# Statistical signature of biconical outflows traced by HI and OVI

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## Angular Distributions of Gas and Metals in the Circumgalactic Medium: Insights into Galaxy Evolution

Understanding the angular distribution of gas and metals in the circumgalactic medium (CGM) offers critical insights into the gas flow processes that regulate galaxy evolution. Gas accretion is often hypothesized to occur preferentially along the disk plane, while metal-enriched winds are thought to outflow along the minor axis, following paths of least resistance. We present an observational study of the azimuthal dependence of gas and metals in the CGM of a statistically significant sample of low-redshift galaxies, leveraging UV absorption-line data obtained using HST/COS. Morphological parameters, such as the inclination angles and position angles, were derived by modeling galaxy light profiles using GALFIT on HST images. We find an enhanced HI covering fraction along both the major and minor axes within 1.5 $R_{\rm vir}$, corresponding to cool accreting gas and the cool phase of outflows, respectively. In contrast, the elevated OVI covering fraction in the CGM along the minor axis points to warm-hot bipolar outflows.

## HST Imaging and Spectroscopic Data

The galaxy pair SBS 0335-052 E&W is connected by a diffuse HI bridge that evidences the onset of merging. On $\sim 1$ kpc scales the E galaxy shows a complex HII morphology, characterised by multiple arcs and arc-crossing filaments. The former trace shells swept up by feedback from super star clusters and the latter indicate regions where the hot gas vents as the shells fragment. We interpret the extended HII structure towards the NW as a large-scale outflow caused by the hot wind fluid penetrating through the porous circum-galactic medium.

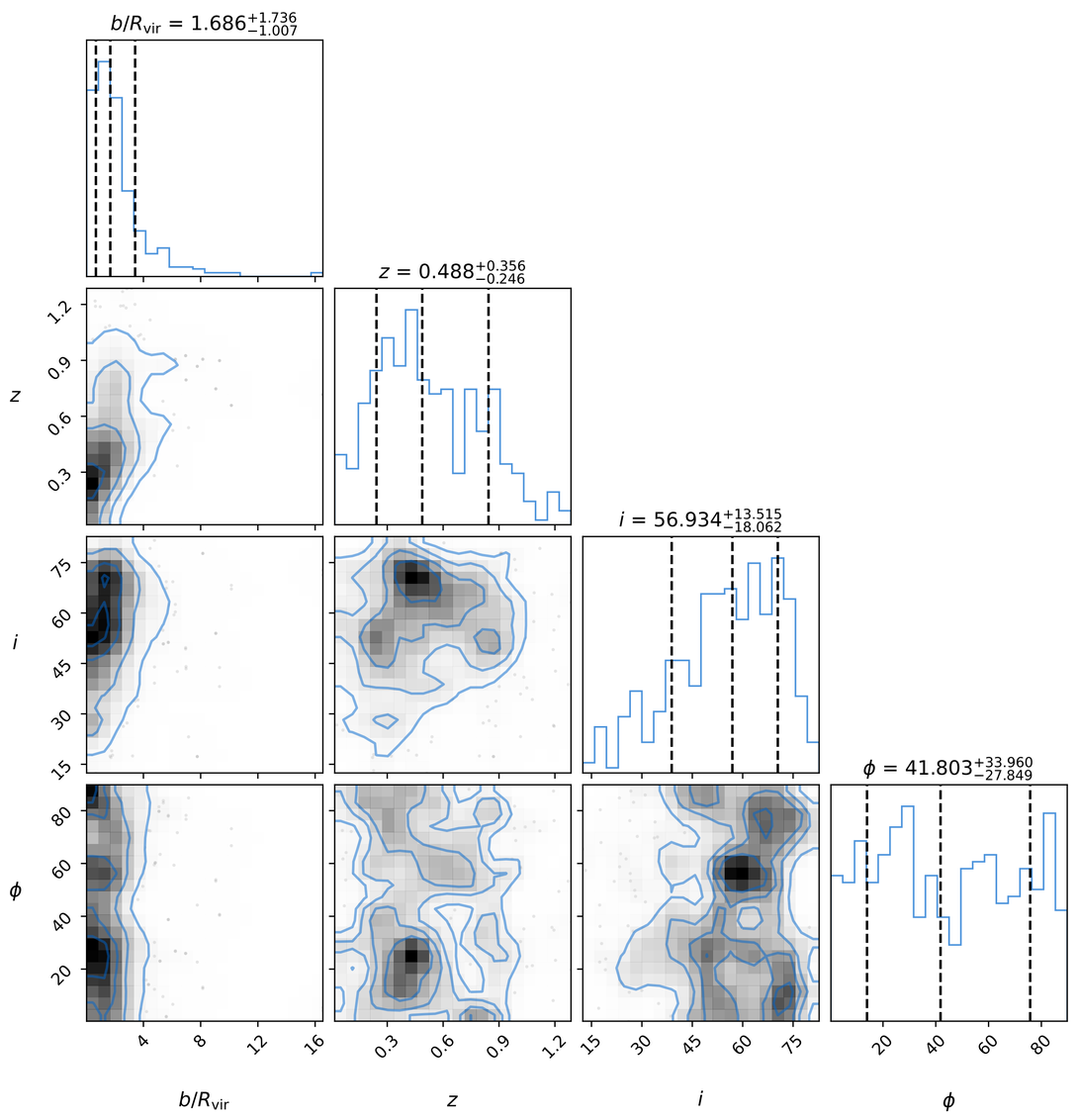


Figure 1: *Top:* 30h JVLA B-configuration observations of SBS 0335-052 system (red contours at $N_{\rm HI} = \{0.7, 1.6, 2.8, 3.6, 5.4\} \times 10^{20}\,{\rm cm}^{-2}$; 7k$\lambda$ tapered data; beam is 15.9″×14.7″ oriented at 66.4°) overlaid on H$\alpha$ narrow-band from MUSE (log-stretch from 0 to $1.25\times10^{-15}\,{\rm erg\,s^{-1}cm^{-2}}$) inset into a colour composite (grz from Pan-STARRS). *Bottom left:* H$\alpha$ from MUSE ($t_{\rm exp.} =$ 1.5 h, cyclic colour map from 0 to $10^{-18}$ to $10^{-15}\,{\rm erg\,s^{-1}cm^{-2}}$ with asinh-scaling; contours ${\rm SB}_{H\alpha} = \{0.75, 1.5, 2.5, 5, 12.5\} \times 10^{-18}\,{\rm erg\,s^{-1}cm^{-2}}$) with untapered HI 21cm from JVLA. *Bottom right:* Untapered JVLA 21cm B-configuration observations (red contours; 6.1″×6.1″ beam at -23.6°). Contour levels represent $N_{\rm HI} = \{6, 9, 11, 14, 18.5, 27.8\} \times 10^{20}\,{\rm cm}^{-2}$. The background HST H$\alpha$ (FR656N) image is displayed with a cyclic asinh-stretch highlighting the bright emission near the super star clusters while also providing contrast for the filamentary loops in the NW.

The untapered HI observations reveal extended HI towards the NW, i.e. towards the direction of the outflow. Moreover, the HI peak is offset from the photometric centre; not an unusual sight in compact star-forming galaxies.

## HII kinematics - indication of conical outflow

The line-of-sight velocity field shows a NW-SE gradient that is, however, significantly perturbed in the centre. This central perturbation is consistent with the expected signal from an expanding shell. Notably, the imprint of this small scale feature stretches out continuously into the extended structure.

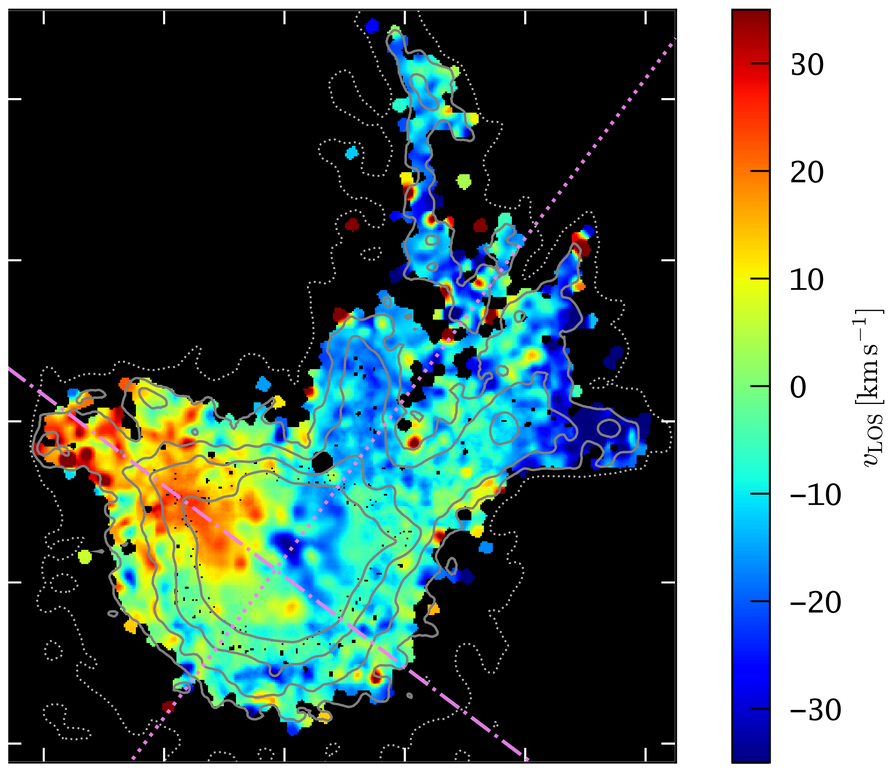


Figure 2: Velocity field of the ionised gas as derived from the MUSE observations. The major- and minor-axes from HI kinematics are delineated as dash-doted and dotted lines, respectively.

## A toy-model as aid to interpret the observations

A simple cone model (opening angle 19°, tilt 52°, inclination 37°) with HII ($T = 2.5 \times 10^4$K, $n = 0.1{\rm cm}^{-3}$) walls of 1.8 kpc thickness and 10 kpc height can reproduce, at least to some extent, the extended H$\alpha$ morphology. We emphasise, that the density is far lower than typical densities of HII gas (100× for even the lower end of HII regions), and we expect this gas is cooler material mixed in with the wind fluid.

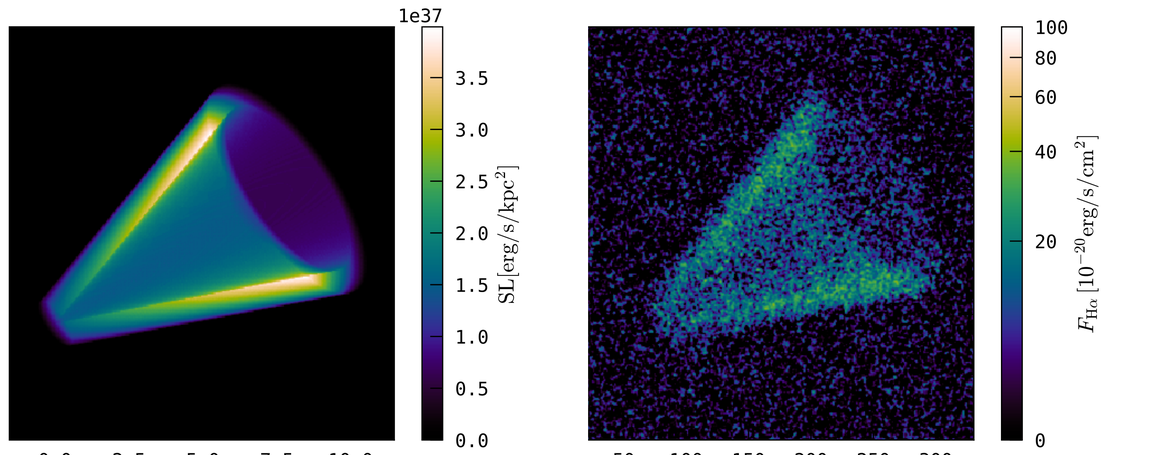


Figure 3: Conic model of hydrogen in ionisation equilibrium with parameters and at dimensions consistent with observations. *Left:* Display in physical coordinates at surface luminosities in cgs units. *Right:* Simulated MUSE observations of the model structure at the distance of SBS 0335-052 and with noise properties similar as in the real data.

## Conclusions

Our observations demonstrate that a compact low-metallicity starburst can drive a beamed outflow through an extended neutral halo. Such outflows can act as channels for the leakage of ionising radiation. Interestingly, the cone direction (NW) is opposite to the age gradient of star clusters (SE) Thus the directionality of Lyman contiuum photon escape could be intrinsically linked to the galaxy formation process. The age gradient is interpreted as propagating star formation. If this is an important building mechanism in the formation of galaxies in the early universe, then we expected beamed ionising radiation leakage into small solid angles from numerous low-mass galaxies during the Epoch of Reionisation. Such a scenario should have effects on the topology of reionisation.