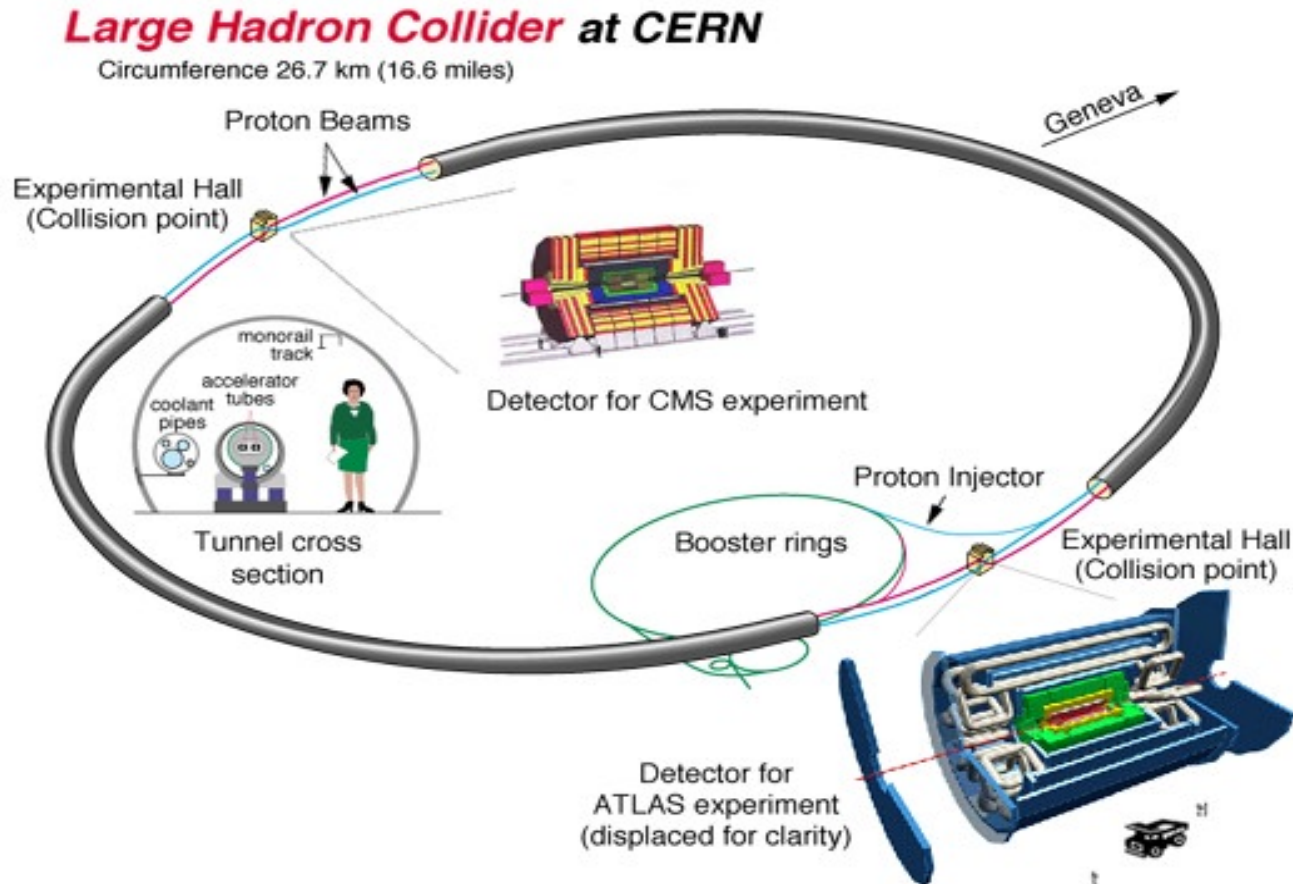


First some Introductory Stuff => On The Web

<http://hep.physics.utoronto.ca/~orr/wwwroot/phy357/PHY357S.htm>

PHY357 = What is the Universe Made Of?



SubAtomic Physics

Nuclear Physics

- Understand the Atomic Nucleus in terms of the interaction of Protons and Neutrons.
- An enormously important subject; both in order to understand matter on Earth and in Stars and the Universe, and for technological reasons

Particle Physics/High Energy Physics

- Understand Reality at its most Basic Level

• Experiment



• Theory

Constituents
Interactions

Why these Constituents and Interactions?
Why this Space-Time

Micro Level ↔ Macro Level → History of Cosmos

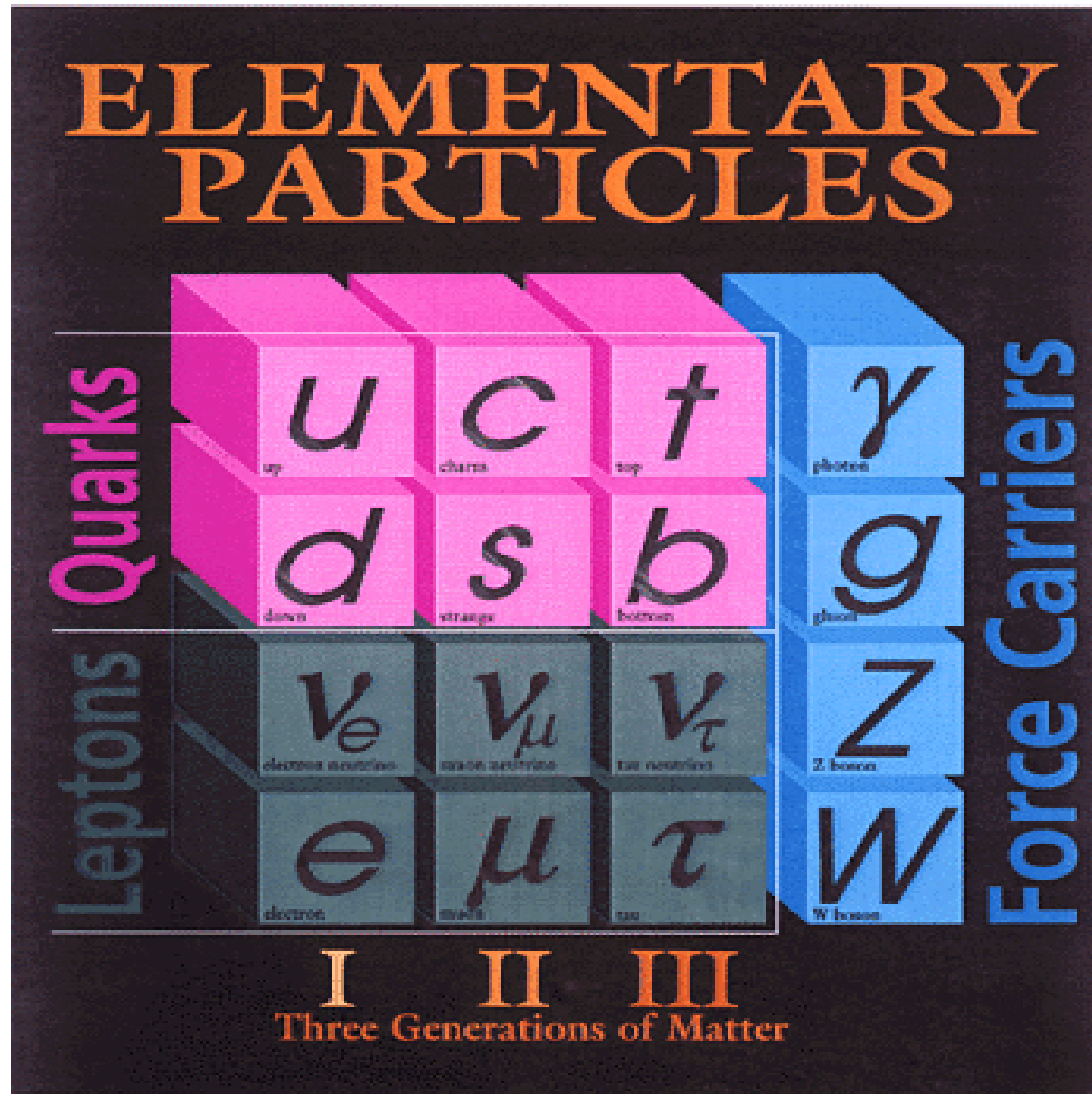
"All these things being considered, it seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, moveable particles of such sizes and figures, and with such other properties, and in such proportion to space, as most conduced to the end for which he formed them; and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary power being able to divide what God himself made in the first creation. While the particles continue entire, they may compose bodies of one and the same nature and texture in all ages: but should they wear away, or break in pieces, the nature of things depending on them would be changed. Water and earth, composed of old worn particles and fragments of particles, would not be of the same nature and texture now, with water and earth composed of entire particles in the beginning. And there, that nature may be lasting, the changes of corporal things are placed only in the various separations and new associations and motions of these permanent particles"

“Now the smallest Particles of Matter may cohere by the strongest Attractions and compose bigger Particles of weaker Virtue; and many of these may cohere and compose bigger Particles whose Virtue is still weaker, and so on for diverse successions, until the Progression ends in the biggest Particles on which the Operations in Chymistry and the Colours of natural Bodies depend, and which by cohering compose Bodies of a sensible Magnitude.

There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of Experimental Philosophy to find them out.”

Isaac Newton, *Opticks*, 1704

Is the Universe Made of These?



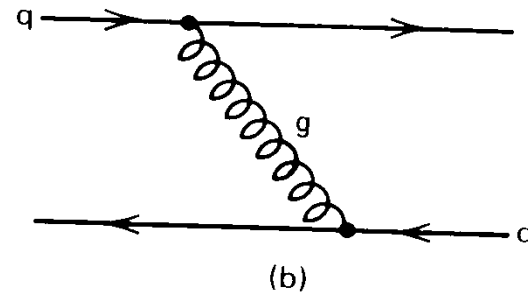
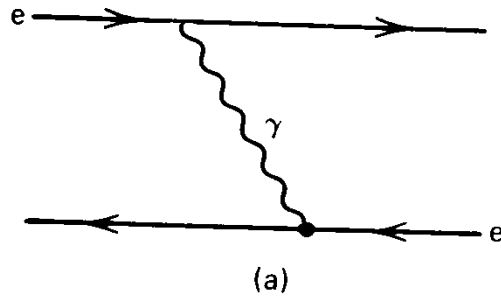
Proton = (u u d) – held together by gluons

Neutron = (u d d)

Quantum Forces

- In Quantum Field Theory, particles interact via:

Exchange of virtual particles



Electrons interact by exchanging:

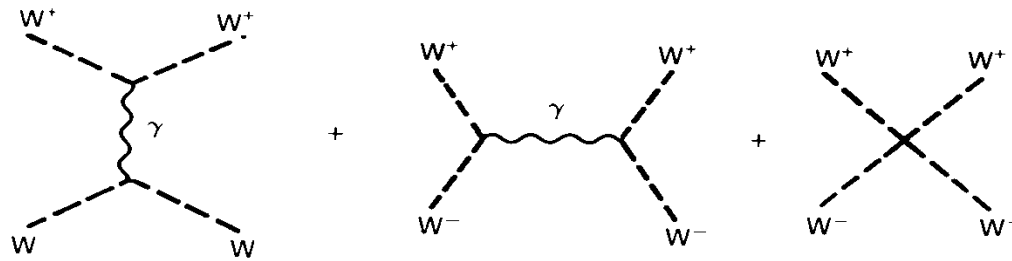
Virtual Photons - EM Force

Quarks interact by exchanging:

Virtual Gluons – Color Force

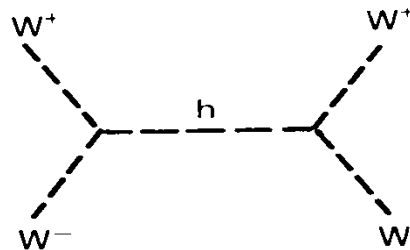
Higgs Boson

- Electromagnetism on its own can be made to give finite results for all calculations.
- Unified Electroweak theory gives infinite results for process like:



- Become finite if include new particle

Higgs |



Spontaneous
Symmetry
Breaking
Renormalizable
Gauge
Theory

- Higgs makes W^\pm Z^0 massive, and actually generates masses of fundamental particles. It is a quantum field permeating the universe.

How Does Higgs Generate Mass?

- In **vacuum**, a photon:
has **velocity c** and has **zero mass**
- In **glass**, a photon:
has **velocity $< c$** , same as an **effective mass**

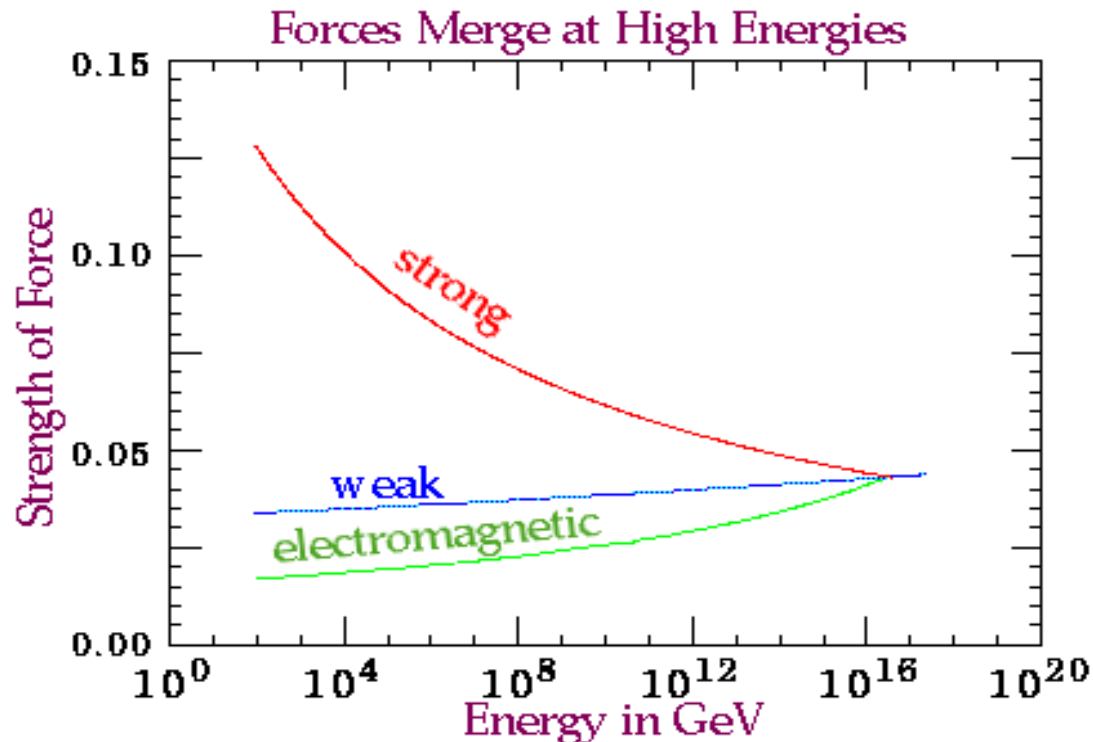
Refractive Index

- This is due to photon interacting with
electromagnetic field in condensed matter
- By analogy can understand **masses of particles**
generated by **Higgs Field** in vacuum

Grand Unification.

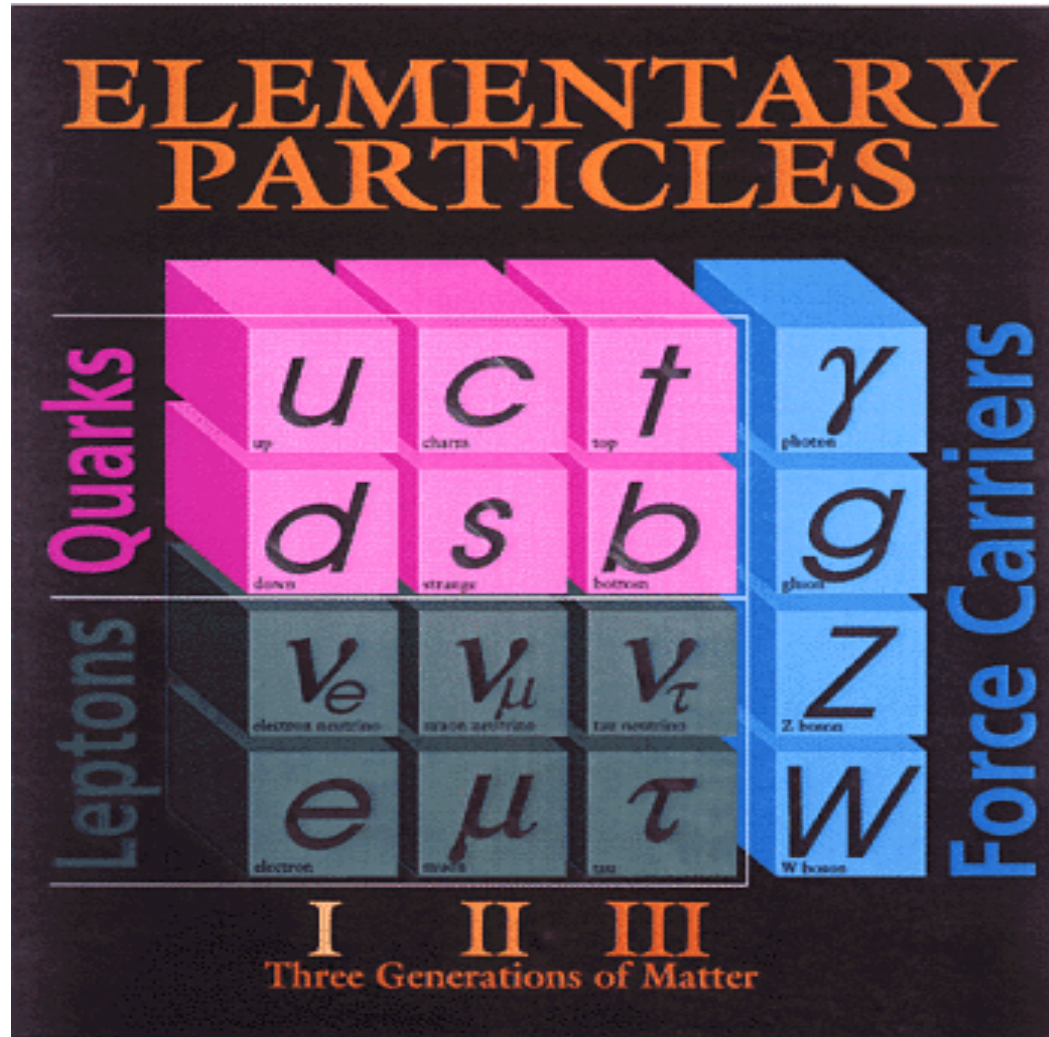
- At a high enough energy
electromagnetism
weak force
strong (colour) force

become aspects of Grand Unified Force

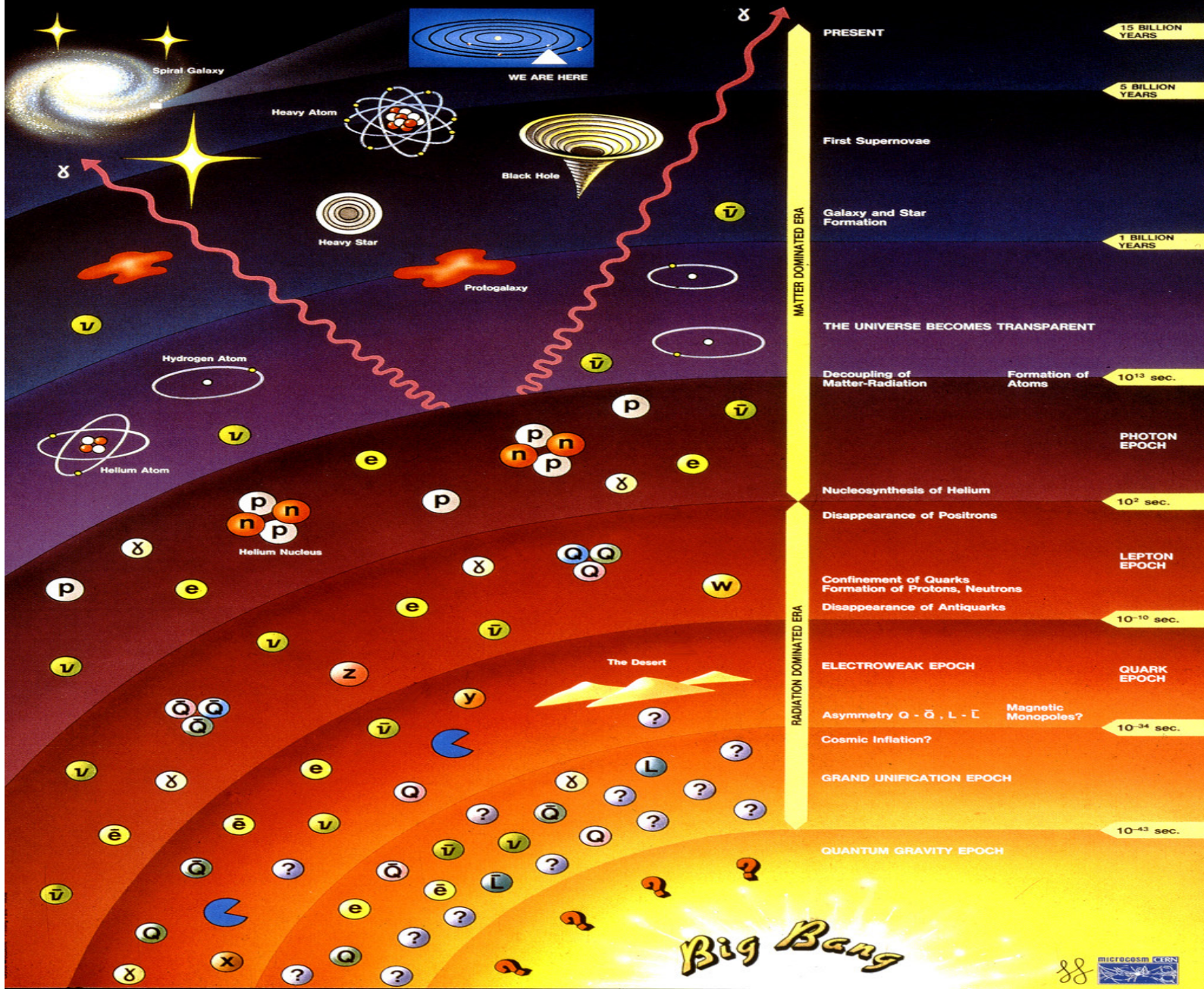


Understand History of Universe?

- What we think (thought?) visible matter is made of.



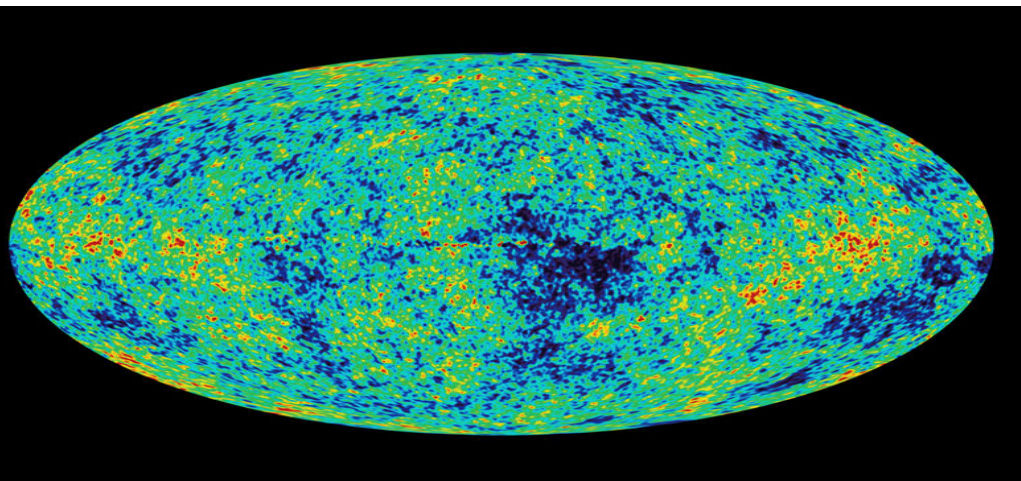
History of the Universe



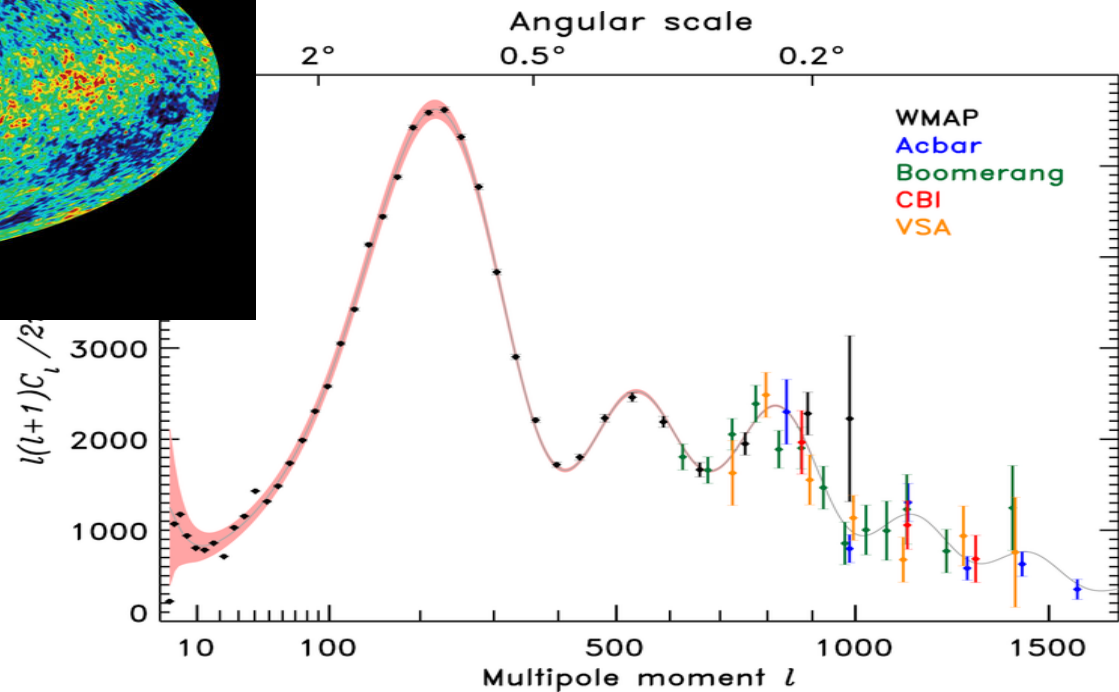
Measuring $\Omega_0 = \rho_0 / \rho_c$

- Amazingly enough can measure
Total matter/energy density in universe
Seems equal to critical density for flat space/time
- Measure temperature fluctuations in remnant of fireball from Big Bang.

$$\Omega_0 = 1.003 \pm 0.013$$



Map of sky temp
~ 3 Kelvin



Density of Standard Model Matter

- Referred to as **Baryonic Matter**
- Density is Ω_B
- If Universe is made of quarks & leptons

$$\Omega_B = \Omega_0 = 1$$

- Ω_B measured from abundance of elements produced in nucleosynthesis of Big Bang.

Deuterium, Helium, Lithium

$$\Omega_B = 0.044$$

$$\Omega_B \neq \Omega_0$$

- Most of Universe is not Standard Model matter. Some kind of **Dark Matter**

Density of All Matter Ω_M

- Can measure density of all matter, whatever its nature, Ω_M , by looking at gravitational motion

rotation curves of galaxies

motion of galactic clusters

Fit to global parameters of Universe

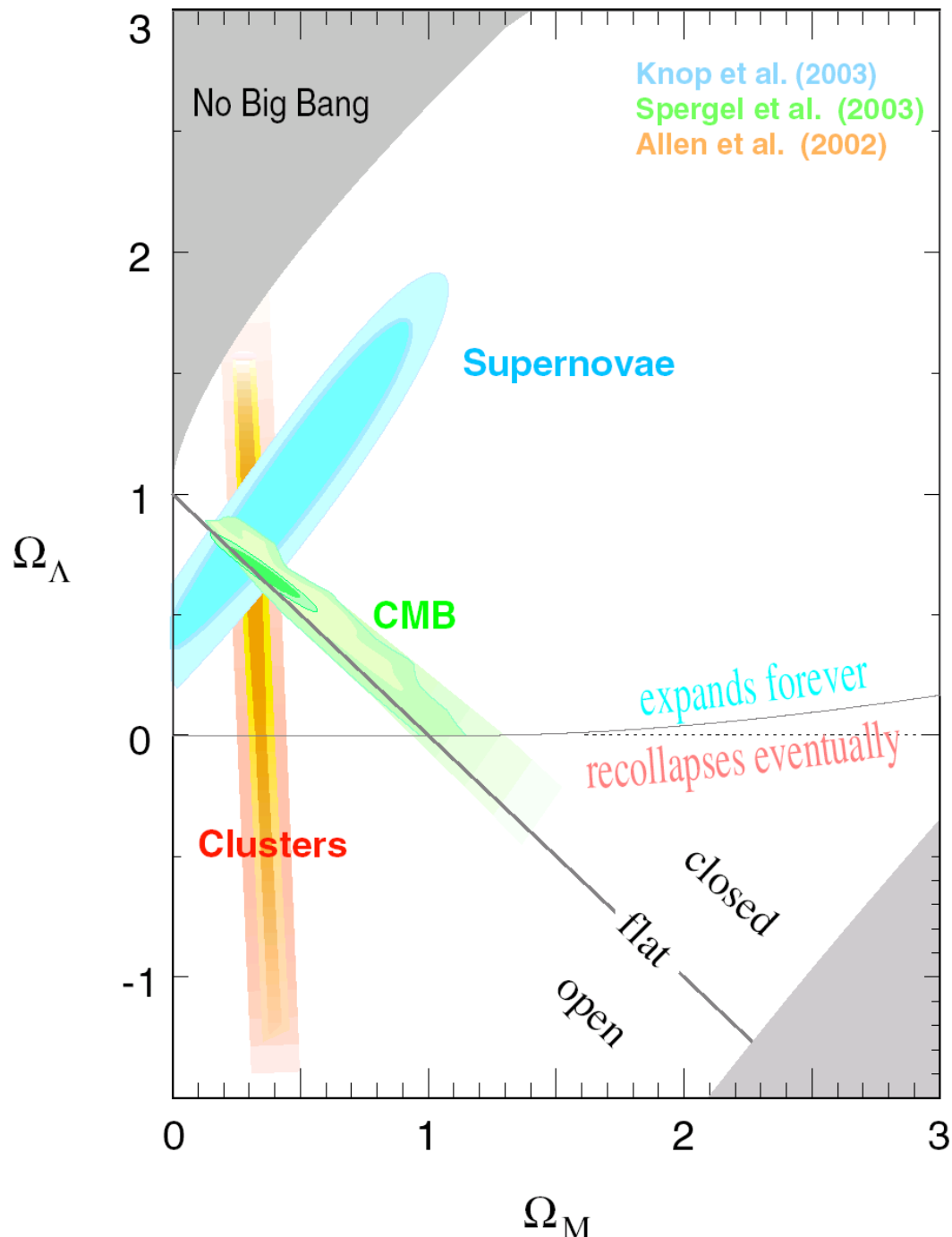
$$\Omega_M = 0.26 \pm 0.012$$

- There is indeed **Dark Matter**

$$\Omega_0 = 1$$

- So even with this **Dark Matter**, cannot account for
- Universe must be **75% Something Else**

Supernova Cosmology Project



Dark Energy Ω_{Λ}

- If the expansion of the Universe is being **slowed down** by gravitational attraction; expect that in **remote past galaxies** were moving apart more **rapidly** than now.
- Observations of **distant supernovae** show that in the past galaxies were moving apart more **slowly**
- **Expansion is accelerating**

$$\Omega_{\Lambda} = 0.85 \pm 0.2$$

$$(0.4 \pm 0.1) + (0.85 \pm 0.2) = 1.25 \pm 0.22$$

$$\Omega_M + \Omega_{\Lambda} = 1$$

- Driven by some quantum field permeating the Universe.

Need for Supersymmetry

- In Grand Unified Theories cannot Unify forces, unless postulate unseen form of matter
 - Higgs mass runs away to Plank Scale
 - Three forces never have same strength
- Unless all particles have supersymmetric sparticle partners (of higher mass)

Fermions		Bosons	
Leptons Quarks	Spin $\frac{1}{2}$	1	Carrier Bosons $\gamma W^+ W^- Z^0 g$
Baryons (qqq)	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$	0, 1, 2, ...	Mesons (q \bar{q})

+

Sleptons

Bosinos

Squarks

Spin 1

Spin 1/2

SUSY + Dark Matter

- Supersymmetric Particles are unstable

Susy \rightarrow *Normal* + *Susy*

- Eventually decay chain ends in Normal matter + lightest SUSY particle
- Lightest SUSY particle cannot interact with normal matter
- Lightest SUSY particle good candidate for

Dark Matter

- Hope to produce

(SUSY - antiSUSY) pairs and Higgs

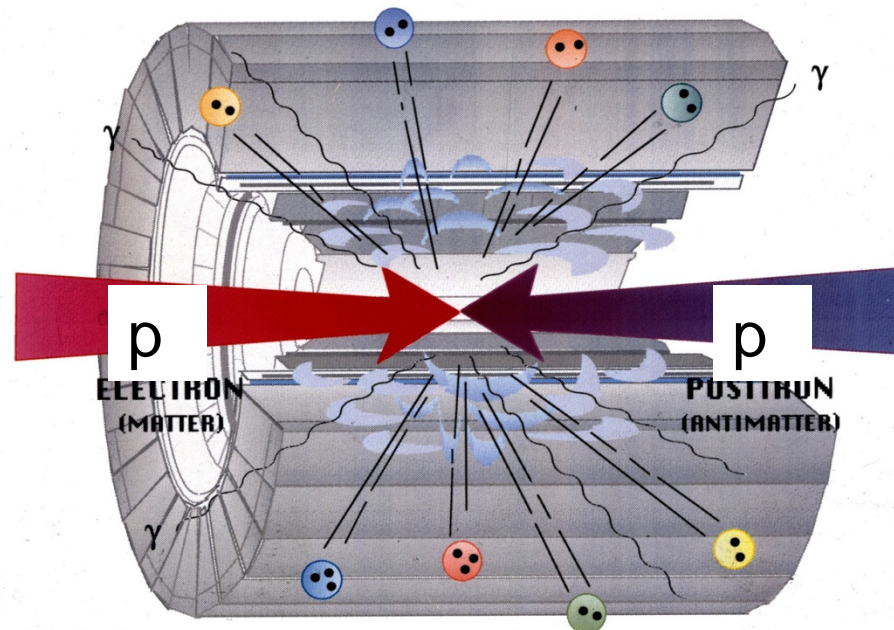
at

Large Hadron Collider

How to Make Matter / AntiMatter?

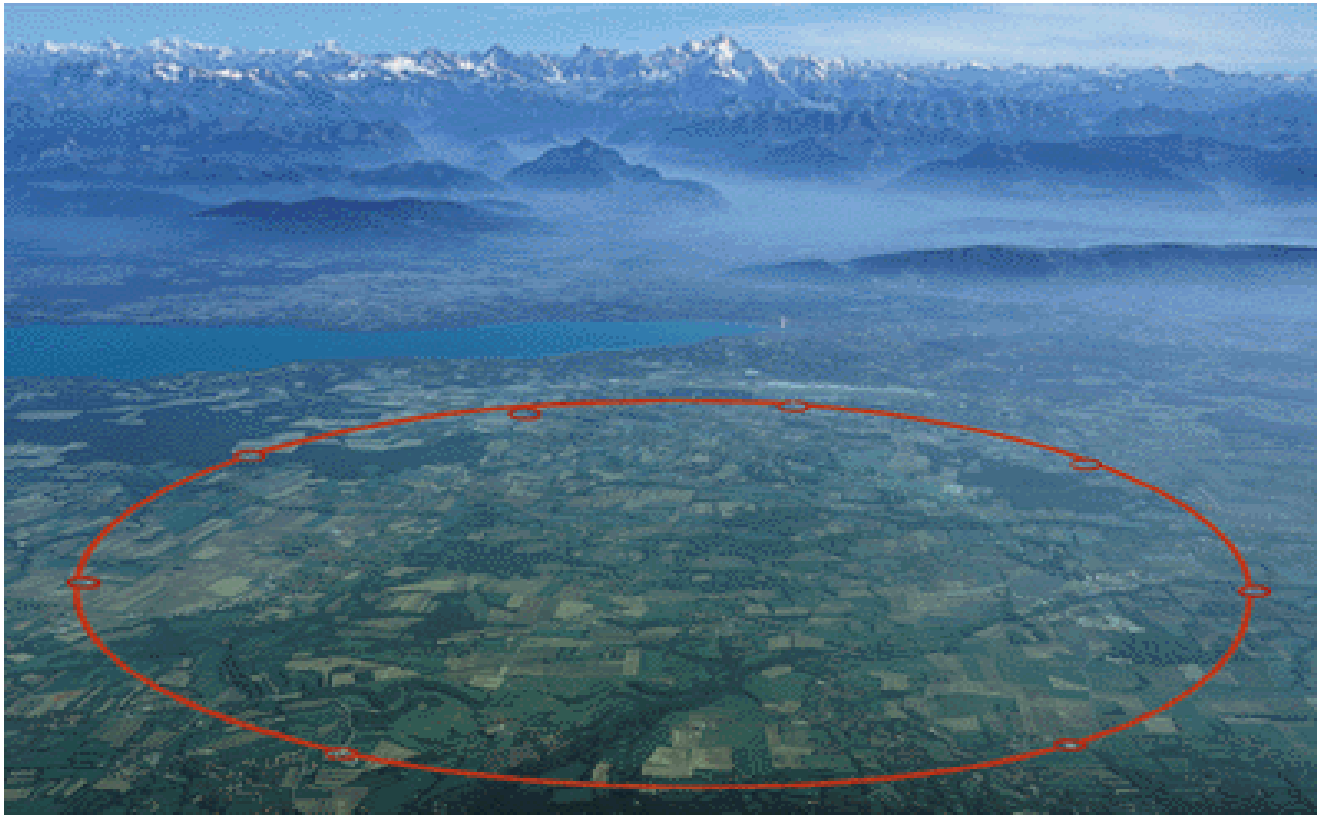
Colliding high energy beams

Energy of beams transformed into mass of new particles



- LHC will be **proton - proton** collider
- For SUSY observation must contain ALL visible energy, in order to infer invisible SUSY

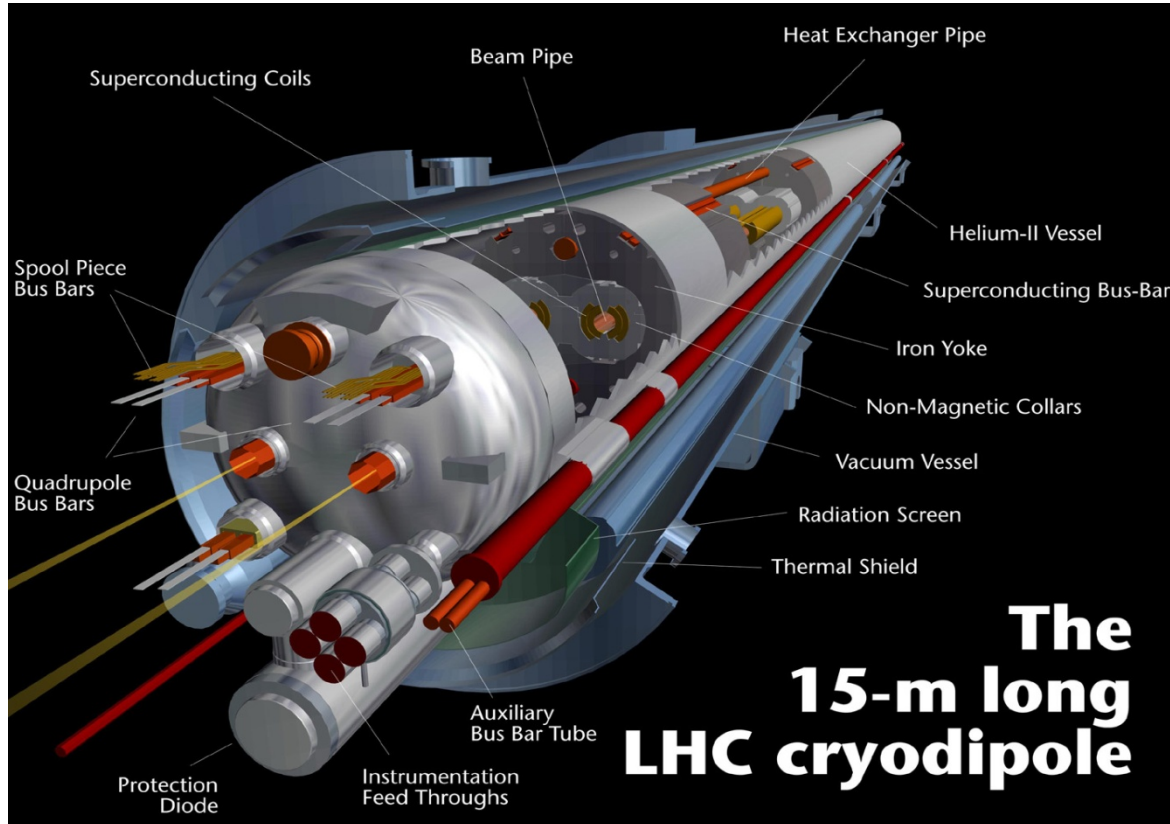
CERN Seen from the Air



- Tunnels of CERN accelerator complex superimposed on a map of Geneva.
- Accelerator is 50 m underground
- 25 km in circumference

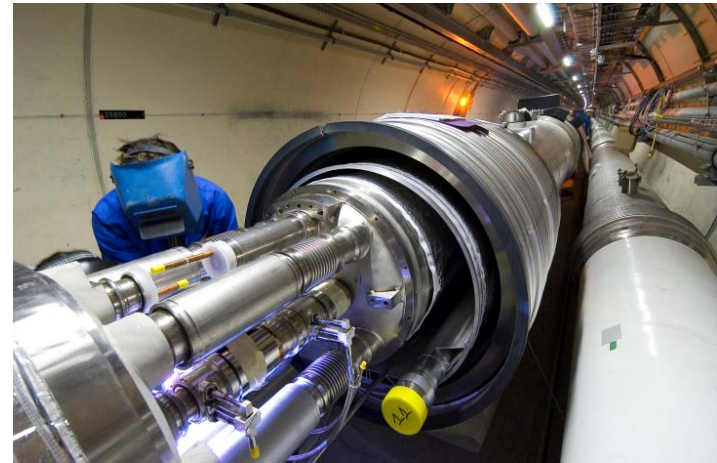
Superconducting Magnet

8 Tesla

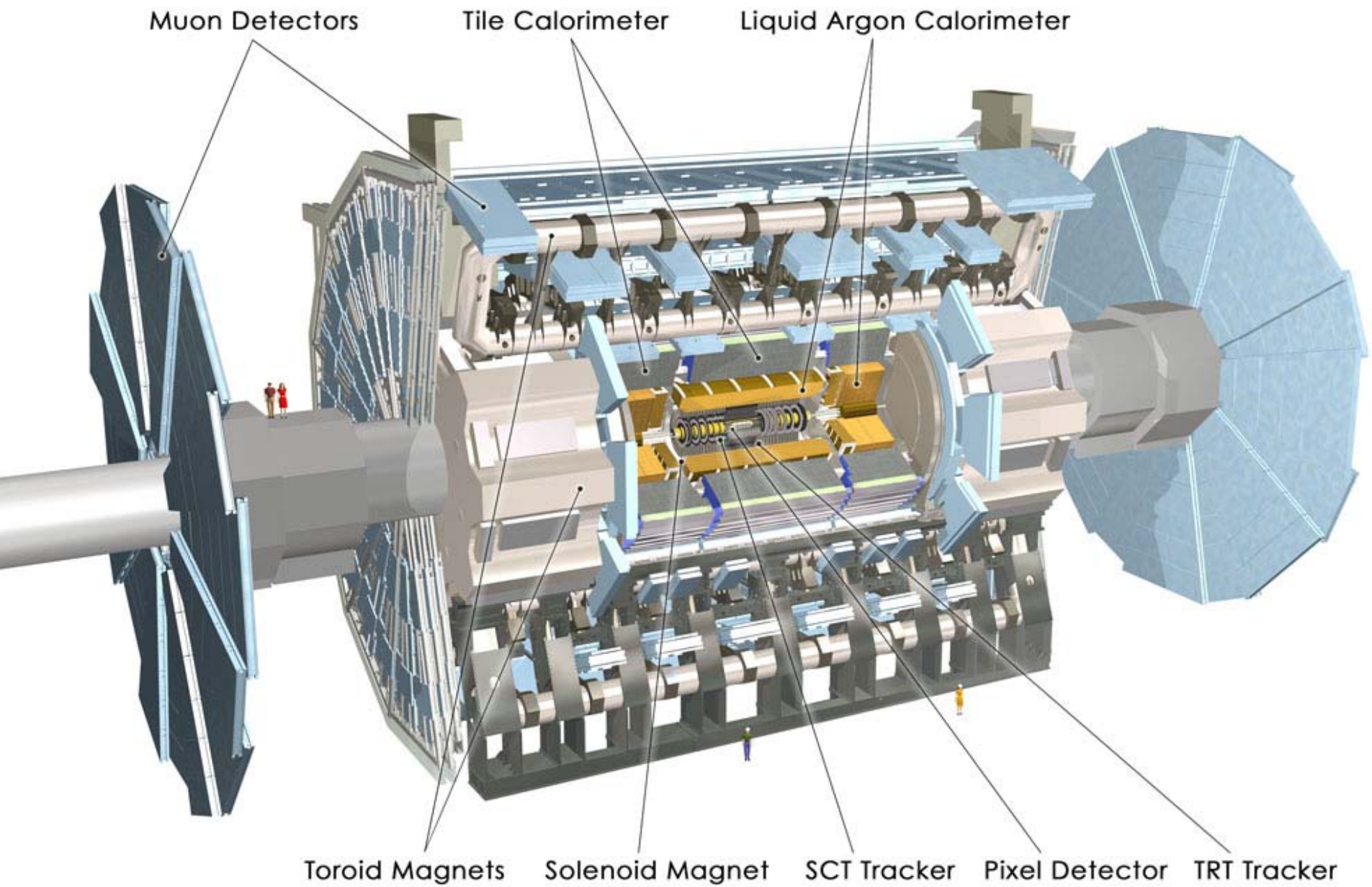


- In order to **accelerate** protons to high energy, must bend them in **circular accelerator**
- **7 TeV** momentum needs intense **magnetic field**

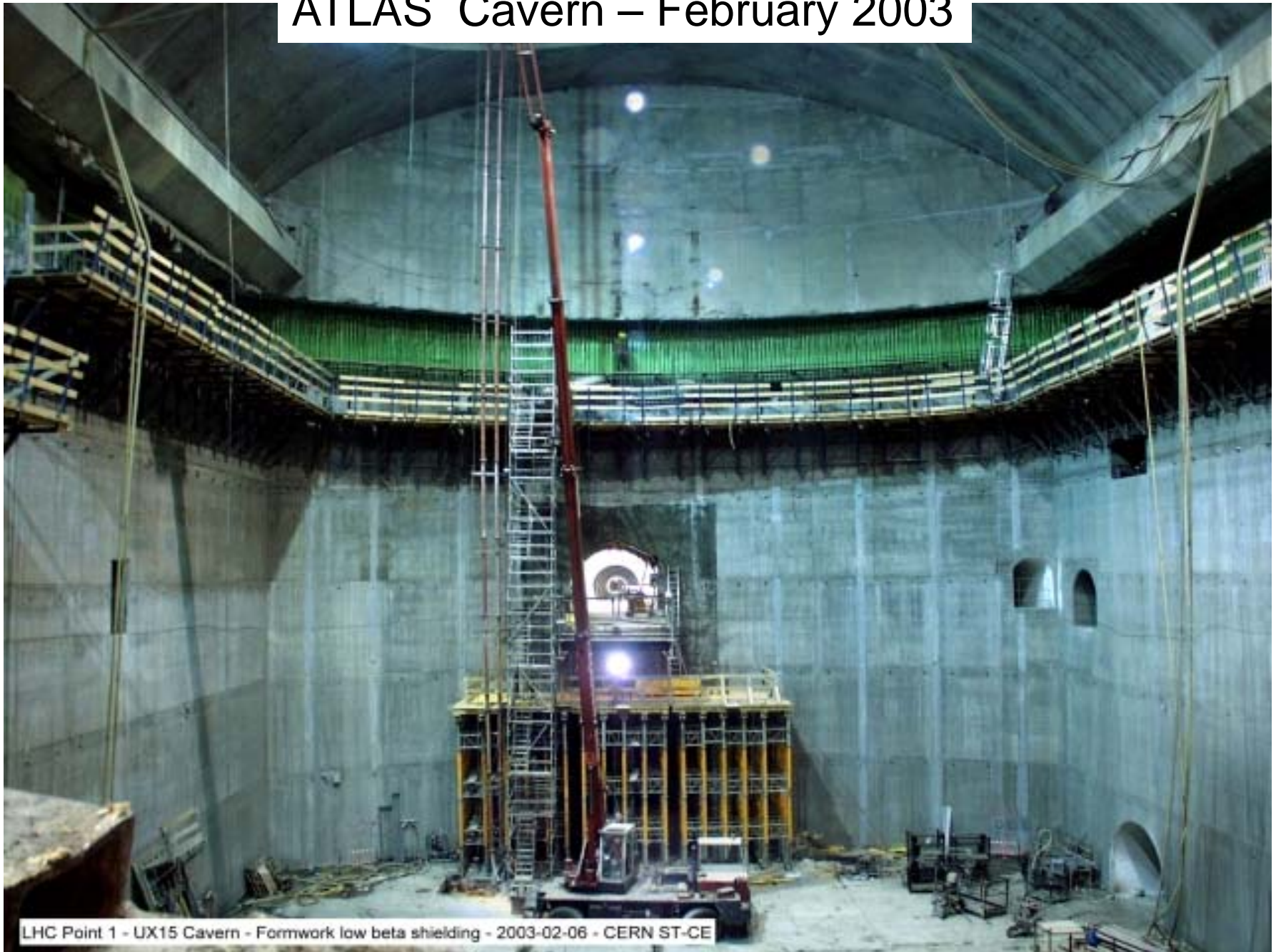
Underground







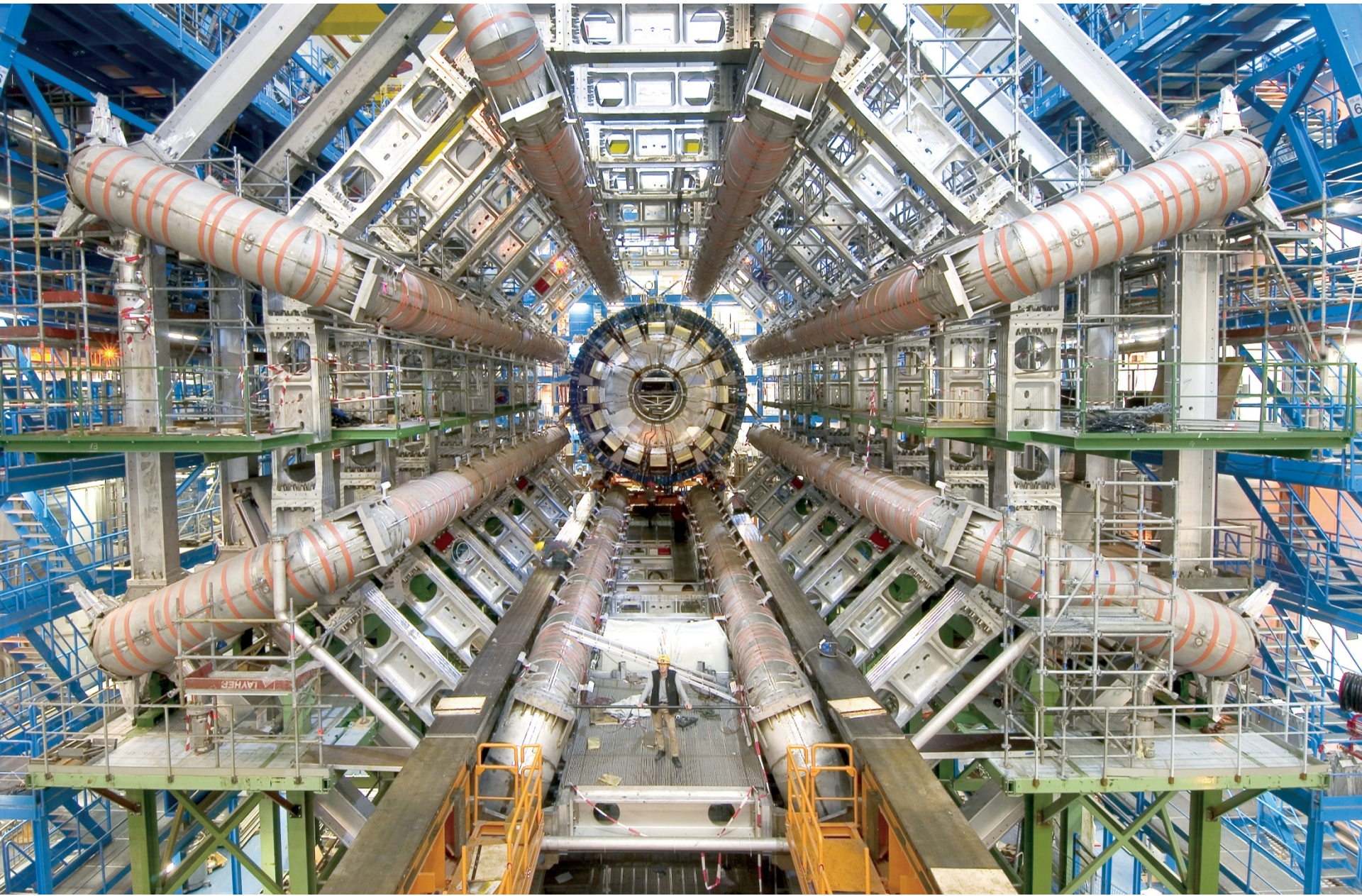
ATLAS Cavern – February 2003



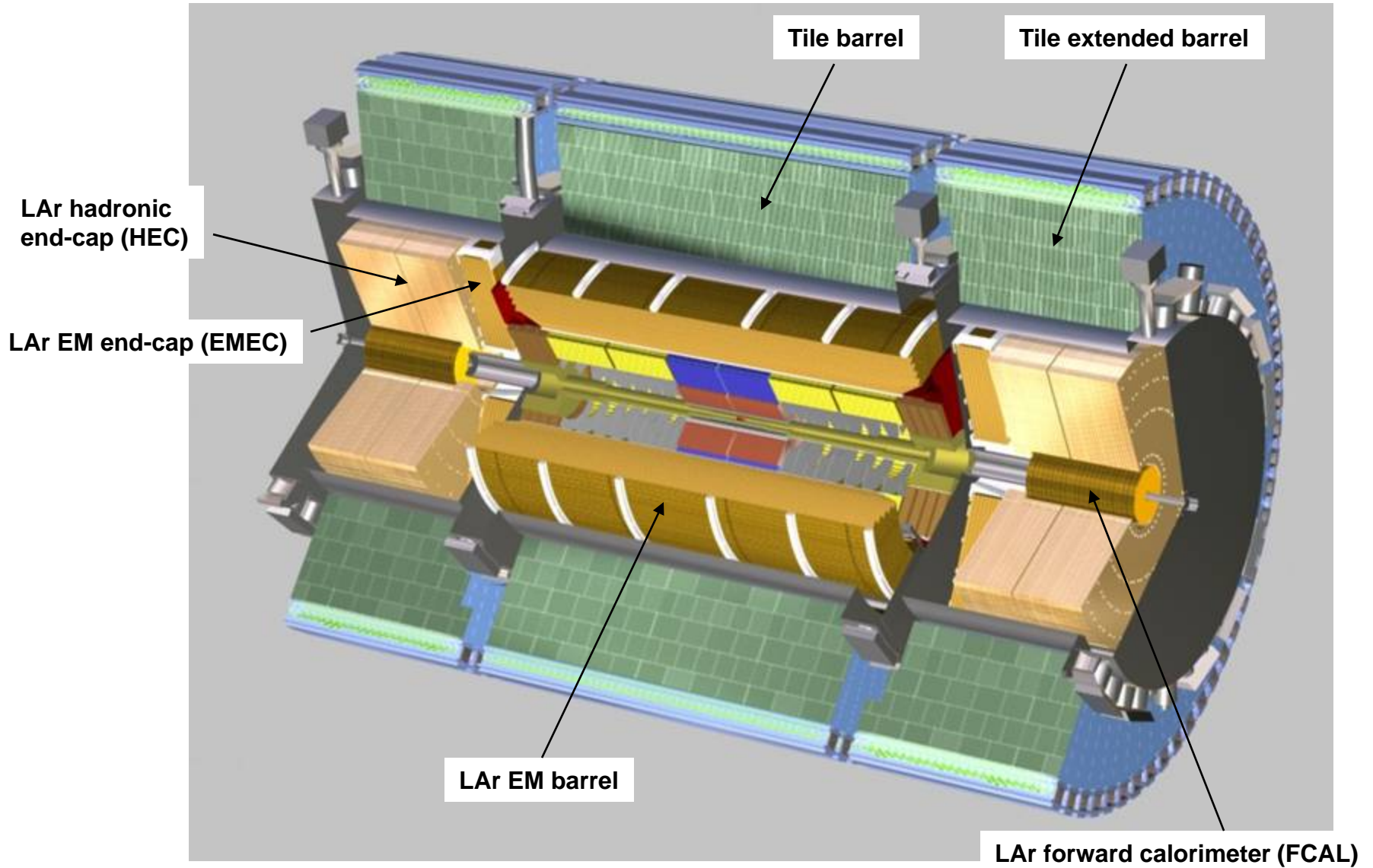
LHC Point 1 - UX15 Cavern - Formwork low beta shielding - 2003-02-06 - CERN ST-CE

ATLAS Cavern – November 2004

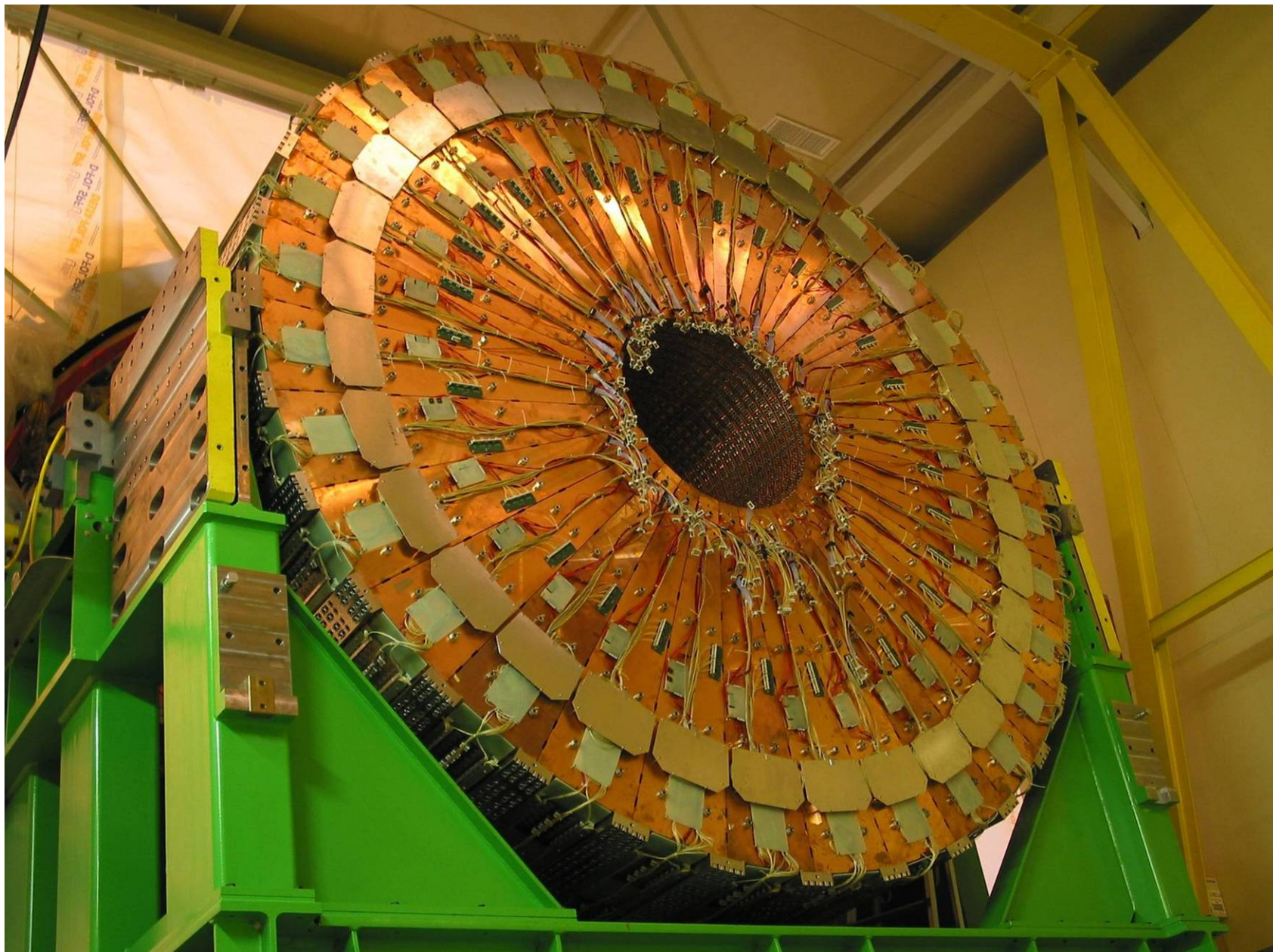




LAr and Tile Calorimeters



HEC 2 A-wheel on the insertion stand, Aug. 2004

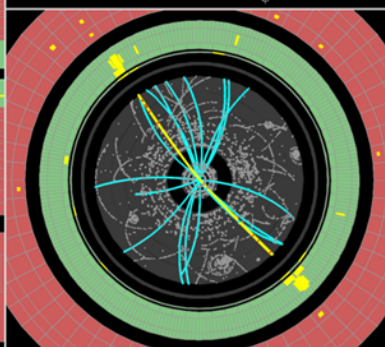
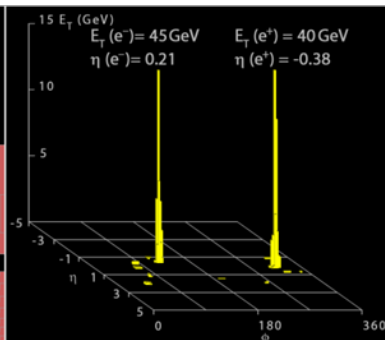
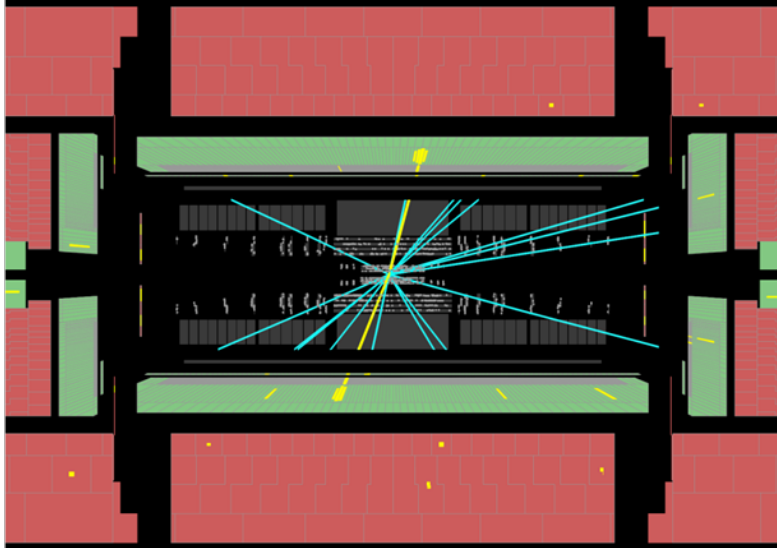


LAr Forward Calorimeters

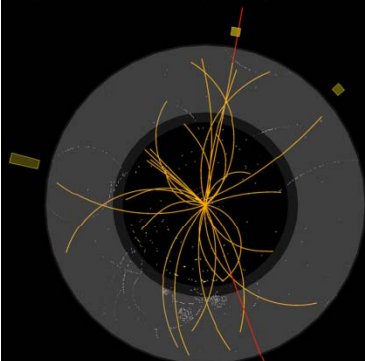


- FCAL C assembly into tube – Fall 2003

Run Number: 154817, Event Number: 968871
 Date: 2010-05-09 09:41:40 CEST
 $M_{ee} = 89 \text{ GeV}$
Z \rightarrow ee candidate in 7 TeV collisions



Run: 154822, Event: 14321500
 Date: 2010-05-10 02:07:22 CEST



$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$
 $M_{\mu\mu} = 87 \text{ GeV}$

**Z \rightarrow $\mu\mu$ candidate
 in 7 TeV collisions**

