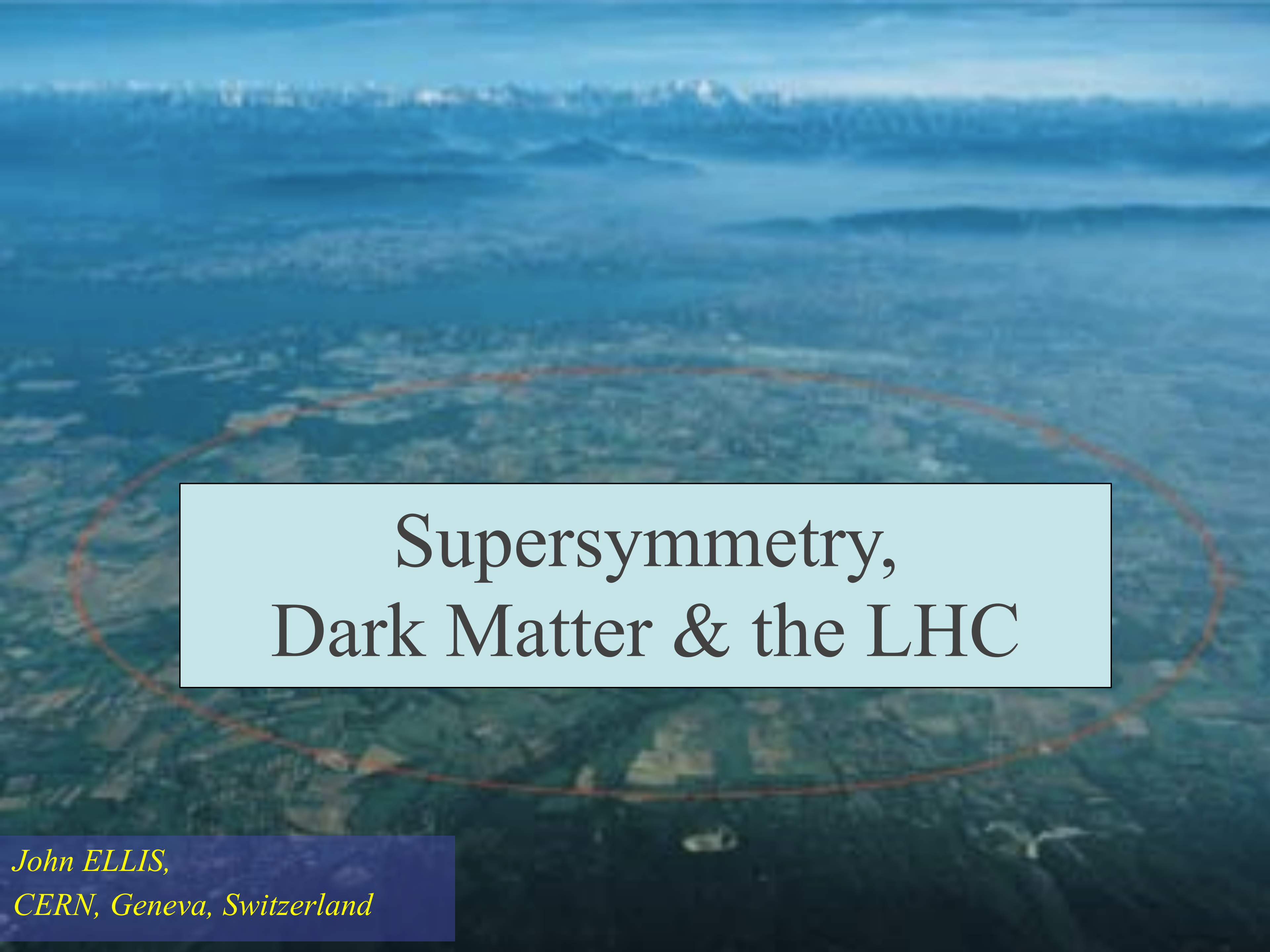


Supersymmetry, Dark Matter & the LHC

John ELLIS,
CERN, Geneva, Switzerland

Where do we come from?

What are we?

Where are we going?

Where do we come from?

What are we?

Where are we going?

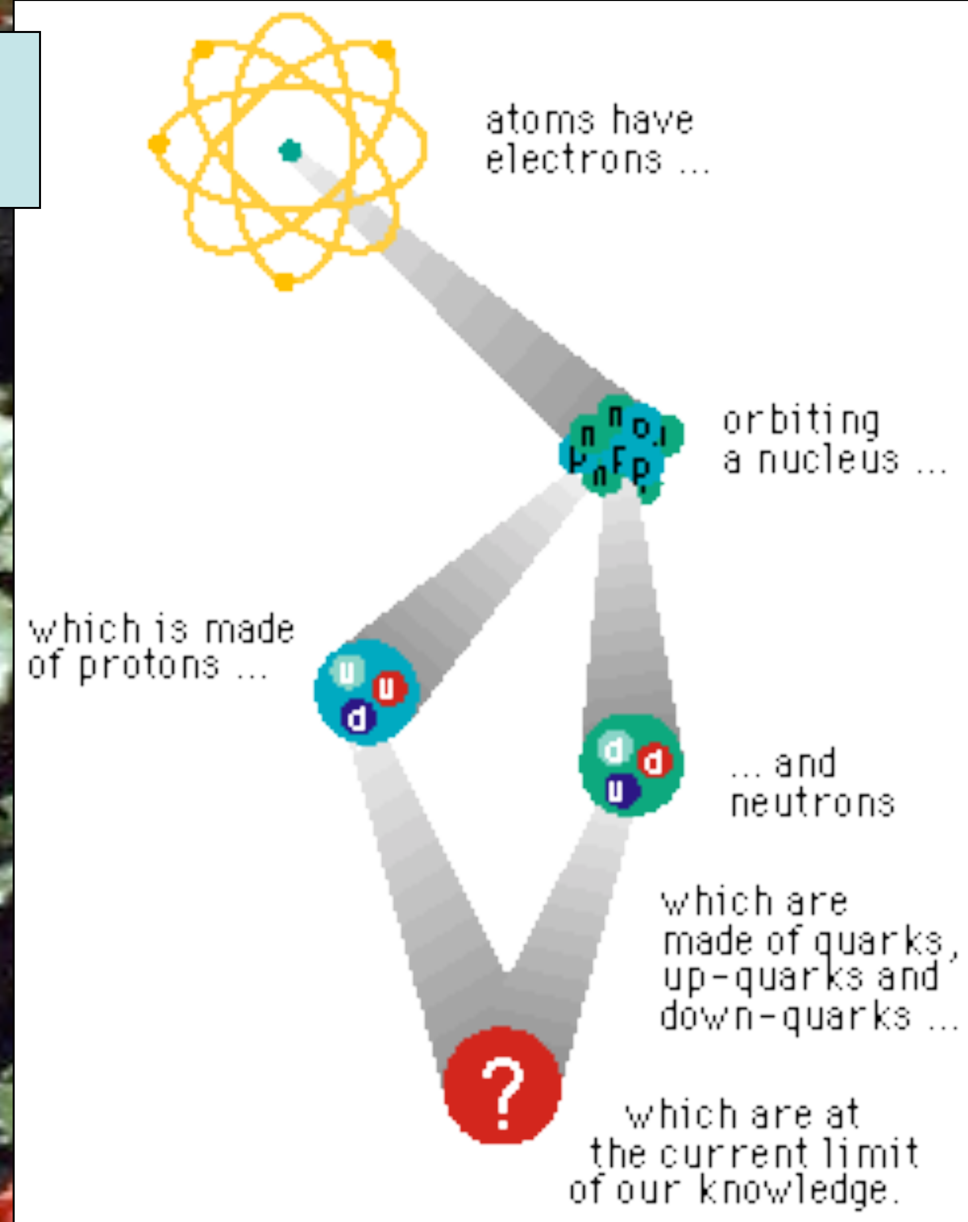
The aim of the Large Hadron Collider:

What is the Universe made of?

Inside Matter

All matter is made of the same constituents

Inside Matter



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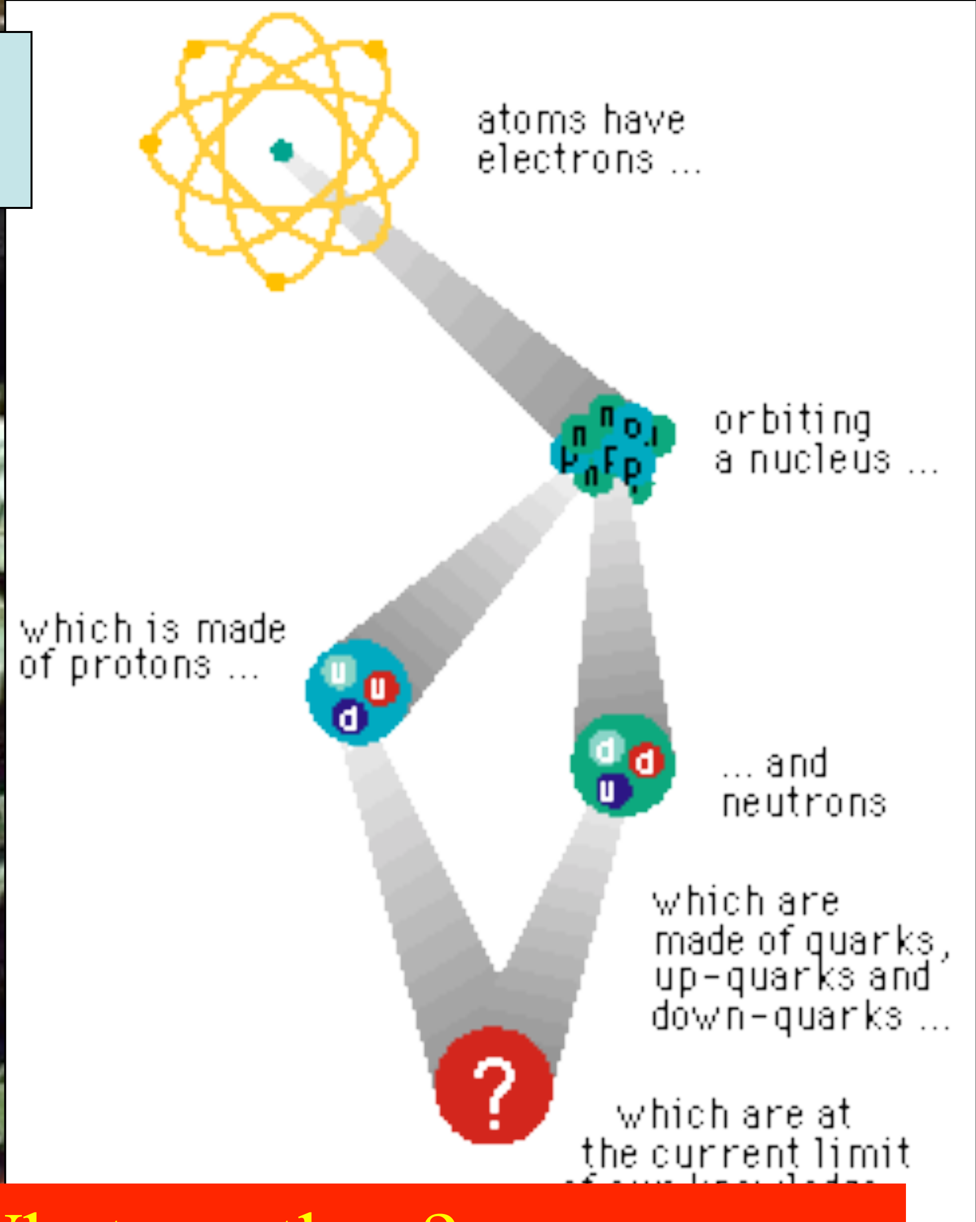
Inside Matter

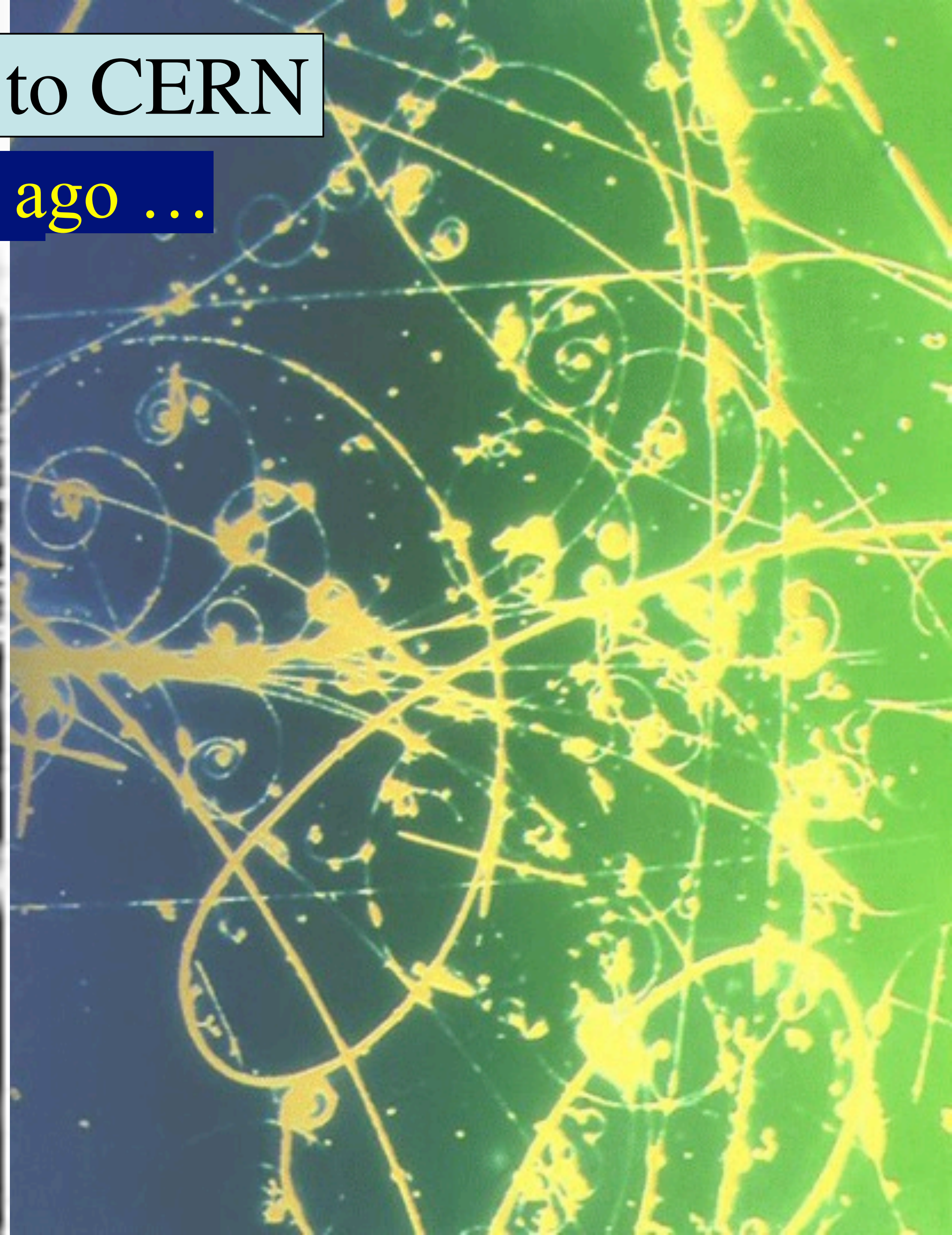


All matter is made of the same constituents

What are they?
What forces between them?

From Cosmic Rays to CERN

Discovered a century ago …



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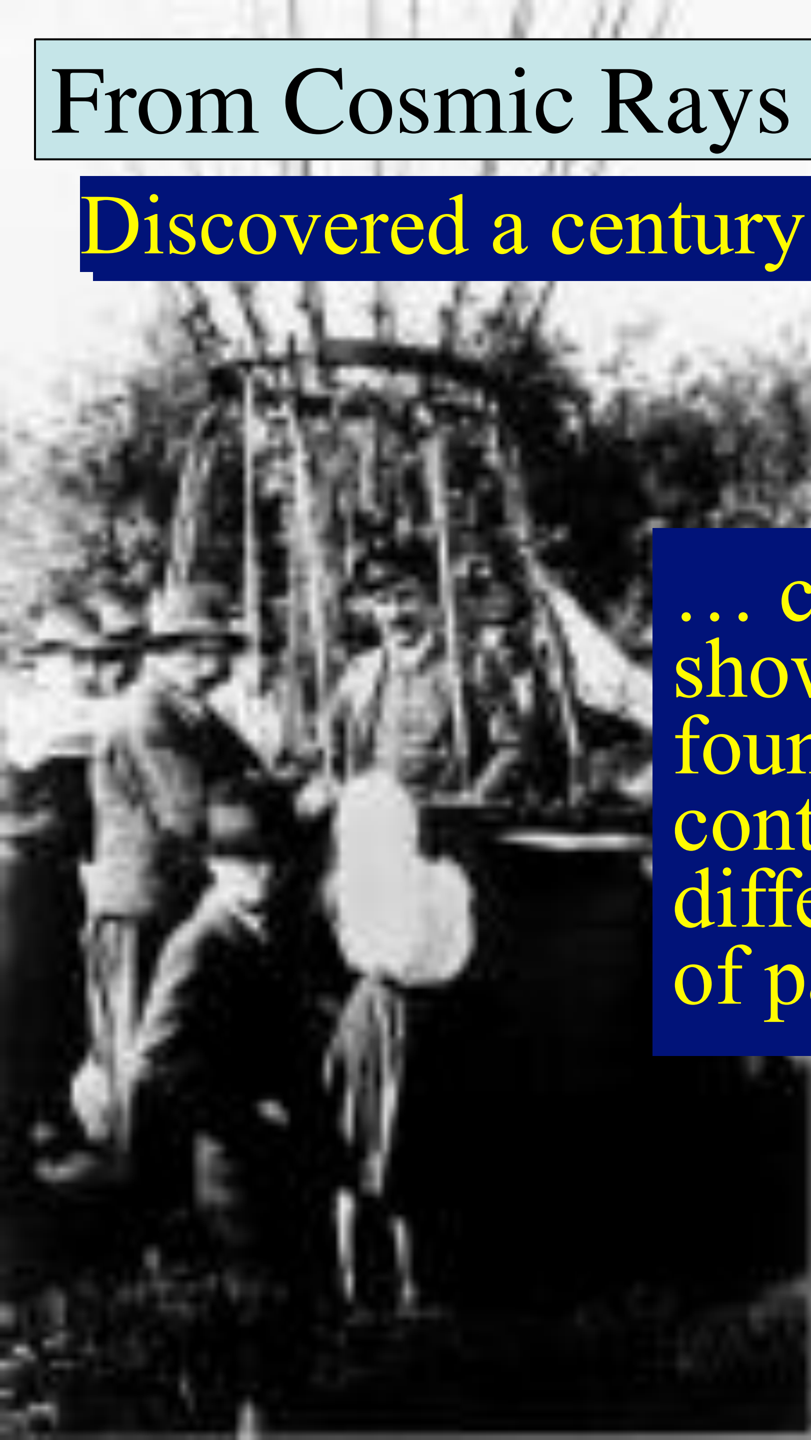

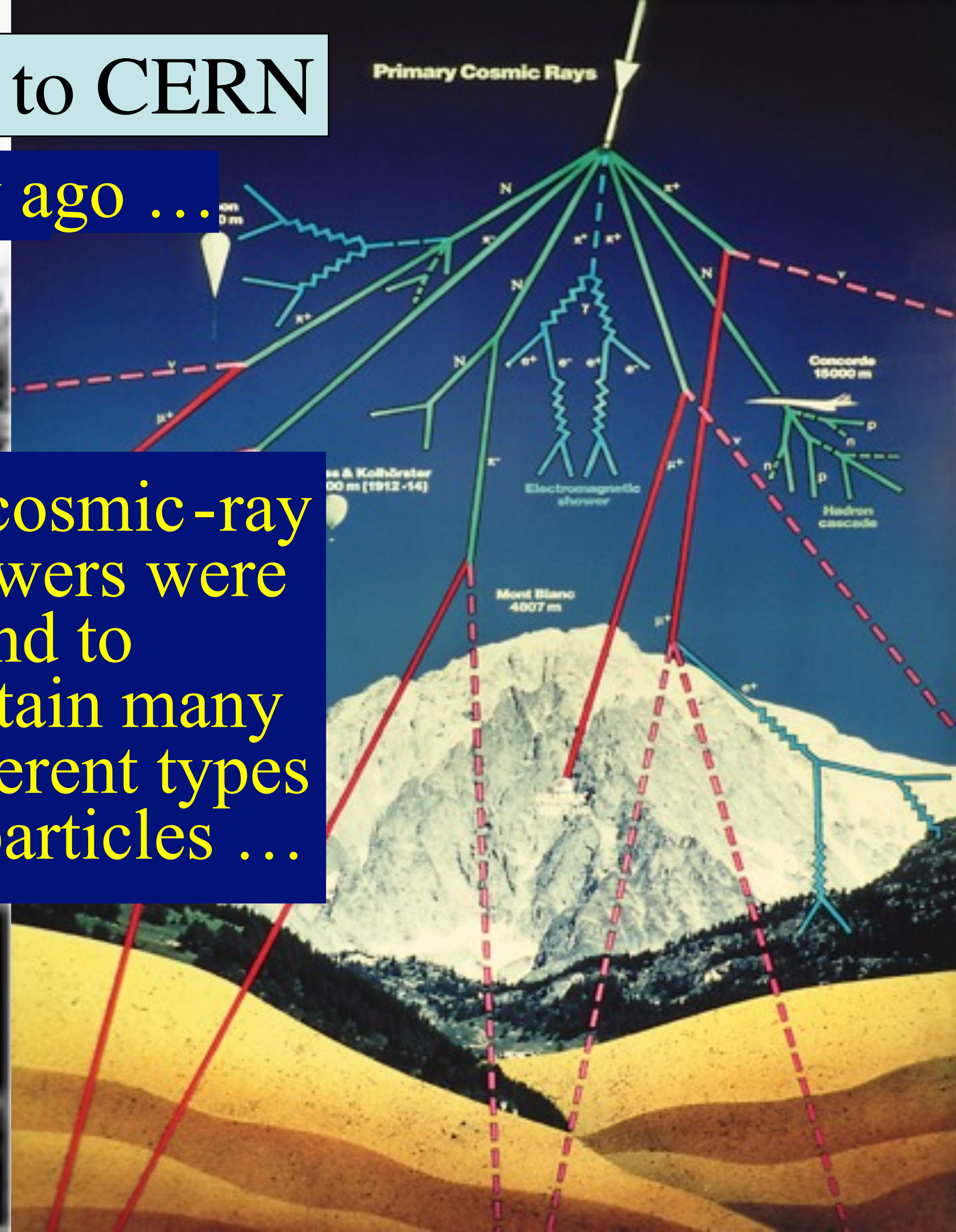

… cosmic-ray showers were found to contain many different types of particles …

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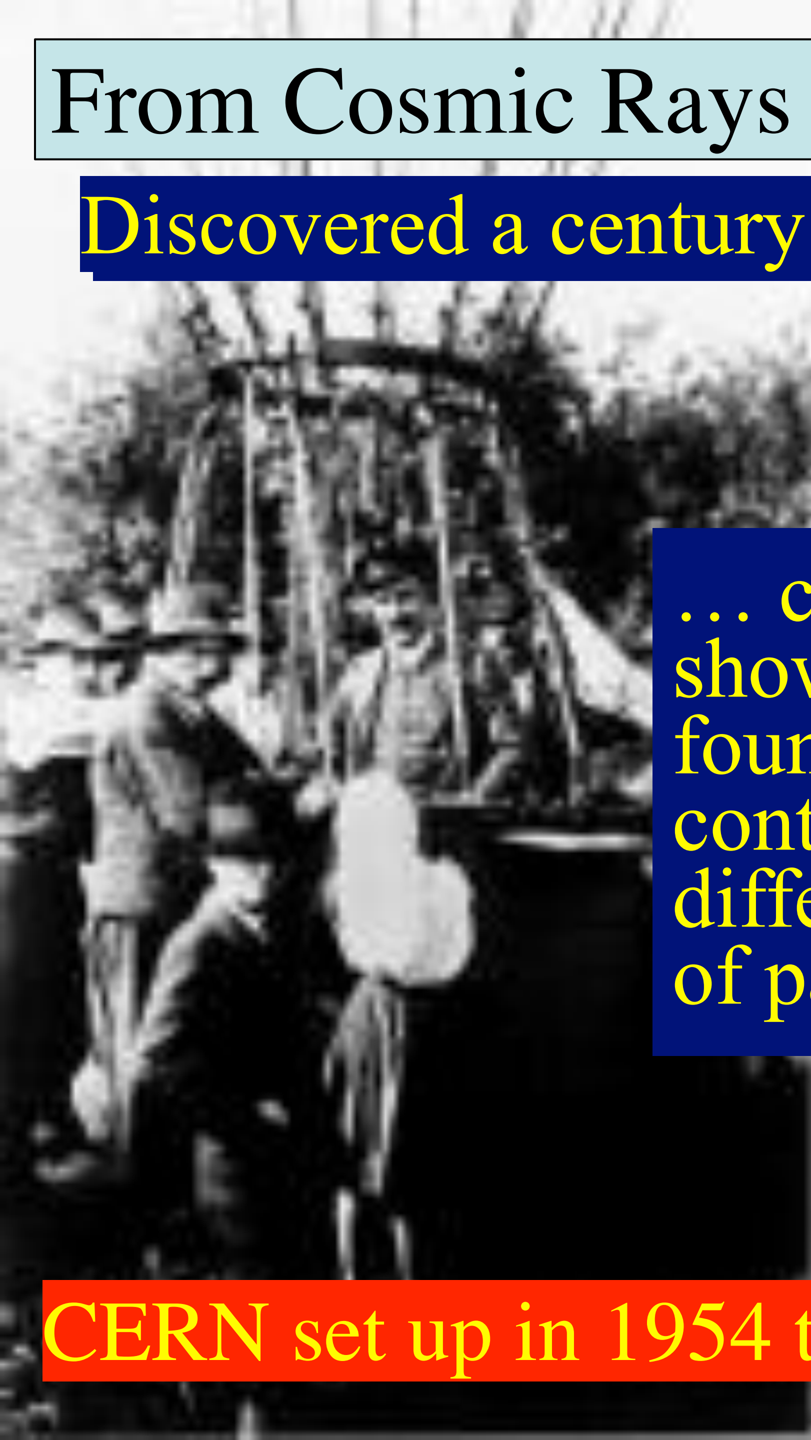

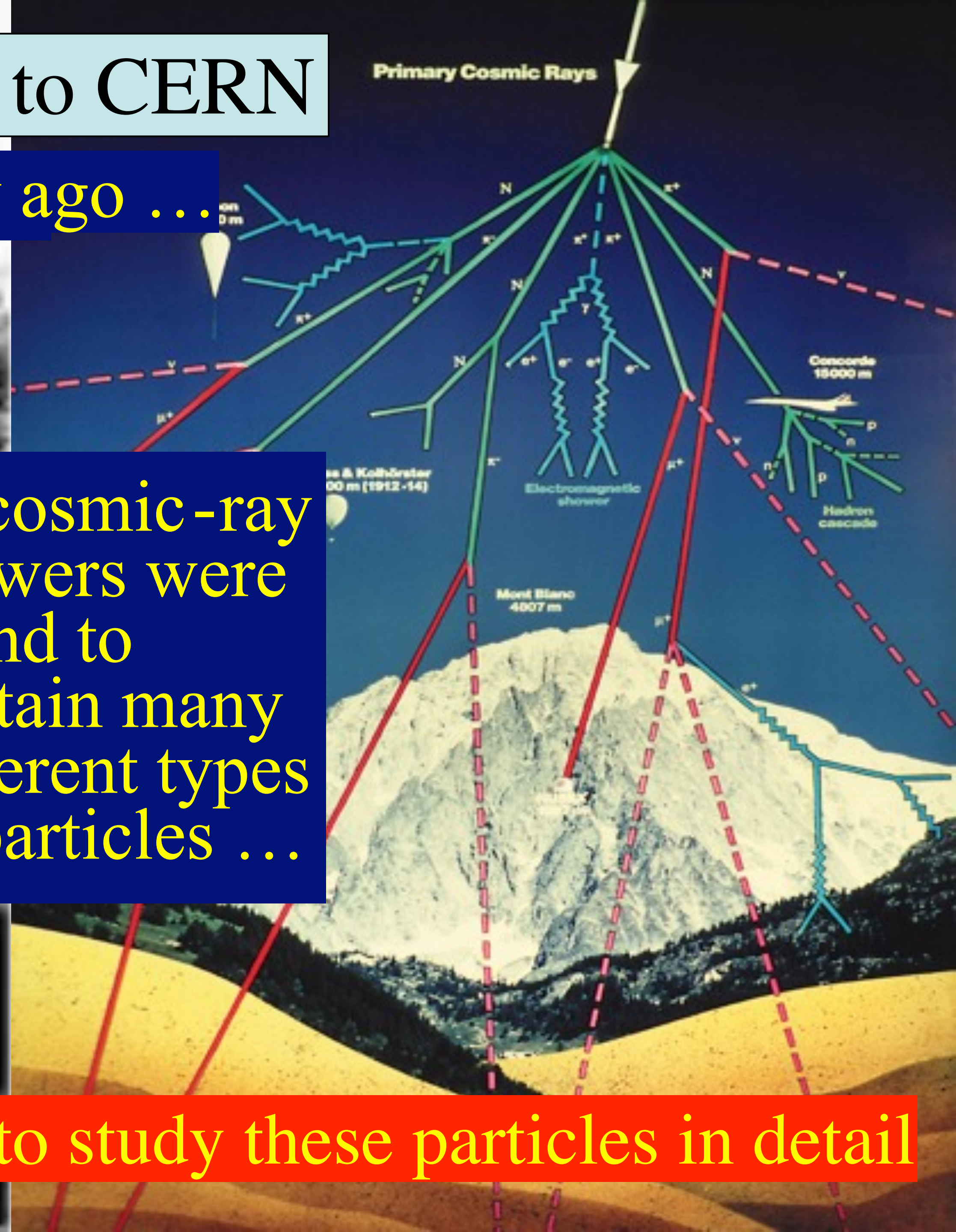

… cosmic-ray showers were found to contain many different types of particles …

CERN set up in 1954 to study these particles in detail

The ‘Standard Model’

The ‘Standard Model’

The matter particles

The ‘Standard Model’

The matter particles

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

The ‘Standard Model’

= Cosmic DNA

The matter particles

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Photon: the Particle of Light

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- Quantum hypothesis introduced by Planck:

$$E = hf$$

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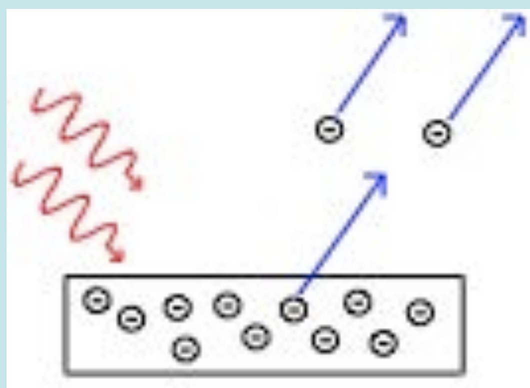

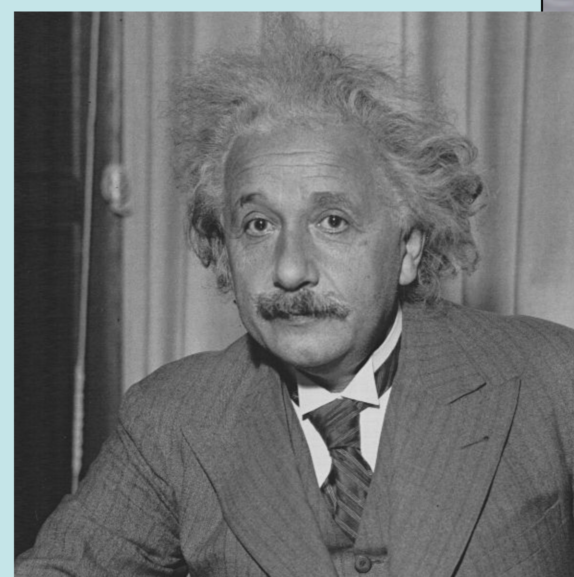

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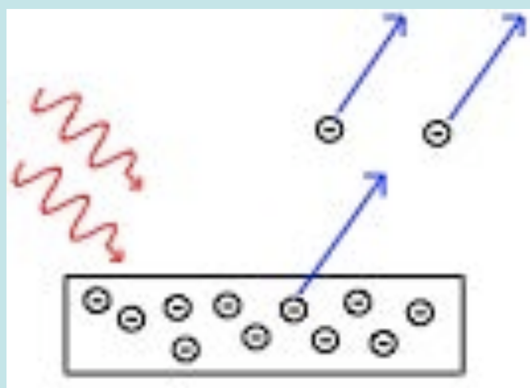

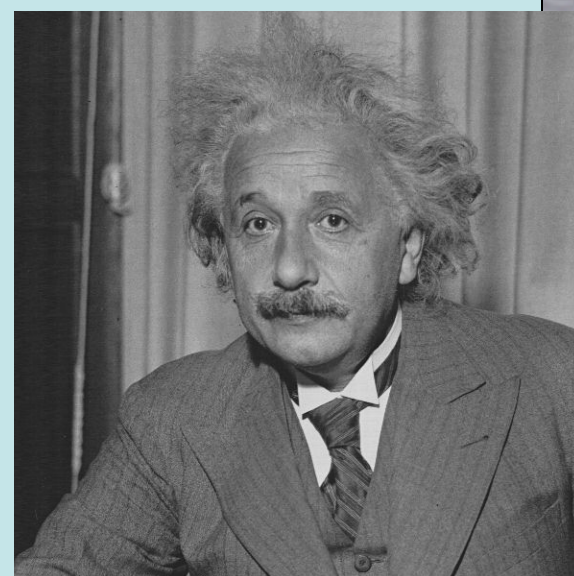

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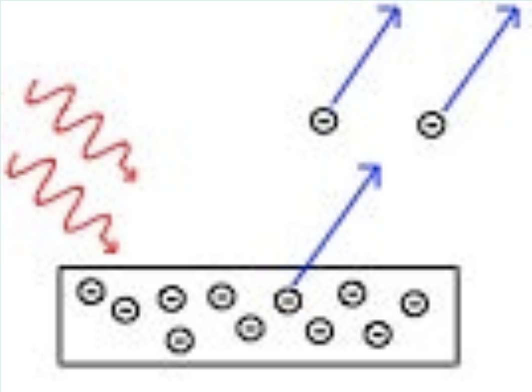

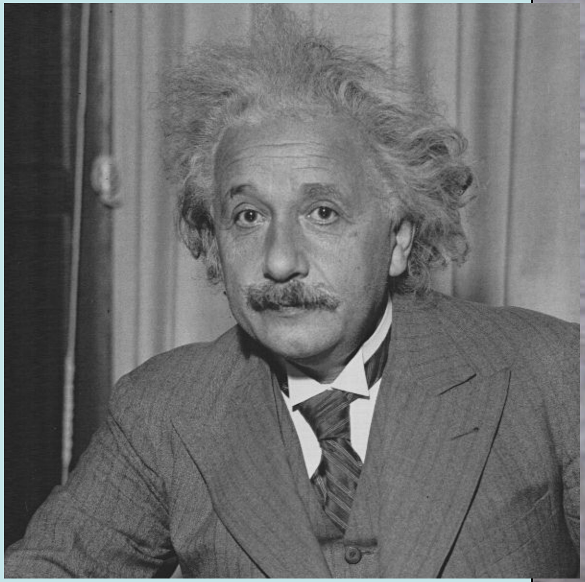

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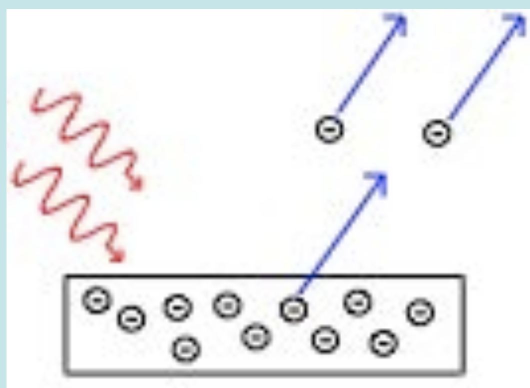

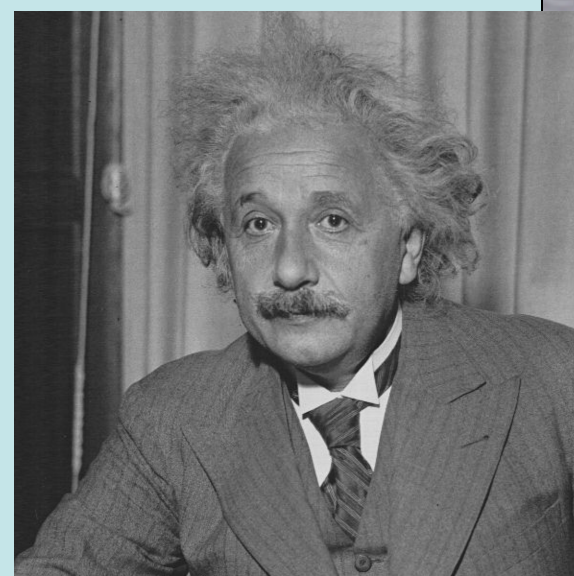

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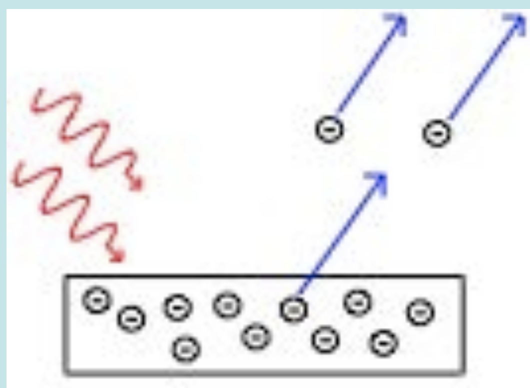

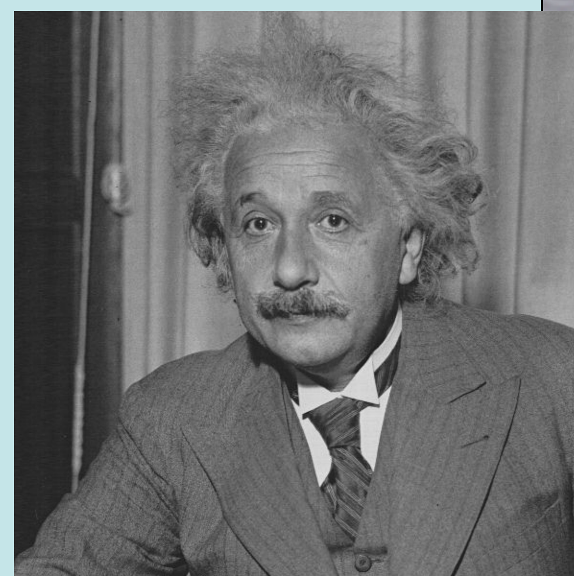

- **First force particle discovered**

Gluon: the Particle of the Strong

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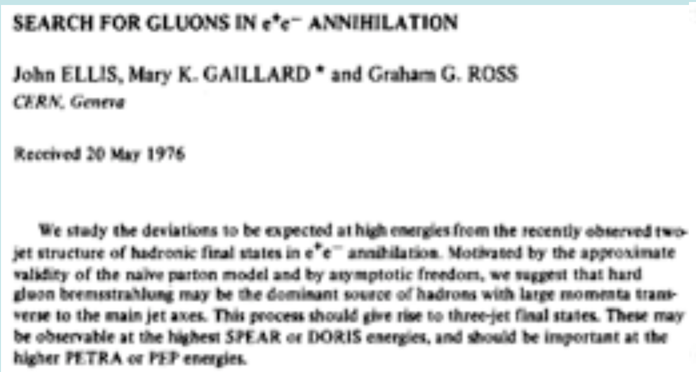

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John ELLIS, Mary K. GAILLARD * and Graham G. ROSS
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Received 20 May 1976

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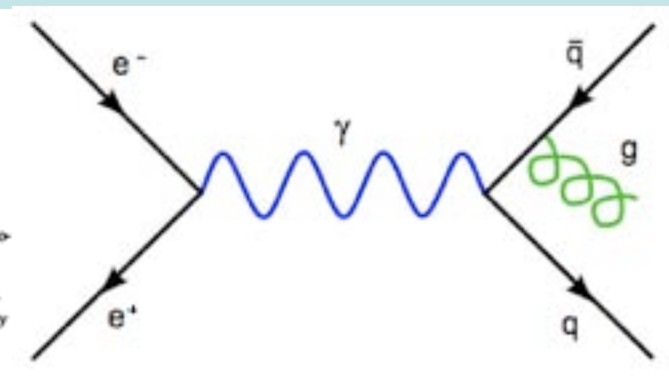

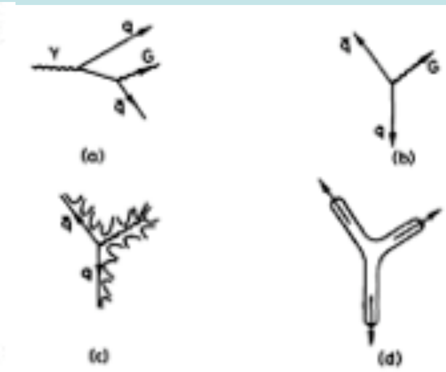

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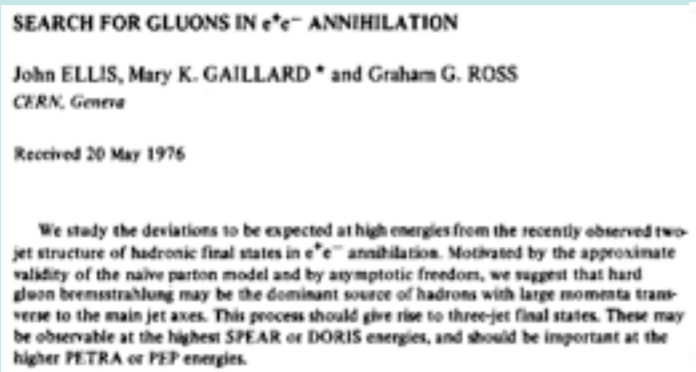

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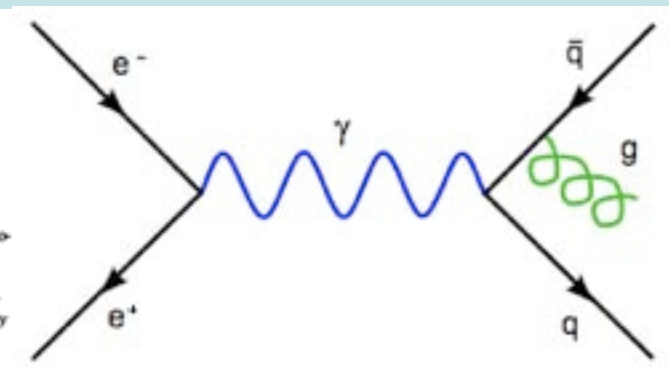

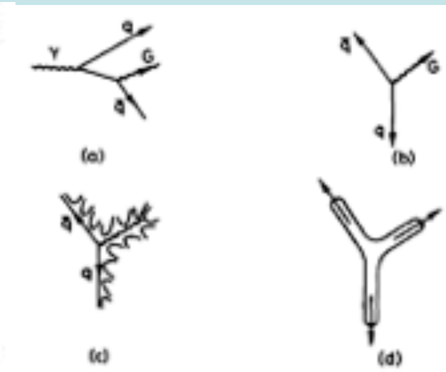

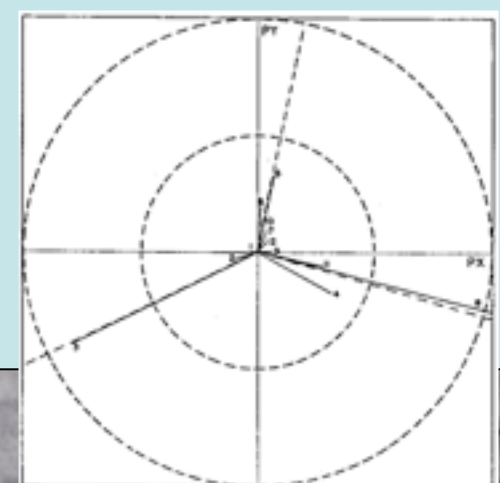

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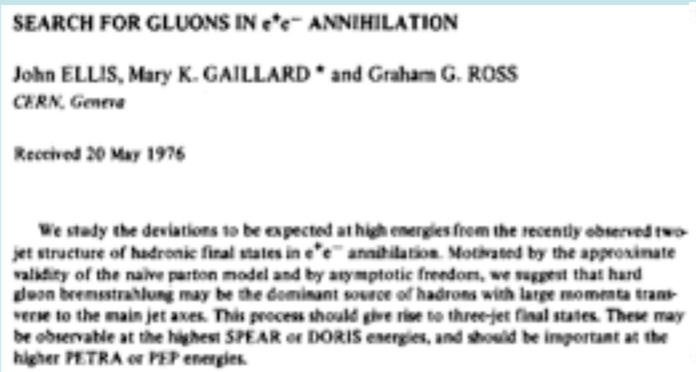

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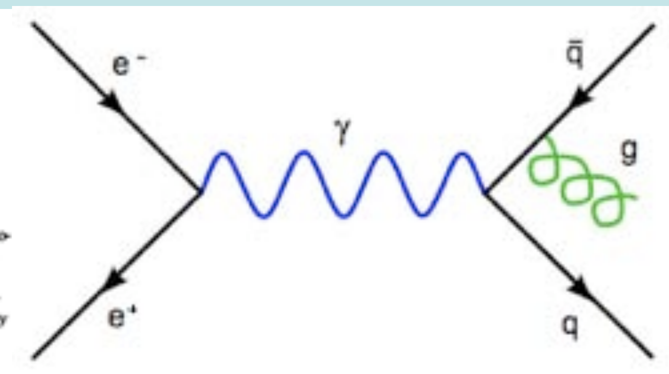

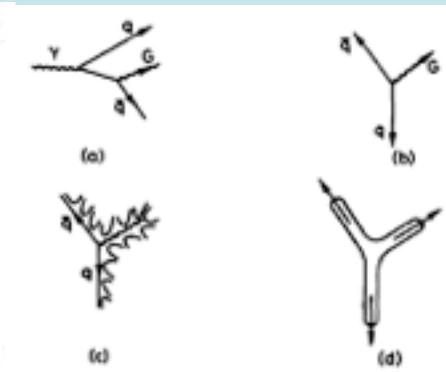

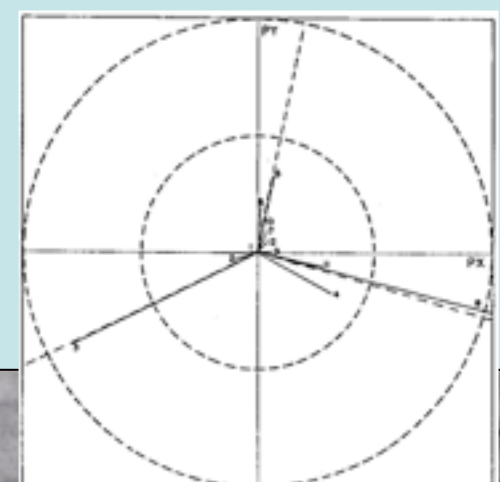

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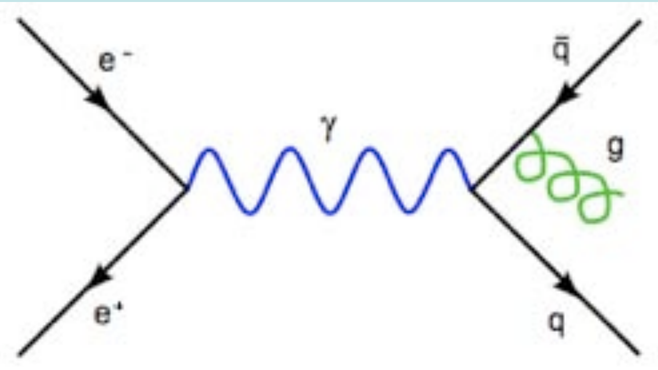
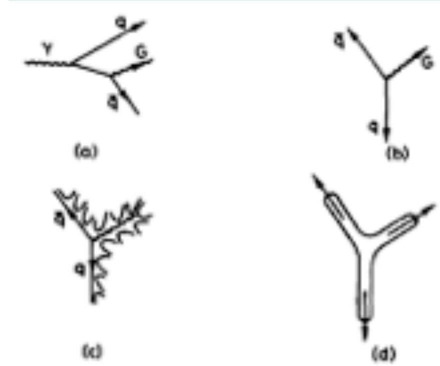
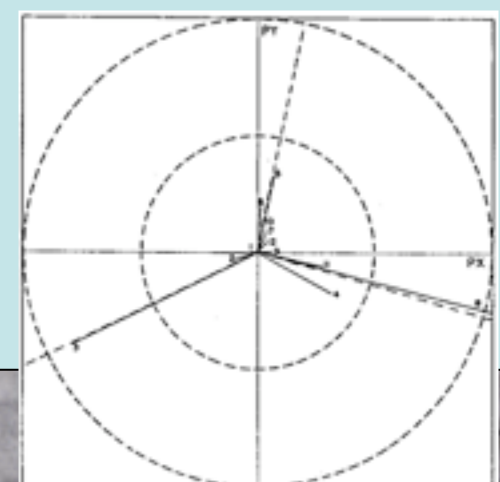




- Jets of hadrons produced by gluons observed at DESY (Hamburg) in 1979



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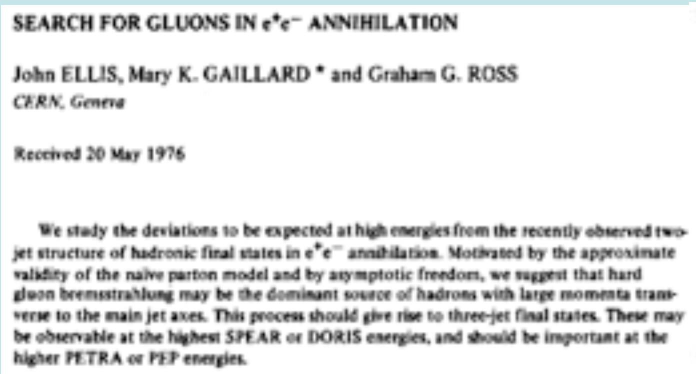

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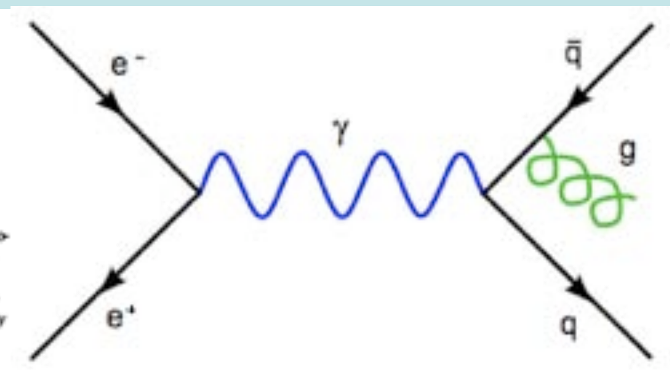

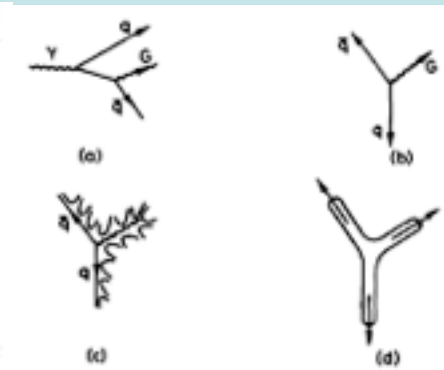

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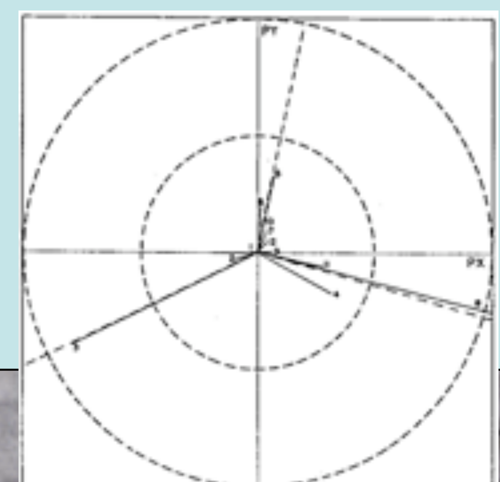


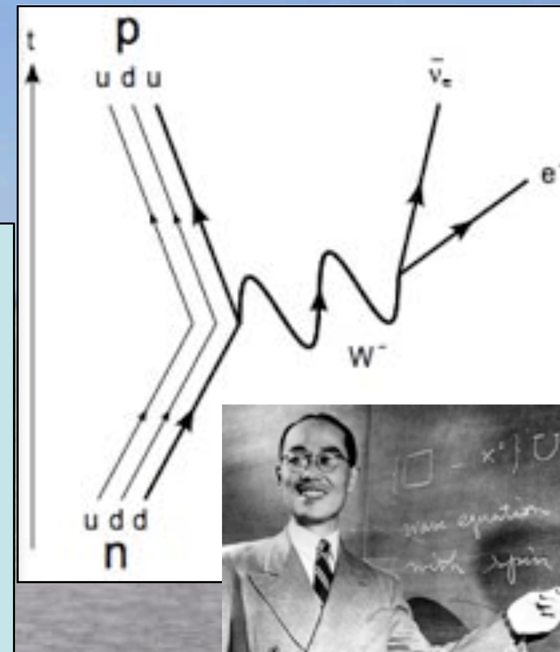
Weak Interactions

Weak Interactions

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

W boson - carrier of weak interaction

postulated by Yukawa



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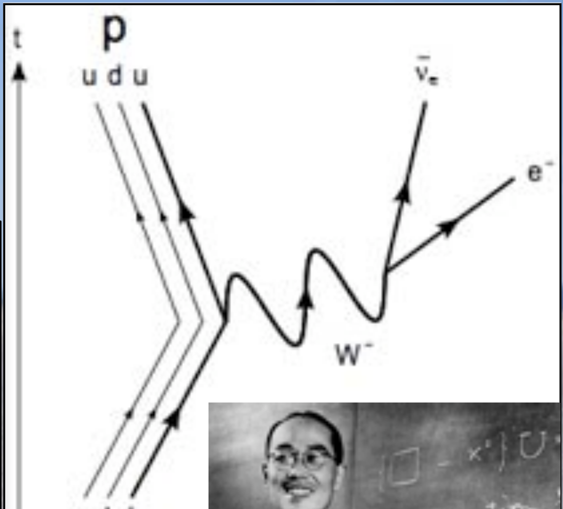
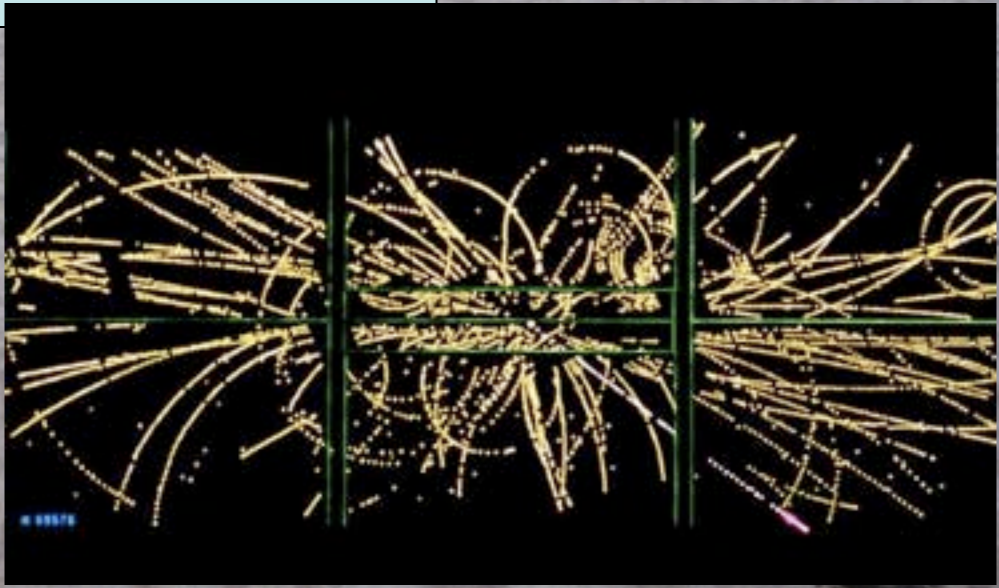
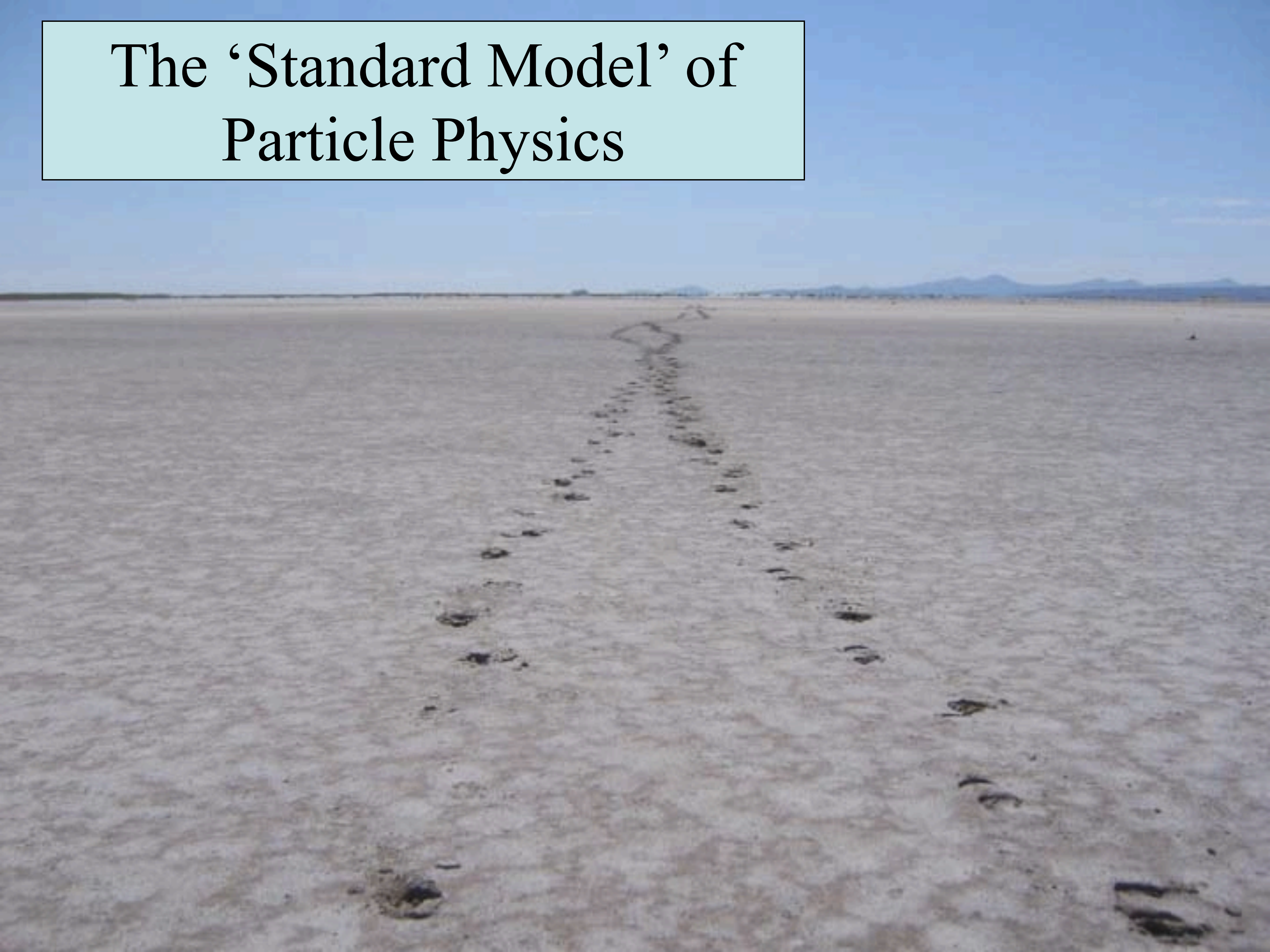


Discovered at CERN in 1983 by Carlo Rubbia et al



The ‘Standard Model’ of Particle Physics



The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow & Weinberg

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Crucial tests in experiments at CERN, etc.

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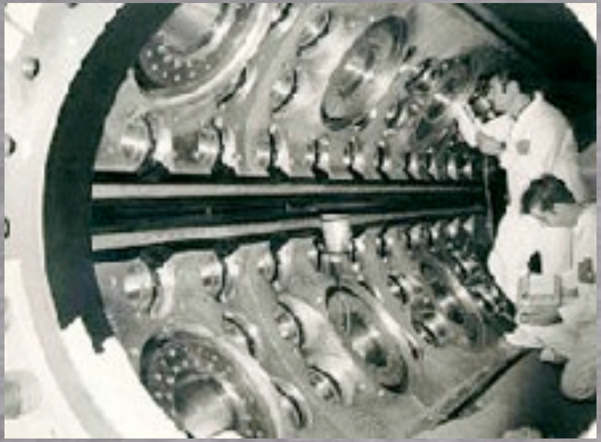

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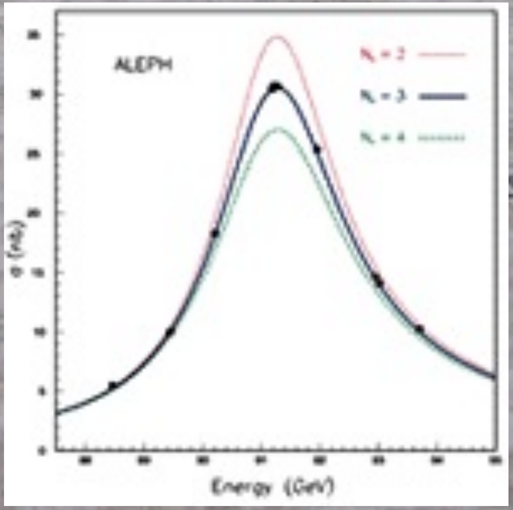

In agreement with all confirmed laboratory experiments

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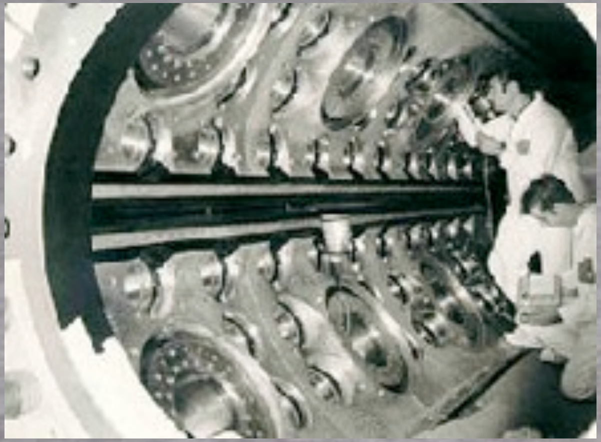

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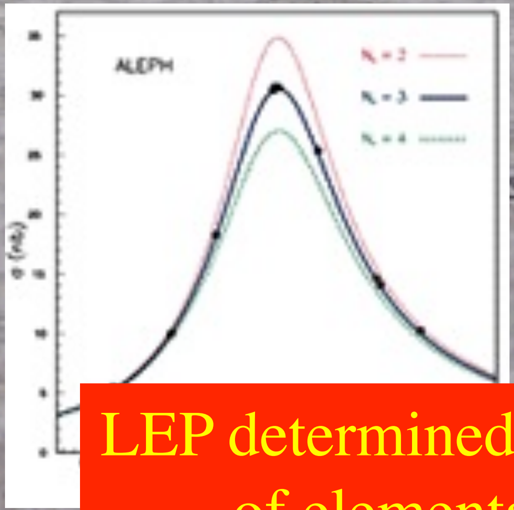

LEP determined how many types of elementary particles

Open Questions beyond the Standard Model

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- What is the origin of particle masses?

Open Questions beyond the Standard Model

- What is the origin of particle masses? due to a Higgs boson?

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Open Questions beyond the Standard Model

- What is the origin of particle masses? due to a Higgs boson? LHC
- Why so many types of matter particles? LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

Why do Things Weigh?

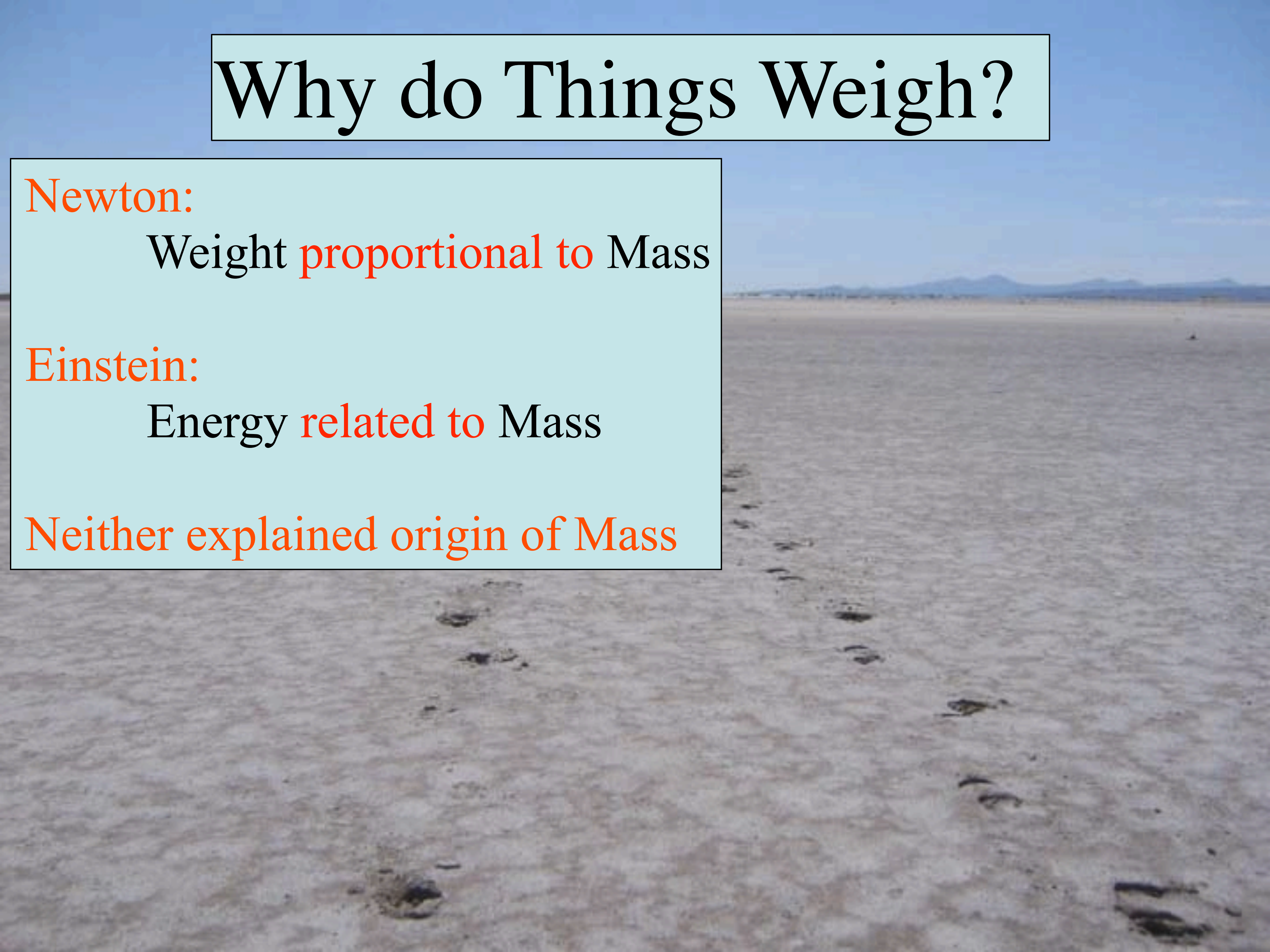
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



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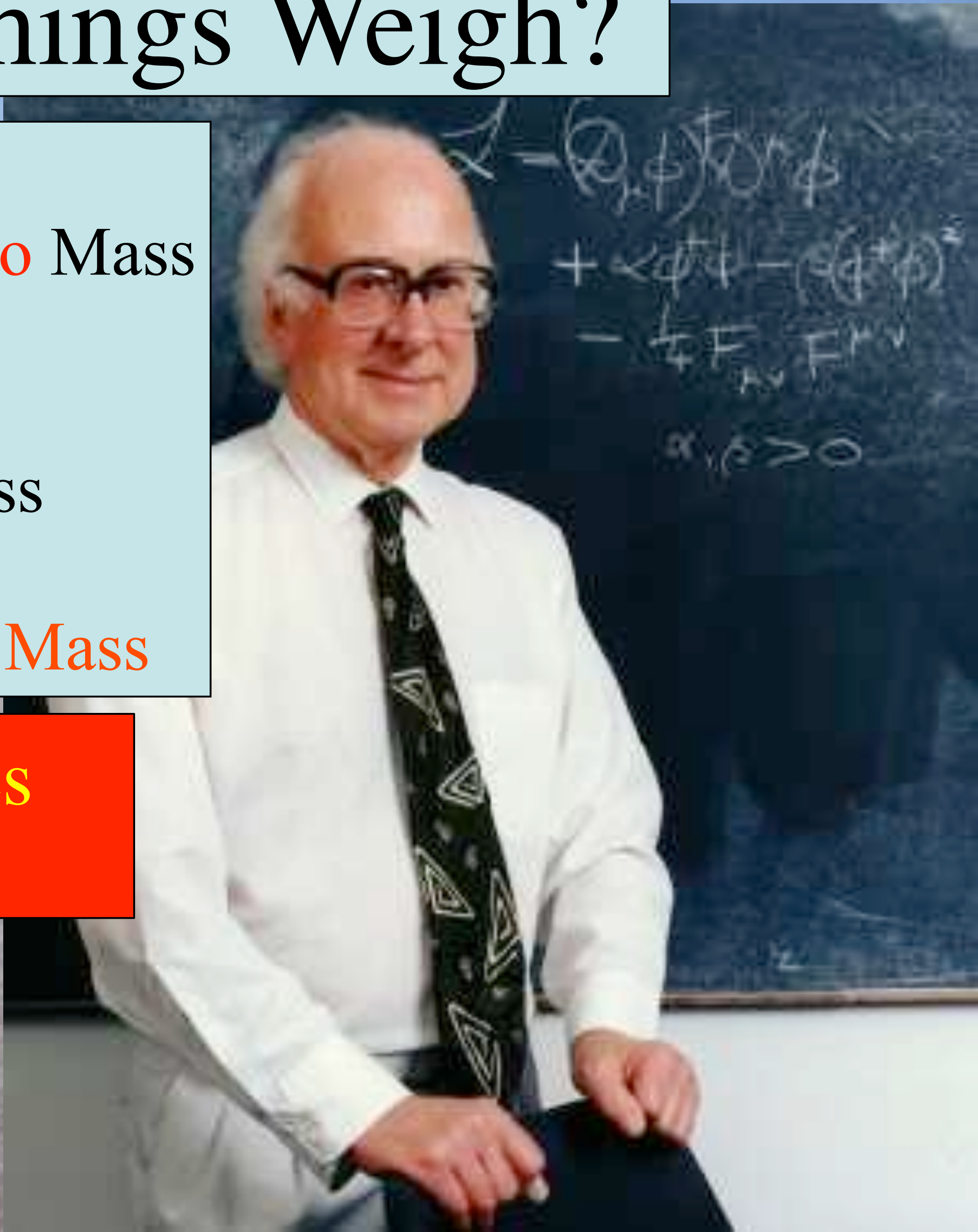

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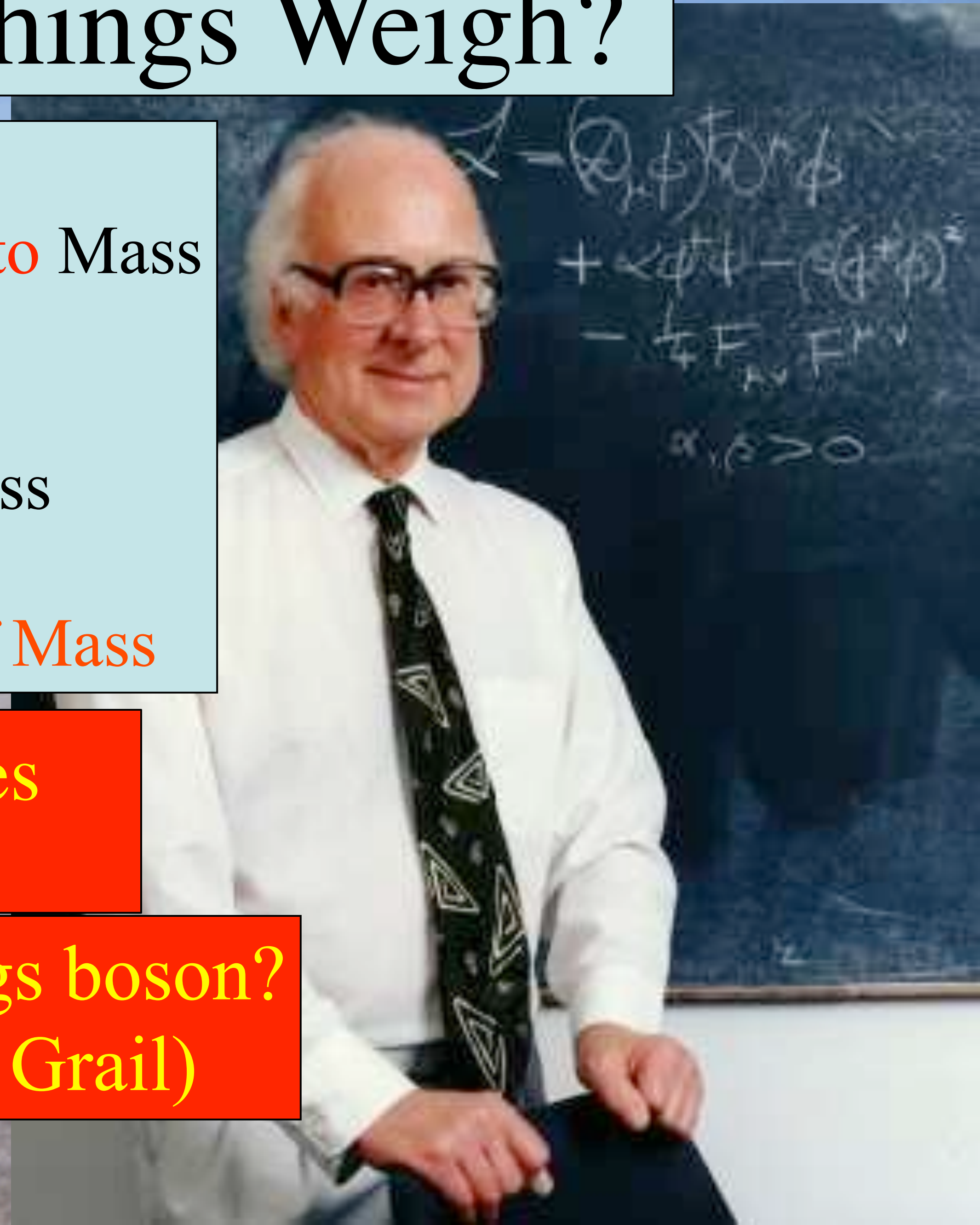
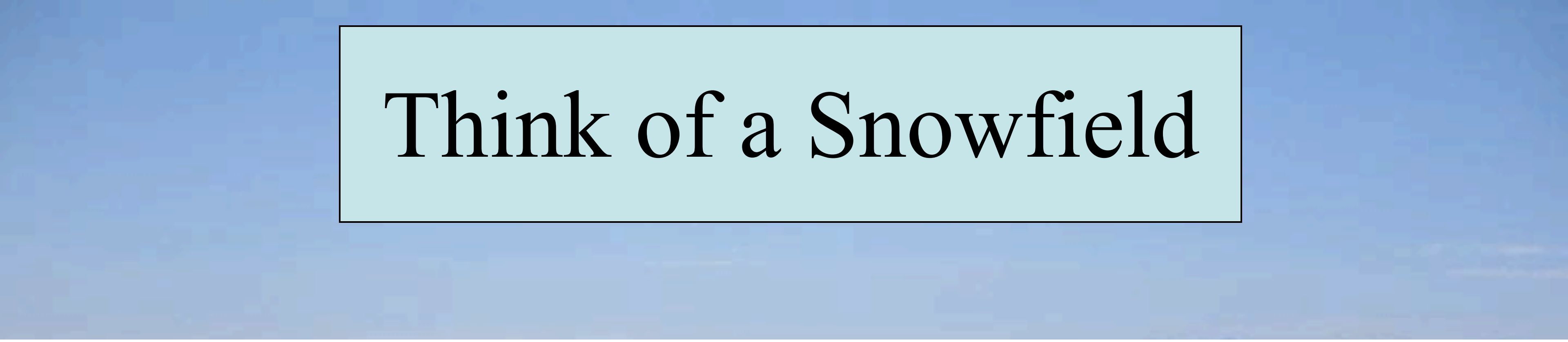
Are masses due to Higgs boson?
(the physicists' Holy Grail)




Think of a Snowfield

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Skier moves fast:
Like particle without mass
e.g., photon = particle of light

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Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

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

Think of a Snowfield

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The LHC will look for the snowflake: The Higgs Boson

Hiker sinks deep,
moves very slowly:
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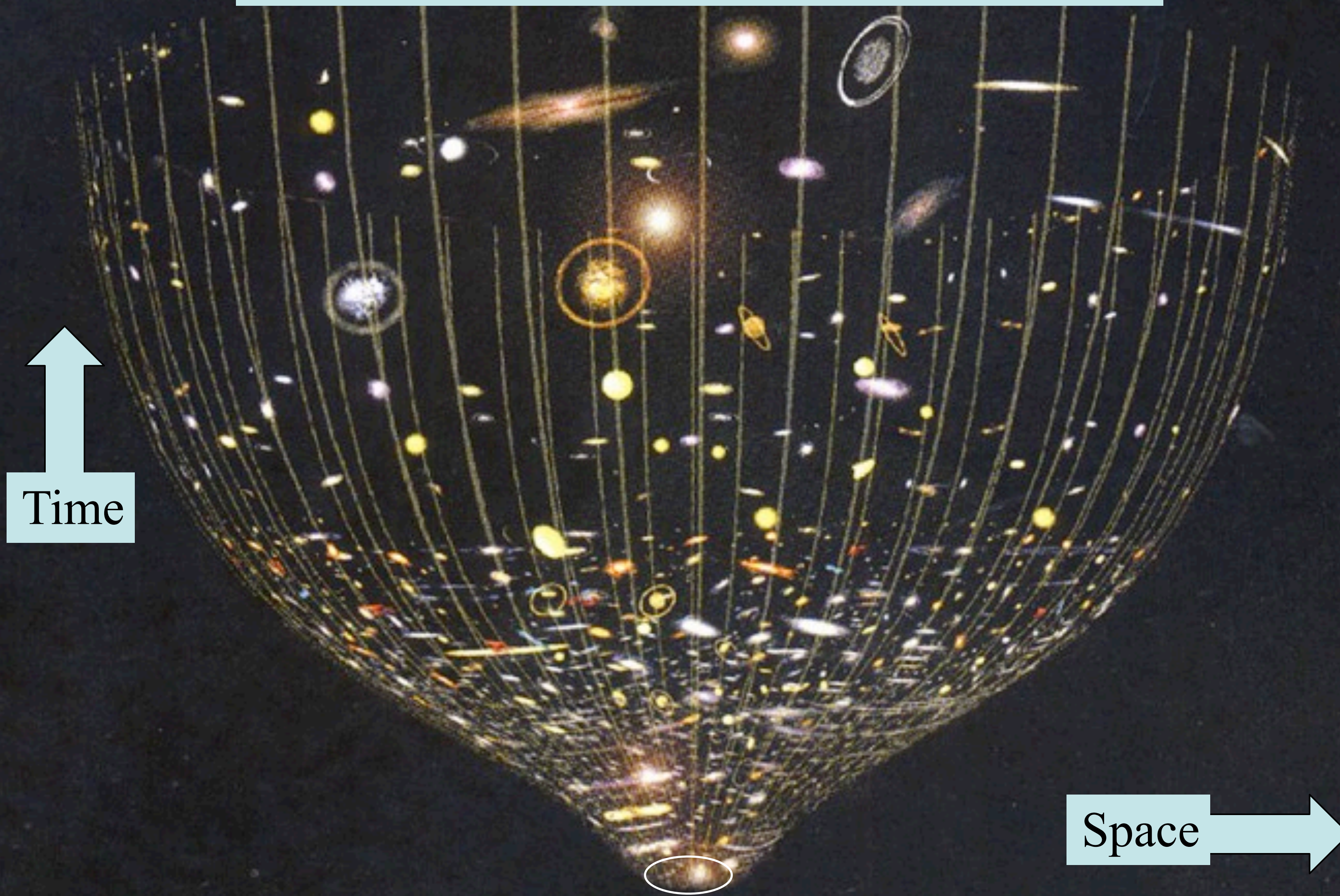
The Universe is Expanding

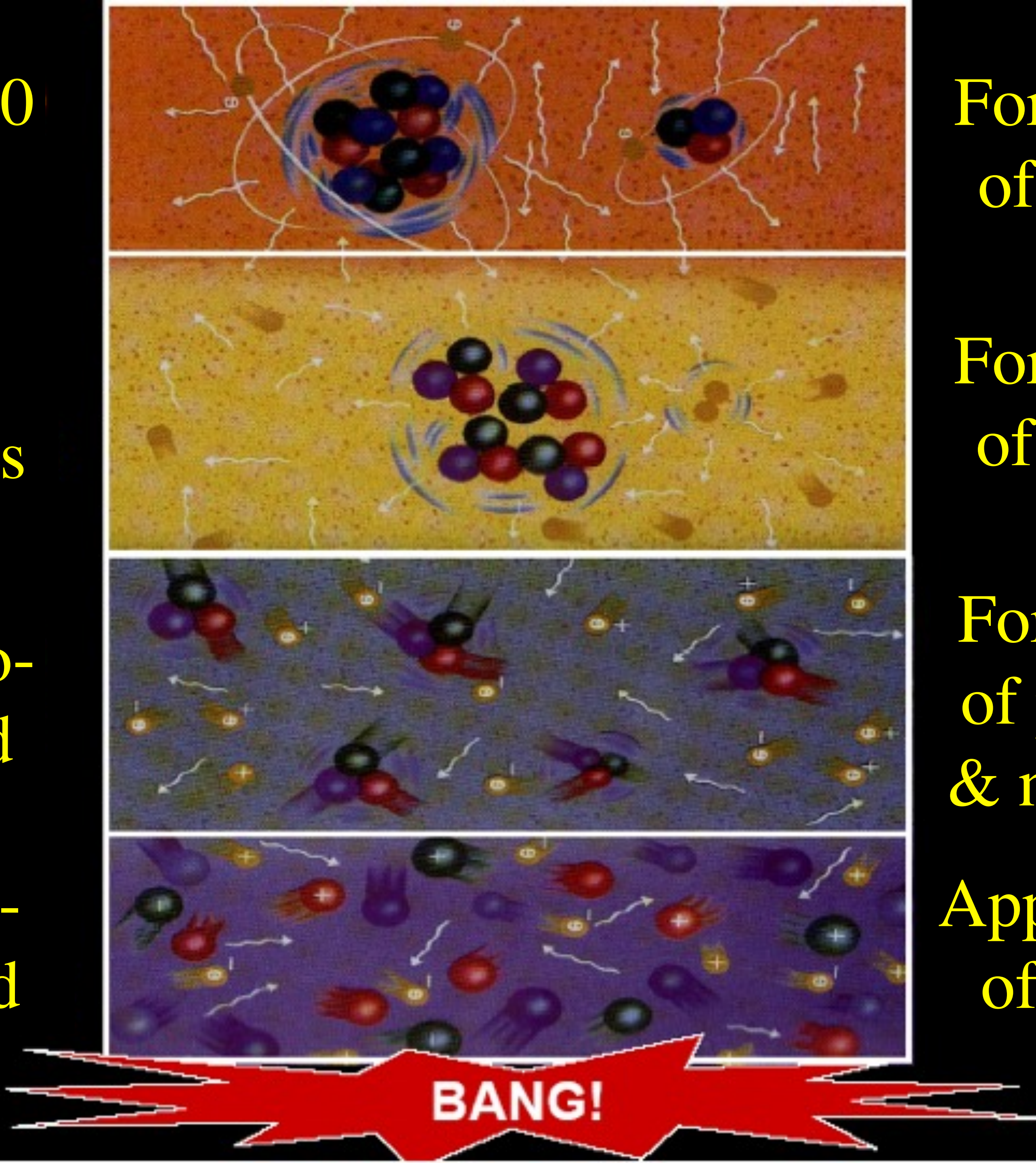


300,000 years — Formation of atoms

3 minutes — Formation of nuclei

1 micro-second — Formation of protons & neutrons

1 pico-second — Appearance of mass?



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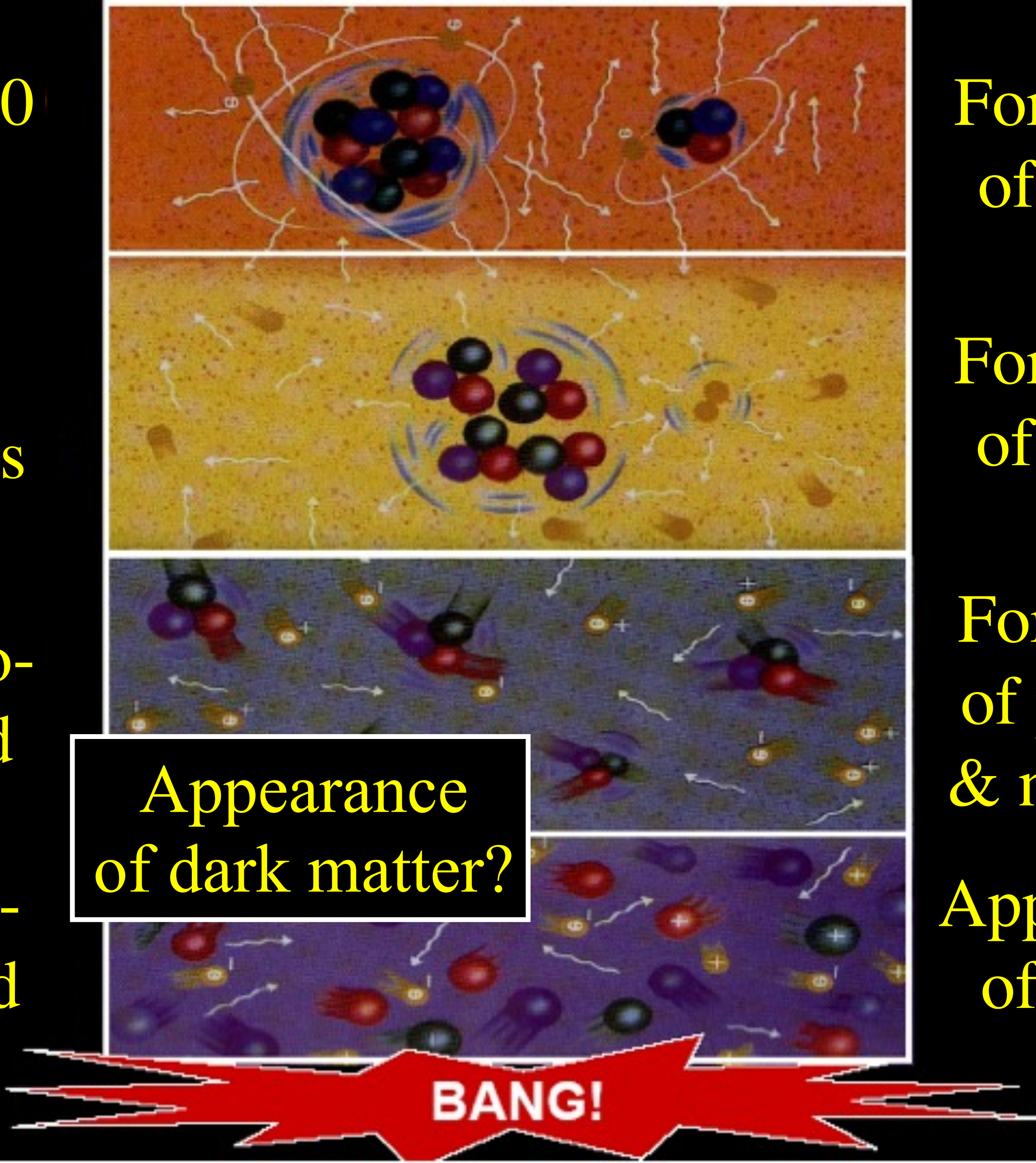
Appearance of dark matter?

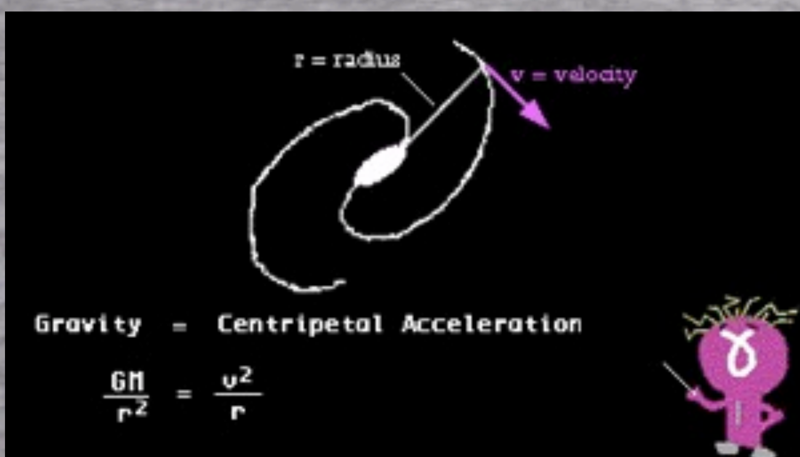
1 pico-second

Appearance of mass?



Evidence for Dark Matter

Galaxies rotate more rapidly than allowed by centripetal force due to visible matter



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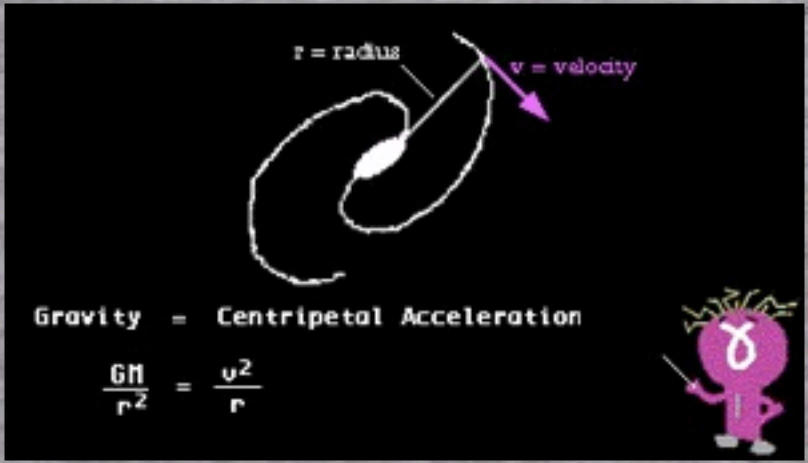

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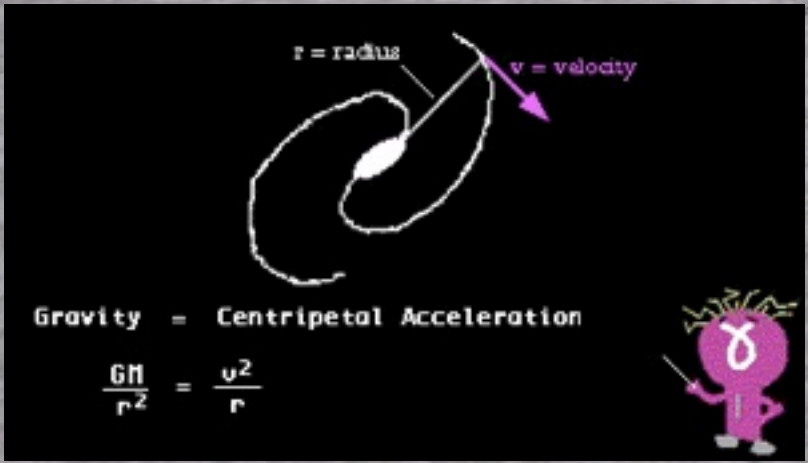

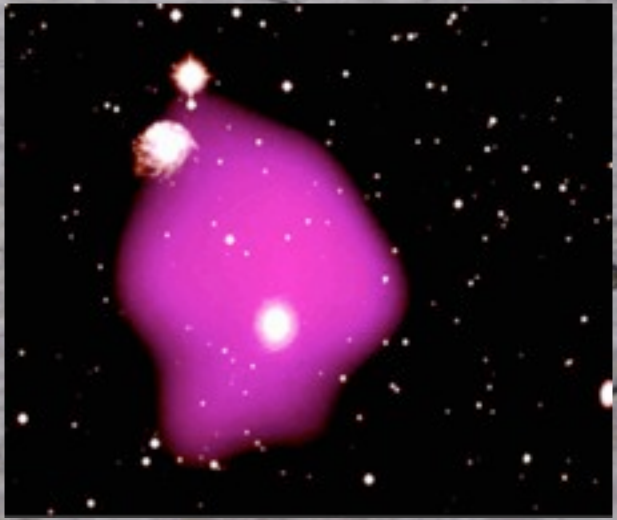

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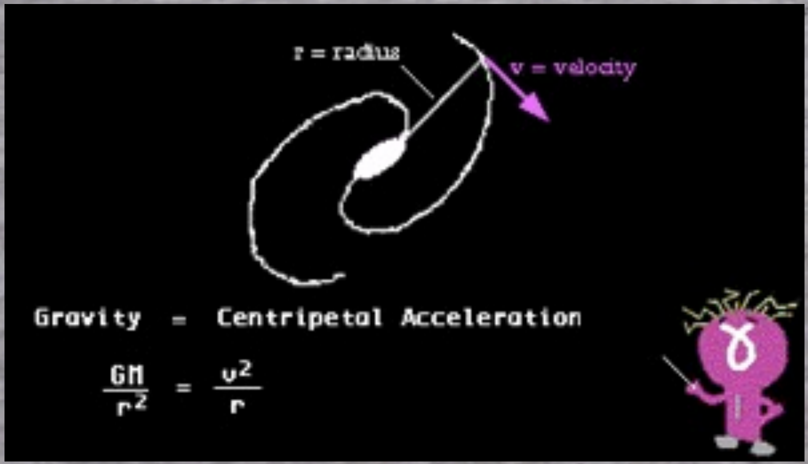

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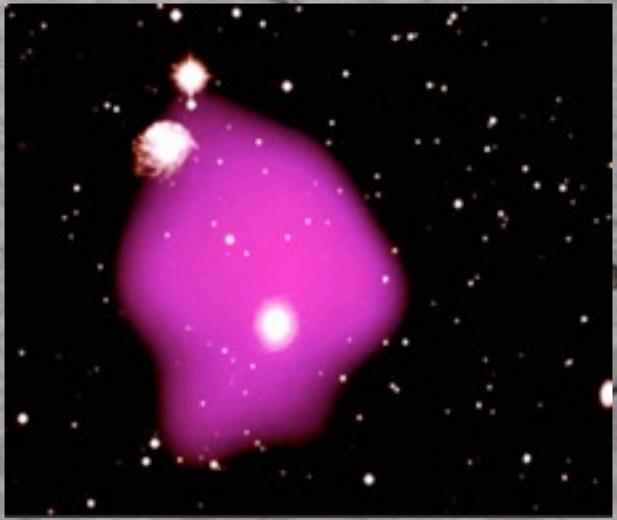

Even a 'dark galaxy' without stars

Dark Matter in the Universe

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

‘Supersymmetric’ particles ?

We shall look for them with the LHC

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A Bitino of Shistory

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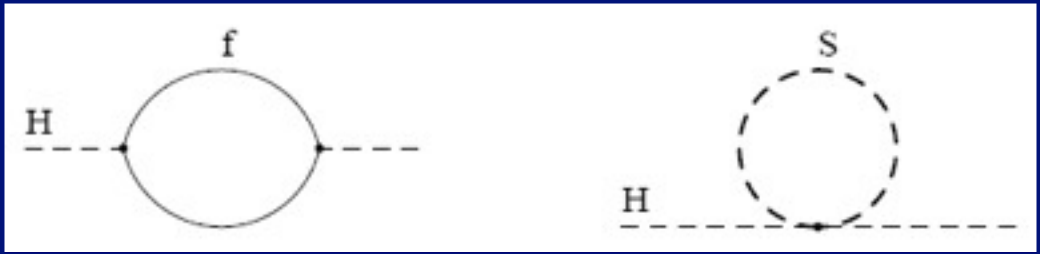

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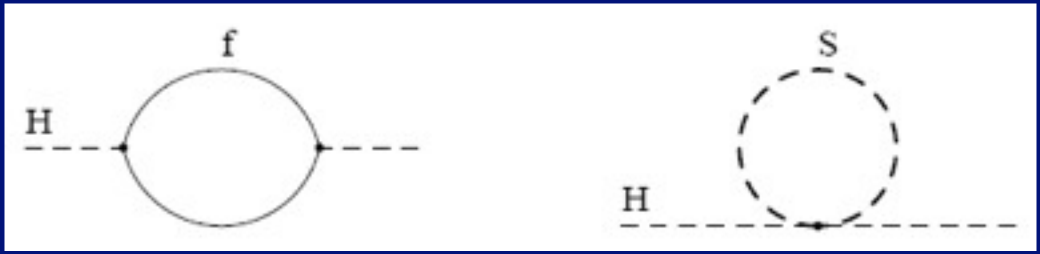

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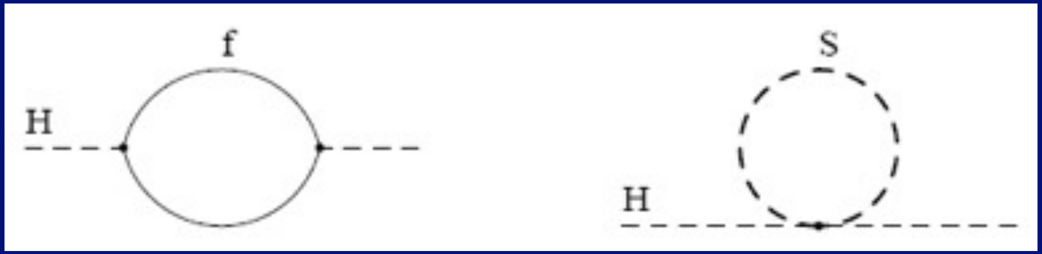

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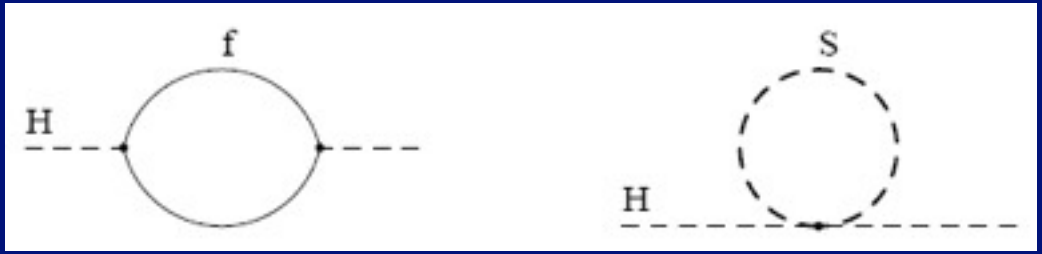

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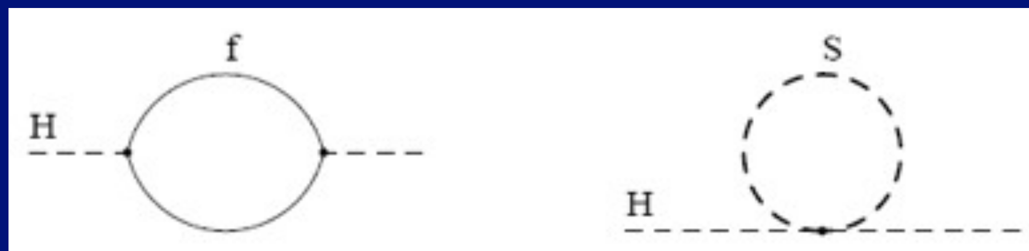

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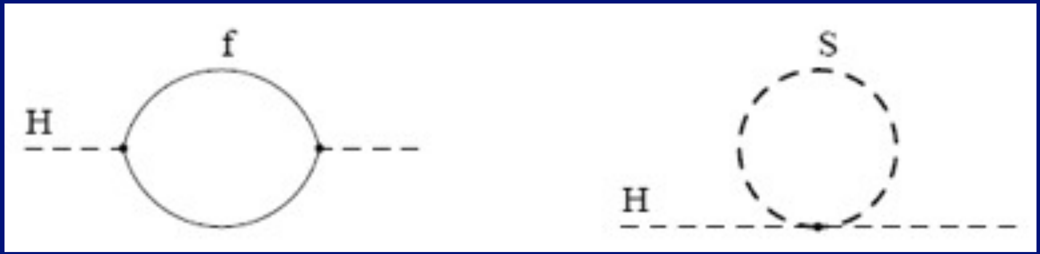

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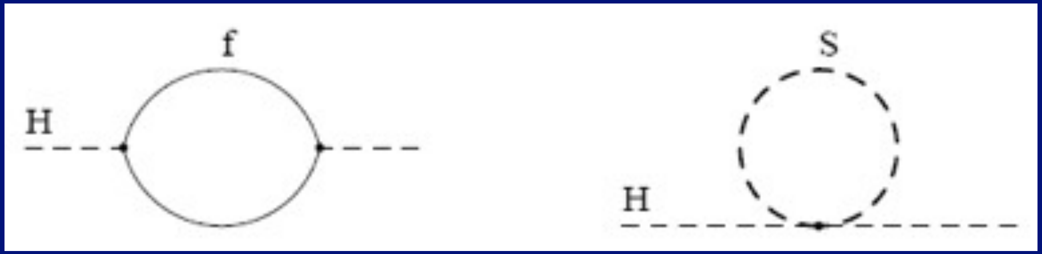

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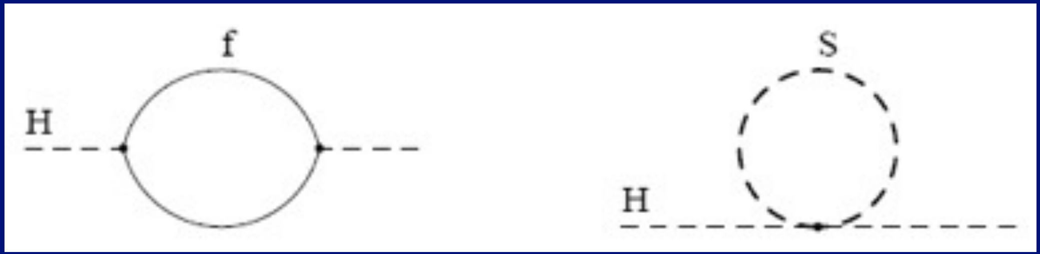

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- 1995: LEP data favour light Higgs boson

Some personal contributions

SLAC-PUB-3171
July 1983
(T/E)

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John Ellis and J. S. Hagelin

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

D. V. Nanopoulos, K. Olive†, and M. Srednicki‡

CERN
CH-1211 Geneva 23, Switzerland

ABSTRACT

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the Lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above ½ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100)eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

(Submitted to Nuclear Physics B)

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

† Address as of July 1, 1983: Fermilab, P.O. Box 500, Batavia, IL 60510.

‡ Address as of Sept. 1, 1983: Dept. of Physics, University of California, Santa Barbara, CA 93106.

November 1990

CERN-TH.5946/90
GEF-TH-26/1990

Radiative corrections to the masses of supersymmetric Higgs bosons

John Ellis
Theory Division, CERN, Geneva, Switzerland

Giovanni Ridolfi
INFN, Sezione di Genova, Italy

and

Fabio Zwirner[1]
Theory Division, CERN, Geneva, Switzerland

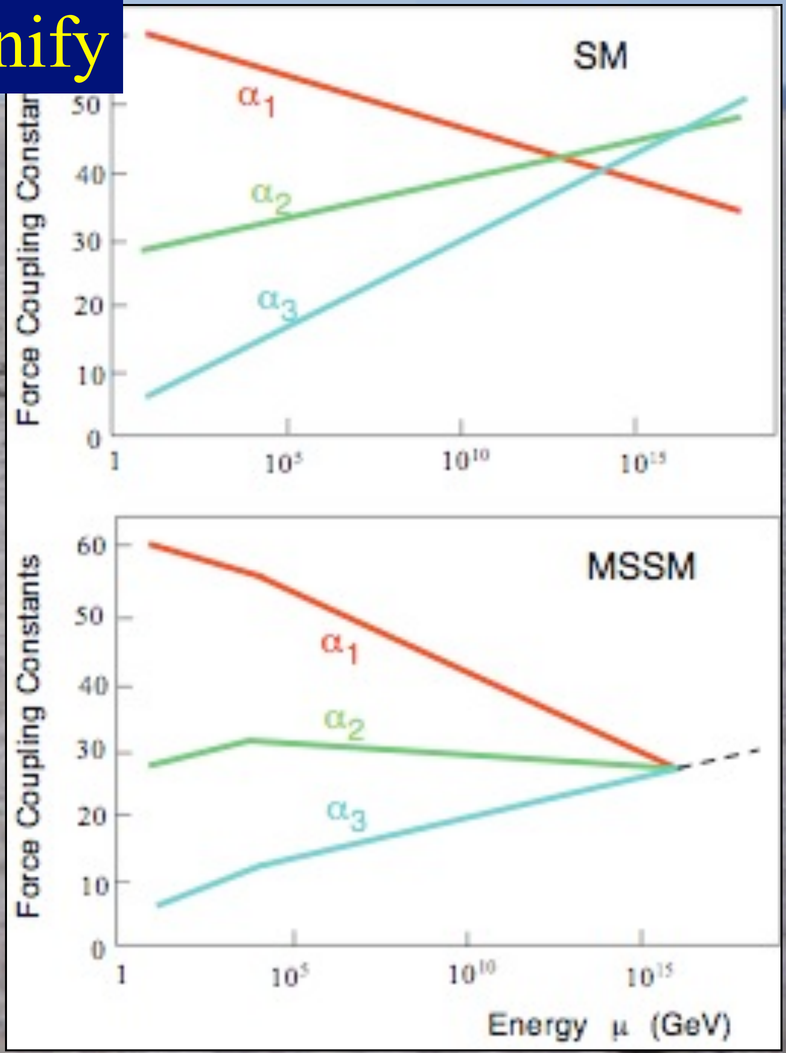
Abstract

The lightest neutral Higgs boson in the minimal supersymmetric extension of the Standard Model has a tree-level mass less than that of the Z^0. We calculate radiative corrections to its mass and to that of the heavier CP-even neutral Higgs boson. We find large corrections that increase with the top quark and squark masses, and vary with the ratio of vacuum expectation values v_2/v_1. These radiative corrections can be as large as $\mathcal{O}(100)$ GeV, and have the effect of *(i)* invalidating lower bounds on v_2/v_1 inferred from unsuccessful Higgs searches at LEP I, *(ii)* in many cases, increasing the mass of the lighter CP-even Higgs boson beyond m_Z, *(iii)* often, increasing the mass of the heavier CP-even Higgs boson beyond the LEP reach, into a range more accessible to the LHC or SSC.

[1] On leave from Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy.

Other Reasons to like Susy

It enables the gauge couplings to unify



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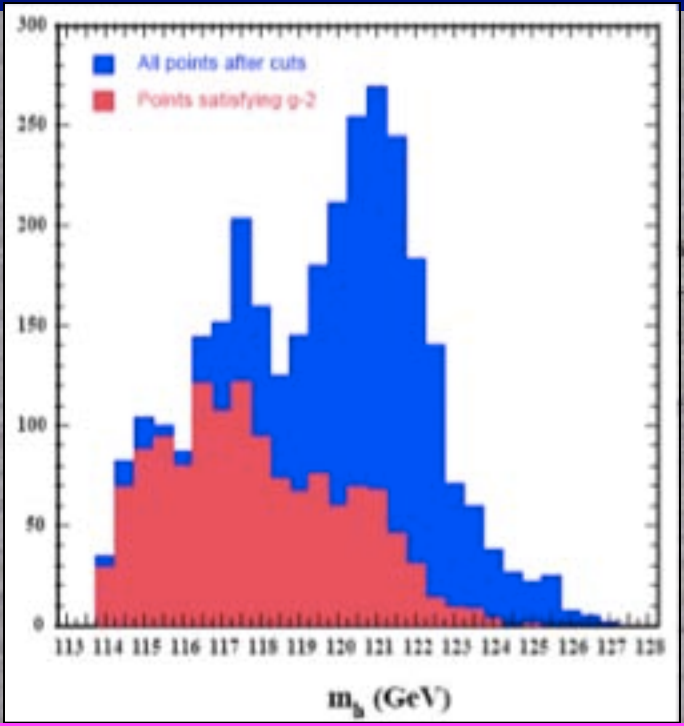
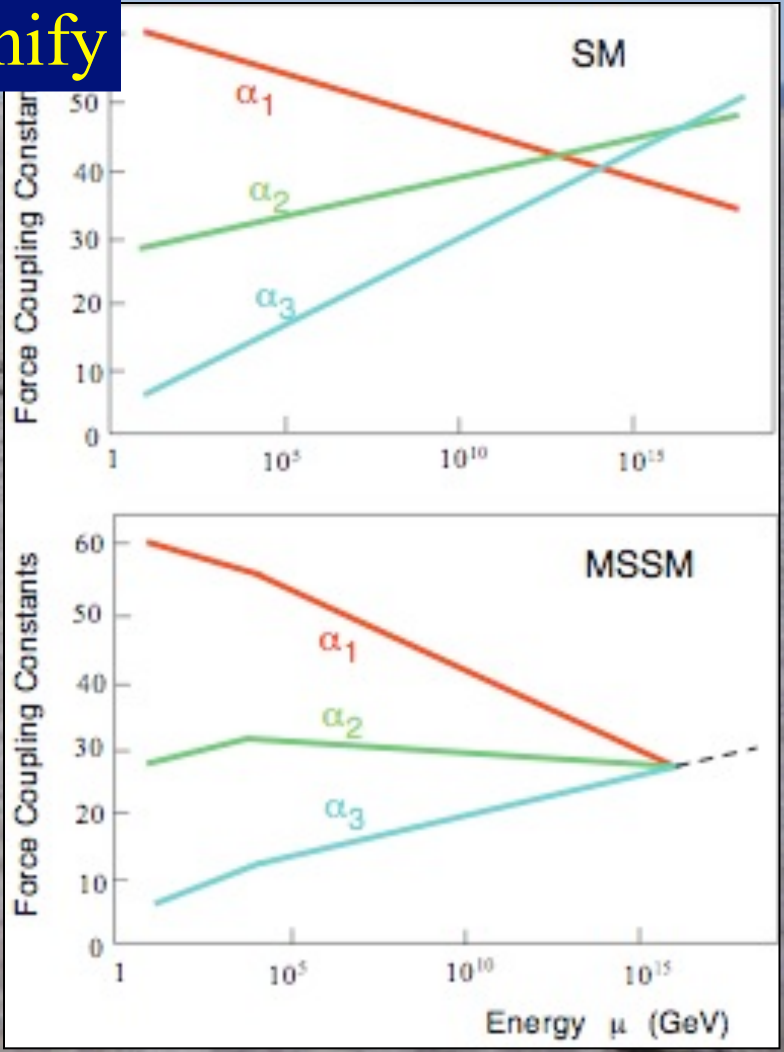


JE, Nanopoulos, Olive + Santoso: hep-ph/0509331



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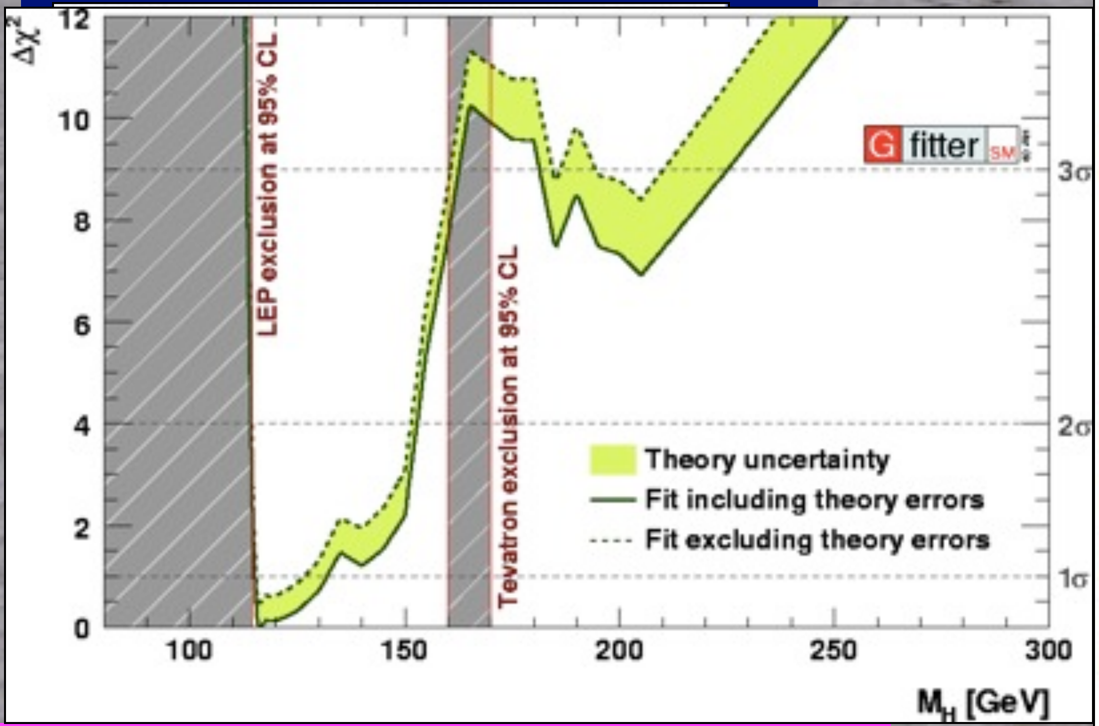
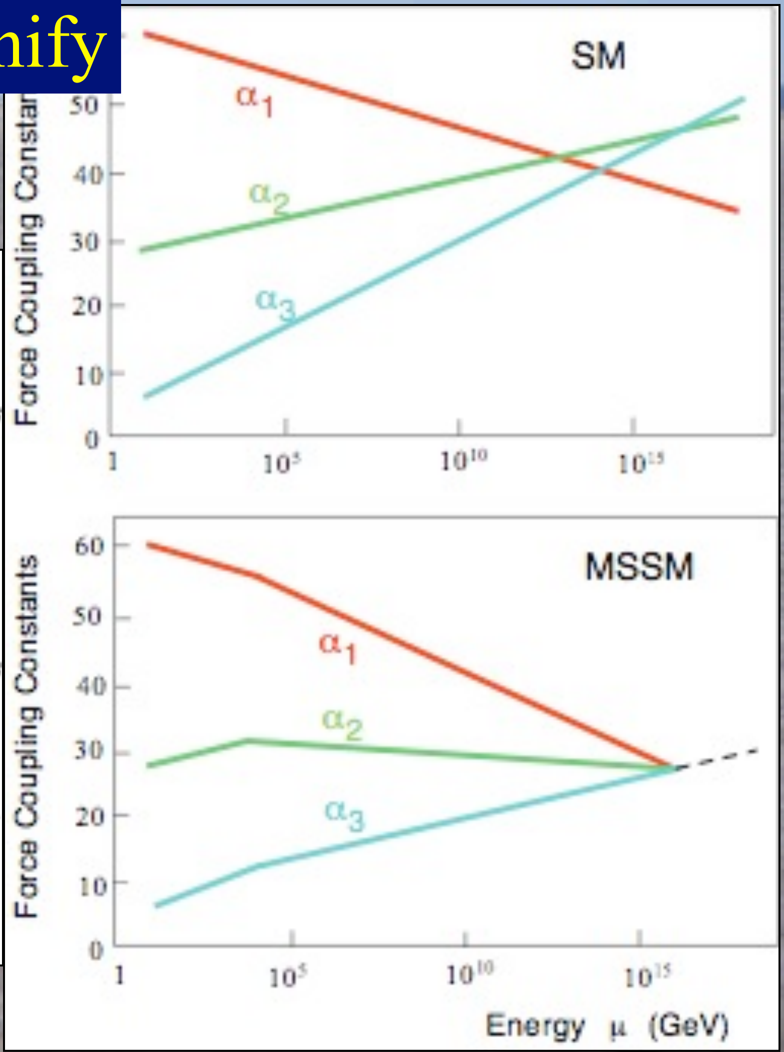


As suggested by electroweak data



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Fayet

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Fayet

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3.3 σ effect in $g_\mu - 2$?

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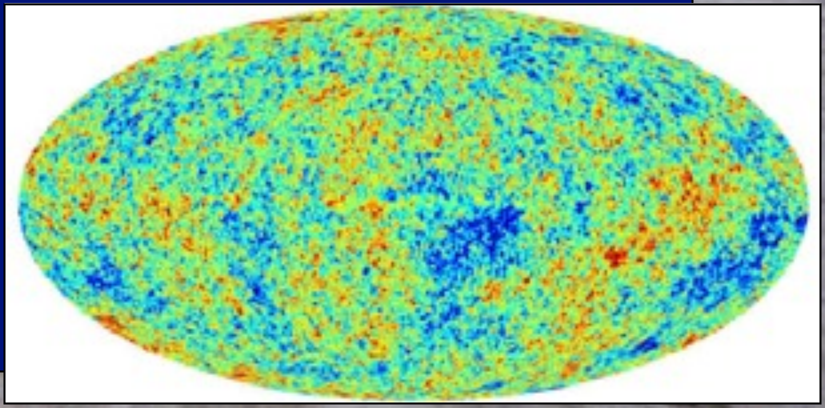

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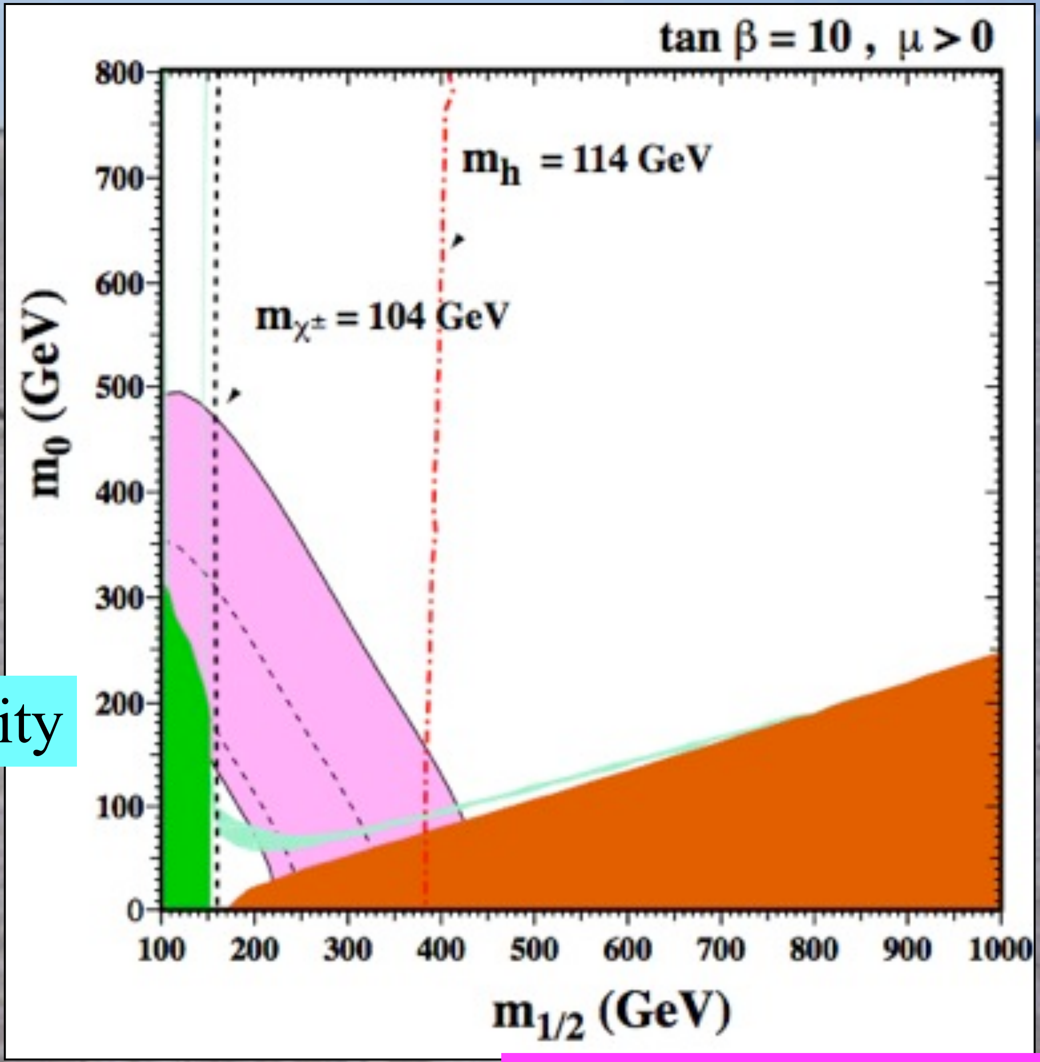

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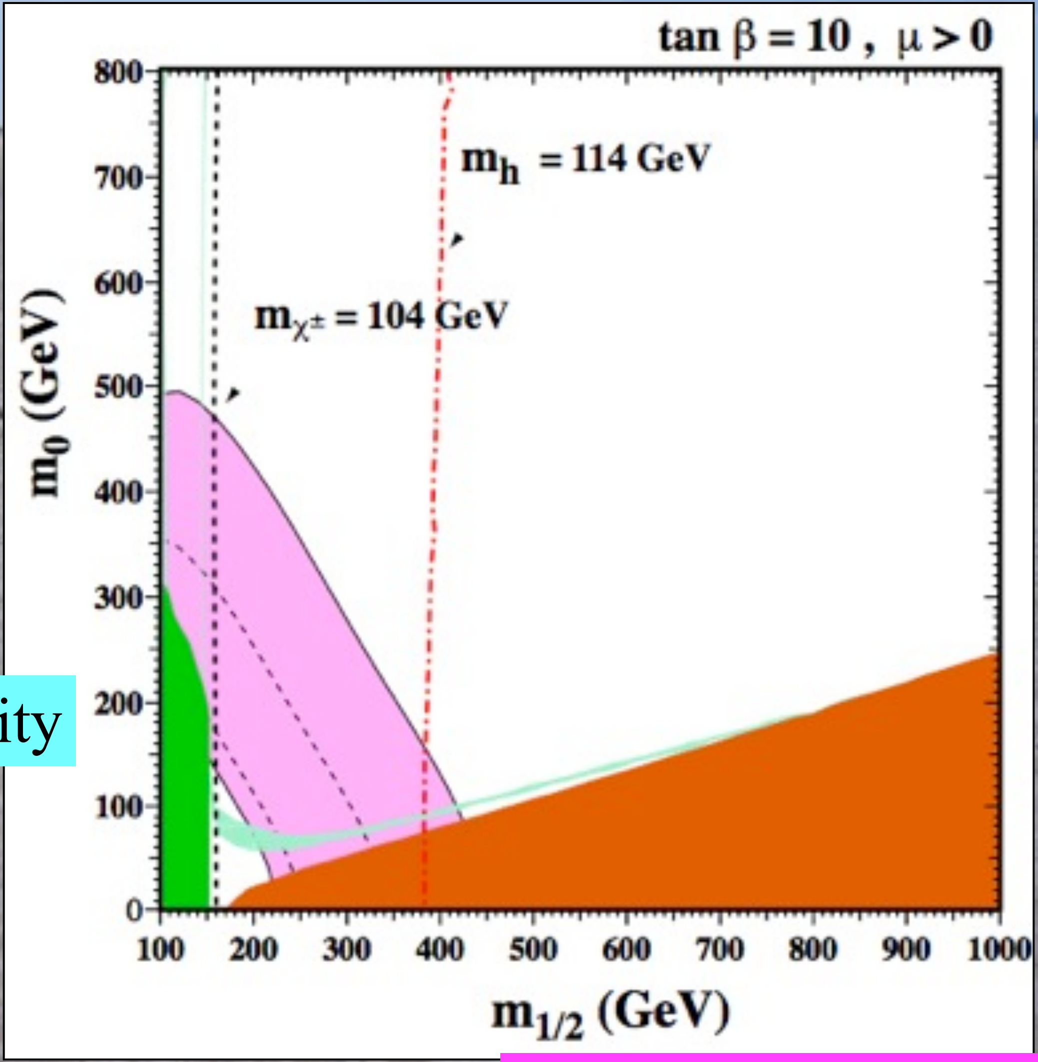

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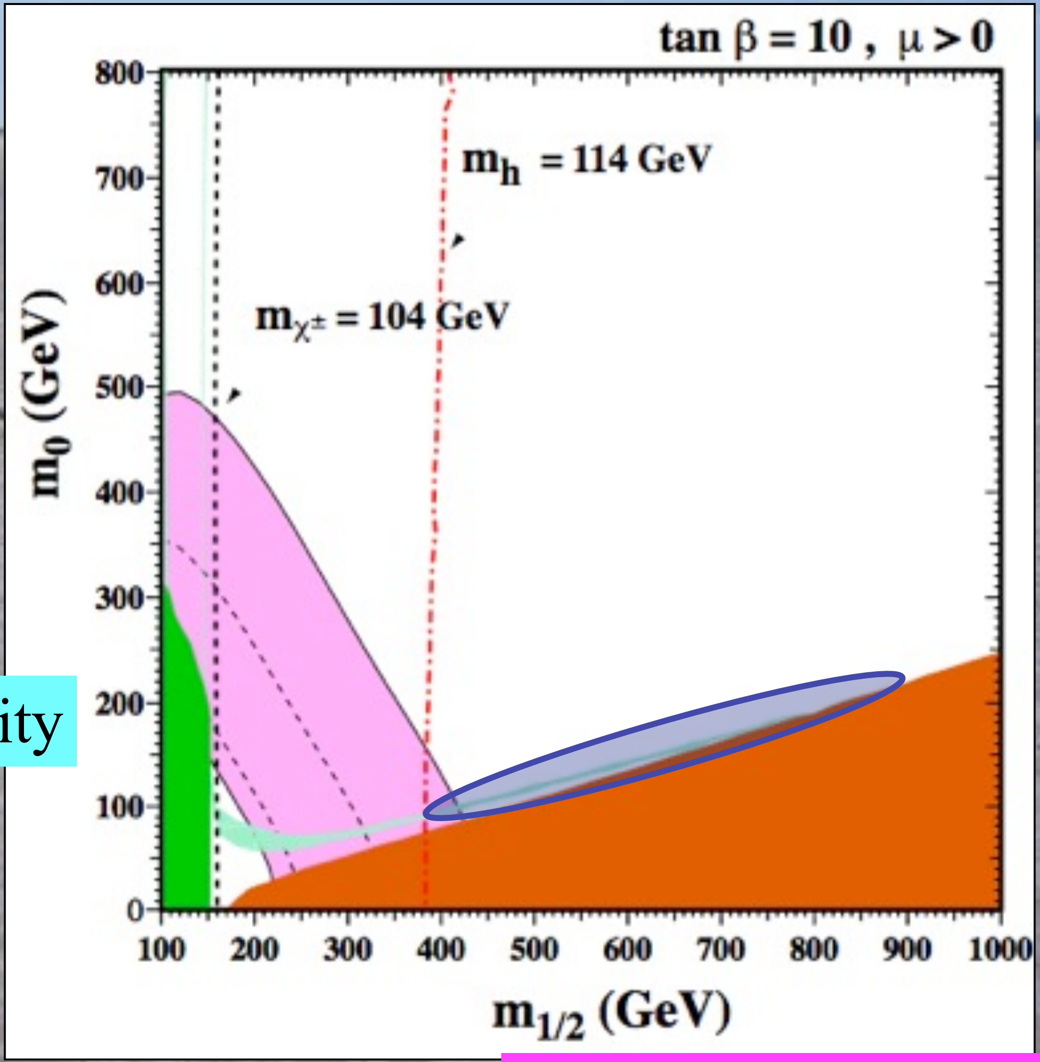

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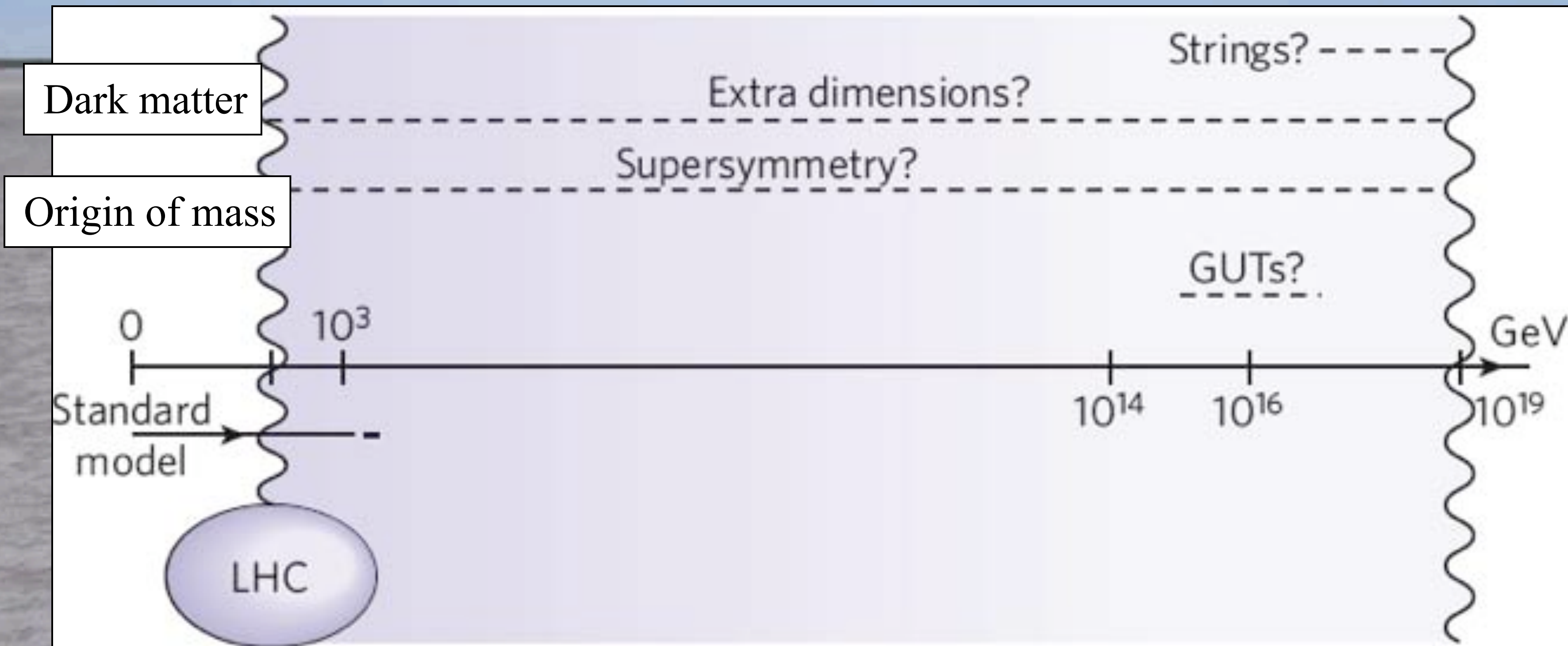

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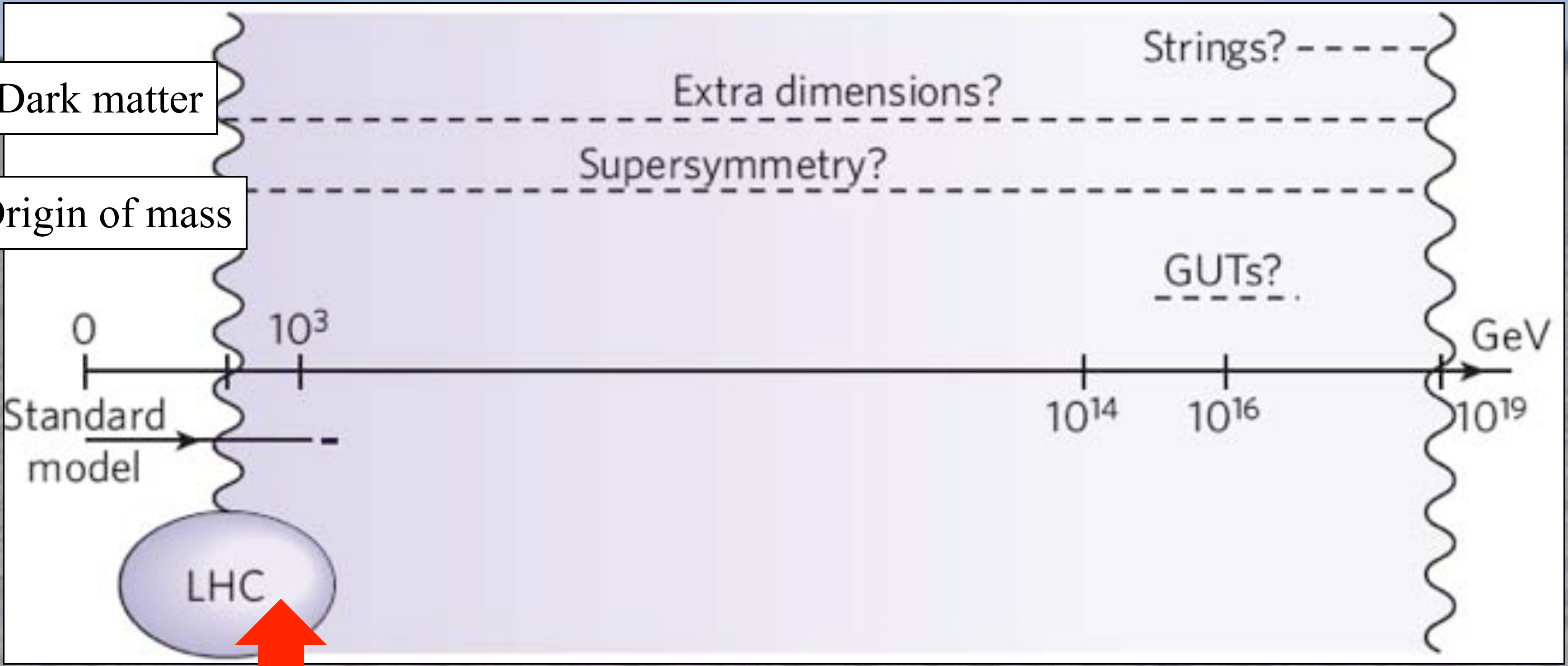

Dark matter

Origin of mass

A lot accessible to the LHC

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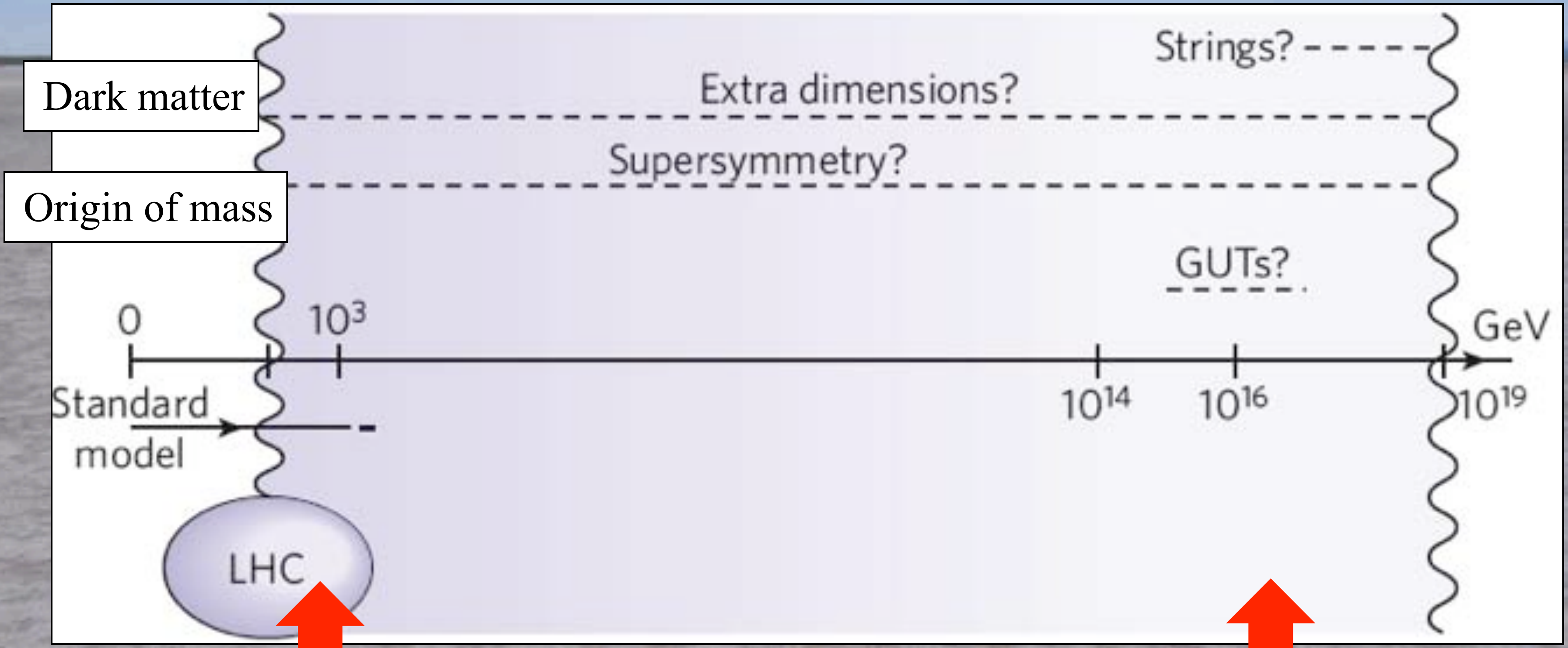
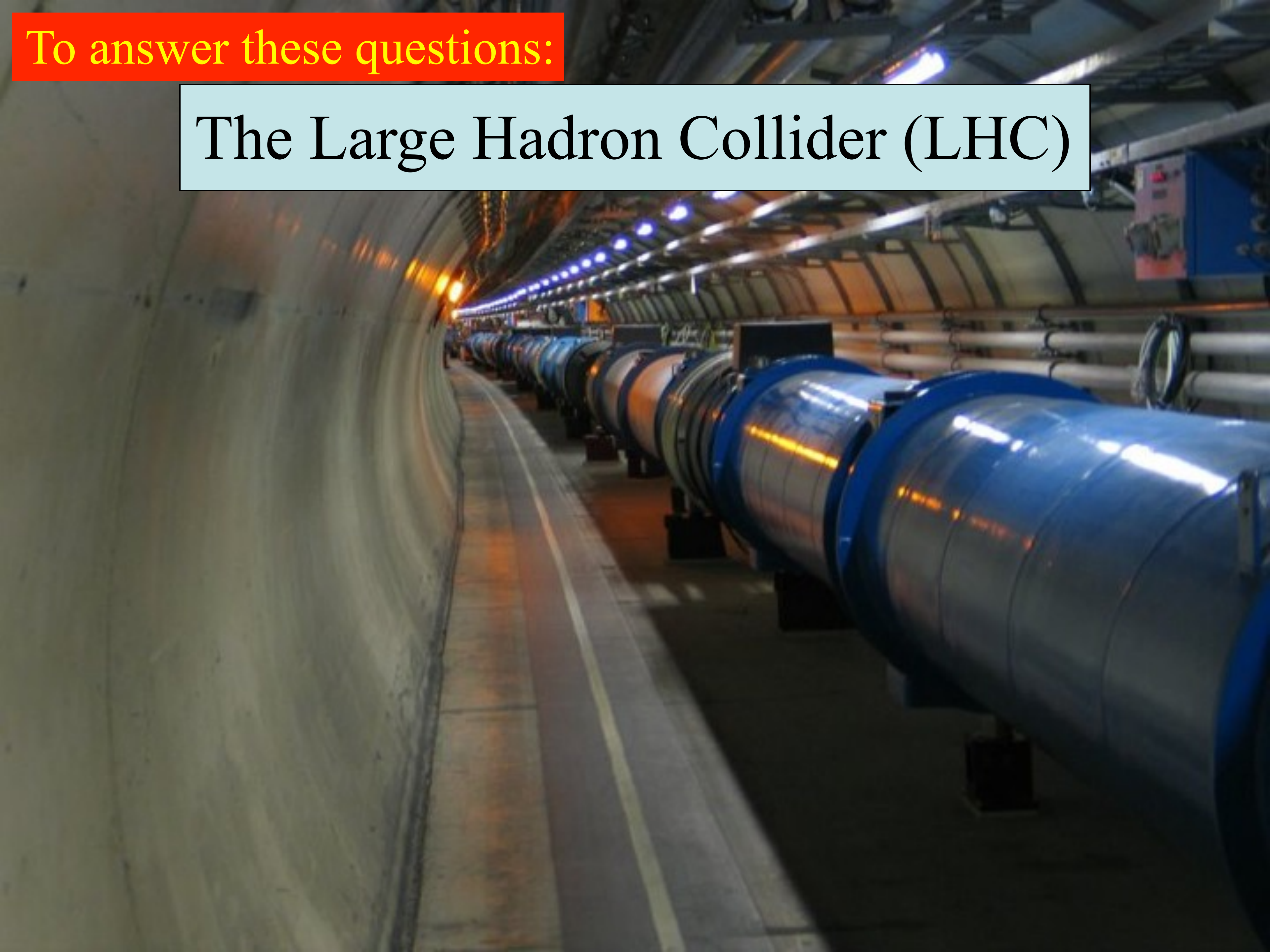


A lot accessible to the LHC

Some accessible only via astrophysics & cosmology

To answer these questions:

The Large Hadron Collider (LHC)



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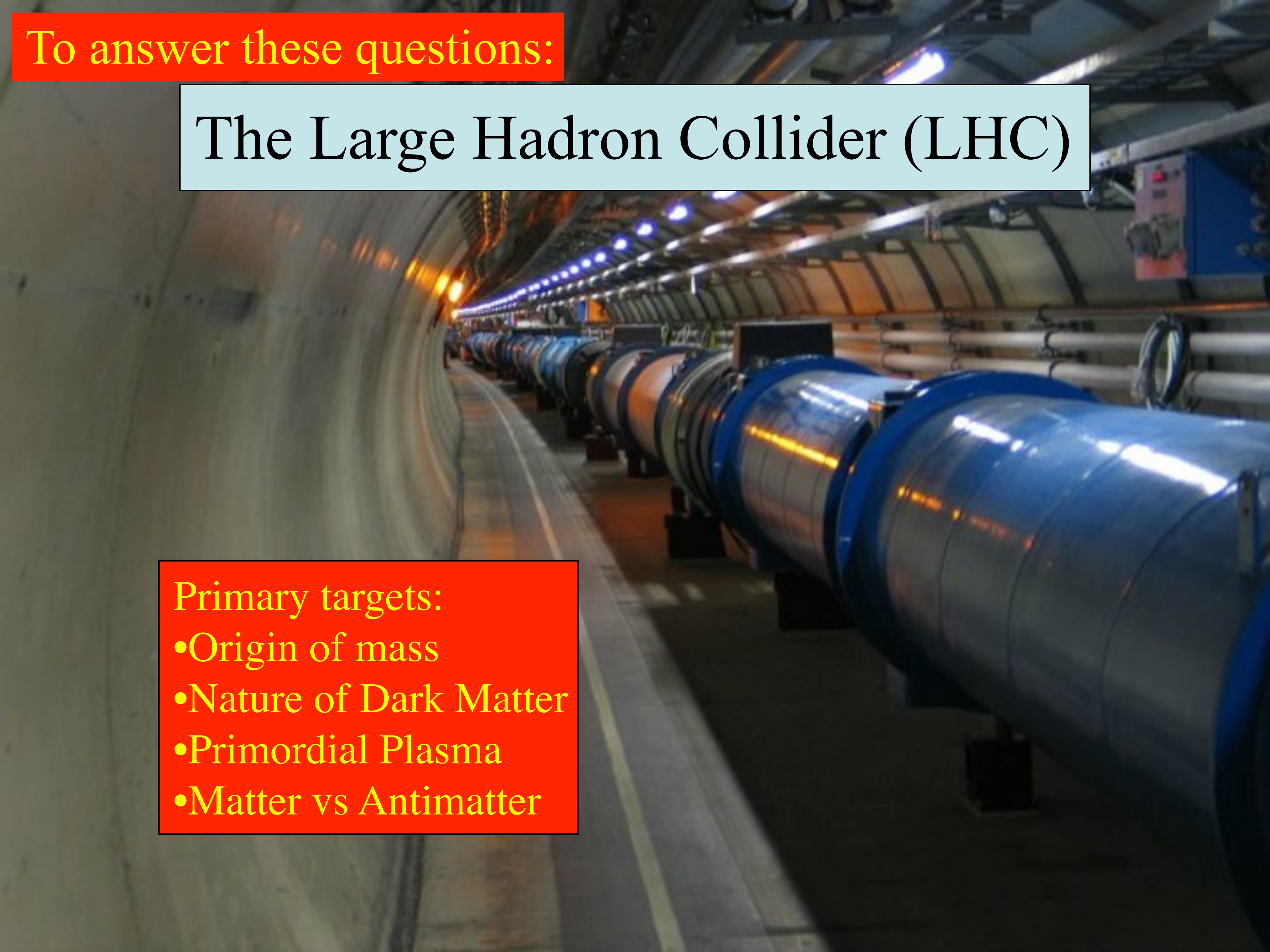
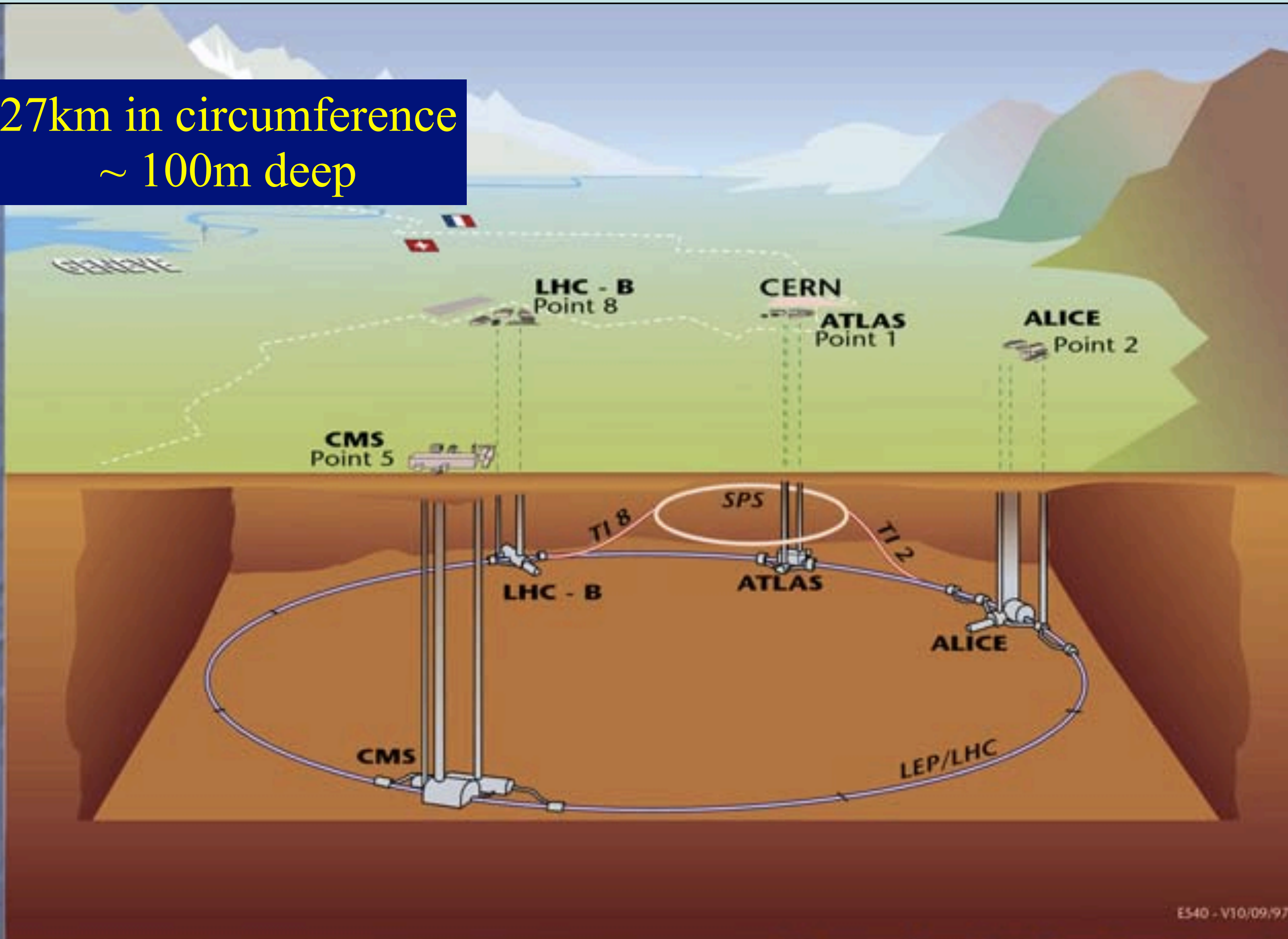


Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

General View of LHC & its Experiments

27km in circumference
~ 100m deep



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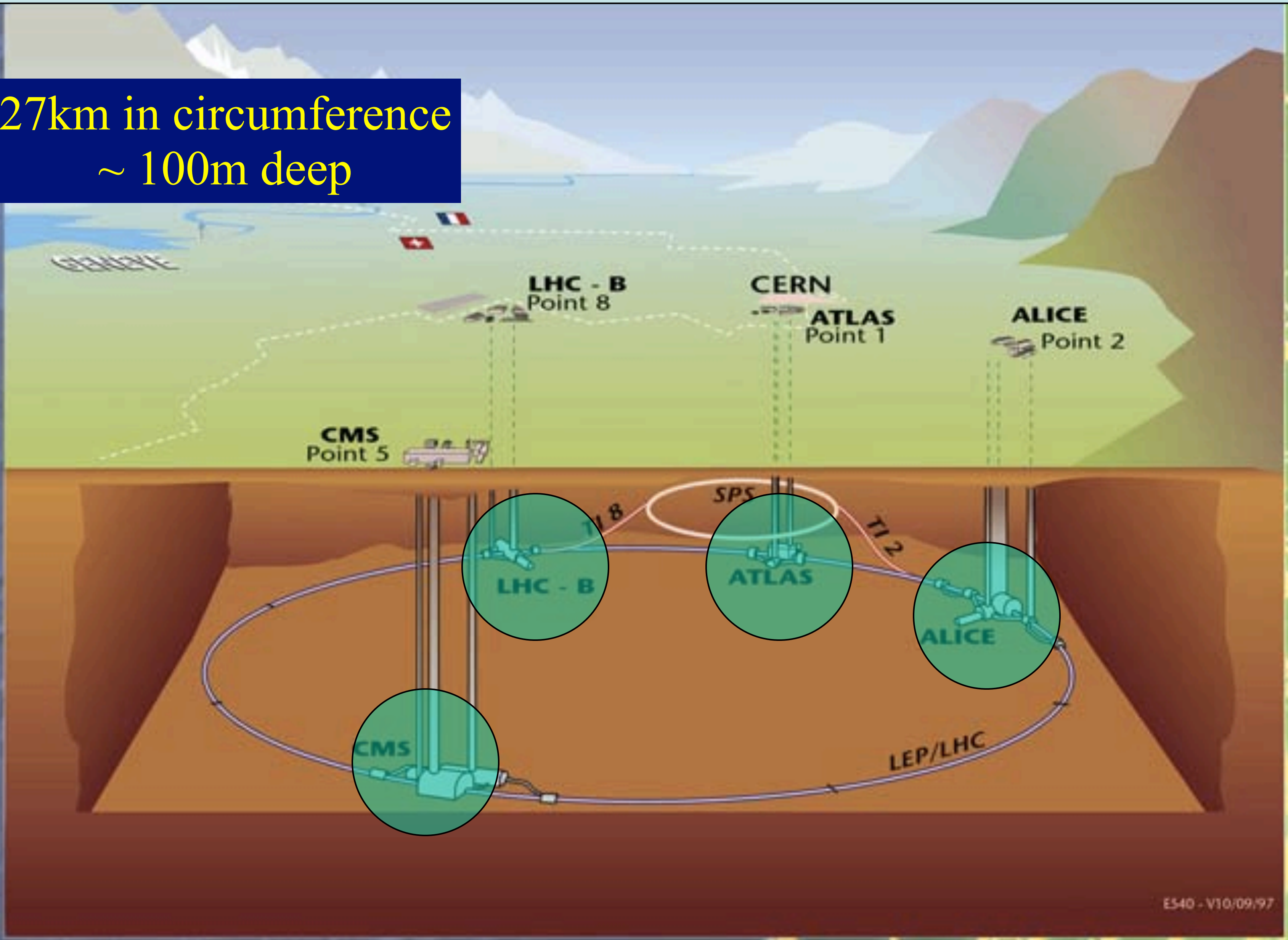
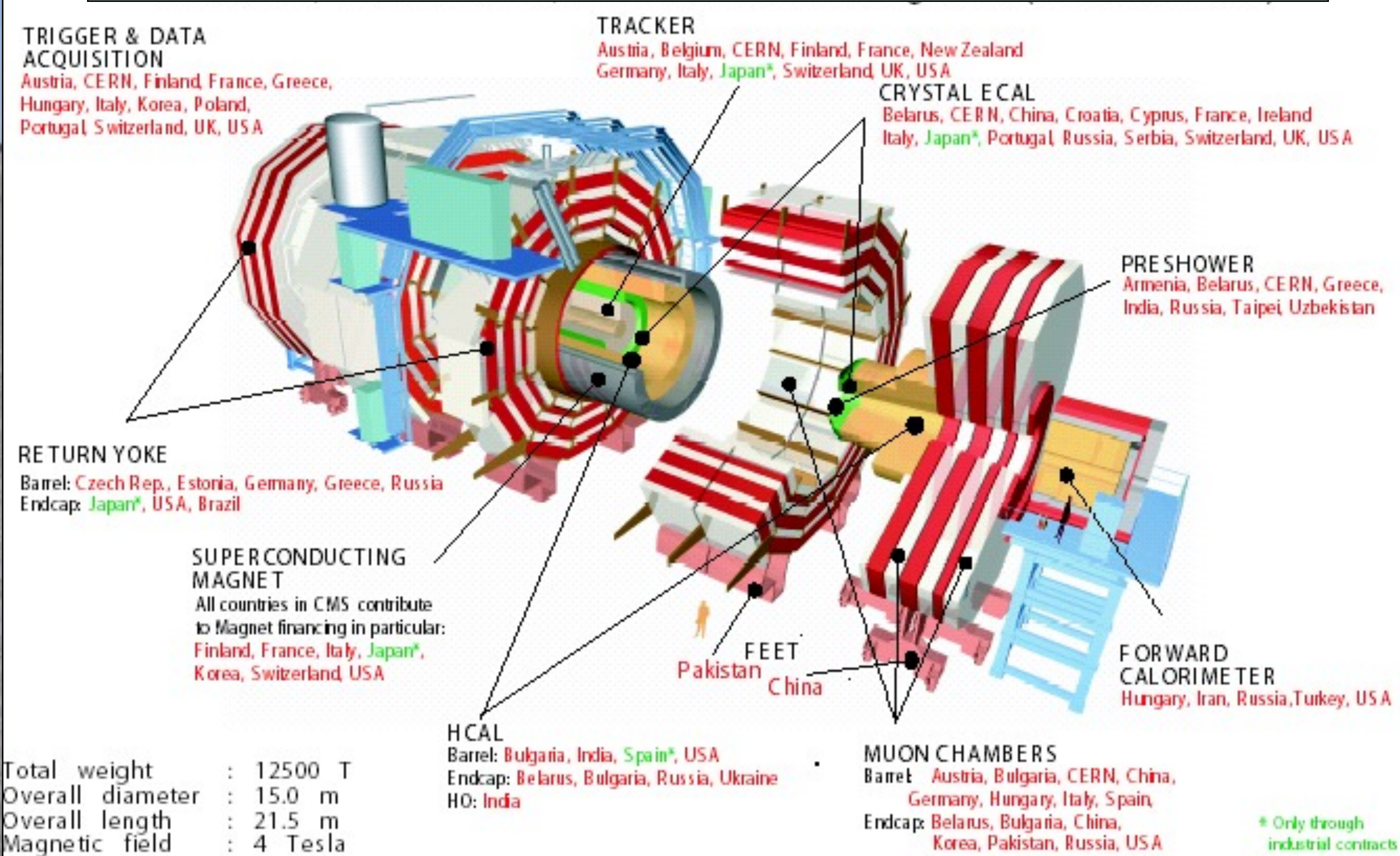


The CMS detector:
search for Higgs and supersymmetry



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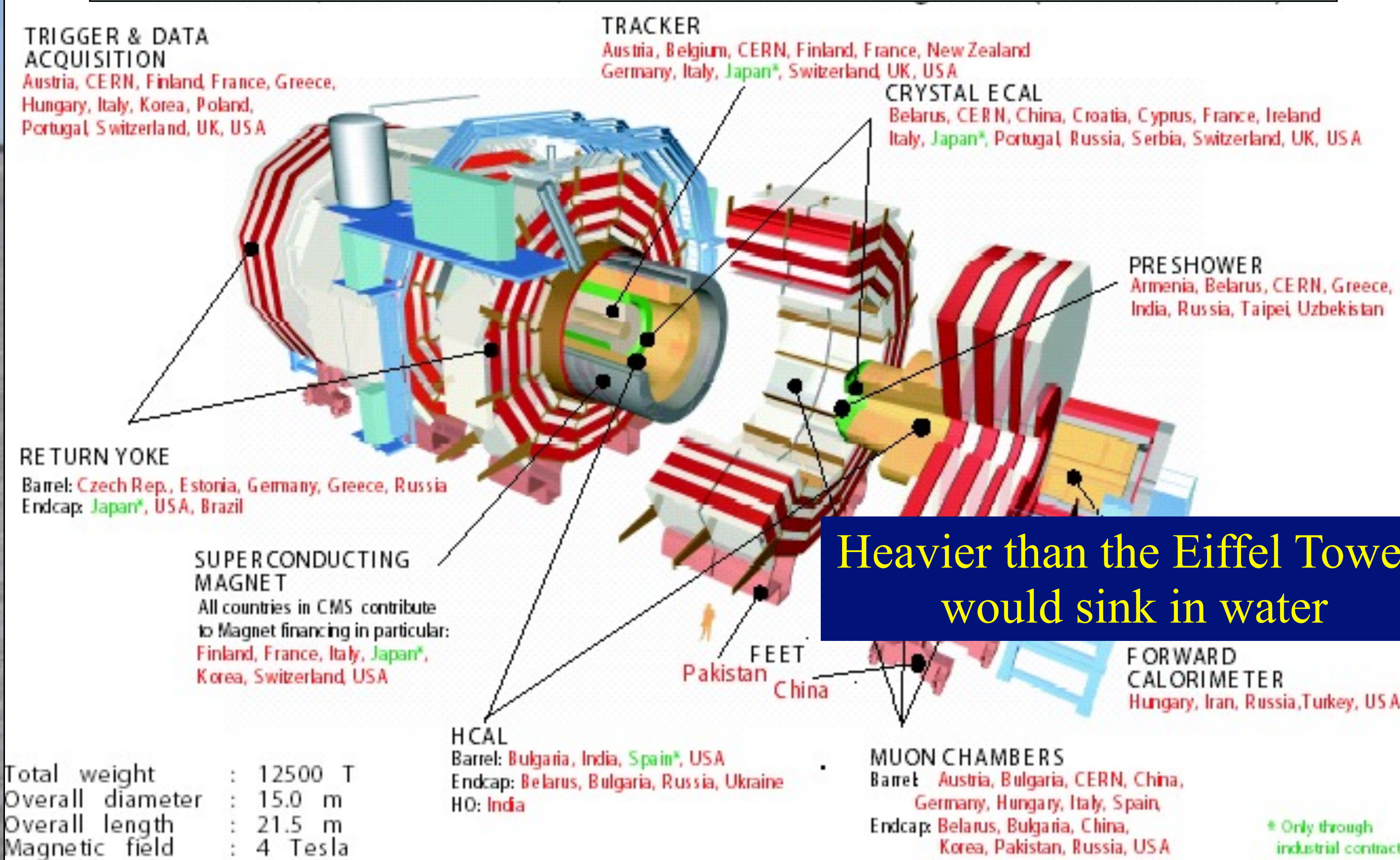

Heavier than the Eiffel Tower: would sink in water

The CMS detector:
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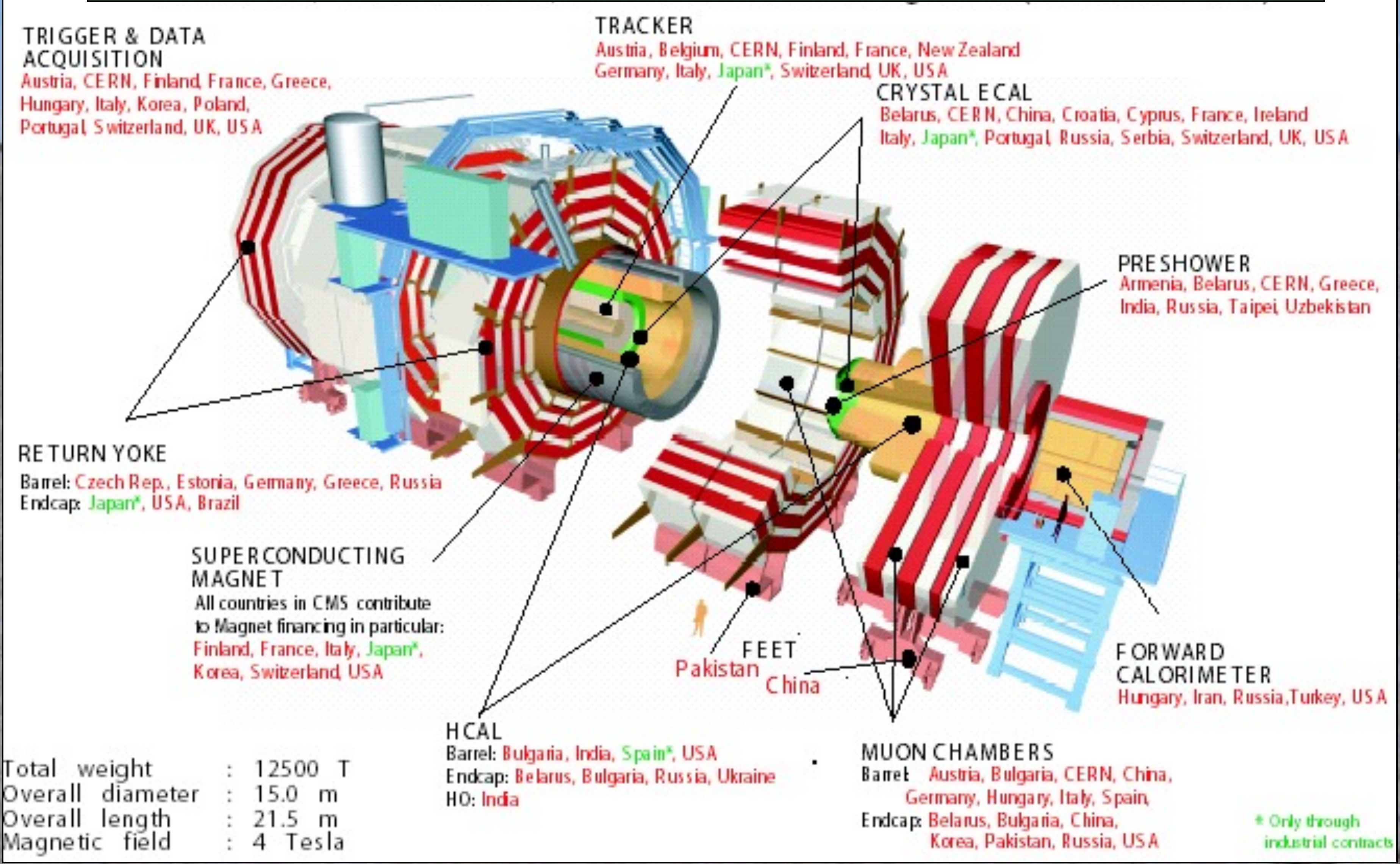

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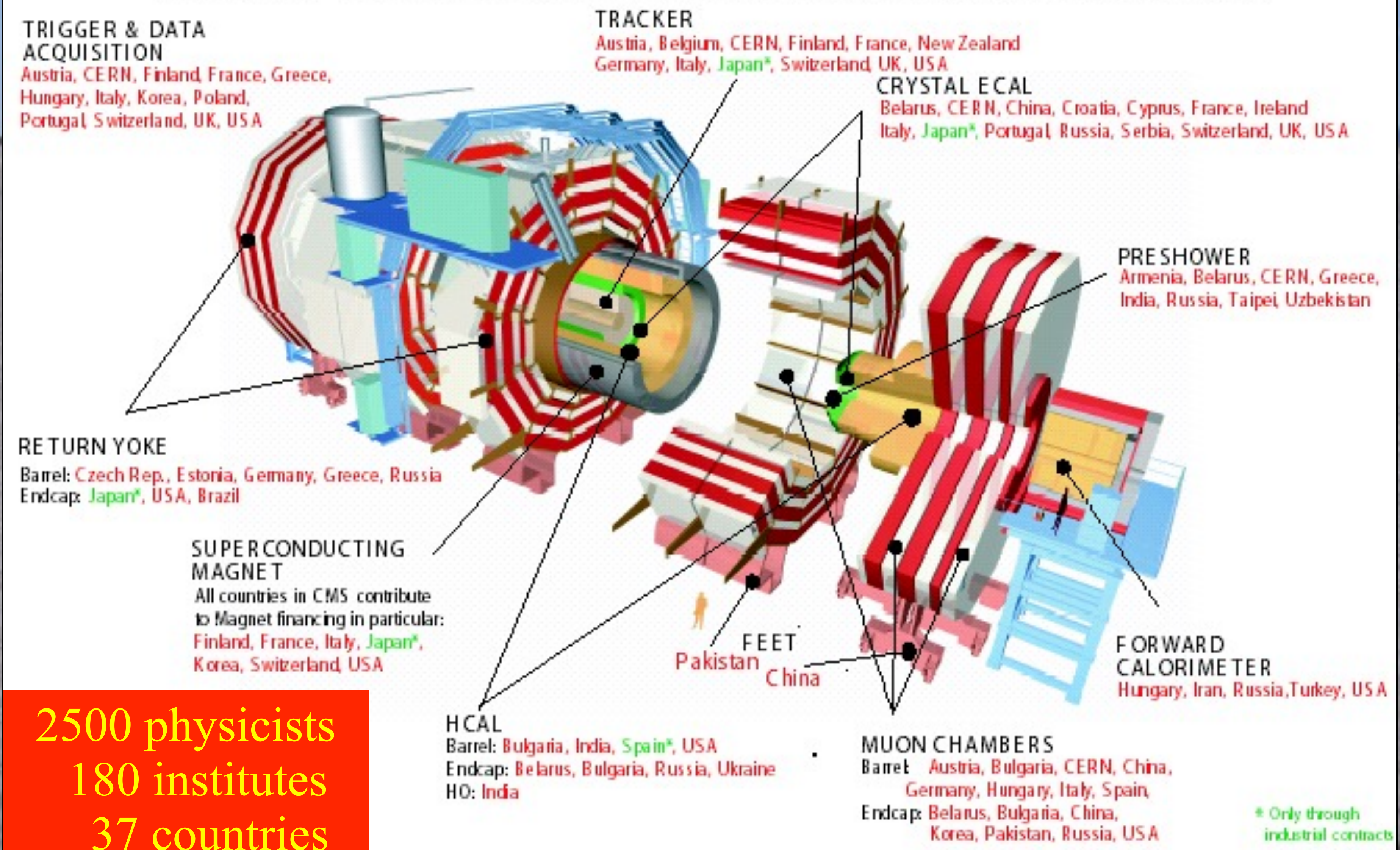
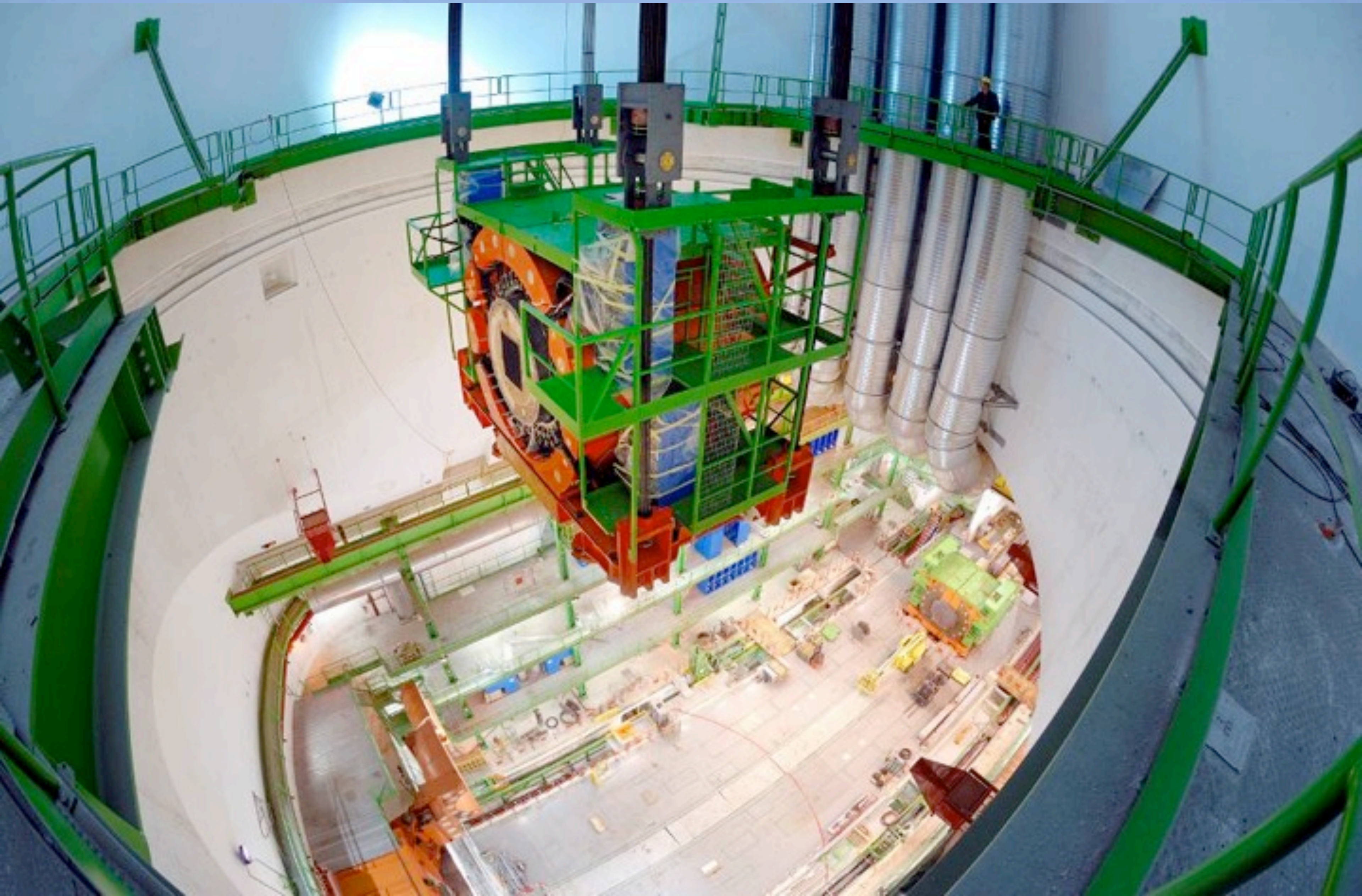


2500 physicists
180 institutes
37 countries

Constructing CMS

Constructing CMS



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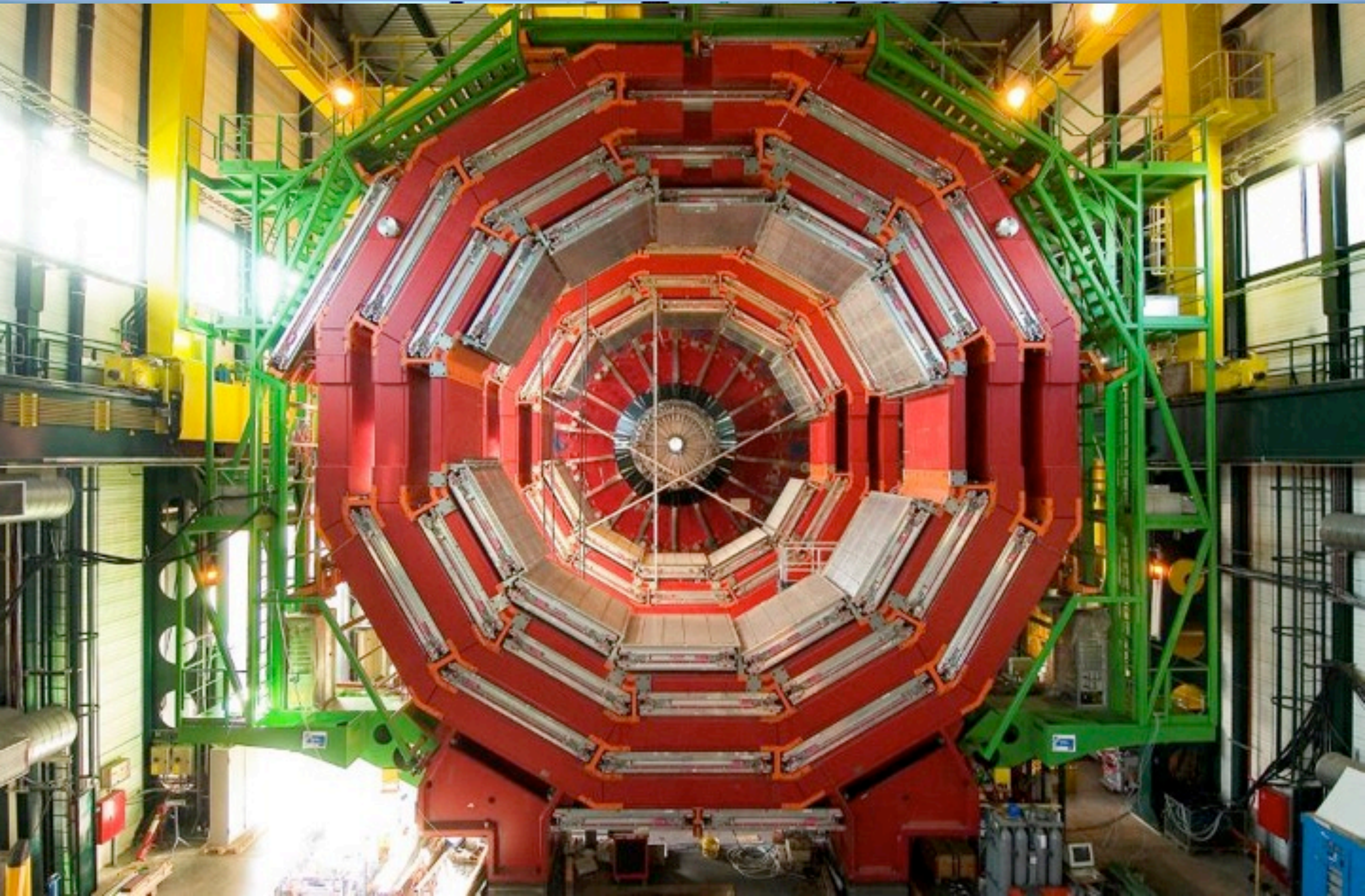

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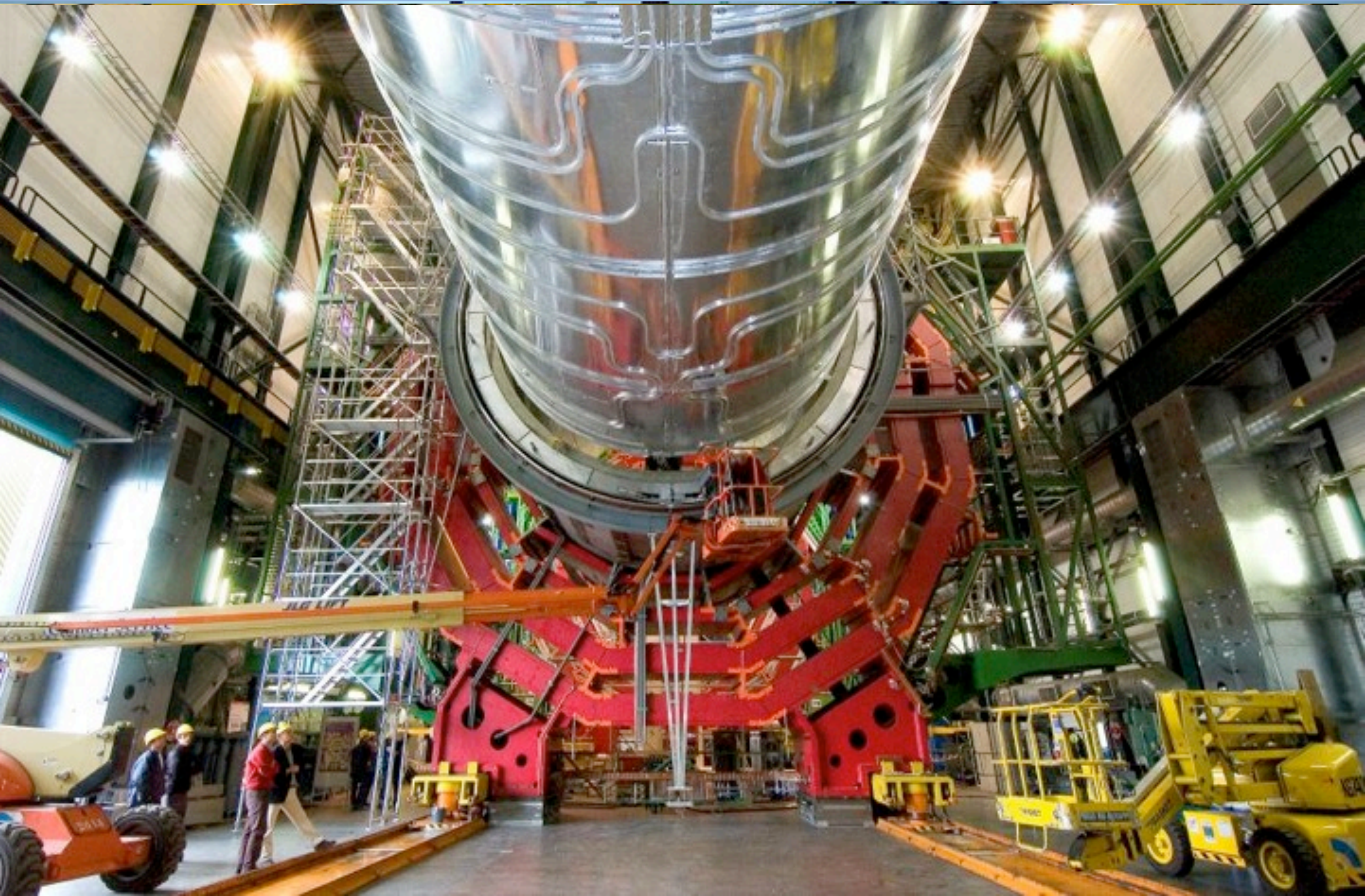

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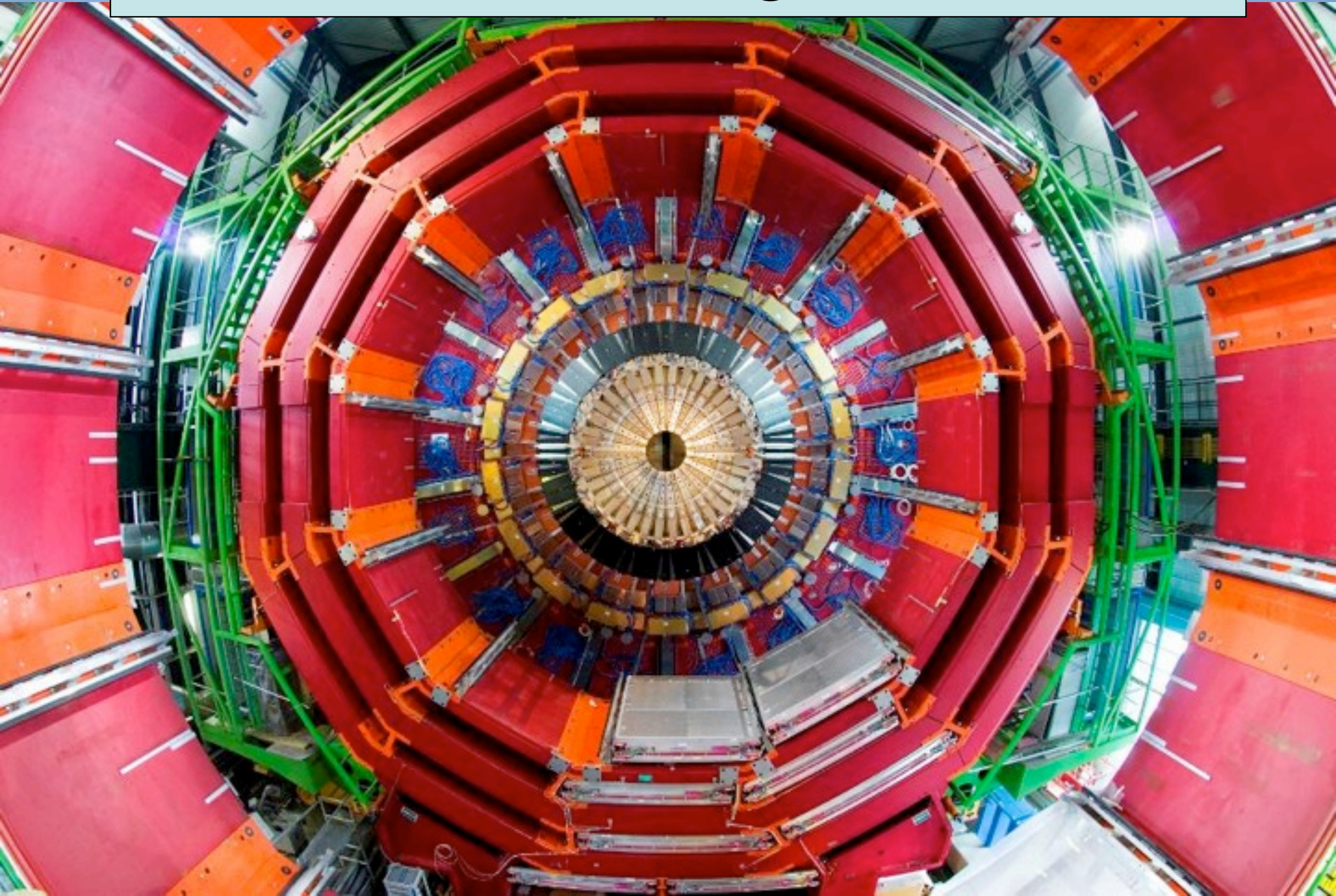

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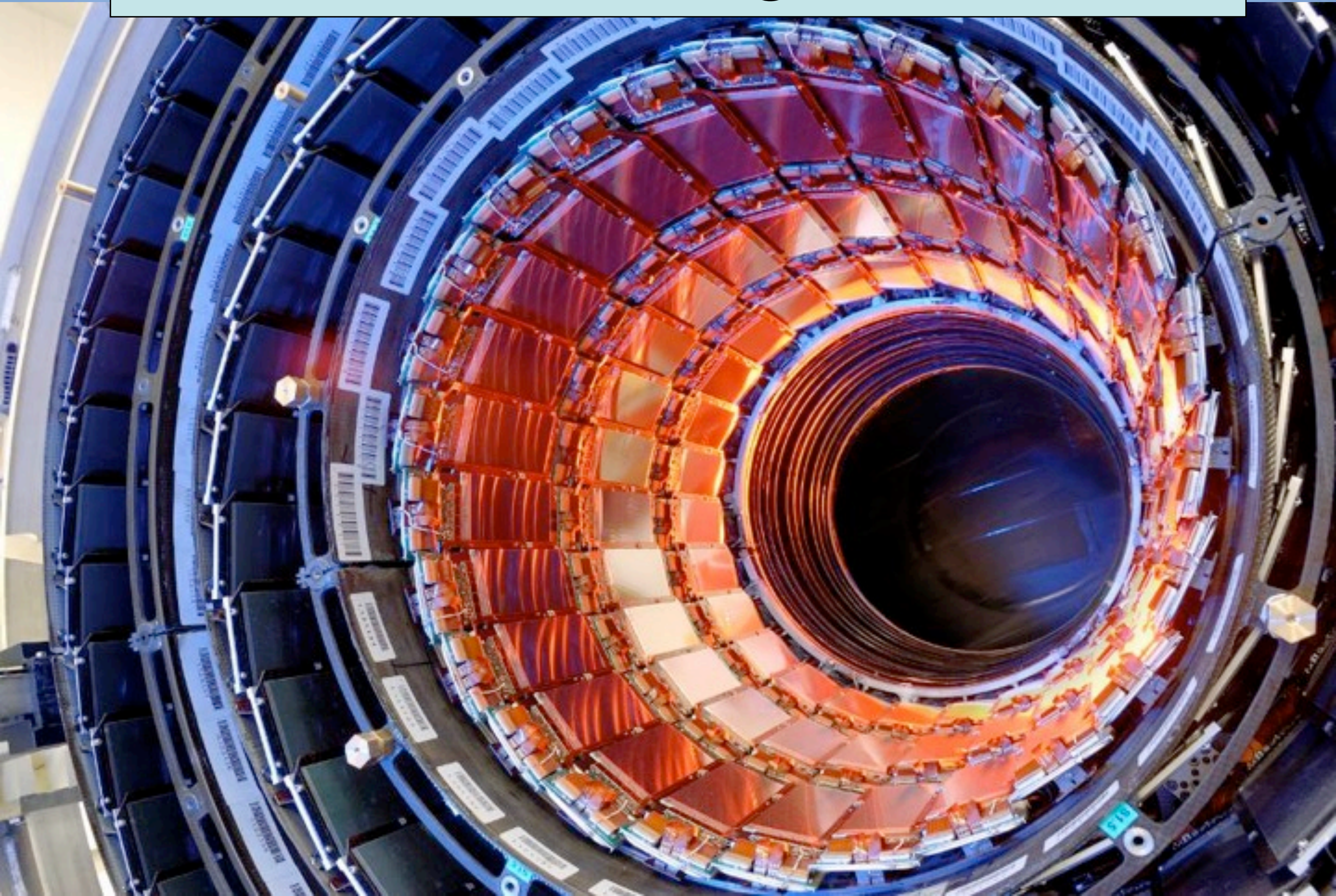
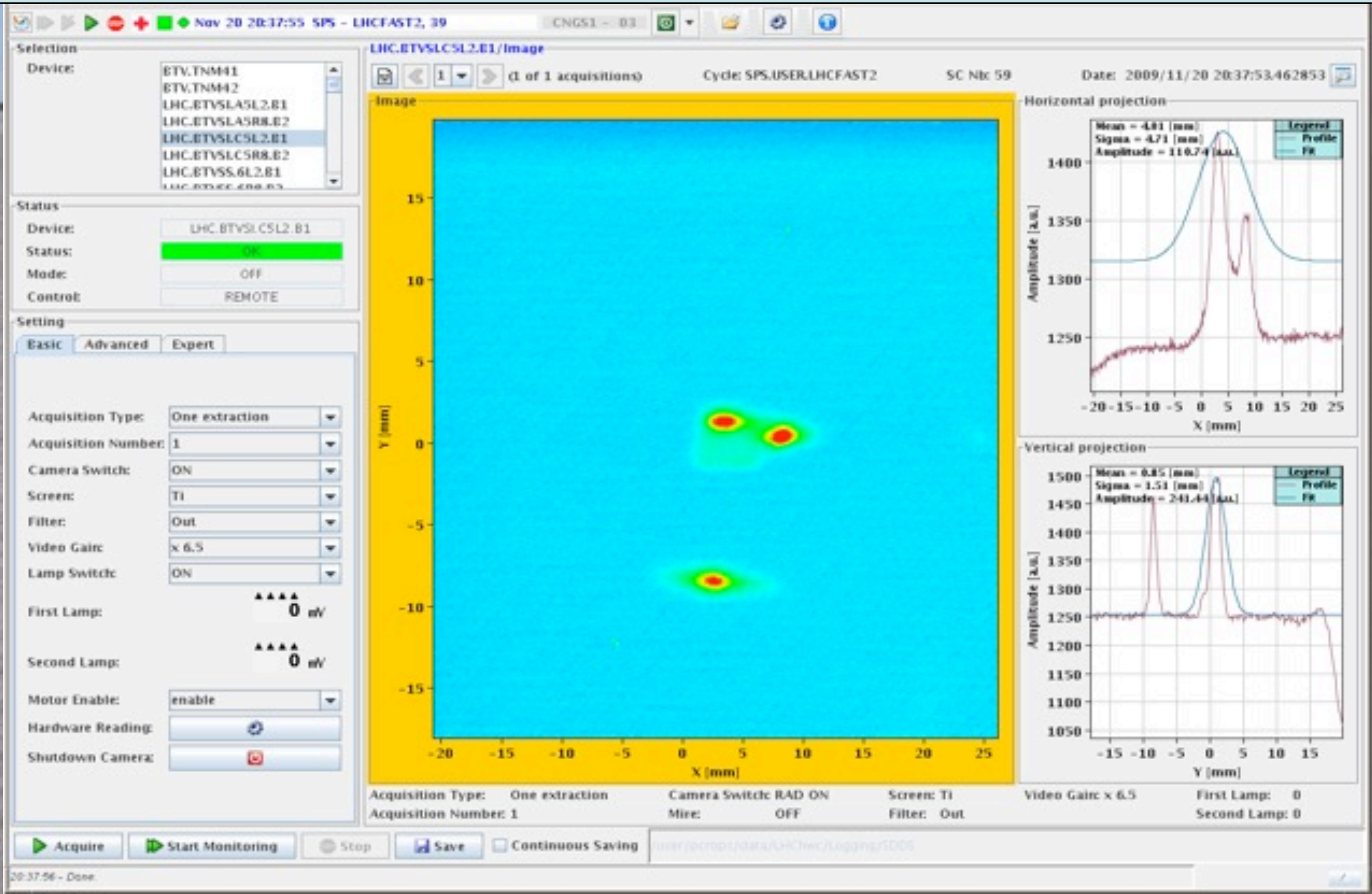


Constructing CMS

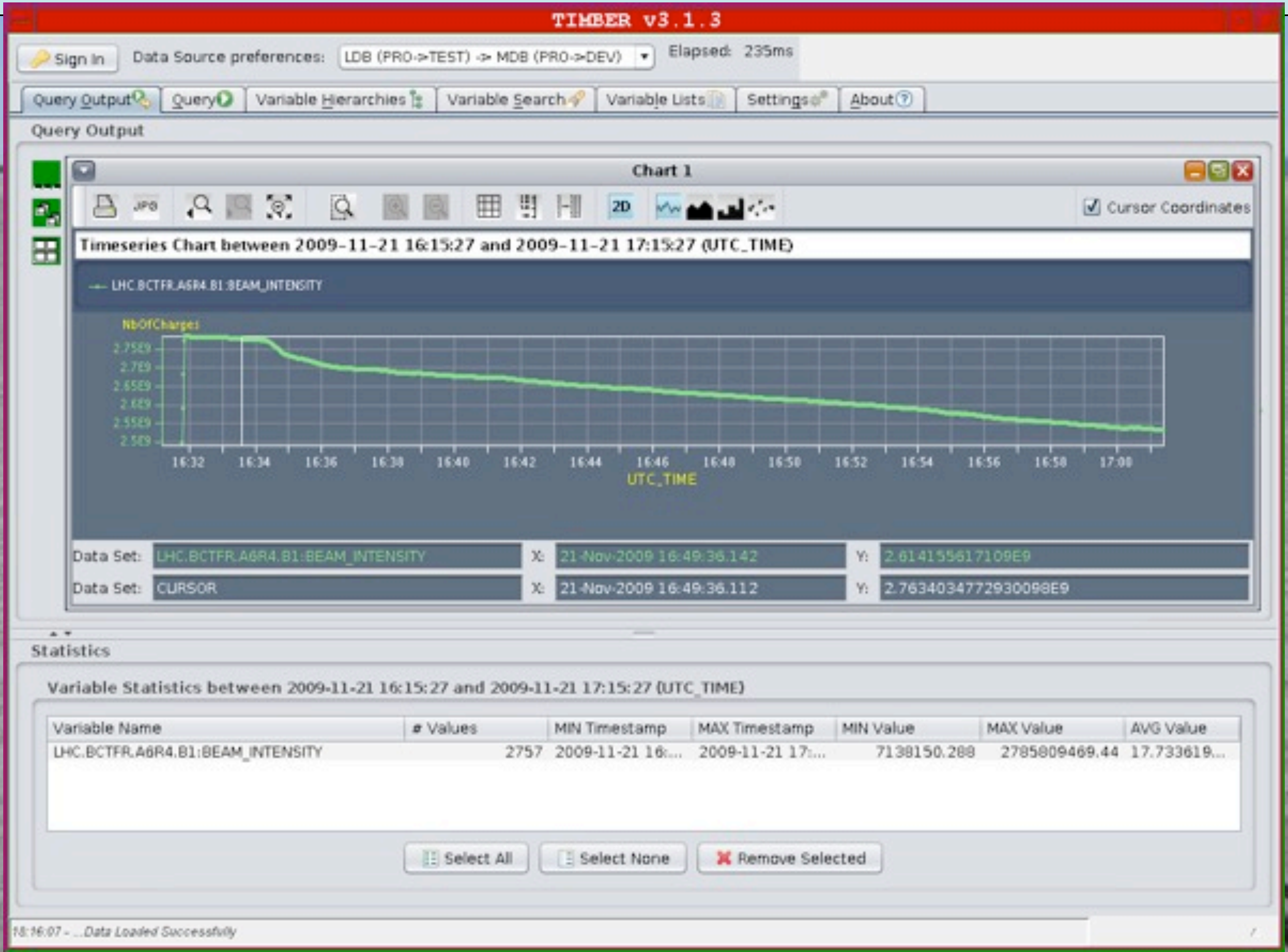
Constructing CMS

Similar crystals used in medical applications

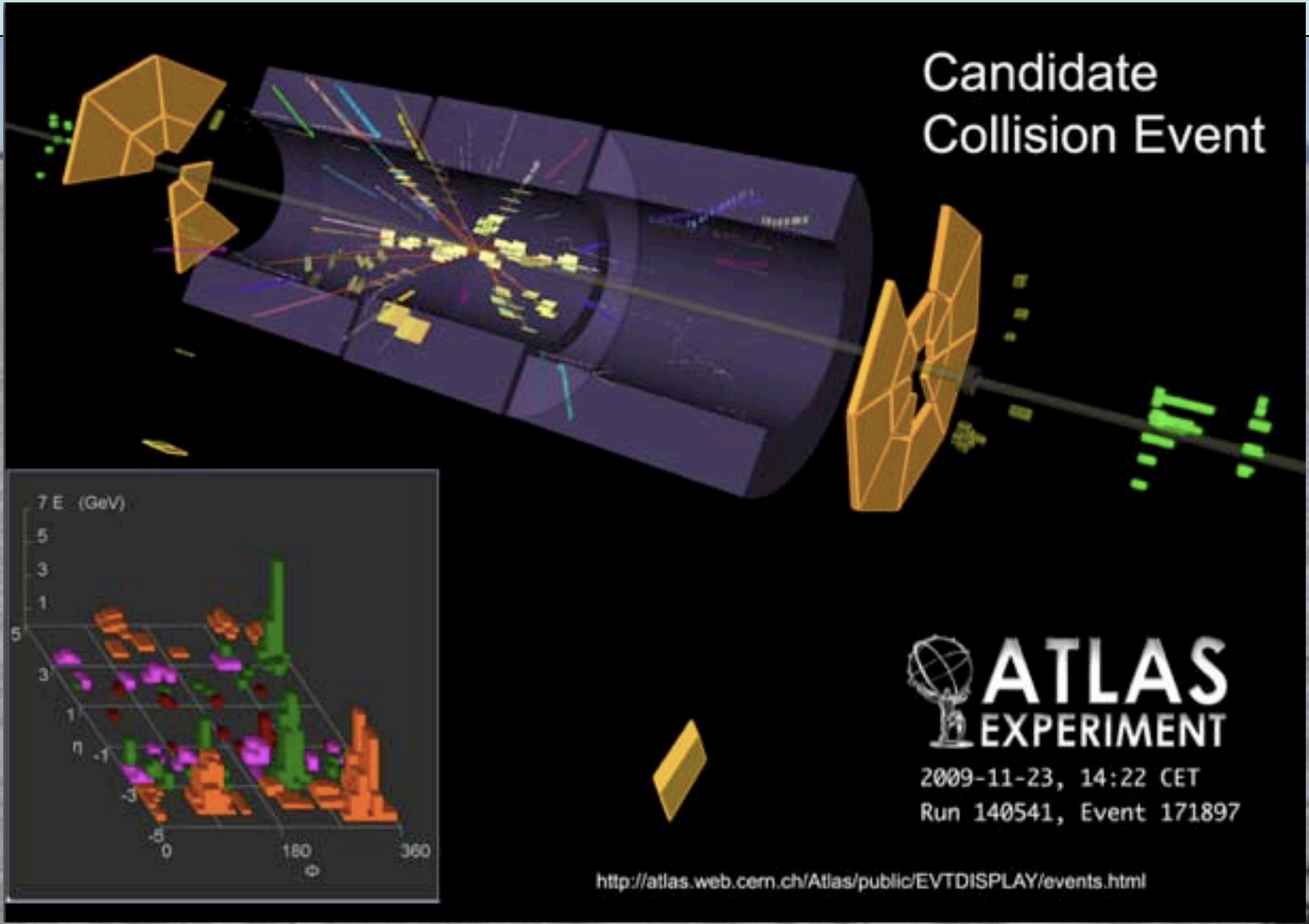
First 2009 Beam Circuits: Friday Nov. 20th @ 8.15pm



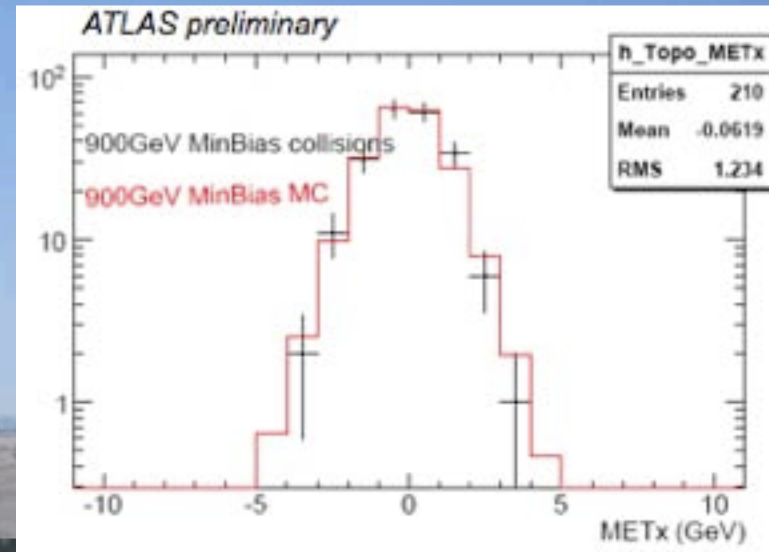
Beam Lifetime ~ 10 Hours



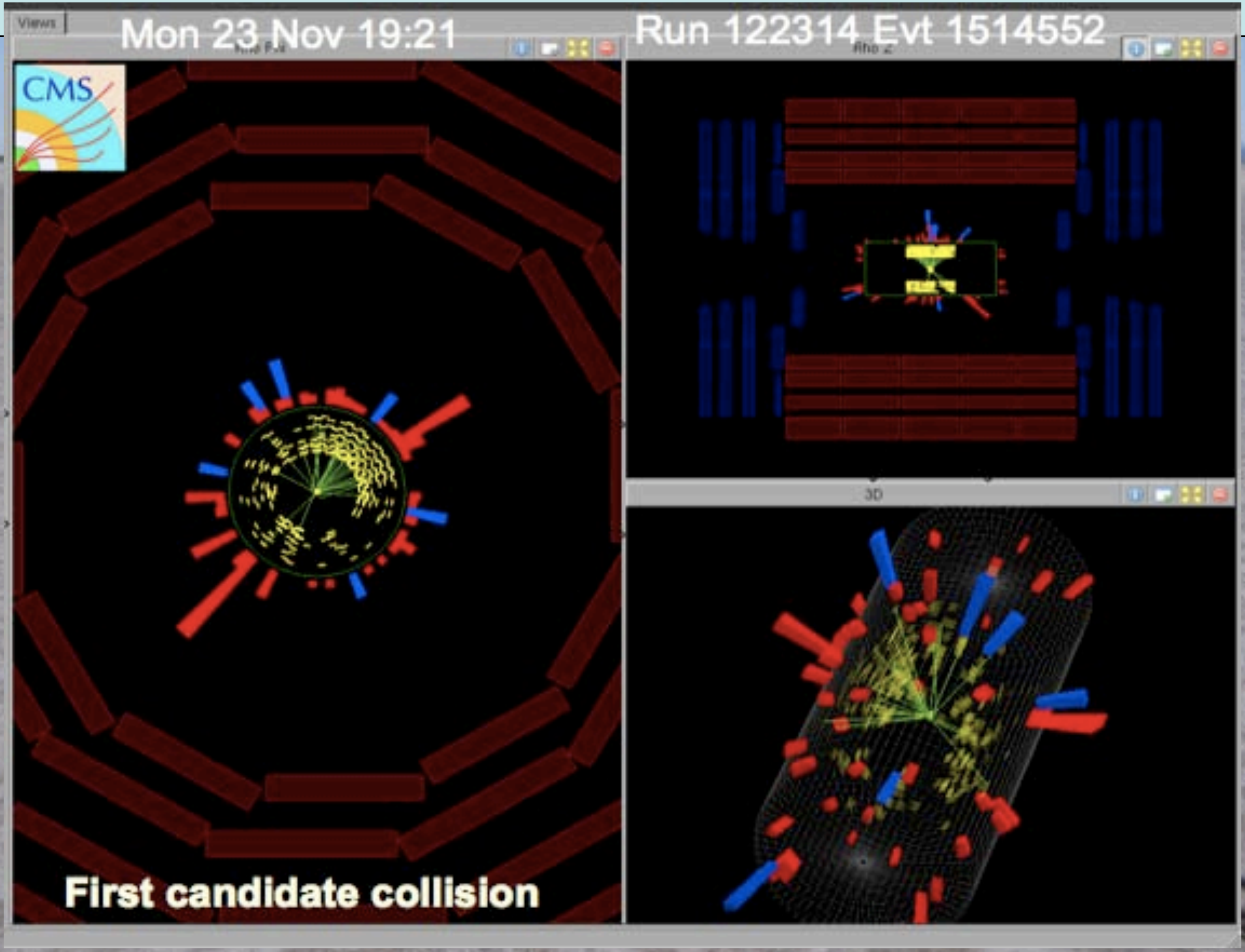
First LHC Collision in ATLAS



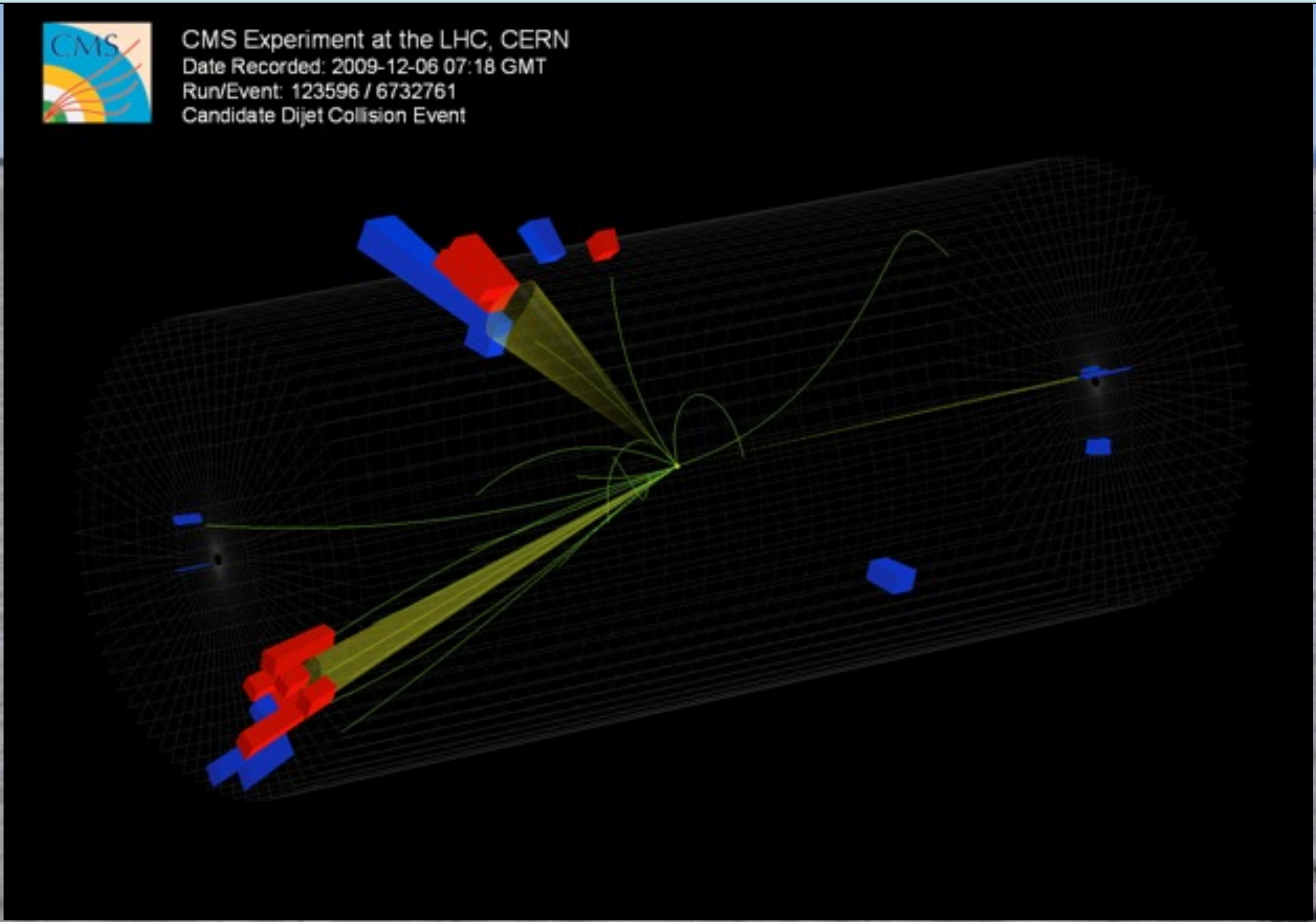
No Supersymmetry yet!



Collision in CMS

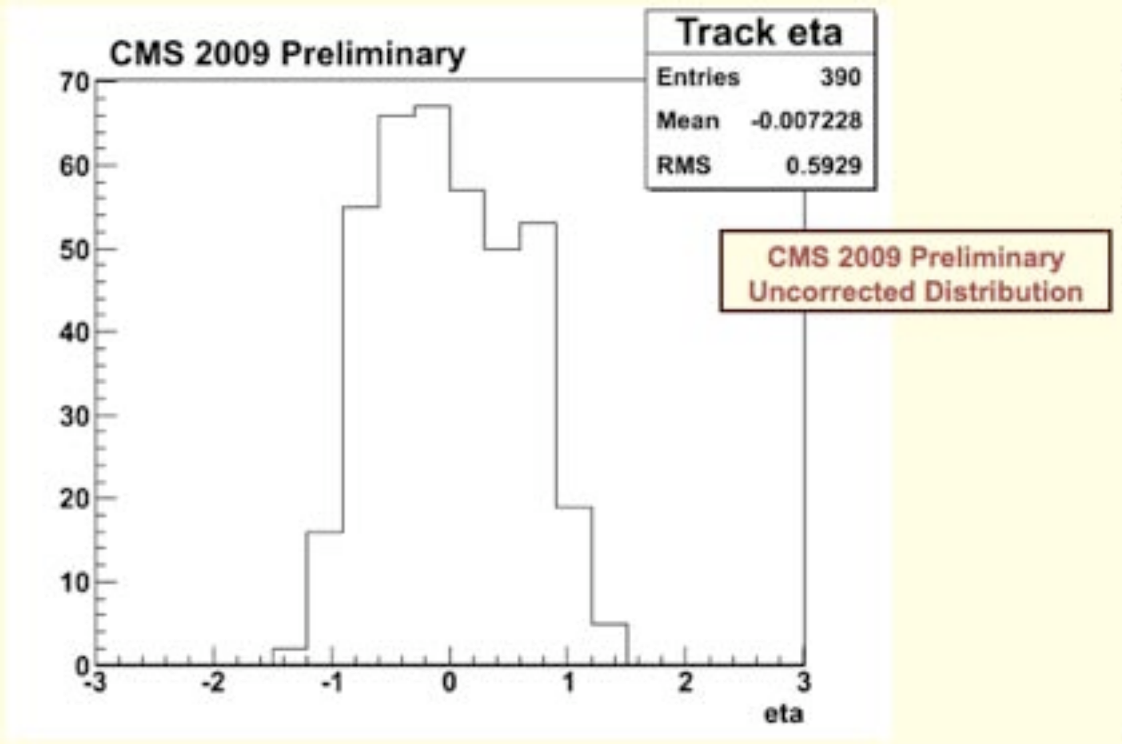


Two-Jet Event in CMS

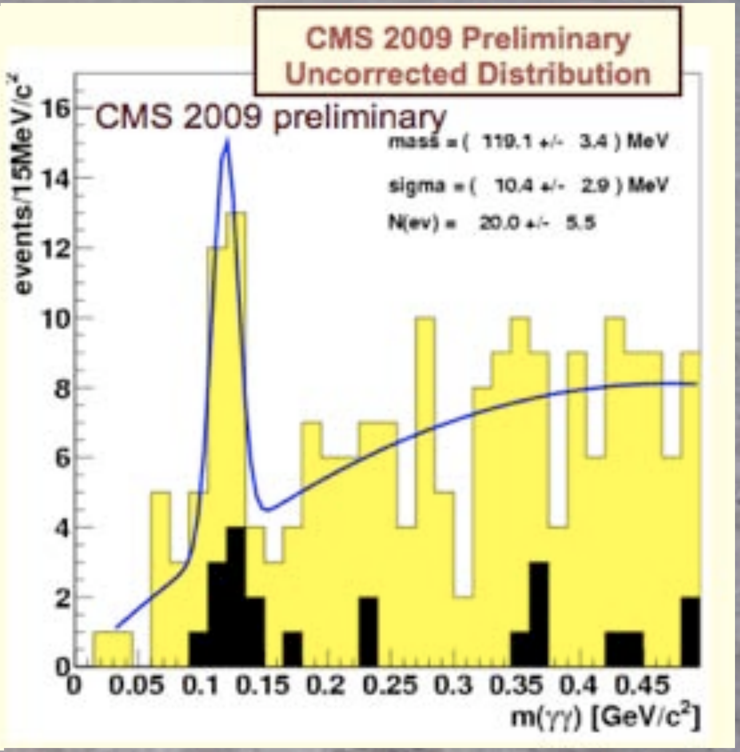


No Higgs yet!

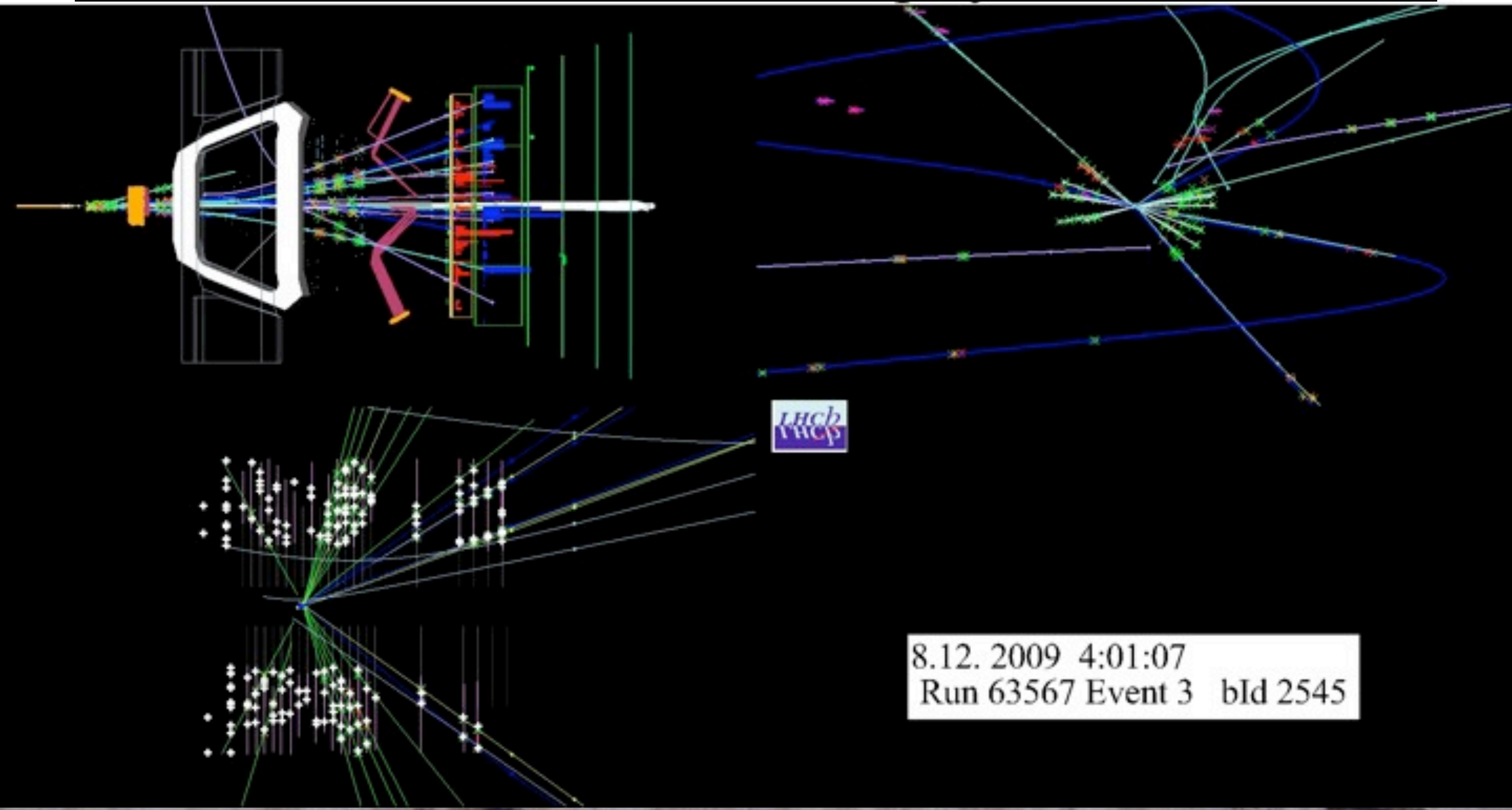
Pseudo-rapidity distribution



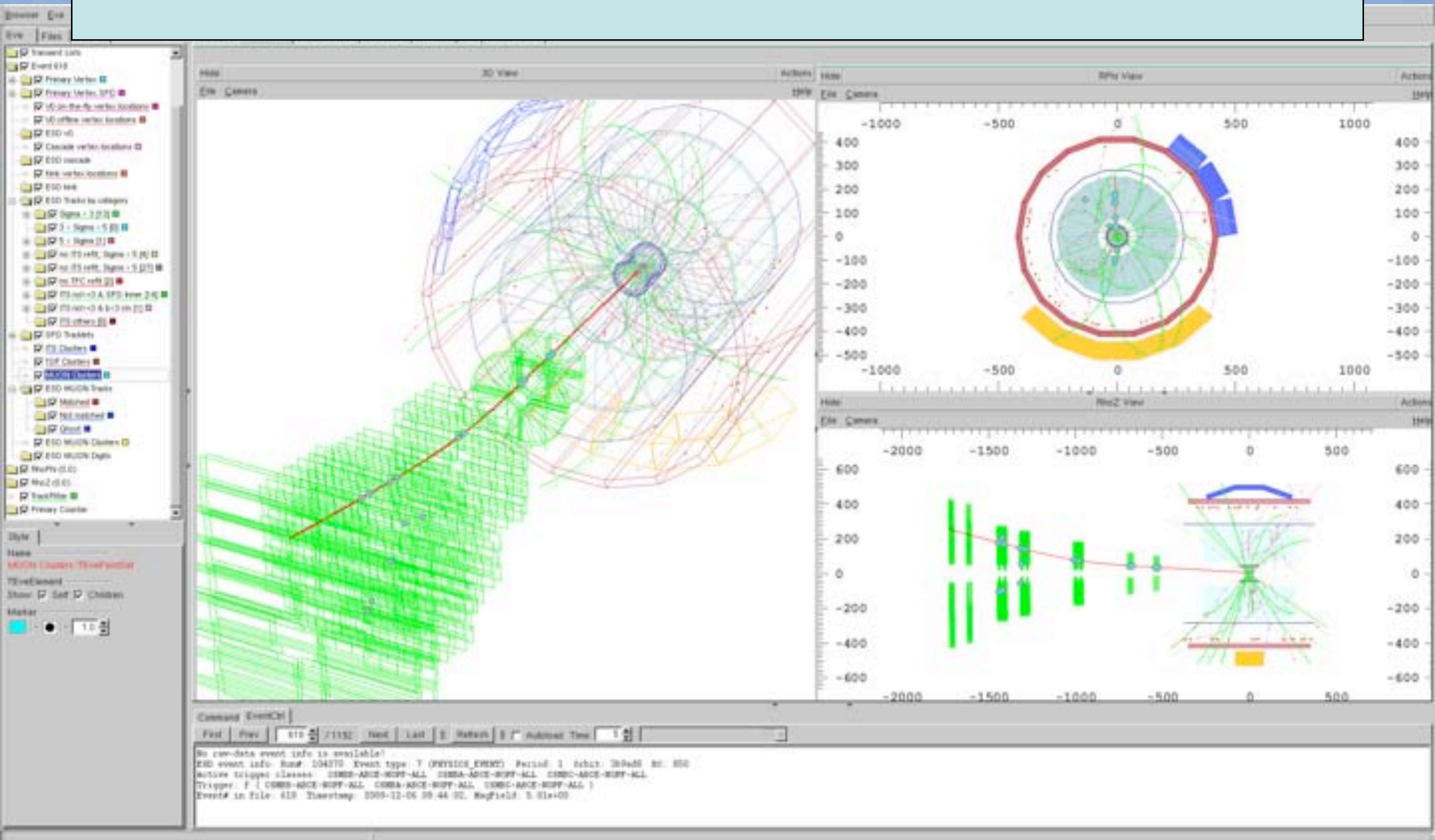
γγ invariant mass distribution



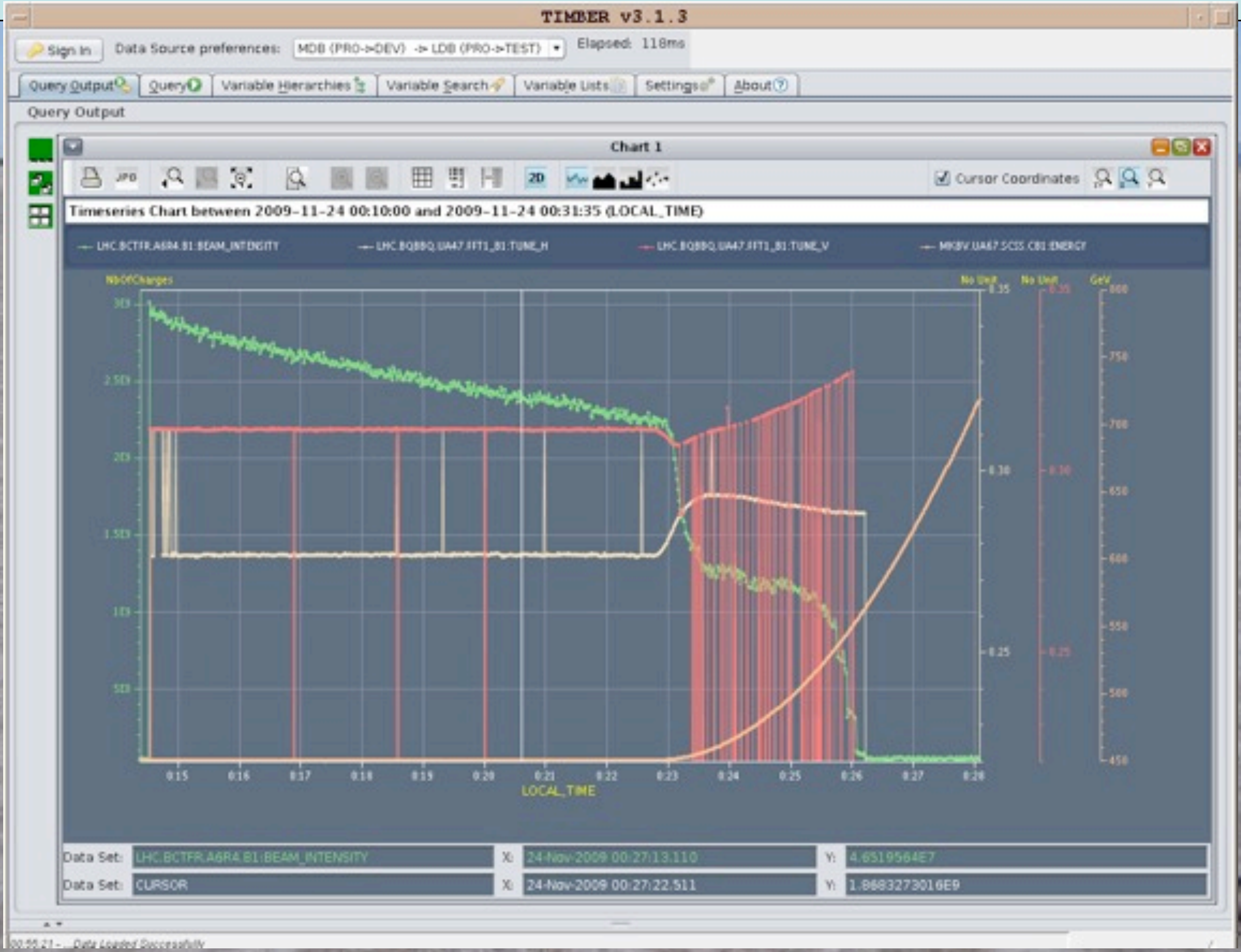
Collision in LHCb



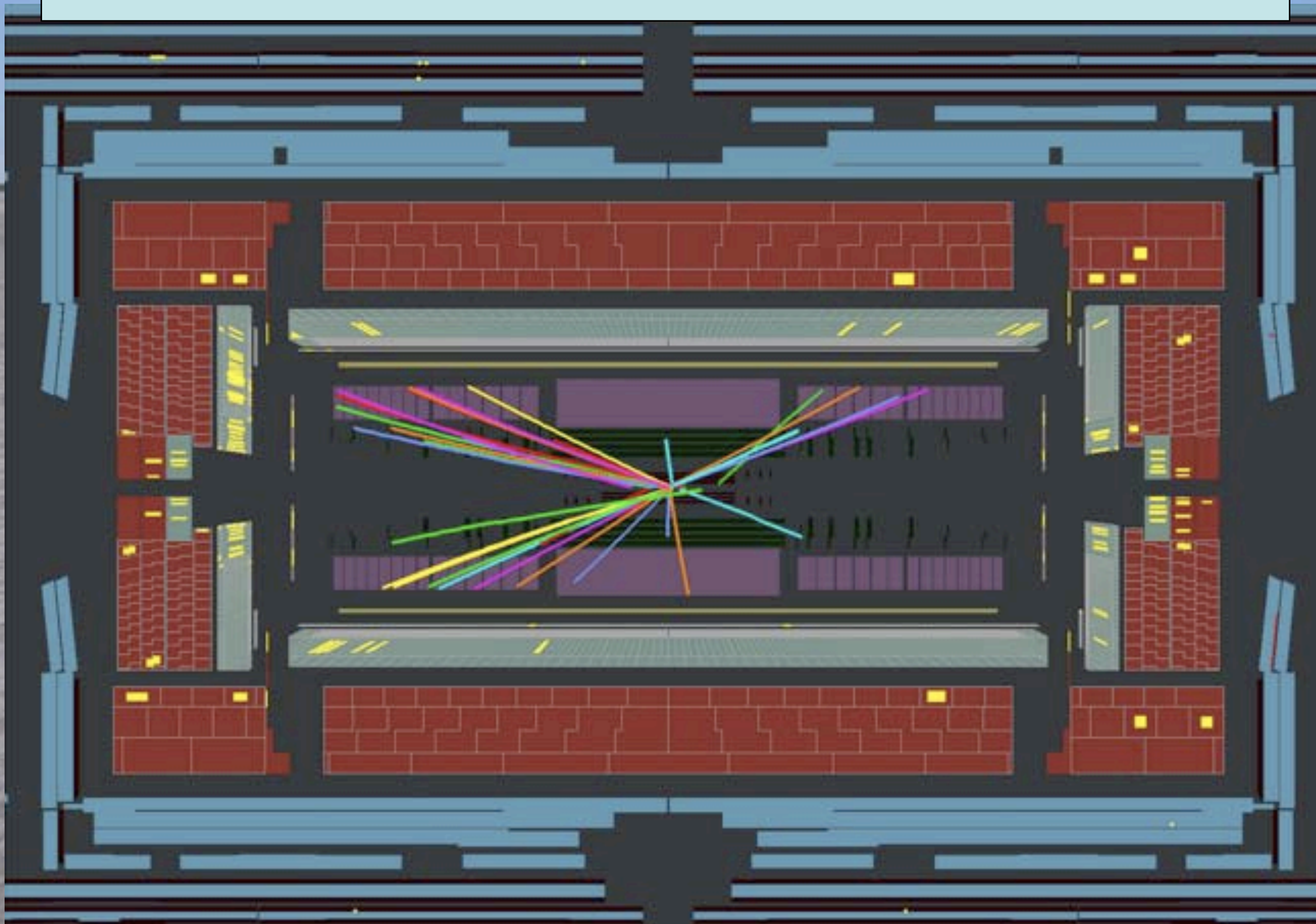
Collision in ALICE



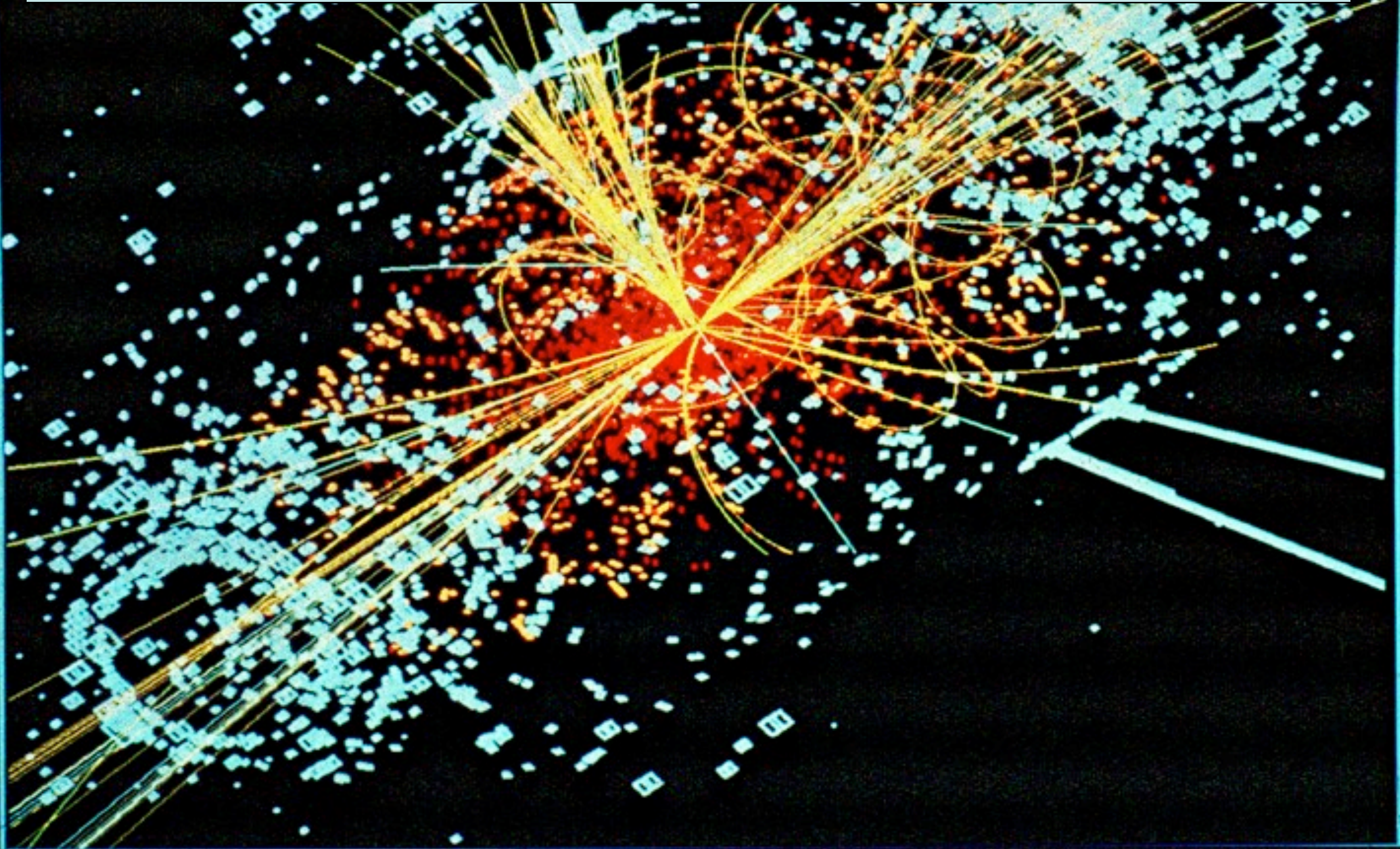
Onward & Upward: First Ramp



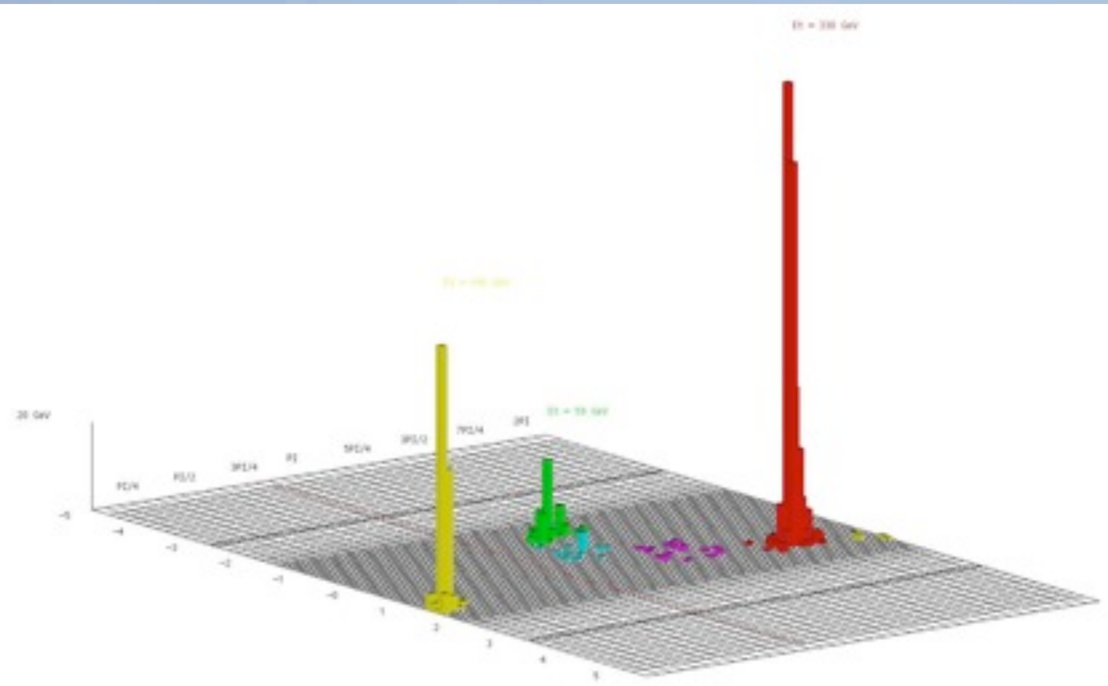
2.36 TeV Collision in ATLAS

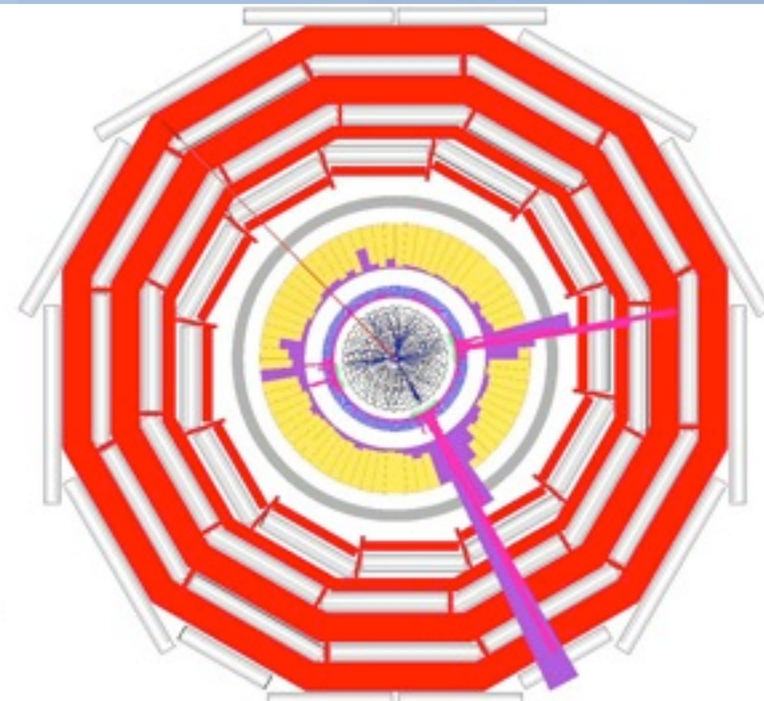


A Simulated Higgs Event



Looking for Dark Matter





Missing energy
taken away by dark matter particles

Minimal Supersymmetric Extension of Standard Model (MSSM)

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} or \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

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$$m_{3/2} = m_0, \ B_\mu = A_\lambda - m_0$$

Non-Universal Scalar Masses

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  e.g., d, s squarks?

  disfavoured by upper limits on flavour- changing neutral interactions

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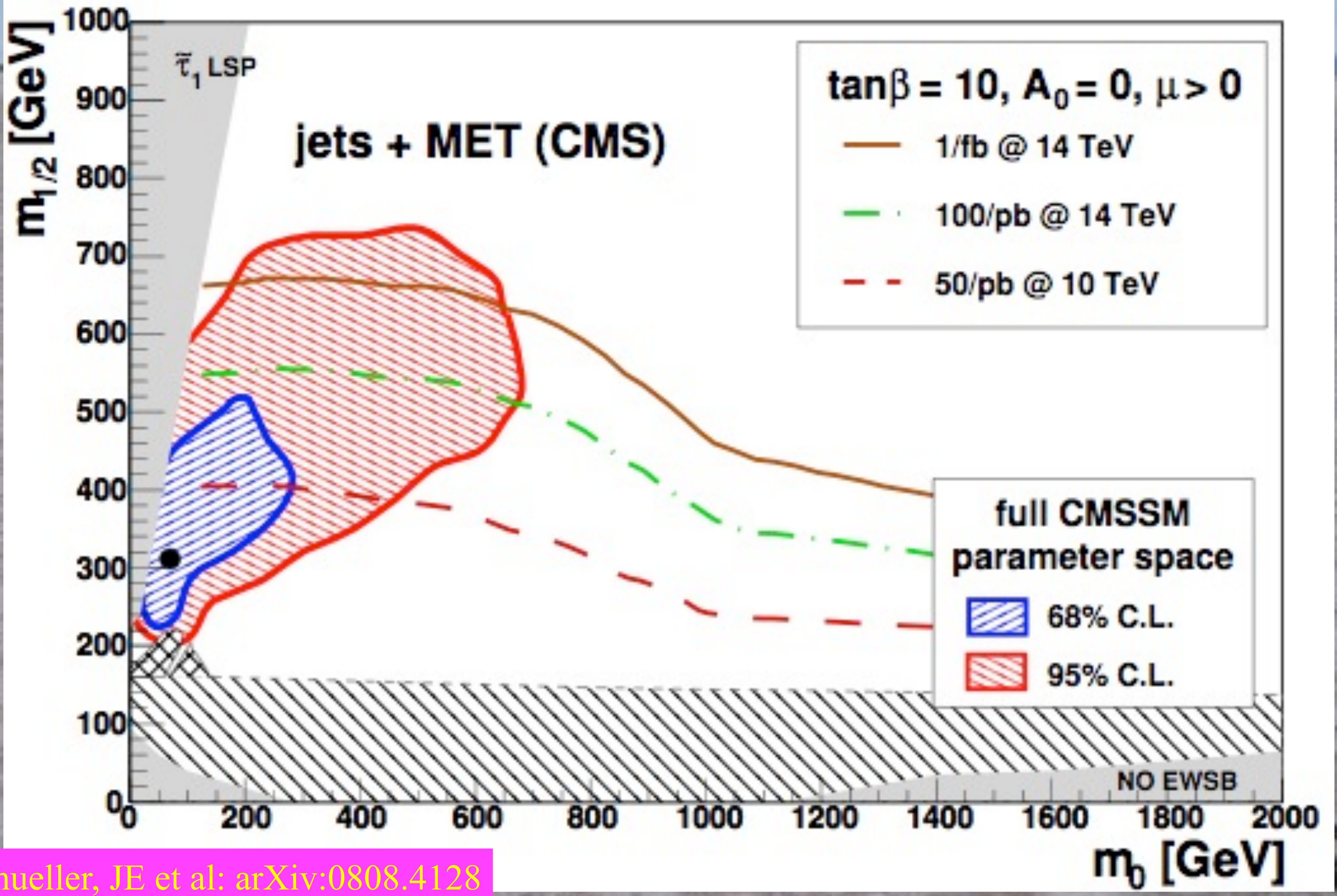
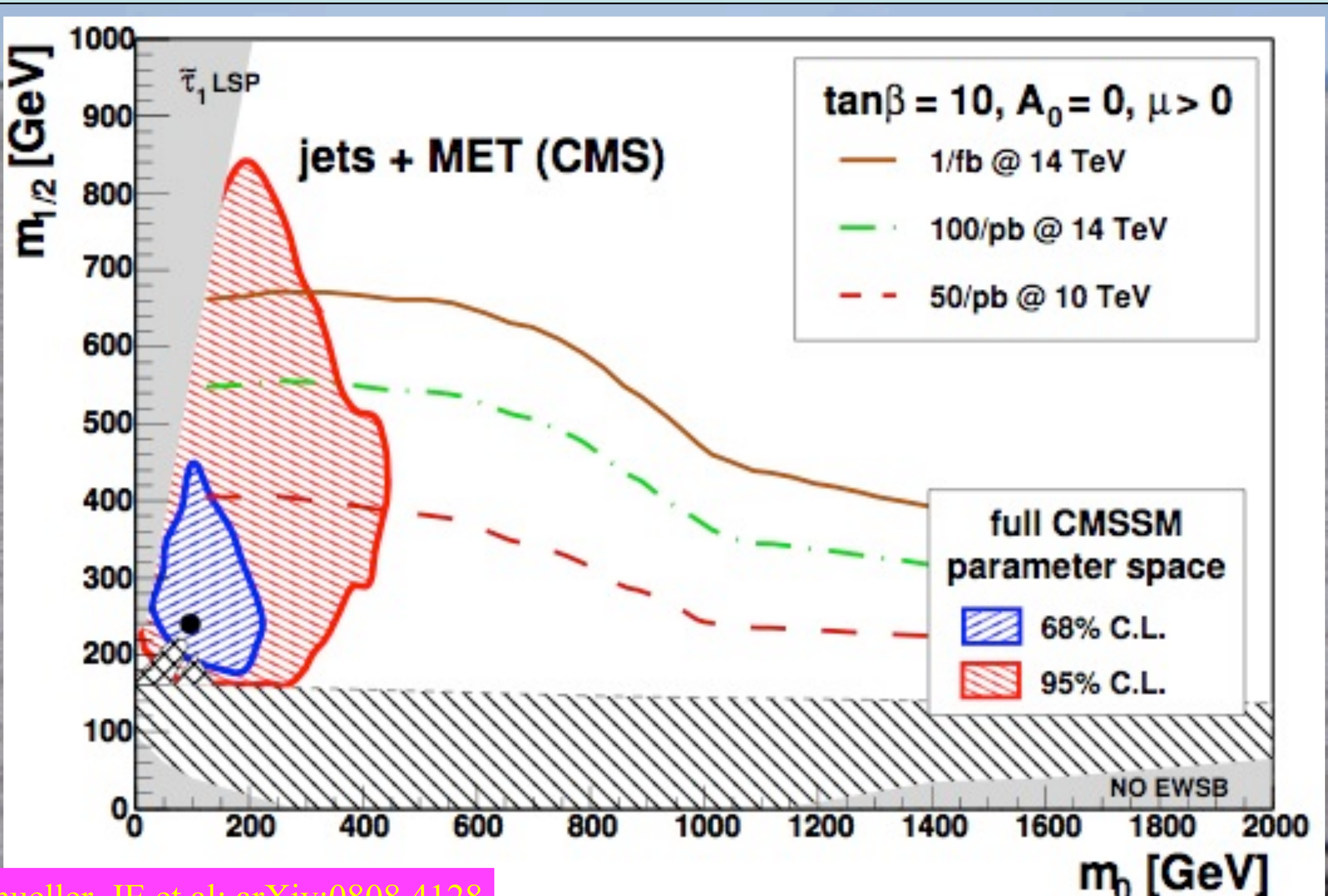
  Why not! 1 or 2 extra parameters in NUHM1,2

How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

How Soon Might the NUHM1 be Detected?



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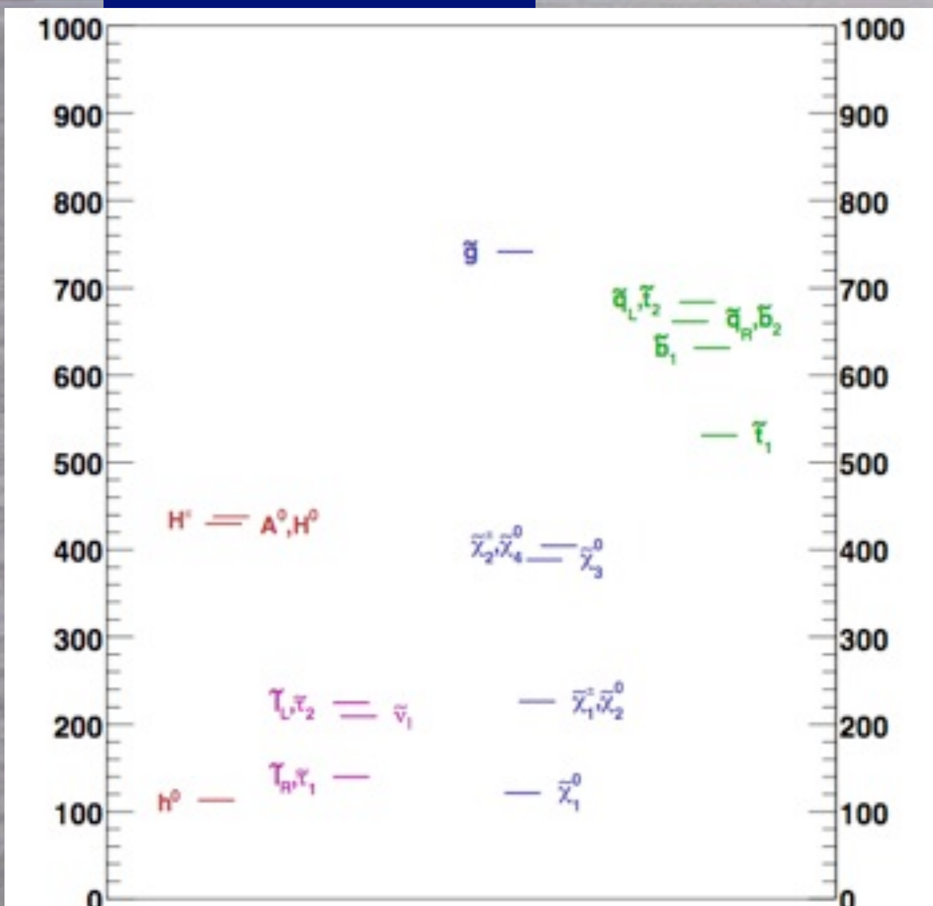
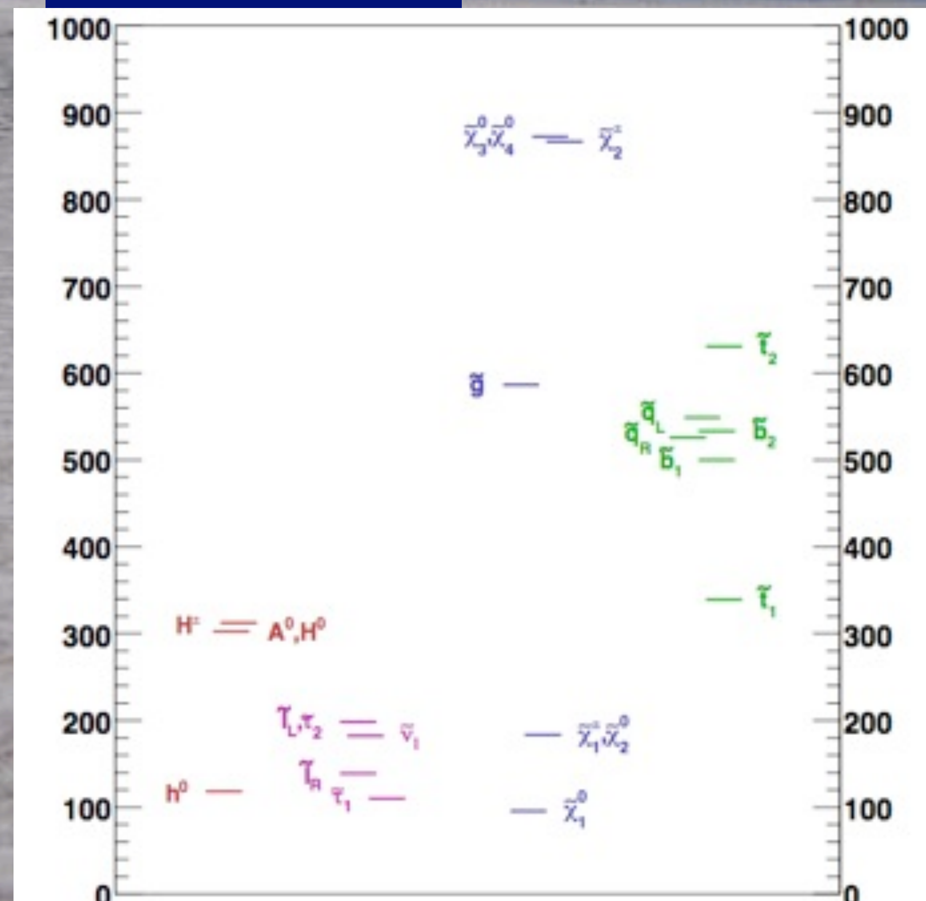
Best-Fit Spectra

CMSSM



NUHM1



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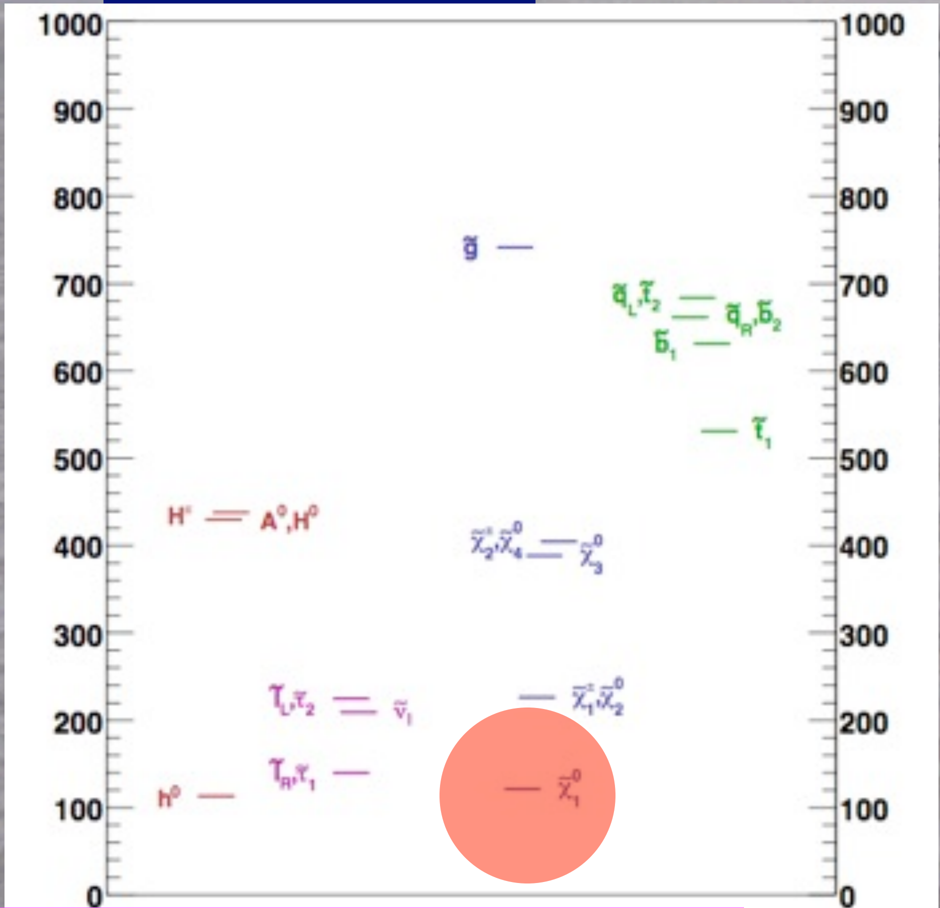
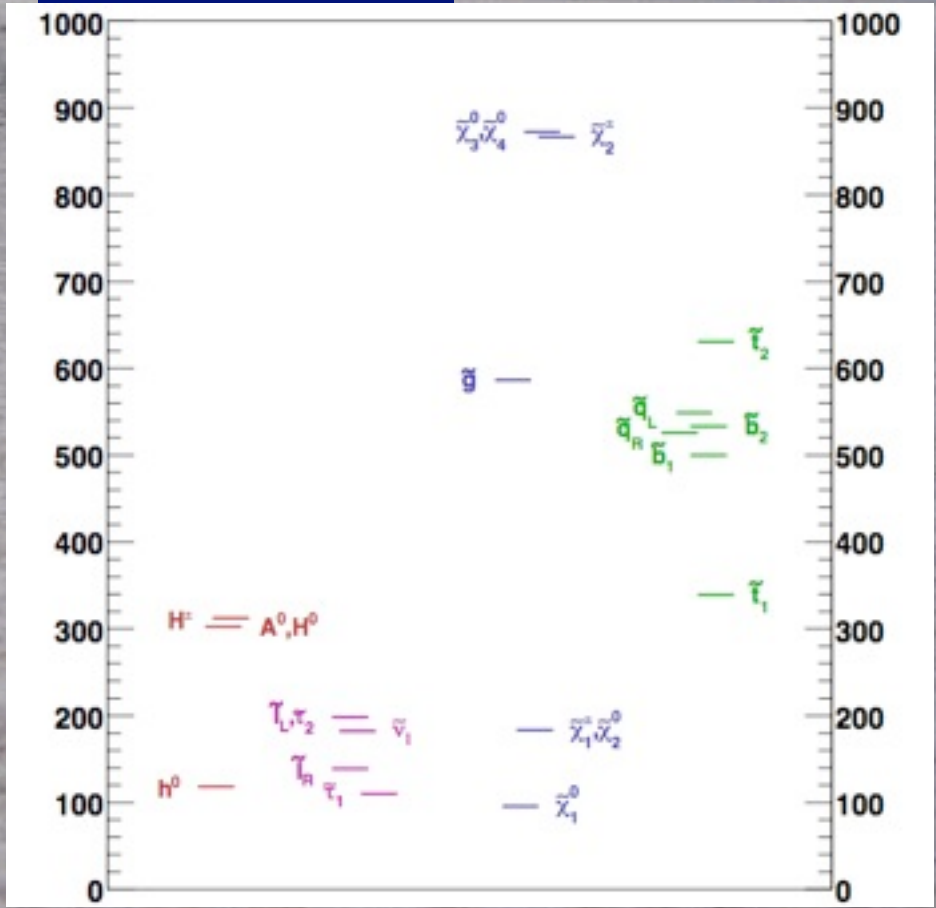


NUHM1



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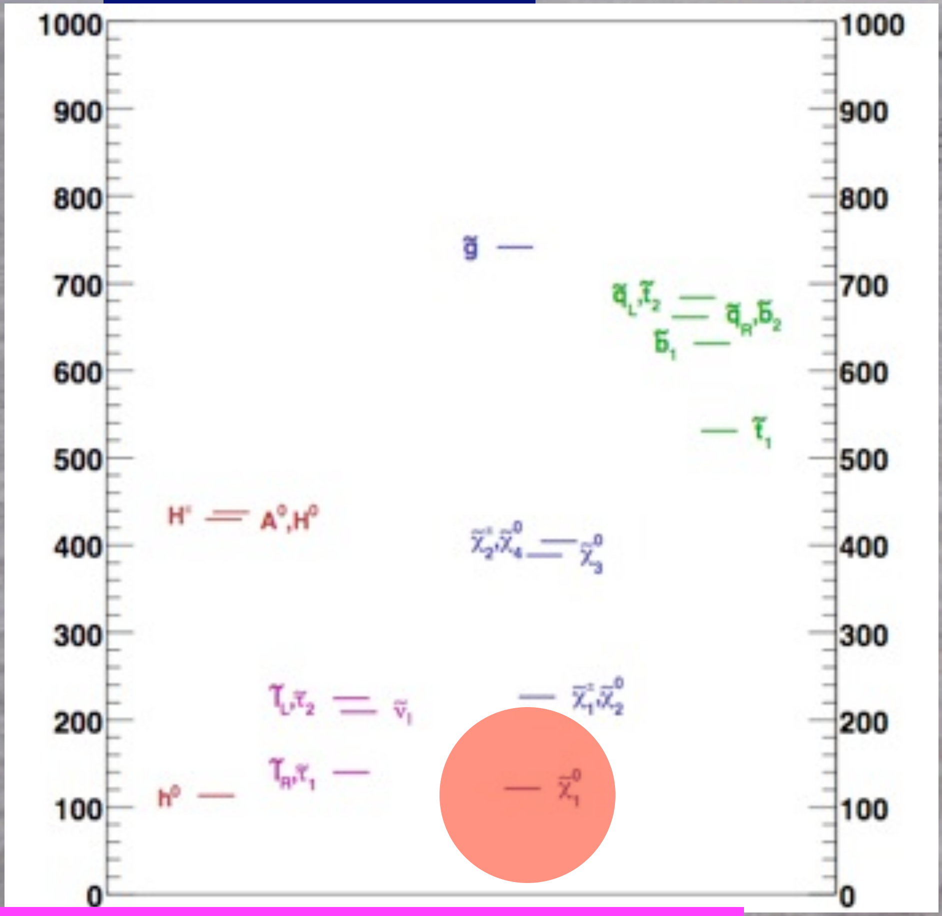
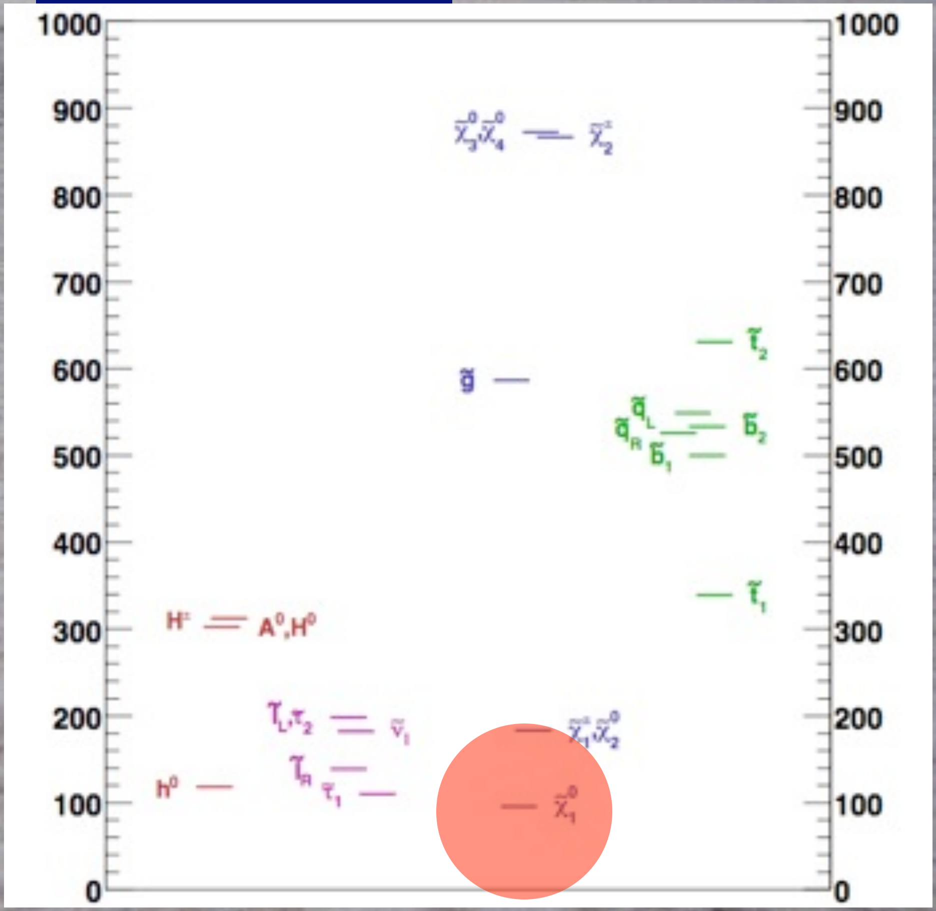


NUHM1



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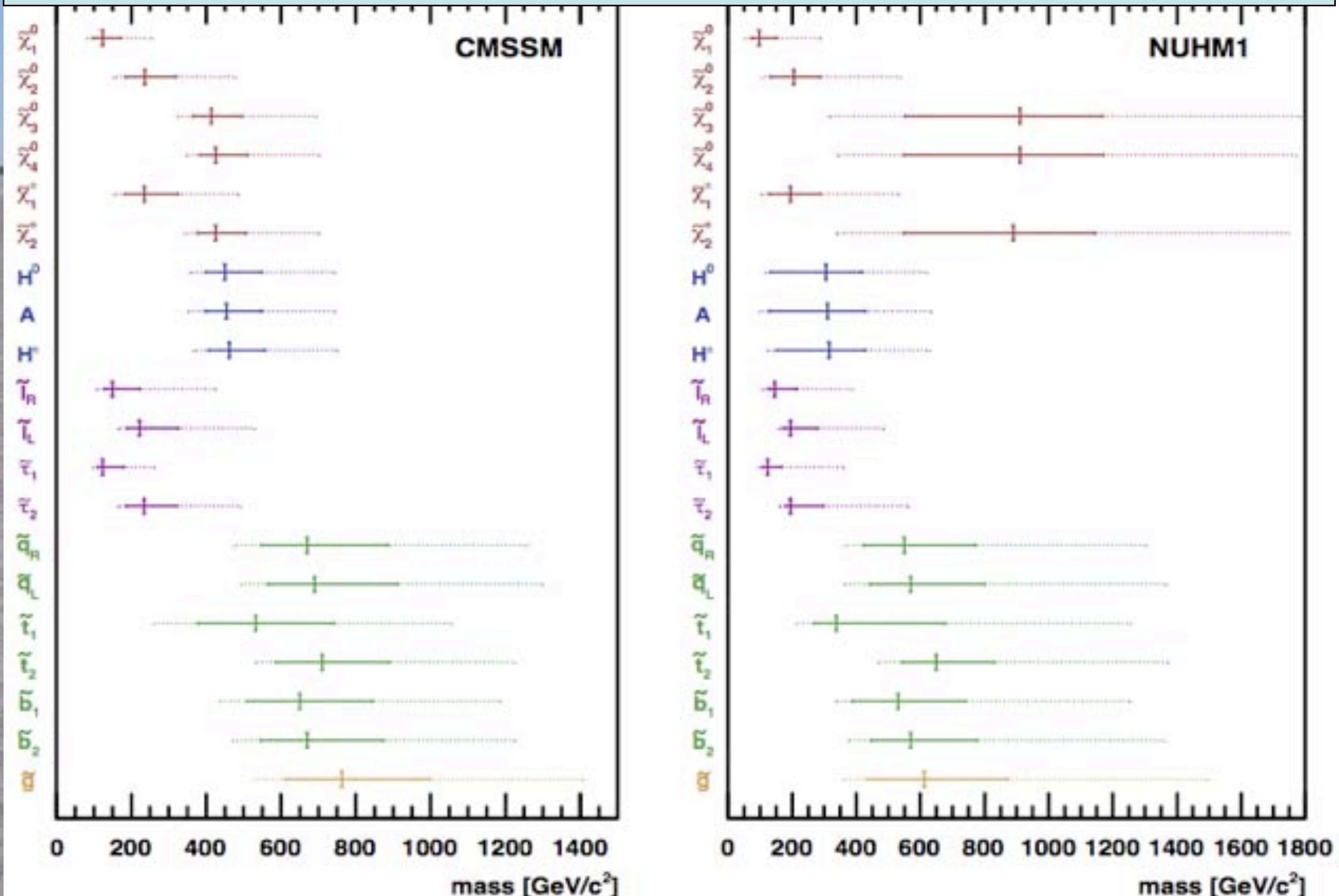
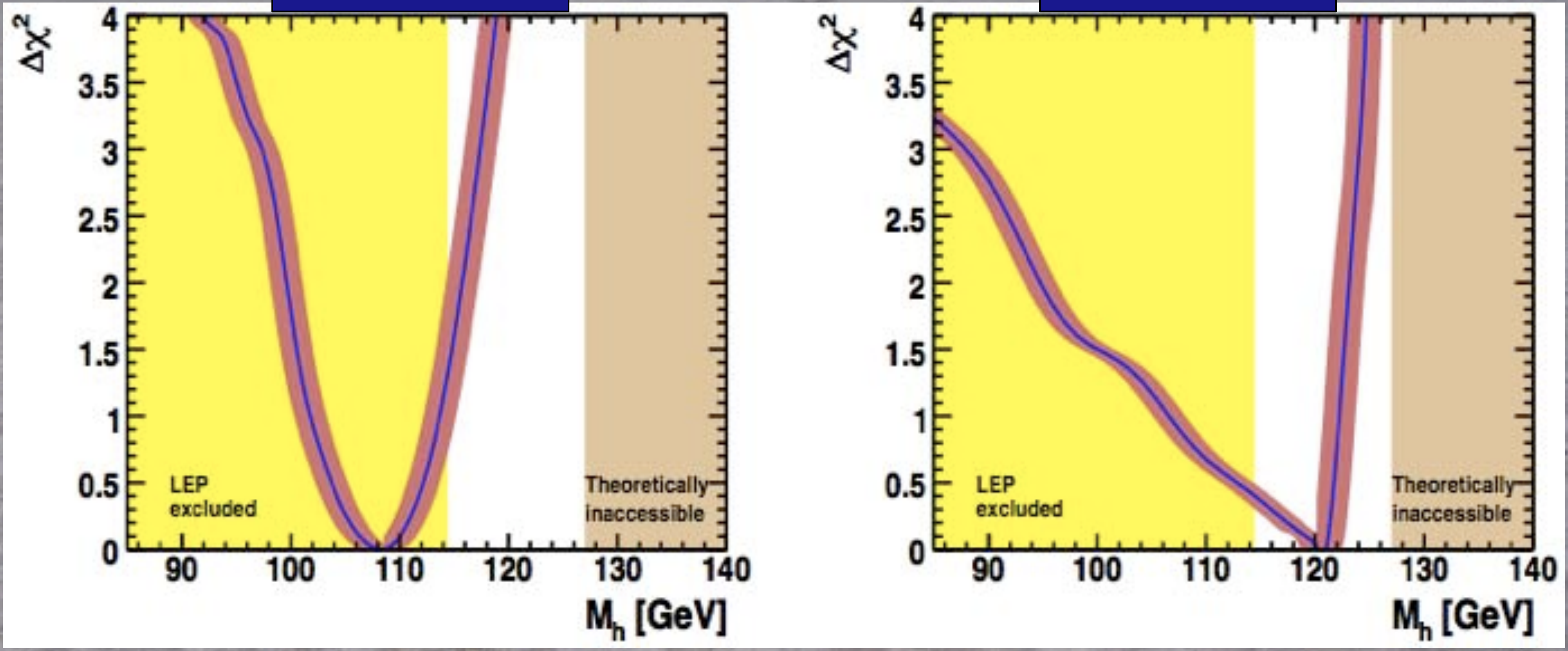
Spectra with likely Ranges



O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for Higgs Mass

CMSSM NUHM1



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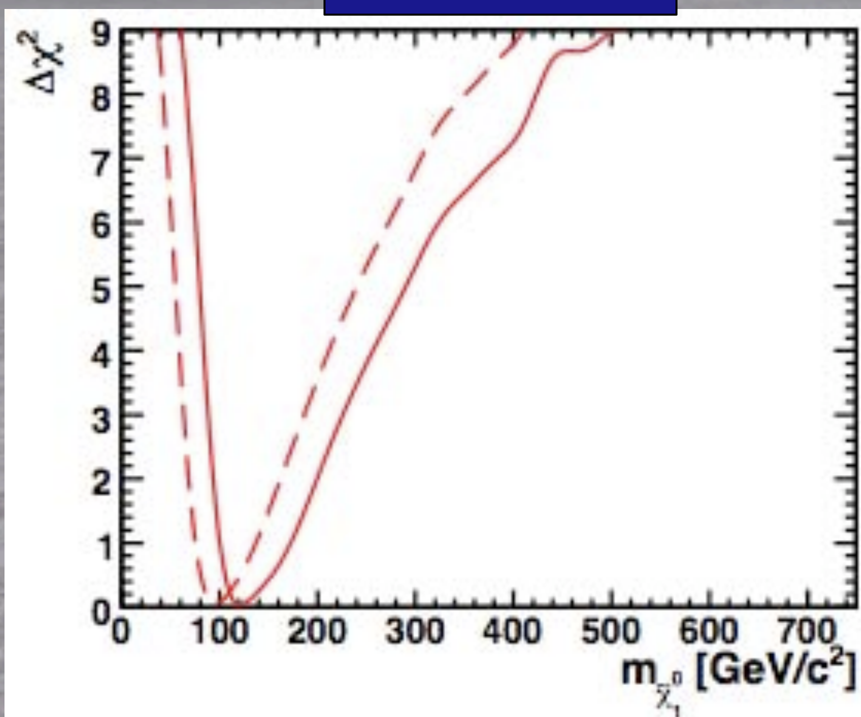
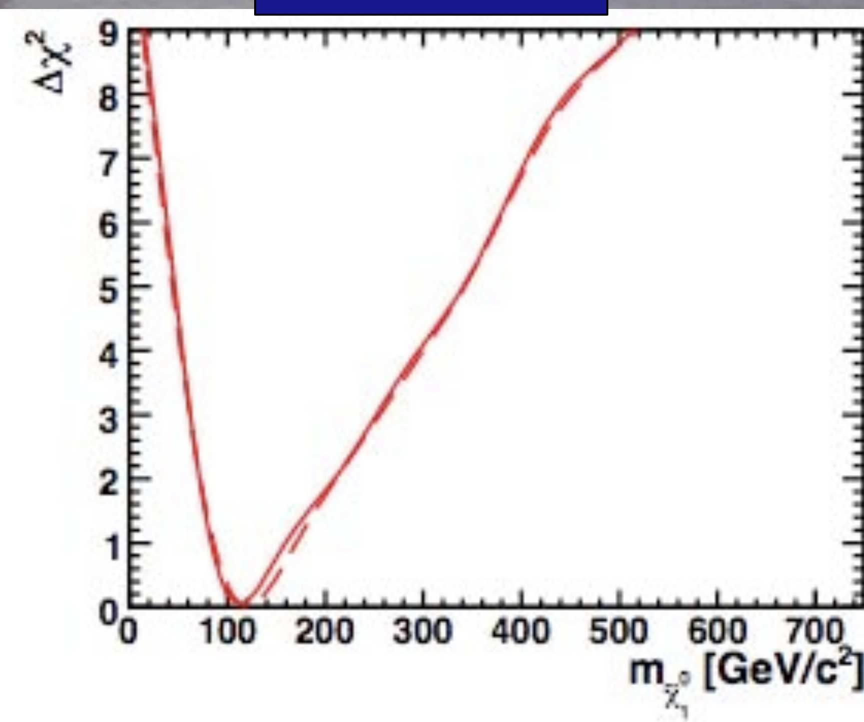
Likelihood Function for Neutralino Mass

CMSSM



NUHM1



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Strategies for Detecting Supersymmetric Dark Matter

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- Annihilation in galactic halo

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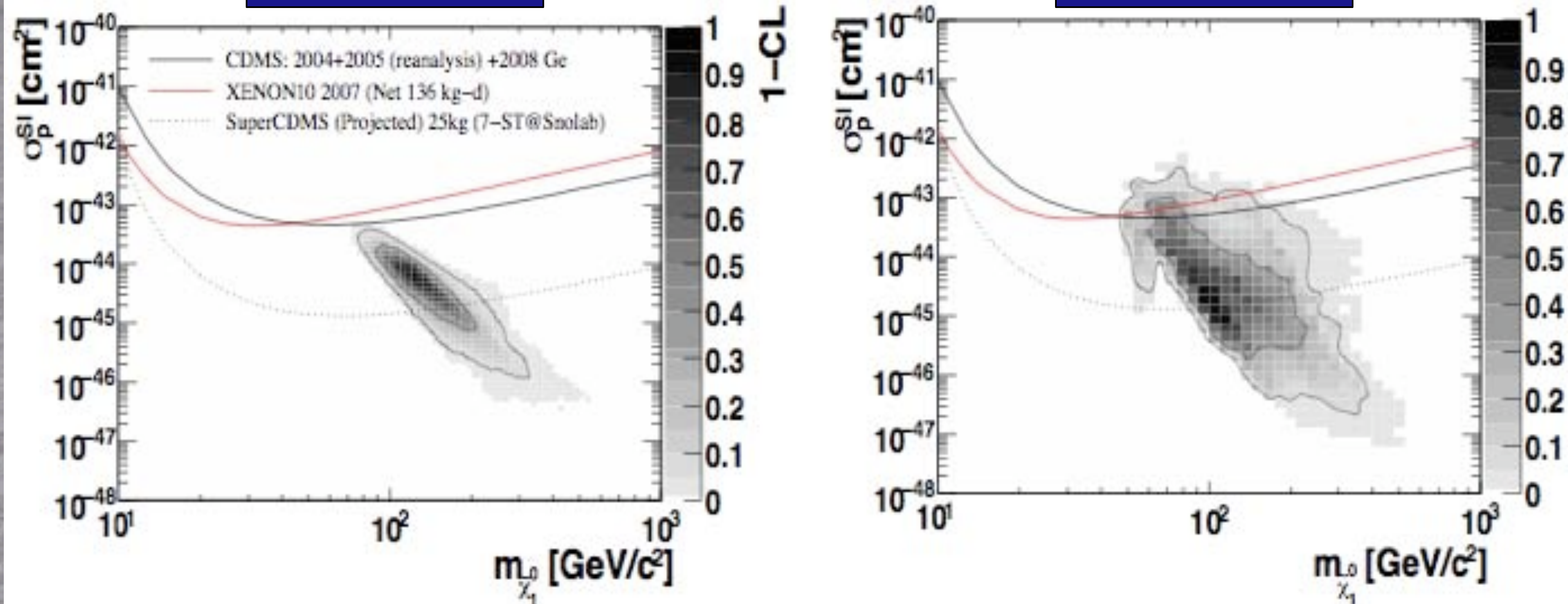
  $\chi + A \rightarrow \chi + A$

Elastic Scattering Cross Sections

CMSSM

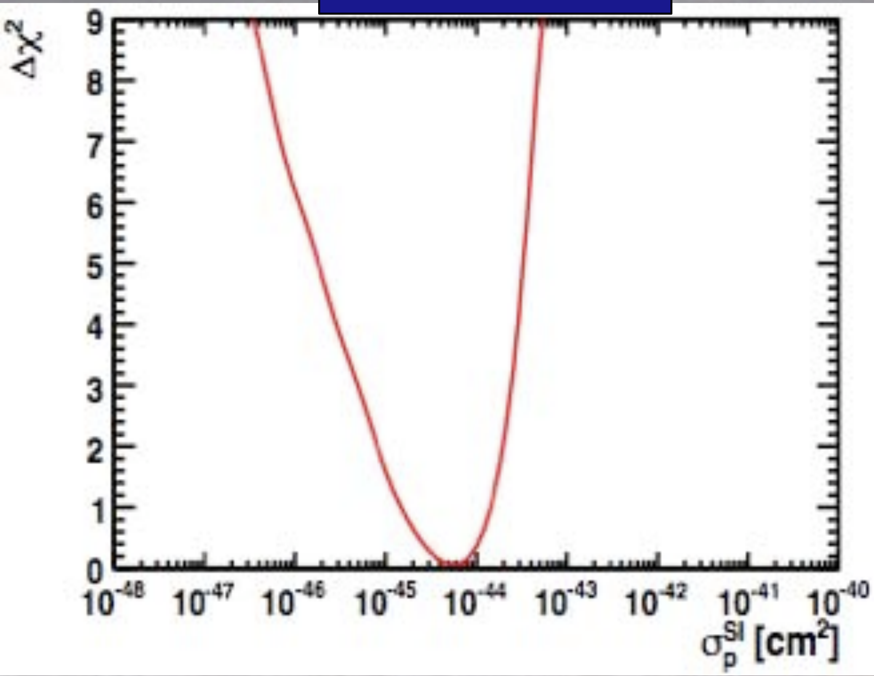
NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for Spin-Independent Dark Matter Scattering

CMSSM



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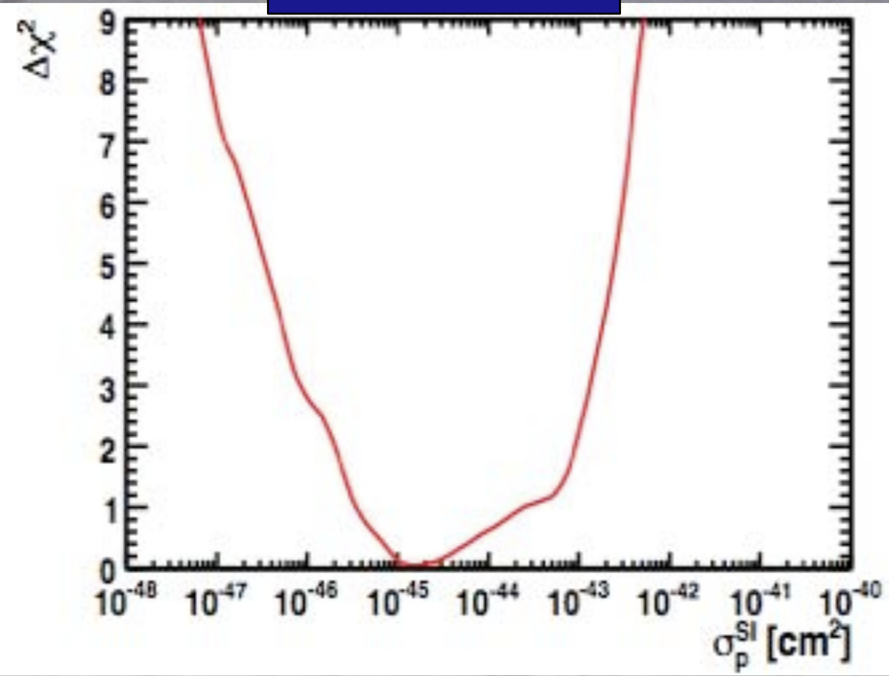

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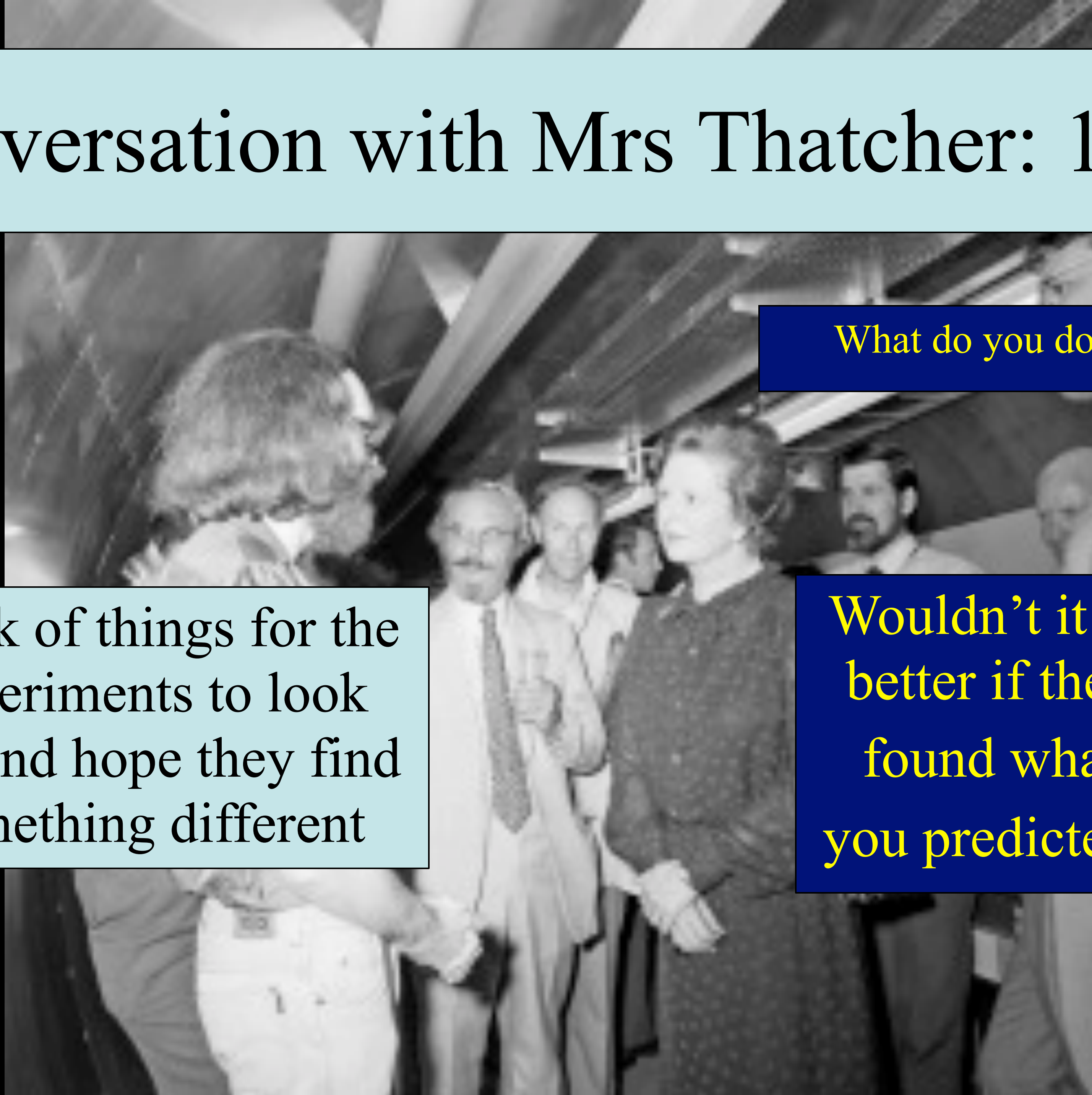

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Wouldn’t it be better if they found what you predicted?

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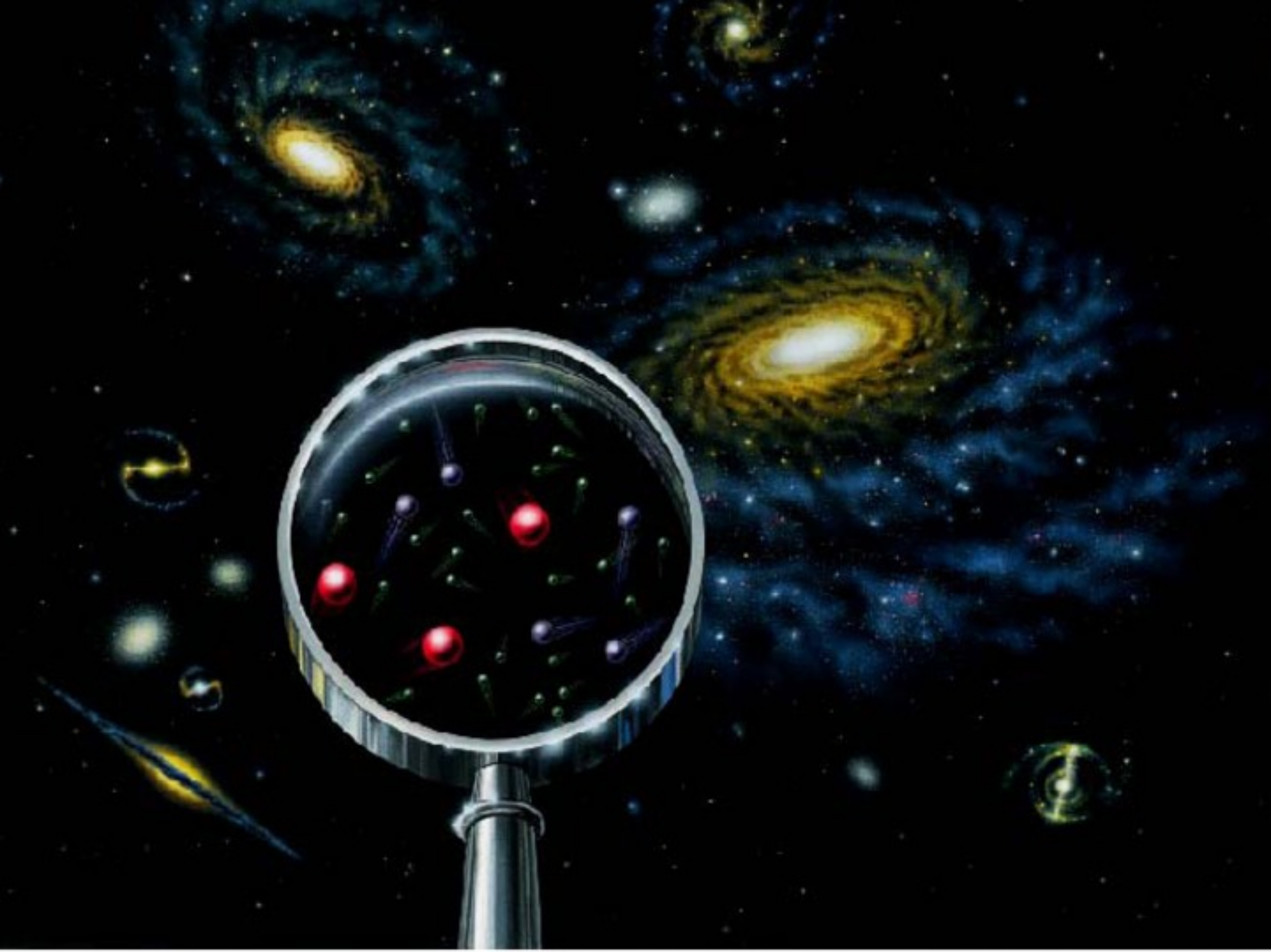
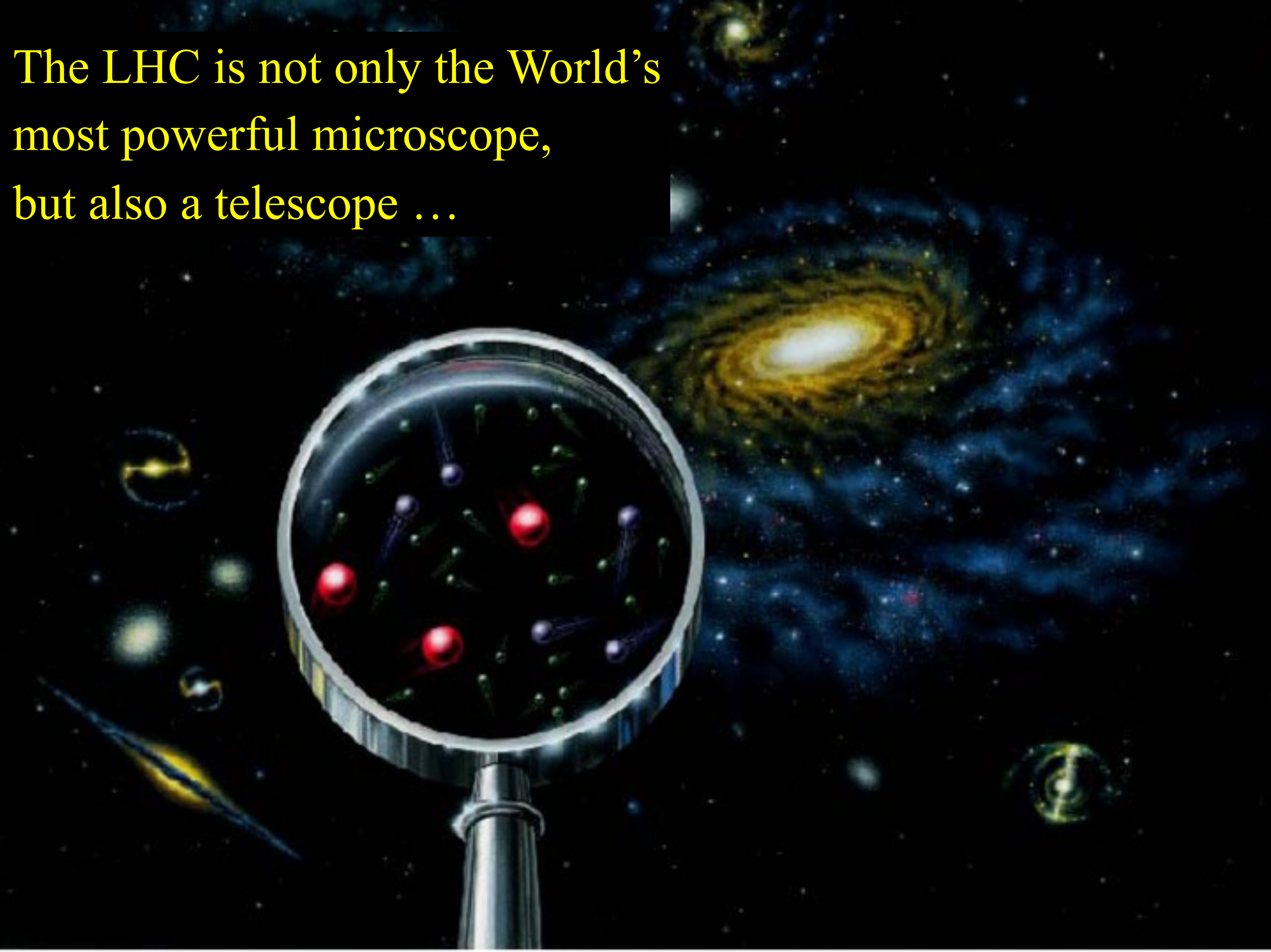


The LHC is not only the World’s most powerful microscope, but also a telescope …



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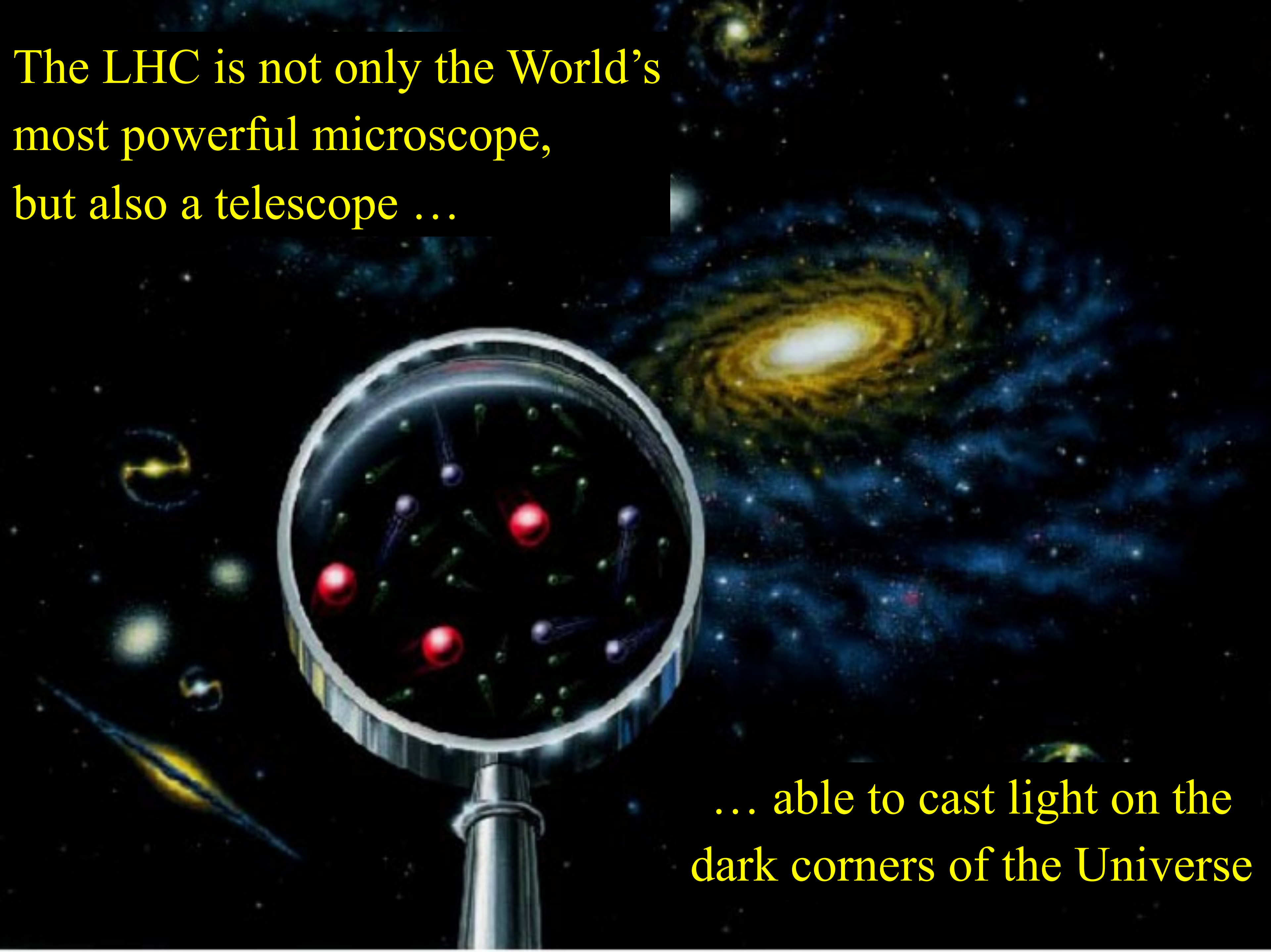

… able to cast light on the dark corners of the Universe

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- Cancel boson loops ⇔ fermions