

# Particle Physics and Gauguin's Questions about the Universe



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

*John Ellis*

**KING'S**  
College  
LONDON

# 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

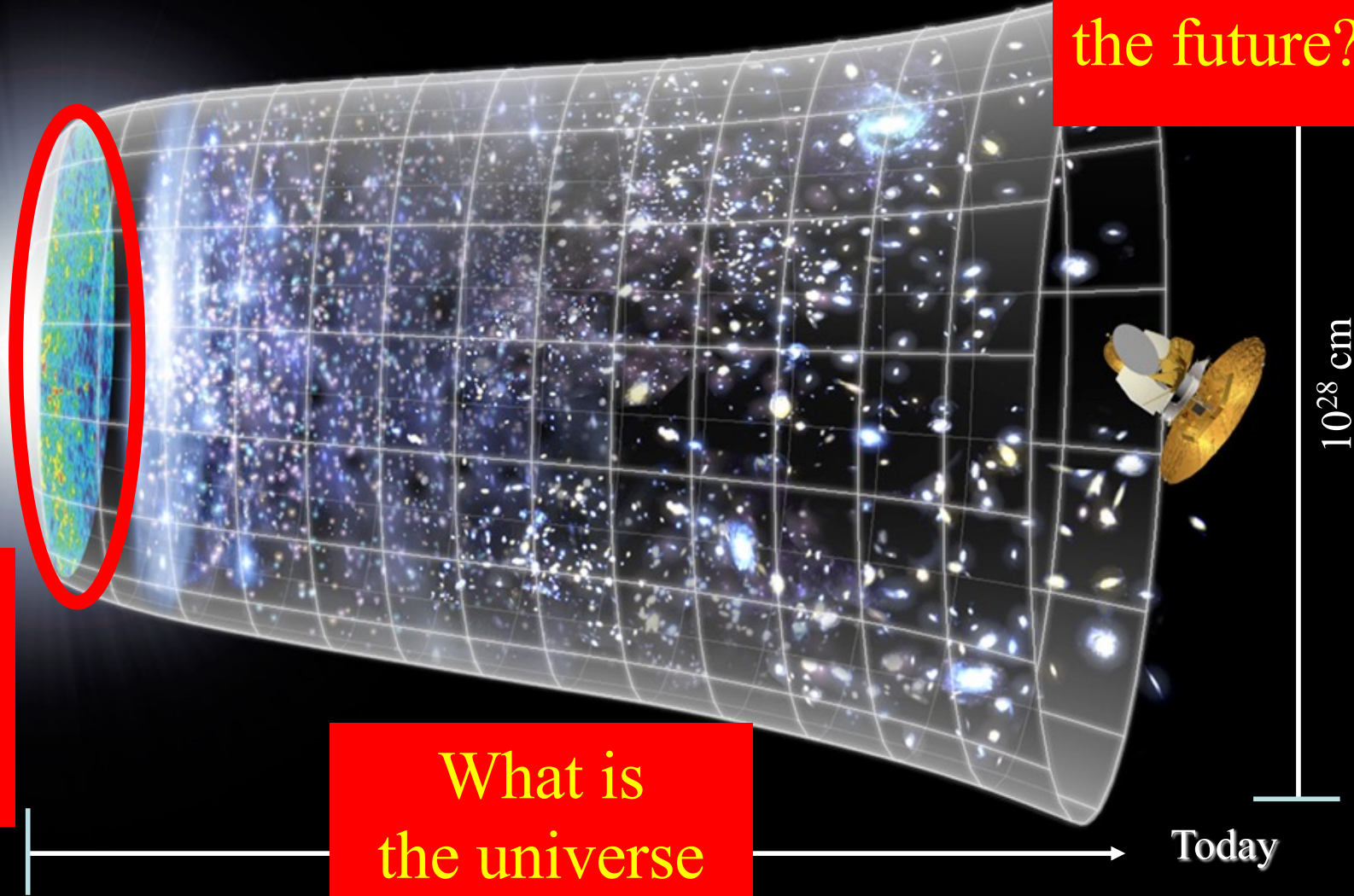
Need physics beyond what we know



# Evolution of the Universe

What will happen in the future?

Big Bang



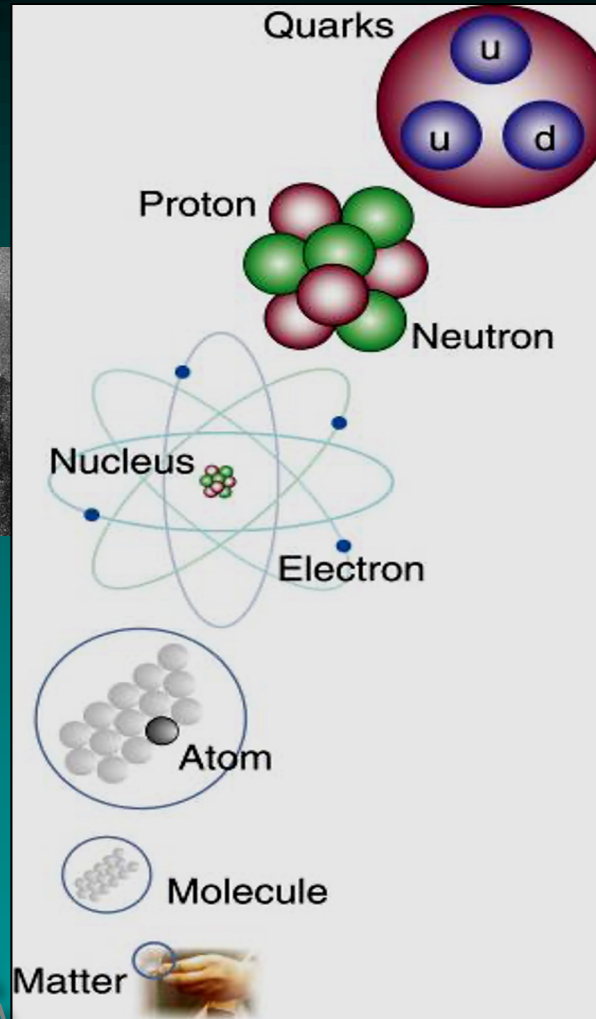
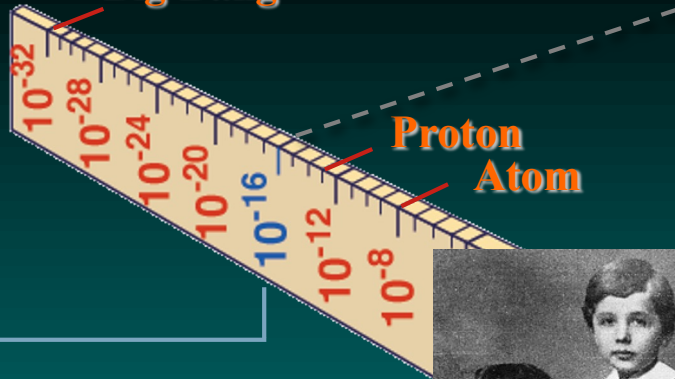
What happened then?

What is the universe made of?

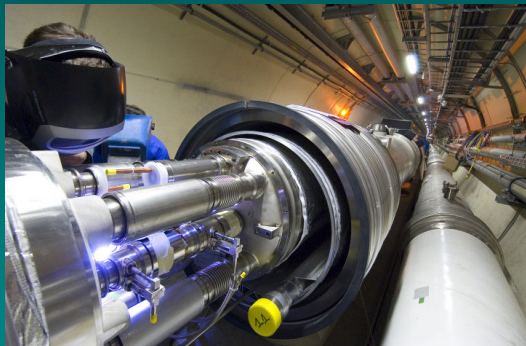
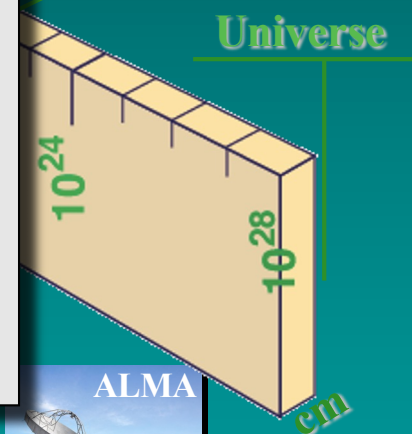
Today

$10^{28}$  cm

Big Bang



Radius of Galaxies



LHC

Super-Microscope



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



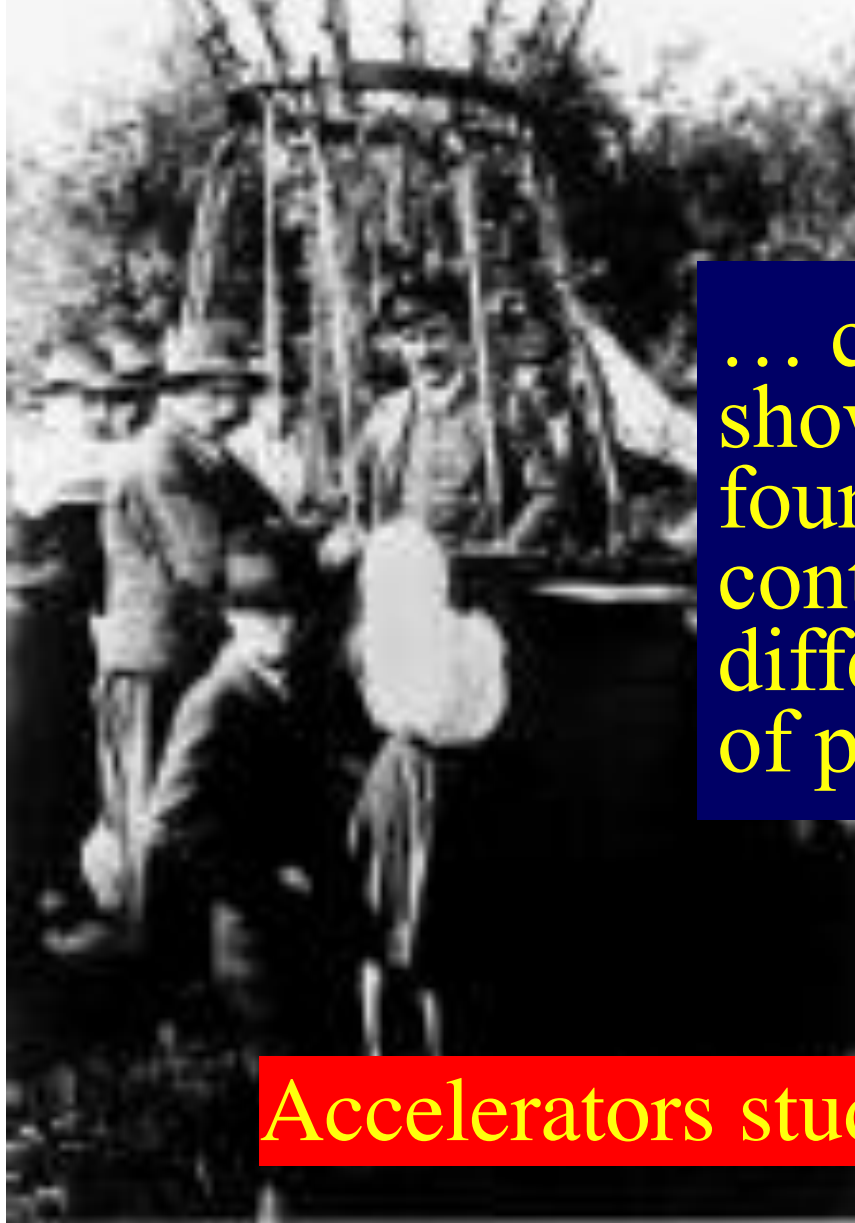
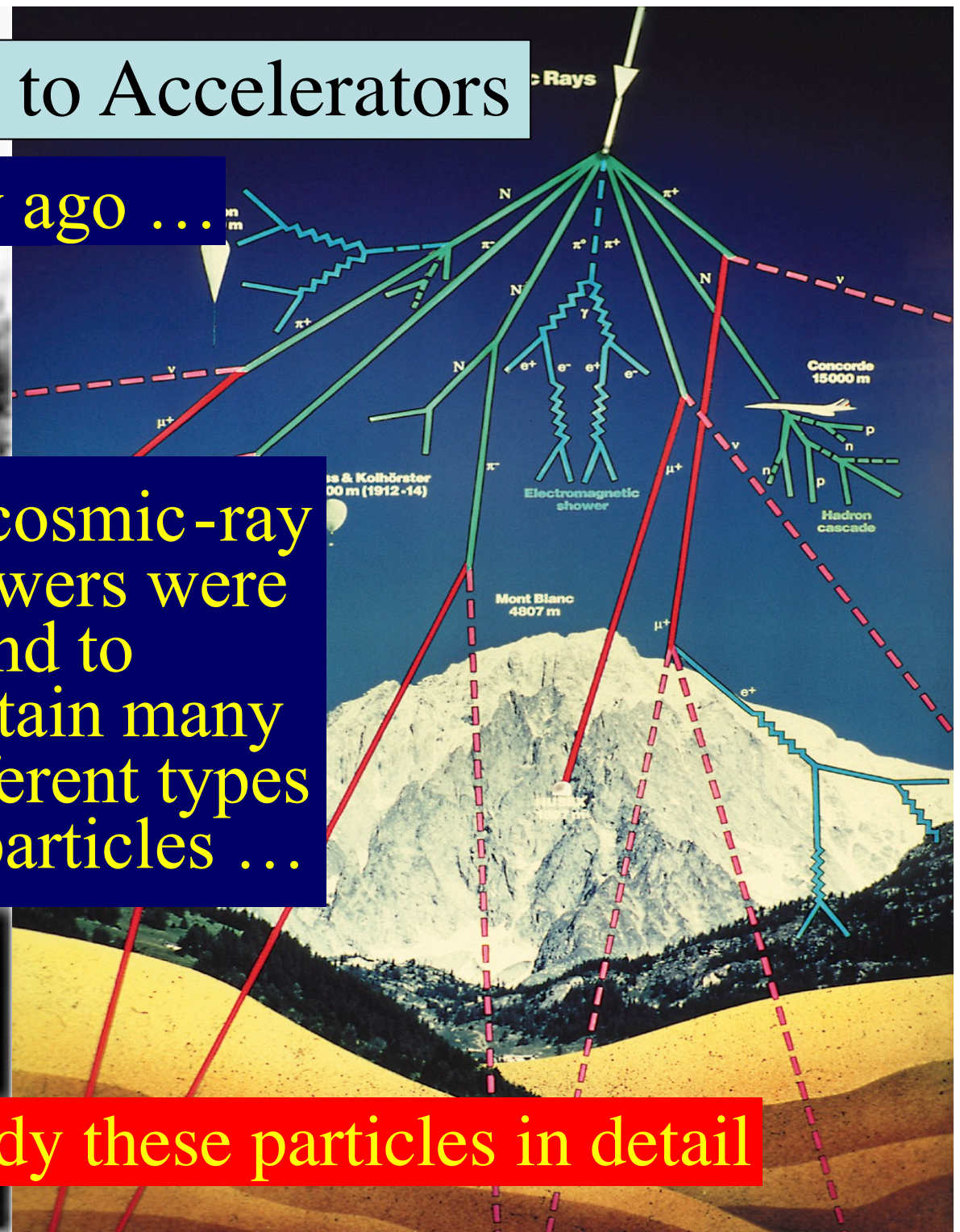


# From Cosmic Rays to Accelerators

Discovered a century ago ...

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

Accelerators study these particles in detail

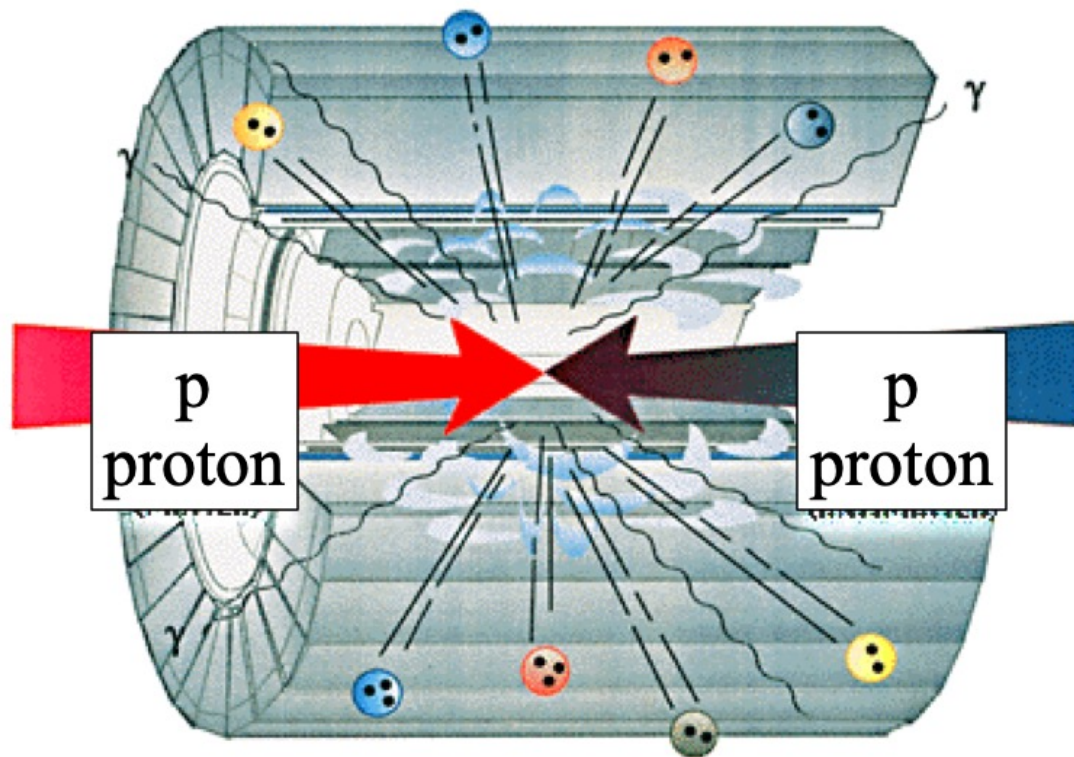




# Experiments with Accelerators

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

## Particle Colliders

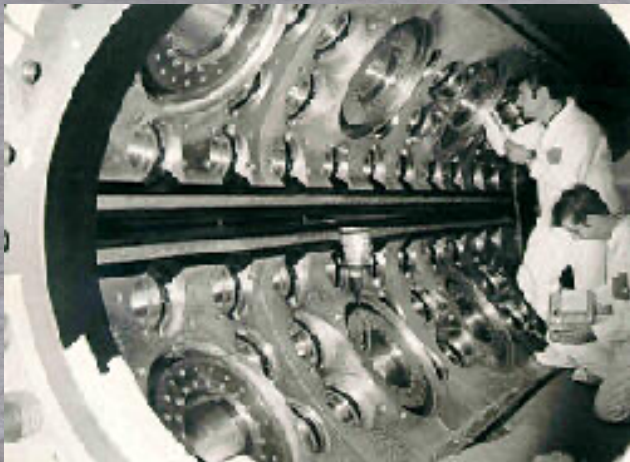


Collisions reproduce the conditions at beginning of Big Bang



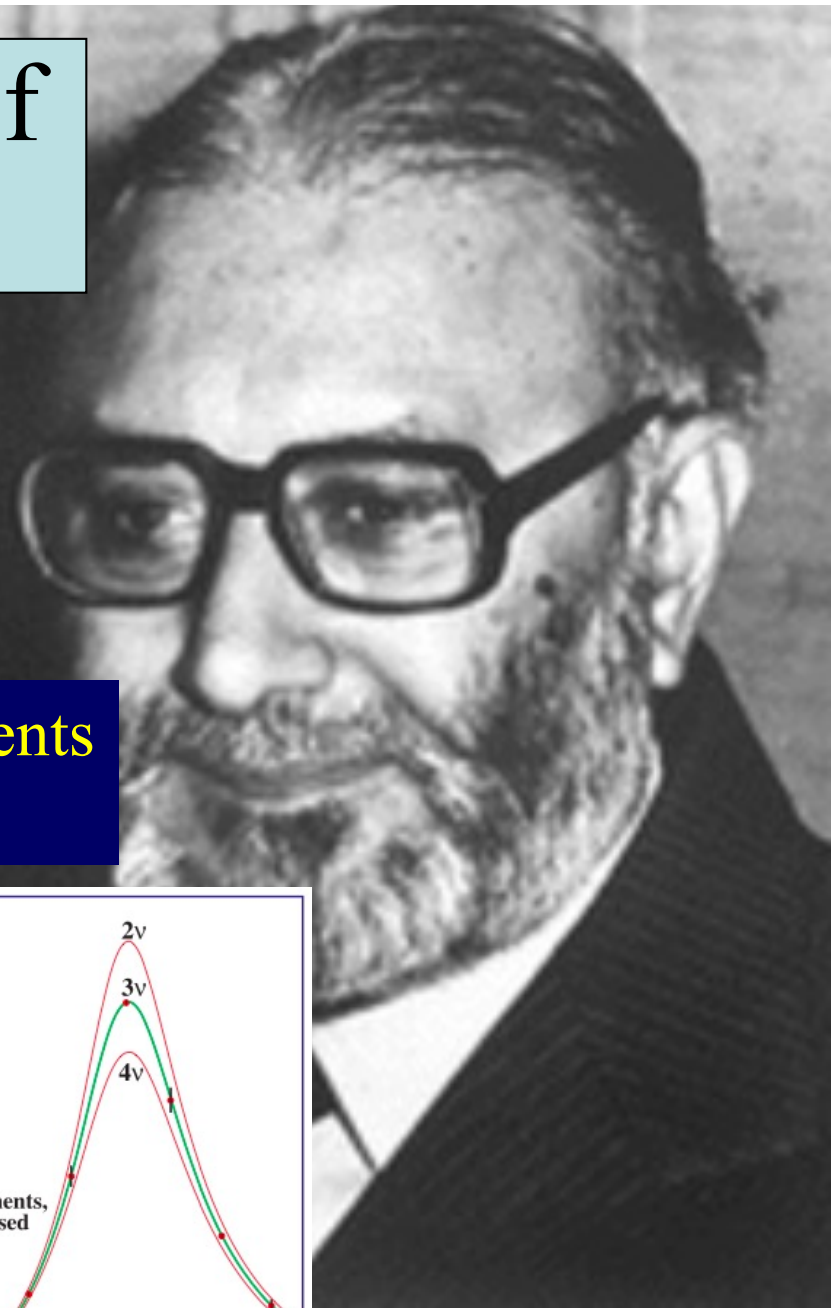
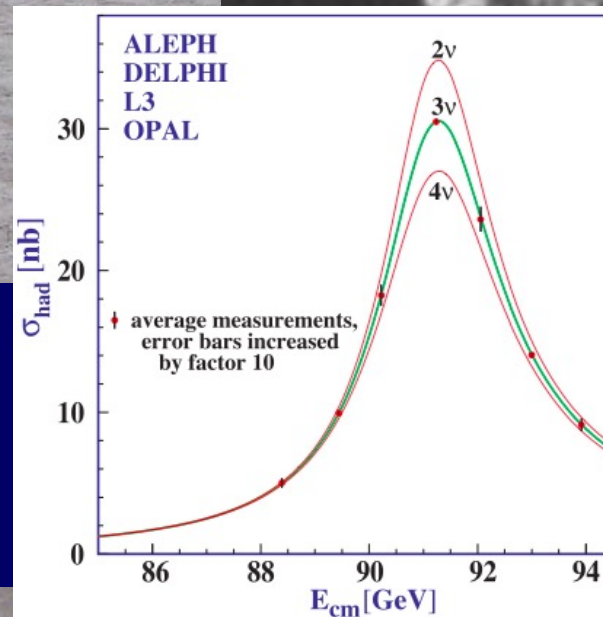
# The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,  
Glashow and Weinberg



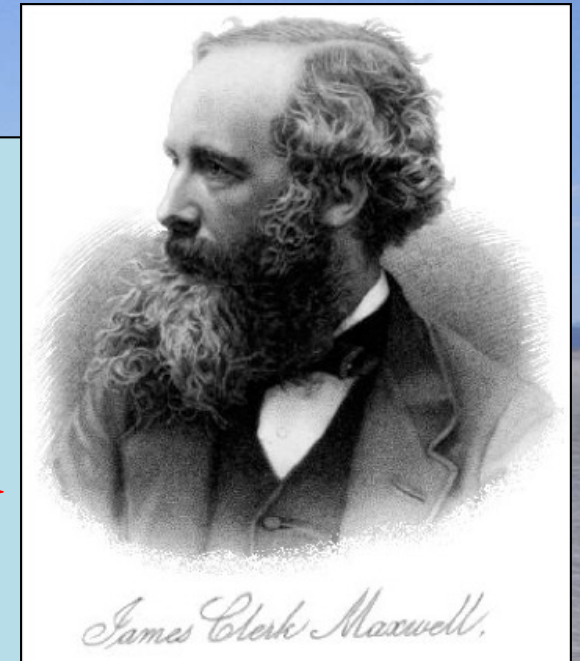
Tested by experiments  
at CERN

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***

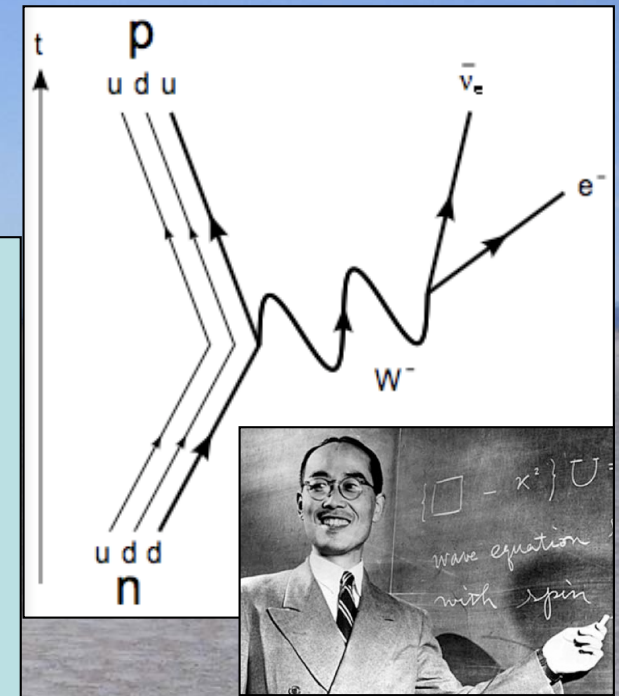




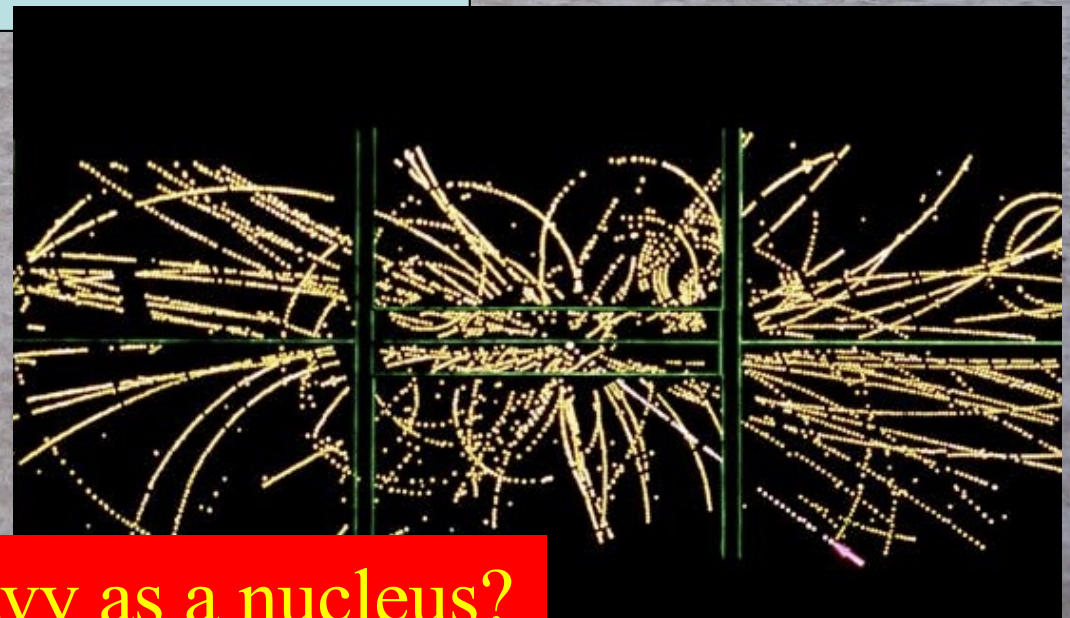
# Weak Interactions

Radioactivity due to weak interactions  
( $\beta$  decay)

**W boson - carrier of weak interaction**  
postulated by Yukawa



Discovered at CERN in  
1983 by Carlo Rubbia et al

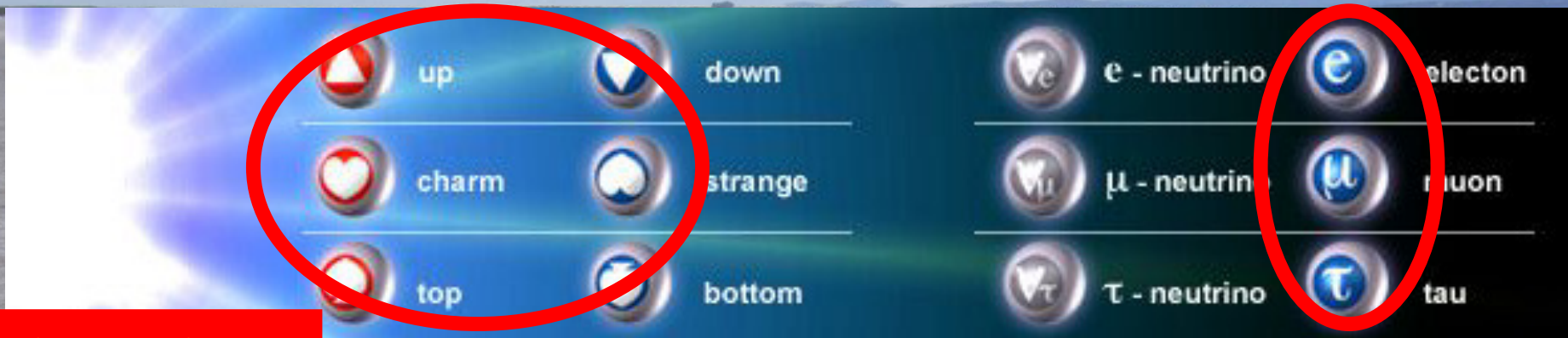


**Why is it as heavy as a nucleus?**



# The 'Standard Model'

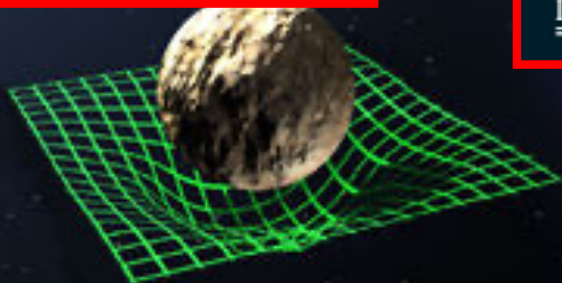
## The matter particles



Where does mass come from?

## The fundamental interactions

KING'S  
College  
LONDON



Gravitation

electromagnetism

weak nuclear force

strong nuclear force

# Why do Things Weigh?

Newton:

Weight **proportional to** Mass

Einstein:

Energy **related to** Mass

Neither explained origin of Mass

Where do the masses  
come from?

Are masses due to Higgs boson?  
(the physicists' Holy Grail)



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:



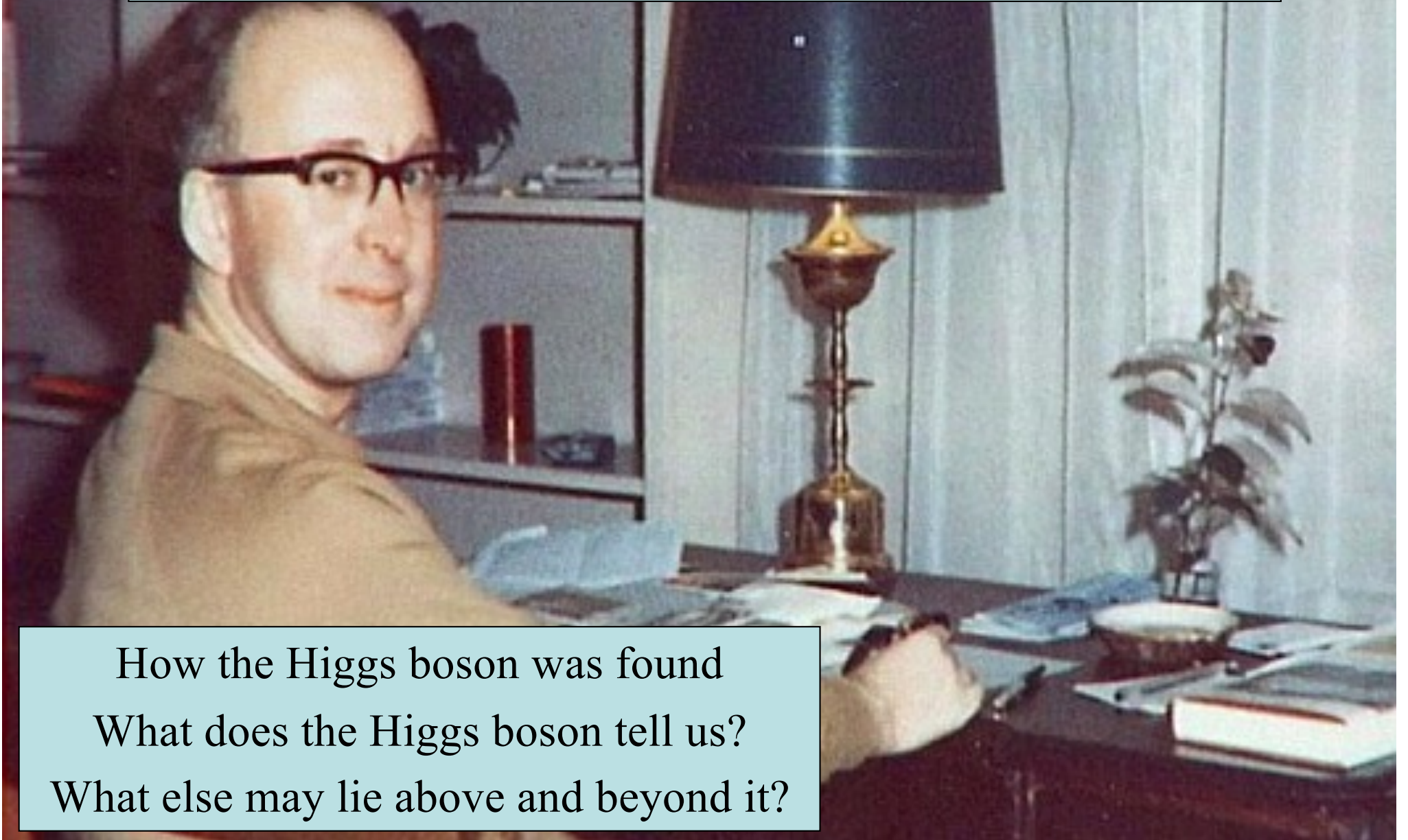
Like particle with mass  
e.g., electron

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

Hiker sinks deep,  
moves very slowly:  
Particle with large mass



# 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. The image shows a vast landscape of agricultural fields and some urban areas. Overlaid on the image are two large, white, circular lines representing the paths of the Large Hadron Collider (LHC). The larger circle represents the main LHC ring, and the smaller circle represents the LHC injection chain. 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:

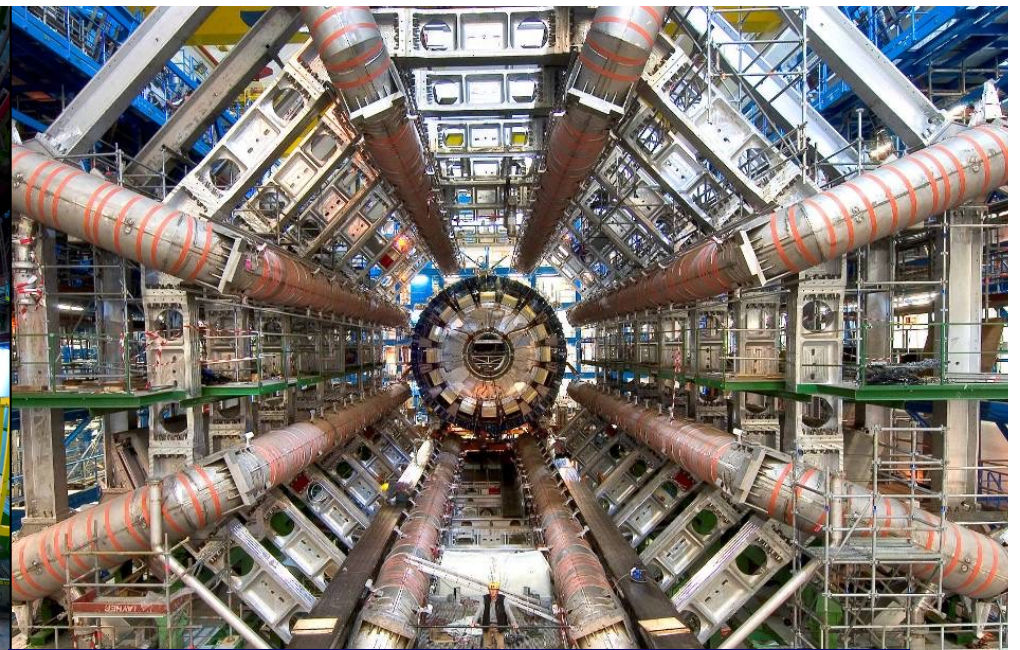
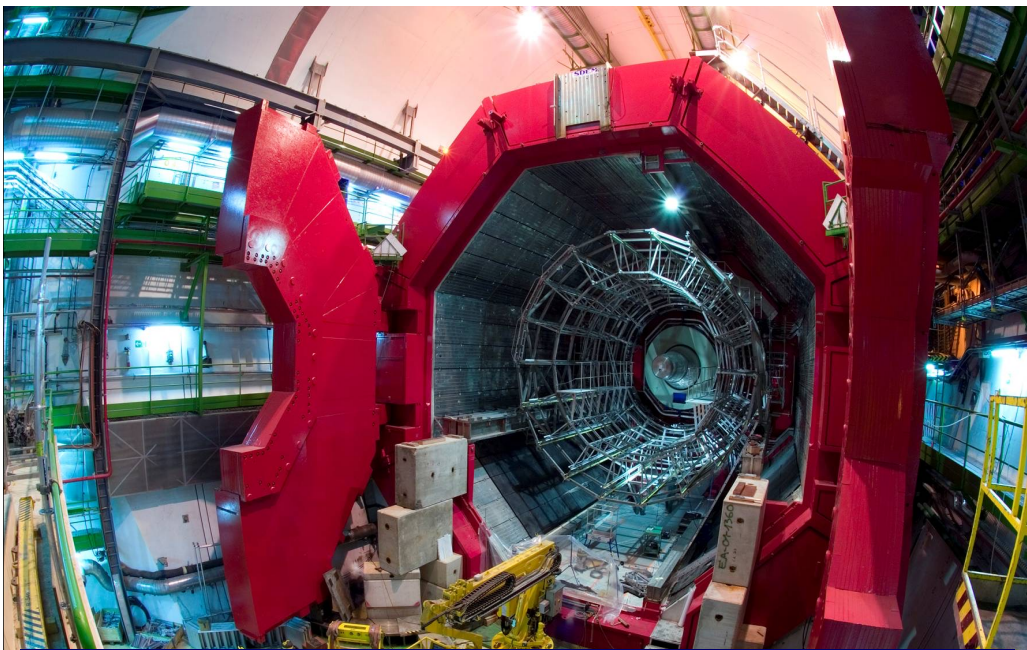
## The Large Hadron Collider (LHC)

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:

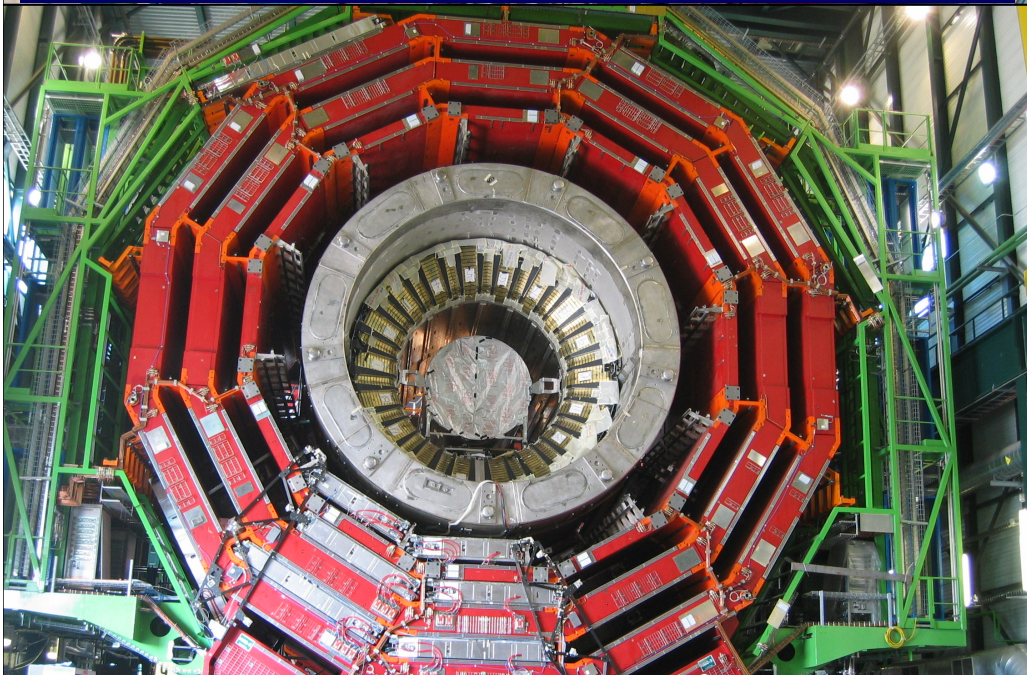
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter





**ALICE: Primordial cosmic plasma**

**ATLAS: Higgs and dark matter**



**CMS: Higgs and dark matter**

**LHCb: Matter-antimatter difference**



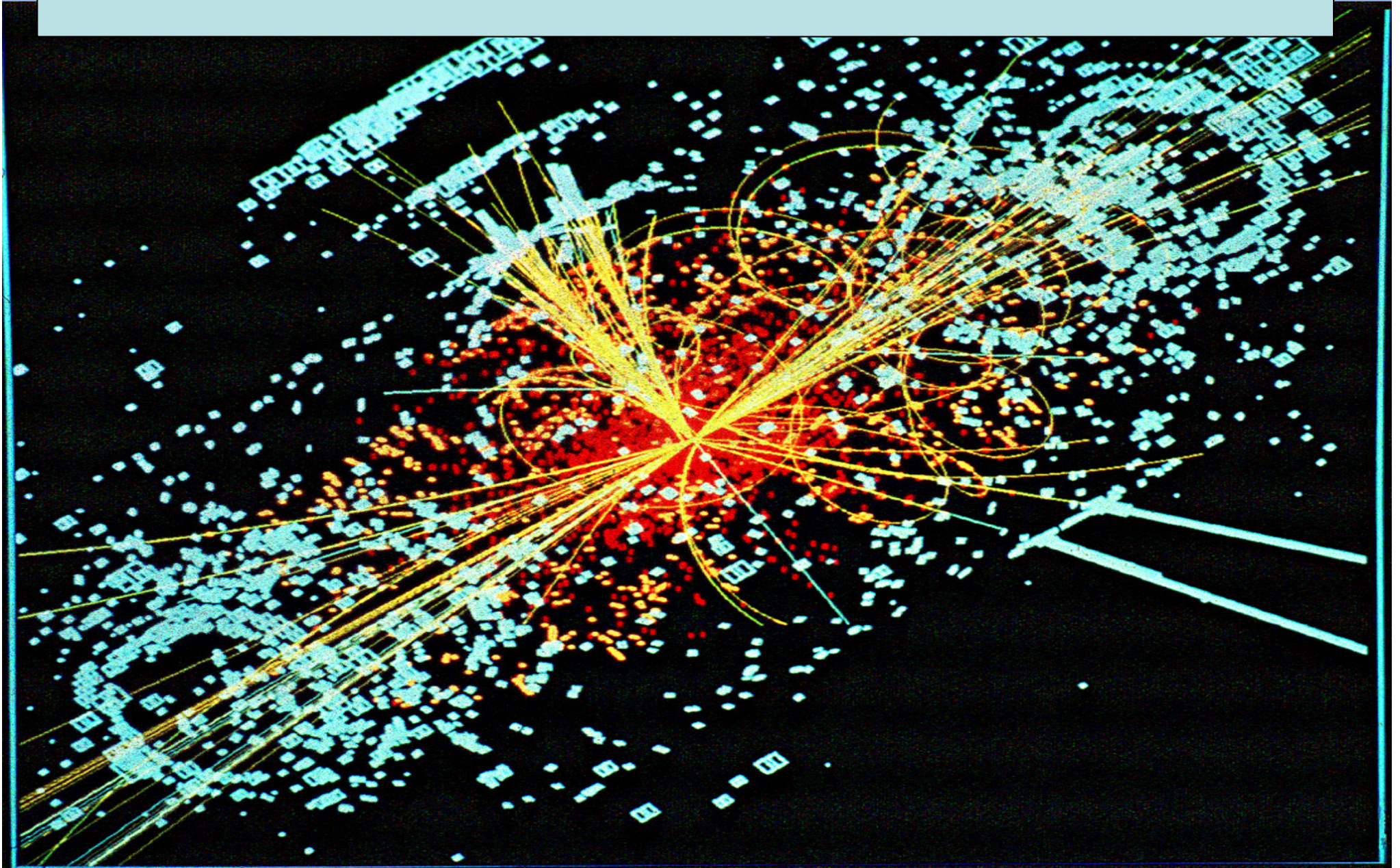
2012: The discovery of the Higgs Boson



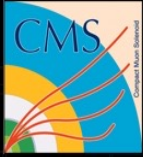
Mass Higgsteria



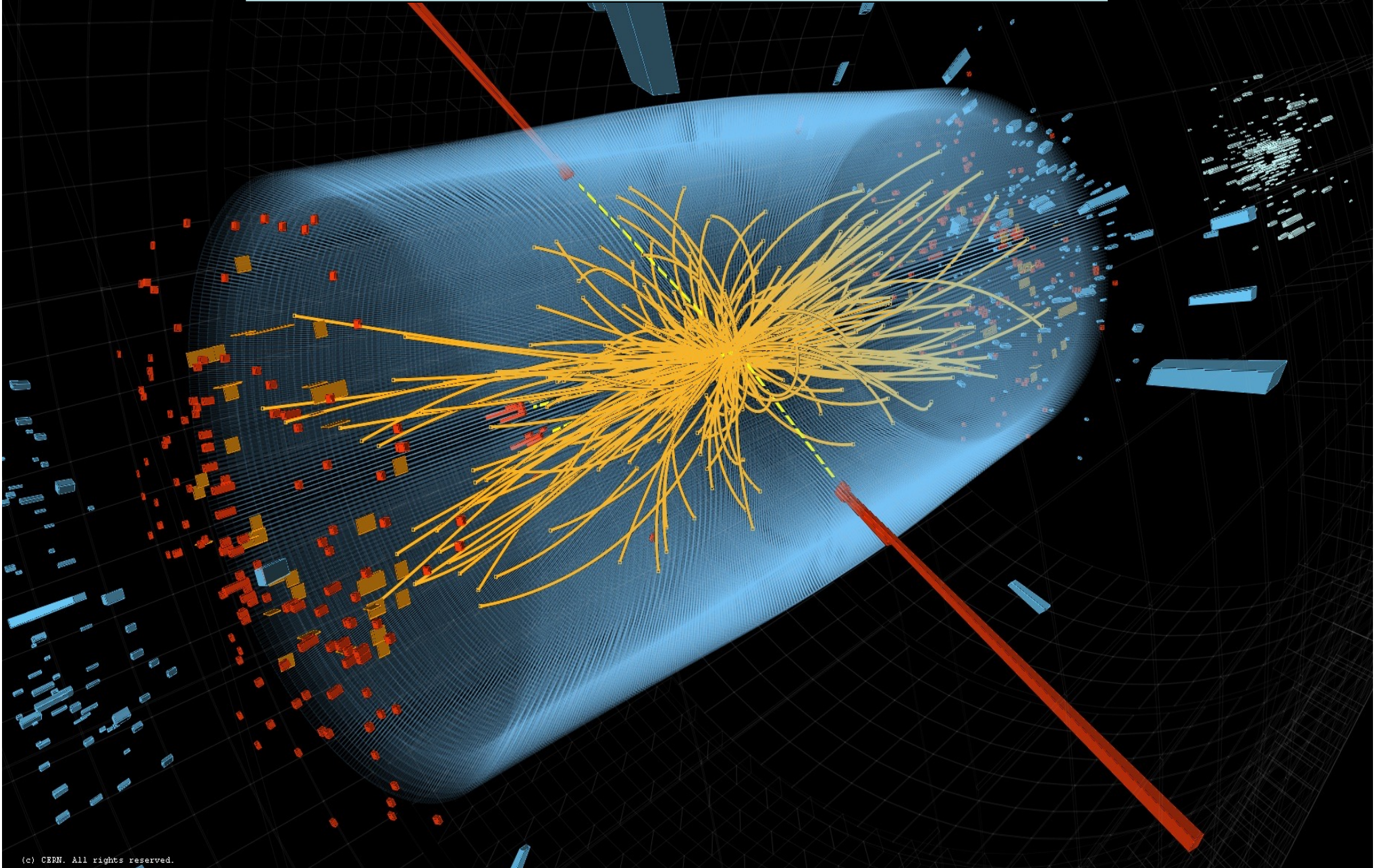
# A Simulated Higgs Event @ LHC





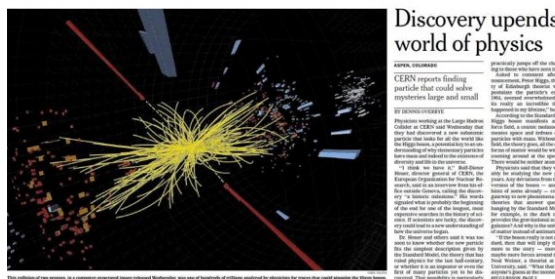


# Interesting Events





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 Monde
Les coups de cœur de la rédaction

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

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
Große Mehrheit im Europaparlament

CHINADAILY
DANGEROUS MOVE
IMPORTANT MATTER
MOVIE PLOT

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
Uratancy hla sie o lezyk Rosyjski
Czaszke Higgsa fizycy najpierw wymyslili, potem szukali 40 lat

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



# 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?

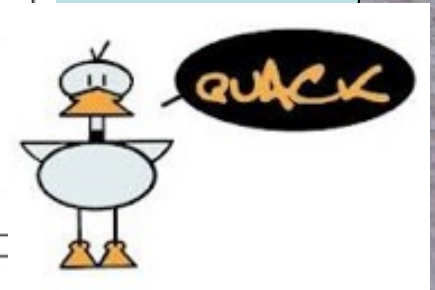
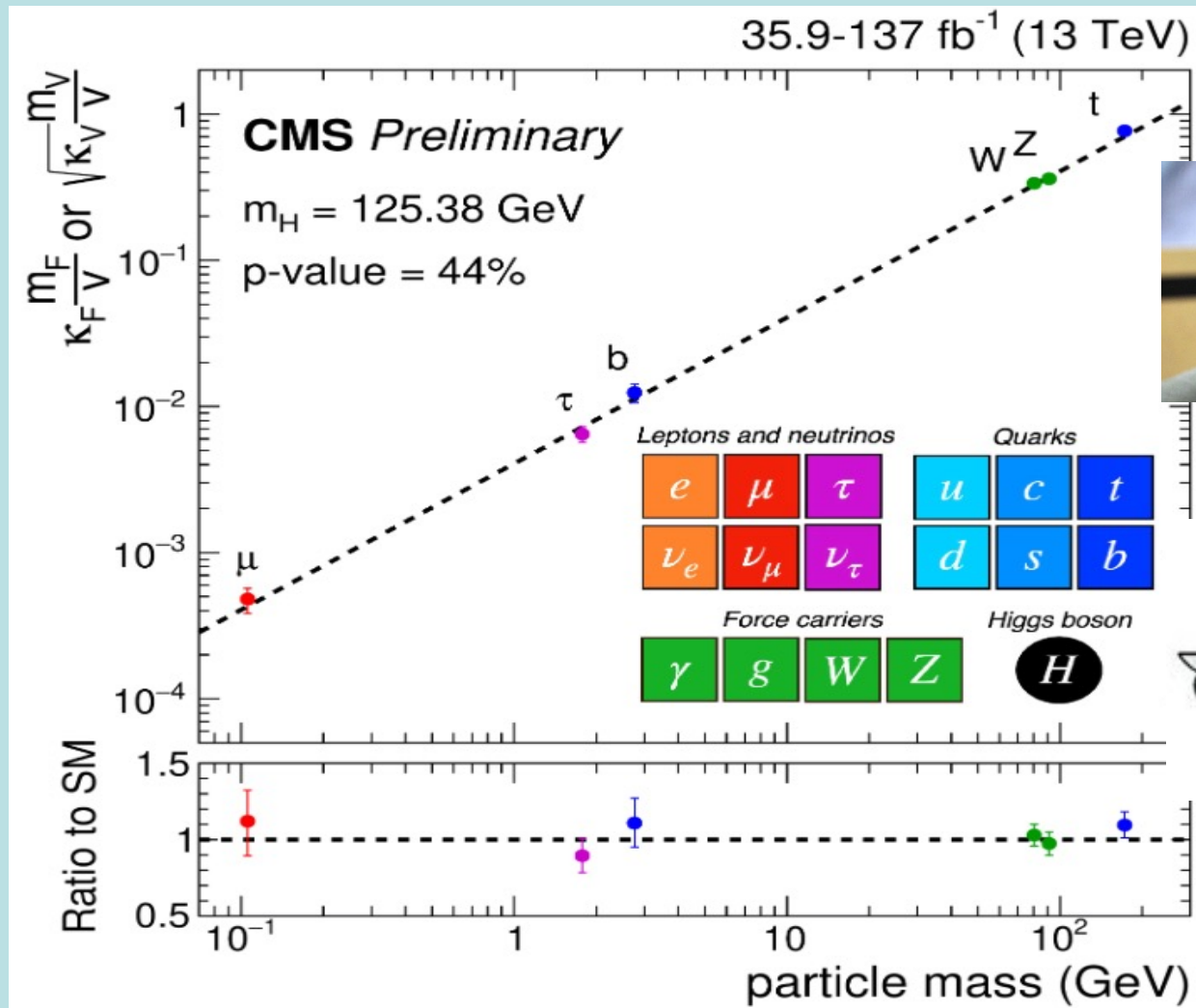
Is it the right shape?

Is it the right size?

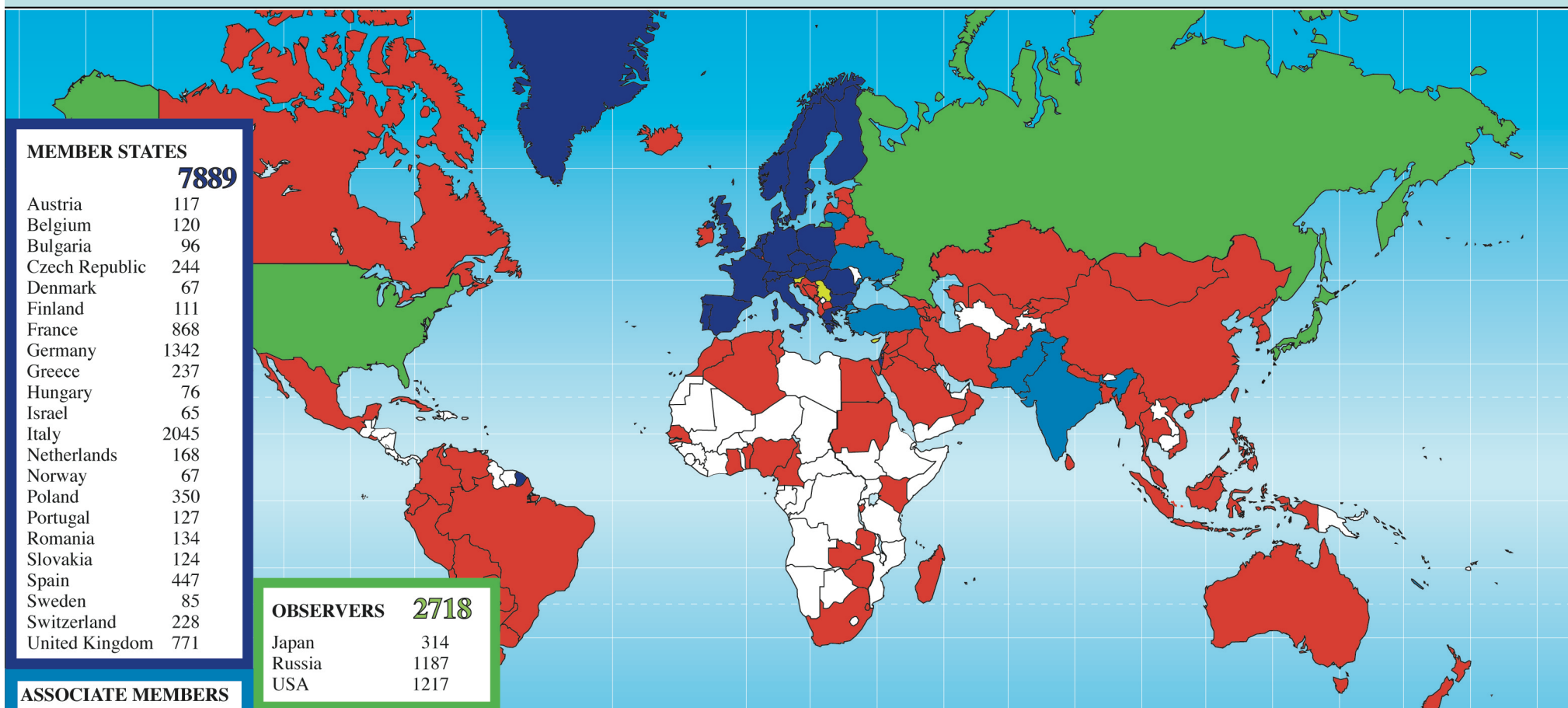


# It Walks and Quacks like a Higgs

- 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	<b>745</b>
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	Jordan	1	Mauritius	1	Paraguay	2	Taiwan	51		
						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](http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf)

[1] = JE & Tevong You, arXiv:1303.3879

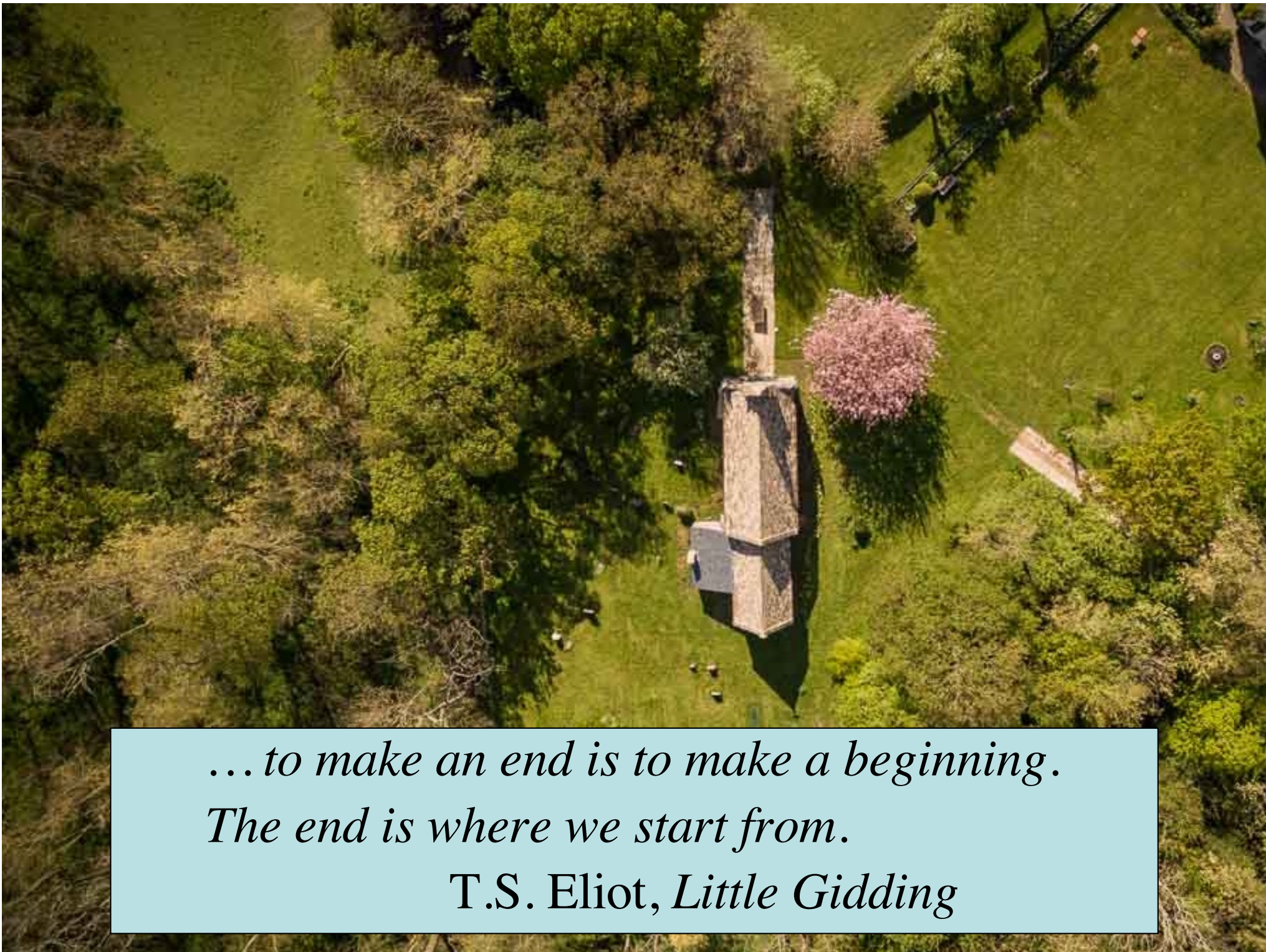


# Without Higgs ...

- ... 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!**

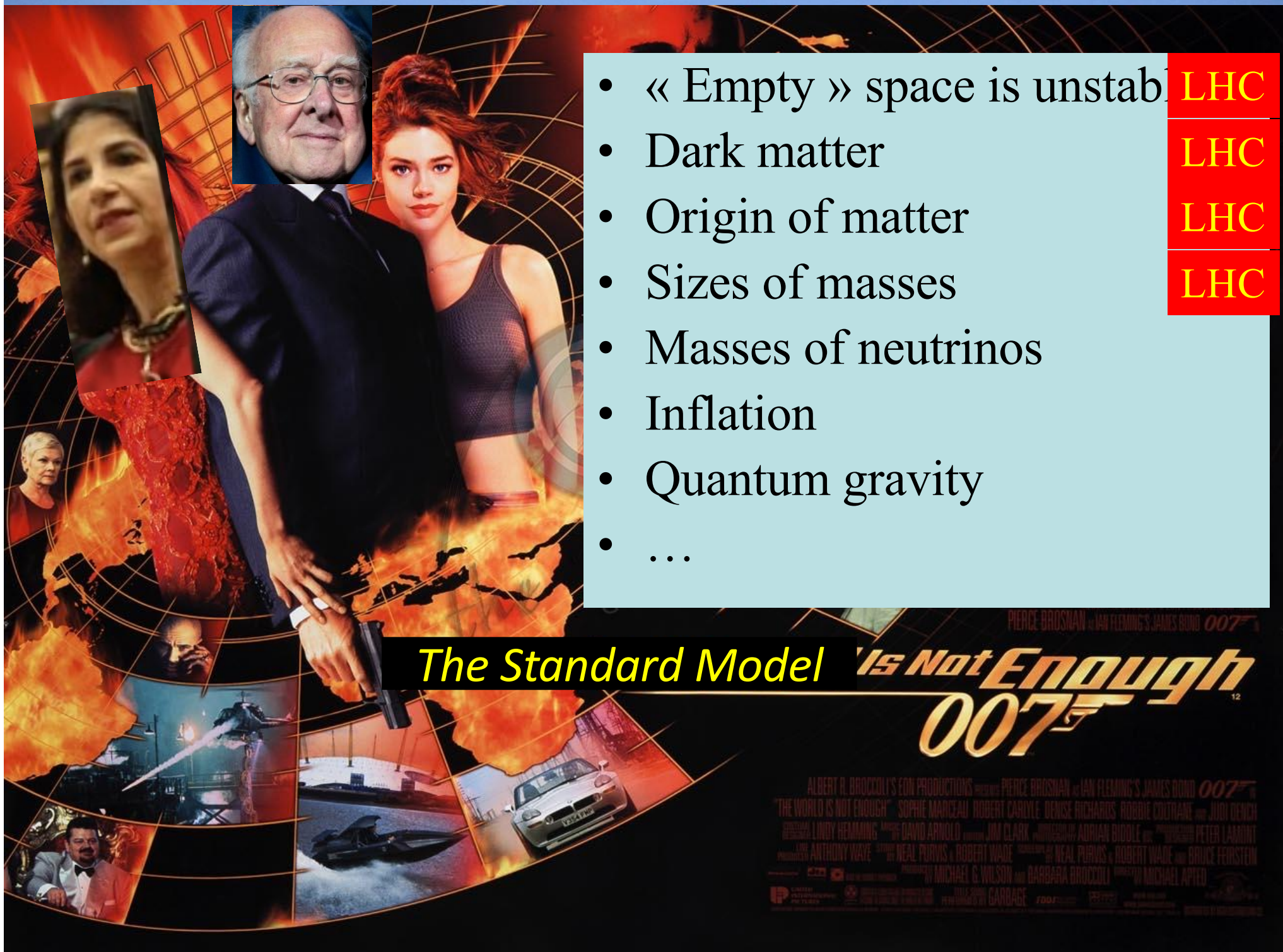




*... to make an end is to make a beginning.  
The end is where we start from.*

*T.S. Eliot, *Little Gidding**





- « Empty » space is unstable
- 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

ALBERT R. BROCCOLLI'S SON PRODUCTIONS PRESENTS PIERCE BRUSNAN in JAMES BOND 007™  
"THE WORLD IS NOT ENOUGH" SOPHIE MARCEAU ROBERT CARVILLE DENISE RICHARDS ROBBIE COLTRANE and JUDI DENCH  
MUSIC BY LINDY HEARNEING COSTUME DESIGNER DAVID ARNOLD EDITOR JIM CLARK EXECUTIVE PRODUCERS JONATHAN ADRIAN BRIDLE PRODUCED BY PETER LARSON  
WRITTEN BY JIM ANTHONY WAYNE PRODUCED BY NEAL PERKINS & ROBERT WADE DIRECTED BY NEAL PERKINS & ROBERT WADE EXECUTIVE PRODUCERS 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 LARSON  
WRITTEN BY JIM ANTHONY WAYNE PRODUCED BY NEAL PERKINS & ROBERT WADE DIRECTED BY NEAL PERKINS & ROBERT WADE EXECUTIVE PRODUCERS 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

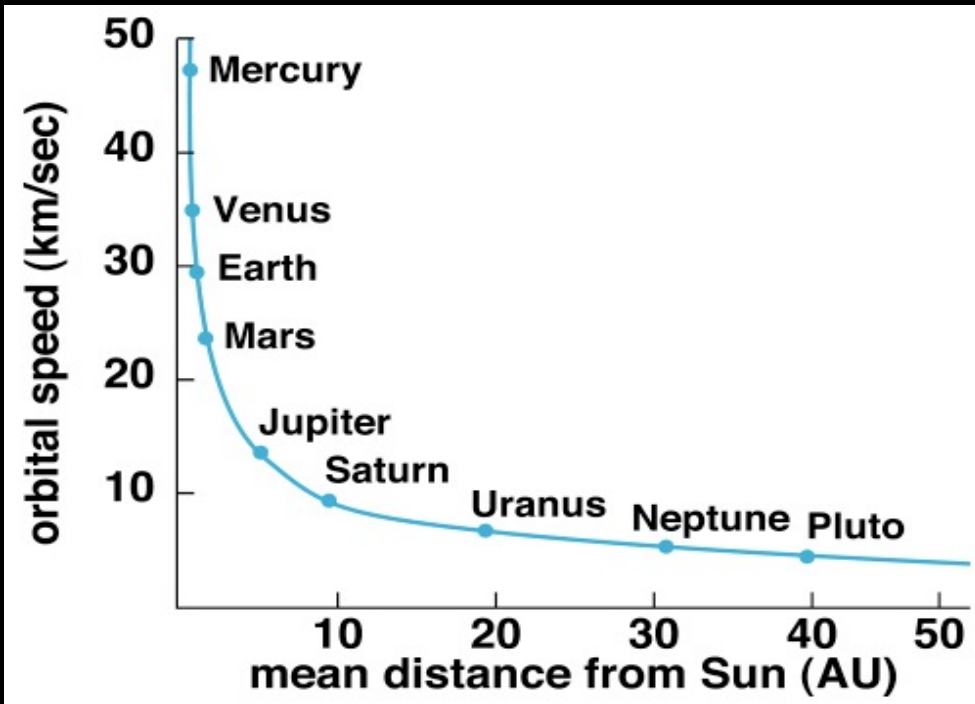
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



Scanned at the American  
Institute of Physics

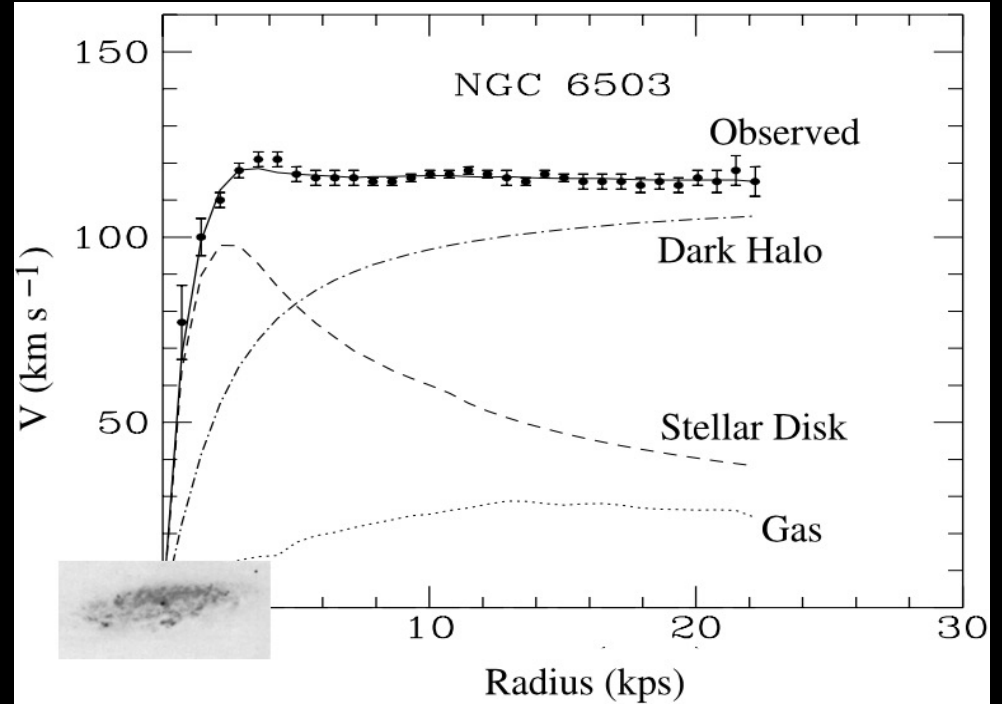
# Rotation Curves

- 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

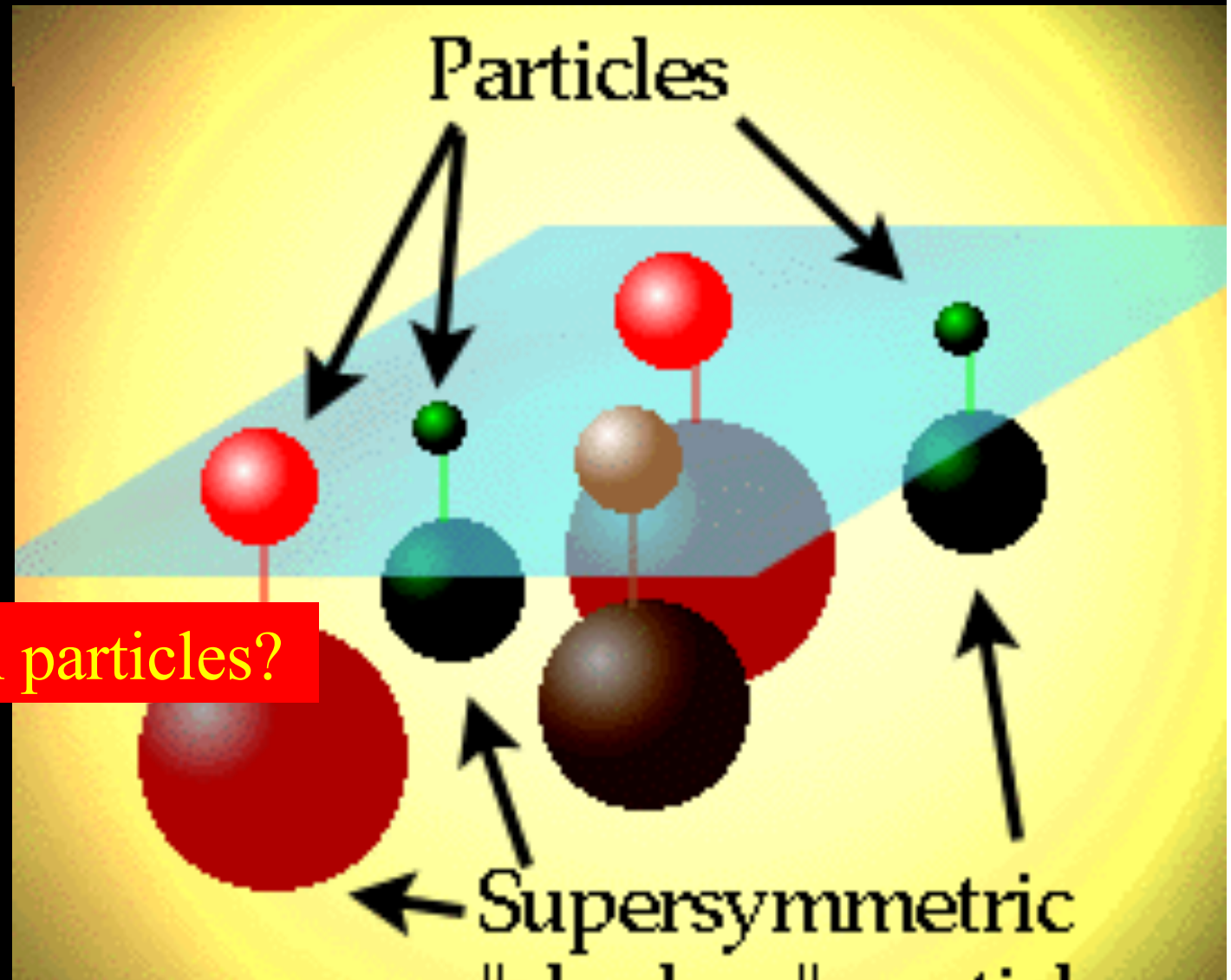


# What is the Dark Matter in the Universe?

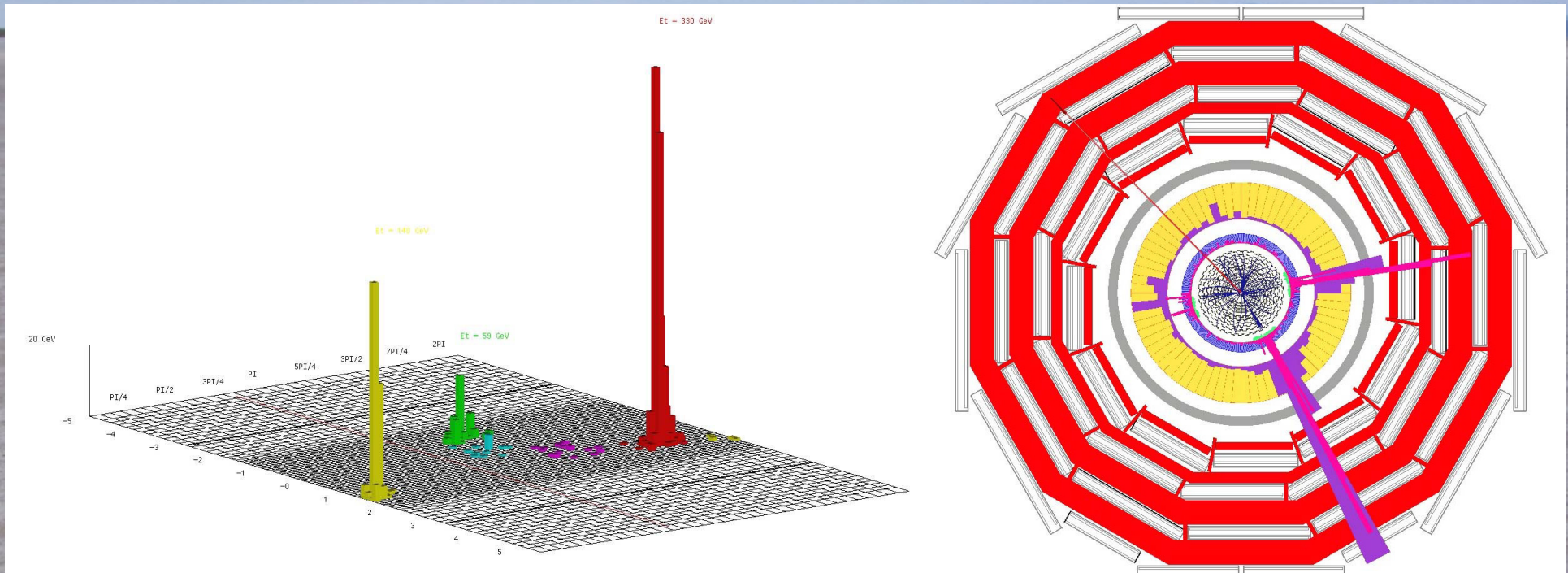
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Made of unknown particles?

We are searching for them at the



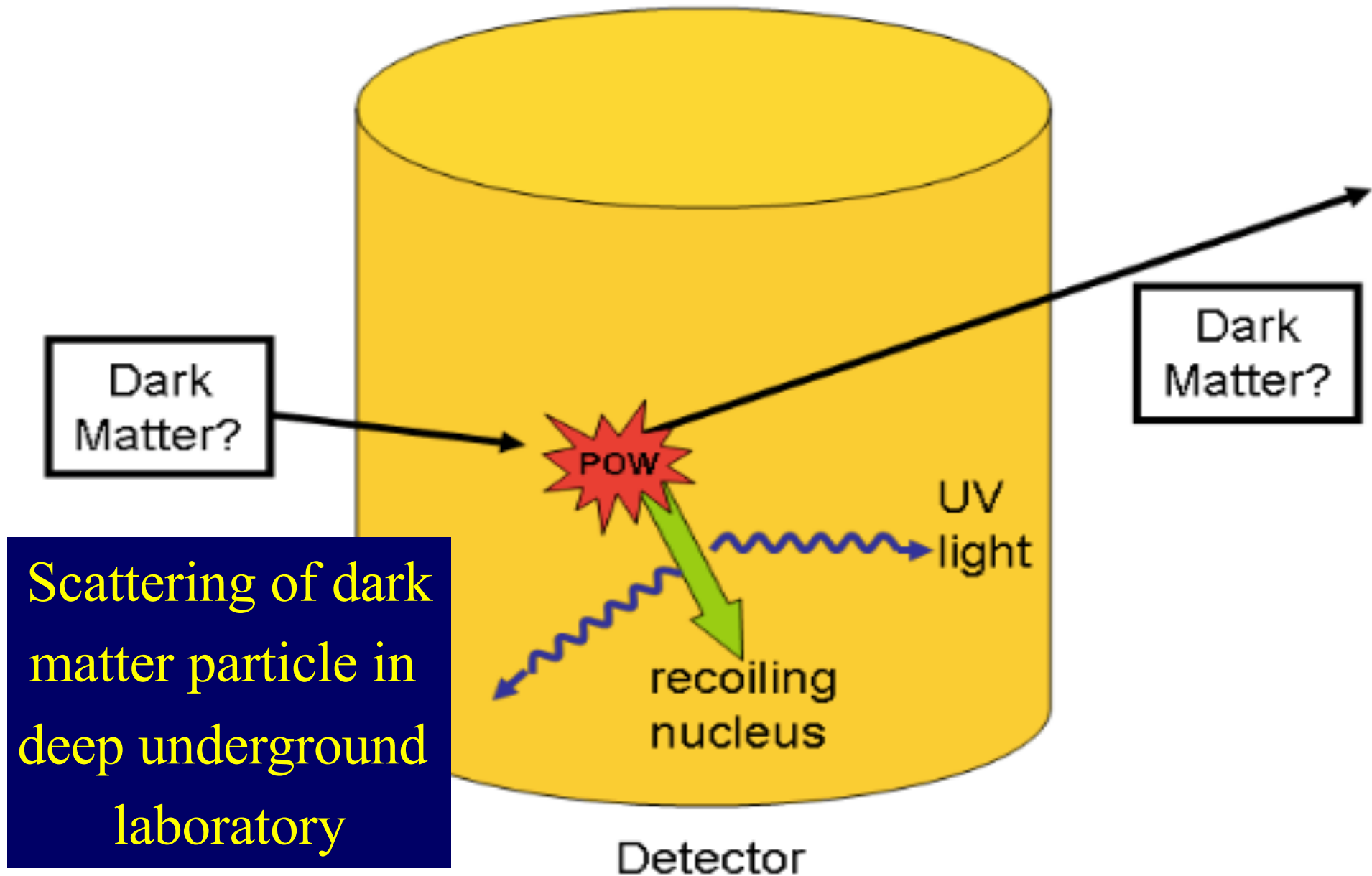
# Classic Dark Matter Signature



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

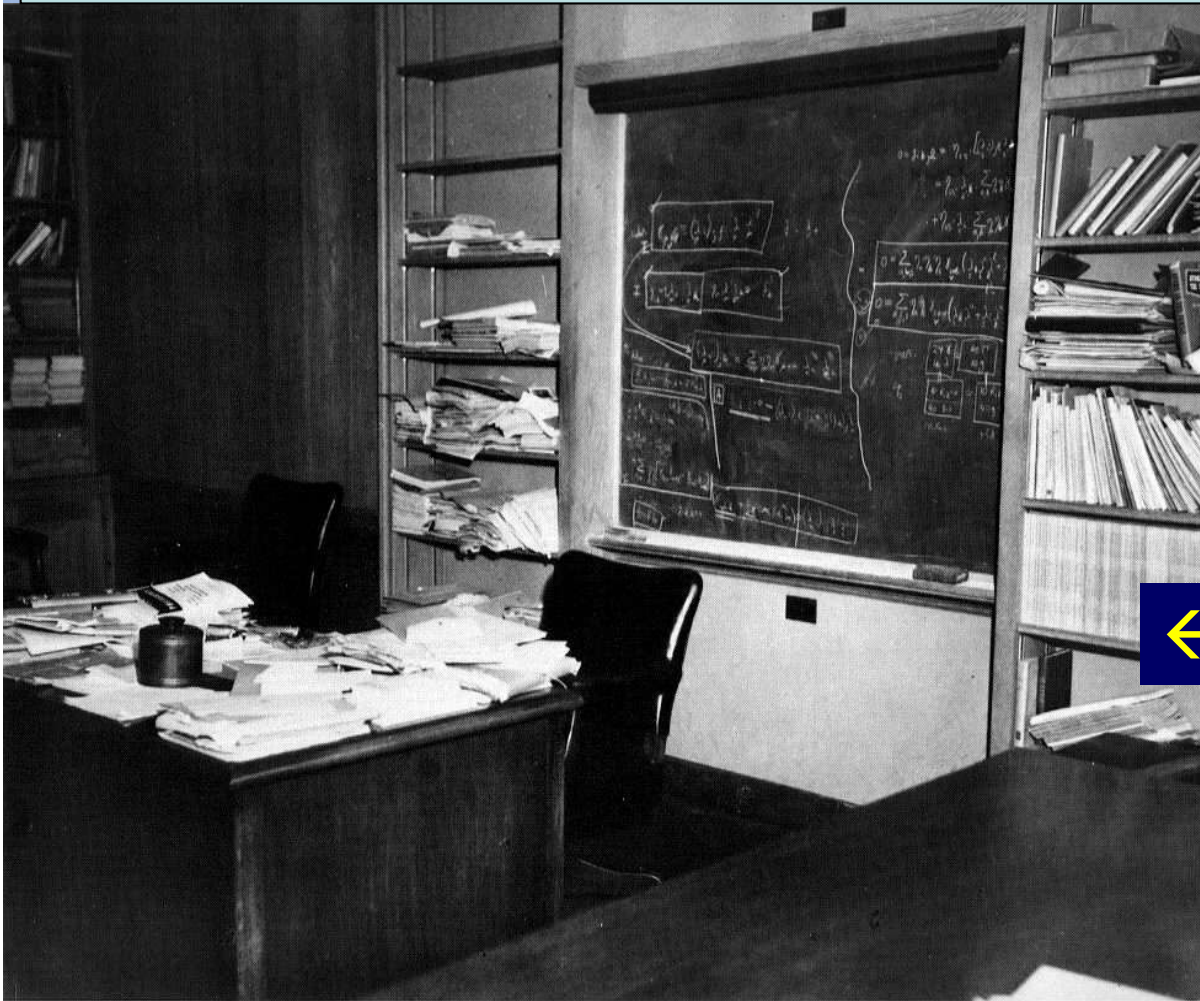
- Need a difference between matter and antimatter  
observed in the laboratory
- Need interactions able to create matter  
predicted by theories  
not yet seen by experiment
- Need the expansion of the Universe  
a role for the Higgs boson?

Will we be able to calculate  
using laboratory data?

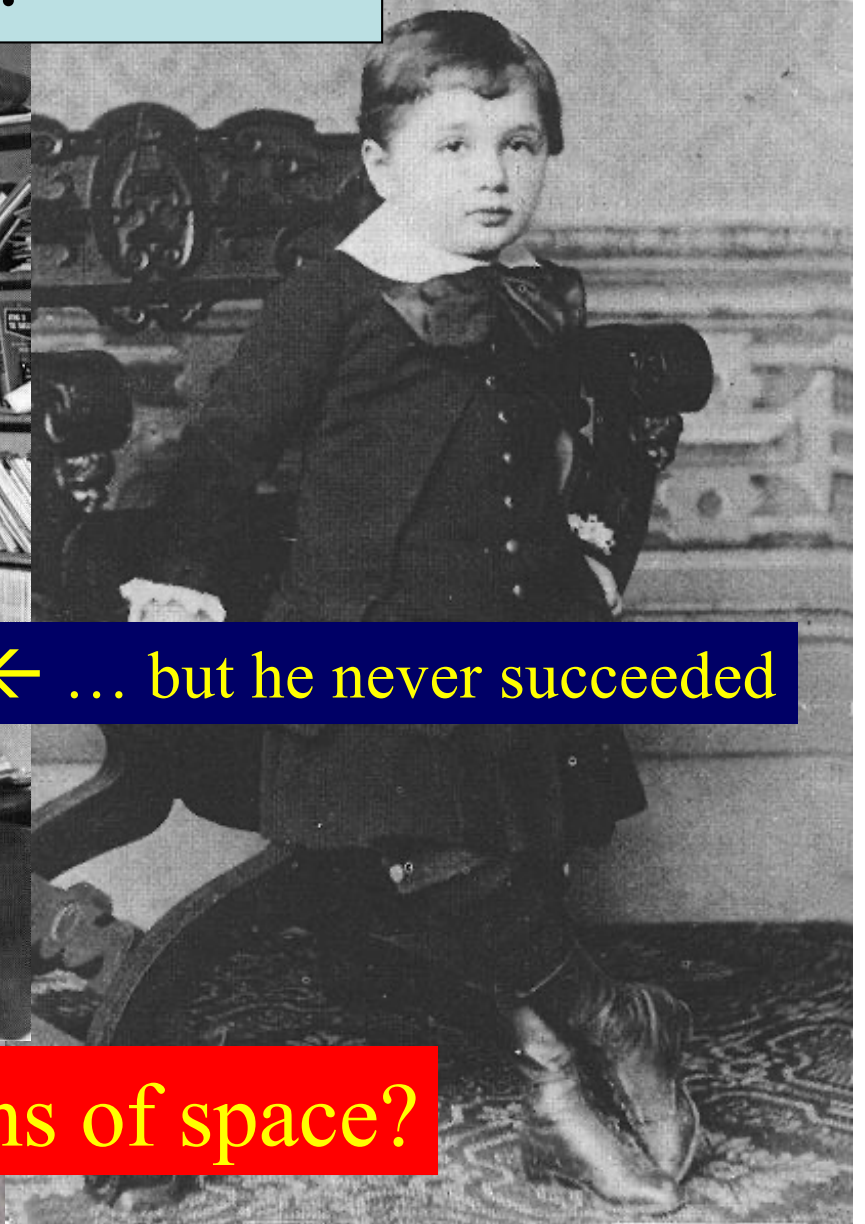




# Unify the Fundamental Interactions: Einstein's Dream ...



← ... but he never succeeded



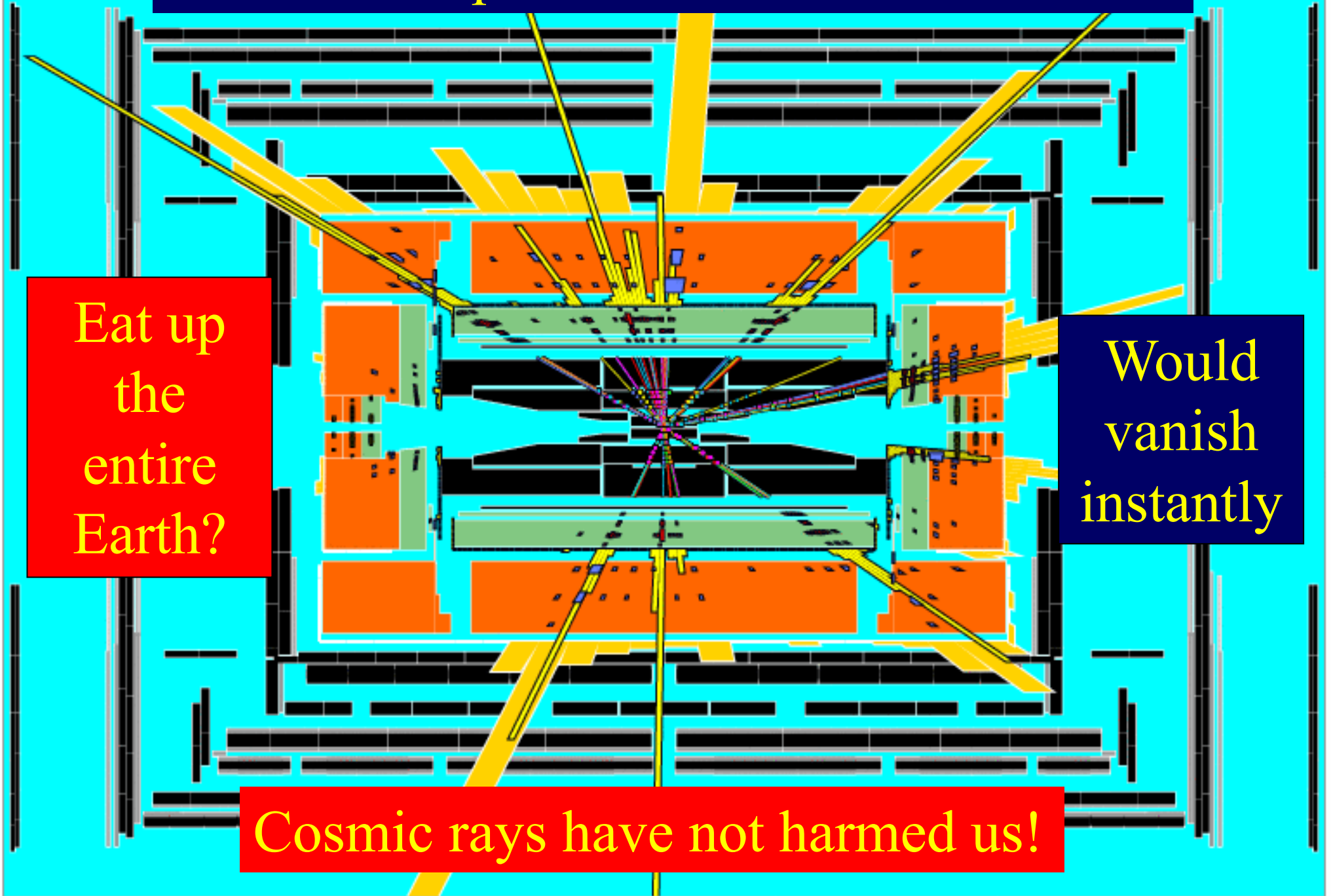
Unification via extra dimensions of space?

# 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