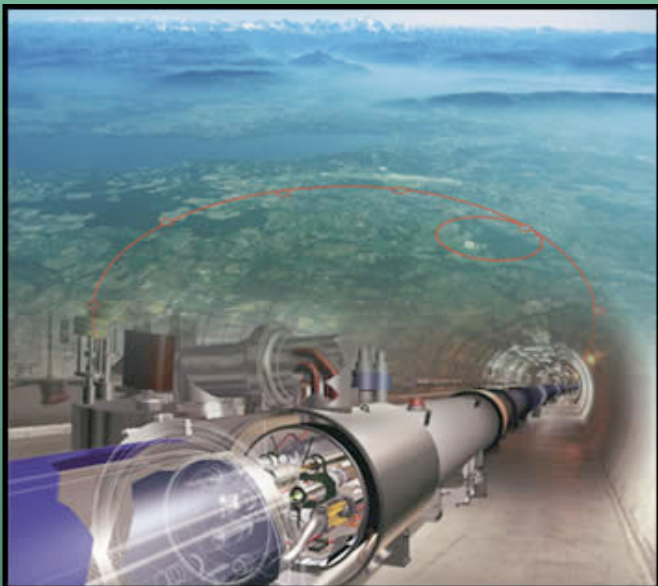
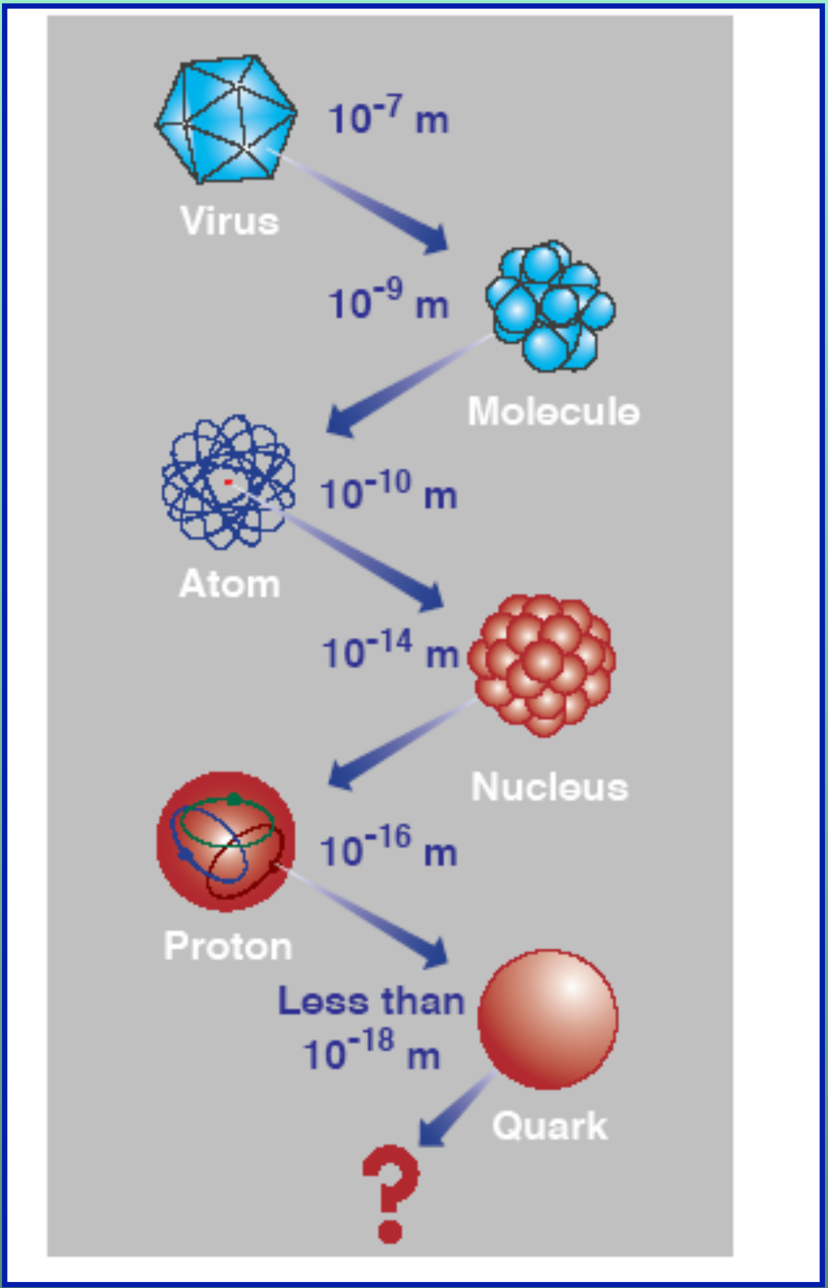
The Big Puzzles of Physics: Searching for the Origin of Mass and Matter in the Universe

Csaba Csáki
Cornell University
Department of Physics

2nd NPKI workshop
Jeju Island
Seeds program



Age old questions:



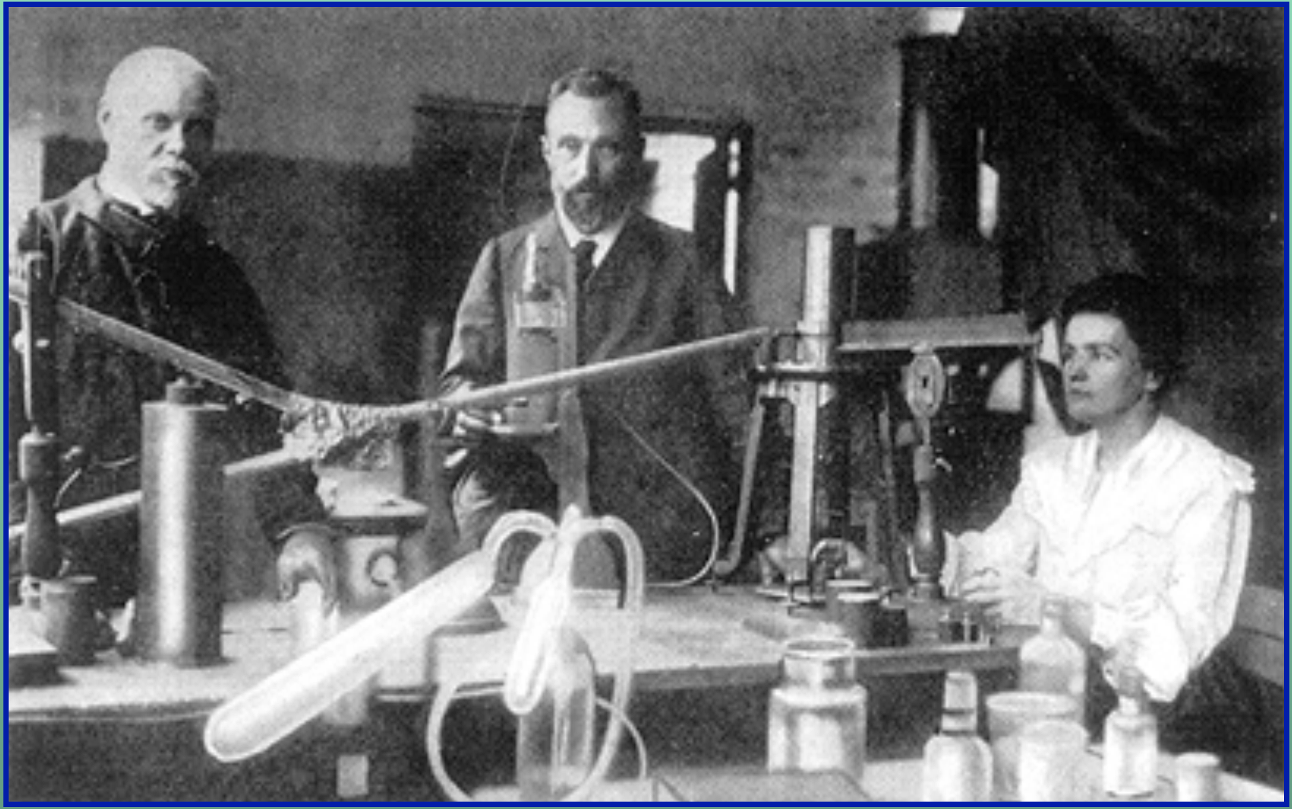
- What are we made of?
- What are the most fundamental constituents of Nature?

Particle physicists study the properties of the smallest known building blocks of matter:

- What are they?
- How do they interact?
- What are their properties?

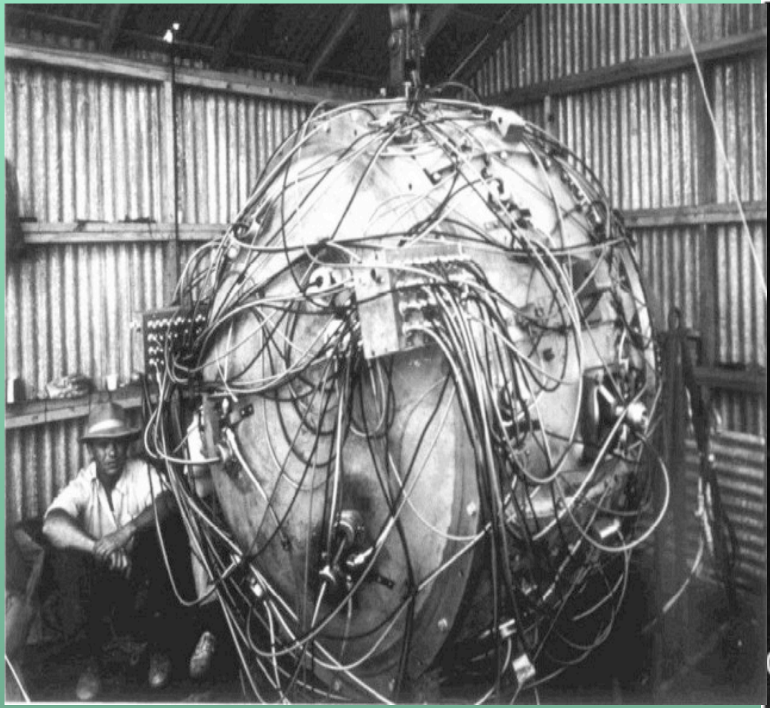
Particle Physics has come a long way over the past 100 years...

From the early days...

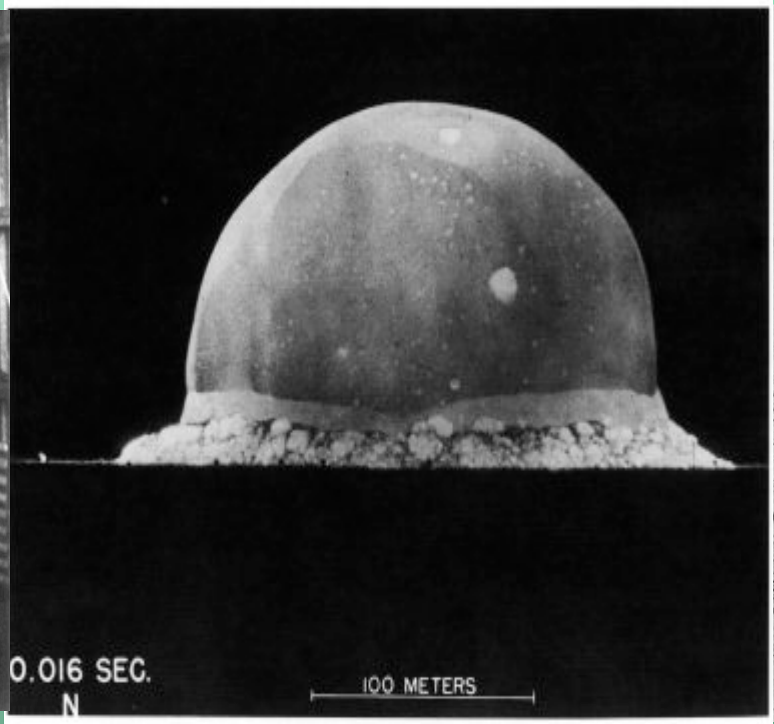


Pierre and Marie Curie and their assistant

...through the nuclear period...



The "gadget"



The Trinity test

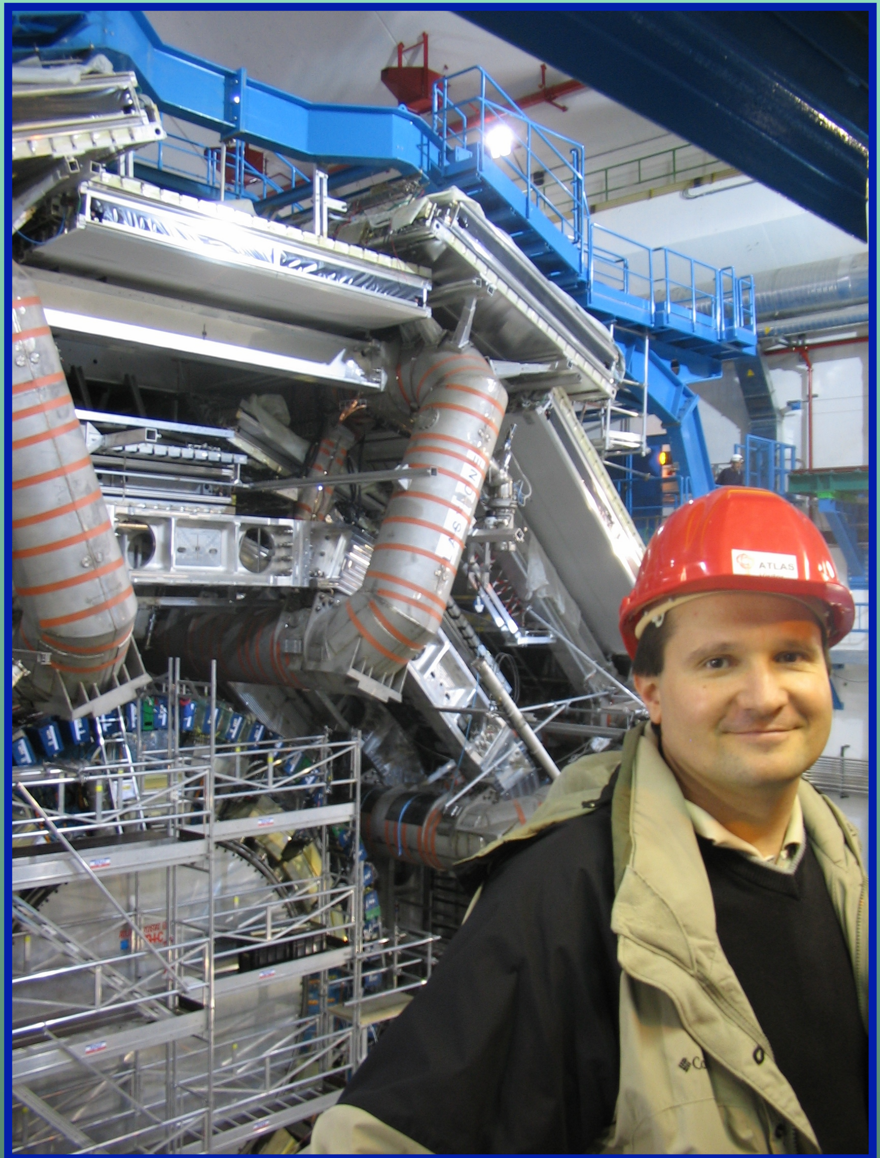
Oppenheimer and Groves

...to modern day particle accelerators:

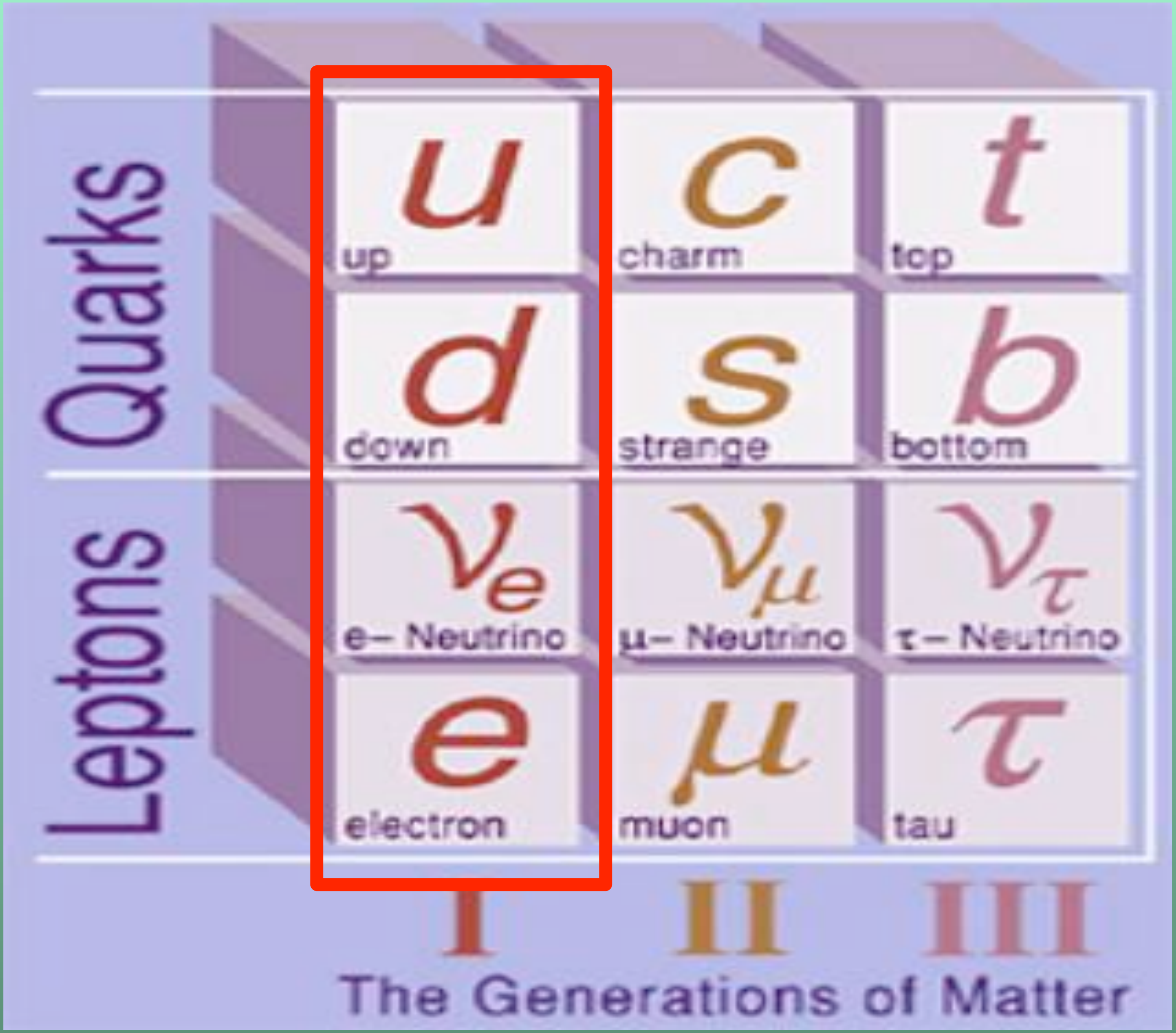
The LHC in Geneva

17 miles circumference

The ATLAS detector



The fundamental matter particles



Also need forces that keep these together!

Four basic forces:

- **Electromagnetic force:**

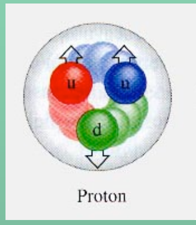
  electricity, radiowaves, light

- **Weak force:**

  origin of radioactivity

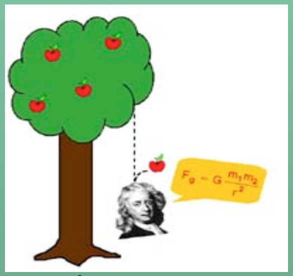
- **Strong force:**

  origin of energy from sun, binds nuclei



- **Gravitational force:**

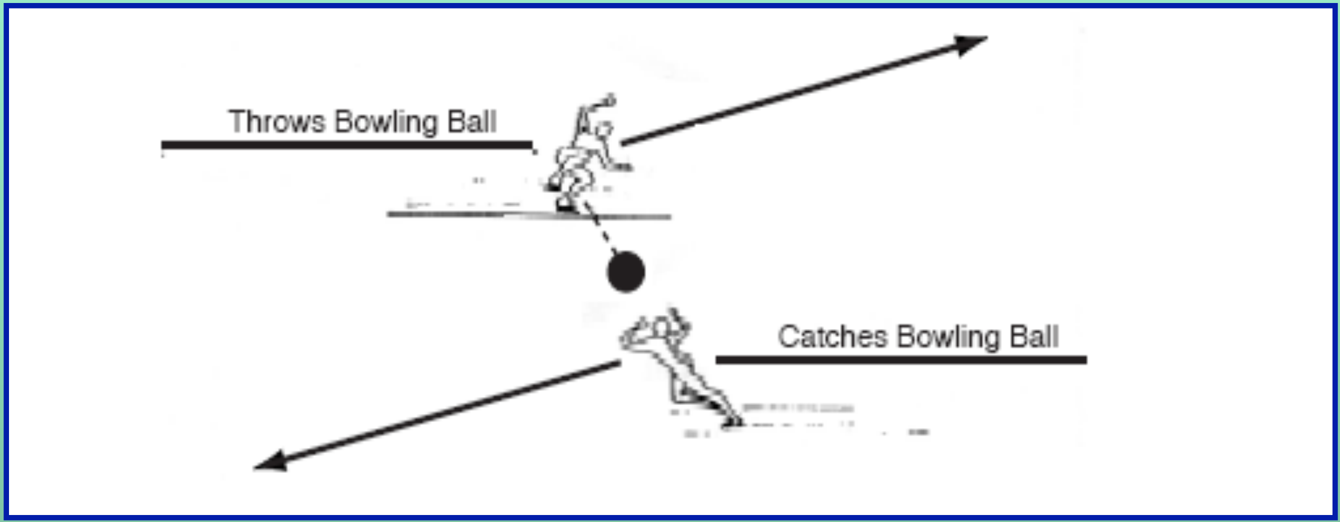
  motion of planets, rockets,...



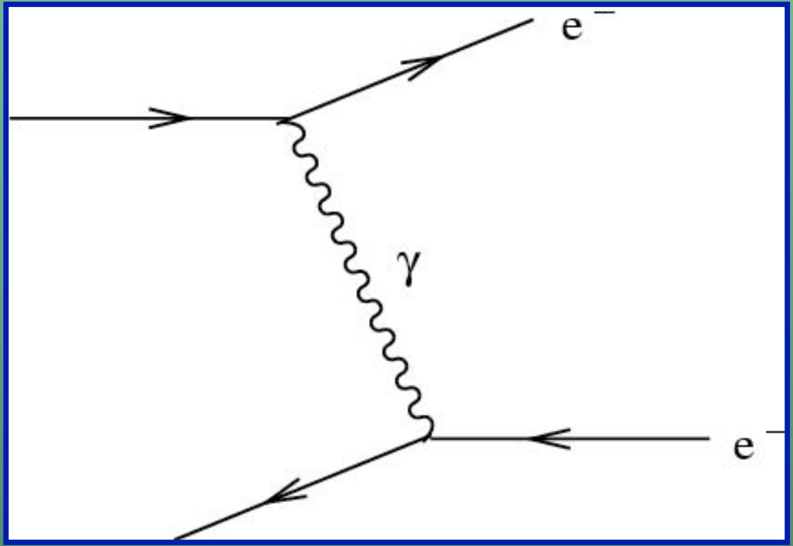
Gravity very weak – a small magnet can balance the effect of the ENTIRE Earth, NOT relevant in accelerators, BUT:

Only one type of gravitational charge, add up – very relevant over long distances (while E&M charges cancel)

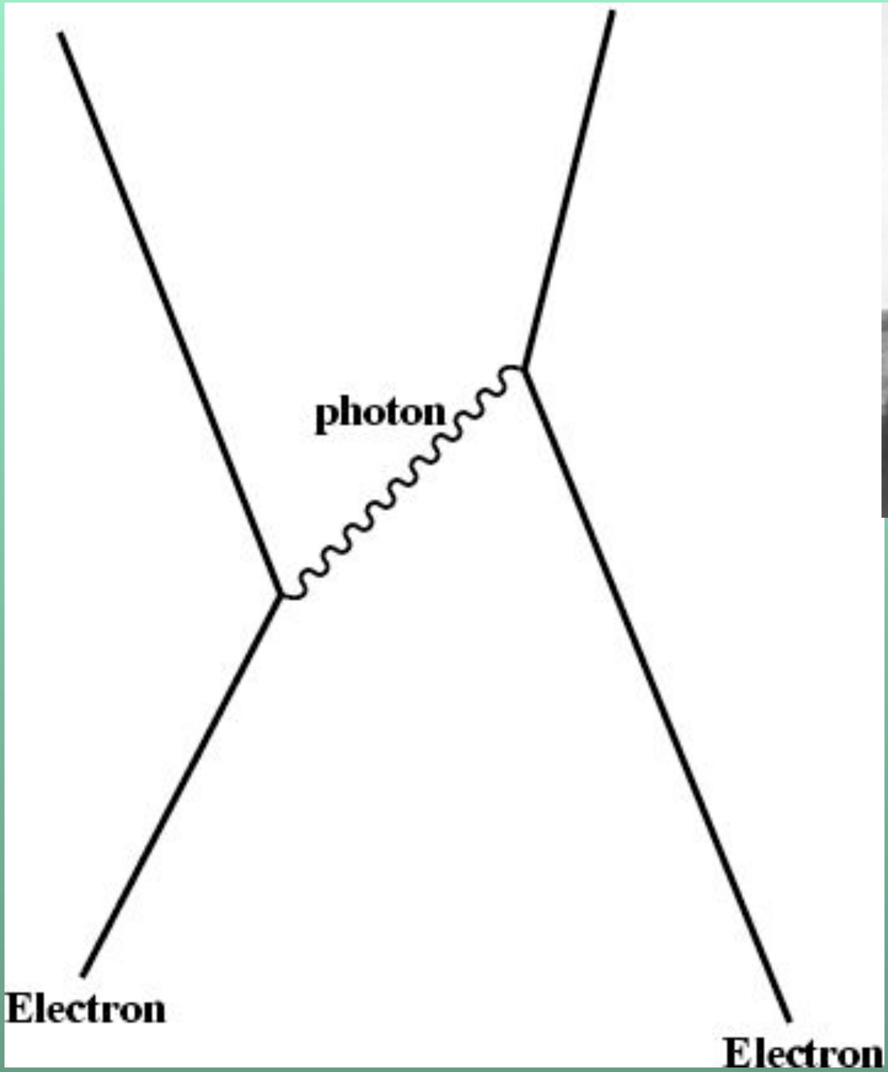
Force between particles: exchange of force carrying particle



For example: Electromagnetic force



Electromagnetic force



Feynman

Electric force is described by emission and absorption of photon – the force carrier of electromagnetism

"Quantum Electrodynamics"

PHYSICAL REVIEW VOLUME 76, NUMBER 6 SEPTEMBER 15, 1949

Space-Time Approach to Quantum Electrodynamics

R. P. Feynman
Department of Physics, Cornell University, Ithaca, New York

(Received May 9, 1949)

In this paper two things are done. (1) It is shown that a considerable simplification can be attained in writing down matrix elements for complex processes in electrodynamics. Further, a physical point of view is available which permits them to be written down directly for any specific problem. Being simply a restatement of conventional electrodynamics, however, the matrix elements diverge for complex processes. (2) Electrodynamics is modified by altering the interaction of electrons at short distances. All matrix elements are now finite, with the exception of those relating to problems of vacuum polarization. The latter are evaluated in a manner suggested by Pauli and Bethe, which gives finite results for these matrices also. The only effects sensitive to the modification are changes in mass and charge of the electrons. Such changes could not be directly observed. Phenomena directly observable, are insensitive to the details of the modification used (except at extreme energies). For such phenomena, a limit can be taken as the range of the modification goes to zero. The results then agree with those of Schwinger. A complete, unambiguous, and presumably consistent, method is therefore available for the calculation of all processes involving electrons and photons.

The simplification in writing the expressions results from an emphasis on the over-all space-time view resulting from a study of the solution of the equations of electrodynamics. The relation of this to the more conventional Hamiltonian point of view is discussed. It would be very difficult to make the modification which is proposed if one insisted on having the equations in Hamiltonian form.

The methods apply as well to charges obeying the Klein-Gordon equation, and to the various meson theories of nuclear forces. Illustrative examples are given. Although a modification like that used in electrodynamics can make all matrices finite for all of the meson theories, for some of the theories it is no longer true that all directly observable phenomena are insensitive to the details of the modification used.

The actual evaluation of integrals appearing in the matrix elements may be facilitated, in the simpler cases, by methods described in the appendix.

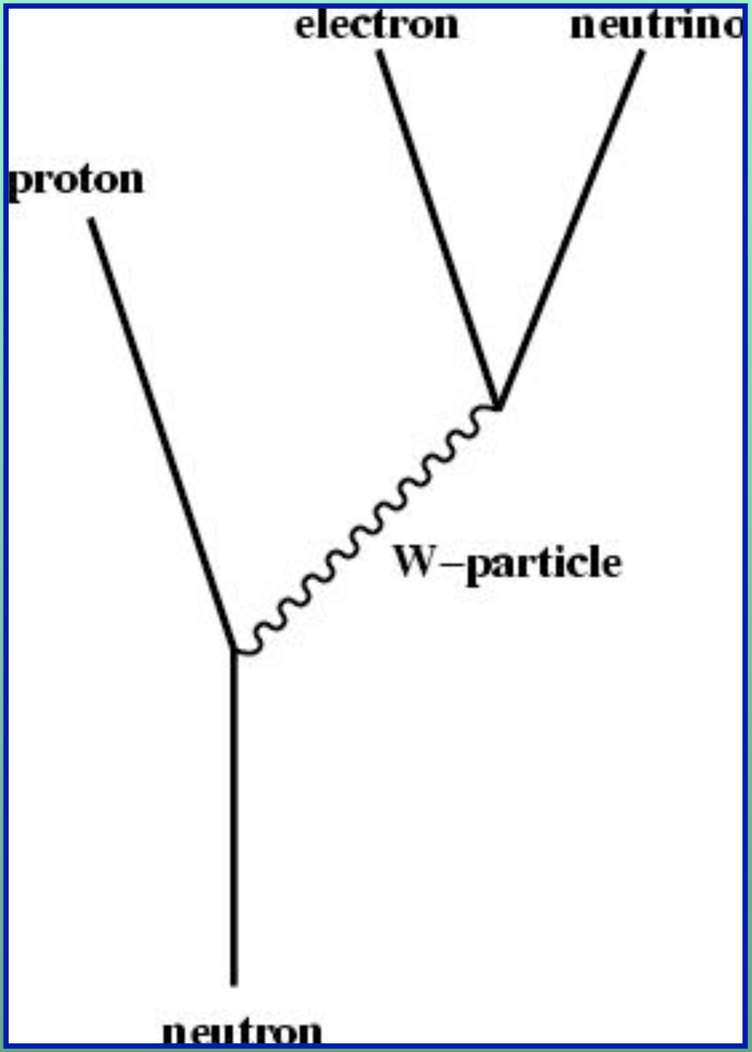
THIS paper should be considered as a direct continuation of a preceding one[1] (I) in which the motion of electrons, neglecting interaction, was ana-

positive energy electrons are involved. Further, the effects of longitudinal and transverse waves can be combined together. The separations previously made

Weak Interactions

Just like electrodynamics, EXCEPT

- Mediating particle MASSIVE
- Mediating particle CHARGED



- Instead of photon, mediating particles W and Z bosons
- Otherwise theory just like the previous one

Unified theory of electroweak interactions

The theorists who predicted the W and Z bosons

Glashow

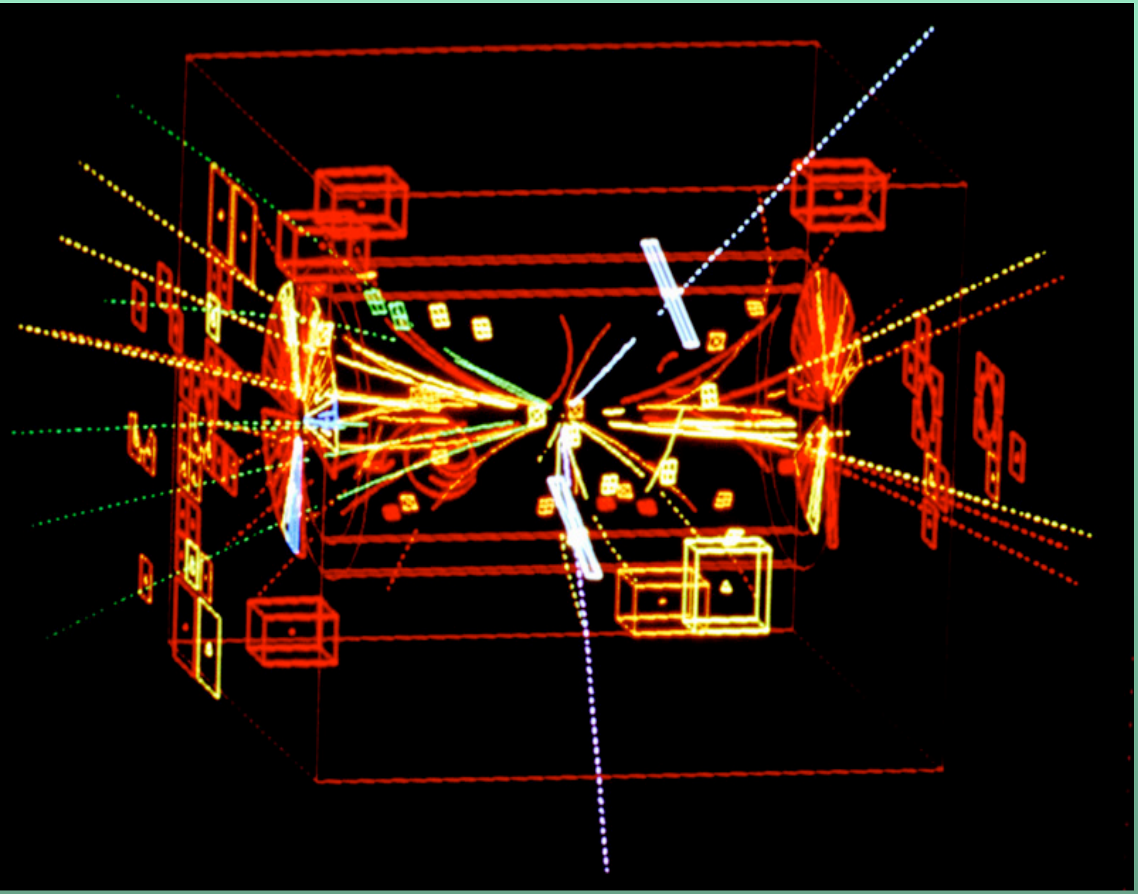
Cornell undergrad

Salam

Weinberg

Cornell undergrad

The discovery of the Z-particle at CERN (Geneva) in 1982



The first event...

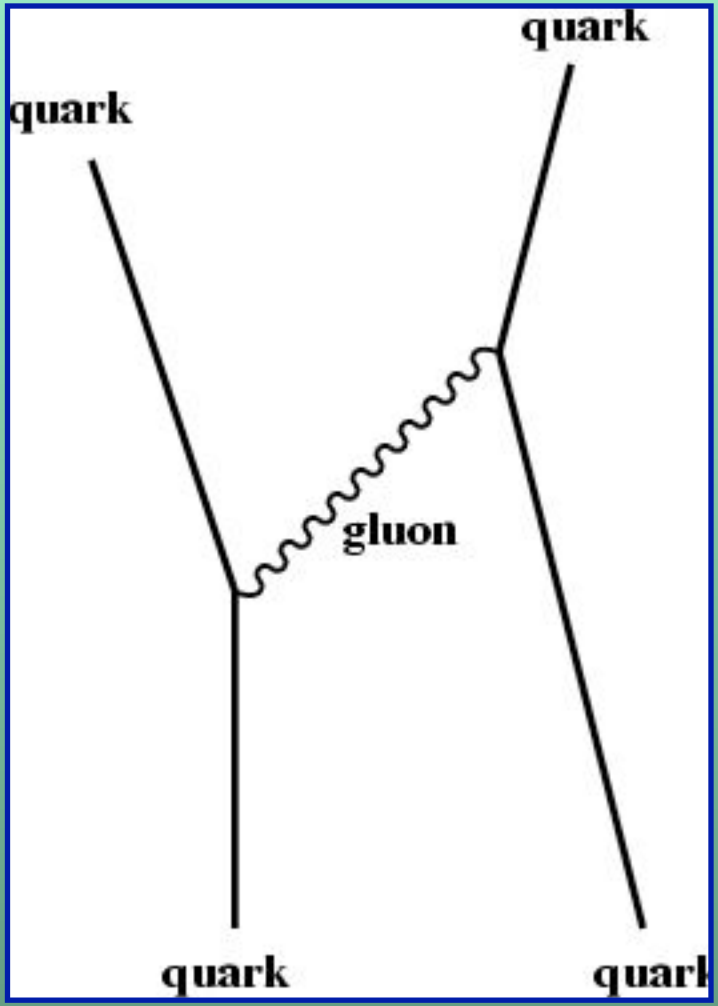
Champagne for the Nobel prize
Rubbia and van der Meer 1984

Strong Interactions

Just like electrodynamics, EXCEPT

- Fundamental particles quarks
- Emission of mediating particle very high probability -- strong interaction...

- Instead of photon, mediating particle gluon (“glues” the quarks into bound state protons, etc)
- Otherwise theory just like the previous one



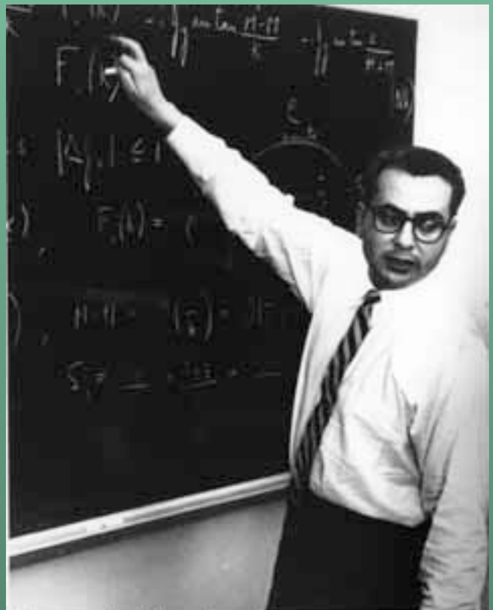
Quarks

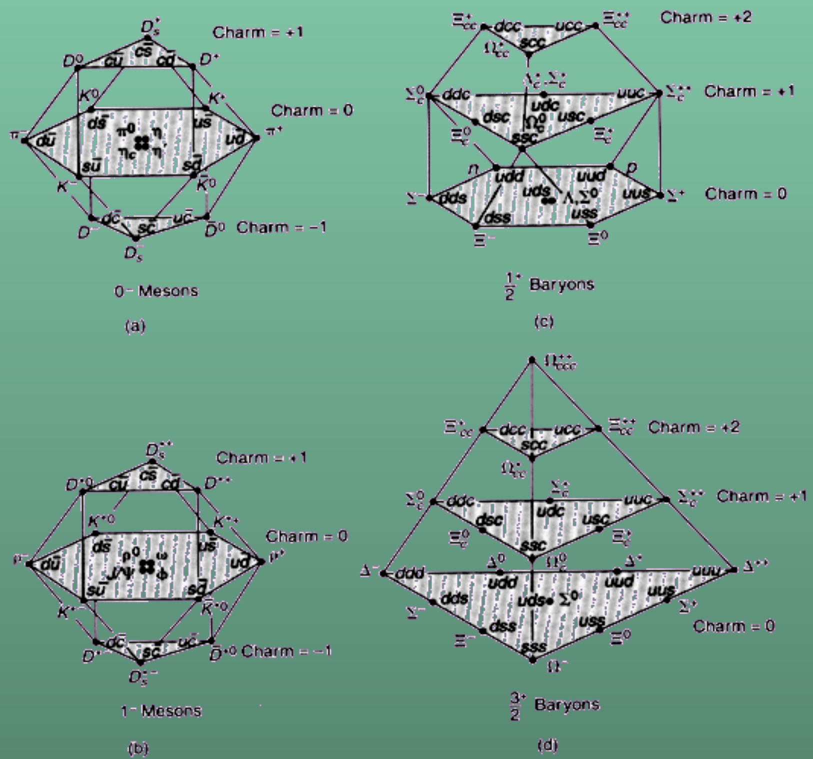
- Basic strongly interacting objects
- Never visible as free particles -- confined
- Form bound states, glued together

proton

Allows to make sense of the 100's of particles observed...

Gell-Mann

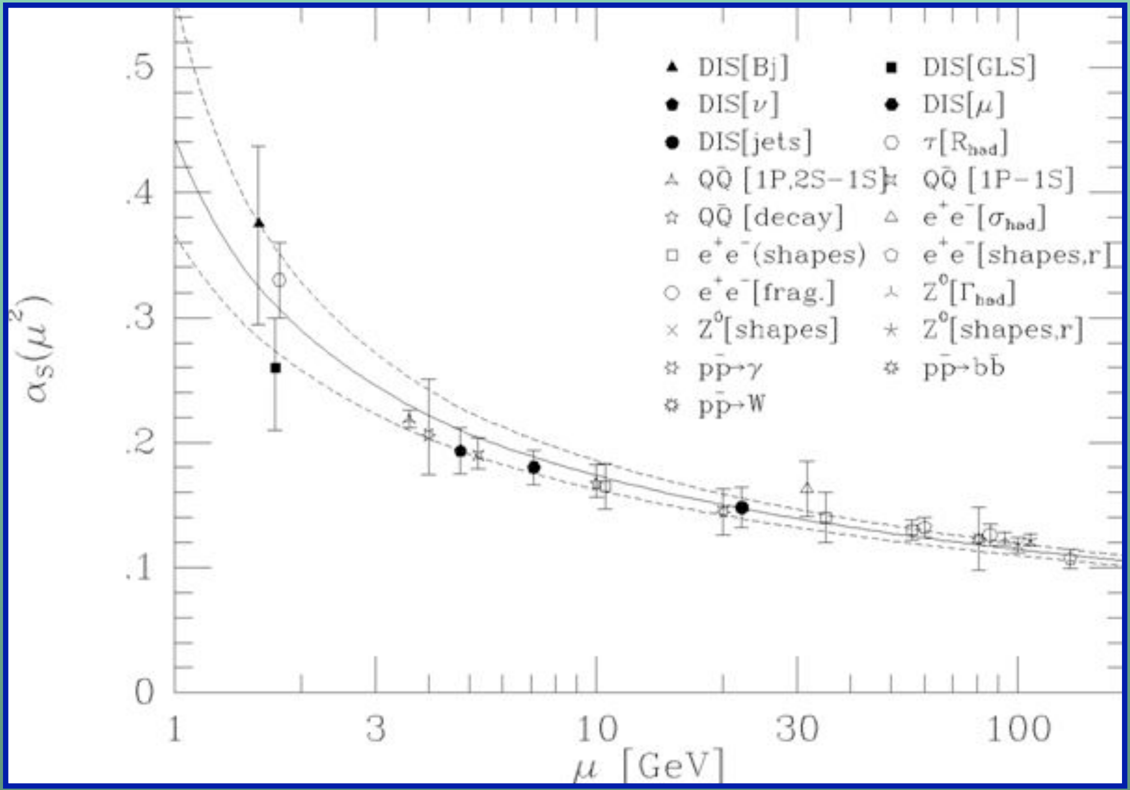




Asymptotic freedom of strong interactions

- Very counter intuitive result
- Interaction gets weaker at high energies
- Strong interaction NOT ALWAYS STRONG!
- Nobel prize of 2004!

Gross Politzer Wilczek



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

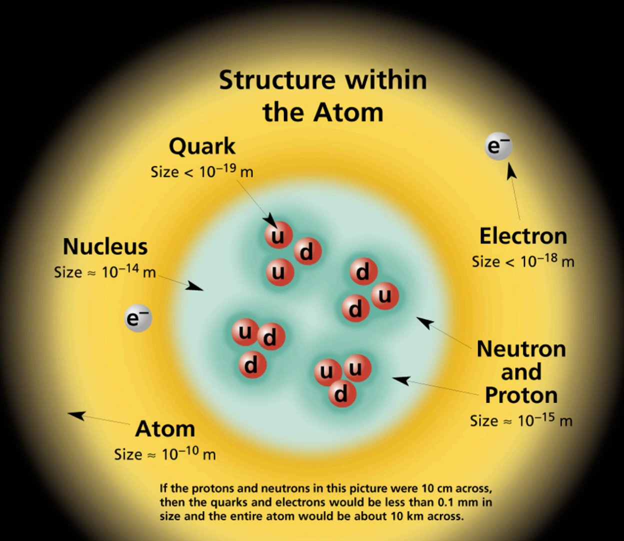
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-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^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



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.

BOSONS

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; 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 (see figure below). 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.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

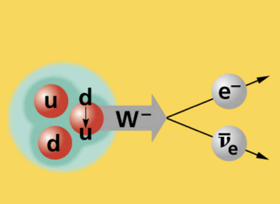
Matter and Antimatter

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, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

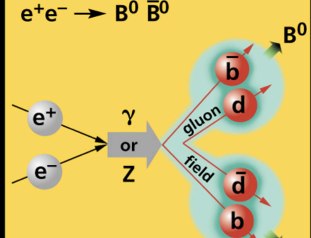
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



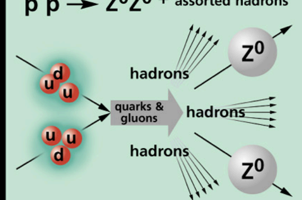
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

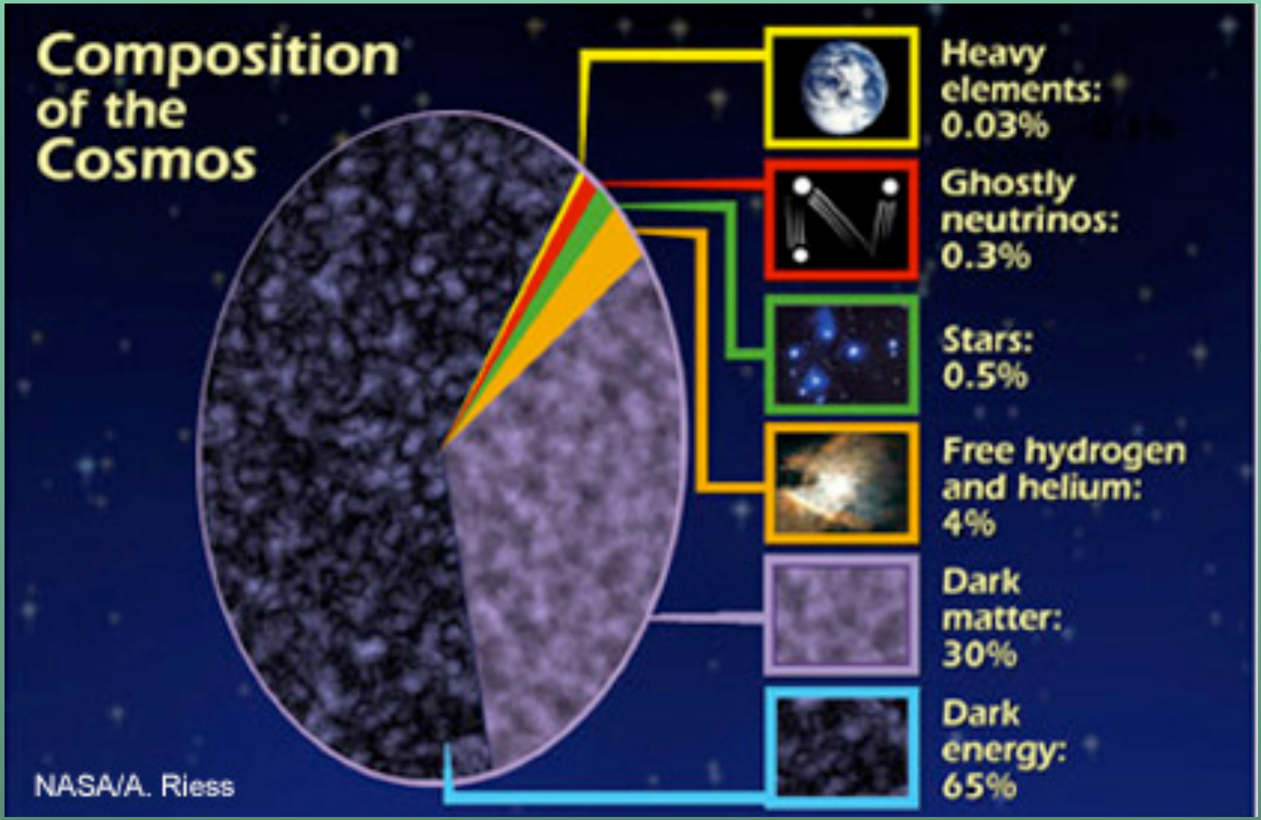
Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

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
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

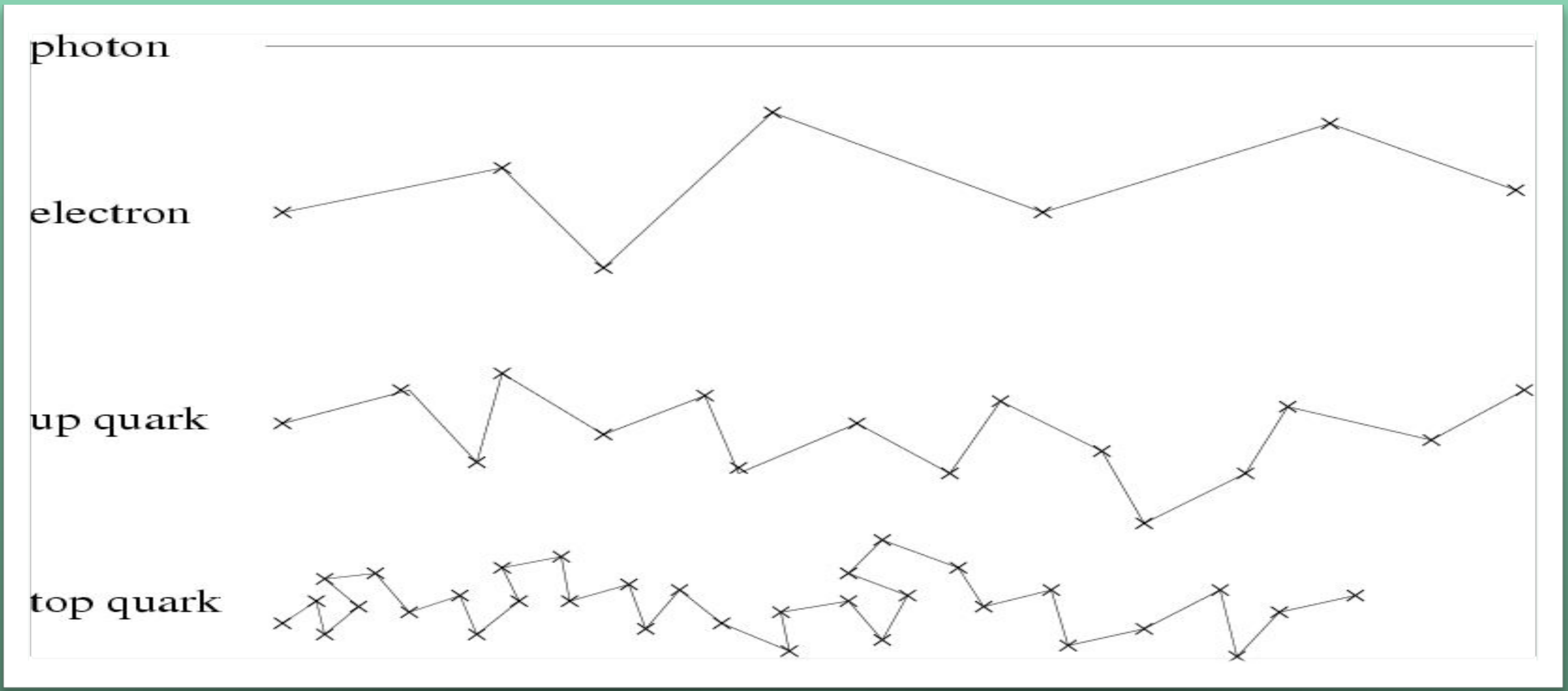
However, some very fundamental questions not or partially answered!

1. Why do particles have a mass?
2. Why are we made of matter (and not anti-matter)?
3. What gives most of the mass of the galaxies?
4. What gives most of the mass of the Universe?



- Entire space is filled with Higgs condensate
- Interaction with condensate slows down motion
- Effectively appears as if particles massive

Somewhat like aether theory, but relativistic (need scalar!)



- Analogy: like a viscous force slowing down the motion
- Ping-pong ball dragged in honey
- More precise analogy:

Different damping forces

$$F_{visc} = -bv$$

$$F_{turb} = -bv^2$$

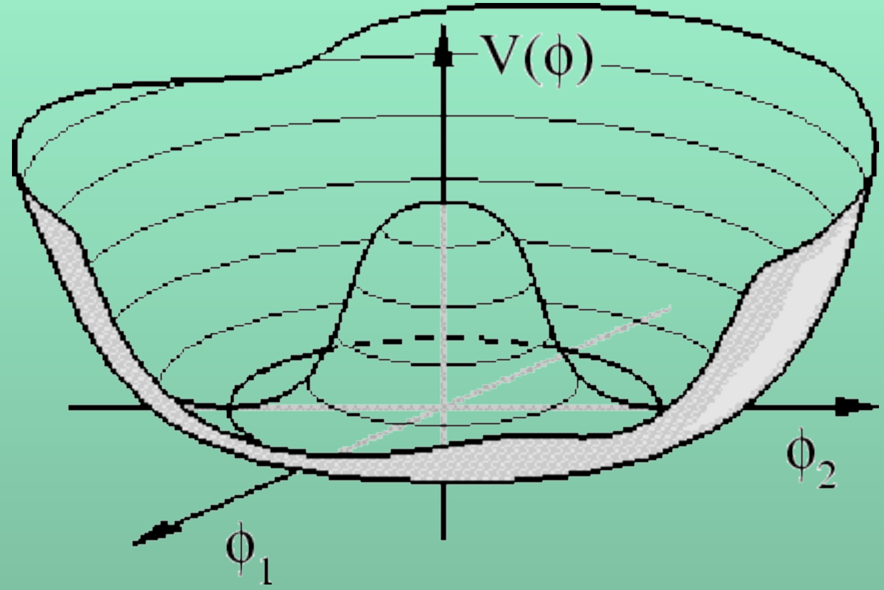
$$F_{Higgs} = -ba$$

$$\vec{F}_{tot} = \sum_i \vec{F}_i - b\vec{a} = 0$$

$$\sum_i \vec{F}_i = b\vec{a}$$

b: effective mass

There should be a Higgs field



Excitations of Higgs field: Higgs boson

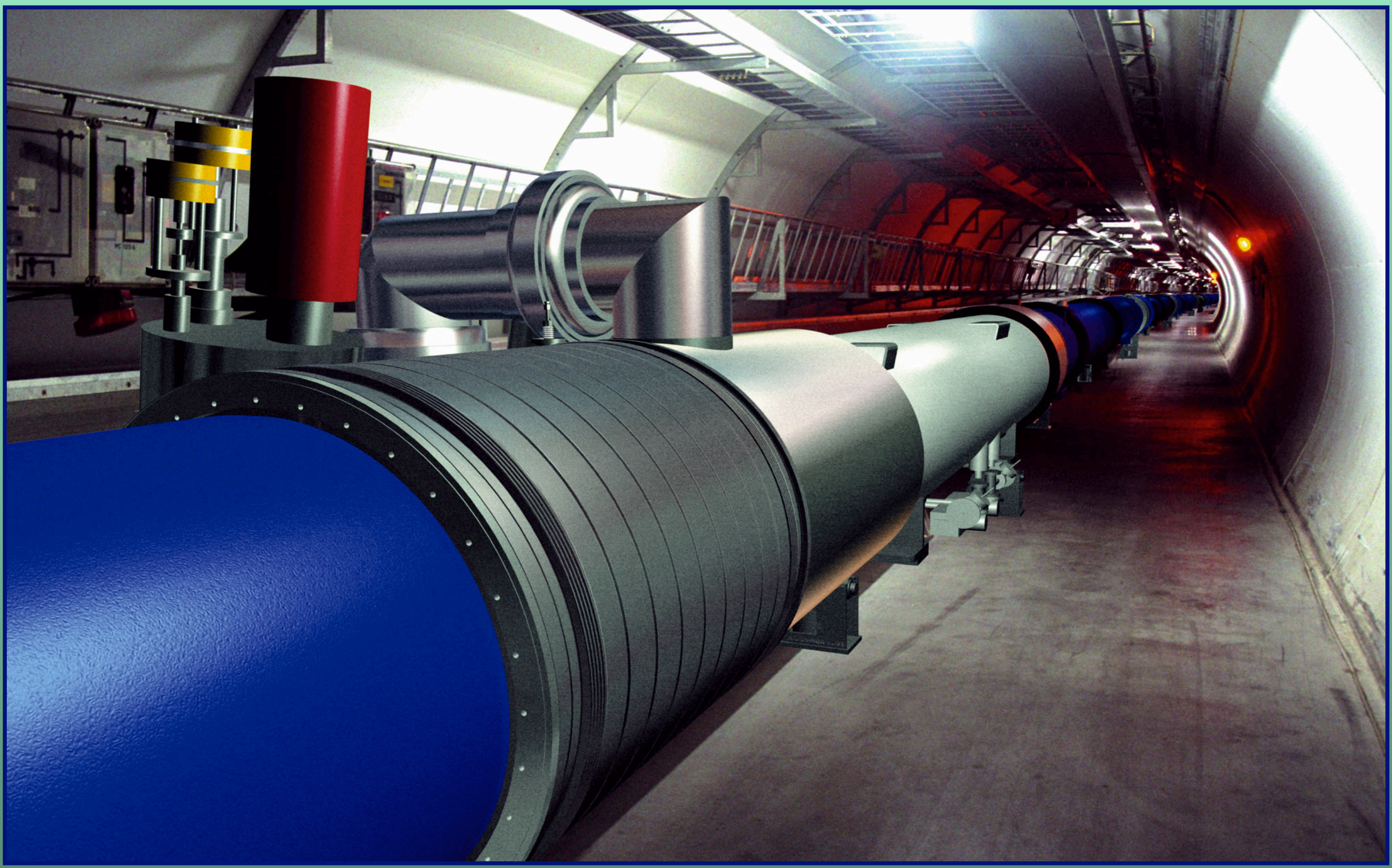
The Higgs discovery: LHC at CERN

European Center for Particle Physics, Geneva, Switzerland

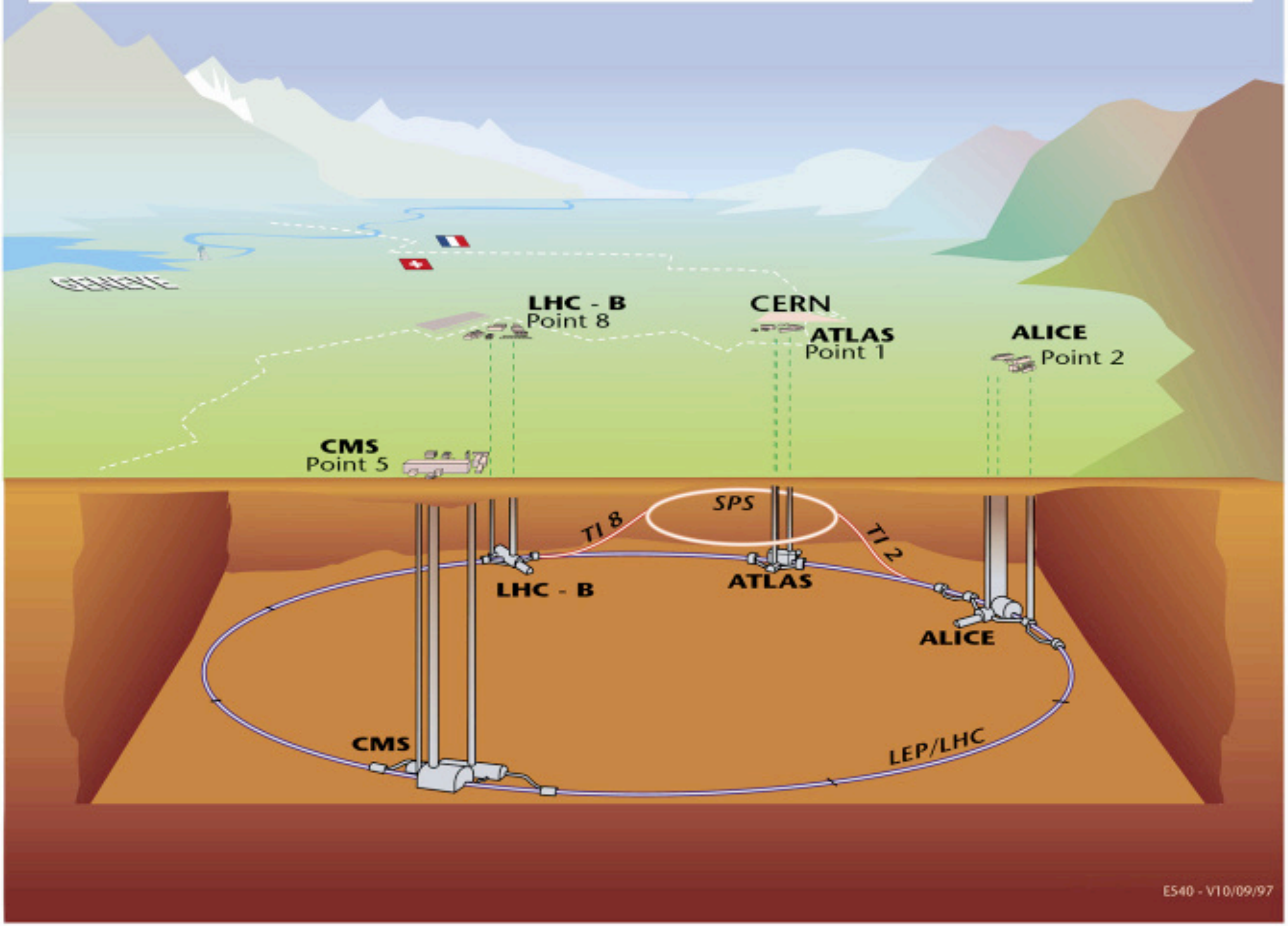
17 miles circumference (multi-billion dollars...)

The Large Hadron Collider (LHC)

Over 6000 scientists, 500 Universities from 80 countries...



Overall view of the LHC experiments.



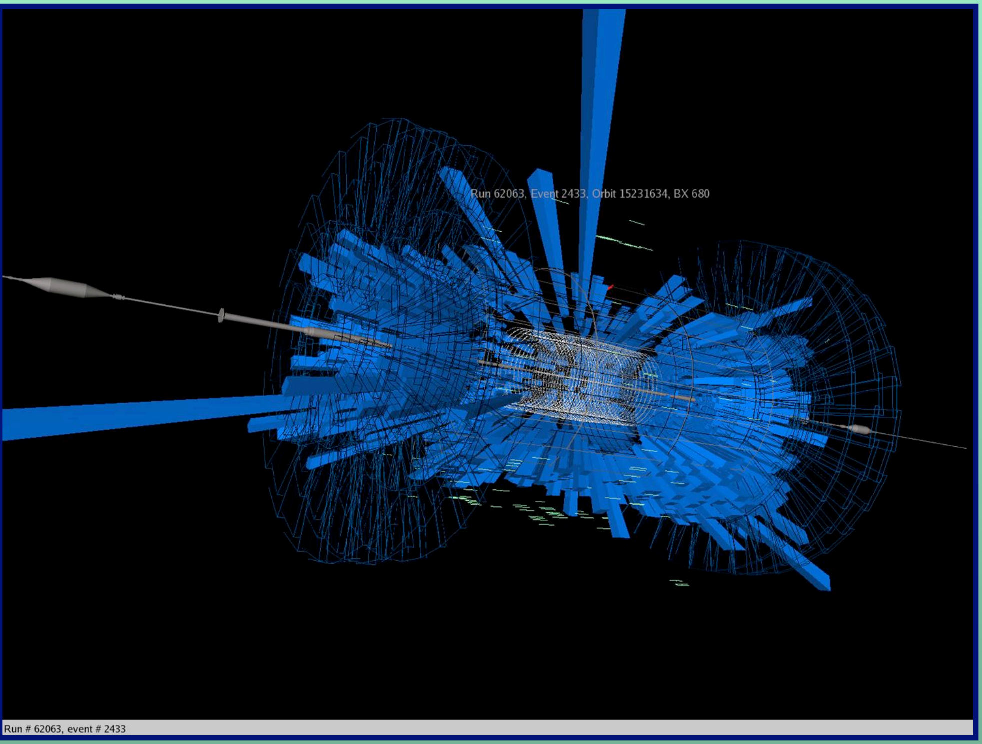
LHC facts

- 9300 magnets
- Biggest refrigerator in the World: 10800 t liquid N, 60 t liquid He to cool to 1.9 K
- Protons accelerated to 7 TeV (first run at 3.5 TeV)
- Ultra-high vacuum: 10^{-13} atm

LHC facts

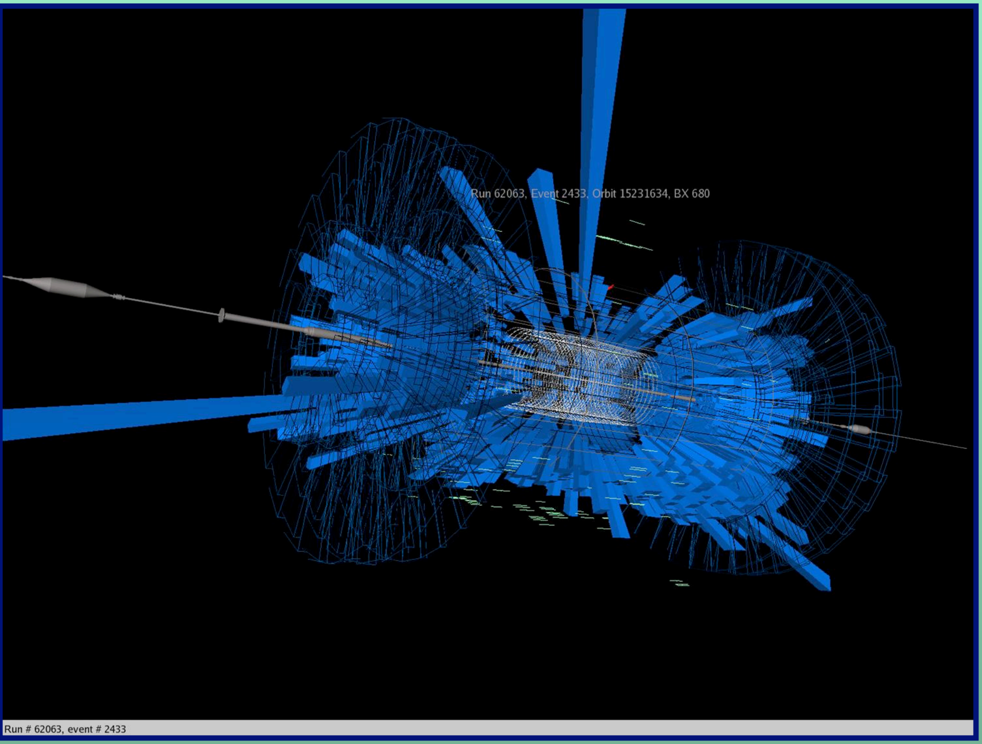
- 600 million collisions per second
- Timing 10^{-9} s accuracy
- Tracks 10^{-6} m accuracy
- Biggest supercomputer: data will fill 100 000 DVD's per year…

LHC startup September 10, 2008



First image from CMS debris of particles in calorimeters

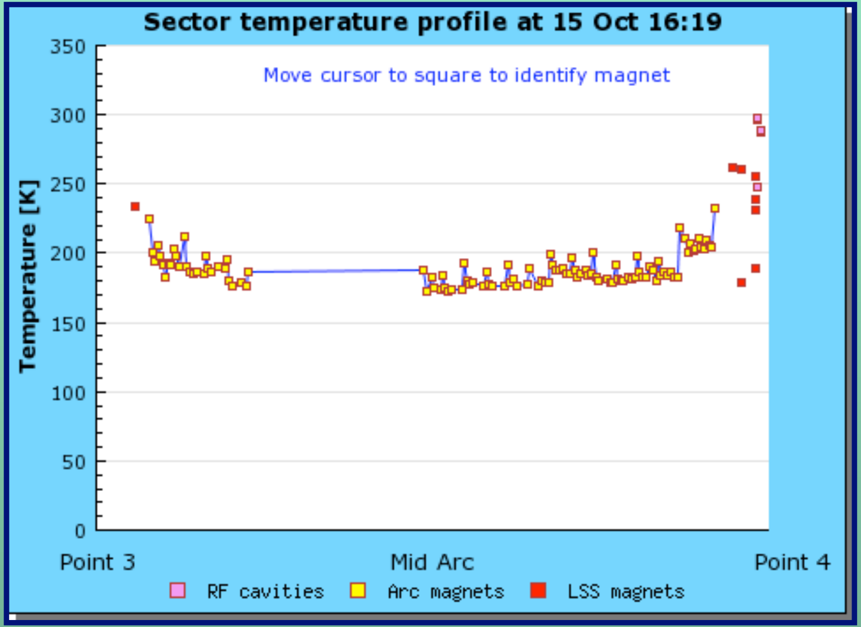
LHC startup September 10, 2008



First image from CMS debris of particles in calorimeters

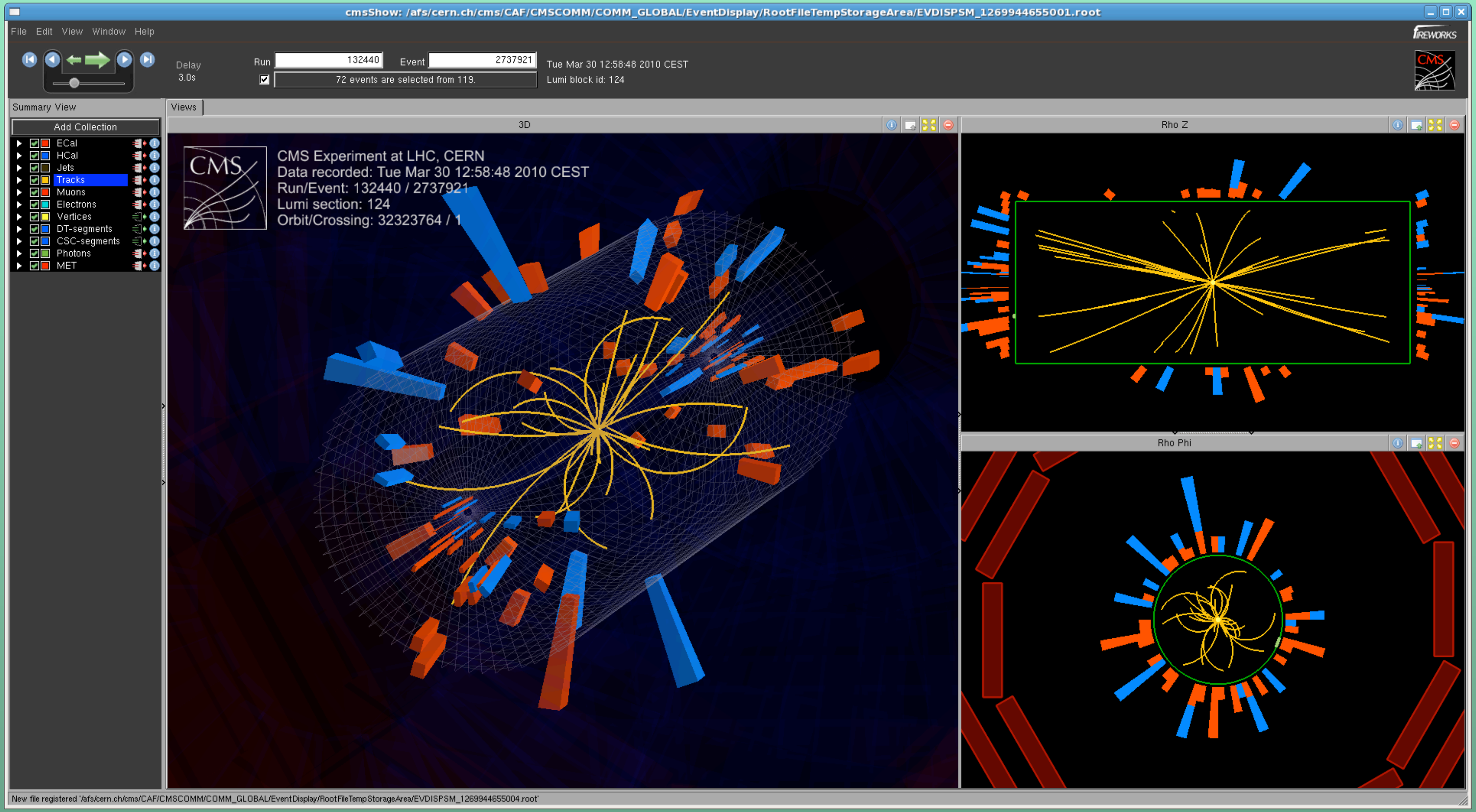
BUT…

Incident on 9/19/08: magnetic quench He leak



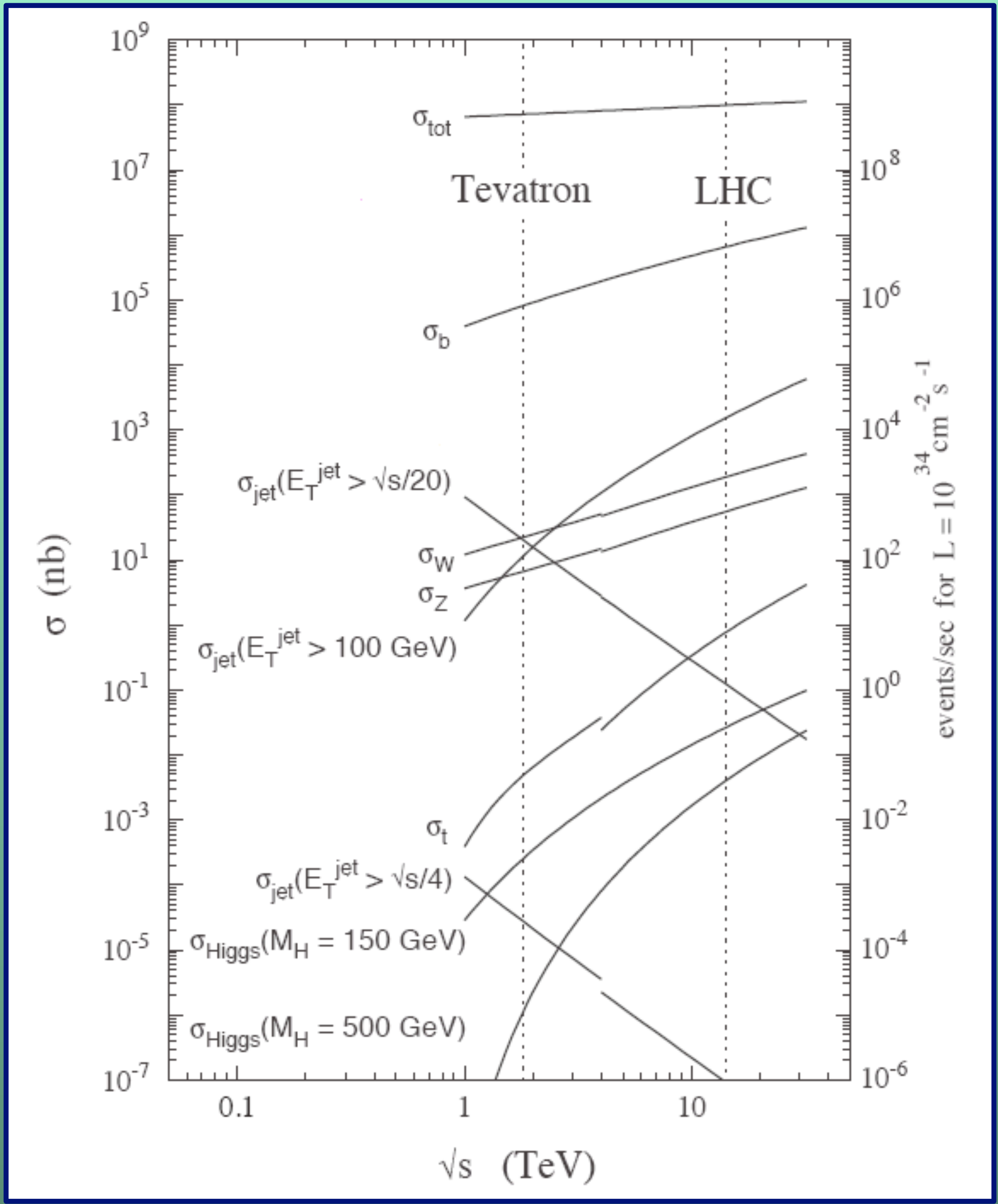
- About 1/3 of magnets in one section damaged
- Took ~1 year to repair until November of 2009
- To avoid similar problem initial energy was 7(8) TeV

First 7 TeV collisions of 3/30 2010



One of the first actual event from CMS!

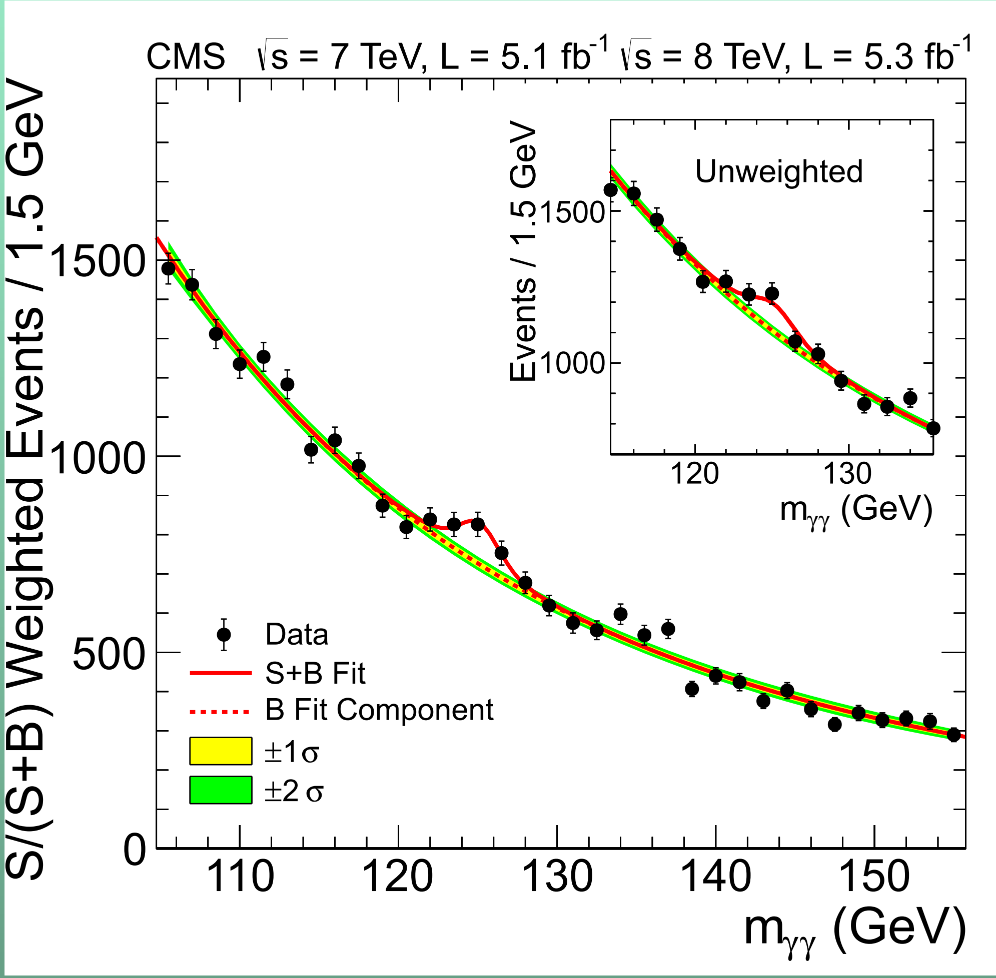
The difficulty...



July 4, 2012

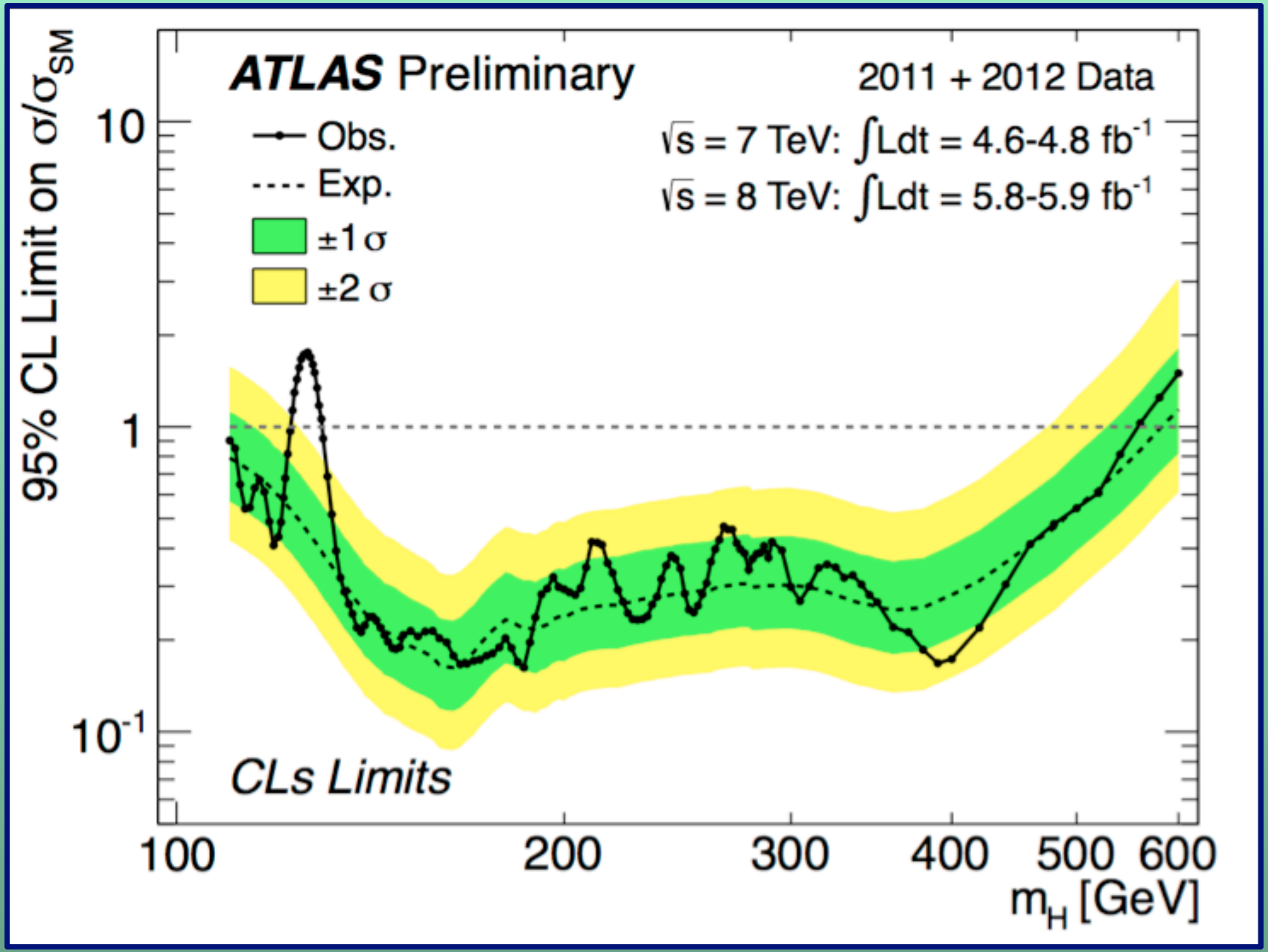
July 4, 2012

Higgs discovery



H→γγ in CMS

Higgs discovery



Combination of all channels in ATLAS

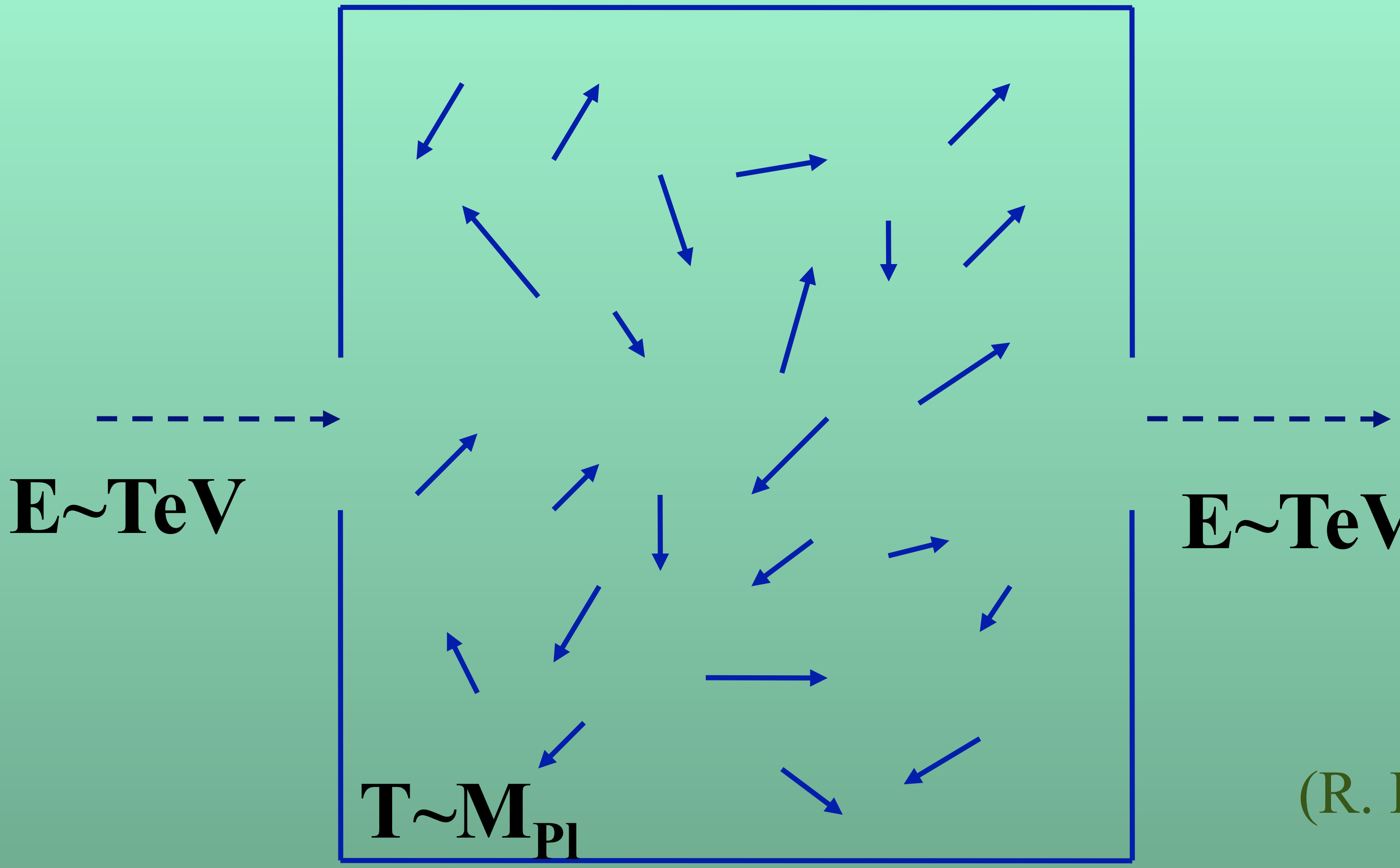
2013 Nobel prize for Higgs & Englert

But: why is there a condensate to begin with?

- What stabilizes the condensate?
- Is the Higgs really a fundamental field?

LHC is also looking for physics related to these issues

A nice analogy



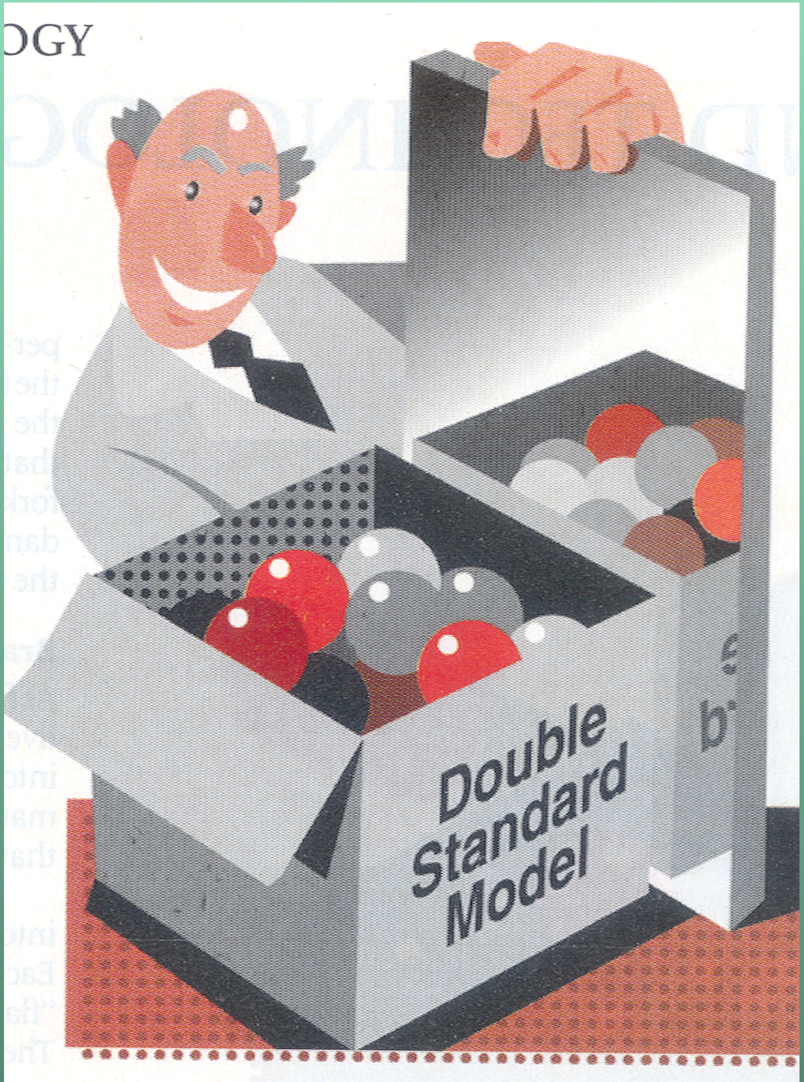
(R. Rattazzi)

- A particle enters a hot thermal bath ($T \sim M_{Pl}$)
- It collides with the very energetic particles
- When it exits its energy is $\sim M_{weak} << M_{Pl}$

Supersymmetry

- Every known particle would have a “superpartner”
- Would explain why condensate is formed

The Economist magazine's view of supersymmetry...



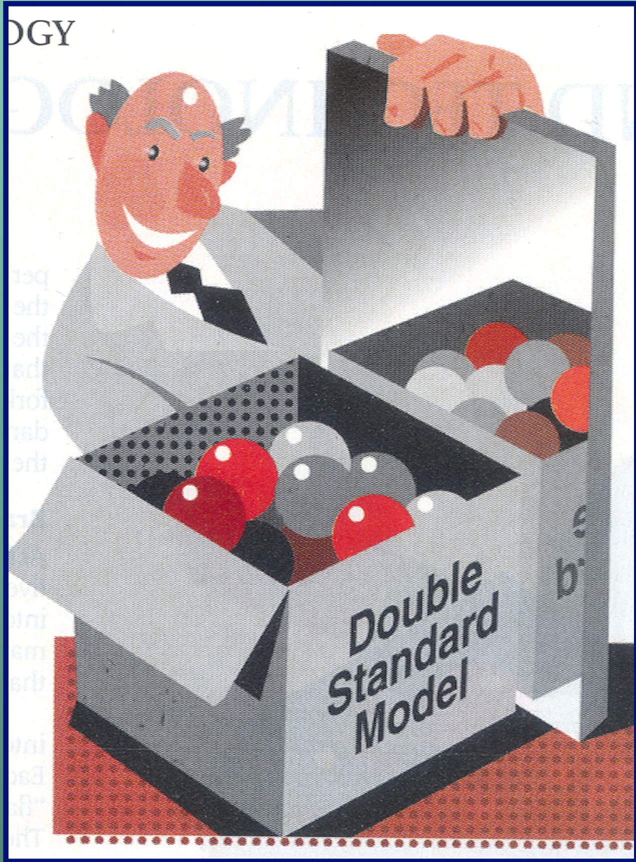
Supersymmetry

- Every known particle would have a "superpartner"
- Would explain why condensate is formed

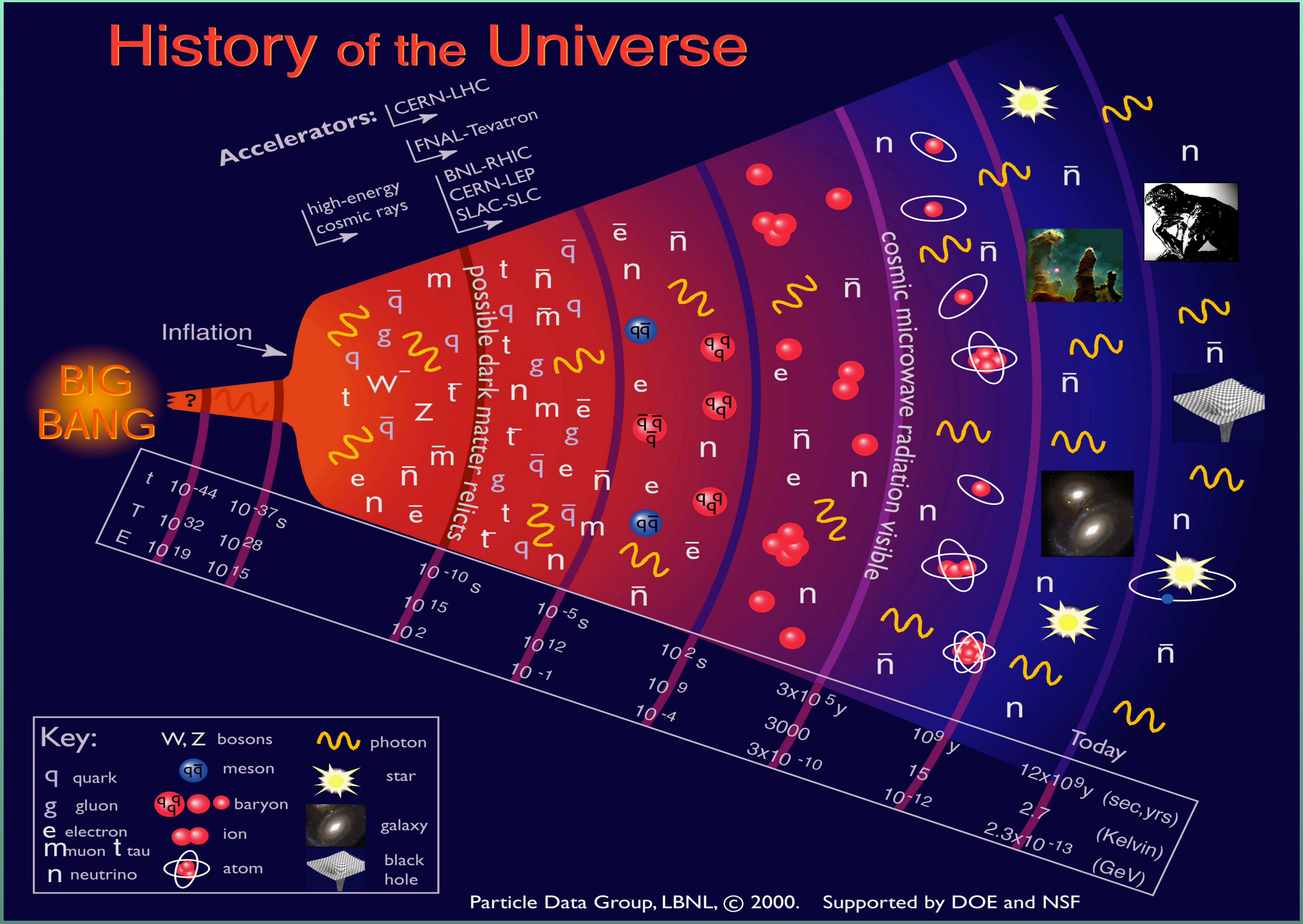
Should appear (should have appeared?) in the range of the LHC!

Every SM particle ⟷ Superpartner

electron	⟷	selectron
quark	⟷	squark
gauge boson	⟷	gaugino
Higgs	⟷	higgsino



Puzzle #2. Why are we made of matter (and not anti-matter)?



- For every particle, there exists an ANTI-particle: just like particle, but opposite charge(s)

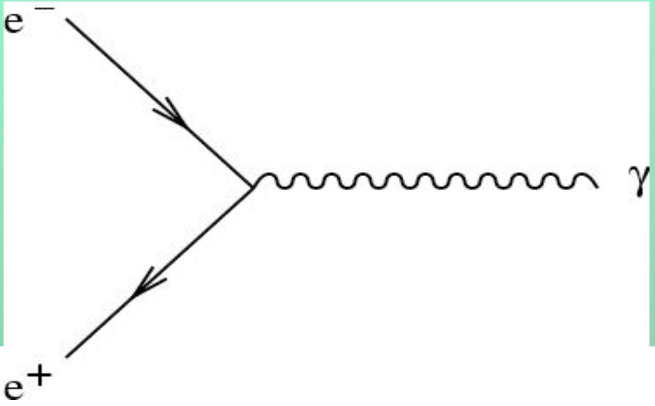
Electron $\longrightarrow$ Positron

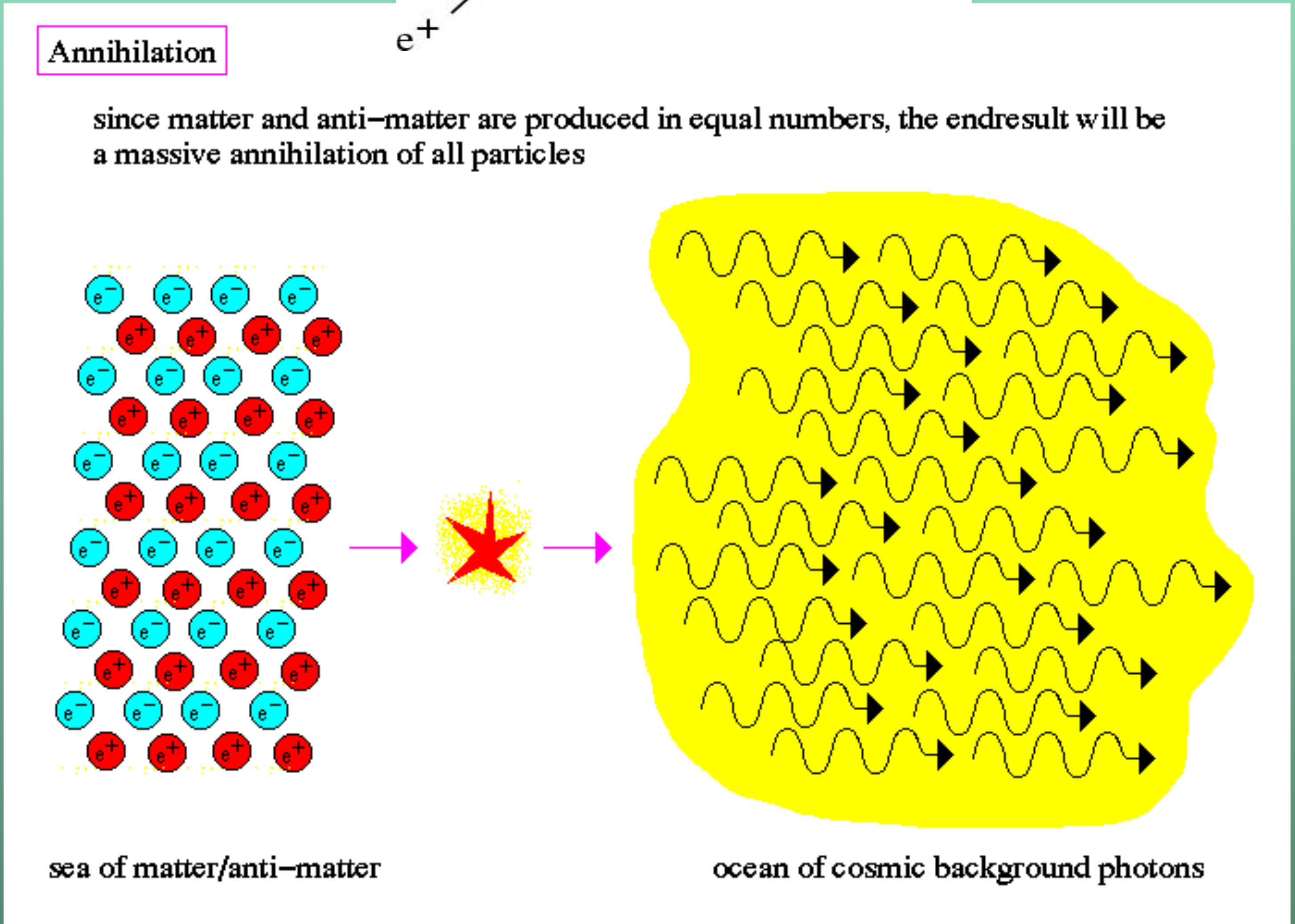
Proton $\longrightarrow$ Antiproton

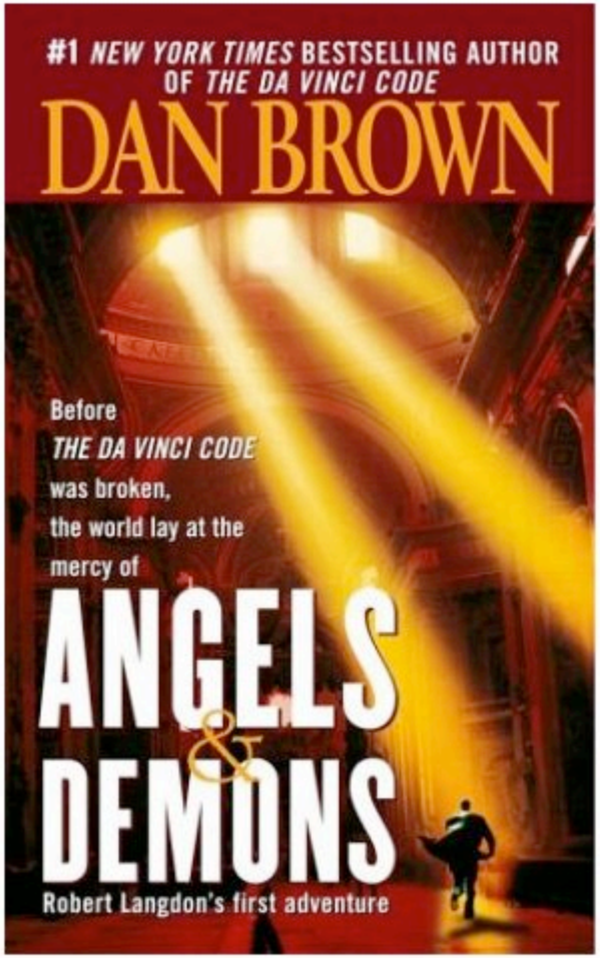
- Everything around us made of matter (not ANTI-matter)

Why?

- Matter and anti-matter annihilate into radiation

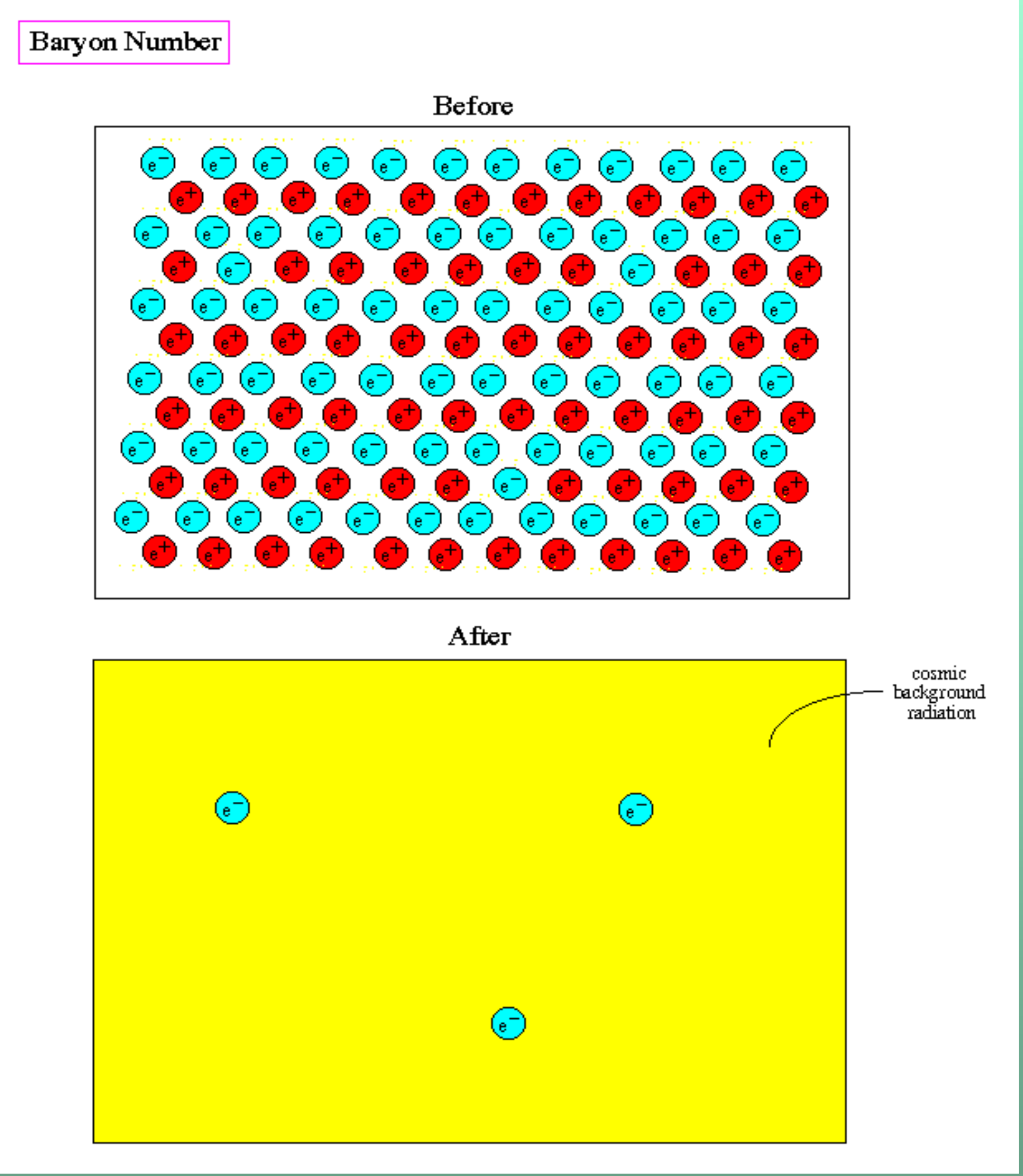





#1 NEW YORK TIMES BESTSELLING AUTHOR
OF THE DA VINCI CODE
DAN BROWN
Before
THE DA VINCI CODE
was broken,
the world lay at the
mercy of
ANGELS
&
DEMONS
Robert Langdon's first adventure


earth
air
fire
water

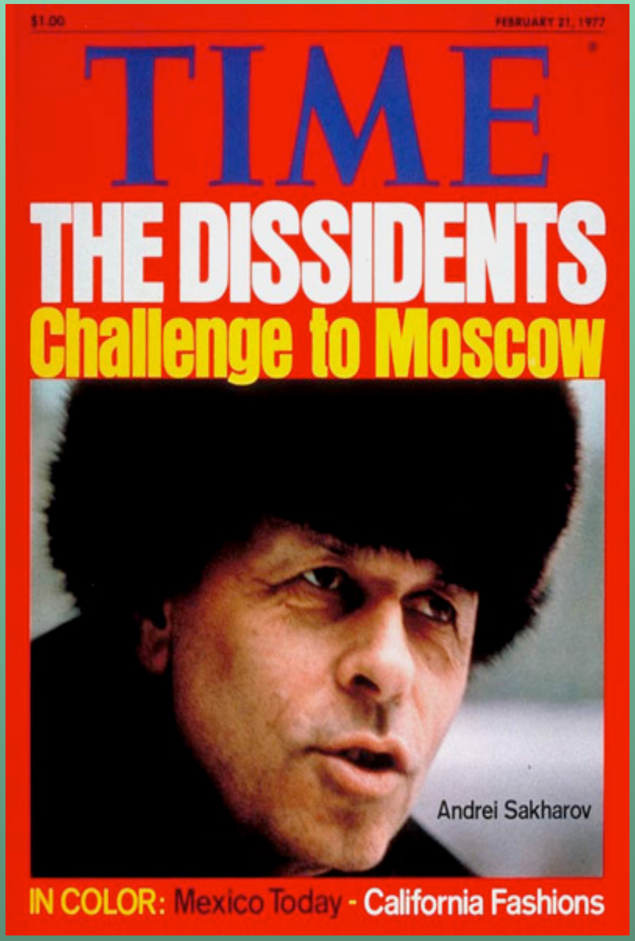

ANNUIT COEPTIS
NOVUS ORDO SECLORUM



Before annihilation: for
10 000 000 000 antimatter
10 000 000 001 matter
particles

- What causes this tiny asymmetry?
- Without this asymmetry we would not be around...
- No one really knows
- One of the hot topics of research

- Sakharov formulated the conditions under which such asymmetry can form.
- Are these conditions satisfied in the Standard Model?
- Need to know parameters very precisely...

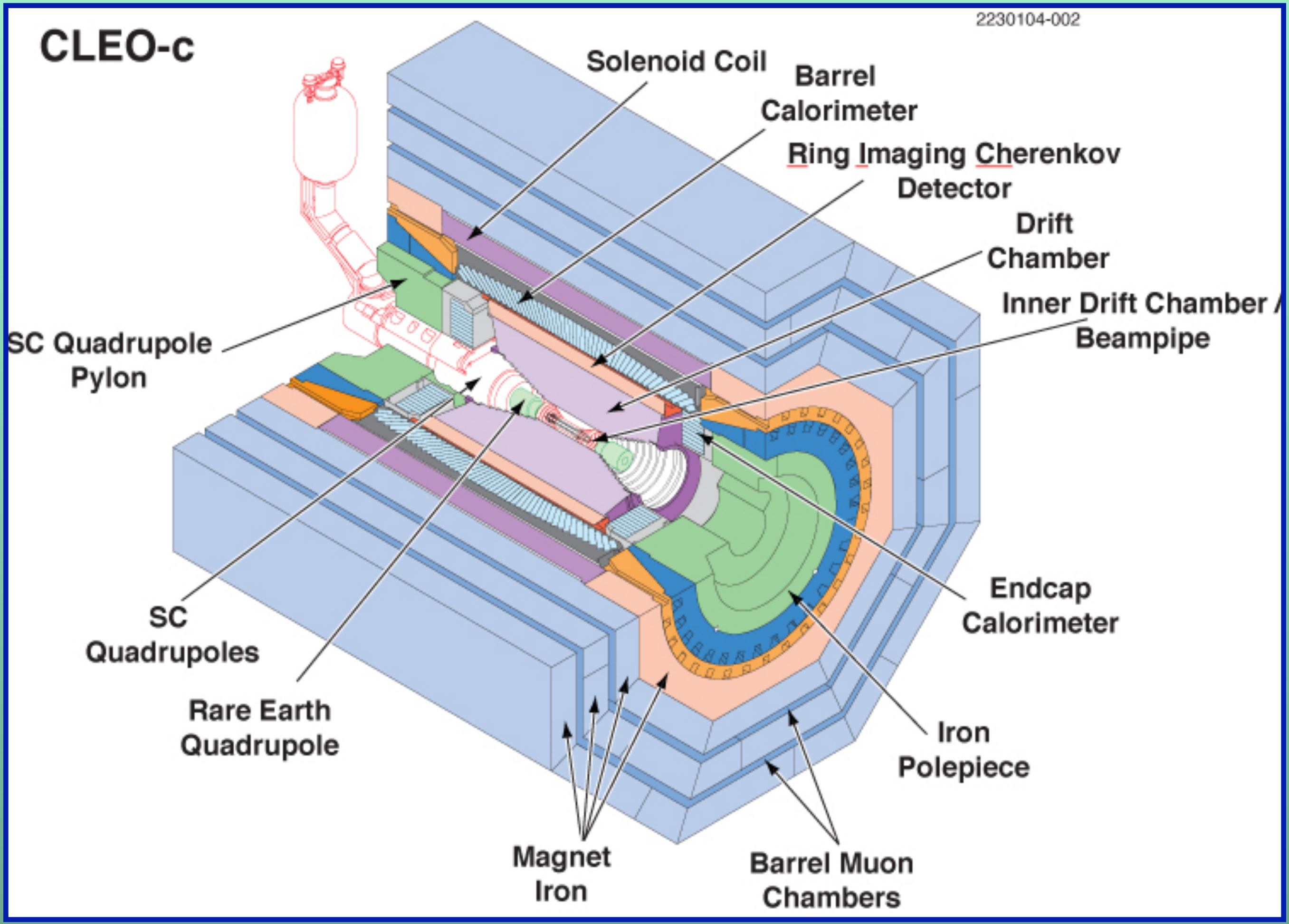


The Cornell Electron Storage Ring

Pioneered measurements of parameters related to asymmetry

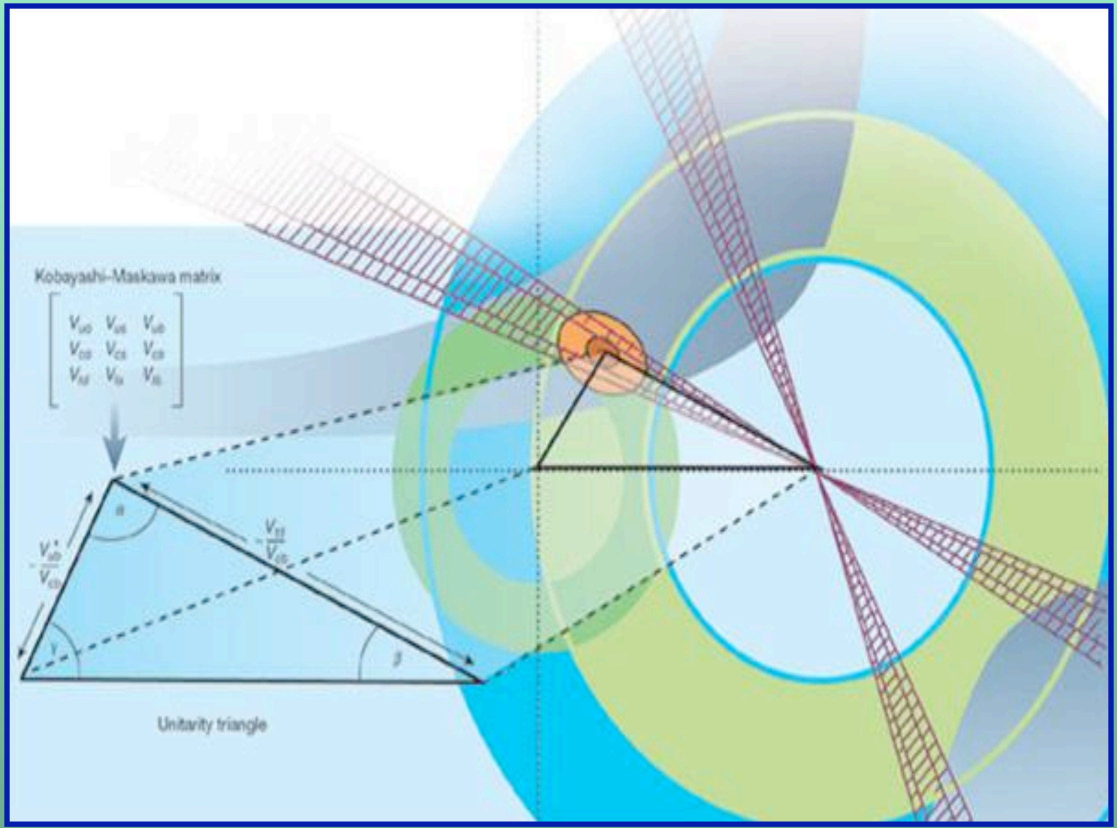
Bethe and McDaniel in the tunnel under Cornell in 1968

The CLEO detector at Cornell

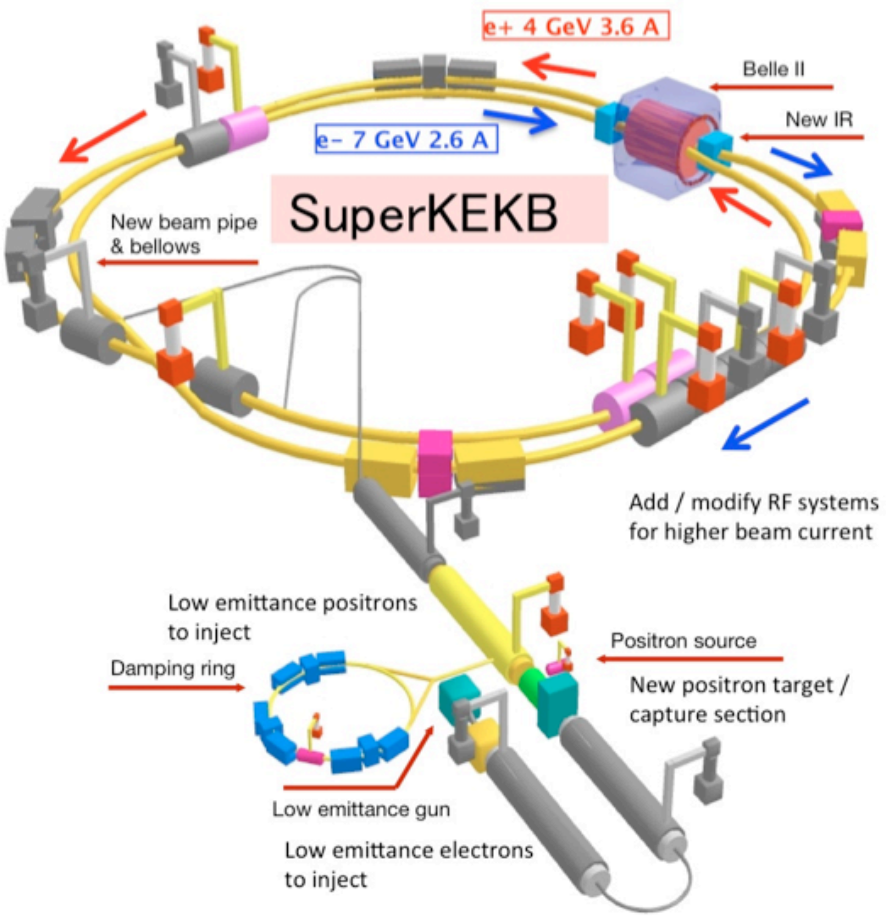


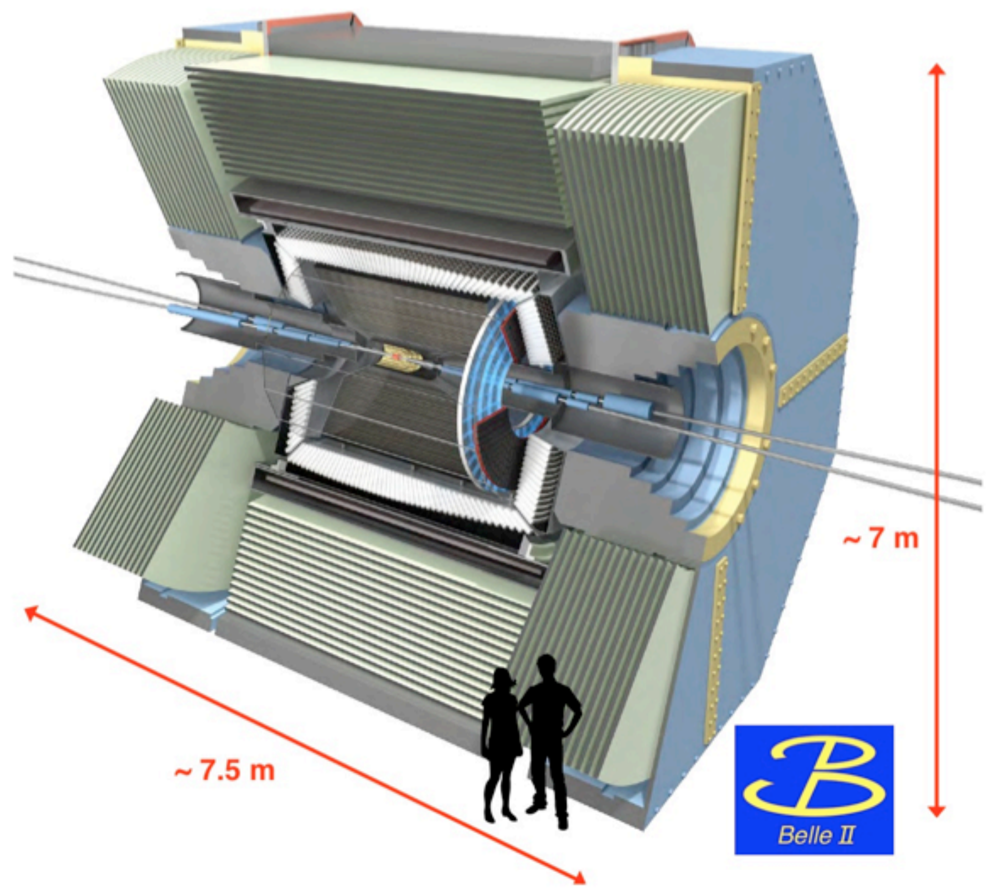
A collaboration of 150 physicists from 25 universities right here at Cornell

Want to find out if standard model has built-in asymmetry of matter and anti-matter



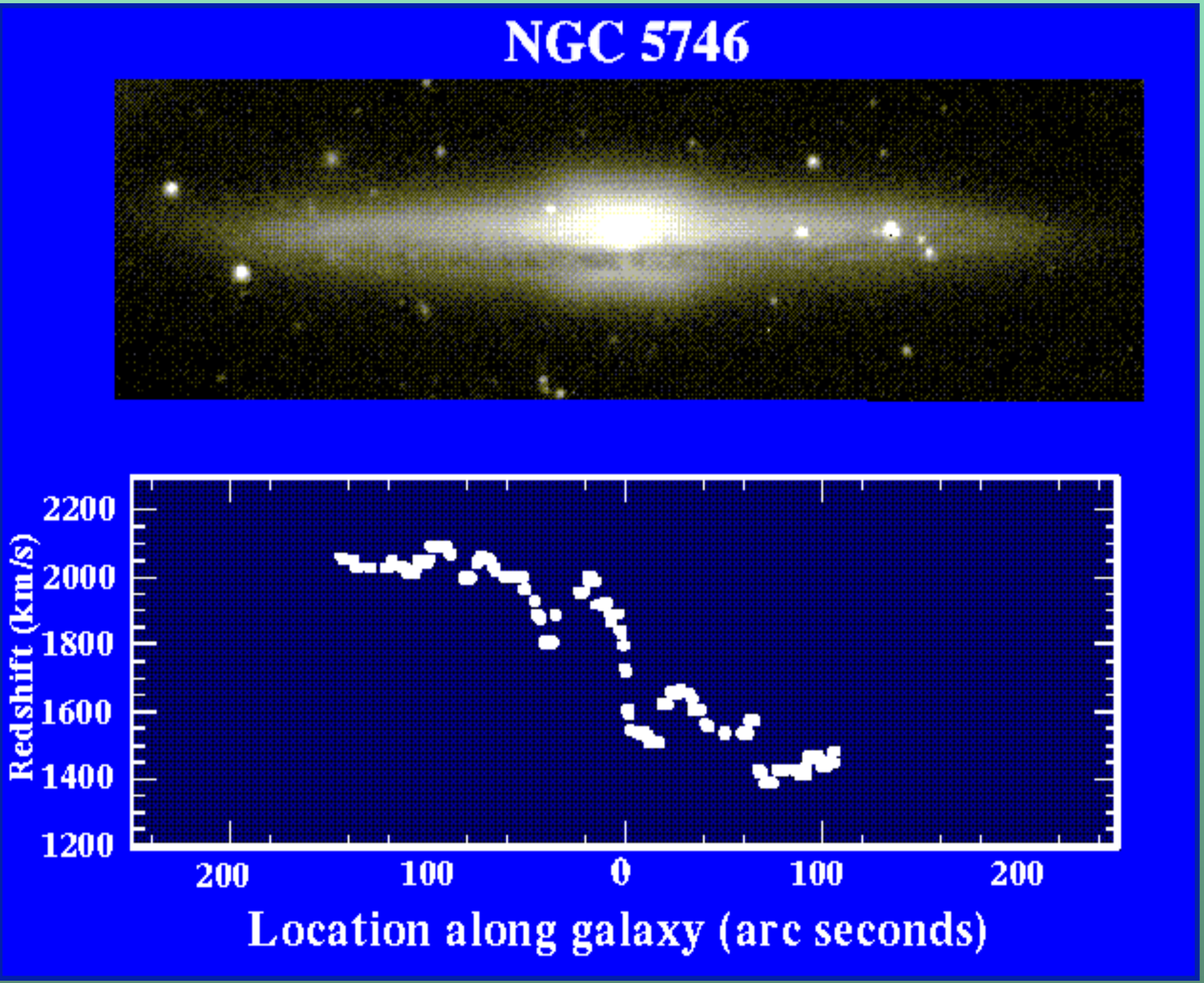
New experiment under construction in Japan to measure relevant parameters of SM to high precision

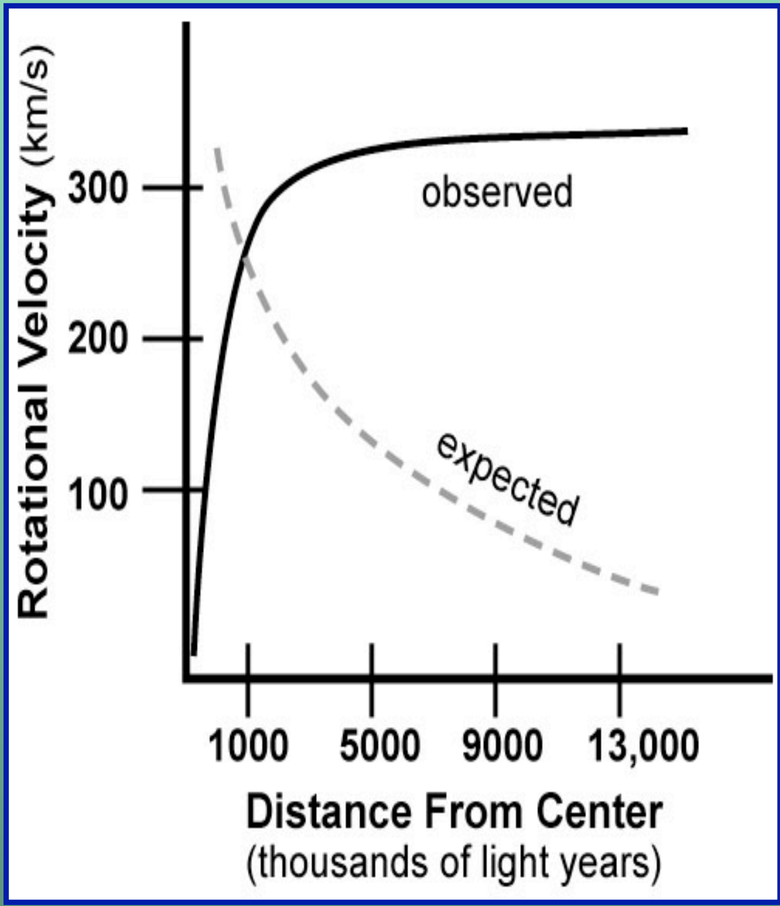




Puzzle #3. Where is all the matter in the Universe?

Some invisible matter seems to be pulling the stars...





What could be the dark matter?

Weakly Interacting Massive Particles WIMPs

Heavy stable particles

Amazingly, supersymmetry, extra dim.

do have particles like that...

For now we don't know...

Search for dark matter:

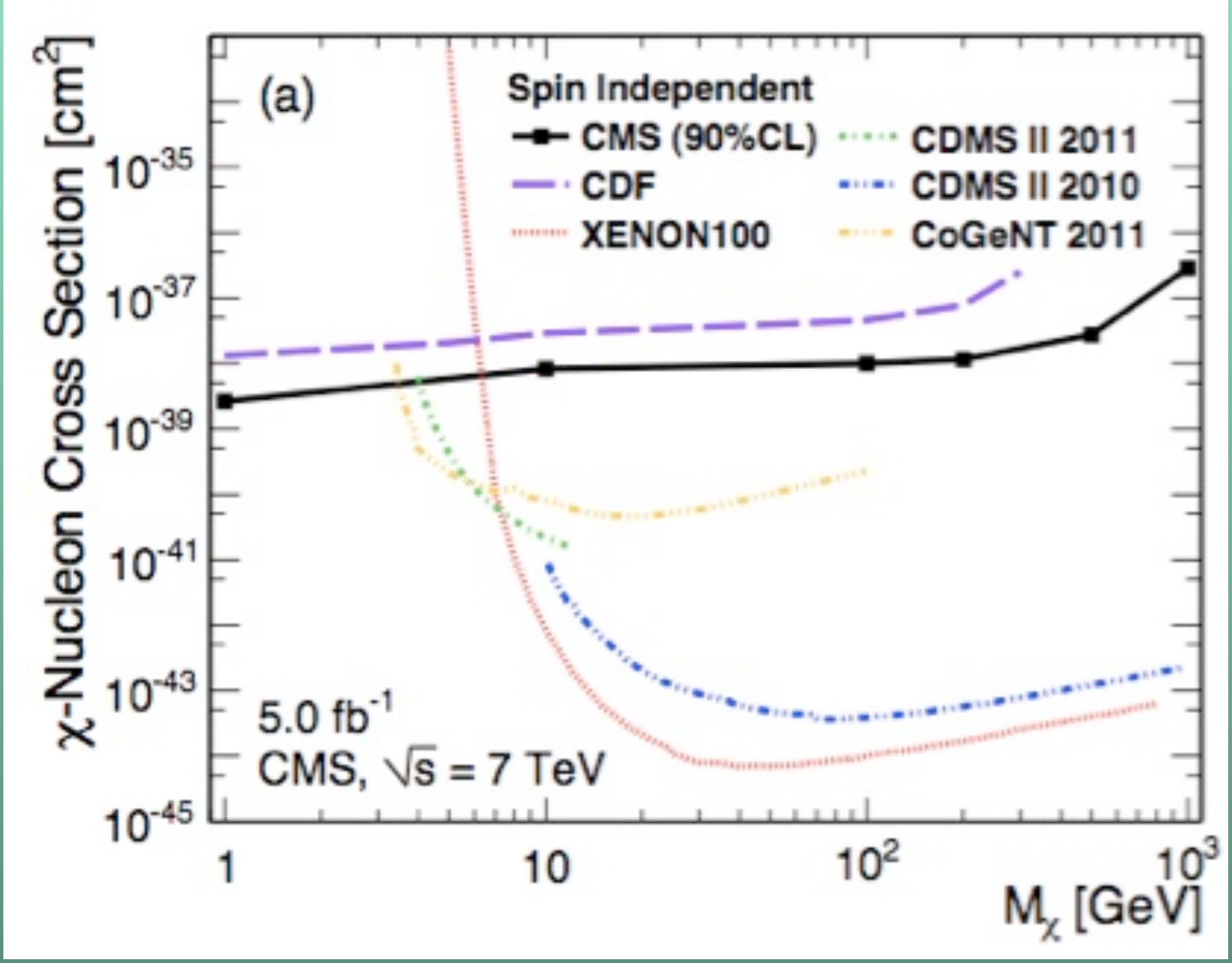
1. LHC could detect WIMP
2. Directly detect DM via recoil of nuclei

Search for dark matter

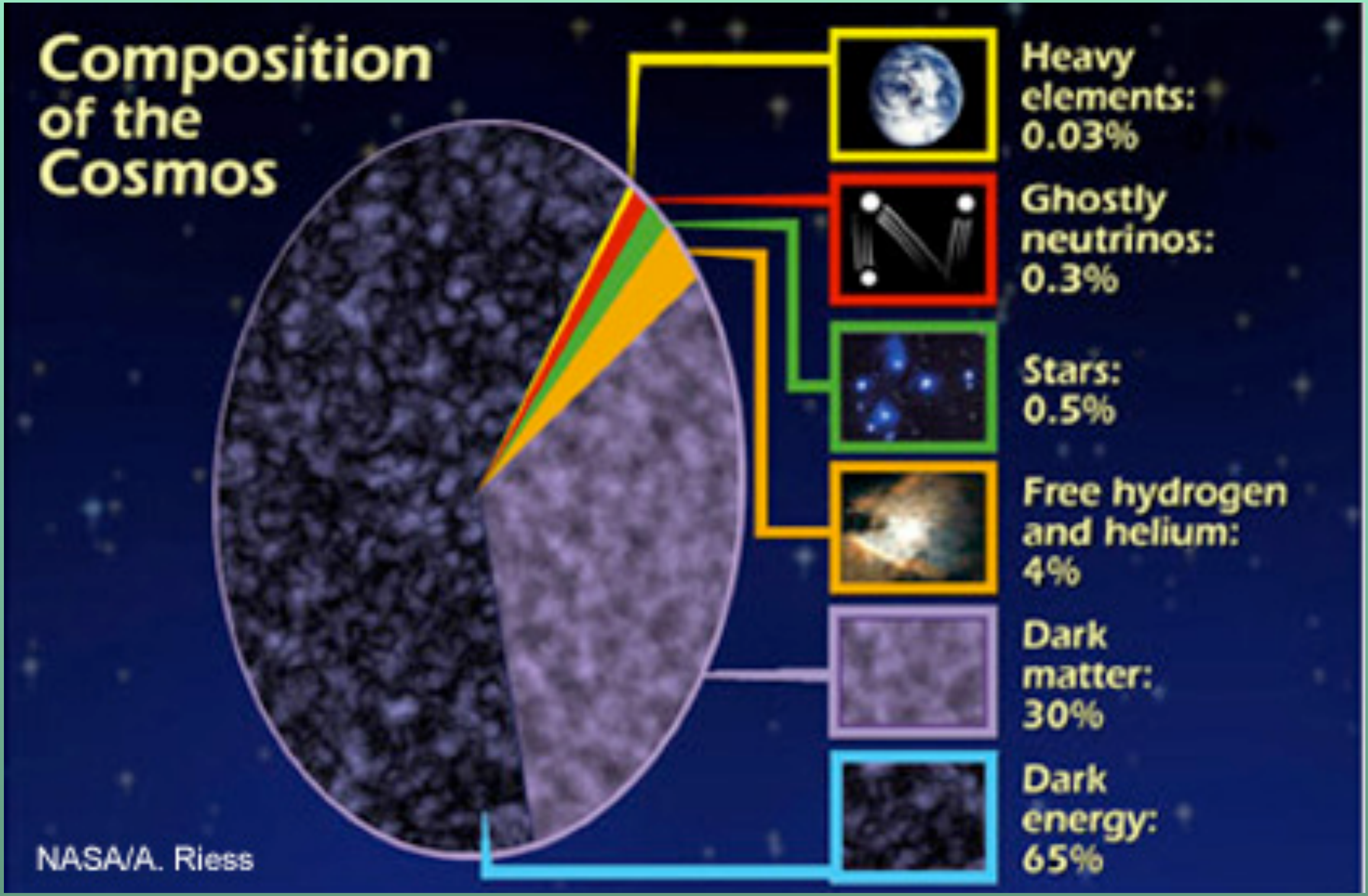
Recoil of nuclei: e.g. LUX experiment

Search for dark matter

Can also be searched at LHC



Puzzle# 4. What makes up most of the energy in the Universe?



How do we know?

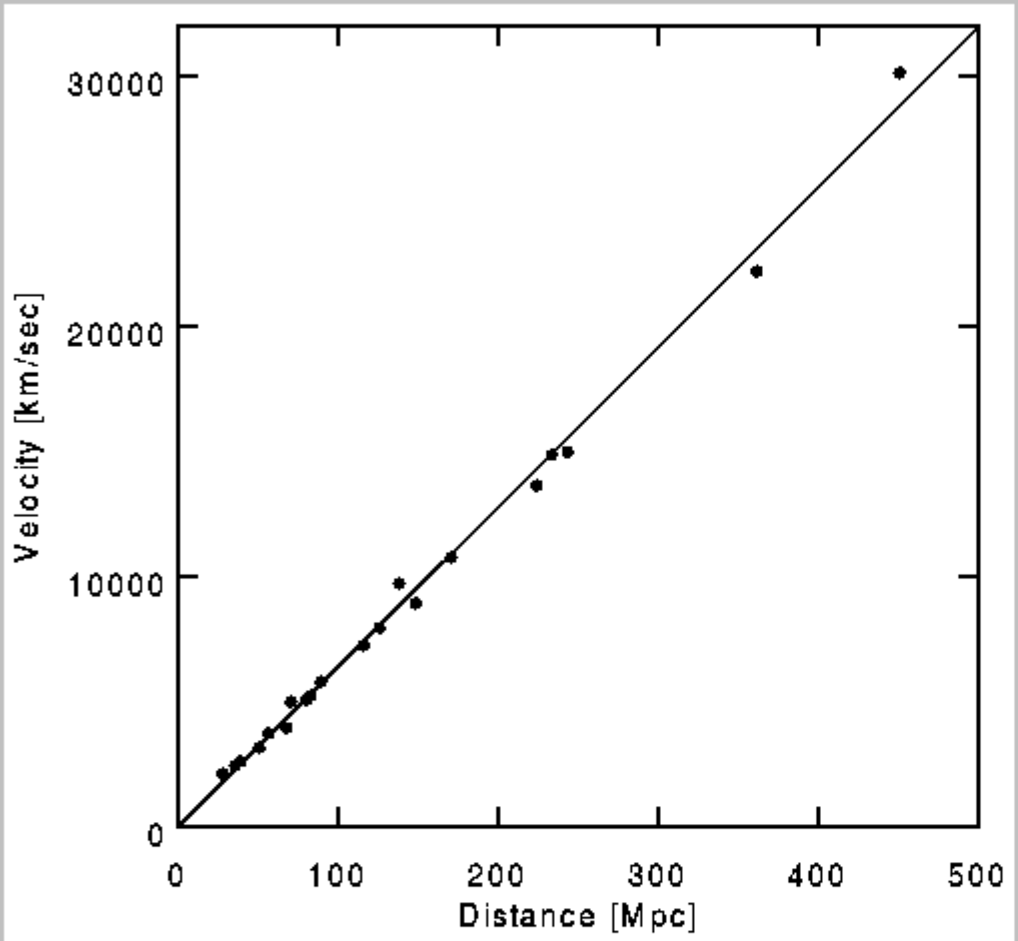
•Einstein originally thought Universe is static (stars did not seem to move on the sky)

•But his theory of gravity (general relativity) seemed to predict that Universe should be EXPANDING

•To reconcile, he introduced “cosmological constant” – a fudge factor in his theory that can give static Universe

But Universe is EXPANDING

Hubble's law

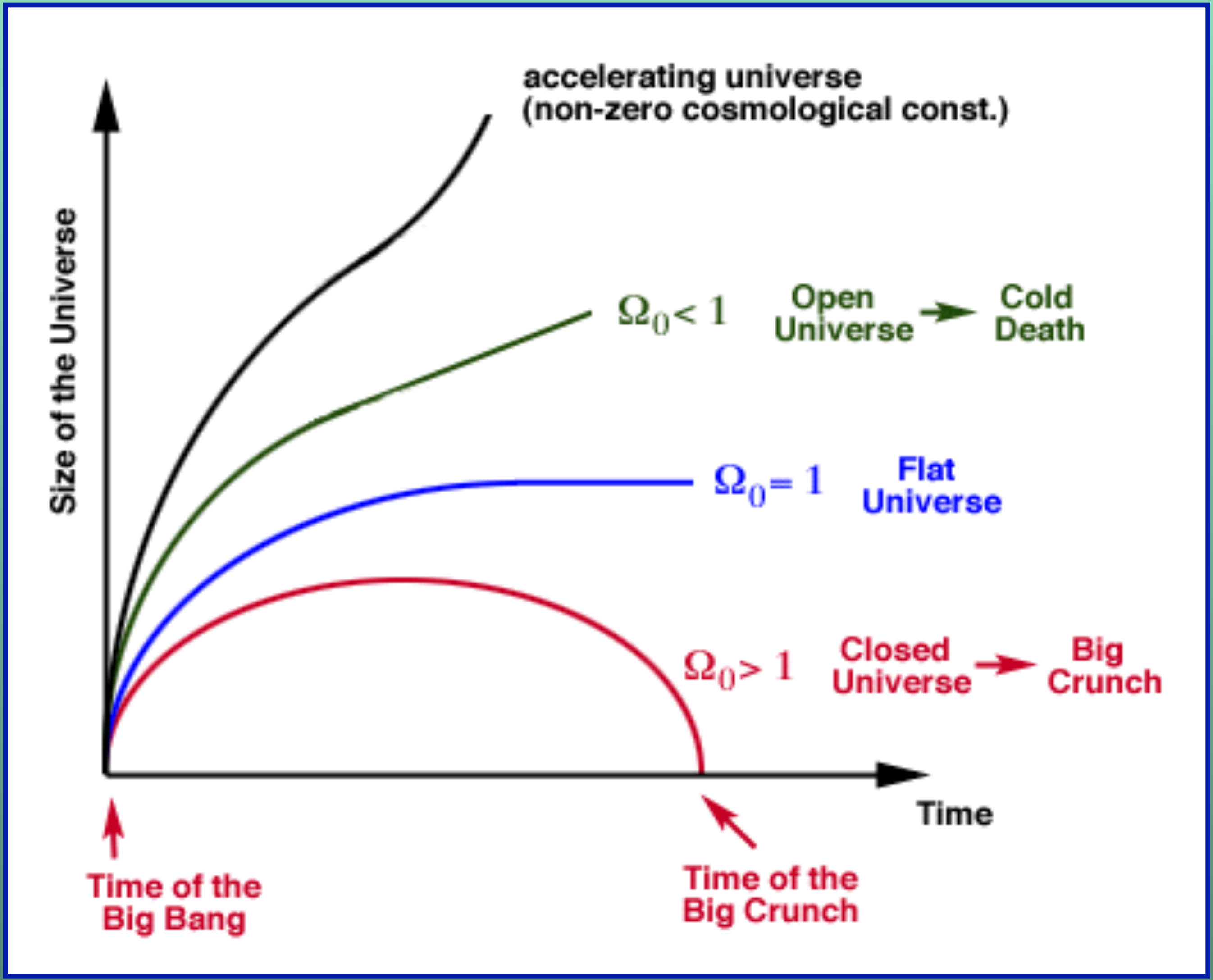


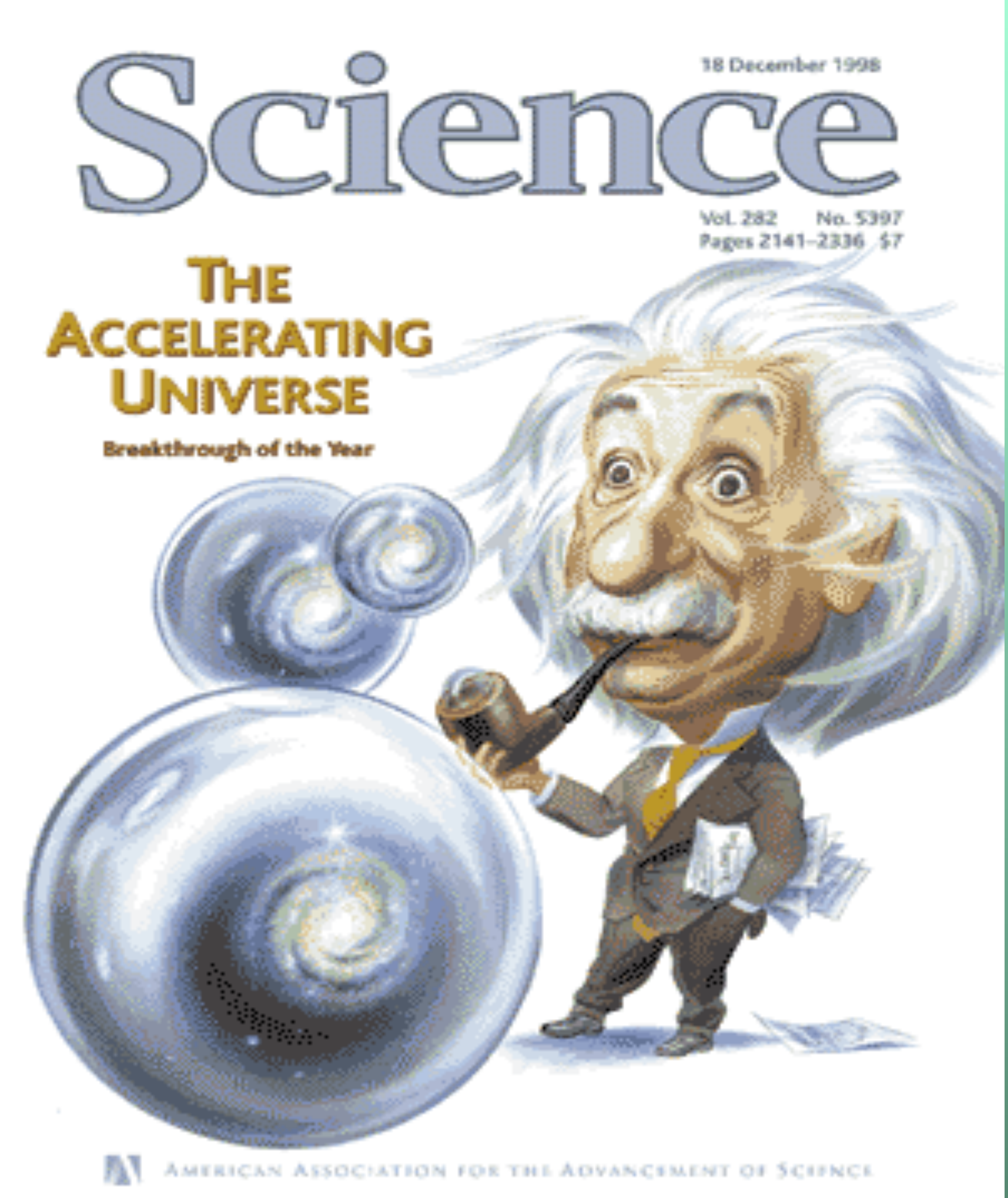
In retrospect, Hubble's law is not that difficult to understand once we have adopted the Cosmological Principle. Say three observers are located in galaxies A, B, and C which are separated by equal amounts. If B is receding away from A with a certain velocity "v", then, by the Cosmological Principle, C must be receding from B at the same exact speed v. This implies, by simply adding the velocities, that C will be receding from A at twice the speed (or 2v). This, of course, is Hubble's Law.

Cosmological constant Einstein's "biggest blunder"?

How does the Universe expand?

- Depends on HOW MUCH matter
- Depends on WHAT KIND of matter (relativistic? non-relativistic?,...)





Adam Riess

Saul Perlmutter

What is this myterious dark energy?

- Einstein's cosmological constant?
- Some other mysterious field?
- Maybe gravitational laws are different at these distances?

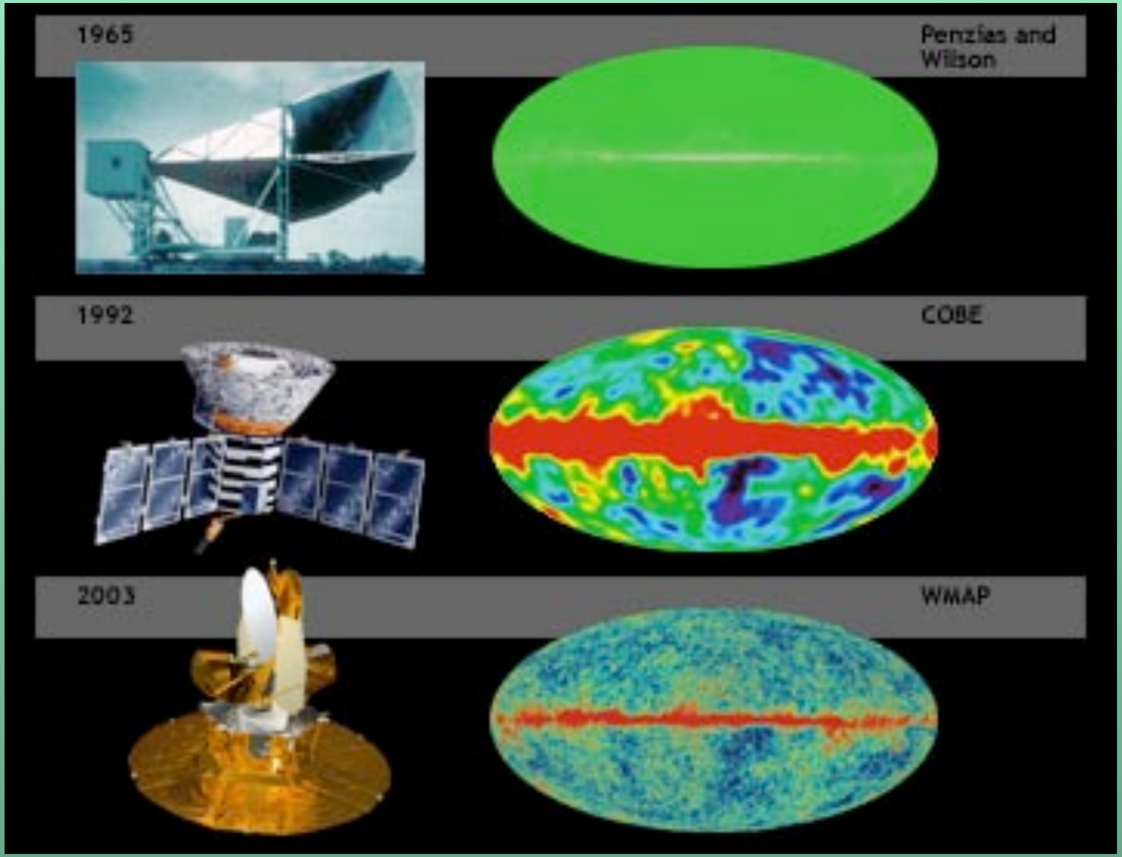
We really don't know, need to keep looking more...

WFIR T

Wide-Field Infrared Survey Telescope

Other ways of checking if there is dark energy

- Measuring cosmic microwave background radiation



- Gravitational lensing, galaxy counts,...

All seem to imply there is dark energy

Summary

Some of the most fundamental questions:

- What is the origin of mass? - Higgs, why condensate, light?
- What is the origin of matter?
- What is dark matter?
- What is dark energy?
- We hope to answer at least some of these within the next decade!
- Bright future for particle physics and cosmology!