Visible and invisible in modern physics[1]

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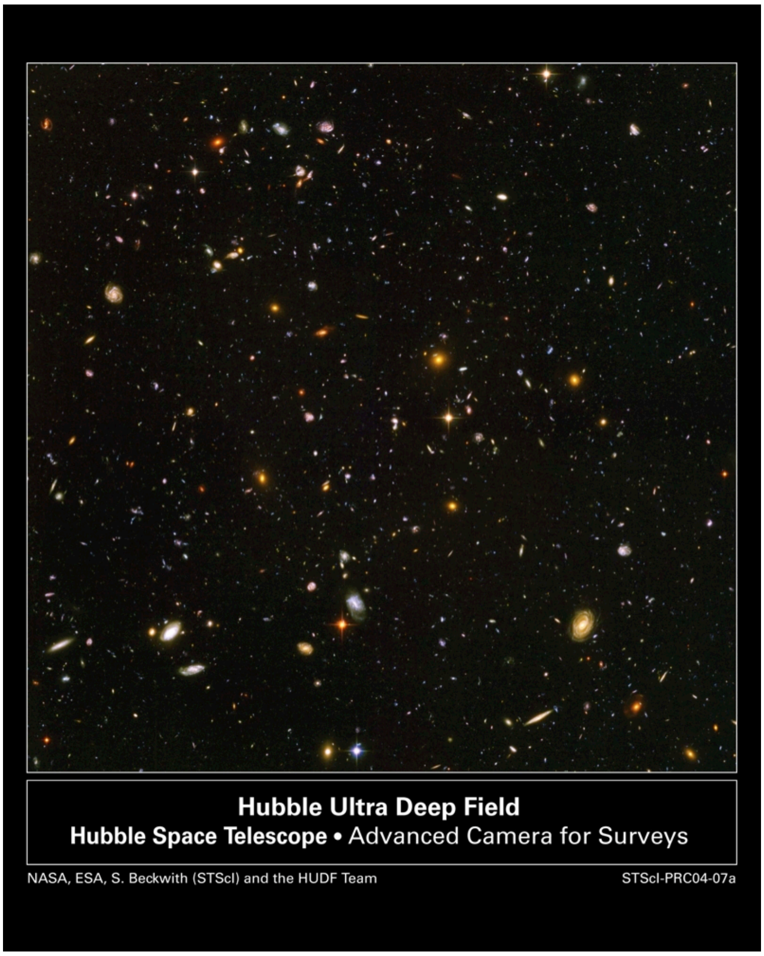
It doesn't take to be an astronomer to be blown away in awe by the breathtaking beauty of this image of the deep sky:



It represents a big cluster of galaxies, as observed by the Hubble Space Telescope. Dalí would have loved that, and who knows what his skies would have been like if he could have seen such an image!

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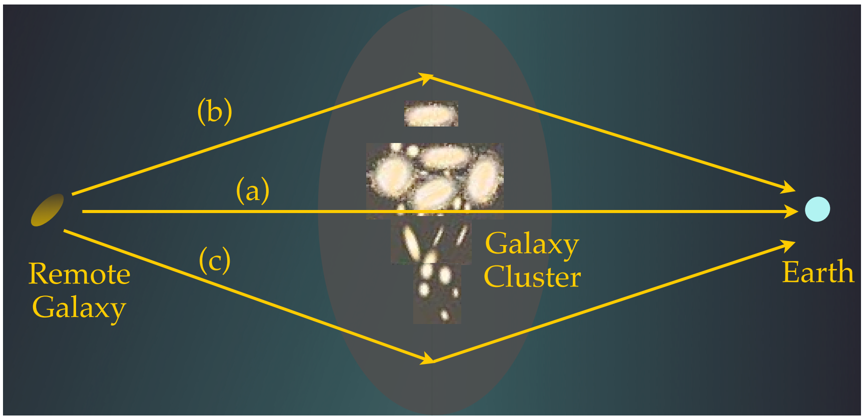
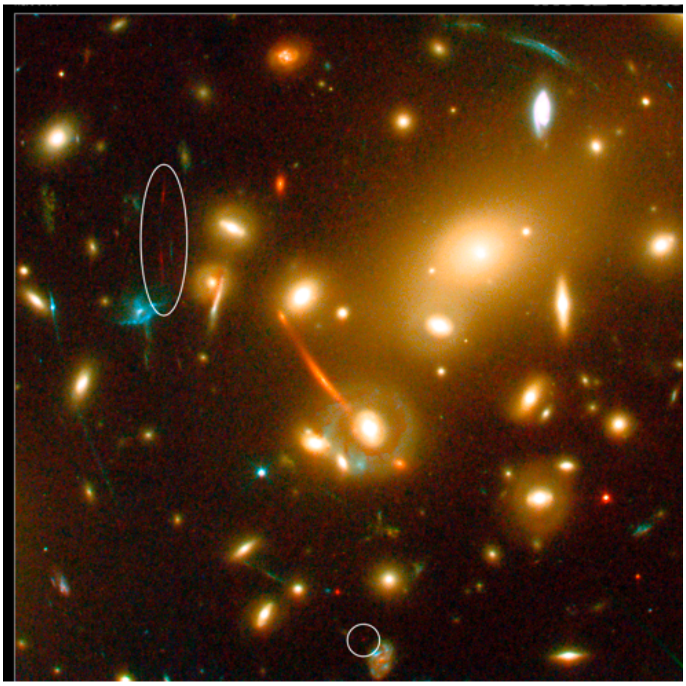
S. Dalí, Ciel, 1931

But for a physicist the most amazing aspect of this picture is not what is visible on it, rather what is invisible! Physicists are convinced in fact that the shining stars and galaxies only represent a minute fraction of the matter contained in this part of the sky. How we know it, is explained by this picture, which shows the so called *gravitational lensing* phenomenon. If a cluster of galaxies is situated right in between us on Earth and a remote galaxy, multiple images of the remote galaxy can reach us. The light ray labeled as (a) will just travel through, and give us the primary image. The light rays (b) and (c) are deflected by the gravitational field of the galaxy cluster, as predicted by Einstein's theory of general relativity, and can be redirected toward us, providing an independent image of the remote galaxy. Therefore the galaxy cluster acts as a kind of lens. The measurement of the deformation and intensity of the multiple images provides us with a determination of the quantity and distribution of matter present in the galaxy cluster, in much the same way as the thickness and shape of a lens determines its magnifying power and chromatic behaviour.





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

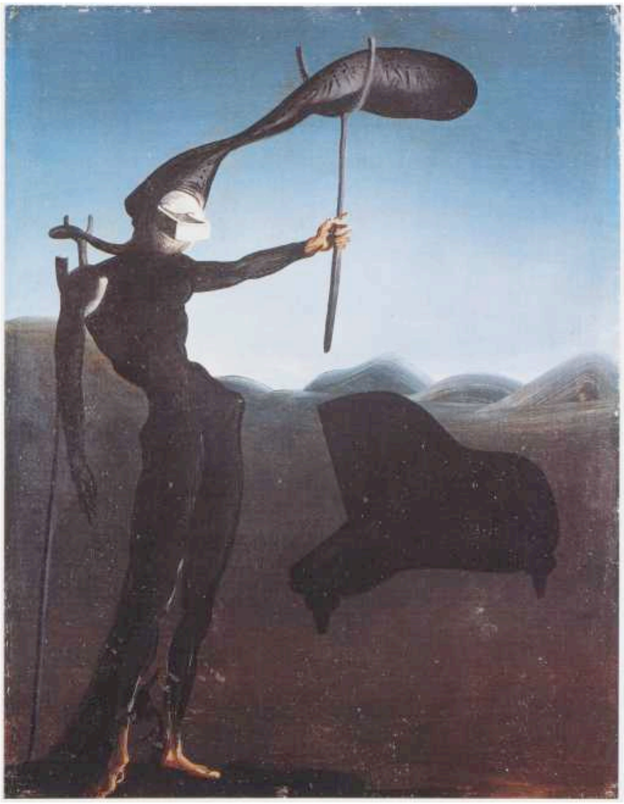
The picture here shows the spectacular image of the galaxy cluster Abell 2218. The elongated shapes are the multiple images of galaxies further away than the Abell cluster, distorted by gravitational lensing. For example, the red arc within the white ellipses on the upper left of the figure is a second image of the red dot inside the circle on the lower centre. The surprising conclusion of the study of this image is that 5 times more matter than what is observed in the form of luminous galaxies is required to explain the

lensing patterns! All of this matter is not visible, yet it dominates the matter content of this region of space.

Surrealist composition with invisible figure, 1936

The message of this example is that for something to be declared invisible, we must know it's there, and if we know it's there, perhaps it's not *truly* invisible any longer. Invisible therefore should not be taken to mean immaterial or inexistent; it is an adjective, and therefore must refer to *something*. This concept must have been very clear to Dalí, as shown by his “Surrealist composition with invisible figures” (1936), where it is the lack of a concrete image of the figures that makes them invisible, but they are nevertheless unmistakably there, as shown by the shapes left on the chair and bed, the figures thus deserving the title of *invisible*.

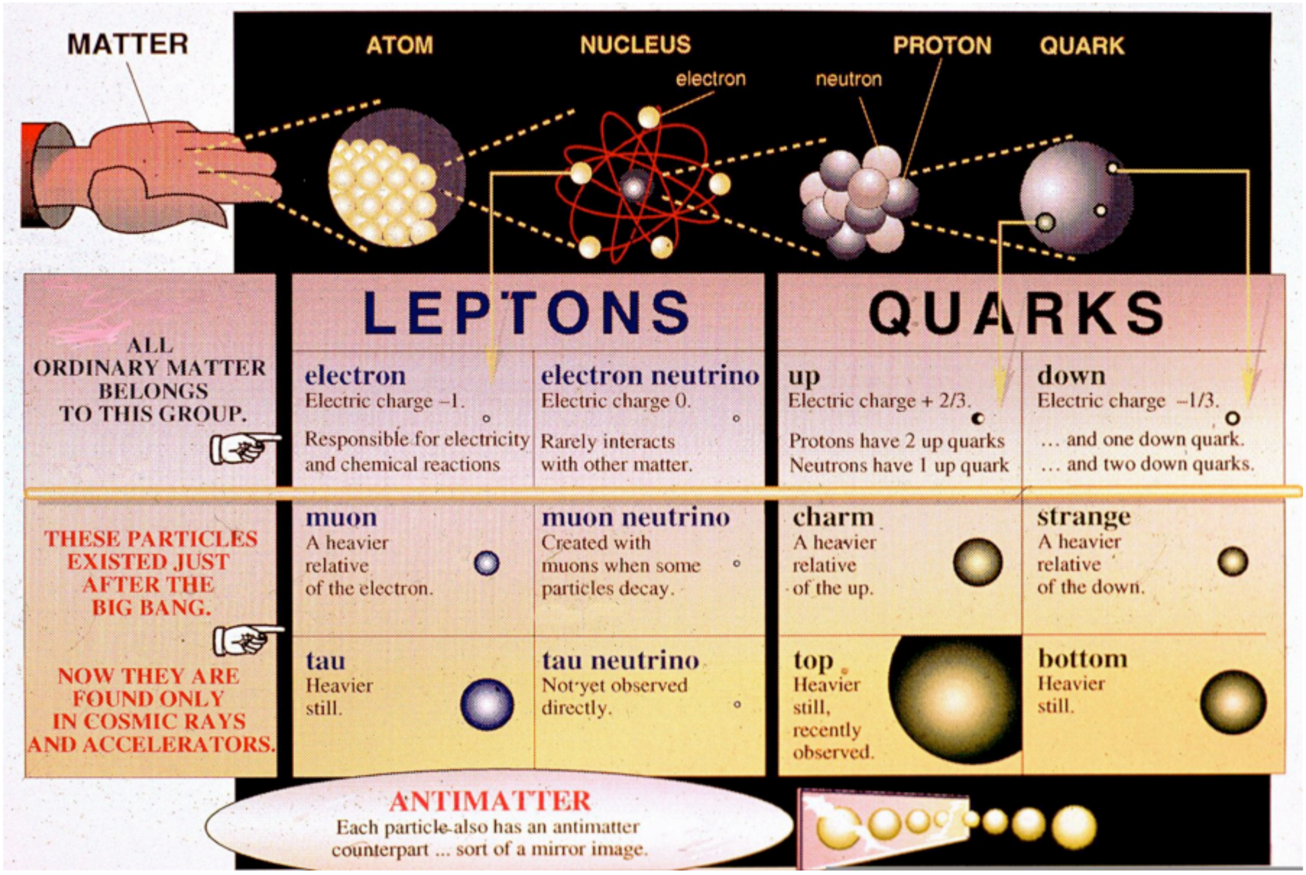
Proving the **existence** of the invisible, namely providing evidence that there is something where there appears to be nothing, turning the invisible into *visible,* is one of the main drivers of scientific progress. It is a very basic process, that moves us from the realm of magic, religion and superstition to the domain of science. This process is far from being a trivial one, and Dalí's “Invisible Harp” (1934) can help us see why. Contrary to the “Surrealist composition …”, where the presence *and* nature of the invisible is clear, here it's not even clear that something is invisible, let alone a *harp.* Having established that there is something of invisible to be talked about, identifying its precise nature is the next step, the step that completes the scientific process. In this presentation I shall provide a few concrete examples of how the exploration of the invisible, and the efforts to make it visible, have contributed to some of the major advances of fundamental physics. The exposition will not represent a systematic history of modern physics, but rather a collection of anecdotes, meant to stimulate your imagination and to bring you closer to the topics that so much stimulated Dalí's creativity.



Invisible harp, 1934

The Standard Model

When we see objects falling, or a pencil rubbed on a sleeve lift a small fragment of paper, or planets move around, we are witnessing the presence of the invisible. With no physical contact between planets, or between the pencil and the paper, what is it that makes them attract each other? Is there *something* responsible for these behaviours, and if so, what is it? These are among the most basic questions that natural philosophers have been asking themselves since the dawn of civilization. Is matter made of some basic and elementary building blocks (*atoms*), or is it possible to continue splitting it into smaller and smaller components? If elementary building blocks (which today we call "elementary particles") exist, what are they? How do they interact with each other? How do these interactions determine the properties of the Universe? Addressing these questions is a way of unveiling the invisible that surrounds us, of giving it substance, and of exploring its consequences for the Universe. Many centuries of work have led us to what we consider a very solid understanding of these issues, summarized in the following scheme, known as *the Standard Model*:



We know that the matter we see and deal with is made out of just 3 elementary particles: the two quarks *up* and *down,* which grouped into triplets as (*uud*), and (*udd*), form the proton and the neutron; and the electron, which orbits around the nucleous made of protons and neutrons, forming an atom. Four fundamental forces (or interactions) govern the behaviour of these elementary particles. (1) The *gravitational* force, whose attraction strength is proportional to the energy – and therefore to the mass – of a body. (2) The *electromagnetic* force, which is sensitive to the electric charge. (3) The *weak* force, which transforms *up* quarks into *down* quarks and vice versa, or electrons intro neutrinos (see later), and drives the nuclear reactions that generate energy inside the Sun or inside a nuclear power plant. (4) The *strong* force, which permanently holds quarks bound inside proton and neutron, and which keeps proton and neutron together inside the nucleous. All the phenomena and forces we observe in nature can be reduced to manifestations of these fundamental forces. Chemistry, for example, is entirely the result of electromagnetism, which controls the inter-

actions between electrons in the atoms. The wind, instead, is the combined result of electromagnetism and gravity: the light from the Sun (electromagnetism) warms the air. Gravity forces cooler air to stay below warmer air, and the relative reshuffling of warm and cool air causes what we call wind. It would be fascinating to spend our time here going through everything we see happening around us, and *deconstruct* it in terms of elementary components and forces! In the laboratory we can manipulate the elementary particles and fundamental forces, and verify with great accuracy the consistency of the Standard Model, proving that the behaviours we describe with our formulae are universal, in the sense for example that the law of electromagnetism that governs the interactions of elementary particles is the same that gives rise to chemistry, and that these laws are the same here and today, as they are somewhere else far away in the Universe, and as they were long time ago (we do this by studying the properties of the light emitted by very remote galaxies, light that was emitted up to billions of years ago). Through these manipulations, we discovered furthermore the existence of two more sets of elementary particles, whose interactions with the 4 fundamental forces are precisely the same as those of electron, neutrino and *up* and *down* quarks. These are shown in the lower two rows of the above table. These two sets are called second and third *family,* or *generation*, where the set comprising the building blocks of ordinary matter is labeled as first family/generation. These particles cannot appear in nature unless we create them, since they have very short lifetimes. That means that once created, they will *decay very rapidly* into elementary particles of the first family. For example the *charm* quark, a member of the 2^{nd} generation, will decay within a billionth of a millisecond into a *strange* quark, an *up* quark, and a *down* antiquark. The *strange* quark will then, within a further billionth of a second, decay itself into a *down* quark, an *up* quark, and a *up* antiquark. These extra families of elementary particles are invisible in our daily life, but nature has chosen to make them part of its clockwork. Why? We don't know, and although we are working hard to answer this question, for the time being we rest content with having unveiled yet another invisible component of our Universe.

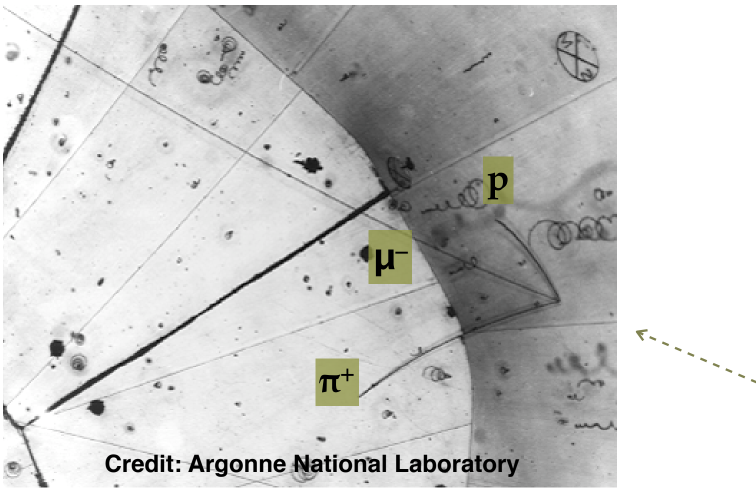
Neutrinos

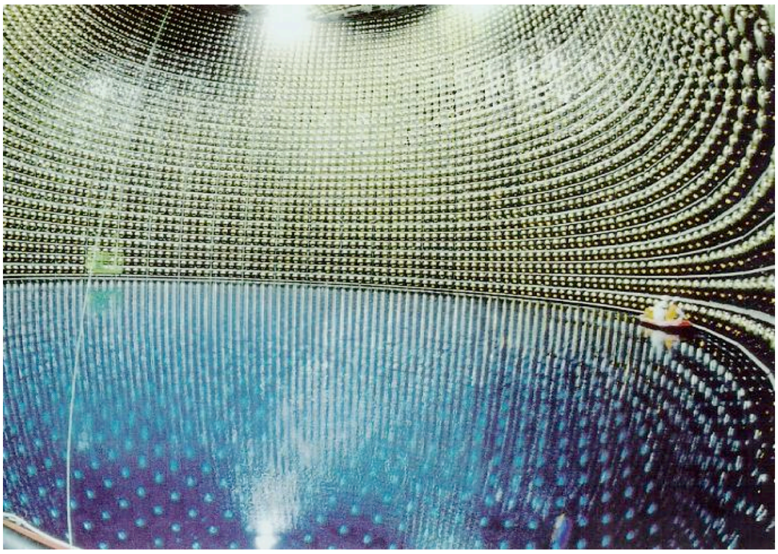
The neutrinos mentioned above provide an excellent example of the process of turning the invisible into visible, so I'll spend few minutes on them. By the mid of 1930 it had become clear that something extremely puzzling was happening in the decay of a radioactive isotope of Helium, ^6He. The following decay to a nucleous of litium and to an electron was observed: $^6He \rightarrow {^6Li} + e^-$. Since the mass of ^6He, m_{He}, is bigger than the mass of ^6Li, m_{Li}, plus the electron mass, m_e, the principle of energy conservation and Einstein's relation $E=mc^2$ require that the energy difference $E= m_{He}\, c^2 - m_{Li}\, c^2 - m_e\, c^2$ should be transformed into kinetic energy for the litium and the electron. A consequence of this is that the velocity of the electron emerging from the decay should always be the same, since the share of energy between litium and electron is fixed by their relative mass. This is like saying that when we fire a bullet with a gun the strength of the recoil is always the same if we fire bullets of the same type. The experiment however showed very clearly that the electron energy varied for each decay, and that on average the electron was moving more slowly that it should have. Many famous physicists were so puzzled that they even went as far as suggesting that in the newly-discovered world of nuclear phenomena one should perhaps give up the principle of energy conservation. It was Wolfgang Pauli who, at the end of 1930, realized

that the solution to the puzzle was not in what was being seen, but in what was *not* being seen. He proposed the existence of a third, invisible, particle produced in the decay of ^{6}He: $^{6}\text{He} \rightarrow {}^{6}\text{Li} + e^{-} + \nu$. This additional particle would take its own share of the available energy, but since it is invisible – meaning that it does not leave a sign of its presence in the experimental apparatus used to detect the electron and the ^{6}Li – it would lead to an apparent loss of energy. Enrico Fermi gave this particle the name of *neutrino*, and developed the theory of its interactions, the *weak interactions,* explaining in particular why it was so elusive. Fermi's theory, which is at the basis of the Standard Model, gives among other things a quantitative understanding of the energy-generation mechanisms inside the Sun. The neutrino from ^{6}He decay is so weakly interacting that not even a slab of iron as thick as the distance between the Sun and the Earth would typically stop it! Only very rarely a neutrino would collide precisely head-on with a nucleous inside a detector, and convert itself into an electron, thus revealing its presence. It took more than 20 years for physicists to observe such a phenomenon, in an experiment in 1954 situated close to a nuclear power plant, a powerful source of neutrinos produced in the nuclear reactions. But Pauli's argument and Fermi's theory were so compelling and accurate in describing nuclear reactions, that everybody was convinced of the existence of neutrinos even if nobody had seen them. The calculations describing controlled nuclear reactions, such as those required to build the nuclear power plants, assumed their existence, and their correct functioning gave implicit evidence, and then implicit *visibility* and concreteness, to the elusive neutrino.

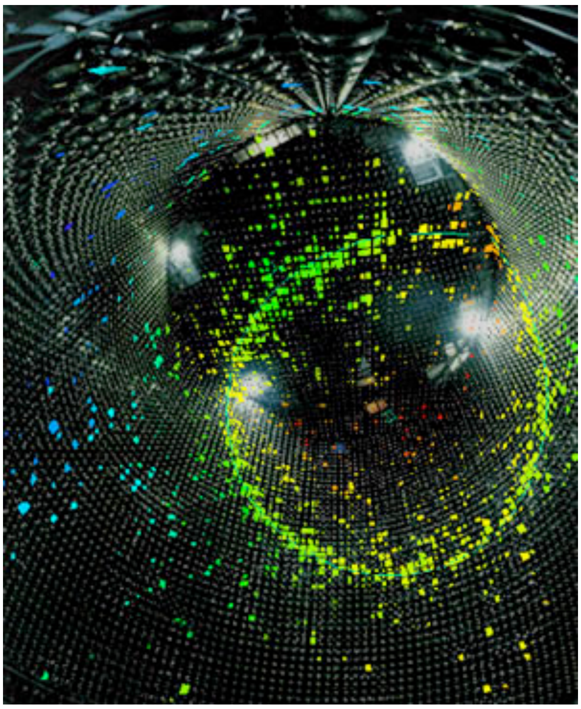
L'homme invisible (1929)

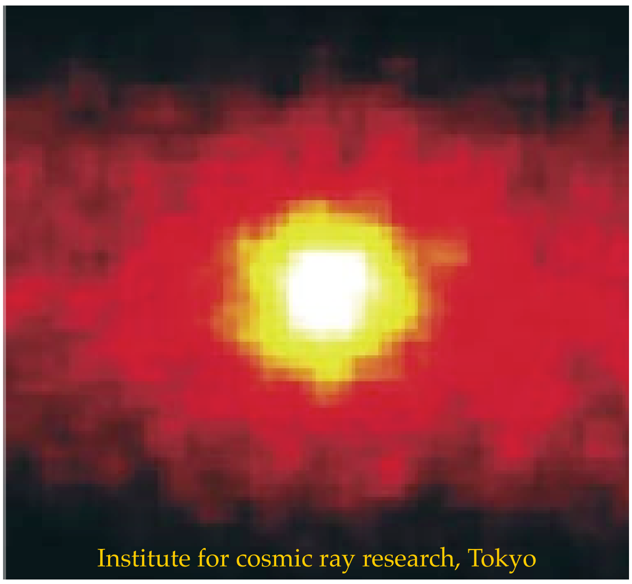
Intense beams of neutrinos are used regularly nowadays to explore the domain of subatomic particles. The image on the right shows the reaction caused by a rare interaction of a neutrino (whose invisible trajectory is shown by the dashed arrow coming in from the right) produced in the decay of a pion (also known as a π meson). The neutrino, which in this case belongs to the second family, hits a proton and transforms itself into a muon (μ^{-}), and the proton into a proton (p) plus a pion (π^{+}). It is precisely their being invisible (namely little prone to interactions) that allows them to penetrate very deeply inside matter, and to offer a very clean and sharp picture of what happens at the shortest possible distances.





To increase the probability of visualizing a neutrino, the detector must have a great target volume, to enable the occasional interaction, and a great array of sensors, capable of observing the reaction products. Today physicists use as detectors large tanks of pure water, like the one shown on the left, holding about 50,000 tons (Superkamiokande, in Japan). The picture shows a raft with physicists as they survey the light detectors situated on the walls of the tank, while the tank is being filled with water. Superkamiokande is capable of detecting neutrinos produced in the earth's atmosphere by cosmic rays, as well as those produced in the innermost core of the Sun. These neutrinos, interacting with the water nucleous, turn into electrons, and these electrons, which inside water travel faster than light would, create a superluminal bang, similar to the supersonic bang caused by airplanes flying faster than sound. This flash of light has a conical shape, and shines the light detectors causing spectacular images like the one shown below. The shape and size of the circle allow us to reconstruct information on the energy and direction of the incoming neutrino. Each detected neutrino is like the shining of a single pixel on a camera. Putting together the image of successive neutrino events, allows us to *fill all pixels,* and reconstruct the full picture. Since neutrinos are produced in the Sun only in its very centre, the picture of the Sun we obtain using neutrinos (shown in this reconstruction below) represents its most central part. Were it not for neutrinos, the core of the Sun would be totally hidden from us. The light we see from the Sun originates from its surface. A photon produced in the Sun's center takes a million years to emerge to the surface, since it is continually absorbed by the dense and opaque solar interior. The invisible neutrino, with its reluctance to interact, is instead allowed to fly through after it's produced, and carries away the secrets about the Sun interior. It's a bit like using X-rays to explore inside our body. But as I said above,



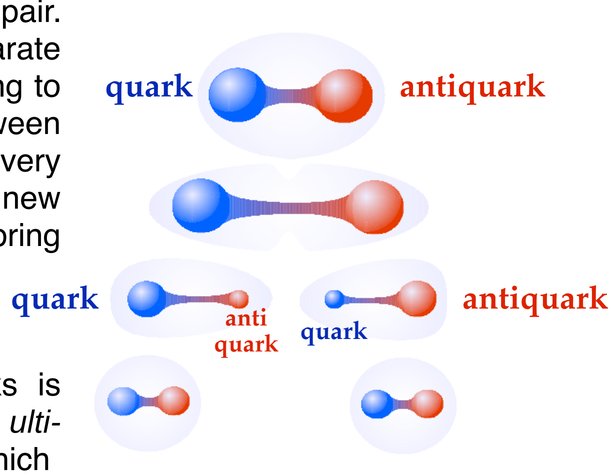


Institute for cosmic ray research, Tokyo

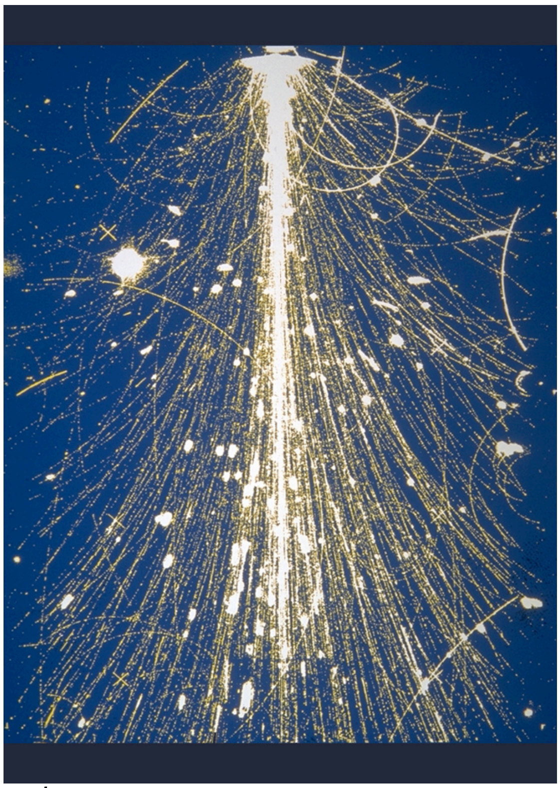
there is no way that any form of electromagnetic radiation (whether X, γ, or other rays) can escape the solar core. It's only the *invisible neutrinos that can make visible for us the invisible part of the Sun*! Mind boggling, paradoxical, totally 100% Dalinian!

Quarks, the ultimate invisible

As I mentioned above, quarks are tightly bound by the *strong* force inside the proton. They can also bind inside other particles, known are mesons, where quarks appear not in groups of three, but as a quark-antiquark pair. An example is given by the pion π^+, mentioned above, which is formed by a quark *up* and an antiquark *down.* We *know* this, even though we have never seen an individual quark. Quarks are permanently confined inside the proton, or inside pions. The force that binds them together is immense, and grows as we try to separate them. It grows so much that as we try to put more energy to separate them, this gets turned into mass, again using Einstein's relation, creating yet more pions, rather than helping separate the original quark-antiquark pair. This is shown is this picture: as we try to separate the quark-antiquark, the energy we are providing to the system concentrates in the region between them – a bit like as if they were connected by a very tight spring – until there is enough to create a new antiquark-quark pair. This creation allows the spring to be broken, but now each of the original quark and antiquark is confined in a new meson, formed with the newly formed antiquark and quark. The *confinement* of quarks is therefore absolute and eternal. I call this the *ultimate invisible*, since contrary to neutrinos, which after all we were able to see with some patience and skill, quarks will forever remain invisible, however real and material their presence and the effects caused by their presence.



Saint surrounded by three π mesons, 1956



… just π mesons ……

Beyond the Standard Model

Having made great progress in the understanding of the basic components and forces of nature, modern physics is in the position to detect its own limits: the Standard Model provides a predictive framework, within which we can ask ourselves whether the observed natural phenomena match our expectations or not. For example, it is precisely using our theory that, looking at the gravitational lensing of far-away galaxies, we can conclude, as discussed at the beginning, that there has to be more matter than we see. Other observations, united with the predictions of the Standard Model, furthermore indicate that this extra matter (which is known with the generic term of *dark matter,* and which appears to form 23% of the universe mass) cannot fit within what is predicted by the Standard Model itself. In other words, it is not made of the usual protons, neutrons or electrons that form ordinary matter, and which appear to make up at most only 5% of the contents of the universe. It is precisely our confidence in the Standard Model that allows us to conclude that it is not enough, and there has to be something more! So one of the leading questions of modern physics is "what's dark matter"? "*Dormeuse, cheval, ou lion*", to cite as alternatives the invisible entities present in Dalí's 1930 painting?

Dormeuse, cheval, lion invisibles, 1930

Another example of the known limits of the Standard Model is its inability to account for the sole existence of matter in the universe. The Standard Model contains a slight asymmetry between matter and antimatter (an effect known as CP violation), but not enough to explain the relative contents of matter, antimatter and radiation that we observe.

Antiprotonic assumption, 1956

In the search of the 4th dimension

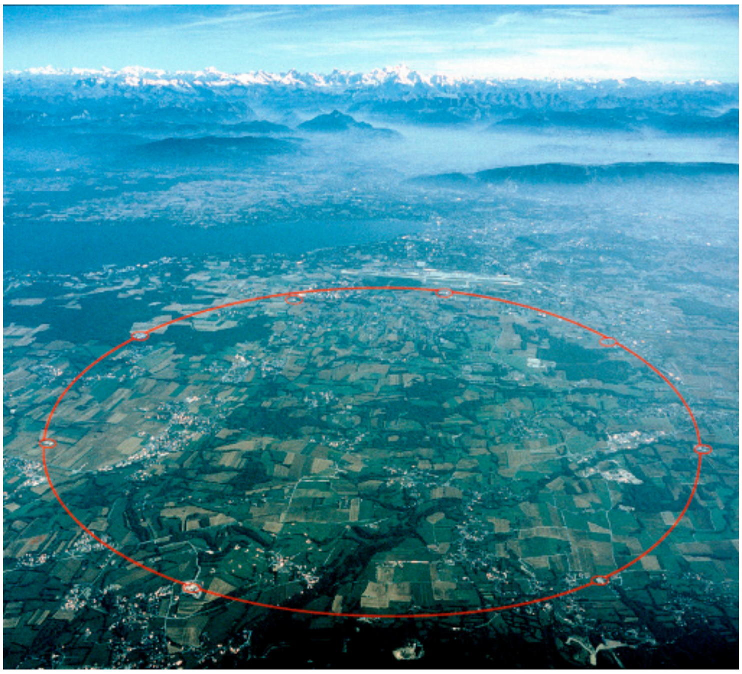
Dalí was fascinated by the idea that we live in 4 dimensions (D=4). Today physicists ask themselves *why* the universe is 4 dimensional. We have moved beyond the stage of simply observing the structure of space and time, and accepting it as a fact of nature. We pretend to look for a rational and unambiguous explanation for this, assuming that nature may have selected 4 dimensions after solving some equation, constrained by nature's own rules, rather than as a random choice. Most of the theories we have developed to understand the origin of gravitational forces suggest, interestingly enough, that the universe should live in more than 4, possibly 10 or 11 dimensions. The contradiction with the observational evidence that D=4 is possibly solved by the idea of *compactification*: the spatial dimensions in addition to the known 3 are *invisible*, they are all very tiny and curled up, so small that we cannot tell the difference between being *here* or *there* in the extra dimensions, since the distance between *here* and *there* is too small to be measured with today's experiments.

The echo of void, 1935

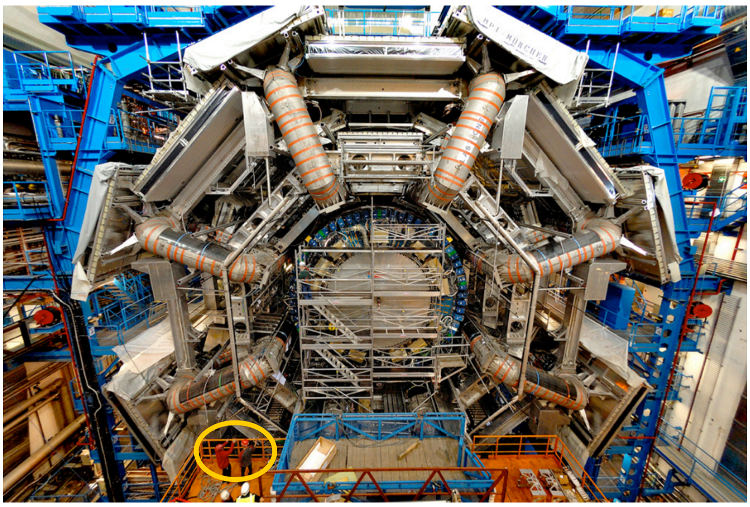
One other big question of modern physics is "what is the structure of vacuum?". What is there, where there appears to be nothing? Does the state of *absolute nothingness* exist in nature? Or, in Dalí's words, what's "the echo of void"?. We shall briefly discuss this in the next section.

The way forward

To start addressing the above questions, physicists are building better and better experiments. New telescopes, based on earth or on satellites, will acquire more precise data on the composition of the universe on cosmological scales. New particle accelerators will allow to seek deeper and deeper inside matter at the shortest distance scales. The next step in this direction will start in 2008, when the Large Hadron Collider (LHC), the largest accelerator of protons ever built, will begin providing data to 4 big experiments. The LHC is expected to provide the first evidence of the so-far invisible *Higgs boson*, the only remaining particle predicted by the Standard Model and yet unobserved. The Higgs boson is a key element of the Standard Model. It is supposed to permeate the universe, uniformly filling the *vacuum* (thus addressing the last question in the previous section). It is by interacting with a *vacuum filled with Higgs field* that particles acquire inertia and a mass. The continuous interactions with this medium prevent a particle from moving at the maximum speed, the speed of light, in the same way light itself is slowed down when it moves through a medium such as water or glass. To prove this theory – which so far has nevertheless received many indirect confirmations, like the theory of neutrinos was well verified even before neutrinos were directly observed – we need to stimulate and detect the vibrations of this *vacuum*. The difference between a *truly empty vacuum* and an *invisibly filled vacuum* – like the vacuum we predict to exist in our world – is that the latter can vibrate, can be stimulated in much the same way we can induce waves in the otherwise still air or water, or on the surface of a table, which we can set in vibration with a powerful punch. These vibrations of the Higgs *vacuum* are the particle that we call the *Higgs boson,* or simply *Higgs*. To induce them requires large amounts of energy (at least enough energy to satisfy Einstein's $E=mc^2$ relation, with m equals to the Higgs mass), well concentrated in space and time, and very heavy particles – since the strength of Higgs interactions grows with the mass of the particles it reacts with – to trigger the process. A possible way of doing it is to annihilate a pair of quark-antiquark from the third generation, which is the heaviest one, or to annihilate a pair of *W* bosons, the massive carriers of the weak force. Ex-

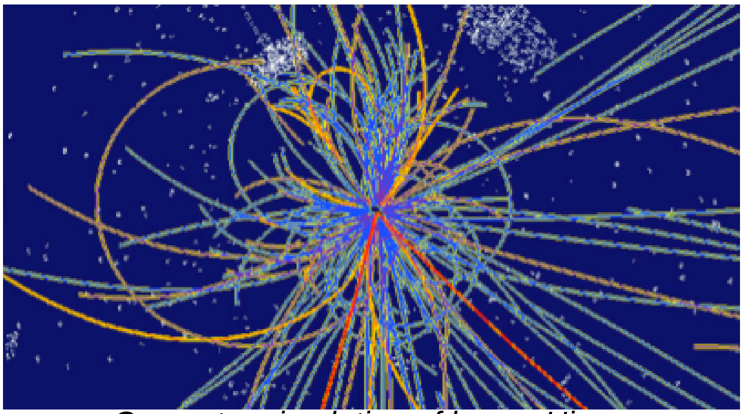


The layout of the 27 km LHC tunnel, 100 m underground at the Swiss-French border near Geneva.

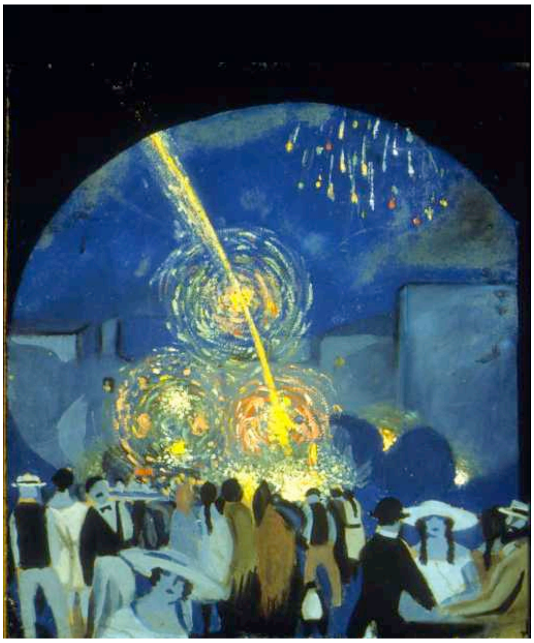


The ATLAS experiment under construction in the LHC tunnel. The two physicists inside the the yellow circle give an idea of the size of the apparatus, which extends over 40m in length and 20m in height

periments before the LHC failed to achieve the energy and the flux of heavy quarks or bosons sufficient to create a Higgs. The LHC was conceived and built to provide both, energy and intensity. We expect that it will take about 2–3 years to collect and analyse the LHC's data, before in some of the "artificial fireworks" that will be produced there, we can unveil the production of a Higgs, the "echo of void".



Computer simulation of how a Higgs event may appear at the LHC.



Els focs artificials, 1922

The second leading goal of the LHC is to uncover the nature of *dark matter*, namely of the invisible particle that appears to dominate the matter content of galaxies, and of the universe as a whole. The approach will be reminiscent of the observations that led to Pauli's 1930 discovery of the neutrino in ^{6}He decay. We expect that the LHC should be able to produce a new heavy particle, whose decay products will contain, in addition to normal visible particles, the particle that forms dark matter. It will be *visible* thanks to its *invisibility:* physicists will know it is there since they will observe that some energy is missing from the decay products. Independently of dark matter, several theoretical ideas introduced to describe possible extensions of the Standard Model – for example the so called *supersymmetric* theories – predict the existence of new particles having the precise properties expected of dark matter, and suggest that they could indeed be produced and observed at the LHC.

While the search for the Higgs and for dark matter represents a search for a *known invisibile*, namely particles that we know must exist even though they have not been seen as yet, the LHC is also open to explore the *unknown invisible*, possible new phenomena whose existence does not appear to be needed to understand what we see in the universe, but which could be hiding behind a corner, ready to reveal themselves. An example of this is the possible observation of a substructure inside quarks or electrons, indicating that they are not truly elementary, but are themselves composed of yet smaller particles. In the case of quarks, given that they are not visible, the concept that they could hide inside something yet more remote from us appears particularly odd, but it could turn out to be true! Another possibility is that as we explore the world at smaller and smaller distances, new extremely weak forces, similar to the weak force of radioactivity, could become apparent. Such expectation is not unjustified: all theories that aim to unify the known fundamental forces in a single unique interaction – the so-called *grand unification theories,* or *GUTs* – predict the existence of other forces in addition to those we know already, since it is only thanks to the existence of these extra forces that the large symmetry required to achieve grand unification can manifest itself.

Conclusions

Great progress has taken place recently in our understanding of the universe. We reached new depths in uncovering the secrets of many invisible aspects of nature. The discovery of new *invisibles*, as discussed with many examples above, has always been the starting point of major new revelations about nature, and a driving theme for physics, and for science in general. The invisible is what stands in between the known and the unknown, whether it's the dark matter than fills the universe, or the source of a lethal disease, whose consequence may be known, visible and tangible, but whose origin is yet undetectable. As such, the quest to make visible the invisible is the quest of civilization to fight the supernatural and acquire control over its own fate. As the Standard Model took modern physics to a new level of understanding, more questions appear on our horizon, which are waiting for an answer: what is the origin of dark matter? where has all the antimatter gone? why three families of elementary particles? are they elementary after all? are there new forces? why do we live in 4 dimensions? New experiments, and new ideas and theoretical insight, will drive this quest; exciting new progress will come, inspiring a future generation of artists, who will carry on Dalí's programme, as summarized in his 'Anti-matter manifesto': "It is with pi-mesons and the most gelatinous and indeterminate neutrinos that I want to paint the *beauty* of the angles and of reality.". Without forgetting that, however far we get, there will probably always be a new layer of unknown invisible in front of us, the invisible hand of nature that decided that, after all, there should be something instead of nothing.

Acknowledgements

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