

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



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

LHC

- How does the Universe evolve?

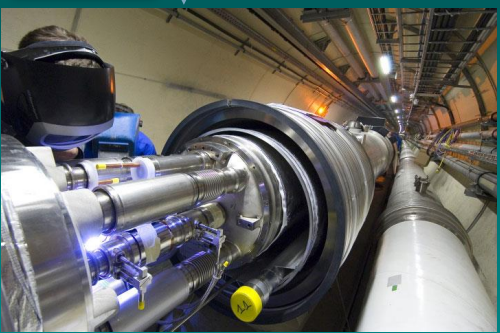
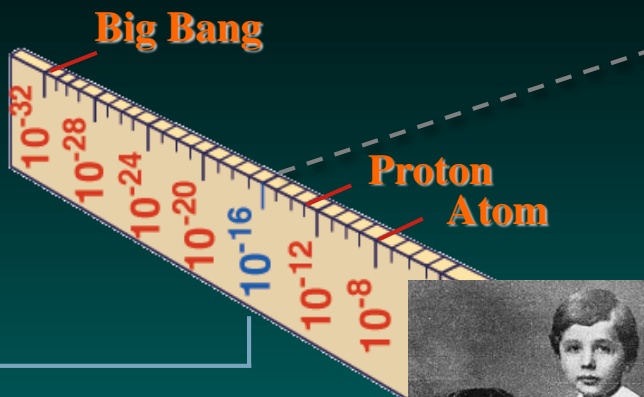
- Why is the Universe so big and old?

LHC

- What is the future of the Universe?

LHC

Our job is to ask - and answer - these questions

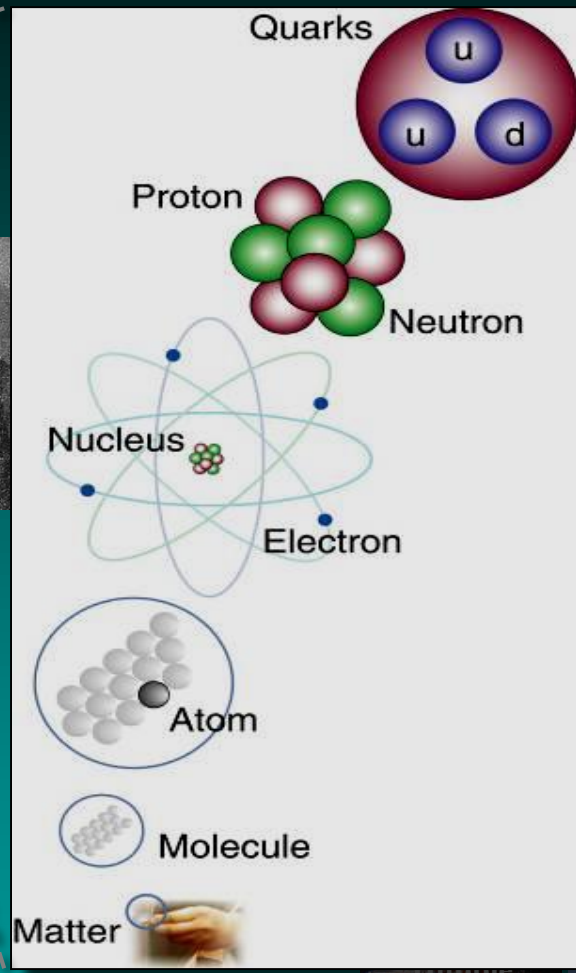


LHC

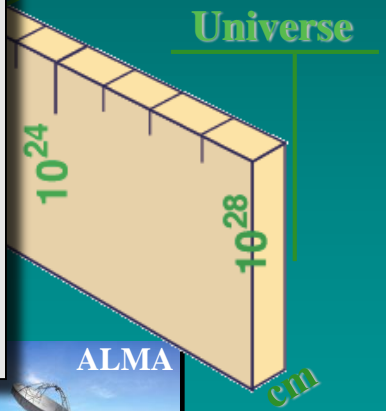
Super-Microscope



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

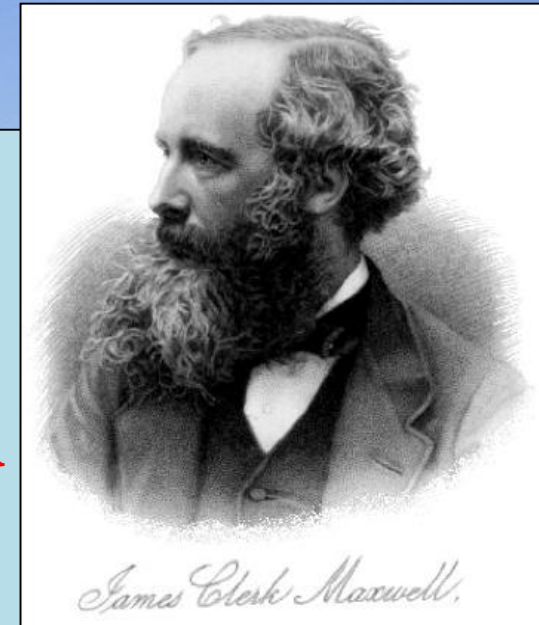


Radius of Galaxies



James Clerk Maxwell

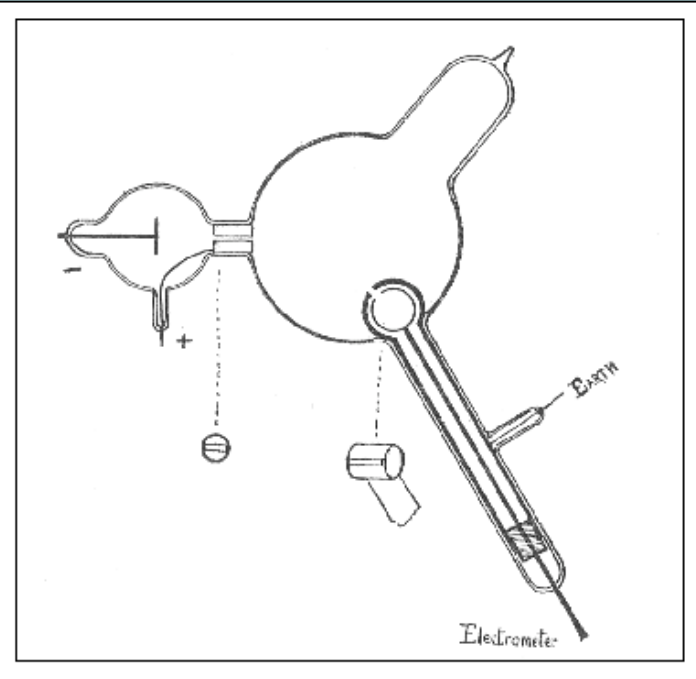
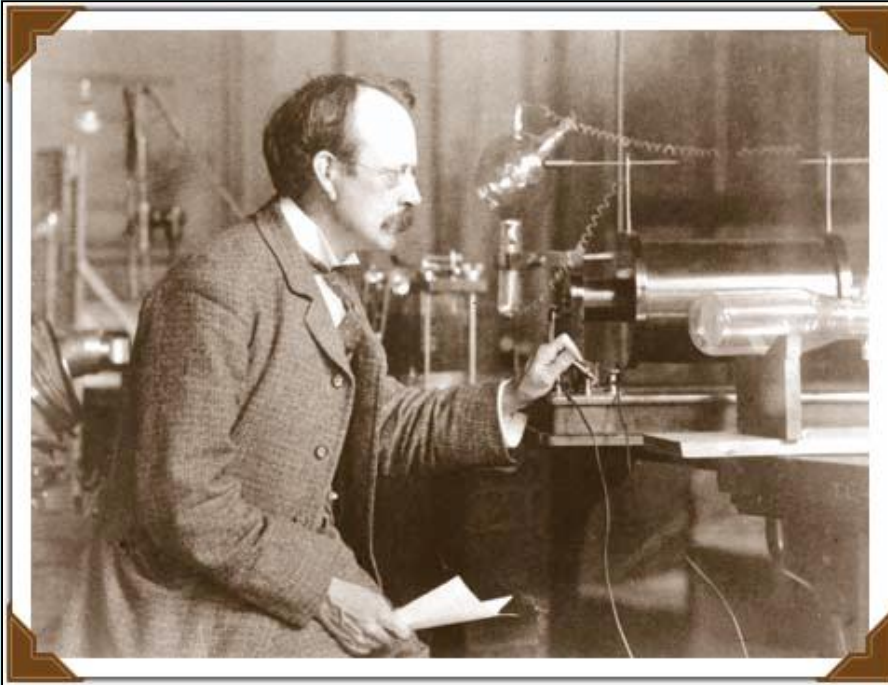
- Professor at King's 1860 – 1865
- The first colour photograph
- **Unified theory of electricity and magnetism**
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light



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

The First Elementary Particle

- Discovered by J.J. Thomson in 1897



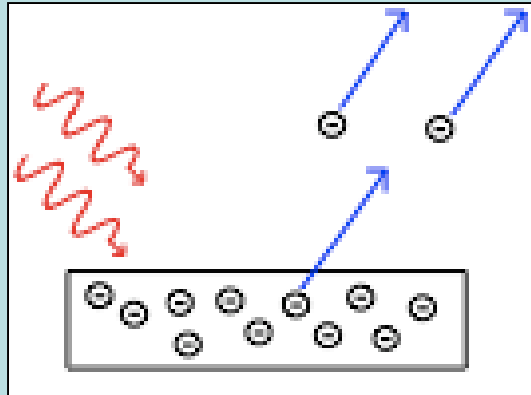
- **The electron** – the basis of the electronic industry
- Old-style TV sets used beams of electrons

Photon: the Particle of Light

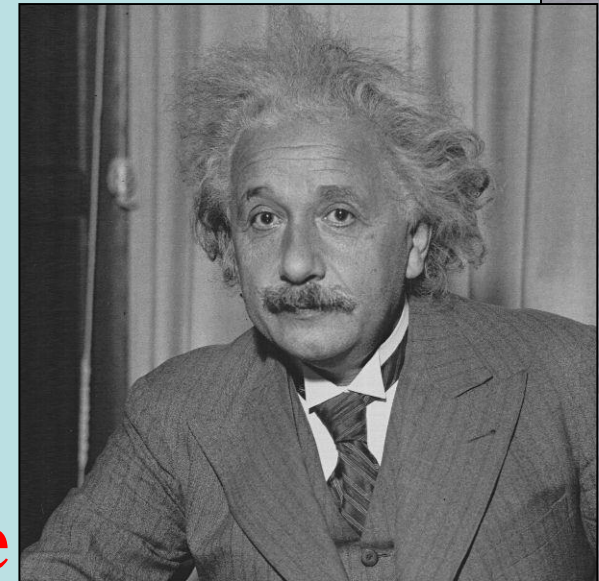
- Quantum hypothesis introduced by Planck:

$$E = hf$$

- Physical reality postulated by Einstein to explain photoelectric effect



- **Motivation for his Nobel Prize**

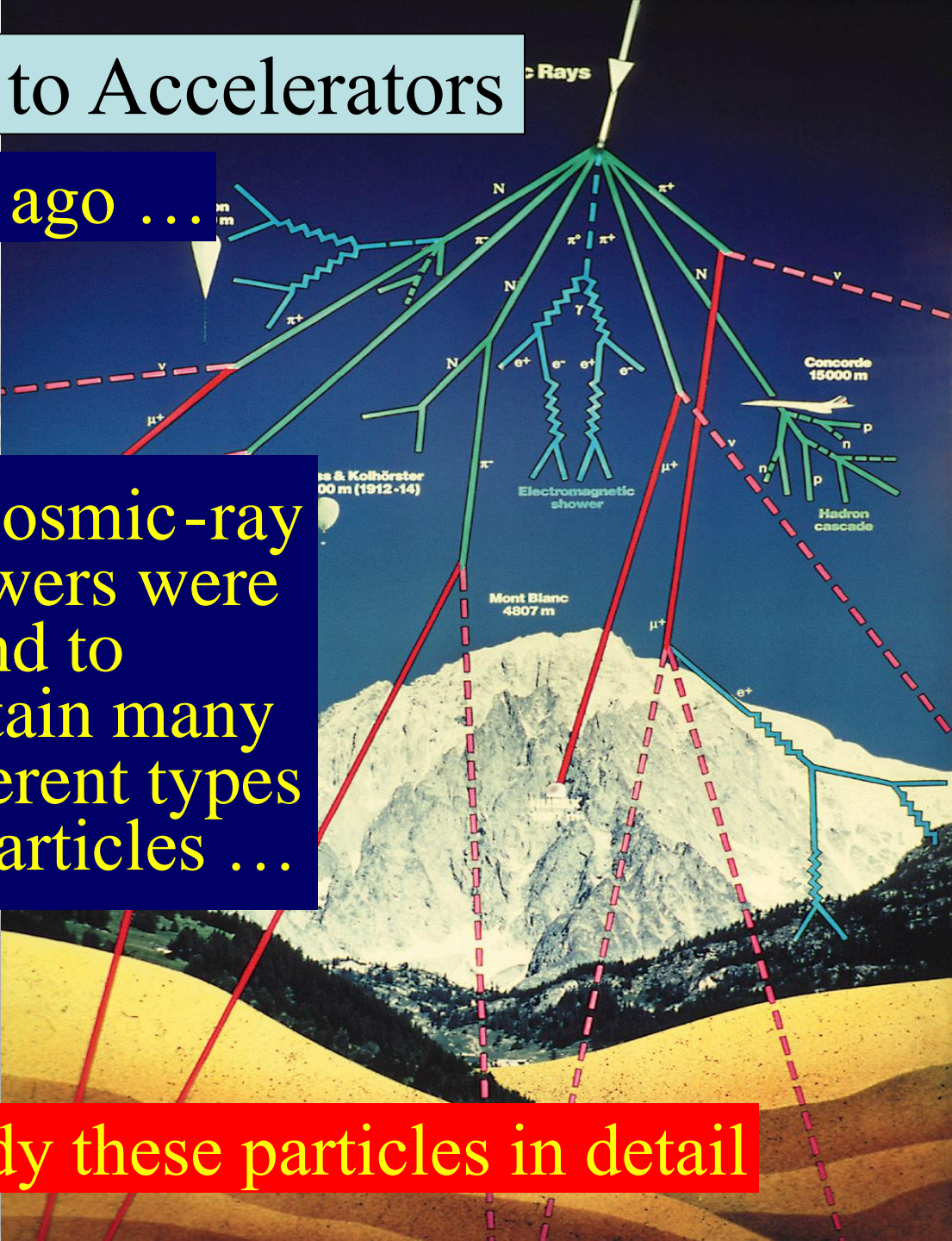
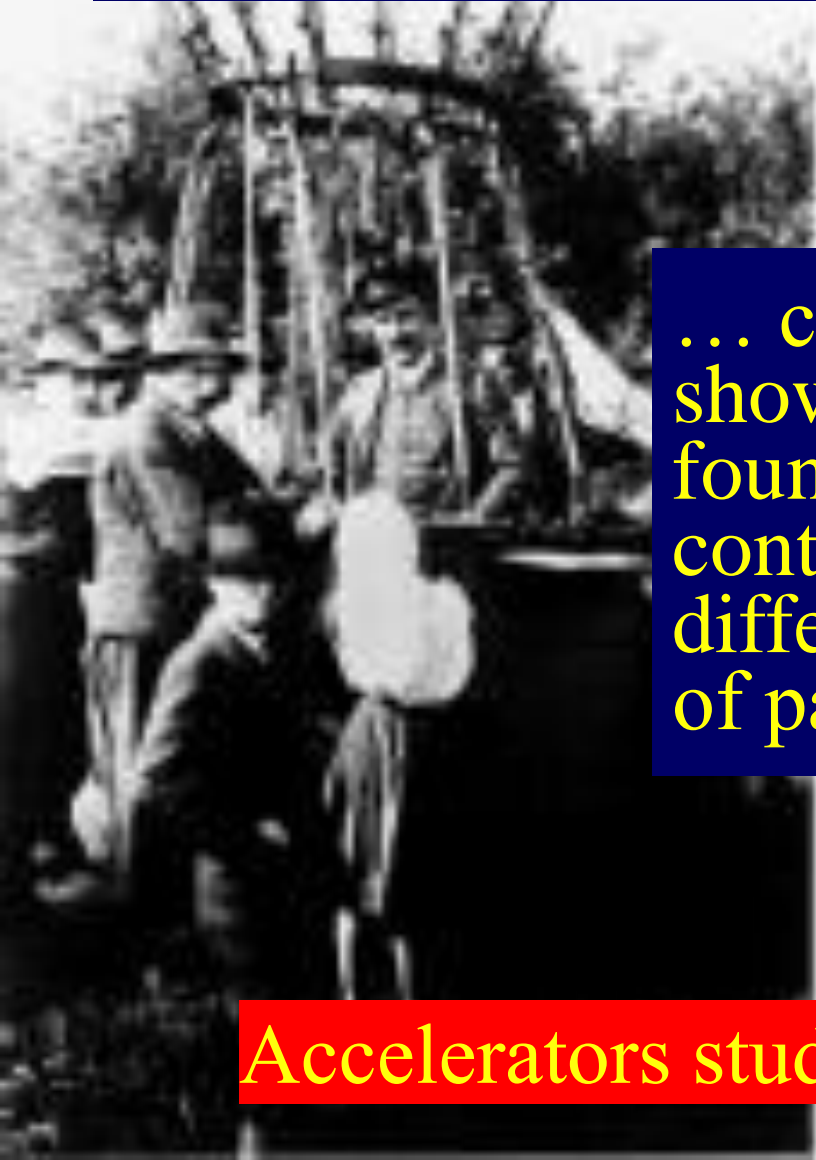


From Cosmic Rays to Accelerators

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 Antimatter

- Existence predicted by Dirac
- The antiparticle of the electron (the positron) was discovered in cosmic rays by Anderson

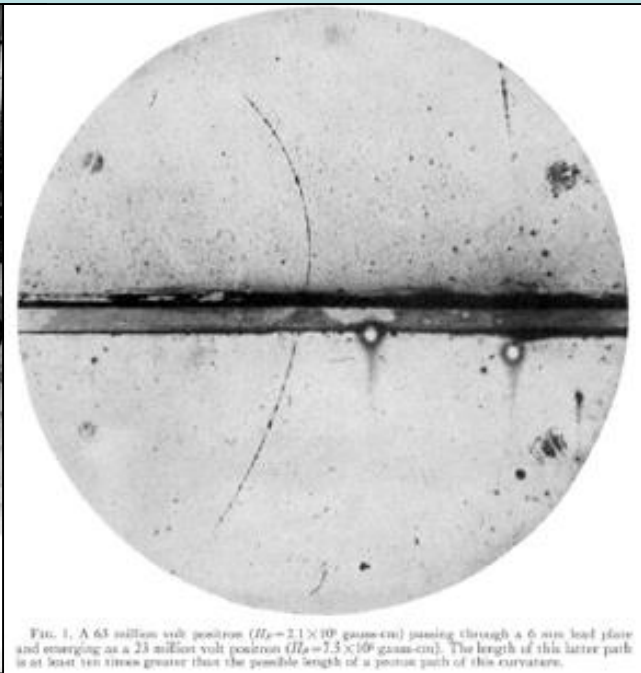


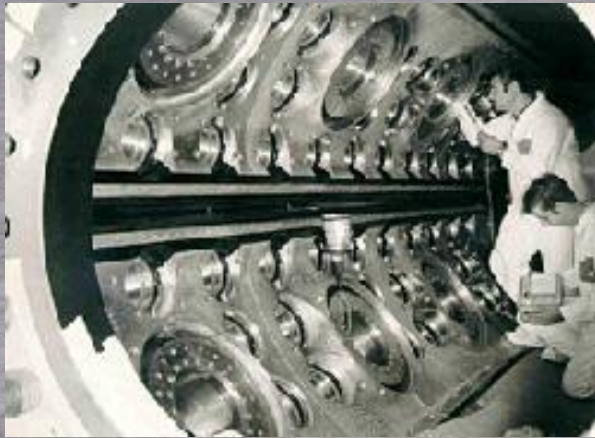
FIG. 1. A 65 million volt positron ($H_0=2.1 \times 10^6$ gauss-cm) passing through a 6 millicentimeter plate and emerging as a 23 millicentimeter positron ($H_0=3.3 \times 10^6$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a positron path of this curvature.

- The same mass as the electron, opposite electric charge
- Used in medical diagnosis (PET scanners)

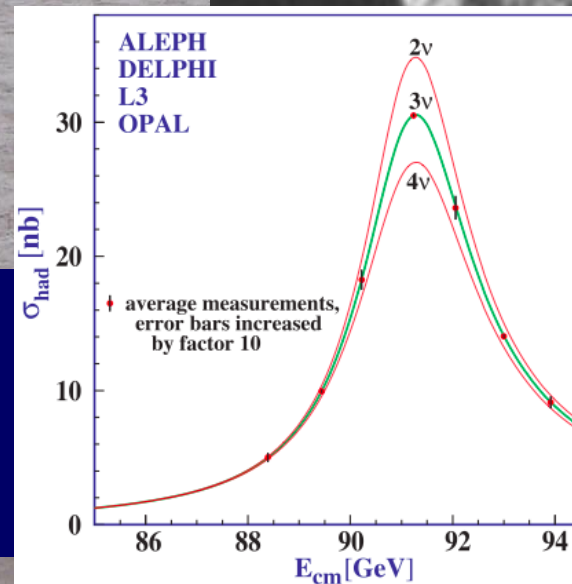
The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow and Weinberg

Tested by experiments
at CERN



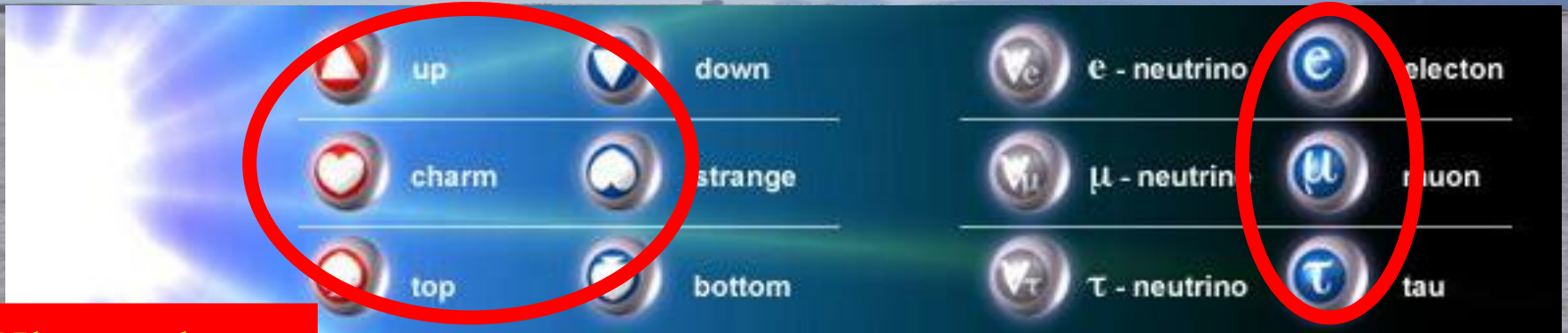
Perfect agreement between
theory and experiments
in all laboratories



The 'Standard Model'

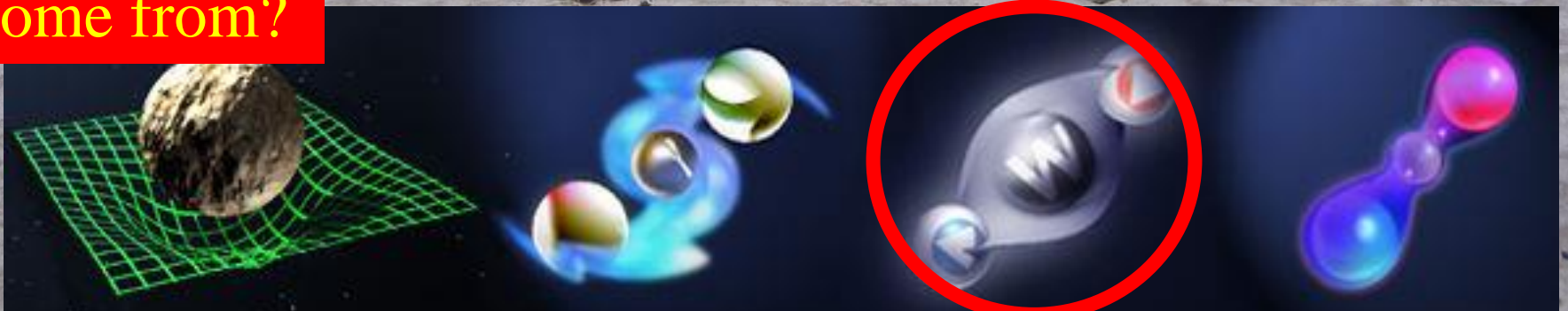
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation

electromagnetism

weak nuclear force

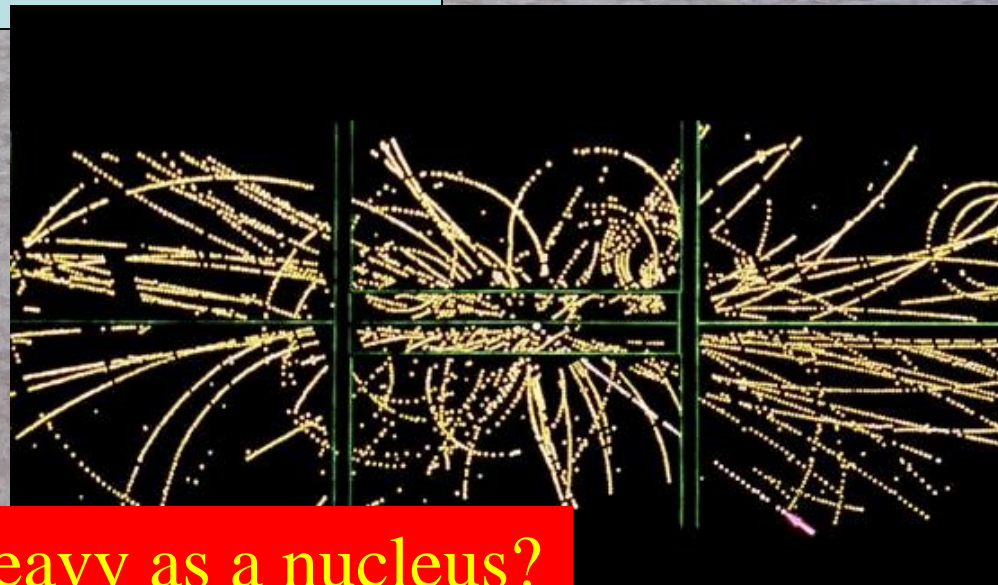
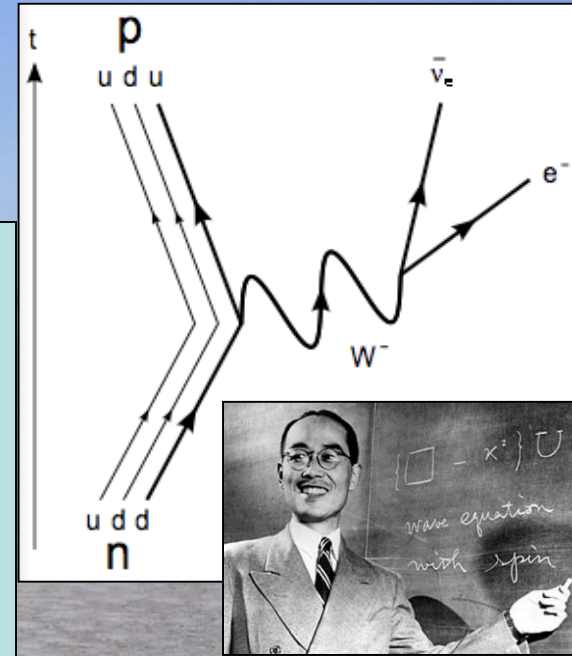
strong nuclear force

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?

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)



KING'S
College
LONDON

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



A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

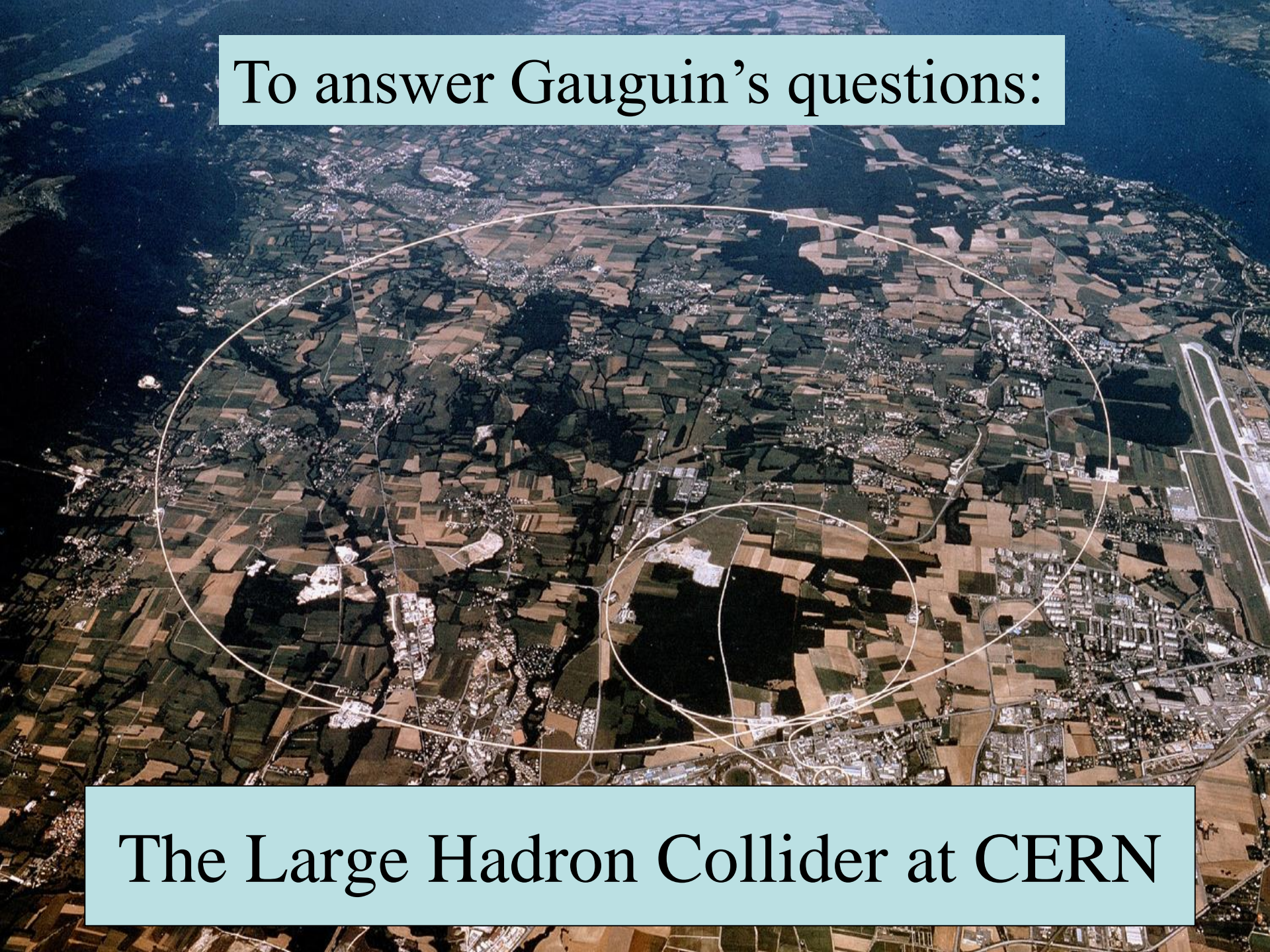
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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

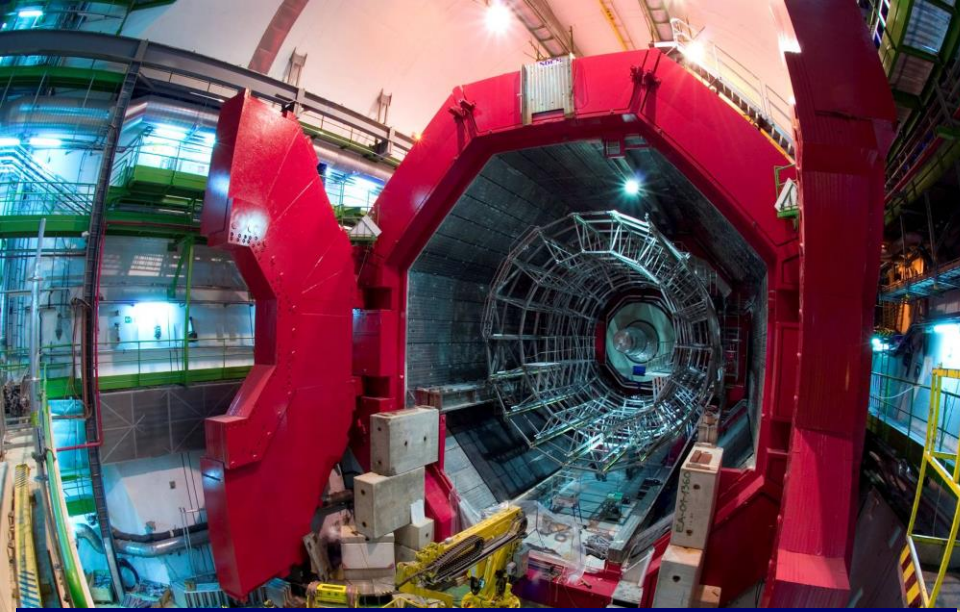
To answer these questions:

The Large Hadron Collider (LHC)

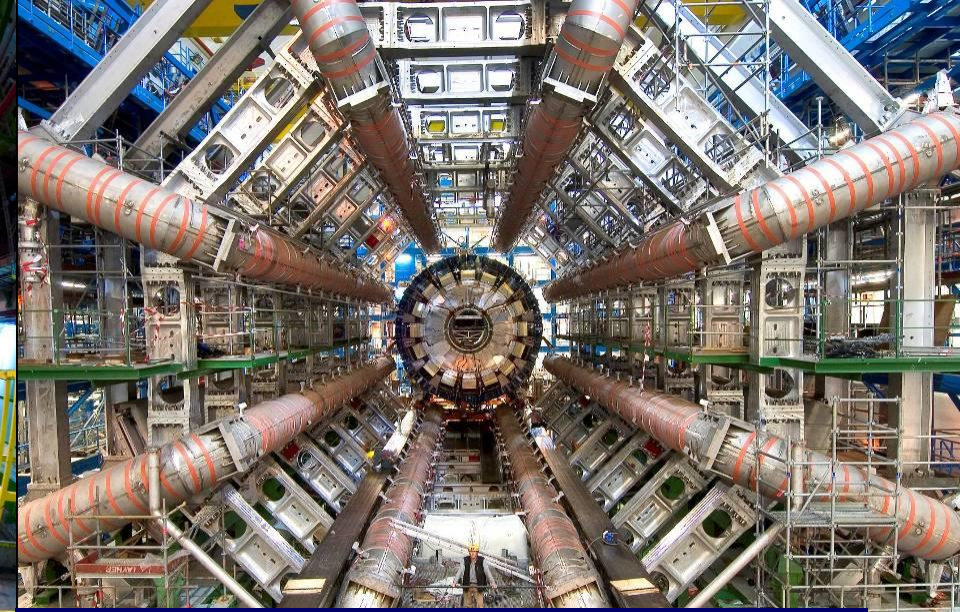
Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:

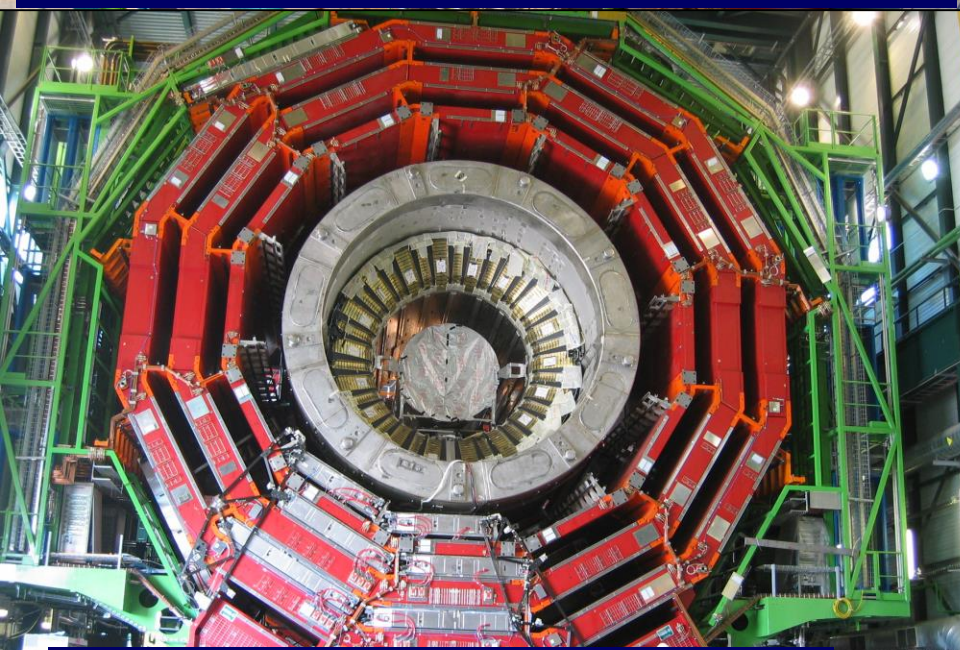
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

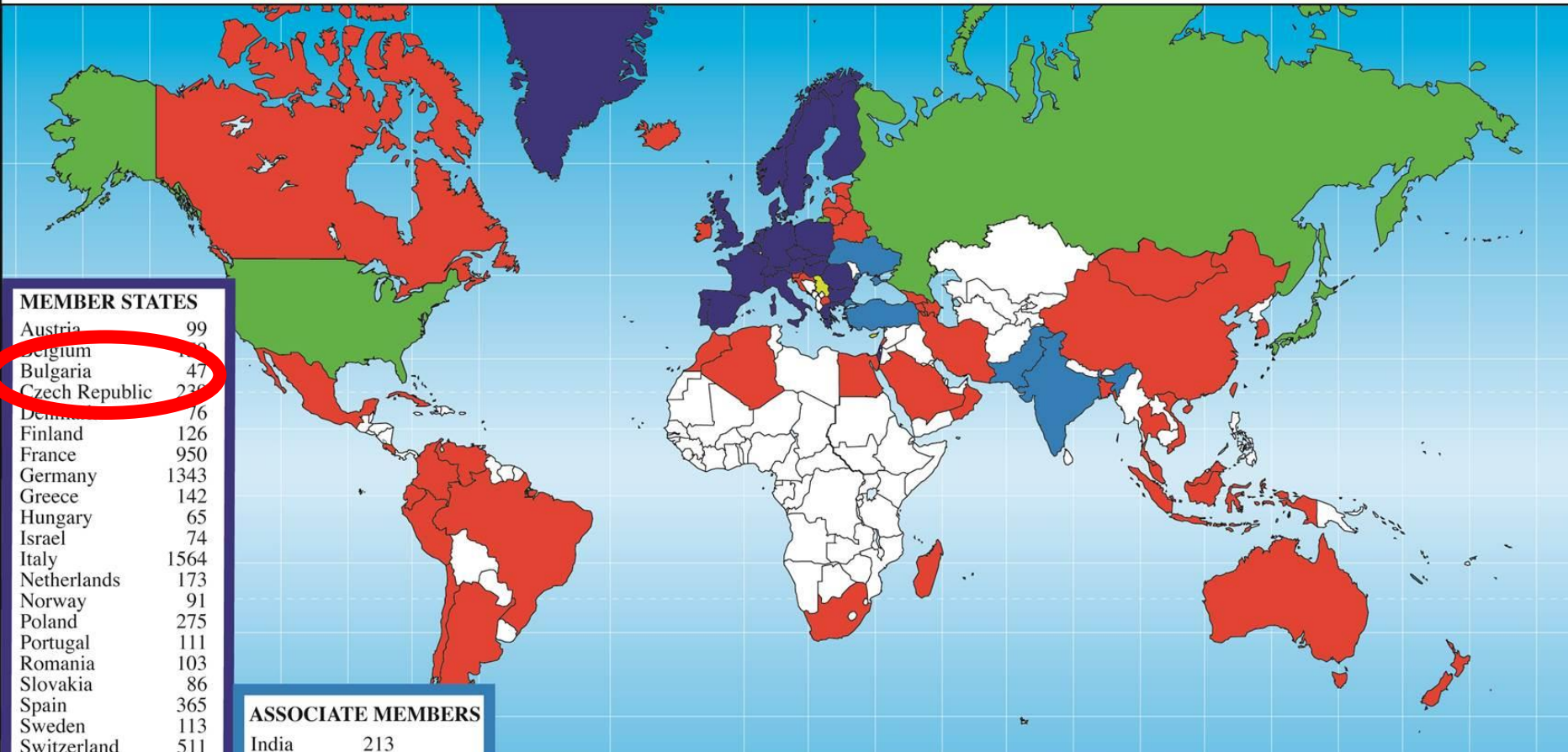


CMS: Higgs and dark matter



LHCb: Matter-antimatter difference

Scientists from around the World



MEMBER STATES

Austria	99
Belgium	129
Bulgaria	47
Czech Republic	228
Denmark	76
Finland	126
France	950
Germany	1343
Greece	142
Hungary	65
Israel	74
Italy	1564
Netherlands	173
Norway	91
Poland	275
Portugal	111
Romania	103
Slovakia	86
Spain	365
Sweden	113
Switzerland	511
United Kingdom	942

7654

ASSOCIATE MEMBERS

India	213
Pakistan	45
Turkey	128
Ukraine	30

416

OBSERVERS

Japan	294
Russia	1046
USA	2018

3358

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus	15
Serbia	35

50

OTHERS

Algeria	1	Chile	19	Hong Kong	21	Malaysia	12	Slovenia	22
Argentina	24	China	216	Iceland	5	Malta	9	South Africa	58
Armenia	19	Colombia	21	Indonesia	9	Mexico	60	Taiwan	74
Australia	39	Costa Rica	1	Iran	34	Mongolia	2	Thailand	17
Azerbaijan	3	Croatia	27	Ireland	9	Morocco	10	TFYROM	2
Bangladesh	4	Cuba	3	Korea	163	New Zealand	8	Venezuela	1
Belarus	23	Ecuador	2	Latvia	1	Oman	3	Viet Nam	1
Brazil	136	Egypt	27	Lebanon	3	Peru	3		
Canada	180	Estonia	16	Lithuania	17	Saudi Arabia	1		
		Georgia	26	Madagascar	2	Singapore	4		

1338

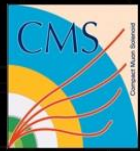
2012: The discovery of the Higgs Boson



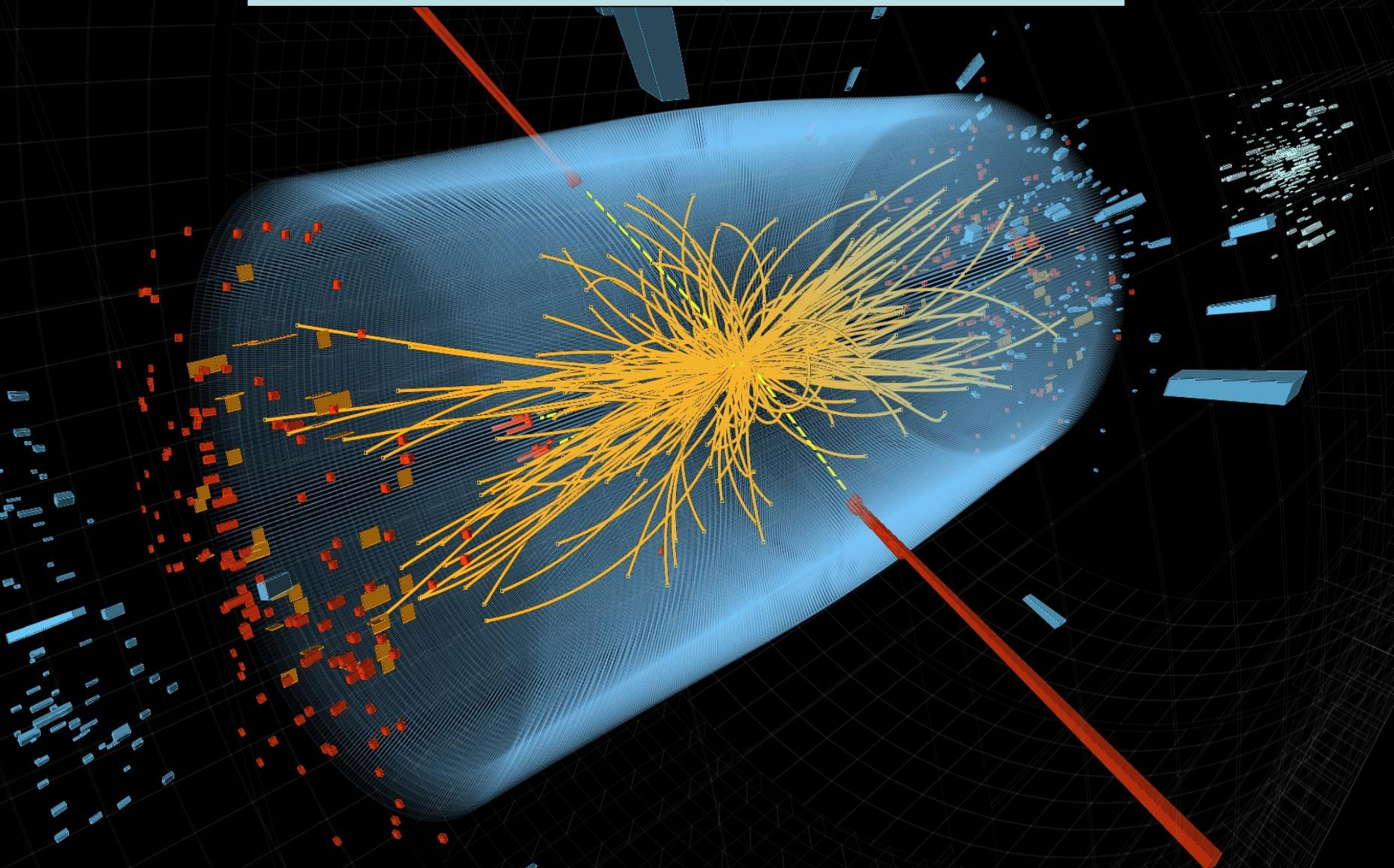
Mass Higgsteria

A Simulated Higgs Event @ LHC

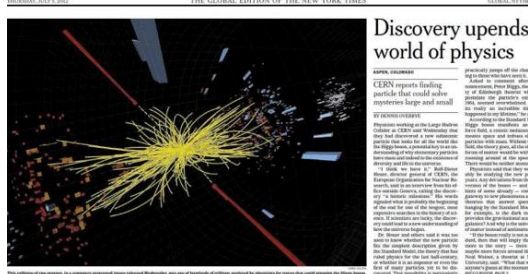




Interesting Events



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

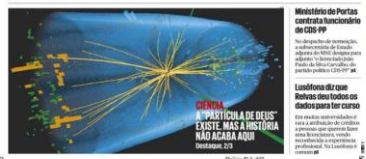


ヒッグス粒子検出 年内に結論

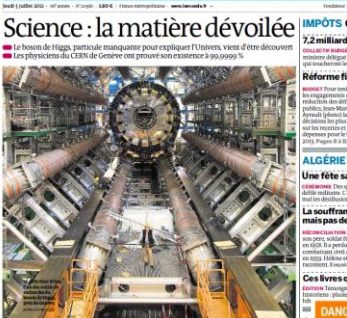
ヒッグス粒子検出 年内に結論
新素粒子検出 年内に結論
日米欧2チーム

Per dia, Deco recebe 87 casos por causa de sobrepeso

Milhares de moradores de bairros sociais em risco de perderem RSI



Science: la matière dévoilée



MK newspaper cover with headlines in Russian: 'ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ', 'МЕТРО СПУСКАЕТ НА ВОДУ'.

AD ALGEMEEN DAGBLAD newspaper cover with headline: 'EINDELIJK BELIJK NA 48 JAAR'.

Frankfurter Allgemeine Zeitung newspaper cover with headline: 'Große Mehrheit im Bundestag'.

The New York Times newspaper cover with headline: 'Physicists Find Elusive Particle Seen as Key to Universe'.

The Gazette newspaper cover with headline: 'falleda la partícula clave para a comprensión del universo'.

CHINADAILY newspaper cover with headline: 'DANGEROUS MOVE'.

THE TIMES OF INDIA newspaper cover with headline: 'Big bang moment: Scientists may have found "God particle"'.

THE HINDU newspaper cover with headline: 'Elusive particle found, looks like Higgs boson'.

CORRIERE DELLA SERA newspaper cover with headline: 'La particella che può svelare i segreti dell'universo'.

gazeta newspaper cover with headline: 'Czastke Higgsa fizycy najpierw wymyślił, potem szukali 40 lat'.

বিশ্বনাথের 'স্বপ্ন' দর্শন newspaper cover with headline: 'স্বপ্ননাথের বিনয় প্রণাম'.

Higgsdependence Day!



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

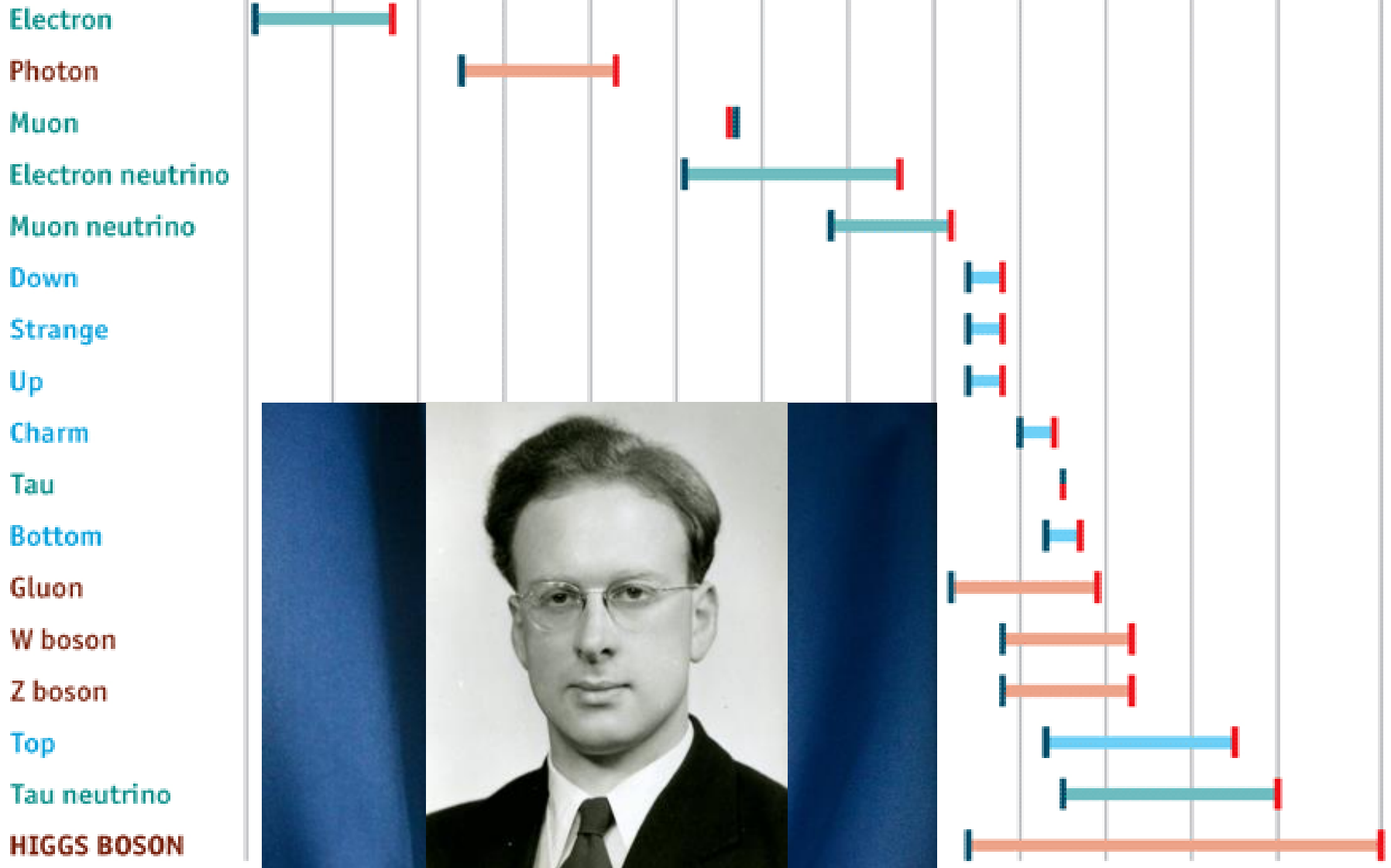
... there would be no heavy nuclei

... weak interactions would not be weak

- Life would be impossible: everything would be radioactive

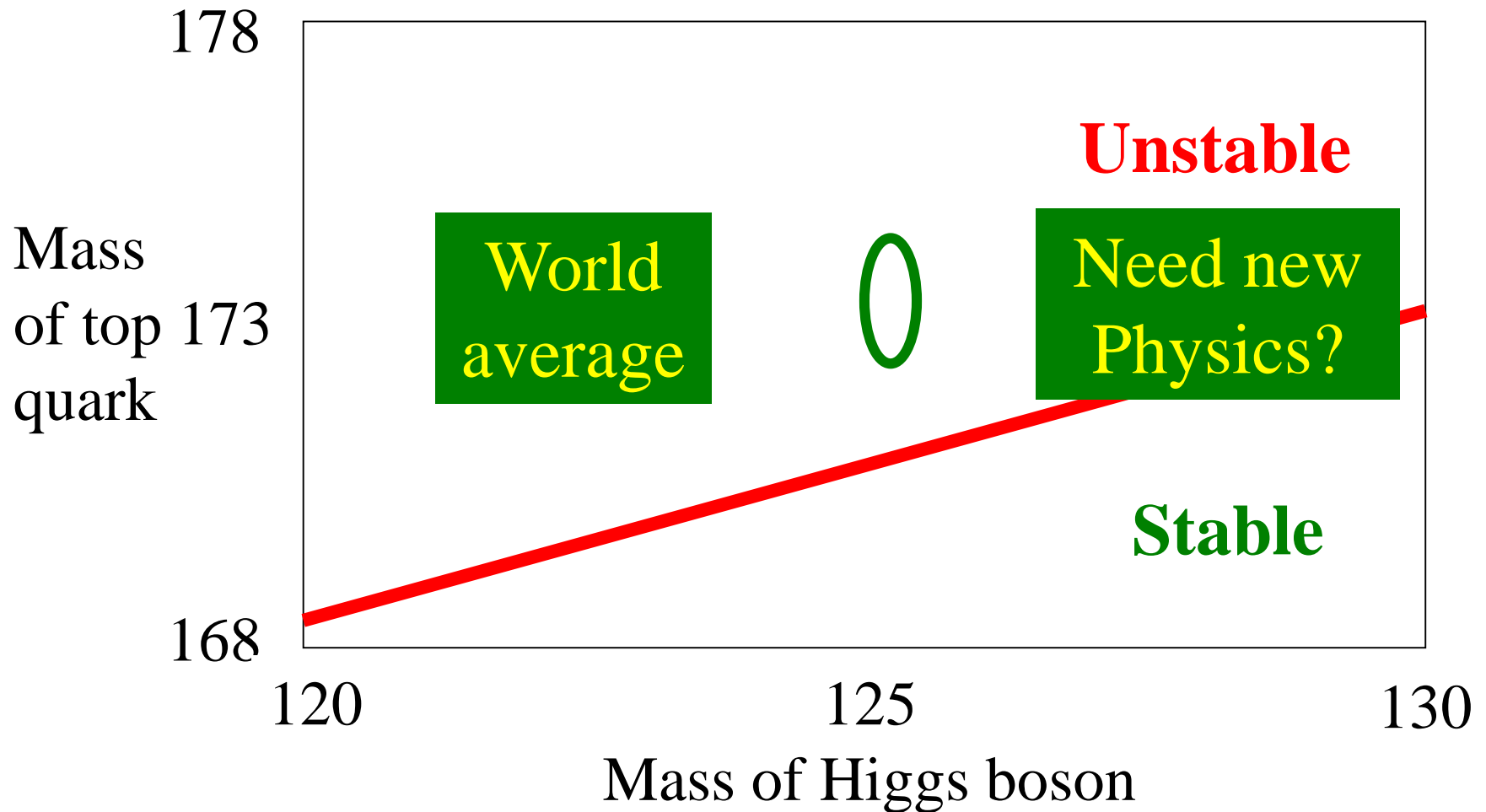
Its existence is a big deal!

Standard Model Particles: Years from Proposal to Discovery



Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?

Fluctuate over barrier
in the early Universe?

Not if
infinite barrier:
Supersymmetry?

We are here

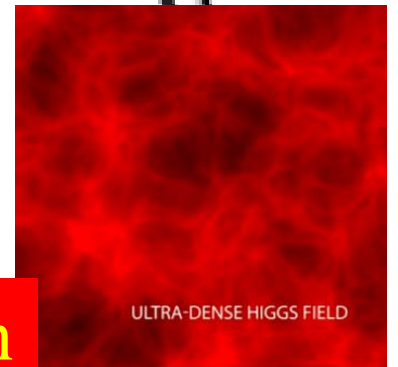


HIGGS FIELD

Tunnel through
barrier now?

Quantum fluctuations

The Big Crunch



ULTRA-DENSE HIGGS FIELD

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?**



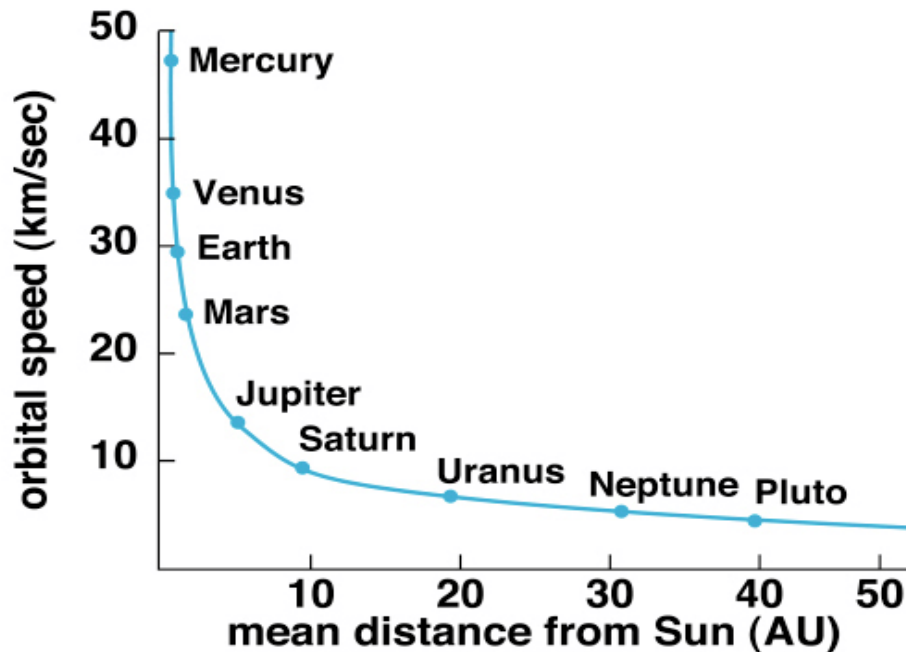
The Rotation Curves of Galaxies

- 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**



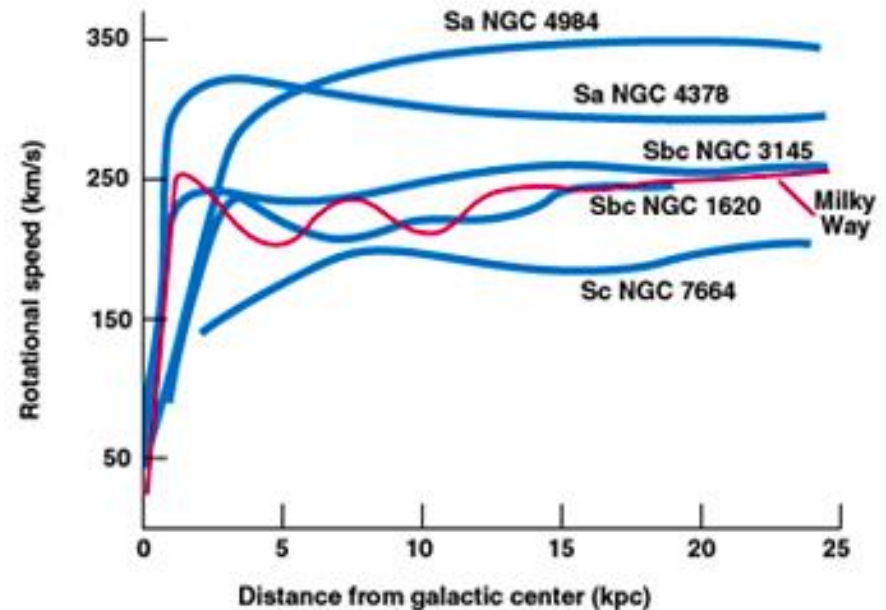
Rotation Curves

- In the Solar System



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

- In galaxies



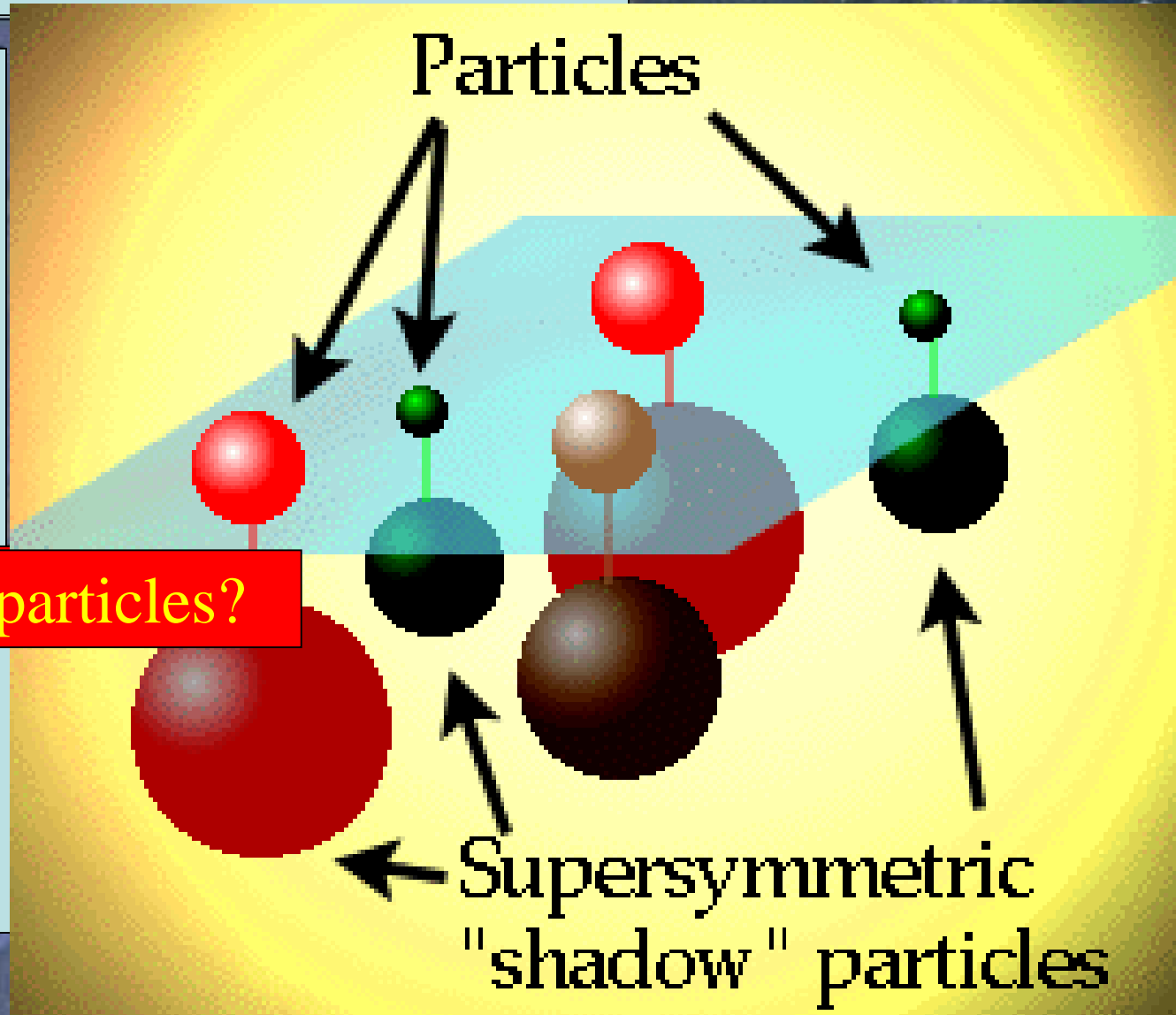
- The velocities do not decrease with distance
- Dark matter spread out

Dark Matter in the Universe

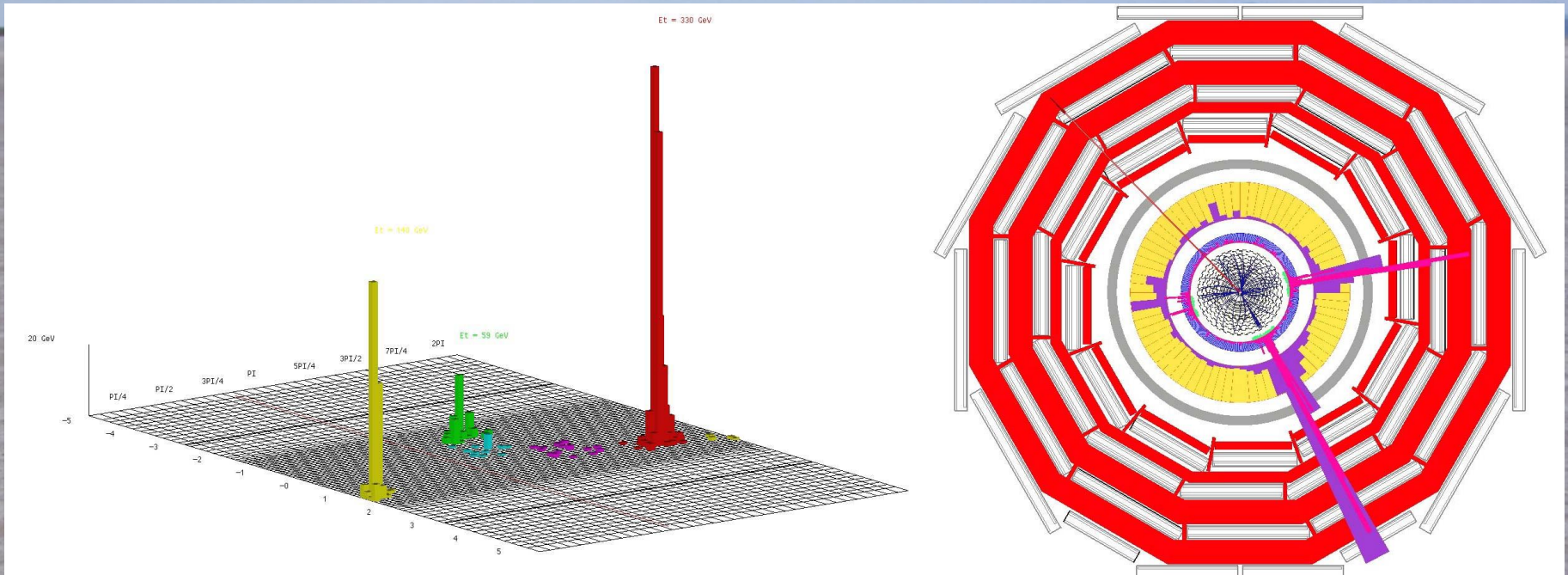
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Supersymmetric particles?

Searching for them at the LHC

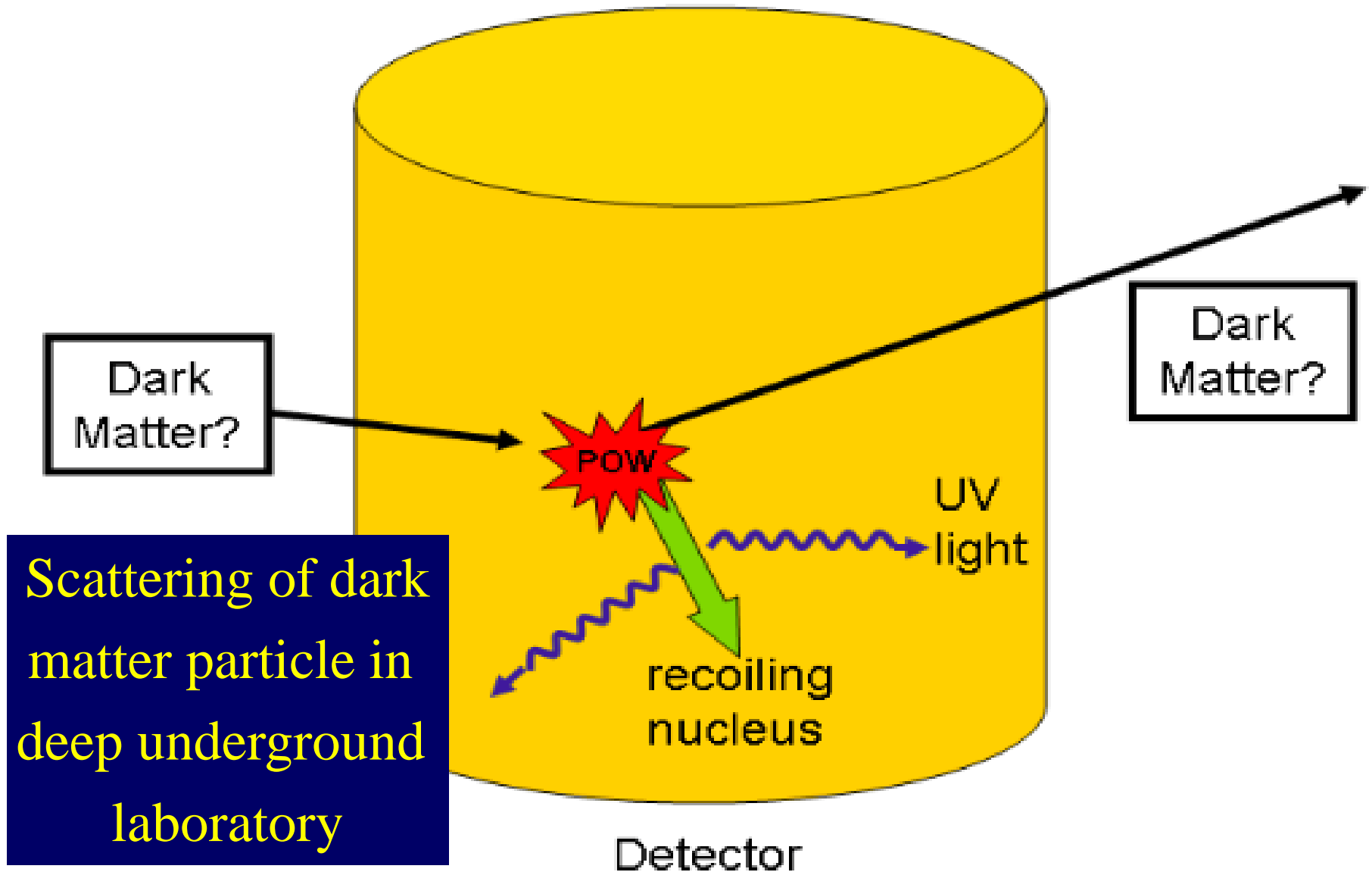


Classic Dark Matter Signature



Missing transverse energy
carried away by dark matter particles

Direct Dark Matter Detection



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

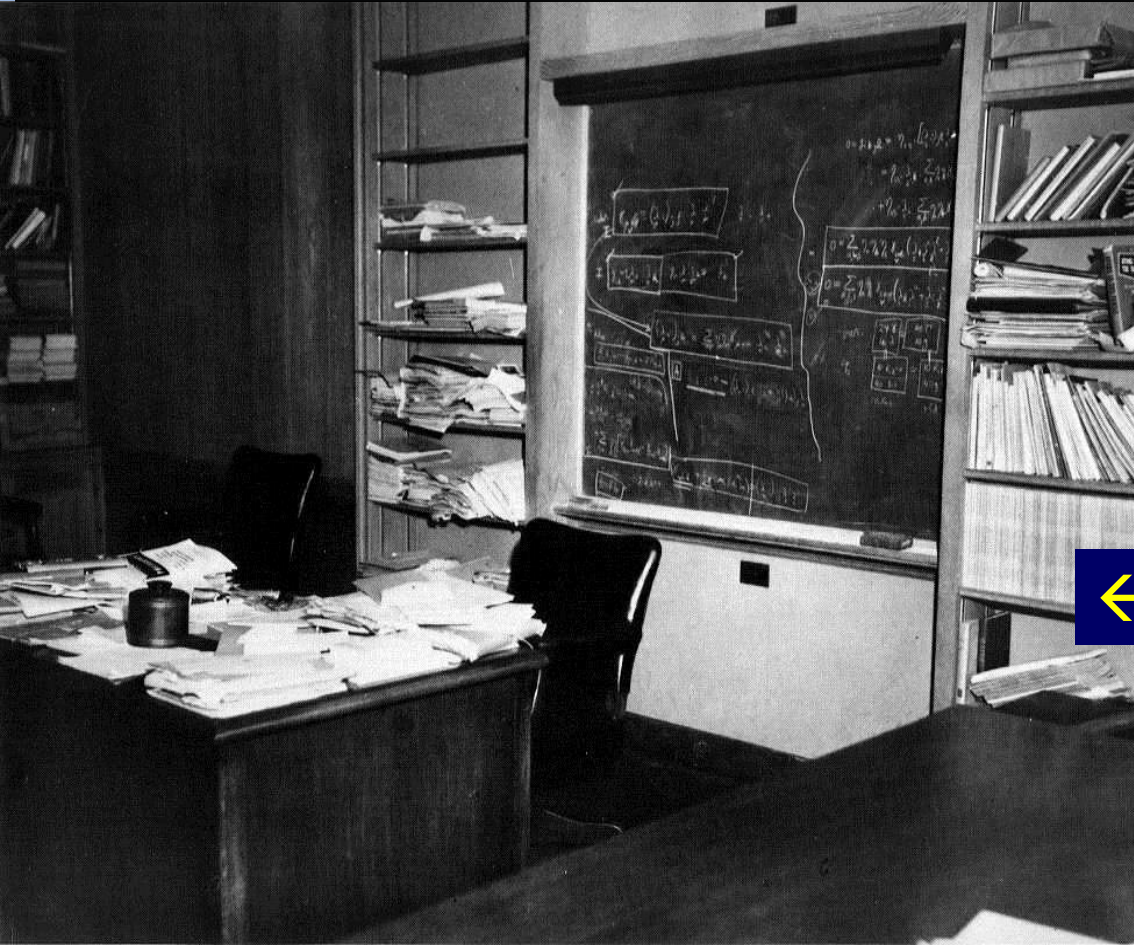


Matter and antimatter not quite equal and opposite: WHY?

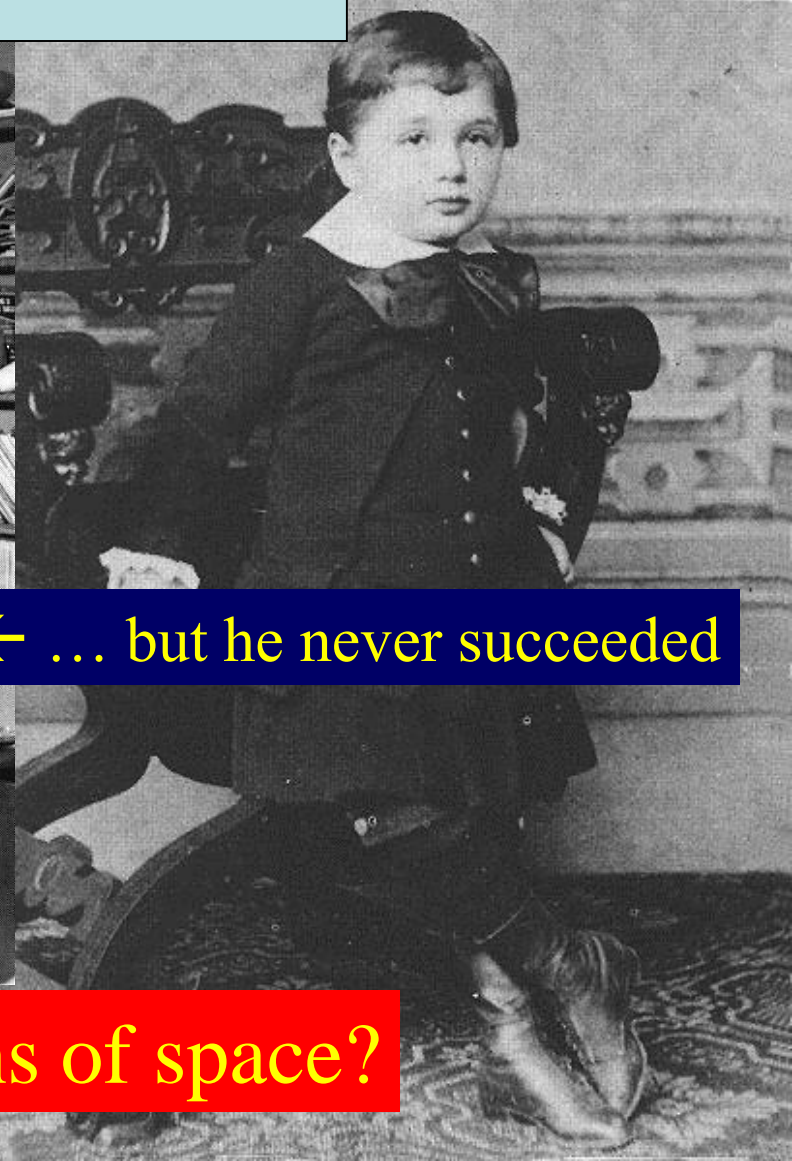
Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

Unify the Fundamental Interactions: Einstein's Dream ...



← ... but he never succeeded



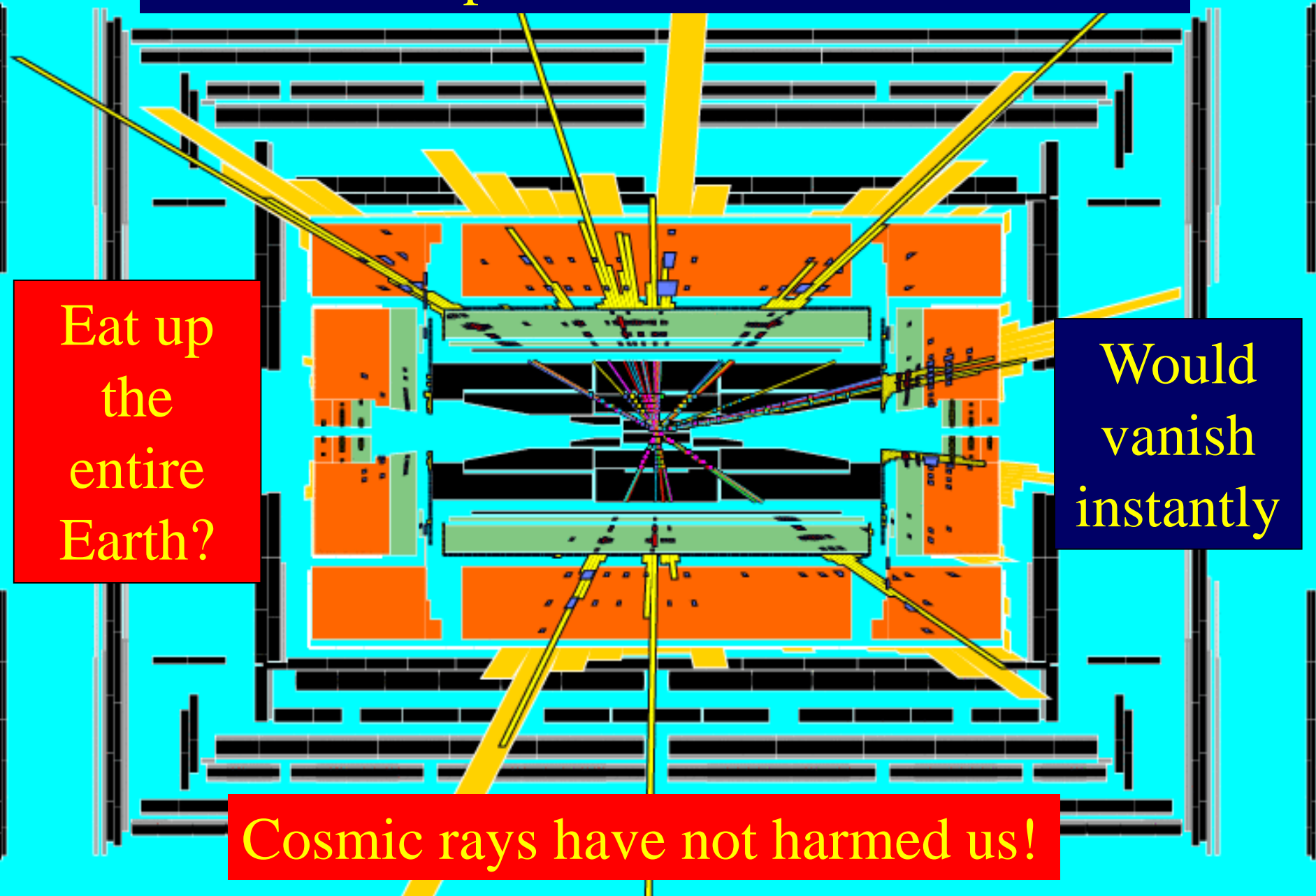
Unification via extra dimensions of space?

Will LHC experiments create black holes?

Eat up
the
entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!



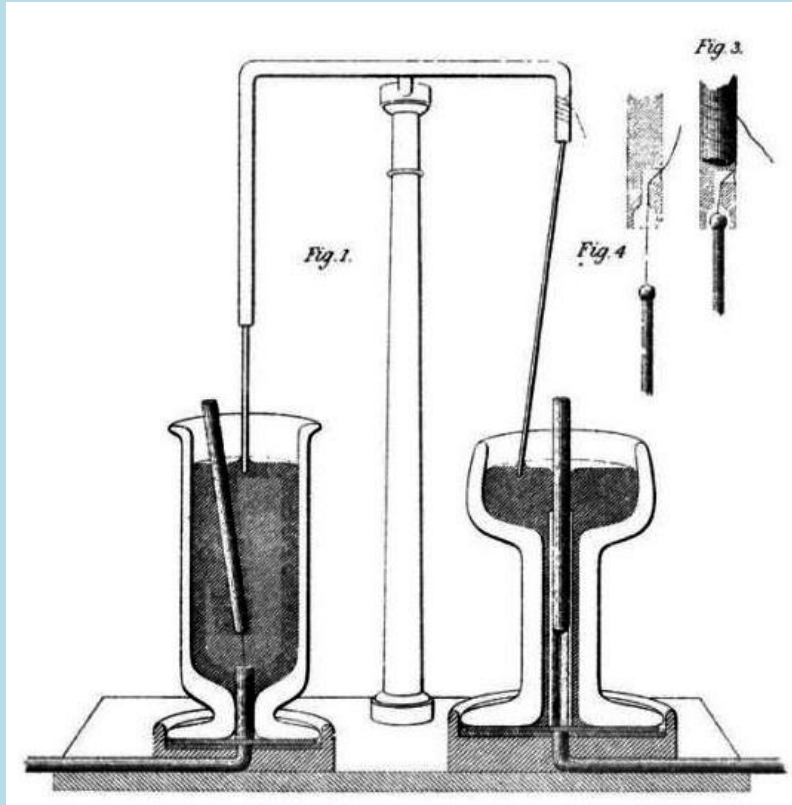
The LHC is the world's most powerful microscope ...



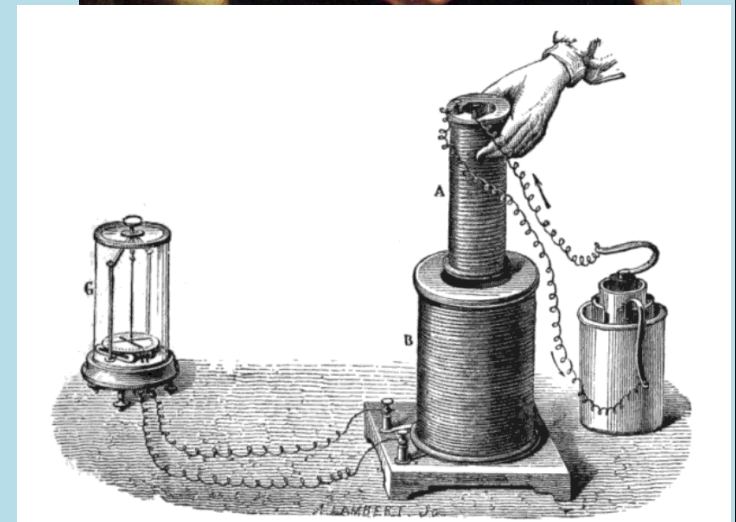
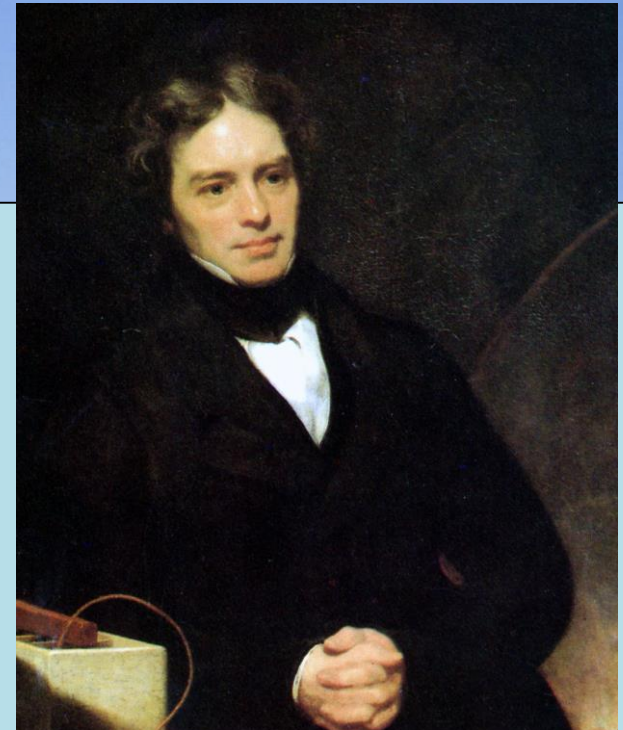
... and also a telescope
addressing Gauguin's
questions

Michael Faraday

- Invented the electric motor



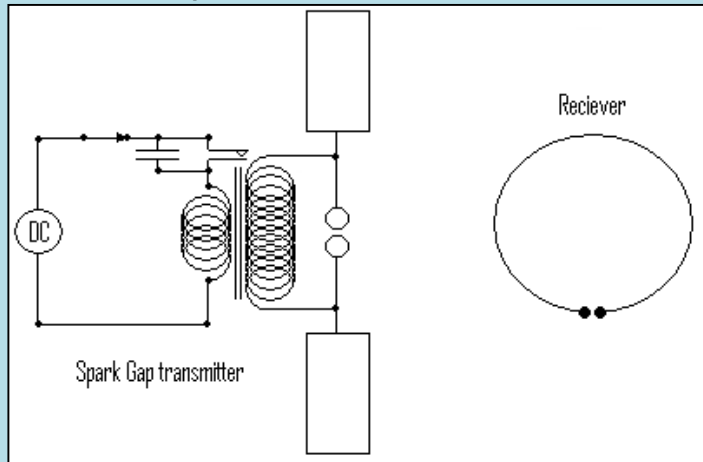
- Discovered induction



Einstein's study had pictures of Newton, Faraday and Maxwell

Electromagnetic Waves

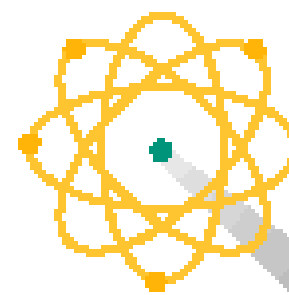
- Proposed by Maxwell
- Discovered by Hertz



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



Inside Matter



atoms have electrons ...



orbiting a nucleus ...

which is made of protons ...



... and neutrons

which are made of quarks, up-quarks and down-quarks ...



which are at the current limit of our knowledge

All matter is made of the same constituents

What are they?
What forces between them?

Maxwell's Equations

- Prototype for describing particle interactions:

**unified
electricity &
magnetism**

$$\nabla \cdot \mathbf{E} = \rho$$

Electric charge

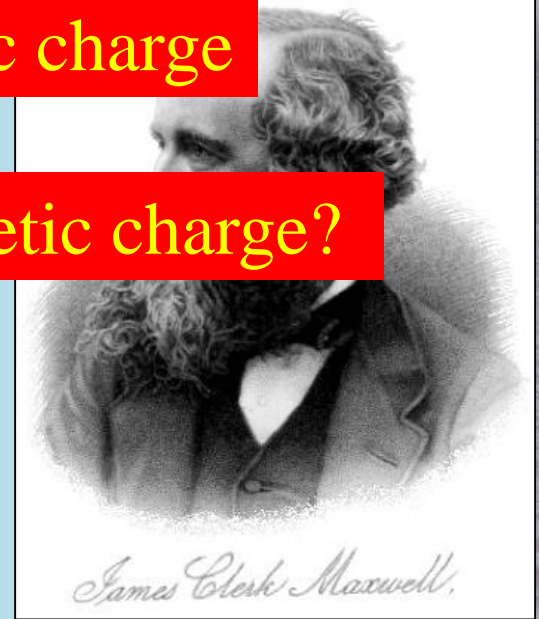
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

Magnetic charge?

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mathbf{j}$$

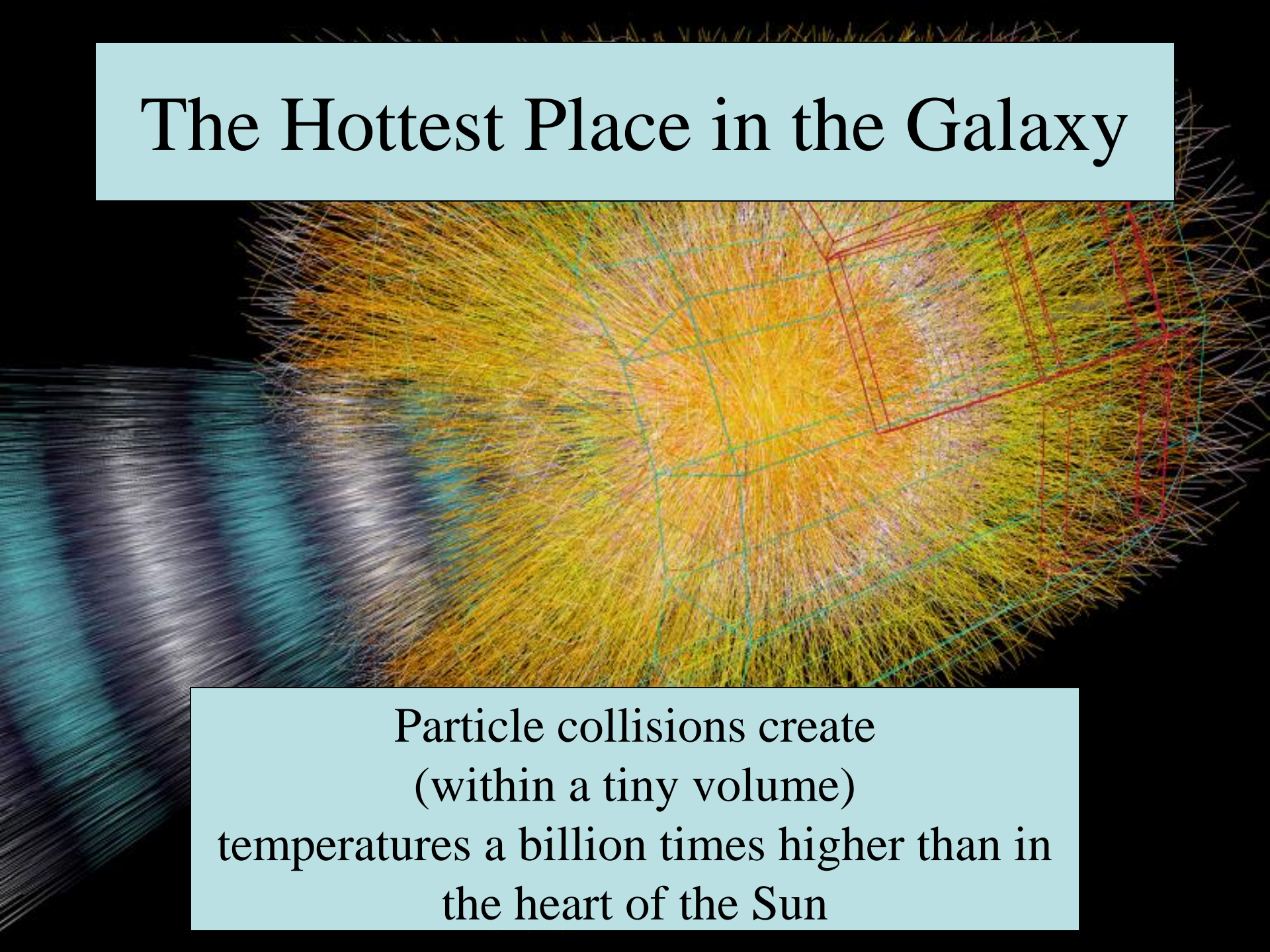
- Basis for Einstein's theories of relativity



James Clerk Maxwell.

There is every probability that you will soon be able to tax it!
*Fraday to William Gladstone, then Chancellor of the Exchequer, when he asked about
the practical worth of electricity*

The Hottest Place in the Galaxy

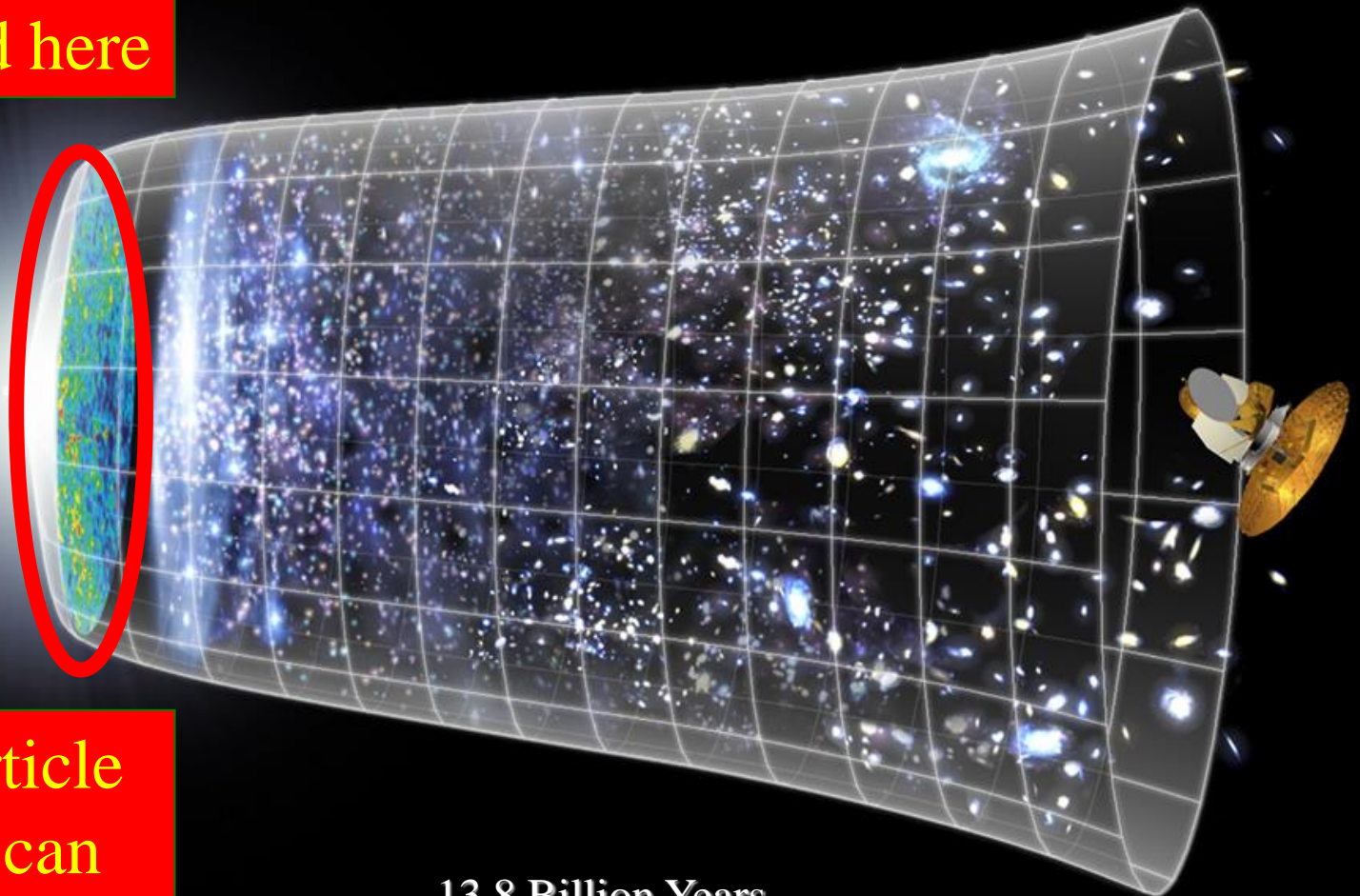


Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in
the heart of the Sun

Evolution of the Universe

Matter and dark matter originated here

Big Bang



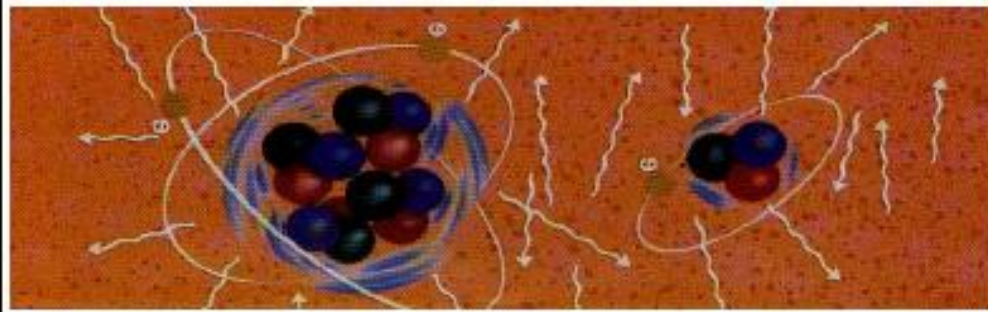
Only particle physics can tell us how

13.8 Billion Years

10^{28} cm

Today

300,000
years



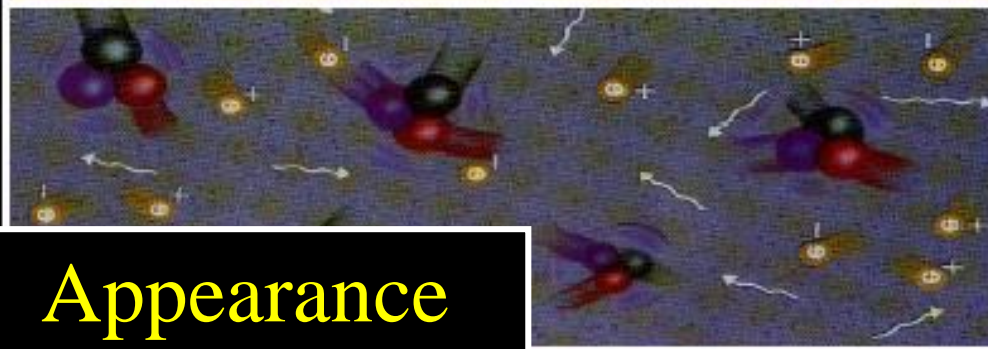
Formation
of atoms

3
minutes



Formation
of nuclei

1 micro-
second



Formation
of protons
& neutrons

1 pico-
second

Appearance
of dark matter?

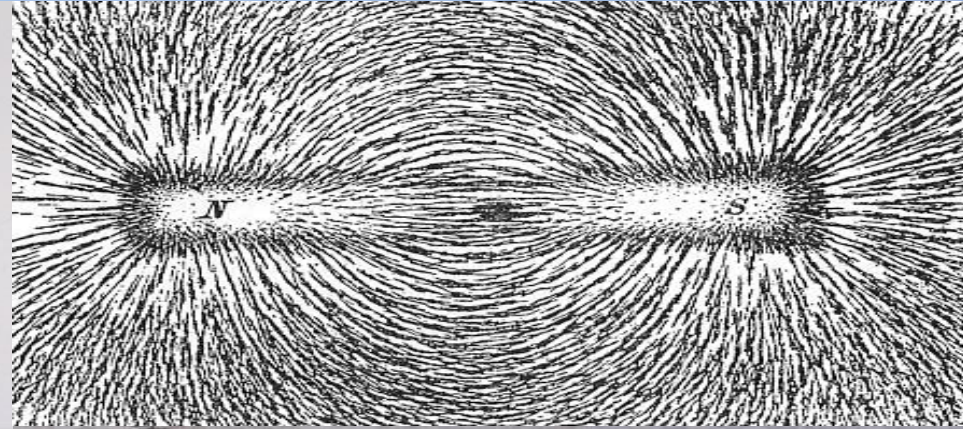


Appearance
of mass?

BANG!

Appearance
of matter?

Electricity and Magnetism



- Electricity:

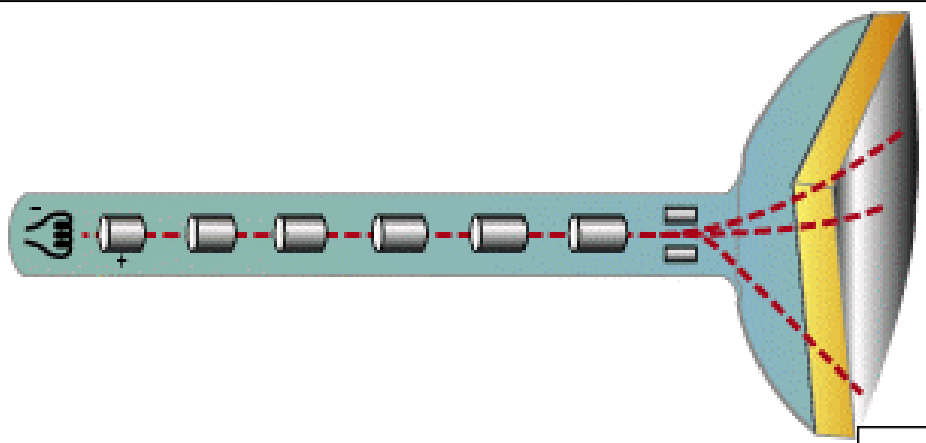
- Named using the Greek word for amber
- Fish, lightning, ...
- Static electricity and electric currents

- Magnetism:

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

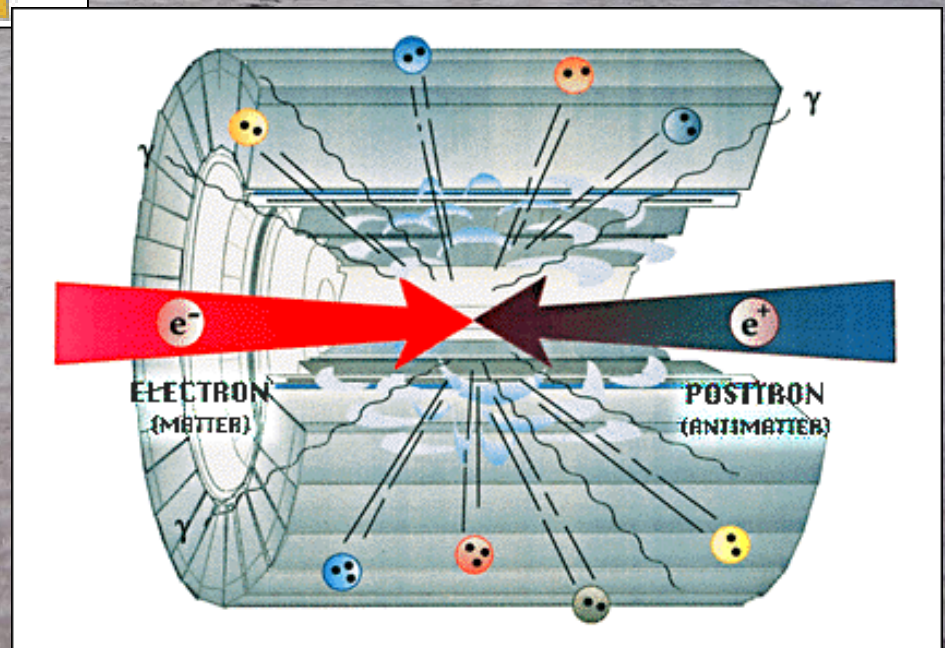
The first fundamental forces to be unified

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 produced

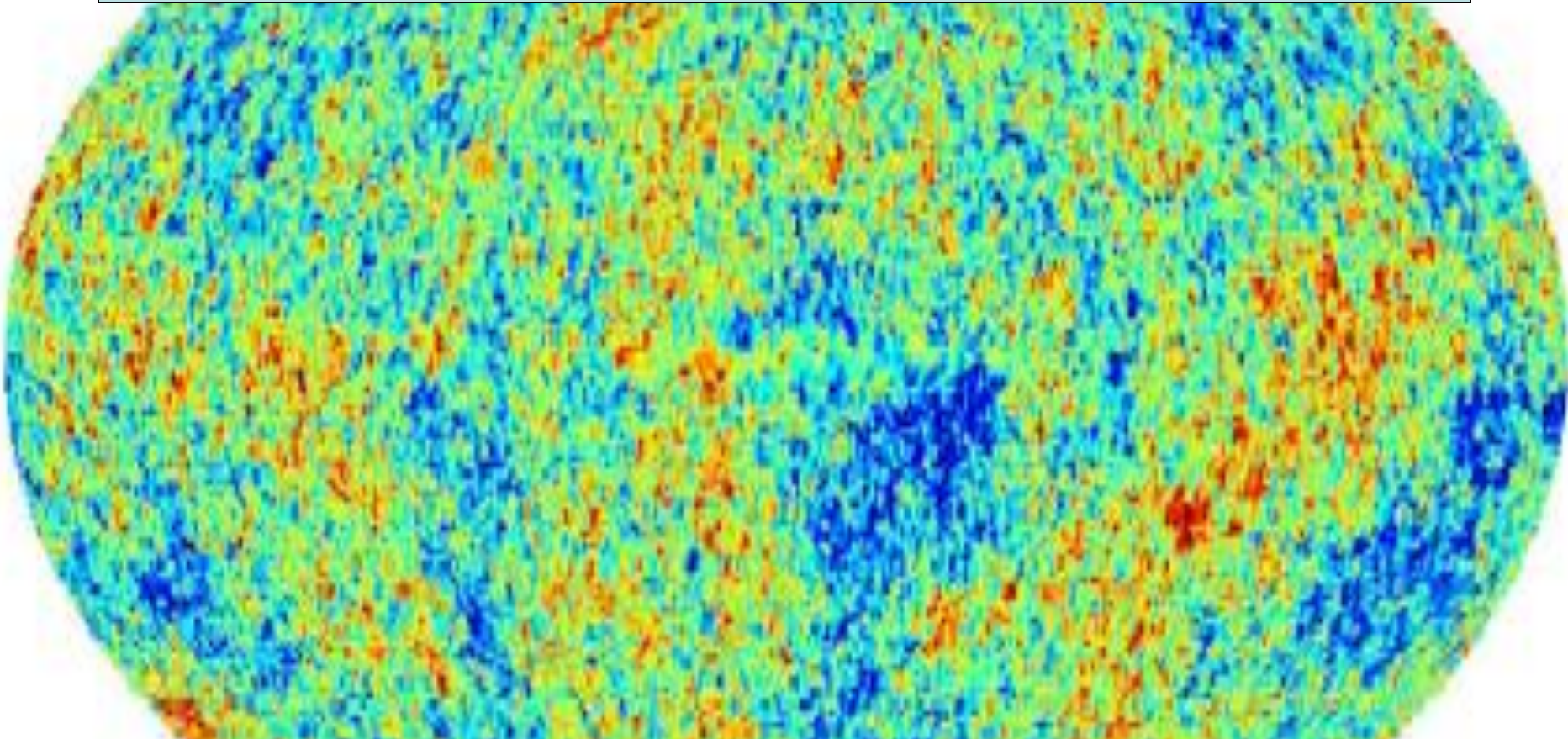


The Emptiest Space in the Solar System

A long, brightly lit tunnel filled with complex machinery and pipes, likely a particle accelerator or synchrotron facility. The perspective is from the end of the tunnel, looking down its length. The walls are lined with various pipes, conduits, and structural elements. The lighting is warm and focused on the central path of the tunnel.

Vacuum similar to interplanetary space:
the pressure in the beam-pipes will be ten
times lower than on the Moon.

Cooler than Outer Space

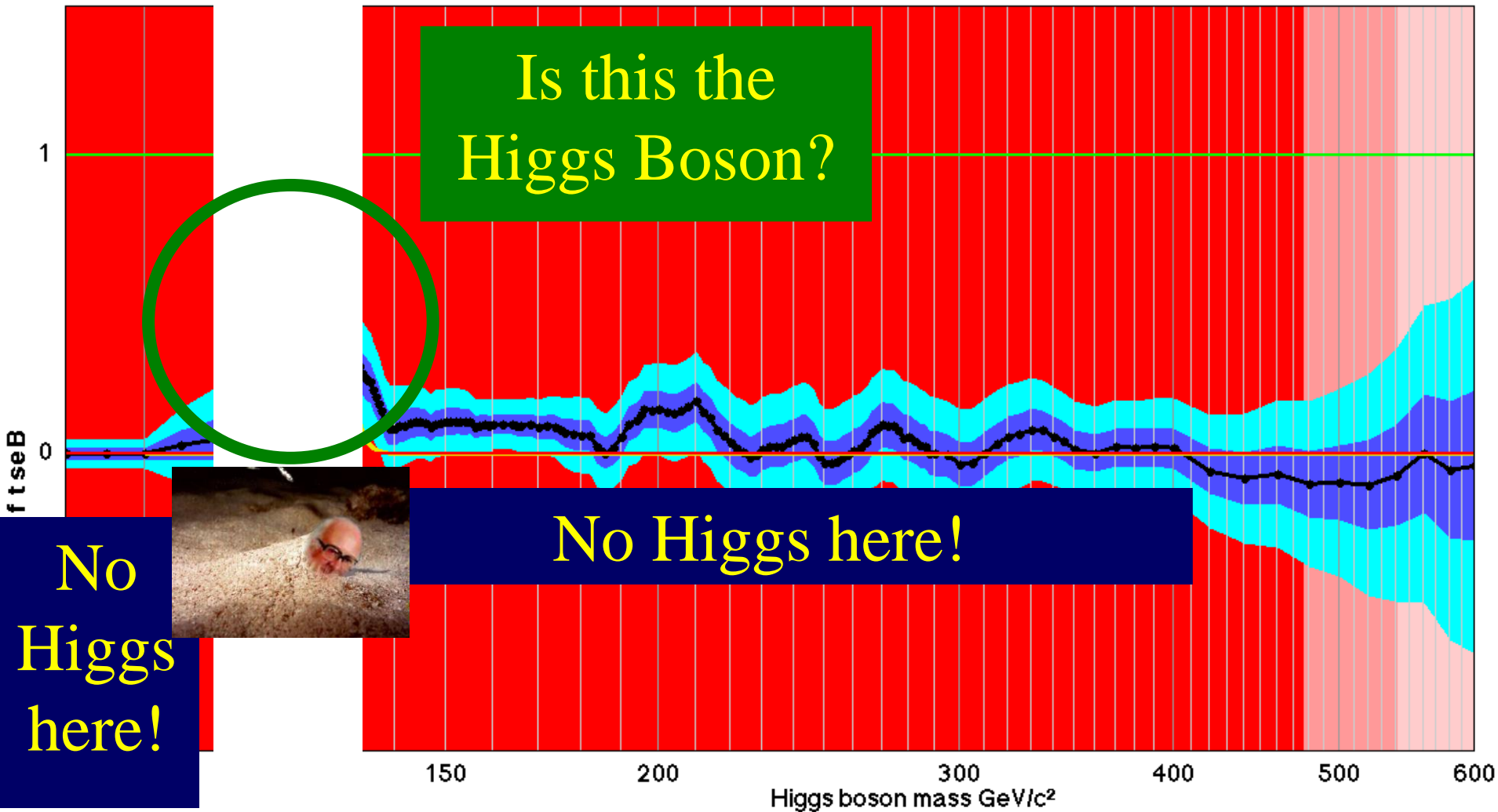


LHC 1.9 degrees above absolute zero = - 271 C
Outer space 2.7 degrees above zero = - 270 C

Unofficial Combination of Higgs Data

1/fb - 10/fb

06/03/2013



The Particle Higgsaw Puzzle



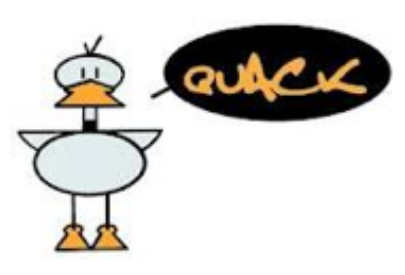
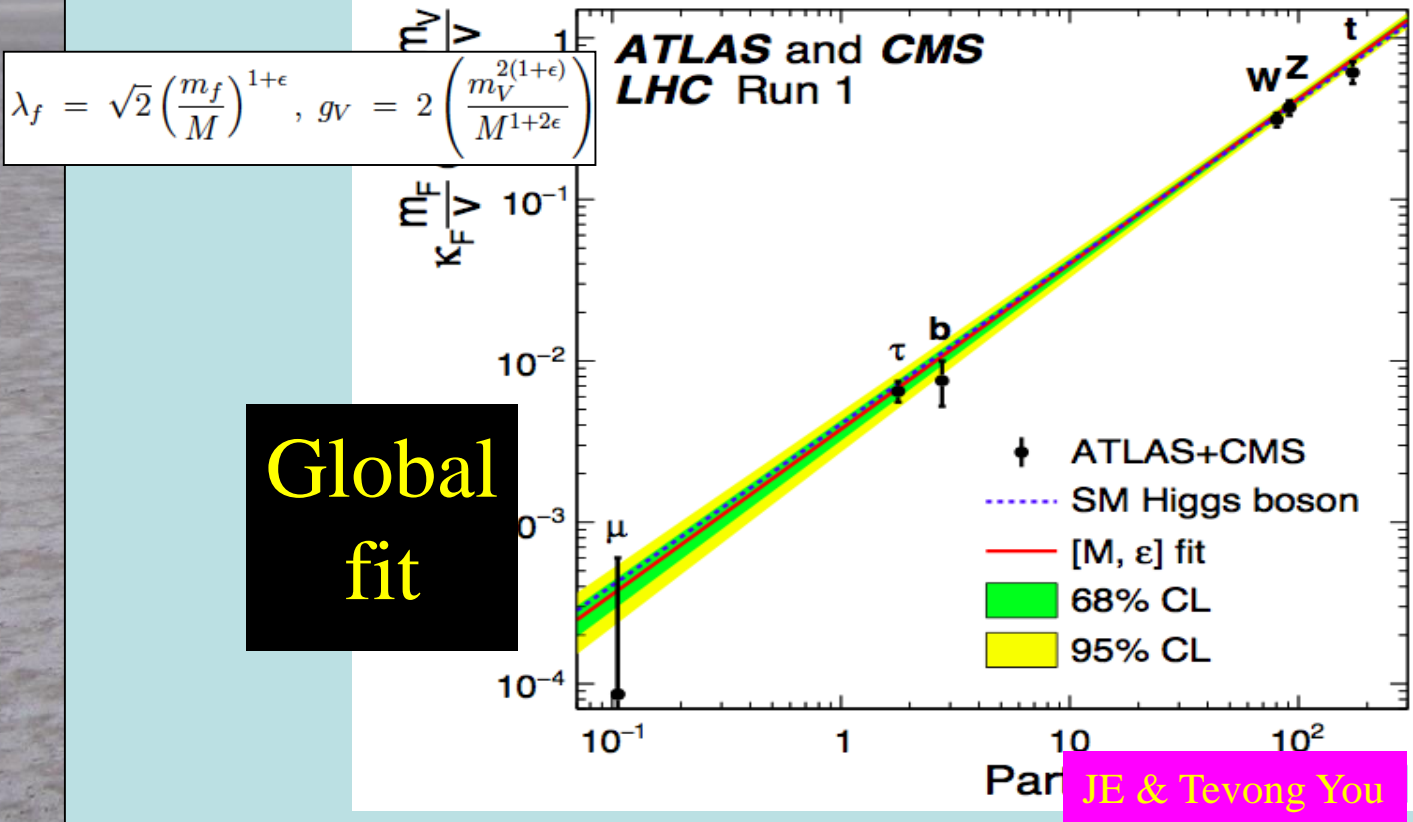
Did the LHC find the missing piece?

Is it the right shape?

Is it the right size?

It Walks and Quacks like a Higgs

- Do couplings scale \sim mass? With scale = v ?



JE & Tevong You

- **Blue** dashed line = Standard Model