2025 Heinrich Hertz Lecture on Physics

DESY

24 Sept 2025

Visible and Invisible in fundamental physics and art

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no artist better than Salvador Dali represents the inspiring power of science, and was more fascinated by the relation of visible and invisible ....

"In the Surrealist period I wanted to create the iconography of the interior world and the world of the marvelous, of my father Freud.

Today the exterior world and that of physics, has transcended the one of psychology.

My father today is Dr. Heisenberg."

S.Dali, 'Anti-matter manifesto' (1958)

Previous page:
S.Dali, The persistence of memory (1931)

Hubble Ultra Deep Field

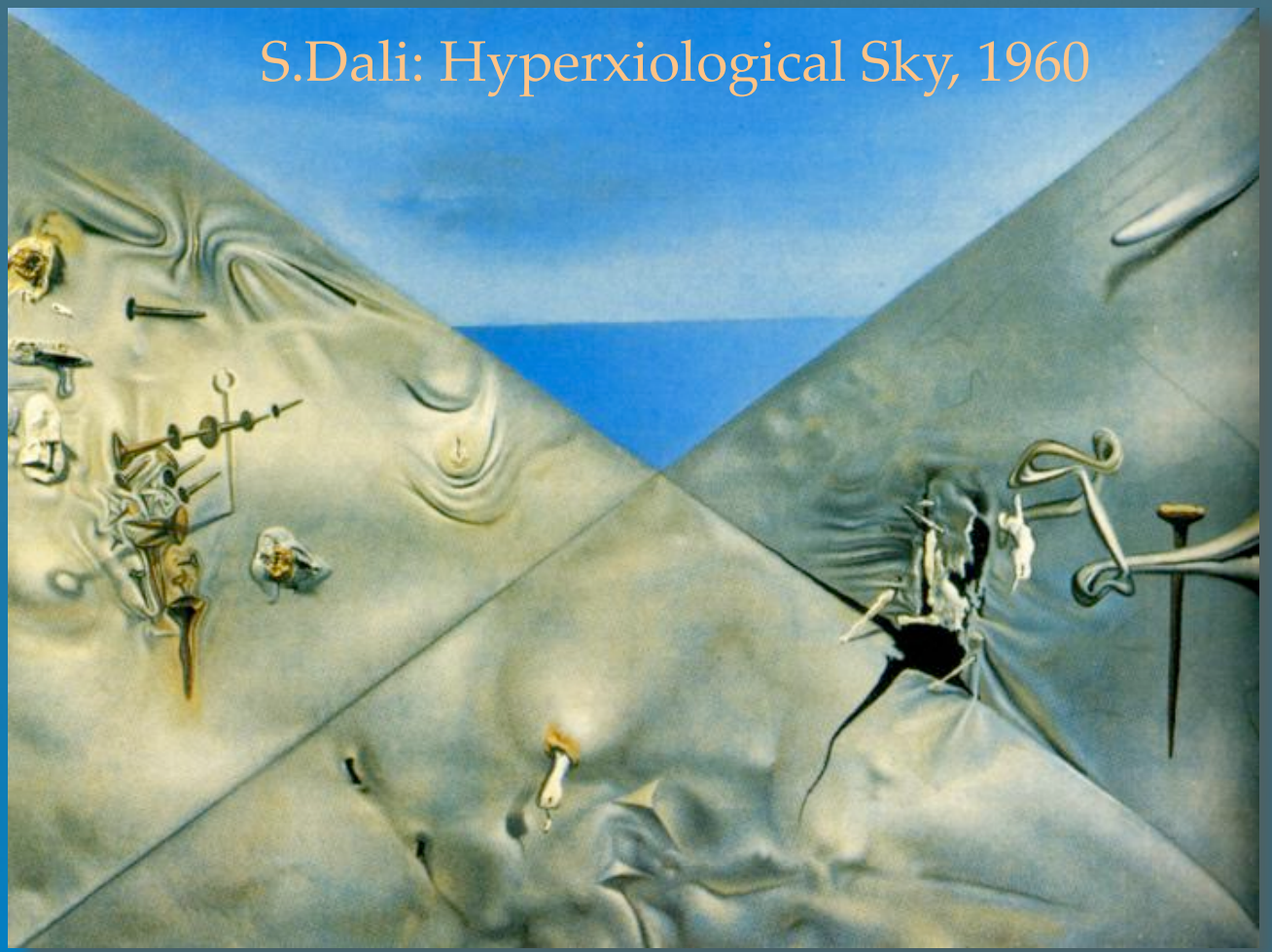
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

S.Dali: Ciel, 1931

S.Dali: Hyperxiological Sky, 1960



"If physicists produce antimatter, let the painters, who are already specialists in angels, paint it."
S.Dali, 1951

Hubble Ultra Deep Field

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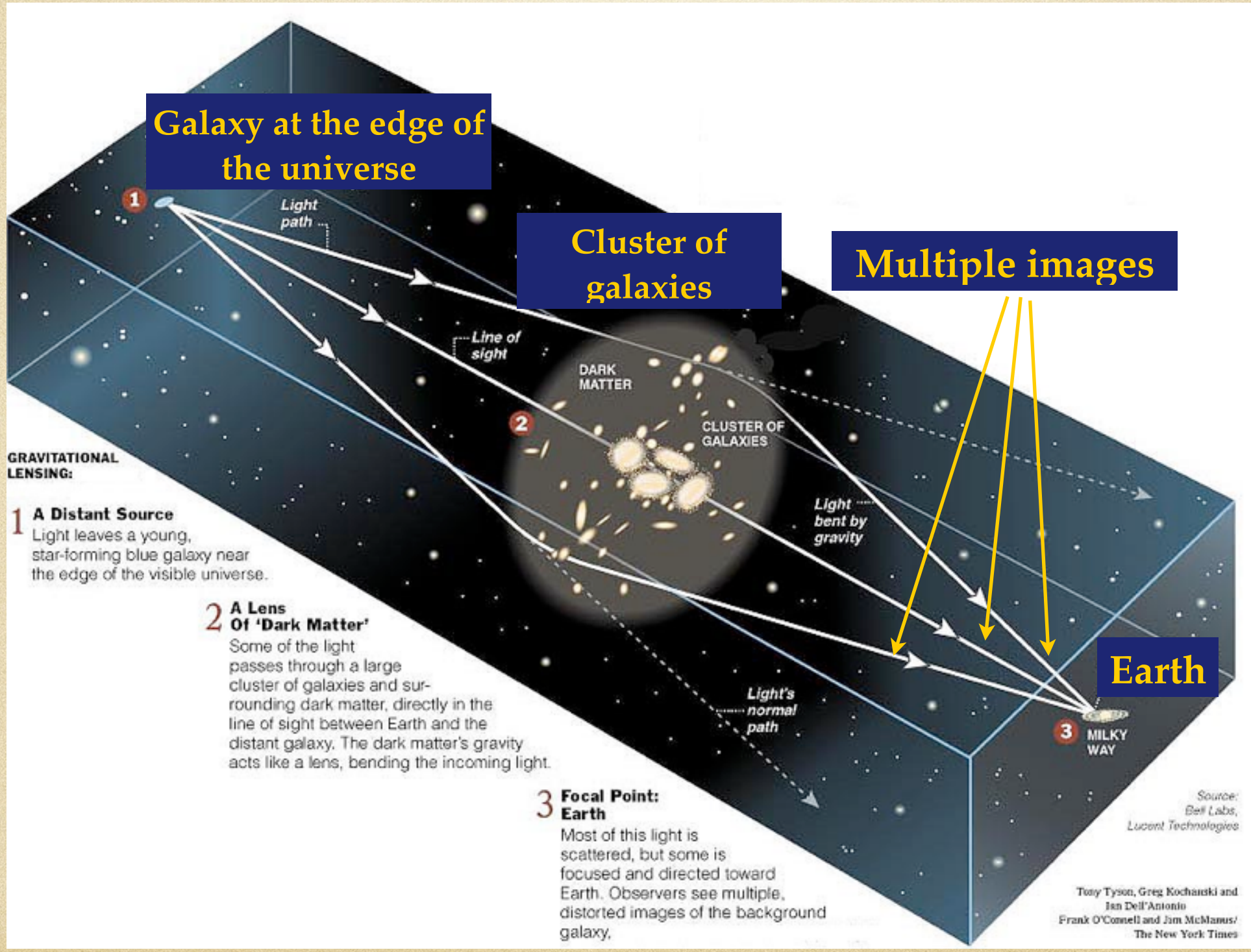
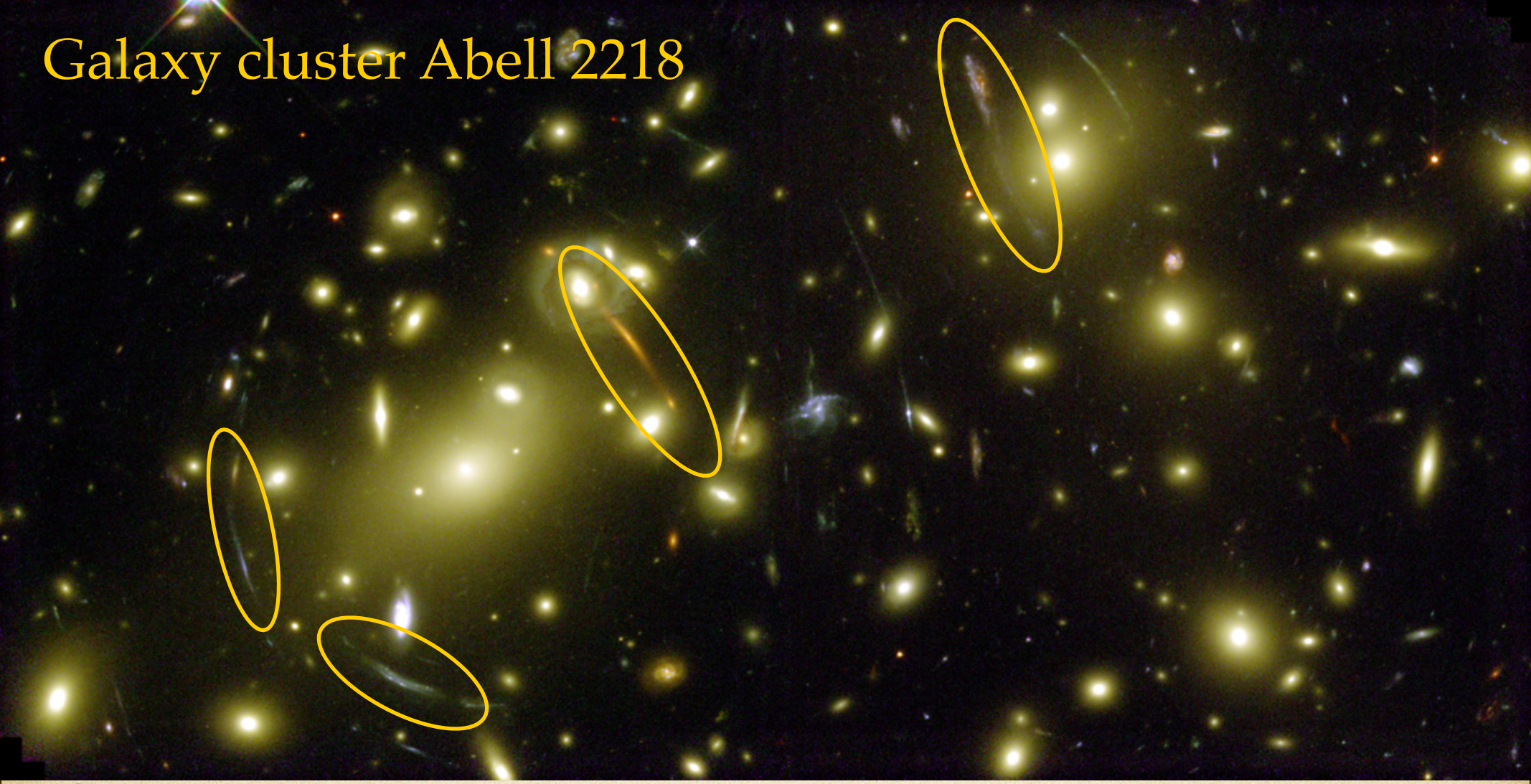
STScI-PRC04-07a

Gravitational lensing



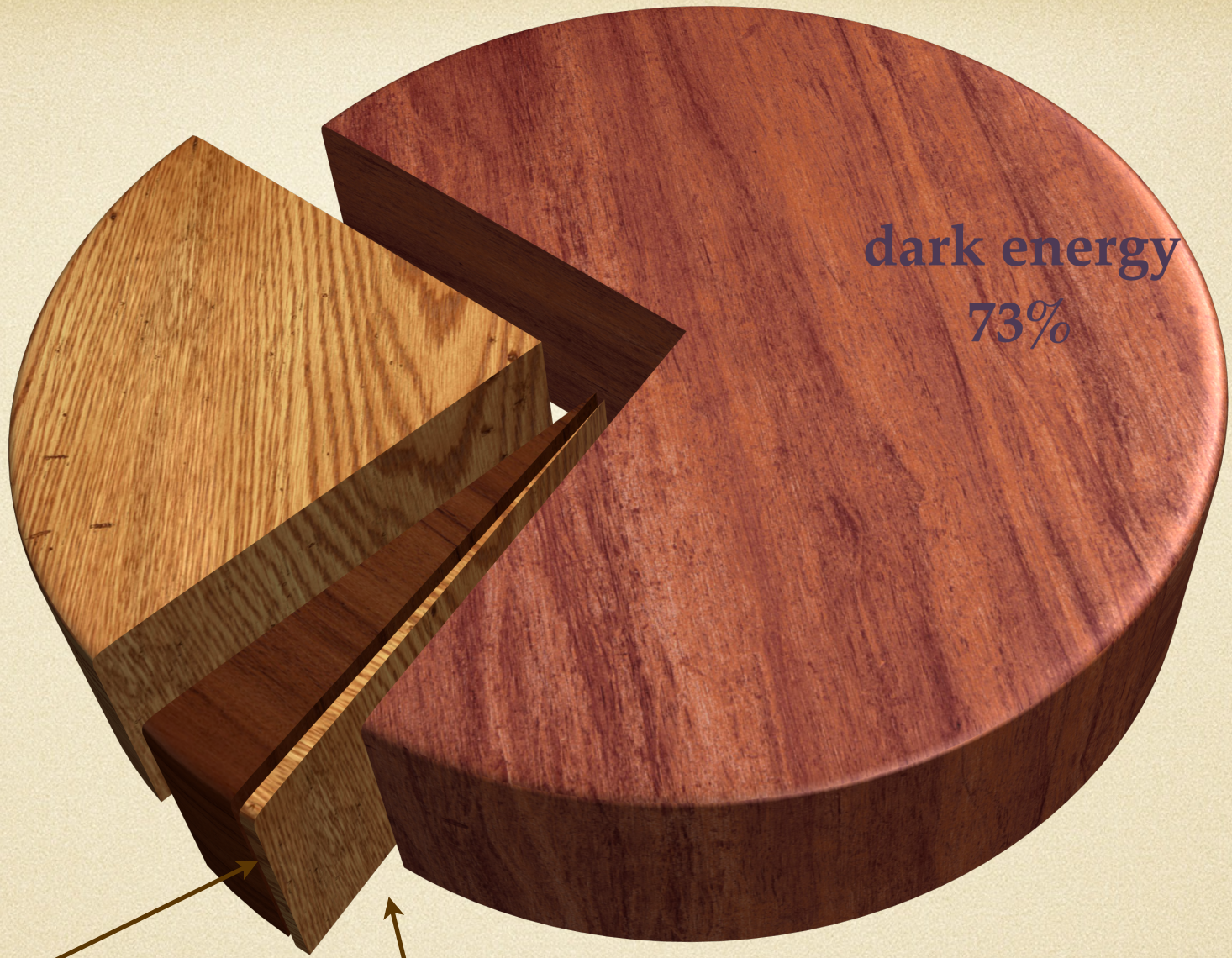
Galaxy cluster Abell 2218



Credits: *European Space Agency, NASA, J.-P. Kneib (Observatoire Midi-Pyrénées) and R. Ellis (Caltech)*

The shape and intensity of lensed images requires the presence of much more mass than what's **visible** in those galaxies !

→ Invisible dark matter


dark energy
73%
dark matter
23%
non-luminous ordinary matter (e.g. planets, dead stars, dust, etc), ~4%
luminous matter (stars, gas) ~0.5%

For something to be declared invisible, we must know it's there, and if we know it's there, it's not *truly* invisible any longer .....

Surrealist Composition with Invisible Figures, 1936

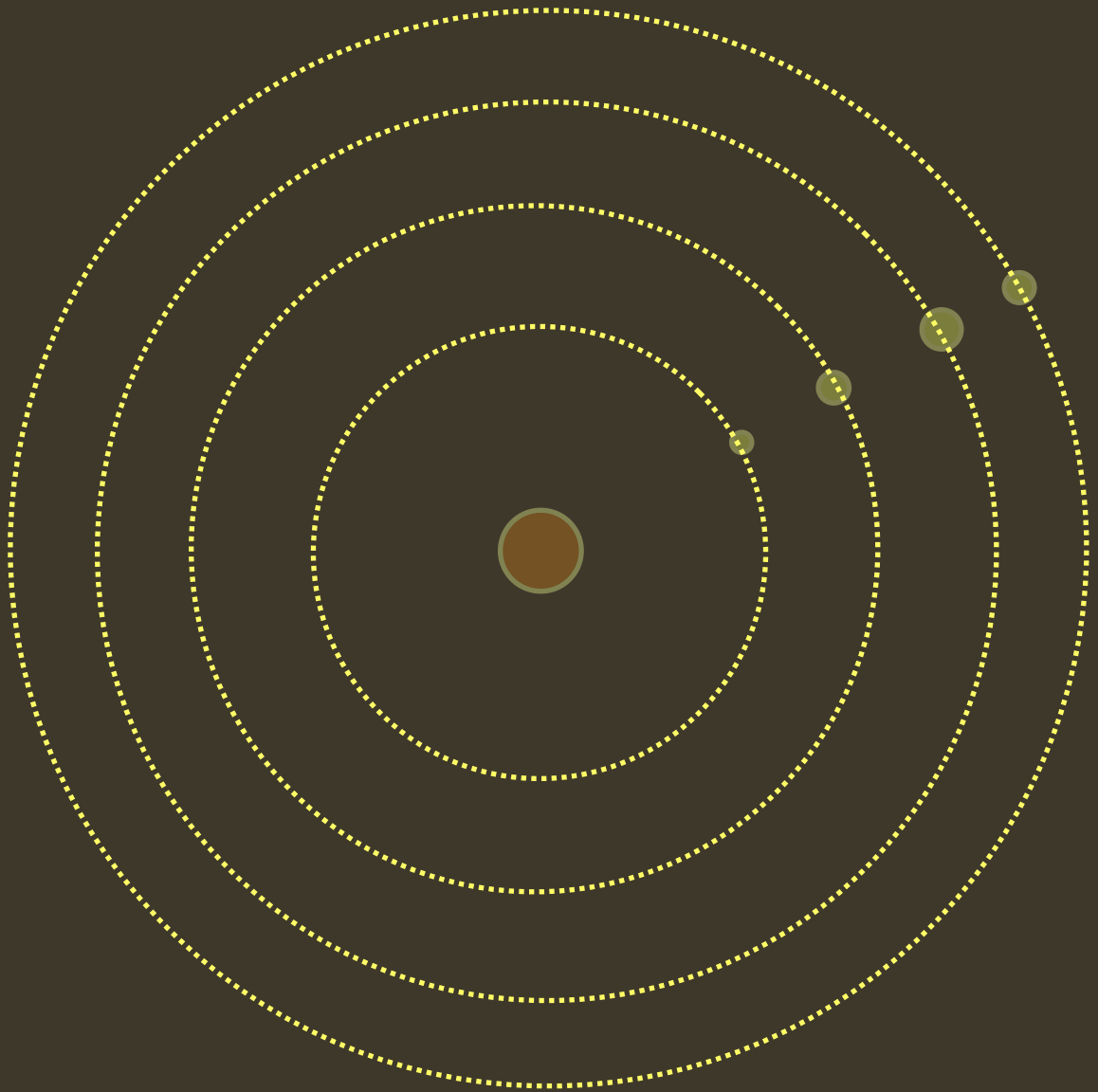
Proving the existence of the invisible, namely providing evidence that there is something where there appears to be nothing, turning the invisible into visible, is one of the main drivers of scientific progress.

It is a very basic process, that moves us from the realm of magic and superstition to the domain of science.

Invisible Harp, 1934

Establishing the **nature** of the invisible is the really crucial step .....

What are the invisible forces that tie things together?
How many, how to they work?



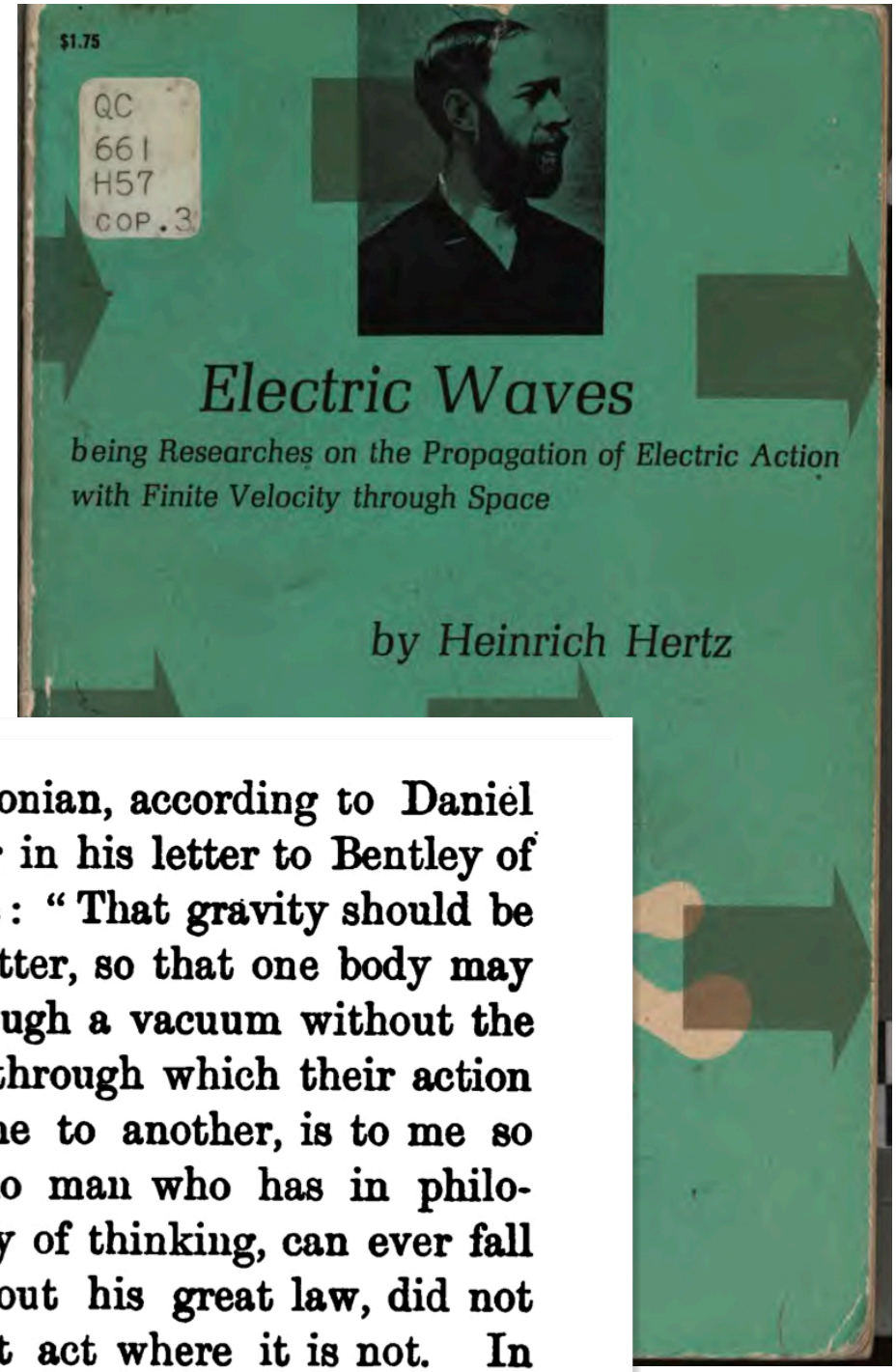
What's hidden inside *things*?
What are *things* ultimately made of?

Heinrich Hertz

- https://en.wikipedia.org/wiki/Heinrich_Hertz
- Born 1857, Hamburg
- PhD 1880, Humboldt Univ Berlin
- Faculty: Kiel, Karlsruhe, Bonn
- Died 1894, Bonn (resting in Hamburg)

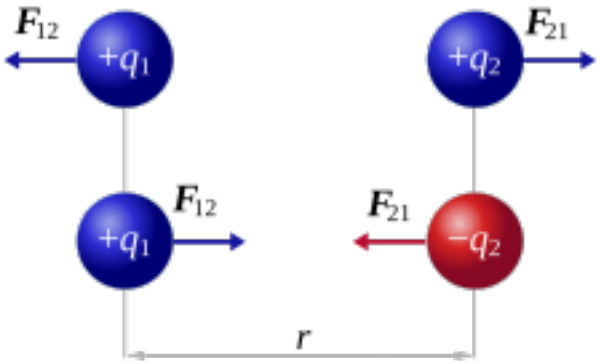
The philosophical context in which Hertz discoveries took place

From Lord Kelvin Preface to the english version of Hertz collected papers on EM wave experiments



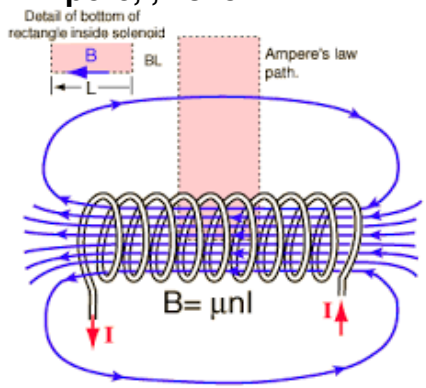
Indeed Newton was not a Newtonian, according to Daniel Bernoulli's idea of Newtonianism, for in his letter to Bentley of date 25th February 1692,[1] he wrote: "That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it." Thus Newton, in giving out his great law, did not abandon the idea that matter cannot act where it is not. In

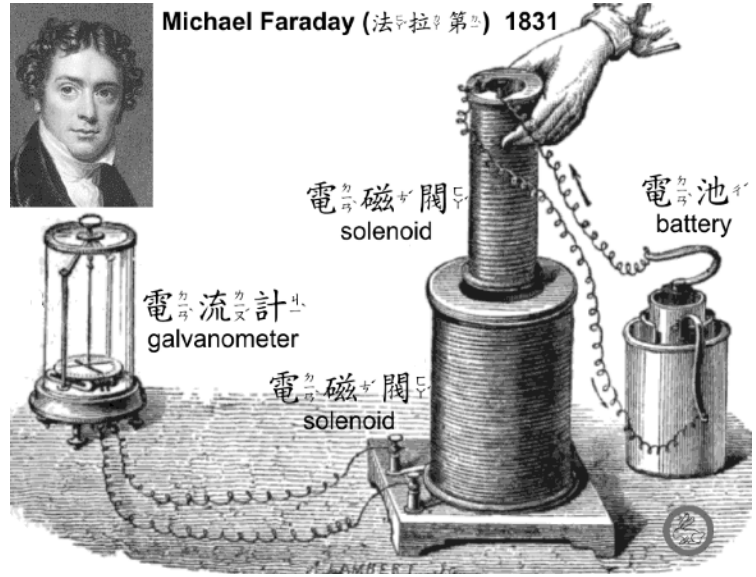
Coulomb, 1785



$$|\boldsymbol{F}_{12}| = |\boldsymbol{F}_{21}| = k_e \frac{|q_1 \times q_2|}{r^2}$$

Ampere, , 1825





Maxwell, 1860

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

EM waves with velocity c_0

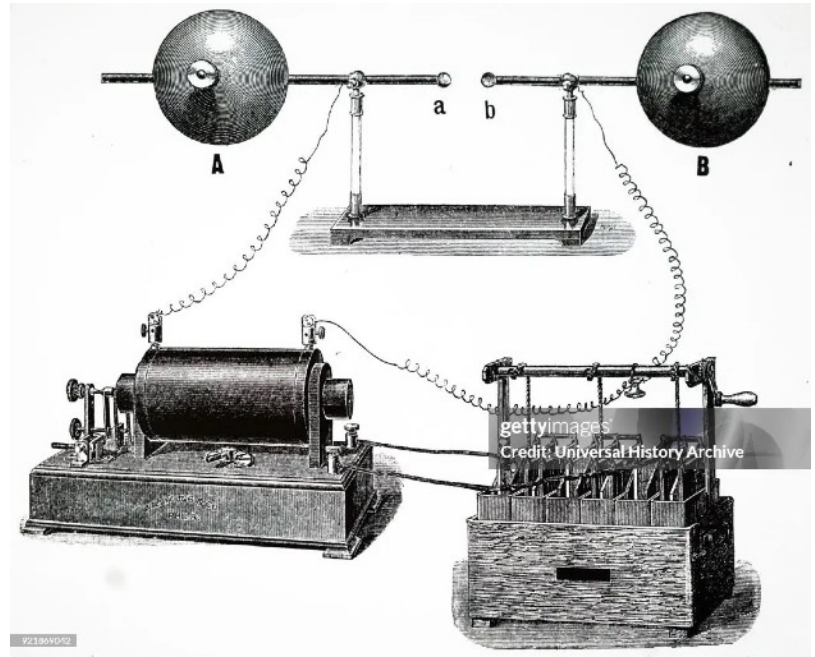
$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = \mathbf{0}$$

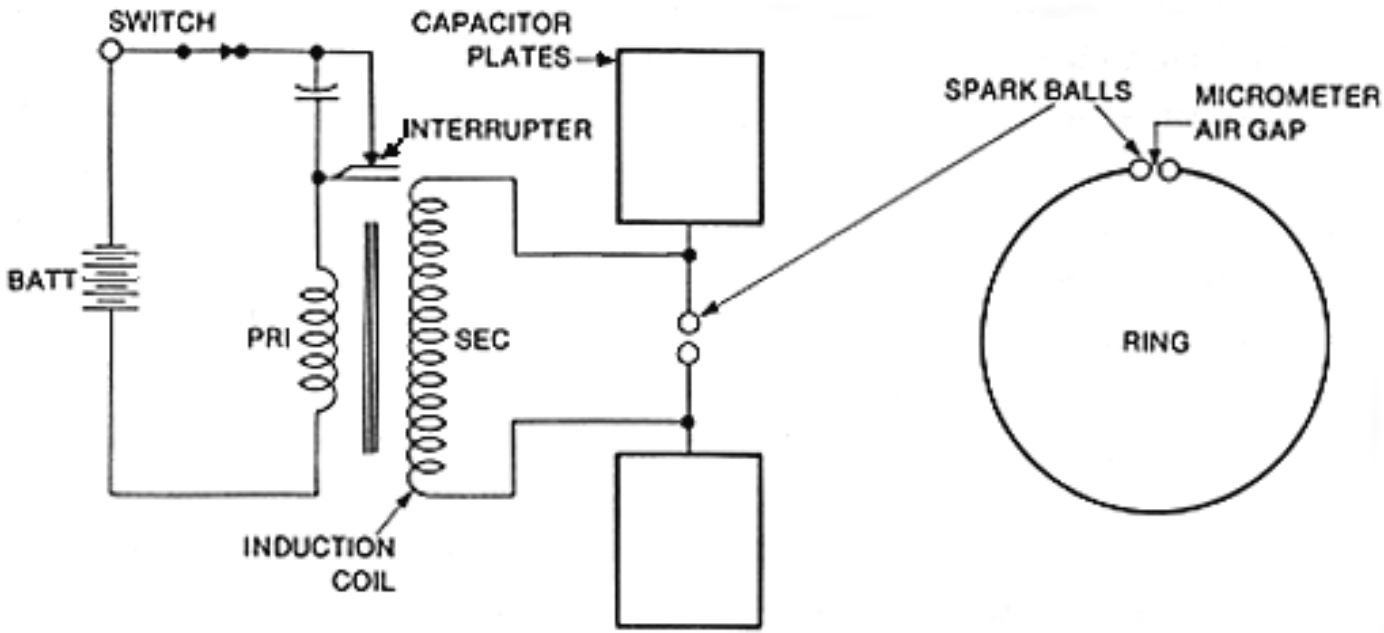
$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = \mathbf{0}$$

Maxwell established that c_0 is numerically equal to the then-known speed of light, and conjectured that light is a type of EM waves. But no other "types" of EM waves were proven to exist, until …

… Hertz experiments (1886-89) proved that indeed EM phenomena lead to the *creation* and *propagation* of waves

=> the *invisible* carriers of EM interactions became *visible*!!





Hertz did not realize the practical importance of his radio wave experiments. He stated that,

It's of no use whatsoever ... this is just an experiment that proves Maestro Maxwell was right—we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.

Asked about the applications of his discoveries, Hertz replied:

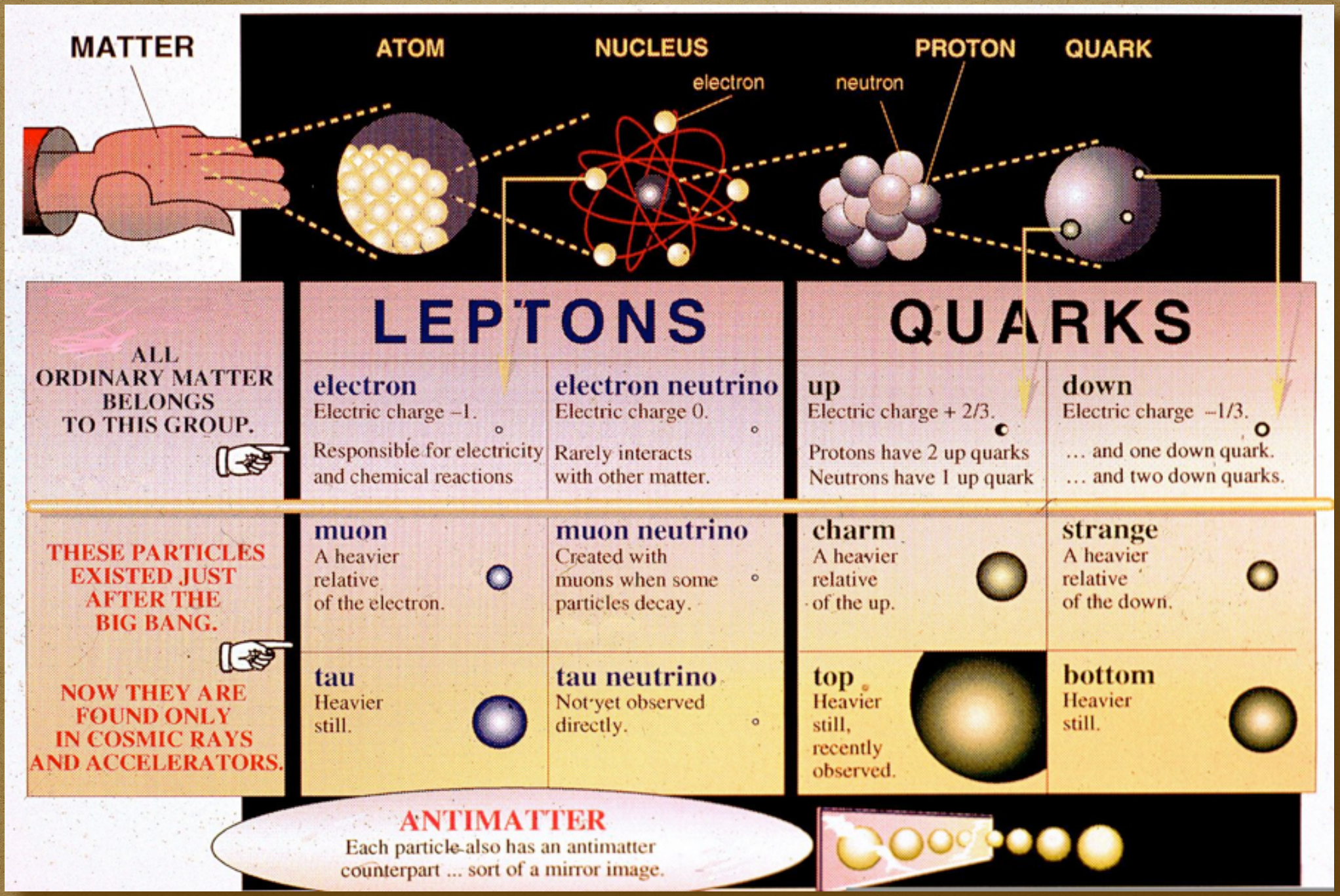
Nothing, I guess

Goal of modern physics: to unveil the invisible, give it substance, and explore its consequences on the universe

what? how?

- Are there fundamental building blocks?
- If so, what are they?
- How do they interact?
- How do they determine the properties of the Universe?

The Standard Model of particle physics



BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

EW symmetry breaking spin=0

H higgs	125	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

The description of the natural phenomena that emerges from the Standard Model agrees **quantitatively** with great precision with all phenomena that we **see** around ourselves, and that we **measure** in the laboratory

The Standard Model provides the underlying explanation of all nuclear, chemical and electrical phenomena, the atomic structure of elements, the electrical / mechanical / thermal behaviour of metals, semiconductors, etc. etc. etc.

A few anecdotes on the role of the invisible in the discovery and understanding of fundamental particles and interactions

Late 20's, a puzzle of the invisible

$^{6}He \rightarrow {}^{6}Li + e^{-}$

If this were all that happens, energy conservation would demand that the energy of the emitted electron be the same for each decay

$$Energy[e^{-}] = Mass[^{6}He] - Mass[^{6}Li]$$

But in some decays the electron is very fast while in others it is very slow.....

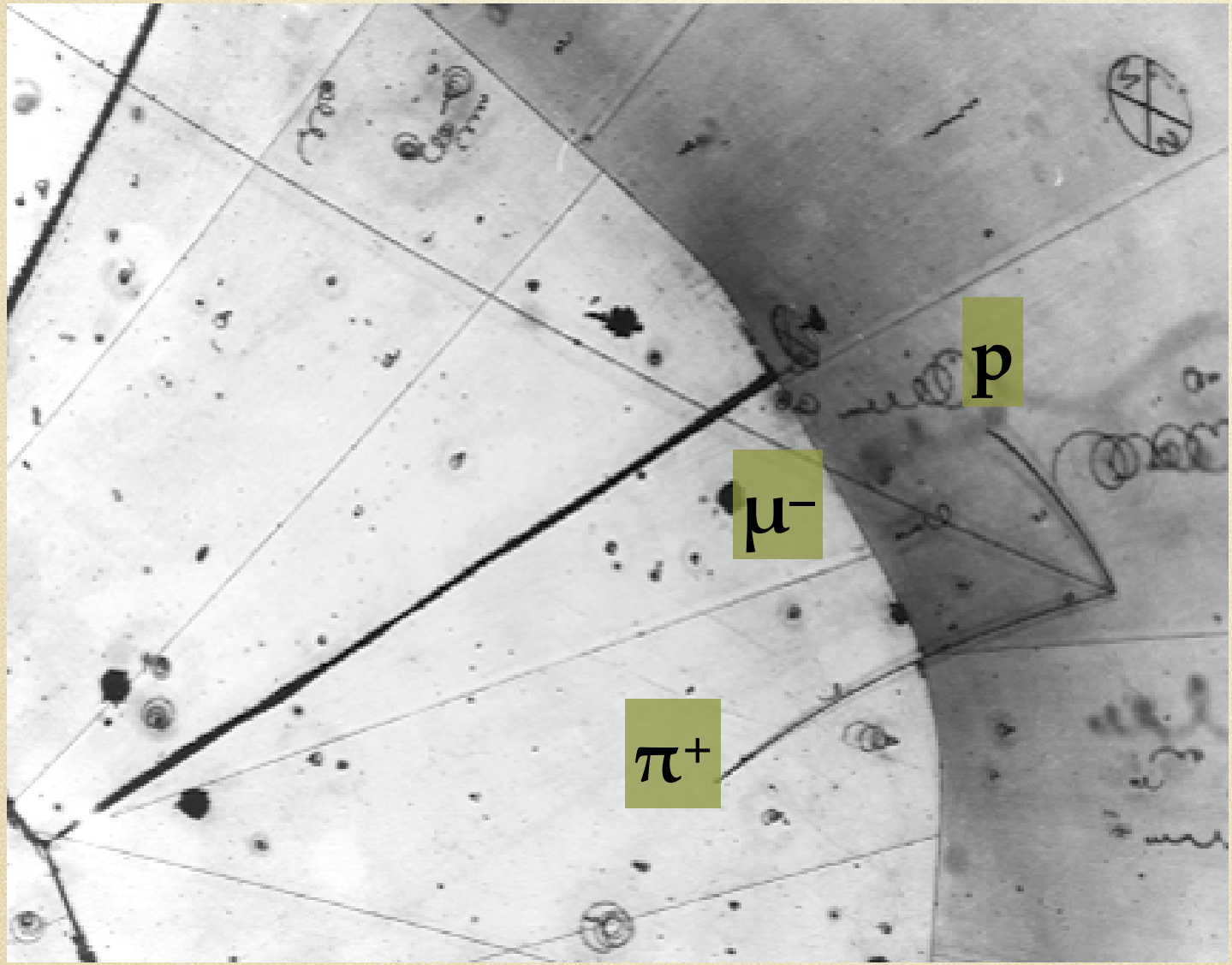
Enter neutrinos ...

After months of speculations, including the possibility that the principle of energy conservation be violated in microscopic quantum phenomena, Wolfgang Pauli (1930) proposes the existence of the **invisible neutrino**

$$^{6}He \rightarrow {}^{6}Li + e^{-} + \nu$$

It took more than 20 years for a neutrino to be directly observed!

(Clyde Cowan and Frederick Reines, 1956)



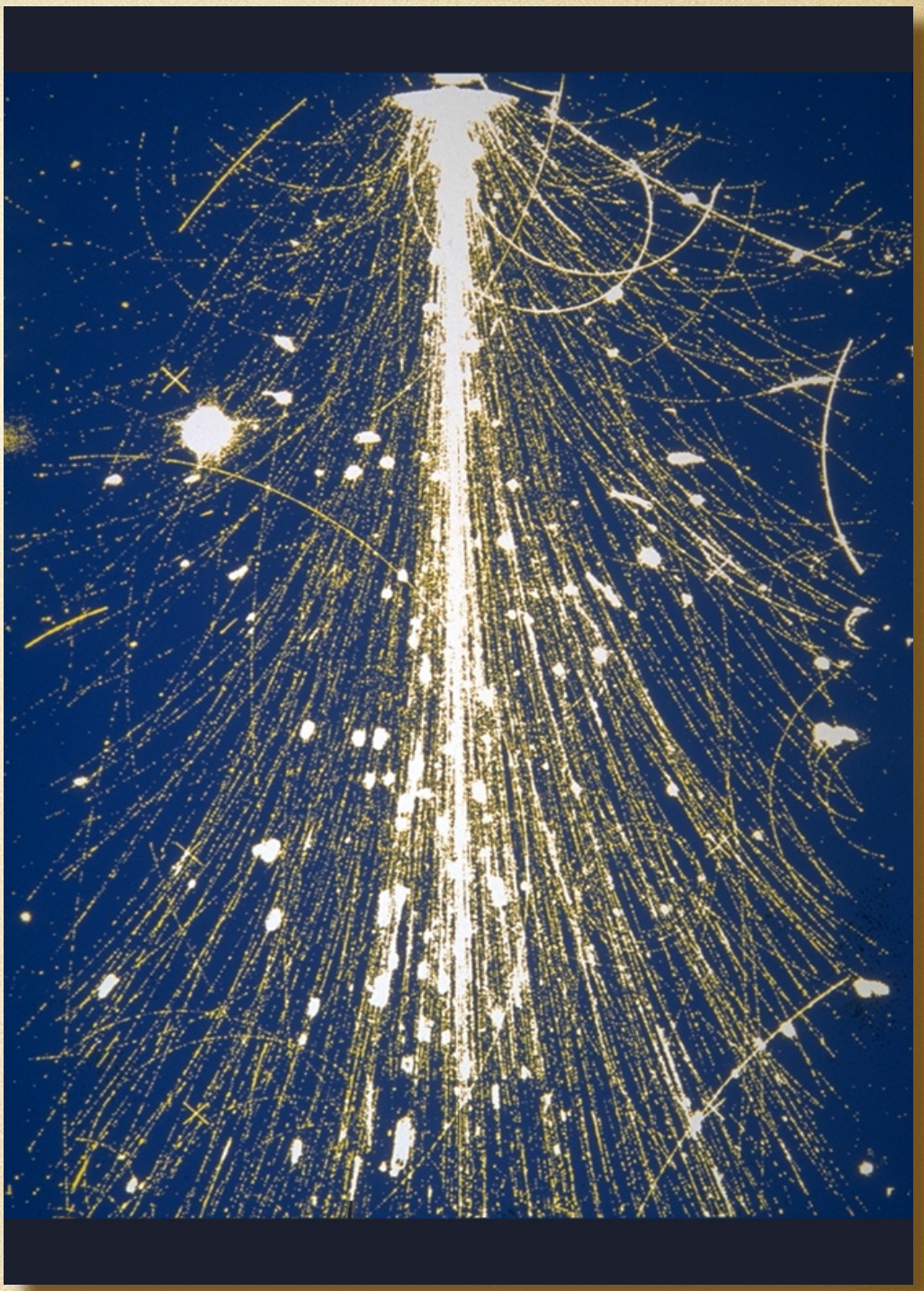
ν from a beam of π mesons

The world's first neutrino observation in a hydrogen bubble chamber. It was found Nov. 13, 1970, in this photograph from the Zero Gradient Synchrotron's 12-foot bubble chamber. The invisible neutrino strikes a proton where three particle tracks originate (lower right). The neutrino turns into a mu-meson, the long center track (extending up and left). The short track is the proton. The third track (extending down and left) is a pi-meson created by the collision. ***Argonne National Laboratory***

"It is with π-mesons and the most gelatinous and indeterminate neutrinos that I want to paint the beauty of the angles and of reality."

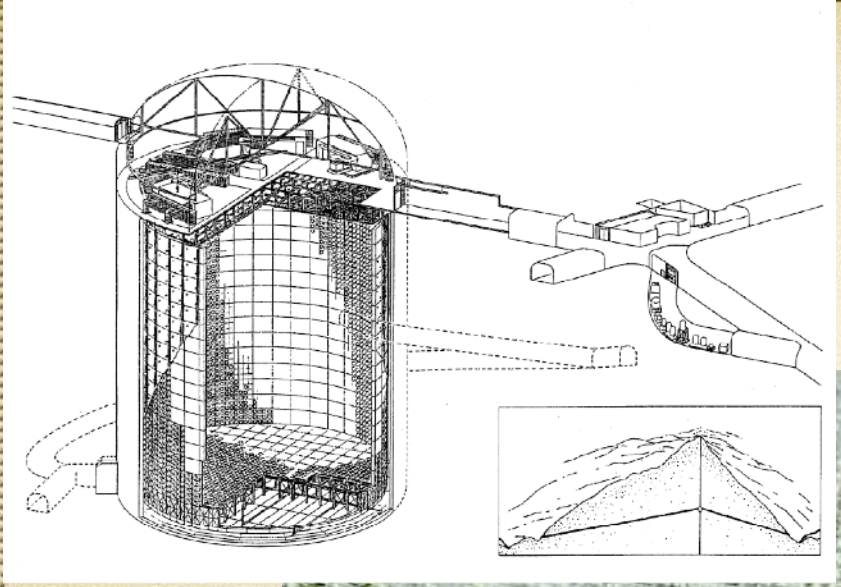
S.Dali, 'Anti-matter manifesto' (1958)

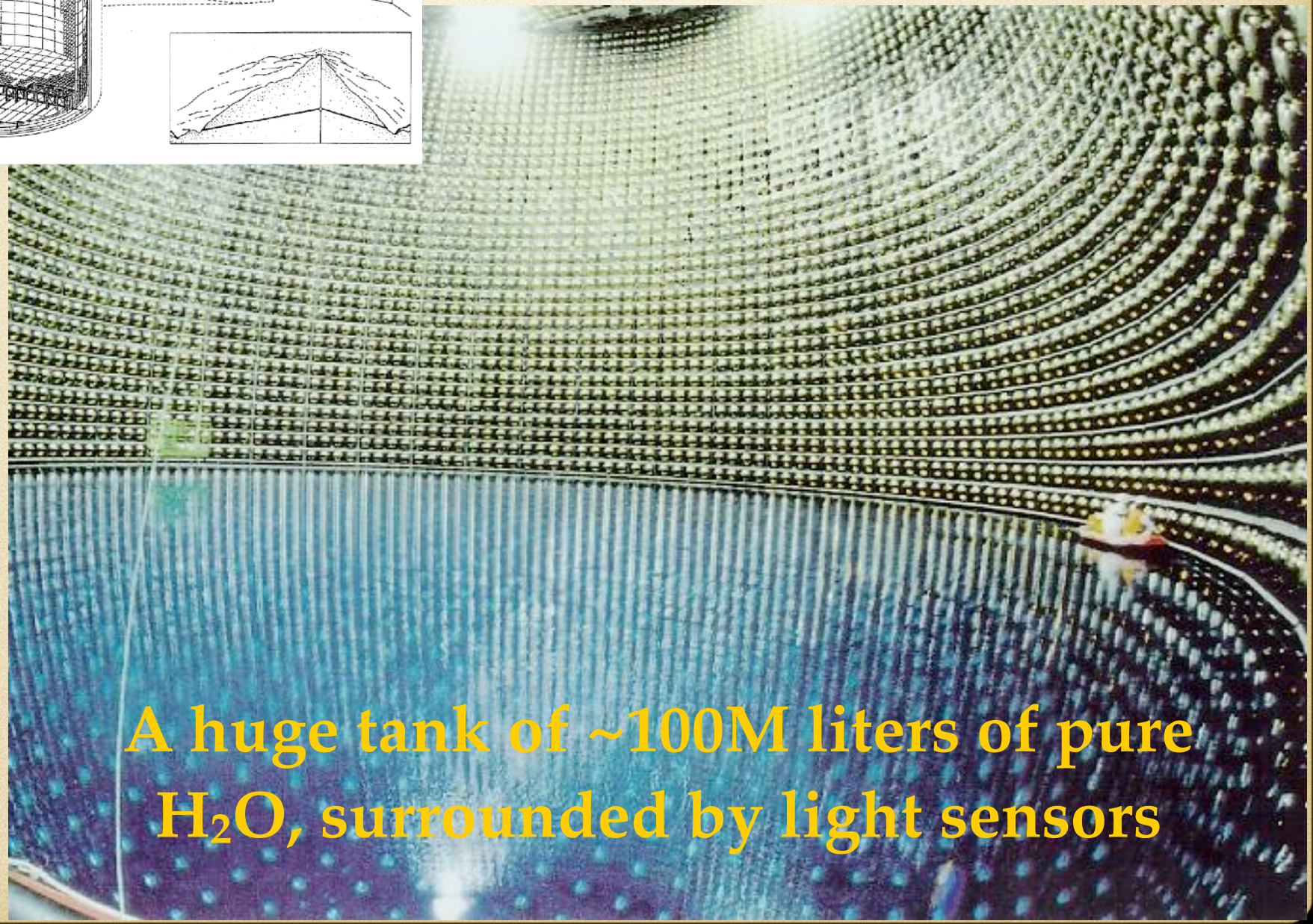
Saint surrounded by three π mesons, 1956



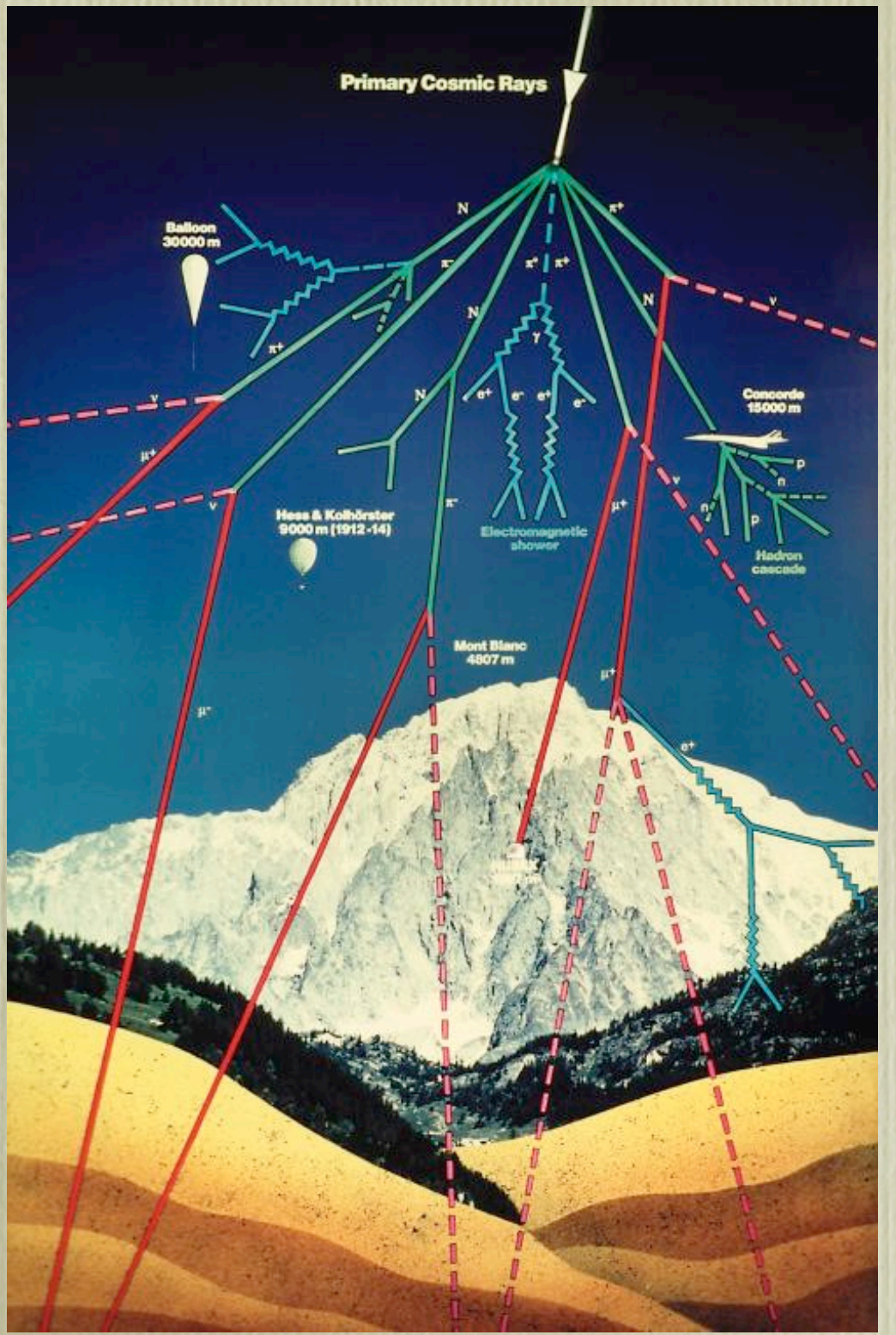
... just π mesons, in a real experiment ...

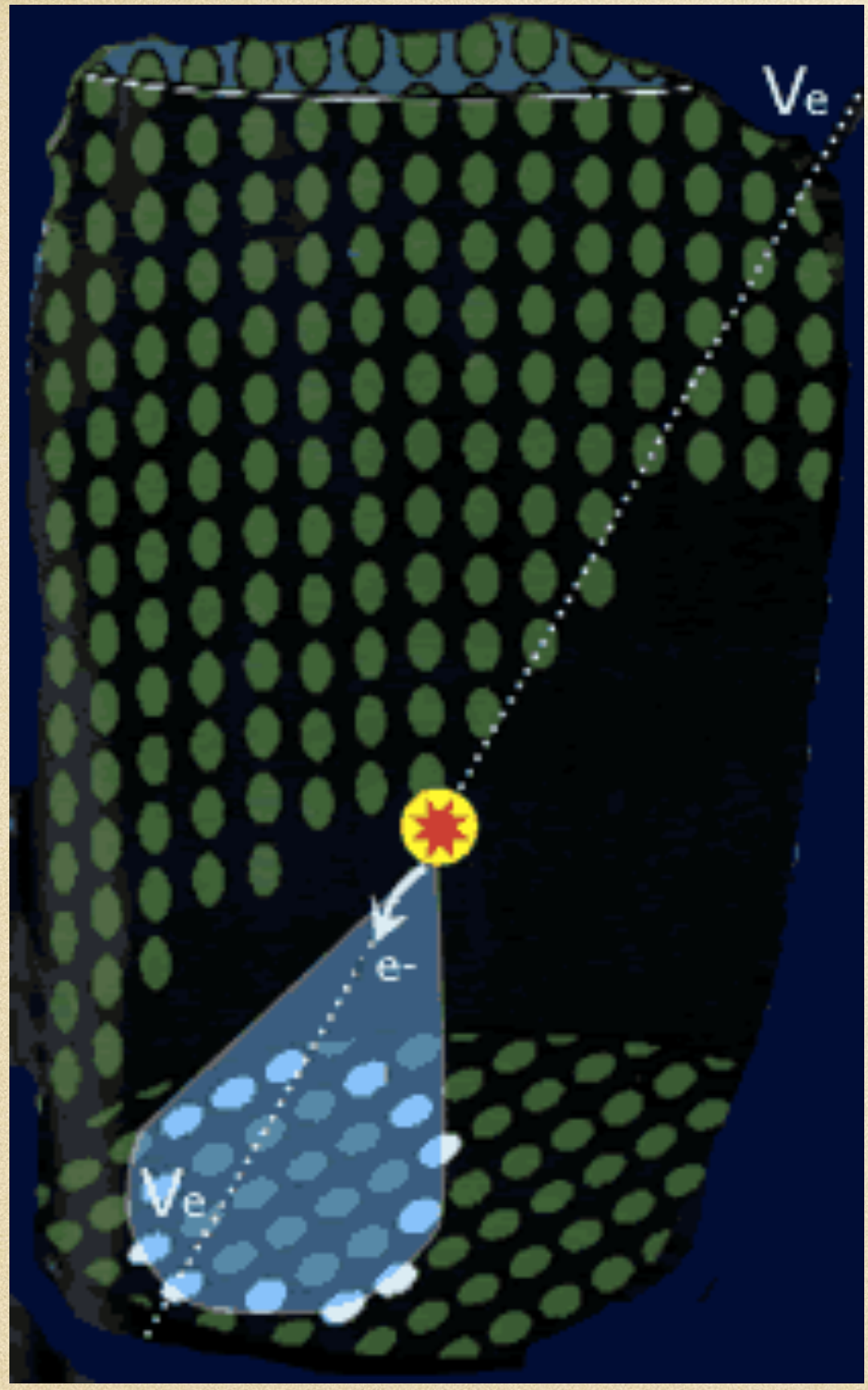
Neutrinos today: Superkamiokande (Japan)





A huge tank of ~100M liters of pure H_2O, surrounded by light sensors

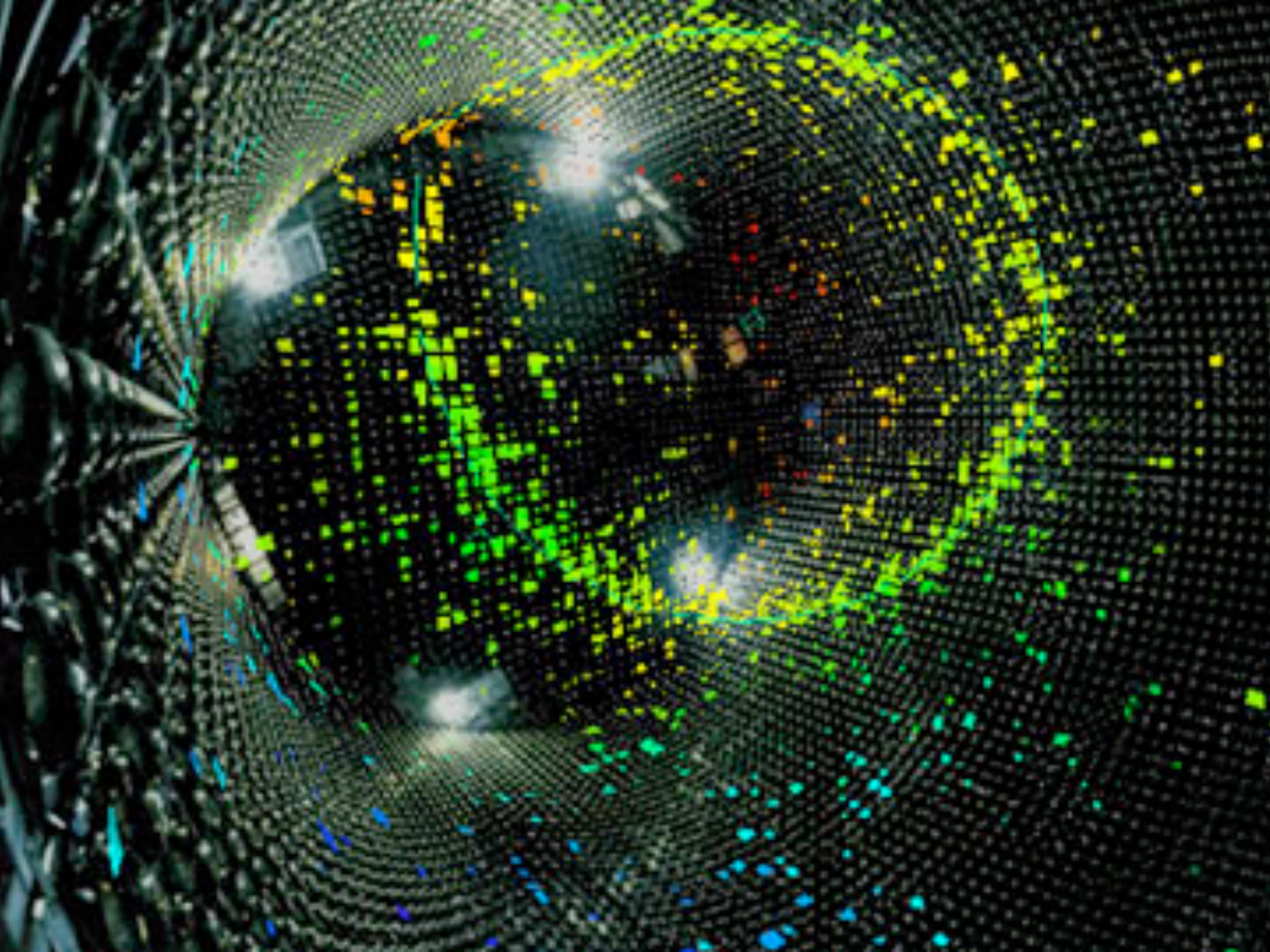

Primary Cosmic Rays
Balloon
30000 m
Hess & Kolhörster
9000 m (1912-14)
Concorde
15000 m
Electromagnetic
shower
Hadron
cascade
Mont Blanc
4807 m



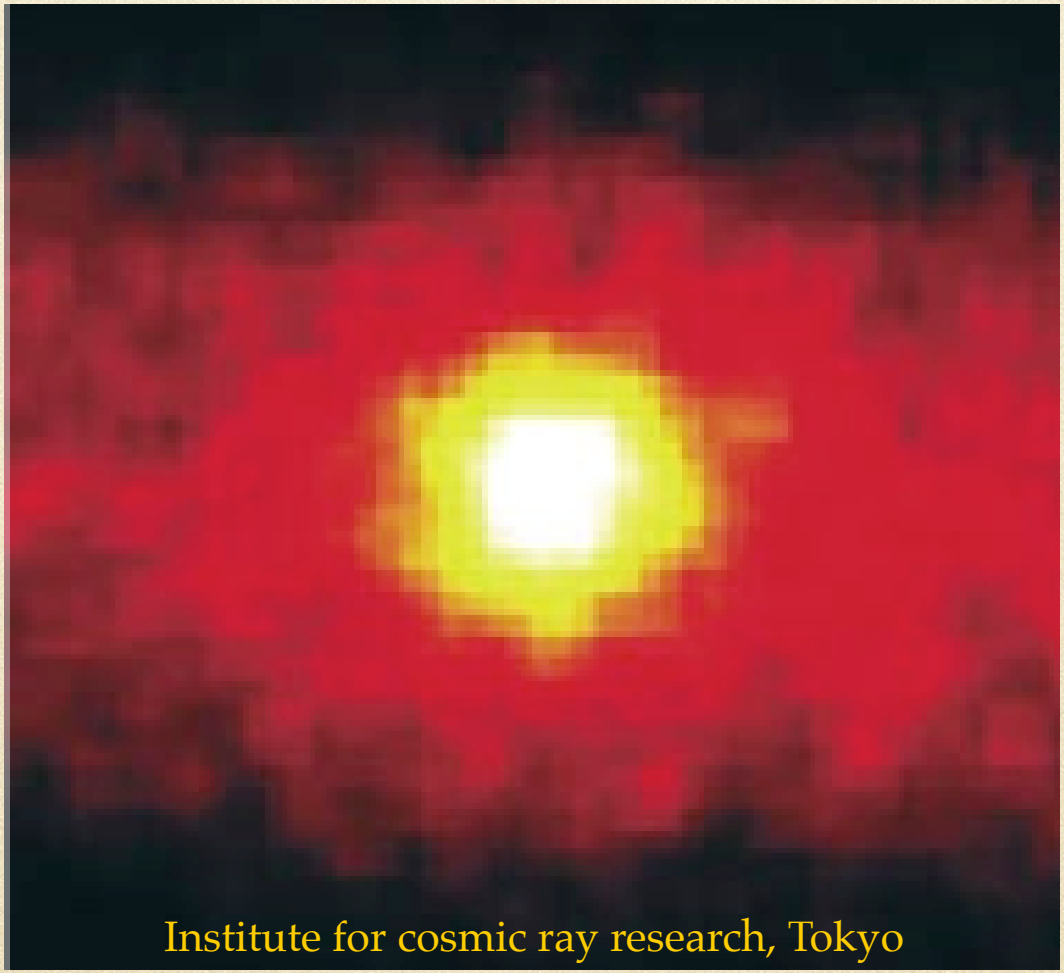
Neutrino from the collision of a cosmic ray with the earth atmosphere, or from the sun

It interacts with an atom in the water, and becomes an electron

The electron travels superluminal in water, and creates a light-bang – the luminous equivalent of a fighter jet supersonic bang – to be detected by the sensors on the surface of the tank



Reconstructing the neutrino direction, and mapping on the sky the position of their origin, allows to use neutrino detectors as “telescopes”: neutrino eyes!



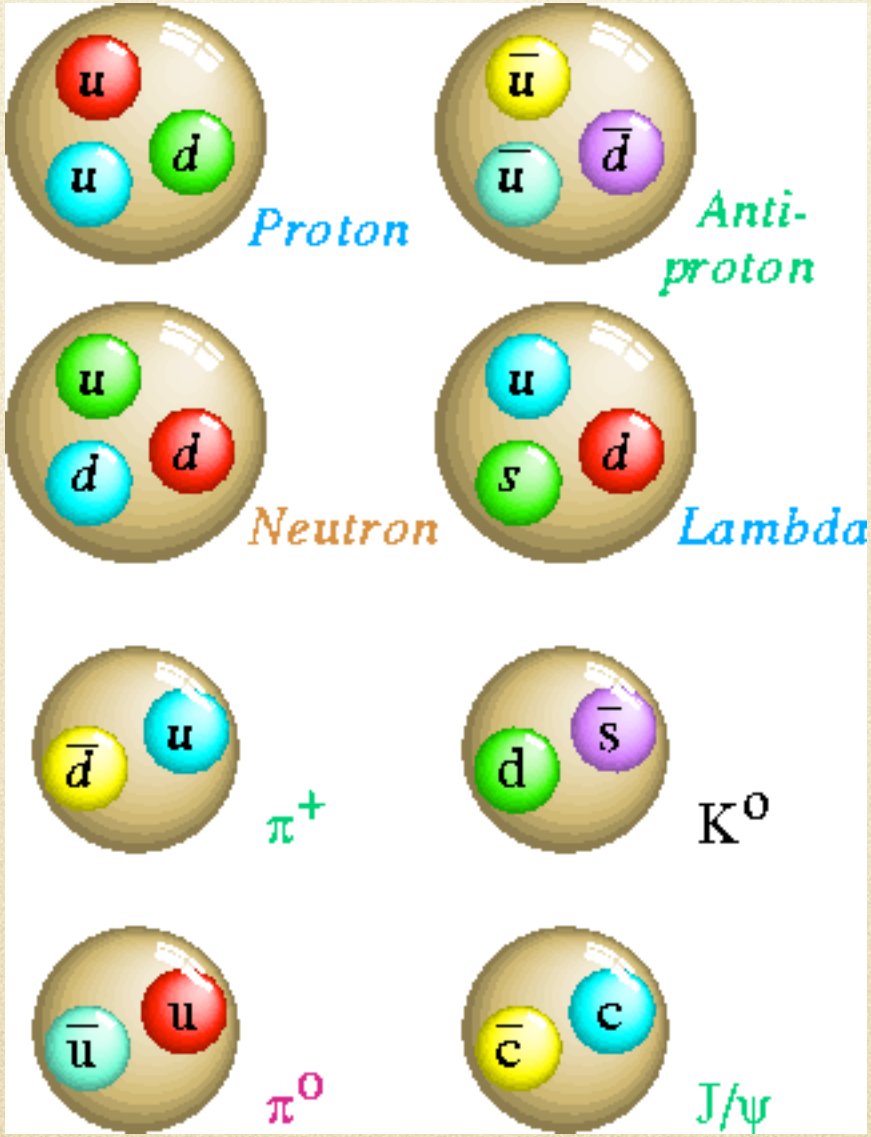
A picture of the invisible part of the Sun, namely its innermost core, where nuclear reactions take place!

100 years after they entered in our understanding of nature, neutrinos are still among the most intriguing elements of the Standard Model (SM)

- what are the precise values of their masses?
- why is their mass so much smaller than all other SM particles?
- are neutrinos their own antiparticles?
- how many types of neutrinos are there?
- are they subject to interactions other than SM ones?
- ….

The continued exploration of neutrino properties forms one of the pillars of the future programme of experimental particle physics worldwide

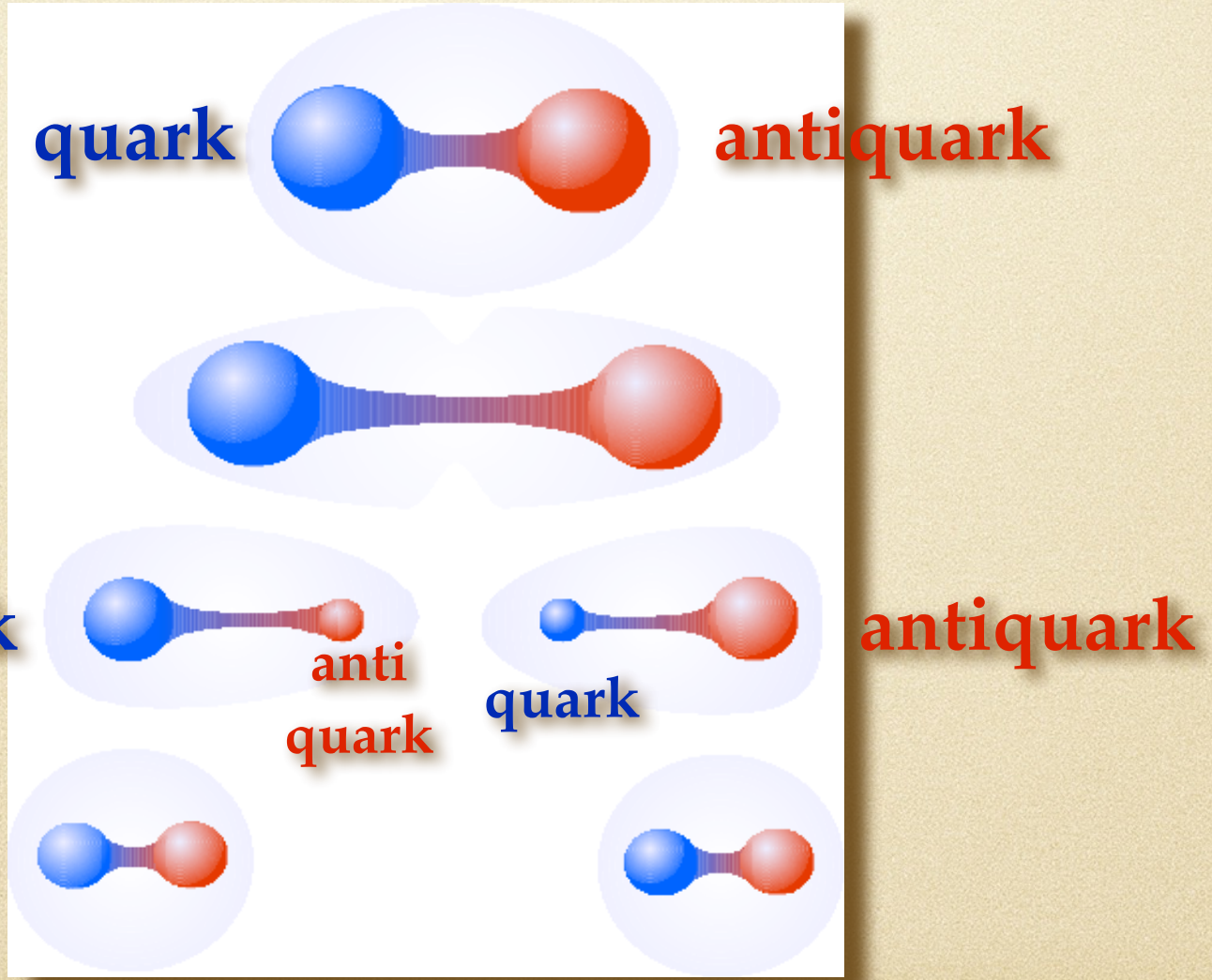
The invisible inner world of protons



The ultimate invisible: quarks inside matter .....

If we try to pull the quarks out of a proton or a pion, the energy we need to win the strong force will eventually convert into a new quark-antiquark pair (using $E=mc^2$), and we'll be left with two **pions ....**

we know quarks are there, but can't get them out!



Some of the main open questions

What's the origin of invisible dark matter ?

L'homme invisible, 1929

Whatever happened to the antimatter in the Universe?

Antiprotonic assumption, ‘56

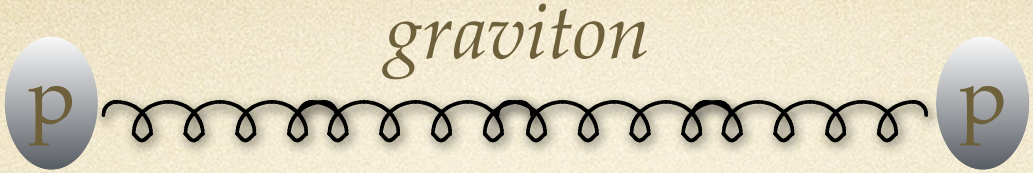
Why do we live in 4 dimensions?

are there more, hidden and invisible dimensions of space-time?

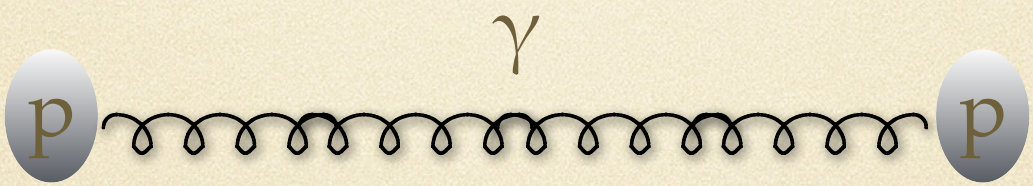
In the search of the 4th dimension (1979)

Gravitational vs Electromagnetic interactions

Gravitational vs Electromagnetic interactions



$$F_{grav} = -\frac{G_{Newton}\, m_p^2}{r^2} \sim -10^{-38}\, \frac{1}{r^2}$$



$$F_{electric} = \frac{G_{Coulomb}\, e_p^2}{r^2} \sim 10^{-2}\, \frac{1}{r^2}$$

$$\Rightarrow \frac{F_{grav}}{F_{electric}} \sim 10^{-36} \quad !!!!$$

10^{-36} is

$$\sim \frac{\text{weight of a brain cell}}{\text{weight of the Earth}}$$

Why is gravity so weak?

We have no clue!

- **Is it anthropic?**
- **Is it a random choice of nature?**
- **Is it the outcome of some unknown underlying dynamics?** (*eg extra dimensions?*)
- **Is it gravity that's weak, or elementary particles that are *unnaturally light*?**

➡ ***what's the origin of particles' masses?***

What is the structure of the vacuum?

Why do particles have a mass?

The echo of void, 1935

The vacuum, and the Higgs field

We call vacuum the state of any volume of the Universe if we were to take away from it all matter and interactions from nearby matter.

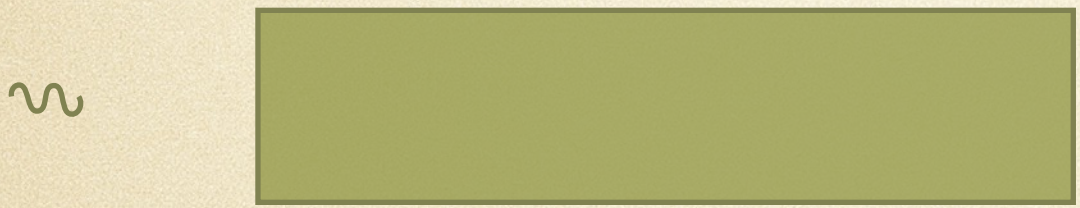
The Standard Model predicts that the vacuum is occupied by a constant density field of the Higgs boson, which we cannot “take away”.

This permeates the Universe like an ether, everywhere and permanently, since about 10^{-10} seconds after the Big Bang

Interacting with this field, particles acquire their mass

The Higgs and particles' masses

Light propagating in a medium is slowed down by its continuos interaction with the medium itself



The time it takes to move across the medium is longer than if light were propagating in the vacuum,

$\Rightarrow c_{medium} < c_{vacuum}$

Think of the Higgs field as being a continuum medium embedding the whole Universe with density v. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than "slowing down", however, the interaction with the Higgs medium gives them "inertia" => mass $\propto v$

In this context, the puzzle of gravity's weakness ($G_{Newton}\, m^2 \ll 1$) becomes

" why $G_{Newton}\, v^2 <<< 1$?? " or

"why is the Higgs field so weak ??"

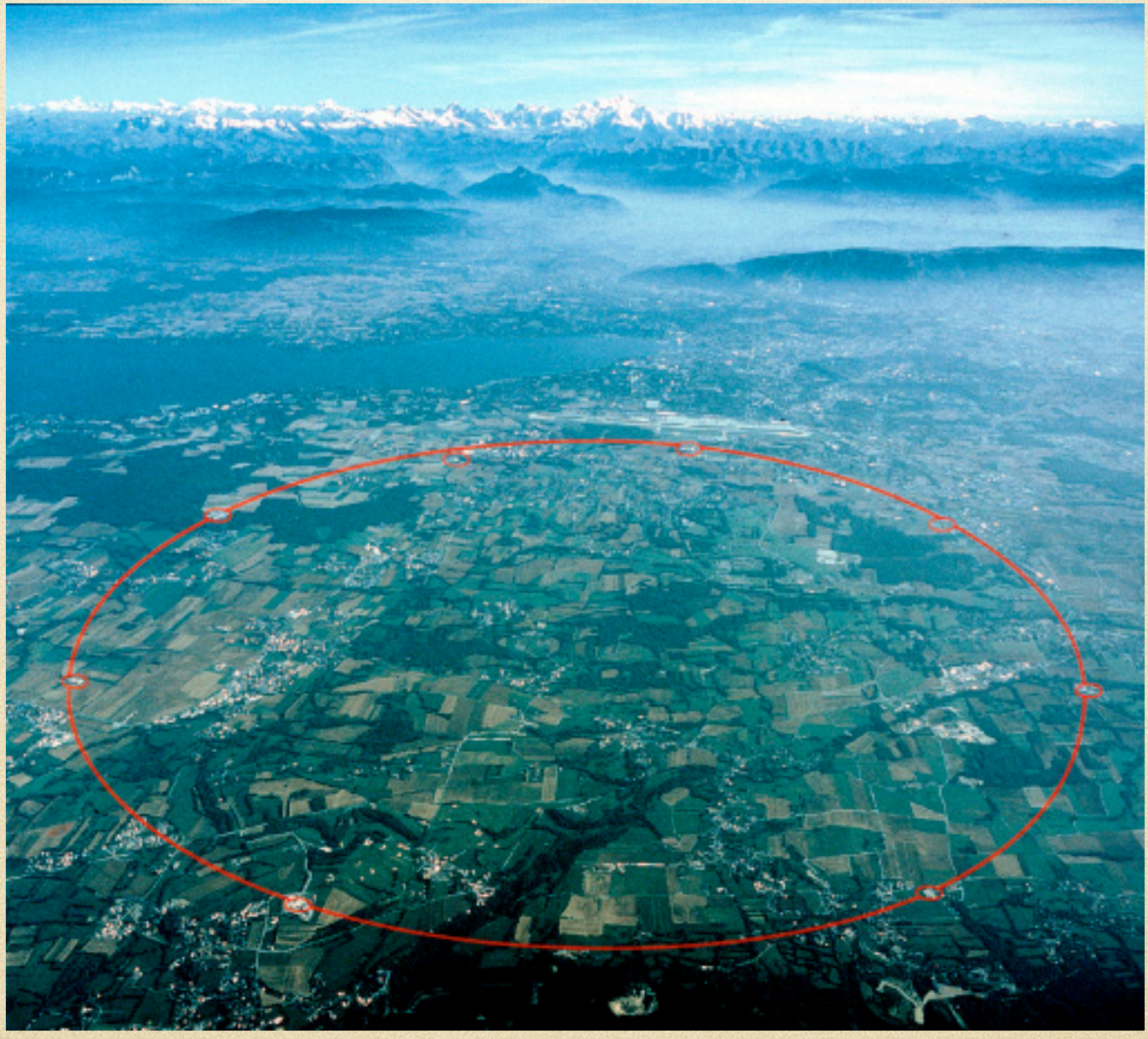
To address this question, we need to find clues through a detailed study of the properties of the Higgs boson

Producing Higgs bosons

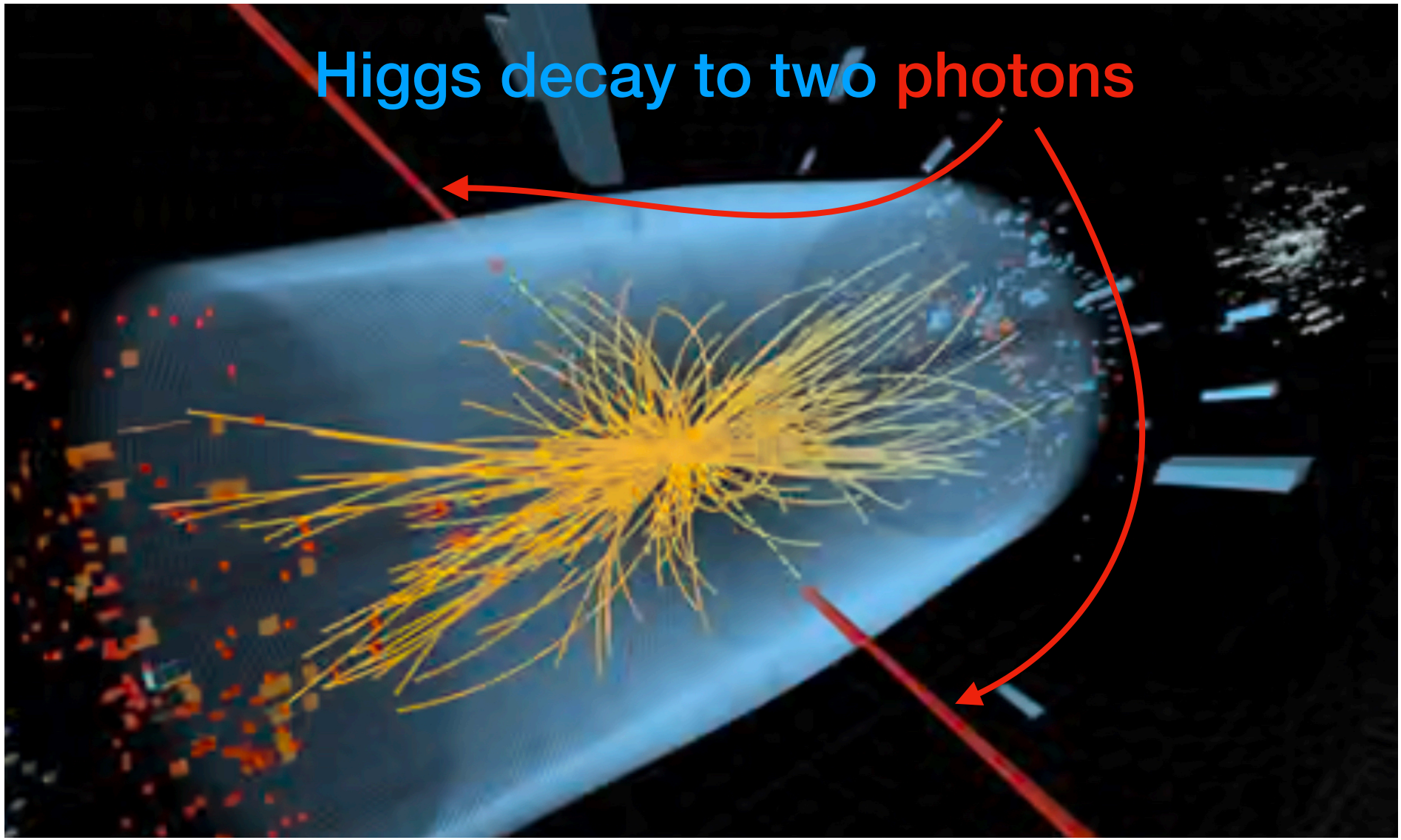
Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we "bang" on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate "**Higgs waves**". These waves manifest themselves as particles, the so-called Higgs bosons

What is required is that the energy available be larger than the Higgs mass
⇒ particle accelerators !!!

The Large Hadron Collider (LHC)



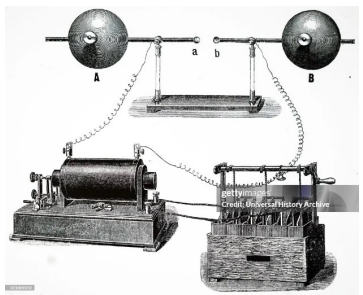
The discovery of the Higgs boson (2012):
signals of Higgs waves, or:
making the invisible "Higgs ether" visible



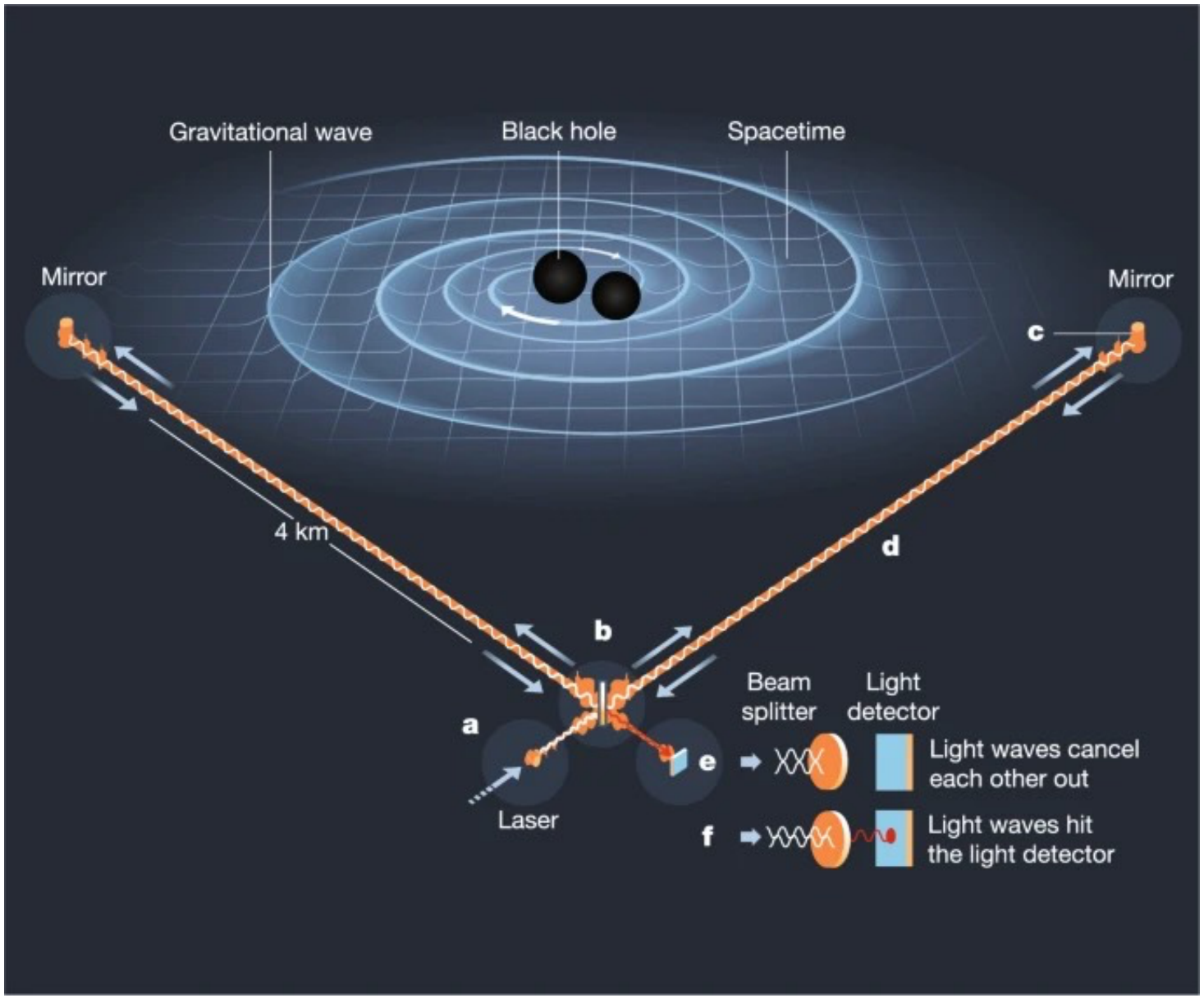
Discovery of gravitational waves

(cfr Hertz's experiment *, and recall Newton's remarks **)

*



** "… that one body may act upon another at a distance without the mediation of anything else …. is a great absurdity …"



Different nature of open mysteries

Find origin of experimental facts that do not belong to the set of phenomena predicted by the Standard Model:

- Dark Matter
- matter/antimatter asymmetry
- neutrino masses

Find origin of facts the Standard Model needs to take as given, but which could hide deeper principles:

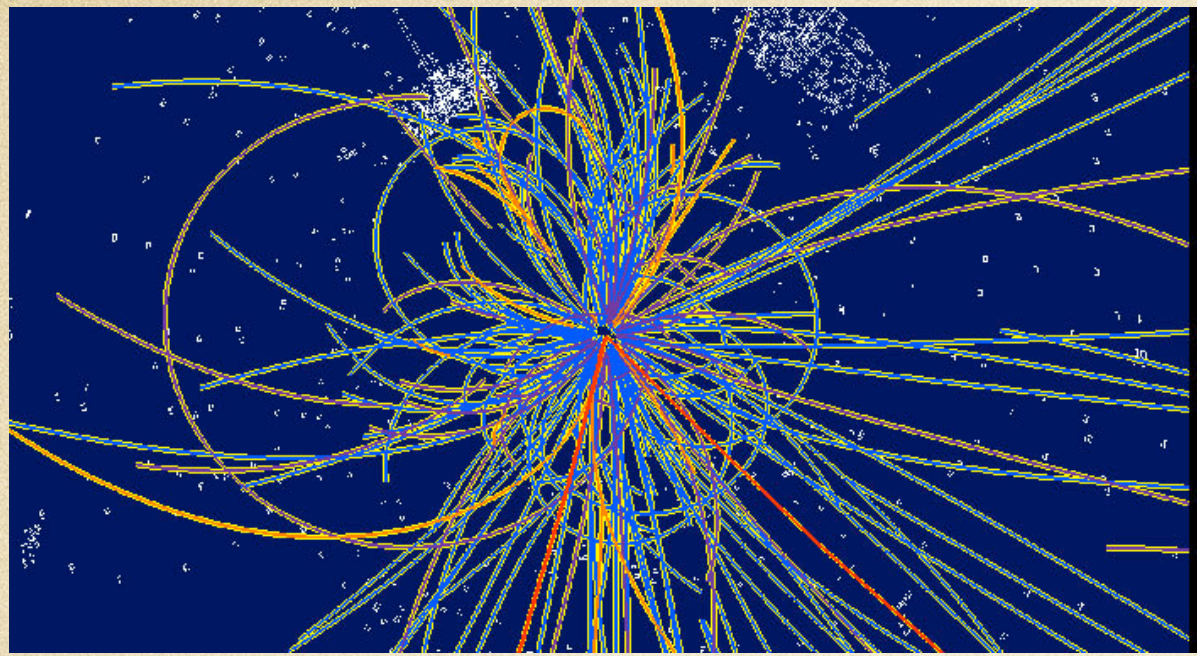
- why 3 families of quarks and leptons?
- why is gravity so weak?

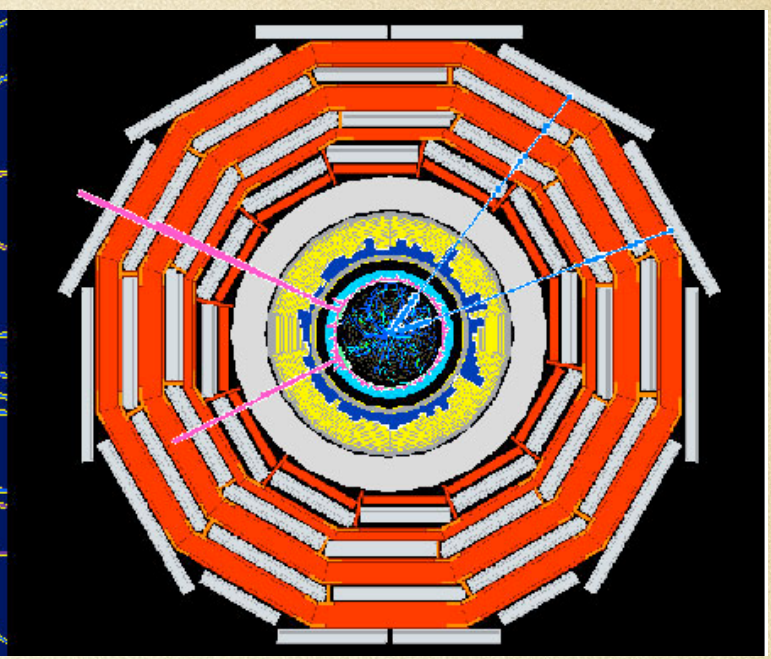
Keep testing SM theoretical framework:

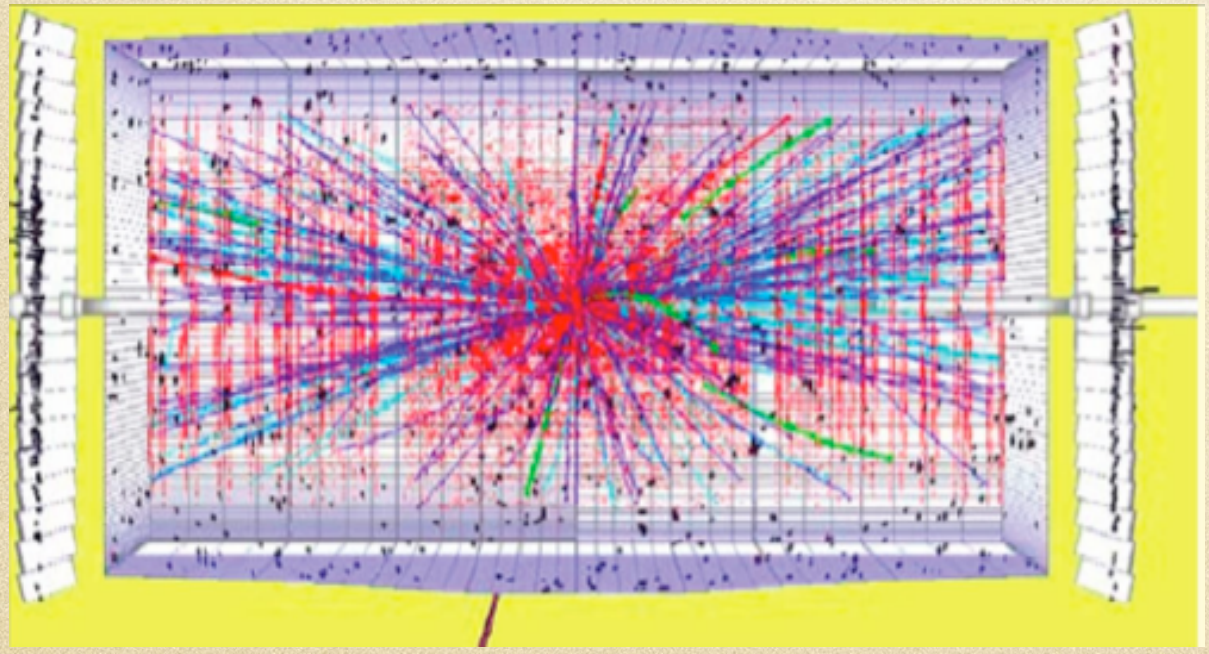
- are quarks and lepton fundamental?
- are there additional forces and interactions?
- are particles really point-like, or are string-like objects the most fundamental entity?
- are there additional space-like dimensions?

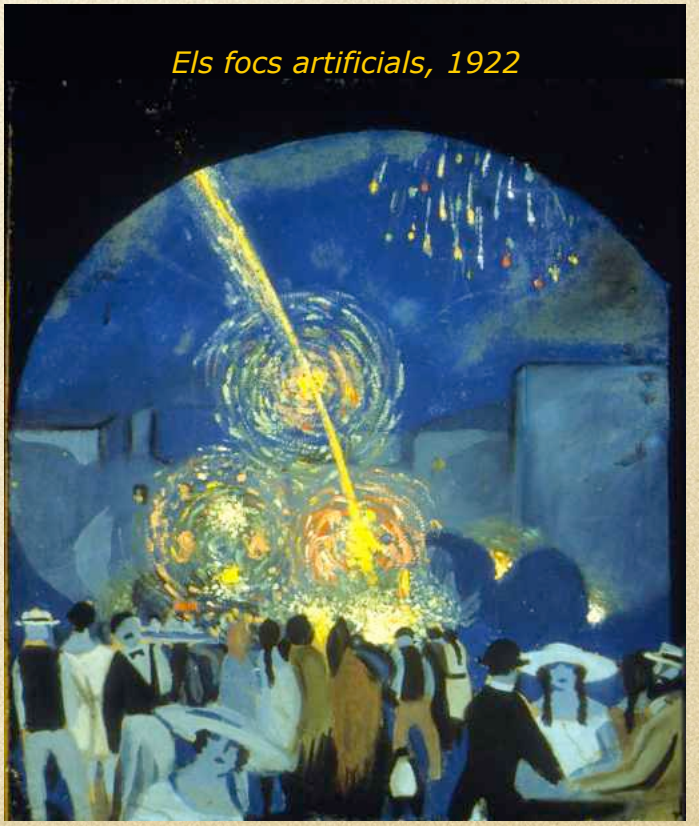
What will the next big discovery be?

- a new (set of) particle(s) (*eg the DM particle, or those predicted by Supersymmetry*)?
- a new interaction (*eg a new weak force, restoring the parity asymmetry of radioactive phenomena*)?
- a new layer of substructure inside those we consider today as elementary particles?
- a new conceptual paradigm (*like the discovery that the speed of light is constant, or energy levels are quantized*)?
- …. all of the above ??

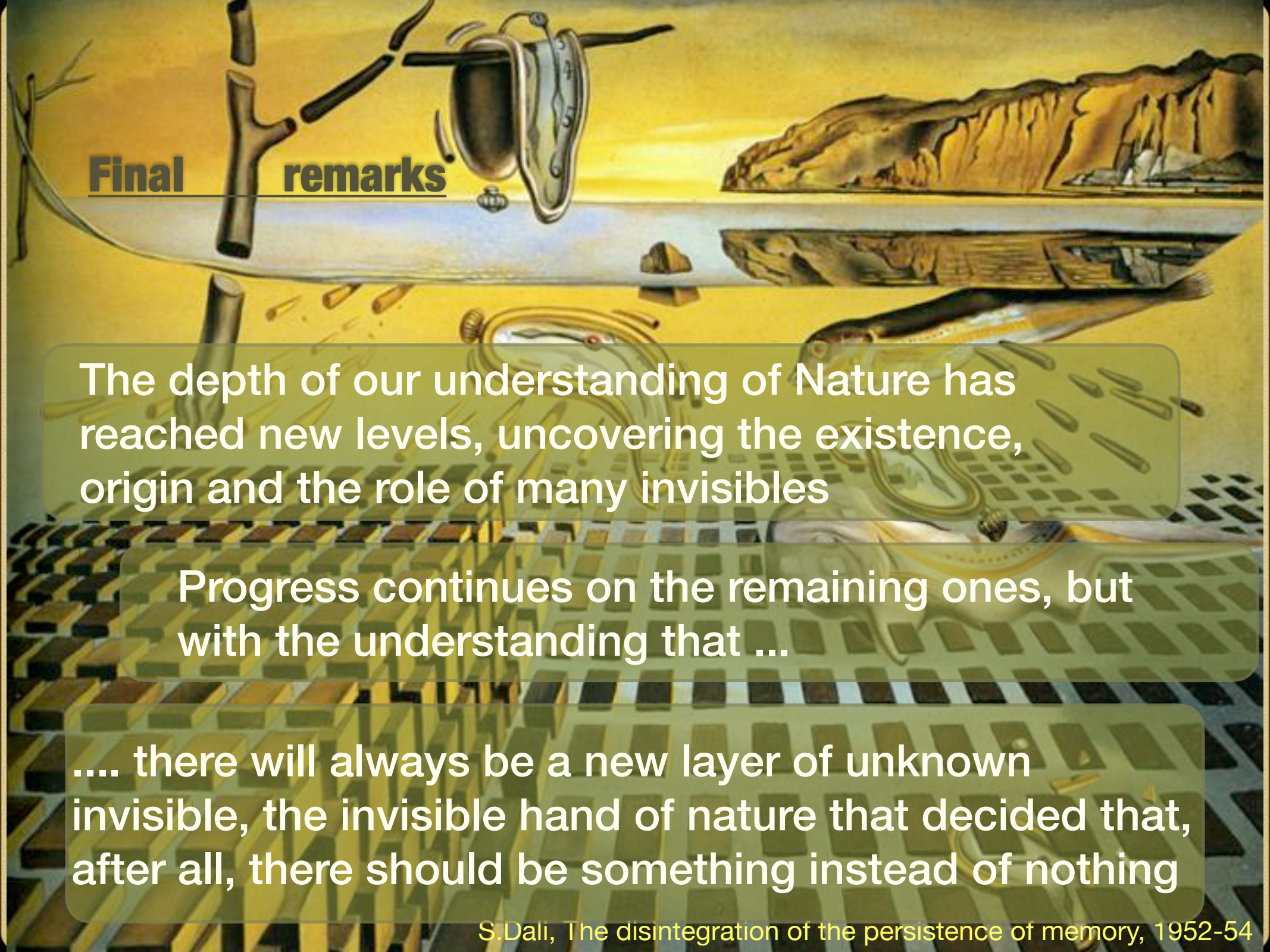








Els focs artificials, 1922



Final remarks

The depth of our understanding of Nature has reached new levels, uncovering the existence, origin and the role of many invisibles

Progress continues on the remaining ones, but with the understanding that ...

.... there will always be a new layer of unknown invisible, the invisible hand of nature that decided that, after all, there should be something instead of nothing

S.Dali, The disintegration of the persistence of memory, 1952-54