Voyage through the Hidden Physics of the Cosmic Web

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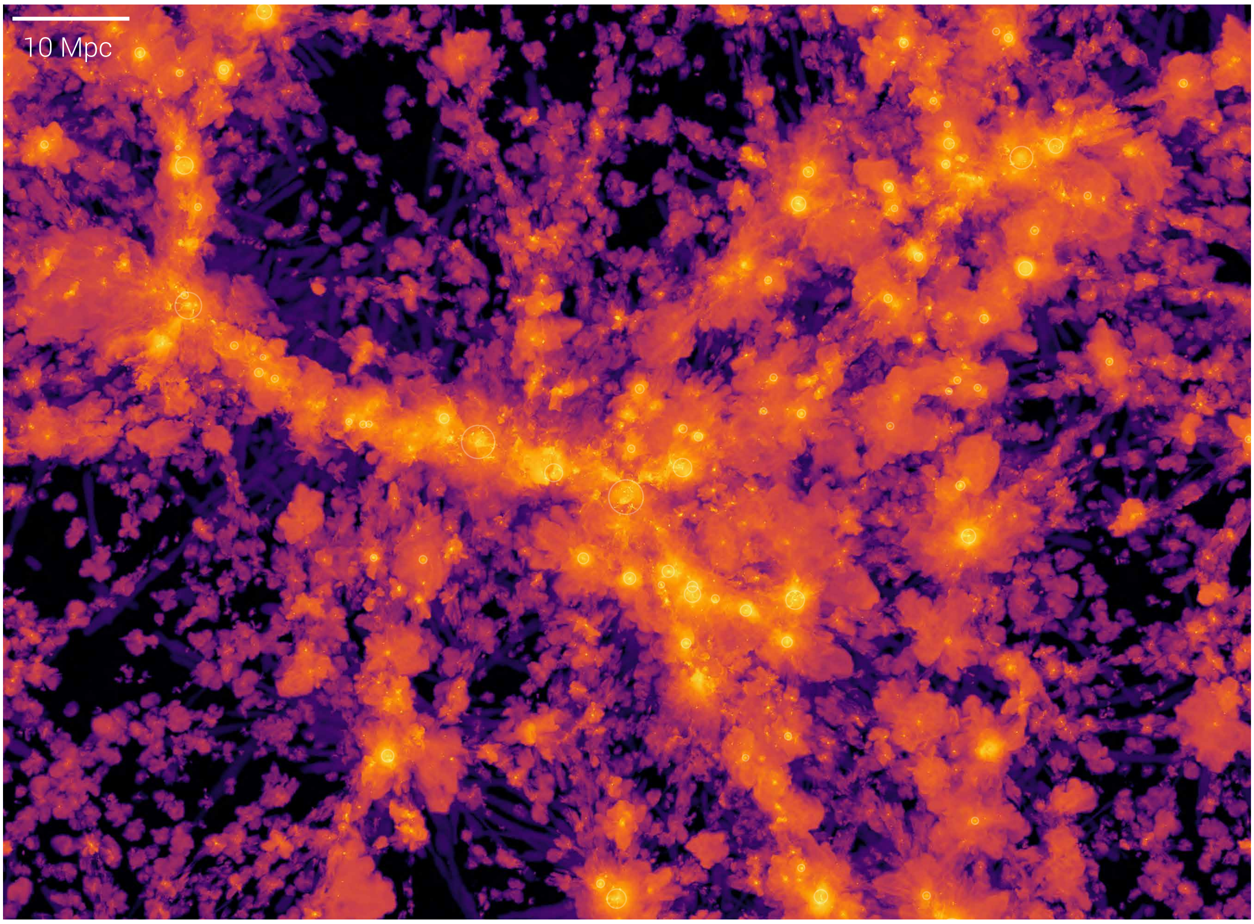

OVII X-ray surface brightness from the IllustrisTNG Simulation

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1 Diffuse matter in the post-*Athena* era

Most of the Universe is invisible: 95% of its contents consist of dark matter and dark energy, which we do not yet understand. But even when it comes to the "normal" standard-model particles, we can only see the tip *of the tip* of the iceberg. A large fraction of the baryons have not been converted into stars, but instead reside in the hot, diffuse medium that fills extended galaxy halos, galaxy groups, galaxy clusters, and the cosmic web. These environments are best probed by observations at soft X-ray wavelengths ($\sim 10-100$ Å), requiring spaceborne observatories.

The majority of X-ray observations so far have naturally focused on the densest, brightest centers of clusters and groups of galaxies, revealing in detail the physics of only a tiny fraction of the hot, diffuse matter that permeates the Universe. Even there, after 20 years of exquisite observations and discoveries with *Chandra* and *XMM-Newton*, many questions still loom. High-resolution X-ray spectroscopy studies of the intra-cluster medium (ICM) are all but lacking, leaving a huge gap in our knowledge of the dynamical nature of this hot, diffuse plasma. The Athena observatory is set to revolutionize this field, and significantly advance our understanding of the "Hot Universe".

> To reveal how the cosmic web is interconnected, we must **survey and physically characterize the vast majority of the very faint warm-hot diffuse baryons in the local Universe**. This poses unique challenges that no existing or planned telescope has been designed to address thus far.

What are we still missing?

1. All of the X-ray instruments approved so far only aim to measure the properties of the ICM in massive galaxy clusters within a limited radial range, typically up to r_{200c} [1]. Mapping the physics, kinematics, and chemistry within the *entire* hot gaseous halo of a single, massive, $M_{\rm virial} \sim 10^{15} M_\odot$, z=0.1 galaxy cluster, expected to extend 4–5 times further than r_{200c} and thus cover more than 5 deg^2 on the sky, would require a whopping mosaic of 1000 pointings with the *Athena* X-IFU, most of these with an exposure time well in excess of 1 Ms (meaning a total observing time of over 30 years). **The most exciting, out-of-equilibrium parts of galaxy clusters, located beyond the virial radius and which are live witnesses to the physics of cosmic accretion, would remain entirely unexplored** in the absence of a new X-ray mission with a significantly larger grasp.
2. Massive, X-ray bright clusters of galaxies are rare, and represent only a small fraction of the matter in the Universe. The far less massive, and far fainter, **soft X-ray emitting halos of $\sim$L* galaxies are poorly understood, although it is in these halos that most of the stars and metals in the Universe were formed**. The dominant emission from these lower-mass halos are in the OVII and OVIII multiplets, where the resolving power of *Athena*'s X-IFU, while excellent and unprecedented at higher energies, is only R$\sim$300. This is insufficient to measure typical velocities of $\sim$ 100 km/s expected to be associated with the cycling of baryons through the circumgalactic medium (CGM). We need a future X-ray mission that will revolutionize the studies of the CGM in galaxies with masses similar to that of the Milky Way, in the same way that *Athena* will revolutionize studies of clusters of galaxies.
3. The diffuse matter permeating large-scale structure (LSS) filaments remains elusive. *Athena* will allow a first systematic study of this so-called Warm-Hot Intergalactic Medium (WHIM), by detecting it in absorption along 200 sightlines towards bright BLLacs and gamma-ray bursts (GRB), and studying its corresponding emission spectrum in a handful of cases. However, these observations are contingent upon the chance existence of bright (and thus rare) background beacons to illuminate the WHIM, and will only probe its properties along sparse and narrow pencil-beam sight lines. Obtaining **a complete 3D picture of the baryons permeating**

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[1] the radius within which the mean enclosed density is 200 times the critical density at the redshift of the cluster

the spatially complex large-scale structure requires wide-field, very sensitive tomographic observations of soft X-ray emission, in combination with absorption studies that can make use of much fainter background sources offering a more uniform sky coverage.

The CGM, cluster outskirts, and WHIM are intimately interrelated. Like blood circulating through the human body, the chemical elements produced in stars, pumped by the energy from supernovae (SNe) and supermassive black holes (SMBH), cycle through the Universe's large-scale structure. Metals often escape the shallow gravitational potential wells of the galaxies where they were produced; from there, they either get re-accreted into the CGM, or become mixed into the diffuse LSS filaments and are then funneled into the outskirts of galaxy clusters, the most massive knots of the cosmic web. To really connect the dots of the large-scale structure and to understand this circulation in detail we need a **Cosmic Web Explorer** that will reach unprecedented X-ray sensitivity limits over unprecedented areas on the sky. Beyond a much larger mirror collecting area and field of view (FoV), a much lower and more stable instrumental background, and an improved spectral resolution at the OVII and OVIII lines, this also requires a very accurate understanding of the X-ray halo of our own Milky Way which acts as a foreground to the faint emission we are searching for. **Only a next-generation mission that will survey a large area of the sky using sensitive, high spatial and spectral resolution, integral field spectroscopy in the soft X-ray band, can fully achieve this goal, building upon previous progress brought about by XRISM[2] and *Athena*[3].**

2 The unknowns of the unseen cosmic web in X-ray light

2.1 The emergent large-scale structures around the knots of the cosmic web

Galaxy clusters are the ultimate manifestation of hierarchical structure formation, and they continue to grow and accrete matter at the present time. The outer regions of galaxy clusters are home to the majority of the diffuse gas in these systems, and bear witness to the complex physics of large-scale structure growth as it happens. A plethora of unexplored structure formation physics is believed to be operating near and beyond the virial radii of galaxy clusters, and these processes are fundamentally different from the physics in the cores of clusters that has been the focus of X-ray cluster science over the past several decades.

An ultimate census of the baryons, even inside massive clusters of galaxies, can only be achieved by (1) mapping the entire volume of clusters in order to identify and characterize substructures on both small and large scales, and (2) accounting for bulk and turbulent gas motions, unresolved clumping, and non-equilibrium phenomena that would otherwise significantly bias the gas density, temperature, metal and mass measurements. **The rich thermal, kinematic and chemical contents of cluster outskirts are the Rosetta stone for understanding the growth of galaxy clusters and their connections to the Cosmic Web, as well as a stepping stone towards exploring the outskirts of massive galaxies and galaxy groups.**

2.1.1 The shocked baryons at the edge of galaxy clusters

The outermost boundary of the X-ray emitting gas halo of galaxy clusters is marked by the so-called "accretion shock" or "external shock". It is here, around 4–5 r_{200c}, that low-temperature, low-density gas accreting from the void regions is heated by strong shocks with Mach numbers of several tens to hundreds, reaching X-ray emitting temperatures during its first infall into the cluster potential (e.g. Ryu et al., 2003; Molnar et al., 2009). "Internal shocks" or "virial shocks" due to mergers and filamentary accretion further increase the entropy of the gas. **Although directly**

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[2] https://global.jaxa.jp/projects/sas/xrism/

[3] https://www.the-athena-x-ray-observatory.eu/