....your key to

enter the

Kingdom of

Plasma

THOR - THEORY OF ULTRA RELATIVISTIC HEAVY ION COLLISIONS

As the name suggests, our network is a project to pursue theoretical studies related to experiments in which ions collide at very high energies. An ion, in case you were wondering, is the name given to an atom which has been stripped bare of its attendant electrons to leave just a tiny nucleus bearing a large positive electric charge. Why should we want to smash ions together, and what we do hope to learn? Well, by smashing things we hope to see what's inside. But smashing ions is both expensive and difficult: to start with, we need a good motivation, and then we need good methods to analyze what we find. Theoretical studies provide both, motivation and method. Many steps have been made, many are still missing. It is indeed a long story... and there are two ways to tell it.

The first: let us start from here and now, in our universe. We know that the ions are made from more elementary building blocks of matter: Quarks. These do exist, we believe, but we never see them! Quarks come in two different forms, called 'up', and 'down'. They make up the protons and neutrons (familiar components of the atomic nuclei), and also particles called mesons (less common, but real objects nevertheless). These are all examples of a family of particles known as 'hadrons'. Three quarks are needed to make a proton or a neutron. A proton has two ups and one down, a neutron one up and two downs. A meson is formed from a quark paired with an antiquark (antiparticles have the same mass as the corresponding particles, but the opposite electric charge).

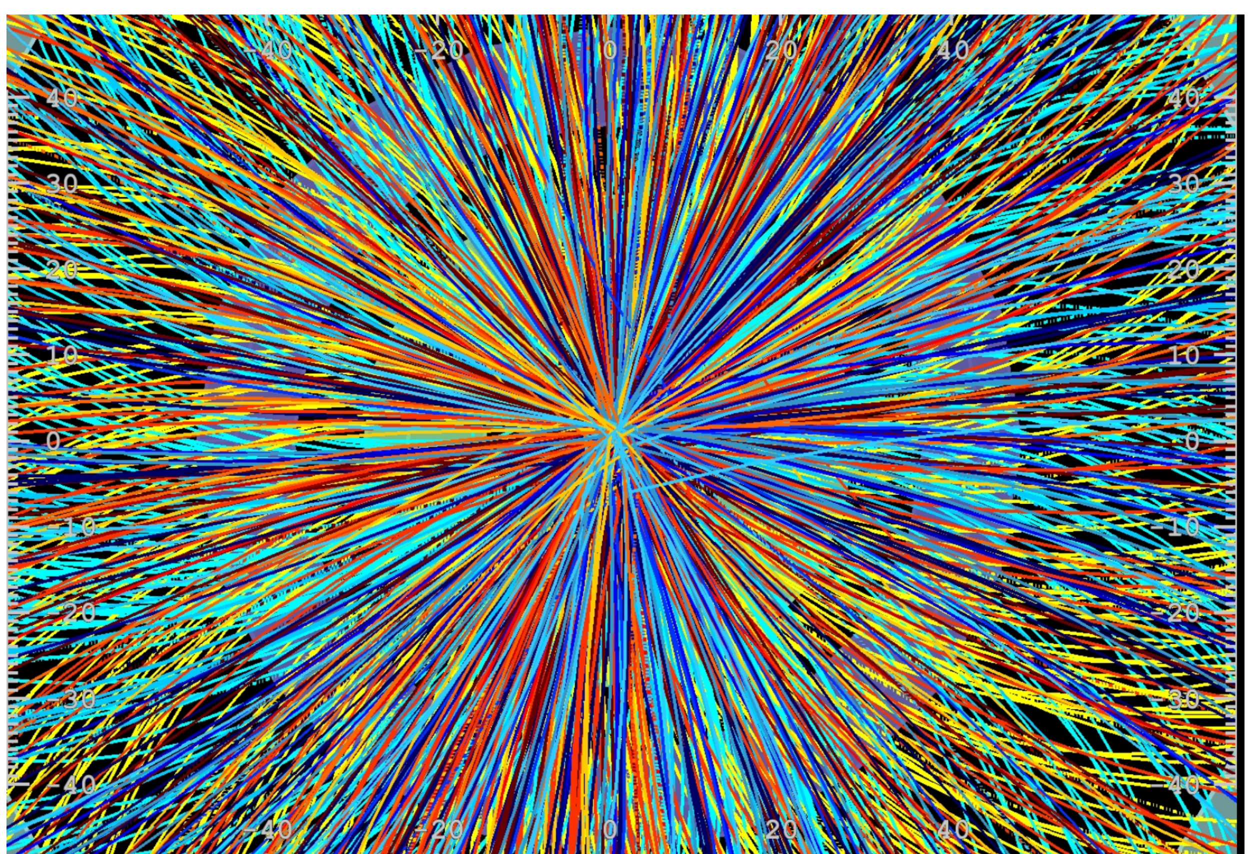
Can we see quarks? Interestingly, the answer is no! Although it's perfectly possible to smash up a proton, a neutron or a meson, the quarks which were inside, instead of becoming free, immediately recombine to form other protons, neutrons, and mesons. In short, quarks do exist, but we have never yet managed to see one in isolation. This property is called *confinement* - we picture the quarks as being connected by a force field which adopts a shape like a sticky strand of glue; the energy grows as the glue tube stretches so the quarks can never get far apart but a rigorous theoretical demonstration is still missing. Indeed, finding such a proof is one of the biggest challenges in theoretical physics!

Despite the lack of a formal proof, confinement is very well verified in experiments: free quarks have been repeatedly searched for, but so far have NEVER been found! Confinement is also nicknamed ‘infrared slavery’: here “infrared” is a technical term indicating long distance (borrowed from the light with the longest wavelength, which is red). Quarks are ‘slaves’ in this sense since however far they are pulled apart they can never be free.

Now… about fifty years ago two physicists called Nicola Cabibbo and Giorgio Parisi wrote an article: *Exponential hadronic spectrum and Quark Liberation*. How is that possible? The main point of their paper was that quarks *can* be free, but only in another, hotter version of our world, which lies in a different ‘phase’. The notion of phases is actually familiar in our everyday experience, and can be explored in the nearest kitchen: ice and steam have very different properties, one being a rigid solid, the other an airy vapour, yet the elementary components of each are the very same H_2O molecules. We regard ice, steam and indeed liquid water as different phases of the same substance, each stable under differing conditions of temperature and pressure.

Similarly, the particle world can also have different phases, comprising the same elementary components, but having vastly different properties. Different phases are separated by a phase transition, which for quarks occurs at an incredibly high temperature, around a trillion degrees: this is why we have not seen free quarks. We live in an 'icy' world on the cold side of the transition, where quarks are confined. On the other side is a phase known as 'quark gluon plasma'. At such enormous temperatures our world would 'melt' and quarks set free into the plasma. . . at least at first sight! But things are not quite that simple; even if the protons and neutrons do fall apart, their component quarks will not become completely free. . . they will remain 'strongly interacting'!! Disappointing news for those who wanted to be free?? Not really. . . in this new phase extremely interesting phenomena are expected. . . for instance, many scientists believe the plasma will resemble a liquid, but a very special, mobile one, which flows almost without effort. Supposing you wanted your quarks still more free... in that case, the temperature would need to be much, much higher, approaching the limits of our current knowledge.

Can we ever observe these amazing phenomena? Well, fortunately, it's not so easy... because if this transition were to happen on a large scale everything in our world would vanish!! But the new phase is indeed realized in the experiments, for example at the LHC particle accelerator at CERN: by colliding ions (which remember are heavy nuclei composed of many protons and neutrons) at close to the speed of light, experimentalists manage to produce the very high temperatures needed to jump through the transition into the other phase.



One lead-ion collision recorded at the LHC by the ALICE experiment

We have learned that the quarks become ‘free’ but remain strongly interacting. Their brief excursion into the plasma phase lasts only a tiny fraction of a second; as soon as the quarks get far from the collision region, they cool down, reenter the influence of our confining world, and become trapped again inside protons, neutrons and mesons. It may sound ‘fantascientific’, but panels of scientists in Europe and in the US were set up to analyze the dangers of such experiments: suppose a tiny number of freed quarks somehow encouraged all the others to deconfine as well? That would mean the end of the universe as we know it. Robust calculations have ruled out this possibility, and indeed we are still here to tell the story! In our world, therefore, we can redeem the quarks from their slavery, but only with extremely complicated and expensive experiments, in which the quarks are set free for just a short time, before finding themselves once more confined within hadrons and nuclei. . .

This is the first way to tell the story... starting from our world of today. There is another: from the Big Bang...

At the very beginning of time, billions of years ago, the universe was a blob of material at an unimaginably high temperature and density. As time has passed, the universe has expanded and cooled down, and during this cooling process may well have passed through one or more 'cosmological' phase transitions. As a result of the transformations occurring while traversing each successive phase, the material world as we know now it has ultimately emerged.

Many of these transitions are still mysterious: in order to understand them better we need to know more about physics beyond our current understanding encapsulated in the 'Standard Model'. The only transition that we can really study and reproduce in a lab is the most recent one: that is, precisely the one from the quark gluon plasma to the confining world of today just discussed.

In the history of the Universe, the transition reproduced in current laboratory experiments first took place spontaneously, a very long time ago: the quarks, initially free at very high temperatures, first started to feel a pull between them, which grew stronger as they cooled, before eventually plunging through the last cosmological phase transition to emerge into what has become our Universe ...forever confined...

[At this point, we cannot resist saying that during this transition another very important thing happened: beforehand the quarks were very light, with indeed practically no mass... while afterwards, they magically became heavy - but that is a story for another time...]

But now back to THOR: if you have read this far we encourage you to browse our other outreach pages where you will find answers to many other questions and discussions.

Now - we want to play a little more with the name THOR we have chosen for our project network, and invite you to enjoy the graphic novel prepared by Simone Gabrielli of the Scuola Romana del Fumetto, with the assistance of Margherita Tomaselli. Throughout the story you can find some of the elements of the physics of ultrarelativistic heavy ion collisions that we have sketched here! We hope you enjoy it!

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