics?→ 4. What can we learn about the universe from the LHC?

Let the the **REAL** journey begin!

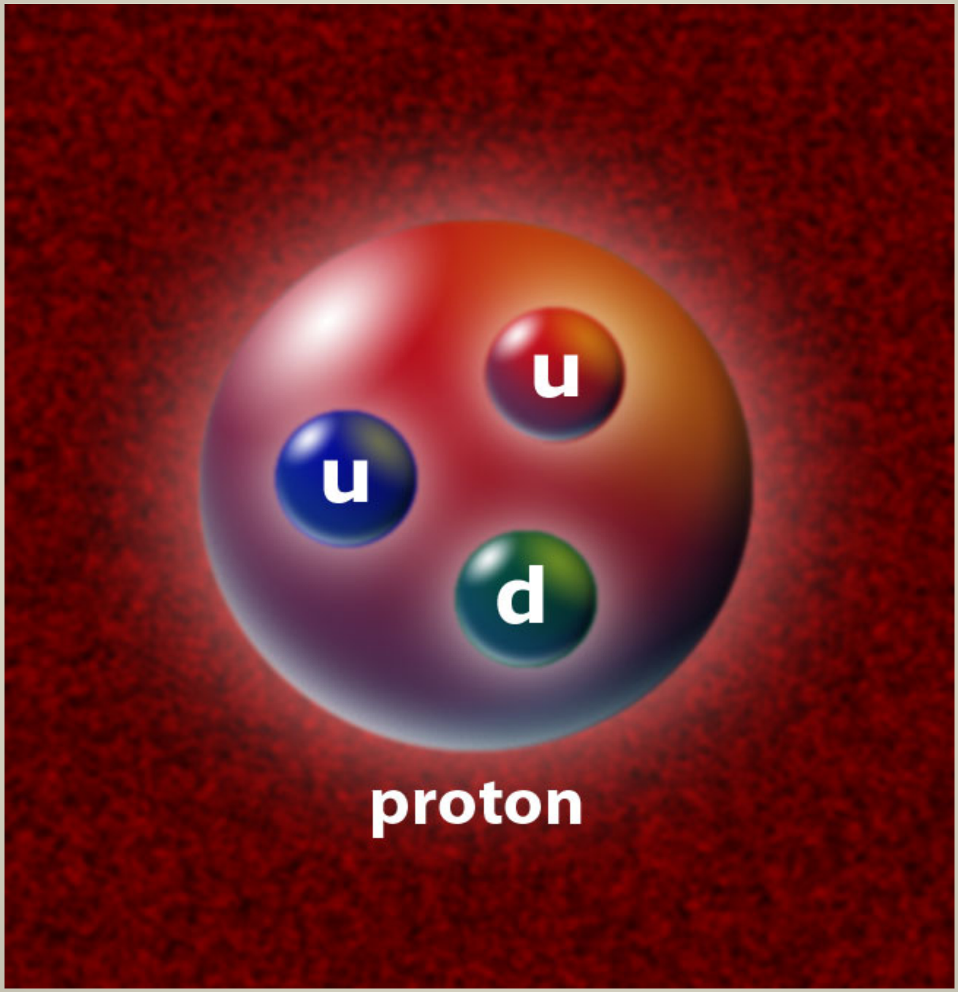
Question #1: How does the LHC work?

Our quest for answers on this part of our journey will be guided by AYANA HOLLOWAY ARCE, a Chamberlain Postdoctoral Fellow at Lawrence Berkeley National Laboratory and a physicst on the ATLAS experiment at CERN. The following slides are based upon her talk at KITP.

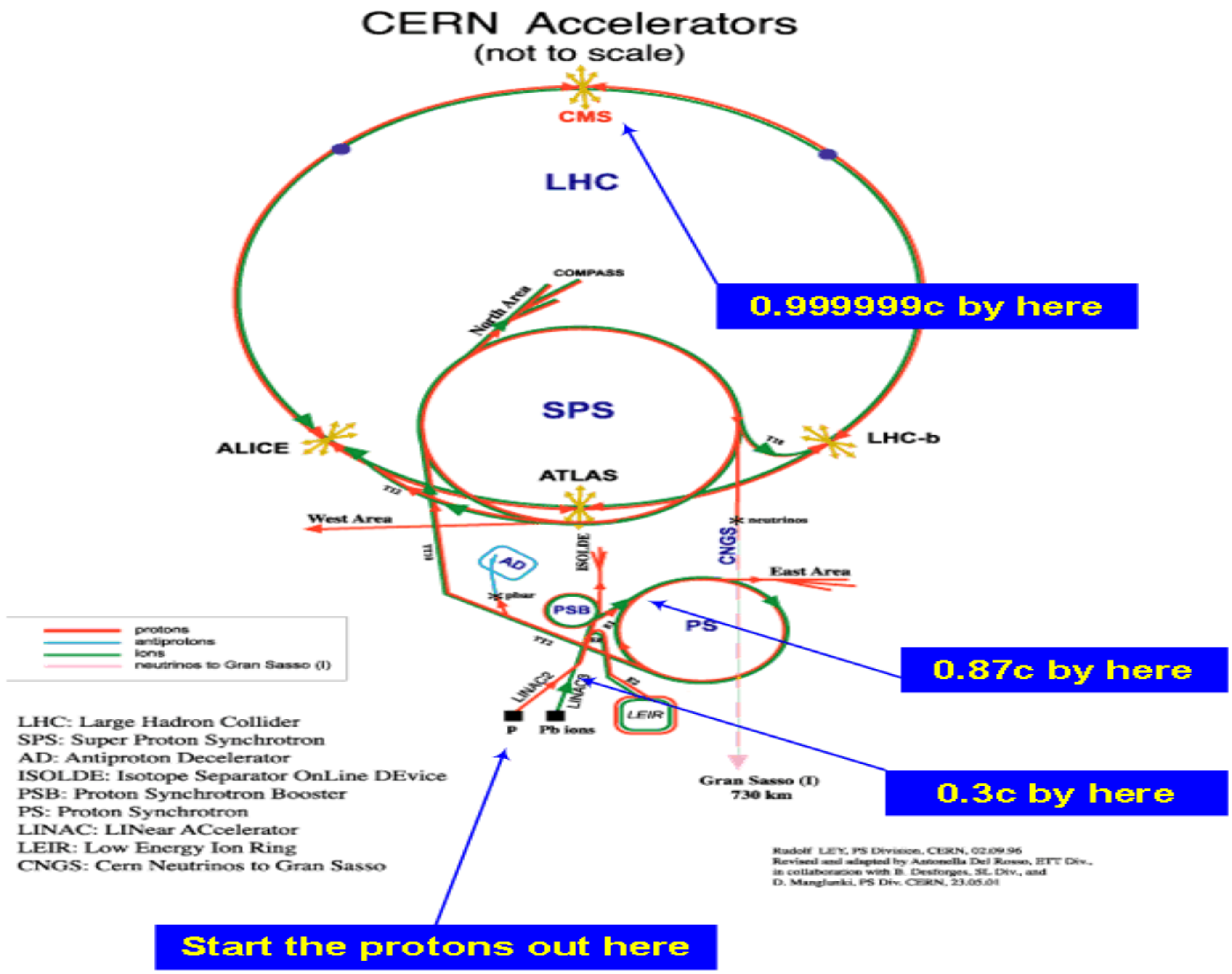
In the beginning…

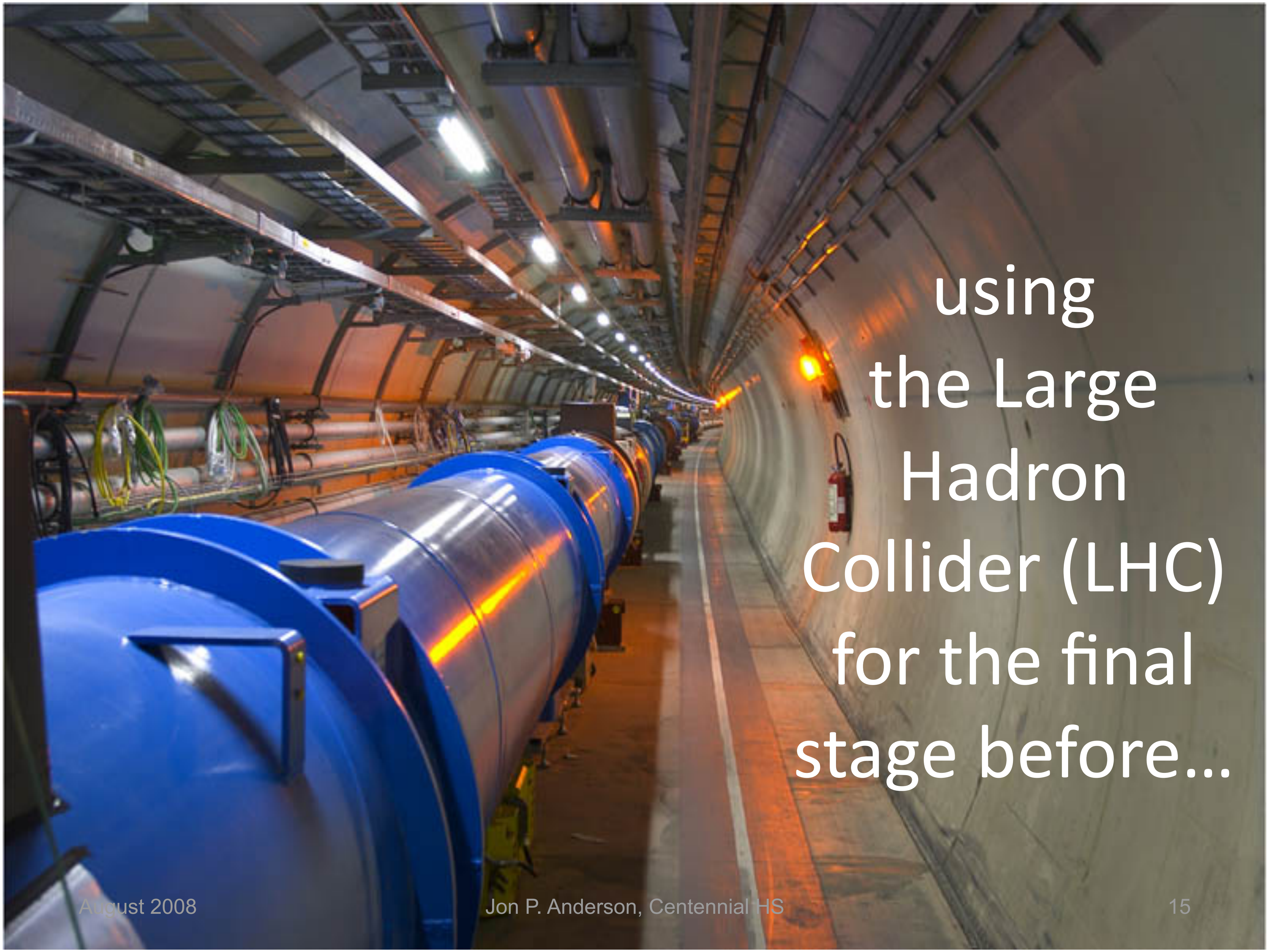
there is
a bottle
of
hydrogen
gas

from which protons (p^+) are extracted



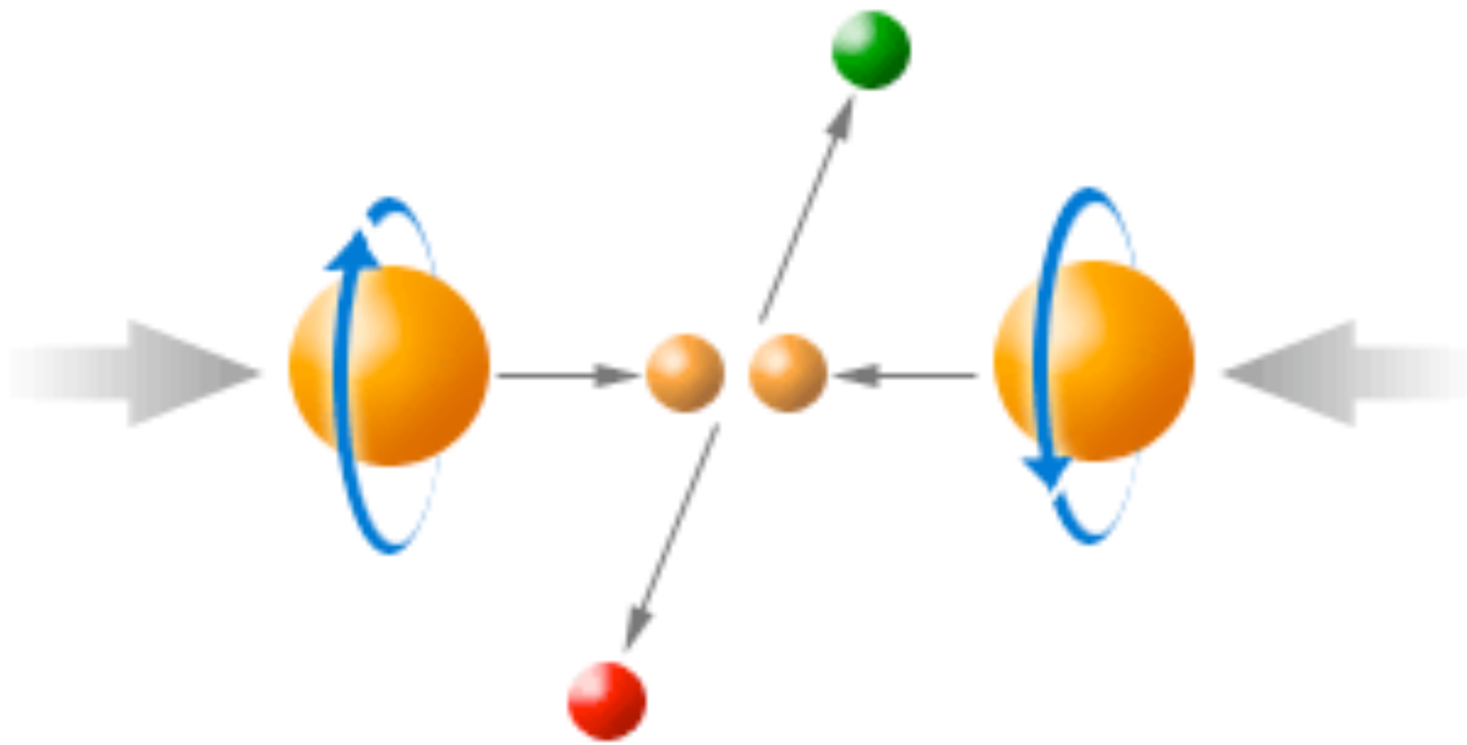
and accelerated to **ALMOST** the speed of light (c)…



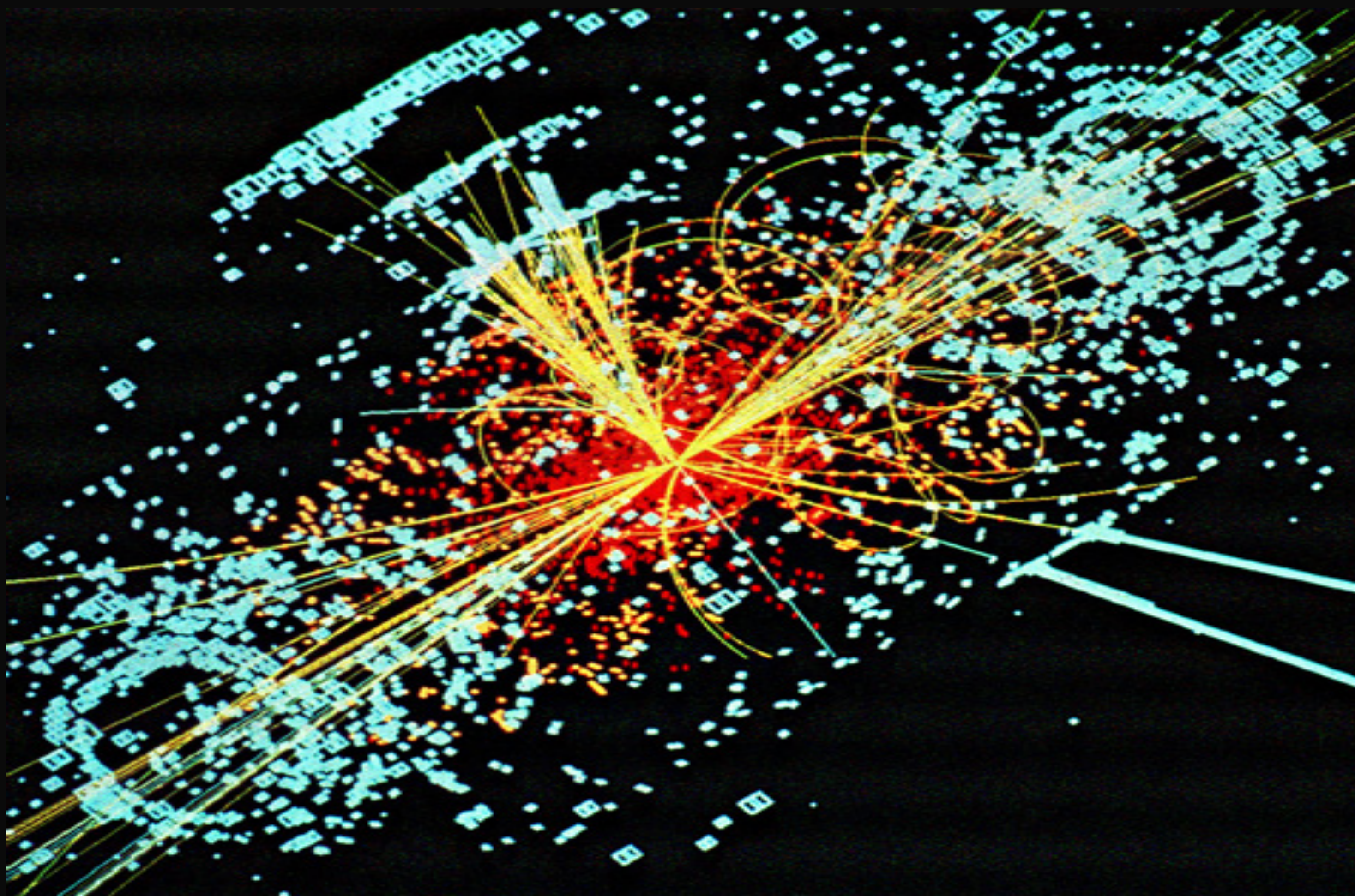


using the Large Hadron Collider (LHC) for the final stage before…

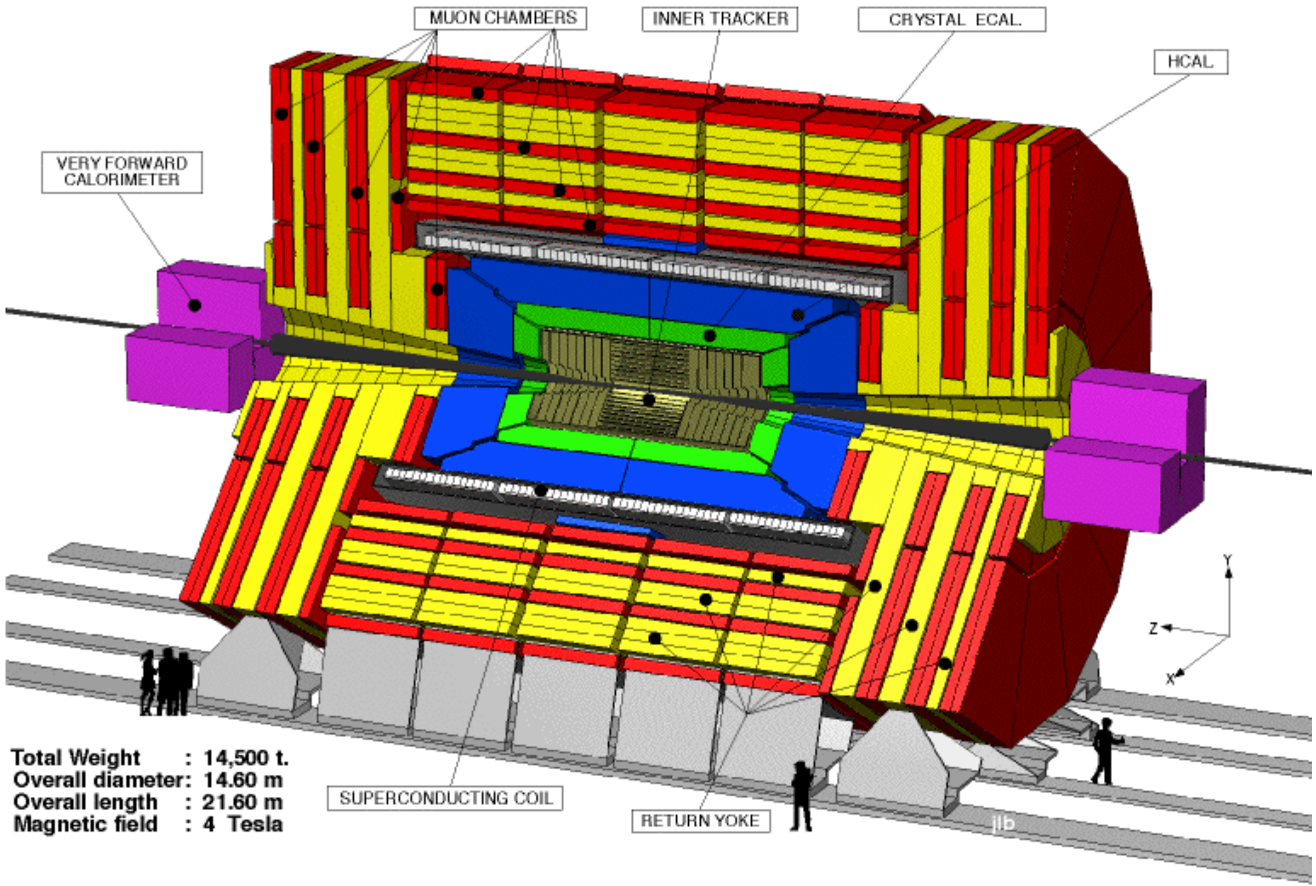
forcing protons traveling in one direction to collide with protons traveling in the opposite direction….



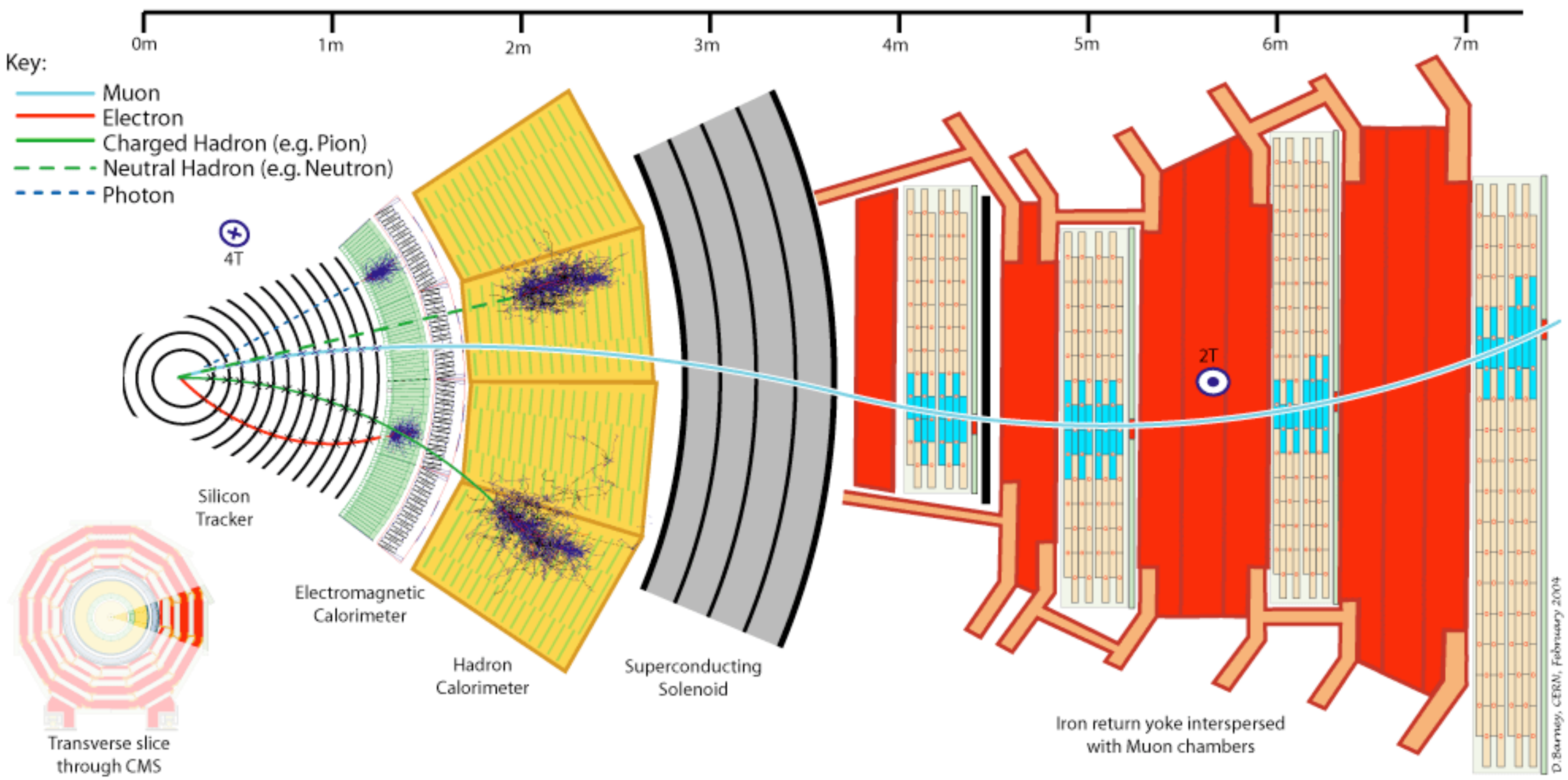
and studying these collisions using huge detectors such as…



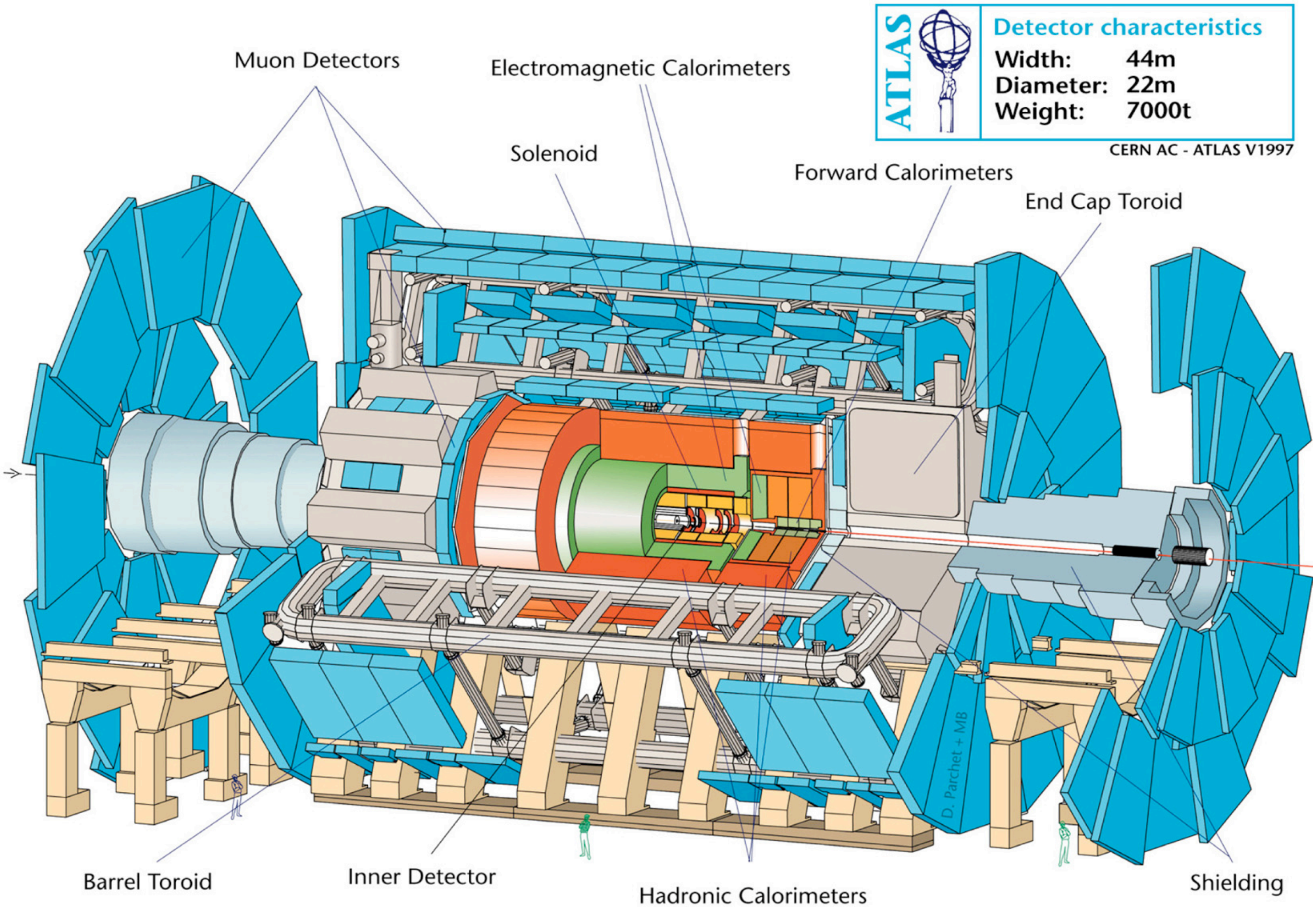
the Compact Muon Solenoid (CMS) which…



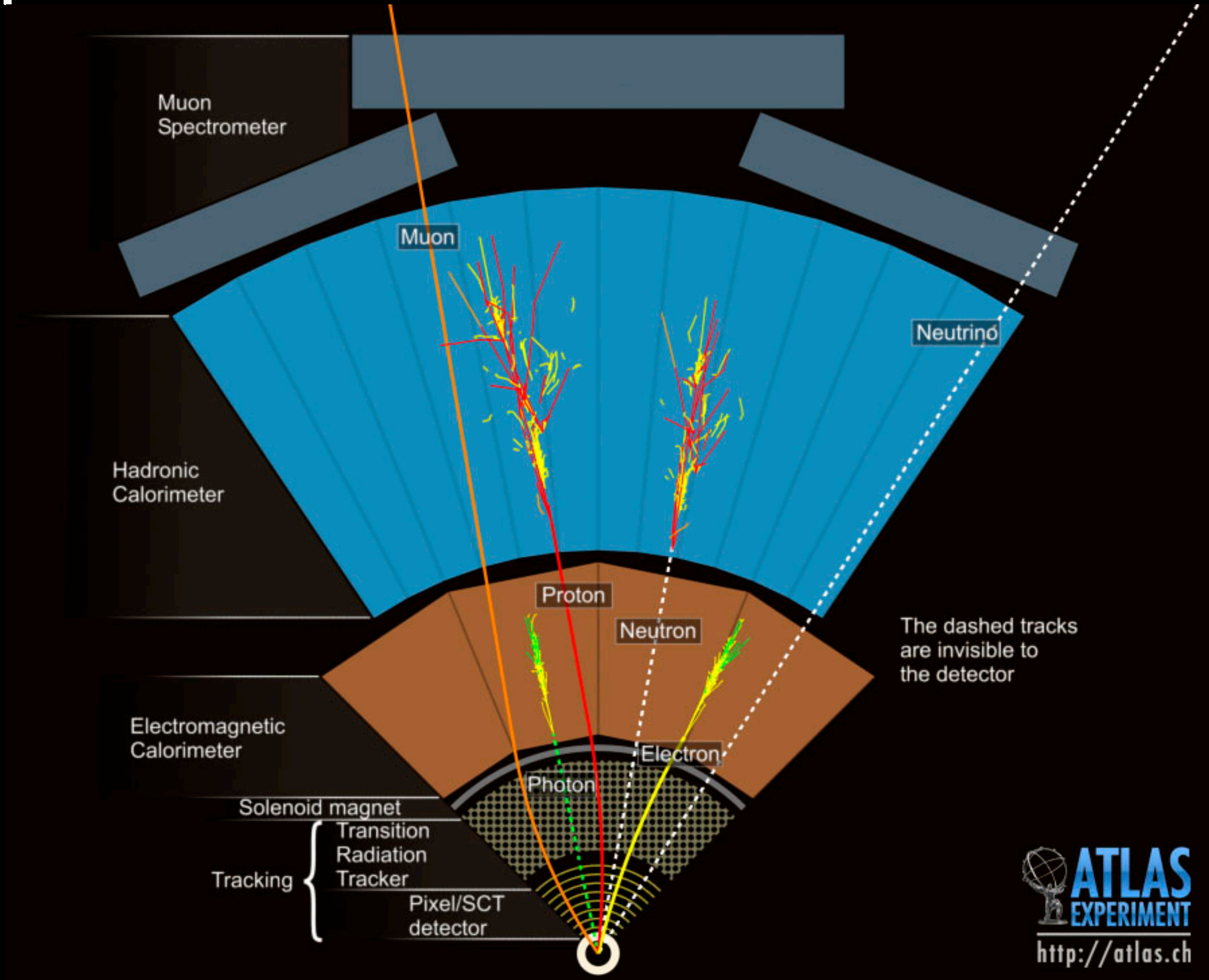
provides the following details and…



A Toroidal **L**HC **A**pparatu**S** (ATLAS) that…



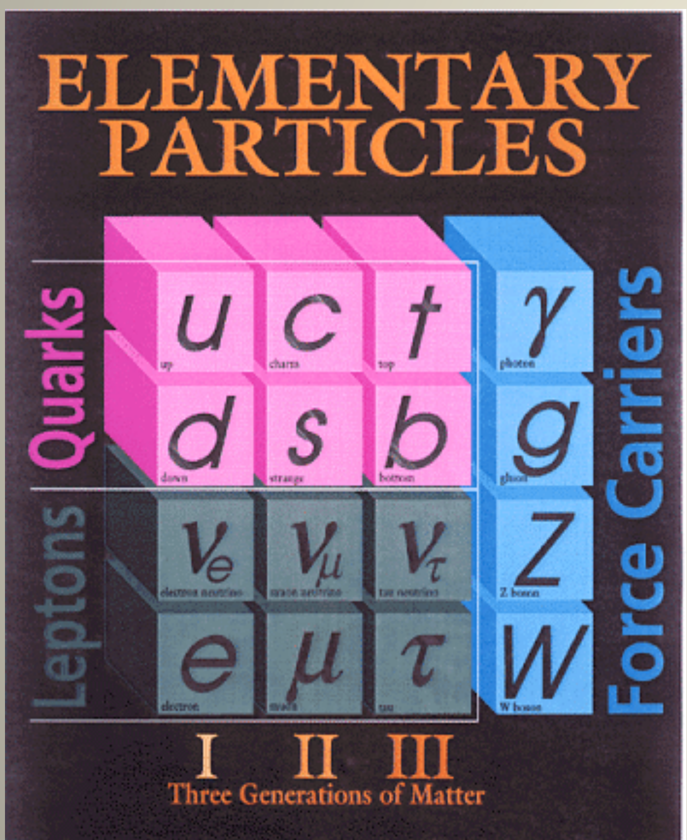
provides the details as shown.

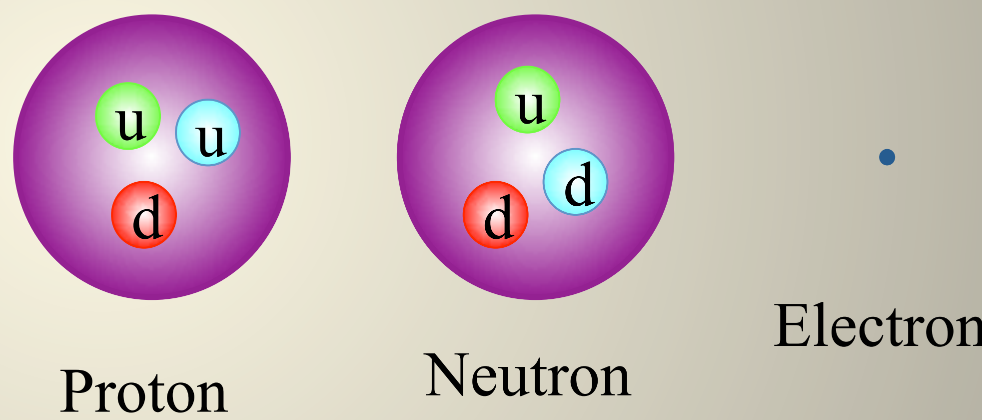


and its all done within view of spectacular Mount Blanc!

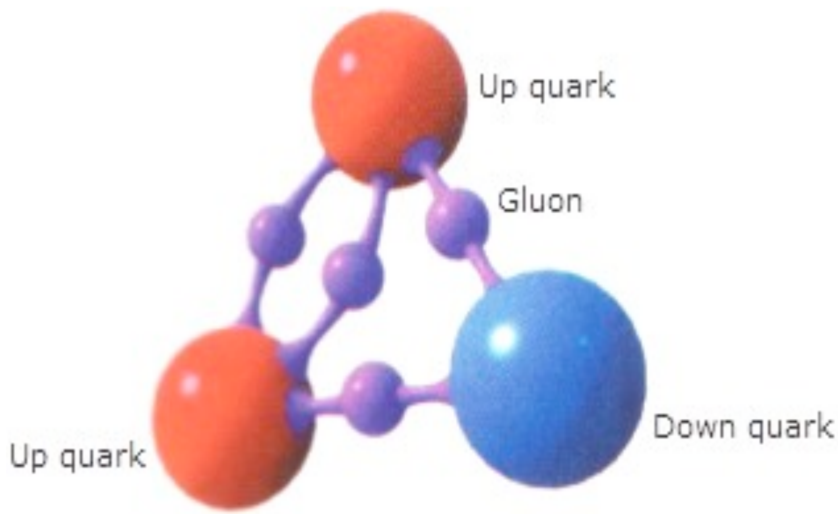
The LHC brings us to the elementary level…

elementary particles, that is!



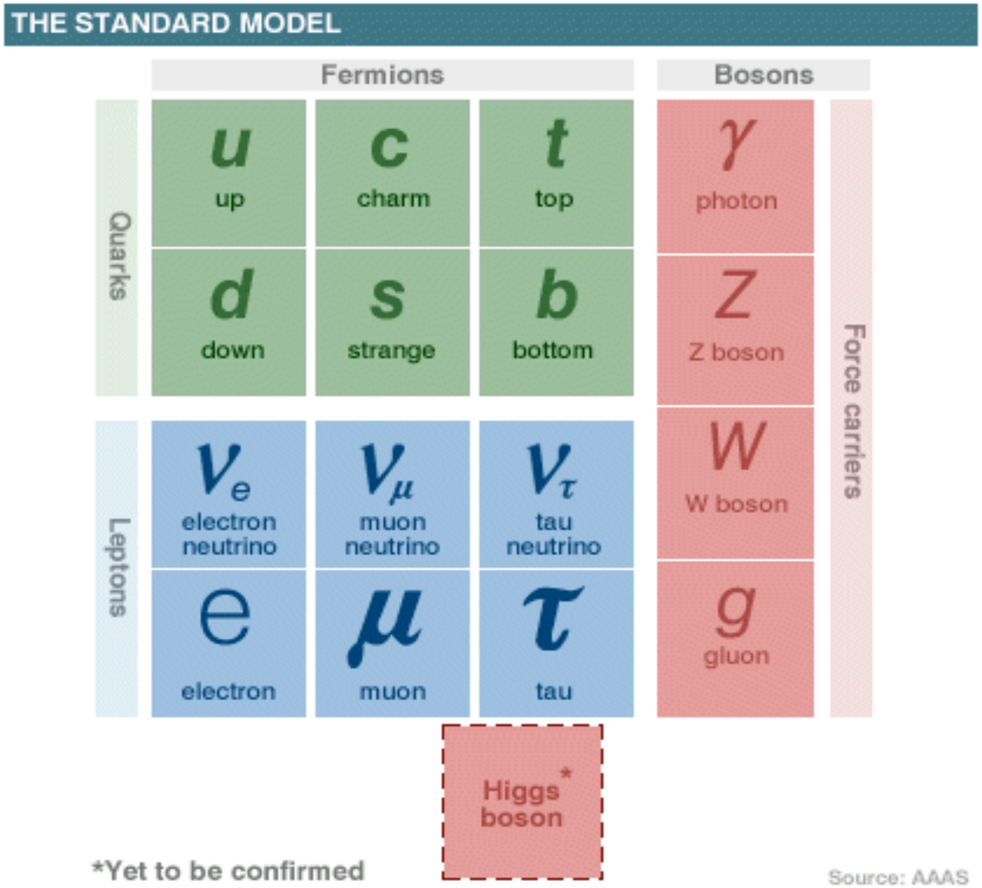


Quark composition of a proton and a neutron (diagrams from *Wikipedia*)



Gluons holding quarks together to form a proton (diagram from *Scientific American*)

Here's a closer look at protons and neutrons, composed of the elementary particles *up quarks (u)* & *down quarks (d)* and held together by *gluons (g).*



- The Standard Model is a theory devised to explain how sub-atomic particles interact with each other
- There are 16 particles that make up this model (12 matter particles and 4 force carrier particles). But they would have no mass if considered alone
- The Higgs boson explains why these particles have mass. Particles acquire their mass through interactions with an all-pervading field, called the Higgs field, which is carried by the Higgs boson.
- There are now signs that the Standard Model will have to be extended by adding new particles that play roles in high-energy reactions.

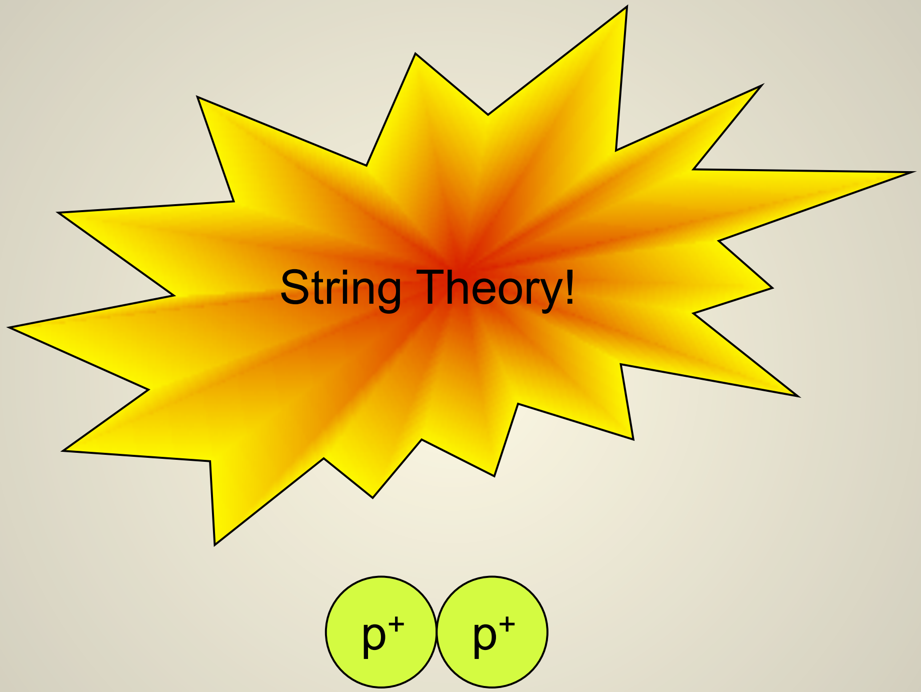
These particles are organized into one nice, neat package known as the Standard Model

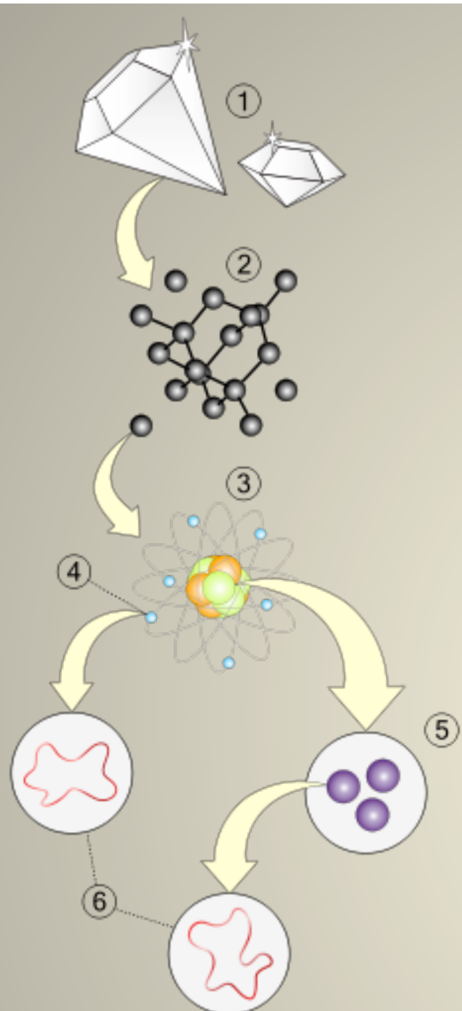
Answers to Question #1

- As we just saw, the LHC is an incredibly complex machine that is designed to probe deeper into the world of particle physics than ever before. This accelerator and the detectors that will capture the data will continue to fascinate and amaze people for years to come. Let's continue on our journey and keep asking questions and maybe even finding answers!

So…why study proton collisions?

- As we know, there are many unanswered questions about the world in which we live.
- This world spans the scale from the universe to particles smaller than a proton.
- Some of the questions and topics that will be explored in the years to come at CERN include:

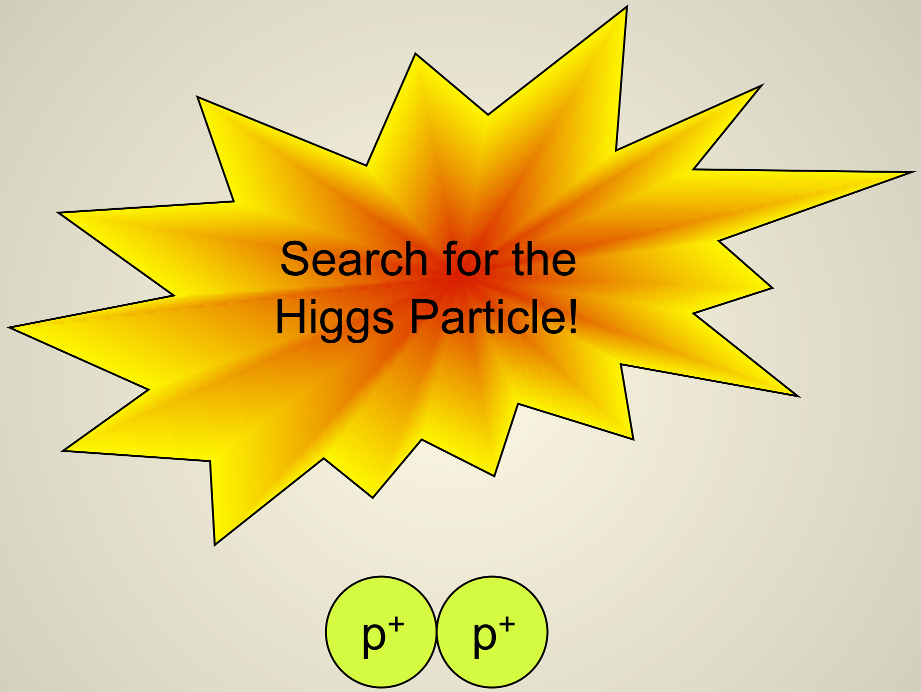

String Theory!
p^+
p^+



Levels of magnification:
1. Macroscopic level - Matter
2. Molecular level
3. Atomic level
4. Subatomic level - Electron
5. Subatomic level - Quarks
6. String level

What is String Theory?

A theory that treats elementary particles as infinitesimal one-dimensional "stringlike" objects rather than dimensionless points in space–time. Different vibrations of the strings correspond to different particles. The most self-consistent string theories propose 11 dimensions; 4 correspond to the 3 ordinary spatial dimensions and time, while the rest are curled up and not perceptible.


Search for the
Higgs Particle!
p+
p+

What (who) is the Higgs?

Yes, this is Peter Higgs and he did propose the existence of the Higgs boson.

Yes, this picture shows that he was found at CERN.

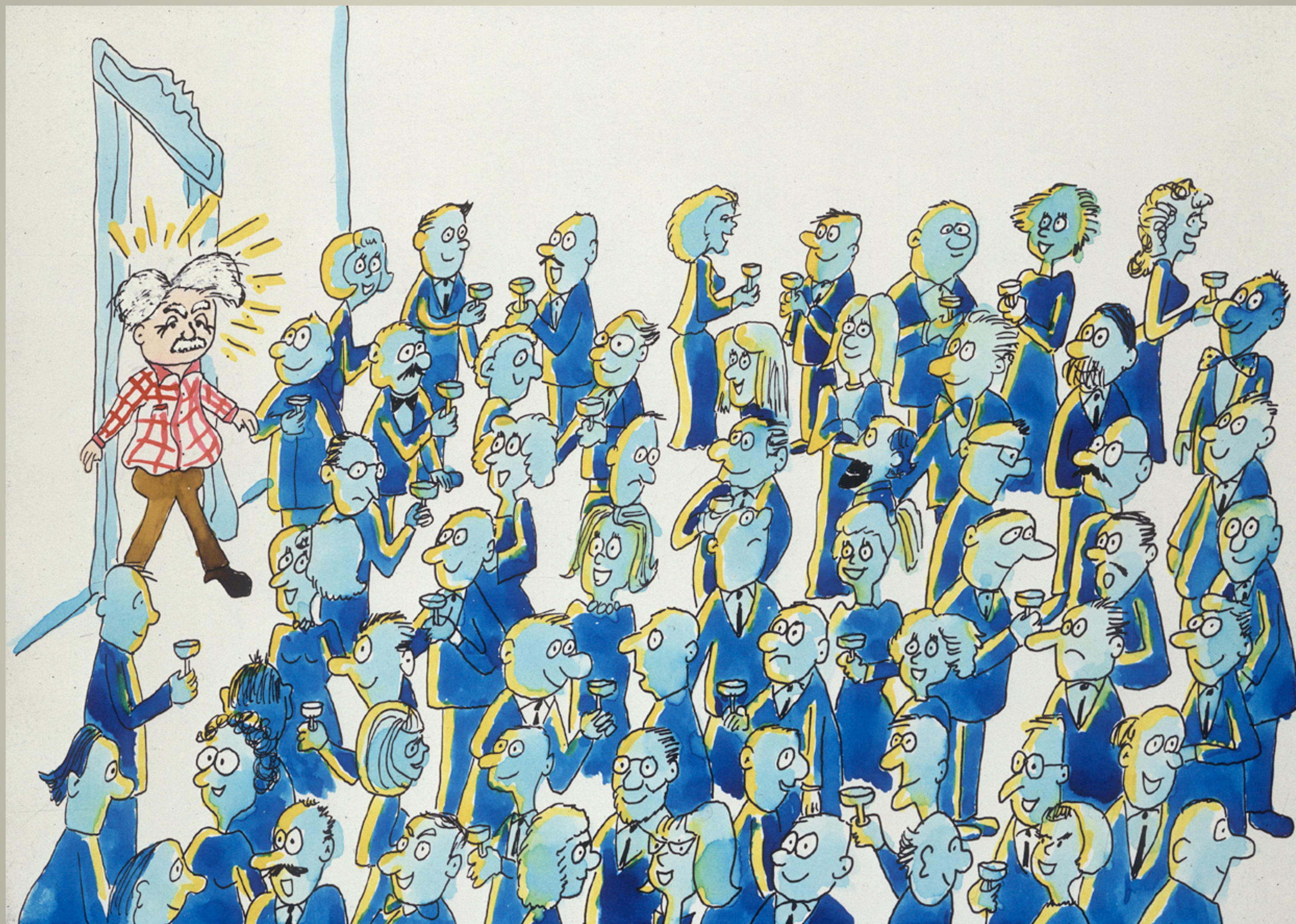
But, this is not the Higgs that is being sought at the LHC.

The Higgs boson in three easy slides

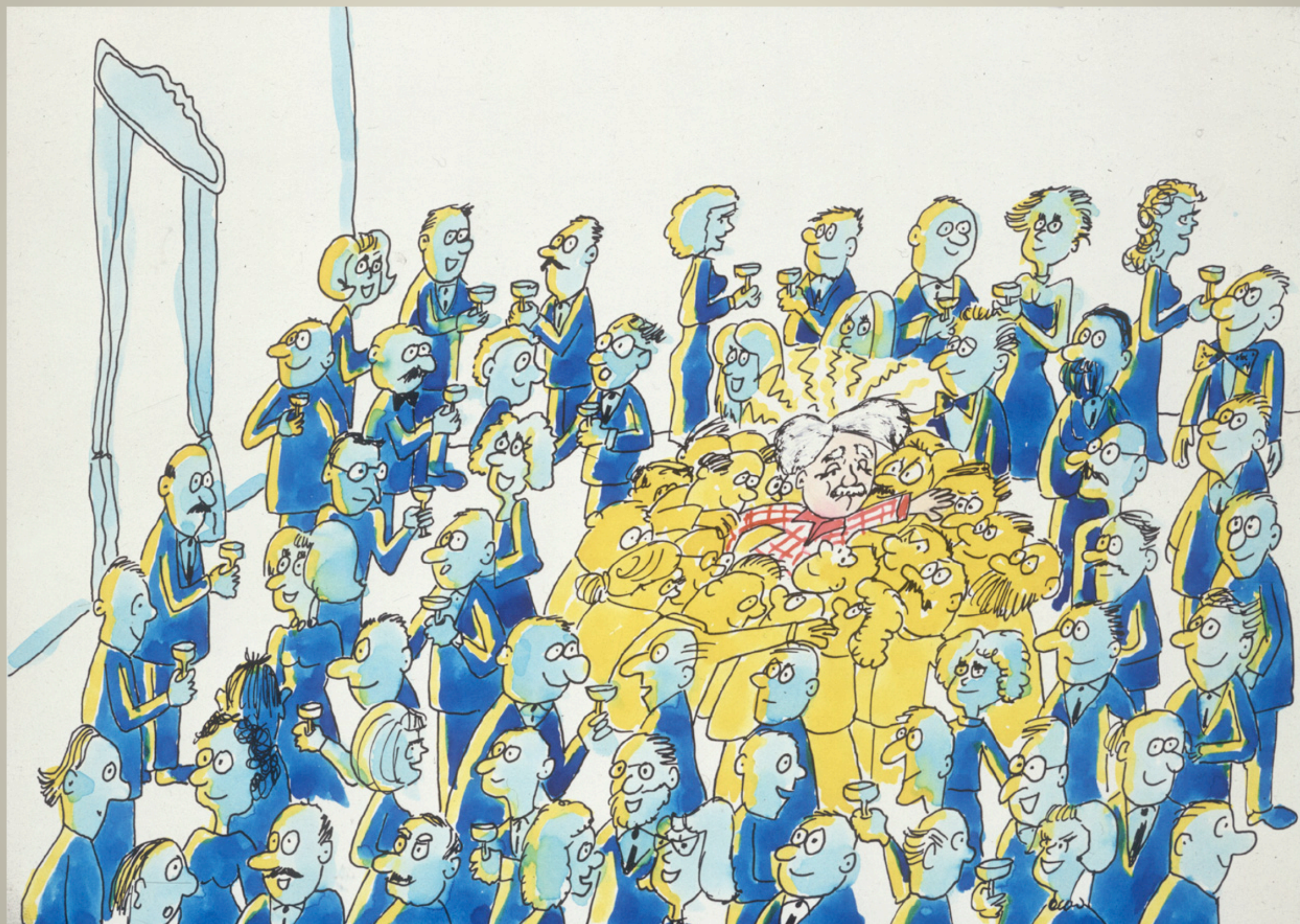
The next three slides are intended to illustrate what many physicists hope to find at the LHC. What's been called the "elusive Higgs boson" and the "God particle" can be described as the mechanism which extends the Standard Model to explain how particles acquire the properties associated with mass. The Higgs boson is the exchange particle in this field.

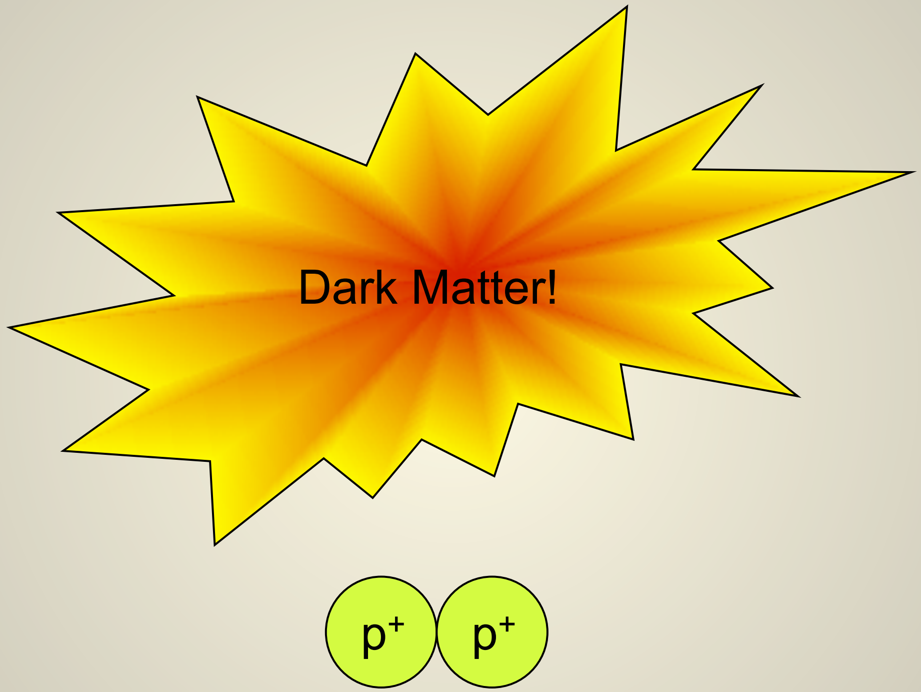
Roomful of people = scattered particles with mass

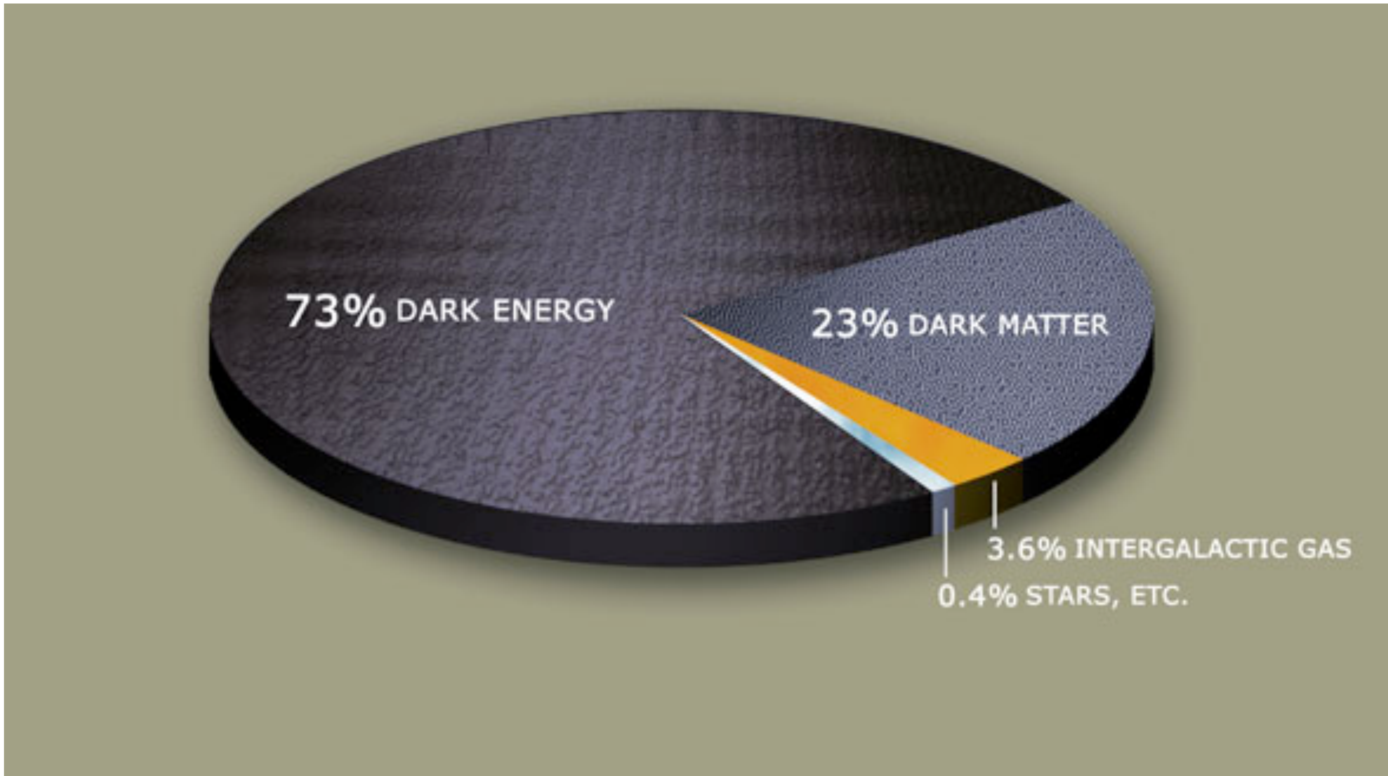
Famous person entering room = massive particle



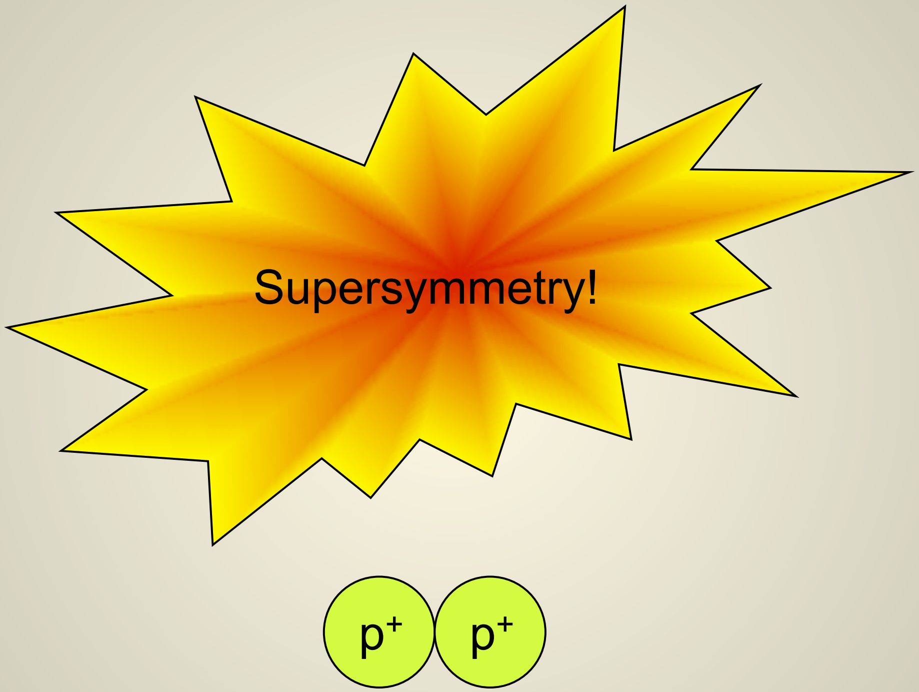
Swarm of people = group of particles = mass




Dark Matter!
p^+
p^+

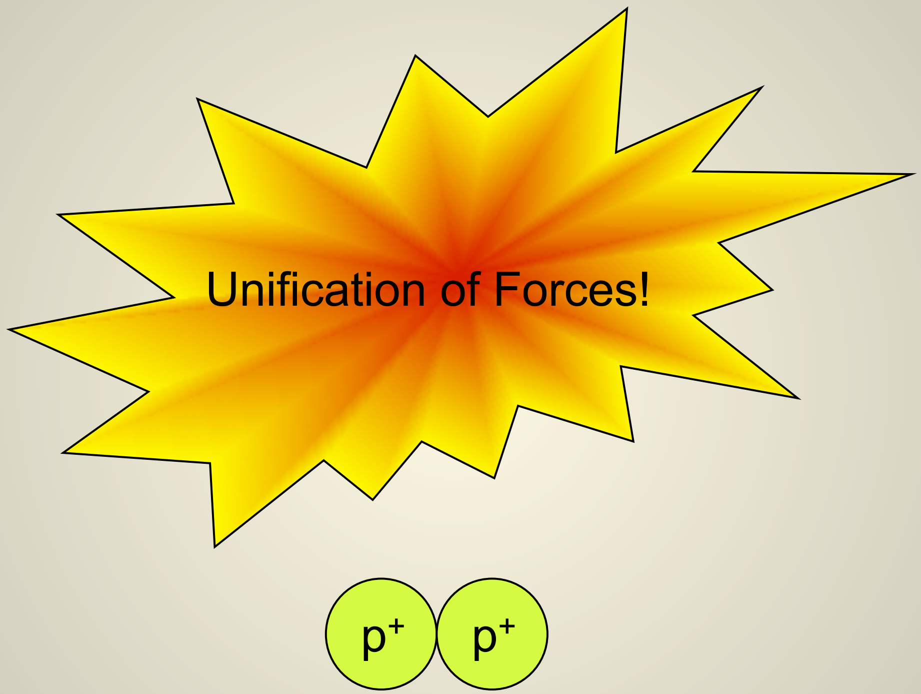


Dark matter is matter that does not interact with the electromagnetic force, but whose presence can be inferred from gravitational effects on visible matter. According to present observations of structures larger than galaxies, as well as Big Bang cosmology, dark matter accounts for the vast majority of mass in the observable universe.


Supersymmetry!
p+
p+

Superwhat?

- **Supersymmetry** (often abbreviated SUSY) is a symmetry that relates elementary particles of one spin to another particle that differs by half a unit of spin and are known as superpartners. In other words, in a supersymmetric theory, for every type of boson there exists a corresponding type of fermion, and vice-versa.
- If supersymmetry exists, it allows the solution of two major puzzles. One is the hierarchy problem - on theoretical grounds there are huge expected corrections to the particles' masses, which without fine-tuning will make them much larger than they are in nature. Another problem is the unification of the weak interactions, the strong interactions and electromagnetism.


Unification of Forces!
p+
p+

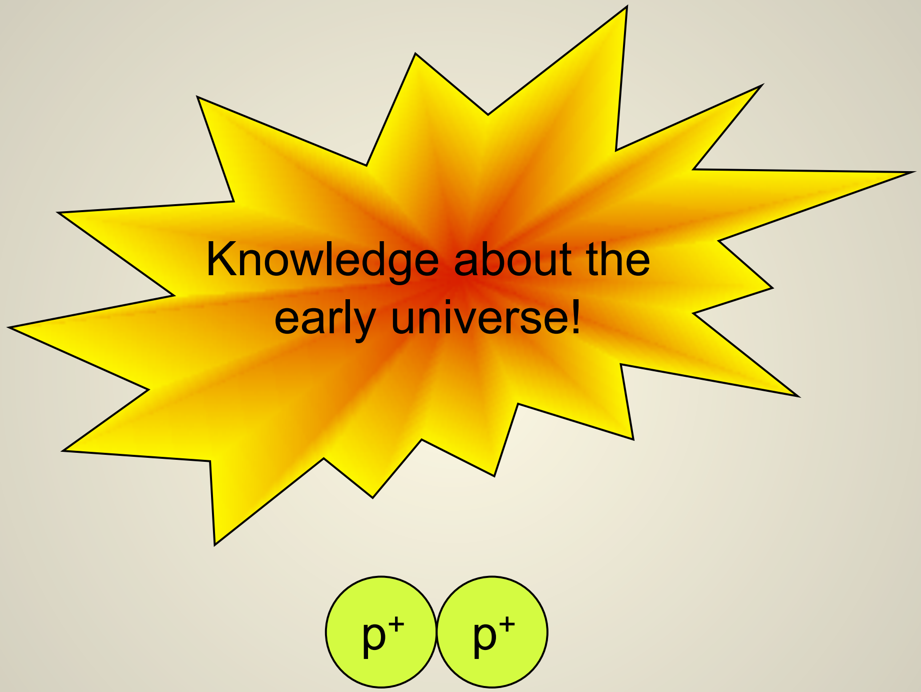
Could these fundamental forces be unified into one? LHC could provide the answer!

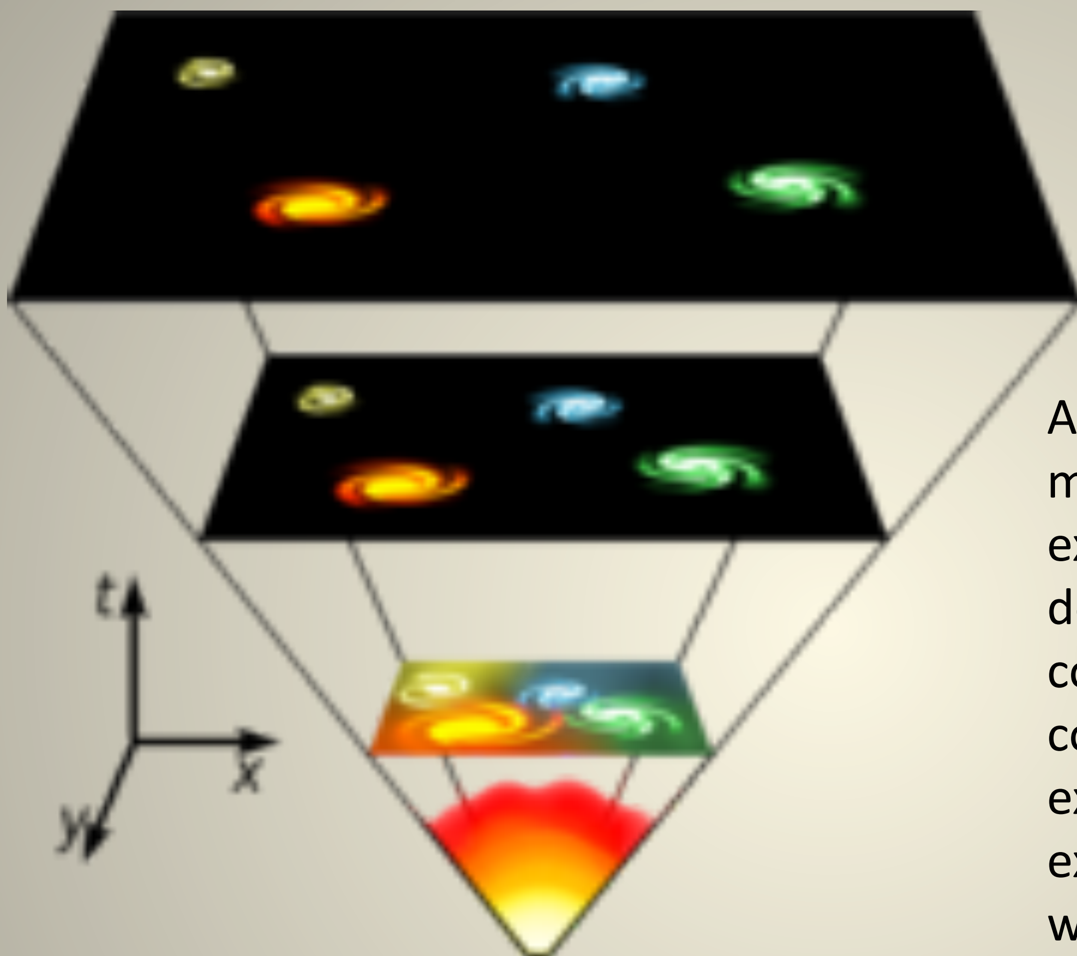
gravity

strong force

weak force

electromagnetism


Knowledge about the
early universe!
p+
p+



According to the Big Bang model, the universe expanded from an extremely dense and hot state and continues to expand today. A common and useful analogy explains that space itself is expanding, carrying galaxies with it, like raisins in a rising loaf of bread. BUT, what did it look like very early in its life? LHC may help answer this question!

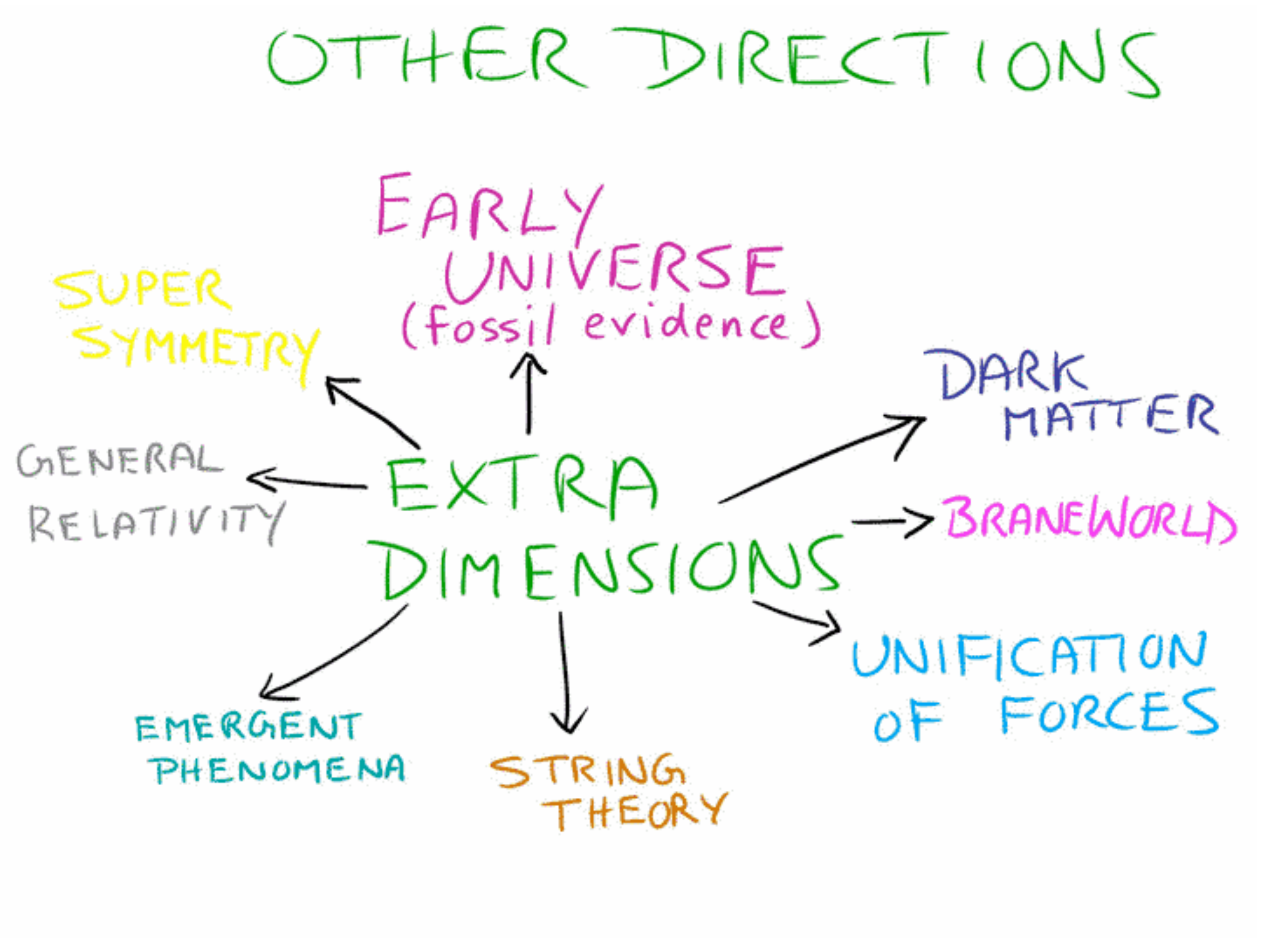
Question #2: What can we learn about our world from the LHC?

Our quest for answers on this part of our journey will be guided by RAMAN SUNDRUM, a Professor of Physics in the Department of Physics and Astronomy of the Johns Hopkins University. His research interests include the unification of electromagnetism and the weak nuclear force as well as the study of Dark Energy.

The expertise of our tour guide for question #2 : Dr. Raman Sundrum

The next several slides (46 – 52) are modified versions of slides that were produced and presented by Dr. Raman Sundrum. They address some of the unanswered questions to which he (and others) will be searching for answers using results obtained from the LHC.

What can we learn about our world from the LHC?



Will it be possible to find the Higgs Boson?

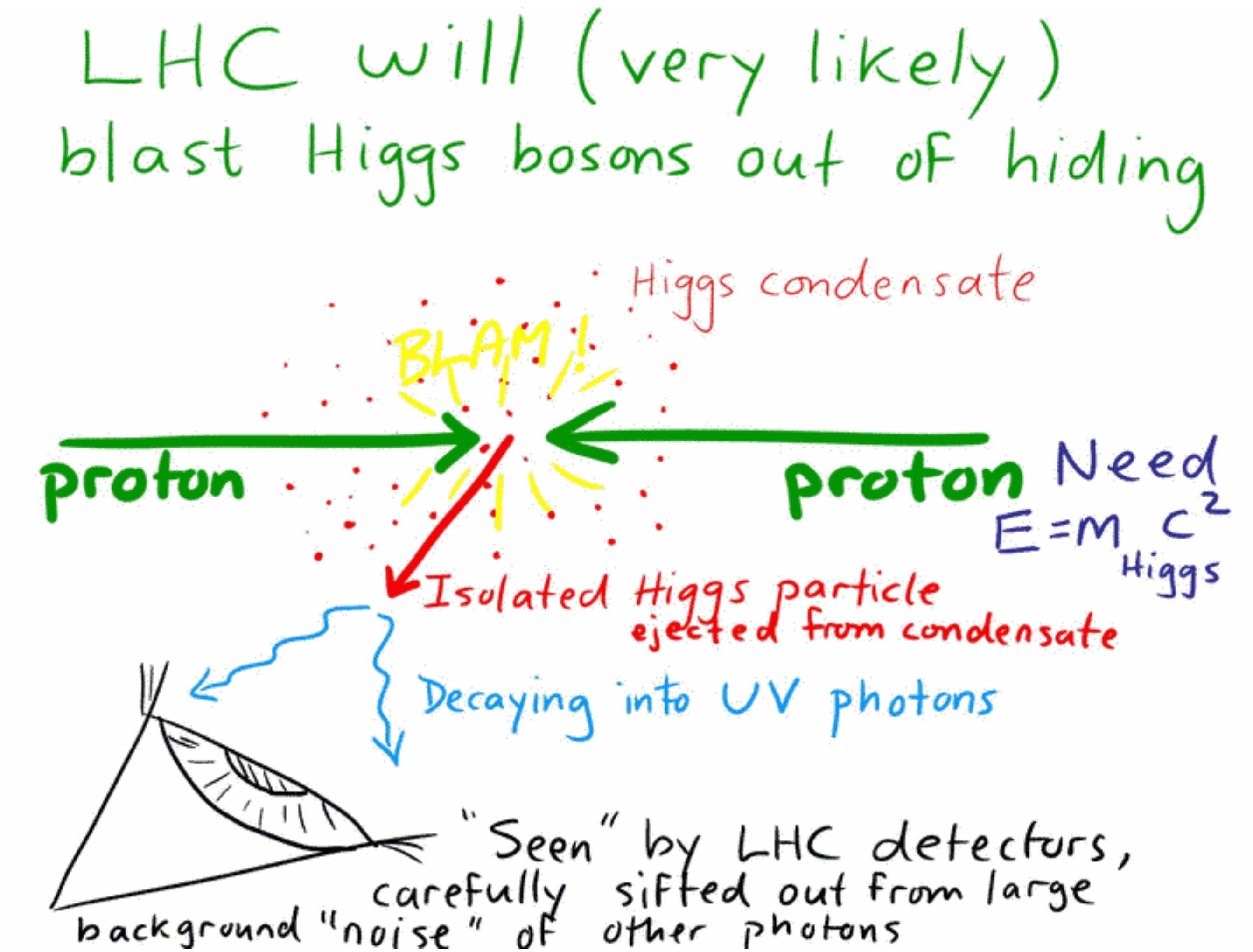
"STANDARD MODEL"

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

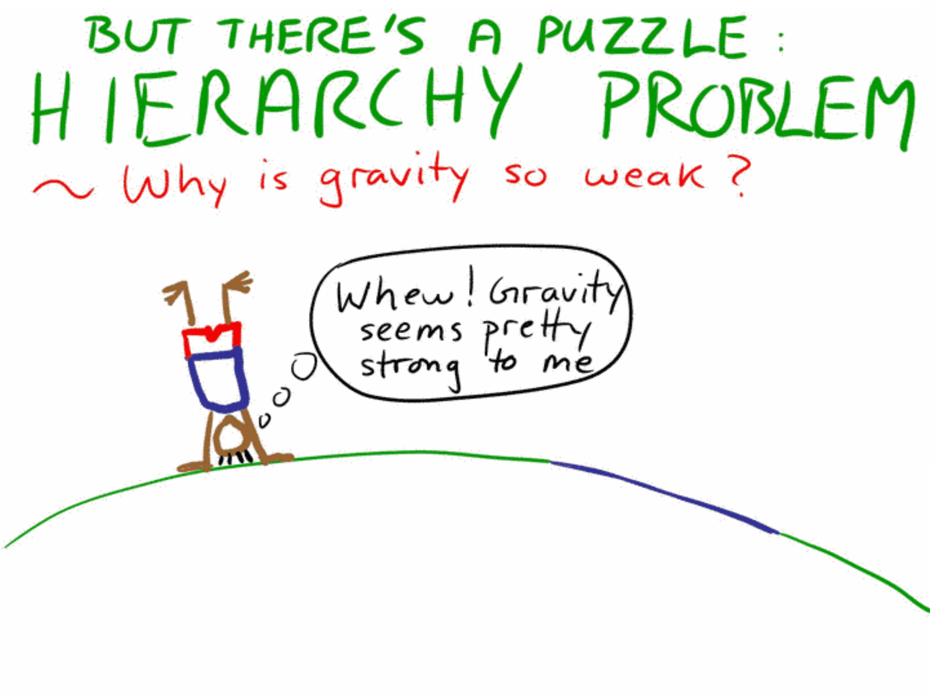
(a) is extremely difficult to detect, evading all tests for an aether etc.

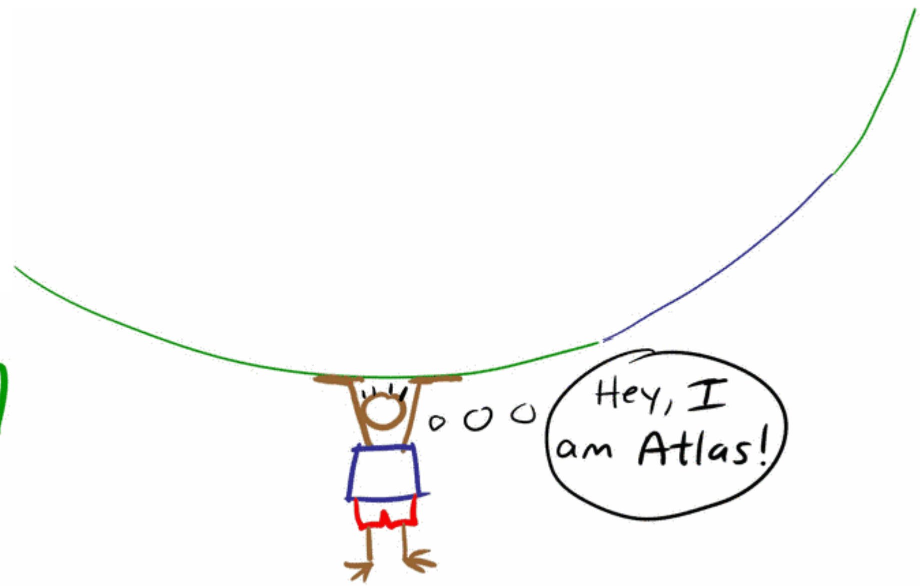
(b) slow down elementary particles below light speed (so they acquire mass)

How will the Higgs boson be found?



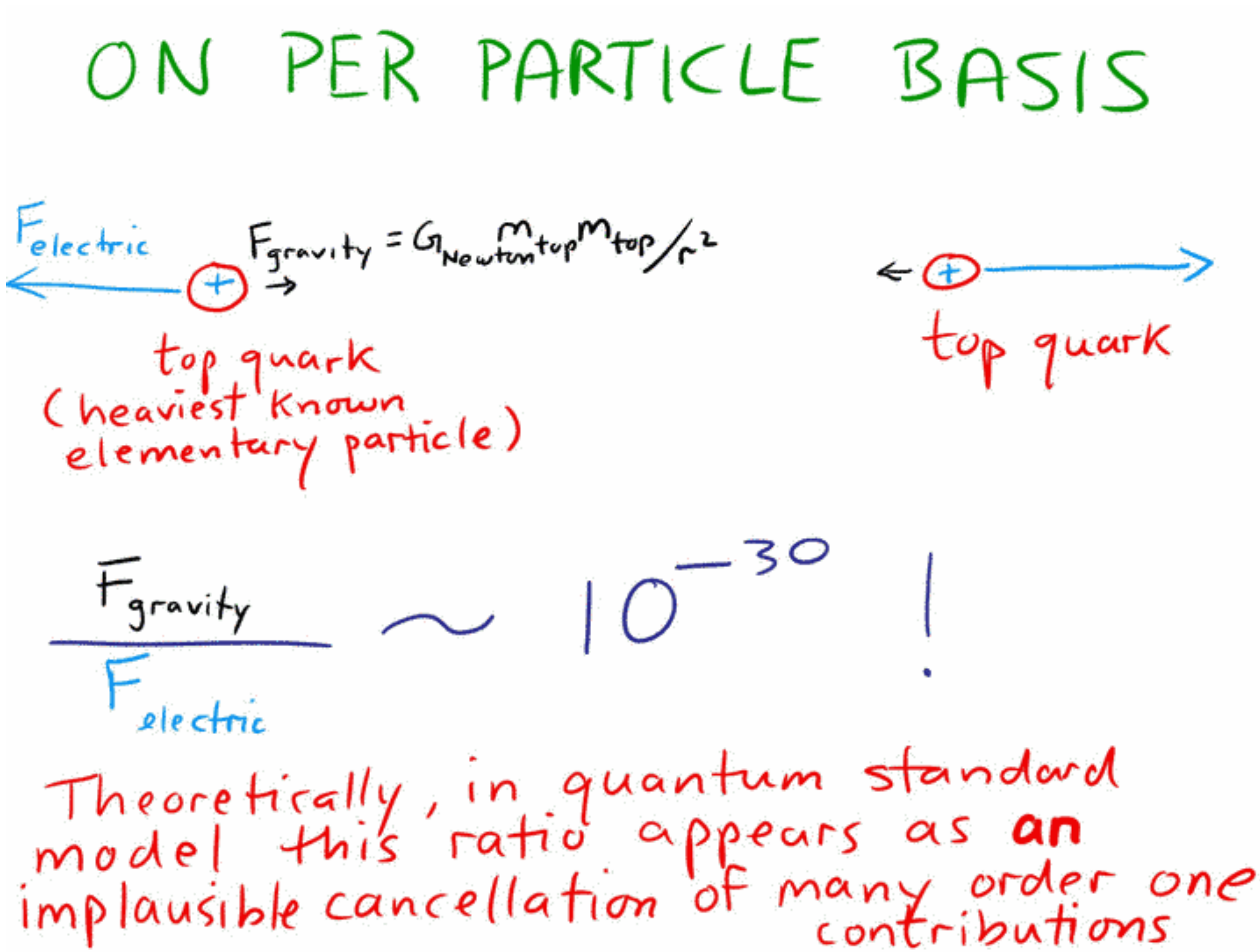
What about unification of forces?





The force that pulls on us is equal and opposite to the force with which we push back

How does the gravitational force compare to the electromagnetic force?



Here is one possible answer to this question

EXTRA DIMENSIONS OF SPACETIME

may resolve this puzzle:

Earlier: Supersymmetry, sometimes called "Fermionic extra dimensions"

BraneWorld scenarios:
"Large Extra Dimensions" Arkani-Hamed, Dimopoulos, Dvali '98
"RS 1" Randall, Sundrum '99

Here we discuss Warped Compactification (or RS) with Bulk Standard Model

How do we think about Extra Dimensions?

And what about the study of string theory at the LHC?

STRING THEORY

is the best developed approach
to the unification of
General Relativity + Quantum Mechanics
replacing fundamental particles by
fundamental STRINGS
and contains extra dimensions
and contains Cosmic HyperMirrors.
and more successful stringy
generalizations of Kaluza & Klein's
unification of forces

Answers to Question #2?

Dr. Sundrum's slides have just shown us that many questions are being pursued and that the answers to these questions could bring valuable insight into our understanding of the world in which we live and how it behaves… Thank you, Dr. Sundrum! Let's continue on our journey and keep asking questions and maybe even finding answers!

Question #3: How can the LHC help us learn about other physics ?

Our quest for answers on this part of our journey will be guided by KEVIN MCFARLAND, a Professor of Physics at the University of Rochester. He is the scientific co-spokesperson of the MINERvA neutrino experiment currently under construction at Fermilab.

The expertise of our tour guide for question #3 : Dr. Kevin McFarland

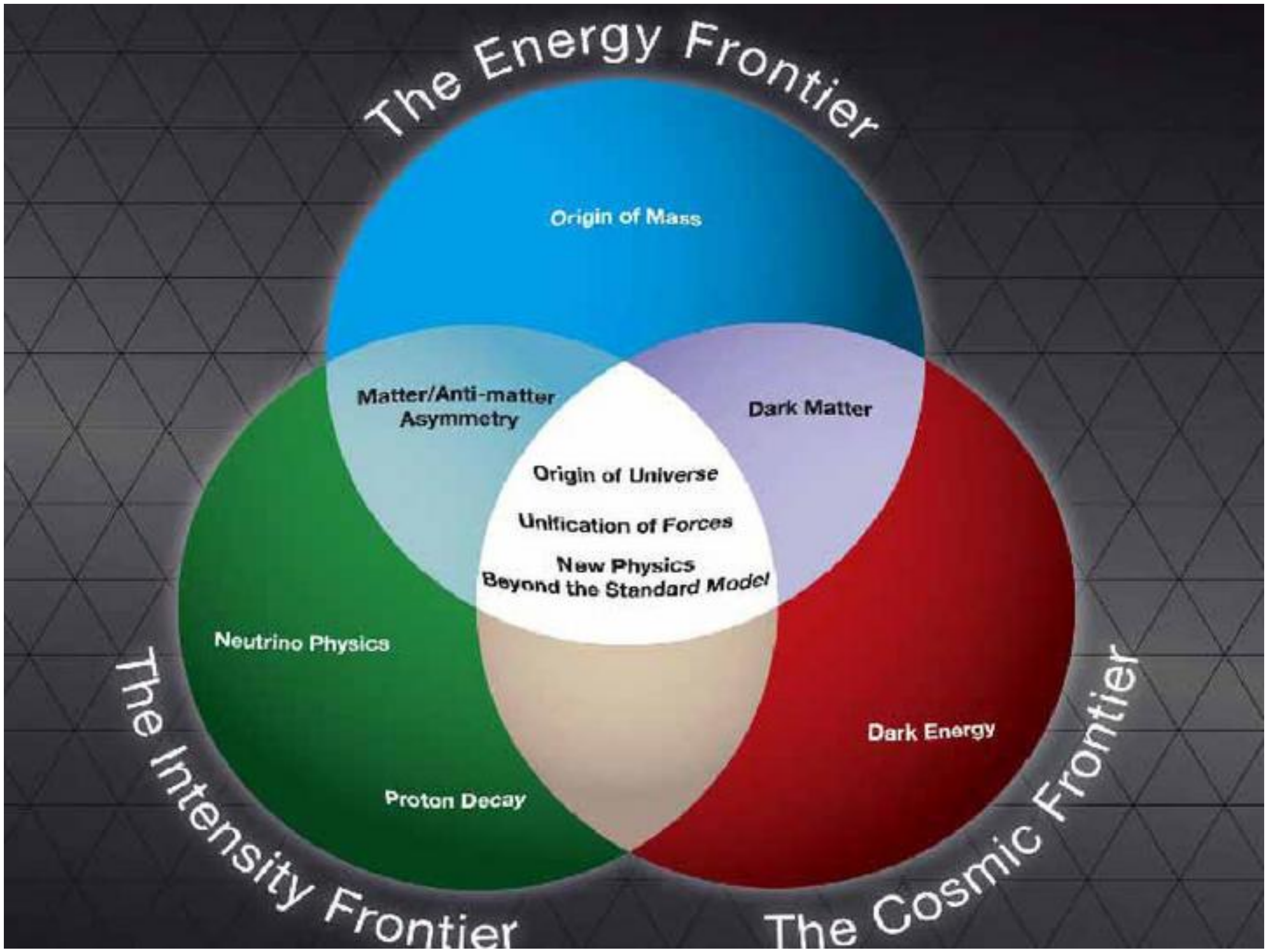
The next several slides (56 – 64) are modified versions of slides that were produced and presented by Dr. Kevin McFarland. They address some of the applications of LHC data and research findings to other particle physics topics and laboratory sites around the world.

Our journey of exploration leads us to new…

Frontiers

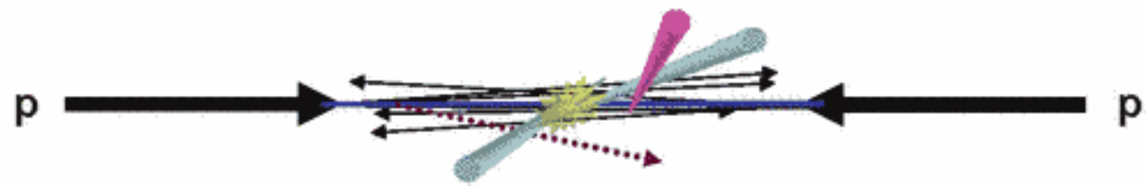
- Particle Physics is a science of exploration
  - We may have good ideas of what we might find, but we do not know until we look
- The frontier of energy (per particle) is our most important tool, *but it is only one tool*

Multiple overlapping frontiers can provide even more answers



What is the *Intensity* Frontier?

- The LHC is optimized for maximum energy in the collision of two protons
  - 14 TeV (or 0.0000002 Joules) per proton pair



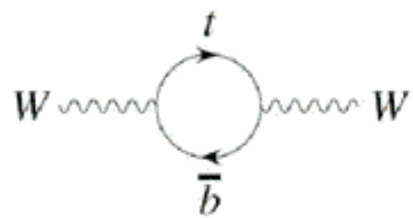
  - occasionally a large fraction of that energy is available for production of new particles
  - therefore, LHC must store and collide many protons to be at the energy frontier

Where is the ***Intensity*** Frontier?

- There are many intensity frontiers
  - Bottom quarks: Stanford (recently ended) and KEK in Japan; next facility in Italy?
  - Charm quarks and tau leptons: Cornell (recently ended), Beijing
  - Weak bosons: successful CERN and Stanford programs concluded in the late 1990s
  - Neutrons and Photons: many facilities, mostly aimed at biological and material sciences
- Active development in particle physics: *proton sources for neutrinos*

What science is done at the ***Intensity*** Frontier?

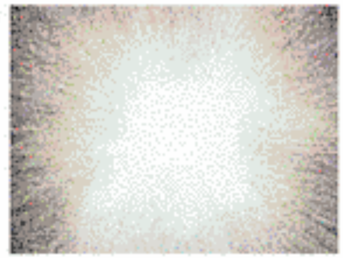
- We study the “shadows” of high energy phenomena with quantum fluctuations



- We explore the most difficult corner of the known building blocks of matter…
  the neutrino

Where are Neutrinos Found?

- We should find neutrinos anywhere there are weak interactions!



- The early Universe
  - Decays of heavy generations left a waste trail of 100/cm^3 of each neutrino species
  - They are (now) very cold and ***slow*** and hard to detect
  - But if they have even a very small mass, they are a significant part of the mass of the universe
    - as much as atoms, according to the latest results

Our Goals for Neutrino Oscillations

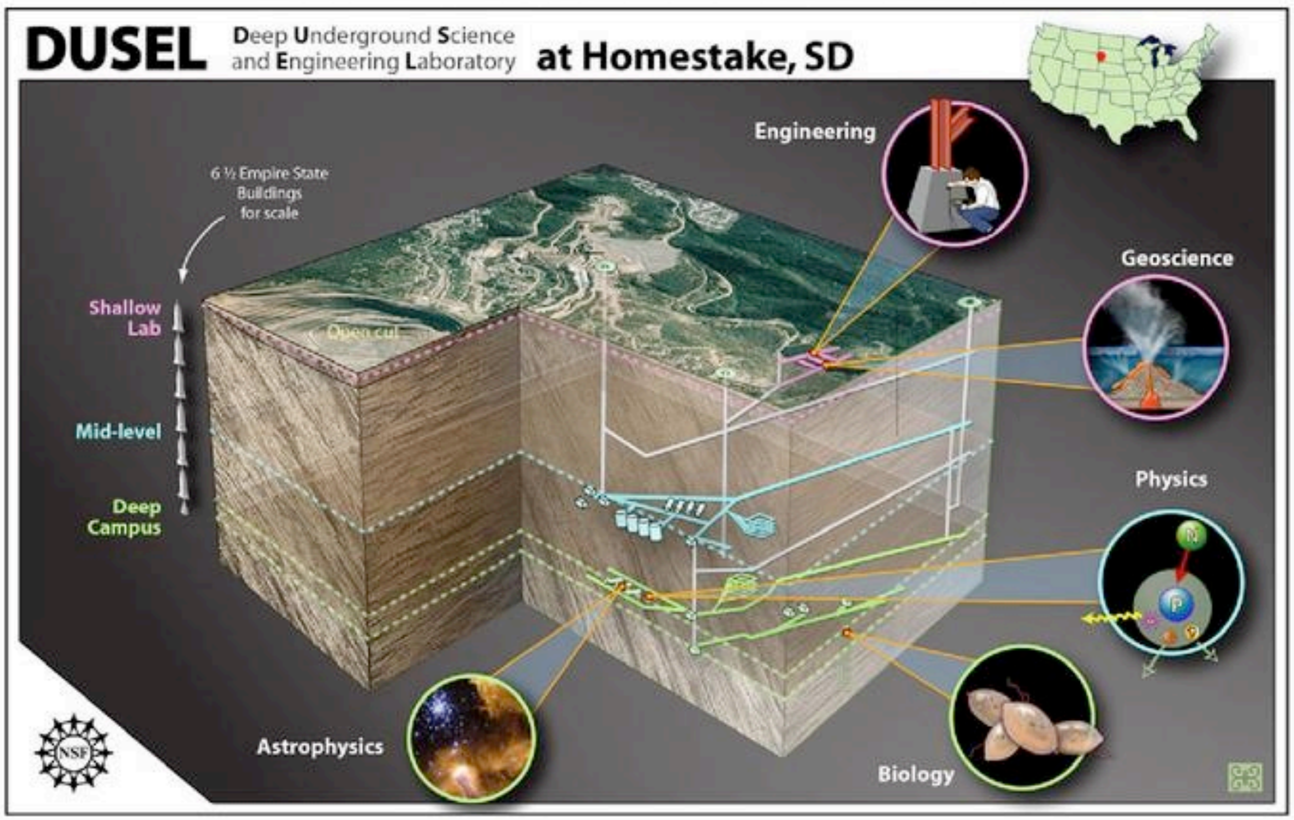
- Can we show that…

  …neutrinos cause a large matter vs. anti-matter asymmetry in the Universe!

  - *Because of three neutrinos, it may be so!*
- We are using intensity frontier accelerators to make neutrinos to study whether or not neutrino anti-neutrino differences seeded this as the Universe cooled…

Possible site for the exploration of other frontiers

A Facility for the Intensity and Cosmic Frontiers…



Our journey to the frontiers of particle physics has led to the following…

Conclusions

- While the LHC is our flagship…

  … particle physics has many frontiers under active exploration

  - These other frontiers inform and motivate our current and future plans for the energy frontier
  - These frontiers also access phenemona the LHC will not address and broaden our reach
    - riskier in the LHC… only a part of our portfolio!

Answers to Question #3?

Dr. McFarland's slides have just shown us that the LHC will assist in answering questions that are being pursued in other locations… Thank you, Dr. McFarland! Let's continue on our journey and keep asking questions and maybe even finding answers!

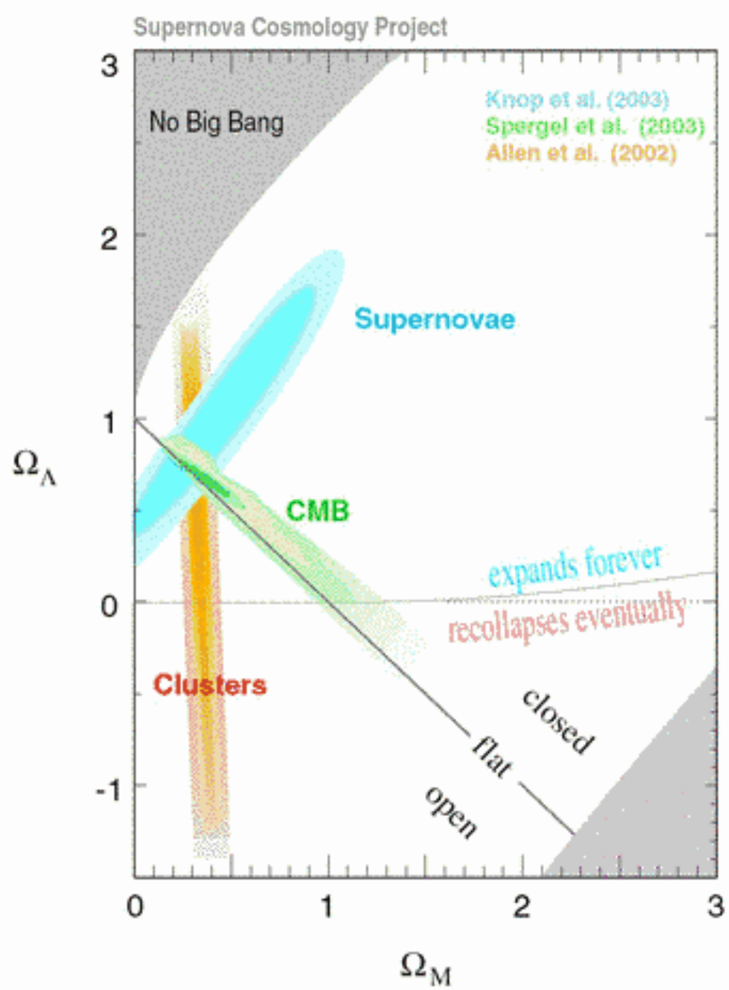
Question #4: What can we learn about the universe from the LHC?

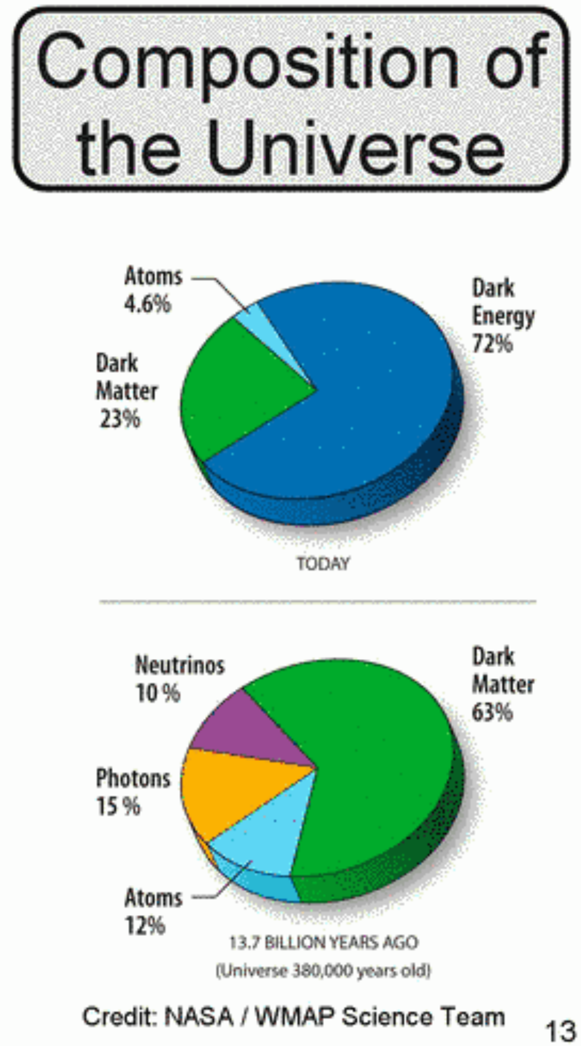
Our quest for answers on this part of our journey will be guided by JAMES WELLS, a Staff Scientist at CERN and Professor of Physics at the University of Michigan. His research interests include the study of elementary particle masses and interactions.

The expertise of our tour guide for question #4 : Dr. James Wells

The next several slides (68 – 74) are modified versions of slides that were produced and presented by Dr. James Wells. They bring us to the questions of missing mass in the universe, what is dark matter, where do we find it, and how do we detect it?

What is the universe made of?





Dark Matter Necessary

Cosmology appears to require existence of dark matter: a special type of matter dissimilar to our own.

These were all rather indirect inferences from early universe cosmology.

Are there more immediate and direct evidences for Dark Matter? Yes. Famous example is galaxy rotation profile.

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The BIG question in cosmology is:

What is the Dark Matter

Many ideas:

- Lightest Supersymmetric Particle (LSP)
- Lightest Kaluza-Klein Excitation of Extra Dimensions
- Technibaryons
- Singlet fermions
- Gravitinos
- Moduli fields
- Axions
- …

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Where is dark matter? Its simple…do the math!

Most Celebrated Example

Supersymmetry: Every particle of the Standard Model (electron, photon, etc.) has a superpartner (selectron, photino, etc.) separated by $\Delta s=1/2$.

Why Supersymmetry? Stabilizes the mass-giving Higgs boson to quantum corrections.

Quantum corrections under control if ~M_Z^2

$$\Delta m_H^2 = \left\{ -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 \right\} + \left\{ \frac{|\lambda_f|^2}{8\pi^2}(\Lambda_{UV}^2 + M_{SUSY}^2) \right\} = \frac{|\lambda_f|^2}{8\pi^2} M_{SUSY}^2$$

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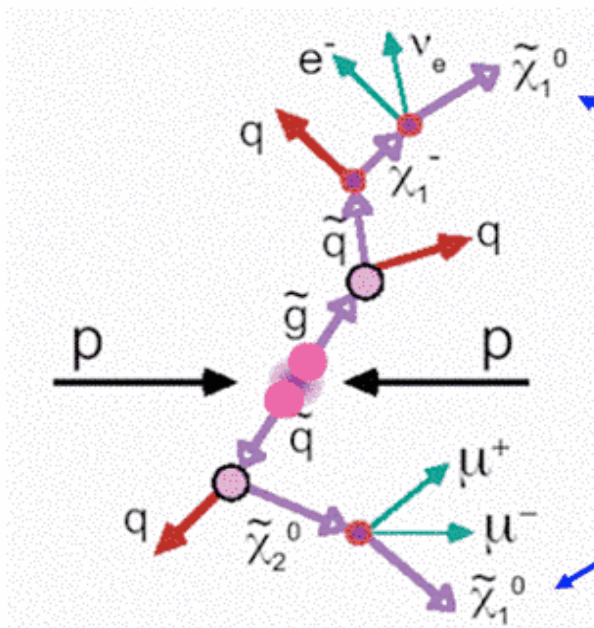
Can the LHC detect a Supersymmetric Particle?

maybe!

Example SUSY Event at LHC



LSP χ is source of much missing energy.

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

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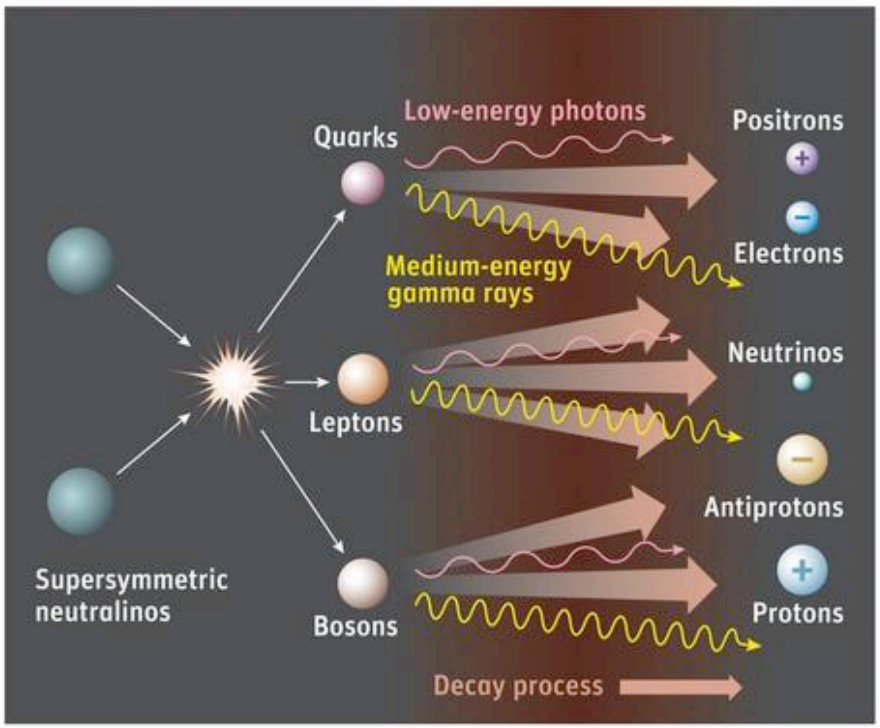
How is dark matter detected?...part 1

Confirming Evidence



Telescope / Gregg Dinderman

Lots of dark matter particles floating around in our galaxy.

Sometimes they find each other and annihilate, producing positrons, antiprotons and photons (gamma rays).

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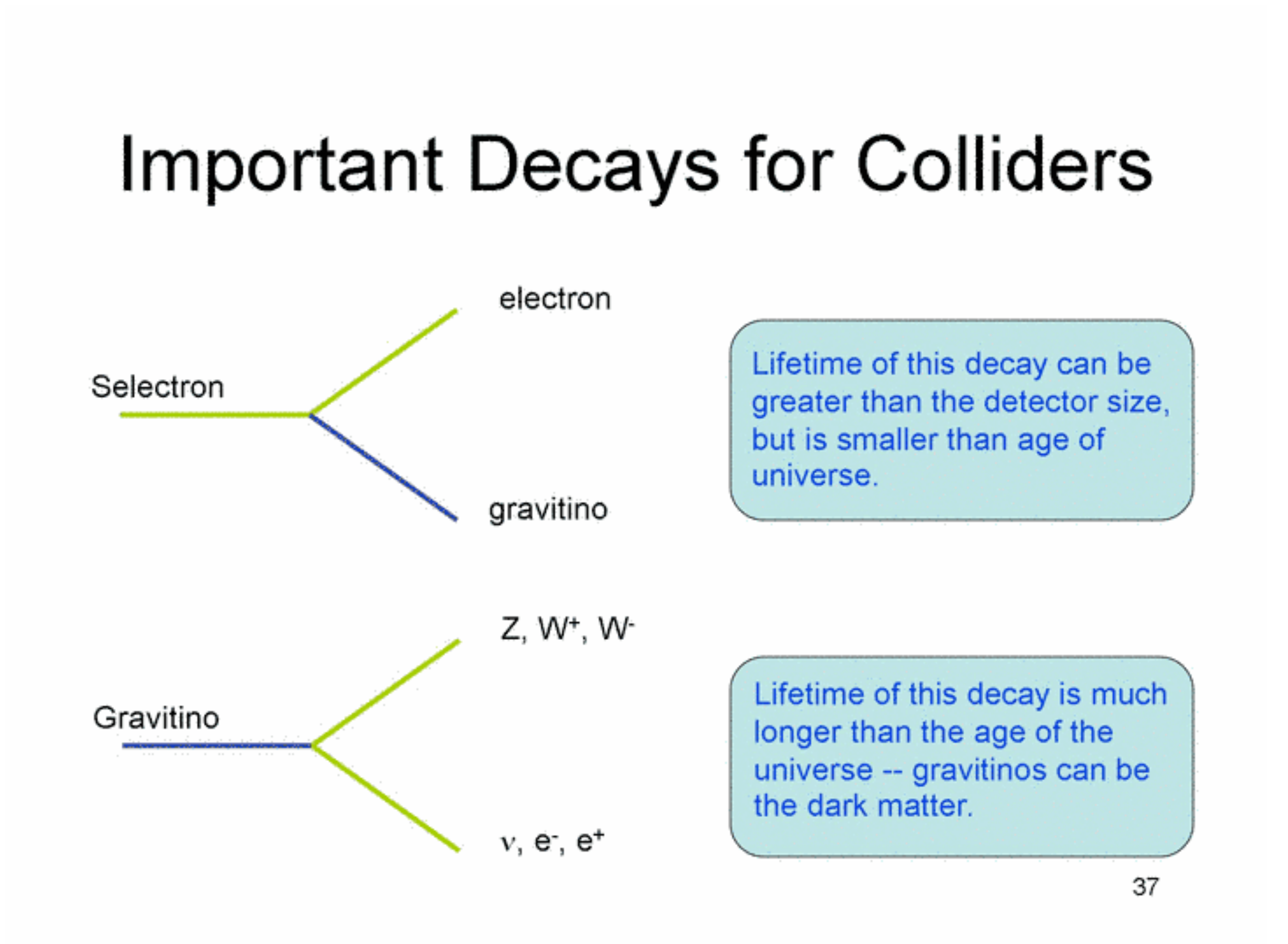
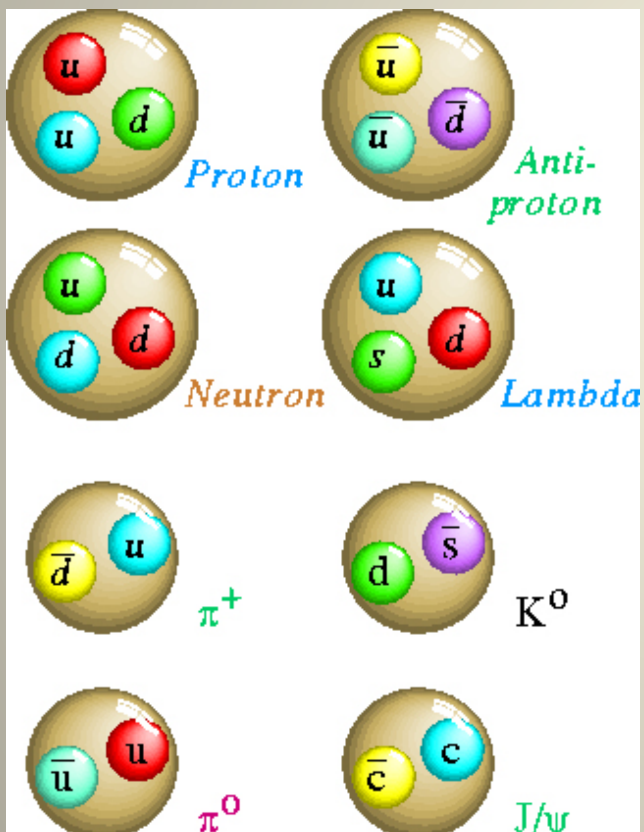
How is dark matter detected?...part 2



Answers to Question #4?

- Dr. Wells's slides have just shown us that the LHC will help answer questions about the composition of the universe and the subatomic particles of which it is composed. Thank you, Dr. Wells!

We have journeyed through possible observations of the world, thanks to the LHC, that span a scale from 10^{-18}m to 10^{26}m…that's 44 orders of magnitude!



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Where do we go next?

That brings this portion of the journey to an end…but not indefinitely…the journey will resume when the LHC starts taking data, answering questions and inspiring new generations of physicists/tour guides. At that time, there will be a new path to follow and new questions to be answered!

Ultimately, the path leads back to…

the LHC!