Recent discoveries have revealed a **hidden code within light**, which is transforming our understanding of the universe. This secret code embedded in starlight can tell us not only what celestial objects are made of but also the story of our cosmic past. Additionally, the spectrum of light, which we cannot see with the naked eye, holds significant information about the universe's history. These findings open up new avenues for research and exploration in astrophysics and cosmology.

How Starlight's secret code unlocks the Universe's past

Looking deep into the Universe can teach us about our cosmic history.

Dr Katie Mack
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When you see photos from a modern telescope of a planet, nebula, or distant galaxy, it's easy to be dazzled by the detailed and intricately beautiful images. But those pictures tell only a small part of the story.

What astronomers usually get the most excited about is a property of the light we can't perceive with our eyes at all: the spectrum. This secret code embedded in starlight can tell us not only what a celestial object is made of, but can also, for the most distant objects in the Universe, tell us the story of our own cosmic past.

As far back as the 18th century, scientists experimenting with lighting chemicals on fire discovered that each substance produced its own pattern of colours when it was burning. It turns out that each element or molecule, when heated, can emit light at certain colours specific to that species.

These emission lines show up as bright bands of colour when the light is spread out in a prism or diffraction grating, creating a telltale pattern that can be used to identify the substance.

If you'd rather not set your sample on fire, you can also identify it by shining a white light through a gas of the stuff: you'll see the same pattern of lines, but this time in the form of dark gaps in the spectrum, known as absorption lines.

In both cases, the lines are caused by electrons shifting between energy levels. Every element has a specific arrangement of levels its electron can be in, which you can picture (somewhat inaccurately) as concentric orbits around the nucleus, with lower energies closer in and higher energies farther out.

When the atom is disturbed, electrons can move between the levels. If you heat a substance (or light it on fire), that kicks electrons up to higher energy levels. When it cools, the electrons fall back down and emit photons (particles of light) at specific energies, which correspond to specific colours.

When you shine light through a gas, the atom can absorb photons at those special colours to boost electrons up. A white light that's passed through arrives on the other side with dark gaps where the photons were stolen by the gas.

When astronomers in the early 1900s applied this principle to astronomical observation, they were suddenly able, just by spreading starlight through a prism, to say exactly what the stars were made of. Each element has a specific pattern of absorption or emission lines, like a unique bar code; identifying those patterns can tell us exactly what elements that light has been passing through.

Now, telescopes around the world, and some in space, use spectroscopy to figure out which elements make up the Universe around us. But these spectra can tell us even more than that, in an indirect but astonishing way.

It has to do with the fact that even though light can be said to be made of particles and photons, it also acts like a wave. And just like with sound, when a light wave is moving quickly away from you, it gets stretched out, going to a lower frequency, or longer wavelength.

With sound, this is why a siren drops in pitch when it rushes past you. We can measure how quickly stars are moving toward or away from us by the way their spectral lines shift along the spectrum, to longer or shorter wavelengths, since the whole barcode shifts together.

When something is moving away from us, the shift is to longer wavelengths – toward red if it's visible light – so that's known as redshift. If it's moving toward us, it's blueshifted. Just seeing a blue or red tint isn't a conclusive sign of motion, though, since lots of things can affect the colour of a star. It's the shifted barcode that really gives the game away.

When it comes to very distant galaxies, though?
They're *all* redshifted.

In this case, it’s not that they’re rushing away from us, exactly, though it looks like that from here. It’s really the fact that the Universe is stretching out – expanding – in between here and there. And as the universe stretches, it stretches out the light, shifting it to redder wavelengths.

This is why the James Webb Space Telescope is an infrared telescope. The galaxies it’s trying to see are redshifted so extremely that they fall out of the visible part of the spectrum entirely, and can only be seen in the infrared.

Measuring the redshifts of distant galaxies tells us how long the light has been travelling and (indirectly) how far away the galaxy is. But it also gives us an invaluable tool to measure the expansion of the Universe at different points in cosmic history.

Astronomers have a pretty tough job, trying to understand and explain objects we’ll never touch or sample, based only on pinpricks of light in the sky. But thanks to the quirks of electron behaviour, and, ultimately, the rules of quantum mechanics), we can gather an astounding amount of information from each light ray that crosses the cosmos to reach us.

Sometimes that data helps us work out the processes of stellar evolution or search for exoplanet atmospheres for traces of life. At other times, those light rays carry with them the story of the cosmos itself.

How new antimatter science could soon explain the existence of everything

Matter comes in many flavours, each with its own unique, intriguing properties.

Dr Katie Mack

This September, a group of researchers at CERN finally, after years of engineering an extraordinarily precise experiment, managed to create and carefully capture a sample of antihydrogen (the antimatter version of hydrogen).

They held the sample in a magnetic field containment so precarious that any slight misalignment would cause it to immediately annihilate against the walls of its container. And then they dropped it.

The ALPHA-g experiment was designed to answer the question of just how 'anti' antimatter really is. Since antimatter was first proposed in the 1920s – initially just as a rather creative way to balance out an equation that seemed to have an extra solution – we’ve learned to produce antimatter in experiments, and we’ve seen evidence for it in high-energy astrophysical environments in space.

As its defining feature, we’ve seen that any contact between a particle of antimatter and its regular-matter counterpart results in annihilation into high-energy radiation.

Despite its violent tendencies, antimatter has generally shown itself to be far less outlandish than its popular reputation suggests. As far as we can tell, an anti-electron, which is called a positron, is exactly like an electron, except it has the opposite charge (+1 instead of -1), and is opposite in ‘parity,’ which means it is like a mirror reflection.

Like other versions of antimatter, the mass of a positron exactly matches that of its regular-matter counterpart. But until ALPHA-g, physicists had yet to experimentally confirm that antimatter's mass acts the same as that of ordinary matter.

Could antimatter – maybe – have some kind of anti-gravity, too? Does antihydrogen (a positron bound to an anti-proton) fall up when dropped, instead of down?

Alas, rather than revealing some dramatic new violation of gravity or a scrapping of some of the most crucial aspects of Einstein's general relativity, the ALPHA-g experiment showed that antimatter does, in fact, fall down. As far as gravity is concerned, antimatter is, really, just matter.

But that might lead one to ask: what is matter, really?

The crux of the matter

What counts as matter in physics depends on the context of the question. The simplest definition of matter is anything that has a rest mass: a mass that is inherent to the particle and exists when it is at rest (as opposed to an 'effective' mass, which depends on its motion).

Atoms, molecules, liquids, solids, gases – all of these are straightforwardly matter, as are the protons, neutrons, and electrons that make them up.

Other mass-having elementary particles, like quarks (which are components of protons and neutrons) and neutrinos (very light particles produced in nuclear reactions), count as matter too.

But what about massless elementary particles, like photons, gluons, or the still-hypothetical graviton? Even though we classify them as particles, they wouldn't count as matter in this context.

Weirdly, things that are definitely not matter can contribute to the mass of something else. In Einstein's general relativity, the gravitational effect of an object is due not just to its matter, but to its energy as well.

In principle, a hot bowling ball should weigh more than an otherwise identical cold one, because the heat energy adds to its gravitational effect.

Similarly, an atom or molecule is just a tiny bit heavier than its constituent particles due to the binding energy of the electromagnetic forces holding it together, even though the electromagnetic field can be said to be made of photons that don't have rest masses and therefore aren't considered matter.

When it comes to protons and neutrons, only a tiny fraction of their mass comes from the mass of their matter components (the quarks). The rest comes from various kinds of energy involved in holding the quarks together.

What could the matter be?

In another category, there's what physicists refer to as 'exotic matter', which broadly includes any substance that is still hypothetical or has properties at odds with what we think of as the rules of the Universe.

Dark matter – a kind of invisible stuff that we think is made of an as-yet undiscovered particle – could be called exotic matter, but in a sense, it seems to be fairly ordinary as far as matter is concerned.

It acts just like regular matter, except without interacting with light. For some truly exotic matter, we could look to hypothetical substances like negative-mass matter, which probably doesn’t exist, but could potentially hold up stable wormholes if it did.

Whatever we call the matter we have, we seem to be very lucky that it exists at all. Our best existing theories of particle physics and the Big Bang seem to suggest that matter and antimatter should have come into existence in the cosmos in equal amounts.

That would have been very bad for all involved, because everything would have been annihilated completely into radiation, with nothing left over.

For reasons we can’t yet fully explain, there seems to have been a slight imbalance, allowing all the antimatter to annihilate away while leaving a bit of regular matter to become the stars, galaxies, planets, and people we see today.

Antimatter experiments like ALPHA-g might give us more insights into not just the nature of matter, but also why any of us exist at all. That’s worth dropping everything for.

Dark energy may be even stranger than we thought

The most mysterious phenomenon in the Universe could be about to spring another surprise on us

Dr Katie Mack

It takes some hubris to name a new project the Dark Energy Spectroscopic Instrument (DESI). After all, dark energy is completely invisible – it gives off no light to be collected and analysed with a spectrograph. In fact, it’s never been seen at all – it has evaded every attempt we've made to image or capture it with even our most advanced telescopes and detector experiments.

As far as we can tell, dark energy is something that is indiscernible, perfectly uniform throughout space and has no interaction at all with matter or light. Its only function, through some as-yet-undetermined mechanism, is to make space expand ever faster.

So how is it, then, that DESI's just-announced first data release is, as promised, shaking up our understanding of dark energy?

There are only a few observational handles we can get on something as frustratingly elusive as dark energy. Since all dark energy does is stretch space-time, testing different theories of dark energy's nature involves learning how that stretching has occurred across cosmic time.

One method is charting the expansion history of the Universe; a related method is to look at how quickly matter built up into galaxies and clusters at different points in our cosmic past.

Measuring the expansion rate generally relies on creating extremely precise 3D maps of matter in the cosmos; charting out lots of distant galaxies, quasars (the bright emission from the vicinity of supermassive black holes) or intergalactic gas, and information about the motion of each object.

That's where the spectroscopy comes in. By analysing the spectrum of the light, we can see how much it's been stretched as the source is pulled away from us by cosmic expansion. Connecting that measured expansion rate with an exact physical distance can give us invaluable information about the evolution of our cosmos (along with some really cool maps).

DESI’s newly released modelling made a splash by hinting that dark energy might have a more complicated history than we normally assume. If these hints hold up, they could reshape our understanding not only of the Universe’s history, but also of our ultimate cosmic fate.

The concordance model of cosmology encapsulates our current best-guess working model of the Universe and its constituents. In this model, dark energy is a cosmological constant: an inherent property of space-time, uniform and unchanging, that essentially just builds a little stretchiness into every bit of space.

With dark energy as a cosmological constant, the observed density of dark energy would always remain the same over time. Unlike matter that dilutes when the space it’s in gets bigger through cosmic expansion, more space just means more cosmological constant contained in that space.

If dark energy were something dynamical, meaning its density or behaviour were changing over time, that change would show up in detailed measurements of the expansion history.

DESI and other surveys tend to report their dark energy results in terms of the so-called ‘equation of state’ parameter, written as w. If dark energy is a cosmological constant, we expect to see $w = -1$, exactly, for all time. If w is anything other than –1, or if it seems to be increasing or decreasing, dark energy must be something else.

DESI’s results provide an intriguing conundrum. When w is assumed to be constant, a value of –1 fits the results just fine. But when the analysis is altered to allow for the possibility that w has been changing, DESI’s new results look different. Combined with other datasets from supernova surveys, they seem to suggest that a varying w, one that was lower in the past and will be higher in the future, matches the data best.

What this would mean for our cosmos is unclear. For a constant w, anything less than –1 is called ‘phantom dark energy’, and its ominous name is earned: it implies a distant future in which dark energy could literally rip apart galaxies, solar systems, stars and even the Universe itself.

Phantom dark energy is disliked by theorists because it seems to break some really important fundamental principles that we think probably hold in the cosmos. While the new results suggest a movement away from the phantom regime, they seem to be implying that those principles could have been broken sometime in the cosmic past, which would give a lot of theorists headaches.

If w really is increasing, that might suggest that dark energy is getting less important over time. That could change our cosmic future in subtle but interesting ways, possibly leading to one in which the expansion of the Universe is no longer accelerating (though probably not allowing the expansion to reverse or stop entirely).

The results from DESI are still just hints, which might disappear in future studies. Still, it’s possible that dark energy has just found a new way to surprise us.

We've made a map of dark matter but still don't know what it is, and that's okay

The exact nature of dark matter remains elusive.

Dr Katie Mack

In early August, astronomers announced that they had created a map of dark matter – the mysterious, invisible stuff that astronomers say underlies all structure in the cosmos – associated with some of the earliest galaxies in the Universe.

Articles reporting the achievement described the innovative observational technique: searching for tiny distortions of patterns in the cosmic microwave background radiation, the backlight of the Universe that originates from the Big Bang. These distortions appear because mass bends space, even if that mass belongs to an invisible kind of matter.

Tellingly though, these reports did not delve into the mystery of what dark matter is, or question whether it even exists. For most astronomers, most of the time, dark matter's fundamental nature is entirely beside the point.

Dark matter, whatever it's made of, is important in our Universe. Studying its distribution helps us understand how galaxies form and helps us discern the entire structure of the cosmos. But are we just fooling ourselves here? Isn't anyone disturbed by the fact that we can't see it, and don't know what it is?

Despite having never directly detected it, scientists do in fact have very good reasons to believe that dark matter is real. The first story that everyone tells is about how galaxies seem to be rotating at impossible speeds.

The stars at the outer edges of spiral galaxies are orbiting around the centre so quickly that if there weren't something providing extra gravity to hold them in, they would have already escaped into intergalactic space, like children flung off a merry-go-round that's spinning too fast.

The proposed solution: an invisible, intangible substance, presumably composed of a collection of particles our earthly experiments have all missed, surrounds and penetrates the misbehaving galaxy, and its mass provides the extra gravity the observations require. Every galaxy (with some possible rare exceptions) is embedded in a roughly spherical clump of dark matter we call a 'halo'.

It's not unreasonable to point to another possibility: maybe we don't need something new to produce more gravity; maybe gravity just acts differently than we thought. This has been the main approach of dark matter sceptics in astrophysics, and when it comes to galaxy rotation, it seems to be an appealing solution.

These modified gravity models work so well to solve the rotation problem that news articles appear in papers and magazines regularly proclaiming that dark matter has been disproven by a simple tweak to Newton's (or Einstein's) laws.

But there's a reason we haven't all thrown out dark matter and embraced the demise of gravity as we know it: the best evidence for dark matter comes from cosmic phenomena occurring on scales much larger than any galaxy, where there are fewer observational complications and where the agreement with theory is incredibly precise.

That preponderance of evidence would be compelling even if we completely ignored galaxy rotation, and there has yet to be a modified gravity theory that can compete with dark matter when it comes to everything else: galaxy shapes, galaxy cluster motions, gravitational lensing, elemental abundances from the early universe, the distribution of galaxies on the largest scales, and even the patterns in the cosmic microwave background light itself.

Even accepting that the astrophysical evidence is strong, it’s understandable to remain uncomfortable with the notion of adding a new particle to the zoo of discovered species without any concrete detection of the particle itself.

Some of the simplest theoretical possibilities for dark matter’s particle properties have already been ruled out. But rather than give up entirely, astronomers and physicists are constantly searching for new, creative ideas for what dark matter might be and why it hasn’t shown up yet.

In spite of the experimental no-shows, when all the evidence is taken into account, the idea that the Universe is absolutely overrun by invisible particles just fits the data best.

There’s an old saying, commonly attributed to statistician George Box, that “all models are wrong, but some are useful.” In cosmology, we sometimes loftily describe our mission as “solving the mysteries of the universe” but in a day-to-day sense, our job is to build and test mathematical models to describe the data we collect.

Not detecting a particle in a detector might make us uncomfortable, but it doesn’t cancel out any of the ways in which we see dark matter’s influence in the cosmos. And there’s no indication that dark matter ought to be something that interacts with detectors at all.

It's still possible some other solution will be found. But whatever it is, it will have to look, observationally, exactly like a collection of invisible, untouchable particles making up most of the matter in the Universe.

Those of us who spend our time exploring the exciting boundary layer between particle physics and cosmology will keep trying to figure out what this stuff is, really, while astronomers poring over new astrophysical data can make use of what we know about its abundance and behaviour to try to solve other cosmic mysteries.

And whatever dark matter is, we can be grateful for its role in bringing all that ordinary matter together, and rest assured that it's likely to continue doing a great job of keeping our Sun from flinging itself off into the void.

It may be one of the basic building blocks of all matter, but there's still a lot we have to learn about the proton

Physicists investigating the properties of the subatomic particle quickly find themselves going down a rabbit hole of complexity and quantum weirdness.

Dr Katie Mack

A proton should be one of the simplest objects in physics. It's a basic building block of all atoms, or, alternatively, the simplest possible atom all by itself, since hydrogen (one positively charged proton plus one negatively charged electron) is still hydrogen when it's ionised.

Most of the atoms in the Universe are hydrogen, as are most of the atoms in your body. In fact, since electrons are tiny and weigh very little, it's straightforward to conclude that you are mostly, specifically, protons.

Given all this, you'd think physicists would understand protons very well by now. You would be wrong.

If you ask your physics teacher what protons are made of, they'll likely tell you protons are made of three smaller particles called quarks. Quarks come in six different types, or 'flavours': up, down, charm, strange, top, and bottom (they were named in the 1960s and 70s), with up and down quarks combining to make protons and neutrons.

Since the up quark has a charge of +2/3 and the down quark has a charge of -1/3, the sums all work out if a +1-charged proton is two ups and a down (2/3 + 2/3 - 1/3 = +1) and a neutral neutron is two downs and an up (-1/3 -1/3 + 2/3 = 0).

So far, so good.

But while the charges add up perfectly, the masses don't. In particle physics, we usually measure mass in terms of energy (interchangeable via that old standard, $E=mc^2$), and for this purpose we'll use units of MeV, for Mega-electron-volts.

If you look up quark masses online, you'll find that the mass of an up quark is around 2 MeV while a down quark is close to 5 MeV. But those same sources will tell you the mass of a proton is a whopping 938 MeV. Our sums are off by about 99 per cent.

Before we panic, we can ask, what else is in the proton? And we have a convenient answer: gluons! Gluons are the aptly named particles that carry the strong nuclear force, just as photons carry light - the electromagnetic force. Gluons are in the proton to hold the quarks together, so surely they must contribute something. But gluons have something else in common with photons: they are entirely massless.

So how do we build a proton that weighs 938 MeV out of three quarks that weigh a total of 9 MeV and a handful of particles with no mass at all?

The answer is even more complicated than you might imagine. For one thing, it's not quite right to say there are three quarks in a proton. Really, a proton is a roiling quantum sea of an uncountable number of quarks, antiquarks, and gluons, constantly shifting in and out of existence by transforming into one another. And those ethereal particles zipping around inside the proton carry kinetic energy, which, via $E=mc^2$, gets us about 60 per cent of the 938 MeV that we need.

The final piece comes from the energy of the strong nuclear force itself. The quarks are not merely bound by the strong force but confined. This is different from gravity or electromagnetism, where the more separation you get, the weaker the attraction – you can, with enough effort, pull magnets apart, or accelerate a rocket away from the Earth. But the strong force will just keep pulling.

There's so much energy tied up in the force itself that even if you manage to pull two bound quarks apart hard enough to overcome their strong force attraction, the energy you had to put in to break that bond will spontaneously create two new quarks, one bound to each of the ones you just separated. Quarks do not like to be separated.

The energy inherent in quark confinement solves the proton mass puzzle, but the calculations of exactly how this term arises, and what its magnitude is, are incredibly complex, and the more you look into them, the more complex they become.

Recent experiments have shown that protons can sometimes be observed containing charm quarks, which is particularly surprising, since charm quarks are more massive than protons are.

Measurements of the proton’s size have been controversial for decades: you get different answers depending on whether you measure it by scattering electrons off the proton or by watching the electron in a hydrogen atom pass right through the proton, which is a thing it does routinely, just on a normal day, because nothing at that scale is sacred at all.

With new, advanced computational techniques, we are making progress. And the measurements are already incredibly precise. If we can unlock the mysteries of this most basic of atomic building blocks, we’ll be closer to understanding the fundamental laws that govern reality itself. Or maybe we’ll discover something even more bizarre hiding within it.