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Stellar Kinematics in the Cosmic Web: Lessons from the SAMI Survey and the Horizon-AGN Simulation

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Abstract. We reconstruct the 3D network of cosmic filaments on Mpc scales across GAMA fields and assign SAMI field galaxies to their nearest filament to estimate the degree of alignment between SAMI galaxies' kinematic axes and their nearest filament in projection. We present the first detection of differential galactic spin alignment trends with local cosmic filaments using IFS kinematics. Low-mass galaxies show a tendency to align their spin with their nearest filament while higher mass counterparts are more likely to display an orthogonal orientation. The stellar transition mass is confidently bracketed between $10^{10.1}\,M_\odot$ and $10^{10.7}\,M_\odot$. In addition, we find that on average, v/σ peaks at a physical distance $d_{\rm fil} = 2.4 + -0.5$ Mpc from the centre of the filaments. A similar trend is recovered in the Horizon-AGN simulation. We also find this trend to be consistent with the build-up of galaxies in rich vorticity quadrants dispatched around filaments identified in the Horizon-AGN simulation.

Keywords. cosmic web, galaxy evolution, integral field spectroscopy, numerical simulations

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1. Introduction

In standard cosmology, the anisotropic distribution of matter on largest scales, referred to as the cosmic web, naturally arises from the anisotropic gravitational collapse of an initially gaussian random field of density perturbations. Haloes form and reside within the overdensities of the cosmic web, accreting smooth material and smaller haloes via filaments they contributed to form in between them (see Bond *et al.* (1996) for details and references). Knots at the intersection of several of the most contrasted filaments house clusters, the largest virialized objects in the universe. On such scales, the filamentary pattern of the cosmic web is apparent in all large-scale galaxy surveys (de Lapparent *et al.* (1986) and Doroshkevich *et al.* (2004), Colless *et al.* (2003), Alpaslan *et al.* (2014)), traced by the galaxy distribution.

This structure conditions the geometry and dynamics of gas and galaxy flows from early times onwards. Simulations predict that gas trapped in collapsed dark matter halos is funnelled through cold filamentary streams shaped by the cosmic filaments and advected towards the centre of forming galaxies to which it transfers angular momentum (see Pichon *et al.* (2011) and Danovich *et al.* (2012) for references). An important prediction from simulations is that low-mass galaxies tend to align their spin with their nearby filament while their more massive counterparts are more likely to display an orthogonal orientation Aragon *et al.* (2007), Hahn *et al.* (2007), Paz *et al.* (2008), Bett *et al.* (2012), Codis *et al.* (2012), Dubois *et al.* (2014), Codis *et al.* (2018). Hints of such a transition have been identified in the SDSS using morphology as a proxy for spin by Tempel *et al.*

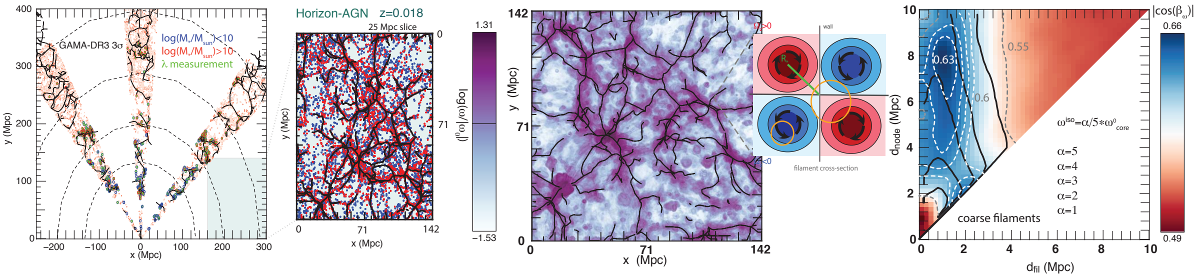

Figure 1. *Left panel:* Network of cosmic filaments across the three GAMA fields that host SAMI galaxies (solid black lines). SAMI galaxies with $M_* > 10^{10}\,M_\odot$ are indicated as red circles, those with $M_* < 10^{10}\,M_\odot$ as blue circles, green filling indicate available v/σ measurements. Pink dots indicate the initial GAMA population. Dashed hemicircles indicate the redshift tiers of the SAMI survey. The right inset shows the galaxy population and filaments extracted in a 25 Mpc thick slice from the Horizon-AGN simulation. *Intermediate panel:* Amplitude of the vorticity field in Horizon-AGN and sketch of the cosmic filament cross-section. *Right panel:* vorticity-filament angle (cosine) in the $d_{\rm fil} - d_{\rm node}$ plane: colours and dashed contours for $|\cos(\beta_\omega)|$ and black contours for amplitude of the vorticity.

(2013) but with limited significance. Overall, this faint signal has therefore remained elusive in observations.

In recent years, a number of galactic properties have been found to correlate with cosmic web features in spectroscopic and photometric surveys Laigle *et al.* (2018), Malavasi *et al.* (2017), Kraljic *et al.* (2018). Among all tracers of this interplay, spin orientations are expected to be independent of purely mass or density driven effects but are harder to obtain. The SAMI Integral Field Spectroscopy (IFS) survey Croom *et al.* (2012) provide high quality $z = 0$ stellar kinematics within one effective radius across a wide range of environments with near kiloparsec resolution and therefore offers an unprecedented opportunity to detect such signals directly on the kinematics of galaxies. Hereafter we present the first detection of spin alignments in the SAMI IFS survey and explore galaxies connection to their large-scale anisotropic environment.

2. Reconstructing the cosmic web: how and why?

We focus on the 761 galaxies of the SAMI DR1 data release Croom *et al.* (2012) found across the G09, G12 and G15 sub-fields of the deep spectroscopic survey GAMA Driver *et al.* (2011). For this sample, precise kinematics measurements of the stellar intrinsic angular momentum, kinematic position angle and v/σ within one effective radius and within elliptical aperture are available. Their computation is extensively described in van de Sande *et al.* (2017), van de Sande *et al.* (2018).

To reconstruct cosmic nodes and filaments on mega-parsec scale, an accurate tracer of the underlying density field over a large volume is required. We use the GAMA survey containing 300 000 galaxies with most stellar masses comprised between 10^8 and $10^{12}\,M_\odot$. The density field is reconstructed directly real space from the distribution of galaxies (weighted by their mass) using a Delaunay tessellation. The tessellated density field is then used as an input for the topology extractor DisPerSe Sousbie *et al.* (2011), which identifies the ridge lines of the density field to produce a contiguous network of segments that trace the spine of the cosmic web, i.e. the cosmic filaments. Filaments are directly trimmed by DisPerSe according to a signal-to-noise criterium expressed as a number of standard deviations σ, here set to 3σ. The projected $3\,\sigma$ network of filaments across GAMA is presented on the left panel of Fig. 1. The left inset illustrates a similar reconstruction across the Horizon-AGN hydrodynamic simulation (Dubois *et al.* (2014)).

Such filaments are crucial to understand galaxy evolution as they inform cosmic flows around them, and therefore the geometry of accretion onto galaxies in their vicinity. It is indeed predicted that the anisotropic collapse of matter onto a filament gives rise to regions of high vorticity (i.e curl of the velocity field $\omega = \nabla \times \mathbf{v}$). The middle panel of Fig. 1 shows the amplitude of the gas vorticity field in Horizon-AGN in shades of purple, with overlaid cosmic filaments. One can notice that vorticity is confined in the immediate vicinity of filaments. Moreover, it is typically aligned with the filament, dispatched in four quadrants of opposite polarity, i.e.whirling in opposite direction, as sketched on the intermediate inset which displays the idealised cross-section of a filament (Pichon *et al.* (2011), Laigle *et al.* (2015), Codis *et al.* (2015)).

The typical scale across which these quadrants are found depends on the scales of extracted filaments and that on which the vorticity is computed. Focusing on our specific filaments and on scales of vorticity which constitute the immediate environment of galaxies (smoothed over $1Mpc$), the right panel of Fig. 1 displays $|\cos(\beta_\omega)|$, the average cosine of the angle between the local vorticity and the nearby cosmic filament in the $d_{\rm fil} - d_{\rm node}$ plane in Horizon-AGN, with $d_{\rm fil}$ the distance of the object (here gas cells) to the nearest filament and $d_{\rm node}$ the distance to the nearest node. Blue areas show regions where an alignment trend is detected, i.e. with $|\cos(\beta_\omega)| > 0.5$. We find that the vorticity is typically aligned with filaments within 2 to 3 Mpc from their spine, with the exception of the immediate proximity of clusters ($d_{\rm node} < 2$Mpc). Interestingly, the peak of alignment is found offset from the spine of the filament, consistently with the existence of quadrants.

In simulations, galaxies growing in such regions are therefore expected to accrete coherently from their surrounding quadrant, hence building their angular momentum parallel to filaments. At later cosmic times, they migrate towards the spine of the filament, overlap quadrants and drift along the filament as they grow in mass. This steady supply of angular momentum is lost and mergers along the filament become the dominant process driving spin evolution, on average flipping the stellar spins orthogonal to the filament (Codis *et al.* (2012), Laigle *et al.* (2015)). The kinematics of galaxies and their distribution therefore bear great promises as tracers of the geometry of cosmic flows. In the following section we look for the signal of this interplay in the kinematics of SAMI galaxies.

3. Evolution of stellar spins in the cosmic web

We assign every SAMI galaxy to its nearest cosmic filament in real space. We then project filaments on the sphere and estimate for each of them a filament position angle. We then compute the angle $\theta^{\rm 2D}_{\rm kin}$ between the kinematic spin axis of each SAMI galaxy (derived from its kinematic axis) and its filament position angle. To detect the spin transition, we split the SAMI sample into two sub-samples according to a given stellar mass threshold $M_{\rm thresh}$. Fig. 2, left panel, shows $\langle\theta_{\rm high}\rangle$, the average spin-filament angle in the higher mass sub-sample, versus $\langle\theta_{\rm low}\rangle$, that in the lower mass sub-sample for $M_{\rm thresh} = 10^{10.4}\, M_\odot$ which gives the highest signal-to-noise ratio. As expected, we find $\langle\theta_{\rm high}\rangle > 45^{\rm o}$ while $\langle\theta_{\rm low}\rangle < 45^{\rm o}$ ($45^{\rm o}$ = uniformly distributed angles). This signal is recovered with a particularly high confidence ($> 2\sigma$) given the extremely low statistics.

The left intermediate panel shows the evolution of $\langle\theta\rangle = \langle\theta^{2D}_{\rm kin}\rangle$ versus median mass, for irregular bins of increasing median mass. This shows a steady increase of the average spin-filament angle with stellar mass, confirming the tendency of stellar spins to flip from parallel to filaments at low-mass to orthogonal to them at high mass. The typical transition mass is bracketed between $10^{10.1}$ and $10^{10.7}$, consistently with numerical studies (Codis *et al.* (2012), Dubois *et al.* (2014), Codis *et al.* (2018)).

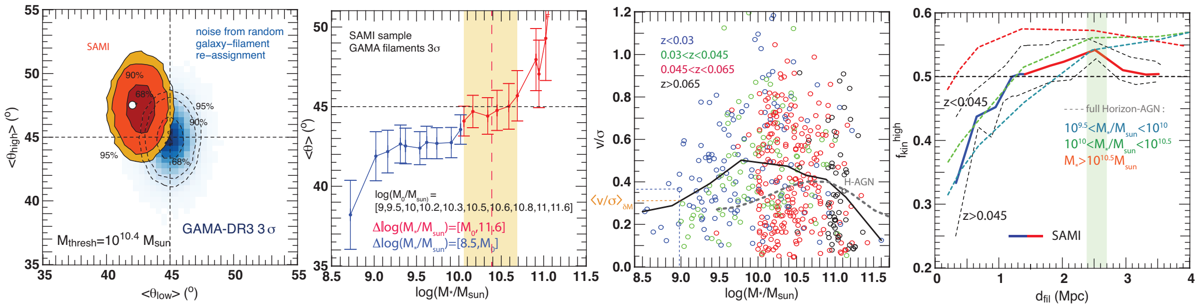

Figure 2. *Left panel:* Average spin-filament angle $\theta^{2D}_{\rm kin}$ for SAMI galaxies with $M_* < 10^{10.4}\, M_\odot$ versus average angle for galaxies with $M_* > 10^{10.4}\, M_\odot$. Shades of blue and dashed contours indicate the distribution of the expected noise, from random re-pairing of galaxies and filaments. Straight black dashed lines show the expectation for uniformly distributed angles (45°).*Middle left panel:* Evolution of $\theta^{2D}_{\rm kin}$ with median stellar mass in SAMI for overlapping bins of increasing median mass. The transition mass in found in the orange shaded area. *Middle right panel*: SAMI population in the $v/\sigma - \log(\mathrm{M}_*/\mathrm{M}_\odot)$ plane, with the average evolution overlaid as a black solid line. Evolution in Horizon-AGN is overlaid as a grey dashed line. *Right panel*: Evolution of $f_{\rm kin}$ in three different mass bins in Horizon-AGN (dashed coloured curves) and in SAMI (solid lines and dashed black lines). Regular bins in distance are used for Horizon-AGN and overlapping bins for SAMI.

To investigate the possible connection with vortical flows, we then follow the evolution of v/σ with respect to $d_{\rm fil}$. To correct from mass driven evolution, we study $f^{\rm high}_{\rm kin} = N_{\rm bin}(\mathrm{gal}|\, \mathrm{v}/\sigma > \langle \mathrm{v}/\sigma \rangle)/\mathrm{N}^{\rm tot}_{\rm bin}$, the fraction of "higher than average rotators" i.e. the fraction (in each distance bin) of galaxies with a v/σ parameter higher than the median for their mass (medians are computed from the SAMI sample as illustrated on the right intermediate panel). The resulting evolution with $d_{\rm fil}$ is displayed on the right panel, for both the SAMI population and the Horizon-AGN population. It is easily notice that $f^{\rm high}_{\rm kin}$ sharply increases away from the filaments until it plateaus or peaks between 2 and 3 Mpc from the spine of the filament. Removing galaxies within 2 Mpc from the nodes of the cosmic web does not qualitatively change the signal. This distribution of fast rotators peaking offset from filaments is consistent with the existence of underlying vorticity quadrants as those found in Horizon-AGN.

4. Conclusion

Reconstructing cosmic filaments from the GAMA survey and correlating them to the kinematics of 761 SAMI galaxies, we find the first kinematic evidence of galaxy spin flips: low-mass galaxies tend to align their angular momentum to their nearby filaments while their higher mass counterparts are more likely to display an orthogonal orientation. The transition mass is estimated between $10^{10.1}$ and $10^{10.7}\, M_\odot$. This is most often interpreted as an effect of mass accretion in vorticity rich regions in the vicinity of filaments, followed by merger activity along the filaments as galaxies grow in mass. Regions of high vorticity, aligned with filaments ate detected in the Horizon-AGN simulation. Following the evolution of galaxies with higher v/σ than what is predicted for their stellar mass with distance to the nearest filament, we find that the fraction of such galaxies increases sharply with $d_{\rm fil}$ before it reaches a peak 2 to 3 Mpc it. Such offset fast rotators are consistent with the existence of vorticity quadrants feeding them with coherent angular momentum but better statistics will be required to explore the effect of environments of various density on the signal and extend this study to the full $d_{\rm fil} - d_{\rm node}$ plane.