'We live in a universe that is just right for us': Study proposes a test for the Anthropic Principle

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https://commons.wikimedia.org/wiki/File:Multiverse.png. Credit: Silver Spoon

The Anthropic Principle—stating that the universe we live in is fine-tuned to host life—was first proposed by Brandon Carter in 1973. Since then, it has sparked significant debate.

Now, a paper published in the *Journal of Cosmology and Astroparticle Physics*, authored by Nemanja Kaloper, a physicist from the Department of Physics and Astronomy at the University of California, Davis, and Alexander Westphal, a professor at the Deutsches Elektronen-Synchrotron (DESY), describes for the first time a way to experimentally test this assumption.

The anthropic principle (AP) can be formulated in different ways. These range from a simple description of the facts—"if we are here observing it, the universe evolved with the conditions necessary for the emergence of intelligent life," known as the weak AP—to something a bit more radical: "the universe had to evolve in a way that led to our existence."

This stronger interpretation, called the strong AP, often ventures into metaphysical territory, suggesting a kind of "design" and moving beyond the realm of scientific inquiry into the universe.

The problem with the AP, according to many scientists, is that it is not particularly useful as a scientific tool because it does not generate testable, quantifiable predictions that could both expand our knowledge and subject the principle to scrutiny. Without this, it remains more of a philosophical conjecture than a scientific hypothesis.

The AP does, however, suggest that for our universe to develop as a hospitable place for carbon-based life, it must have started with a set of rather specific initial conditions. We infer this by observing, for example, the values of certain constants used in the equations that describe the universe—such as the gravitational constant, the electron charge, and Planck's constant—which must be "just right." Otherwise, we would have a very different and, most importantly, inhospitable universe.

By establishing the precise initial conditions implied by the AP and calculating, based on current physical models, how the universe would have evolved to its present state, we could compare the outcome to actual astronomical observations. Any discrepancies between theory and reality would provide a measure of the validity of the AP.

The new work by Nemanja Kaloper and Alexander Westphal offers some specific predictions that could find observational confirmation in the coming years.

To understand their proposal, some key elements in cosmological research must be outlined:

Cosmic inflation

In the earliest moments of its existence, the universe underwent a period of rapid expansion: in just 10^{-36} seconds, it grew from an infinitesimal size (almost zero) to a macroscopic scale (some theories describe it as the size of a grape or a soccer ball). After this, the expansion slowed down, continuing at rates similar to those we observe today.

The physics during this early phase was highly unusual, dominated by quantum phenomena (governing the infinitely small) that influenced the subsequent evolution, enabling the formation of structures—galaxies, stars, and so on—that we see today. Although direct evidence for cosmic inflation has not yet been found, it is a robust theory with anticipated observational confirmations in the coming years.

Dark matter

You've probably heard of it: experimental observations tell us that a significant portion of the universe—about five-sixths of its matter—is composed of something we cannot directly observe. We call it dark matter, but its true nature remains unknown. Many hypotheses have been proposed, all awaiting experimental confirmation, which is expected in the near future.

Axions

One of the candidates for dark matter is the axion. These particles—or, more likely, an entire class of particles—are extremely light (much lighter than the electron, for instance). Axions were initially proposed to explain a quantum phenomenon known as CP symmetry violation, which involves the weak nuclear interaction, one of the four fundamental forces (the others being gravity, electromagnetism, and the strong nuclear interaction).

However, researchers noticed that certain characteristics of axions—believed to have formed in great abundance during cosmic inflation—align with those expected for dark matter, such as their minimal interactions with both themselves and ordinary matter. Observations of black holes could confirm their existence in the coming years.

Testing the AP involves combining these three elements.

"It is possible that the LiteBIRD satellite discovers primordial gravity waves close to the current limits, which match high-scale inflation," explains Kaloper. "Most cosmologists would feel this confirms high-scale inflation." LiteBIRD (Lite (Light) Satellite for the Study of B-mode Polarization) is an experiment that the Japanese Aerospace Exploration Agency (JAXA) plans to launch in 2032.

"It is also possible that we discover signs of ultralight axions by surveying supermassive black holes in the universe. The axions affect the spin-to-mass ratio of black holes, and this could be observed," Kaloper continues. Many experiments are already studying black holes, with more set to begin operating in the near future.

"Finally," adds Kaloper, "it is possible that future direct dark matter searches discover that dark matter is predominantly not made up of ultralight axions. In which case, we'd think that the anthropic principle fails."

However, this outcome is not guaranteed.

"On the other hand, if direct dark matter searches find that dark matter is, in fact, ultralight axion," Kaloper continues, "then I think we'd agree that the anthropic principle in fact passed this test; indeed, this might happen."

"I find it particularly interesting that both of these options might be experimentally tested in the not-too-distant future," Kaloper concludes.

"And that—as far as my collaborator and I know—our specific example is the first case where the anthropic principle might actually fail the test, as opposed to simply declaring that it does not apply.

"The point is, that the presence of high-scale inflation and ultralight axions with masses $m > 10^{-19}$ eV would imply that dark matter 'must' be an axion: for typical initial conditions, we'd end up with way too much dark matter, and we'd desperately need the anthropic principle to constrain it.

"To find that axion is not dark matter, we'd infer that the initial conditions were not just unlikely (which can be fixed anthropically) but extremely unlikely, which really does not even fall under the domain of anthropic reasoning."

So, we will need to wait a few more years, perhaps even longer, to gather all the necessary evidence to either falsify or confirm the anthropic principle. But what if it proves unable to pass the test?

"Without changing any of the other premises (universality of gravity, early inflation and superradiant phenomena), the failure of our simple formulation of anthropics would suggest that different rules govern the initial conditions," explains Kaloper.

"Either different initial conditions are not equally probable, some being biased by new dynamics as yet not understood, or that some initial conditions are altogether impossible. Alternatively, the real theory of cosmology might be more complicated than we thought."

"One could also imagine more dramatic scenarios, but at least for now, to me those seem as flights of fancy," concludes Kaloper.

More information: Falsifying Anthropics, *Journal of Cosmology and Astroparticle Physics* (2024). iopscience.iop.org/article/10. … 475-7516/2024/12/017 , On Arxiv: arxiv.org/abs/2404.02993

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