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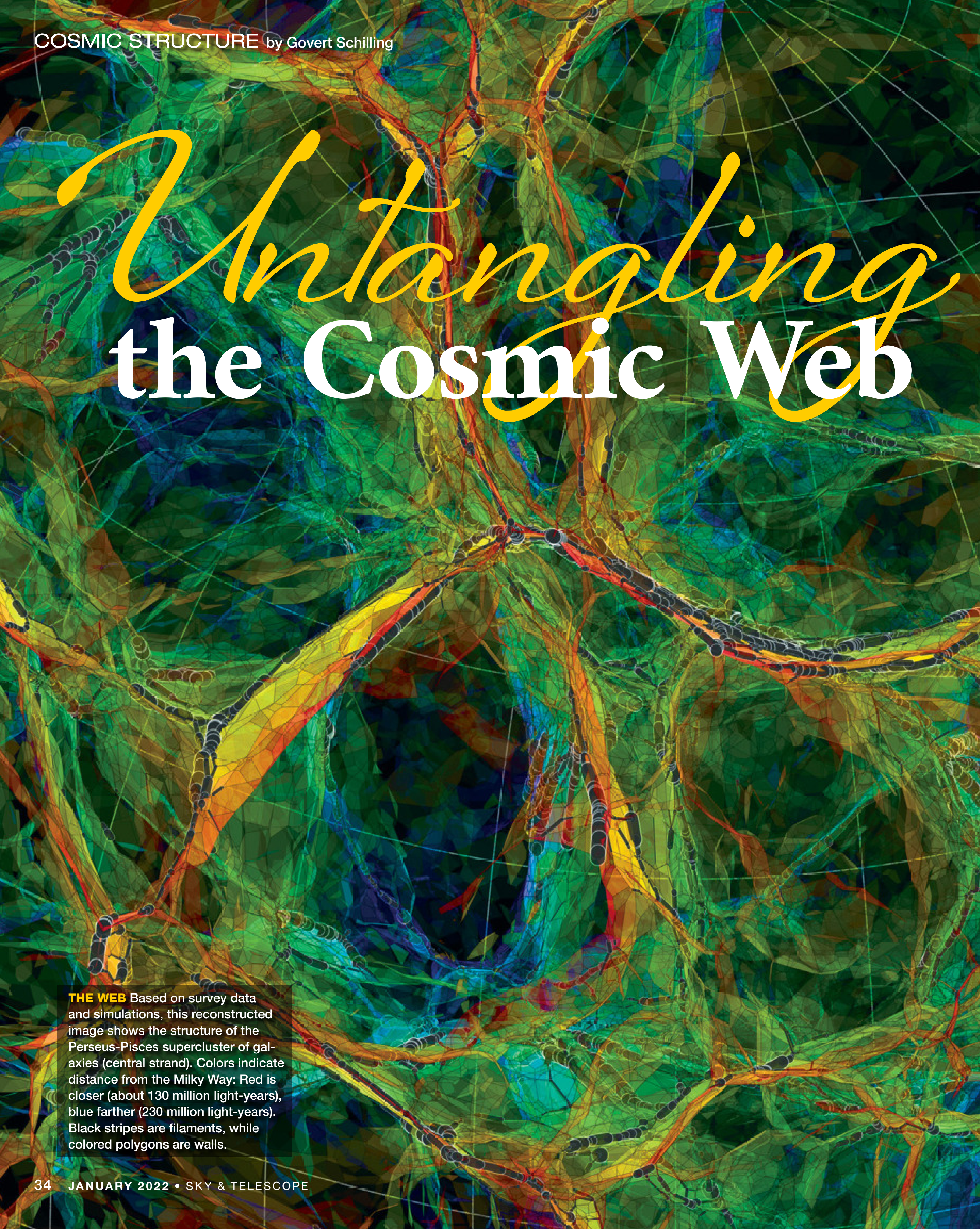
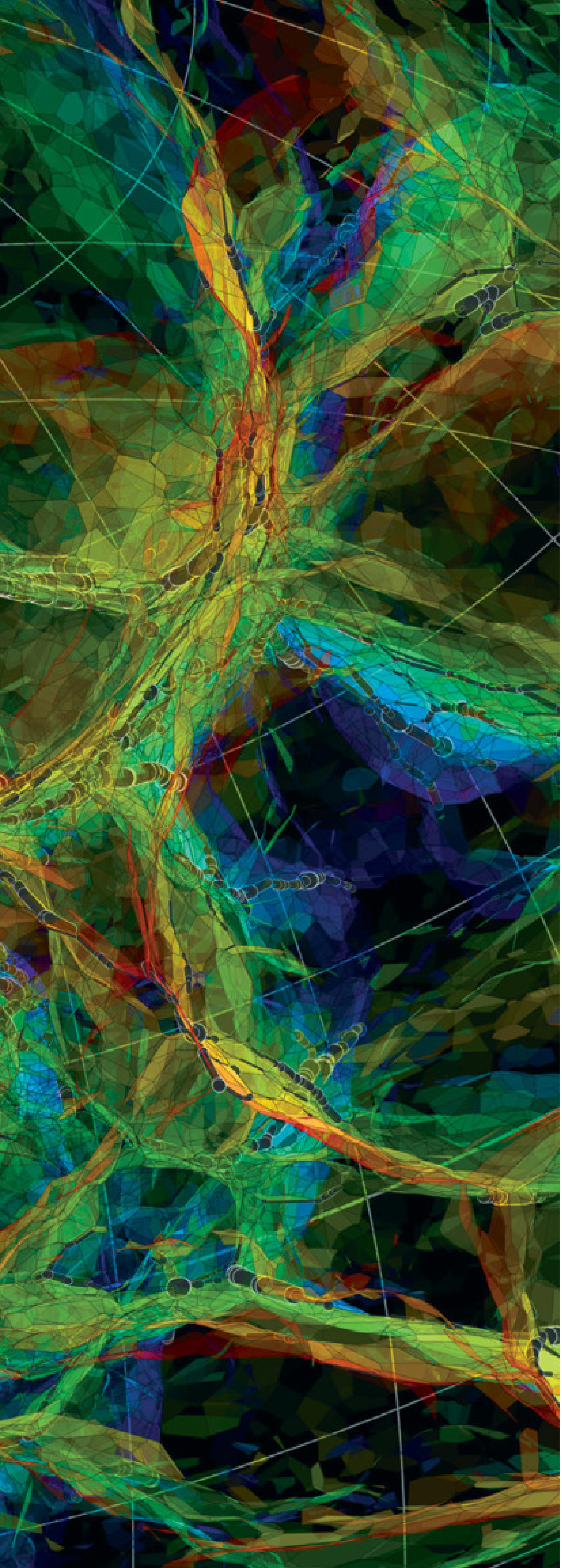
by Govert Schilling

Untangling the Cosmic Web



THE WEB Based on survey data and simulations, this reconstructed image shows the structure of the Perseus-Pisces supercluster of galaxies (central strand). Colors indicate distance from the Milky Way: Red is closer (about 130 million light-years), blue farther (230 million light-years). Black stripes are filaments, while colored polygons are walls.



JOHAN HIDDING

Astronomers are slowly mapping the long-hidden filaments that connect galaxies.

We live in a hierarchical cosmos. Earth is one of eight planets orbiting a middle-of-the-road star in a spiral arm of the Milky Way, which, in turn, is in the outskirts of a cluster of similar galaxies. Galaxies are often seen as the "building blocks" of the universe. But the truth is that galaxies and their groups and clusters are interconnected by hard-to-observe tendrils, just like towns and cities are interconnected by roads and highways. And although mysterious dark stuff is the main component of this cosmic web, the structure also contains at least 30% of all "normal" (so-called *baryonic*) matter in the universe.

The web-like, large-scale structure of the universe was first predicted by renowned Soviet theorist Yakov Zeldovich, back in 1970. That same decade, astronomers made the first crude 3D maps of our cosmic surroundings, confirming that galaxies are indeed distributed unevenly throughout space. As has been revealed over and over again by ever-larger survey programs, galaxies are concentrated in thin walls and more prominent filaments, interspersed by large voids that may well be a few hundred million light-years across (*S&T:* Oct. 2018, p. 12). Massive clusters mark the nodes where three or more filaments meet.

But initially, no one knew whether or not the space between the galaxies in the filaments was truly empty.

That changed in the 1980s, with the first computer simulations of the growth of cosmic structure over time. Dominated by the gravity of mysterious dark matter, which comprises some 85% of all gravitating stuff, such simulations predicted that the nearly homogeneous post-Big Bang universe of 13.8 billion years ago should indeed have evolved into an expanding cobweb- or soapsuds-like pattern. So yes, if cosmic matter condenses into galaxies, you would expect those to be arranged in filamentary configurations, as shown by observations. But according to the simulations, large amounts of matter — both dark and baryonic — should still be present in the underlying cosmic web.

Today, state-of-the-art simulations like IllustrisTNG (The Next Generation) and Evolution and Assembly of Galaxies and Their Environments (EAGLE), run by international collaborations on some of the most powerful supercomputers in the world, reveal the process in detail, taking into account not only the gravitational pull of dark matter but

Filaments

The cosmic web comprises voids, filaments, walls, and nodes. Filaments make up only about 5% of the cosmic volume, but they may contain half of all baryonic mass (estimates vary).

also the "push" of dark energy — the mysterious force behind the observed acceleration of cosmic expansion (*S&T:* May 2018, p. 14). According to Joop Schaye (Leiden University, The Netherlands), the principal investigator of the EAGLE simulation, no one questions the existence of intergalactic material in the cosmic web. "But of course, observers always want to really see it first," he says.

10%
Fraction of the universe's baryons in galaxies

Background Beacons

While the web-like pattern is clearly visible in large 3D galaxy surveys, observing its intergalactic content is a real challenge. Remember that most of it is dark matter, which is invisible by definition. In the early universe, the baryonic gas in the filaments has a very low density (in a terrestrial laboratory, we would call it a perfect vacuum), and temperatures are on the order of 10,000 kelvin. Over time, the structures grow larger and more massive, and shocks further heat the gas. But even at temperatures of millions of degrees, this plasma is generally much too tenuous to be easily seen.

Only at the endpoints of the tendrils, close to galaxy clusters and individual galaxies (where it's more commonly known as the *circumgalactic medium*), the cosmic web has a significantly higher density, up to hundreds of times the average density in the universe. Here, primordial gas flows into galactic halos and disks, ultimately feeding the birth of new stars. Through stellar winds and supernova explosions, galaxies also blow processed gas back into space. Some of this material ends up in the cosmic web again, enriching the filaments with heavy elements (*metals* in astronomical parlance) that are produced by stellar nucleosynthesis. "The details of this feedback mechanism are still not well understood," says Schaye. "We don't know how far these metals can end up from their parent galaxy."

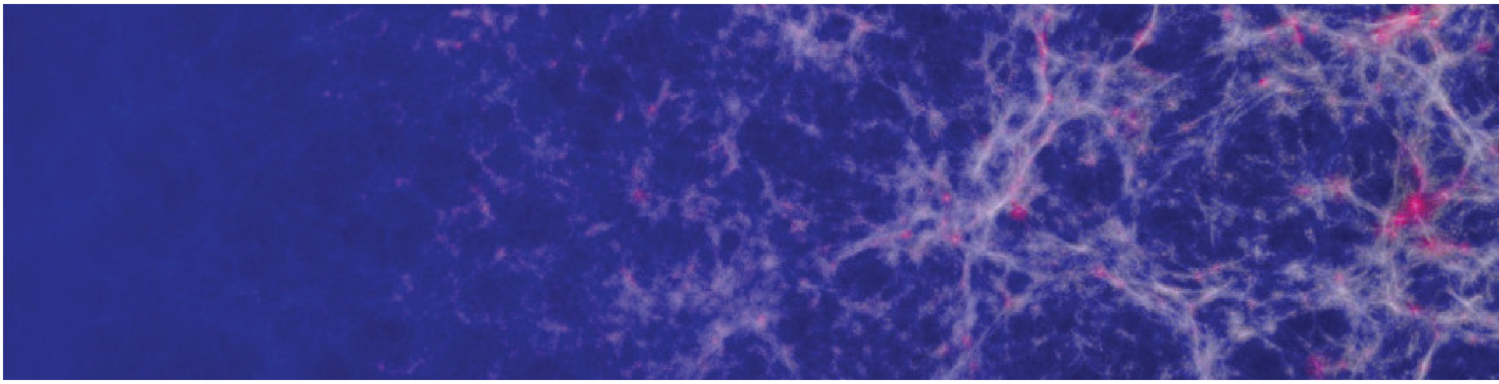
One way to detect relatively cold, tenuous gas in intergalactic space is by looking at the absorption fingerprint it leaves in the light of background beacons, such as bright quasars. Neutral hydrogen atoms preferentially absorb ultraviolet photons with a wavelength of 121.6 nanometers, which provide the right amount of energy to help the atom's single electron jump from its ground state to the next quantum level up. The resulting absorption line in the quasar's spectrum will be observed at a longer wavelength here on Earth, depending on the distance to the absorber and the corresponding redshift due to cosmic expansion. Usually, quasar spectra contain a "forest" of these *Lyman-alpha lines*, produced by a large number of absorbers at various distances along the line of sight.

The problem is figuring out the true nature of the absorbers. Most of the detectable ones are probably individual galaxies or galactic halos (indistinguishable because of their remoteness), which produce a relatively strong absorption signal. Because only neutral (that is, cool) hydrogen produces the Lyman-alpha line, the approach only works as a way to detect the cosmic web at very large distances, corresponding to early times when the web's temperature was still really low. Closer to home, in more recent cosmic epochs, the tendrils of the cosmic web are expected to be much hotter — astronomers sometimes call it the *warm-hot intergalactic medium*, or WHIM — and thus there's little neutral hydrogen. Here, at distances of a few billion light-years, other detection techniques are needed.

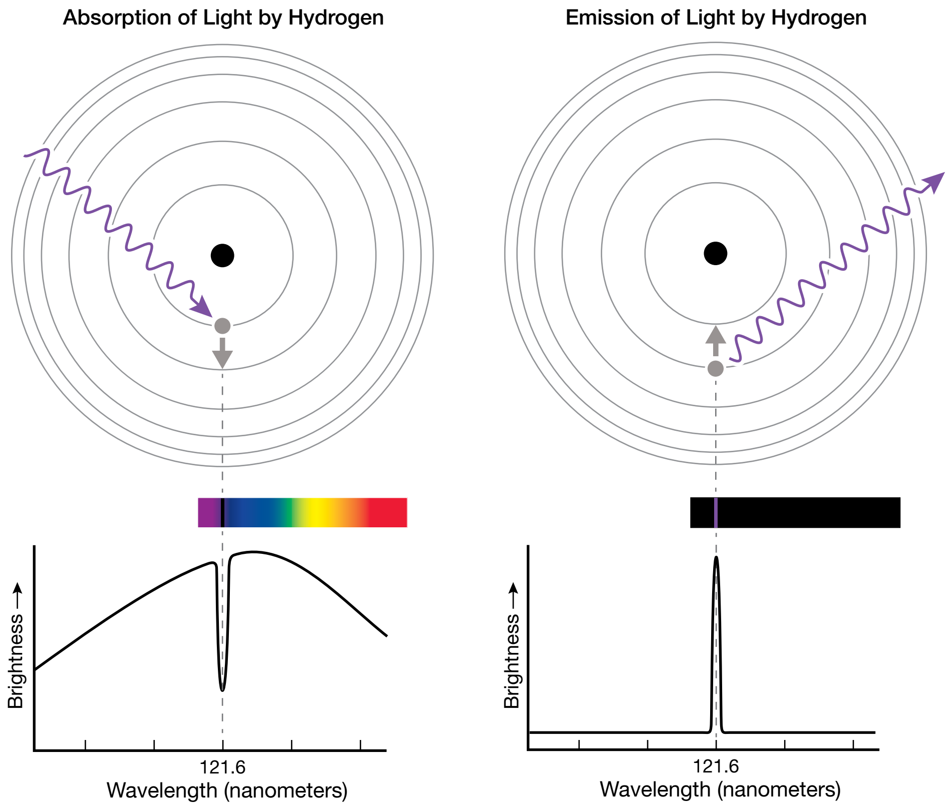
That's where X-ray astronomy comes in. As mentioned above, the evolved cosmic web contains a smattering of heavy elements, including oxygen atoms — the most abundant metal in the universe. Because of the gas's high temperature, the oxygen atoms are highly ionized: Many of them have only one or two of their original eight electrons left. Ionized oxygen absorbs X-ray photons at a handful of particular energies, leaving characteristic dips in the brightness of background X-ray sources.

Because this technique focuses on the relatively nearby universe, it's easier to check whether intervening galaxies cause the absorption features. If not, the features may be due to tenuous patches of the cosmic web. Using NASA's Chandra X-ray Observatory, launched in 1999, astronomers made the first tentative WHIM detections more than 20 years ago. "But it's incredibly hard," notes cosmic-web expert Rien van

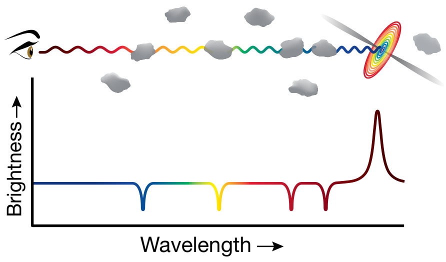
▼ **GROWING WEB** Over time (left to right), matter in the universe has collected in a web-like structure. Redder colors indicate hotter gas temperatures, while more intense color indicates higher gas density. The strip spans about 300 million light-years vertically.



EAGLE PROJECT



◀ **LYMAN ALPHA** *Left:* To move to a higher energy level in the atom, an electron must absorb a photon; to move to a lower level, it must emit a photon. The transition between the first and second energy levels involves an ultraviolet photon of wavelength 121.6 nm, known as Lyman alpha. *Below:* Quasars emit strongly at visible and ultraviolet wavelengths (including Lyman alpha), and that light is absorbed by hydrogen clouds between the quasar and us. But because all the clouds and the quasar lie very far away, the Lyman-alpha lines are redshifted to longer wavelengths. The more distant the absorber or emitter, the redder the wavelength. The numerous clouds between us and a quasar create a comb-like pattern in the quasar's spectrum called the *Lyman-alpha forest*.



GREGG DINDERMAN / *S&T*, SOURCES: EDWARD WRIGHT AND NASA / ESA / LEAH HUSTAK (STSCI)

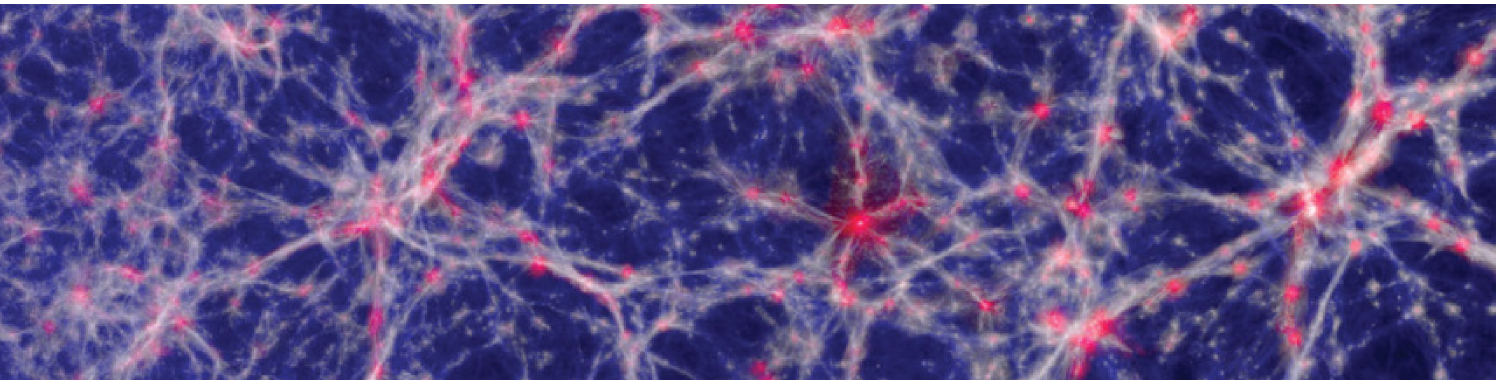
de Weijgaert (University of Groningen, The Netherlands). The universe makes far more low-energy photons than high-energy ones, and X-ray photons are rare. "You need an extremely energetic or very nearby quasar as a background source, and even then, X-ray astronomy is really about counting individual photons."

Alternative Approaches

Little wonder, then, that people have tried other means to detect the elusive intergalactic filaments. For instance, Jörg Dietrich (now at University Observatory Munich) and his colleagues found evidence for an invisible but massive bridge between galaxy clusters Abell 222 and 223 (some 2½ billion light-years away), using a technique known as weak gravitational lensing. In their 2012 *Nature* paper, they described how tiny distortions in the shapes of tens of thousands of remote background galaxies reveal the existence of a 60-million-light-year-long filament between the clusters, weighing in at some 80 trillion solar masses. The find has been hailed as "the first robust detection of a dark matter filament."

Later that year, Mathilde Jauzac (now at Durham University, UK) and her colleagues published a similar result in *Monthly Notices of the Royal Astronomical Society*. Through weak lensing, they were able to make a crude 3D reconstruction of what appears to be a huge filament, funneling matter into the massive cluster MACS J0717.5+3745, which is so far away that its light took more than 5 billion years to reach us.

And weak lensing isn't the only alternative game in town to track down cosmic-web filaments. In a 2013 paper in *Astronomy & Astrophysics*, the Planck Collaboration described



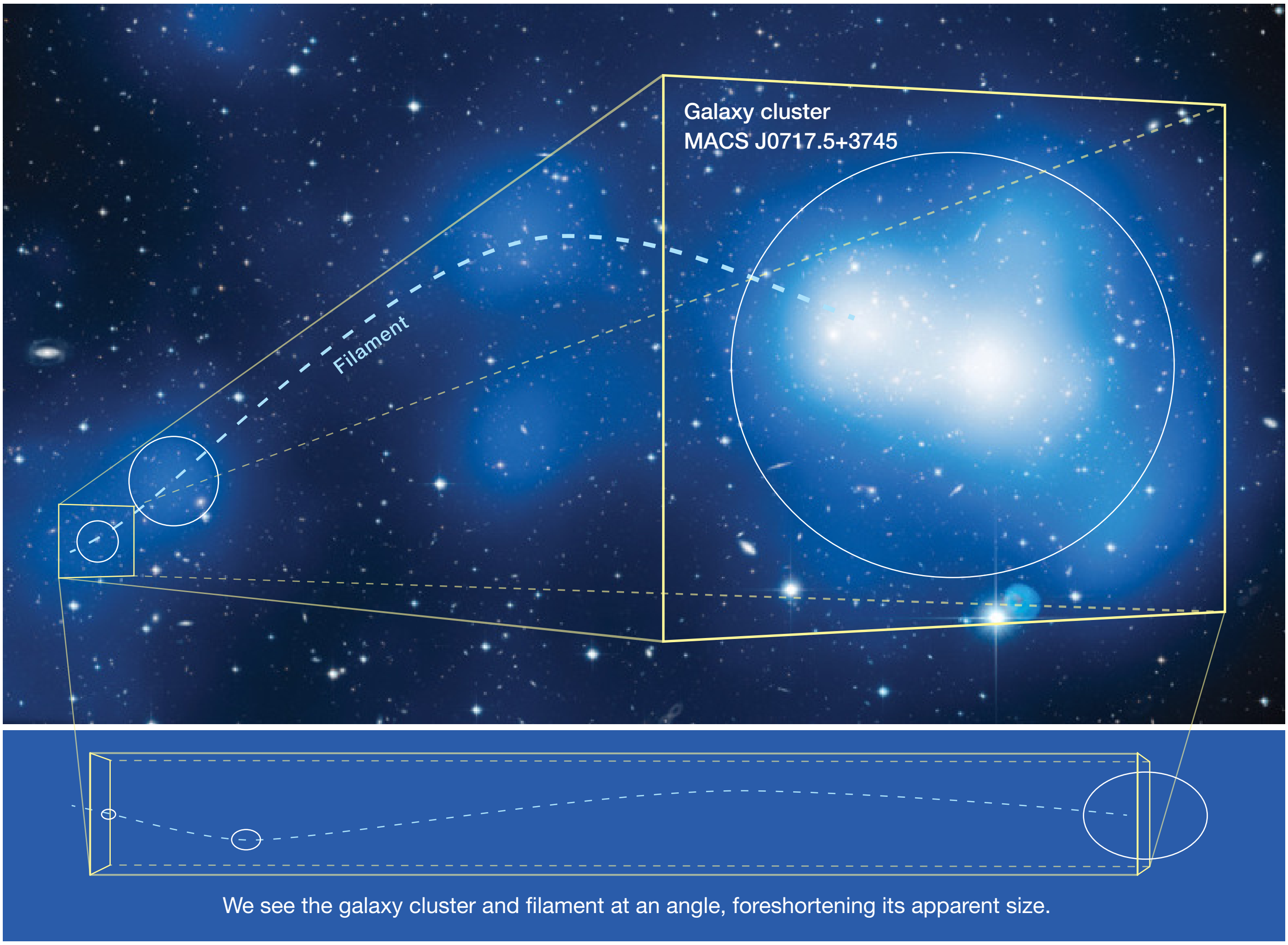
how the cosmology probe found evidence for a bridge between the merging cluster pair Abell 399 and 401. Photons in the cosmic microwave background receive an energy kick from interactions with free electrons in the cosmic web, slightly distorting the observed spectrum — a process known as the (thermal) *Sunyaev-Zeldovich* (SZ) *effect*, after the two scientists who first described it.

Astronomers have also applied both cosmic-web detection techniques — weak lensing and the SZ effect — to observations of many tens of thousands of galaxy pairs. After scaling and rotating the observations to the correct degree, they can be stacked and analyzed as an ensemble. Thus, over the past five years, several teams of researchers found statistically significant evidence for the existence of large-scale inter-galaxy filaments that contain a huge fraction of all the baryonic matter in the universe.

Which is not to say that the interest in more direct detections or real images has declined. While X-ray astronomers such as Fabrizio Nicastro (National Institute of Astrophysics, Italy) still make incidental "pencil-beam" detections by studying absorption features in quasar spectra — which can provide useful information on gas temperatures — others have begun to create real maps of the cosmic web, albeit over relatively small regions of the sky. As an example, the German eROSITA telescope, mounted on the Russian Spectrum-Roentgen-Gamma spacecraft, may have detected the very weak X-ray *emission* of hot gas in between the galaxy clusters Abell 3391 and 3395. In the March 2021 *Astronomy & Astrophysics*, Thomas Reiprich (University of Bonn, Germany) and his colleagues cautiously describe the result as "tantalizing hints" of hot gas in a cosmic-web filament.

The First Real Image

Lyman-alpha detections are also very much back in vogue. For many years now, Khee-Gan Lee (now at the Kavli Institute for the Physics and Mathematics of the Universe, Japan) has been constructing huge maps of the distribution of neutral gas in the cosmic web by using sky positions and distances



We see the galaxy cluster and filament at an angle, foreshortening its apparent size.

▲ **DARK FILAMENT** By carefully measuring how the dark matter in and around the galaxy cluster MACS J0717.5+3745 warped the apparent shapes of background galaxies, astronomers were able to map the invisible matter's location (blue). Additional observations revealed the filament's 3D structure and that the part farther from the cluster extends away from us *(bottom)*.

NASA / ESA / HARALD EBELING (UNIVERSITY OF HAWAI'I, MANOA) / JEAN-PAUL KNEIB (LAM)

of hundreds of Lyman-alpha absorbers in the COSMOS field — an area in the constellation Sextans that many major telescopes have studied in detail in order to explore galaxy evolution. Thanks to their instrument's sensitivity, Lee and his colleagues do not restrict themselves to bright quasars as background beacons. Instead, they also use fainter star-forming galaxies, which are much more numerous. "This [provides] an unprecedented view of the cosmic web, which has never been mapped at such vast distances," Lee said in a 2014 press statement.

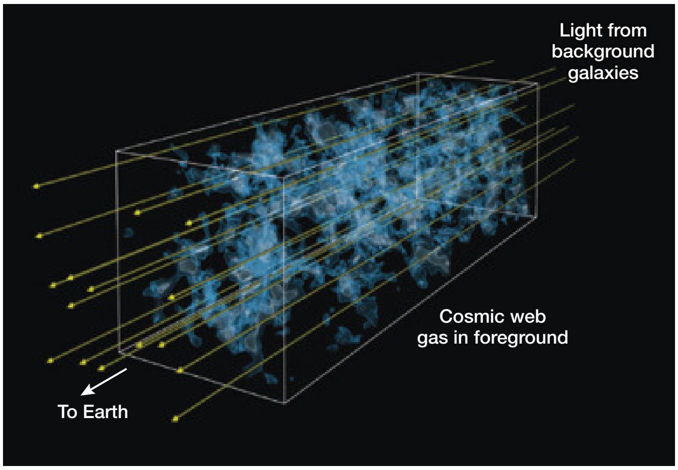
Because of the huge distances and corresponding large redshifts of the absorbing systems, the Lyman-alpha absorption lines are conveniently shifted from the ultraviolet into the visible part of the spectrum, where astronomers can measure them with the Low Resolution Imaging Spectrometer (LRIS) on the 10-meter Keck I telescope at Mauna Kea, Hawai'i. Using special-purpose computer algorithms, the data are then converted into 3D maps. Eventually, Lee's CLAMATO survey (for COSMOS Lyman-Alpha Mapping And Tomography Observations) is expected to cover a remote region of the universe some 230 million light-years wide and almost a billion light-years in depth.

Most recently, in another March 2021 study, scientists revealed what they described as the first real image of intergalactic matter in the cosmic web. Not that anyone doubted its existence anymore, "but really seeing an image is of course much more convincing," says study leader Roland Bacon (University of Lyon, France).

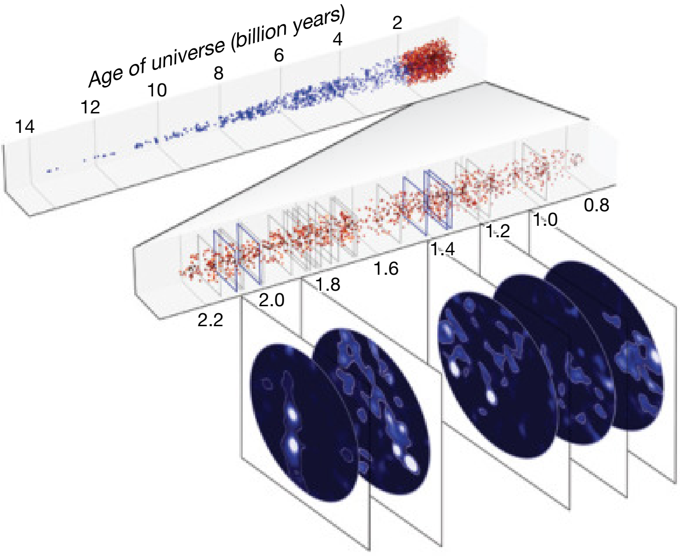
Bacon and his colleagues used the sensitive Multi-Unit Spectroscopic Explorer (MUSE) spectrograph of the European Southern Observatory's Very Large Telescope in Chile to map the incredibly faint Lyman-alpha *emission* of remote swirls of intergalactic hydrogen gas in the Hubble Ultra Deep Field. "This is the most well-known part of the universe," says Bacon, "so there's a lot of interesting science you can do here with long observing times."

Between August 2018 and January 2019, MUSE was trained on this small area (in the southern constellation Fornax, the Furnace) for a total of no less than 140 hours. According to Bacon, getting awarded so much observing time was the biggest challenge. "Of all the instruments on the VLT, MUSE is the one most in demand," he says.

The faint glow of the cosmic web's hydrogen gas is a form of fluorescence. As mentioned before, neutral hydrogen atoms get excited when they absorb ultraviolet photons with a wavelength of 121.6 nm. But eventually, the electrons fall back to their lowest energy level, emitting photons of the same wavelength in the process. Since these are emitted in all possible directions, the Lyman-alpha *emission* signal is much fainter than the *absorption* signal. However, while studying absorption lines in the spectrum of a single background source only gives you information on one tiny part of the cosmic web, the emission signal can provide you with an image (albeit extremely faint) of the whole structure.



▲ **3D MAPPING** The CLAMATO project uses distant background galaxies to look for intervening hydrogen clouds that absorb some of the galaxies' light. The imprint enables astronomers to reconstruct the cosmic web that the light traversed.



▲ **COSMIC SLICE** Astronomers picked up the signal of Lyman-alpha emission from hydrogen at different times in the first 2 billion years of cosmic history (red, top). They found 22 notably dense regions (gray rectangles, center), five of which contained especially prominent filaments (blue rectangles and bottom row).

SLICE OF COSMIC MAP: KHEE-GAN LEE (MPIA) AND CASEY STARK (UNIV. OF CALIFORNIA, BERKELEY); COSMIC SLICE: ROLAND BACON / DAVID MARY

Bacon and his colleagues were not the first to detect Lyman-alpha emission from intergalactic gas. It had already been observed in 2014, in the proximity of a luminous quasar that acted as a flashlight. Not much later, the Cosmic Web Imager — a dedicated instrument pioneered by Christopher Martin (Caltech) — started to reveal ever-stronger hints of filamentary structures. And in 2019, a team led by Hideki Umehata (University of Tokyo) used the MUSE spectrograph to detect structures between individual galaxies in a remote protocluster. But the new observations are the first to reveal cosmic-web filaments in the early universe, 1 to 2 billion years after the Big Bang. The structures have lengths of up to 15 million light-years.

A Bright Future

The most surprising part of Bacon's work is that the photons exciting the hydrogen gas appear to come from large numbers of extremely small, star-forming galaxies hidden in the filaments. According to Bacon, the dwarf galaxies weigh in at just a million solar masses or so. "If our interpretation is correct," he says, "the number of galaxies in the early universe that are forming stars is huge." Billions of these tiny galaxies may have been responsible for re-ionizing the universe at the end of the so-called Dark Ages, a few hundred million years after the Big Bang.

The new results provide additional observational constraints to cosmologists like van de Weijgaert, who try to model the evolution of the large-scale structure of the universe. "But don't forget that dark matter is the main component of the cosmic web," he says. "The big question is to what extent the gas distribution is representative for the web as a whole." Building on work by Francisco-Shu Kitaura (now at the Institute for Astrophysics in the Canary Islands, Spain), van de Weijgaert's PhD student Johan Hidding has reconstructed the dark matter distribution in the local universe out to some 300 million light-years by meticulously "tweaking" supercomputer simulations until they exactly reproduce the observed distribution of real galaxies. Eventually, his eye-catching reconstructions (see page 34) may provide much more detailed information on the evolution and the current locations of cosmic-web filaments and on the density of intergalactic gas in the local universe, Hidding says.

▼ **FILAMENT** One of the hydrogen filaments (blue) discovered using the MUSE instrument in the Hubble Ultra-Deep Field (background image). The structure stretches across 15 million light-years.

▲ **XRISM TELESCOPE** Scheduled to launch in 2022, this X-ray telescope may help astronomers explore cosmic structure.

Massive galaxy surveys will also yield a wealth of detailed information about the cosmic web, enabling cosmologists to explore the precise way in which dark matter and dark energy have shaped the large-scale structure of the universe. Prime examples are the recently completed Dark Energy Survey (DES), the ongoing Dark Energy Spectroscopic Instrument (DESI) survey, the upcoming Legacy Survey of Space and Time (LSST), and the future space-based galaxy surveys of ESA's Euclid and NASA's Nancy Grace Roman Space Telescope. Next-generation ground-based telescopes like the European Southern Observatory's 39-meter Extremely Large Telescope, outfitted with sensitive integral-field spectrographs, will vastly surpass the recent achievements of the VLT's MUSE instrument. And future X-ray observatories — in particular the Japanese-American X-Ray Imaging and Spectroscopy Mission (XRISM) and the European Advanced Telescope for High-Energy Astrophysics (Athena) — have high enough sensitivity and spectral resolution to detect hundreds of tenuous intergalactic filaments.

As theories and simulations become more sophisticated over time, and observations ever more detailed, the study of the elusive cosmic web will likely remain a fecund interaction between the two approaches for quite some time to come. In the past, theoretical insights have usually guided cosmologists' interpretation of their sparse observational data. But in the end, the real universe has the last word. Before long, we could be witnessing how theories follow observations, instead of the other way around.

■ Contributing editor **GOVERT SCHILLING**'s new book on the search for dark matter, *The Elephant in the Universe*, will be published this spring by Harvard University Press.

FILAMENT: ROLAND BACON / DAVID MARY / ESO / NASA; XRISM TELESCOPE: NASA