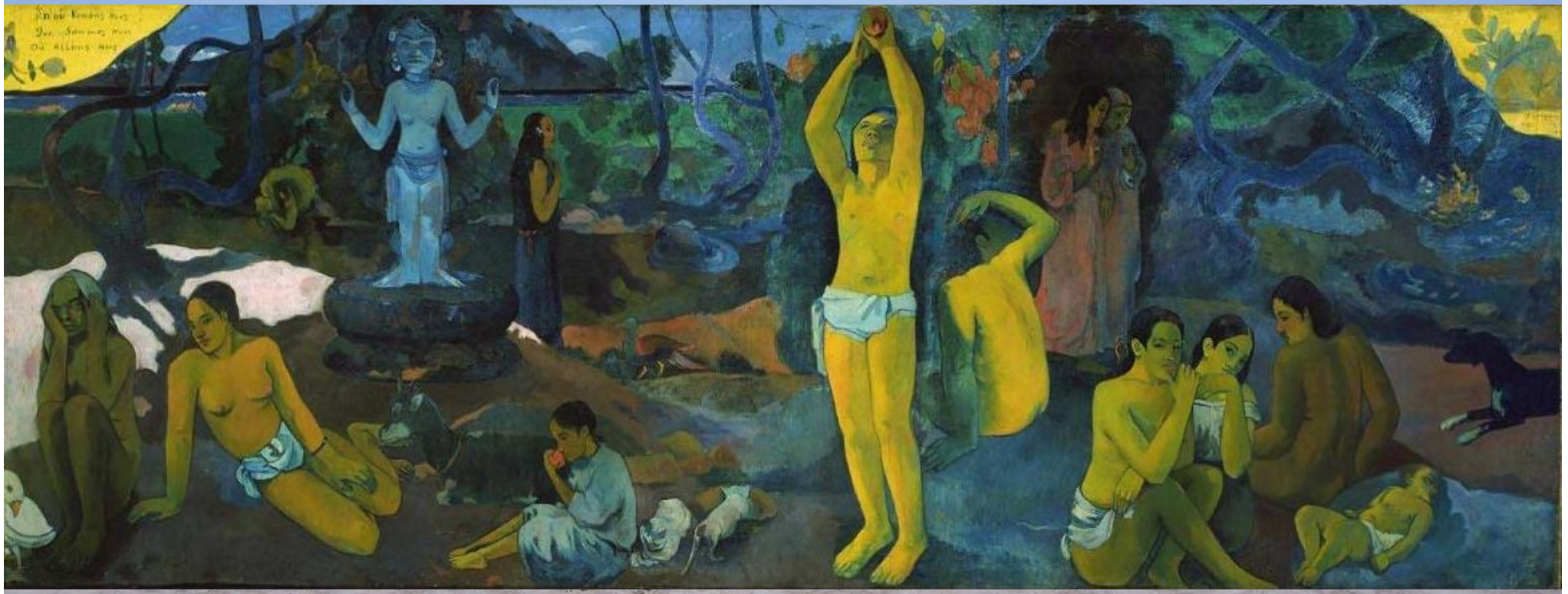
Answering Gauguin's Questions about the Universe



What are we?

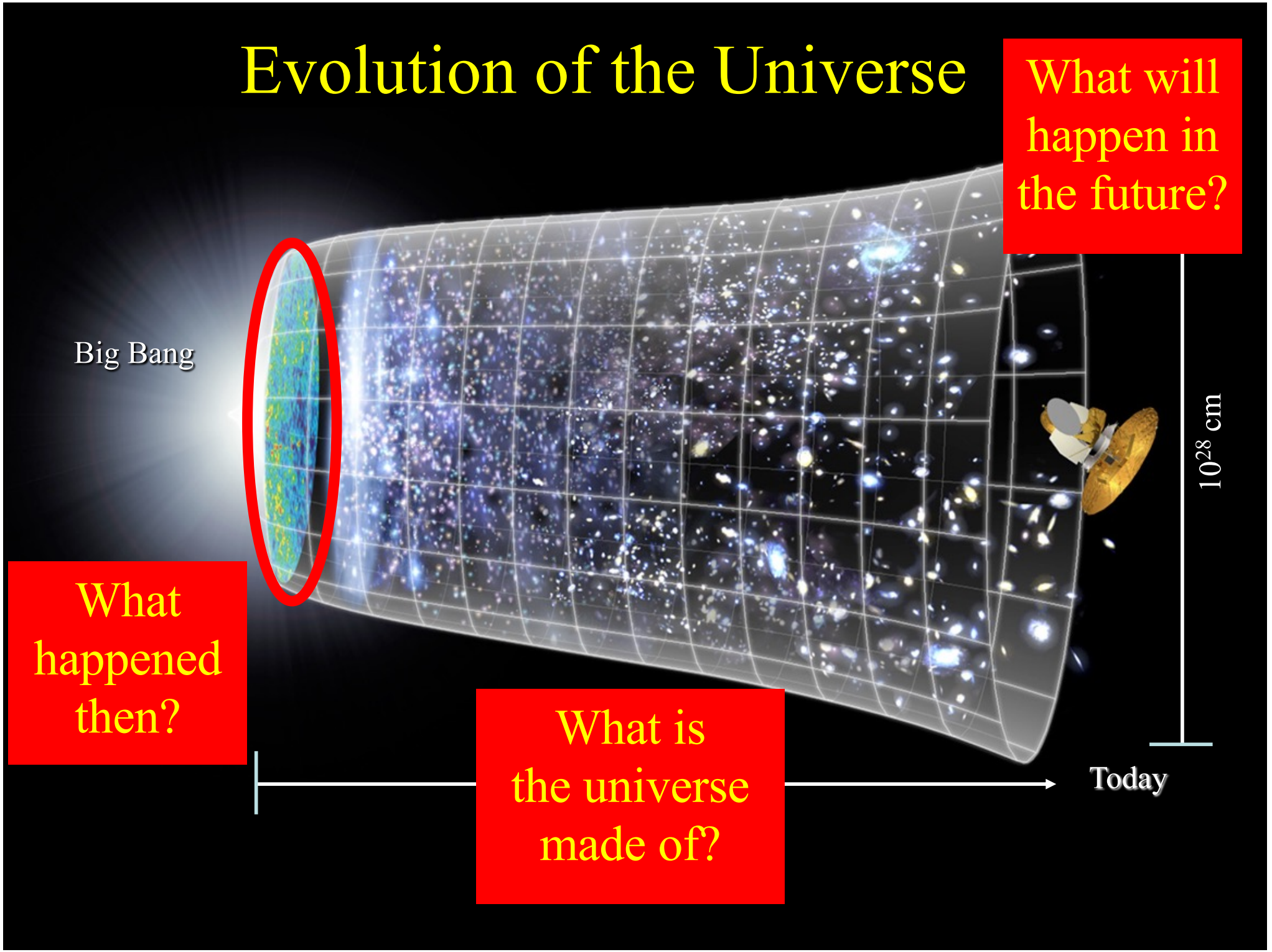
Where do we come from?

Where are we going?

John Ellis

KING'S College LONDON

Evolution of the Universe



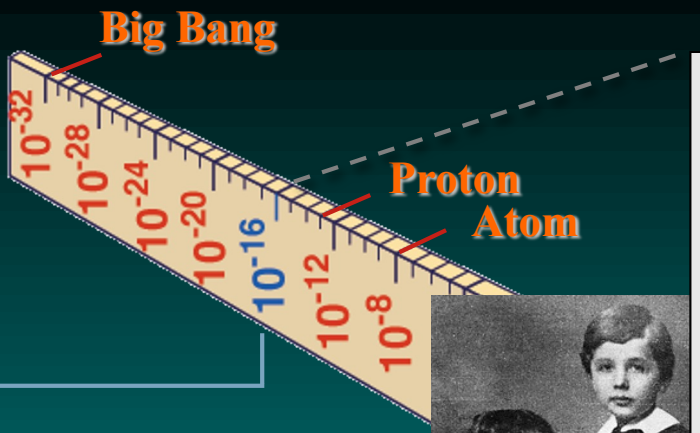
Gauguin's Questions in the Language of Particle Physics

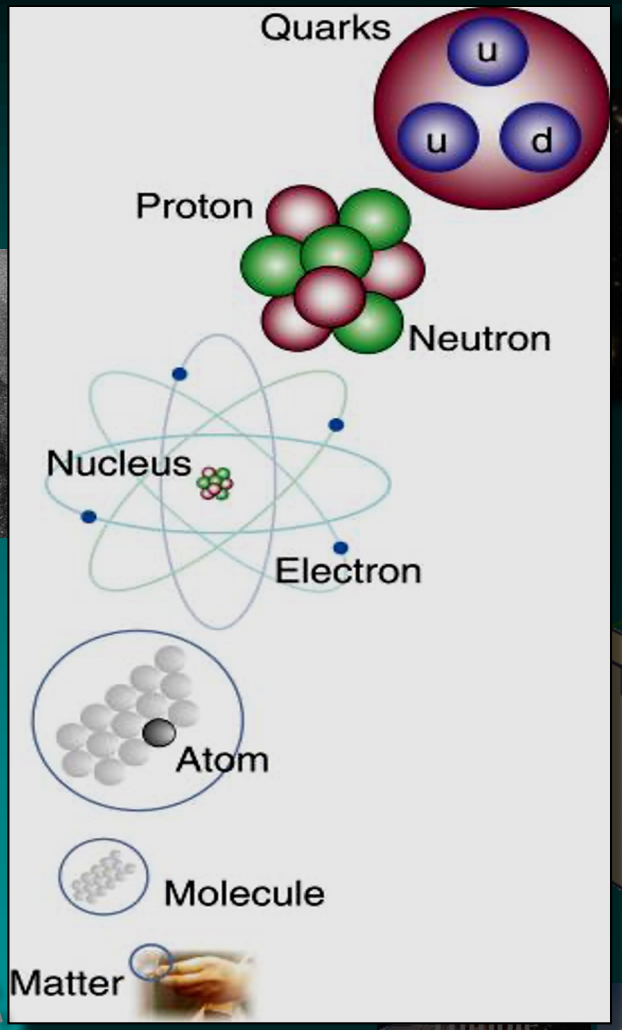
- What is matter made of?
  - Why do things weigh?

- 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





Radius of Galaxies

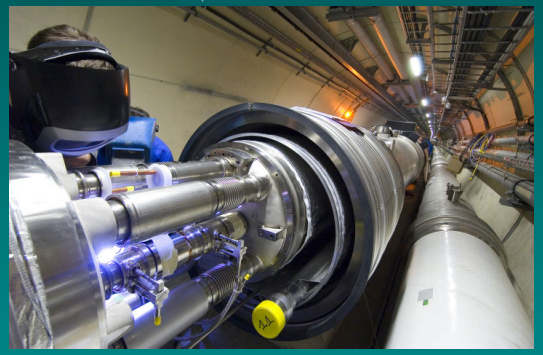
Universe

10^{24}

10^{28}

cm

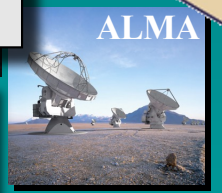
CERN



LHC

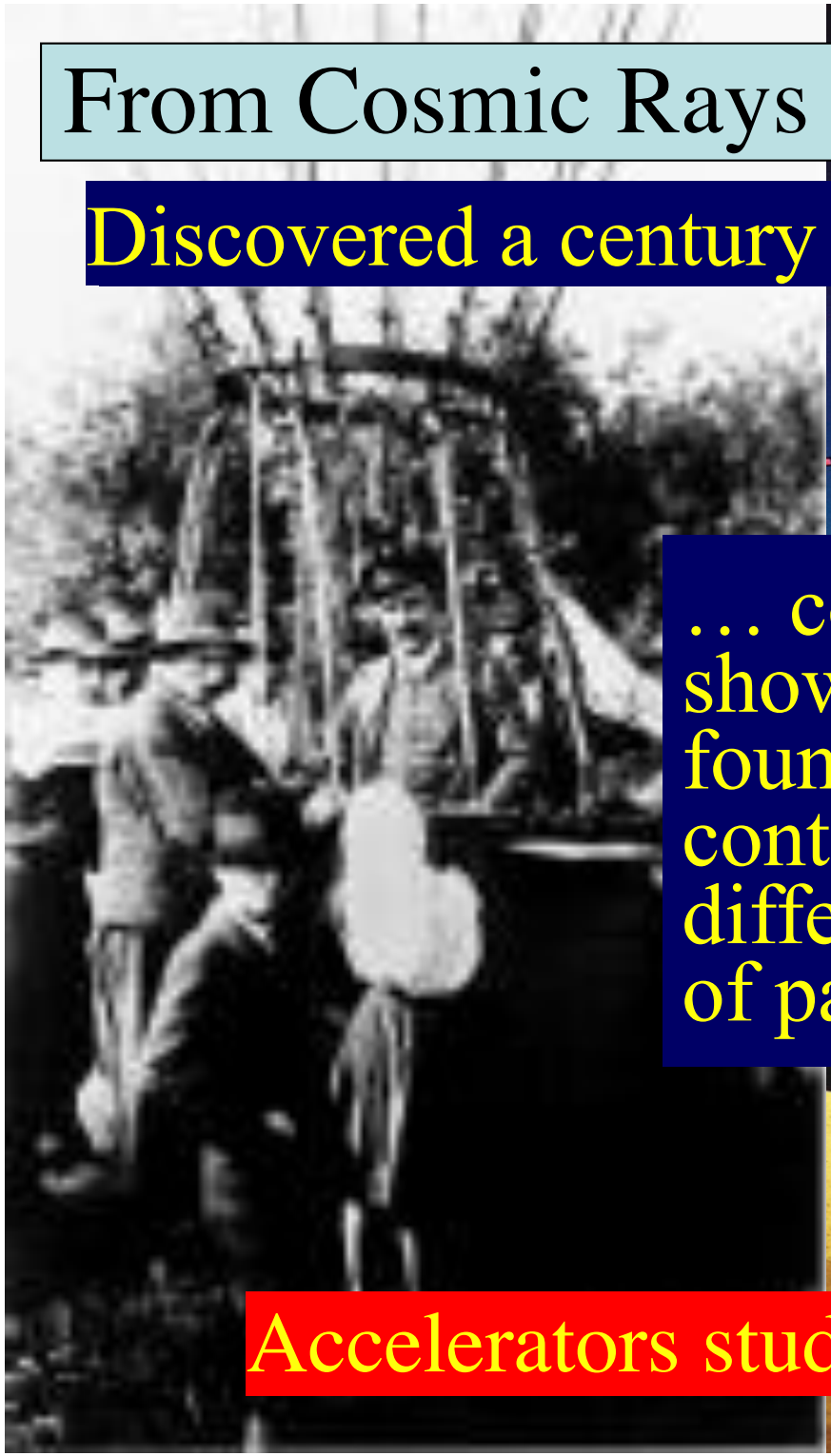
Super-Microscope

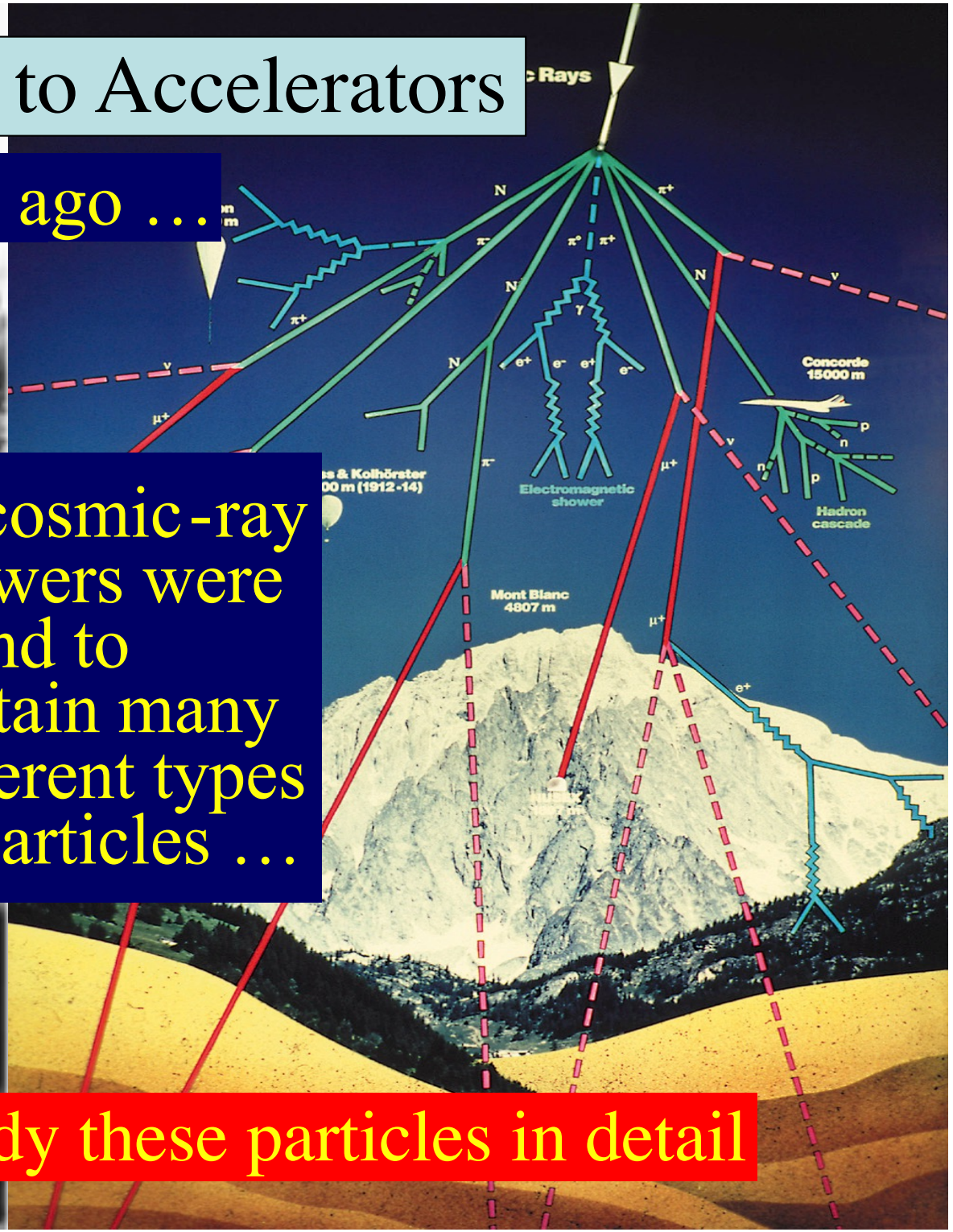
Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology



From Cosmic Rays to Accelerators

Discovered a century ago …



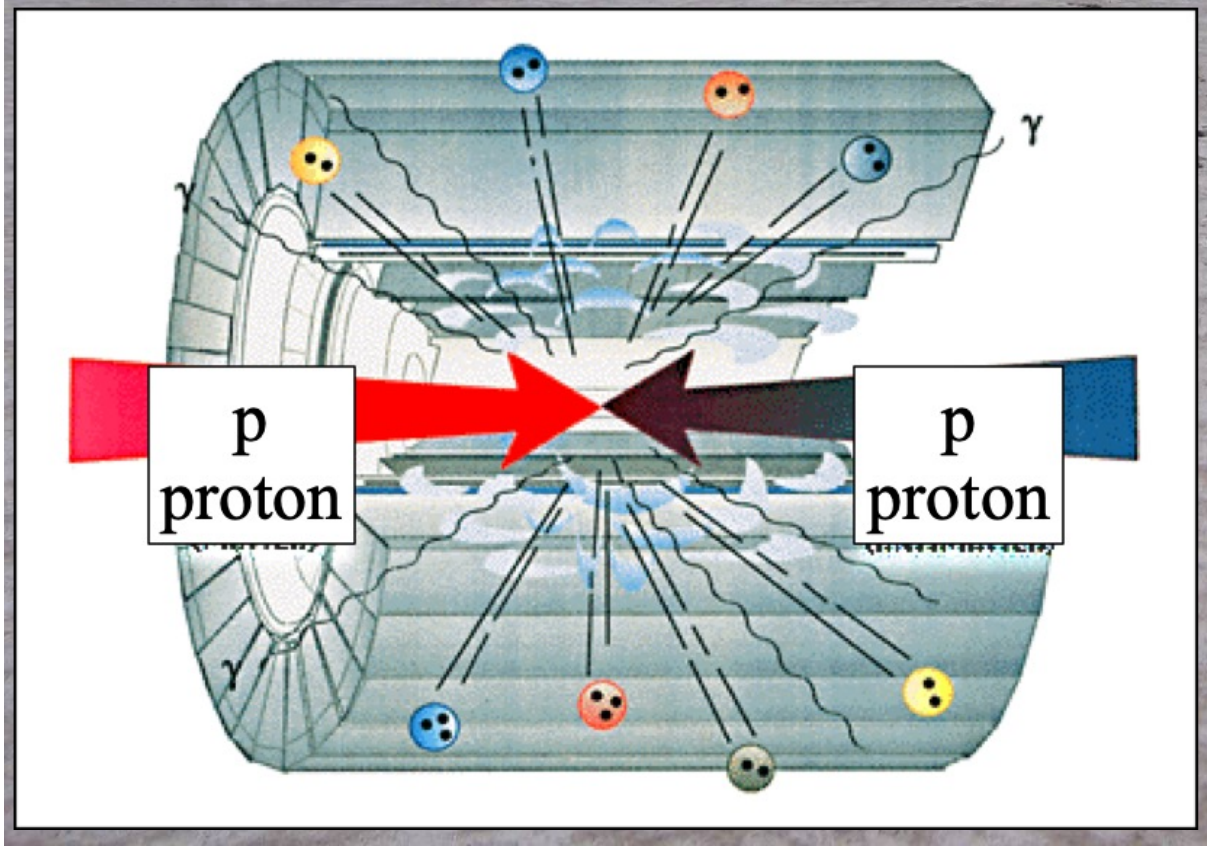


… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

Experiments with Accelerators

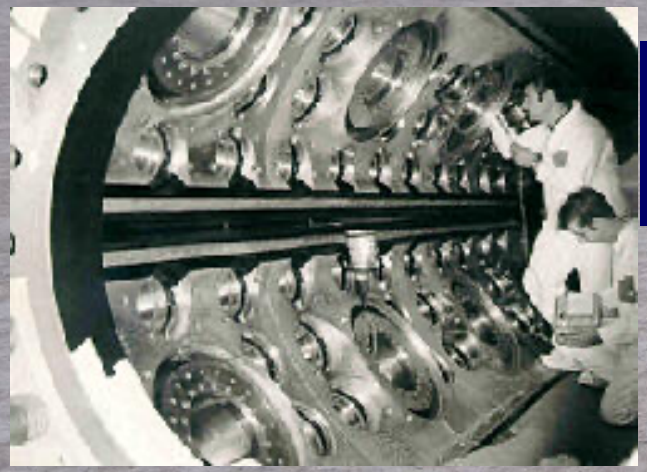
In order to study particles, we need super-microscopes using high energies to probe small distances:
Particle Colliders



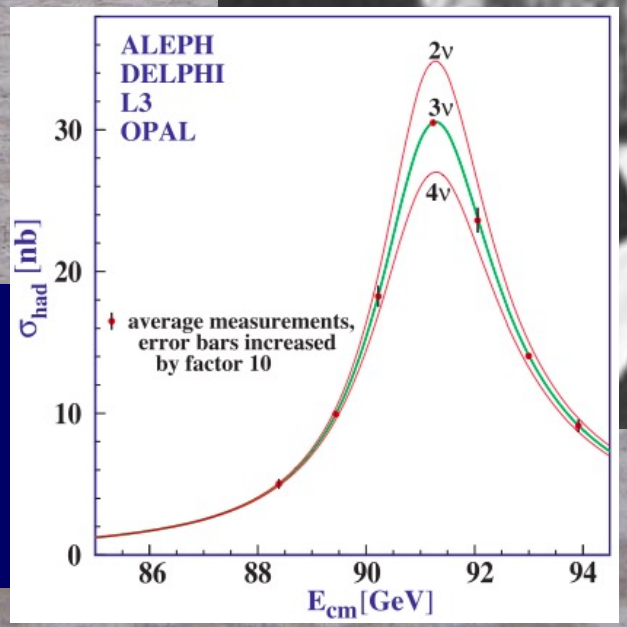
Collisions reproduce the conditions at beginning of Big Bang

The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

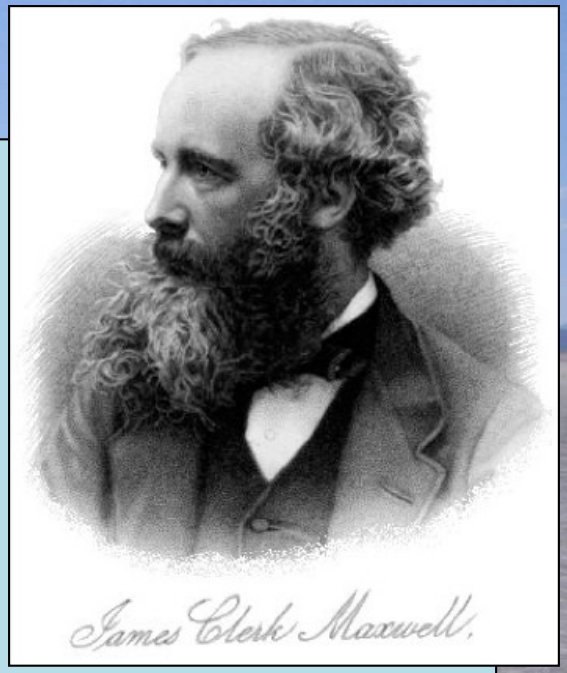


Tested by experiments at CERN



Perfect agreement between theory and experiments in all laboratories

James Clerk Maxwell



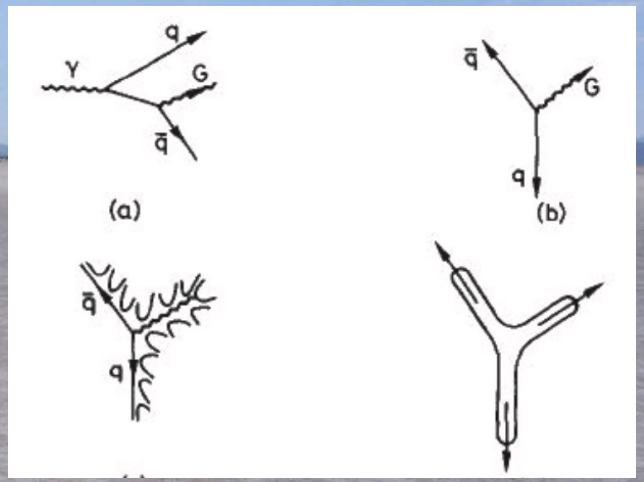
- Professor at King's 1860 – 1865
- The first colour photograph
- **Unified theory of electricity and magnetism**
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- …

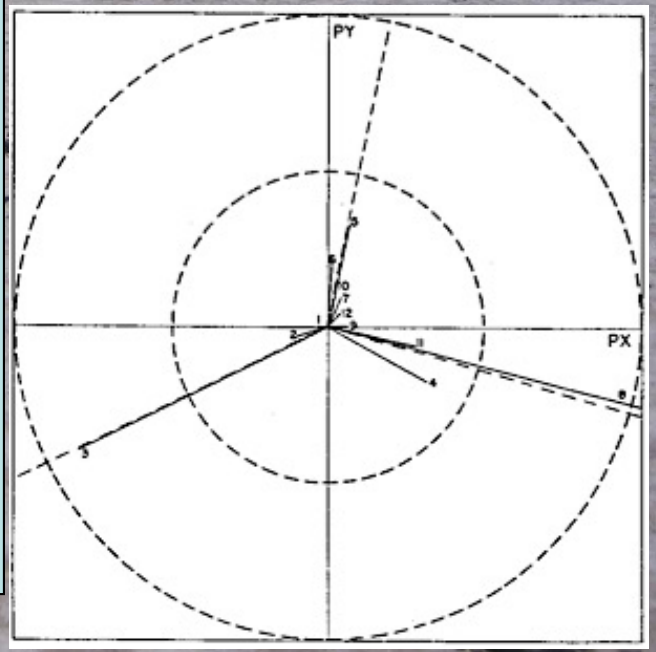
KING'S College LONDON

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

Strong Nuclear Interactions

- Theory modelled after Maxwell
- Carried by massless ‘gluons’, analogues of photon
- JE, Mary Gaillard, Graham Ross suggested discovery method in 1976
- Radiation of gluon by quark
- Discovered at DESY laboratory in Hamburg in 1979
- **Second force particle discovered**



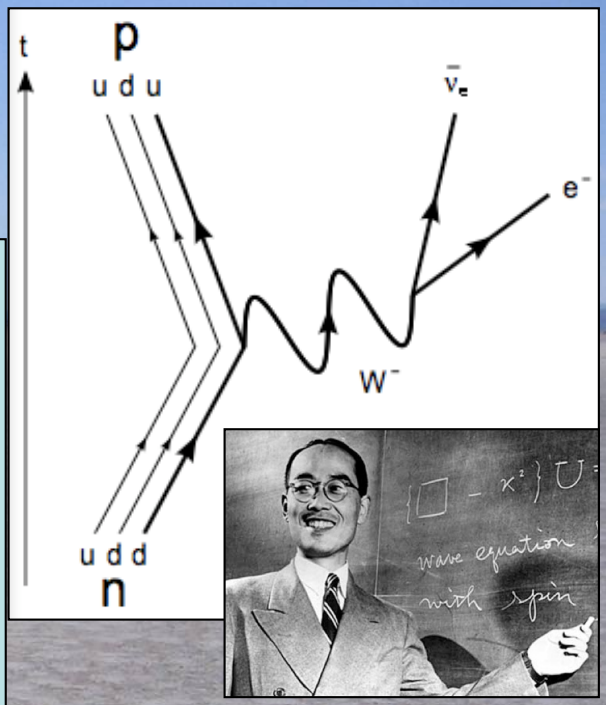


Weak Interactions

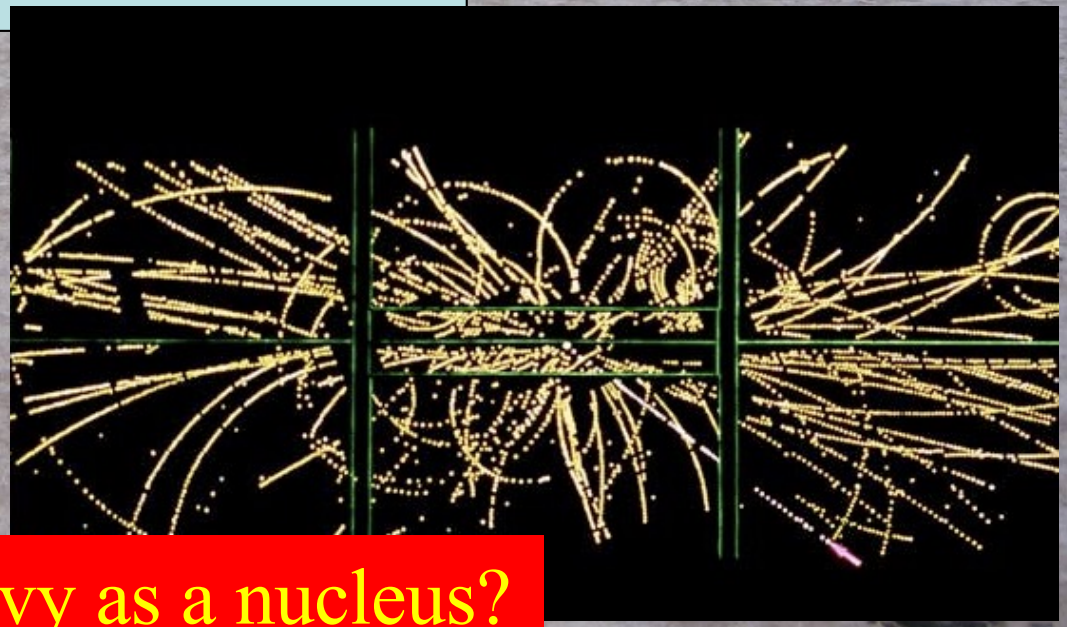
Radioactivity due to weak interactions
(β decay)

W boson - carrier of weak interaction

postulated by Yukawa



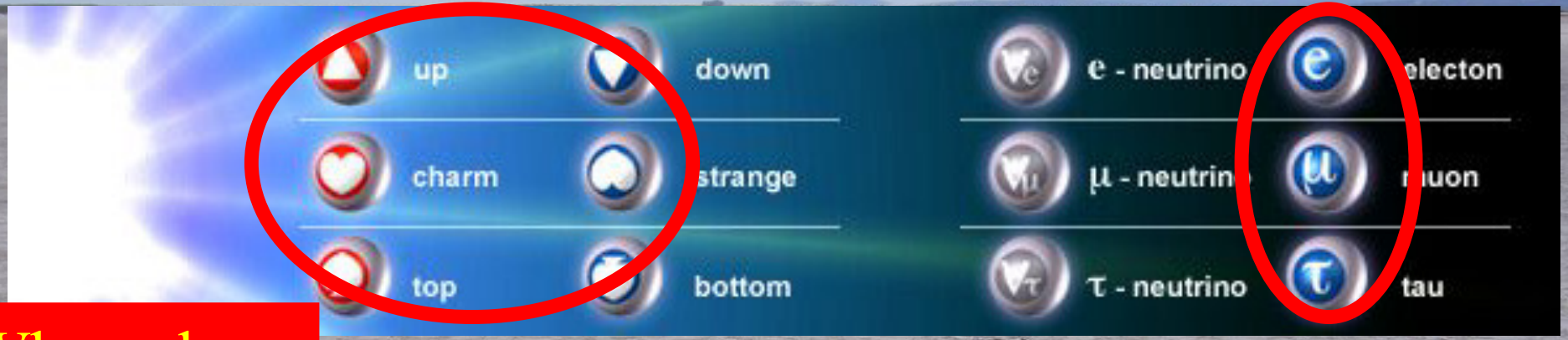
Discovered at CERN in
1983 by Carlo Rubbia et al



Why is it as heavy as a nucleus?

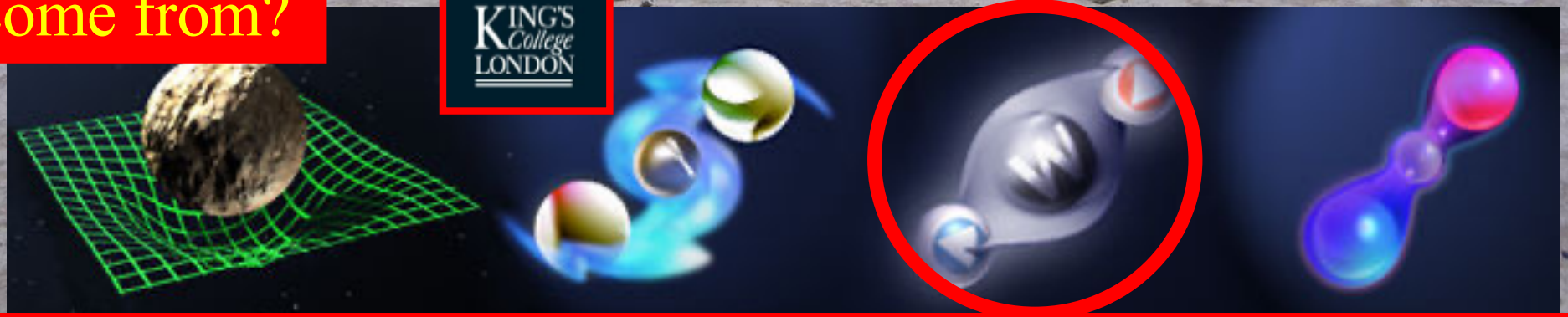
The ‘Standard Model’

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

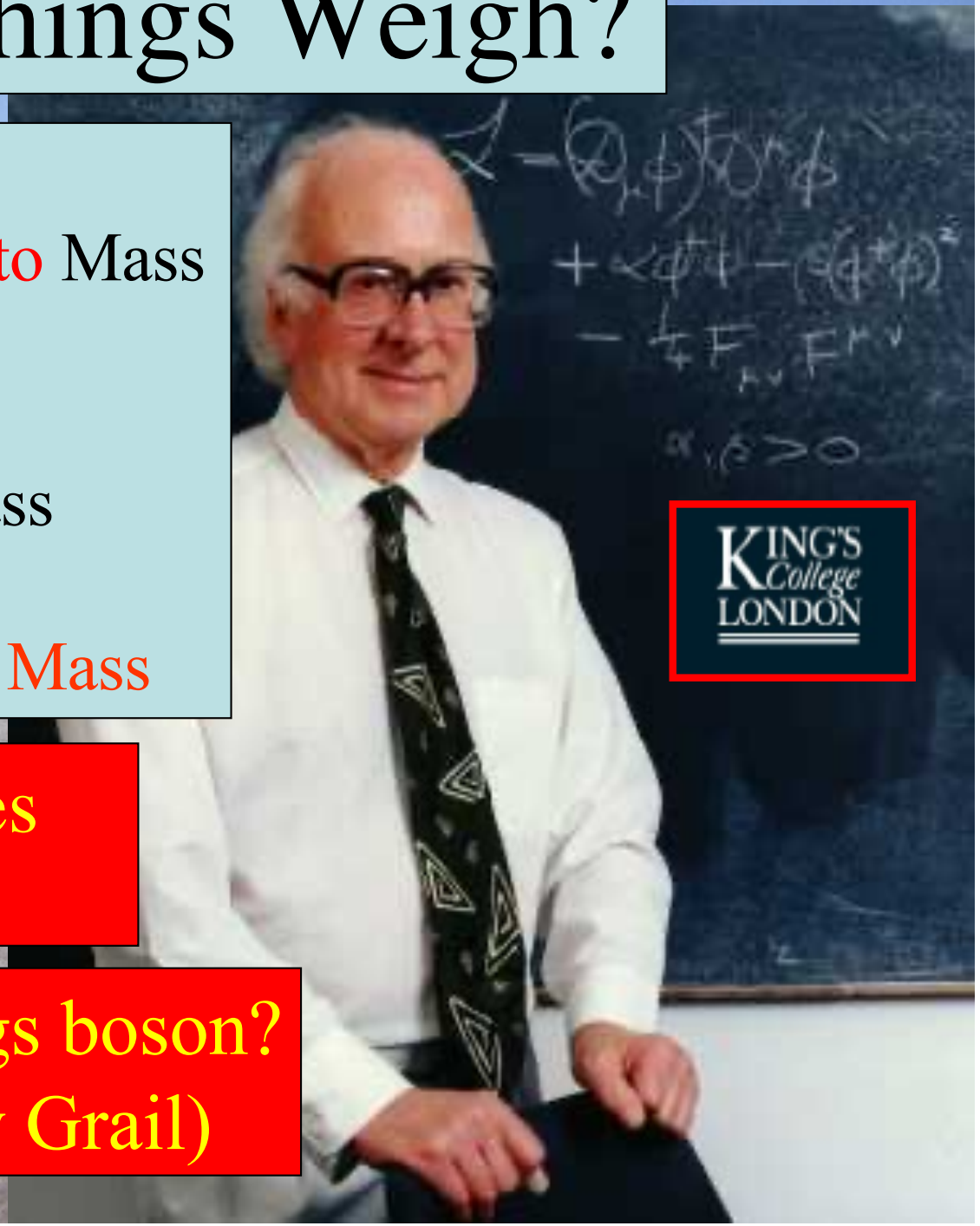
Newton:

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

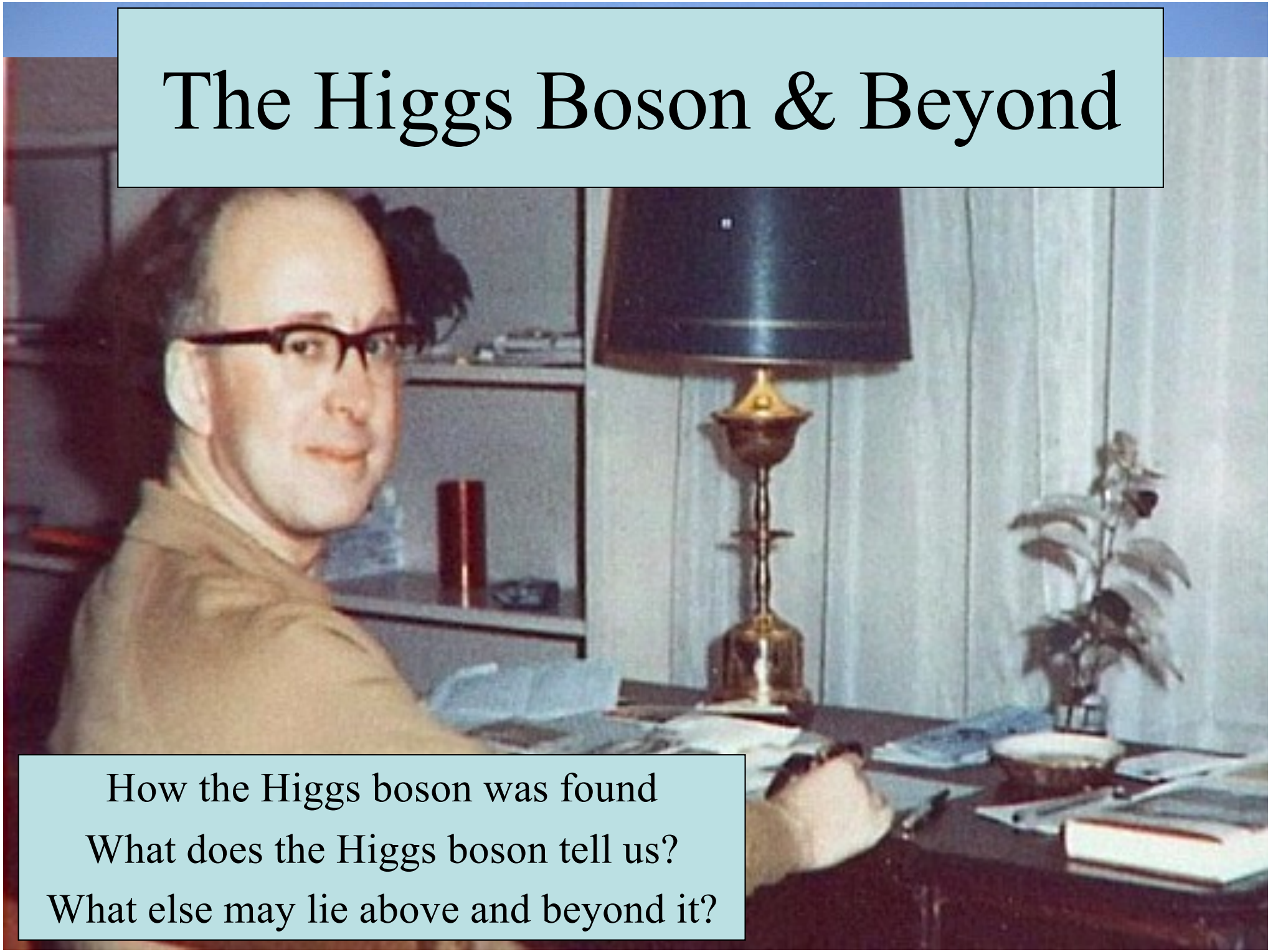
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

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

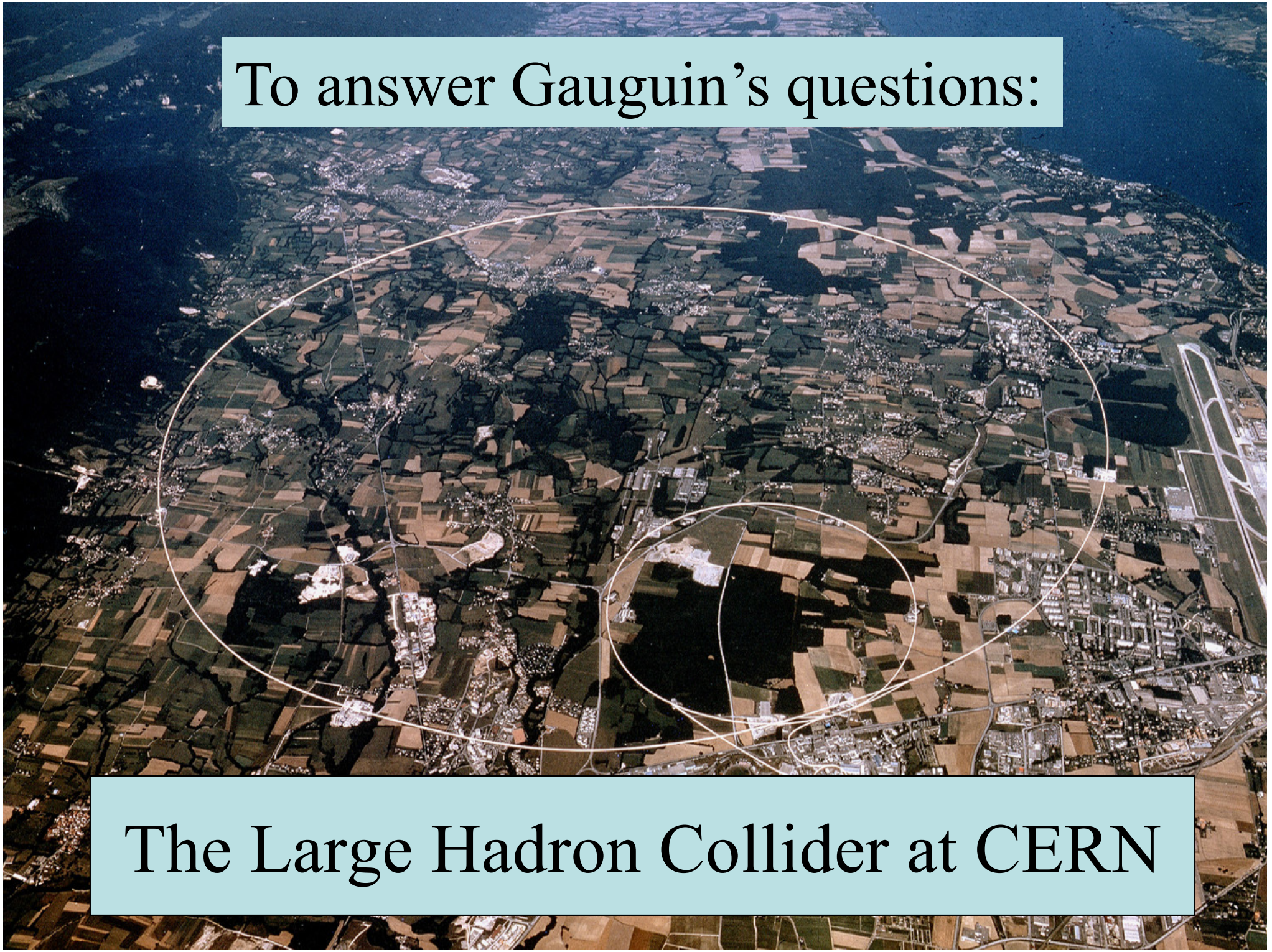
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

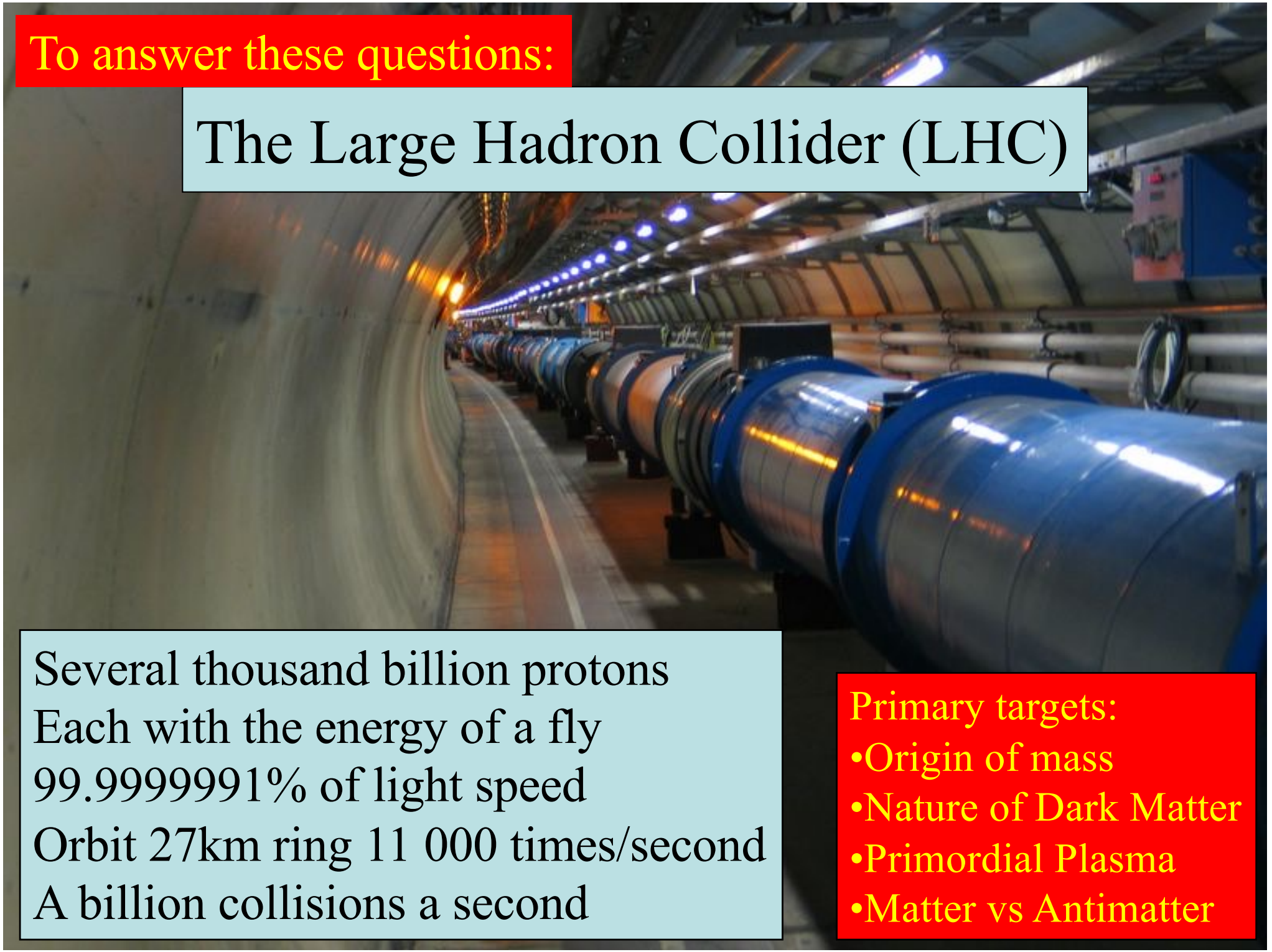
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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



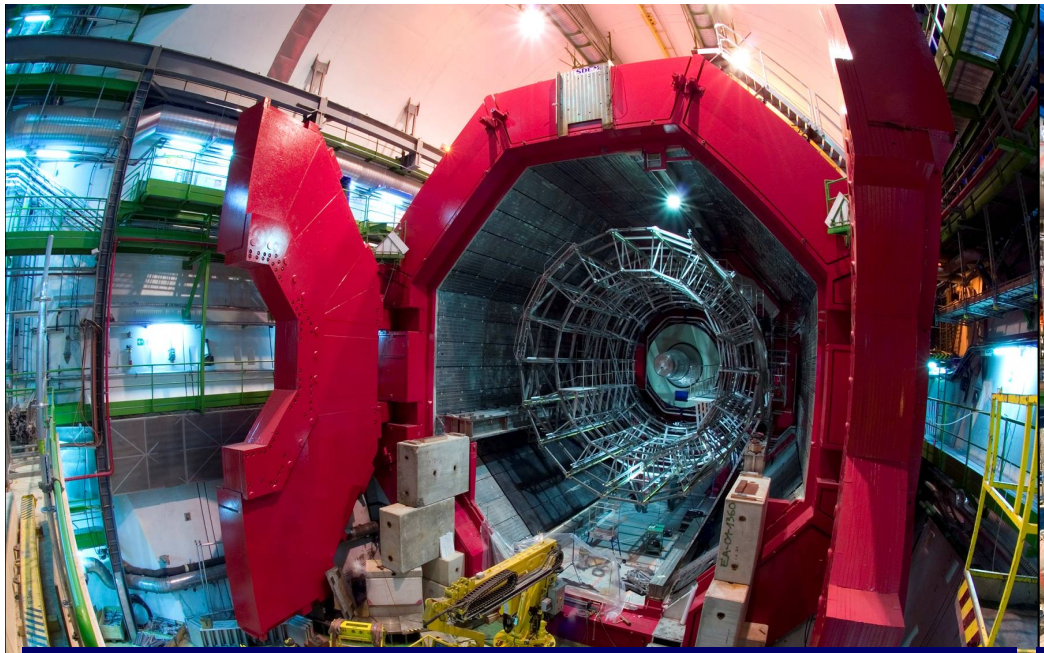
To answer these questions:

The Large Hadron Collider (LHC)

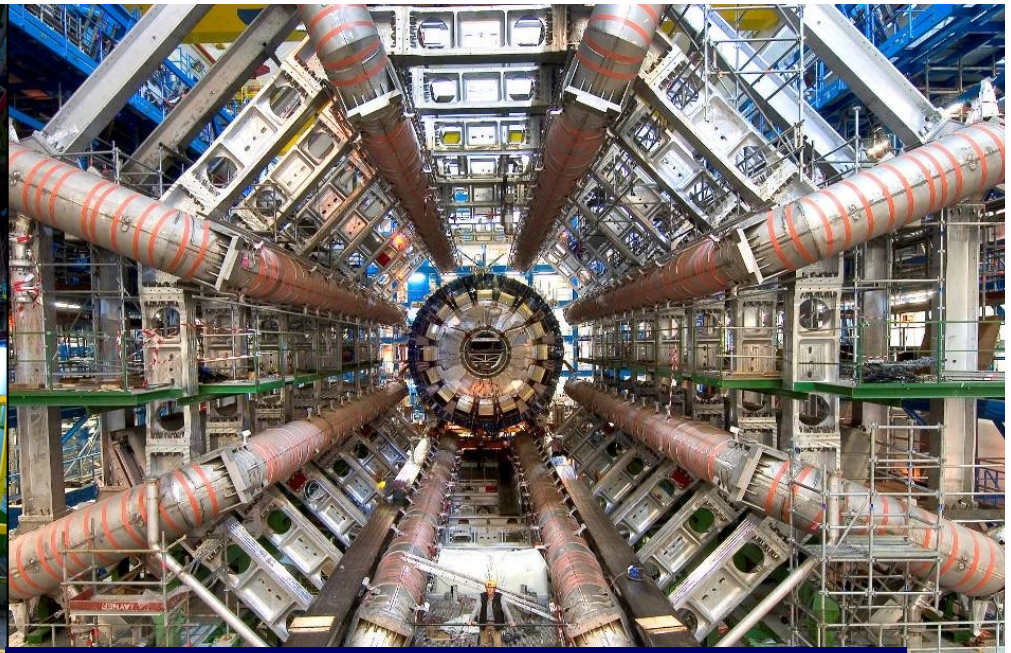
Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:

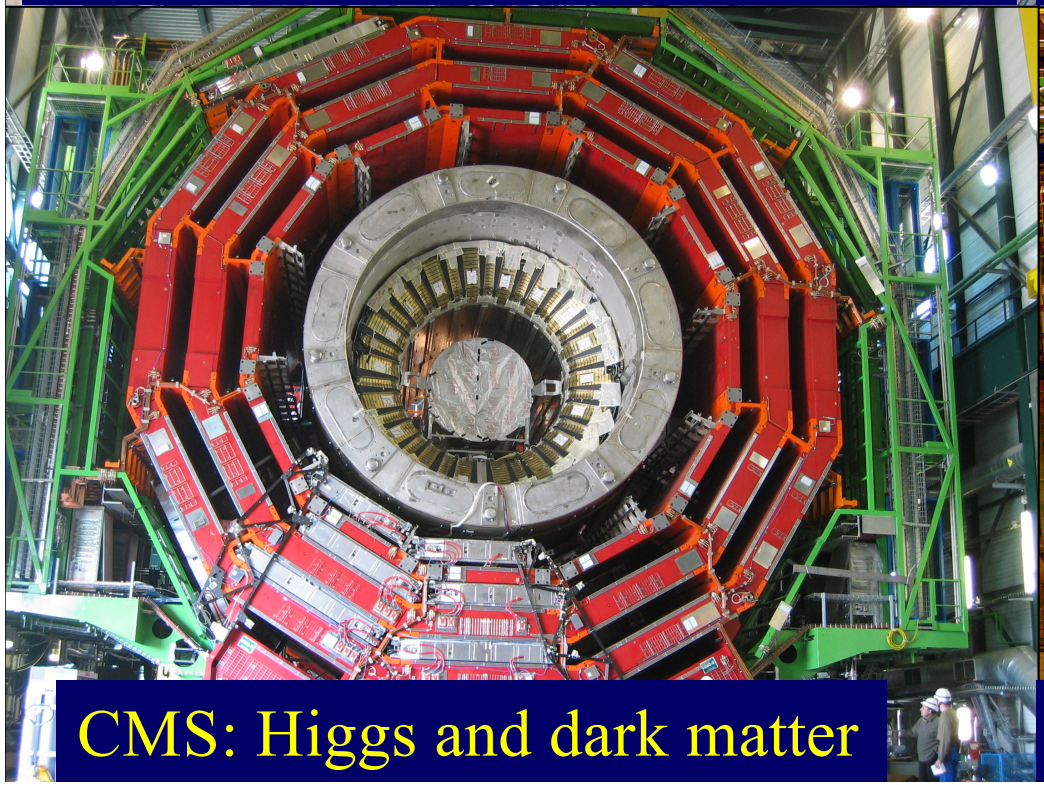
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



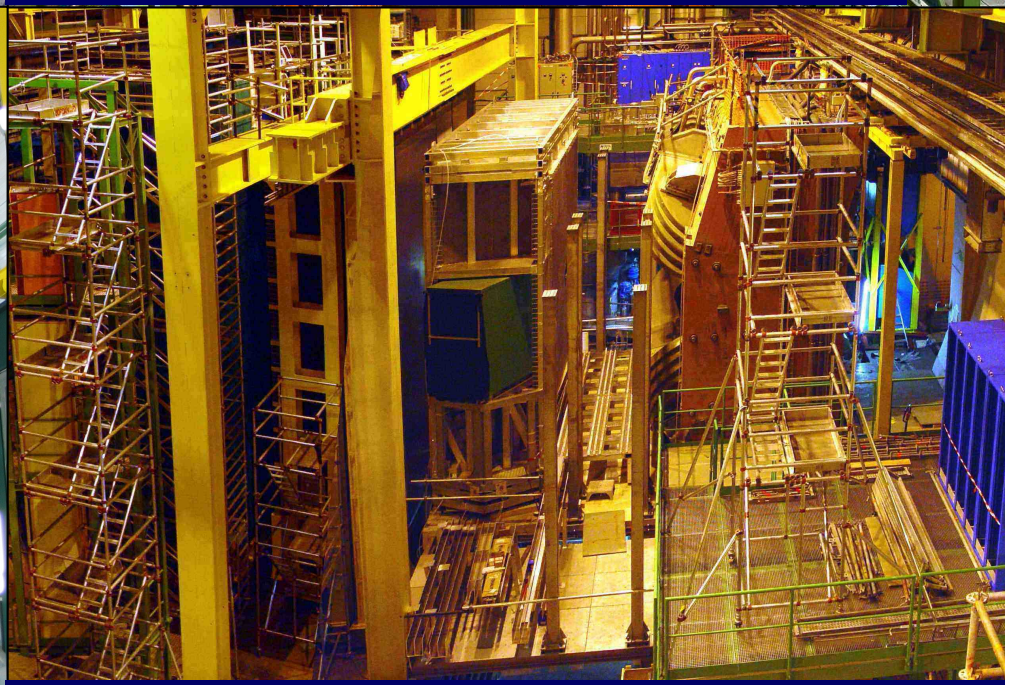
ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

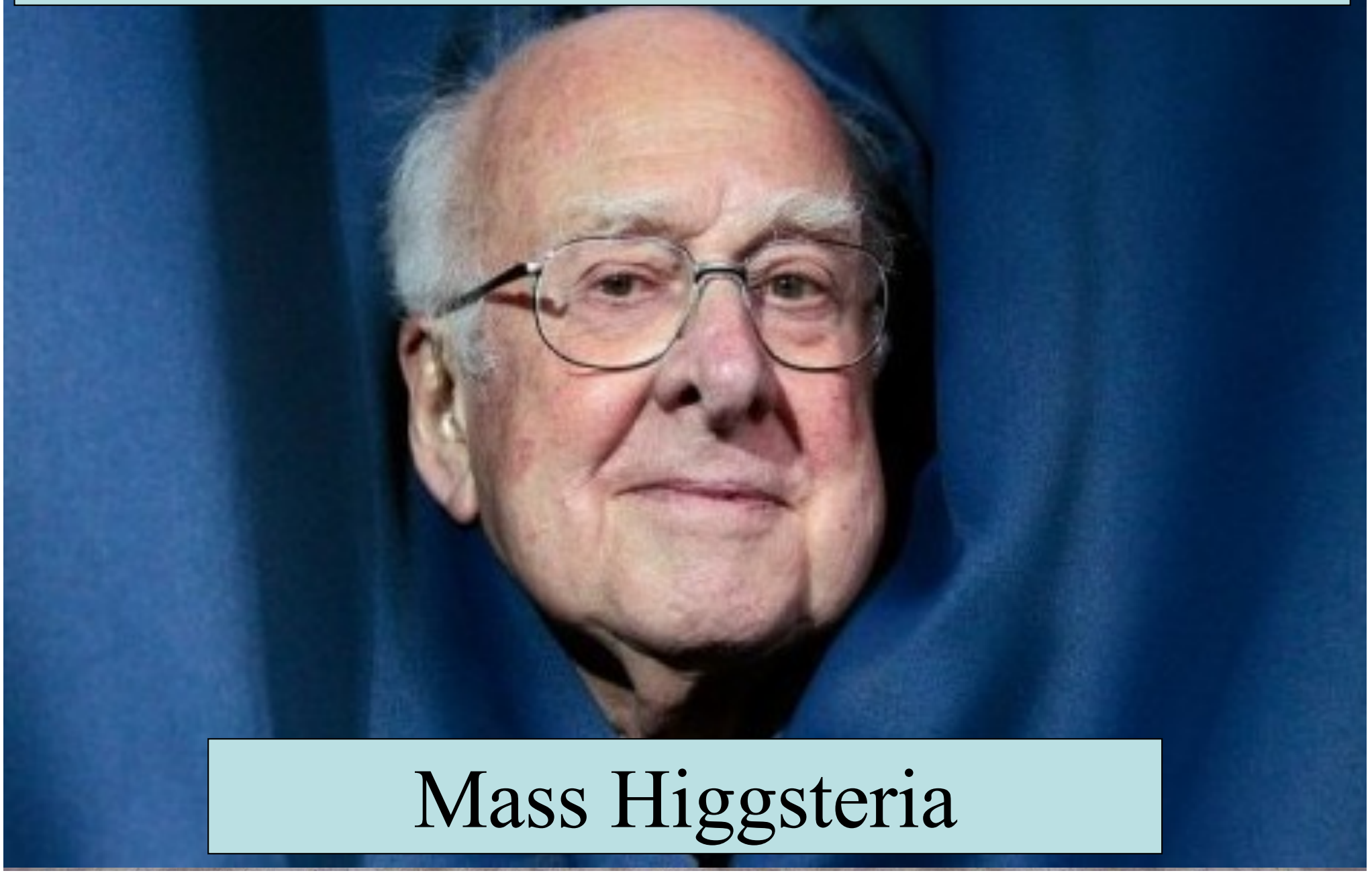


CMS: Higgs and dark matter



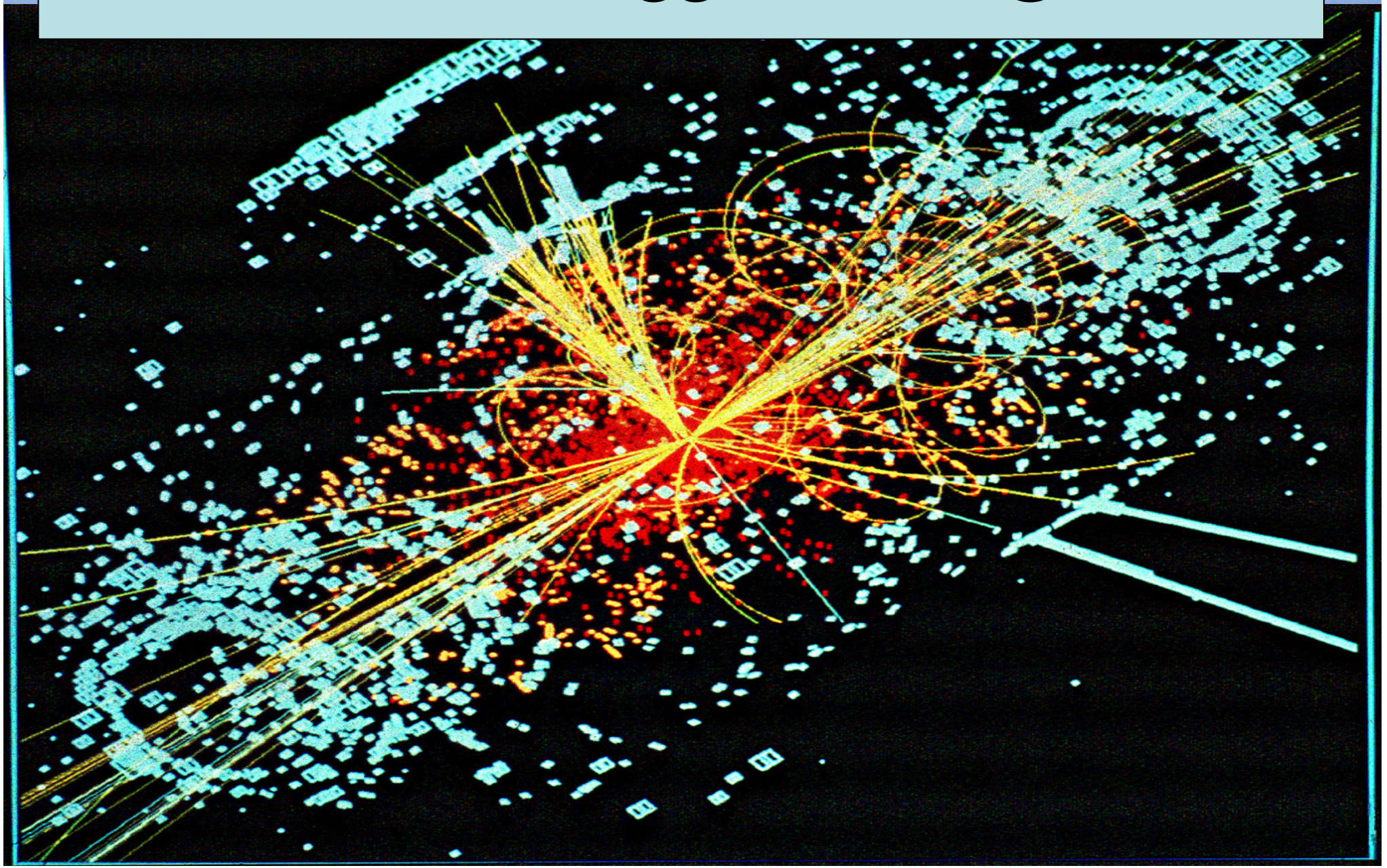
LHCb: Matter-antimatter difference

2012: The discovery of the Higgs Boson

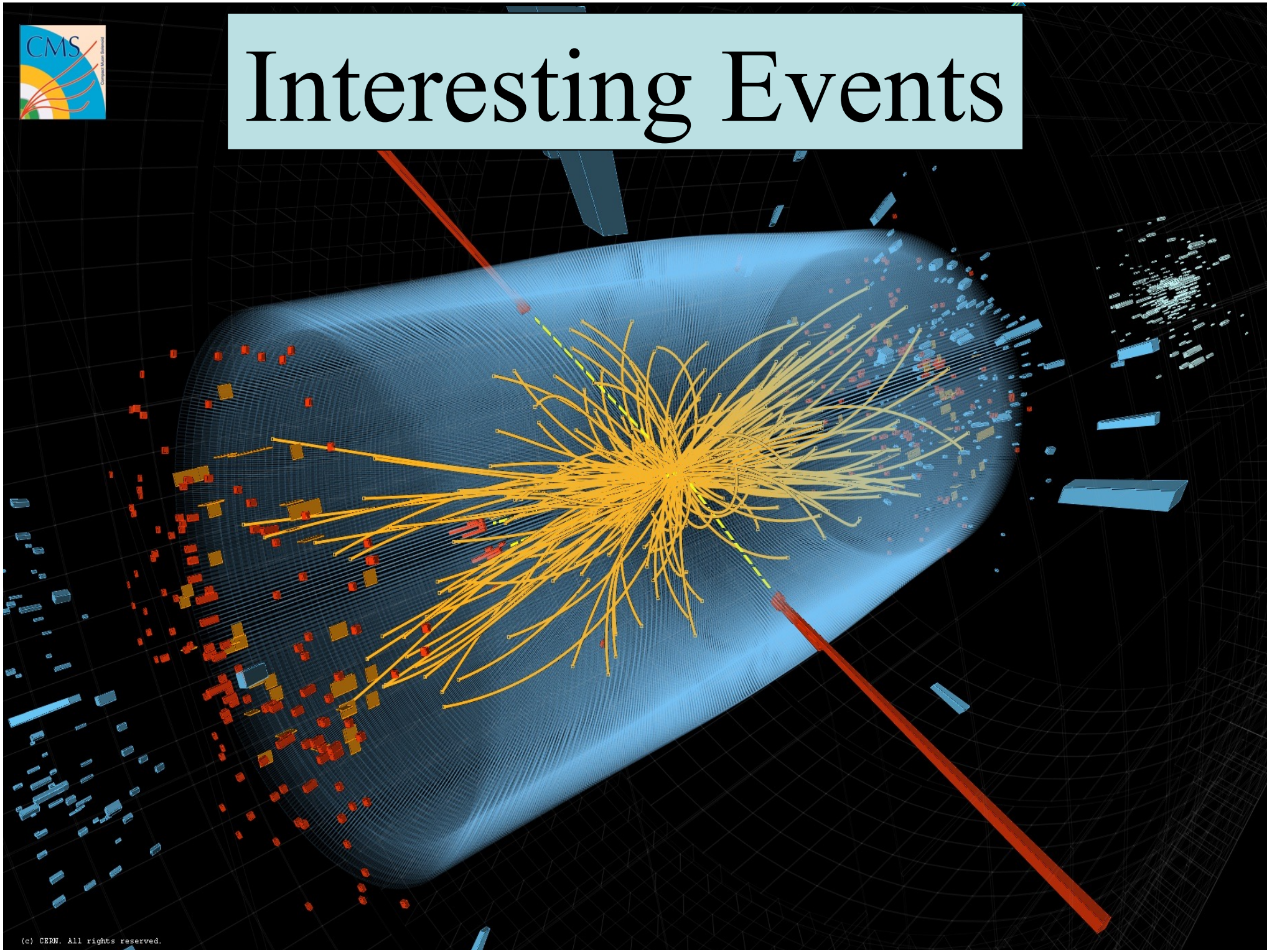


Mass Higgsteria

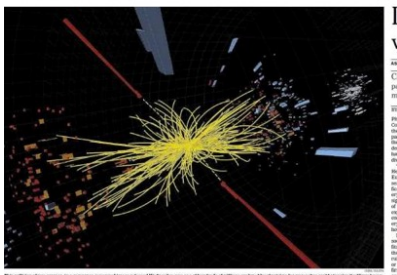
A Simulated Higgs Event @ LHC



Interesting Events



July 4th 2012
The discovery of a new particle



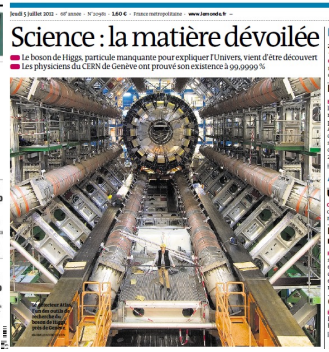
Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

ヒッグス粒子 発見か

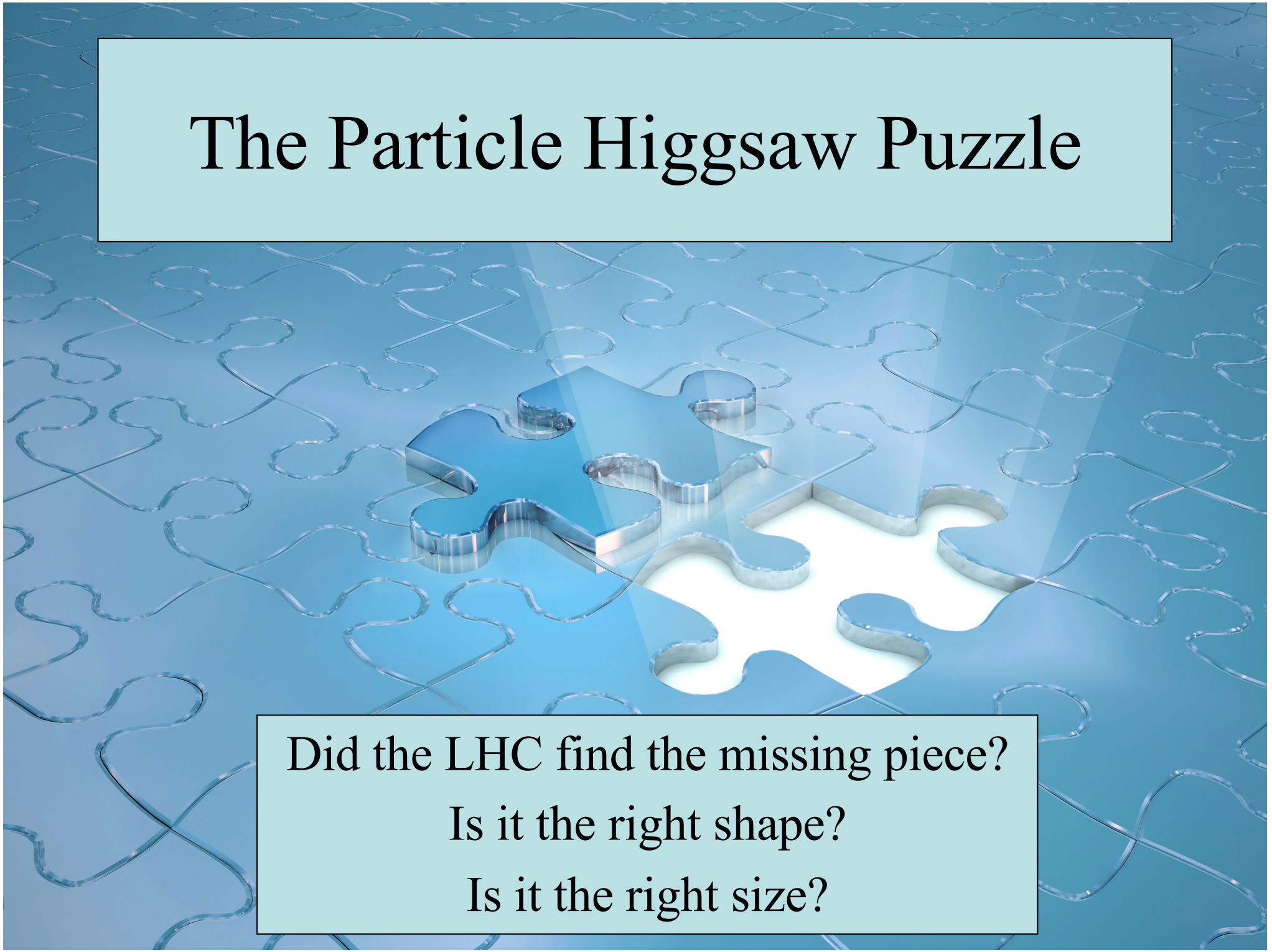
年内に結論

日米欧2チーム



Higgsdependence Day!

The Particle Higgsaw Puzzle



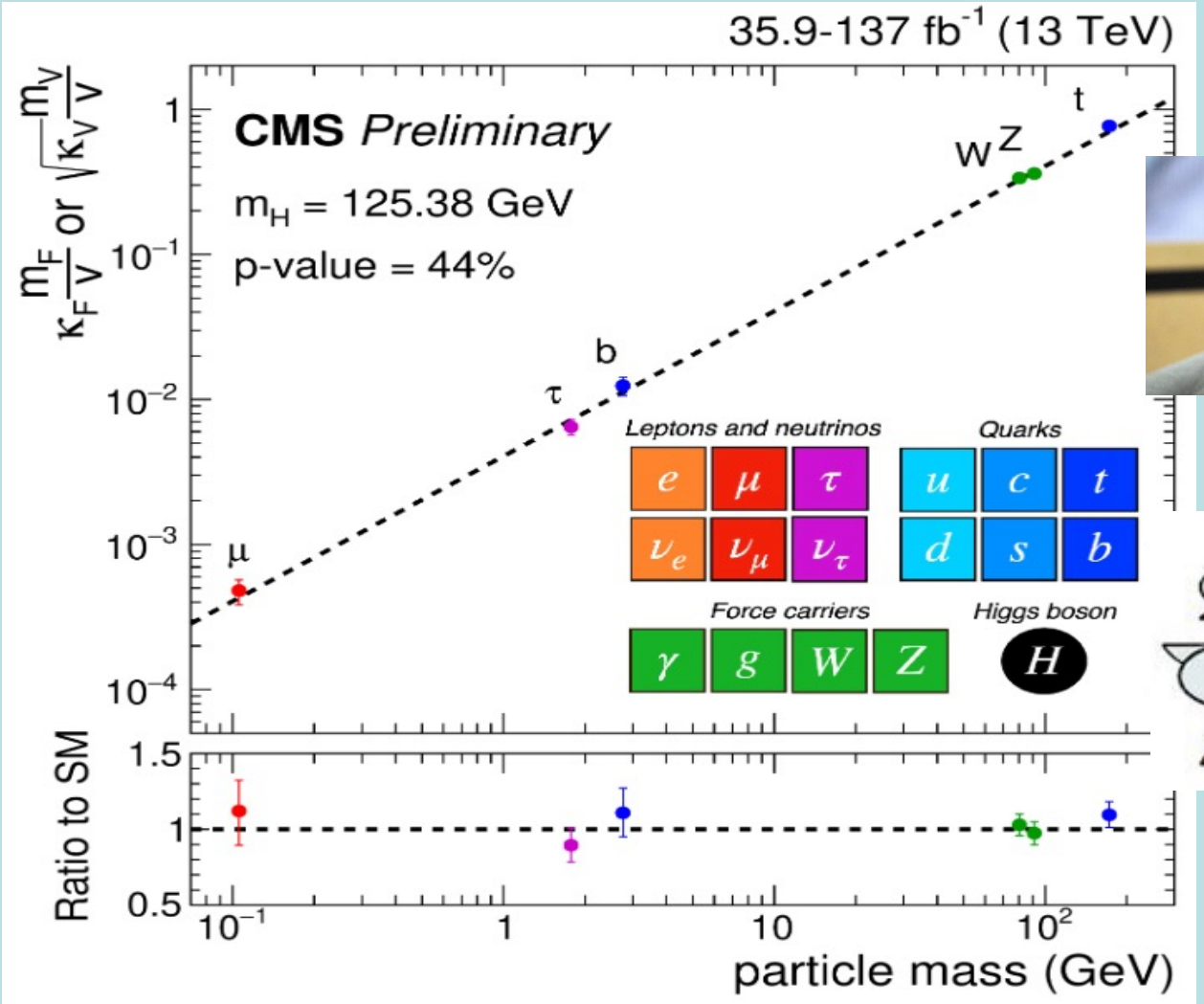
Did the LHC find the missing piece?

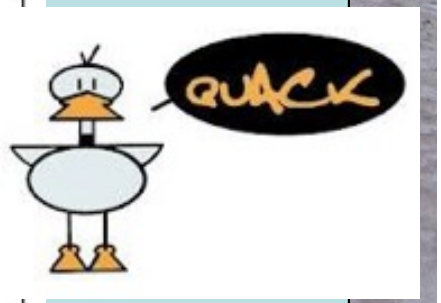
Is it the right shape?

Is it the right size?

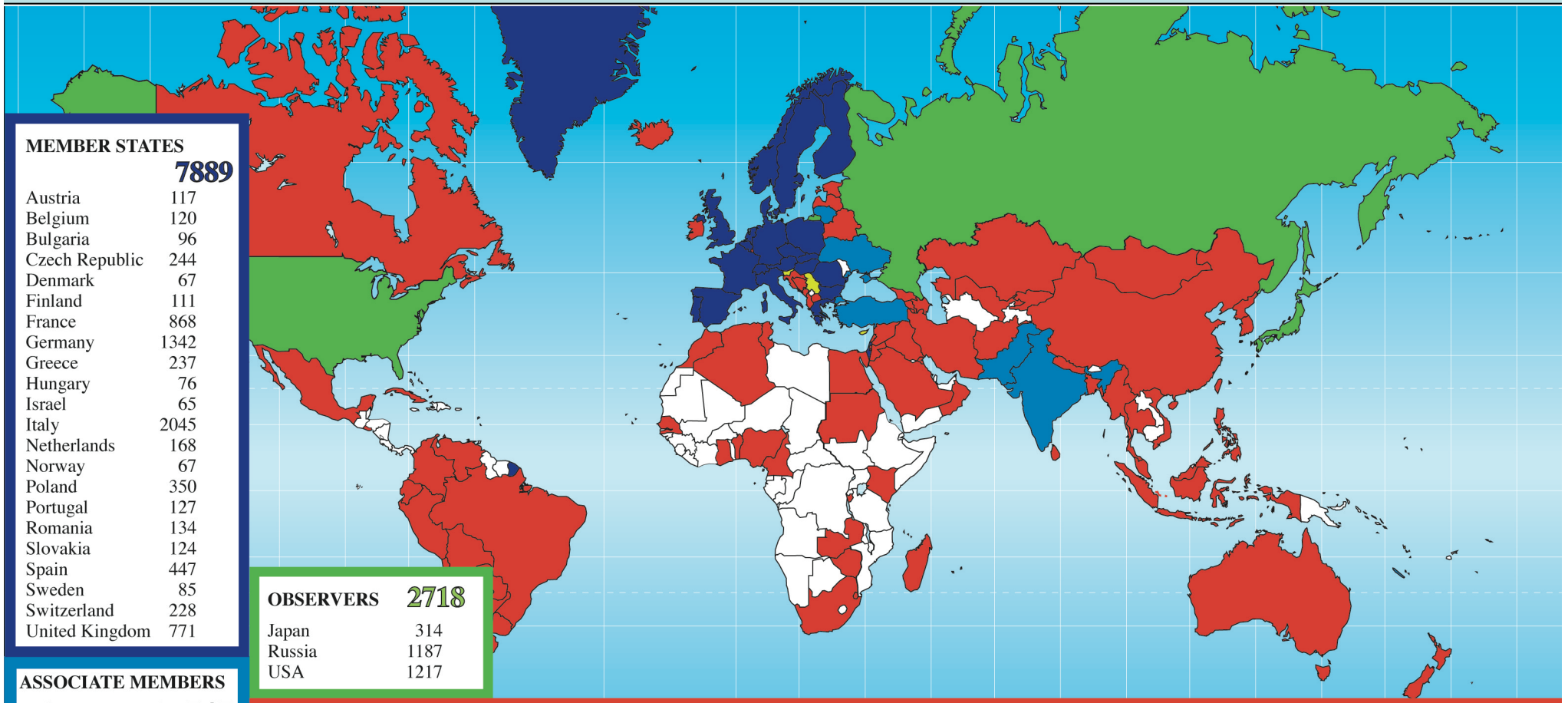
It Walks and Quacks like a Higgs

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





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**

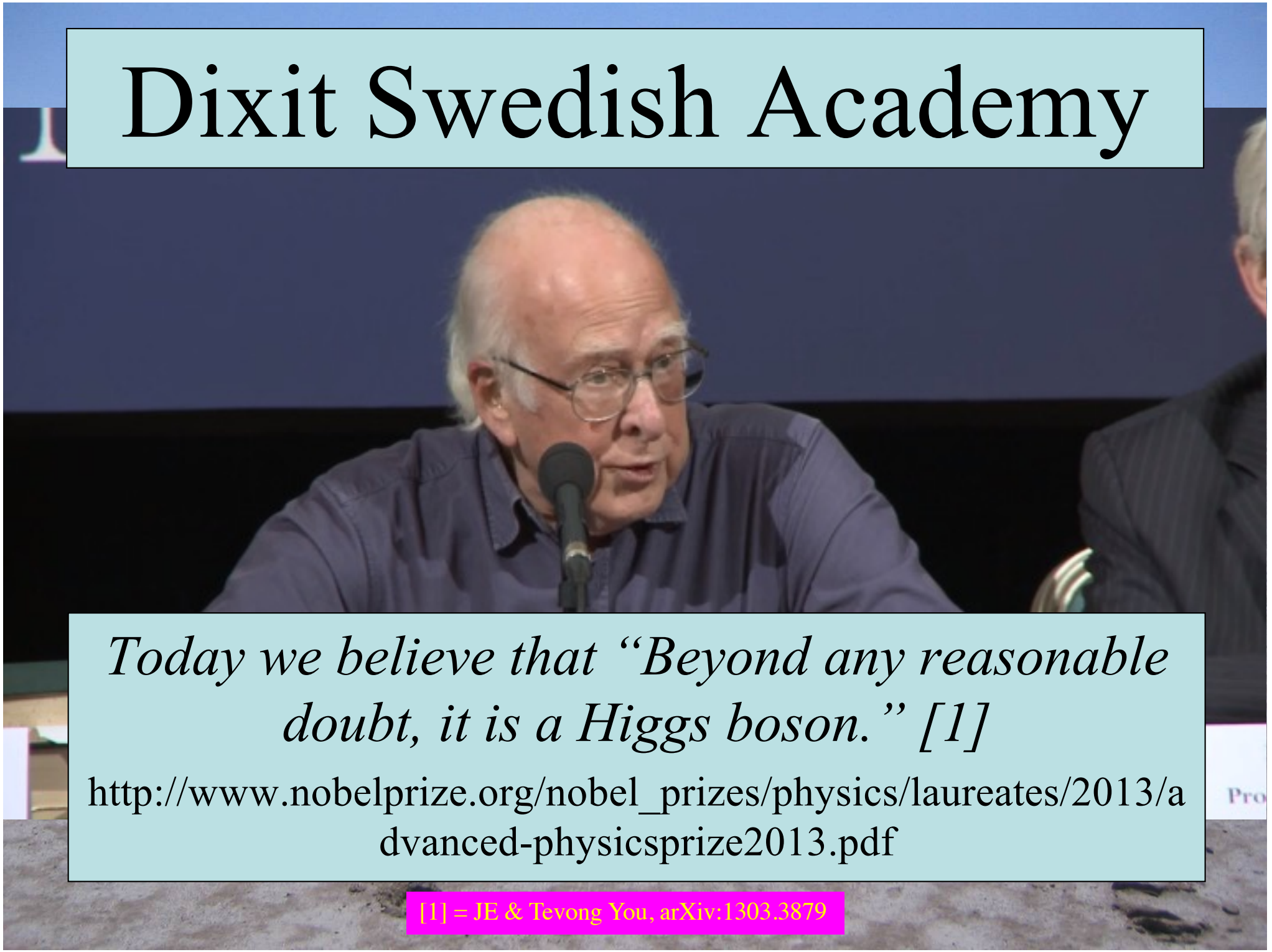
Cyprus	26
Serbia	57
Slovenia	35

OTHERS **1872**

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


Russian naval shells reused
in the CMS experiment

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

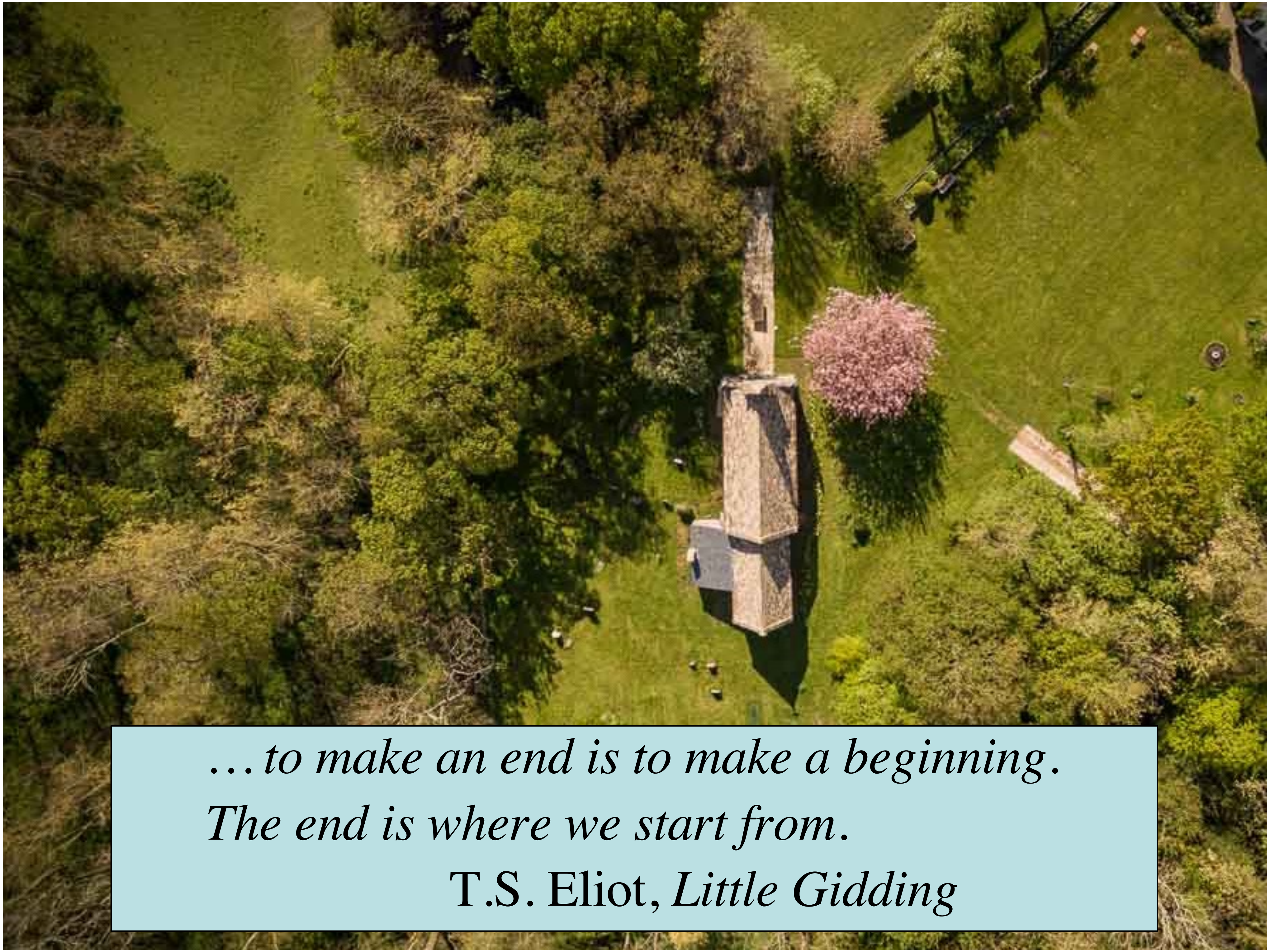
- massless electrons would escape at the speed of light

… there would be no heavy nuclei

… weak interactions would not be weak

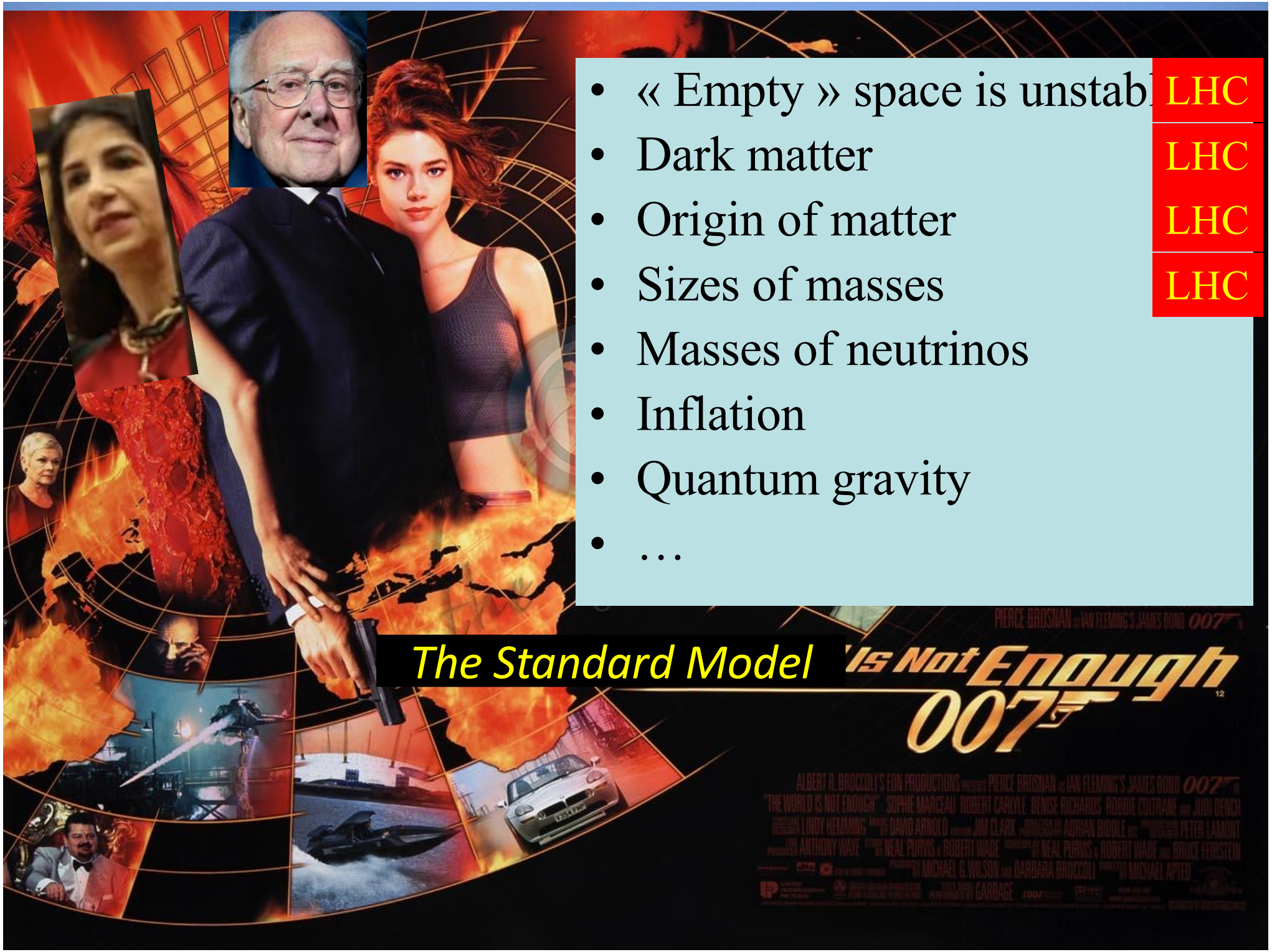
- Life would be impossible: everything would be radioactive

Its existence is a big deal!



…to make an end is to make a beginning.
The end is where we start from.

T.S. Eliot, *Little Gidding*

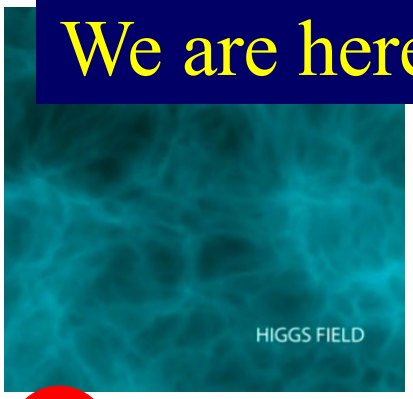

• « Empty » space is unstab
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• …
LHC
LHC
LHC
LHC
The Standard Model
Is Not Enough
007

Will the Universe Collapse? Should it have Collapsed already?

Fluctuate over barrier in the early Universe?

Not if infinite barrier: Supersymmetry?

We are here



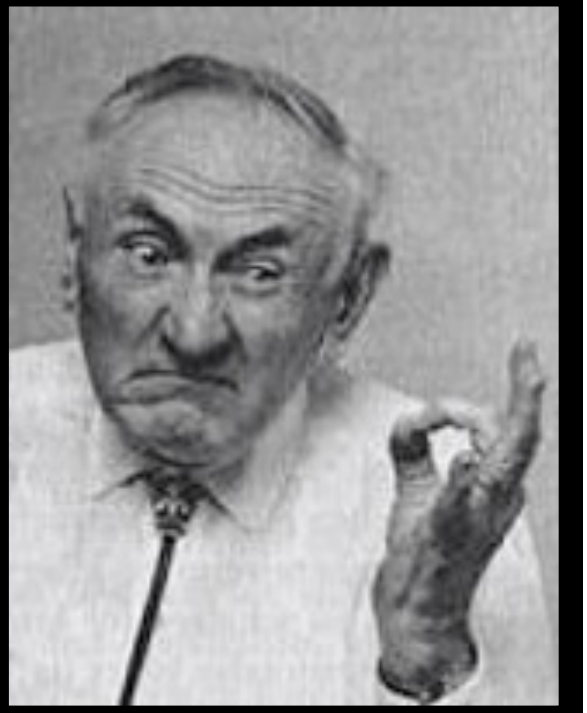
Tunnel through barrier now?

Quantum fluctuations

The Big Crunch

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

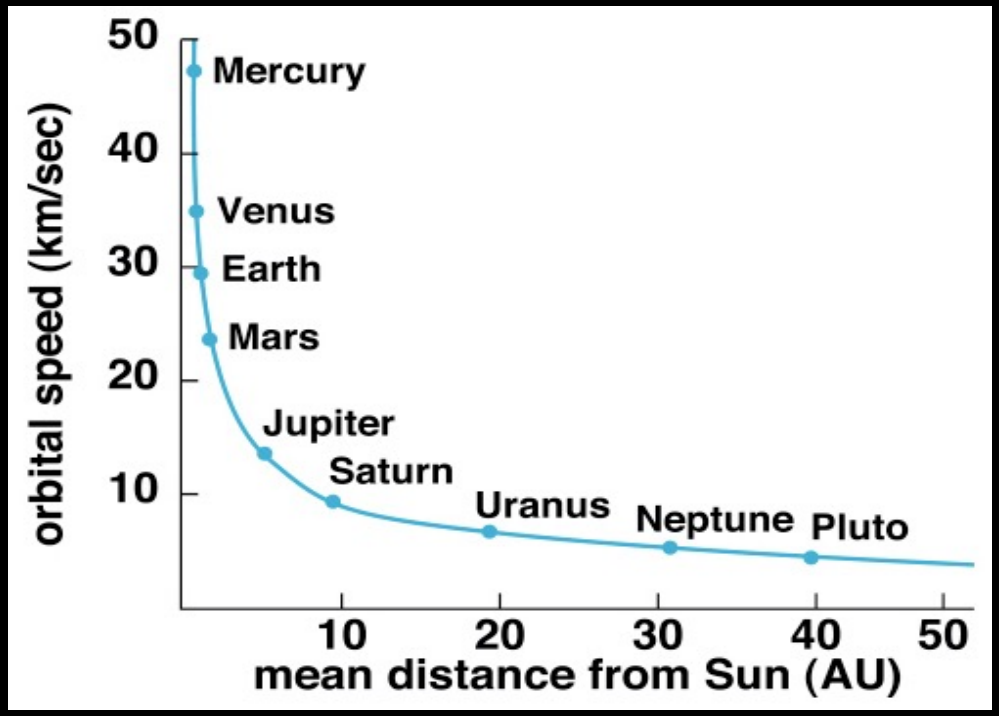
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

- **Further strong evidence for dark matter**

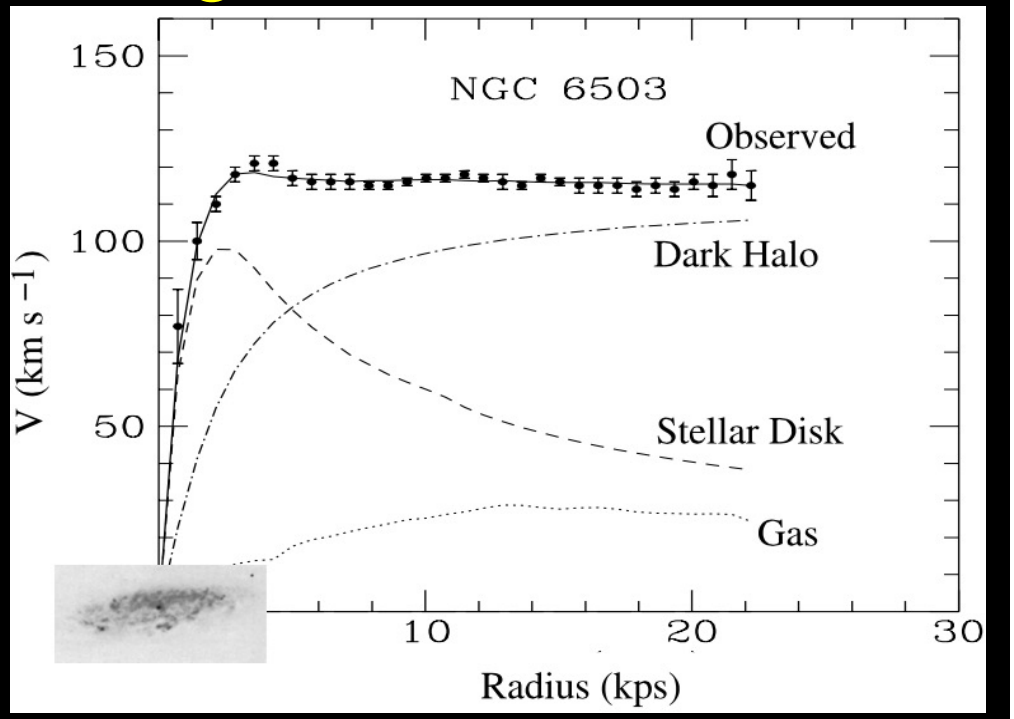
Rotation Curves

- In the Solar System



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

- In galaxies



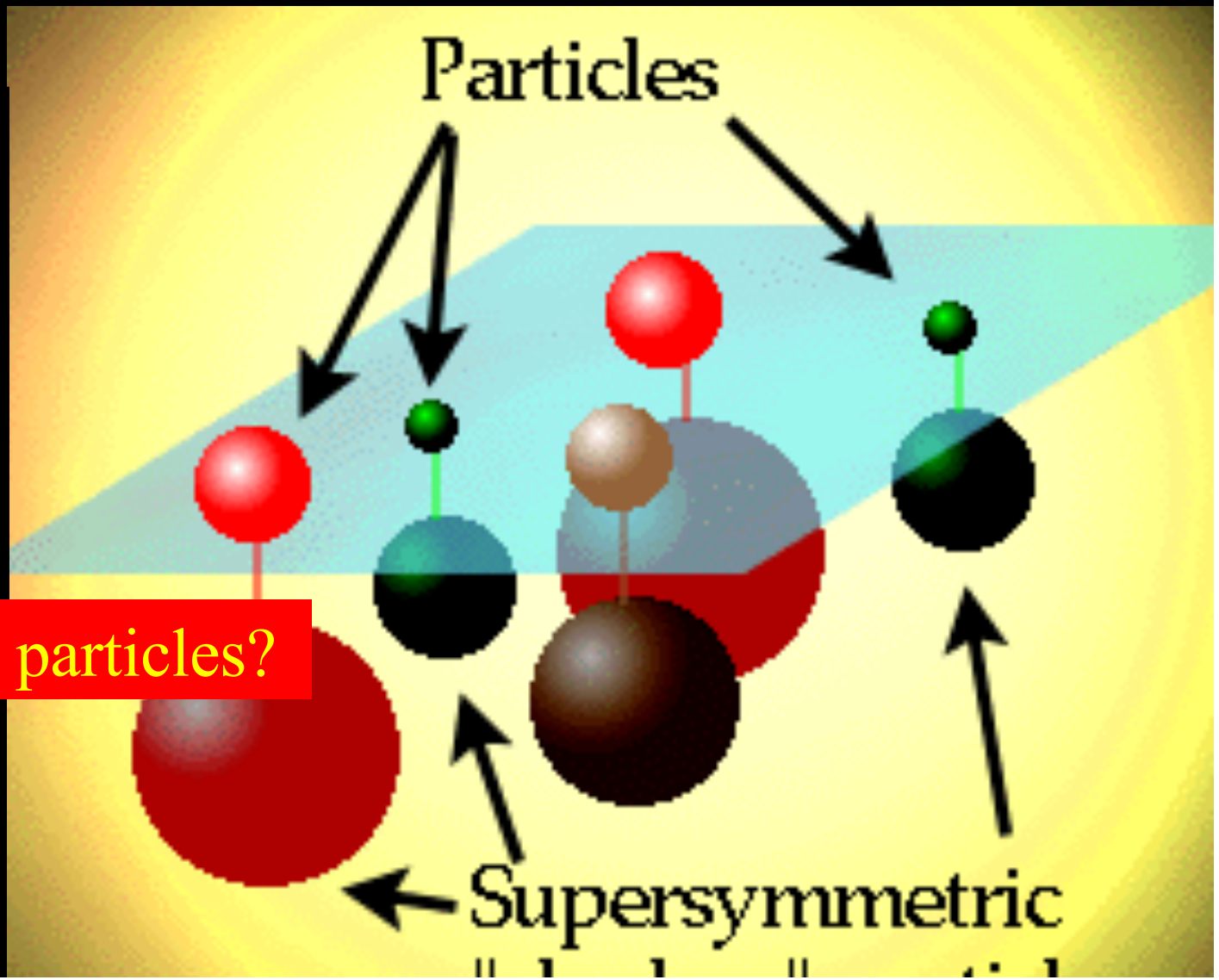
- The velocities do not decrease with distance
- Dark matter spread out

What is the Dark Matter in the Universe?

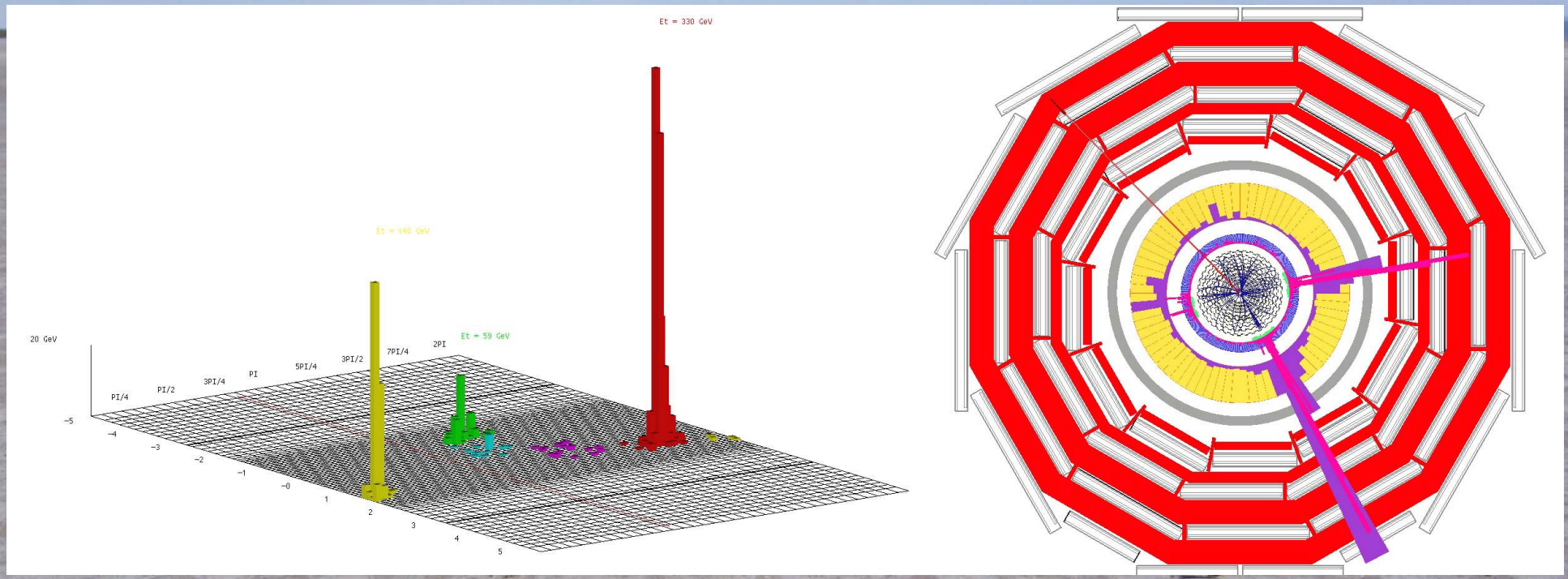
Astronomers say that most of the matter in the Universe is invisible
Dark Matter

Made of unknown particles?

We are searching for them at the

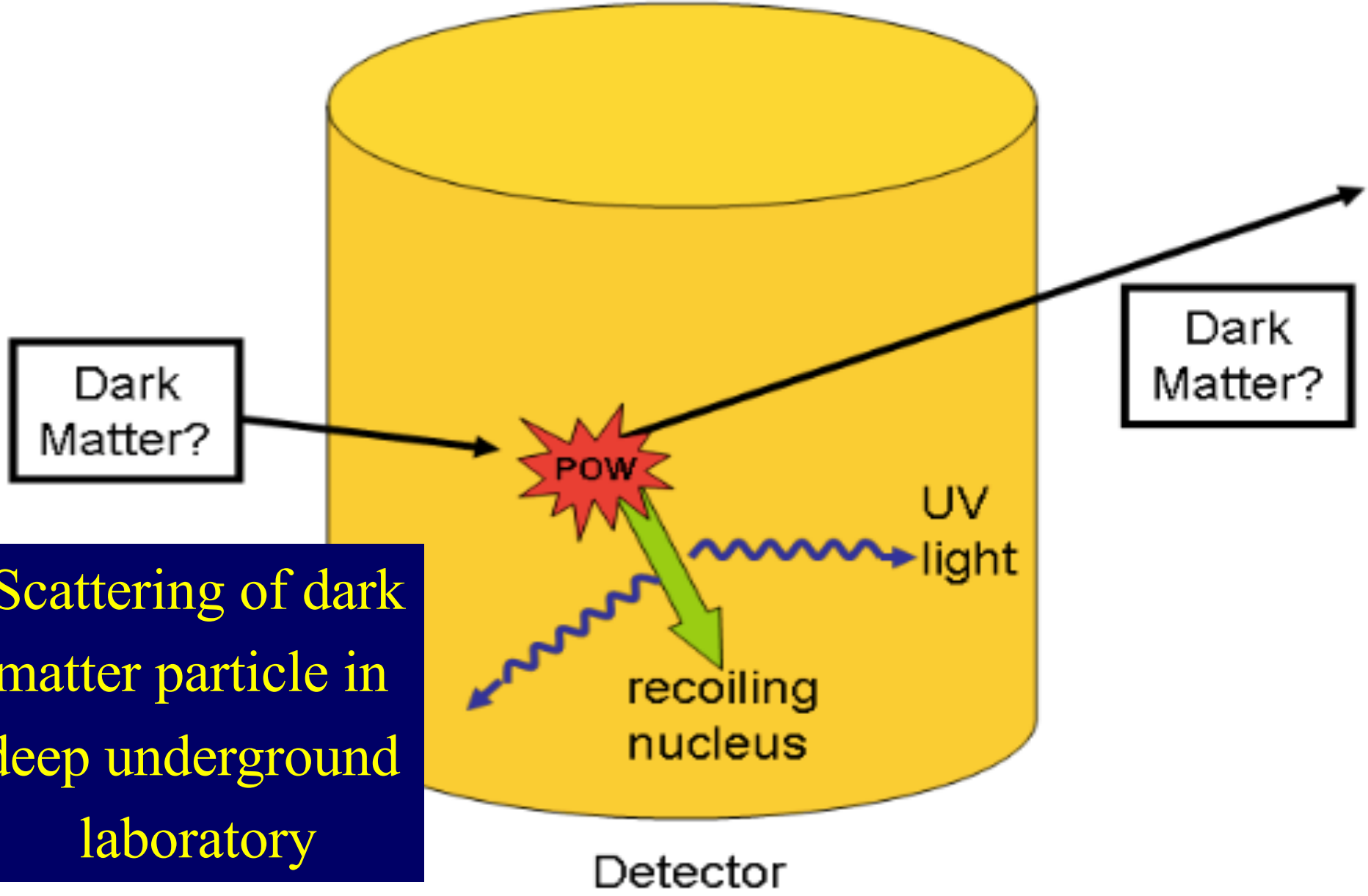


Classic Dark Matter Signature



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

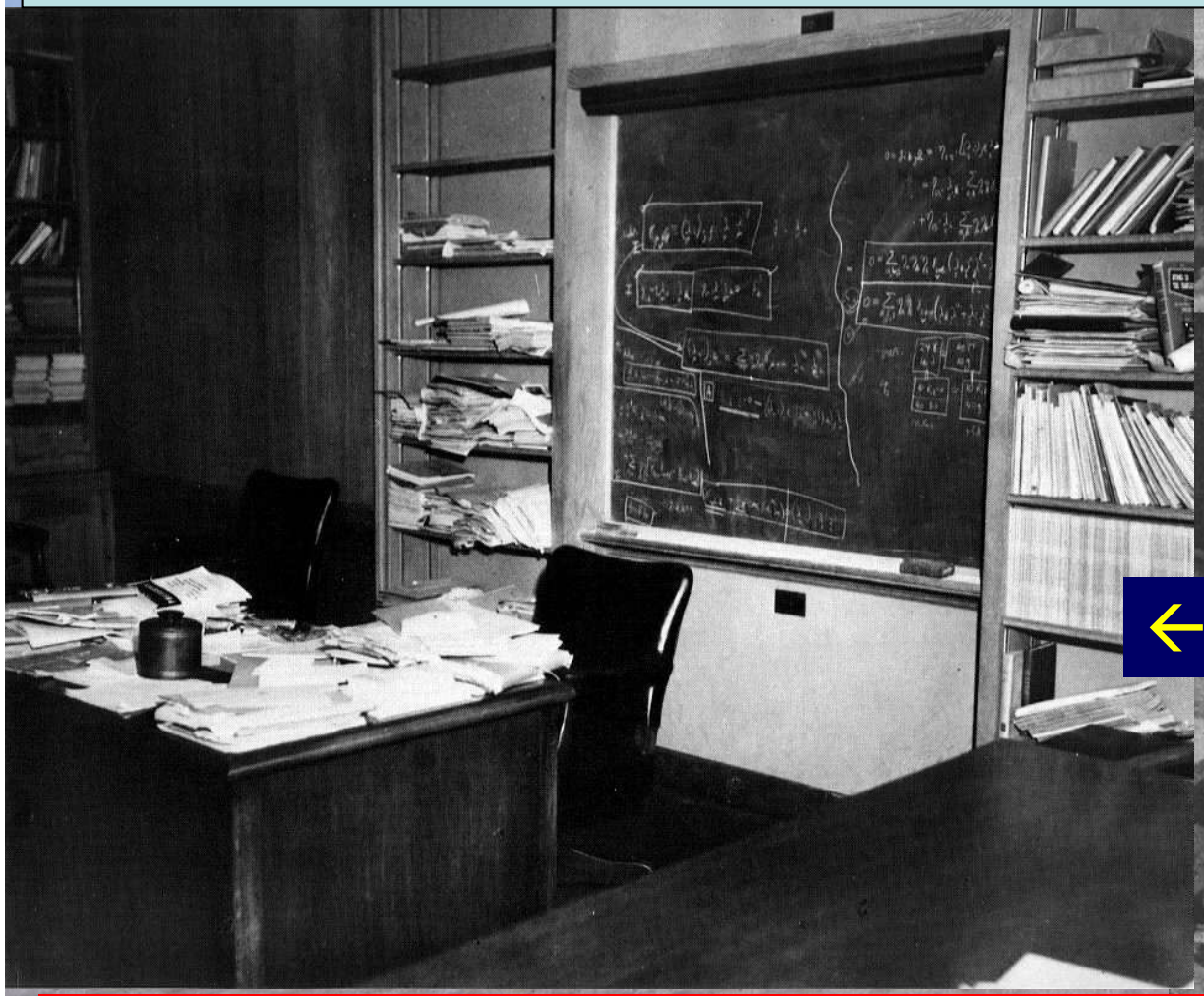
How to Create the Matter in the Universe?

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?

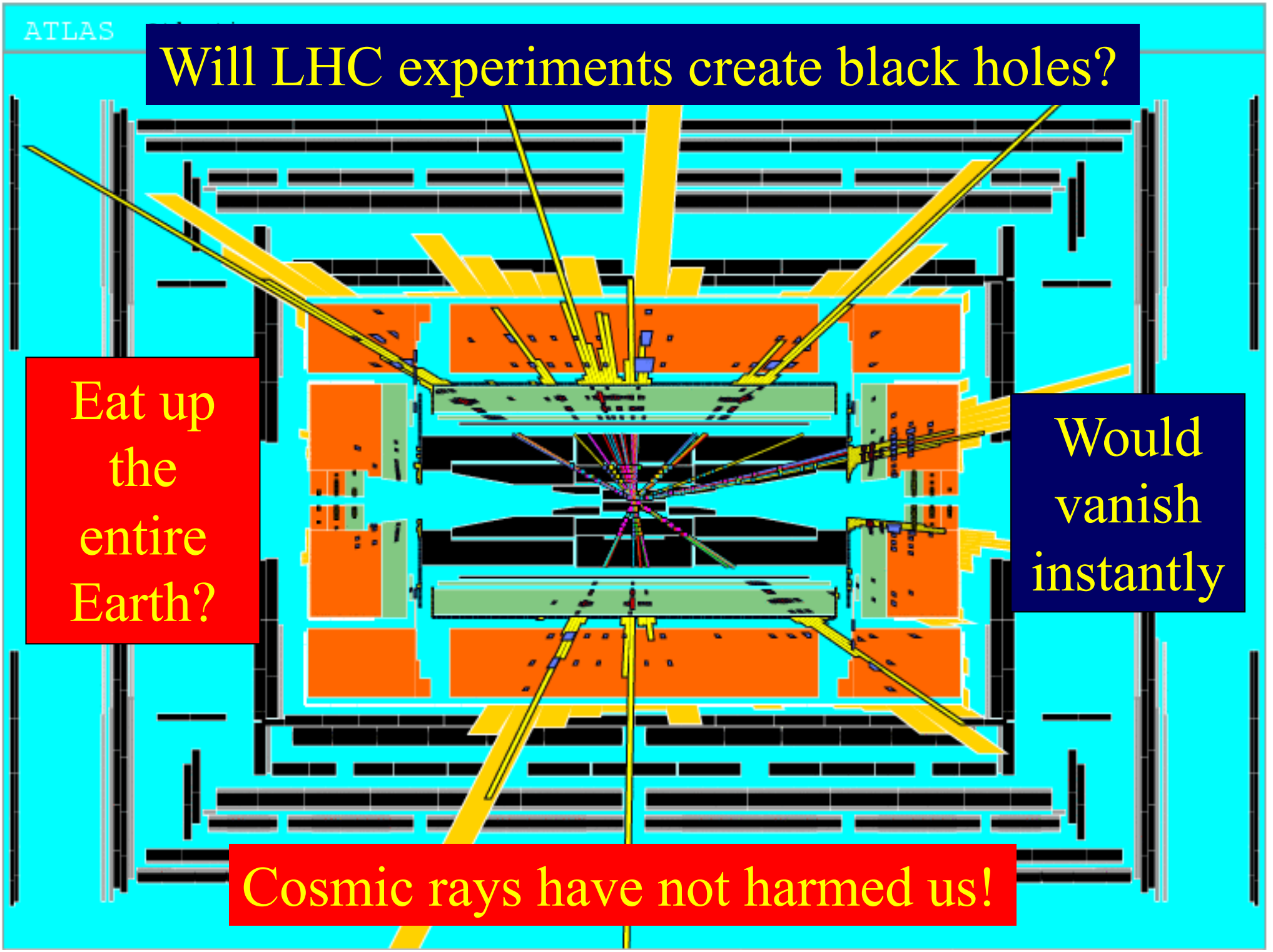
Will we be able to calculate using laboratory data?

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!


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