

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?

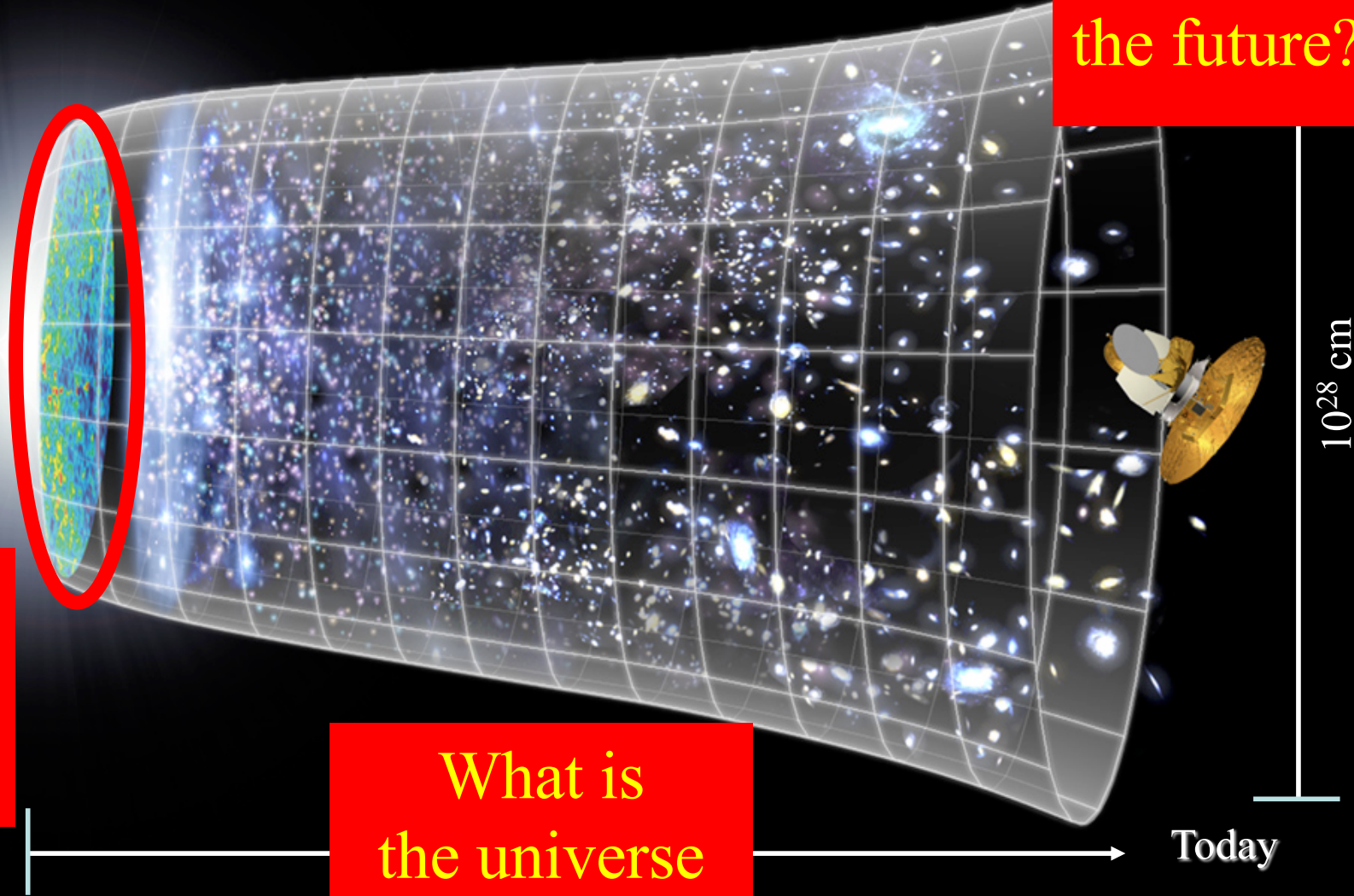
John Ellis

KING'S
College
LONDON

Evolution of the Universe

What will happen in the future?

Big Bang



What happened then?

What is the universe made of?

Today

Gauguin's Questions in the Language of Particle Physics

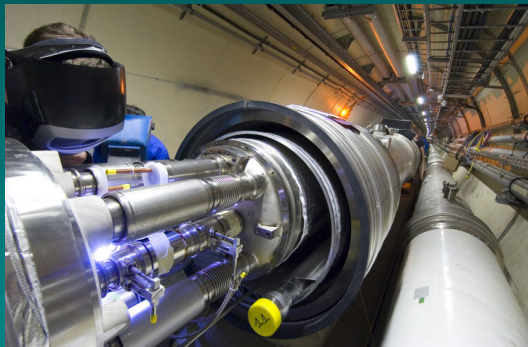
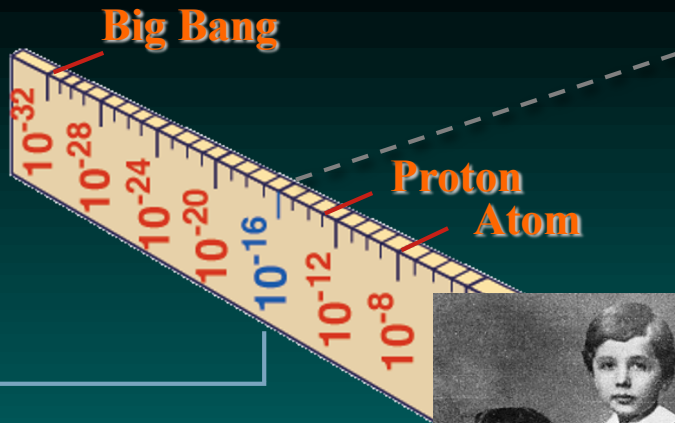
- What is matter made of?
 - Why do things weigh?



- 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

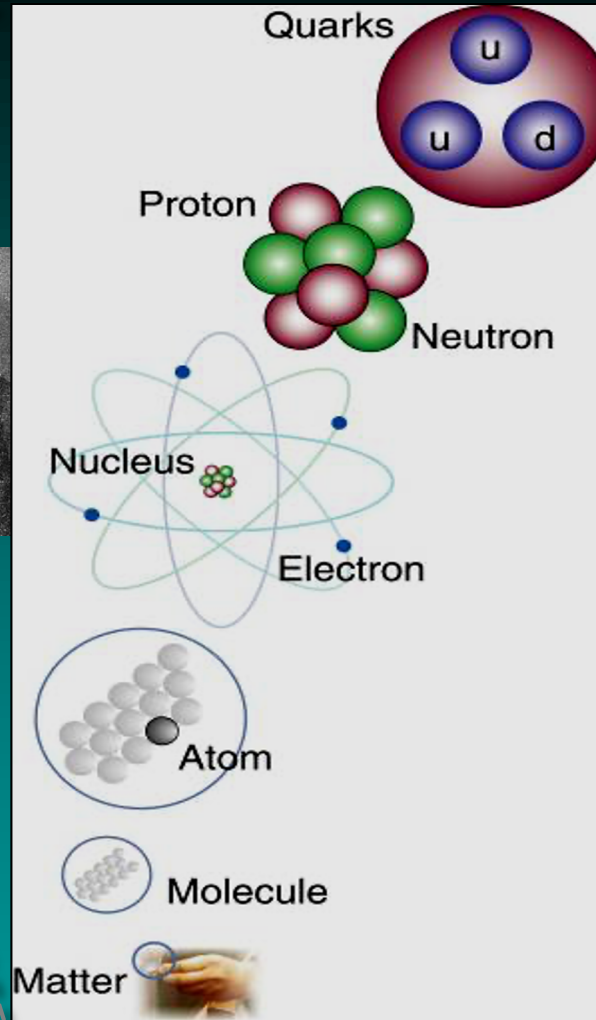
Need physics beyond what we know



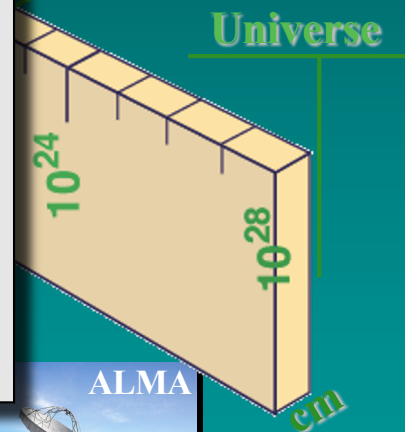
Super-Microscope



LHC



Radius of Galaxies



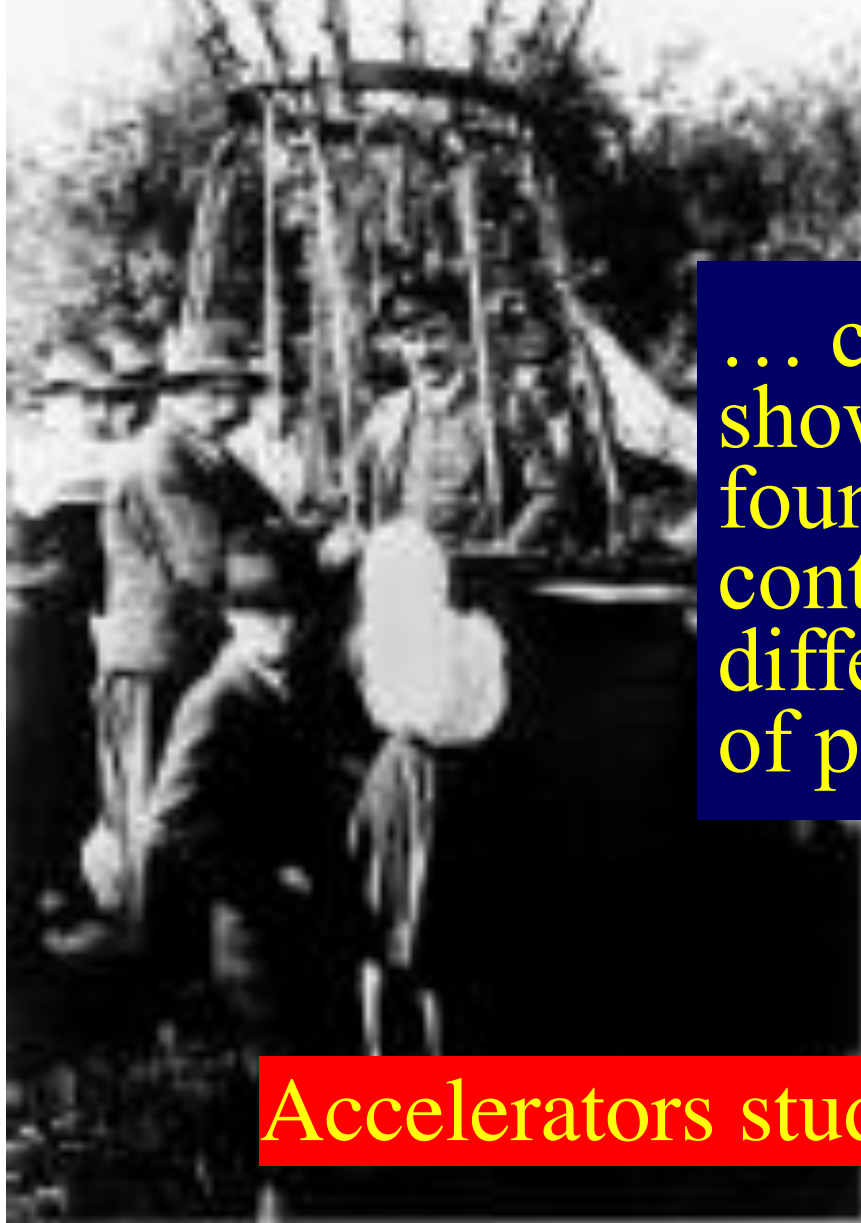
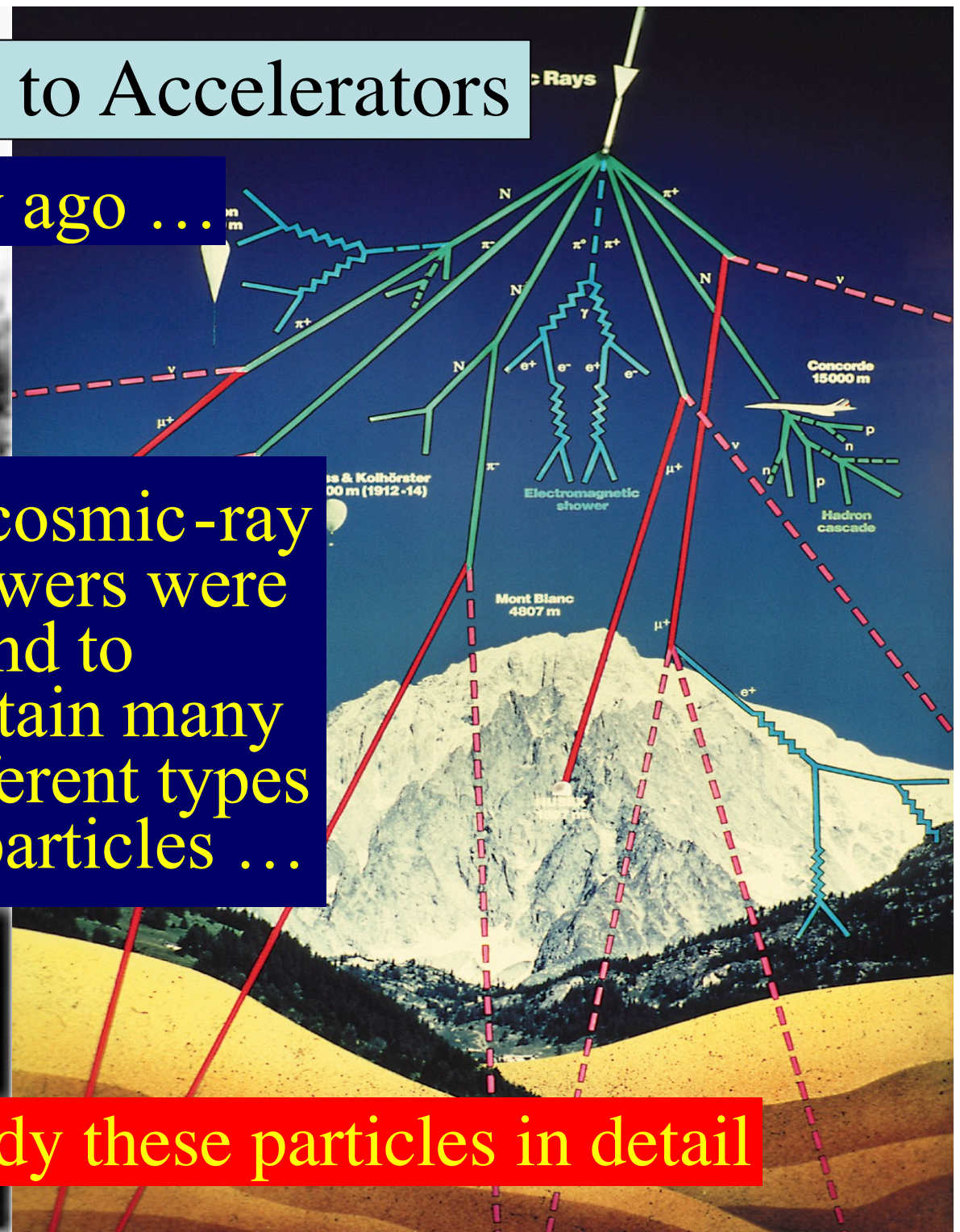
Study physics laws of first moments after Big Bang
 increasing Symbiosis between Particle Physics,
 Astrophysics and Cosmology

From Cosmic Rays to Accelerators

Discovered a century ago ...

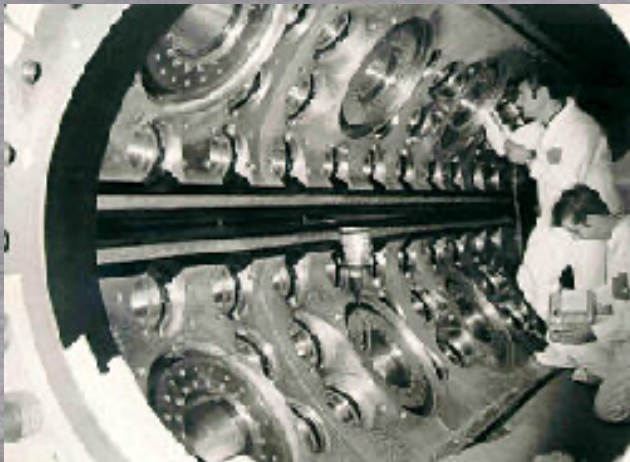
... cosmic-ray showers were found to contain many different types of particles ...

Accelerators study these particles in detail



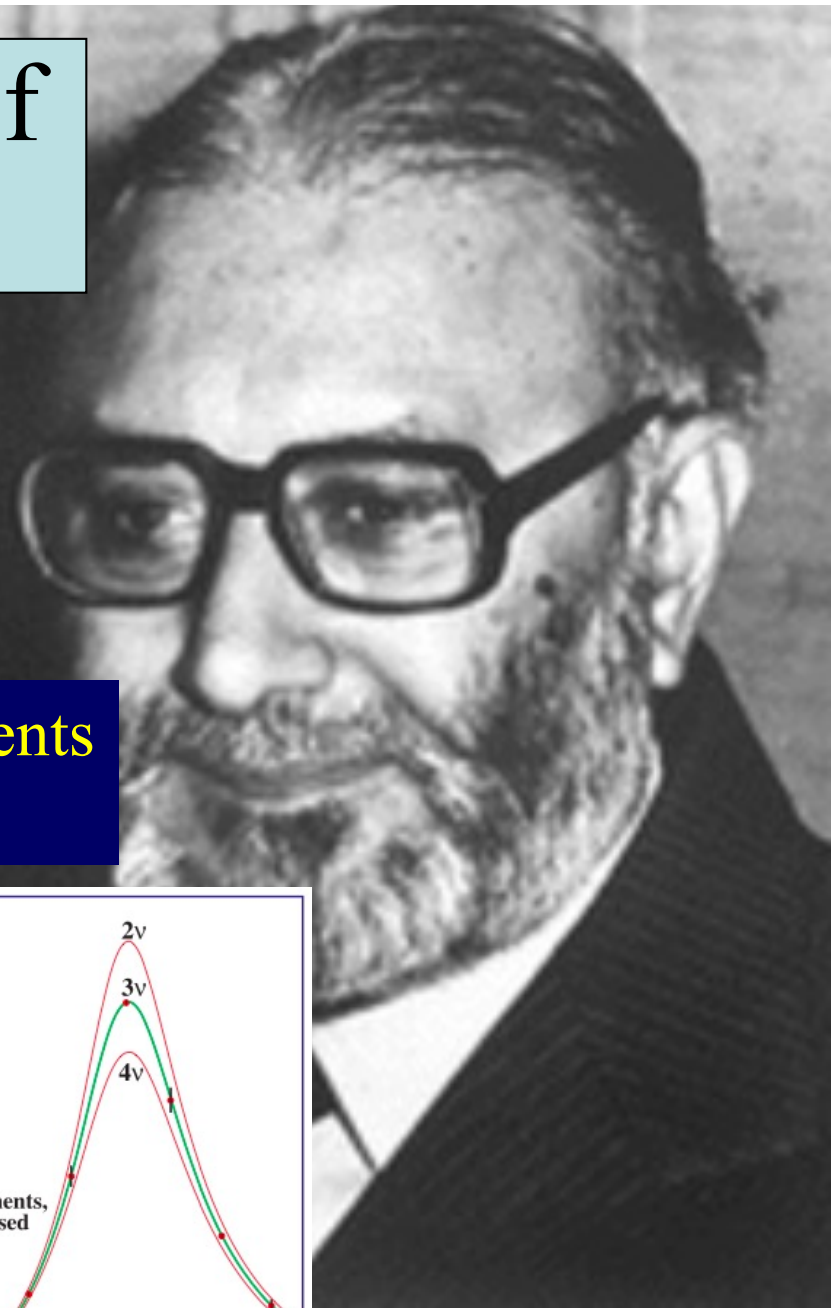
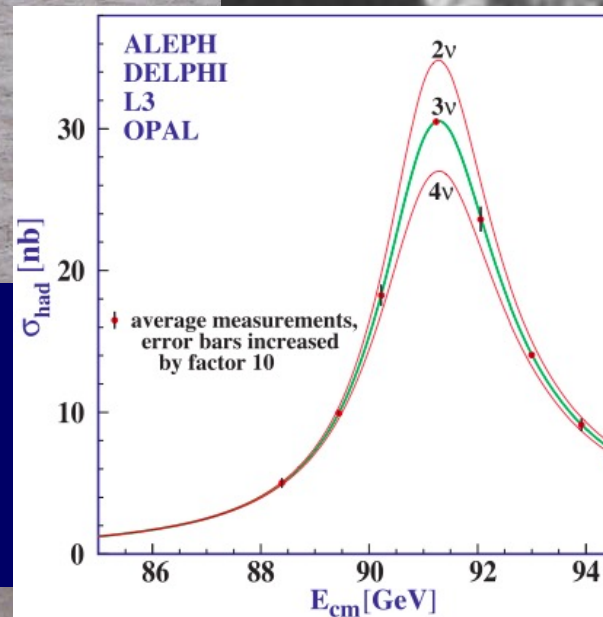
The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow and Weinberg



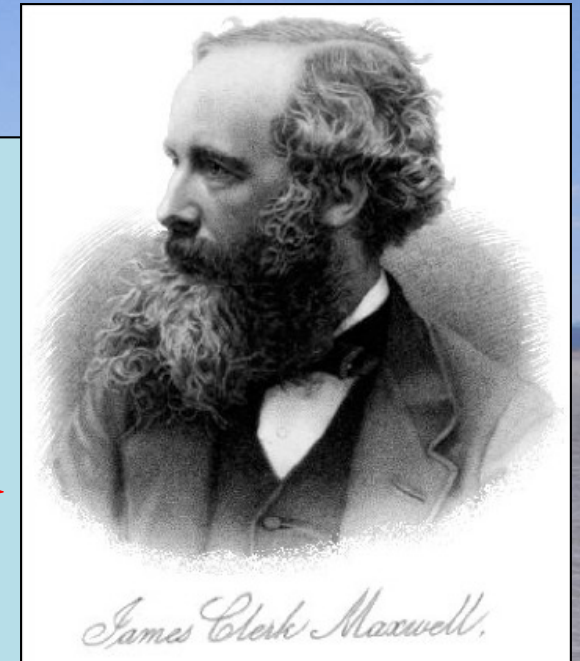
Tested by experiments
at CERN

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

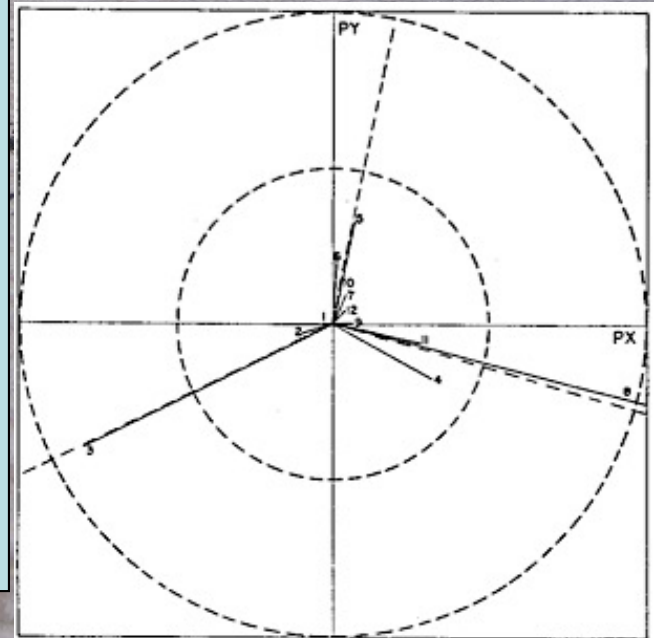
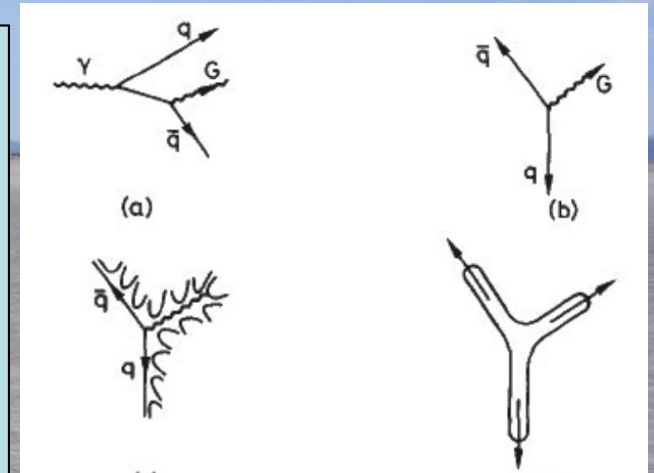


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• ... **One scientific epoch ended and another began with James Clerk Maxwell - *Albert Einstein***

Strong Nuclear Interactions

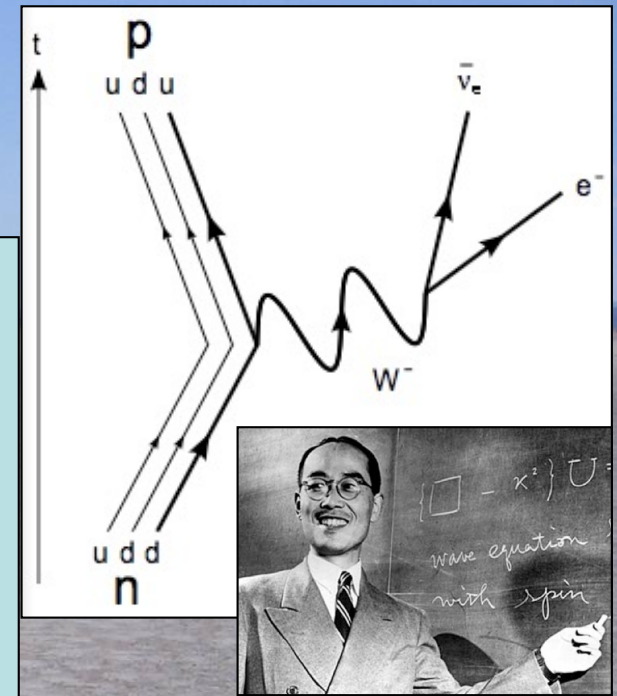
- Theory modelled after Maxwell
- Carried by massless ‘gluons’, analogues of photon
- JE, Mary Gaillard, Graham Ross suggested discovery method in 1976
- Radiation of gluon by quark
- Discovered at DESY laboratory in Hamburg in 1979
- **Second force particle discovered**



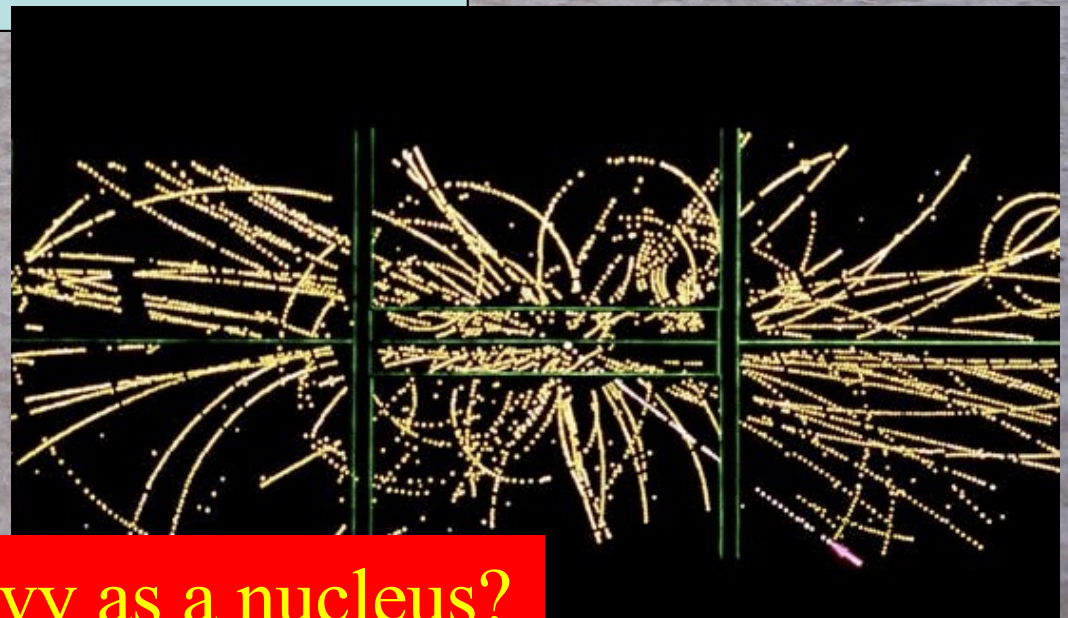
Weak Interactions

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

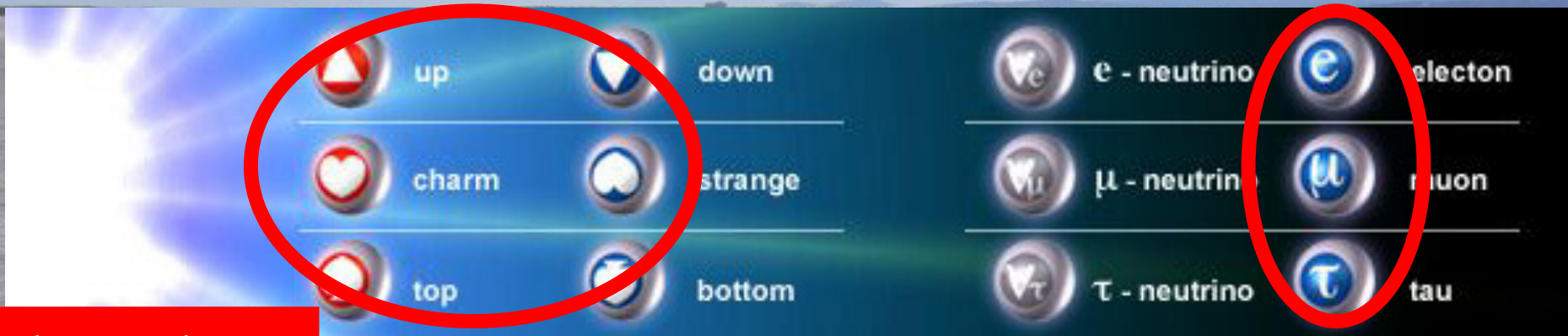


Why is it as heavy as a nucleus?

The 'Standard Model'

= Cosmic DNA

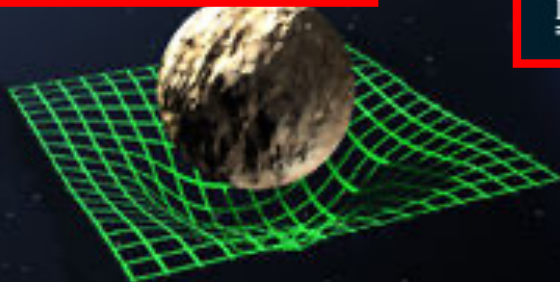
The matter particles



Where does mass come from?

The fundamental interactions

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Gravitation

electromagnetism

weak nuclear force

strong nuclear force

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:

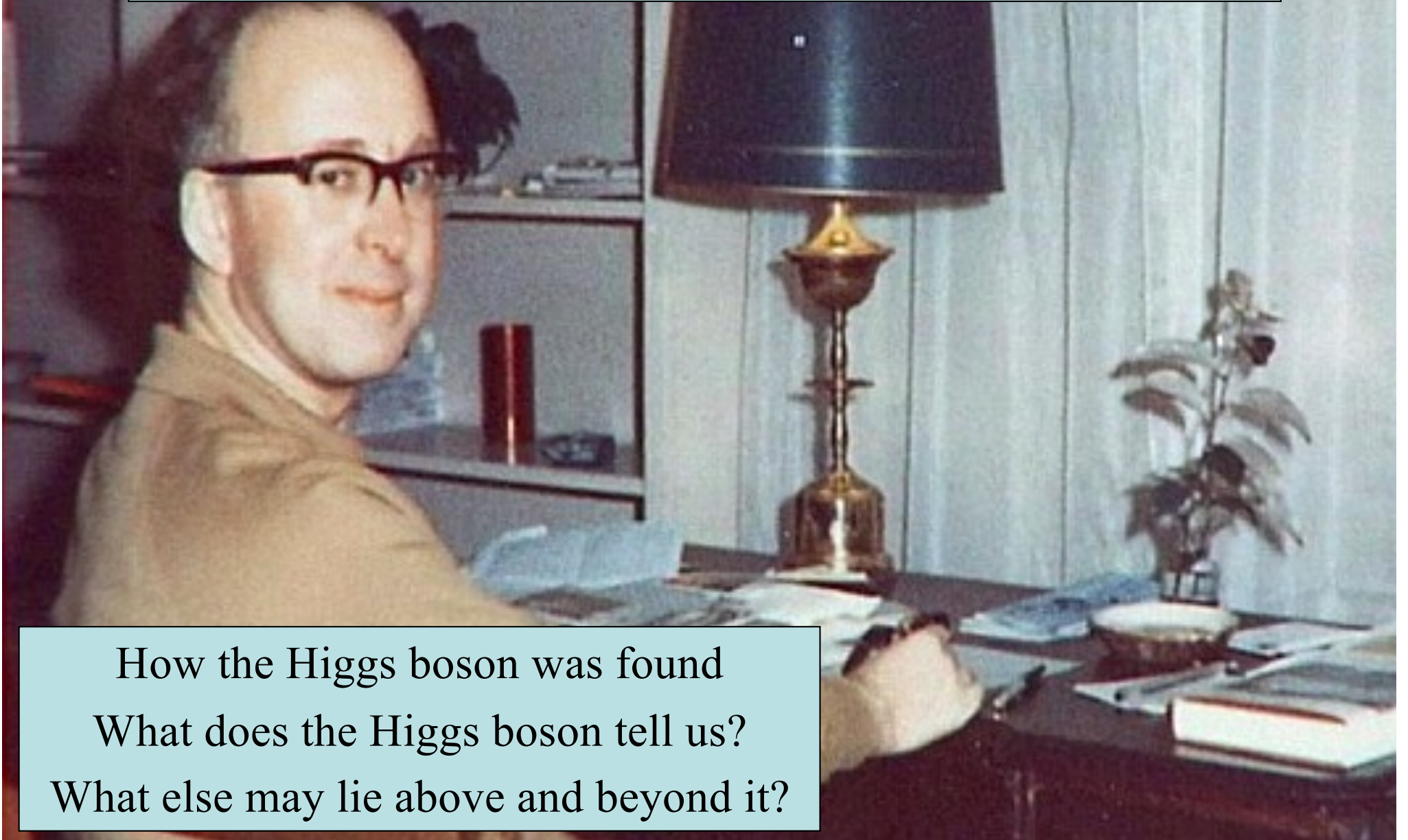
Like particle with mass
e.g., electron

**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.

An aerial photograph of the CERN facility in Geneva, Switzerland, showing a vast landscape of agricultural fields and some urban areas. Overlaid on the image are two large, concentric white circles representing the paths of the Large Hadron Collider (LHC) and its predecessor, the Large Electron-Positron collider (LEP). The LHC path is the larger, outer circle, and the LEP path is the smaller, inner circle. The text 'To answer Gauguin's questions:' is written in a black serif font on a light blue rectangular background at the top of the image.

To answer Gauguin's questions:

The Large Hadron Collider at CERN

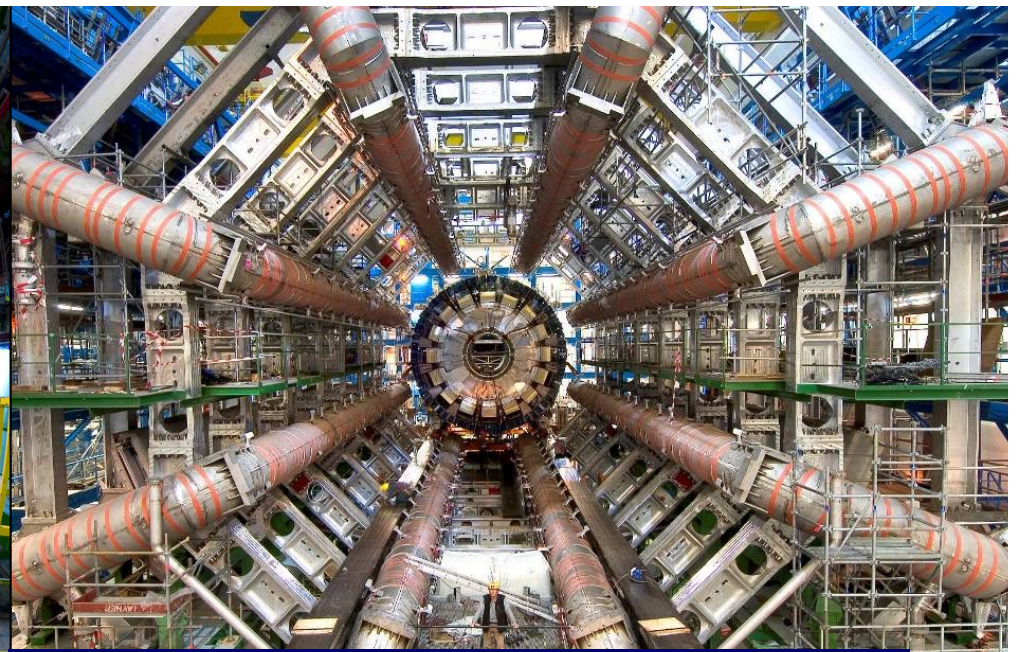
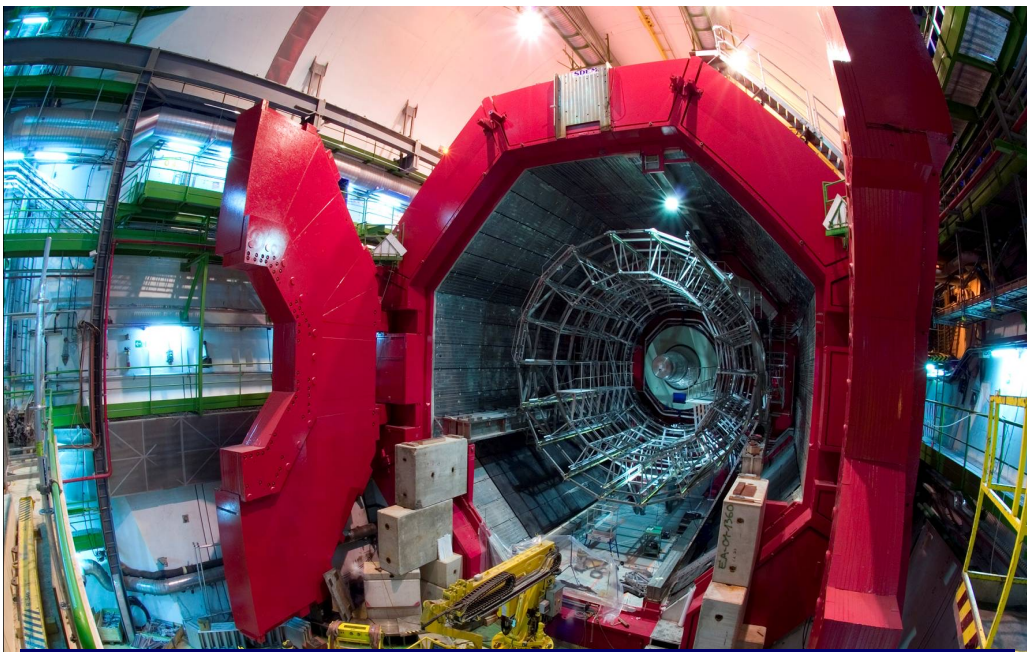
To answer these questions:

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

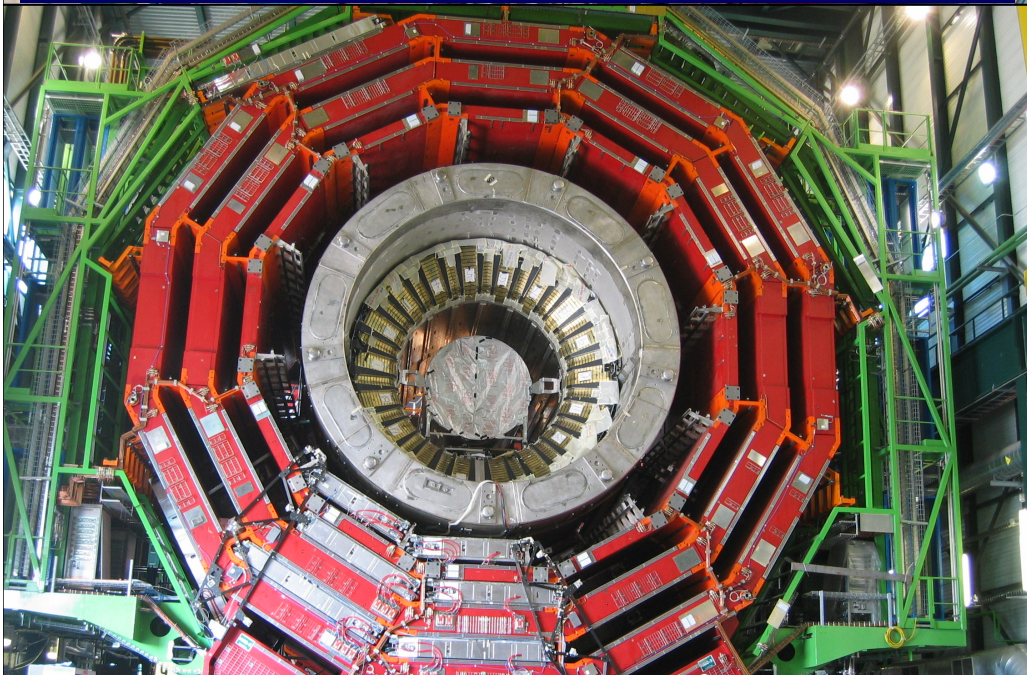
Primary targets:

- 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

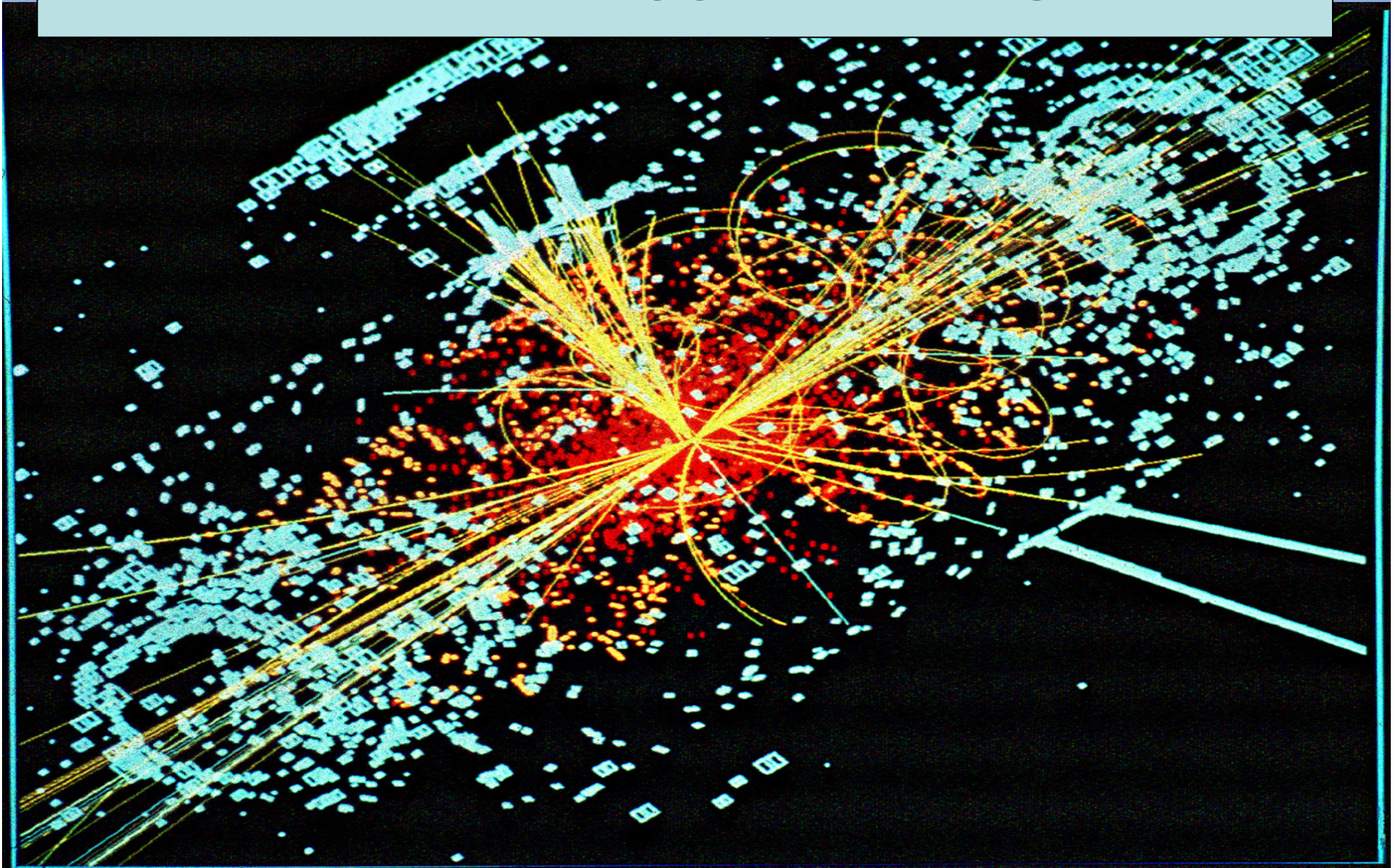
LHCb: Matter-antimatter difference

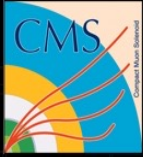
2012: The discovery of the Higgs Boson



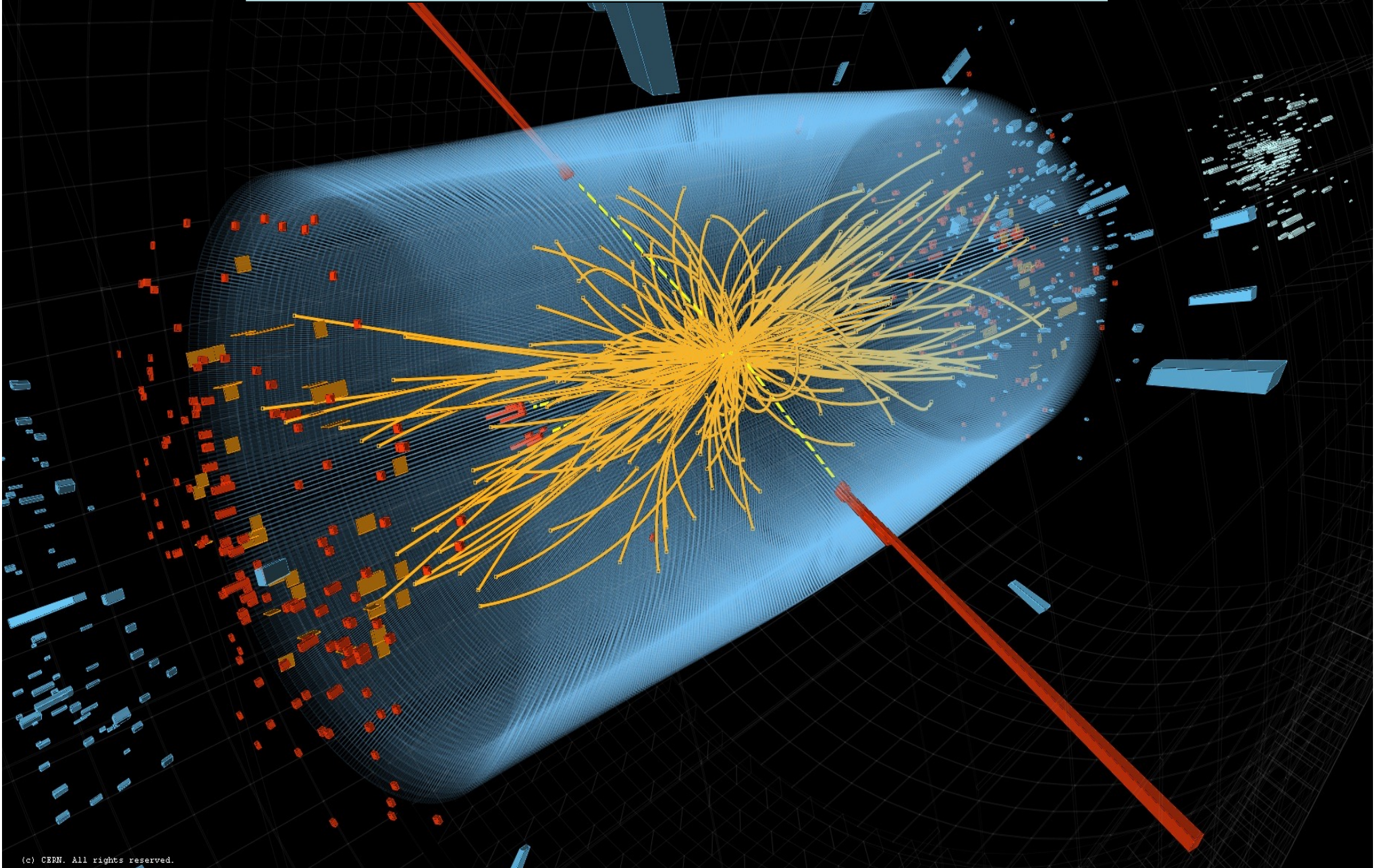
Mass Higgsteria

A Simulated Higgs Event @ LHC

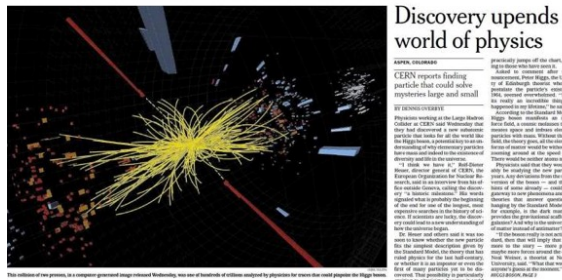




Interesting Events



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

The Economist
A giant leap for science
Finding the Higgs boson



ヒッグス粒子発見か
新素粒子検出 年内に結論
日米欧2チーム

Le Monde
Science : la matière dévoilée
Milhares de moradores de bairros sociais em risco de perderem RSI



Le coup de cœur de la rédaction
ALGÈRE L'INDÉPENDANCE
Une fête sans panache

MK
ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ
«КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ

AD ALGEMEEN DAGBLAD
EINDELIJK GELIJK NA 48 JAAR
Zieke Kaj en zijn moeder toch samen in de VS

Frankfurter Allgemeine
Masse mach's
Die Technik
Feiler im System

CHINADAILY
hallada la partícula clave para a comprensión del universo
Iron Man film company looks to China for screen success

THE HINDU
Elusive particle found, looks like Higgs boson
CERN physicists hail evidence of game-changing discovery of subatomic particle

CORRIERE DELLA SERA
La particella che può svelare i segreti dell'universo
L'azienda in ostaggio

gazeta
Czaszkie Higgsa fizycy najpierw wymyślił, potem szukali 40 lat
BOSKA MASA

বিশ্বজ্ঞানের 'ঈশ্বর' দর্শন
সত্যেন্দ্রনাথকে বিনয় প্রণাম
'পেয়েছি, যা খুঁজছিলাম'

The Gazette
EL PAIS
hallada la partícula clave para a comprensión del universo

The Gazette
EL PAIS
hallada la partícula clave para a comprensión del universo

CHINADAILY
hallada la partícula clave para a comprensión del universo

THE TIMES OF INDIA
Big bang moment: Scientists may have found 'God particle'

Higgsdependence Day!



The Particle Higgsaw Puzzle

A 3D rendering of a blue puzzle with one piece missing, set against a background of a blue wavy pattern. The missing piece is a light blue color, contrasting with the darker blue of the other pieces. The puzzle is centered in the image, and the background consists of a repeating pattern of blue, wavy, interconnected lines.

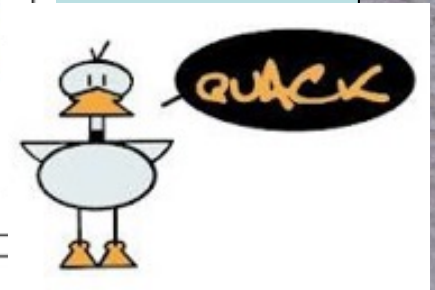
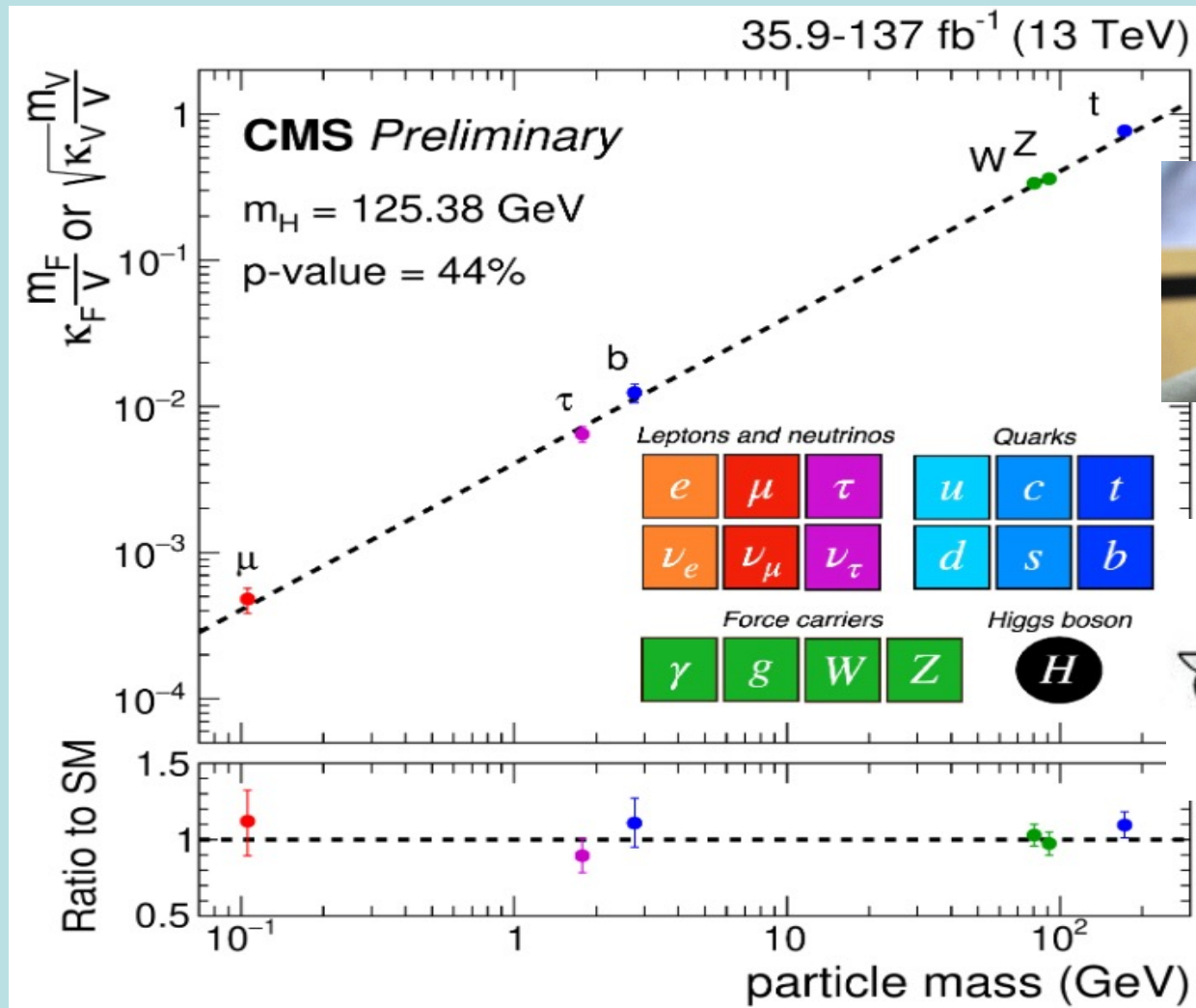
Did the LHC find the missing piece?

Is it the right shape?

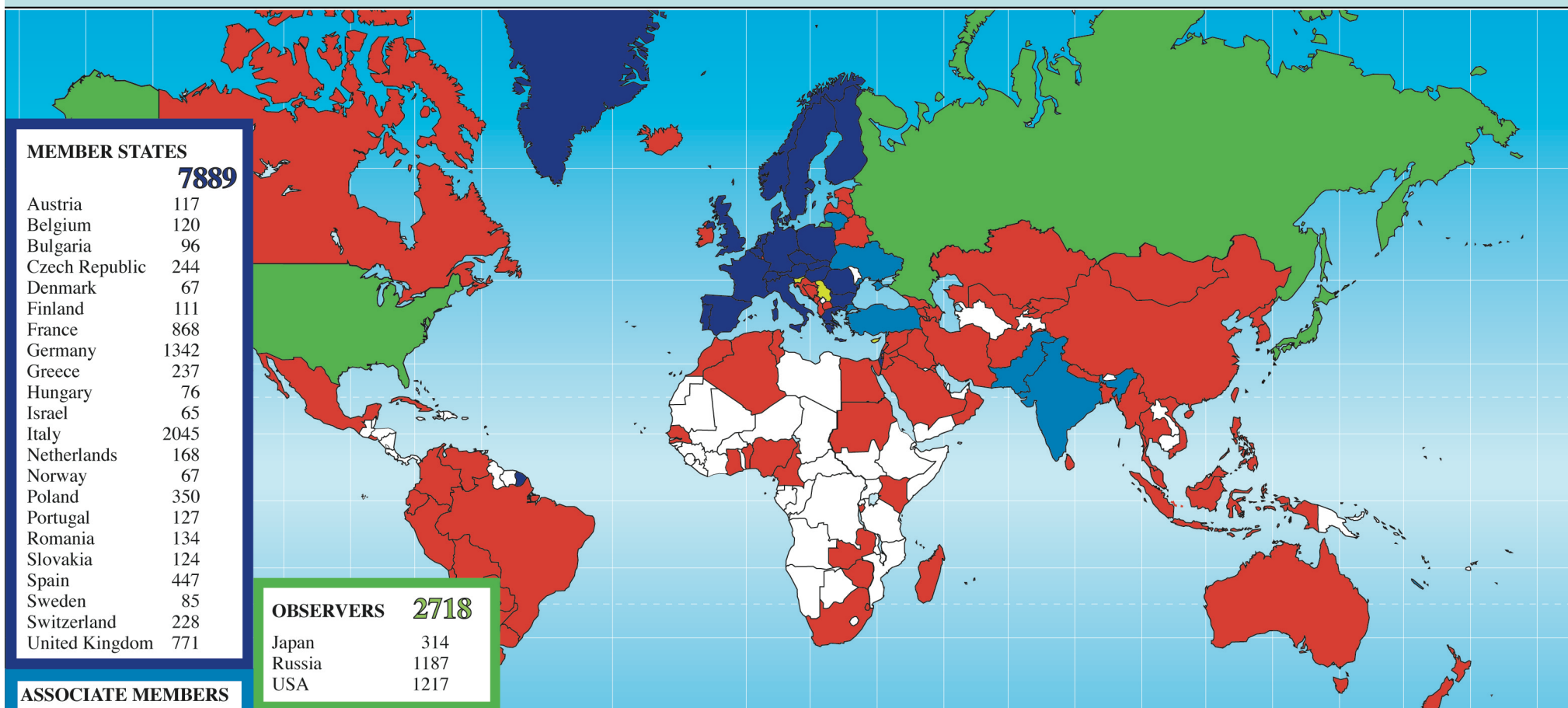
Is it the right size?

It Walks and Quacks like a Higgs

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



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

| | | |
|-----------|-----|------------|
| India | 357 | 745 |
| 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 | Burundi | 1 | Estonia | 15 | Korea Rep. | 185 | Morocco | 20 | Saudi Arabia | 2 | Tunisia | 5 |
| Argentina | 27 | Cameroon | 1 | Georgia | 46 | Kyrgyzstan | 1 | Myanmar | 1 | Senegal | 1 | Uruguay | 1 |
| Armenia | 19 | Canada | 161 | Ghana | 1 | Latvia | 2 | Nepal | 10 | Singapore | 4 | Uzbekistan | 4 |
| Australia | 31 | Chile | 20 | Hong Kong | 1 | Lebanon | 23 | New Zealand | 5 | South Africa | 56 | Venezuela | 10 |
| Azerbaijan | 10 | China | 510 | Iceland | 3 | Luxembourg | 2 | Nigeria | 3 | Sri Lanka | 6 | Viet Nam | 13 |
| Bangladesh | 11 | Colombia | 45 | Indonesia | 11 | Madagascar | 4 | North Korea | 1 | Sudan | 1 | Zambia | 1 |
| Belarus | 48 | Croatia | 41 | Iran | 51 | Malaysia | 15 | Oman | 3 | Swaziland | 1 | Zimbabwe | 2 |
| Benin | 1 | Cuba | 12 | Iraq | 1 | Malta | 9 | Palestine (O.T.) | 7 | Syria | 1 | | |
| | | Ecuador | 6 | Ireland | 16 | Mauritius | 1 | Paraguay | 2 | Taiwan | 51 | | |
| | | | | 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]

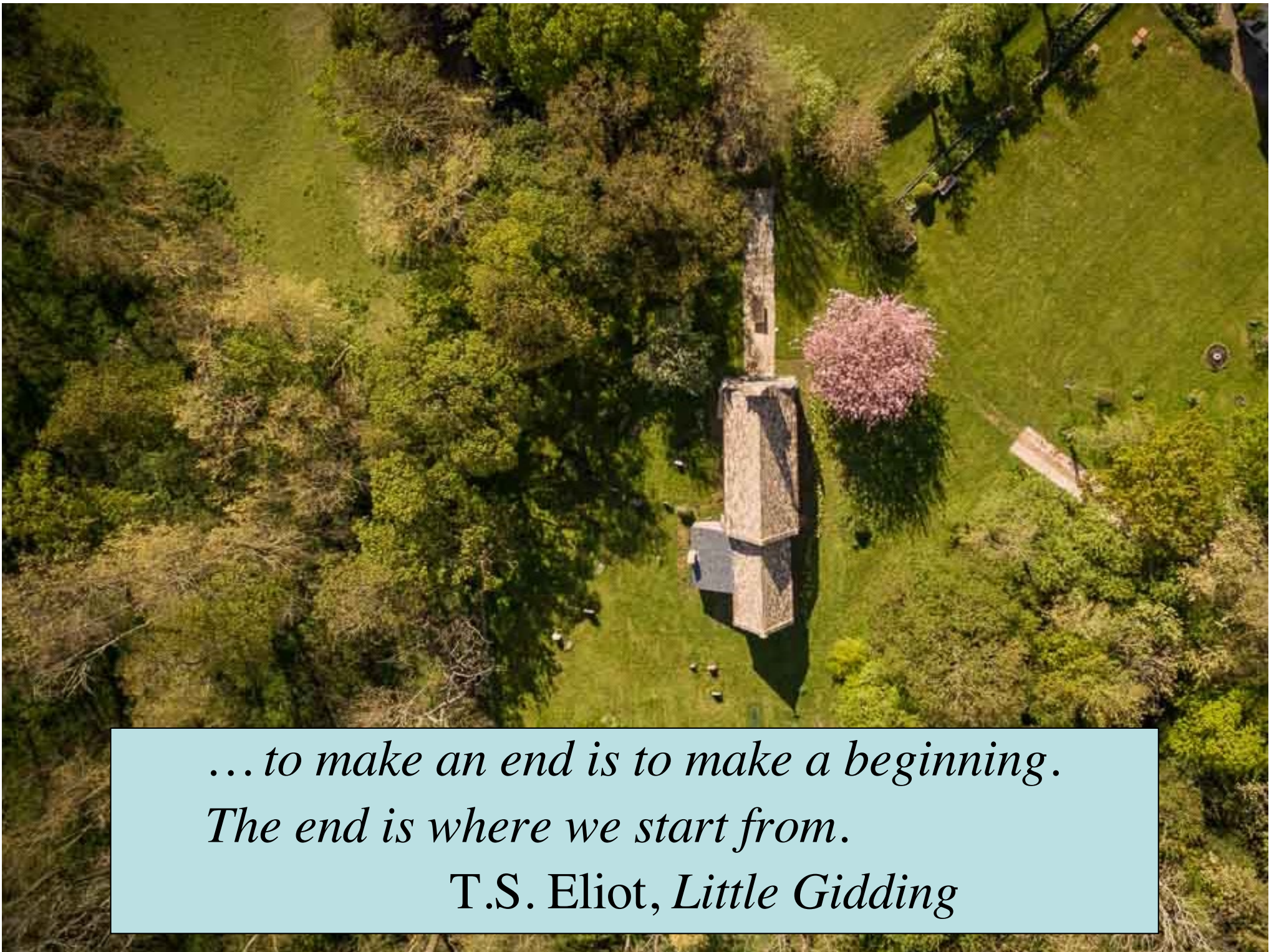
http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[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

Everything about Higgs is Puzzling

$$\mathcal{L} = yH\psi\bar{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 + \dots$$

- Pattern of Yukawa couplings y :
 - **Flavour problem**
- Magnitude of mass term μ :
 - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ :
 - **Stability of electroweak vacuum**
- Cosmological constant term V_0 :
 - **Dark energy**

Additional interactions?

Should it have Collapsed already?

Fluctuate over barrier
in the early Universe?

Not if
infinite barrier:
Supersymmetry?

We are here



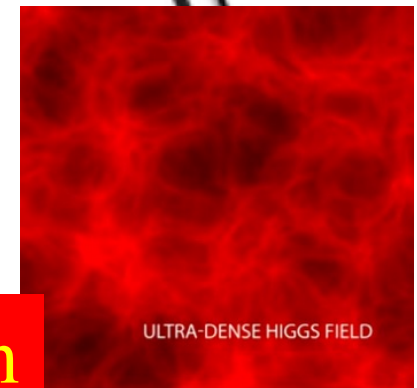
HIGGS FIELD



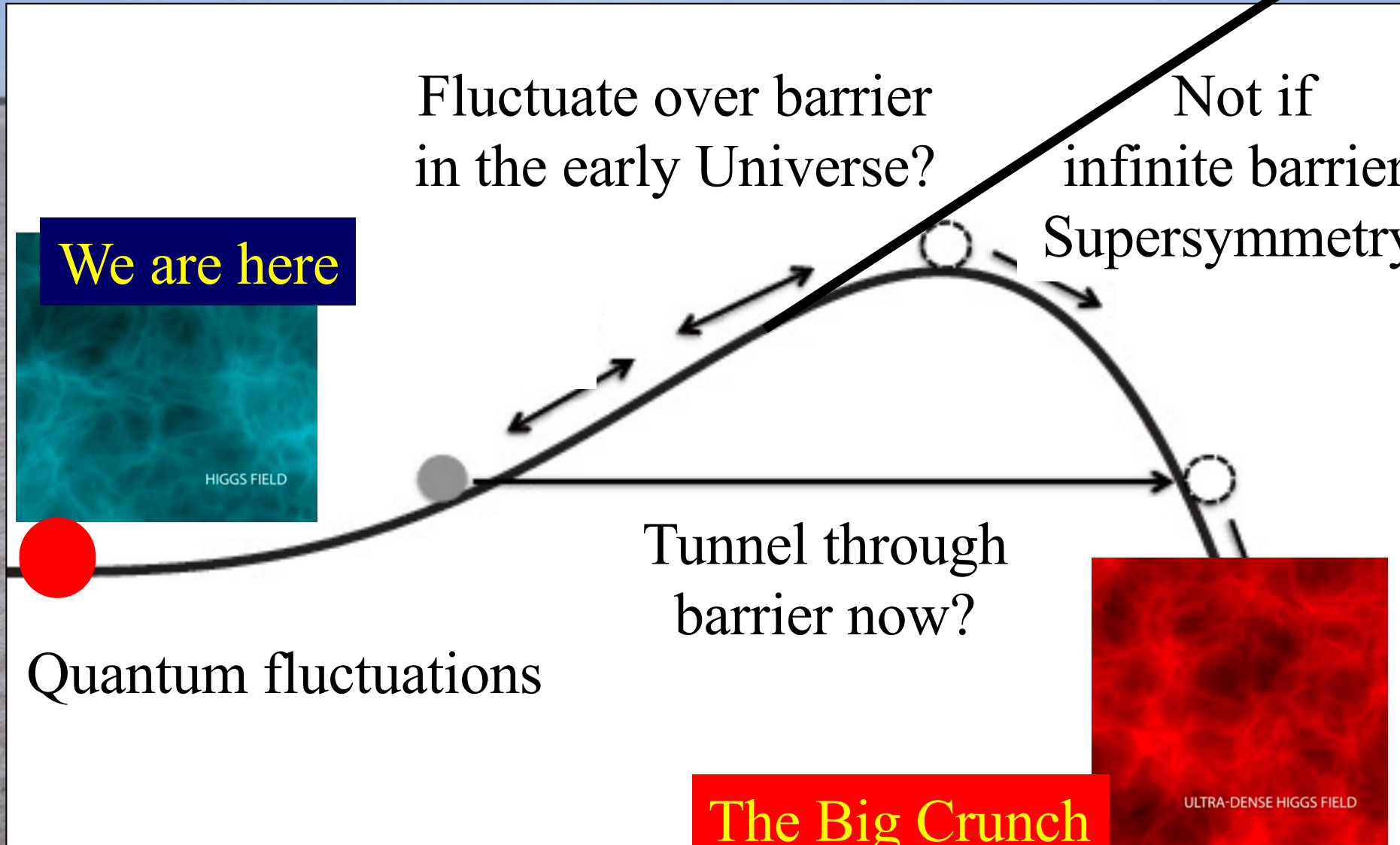
Quantum fluctuations

Tunnel through
barrier now?

The Big Crunch



ULTRA-DENSE HIGGS FIELD





- « Empty » space is unstable
- Dark matter
- Origin of matter
- Sizes of masses
- Masses of neutrinos
- Inflation
- Quantum gravity
- ...

LHC
LHC
LHC
LHC

The Standard Model

PIERCE BROSNAN in JAMES BOND 007™
'Is Not Enough
007™

ALBERT R. BROCCOLLI'S SON PRODUCTIONS presents PIERCE BROSNAN in JAMES BOND 007™
'THE WORLD IS NOT ENOUGH' SOPHIE MARCEAU ROBERT CARVILLE DENISE RICHARDS RODRIGUE CROTHAN and JUDI DENCH
MUSIC BY LINDY HEARNING COSTUME DESIGNER DAVID ARNOLD EDITOR JIM CLARK EXECUTIVE PRODUCERS JONATHAN ADRIAN BRIDLE PRODUCED BY PETER LADDINI
WRITTEN BY ANTHONY WAKE DIRECTED BY NEAL PURVIS & ROBERT WARD EXECUTIVE PRODUCERS NEAL PURVIS & ROBERT WARD PRODUCED BY BRUCE FENSTEIN
PRODUCED BY MICHAEL G. WILSON AND BARBARA BROCCOLLI EXECUTIVE PRODUCERS MICHAEL APPEL
CASTING BY JUDITH WILSON COSTUME DESIGNER DAVID ARNOLD EXECUTIVE PRODUCERS JONATHAN ADRIAN BRIDLE PRODUCED BY PETER LADDINI
WRITTEN BY ANTHONY WAKE DIRECTED BY NEAL PURVIS & ROBERT WARD EXECUTIVE PRODUCERS NEAL PURVIS & ROBERT WARD PRODUCED BY BRUCE FENSTEIN
PRODUCED BY MICHAEL G. WILSON AND BARBARA BROCCOLLI EXECUTIVE PRODUCERS MICHAEL APPEL

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

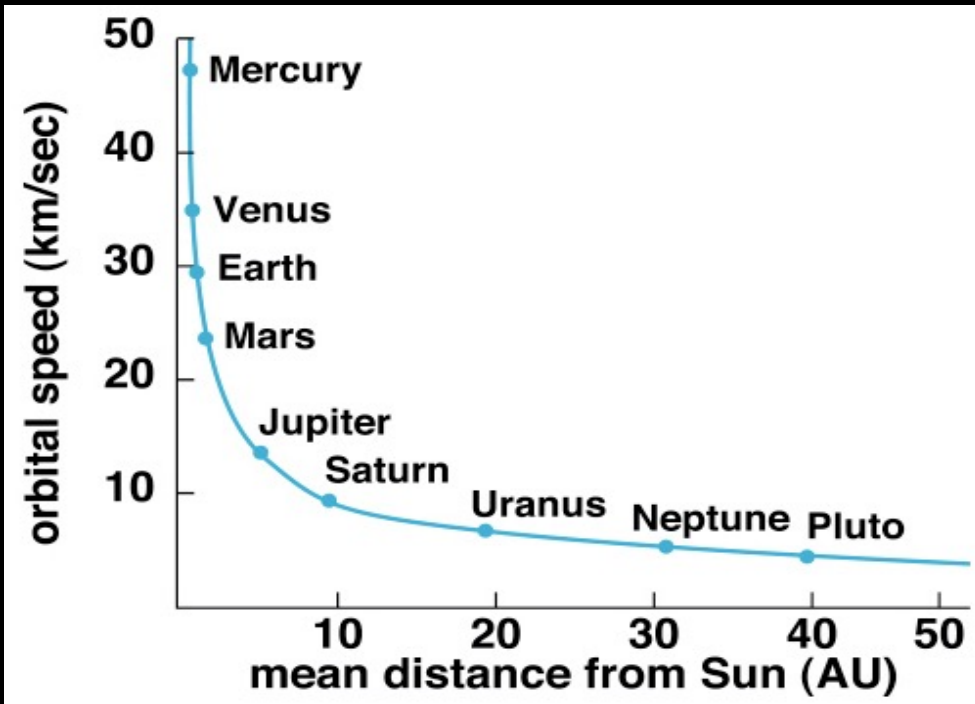
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



Scanned at the American
Institute of Physics

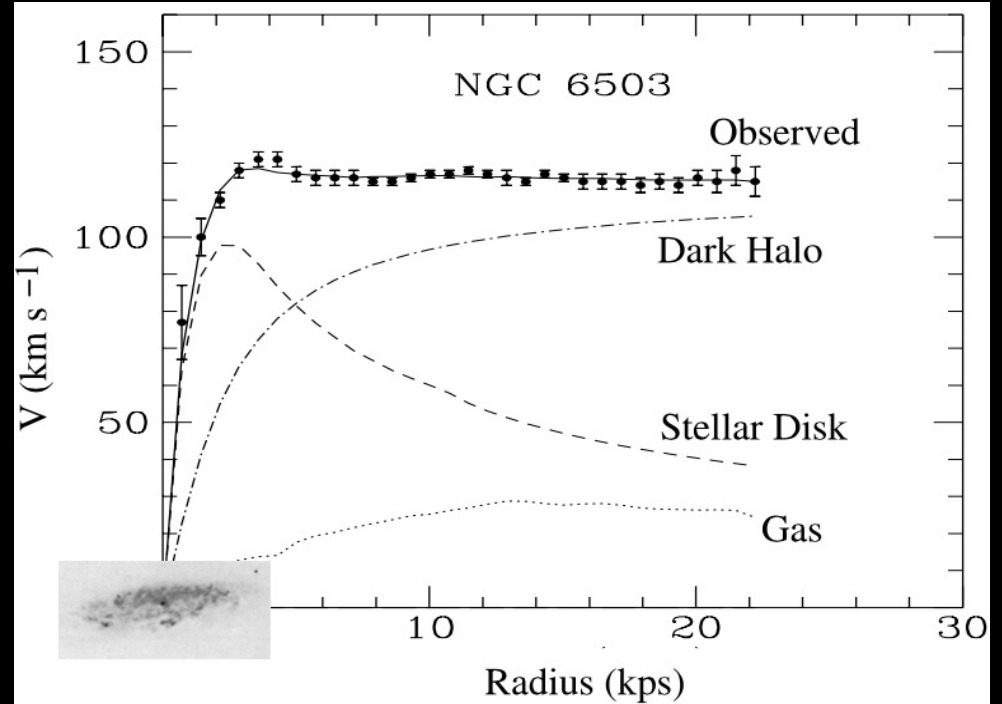
Rotation Curves

- In the Solar System



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

- In galaxies



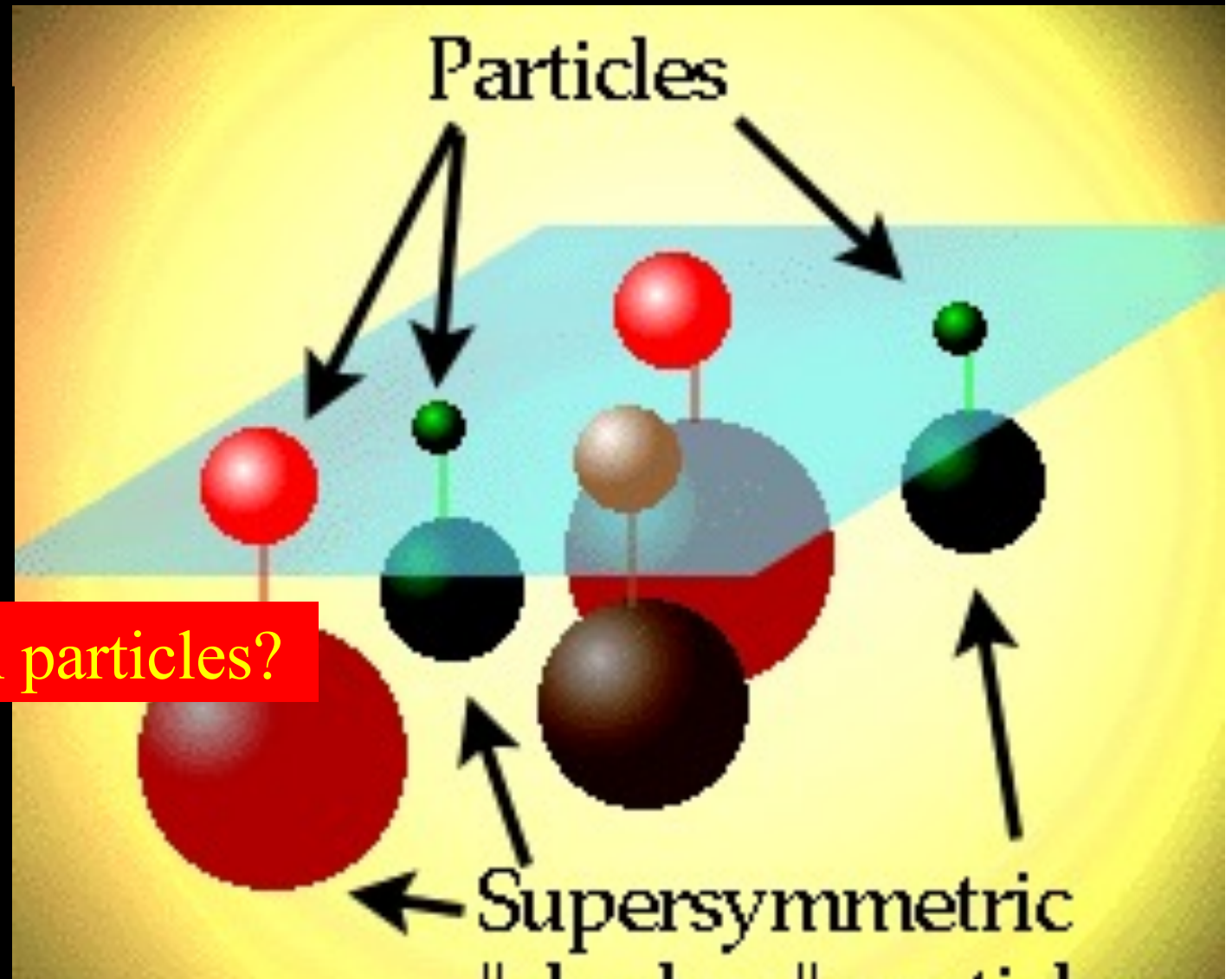
- The velocities do not decrease with distance
- Dark matter spread out

What is the Dark Matter in the Universe?

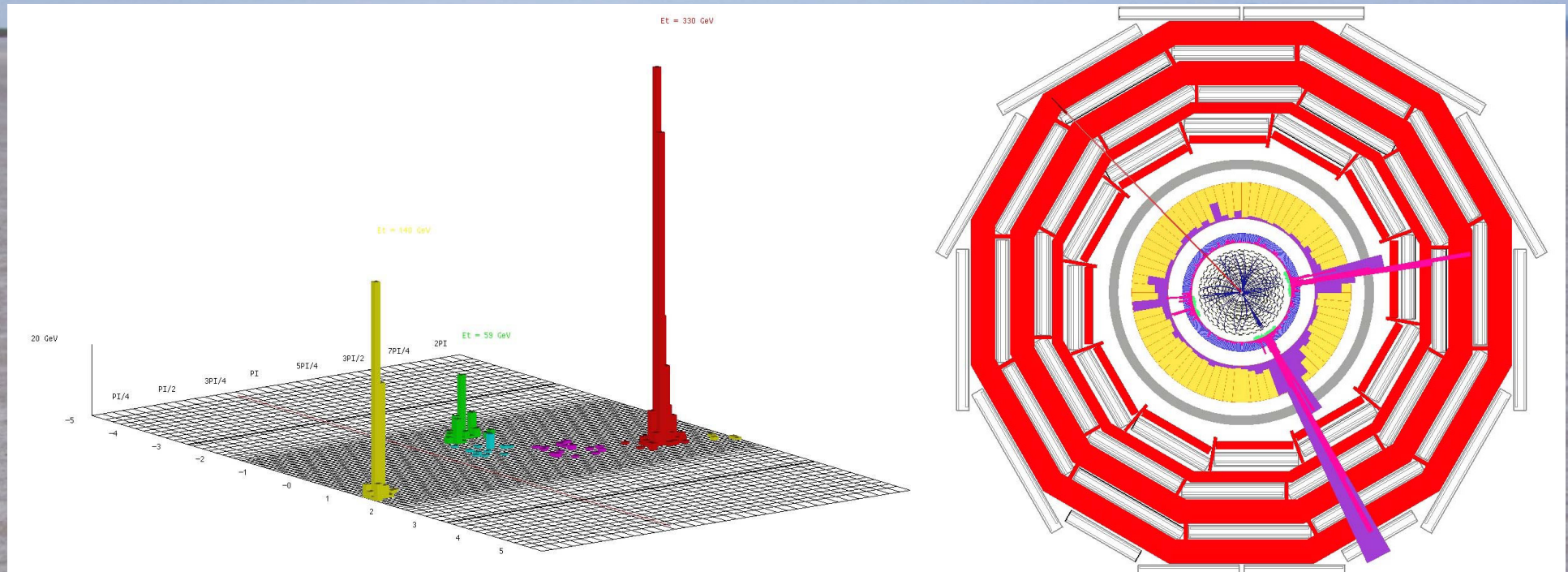
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Made of unknown particles?

We are searching for them at the

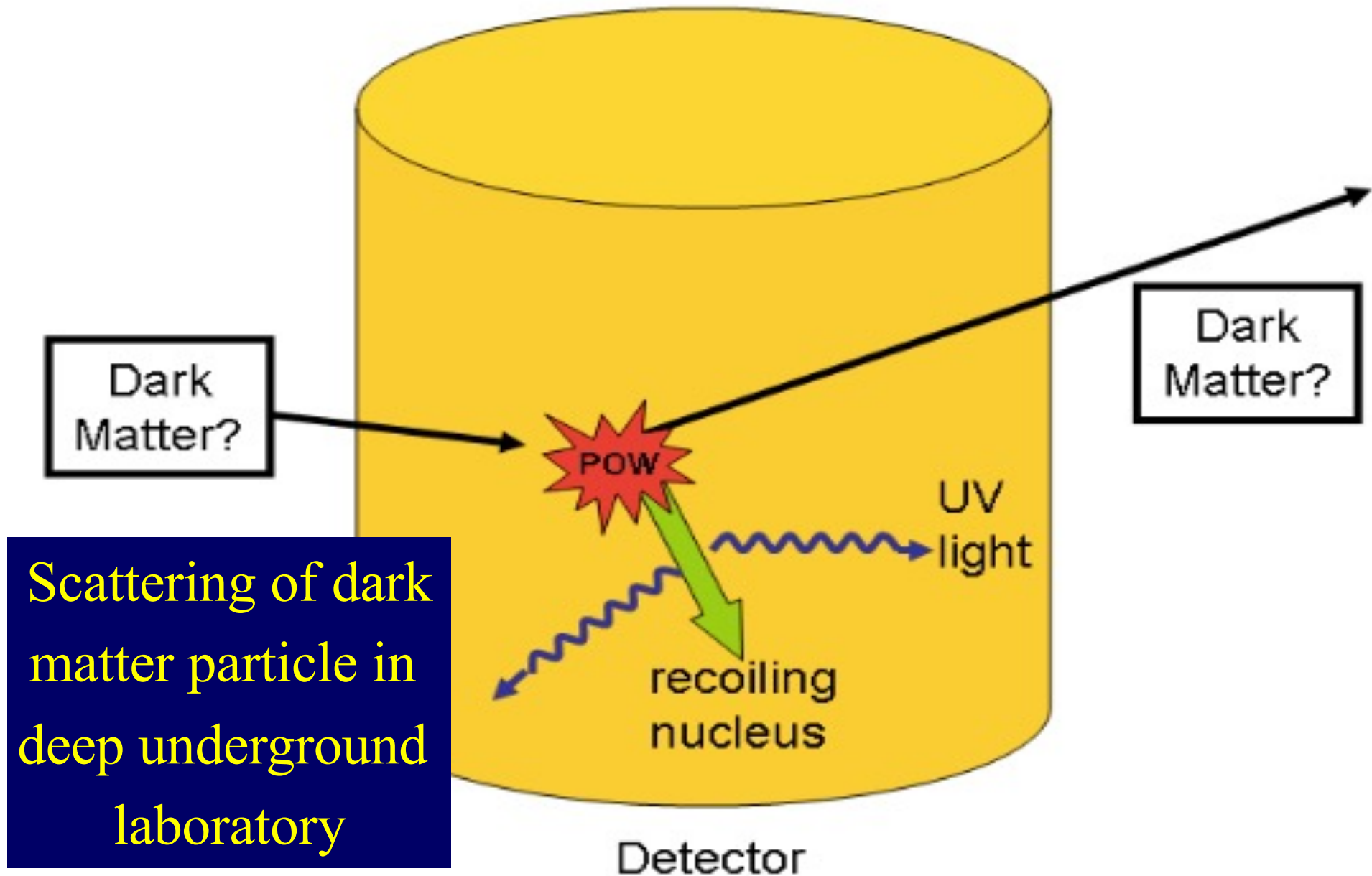


Classic Dark Matter Signature



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

How to Create the Matter in the Universe?

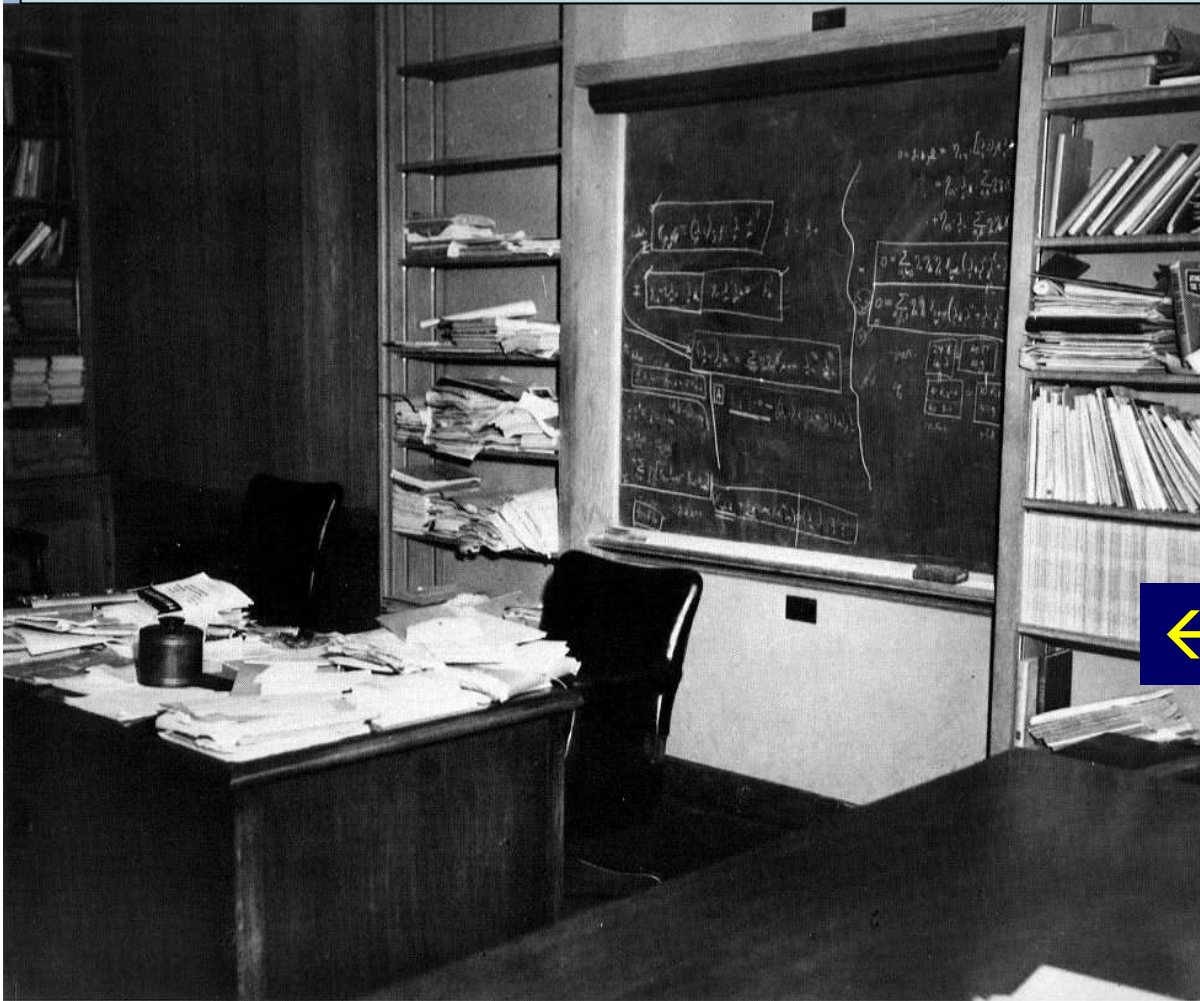
Sakharov

- 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



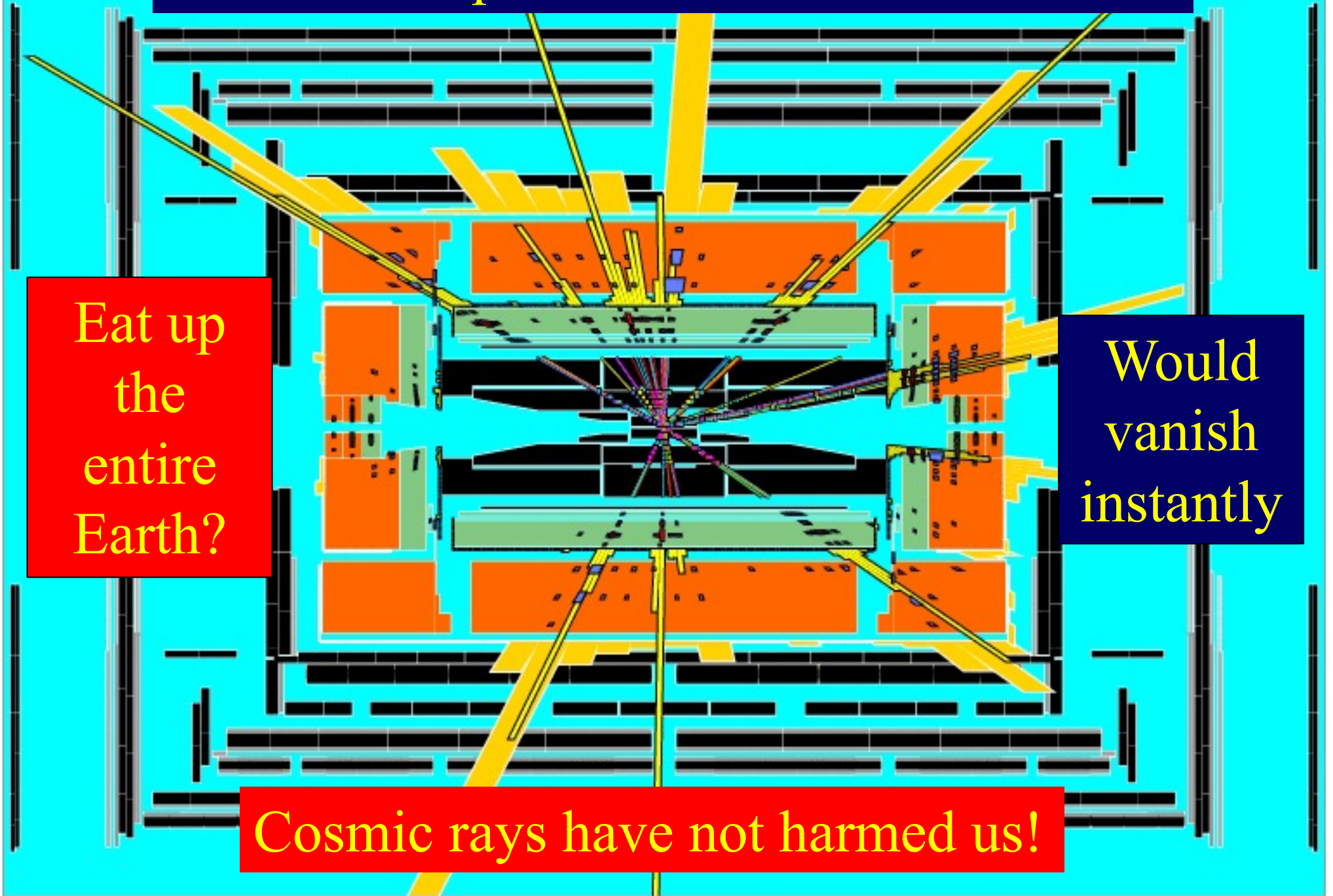
Unification via extra dimensions of space?

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