

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



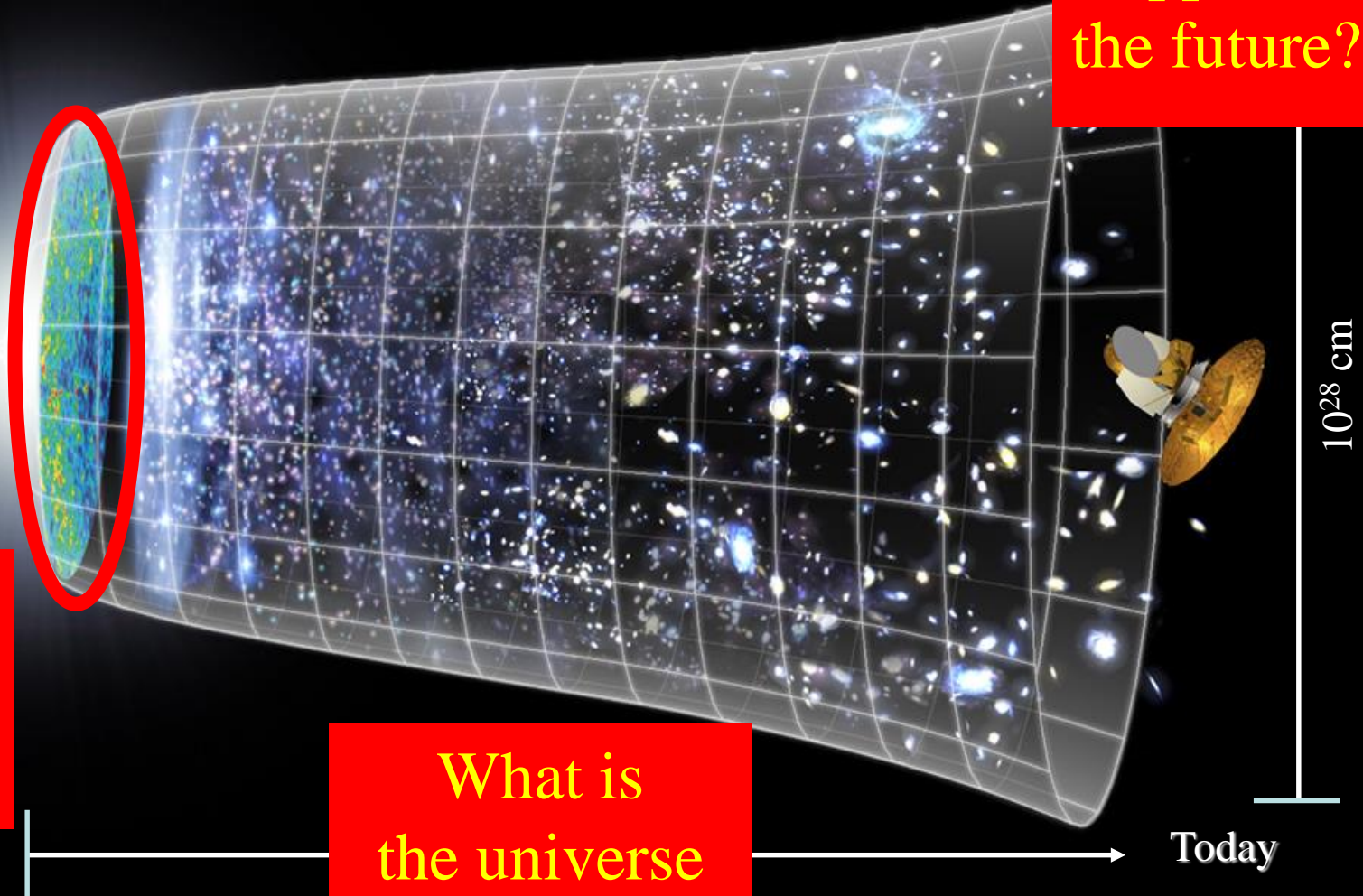
The aim of particle physics:
What is matter in the Universe made of?

John Ellis

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

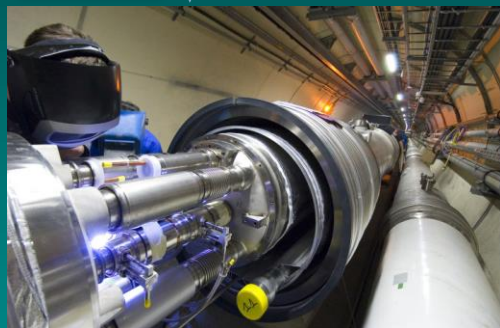
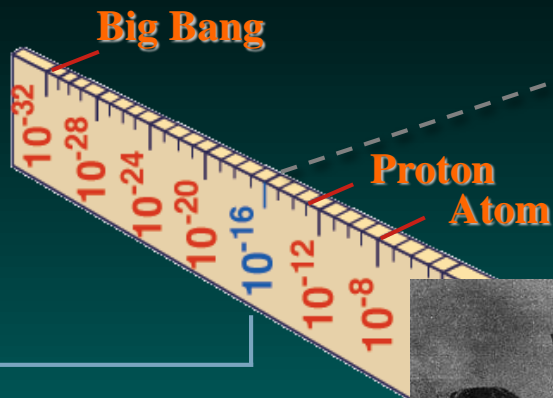
- What is matter made of?
 - Why do things weigh?



- 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

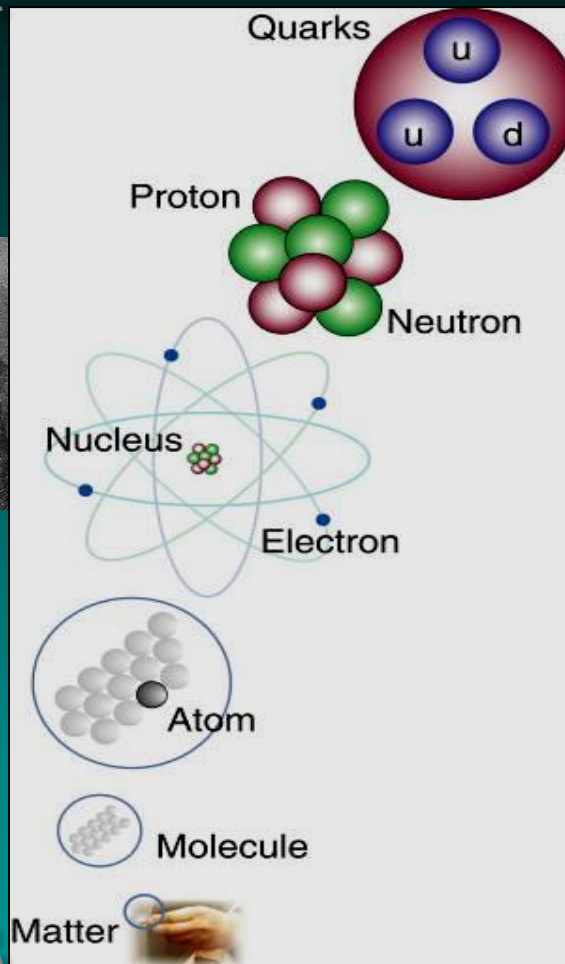
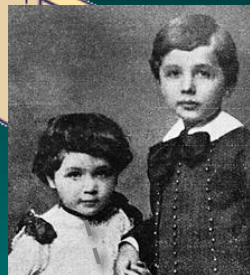


LHC

Super-Microscope

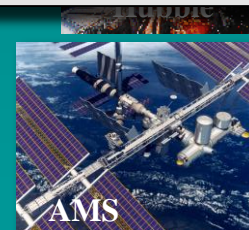
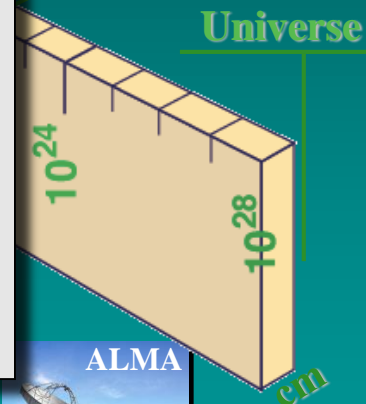


Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology



Radius of Galaxies

Universe



AMS

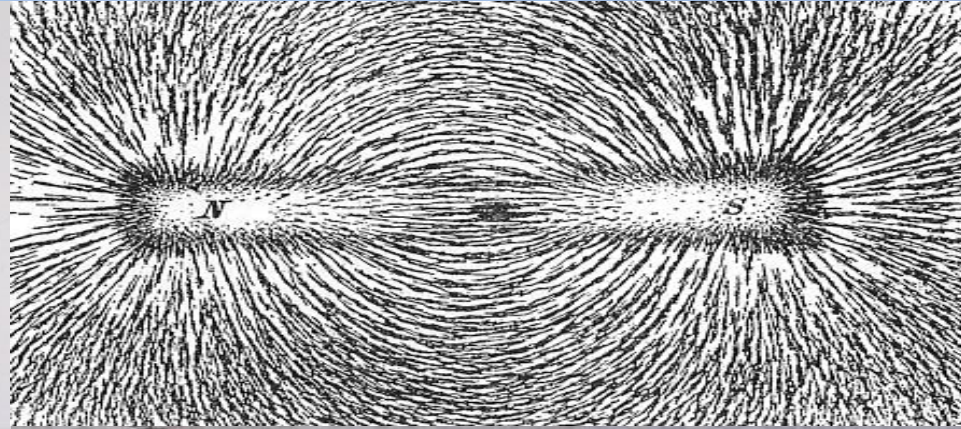


ALMA



VLT

Electricity and Magnetism



- Electricity:

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

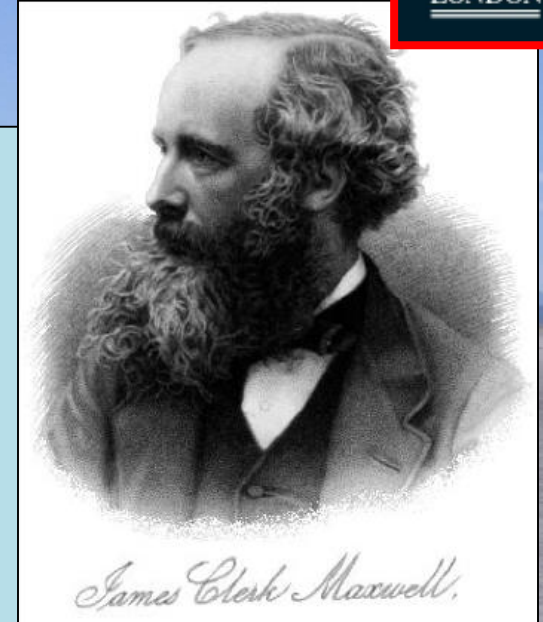
- Magnetism:

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

Who could have foreseen their importance for technology?

James Clerk Maxwell

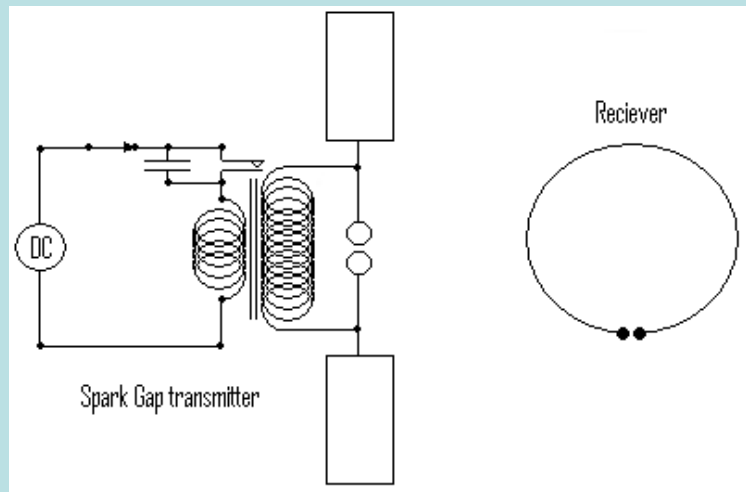
- Professor at King's 1860 – 1865
- The first colour photograph
- Unified theory of electricity and magnetism
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- ...



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

Electromagnetic Waves

- Discovered by Hertz in 1887

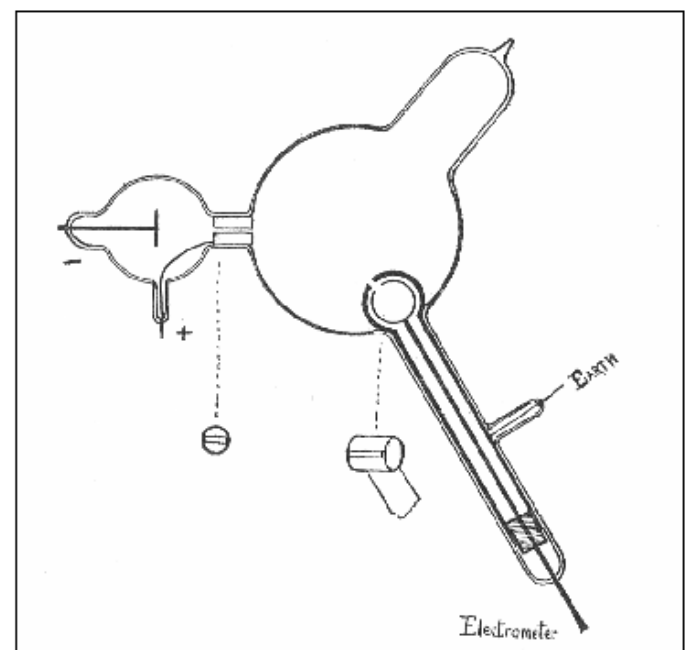
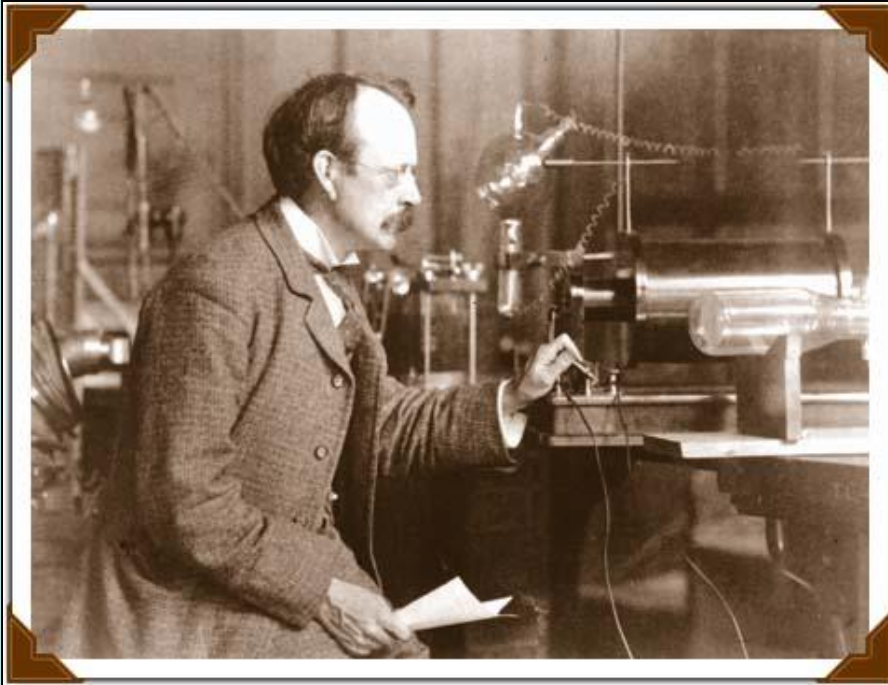


- A lot to answer for
- Nobody knows where fundamental physics may lead**



The First Elementary Particle

- Discovered by J.J. Thomson in 1897



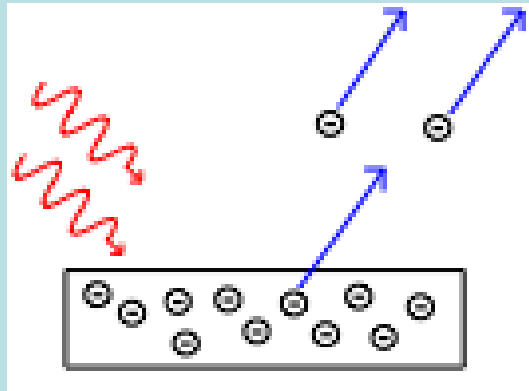
- The electron** – the basis of the electronic industry
- An accelerator in your home: old-style TV sets used beams of electrons

Photon: the Electromagnetic Quantum

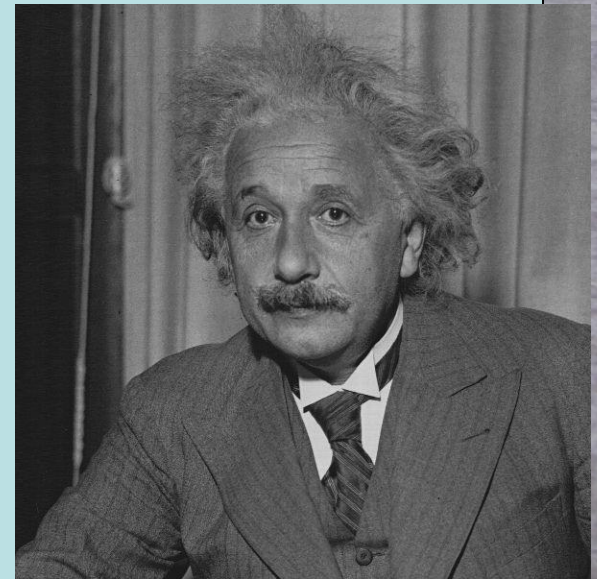
- Quantum hypothesis introduced by Planck:

$$E = hf$$

- 1905: Physical reality postulated by Einstein to explain photoelectric effect



- First force particle discovered**

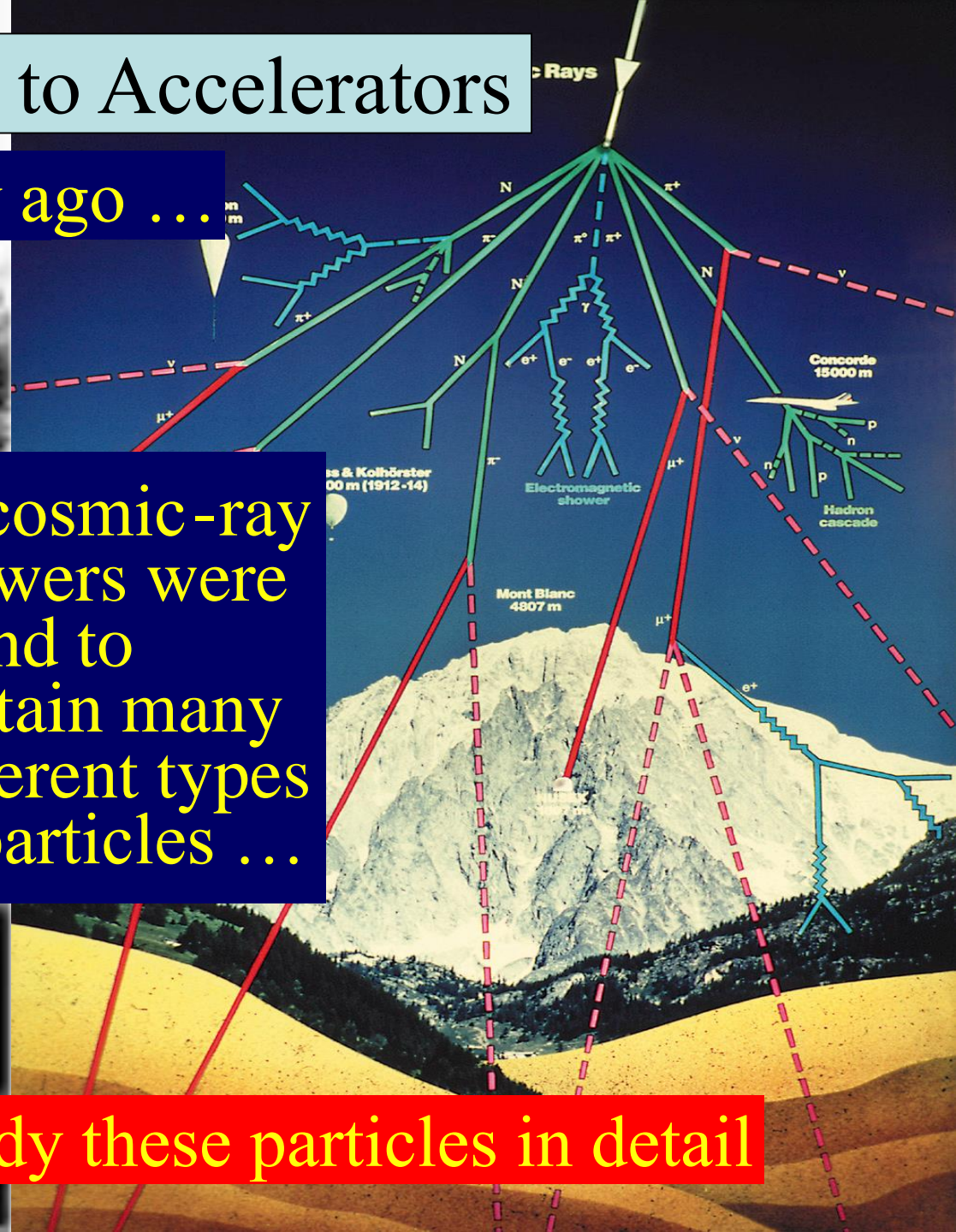


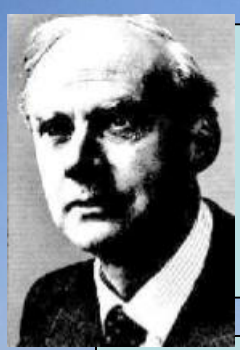
From Cosmic Rays to Accelerators

Discovered a century ago ...

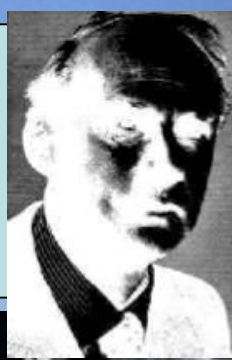
... cosmic-ray showers were found to contain many different types of particles ...

Accelerators study these particles in detail

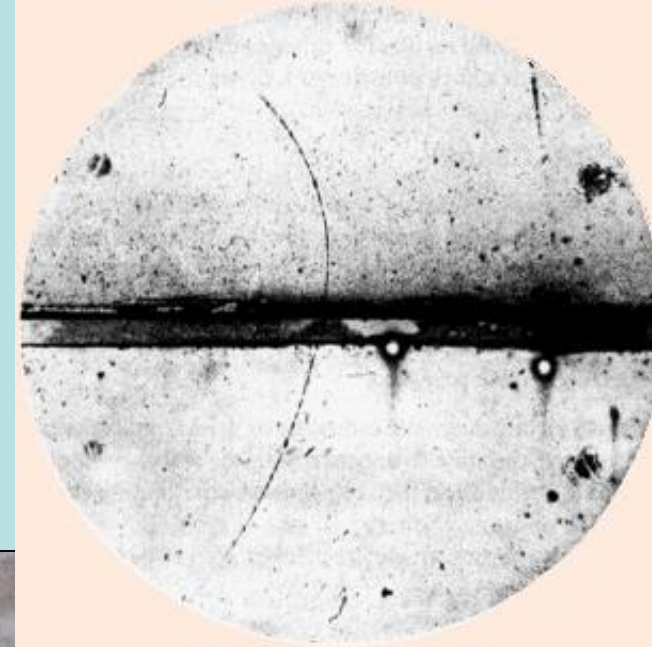




The Discovery of the Positron

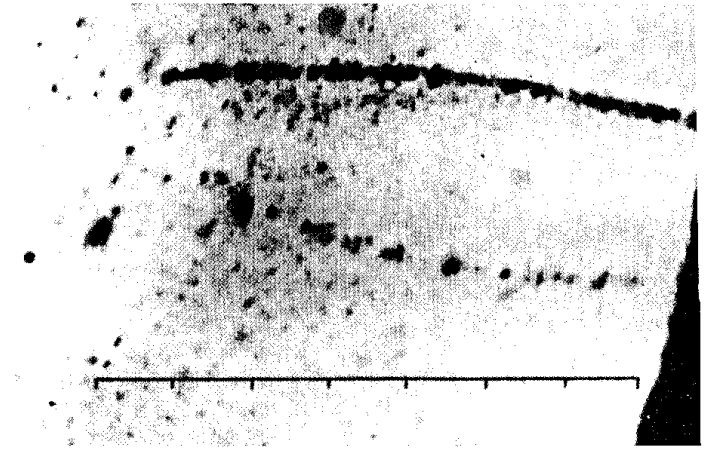


- Predicted by Dirac in 1928
- Discovered in cosmic rays by Anderson in 1932
- Bent opposite to electron, small mass
- Now used in Positron Emission Tomography (PET) for medical diagnosis



The Discovery of the Muon

- NOT predicted
- Observed in cosmic rays by Kunze in 1932
- Larger bending radius than the positron
- Ionizes less than proton
- Passing through us all the time
- ***“Who ordered that” – I.I. Rabi***



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle with a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

1950s: a Zoo of 'Particles'

With new accelerators and detectors,
the "particle zoo" grew to more than ~ 200 'elementary particles'

$\pi^+ \pi^- \pi^0$

Pions

$K^+ K^- K^0$

Kaons

η'

Eta-Prime

η

Eta

ϕ

Phi

$\rho^+ \rho^- \rho^0$

Rho

MESONS

$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$

Delta

Λ^0

Lambda (strange!)

$\Sigma^+, \Sigma^0, \Sigma^-$

Sigma (strange!)

Ξ^0, Ξ^-

Sigma(very strange!)

BARYONS

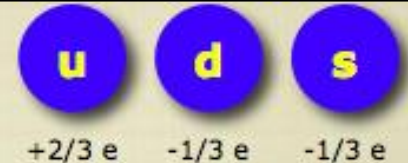
1960s: Order out of Chaos: Quarks



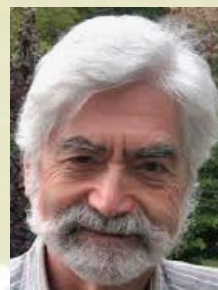
Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963
(G. Zweig, 1963, CERN)

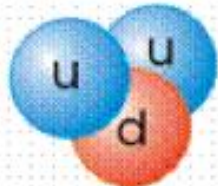
- 1) 3 types of "quarks" : up, down, strange
- 2) Carry electric charges: $+2/3$, $-1/3$, $-1/3$
- 3) Appear in combinations:
Meson = quark+antiquark
Baryon = quark(1) + quark(2) + quark(3)



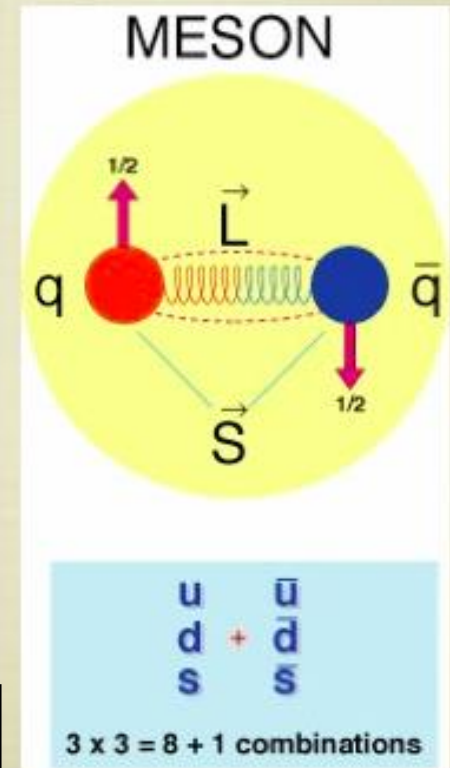
Also suggested
independently by
Zweig, Peterman
@ CERN



The Proton



The Neutron

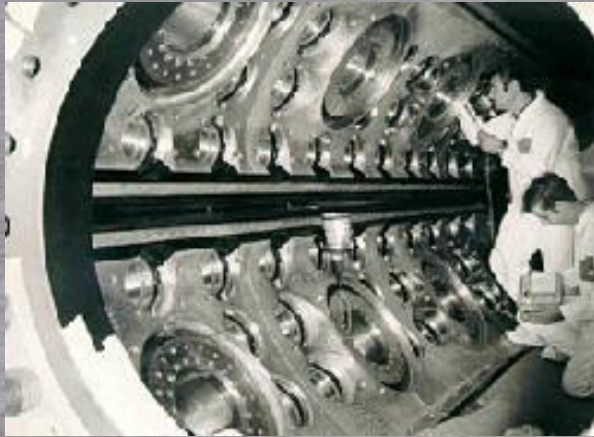


Quarks held together by gluons?

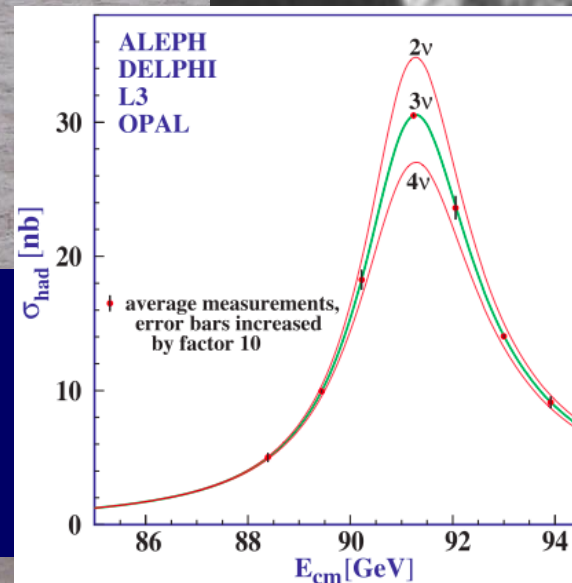
The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow and Weinberg

Tested by experiments
at CERN



Perfect agreement between
theory and experiments
in all laboratories



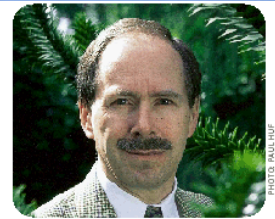
Towards the Standard Model

1971/2

- Gauge theories are renormalizable



Martinus Veltman
Professor Emeritus at the University of Michigan, Ann Arbor, USA, formerly at the University of Utrecht, Utrecht, the Netherlands.



Gerardus 't Hooft
Professor at the University of Utrecht, Utrecht, the Netherlands.

1973

- Kobayashi and Maskawa show how to include CP violation in the Standard Model

1973

- Neutral currents in Gargamelle

1974

- J/Ψ discovered

1975/6

- Tau lepton and charmed particles discovered



1976

Gluon Radiation in e^+e^- Annihilation

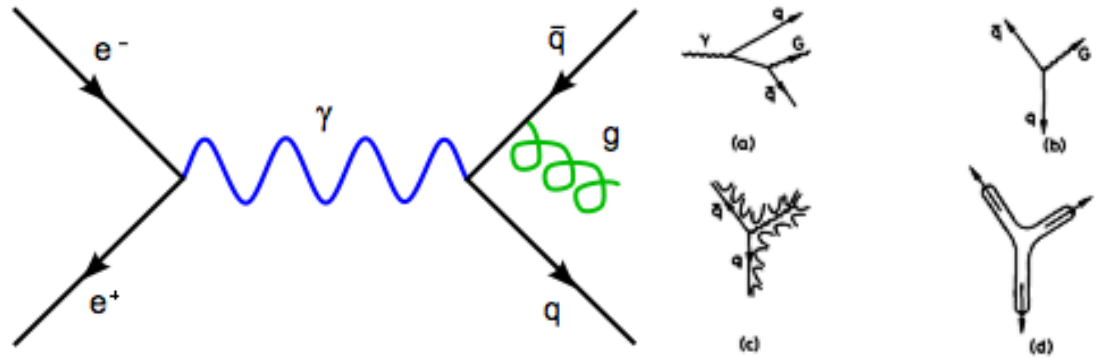
- Discovery method suggested by JE, Mary Gaillard, Graham Ross:

SEARCH FOR GLUONS IN e^+e^- ANNIHILATION

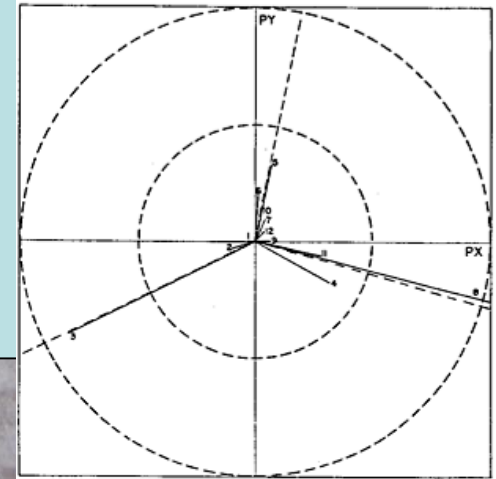
John ELLIS, Mary K. GAILLARD * and Graham G. ROSS
CERN, Geneva

Received 20 May 1976

We study the deviations to be expected at high energies from the recently observed two-jet structure of hadronic final states in e^+e^- annihilation. Motivated by the approximate validity of the naive parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axes. This process should give rise to three-jet final states. These may be observable at the highest SPEAR or DORIS energies, and should be important at the higher PETRA or PEP energies.



- Jets of hadrons produced by gluons DESY (Hamburg) in 1978
- Second force particle discovered**



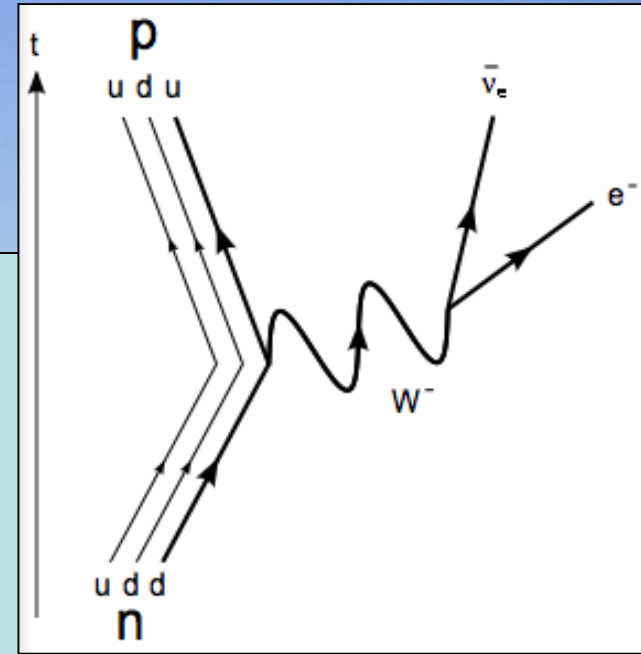
1983

Weak Interactions

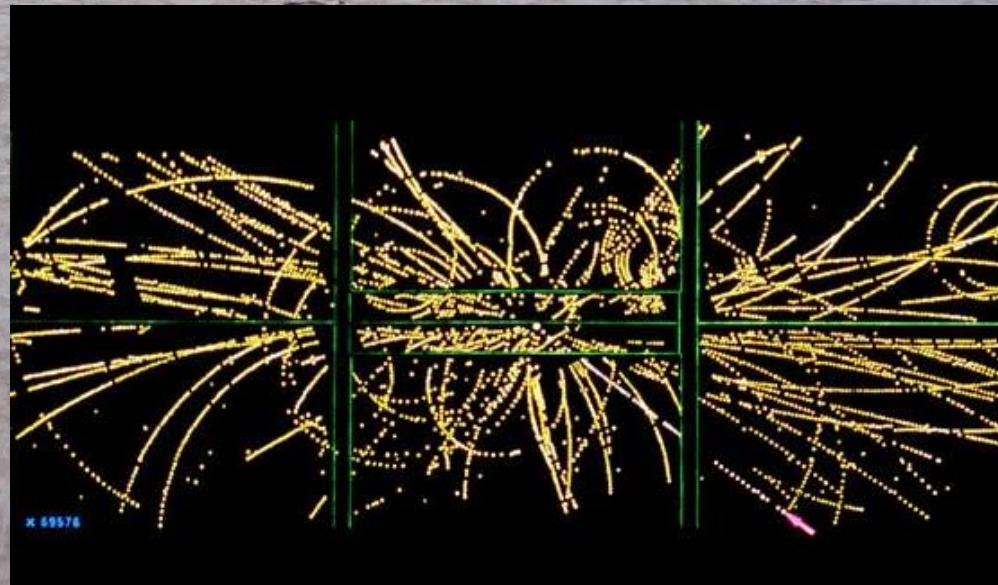
Radioactivity due to charged-current weak interactions (β decay)

W boson - carrier of weak interactions

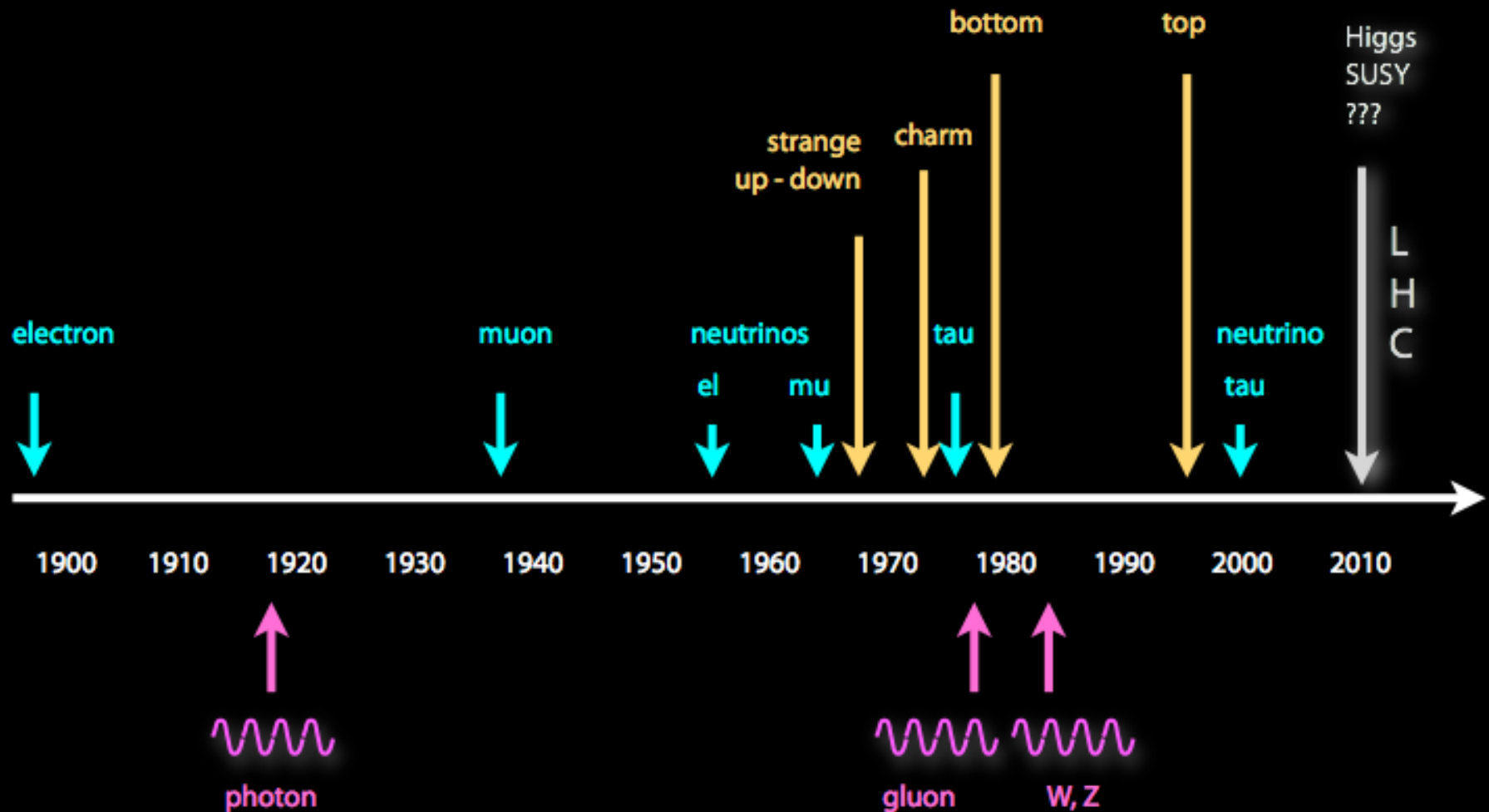
Predicted to weigh ~ 80 GeV



Discovered at CERN in
1983 by Carlo Rubbia et al



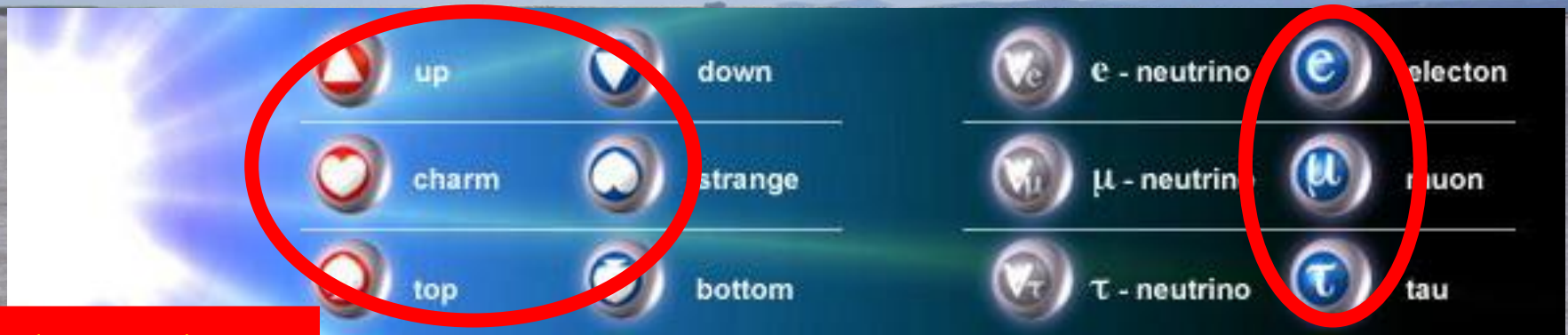
Particles: the Story so far



The 'Standard Model'

= Cosmic DNA

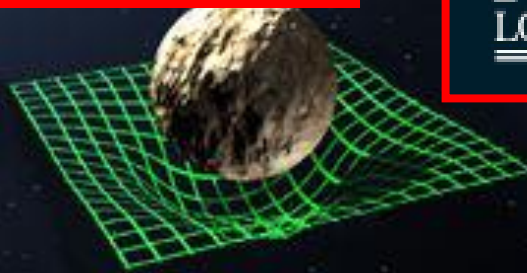
The matter particles



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)



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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

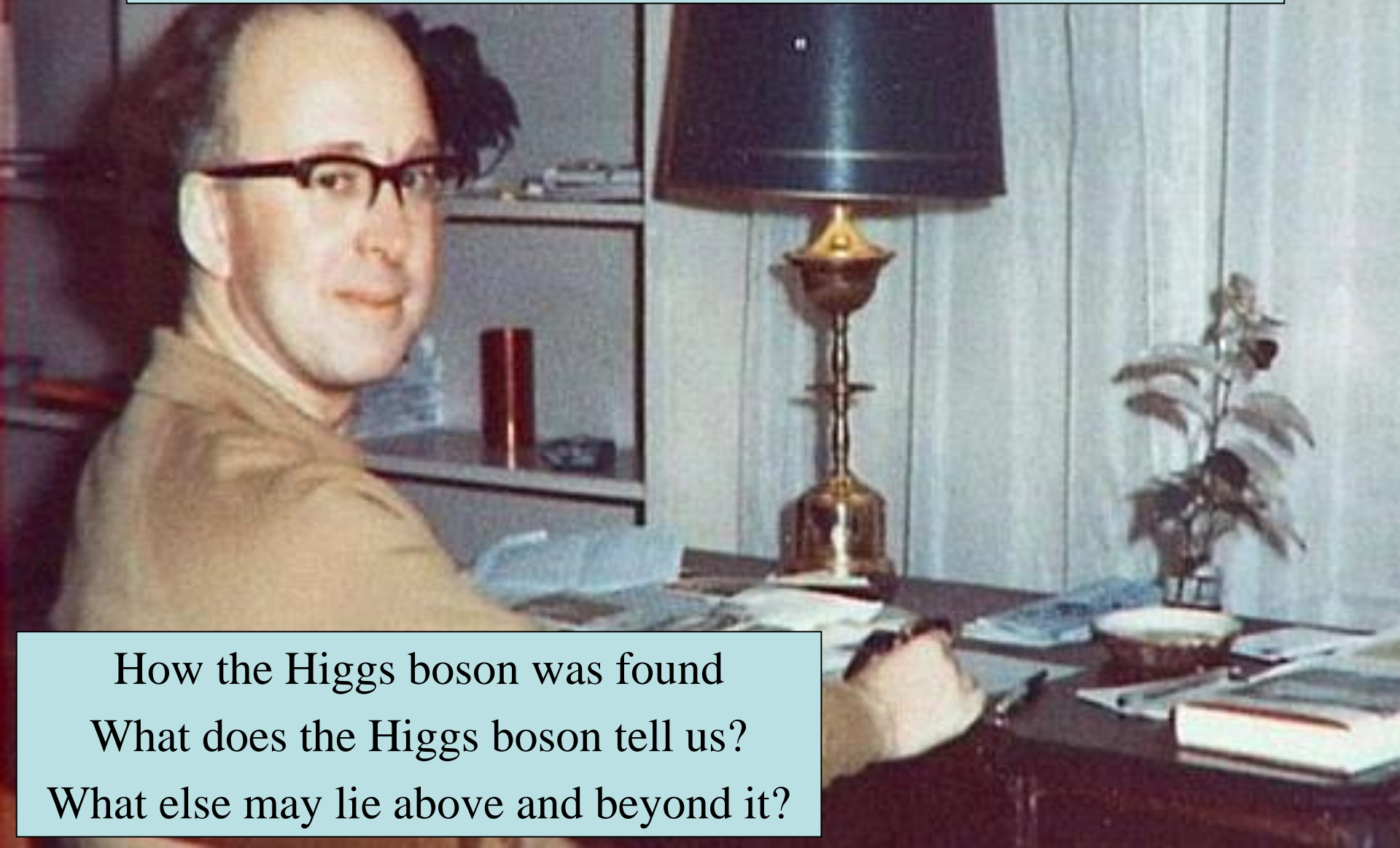


**The LHC discovered
the snowflake:
The Higgs Boson**

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?

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

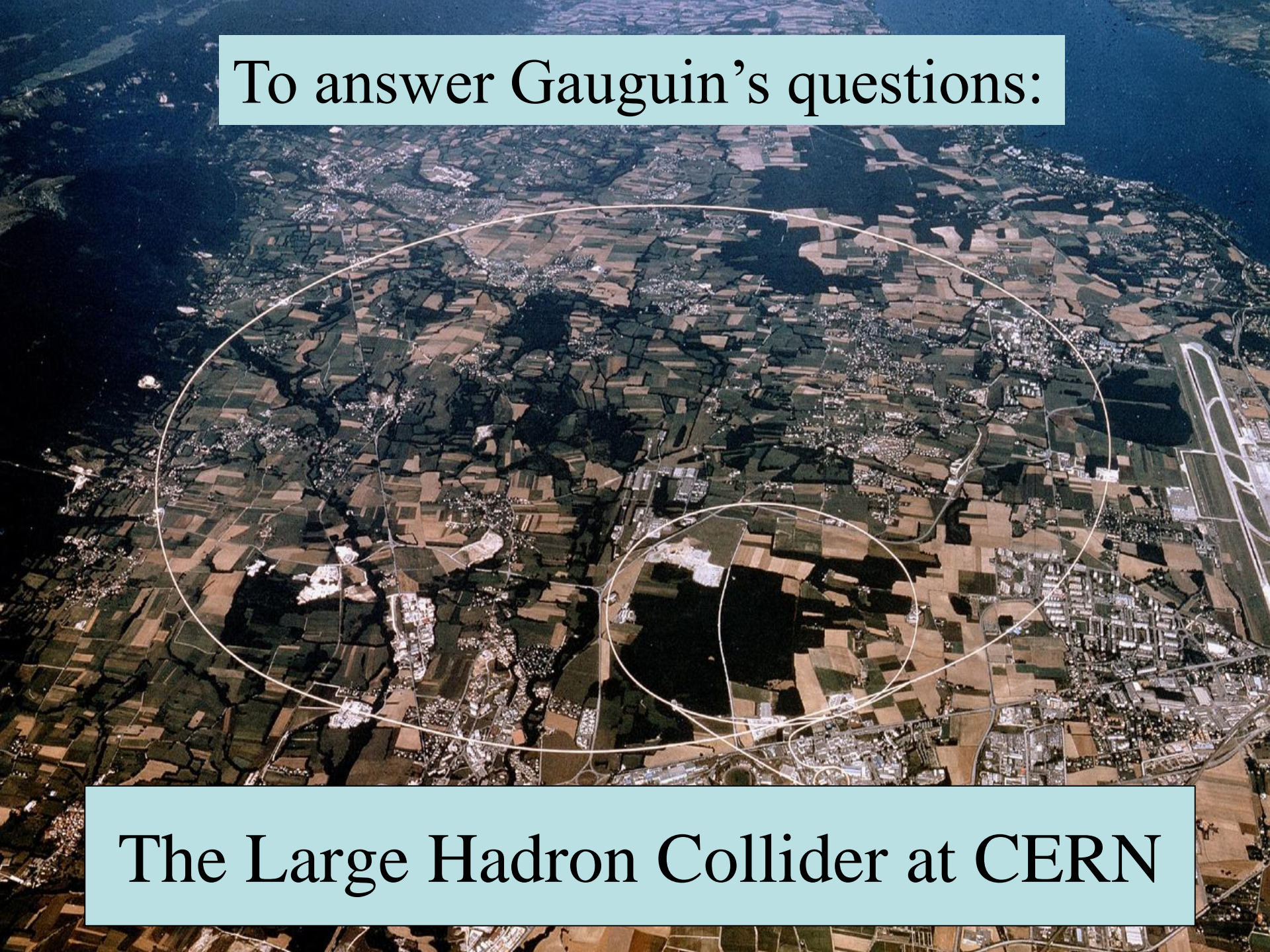
John ELLIS, Mary K. GAILLARD ^{*} and D.V. NANOPOULOS ^{**}
CERN, Geneva

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.

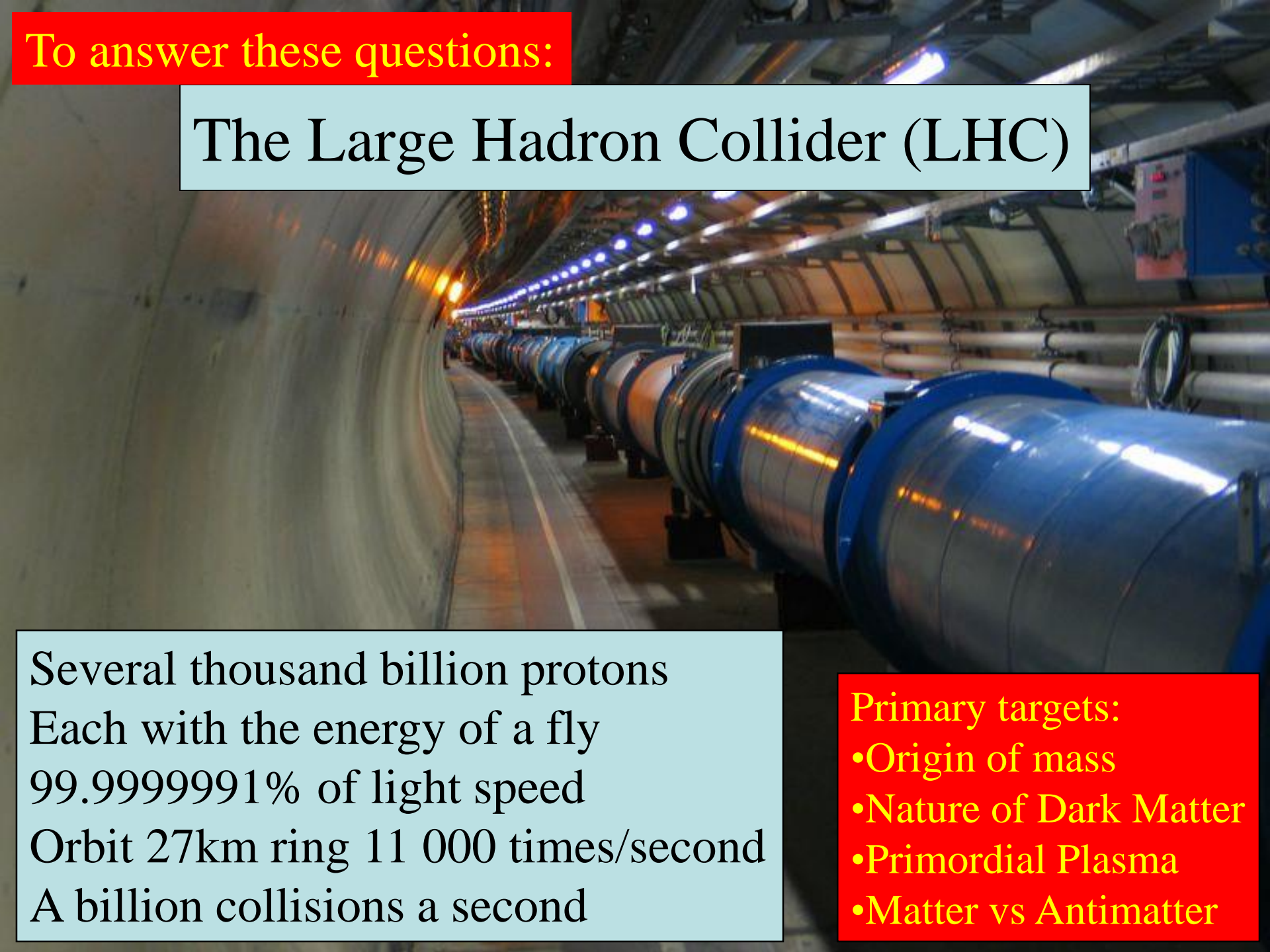
To answer Gauguin's questions:



The Large Hadron Collider at CERN

To answer these questions:

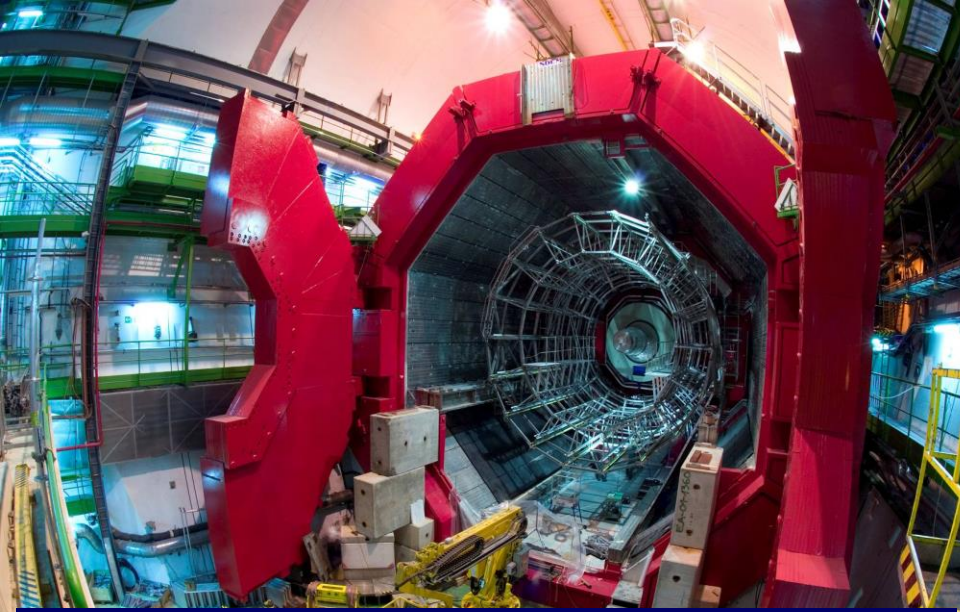
The Large Hadron Collider (LHC)



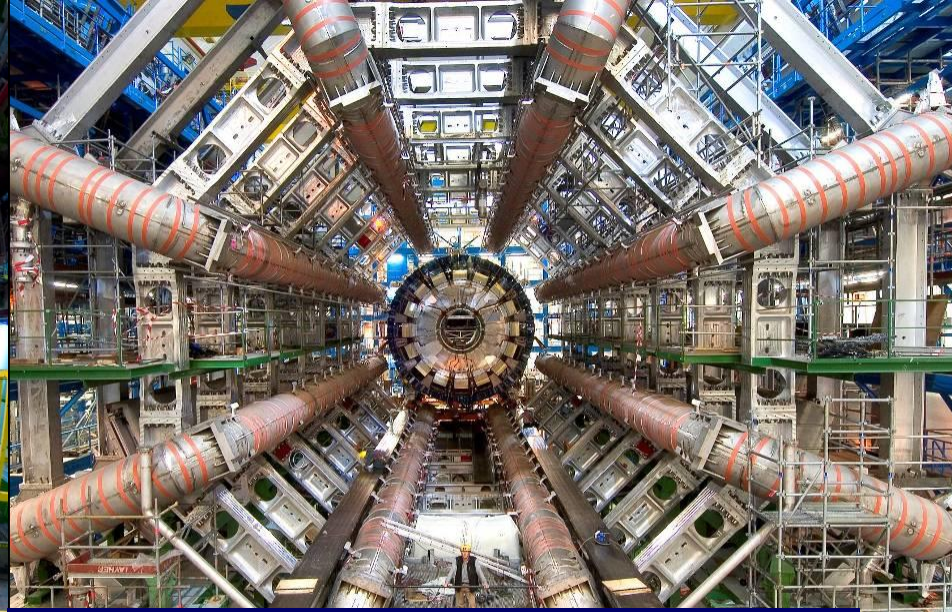
Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:

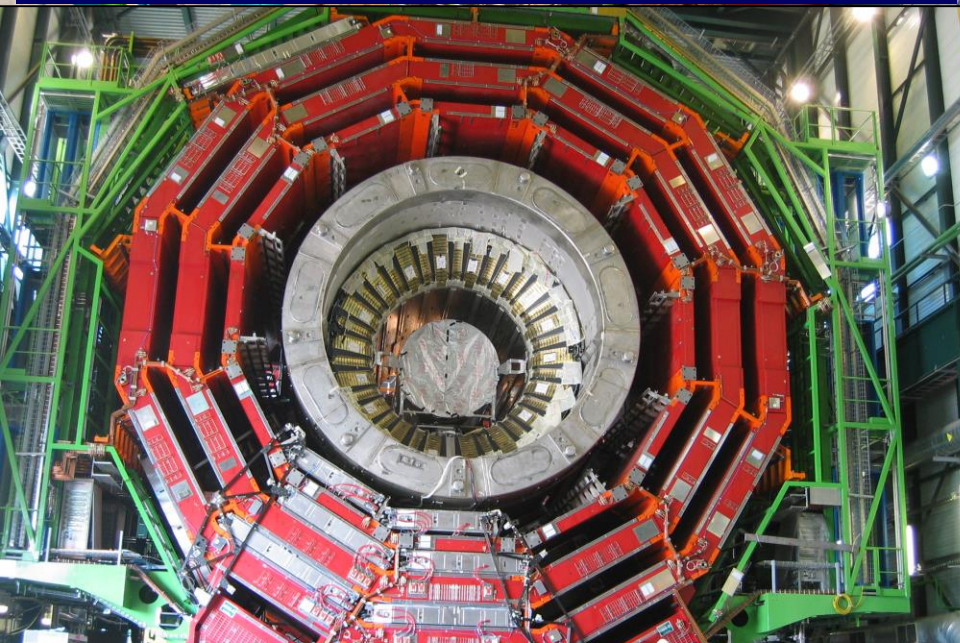
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

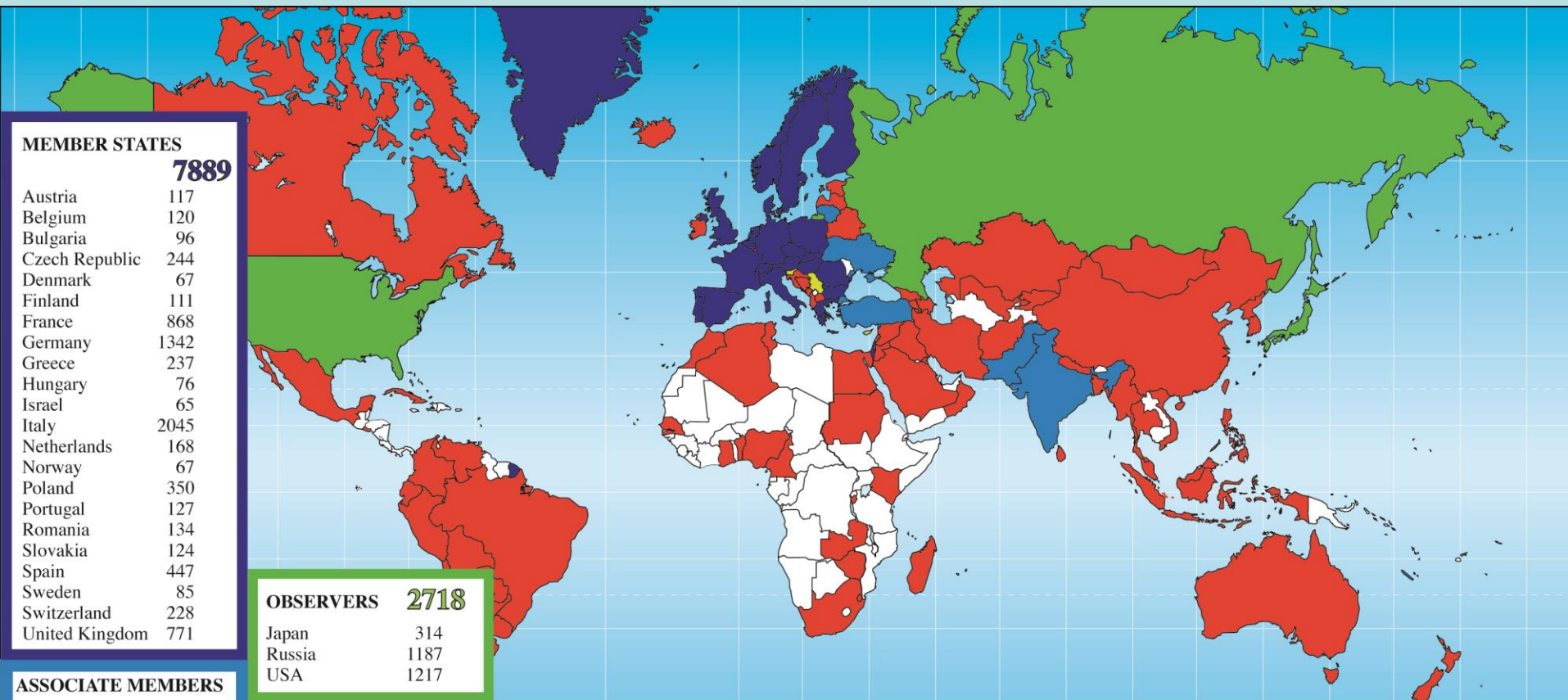


CMS: Higgs and dark matter



LHCb: Matter-antimatter difference

Scientists from around the World



ASSOCIATE MEMBERS

India	357	745
Lithuania	35	
Pakistan	65	
Turkey	173	
Ukraine	115	

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus	26	118
Serbia	57	
Slovenia	35	

OTHERS 1872

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

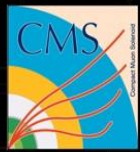
2012: The discovery of the Higgs Boson



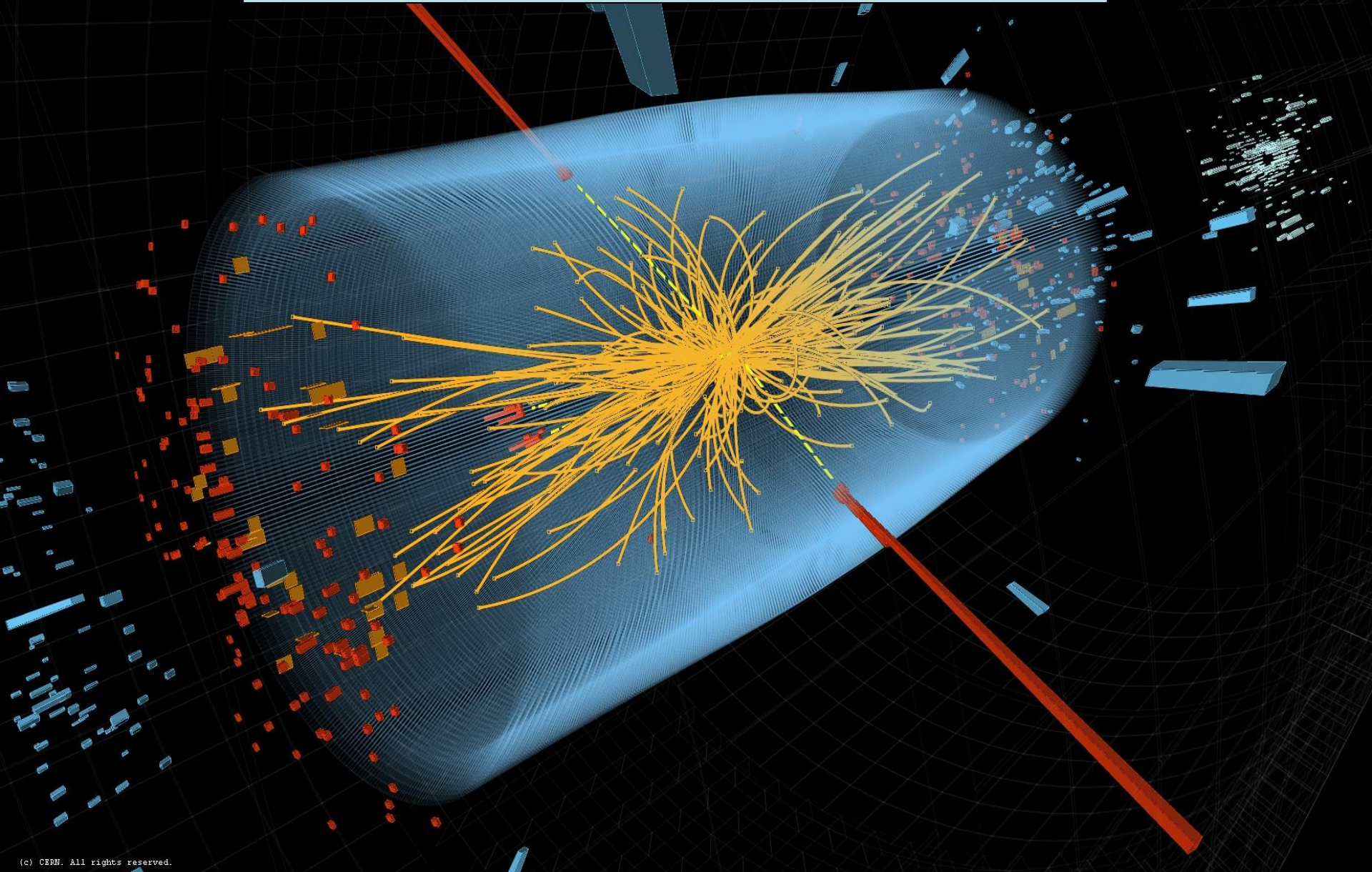
Mass Higgsteria

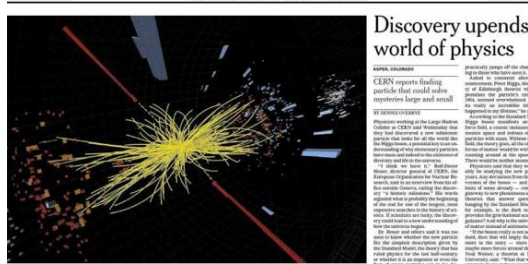
A Simulated Higgs Event @ LHC





Interesting Events





Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

PARIS, July 4 (AP) — The discovery of a new particle, which scientists say is the Higgs boson, has upended the world of physics. The particle, which was found at the Large Hadron Collider (LHC) in Geneva, Switzerland, is the last missing piece of the Standard Model of particle physics. It explains how particles get their mass. Without it, the universe as we know it would not exist.

July 4th 2012 The discovery of a new particle

"All the News That's Fit to Print"

Oil Backed Up, Iranians Put It On Idled Ships

Submarine at Tientsin as Embargo Tightens

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SEBASTIEN LECHEZ

More Algeria Men With Conservative Values Within His Party

WOLFGANG KLEIN

Physicists Find Elusive Particle Seen as Key to Universe

PHYSICISTS AT CERN IN GENEVA HAVE APPROVED THE DISCOVERY OF A SUBATOMIC PARTICLE THAT BECKONS TO THE PHYSICS COMMUNITY AS THE HIGGS BOSON.



Physicists at CERN in Geneva have approved the discovery of a subatomic particle that beckons to the physics community as the Higgs boson.

The Economist

In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Leonardo da Vinci met the

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
日米欧チーム

Per dia, Deco recorre 87 casas por causa de sobrevivimento p54

HOJE TEROS MARVEL
Cronica de um dia no mundo
PIPERA, Homem Aranha, Integral: Frank Miller, por aprox. +4.906

Milhares de moradores de bairros sociais em risco de perderem RSI

A mudança está a passar despercebida, mas deve afectar milhares de beneficiários de RSI que vivem em habitação social: agora, morar numa casa comunitária é uma forma de exclusão social.

Ministério do Trabalho
Caso de um trabalhador que foi despedido por não ter sido avisado de uma reunião de trabalho.

Laufos de que
Relatos de todos os países para o caso.

CELEBRAR A PARTICULA DE DEUS
EXISTE MAS A HISTORIA NAO ACABA AQUI

Page 6-140

Science : la matière dévoilée

Le boson de Higgs, particule manquante pour expliquer l'univers, vient d'être découvert. Les physiciens du CERN de Genève ont prouvé son existence à 5 sigma.

IMPÔTS CE QUI VA CHANGER

7,2 milliards de plus dès 2012

Réforme fiscale à l'automne

ALGÉRIE L'INDÉPENDANCE

Une fête sans panache

Ces livres qui explorent l'histoire

DANGEROUS MOVE

Freeing captured animals may lead to disasters

IMPORTANT MATTER

Scientists claim to have discovered 'God particle'

MOVIE PLOT

Iron Man film company looks to China for screen success

Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Masse macht's

Die Tübinger

Faktor im System

Große Mehrheit im

The Gazette

MONTREAL, THURSDAY, JULY 5, 2012 SINCE 1781 BREAKING NEWS AT 9:00 AM

EL PAIS

EL PERIÓDICO GLOBAL EN ESPAÑOL

A solas con la prueba del VIH

De Villota pierde en los Juegos

Pistorius estará en los Juegos

fallada la partícula clave para a comprensión del universo

La Audiencia Nacional imputa a toda la cúpula de Bankia

В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНОМУ ТЕЛЕФОНУ

WWW.MK.RU

№144 (15.980)

5 июля 2012

ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ

«КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ

МЕТРО СПУСКАЕТ НА ВОДУ

THE HINDU

INDIA'S NATIONAL NEWSPAPER SINCE 1878

RARE CHOLA INSCRIPTIONS

MAY HAVE BEEN POISONED

SUBBARAO ON MFIS

BAHANE RETURNS

AD ALGEMEEN DAGBLAD

Eindelijk gelijk na 48 jaar

Zieke Kaj en zij moeder toch samen in de VS

Fluit Tine bei Gedenkstunde in Karlsruhe

Masse macht's

Die Tübinger

Faktor im System

Große Mehrheit im

CHINADAILY

THURSDAY, July 5, 2012

THE TIMES OF INDIA

UNDER FIVE FOOT CROWN
AKHILESH BOI'S BACK
CAR ROMANCE FORMS II

ADJUSTING TO USEL PRICE
BETTER THAN TAKING
CARS, SAYS MONTEKIS

SET FOR OLYMPIC HISTORY
TO RUN 400M & RELAY

Big bang moment: Scientists may have found 'God particle'

Adarsh scam: Finally, CBI chargesheets 13

Elusive particle found, looks like Higgs boson

CERN physicists had evidence of game-changing discovery of subatomic particle

PHYSICISTS AT CERN IN GENEVA HAVE APPROVED THE DISCOVERY OF A SUBATOMIC PARTICLE THAT BECKONS TO THE PHYSICS COMMUNITY AS THE HIGGS BOSON.

CORRIERE DELLA SERA

Fondato nel 1876

Geopolitica

Contaminazione

Caso di Corriere

Scienza scientifica

La particella che può svelare i segreti dell'universo

UN'AVVENA IN OSTACOLO

Il governo di Roma è in ostacolo

La particella che può svelare i segreti dell'universo

Czaskie Higgsa fizycy najpierw wymyślił, potem szukali 40 lat

BOSKA MASA

Po tym odkryciu świat już nigdy nie będzie taki sam. Należące do masywnej w rzeczywistości subatomowej cząstki nazywanej bosonem Higgsa - partiami w fizyce i kosmologii.

gazeta

WYBORCZA.PL

Ukraincy biją się o Jędrzyński

Czaskie Higgsa fizycy najpierw wymyślił, potem szukali 40 lat

BOSKA MASA

Po tym odkryciu świat już nigdy nie będzie taki sam. Należące do masywnej w rzeczywistości subatomowej cząstki nazywanej bosonem Higgsa - partiami w fizyce i kosmologii.

আনন্দবাজার পত্রিকা

বিজ্ঞানের 'ঈশ্বর' দর্শন

সত্যেন্দ্রনাথ বোস

বিনয় প্রণাম

Higgsdependence Day!



The Particle Higgsaw Puzzle



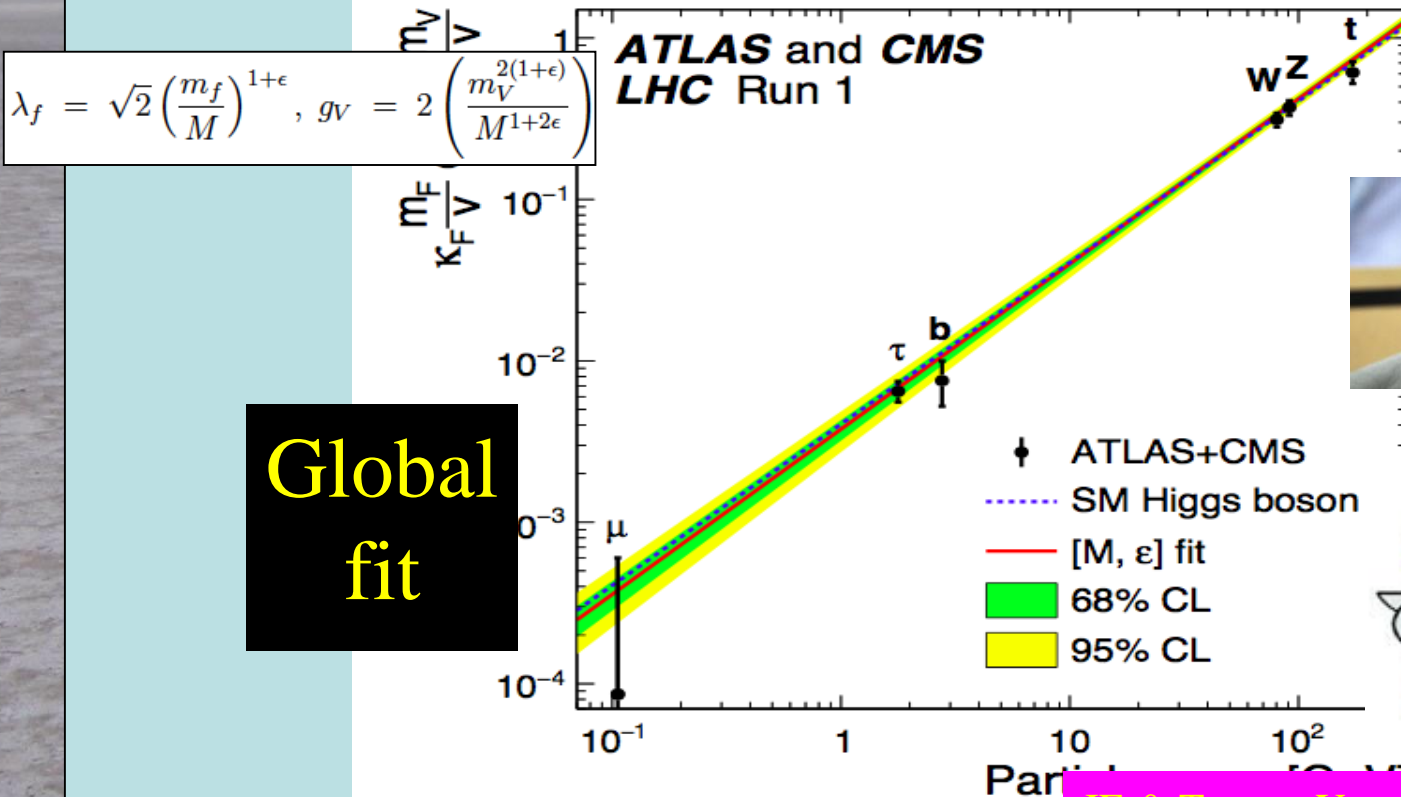
Is LHC finding the missing piece?

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 ?



quack

JE & Tevong You

- Blue** dashed line = Standard Model

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
- Properties of neutrinos
- Cosmological inflation
- Quantum gravity
- ...

LHC

LHC

LHC

LHC

LHC

The *Standard Model*

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

ALBERT R. BROCCOLI'S EON PRODUCTIONS PRESENTS PIERCE BROSNAN as IAN FLEMING'S JAMES BOND 007
"THE WORLD IS NOT ENOUGH" SOPHIE MARCEAU ROBERT CARLYLE DENISE RICHARDS ROBBIE COLTRANE and JUDI DENCH
MUSIC BY DAVID ARNOLD COSTUME DESIGNER JIM CLARK EDITOR ADRIAN BRIDLE EXECUTIVE PRODUCERS PETER LAMONT
PRODUCED BY ANTHONY WAVE WRITTEN BY NEAL PURVIS & ROBERT WADE DIRECTED BY NEAL PURVIS & ROBERT WADE PRODUCED BY MICHAEL C. WILSON AND BARBARA BROCCOLI PRODUCED BY MICHAEL APYED
CASTING BY JILL GIBB GARRAGE FORD FILMS PRESENTS A PIERCE BROSNAN FILM THE WORLD IS NOT ENOUGH

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

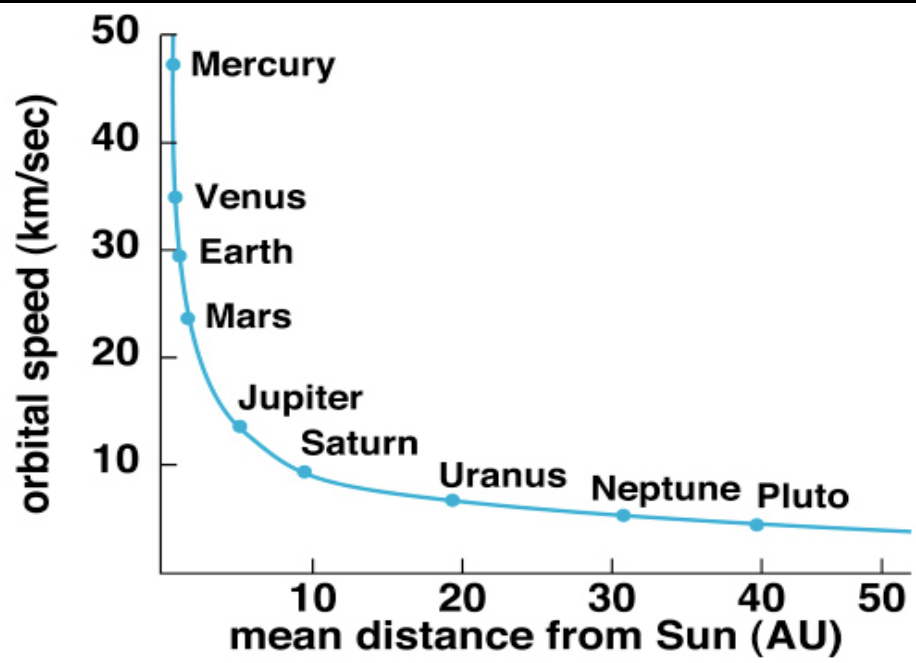
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



Scanned at the American
Institute of Physics

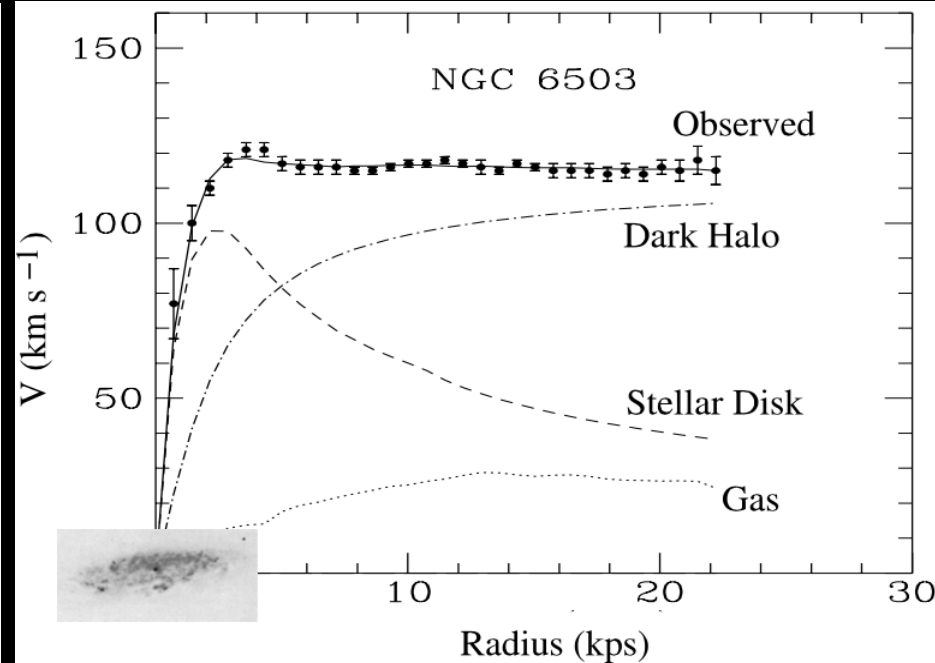
Rotation Curves

- In the Solar System



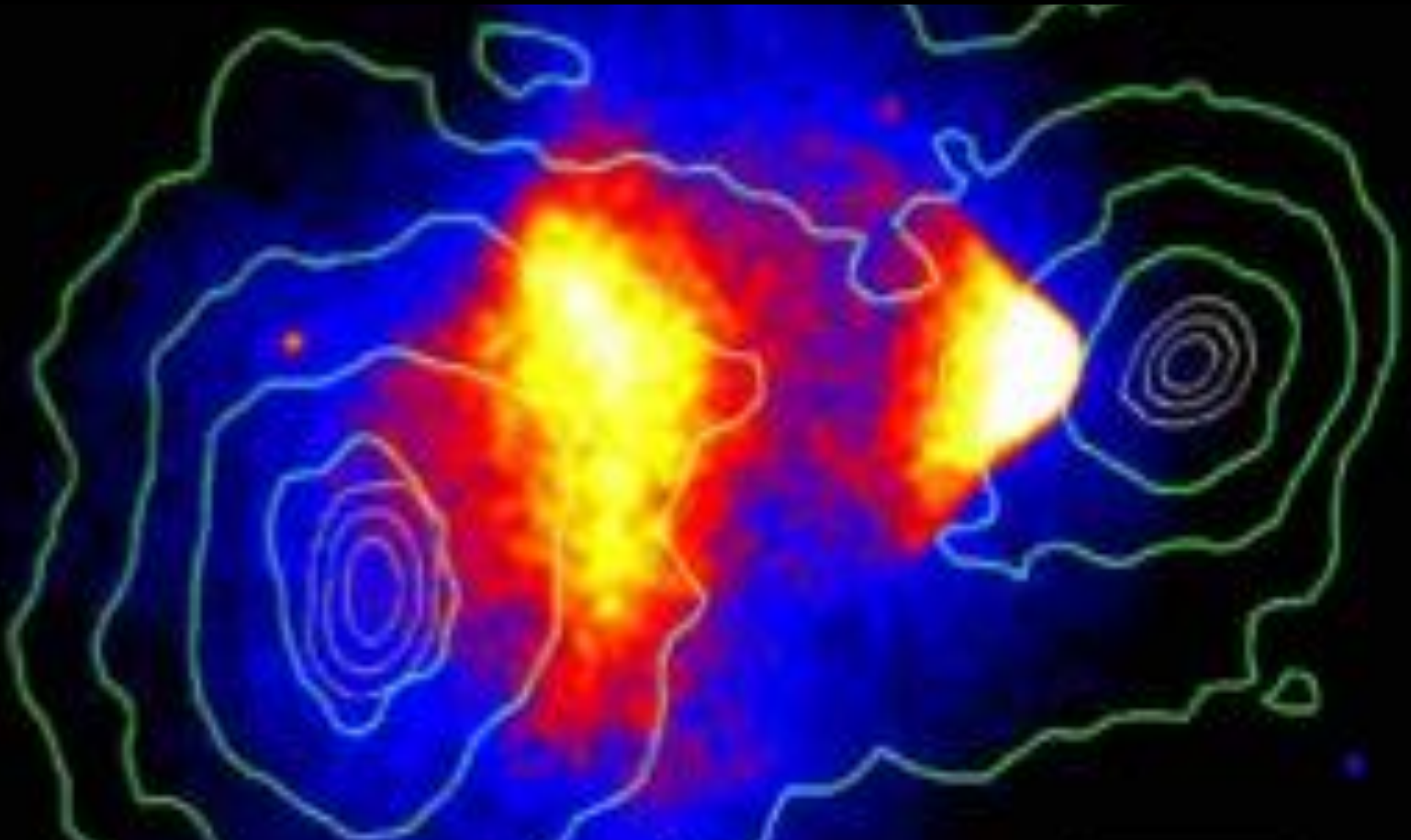
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



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

Biggest Collider in the Universe?



Collision between 2 clusters of galaxies:
Gas interacts, heats and stops
Dark matter passes through

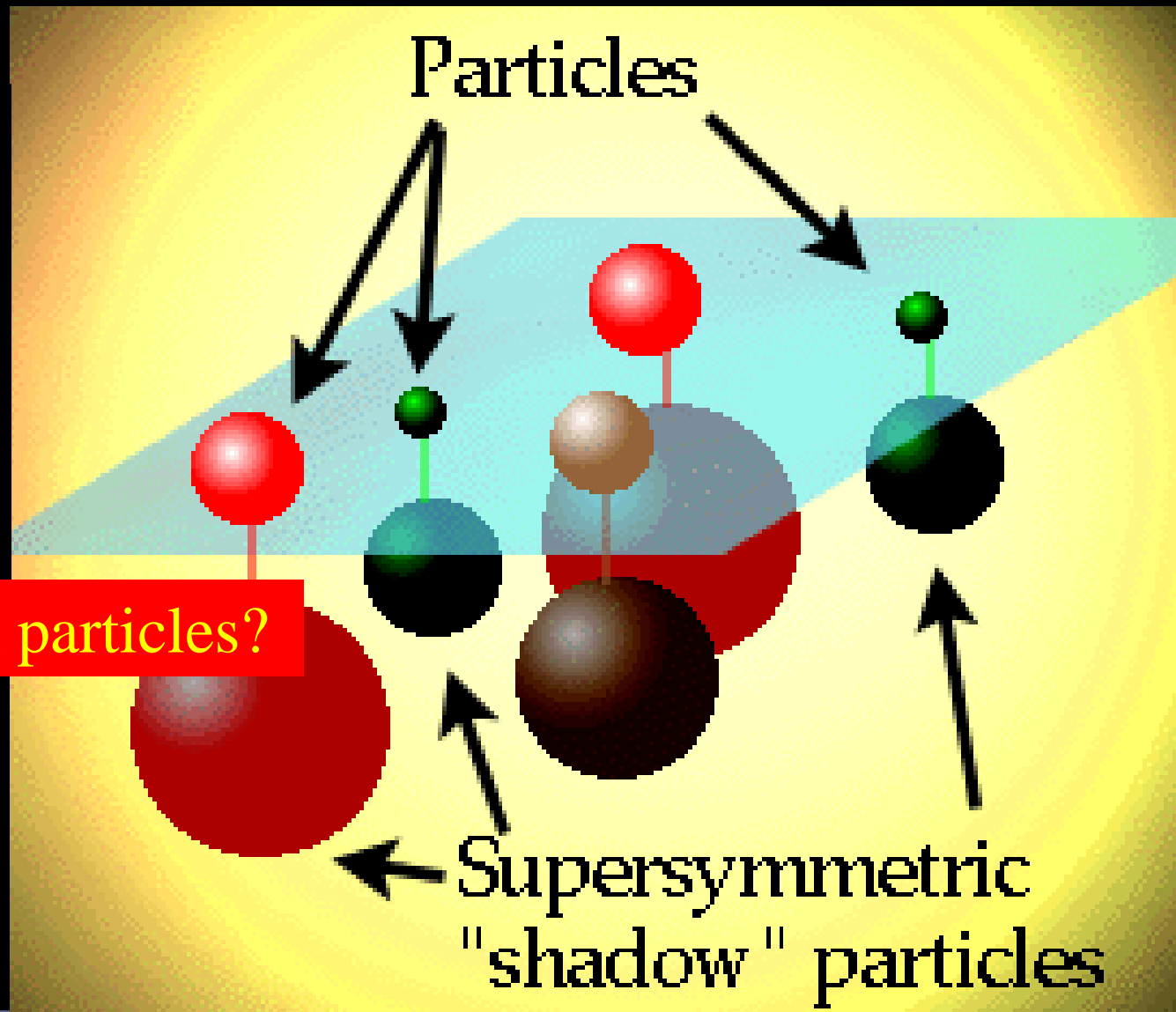
Clowe et al, 2006

What is the Dark Matter in the Universe?

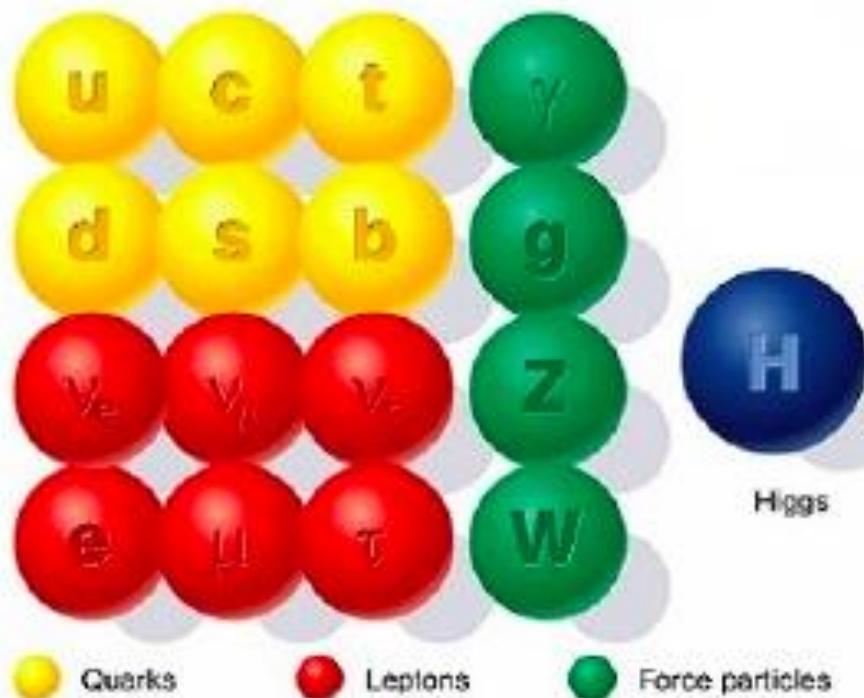
Astronomers say
that most of the
matter in the
Universe is
invisible
Dark Matter

Made of unknown particles?

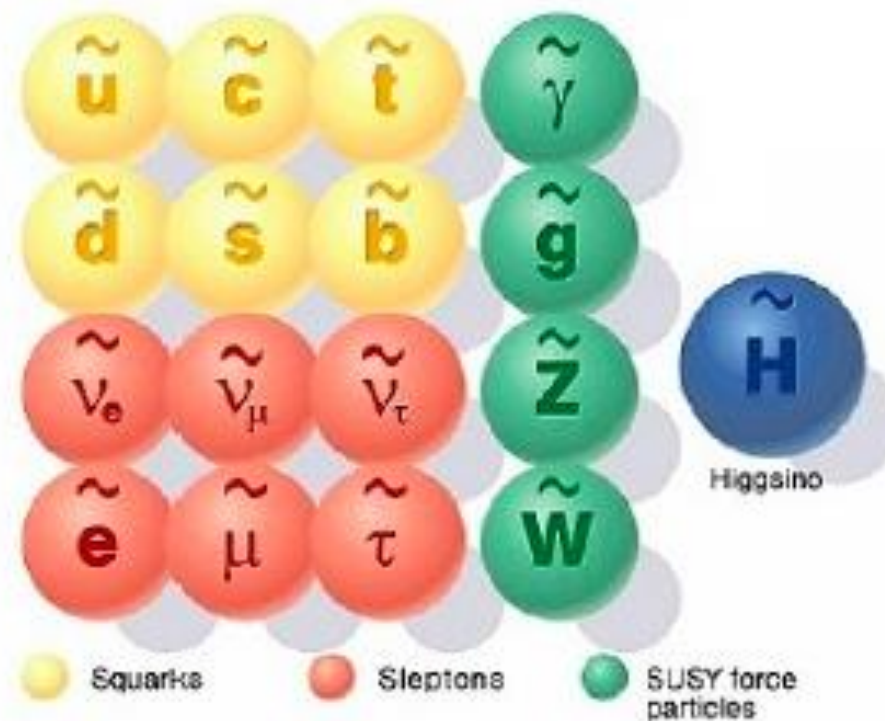
We are
searching for
them at the
LHC



Minimal Supersymmetric Extension of the Standard Model

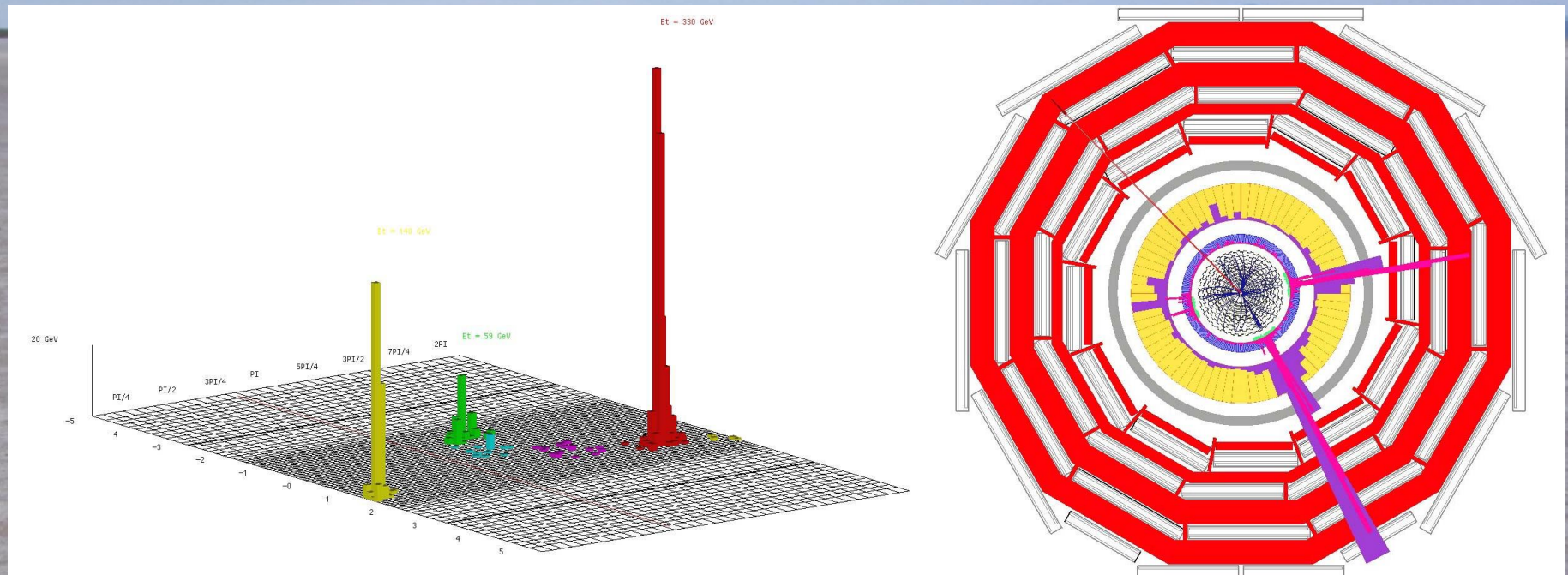


Standard particles



SUSY particles

Classic LHC Dark Matter Signature

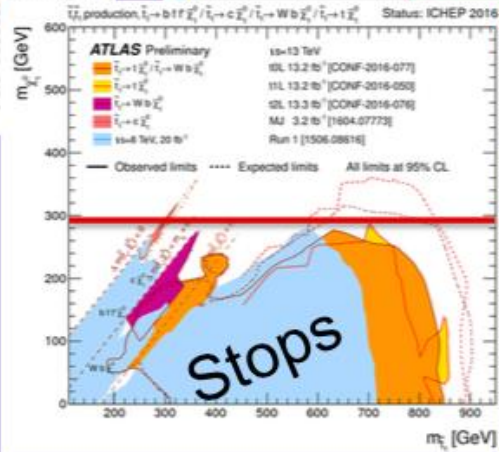
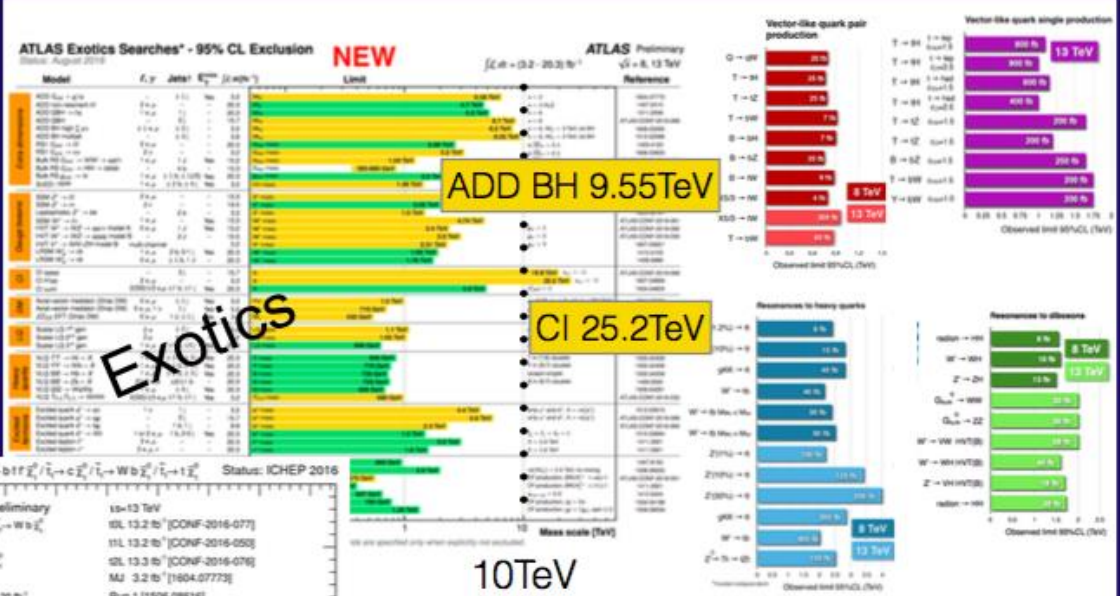
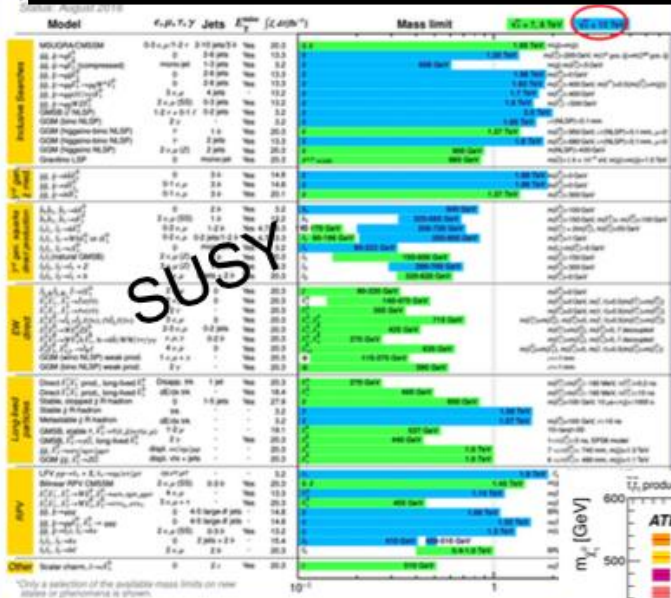


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

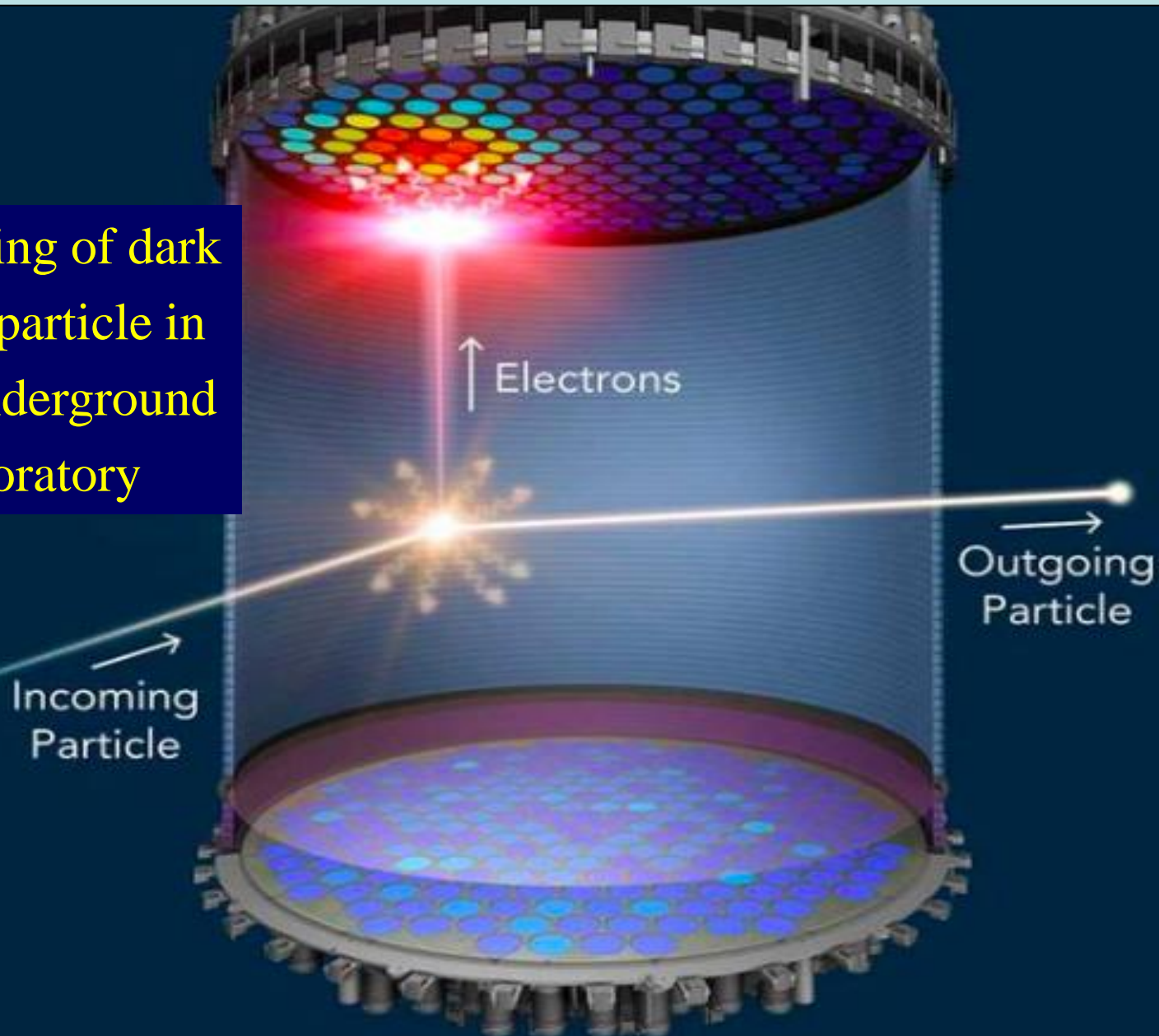
Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory



General Interest in Antimatter Physics



Physicists cannot make enough for
Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
same mass
opposite internal properties:
electric charge, ...

Discovered in cosmic rays
Studied using accelerators
Used in PET scanners

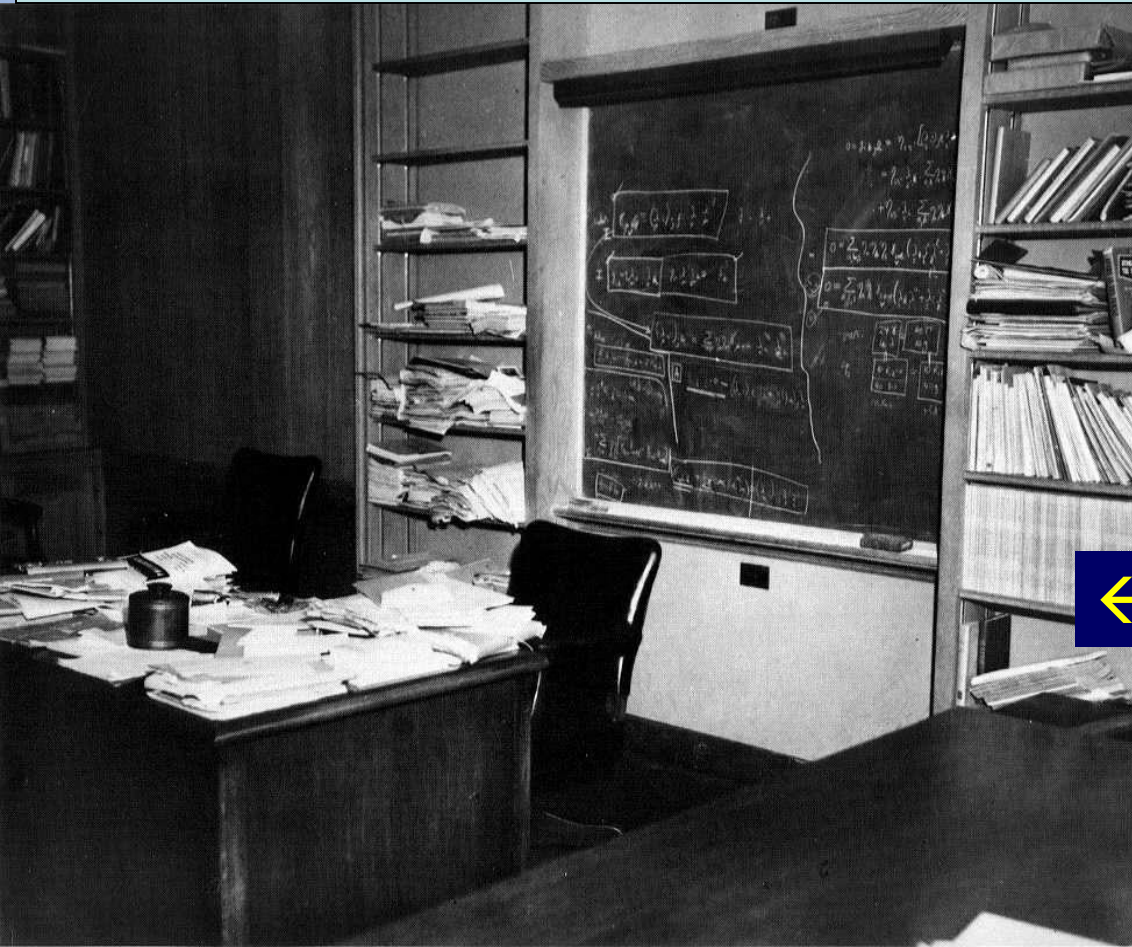


Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

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



← ... but he never succeeded

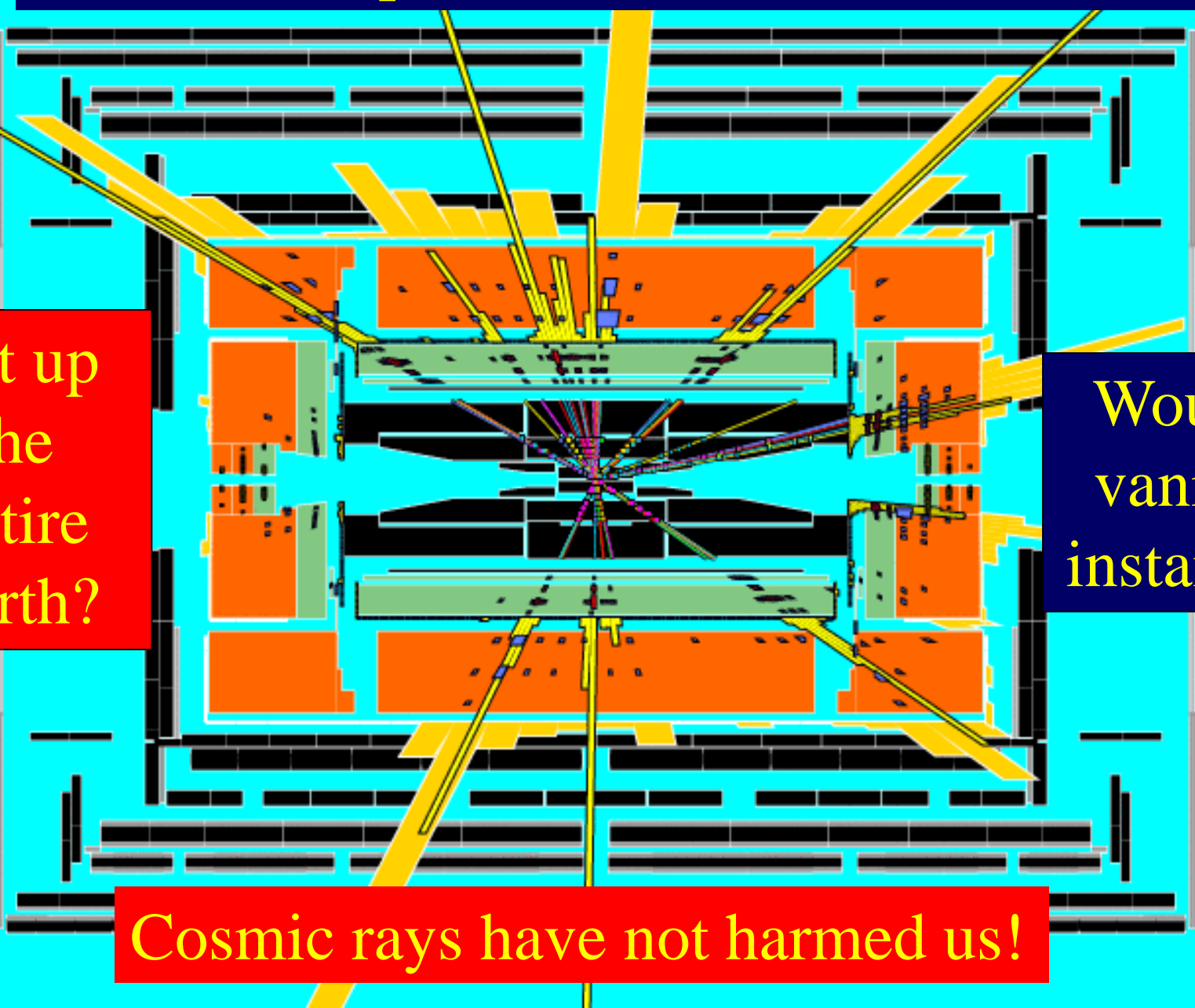
Unification via extra dimensions of space?

Will LHC experiments create black holes?

Eat up
the
entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!



Standard Model Particles: Years from Proposal to Discovery

Electron

Photon

Muon

Electron neutrino

Muon neutrino

Down

Strange

Up

Charm

Tau

Bottom

Gluon

W boson

Z boson

Top

Tau neutrino

HIGGS BOSON

Lovers of physics
Beyond the SM:
be patient!



Summary

Visible matter

Standard Model

**Dark Matter
&
Dark Energy**

