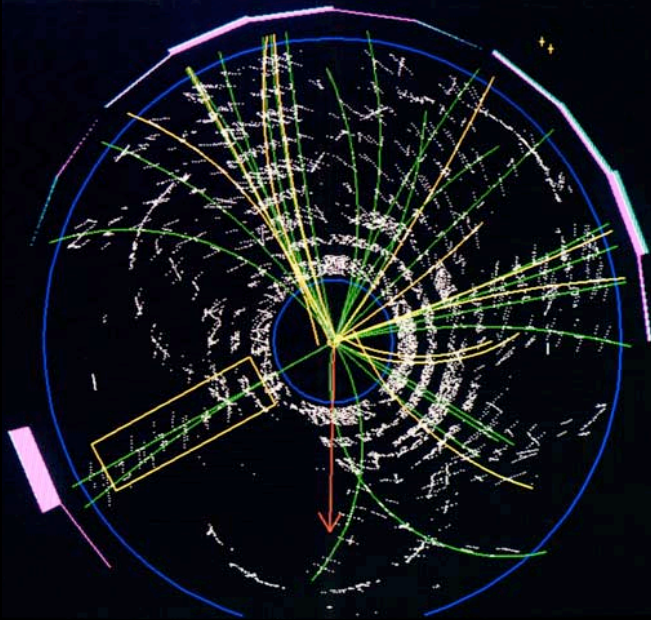


To the Top and Beyond: Particle Physics and the New Century

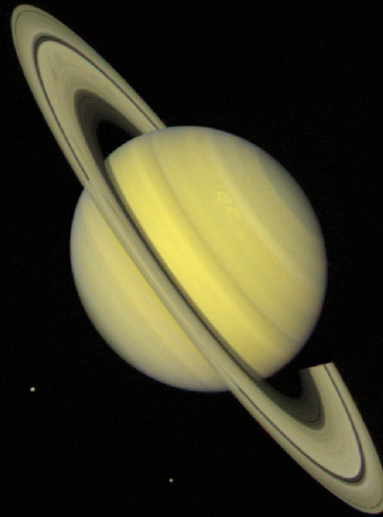
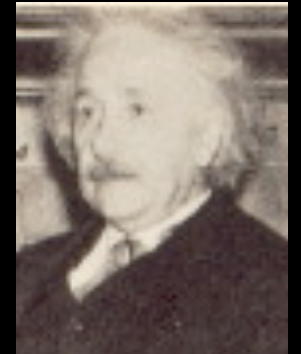


Professor Robin D. Erbacher
University of California, Davis

**What is the world made of?
What holds the world together?
Where did the universe
come from?**

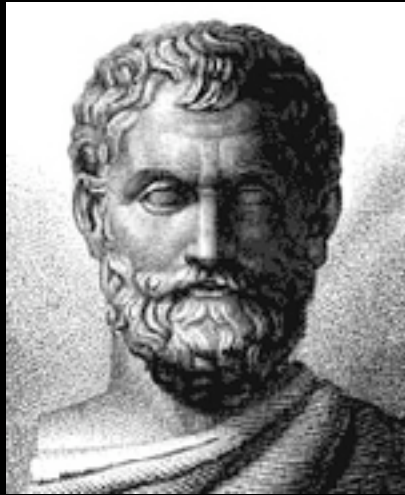


What is the World Made Of?



Ancient Greeks

Empedocles
(490-430 BC)



Four
Fundamental
elements



Atoms:
Indivisible,
Space between



Democritus
(460-370 BC)



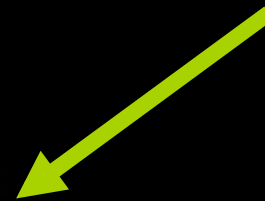
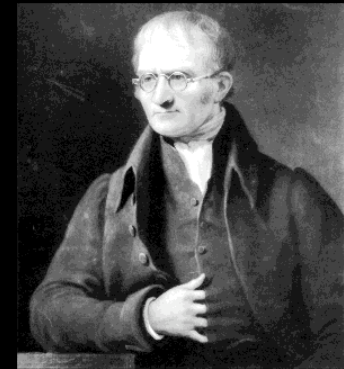
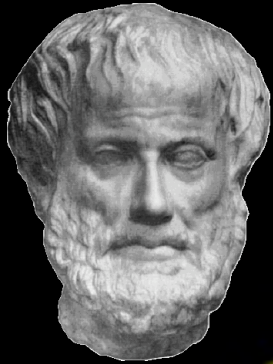
**“By Convention there is color,
by convention sweetness,
by convention bitterness,
but in reality there are atoms and space.”**
-Democritus (400 BC)



Atom = Mushy Ball (c. 1900)

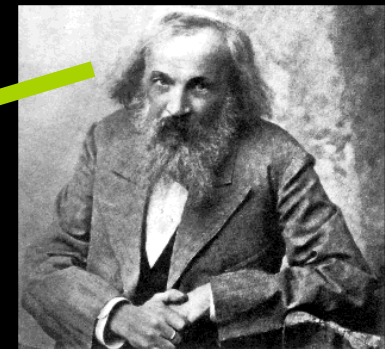
Depths of Matter

Aristotle
(384–322 BC)



Dalton, 1803

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Ha	Unh	Ns	Hs	Mt	Uun	Uuu	Uub	Dy	Ho	Er	Tm	Yb	Lr
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

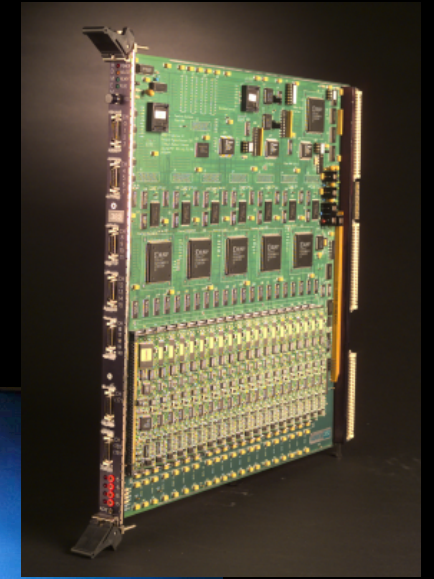
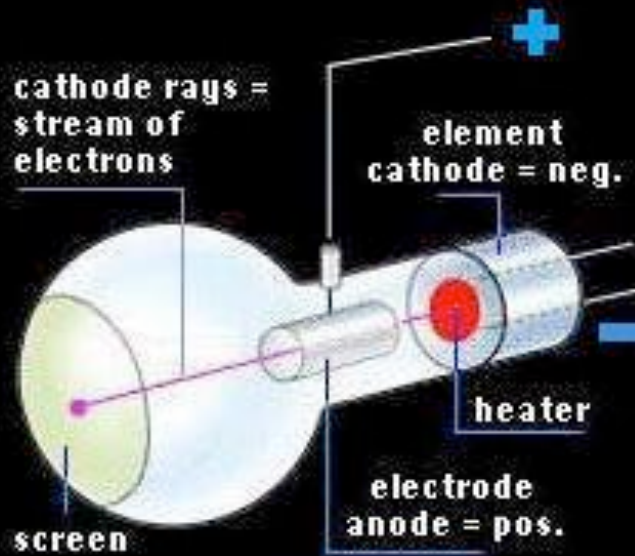


Mendeleev, 1869



J.J. Thomson

Electron is Discovered!

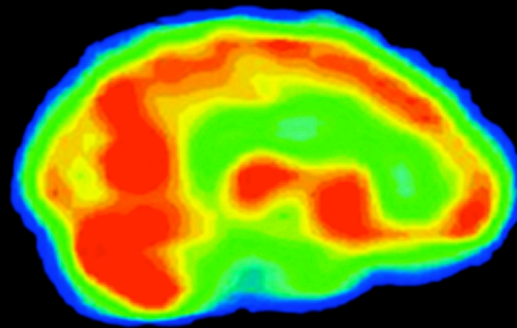
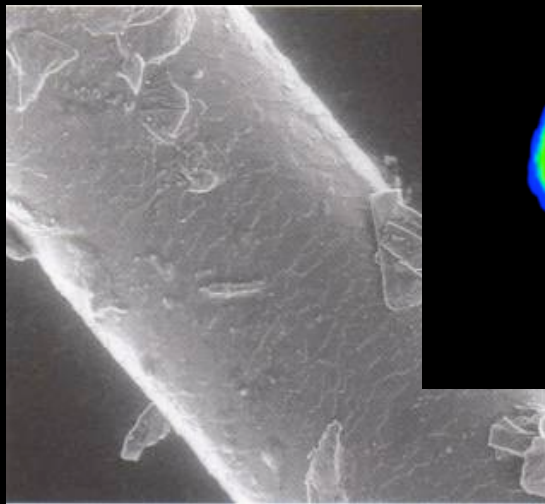
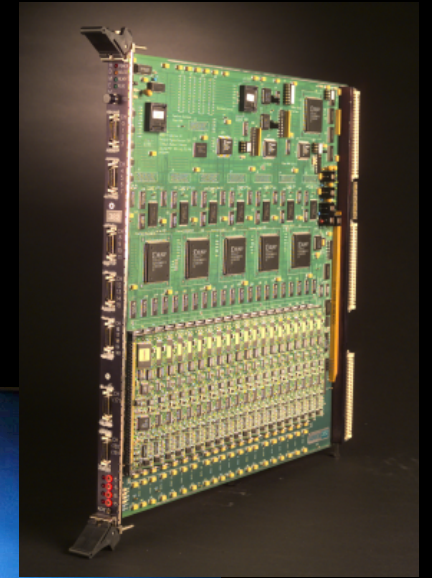
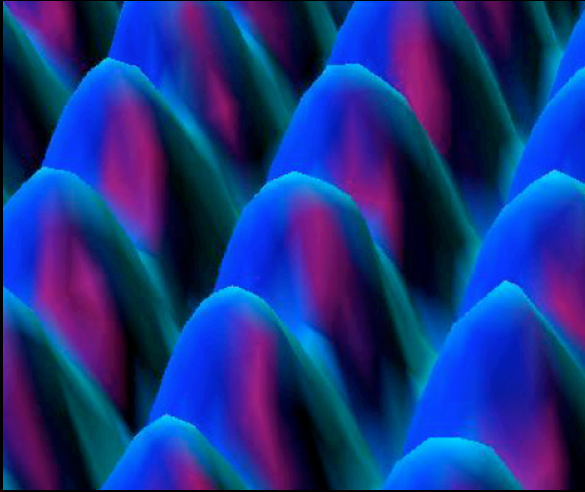


J.J. Thomson, 1895

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of a hydrogen atom?”

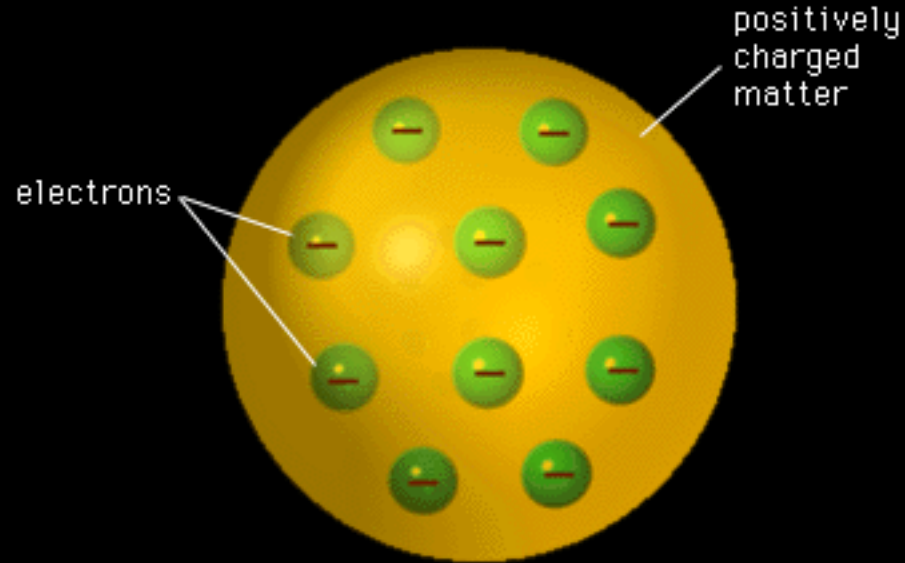


Electron is Discovered!



What are Atoms Made of?

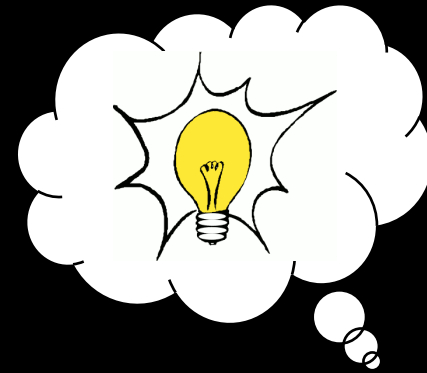
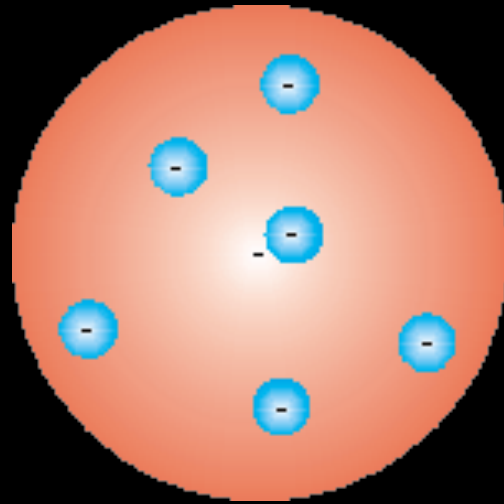
“Plumb
pudding”



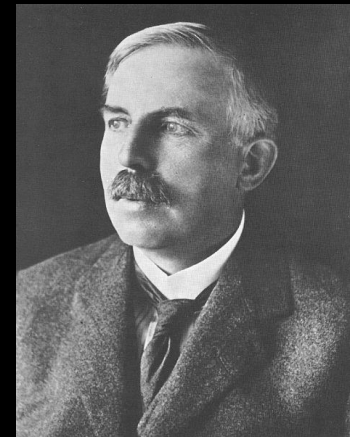
©1998 Encyclopaedia Britannica, Inc.

Thomson Model of the Atom

First Particle Physics Experiment



Atomic model circa 1905

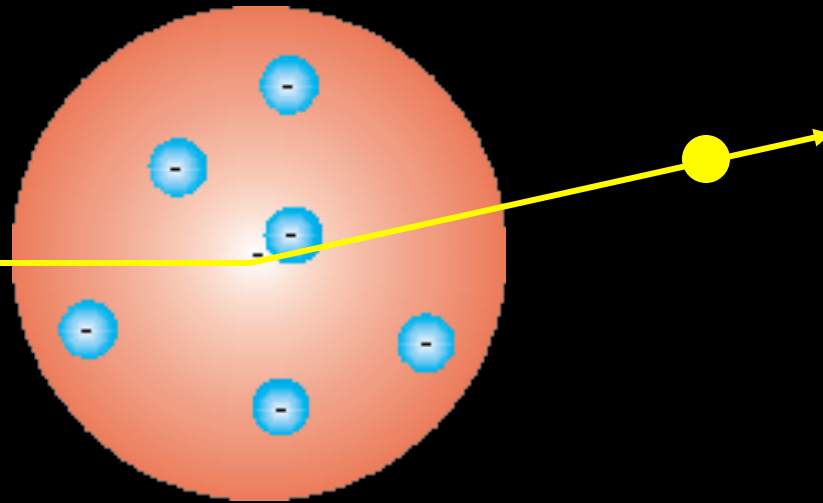


Ernest Rutherford

Rutherford's Experiment, 1909

Rutherford expected:

beam of
 α particles

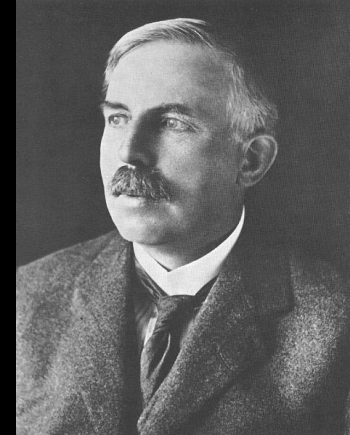
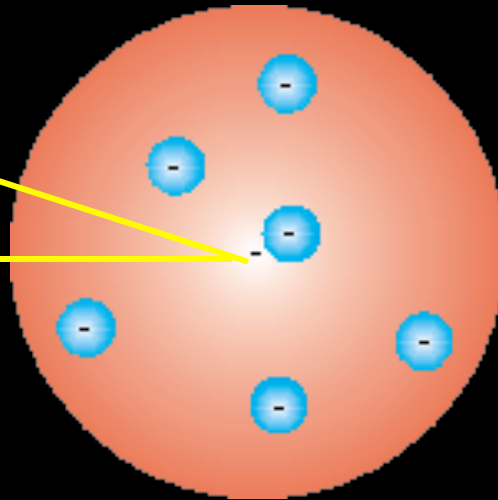


(Geiger and Marsden: grad students)

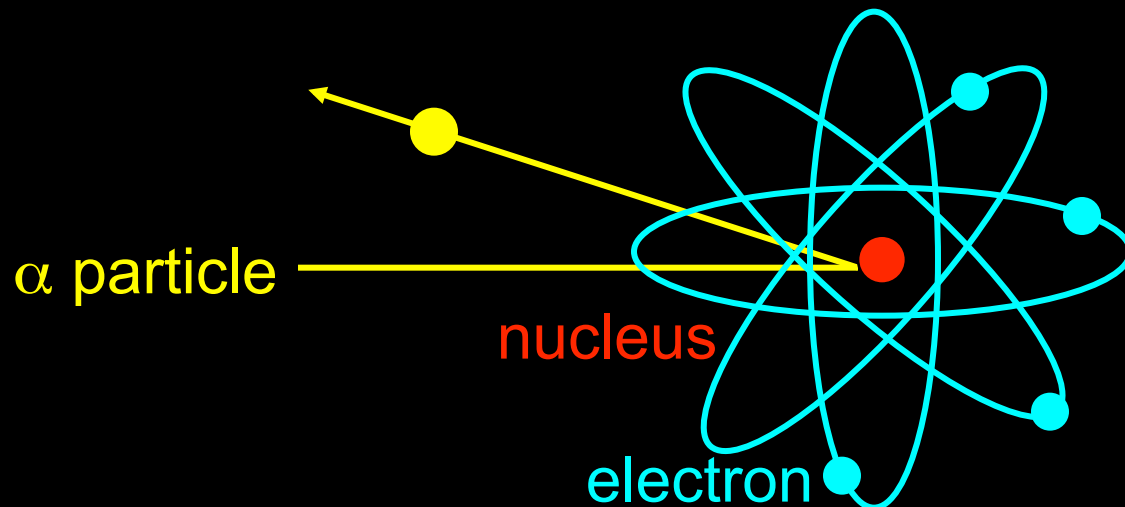
Rutherford's Experiment, 1909

He found:

beam of α particles



Led to new model of atom



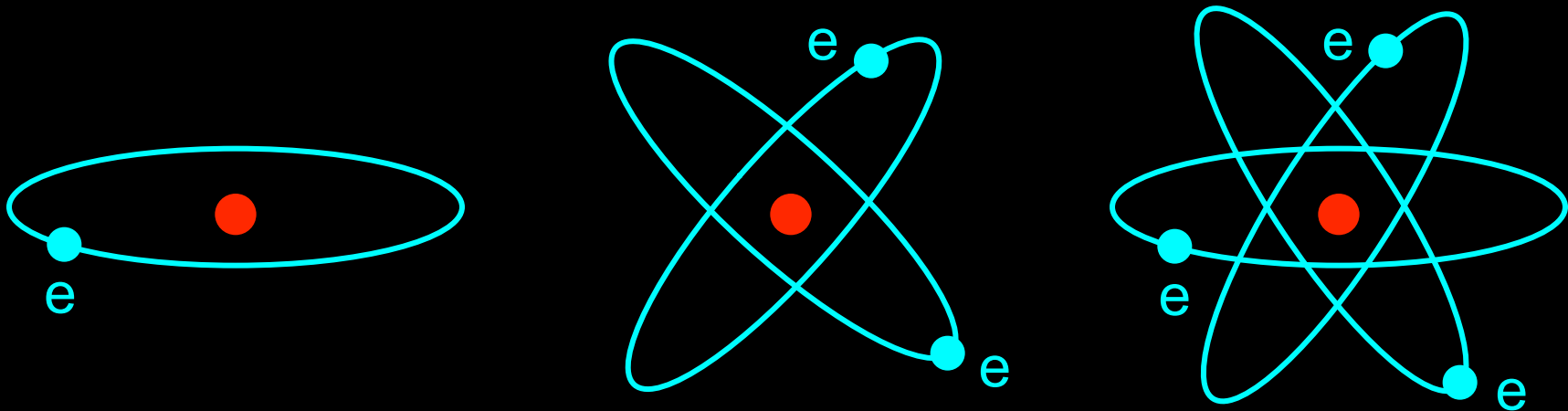
size:

$$\frac{\text{Nucleus}}{\text{Atom}} = \frac{\text{Fly}}{\text{Cathedral}}$$

'like a fly in a cathedral'

Once we glimpsed the fly in the cathedral, we needed to know more, to catch it, examine it, dissect it!

What is nucleus made of?



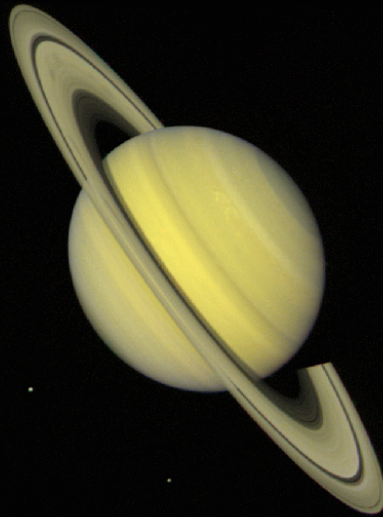
a single fundamental particle? - many of them?



made of a smaller thing or smaller things?

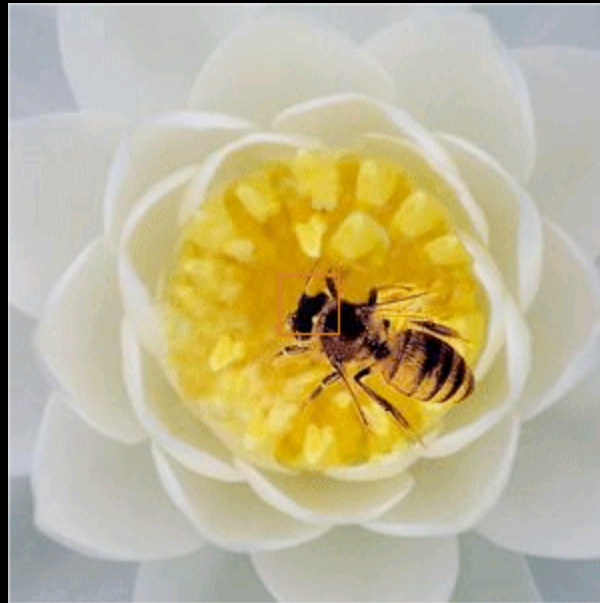
different nuclei = different quantities of 'same' small things?

What is the World Made Of?



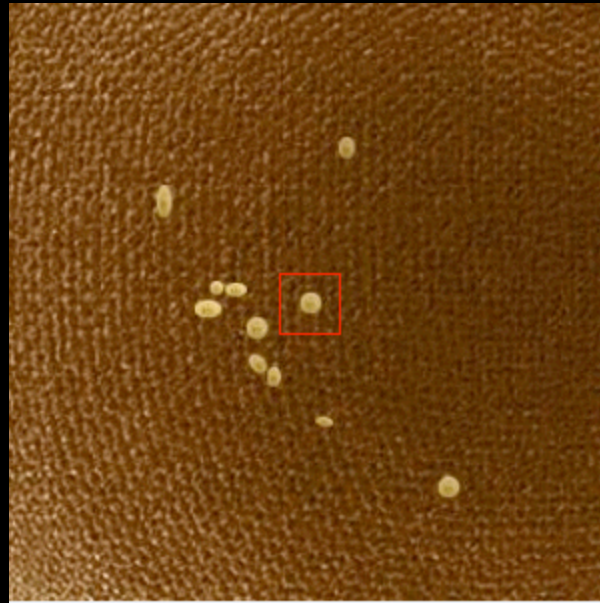
From atoms to electrons and nucleons... what smaller?

**Need Powerful Tools to
See Tiny Things**



← 100 mm →

Seeing it at 100 times smaller scale



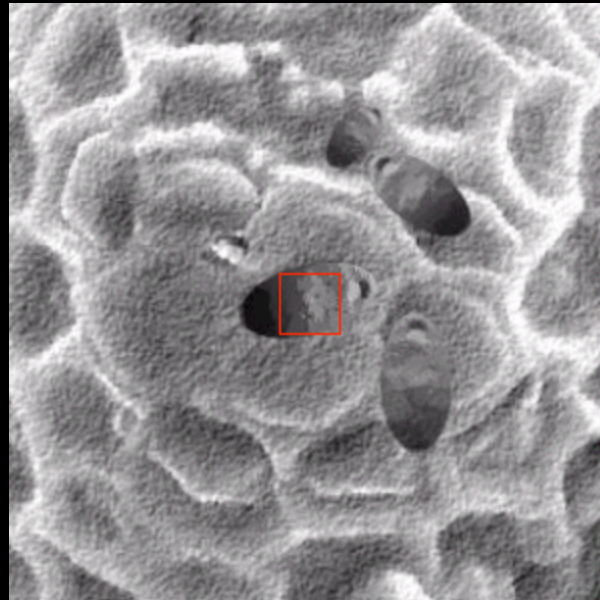
pollen

← 1 mm →

Another 100 times smaller



Optical Microscope
using beam of light



bacteria

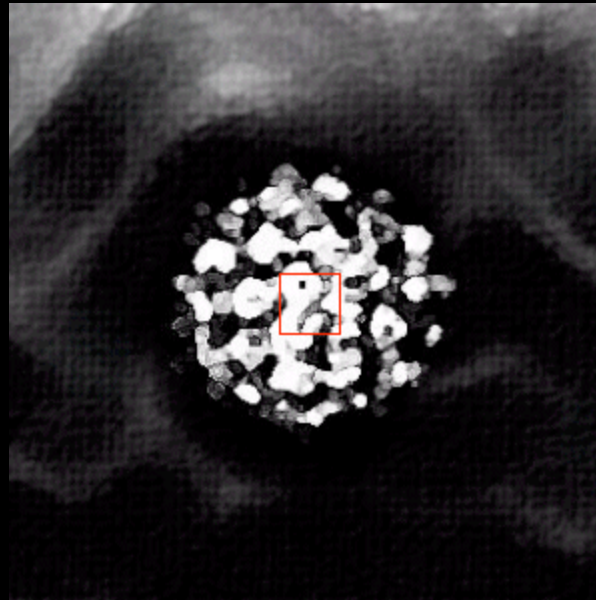
← 0.01 mm →

Another 100 times smaller

Needed to change technology.



Electron Microscope
using beam of particles
(small accelerator)



virus

← 0.0001 mm →

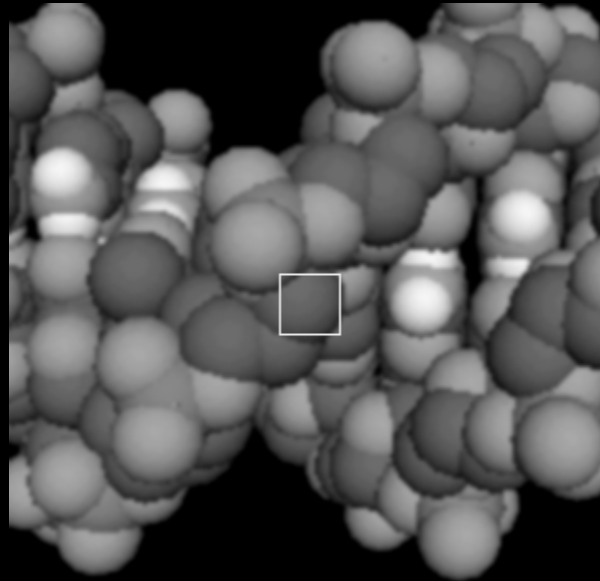
Another 100 times smaller

X Ray machine



Needed to change technology again.

using beam of x-rays
(accelerator!)



Atoms in DNA

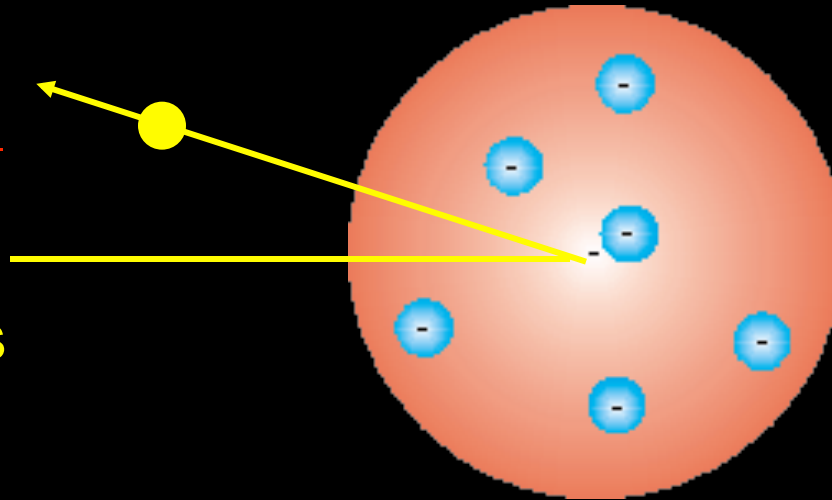
← 0.000001 mm →

Another 100 times smaller

To probe deeper: Needed to use smaller particles as probes ! The birth of particle accelerators...

He found:

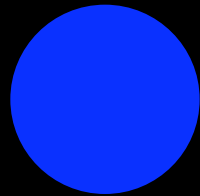
beam of
 α particles



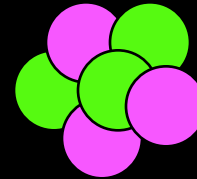
Rutherford Discovered the Nucleus
using a beam of alpha particles
(Alpha particles are Helium Ions)

Use Accelerators as Powerful Microscopes

They make higher energy *particle beams*
that allow us to see smaller things.



seen by
low energy beam
(poorer resolution)



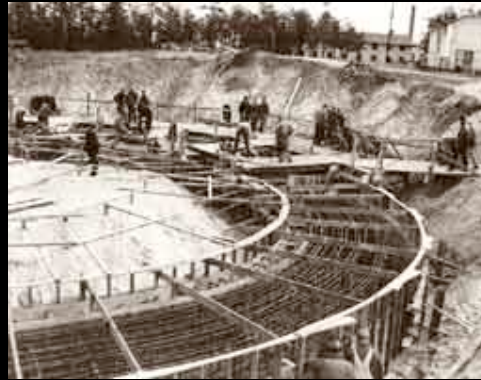
seen by
high energy beam
(better resolution)

Particle Accelerators!

Lawrence
Berkeley Lab



Ernest Lawrence
(1901 - 1958)



Can Huge New Atom Guns Shoot Out Biggest Secrets?

Gigantic ring-shaped machines, with 10-billion-electron-volt wallop, may transform energy into matter.

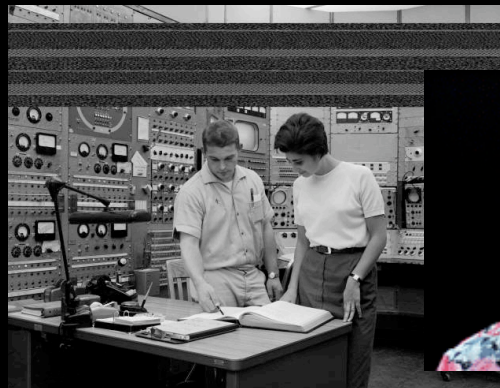
By Alden P. Armagnac
Drawings by Ray Pioch

1949

SUPPOSE that a bullet could be fired 150,000 miles, six times the distance around the world. Suppose that it could be given a shove to speed it up every 150 yards. Suppose, too, that it could be so aimed and guided throughout this long, fast flight that

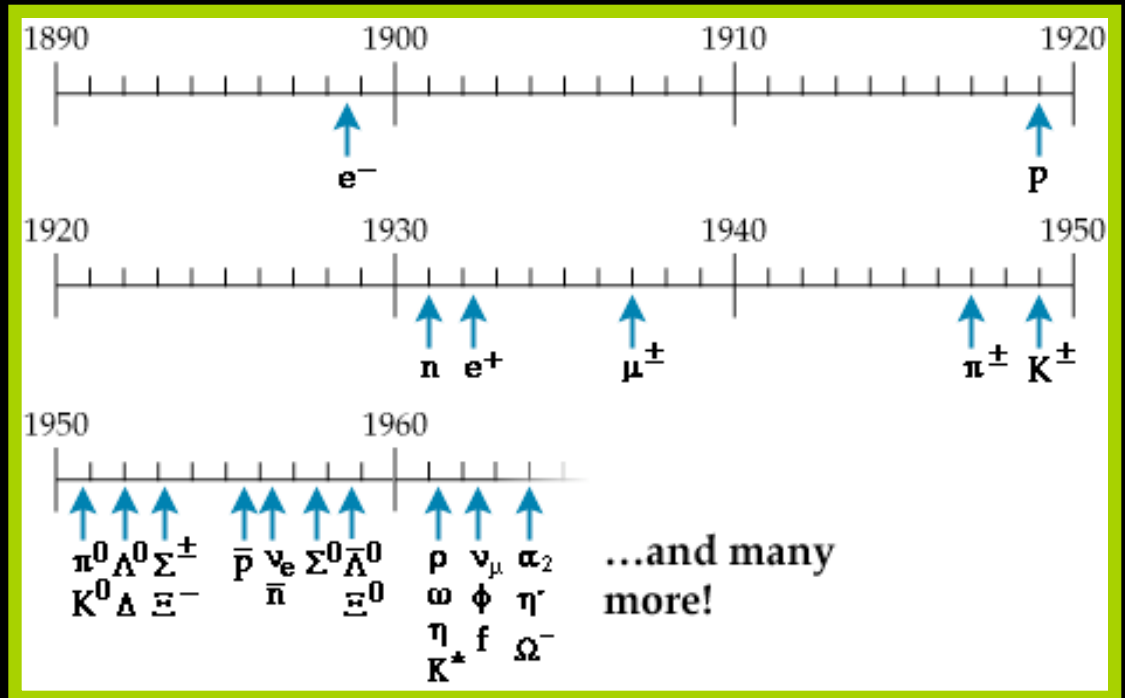
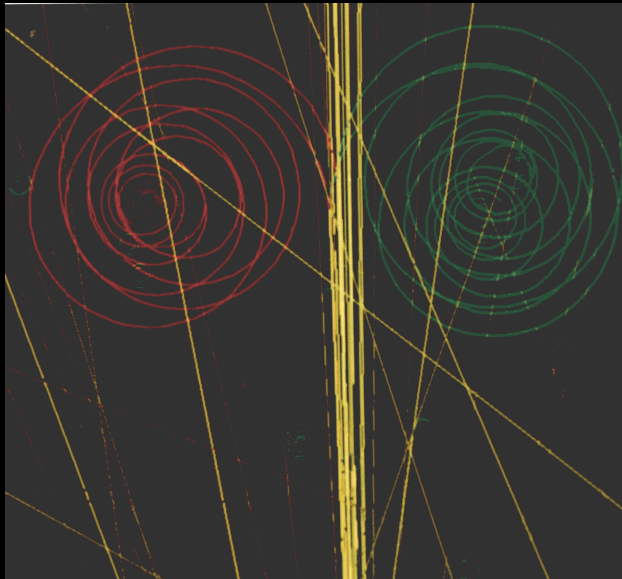
electron-volt accelerator for the University of Birmingham. Two American machines will be even mightier. Both are designed to reach 10 billion electron volts, 50 times the power of the greatest in use today.

Dr. Ernest O. Lawrence, the inventor of

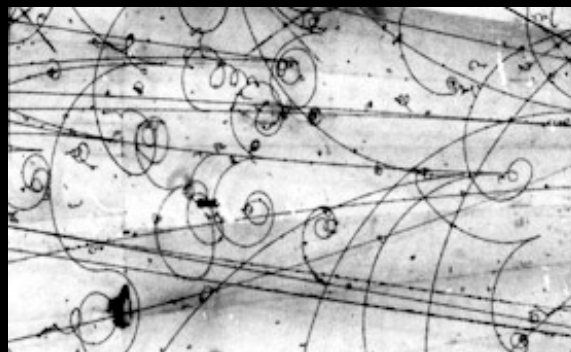


Many campuses began to build accelerators to study subatomic particles.

New Types of Matter...



1950s and '60s:
Zoo of particles found,
various properties...
→ *Is there a pattern?*



Fermilab Bubble Chamber Photo

The Quark Idea



“Three quarks
for Muster Mark!”

1964



Zweig

What if 3 smaller particles with different charge and properties combine together to explain this zoo?

* *Finnegan's Wake*, J. Joyce

The Stanford two-mile electron linear accelerator (SLAC)



Quarks are Found!

Quarks detected: 1968!

Science 29 May 1992:
Vol. 256, no. 5061, pp. 1287 - 1293
DOI: 10.1126/science.256.5061.1287

[< Prev](#) | [Table of Contents](#) | [Next](#)

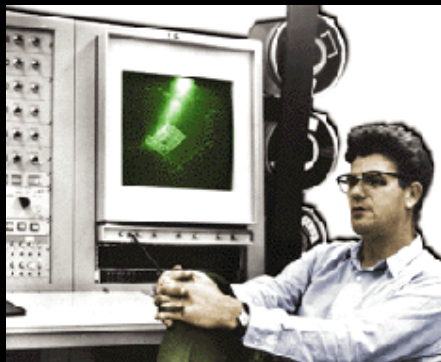
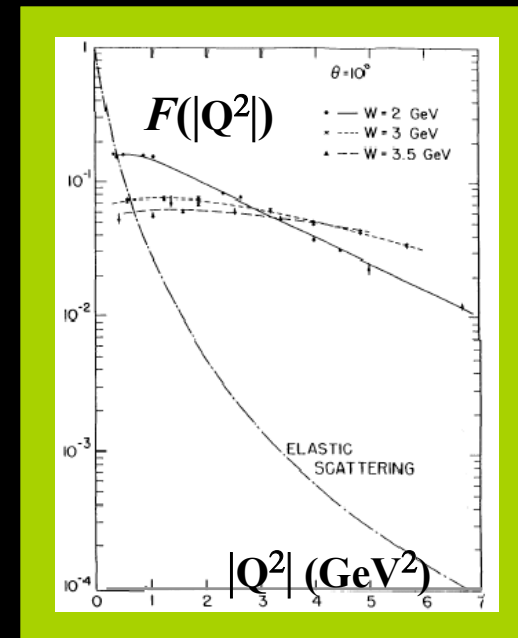
ARTICLES

The Discovery of Quarks

Michael Riordan ¹

¹ Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Quarks are widely recognized today as being among the elementary particles of which matter is composed. The key evidence for their existence came from a series of inelastic electron-nucleon scattering experiments conducted between 1967 and 1973 at the Stanford Linear Accelerator Center. Other theoretical and experimental advances of the 1970s confirmed this discovery, leading to the present standard model of elementary particle physics.



Experiments conducted from 1966-1978 by Richard Taylor (SLAC), Henry Kendall (MIT), and Jerome Friedman (MIT) studied how high-energy electrons bounce off the protons and neutrons in a target. Their results showed more electrons bouncing back with high energy at large angles than could be explained if protons and neutrons were uniform spheres of matter.

Quarks are Found!

Quarks detected: 1968!

Science 29 May 1992:
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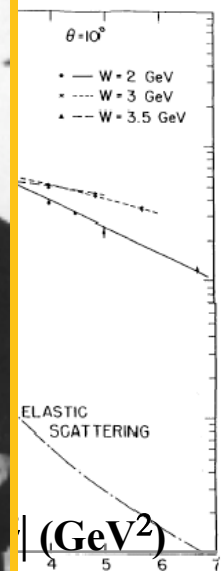
ARTICLES

The Discovery of Quarks

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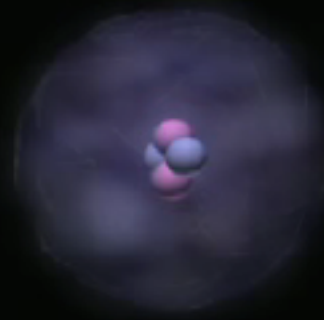
NOBEL

1990 Nobel Prize in Physics: Quarks Revealed!



Structure Inside Protons and Neutrons

Peeking inside the atom...



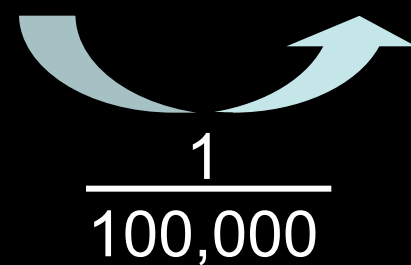
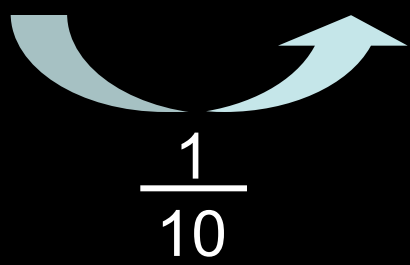
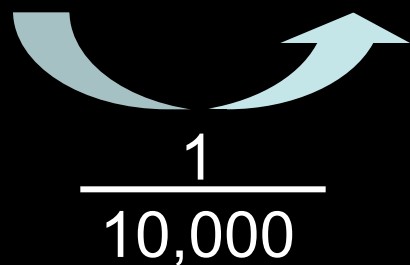
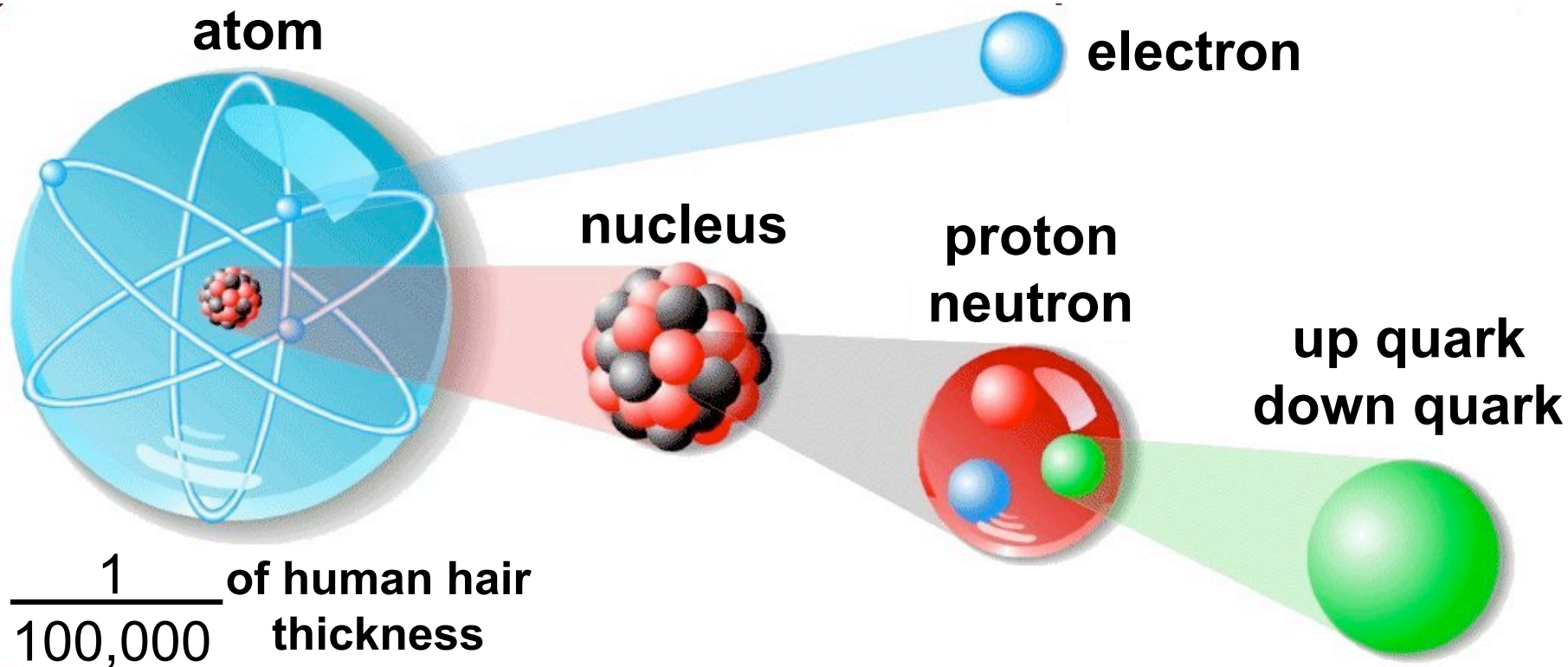
Video clip

~90 years ago

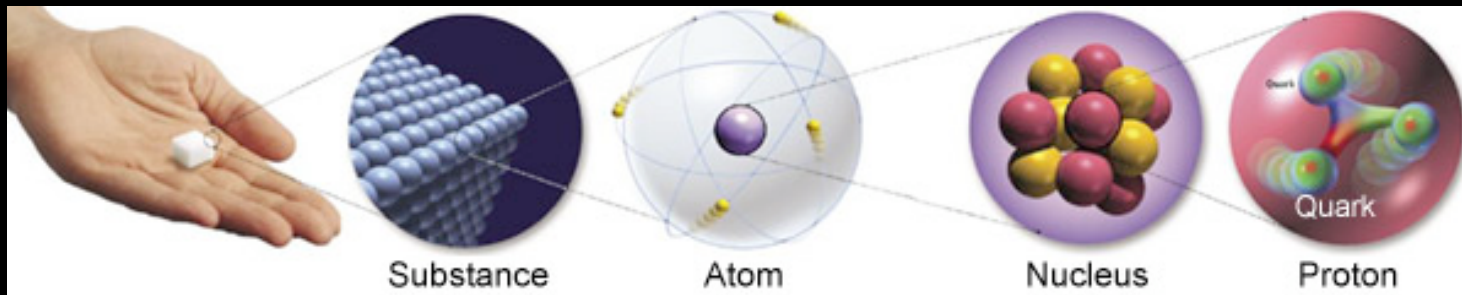
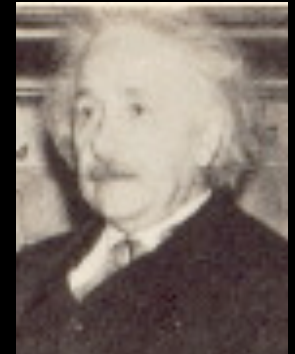
~60 years ago

~40 years ago

Present



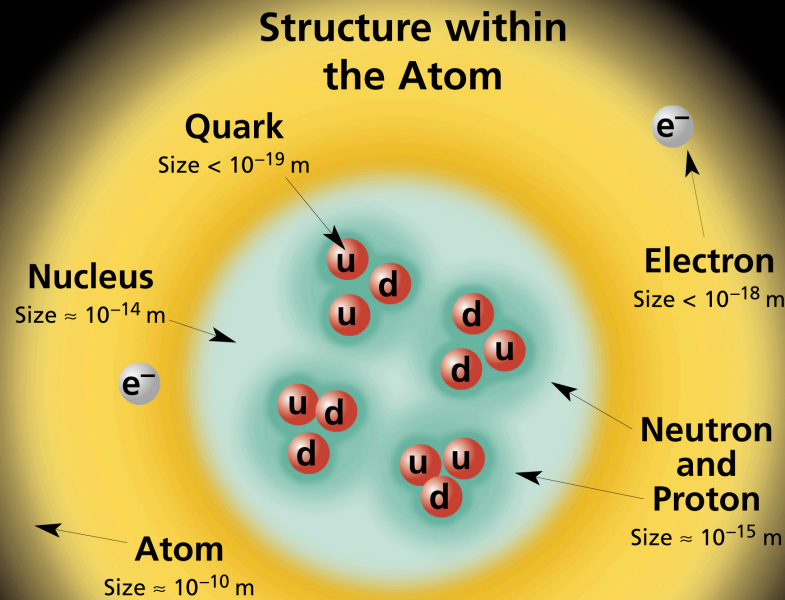
What is the World Made Of?



What, then, is fundamental?

The Nature of Matter

Could there be more quarks?
Or something smaller?

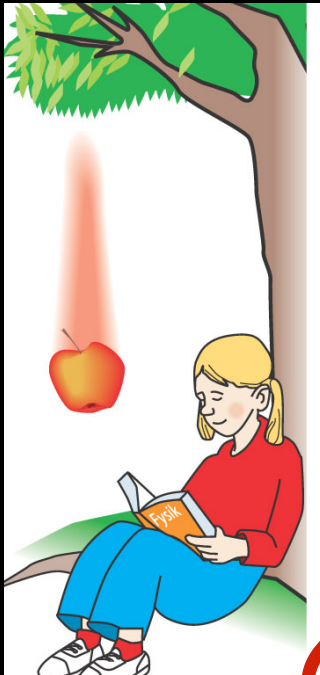


If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

**Atoms as we know
them today**

What Holds it all Together?

Gravitational Force



Issac Newton
(1642 - 1727)

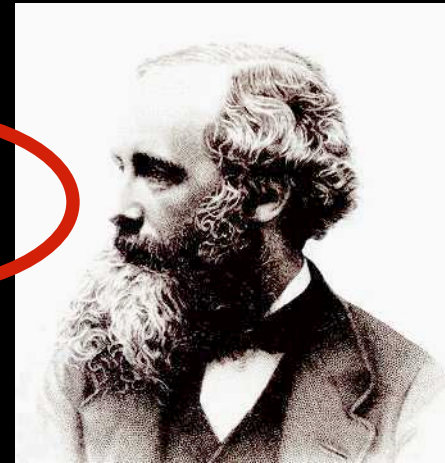
Graviton



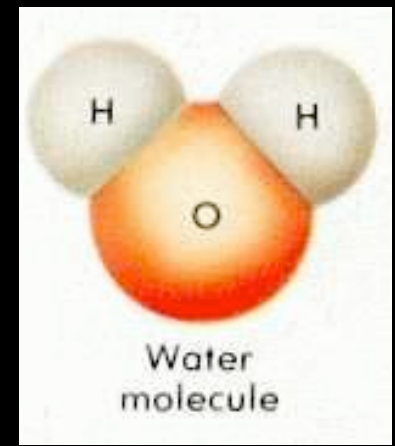
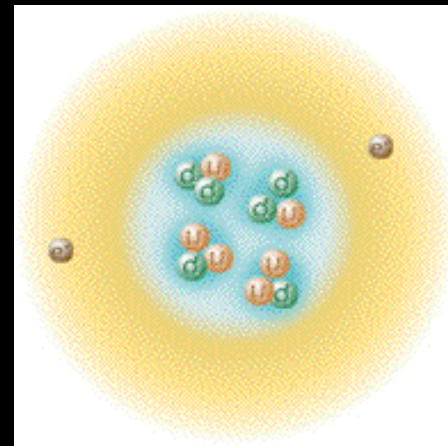
Electromagnetic Force

Photons

γ



James Clerk Maxwell
(1831 - 1879)

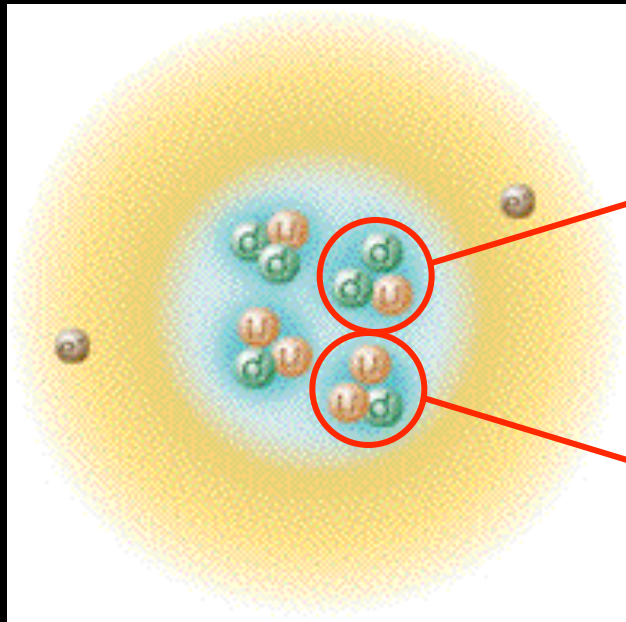


Weak Force



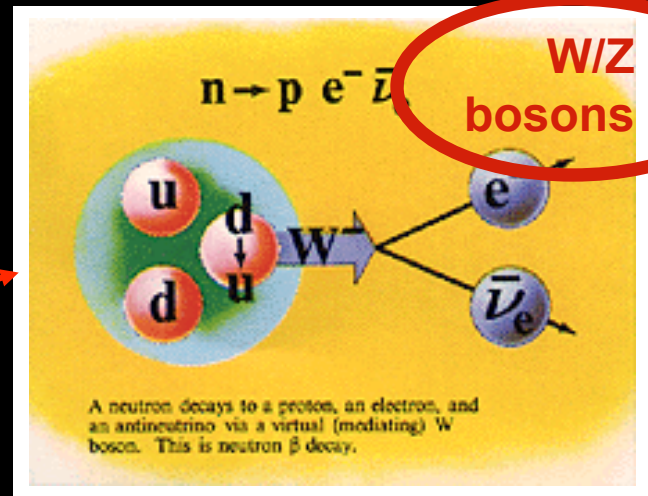
Enrico Fermi
(1901 - 1954)

neutron decay

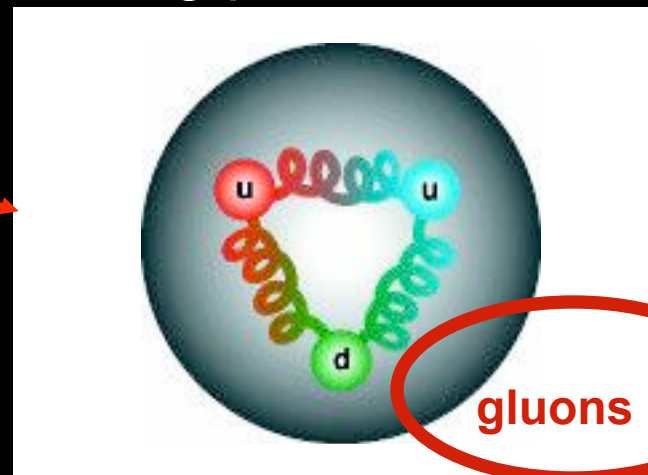


Strong Force

radioactive decays

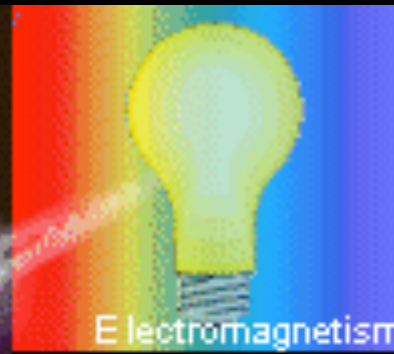
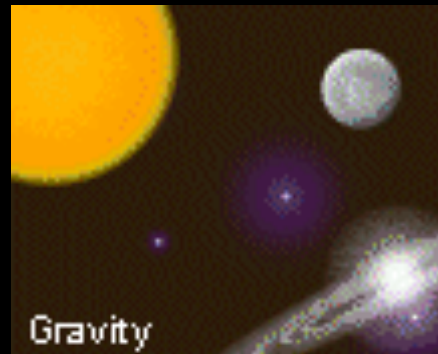


holding proton, nucleus



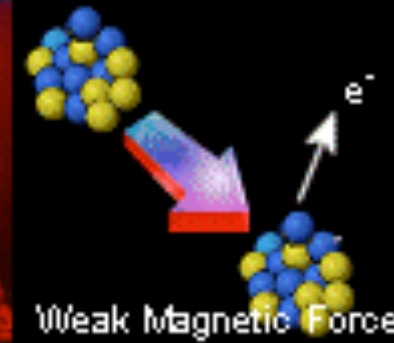
Four Fundamental Forces

graviton



Gamma ray,
Photon γ

gluon

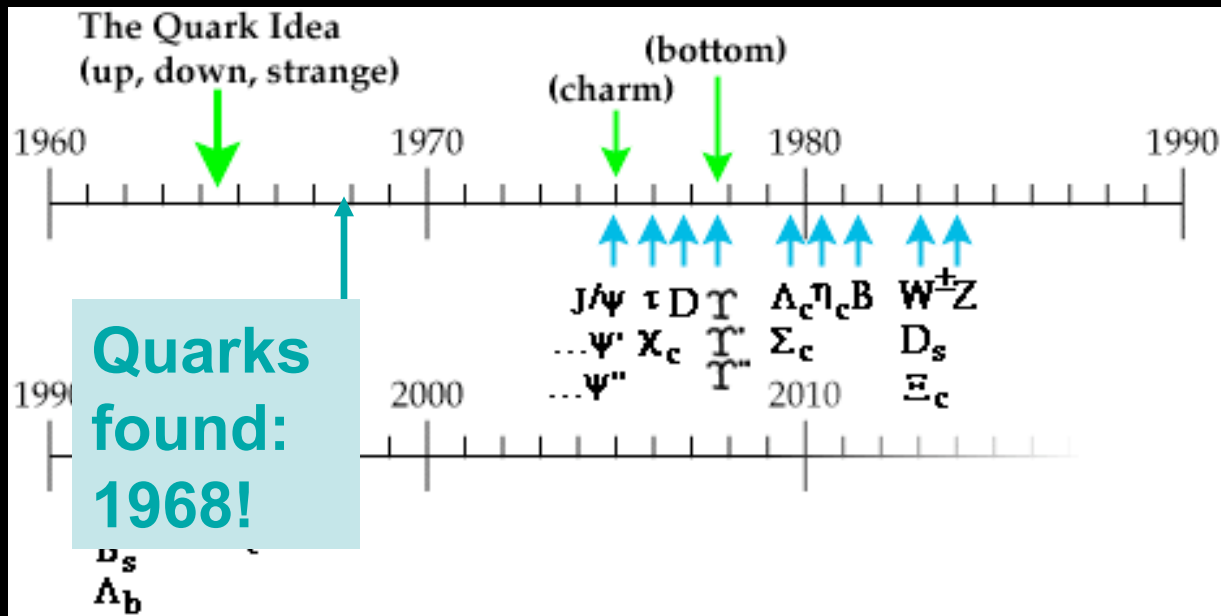


W, Z

“Mediated” by particles called bosons!

* Graviton not discovered yet.

Meanwhile...



Meanwhile...

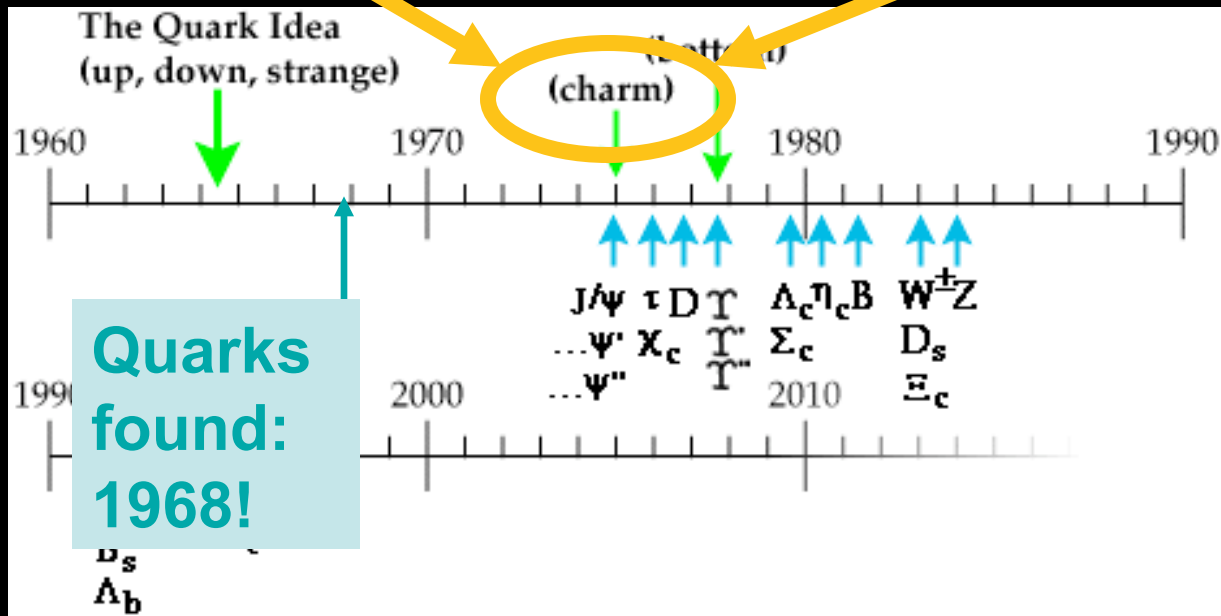
Long Island, NY

Menlo Park, CA

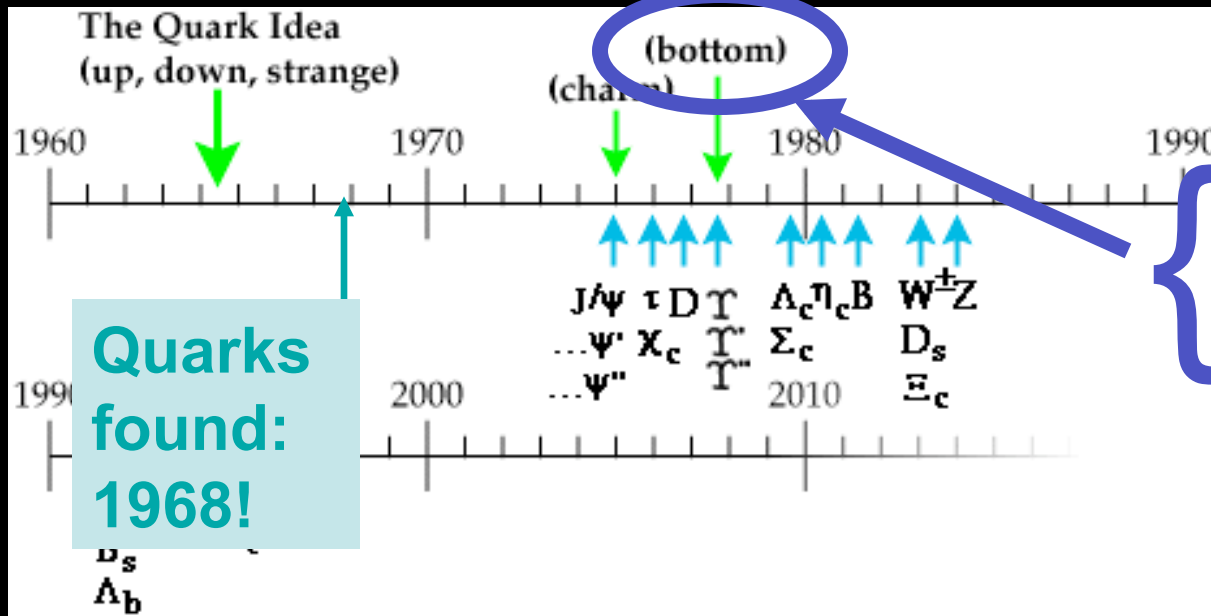
Brookhaven National Laboratory

Office of Science / U.S. Dept. of Energy

SLAC



Meanwhile...

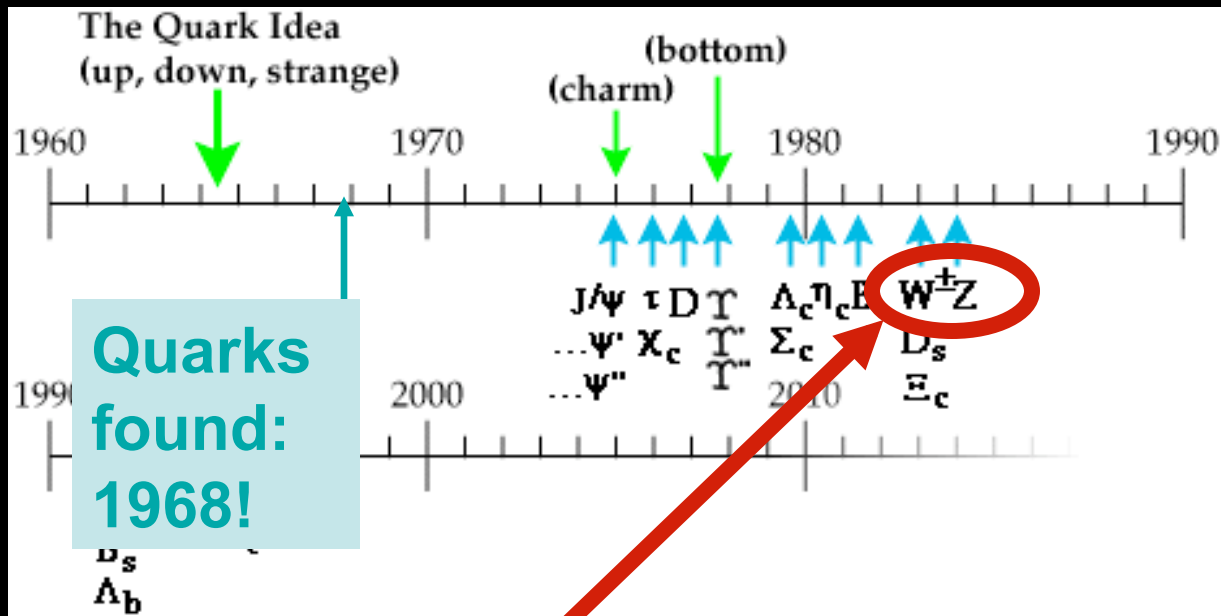


Chicago, IL

 Fermilab



Meanwhile...



Geneva, Switzerland



Quark Discoveries

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

- Quarks (**u,d,s**) were postulated in 1964, discovered at SLAC in 1968

- The charm quark **c** was discovered in 1974 by Brookhaven and SLAC

$$\begin{pmatrix} c \\ s \end{pmatrix}$$
$$\begin{pmatrix} \dots \\ b \end{pmatrix}$$

- The bottom quark **b** was discovered In 1977 at Fermilab

The bottom quark needed a partner...
and the race was on!

Race for the Top Quark

- 1974 - Charm quark discovered (Brookhaven/SLAC) at 1.2 GeV
- 1977 - Bottom (*beauty*) quark discovered (Fermilab) at 4 GeV.

Top quark expected at 15-20 GeV!

- 1979 - 1989 PEP collider (SLAC), PETRA collider (Germany), TRISTAN collider (Japan) all *ruled out* top (truth) at < 30 GeV.
- 1983 - SpS proton collider at CERN *discovered* W, Z bosons!
- 1988 - 1989 Tevatron collider (Fermilab) *ruled out* top < 72 GeV.
- 1982 - 1989 SpS *ruled out* top at < 69 GeV.

Game over!

Everyone wanted the “*truth*” first!

Fermilab only could reach the energy needed...

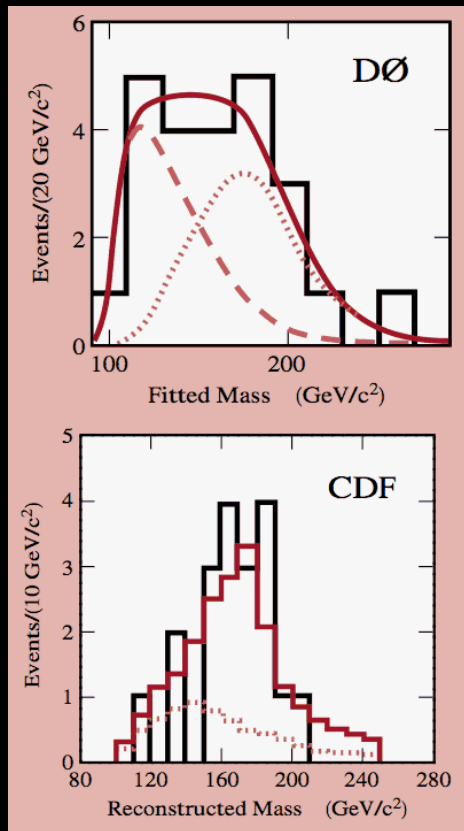
CLIMBING THE WORLD'S 14 HIGHEST PEAKS

NO SHORTCUTS TO THE TOP



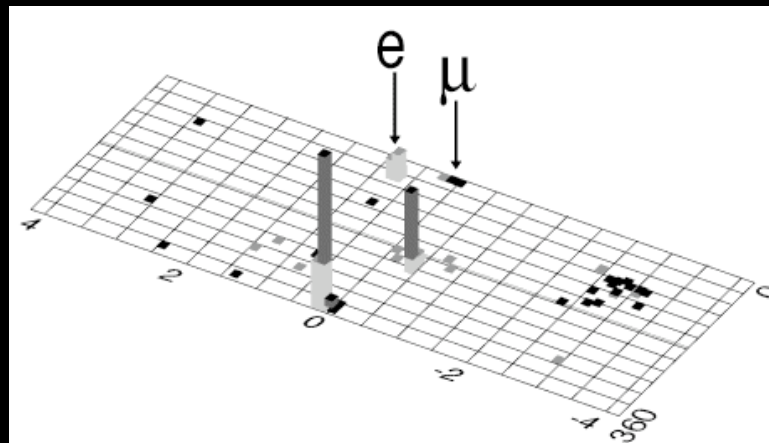
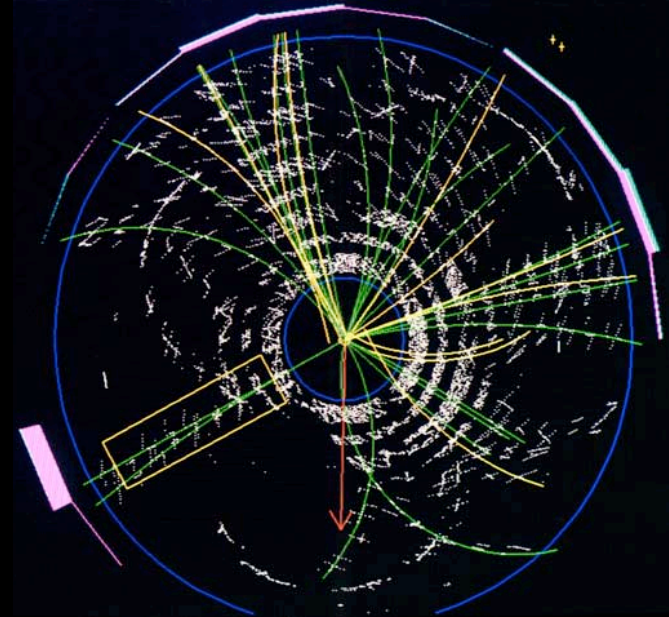
ED VIESTURS WITH DAVID ROBERTS

Top Quark Discovered!



1994 - 1995

175 GeV !



Discovery is Exciting!

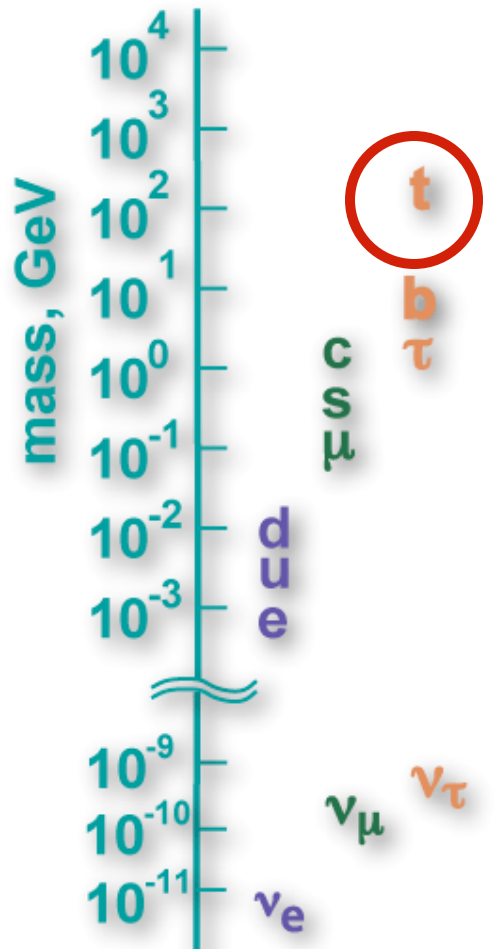


Adding something to the core of human knowledge is profoundly satisfying.



The Standard Model

Periodic Table of the Particles

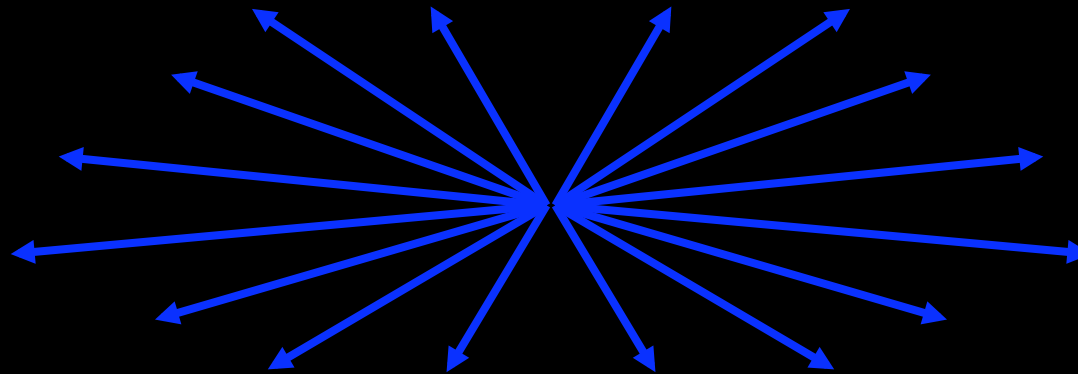


	matter: fermions			forces: bosons
quarks	u	c	t	g
	d	s	b	
leptons	e	μ	τ	W
	ν_e	ν_μ	ν_τ	Z
				γ

Accelerators

Accelerators are our tools to discovery!

We can create particles with very large masses, and explore Nature beyond what exists today.



Modern Particle Accelerators are *Gigantic!*

PEP-II, SLAC, Palo Alto, USA



KEKb, KEK, Tsukuba, Japan



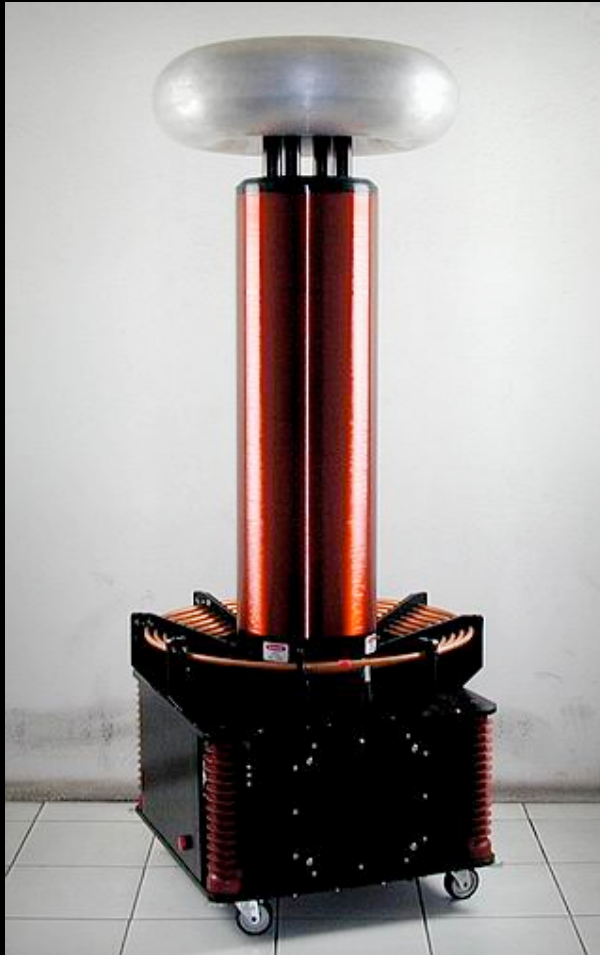
HERA, DESY, Hamburg, Germany



Tevatron, Fermilab, Chicago, USA



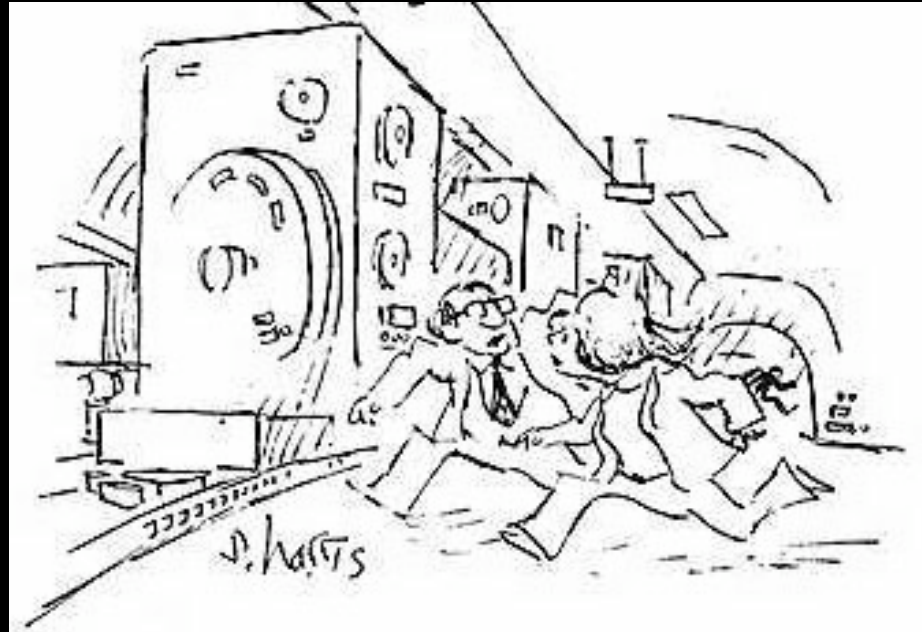
Tesla Coils





Accelerators
achieve more
than a million
times these
energies!

All Sped Up!



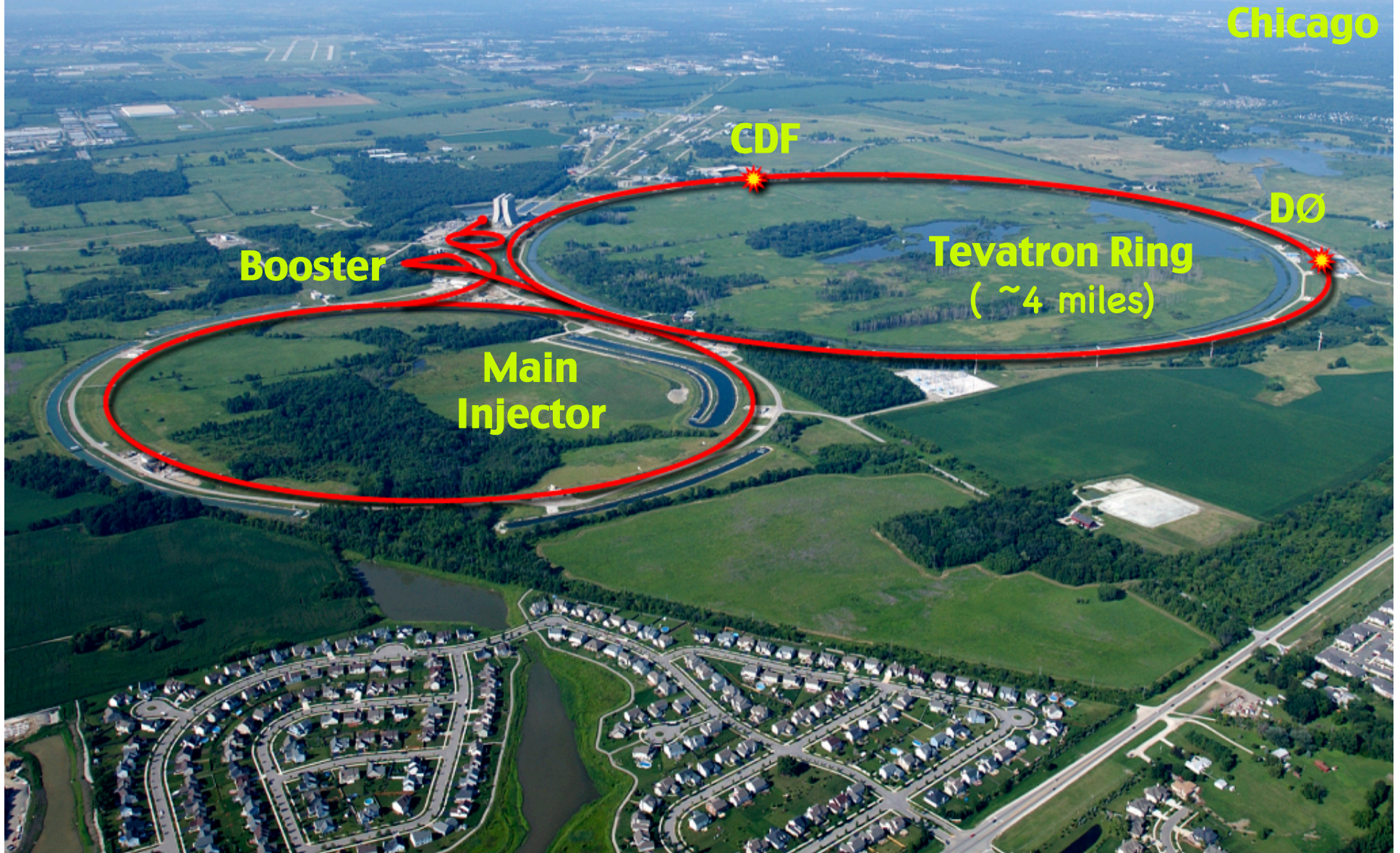
“It started with just the particles being Accelerated, but now everything Around here has speeded up!”

Where Top Quarks are Produced

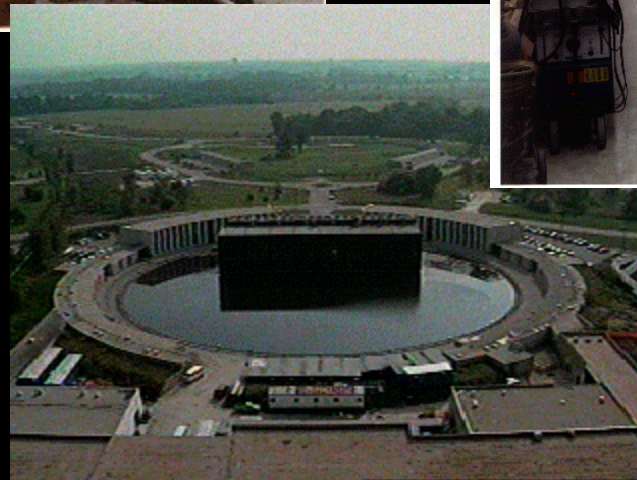
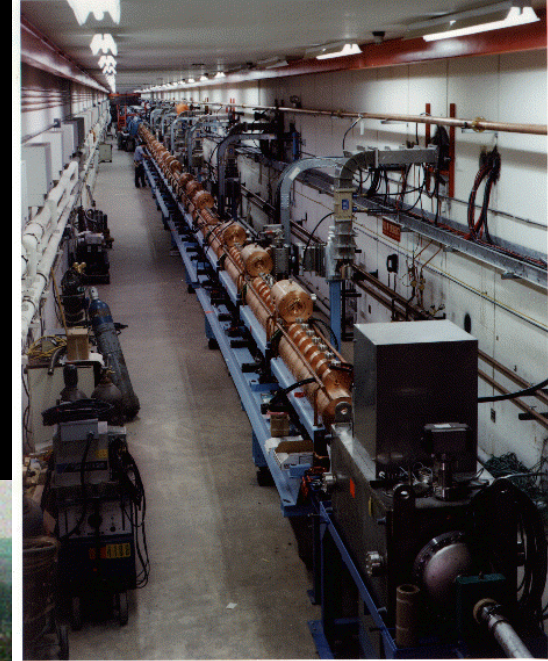
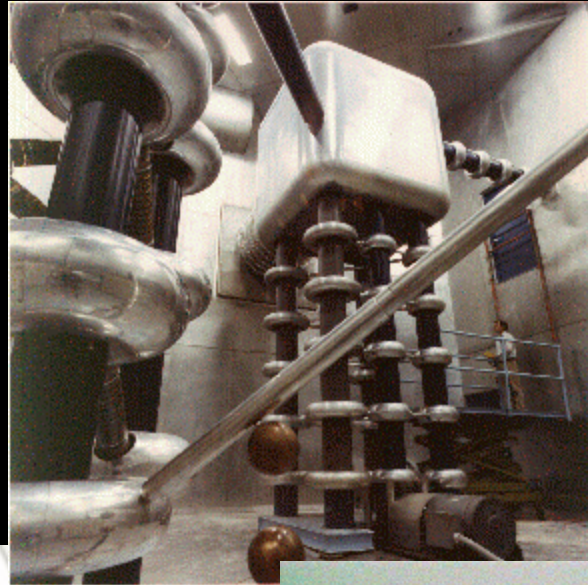


Fermi National Accelerator
Laboratory, near Chicago, IL

World's Most Powerful Accelerator: Fermilab's Tevatron



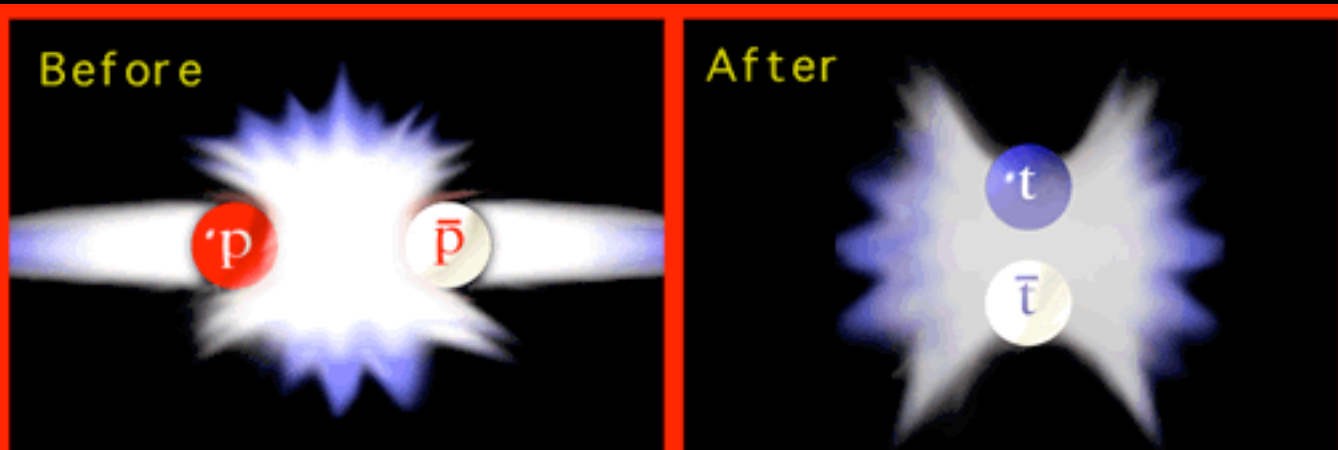
Chain of Accelerators





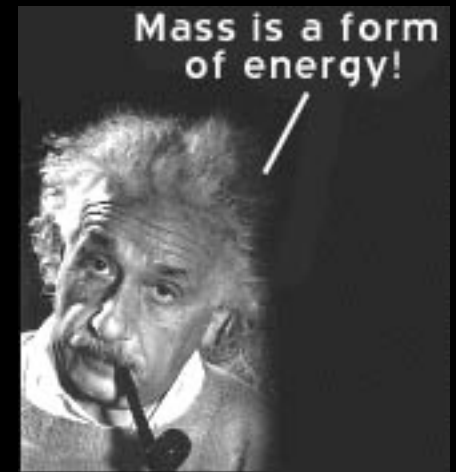
Video clip

$$E = mc^2$$

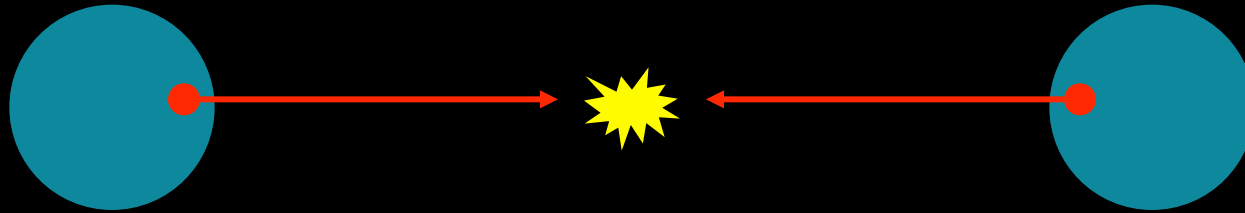


$$E = mc^2$$

The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.



Challenges



thickness of human hair

2 million collisions per second

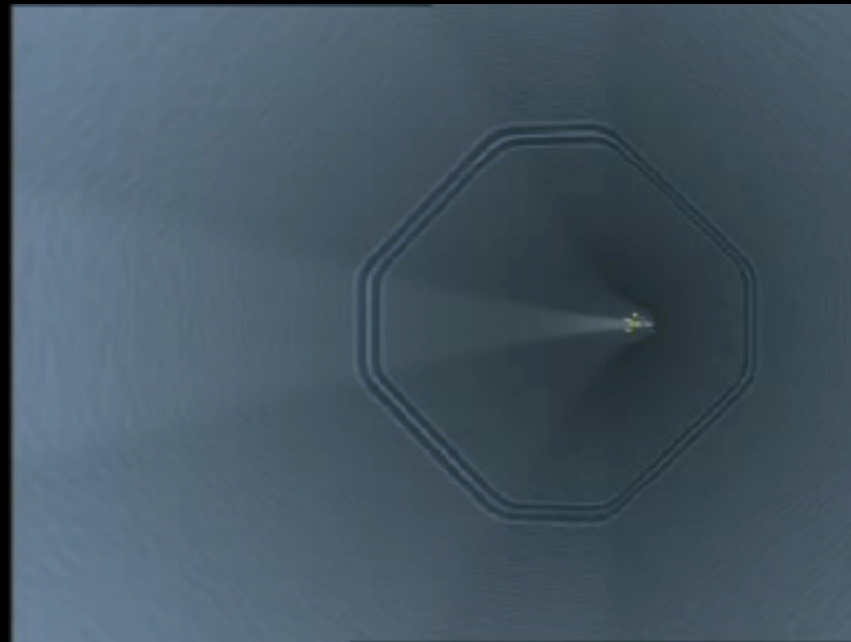


one out of one million



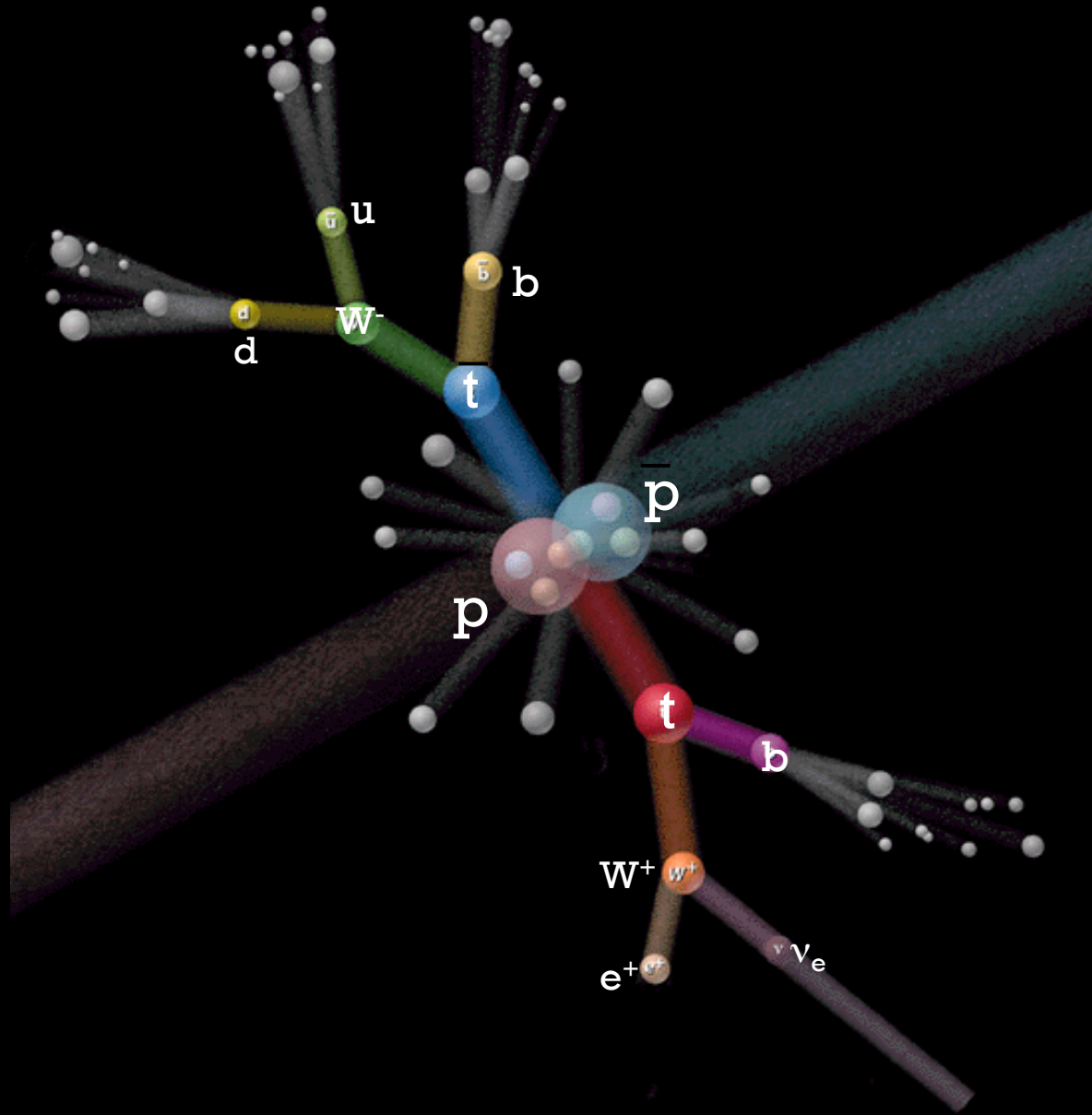
one out of ten billion

Proton / anti-Proton Collisions

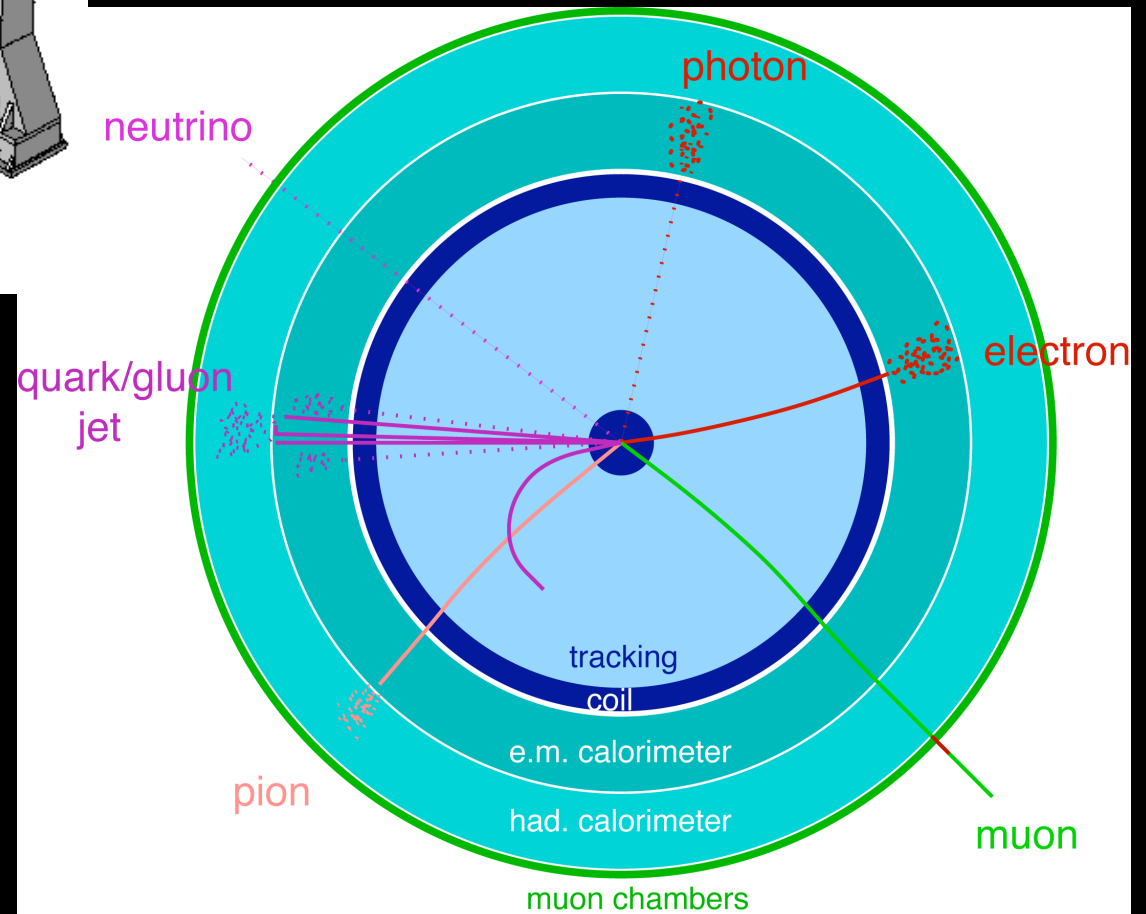
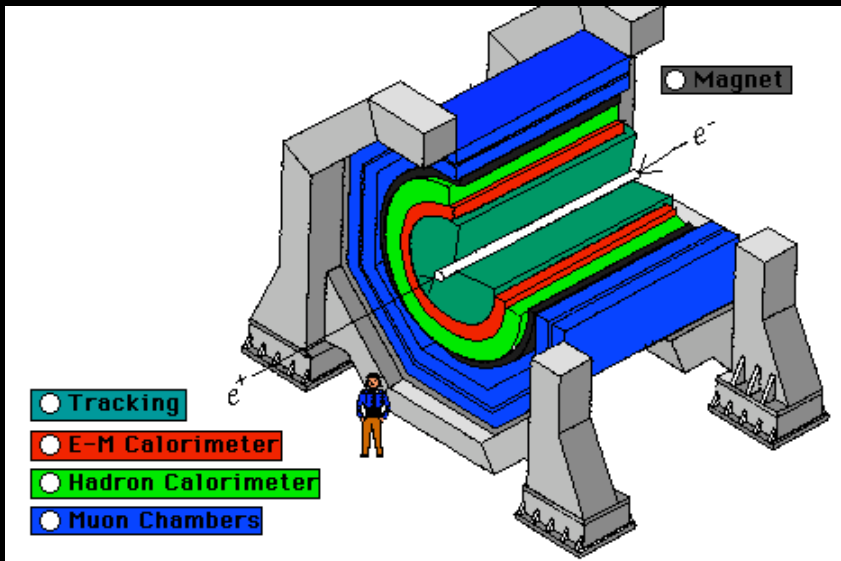


Video clip

Collisions Producing Top Quarks!

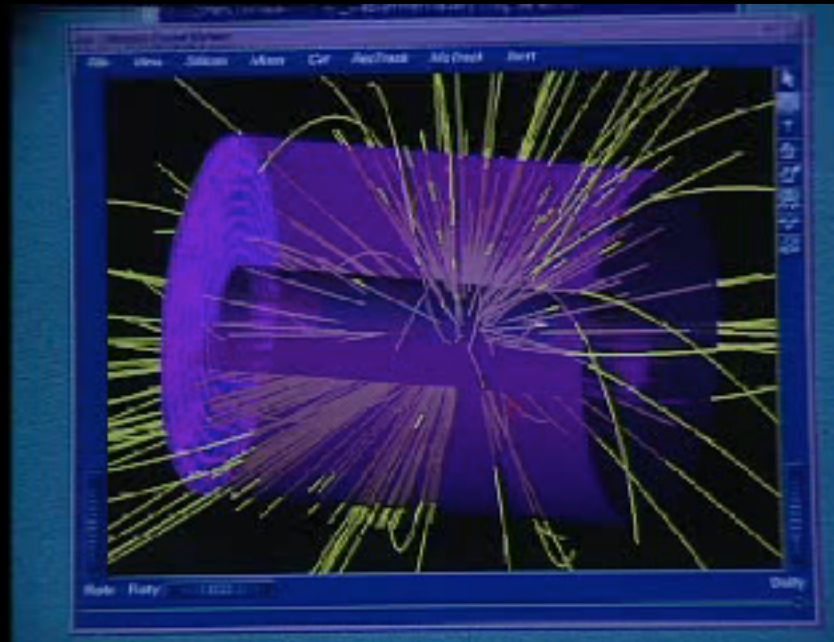


How we “see” particles



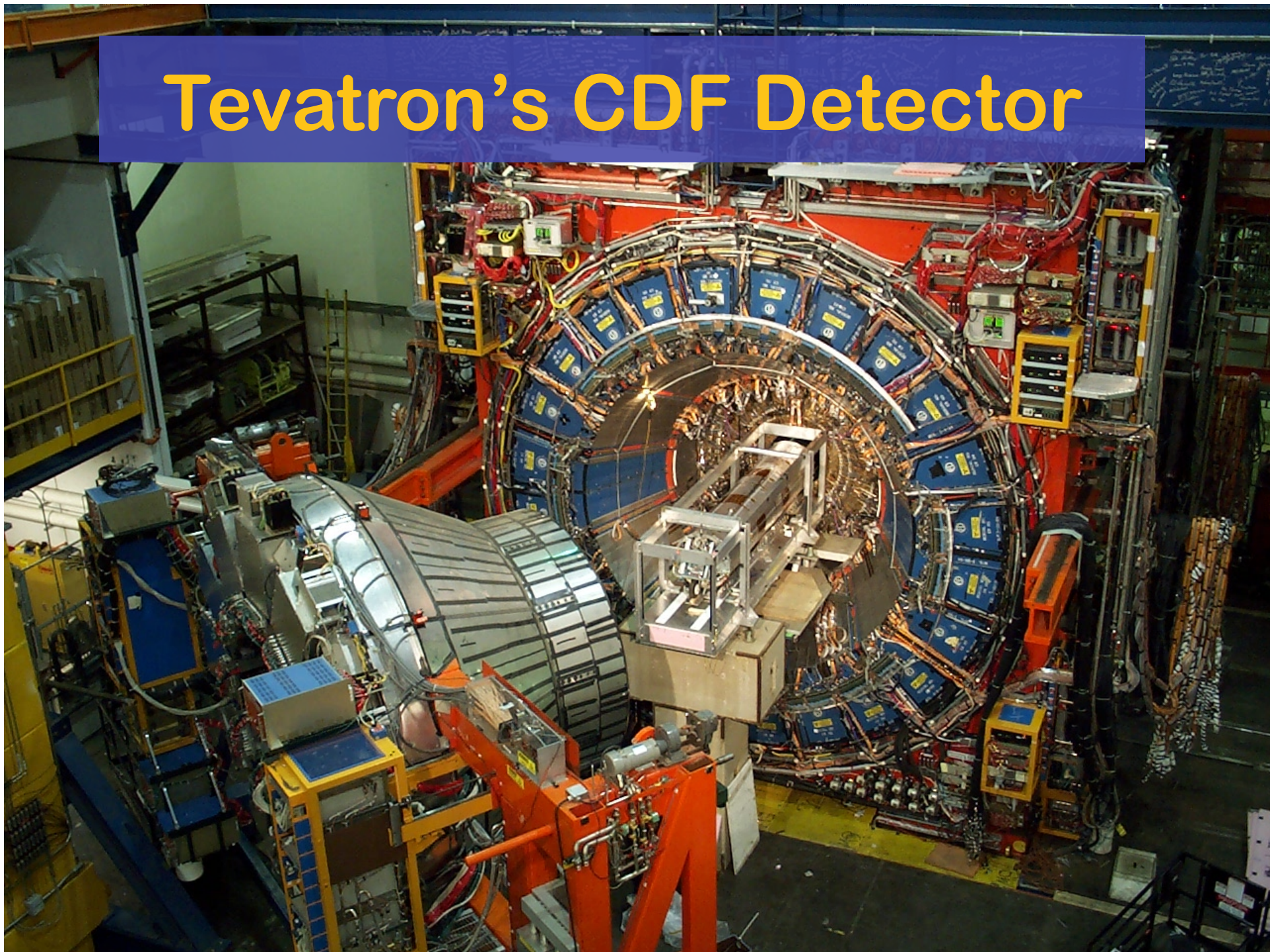
Most collider detectors are similar...

How we “see” particles

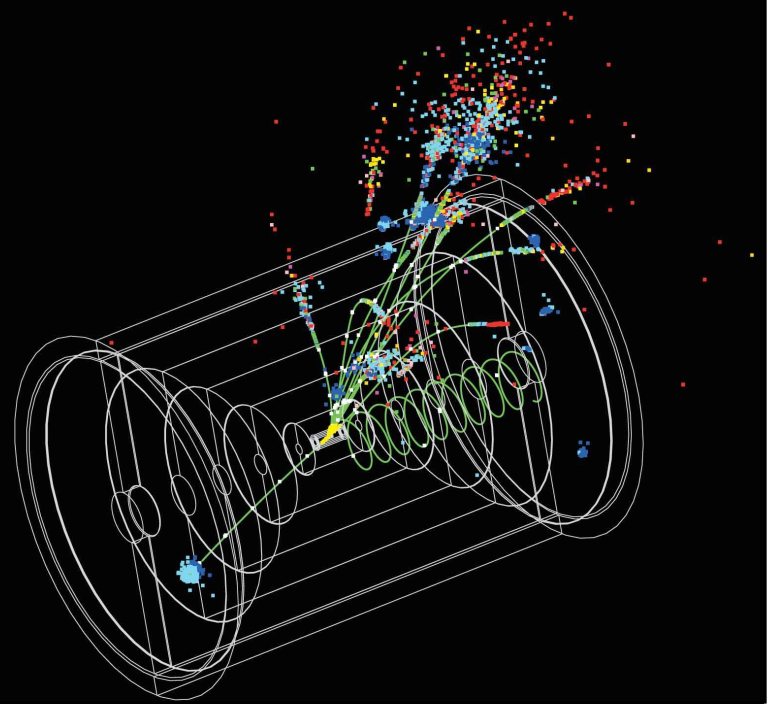
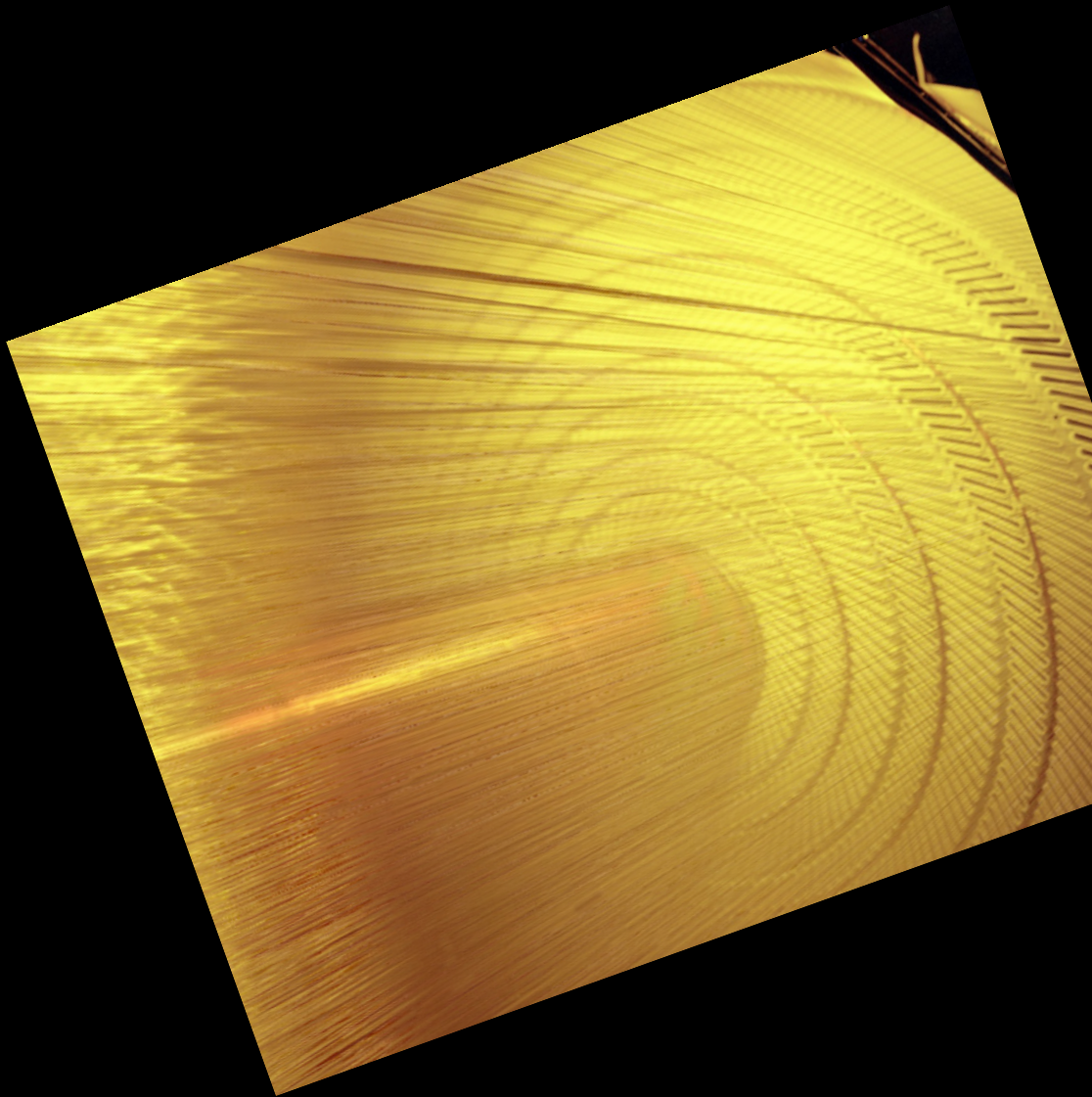


Video clip

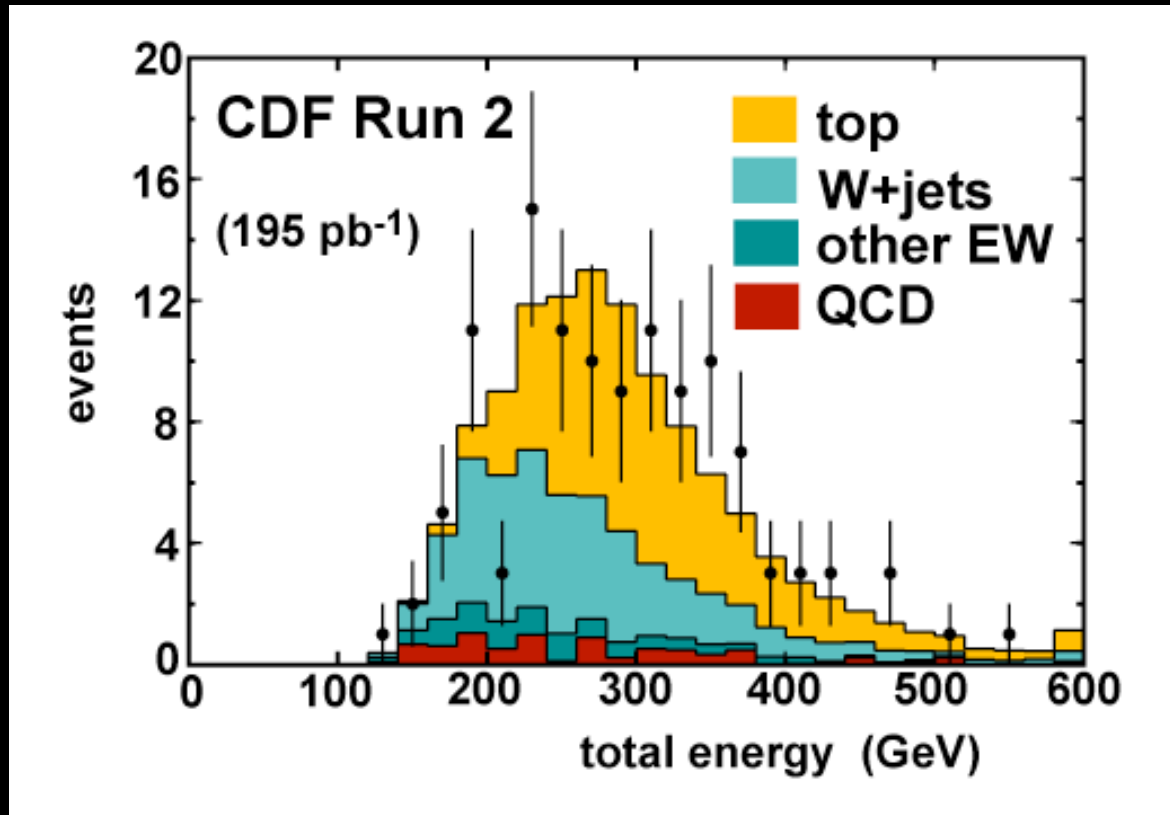
Tevatron's CDF Detector



One piece of the detector has 30,000 high-voltage wires
thickness of human hair

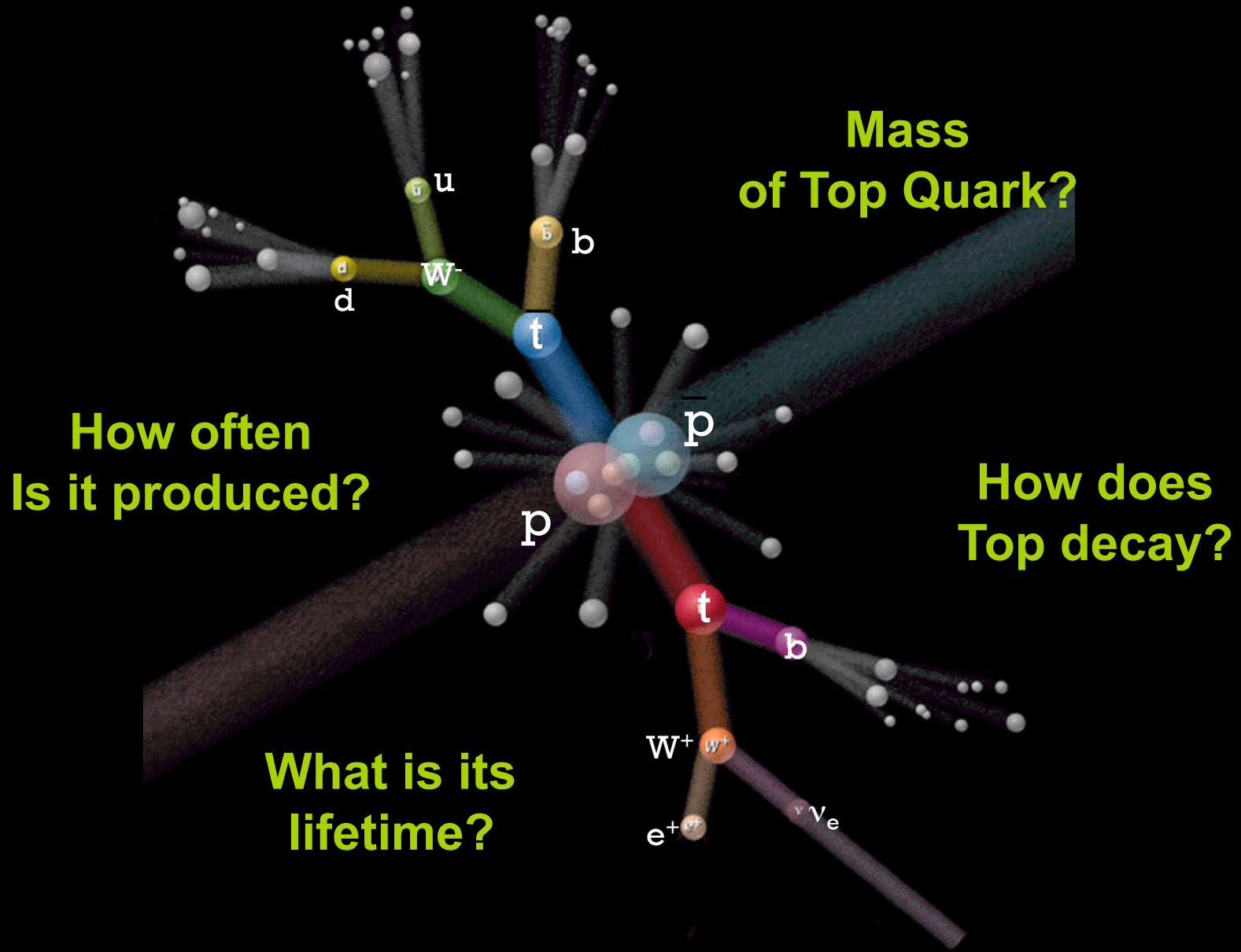


Top Re-Discovered



Turn of this century... Tevatron "Run 2"

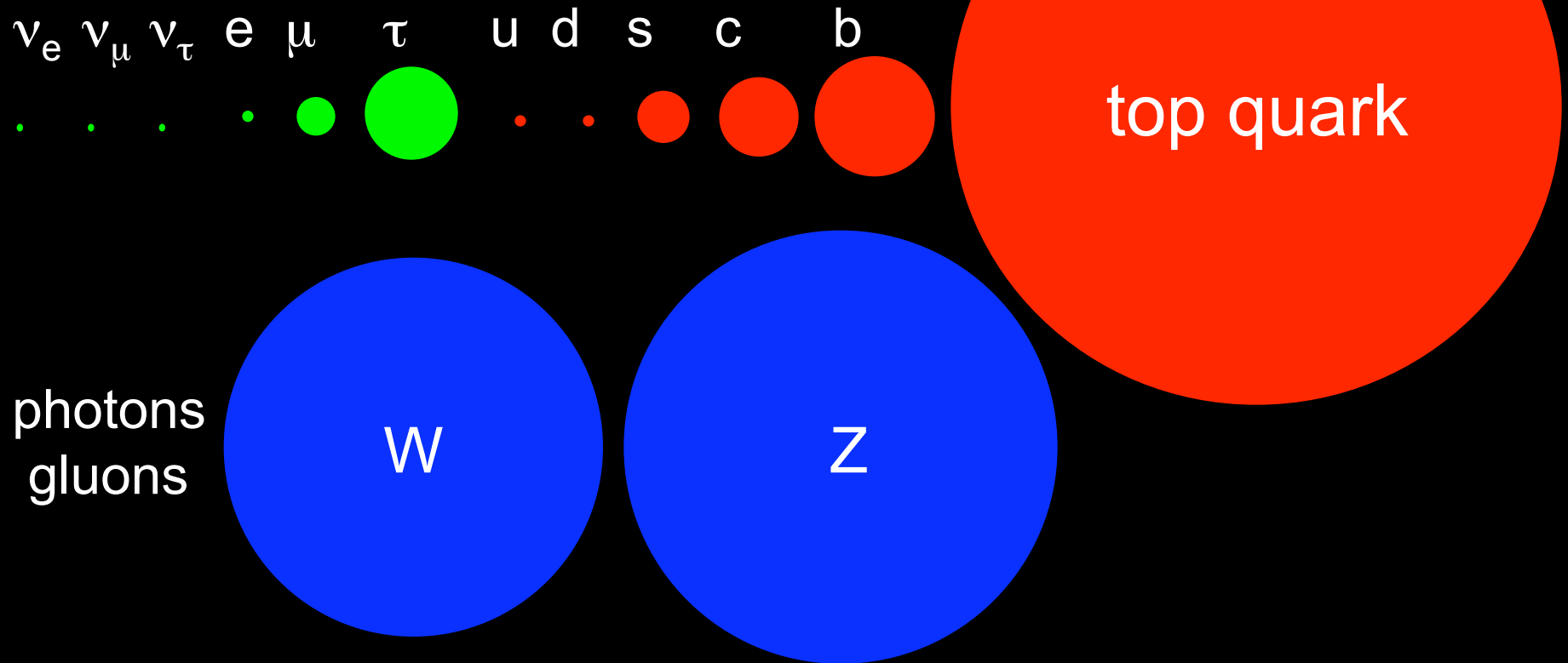
Studying the Top Quark



Top quarks are one of the more sexy things to study at the Tevatron



Why is Top So Heavy?

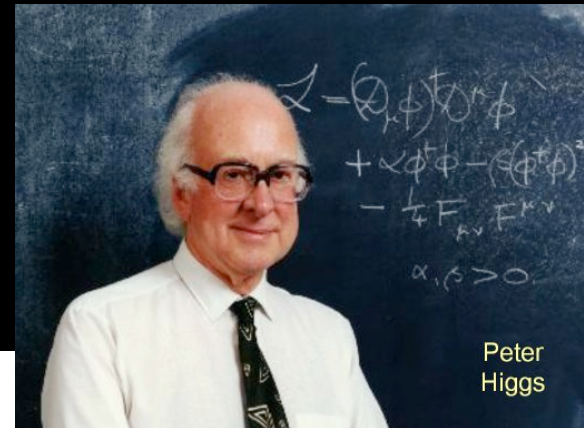


“Why are there so many particles?”

“Where does mass come from?”

Higgs Boson

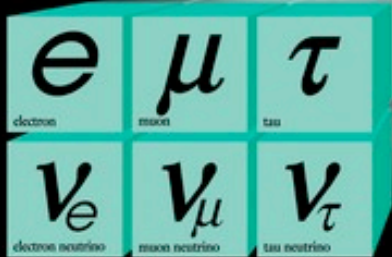
Not yet discovered!!!



Quarks



Forces



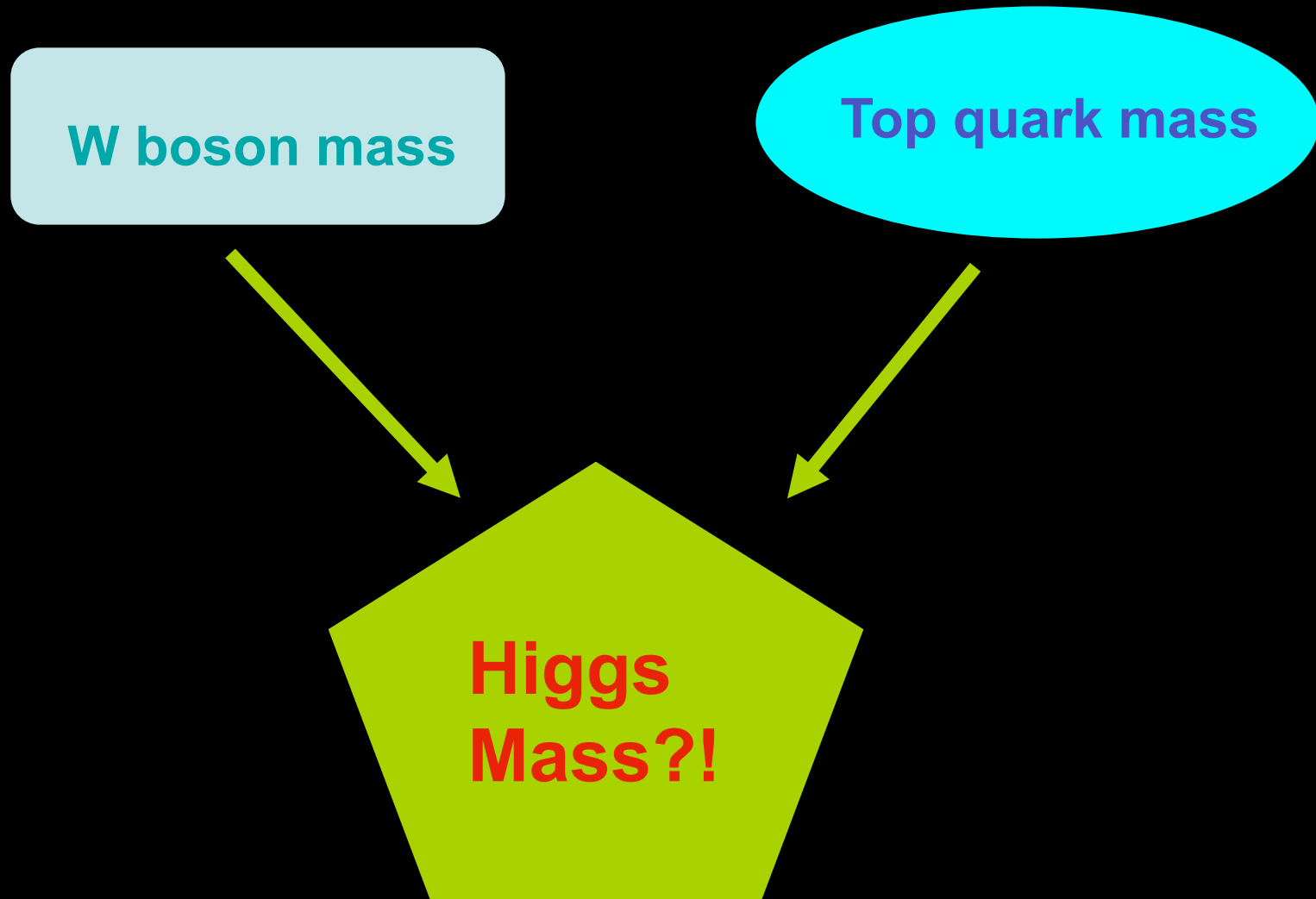
Leptons



Standard Model predicts a new, 5th interaction.

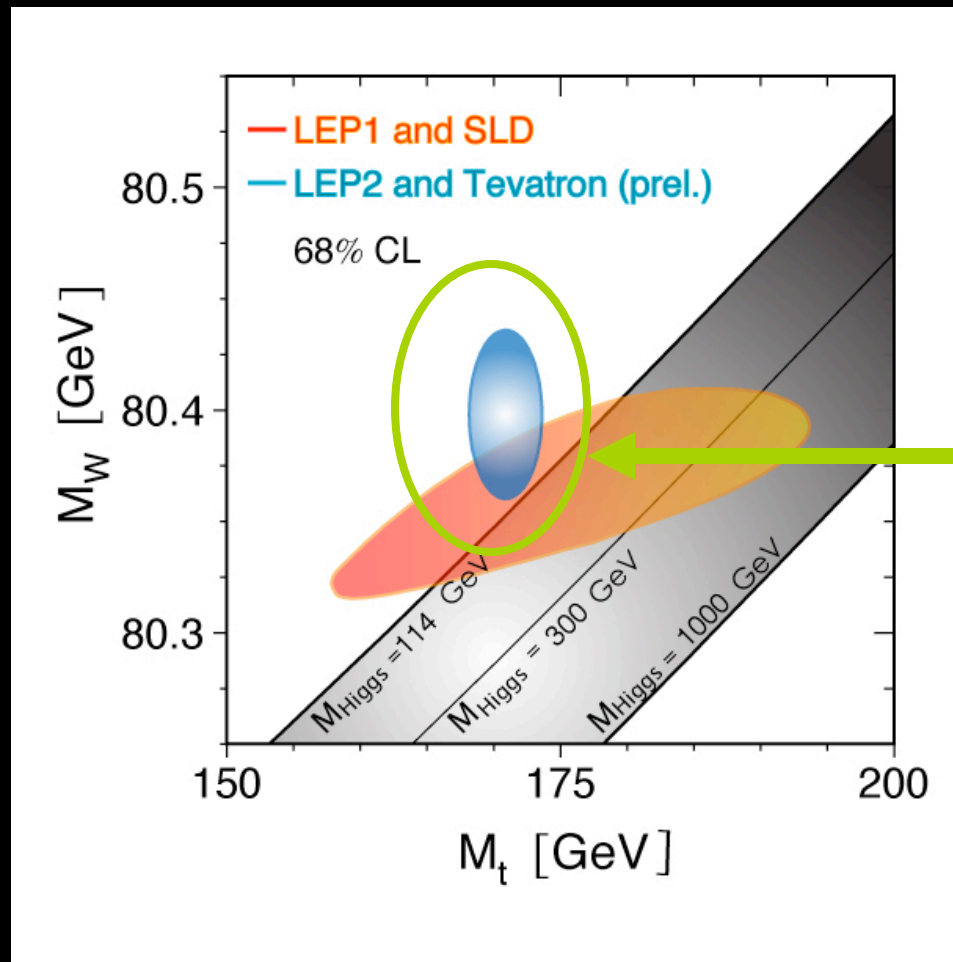
→ The hunt for Higgs is underway!

Top is Pointing to the Higgs?



Top is Pointing to the Higgs?

W boson mass



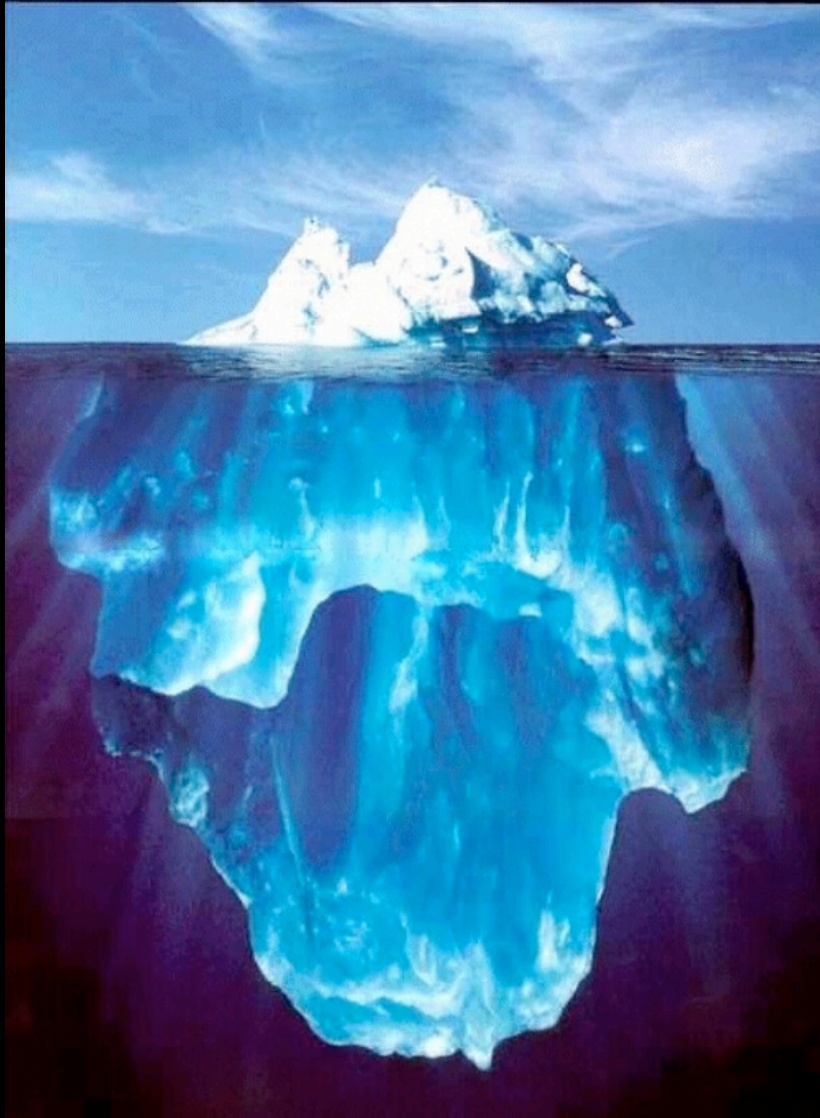
Higgs
Mass?!

Top quark mass

Top and Higgs...

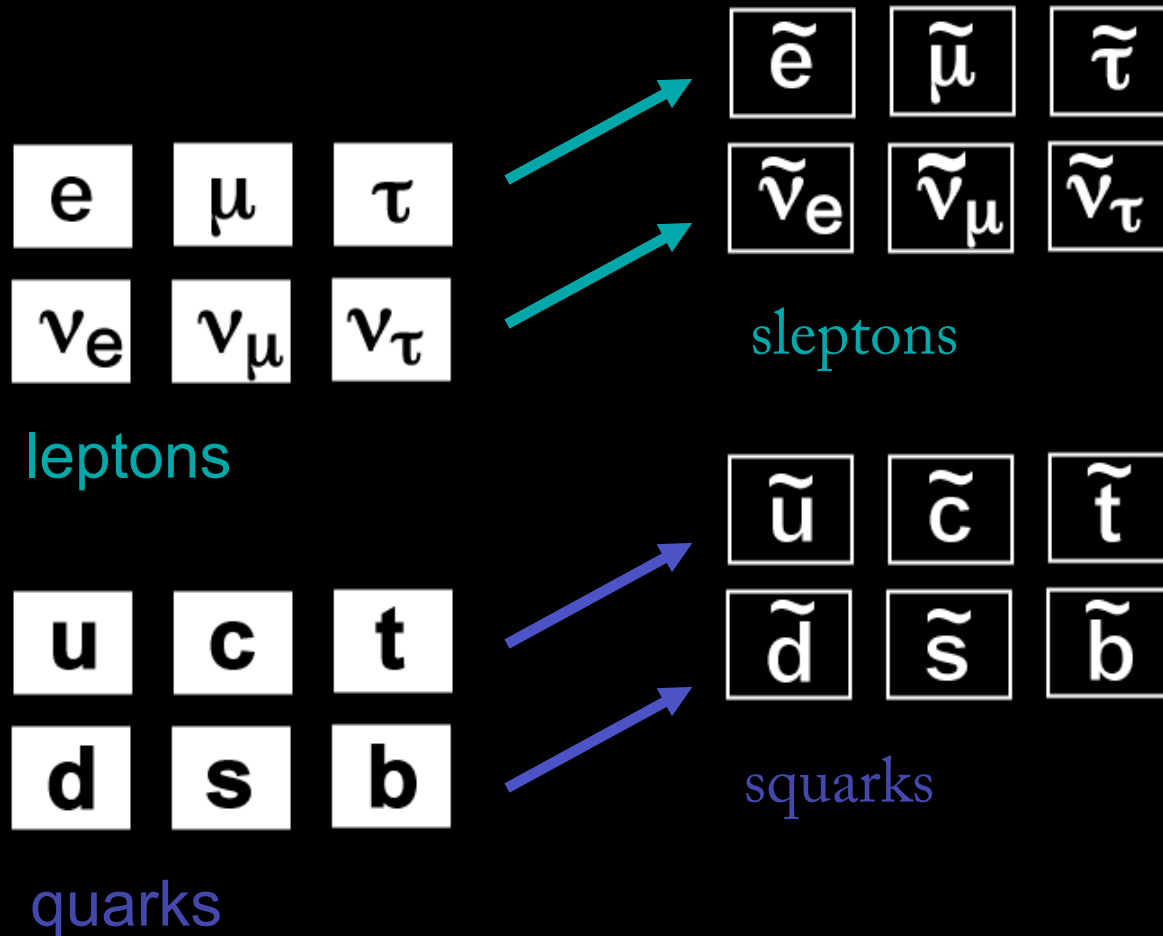


Top and Higgs...



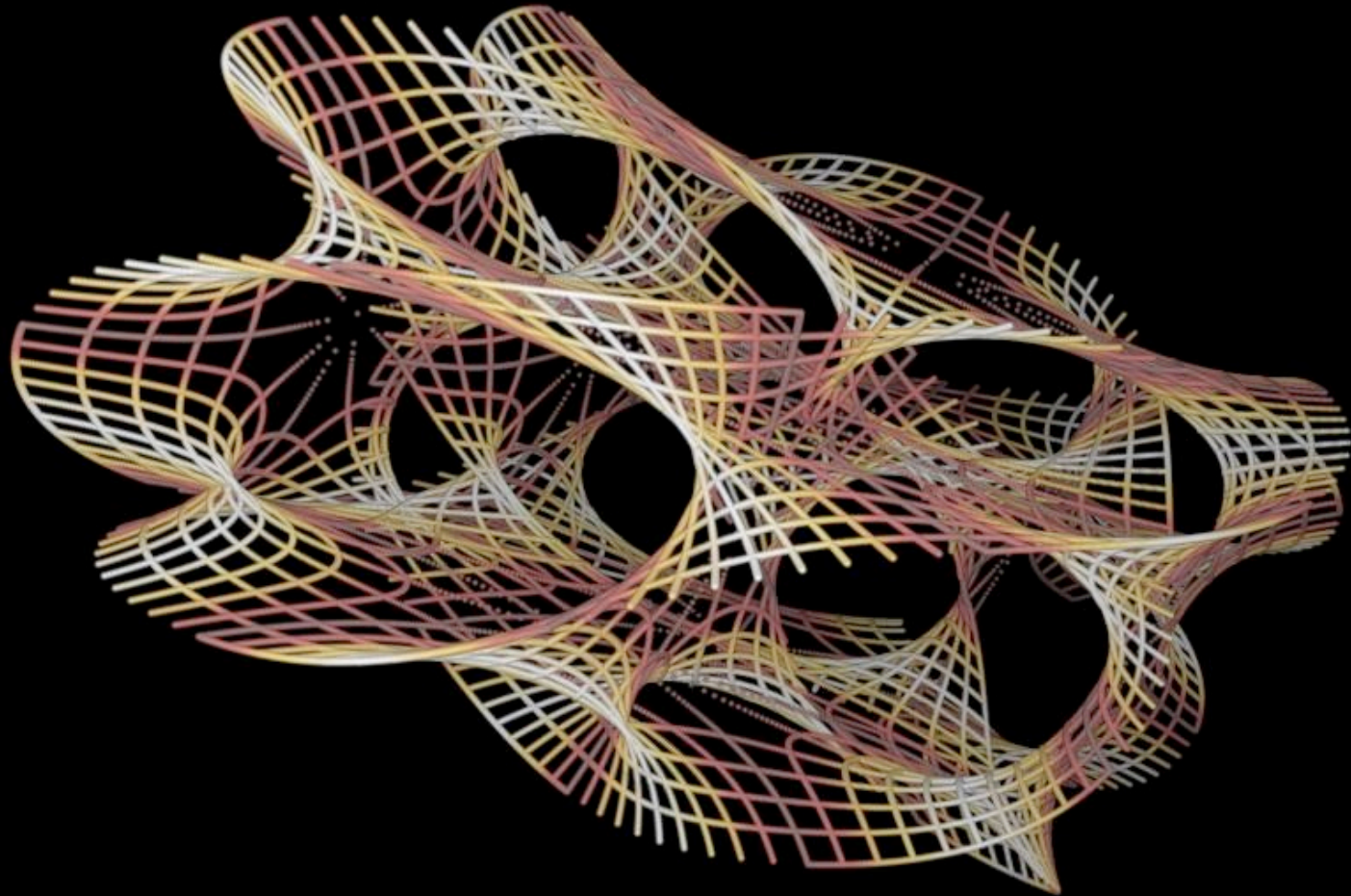
...may be just the tip
of a new particle
physics iceberg!..

supersymmetry



sparticles to match all the particles we already know!

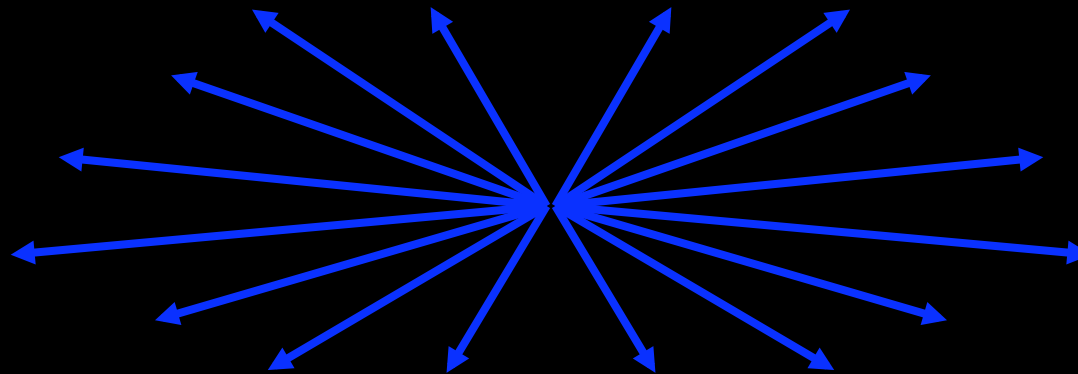
Extra Dimensions



Time machines

Accelerators are also **Time Machines**

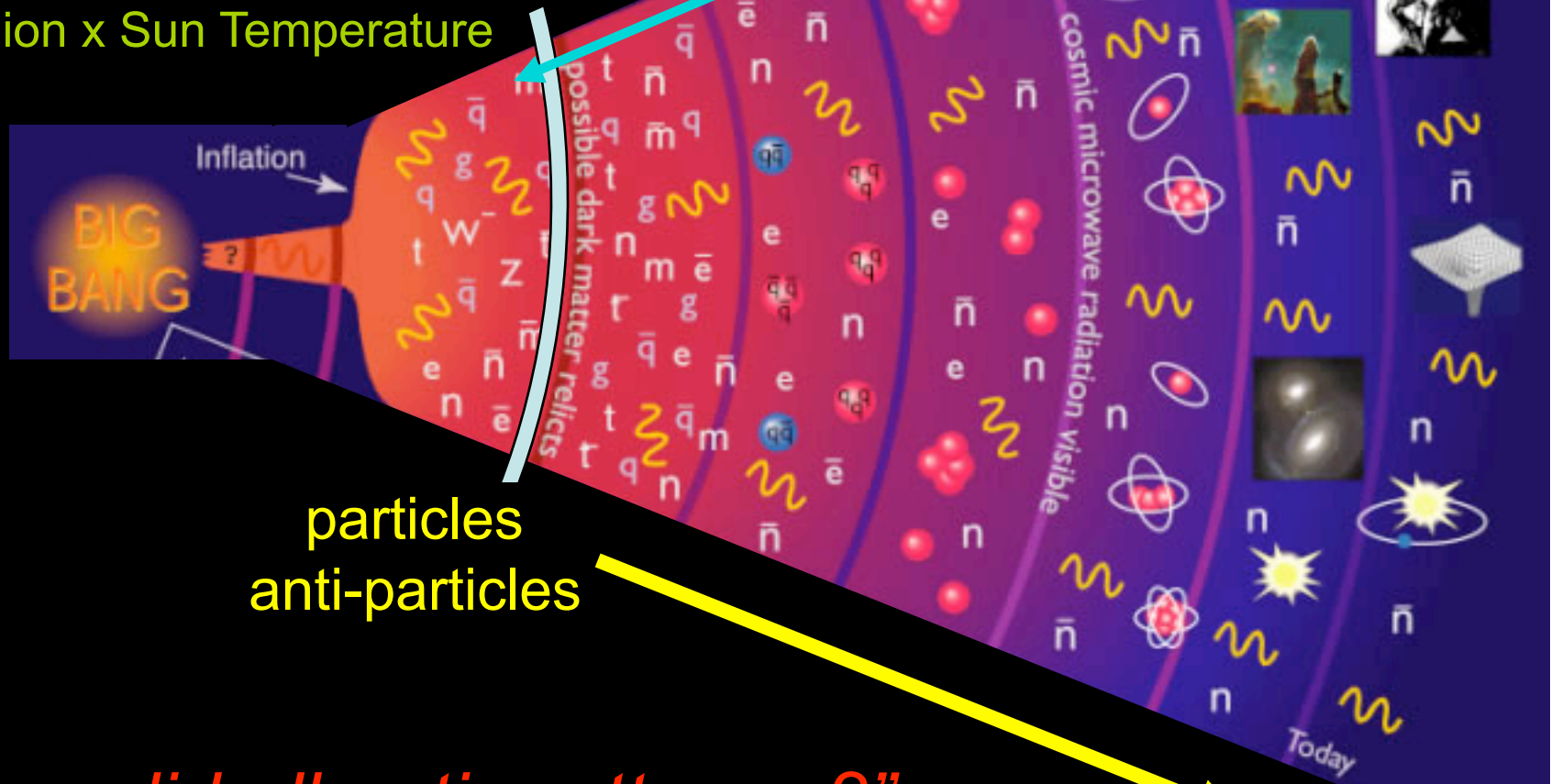
because they make particles last seen
in the earliest moments of the universe.



Modern Colliders Create

particles that existed in the universe only
~0.001 nano second after Big Bang.

100 million x Sun Temperature

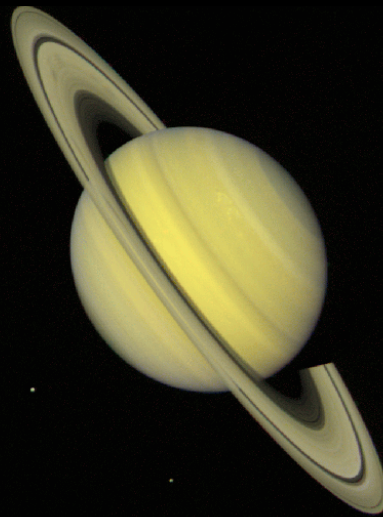
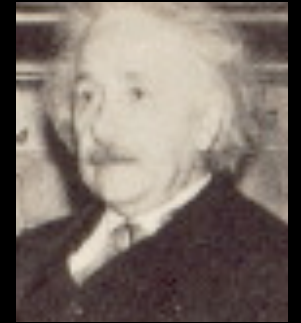


“Where did all anti-matter go?”

particles

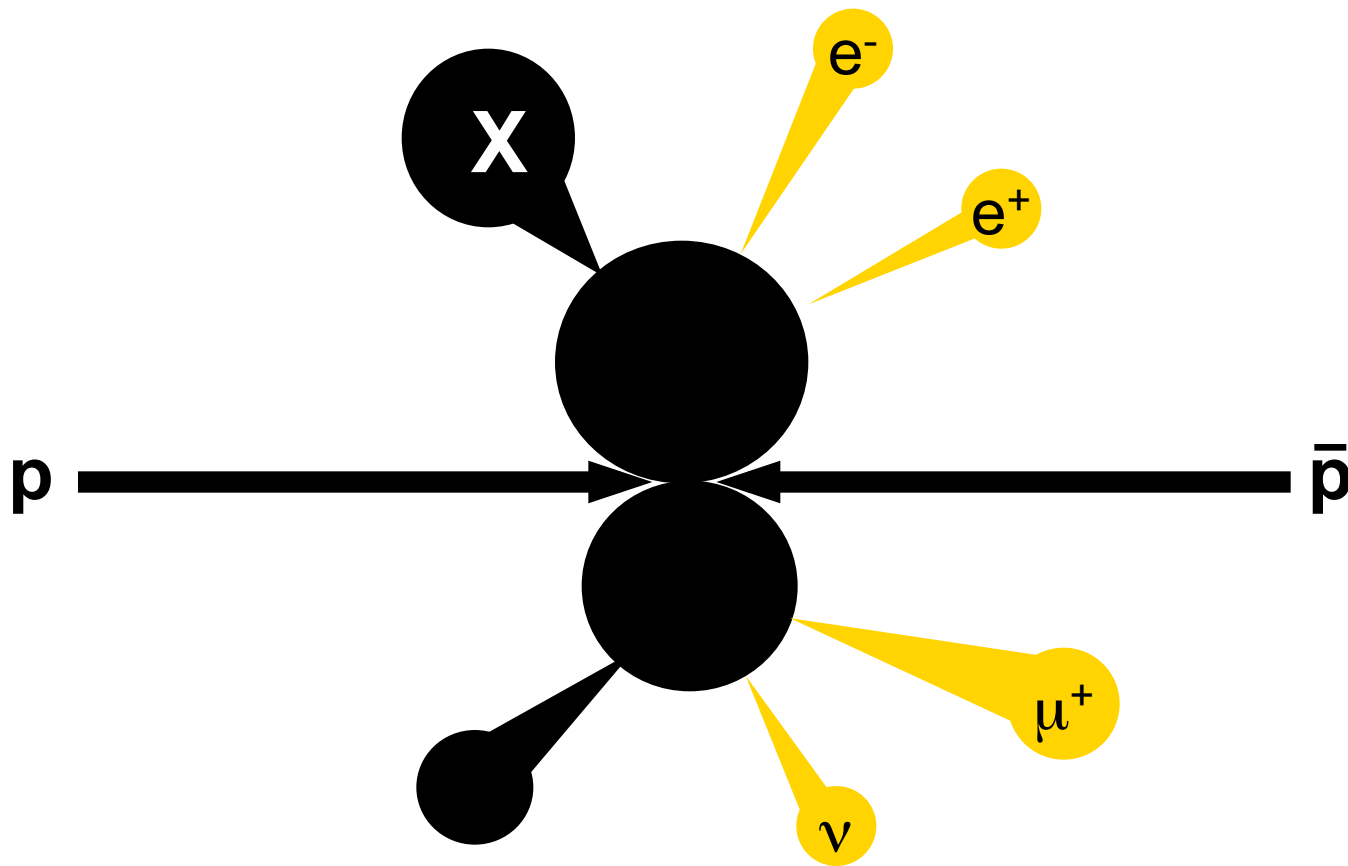
~~Everything~~ is made of electrons, up quarks and down quarks.

Everything that we can see



Need much more (x4) mass than what we see -
Dark Matter *What is it?*

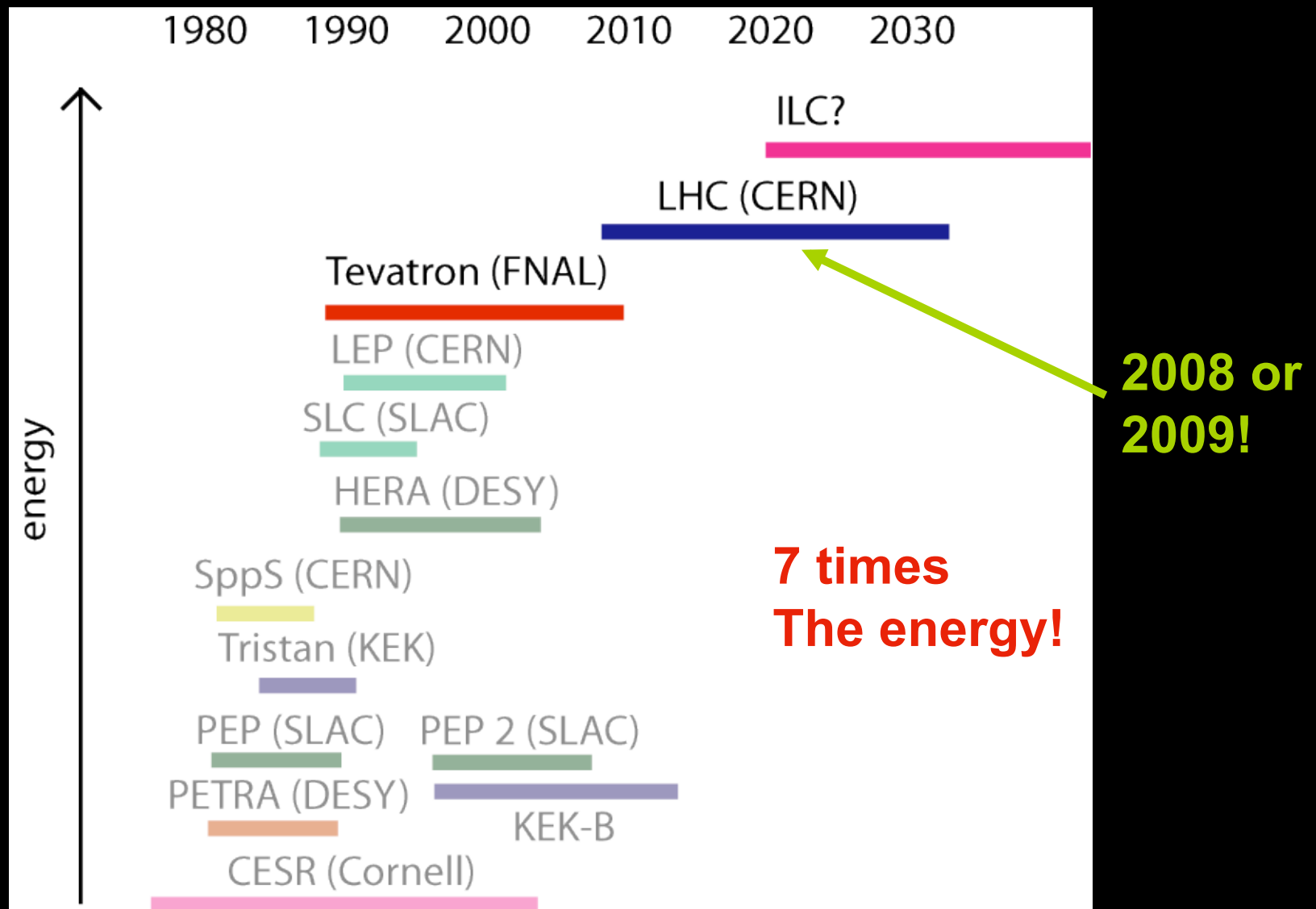
Searching for Dark Matter!



Lesson of the 20th Century

The human scale of space and time is not privileged for understanding Nature, and may even be disadvantaged.

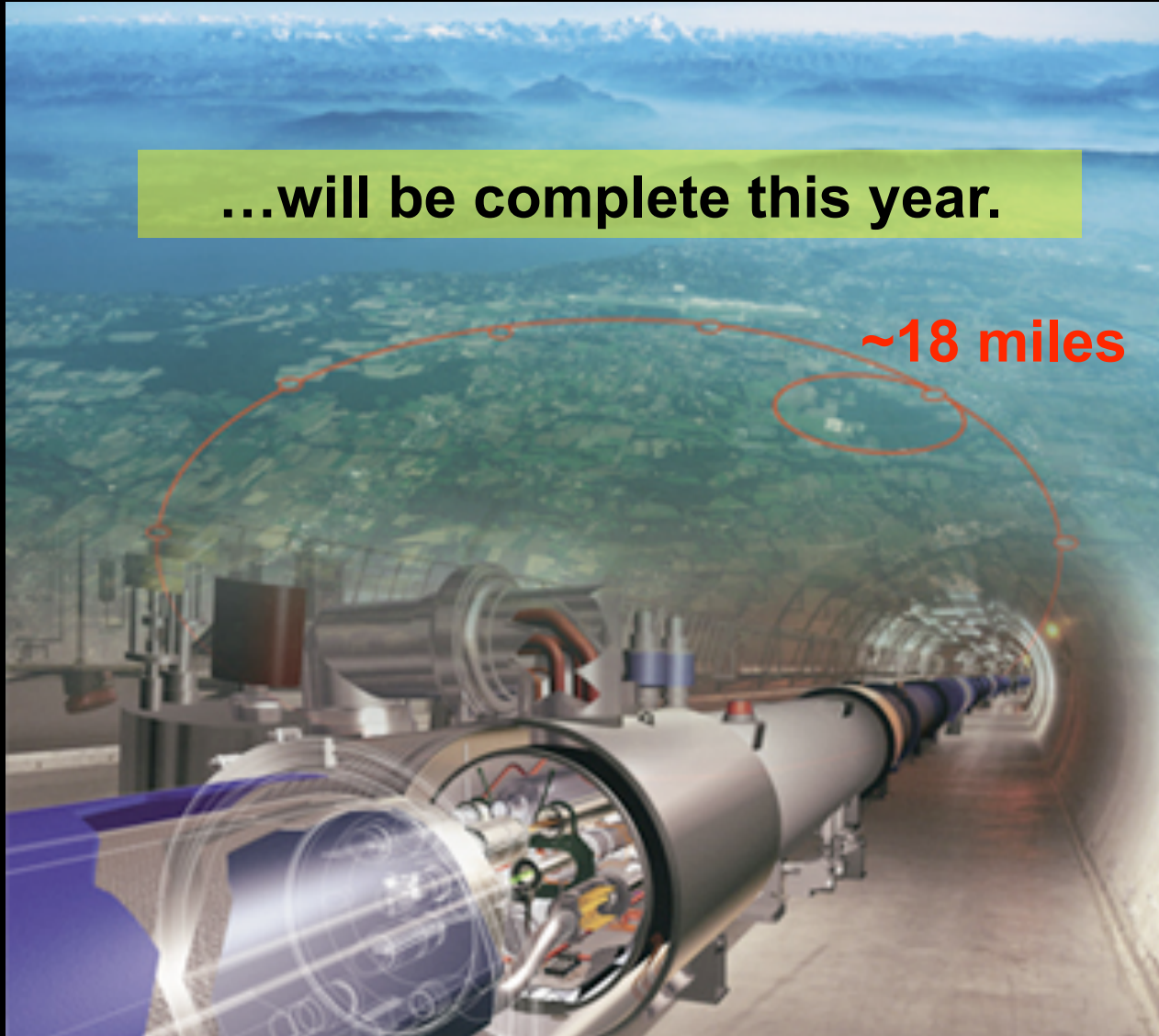
Next Energy Regime



Large Hadron Collider

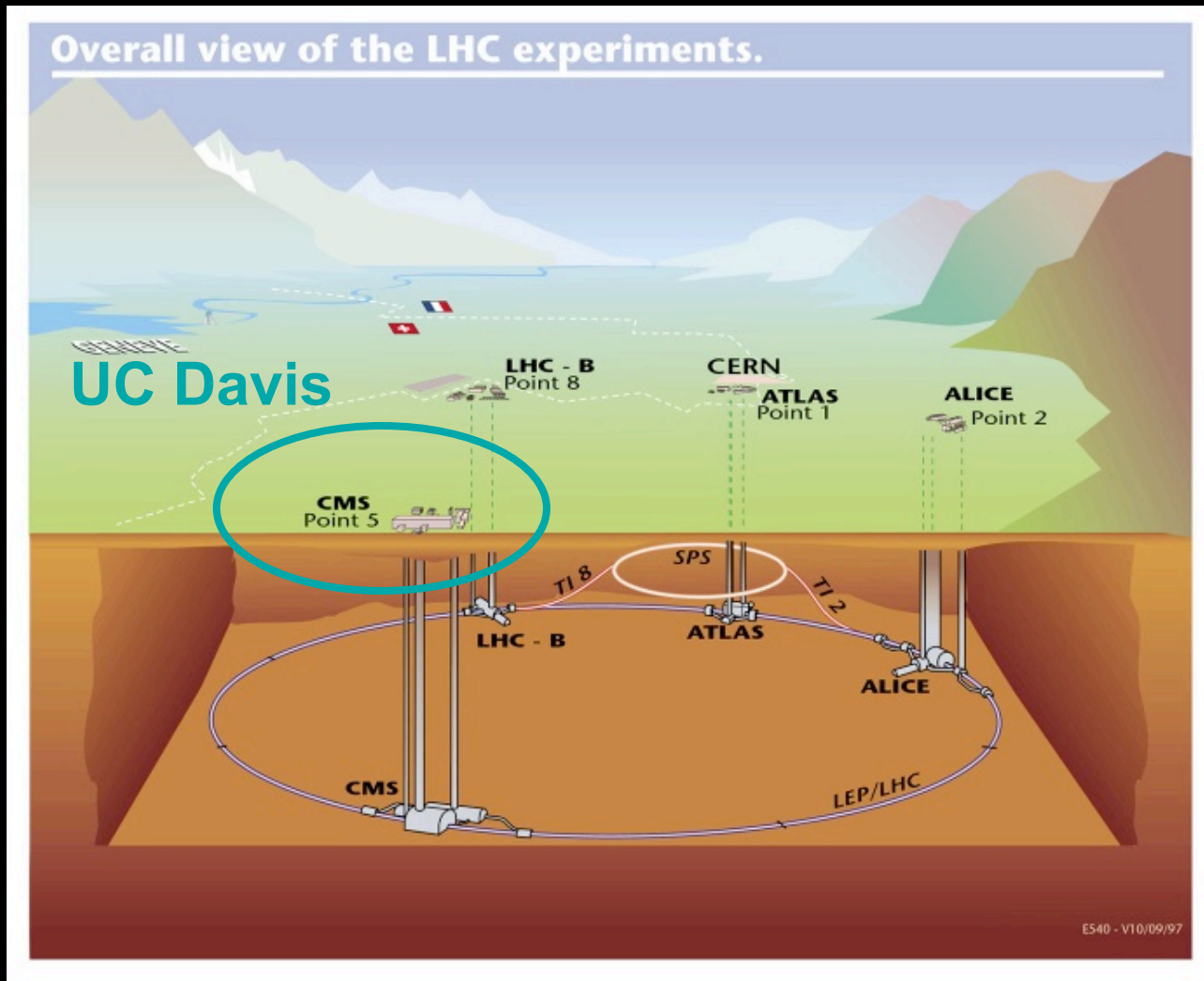
...will be complete this year.

~18 miles



CERN, Geneva, Switzerland

Next energy regime



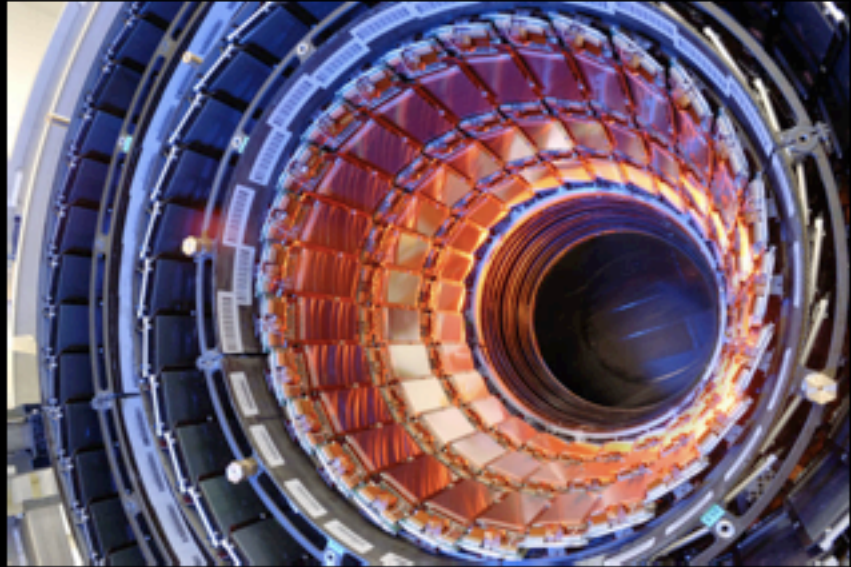
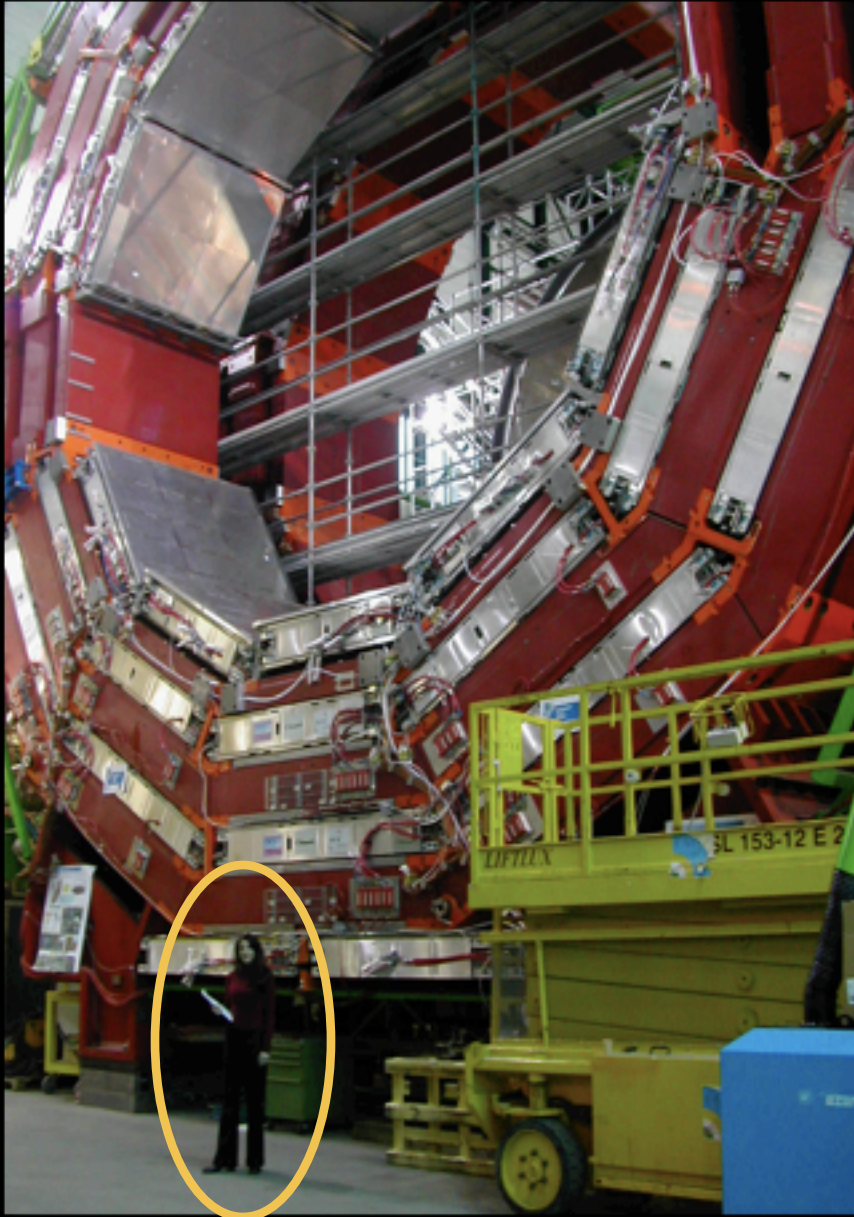
CERN, Geneva, Switzerland

Large Hadron Collider

As the Tevatron winds down...



LHC will open a new window!



LHC Experiments are very, very big!

Discoveries to come



Dark Matter

Electroweak Baryogenesis

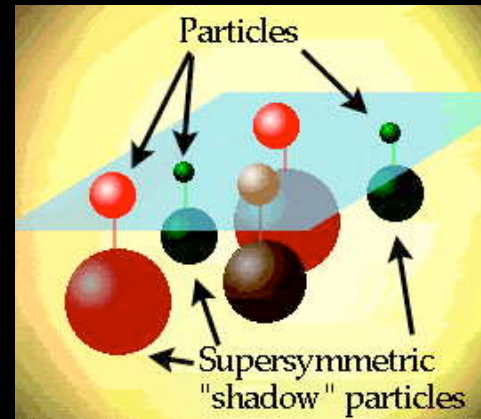
Higgs

Particle Mass Hierarchy

Dark Energy

Gravity

Grand Unified Theories



Extra Dimensions

 *string theory*

Coming Revolution

[Scientific American Magazine](#) - February, 2008

The Coming Revolutions in Particle Physics

The current Standard Model of particle physics begins to unravel when probed much beyond the range of current particle accelerators. So no matter what the Large Hadron Collider finds, it is going to take physics into new territory
By Chris Quigg

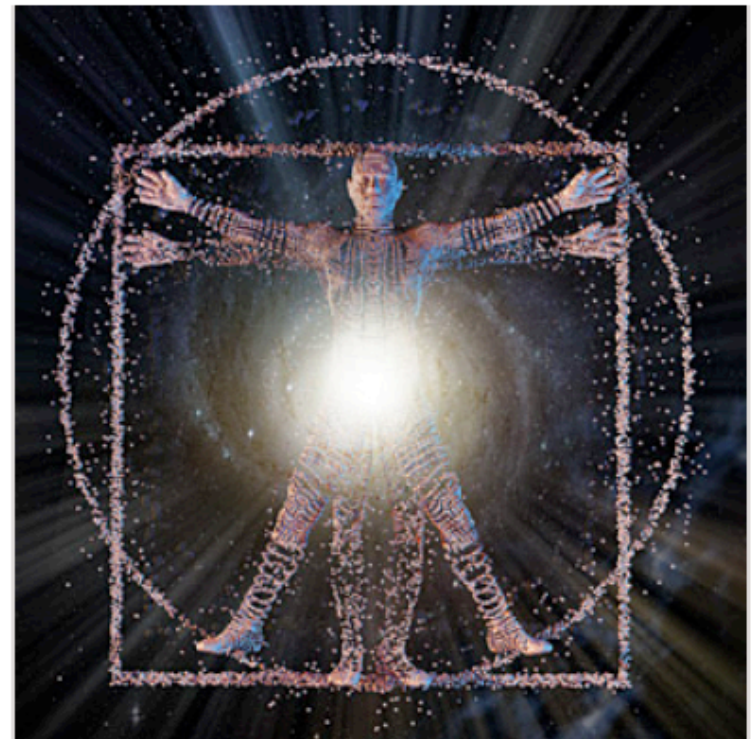
KEY CONCEPTS

The Large Hadron Collider (LHC) is certain to find something new and provocative as it presses into unexplored territory.

“The LHC is certain to find something new and provocative...”

of symmetry. Symmetries underlie the interactions of the Standard Model but are not always reflected in the operation of the model. Understanding why not is a key question.

Scientific American, Feb. 2008!



[BACK](#)

[NEXT](#)

Vitruvian Man Studying the world with a resolution a billion times finer than atomic scales, particle physicists seek a deeper understanding of the everyday world and the evolution of the universe.
Ken Brown



The Future

A cornucopia of familiar particles spraying out from each collision will include, just occasionally, something new and wonderful.

- Sum Films

The Beginning...