Course outline

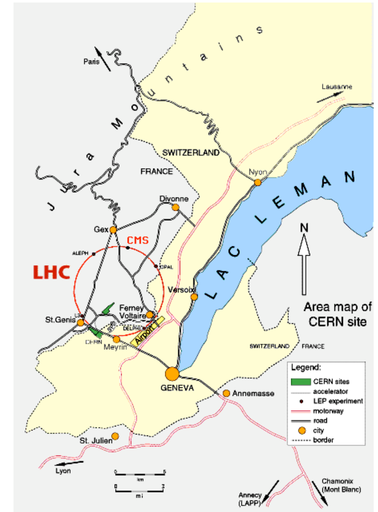
Syllabus - The Physics of the Large Hadron Collider

* Introduction – major outstanding problems in particle physics
* The Standard Model of particle physics, and its problems & extensions
    - o A tour of QFT and the Standard Model
    - o Symmetries, Gauge invariance
    - o Spontaneous symmetry breaking
    - o The Higgs
    - o Fermion masses
    - o The top quark
    - o Grand unification, proton decay, LeptoQuarks
    - o Search for the Higgs at the TeVatron, LHC and the ILC
    - o The Hierarchy problem
* The LHC
    - o Particle accelerators and colliders
    - o Luminosity, cross-sections, reaction rates, decay rates
    - o Particle detectors: vertex detectors, solenoidal trackers, calorimeters, muon detectors ...
    - o Events at the LHC
* Supersymmetry
    - o The last great symmetry
    - o Solution to the hierarchy problem
    - o Grand Unification in SUSY
    - o Dark Matter candidates in SUSY
    - o Finding SUSY at the LHC
* CPV and Baryon asymmetry of the universe
    - o CP violation in the quark sector
    - o Neutrino masses, Majorana, mixing and CP violation
    - o LHC-b
* Physics at the Planck scale, Quantum gravity
    - o Why is gravity so weak?
    - o string theory, extra dimensions
    - o KK particles, gravitons, and black holes at the LHC

The Standard Model

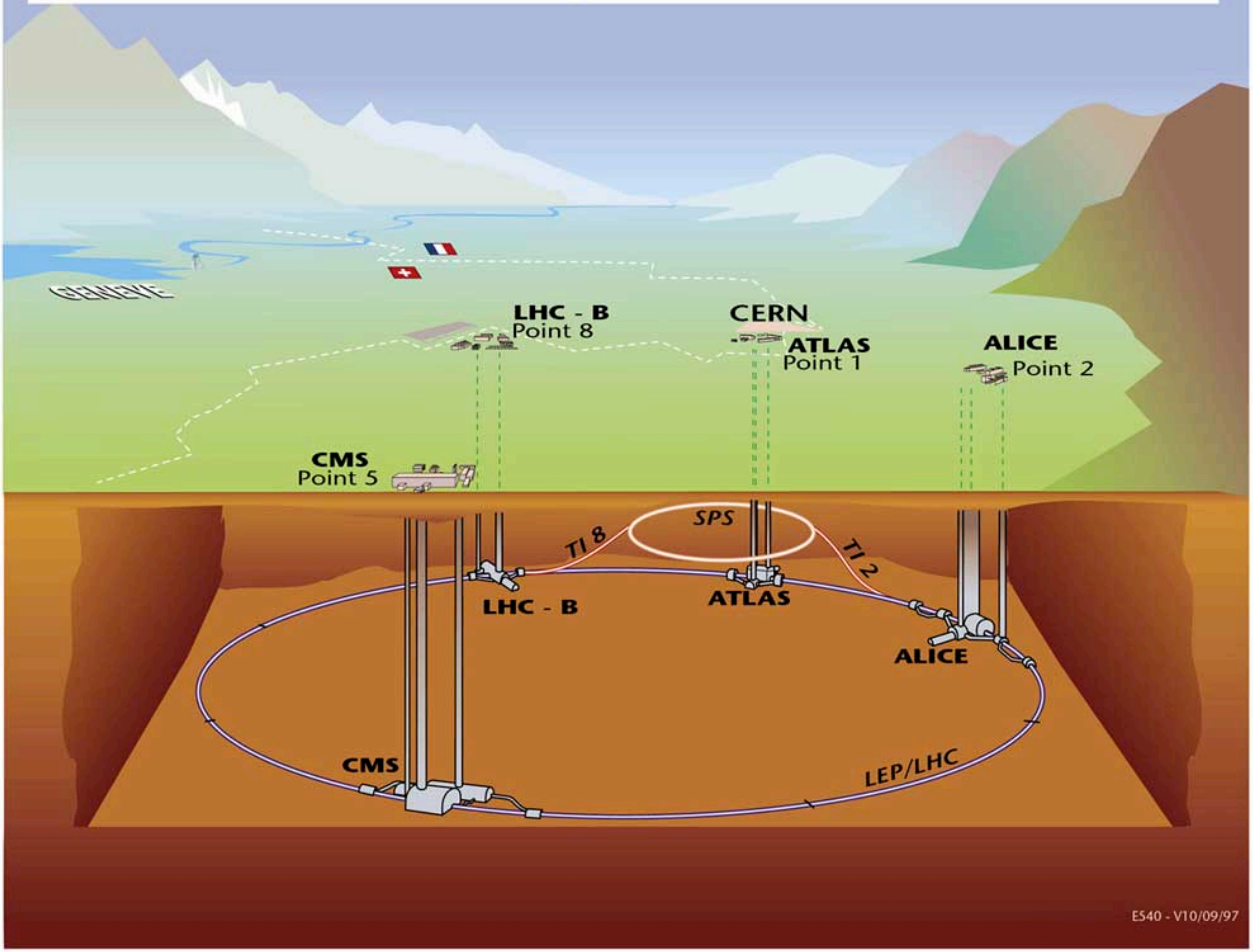
Beyond the Standard Model

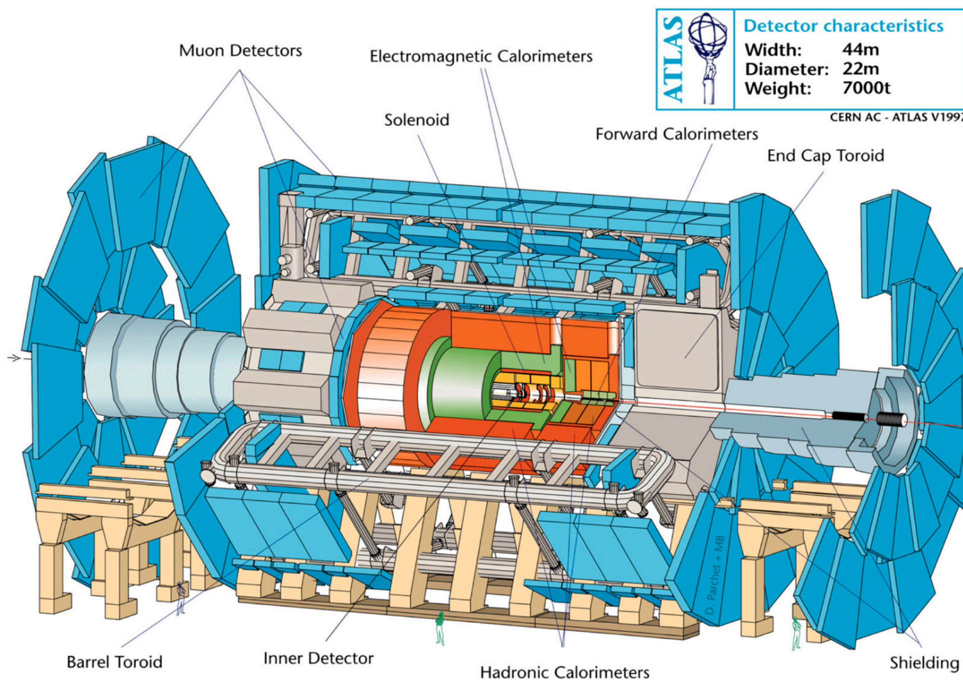
What is the LHC?

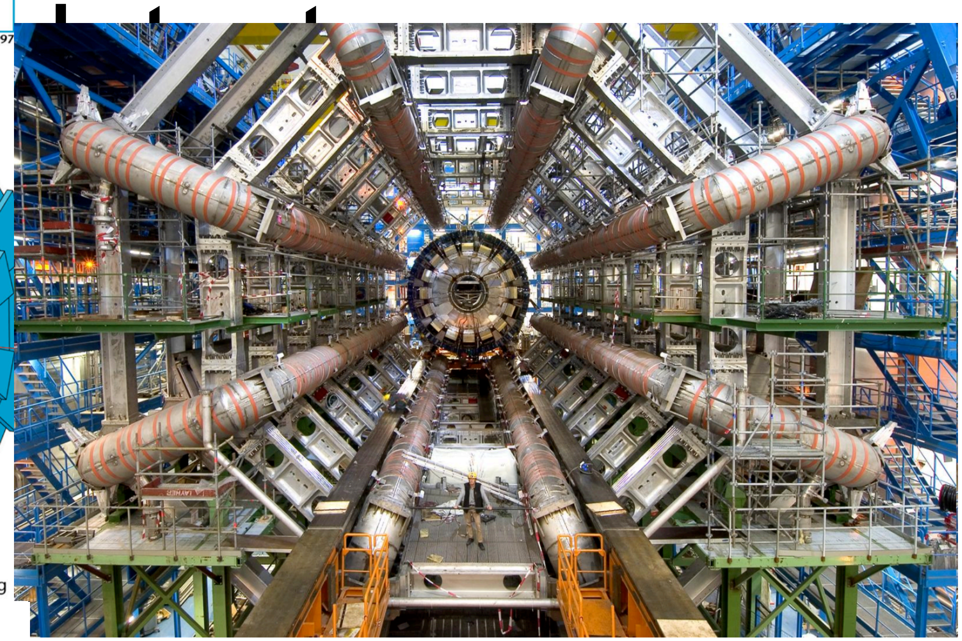


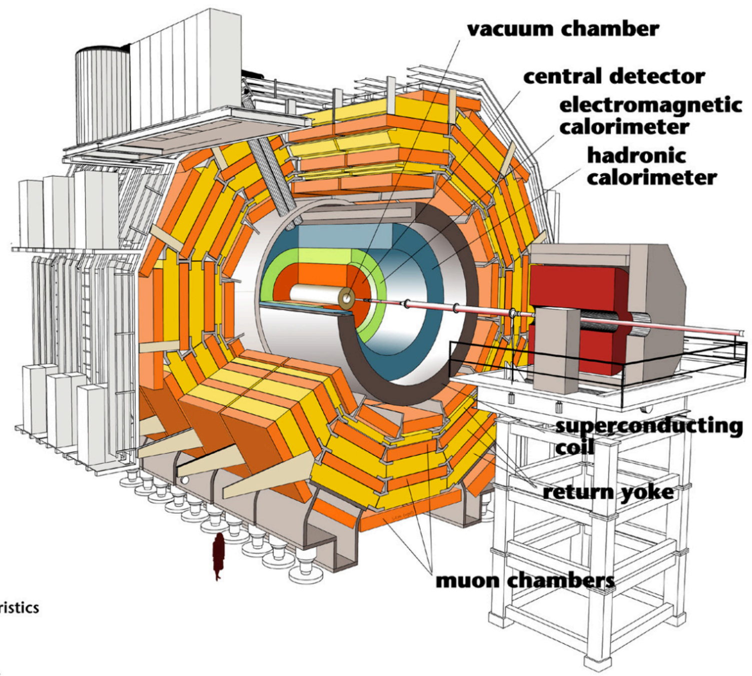
- The Large Hadron Collider is at CERN, the European Center for Particle Physics near Geneva, Switzerland.
- The Collider lives in a circular tunnel 27 km in circumference, ~100 m under the border between Switzerland and France.
- It will collide bunches of protons at a total center-of-mass energy of 14 TeV (7+7), 40M times per second, with very high luminosity.
- It is the latest of a long line of similar accelerators at CERN and around the world, reaching to ever-higher energy and luminosity.
- It cost more than $9B to build, not including the tunnel.
- It is advertised to be the most complex instrument ever built.

Overall view of the LHC experiments.



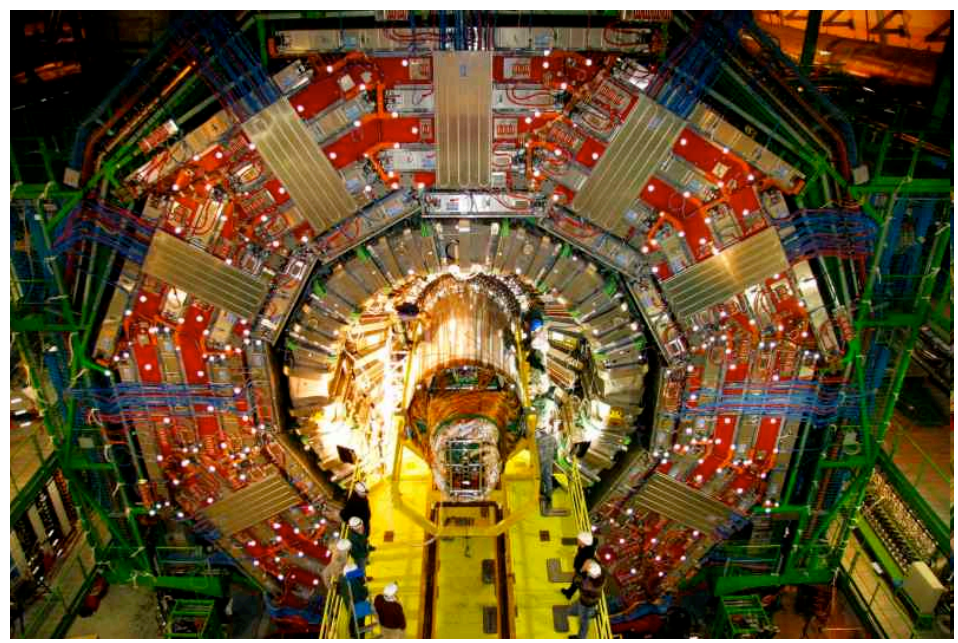






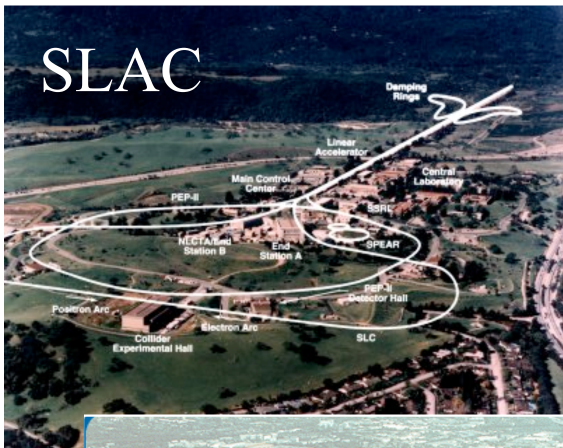
Detector characteristics

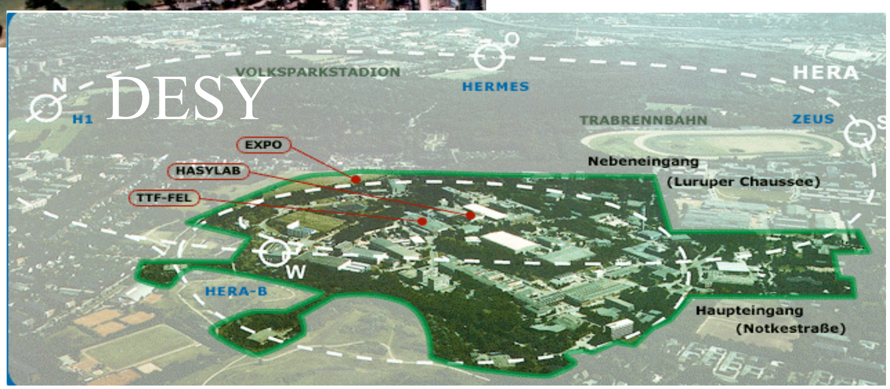
Width: 22m
Diameter: 15m
Weight: 14'500t

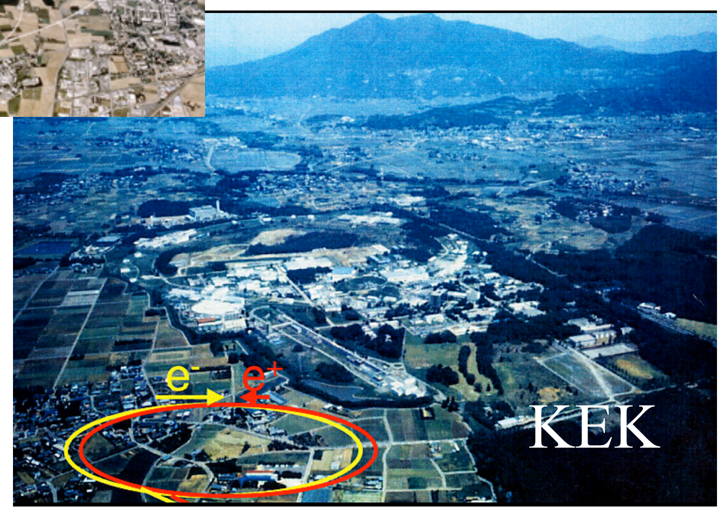


Accelerator labs around the world

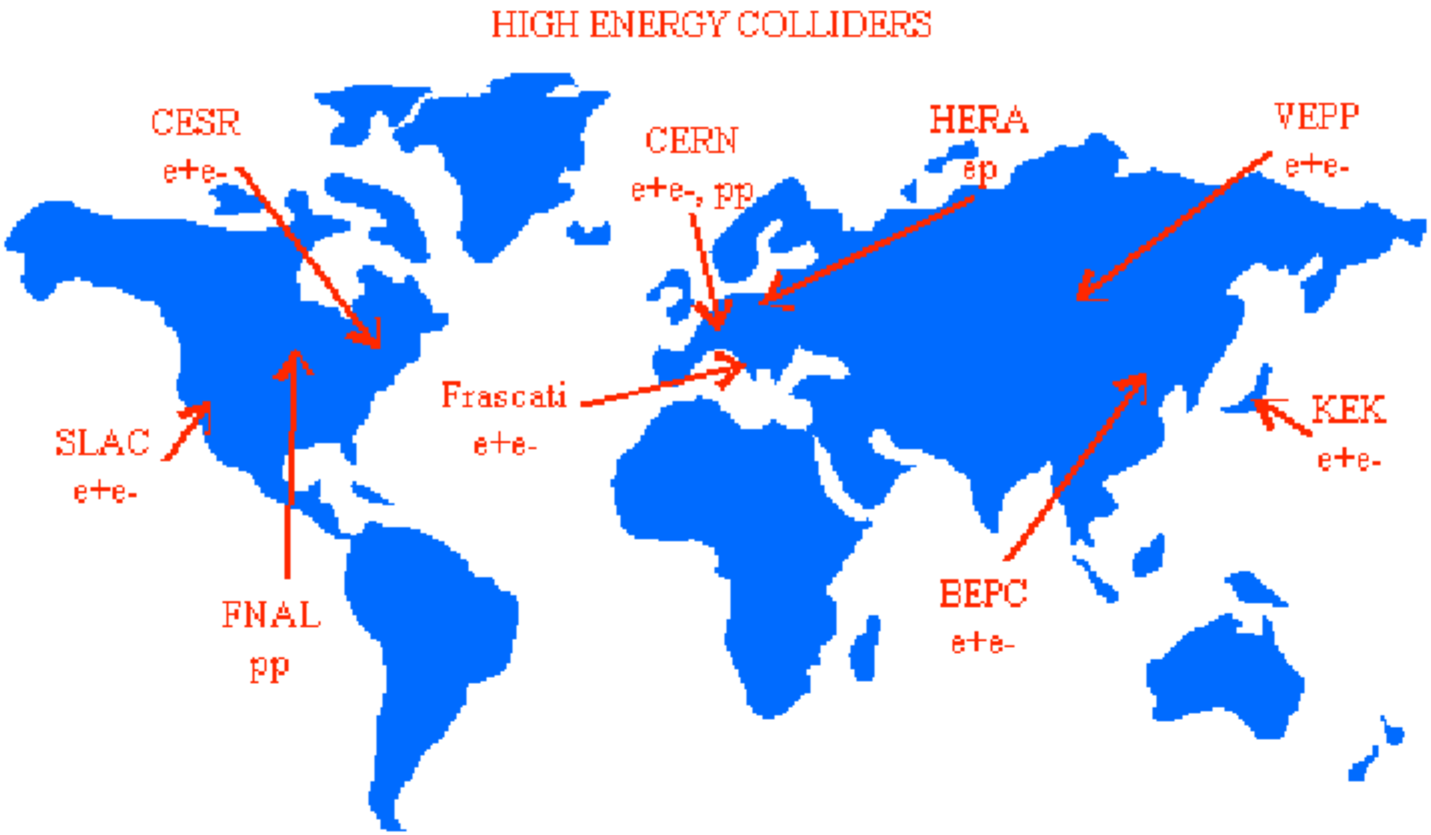
- CERN, Geneva, Switzerland (SPS, ν beams, LEP, LHC)
- Fermilab, Batavia, Illinois (Tevatron, ν beams, fixed target)
- SLAC (PEP, PEP-II, SLC)
- DESY, Hamburg, Germany (PETRA, HERA)
- KEK, Tsukuba, Japan (KEK-B, ν beams, fixed target)
- CESR/Cornell, BEPC/Beijing, DAΦNI/Frascati, VEPP (Novisibirsk), etc



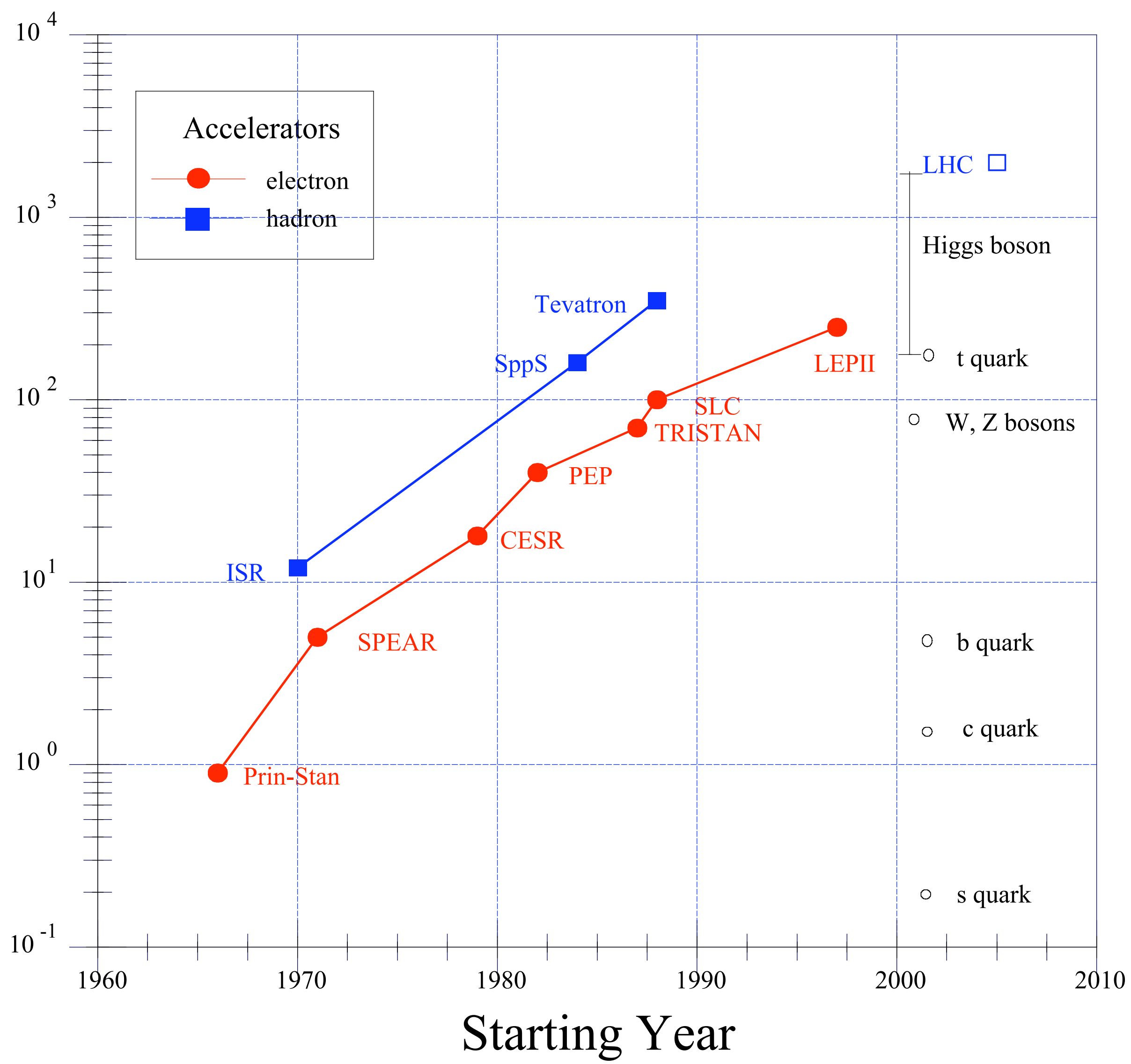




Colliders around the world



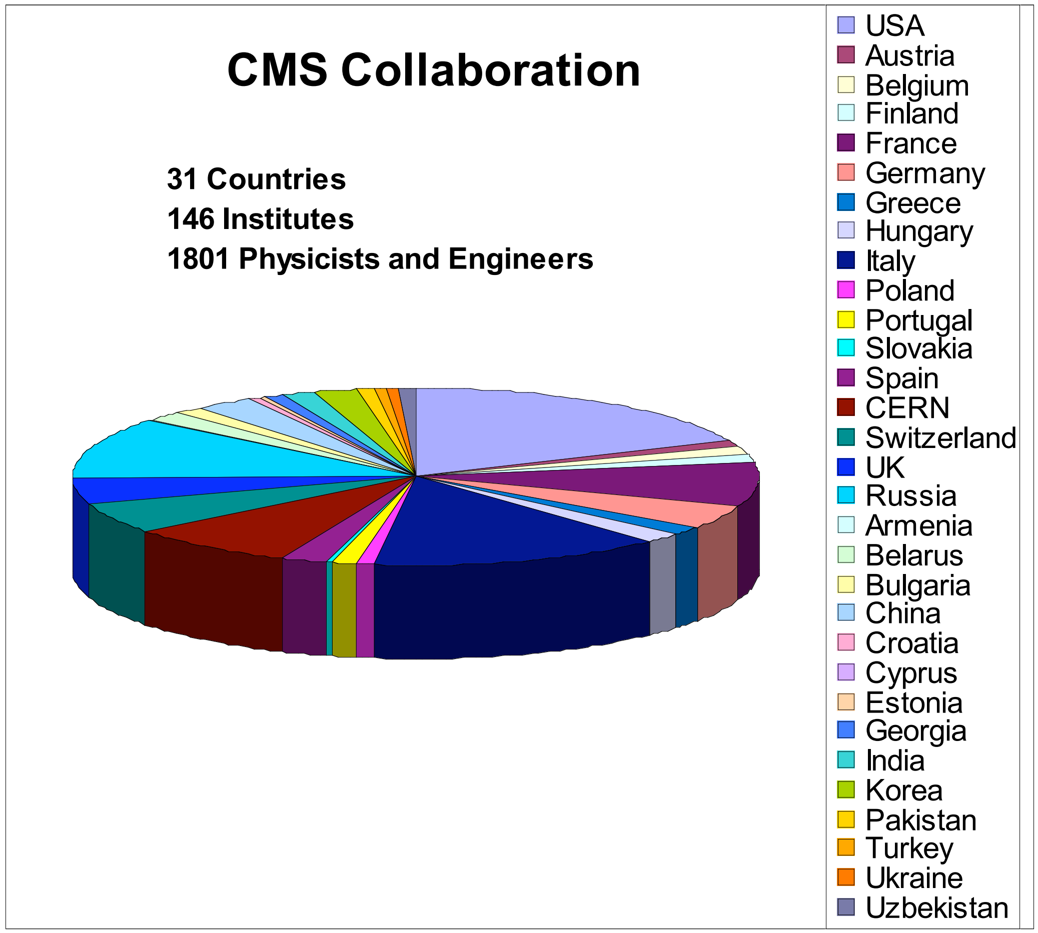
The march to higher energies



The LHC is a machine of superlatives

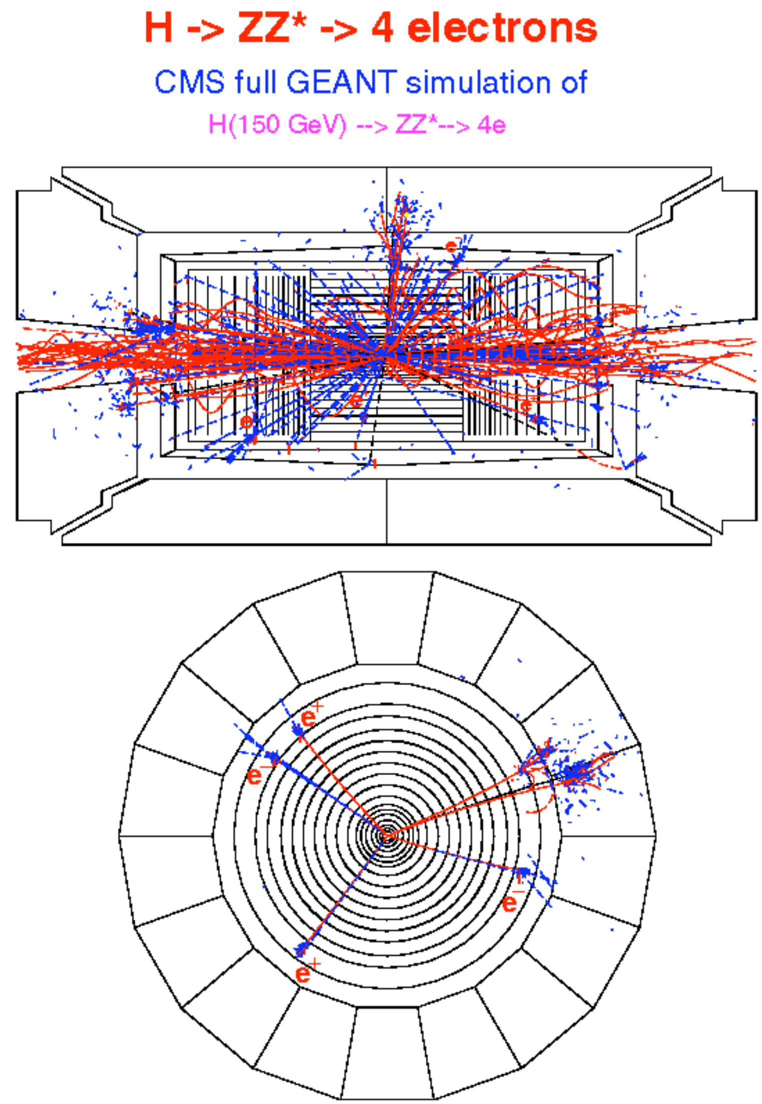
- Cost: at least $9B, not including the tunnel
- Number of physicists and engineers participating, around the world: more than 10,000
- Number of collisions per second at design luminosity: 600 million
- Number of superconducting magnets: over 1100, at 1.9K
- Peak magnetic dipole field: 8.3 Tesla
- The magnet wire can stretch to the Sun and back 5 times.
- The 7 TeV protons travel at 0.999999991 of the speed of light, circulating 11,000 times per second.
- The two large detectors, CMS and ATLAS, weigh 7,000 and 12,500 tons each, cost ~ $600M each, and have ~100M channels of electronic readout each.
- The CMS magnet contains more iron than the Eiffel Tower.
- ALICE, LHC-b and TOTEM are smaller but still large compared with the biggest and most complex detectors built in the past.
- Together they will generate 700 MB/s of data, or 15 PB per year, analyzed by ~100,000 computers around the world.
- The LHC+detectors require 120 MW of power, about as much as the Canton of Geneva.

The CMS collaboration
the world's largest scientific collaboration



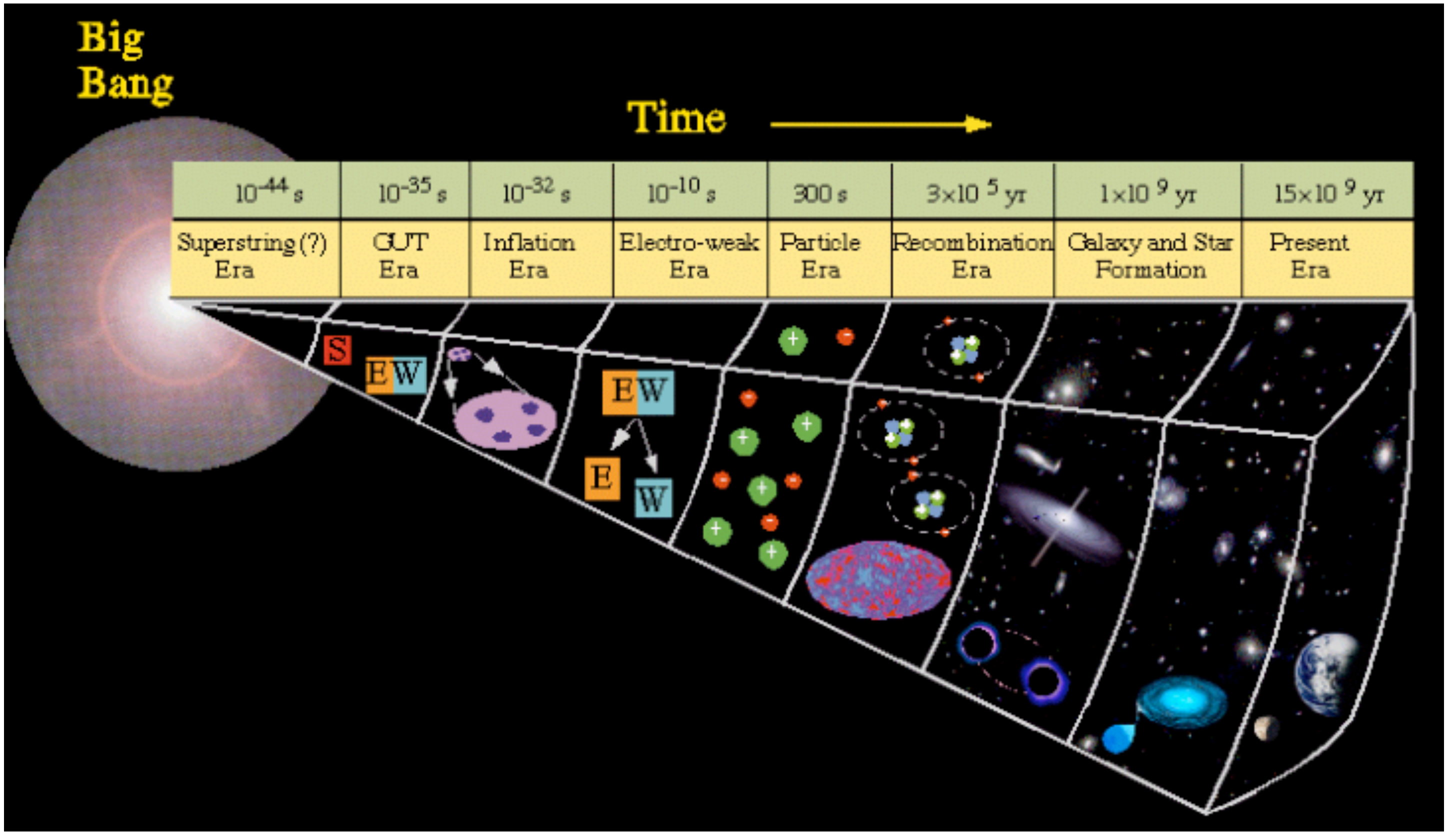
A high-energy collision in an LHC detector

- The high energy pp collisions at the LHC will be governed, mostly, by the physics described in the Standard Model of particle physics.
- But its main purpose, at the energy frontier, is to reveal new phenomena beyond the Standard Model.
- There are many reasons to expect that new and very interesting phenomena will reveal themselves at the LHC.
- The LHC is a **discovery machine.**



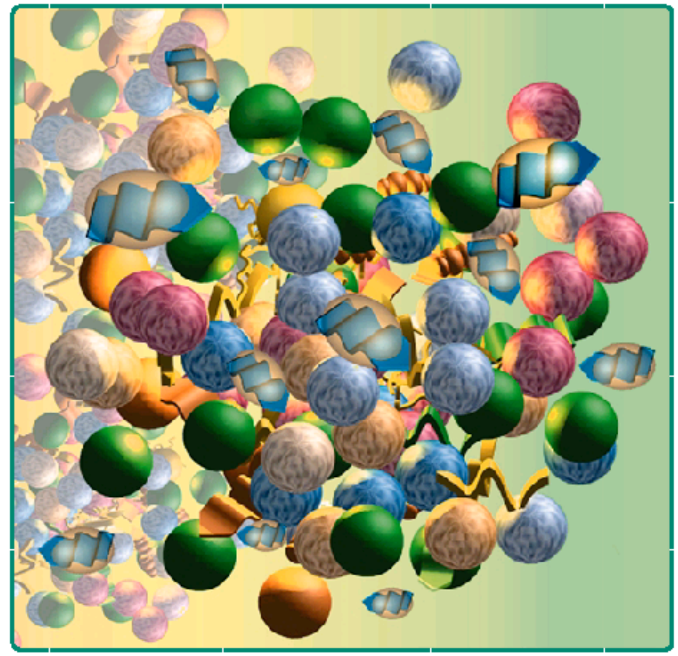
Particle physics and cosmology

- The LHC collisions concentrate a huge amount of energy in a tiny space, recreating the conditions in the very early universe.
- The LHC may reveal deep symmetries between matter, energy, space and time; the nature of dark matter; the existence of extra dimensions; the connection between quantum physics and gravity; … phenomena that have not manifested themselves since the Big Bang.



Particle physics and cosmology

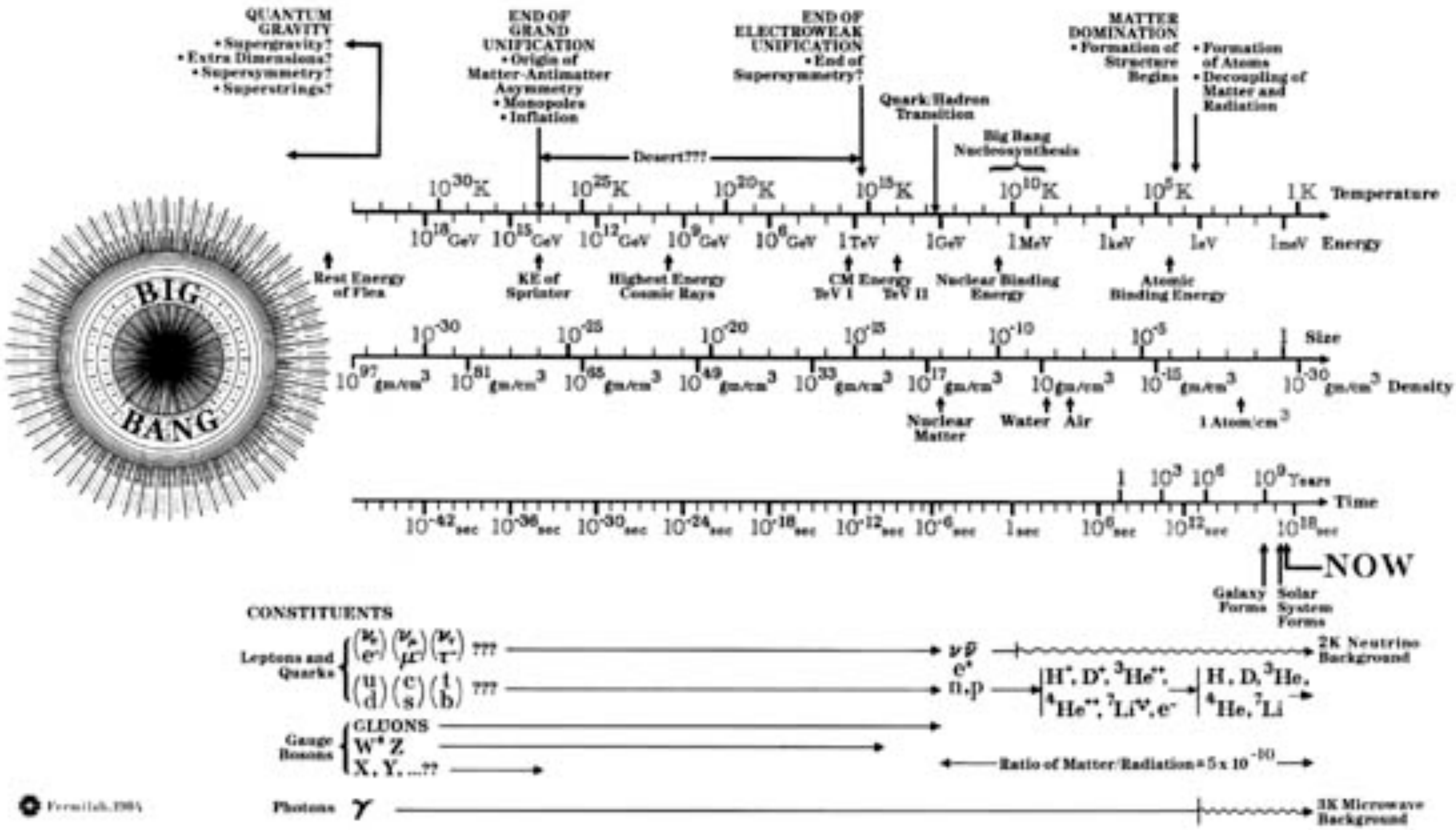
- Particle physics is as much about the very large (the early moments of the big bang) as about the microscopically small.
- In the early moments of the big bang, the universe was hot, thermal, a “soup” of elementary particles.
- Attempting to understand the dynamics of the evolution of the universe at those early moments (such hubris!) requires an understanding of particle physics.
- Closer we get to the big bang, the higher the temperatures / energies; before about 10^{-10} seconds after the BB (particles separated by 10^{-18} m, mean energies > 10^{15}K = 100 GeV), we don’t know the physics!

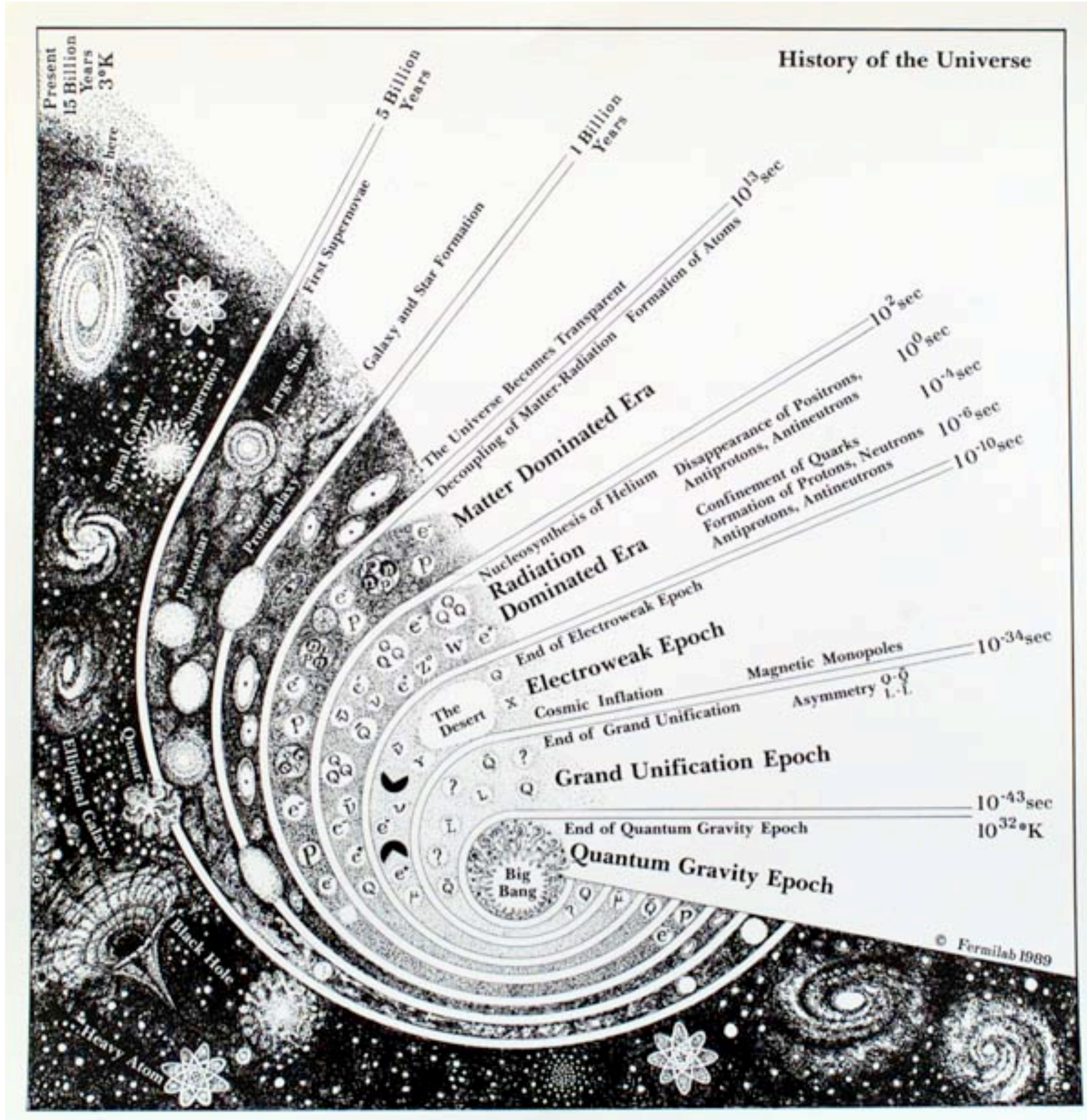


$t \approx 10^{-10}$ s, 10^{15} K (100 GeV, 10^{-18} m) : Electromagnetic and Weak Forces separate

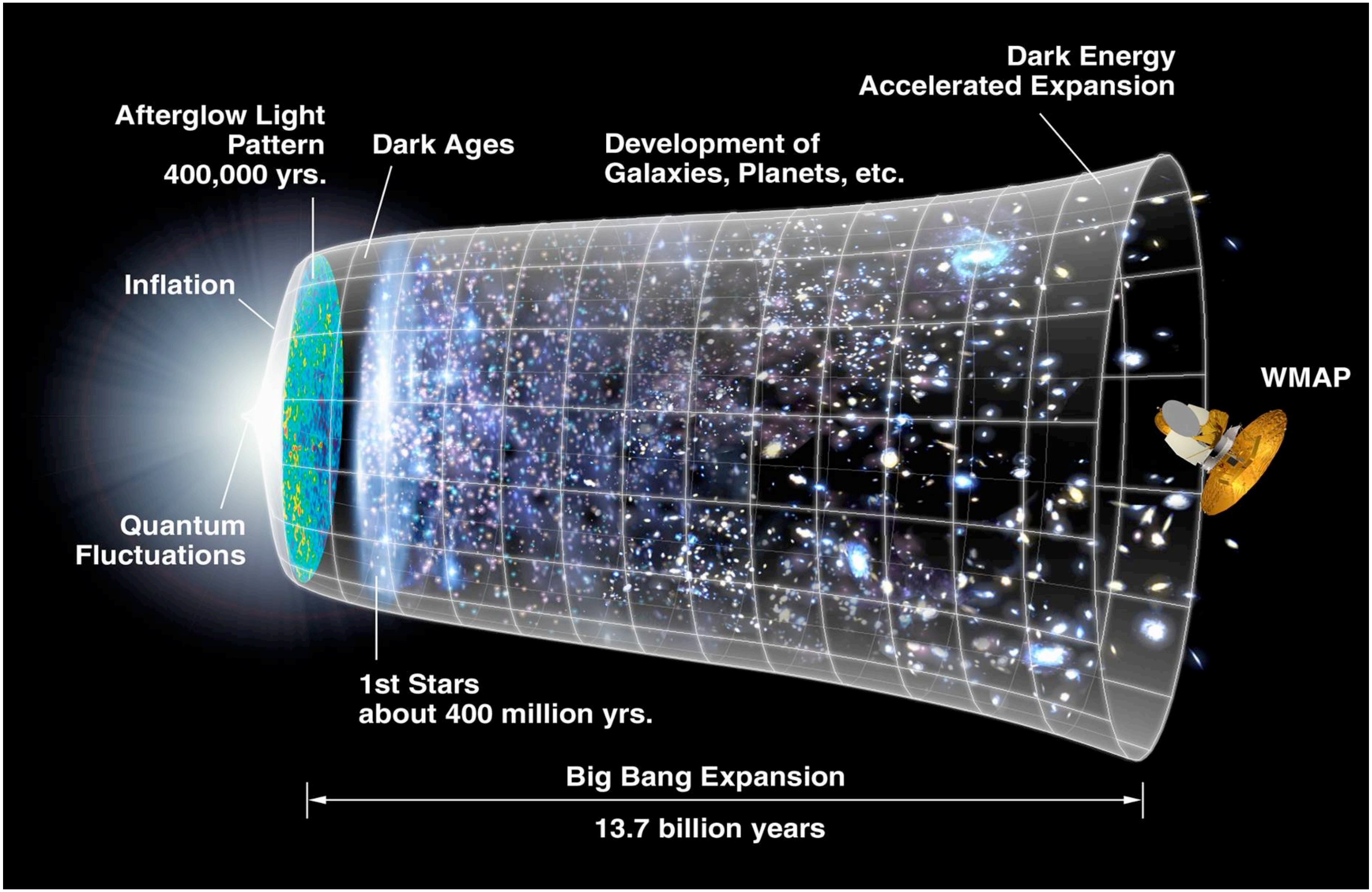
The energy density corresponds to that at LEP. As the temperature fell the weak force "freezes" out and all four forces become distinct in their actions. The antiquarks annihilate with the quarks leaving a residual excess of matter. W and Z bosons decay. In general unstable massive particles disappear when the temperture falls to a value at which photons from the black-body radiation do not have sufficient energy to create a particle-antiparticle pair.

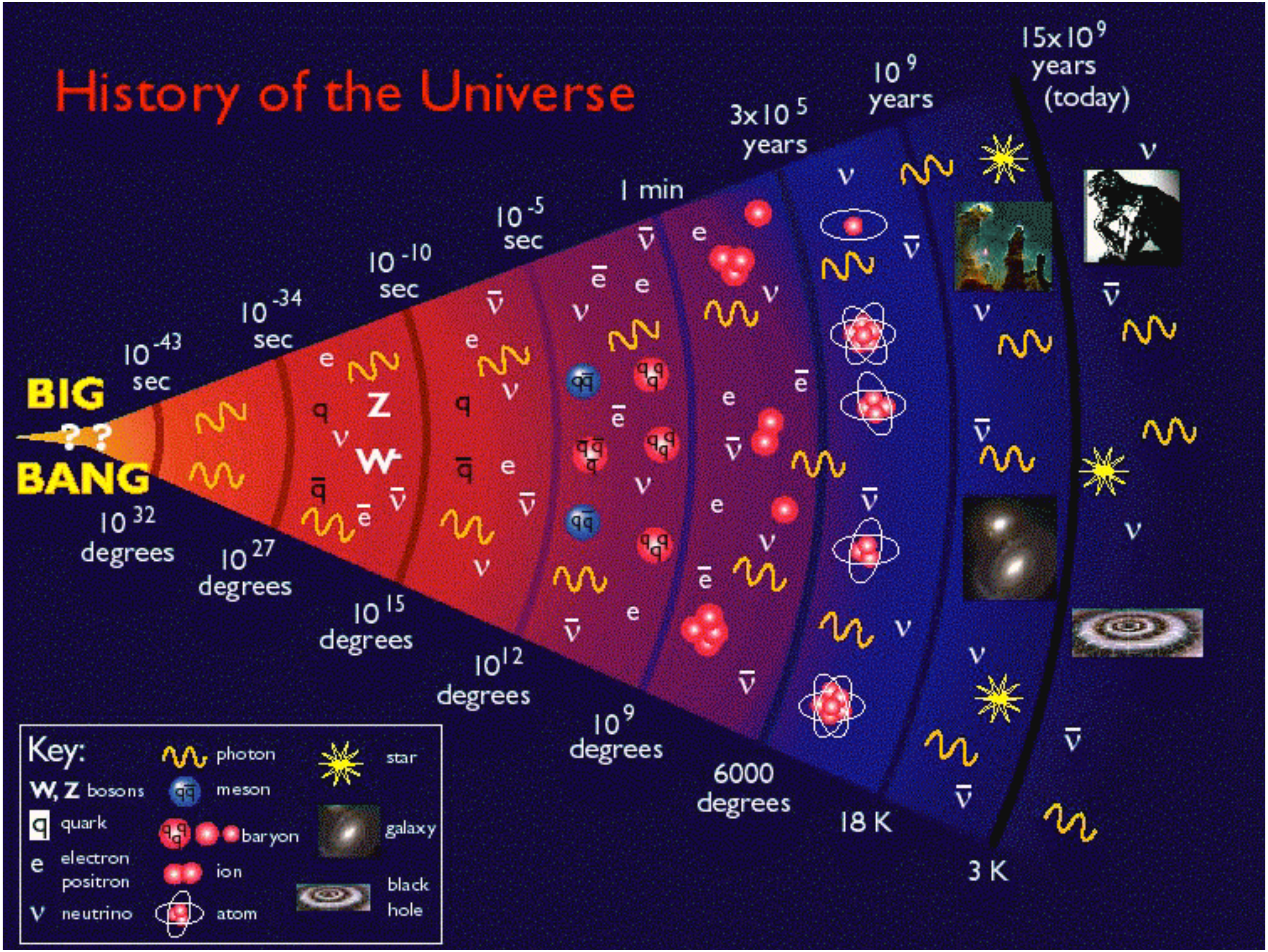
Time, size, density, energy, temperature during the Big Bang





Fermilab history of universe


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


History of the Universe
BIG BANG
10^-43 sec
10^-34 sec
10^-10 sec
10^-5 sec
1 min
3x10^5 years
10^9 years
15x10^9 years (today)
10^32 degrees
10^27 degrees
10^15 degrees
10^12 degrees
10^9 degrees
6000 degrees
18 K
3 K
Key:
photon
star
W, Z bosons
meson
quark
baryon
galaxy
electron positron
ion
neutrino
atom
black hole