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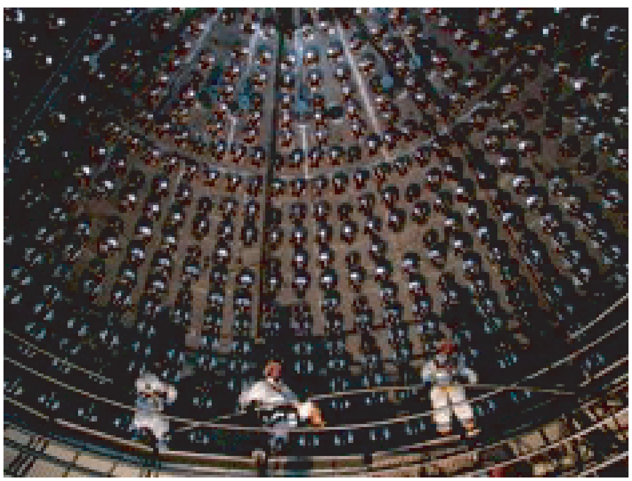
INVESTIGATING THE ENERGY OF THE UNIVERSE: THE GRAN SASSO NATIONAL LABORATORIES

When we imagine a large nuclear physics laboratory we might think of a place where energy is produced, like in a nuclear power plant, or of a place where more efficient ways of producing energy are studied. Or even a place, like a large particle accelerator, where elementary particles such as protons are brought to an energy corresponding to that prevailing at the birth of the Universe.

The Gran Sasso Laboratories are none of this. In the Laboratories electrical power is used to run the electronic devices of the experimental apparata. Energy is neither produced nor converted into particles (with a small exception that we will describe that later).



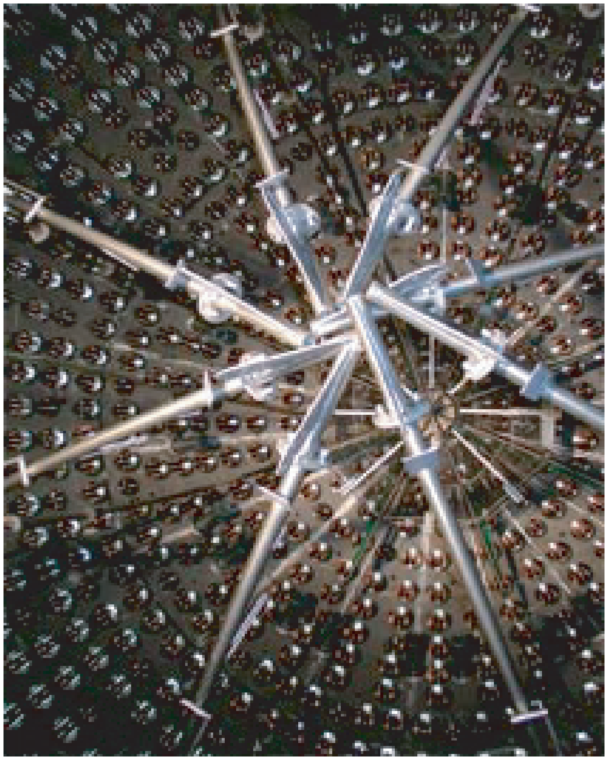
Inside of the BOREXINO experiment sphere — Photo> PAOLO LOMBARDI INFN-MI/ LNGS

It is now appropriate to give a very sketchy description of our Universe.

From a merely anthropic point of view, the Universe can be considered as a gigantic (in fact the biggest possible) machine producing energy, or, better, converting gravitational energy into all kinds of radiation, especially light and heat (that are indispensable for life).

This description of the Universe does not intend suggesting a causal connection: this is only what man thinks the Universe produces. It is fair to add, however, that even a Universe slightly different from this would make antropomorphic life very difficult. Let's now take a snapshot of the Universe when it was only a few hundred million years 'old' (its age is now estimated to be approximately 14 billion years). At that stage, the Universe contained matter (essentially hydrogen and helium with traces of some heavier elements) and possibly some form of exotic matter that nowadays is called 'dark'. There was also very little light: stars had not yet formed and only 'light' – or rather some form of invisible radiation - remained as an echo of the Big Bang which gave birth to the Cosmos. Matter has formed a tenuous gas 'almost' uniformly distributed.

This 'almost' is extremely important: if the gas filling the Universe had been completely uniform, it would have been extremely difficult for the present Universe to emerge. Being matter distribution not exactly uniform, gravitational force was stronger where matter concentrated. These concentrations of matter attracted more matter, that generated more gravity... and so on until "structures", (that is Galaxies and stars), were formed. Matter was no longer uniformly distributed but in clumps, more or less like in the present Universe.



Inside of the BOREXINO experiment sphere

Photo> PAOLO LOMBARDI INFN-MI/ LNGS

Let's now discuss what happens in a matter clamp before it becomes a star. At first, only gravity is acting: matter in its thicker region attracts more matter and becomes thicker, with a stronger gravity and so on. But with increasing density, gas atoms begin to scatter and their temperature increases. At this point, the transformation of gravitational energy into heat takes place. At the beginning of the past century this was thought to be the mechanism fuelling the Sun: a hot gas emits radiation, i.e. light. However, simple computations showed that this production of energy would have lasted much less than the age of the Sun (that is, at least, 5 billion years). There must be another energy process that makes the Sun shine.

Clearly, a different source of energy is acting and that is nuclear fusion. When the gravitational force is very strong and consequently gas density is high, collisions among atoms are extremely frequent: at first atoms lose their electrons, then nuclei themselves melt. For instance, 4 protons can merge and form a helium nucleus, made up of two protons and two neutrons. The neutrons are originated by the transmutation of the protons (with emission of an anti-electron and a "neutrino") and are 'lighter' (i.e. have smaller mass) than protons.

The mass difference is converted into energy, the same energy that makes our Sun and all stars shine. Actually, it is not so simple: turning from hydrogen nuclei into helium nuclei requires many intermediate steps, but the result is essentially the same, with a more copious neutrinos production.

That's where, the Gran Sasso Laboratories enter the story: neutrinos emitted by the Sun are very important to study the energy production processes of the Universe and, at the same time, neutrino properties. For instance, radiation generated by nuclear fusion has a large probability of interacting with the surrounding gas and it takes millions of years to emerge from the Sun in the form of light and heat. On the other hand, neutrinos have a very small collision probability and travel essentially undisturbed from the interior of the Sun towards us.

Clearly, a low collision probability implies that neutrinos are extremely difficult to observe: very large detectors are needed and they must be screened from all kinds of radiation that normally bombard the Earth. Large detectors need to be placed in an underground laboratory like the Gran Sasso. Indeed, the Gallex (later GNO) experiment has been the first to detect neutrinos produced by the main cycle of nuclear reactions producing energy in the Sun.

The results of more than 40 years of research world wide have shown that the internal behaviour of the Sun is well described by astrophysical theory, but neutrinos have an 'anomalous' behaviour and change 'identity' on their way and, consequently, their number seems to be reduced.

Several experiments are under construction at the Gran Sasso Laboratories to better study the behaviour of neutrinos: Borexino will use neutrinos produced by the Sun, while Opera and Icarus will detect those artificially produced in the SPS accelerator at CERN (Geneva) and 'sent' towards Gran Sasso where they will arrive after a 700 km underground journey. Other smaller and extremely precise experiments are functioning or are under construction. Not all the experiments in the Laboratories are "passive". A very small accelerator is also running. This accelerator (LUNA, for Laboratory for Underground Nuclear Astrophysics) is designed to study some of the reactions fuelling the stars. Some of these reactions have such a small probability to happen that they are completely lost in the natural radiation of the Earth and again the best way to study them is in an underground Laboratory. It is interesting to notice that the study of one of these reactions has changed our knowledge of the age of the Universe. Some stars part of the so-called 'globular clusters' have been found to be older than the estimated age of the Universe by around a billion years, because the nuclear reactions inside them are much slower than expected. Since they cannot be older than the Universe, it has been possible to date the age of the Universe more accurately.

Energy is crucial even in the death of stars. When some kinds of stars die, they emit energy, mostly in the form of neutrinos. This process is called SuperNova. In the explosion, a star becomes as bright as the Galaxy

that contains it, for a period of days or weeks.The latest SuperNova explosion took place in 1987, in a Galaxy close to ours, the Large Magellanic Cloud. Unfortunately, at that time, our laboratory was still under construction and no experiment was running yet.
However two experiments, in the USA and Japan, did detect a signal in the form of a bunch of neutrinos. The LVD (Large Volume Detector) experiment is now running in the Laboratory and it is precisely looking for the next SuperNova explosion.

Describing the process that gives birth to galaxies and stars, we refer to a kind of exotic matter called 'dark'. There are many hints that, together with matter it give rise to a process in which energy is produced. There exists a different kind of matter that produces gravitational energy but not other kinds of energy; from here the term 'dark'.

One of the most important indications of its existence is the quantity of matter in the Galaxies we now have in the Universe. More matter than the one we actually see today, would have been necessary for these galaxies to form in the time they had.
At the moment, there are only hypoteses on the nature of 'dark matter', but what is certain is that, if it exists, it is even more difficult to detect than neutrinos, since it has an even lower probability to interact with 'normal' matter.
Yet, several experiments in the world are dedicated to the identification of these weak signals and some of them are operational or under construction at Gran Sasso. In particular, the DAMA (DArk MAtter) experiment was giving some evidence of the detection of Dark Matter particles. Clearly this result, if confirmed, would provide fundamental information on the nature of the Universe.

The mysteries of the Cosmos do not stop here. For a few years, scientists have suspected that, there is an even more exotic component of the Universe.
This would be an associated form of energy present even in absence of normal or dark matter: we can describe the Universe as a battery that stores energy in its own structure.
This energy has been called 'dark' or even 'quintessence'. Essentially nothing is known of its origin. Einstein himself did predict its existence, but later called this prediction 'the biggest blunder' of his scientific life. In some particular conditions, this 'dark energy' can transmute and become 'normal' energy, i.e. radiation, much in the same way as a short-circuited battery generates a spark. It is now believed that such a 'spark' in the very first moments of life of the Universe generated what we now call the 'Big Bang'.

But essentially nothing is known about the future effects of 'dark energy'. Presently it seems that it produces a slight acceleration on the expansion of the Universe.

But, again, this is a different story and we will know more in future years or decades...