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Physics

Rethinking reality: Is the entire universe a single quantum object?

In the face of new evidence, physicists are starting to view the cosmos not as made up of disparate layers, but as a quantum whole linked by entanglement

By Heinrich Päs

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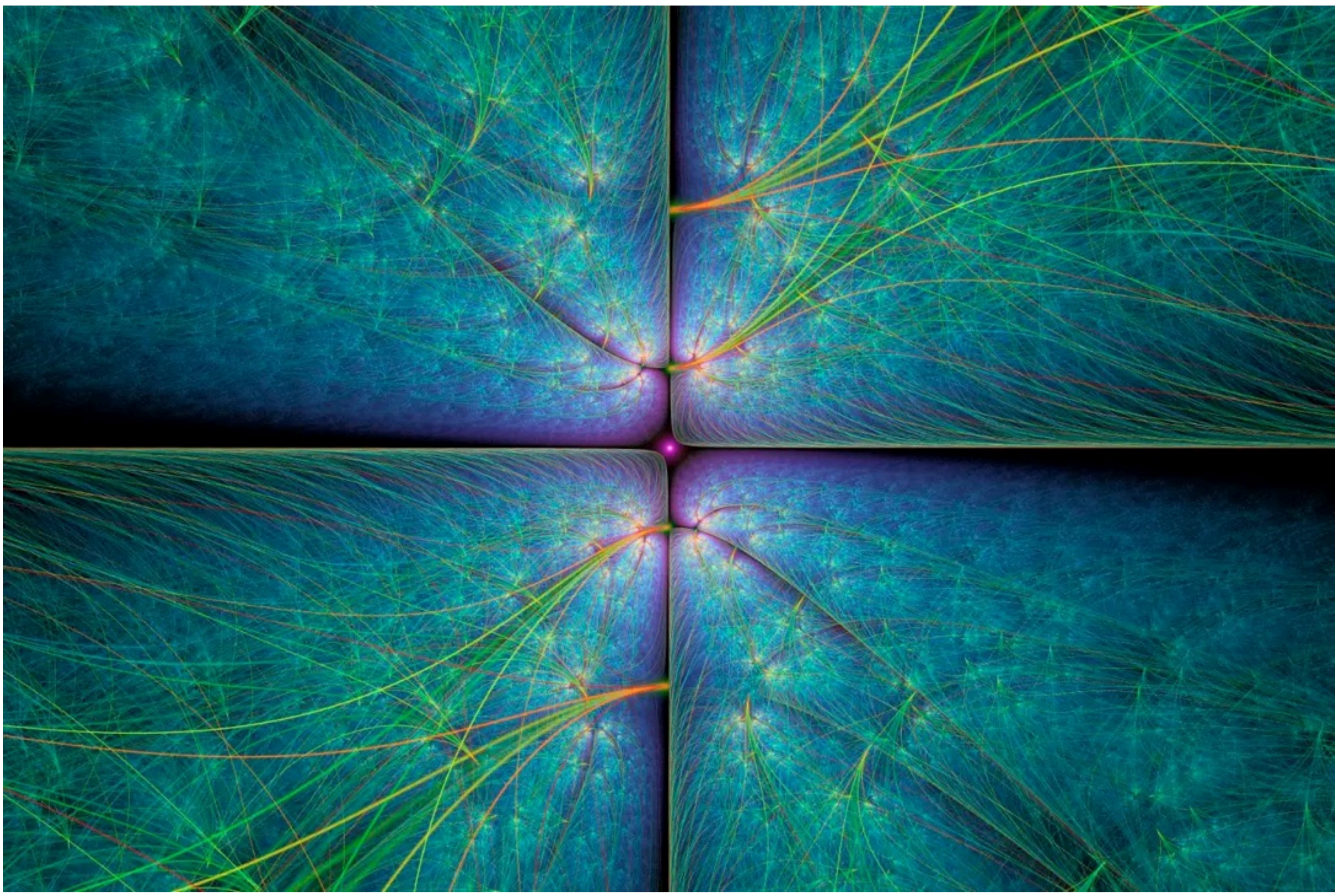

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IMAGINE you could see through everyday objects to the stuff they are made of. If you zoomed in on the arm of a chair, say, you would see that it is made of atoms. Zoom in again and you would see that those atoms contain subatomic particles called protons

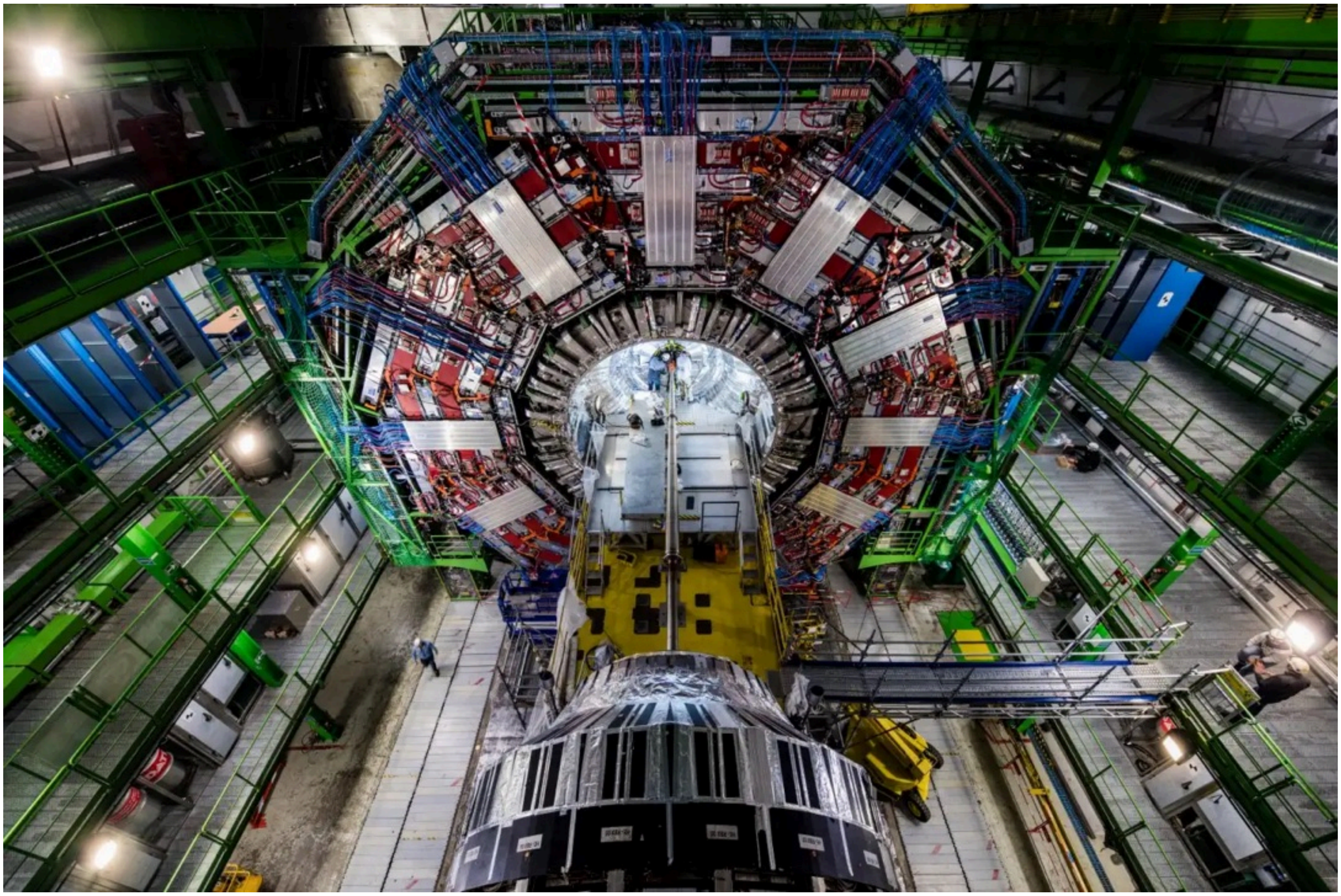
/article/2335724-protons-inside-some-types-of-hydrogen-and-helium-are-behaving-weirdly/, neutrons and electrons. Zooming further still, you would see that the protons and neutrons are composed of quarks 🔗 /article/mg24332500-900-what-the-quark-why-matters-most-basic-building-blocks-may-not-exist/.

These are the layers of reality, and this is how physicists understand the universe: by breaking everything down into its constituent parts, an approach known as reductionism 🔗 /article/mg25433880-300-a-rethink-of-cause-and-effect-could-help-when-things-get-complicated/. As a particle physicist, I grew up on this philosophy. It has brought physics a long way – it is how we built our current picture of matter and its workings, after all. But now, with further progress stalling, I am convinced we need to go about things differently from here.

Rather than zooming ever further inwards, I think we need to zoom out. In doing so, we may see that everything there is, including such seemingly fundamental things as space and time, fragment out of a unified whole. This might sound like philosophy or mysticism, but it is in fact a direct result of applying quantum mechanics to the entire cosmos. When you do that, you realise that the universe isn't fundamentally made of separate parts at all, but is instead a single, quantum object.

It is a radical idea, and one we are just beginning to test experimentally. But if it is correct, it could help solve some of the most puzzling mysteries in physics and upend the way we think about the universe.

For almost a century, physicists attempting to understand the most fundamental layers of reality have been inadvertently describing systems without knowing what is going on inside them. In the 1930s, when Enrico Fermi worked out how a neutron decays into a proton and spits out an electron 🔗 https://arxiv.org/abs/1803.07147 – known as beta decay – he did so only by considering the electrons, protons and neutrons involved. Only decades later, when physicists discovered an intermediary particle called the W boson 🔗 /article/2315418-particle-physics-could-be-rewritten-after-shock-w-boson-measurement/, did they realise there was a deeper layer of interactions playing out at tinier scales.



▲ **The dearth of discoveries at the LHC has caused a crisis**
Brice, Maximilien/Cern

From today's perspective, Fermi's description is the prime example of an effective field theory 🔗 https://arxiv.org/abs/hep-th/0701053 (EFT), a mathematical framework that allows us to divide reality into different size scales and analyse them separately. In this way, physics behaves like a set of Russian Matryoshka dolls, where you can understand the outer doll without knowing anything about the dolls inside.

Effective field theory

An EFT is the name given to any work that exploits this idea. Whenever physicists want to describe effects beyond an established but incomplete theory, without specifying what the new physics is, they use EFTs. "Everything is an EFT," says Cliff Burgess 🔗 https://physics.mcmaster.ca/~cburgess/cburgess/, a physicist at McMaster University in Hamilton, Canada, who has written a book about the approach.

Crucial to EFTs is the concept that the different size scales of the universe correspond to different energies. At the largest distances are the lowest energies, while the tiniest parts of reality are associated with the highest energies. Fermi didn't have a particle accelerator like the Large Hadron Collider (LHC) 🔗 /article-topic/large-hadron-collider/, so he couldn't reach the high energies needed to reveal the smaller-scale reality of the W boson.

Fermi's description works well for nuclear physics 🔗 /definition/strong-nuclear-force/, though, and was an approximation of an even better, more fundamental theory: the standard model of particle physics, our best picture of matter and its workings. Now we know that the standard model is also incomplete, since it doesn't include gravity, a particle for the universe's enigmatic dark matter 🔗 /definition/dark-matter/ or a mechanism to generate the perplexing masses of subatomic particles called neutrinos. When this became clear, physicists realised that the standard model itself was also an EFT.

For all the convenience they provide, EFTs might be obscuring a truer understanding of the universe. This is because they introduce problems. One that particle theorists have been worried about for years involves the Higgs boson, the particle responsible for giving mass to quarks and electrons. In theories like the standard model 🔗 /definition/quantum-field-theory/, particles can temporarily change into short-lived particles, known as virtual particles, only to quickly decay back into the original particle. In a quirk of quantum mechanics, the rules that govern the world of particles, these fluctuations contribute to a particle's mass. The extent of this contribution depends on the highest energy the virtual particles may have.

Importantly, working out the contributions to a particle's mass depends on the boundaries of energy within which the standard model applies – or the size of the Russian doll. As far as we know, the upper energy threshold is the Planck scale, the smallest scale there is and the point at which gravitational effects become important and the standard model must be replaced by something that unites gravity and quantum mechanics. According to this idea, the mass of the Higgs boson is expected be determined by the Planck scale. But the prediction is 17 orders of magnitude larger than the actual mass we measured when the particle was eventually discovered at the LHC.

The only way around this conundrum is to accept that totally unrelated contributions to the Higgs mass from fleeting virtual particles just so happen to almost completely cancel each other out. This makes the conditions we see in our universe as unlikely as a pencil balancing on its tip. It is known as the fine-tuning problem.

To make sense of the universe, physicists divide reality up much like a Russian doll
Sefa Karacan/Anadolu Agency/Getty Images

A similar puzzle crops up in cosmology, too. This one involves dark energy /definition/dark-energy/, the mysterious force that propels the accelerated expansion of the universe. The expansion is thought to be caused by the energy stored in the vacuum of space. But here, our observed reality differs even more from prediction: the value of the vacuum energy we measure is some 30 orders of magnitude too small /article/mg25533992-700-5-mind-bending-numbers-that-could-reveal-the-secrets-of-the-universe/.

Particle physics in crisis

There have been some attempts to solve these two puzzles. An approach known as supersymmetry, for example, predicts new particles that cancel the quantum fluctuations produced by standard model particles. An alternative solution involves additional dimensions of space-time https://arxiv.org/abs/hep-ph/9803315. This idea – proposed by Nima Arkani-Hamed https://www.ias.edu/sns/arkani, now at the Institute for Advanced Study in Princeton, New Jersey, and his colleagues – says that gravity may leak out into these extra dimensions, making it look weaker than it actually is. Models based on this idea predict a lower Planck scale, meaning a smaller Higgs mass. The extra dimensions are invisible since they are curled up so tightly that they have escaped experimental detection so far.

Both supersymmetry and the extra dimensions idea predicted the discovery of new physics at the LHC, in the form of either new supersymmetric particles or excitations in quantum fields that would run around the curled-up dimensions. So far, however, the LHC has found the Higgs boson and nothing else. The possible solutions to the fine-tuning problem have become increasingly fine-tuned themselves, because the LHC keeps ruling out hiding places.

In short, particle physics is in crisis 🔗 https://arxiv.org/abs/1710.07663. This is why a small group of theorists, including me, has recently started to explore another, radical approach – one that proposes an alternative to reductionism as we know it. Instead of treating the different energy scales of the universe separately, it treats them as if they all have some bearing on each other.

To understand how this works, consider an analogy used by physicists that invokes the boundaries where the colours of a rainbow become invisible. At the highest energies, and therefore lowest sizes, beyond the violet colour in a rainbow is what we call the ultraviolet (UV). At the lowest energies and largest sizes, you have what we call the infrared (IR). In between the two, in the visible part of the rainbow, is the realm in which the standard model works.

It has been generally accepted for a while that the model stops working at the infinitesimal sizes and high energies of the Planck scale. This is what we call the UV region, where the effects of quantum gravity would kick in. But in the late 1990s, Andrew Cohen 🔗 https://www.bu.edu/physics/profile/andrew-cohen/ at Boston University in Massachusetts, along with David Kaplan 🔗 https://physics-astronomy.jhu.edu/directory/david-kaplan/ and Ann Nelson 🔗 https://en.wikipedia.org/wiki/Ann_Nelson, then at the University of Washington in Seattle, wondered if there was also a limit at the very large distances, or low energies, that we call the infrared.

While studying black holes, Cohen and his colleagues calculated that there is a maximum length 🔗 https://arxiv.org/abs/hep-th/9803132, or minimum energy, at which the standard model stops being valid. Beyond it, gravity takes over. It might seem intuitive that if there is a lower limit, there must also be an upper one. But crucially the researchers found that these seemingly unrelated cutoffs aren't independent of each other. In other words, the physics at these vastly different energy scales seems to be related – a phenomenon dubbed UV/IR mixing.

The calculations didn't suggest any concrete values for the low-energy cutoff. So Cohen and his collaborators tried out the largest scale they could think of: the radius of the observable universe. In a further fascinating twist, the corresponding UV cutoff to this IR cutoff turned out to be exactly the tiny energy value of the universe's dark energy – not the Planck scale, after all. If the virtual particles contributing to dark energy abide by this limit, that could explain why these effects don't drive dark energy to ridiculously large values.

For a long time, no one took much notice of this result. Most people had their sights set on supersymmetry and its ability to resolve the problem of the Higgs particle. But recently the crisis in physics has become more apparent, as many potential solutions to the fine-tuning problem have fallen away. As a result, the insights of Cohen and his colleagues have been receiving a huge amount of interest from theorists like myself. I started to wonder: if UV/IR mixing might help to solve the dark energy problem, could it also assist with the second major problem in fundamental physics, namely the unbearable lightness of the Higgs?

To answer this question, Tom Kephart at Vanderbilt University 🔗 https://www.vanderbilt.edu/AnS/physics/cv/kephart.htm in Tennessee and I first attempted to work out what the IR cutoff might be for the Higgs boson based on the limited lifetime of the particle. We determined a UV cutoff that is 11 orders of magnitude below the Planck scale. It is better than what we had, and yet still a million times too large for the Higgs mass we see. Adding extra dimensions could resolve the problem entirely.

Over recent years, theorists like me have tried several other ways to solve the Higgs problem using variations of UV/IR mixing – each coming from various angles. Some, like ours, take their inspiration from Cohen and his colleagues' work on black holes. Others were born in string theory, which suggests everything is made of unbelievably tiny strings. None of the attempts so far is supported by experimental evidence, but they may get us a step in the right direction. A few of them even point to one fundamental property of underlying reality that could be causing this mixing to happen, with big implications for how we see the universe.

Quantum entanglement

Quantum entanglement 🔗 /article/dn20711-how-to-make-quantum-entanglement-last/ is usually described as a startling correlation between quantum objects. Prepare two particles in a particular way and a measurement of one immediately fixes the other, regardless of the distance between them. But these correlations can be thought of as proof of the fact that entangled quantum systems can't be understood as being made out of parts: they are one and the same. Just as this indivisibility links faraway particles, it also can link quantum effects at different energies. In other words, quantum entanglement could be responsible for the UV and the IR scales of the universe seemingly talking to each other.

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As we proceed up the size scale and down in energy, the effects of lower energies could be broken by a process called decoherence. This well-understood quantum phenomenon hides entanglement from the eye of a local observer. It is the reason why we experience no quantum weirdness in our daily lives.

Some work has found a relationship between entanglement and UV/IR mixing, but the bounds in Cohen and his colleagues' study were caused by gravity rather than entanglement. Excitingly, recent work by leading researchers in string theory offers a solution: by suggesting gravity itself may be entanglement in disguise.

It is a bold idea, but I suspect entanglement causes UV/IR mixing. If so, there are huge implications for understanding reality at its most fundamental. If entanglement can be applied to the entire cosmos, then instead of everything being made of smaller and smaller pieces, it would turn the universe into "a single, indivisible unit", in the words of quantum pioneer David Bohm. All objects in existence would be encoded in a universal wave function, a mathematical entity that describes a single, entangled state.

Soon, we may know if this matches up with reality. Cohen and his collaborators suggested UV/IR mixing would affect the interaction of electrons or subatomic particles called muons with electromagnetic fields, showing up as a mismatch between the standard model's predictions and measurements. And the phenomenon may crop up in other processes, too. One example my colleagues and I are currently exploring 🔗 https://arxiv.org/abs/2306.15313 relates to neutrino masses 🔗 /article/mg24632870-700-why-neutrinos-are-the-strangest-particles-in-the-standard-model/. Unlike any other particles, the almost non-existent masses of the elusive neutrinos can be entirely generated by virtual particles, according to some models. This means they should be more sensitive than other particles to any UV/IR mixing effects.

If we do find evidence to support this idea, it would dramatically alter the way we conceive of the cosmos. It would mean we could not only see a world in a grain of sand, as the poet William Blake once said, but we could also quite literally see the entire universe in its tiniest pieces and particles. While this might sound like just a different way of going about physics, it is much more than that. I believe that we are on the way to a completely new understanding of how the universe is put together.

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