# Cosmic tango between the very small and the very large

July 30 2020, by Gail McCormick

Tiny quantum fluctuations in the early universe explain two major mysteries about the large-scale structure of the universe, in a cosmic tango of the very small and the very large. A new study by researchers at Penn State used the theory of quantum loop gravity to account for these mysteries, which Einstein's theory of general relativity considers anomalous. Credit: Dani Zemba, Penn State

While Einstein's theory of general relativity can explain a large array of fascinating astrophysical and cosmological phenomena, some aspects of the properties of the universe at the largest-scales remain a mystery. A new study using loop quantum cosmology—a theory that uses quantum mechanics to extend gravitational physics beyond Einstein's theory of general relativity—accounts for two major mysteries. While the differences in the theories occur at the tiniest of scales—much smaller than even a proton—they have consequences at the largest of accessible scales in the universe. The study, which appears online July 29 in the journal *Physical Review Letters*, also provides new predictions about the universe that future satellite missions could test.

While a zoomed-out picture of the universe looks fairly uniform, it does have a large-scale structure, for example because galaxies and dark matter are not uniformly distributed throughout the universe. The origin of this structure has been traced back to the tiny inhomogeneities observed in the Cosmic Microwave Background (CMB)—radiation that was emitted when the universe was 380 thousand years young that we can still see today. But the CMB itself has three puzzling features that are considered anomalies because they are difficult to explain using known physics.

"While seeing one of these anomalies may not be that statistically remarkable, seeing two or more together suggests we live in an exceptional universe," said Donghui Jeong, associate professor of astronomy and astrophysics at Penn State and an author of the paper. "A recent study in the journal Nature Astronomy proposed an explanation for one of these anomalies that raised so many additional concerns, they flagged a 'possible crisis in cosmology.' Using quantum loop cosmology, however, we have resolved two of these anomalies naturally, avoiding that potential crisis."

Research over the last three decades has greatly improved our understanding of the early universe, including how the inhomogeneities in the CMB were produced in the first place. These inhomogeneities are a result of inevitable quantum fluctuations in the early universe. During a highly accelerated phase of expansion at very early times—known as inflation—these primordial, miniscule fluctuations were stretched under gravity's influence and seeded the observed inhomogeneities in the CMB.

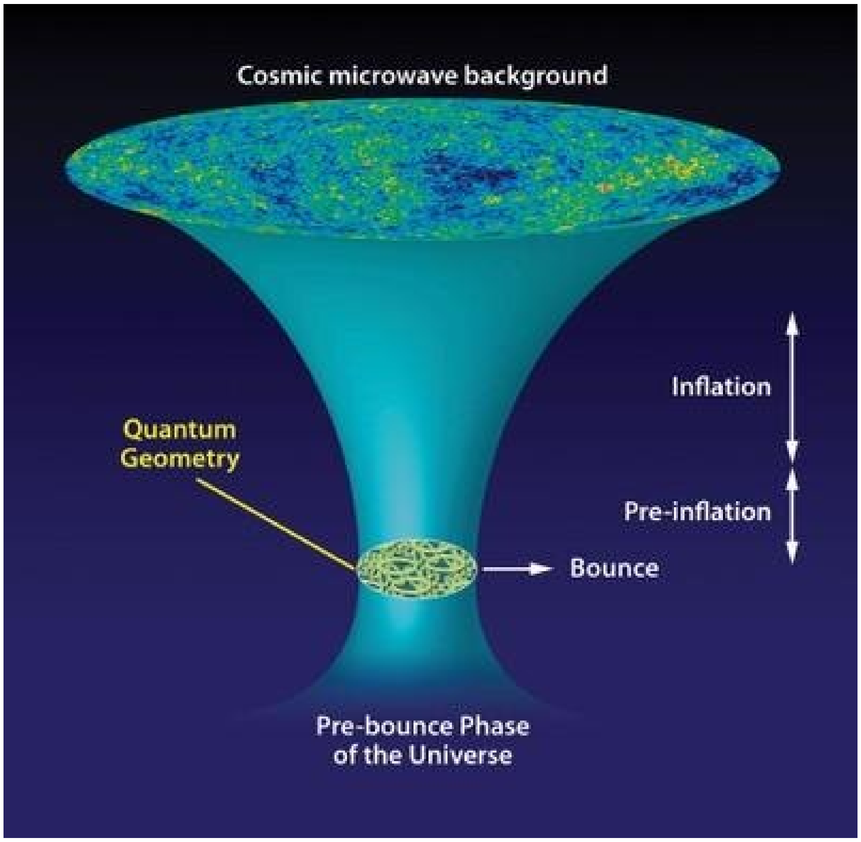

Diagram showing evolution of the Universe according to the paradigm of Loop Quantum Origins, developed by scientists at Penn State. Credit: Alan Stonebraker. P. Singh, Physics 5, 142 (2012); APS/A. Stonebraker

"To understand how primordial seeds arose, we need a closer look at the early universe, where Einstein's theory of general relativity breaks down," said Abhay Ashtekar, Evan Pugh Professor of Physics, holder of the Eberly Family Chair in Physics, and director of the Penn State Institute for Gravitation and the Cosmos. "The standard inflationary paradigm based on general relativity treats space time as a smooth continuum. Consider a shirt that appears like a two-dimensional surface, but on closer inspection you can see that it is woven by densely packed one-dimensional threads. In this way, the fabric of space time is really woven by quantum threads. In accounting for these threads, loop quantum cosmology allows us to go beyond the continuum described by general relativity where Einstein's physics breaks down—for example beyond the Big Bang."

The researchers' previous investigation into the early universe replaced the idea of a Big Bang singularity, where the universe emerged from nothing, with the Big Bounce, where the current expanding universe emerged from a super-compressed mass that was created when the universe contracted in its preceding phase. They found that all of the large-scale structures of the universe accounted for by general relativity are equally explained by inflation after this Big Bounce using equations of loop quantum cosmology.

In the new study, the researchers determined that inflation under loop quantum cosmology also resolves two of the major anomalies that appear under general relativity.

"The primordial fluctuations we are talking about occur at the incredibly small Planck scale," said Brajesh Gupt, a postdoctoral researcher at Penn State at the time of the research and currently at the Texas Advanced Computing Center of the University of Texas at Austin. "A Planck length is about 20 orders of magnitude smaller than the radius of a proton. But corrections to inflation at this unimaginably small scale simultaneously explain two of the anomalies at the largest scales in the universe, in a cosmic tango of the very small and the very large."

The researchers also produced new predictions about a fundamental cosmological parameter and primordial gravitational waves that could be tested during future satellite missions, including LiteBird and Cosmic Origins Explorer, which will continue improve our understanding of the early universe.

**More information:** Abhay Ashtekar et al, Alleviating the Tension in the Cosmic Microwave Background using Planck-Scale Physics, *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.125.051302

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