

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?

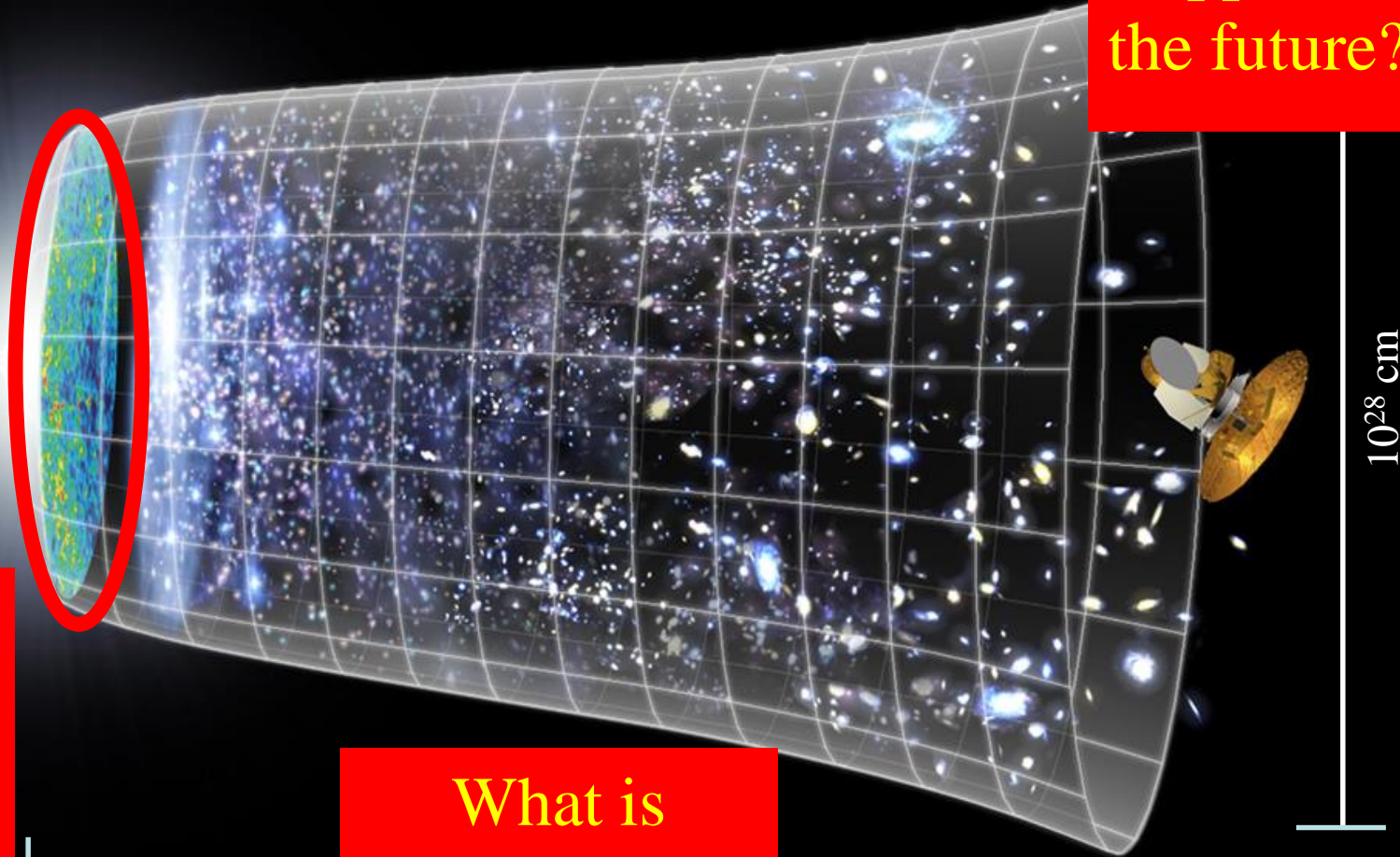
John Ellis

KING'S
College
LONDON

Evolution of the Universe

What will happen in the future?

Big Bang



10^{28} cm

Today

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 Universe?

LHC

- How does the Universe evolve?

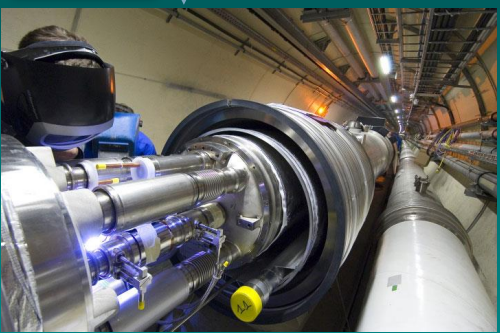
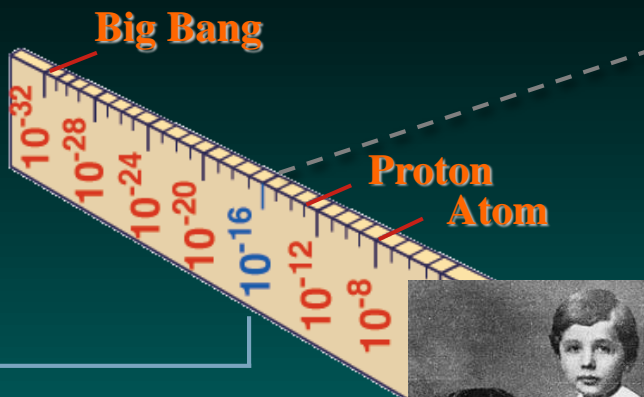
- Why is the Universe so big and old?

LHC

- What is the future of the Universe?

LHC

Our job is to ask - and answer - these questions

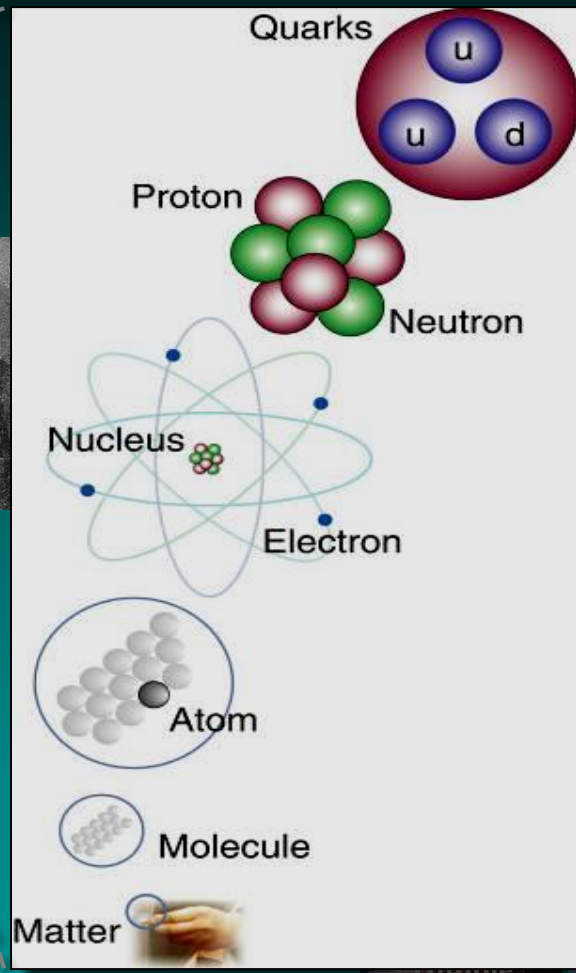


LHC

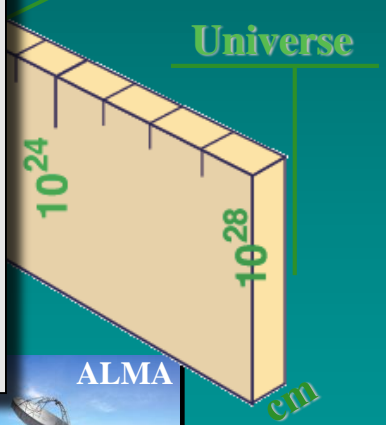
Super-Microscope



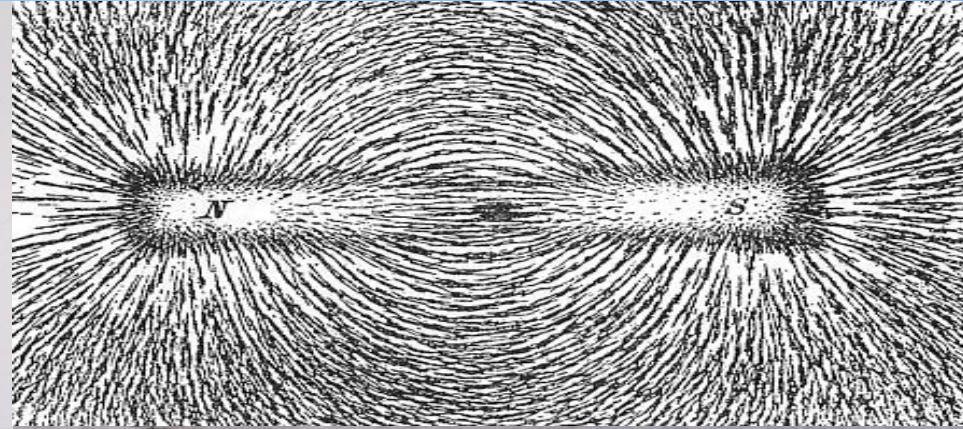
Study physics laws of first moments after Big Bang
 increasing Symbiosis between Particle Physics,
 Astrophysics and Cosmology



Radius of Galaxies



Electricity and Magnetism



- Electricity:

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

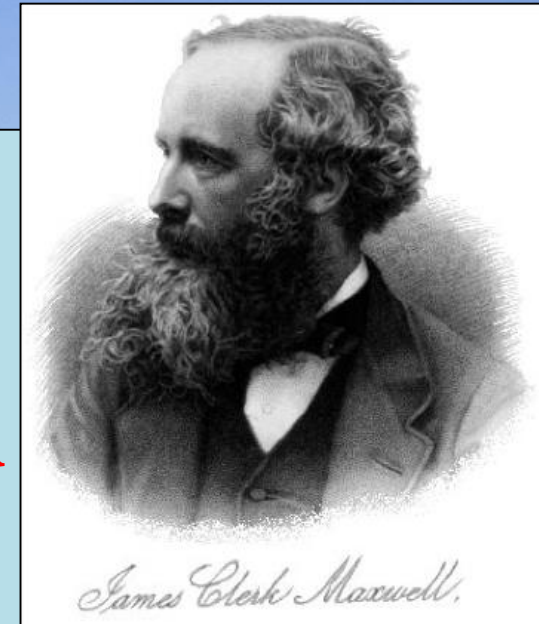
- Magnetism:

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

The first fundamental forces to be unified

James Clerk Maxwell

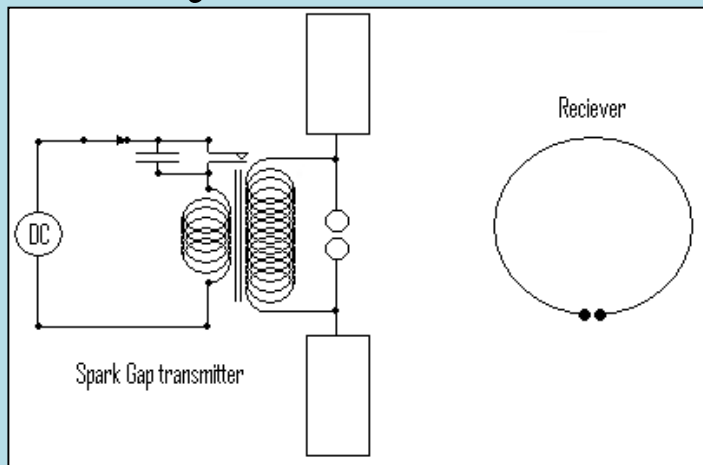
- Professor at King's 1860 – 1865
- The first colour photograph
- **Unified theory of electricity and magnetism**
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light



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

Electromagnetic Waves

- Proposed by Maxwell
- Discovered by Hertz



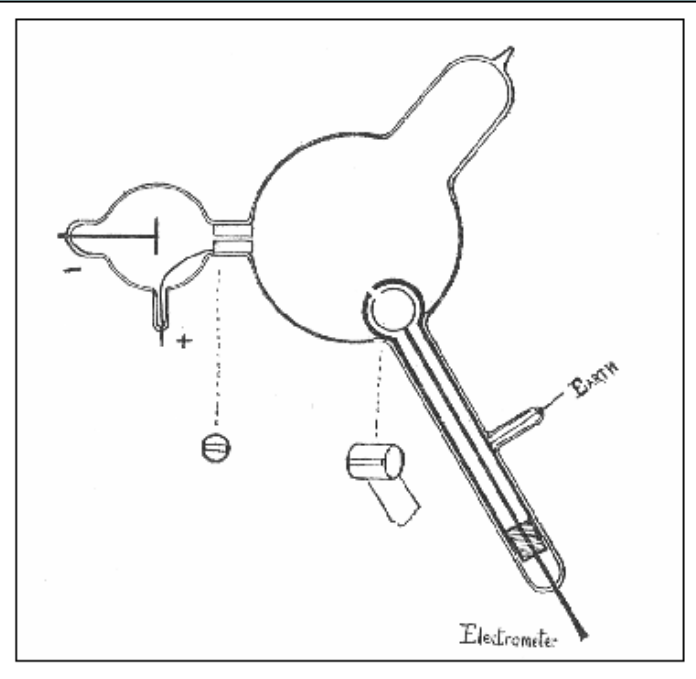
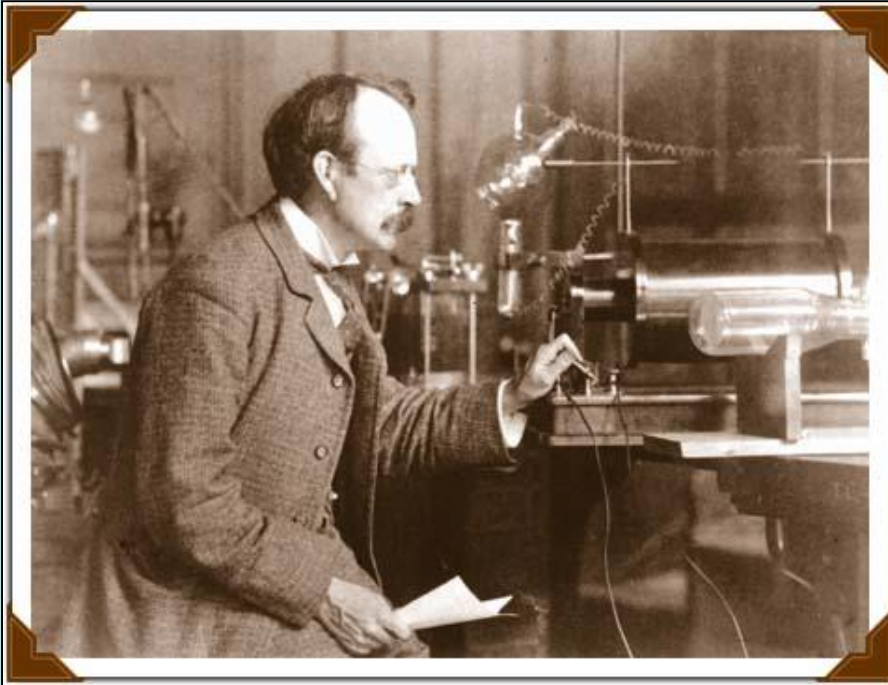
- A lot to answer for
- **Nobody knows where fundamental physics may lead**

Gravitational waves?



The First Elementary Particle

- Discovered by J.J. Thomson in 1897



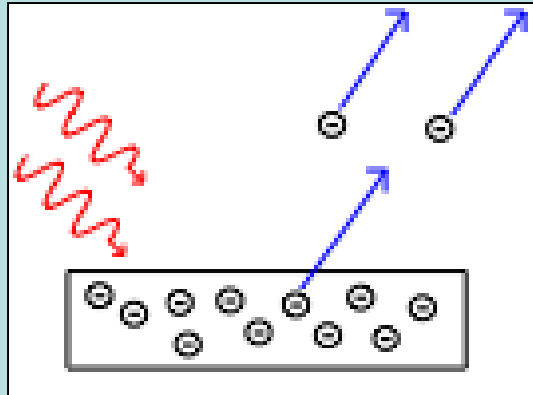
- **The electron** – the basis of the electronic industry
- Old-style TV sets used beams of electrons

Photon: the Particle of Light

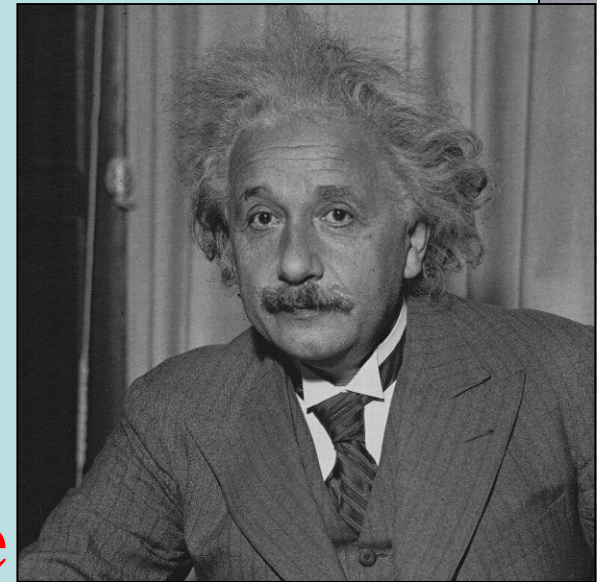
- Quantum hypothesis introduced by Planck:

$$E = hf$$

- Physical reality postulated by Einstein to explain photoelectric effect



- **Motivation for his Nobel Prize**

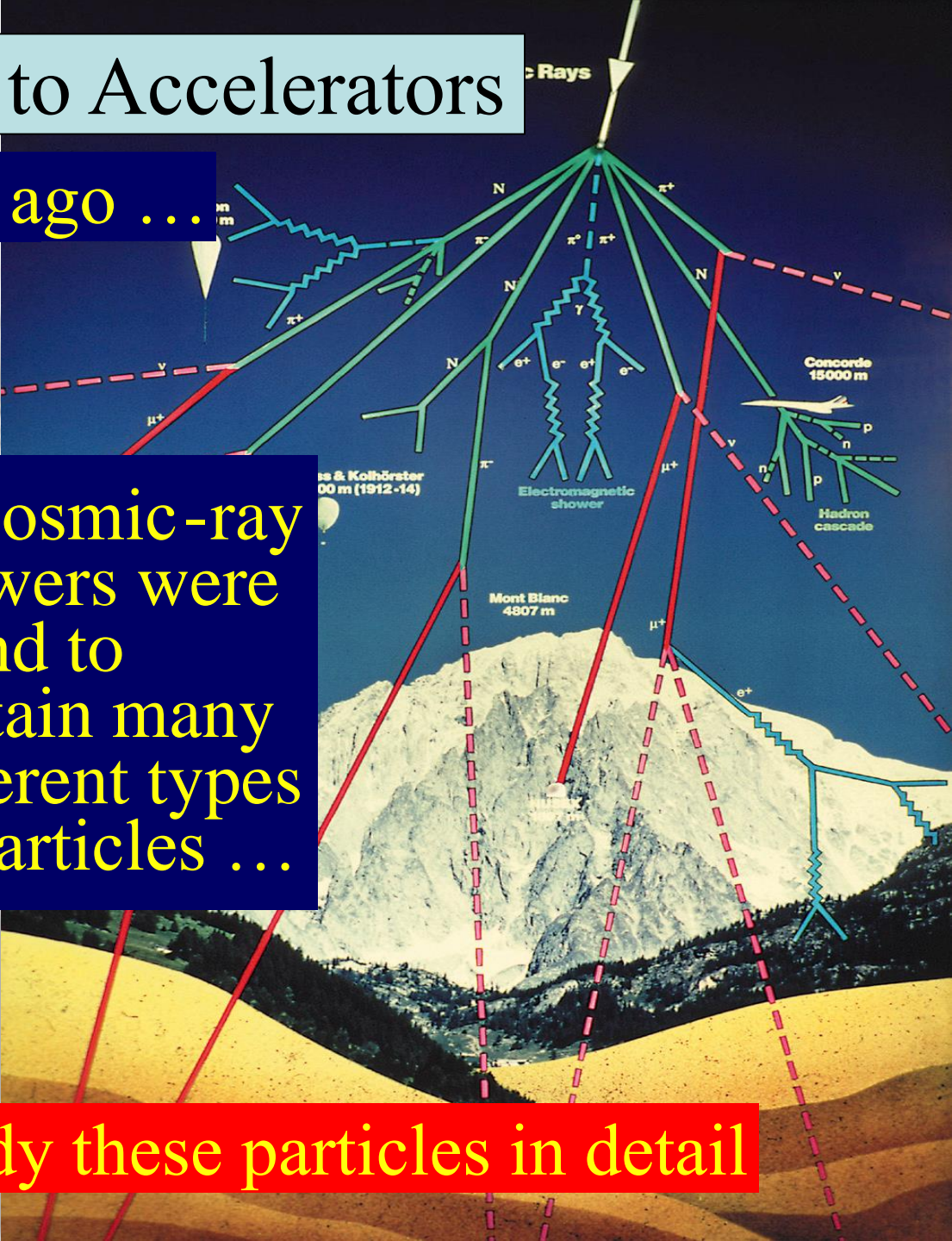
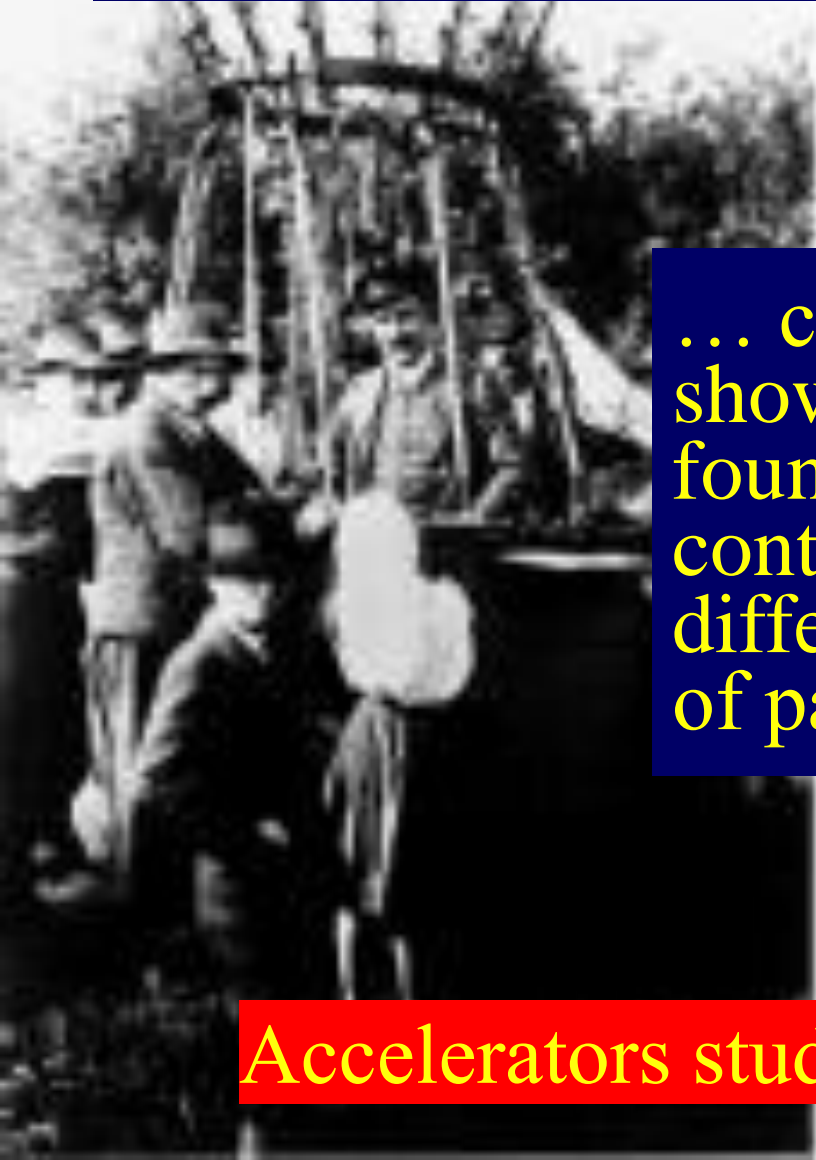


From Cosmic Rays to Accelerators

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

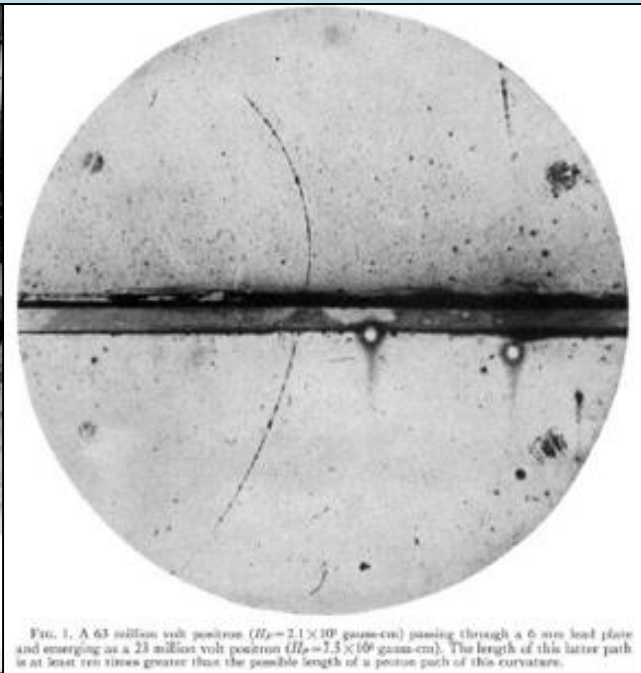
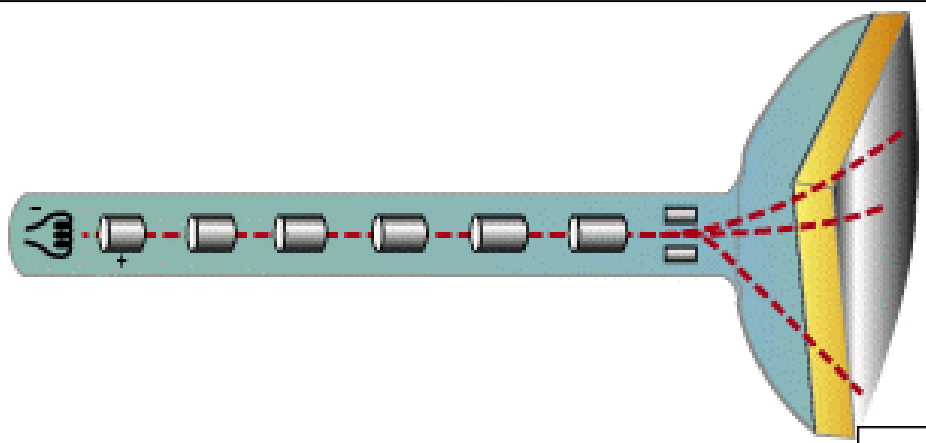


FIG. 1. A 65 million volt positron ($H_p=2.1 \times 10^6$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H_p=1.3 \times 10^6$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a positron path of this curvature.

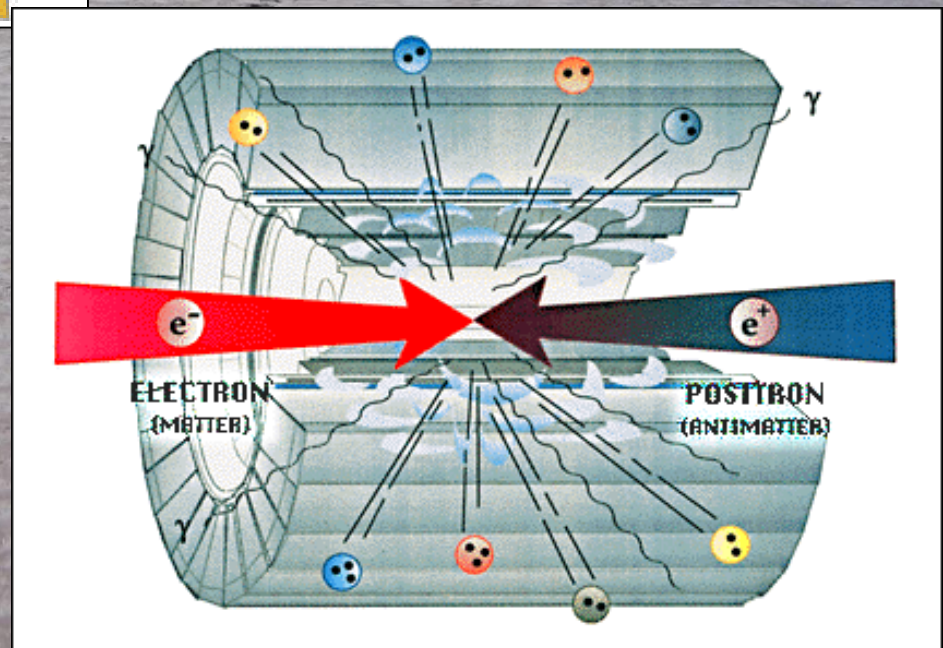
- The same mass as the electron, opposite electric charge
- Used in medical diagnosis (PET scanners)

Experiments at Accelerators



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

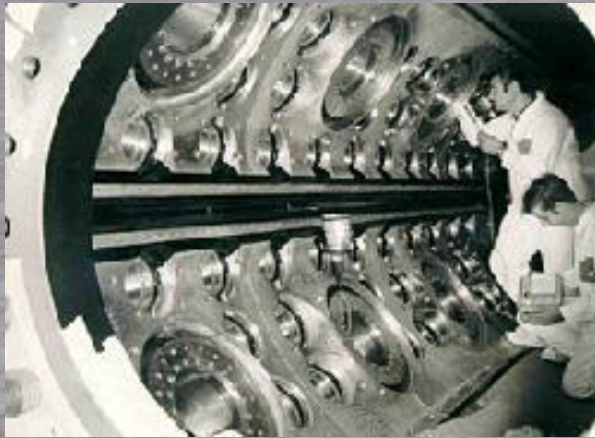
Collisions take place inside large detectors that observe and measure the particles produced



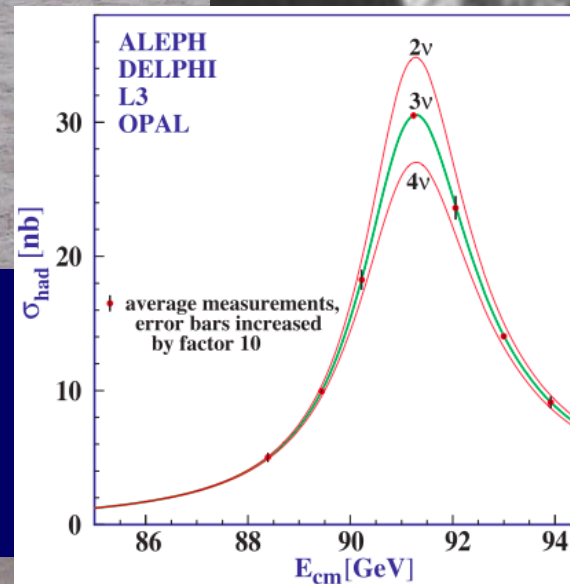
The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow and Weinberg

Tested by experiments
at CERN



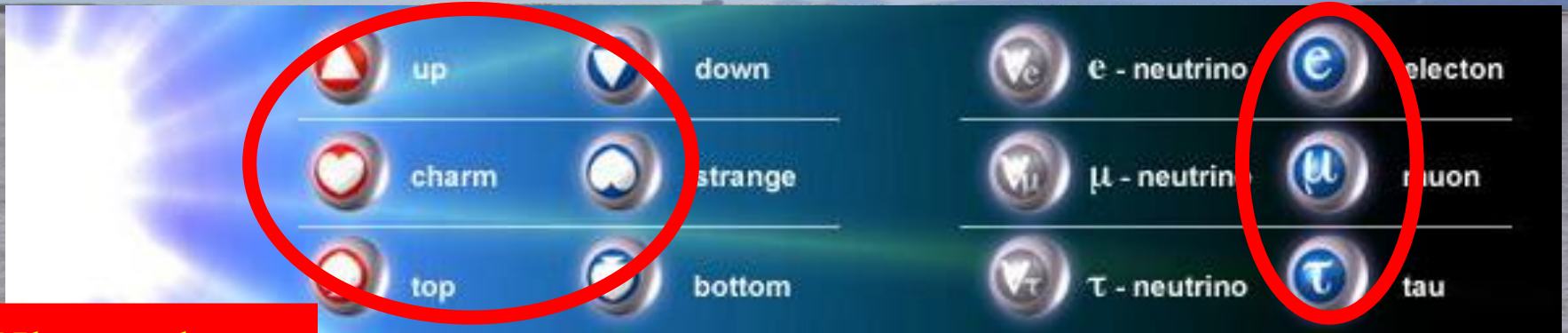
Perfect agreement between
theory and experiments
in all laboratories



The 'Standard Model'

= Cosmic DNA

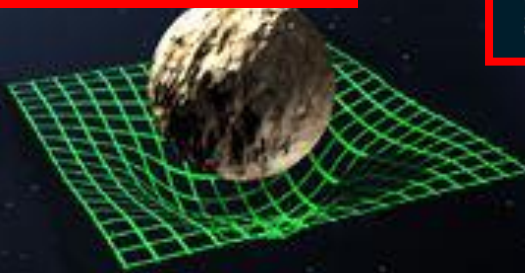
The matter particles



Where does mass come from?

The fundamental interactions

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Gravitation

electromagnetism

weak nuclear force

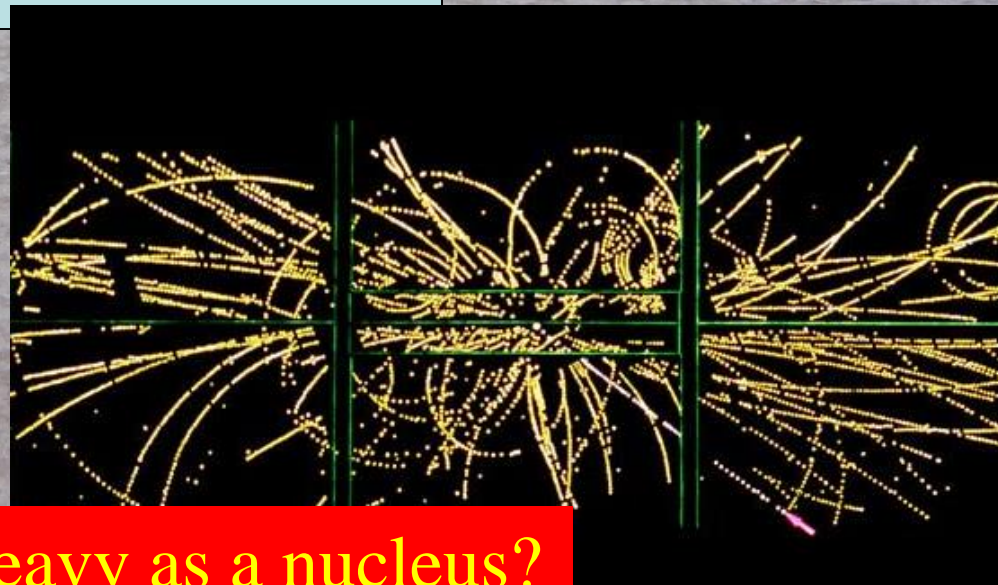
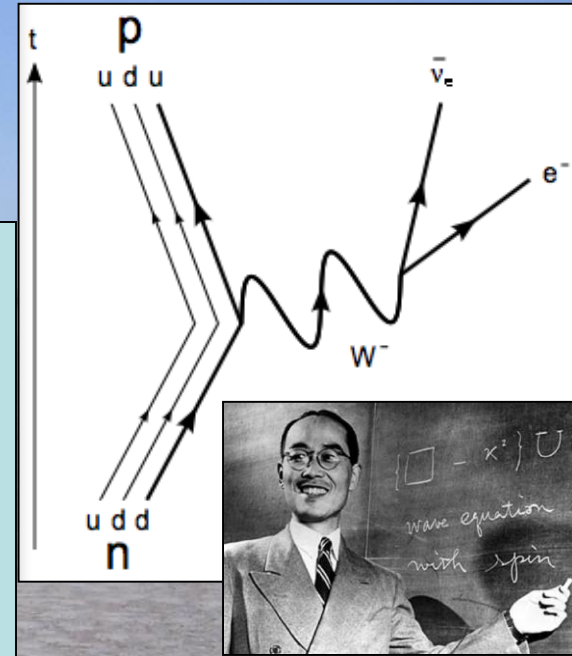
strong nuclear force

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)



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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



Hiker sinks deep,
moves very slowly:

Particle with large mass



**The LHC discovered
the snowflake:
The Higgs Boson**

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

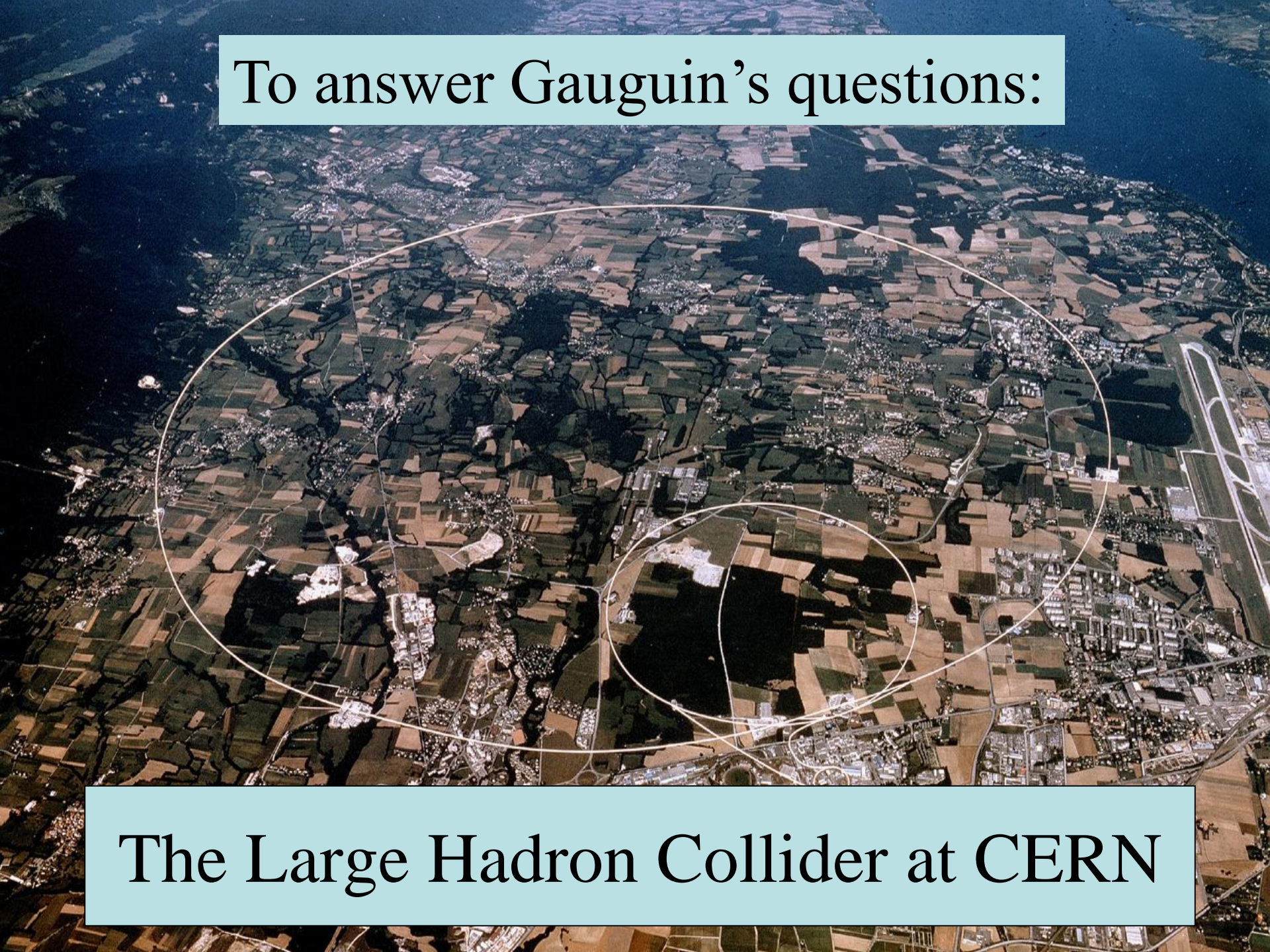
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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:

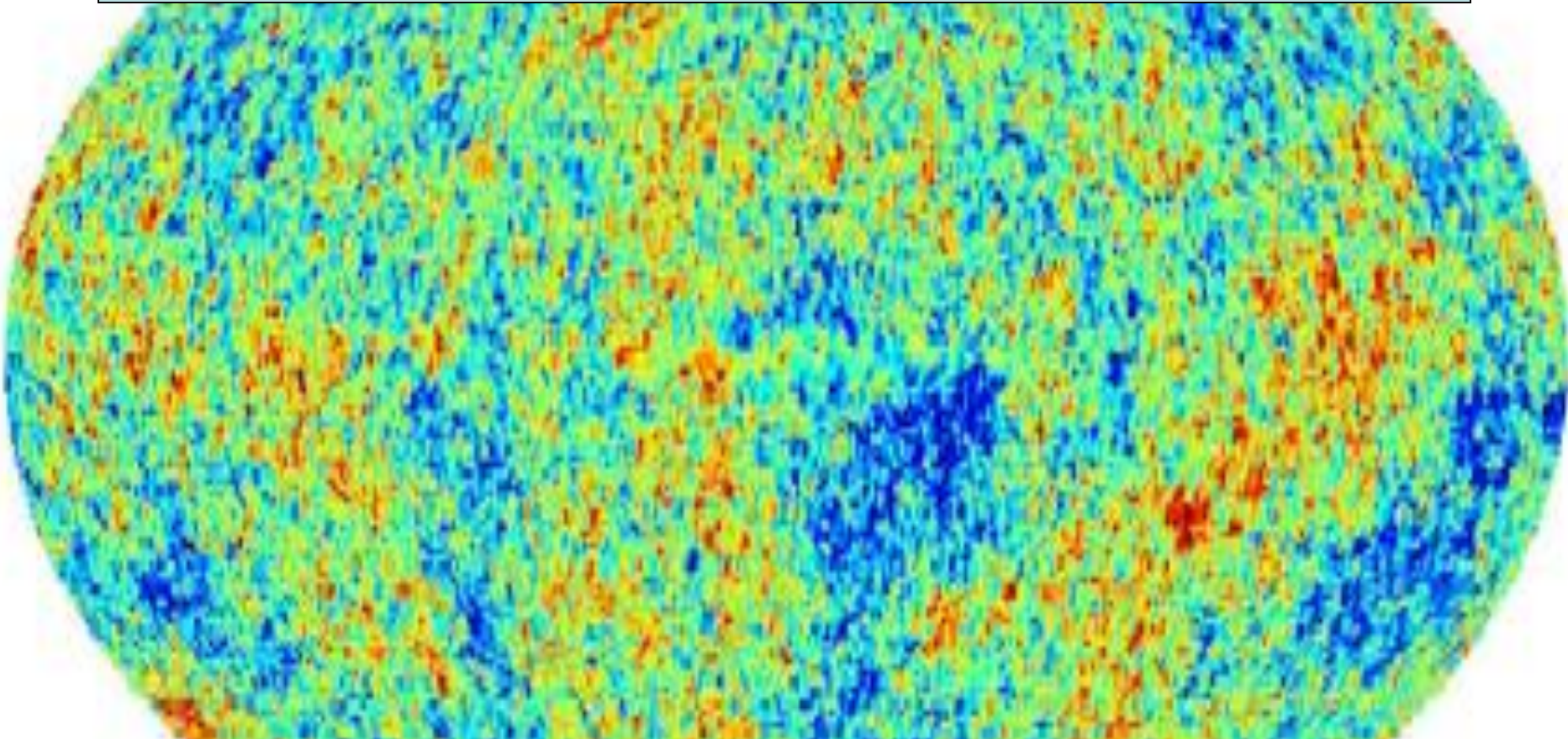
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

The Emptiest Space in the Solar System

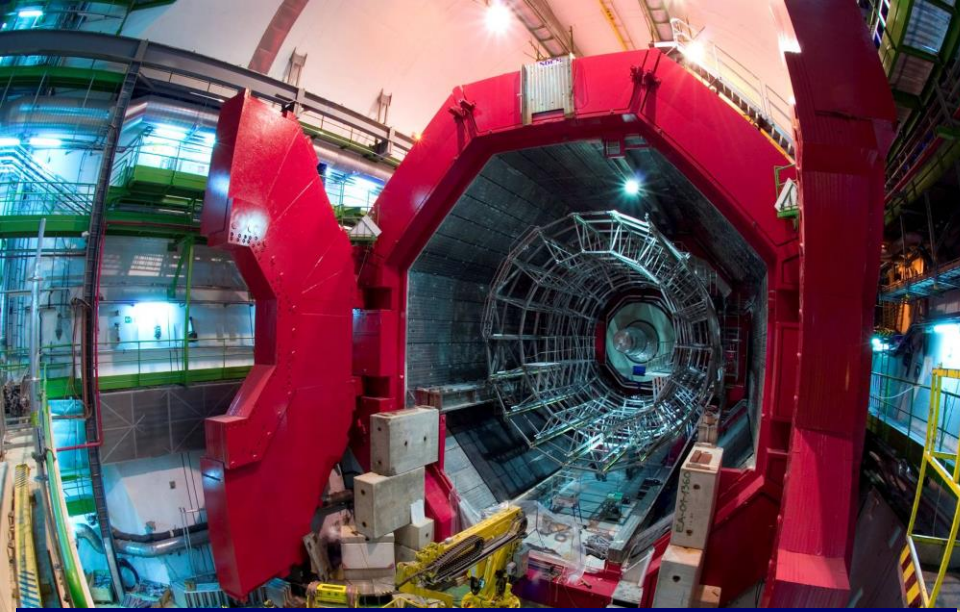
A long, brightly lit tunnel filled with complex machinery and pipes, likely a particle accelerator or synchrotron facility. The tunnel is filled with various components, including large cylindrical structures, pipes, and electrical conduits. The lighting is warm and focused on the machinery, creating a sense of depth and scale. The overall atmosphere is one of a highly technical and industrial environment.

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

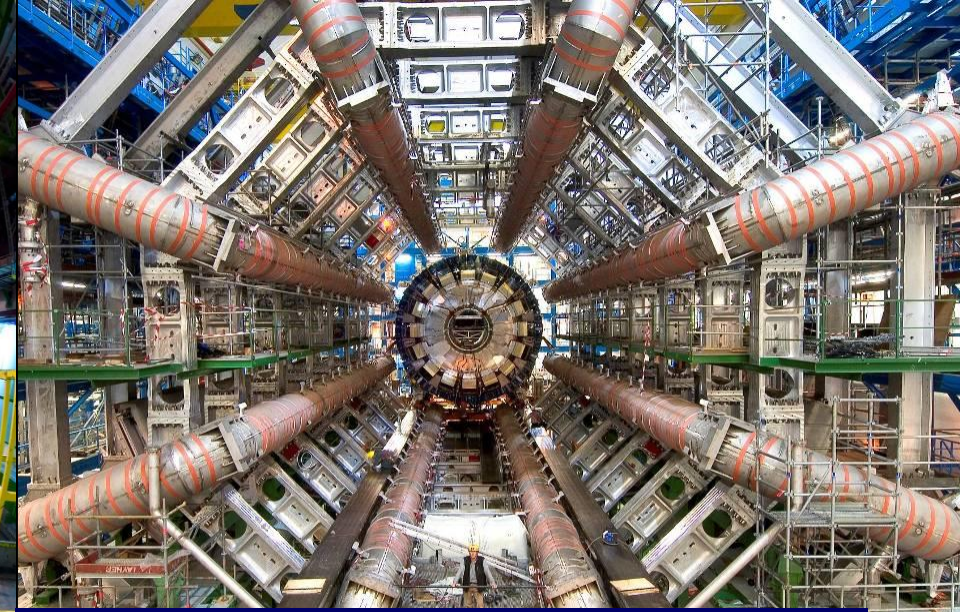
Cooler than Outer Space



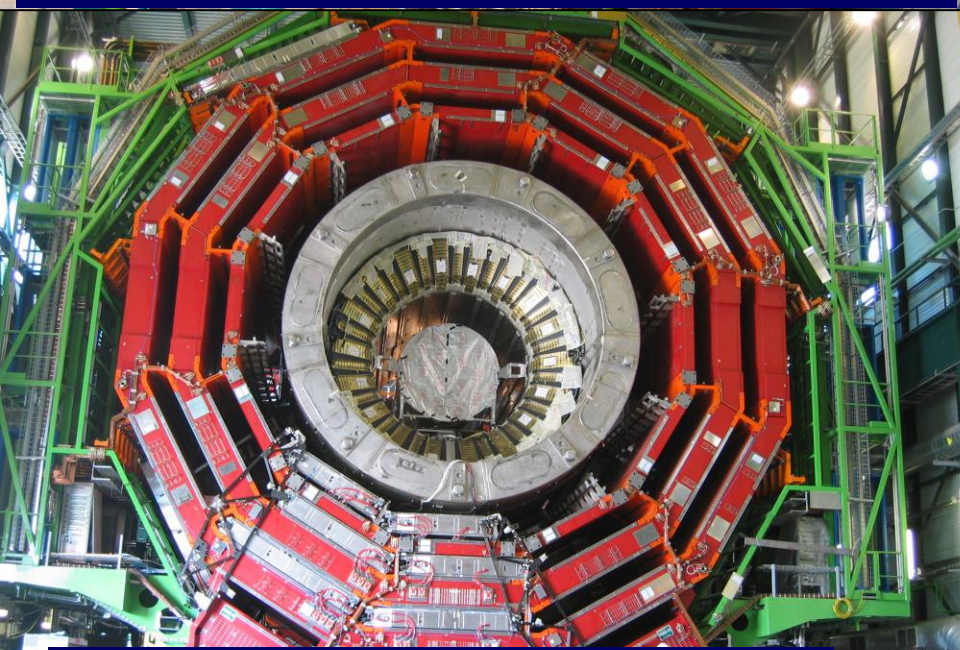
LHC 1.9 degrees above absolute zero = - 271 C
Outer space 2.7 degrees above zero = - 270 C



ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter



CMS: Higgs and dark matter



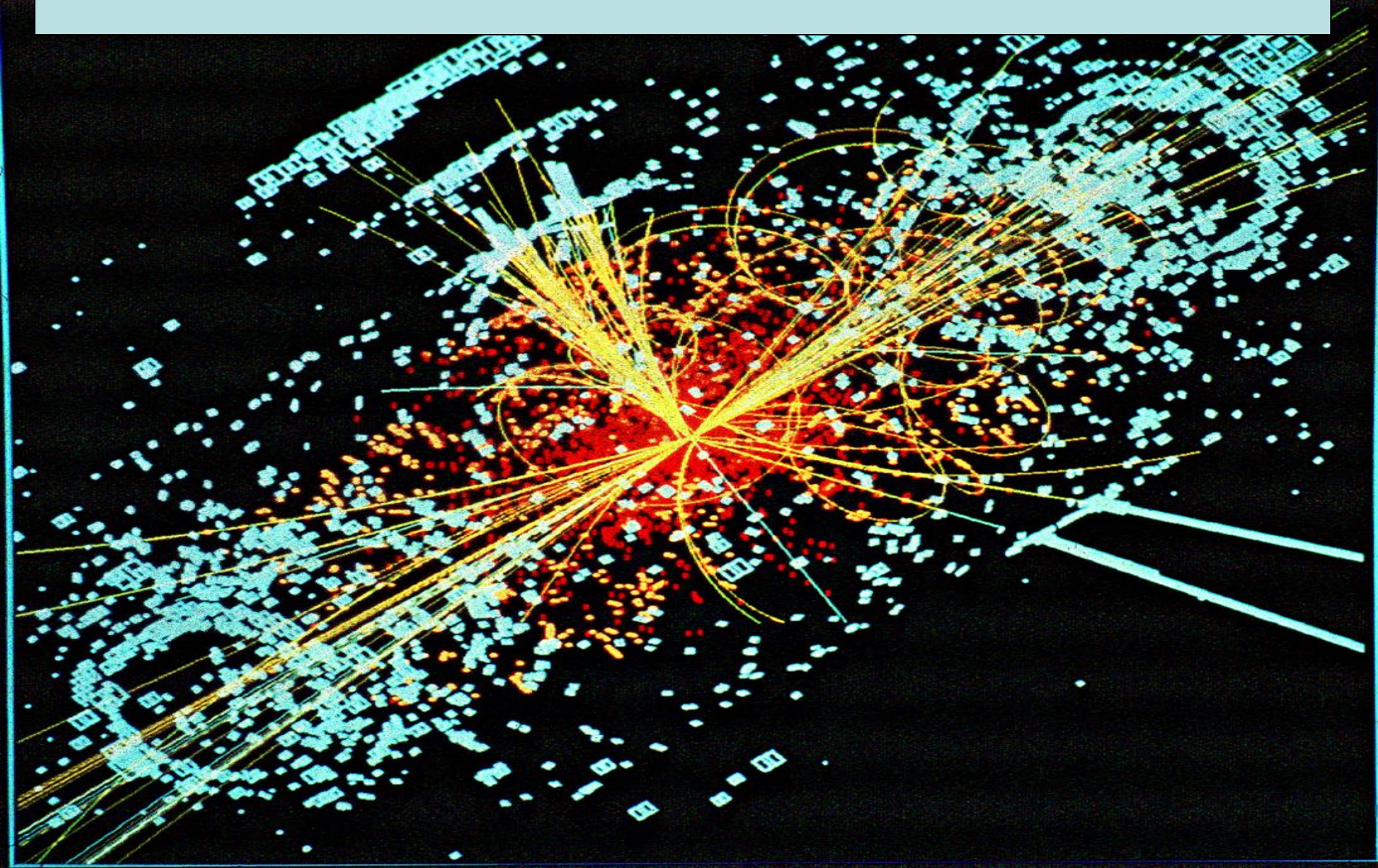
LHCb: Matter-antimatter difference

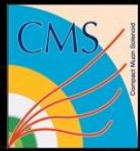
2012: The discovery of the Higgs Boson



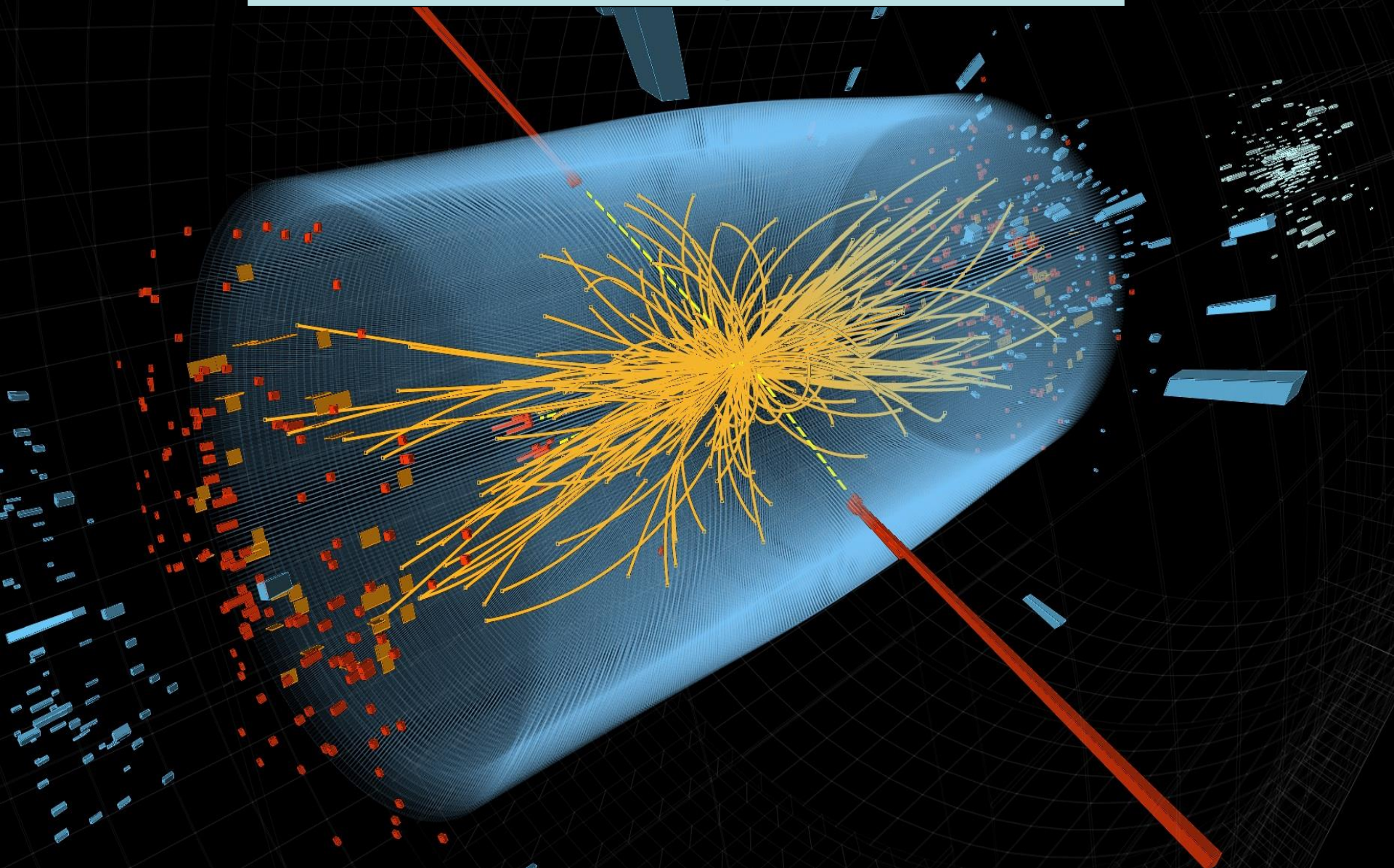
Mass Higgsteria

A Simulated Higgs Event @ LHC

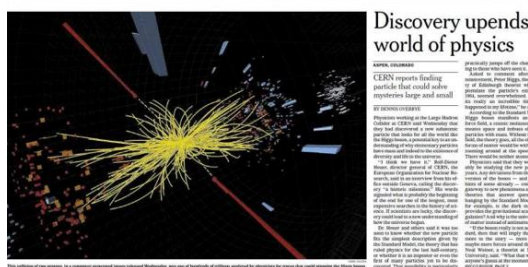




Interesting Events



July 4th 2012
The discovery of a new particle



Discovery upends world of physics

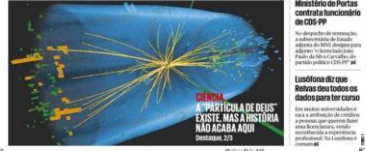
CERN reports finding particle that could solve mysteries large and small



新素粒子検出 年内に結論
ヒッグス粒子発見か

ヒッグス粒子検出 年内に結論
新素粒子検出 年内に結論

Milhares de moradores de bairros sociais em risco de perderem RSI



Science: la matière dévoilée



MK newspaper cover with headline 'ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ' and other news items.

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

Frankfurter Allgemeine Zeitung newspaper cover with headline 'Zieke Kaj en zijn moeder toch samen in de VS'.

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'.

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 partucula clave para a comprension del universo'.

CHINADAILY newspaper cover with headline 'Big bang moment: Scientists may have found 'God particle''.

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

গণিত বিজ্ঞানের 'স্বপ্ন' দর্শন newspaper cover with headline 'Big bang moment: Scientists may have found 'God particle''.

Higgsdependence Day!



The Particle Higgsaw Puzzle



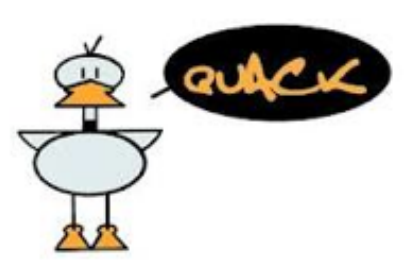
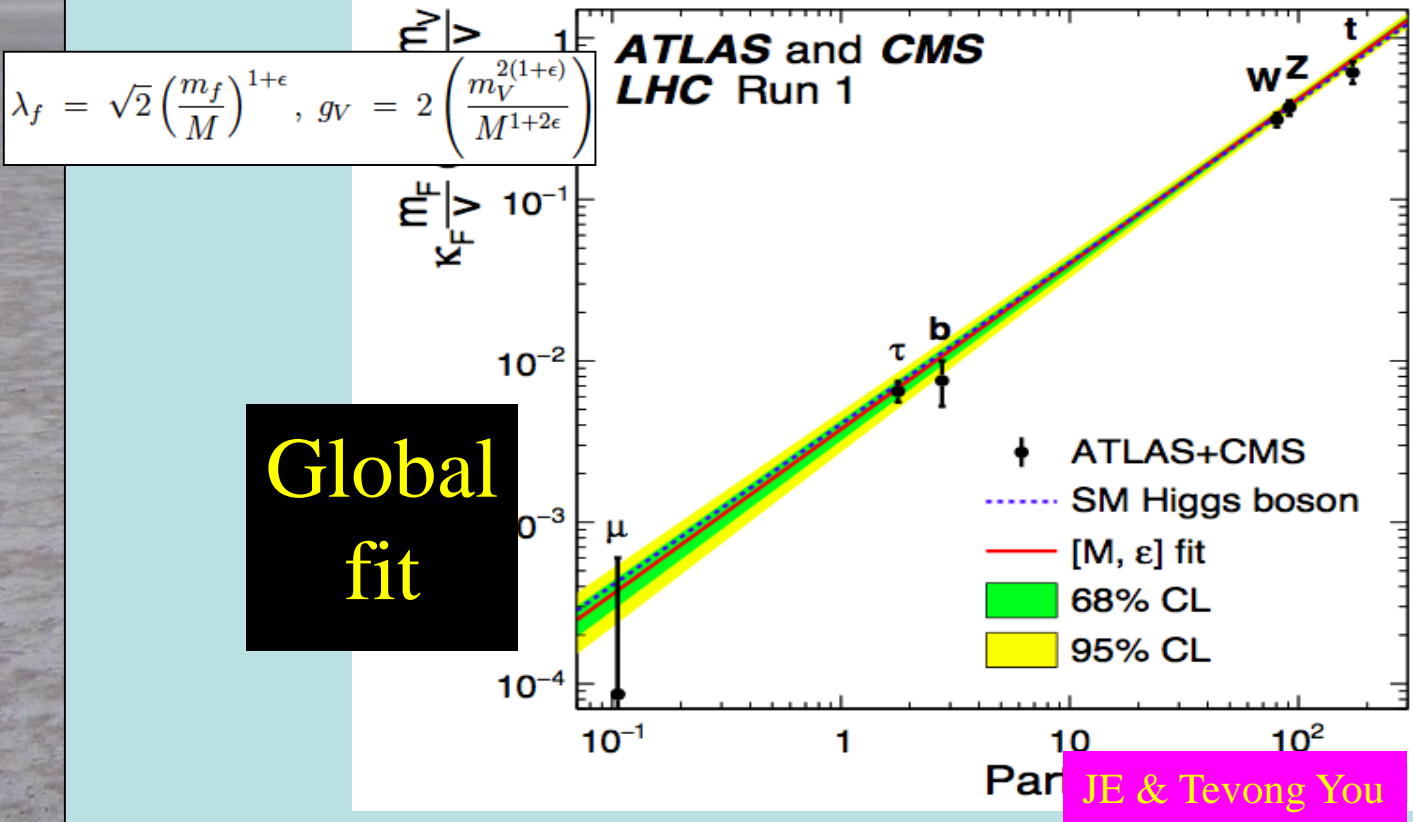
Did the LHC find the missing piece?

Is it the right shape?

Is it the right size?

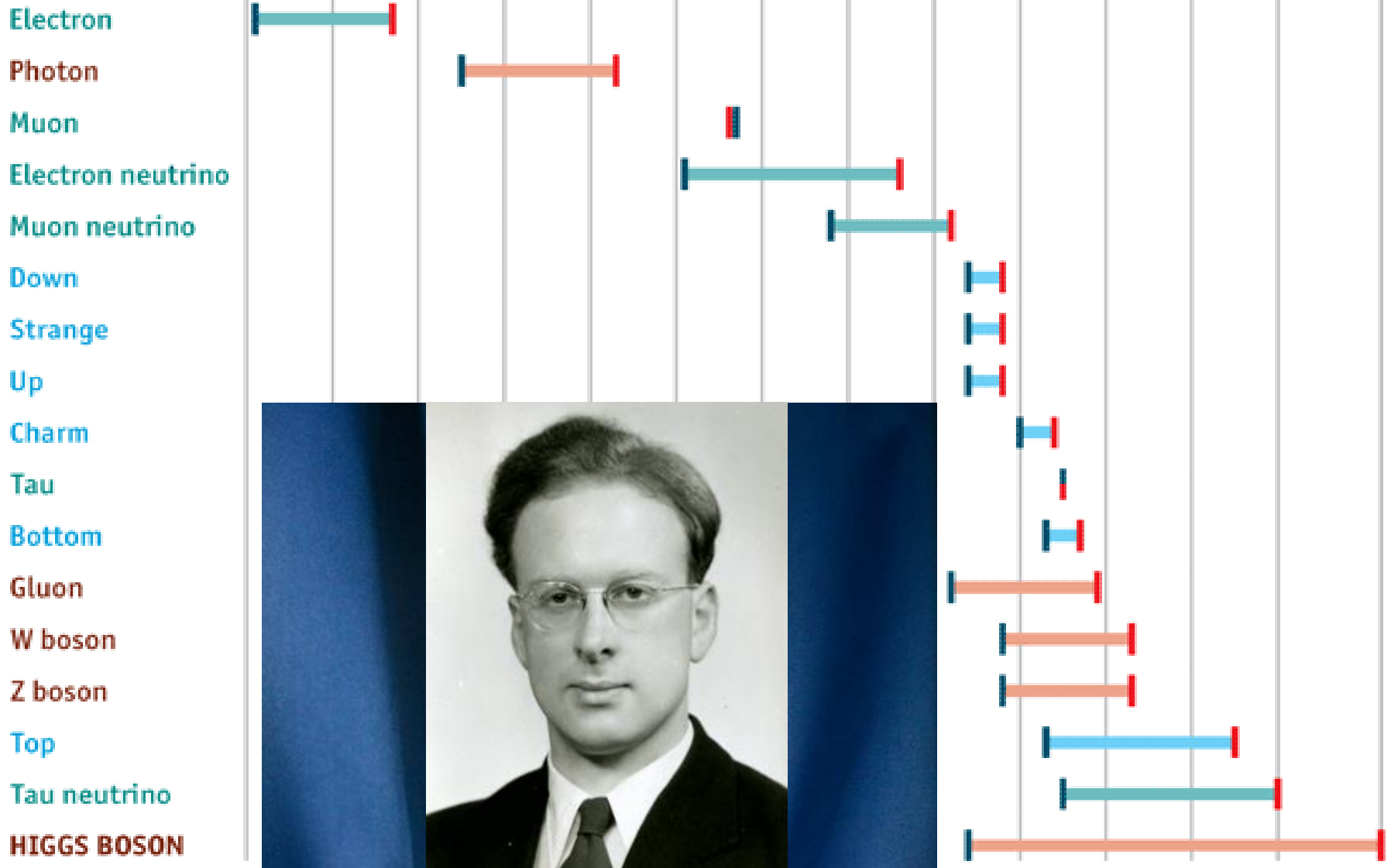
It Walks and Quacks like a Higgs

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

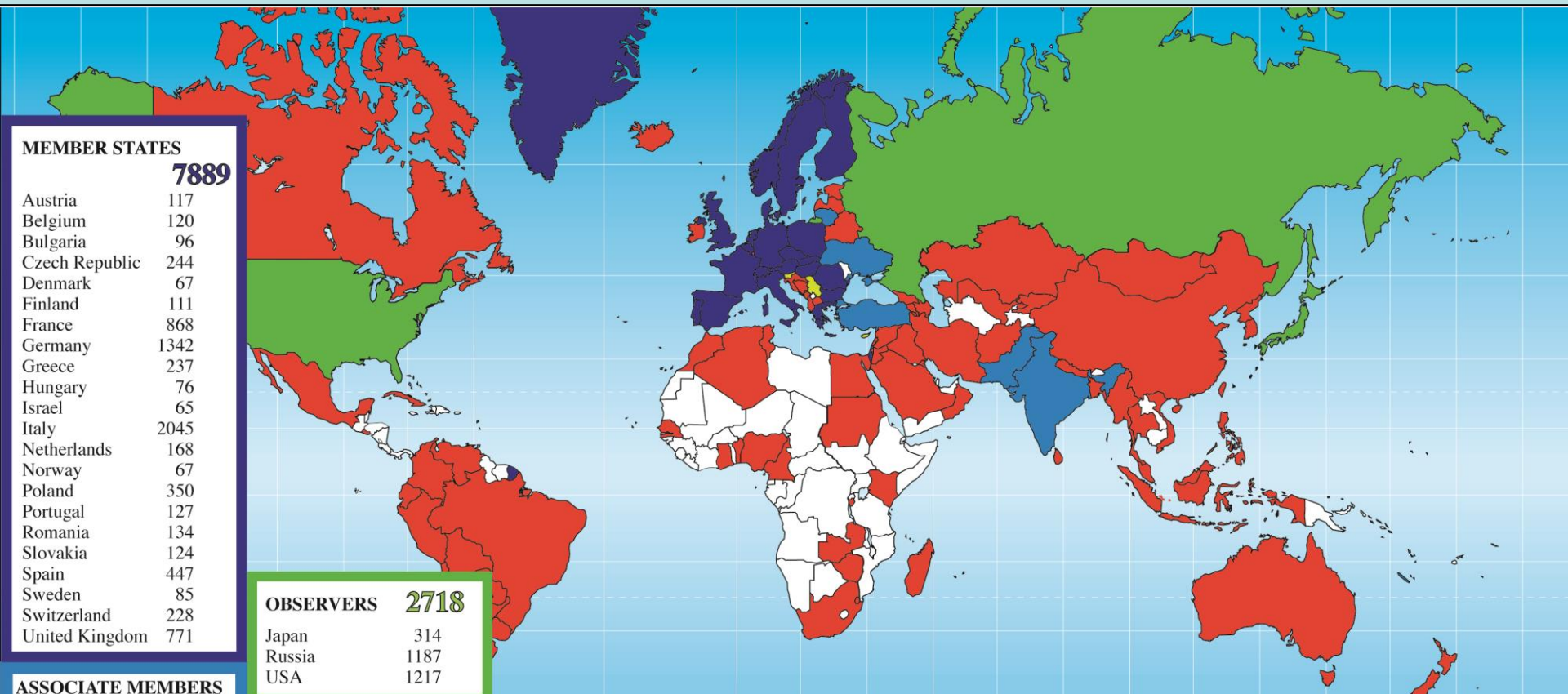


- Blue** dashed line = Standard Model

Standard Model Particles: Years from Proposal to Discovery



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				

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 unstable
- Dark matter
- Origin of matter
- Sizes of masses
- Masses of neutrinos
- Inflation
- Quantum gravity
- ...

LHC
LHC
LHC
LHC
LHC

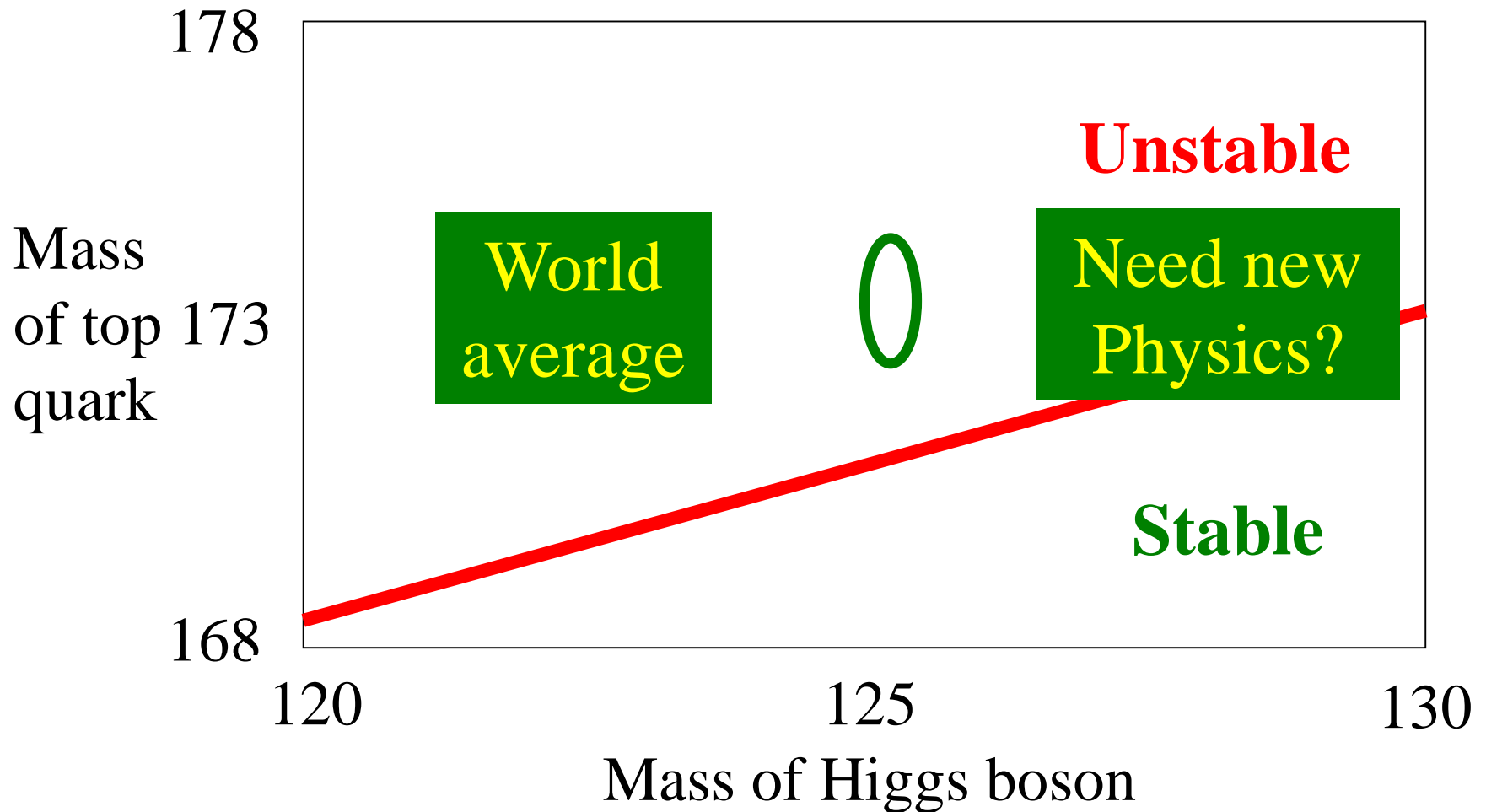
The Standard Model

PIERCE BROSNAN in IAN FLEMING'S JAMES BOND 007™
Is Not Enough
007™

ALBERT R. BROCCOLLI'S SON PRODUCTIONS PRESENTS PIERCE BROSNAN in IAN FLEMING'S JAMES BOND 007™
"THE WORLD IS NOT ENOUGH" SOPHIE MARQUEAU ROBERT CARULLE DENISE RICHARDS ROBBIE COLTRANE and JIMU DENCH
DESIGNED BY LINDY HEARMON COSTUME DESIGNER DAVID ARNOLD EXECUTIVE PRODUCERS JIM CLARK JIMMIEWAY ADRIAN BUDDE and JIMMIEWAY PETER JARANT
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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

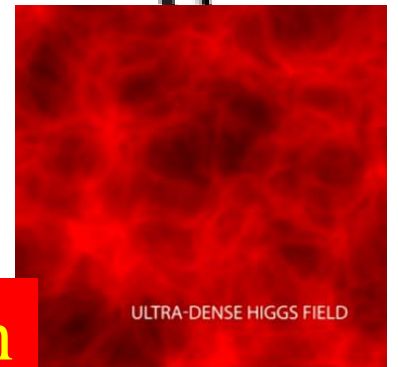


HIGGS FIELD

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

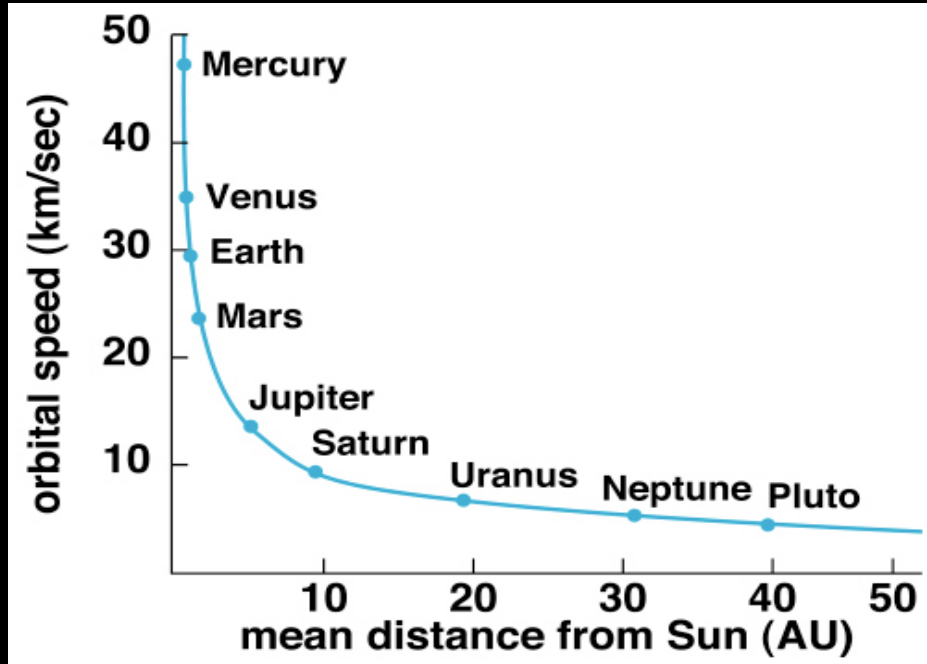
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



Scanned at the American
Institute of Physics

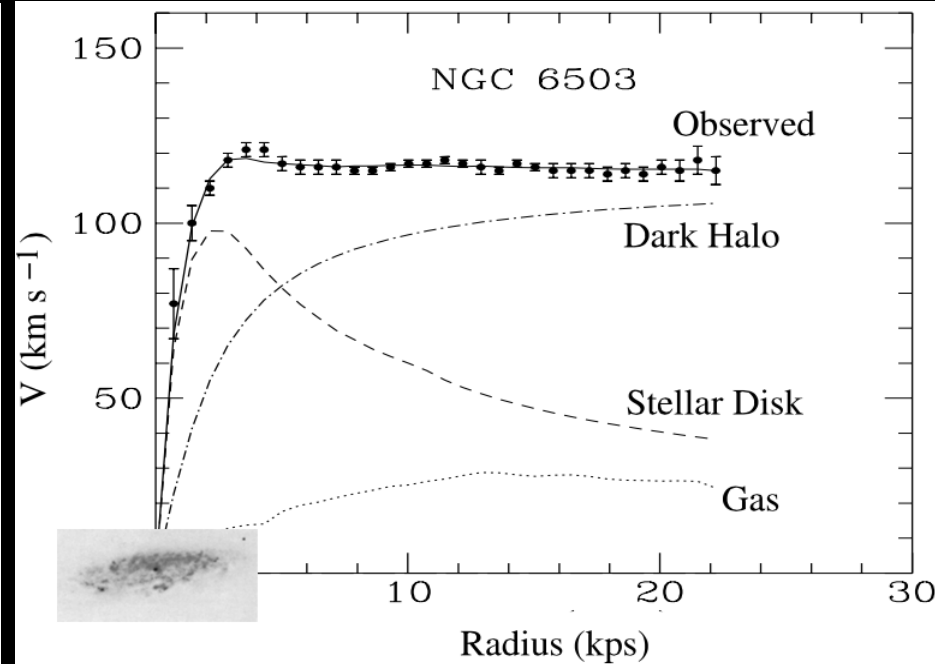
Rotation Curves

- In the Solar System



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

- In galaxies



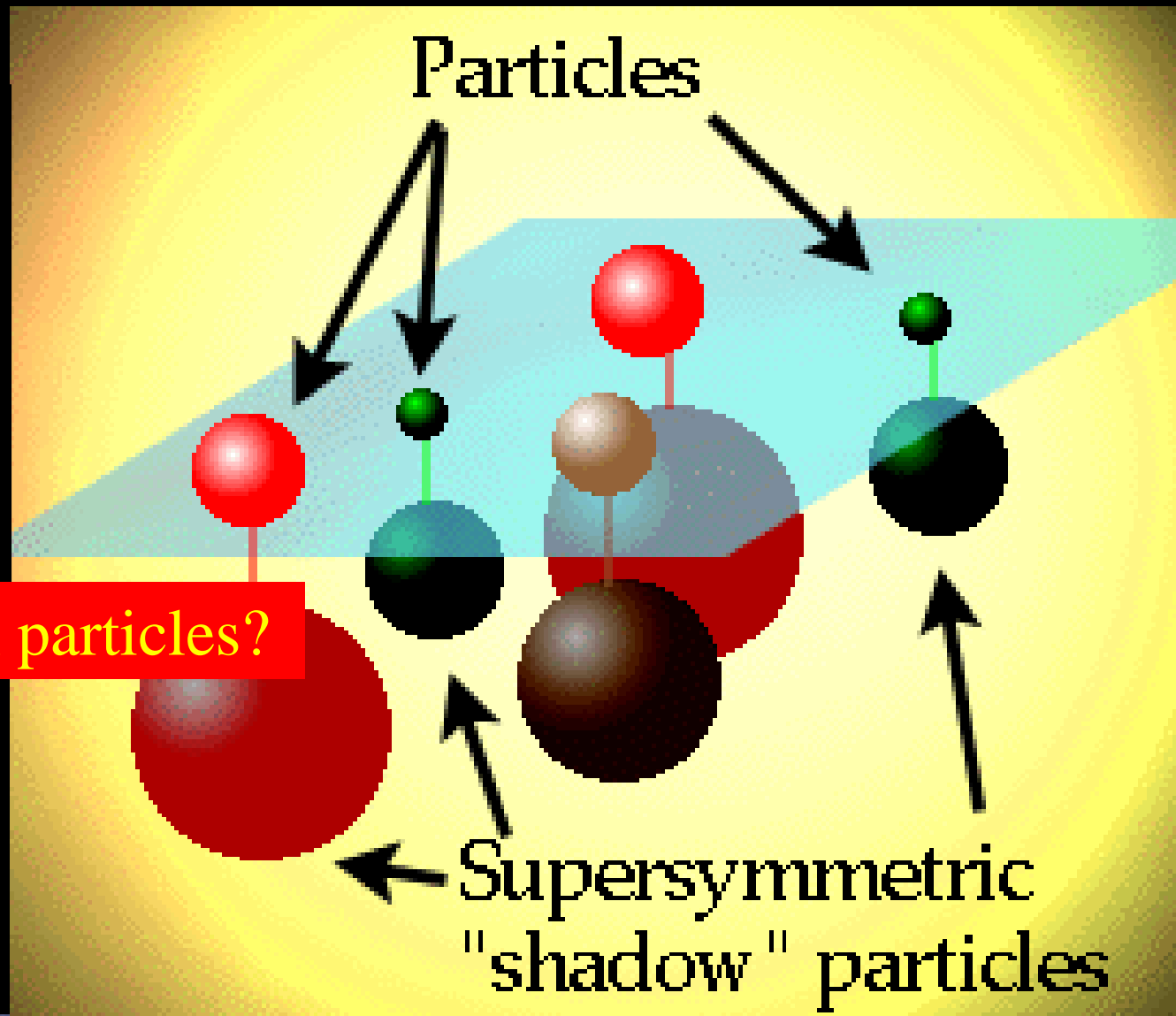
- The velocities do not decrease with distance
- Dark matter spread out

What is the Dark Matter in the Universe?

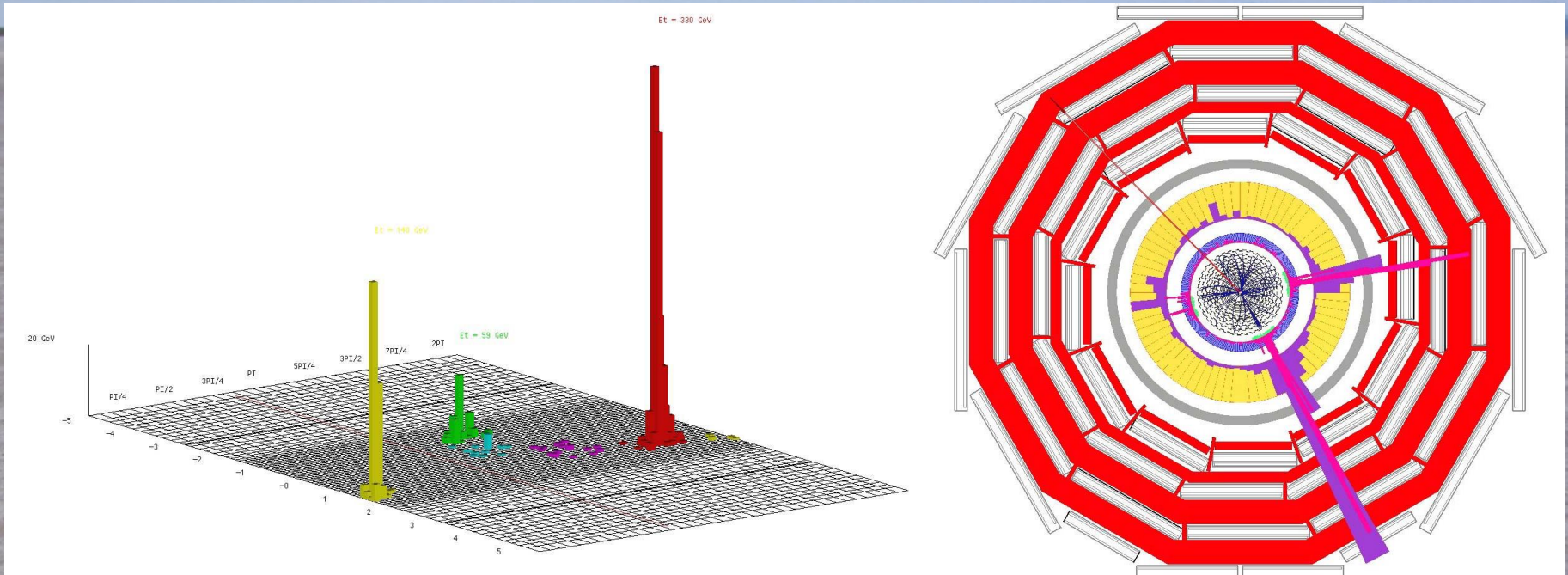
Astronomers say
that most of the
matter in the
Universe is
invisible
Dark Matter

Made of unknown particles?

We are
searching for
them at the
LHC

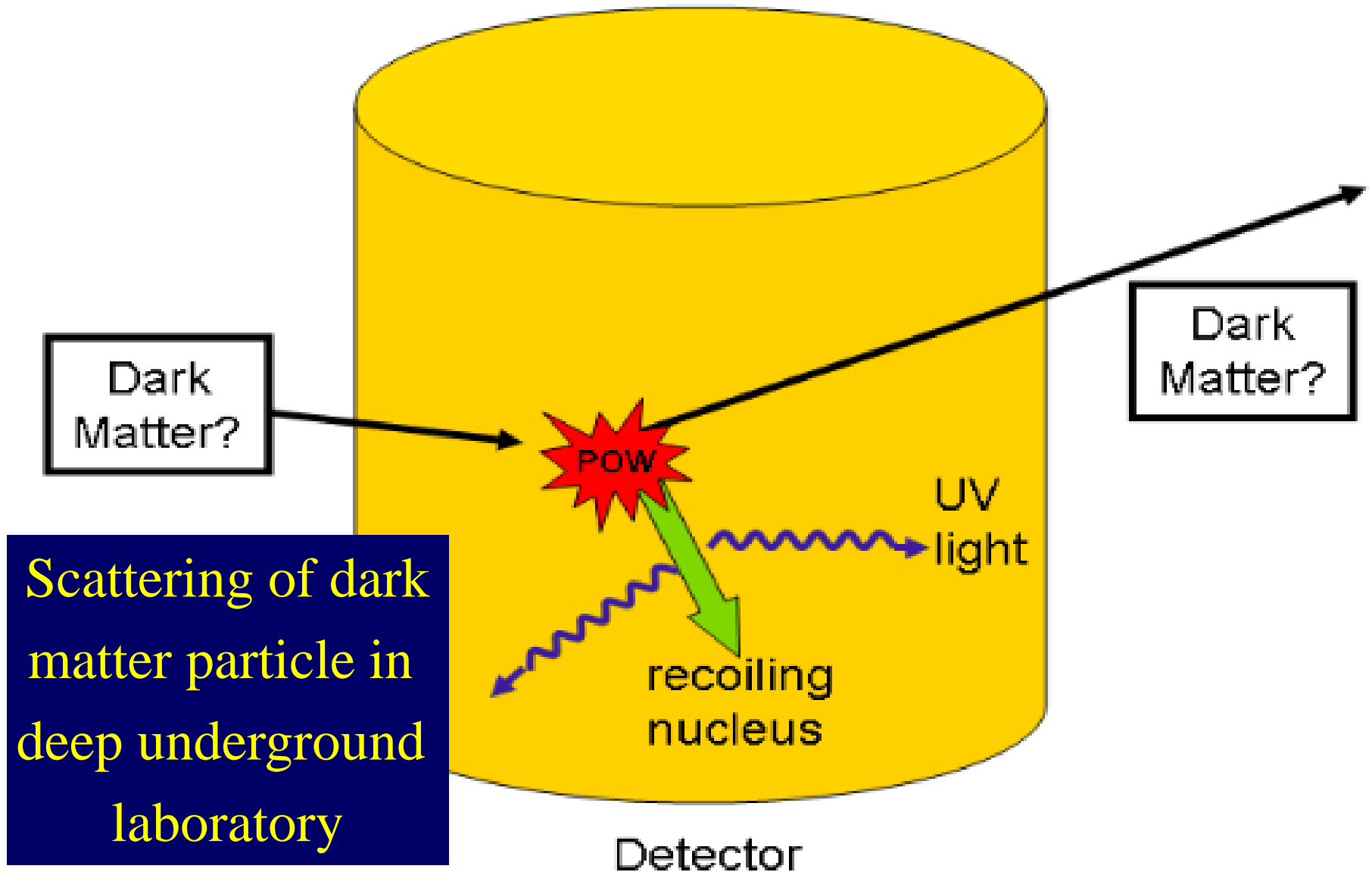


Classic Dark Matter Signature



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

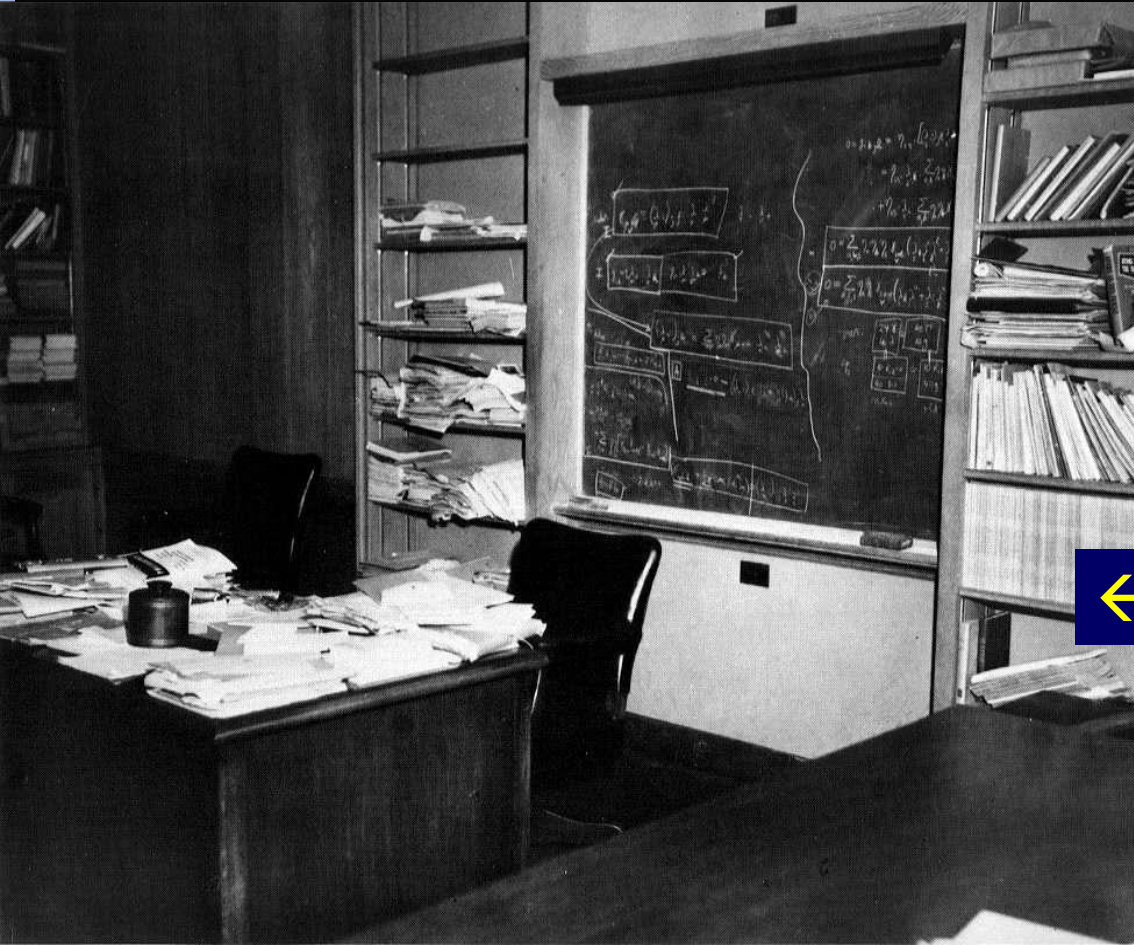


Matter and antimatter not quite equal and opposite: WHY?

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



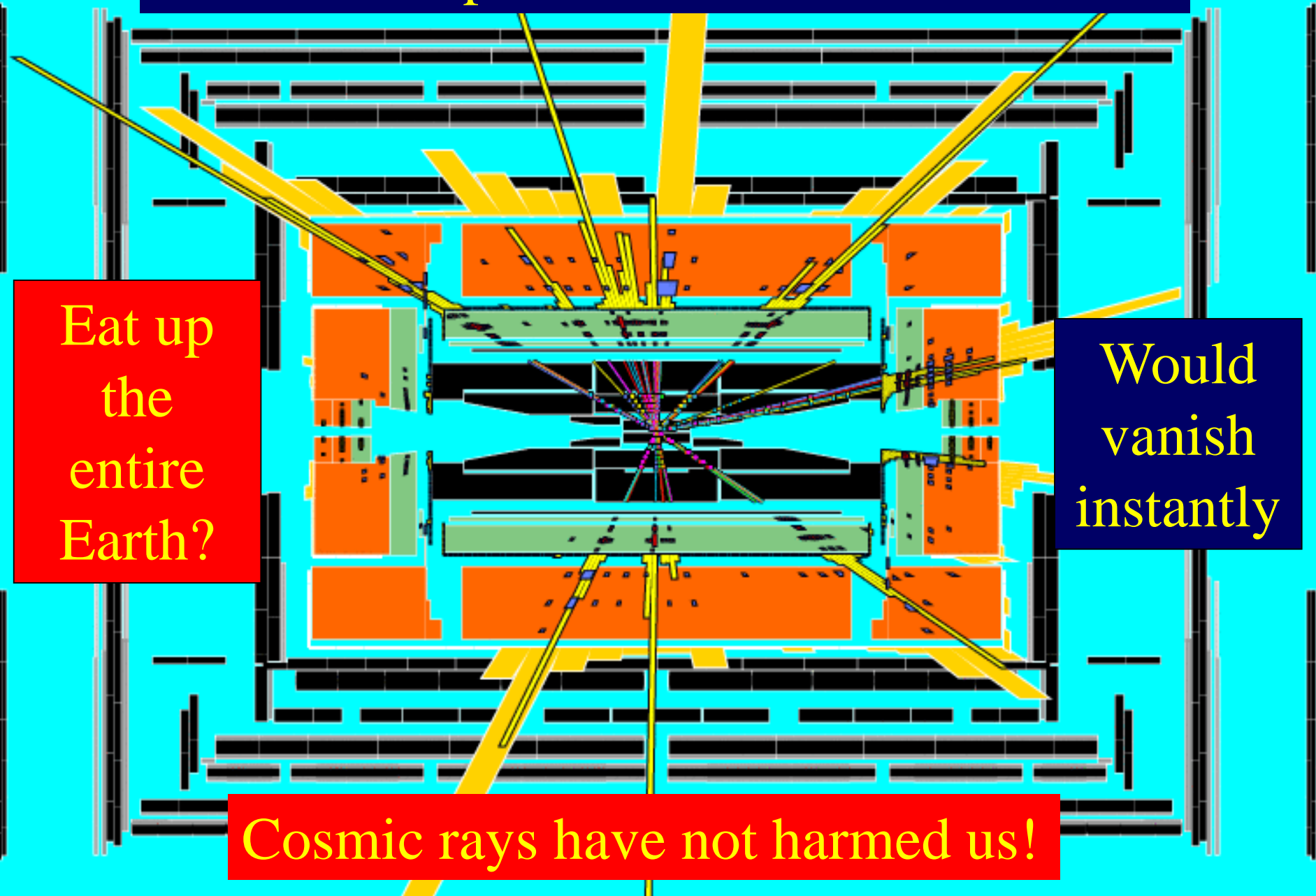
Unification via extra dimensions of space?

Will LHC experiments create black holes?

Eat up
the
entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!



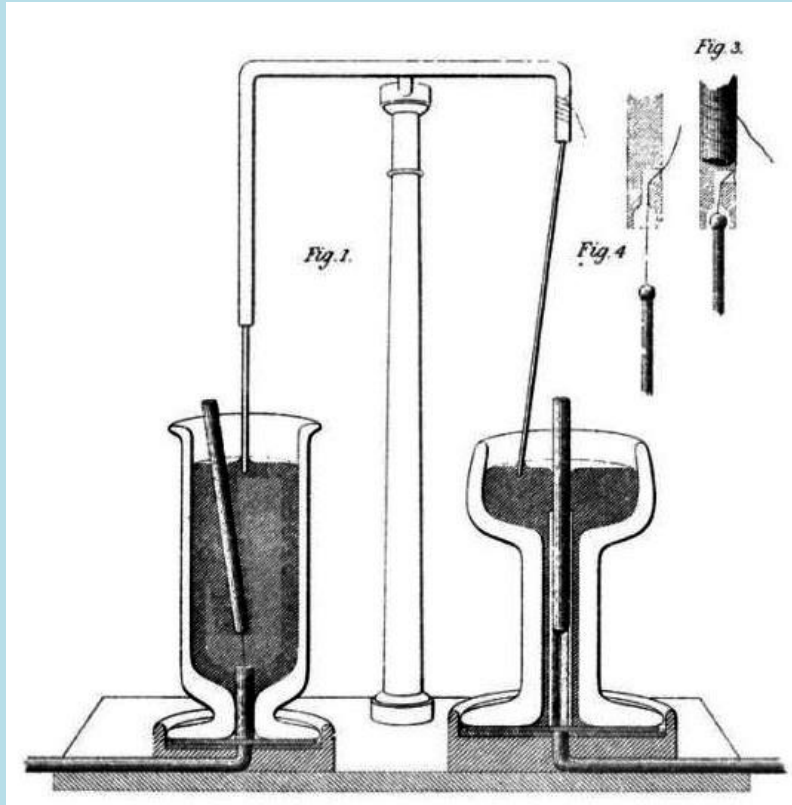
The LHC is the world's most powerful microscope ...



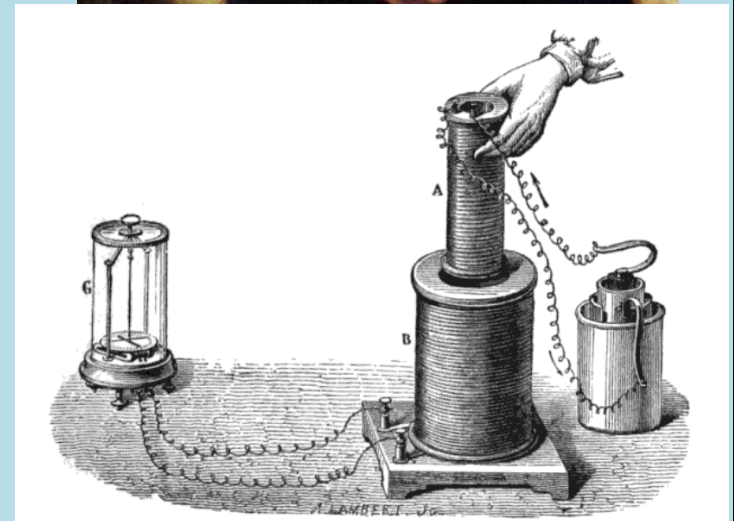
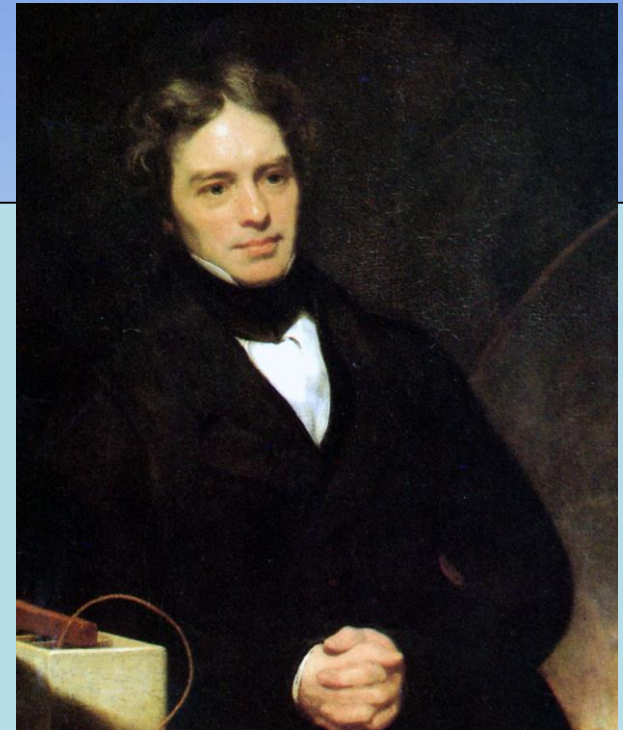
... and also a telescope
addressing Gauguin's
questions

Michael Faraday

- Invented the electric motor

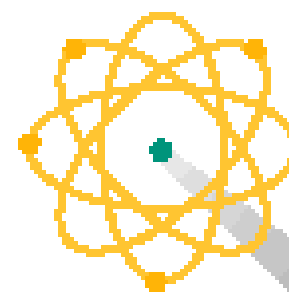


- Discovered induction



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

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

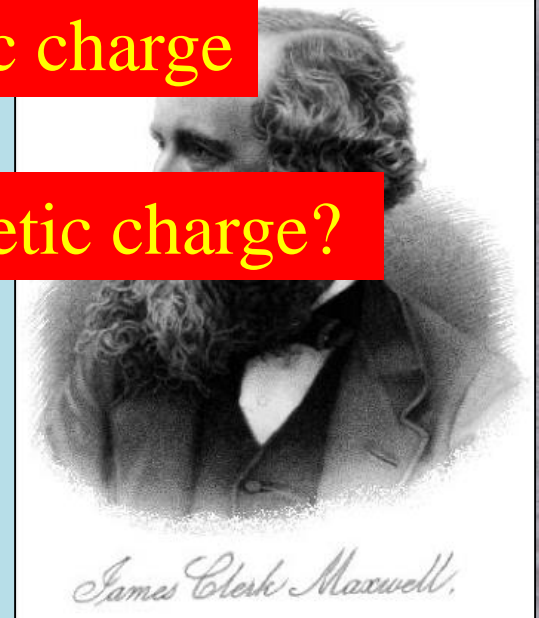
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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

Magnetic charge?

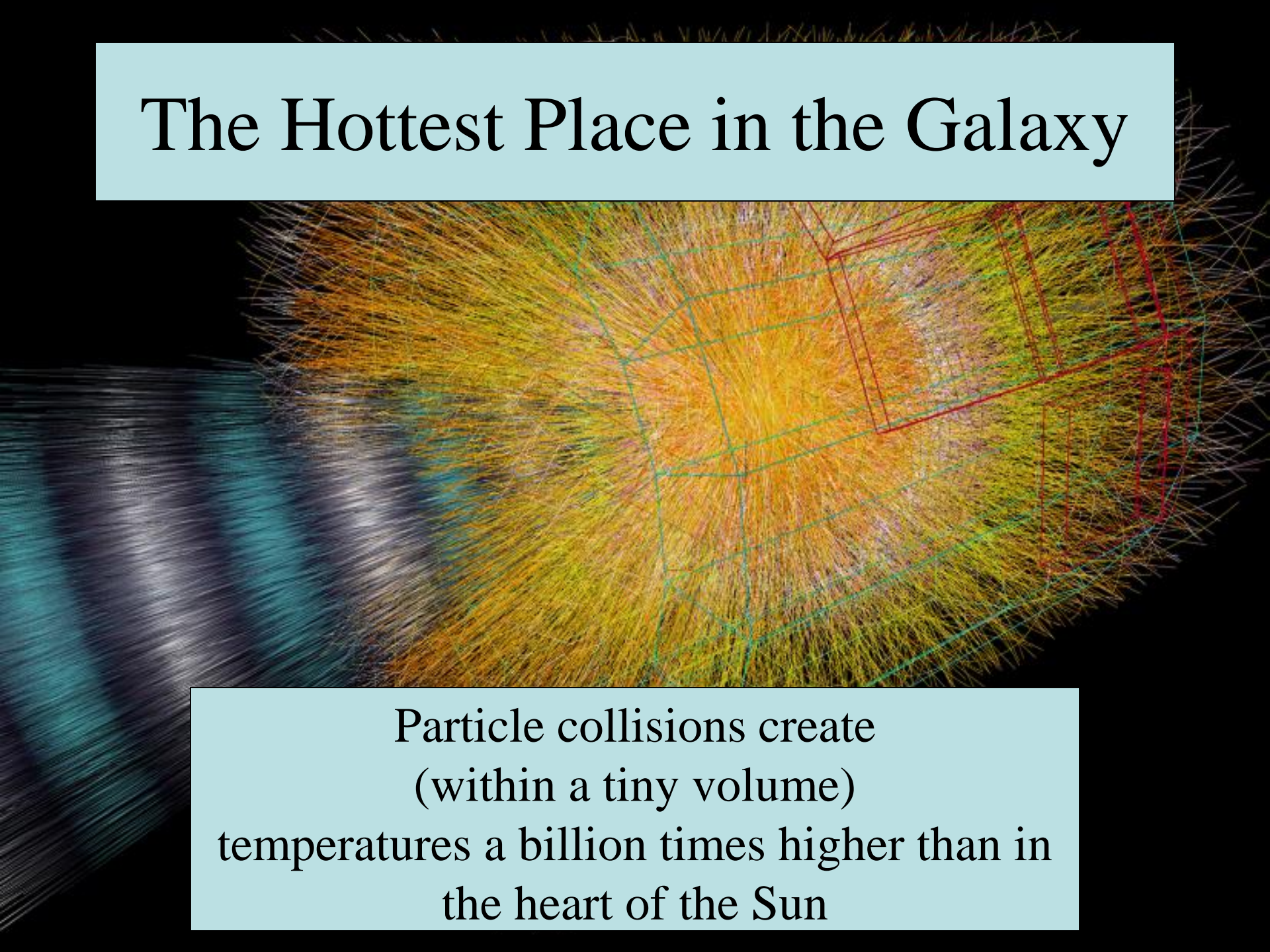
$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mathbf{j}$$

- Basis for Einstein's theories of relativity



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

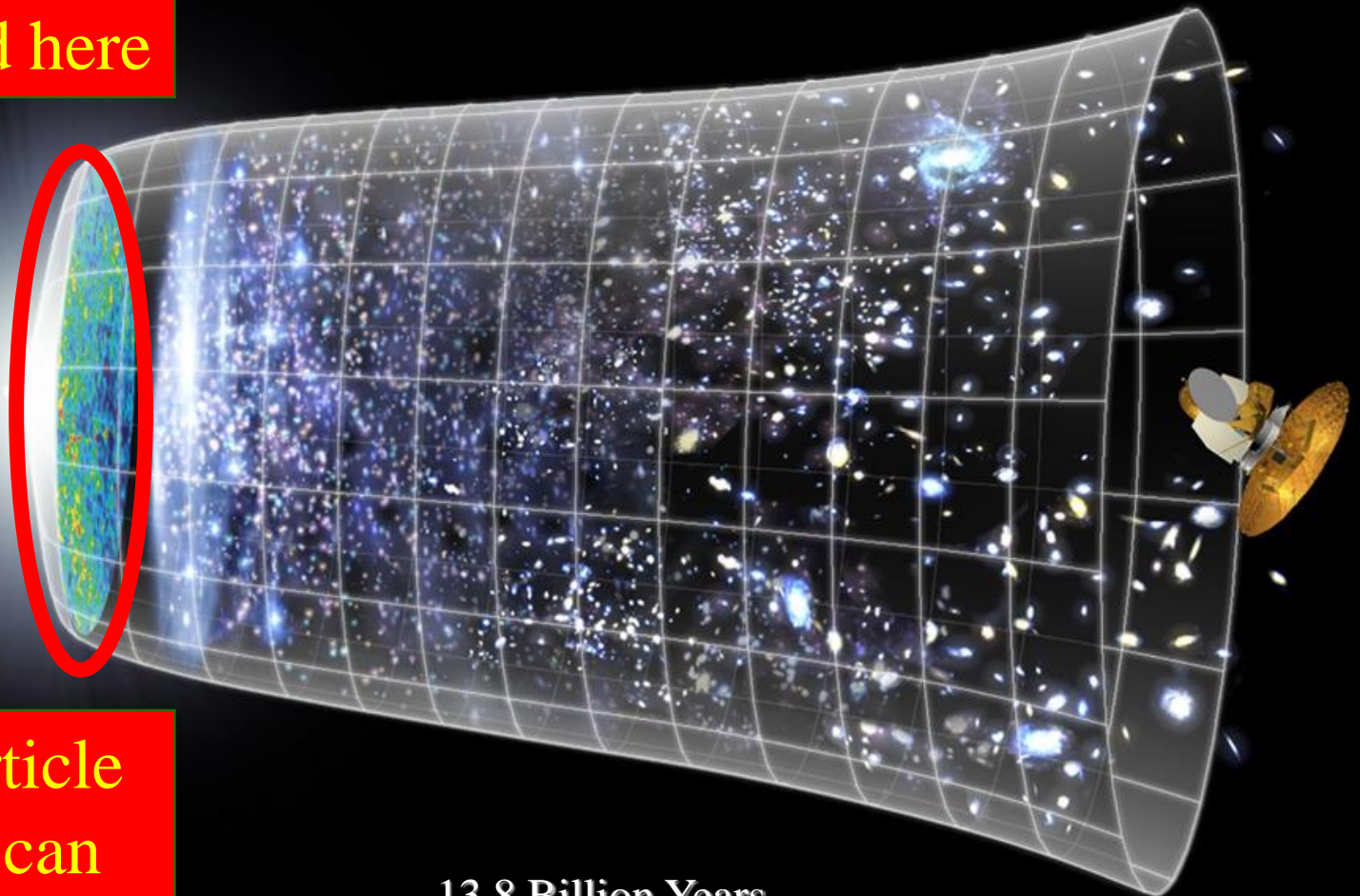


Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in
the heart of the Sun

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