How do filaments form?

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What's the problem?

Filaments play a crucial role in funneling material towards star formation in molecular clouds but their typical properties and main formation scenarios are still highly debated (Hacar et al. 2022).

Proposed formation mechanisms include the intersection of shock-compressed sheets, velocity perturbations within shock-compressed layers, material flows within bent oblique MHD shock fronts, gravity-induced fragmentation of sheet-like clouds, and turbulent shear flows stretching of existing clumps (Abe et al. 2021).

We can quantify the role of the individual mechanisms be systematically comparing density, velocity and magnetic field structure. Using a wavelet analysis of filamentary structures combined with a directional cross-correlation approach we compare the solumn density and velocity profiles of filaments formed in simulations and observations to reveal the nature of their formation.

Wavelet decomposition

In Ossenkopf-Okada & Stepanov (2018) we proposed an anisotropic wavelet decomposition to identify and quantify anisotropic structures measuring the power of filamentary column density fluctuations thereby allowing for a gravitational stability analysis of filaments.

Here, we modify and apply the method for a morphological analysis of the data to provide an independent quantification of filament properties. We switch from a complex wavelet

$$\psi(x, y) = \left[\exp(2\pi\imath x) - \exp(-\pi^2 b^2)\right] \exp\left(\frac{-x^2 - y^2}{b^2}\right)$$

to the corresponding two real wavelets, separately measuring the spines or wings of the filaments:

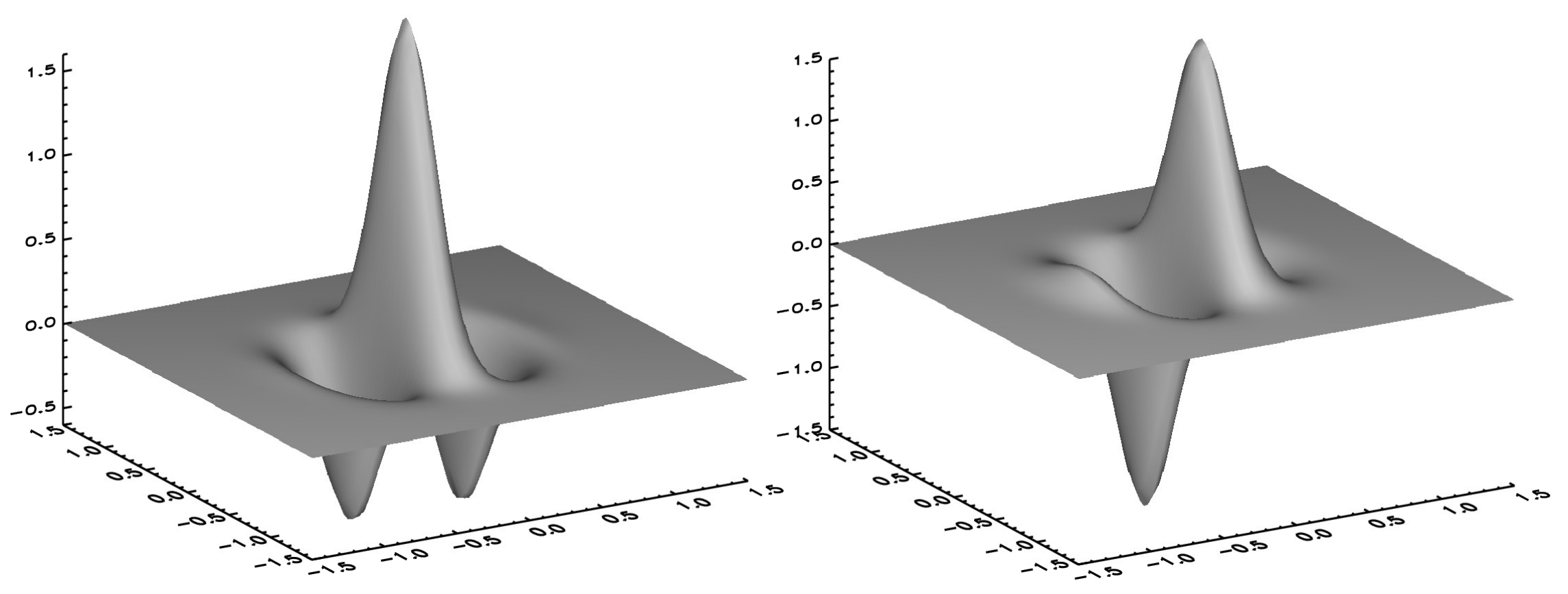


FIGURE 1: Two-dimensional wavelets used for the analysis. The left plot shows the real (cosine) contribution of *ψ(x,y)* being symmetric, the right plot shows the anti-symmetric (sine) part. For the analysis, the wavelet is stretched by a factor *s* and rotated by an angle *φ*.

In this way we can independently determine the location of the spines and the edges of the filaments as a function of the size scale, measuring their distribution and the width of the filaments from the distance between opposite wings.

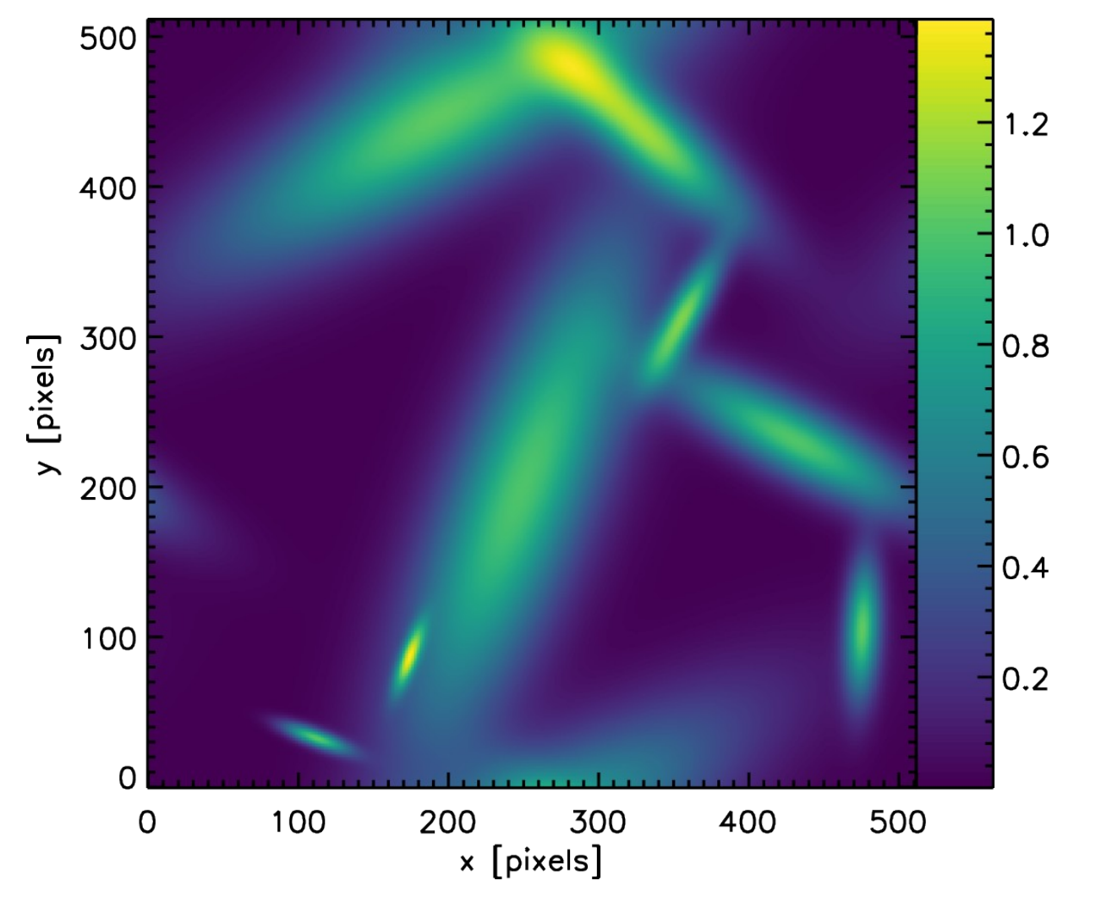
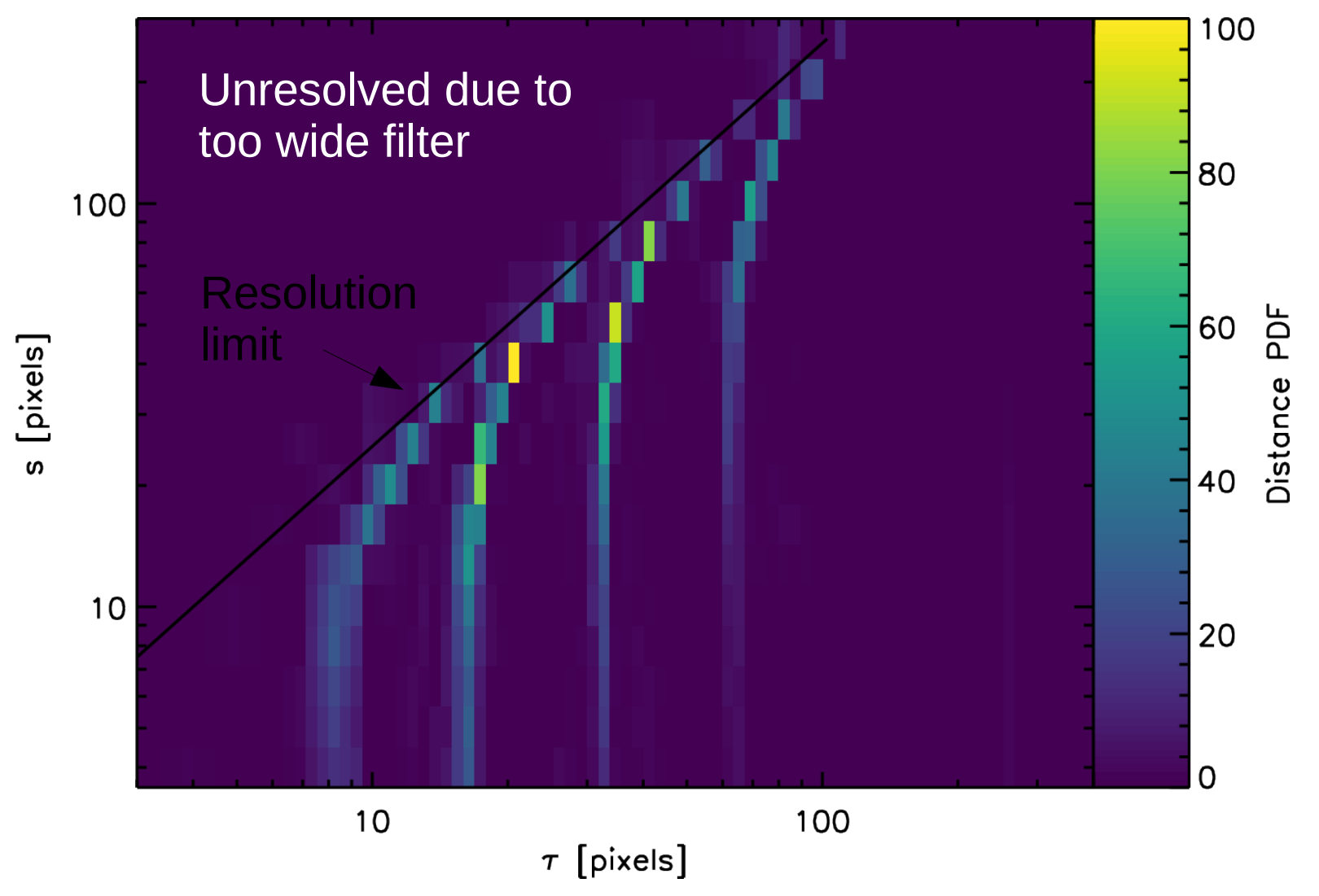


FIGURE 2: Analysis of test data set consisting of 8 Gaussian clump filaments (upper plot). The lower plot shows the distribution of wing distances, measured as peaks in the sine-wavelet filtered map, perpendicular to the local anisotropy. The distances are shown on the *x*-axis. On the *y*-axis we modify the size of the filter function *s*. Colors give the number of counts. We clearly see the four filaments widths.



Filament and shock characterization

We apply the analysis to the large scale mapping of the Orion Molecular Cloud in CO isotopologues by Kong et al. (2018) that simultaneously provides column density and velocity information.

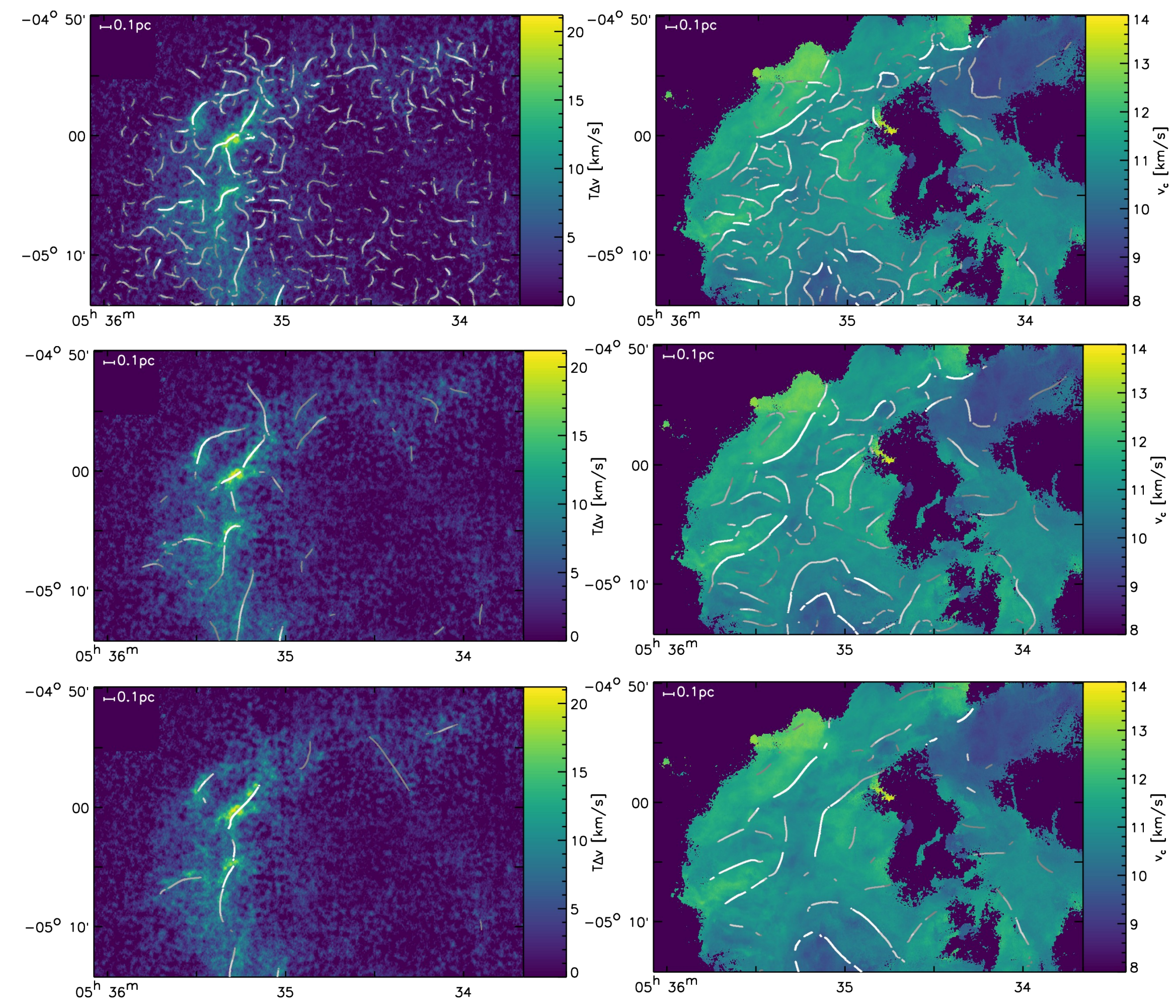


FIGURE 3: Spine identification for column density filaments (left panels) and shocks seen as elongated gradients in the centroid velocities (right panels) from the C^{18}O 1-0 and ^{13}CO 1-0 line observations of the Orion Molecular Cloud using anisotropic wavelets. From top to bottom the wavelet kernel width is varied between s = 0.14, 0.29, and 0.58 pc, thereby being most sensitive to filament widths of FWHM = 0.057-0.1, 0.11-0.2, and 0.23-0.4 pc, respectively. The gray level of the spines indicates the amplitude of the anisotropic wavelet coefficients, measuring the filament contrast. Brighter lines represent higher amplitudes, i.e., stronger filaments. The shown map shows only a small subset of the observational data.

The size spectrum of wavelet coefficients provides a measure for the filament width that is free of any prior assumptions on the structure (see e.g. Panopoulou et al. 2017).

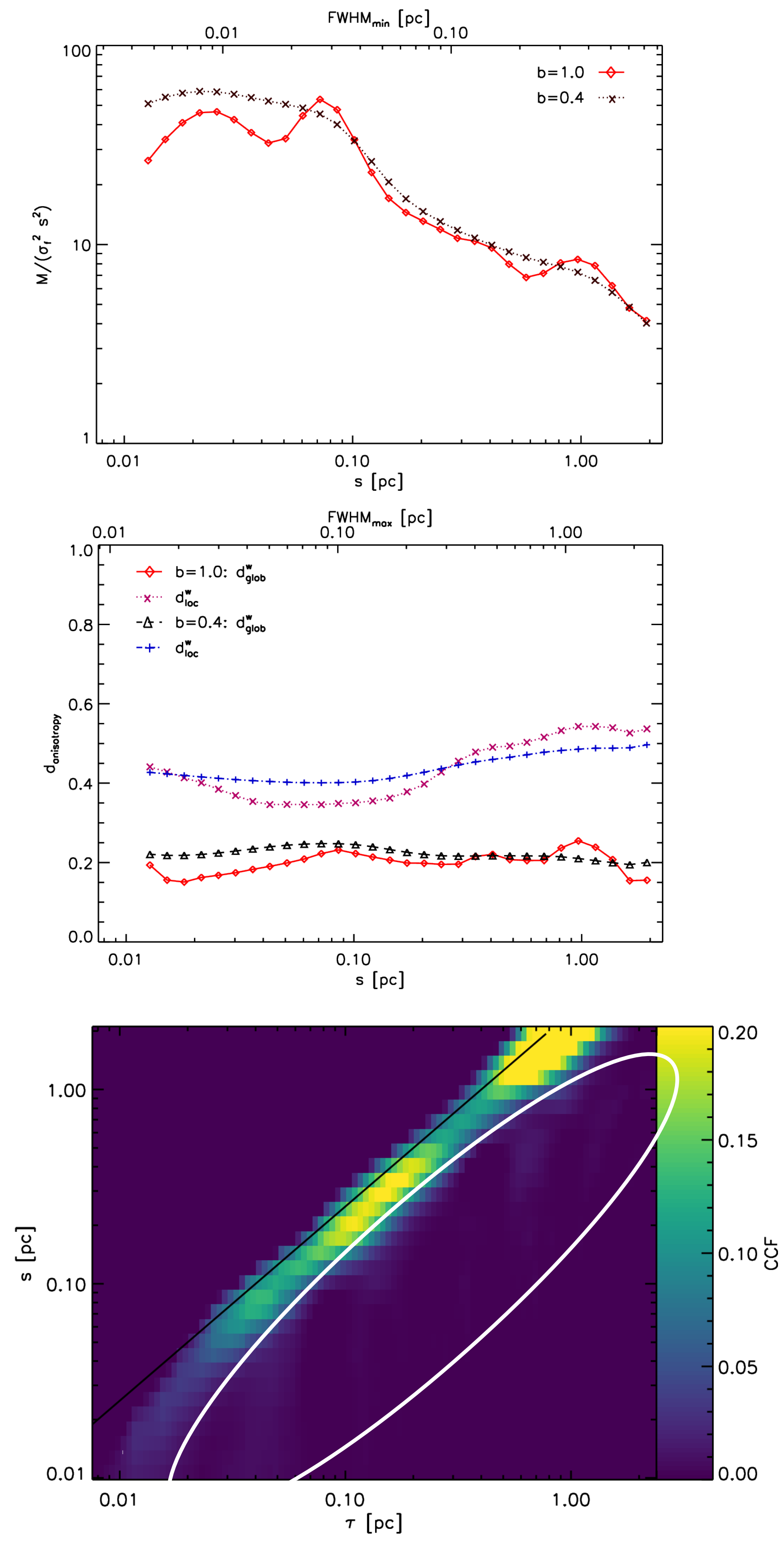


FIGURE 4: Wavelet analysis of the whole C^{18}O 1-0 column density map. The upper panel shows the fluctuation strength as a function of size, the middle panel the degree of anisotropy and the lower panel the width statistics equivalent to Fig. 2.

There is a surplus of structure with a characteristic size below 0.1pc, but a low degree of anisotropy. Filaments are found at all larger scales with two weak abundance peaks at 0.13pc and 0.5pc.

Comparison to simulations

The same approach can be used in simulations with full control of the different filament formation mechanisms. We use the high-resolution hydrodynamic simulations of Federrath et al. (2021). The simulations suggest a change in the scaling behaviour from supersonic to subsonic turbulence at the sonic scale at 0.0125L$_{\rm domain}$.

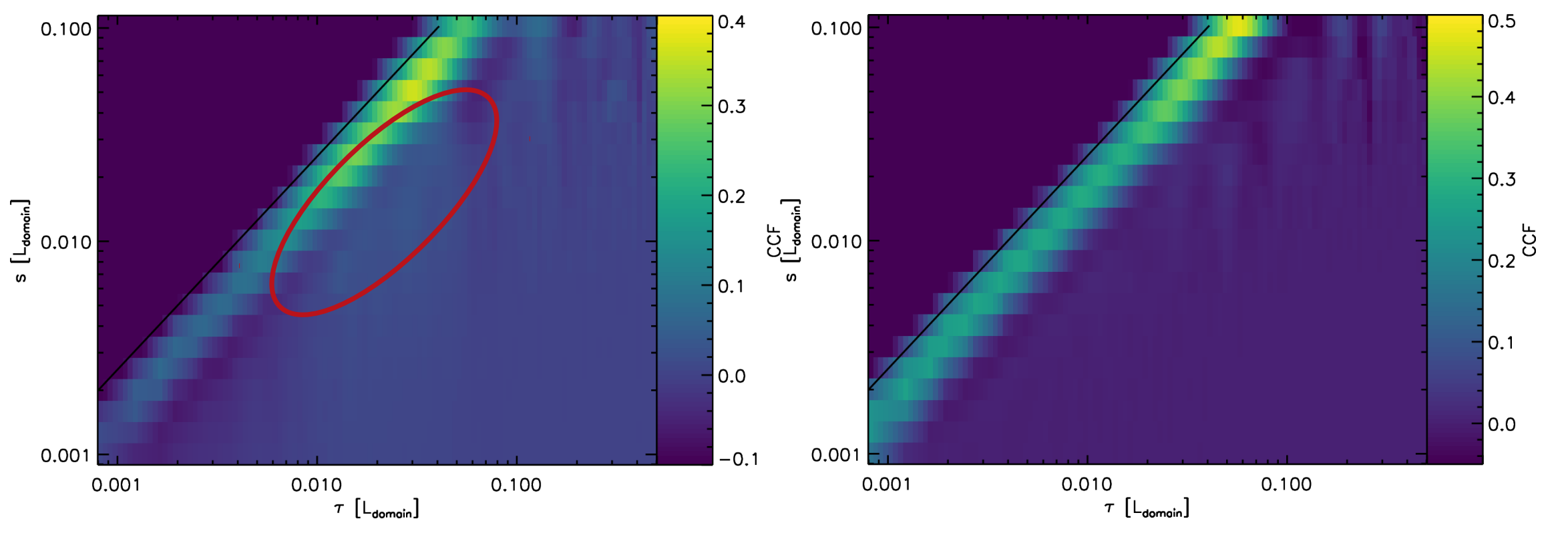


FIGURE 5: Width statistics of filaments (left) and shocks (right) in the hydrodynamic simulations of Federrath et al. (2021). The sonic scale is weakly visible in the density structure but not pronounced. There is a continuous drop of anisotropic velocity structures towards smaller scales with no break at the sonic scale.

By comparing the spatial correlation between column density filaments and centroid velocity gradients in simulations and observations we can quantify the role of the velocity field in the filament formation.

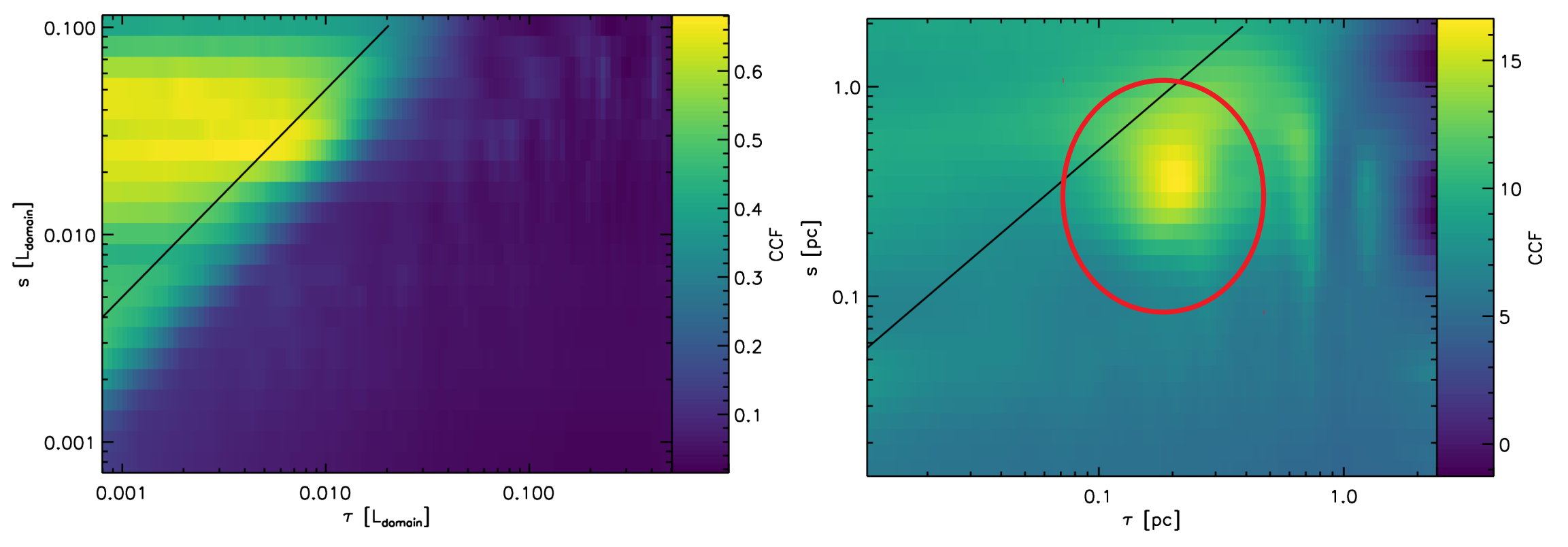


FIGURE 6: Comparison of the directional cross correlation between column density filaments and velocity gradients in the hydrodynamic simulations (left) and the Orion observations (right).

For the hydrodynamic simulations, we confirm the compressive role of the turbulence where density filaments form at the location of steep velocity gradients. We find a perfect correlation within the resolution limit.

The Orion Molecular Cloud observations show a completely different picture with basically no match between velocity gradients and density filaments (already visible in Fig. 3). A prominent offset of 0.2pc ≈ 100arcsec can be attributed to a single velocity structure west of the Integral Shaped Filament.

Results

- In the hydrodynamic simulations **elongated shocks quickly dissipate below the sonic scale**, not providing coherent structures any more. In contrast column density filaments also occur below the sonic scale.
- Filaments in the Orion Molecular Cloud exist on every resolved scale, but there is a slight surplus of filament widths around 0.1pc.
- The filaments in Orion are **not** formed through converging flows.
  - Formation through external **turbulence and gravity-driven flows** can be **excluded**.
- Local **radiative feedback or magnetic fields** must be responsible for the wide range of spatial offsets between the filaments seen as intensity peaks and gradients in the velocity profiles.

References:

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