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HERE'S WHAT HAPPENS AT THE END OF THE UNIVERSE

Science Focus

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ELECTRIC AEROPLANES?

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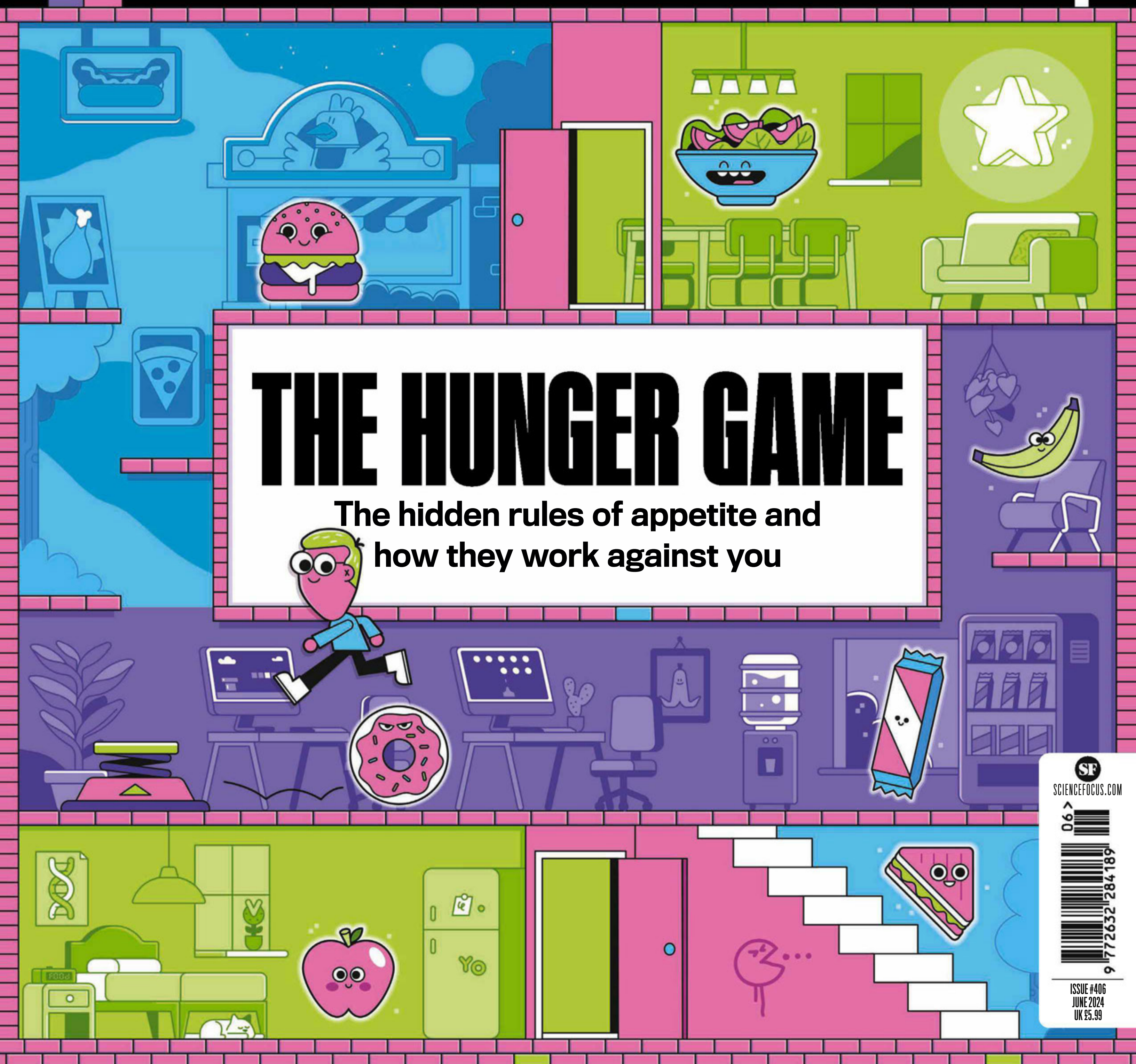
HACK YOUR MOTIVATION



THE HUNGER GAME

The hidden rules of appetite and how they work against you

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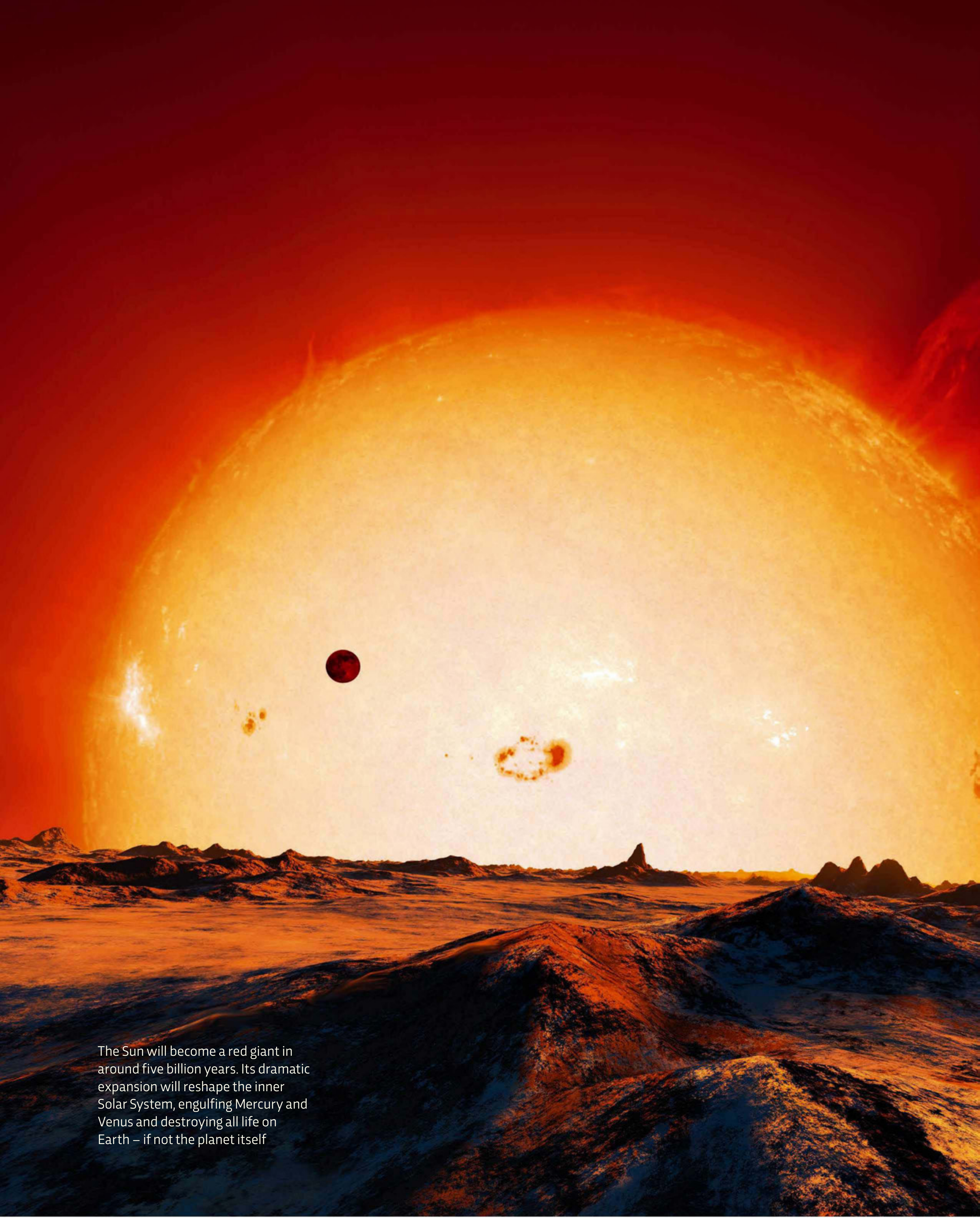

The Sun will become a red giant in around five billion years. Its dramatic expansion will reshape the inner Solar System, engulfing Mercury and Venus and destroying all life on Earth – if not the planet itself

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HOW THE UNIVERSE WILL END

A colossal supercollider now in the early stages of development may one day help us predict the ultimate fate of the Universe. With it, scientists will be trying to find a hidden instability built into the fabric of existence… an instability that could destroy everything

by DR ALASTAIR GUNN

Most cultures have stories and myths detailing the end of days, from the eventual fate of humans to what will happen to our world and any other realms inhabited by their respective deities. These legends often promise the arrival of a reorganised existence after the cataclysm, a paradise.

But what does modern science have to say about the end of days – or to put it in more scientific terms, the end of the Universe?

We know that Earth, if it's not destroyed by us or an errant asteroid first, will likely be incinerated when the Sun expands into a red giant. Luckily, that's not likely to happen for at least another five billion years.

As for the Universe as a whole, do we have any understanding of when and how it will come to an end?

We can look to modern cosmology for some intriguing possible answers. And with the European Organisation for Nuclear Research, aka CERN, currently developing the Future Circular Collider (FCC) – a gargantuan 'atom smasher' almost three times bigger than the Large Hadron Collider (LHC) – we're one step closer to knowing which one is likely to be right.

FREEZE, CRUNCH OR RIP

In exploring the various theories, it all comes down to the balance between the expansion of the Universe and the pull of gravity. In one scenario, gravity may not be strong enough to stop the Universe from expanding, meaning it'll continue to do so forever.

As all the energy eventually becomes uniformly distributed, the Universe will become darker and colder. Even black holes will evaporate as the Universe becomes a near-vacuum of subatomic particles and photons, an endless and timeless void where nothing ever happens. This is called the 'Big Freeze' (or, conversely, 'Heat Death').

But, according to a second theory, if gravity is strong enough to overcome expansion then the Universe will one day start to contract again. Eventually, it'll collapse in on itself to eventually become a compact fireball, before vanishing into the 'singularity' from which it came. The 'Big Crunch', as it's called, will swallow all matter and energy, as well as space and time.

To determine which of these possibilities will happen, astronomers need to know the expansion rate of the Universe (and how it changes over time), as well as its total matter and energy →

→ content. This amounts to knowing the 'shape' of the Universe, which can be found with the cosmic microwave background, the relic afterglow of the Big Bang. As sound waves moved through the early Universe, there were small variations in temperature, and the size of these hot and cold spots depended on the geometry of space. It's something akin to taking a vast trigonometry measurement across the entire cosmos. The results show that the Universe is almost certainly 'flat', meaning that its density is just sufficient to halt the expansion after an infinite time.

A third theory concerns the mysteries of 'dark energy.' Astronomers have found that the expansion of the Universe is actually accelerating due to dark energy, and if this acceleration continues the expansion will overcome all the forces of nature. The result will be the 'Big Rip.' All matter, and space-time itself, will be ripped apart and destroyed. Estimates say this could happen in about 22 billion years.

INSIDE THE GOD PARTICLE

Yet, there's another, and more ominous, way that the Universe may end. This is called the 'Big Slurp' and its likelihood depends not on the vastness of the Universe, but on one of its tiniest components: the Higgs boson.

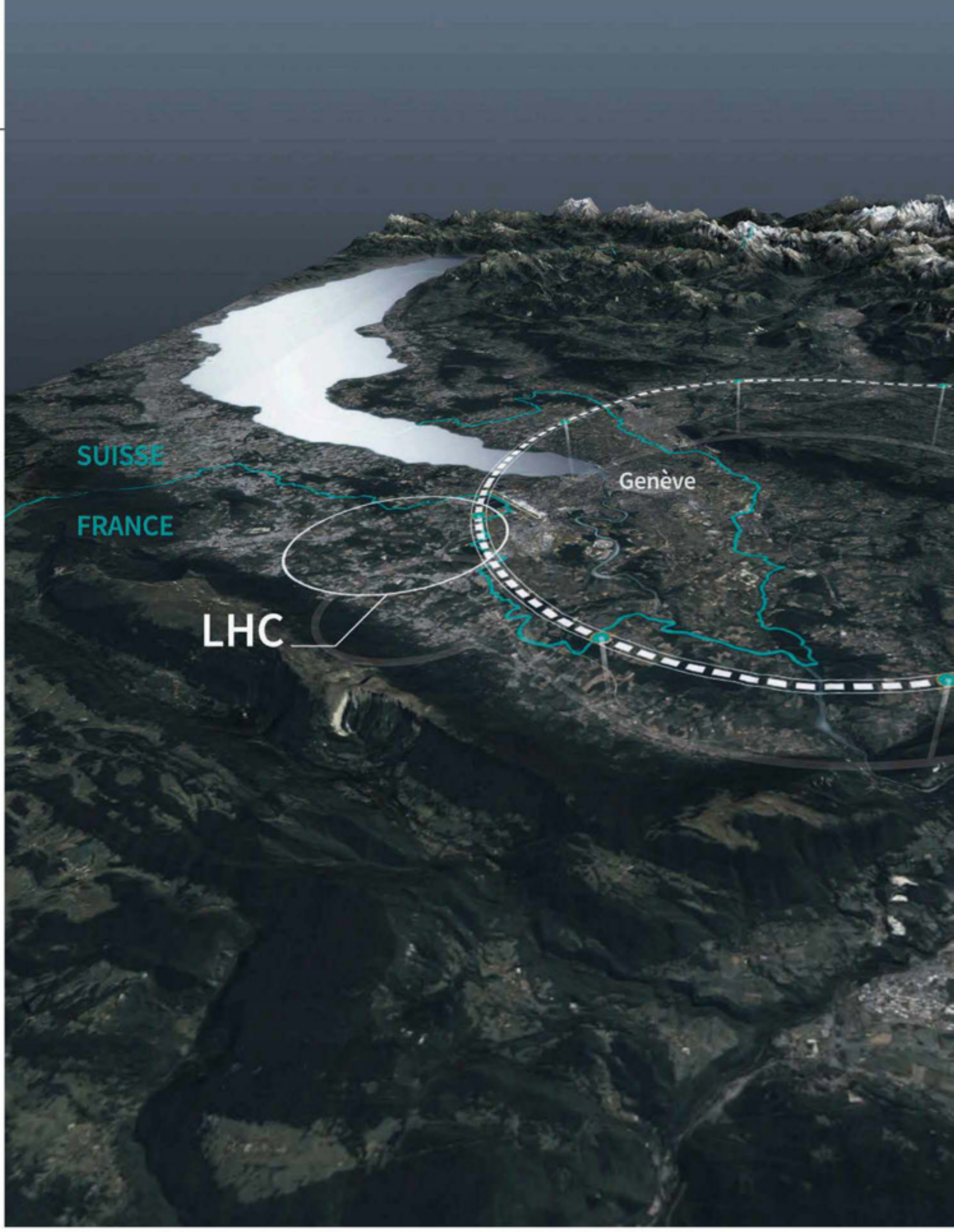
To understand the 'Big Slurp', we need to enter the quantum world. Quantum theory shows that all particles in the Universe are local excitations, or fluctuations, of quantum fields. Each of the 12 known matter particles has its own quantum field, and there are also fields for the four fundamental forces of nature (namely: gravity, electromagnetism, the strong nuclear force and the weak nuclear force). So, for example, photons (light particles) are fluctuations of the electromagnetic field.

The Higgs boson – termed the 'God particle' because it's the reason that matter has mass – is the particle associated with the Higgs field. All elementary particles (except photons and gluons) are endowed with mass by their interactions with the Higgs field. Solid objects, including you, are only solid objects because of it.

First postulated by the physicist Prof Peter Higgs and his colleagues in 1964, the Higgs boson was discovered in July 2012 by scientists at CERN's current atom-smasher, the LHC. The particle they found weighed 125.1 gigaelectron volts (GeV), which is about 133 times heavier than the proton. It was a scientific breakthrough that gave new credence to our theories of the Universe.

"Colliders are the most powerful microscopes we have to study nature at the smallest scales and during the early moments of the Universe," says Prof Christophe Grojean, a leading physicist at the Deutsches Elektronen-Synchrotron (DESY) research centre in Germany, who specialises in the Higgs boson. "The properties of particles and forces, in the quantum world, have determined how the Universe at large has evolved."

But soon after its discovery, scientists found a worrying problem with the Higgs boson: the particle's mass appears to be perilously close to giving it an inherent instability. An instability that just might be the thing that spells the end of the Universe.

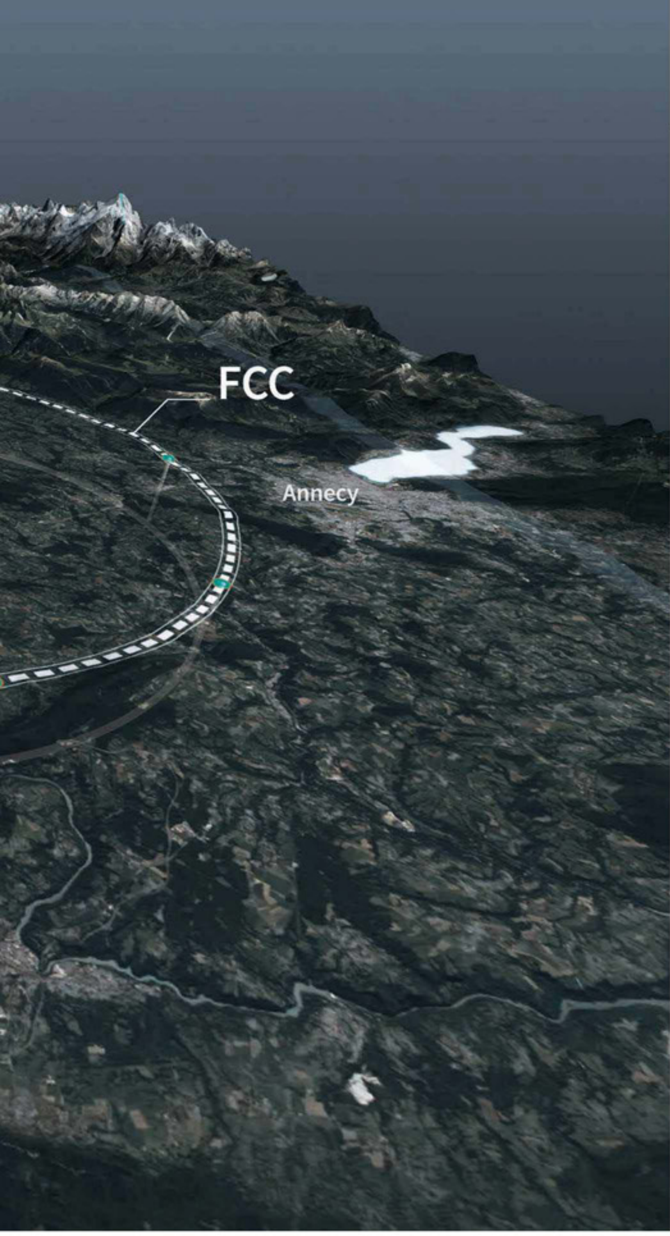


ABOVE A schematic map from CERN shows the potential location of the Future Circular Collider, which will dwarf the Large Hadron Collider

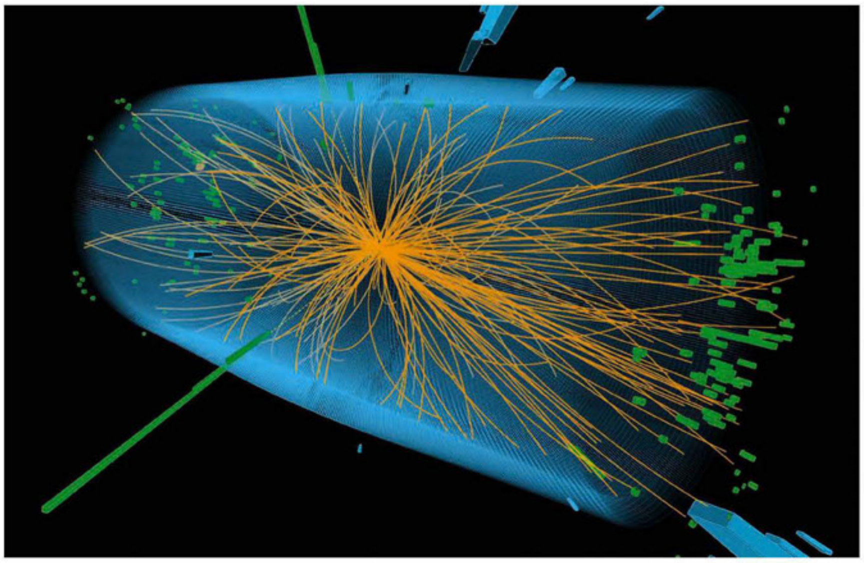
LIVING IN A FALSE VACUUM

It turns out that the Higgs field always has some value associated with it, even when no Higgs particles are present. There's a background, non-zero 'vacuum energy.' Physics requires that the vacuum energy sits at a minimum in the absence of particles, but the trouble is that there isn't a single minimum in the energy of the Higgs field.

Imagine a ball rolling into a valley and, on the way, it gets trapped in a gully. While the ball may be stable in the gully, it hasn't attained its minimum energy by reaching the valley floor.



"THE HIGGS BOSON'S MASS APPEARS TO BE PERILOUSLY CLOSE TO GIVING IT AN INHERENT INSTABILITY"



ABOVE A representation of the results of particle collisions inside the Large Hadron Collider. This image was released in 2015, after CERN scientists got their most accurate measurement of the mass of the Higgs boson to date

FCC STUDY AT CERN X2

The Higgs field can be trapped in just such an energy gully, rather than the lowest-possible energy state. Physicists refer to this as a 'metastable' state and describe the resulting background energy as a 'false vacuum.'

At the very moment of the Big Bang, the Universe was so hot and dense that the Higgs field didn't operate. It was zero everywhere and no particles had mass. Then, almost instantaneously, the Higgs field flipped on, giving matter its substance and starting the processes we see governing nature today, allowing us – and everything else – to exist.

The question is whether the Higgs field flipped into its lowest energy state or was trapped in a metastable state. Our best measurements to date suggest the latter, implying that we're living in a Universe with a false vacuum.

That raises a further question: what if the Higgs field suddenly flipped to a lower energy state? "The Higgs field sets the size of atoms, ensures the proton is lighter than the neutron and guarantees the stability of matter," says Grojean. "So, a vacuum decay would be bad news for the Universe."

There would be completely different constants of nature, where physics, chemistry and biology would work in totally different ways, if at all. The Universe would collapse into an entirely new state, destroying and recreating itself in a puff of energy. What that new Universe might look like we have no way of telling and, of course, we wouldn't be around to find out. This is the fate that would befall us in the Big Slurp.

A vacuum decay could be triggered with enough energy concentrated in a small enough volume. But calculations suggest there's no known process for achieving this. "The decay rate could have been much faster in the early Universe", says Prof John Ellis of King's College London and a veteran of the CERN Department of Theoretical Physics. "So, it's a puzzle that the vacuum didn't decay a long time ago."

There's one last twist, however. The Higgs field is subject to the rules of quantum physics and there's a process, called 'tunnelling', which allows the Higgs field to jump spontaneously to a different energy state. It's as if that ball trapped in the gully simply tunnels right through the ground to escape. →

→ While quantum tunnelling can't be predicted because it's a random process, we can calculate the probability of it happening. Thankfully, it turns out to be extremely unlikely, occurring perhaps once in 10^{100} years (1 followed by 100 zeroes). The age of the Universe pales into insignificance in the face of those odds.

Does that mean we're safe after all? Well, just because something happens rarely, doesn't mean it can't happen. Needless to say, physicists would like to find out whether the Higgs field is indeed in a metastable state and, hence, what the eventual fate of the Universe may be.

LOOK TO THE FUTURE

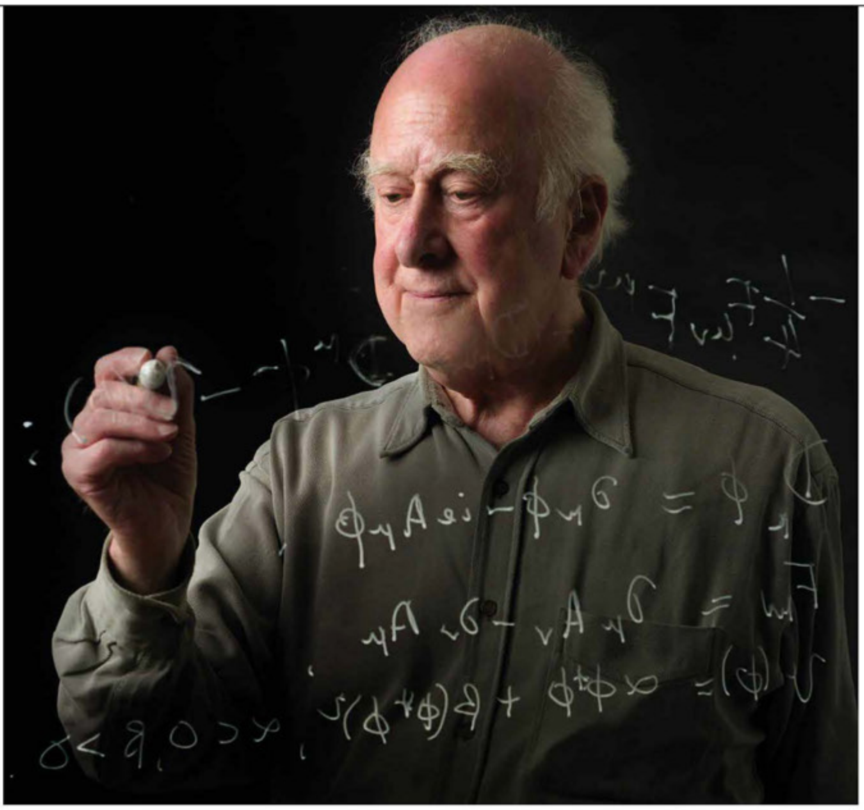
To get to the root of this problem, scientists need to measure, with sufficient accuracy, the Higgs mass, the top quark mass and the 'strong coupling constant.' The latter describes the strength of the strong nuclear force, which holds atomic nuclei (and quarks) together. These values determine the shape of the Higgs' energy valley.

Experiments at the LHC have determined the mass of the Higgs boson with a precision of about 0.1 per cent. The mass of the top quark is known to an accuracy of almost 0.2 per cent, while the strong coupling constant is known to better than one per cent. But for a full investigation, scientists require an order of magnitude improvement in the sensitivity and resolution of the atom smasher. This is where the FCC comes in.

CERN hopes the FCC, which will be the largest and most powerful supercollider ever built, will take over from the LHC in the quest to understand the quantum world. Like its predecessor, the FCC will generate head-on collisions between particles. Two particle beams will be sent in opposite directions through ultra-high-vacuum rings, accelerated to almost the speed of light by strong superconducting electromagnets. The beams then collide in one of the detector instruments, creating a cascade of other particles that are measured and analysed.

The FCC will occupy a new circular tunnel with a 90km (56-mile) circumference and span the French-Swiss border at an average depth of 200m (650ft). Eight surface sites will allow four instruments to tap into the swarm of high-speed particles that are accelerated around the ring. When the FCC starts colliding particles – which will be, if all goes to plan, in the mid-2040s – the tunnel will house an electron-positron collider. A second instrument, a hadron-hadron collider, will be installed in the same tunnel by the 2070s.

Since energy and mass are related through Albert Einstein's famous $E = mc^2$ formula, the more energy the collider particles have, the higher the mass of the collision 'products.' Many of the problems in modern particle physics involve heavy particles (such as the Higgs boson), so physicists are keen to build bigger and more powerful colliders.



ABOVE British theoretical physicist Prof Peter Higgs won the Nobel Prize for his work on the particle that bears his name, which was first observed in 2012

> "A REORGANISATION OF THE UNIVERSE MAY ALREADY BE TRAVELLING OUT FROM THE SITE OF THE COLLAPSE"

The current maximum collision energy of the LHC is around 13.6 teraelectron volts (TeV). The second incarnation of the FCC (hadron-hadron) will have a maximum collision energy of about 100 TeV. Despite this, there's no danger the FCC will trigger a vacuum decay, as its energy is a mere billionth of what would be required.

"Probing the vacuum instability hypothesis isn't among the key drivers of the FCC," says Grojean, who is directly involved in the development of the instrument. "But it will improve our knowledge of the intimate structure of matter and help decipher the nature of space-time at the smallest scales."

With all the unknowns around the Higgs field – some scientists believe there must be some error in our calculations and that it isn't in a metastable state at all, while others believe there must be undiscovered physics that would remove the instability – the FCC is our best bet for resolving them.

DEATH BY BUBBLE

So, while work continues to develop the FCC, we are left with the question: what would actually happen if the Higgs field did suddenly change and cause a vacuum decay? "Physics and cosmology would be completely different, making life impossible. The Universe would collapse upon itself. All objects in the Universe would cease to exist," warns Prof Ellis.

Theory shows that a bubble would form, inside of which the existing laws of nature have collapsed and new ones formed. Matter and energy have transformed or disappeared. The fundamental forces of nature are different, or no longer exist. The bubble expands, racing through the Universe at the speed of light, destroying everything in its path.

And there's always the possibility that, somewhere in the Universe, such a cataclysmic vacuum decay may already have happened. A reorganisation of the Universe may already be travelling out from the site of the collapse. We're just waiting for it to arrive and we wouldn't see it coming.

In his classic 1978 sci-fi comedy *The Hitchhiker's Guide to the Galaxy*, the author Douglas Adams wrote: "There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened." It seems Adams could well have been right, on both counts.

Terrifying as that might sound, though, there's really no need to lose any sleep over a potentially imminent vacuum decay of the Universe. At least, that's based on the time frame put forward by Ellis.

"Spontaneous vacuum decay would occur far in the future, long after the dying Sun eats up the Earth."

Nevertheless, it would be nice to know whether the Universe is in a stable or metastable state. Hopefully, by the time we reach the halfway point of this century, the FCC will be able to provide some clues. **SF**

ABOVE Technicians work on improving the Large Hadron Collider's hardware during one of its shutdowns in between experimental runs

CERN X2

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