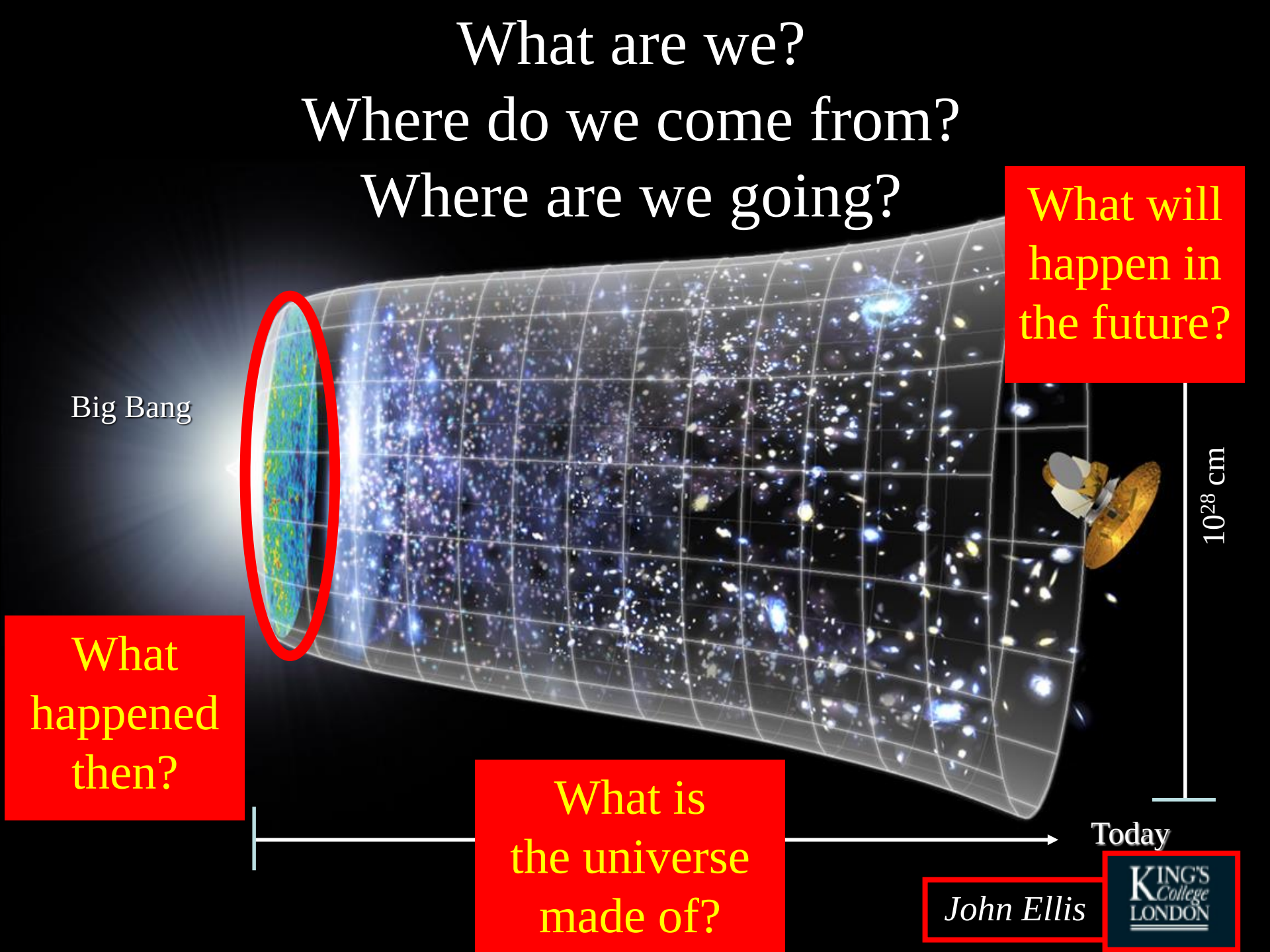
What are we?
Where do we come from?
Where are we going?

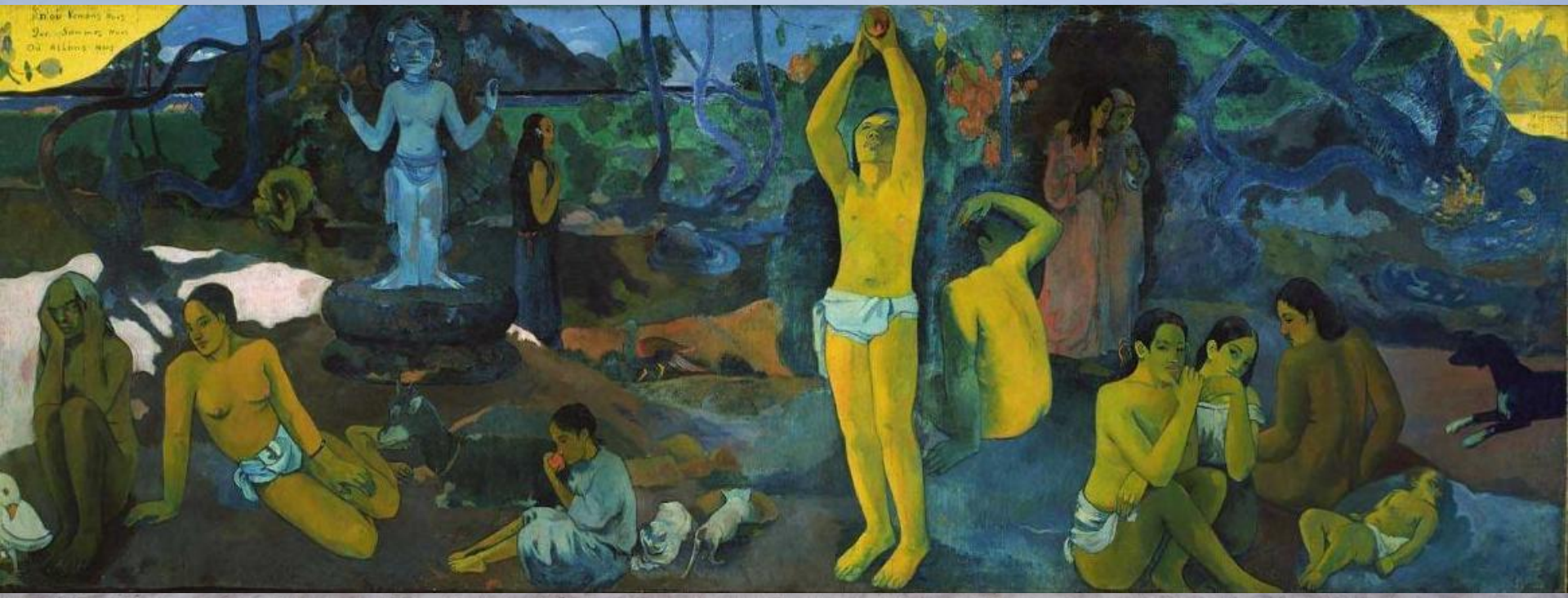


John Ellis
KING'S College LONDON

“Where do we come from?

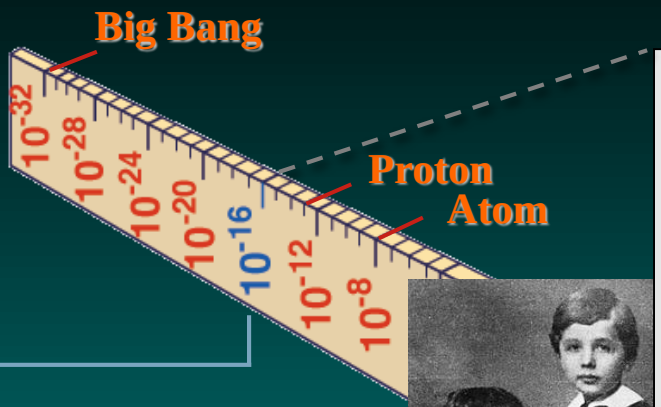
What are we?

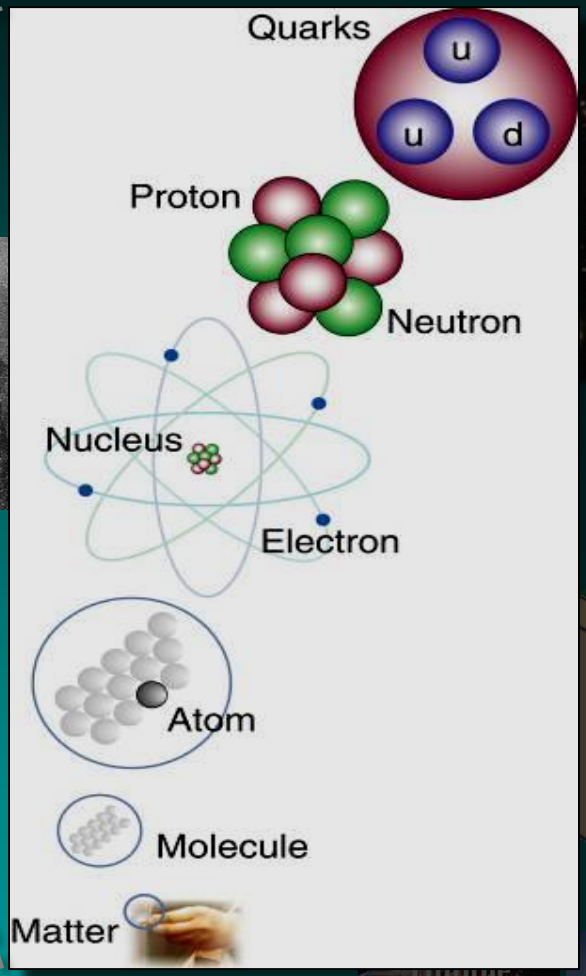
Where are we going?”

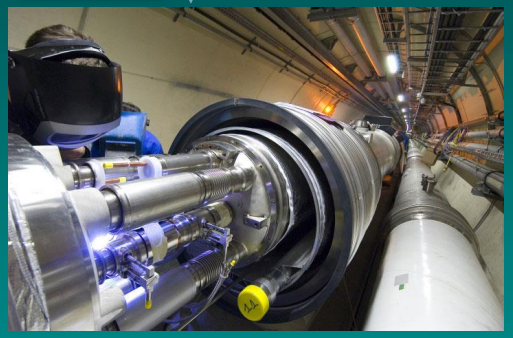


The aim of particle physics, CERN & the LHC:
What is the Universe made of?

/Users/johne/Desktop/YoungEinsteins.png







LHC

Super-Microscope

Radius of Galaxies

Universe

10^{24}

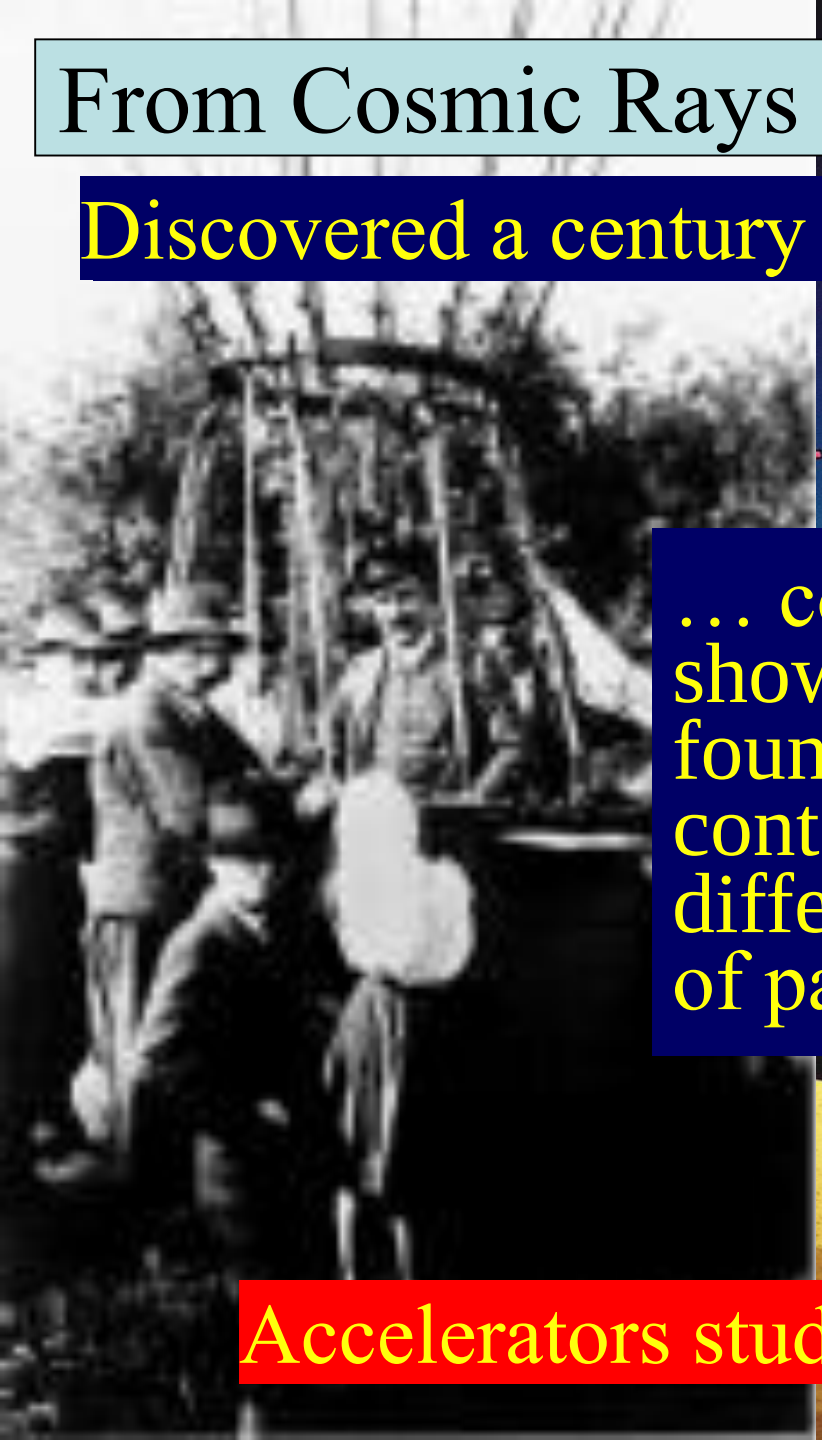
10^{28}

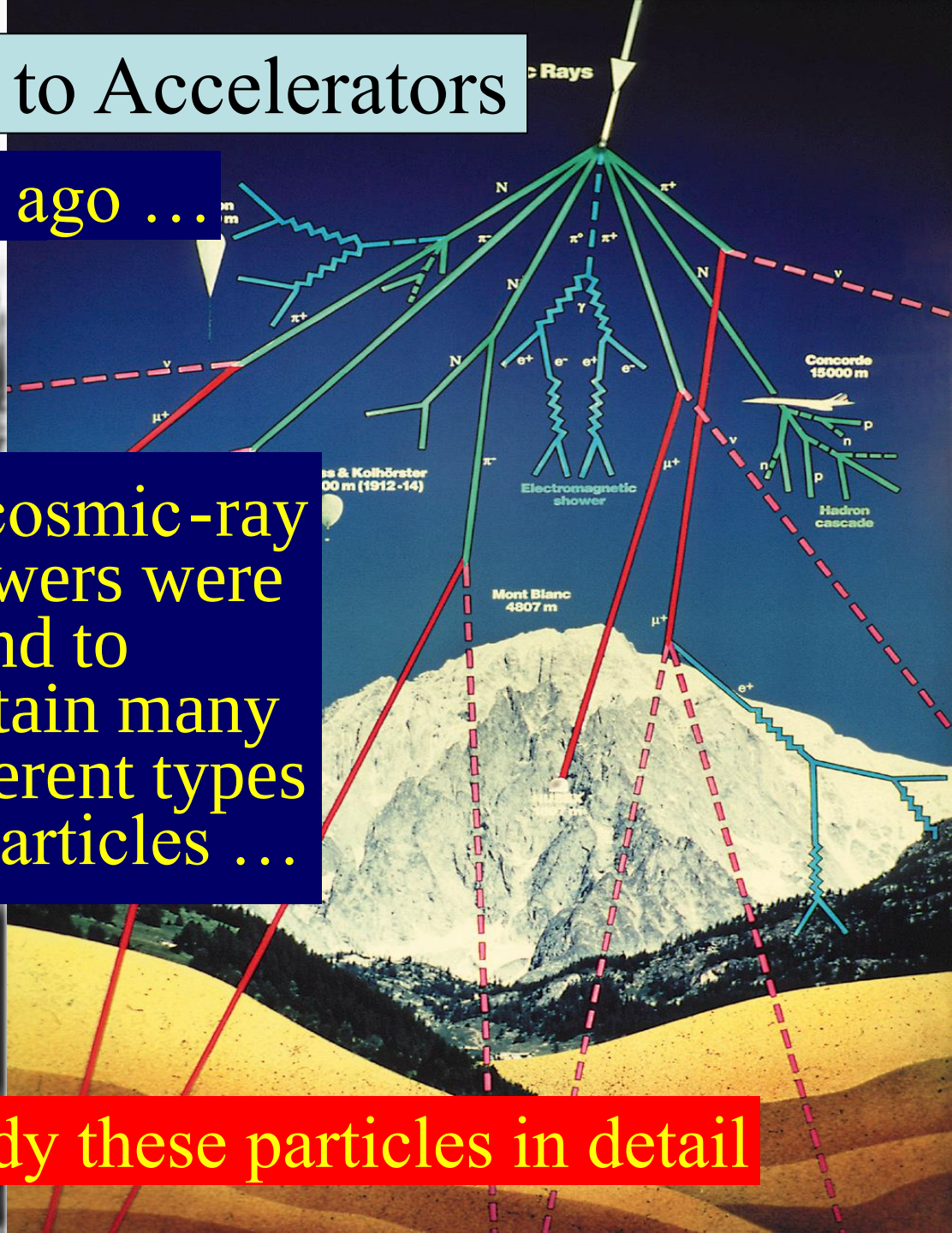
cm

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

From Cosmic Rays to Accelerators

Discovered a century ago …

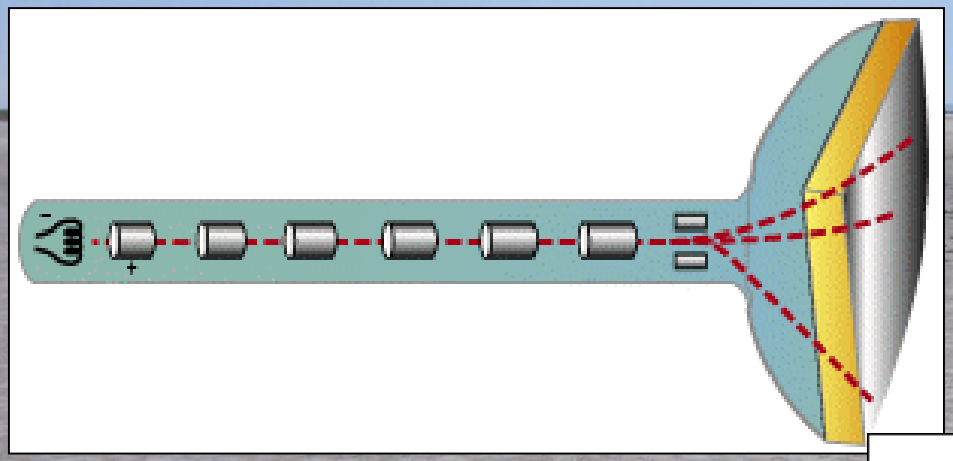




… cosmic-ray showers were found to contain many different types of particles …

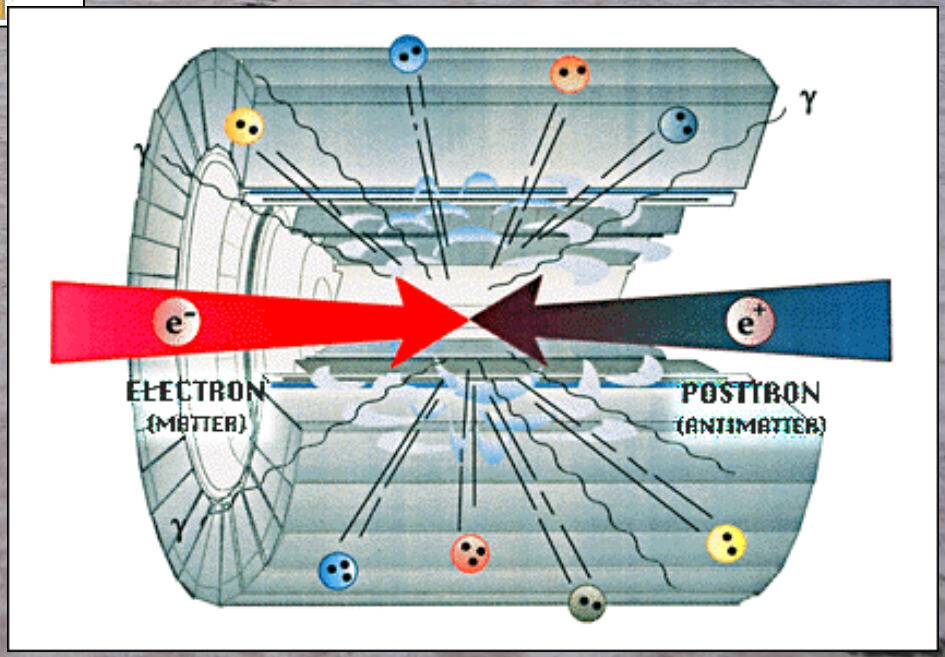
Accelerators study these particles in detail

Experiments at Accelerators

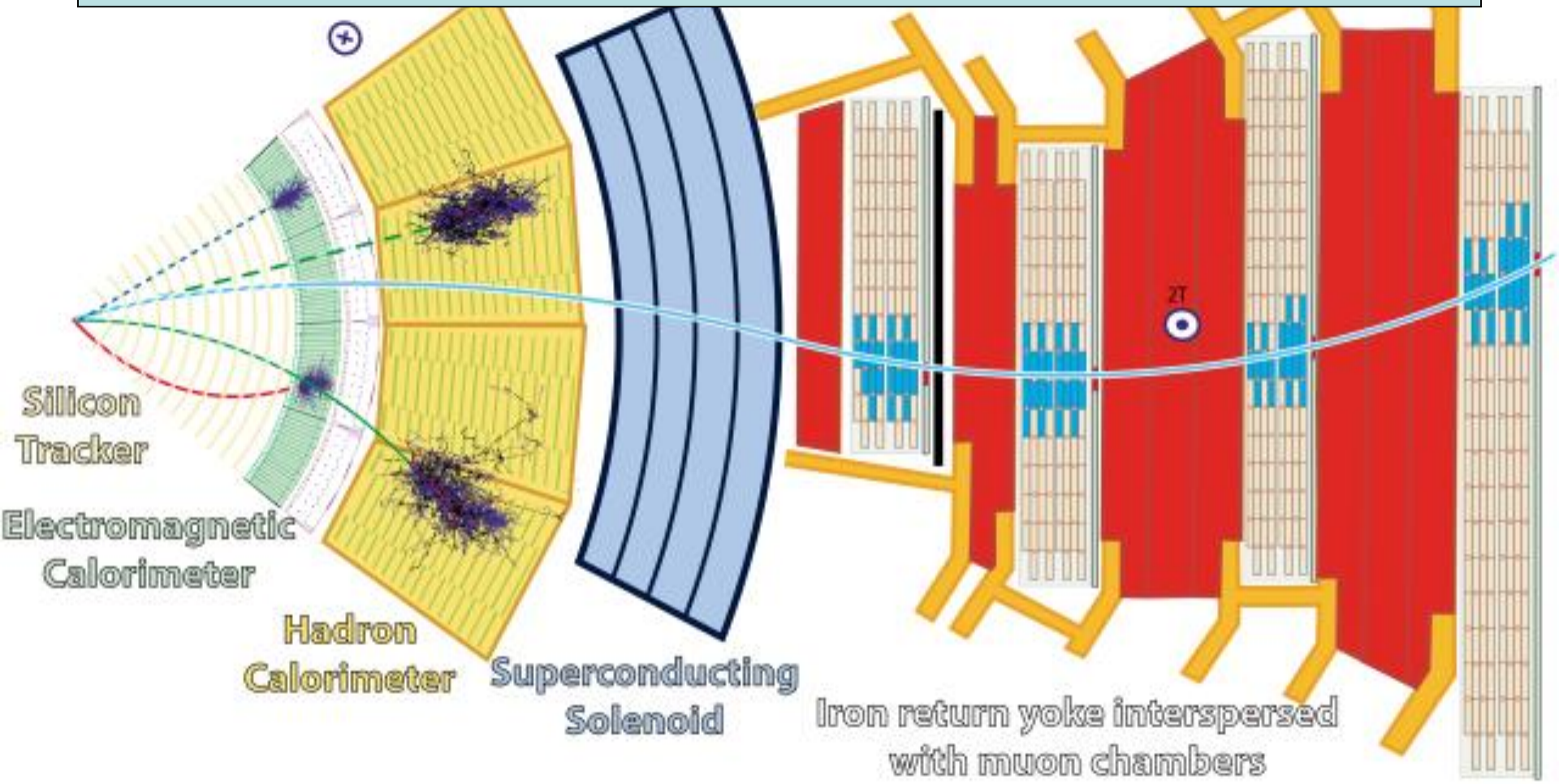


Large accelerators are based on same principles as old TV set
Accelerate and direct particle beams using electric and magnetic fields

Collisions take place inside large detectors that observe and measure the particles peoduced



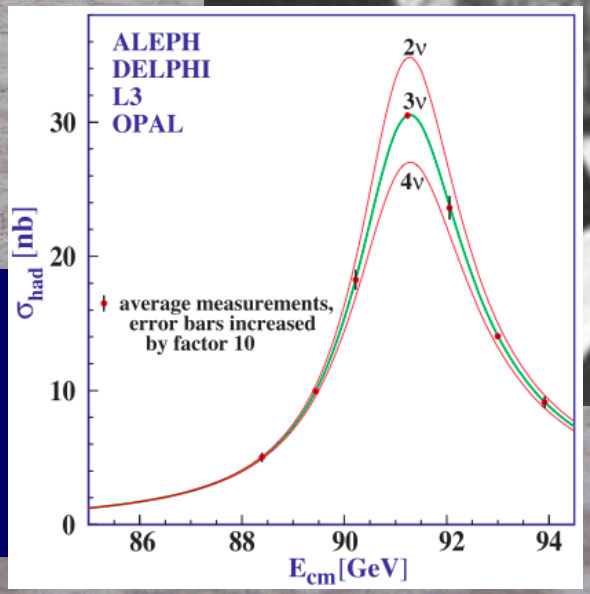
A Typical Particle Detector



The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

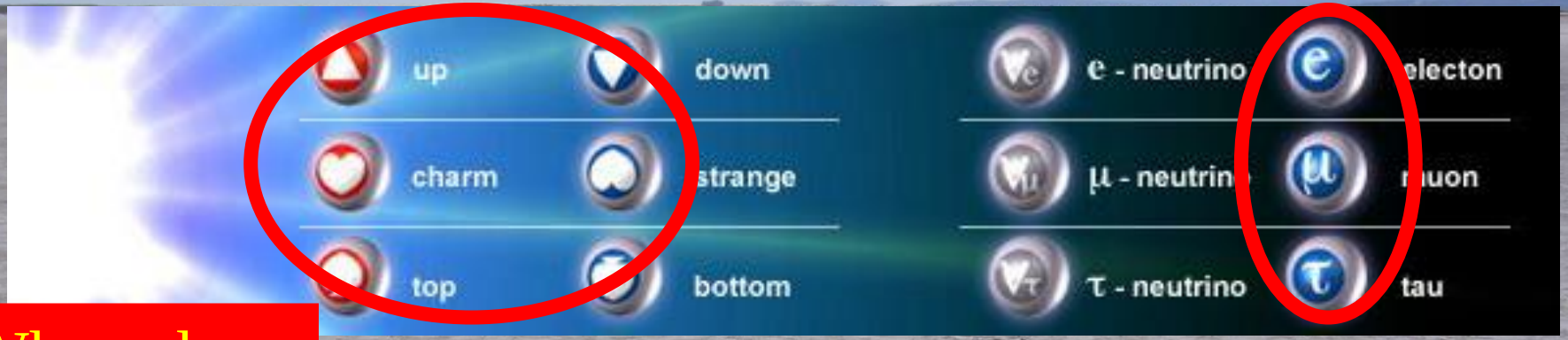


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

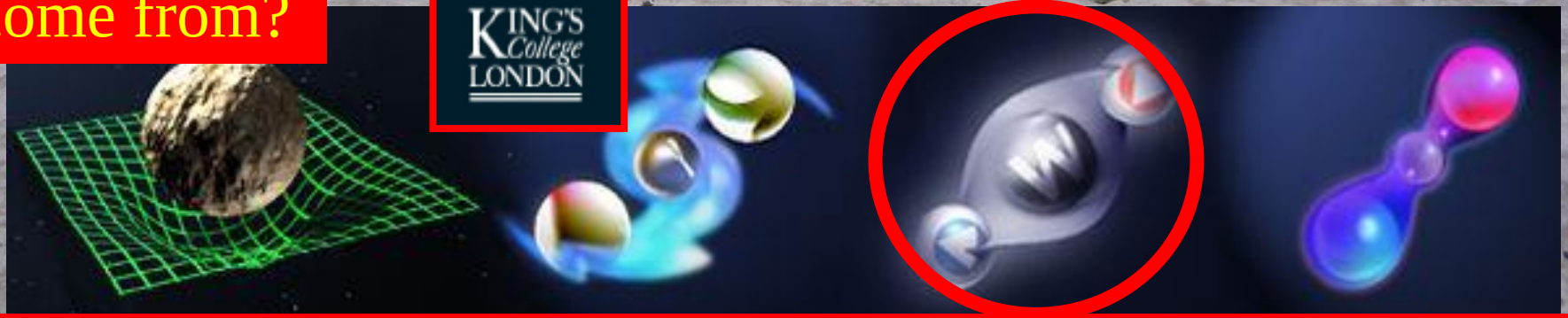
= Cosmic DNA

The matter particles



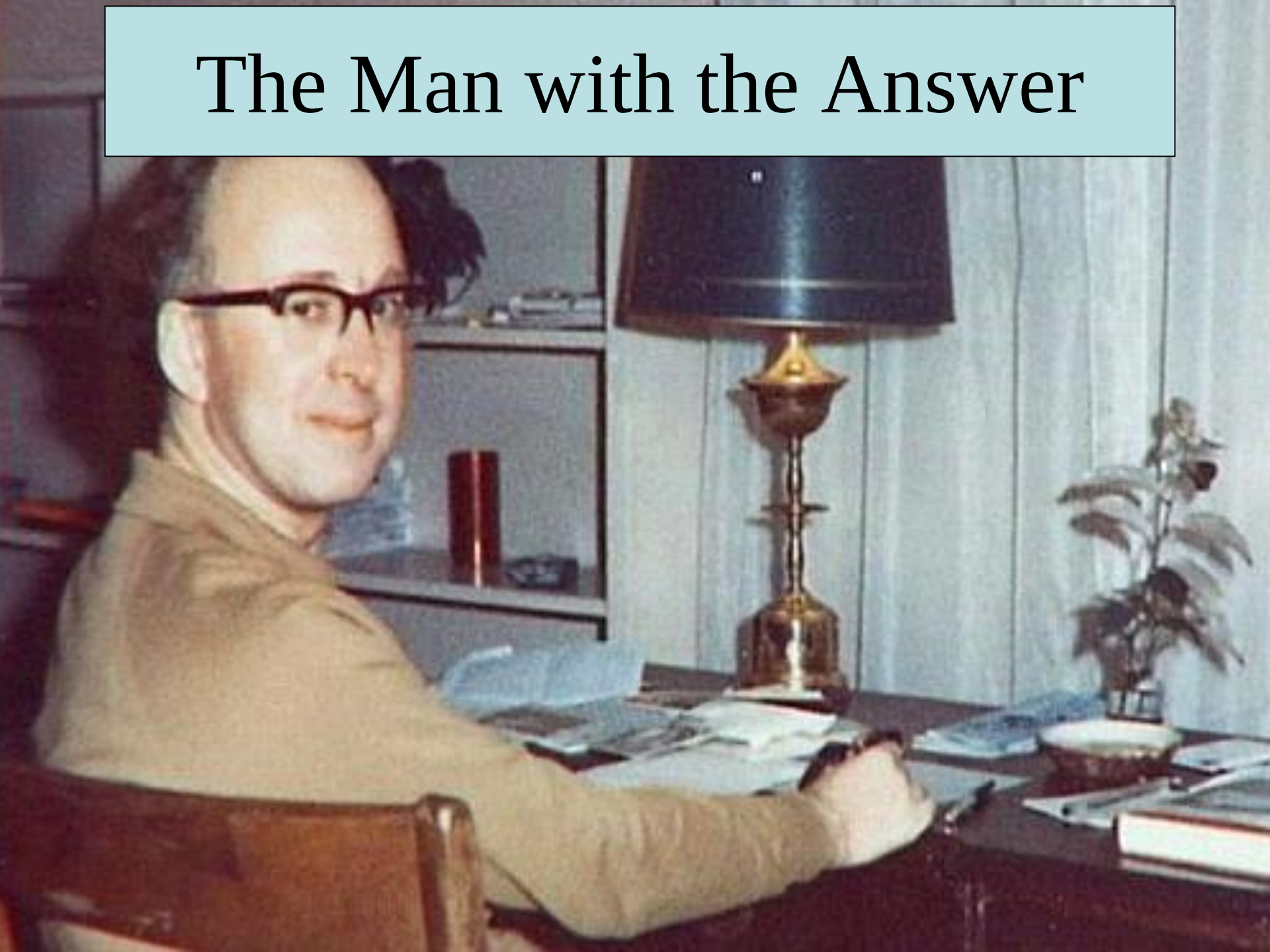
Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

The Man with the Answer



Why do Things Weigh?

Newton:

Weight proportional to Mass

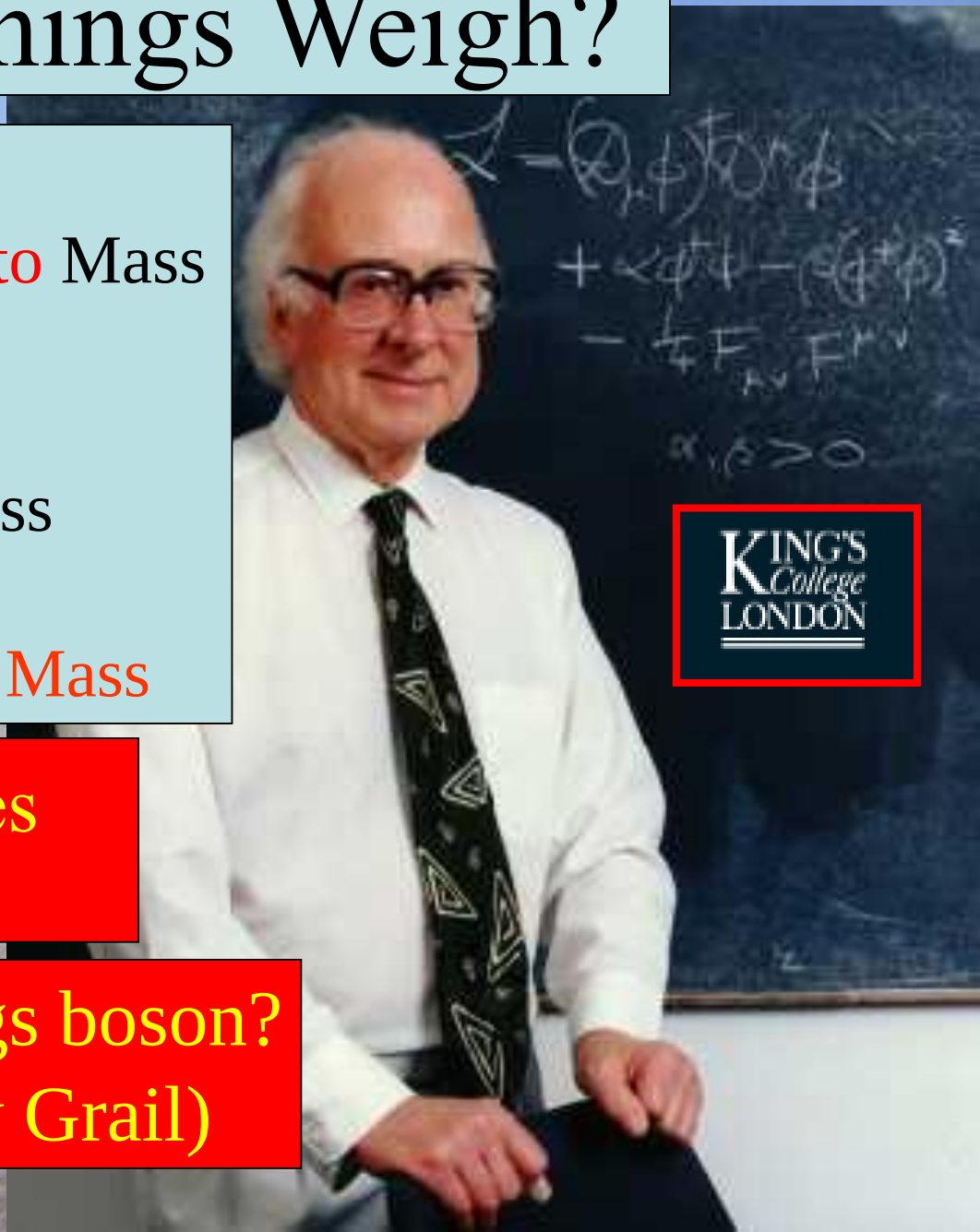
Einstein:

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 found the snowflake: The Higgs Boson

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

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
  - Why do things weigh?

- What is the origin of matter? LHC
- What is the dark matter that fills the Univers LHC
- How does the Universe evolve?
- Why is the Universe so big and old? LHC
- What is the future of the Universe? LHC

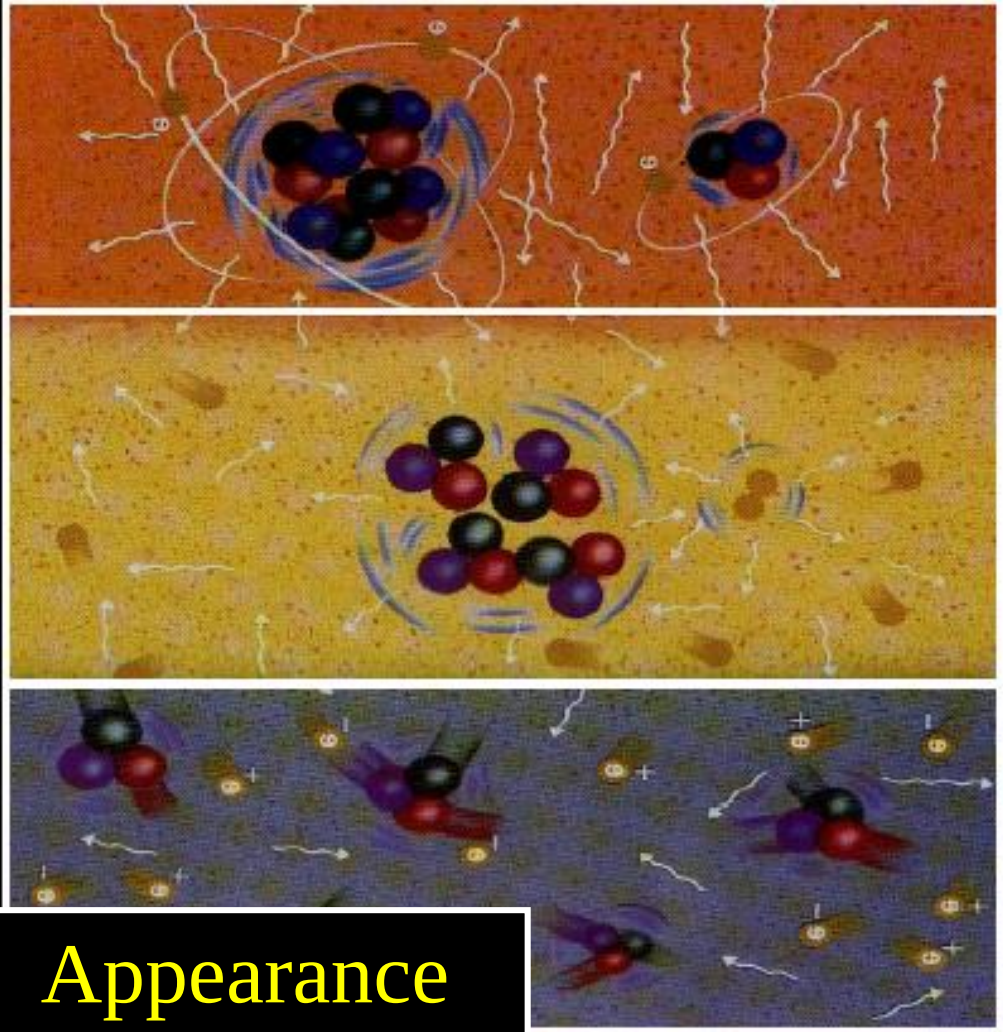
Our job is to ask - and answer - these questions

300,000 years

3 minutes

1 micro-second

1 pico-second



Formation of atoms

Formation of nuclei

Formation of protons & neutrons

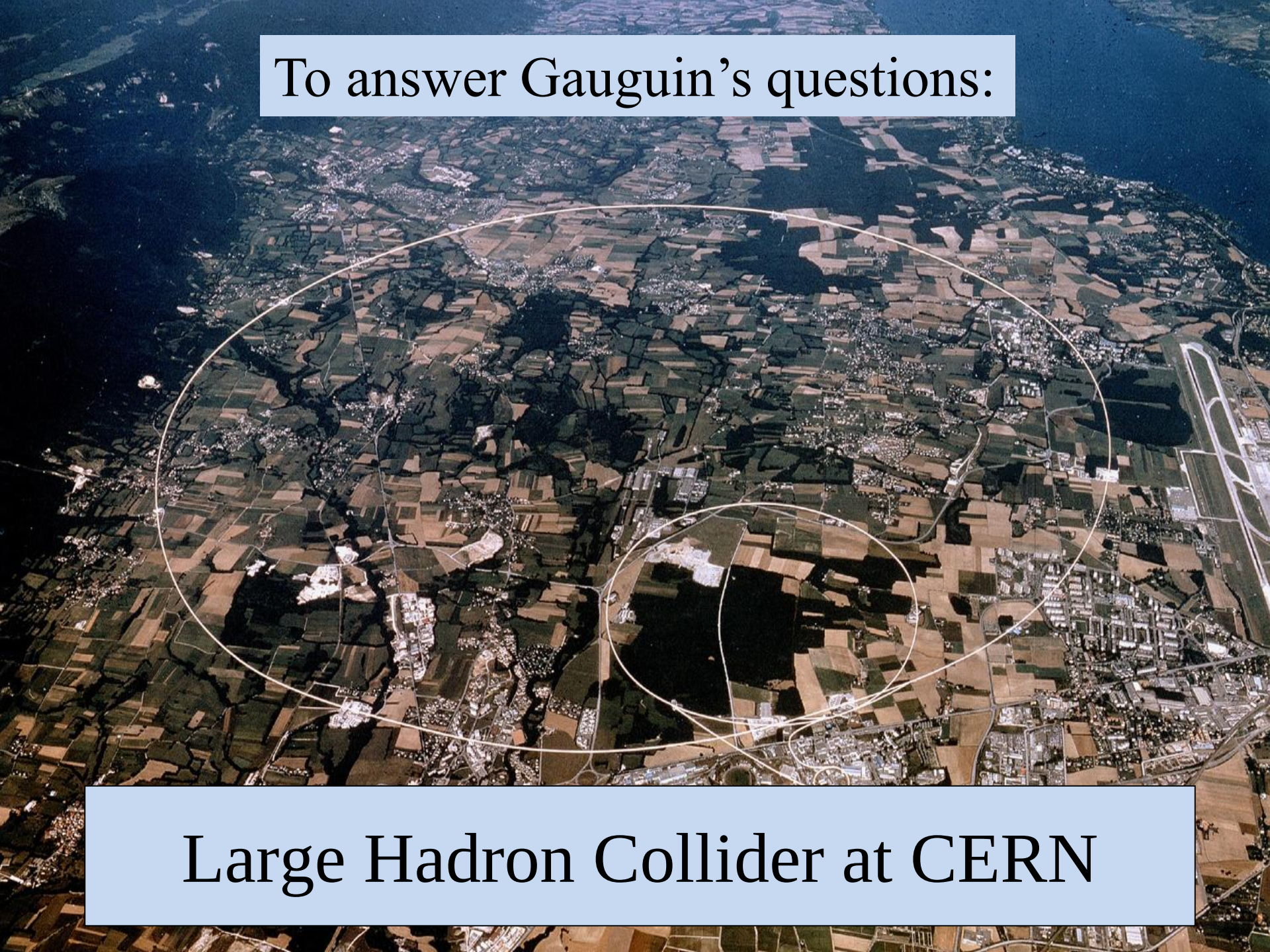
Appearance of mass?

Appearance of dark matter?

Appearance of matter?

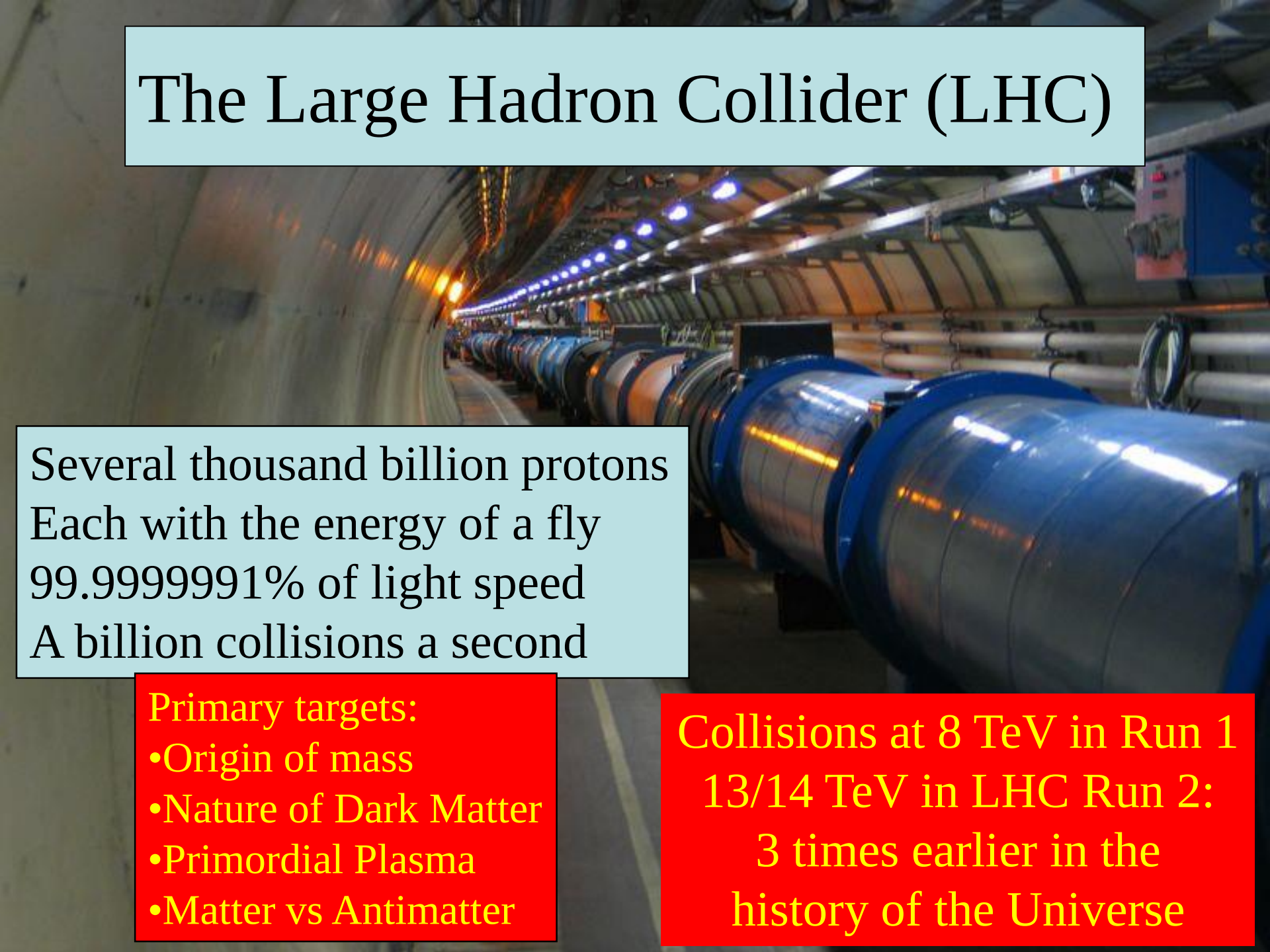
BANG!

To answer Gauguin's questions:



Large Hadron Collider at CERN

The Large Hadron Collider (LHC)

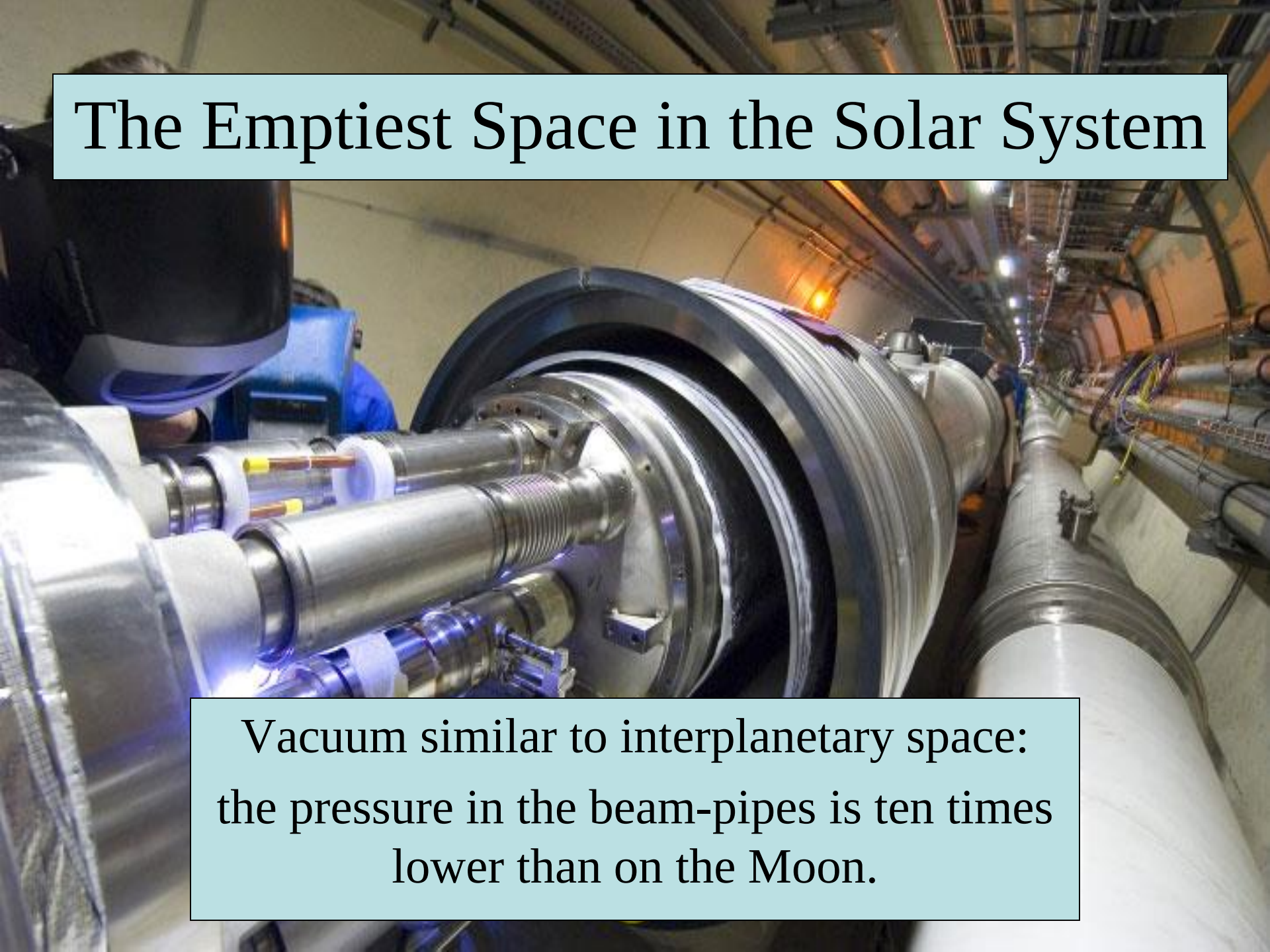


Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
A billion collisions a second

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

Collisions at 8 TeV in Run 1
13/14 TeV in LHC Run 2:
3 times earlier in the
history of the Universe

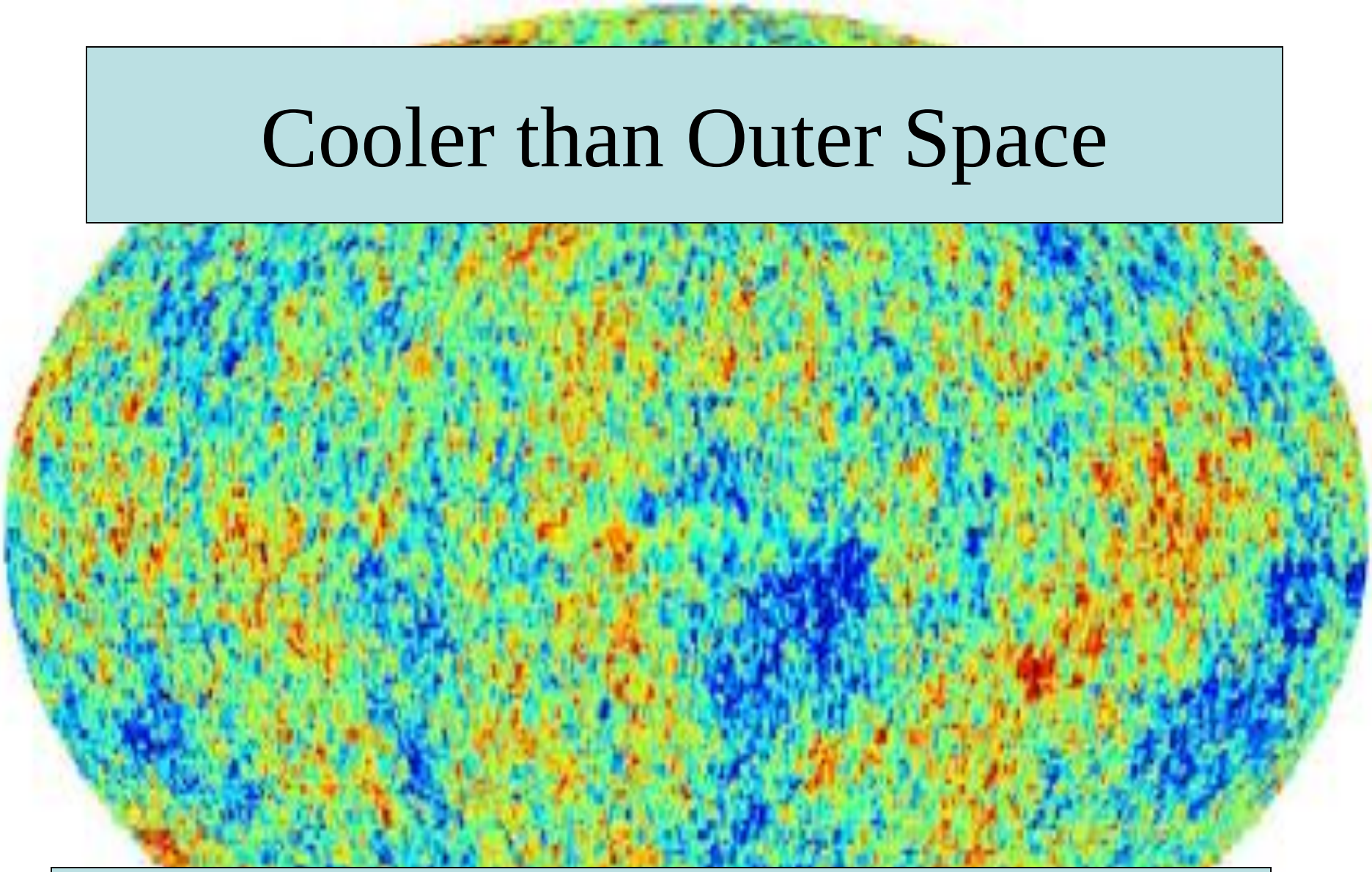
The Emptiest Space in the Solar System



Vacuum similar to interplanetary space:

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

Cooler than Outer Space

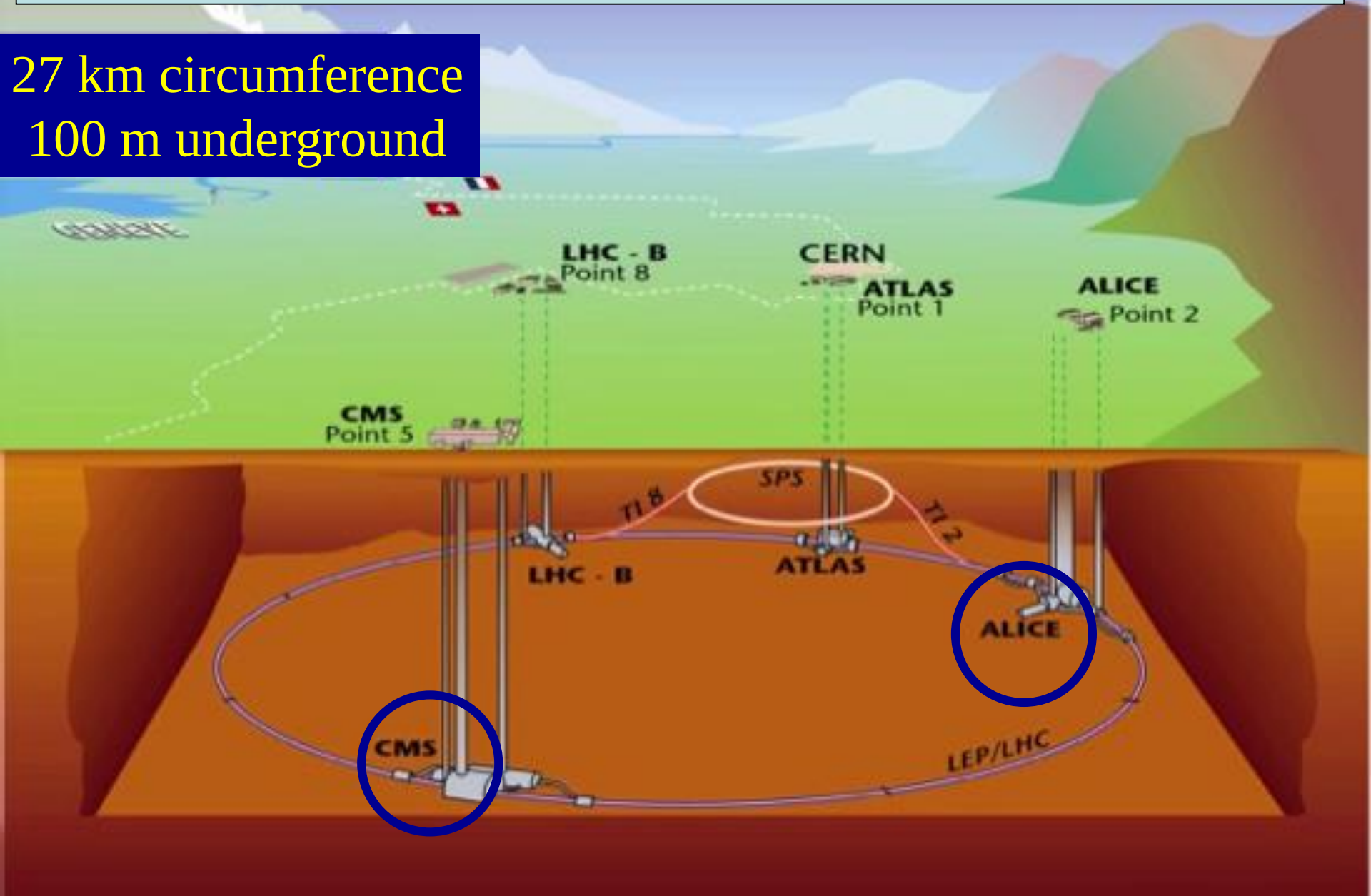


LHC 1.9 degrees above absolute zero = - 271 C

Outer space 2.7 degrees above zero = - 270 C

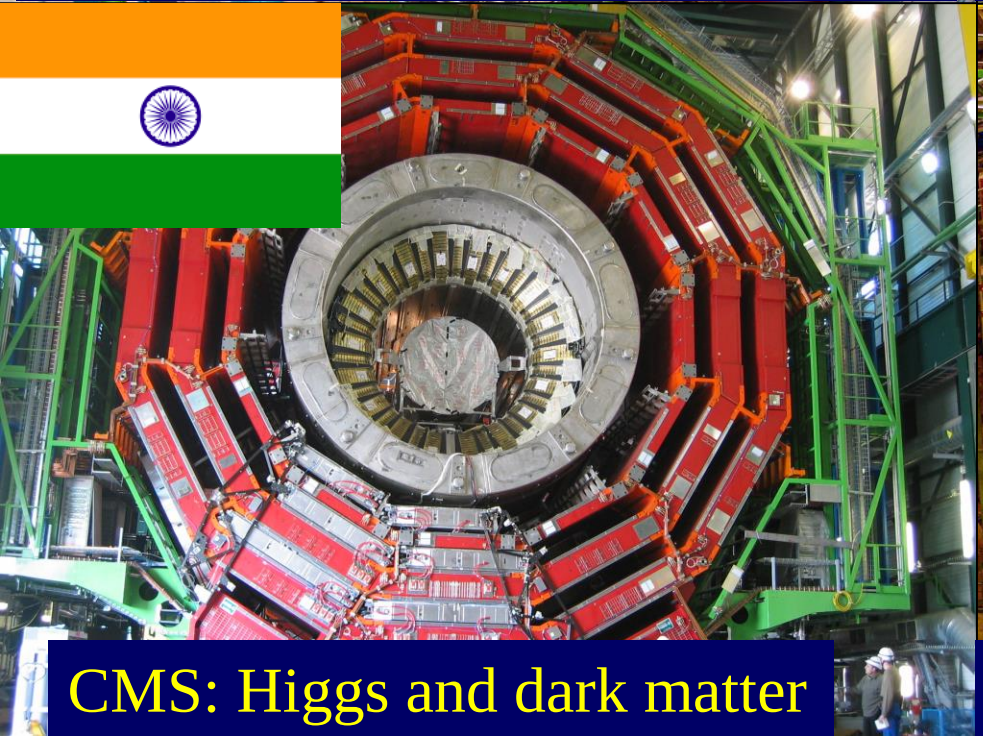
Overall View of the LHC and its Experiments

27 km circumference
100 m underground



ALICE: Primordial cosmic plasma

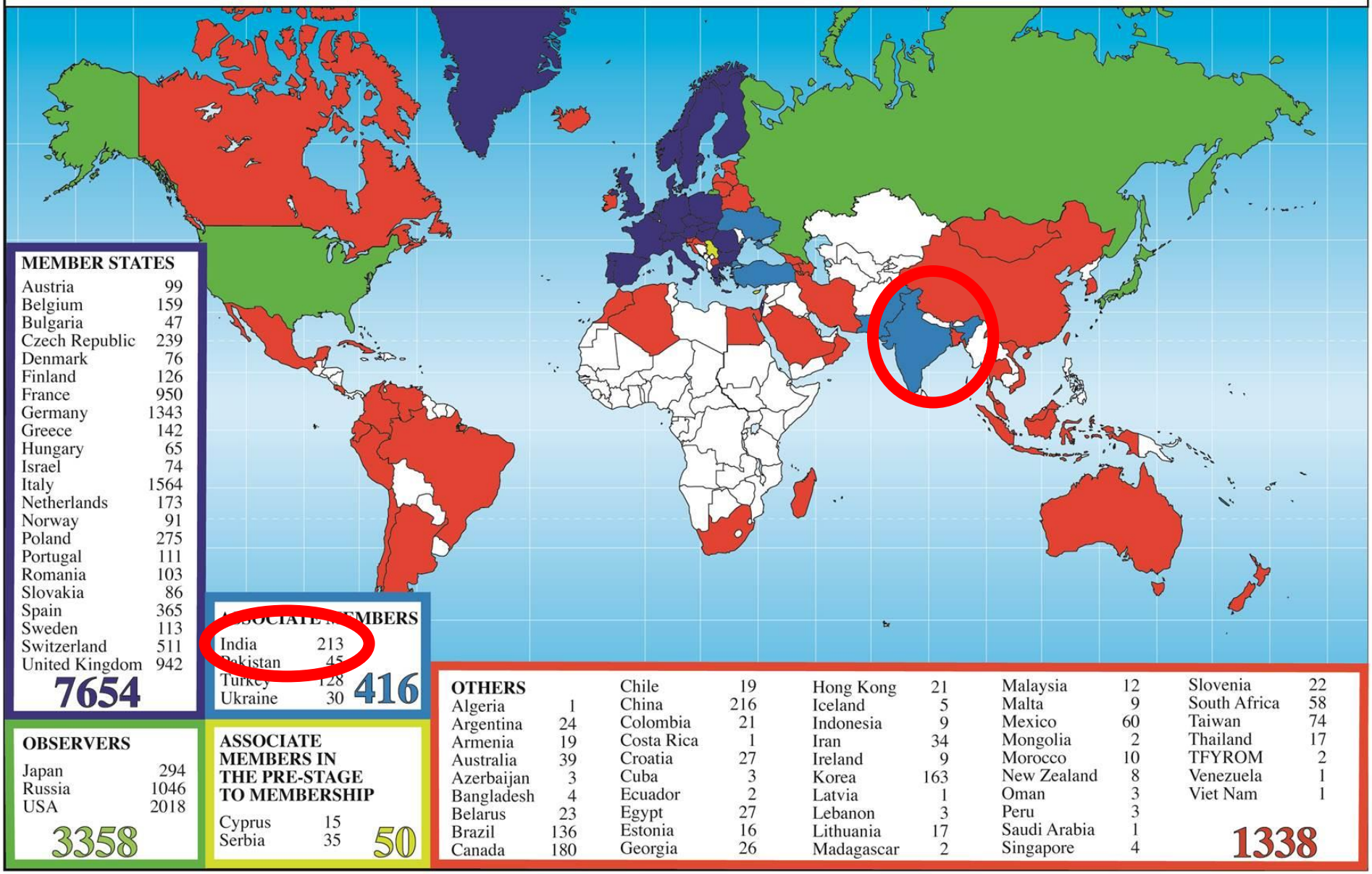
ATLAS: Higgs and dark matter



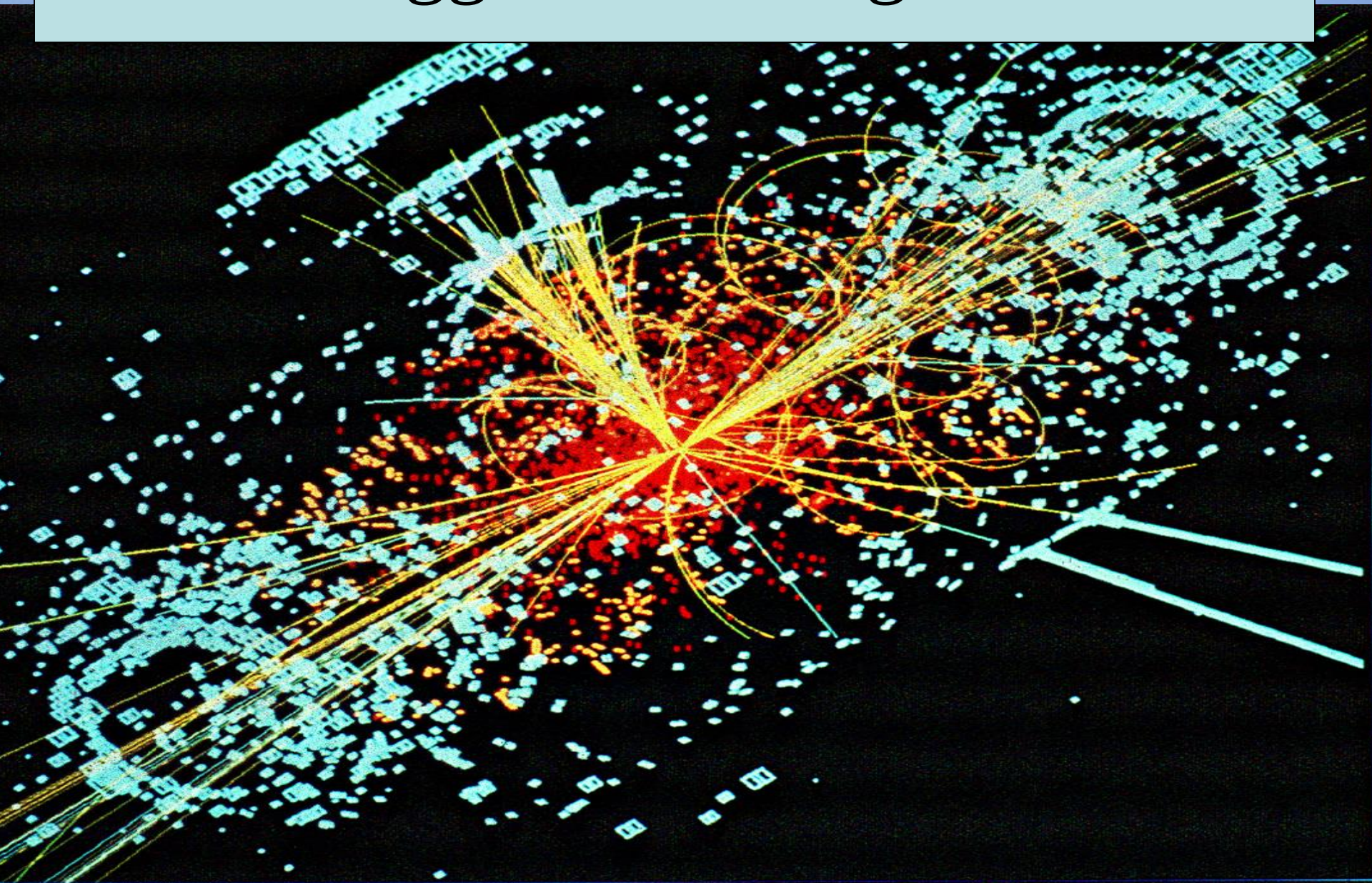
CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

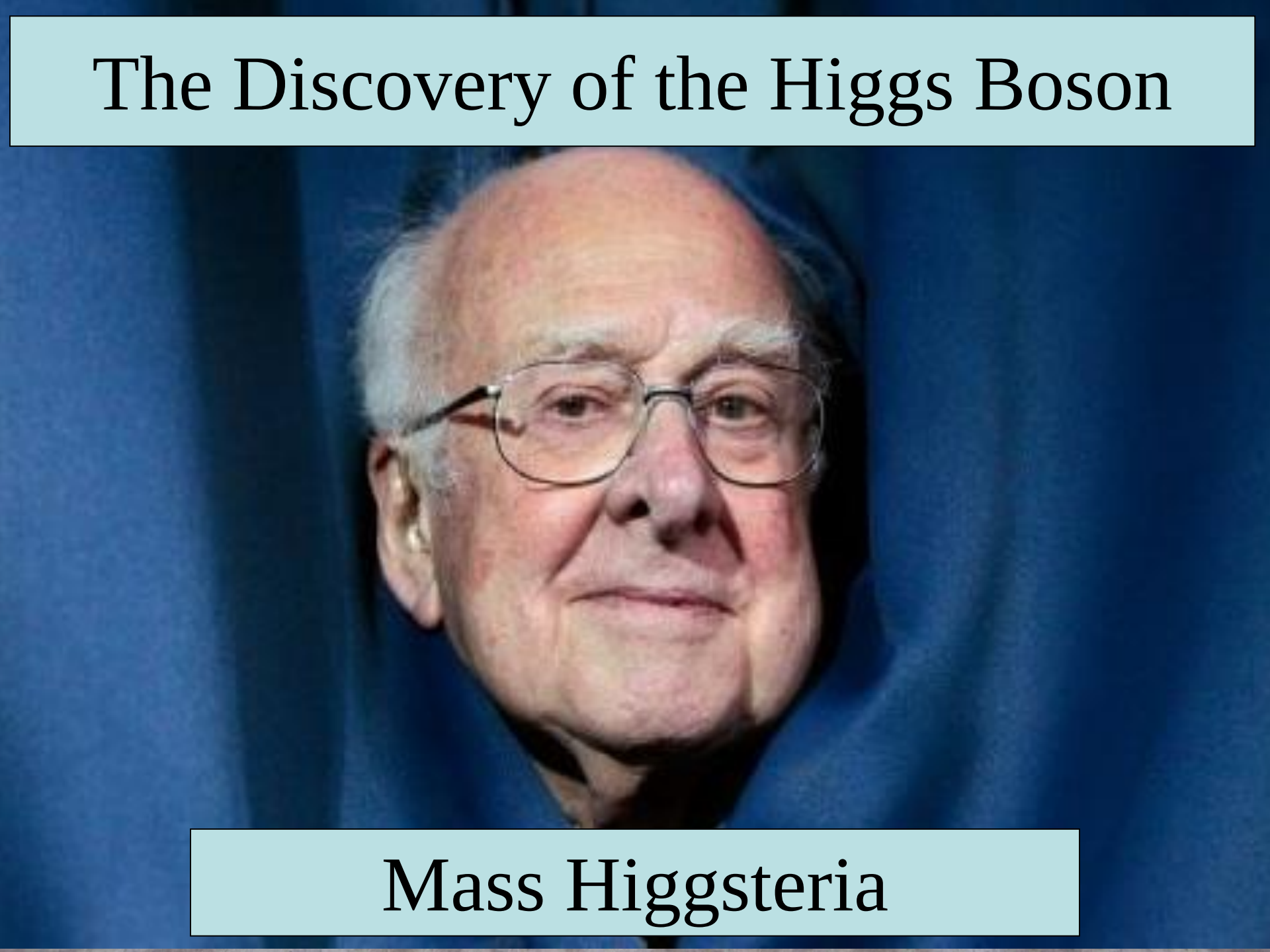
Scientists from around the World



What a Higgs Boson might look like

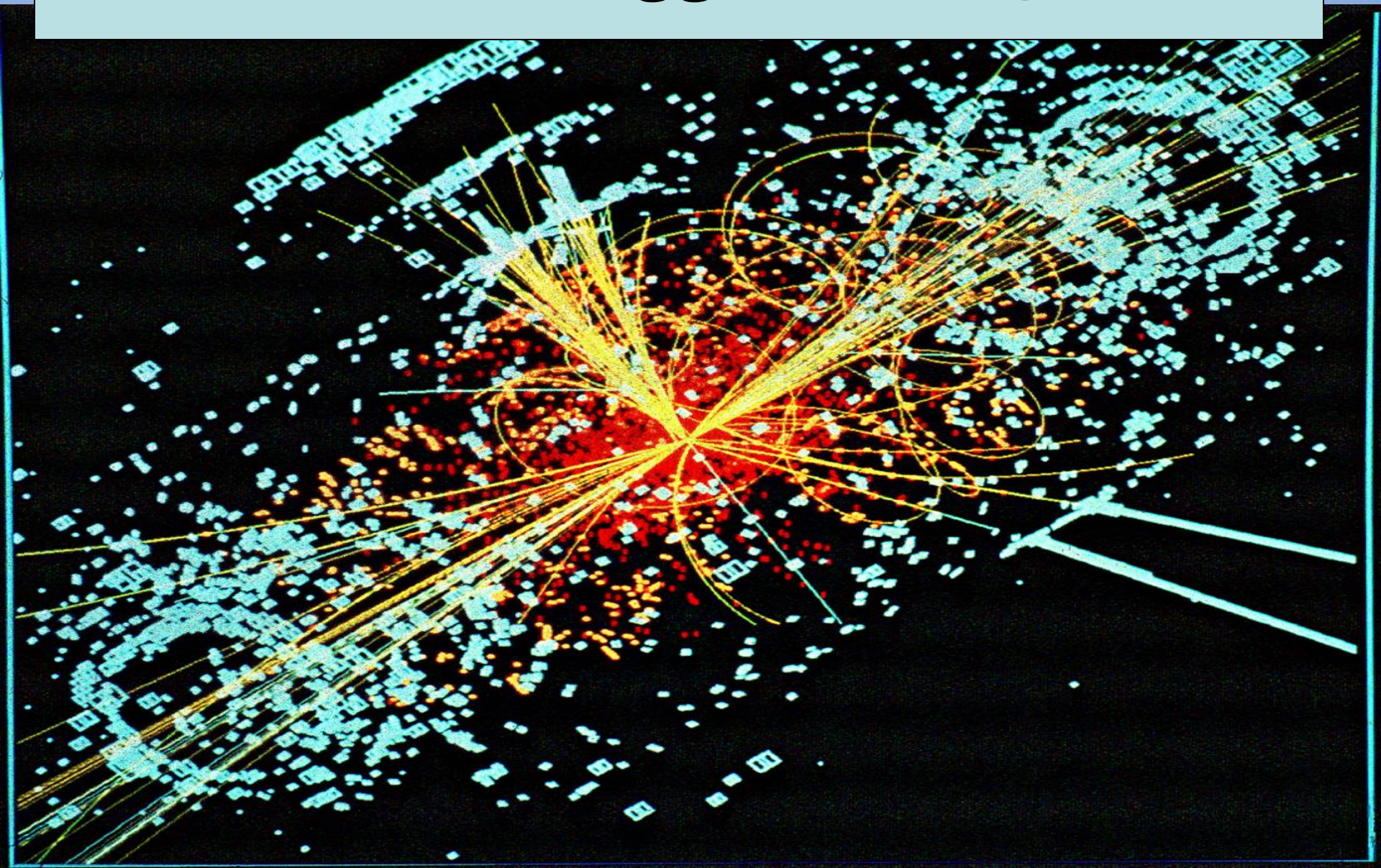


The Discovery of the Higgs Boson

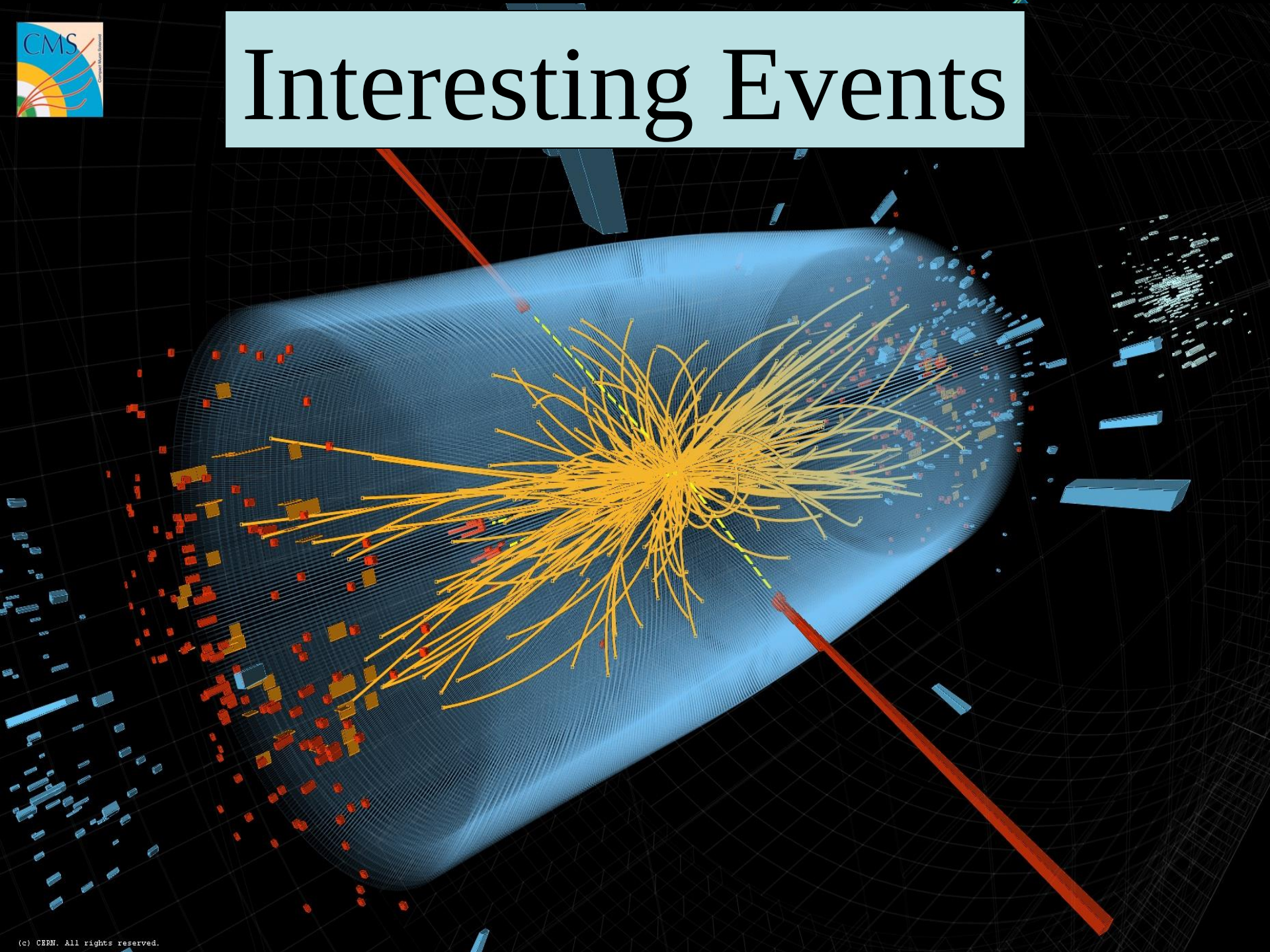


Mass Higgsteria

A Simulated Higgs Event @ LHC



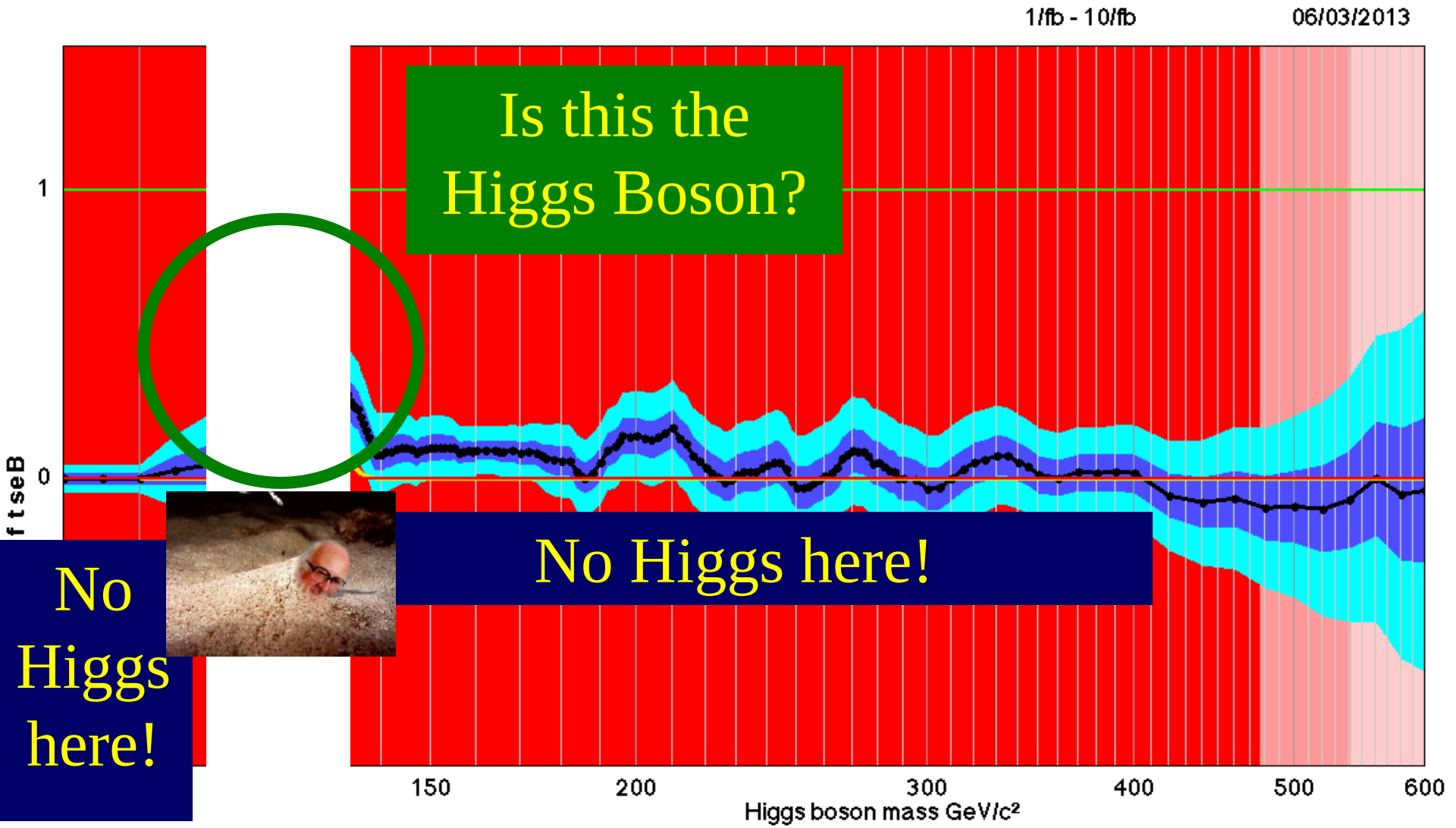
Interesting Events



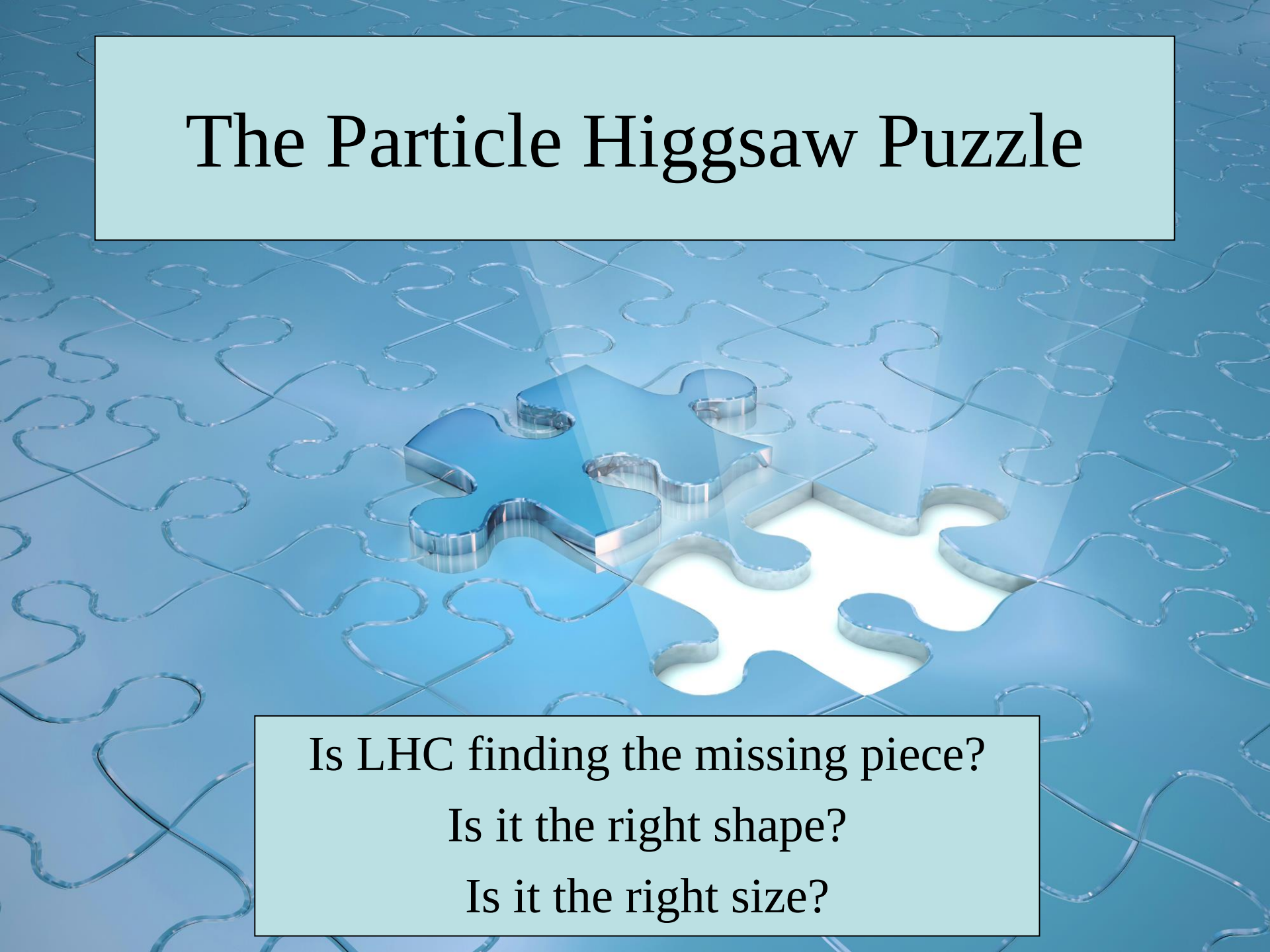
July 4th 2012
The discovery of a new particle

Higgsdependence Day!

Unofficial Combination of Higgs Data



The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

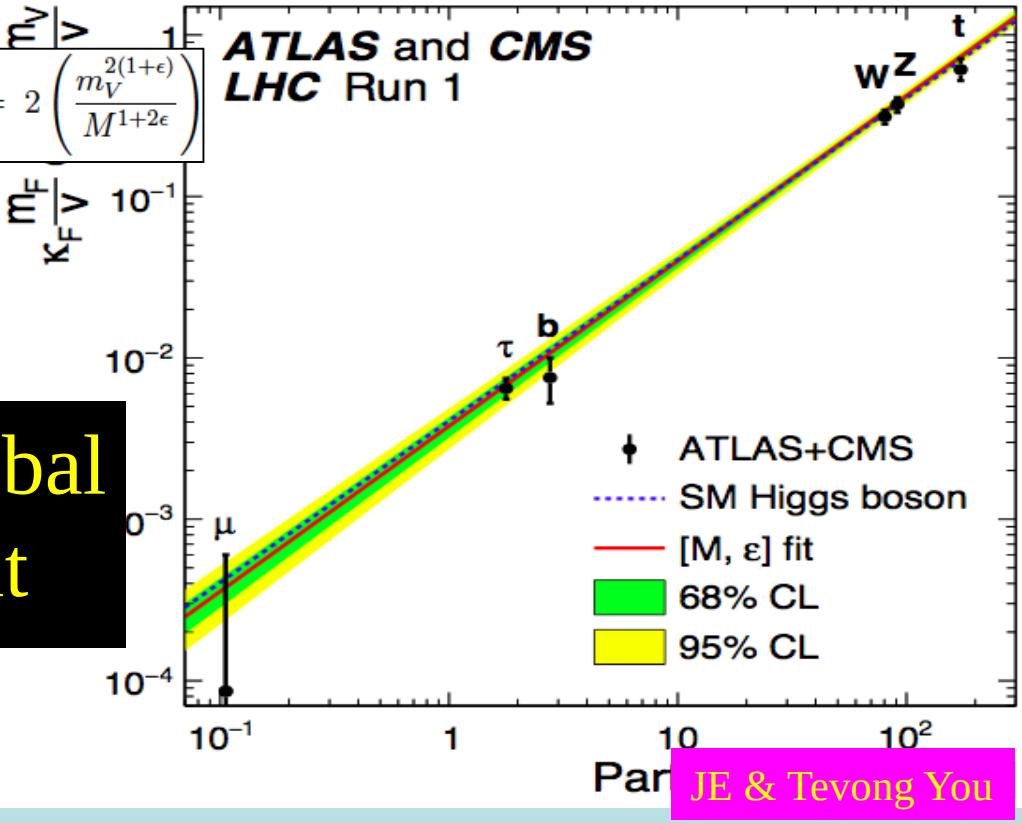
Is it the right shape?

Is it the right size?

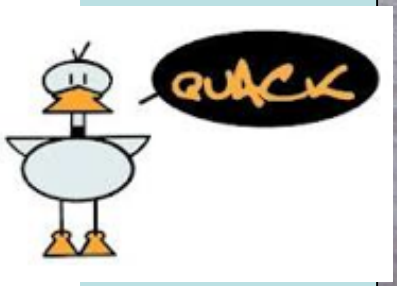
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



Global fit



JE & Tevong You

- **Blue** dashed line = Standard Model

Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

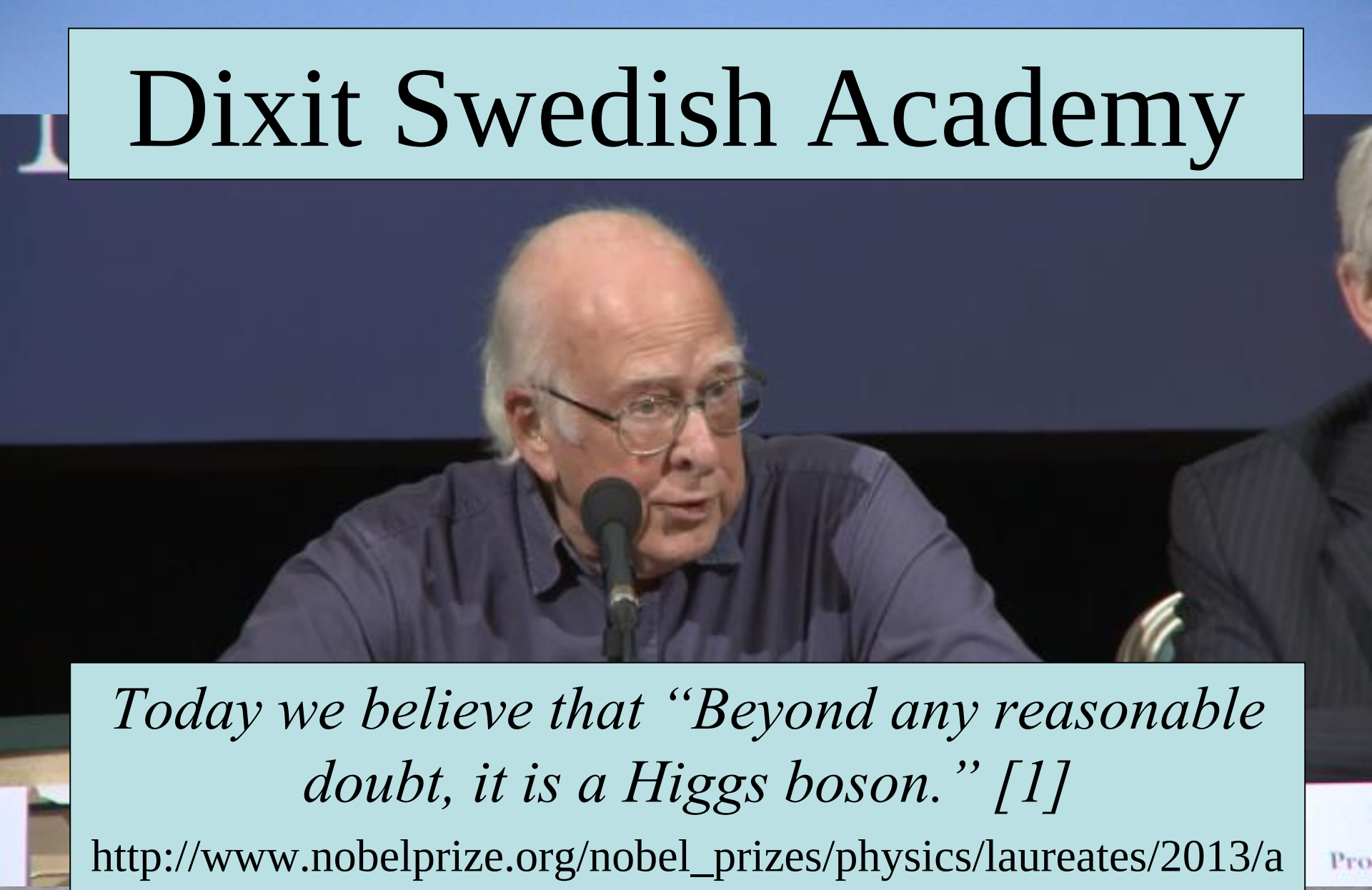
… there would be no heavy nuclei

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

Dixit Swedish Academy



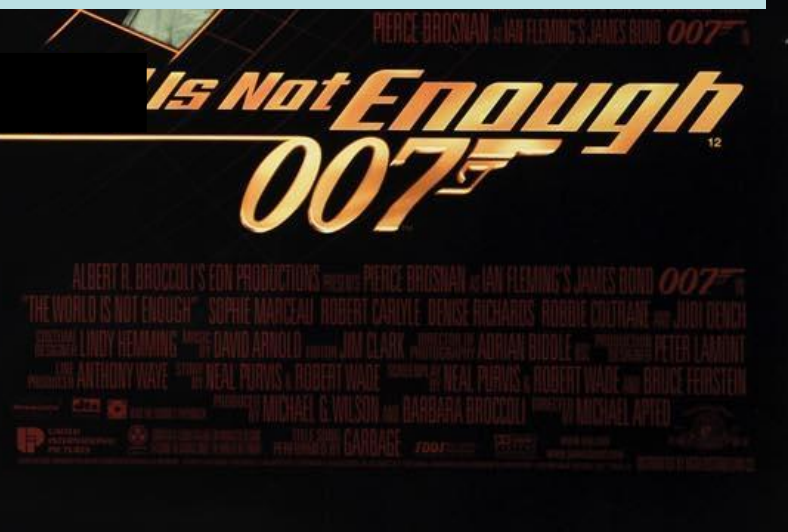
Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

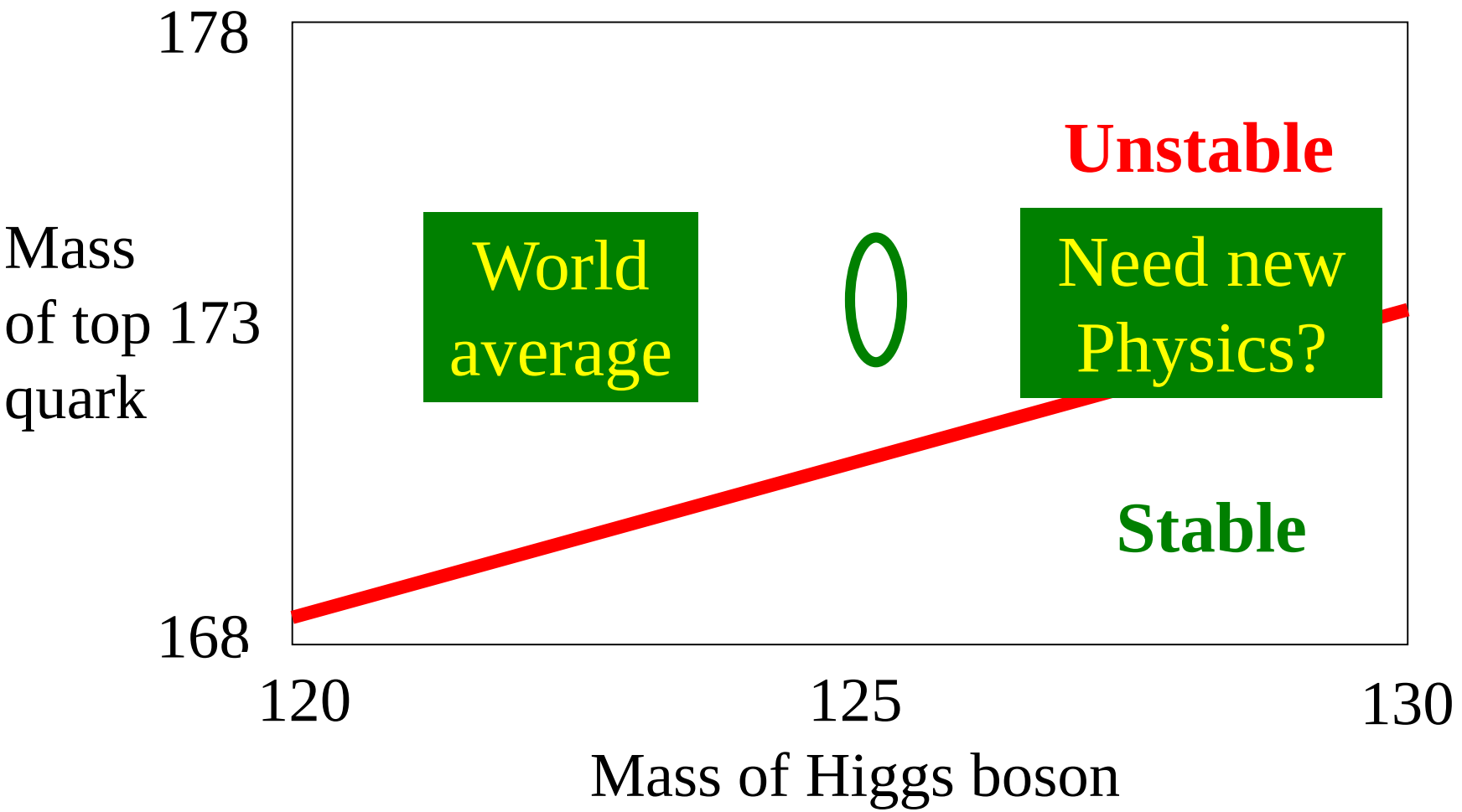
- « Empty » space is unstable LHC
- Dark matter LHC
- Origin of matter LHC
- Sizes of masses LHC
- Masses of neutrinos
- Inflation LHC
- Quantum gravity
- …

The Standard Model

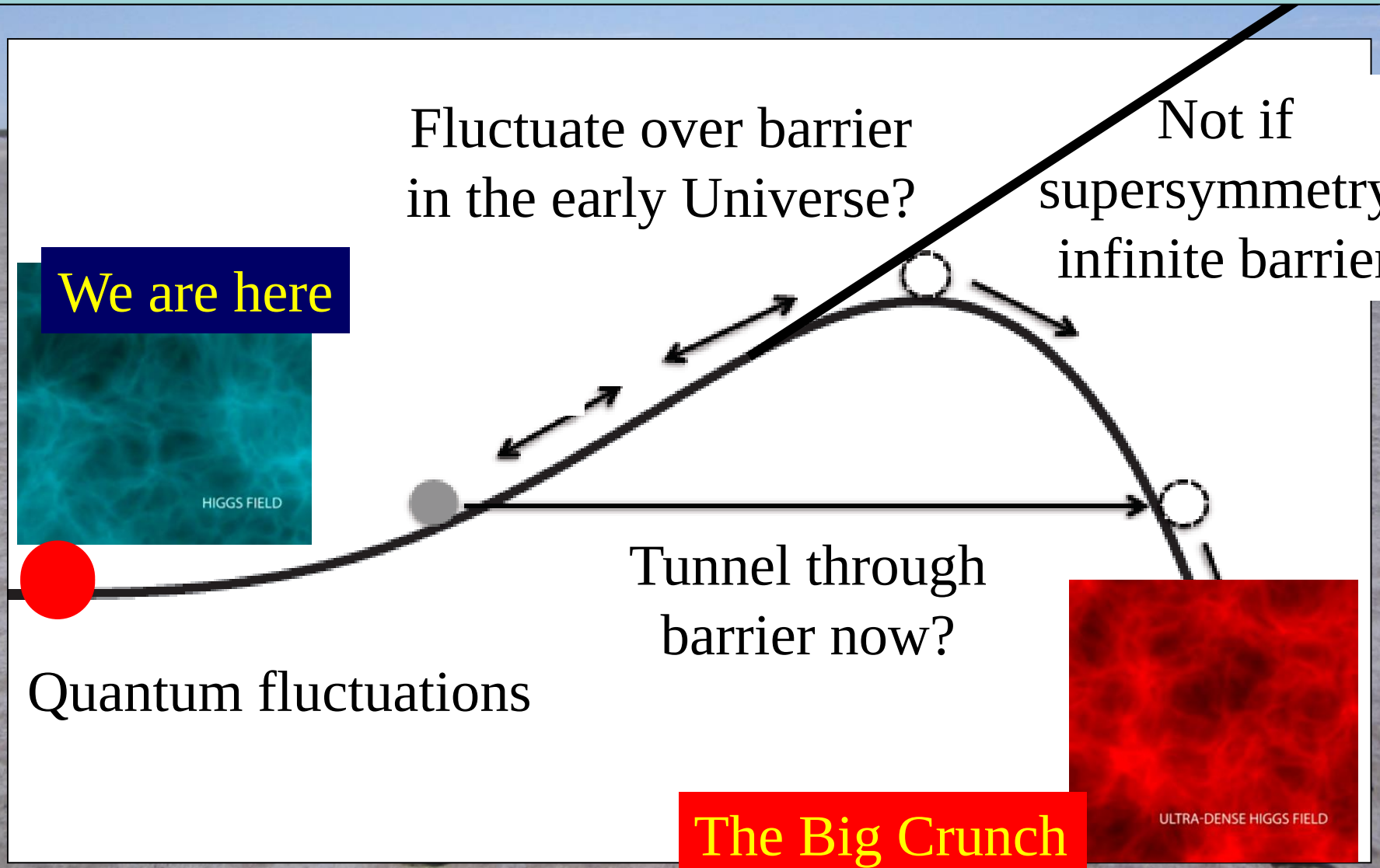


Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark

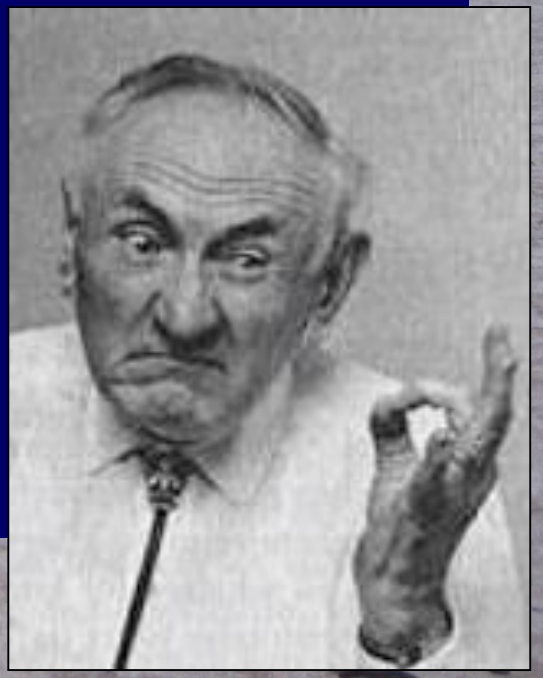


Should it have Collapsed already?



The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**



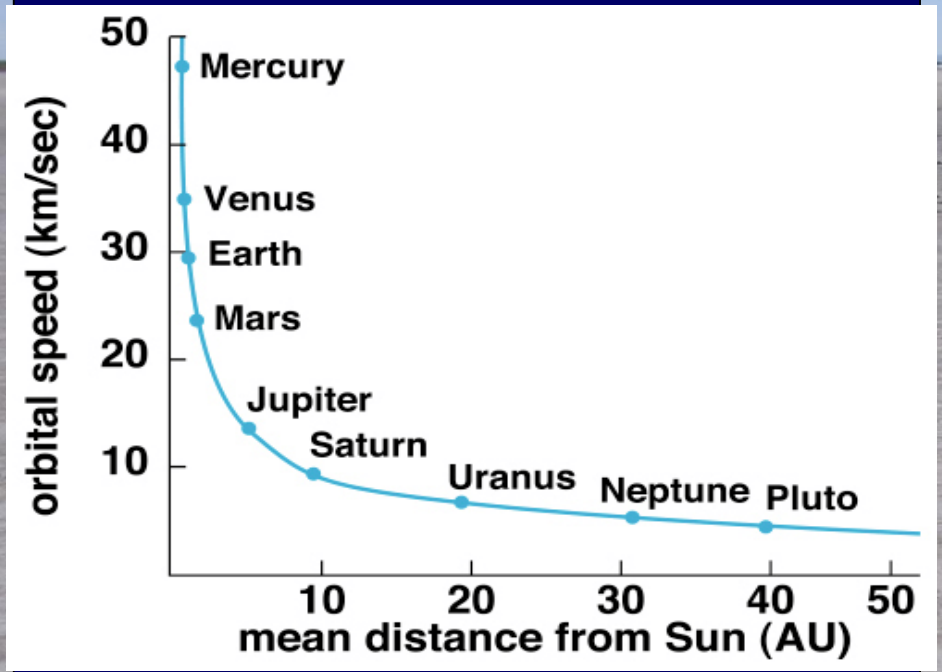
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

- **Further strong evidence for dark matter**

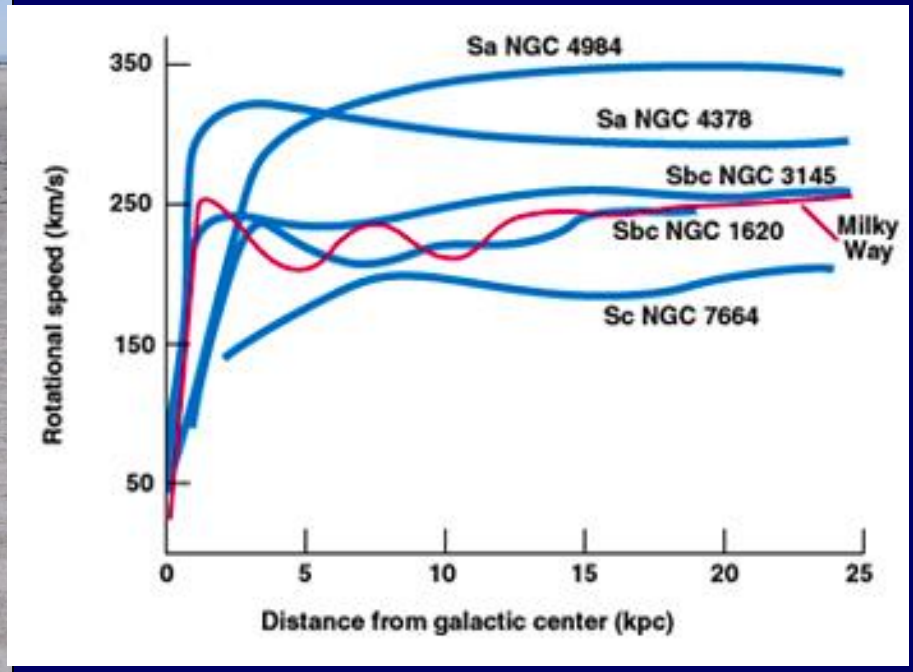
Rotation Curves

- In the Solar System



- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



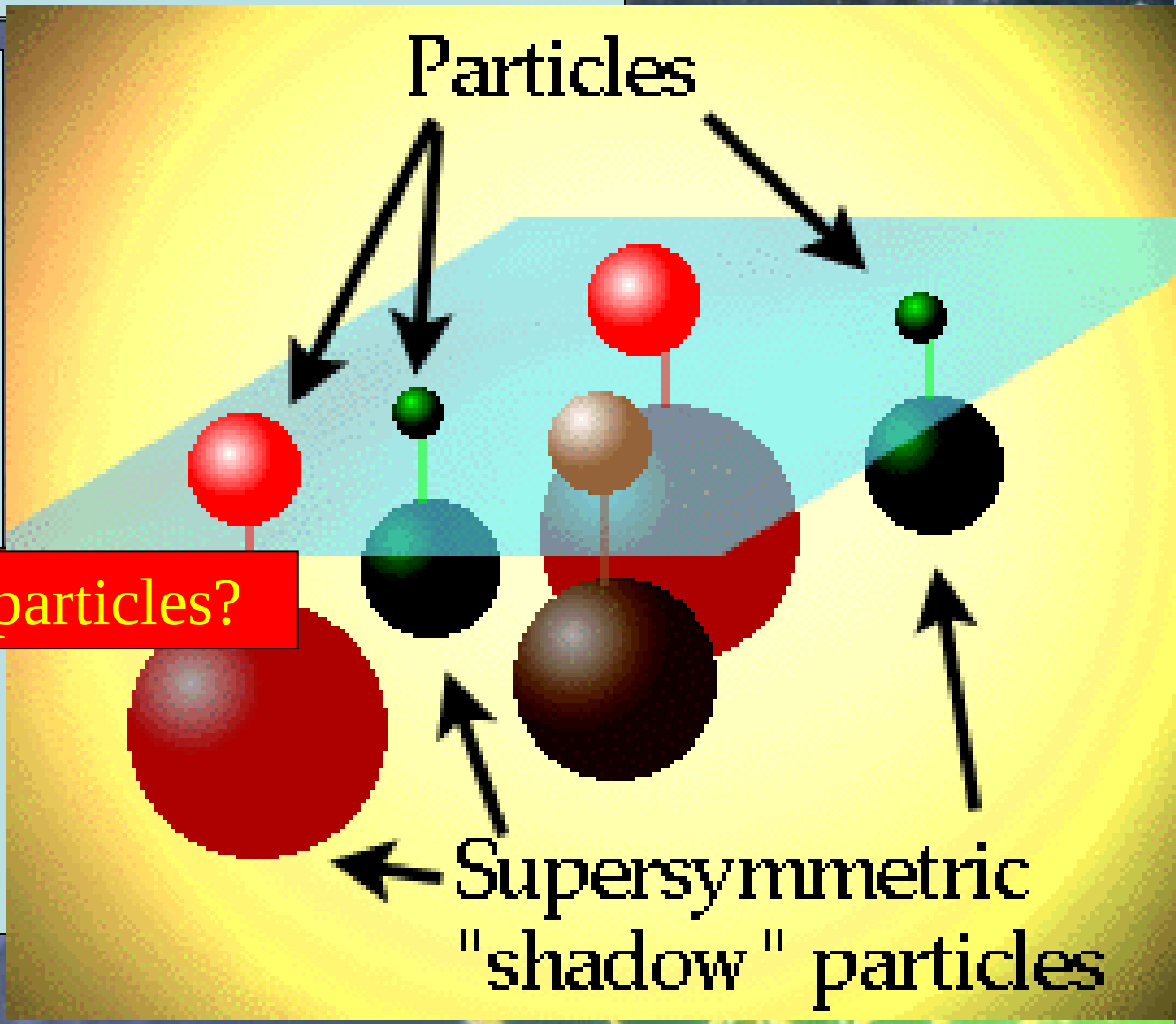
- The velocities do not decrease with distance
- Dark matter spread out

Dark Matter in the Universe

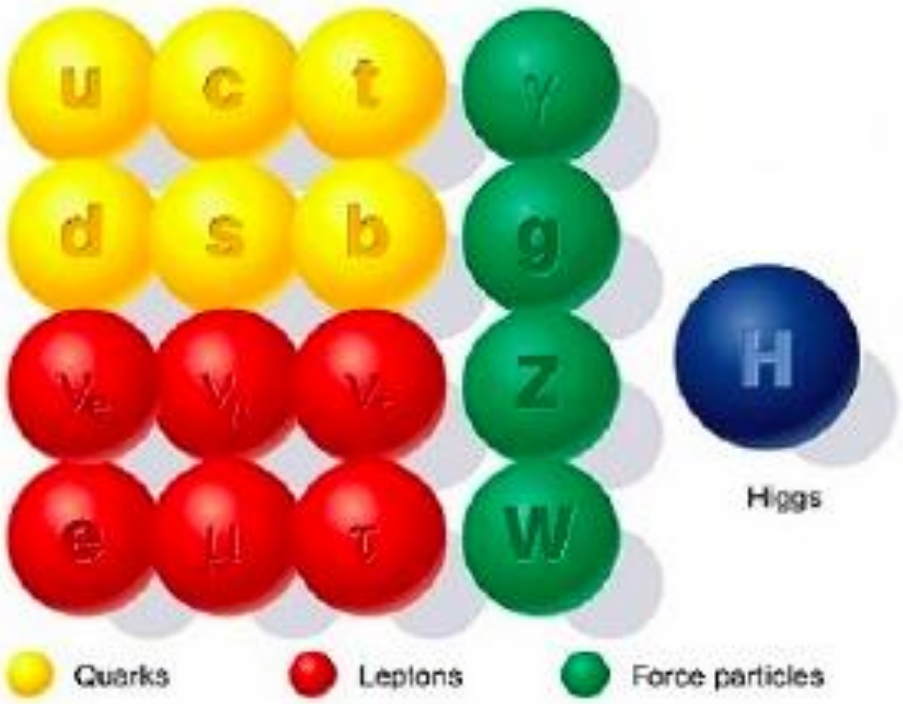
Astronomers say that most of the matter in the Universe is invisible Dark Matter

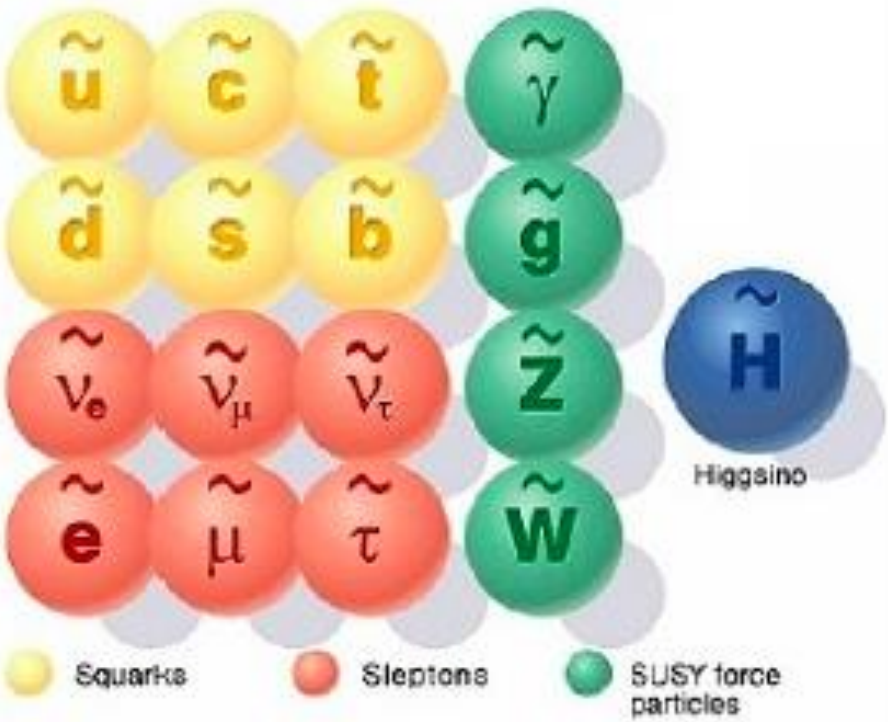
Supersymmetric particles?

Searching for them at the LHC



Minimal Supersymmetric Extension of the Standard Model

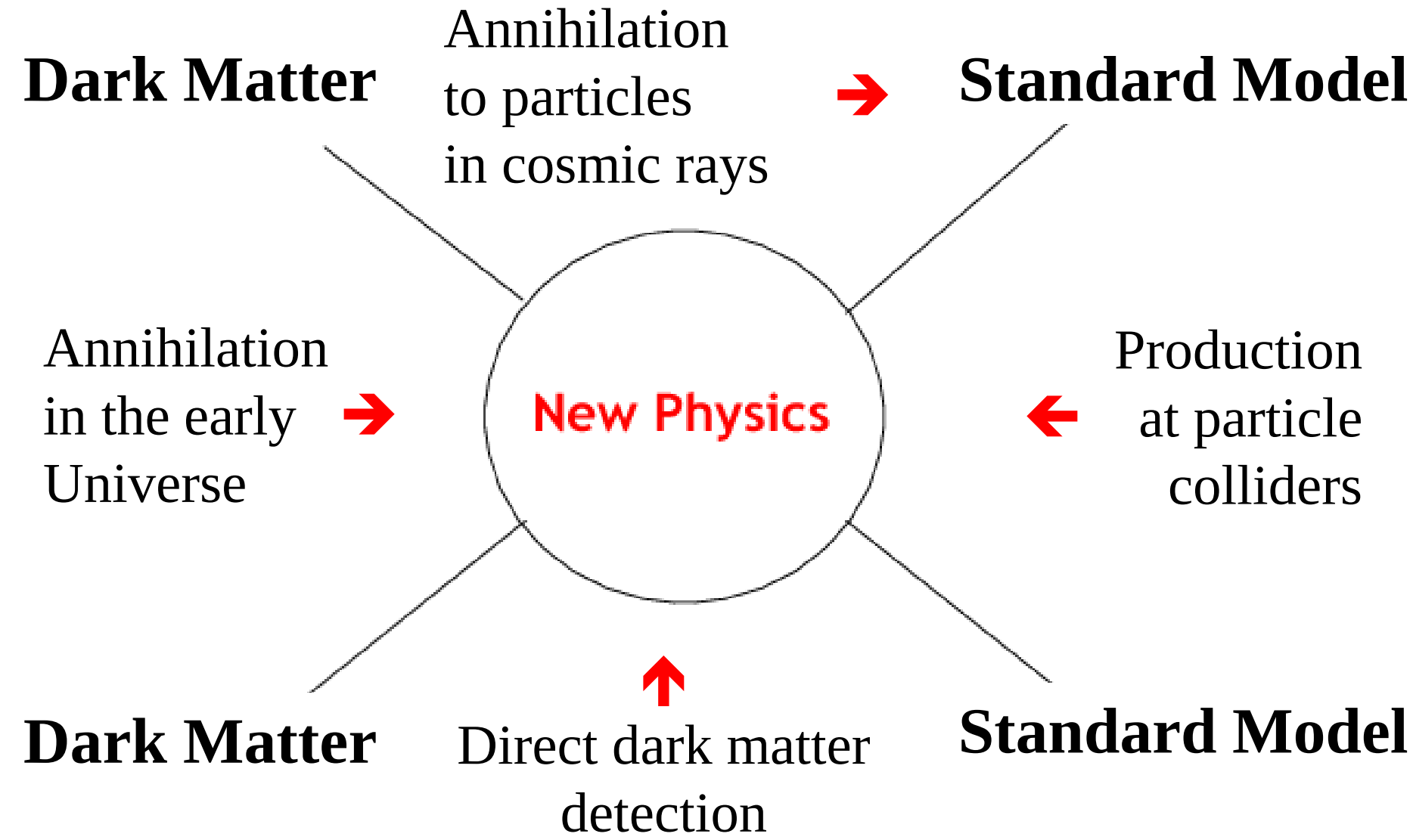




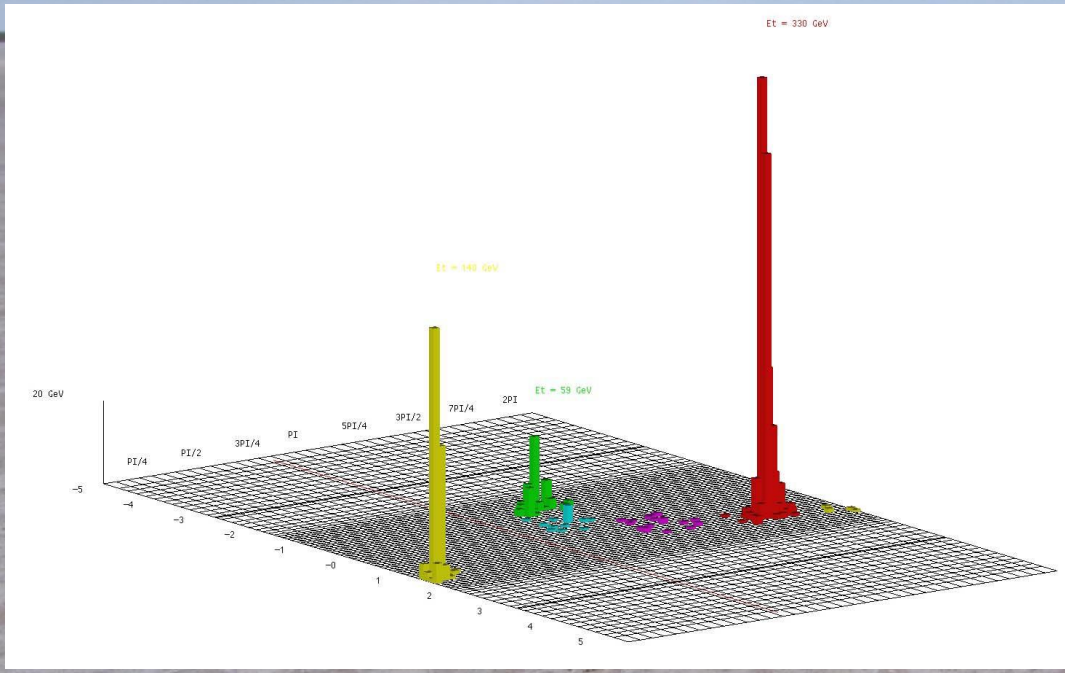
Standard particles **SUSY particles**

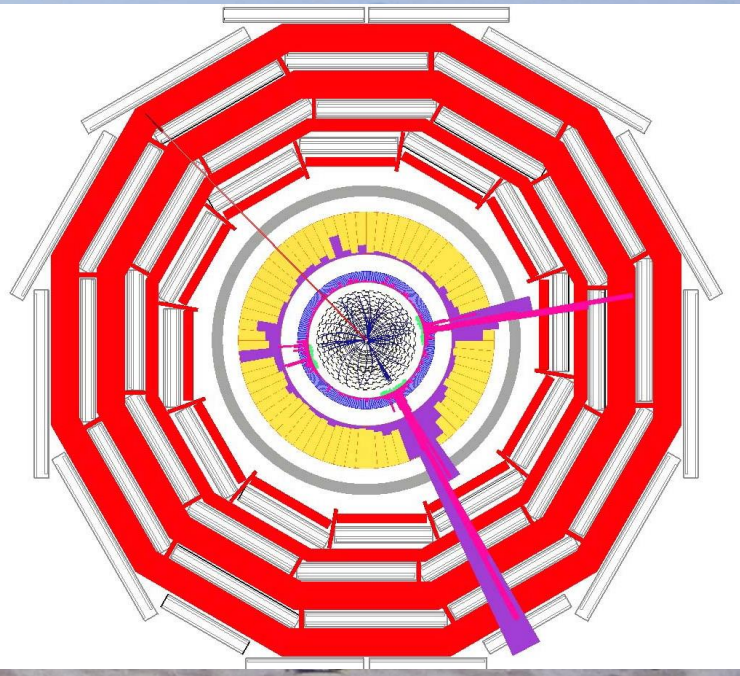
Would help fix sizes of particle masses

Searches for Dark Matter



Search for Dark Matter at the LHC



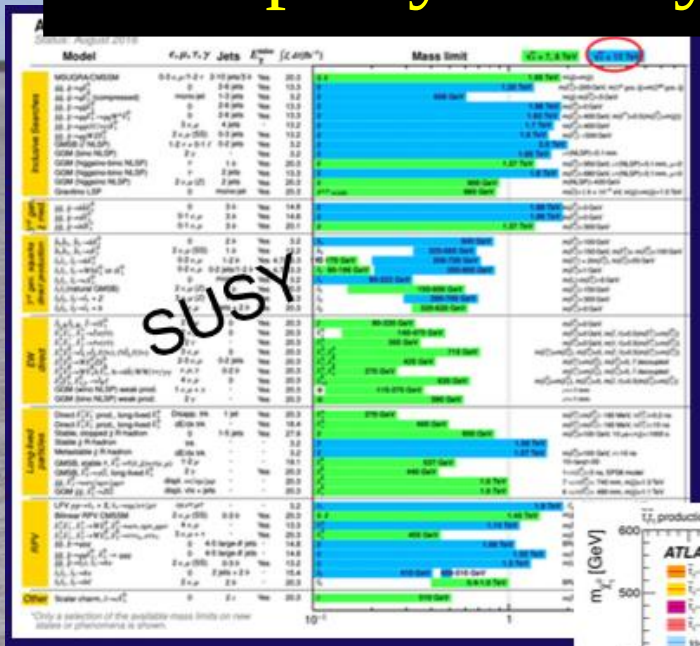


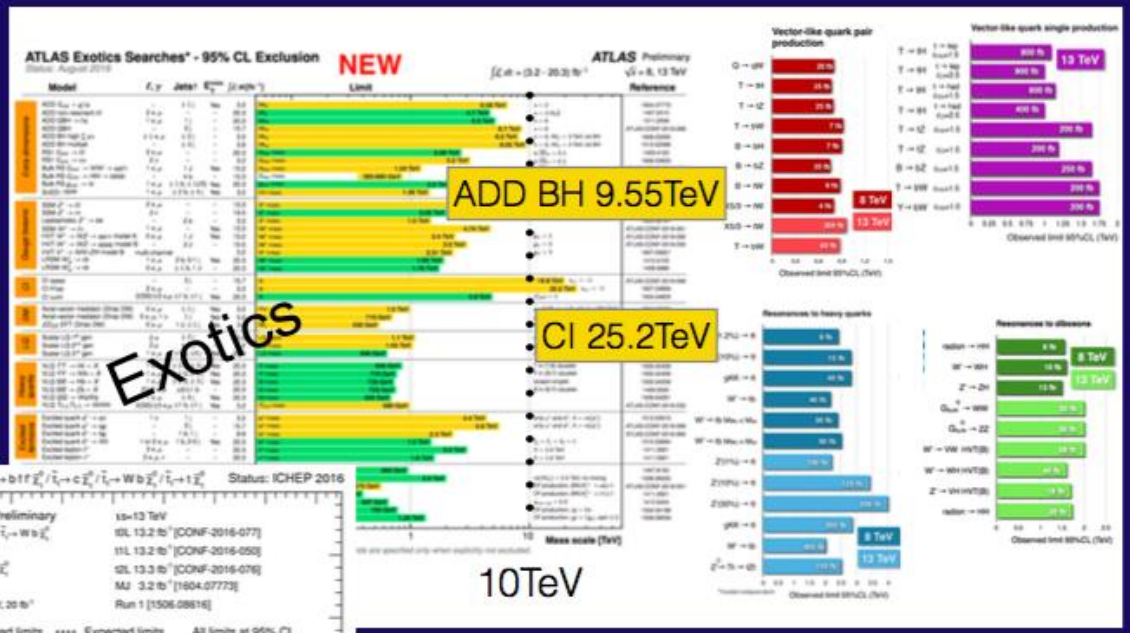
Missing transverse energy
carried away by dark matter particles

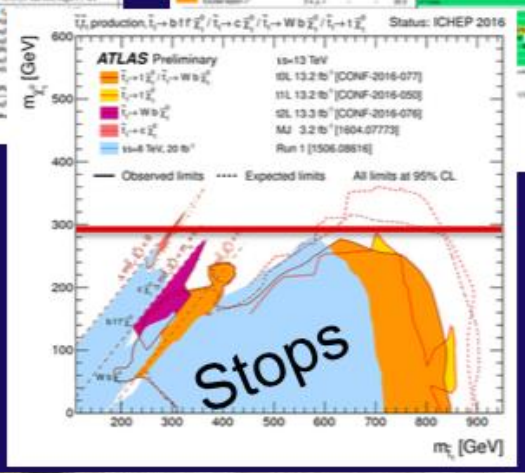
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either

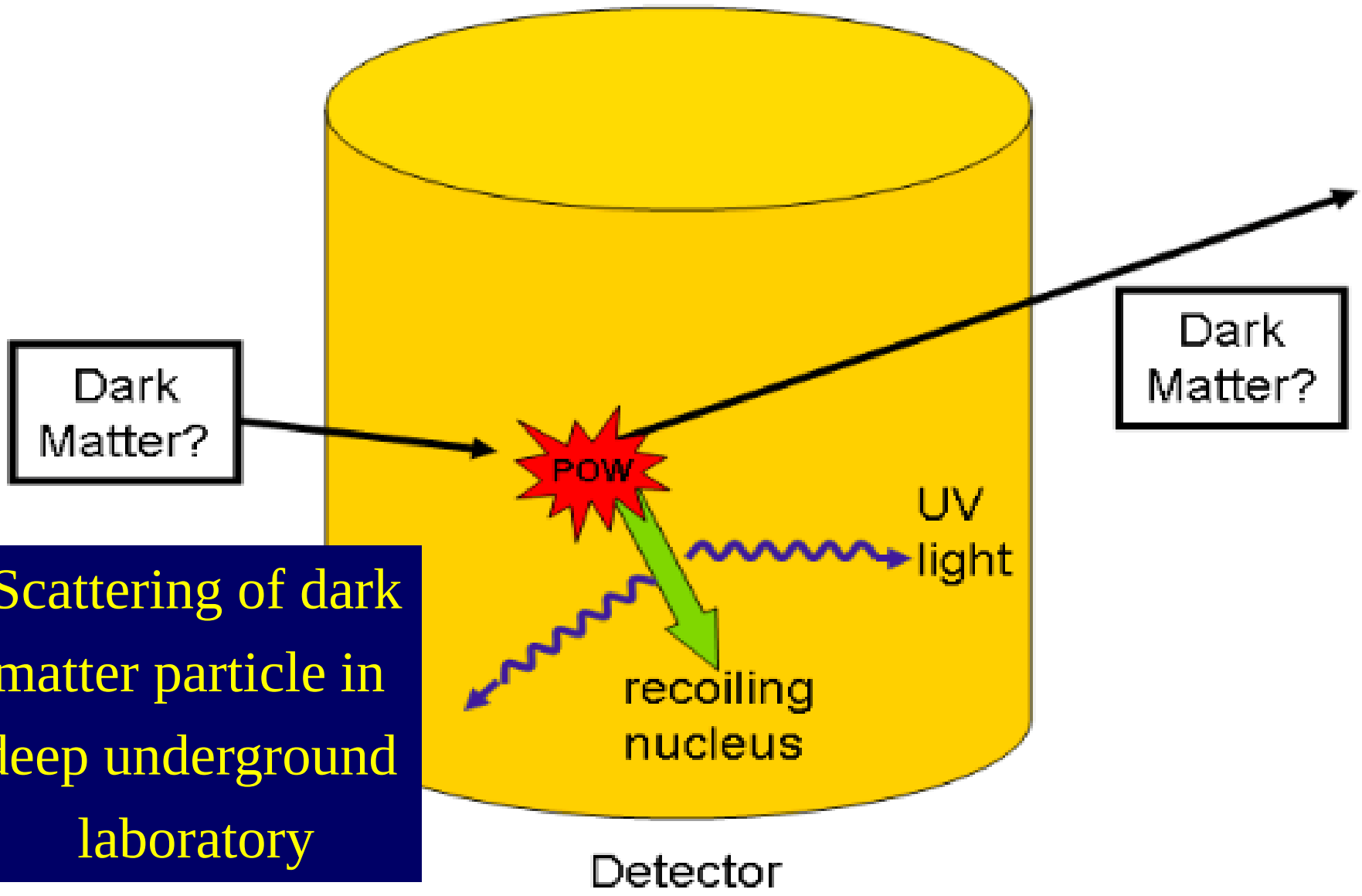






How else to search for Dark Matter?

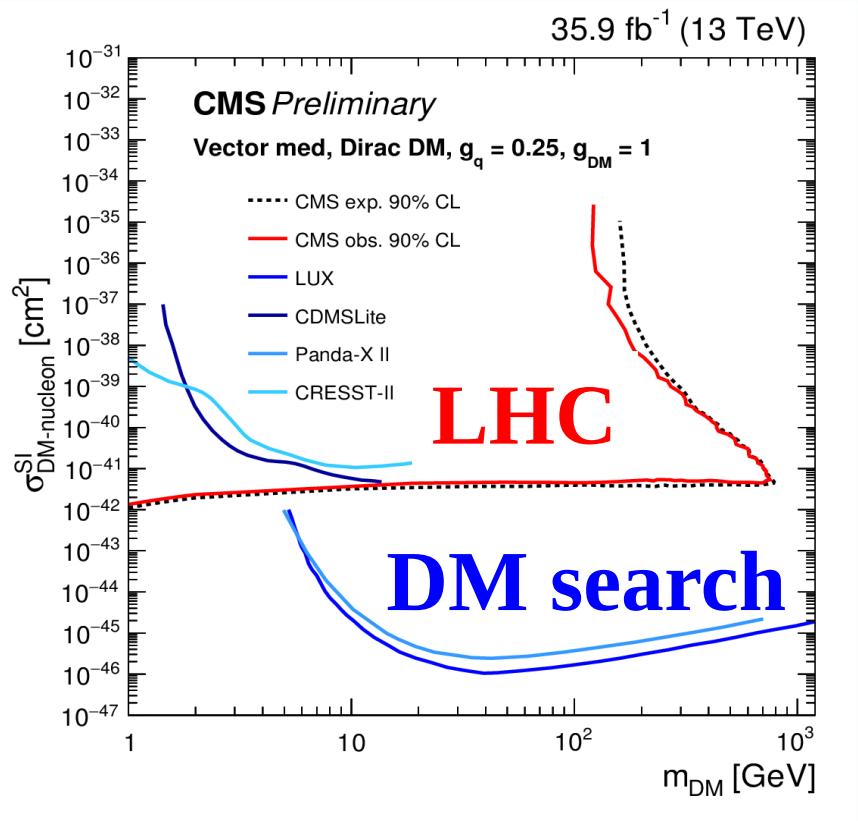
Direct Dark Matter Detection

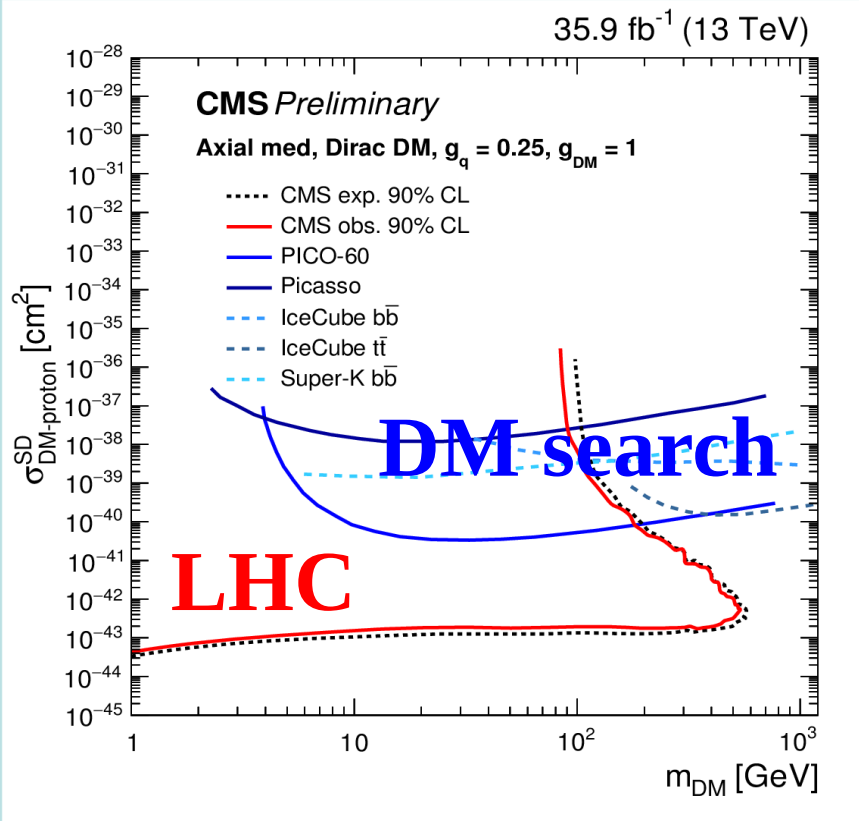


Scattering of dark matter particle in deep underground laboratory

LHC vs Dark Matter Searches

- Compilation of present sensitivities





- Complementarity between LHC and direct searches

General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

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

Used in PET scanners

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

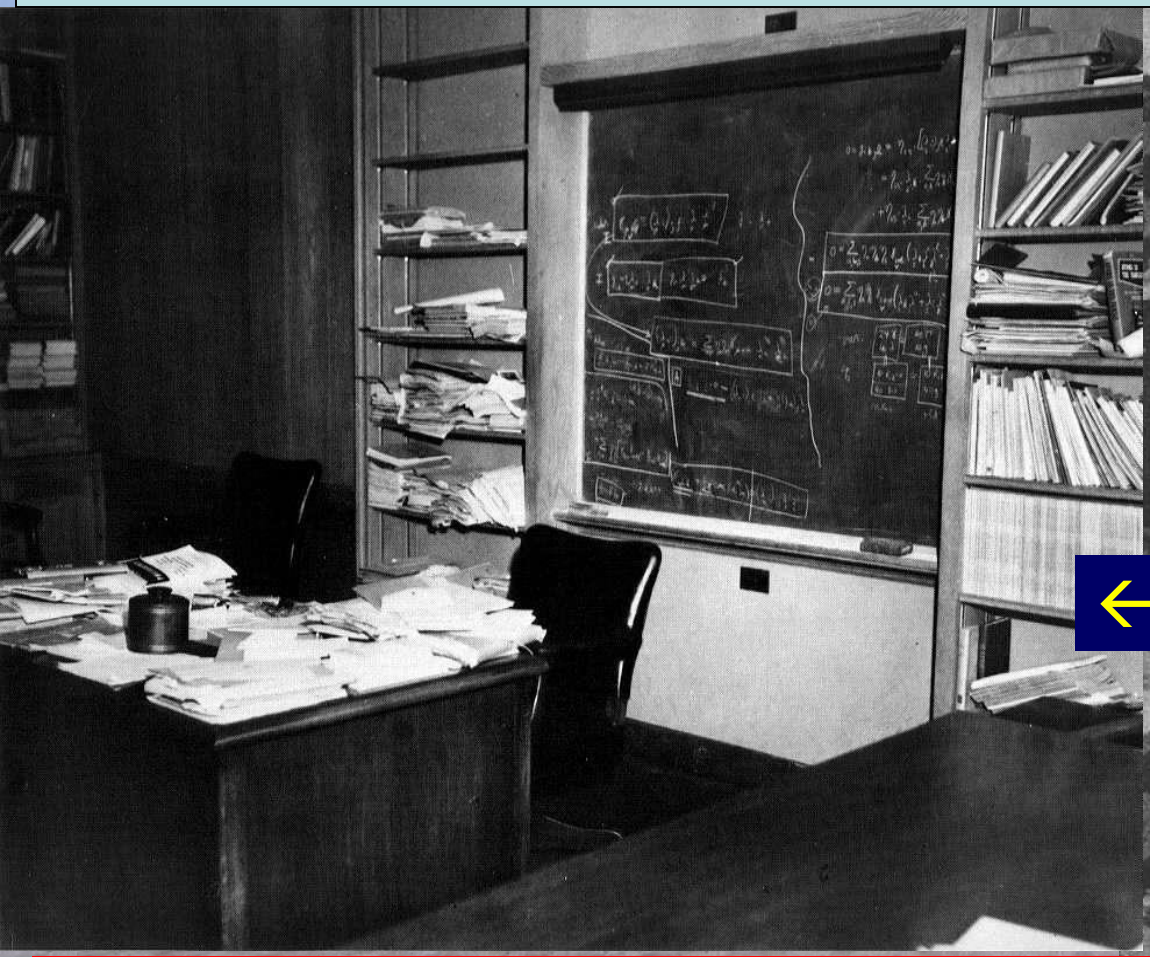
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  predicted by theories
  not yet seen by experiment
- Need the expansion of the Universe
  a role for the Higgs boson?

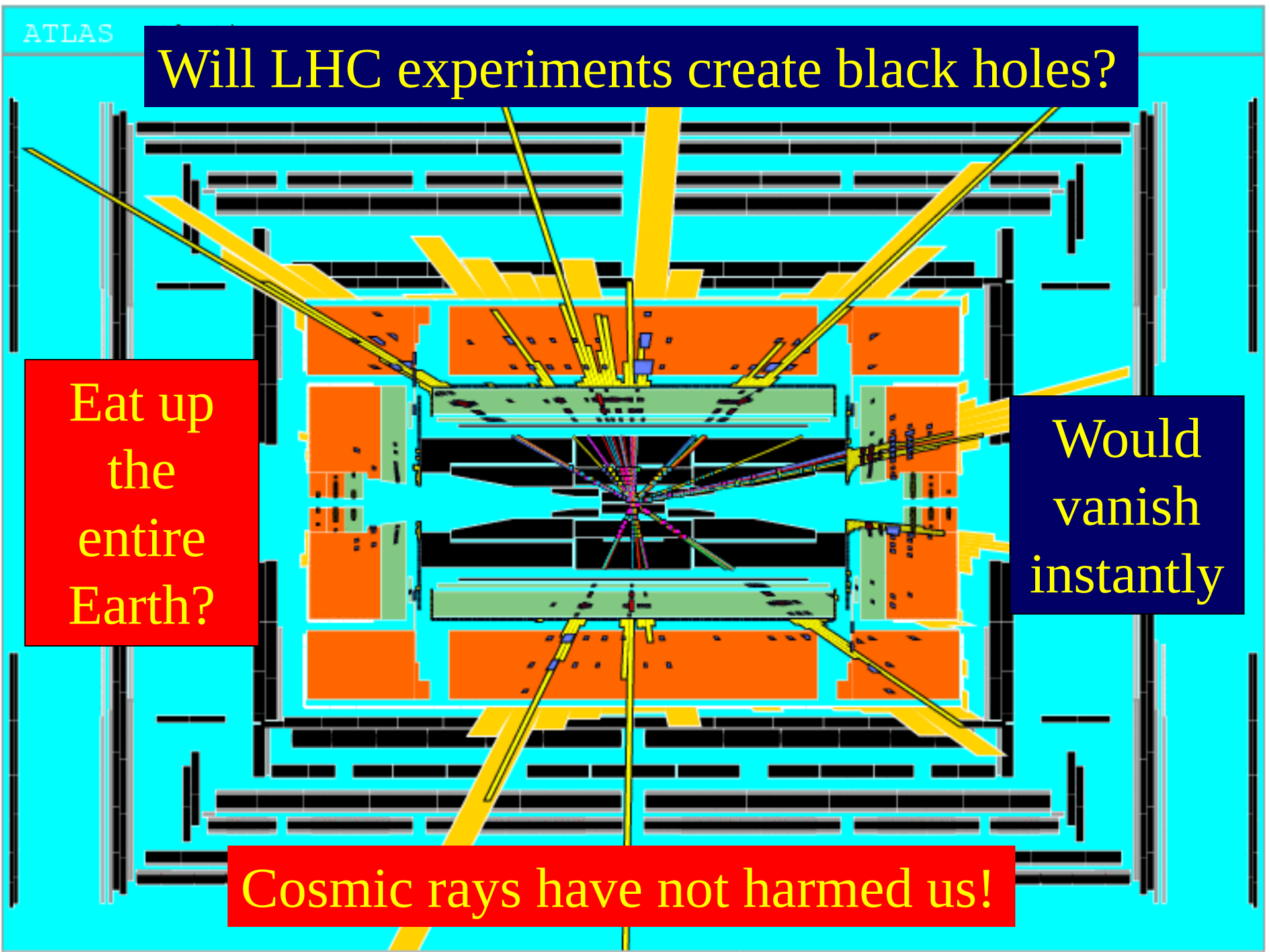
Will we be able to calculate using laboratory data?

Unify the Fundamental Interactions: Einstein's Dream …

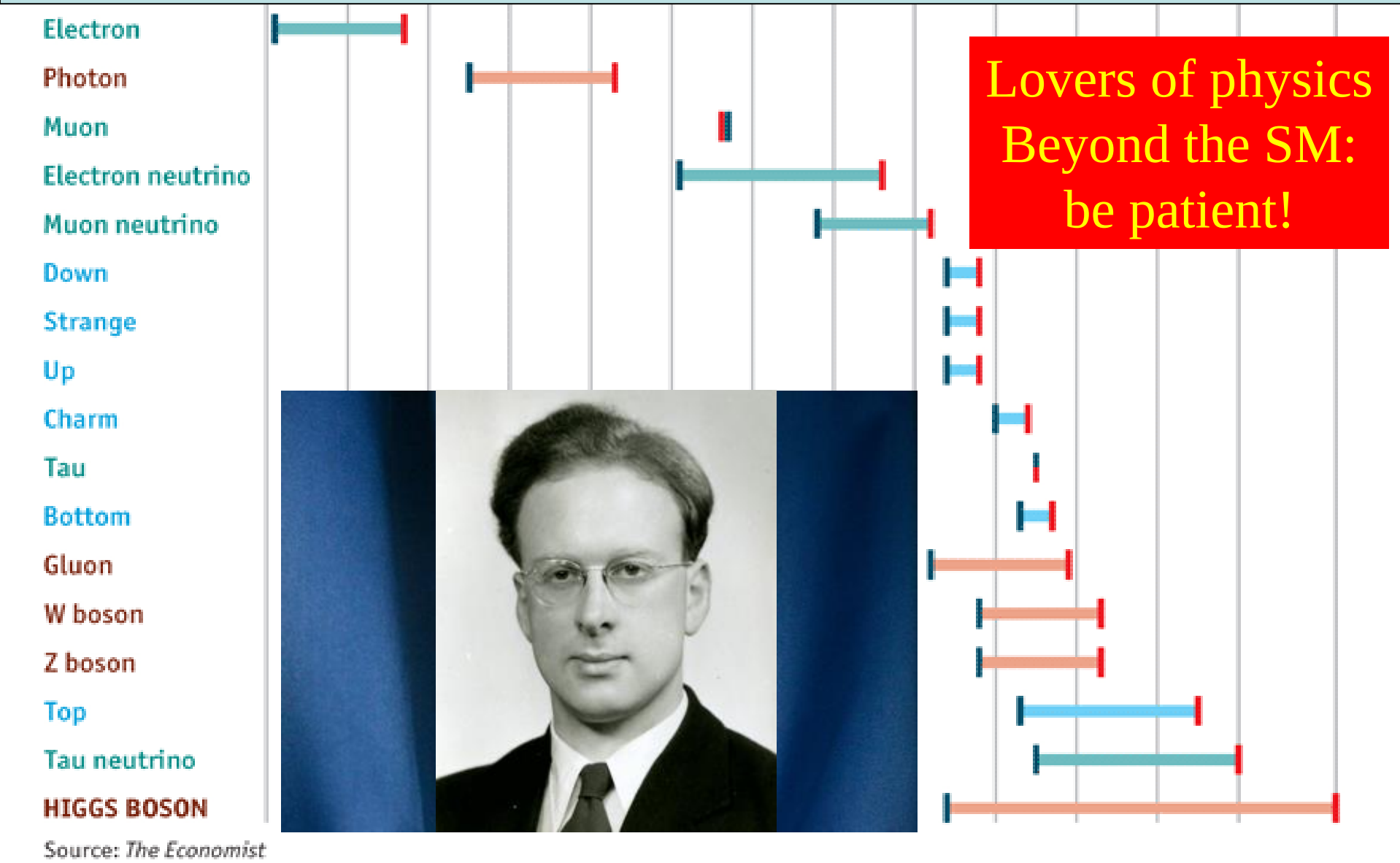


← … but he never succeeded

Unification via extra dimensions of space?


ATLAS
Will LHC experiments create black holes?
Eat up the entire Earth?
Would vanish instantly
Cosmic rays have not harmed us!

Standard Model Particles:
Years from Proposal to Discovery



Summary