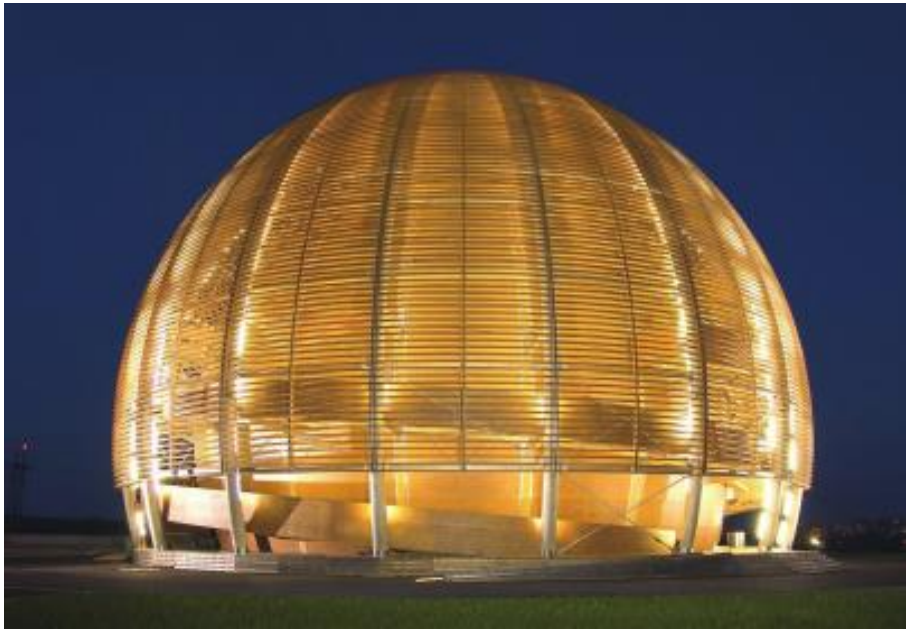
Introduction to Particle Physics (Theory)

I. Antoniadis

CERN



Particle physics: structure of matter & fundamental forces

Experimental tools: Particle colliders at very high energies $\Rightarrow$

physical laws of nature at very short distances

- LEP2 (CERN): electron - positron collisions at 200 GeV * $\rightarrow 10^{-17}$ m
- TEVATRON (USA): protons - antiprotons at 2 TeV $\rightarrow 10^{-18}$ m
- LHC (CERN): proton - proton collisions at 14 TeV ** $\rightarrow 10^{-19}$ m

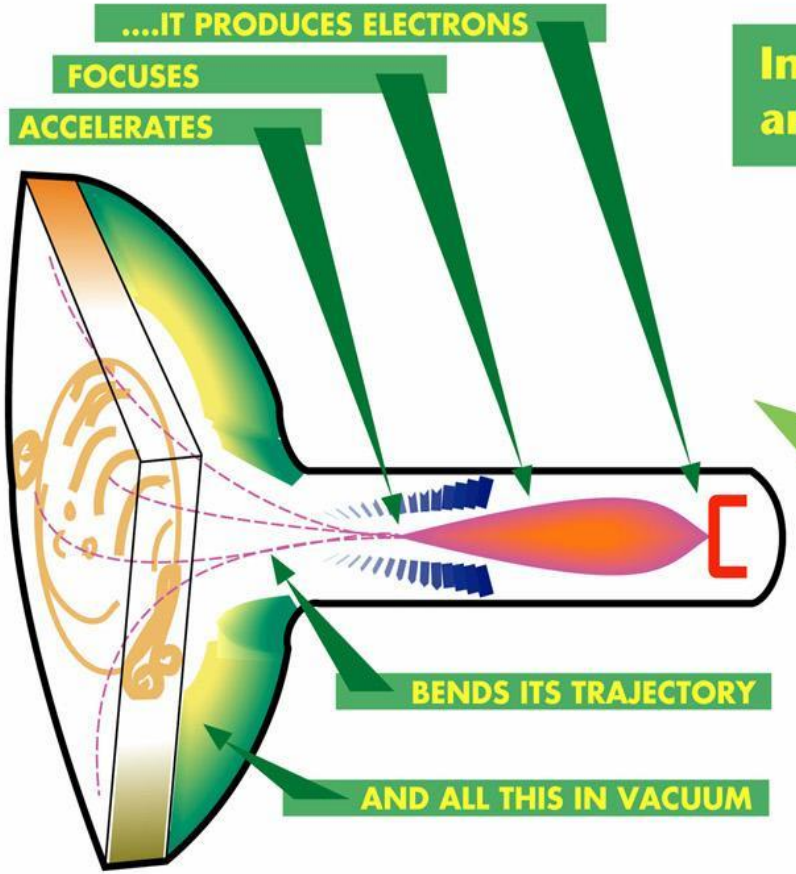
Th description: simple mathematical theories with predictive power

encoding the symmetries of physical phenomena

* 1 GeV $\simeq$ proton rest mass ($E = mc^2$) $\rightarrow 10^{-15}$ m

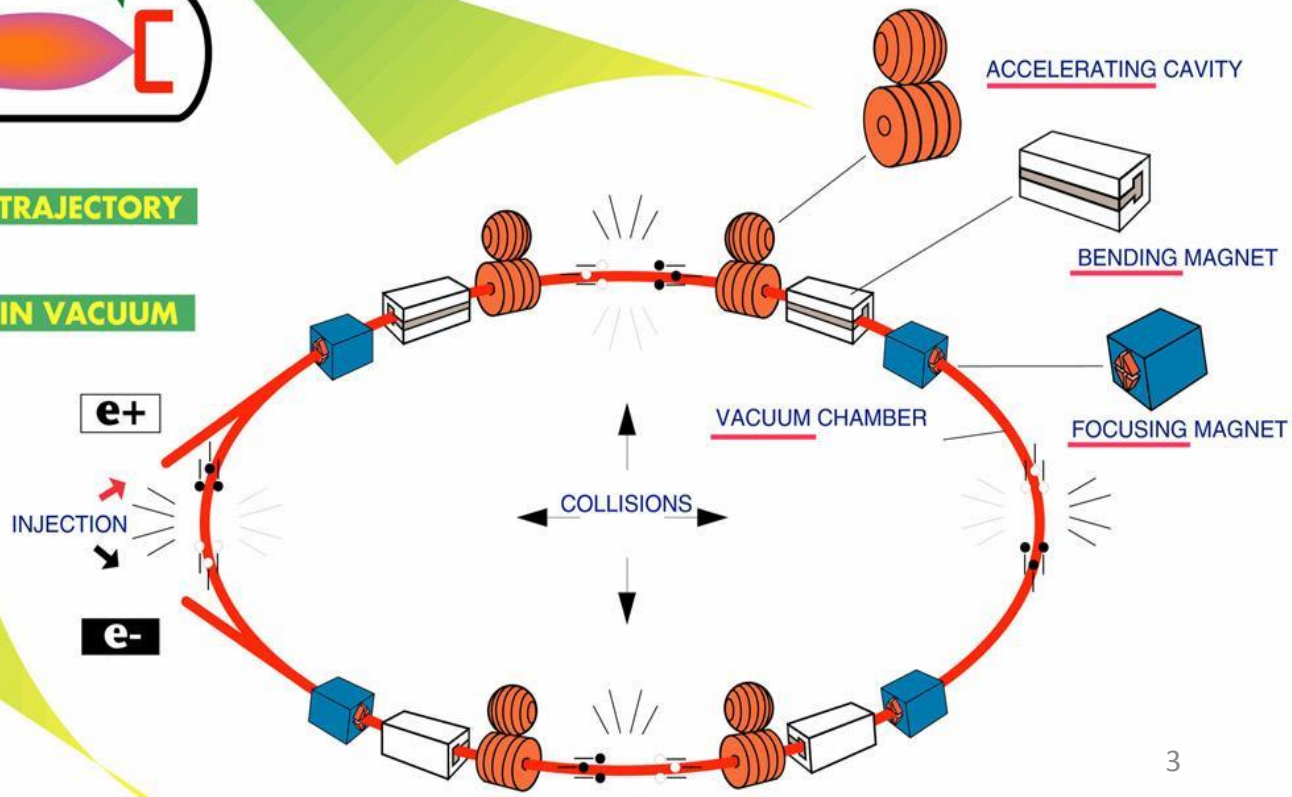
** for the moment 8 TeV 1 TeV = 1000 GeV

DID YOU KNOW YOUR TELEVISION SET IS AN ACCELERATOR ?



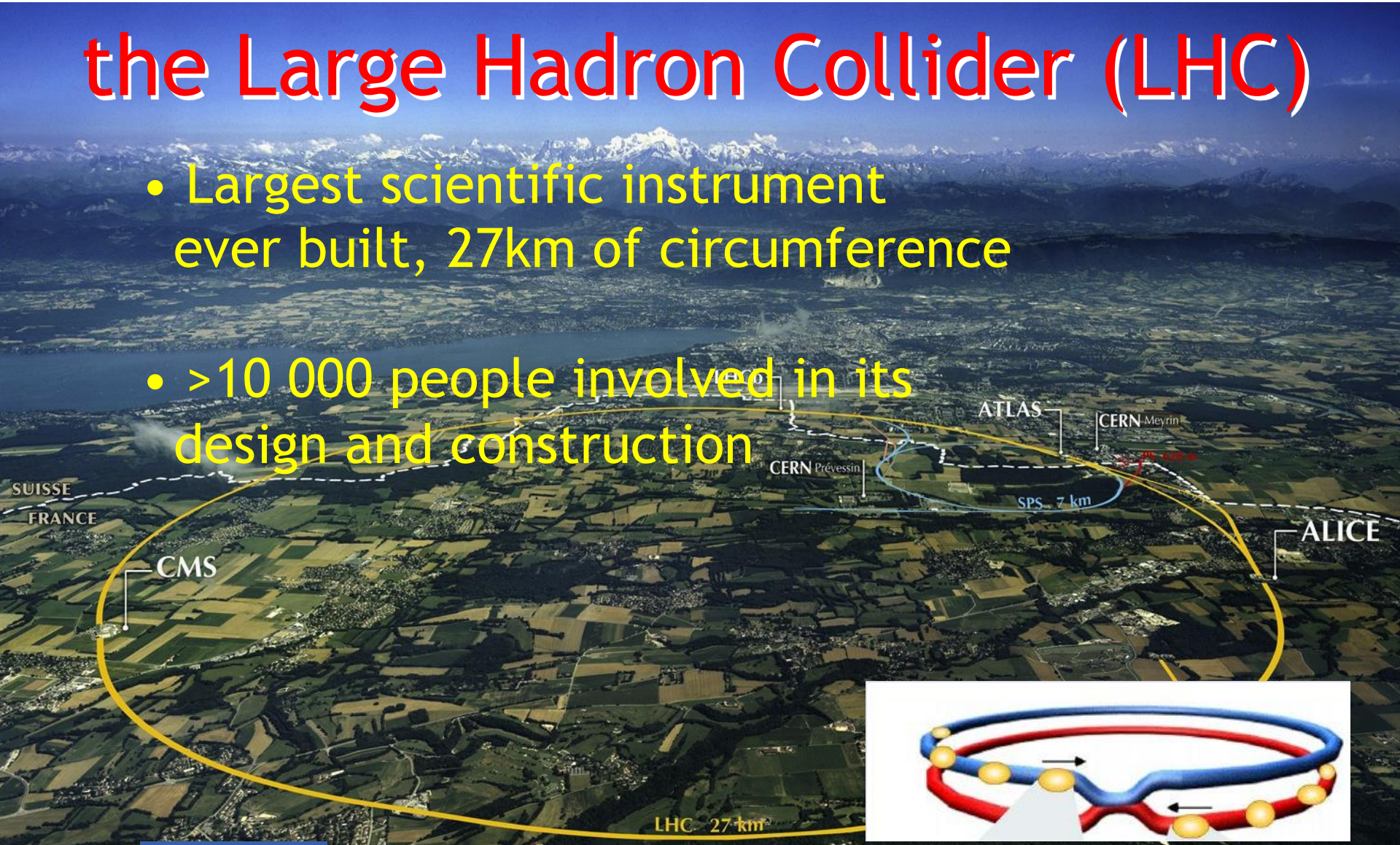
In your TV set, the electrons are accelerated to 20000 volts.

In LEP, they are accelerated to 100 000 000 000 volts.



the Large Hadron Collider (LHC)

- Largest scientific instrument ever built, 27km of circumference
- >10 000 people involved in its design and construction



at CERN *Accelerating Science and Innovation*

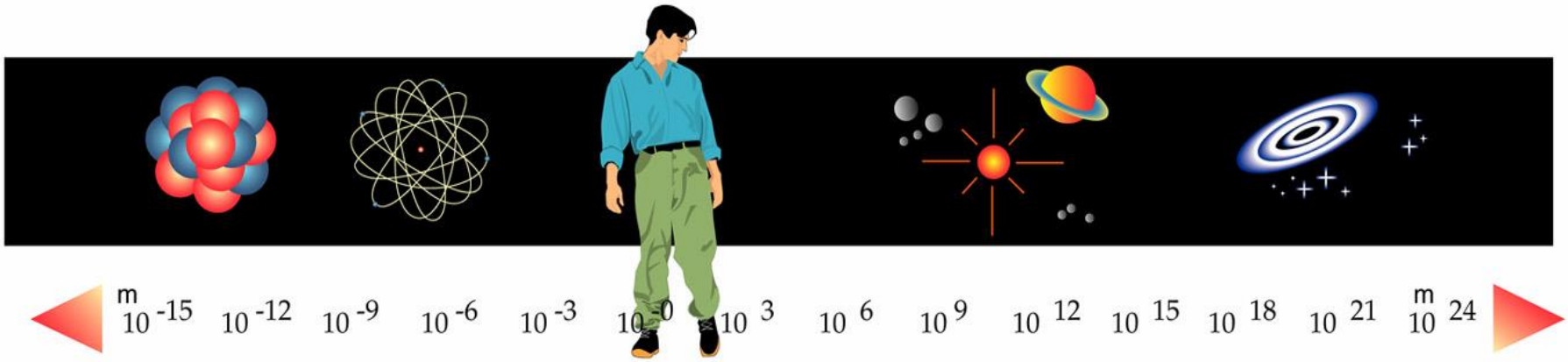

The LHC is the world's most powerful microscope …
… and also a telescope

La physique des particules étudie la matière dans ses dimensions les plus petites.

Particle physics looks at matter in its smallest dimensions.

L'astrophysique étudie la matière dans ses dimensions les plus grandes.

Astrophysics looks at matter in its largest dimensions.



m
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} m 10^{24}

Microscopes
Microscopes

Jumelles
Binoculars

Telescopes optiques & radio
Optical & radio telescopes

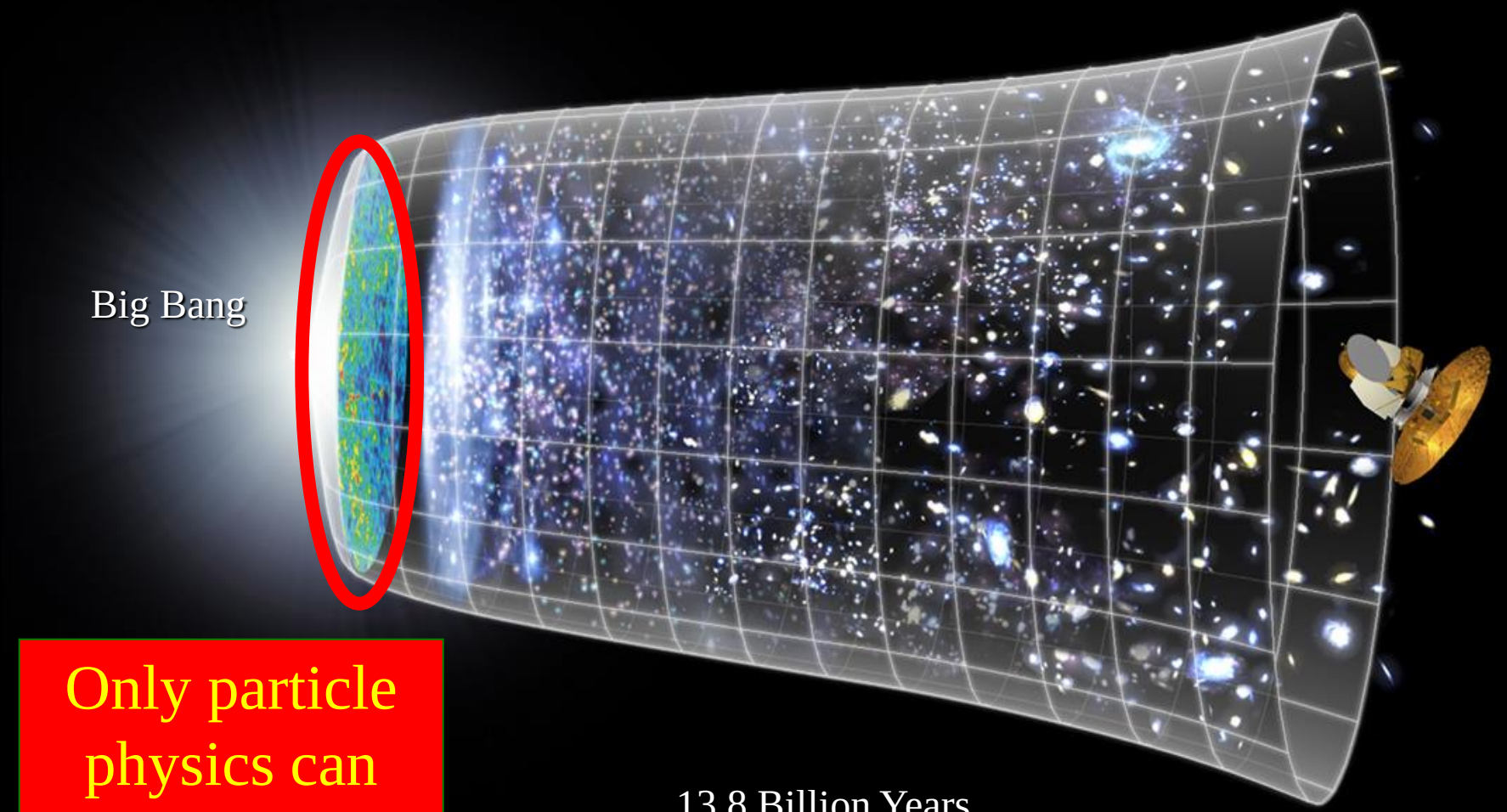
L'oeil nu.
Naked eye

Accélérateurs et détecteurs
Accelerators and detectors

THE TWO FRONTIERS OF PHYSICS

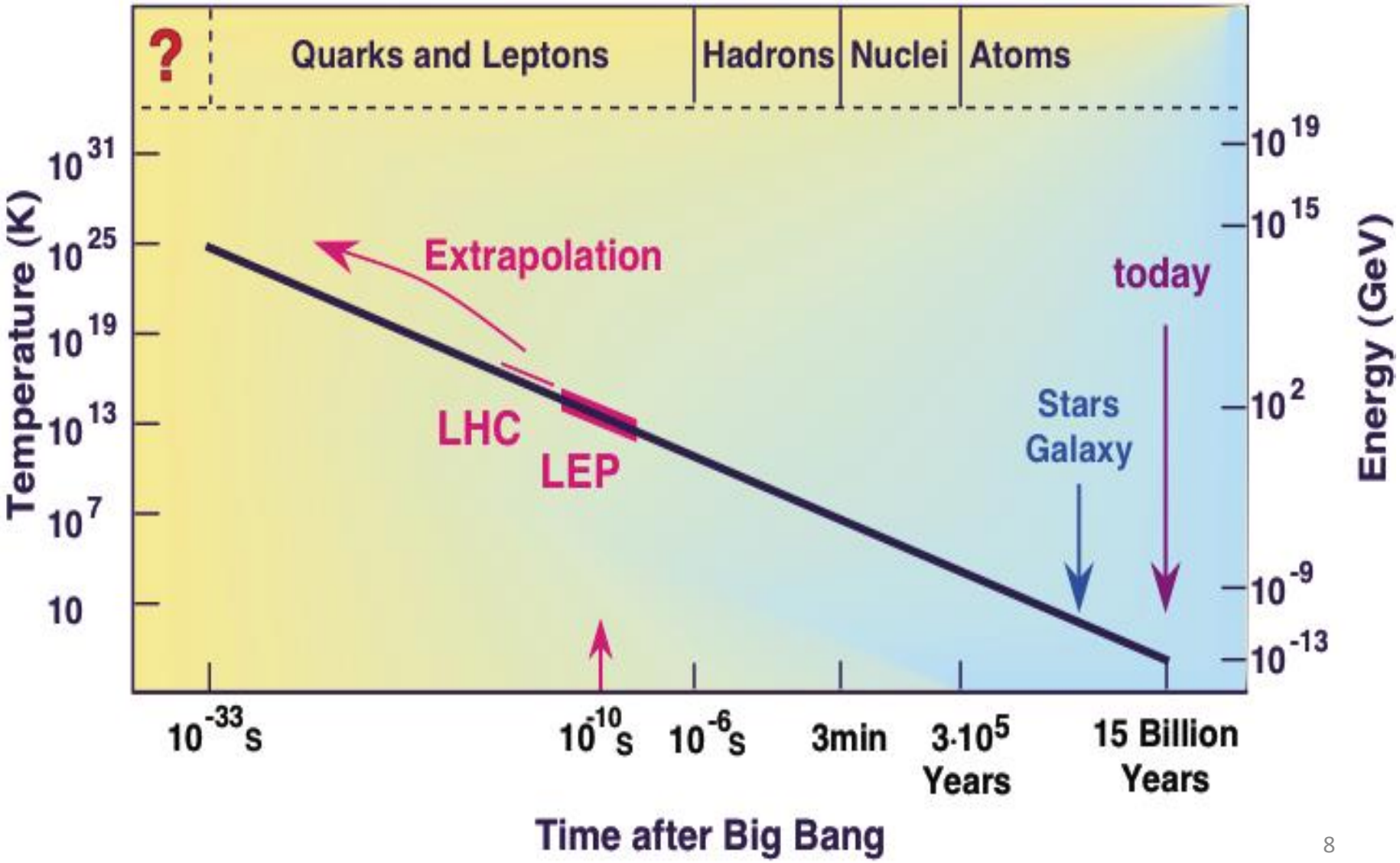
LES DEUX FRONTIERES DE LA PHYSIQUE

Evolution of the Universe



Only particle physics can tell us what happened here

Evolution of the Universe



Major discoveries → fundamental constants

- Thermodynamics : $E = k_B T$

  k_B = Boltzmann constant

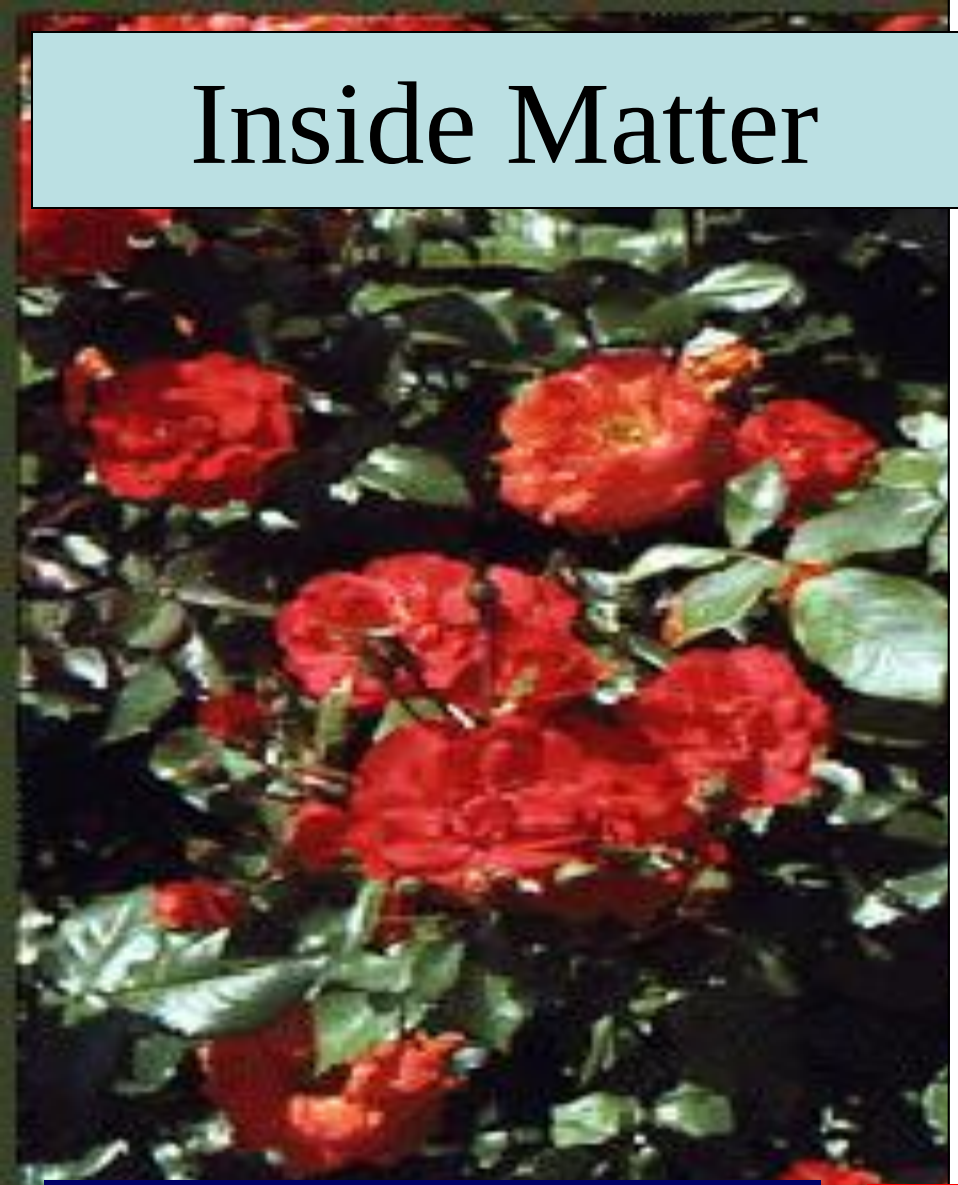
- Special relativity : $E = mc^2$

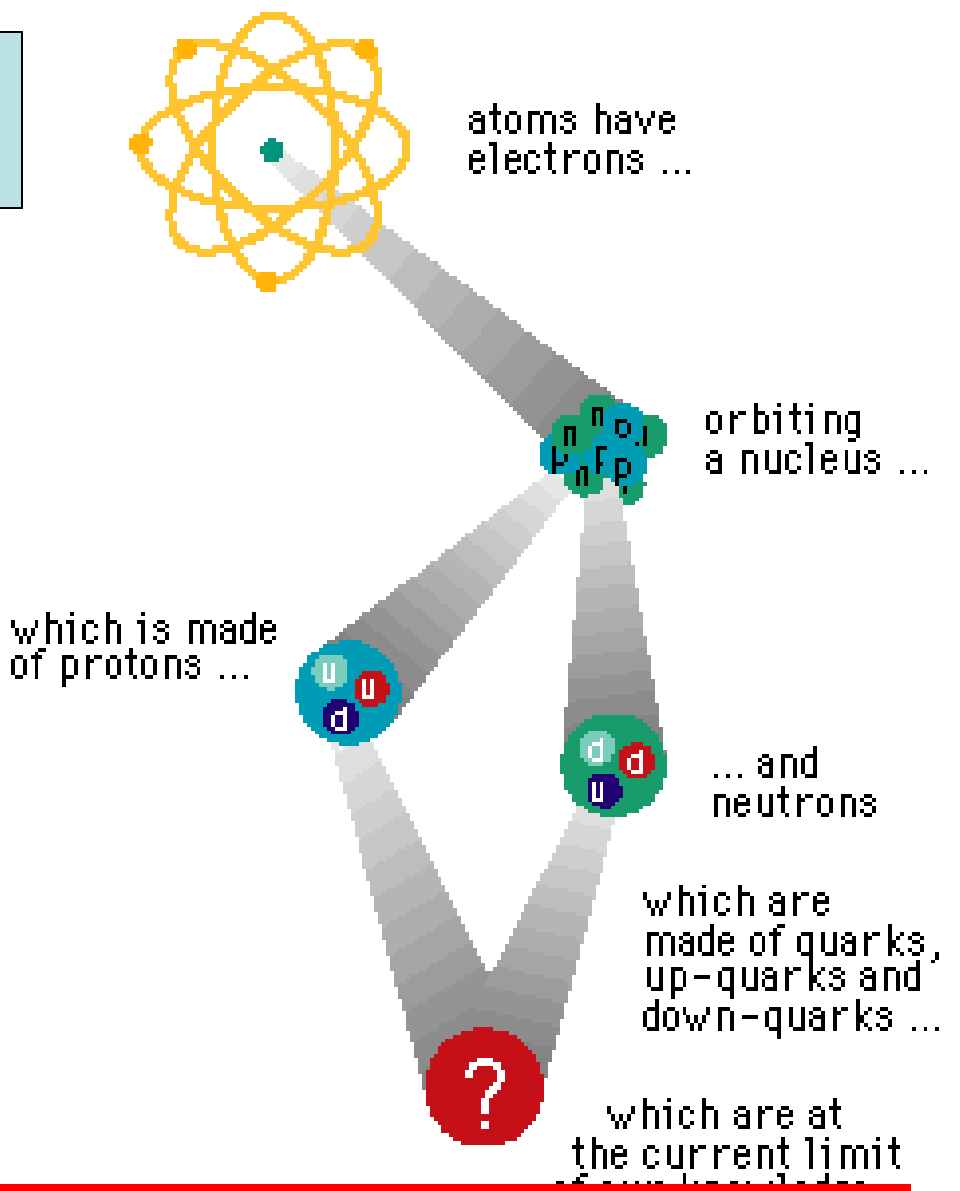
  c = speed of light

- Quantum mechanics : $L \geq h/E$

  h = Planck constant

Inside Matter



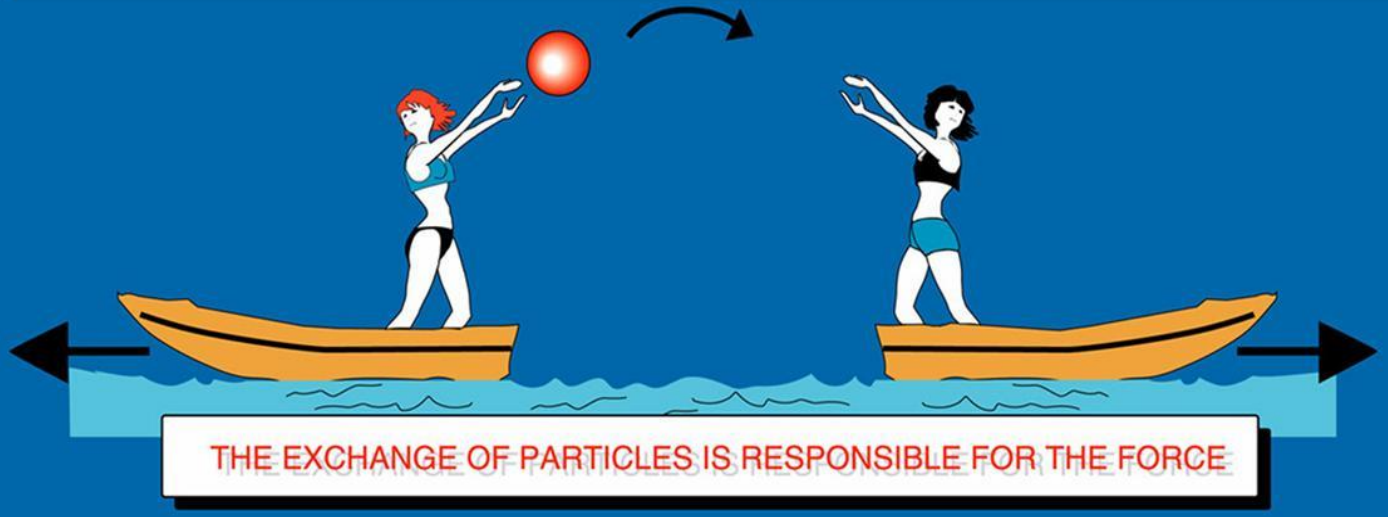


All matter is made of the same constituents

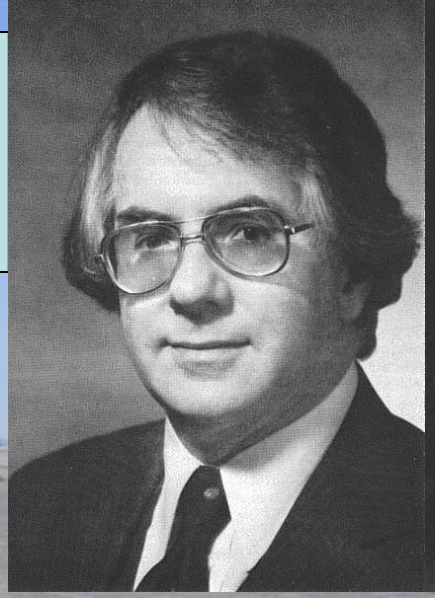
What are they?
What forces between them?

The forces in Nature

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	~ 10^{-3}	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	~ 10^{-5}	BOSONS Z^{o} , W+ , W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	~ 10^{-38}	GRAVITONS (?)	HEAVENLY BODIES

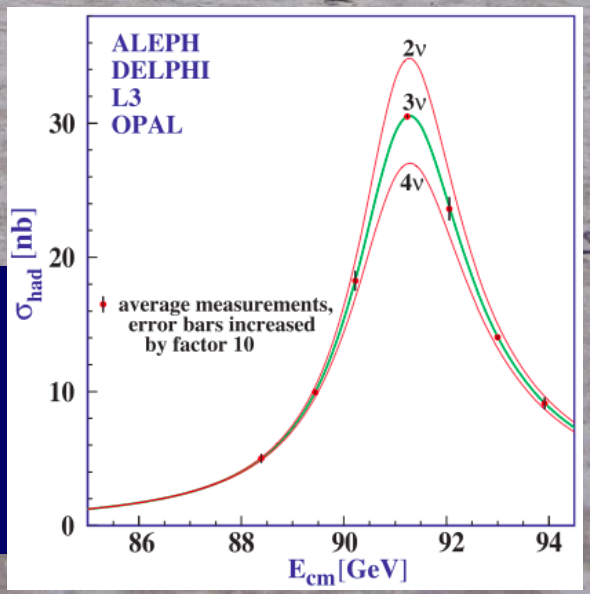


The ‘Standard Model’ of Particle Physics



Proposed by Glashow, Salam and Weinberg

Tested by experiments at CERN

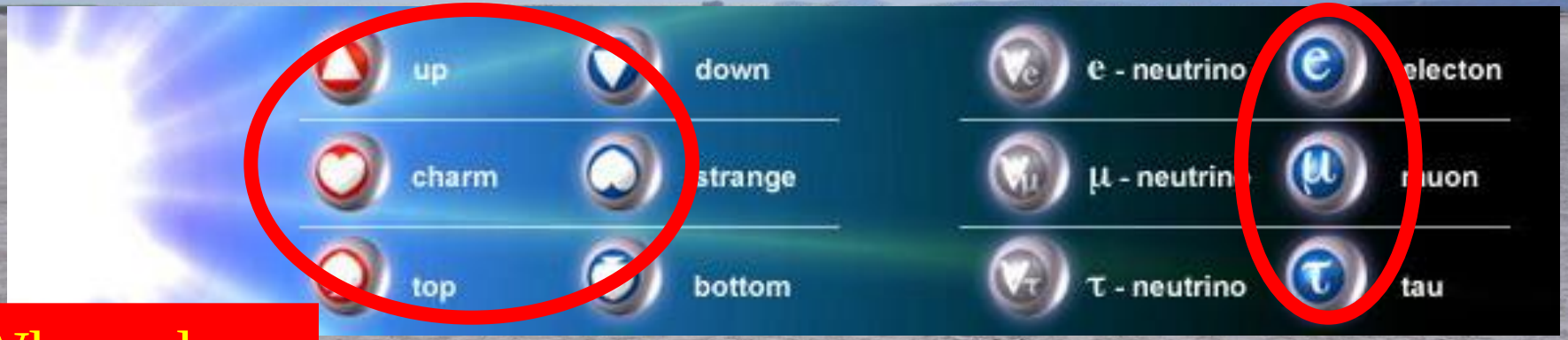


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

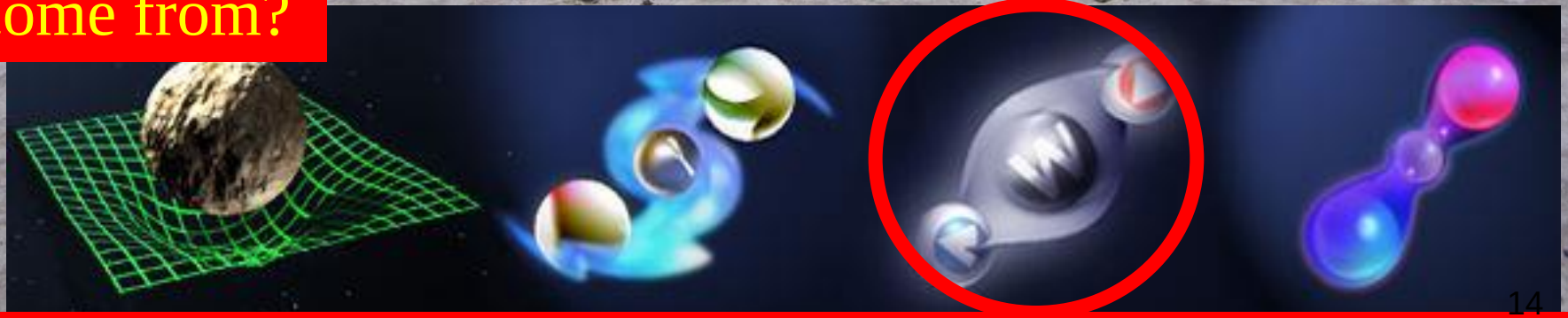
= Cosmic DNA

The matter particles : quarks and leptons



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

The Standard Model of Particle Physics :
electro-weak + strong forces

- Quantum Field Theory : Quantum Mechanics + Special Relativity
- Symmetry principle : gauge invariance

Very accurate description of physics at present energies

17 parameters

Several Nobel Prizes :

- Theory — Glashow, Salam, Weinberg 79
- Discovery of $W^{\pm}$, Z at CERN — Rubbia, Van Der Meer 84
- Theoretical consistency — t'Hooft, Veltman 99
- Asymptoyic freedom of strong force — Gross, Politzer, Wilczek 04

Electroweak Symmetry

Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad s$$

particles in pairs

Electroweak Symmetry

Leptons

Quarks

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}$$

particles in pairs

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix}$$

discovery of the 4th quark

Glashow-Iliopoulos-Miani 1974

Richter-Ting Nobel Prize 1976

also Quantum Chromodynamics $\Rightarrow$ quarks in three 'colors'

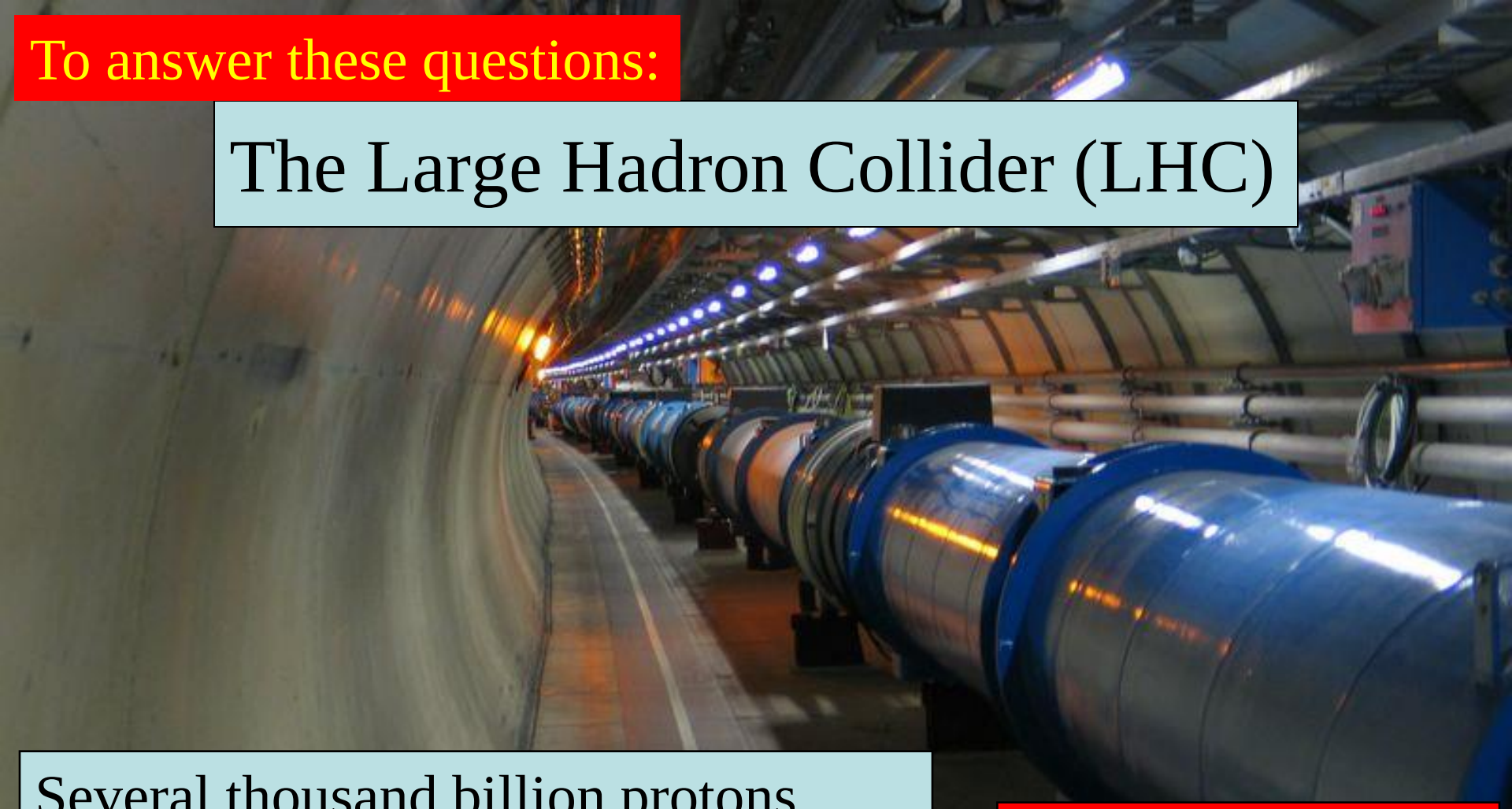
e.g.: $u \rightarrow$ (u, u, u)

Open Questions within & beyond the Standard Model

- What is the origin of particle masses? LHC
  due to a Higgs boson?
- 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

To answer these questions:

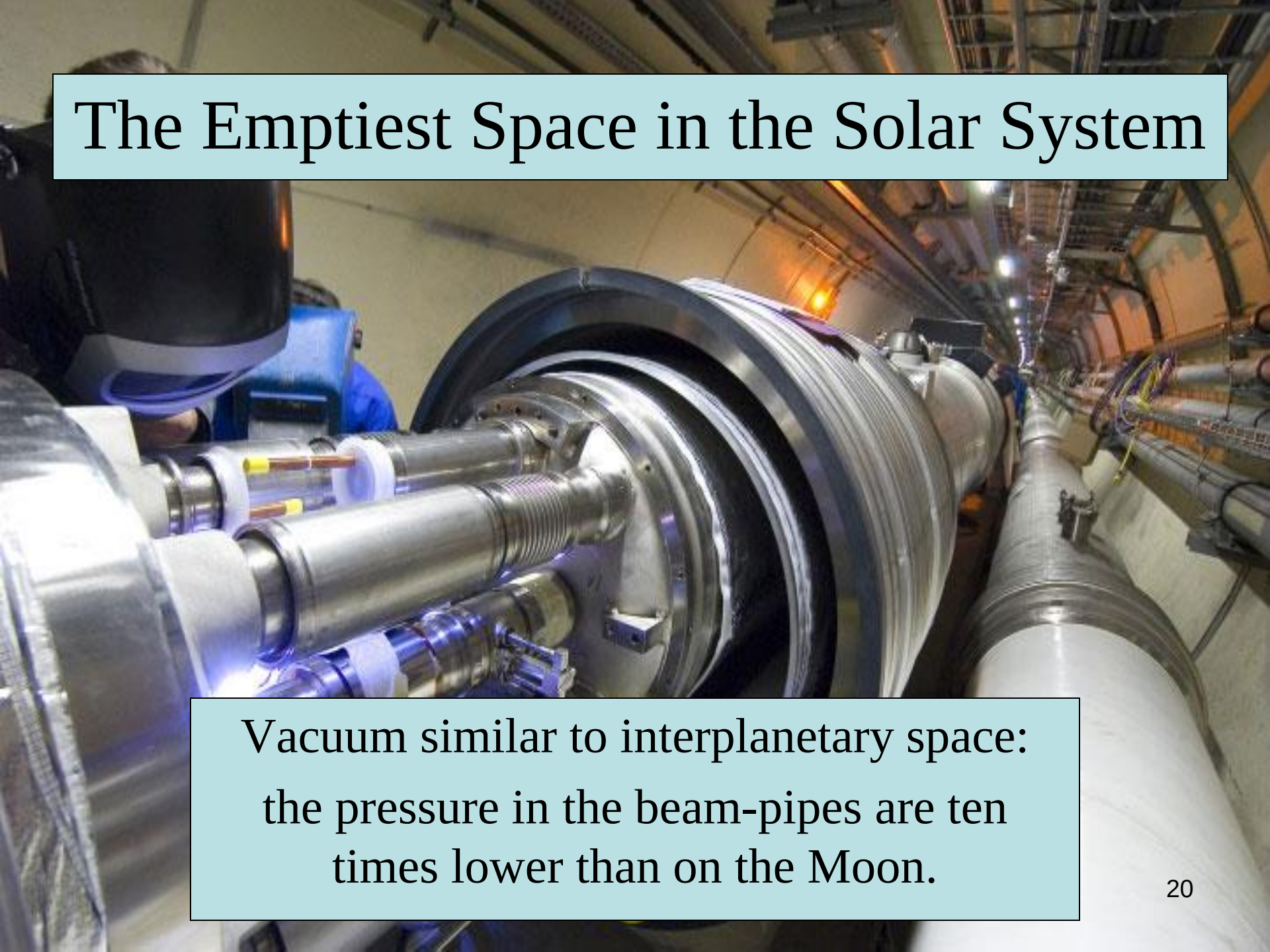
The Large Hadron Collider (LHC)



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

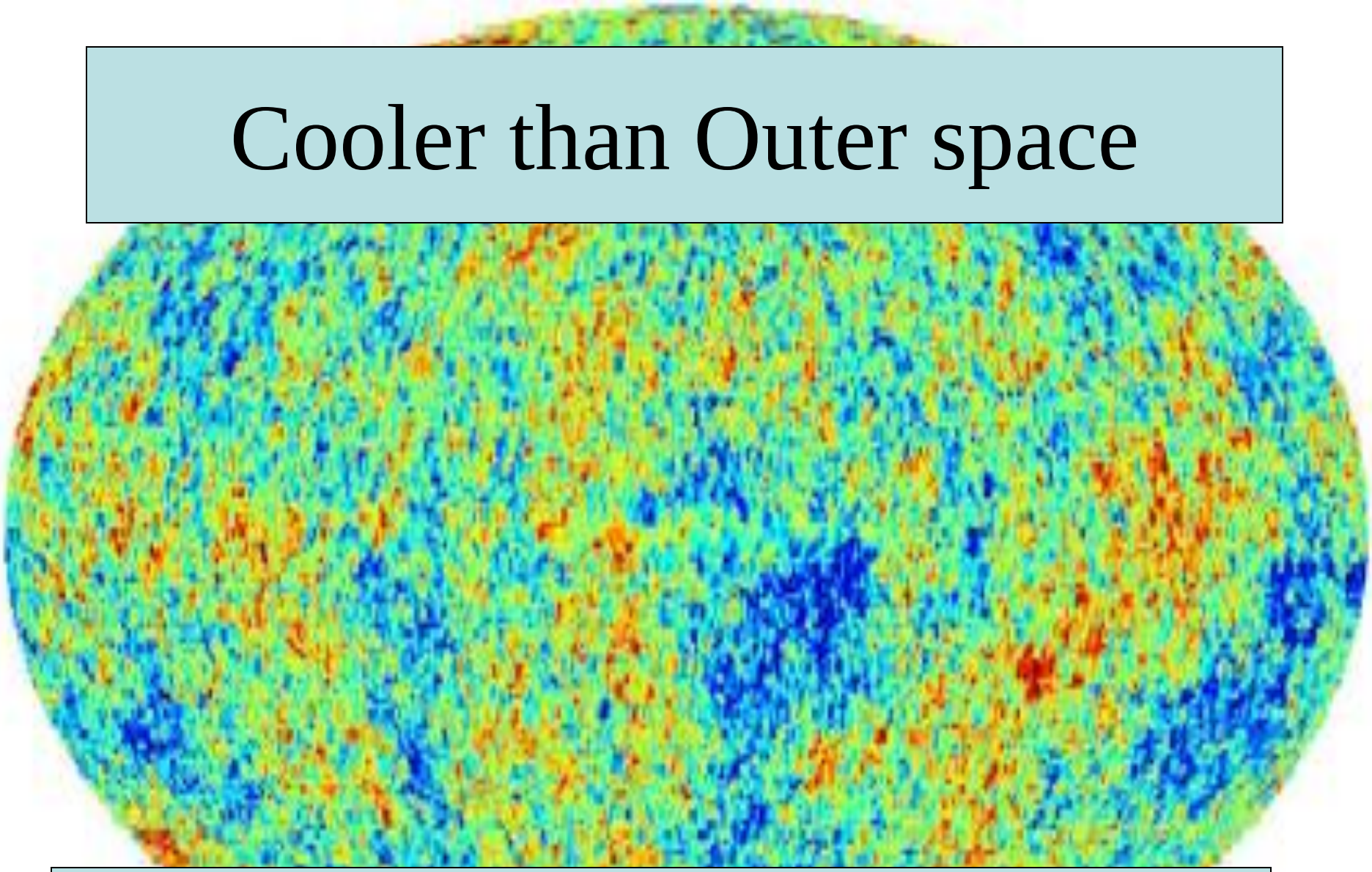
The Emptiest Space in the Solar System



Vacuum similar to interplanetary space:

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

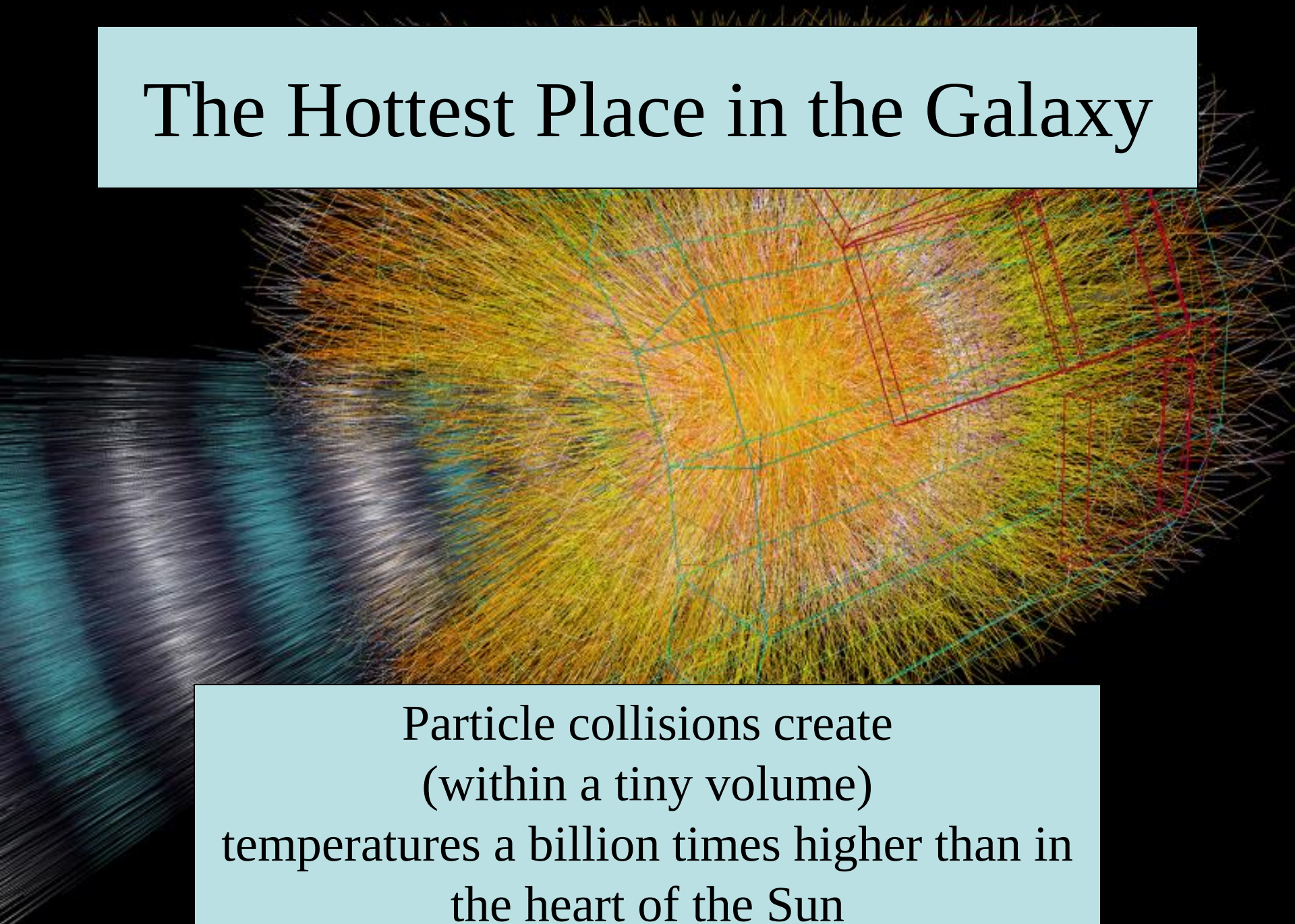
Cooler than Outer space



LHC 1.9 degrees above absolute zero = - 271 C

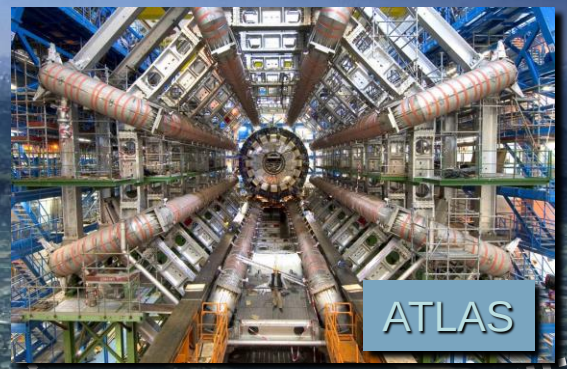
Outer space 2.7 degrees above zero = - 270 C

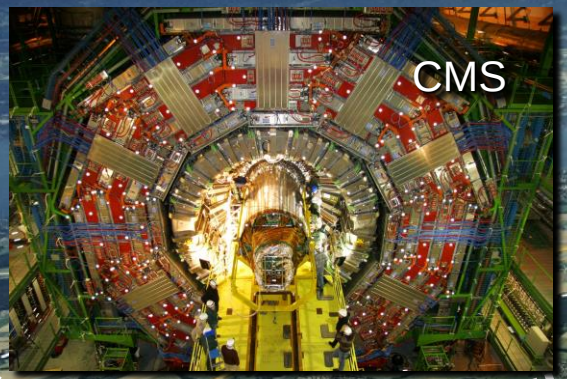
The Hottest Place in the Galaxy



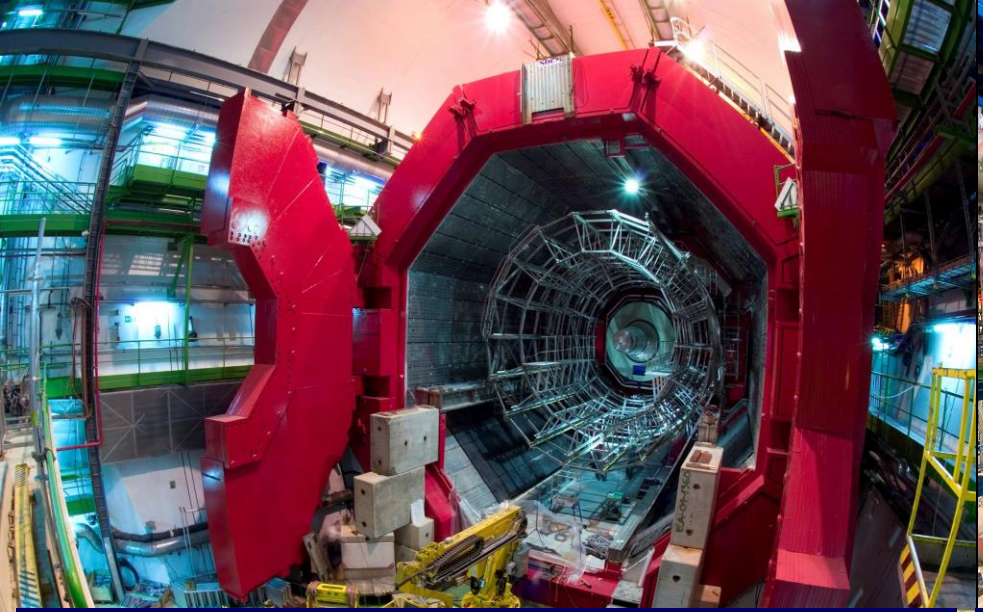
Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in the heart of the Sun

Enter a New Era in Fundamental Science

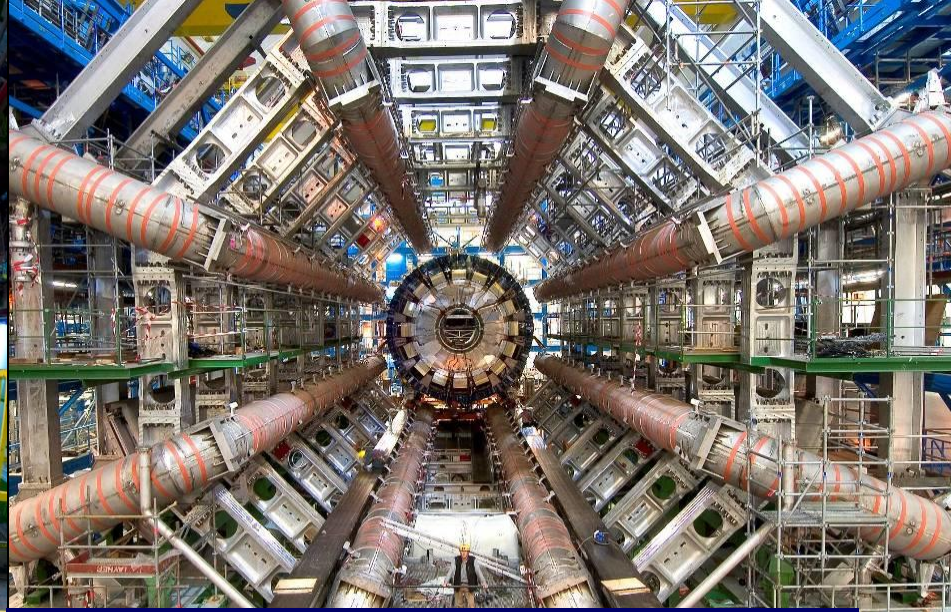




Exploration of a new energy frontier
in p-p and Pb-Pb collisions



ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

Why do Things Weigh?

Newton:

Weight proportional to Mass

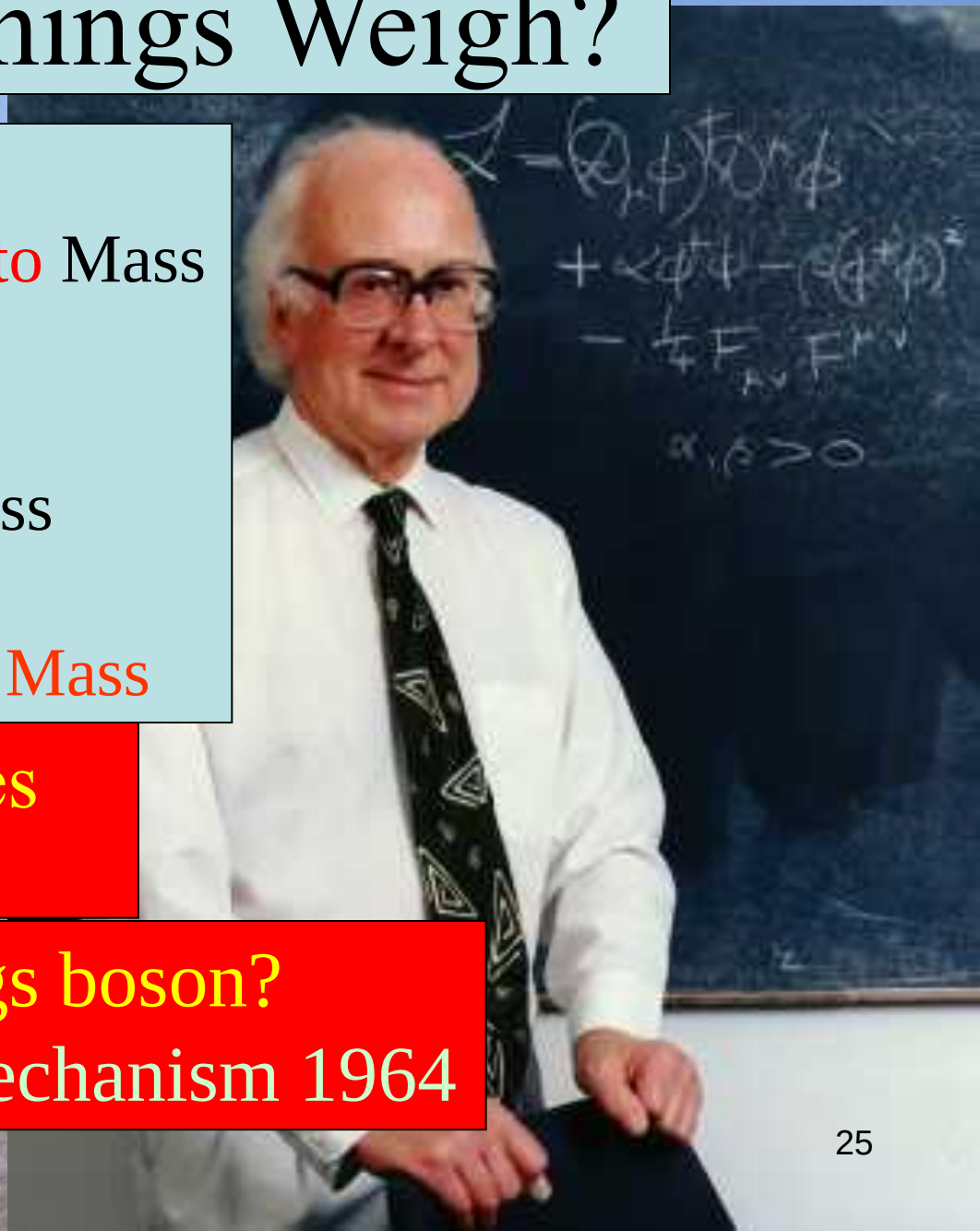
Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson?
Brout-Englert Higgs mechanism 1964



Think of a Snowfield

The LHC looks for the snowflake: The Higgs Boson

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

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

Without Higgs …

… there would be no atoms

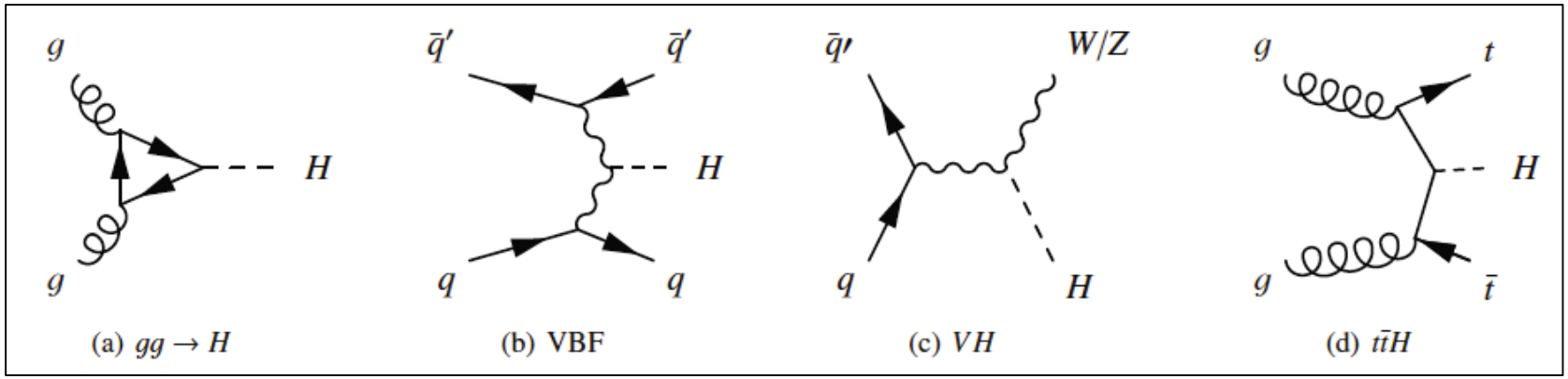
- Electrons would escape at the speed of light

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

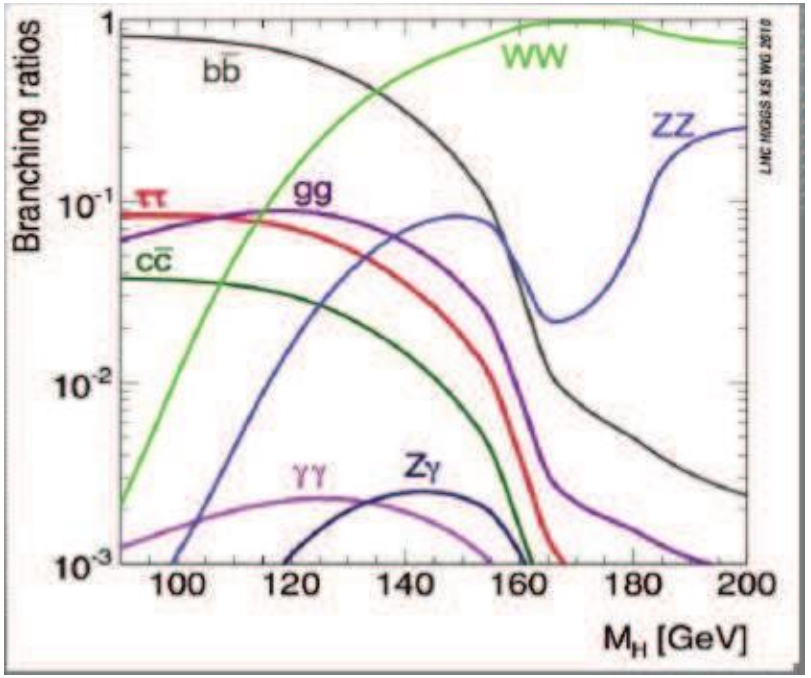
Search for the Higgs-Boson at the LHC



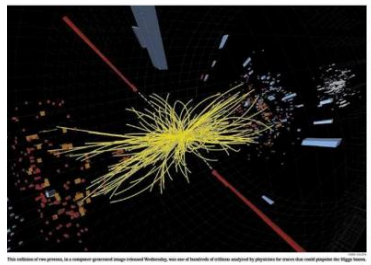
- Gluon fusion
- Vector Boson fusion
- Associated

↑

Analyze : (production modes)
x (decay possibilities) ➔

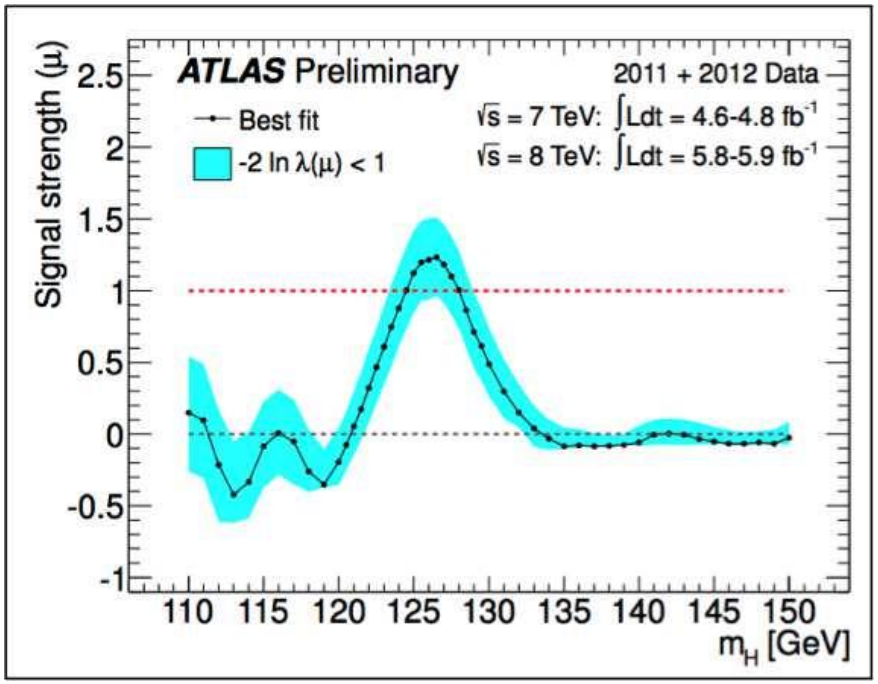


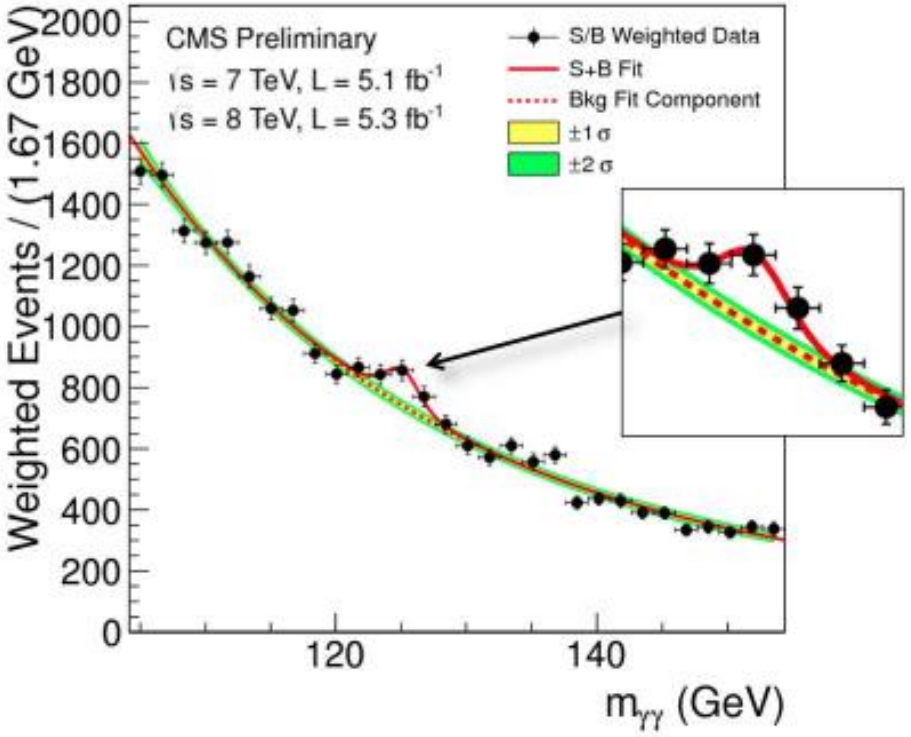
July 4th 2012
The discovery of a new particle



Discovery upends world of physics

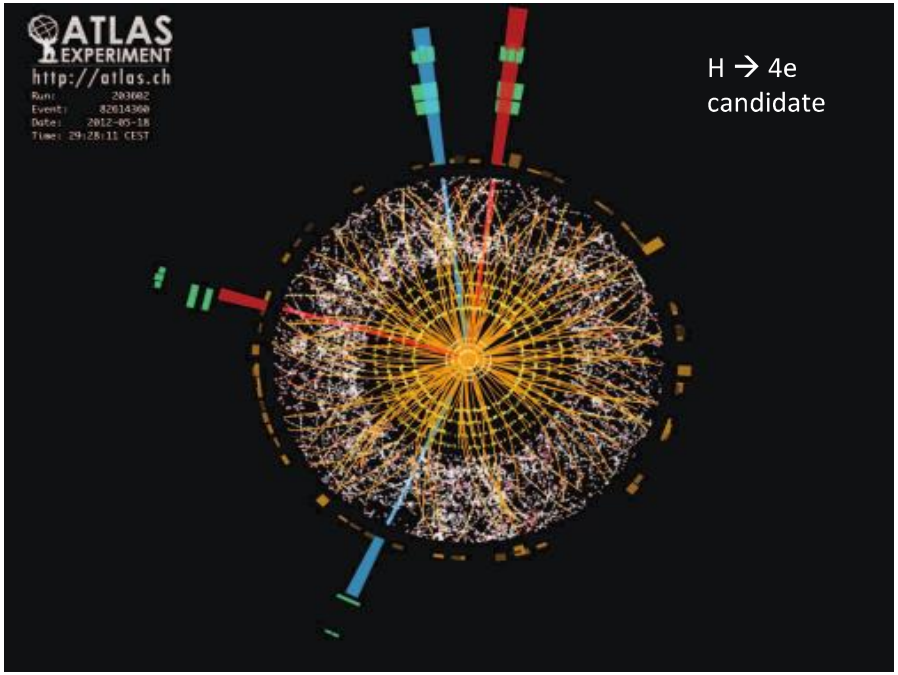
Higgs Boson discovery at the LHC



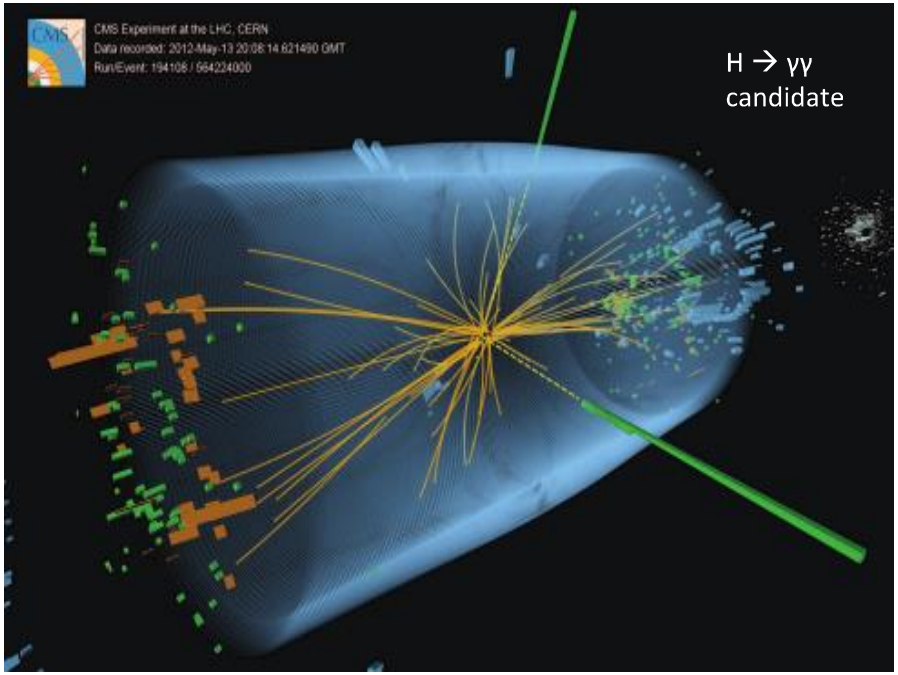


$m_H = 125.5 \pm 0.2\,(\text{stat.}) \pm 0.5\,(\text{syst.})$ $m_H = 125.7 \pm 0.3 \pm 0.3$ GeV

Possible Higgs boson events

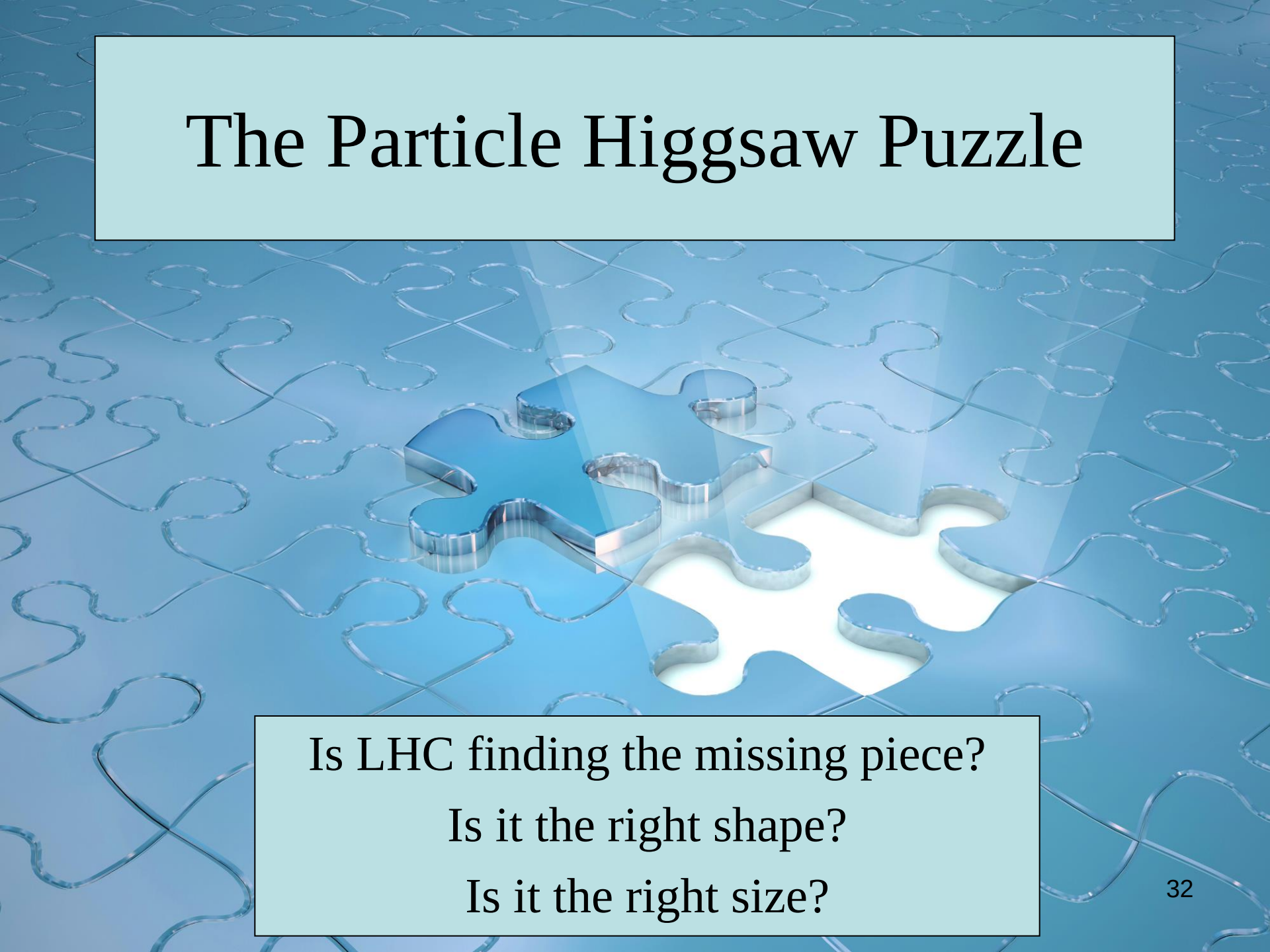


H → 4e candidate



H → γγ candidate

The Particle Higgsaw Puzzle

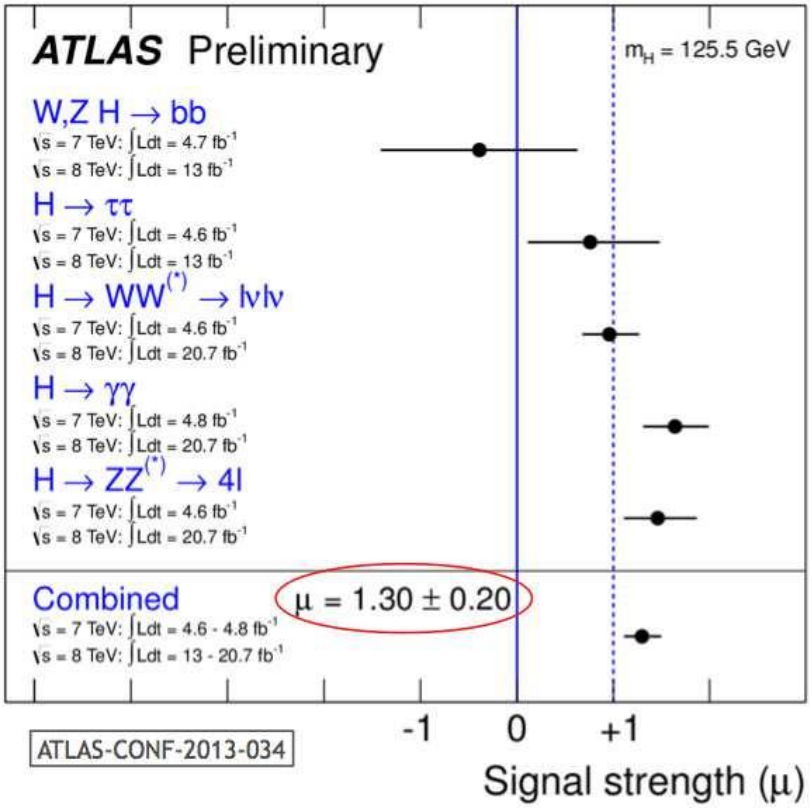


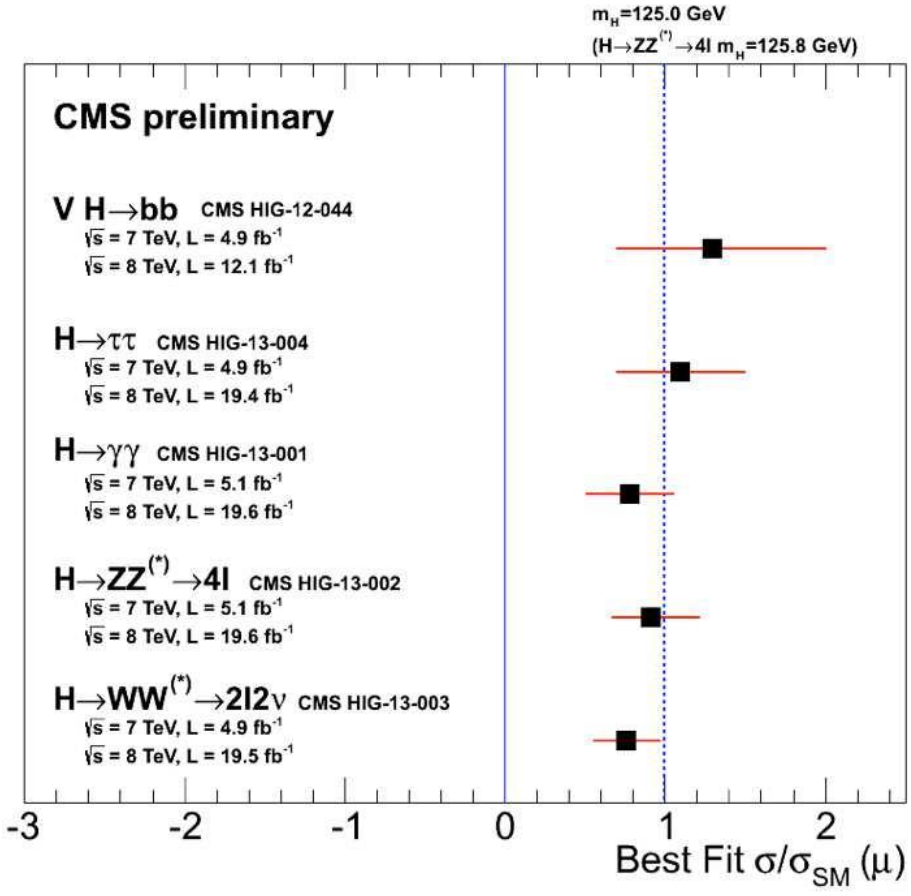
Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

Couplings of the new boson vs SM Higgs





- Agreement with Standard Model Higgs expectation at 1.5 σ
- Measurement of its properties and decay rates currently under way

François Englert Peter Higgs

Open Questions within & beyond the Standard Model

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

Dark Matter in the Universe

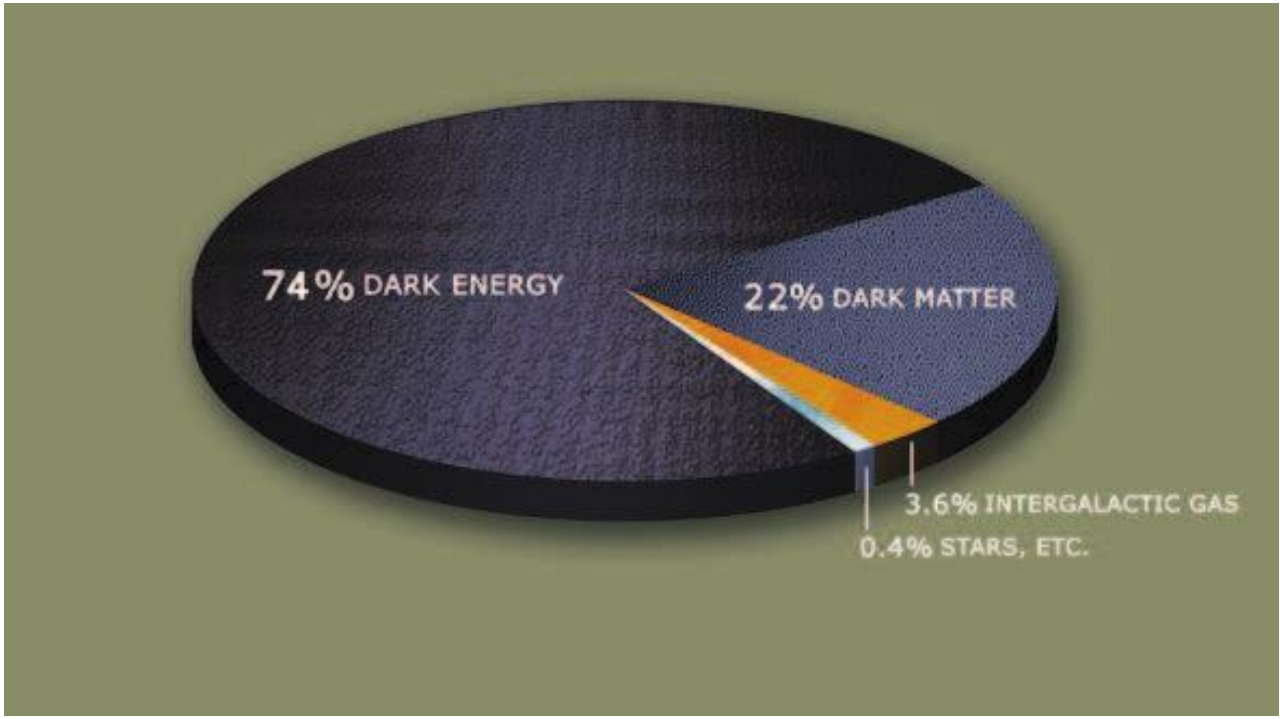
Astronomers say that most of the matter in the Universe is invisible Dark Matter

We will look for it with the LHC

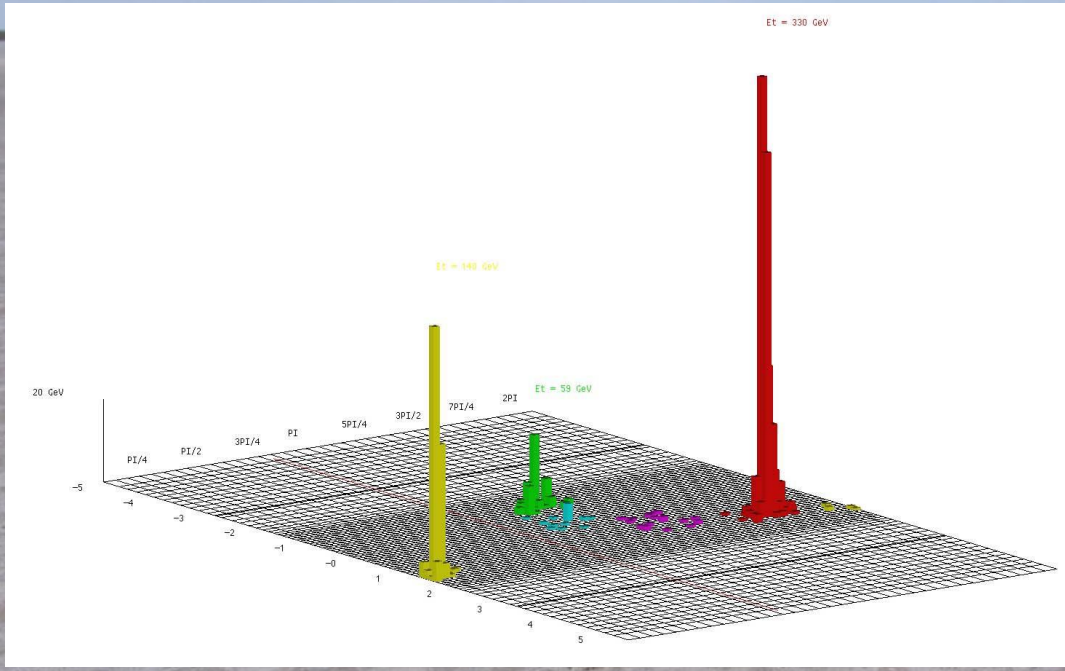
What our Universe is made of ?

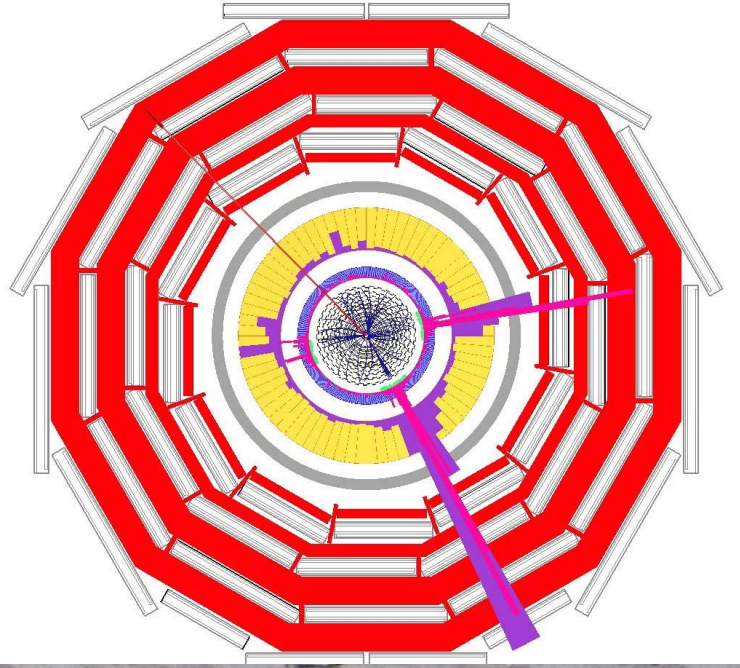
- Ordinary matter: only a tiny fraction
- Non-luminous (dark) matter: $\sim 25\%$

  Natural explanation: new stable Weakly Interacting Massive Particle in the LHC energy region
- Unknown relativistic dark energy: $\sim 70\%$



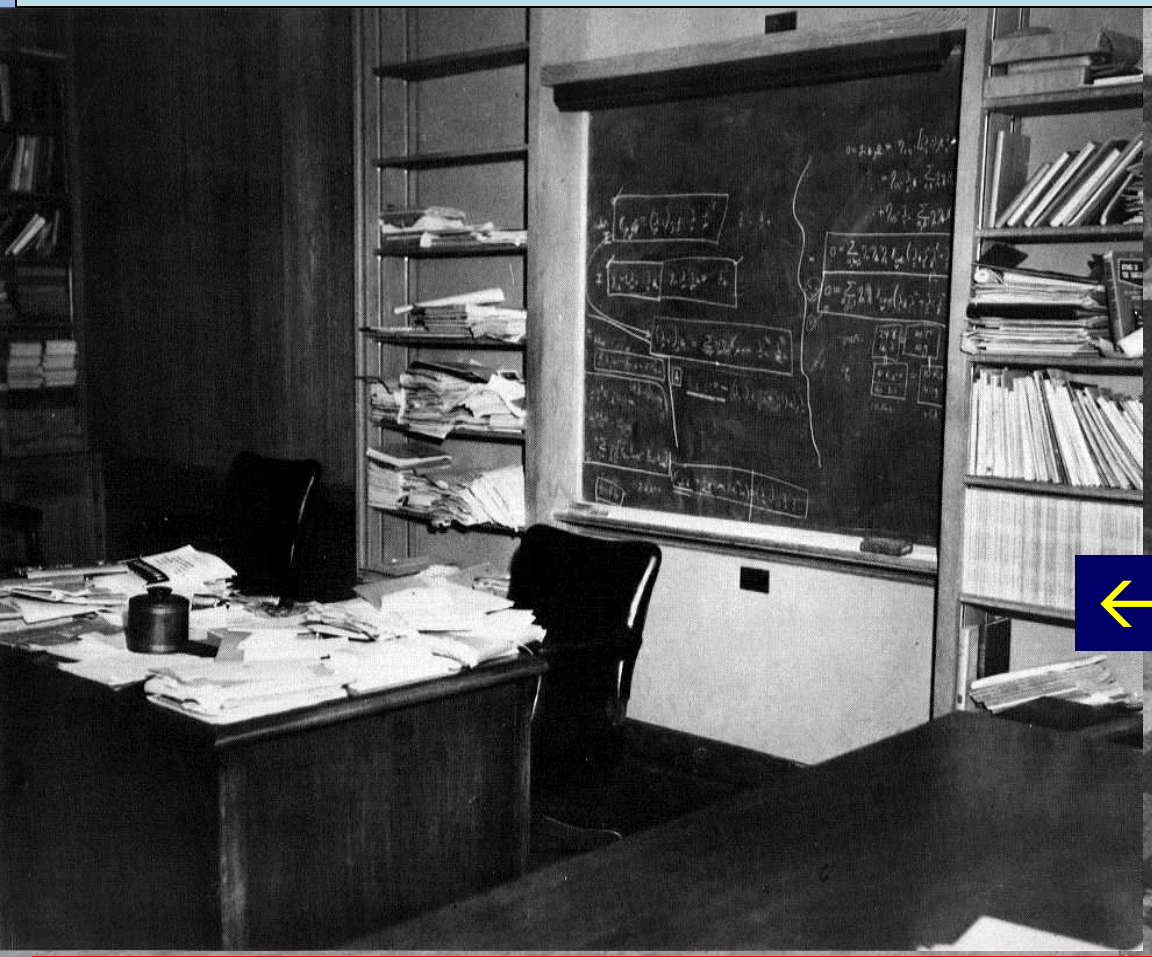
Classic Dark Matter Signature





Missing transverse energy
carried away by dark matter particles

Unify the Fundamental Interactions: Einstein's Dream …

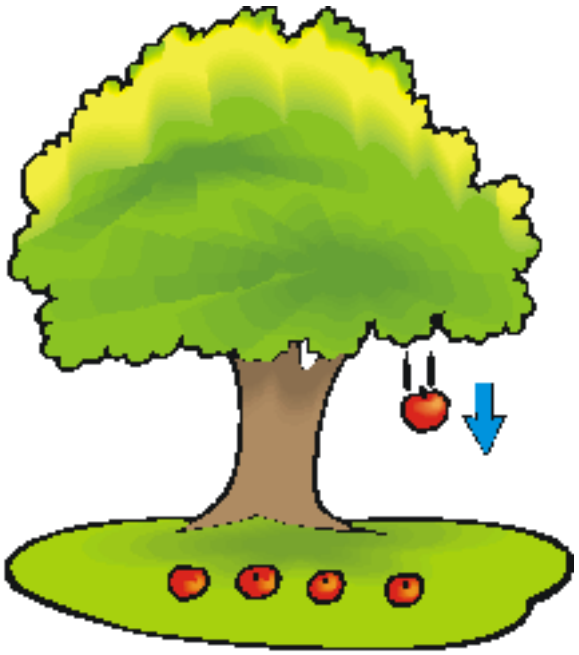


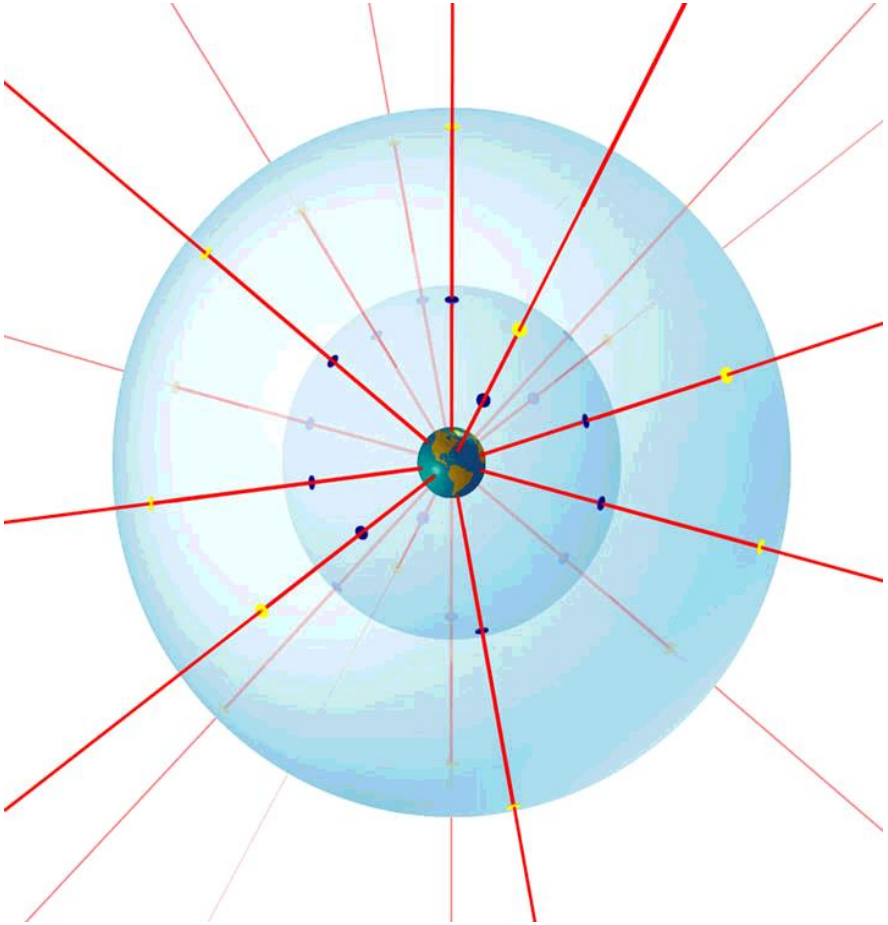
← … but he never succeeded

Unification via extra dimensions of space?

Gravity force

Newton's law: force decreases with the area





Gravity : dominant force in astrophysics but irrelevant in particle physics

$m \bullet \longleftarrow r \longrightarrow \bullet\, m$ $\qquad F_{\rm grav} = G_N \dfrac{m^2}{r^2}$ $\qquad G_N^{-1/2} = M_{\rm Planck} = 10^{19}$ GeV

Compare with electric force: $F_{\rm el} = \dfrac{e^2}{r^2} \Rightarrow$

effective gravitational 'charge' $G_N m^2$ or in general $G_N E^2$ at energies E

$$E = m_{\rm proton} \Rightarrow \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m_{\rm proton}^2}{e^2} \simeq 10^{-40}$$

$\Rightarrow$ Gravity is very weak !

However theories with extra dimensions modify Newton's law

and predict strong gravity effects at high energies

Main Beyond the Standard Model proposals

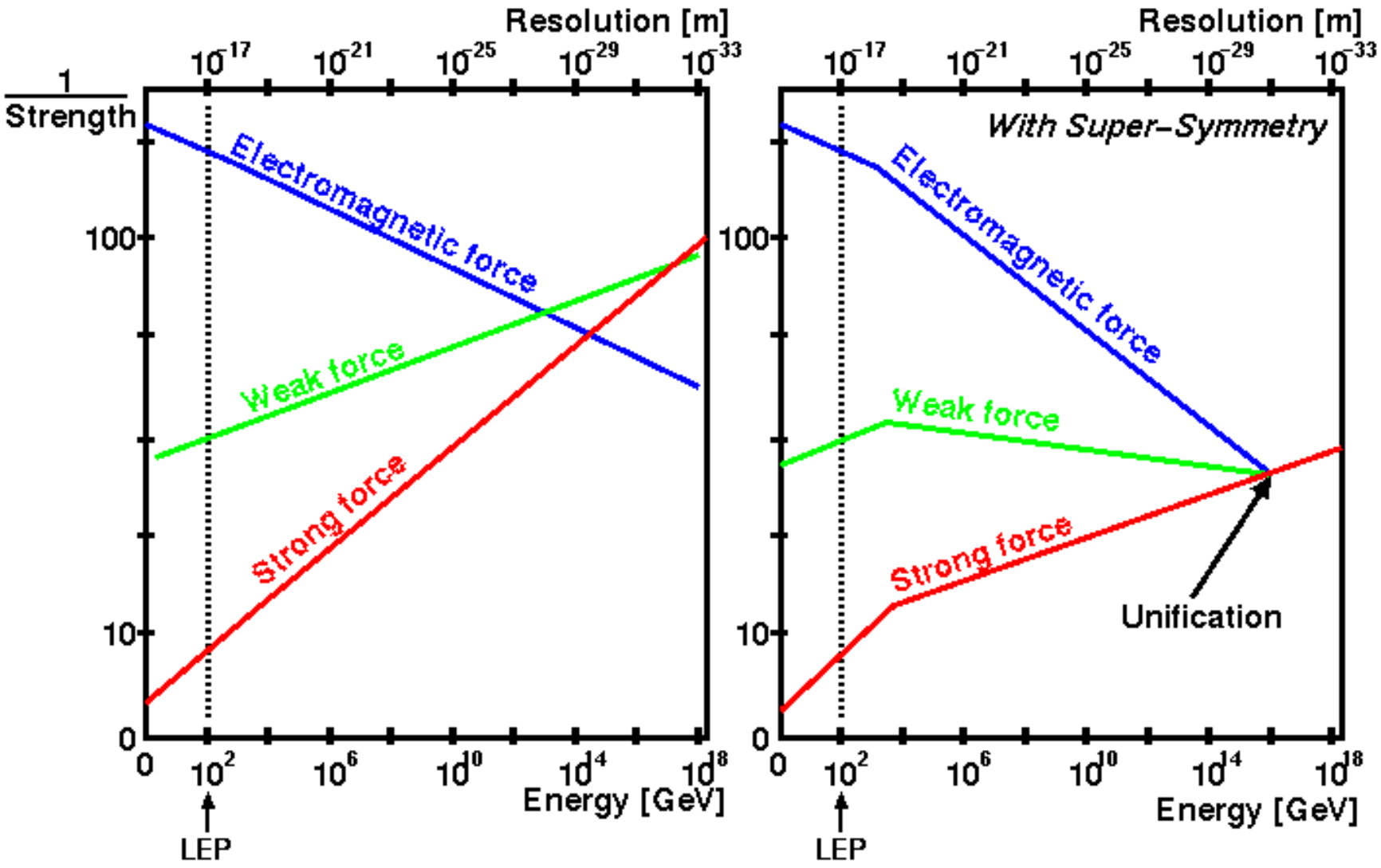
Supersymmetry: every particle has a superpartner

- realize unification of Standard Model forces
- natural dark matter candidate (lightest supersymmetric particle)
- prediction of light Higgs
- rich spectrum of new particles within LHC reach

String Theory: replaces point particles by strings

- quantum gravity
- framework for unification of all interactions
- prediction of new dimensions of space
- spectacular new phenomena if string scale in the TeV region

Energy evolution of the three force inverse-intensities



Supersymmetry ➔ unification of forces at around 10^{16} GeV

Conclusions

Confirmation of the Higgs scalar discovery at the LHC :

important milestone of the LHC research program

LHC and Particle physics enters a new era with possible new discoveries

unveiling the fundamental laws of Nature