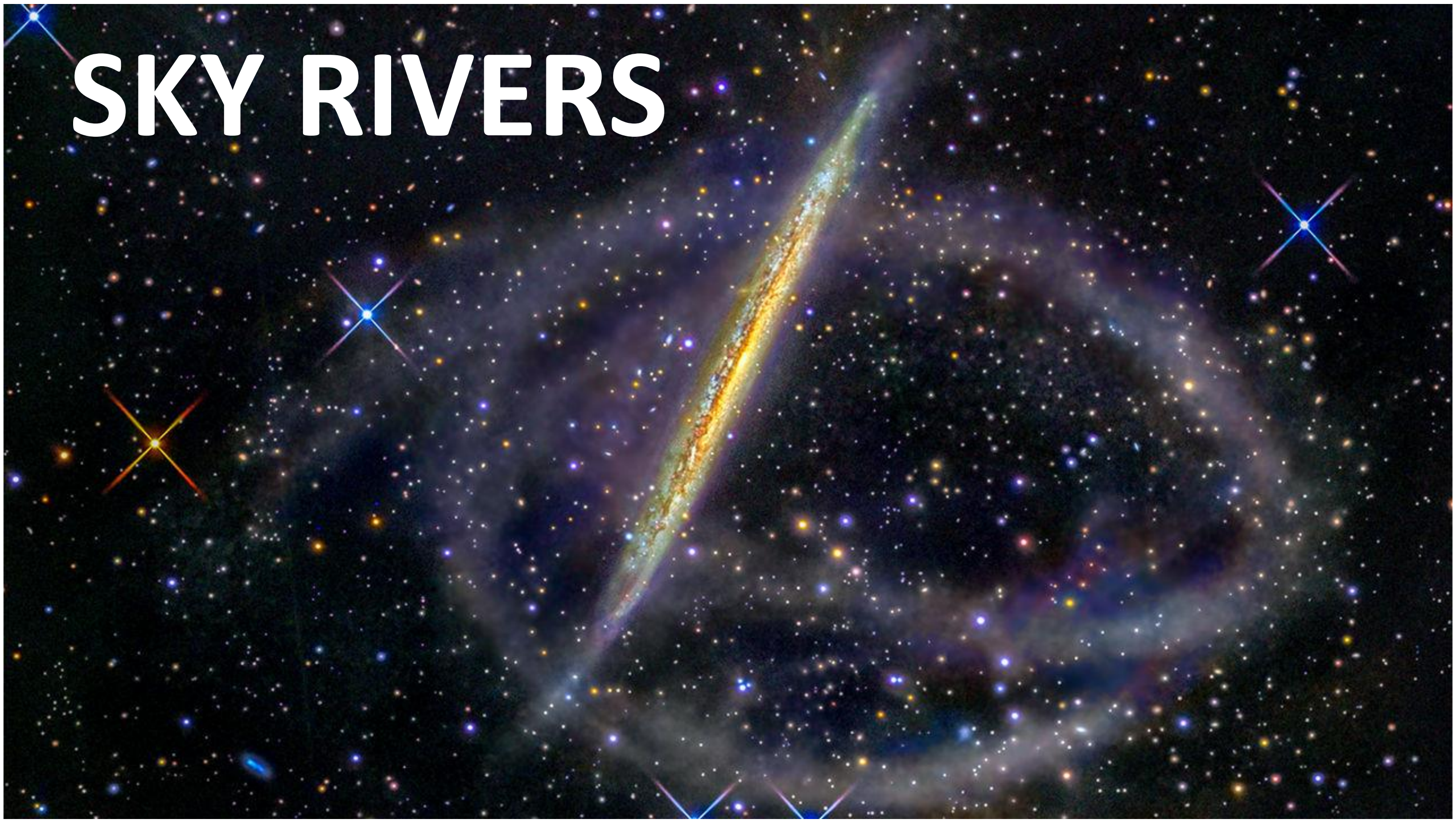


SKY RIVERS

Streams of stars surround the galaxy NGC 5907, relics of a shredded dwarf galaxy. Dozens of streams have recently been found around the Milky Way. R. JAY GABANY/COSMOTOGRAPHY

Streams of stars reveal the galaxy’s violent history—and perhaps its unseen dark matter

By Eric Hand
Oct. 4, 2018 , 9:30 AM

At 4 a.m. on Zero Day, Ana Bonaca woke up in her Manhattan hotel in a state of excitement. She made her way through the hushed streets of New York City with several other early bird astronomers. "It was still dark, and raining," says Bonaca, a Harvard University postdoc. At the Flatiron Institute, a new and lavishly funded center for computational science, they settled into a conference room on the empty third floor. The hunt for galactic ghosts—witnesses to the Milky Way's violent history—was about to begin.

Zero Day was the name for an impending data release from Gaia, a European Space Agency satellite mapping the Milky Way. At 6 a.m. on 25 April, the mission was to release positions and motions for more than a billion stars, all at once, as a model of open science and a way to prod publication-hungry astronomers into action. "It was a radical way to release the data," says Adrian Price-Whelan, a Princeton University postdoc who also arrived early at the Flatiron

Institute. "Everyone felt pressure." By day's end, nearly 70 astronomers would converge there, some from as far away as Australia, to sift through the data together.

Many planned to study the stars of the Milky Way's whirling disk. But Bonaca and Price-Whelan's interests were farther afield. They would be examining the galaxy's halo, a sparse and roughly spherical region of stars that envelops the disk like a snow globe. Stretching across that firmament, they knew, were stellar streams: the filamentous remains of neighboring small galaxies and star clusters that had been disemboweled as they fell into the Milky Way's gravitational grasp. "They're almost like necklaces of stars," Bonaca says.

With astronomical surveys like Gaia pushing into the far reaches of the Milky Way's halo, the study of stellar streams is entering a golden age. Even before Gaia, astronomers were finding streams in data from ground-based observing campaigns such as the Sloan Digital Sky Survey and the Dark Energy Survey. "There has been an explosion in the number of streams that has been accelerating as more surveys come out," says Kathryn Johnston, a galactic dynamicist at Columbia University. In just the past 2 years, the count has more than doubled, passing 60.

It is more than mere stamp collecting, says Vasily Belokurov, an astronomer at the University of Cambridge in the United Kingdom. "Before, we were looking at them in awe," he says. "Now, we are starting to use them as tools." The streams are particularly useful for what astronomers call galactic archaeology—rewinding the cosmic clock to reconstruct the assembly of the Milky Way. They also are being used as exquisitely sensitive scales to measure the galaxy's mass.

The third possible application for stellar streams is perhaps the most intriguing. Patrolling the outskirts of the galaxy's halo, the streams are well-positioned to reveal the presence of dark matter, the unseen stuff thought to dominate ordinary matter by a ratio of nearly six to one. Because the streams are so fragile, theorists say, collisions with marauding clumps of dark matter could leave telltale scars, potential clues to its nature.

One stream in particular interested Bonaca and Price-Whelan, who knew each other but had never collaborated. As Zero Day began, David Hogg, an astronomer at New York University in New York City who helped organize the Flatiron workshop, suggested they see what Gaia had to say about GD1, one of the longest and most slender streams in the sky. GD1 had been studied since its discovery in 2006, but Hogg wondered whether there might be surprises in the sharper picture that Gaia promised. "We didn't appreciate the scope of his intuition until much later," Price-Whelan says.

“Before, we were looking at them in awe. Now, we are starting to use them as tools.”

Vasily Belokurov, University of Cambridge

The accepted story of our galaxy goes like this: Soon after the big bang 13.8 billion years ago, dark matter coalesced under its own gravity into a cosmic web of clumps and filaments. Ordinary matter—clouds of hydrogen gas—settled into those gravitational wells and ignited to form the first stars, nestled in the first, small galaxies. Bigger galaxies like our own grew [by gobbling up their small neighbors]().

Several hundred miniature galaxies and star clusters still orbit the Milky Way today, and astronomers have long looked for evidence that they are succumbing to our galaxy's gravity. The first sign would be "tidal tails"—growths on opposite sides of the satellite galaxies and clusters, analogous to the bulging ocean tides on opposite sides of Earth. On Earth, the ocean tide on the side facing the sun or moon is intuitive: Gravity is stronger there. But the tide bulges on the opposite side, too, where gravity is weaker, as the solid earth is tugged out from under the ocean. Replace the sun or moon with the Milky Way, and the same mechanism shapes the satellites.

In the 1990s, computer models showed the tails were just the beginning. Under the Milky Way's influence, stars would unspool from both sides of a satellite until the thread ran out. Crucially, the models showed that the streams could persist for billions of years, through multiple galactic orbits, before being shredded into anonymity. Therefore, many of the Milky Way's recent acquisitions should still be visible. "My generation was the one that realized we should start seeing them around our own galaxy," Johnston says. "And then indeed we did."

Astronomers first saw star streams veiling the fringes of nearby large galaxies. Discerning those tenuous smears of stars around our own galaxy is far harder, given Earth's vantage inside the Milky Way's star-rich disk. Yet in 1994, astronomers stumbled on the first homegrown example: Sagittarius, named after the constellation in which it was discovered. It was a lumpy dwarf galaxy in the final throes of being devoured, hanging off the bottom of the Milky Way. At first, researchers saw mere hints of it. But in 2003, an infrared survey sensitive to the rare, red giant stars in the stream showed how it wraps around the Milky Way like a claw.

Gravity's rainbows

The Milky Way's gravity stretches satellite galaxies and star clusters into long, slender streams. They show how galaxies grow by consuming their neighbors, and can be used to measure our galaxy's mass. Furthermore, gaps in the streams could mark the sites of encounters with dark matter, the unseen stuff that constitutes 85% of the universe's mass.

A halo of darkness

The Milky Way resides in a vast halo of dark matter that could be anywhere from semispherical to globe shaped. Star streams could yield clues to its shape, and whether it contains subhalos—denser clumps of dark matter.

Palomar 5 (Pal5) stream

Pal5 was discovered in 2001 as the first thin stream formed from a globular cluster. Its current orbit takes it far over the galactic center.

Globular clusters

These hives typically hold 100,000 stars or fewer and give rise to long, thin streams.

GD-1 stream

Discovered in 2006, GD-1 is the longest known thin stream, stretching across more than half the northern sky. It contains a gap that could be the scar of a dark matter collision 500 million years ago.

Dwarf galaxy

With millions of stars, dwarf galaxies form fatter streams.

Drawn and quartered

Streams are created by the tidal forces of the Milky Way's gravity. Gaps in streams could point to dark matter encounters.

Stream formation

1 A dwarf galaxy or globular cluster strays too close to the galaxy.

2 Tidal tails form because of differences in the pull of the Milky Way on opposite sides.

3 The leading and trailing tails rotate to parallel the satellite galaxy's orbit.

Gap formation

1 A mature stream orbits around the Milky Way.

2 A dark matter subhalo crosses the stream, causing fishhook-shaped spurs to form.

3 The spurs settle back into the stream, leaving a gap between thickened edges.

A surge of streams

New sky surveys have accelerated discoveries of distant streams.

1 Hints of the first stream, Sagittarius, discovered.

2 Data from the Sloan Digital Sky Survey spur discoveries.

3 Gaia, the Dark Energy Survey, and Pan-STARRS drive a new surge.

(GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) ADRIAN PRICE-WHELAN AND CARL GRILLMAIR

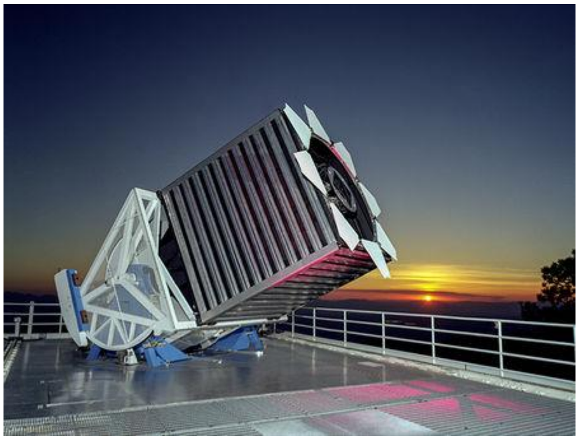
The spectacular find was a vindication for what astronomers call the hierarchical theory of galaxy formation: Here was the voracious Milky Way, caught in the act of eating a smaller cousin. But Sagittarius wasn't a stellar stream so much as an Amazonian river of stars, too mixed up with the Milky Way to be much use for gauging the galaxy's mass and makeup.

Better would be the thinner, more distant streams expected to form from globular clusters, the second kind of Milky Way satellite. Whereas dwarf galaxies hold millions of stars, globular clusters typically contain fewer than 100,000. The Sloan survey, a catalog of millions of stars and galaxies, was providing just the sort of deep, all-sky data that might reveal such slender streams. Almost overnight in 2001, astronomers discovered Palomar 5 (Pal5): a long, thin stream hovering above the galactic center. Carl Grillmair, an astronomer at the California Institute of Technology (Caltech) in Pasadena, soon found that Pal5 stretched a full 24° across the sky.

Then he found an even longer stream. Grillmair was perfecting a technique to distinguish distant stream stars from crowds of foreground stars. He knew dwarf galaxies and globular clusters, the wellsprings for streams, are ancient and metal-poor; as a result, their stars tend to be bluer than average. So he examined slices of the sky at ever fainter magnitudes—the equivalent of looking ever farther out into the halo—and filtered by color. By stacking the slices and moving through them like a flip book, he could see when a population of bluish stars jumped out. "I'd watch these movies—out, back, out, back—through the galactic halo."

One weekend in late 2005, soon after the Sloan survey released fresh data, Grillmair remembers scrolling through a virgin part of the sky on his home computer. His wife looked over his shoulder. "Do you see that?" he recalls asking her. "Is that real?"

It was real: an impossibly thin stream stretching across 60°, or a third of the sky's hemisphere. It was about 26,000 light-years away from Earth, far removed from the galactic center and its convulsive effects.



The Sloan Digital Sky Survey, which uses a 2.5-meter telescope at Apache Point Observatory in New Mexico, was responsible for most of the first stellar stream discoveries. REIDAR HAHN/FERMILAB/SCIENCE SOURCE

The Gossamer stream, called GD1 after Grillmair and his Caltech collaborator Odysseas Dionatos, was the first of more than a dozen streams Grillmair later discovered—more than anyone else. But its distance and seeming fragility have made it a favored tool for astronomers trying to weigh the galaxy. Crude mass readings can be gleaned from stars or gas in the disk, which whirl around the galactic center: The faster they orbit, the greater the mass tugging them inward must be. "This is how [Johannes] Kepler and [Isaac] Newton figured out gravitational forces in the solar system," says Jo Bovy, an astrophysicist at the University of Toronto in Canada. But stars in the roiling disk rarely move in perfect circles, which throws off the measurements. And the technique tells you only about the mass of the disk, whereas most of the Milky Way's mass resides in its large dark matter halo.

Intact dwarf galaxies and globular clusters lie farther out and are sensitive to the halo mass, but their orbital paths are unknown. Astronomers use their average motions to make mass estimates, but the results vary wildly, between 700 billion times the mass of the sun and several times that much. Astronomers aren't sure whether the Milky Way weighs more or less than Andromeda, our nearest major galaxy.

In contrast, the shape of a stream clearly indicates how individual stars are moving. "You have lots of test particles lined up for you on the sky," Belokurov says. To measure the enclosed mass out to the orbit of the stream, astronomers need only know the stream's shape and the speed of the stars along its path. The farther out and longer the stream, the better. In 2016, Bovy used Pal5 and GD1 to calculate the Milky Way's total mass: 800 billion solar masses, on the skinnier side of the estimates and much less than Andromeda.

The streams also let Bovy work out the shape of the inner part of the dark matter halo. An earlier analysis based on the Sagittarius stream had suggested a hockey puck, perpendicular to the disk, but Bovy's result was reassuringly conventional: a slightly flattened sphere. As astronomers begin to discover streams even more distant than GD1 and Pal5, they should be able to trace the outer part of the halo, which could take on stranger shapes, like that of a squashed pickle. "That's the dream for all of us," says Denis Erkal, an astrophysicist at the University of Surrey in the United Kingdom.

Other streams could map mass in finer detail. The Tucana III stream, for instance, discovered in data from the Dark Energy Survey, appears to have had a close encounter with the Large Magellanic Cloud—the Milky Way's largest satellite galaxy—several hundred million years ago. Erkal is hoping the imprint left on Tucana III by that encounter could be used to weigh that satellite. Similarly, the Ophiuchus stream passes close to the Milky Way's bar, a linear feature in the galaxy's central bulge. Distortions in the stream might trace the mass of the bar and how fast it rotates.

Astronomers with the Dark Energy Survey, which uses the 4-meter Blanco telescope in Chile, discovered 11 new stellar streams this year. BABAK TAFRESHI/NATIONAL GEOGRAPHIC CREATIVE

At the Flatiron, Price-Whelan was hoping to map GD1 in finer detail than ever before. By 8 a.m. on Zero Day, fortified by free food and coffee, the astronomers were engrossed in getting Gaia data onto their laptops. Price-Whelan asked for the 80°-by-10° swath of sky that includes GD1. He slimmed the download by trying to exclude foreground stars that polluted the view of GD1. By 10 a.m., he had a streamlined, 1-gigabyte file, which he shared with Bonaca on a thumb drive.

The Gaia information was alluring to the two researchers because it contained the stars' motion across the sky. Most stellar streams had been discovered through some variation of Grillmair's filtering scheme, which offers a snapshot of a stream's probable members. But the stars in a stream also flow along paths that reflect the orbit of the disrupted satellite galaxy or star cluster. Gaia was the first sky-mapping effort to measure those "proper motions" for distant stars all at once. It was a whole new way of seeing streams.

Proper motions were especially powerful for picking out GD1 stars, Price-Whelan knew, because the stream orbits the Milky Way counter to the whirling stars of the disk. By sorting for stars with radically different motions from the rest, he cut the more than 2 million stars he had in his sky swath down to about 70,000 that were more likely to be a part of GD1.

While Price-Whelan fine-tuned his velocity cuts, Bonaca used another technique to further sharpen the picture. She set out to cross-match his probable GD1 stars with her own set, which she had sifted on the basis of color and faintness from data gathered by Pan-STARRS, a ground-based survey in Hawaii. In her hotel room after the second day of the workshop, she finally succeeded and made a quick plot. It revealed 1300 stars in GD1, which she and Price-Whelan would soon trace across 100° of the sky.

The detailed picture of the stream also showed something more. "OMG," she wrote when she emailed it to Price-Whelan. Next, she sent the picture to her former graduate school adviser. "My turn not to sleep," she wrote.

When they returned for the third and final day of the Flatiron workshop, Bonaca and Price-Whelan found a quiet glass-walled conference room. "Everyone sensed we were doing something that was not to be interrupted," Bonaca says.

The reason for their intensity was simple: They were seeing two gaps in GD1, as clear as day. One was the original location of the progenitor star cluster, its stars now drained away into the stream. The second gap was far more exciting. Though neither dared say it out loud, both were thinking: Here was the possible scar of a dark matter collision.

They showed the plot to Johnston, who had been Price-Whelan's graduate school adviser. She was stunned not only by the gap itself, but also by a peculiar structure on one side: a spur of stars, off the main track, as though the stream had folded back on itself. It reminded her of a feature her old simulations had predicted for a dark matter collision. "When I saw that, I was real excited," Johnston recalls. "I pulled up our old papers and said, ‘Look, look, there it is!’"

Paranoid that other astronomers were pursuing the same trail, Bonaca and Price-Whelan didn't let up. After the workshop ended, they set up shop in coffee houses around New York City. "We wrote all weekend," Price-Whelan says. Around noon on 1 May—less than a week from the start of Zero Day—he posted their paper on the arXiv server and submitted it to *The Astrophysical Journal Letters*.

The 8.4-meter Large Synoptic Survey Telescope, set to open in Chile in 2022, will find streams in the most distant reaches of the Milky Way’s halo. GIANLUCA LOMBARDI/CCA 4.0

In the paper, published in August, Bonaca and Price-Whelan hint that GD1 was the victim of a galactic hit-and-run. In the prevailing models of galaxy formation, dark matter forms not only a giant semispherical orb—the halo itself—but also much smaller clumps of extra-dense dark matter that roam the larger halo. Some of those "subhalos" might be big enough to form the seeds of dwarf galaxies, but those weighing less than a billion solar masses would be too small to attract any ordinary matter. Starless, they would be invisible but for their gravitational distortions of other objects. Streams, being so long and fragile, would be especially likely to bear such scars.

Subhalos are not the only objects that can wound the streams. Giant clouds of gas living near the disk also could plow through them. But the gap in GD1 was telling, not only because the stream's distant orbit probably puts it beyond the reach of the gas clouds, but also because of the gap's fine-grained structure—especially the spur that so captivated Johnston.

When a subhalo passes through a stream, stars both ahead of and behind the collision site should be gravitationally tugged toward the massive intruder. Stars ahead of it will lose rotational momentum and slip to a lower orbit around the Milky Way, where paradoxically they pick up speed and overtake other stream stars. Stars in the trailing edge gain rotational momentum and rise to a higher orbit, where they slow down and lag behind the stream. The result is fishhook-shaped spurs, visible on one or both sides of the gap, which eventually settle back into the stream.

To Erkal, the gap and spur suggest a dark matter subhalo collided with GD1. "I'd say it's very promising."

Others are not yet convinced. "Seeing a gap in one single stream is interesting—definitely interesting—but it's not incontrovertible evidence," says Alex Drlica-Wagner, an astronomer at Fermi National Accelerator Laboratory in Batavia, Illinois.

Confirmation would do more than just validate the existence of subhalos and the models of galaxy formation that predict them. By compiling statistics across many streams on the number and size of the gaps, astronomers might learn about the nature of dark matter itself. Warm, light dark matter particles would move too fast to clump into subhalos, leaving the streams unscarred by dark matter. The presence of gaps could imply colder, heavier dark matter particles, with smaller, more numerous gaps pointing to greater masses.

Physicists are also trying to determine the nature of dark matter particles by snaring them in detectors on Earth. They've seen nothing so far, but the measurements have tended to rule out extremely heavy particles. "We're approaching the problem from two sides," Belokurov says. "Hopefully one day we'll meet in the middle."

Then again, the detectors might see nothing. The ground-based experiments all make a big assumption: that dark matter interacts with ordinary matter in some as yet unknown way, other than gravity. Many detectors, for example, are designed to pick up a tiny recoil from a dark matter particle's collision with the nucleus of a heavy atom in the detector. But that approach is moot if dark matter interacts with ordinary matter only through the force of gravity. Then the only way to narrow down dark matter's properties might be to look for stream gaps caused by subhalos, Erkal says. "That's what I write on all my grant proposals."

“Seeing a gap in one single stream is interesting—definitely interesting—but it’s not incontrovertible evidence.”

Alex Drlica-Wagner, Fermi National Accelerator Laboratory

The Gaia satellite will gather data for several more years, pushing out to more distant stars and streams. And new streams are still turning up in the data released on Zero Day. A team led by Rodrigo Ibata, an astronomer at Strasbourg Observatory in France who helped discover Sagittarius, has already found six new streams in the Gaia data. The researchers are working on finding more, using an algorithm that automatically identifies streams. Grillmair knows his days as the stream king are probably numbered. "I will be very shortly eclipsed," he says.

And that's even before the arrival of the Large Synoptic Survey Telescope in Chile, which will turbocharge the search for streams when it begins operations in 2022. With its giant 8.4-meter mirror, it will catalog some 10 billion stars, out to the very edge of the halo. Astronomers are also making headway in planning high-throughput spectroscopy surveys, which would make it possible to assign stars to streams according to their chemical makeup. "It's like DNA matching," Grillmair says.

For their part, Bonaca, Price-Whelan, and Hogg are taking the next step on GD1—doing the detailed modeling to confirm that the gap and spur are the result of a dark matter collision. Bonaca says her latest runs suggest a crash with a subhalo weighing a few million solar masses that occurred some 500 million years ago. But she's still not sure. She wants time on the Hubble Space Telescope to zoom in on the region of the gap and spur, where she hopes to see many faint red dwarfs—common stars, which her current filtering method excludes, that could be members of GD1. By observing across several years, she may be able to obtain proper motions for the red dwarfs, allowing her to decide whether to assign them to the stream.

"We want to go deeper in those regions to be more confident," she says. Ultimately, she might be able to estimate the angle and velocity of the collision. That, in turn, could point to the location of the subhalo today.

As much as it is a golden age for astronomers studying streams, it is also a golden age for the streams themselves. The Milky Way is entering late middle age. Plenty of streams have been scattered into oblivion, but plenty remain in orbit. And hundreds of pristine satellite galaxies await their transformation into streams. The balance is changing, however. Already, dead dwarf galaxies outnumber living ones. Eventually—give it 10 billion years or so—the last streams will dissolve into the halo and lose the memory of their origin. The ghosts will become ghostlier, and the halo will homogenize. The rivers of stars will become one with the sea.

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