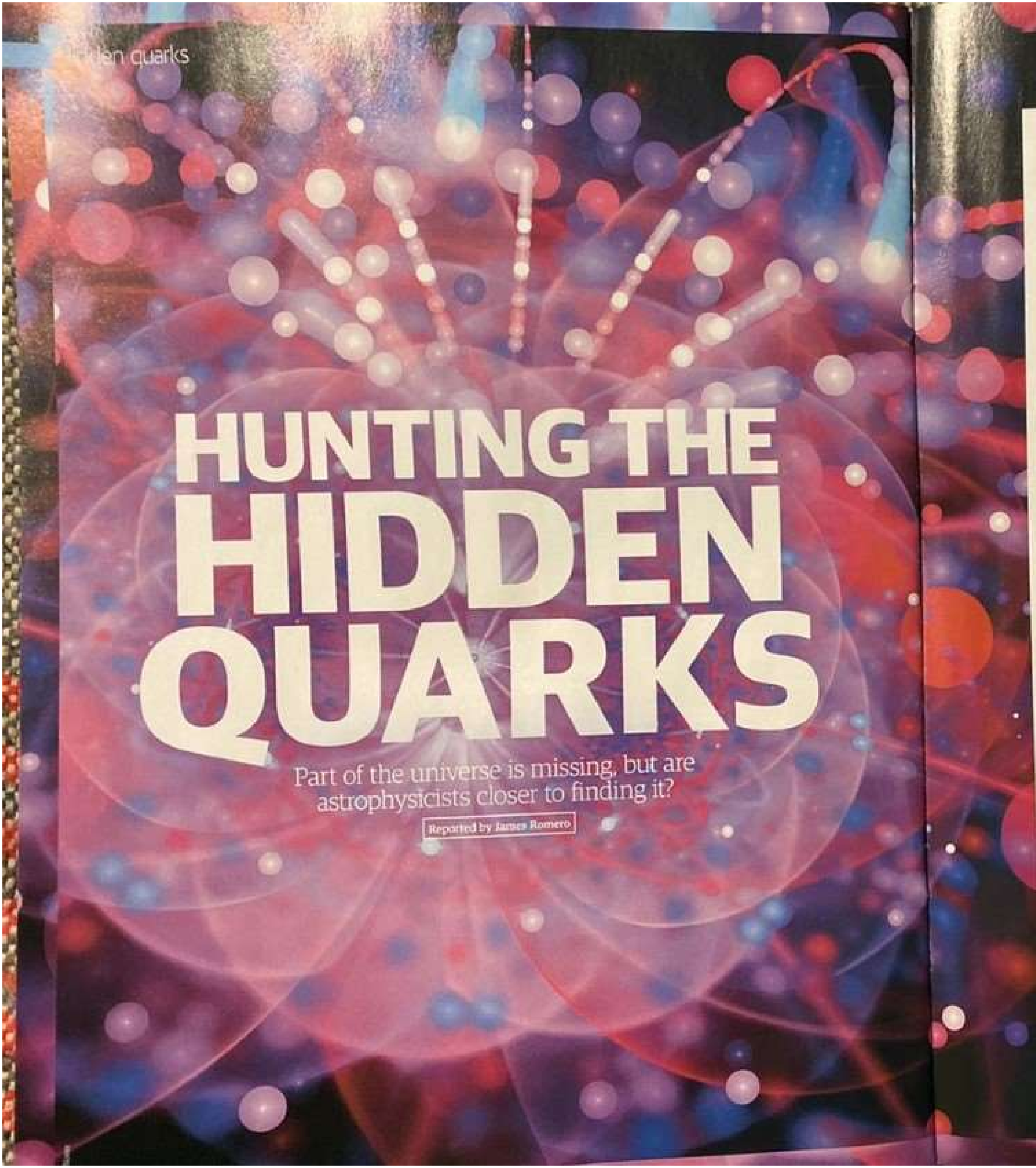


HUNTING THE HIDDEN QUARKS

Part of the universe is missing, but are astrophysicists closer to finding it?

Reported by James Romero

"These objects now form the basis for our physical understanding of the universe," read the California Institute of Technology press notice issued in May 2019. It was released to mark the passing of the man who had given the world the fundamental building blocks of nature. Murray Gell-Mann named his discovery the 'quark', though discovery is probably the wrong word. The quark was only proposed back in 1964 to provide a tidy solution to a messy situation particle physics had found itself in.

At this time many new particles of different sizes and charges were being discovered in various small accelerators around the world. There was little sense of how many more scientists might find, and how the members of this growing family related to each other. Gell-Mann, along with George Zweig, provided a pleasing answer. Their independently derived theory challenged the proton and neutron's fundamental building-block status inside the atom. Instead they showed how they, and many other particles, were actually different combinations of the same underlying particle.

In the half a century that has passed since, theoretical physicists have elaborated on this initial proposal, giving the quark a host of properties and characteristics. In modern physics textbooks quarks are governed by quantum chromodynamics (QCD), a quantum field theory which describes the 'strong interaction' between them as force mediated by force-carrier particles called gluons.

We know quarks come in six different types, or flavours, named up, down, strange, charm, bottom and top. They also have a property called spin that gives them a form of angular momentum, like a quantum spinning top, and a charge, described as a variety of colours. And like all particles or quantum entities they behave as waves as well as particles. However, despite all this progress, for experimental physicists the quark remains a more elusive customer. Hiding among its own, scientists have been unable to separate one and investigate it in isolation.

The 50-year story of the quark has allowed us to understand what makes up the stuff of the cosmos, describe and predict new particles and journey back to the origin of all matter, just after the Big Bang. It's also a story which may enter a new chapter following recent theories that individual quarks could finally be found out there in the cosmos, or even produced here on Earth, giving experimentalists their own moment of discovery.

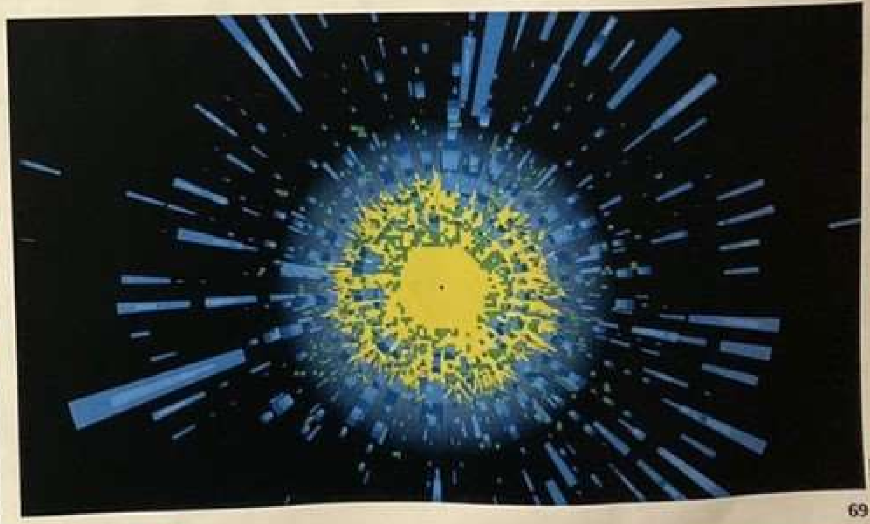
Despite a lack of direct observation, the first supporting evidence for the quark came only a few years after Gell-Mann's original proposal. Experiments at the Stanford Linear Accelerator Center in the late-1960s fired electrons at protons and observed they were bouncing off at weird angles. It suggested they were being deflected by something inside. This support for quark theory didn't explain why certain combinations of quarks produced particles, but others didn't. For example, while three quarks formed baryons like protons and neutrons, and pairs of quarks formed particles called mesons, individual quarks were not allowed.

This aversion to singledom was explained by the theory of confinement, which suggested that in order to achieve so-called confinement between two quarks within a hadron – any particle made up of quarks – ever-increasing amounts of energy are required. Eventually this energy becomes so great

Above: Gell-Mann's quark showed that protons, neutrons and other particles were actually combinations of the same underlying particle

Below: One of the first-ever xenon-xenon collision events was recorded by CERN's CMS experiment in 2017

"We know quarks come in six types, or flavours, named up, down, strange, charm, bottom and top"



What is a quark?

They make up all matter

Quarks are elementary particles that form the components of the atomic nucleus' protons and neutrons. They are therefore building blocks of all ordinary matter in the universe.

They are ruled by gluons

Quarks are governed by quantum chromodynamics (QCD), a theory that describes the 'strong interaction' between individual quarks through a force-carrier particle called the gluon.

They come in different flavours

We know quarks come in six different types, or flavours: up, down, strange, charm, bottom and top.

They behave like a quantum spinning top

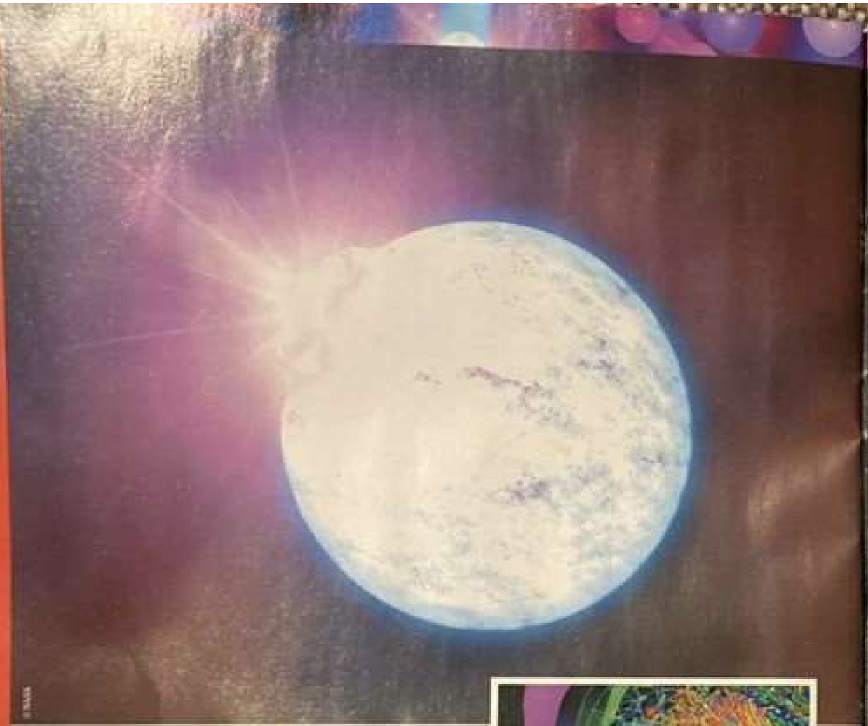
Quarks have another property called spin that gives them a form of angular momentum, like a quantum spinning top.

They don't like their own company

While combinations of three quarks form hadrons, and pairs form mesons, the theory of confinement makes it seemingly impossible for quarks to appear on their own.

Except for the largest

The top quark was the most massive elementary particle when discovered in 1995 at Fermilab. Its size means it decays before it can form a hadron particle, thus providing fleeting evidence of an isolated quark.



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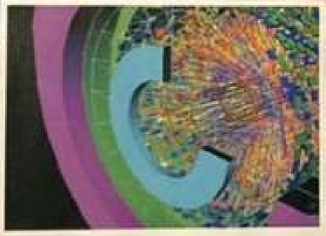


Above: Could the signals from neutron stars contain evidence of deconfined quarks sitting on exotic domain walls inside?

Right: A computer rendering of quark-gluon plasma producing collisions between beams of gold ions at the Relativistic Heavy Ion Collider

that it spontaneously produces a quark-antiquark pair, turning the initial hadron into a pair of hadrons instead of producing an isolated quark. Because of this property, some took issue with the quark's label as a fundamental building block of matter. "If it's always inside something else, should we really think about it as an elementary particle?" jokes Zohar Komargodski of the Weizmann Institute of Science in Israel, quoting the naysayers.

If isolation isn't possible, what about direct measurement of the individual contribution of a quark to the properties of the particles they make up? Here again there were challenges. Protons are made up of three quarks: two up and one down. As a result the proton's charge of plus one adds up nicely, with two up quarks contributing plus two thirds each, and one down contributing minus one-third. However, using angular momentum mathematics to explain the proton's spin of a half proved more difficult. In fact, experiments in the 1980s that smashed high-energy particles into the proton showed the three quarks contributed only around 30 per cent to the proton's spin.

A clue to the answer may come from an oversimplification in the statement 'the proton is made out of three quarks'. In fact, there is a probability for more quarks inside the proton, not to mention the potential contribution of the gluons. "Inside the proton is a soup that potentially has many other particles," says Komargodski, who is not particularly worried by this spin discrepancy, often referred to as a 'crisis'. "The proton spin crisis is not a real thing. It's just an experimental question. The theory is well understood and everything works."

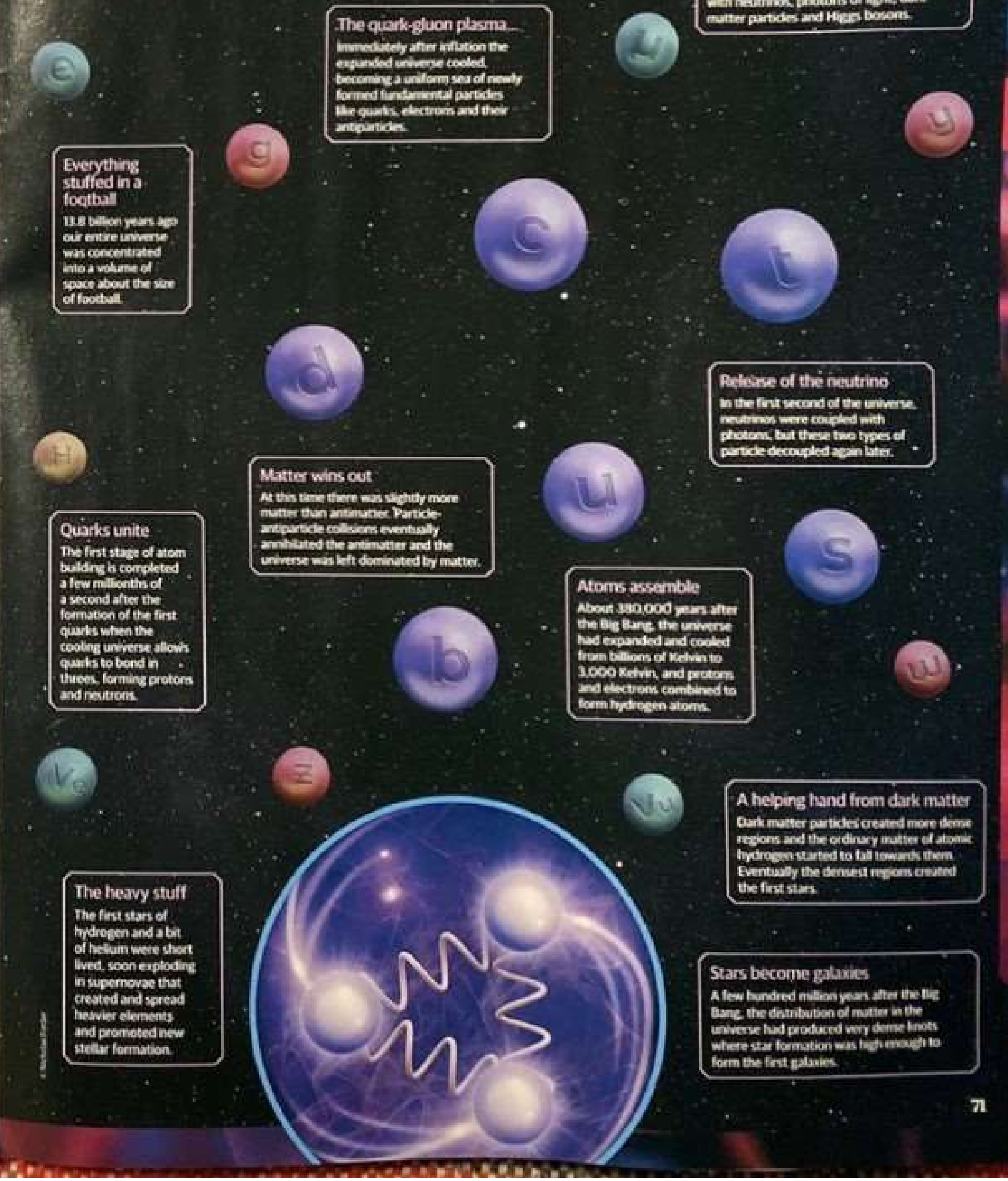
While Komargodski is happy to move on, confinement theory holds true, keeping our elementary building blocks bundled up inside baryon and meson cloaks. As a result, advances in our understanding of physics on this scale is left reliant on indirect measure and theoretical mathematics, akin to the study of black holes. "We don't measure quarks; we make inferences, and sometimes the calculations are off, but then we figure out how to correct those mistakes," says Nobuo Sato, a nuclear theorist at the Jefferson Lab National Accelerator Facility in the US.

Though quark deconfinement remains elusive, we do have indirect evidence of one particular quark existing fleetingly in isolation. The top quark was the most massive of all elementary particles when it was discovered in 1995 at Fermilab. Its size means it decays too quickly to form a hadron particle, so the top quark isn't really a fundamental building block of matter. However, evidence of its

> "We don't measure quarks, we make inferences, and sometimes the calculations are off" **Nobuo Sato**

The history of the universe in particles

As the cosmos cooled after the Big Bang, elementary particles began to form and combine into the stuff of space-time



Everything stuffed in a football

13.8 billion years ago our entire universe was concentrated into a volume of space about the size of football.

The quark-gluon plasma...

Immediately after inflation the expanded universe cooled, becoming a uniform sea of newly formed fundamental particles like quarks, electrons and their antiparticles.

...with a few extra ingredients

Alongside these components of the atom, the so-called 'Quark Epoch' was also filled with neutrinos, photons of light, dark matter particles and Higgs bosons.

Release of the neutrino

In the first second of the universe, neutrinos were coupled with photons, but these two types of particle decoupled again later.

Matter wins out

At this time there was slightly more matter than antimatter. Particle-antiparticle collisions eventually annihilated the antimatter and the universe was left dominated by matter.

Quarks unite

The first stage of atom building is completed a few millionths of a second after the formation of the first quarks when the cooling universe allows quarks to bond in threes, forming protons and neutrons.

Atoms assemble

About 380,000 years after the Big Bang, the universe had expanded and cooled from billions of Kelvin to 3,000 Kelvin, and protons and electrons combined to form hydrogen atoms.

A helping hand from dark matter

Dark matter particles created more dense regions and the ordinary matter of atomic hydrogen started to fall towards them. Eventually the densest regions created the first stars.

The heavy stuff

The first stars of hydrogen and a bit of helium were short lived, soon exploding in supernovae that created and spread heavier elements and promoted new stellar formation.

Stars become galaxies

A few hundred million years after the Big Bang, the distribution of matter in the universe had produced very dense knots where star formation was high enough to form the first galaxies.

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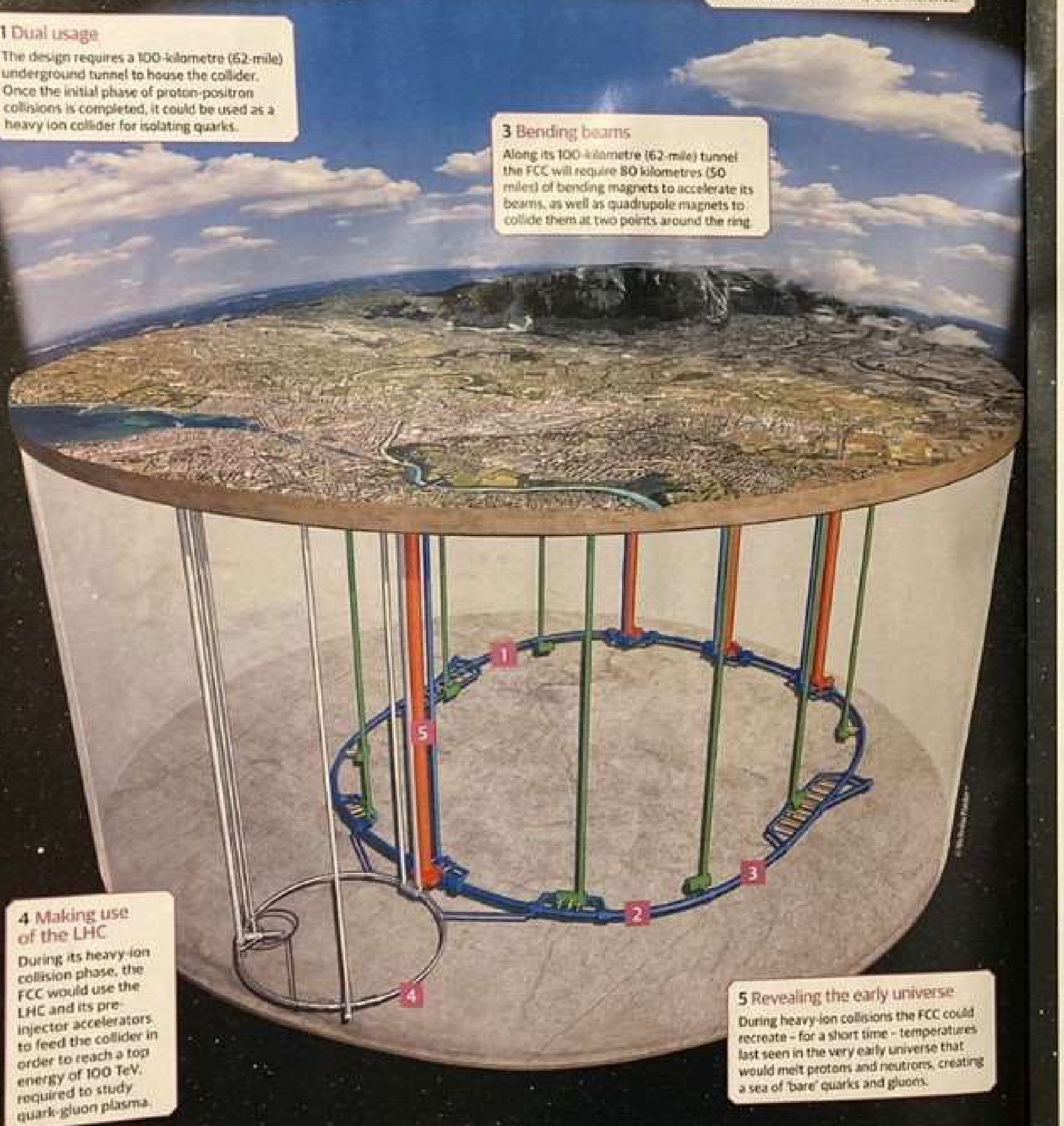
The Future Circular Collider

Proposals for a replacement to the Large Hadron Collider could achieve temperatures to probe the quark-filled early universe



1 Dual usage

The design requires a 100-kilometre (62-mile) underground tunnel to house the collider. Once the initial phase of proton-positron collisions is completed, it could be used as a heavy ion collider for isolating quarks.

2 Smoothing the path

One advantage of the longer tunnel is that it will let thin beams of particles travel around without having to navigate curves that are quite as tight as at the LHC, with its 27-kilometre (16.8-mile) circumference.

3 Bending beams

Along its 100-kilometre (62-mile) tunnel the FCC will require 80 kilometres (50 miles) of bending magnets to accelerate its beams, as well as quadrupole magnets to collide them at two points around the ring.

4 Making use of the LHC

During its heavy-ion collision phase, the FCC would use the LHC and its pre-injector accelerators to feed the collider in order to reach a top energy of 100 TeV, required to study quark-gluon plasma.

5 Revealing the early universe

During heavy-ion collisions the FCC could recreate – for a short time – temperatures last seen in the very early universe that would melt protons and neutrons, creating a sea of 'bare' quarks and gluons.

fleeting existence as an elementary singleton can be observed. "We can't literally see a top quark, just the aftermath of its decay," says Tara Shears of the University of Liverpool. "But if we can trace and identify the particles it has decayed to, we can reconstruct that top quark and study its behaviour."

While the top quark is unable to form hadrons, what we can learn about it from indirect observation, combined with our exploration of its more compatible cousins through QCD modelling, is providing useful. Lattice QCD is a theoretical framework which uses a four-dimensional grid of points to represent the three dimensions of space and one of time. Based on our broader understanding of quarks, it has proven enormously successful in predicting the masses of many hadrons. "The fact that lattice QCD can provide a simulation whereby, just starting from quarks and gluons, you can describe all the spectrum of hadrons, that's a success," says Sato.

As these QCD models continue to deliver experimentally testable predictions, the appetite for the deconfined hadron quark could have waned. However, in the 2000s interest in another object from QCD, called a domain wall, put it back on the agenda. Domain walls are not three-dimensional particles, but two-dimensional surfaces. And, critically, they only cost a finite amount of energy to create.

QCD mathematics suggests that if you place your proton or neutron on a domain wall, its constituent quarks deconfine. Even more interestingly, physicists like Shigehiro Yasui at Keio University in Tokyo are discussing whether they might exist in nature, inside neutron stars. Could the signals astronomers regularly receive from neutron stars contain evidence of deconfined quarks sitting on exotic domain walls inside? "It's hard to say. It's something that people are thinking about," says Komargodski.

In the meantime, another possibility for deconfining quarks has arisen. In 2011 Nu Xu of the Lawrence Berkeley National Laboratory showed hadrons melt at temperatures around 2 trillion degrees. The result is a soup of deconfined elementary particles called a quark-gluon plasma. One way to achieve such temperatures is to go back in time. The universe in the microseconds after the Big Bang was an intensely hot, energetic liquid of fundamental particles. As it cooled, hadrons and then atoms began to form.

While astronomers cannot peer back this far, there is another less exotic place where scientists can explore this early fleeting phase of matter. In Long Island, New York, the Relativistic Heavy Ion Collider (RHIC) is smashing together large ions, like gold, at near light speed, generating temperatures 250,000-times hotter than within the Sun's core.

As we await attempts to reach such temperatures here on Earth, the case for a universe of matter built on QCD-described quarks is strong, even if we're unable to isolate the protagonists. However, anyone arguing for quarks' place on the bottom rung of the elementary particle ladder will have challengers from proponents of another famous theory.

In string theory, everything has internal structure because everything is made out of strings. And while there is no evidence for internal quark structure as yet, Komargodski doesn't rule anything out, especially with proposals for the Future Circular Collider (FCC) providing a powerful subatomic microscope to replace the Large Hadron Collider (LHC). "It's like in the 1940s. People did not know that the proton had any internal structure because their microscopes were not strong enough."

While some are seeking answers to fundamental questions inside the quark, many more mysteries remain at the larger scale of individual quark interactions. Sato's team is looking at how quarks and gluons create the emergent phenomenon we measure in protons and neutrons. "The validity of QCD is backed up by its predictive power. However, that doesn't mean that we actually understand how these strong interactions create what we are ultimately made of," he says.

But even these larger scale questions present epic technological challenges. If you were trying to scale up an experiment so individual quarks and gluons are the size of the Earth, the smallest scale detector we can build would need to be located outside the Milky Way. "Imagine someone outside the galaxy trying to measure the light from Earth and figuring out what's going on. This is more or less what we want to do inside the nucleus in terms of quarks and gluons," says Sato.

For half a century the science of quarks has emerged, evolved and matured. Now it is beginning to offer answers to the origin and fundamental make-up of everything in the universe, and all without us having directly observed a solitary building block. "To me, the simplest and most unifying feature is not seeing and studying a single quark. It is understanding the underlying law of nature that gives rise to this behaviour. And that's really satisfying," says Shears. "It doesn't matter that I don't have an up quark signal in my experiment – that's not the way the world works."

Above: The SLAC National Accelerator Laboratory in Stanford has played a fundamental role in the discovery of quarks

Below: The RHIC collider aims to recreate conditions in the universe moments after the Big Bang

How we might isolate the quark

Our hopes of isolating a quark are dependent on particle accelerators like the Relativistic Heavy Ion Collider, smashing together large ions at near light speed. Alternatively we could search for them in nature within the cosmic microwave background formed in the early universe, or in the centre of modern neutron stars.