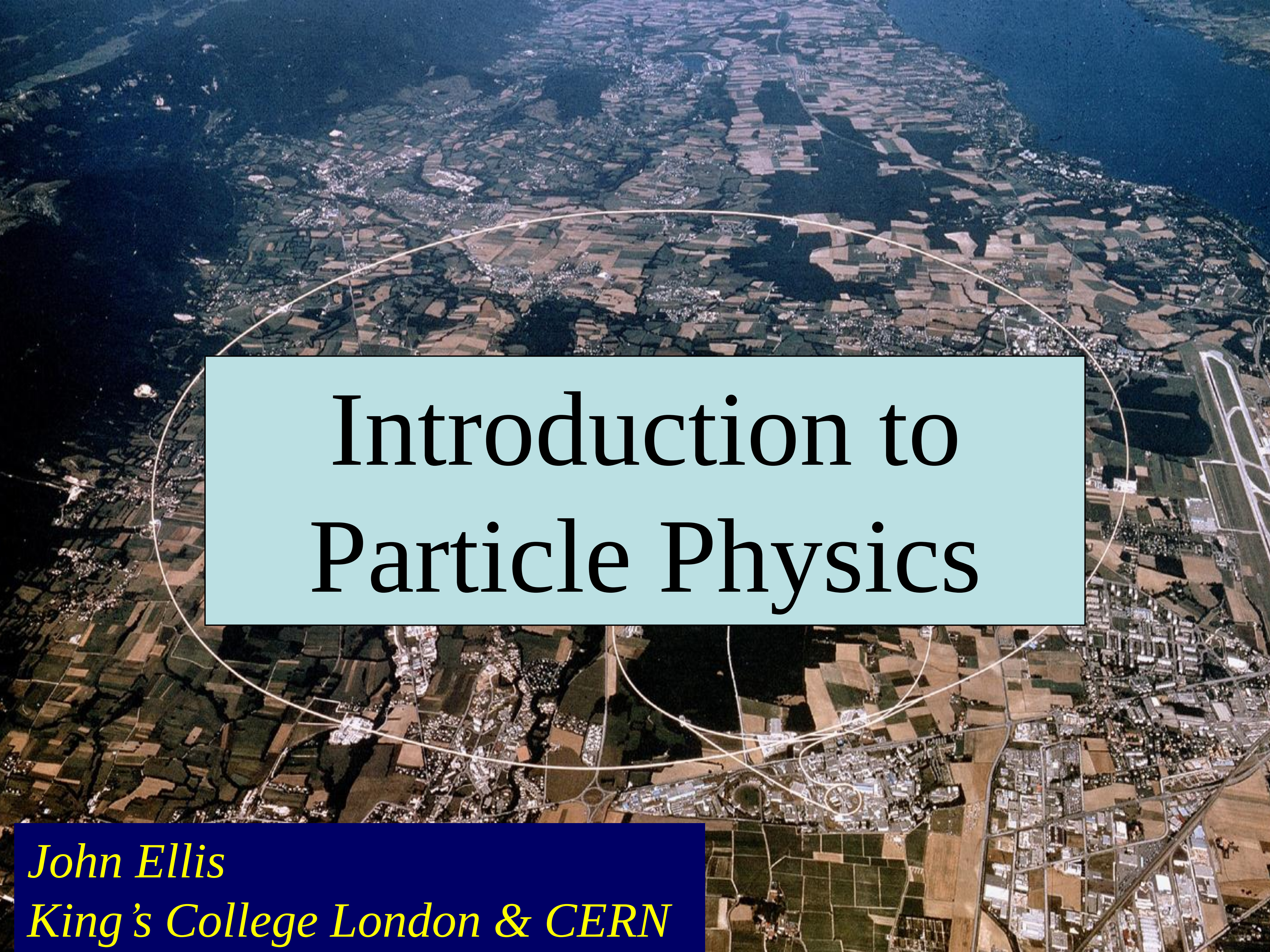
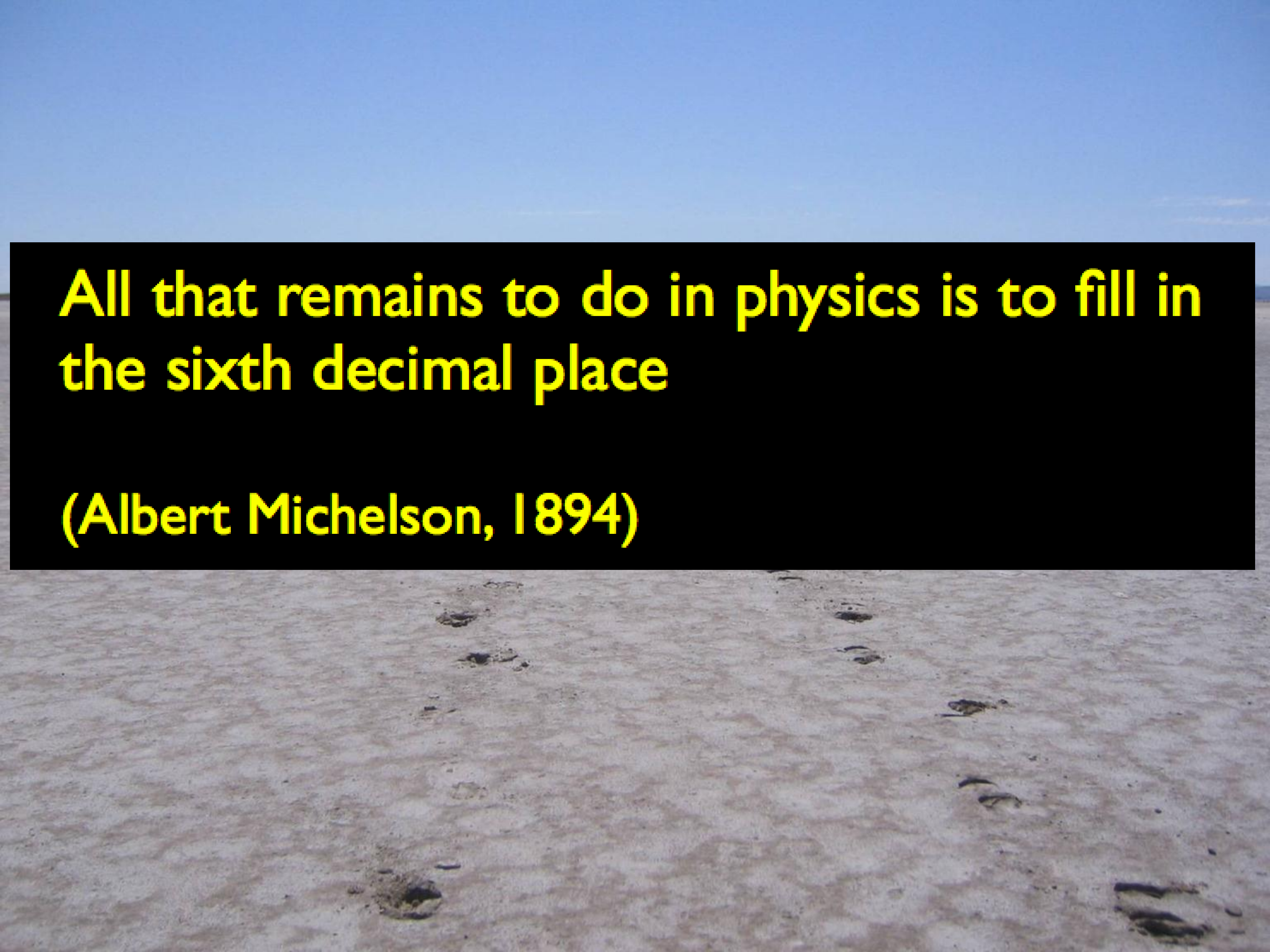
Introduction to Particle Physics



John Ellis
King's College London & CERN



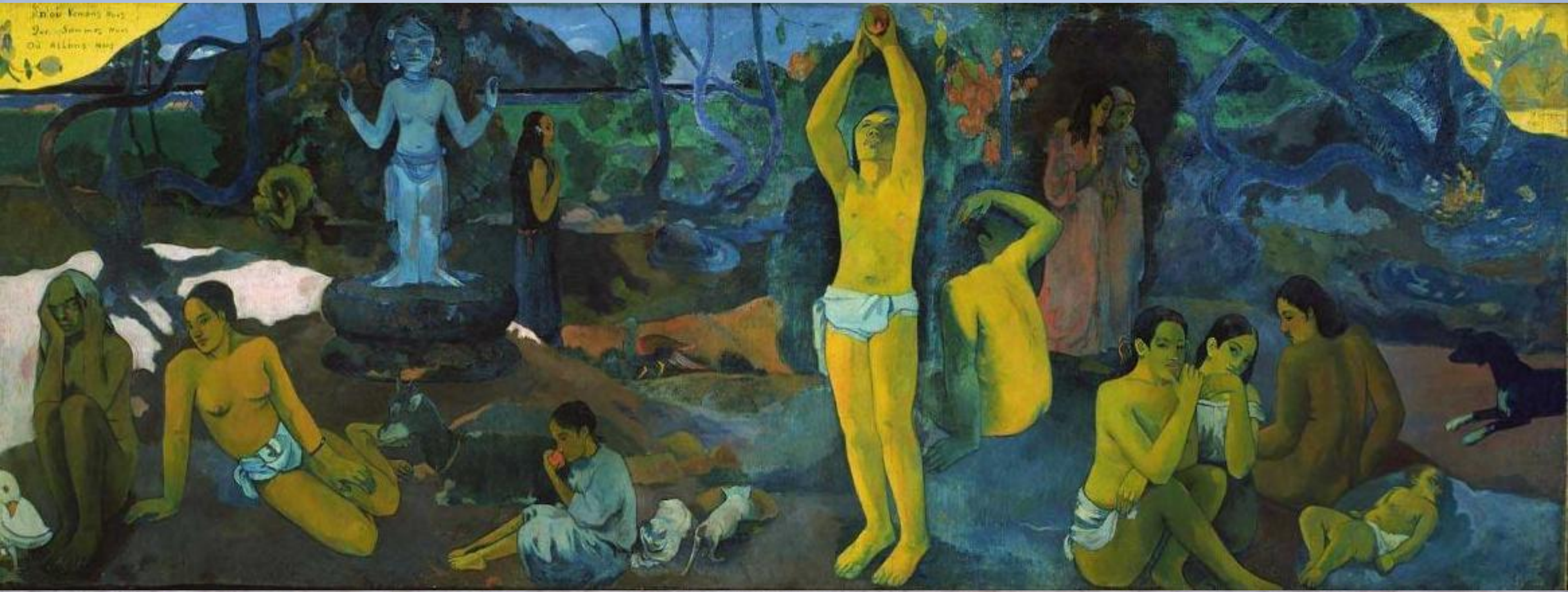
All that remains to do in physics is to fill in the sixth decimal place

(Albert Michelson, 1894)

“Where do we come from?

What are we?

Where are we going?”



The aim of particle physics, CERN & the LHC:

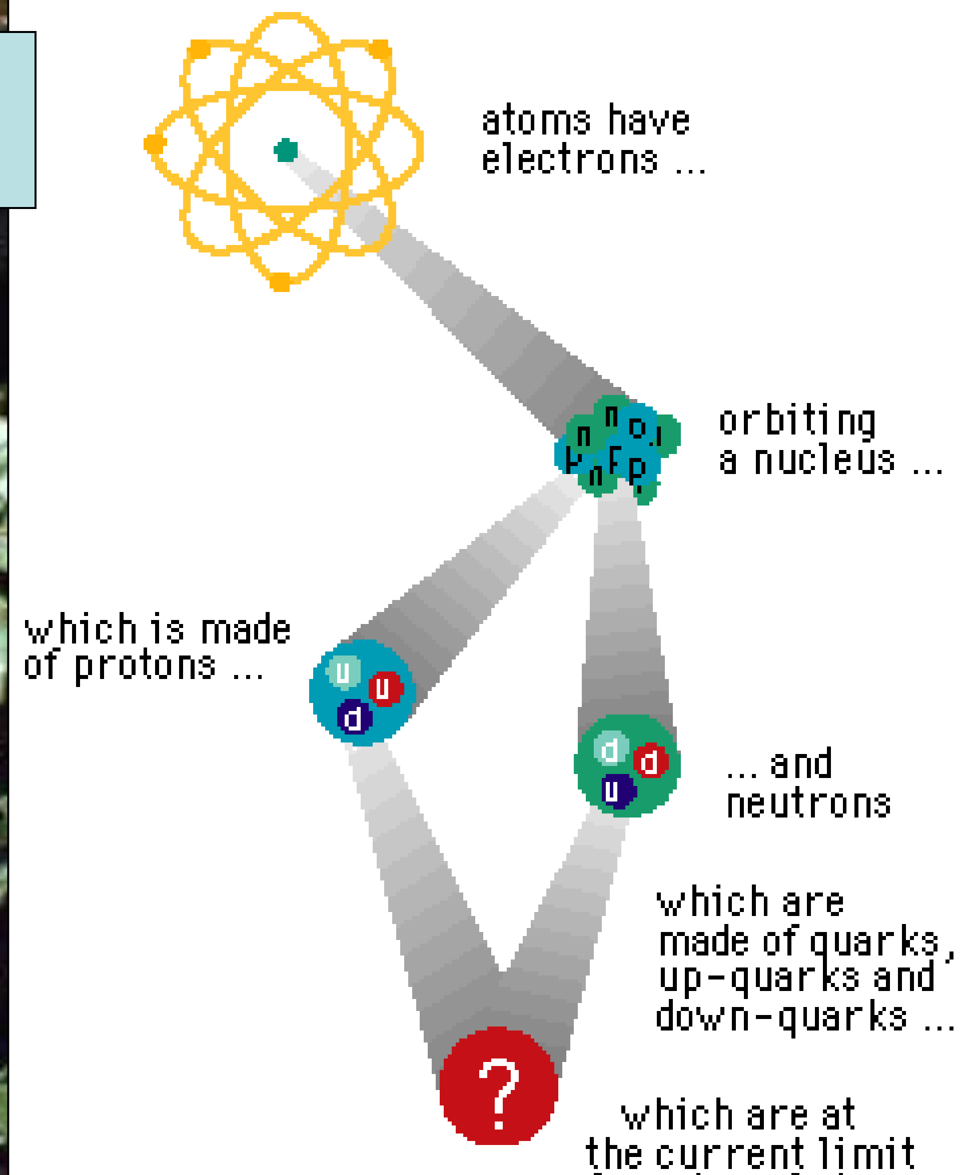
What is the Universe made of?

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
- Why do things weigh?
- What is the dark matter that fills the Universe?
- How does the Universe evolve?
- What is the origin of matter?
- Why is the Universe so big and old?
- Are there additional dimensions of space?

Our job is to ask - and answer - these questions

Inside Matter

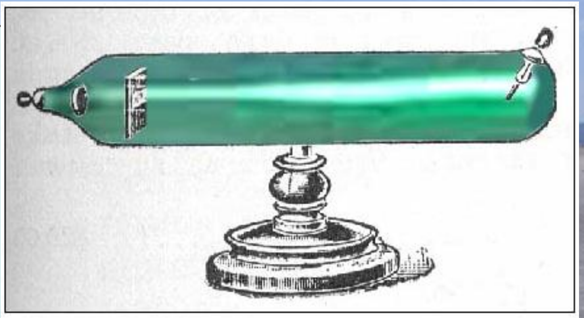


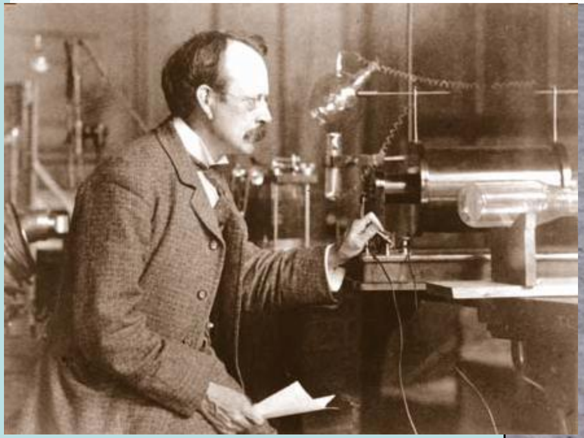
All matter is made of the same constituents

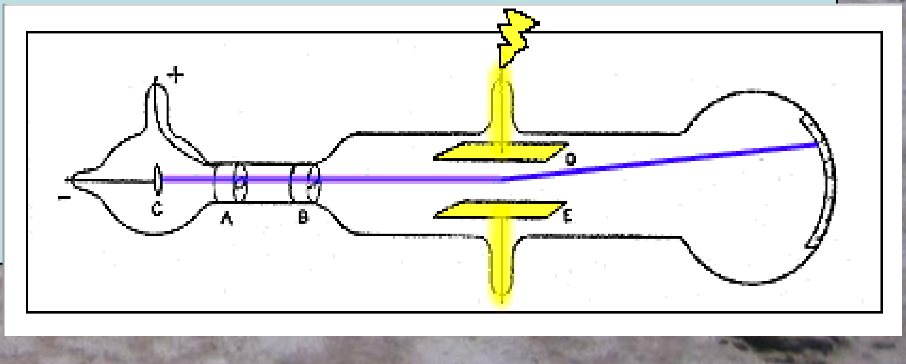
What are they?
What forces between them?

Electron: the first Elementary Particle to be discovered

- 1859: Cathodes emit mysterious rays
- J.J. Thomson suggested they might be constituents of atom
- 1897: Showed they were bent by electric field
- Measured mass/charge to be very small







Maxwell’s Equations

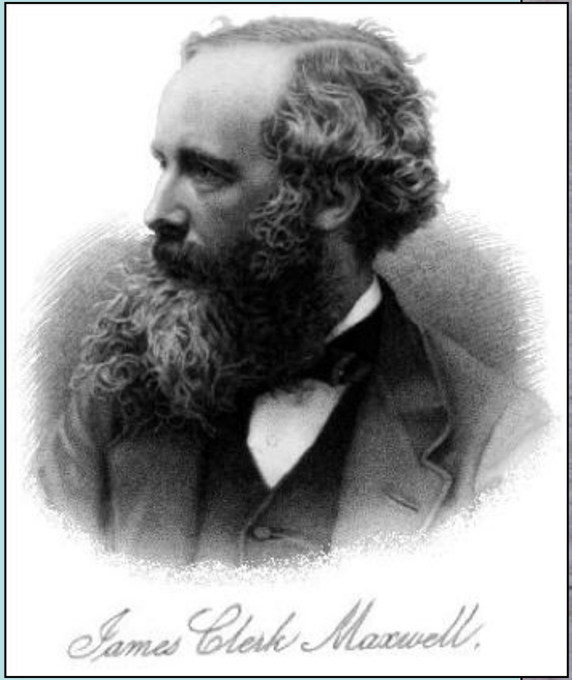
- Prototype for Describing Particle Interactions:

unified electricity & magnetism

$$\nabla \cdot \mathbf{E} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

- Predicted electromagnetic waves

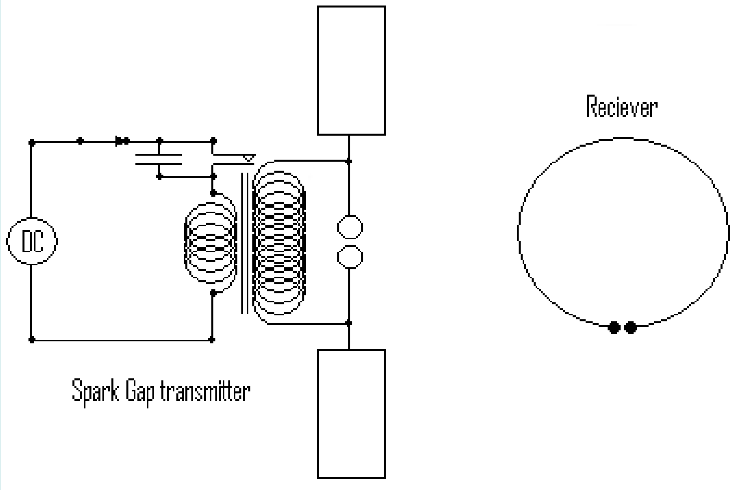
$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad \nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2}.$$



- 1861 -1865

Electromagnetic Waves

- Discovered by Hertz in 1887



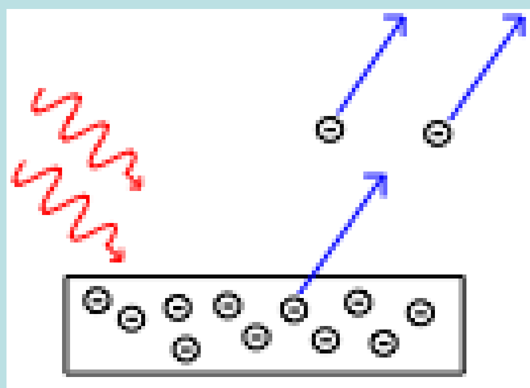
- A lot to answer for ….
- **Nobody knows where fundamental physics may lead**

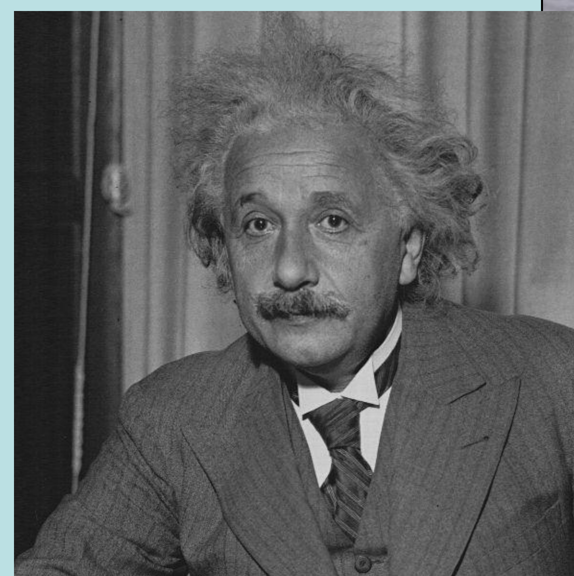
Photon: the Electromagnetic Quantum

- Quantum hypothesis introduced by Planck:

$$E = hf$$

- 1905: Physical reality postulated by Einstein to explain photoelectric effect

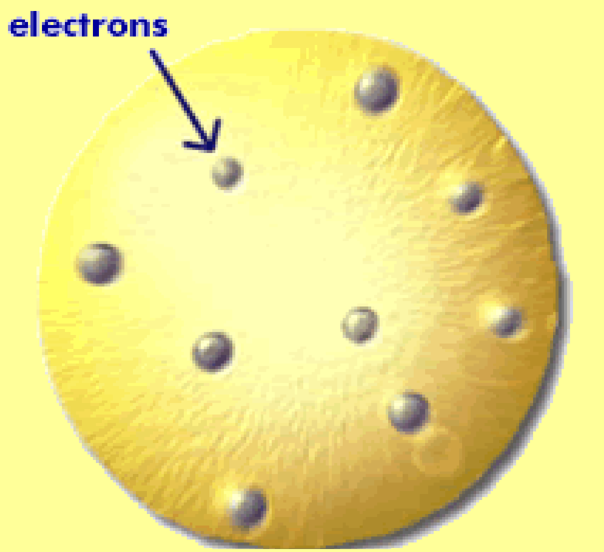


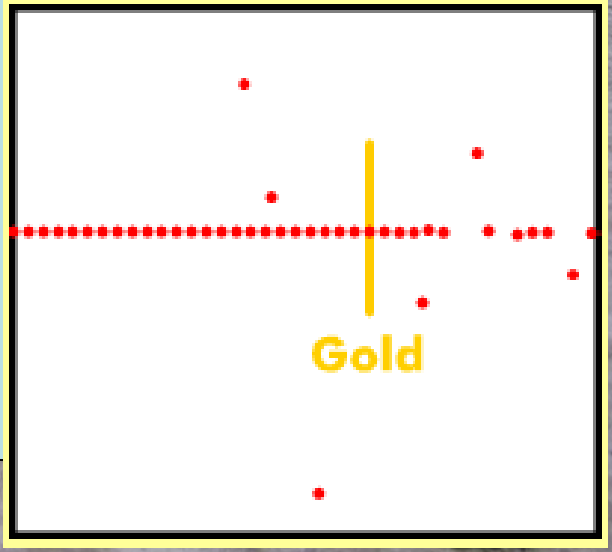


- **First force particle discovered**

The Discovery of the Nucleus

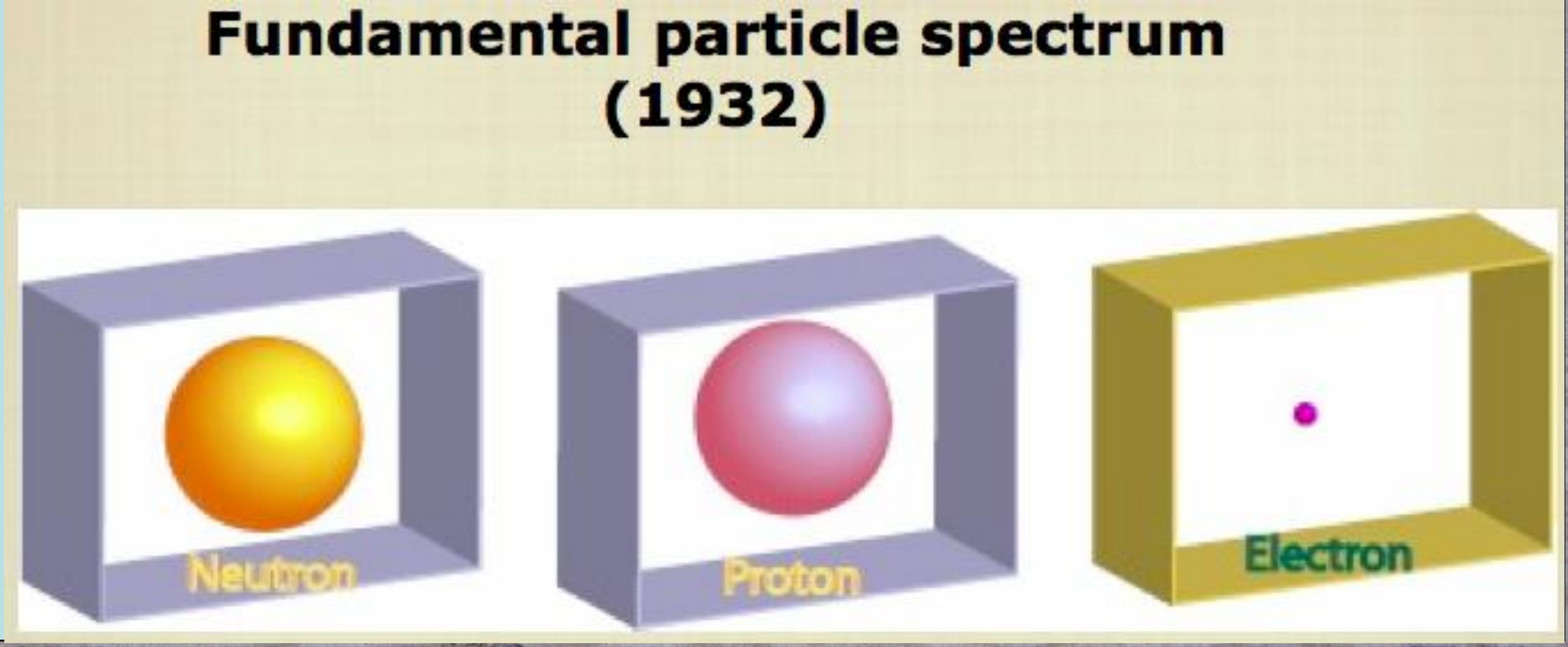
- J.J. Thomson suggested ‘plum pudding’ model of atom
- Geiger & Marsden showed α particles could scatter through large angles
- 1910: Rutherford: small, hard nucleus inside atom





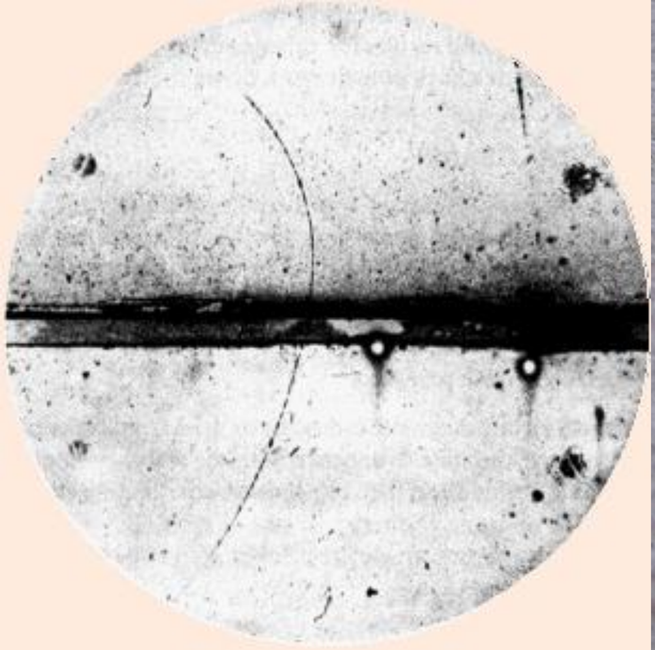
The Discovery of the Neutron

- How to explain masses, charges of nuclei?
- Cannot contain electrons: unseen neutral particles



The Discovery of the Positron

- Predicted by Dirac in 1928
- Discovered in cosmic rays by Anderson in 1932
- Bent opposite to electron, small mass
- Now used in Positron Emission Tomography (PET) for medical diagnosis



Radioactivity: the Weak Force

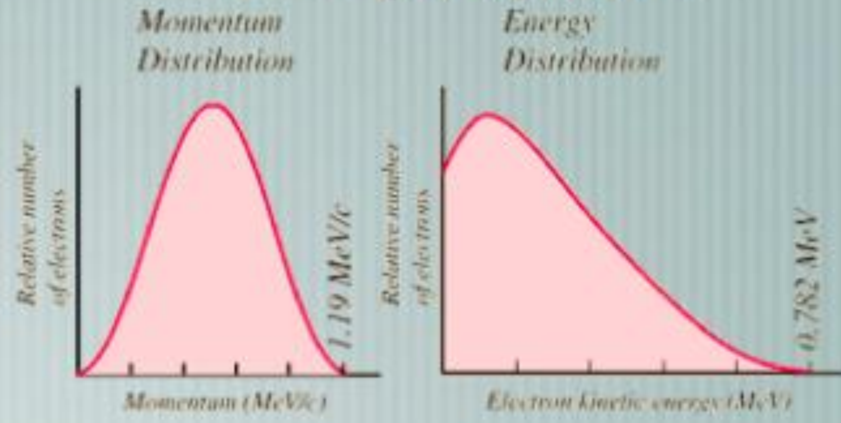
The “Weak Interaction” - Radioactivity

1896: Henri Becquerel discovered radiation from U crystals

1898: Marie and Pierre Curie : ionizing radiation from ‘Pechblende’ (U + Polonium)

1911: Continuous (?) energy spectrum of ‘beta’-rays (electrons) - energy conservation?

Z --> (Z+1) + e ?

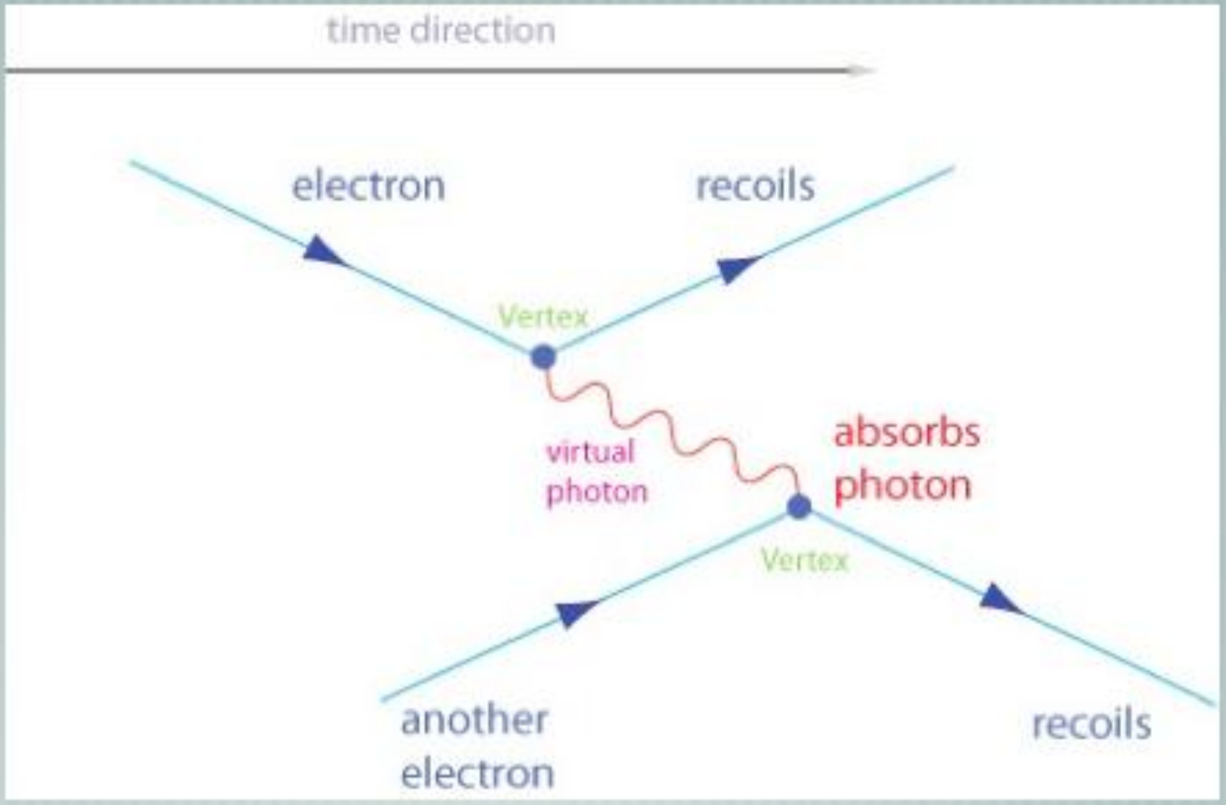


1930: Wolfgang Pauli postulates existence of ‘neutrino’: **n --> p + e + ν**

Understanding Electromagnetism

Quantum Electrodynamics

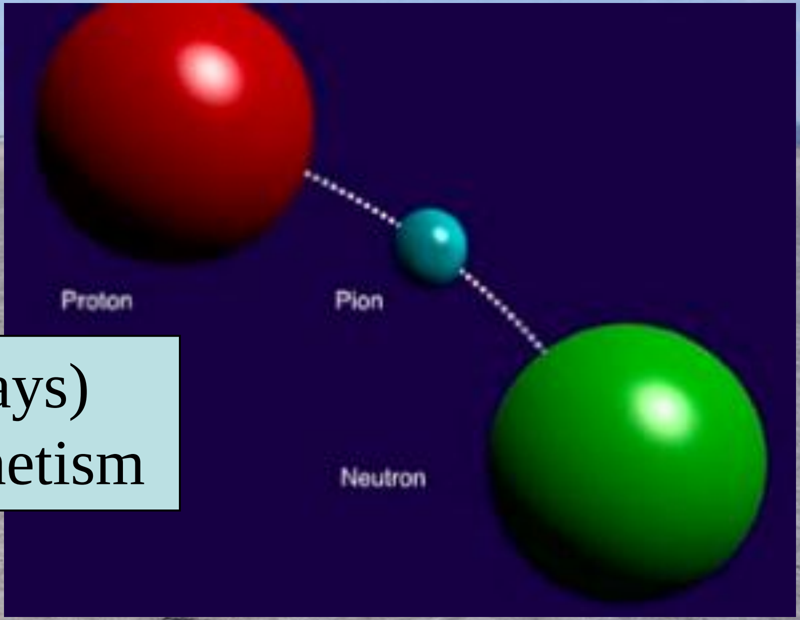
Feynman, Tomonaga, Schwinger



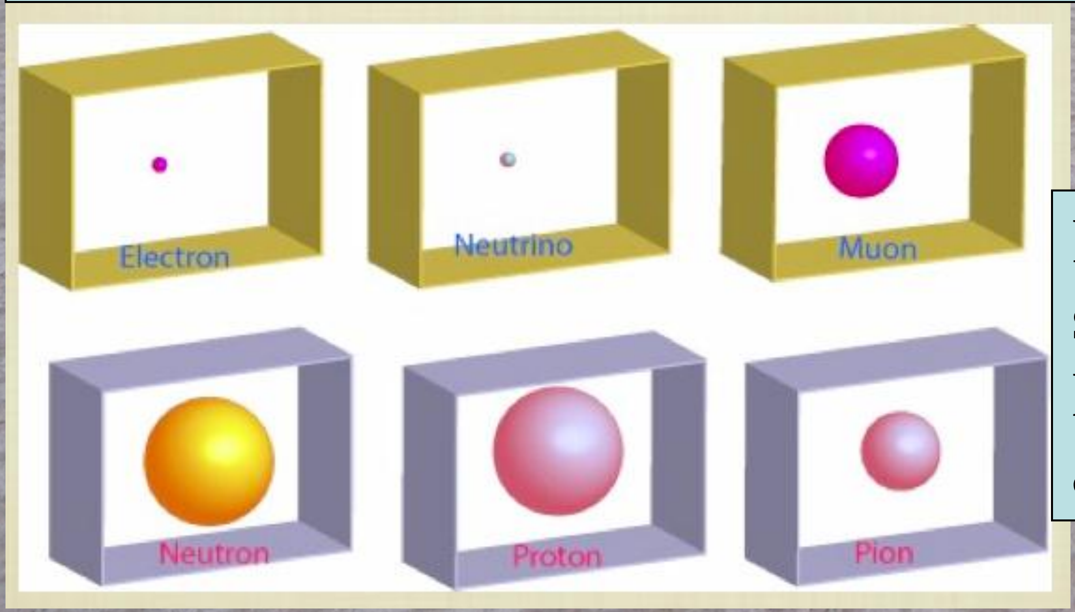
1948

The Strong Nuclear Force

What holds nuclei together?



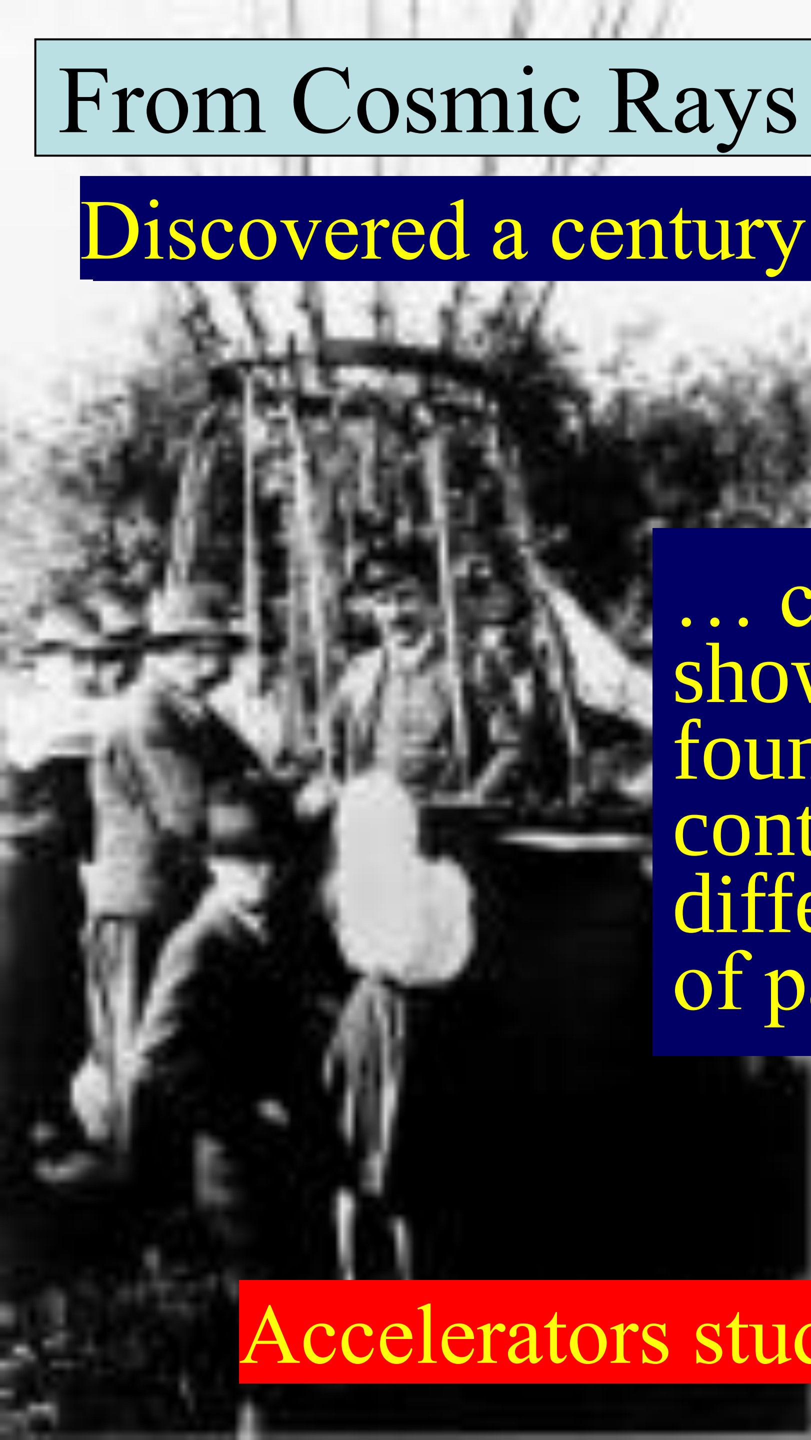
Thought to be carried by pions (cosmic rays)
Analogy to photons carrying electromagnetism

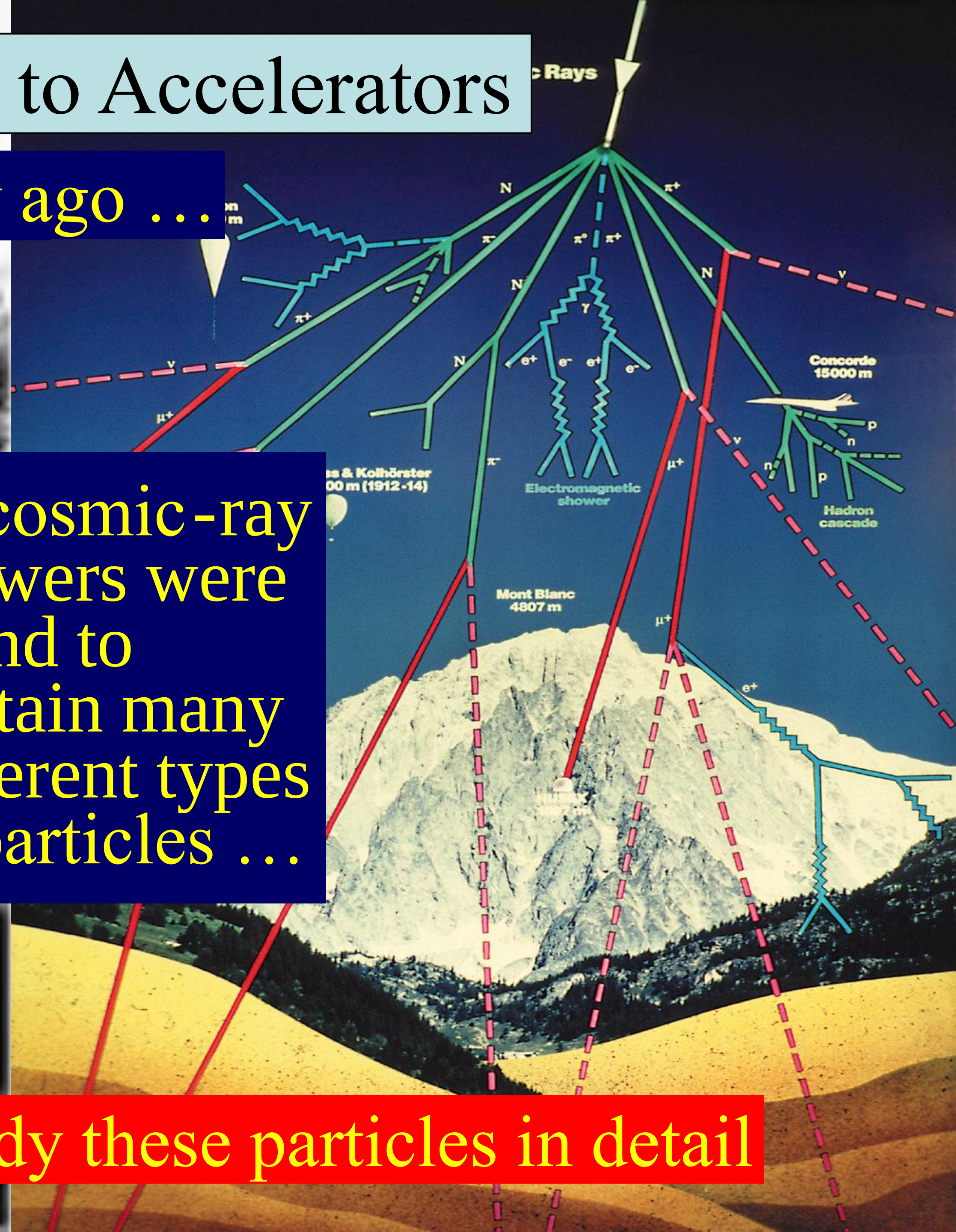


Particle physics around 1948
starting to look messy:
Muon (heavy electron)
also discovered in cosmic rays

From Cosmic Rays to Accelerators

Discovered a century ago …

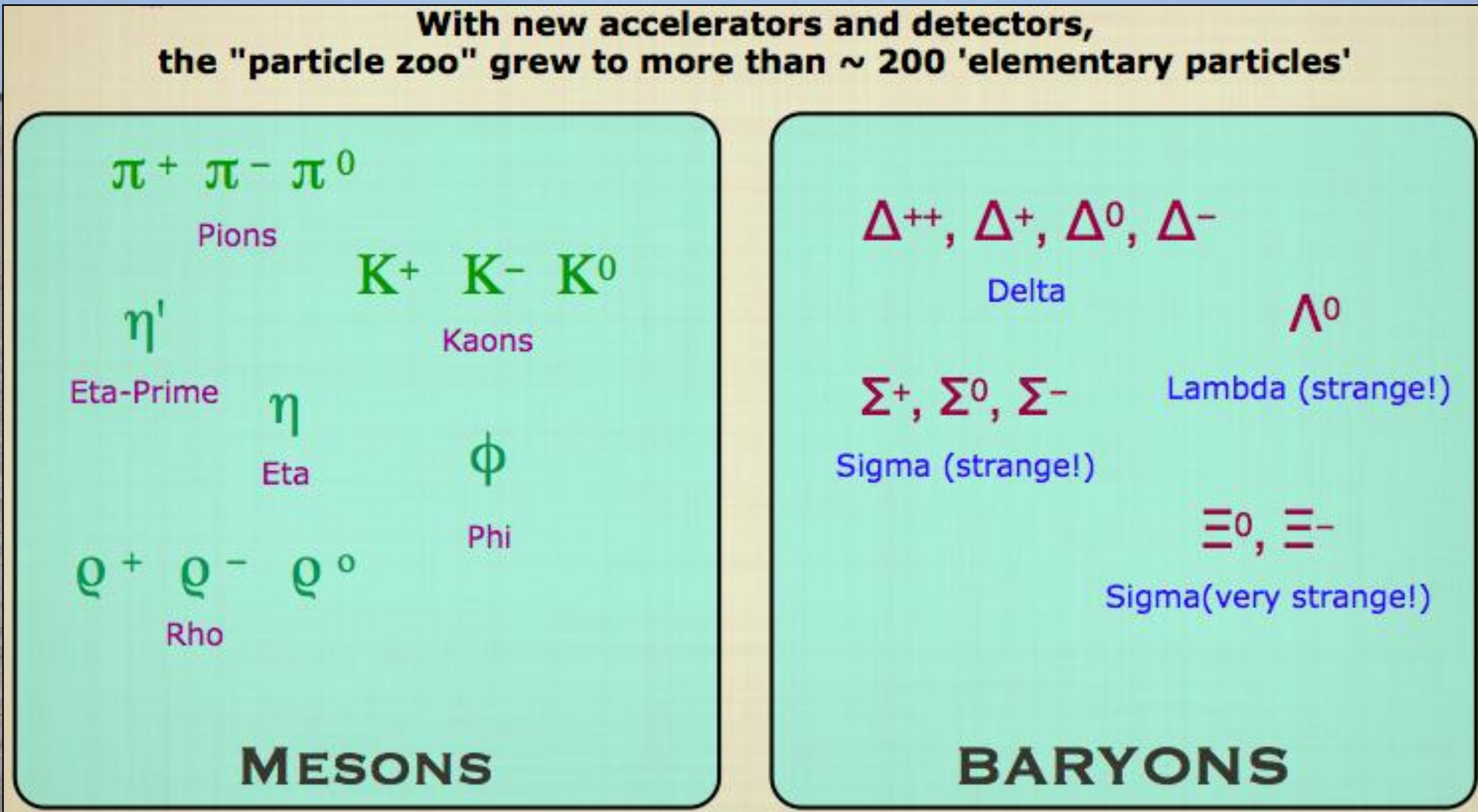




… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

1950s: a Zoo of ‘Particles’



1960s: Order out of Chaos: Quarks

Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

1) 3 types of "quarks" : up, down, strange

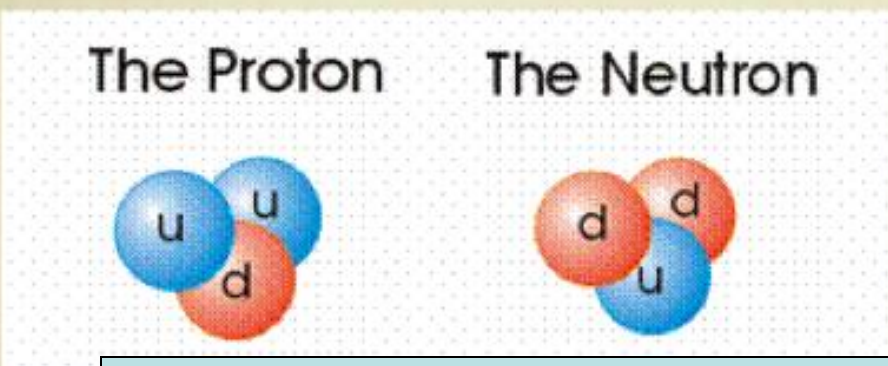
+2/3 e -1/3 e -1/3 e

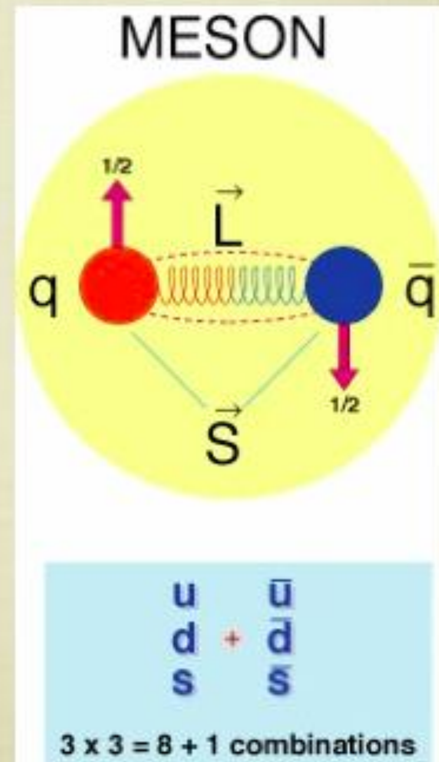
2) Carry electric charges: +2/3, -1/3, -1/3

3) Appear in combinations:

Meson = quark+antiquark

Baryon = quark(1) + quark(2) + quark(3)

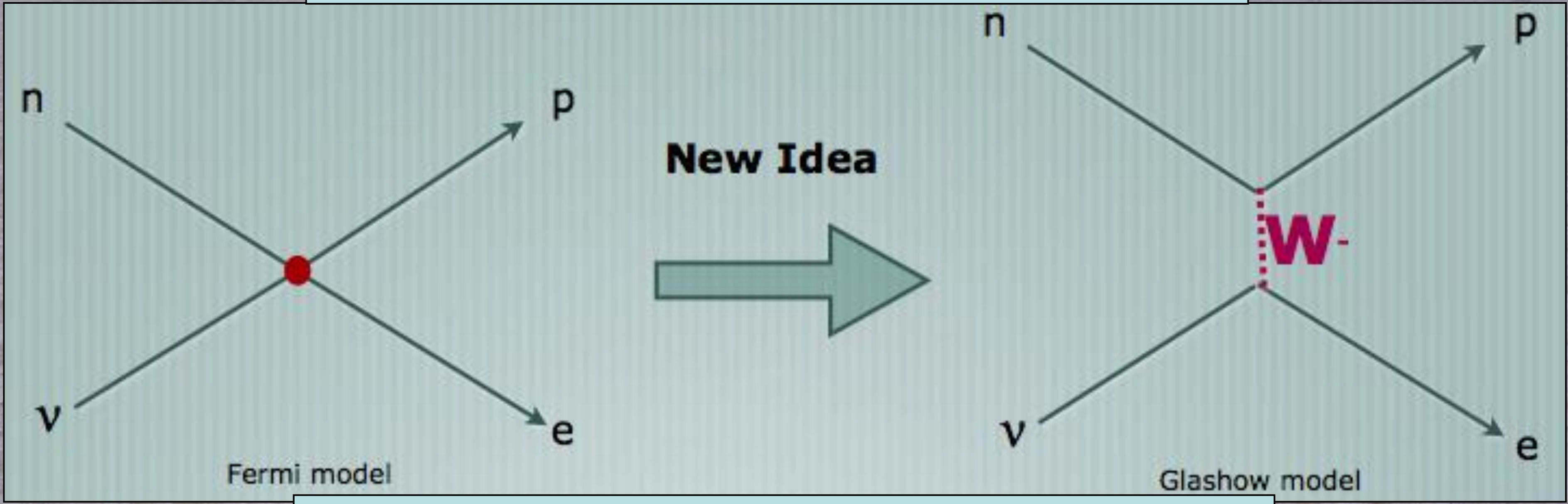




Quarks held together by gluons?

Towards a Theory of the Weak Force

Gets stronger at higher energies
Impossible to calculate reliably
Carrier W particle, like photon?



1933

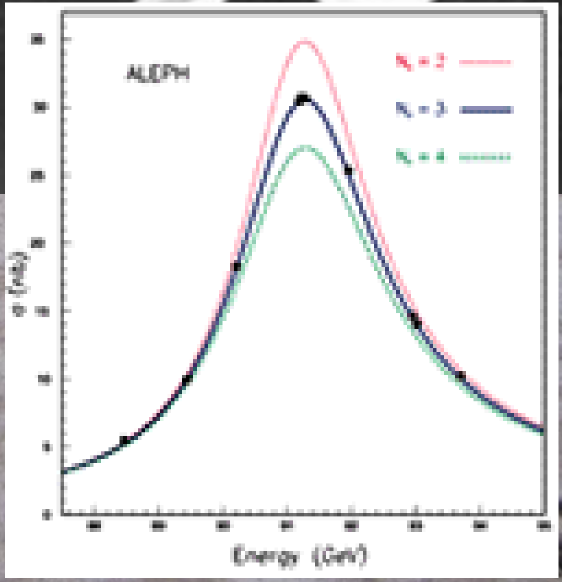
W Must be heavy, ~ 100 GeV
Where does its mass come from?

1960

The ‘Standard Model’ of Particle Physics

Proposed byAbdus Salam, Glashow and Weinberg

Tested by experiments at CERN



Perfect agreement between theory and experiments in all laboratories

Gluon Radiation in e^+e^- Annihilation

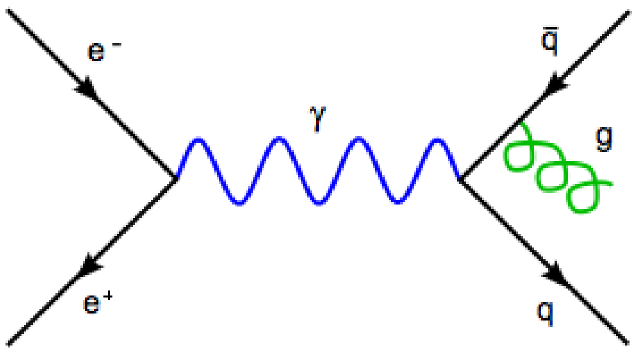
- Discovery method suggested by JE, Mary Gaillard, Graham Ross:

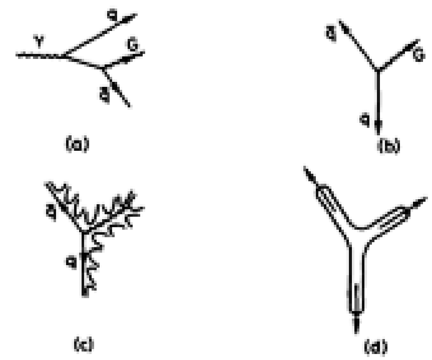
SEARCH FOR GLUONS IN e^+e^- ANNIHILATION

John ELLIS, Mary K. GAILLARD * and Graham G. ROSS
CERN, Geneva

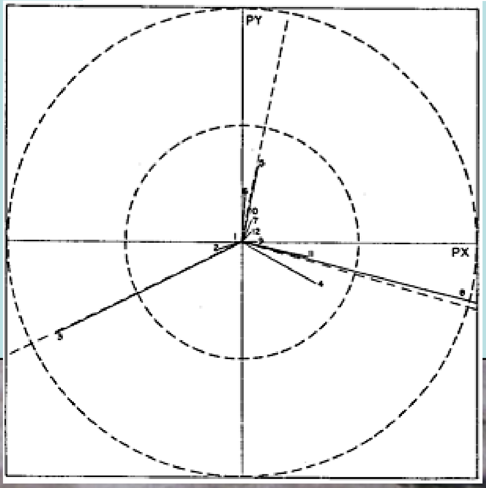
Received 20 May 1976

We study the deviations to be expected at high energies from the recently observed two-jet structure of hadronic final states in e^+e^- annihilation. Motivated by the approximate validity of the naïve parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axes. This process should give rise to three-jet final states. These may be observable at the highest SPEAR or DORIS energies, and should be important at the higher PETRA or PEP energies.





- Jets of hadrons produced by gluons DESY (Hamburg) in 1978



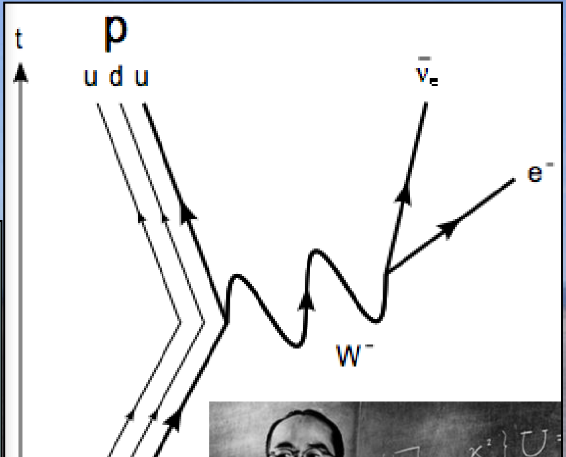
- **Second force particle discovered**

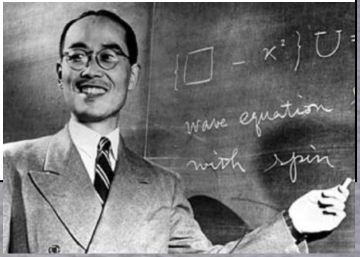
Weak Interactions

Radioactivity due to charged-current weak interactions (β decay)

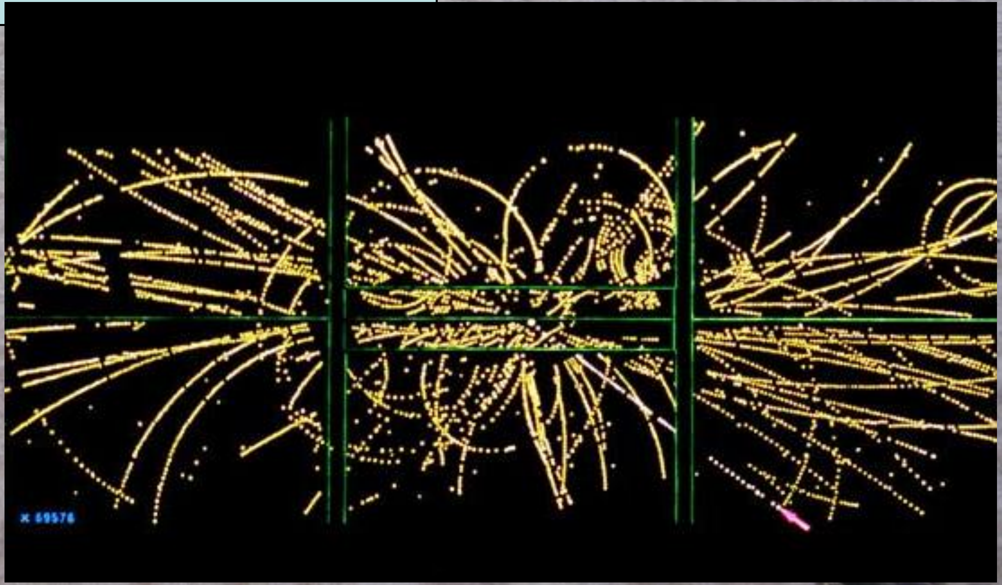
W boson - carrier of weak interaction

postulated by Yukawa

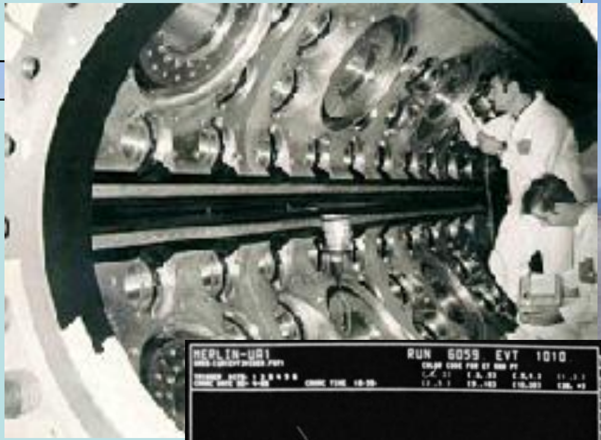


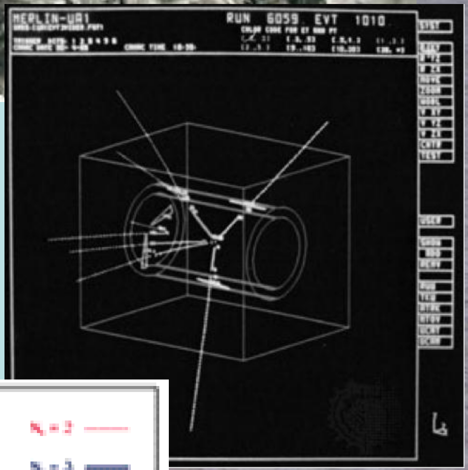


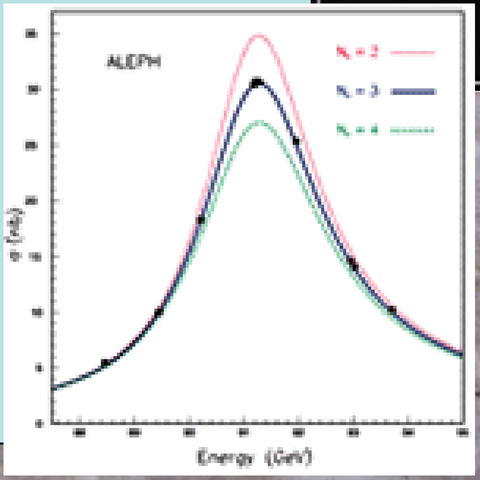
Discovered at CERN in 1983 by Carlo Rubbia et al



Neutral-Current Weak Interactions





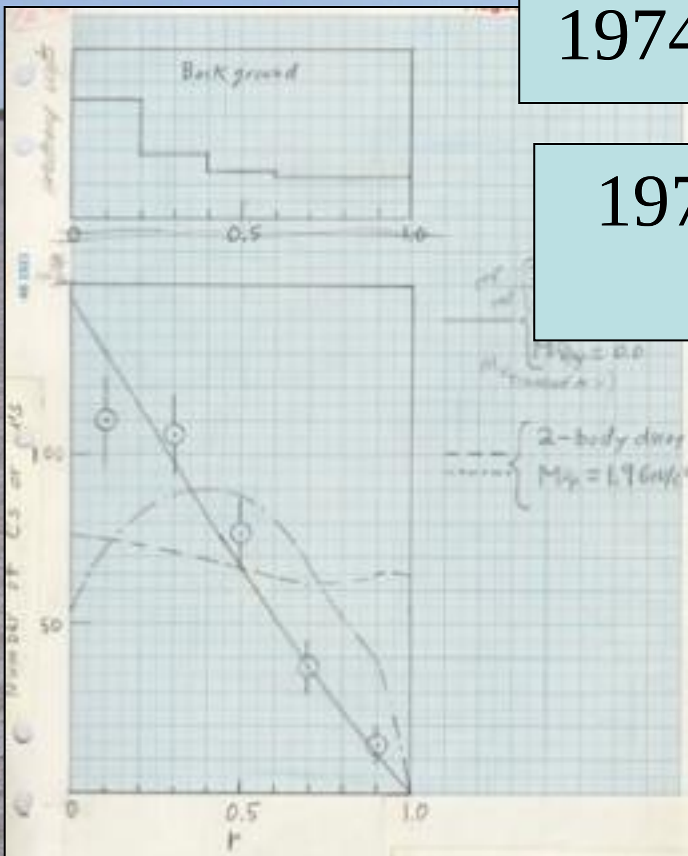


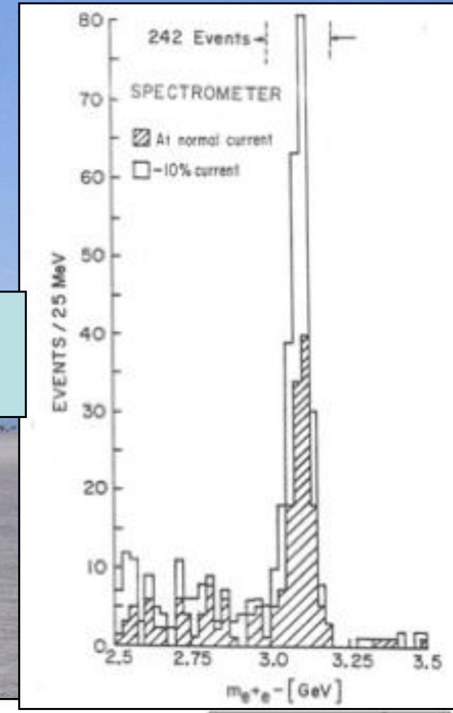
- Discovered at CERN in 1973 by Gargamelle Collaboration
- **Breakthrough leading to the Standard Model**
- Carrier particle (Z boson) discovered at CERN in 1983 by Rubbia et al
- Measured in great detail at CERN in 1990s
- **Accurate confirmation of the Standard Model**

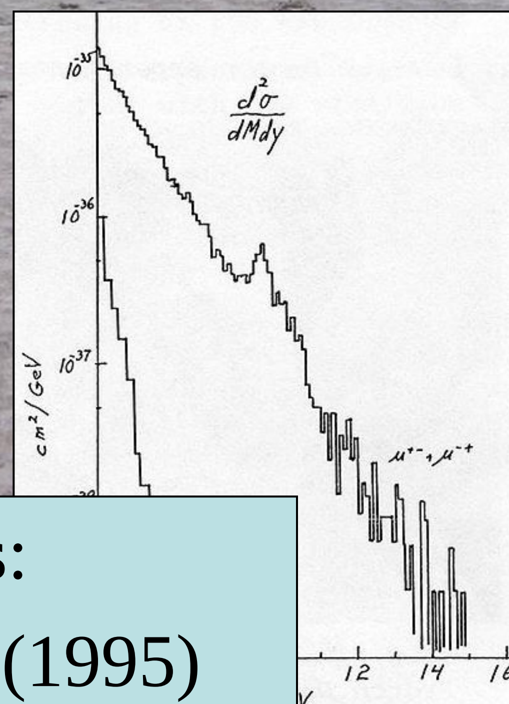
More new Particles

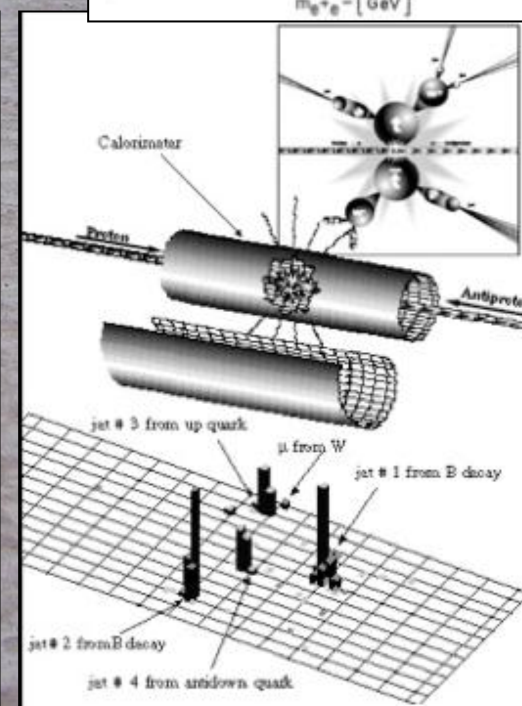
1974 - Fourth quark: charm

1975 - Another heavy electron: τ





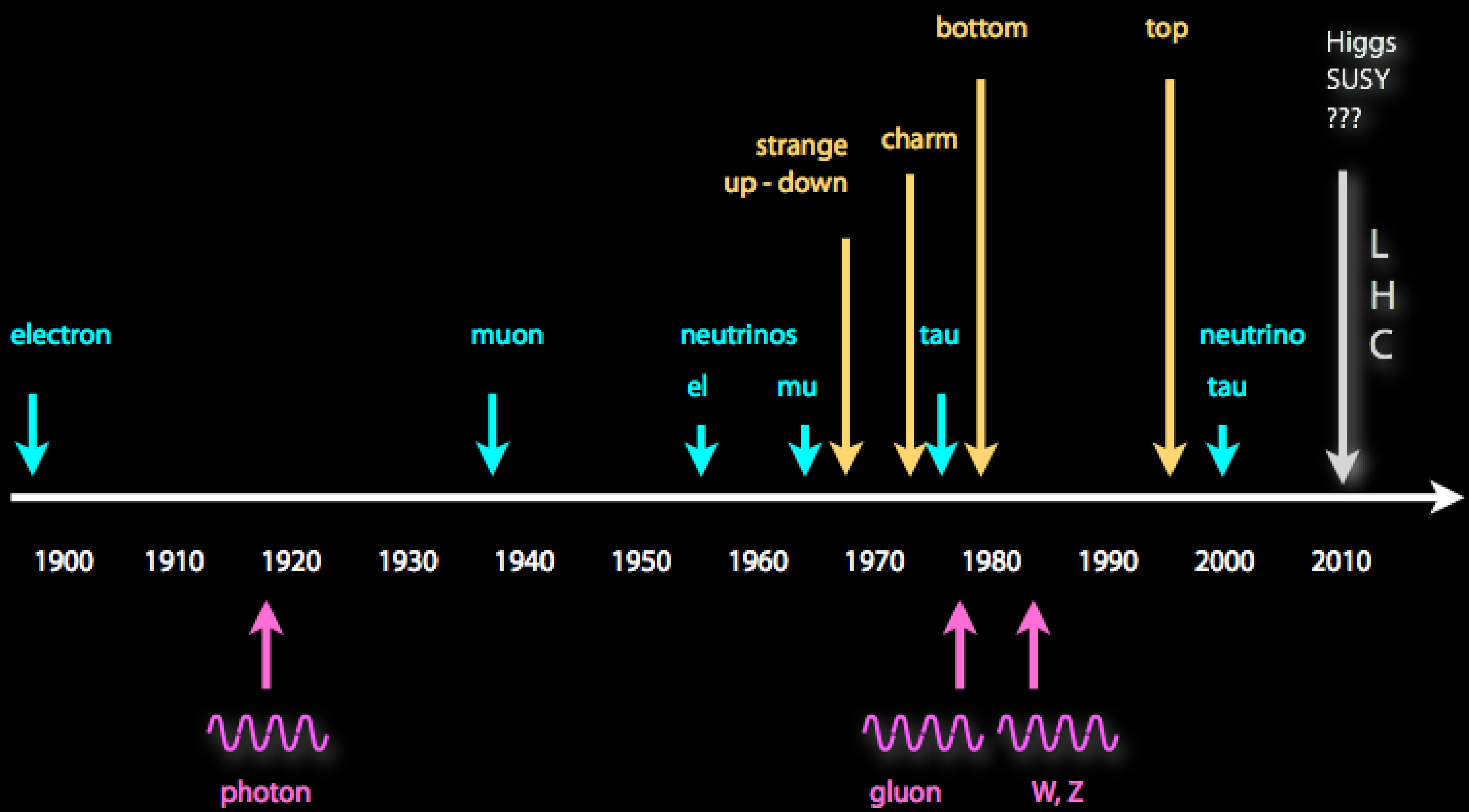




Two more quarks:

bottom (1977) and top (1995)

Particles: the Story so far



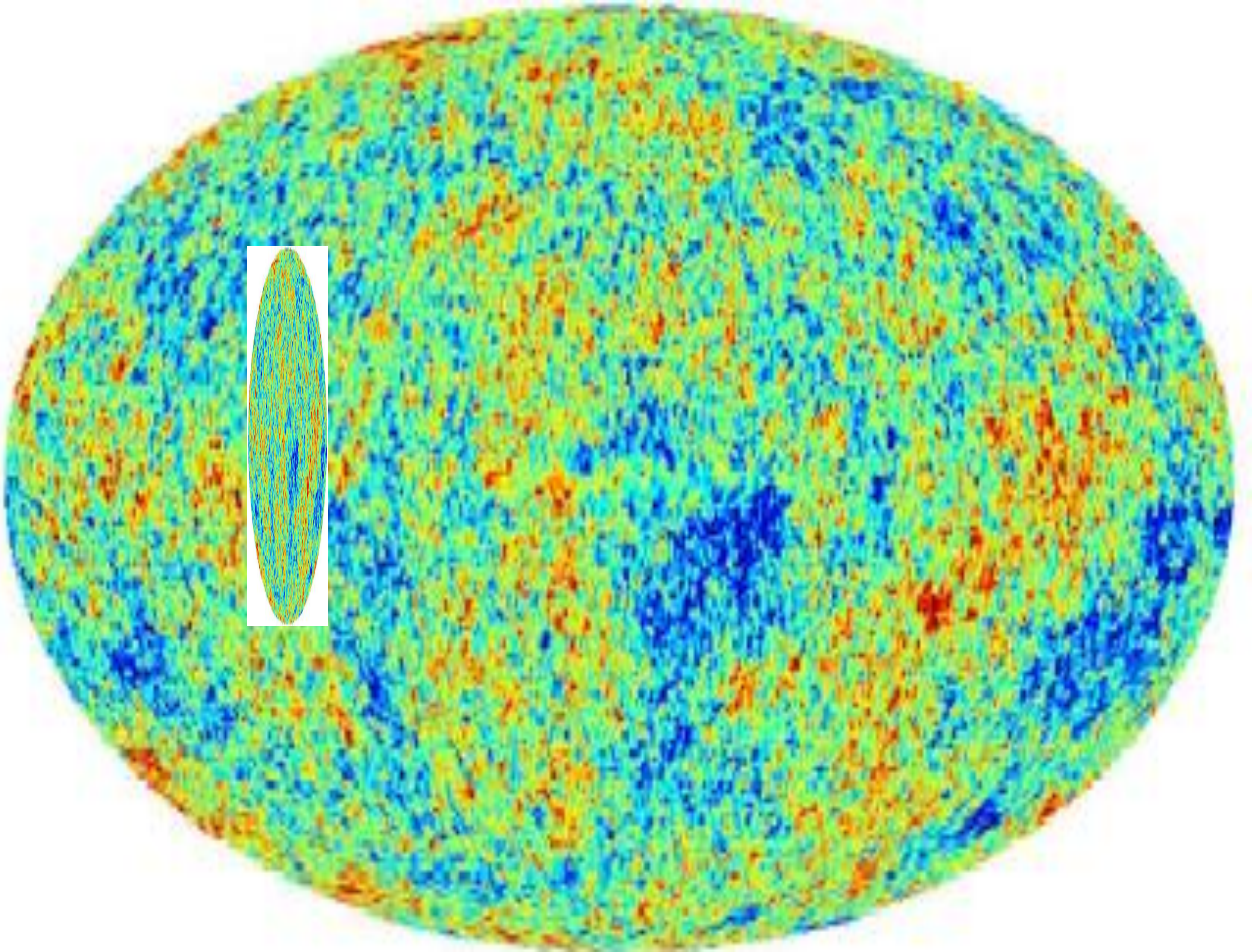
The ‘Standard Model’

= Cosmic DNA

The matter particles

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force



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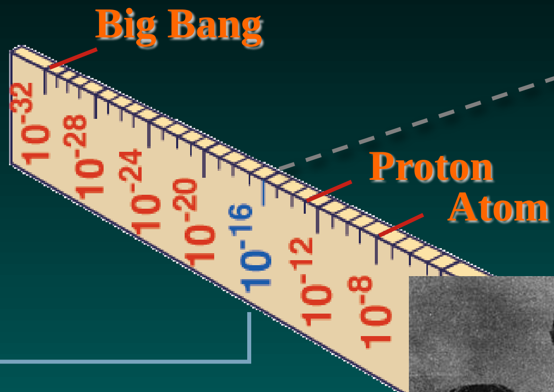
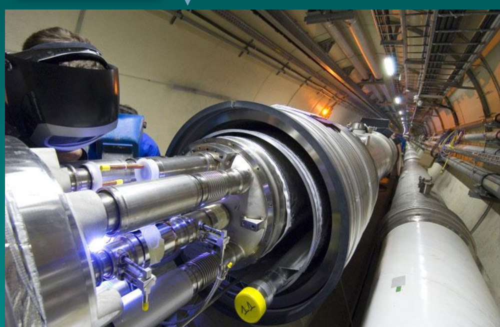
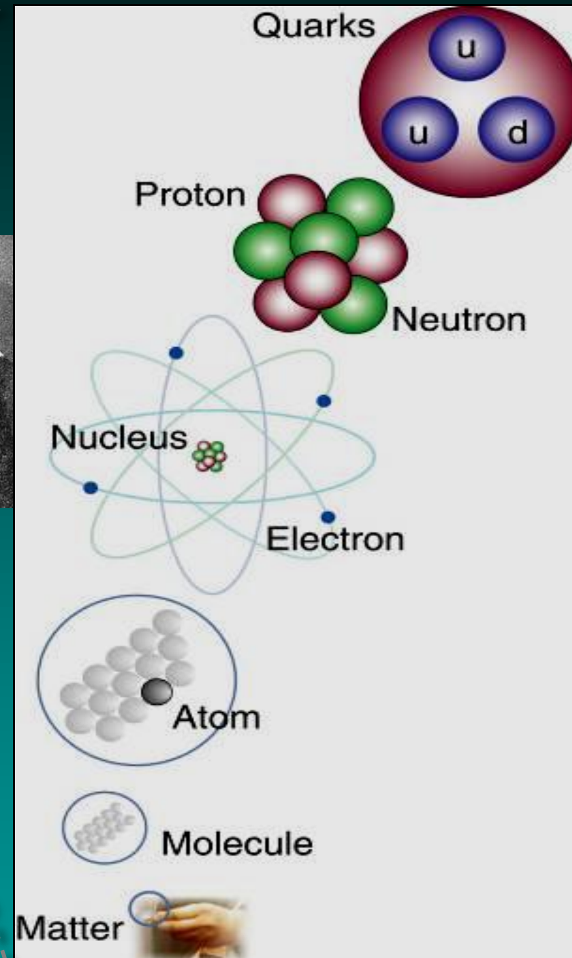
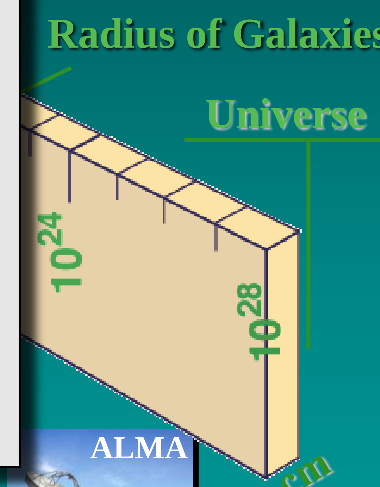








LHC

Super-Microscope

Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The Young Universe

- Age: t → zero
- Size: a → zero
- Temperature: T → high

  $T \sim 1/a,\ t \sim 1/T^2$
- Energies: $E \sim T$
- Orders of magnitude:

  t ~ 1 second

  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

Need particle physics to describe the very early Universe

300,000 years

Formation of atoms

3 minutes

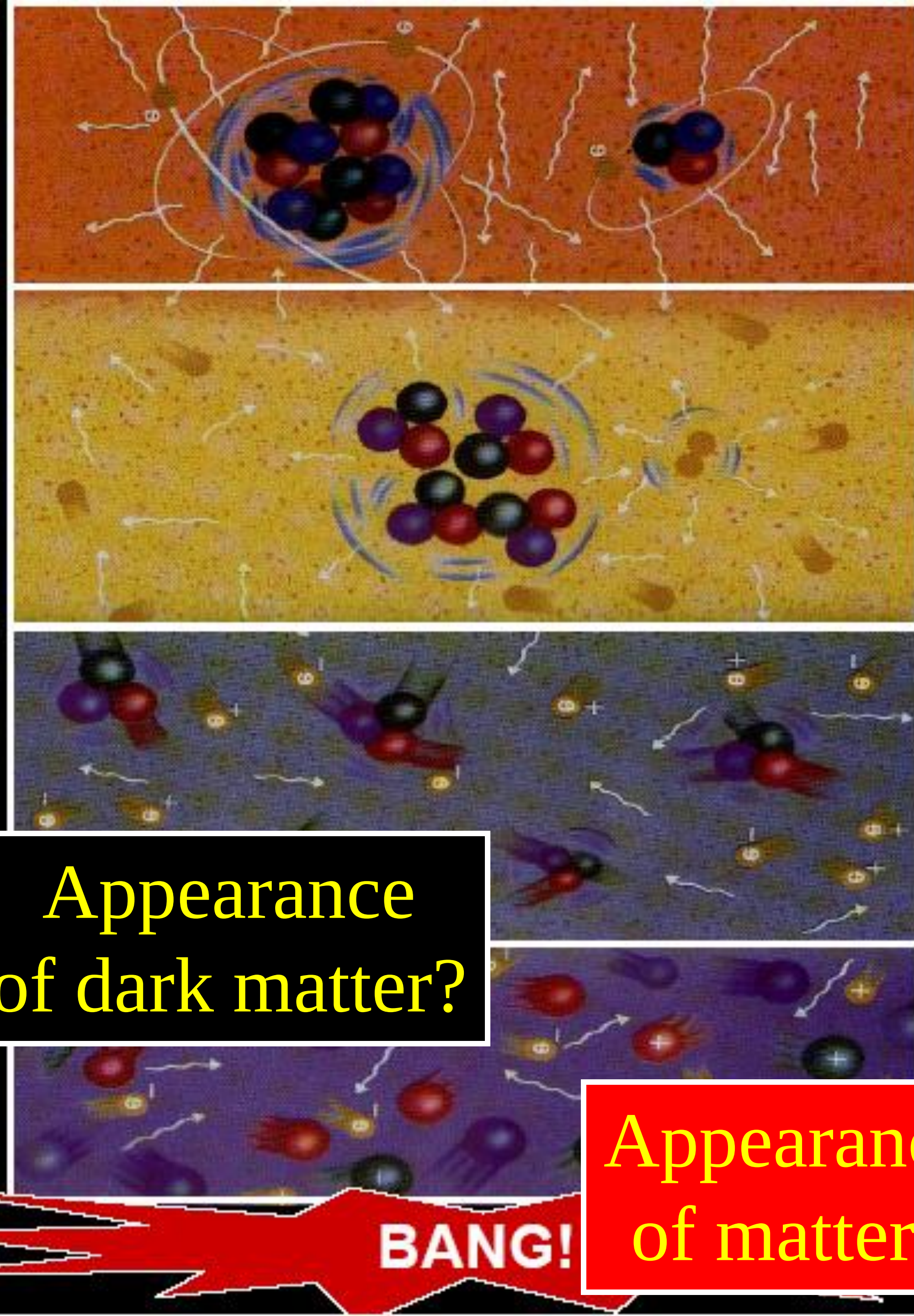
Formation of nuclei

1 micro-second

Formation of protons & neutrons

1 pico-second

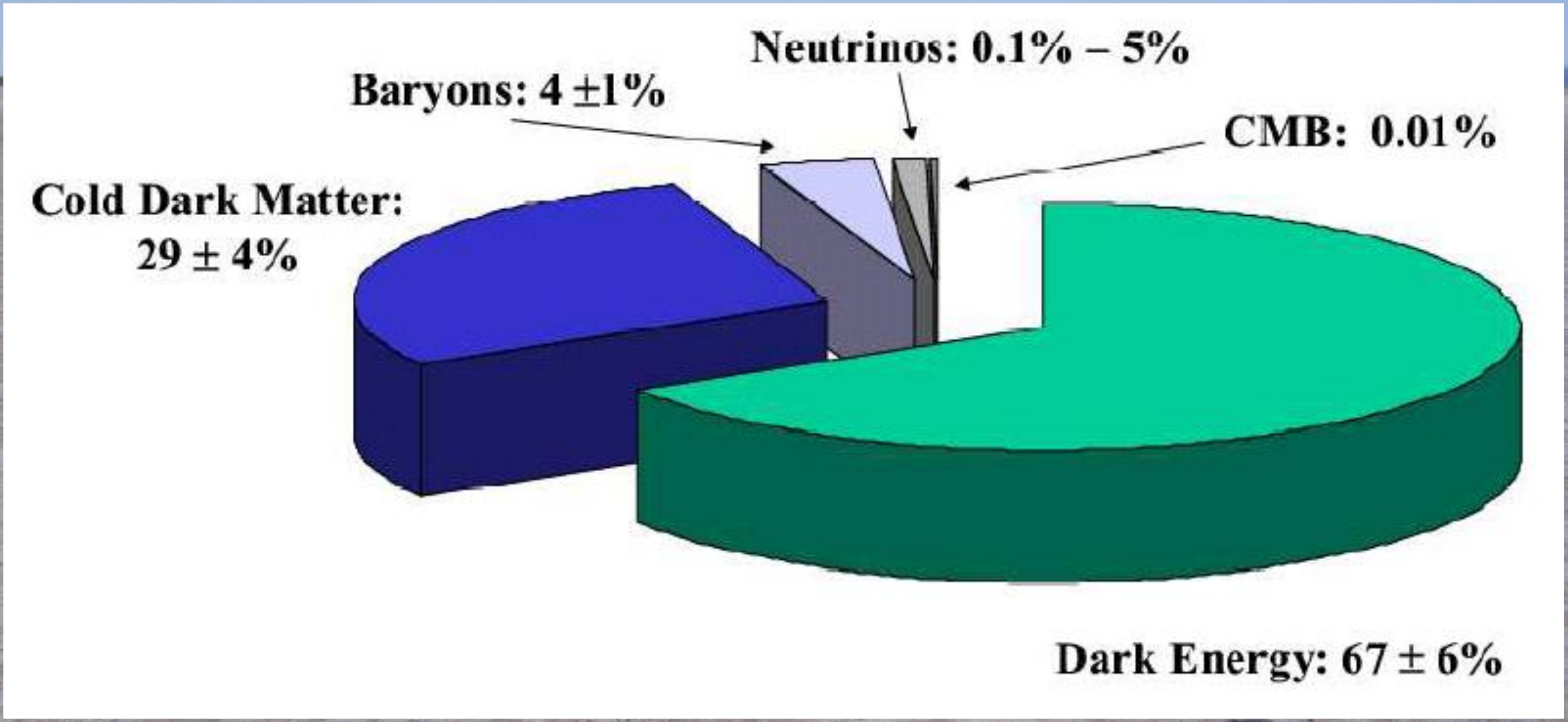
Appearance of mass?



Appearance of dark matter?

Appearance of matter?

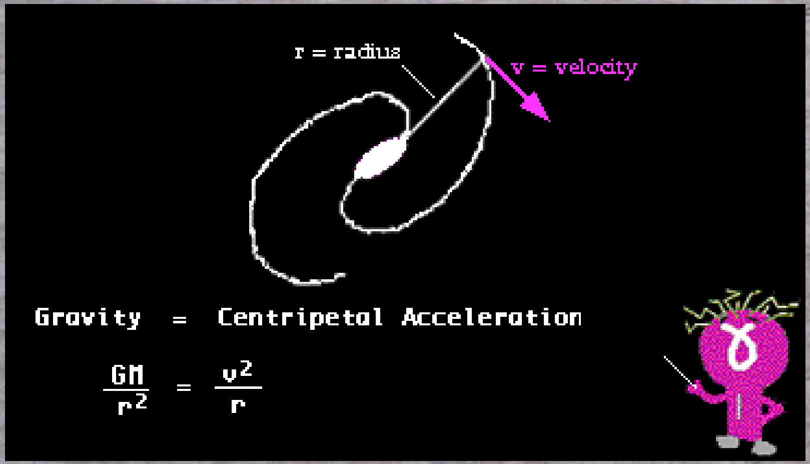
Strange Recipe for a Universe



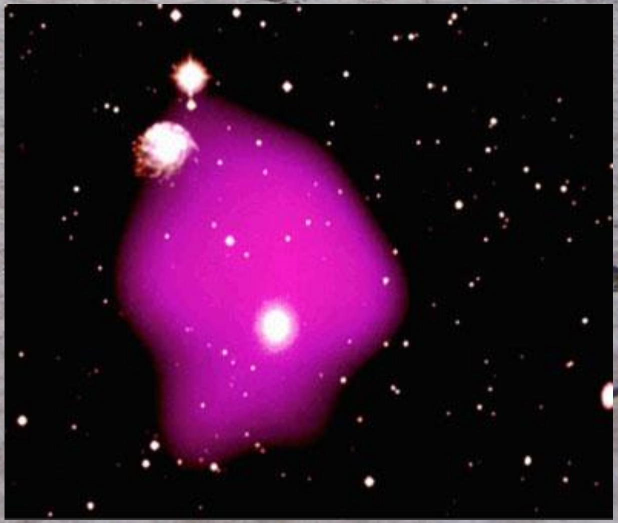
The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Evidence for Dark Matter

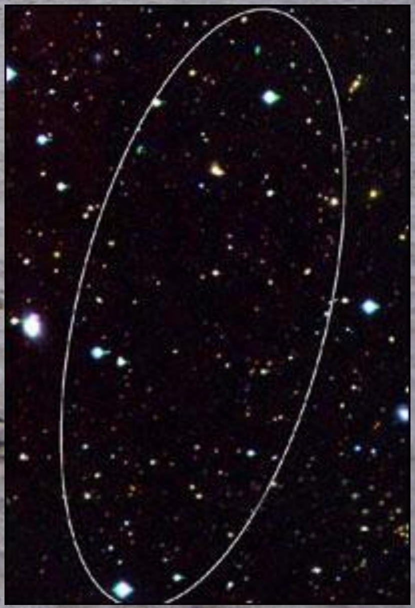
Galaxies rotate more rapidly than allowed by centripetal force due to visible matter



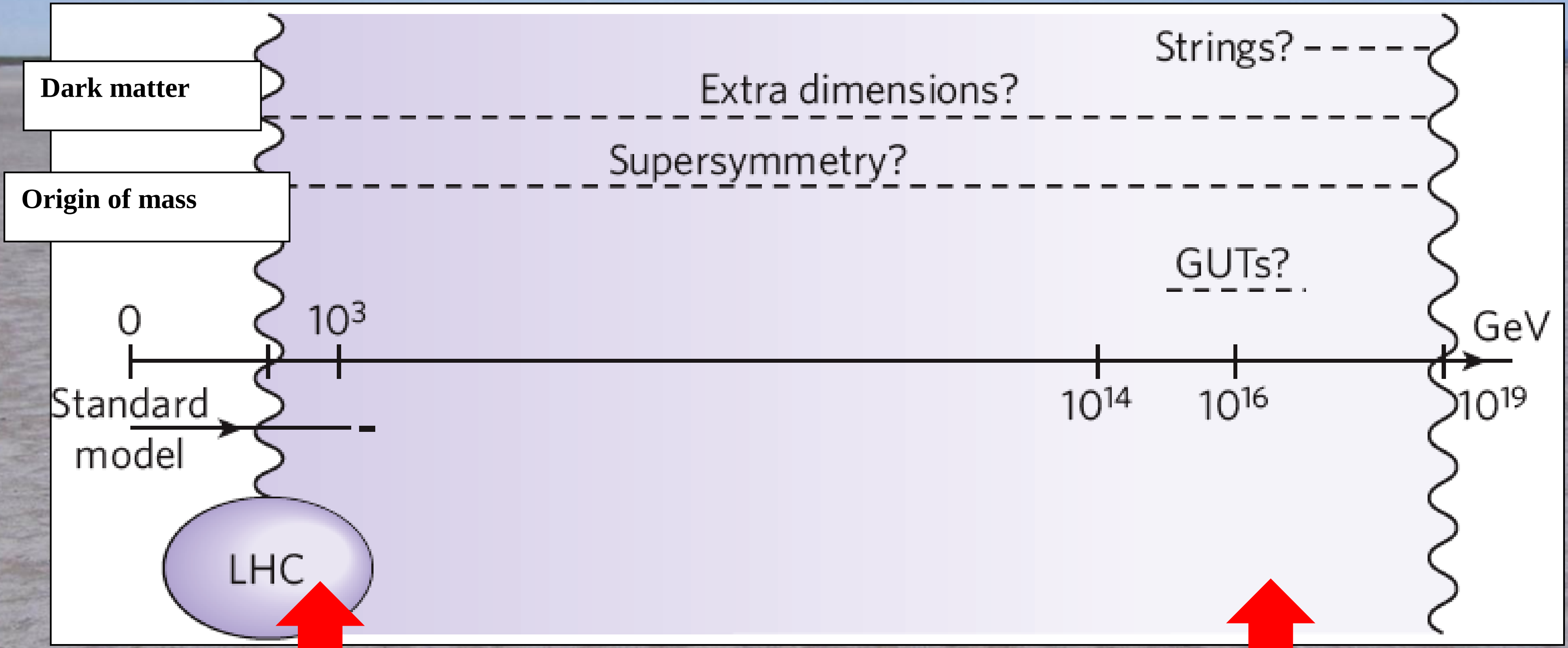
X-ray emitting gas held in place by extra dark matter



Even a 'dark galaxy' without stars



At what Energy is the New Physics?



A lot accessible to the LHC

Some accessible only via astrophysics & cosmology

Open Questions beyond the Standard Model

- What is the origin of particle masses? due to a Higgs boson? LHC
- Why so many types of matter particles? LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

Why do Things Weigh?

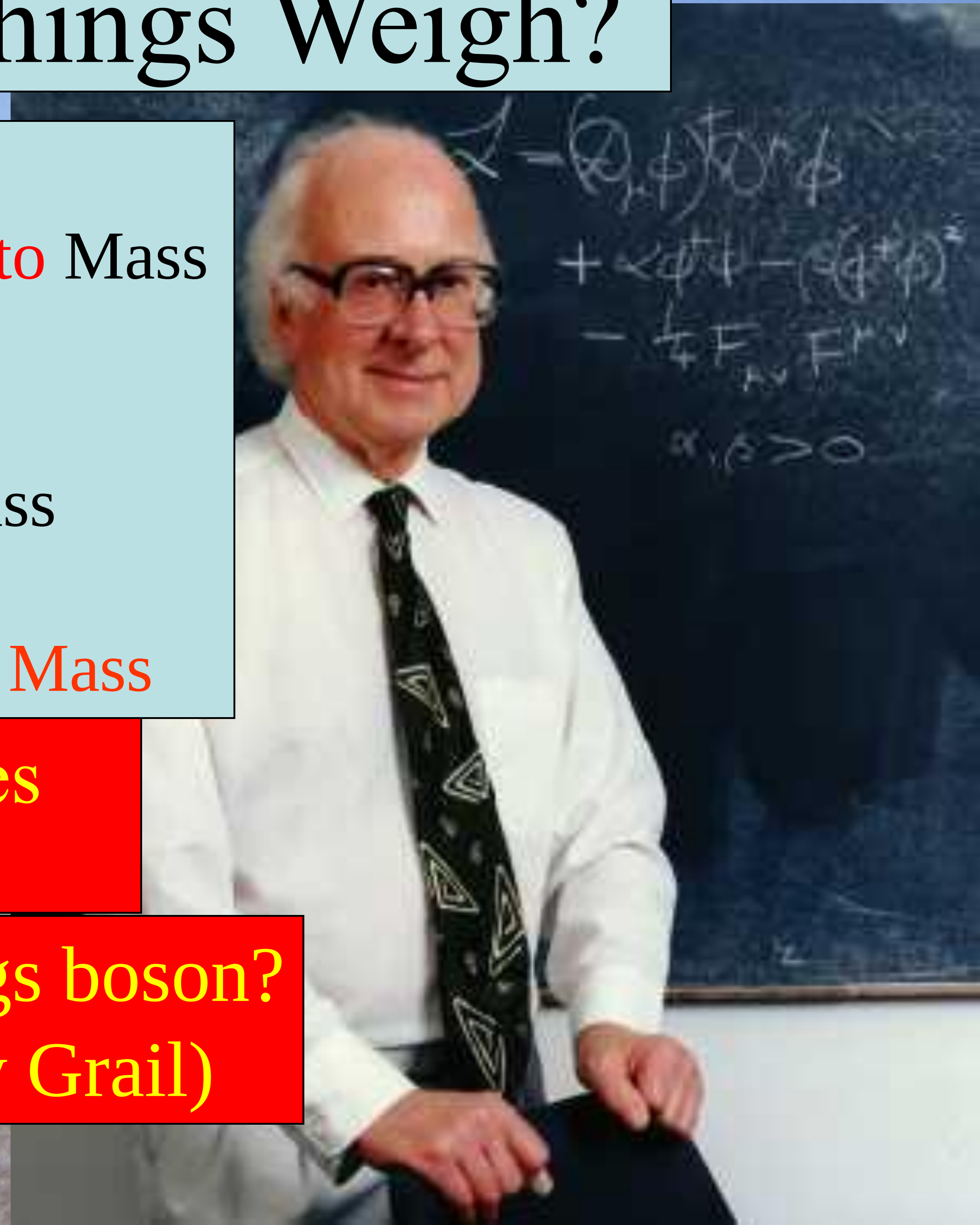
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)

Think of a Snowfield

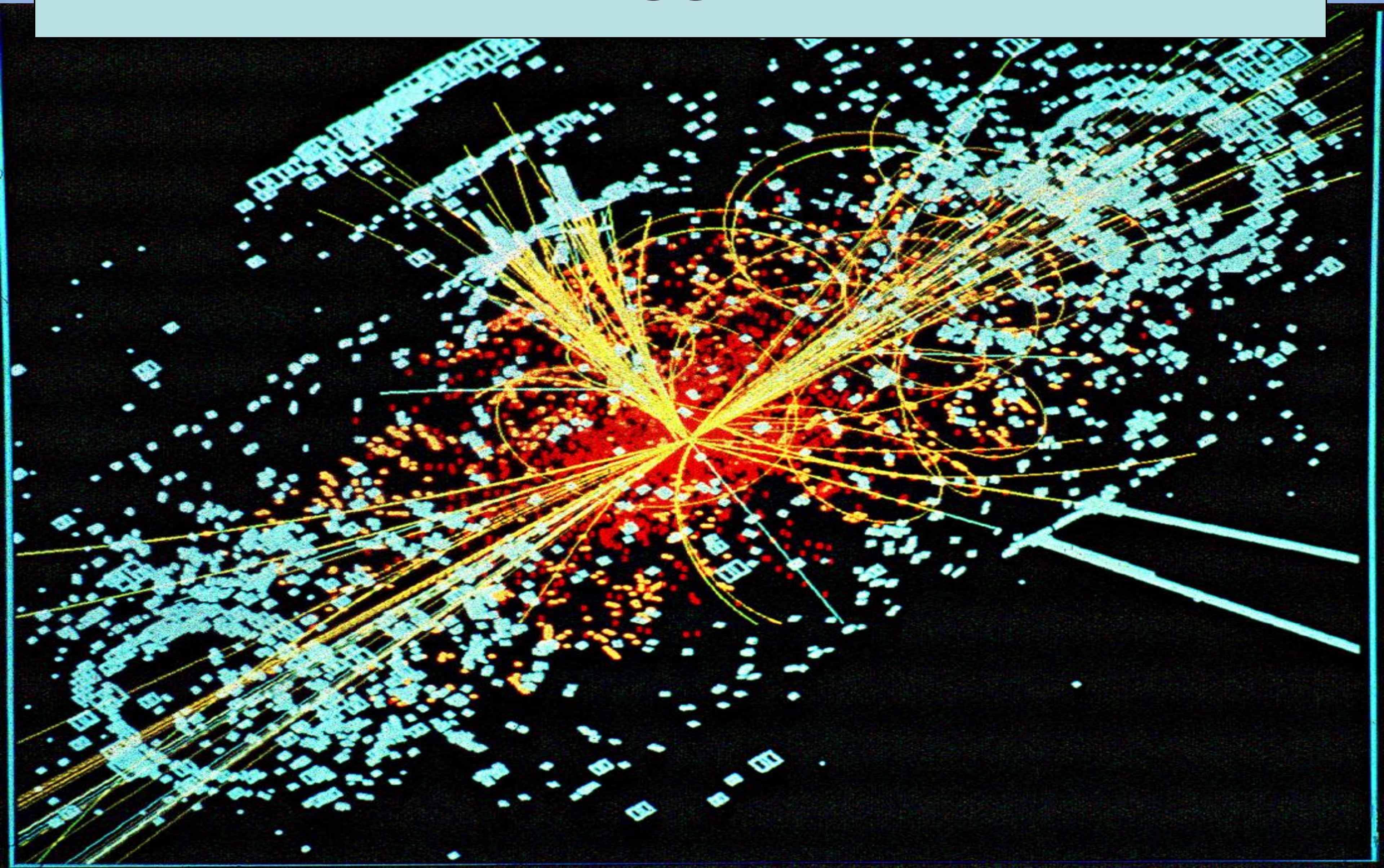
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC will look for the snowflake: The Higgs Boson

Hiker sinks deep,
moves very slowly:
Particle with large mass

A Simulated Higgs Event @ LHC

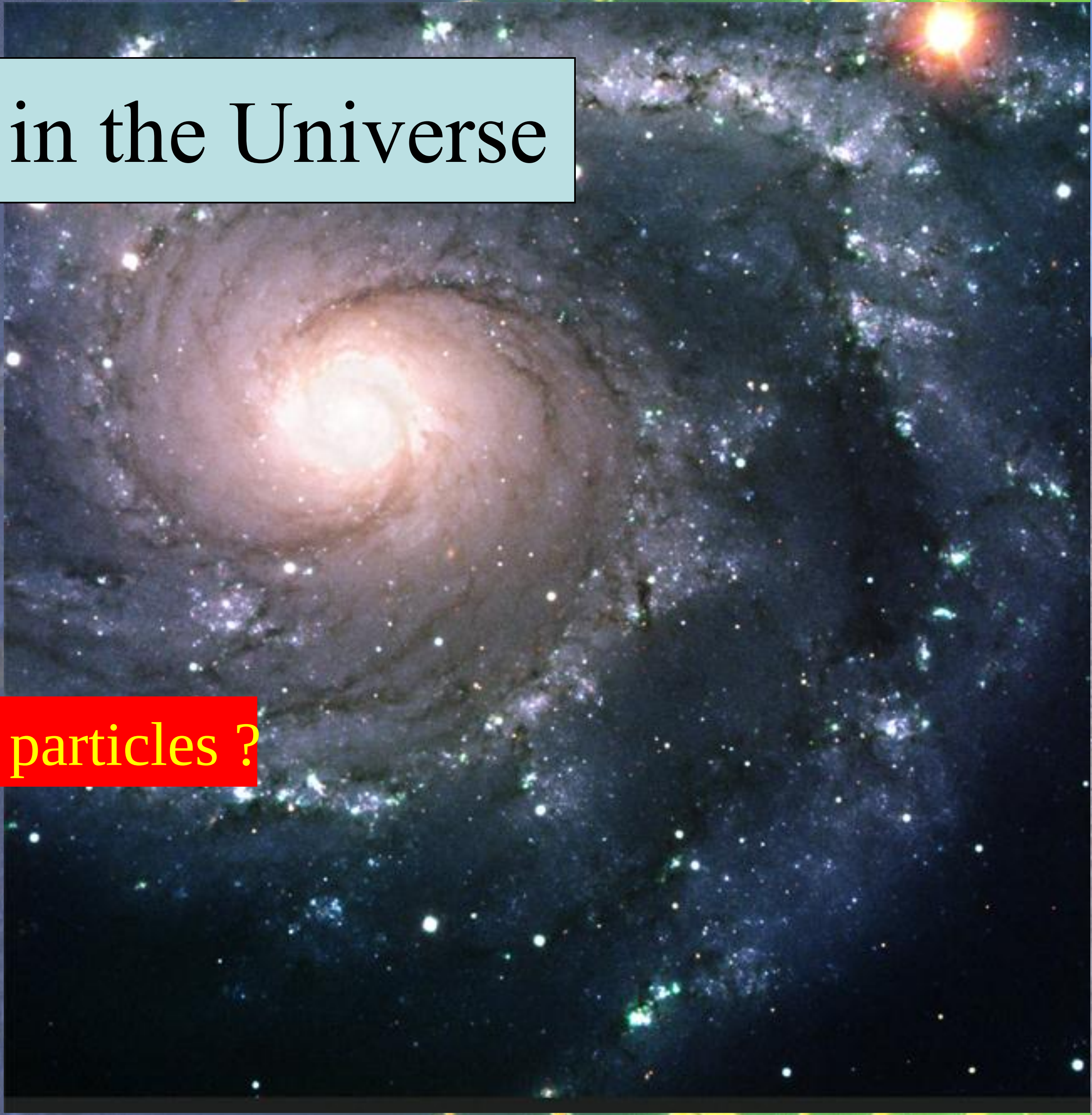


Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

'Supersymmetric' particles ?

We shall look for them with the LHC



Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

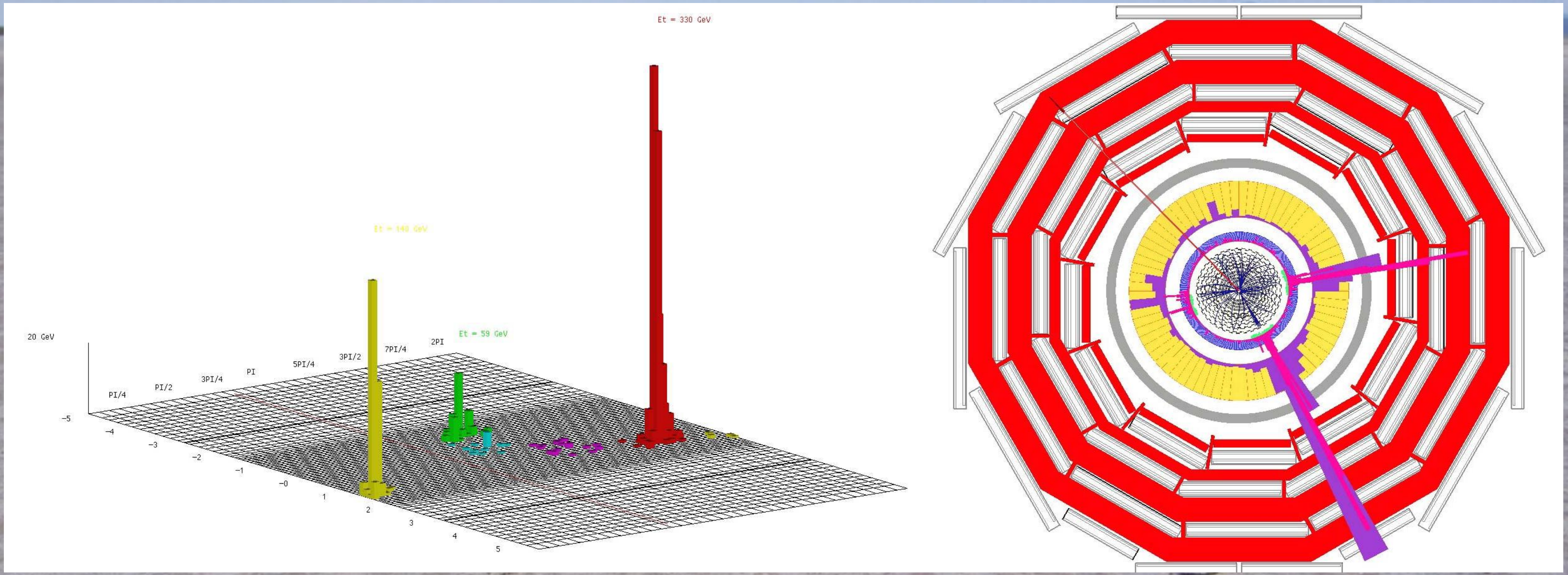
0 - ½ - 1 - 3/2 - 2

Higgs - Electron - Photon - Gravitino - Graviton

(Every particle is a 'ballet dancer')

- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

Classic Supersymmetric Signature



Missing transverse energy
carried away by dark matter particles

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

Studied using accelerators

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

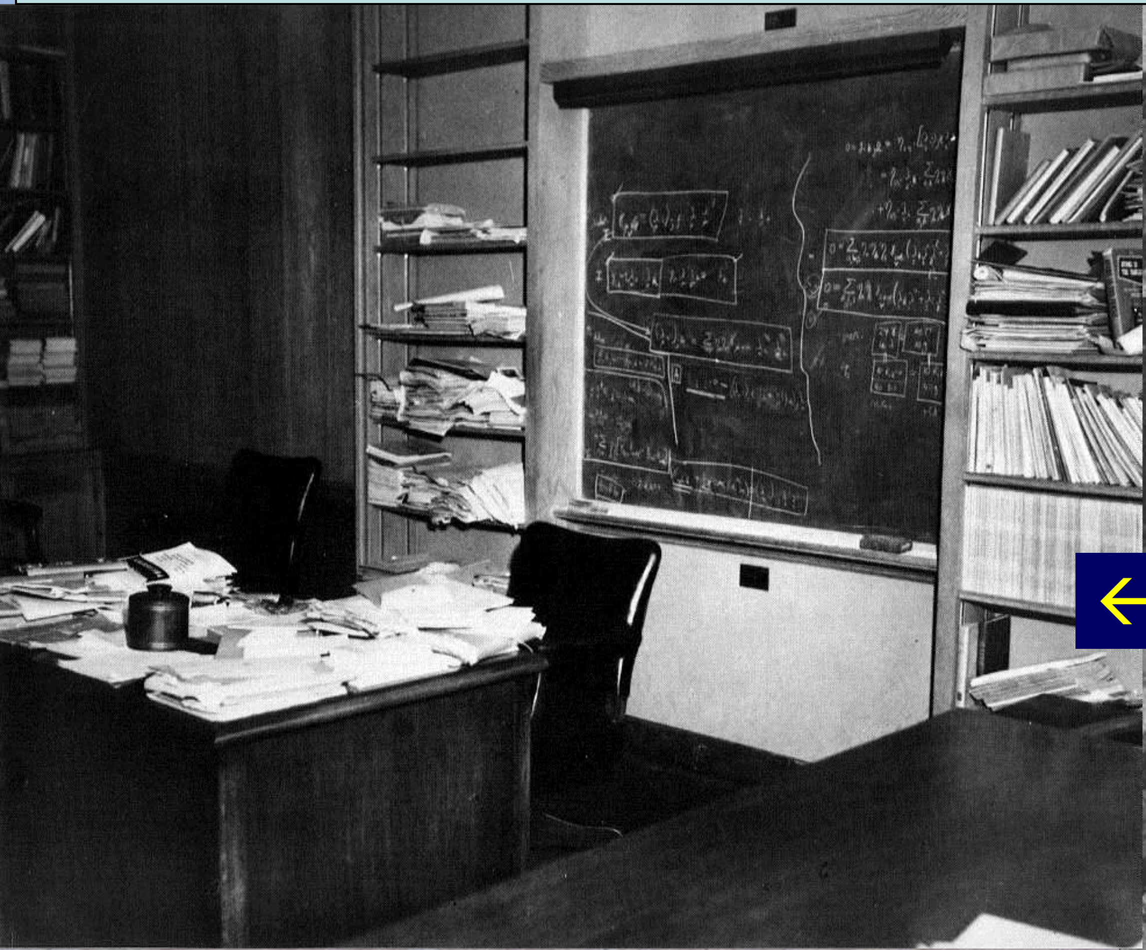
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  present in unified theories
  not yet seen by experiment
- Must break thermal equilibrium
  Possible in the decays of heavy particles

Will we be able to calculate using laboratory data?

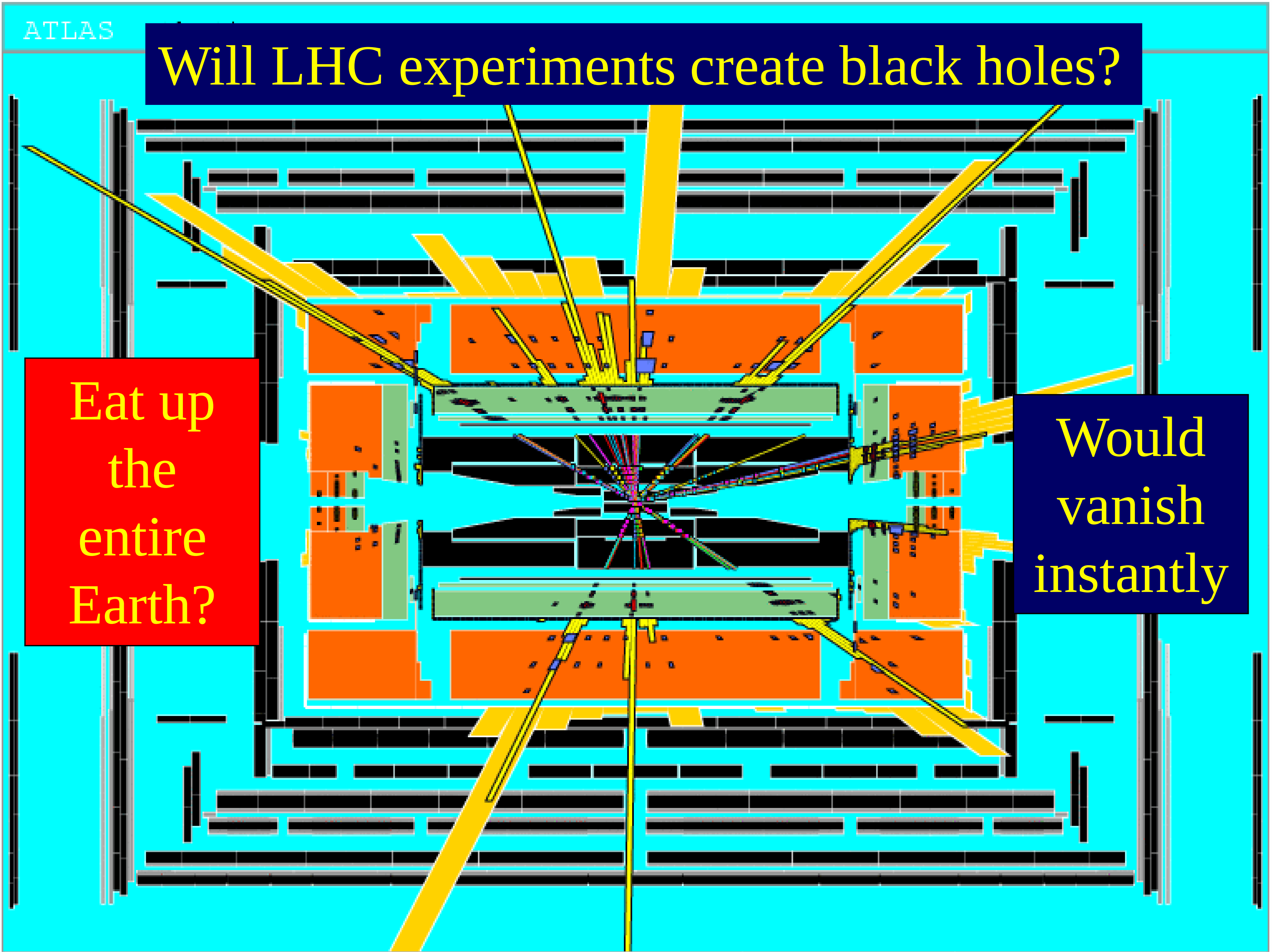
Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

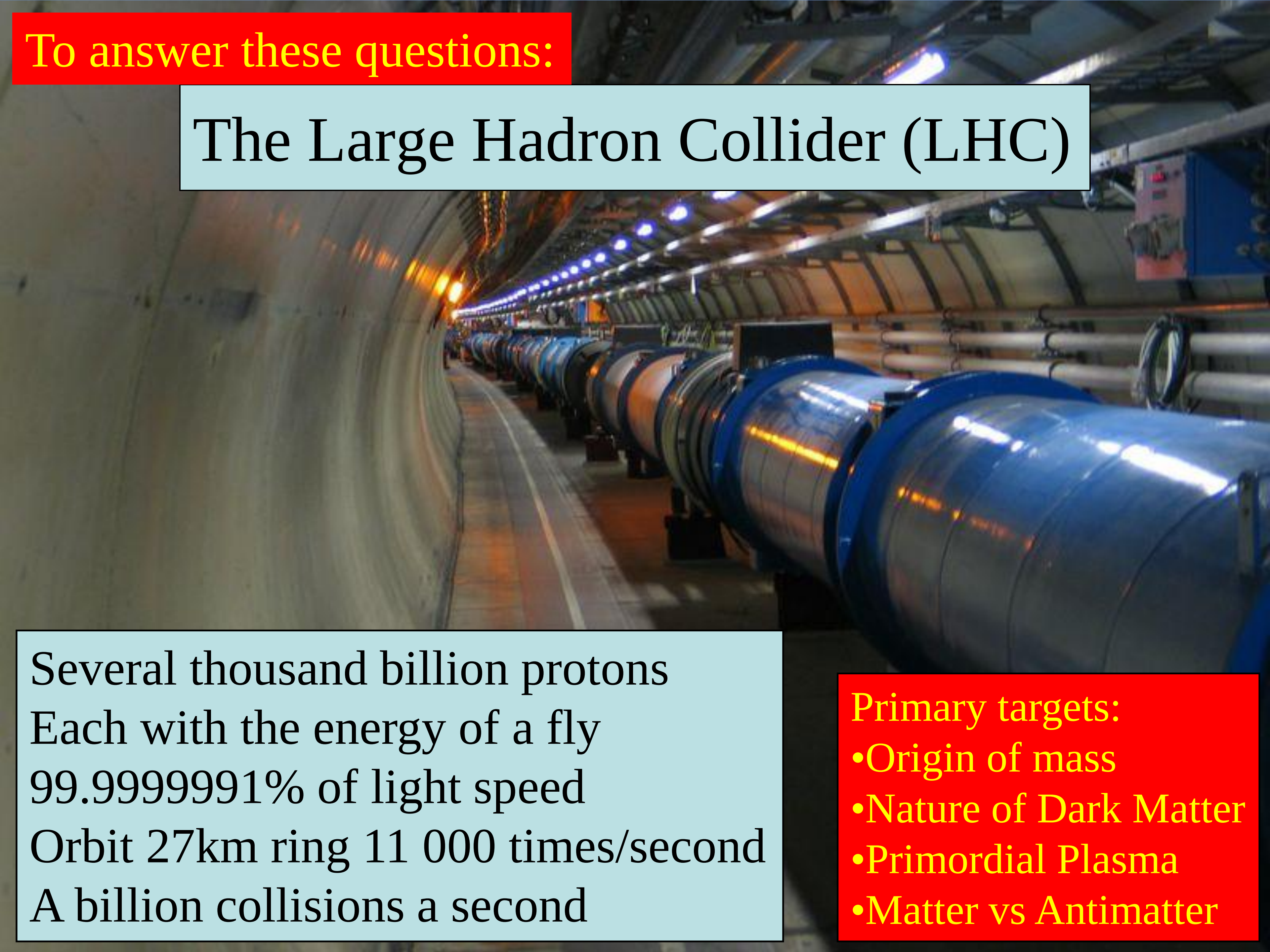
Unification via extra dimensions of space?

Will LHC experiments create black holes?



Eat up the entire Earth?

Would vanish instantly

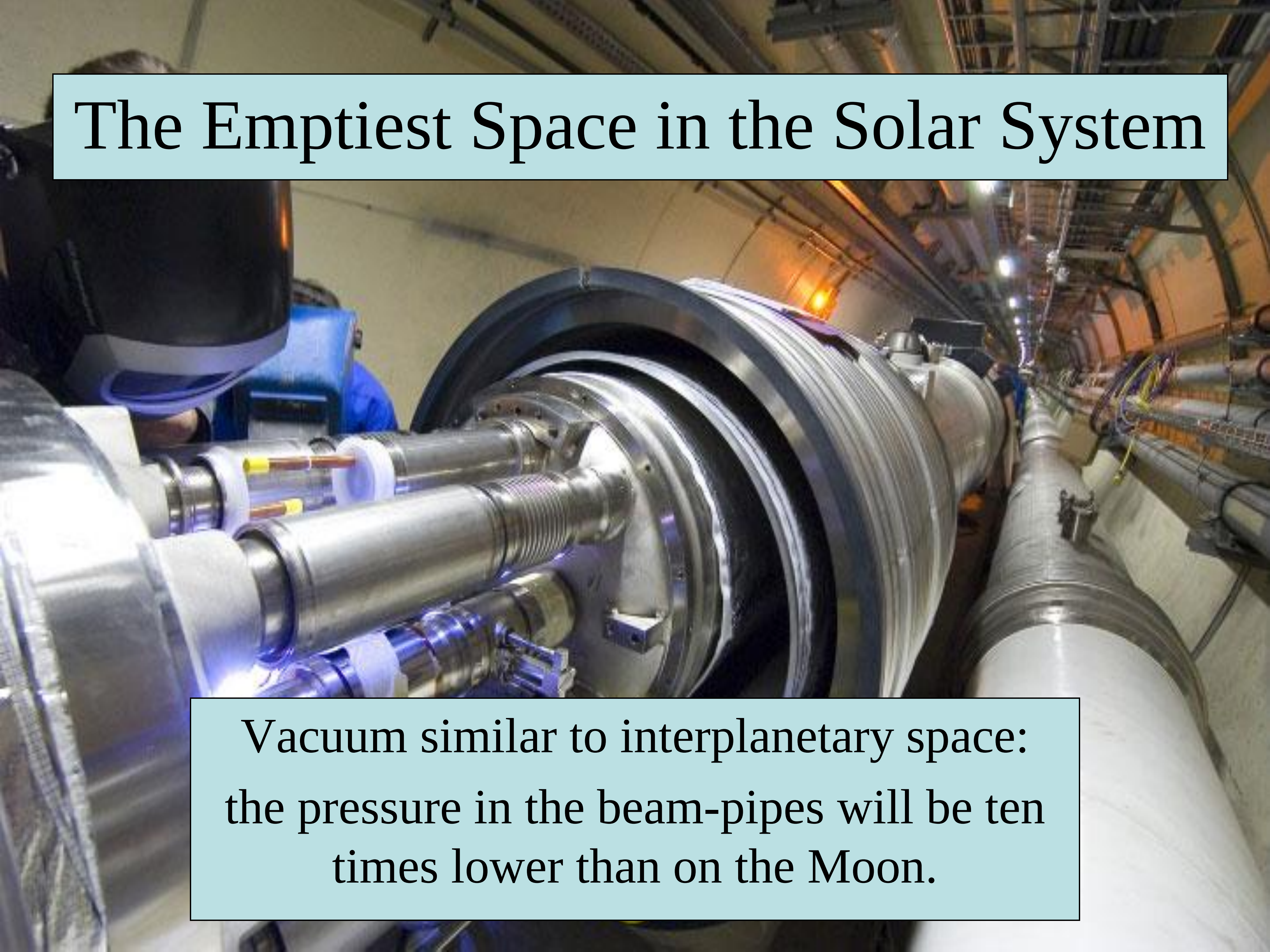


To answer these questions:

The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

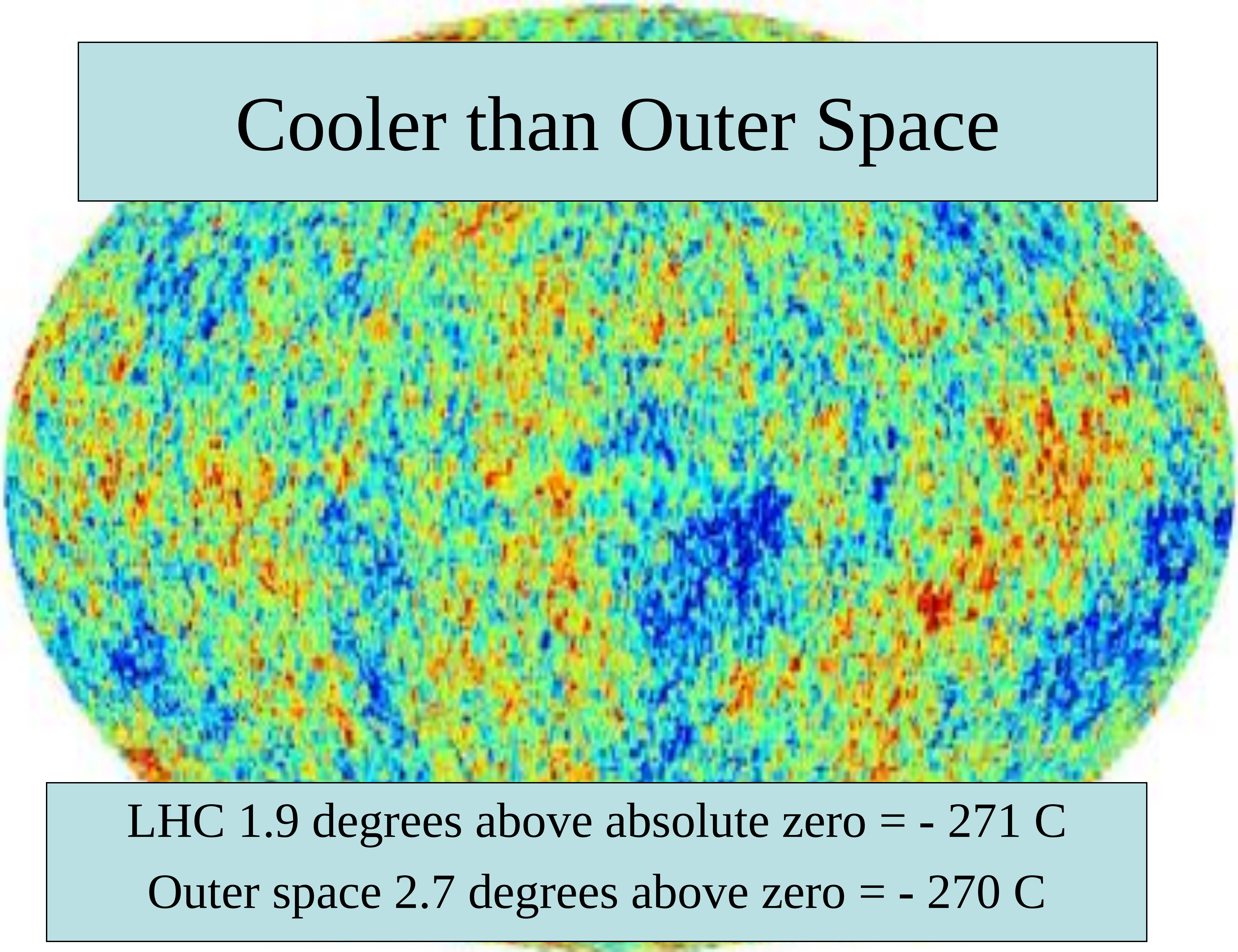


The Emptiest Space in the Solar System

Vacuum similar to interplanetary space:

the pressure in the beam-pipes will be ten times lower than on the Moon.

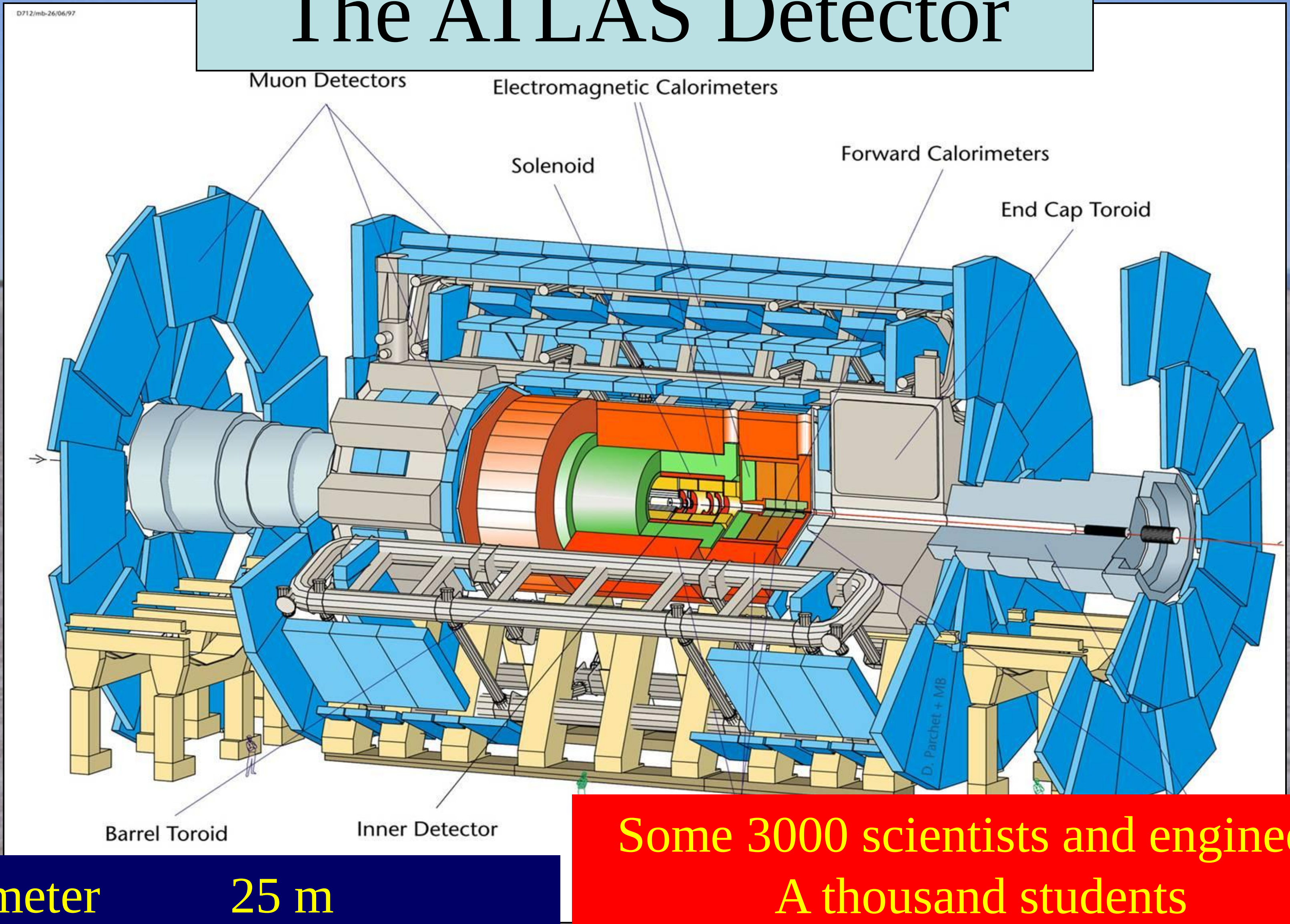
Cooler than Outer Space



LHC 1.9 degrees above absolute zero = - 271 C

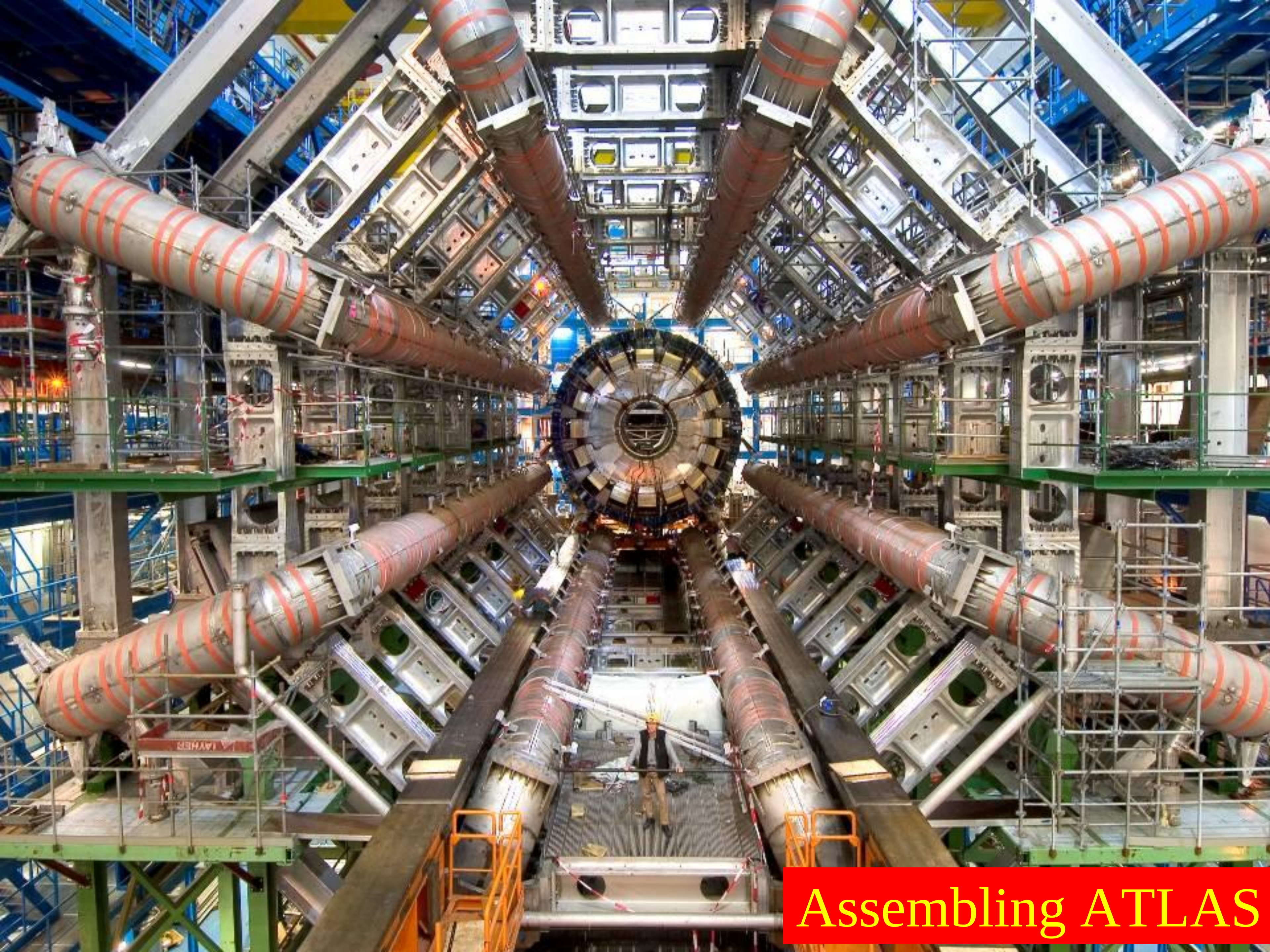
Outer space 2.7 degrees above zero = - 270 C

The ATLAS Detector

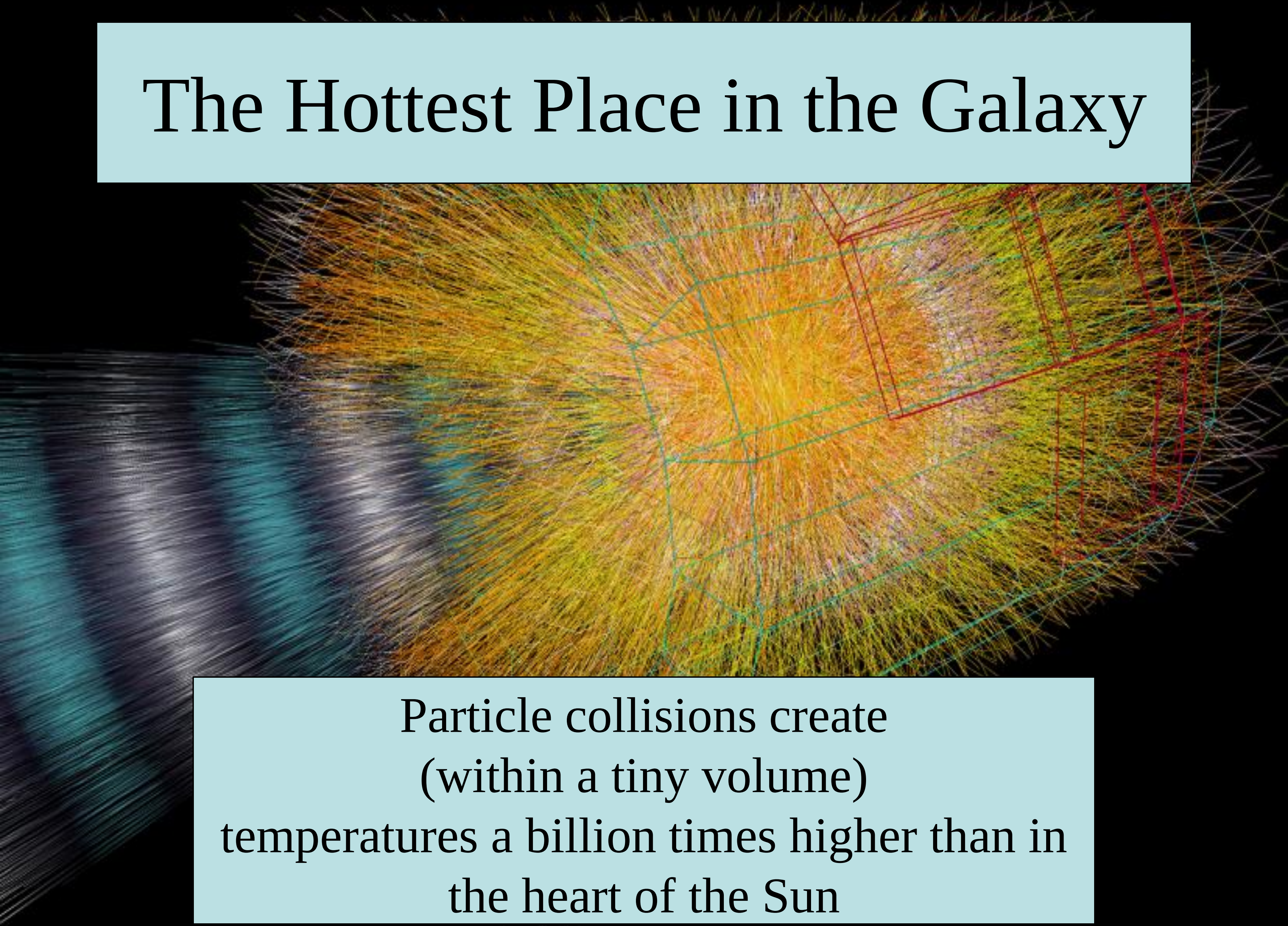


Diameter 25 m
Total length 46 m
Overall weight 7000 tons

Some 3000 scientists and engineers
A thousand students
Nearly 40 countries
More components than a moon rocket


Assembling ATLAS

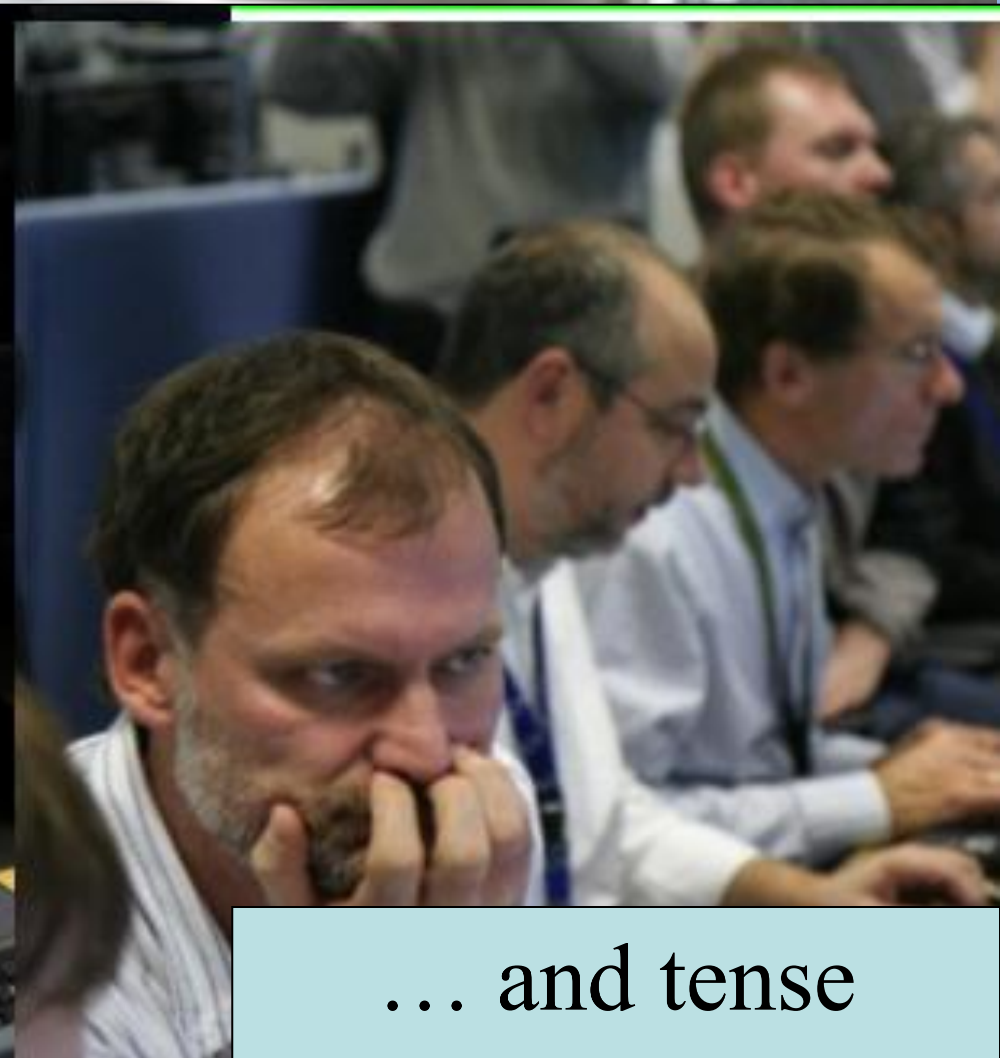
The Hottest Place in the Galaxy



Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in
the heart of the Sun

A billion people watched on TV

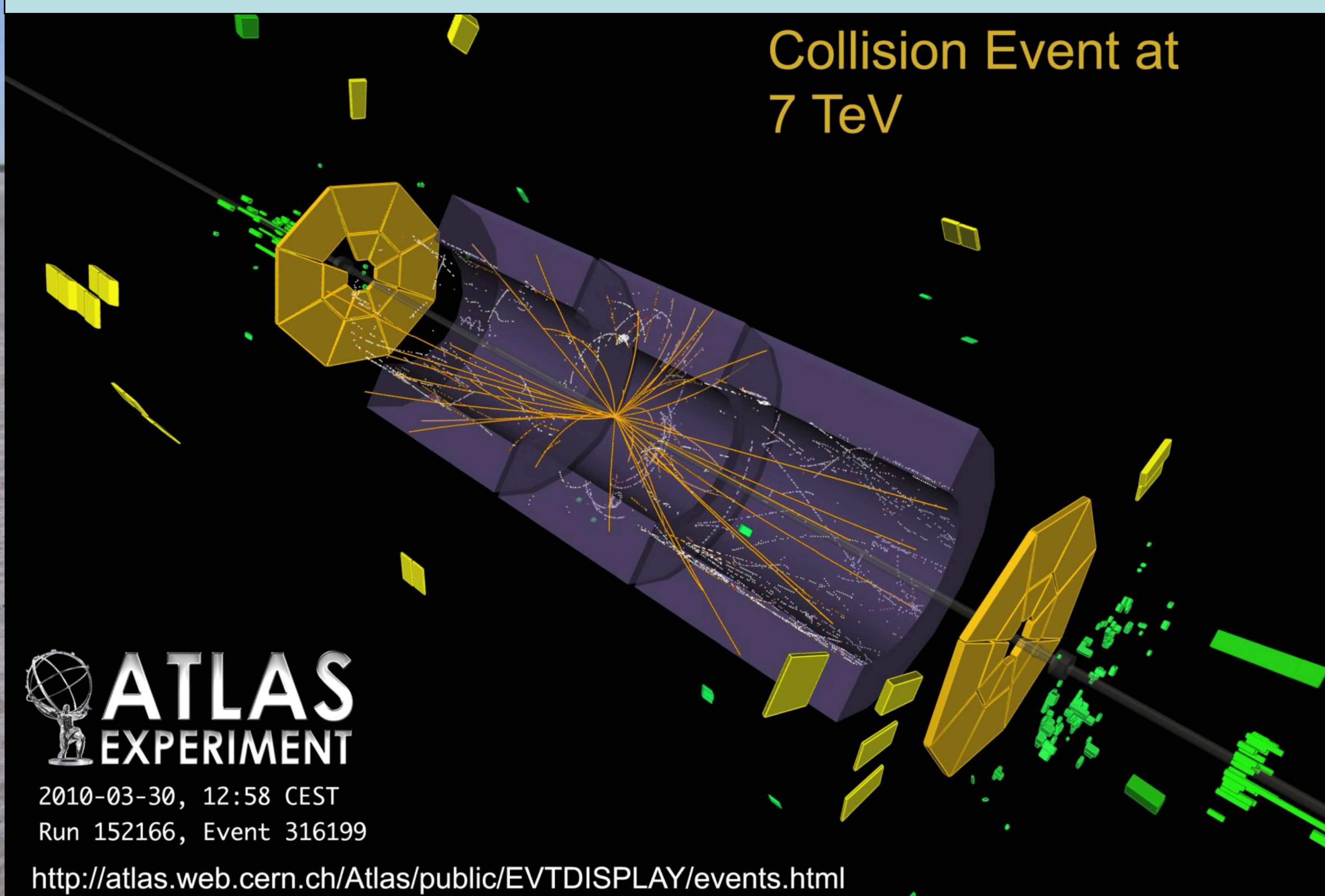
Concentration, Anxiety …



… and tense anticipation

Nov. 20th 2009: Jubilation

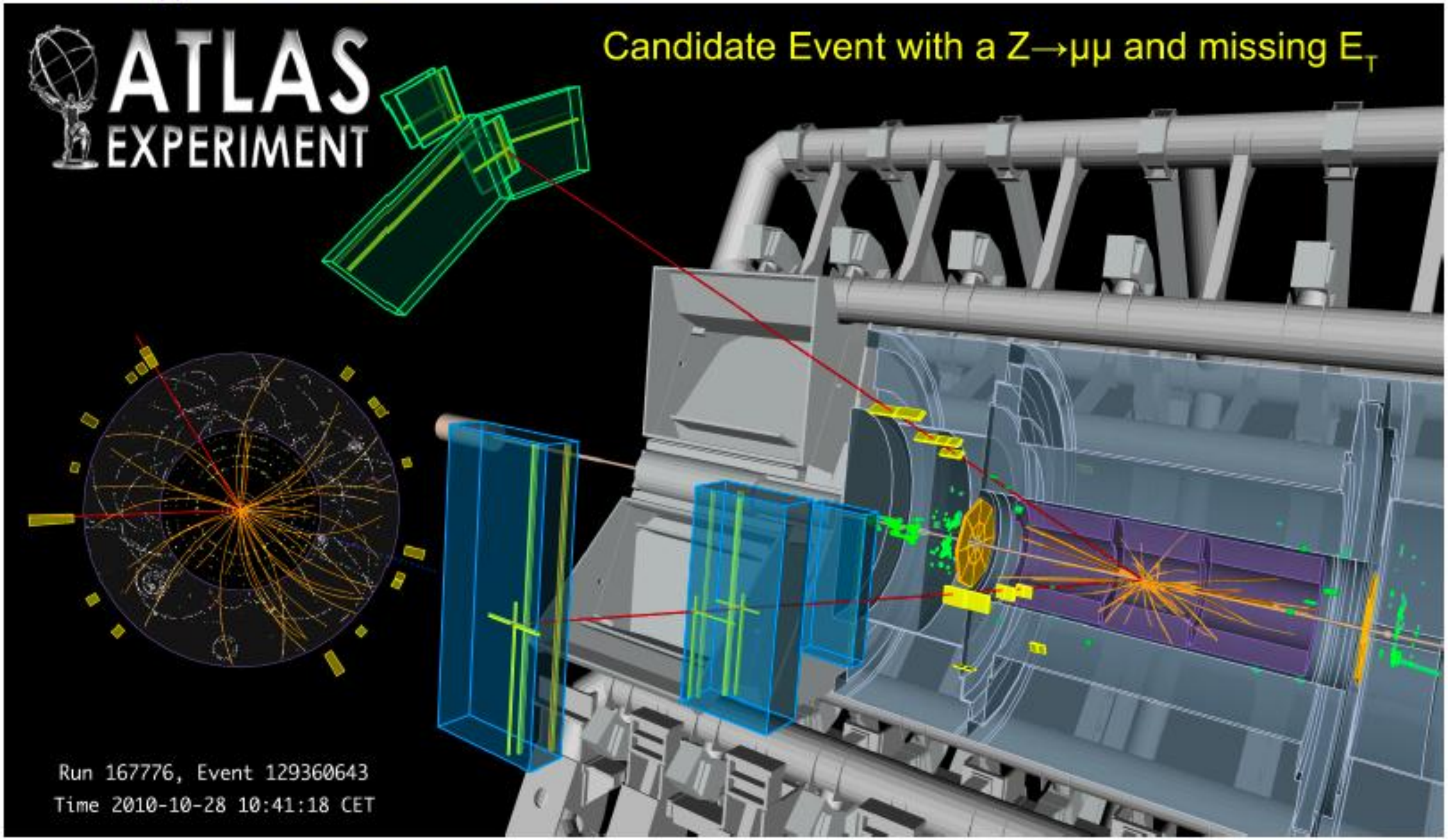
First High-Energy LHC Collision



First Higgs Events at the LHC

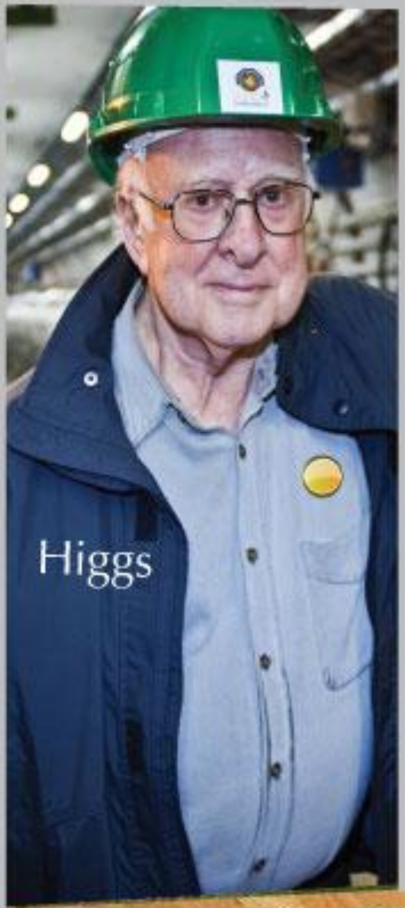
Interesting Events

$m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



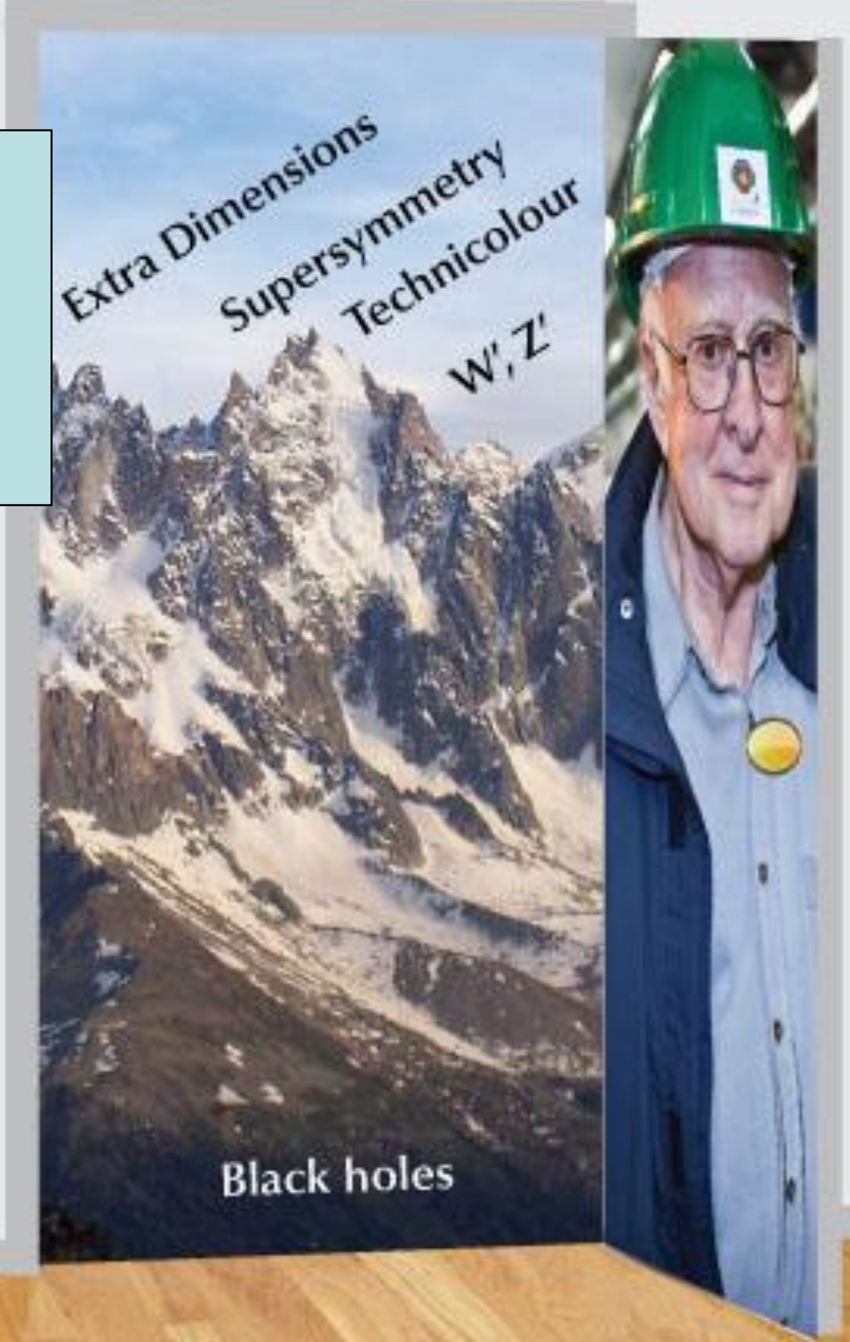
No black holes yet!

Imagine a Room …



… Open The Door

What lies Beyond?

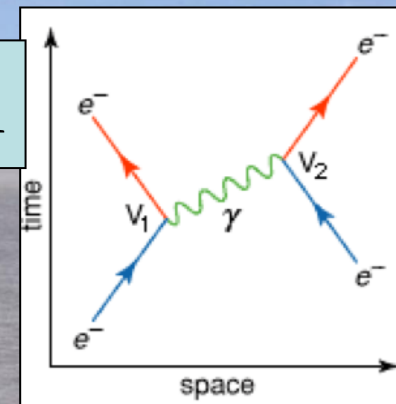


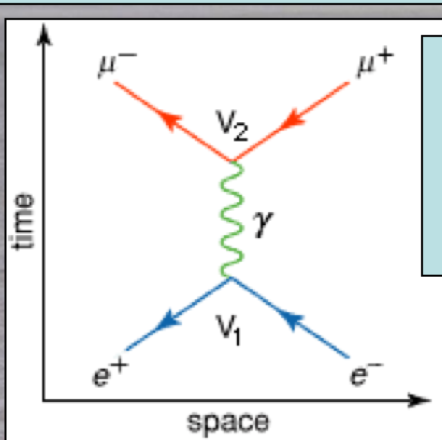
The LHC is not only the World’s most powerful microscope,
but also a telescope

Looking towards
the beginning of time

Discoveries of Force Particles

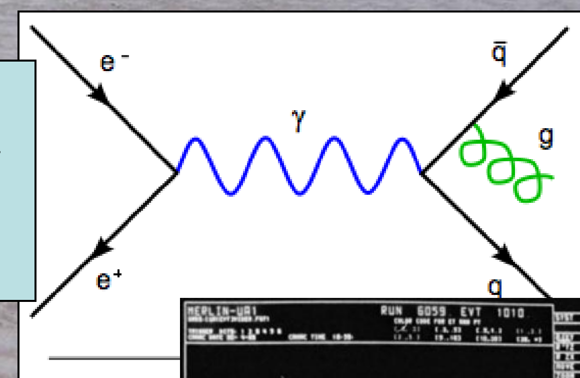
Photon exchange in electromagnetism

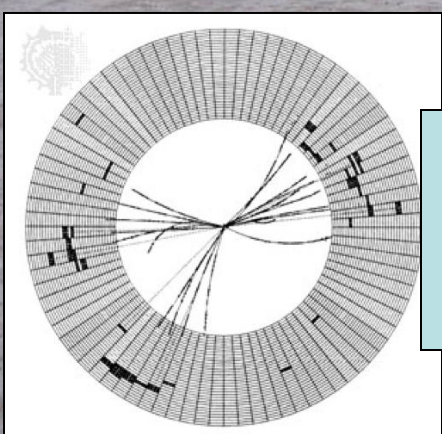




Electron-positron annihilation

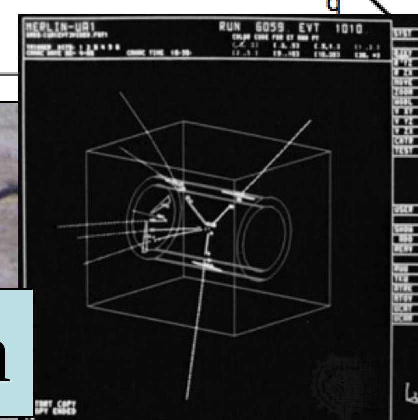
With radiation of a gluon





Experimental evidence for gluon

Evidence for weak boson



Quantum Electrodynamics

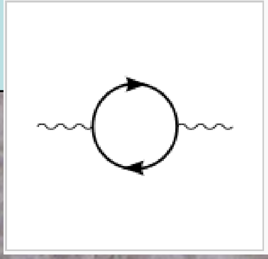
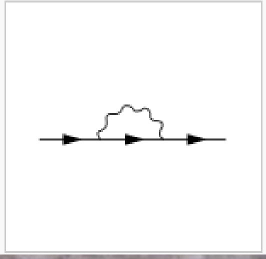
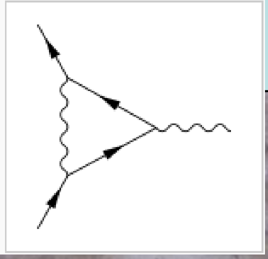
- Lagrangian of QED:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Equations of motion:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \right) - \frac{\partial \mathcal{L}}{\partial \psi} = 0 \qquad \partial_\nu F^{\nu\mu} = e\bar{\psi}\gamma^\mu\psi$$

- Renormalizable quantum field theory
- Successful accurate predictions in perturbation theory:
  - 10^{-12} for anomalous magnetic moment of electron, **but muon?**

The Strong Nuclear Interactions

- Quantum chromodynamics: gluon fields acting on quarks:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu$$

- Only theory able to explain 'asymptotically free' quarks confined inside nuclear particles

$$\alpha_s(k^2) \stackrel{\text{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)}$$

- Many proofs of existence of quarks
- **But how to prove existence of gluons?**