

Ripples in Space: How Quantum Wiggles Grew into the Cosmic Web

From Yikai Zhu to my 12-year-old self

I'm now a graduate student working at the intersection of particle physics and cosmology. This field is unique and attractive for two main reasons. To begin with, it joins the tiniest laws of nature (particle physics) with the largest structures ever seen (our Universe). Another reason is that cosmology is not an experimental science in the usual laboratory sense. Just like palaeontologists dig deep into the earth and rock to study ancient plants and animals, cosmologists use large expensive telescopes to look into deep space. Because light travels at a limited speed, we can't see the current status of a distant object. Rather, we see a snapshot of its history. So the farther we look into space, the earlier the stage of universe we observe. Imagine possessing an omnipotent eye: you could see the entire history of the universe simply by staring at the sky.

There is an abundance of exciting topics in this field. But here I elaborate on one that appeals to me the most—the possible quantum origin of the structure of our universe.

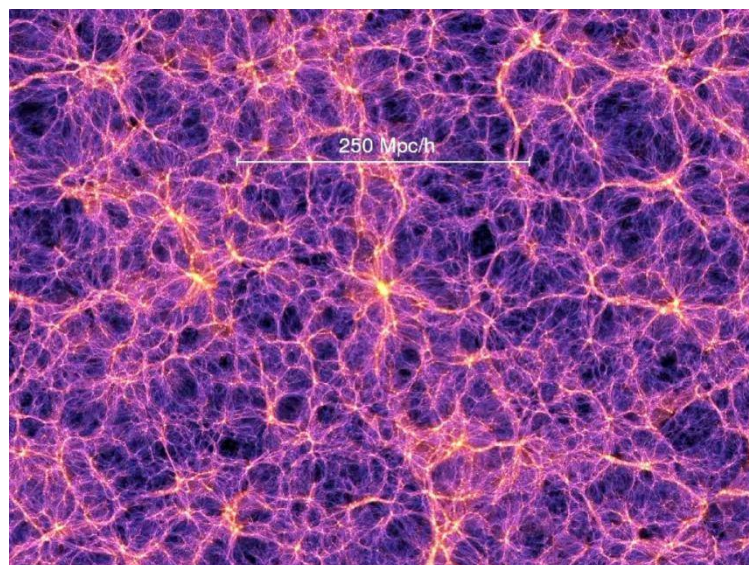


Image 1 A three-dimensional, simulated visualization of the Universe showing galaxies organized into the cosmic web[1]

Above is the cosmic web that contains hundreds of billions of galaxies spread across vast filaments and clusters in our observable universe. Roughly, each of these galaxies resembles our Milky Way Galaxy. Each contains hundreds of billions of solar systems just like the one we call home. Despite these structures, our universe looks almost perfectly homogeneous on the largest observable scale. This fact is even more striking when you look at what is known as the Cosmic Microwave Background (CMB). It is an ancient afterglow of the hot Big Bang plasma: faint radio-like light that fills every direction in the sky, released when the Universe was only 380 000 years old—long before the first stars formed. Sensitive satellites map it as a mottled pattern of warmer and cooler spots, which is amplified in the figure below. The actual magnitude of fluctuation is just one in a hundred thousand. It's as if God sprinkled frosting on his perfectly smooth cake— though, admittedly, the green color might not be the most appetizing.

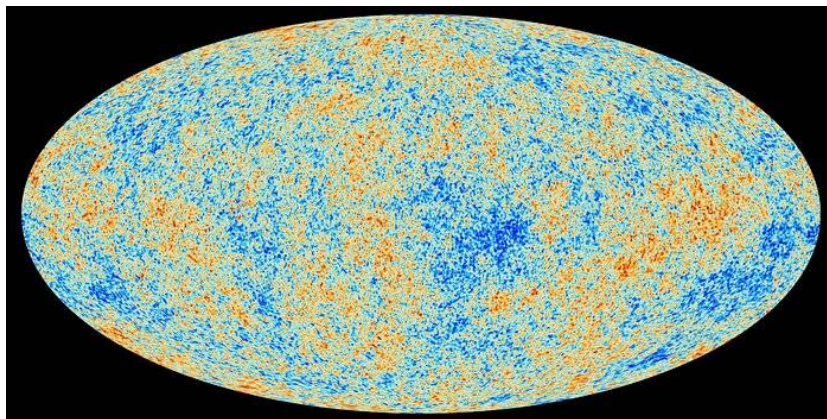


Image 2 Cosmic Microwave Background[2]

If you're a little confused by some of the terminology essential to cosmology — such as 'the Big Bang' — I recommend the popular book *The First Three Minutes* by Steven Weinberg. I barely knew any modern physics after the 1940s until the later years of my undergraduate studies. Reading popular-science books like these would have exposed me to these exciting ideas much earlier and given me a great head start. I would have greatly appreciated it if someone had introduced similar resources to me when I was 12 years old. I also encourage you to learn mathematics early and as much as you like, taking advantage of youth and ample time. It will give you a free commute pass during your journey in physics.

Now, back to the main topic. There is something unsettling about the Big Bang. We know gravity is attractive, and indeed, for ordinary matter the cosmic expansion should be decelerating. That is, something must have given our universe a kick-off. We must understand the initialization of the Big Bang! People are even more shocked to find what is called the homogeneity problem.

To understand the homogeneity problem, let's simulate cosmic expansion on a large, steadily stretching rubber sheet. The speed of light, although the fastest in nature, is actually unimpressive on cosmic scales—rather like ants crawling on Earth. Imagine an ant moving slowly on this rubber sheet. Assuming steady stretching, we can calculate the furthest point this ant can reach in a given time window. Yet when we look, the ant has travelled so much further than we expected. Then, the only possible explanation is that someone must have given the rubber sheet a sharp tug. In our universe, the ant becomes light—the fastest messenger that can exchange information between different areas. Noting that information has been exchanged between areas more distant than expected, physicists believe that our Universe must have experienced such a sharp tug, now termed inflation. If our understanding of the laws of gravity (general relativity) and physics is correct on the largest scale, inflation must have happened.

Inflation is a beautiful theory that provides a simultaneous solution to multiple problems of the Big Bang, including the homogeneity problem mentioned earlier. Yet its details remain unknown. Above this almost perfectly homogeneous background, there are still small fluctuations in both light (CMB) and matter. For matter, these little fluctuations eventually grew into lumps that collapsed into stars and galaxies; for CMB, the relic pattern is more transparent. Large-scale homogeneity and small-scale fluctuations—such a separation of scale—at first sight, is a bit unusual. It's as if some invisible force constrained, or fine tuned these fluctuations. But such scenario arises naturally if we consider quantum fluctuations—random, unavoidable, tiny jitters of

energy that even empty space cannot keep still. Each speck of quantum dust was stretched from sub-atomic size to something as large as the distance between today's stars, by inflation. This is another triumph of the inflation theory: it provides a natural explanation of the origin of cosmic structure.

You might now be wondering — where do I, as a graduate student at Utokyo, fit into all this? Part of my research is trying to find a way to ascertain the truth of a quantum seeded structure. This is called the cosmological Bell test. The name comes from the famous 2022 Nobel Prize winning Bell test, which studies special properties of quantum states which resemble nothing in our daily experience. Unfortunately, details of my research are beyond the scope of an essay targeted at 12-yo audience. Beyond the grand narratives, the true magic of physics lies in the details. And you have to see it with your own eyes and mind.

I hope the reader finds this very short essay informative and illuminating. It covers only a tiny corner of what people do in particle physics and cosmology—or theoretical physics in general. I haven't touched on dark matter and dark energy either, which are the most prominent mysteries in modern physics. The intended readers are around twelve years old, so you've still got a long way to go before fully grasping these topics. But trust me, the view is worth the effort, and you will find your own niche along the way,—probably in something not mentioned here or even remotely related to these topics.

References

- [1]Source: https://wwwmpa.mpa-garching.mpg.de/galform/data_vis Credit: Credit: Springel et al. (Virgo Consortium), the Max-Planck-Institute for Astrophysics
- [2]Source: <https://noirlab.edu/public/images/CMB/> Credit: ESA and the Planck Collaboration