PROBING THE ASSEMBLY OF THE COSMIC WEB

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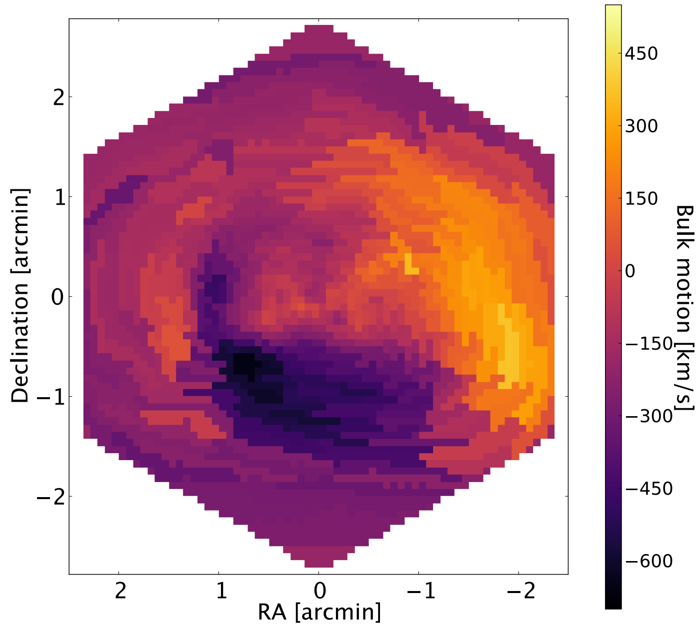
Matter in the Universe is distributed in a foam-like structure of voids and filaments called the "cosmic web". Galaxy clusters form at the nodes of this web where the filaments intersect and the matter density is highest. Clusters can contain thousands of galaxies, measure millions of light-years across, and have total masses up to one thousand million million (10^{15}) times that of the Sun.

Despite their name, galaxies comprise less than 5% of the total mass of a galaxy cluster. About 85% of their mass consists of dark matter, which can be detected only indirectly. The remaining 10% of the mass is contained in an extended plasma called the intra-cluster medium (ICM) that fills the space between the galaxies. The plasma is extremely rarefied and exceptionally hot (more than 10 million degrees), and cools over cosmic timescales by emission of X-ray photons generated by thermal collisions within the plasma. The ICM is thus the major "visible" component of clusters.

Clusters grow through a hierarchical assembly process, accreting matter along the filaments under the gravitational pull of their major constituent, the dark matter. Most of this accretion is "quiet", but occasionally mergers occur between objects of similar mass. These major mergers between clusters are the most energetic events in the Universe since the Big Bang. They drive thousand-light-year-long shockwaves travelling at thousands of kilometers per second into the ICM plasma, heating the gas and generating bulk and turbulent motions that can last for more than a billion years. These motions should be detectable in many clusters owing to their long lifetimes. However obtaining clear evidence of these gigantic cosmic collisions on the ICM plasma has proven challenging.



Reconstructed bulk motion map of the hot gas in a galaxy cluster from a simulated Athena X-ray Field Unit (X-IFU) observation. X-ray spectral line shifts from nearly 4 000 pixels have been computed from a numerical simulation of a galaxy cluster, allowing bulk motions of more than ~ ± 500 kilometres per second to be measured in this particular example. X-IFU observations of a sample of such objects will give unique insights into the assembly of these massive structures.

High-resolution X-ray spectroscopy offers the possibility of direct detection of bulk and turbulent motions in the ICM plasma through measurement of the shifting and broadening of emission lines. To date, turbulent line broadening has been detected in only one cluster. The recent observation of the Perseus cluster by the Hitomi satellite allowed measurement of a modest amount of turbulence ($< 164 \pm 10$ km s^{-1}) very close to the core. However, energy input by jets from the central supermassive black hole likely created this turbulence, not the cluster assembly process itself.

The Athena X-IFU is designed to be able to measure line broadening at levels 25 times more sensitive than Hitomi, and on spatial scales 12 times smaller. Its thousands of detectors will allow mapping of the line-of-sight bulk and turbulent velocity field of the ICM plasma in many merging galaxy clusters on unprecedented spatial scales, inside and beyond the core. It will allow us to link these bulk and turbulent motions to the assembly of the "cosmic web", and give unparalleled insights into the physics of the ICM plasma during these extreme events.

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