

The Big & Small Pictures

From particle physics to cosmology

John Ellis

6th African School of Fundamental Physics & Applications
Marrakech, Morocco, July 2021

KING'S
College
LONDON

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?

Evolution of the Universe

What will
happen in
the future?

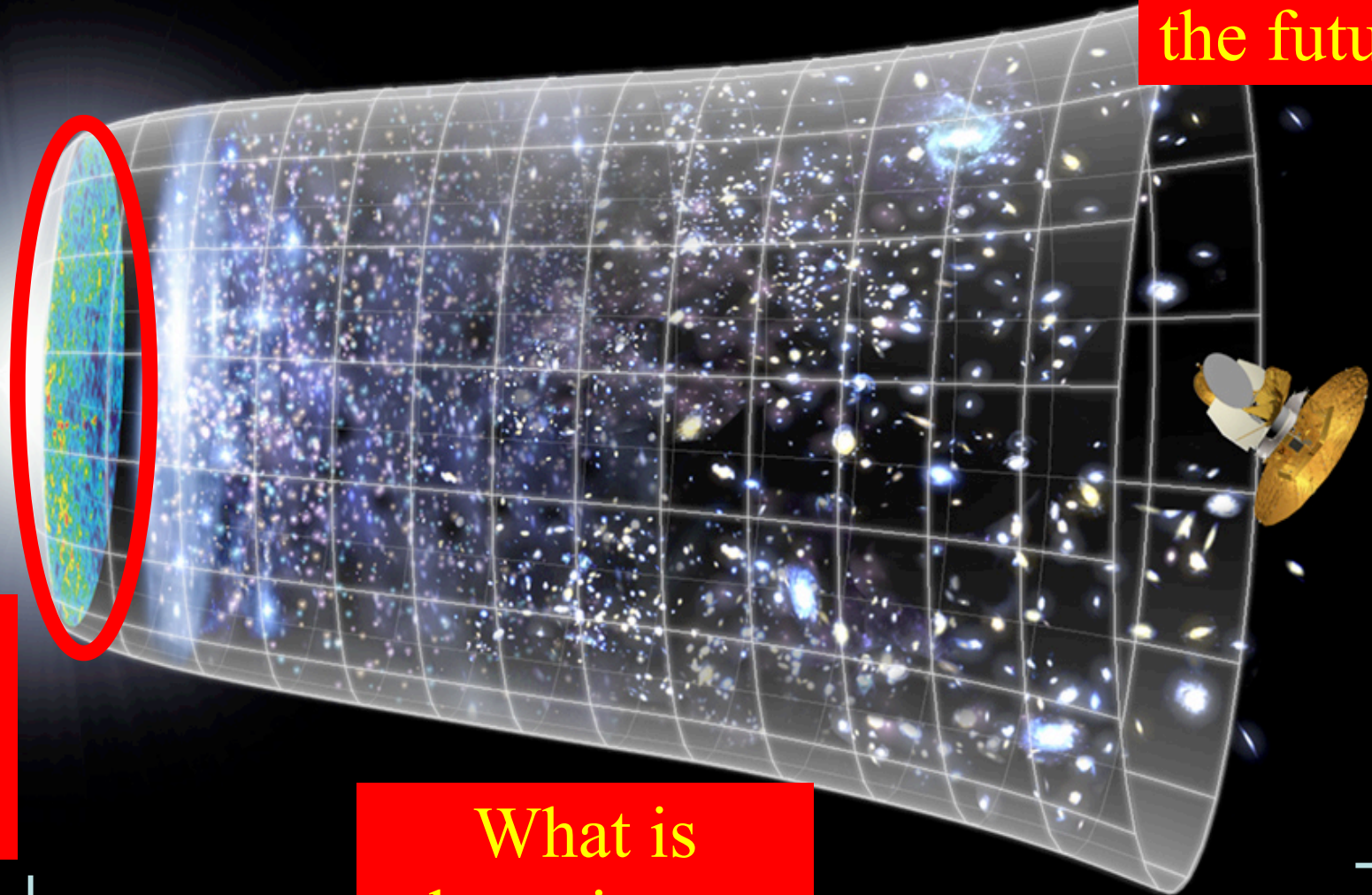
Big Bang

What
happened
then?

What is
the universe
made of?

Today

10^{28} cm



Gauguin's Questions in the Language of Particle Physics

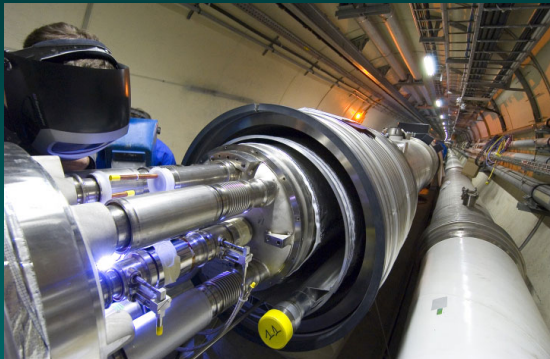
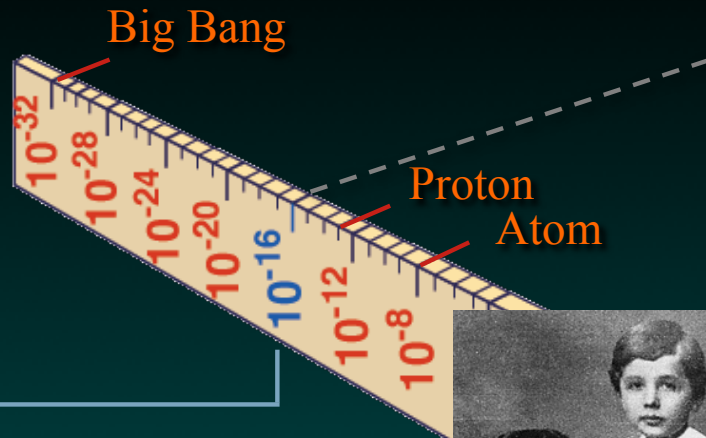
- What is matter made of?
 - Why do things weigh?



- 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

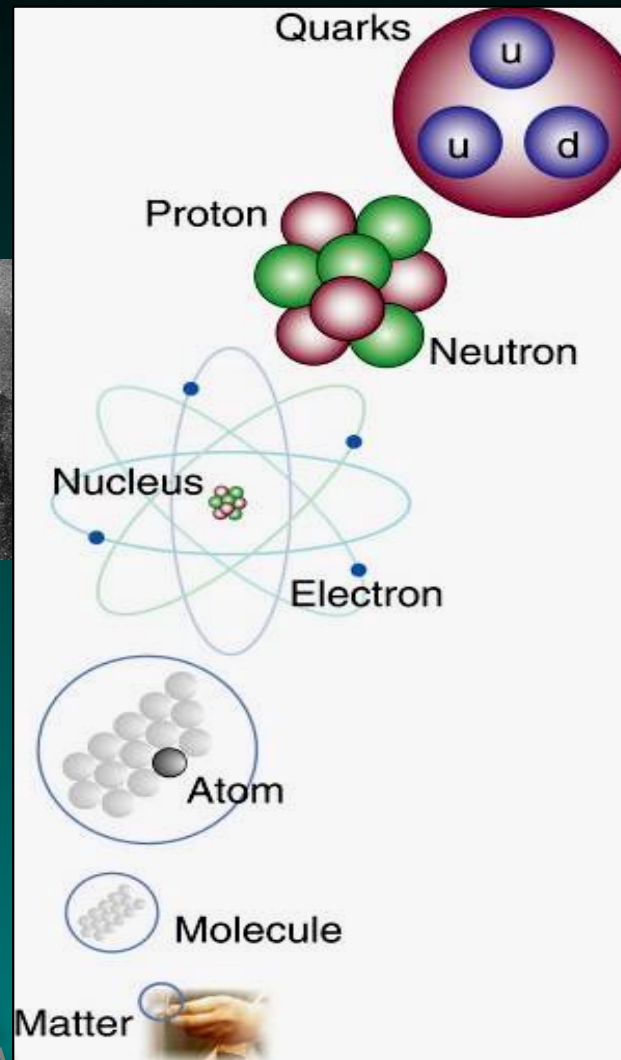


LHC

Super-Microscope

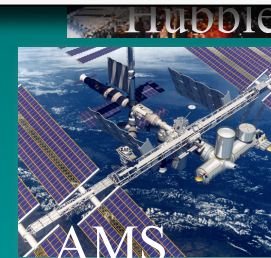
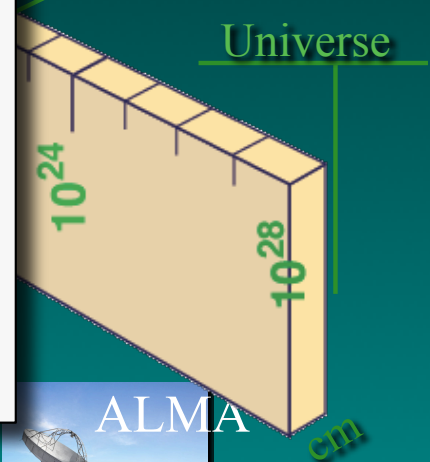


Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

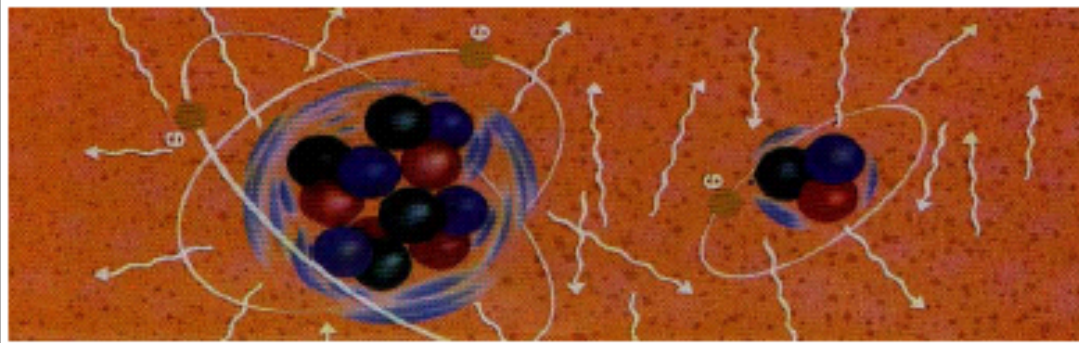


Radius of Galaxies

Universe

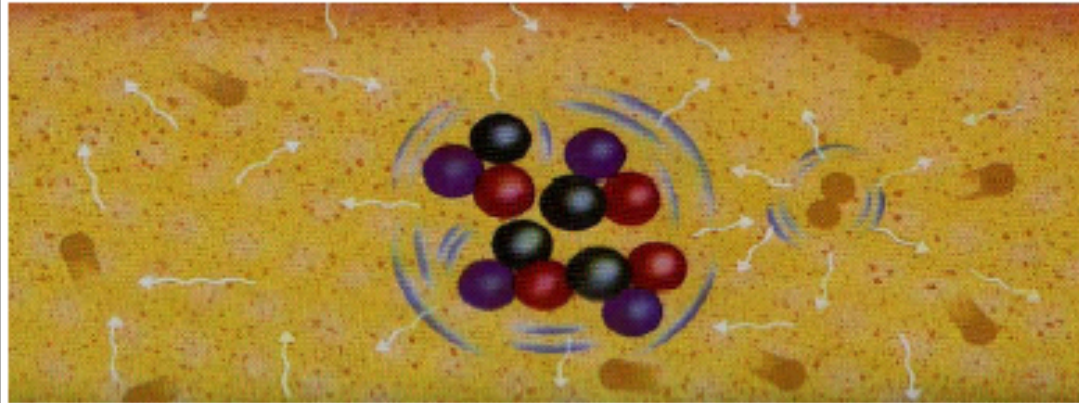


300,000
years



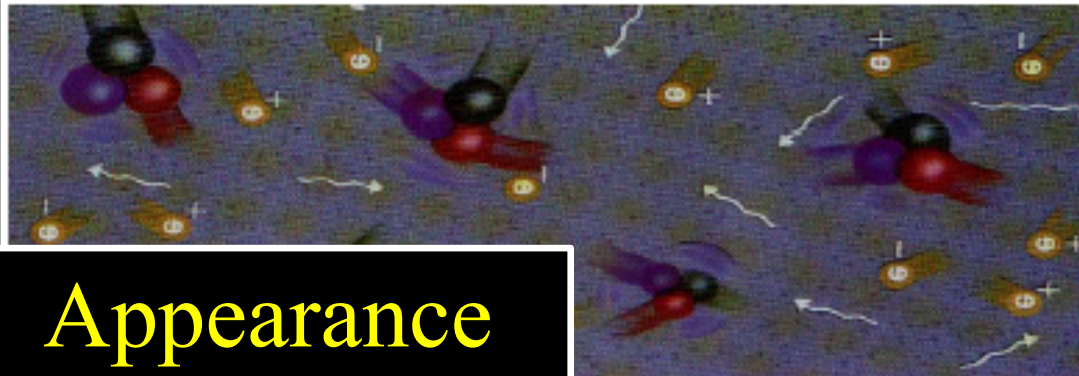
Formation
of atoms

3
minutes



Formation
of nuclei

1 micro-
second



Formation
of protons
& neutrons

1 pico-
second

Appearance
of dark matter?



Appearance
of mass?

Appearance
of matter?

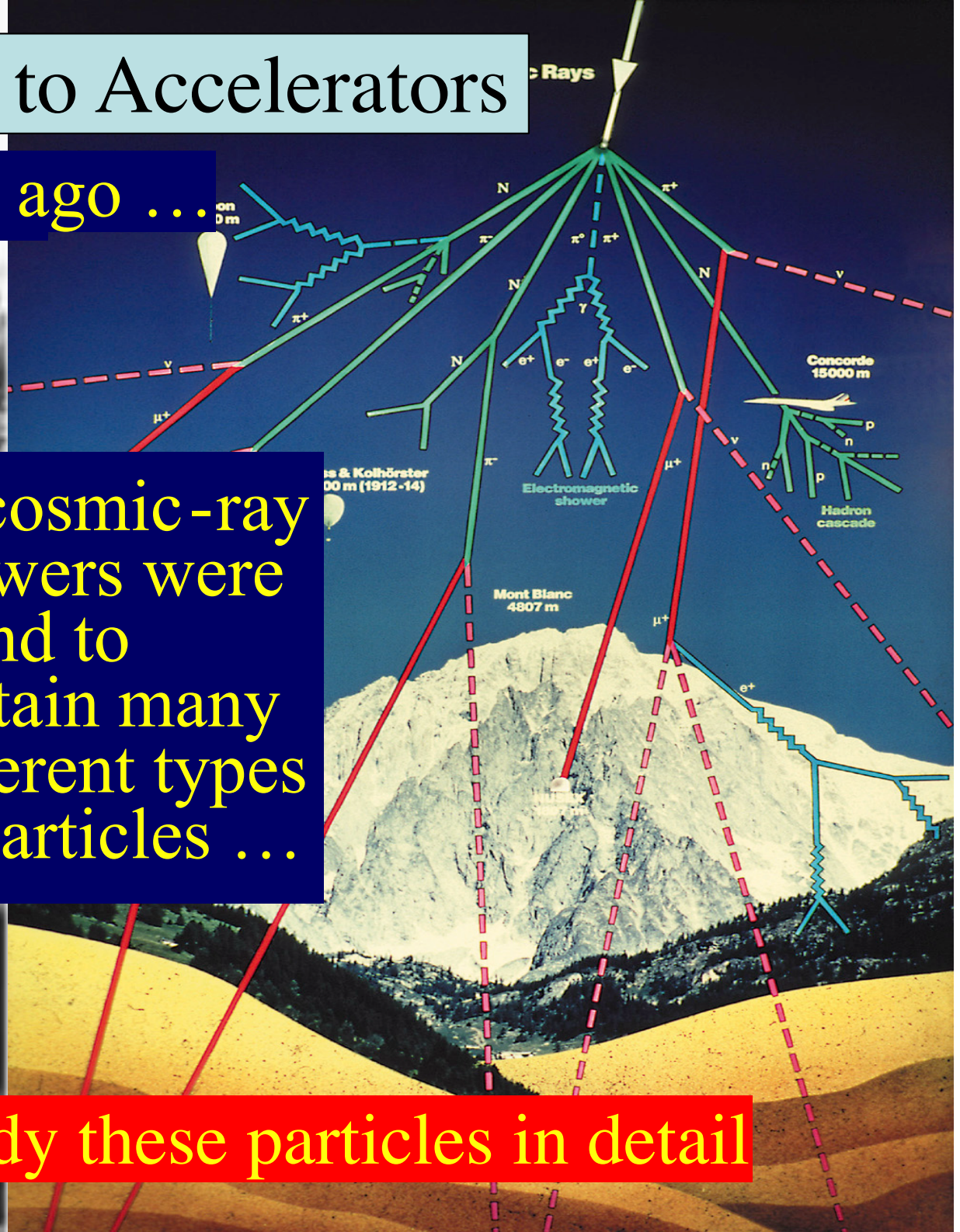
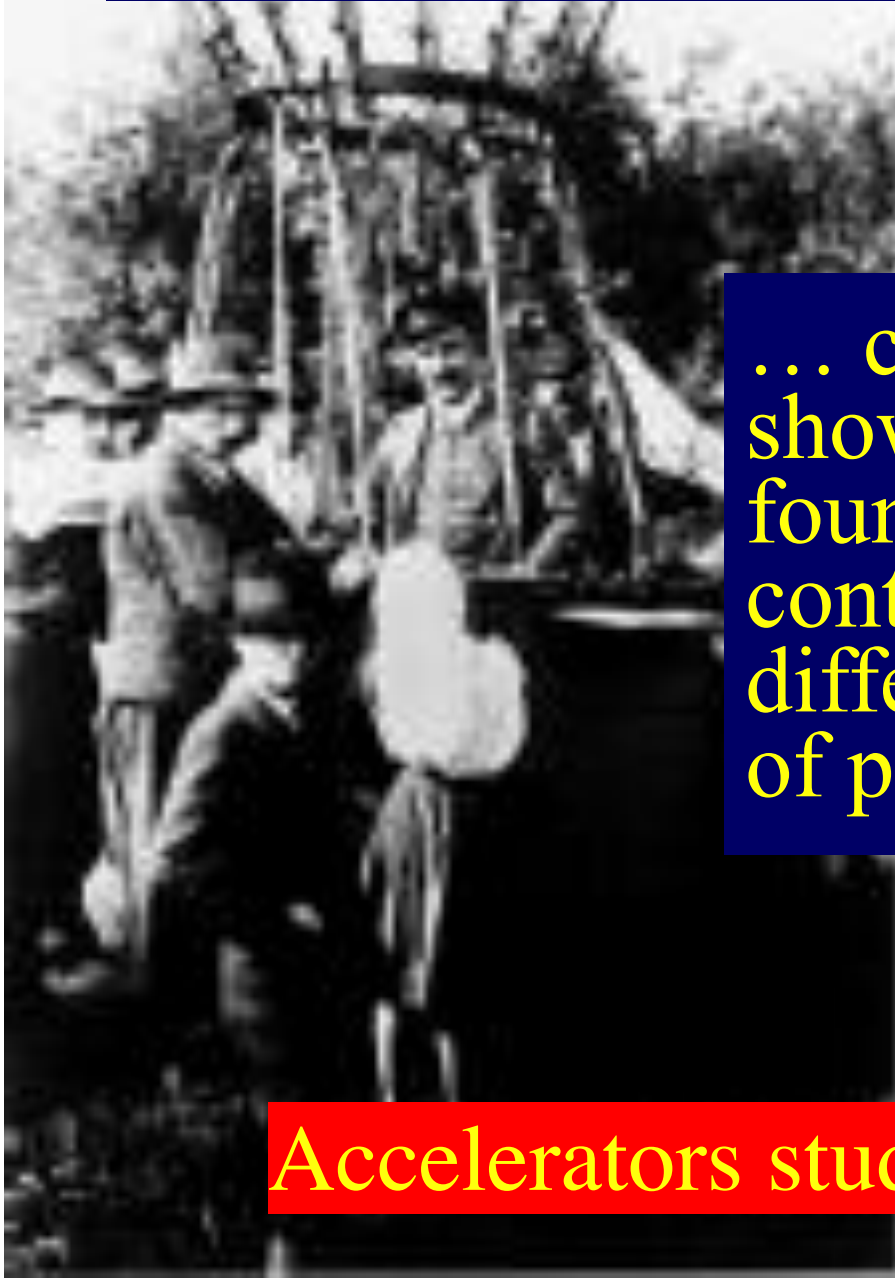
BANG!

From Cosmic Rays to Accelerators

Discovered a century ago ...

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

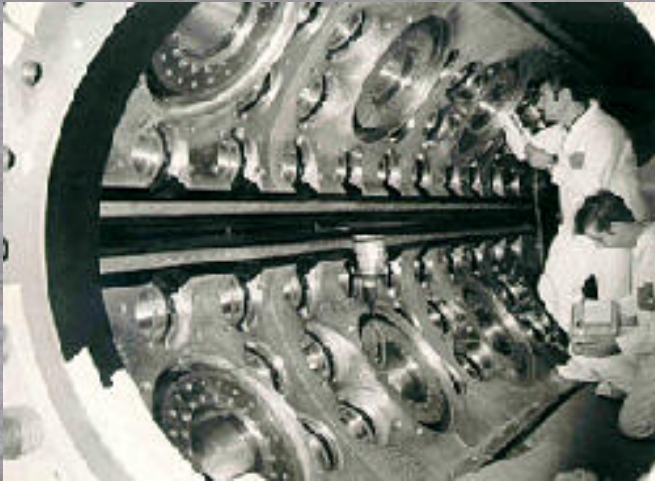
Accelerators study these particles in detail



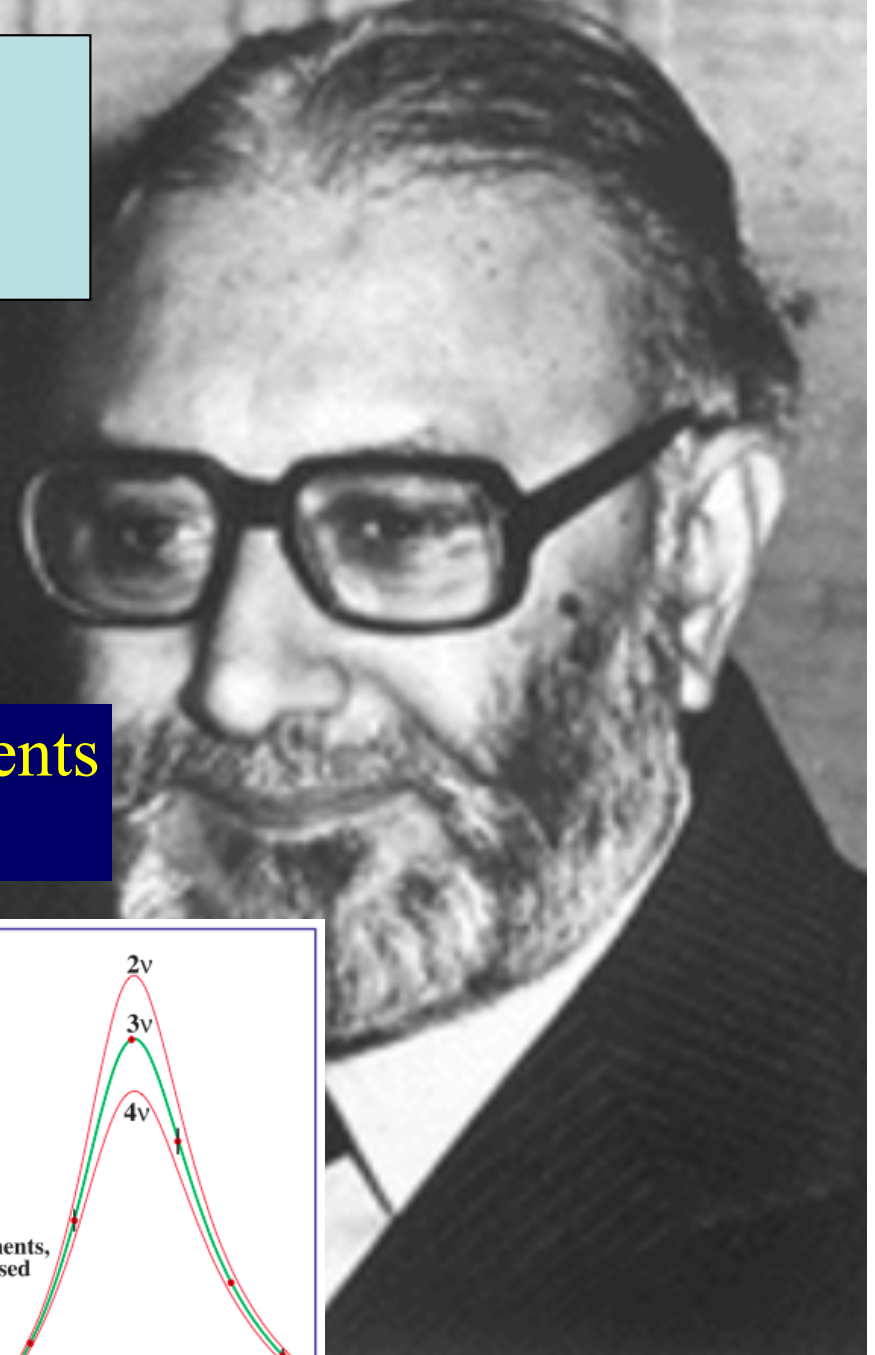
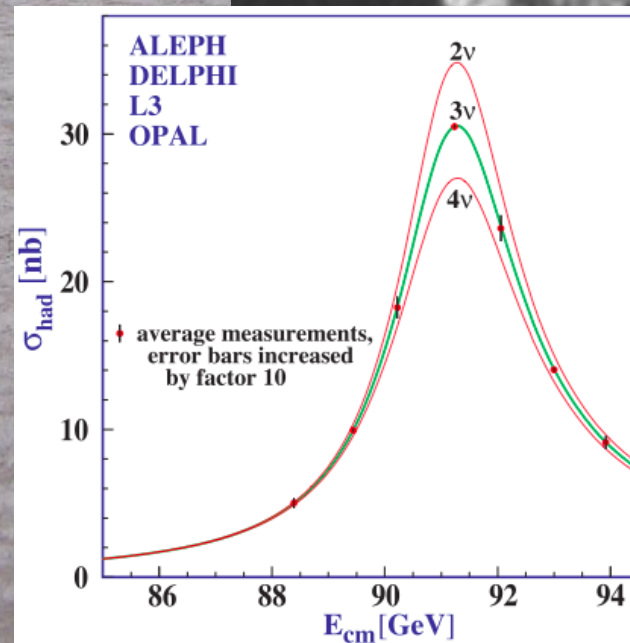
The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow and Weinberg

Tested by experiments
at CERN



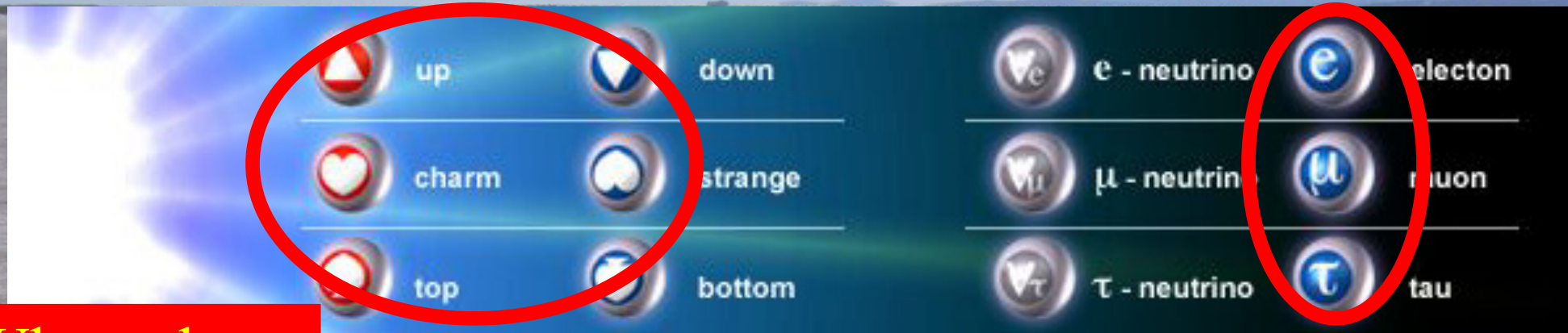
Perfect agreement between
theory and experiments
in all laboratories



The 'Standard Model'

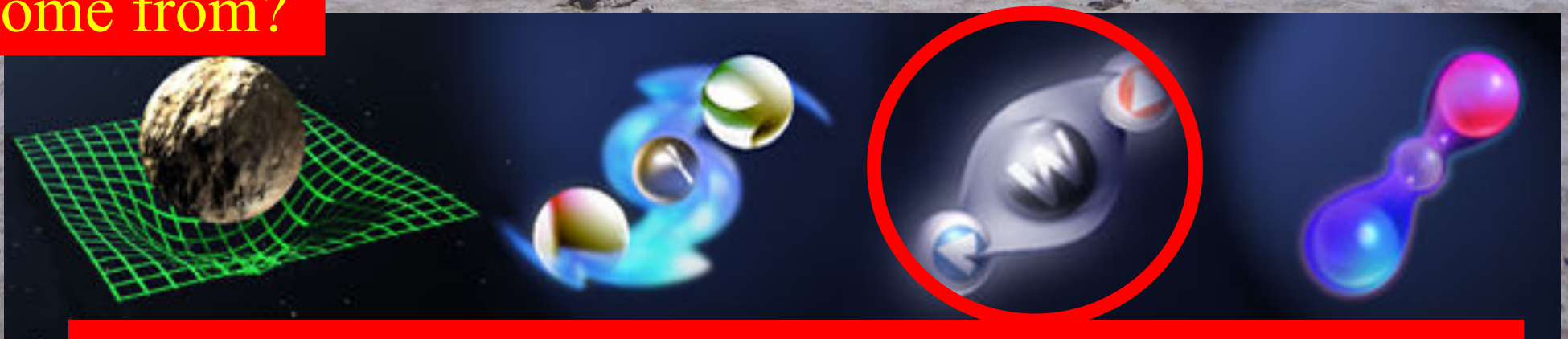
= Cosmic DNA

The matter particles



Where does
mass
come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

Newton:

Weight **proportional to** Mass

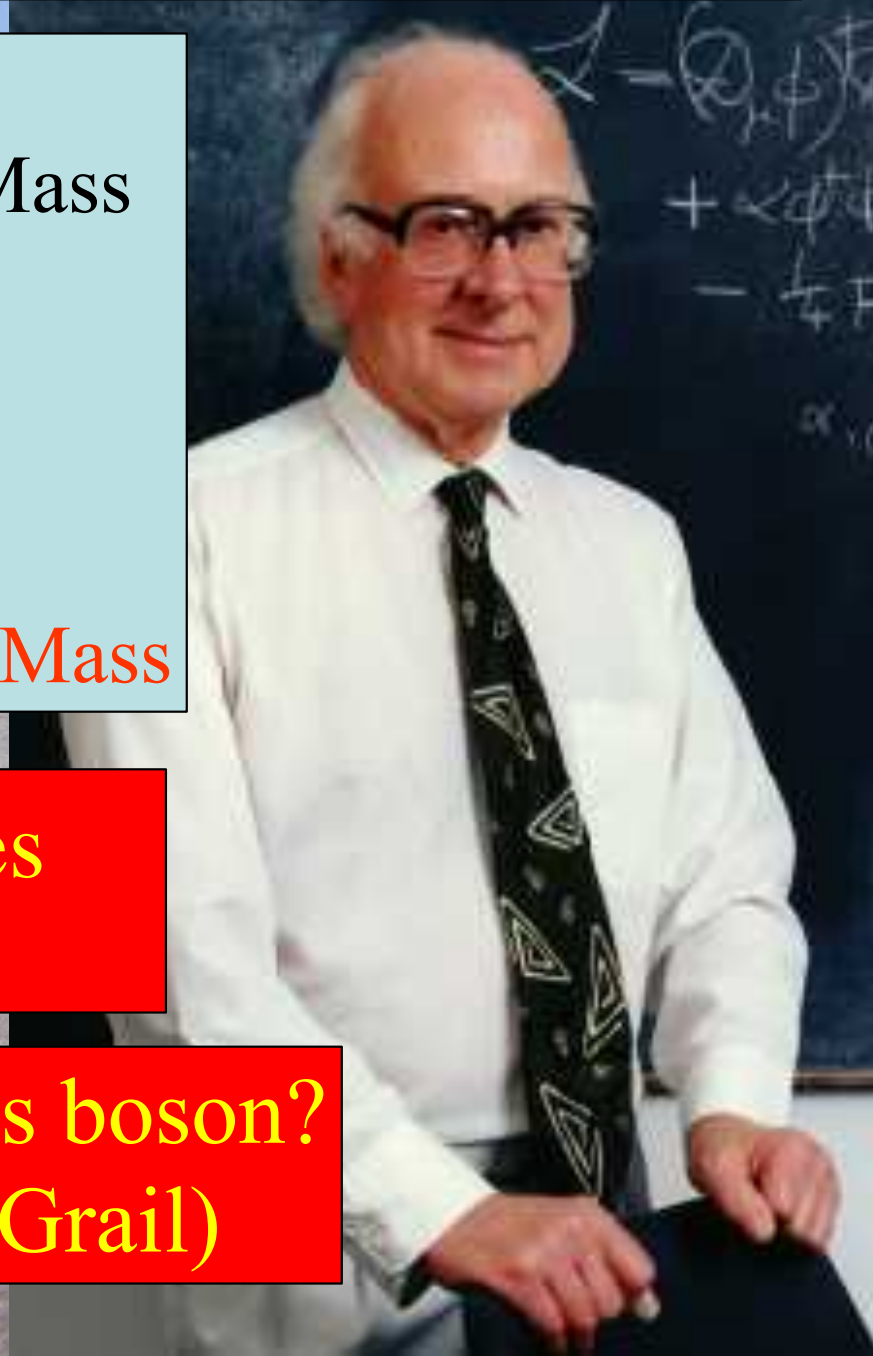
Einstein:

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)



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



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.

An aerial photograph of the CERN Large Hadron Collider (LHC) facility. The LHC's circular tunnel is visible as a thin white line winding through a patchwork of green and brown agricultural fields. The landscape is divided into numerous small, irregular plots. In the lower right, a more developed area with buildings and roads is visible, along with a portion of an airport runway. The overall scene is captured from a high altitude, showing the vast scale of the facility relative to the surrounding terrain.

To answer Gauguin's questions:

The Large Hadron Collider at CERN

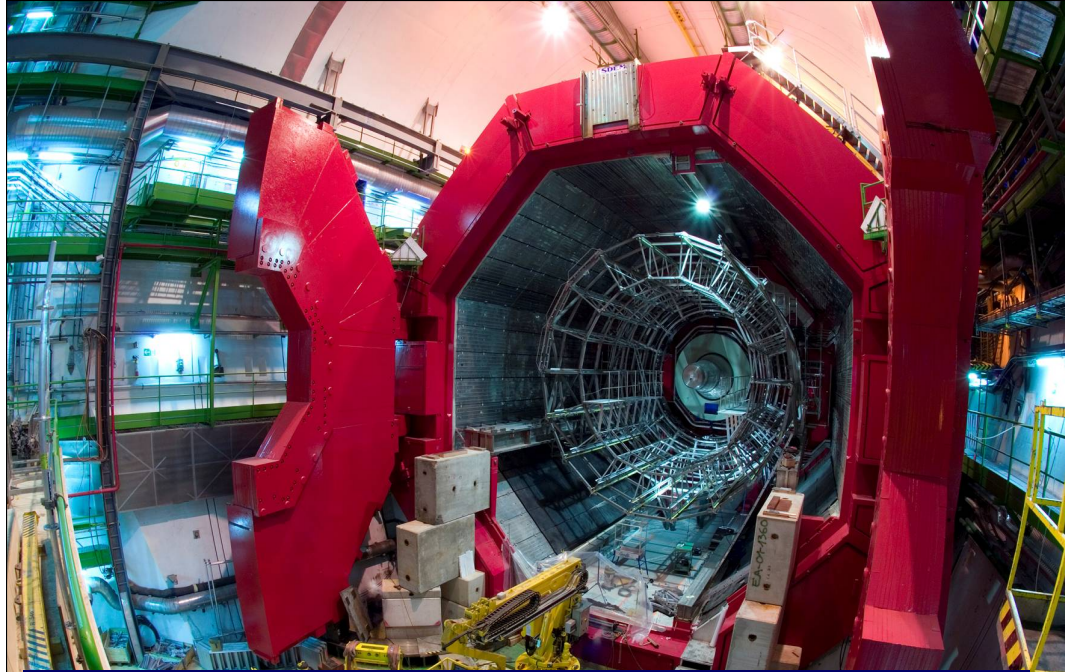
To answer Gauguin's questions:

The Large Hadron Collider (LHC)

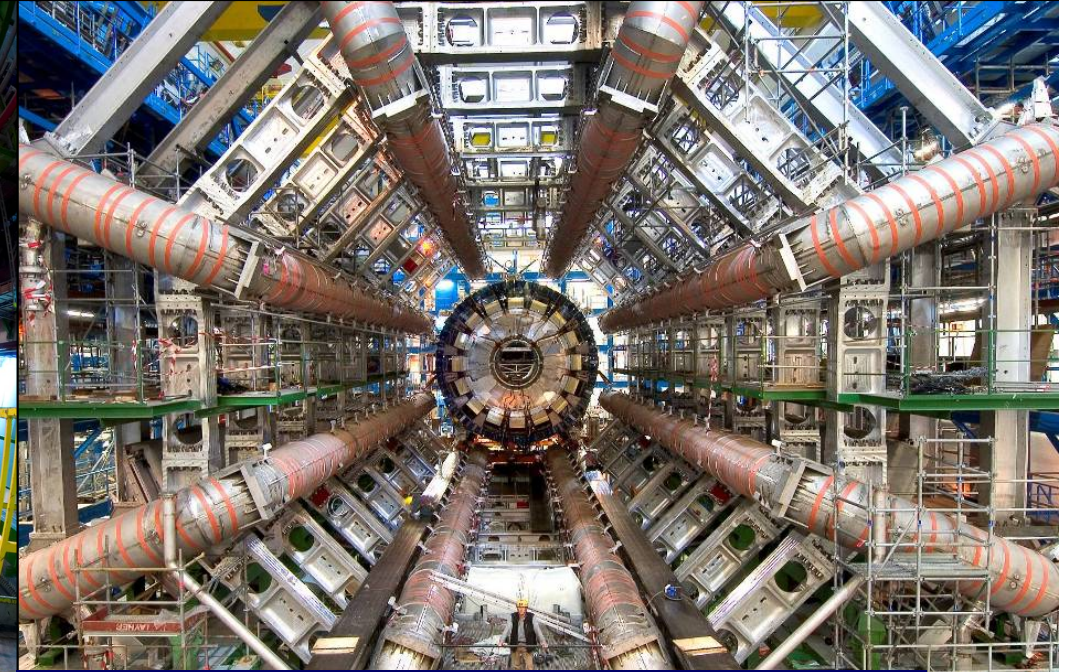
Several thousand billion protons
Each with the energy of a fly
99.99999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:

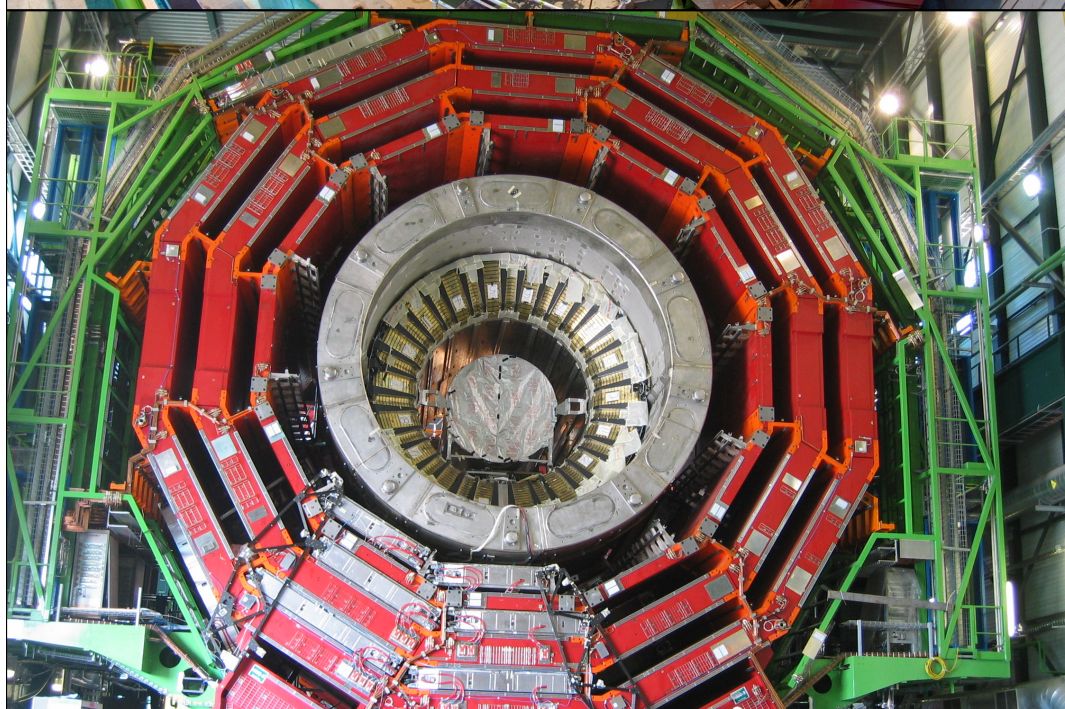
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



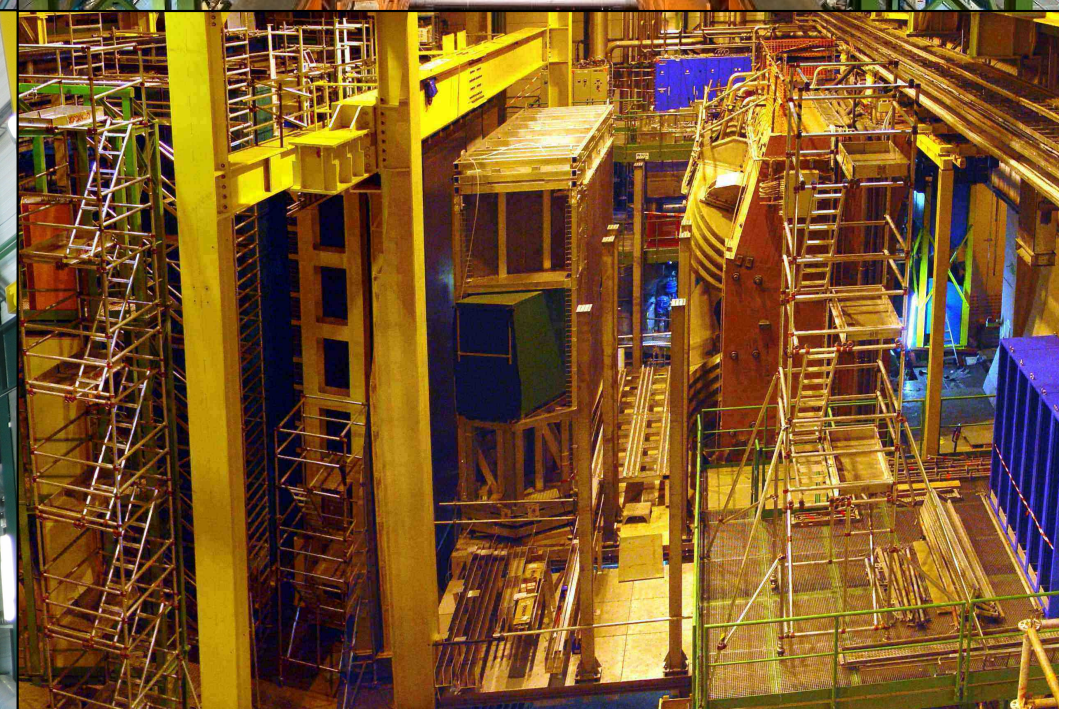
ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

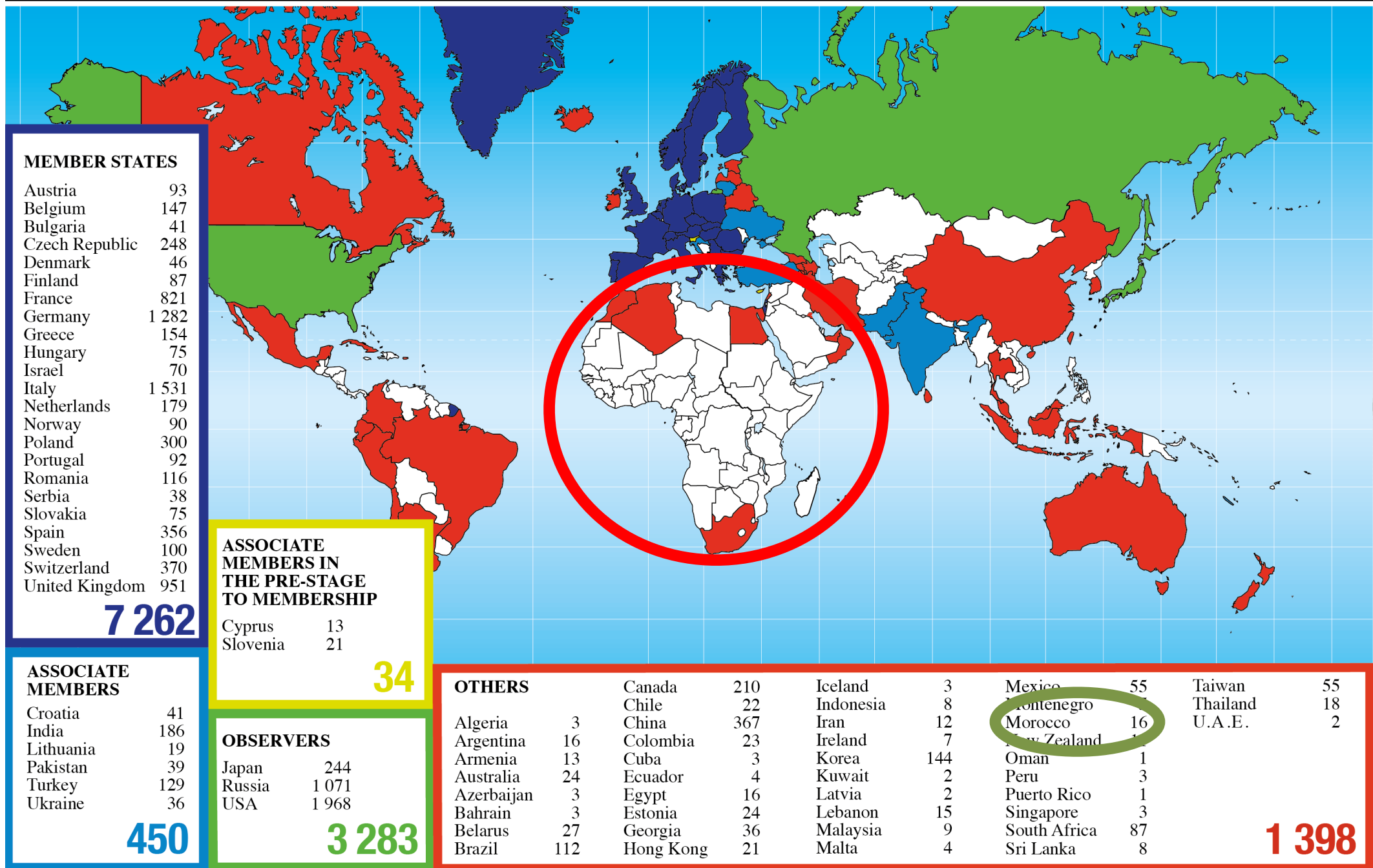


CMS: Higgs and dark matter



LHCb: Matter-antimatter difference

Scientists from around the World



Scientists' Home Countries

MEMBER STATES

7 246

Austria	100
Belgium	114
Bulgaria	72
Czech Republic	221
Denmark	50
Finland	72
France	773
Germany	1 207
Greece	221
Hungary	78
Israel	58
Italy	1 886
Netherlands	169
Norway	62
Poland	317
Portugal	97
Romania	145
Serbia	49
Slovakia	129
Spain	411
Sweden	75
Switzerland	204
United Kingdom	736

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

54

Cyprus	21
Slovenia	33

ASSOCIATE MEMBERS

771

Croatia	46
India	370
Lithuania	31
Pakistan	63
Turkey	164
Ukraine	97

OBSERVERS 2 518

Japan	273
Russia	1 129
USA	1 116

OTHERS

Albania	4	Bolivia	2	Ecuador	10	Iraq	1	Malaysia	19	Palestine	7	Taiwan	47
Algeria	9	Bosnia & Herzegovina	2	Egypt	26	Ireland	14	Malta	5	Paraguay	1	Thailand	23
Argentina	22	Bostwana	1	El Salvador	1	Jamaica	1	Mexico	81	Peru	6	Tunisia	5
Armenia	18	Brazil	121	Estonia	16	Jordan	1	Mongolia	2	Philippines	3	Uruguay	1
Australia	29	Burundi	1	Georgia	53	Kazakhstan	12	Montenegro	8	Saint Kitts and Nevis	1	Uzbekistan	3
Azerbaijan	8	Cameroon	1	Ghana	1	Kenya	1	Morocco	26	Saudi Arabia	3	Venezuela	10
Bahrain	3	Canada	161	Gibraltar	1	Korea	158	Myanmar	7	Senegal	1	Viet Nam	9
Bangladesh	5	Chile	20	Guatemala	1	Kyrgyzstan	1	Nepal	8	Singapore	4	Yemen	1
Belarus	49	China	570	Hong Kong	1	Latvia	4	New Zealand	6	South Africa	58	Zambia	1
Benin	1	Colombia	36	Honduras	1	Lebanon	23	Nigeria	2	Sri Lanka	6	Zimbabwe	2
		Congo	1	Iceland	5	Lesotho	1	North Korea	3	Sudan	2		
		Costa Rica	1	Indonesia	11	Luxembourg	3	North Macedonia	2	Syria	2		
		Cuba	16	Iran	48	Madagascar	1	Oman	1				

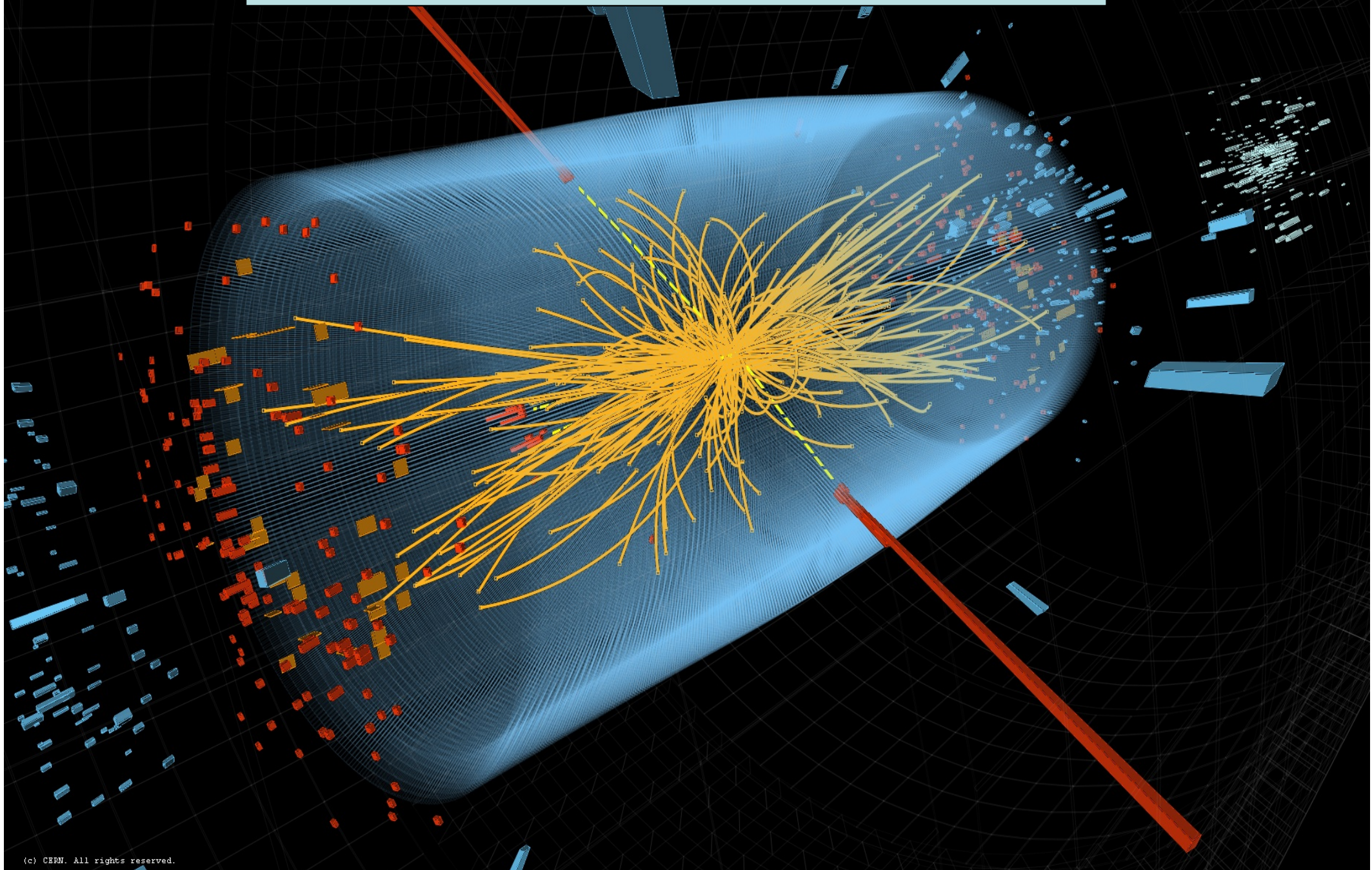
1 837

2012: The discovery of the Higgs Boson



Mass Higgsteria


Interesting Events



Higgsdependence Day!



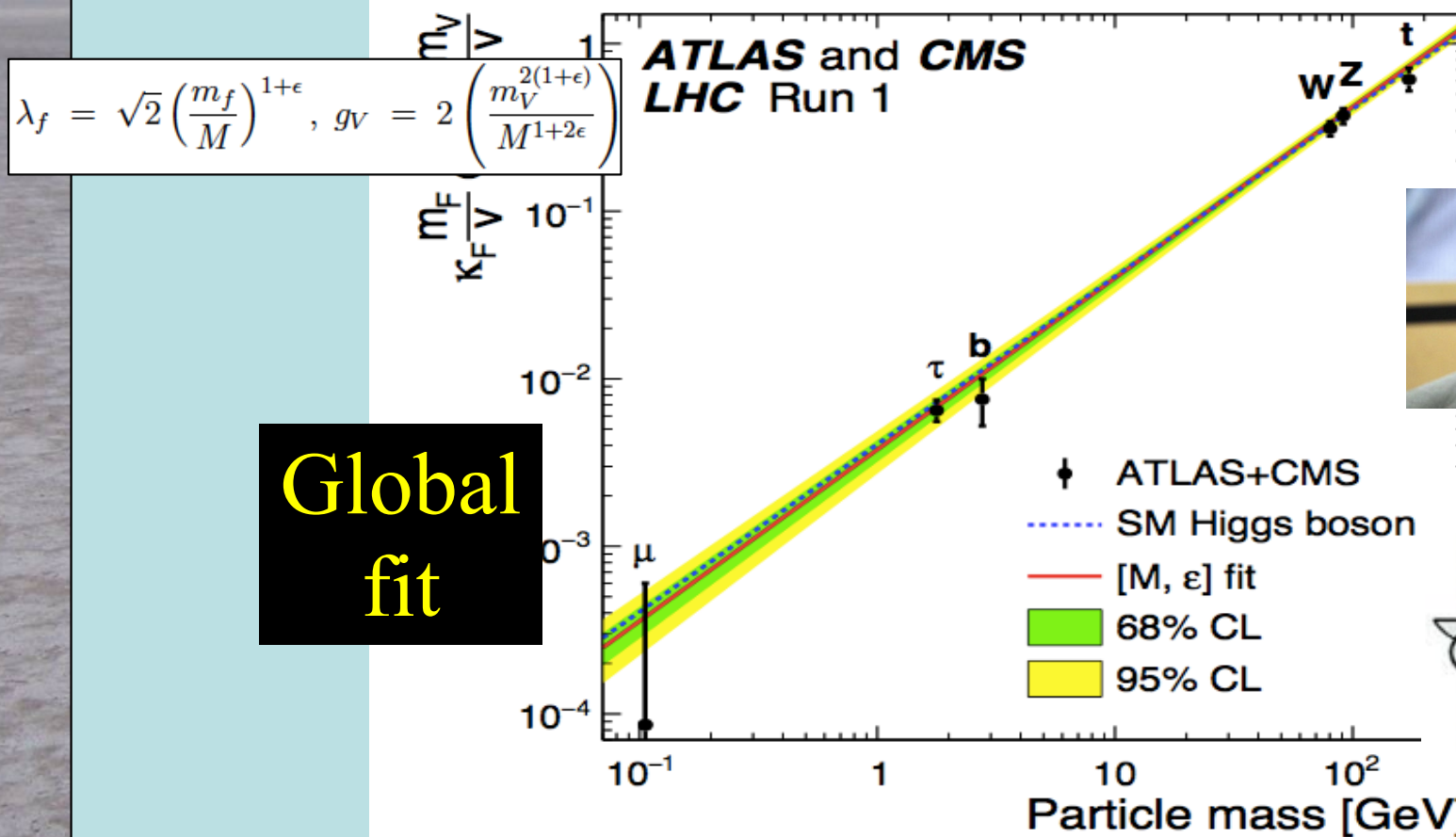
The Particle Higgsaw Puzzle



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

- Blue dashed line = Standard Model

Dixit Swedish Academy

Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]

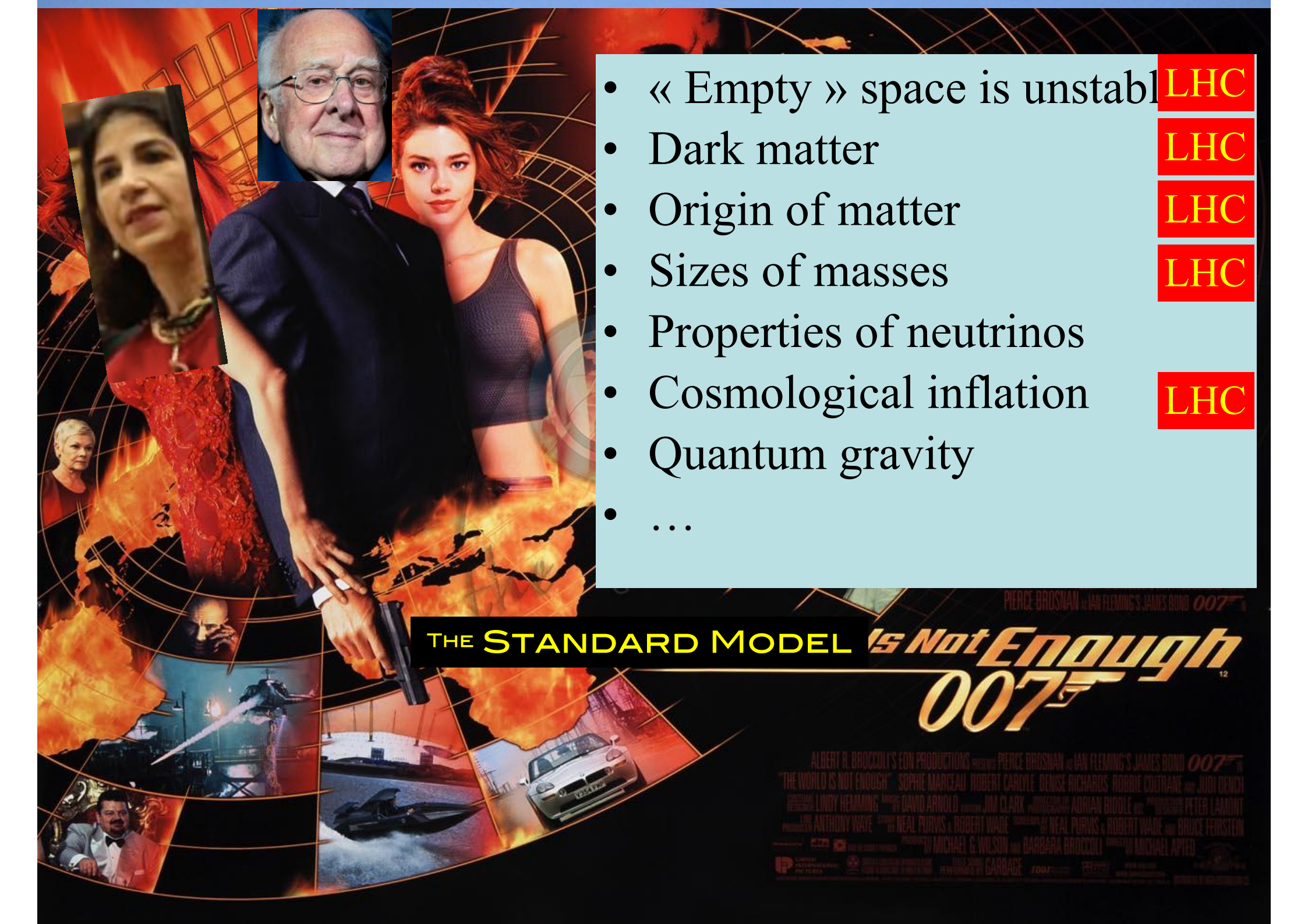
http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[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

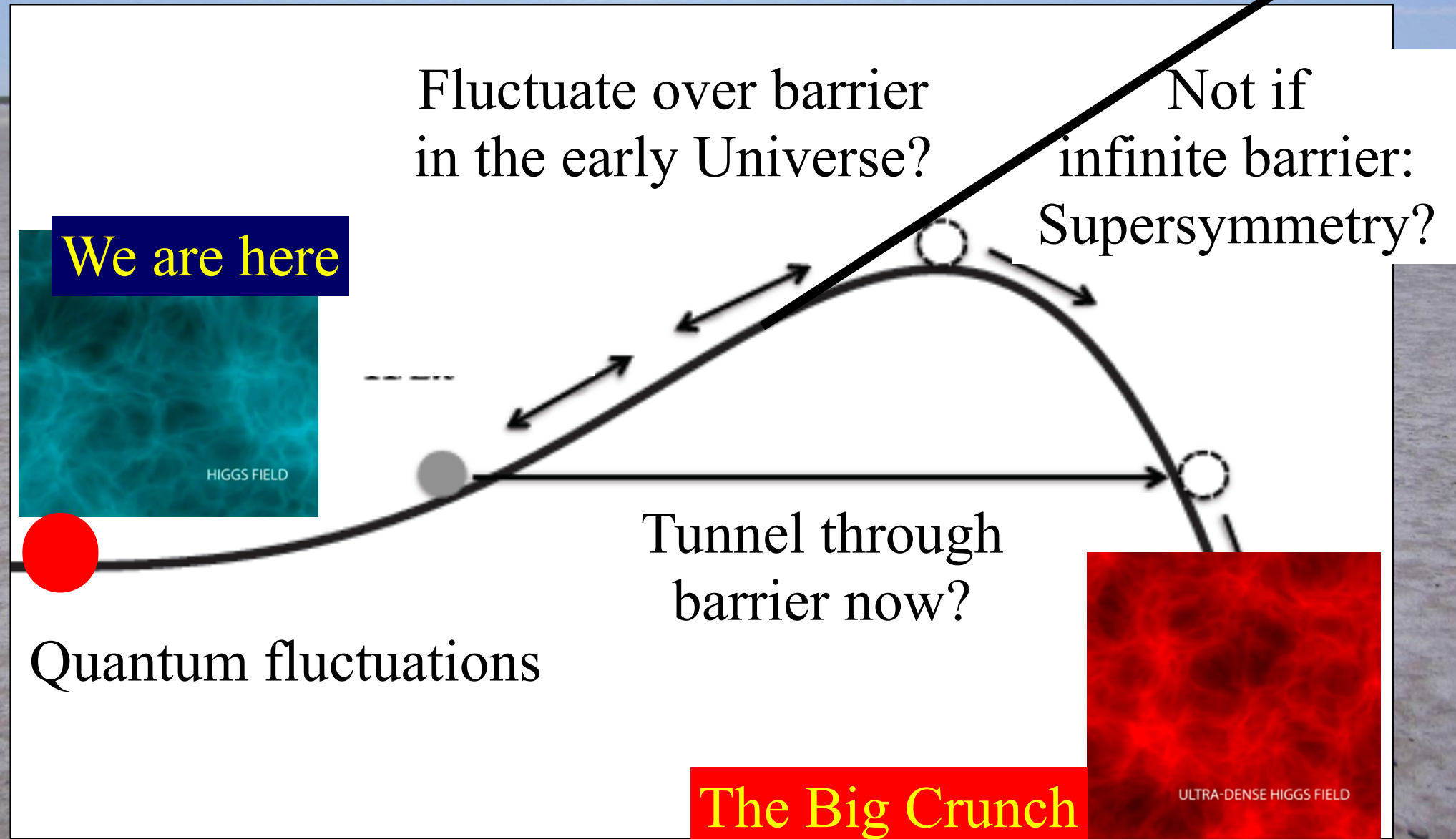
Its existence is a big deal!

- 
- « Empty » space is unstable **LHC**
 - Dark matter **LHC**
 - Origin of matter **LHC**
 - Sizes of masses **LHC**
 - Properties of neutrinos
 - Cosmological inflation **LHC**
 - Quantum gravity
 - ...

THE STANDARD MODEL *Is Not Enough*
007[™]

ALBERT R. BROCCOLI'S EDN 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
SCREENPLAY BY LINDY HEMMING MUSIC BY DAVID ARNOLD EDITOR JIM CLARK PRODUCTION DESIGNER ADRIAN BIDDLE COSTUME DESIGNER PETER LAMONT
EXECUTIVE PRODUCERS ANTHONY WAVE PRODUCED BY NEAL PURVIS & ROBERT WADE DIRECTED BY NEAL PURVIS & ROBERT WADE PRODUCED BY MICHAEL G. WILSON AND BARBARA BROCCOLI
PRODUCED BY MICHAEL G. WILSON AND BARBARA BROCCOLI DIRECTED BY MICHAEL APTED
CASTING BY JILL HARRIS
COSTUME DESIGNER PETER LAMONT
PRODUCTION DESIGNER ADRIAN BIDDLE
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DIRECTED BY MICHAEL APTED

Should it have Collapsed already?



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?**



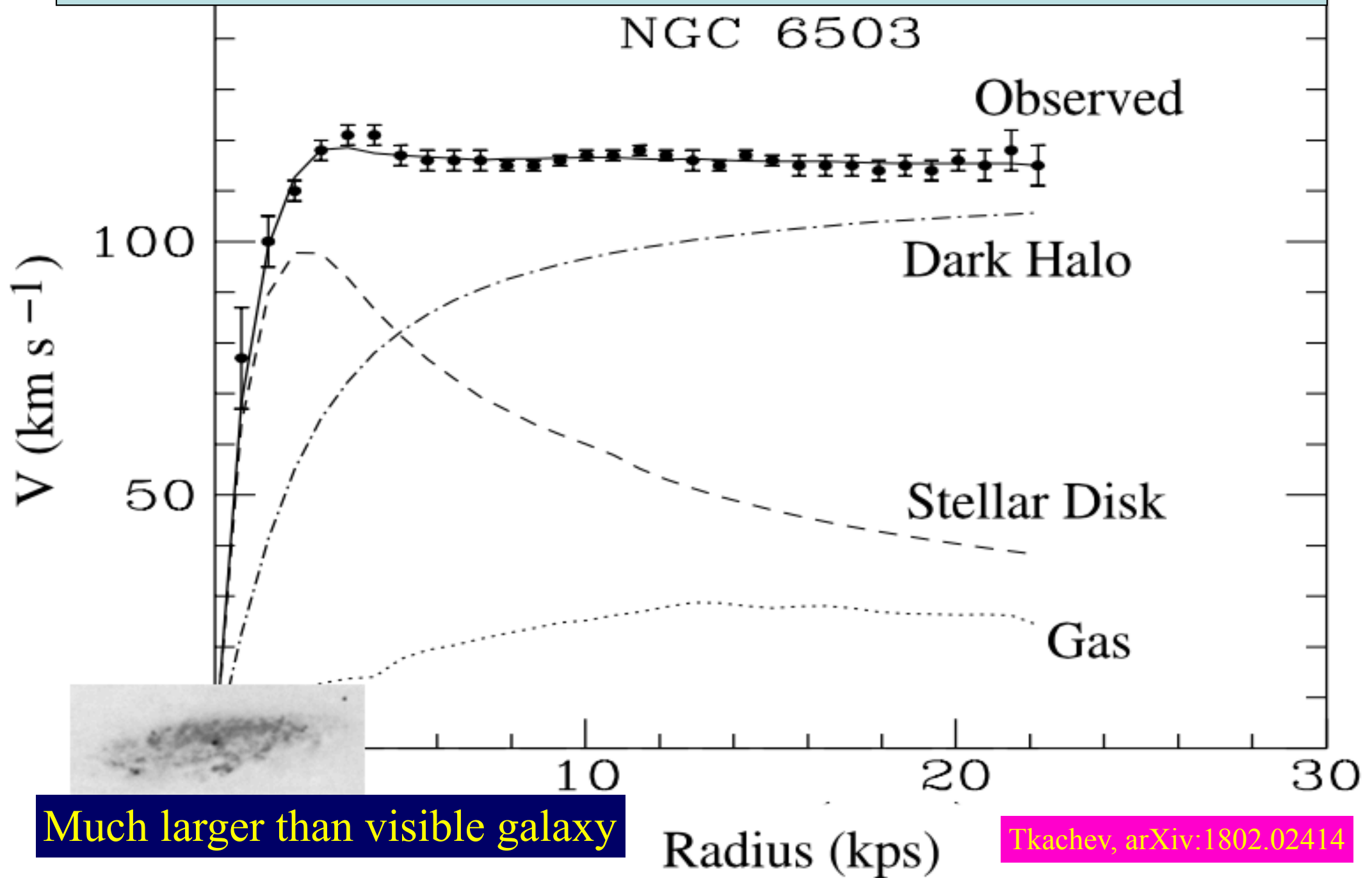
The Rotation Curves of Galaxies

- 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**
- Also:
 - Structure formation, cosmic background radiation, ...



Scanned at the American
Institute of Physics

Sample Rotation Curve: NGC 6503

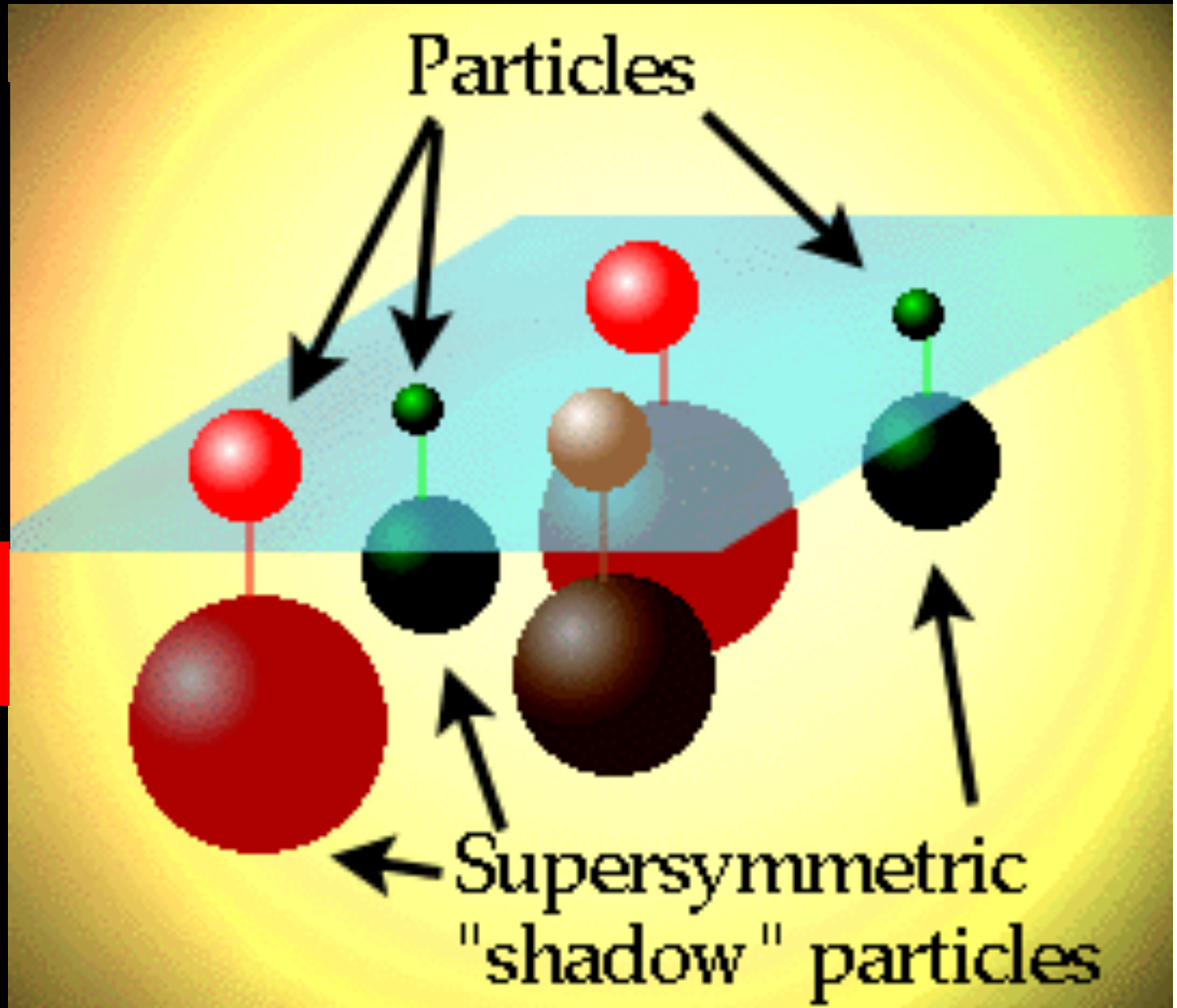


What is the Dark Matter in the Universe?

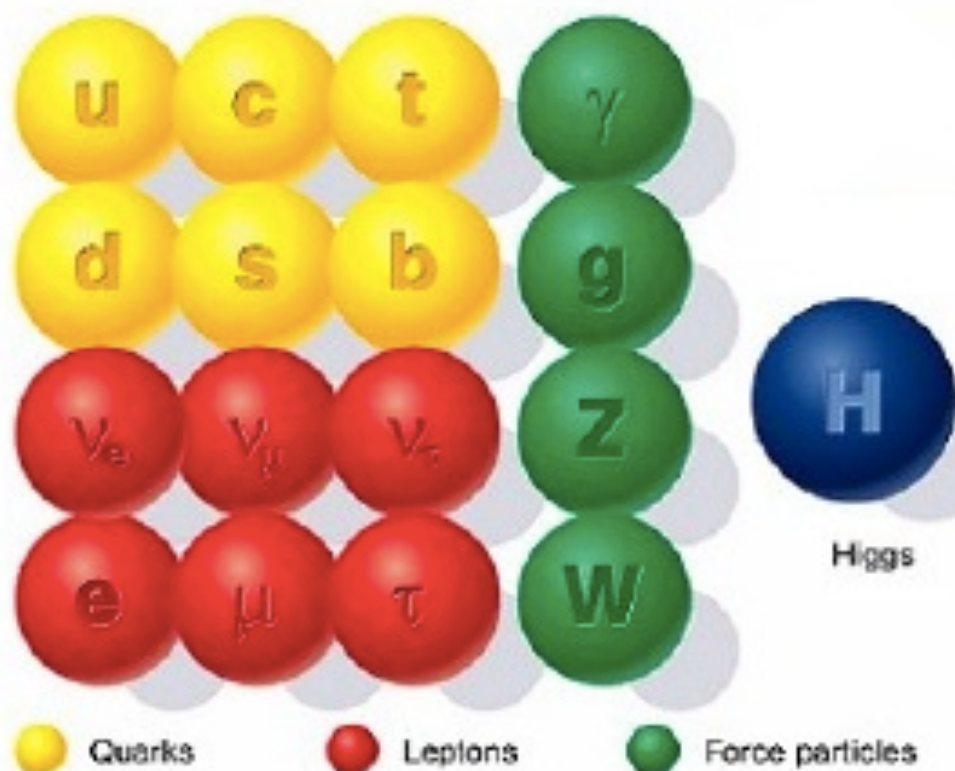
Astronomers say
that most of the
matter in the
Universe is
invisible
Dark Matter

Made of unknown
particles?

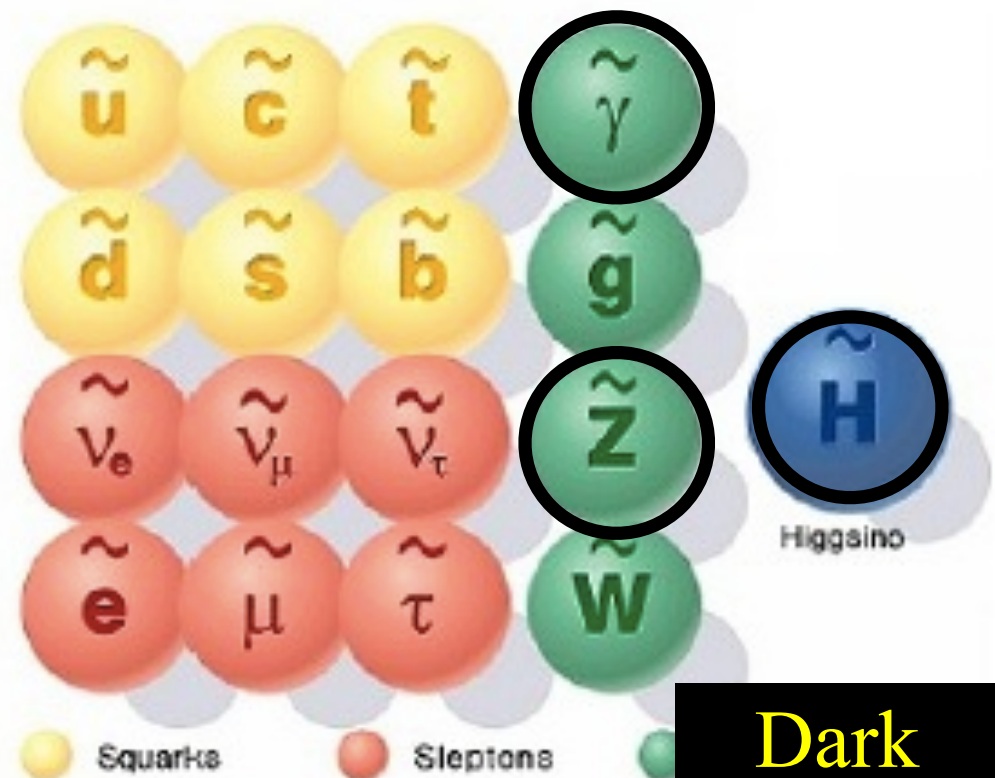
We are
searching for
them at the
LHC



Minimal Supersymmetric Extension of the Standard Model



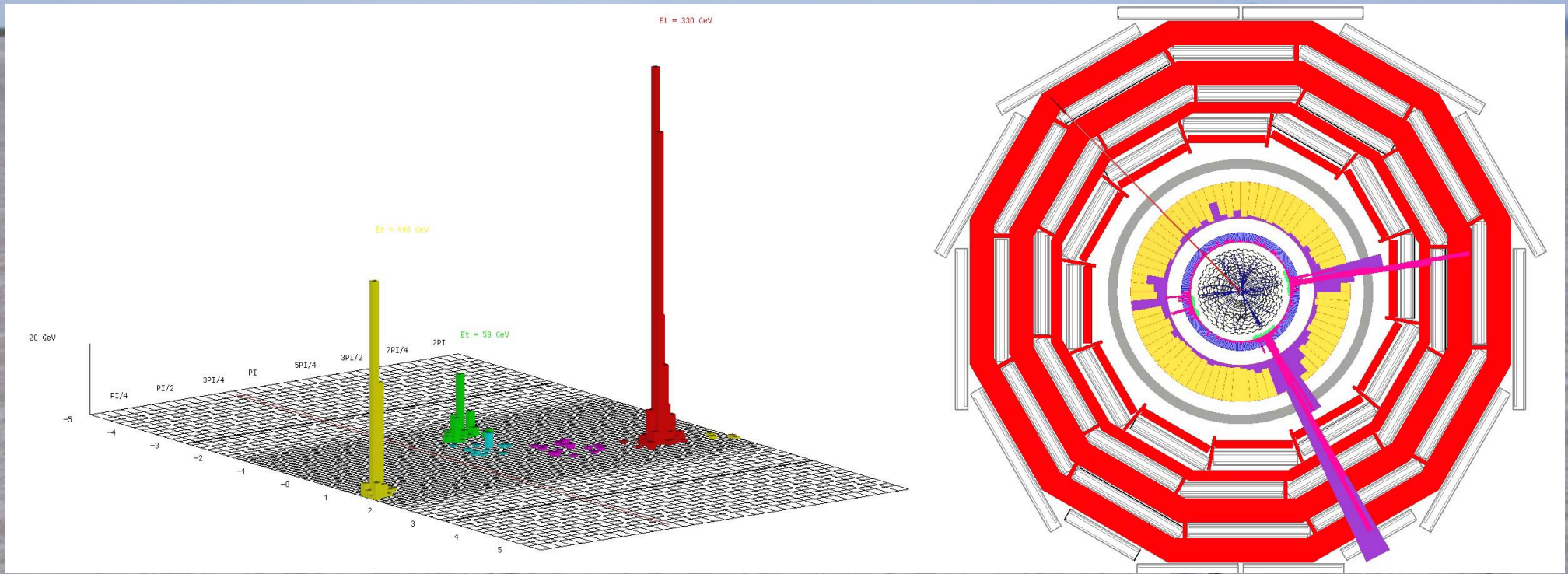
Standard particles



SUSY particles

**Dark
Matter?**

Classic Dark Matter Signature

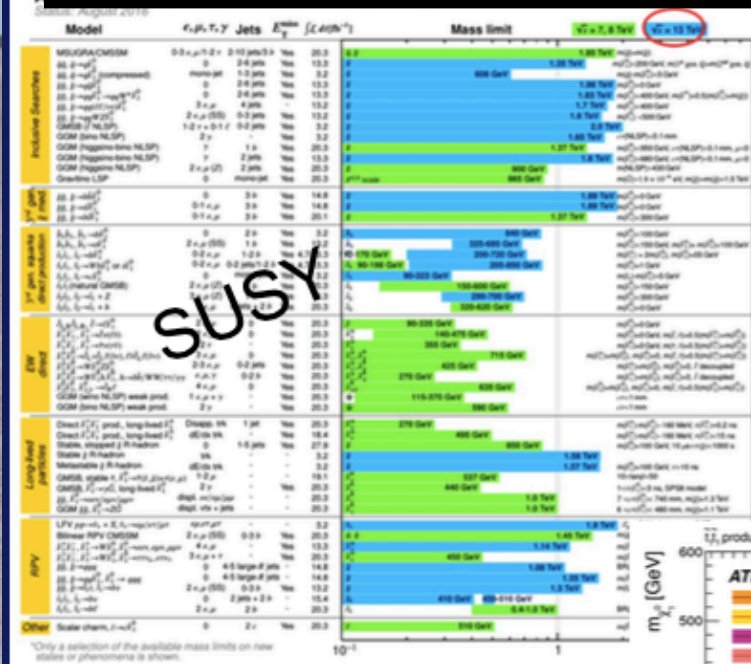


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

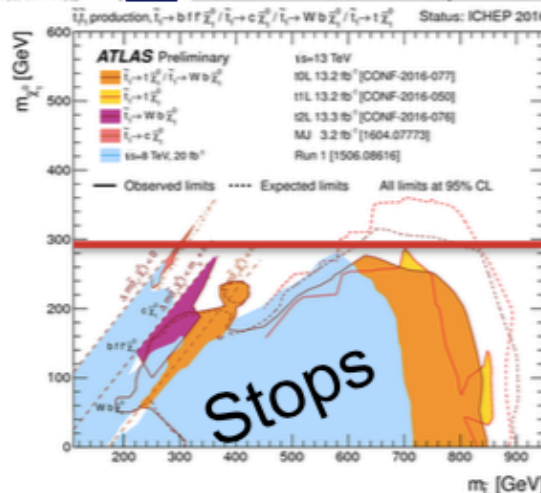
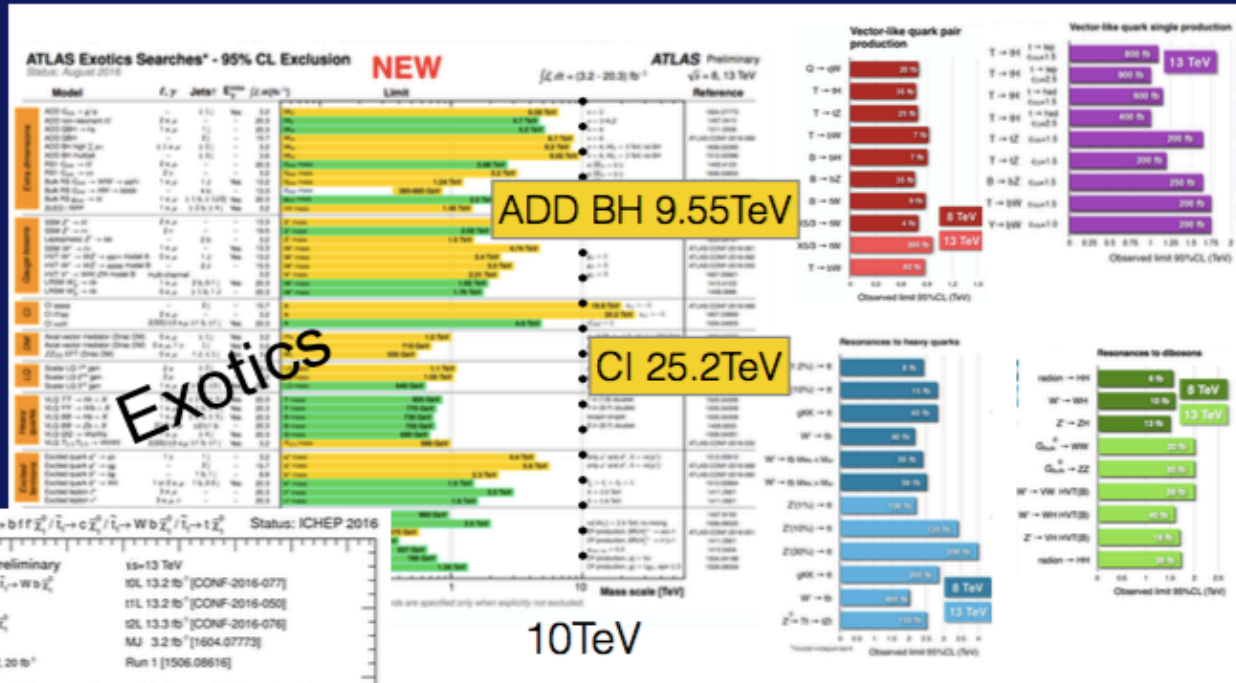
No supersymmetry

Nothing else, either



SUSY

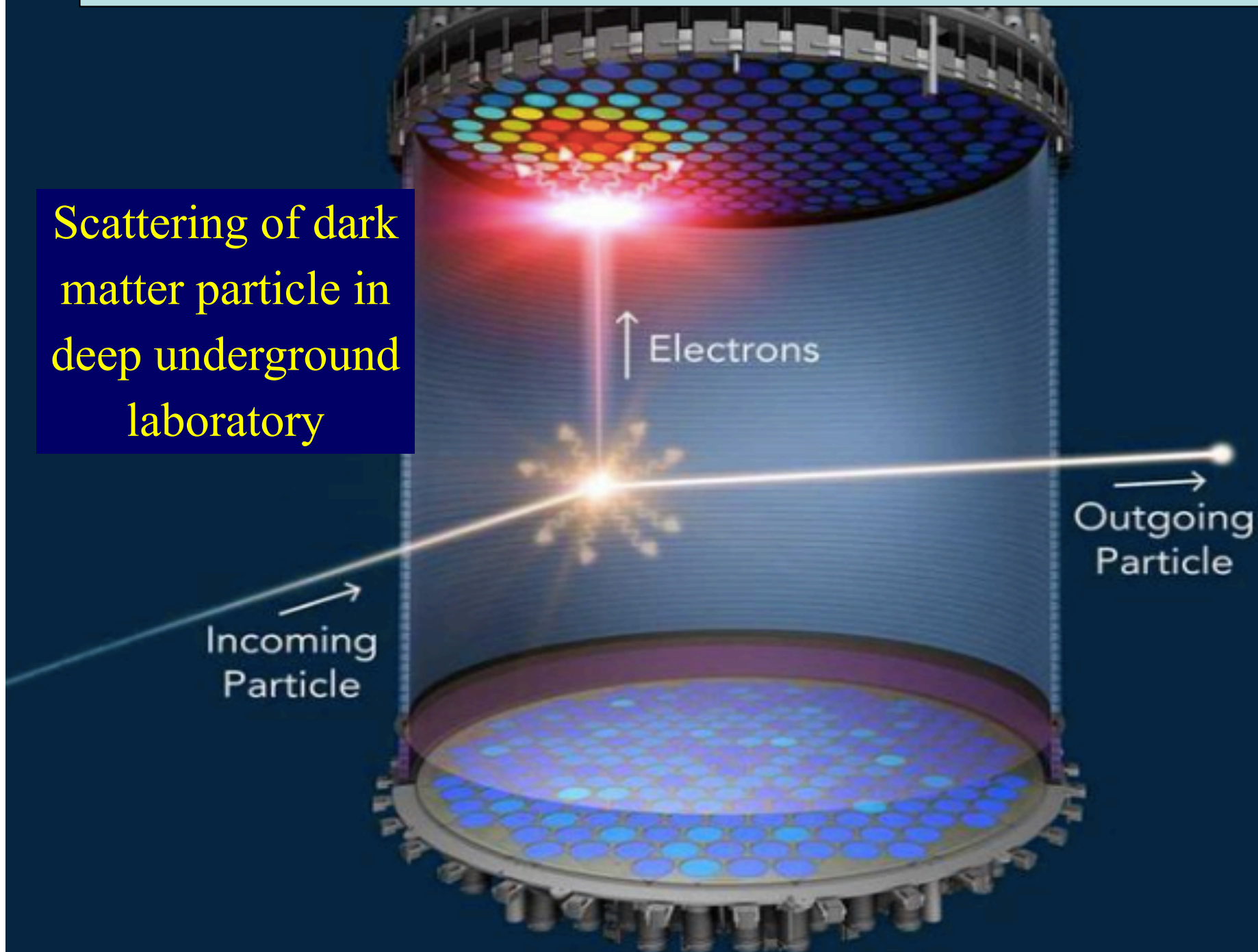
Exotics



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

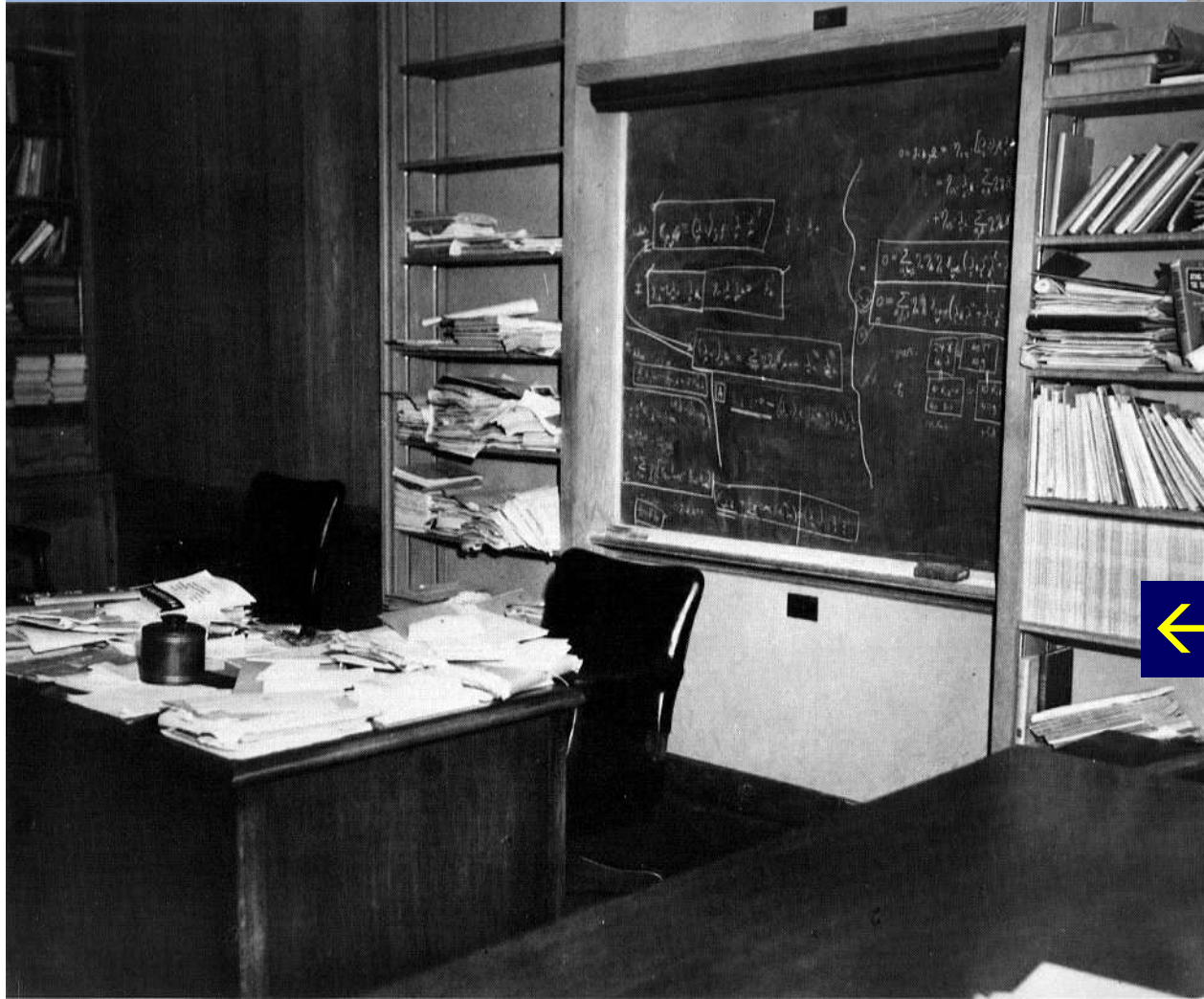


Matter and antimatter not quite equal and opposite: WHY?

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?

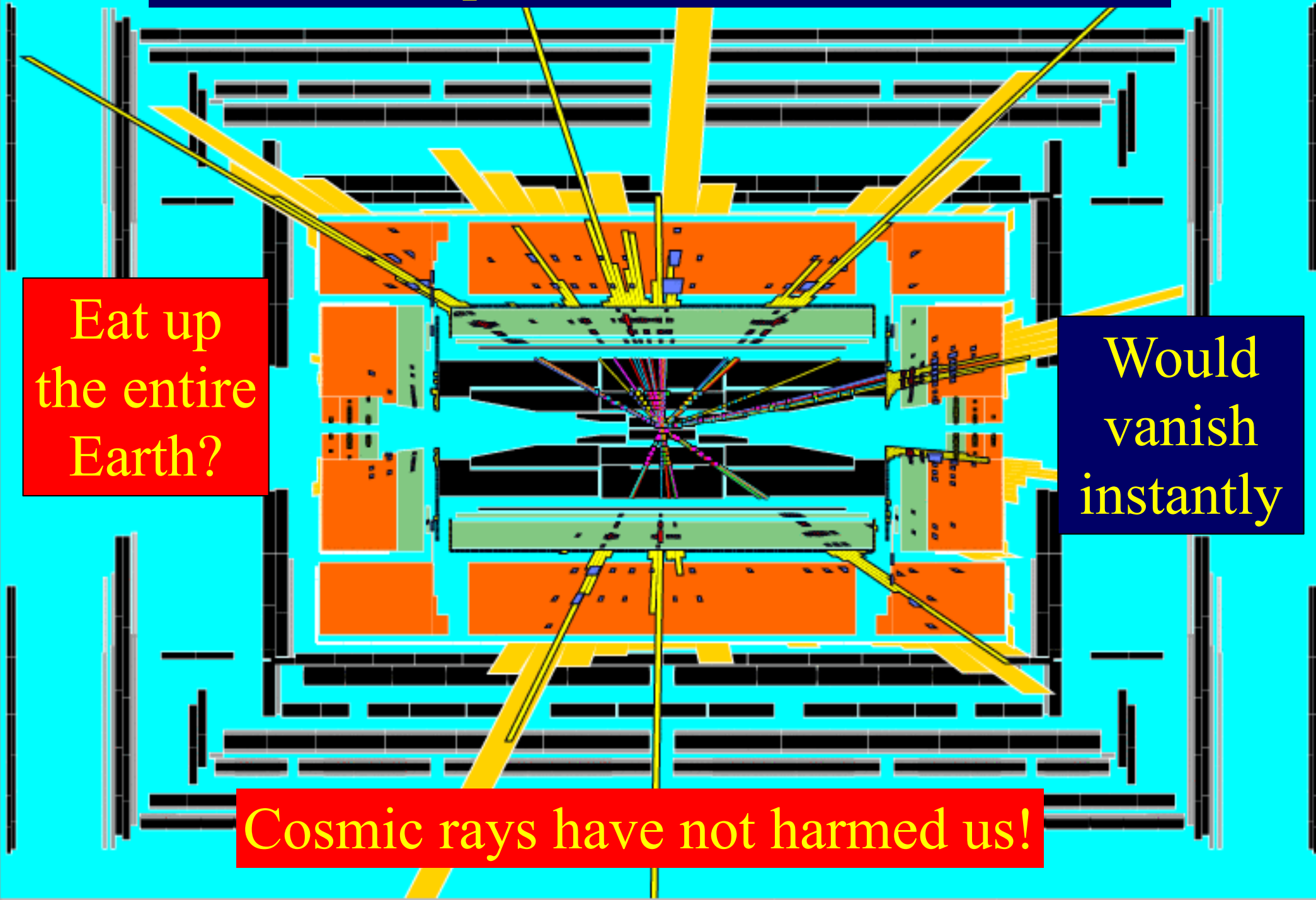


Will LHC experiments create black holes?

Eat up
the entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!



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

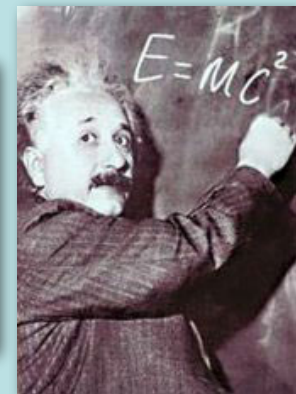


... and also a telescope
addressing Gauguin's
questions

The Missions of CERN

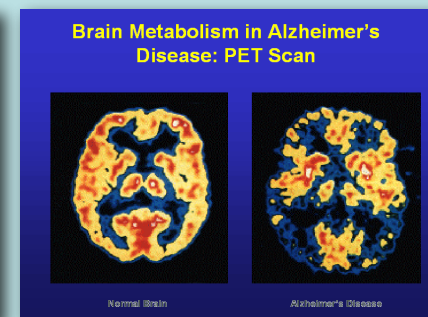
❑ **Push forward** the frontiers of knowledge

E.g. the secrets of the Big Bang ...what was the matter like within the first moments of the Universe's existence?

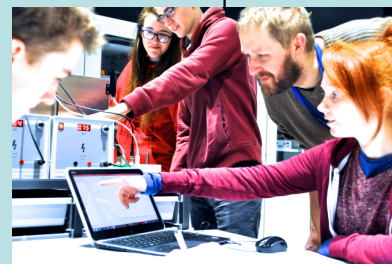


❑ **Develop new technologies** for accelerators and detectors

Information technology - the Web and the GRID
Medicine - diagnosis and therapy



❑ **Train scientists and engineers** of tomorrow



❑ **Unite people** from different countries and cultures



CERN: where the World-Wide Web was born 30 years ago

Where would we be today without the WWW?

Communications
Commerce
Entertainment

Tim Berners-Lee

Invented so that physicists could share their data

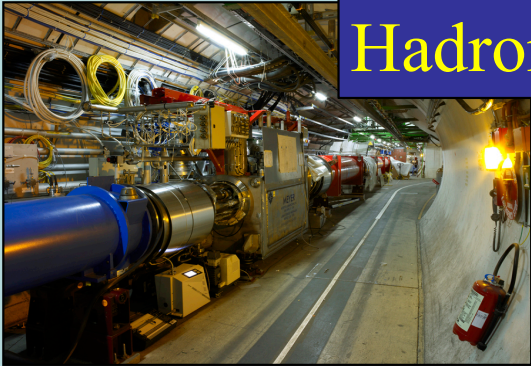
What would we do without the WWW?

- In the time of CoViD-19:
 - Communication
 - News
 - Scientific results
 - Videoconferences: Zoom, Skype, ...
 - Social networks: Facebook, Twitter, ...
 - Business:
 - Home working, online shopping, ...
 - Entertainment
 - Music: Spotify, ...
 - Films: Netflix, ...

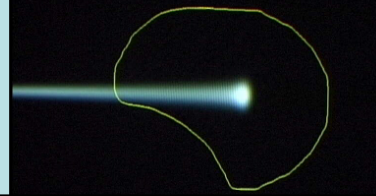


Medical Applications: Examples of Particle Physics Spin-off

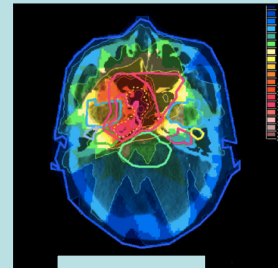
Hadron Therapy



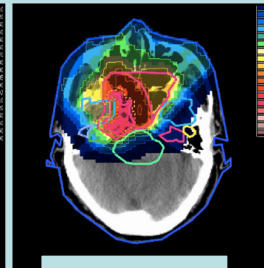
Tumour Target



Protons, light ions



X-ray



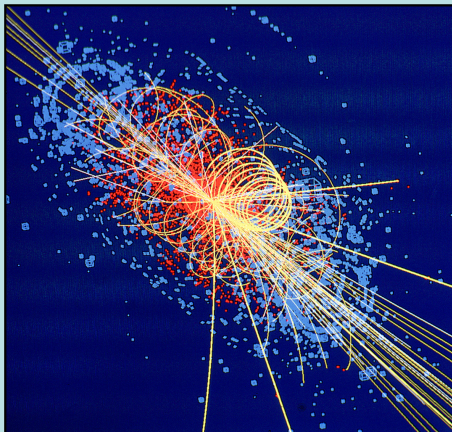
Protons

Leadership in ion beam therapy now in Europe and Japan

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

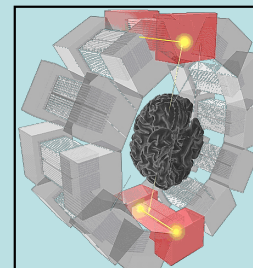
>100'000 patients treated worldwide (45 facilities)
>50'000 patients treated in Europe (14 facilities)

Medical imaging

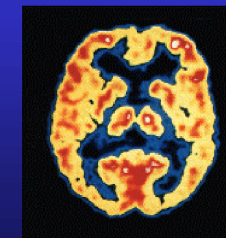


Detecting particles

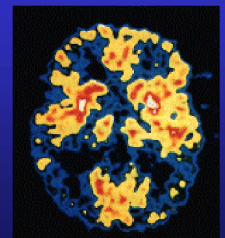
PET Scanner



Brain Metabolism in Alzheimer's Disease: PET Scan

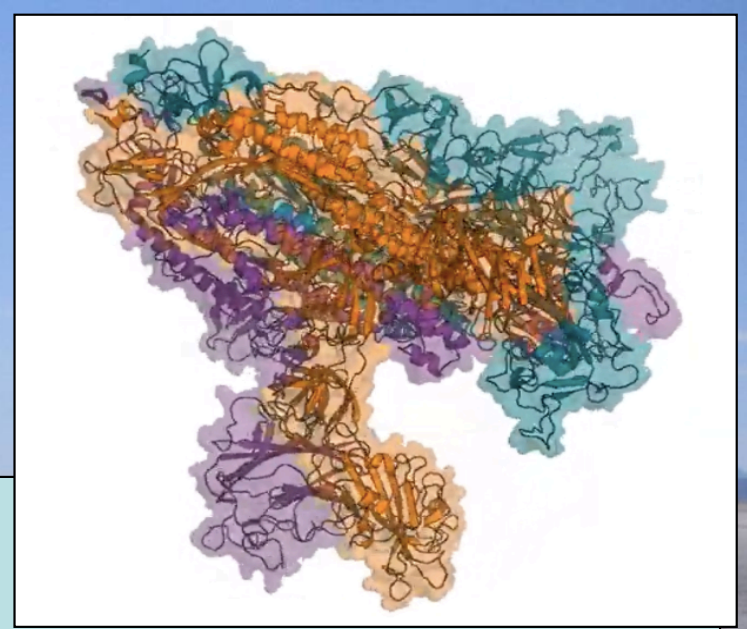


Normal Brain



Alzheimer's Disease

Analyzing Virus Protein Structure



- CERN was already contributing to Folding@Home
- Using worldwide computing Grid developed to analyze LHC data
- Contributed computing resources from LHC experiments
 - Among top 10 worldwide
 - 1M computing cores running millions of jobs per day

2022: UN International Year of **Basic Sciences for Development**

Economic & human development



Innovation



Technology



Applied science



Fundamental science