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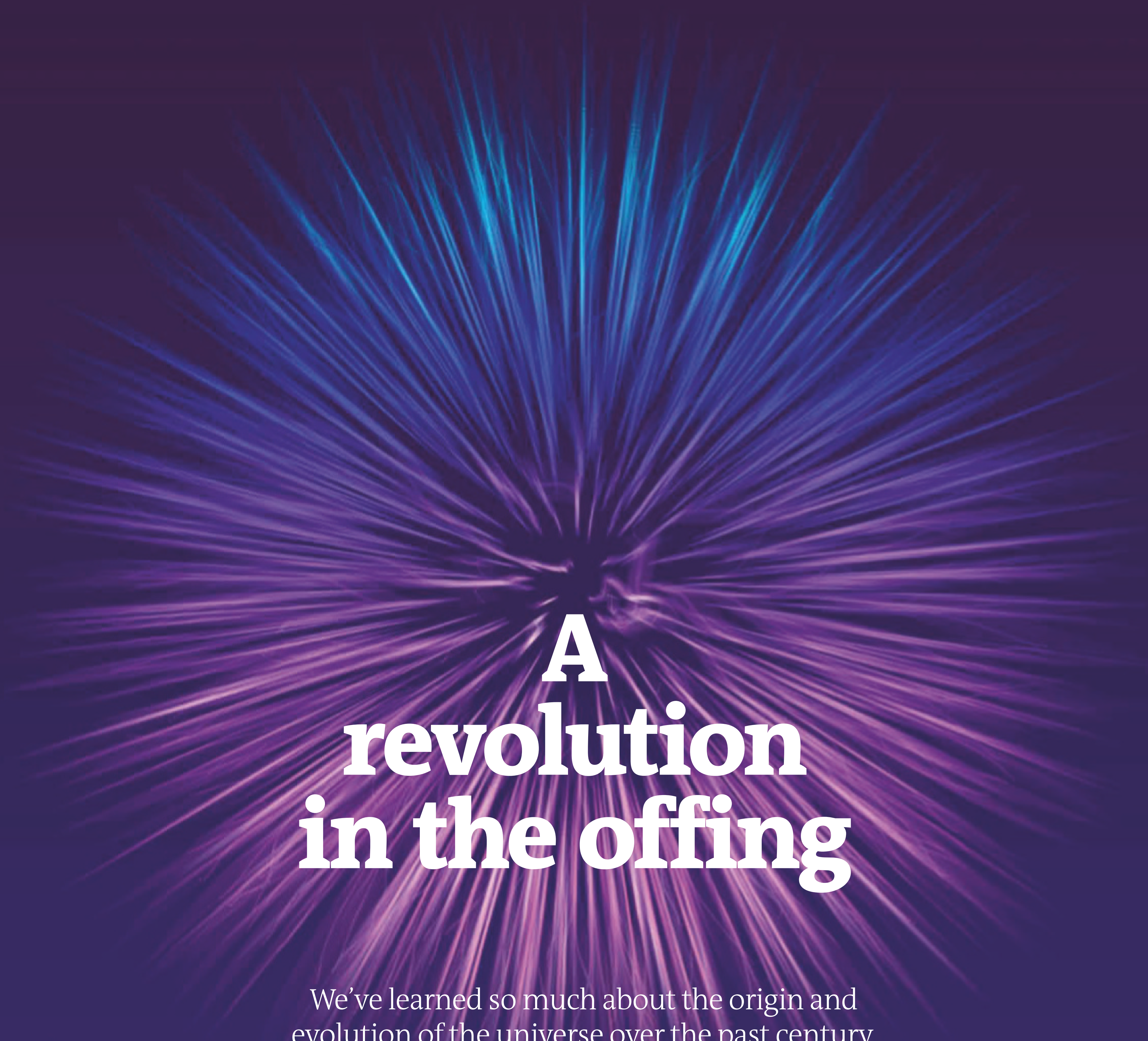

A revolution in the offing

We've learned so much about the origin and evolution of the universe over the past century, cosmologist **Dan Hooper** told a recent *New Scientist* online event – but there are signs our theories might soon have to radically change

THROUGHOUT all of human history, people have looked up at the night sky and wondered about the universe and how it came to be. But in one respect, we're very different from our ancestors: we more or less understand what we're looking at.

Take an image from the Hubble Ultra Deep Field, for example. We know the blotches of light on it are not stars, but entire galaxies similar to own Milky Way. And because it takes time for light to travel through space, we're not seeing what these galaxies look like today, but rather what they were like over 13 billion years ago, a few hundred million years after the big bang.

A little over a century ago, scientists didn't have the faintest understanding of our universe's distant past, and they certainly knew nothing about its origin. We didn't have the tools even to conceptualise questions about how the universe might change or evolve. All of that changed with Albert Einstein. With his general theory of relativity, he how showed how space isn't static and unchanging. It can be curved; it can warp and deform; it can expand and contract.

In 1929, Edwin Hubble observed that the universe is in fact changing. Every galaxy is receding from us; every two points in space are getting farther apart from each other as time advances. The universe is expanding.

If the universe were smaller in the past, and we know how much matter and energy it contains, we can deduce that its matter and energy density must once have been higher. Billions of years ago, it must have been in a denser, hotter state, and expanded into the cooler world we see today. That is the basic premise of the big bang theory.

According to this picture, wind back to some 380,000 years after the big bang, and we reach a point when the universe had first cooled enough for atoms to form. It suddenly became transparent to radiation, dumping an enormous amount of light into the cosmos that's been propagating throughout space ever since. Today we see this light as the cosmic microwave background, a sea of radiation cooled to 2.7 degrees above absolute zero. Its existence gives us confidence that we understand the universe and its evolution from this point right up to the present day.

Going back even further, to the first seconds and minutes after the big bang, we encounter a time when the universe was about a billion degrees, 100 times as hot as the sun's core, and functioning as a giant nuclear fusion reactor. We can predict how much deuterium, tritium, helium, lithium and beryllium we think should have been made in this era – and again, the predictions agree with what we observe today.

Going back even further, we can't make direct observations, but we can recreate the conditions of the early universe using particle accelerators such as the Large Hadron Collider near Geneva, Switzerland. The LHC accelerates protons to about 99.999997 per cent of the speed of light and collides them head on at a rate of about 600 million times every second, exploiting Einstein's famous equation $E = mc^2$ to convert as much of the energy released as we possibly can into mass. This allows us to create a variety of exotic forms of matter that are very rare in our universe now, but were extremely common in the incredibly hot first trillionth of a second after the big bang.

> **"You might think we know a lot about the universe's first fraction of a second That just isn't true"**

From all I'm saying here, you might now be under the impression that we know a lot, and with a great deal of confidence, about the universe's first small fraction of a second. But sadly, that just isn't true. I'm going now to talk about four puzzles or problems that cosmologists have discovered or revealed over the last few decades, which all point to something missing in our understanding. To solve them, I increasingly think we're going to have to radically rethink what we think we know about the universe's very early history.

The first puzzle has to do with the simple fact that atoms exist. Everything we know from particle accelerators and other such experiments tells us that, for every kind of matter that exists in the universe, there exists a kind of equal and opposite mirror version, antimatter. When you create more matter, you create an equal amount of antimatter; when you destroy one of them, you destroy the other along with it. So whatever created the universe's matter should have created an equal amount of antimatter. As the universe expanded and cooled in its first fraction of a second, we calculate that matter and antimatter should have destroyed each other almost entirely. There should be no atoms, no molecules, no stars, no galaxies, no planets and no life.

Our second puzzle has to do with matter, too, but not the kind that consists of atoms. It is "dark" matter that doesn't appreciably reflect, radiate or absorb light. Since the 1970s, astronomers have been measuring how fast stars in other galaxies are moving in their orbits. They've consistently found that stars in galactic outskirts are moving too fast for the amount of visible material the galaxies contain. Nearly all galaxies seem to contain a small amount of visible material, compactly located in the centre of a larger "halo" of dark matter.

Making some assumptions about how dark matter must work, we can create computer models to find out how it would have impacted the universe's evolution. When we do that, we find near-perfect agreement with the distribution of galaxies and clusters of galaxies we see in the >

The Hubble Ultra Deep Field pictures the cosmos over 13 billion years ago

NASA; ESA; G. ILLINGWORTH, D. MAGEE, AND P. OESCH, UNIVERSITY OF CALIFORNIA, SANTA CRUZ; R. BOUWENS, LEIDEN UNIVERSITY; AND THE HUDF09 TEAM

universe today. With dark matter, we can explain it; without dark matter, we can't.

If you'd asked me what the dark matter consists of maybe 10 or 15 years ago, I would have given you a very confident-sounding answer about how it was probably made up of "WIMPs", short for weakly interacting massive particles. We thought we knew how to detect these particles, so we built impressive, super-sensitive detectors for them deep underground in places like the Gran Sasso laboratory in Italy – but we still haven't observed any dark matter particles.

Our third puzzle has to do with how fast our universe has been expanding over time. General relativity gives you basically three possibilities. You can have a universe that expands for a while, reaches a maximum size and then starts to contract; you can have a universe that expands forever, but with its expansion slowing down; or you can live on the boundary between those two cases, and have a universe that gets bigger for a while and then approaches a maximum size.

For decades, cosmologists set out to try to measure which of these three cases describes our universe. And the answer turned out to be: none of the above. Instead of slowing down, in the past few billion years our universe's expansion rate has been getting faster. The universe is accelerating.

Within the context of Einstein's theory, the only way to explain this behaviour is to posit that space itself contains a fixed density of "dark energy". Unlike matter and other forms of radiation, dark energy doesn't get diluted as space expands, so it plays an increasingly important role, ultimately driving the universe to speed up its expansion rate.

The fourth and final puzzle has to do with the extremely early universe, maybe something like 10^{-32} seconds after the big bang. If you take the big bang theory as it was envisioned in the 1960s and 1970s, it is very hard to explain why our universe is so uniform, and also what we call geometrically flat – basically, it follows the rules of conventional Euclidean geometry. There's no reason why either of these things should be.

In the 1980s, physicists began to posit an explanation: cosmic inflation. In its very early stages, our universe expanded in explosive fashion, growing exponentially by a factor of something like 10^{75} in volume over a very, very brief period of time, smoothing itself out as it did so. The best thing is that inflation made some very specific predictions about patterns of light we would observe in the cosmic microwave background – and we have observed them.

"We're going to have to radically rethink the universe's early history"

One thing that I find really compelling – or exciting, anyway – about inflation, is it takes even a very tiny amount of space, and it rapidly turns it into a multitude of universes: a multiverse. Quantum physics says that different patches of that space will stop inflating at different times, essentially creating something like our universe. But this doesn't happen just once; in fact it happens without limit. Inflation seems to lead inevitably to the conclusion that there should be an infinite or nearly infinite number of universes in existence, some maybe a lot like ours, some very different.

That gives us a lot to ponder about the possible varieties of existence we might find throughout the multiverse. But all these puzzles give us also a lot of reason to doubt that we understand the whole story of the first fraction of a second of the universe.

It brings to mind a question I'm fond of asking my colleagues: what would it have been like to be a physicist in 1904? The reason I pick 1904 is because it's when physicists seem to have had the most confidence that they really understood the universe. Newtonian physics had reigned supreme for over two centuries. It had been applied to problem after problem, and it just kept working. There was every reason to think that Newtonian physics could just be applied to anything – heat, electricity, magnetism – if we just thought long and hard enough about it.

But back then there were also a few loose ends; a few problems and puzzles that hadn't been resolved. One was the way light seemed always to travel at the same unvarying speed, no matter what frame of reference you were in. Another was how Mercury's orbit didn't fit what was predicted by Newtonian physics. People had posited that maybe there was an additional planet out there called Vulcan that had perturbed Mercury's orbit, but no one had ever been able to see it.

A third puzzle was that no one knew how the sun got its energy. Geologists had already shown us that Earth and the sun were billions of years old. Even if the mass of the sun were made of some fuel like gasoline or coal, it should have run out of energy a long ago. And then a fourth puzzle: Newtonian physics couldn't explain the inner workings of atoms. It predicted they were unstable, and couldn't say why particular atoms gave off special patterns of light, what we call spectral lines.

The resolution to these problems was not an incremental change of Newtonian physics. It came with a revolution ushered in by Albert Einstein and people who followed his work. In 1905, Einstein introduced his theory of relativity that explained the uniform speed of light, and would eventually explain the Mercury's orbit. When you combined relativity with what we learned about quantum physics, we could explain the nuclear fusion that powers the sun, and begin to understand the inner workings of the atom. The revolution that came forth in 1905 tore down Newtonian physics and left something else, something that would have been unimaginable in 1904, in its place.

Right now as a cosmologist, I wonder if 2020 is the 1904 of cosmology. I hope so, because that means in 2021, or some other short time down the road, we are going to have a revolution that will be very exciting to live through. Of course, I could be wrong. But that's what I'm hoping for, that's what I'm excited about – and all these puzzles make me think that it's at least a little more likely. ■

Dan Hooper is head of the theoretical astrophysics group at Fermilab in Illinois and author of *At the Edge of Time: Exploring the Mysteries of Our Universe's First Seconds*. This is an edited version of a talk he gave at a *New Scientist* online event on 9 July 2020

Your big bang questions answered

Dan Hooper also took questions from audience members after his talk. Here's a selection of the best

WHAT COLOUR WAS THE BIG BANG?

That's a great question. As it turns out, it depends exactly how close to the big bang you're asking about. When the first atoms were forming a few hundred thousand years after the big bang, the whole universe was filled with a 3000-degree plasma of electrons and protons and light. At 3000 degrees, things would have looked bright red throughout space. But as you go further back things would have got hotter and hotter. They would have looked bluer and bluer and eventually white. Ultimately, it would cease to be light that you could even see with your eye – it would look increasingly ultraviolet.

HOW DO WE KNOW THE UNIVERSE IS 13.8 BILLION YEARS OLD?

There are a lot of different ways we measure this, from its expansion history and from detailed temperature patterns we observe in the cosmic microwave background, for example. If you'd asked cosmologists this 20 years ago, you would have got a wide variety of answers: some might have said 8 billion, some 20 billion. But over time, we've measured things better and better, and there's total agreement. I'm not saying it couldn't be 13.85 or 13.75, but within a small margin of error it's right around 13.8.

IF DARK MATTER ISN'T WIMPS, WHAT DO YOU THINK IT IS MADE OF?

I have a pretty open mind right now. Just to be clear, I still think it could be WIMPs, but if it's not, we have a bunch of ideas that are all appealing. One is particles called axions which are very, very light, and were produced through kind of exotic mechanisms in the early universe. They would solve a bunch of problems. I also work a lot on "hidden sector" theories, where there are a variety of forms of matter and energy that all interact among themselves, but don't directly interact with any of the forms of matter that we know or can observe in particle accelerators. But there are hundreds of viable dark matter candidates. Our goal is ideally to discover which one or ones are correct, but if we can't do that, at least rule out as many contenders as we possibly can.

WHAT HAPPENED BEFORE THE BIG BANG?

That's a kind of tricky one to answer. If you take the classic version of the big bang, before people started to talk about cosmic inflation, then people like Stephen Hawking and Roger Penrose and others worked out that if you run those equations of general relativity backwards, you eventually reach what we call a space-time singularity, at which point space and time really came into existence. So you can't talk about what happened before that, any more than you can talk about what's north of the North Pole.

But if inflation happened, those singularity theorems are kind of thrown out the window. Inflation could have gone on forever, expanding exponentially without limits, popping off pocket universes, one after the other, for all time.

But I think we should be pretty humble about what might have set off inflation. We don't know. Anyone who gives you a very competent sounding answer to this question at this point in our intellectual history probably should put some more caveats on their answer.