A filament of dark matter between two clusters of galaxies

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It is a firm prediction of the concordance cold-dark-matter cosmological model that galaxy clusters occur at the intersection of large-scale structure filaments. The thread-like structure of this 'cosmic web' has been traced by galaxy redshift surveys for decades. More recently, the warm–hot intergalactic medium (a sparse plasma with temperatures of $10^7$ kelvin to $10^8$ kelvin) residing in low-redshift filaments has been observed in emission and absorption. However, a reliable direct detection of the underlying dark-matter skeleton, which should contain more than half of all matter, has remained elusive, because earlier candidates for such detections were either falsified or suffered from low signal-to-noise ratios and unphysical misalignments of dark and luminous matter.

Here we report the detection of a dark-matter filament connecting the two main components of the Abell 222/223 supercluster system from its weak gravitational lensing signal, both in a non-parametric mass reconstruction and in parametric model fits. This filament is coincident with an overdensity of galaxies and diffuse, soft-X-ray emission, and contributes a mass comparable to that of an additional galaxy cluster to the total mass of the supercluster. By combining this result with X-ray observations, we can place an upper limit of 0.09 on the hot gas fraction (the mass of X-ray-emitting gas divided by the total mass) in the filament.

Abell 222 and Abell 223, the latter a double galaxy cluster in itself, form a supercluster system of three galaxy clusters at a redshift of $z = 0.21$ (ref. 13), separated on the sky by about 14°. Gravitational lensing distorts the images of faint background galaxies as their light passes massive foreground structures. The foreground mass and its distribution can be deduced from measuring the shear field imprinted on the shapes of the background galaxies. Additional information on this process is given in the Supplementary Information. The mass reconstruction in Fig. 1 shows a mass bridge connecting Abell 222 and the southern component of Abell 223 (Abell 223-S) at the 4.1σ significance level. This mass reconstruction does not assume any model or physical prior probability distribution on the mass distribution.

To show that the mass bridge extending between Abell 222 and Abell 223 is not caused by the overlap of the cluster halos but is in fact due to additional mass, we also fitted parametric models to the three clusters plus a filament component. The clusters were modelled as elliptical Navarro–Frenk–White (NFW) profiles with a fixed mass-concentration relation. We used a simple model for the filament, with a flat ridge line connecting the clusters, exponential cut-offs at the filament endpoints in the clusters, and a King profile describing the radial density distribution, as suggested by previous studies. We show in the Supplementary Information that the exact ellipticity has little impact on the significance of the filament.

The best-fit parameters of this model were determined using a Monte Carlo Markov chain and are shown in Fig. 2. The likelihood-ratio test prefers models with a filament component with 96.0% confidence over a fit with three NFW halos only. A small degeneracy exists in the model between the strength of the filament and the virial radii of Abell 222 and Abell 223-S. The fitting procedure tries to keep the total amount of mass in the supercluster constant at the level indicated by the observed reduced shear. Thus, it is not necessarily the case that sample points with a positive filament contribution indeed have more mass in the filament area than has a three-clusters-only model. This is because the additional filament mass...
might be compensated for with lower cluster masses. We find that the integrated surface mass density along the filament ridge line exceeds that of the clusters-only model in 98.5% of all sample points.

This indicates that the data strongly prefers models with additional mass between Abell 222 and Abell 223-S and that this preference is stronger than the confidence level derived from the likelihood-ratio test. The difference is probably due to the oversimplified model, which is not a good representation of the true filament shape. The data, on the other hand, is not able to constrain more complex models. Extensions to the simple model that we tried were replacing the flat ridge line with a parabola and replacing the King profile with a cored profile leaving the exponent free. The latter was essentially unconstrained. The parabolic ridge line model produced a marginally better fit that was, however, statistically consistent with the flat model. Moreover, the likelihood-ratio test did not find a preference for the parabolic shape.

The virial masses inferred from the Monte Carlo Markov chain are lower than those reported earlier for this system\textsuperscript{10}, which were obtained from fitting a circular two-component NFW model to Abell 222 and Abell 223. In contrast to this approach, our more complex model removes mass from the individual supercluster constituents and redistributes it to the filament component. Reproducing the two-component fit with free concentration parameters, as done in the previous study\textsuperscript{10}, we find (where \( M_\odot \) is the mass of the Sun): \( M_{200}(\text{Abell 222}) = (2.7^{\pm 0.5}) \times 10^{14} \ M_\odot \), which is in good agreement with ref. 10, and \( M_{200}(\text{Abell 223}) = (3.4^{\pm 1.0}) \times 10^{14} \ M_\odot \), which overlaps the 1σ error bars of the earlier study\textsuperscript{10}. Throughout, all error bars are single standard deviations.

The detection of a filament with a dimensionless surface mass density of \( \kappa = 0.03 \) is unexpected. Simulations generally predict the surface mass density of filaments to be much lower\textsuperscript{10} and undetectable individually\textsuperscript{14}. These predictions, however, are based on the assumption that the longer axis of the filament is aligned with the plane of the sky and that we look through the filament along its minor axis. If the filament were inclined with respect to the line-of-sight and we were to look almost along its major axis, the projected mass could reach the observed level.

A timing argument\textsuperscript{19-20} can be made to show that the latter scenario is more plausible in the Abell 222/223 system. In this argument we treat Abell 223 as a single cluster and neglect the filament component, so that we have to deal only with two bodies, Abell 222 and Abell 223. The redshifts of Abell 222 and Abell 223 differ by \( \Delta z = 0.005 \), corresponding to a line-of-sight separation of 18 megaparsecs if the redshift difference is entirely due to Hubble flow. Let us assume for a moment that the difference is caused only by peculiar velocities. Then at \( z = \infty \), the clusters were at the same location in the Hubble flow. We let them move away from each other with some velocity and inclination angle with respect to the line-of-sight and later turn around and approach each other. The parameter space of total system mass and inclination angle that reproduces the observed configuration at \( z = 0.21 \) is completely degenerate. Nevertheless, to explain the observed configuration purely with peculiar velocity, this model requires a minimum mass of \( (2.61 \pm 0.05) \times 10^{15} M_\odot \) with an inclination angle of 46°, where the error on the mass is caused solely by the uncertainty of the Hubble constant. Because this is more than ten standard deviations above our mass estimate for the sum of both clusters, we infer that at least part of the observed redshift difference is due to Hubble flow, and that we are looking along the filament’s major axis.

The combination of our weak-lensing detection with the observed X-ray emission of 0.91 ± 0.25 keV warm–hot intergalactic medium plasma\textsuperscript{4} allows us to constrain the hot gas fraction in the filament. Assuming that the distribution of the hot plasma is uniform and adopting a metalliclicity of \( Z = 0.2 Z_\odot \), the mass of the X-ray-emitting gas inside a cylindrical region with radius 330 kiloparsecs centred on (01 h 37 min 45.00 s, 12° 54′ 19.6″; see Fig. 3) with a length along our line-of-sight of 18 megaparsecs, as suggested by our timing argument, is \( M_{\text{gas}} = 5.8 \times 10^{12} M_\odot \). The assumption of uniform density is

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**Figure 2** Posterior probability distributions for cluster virial radii and filament strength. Shown are the 68% and 95% confidence intervals on the cluster virial radii \( r_{200} \) (within which the mean density of the clusters is 200 times the critical density of the Universe) and the filament strength \( \kappa_0 \). The confidence intervals are derived from 30,000 Monte Carlo Markov chain sample points. The filament model is described by 

\[
\kappa_0(r) = \kappa_0 \{ 1 + \exp \left( \frac{r - r_c}{r_e} \right) \}^{-1},
\]

where the coordinate \( \theta \) runs along the filament ridge line and \( r \) is orthogonal to it. This model predicts the surface mass density at discrete grid points from which we computed our observable, the reduced shear, via a convolution in Fourier space. The data cannot constrain the steepness of the exponential cut-off at the filament endpoints \( \sigma \) and the radial core scale \( r_c \). These were fixed at their approximate best-fit values of \( \sigma = 0.45 \) megaparsecs and \( r_c = 0.54 \) megaparsecs. The data also cannot constrain the cluster ellipticity and orientation. These were held fixed at the values measured from the isodensity contours of early-type galaxies\textsuperscript{21}. The ratios of minor to major axes and the position angles of the ellipses are (0.63, 0.69, 0.70) and (65°, 34°, 3°) for Abell 222, Abell 223-S, and Abell 223-N, respectively. We further explore the impact of cluster ellipticity on the filament detection in the Supplementary Information.
the inferred mass is higher but consistent within one standard error is small owing to the highly correlated noise of the smoothed M causes only a 5% error. In the reconstructed...X-rays detectable by the European Space Agency’s X-ray Multi-Mirror Mission (XMM-Newton) space telescopes.24

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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