Quanta magazine

Clashing Cosmic Numbers Challenge Our Best Theory of the Universe

By Liz Kruesi

January 19, 2024

As measurements of distant stars and galaxies become more precise, cosmologists are struggling to make sense of sparring values.

Scientists working to solve the biggest puzzle of them all — how the universe works — are running into trouble.

Kouzou Sakai for *Quanta Magazine*

In the early 2000s, it seemed that cosmologists had solved the largest and most complex puzzle of all: how the universe works.

"There was this amazing moment when all of a sudden, all the pieces in cosmology snapped together," said J. Colin Hill, a theoretical cosmologist at Columbia University.

All the ways of studying the universe — mapping galaxies and their larger structures, catching catastrophic stellar explosions called supernovas, calculating distances to variable stars, measuring the residual cosmic glow from the early universe — told stories that "seemed to overlap," Hill said.

The glue that held the stories together had been discovered a few years earlier, in 1998: dark energy, a mysterious force that, rather than gluing the cosmos together, is somehow causing it to expand ever more speedily instead of slowing down over time. When scientists included this cosmic something in their models of the universe, theories and observations meshed. They drafted what is now known as the standard model of cosmology, called Lambda-CDM, in which dark energy makes up nearly 70% of the universe, while another mysterious dark entity — a type of invisible mass that seems to interact with normal matter only through gravity — makes up about 25%. The remaining 5% is everything we can see: the stars, planets and galaxies that astronomers have studied for millennia.

But that moment of tranquility was only a brief respite between times of struggle. As astronomers made more precise observations of the universe across the sweep of cosmic time, cracks began to appear in the standard model. Some of the first signs of trouble came from measurements of variable stars and supernovas in a handful of nearby galaxies — observations that, when compared with the residual cosmic glow, suggested that our universe plays by different rules than we thought, and that a crucial cosmological parameter that defines how fast the universe is flying apart changes when you measure it with different yardsticks.

Cosmologists had a problem — something they called a tension, or, in their more dramatic moments, a crisis.

Atop Hawai‘i’s Maunakea, the Subaru Telescope (far left) recently completed a five-year survey of millions of galaxies.

Alamy Stock Photo

Those discordant measurements have only become more distinct in the decade or so since the first cracks emerged. And this discrepancy isn’t the only challenge to cosmology’s standard model. Observations of galaxies suggest that the way in which cosmic structures have clumped together over time may differ from our best understanding of how today’s universe should have grown from seeds embedded in the early cosmos. And even more subtle mismatches come from detailed studies of the universe’s earliest light.

Other inconsistencies abound. “There are many more smaller problems elsewhere,” said Eleonora Di Valentino, a theoretical cosmologist at the University of Sheffield. “This is why it’s puzzling. Because it’s not just these big problems.”

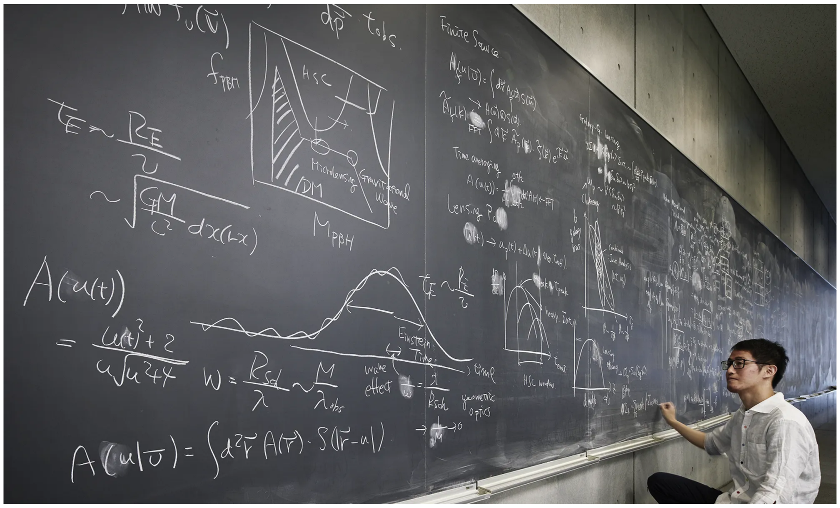
To alleviate these tensions, cosmologists are taking two complementary approaches. First, they’re continuing to make more precise observations of the cosmos, in the hope that better data will reveal clues as to how to proceed. In addition, they are finding ways to subtly tweak the standard model to accommodate the unexpected results. But these solutions are often contrived, and if they solve one problem they often make others worse.

“The situation right now seems like a big mess,” Hill said. “I don’t know what to make of it.”

Warped Light

To characterize our universe, scientists use a handful of numbers, which cosmologists call parameters. The physical entities that these values refer to are all gears in a giant cosmic machine, with each bit connected to the others.

One of those parameters relates to how strongly mass clumps together. That, in turn, tells us something about how dark energy operates, as its accelerating outward push conflicts with the gravitational pull of cosmic mass. To quantify clumpiness, scientists use a variable called S_8. If the value is zero, then the universe has no variation and no structure, explained Sunao Sugiyama, an observational cosmologist at the University of Pennsylvania. It’s like a flat, featureless prairie, with not even an anthill to break up the landscape. But if S_8 is closer to 1, the universe is like a huge, jagged mountain range, with massive clumps of dense matter separated by valleys of nothingness. Observations made by the Planck spacecraft of the very early universe — where the first seeds of structure took hold — find a value of 0.83.



Sunao Sugiyama of the University of Pennsylvania led an analysis suggesting that matter could be distributed throughout the cosmos a bit differently than theories predict.

Koji Okumura/ Forward Stroke Inc.

But observations of recent cosmic history don't quite agree.

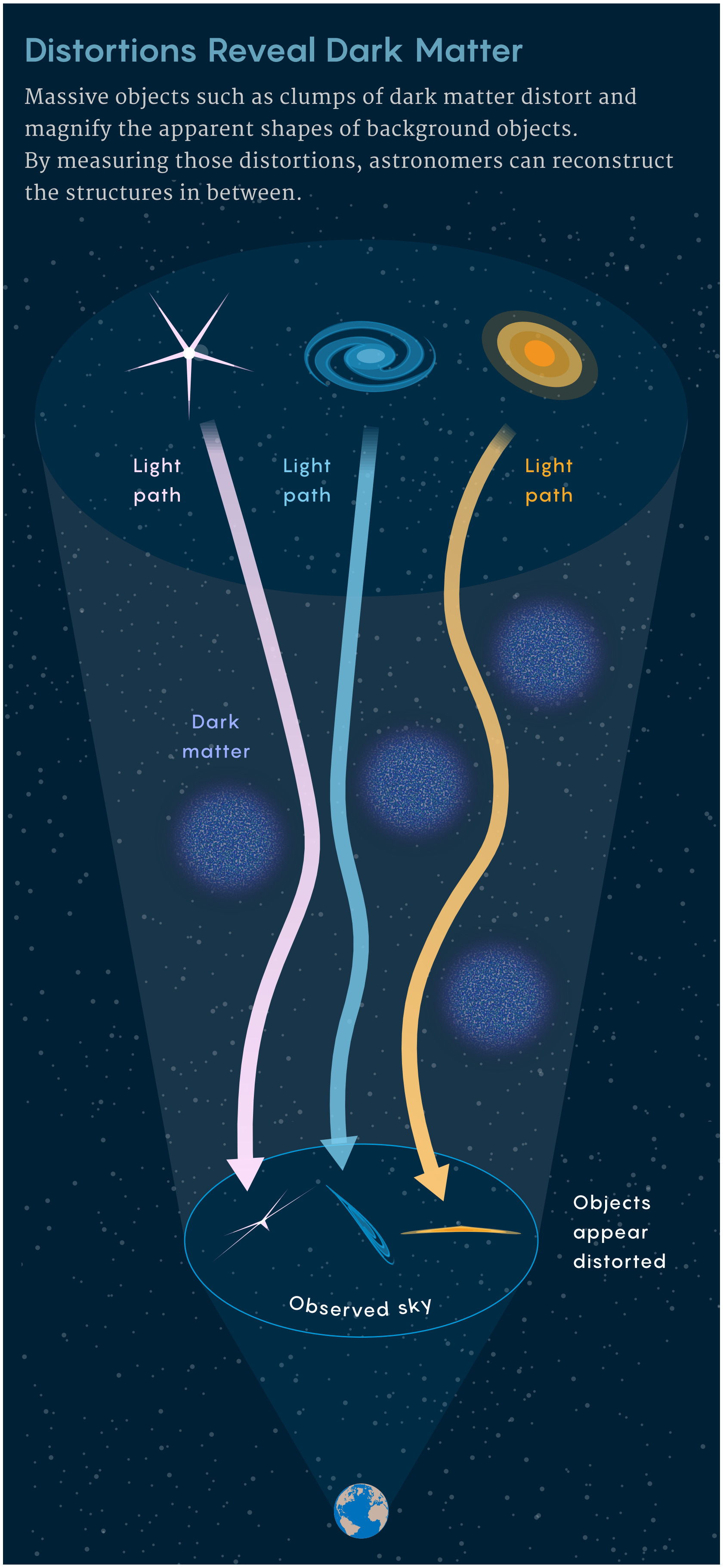
To compare the clumpiness in today's universe with measurements of the infant cosmos, researchers survey how matter is distributed over large swaths of sky.

Accounting for visible galaxies is one thing. But mapping the invisible network upon which those galaxies lie is another. To do that, cosmologists look at tiny distortions in the galaxies' light, because the path light takes as it weaves through the cosmos is warped as the light is deflected by the gravitational heft of invisible matter.

By studying these distortions (known as weak gravitational lensing), researchers can trace the distribution of dark matter along the paths the light took. They can also estimate where the galaxies are. With both bits of information in hand, astronomers create 3D maps of the universe's visible and invisible mass, which lets them measure how the landscape of cosmic structure changes and grows over time.

Over the past few years, three weak-lensing surveys have mapped large patches of the sky: the Dark Energy Survey (DES), which uses a telescope in Chile's Atacama desert; the Kilo-Degree Survey (KIDS), also in Chile; and most recently, a five-year survey from the Subaru Telescope's Hyper Suprime-Cam (HSC) in Hawaiʻi.

A few years ago, the DES and KIDS surveys produced S_8 values lower than Planck's — implying smaller mountain ranges and lower peaks than what the primordial cosmic soup set up. But those were just tantalizing hints of flaws in our understanding of how cosmic structures grow and conglomerate. Cosmologists needed more data and were eagerly awaiting the Subaru HSC results, which were published in a series of five papers in December.


Distortions Reveal Dark Matter
Massive objects such as clumps of dark matter distort and magnify the apparent shapes of background objects.
By measuring those distortions, astronomers can reconstruct the structures in between.
Light path
Light path
Light path
Dark matter
Objects appear distorted
Observed sky

Merrill Sherman/*Quanta Magazine*

The Subaru HSC team surveyed tens of millions of galaxies covering about 416 square degrees on the sky, or the equivalent of 2,000 full moons. In their patch of sky, the team calculated an S_8 value of 0.78 — in line with the initial results from earlier surveys, and smaller than the measured value from the Planck telescope's observations of the early universe's radiation. The Subaru team is careful to say that their measurements only "hint" at a tension because they haven't quite reached the level of statistical significance that scientists rely on, although they're working on adding another three years of observations to their data.

"If this S_8 tension is really true, there's something which we do not understand yet," said Sugiyama, who led one of the Subaru HSC analyses.

Cosmologists are now poring over the details of the observations to suss out sources of uncertainty. For starters, the Subaru team estimated the distances to most of their galaxies based on their overall color, which could lead to inaccuracies. "If you got the [average] distance estimates wrong, you would get some of your cosmological parameters you care about wrong as well," said team member Rachel Mandelbaum of Carnegie Mellon University.

On top of that, these measurements aren't easy to make, with subtle complexities in interpretation. And the difference between a galaxy's warped appearance and its actual shape — the key to identifying invisible mass — is often very small, said Diana Scognamiglio of NASA's Jet Propulsion Laboratory. Plus, blurring from Earth's atmosphere can slightly alter the shape of a galaxy, which is one of the reasons why Scognamiglio is leading a weak-lensing analysis using NASA's James Webb Space Telescope.

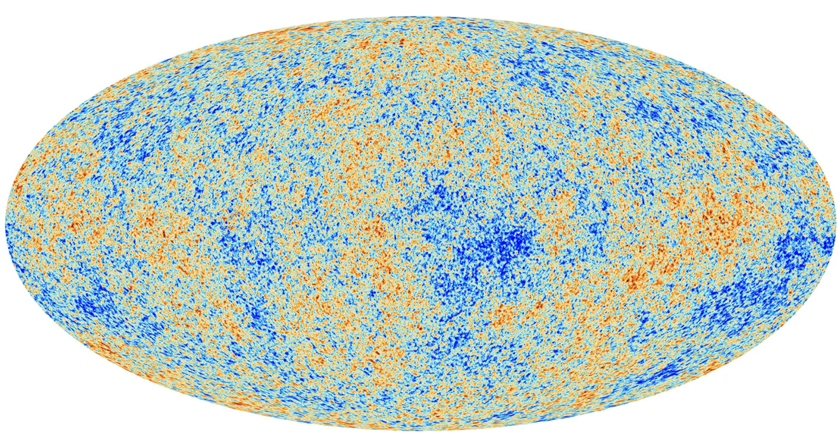
Adding more confusion, scientists with the DES and KIDS teams recently reanalyzed their measurements together and derived an S_8 value closer to the Planck results.

So for now, the picture is messy. And some cosmologists aren't yet convinced that the various S_8 measurements are in tension. "I don't think there's an obvious hint of a major catastrophic failure there," Hill said. But, he added, "it's not implausible that there could be something interesting going on."

Where Cracks Are Evident

A dozen years ago, scientists saw the first hints of trouble with measurements of another cosmological parameter. But it took years to accumulate enough data to convince most cosmologists that they were dealing with a full-on crisis.

In brief, measurements of how fast the universe is expanding today — known as the Hubble constant — don't match the value you get when extrapolating from the early universe. The conundrum has become known as the Hubble tension.



The cosmic microwave background, seen here as measured by the Planck mission, is an imprint of the first light that traveled freely in the infant universe.

ESA and the Planck Collaboration

To calculate the Hubble constant, astronomers need to know how far away things are. In the nearby cosmos, scientists measure distances using stars called Cepheid variables that periodically change in brightness. There's a well-known relationship between how fast one of these stars swings from brightest to faintest and how much energy it radiates. That relation, which was discovered in the early 20th century, allows astronomers to calculate the star's intrinsic brightness, and by comparing that to how bright it appears, they can calculate its distance.

Using these variable stars, scientists can measure the distances to galaxies up to about 100 million light-years from us. But to see a bit farther away, and a bit further back in time, they use a brighter mile marker — a specific type of stellar explosion called a type Ia supernova. Astronomers can also calculate the intrinsic brightness of these "standard candles," which allows them to measure distances to galaxies billions of light-years away.

Over the past two decades, these observations have helped astronomers pin a value on how fast the nearby universe is expanding: roughly 73 kilometers per second per megaparsec, which means that as you look further away, for each megaparsec (or 3.26 million light-years) of distance, space is flying away 73 kilometers per second faster.

But that value clashes with one derived from another ruler embedded in the infant universe.

In the very beginning, the universe was searing plasma, a soup of fundamental particles and energy. "It was a hot mess," said Vivian Poulin-Détolle, a cosmologist at the University of Montpellier.

A fraction of a second into cosmic history, some occurrence, perhaps a period of extreme acceleration known as inflation, sent jolts — pressure waves — through the murky plasma.

Then, as the universe cooled, light that was trapped in the elemental plasma fog finally broke free. That light — the cosmic microwave background, or CMB — reveals those early pressure waves, just as the surface of a frozen lake holds onto the overlapping crests of waves frozen in time, Poulin-Détolle said.

Cosmologists have measured the most common wavelength of those frozen pressure waves and used it to calculate a value for the Hubble constant of 67.6 km/s/Mpc, with an uncertainty of less than 1%.

The peculiarly discordant values — roughly 67 versus 73 — have ignited a fiery debate in cosmology that is still unresolved.

Astronomers are turning to independent cosmic mile markers. For the past six years, Wendy Freedman of the University of Chicago (who has worked on the Hubble constant for a quarter century) has focused on a type of old, red star that typically lives in the outer portions of galaxies. Out there, fewer overlapping bright stars and less dust can lead to clearer measurements. Using those stars, Freedman and her colleagues have measured an expansion rate of around 70 km/s/Mpc — "which is actually in pretty good agreement with the Cepheids," she said. "But it's also in pretty good agreement with the microwave background."

Wendy Freedman, a cosmologist at the University of Chicago, is using multiple cosmic mile markers to measure how fast the universe is expanding.

Nancy Wong

She has now turned to JWST's powerful infrared eye to approach the problem. With her colleagues, she is measuring distances to these giant red stars in 11 nearby galaxies while simultaneously measuring the distances to Cepheids and a type of pulsating carbon star in those same galaxies. They expect to publish the results sometime this spring, but already, she said, "the data look really spectacular."

"I'm very interested to see what they find," said Hill, who works to understand models of the universe. Will these new observations widen the cracks in cosmology's favorite model?

A New Model?

As observations continue to constrain these crucial cosmological parameters, scientists are trying to fit the data to their best models of how the universe works. Perhaps more precise measurements will solve their problems, or maybe the tensions are just an artifact of something mundane, like quirks of the instruments being used.

Or maybe the models are wrong, and new ideas — “new physics” — will be needed.

“Either we haven’t been clever enough to come up with a model that actually fits everything,” Hill said, or “there may be, in fact, multiple pieces of new physics at play.”

J. Colin Hill, a theoretical cosmologist at Columbia University, is trying to resolve a disagreement between astronomical observations and our standard model of how the universe works.

John Smock/Simons Foundation

What might they be? Perhaps a new fundamental force field, Hill said, or interactions among dark matter particles that we don’t yet understand, or new ingredients that aren’t yet part of our description of the universe.

Some new physics models tweak dark energy, adding a surge of cosmic acceleration in the early moments of the universe, before electrons and protons glommed onto each other. “If the expansion rate could somehow be increased, just a little bit for a little while in the early universe,” said Marc Kamionkowski, a cosmologist at Johns Hopkins University, “you can resolve the Hubble tension.”

Kamionkowski and one of his graduate students proposed the idea in 2016, and two years later they outlined some signatures that a high-resolution cosmic microwave background telescope should be able to see. And the Atacama Cosmology Telescope, perched on a mountain in Chile, did see some of those signals. But since then, other scientists have shown that the model creates problems with other cosmic measurements.

That kind of fine-tuned model, where an additional type of dark energy surges for a moment and then fades out, is too complicated to explain what’s happening, said Dragan Huterer, a theoretical cosmologist at the University of Michigan. And other proposed solutions to the Hubble tension tend to match observations even more poorly. They’re “hopelessly tuned,” he said, like just-so stories that are too specific to be in step with the long-held idea that simpler theories tend to win out against complex ones.

Data coming in the next year may help. First up will be the results from Freedman’s team looking at different probes of the nearby expansion rate. Then in April, researchers will reveal the first data from the largest cosmological sky survey to date, the Dark Energy Spectroscopic Instrument. Later in the year, the Atacama Cosmology Telescope team — and researchers making another primordial background map using the South Pole Telescope — will likely release their detailed results of the microwave background at higher resolution. Observations on the more distant horizon will come from the European Space Agency’s Euclid, a space telescope that launched in July, and the Vera C. Rubin Observatory, an all-sky mapping machine being built in Chile that will be fully operational in 2025.

The universe might be 13.8 billion years old, but our quest to understand it — and our place within it — is still in its infancy. Everything in cosmology fit together just 15 years ago, in a brief period of tranquility that turned out to be a mirage. The fissures that appeared a decade ago have split wide open, creating bigger rifts in cosmology's favorite model.

"Now," Di Valentino said, "Everything has changed."

Editor's note: Multiple scientists mentioned in this article have received funding from the Simons Foundation, which also funds this editorially independent magazine. Simons Foundation funding decisions have no influence on our coverage. More details are available here.