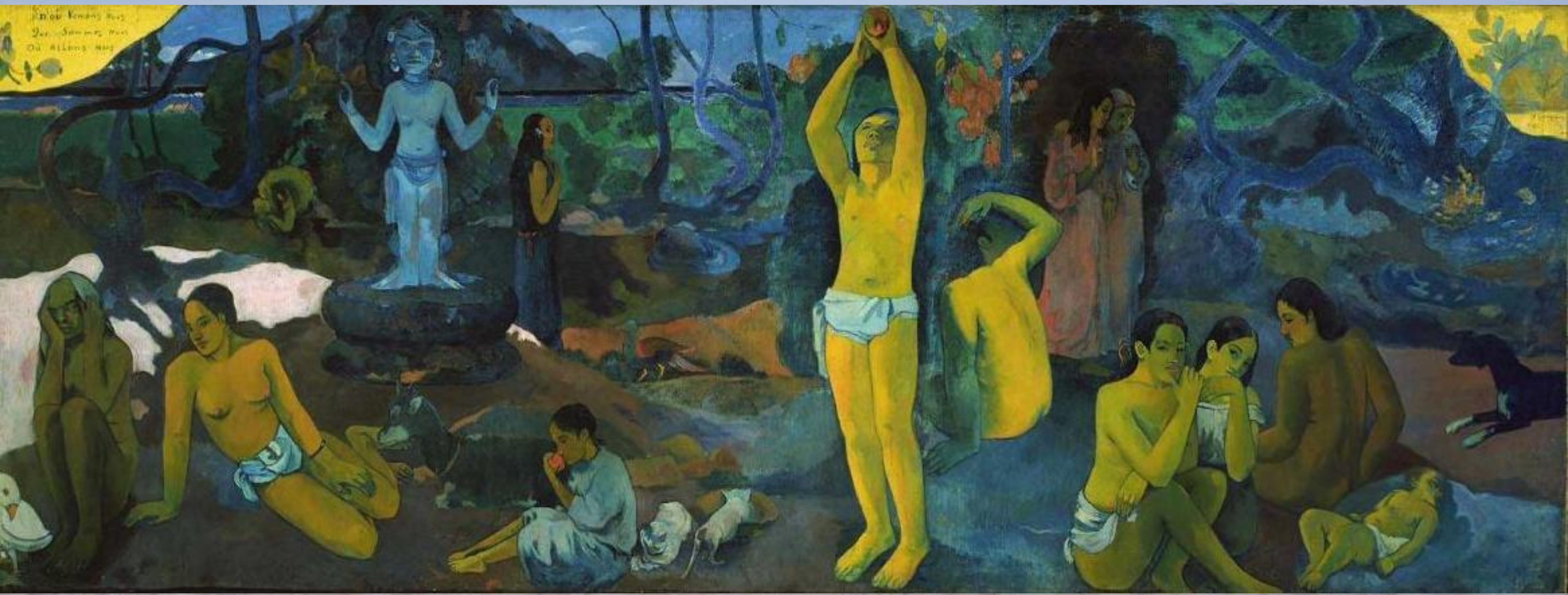
What are we?

Where do we come from?

Where are we going?



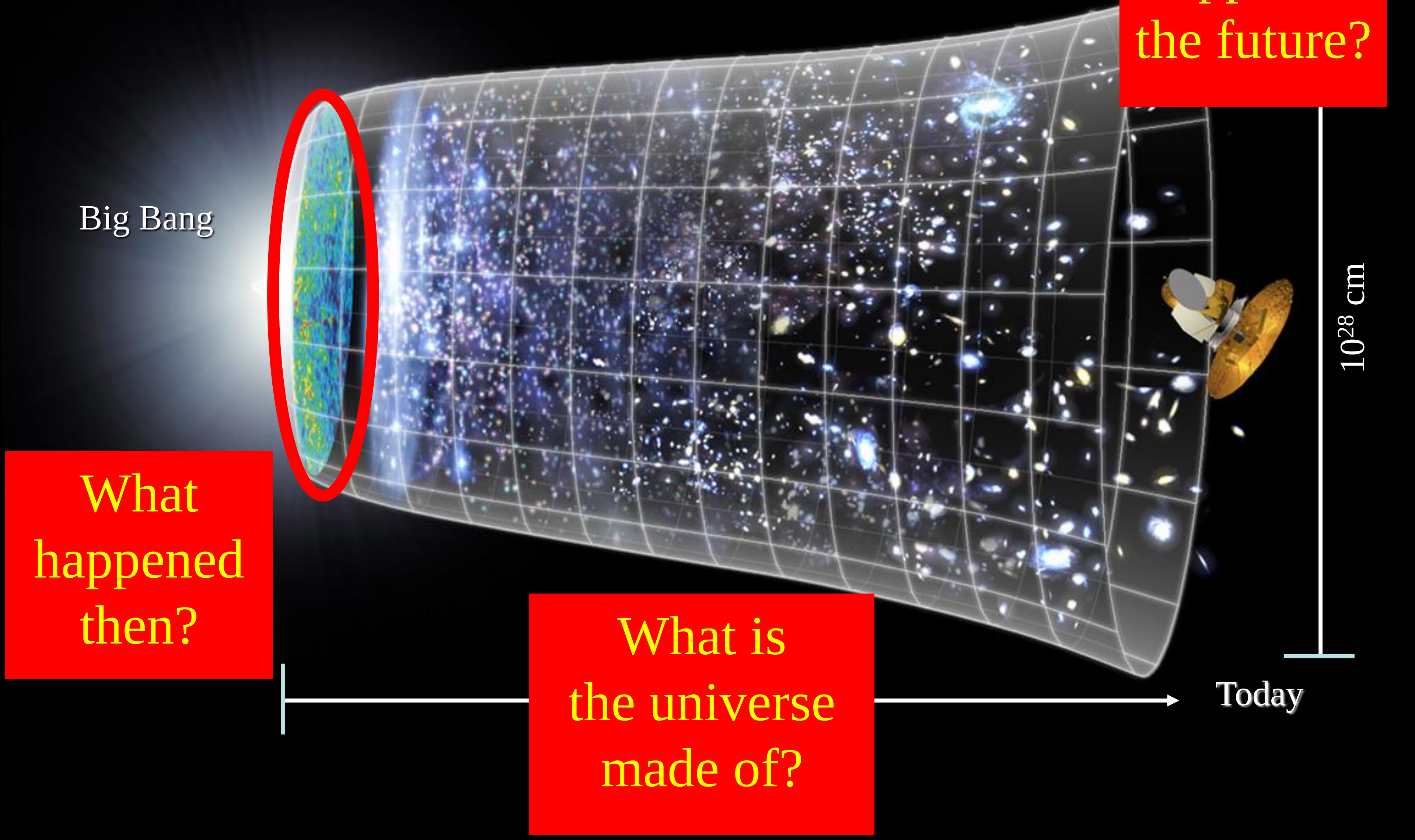
The aim of particle physics:

What is matter in the Universe made of?

John Ellis

KING'S College LONDON

Evolution of the Universe



Gauguin’s Questions in the Language of Particle Physics

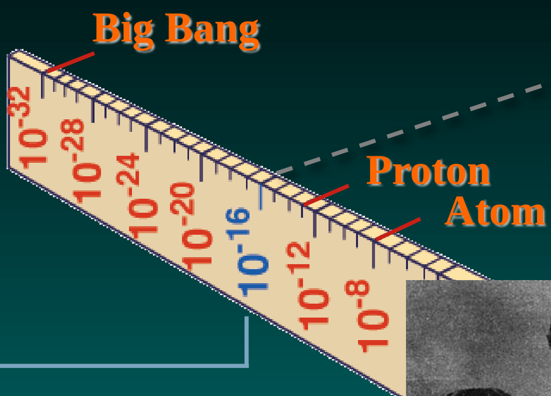
- What is matter made of?
  - Why do things weigh?

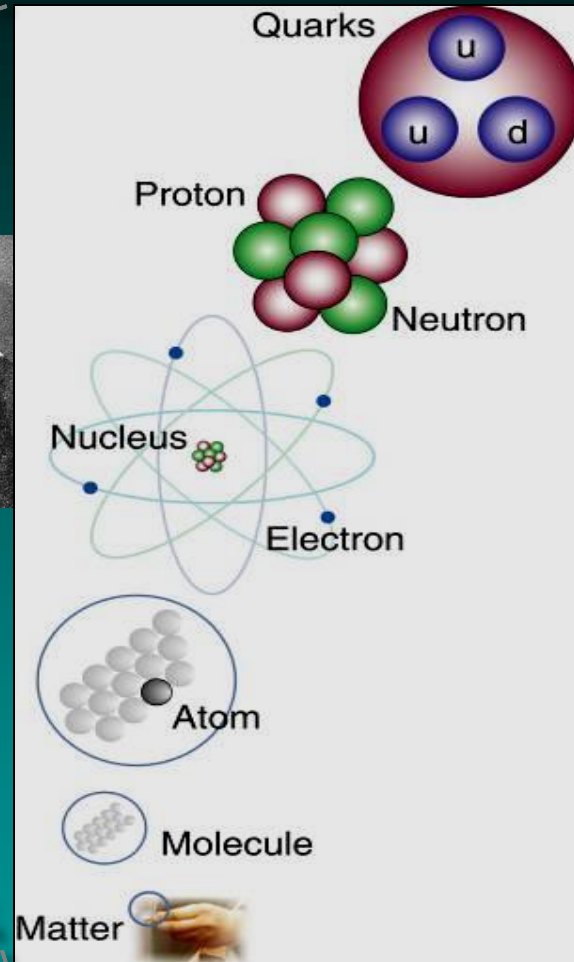
- What is the origin of matter? LHC
- What is the dark matter that fills the Univ LHC
- How does the Universe evolve?
- Why is the Universe so big and old? LHC
- What is the future of the Universe? LHC

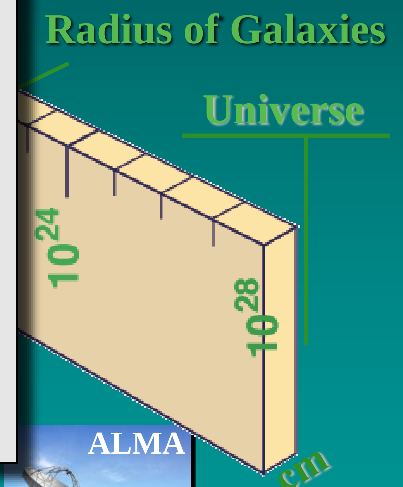
Our job is to ask - and answer - these questions

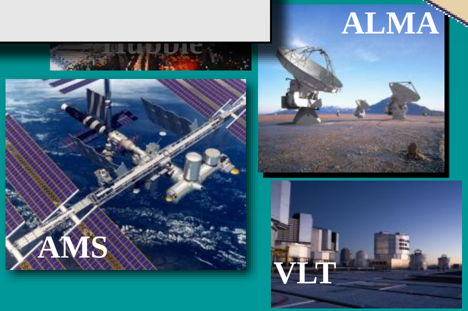
Need physics beyond what we know

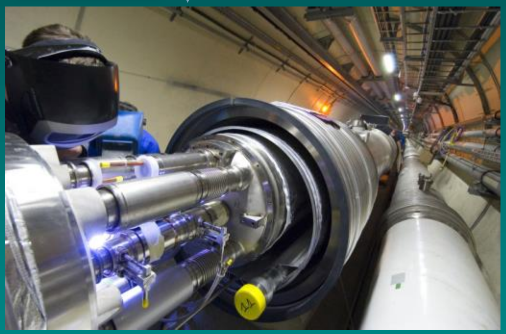
/Users/johne/Desktop/YoungEinsteins.png









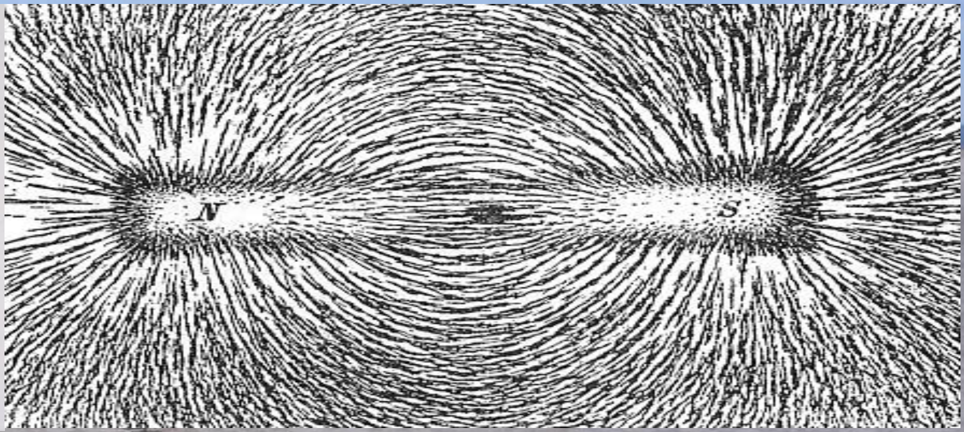


LHC

Super-Microscope

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

Electricity and Magnetism



- Electricity:
  - Named using the Greek word for amber
  - Fish, lightning, …
  - Static electricity and electric currents

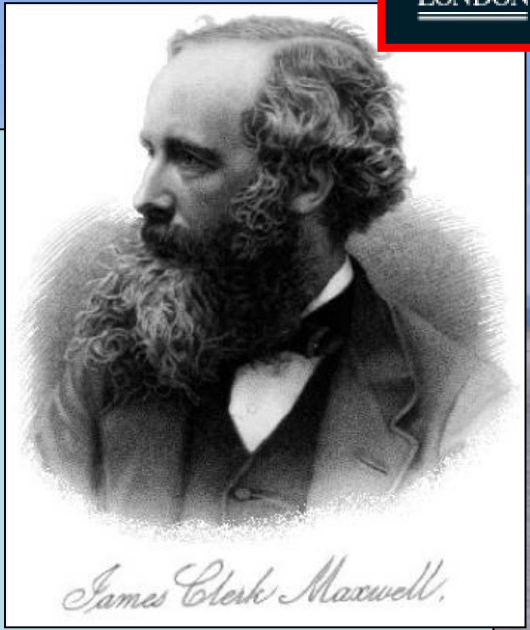
- Magnetism:
  - Named for the region of Greece where lodestones were found
  - Used for navigation from 12th century

Who could have foreseen their importance for technology?

James Clerk Maxwell

KING'S College LONDON

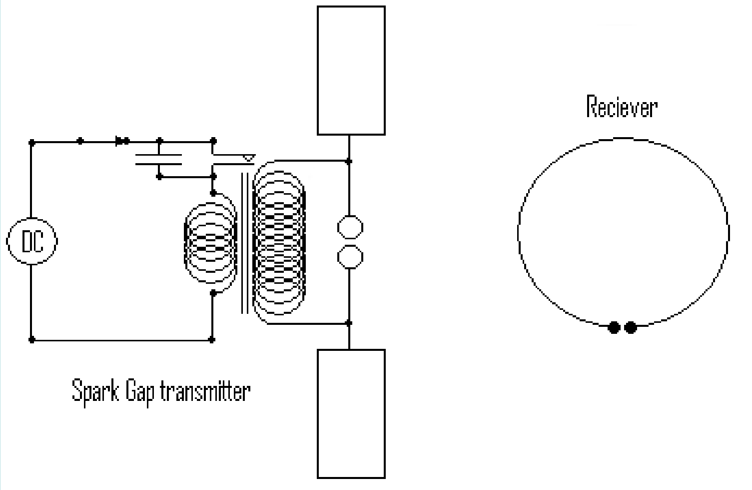
- Professor at King's 1860 – 1865
- The first colour photograph
- Unified theory of electricity and magnetism
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- …



"One scientific epoch ended and another began with James Clerk Maxwell" - *Albert Einstein*

Electromagnetic Waves

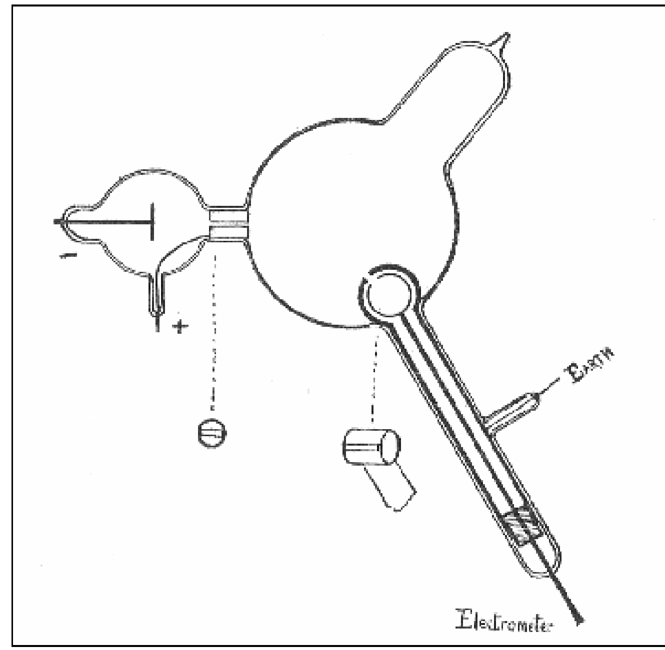
- Discovered by Hertz in 1887



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

The First Elementary Particle

- Discovered by J.J. Thomson in 1897



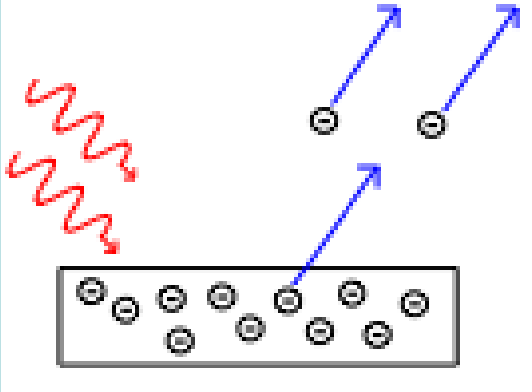
- **The electron** – the basis of the electronic industry
- An accelerator in your home: old-style TV sets used beams of electrons

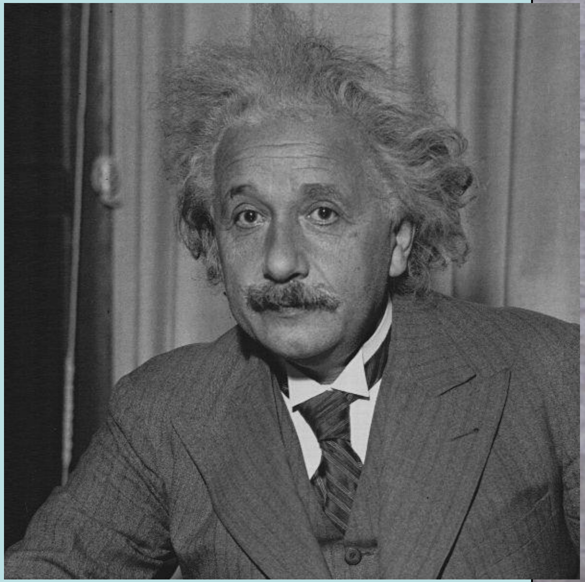
Photon: the Electromagnetic Quantum

- Quantum hypothesis introduced by Planck:

$$E = hf$$

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

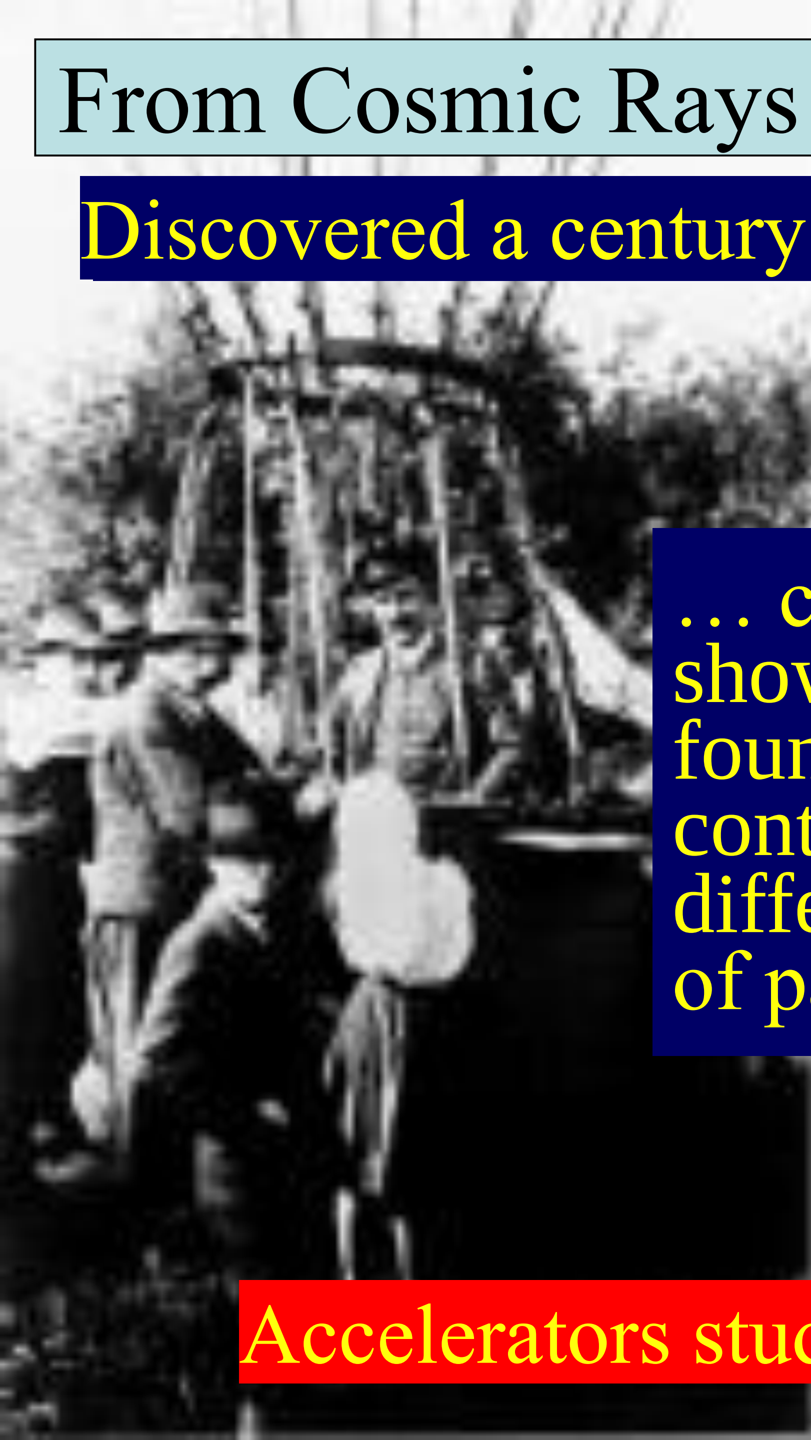


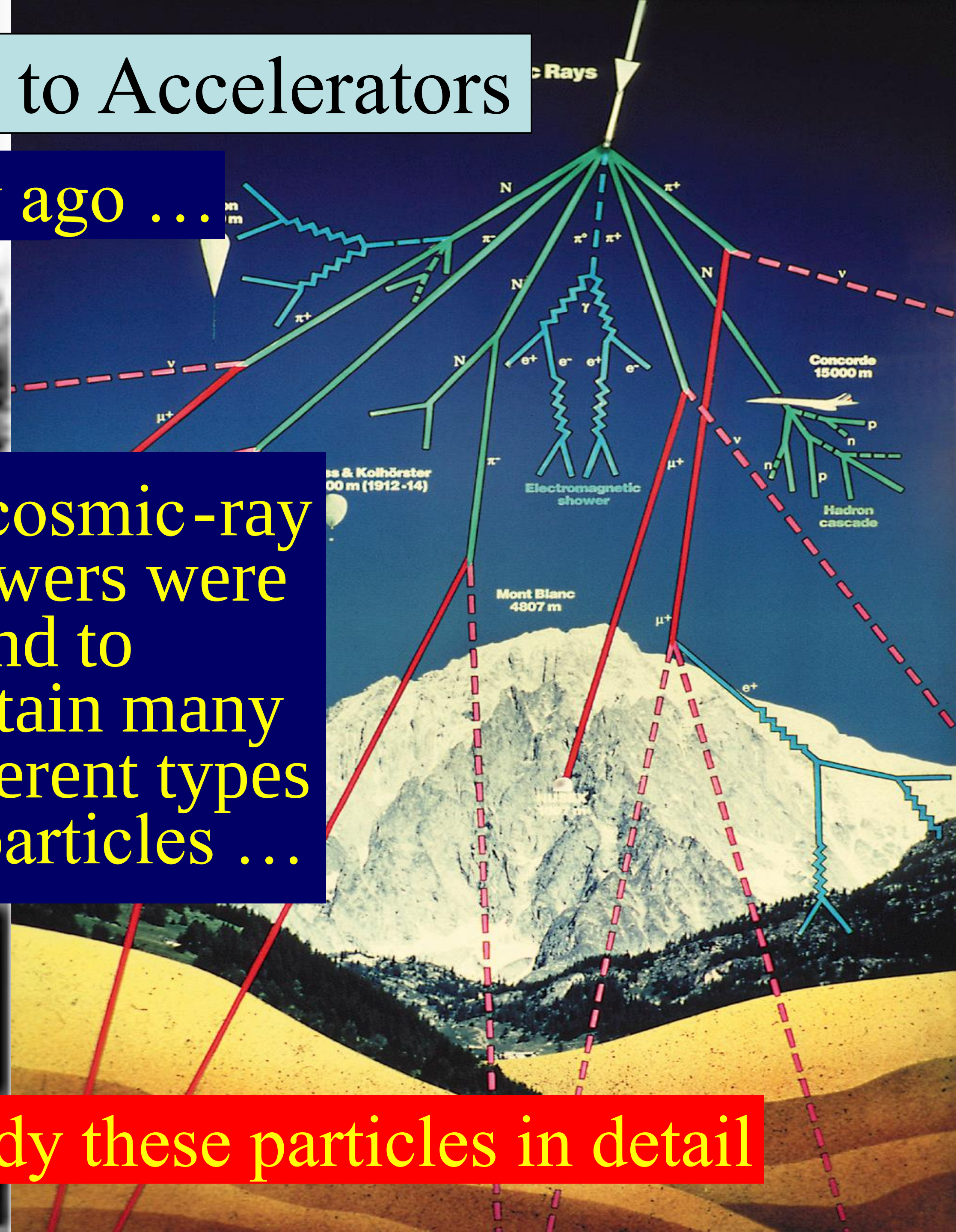


- **First force particle discovered**

From Cosmic Rays to Accelerators

Discovered a century ago …



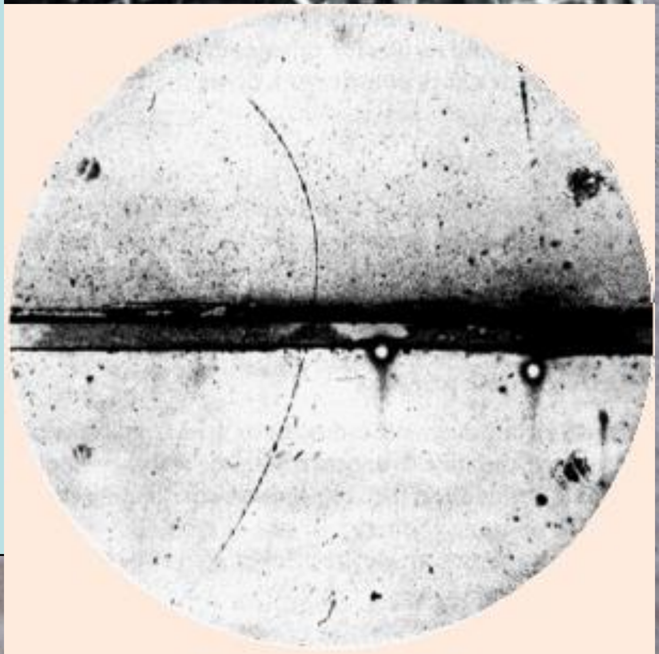


… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

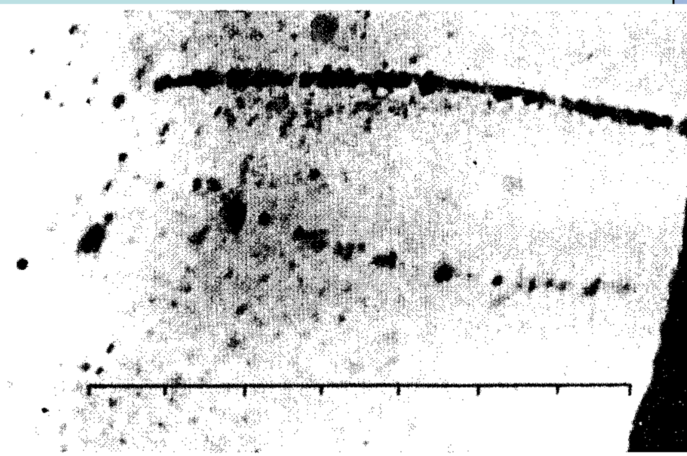
The Discovery of the Positron

- 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



The Discovery of the Muon

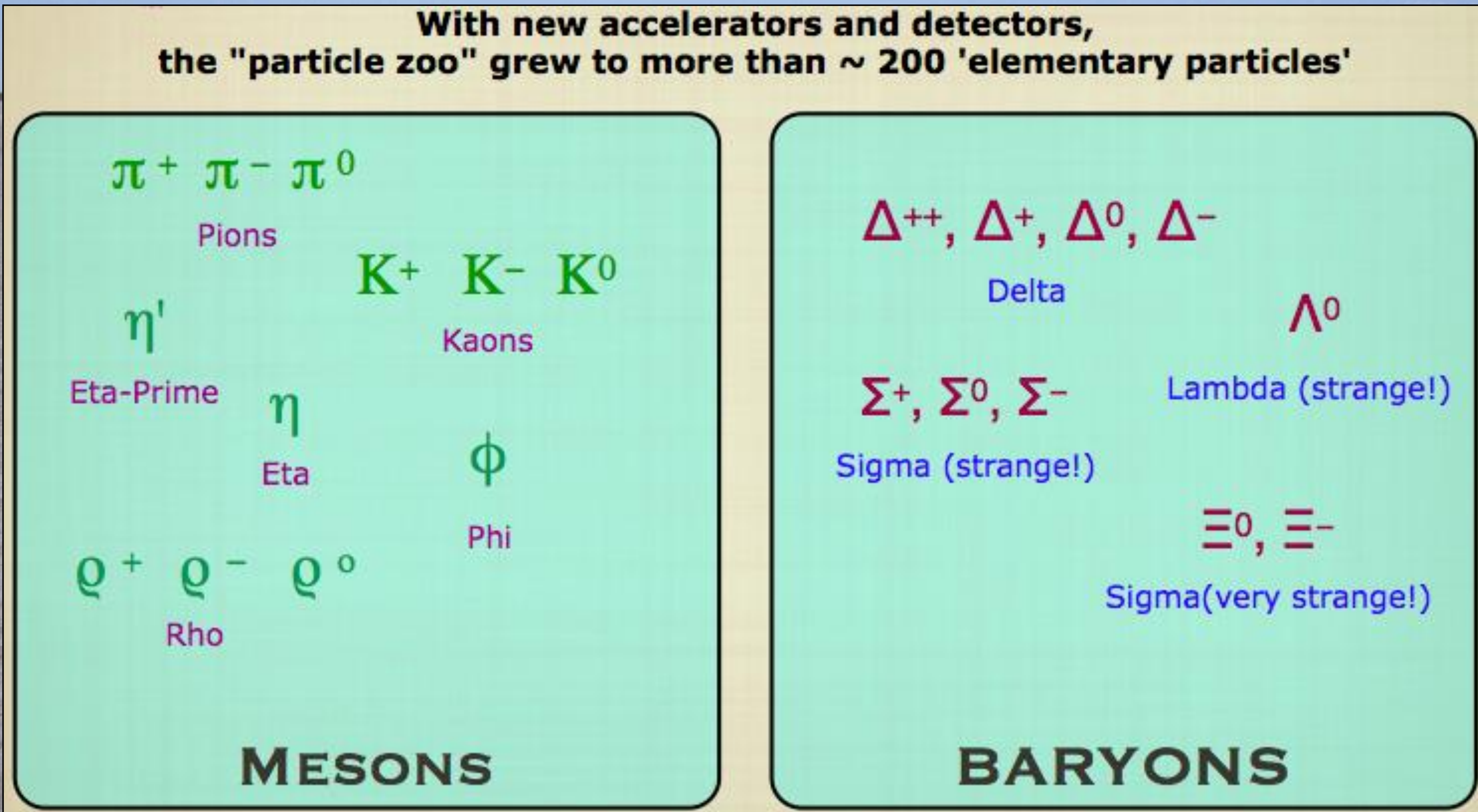
- NOT predicted
- Observed in cosmic rays by Kunze in 1932
- Larger bending radius than the positron
- Ionizes less than proton
- Passing though us all the time
- ***“Who ordered that”* – I.I. Rabi**



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

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)

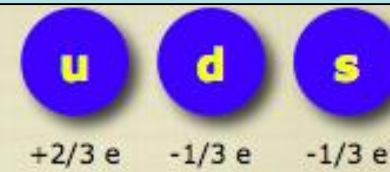
1) 3 types of "quarks" : up, down, strange

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

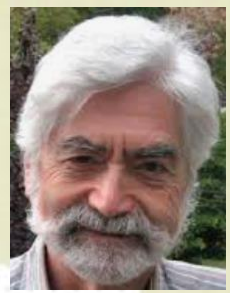
3) Appear in combinations:

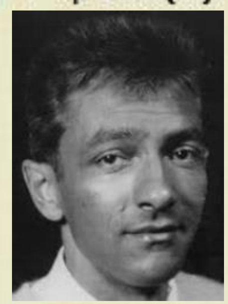
Meson = quark+antiquark

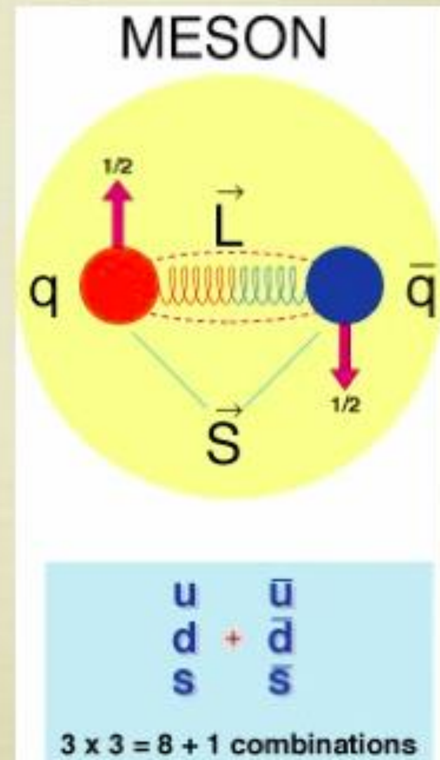
Baryon = quark(1) + quark(2) + quark(3)

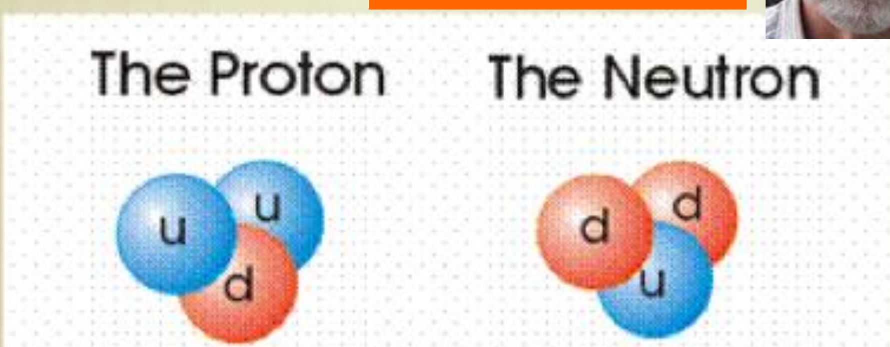


Also suggested independently by Zweig, Peterman @ CERN



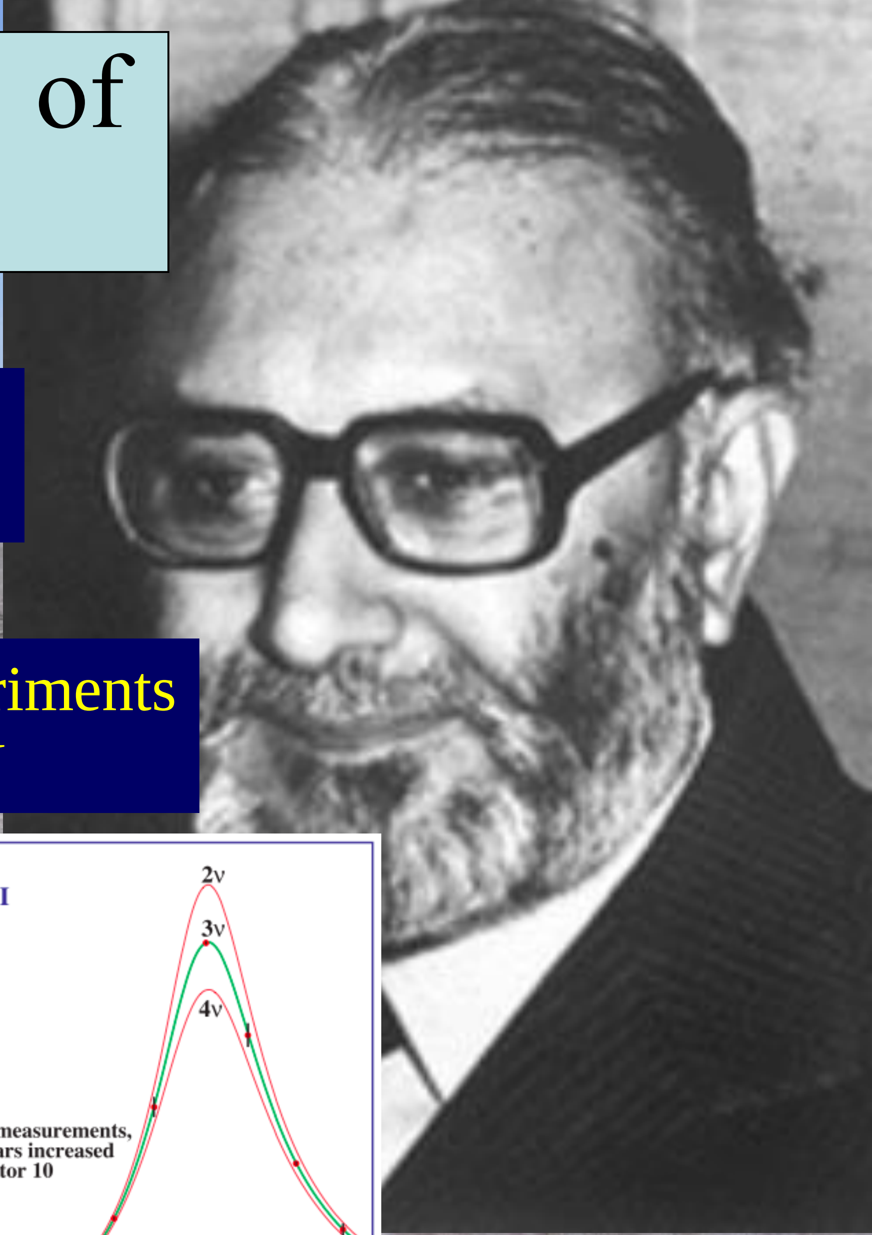






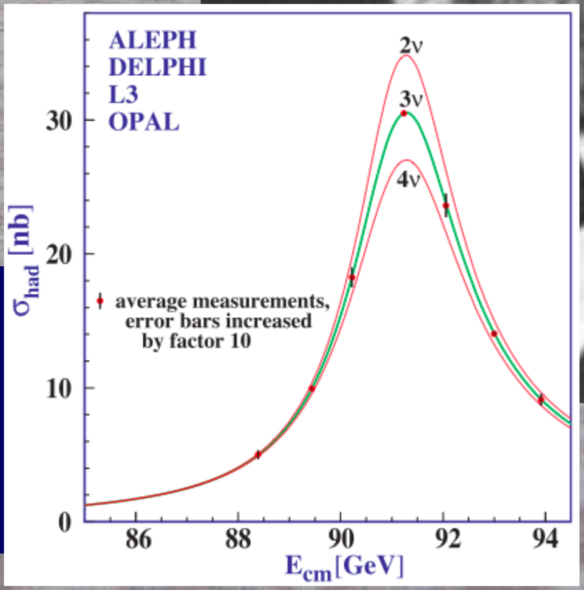
Quarks held together by gluons?

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

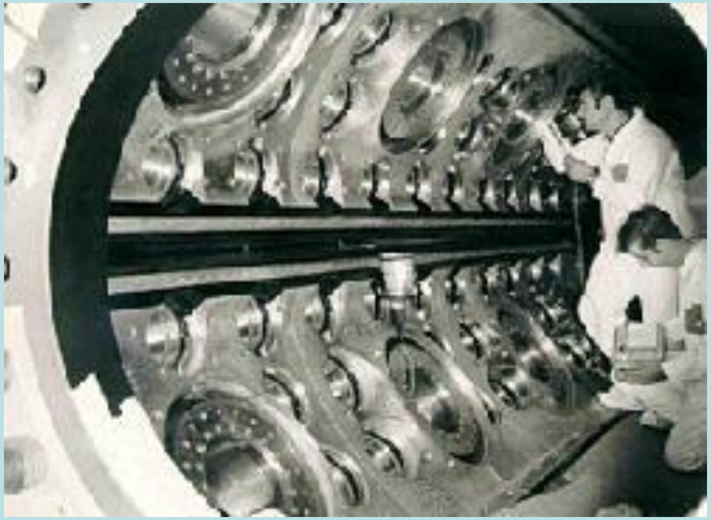
Towards the Standard Model

1971/2

- Gauge theories are renormalizable

1973

- Kobayashi and Maskawa show how to include CP violation in the Standard Model



1973

- Neutral currents in Gargamelle

1974

- J/Ψ discovered

1975/6

- Tau lepton and charmed particles discovered

1976

Gluon Radiation in e^+e^- Annihilation

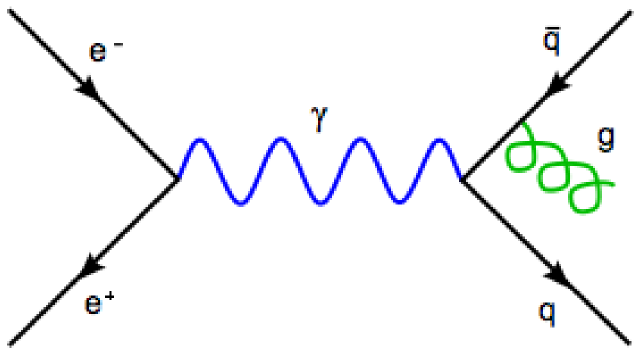
- Discovery method suggested by JE, Mary Gaillard, Graham Ross:

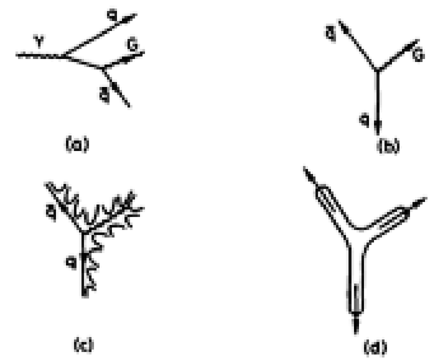
SEARCH FOR GLUONS IN e^+e^- ANNIHILATION

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

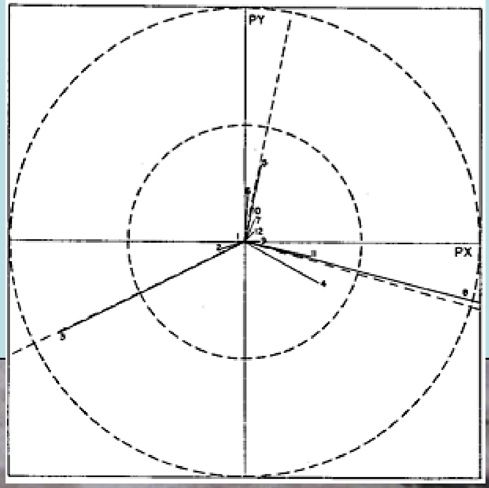
Received 20 May 1976

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**

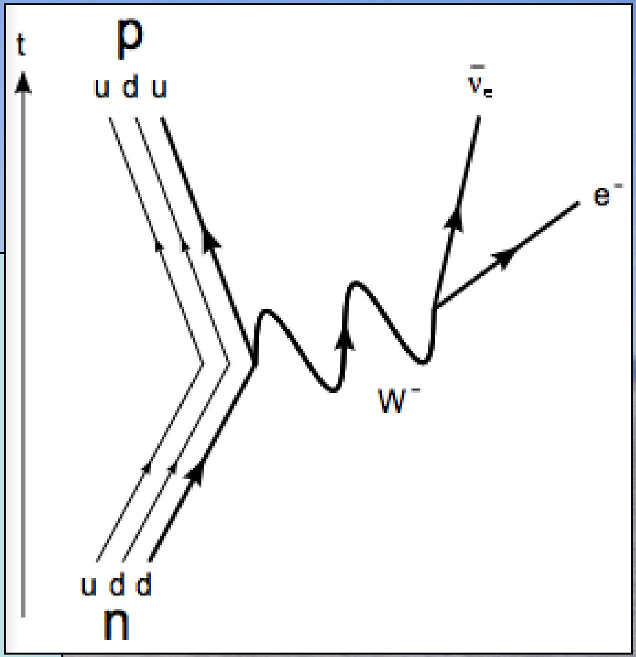
1983

Weak Interactions

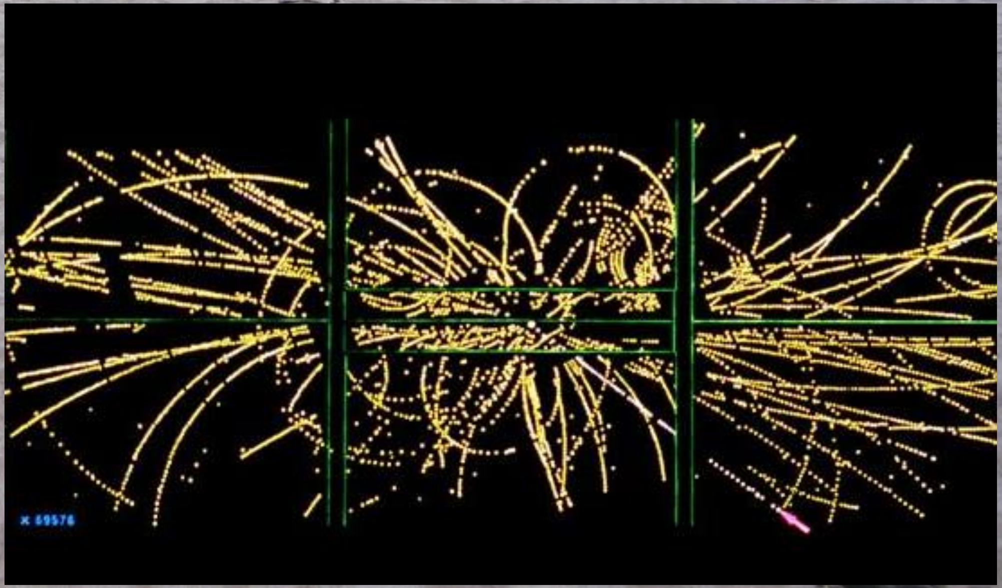
Radioactivity due to charged-current weak interactions (β decay)

W boson - carrier of weak interactions

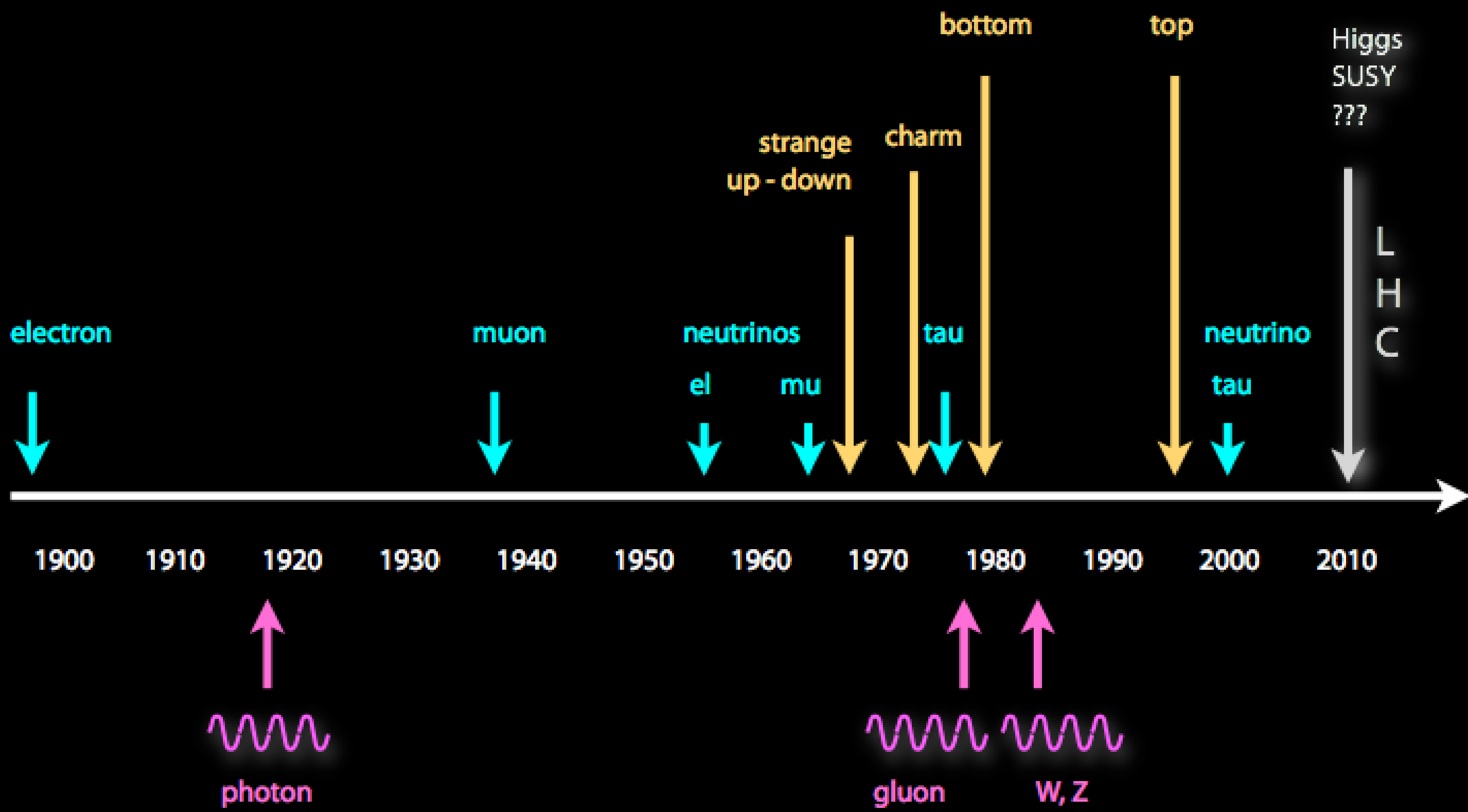
Predicted to weigh ~ 80 GeV



Discovered at CERN in 1983 by Carlo Rubbia et al



Particles: the Story so far



The ‘Standard Model’

= Cosmic DNA

The matter particles

Where does mass come from?

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

Newton:

Weight proportional to Mass

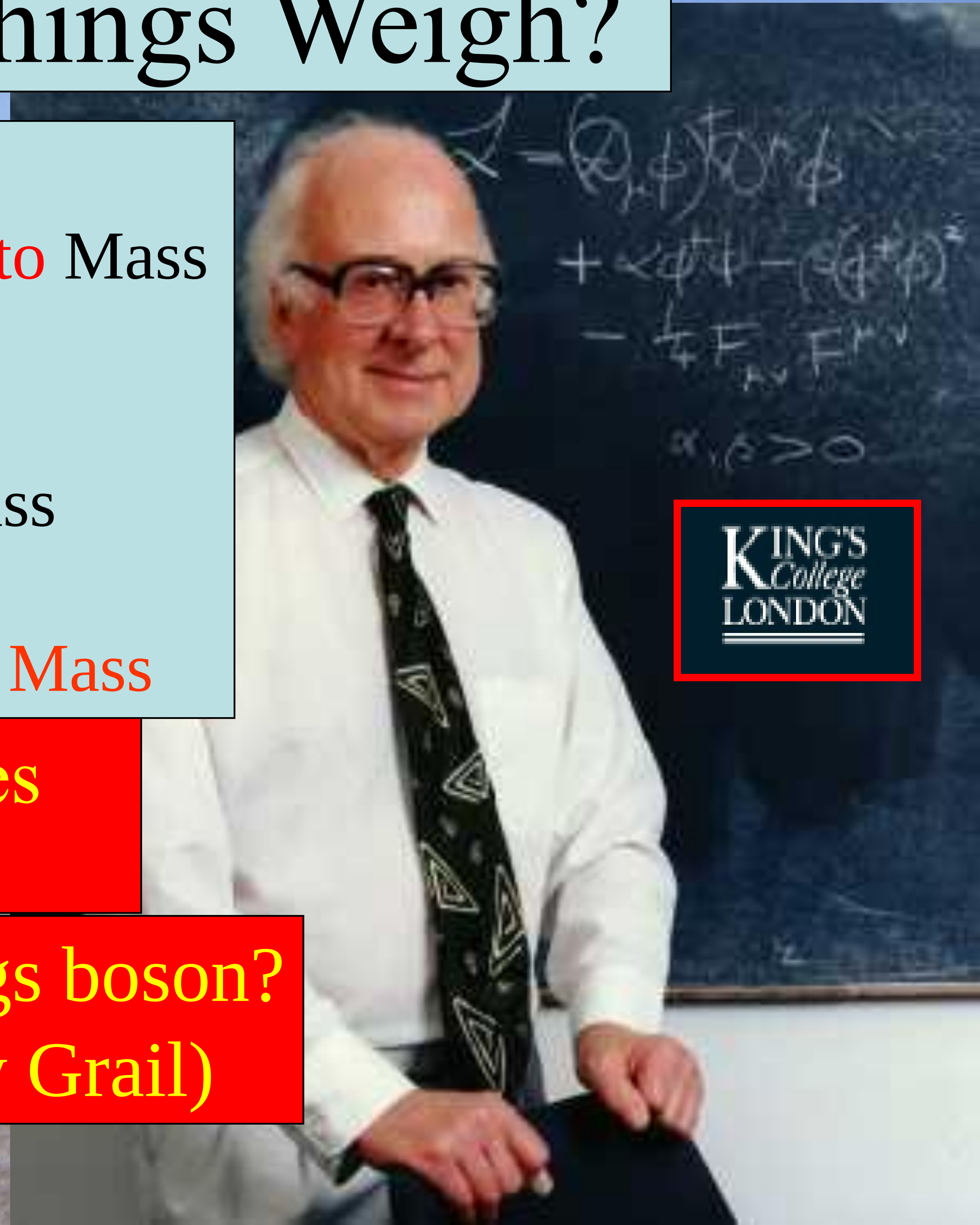
Einstein:

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

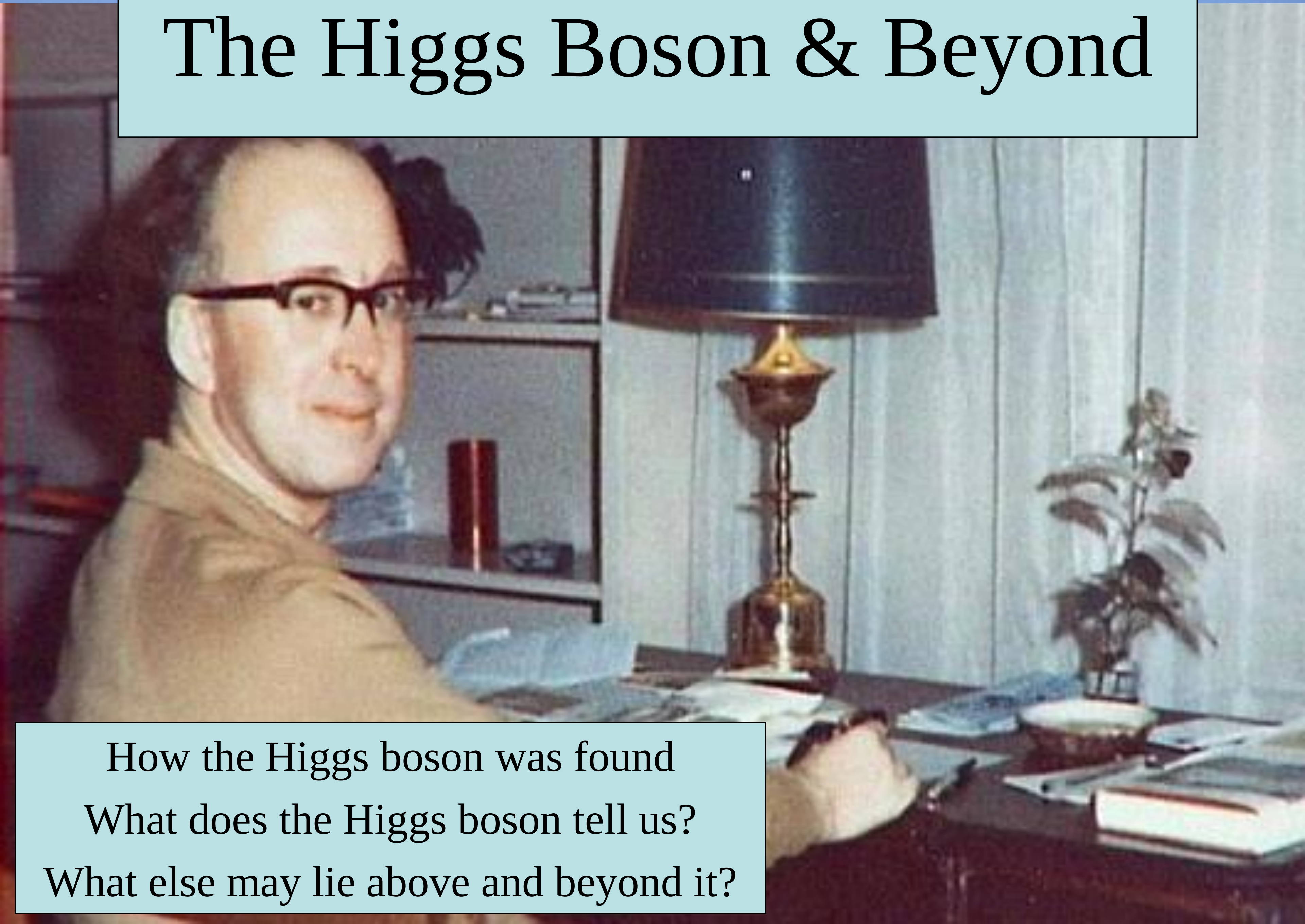
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

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

The LHC discovered the snowflake: The Higgs Boson

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

The Higgs Boson & Beyond



How the Higgs boson was found

What does the Higgs boson tell us?

What else may lie above and beyond it?

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

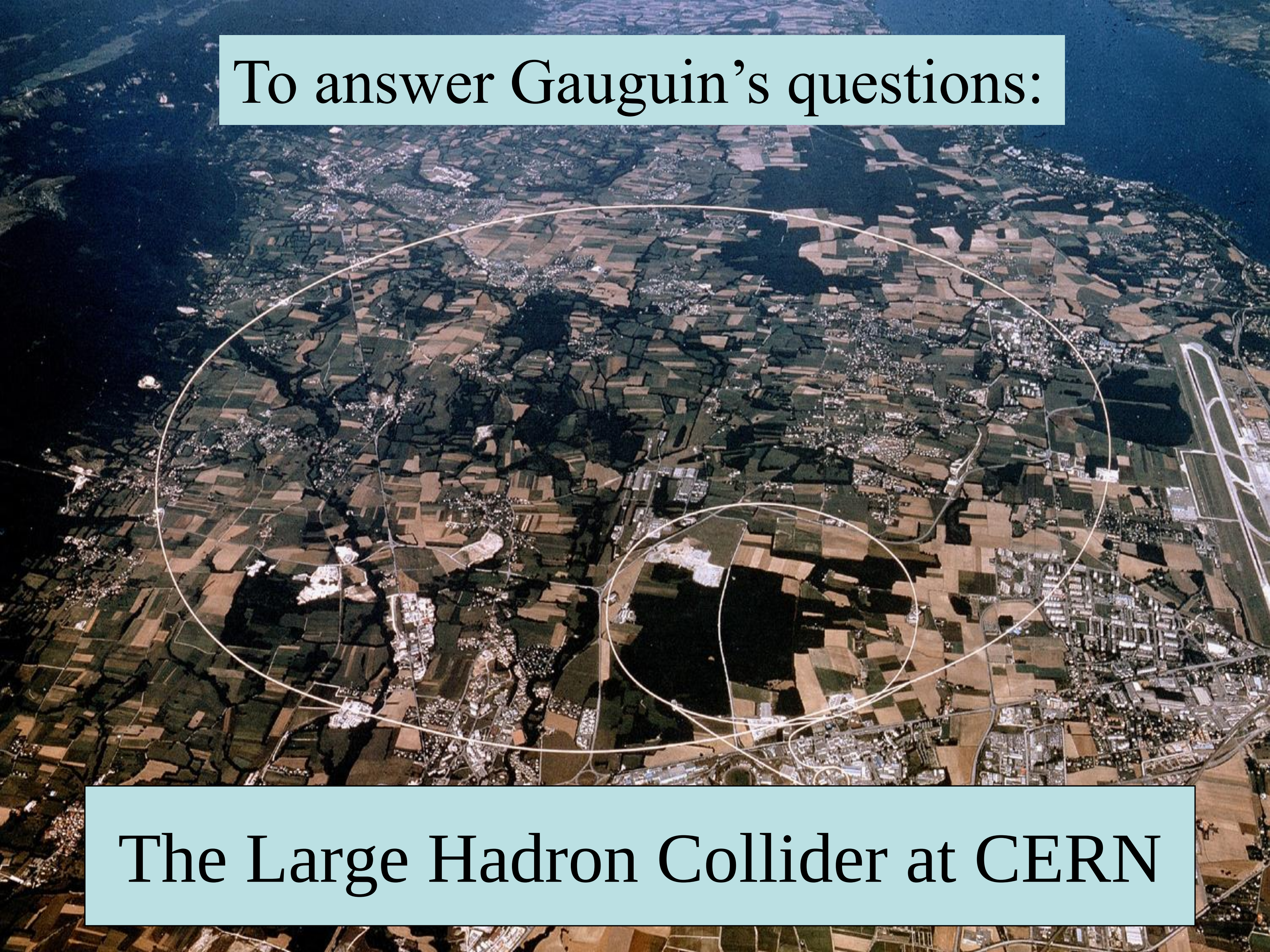
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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.

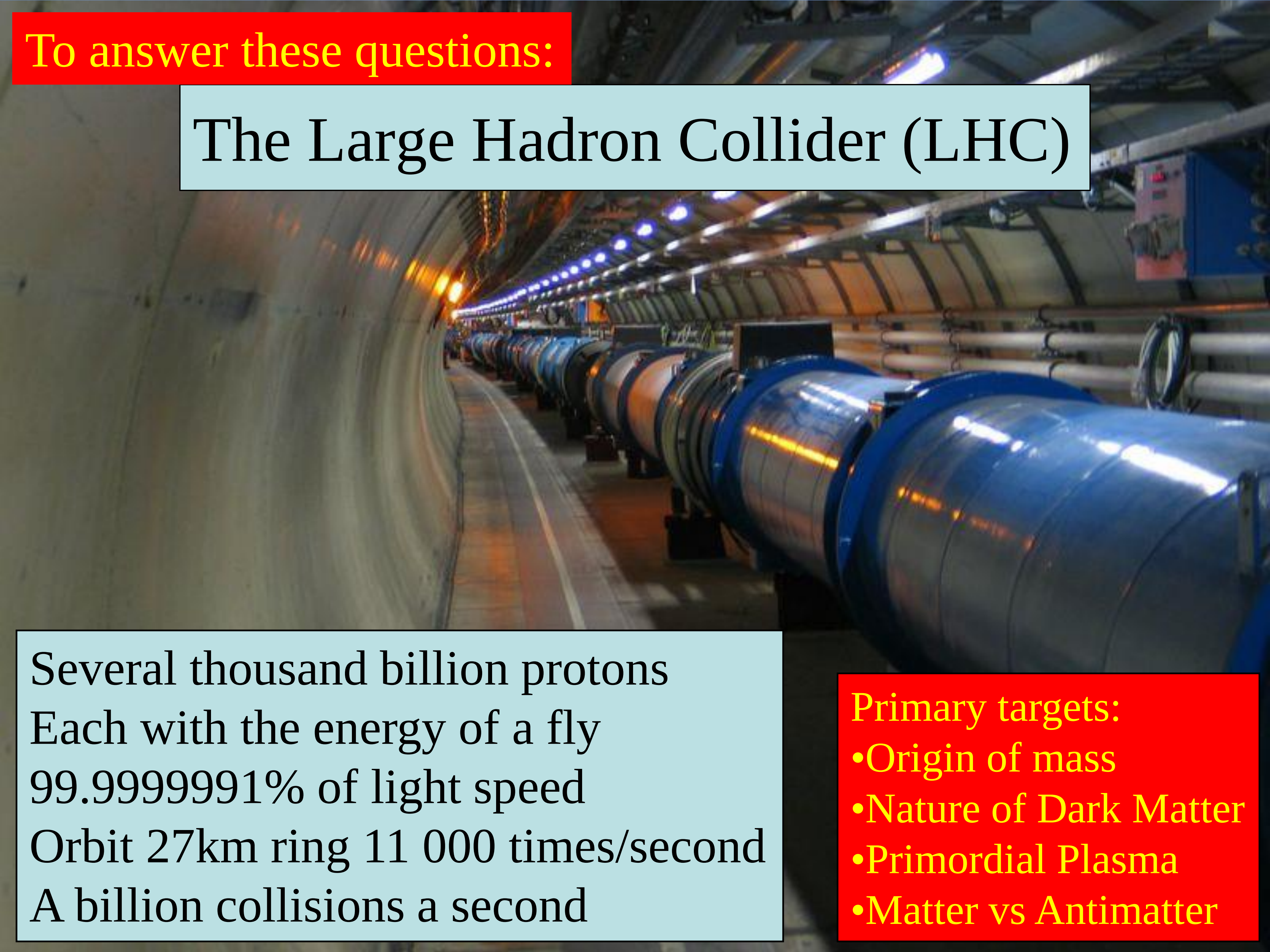
To answer Gauguin’s questions:



The Large Hadron Collider at CERN

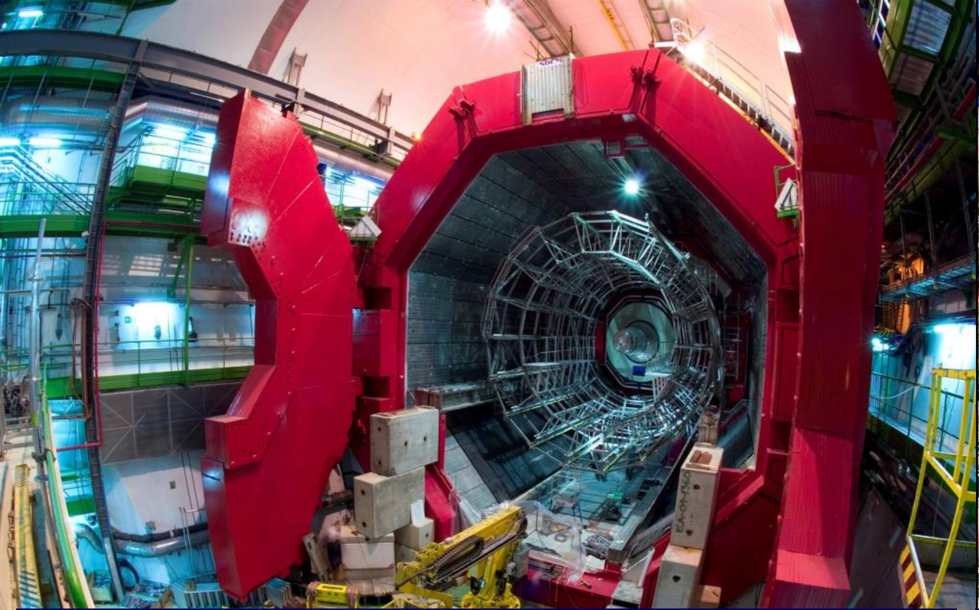
To answer these questions:

The Large Hadron Collider (LHC)

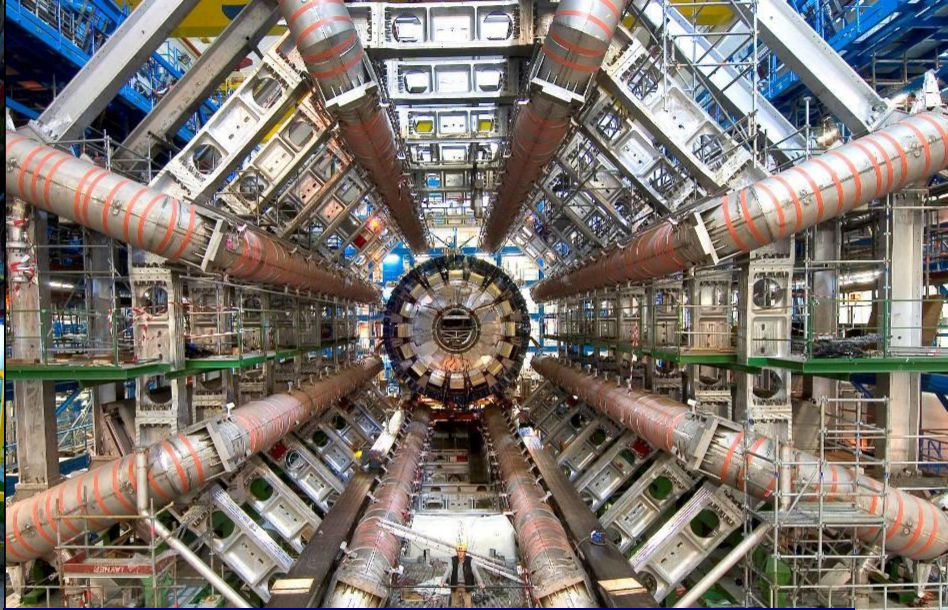


Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

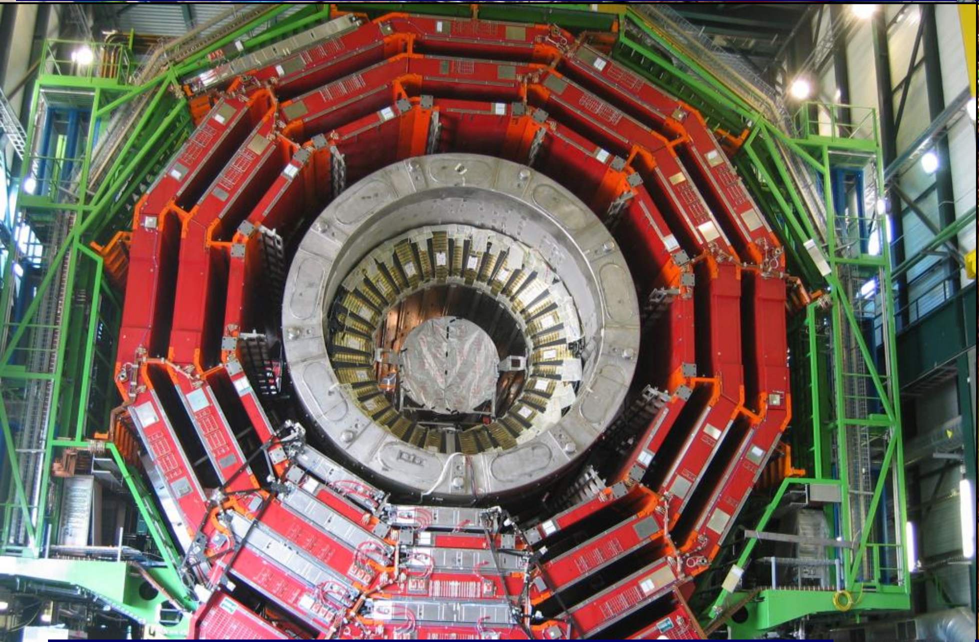
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



ALICE: Primordial cosmic plasma



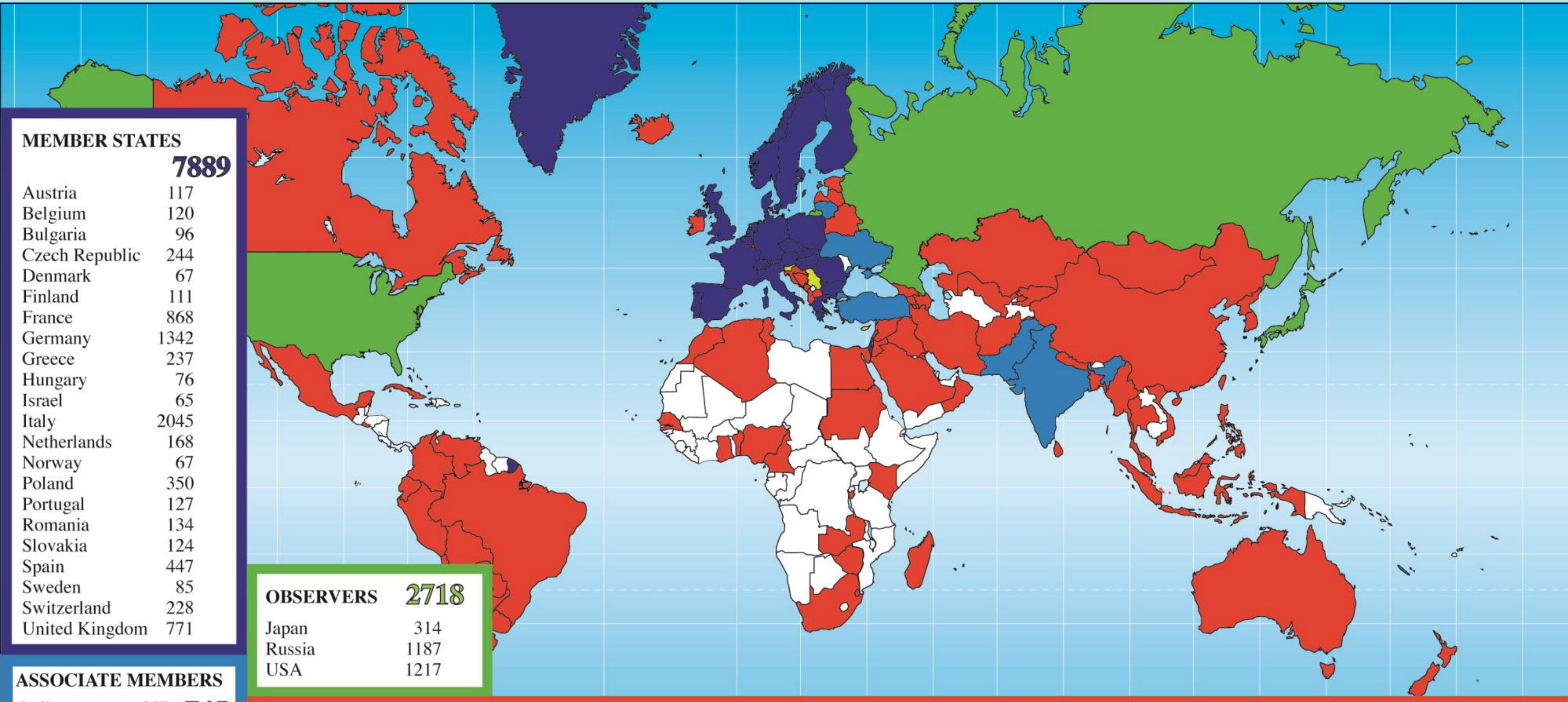
ATLAS: Higgs and dark matter



CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

Scientists from around the World



MEMBER STATES 7889

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

OBSERVERS 2718

Japan	314
Russia	1187
USA	1217

ASSOCIATE MEMBERS 745

India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

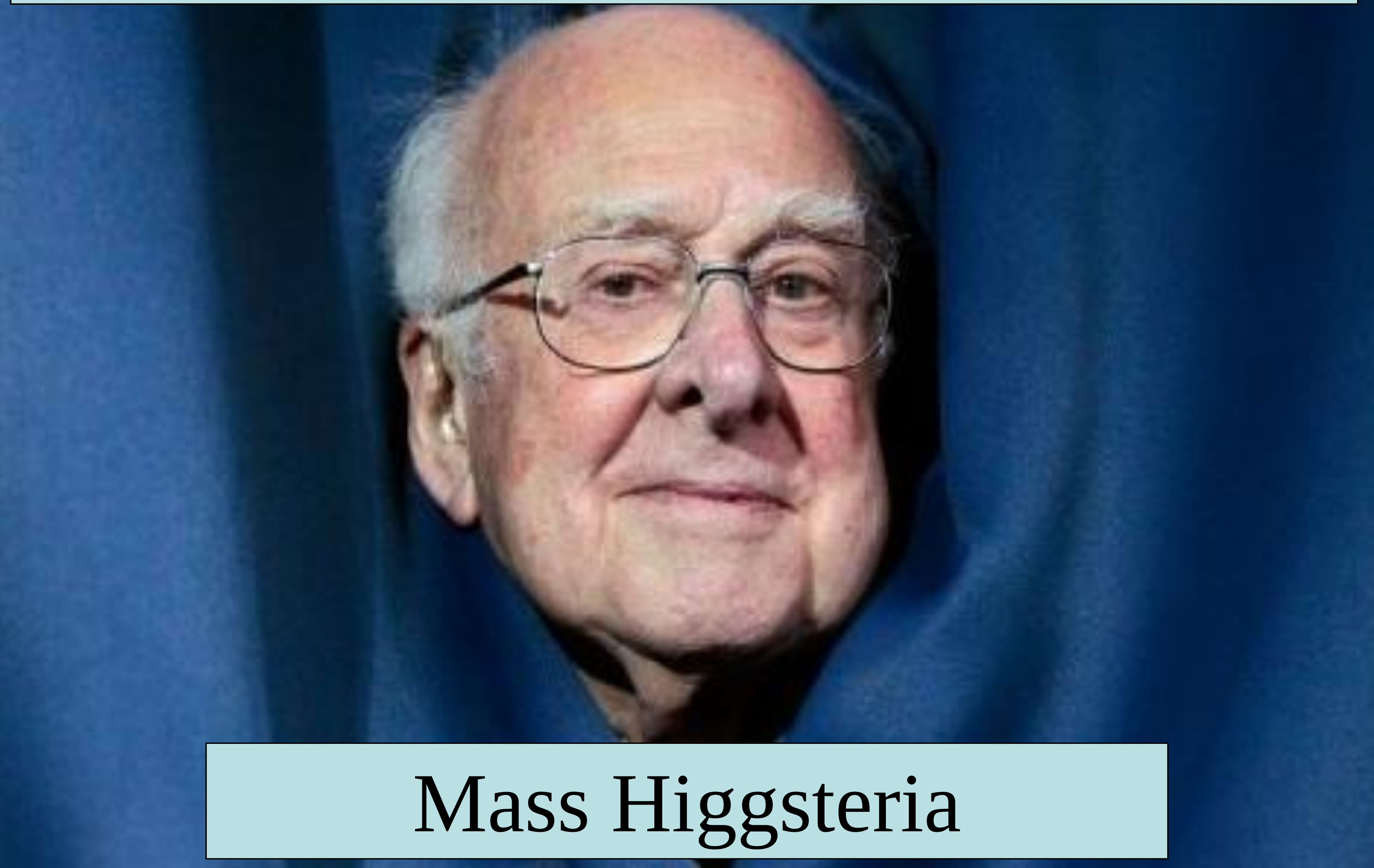
ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 118

Cyprus	26
Serbia	57
Slovenia	35

OTHERS 1872

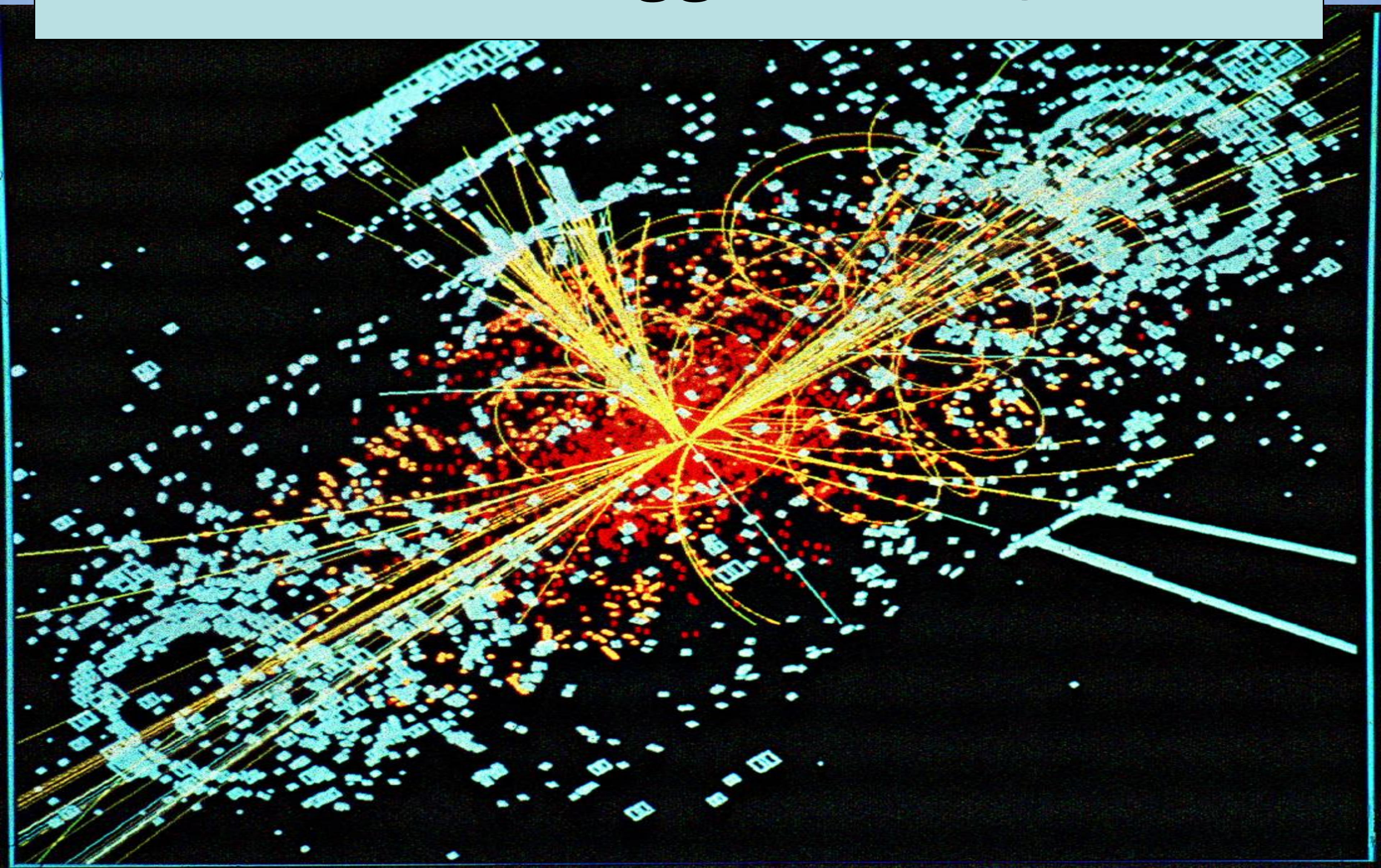
Afghanistan	1
Albania	3
Algeria	14
Argentina	27
Armenia	19
Australia	31
Azerbaijan	10
Bangladesh	11
Belarus	48
Benin	1
Bolivia	4
Bosnia & Herzegovina	2
Brazil	135
Burundi	1
Cameroon	1
Canada	161
Chile	20
China	510
Colombia	45
Croatia	41
Cuba	12
Ecuador	6
Egypt	31
El Salvador	1
Estonia	15
Georgia	46
Ghana	1
Hong Kong	1
Iceland	3
Indonesia	11
Iran	51
Iraq	1
Ireland	16
Jordan	1
Kazakhstan	5
Kenya	3
Korea Rep.	185
Kyrgyzstan	1
Latvia	2
Lebanon	23
Luxembourg	2
Madagascar	4
Malaysia	15
Malta	9
Mauritius	1
Mexico	82
Mongolia	2
Montenegro	11
Morocco	20
Myanmar	1
Nepal	10
New Zealand	5
Nigeria	3
North Korea	1
Oman	3
Palestine (O.T.)	7
Paraguay	2
Peru	7
Philippines	3
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	56
Sri Lanka	6
Sudan	1
Swaziland	1
Syria	1
Taiwan	51
Thailand	22
T.F.Y.R.O.M.	2
Tunisia	5
Uruguay	1
Uzbekistan	4
Venezuela	10
Viet Nam	13
Zambia	1
Zimbabwe	2

2012: The discovery of the Higgs Boson

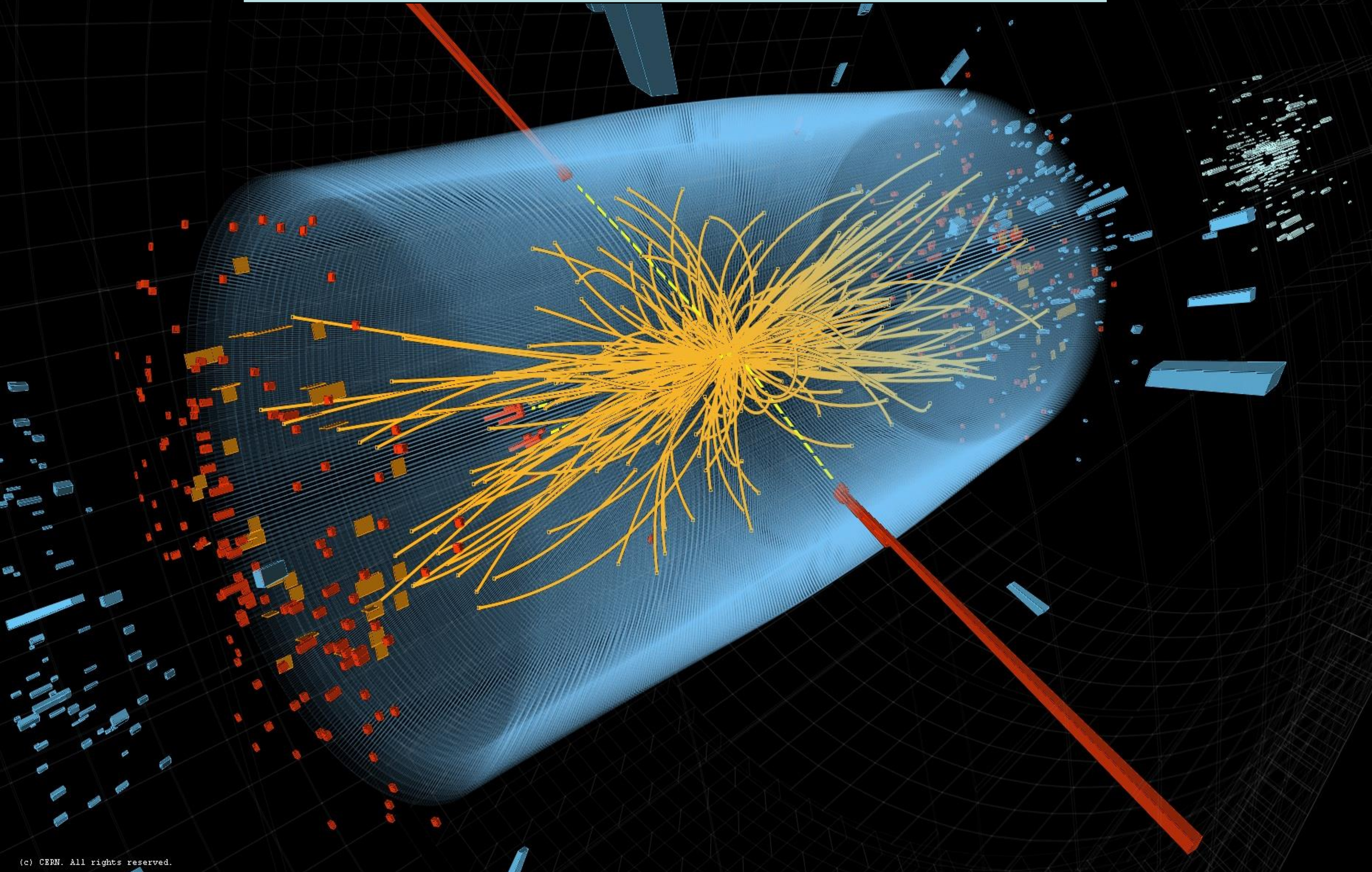


Mass Higgsteria

A Simulated Higgs Event @ LHC



Interesting Events



July 4th 2012
The discovery of a new particle

Higgsdependence Day!

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

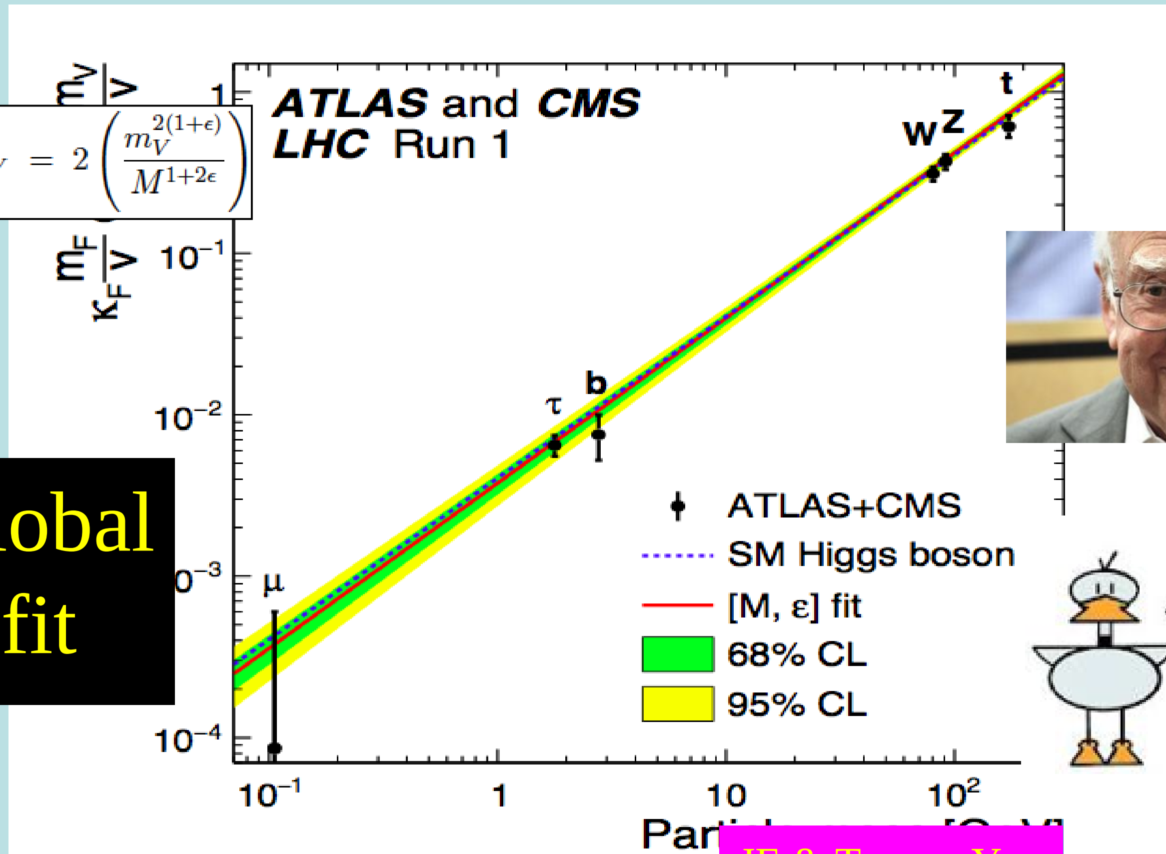
Is it the right shape?

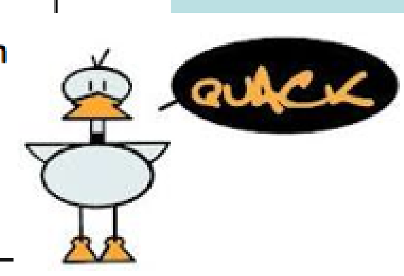
Is it the right size?

It Walks and Quacks like a Higgs

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

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



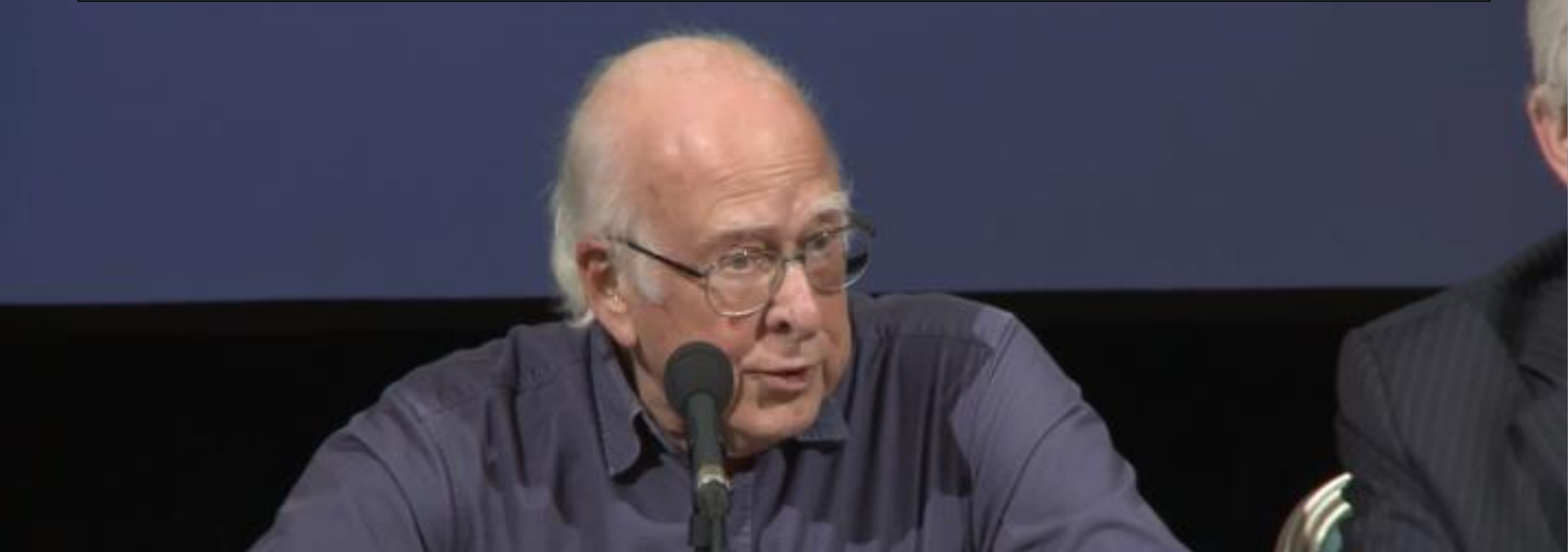


Global fit

JE & Tevong You

- **Blue** dashed line = Standard Model

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

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!

- « Empty » space is unstab LHC
- Dark matter LHC
- Origin of matter LHC
- Sizes of masses LHC
- Properties of neutrinos
- Cosmological inflation LHC
- Quantum gravity
- …

The Standard Model

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?**

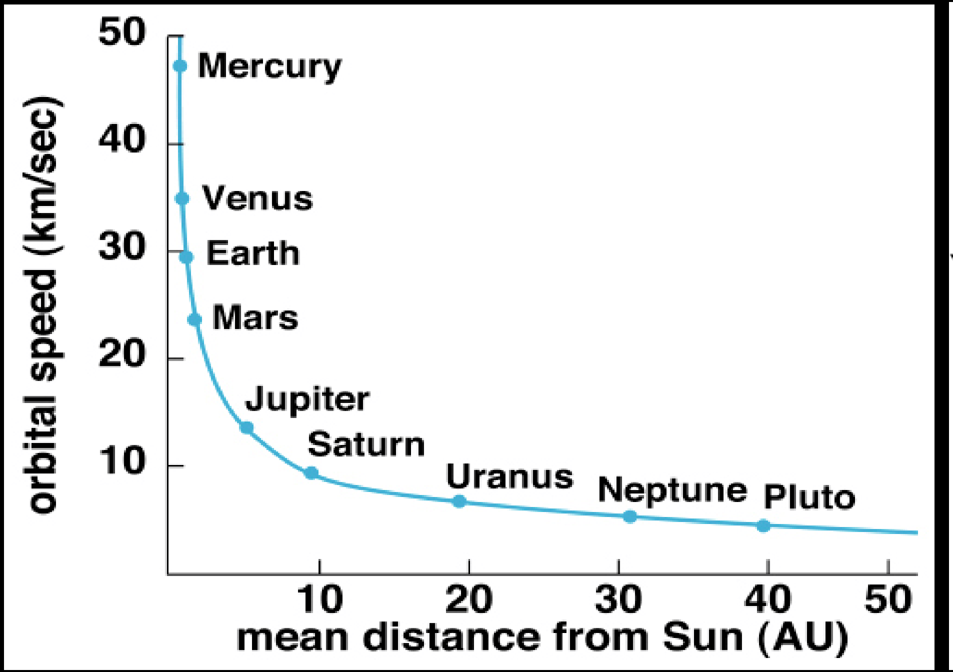
The Rotation Curves of Galaxies

- 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**

Scanned at the American Institute of Physics

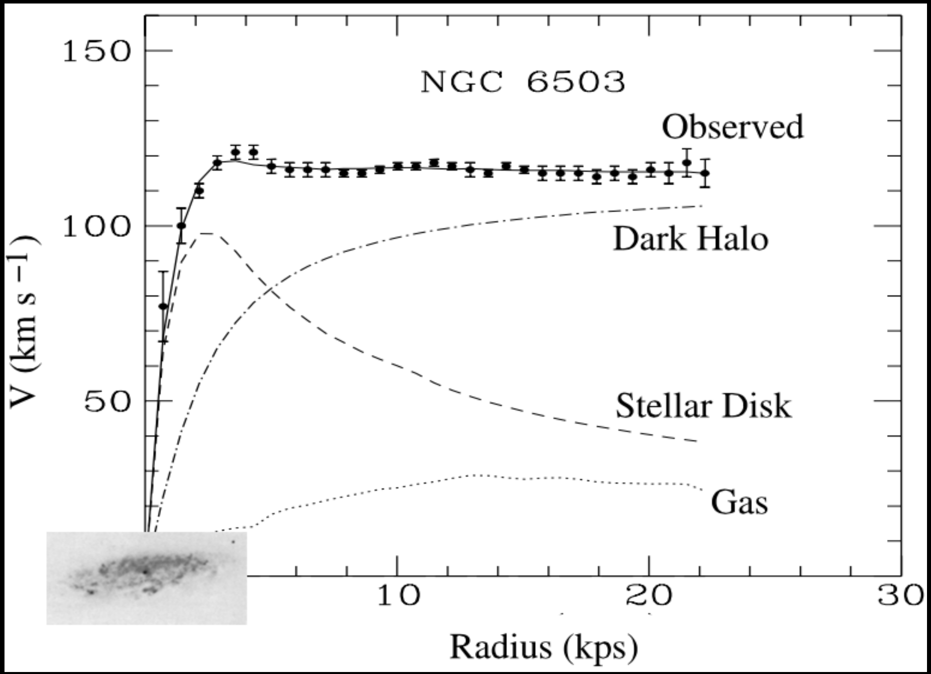
Rotation Curves

- In the Solar System



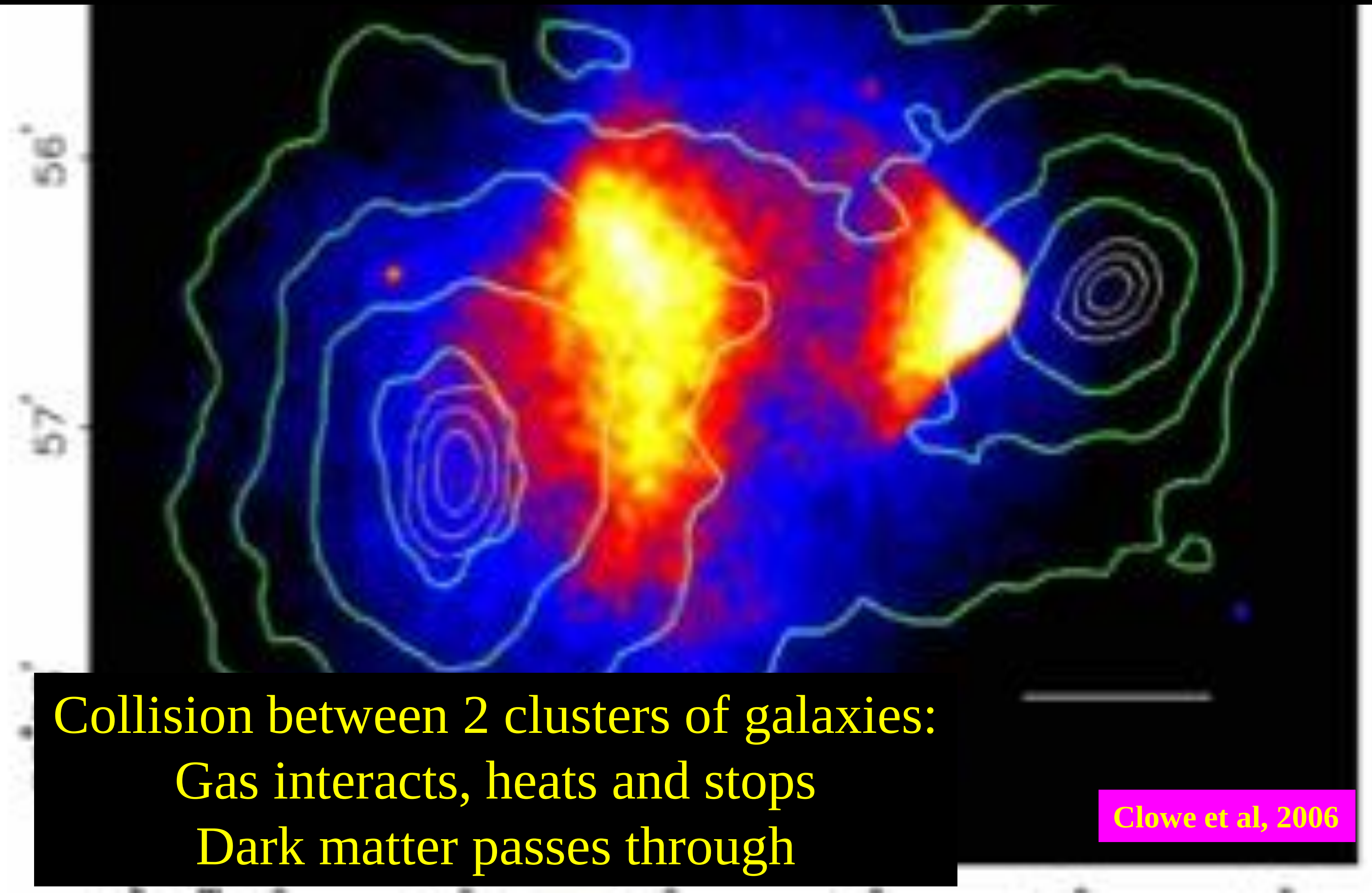
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



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

Biggest Collider in the Universe?



Collision between 2 clusters of galaxies:
Gas interacts, heats and stops
Dark matter passes through

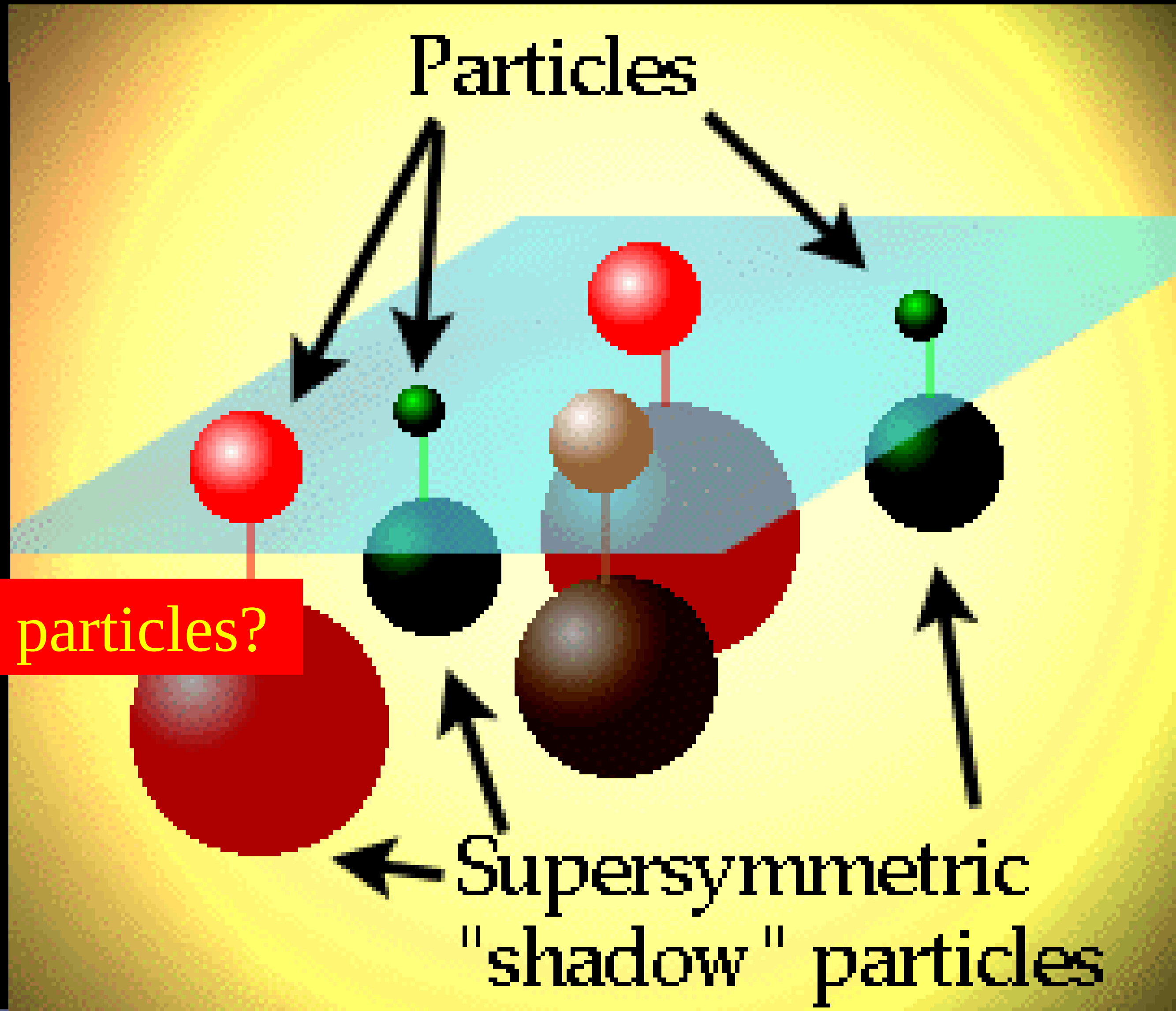
Clowe et al, 2006

What is the Dark Matter in the Universe?

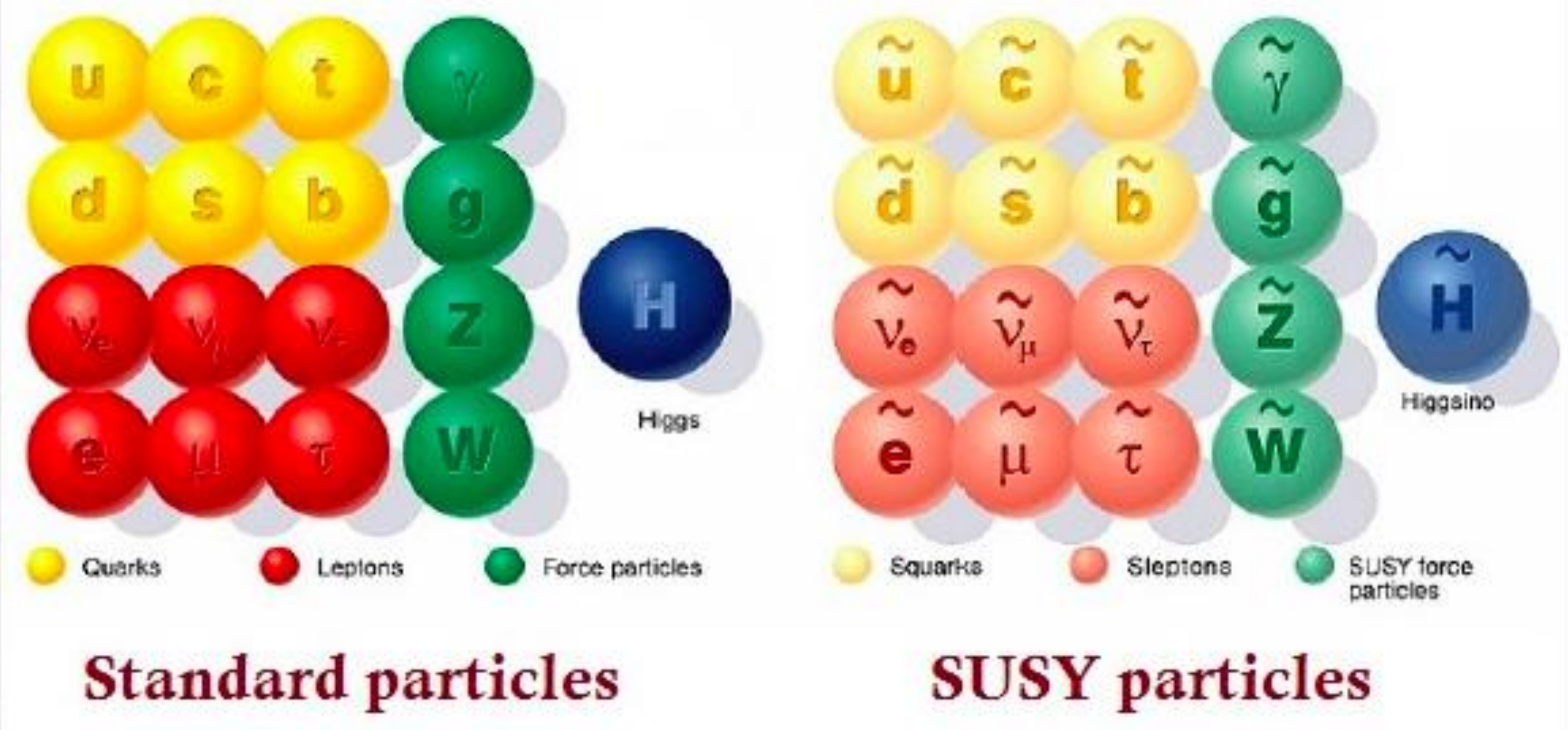
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Made of unknown particles?

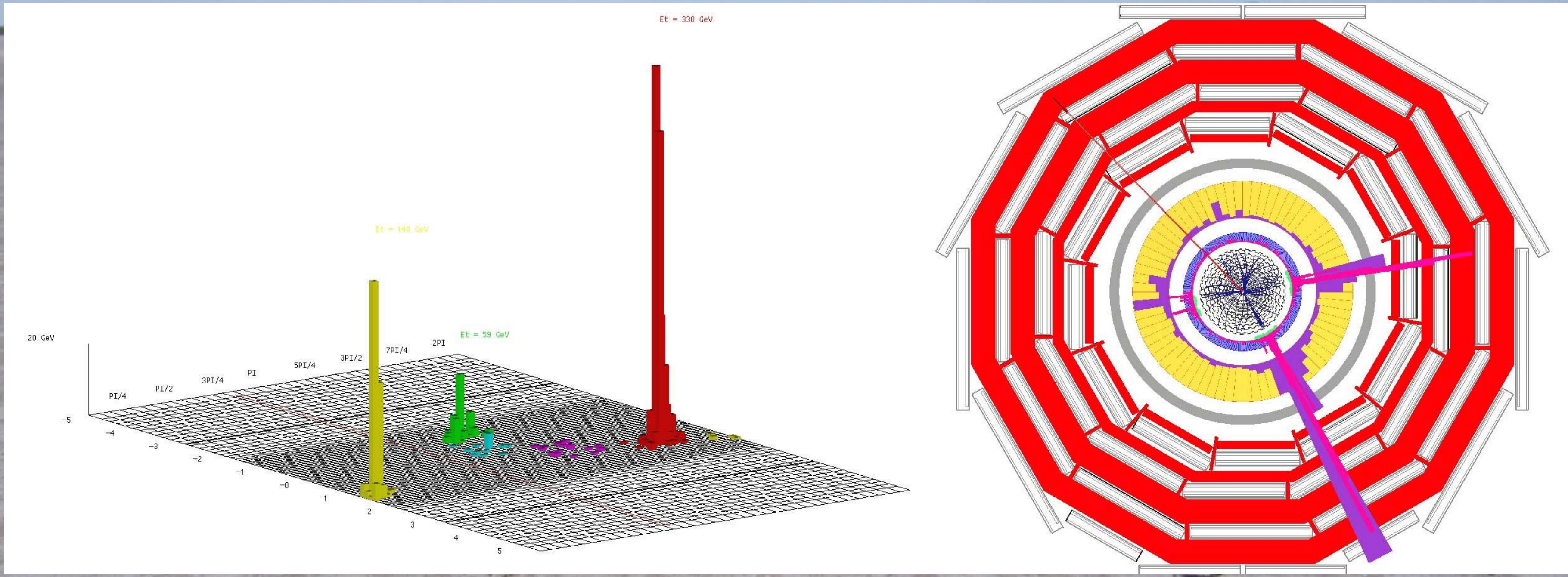
We are searching for them at the LHC



Minimal Supersymmetric Extension of the Standard Model



Classic LHC Dark Matter Signature

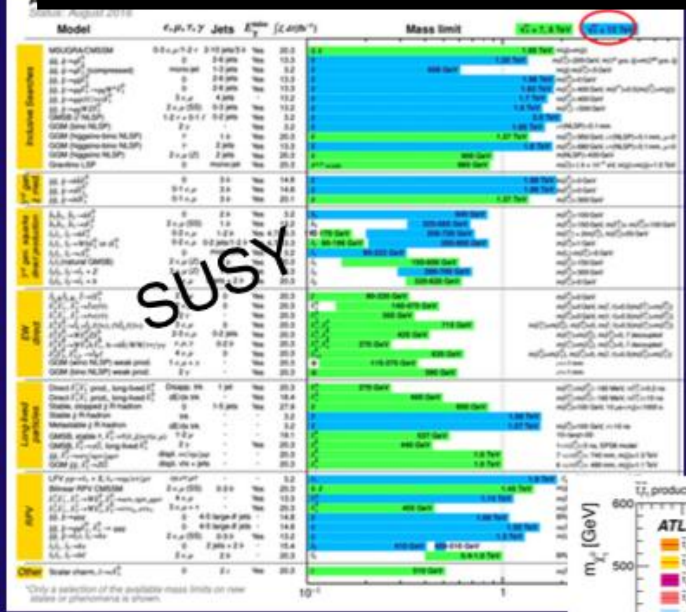


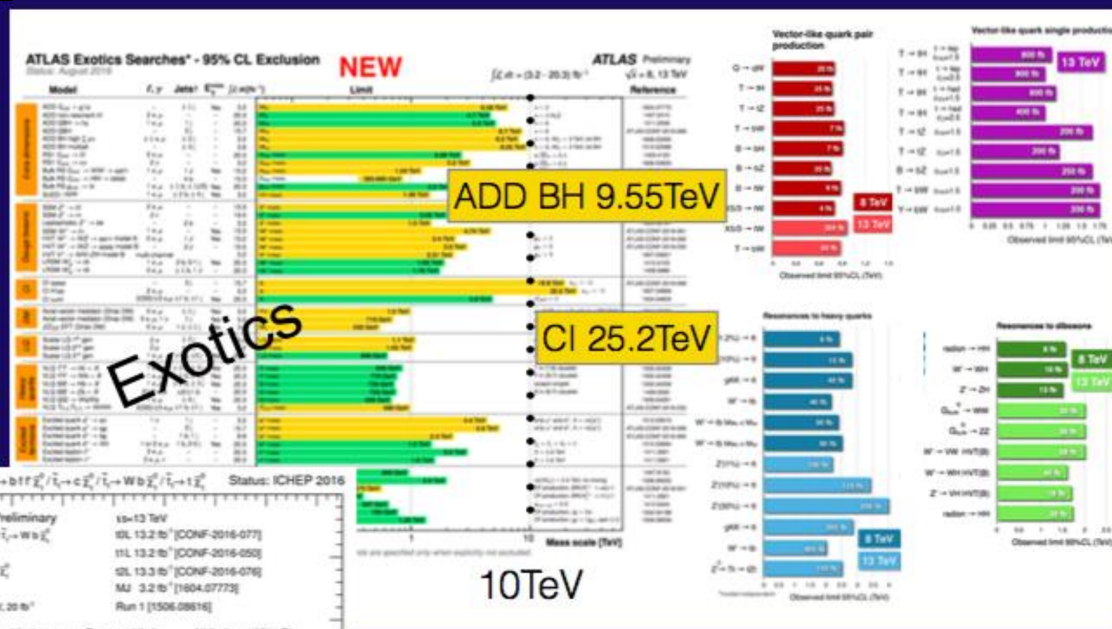
Missing transverse energy
carried away by dark matter particles

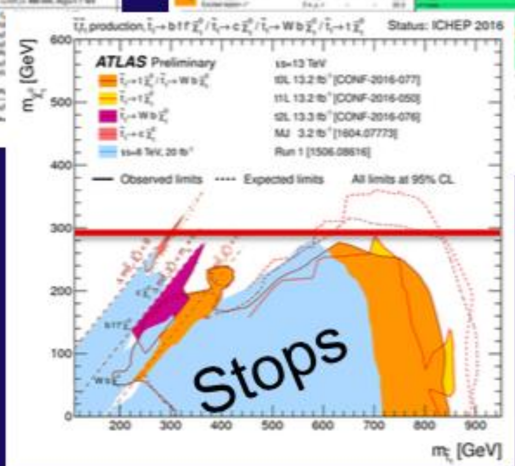
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



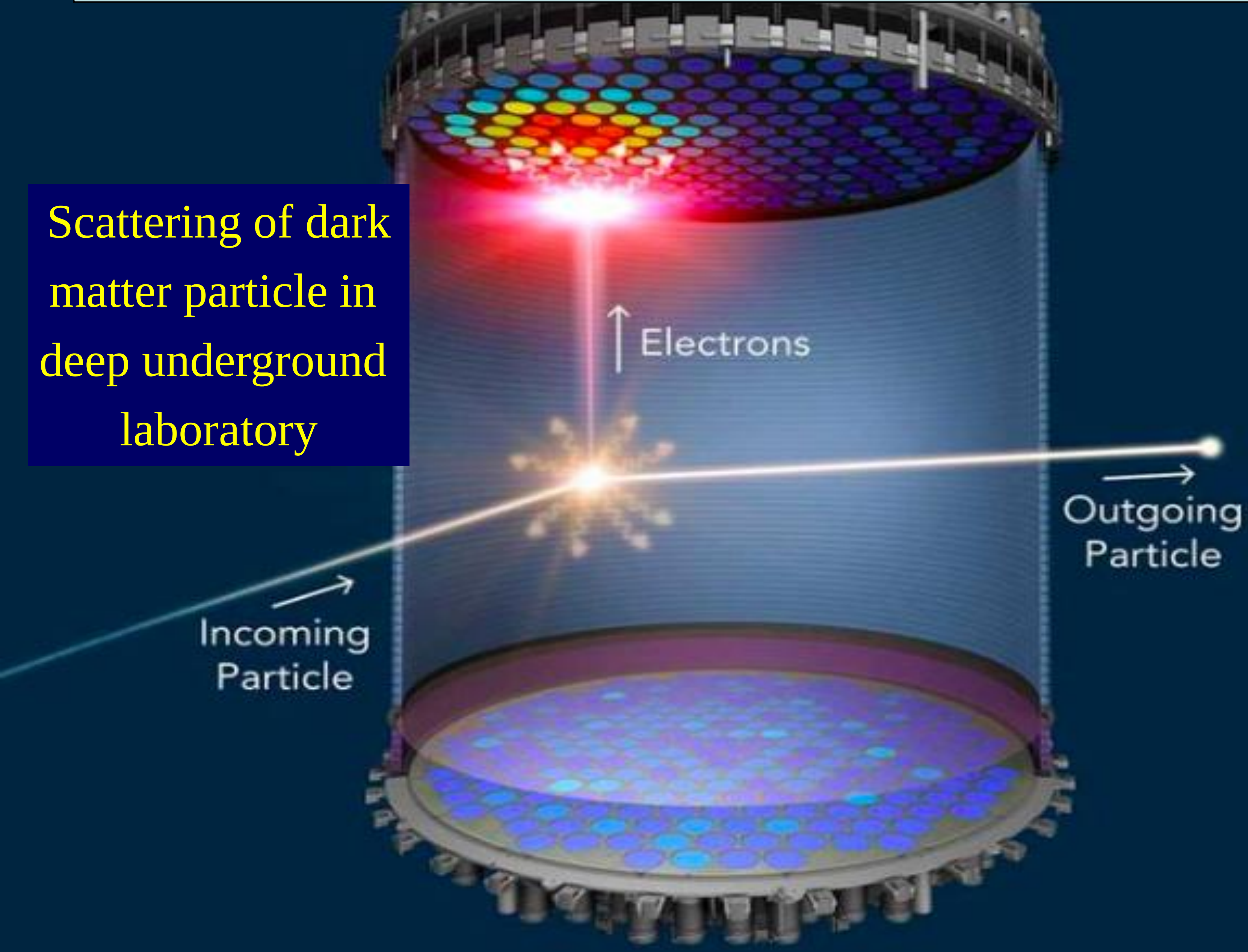




More of same?
Unexplored nooks?
Novel signatures?

Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory



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

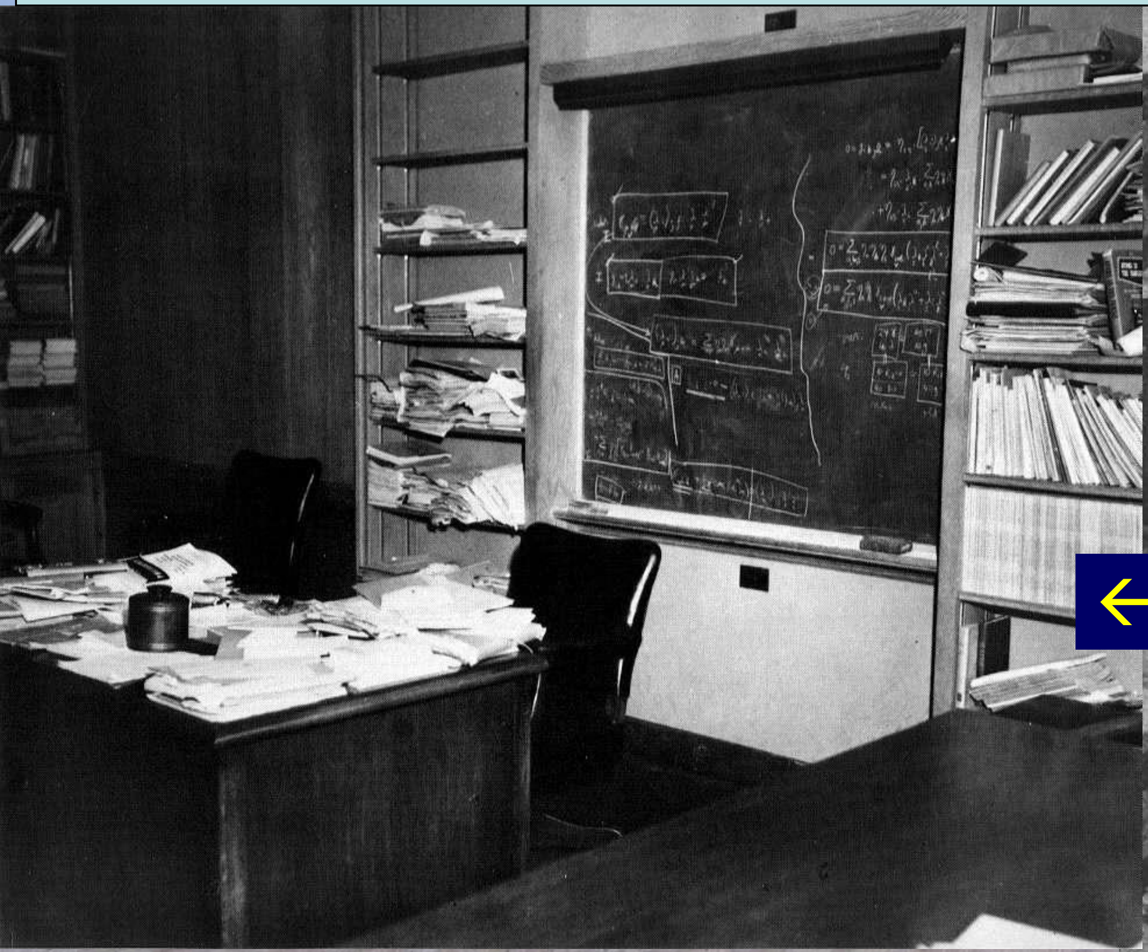
Used in PET scanners

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

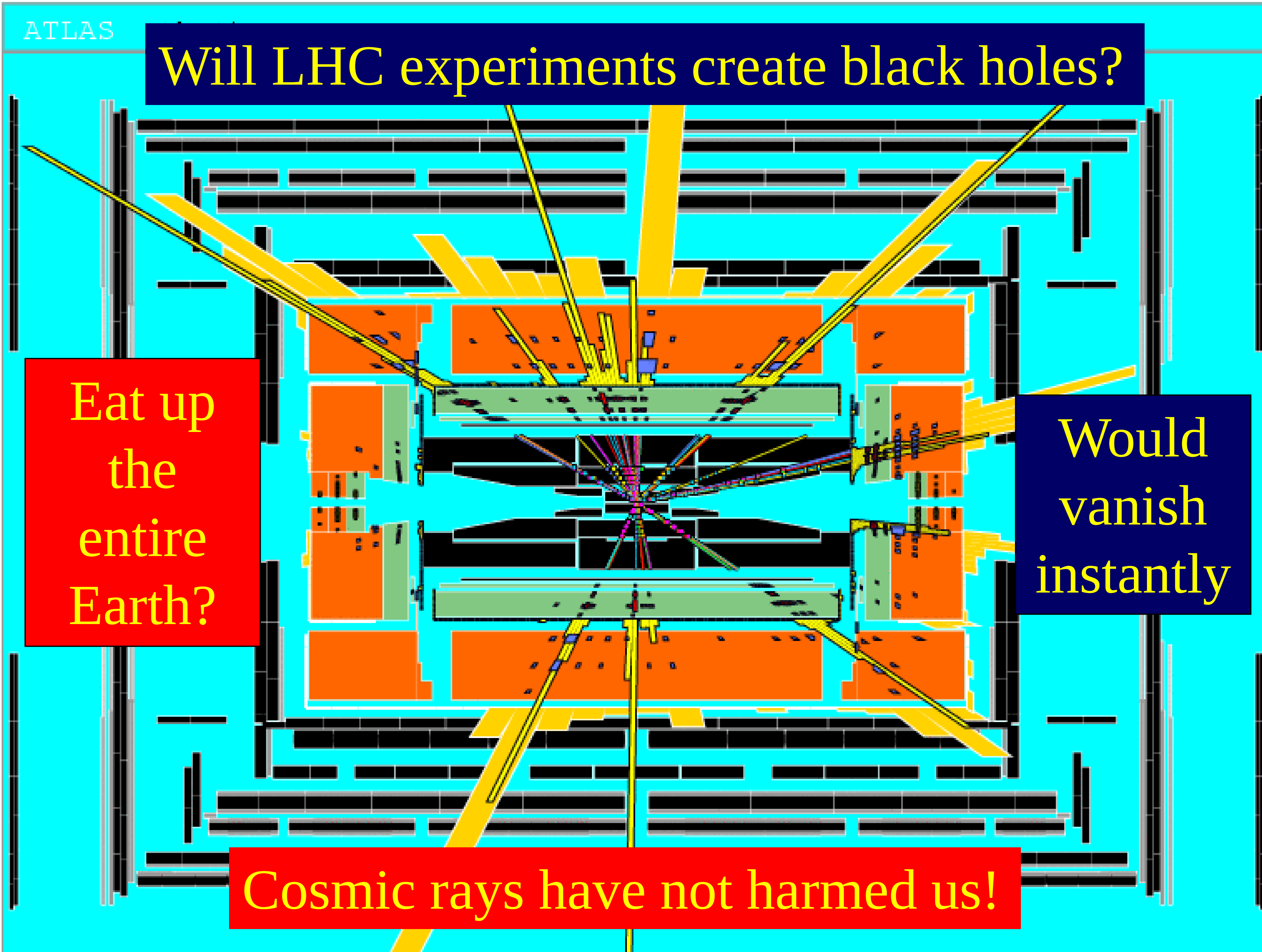
Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Unification via extra dimensions of space?

Will LHC experiments create black holes?



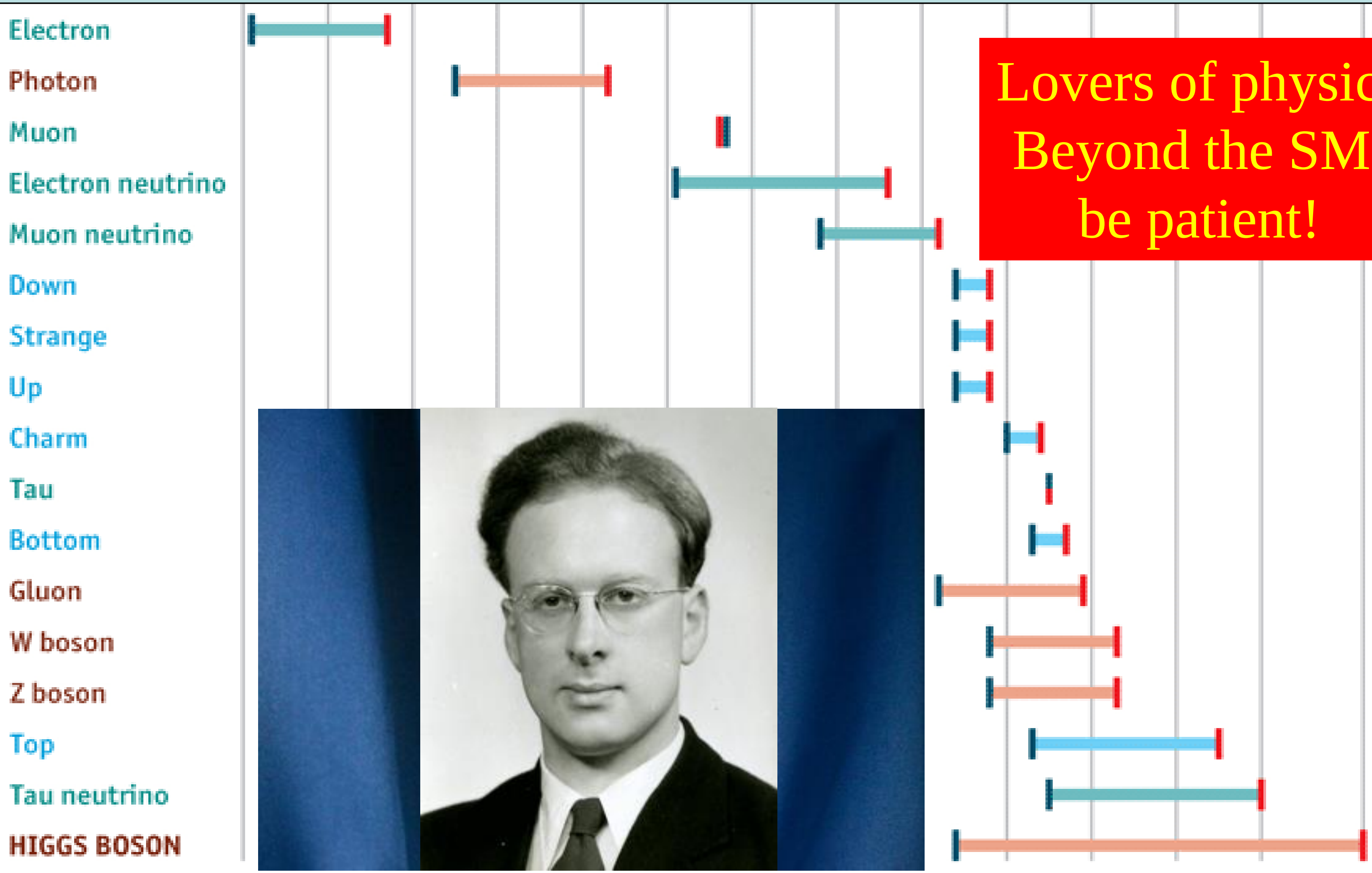
Eat up the entire Earth?

Would vanish instantly

Cosmic rays have not harmed us!

Standard Model Particles:

Years from Proposal to Discovery



Source: *The Economist*

Lovers of physics Beyond the SM: be patient!

Summary