La Ricerca della Semplicità
In Search of Simplicity

Luciano Maiani
Università di Roma La Sapienza, Roma, and CERN, Ginevra

La vita e' complicata. Una camminata in campagna in un giorno di maltempo, ci mostra a quante forze siamo sottoposti, vento, pioggia, camminare nel fango, per non parlare di rami che cadono, possibili fulmini, …forze che agiscono in modo variabile, spesso imprevedibile… come se fossero mosse da esseri nascosti che dobbiamo tenerci buoni con preghiere, offerte e sacrifici

Ma l'osservazione piu' attenta mostra che ci sono regolarita' che permettono di collegare almeno alcuni aspetti della realta' a leggi di Natura immutabili, liberandoci da credenze e superstizioni.

Prima tra queste, l'osservazione del moto delle stelle che ha permesso di predire eclissi, allineamenti di pianeti e altri fenomeni celesti.

…E la rivoluzionaria ipotesi dell'atomo da parte dei filosofi-scienziati greci

Life is complicated. A walk in the countryside in a stormy day shows to how many forces we are subject to, wind, rain, walking in the mud…not to speak about falling branches, lightening…forces that act in an irregular, often unpredictable way as if moved by hidden entities that we must make happy with prayers, offers and sacrifices.

But more a careful observation shows that there are regularities that allow us to relate at least some aspects of reality to permanent laws of Nature, freeing us from beliefs and superstitions.

First among them, the observation of the motion of the stars that led to predict eclipses, conjunction of planets and other celestial phenomena.

Alfonso X di Castiglia (1221-1284) a proposito del Sistema Tolemaico.

Se il Signore Onnipotente mi avesse consultato prima di imbarcarsi nella creazione di tutto questo, avrei raccomandato qualcosa di più semplice.

Richard Feynman

Se in un cataclisma dovesse andare perduto tutto il sapere scientifico e potessimo passare una sola frase alle prossime generazione, quale affermazione potrebbe contenere il massimo di informazione nel minimo di parole? Credo sarebbe :

tutte le cose sono fatte di atomi

piccole particelle in movimento perpetuo, che si attraggono quando sono distanti e si respingono quando vengono schiacciate una sull'altra. a' di informazione
In questa semplice frase c'e' un enorme quantita' di informazione sul mondo, se solo applichiamo un po' di immaginazione e di riflessione.

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is :

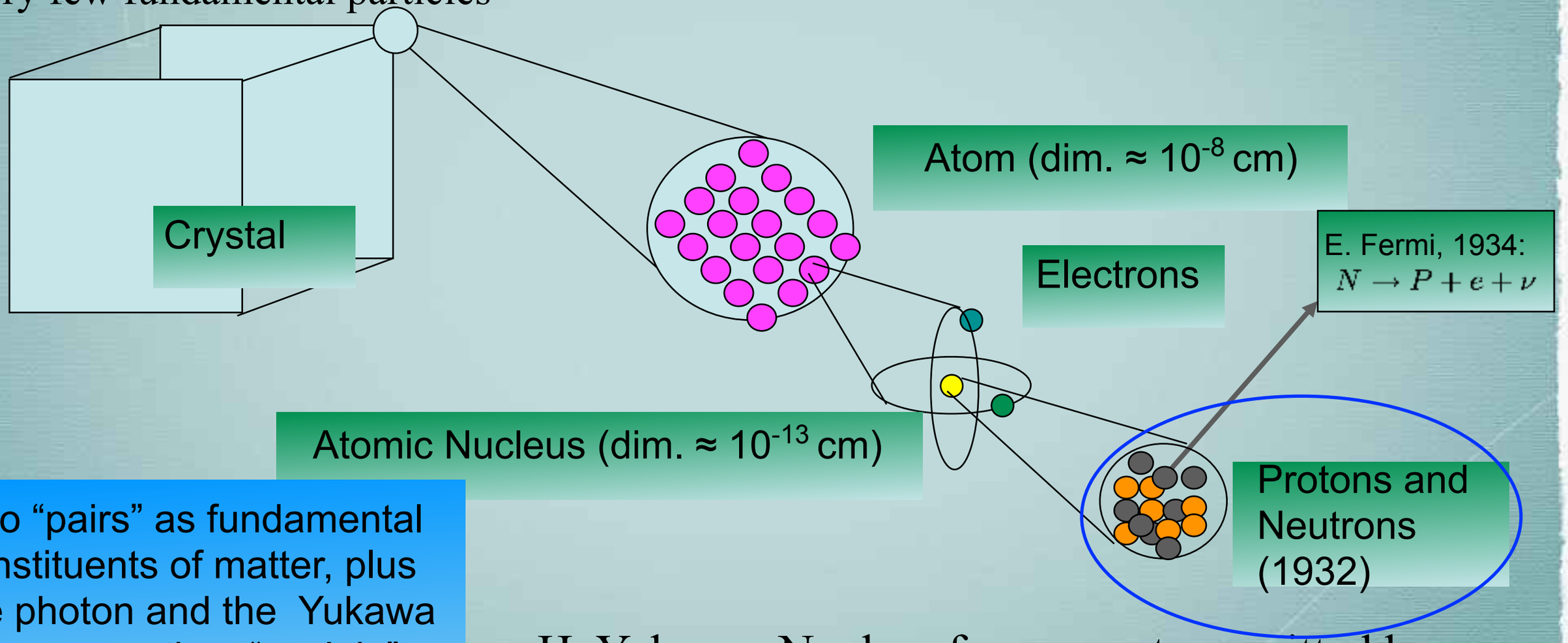
all things are made of atoms

little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.
In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

Lectures on Physics (1964)

1. Matter constituents and interactions after neutron's discovery (1932)

- What we are told at school;
- quite adequate, even today, for a first orientation;
- three fundamental forces plus gravity: electromagnetic, strong (nuclear), weak (beta decay);
- very few fundamental particles



Two "pairs" as fundamental constituents of matter, plus the photon and the Yukawa meson: can they "explain" all we see in the World?

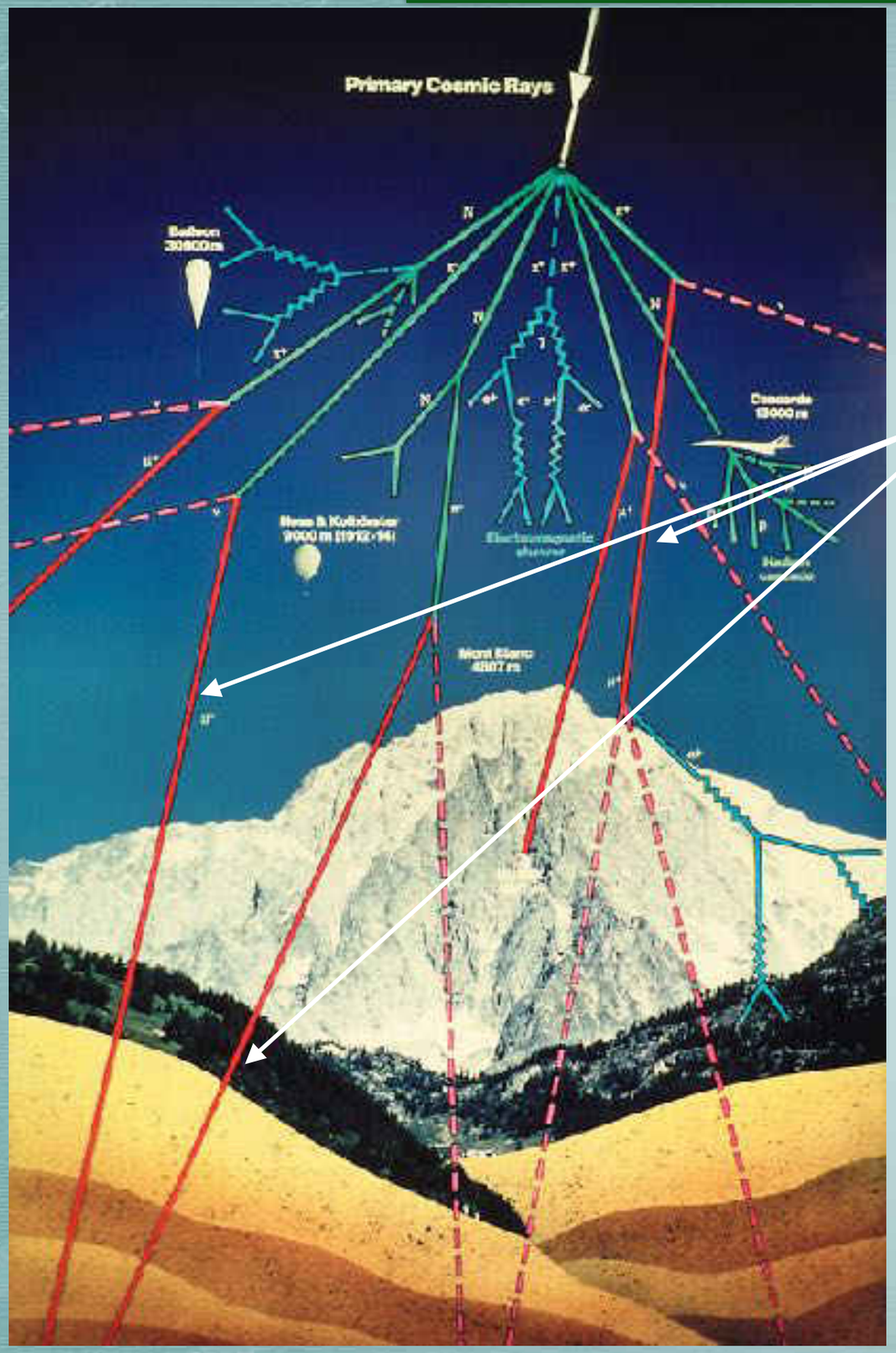
$$\begin{pmatrix} P \\ N \end{pmatrix}, \begin{pmatrix} \nu \\ e \end{pmatrix}; \quad W,\ \gamma,\ \pi$$

H. Yukawa. Nuclear forces are transmitted by a particle: the π meson, with mass ≈ 200 times the electron's mass

The E. Fermi group was active in Roma in the 30s, up to 1939, when E. Fermi left for the US. They were known as the “ Panisperna Boys”, from the address of the Physics Department located in Roma, via Panisperna

The Via Panisperna boys: (from right) Fermi, Rasetti, Amaldi, Segre’, D'Agostino.
The young Bruno Pontecorvo was also part of the group but does not appear: he was behind the camera, taking the picture

2. The mesotron and the particle revolution



•In 1937, C. Anderson and S. Neddermeyer discover a new particle in the debris of cosmic ray collisions with the atoms of the upper part of the atmosphere.

•The new particle has a mass intermediate between the electron and proton assess and is dubbed "***mesotron***".

•Its mass is close to the mass predicted by Yukawa for the π meson, as to suggest that: "***mesotron"= π meson***: the last missing boson!

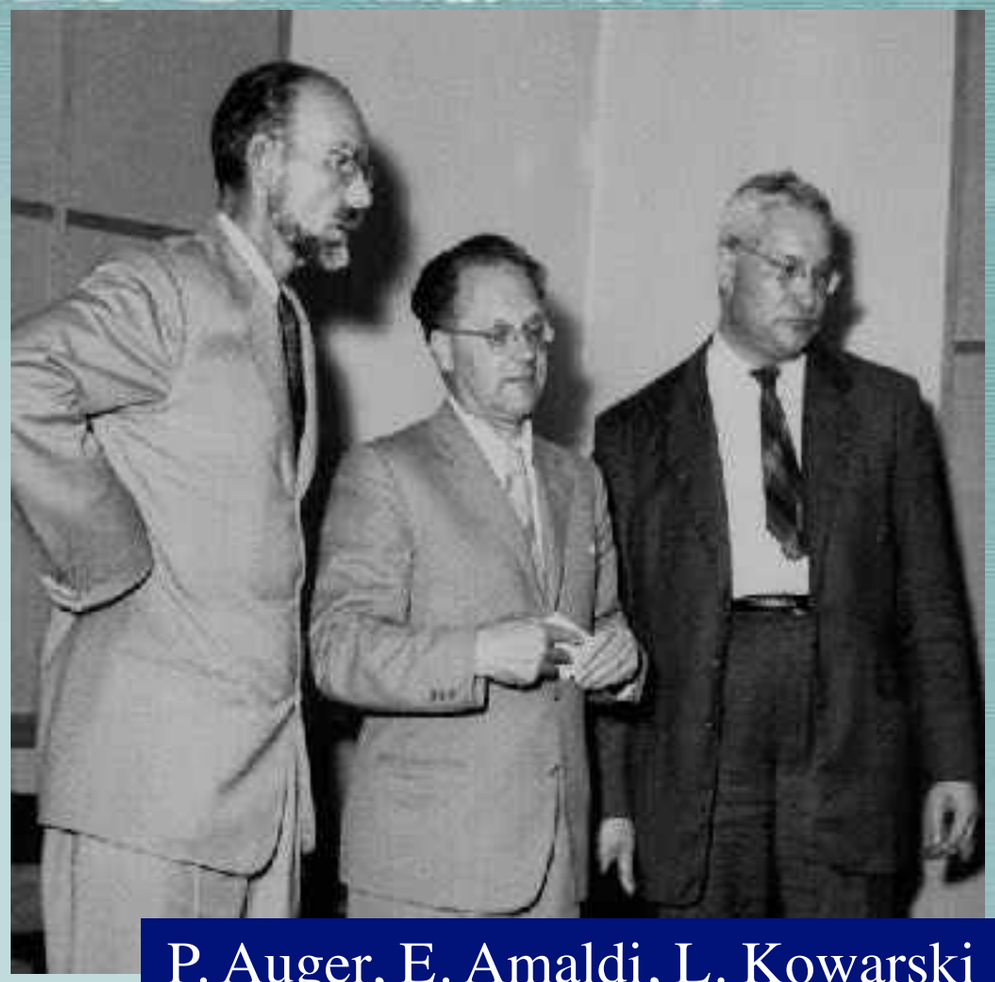
•It looked so reasonable that everybody was convinced…

From Cosmic Rays to Particle Accelerators

- 1946 (Rome). M. Conversi, E. Pancini e O. Piccioni: the mesotron (today "μ particle") is not the carrier of nuclear forces, ***mesotron ≠ π meson***
- The mesotron is a heavier copy of the electron, as suggested by B. Pontecorvo in 1947.
- I. Rabi commented: *who ordered that* ?????
- 1940-1960: a new ***particle zoo*** emerges from cosmic ray studies: the "strange" particles;
- the "new particles" are not present in the ladder of the constituents of matter: atom, nucleous, nucleons…
- …. but they must have a role in the architecture of fundamental forces
- …and can be studied in depth only in the high energy collisions which are abundantly produced with *particle accelerators*.

Long term visions

".. a laboratory or institution where it would be possible to do scientific work, but somehow beyond the framework of the different participating states. Being the product of a collaboration between a large number of European countries, this body could be endowed with more resources than national laboratories and could, consequently, undertake tasks which, by virtue of their size and cost, were beyond their scope "(L. De Broglie, 1949)

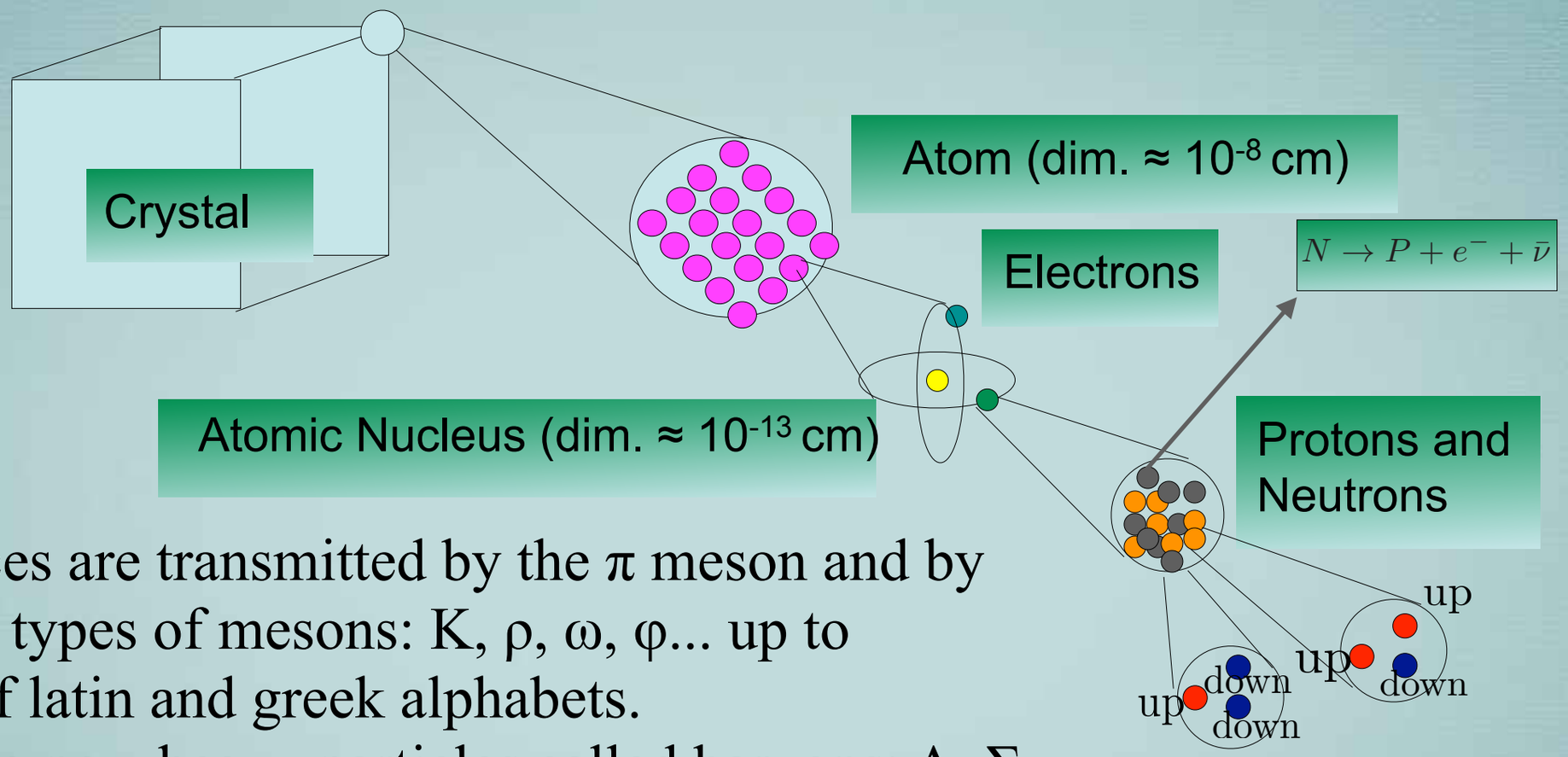


P. Auger, E. Amaldi, L. Kowarski

"Their goal was not merely to construct a medium-sized accelerator, it was to awaken Europe and, through the construction of a giant accelerator, to make her understand the urgency and necessity of developing fundamental scientific research on a large scale as had happened in the US since the war".
(The History of CERN, Vol.1, p.130)

Established in 1954, CERN is the European Laboratory for Elementary Particle physics.

3. Quarks, a new level of reality (M. Gell-Mann, G. Zweig)



Nuclear Forces are transmitted by the π meson and by several other types of mesons: K, ρ, ω, φ... up to exhaustion of latin and greek alphabets.
There are also new heavy particles called baryons: Λ, Σ…

Baryons and Mesons are made by quarks: (qqq) and (q-anti q) respectively, including a third type of quark: the ***strange quark.***

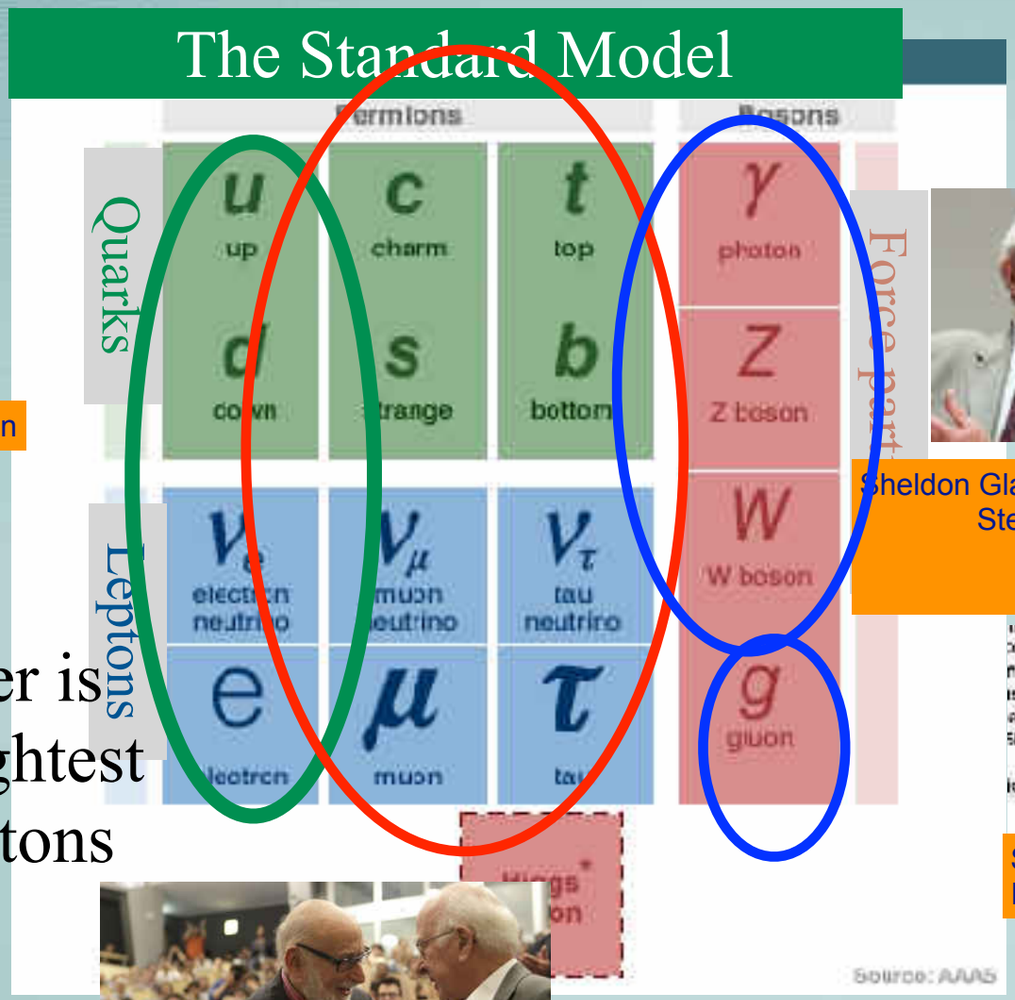
$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Three Quarks for Master Mark!
Gell-Mann, 1963, from: *The Finnegan's Wake* of James Joyce

Constituentsof matter and fundamental forces (circa 2016)

Murray Gell-Mann

The Standard Model



Ordinary matter is made of the lightest quarks and leptons

Nicola Cabibbo

Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste

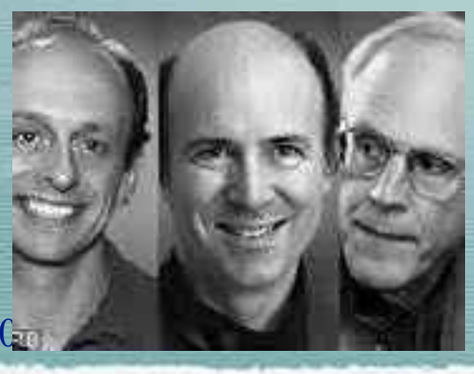
Carlo Rubbia

Sheldon Glashow, John Iliopoulos, Luciano Maiani

Makoto Kobayashi , Toshihide Maskawa

Robert Englert e Peter Higgs

Heavier quarks are unstable: what is their role in the Universe?

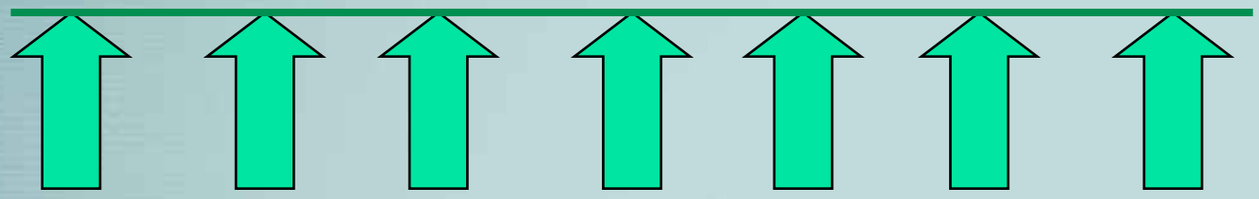


Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free Gross&Wilczeck, Politzer (1973)

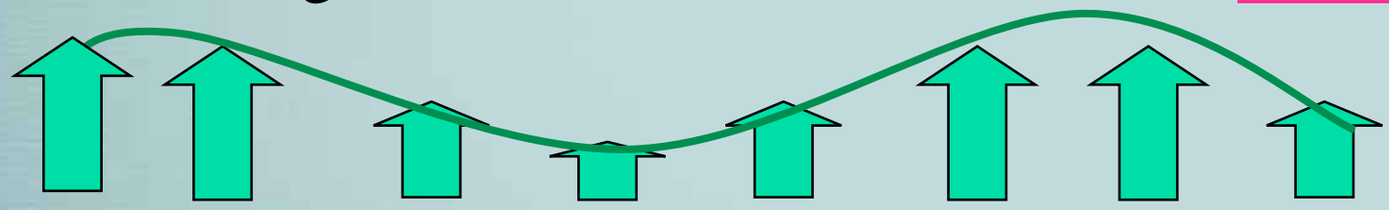
The Higgs Boson

The origin of masses

• A field fills all space and it interacts with particles;
• The field is able to "distinguish" between particles, according to their symmetry properties…W, Z, quarks.. take a mass, photon stays at zero mass.



• Collisions generate waves…



•VACUUM is like the surface of a perfectly calm lake.

... which correspond to a new particle: the **HIGGS BOSON**

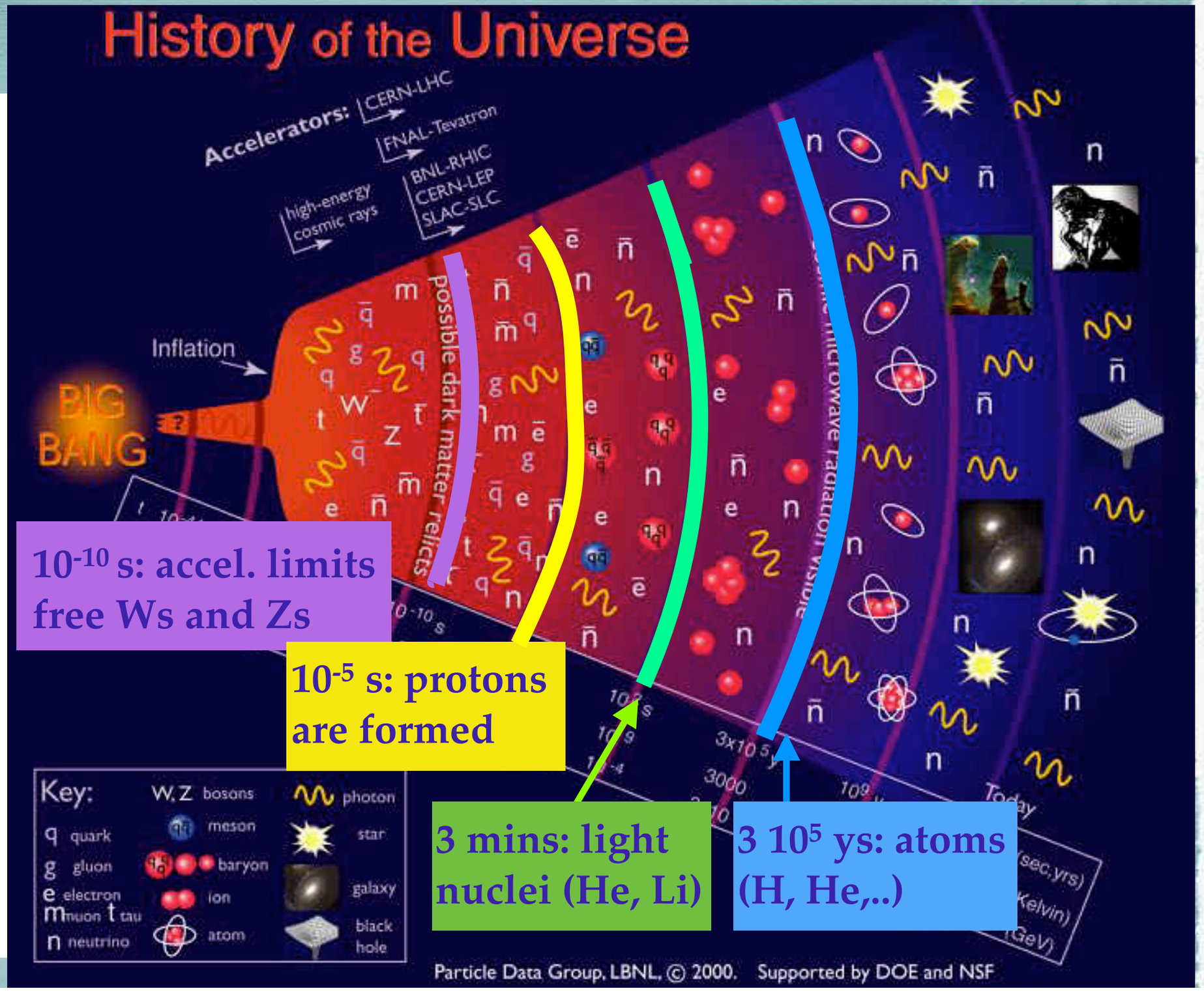
• The Higgs boson is needed for theory to agree with Nature... but the Higgs mechanism gives a vision of Vacuum which may explain new phenomena : (inflation, chaotic universe, …)

Peter Higgs @ Erice, 2007 (with Verònica Riquer)

4. BIG BANG

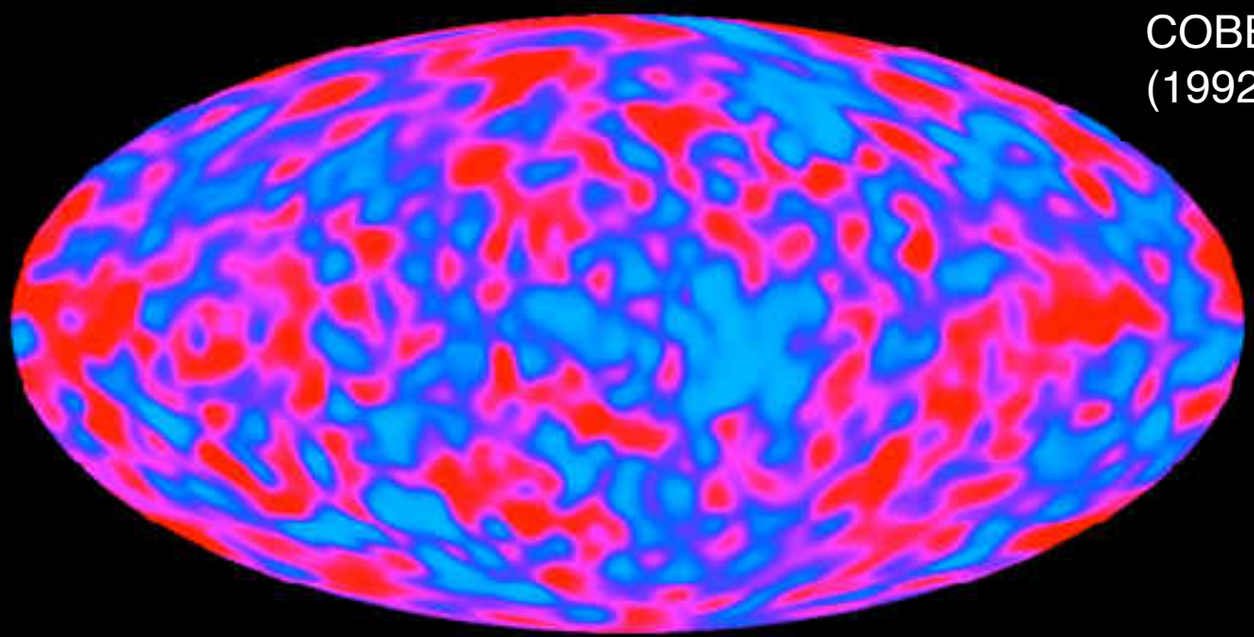
Particle accelerators are « time machines » where we can reproduce the conditions of the primordial Universe when it was populated by unstable particle of all generations

..and primordial fluctuations have generated the « seeds » of today cosmic structures: clusters of galaxies, galaxies, stars planets.



With the Standard Theory we describe the conditions of the Universe ***3 minutes*** after Big Bang (when light nuclei where produced) down to ***10^{-5} secs*** protons formed from the primordial soup of quarks and gluons) to ***10^{-10} secs*** (limit of present accelerators).

http://aether.lbl.gov/www/projects/cobe/

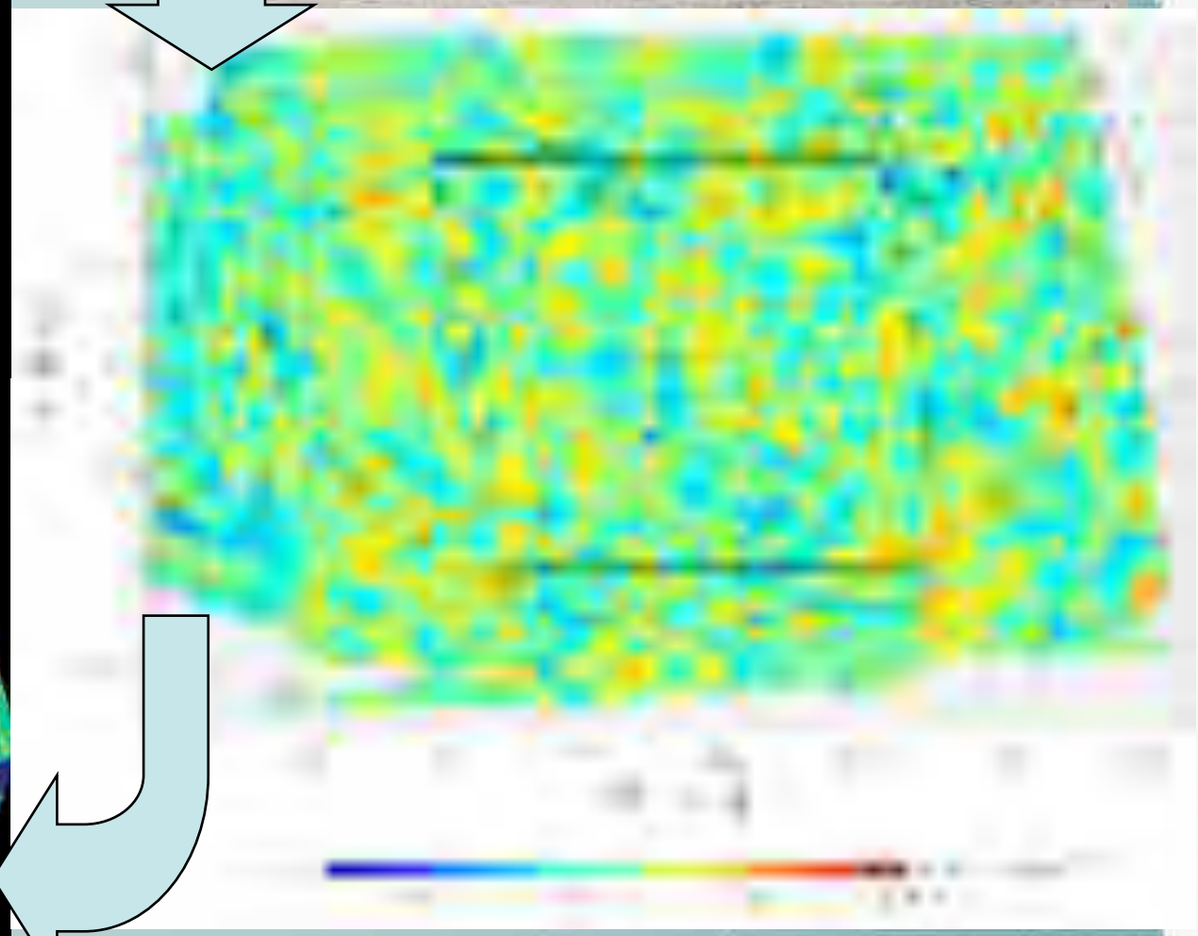


COBE
(1992)

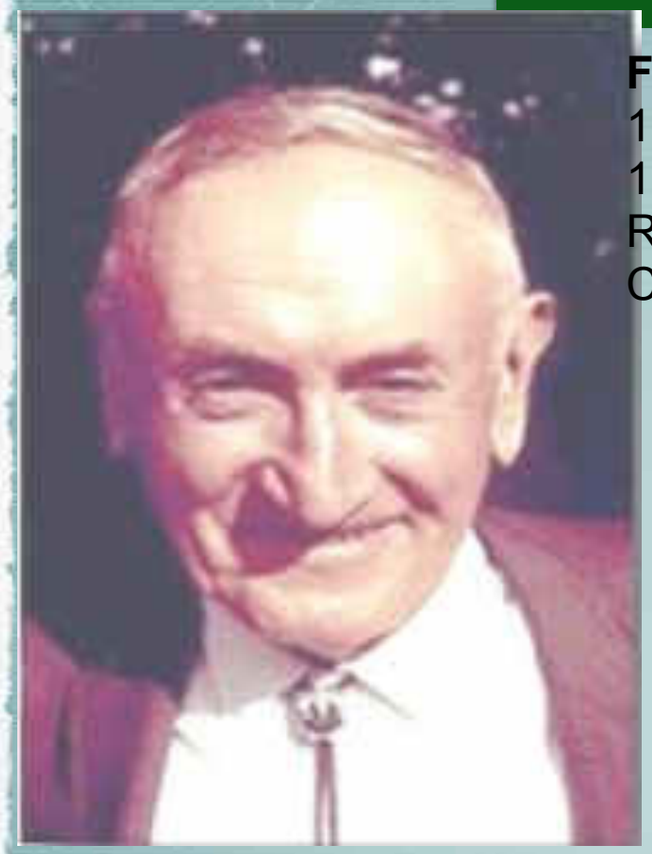
Boomerang (2002)

WMAP

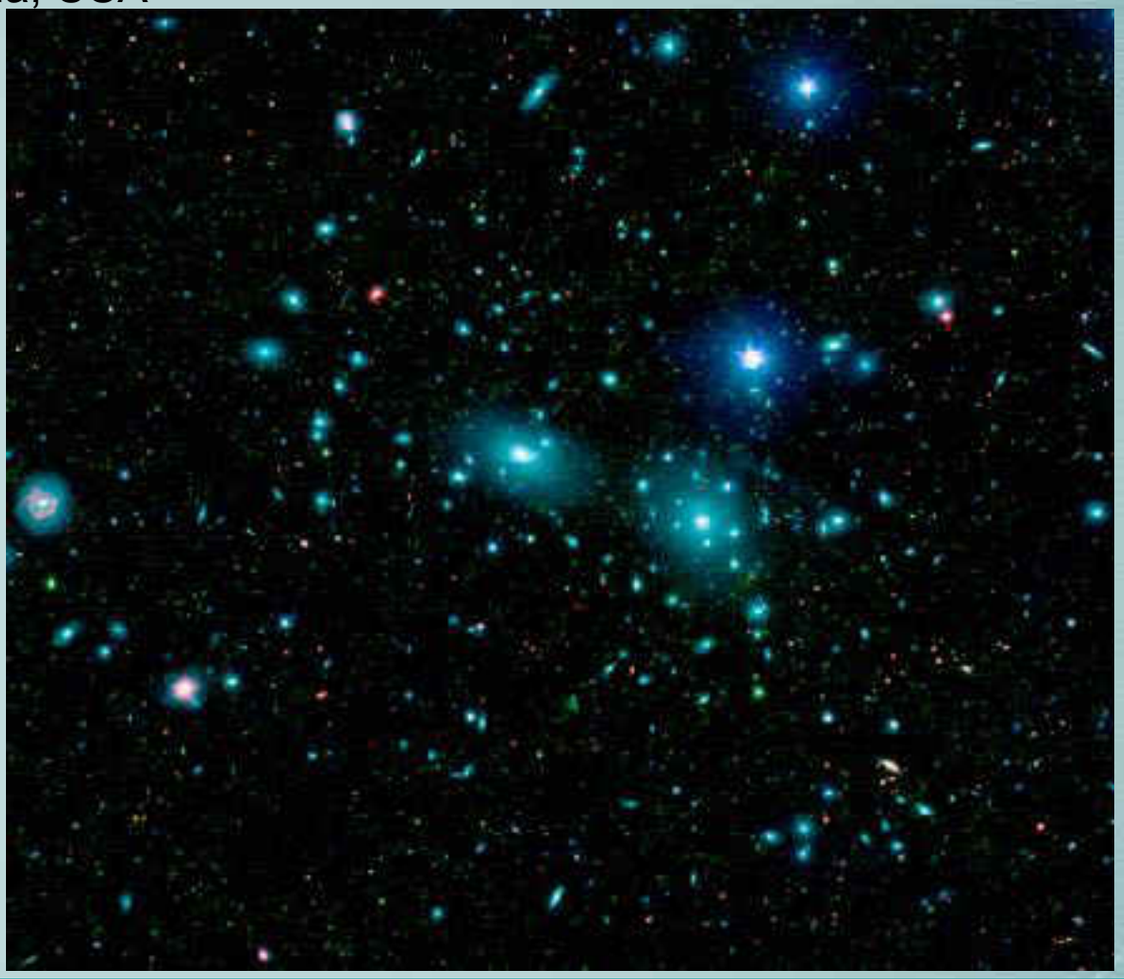
(2003)



Fritz Zwicky discovers "Dark Matter" in Coma Cluster



Fritz Zwicky
1898 Varna, Bulgaria
1974 Pasadena, California, USA
Resident: USA
Citizenship: Swiss



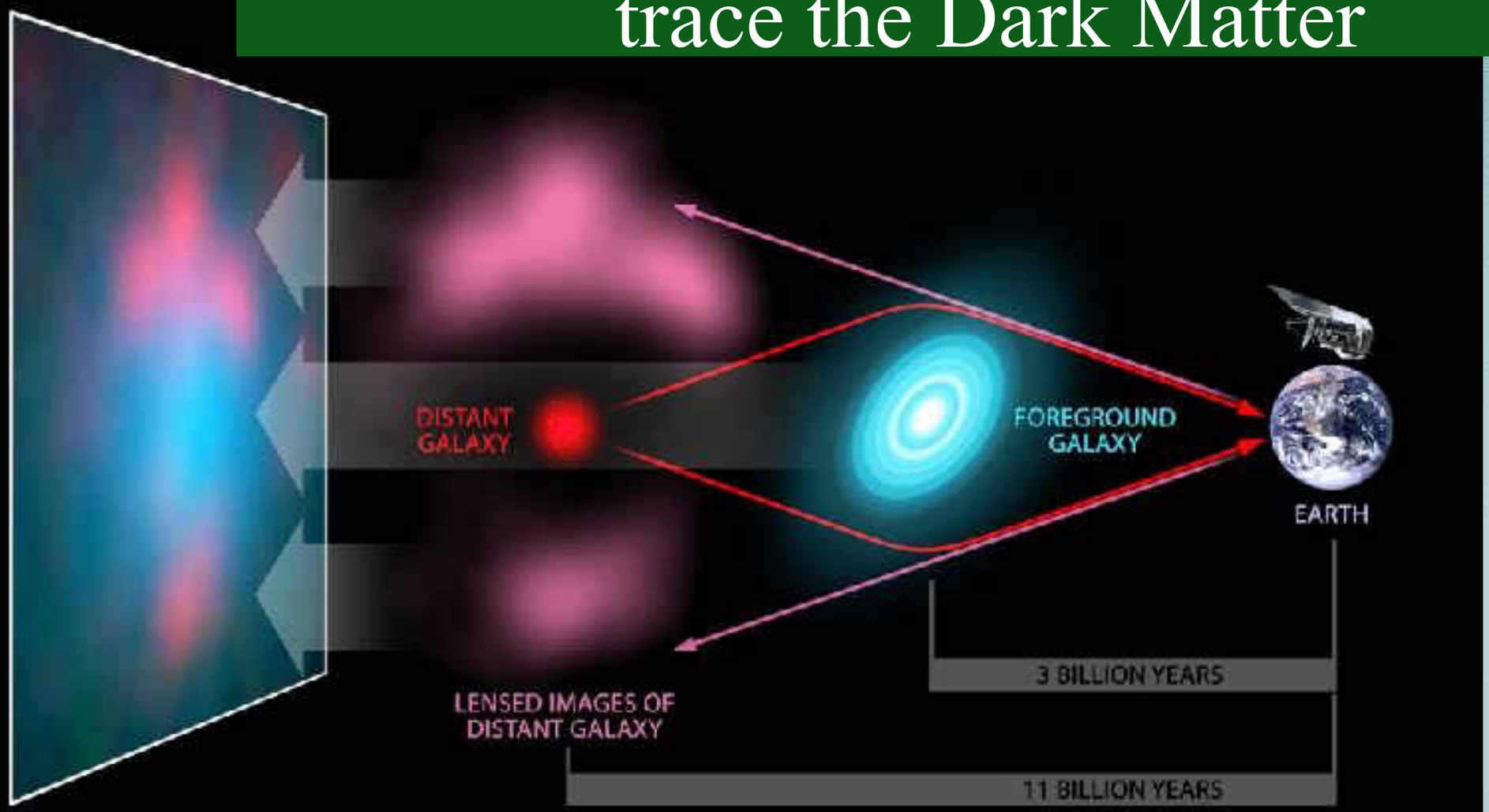
In the years 30's, Zwicky discovered an anomalous ratio of mass to luminosity in the cluster of Galaxie in the constellation Coma. Zwicky interpreted the anomaly as due to some kind of "dark matter", (non luminous), in addition to the normal matter that makes stars, gases and dust in Galxies.

COMA CLUSTER, made by thousands Galaxies.

Data from Spitzer Space Telescope and Sloan Digital Sky Survey.

© NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.

Galaxies act as Gravitazional Lenses: trace the Dark Matter



The Large Hadron Collider at CERN may be able to produce the particles that make the Dark Matter and study them (as was done for the new particles of the fifties): we are looking for them now!


Gravitational Lens in Abell 2218 HST · WFPC2

5. LHC at CERN-protagonists

CERN and the LEP-LHC tunnel, between Geneva and Gex

Italian Companies in LHC

- 17% of LHC contracts have been attributed to Italian companies after call for tenders in open competition (Italian contribution to CERN: 12% of budget)
- essential role of INFN to provide necessary know-how
- exemplary case of research-industry collaboration

Superconducting cables

- LHC used 1200 tons of superconductiong cable, for a total lenght of 7000 km
- during construction, LHC has been the largest single buyer of Niobium-Titanium cables
- one Nb-Ti bar 0 .9m long and 0.2 m diameter gives rise, after extrusion to 9000 filaments of 7 micron diameter and 30 km lenght.

Magnet production

•Magnets protptypes have been developed at CERN in collaboration with European research institutions (INFN for Italy) and European compnies (ALSTOM, NOELL, ANSALDO)

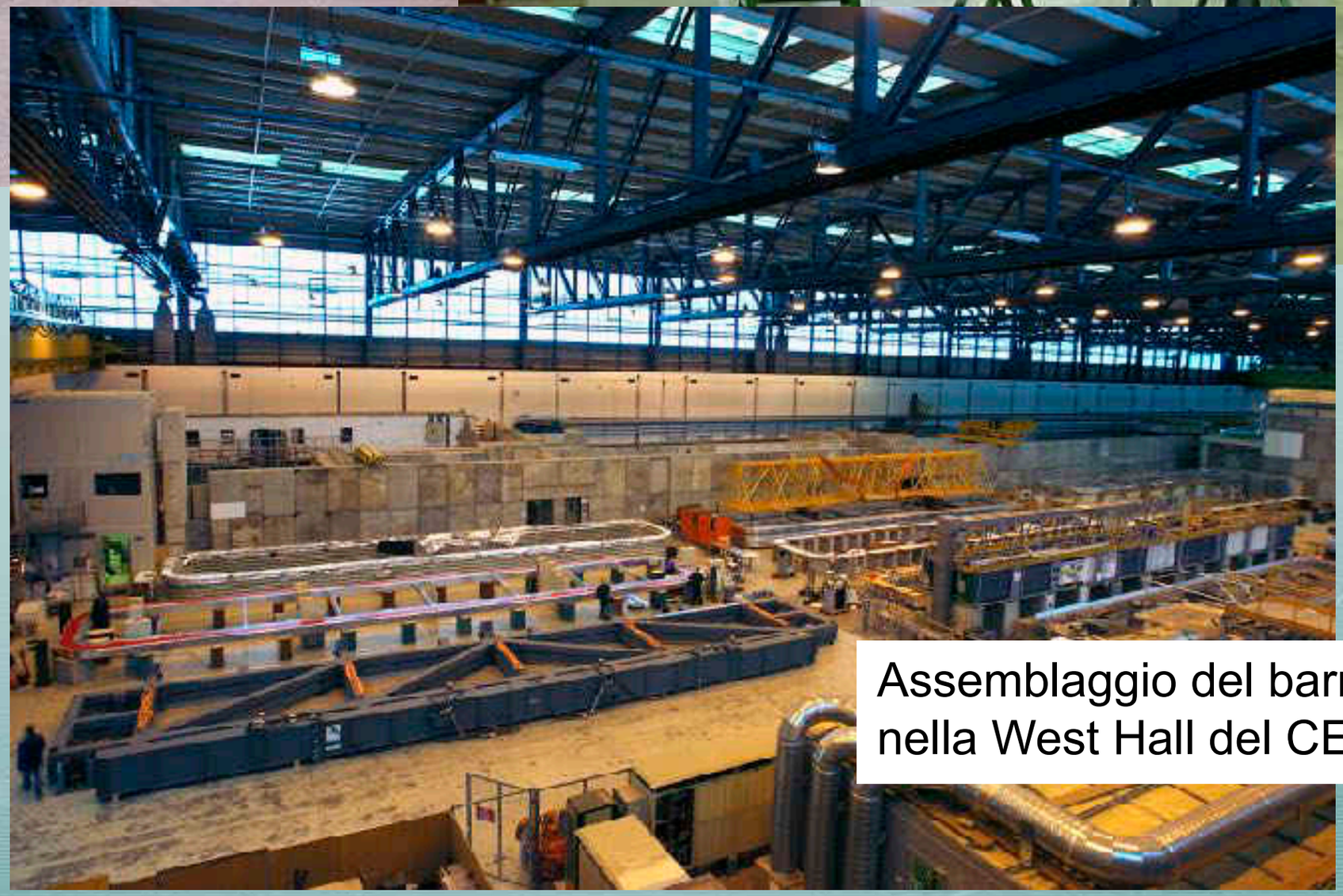
•in this way it has been possible to transfer advanced technologies to European companies

• that are now using them for Nuclear Fusion facilities like ITER.

Superconducting Magnets in stock and installed in the LHC tunnel

ATLAS

Bobina superconduttrice in ANSALDO



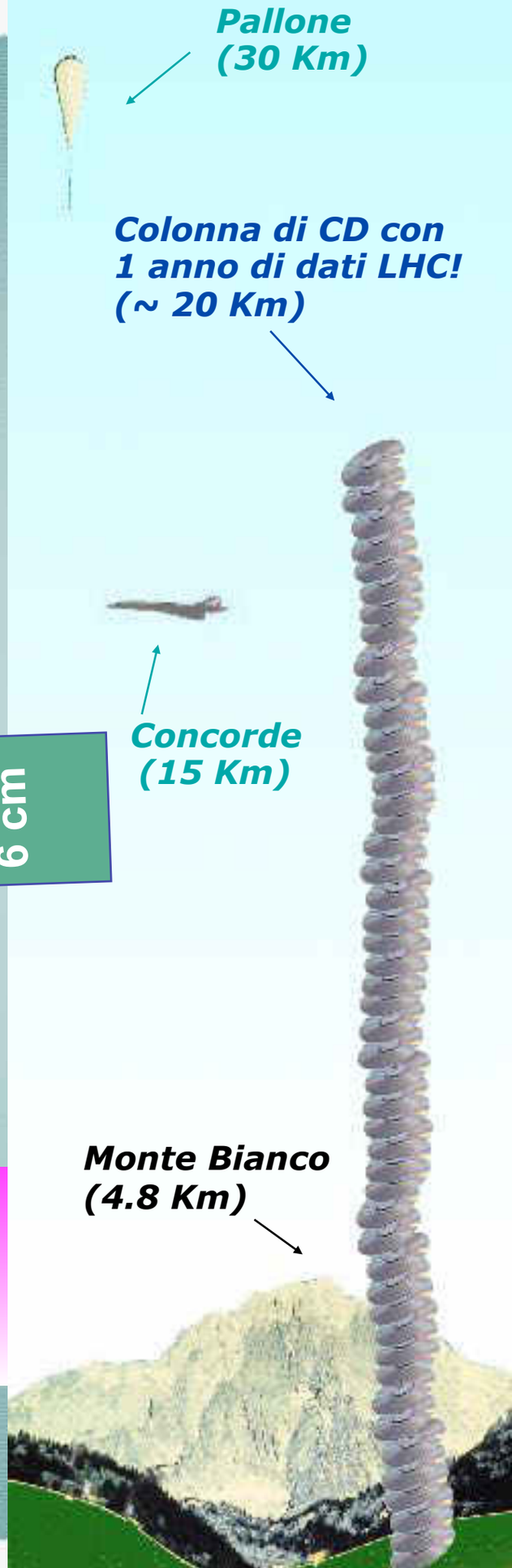
Assemblaggio del barrel toroid nella West Hall del CERN

Il Calcolo per LHC

Produzione Annuale di dati:12-14 PetaBytes/ anno

Calcolo per LHC: 100.000 PC di oggi

Calibrazione, Recostruzione, Simulazione, Analisi, Infrastruttura e Grid software



6. LHC Challenges and discoveries

- Find the Higgs Boson

The Origin of mass

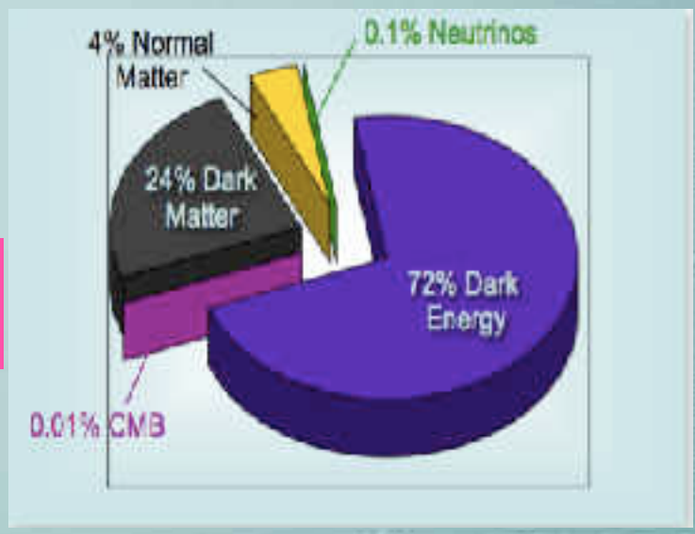
- Find the Supersymmetric Particles

The Origin of Spin

The Unification of Forces **requires** a Symmetry to relate different spins: this is the SUPERSYMMETRY discovered at CERN in the 70s by J. Wess and B. Zumino

- Identify the nature of the Dark Matter

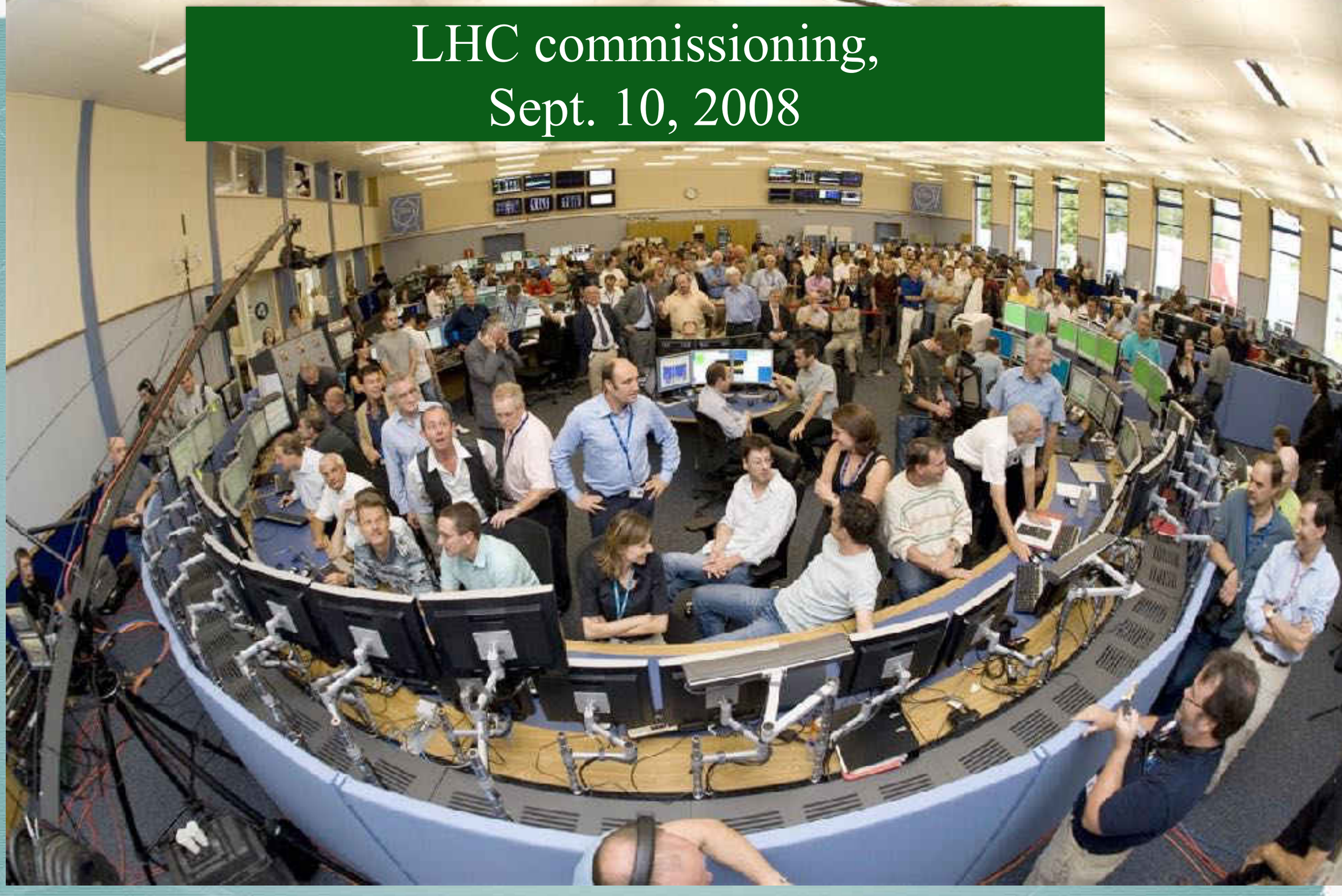
Cosmic Supersymmetry ?



- Test for new space-dimensions

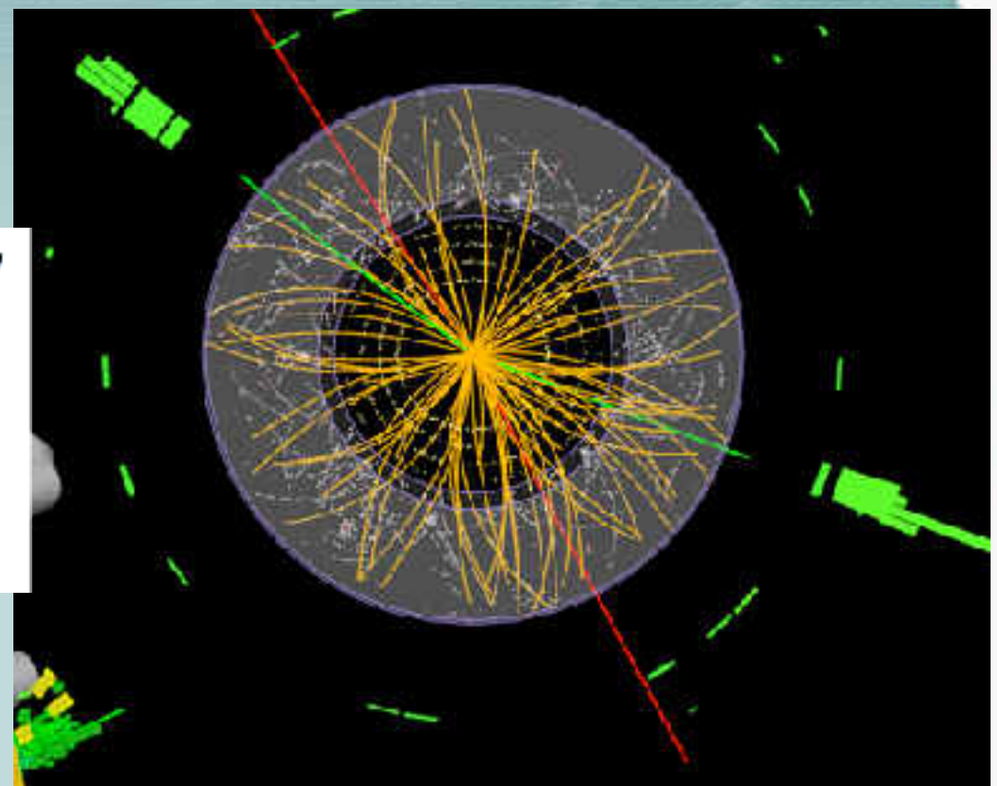
- The String formulation of Quantum Gravity is not consistent in 3+1 dimensions. Curved extra-dimensions are needed.
- How small is R ?

LHC commissioning, Sept. 10, 2008



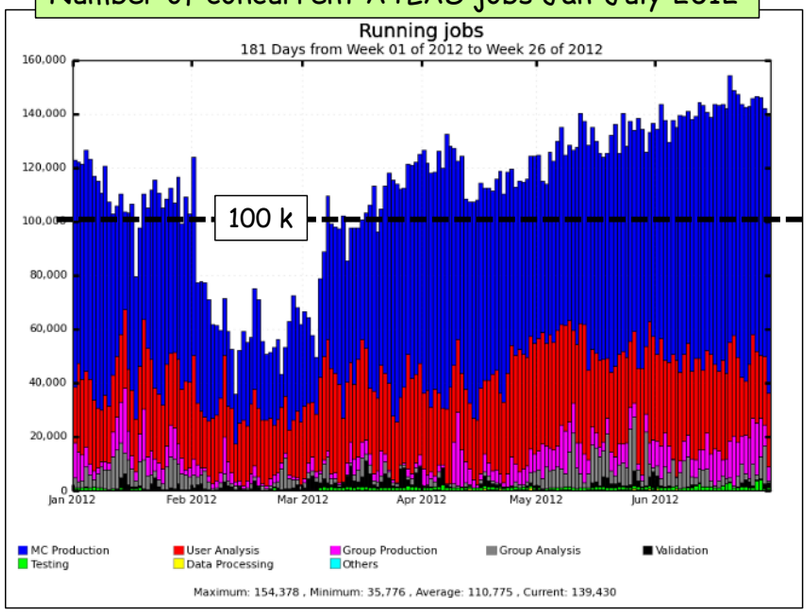
CMS and ATLAS

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !



It would have been impossible to release physics results so quickly without the outstanding performance of the Grid (including the CERN Tier-0)

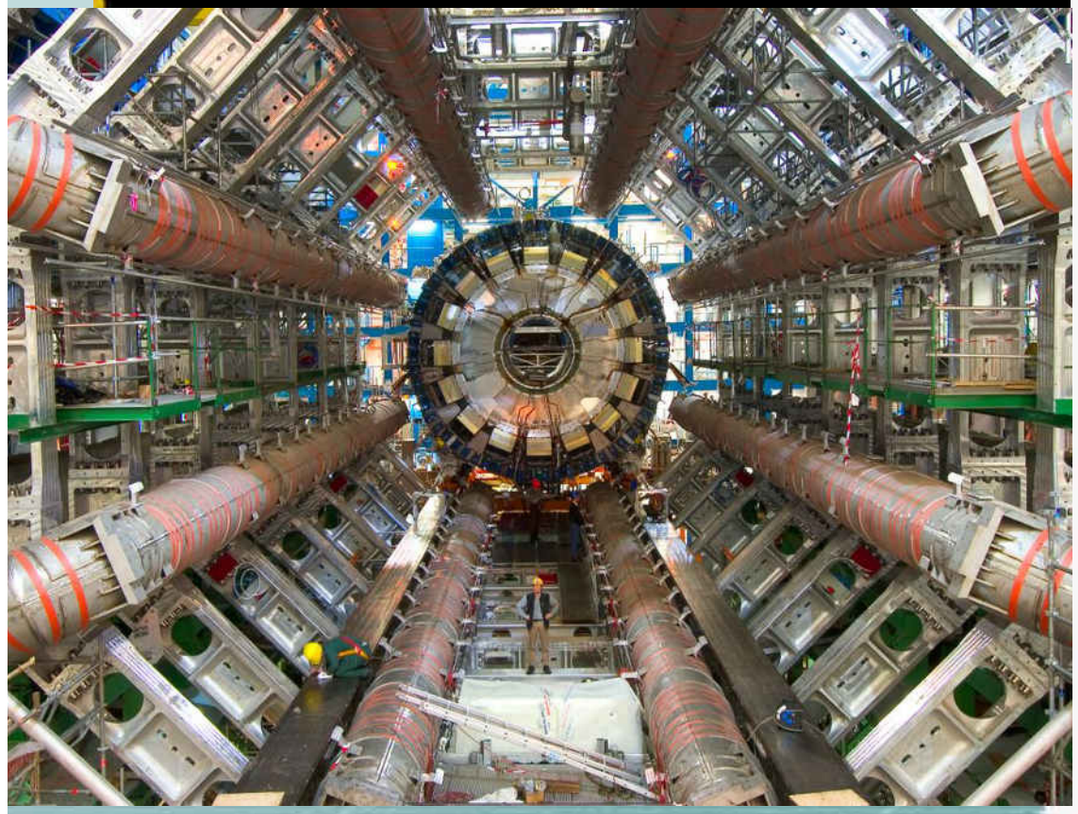
Number of concurrent ATLAS jobs Jan-July 2012



Includes MC production, user and group analysis at CERN, 10 Tier1-s, ~ 70 Tier-2 federations → > 80 sites

> 1500 distinct ATLAS users do analysis on the GRID

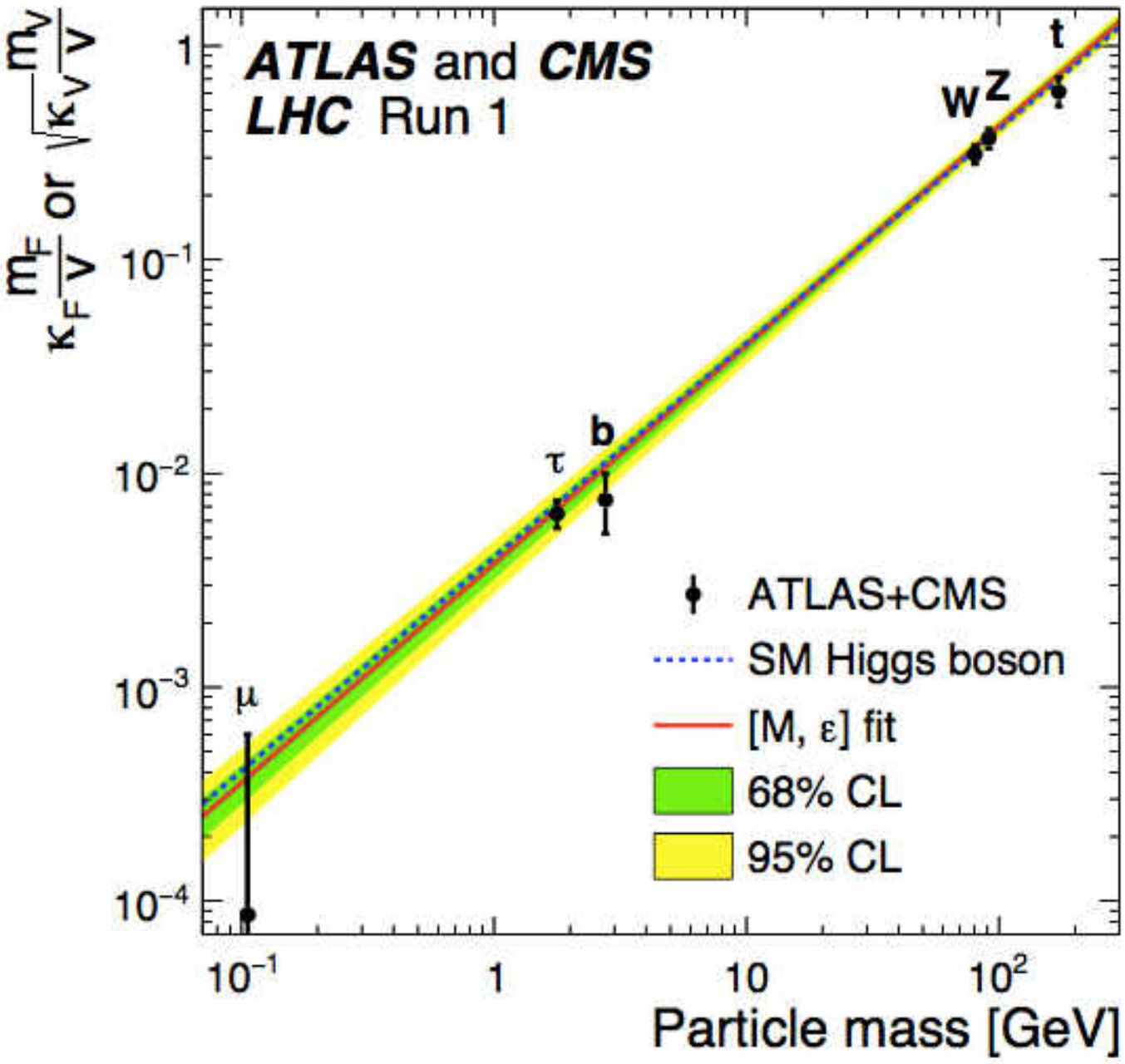
- Available resources fully used/stressed (beyond pledges in some cases)
- Massive production of 8 TeV Monte Carlo samples
- Very effective and flexible Computing Model and Operation team → accommodate high trigger rates and pile-up, intense MC simulation, analysis demands from worldwide users (through e.g. dynamic data placement)



12

Discovery (July 4th, 2012)

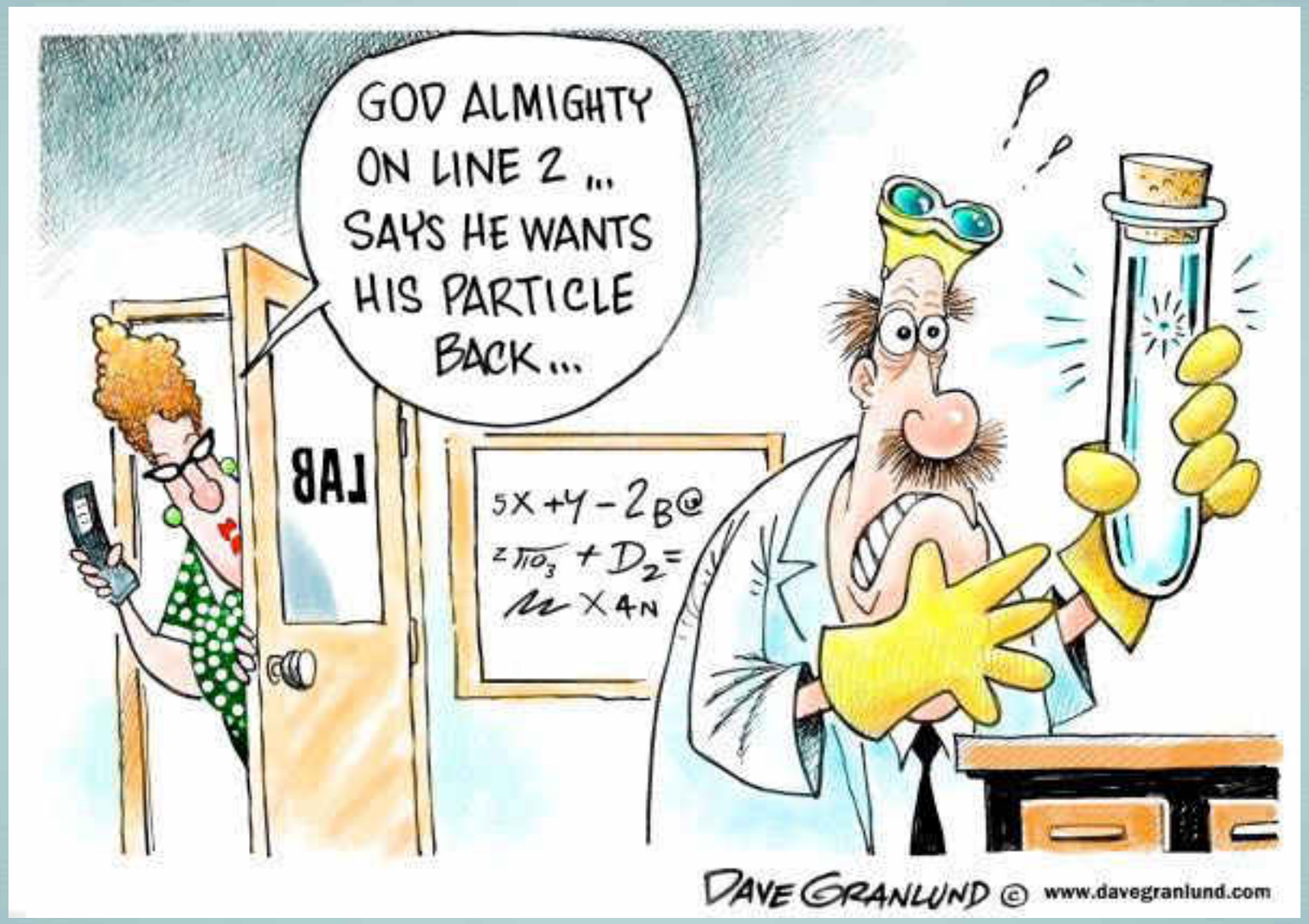
Higgs boson branching ratios vs. particle masses



- The dashed (blue) line indicates the predicted dependence on the particle mass in the case of the SM Higgs boson.

- As expected…but very unconventional
- the first ***scalar*** elementary particle
- coupled not to currents but to masses
- ***the true signature of the Higgs mechanism***

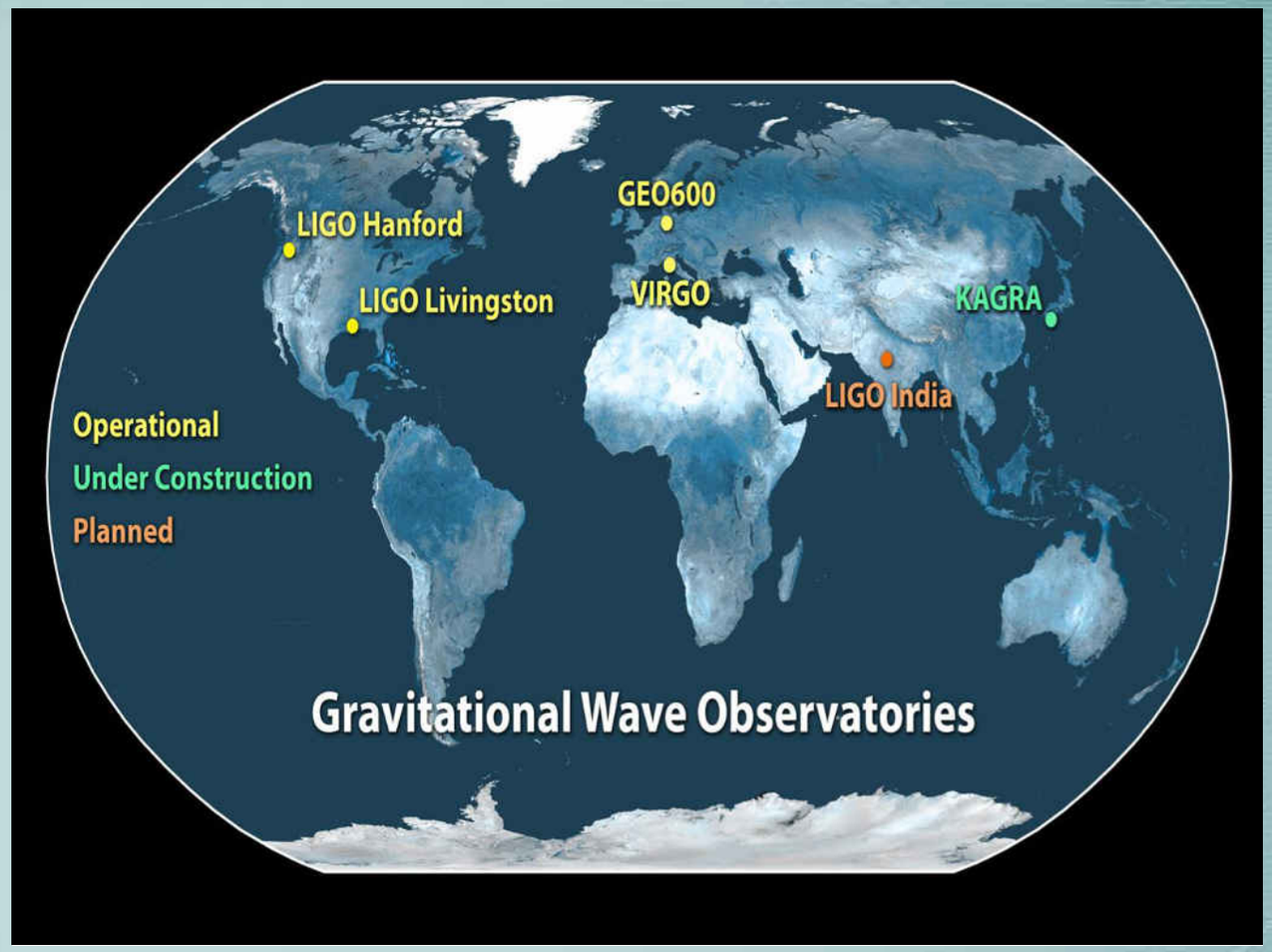
The “God particle”



7. Frontiers: Gravitational Waves from catastrofic events in Cosmos

•Catastrophic collapses of stars produce bursts of ***Gravitational Waves***

•ripples in space and time that propagates with the volocity of light and can be seen by the deformation of massive objects caused by their passage



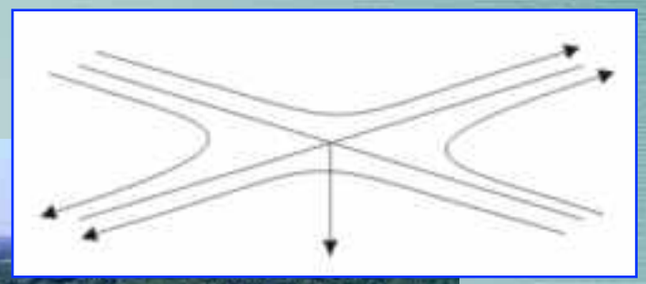
• In Italy: pioneered in by E. Amaldi and G.Pizzella (1970)

•continued by A. Giazotto, M. Cerdonio, G. V. Pallottino, F. Ricci and others with Criogenic Antennae and Laser Interferometers.

La frontiera piu' promettente

- Interferometri laser su lunga distanza
- misurano le fluttuazioni dello spazio-tempo dovute al passaggio di un'onda gravitazionale, ad es. dovuta alla coalescenza di due pulsar
- Negli USA: LEGO observatory in due siti, Hanford e Livingstone
- In Italia: Virgo-European Gravitational Observatory (Cascina, Pisa)

LIGO @ Hanford e Livingstone, USA

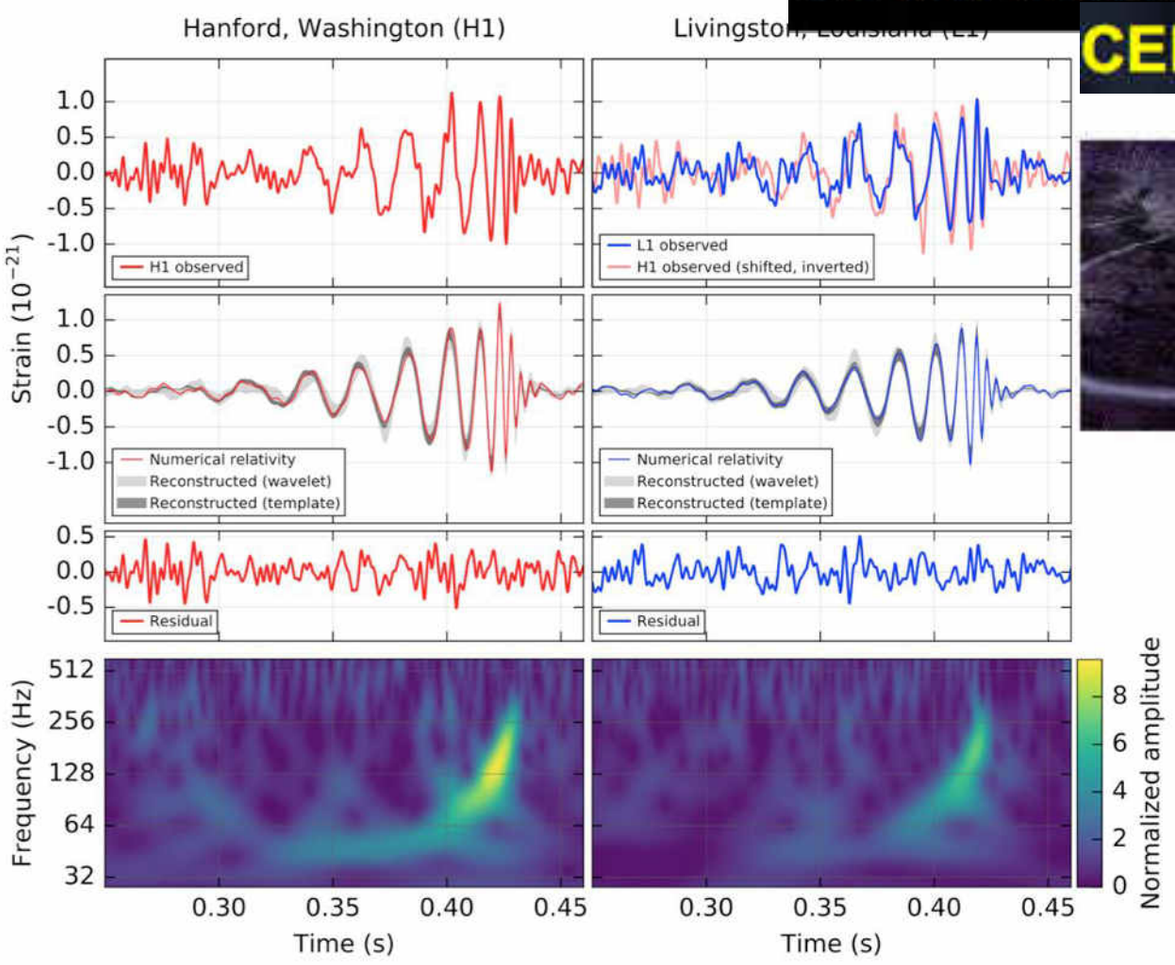


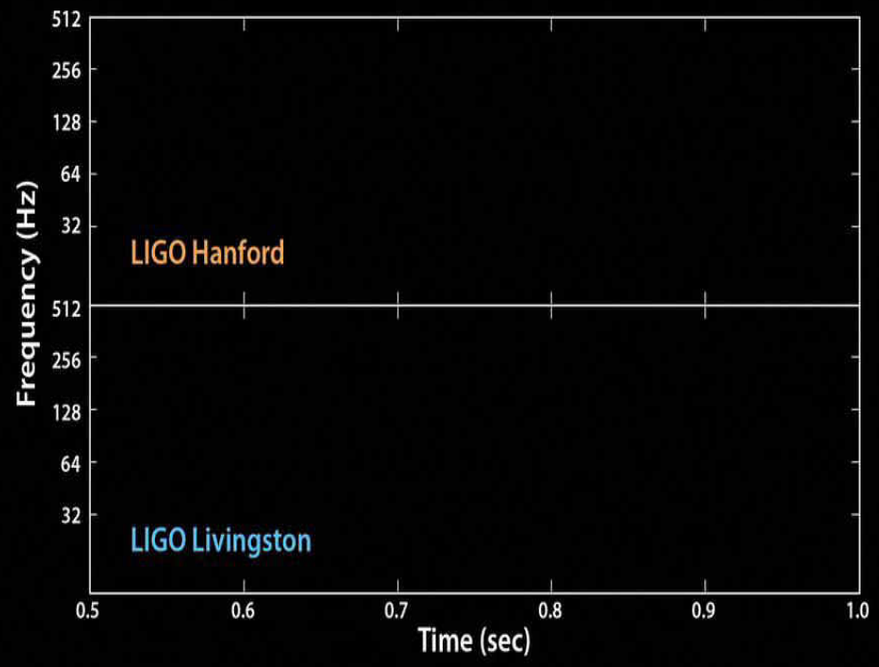
Osservatorio VIRGO @ Cascina, PISA

GW150914

David Reitze
LIGO Laboratory
California Institute of Technology

CERN Colloquium, CERN, August 29, 2017





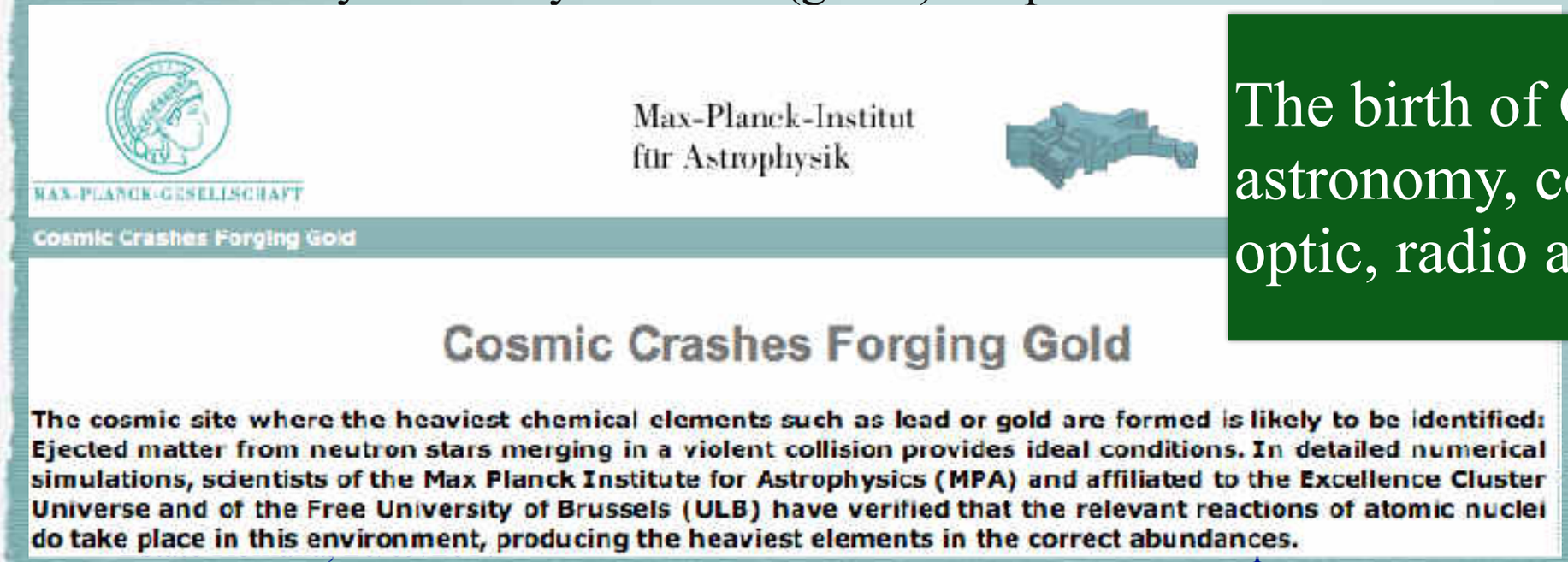
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" Phys. Rev. Lett. 116, 061102 (2016)

2

Coalescence of binary system of neutron stars

Loosing energy by emission of gravitational waves, stars become closer and closer until they fall into each other in a catastrophic clash

- Ligo-Virgo can identify the direction from where gravitational waves are coming
- optical-radio telescopes can be pointed in that direction to study the post-collapse supernova
- is this the way the heavy elements (gold..) are produced in the Universe ??


Max-Planck-Institut
für Astrophysik
MAX-PLANCK-GESELLSCHAFT
Cosmic Crashes Forging Gold

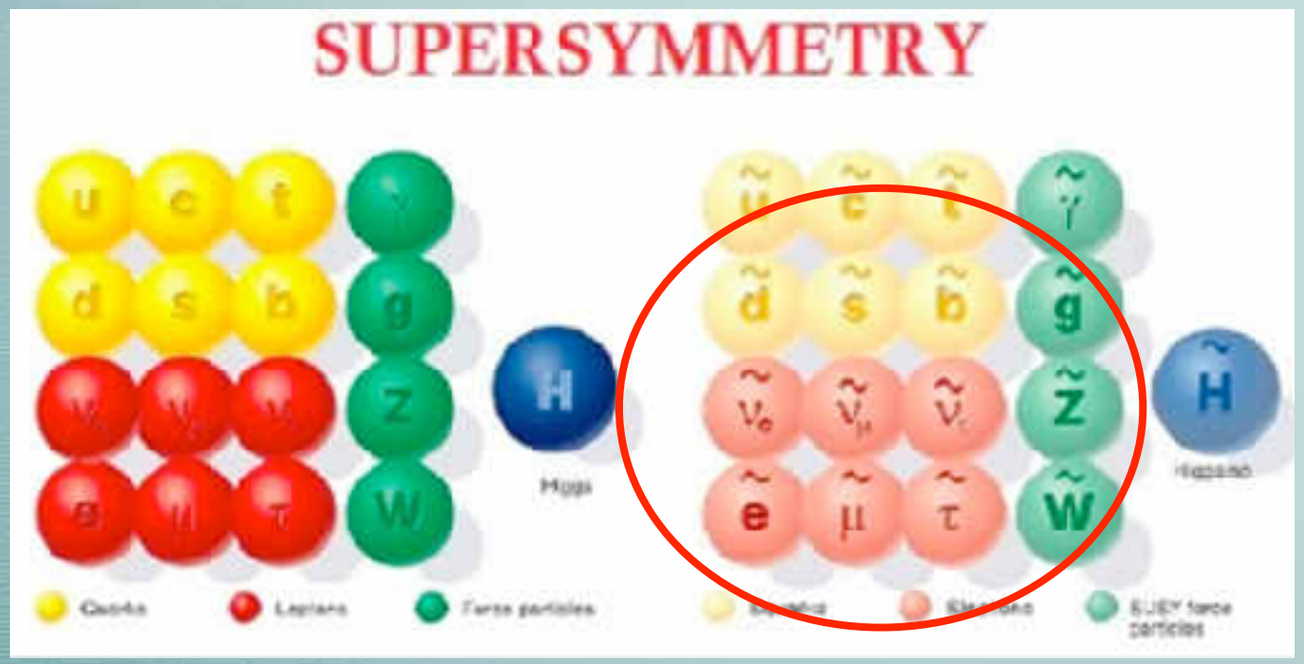
Cosmic Crashes Forging Gold

The cosmic site where the heaviest chemical elements such as lead or gold are formed is likely to be identified: Ejected matter from neutron stars merging in a violent collision provides ideal conditions. In detailed numerical simulations, scientists of the Max Planck Institute for Astrophysics (MPA) and affiliated to the Excellence Cluster Universe and of the Free University of Brussels (ULB) have verified that the relevant reactions of atomic nuclei do take place in this environment, producing the heaviest elements in the correct abundances.

The birth of Gravitational Wave astronomy, complementing optic, radio and neutrinos !!!

8. The High Energy Frontier: Supersymmetry ?

- New simmetry and new particles may be waiting for us at highest energies of the LHC
  - to explain the Dark Matter
  - to understand the unification of all interactions
  - including the still misterious force of Gravity

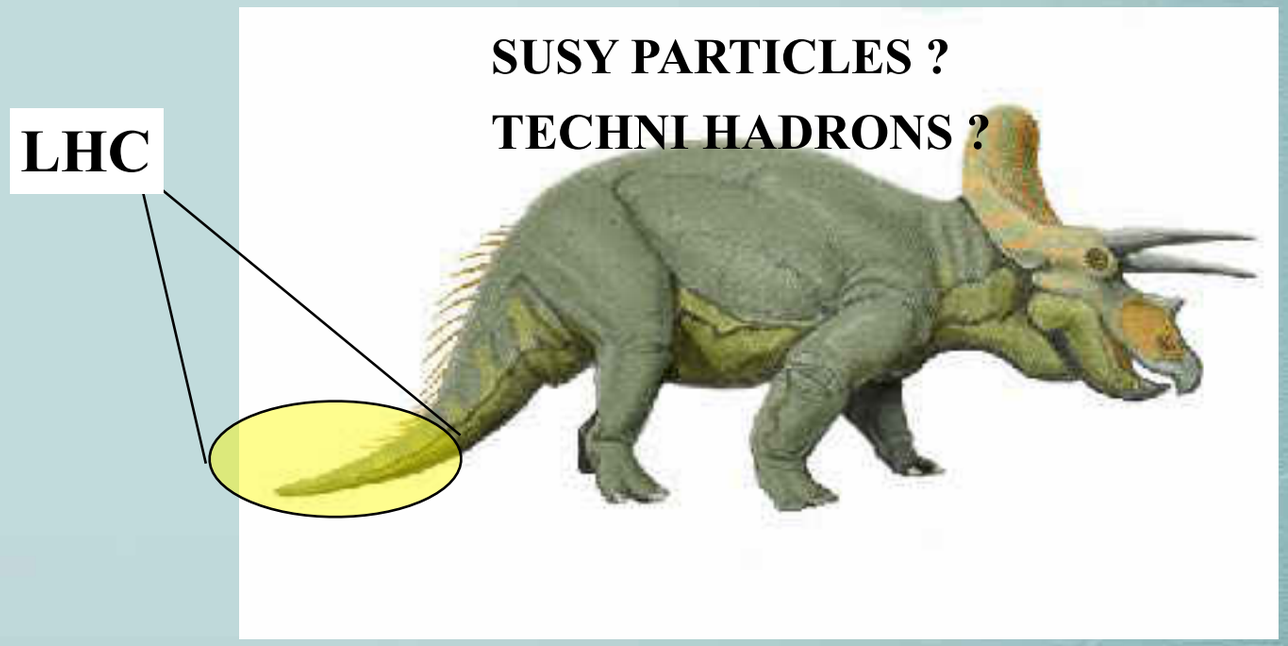


An entire world of new particles to discover!!

What's next?

- LHC Run2: ongoing
- LHC+: a factor 10 more luminosity, will bring the discovery potential above 3 TeV (?)
- With the LHC energy limitation, it is not likely that we can see all particles implied by SUSY or by other theories and find out which is the next step BEYOND the STANDARD THEORY

- but we may be able to see the tail of the dinosaur....

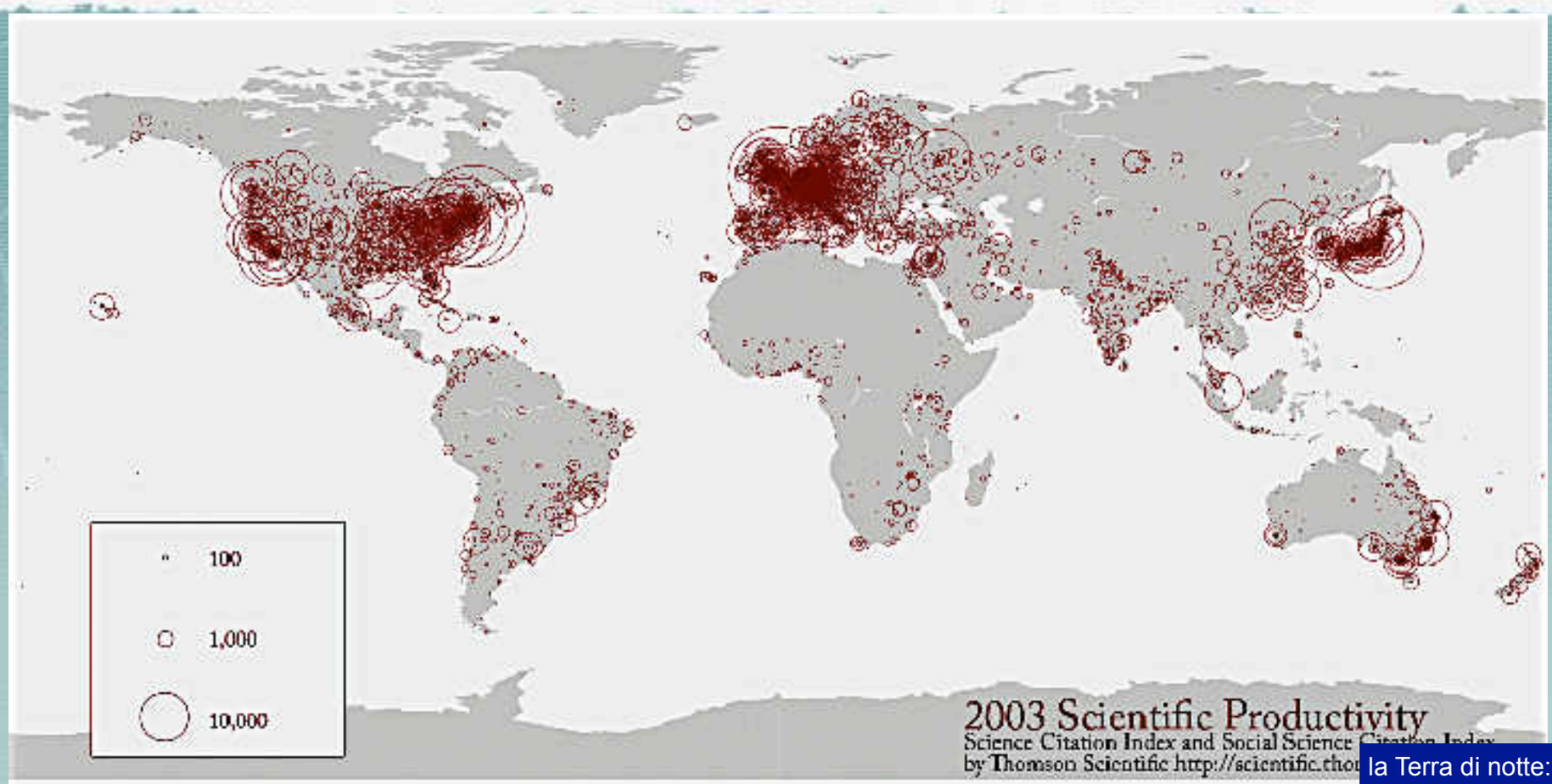


- we may have guessed some real point…. compositeness, supersymmetry …but there are so many things we do not fully understand (dark matter, hierarchy, strong interactions) that the physics we will find there ***has to be entirely new, strange and unexpected***.

Dreams about the future??

- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted in the last 100 years

1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europa
2030's: Regional Laboratories in Europe, America, Asia … will they unite in a Global Accelerator Network - The World ??



Börner, Katy. *Atlas of Science: Visualizing What We Know*. (2010). The MIT Press. Pg 2.

la Terra di notte:
dove c'è ricerca e dove non c'è ...

"If this importance (of Science) has been cast sometime into doubts, it is because the efforts of mankind toward its most beautiful aspirations have been imperfect…

Above all, it is by this daily effort toward more science that mankind has reached the exceptional place that she occupies on Earth.

We must belong to those who.... believe, invincibly, that science will triumph over ignorance and war."

Marie Curie , 1926