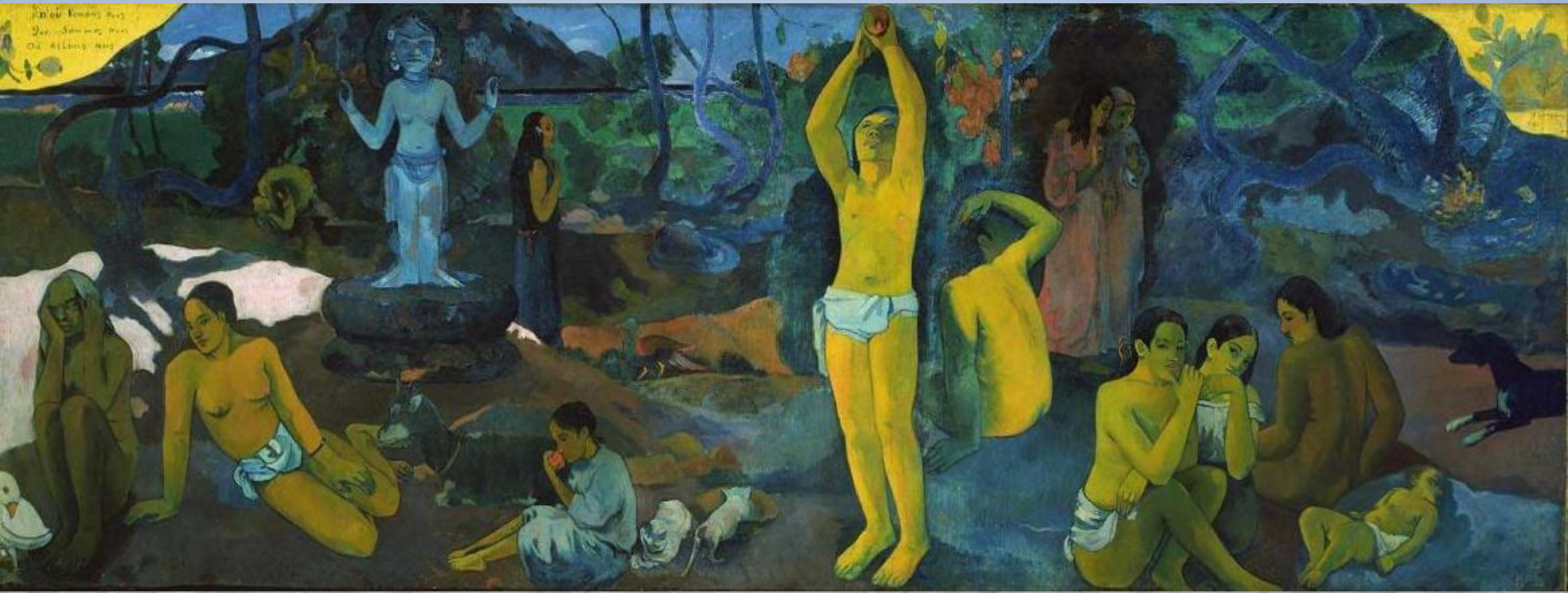
What are we?

Where do we come from?

Where are we going?



The aim of particle physics:

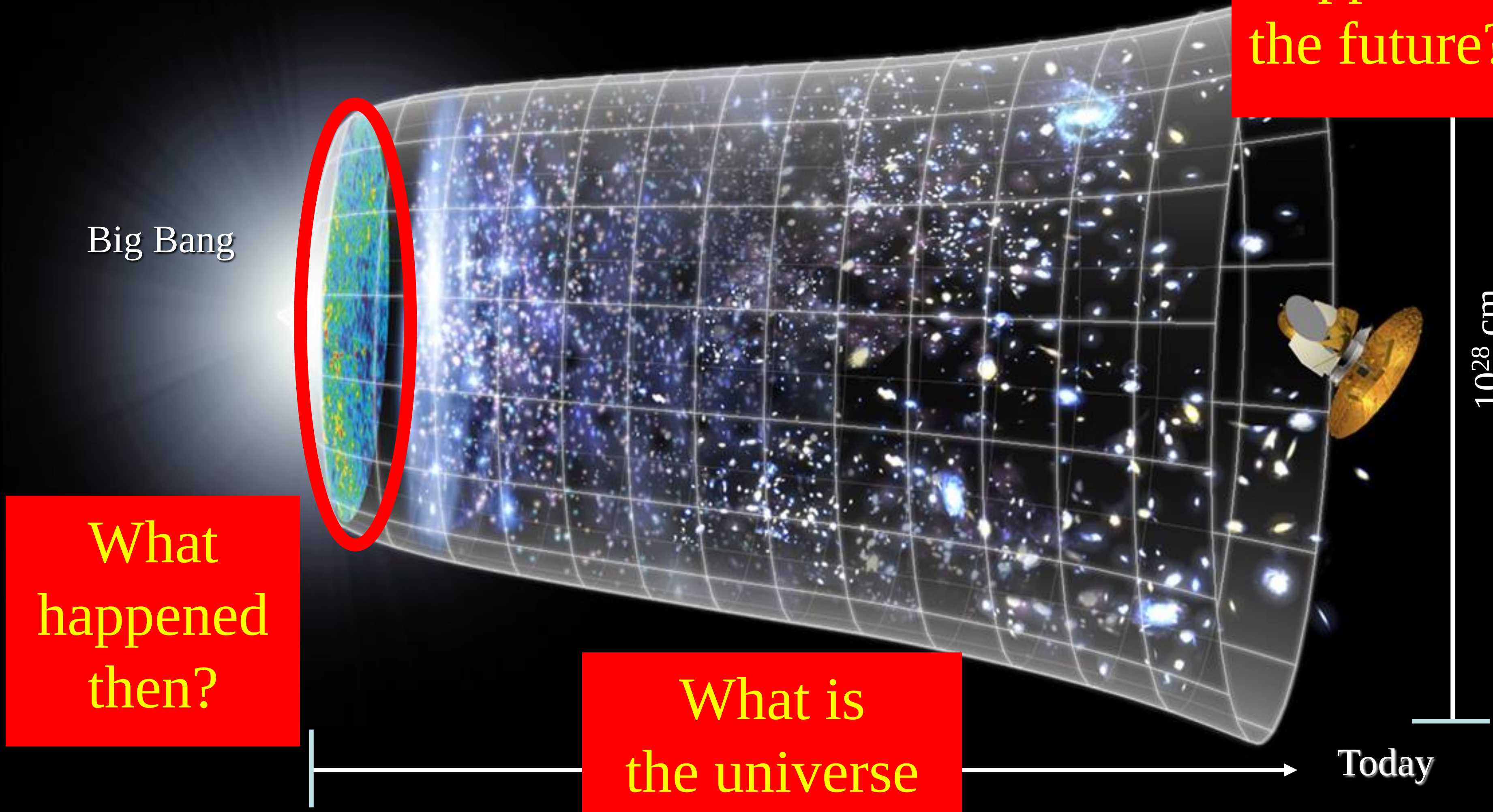
What is matter in the Universe made of?

John Ellis

KING'S College LONDON

Evolution of the Universe

What will happen in the future?



What happened then?

What is the universe made of?

Gauguin’s Questions in the Language of Particle Physics

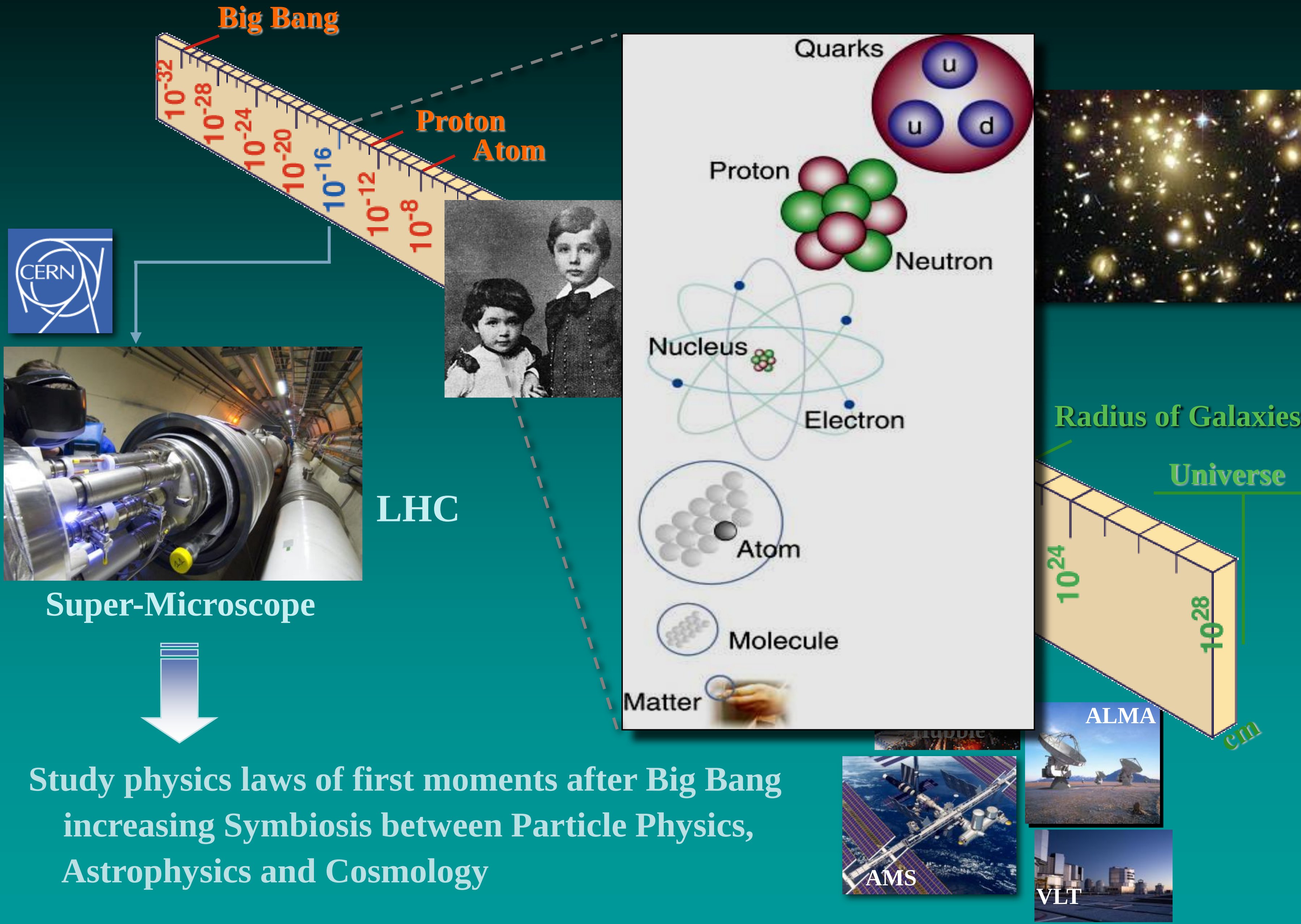
- What is matter made of?
  - Why do things weigh?

- What is the 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 the Standard Model

/Users/johne/Desktop/YoungEinsteins.png

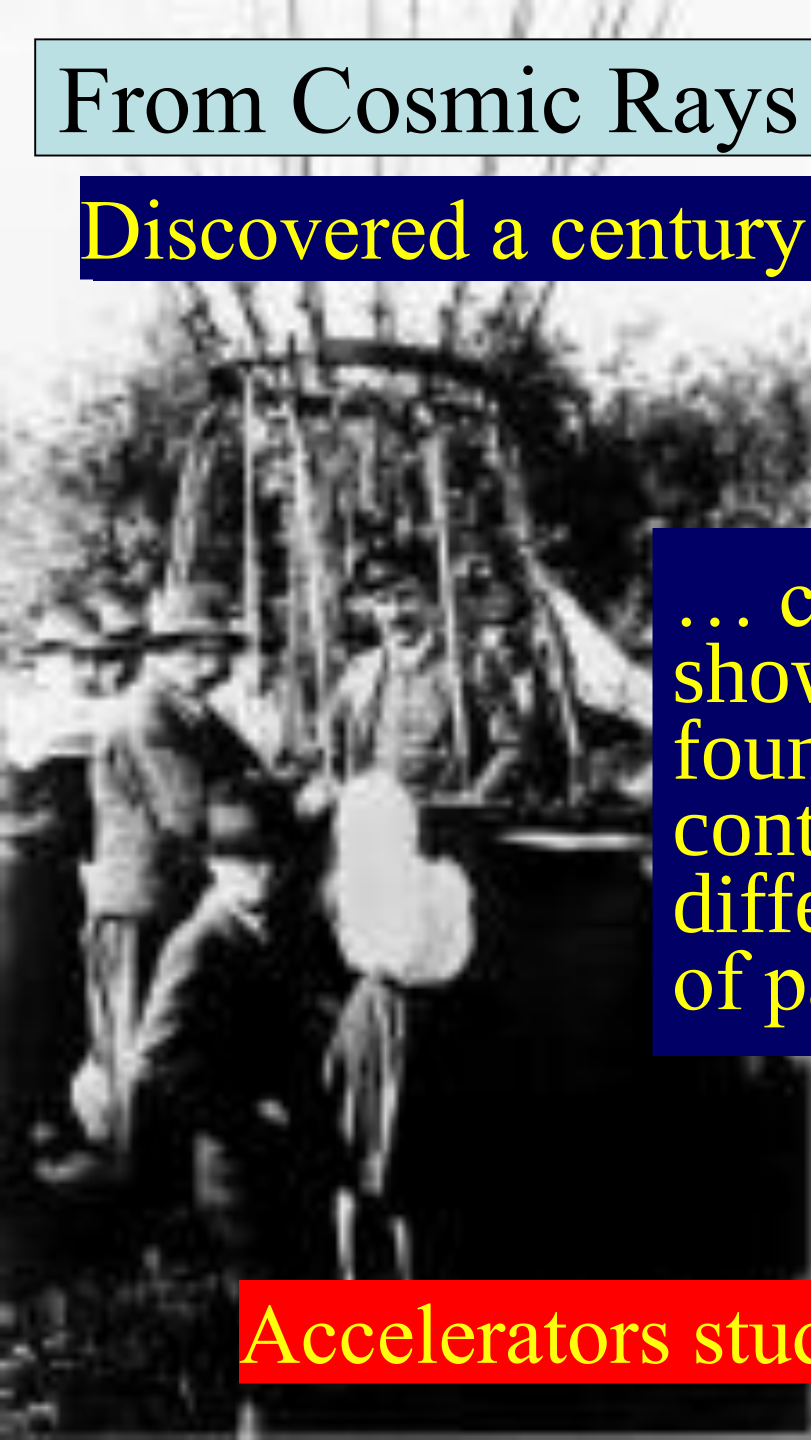


LHC

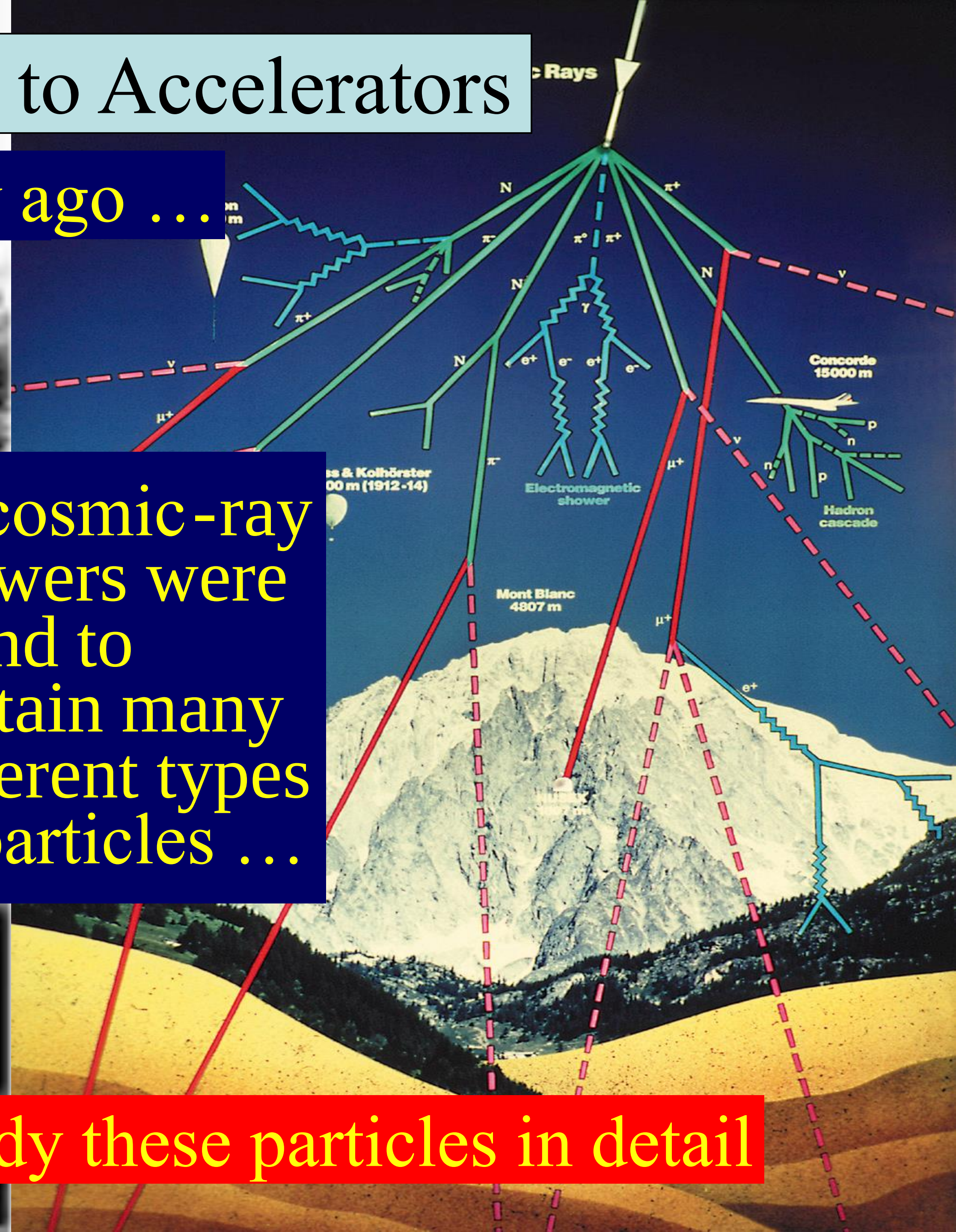
Super-Microscope

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

From Cosmic Rays to Accelerators



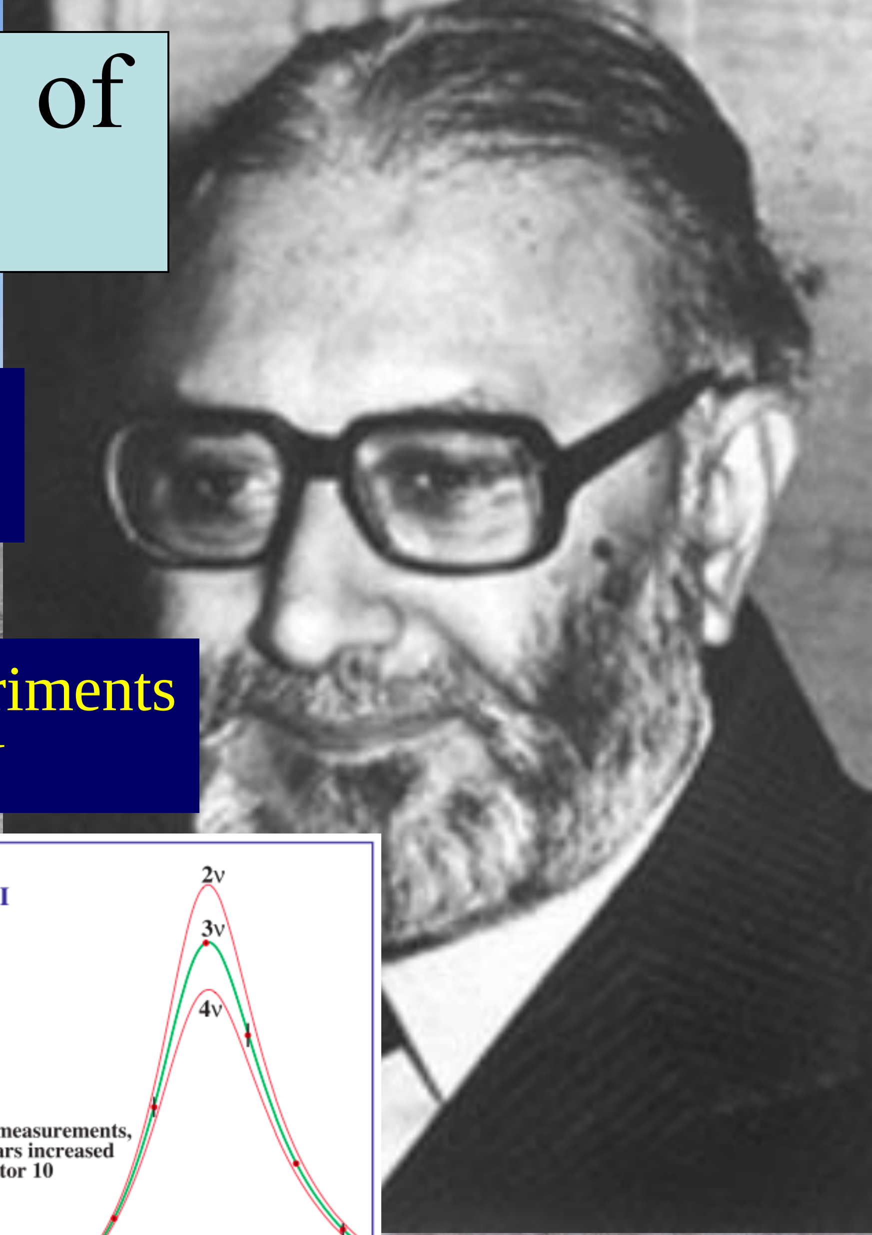
Discovered a century ago …



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

Accelerators study these particles in detail

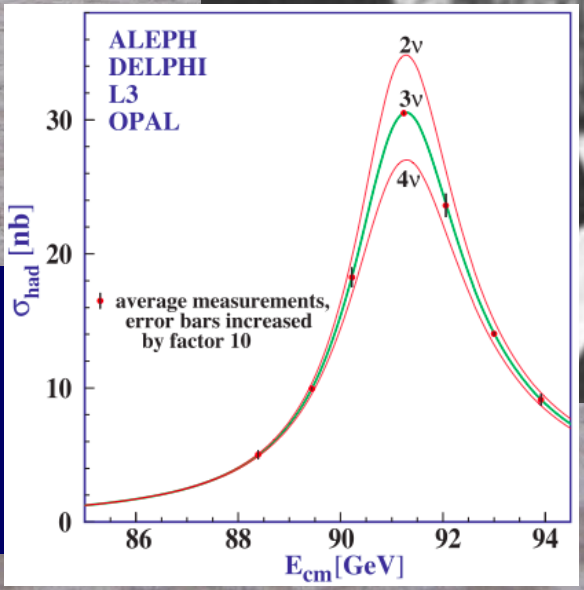
The ‘Standard Model’ of Particle Physics



Proposed byAbdus Salam, Glashow and Weinberg

Tested by experiments at CERN

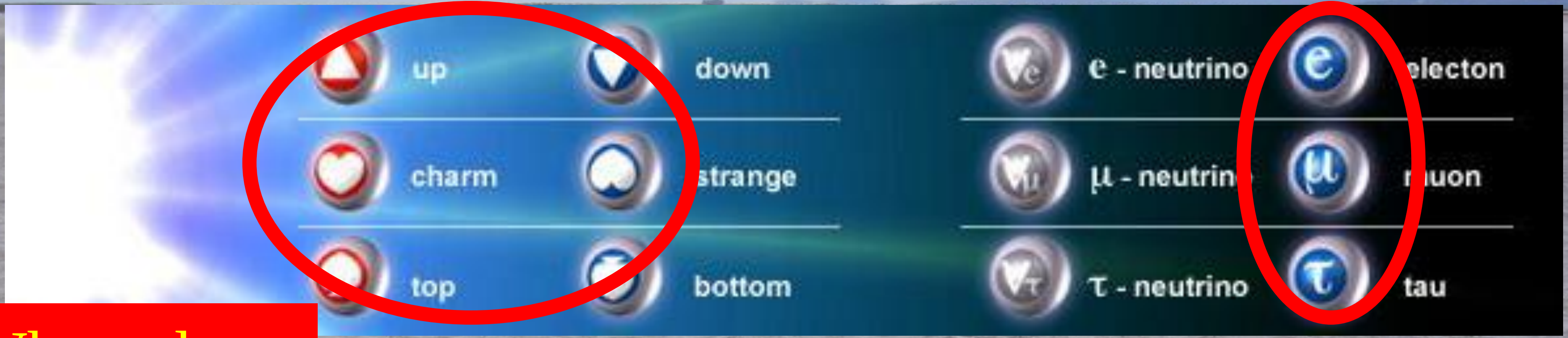
Perfect agreement between theory and experiments in all laboratories



The 'Standard Model'

= Cosmic DNA

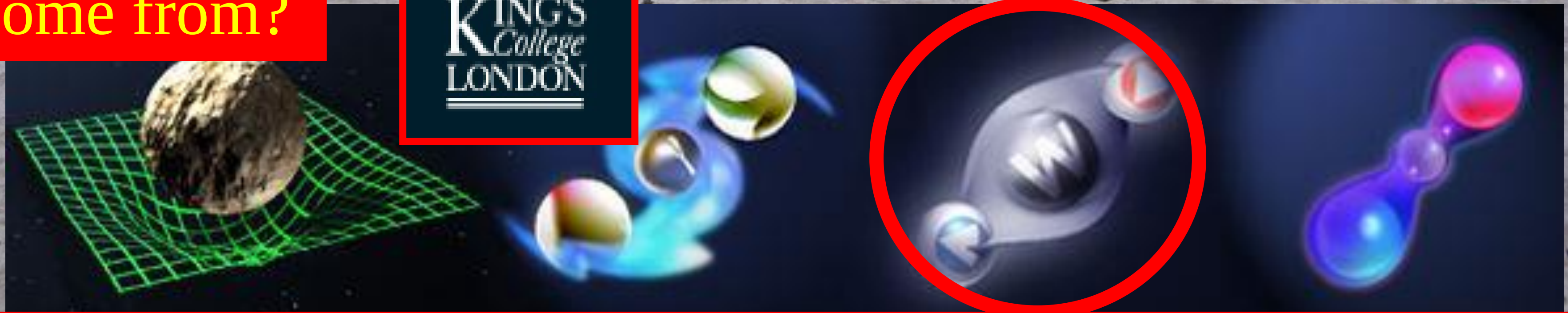
The matter particles



Where does mass come from?

The fundamental interactions

KING'S College LONDON



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

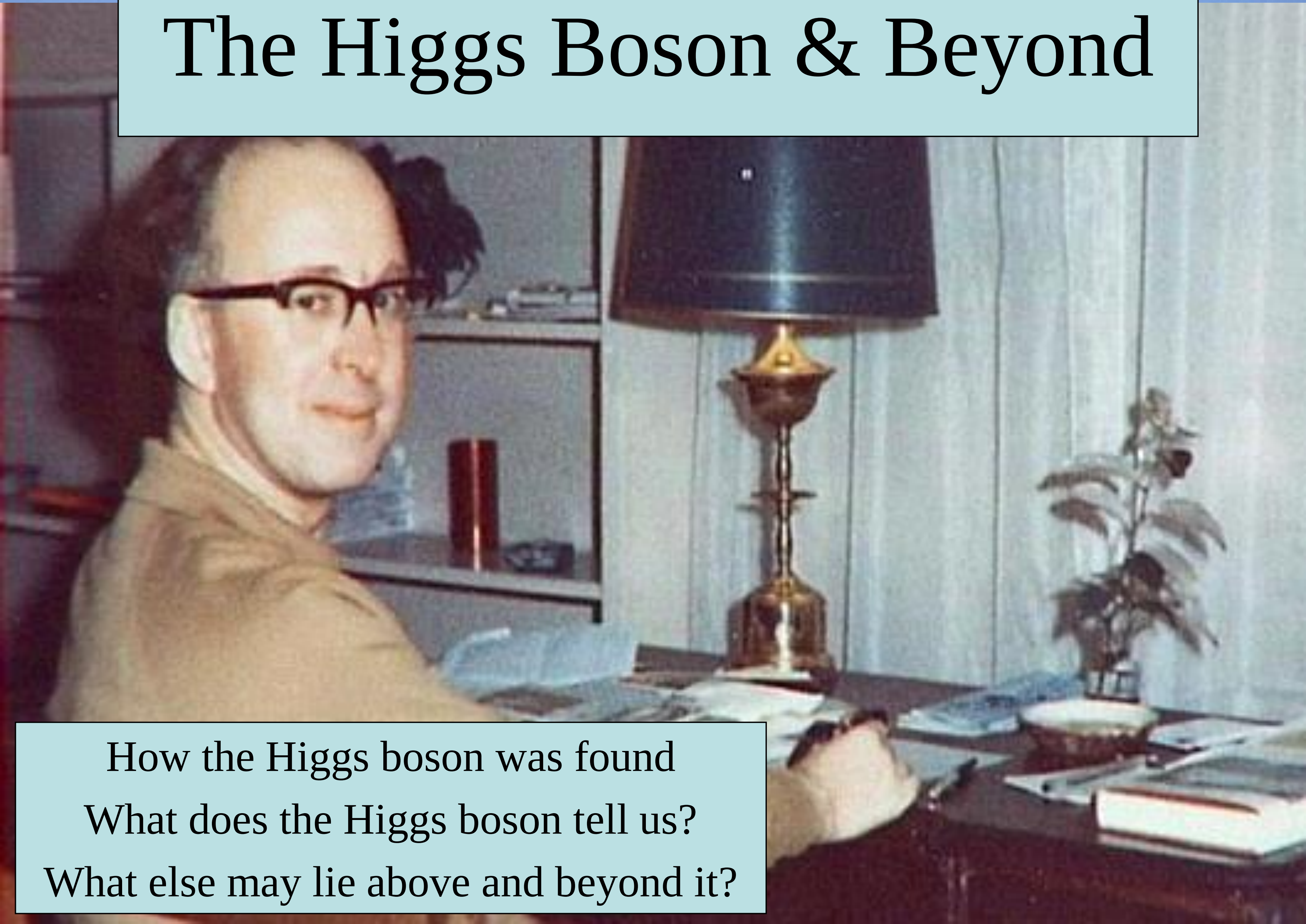
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

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?

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

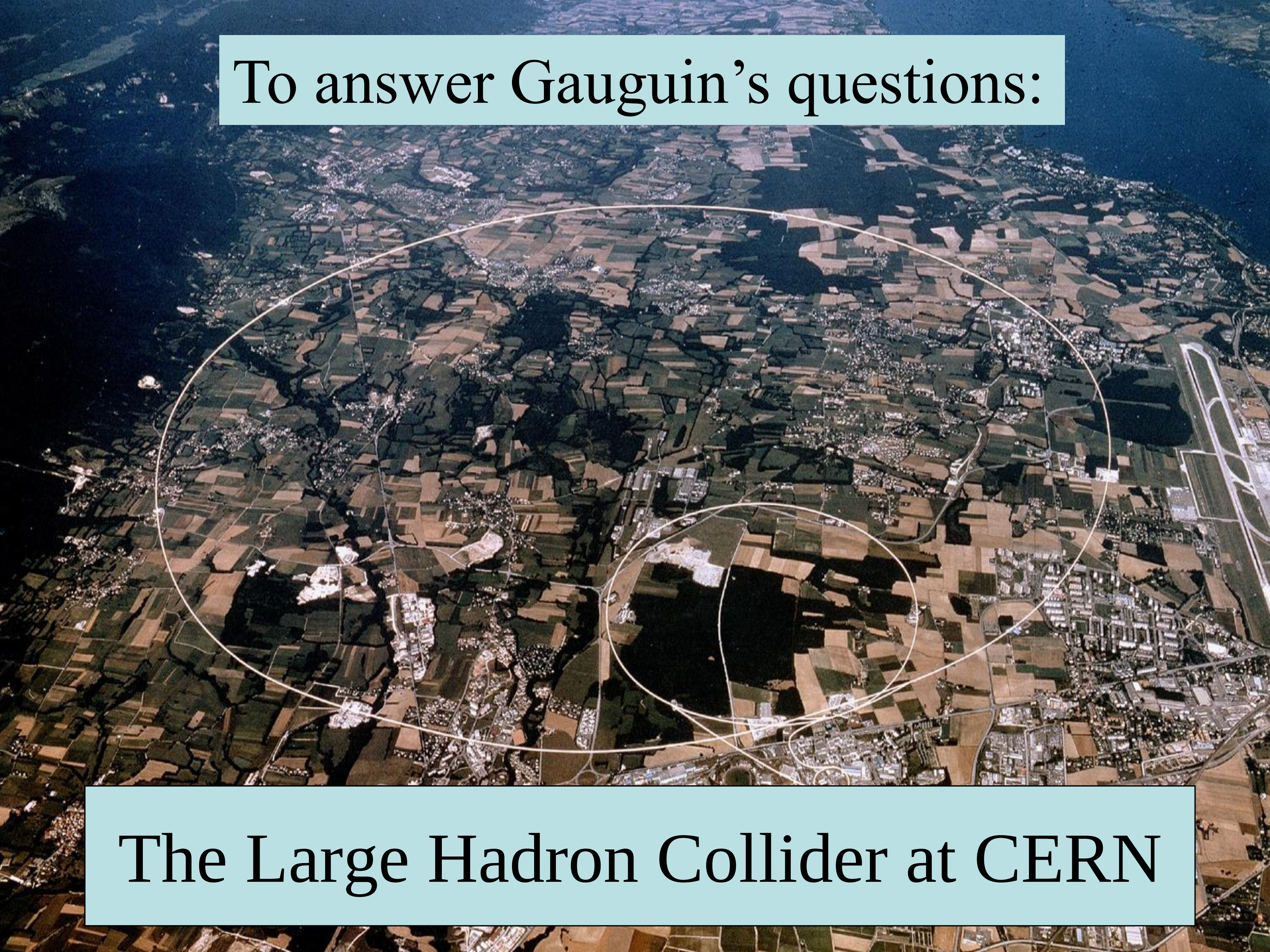
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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.

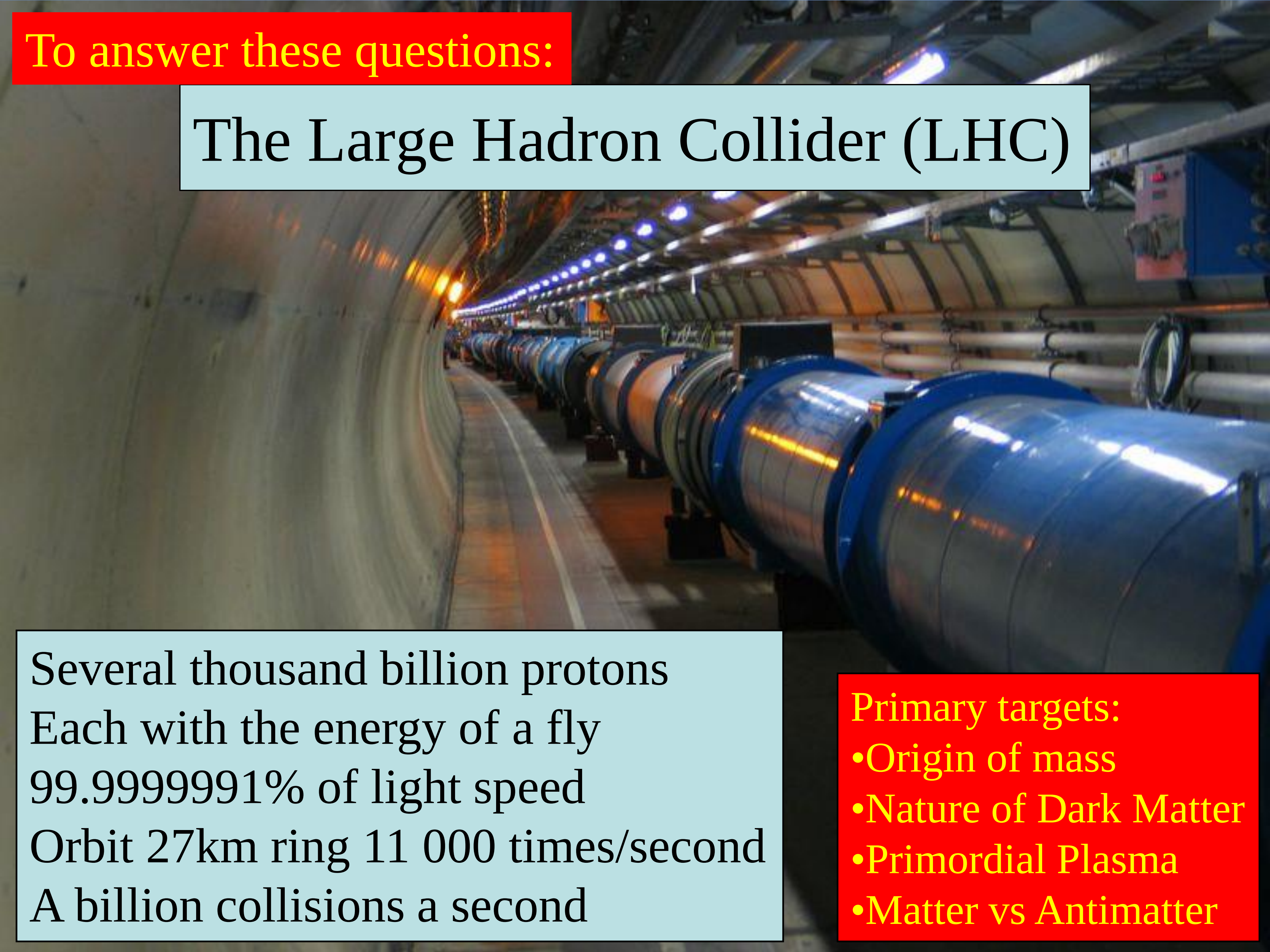
To answer Gauguin's questions:



The Large Hadron Collider at CERN

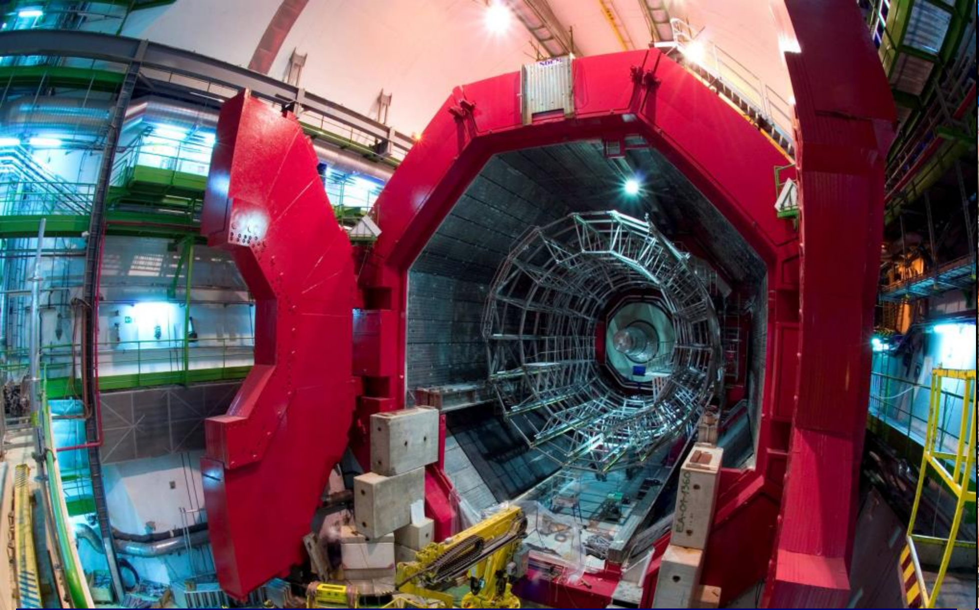
To answer these questions:

The Large Hadron Collider (LHC)

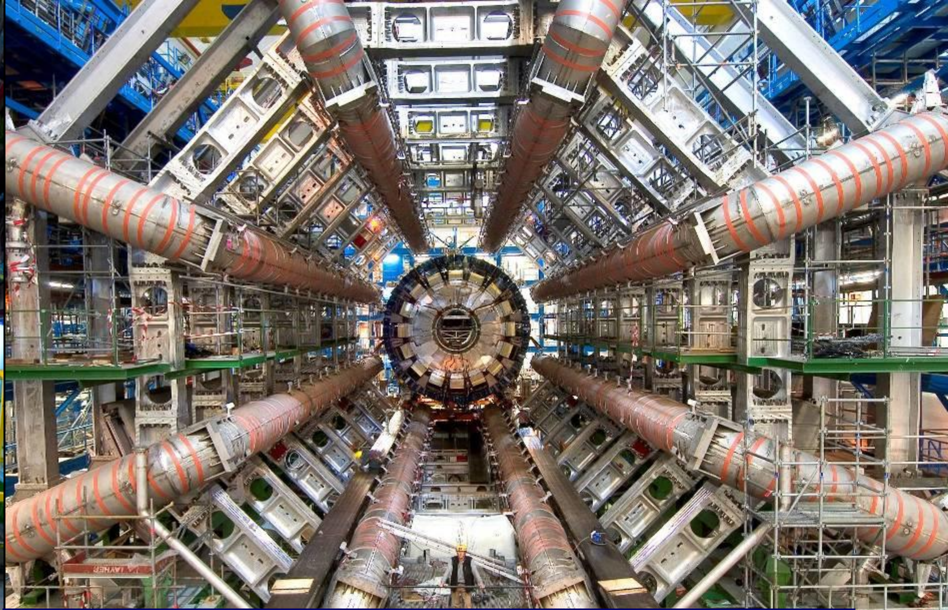


Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

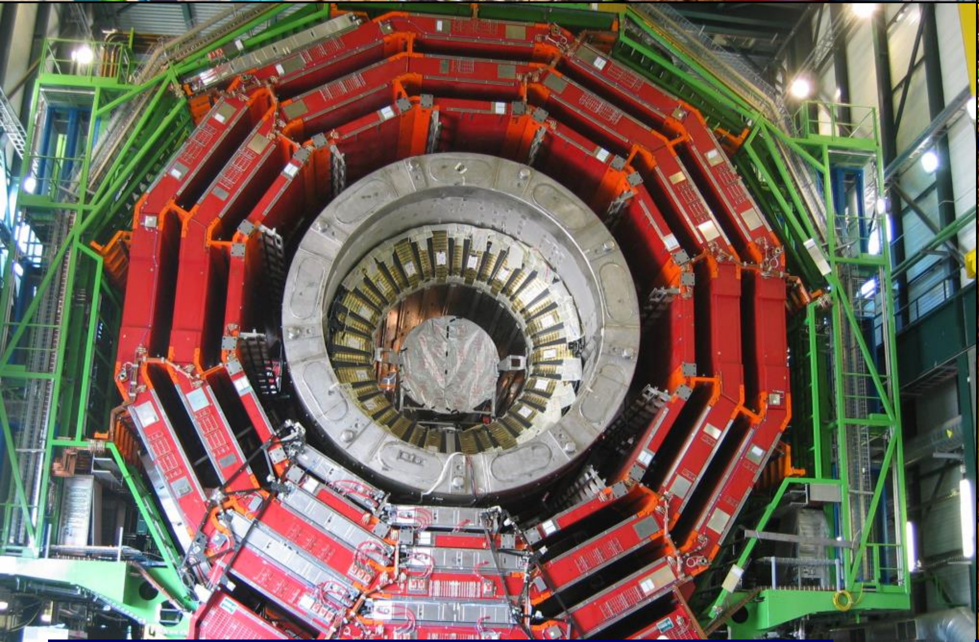
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



ALICE: Primordial cosmic plasma



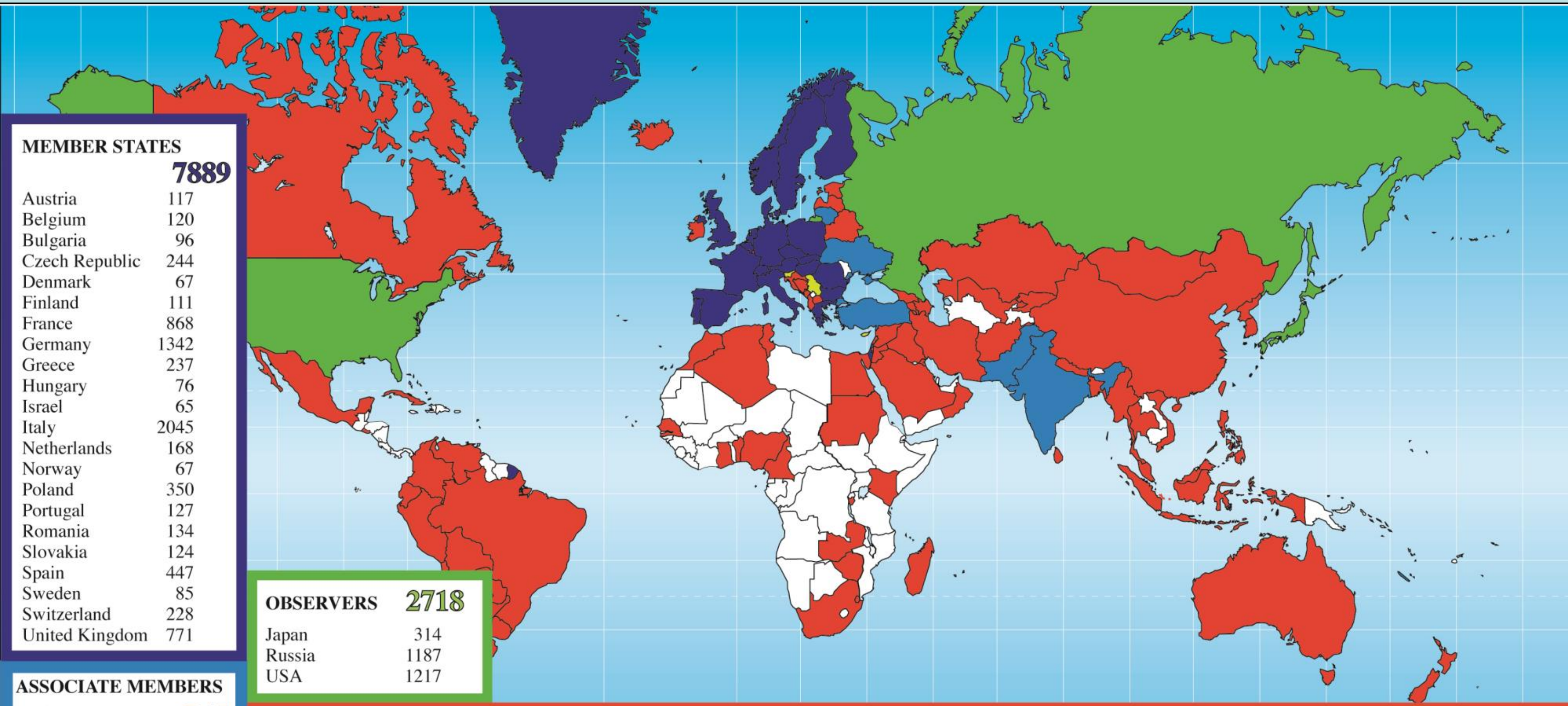
ATLAS: Higgs and dark matter



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

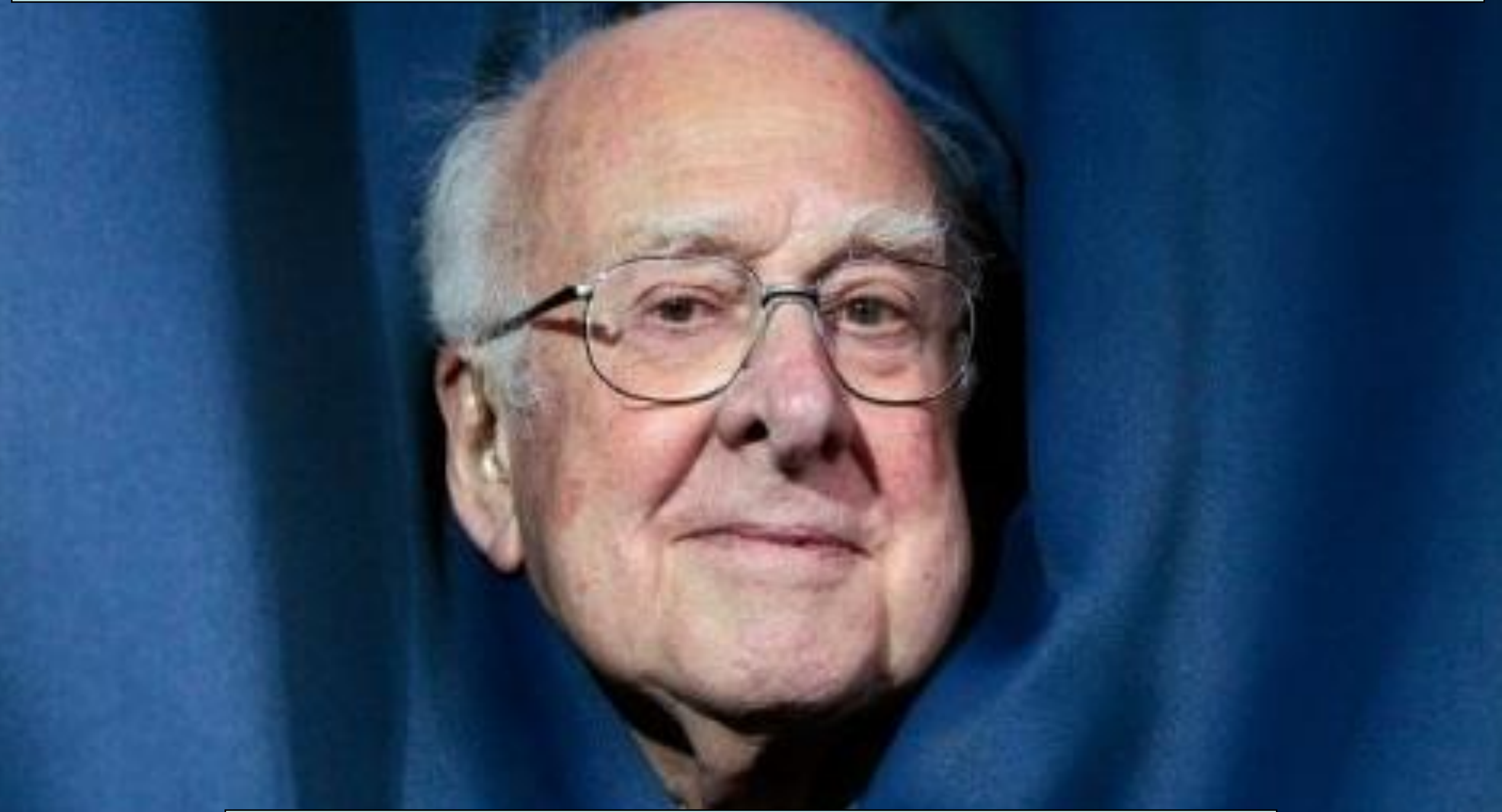
OBSERVERS	2718
Japan	314
Russia	1187
USA	1217

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

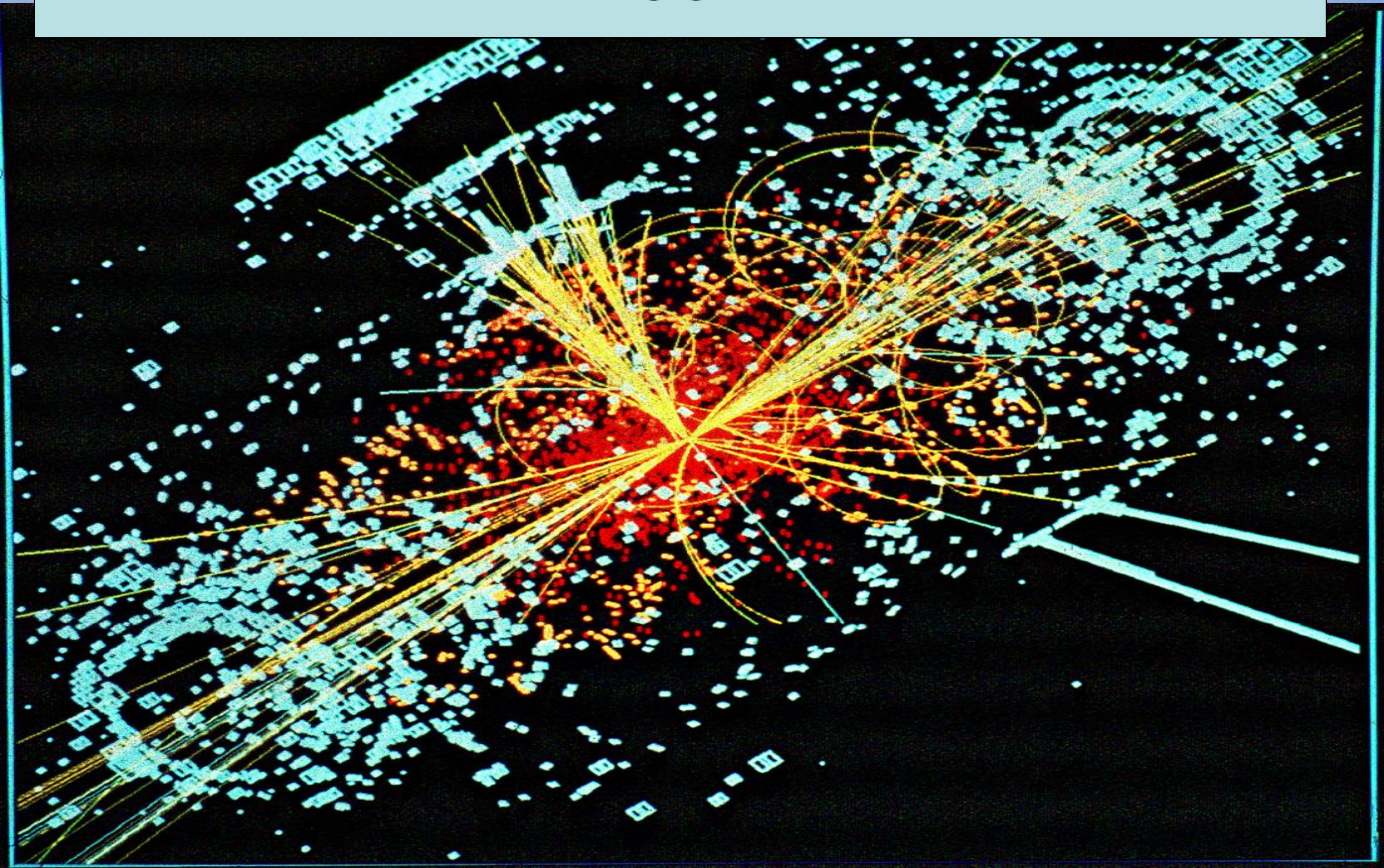
OTHERS	1872
Afghanistan	1
Albania	3
Algeria	14
Argentina	27
Armenia	19
Australia	31
Azerbaijan	10
Bangladesh	11
Belarus	48
Benin	1
Bolivia	4
Bosnia & Herzegovina	2
Brazil	135
Burundi	1
Cameroon	1
Canada	161
Chile	20
China	510
Colombia	45
Croatia	41
Cuba	12
Ecuador	6
Egypt	31
El Salvador	1
Estonia	15
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

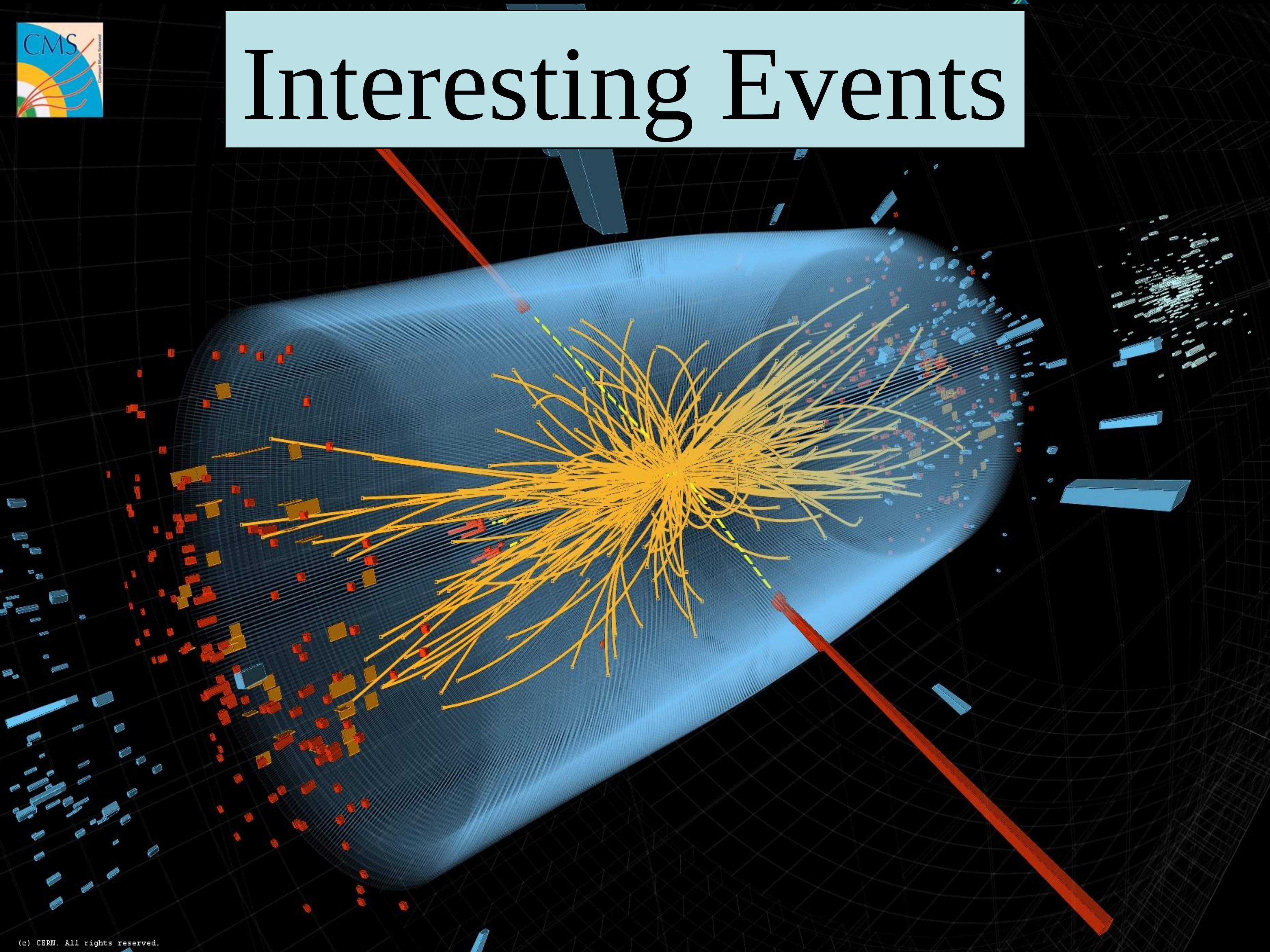


Mass Higgsteria

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?

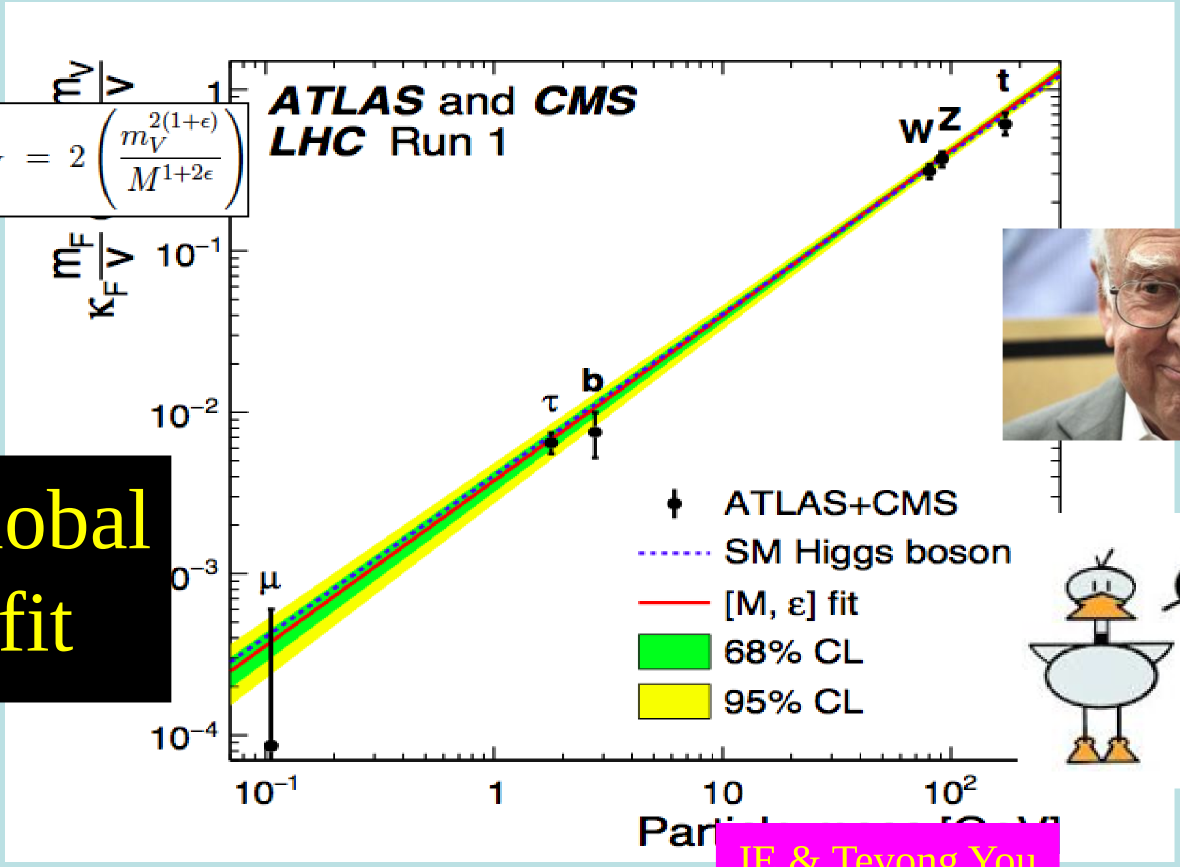
Is it the right size?

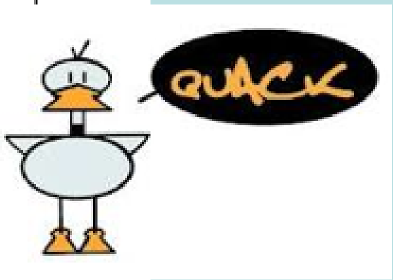
It Walks and Quacks like a Higgs

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

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

Global fit

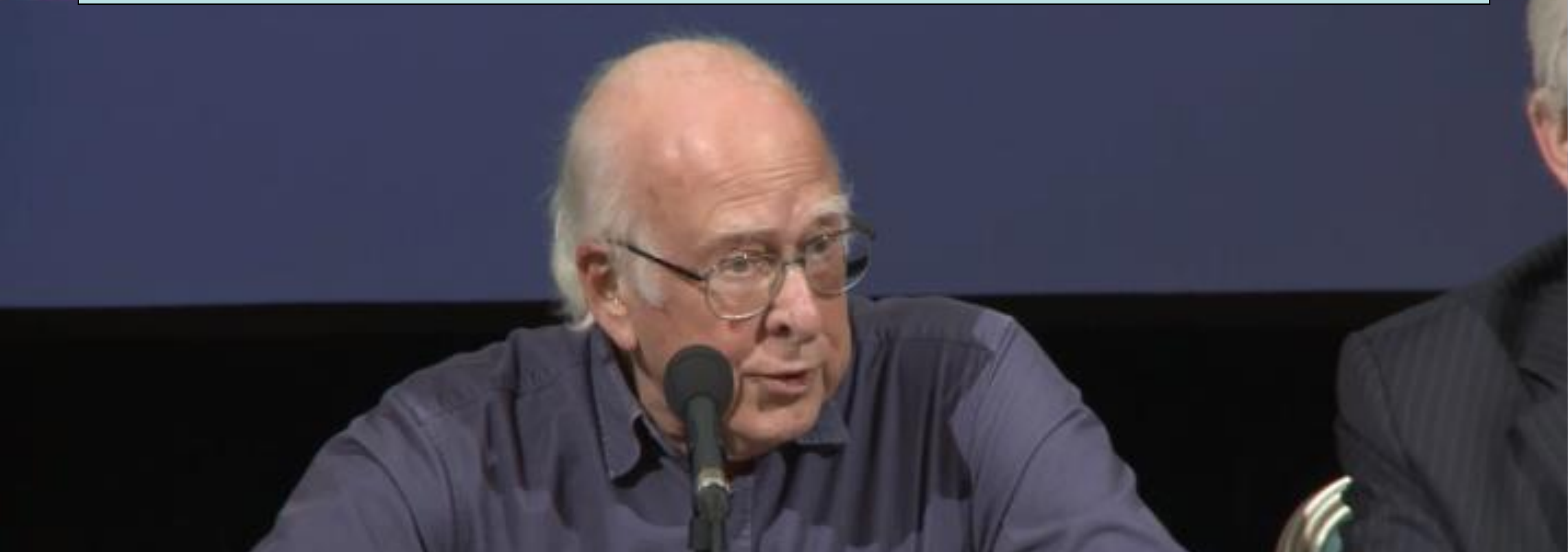




JE & Tevong You

- **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

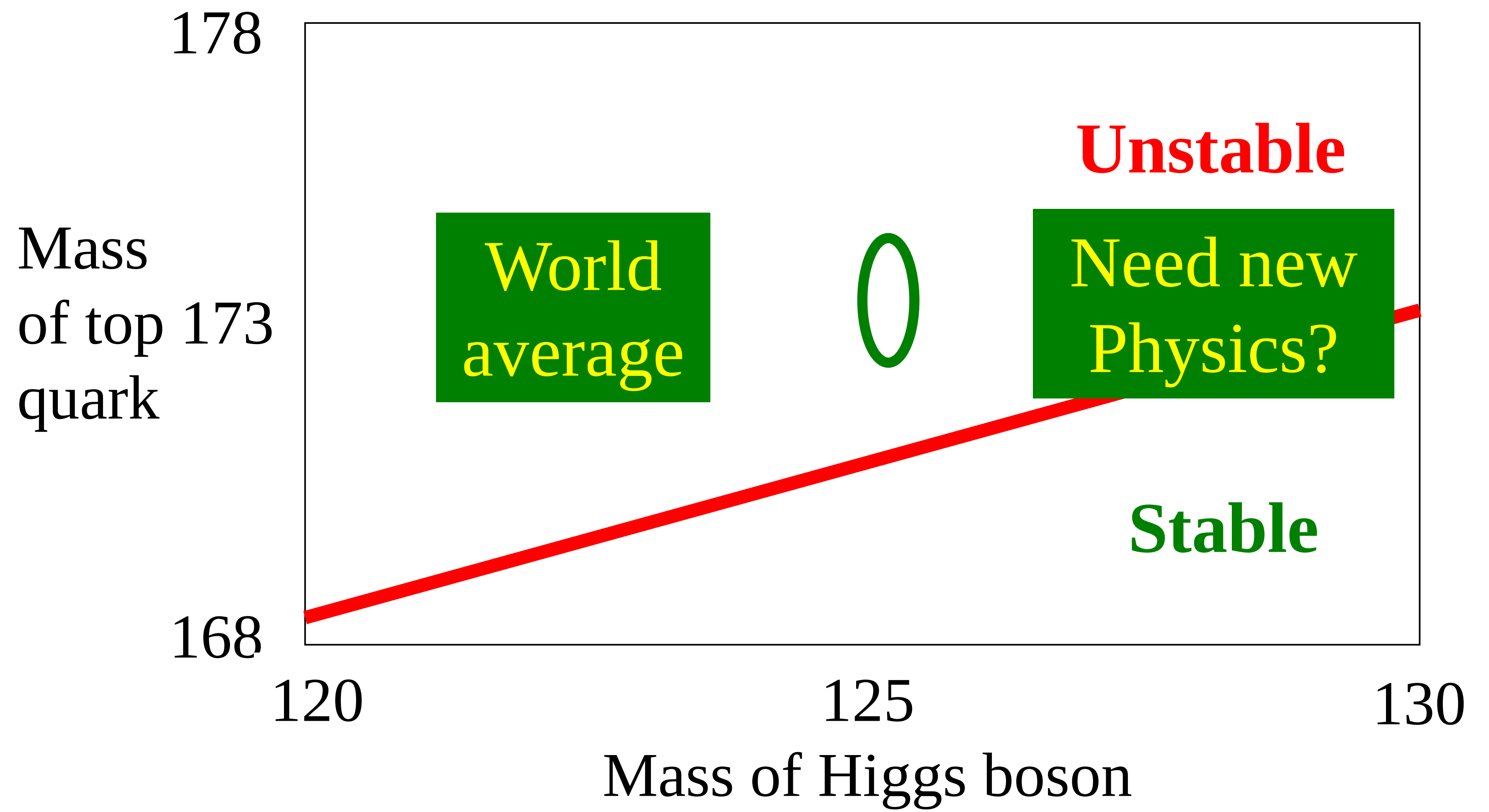
– Life would be impossible: everything would be radioactive

Its existence is a big deal!

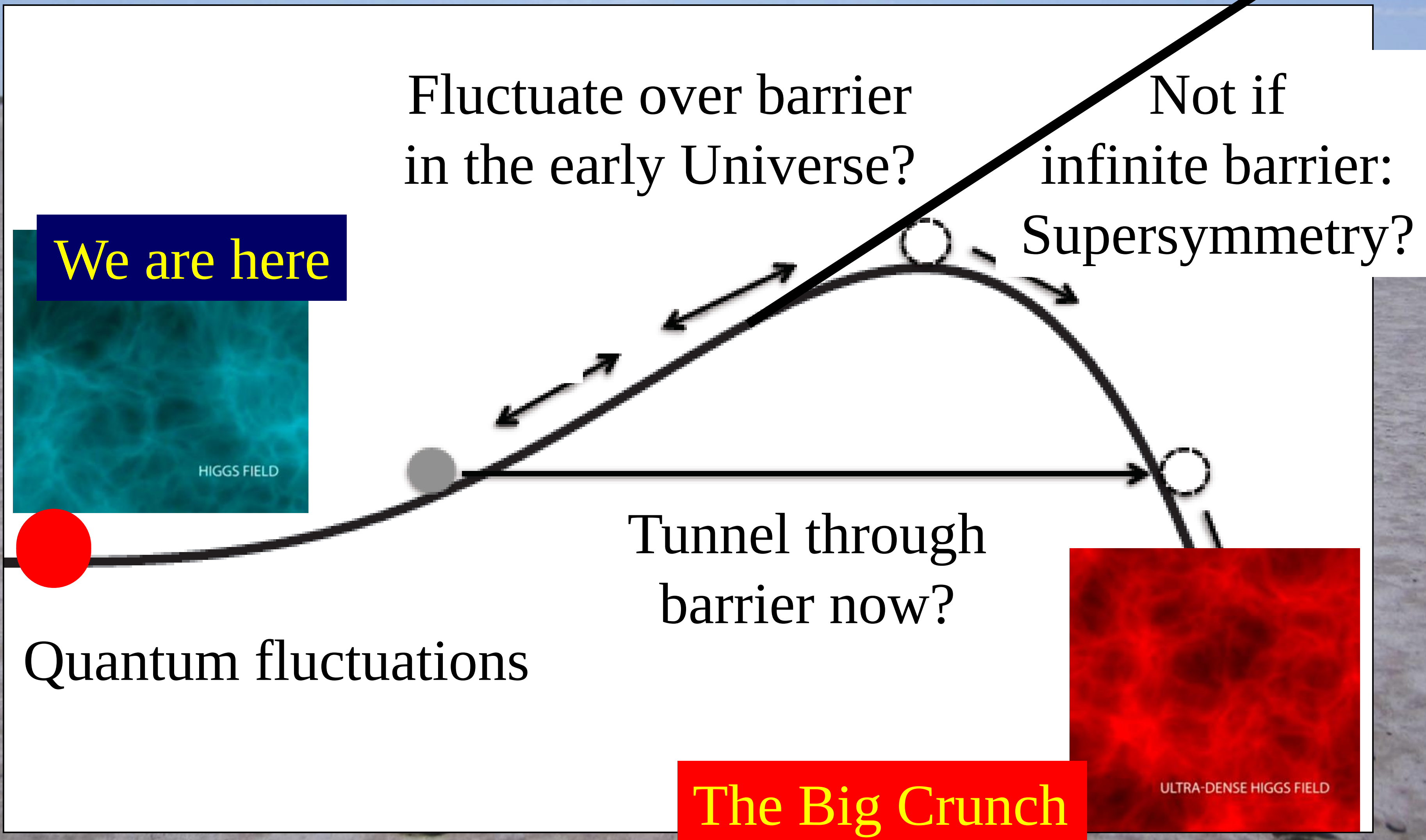
- « Empty » space is unstab LHC
- Dark matter LHC
- Origin of matter LHC
- Sizes of masses LHC
- Properties of neutrinos
- Cosmological inflation LHC
- Quantum gravity
- …

Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?



What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Supersymmetry?

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

0 - ½ - 1 - 3/2 - 2

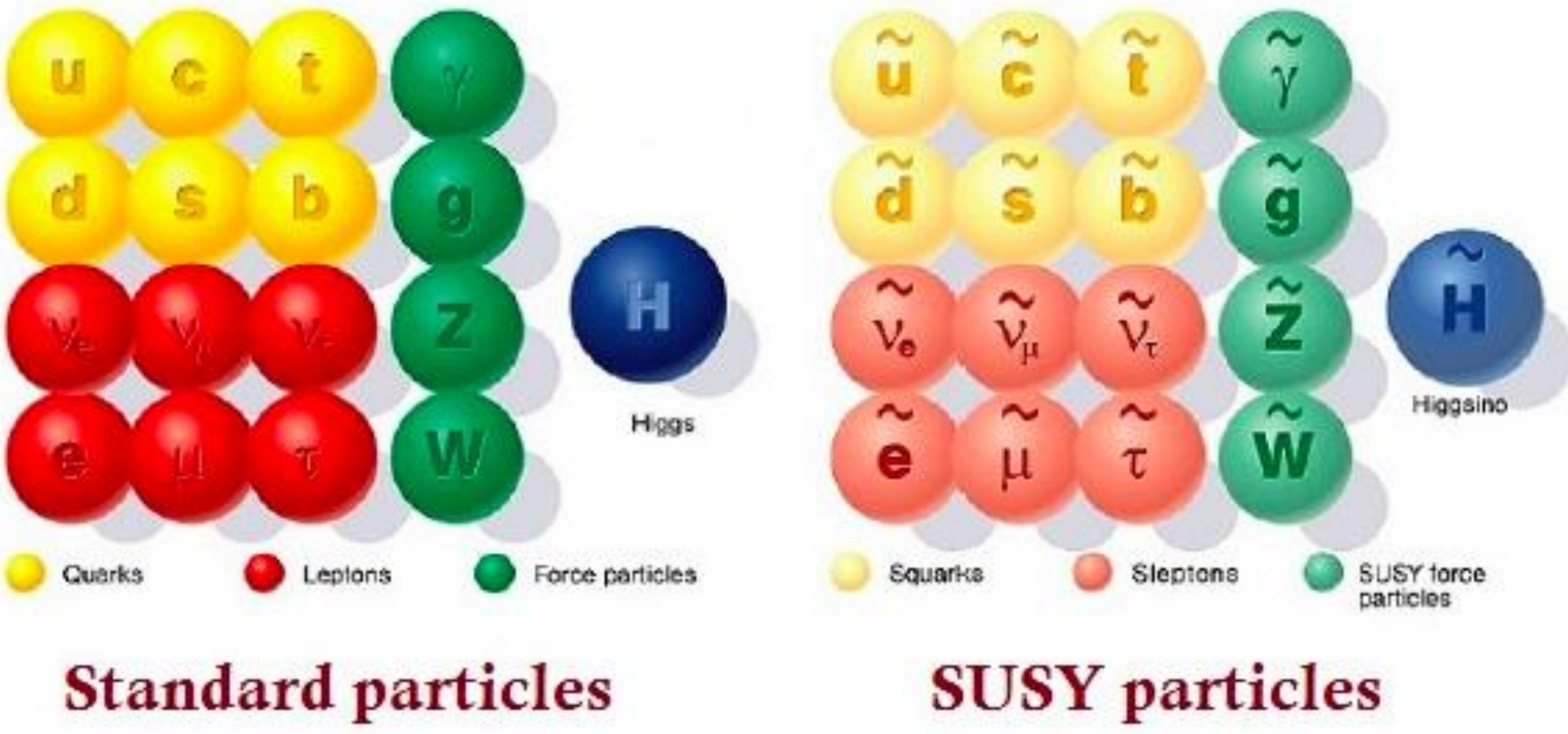
Higgs - Electron - Photon - Gravitino - Graviton

(Every particle is a 'ballet dancer')

(pirouette at different speeds)

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

Minimal Supersymmetric Extension of 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?**

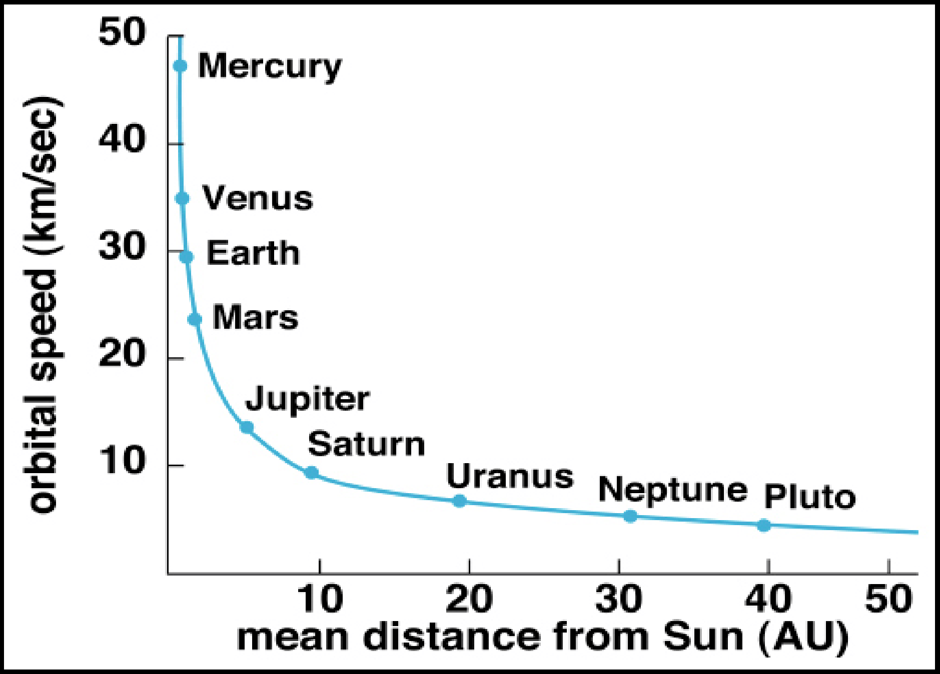
The Rotation Curves of Galaxies

- 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

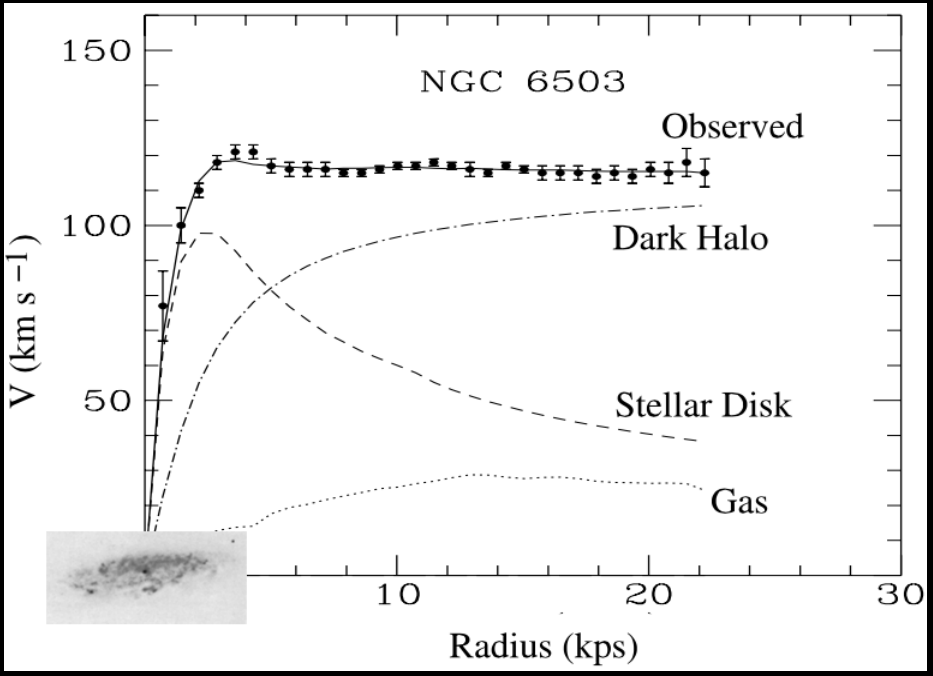
Rotation Curves

- In the Solar System



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

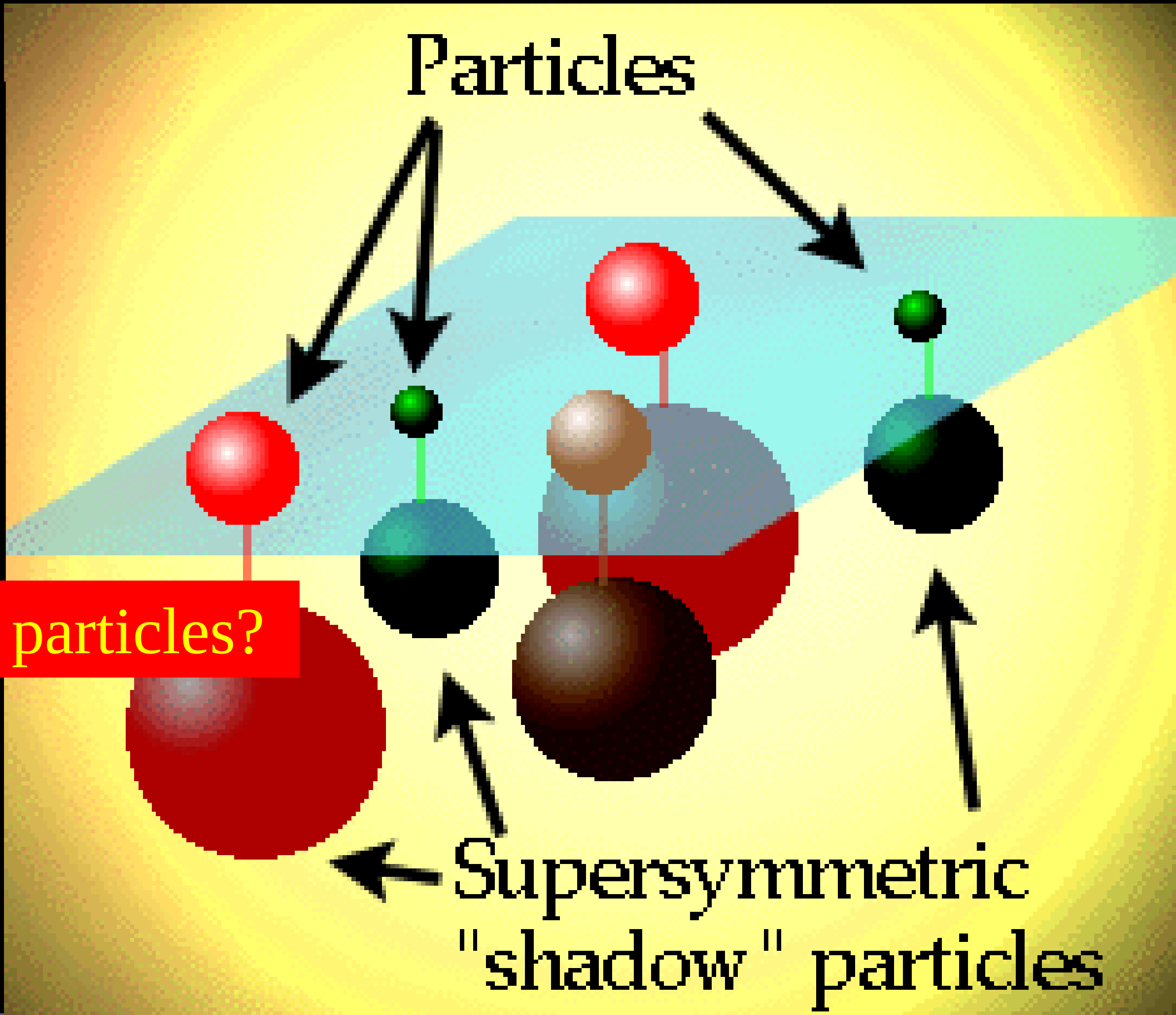
- In galaxies



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

What is the Dark Matter in the Universe?

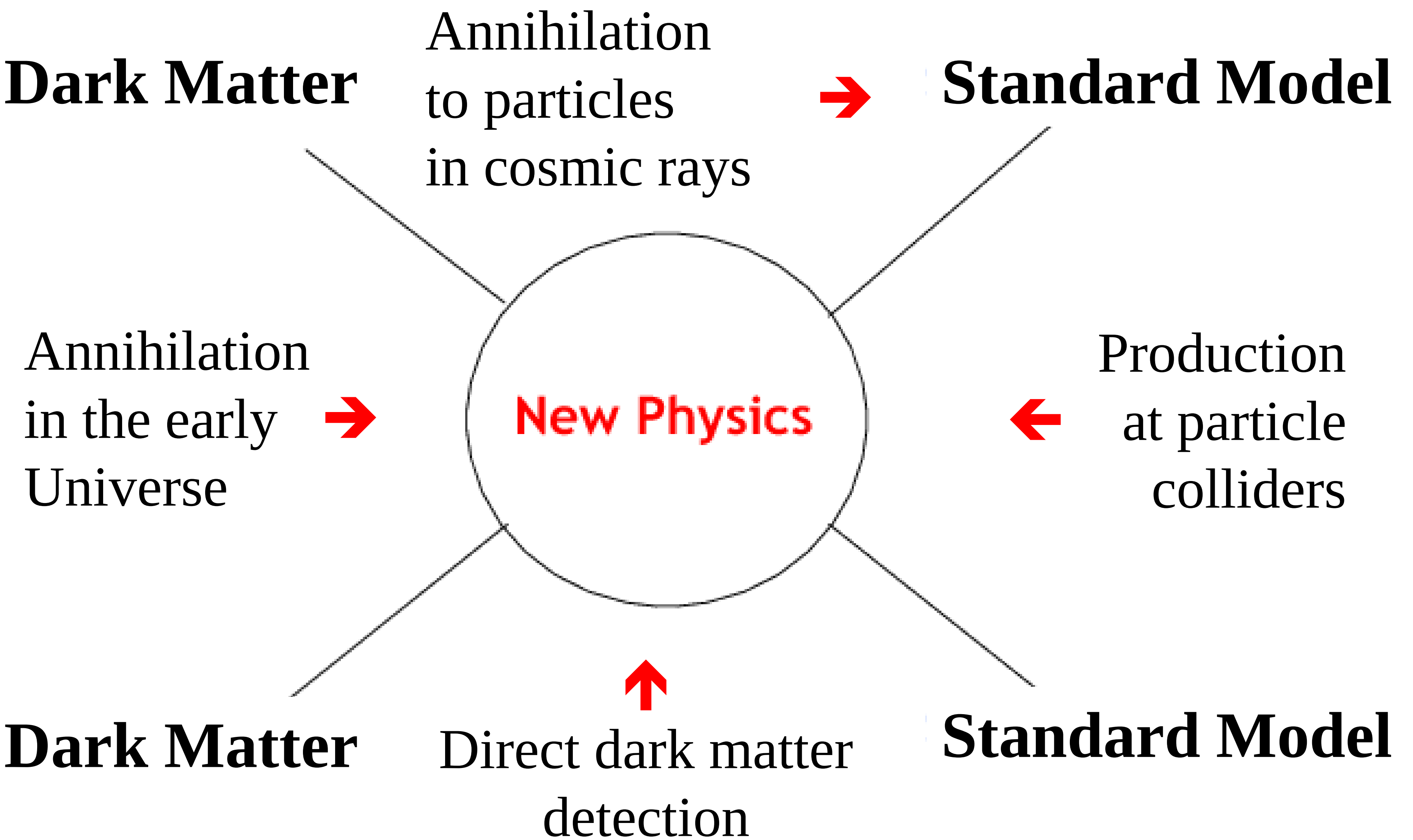
Astronomers say that most of the matter in the Universe is invisible Dark Matter



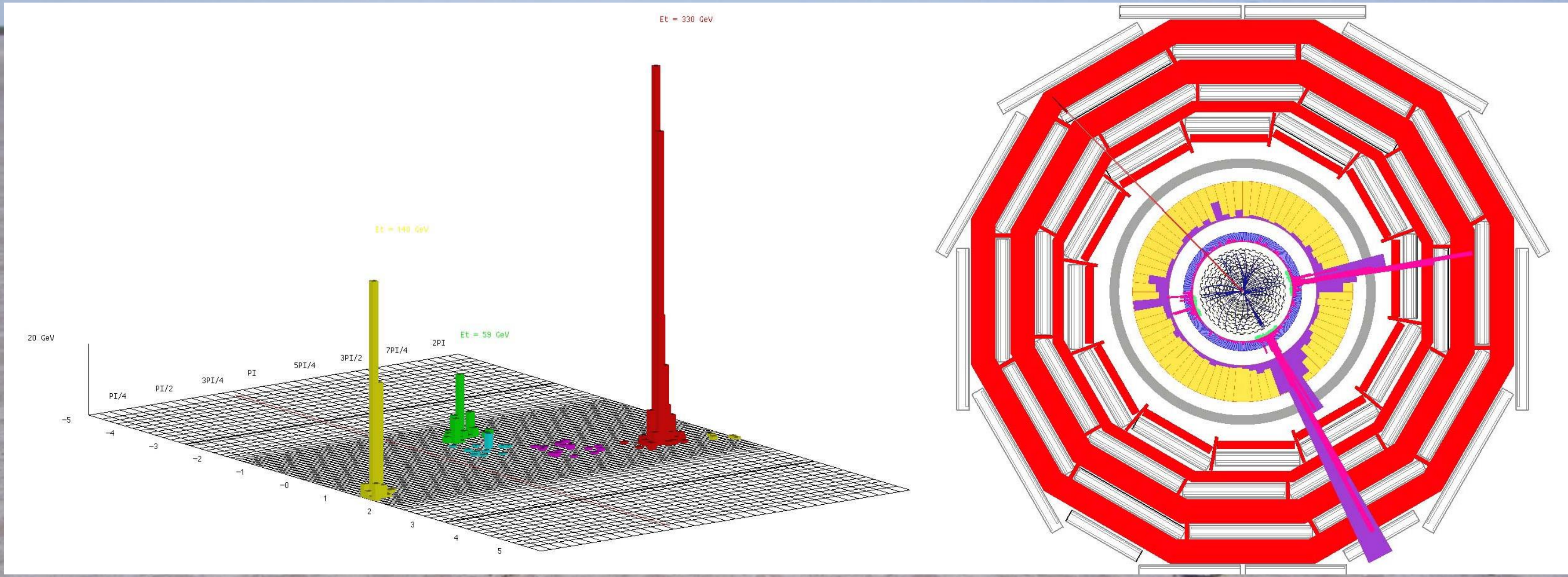
Made of unknown particles?

We are searching for them at the LHC

Searches for Dark Matter

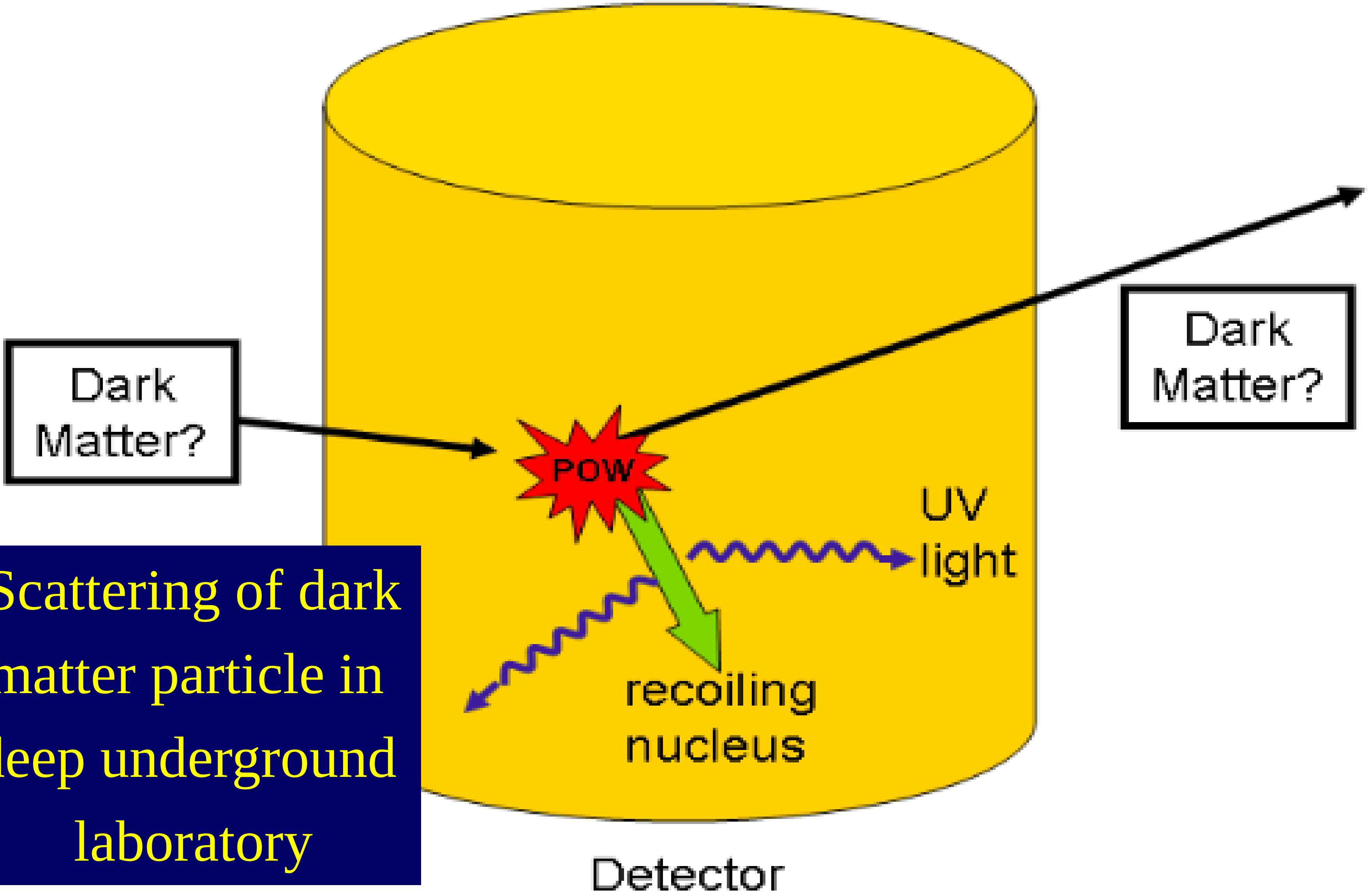


Classic Dark Matter Signature



Missing transverse energy carried away by dark matter particles

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, …

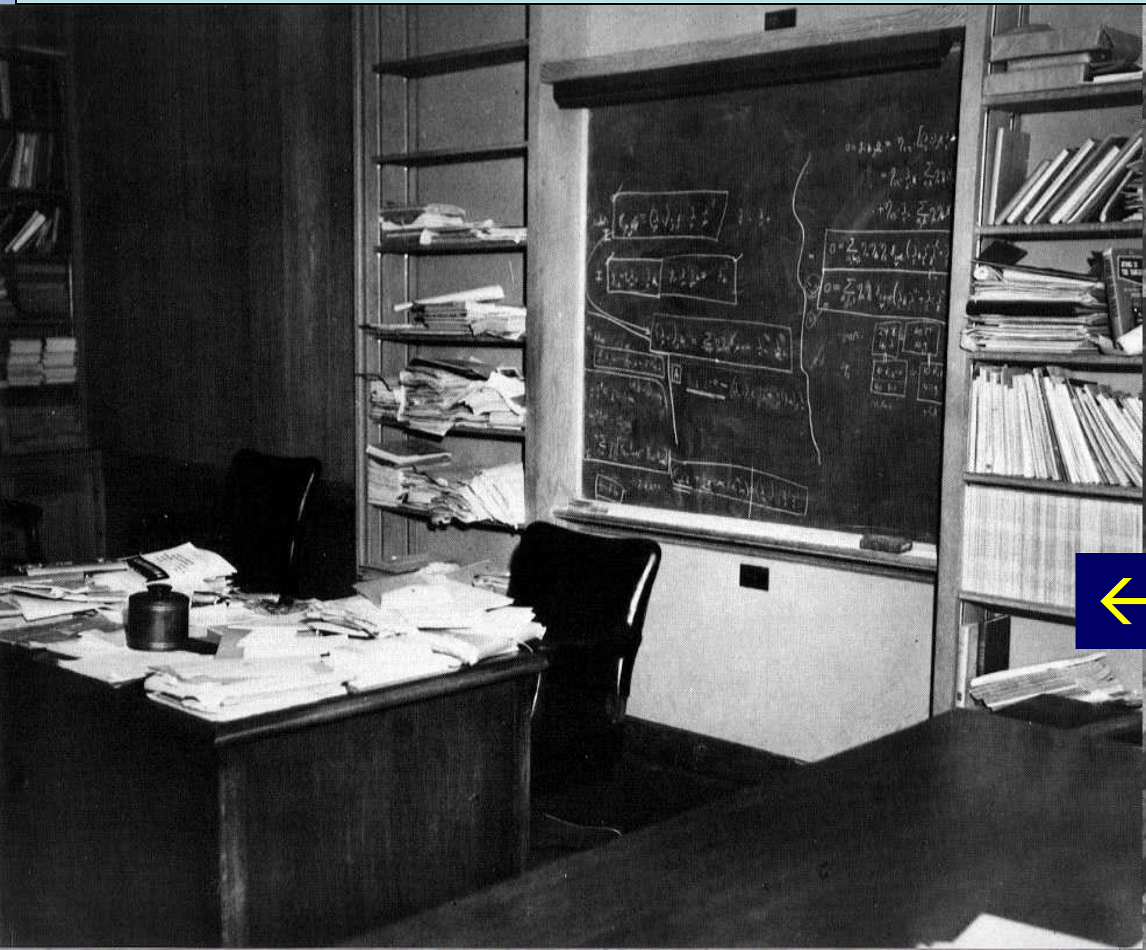
Discovered in cosmic rays
Studied using accelerators
Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

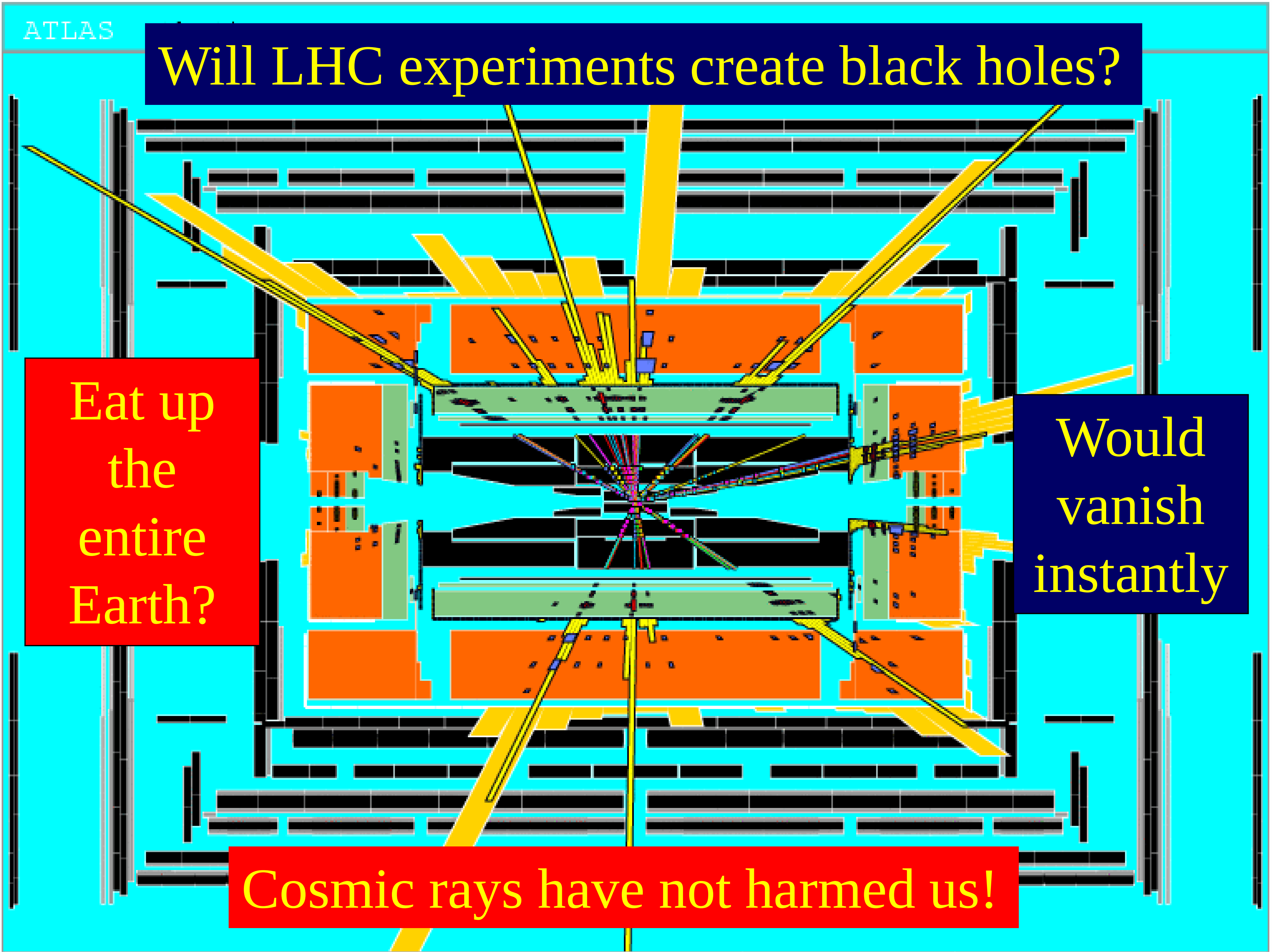
Experiments at LHC and elsewhere looking for answers

Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Unification via extra dimensions of space?


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


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