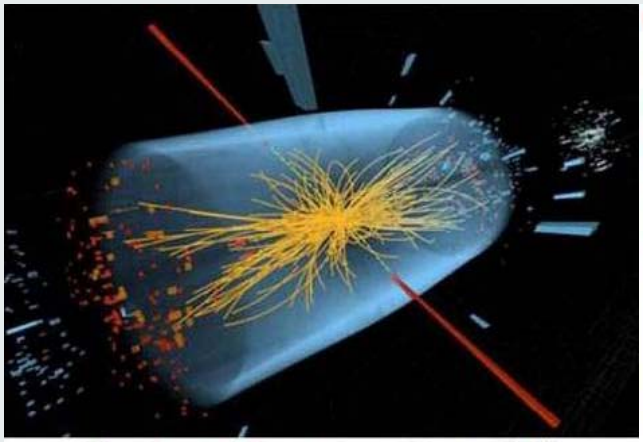
FUNDACIÓN VALENCIANA DE ESTUDIOS AVANZADOS

Fundacion Valenciana de Estudios Avanzados

Ciclo Arquitectura Cósmica II 26 September 2013

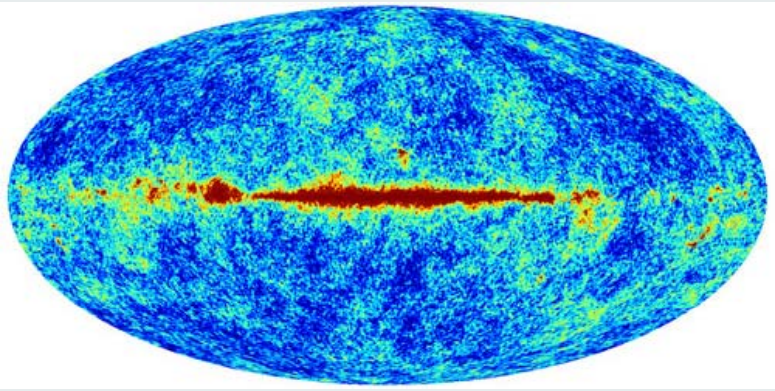
THE HIGGS BOSON AND THE FRONTIERS OF PHYSICS

CERN DISCOVERS HIGGS BOSON. *One of many proton-proton collisions at LHC.*



TIME REVERSAL VIOLATION.
First observation of Time Reversal Violation in the time evolution of entangled neutral B mesons

MAJORANA FERMIONS. *Looking for Majorana fermions in a solid.*



PLANCK COLLABORATION SKY MAP
Cosmic Microwave Background Radiation

José Bernabéu – IFIC Valencia

THE FRONTIERS

➢ The advance of knowledge in Science is measured by

the degree of synthesis,
the explanation of novel observed phenomena,
the unification which allows the increase of the validity domain, ...

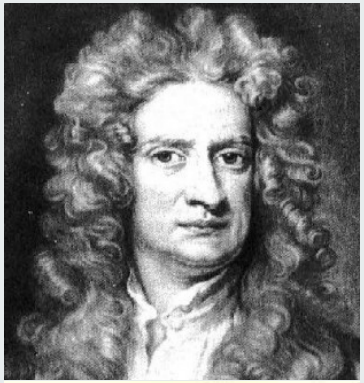
➢Novel open problems not glimpsed before appear, and its resolution leads to a deeper understanding and the formulation of new questions.

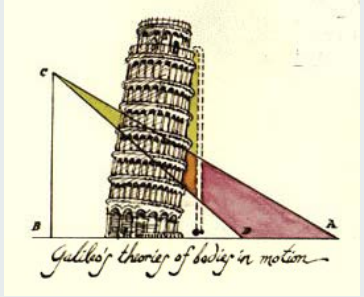
➢I do not have a linear vision of the advance of Science, on the contrary there are many frontiers.

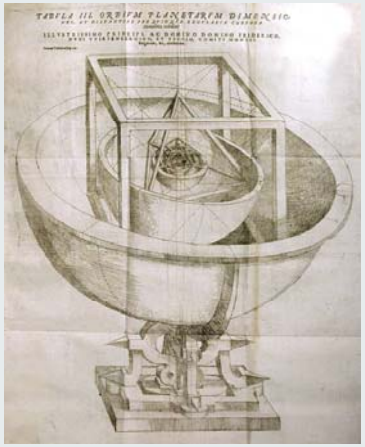
"The advance of knowledge generates and increases the number of questions in the frontiers"

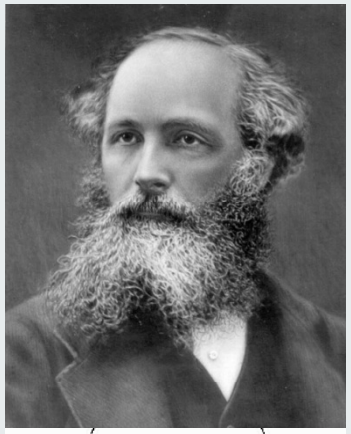
UNIFICATION

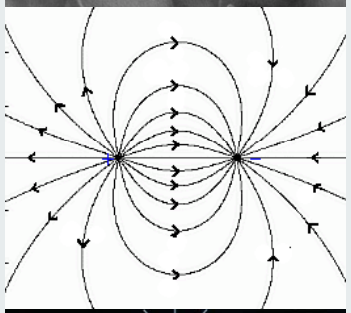
➢A very effective way of gaining land for KNOWLEDGE is UNIFICATION, with the convergence of two or more fields which were separated:

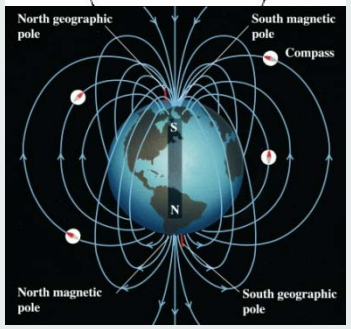


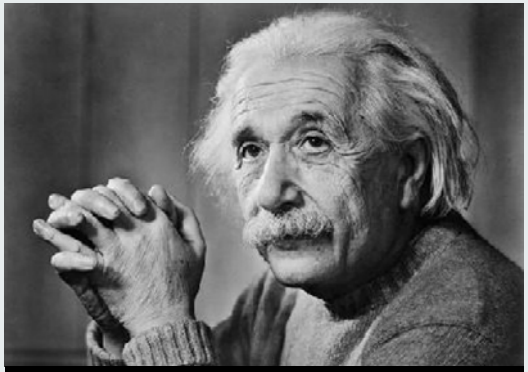




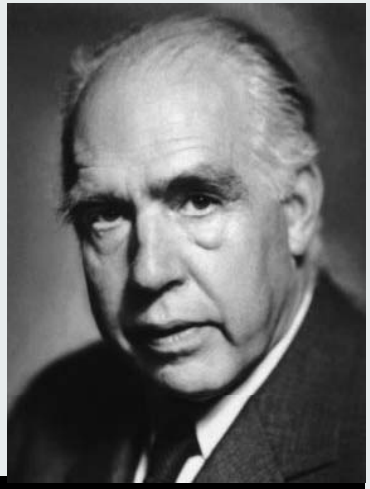




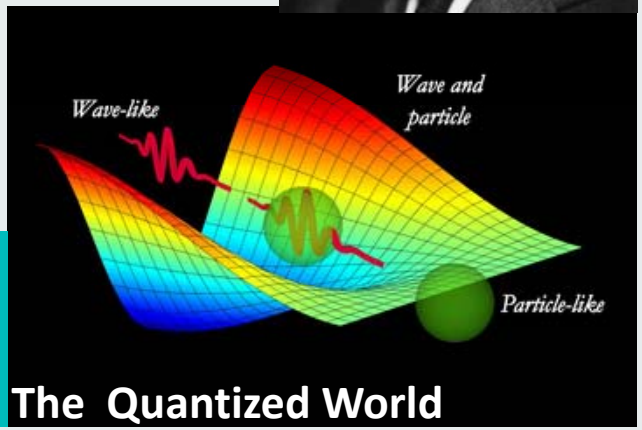




$$E_0 = m\,c^2$$

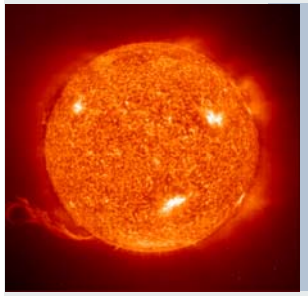


$$\lambda = \frac{h}{p}$$

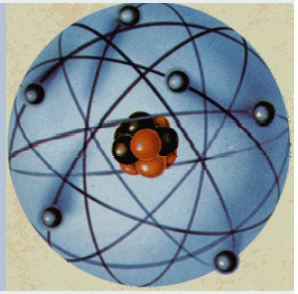


UNIFICATION & SCALES

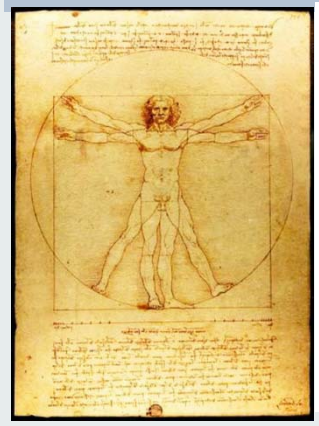
In the last decades, there have been spectacular unifications:

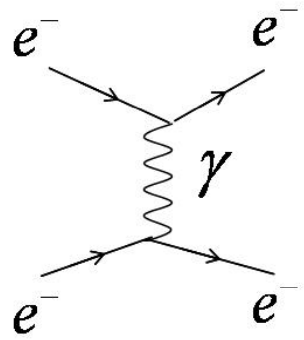


❖ Between the weak force responsible,
for example, of energy generation in the stars,
and the electromagnetic force responsible,
for example, of the existence of aggregate matter.

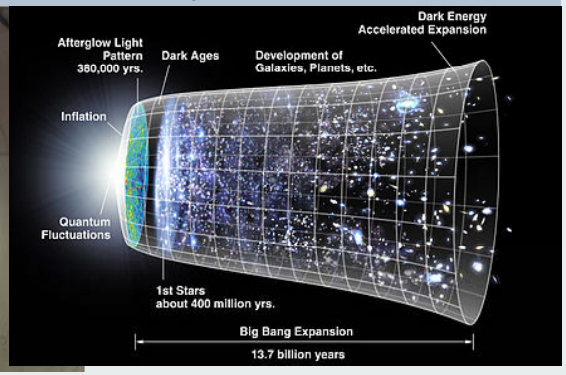


❖ Between Symmetries of the
Physical Laws and
the Dynamics of the Interactions

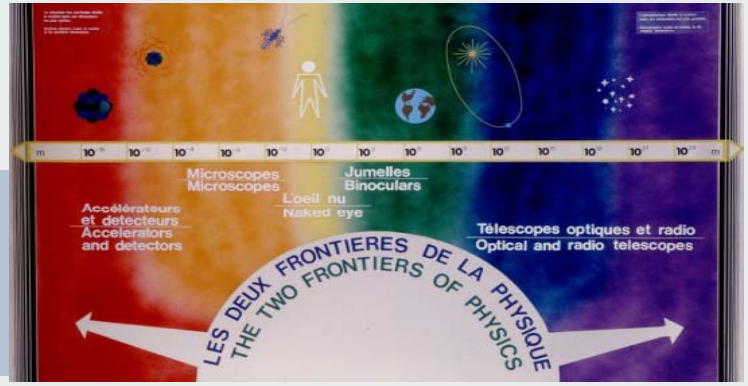




❖Between Particle Physics and
The Physics of the Early Universe



❖ The last Unification connects
the smallest and largest scales in distances
from 10^{-19} m to 10^{+26} m : THE UNITY OF PHYSICS



TOP BREAKTHROUGHS IN PHYSICS IN THE LAST YEAR

Physics World journal revealed its first 3 Top Breakthroughs in Physics in 2012:

At different distance scales (in m)

- 10^{-19} Higgs
- 10^{-17} TRV
- 10^{-7} Majorana
- 10^{+25} Planck

➢ One glorious week in July 2012 when physicists working on the ATLAS and CMS experiments at CERN announced that they had discovered a "Higgs-like particle". These findings have been confirmed in the last year, so that IT IS a Higgs Boson. Why so important?

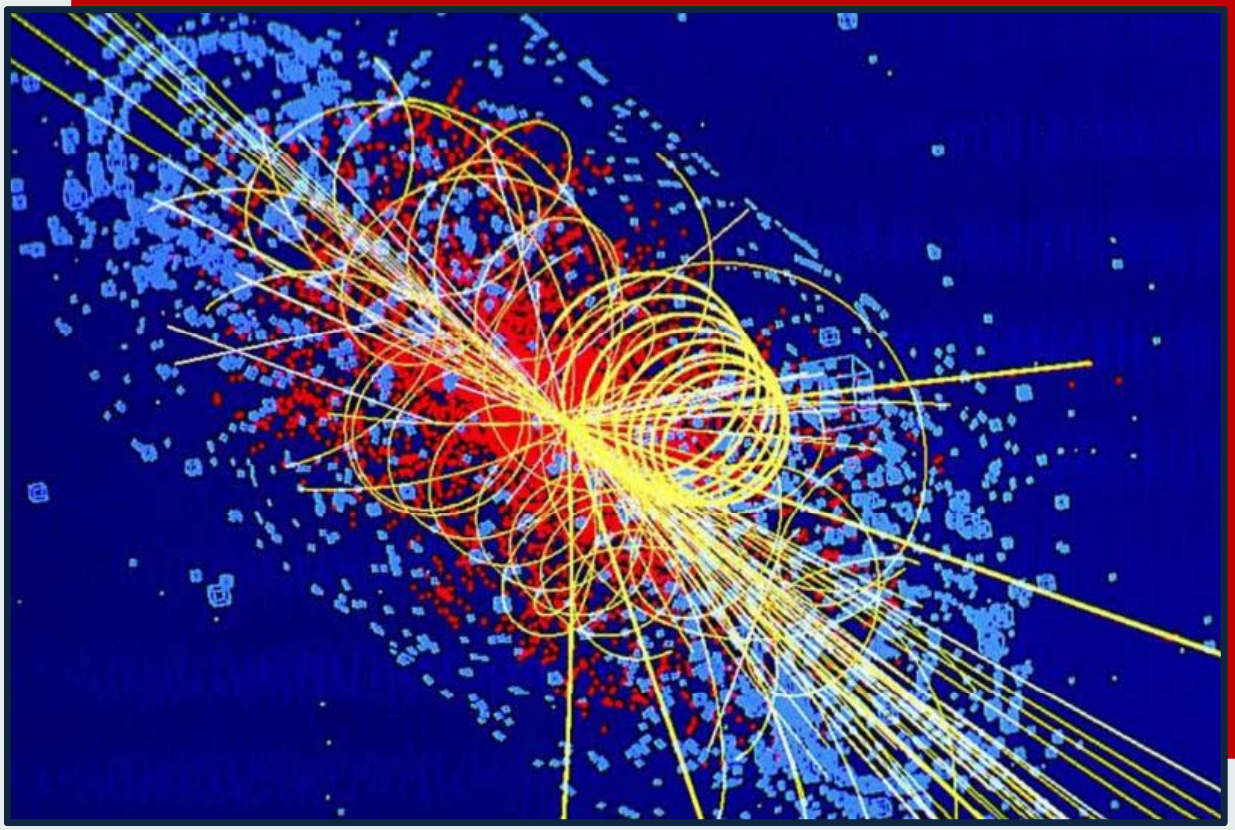
➢ 48 years after the discovery of asymmetry between matter and antimatter came a direct observation of Time-Reversal Violation (TRV) for unstable particles detected by BABAR. The conceptual basis for this bypass was proposed at IFIC Valencia making use of quantum entanglement.

➢ Majorana-like quasiparticles could be lurking in materials with special topological properties. Leo Kouwenhoven and colleagues at Delft University have spotted the first hints of Majorana fermions at the interface between a topological superconductor and a semiconductor.

In addition,

➢ Planck Spacecraft of ESA was launched in May 2009, reaching the Earth/Sun L2 point in July, and by February 2010 had successfully started a second all-sky survey. On March 2013, the mission's all-sky map of the Cosmic Microwave Background Radiation was released.

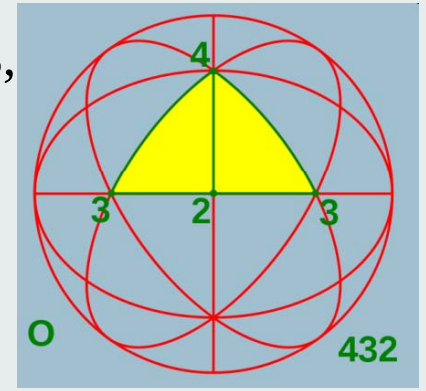
THE HIGGS BOSON : ONE YEAR ON



Why is this discovery so important ?

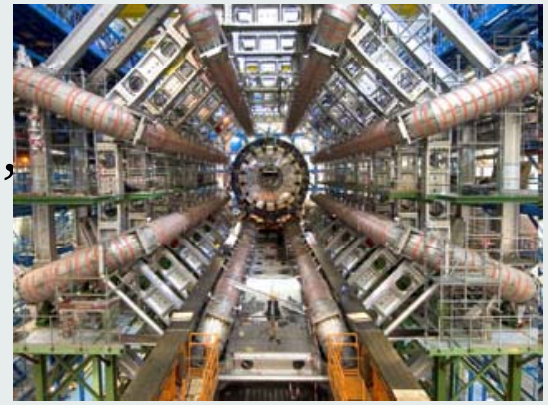
SYMMETRY OF OBJECTS

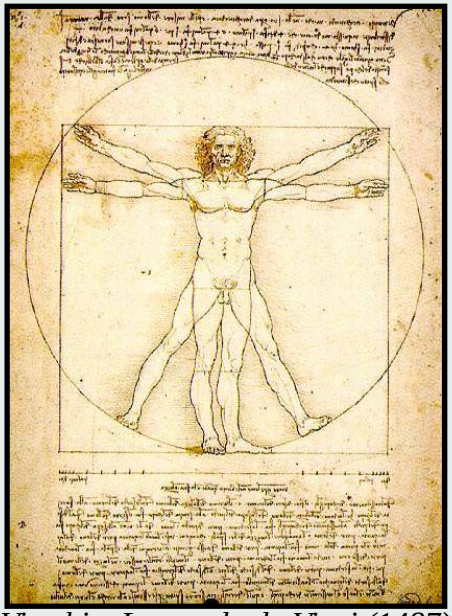
Characteristic feature of geometric forms,



Symmetry Group of sphere

of material objects,


ATLAS experiment of LHC


Vitrubio, Leonardo da Vinci (1487)

of biological bodies,

related to their invariance under

definite transformations.

One object is symmetric if, after a transformation is applied, the result remains the same: it remains "invariant".

SYMMETRY BREAKING

This three-span arch, painted bright blue and orange, appears perfectly symmetric when viewed directly from below, but has a carefully calculated asymmetry from its other views.

The former Fermilab Director R.R. Wilson freely adopted the style of the sculptor A.Calder for giving an example of Symmetry and Symmetry Breaking, which are so important in the field of elementary particle physics.

SYMMETRIES IN THE LAWS OF PHYSICS

CONSTITUYENTES ELEMENTALES DE LA MATERIA

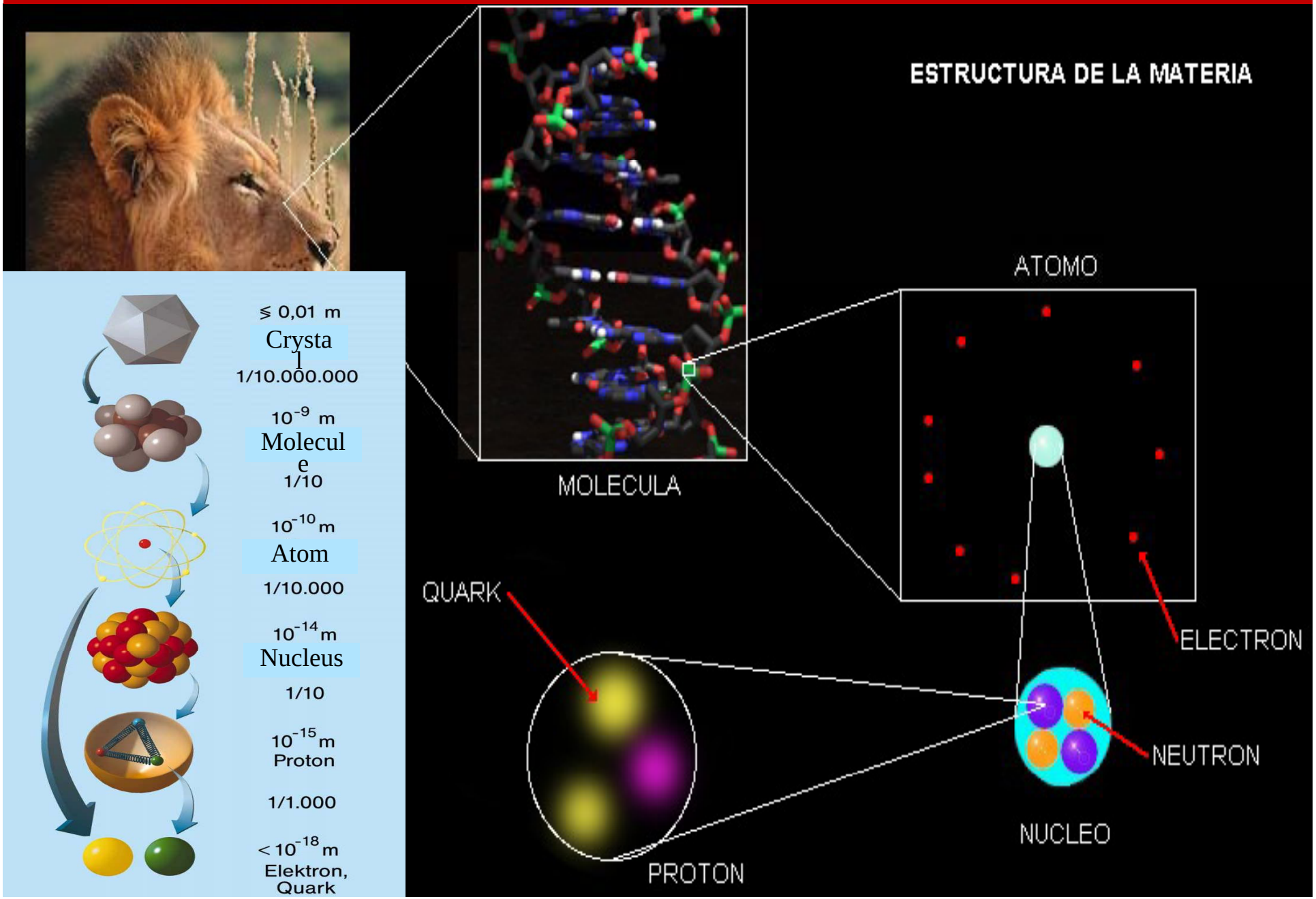
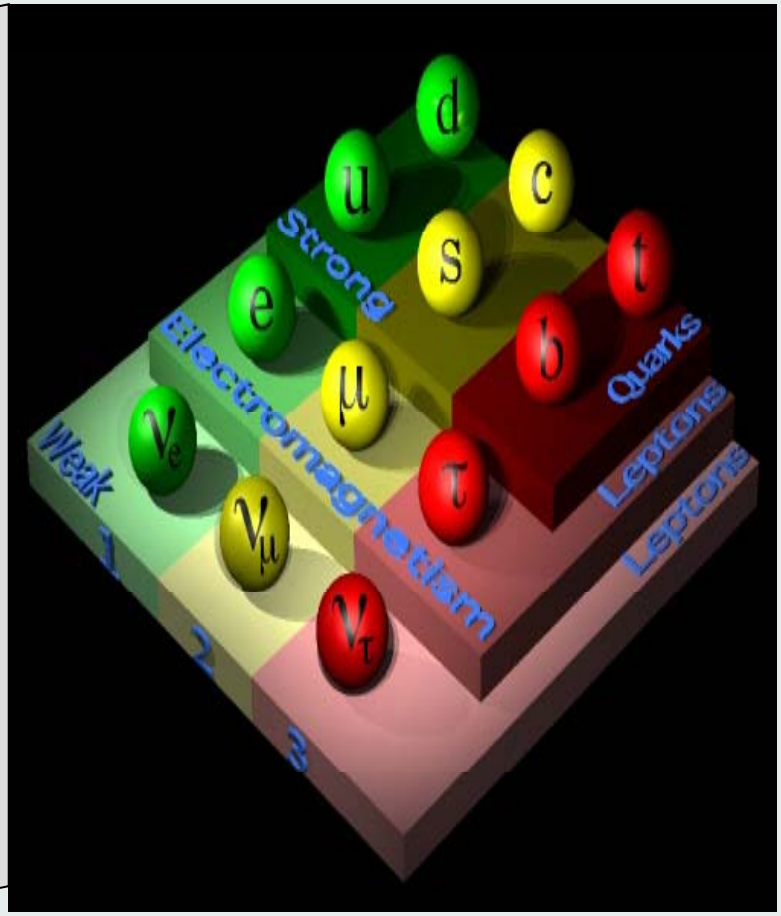
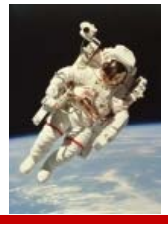
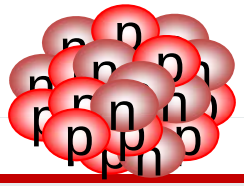


TABLA PERIÓDICA DE LAS PARTÍCULAS ELEMENTALES



LAS FUERZAS FUNDAMENTALES

Fuerza	Cuanto	Masa	Alcance
Gravedad 	gravitón ?	0	∞
Electromagnética 	fotón	0	∞
Débil $n \rightarrow p + e^- + \bar{\nu}_e$ $\nu + p \rightarrow \nu + X$	$W^{\pm}$, Z	80, 90 GeV	~.001 fm
Fuerte entre quarks  	gluones	0	O(1) fm (confinamiento)

THE STANDARD MODEL IN A NUTSHELL

➢ The elementary constituents of matter, quarks and leptons, are organized in three families with the same electro-weak quantum numbers. They have increasing mass values.

➢ All elementary fermions, except (?) neutrinos, have a non-vanishing charge and their corresponding ANTIPARTICLES.

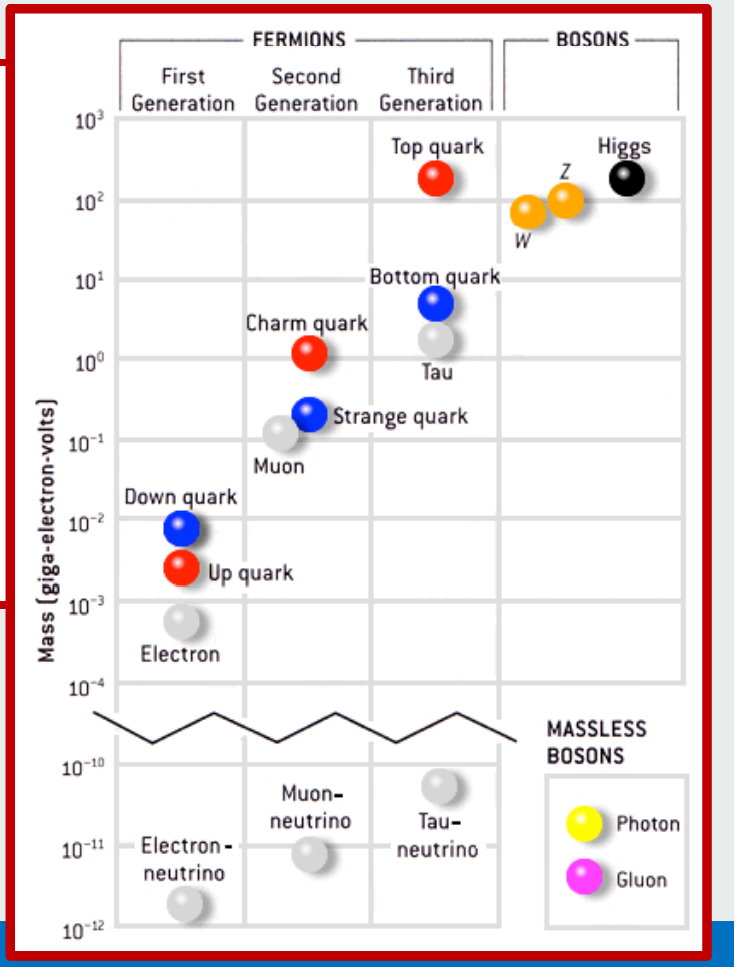
➢ INTERACTIONS are induced by requiring the SYMMETRY under (local) gauge-invariance.

strong electroweak

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

EWSB: Higgs

$$U(1)_{em}$$



➢ All predicted interactions agree with experimental results. They are "Exchange Forces" MEDIATED by the GLUON for strong interaction of the quarks, the PHOTON for electromagnetic interactions of charged particles, the $W^{\pm}$ and Z for weak interactions.

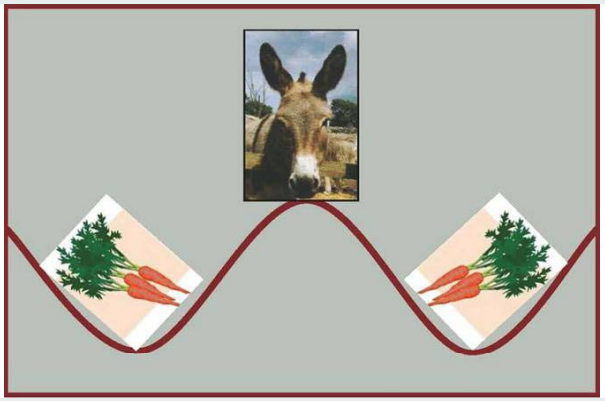
➢ BUT... the symmetry is EXACT only if particles are all MASSLESS, like the photon. Then, WHAT IS THE ORIGIN OF MASS?

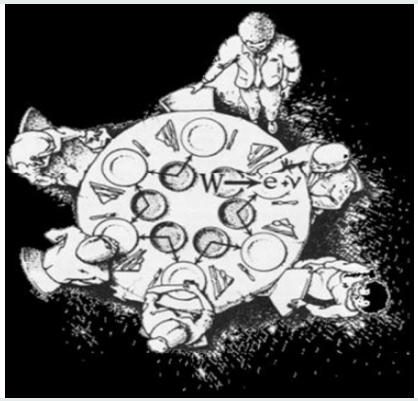
➢ One needs a special way of BREAKING the symmetry: HIGGS MECHANISM.

BROUT-ENGLERT-HIGGS MECHANISM

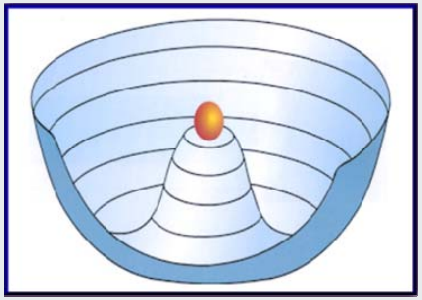
- ORIGIN OF MASS from SPONTANEOUS ELECTROWEAK SYMMETRY BREAKING (SEWSB):

A symmetric Law of Physics can lead to asymmetric solutions





➢ To define a Quantum Field Theory, one has to specify not only the physical law, but also the QUANTUM VACUUM, the lowest energy state from which particles are created and annihilated.



➢ SEWSB means { the physical law is symmetric .
the vacuum is asymmetric. How?

➢ Space-time is filled with a "medium", a field with the interaction like a "mexican hat". Instead of a unique symmetric lowest energy state, there are many possible vacua. One choice breaks the symmetry.

➢ The particle created from the new vacuum is the HIGGS BOSON, a remnant of the Brout-Englert-Higgs Mechanism, hence its importance.

➢ The signature of the Higgs: its coupling to all particles is given by their mass. The ORIGIN OF MASS comes from the asymmetry of the new vacuum.

EL LABORATORIO EUROPEO DE FISICA DE PARTICULAS: CERN

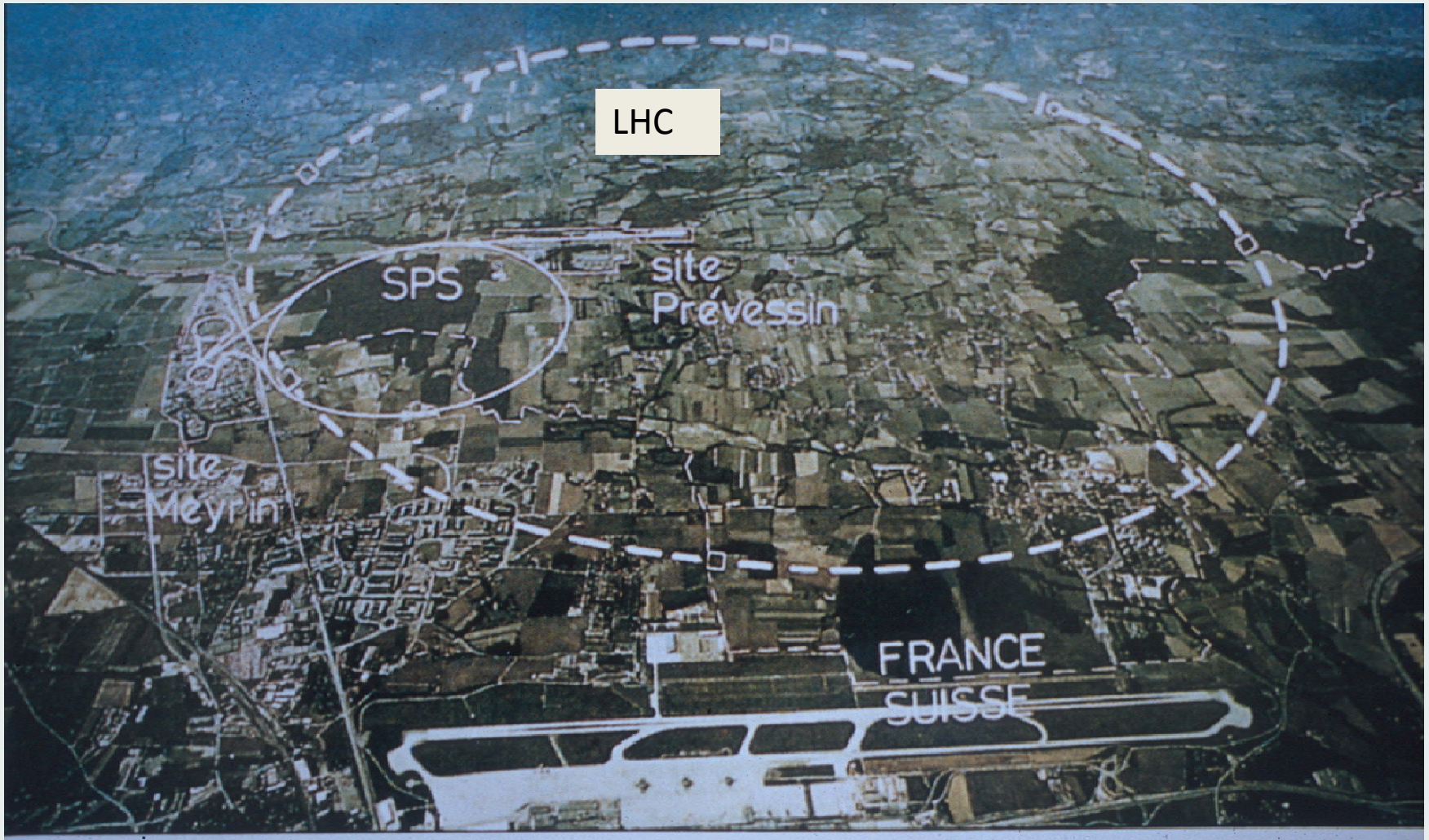
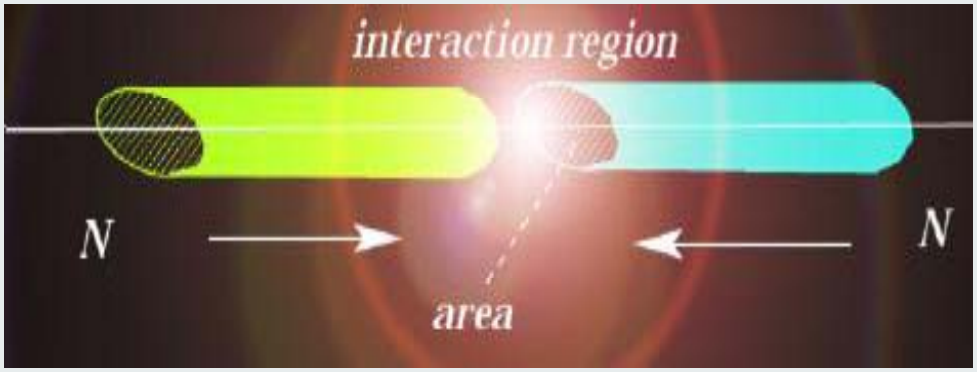


Figura 1.– Visita aérea del CERN con las montañas del Jura al fondo.

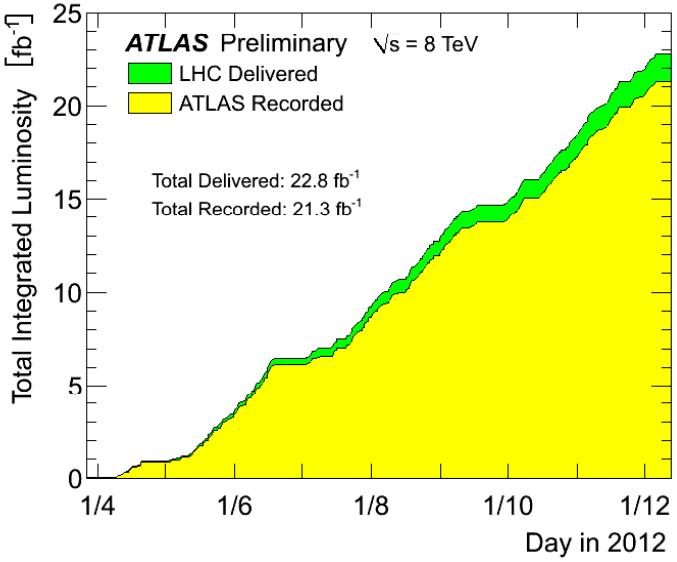
LARGE HADRON COLLIDER

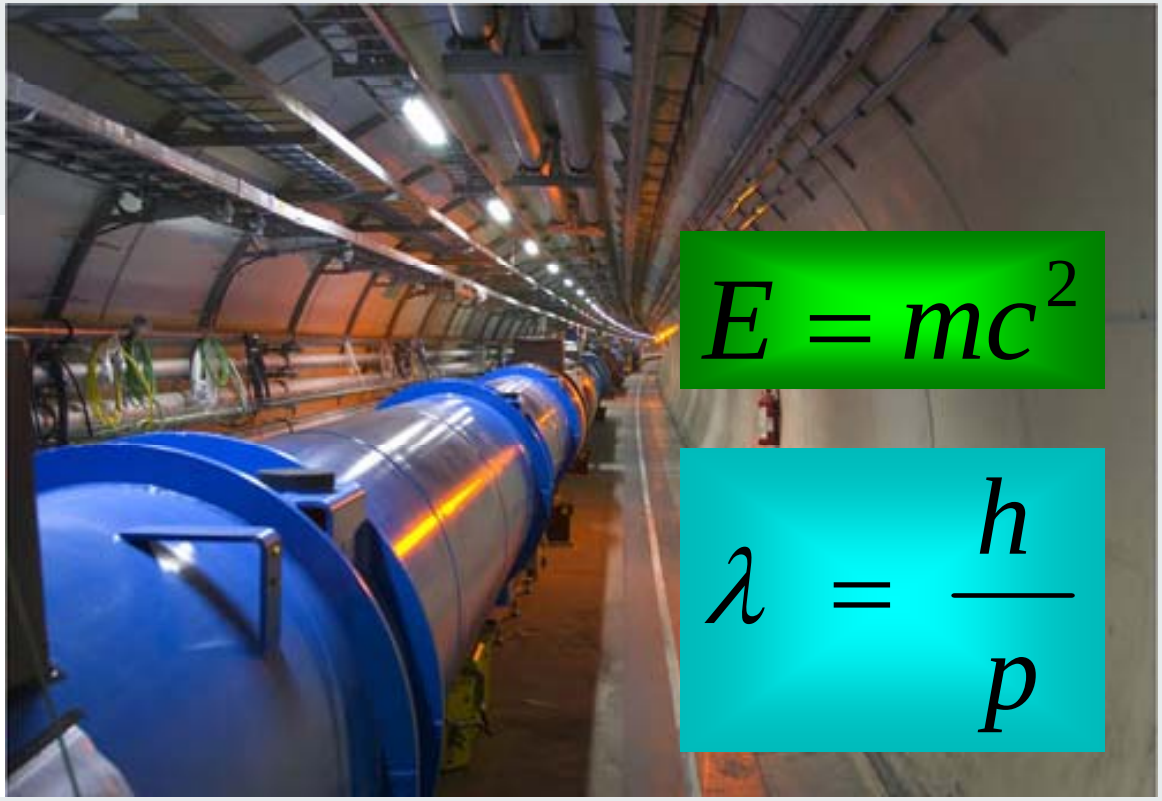
The most important parameters are Energy and Luminosity



The LUMINOSITY value,
10^{34} cm^{-2}· s^{-1} , means that
the LHC detectors
might produce **10^{34} collisions per second and per cm^2**.

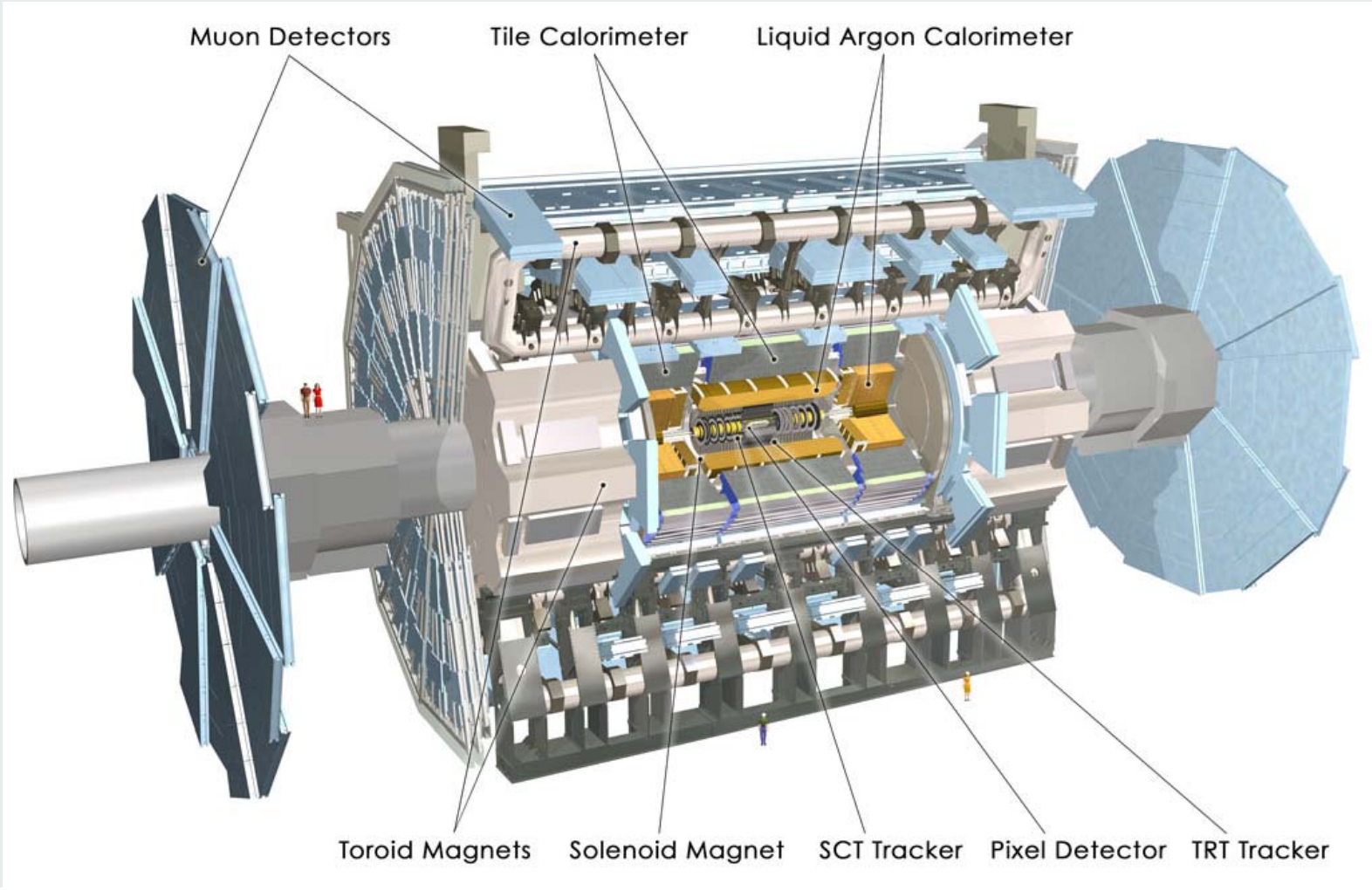
1TeV= 10^{12} eV



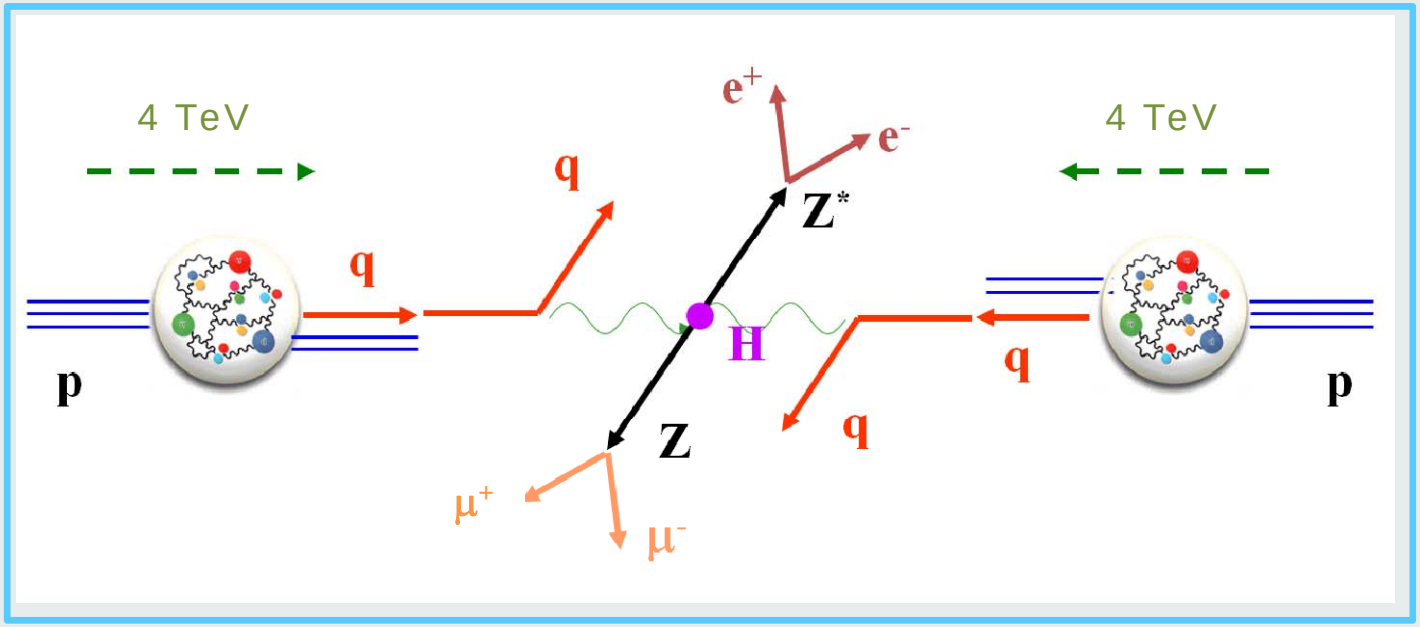


DETECTORES DE PARTICULAS

ATLAS: Instalado en el LHC del CERN. IFIC ha contribuido al Subdetector Interno de Trazas y al Calorímetro Hadrónico. Actualmente los grupos del IFIC contribuyen al análisis de datos reales registrados en el Detector ATLAS.



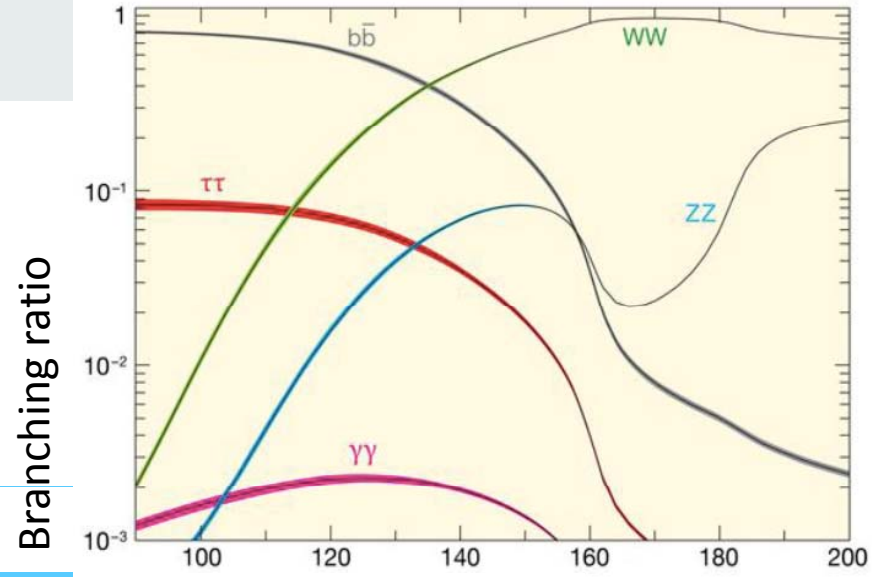
HIGGS BOSON PRODUCTION AND DECAY



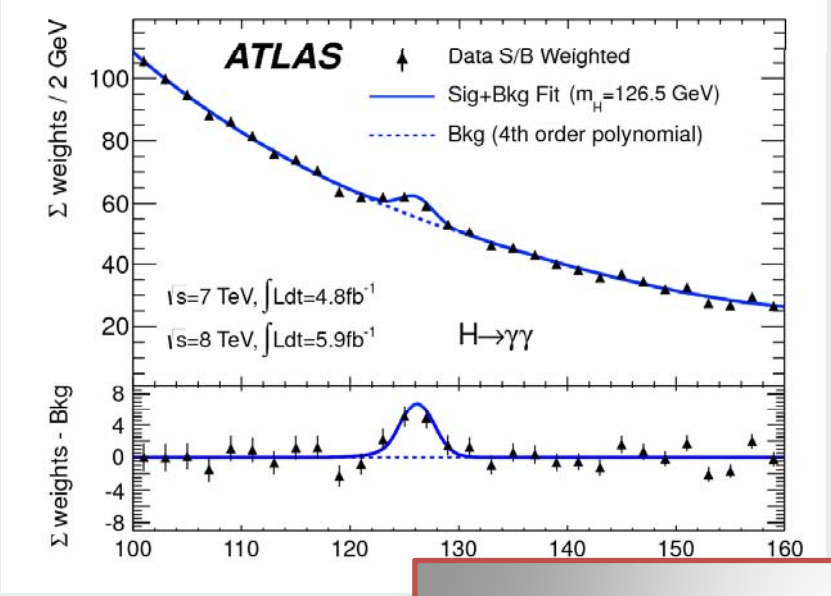
$$E_0 = mc^2$$

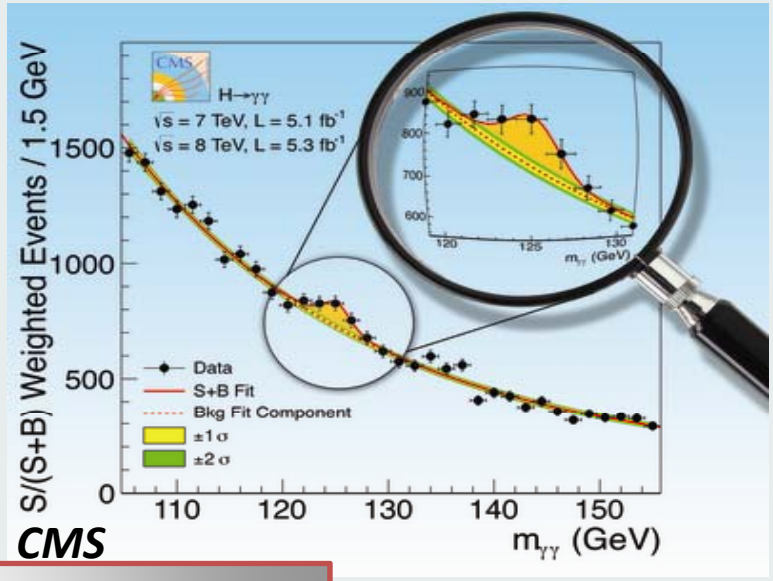
$$\lambda = \frac{h}{p}$$

- L = 10^{+34} protons per cm^2 per sec → 10^8 collisions per sec in the detectors → 2 Higgs per minute.
- Different production modes, with different probabilities.
- Different Decay modes, with different probabilities depending on the Higgs Boson Mass

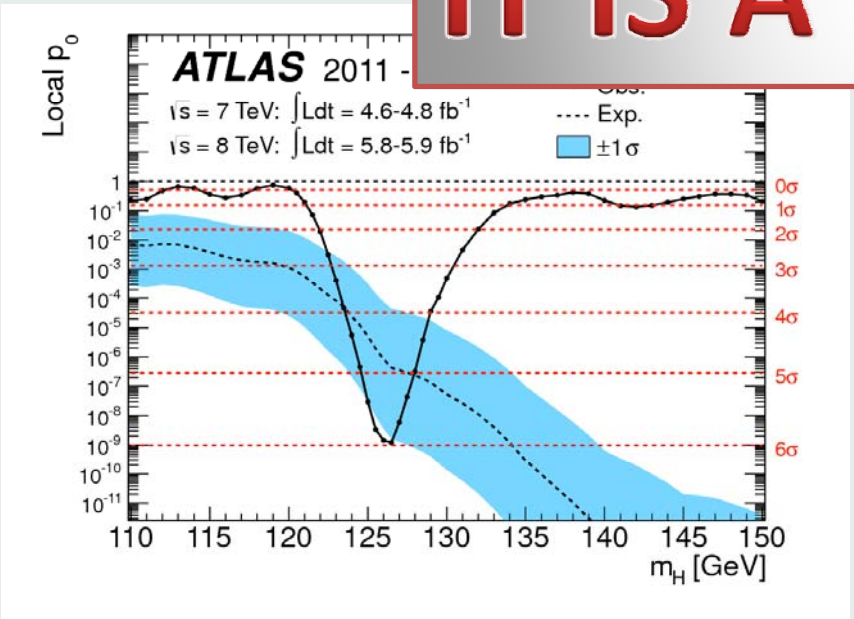


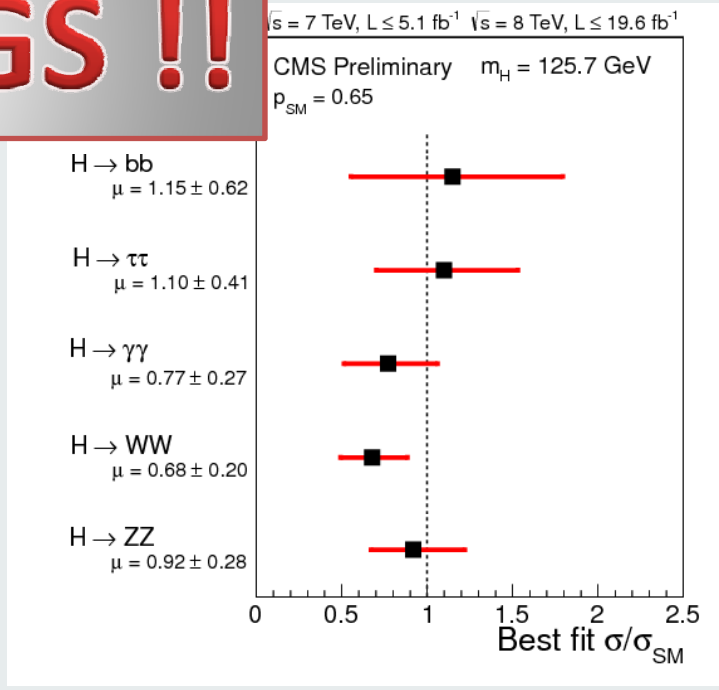
HIGGS BOSON DISCOVERY -> THE DATA



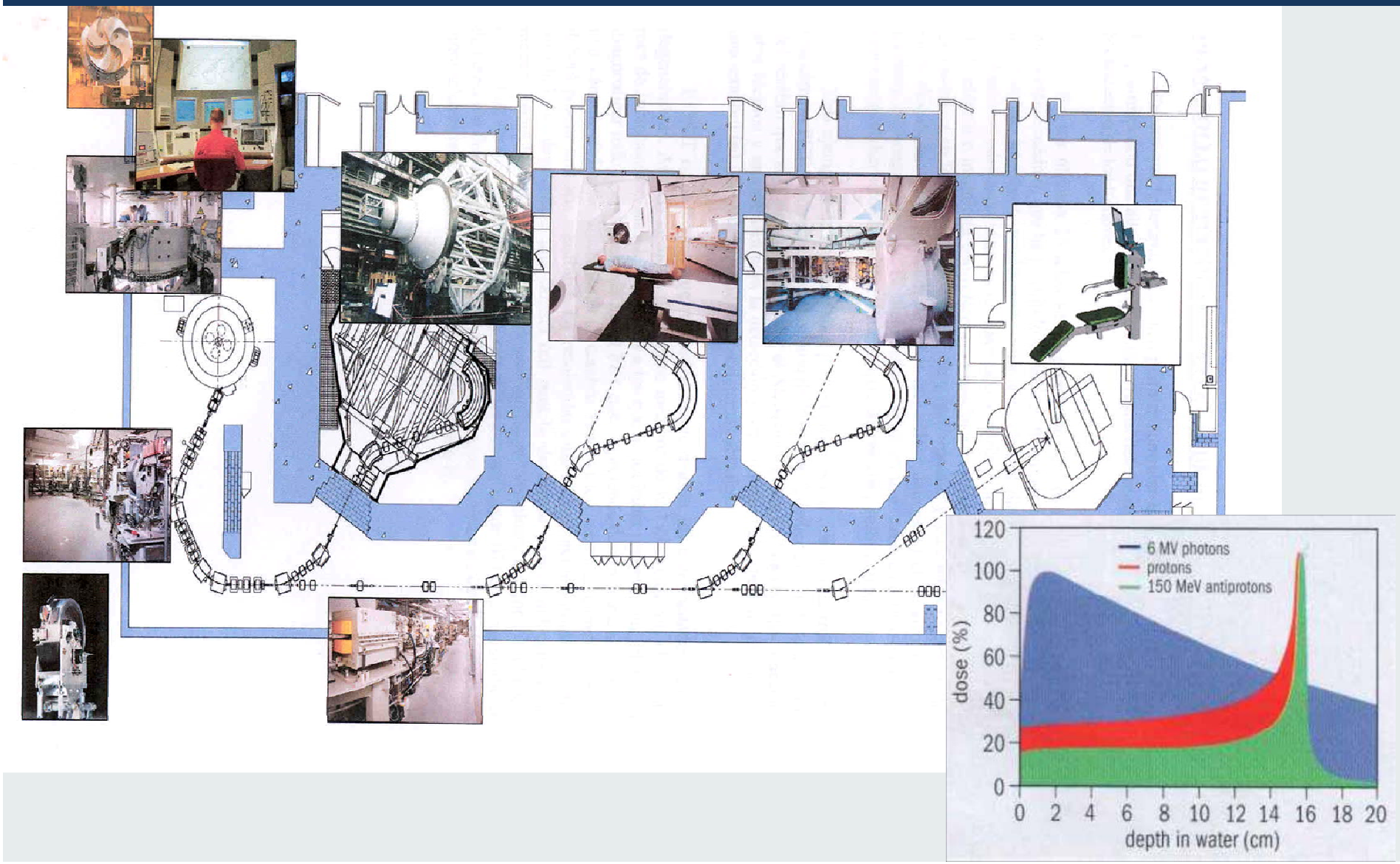


IT IS A HIGGS !!

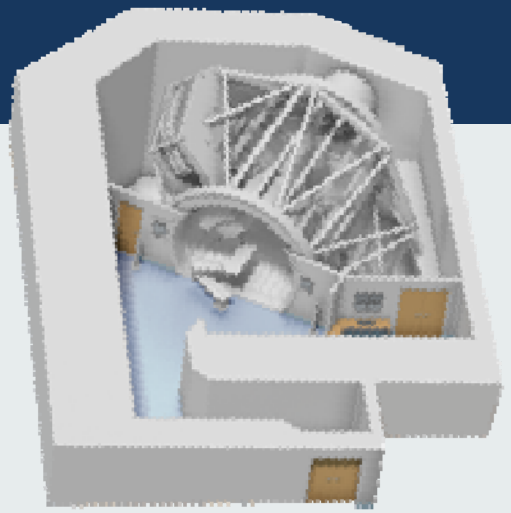


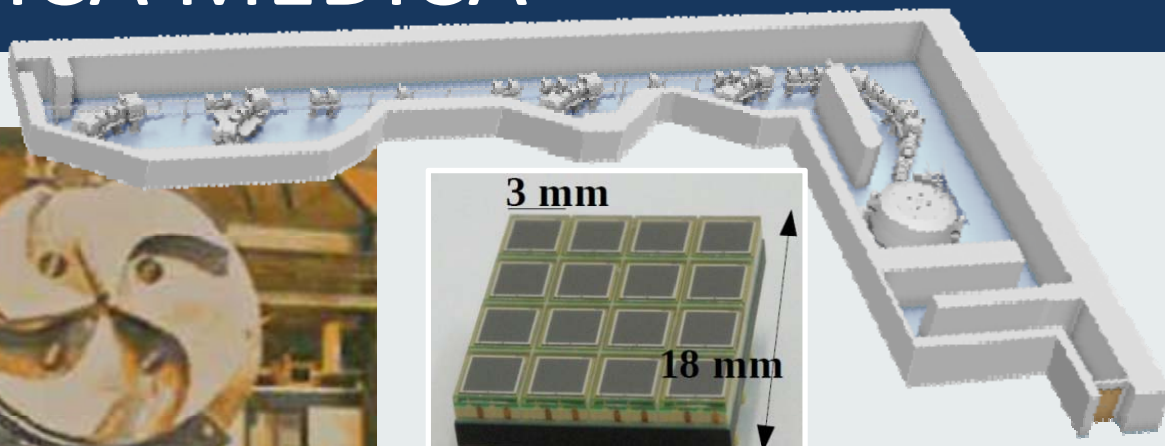


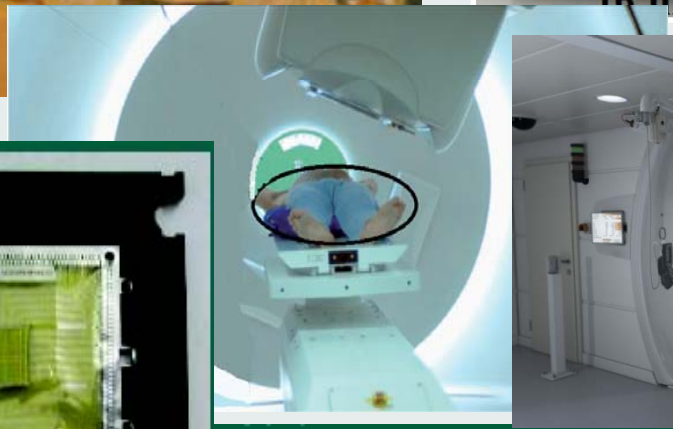
APLICACIÓN DE LA FISICA DE PARTICULAS A LA MEDICINA: PROTON-TERAPIA

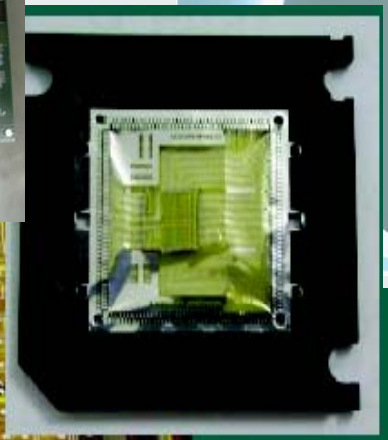


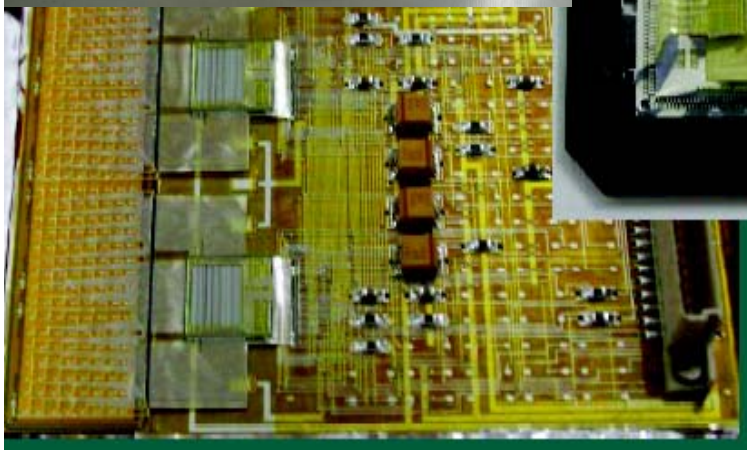
FÍSICA MÉDICA

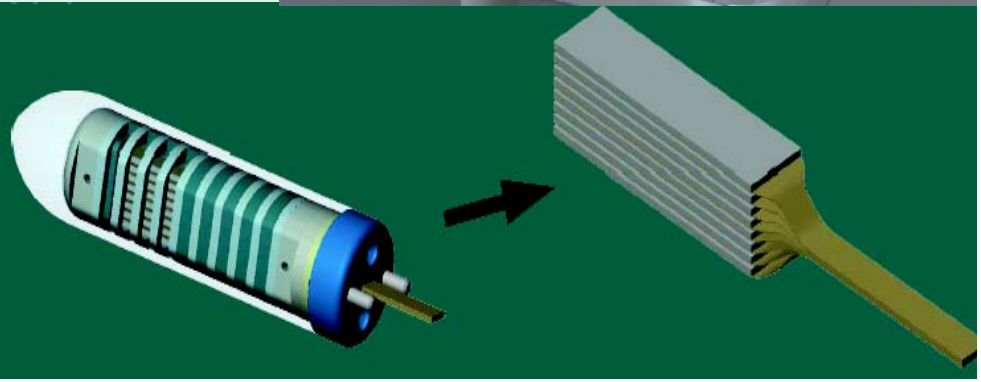






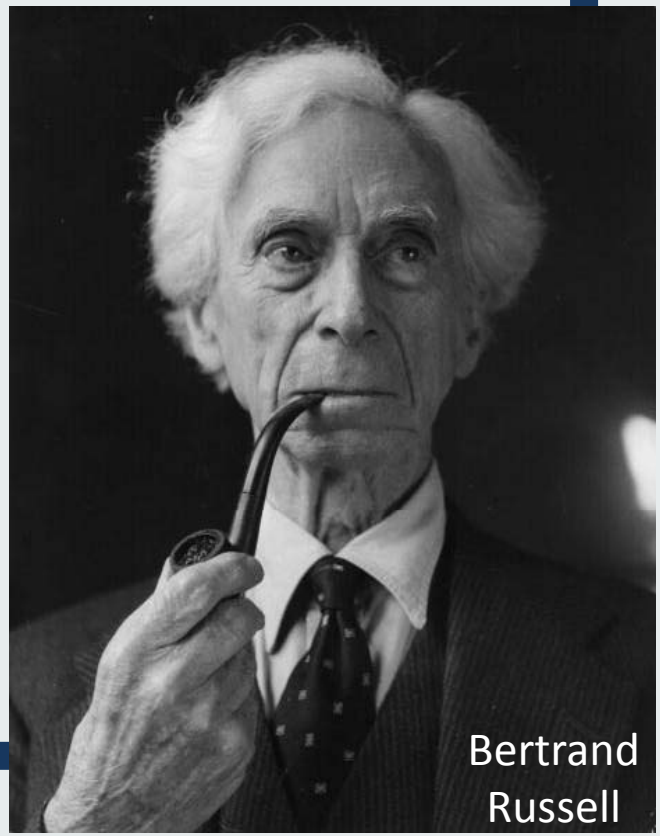






THE SCIENTIFIC PERSPECTIVE

Towards advanced scientific societies



Bertrand Russell

THE GROWTH OF SPANISH PHYSICS

- XX Century was the century of Physics.
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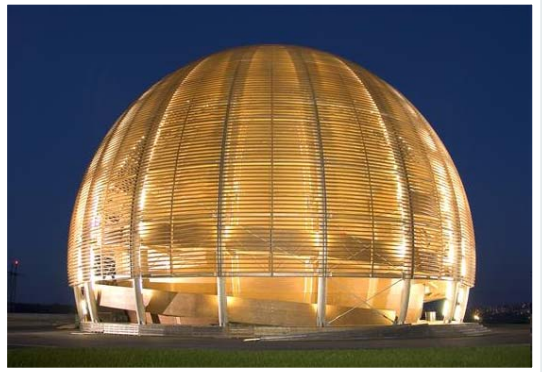

BUT… THE DOWNFALL

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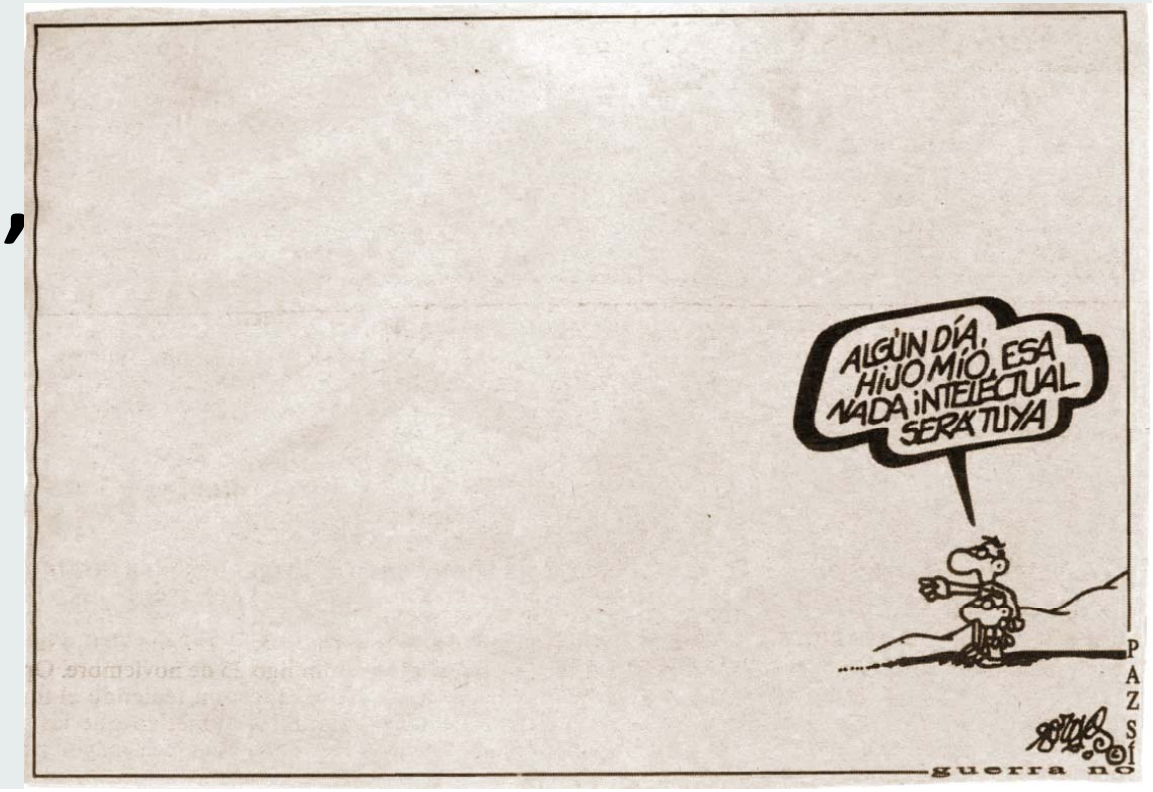
In Spanish & for Spain

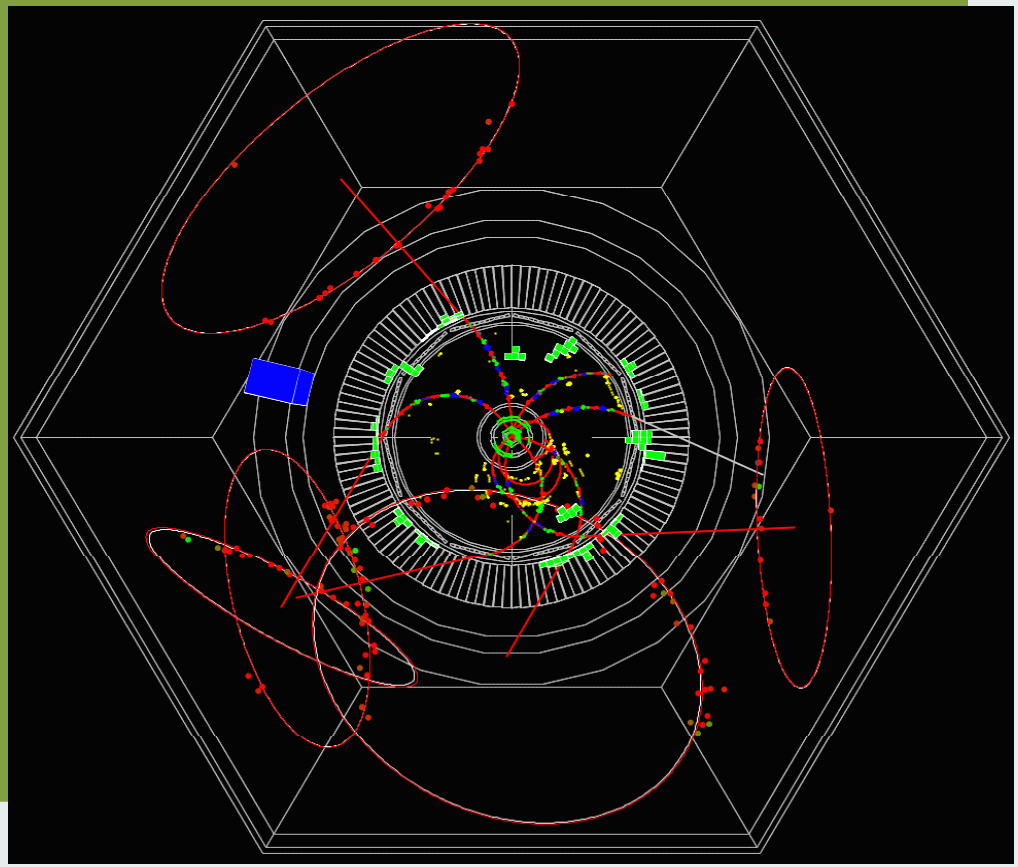
"Una sociedad que alega que, en tiempos de crisis, no se ha de invertir en ciencia, especialmente en personal científico altamente cualificado, incumpliendo compromisos de BOE, es no-fiable, ciega, enferma y suicida, porque no tiene futuro".



BACK-UP

TIME REVERSAL VIOLATION

Why 48 years after CP Violation?

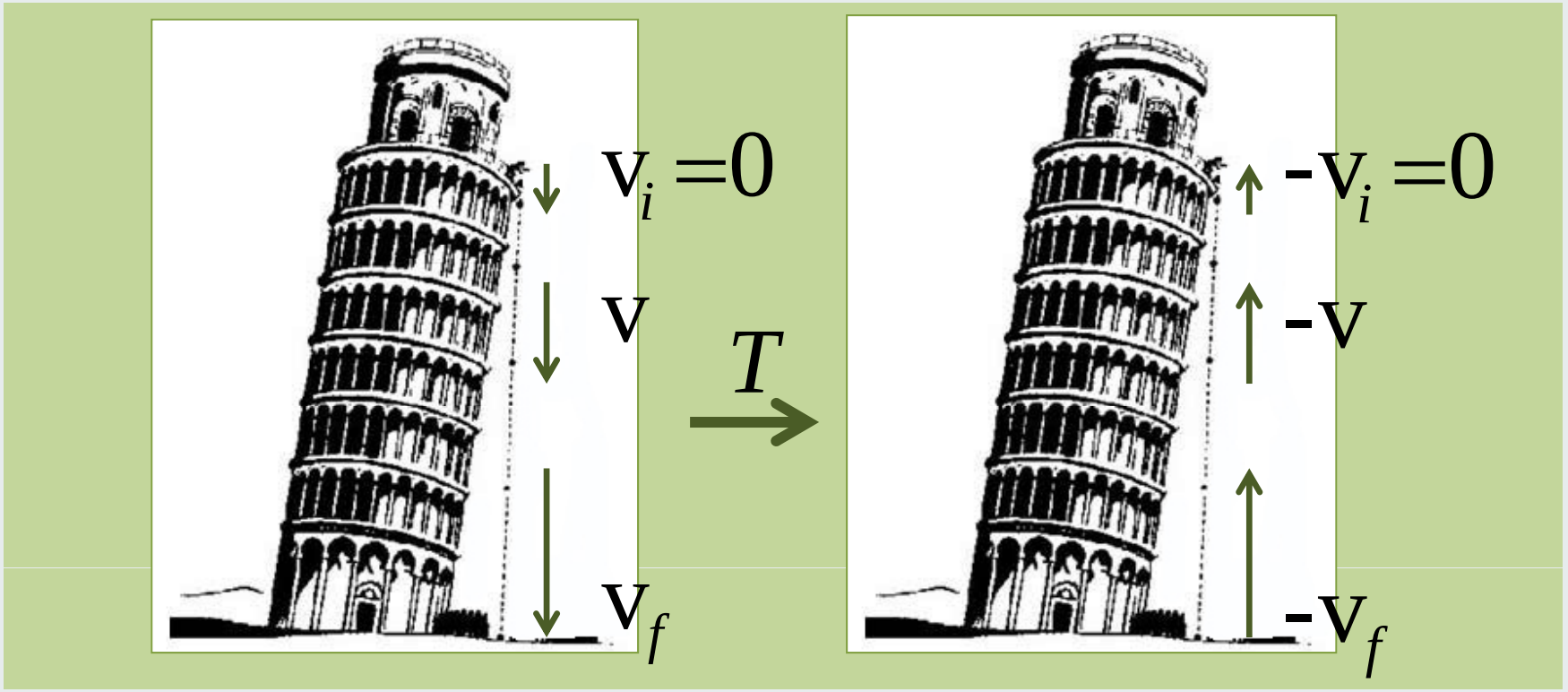


> 1964	CPV observed in the $K^0 - \overline{K}^0$ and (later) $B^0 - \overline{B}^0$ systems: unstable particles.
CPT-"Theorem"	TRV expected in these systems as well.
< 1999	L. Wolfenstein (and others): "For a decaying state, its T-transformed does not exist“ ➡ "Impossible" test of T-symmetry!
= 1999	**Bypass to "No-Go" by means of Quantum Entanglement.**
CONCEPT	M.C. Bañuls, J.B., PLB (1999), NPB (2000); scrutinized by L. Wolfenstein, IJMP(1999); H. Quinn, JPCS(2009); V. Rubakov; T. Nakada; F. Botella, … *“it would appear to be a true TRV effect”*
METHOD, PROPOSAL & SIMULATION	J.B., F. Martínez-Vidal, P. Villanueva-Pérez, JHEP (2012)
EXPERIMENTAL RESULT	**BABAR Collaboration, PRL (2012)**

WHAT IS "TIME REVERSAL"?

- A symmetry transformation, T, that changes one physical system into another with an inverted sense of time evolution is called Time Reversal.

In classical mechanics, this corresponds to substituting for each trajectory $\vec{r} = \vec{r}\,(t)$ the trajectory $\vec{r} = \vec{r}\,(-t)$, to moving along the given trajectory with the opposite velocity at each point.



TIME REVERSAL INVARIANCE ?

- If the original trajectory is dynamically possible, it is not necessary, in general, that the time reverse trajectory be so for the same dynamics.

- One would need that the equation of motion remains invariant in form under the transformation

$$t \to -t, \quad \vec{r} \to \vec{r}, \quad \vec{p} \to -\vec{p}$$

In our elementary example, one would need to neglect velocity-dependent friction:

$$\frac{d\,\vec{p}}{d\,t} = \vec{F}(\vec{r}) \quad \textbf{INVARIANT;} \qquad \frac{d\,\vec{p}}{d\,t} = \vec{F}(\vec{r},\vec{v}) \quad \textbf{VIOLATED}$$

- We are interested in the fundamental laws of Physics, from Newton's law to the behaviour of elementary constituents of matter and their interactions.

SYMMETRIES IN THE LAWS OF PHYSICS

➢ In Quantum Mechanics, there is an operator U_T implementing the T-symmetry acting on the states of the physical system, such that

$$U_T\,\vec{r}\,U_T^{+}=\vec{r},\; U_T\;\vec{p}\,U_T^{+}=-\vec{p},\; U_T\vec{s}\,U_T^{+}=-\vec{s}$$

By considering the commutator $[r_j,\,p_K]=i\hbar\delta_{jK}I$

the operator U_T must be ANTI-UNITARY:

UNITARY- for conserving probabilities, ANTI- for complex conjugation

ANTIUNITARITY introduces many intriguing subtleties:

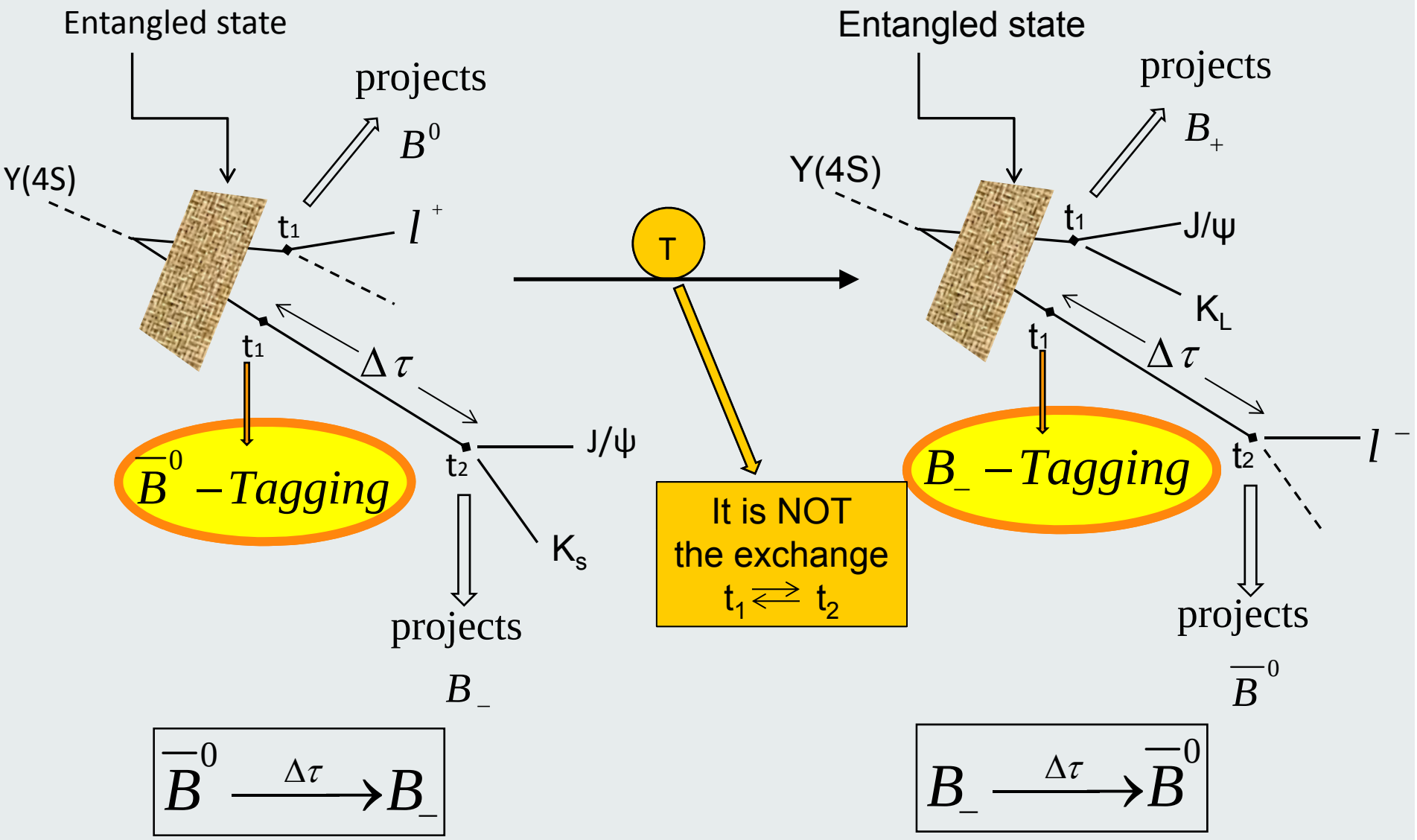
$$S_{i\to f}\xrightarrow{\;T\;}S_{U_T f\to U_T i}$$

T - Violation means Asymmetry under

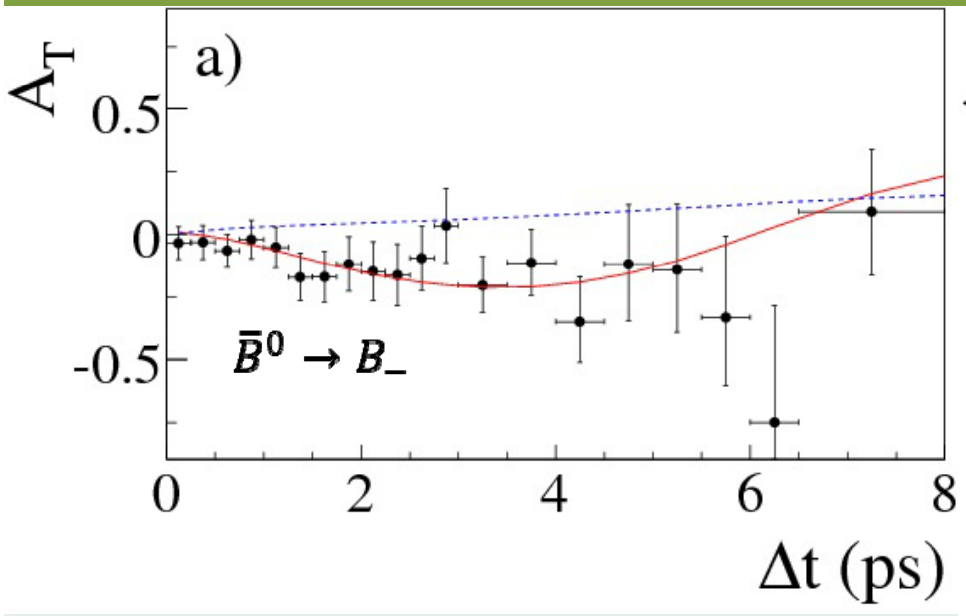
Interchange in ⟷ out states

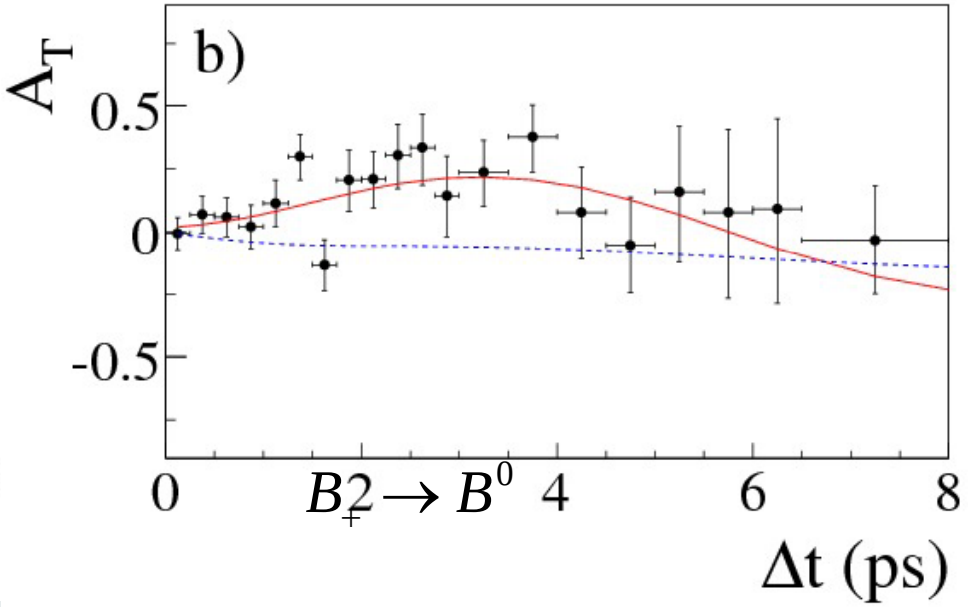
➢ **A direct evidence for TRV would mean an experiment that, considered by itself, clearly shows TRV INDEPENDENT of, and unconnected to, the results for CPV**

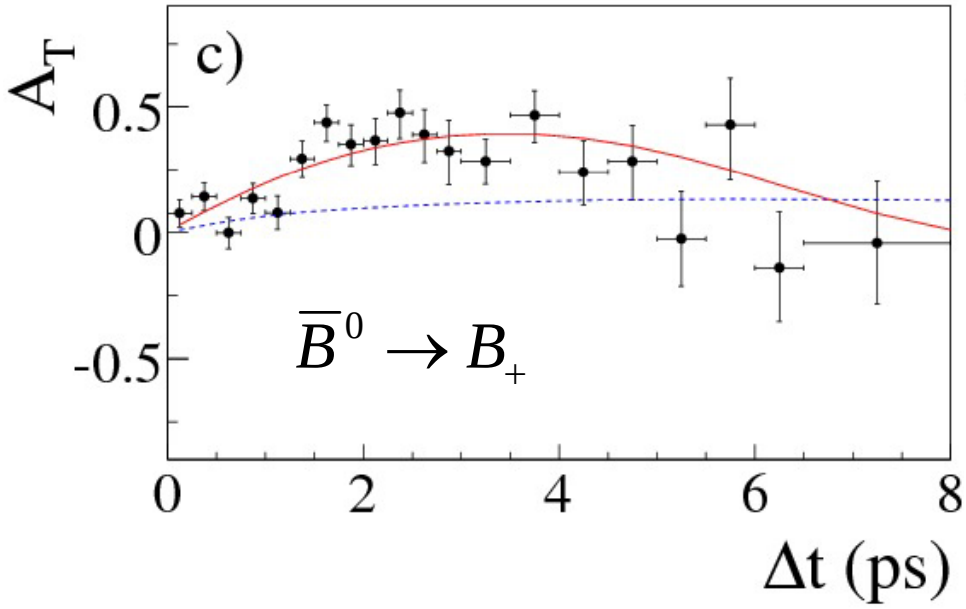
WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

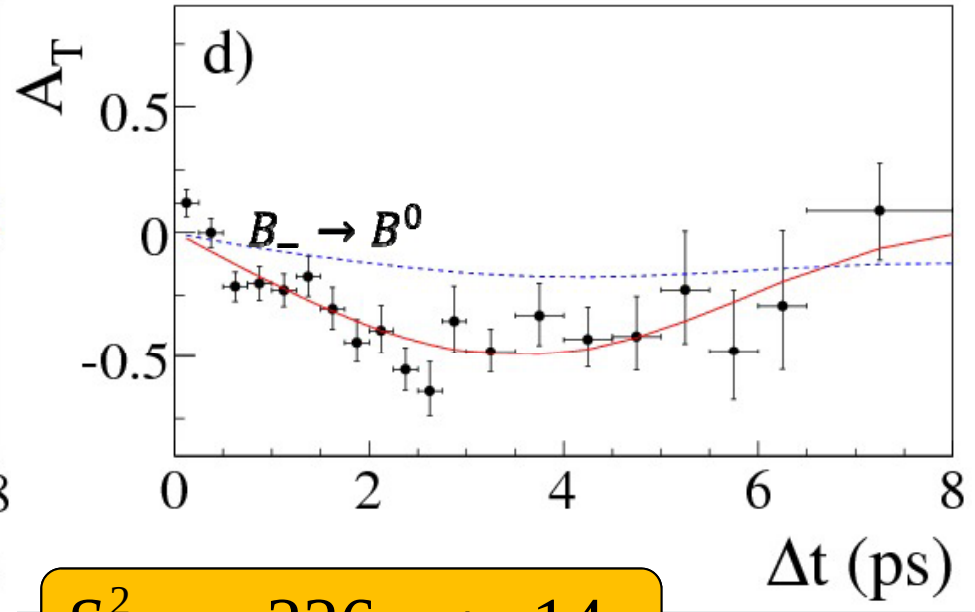


T RAW ASYMMETRIES & SIGNFICANCE



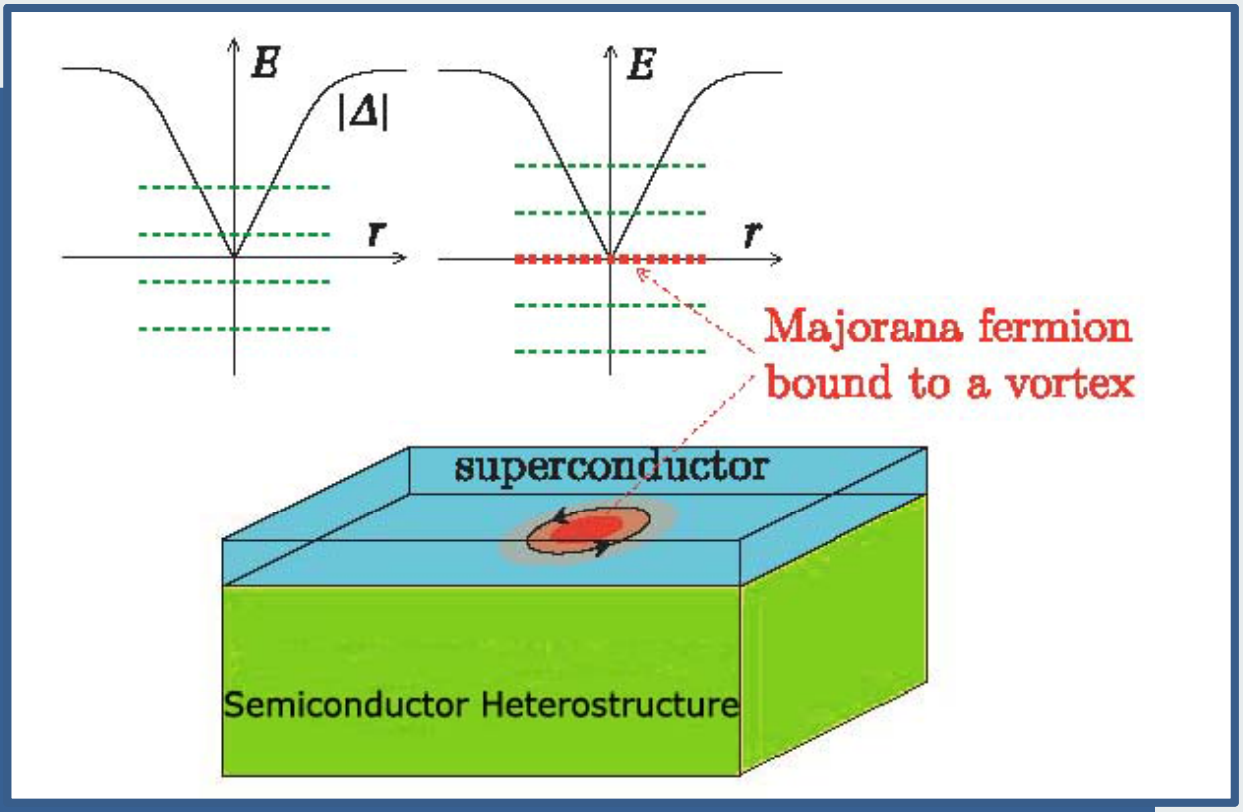






$$S^2_{NoT} = 226 \Rightarrow 14\sigma$$

Majorana fermion in a solid is a quasiparticle excitation in a superconductor



MAJORANA RETURNS

WHAT IS A (fundamental) MAJORANA FERMION ?

1937 - A year before he mysteriously disappeared at Mediterranean sea, Ettore Majorana found solutions of Dirac Equation which are not Dirac Fermions.

A Dirac fermion has DIFFERENT particle and antiparticle entities distinguished by a charge, with a total of 4 degrees of freedom:

D_L^- - Parity - D_R^-

Charge Conjugation

D_L^+ D_R^+

➢ A Majorana fermion is its OWN ANTIPARTICLE:
there is no definite charge to be conjugated, with only 2 degrees of freedom.

➢ Electrons are Dirac particles. Anything in Nature fits Majorana's prediction?
Neutrinos exist: Are they Majorana?
We still do not know! If NO lepton charge, becomes allowed:

$^{A}Z \rightarrow {}^{A}(Z+2) + e + e$

Search at Underground Labs Gran Sasso (GERDA, CUORE), LSC (NEXT), ...

LSC
Laboratorio Subterráneo de Canfranc

➢Dark Matter exists,
BUT ...we do not know its nature: Neutralinos?
Neutralinos would be Majorana: Search for its detection at Underground Labs and its Production at LHC.

WHAT IS A MAJORANA FERMION IN A SOLID?

✓1ST They are not fundamental particles:
the constituents in condensed matter physics are electrons and ions.

✓2ND They are not even "fermions" with the statistics associated
to an antisymmetric wave function under permutations.

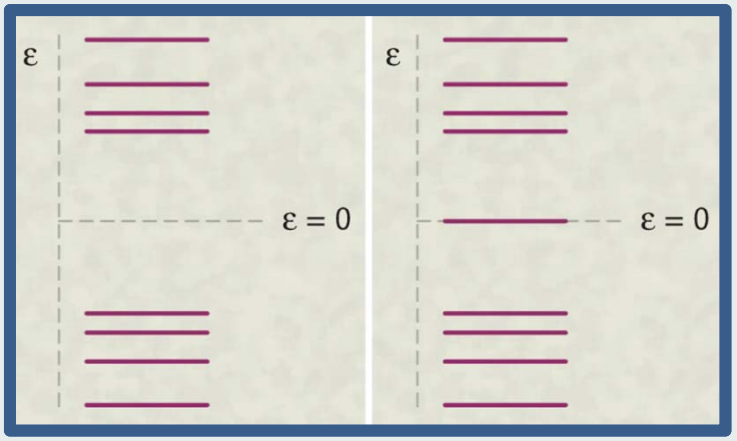
➢ In conventional metals, electron and hole excitations can annihilate,
but carrying opposite charge they are not Majorana fermions.

➢Superconductors are a natural ground: Cooper pair condensates violate charge conservation, the superselection rule is lost and quasiparticles involve

Superposition of electrons and holes

BUT... this is still not sufficient for a Majorana fermion, with s-wave superconductors:
paired electrons carry opposite spin components.
Whereas charge prevents Majorana from a metal,
spin is the culprit in conventional Superconductors.

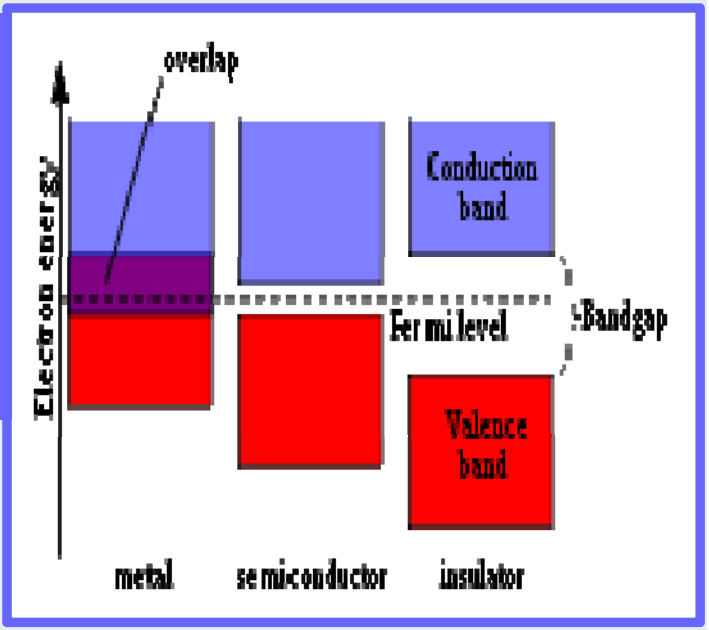
➢ Special superconductors allow the Majorana fermion to be bound to a defect at zero energy



→ the combined object is a Majorana bound state or Majorana zero mode

NON ABELIAN ANYONS

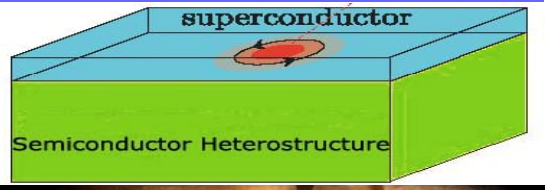
- Exchange statistics characterizes how wave functions transform under interchange of indistinguishable particles.
- Direct path from Particle Statistics to the existence of Metals, Superfluids, Superconductors and many other quantum phases

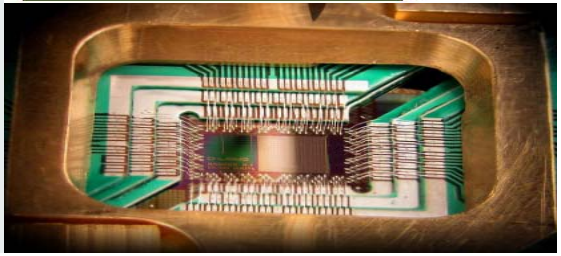


For topological reasons, 2D systems allow for particles whose statistics is neither fermionic nor bosonic → ANYONS

Abelian Anyons	Upon exchanging	Non-Abelian Anyons
The wave function acquires a statistical phase exp(i θ) intermediate between -1 and +1 .		The wave function is NOT eigenstate of the permutation, ***it changes to a fundamentally different quantum state.*** Subsequent exchanges do not commute.

- Non-Abelian statistics arises in a 2D spinless p + i p superconductor able to generate Majorana bound states trapped in a vortex. Different sources can provide these defects: junction to 3D topological insulator, to Semiconductor Heterostructure, ...
- The non-Abelian statistics for Majorana bound states in a solid allows to use them as a building block for a topological quantum computer, opening to a higher number of QUBITS.



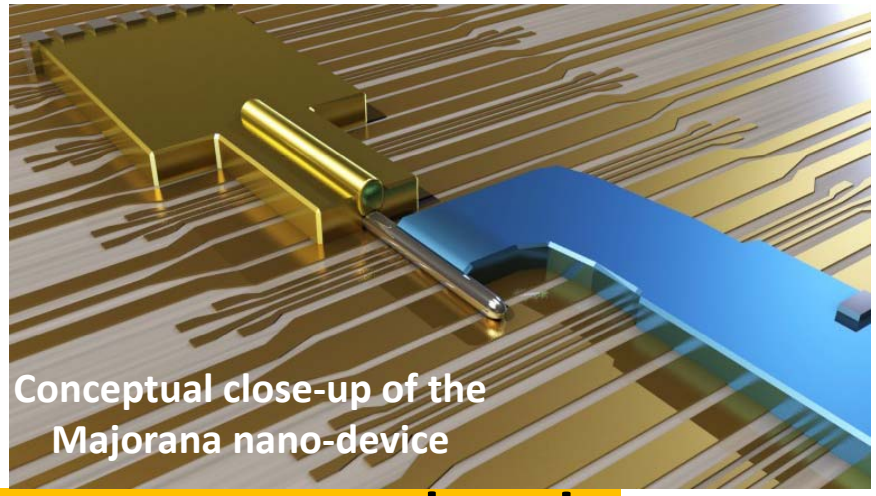


EXPERIMENTS IN SUPERCONDUCTIVITY

2008 → Fu & Kane groundbreaking theoretical development → prediction that Majorana bound states can appear at the interface between topological insulators and superconductors.

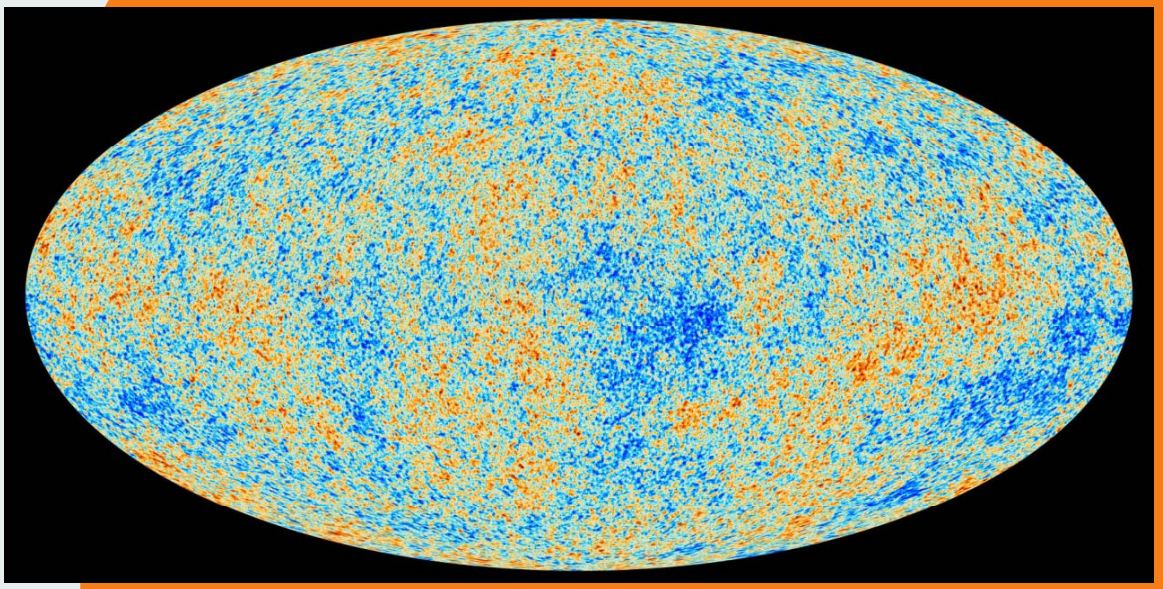
2012 → An experiment involving indium antimonide nanowires, connected to a circuit with a gold contact at one end and a slice of superconductor at the other, reports a positive result.

➢This experiment from Delft University followed the proposal for a solid state manifestation of Majorana bound states in semiconducting wires. When exposed to a moderately strong magnetic field (Zeeman effect), the device showed **a peak electrical conductance at zero voltage!**



Conceptual close-up of the Majorana nano-device

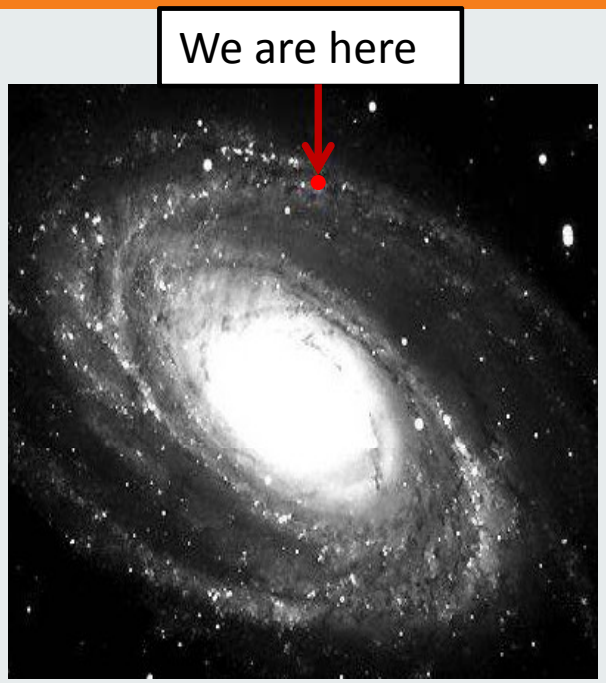
➢The result is consistent with the formation of a pair of Majorana bound states, one at either end of the region of the nanowire in contact with the superconductor. These spatially separated pairs have a **long-distance quantum link, L=100 nm, robust to decoherence.**



PLANCK reveals an almost perfect Universe, but … some peculiar unexplained features may well require new physics to be understood.

THE UNIVERSE ACCORDING TO PLANCK

(FIRST) COPERNICAN REVOLUTION

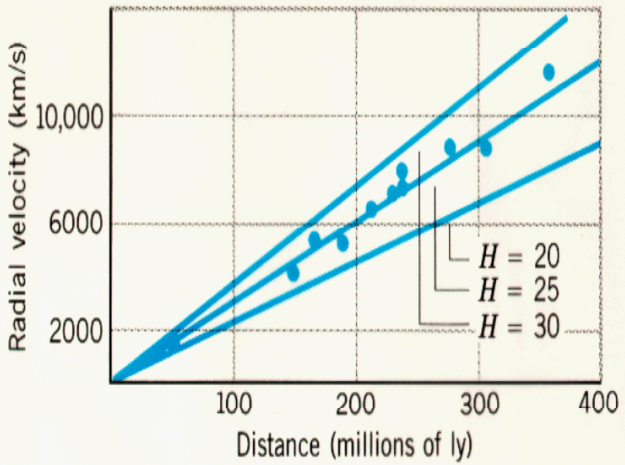


Red-shift is NOT Doppler effect

Hubble ‘s Law

$$v = Hd$$

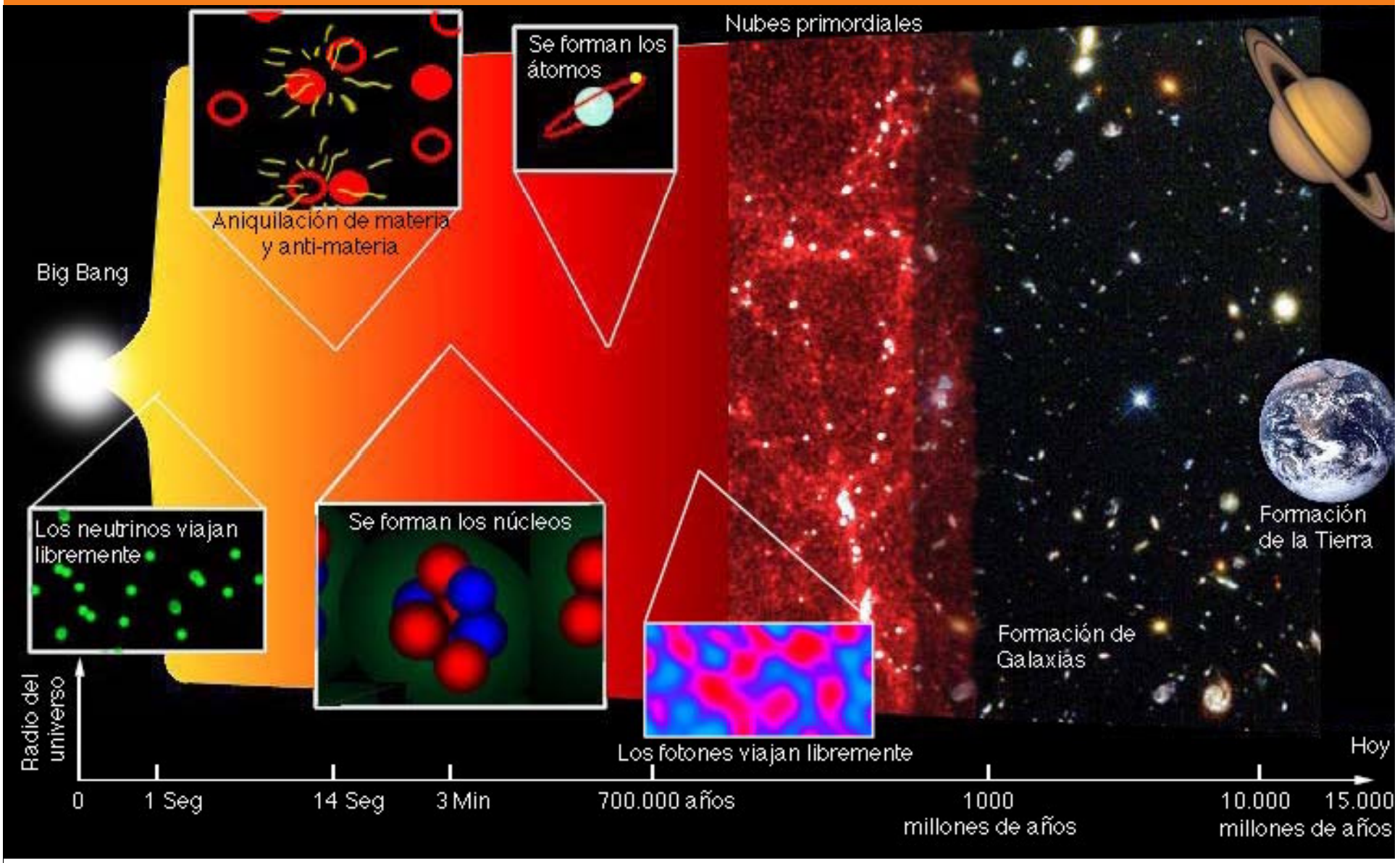
Age of de Universe $H^{-1} \approx 1.4 \times 10^{10}$ years



Hubble plot using Tully – Fisher relation and infrared fluxes for nearby calibrating galaxies to estimate the distances to eleven clusters of galaxies.

COSMOLOGICAL PRINCIPLE

HISTORY OF THE UNIVERSE

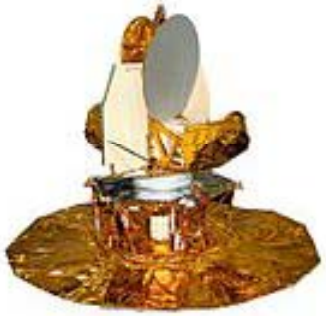


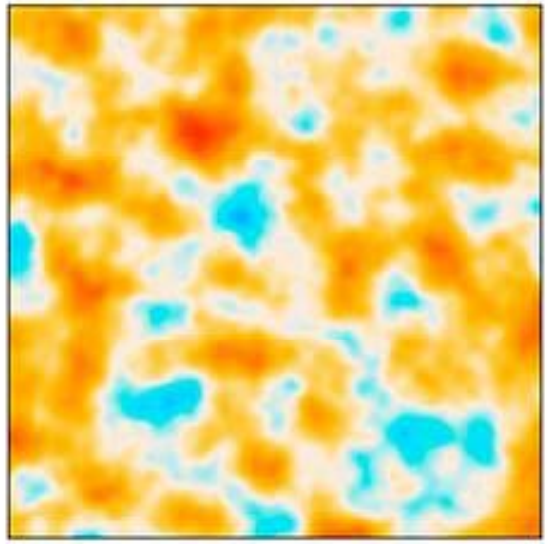
Two Cosmological Methods:

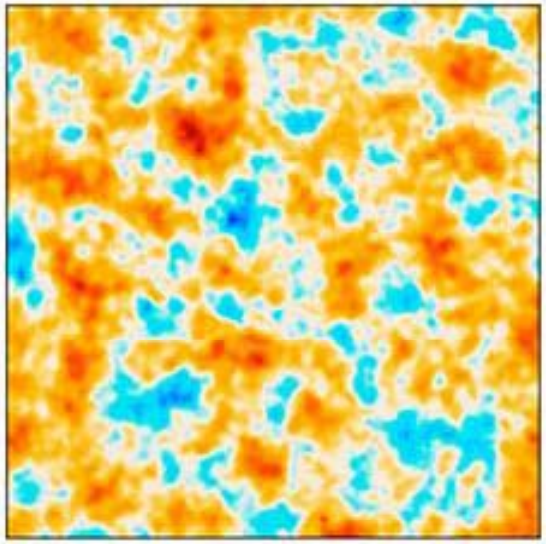
1- Observing Far→Early Times → Supernova I Survey

2- RELICS→ CMBR at time of (RE) COMBINATION

MODERN COSMOLOGY



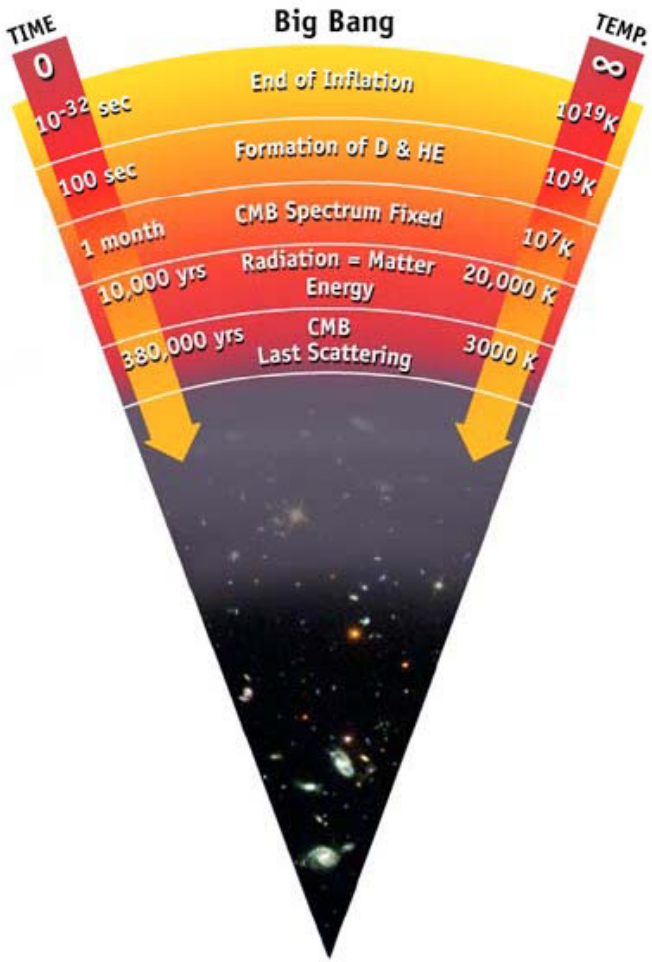




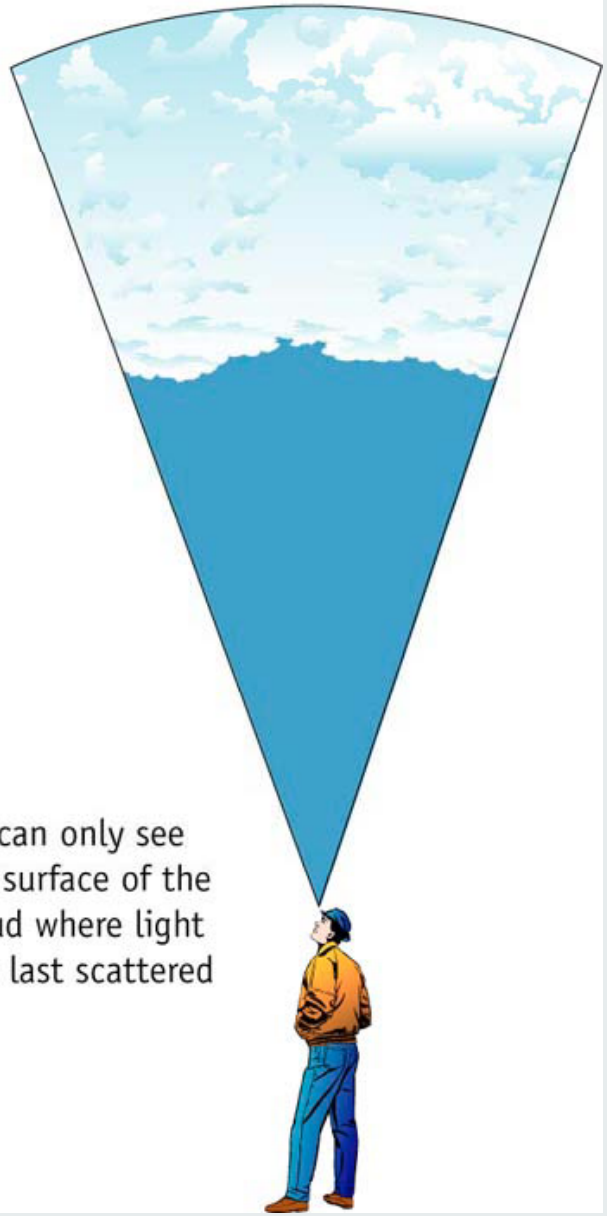
COBE WMAP Planck

Precision in temperature fluctuations of sky-map

LAST-SCATTERING SURFACE



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



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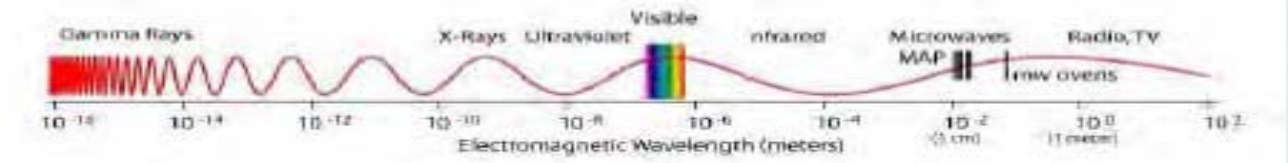
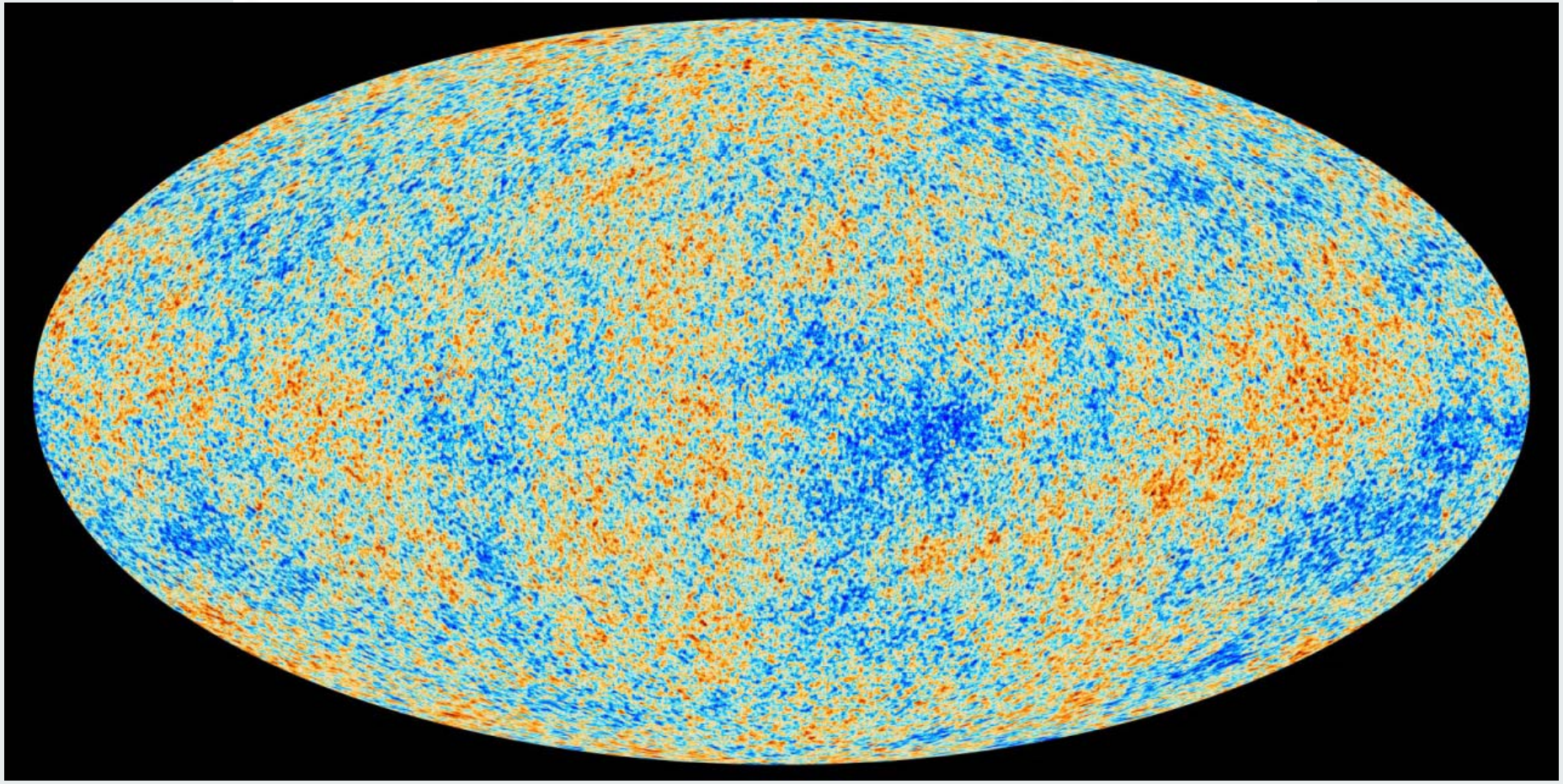


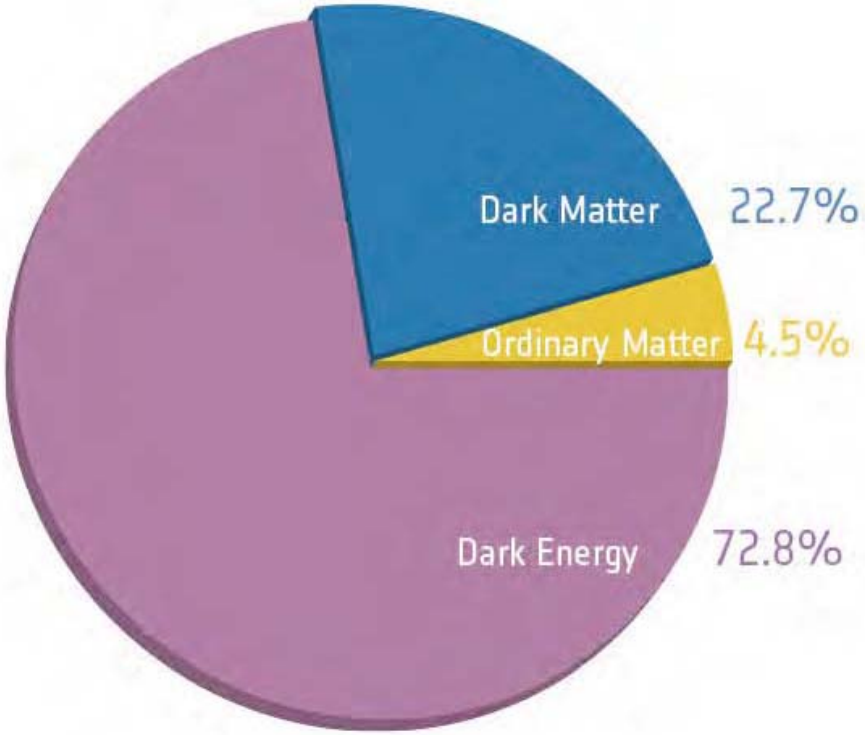


Planck Cosmology Paper/Prepints

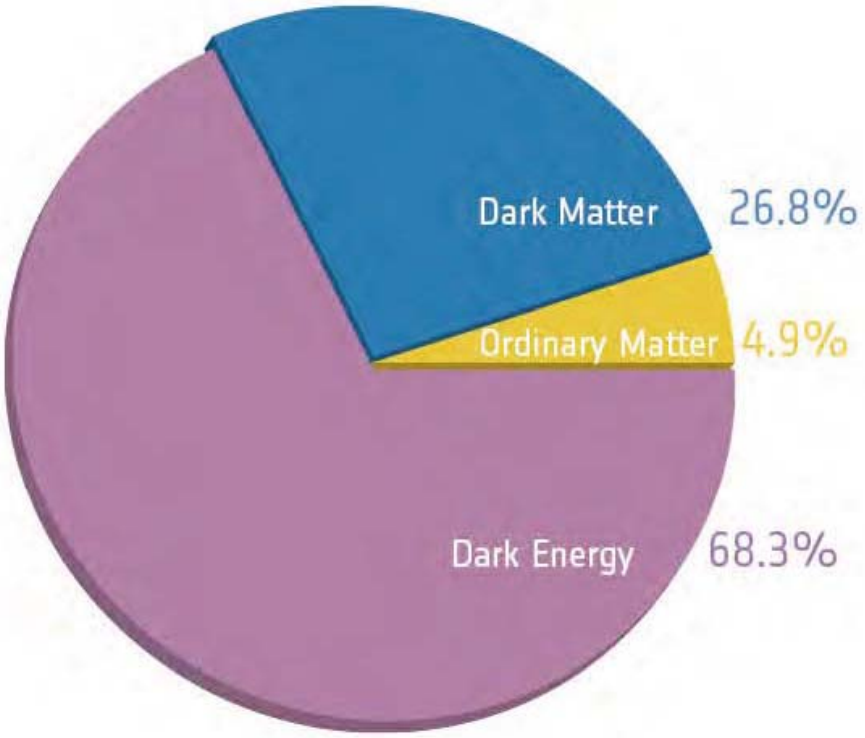
http://www.sciops.esa.int/index.php?project=PLANC&page=Planck_Pubished_Papers

SECOND COPERNICAN REVOLUTION

Energy-Matter Content of the Universe



BEFORE PLANCK



AFTER PLANCK

(i) Darker (more Visible & Dark Matter than previously thought)
(ii) "Lighter" (Less Dark Energy)
(iii) Slower Hubble cosmic expansion H=67.17km/s/Mpc within 2%
(iv) Older (13.8 billion years, 100 million years older than previously thought)
(v) "Lopsided" & Large Cold Spot on one side: Cosmological Principle ?

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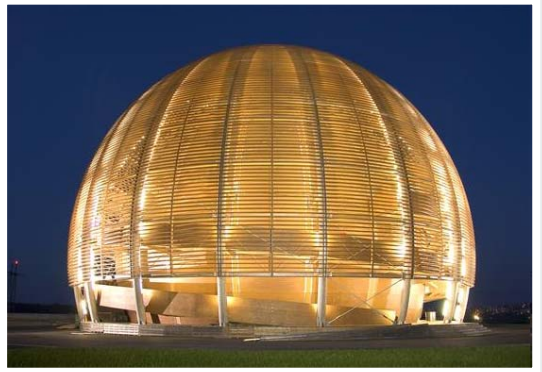

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