

Why the Void Between Galaxies Burns

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There is a version of space that most people carry around in their heads: cold, dark, empty. The gaps between galaxies as a kind of cosmic silence, the universe thinning out to nothing between the islands of light. That picture is wrong. The space between galaxies is filled with a fully ionized plasma sitting at temperatures between one hundred thousand and ten million Kelvin. It is hotter than the outer atmosphere of the sun. It contains roughly half of all ordinary matter in the observable universe. And for most of the history of modern astronomy, we could not see it at all.

The Architecture of Everything

Before getting to the heat, it helps to understand the structure. At the largest scales, the universe organizes itself into what cosmologists call the cosmic web: a network of filaments, nodes, walls, and voids that spans hundreds of millions of light-years in every direction.

Filaments are the threads connecting galaxy clusters. A typical one stretches between five hundred and eight hundred million light-years in length. The Milky Way is roughly one hundred thousand light-years across. A single cosmic filament is, at minimum, five thousand Milky Ways laid end to end. These are the longest known structures in the universe.

Nodes sit at filament intersections: galaxy clusters, the most massive gravitationally bound objects that exist. Walls are flattened sheets of matter separating the voids. And voids are the vast underdense interiors that constitute roughly eighty percent of the universe's total volume.

The filaments are not just structural scaffolding. They are thermally active. The gas inside them is a plasma at temperatures that dwarf anything in everyday experience, produced not by any burning or fusion but by the simplest thing gravity can do: make matter fall.

The space between galaxies is not a frozen void. It is one of the universe's most sustained heating operations, running continuously across billions of light-years.

The Missing Baryon Problem

The physics of the first few minutes after the Big Bang, a process called Big Bang nucleosynthesis, makes a specific and testable prediction about how much ordinary matter the universe should contain. The cosmic microwave background confirms the same number independently. Ordinary matter, called baryonic matter, should constitute approximately five percent of the total energy content of the universe.^[1]

Astronomers catalogued what they could find. Stars inside galaxies. Hot gas in galaxy clusters. Diffuse cool gas visible in absorption against background quasars. Warm halos surrounding galaxies. They added everything up.

The total came up thirty to forty percent short of the prediction. Nearly half of all the ordinary matter the universe was supposed to have made was simply not appearing in any census of the local cosmos. This became known as the missing baryon problem, and it remained genuinely open for roughly three decades.

The matter was not gone. It was hiding in a form that the instruments built to survey the universe were poorly equipped to detect. And the reason for that invisibility comes directly from the temperature of the gas.

Why Deep Space Is Hotter Than the Sun

The mechanism behind WHIM heating is gravity, operating at cosmological scales. As gas flows toward overdense regions along the filaments of the cosmic web, it accelerates. Given enough distance, infall velocities reach hundreds of kilometers per second. When that infalling gas becomes supersonic relative to the medium it is entering, a shock front forms at the boundary between the flow and the denser accumulated material ahead of it.

At that boundary, organized kinetic energy converts abruptly into random thermal motion. The shock does not spread this conversion over time. It happens at a surface

whose physical thickness is comparable to the mean free path of the particles crossing it. Cold on one side. Hot on the other.

The post-shock temperature follows from the Rankine-Hugoniot conditions. For a strong shock where the Mach number $M \gg 1$, the downstream temperature is:

$$T_{\text{post}} = \frac{3}{16} \cdot \frac{\mu \, m_p}{k_B} \cdot v_{\text{shock}}^2$$

where μ is the mean molecular weight of the gas, m_p is the proton mass, k_B is the Boltzmann constant, and v_{shock} is the shock velocity. Temperature scales with the square of velocity. Double the infall speed and the post-shock temperature quadruples. For gas falling into a massive galaxy cluster at five hundred to one thousand kilometers per second, this yields temperatures of one to thirty million Kelvin.^[2]

The sun's photospheric surface sits at 5,773 K. The solar corona, the sun's outer atmosphere, reaches one to two million K. The WHIM at its upper end, confirmed by the eROSITA X-ray survey at a best-fit temperature of $10^{6.84}$ K, is five to ten times hotter than the solar corona. This is the normal condition of the gas filling the filaments of the cosmic web.

The Mach Number of the Cosmic Web

The strength of a shock is encoded in its Mach number: the ratio of the flow velocity to the local speed of sound in the pre-shock medium.

$$M = \frac{v_{\text{flow}}}{c_s} \quad \text{where} \quad c_s = \sqrt{\frac{\gamma \, k_B \, T}{\mu \, m_p}}$$

In the pre-shock intergalactic medium at temperatures near 10,000 K, the sound speed is roughly ten to fifteen kilometers per second. Gas infalling at five hundred kilometers per second therefore has a Mach number near forty. At the outermost boundaries of cosmic filaments, where pristine void gas meets the heated medium for the first time, Mach numbers routinely reach one hundred to one thousand.

These are called external accretion shocks. They are the strongest shocks in the universe and the primary source of WHIM heating. Internal merger shocks inside galaxy clusters, driven by clusters colliding with each other, operate at only Mach two to four because the pre-shock medium is already hot and has a high sound speed.

The gas that crosses an external accretion shock for the first time is changed permanently. Cold infalling plasma enters. Hot WHIM emerges. That conversion has been running at every filament boundary across the observable universe for billions of years.

Why It Was Nearly Impossible to See

The WHIM's invisibility is not a coincidence. It is a direct physical consequence of its temperature and density.

The two main tools for detecting diffuse intergalactic gas are UV absorption spectroscopy and X-ray emission imaging. Both fail for the WHIM, but for different reasons.

UV absorption works by detecting neutral hydrogen leaving spectral fingerprints in quasar spectra. At WHIM temperatures, neutral hydrogen cannot survive. The thermal energy strips electrons from protons continuously. There is no neutral hydrogen to detect.

X-ray emission imaging works for hot, dense gas like the intracluster medium inside galaxy clusters. X-ray emissivity scales as the square of electron density:

$$\epsilon_X \propto n_e^2 \cdot \Lambda(T)$$

where $\Lambda(T)$ is the cooling function. The WHIM has electron densities below 10^{-4} cm^{-3} , compared to 10^{-3} cm^{-3} in cluster cores. The emissivity difference is a factor of one hundred or more. The WHIM's X-ray signal per unit volume is far too faint for direct imaging against the background.^[3]

The WHIM sits in the gap between these two windows. Too hot for UV, too cool and diffuse for X-ray. Half the ordinary matter in the universe, essentially transparent to

every survey tool built before anyone knew to look for it.

Three Ways Astronomers Finally Found It

Quasar Absorption Lines

Oxygen ions at WHIM temperatures exist in specific ionization states that absorb at characteristic wavelengths. O VI absorbs in the far ultraviolet and traces the cooler WHIM below one million K. O VII and O VIII absorb at X-ray wavelengths around 21.6 and 18.97 angstroms respectively, tracing the hotter gas.

In 2018, Nicastro and colleagues used XMM-Newton to study the X-ray spectrum of the blazar 1ES 1553+113, reporting two O VII absorbers at redshifts of 0.4339 and 0.3557. The detection reached approximately 3.5 sigma significance, below the conventional five-sigma threshold but consistent with WHIM column densities predicted by simulations.^[4]

Fast Radio Bursts and the Dispersion Measure

Fast radio bursts are millisecond radio pulses from extragalactic sources, most likely magnetars. They were discovered accidentally in 2007 in archival pulsar survey data. What makes them useful for the missing baryon problem is a fundamental property of radio wave propagation through plasma.

Lower frequencies travel slightly slower through ionized gas than higher frequencies, causing a broadband pulse to arrive spread in time. The dispersion measure DM integrates the free electron column density along the entire line of sight:

$$DM = \int_0^d n_e \, dl \quad \left[\text{pc cm}^{-3} \right]$$

When an FRB is localized to its host galaxy and the Milky Way and host contributions are subtracted, the residual DM traces intergalactic electrons directly. Macquart and colleagues formalized in 2020 that the average intergalactic DM increases linearly with redshift, consistent with the missing baryons being distributed through the cosmic web. Researchers at the Harvard-Smithsonian Center for Astrophysics subsequently reported that three-quarters of the missing baryons have been confirmed in the

intergalactic medium through FRB dispersion measurements.

eROSITA and the Stacking Detection

The SRG/eROSITA satellite completed four all-sky X-ray surveys between 2019 and 2022. No individual filament is bright enough for direct detection. But 7,817 filaments, identified optically from Sloan Digital Sky Survey galaxy catalogues, stacked together produce a cumulative signal.

Signal adds coherently. Noise adds in quadrature, growing more slowly. With enough objects stacked, the combined signal-to-noise ratio rises to detectable levels even when no individual object produces one.

The stacked X-ray signal from 7,817 filaments reached nine-sigma significance. After removing contamination from galaxies, AGN, and unresolved point sources, the WHIM-specific residual reached 5.4 sigma. The best-fit temperature was $10^{6.84}$ K, approximately 6.9 million degrees, near the upper boundary of the predicted WHIM temperature range.^[5]

In 2025, a team achieved the first direct spectroscopic detection of a single filament: a 7.2 megaparsec strand inside the Shapley supercluster, observed with XMM-Newton, measured at approximately two million Kelvin with a density of roughly 10^{-4} particles per cubic centimeter. Not a statistical average. One specific object, characterized.

A Second Heater: Supermassive Black Holes

Gravitational shock heating is the dominant source of WHIM thermal energy, but it has a secondary contributor. Active galactic nuclei, galaxies whose central supermassive black holes are accreting at high rates, drive jets and winds that deposit thermal and mechanical energy into the surrounding medium.

Some of this energy reaches beyond the host galaxy into the intergalactic medium. AGN jets in the most powerful sources extend for millions of light-years, terminating in bow shocks that heat the surrounding gas. Even without jets, AGN-driven winds push metal-enriched gas outward into the filaments.

AGN activity peaked near redshift two, when the universe was roughly three billion years old. The energy deposited during that epoch is still present in the thermal state of the intergalactic medium today. The WHIM's temperature structure carries a record of both processes: the ongoing gravitational infall, and the historical energy injection from billions of years of black hole growth across the universe.

The CMB Carries the Imprint

There is a third observational approach: the thermal Sunyaev-Zel'dovich effect. When cosmic microwave background photons pass through hot ionized gas, they scatter off free electrons and gain energy. The amplitude of the effect is measured by the Compton y-parameter:

$$y = \frac{\sigma_T}{m_e c^2} \int n_e \, k_B T_e \, dl$$

where σ_T is the Thomson scattering cross-section, m_e is the electron mass, c is the speed of light, and the integral runs over electron pressure along the line of sight.

In 2019, de Graaff and colleagues stacked the Planck satellite's Compton y-map at the positions of over one million galaxy pairs from the CMASS catalogue, recovering a residual tSZ signal consistent with filamentary WHIM gas at a significance of 2.9 sigma. The recovered y-parameter of $(0.6 \pm 0.2) \times 10^{-8}$ is consistent with WHIM models.

The CMB photons that left their source 380,000 years after the Big Bang, before any filament or galaxy existed, are arriving at our detectors having passed through the WHIM on the way. The oldest signal in the universe carries a faint thermal imprint from the hottest ordinary gas in the cosmos.

What Comes After: NewAthena

Every confirmed WHIM detection so far has been made at the edge of instrumental sensitivity. The eROSITA result required stacking thousands of filaments. The XMM-Newton absorption detections are marginal. The tSZ signal is below the conventional

detection threshold.

The NewAthena X-ray observatory, currently scheduled for launch in the early 2030s, is the first instrument designed from the ground up with WHIM detection as a primary science goal. Its X-ray Integral Field Unit is a transition edge sensor micro-calorimeter operating at 50 millikelvin, measuring individual X-ray photon energies with a spectral resolution of 2.5 electron-volts across the 0.2 to 12 keV band.

That resolution, combined with an effective collecting area roughly ten times larger than XMM-Newton at one keV, will allow detection of O VII and O VIII absorption features that are currently invisible. The science goal is a catalogue of hundreds of confirmed WHIM absorbers at well-characterized redshifts, mapping the intergalactic medium out to redshift one, a lookback time of approximately eight billion years.^[6]

Mapping the WHIM to redshift one is not just extending the current survey. It is building a thermal history of the cosmic web across eight billion years of structure formation. Whether the WHIM baryon fraction grew over time as simulations predict, whether AGN feedback leaves a measurable signature in the redshift evolution of filament temperatures, whether the details of shock heating match the Lambda-CDM model at percent-level precision: these are the questions NewAthena will answer.

What We Actually Know

The missing baryon problem is, to a first approximation, solved. Three converging lines of evidence now point to the same answer: roughly half of all ordinary matter in the universe resides in the warm-hot intergalactic medium, a diffuse ionized plasma filling the filaments of the cosmic web at temperatures between one hundred thousand and ten million Kelvin.

The heating mechanism is understood. Gas falls toward overdense regions under gravity, reaches supersonic velocities, and thermalizes at accretion shock boundaries with Mach numbers reaching into the hundreds at filament edges. The potential energy stored in the large-scale structure of the universe converts to thermal energy at those boundaries, and the product is a plasma hotter than the outer atmosphere of the nearest star.

The detection is confirmed, statistically if not yet in every individual case. eROSITA's stacking result, the FRB baryon census, the Shapley filament spectroscopy, the marginal tSZ signal from Planck: they converge on a consistent picture.

What remains is precision. The temperature distribution across filament populations. The metallicity gradient from filament core to edge. The evolution of the WHIM baryon fraction from redshift one to zero. The relative contributions of gravitational shock heating and AGN feedback as a function of environment and cosmic time.

The universe is cooling on average, trending toward the thermodynamic floor that has been its destination since the first second. Simultaneously, in the filaments threading through everything, gravity keeps converting potential energy to heat, maintaining plasma at millions of degrees across distances that make every galaxy look small.

The void is not cold. It never was. We just needed the right instruments to stop mistaking silence for absence.

[1] The baryon density parameter $\Omega_b h^2 = 0.02237 \pm 0.00015$ from Planck Collaboration (2020), consistent with independent measurements from Big Bang nucleosynthesis light element abundances.

[2] Rankine-Hugoniot strong shock limit for a monatomic ideal gas with adiabatic index $\gamma = 5/3$. The compression ratio approaches 4 as $M \rightarrow \infty$.

[3] For comparison, the WHIM emissivity at $n_e = 10^{-5} \text{ cm}^{-3}$ and $T = 10^7 \text{ K}$ is roughly $10^{-32} \text{ erg s}^{-1} \text{ cm}^{-3}$, versus $10^{-30} \text{ erg s}^{-1} \text{ cm}^{-3}$ for typical cluster core conditions at similar temperatures.

[4] Nicastro, F. et al. (2018). Observations of the missing baryons in the warm-hot intergalactic medium. *Nature*, 558, 406-409. The detection significance for individual absorbers was 2.1 and 2.8 sigma respectively; the combined significance was reported at approximately 3.5 sigma.

[5] Zhang, X. et al. (2024). The SRG/eROSITA all-sky survey: X-ray emission from the warm-hot intergalactic medium in cosmic filaments. *Astronomy and Astrophysics*. The 40% contamination fraction estimate assumes a model of unresolved AGN and X-ray

binary contributions consistent with known source population statistics.

[6] The NewAthena X-IFU effective area at 1 keV is approximately 1 m^2 , compared to roughly 0.1 m^2 for XMM-Newton's EPIC-pn at the same energy. Spectral resolution of 2.5 eV FWHM across the soft X-ray band enables velocity-resolved absorption line spectroscopy of intergalactic gas for the first time.