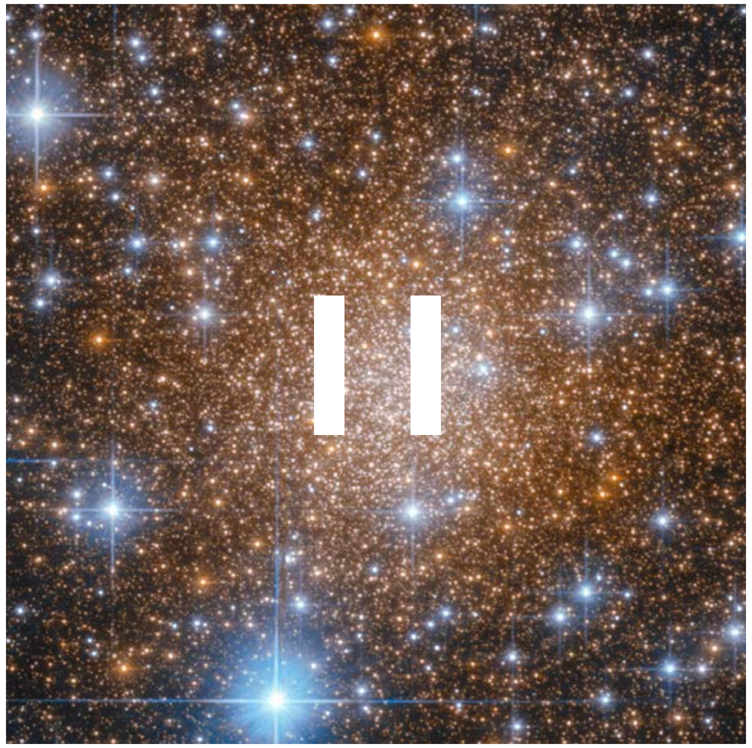

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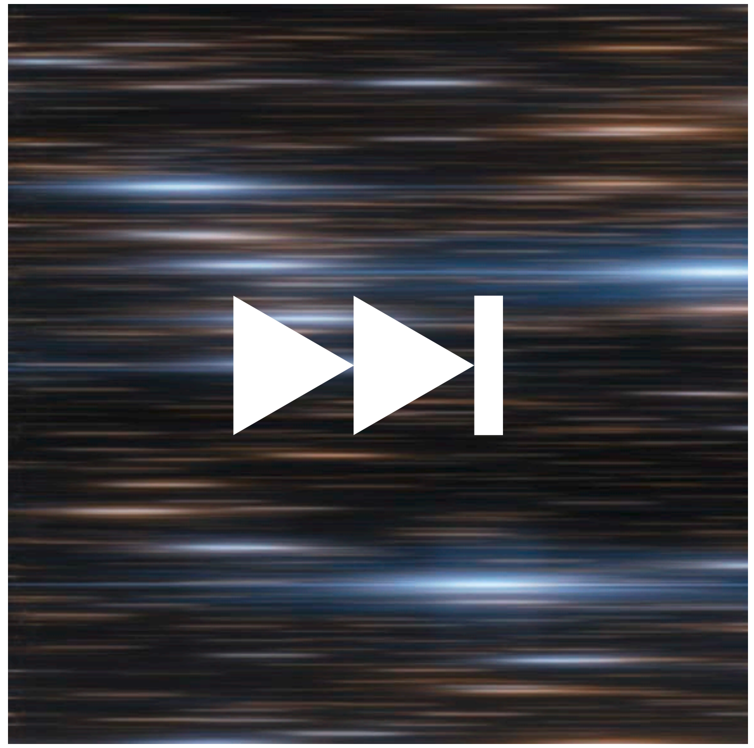


The universe on pause

A bold new idea suggests cosmic history contains hidden periods of stillness. If correct, it could explain the origins of dark matter and much more, says **Miriam Frankel**

ASK someone how the universe began and they will probably reply with those three familiar words: the big bang. But as recently as the 1960s, cosmologists hotly debated this matter. On the other side of the argument to the big bang was the idea of an unchanging "steady state" universe, the density of which was kept the same by continually adding new matter as it expanded.

In the end, observations ruled out the idea of a steady state universe and cemented the place of the big bang in the canon of cosmology. That primordial explosion started a process of continual expansion, and today cosmologists view the universe as a place of constant flux.

But now a bold group of cosmologists is questioning all that. To be clear, this isn't a return to the steady state universe, but something altogether more intriguing. The researchers are proposing that the universe's history may have been punctuated by spells of eerie stillness. These periods of cosmic stasis could arise in such a way that they replace whole epochs of conventional cosmic history or become spliced within that timeline.

Bold is certainly the word for this hypothesis. "It's pointing to a whole different family of possibilities that before this we didn't realise could happen," says Adrienne Erickcek at the University of North Carolina at Chapel Hill, who wasn't involved in the work. But if these static periods do exist, they could solve all manner of conundrums, including what dark matter is made of. Even more exciting, these ideas may soon be testable.

Before we write alternate histories of the universe, let's first lay down the traditional timeline. The big bang kicked things off some 14 billion years ago, causing space to balloon. As it continued, this expansion caused the universe's energy to shift its distribution between different forms. Today, cosmologists think of the history of the cosmos as being divided into a series of epochs, each of which is dominated by a different form of energy (see "History rewritten", overleaf).

The first was the inflation epoch, a period of rapid acceleration lasting a tiny fraction of a second. This was dominated by a form of energy intrinsic to the vacuum of space-time, generated by a hypothetical elementary particle called the inflaton. After inflation, the universe underwent a reheating epoch, during which this vacuum energy was converted into matter, which then decayed to radiation. This led to the radiation epoch, so called because at first there was much more energy – in the form of radiation, such as photons – than matter. But as the universe expands, radiation dilutes quicker than matter, so, after about 50,000 years, this turned into the matter epoch.

Over the next 10 billion years, matter evolved in complexity from atoms and molecules to stars, galaxies and vast cosmic webs. But as the universe continued to grow, it eventually became dominated by another kind of mysterious vacuum energy called dark energy, which doesn't dilute as space-time expands. We live in this dark energy epoch, often considered to be the final era, in which the cosmos expands ever faster while matter incessantly dilutes.

In the eyes of most cosmologists, the passage between these epochs is an inevitable, unceasing march. "This has been standard lore since the beginning of [modern] cosmology," says Keith Dienes at the University of Arizona.

But the consensus that the universe's energy continually transmutes is now being challenged by Dienes and his collaborators: Lucien Heurtier at King's College London, Fei Huang at the Weizmann Institute of Science in Israel, Tim Tait at the University of California, Irvine, and Brooks Thomas at Lafayette College in Pennsylvania. In a slew of recent papers, the team raises the striking possibility that novel epochs characterised by stillness could have arisen for extended periods in our cosmic past – and may come about again in the future.

A balancing act

In these epochs of cosmic stasis, the amount of energy in the form of matter, radiation and even dark energy remains fixed, even though the universe is expanding. There is no single kind of energy dominating during periods of cosmic stasis. Instead, a peculiar kind of balancing act exists between them all.

It may seem forward to suggest rewriting cosmic history in this way, and to be fair, it wasn't originally the researchers' intention. They were initially investigating ideas to do with as-yet undiscovered particles. Specifically, they were interested in the idea of "towers" – sets of particles related to each other by certain properties, such as their masses. These could be the heavier "superpartners" of known particles predicted by a hypothesis called supersymmetry, for example, or a family of dark matter particles hiding in extra dimensions, such as "axion" particles manifested by string theory, which suggests everything is made up of vibrating one-dimensional strings. Axions are a possible explanation for dark matter, dark energy and inflation, among other puzzles.

It isn't clear if any of these ideas is right, but many physicists reckon there must be undiscovered particles of some description. "Dark matter is definitely a sign that the standard model of particle physics is incomplete," says Erickcek. "There are more particles out there than we thought".

In the spring of 2020, while working with Dienes, Heurtier simulated whether such towers of particles would affect inflation or its aftermath because of how matter decayed. "I started building a code, putting a lot of different particles in there," he recalls. "And we were always seeing in the simulation that matter and radiation would balance each other in a weird way." Whatever type of particle tower they began with, the simulation naturally evolved towards at least one extended period of stasis. "We literally ›

"It is even possible that we are entering or leaving a period of stasis now"

fell upon it – this is what the universe does if there are towers of particles," says Dienes.

In 2022, the five collaborators published the recipe for static epochs of matter and radiation. A year later, they showed that stasis still occurs if you add dark energy to the mix: matter, radiation and dark energy could all share the energy density of the universe in fixed proportions, without one taking over. They found that epochs of cosmic stasis may replace existing epochs or find themselves spliced within the orthodox timeline.

Why does this happen? Ultimately, stasis occurs because heavier particles in these towers decay into lighter ones, emitting radiation in the process. As described earlier, when the universe expands, radiation dilutes faster than matter. But in this new view, the shortfall in radiation is filled in by new radiation from decaying particle towers. Similarly, all those extra particles mean that matter doesn't dilute as quickly relative to dark energy, allowing the universe to also have a balance. "The idea that you could 'pause' the universe is really interesting," says Erickcek. "Usually expansion [means] evolution. Stasis is a counterexample to that: you can still be expanding and not change the energy balance of the universe."

There are many ways stasis can happen. Exactly when and how it appears depends on which ideas from beyond the standard model of particle physics you use, as that determines how many particles are in the towers, what the masses of those particles are and their rates of decay to lower levels in the towers.

It is even possible that we are entering or leaving a period of stasis now, says Heurtier. We know that the energy mixture of the universe has changed in relatively recent history because dark energy currently dominates, but a few billion years ago the universe was mostly made up of matter. Simulations show that large fluctuations like this can happen at the beginning or tail end of stasis periods, says Heurtier.

If we are leaving a period of stasis, or if stasis emerged during the matter-dominated epoch, this may help resolve a cosmological puzzle called the Hubble tension. This is a small but significant mismatch between how quickly we measure the universe to be expanding now and how quickly we expect it to be expanding.

The expectation is calculated by taking measurements of the cosmic microwave background (CMB), an afterglow emitted 380,000 years after the big bang, and then winding the clock forwards until today. However, that calculation depends on assumptions about what the energy content of the universe was immediately before, during and after the CMB was produced. "Perhaps this extrapolation is wrong because the traditional models haven't taken into account periods of stasis during which different kinds of energy coexist," says Heurtier.

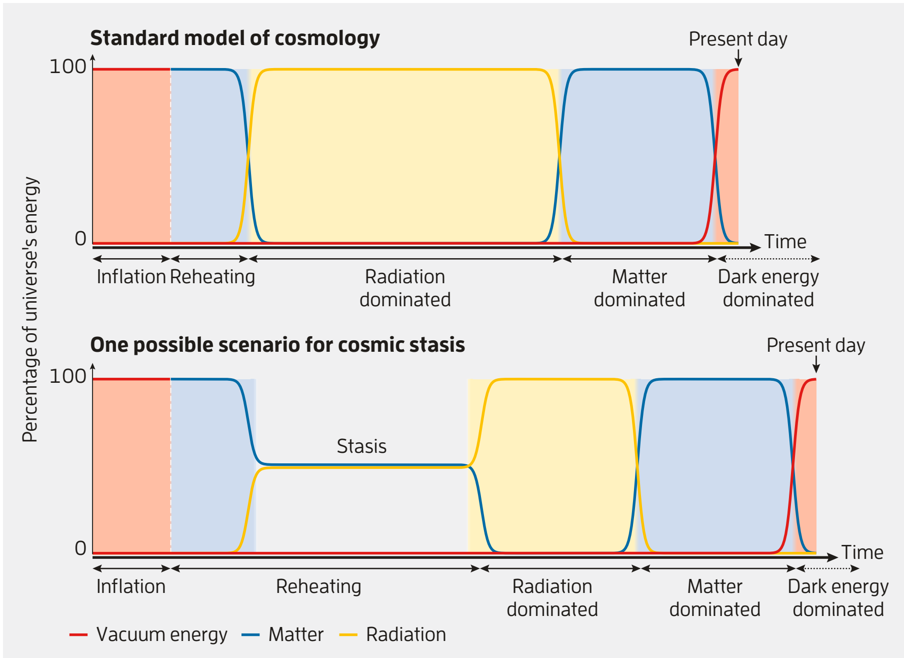
What we do know is that stasis can't happen in the period just before the CMB was emitted. Astrophysicists have made very precise measurements of this radiation, which neatly aligns with radiation measurements from an even earlier period, when light atomic nuclei such as helium were first created, called the big bang nucleosynthesis. All radiation is accounted for within this window of time, but stasis, by definition, requires the production of new radiation, either from decaying matter or, in some models, from dark energy. So these measurements rule out stasis epochs between 1 minute and 380,000 years after the big bang, says Erickcek.

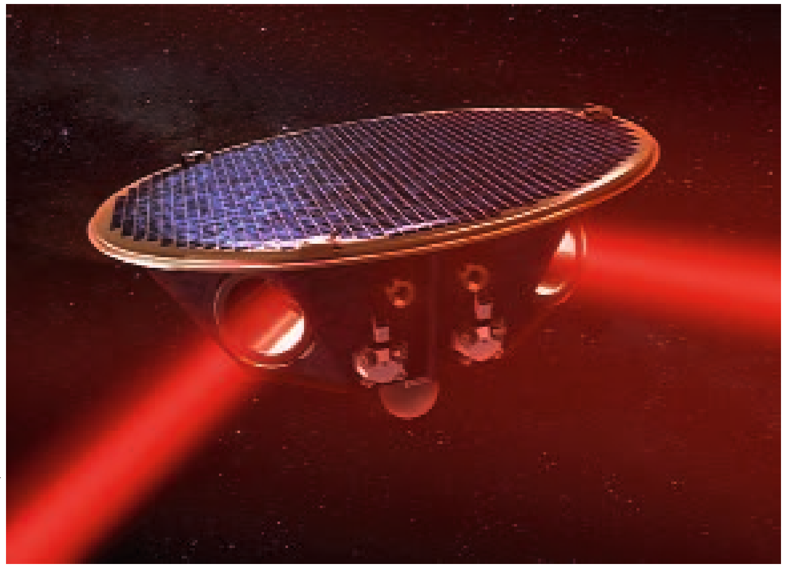
This means a period of stasis is more likely to come about during that first minute before big bang nucleosynthesis – a pause after the big bang, if you will. "That is when we're imagining these things would have occurred," says Dienes. Although that sounds like just the briefest flash in time, this first minute was exceptionally consequential.

That becomes clear when you think of the past in cosmologists' preferred measure of time: the "*e*-fold". This way of thinking allows us to talk about the universe's age in terms of how quickly it expands, with each *e*-fold corresponding to the universe's volume increasing by a factor of roughly 2.718 – meaning it expands exponentially according to the mathematical constant *e*. The universe's entire history has taken place over about 120 e-folds, but this first minute of existence would correspond to about 50 to 60 of those *e*-folds. In that sense, this period accounts for about half of the universe's history – any new stasis epochs that arise here may substantially alter the universe's age in *e*-folds.

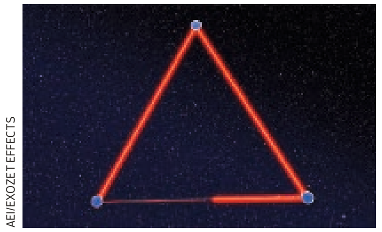
History rewritten

In conventional cosmology (top), the universe's history is divided into five epochs in which one form of energy dominates. But new research suggests that our past includes periods of stasis (below), where energy in the form of matter, radiation and vacuum energy were held in balance





Wobbles in the lasers of the upcoming LISA telescope array may offer evidence of cosmic stasis



We still know very little about what happened before the big bang nucleosynthesis, including how inflation and reheating took place. "We really don't have data about that," says Dienes.

In standard models of inflation, energy stored in the inflaton field starts the expansion. But it isn't clear exactly what this field is and why, after a tiny fraction of a second, it comes to an end. To explain that, physicists have to make a lot of assumptions, adding very specific features to the mysterious field. What's more, traditional inflation automatically dilutes both matter and radiation, leaving the universe cold and empty when it ends. To get around that, we have to assume that some sort of reheating process took place that populated the cosmos with matter and radiation again. Then, somehow, this period transitions to the radiation-dominated epoch of the traditional timeline.

If all that sounds like rather a post-hoc rationalisation, it is. Towers of particles which necessarily cause periods of stasis, however, could smooth things over. For example, particle towers produced during reheating would populate the universe with matter and radiation as they decay. Then, after the entire tower has decayed, only radiation would remain. "From this point forward, we would rejoin the standard timeline," says Dienes.

Similarly, decaying particle towers can naturally lead to a universe that contains a large proportion of vacuum energy. This would rapidly accelerate the expansion of the universe for a sustained period of time. In other words, according to the team's latest paper from June 2024, which is yet to be peer-reviewed, inflation could actually be a period of cosmic stasis.

Unlike conventional models of inflation, stasis explains how inflation ended without having to make extra assumptions. When the tower of particles has decayed, inflation ends of its own accord. And at that point, there would be loads of radiation present, so there is no need for reheating.

Proving the pause

Exploring periods of stasis is worthwhile, says string theorist Joseph Conlon at the University of Oxford. However, he points out that many of these models entail towers with very heavy particles that decay too quickly to have a cosmological impact. On the other hand, if the particles involved were light, they would produce large extra dimensions – and since those haven't yet been spotted, that is a mark against the hypothesis.

Still, there are several ways in which near-future observations could find evidence of cosmic stasis in its various forms, one of which involves gravitational waves. We now routinely detect these ripples in space-time, typically produced by the collision of massive objects such as black holes. And in 2023, a fainter hum called the gravitational wave background was detected. This lower-level oscillation of space-time may have been initiated during inflation, among other possibilities. In the next decade, space telescopes such as the Laser Interferometer Space Antenna (LISA) plan to map this background hum in detail in order to decipher its origin.

Dienes and his team are now figuring out how these observations would be affected by epochs of cosmic stasis. Adding new *e*-folds of time into the inflation epoch would change the predictions made by existing models, says Erickcek. Meanwhile, other periods of stasis would leave a unique imprint on the gravitational wave background, says Huang.

Another possibility is that early periods of cosmic stasis would alter how matter is structured on small scales because the presence of radiation tends to prevent matter from clumping. This means lumps of dark matter would be smaller than those predicted by standard cosmology.

Astrophysicists are becoming adept at detecting these slight differences by observing how dark matter warps the light from stars behind them, an effect called microlensing. Likewise, timing arrays based on pulsars, astronomical objects that emit bright bursts of radiation at well-defined intervals, can detect small changes due to gravitational tugs from lumps of dark matter. "It's hard – but there's hope," says Erickcek.

Already, others are beginning to explore the new paradigm of cosmic stasis. In August 2024, James Halverson and Sneh Pandya at Northeastern University in Massachusetts found that cosmic stasis arises from decaying towers of axions within models of string theory known as the axiverse.

Less than a century ago, the big bang seemed counterintuitive to most cosmologists. Now, the team who stumbled upon stasis hope that other researchers will embrace the unexpected once again and see that stillness may be as innate a part of the universe as change. Assuming that towers of particles exist, says Thomas, "some kind of stasis is likely going to be a part of nature". ∎

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