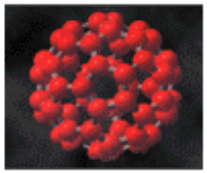
High Energy Particle Physics at the University of Tennessee

Stefan M. Spanier

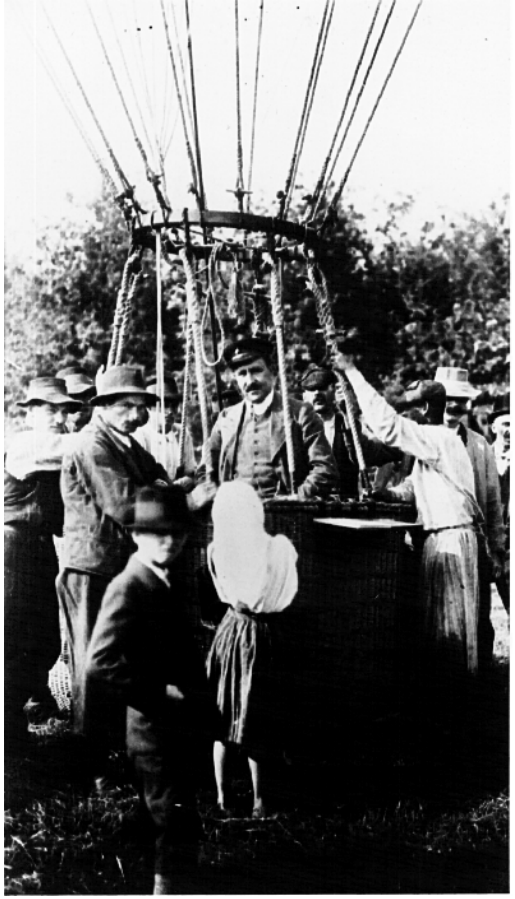


The University of Tennessee
Department of
Physics & Astronomy

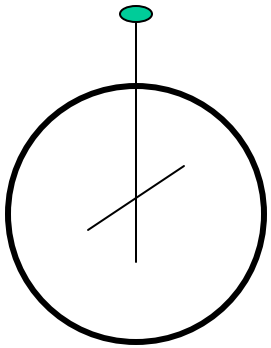
• Cosmic Rays - Particle Physics: The Beginnings

- 1785 - Coulomb notices that a charged body left in air gradually loses its charge.
- 1905 - Rutherford concludes radioactivity in the earth is responsible.
- 1912 - Victor Hess reaches 5350 m altitude in a hydrogen filled balloon and shows conclusively that the rate of discharge increases significantly with height. He concludes that there is an extraterrestrial source of radiation.

(receives Nobel prize 1936)



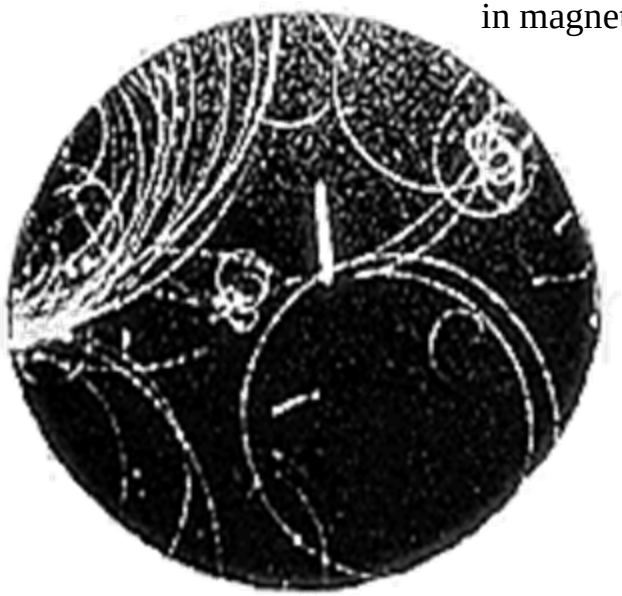
Electrometer:



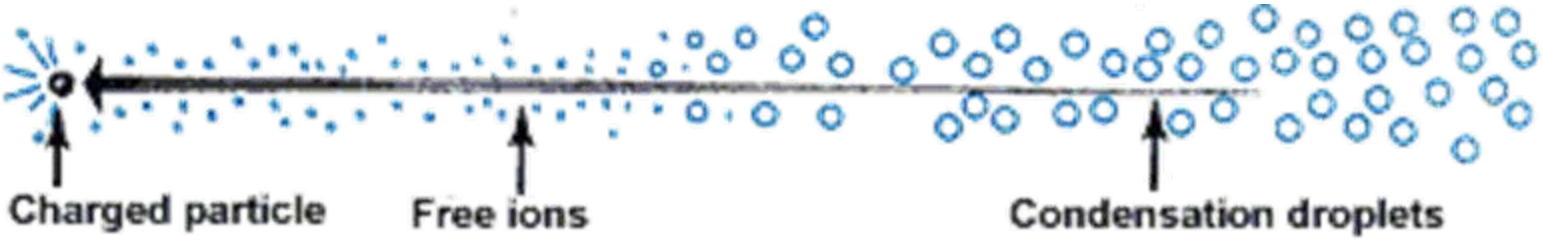
- Cloud Chamber as Particle Detectors

Chamber filled with supersaturated vapor (water)

in magnetic field



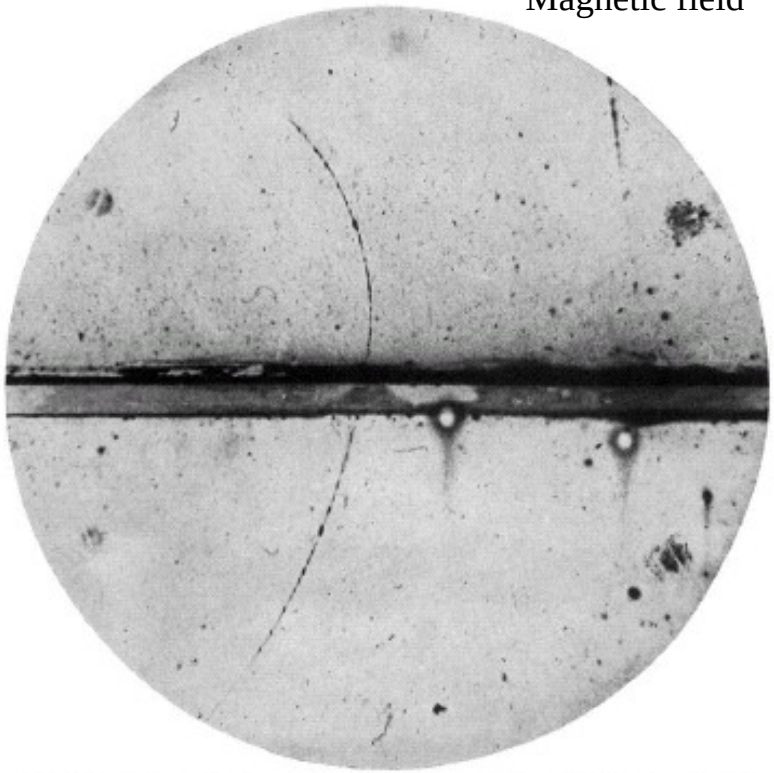
Expand and illuminate to take photograph



• The positive electron - First Discovery of Anti-Particles

1932 C.D.Anderson (Caltech)

Magnetic field



} *6 mm of lead*

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Fits into theory: P.A.M Dirac

relativistic wave equation for electrons predicts the existence of particles with charge opposite to electrons but same mass.

➔ Equation is invariant under C-parity transformation (fundamental symmetry)

$$C\, e^- = e^+$$

➔ Other important symmetry is parity P: $P\,\vec{r} = -\vec{r}$

How does it get produced ?

- Particle detection

Detection of elementary particles is based on their interaction with matter.

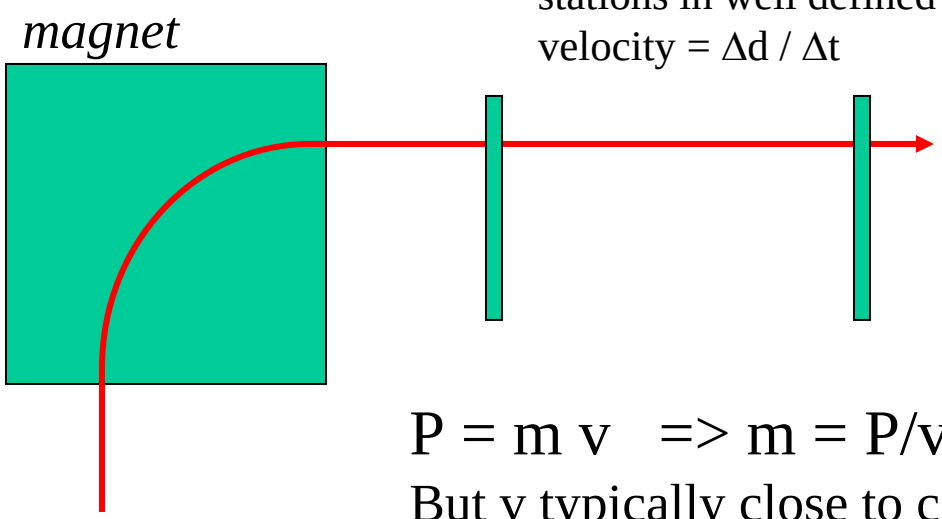
1937 Neddermeyer, Anderson find a heavy particle, but not as heavy as the proton in cosmic rays → the muon

→ check the energy loss of the particle in a metal plate and its momentum (curvature) in magnetic field

Another idea of resolving a particles mass:

Curvature ~ momentum P

Measure time of flight, Δt, through two stations in well defined distance Δd
velocity = $\Delta d / \Delta t$



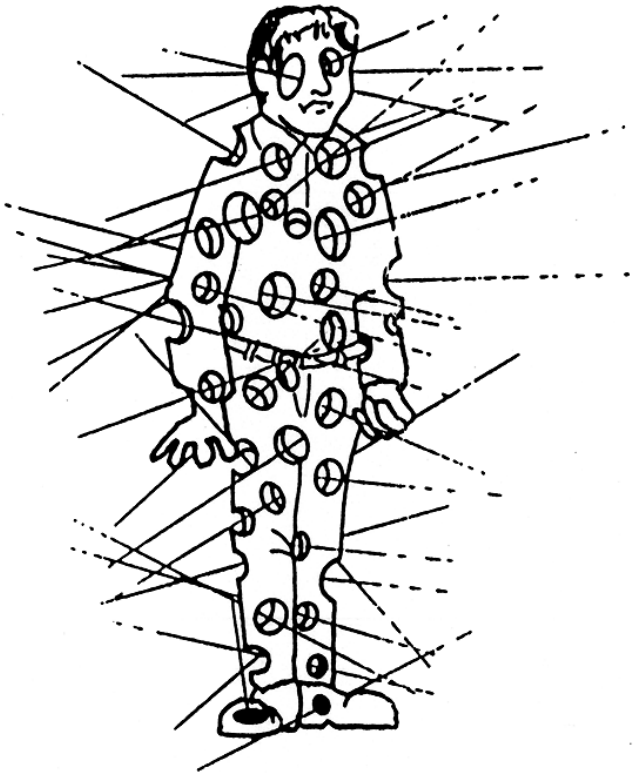
$P = m\,v \quad \Rightarrow m = P/v$

But v typically close to c, speed of light

therefore $m = m_0\,\gamma$, m_0= rest mass

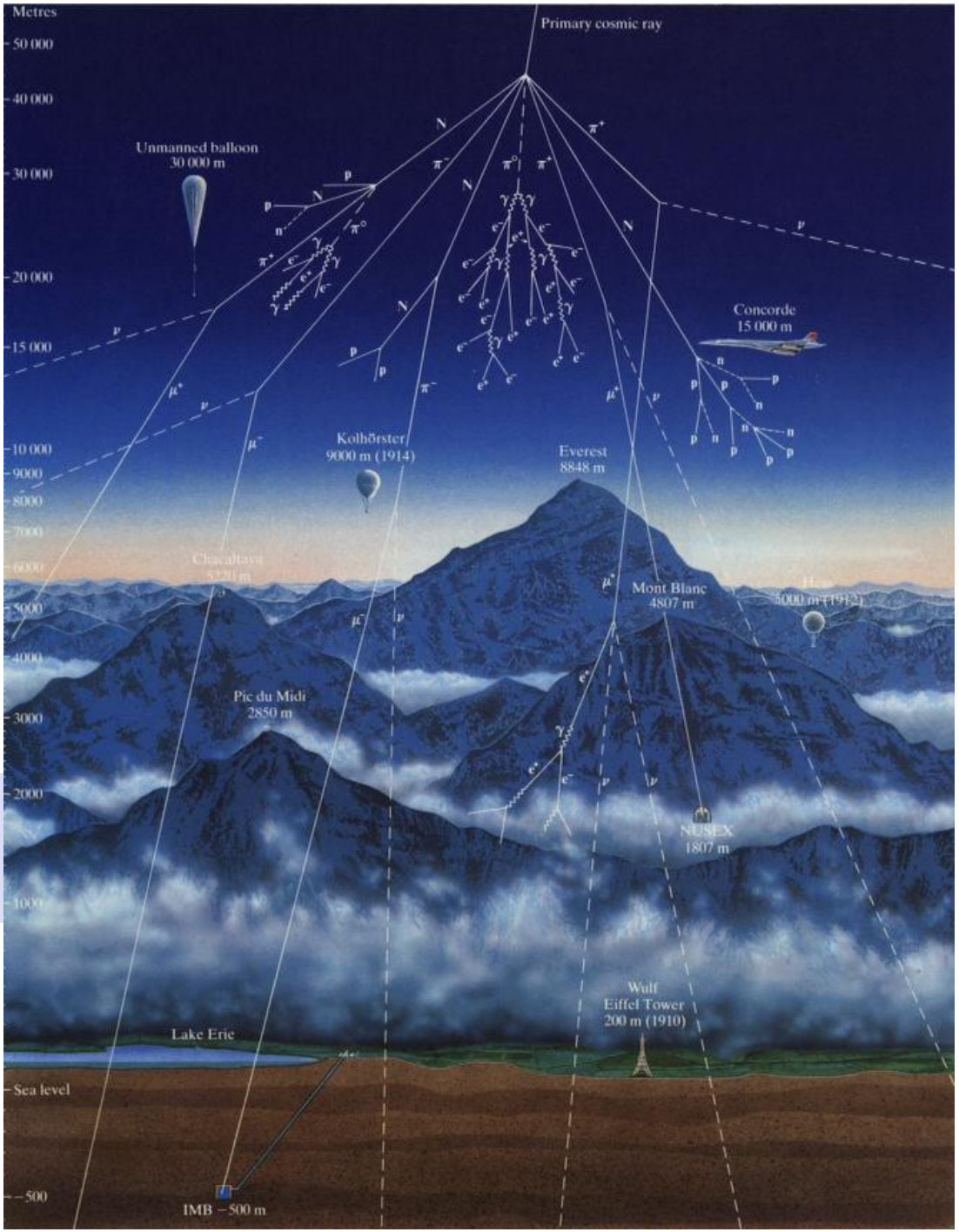
and for limited momentum range

- Cosmic ray laboratory



Cosmic Rays continually bombard the Earth. In fact, a large amount of cosmic rays will pass through a person every hour!

Cosmic rays are very energetic, but not sufficiently reliable and their rates are low !



• Why reliable energy ? Resolution of smaller Dimensions

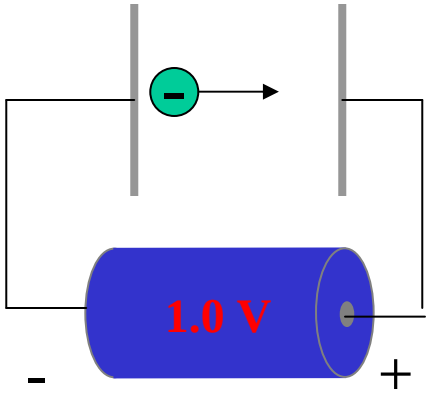
Wavelength ≈ dimension to be resolved

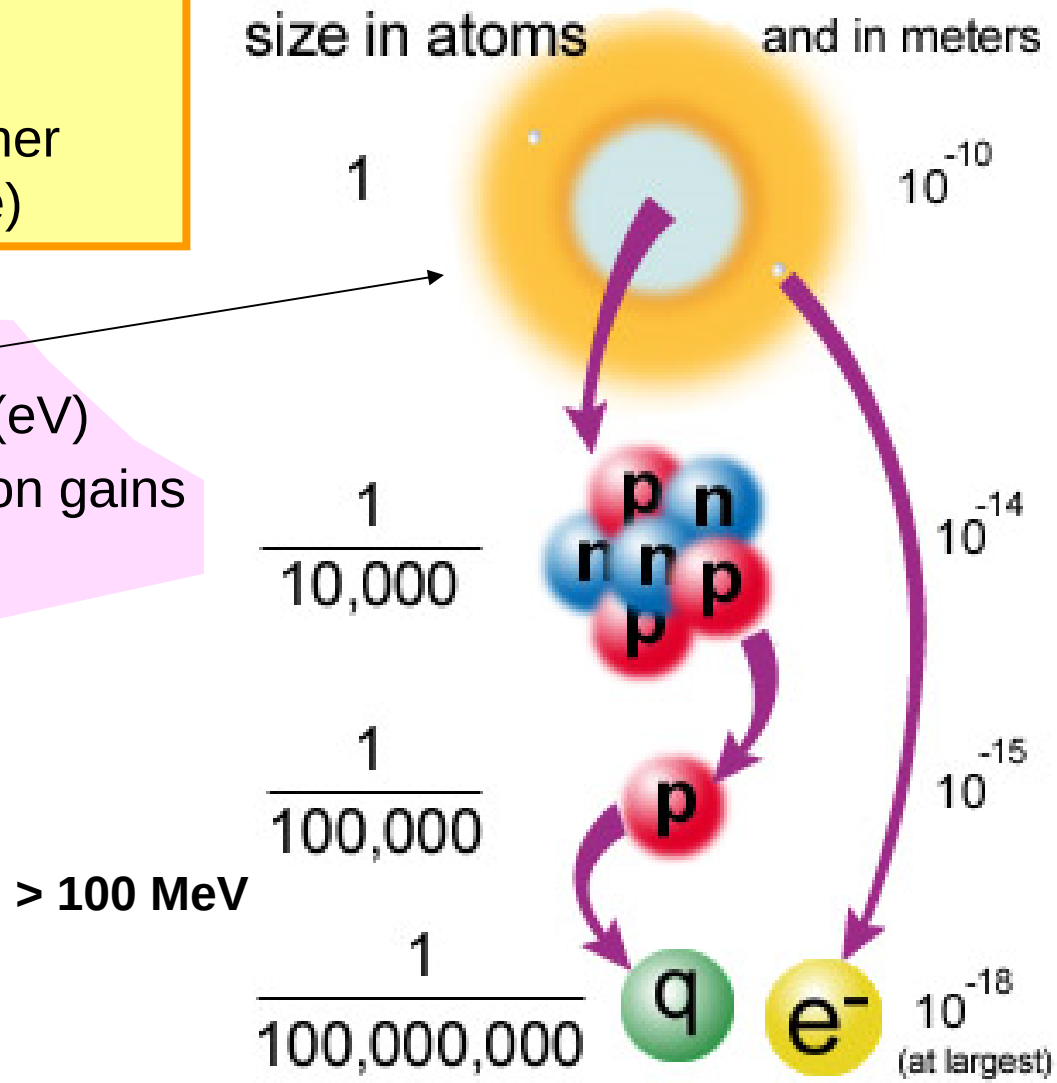
Wavelength ∝ 1/Energy

➔The smaller dimension the higher the energy of the light (particle)

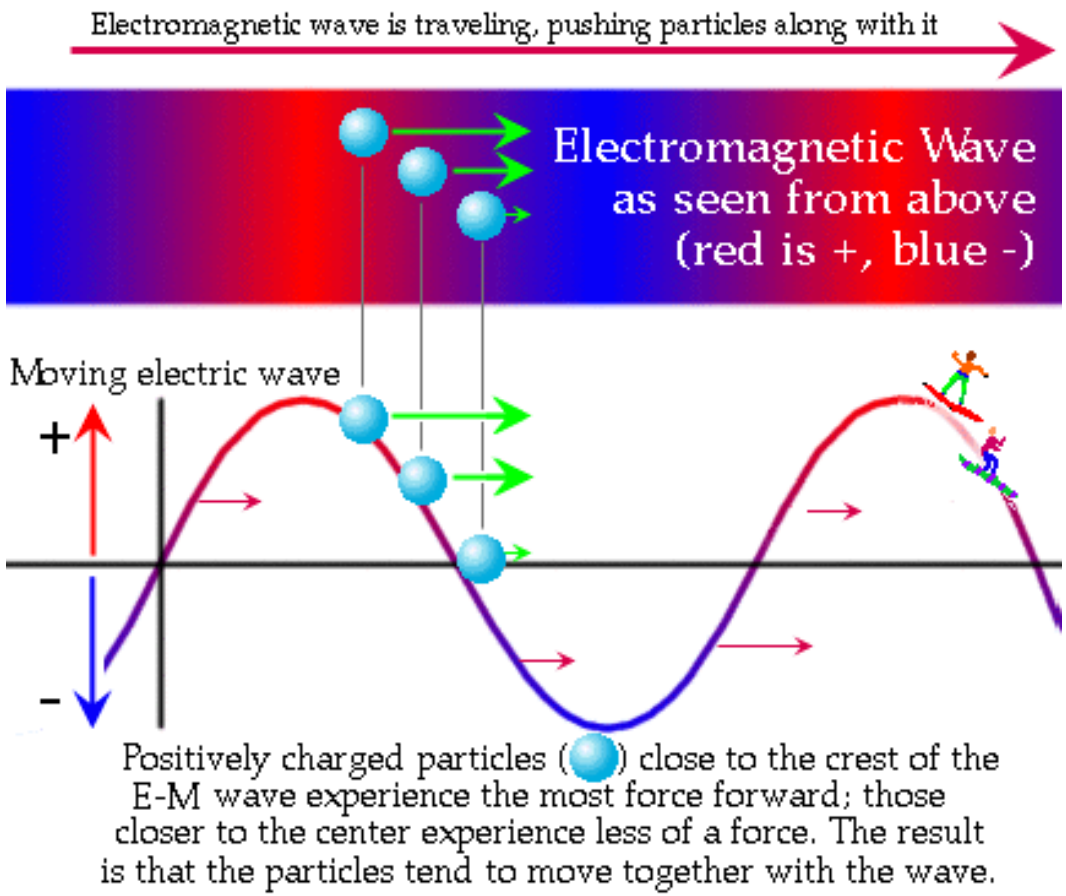
Energy ≈ 10 kilo electron Volt (eV)

1eV = kinetic energy an electron gains in a electric field of 1 Volt

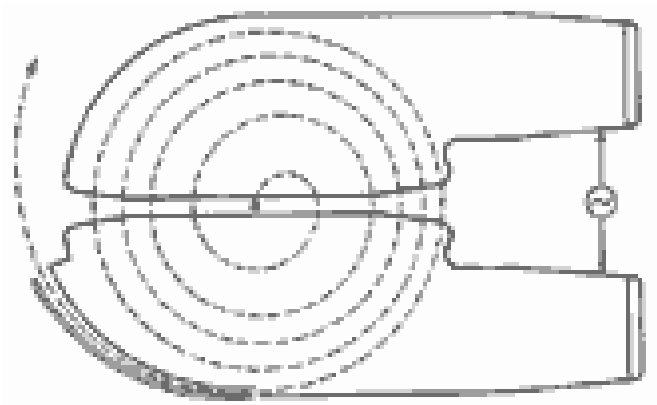




- Accelerators

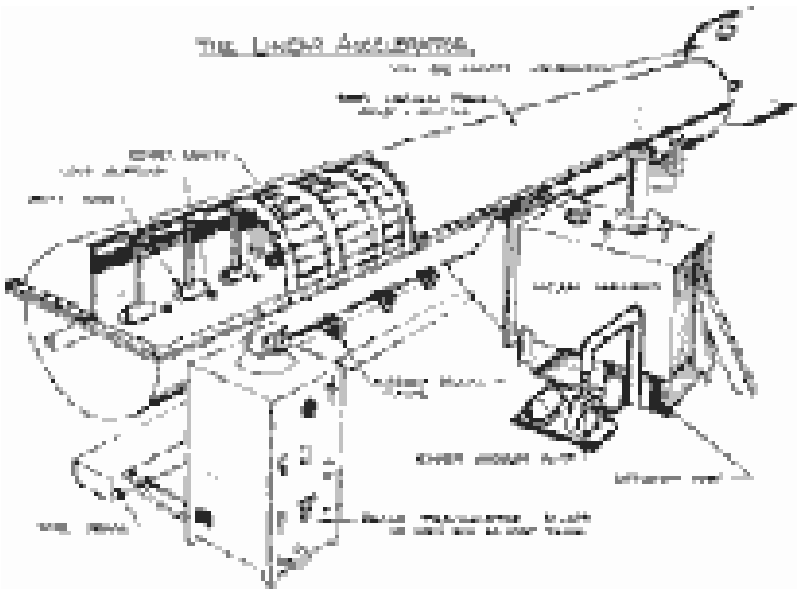


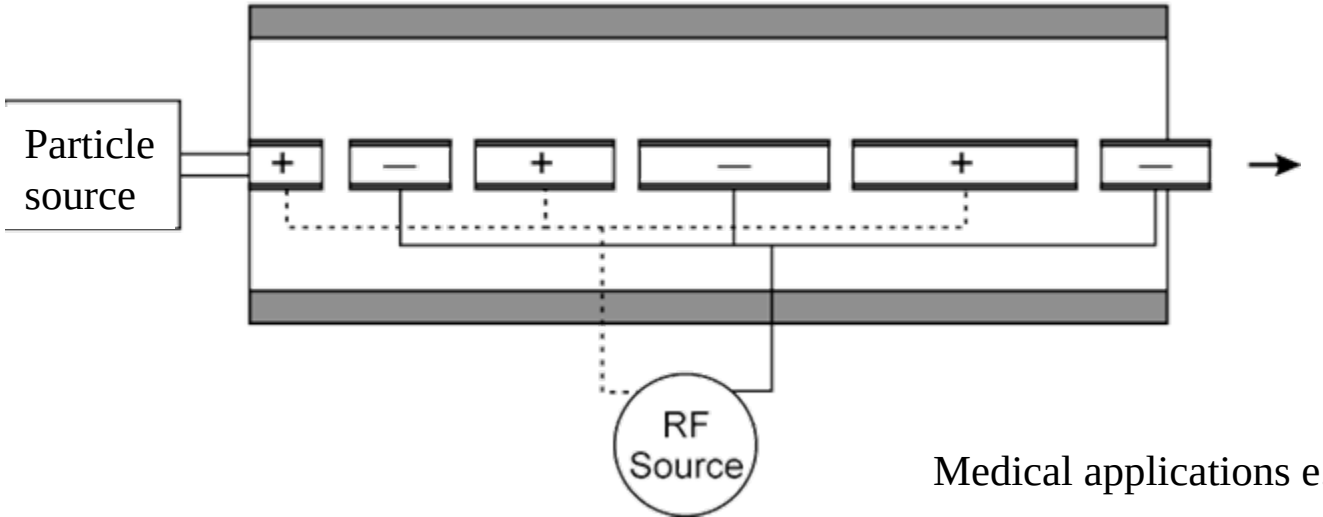
Synchrocyclotron: let particles run in a circle within a magnetic field and give them kicks with the electrical field at the same place in the right moment



But: Synchrotron Radiation ➔ Beam Energy Loss $\propto$ E^4

- Linear Accelerators





Medical applications e.g. tumor treatment.

- Stanford Linear Accelerator Center

San Francisco

Stanford
Palo Alto

- **2 mile long accelerator (can be seen from moon)**
- **Final energy of 45 GeV for electrons/positrons**
- **Used to fill PeP II B-factory to measure CP violation**

- What have we learned → Standard Model

fundamental ?

particles | *anti-particles*

Quarks

B=1/3

Baryon number

Charge

+ 2/3

- 1/3

u	c	t
d	s	b

Leptons

L=1

Lepton number

-1

0

e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

mass

C

$\bar{d}$	$\bar{s}$	$\bar{b}$
$\bar{u}$	$\bar{c}$	$\bar{t}$

Charge

+ 1/3

- 2/3

B=-1/3

$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
e^+	μ^+	τ^+

0

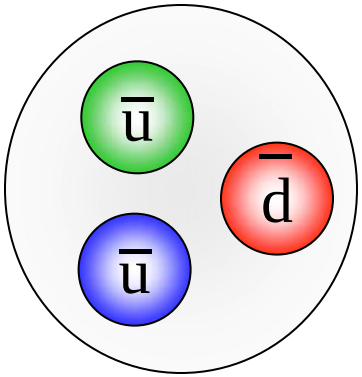
+1

L=-1

Standard Model

C: Charge conjugation symmetry

anti-proton $\bar{p}$:



$C\,\bar{p} = p$

In accelerators (cosmic rays) particles and anti-particles are created and annihilate in pairs !

- What have we learned → Standard Model

4 fundamental forces:

Electric	Maxwell	electroweak	*Photons*	*m=0*
Magnetic				
Weak			*W^+, W^-, Z^0*	*m= 80, 90 GeV*
Strong			*Gluons*	*m = 0*
Gravity			*Gravitons*	*?*

>100 GeV
Standard Model

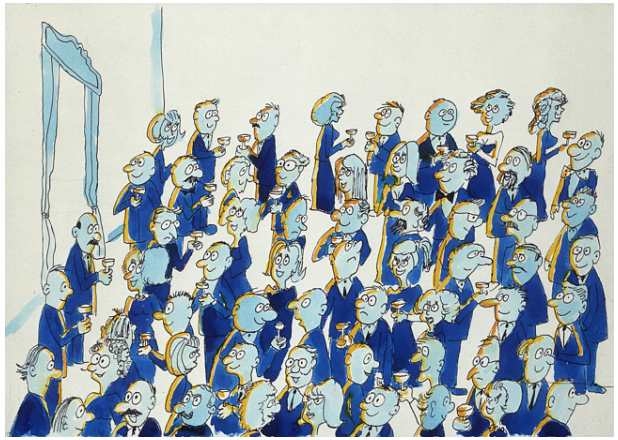
today's accelerators just about …

~ 10^{15} GeV ?
GUT scale
coupling constants unify

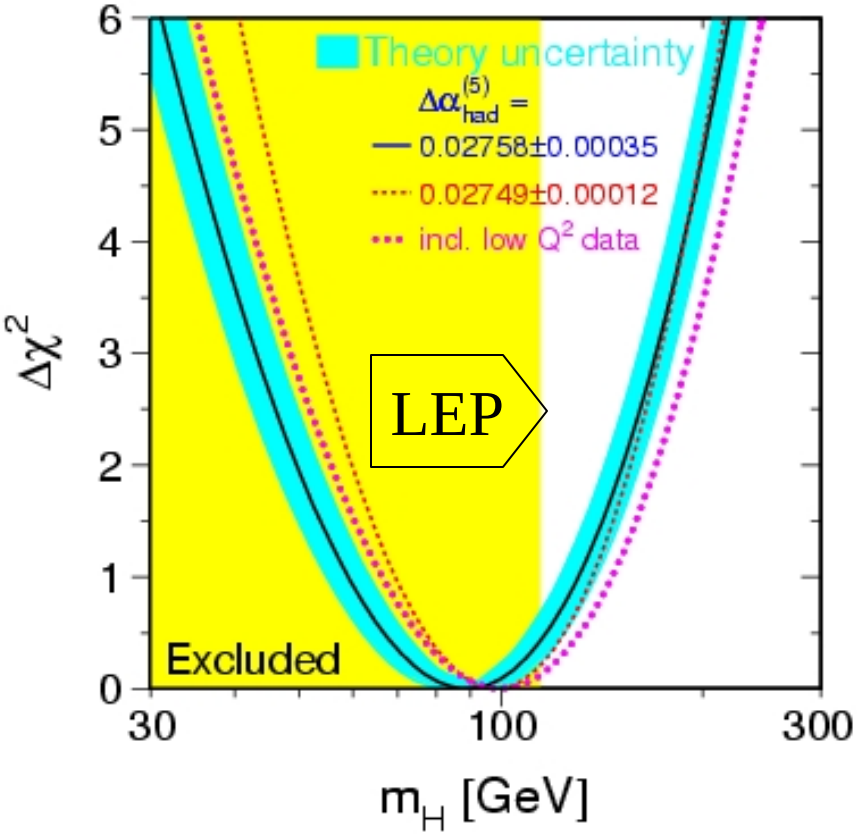
Planck energy
~ 10^{19} GeV

The particle masses …

- Standard Model Symmetry Breaking ?

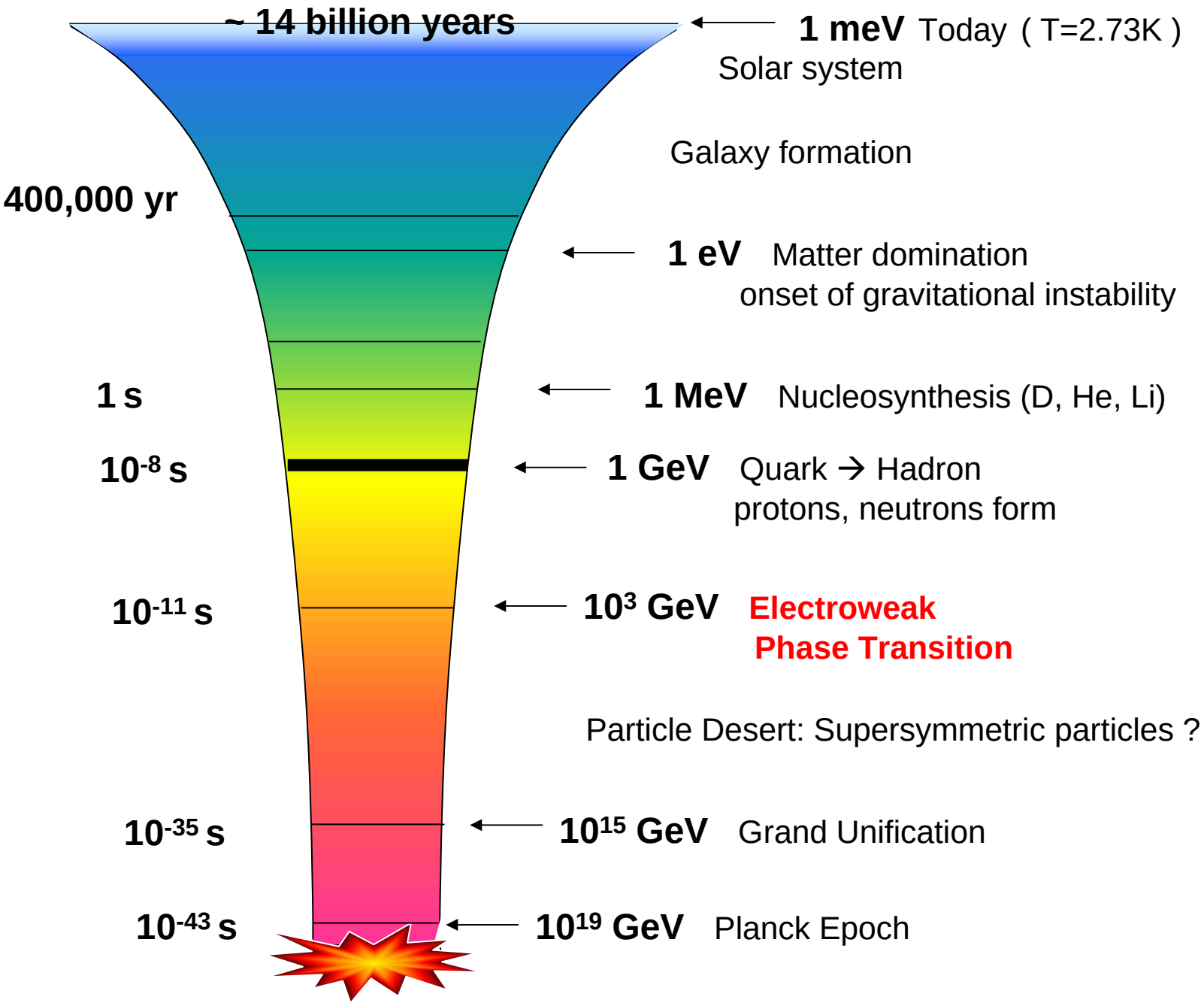


Higgs Mass = 100 .. 300 GeV ?

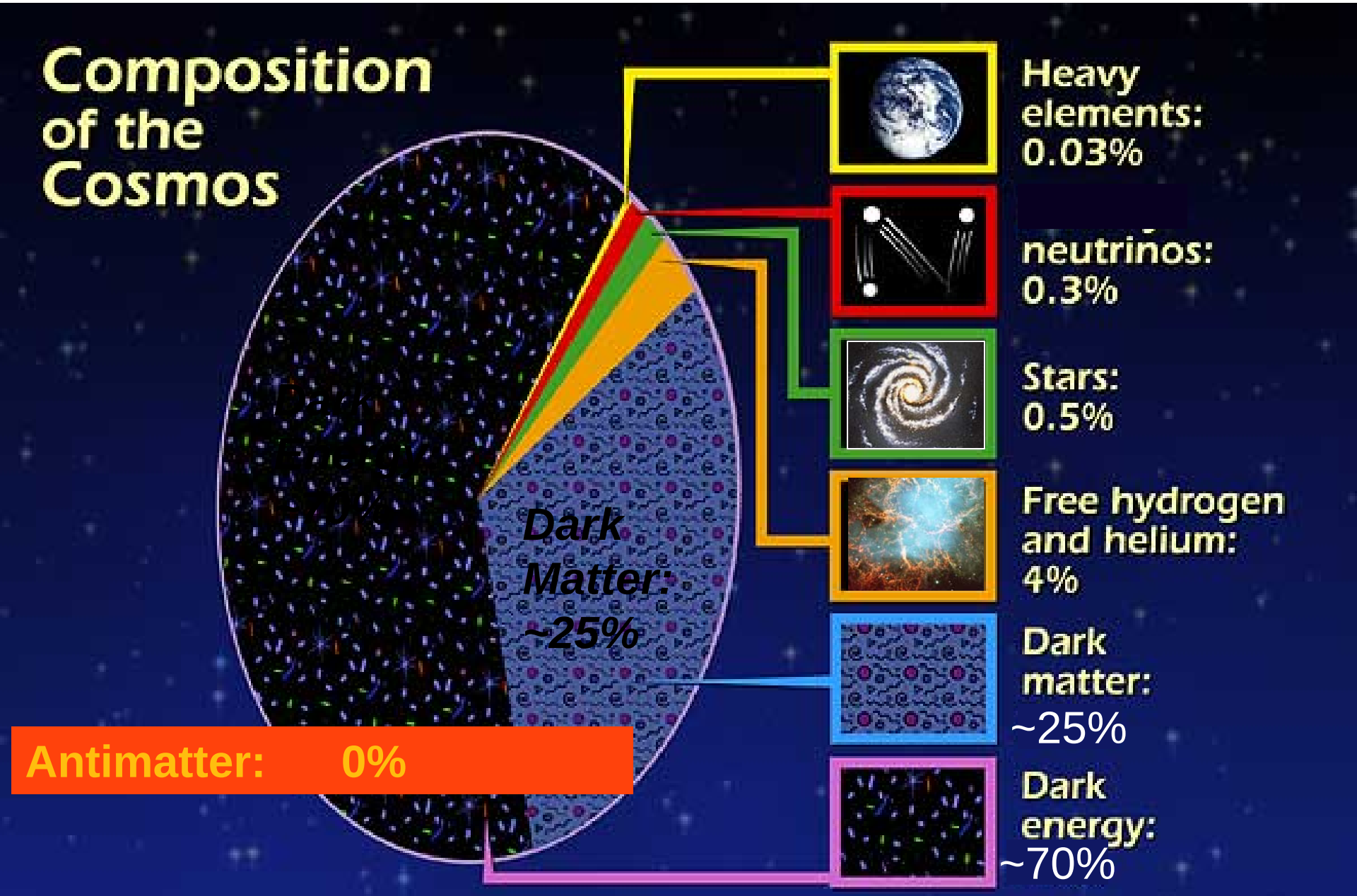


rticle generation

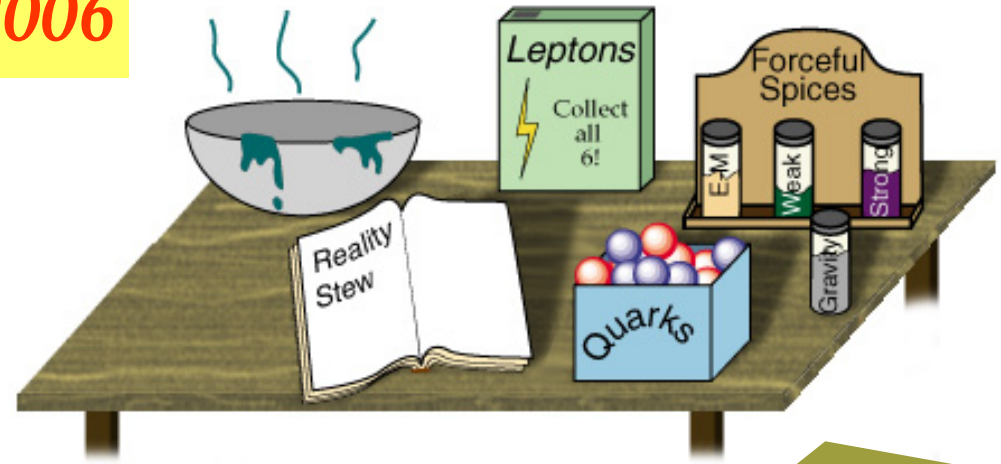
- Evolution of the Universe ?



• Energy Budget of the Universe



The Standard Model in 2006



The *Standard Model* is not complete; there are still many unanswered questions, such as:

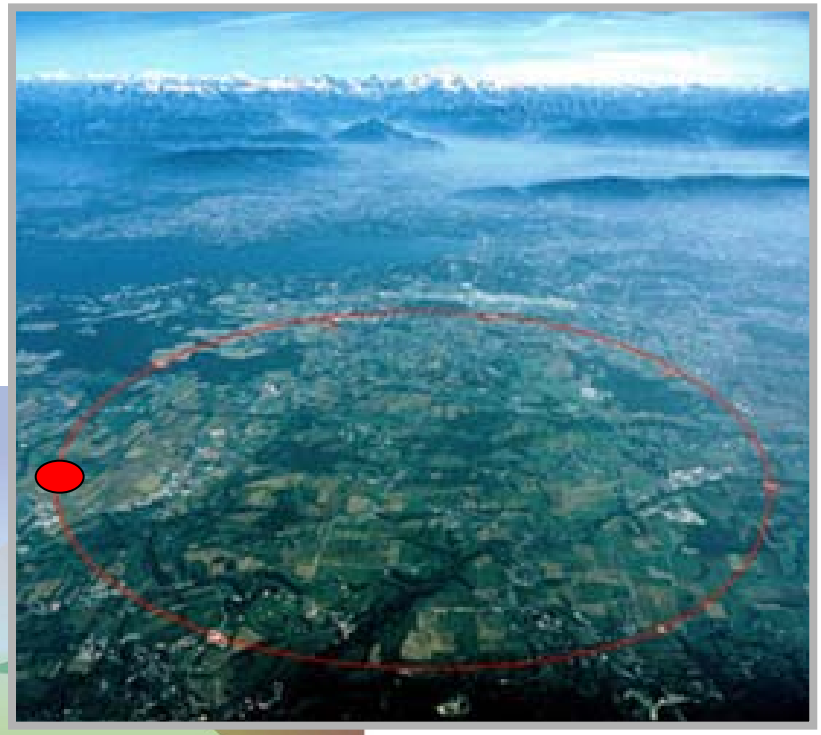
- **Why can't the Standard Model predict a particle's mass ?**
- **Are quarks and leptons actually fundamental ?**
- **Why are there exactly three generations of quarks and leptons?**
- **Why do we observe matter and almost no anti-matter in the Universe ?**
- **What is this "dark matter“ ?**
- **How does gravity fit into all of this?**

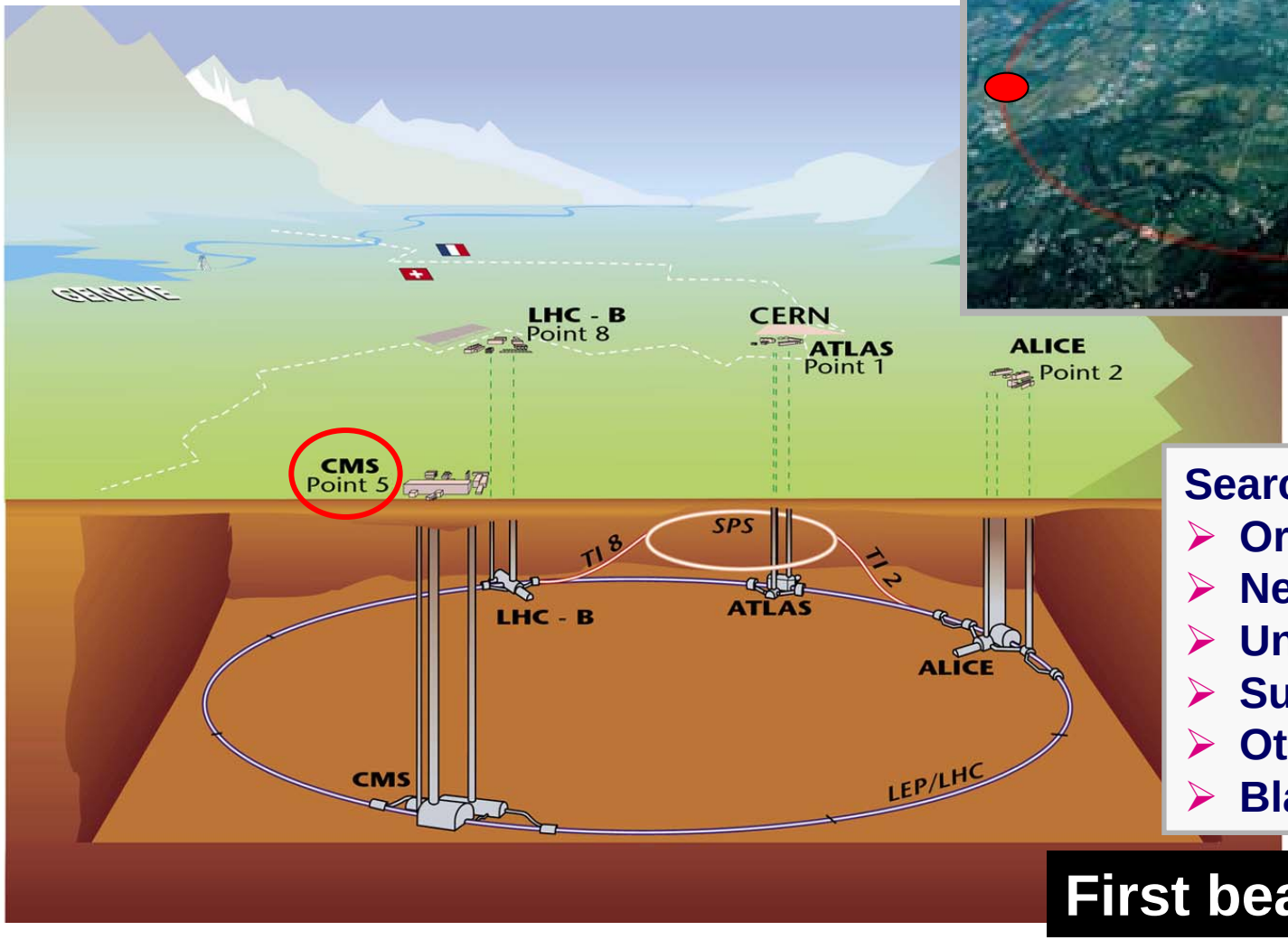
....

LHC *is the tool for a fundamental breakthrough*

• The LHC Project

- Proton-proton collider (14 TeV energy)
- 27 km in circumference, 50-175m deep
- between Jura mountains (France) and Lake Geneva (Switzerland)





Search for

- **Origin of Mass**
- **New forces**
- **Universe origin**
- **Supersymmetry**
- **Other new particles**
- **Black Holes**

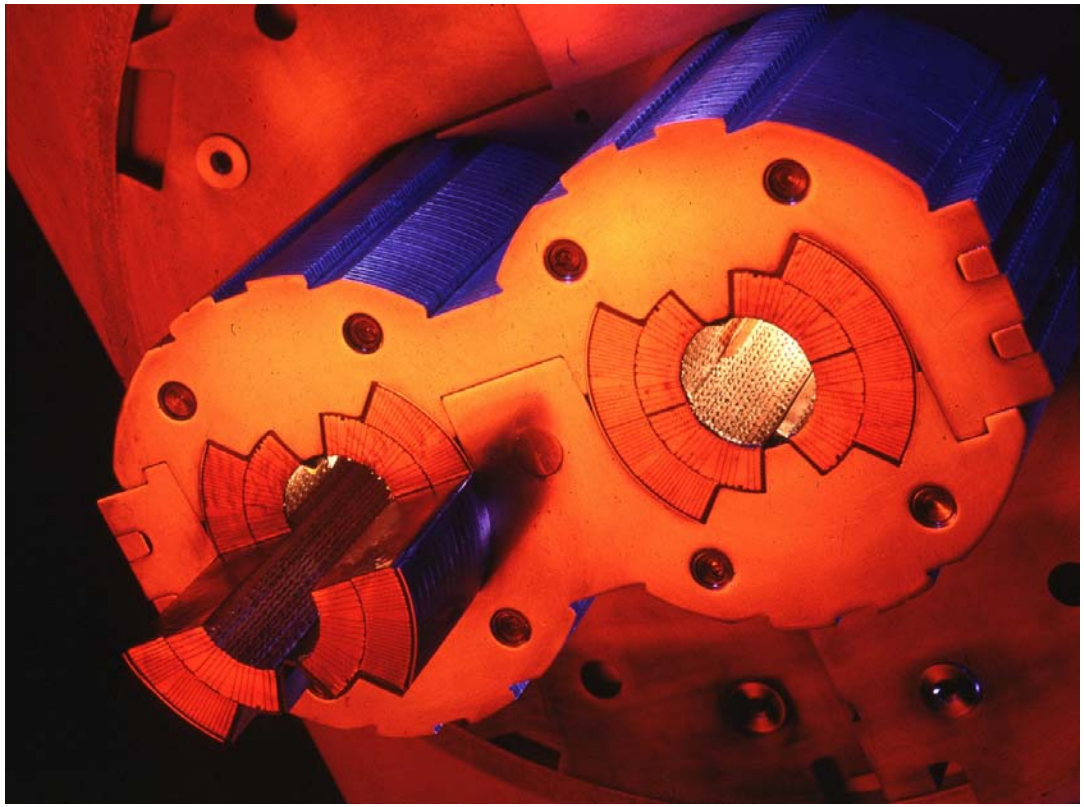
First beams fall 2007 !

- **The LHC**

> 2808 proton bunches/ring
> ~10^{11} protons/bunch
> Beam current: 584 mA

> Collision every 25 ns
> Beam stays for 10 hours after fill (30min energy ramp)

Accelerator tunnel



Energy stored/beam: 360 MJ

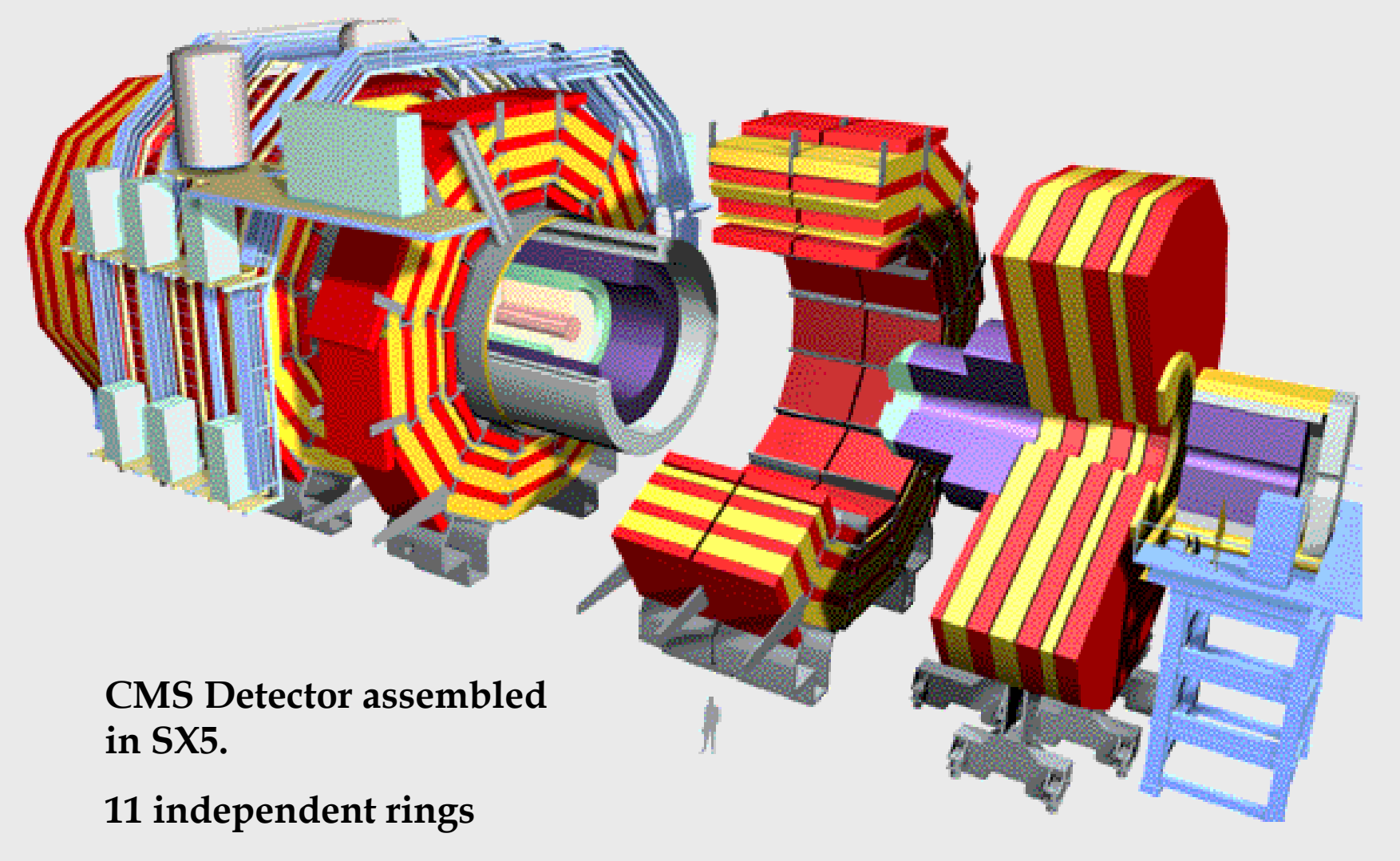
Superconducting magnets:
1232 dipole magnets (bending)
~500 quadrupole magnets (focus)

Energy stored in magnets: 700GJ

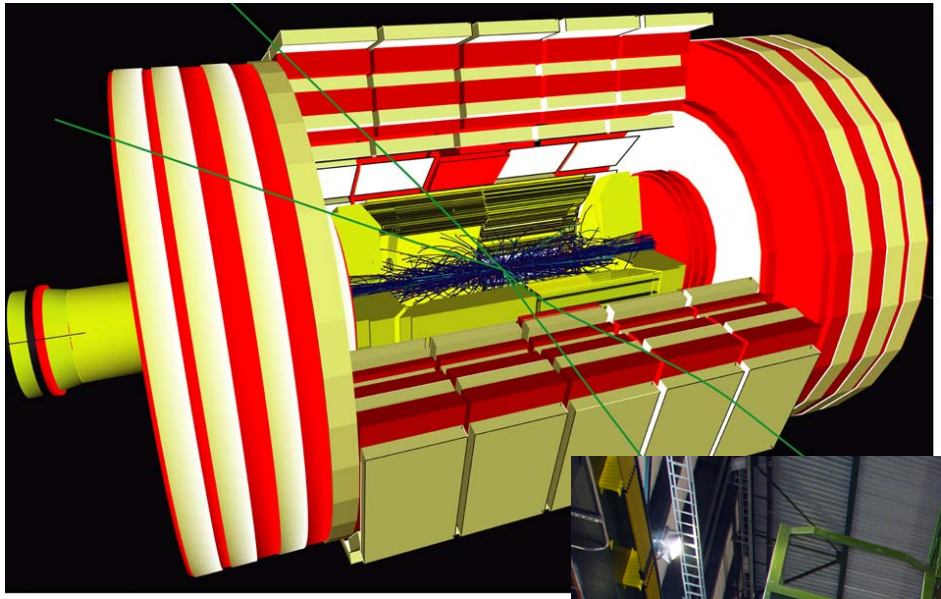
→ **Particle losses fatal !**

superconducting dipole magnet

- **The Compact Muon Solenoid (CMS) Detector**

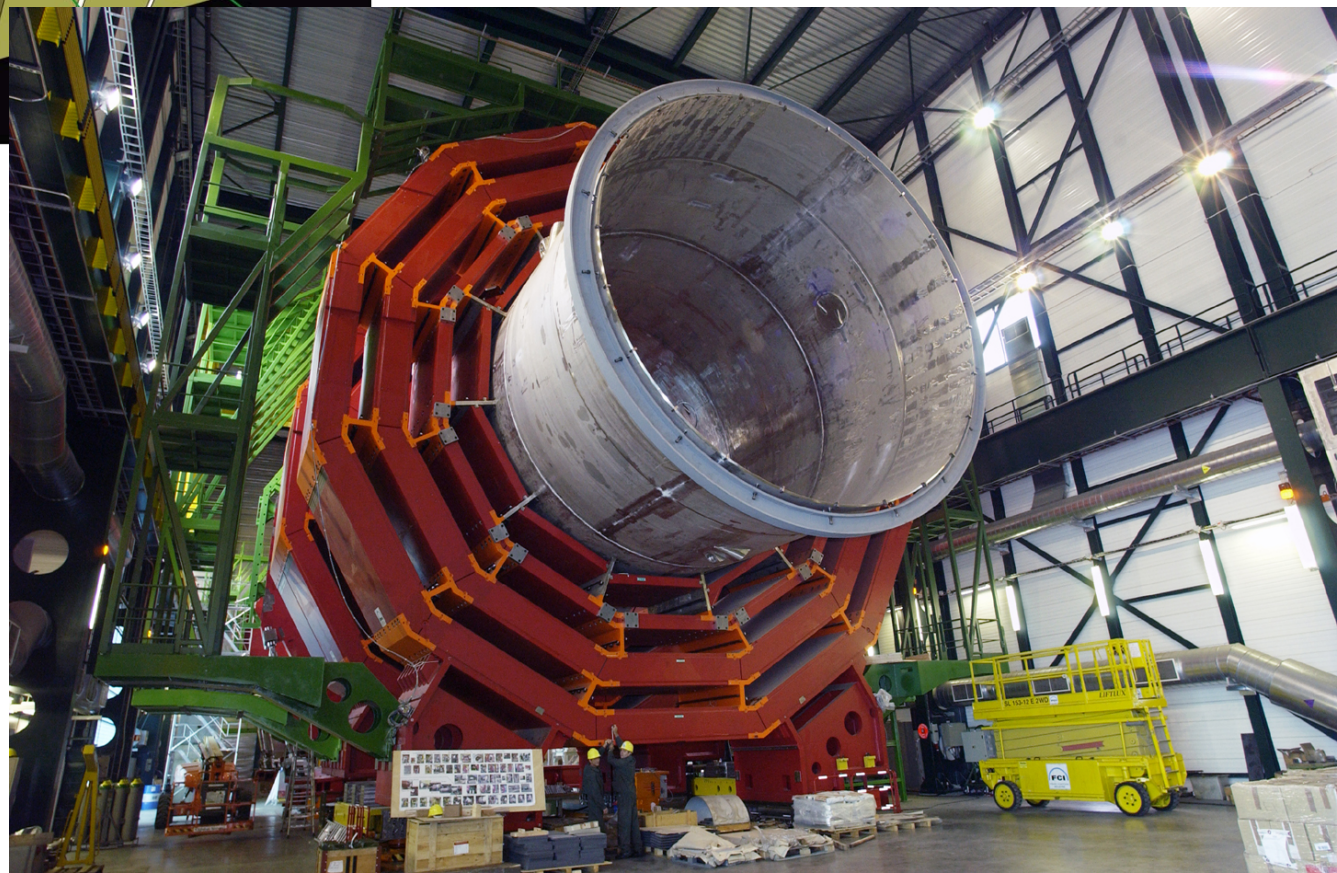


• The Compact Muon Solenoid (CMS) Detector



4 Tesla magnetic field

Solenoid Magnet Assembly

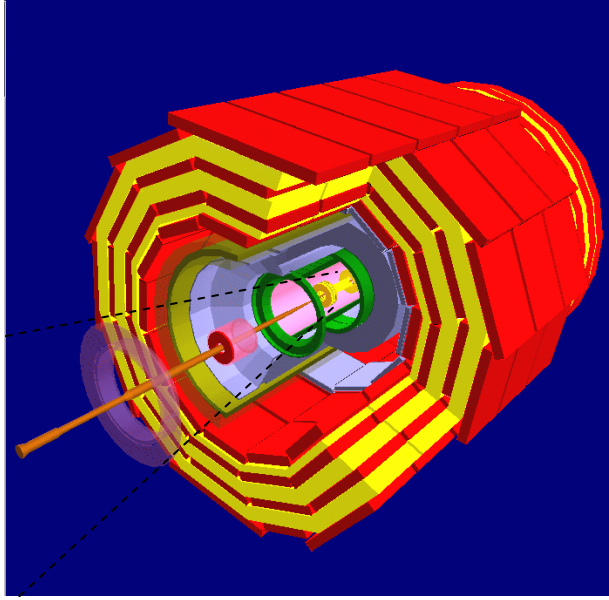


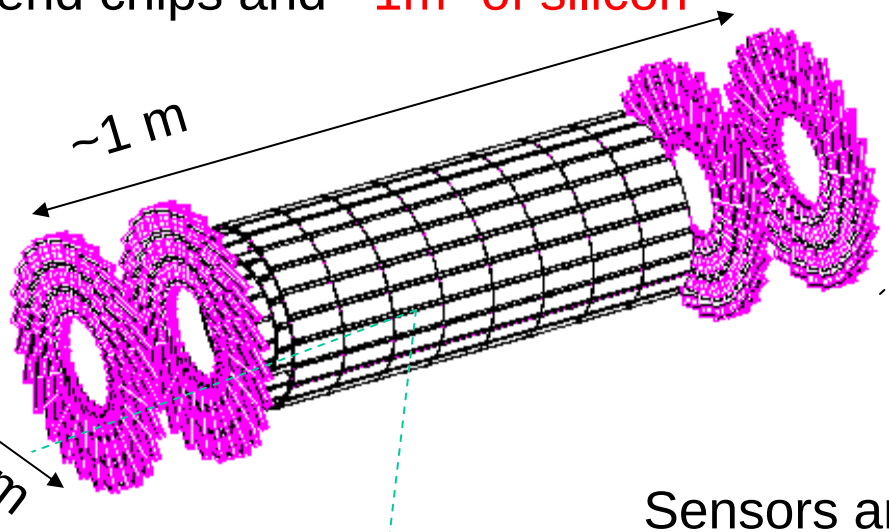
Higgs → 4 muons

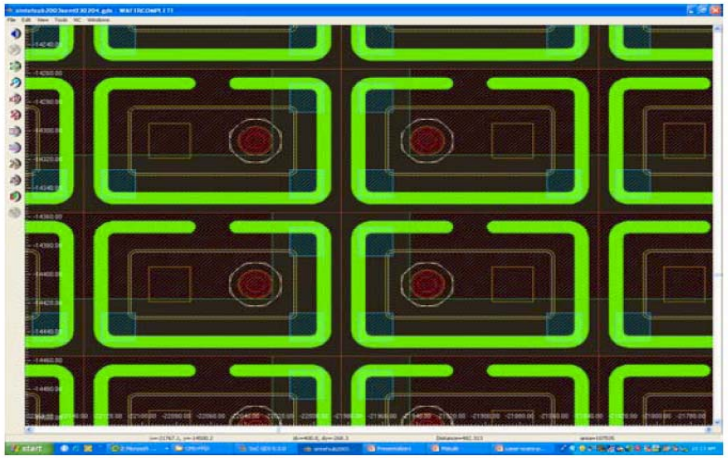
USCMS
THE COMPACT MUON SOLENOID

• The CMS Pixel Detector

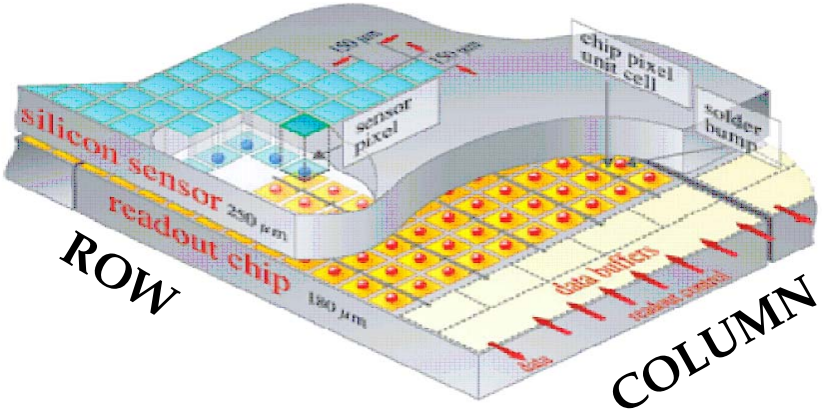
- 3-d tracking with about 66 million channels
- Barrel layers at radii = 4.3cm, 7.2cm and 11.0cm
- Pixel cell size = 100 µm x 150 µm
- ~15k front-end chips and ~1m^2 of silicon



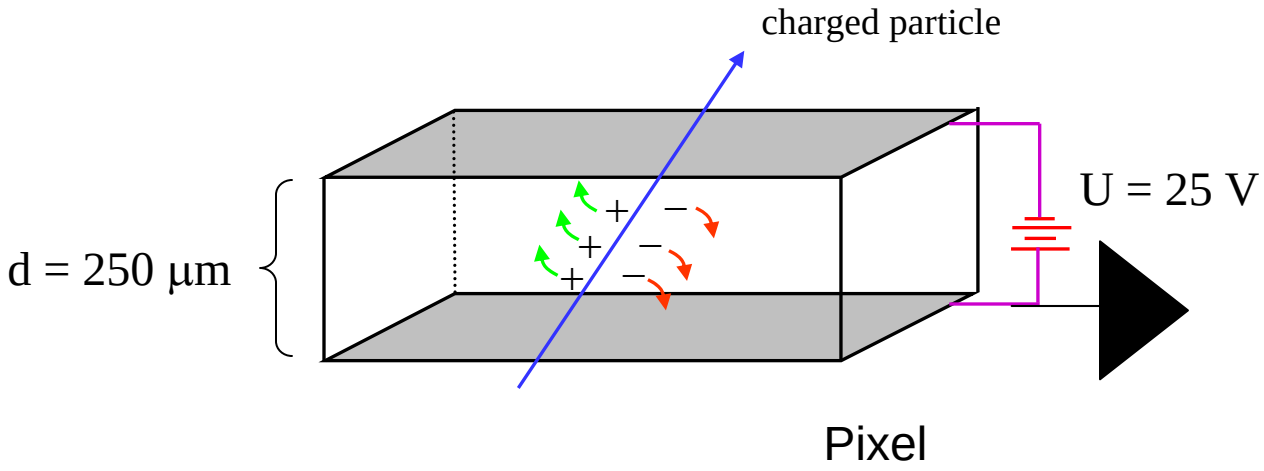




Sensors are bump-bonded to the readout chips



- **Silicon Detector**

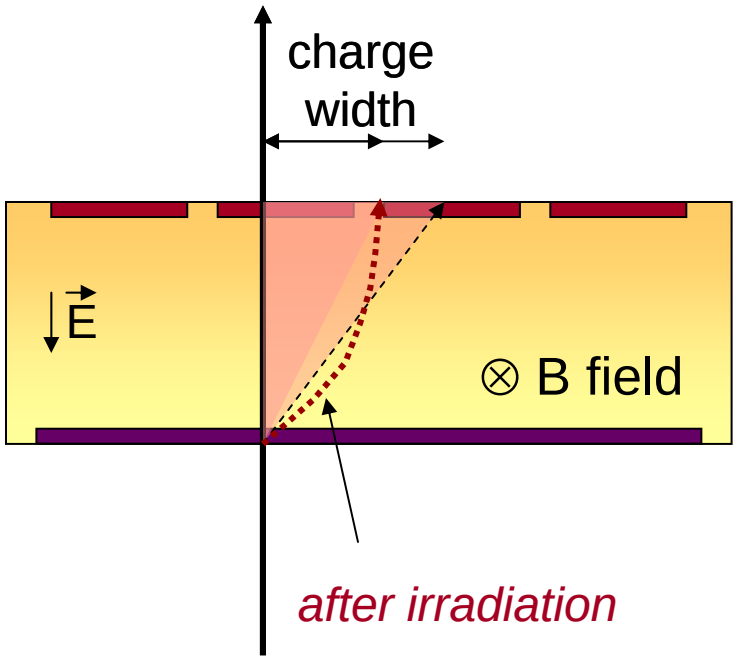


- Charged particle creates free electrons and holes in silicon while passing (deposits small fraction of its energy)
  → For minimum-ionizing particle ~ 20,000 electrons

- Silicon pixel (strip) detector works like a *semi-conductor diode* in reverse bias with large depletion zone (no free charges)
  → very large electric field E ~ 10^5V/m pulls charges
  → very short collection time (few ns)

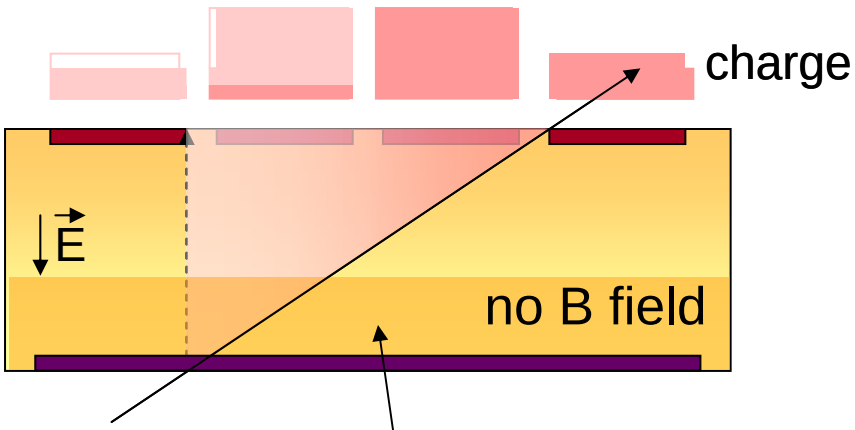
• The CMS Pixel Detector - Radiation Effects

r-ϕ plane



Irradiation modifies
the electric field profile:
varying Lorentz deflection

r-z plane



Irradiation causes
charge carrier trapping

• The LHC Computing

- 1 billion proton-proton collision events per second in detector
- 100 events of interest/second recorded permanently (trigger/filter)

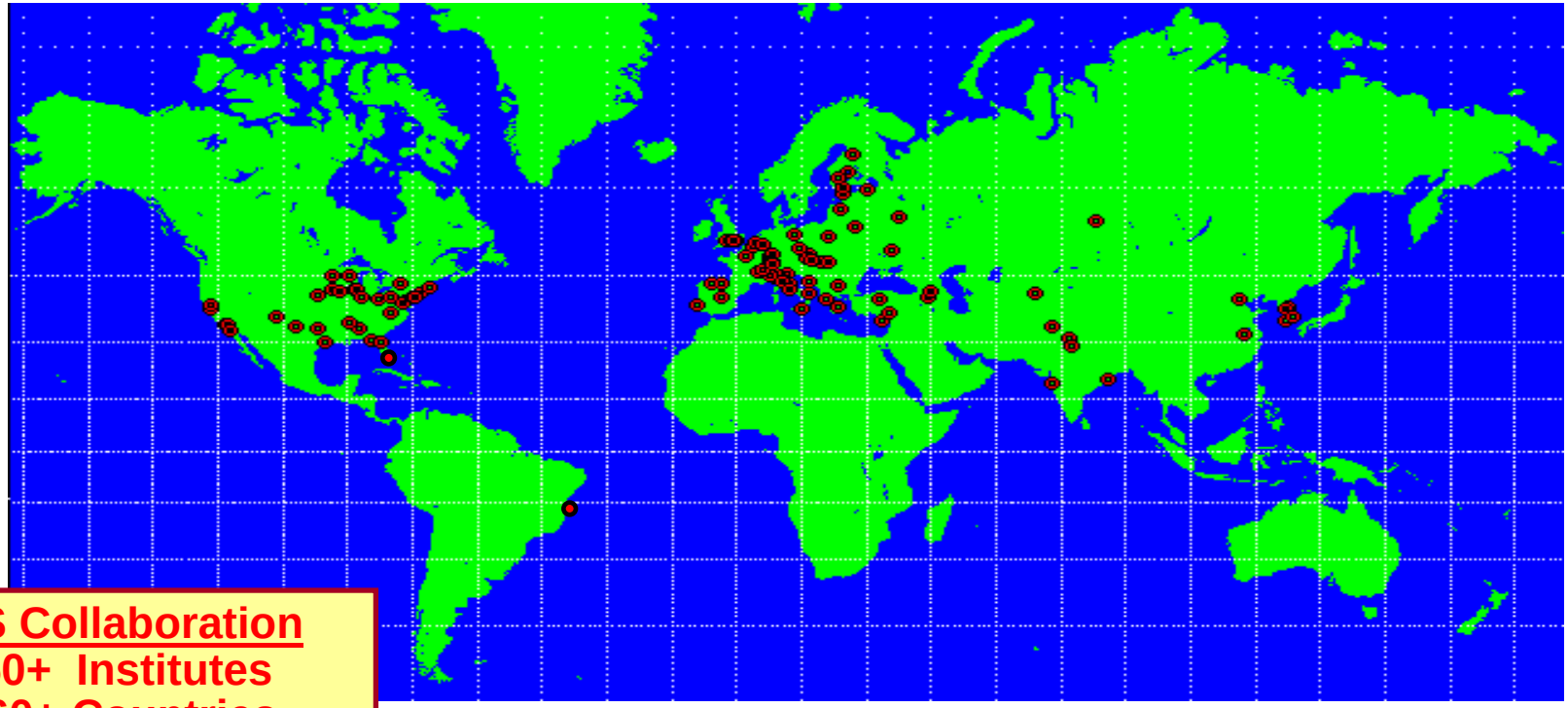
➔ 1 GByte/second

+ Raw data, processed data, simulated events

➔ 15 PetaBytes/ year (= 15 M GBytes/year = 20 M CDs)

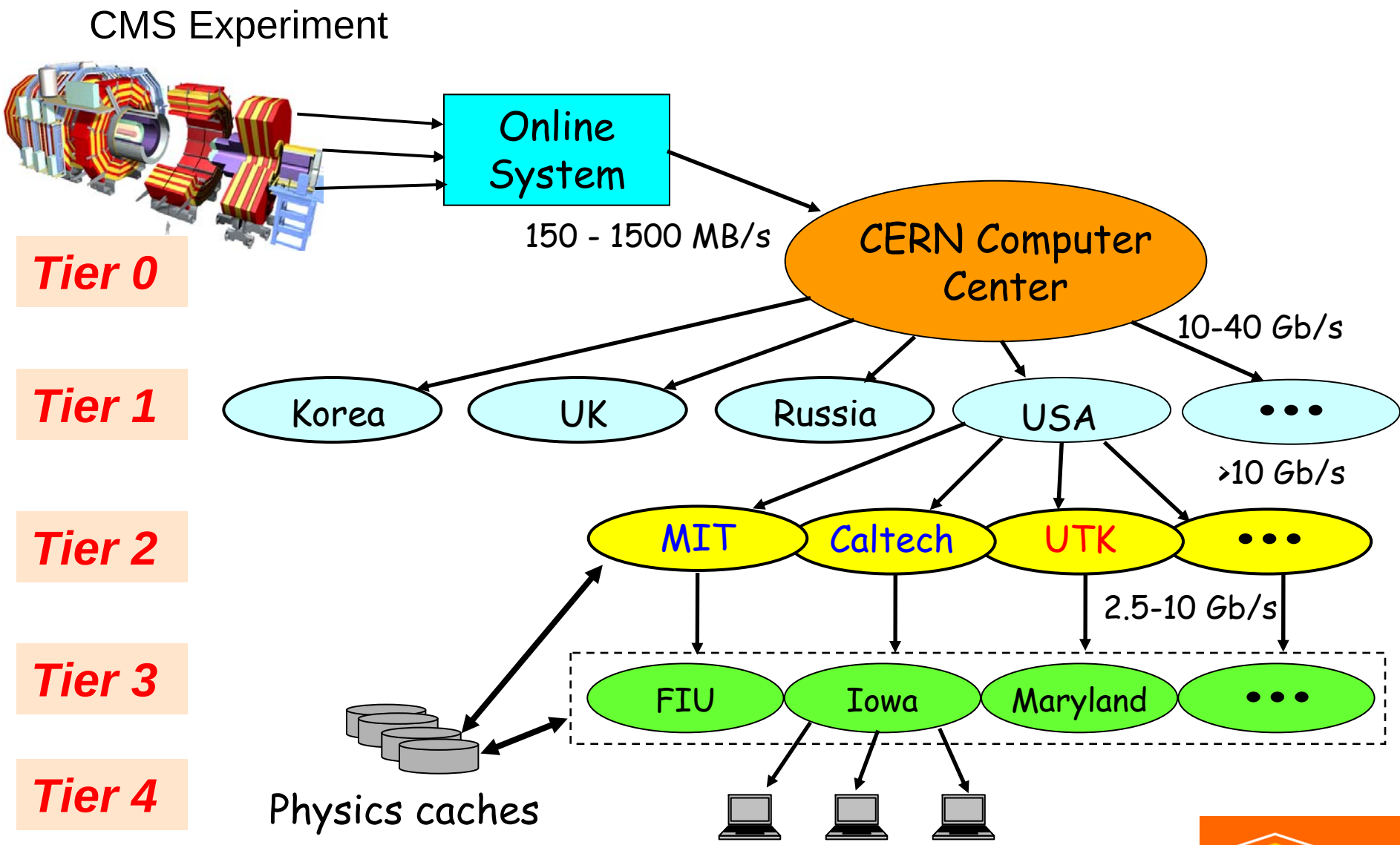
➔ computing power equivalent: ~ 100,000 standard PC processors.

• … needs **global** distribution of people & resources



CMS Collaboration
250+ Institutes
60+ Countries

- **The LHC Global Data GRID (2007+)**



…within the framework of the OpenScienceGrid (OSG)

Open Science Grid

• *Conclusion*

- High Energy Particle Physics (HEP) has answered many fundamental questions.
- In the energy regime below 100 GeV the picture appears complete
- but beyond this energy HEP opened many new questions

- LHC is the machine for a fundamental breakthroughs
- HEP is a challenging environment with many new technology developments to prepare for discoveries

We are involved in

- CP violation & Search for New Physics at BaBar, SLAC
- Readout and commissioning of pixel detector for CMS/LHC
- Beam radiation protection for the pixel detector at CMS
- Future radiation hard pixel detector development with PSI Switzerland
- GRID computing center at UT; R&D with UT's Computer Science Dpt.
- Search for new particles and interactions *beyond the Standard Model*