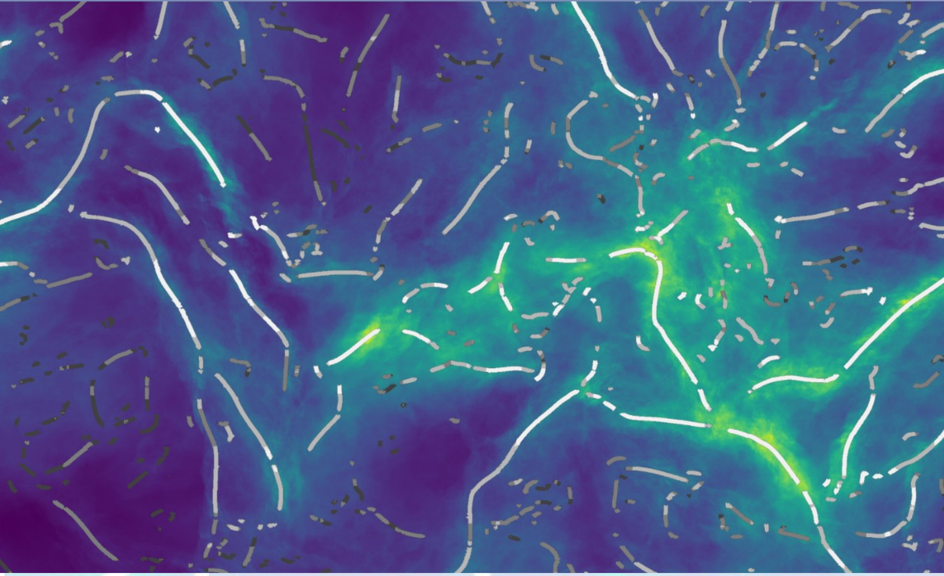

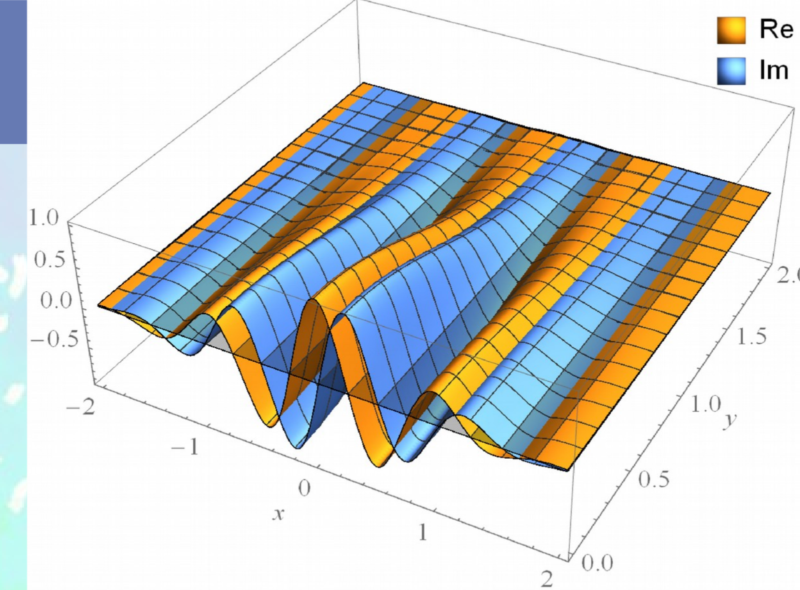

Wavelets to characterize filament spines and shocks

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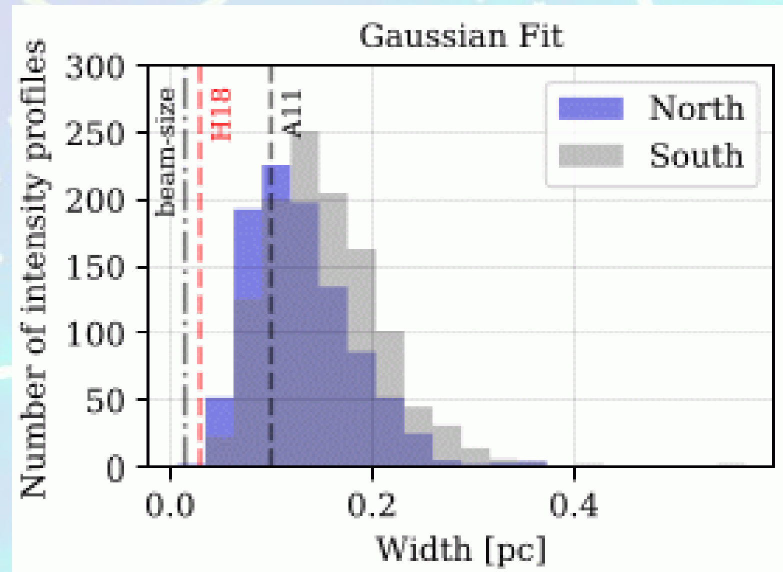
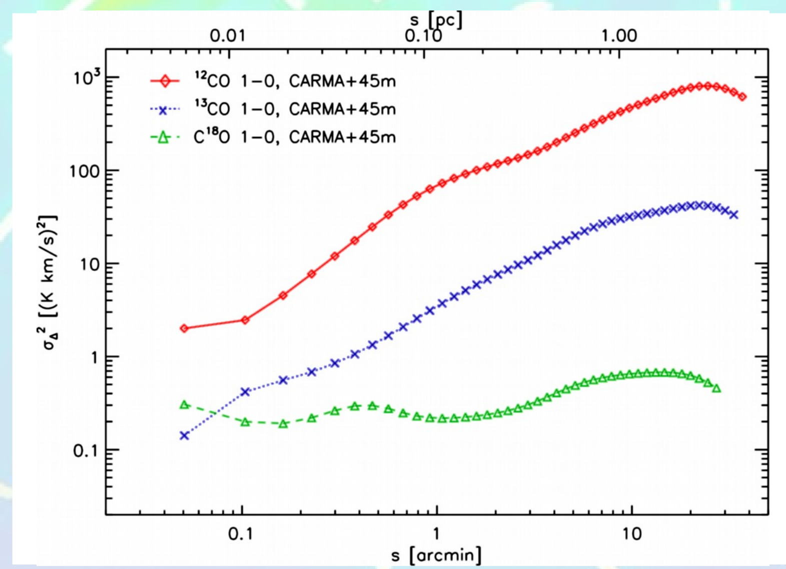
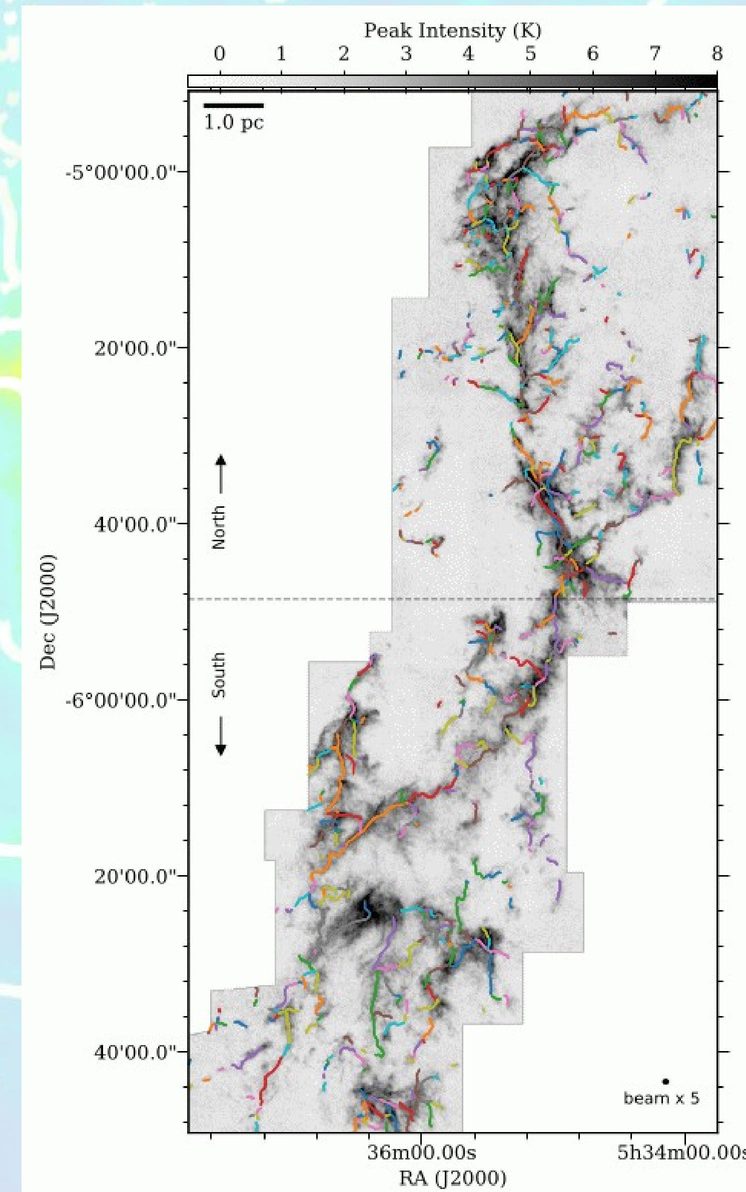
The starting question

Is there a universal filament width of ~ 0.1pc? (e.g. André et al. 2010, Arzoumanian et al. 2019, ...)

- Example: Large-scale Orion-A mapping in $C^{18}O$ (Kong et al. 2018)
  - DisPerSe + FilChap (Suri et al. 2019) → 0.1pc
  - biased by "ruler parameters" (Panopoulou+ 2016)
  - Power spectrum/ Δ-variance show no prominent scale



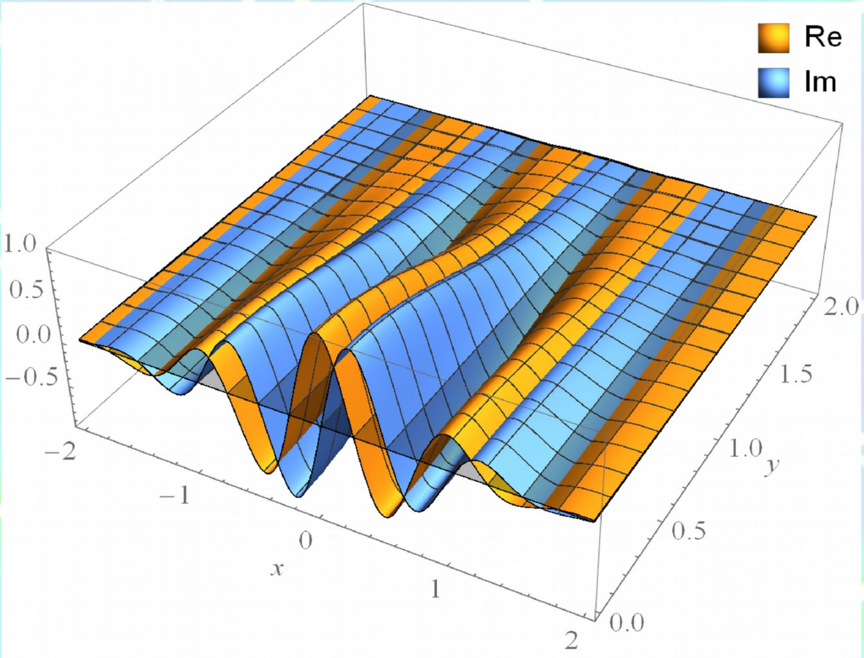




→ need for an unbiased filament measure

Ossenkopf-Okada & Stepanov (2018)

Use anisotropic wavelets for filaments



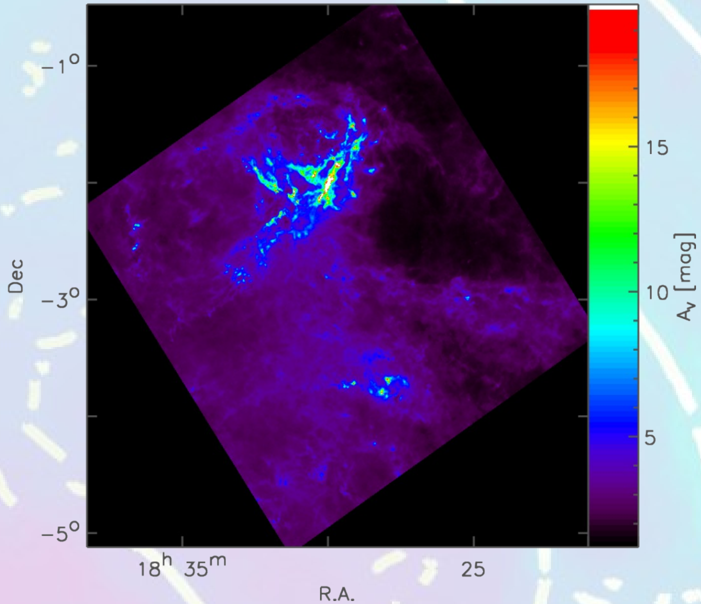
- Convolution of the maps with a complex anisotropic wavelet:

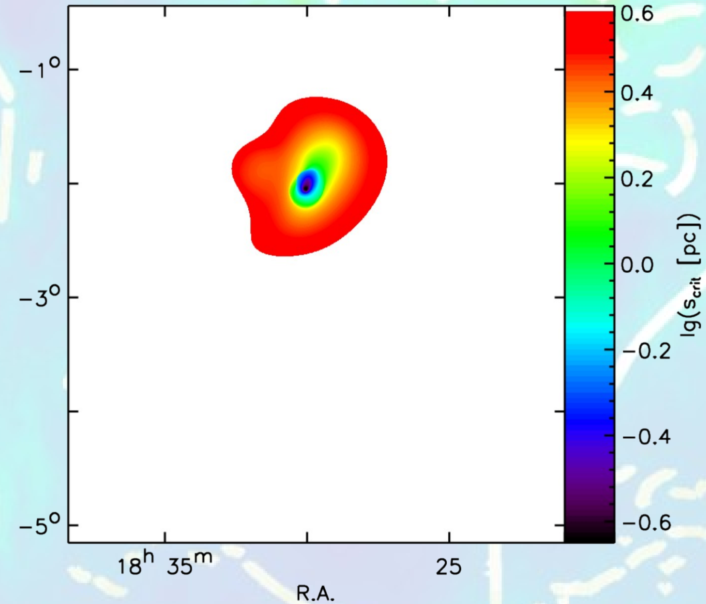
  (Similar approach: Robitaille et al. 2014)

  – Characterizes spectrum of scales of isotropic and anisotropic perturbations

  – Measures direction of anisotropy

  – Allows for stability analysis against spherical and cylindrical collapse





Area in Aquila that will undergo anisotropic collapse, colors give time scale

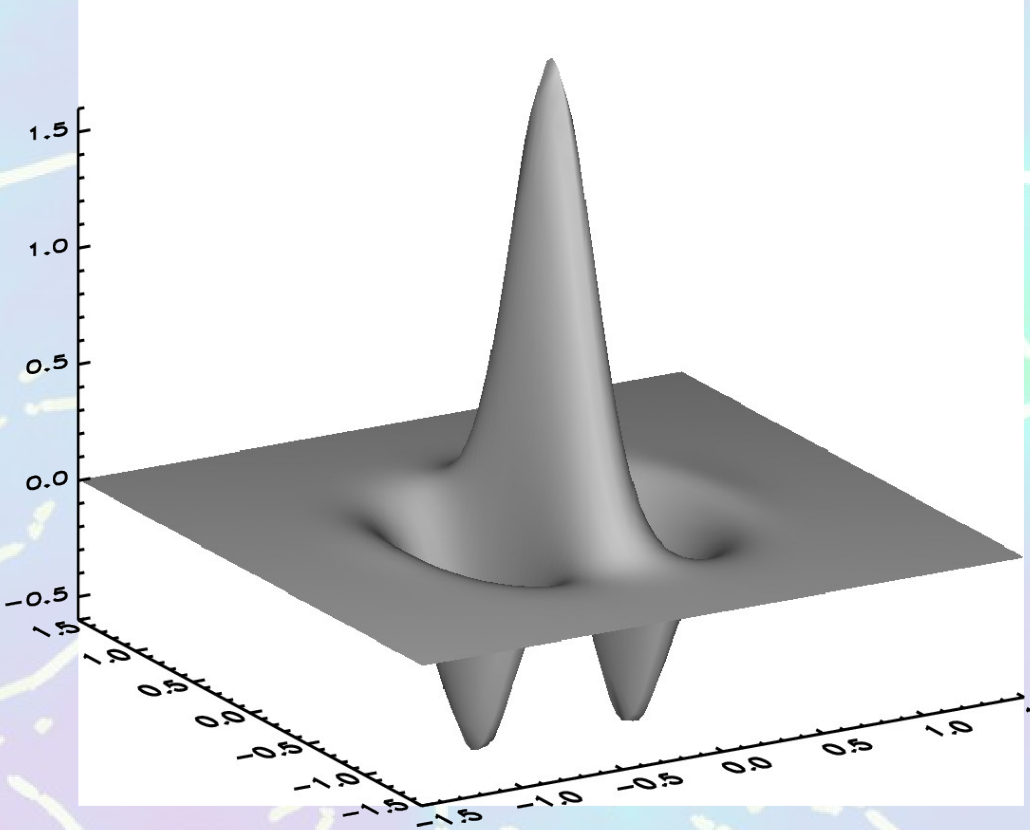
But:

- wavelets only show variances
- perturbations do not distinguish between peaks and valleys

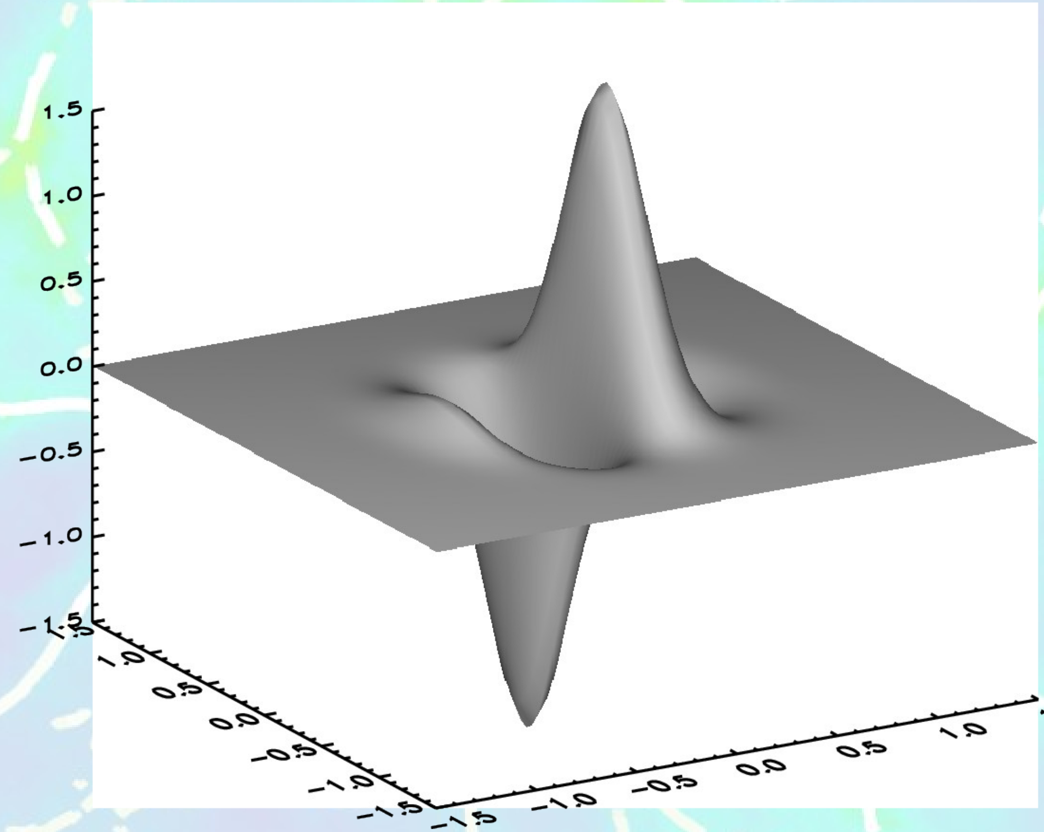
Solution

Switch to real wavelets, consider amplitudes, not variances

- Look for peaks in filtered maps
  - Cosine-term measures filaments
  - Sine-term measures gradients, e.g. shocks



Symmetric (cos) wavelet



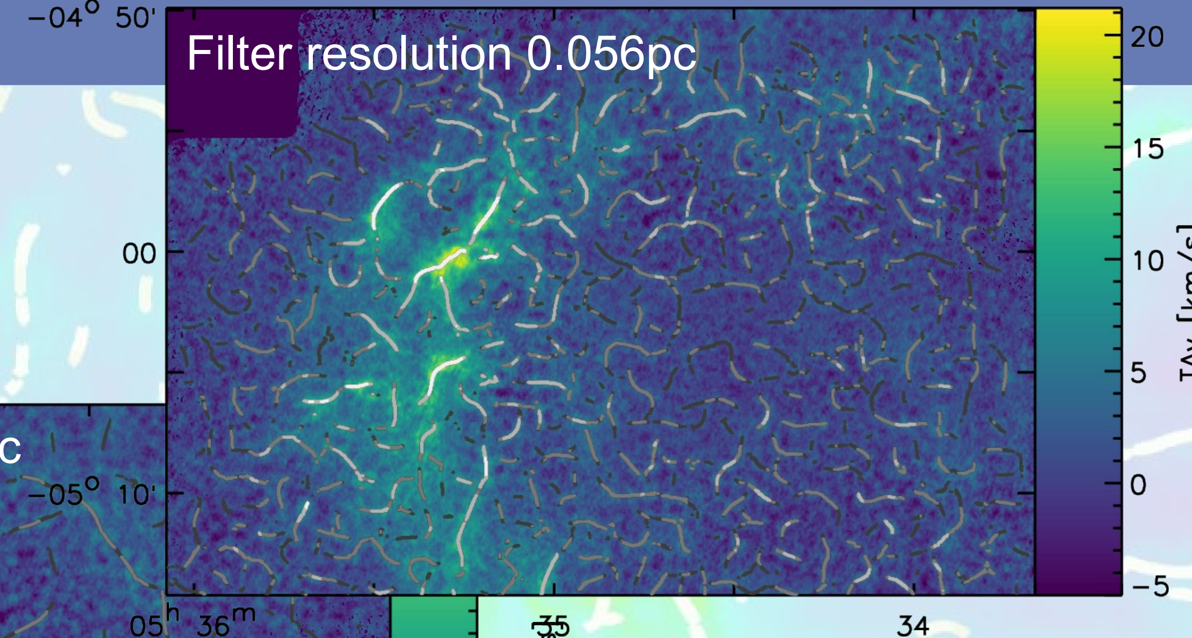
Antisymmetric (sin) wavelet

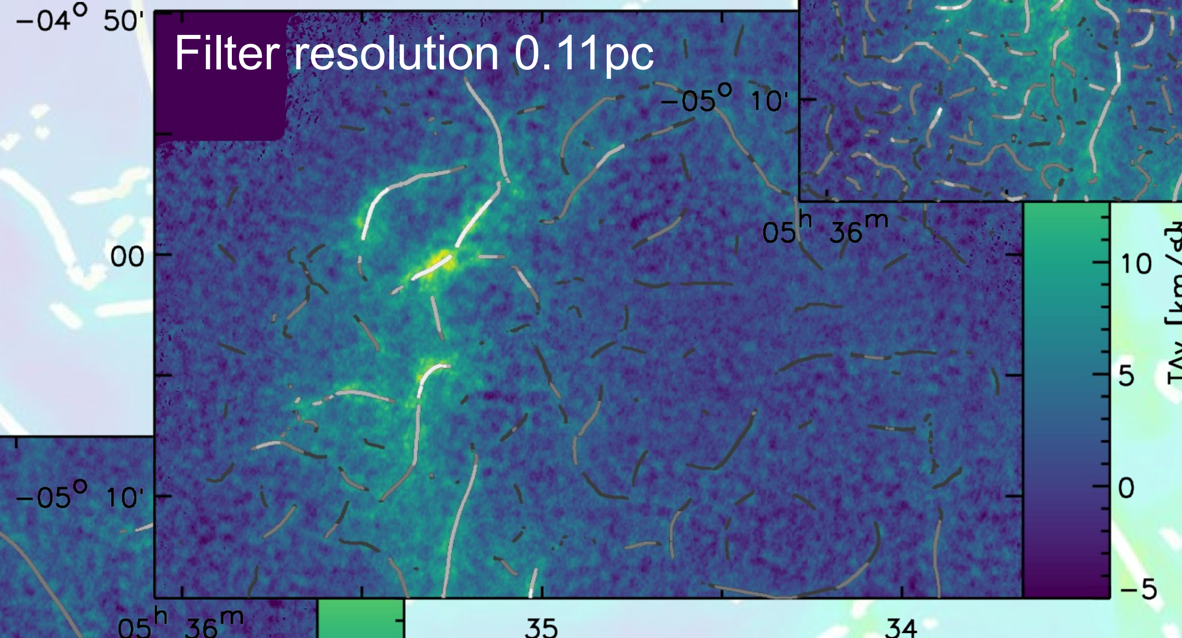
(similar to HRO-filter by Soler et al. 2013)

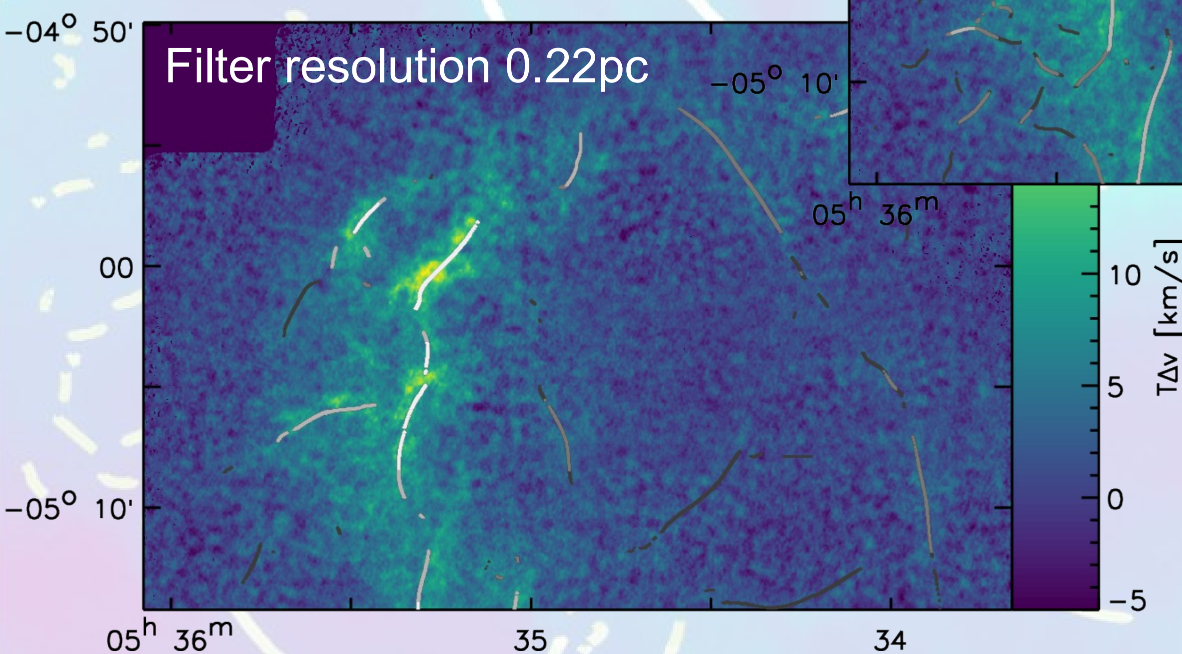
Orion $C^{18}O$ map (Northern subsection)

Filament spines as directional peaks:

- Different filter sizes still find different filaments
- All filaments can be confirmed by eye

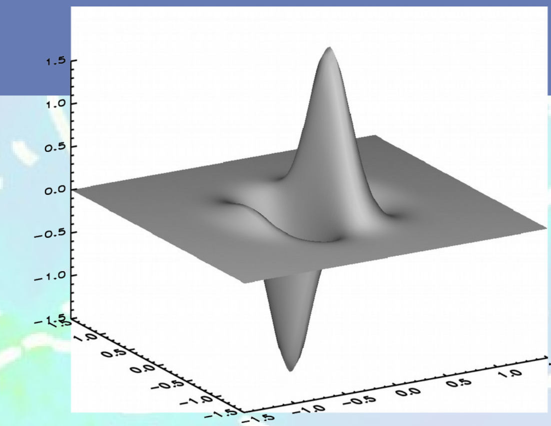






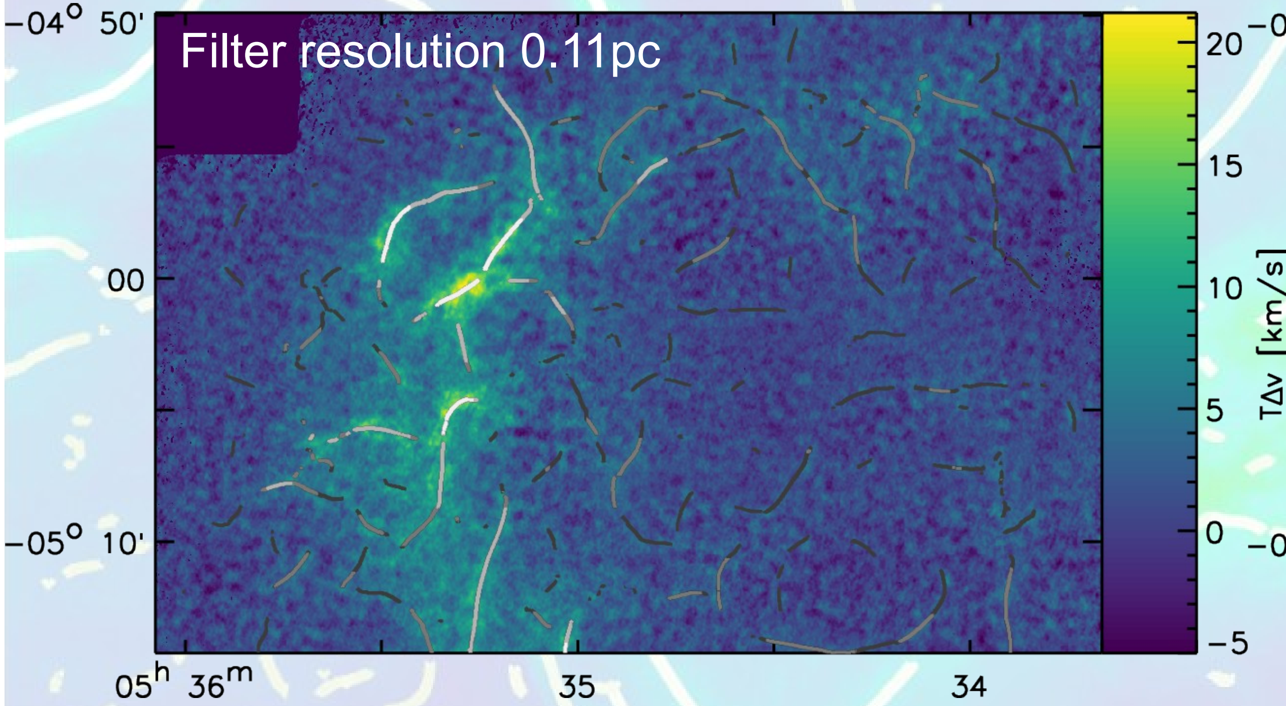
- No obvious dominance of 0.1pc filaments

Filament width

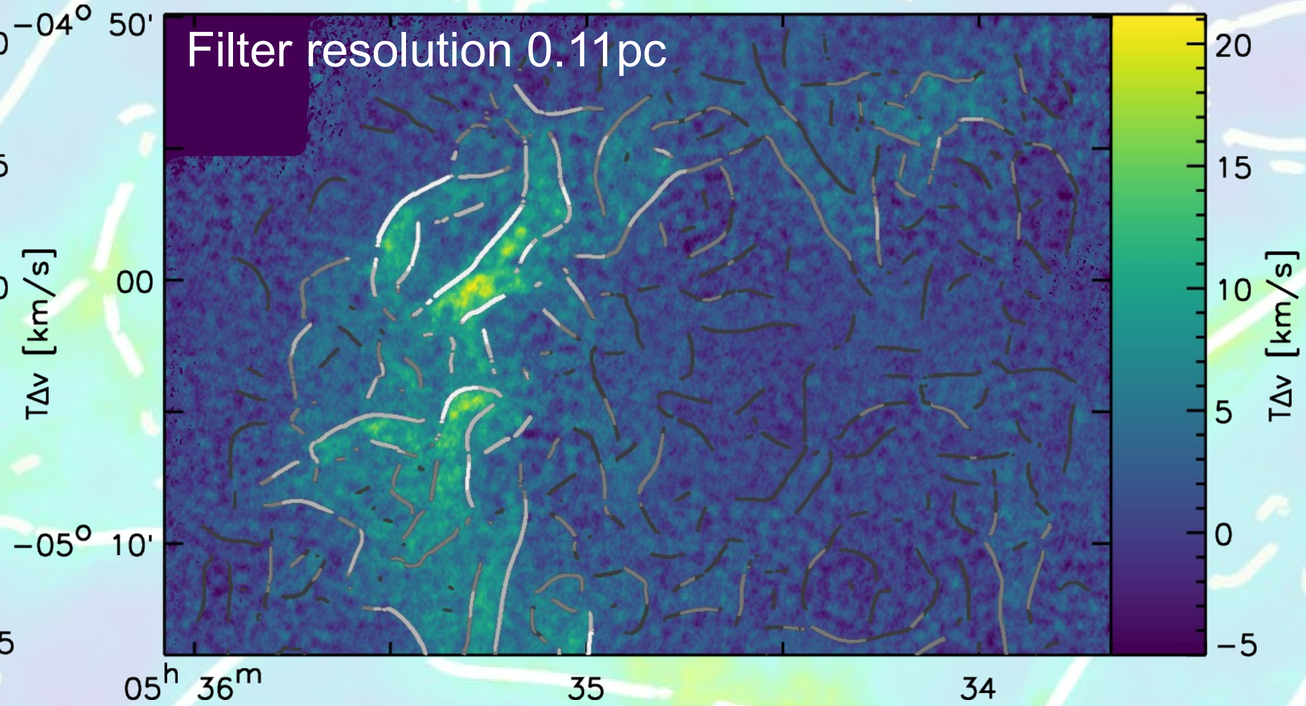


Expoit sin-wavelets to detect wings

- Peaks in sine-filtered map correspond to wings



Spines from cos-filtered map

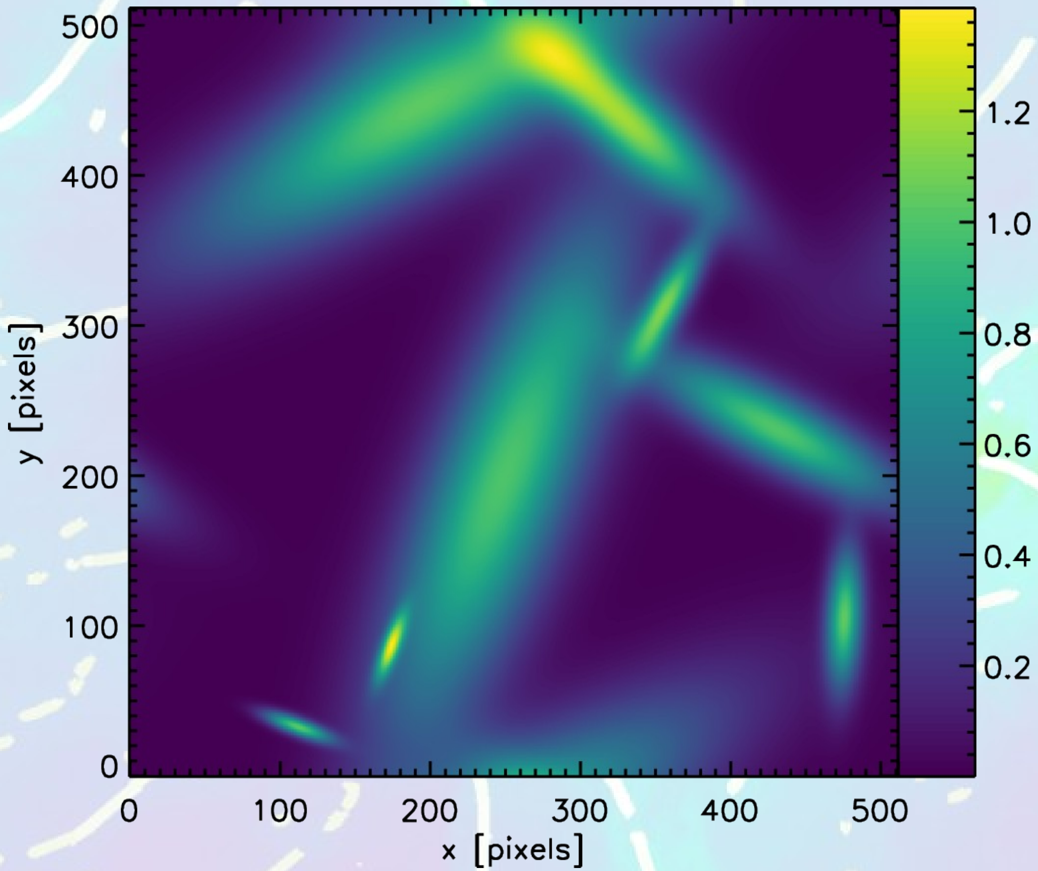


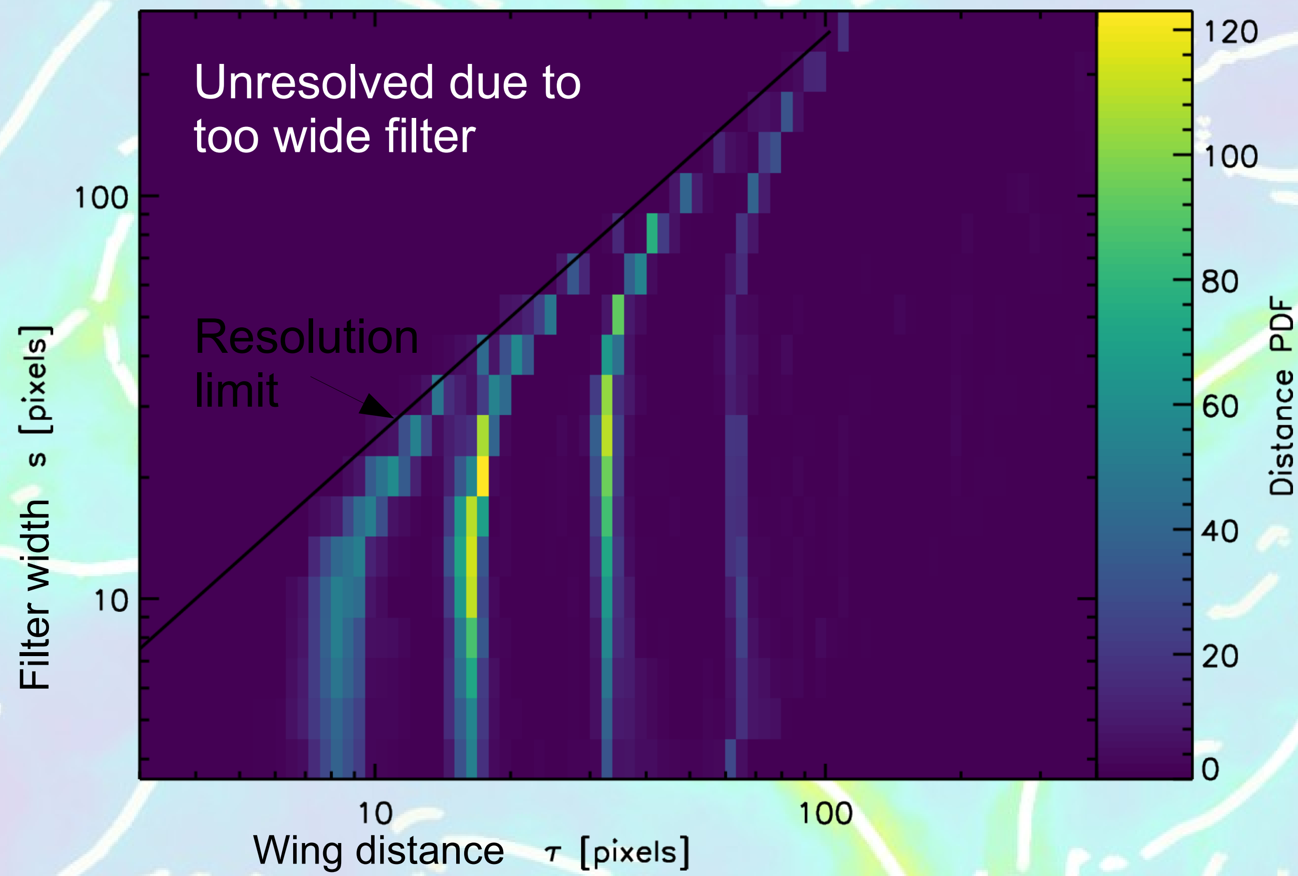
Wings from sin-filtered map

- Distance between wings → independent measure for filament width

Superposition of Gaussian filaments

- Measured wing distance as a funtion of the filter width

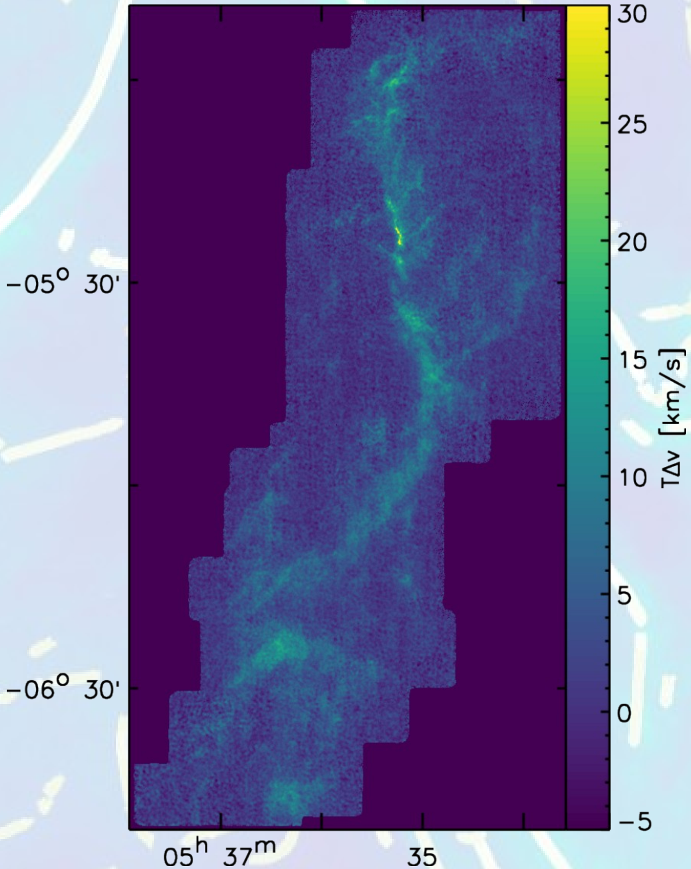




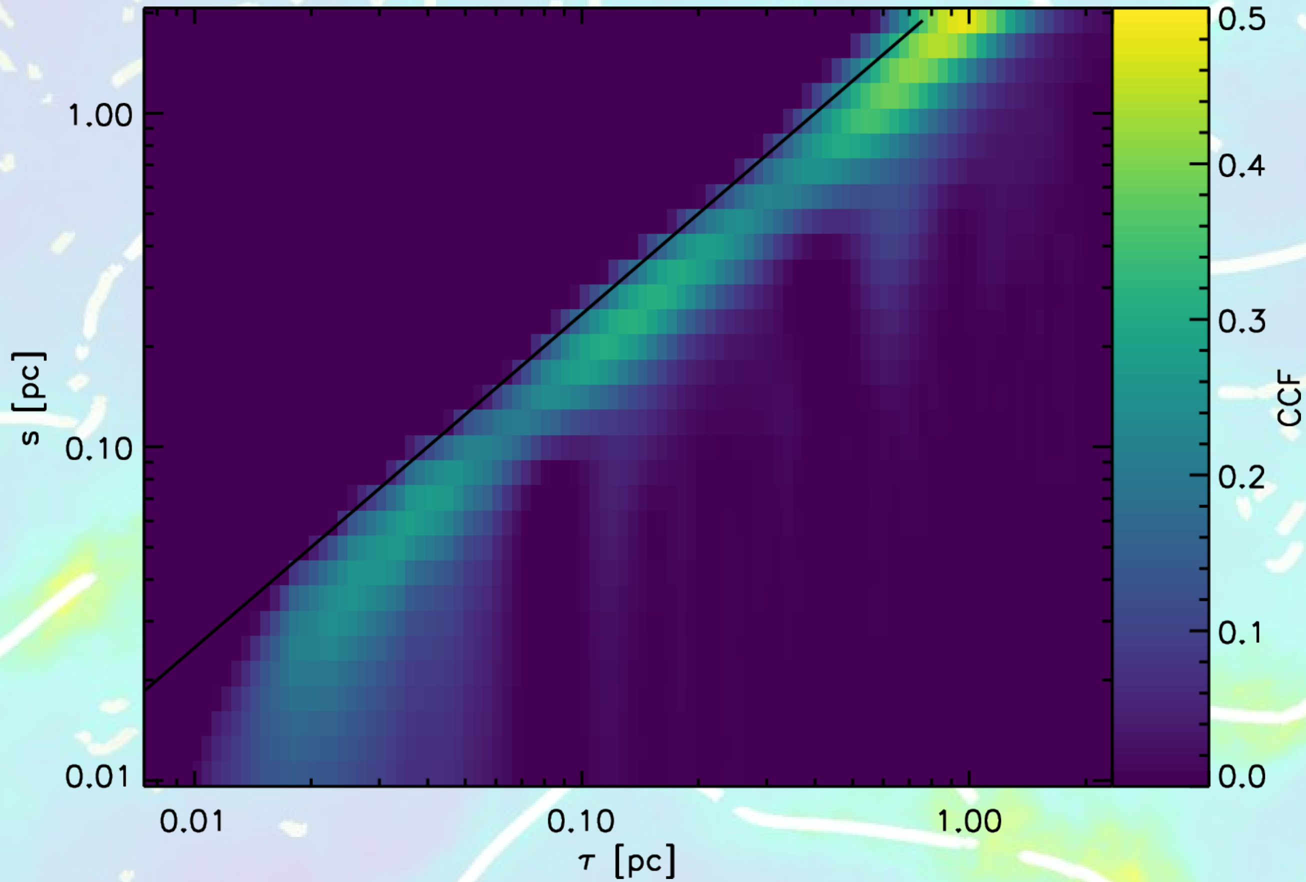
- Reliable width measurement + good sensitivity at 3..4 times the resolution limit

Orion $C^{18}O$ map

Statistics over the whole map



Line-integrated $C^{18}O$ 1-0 map



Distribution of widths from wing distances

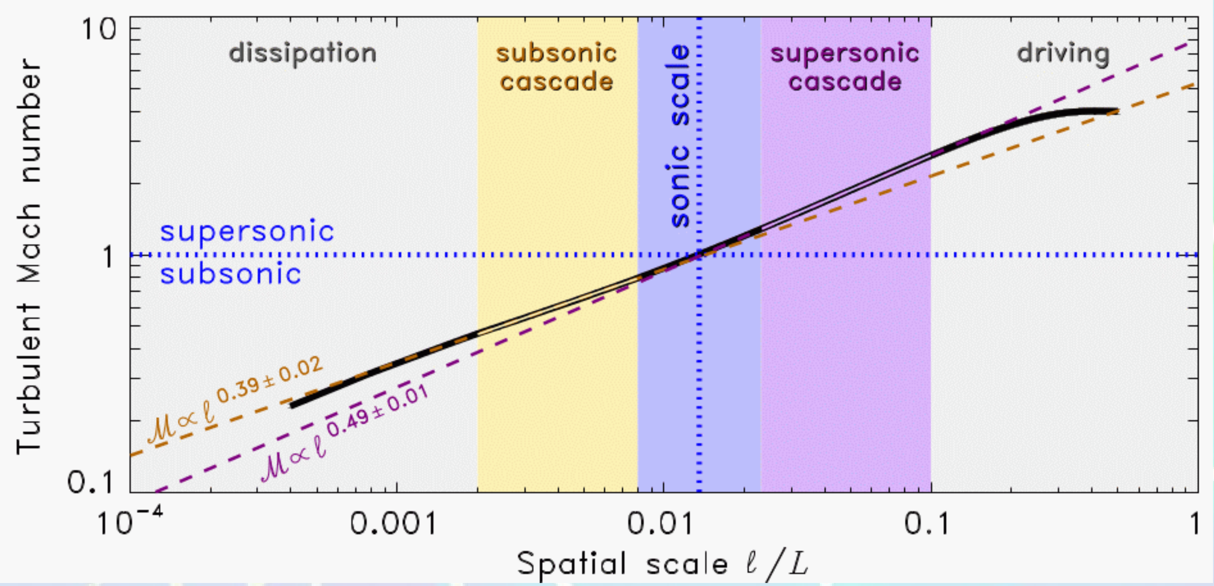
- Peak at 0.11pc confirmed, but two other peaks more dominant:
  - 0.03pc from known artifact in the data, 0.6pc as width of the whole integral-shape filament

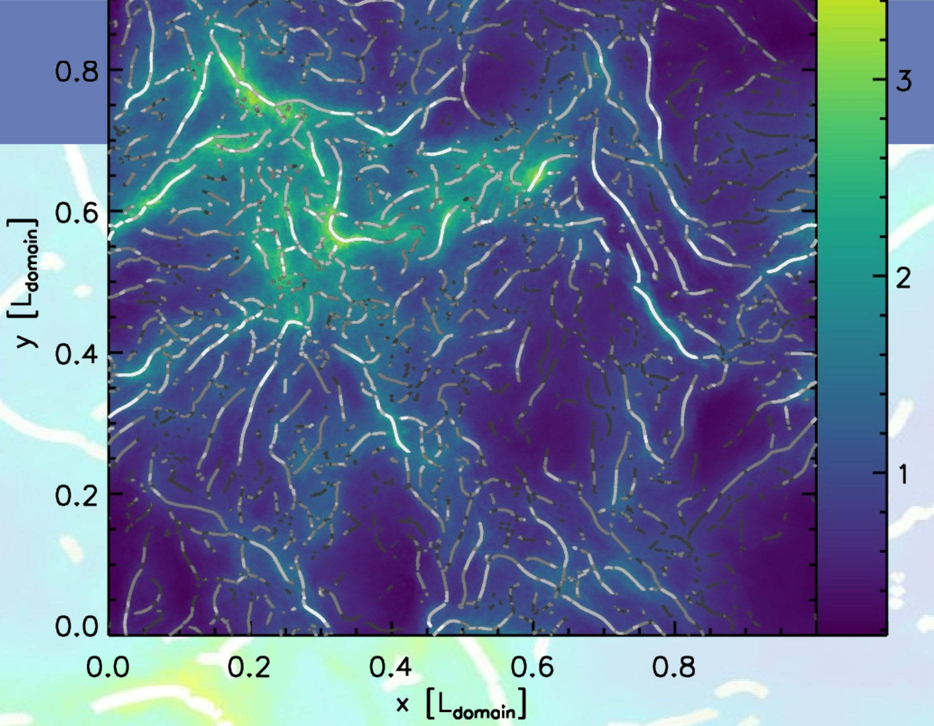
Hydrodynamic simulations

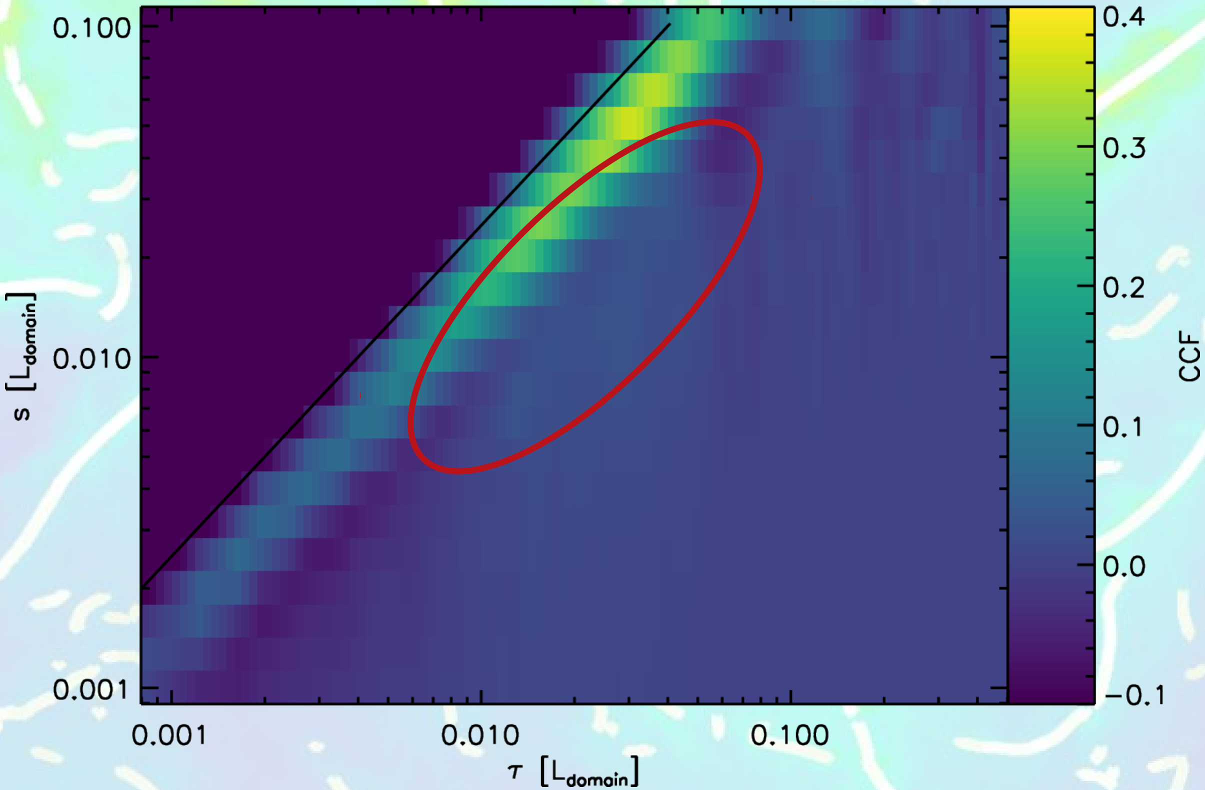
World's largest supersonic turbulence simulation

(10048[3] pixels, Federrath 2020)

- Prediction of a characteristic filament width around the sonic scale





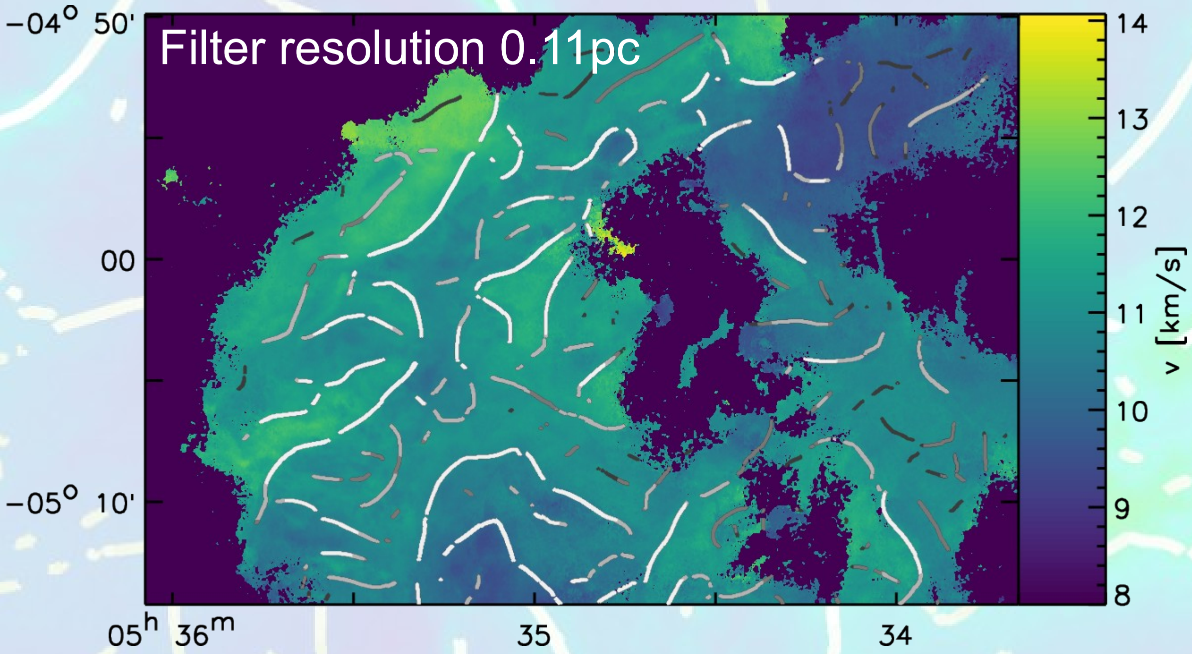


- Confirmed, but very broad distribution
  - Scale not really pronounced

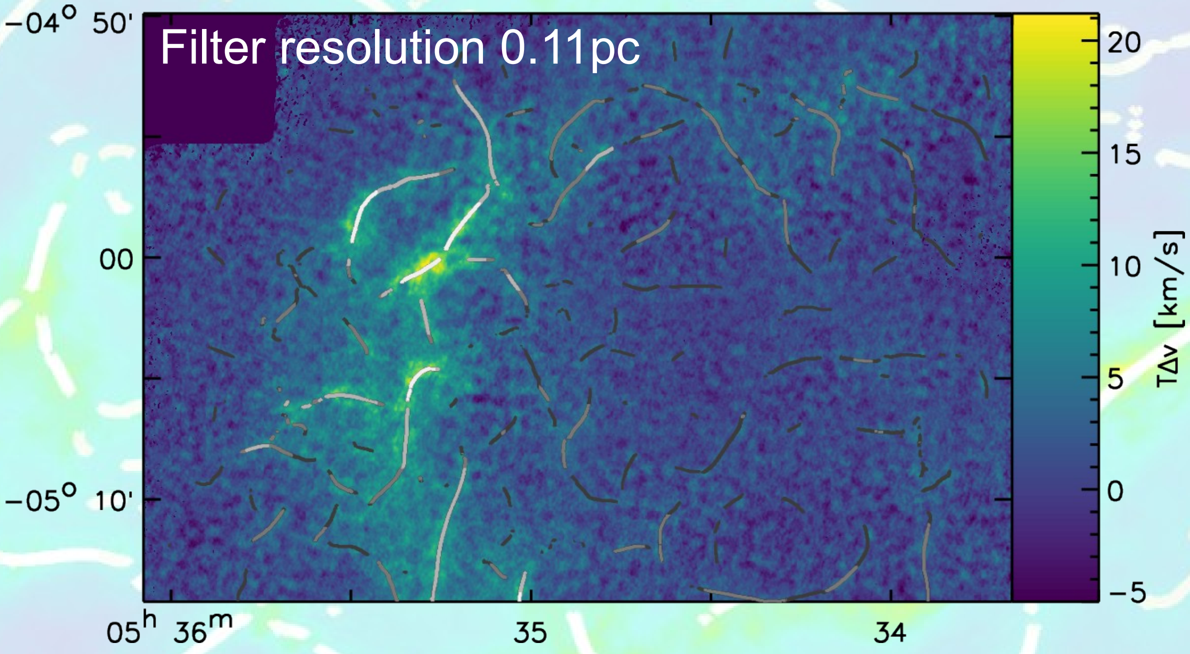
Search for shocks

Gradient search by sin-wavelet to look for velocity steps

Apply to velocity map:



Shocks from sin-filtered velocity centroid map



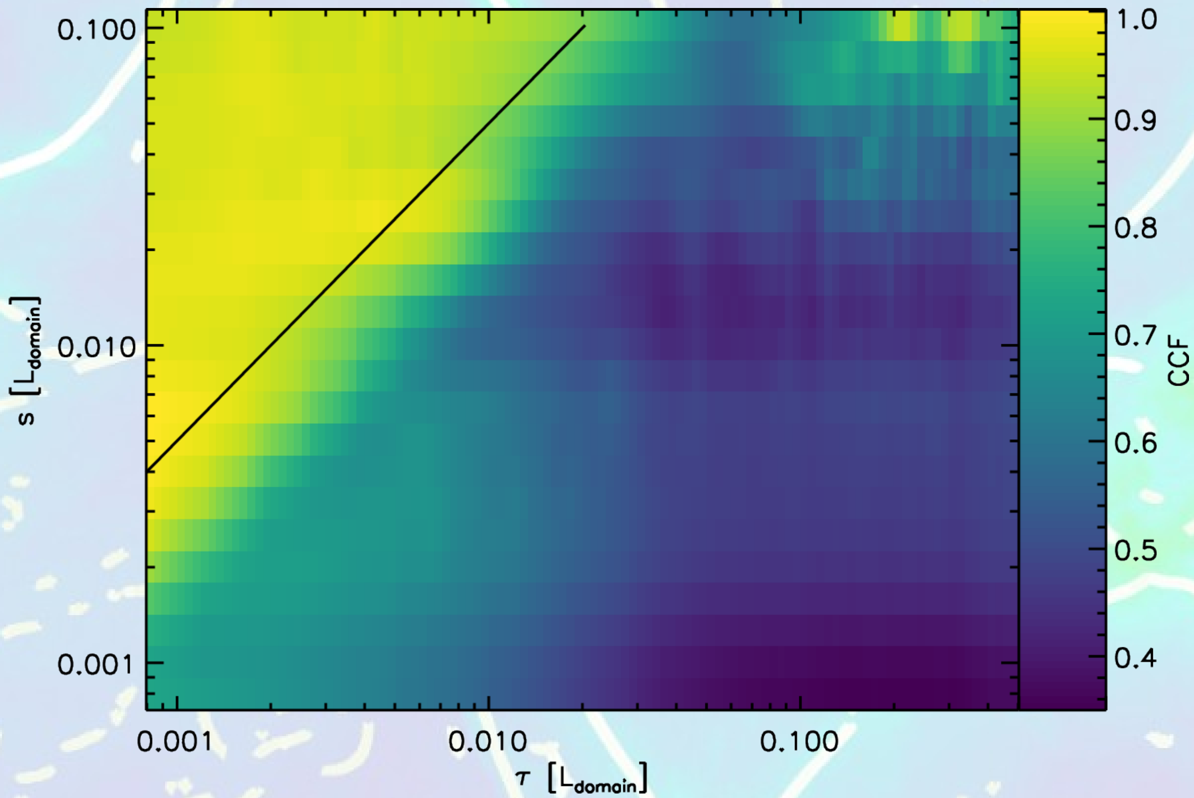
Compare to filament spines from cos-filtered intensity map

- Are filaments produced by shocks?

Are filaments produced by shocks?

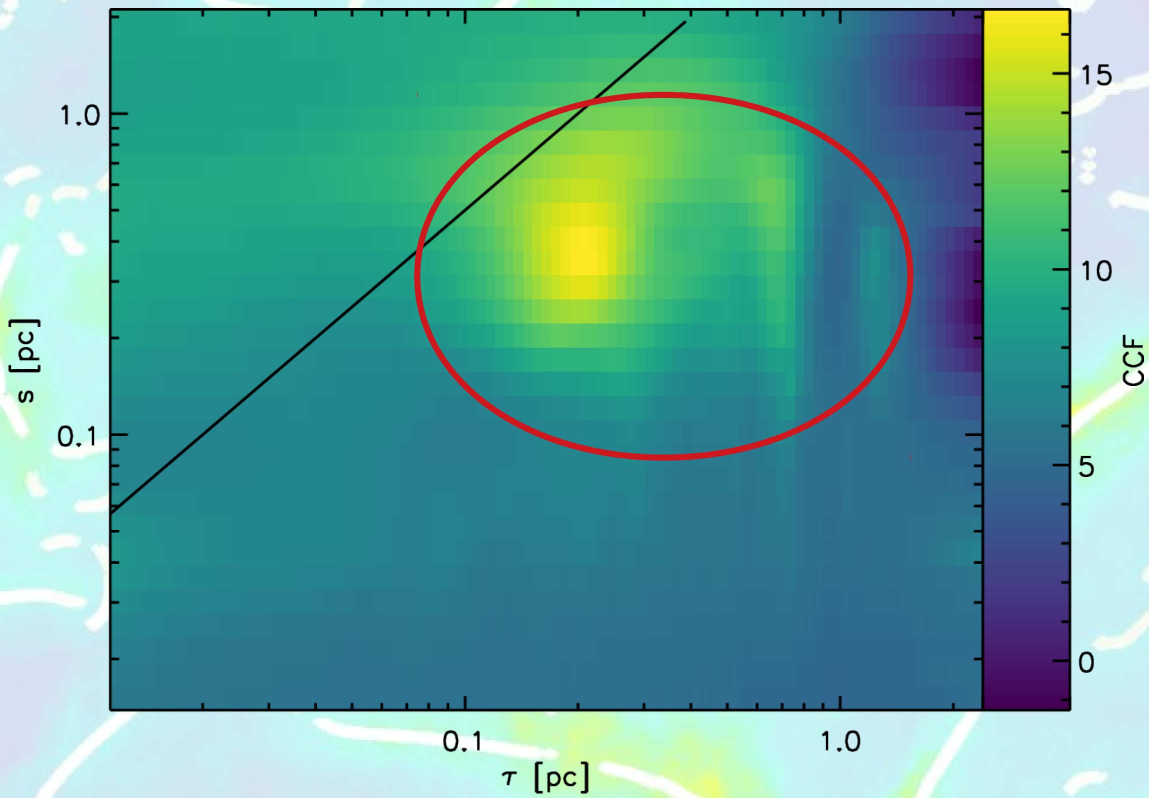
Measure distance between shocks and filaments

HD simulations



Shocks and filaments always on top of each other

Orion data



Two characteristic offsets between shocks and filaments

- Filaments in turbulence simulations produced by supersonic shocks
- Filaments in Orion produced by different mechanism

Summary

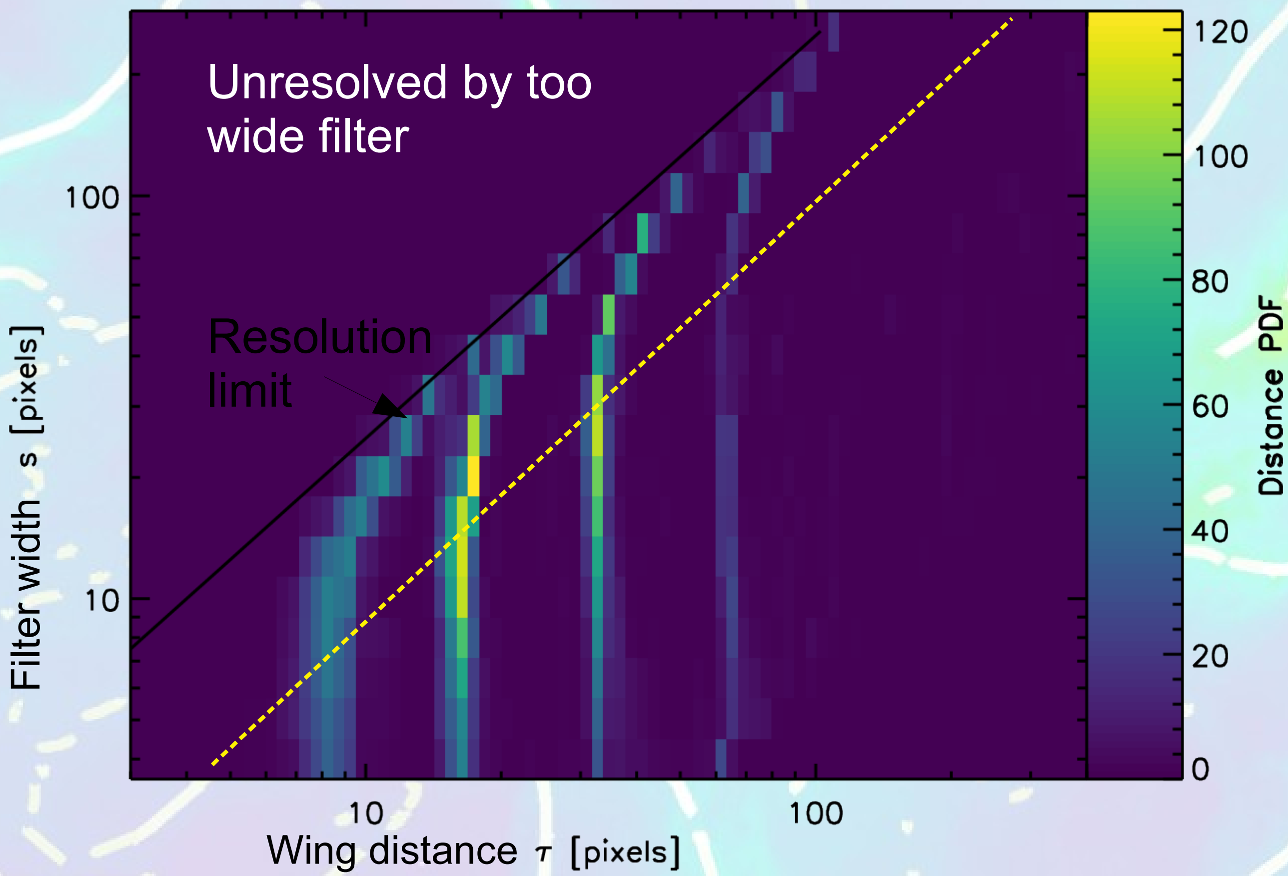
Anisotropic wavelets are an unbiased approach to characterize filaments

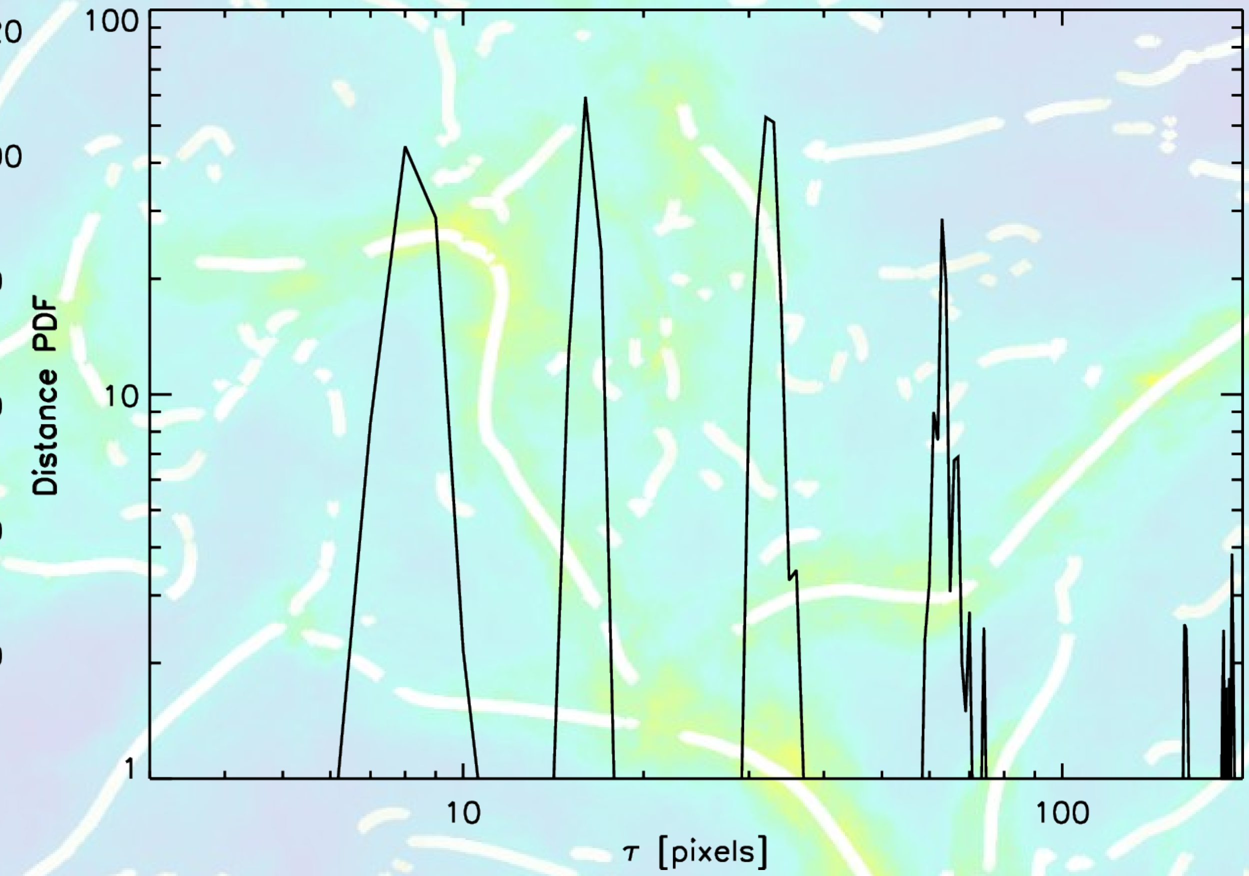
- Compare gradients and peaks
  - Measure filament widths
    - Some prominent structure at 0.1pc width detected, but not globally dominant
  - Compare shocks and column density filaments
    - Filaments in supersonic turbulence created by shocks
    - Does not apply to filaments in Orion

Test case

Superposition of Gaussian filaments

- Measured wing distance as a funtion of the filter width





- Reliable width measurement + good sensitivity at 3..4 times the resolution limit

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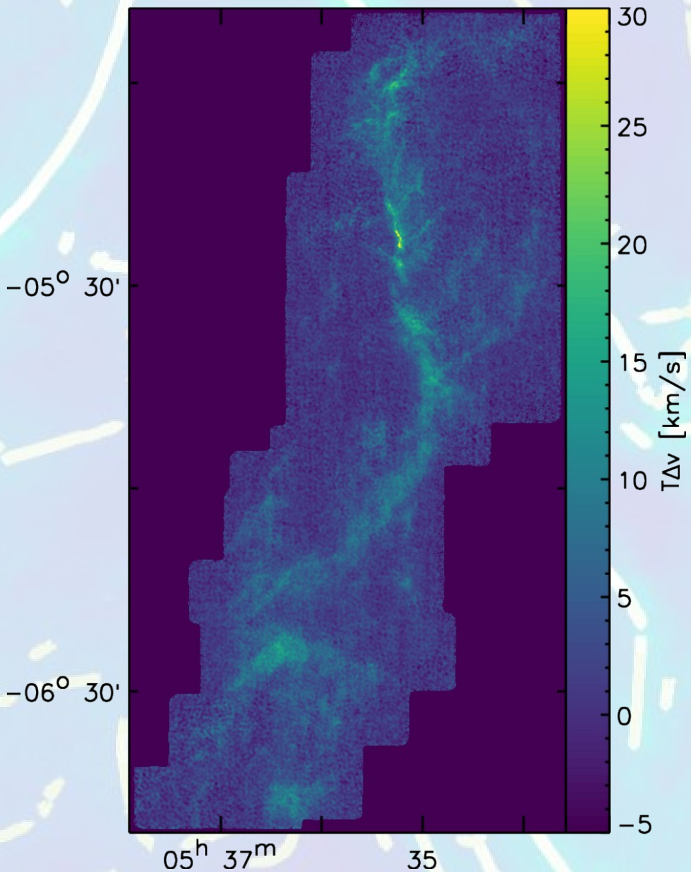
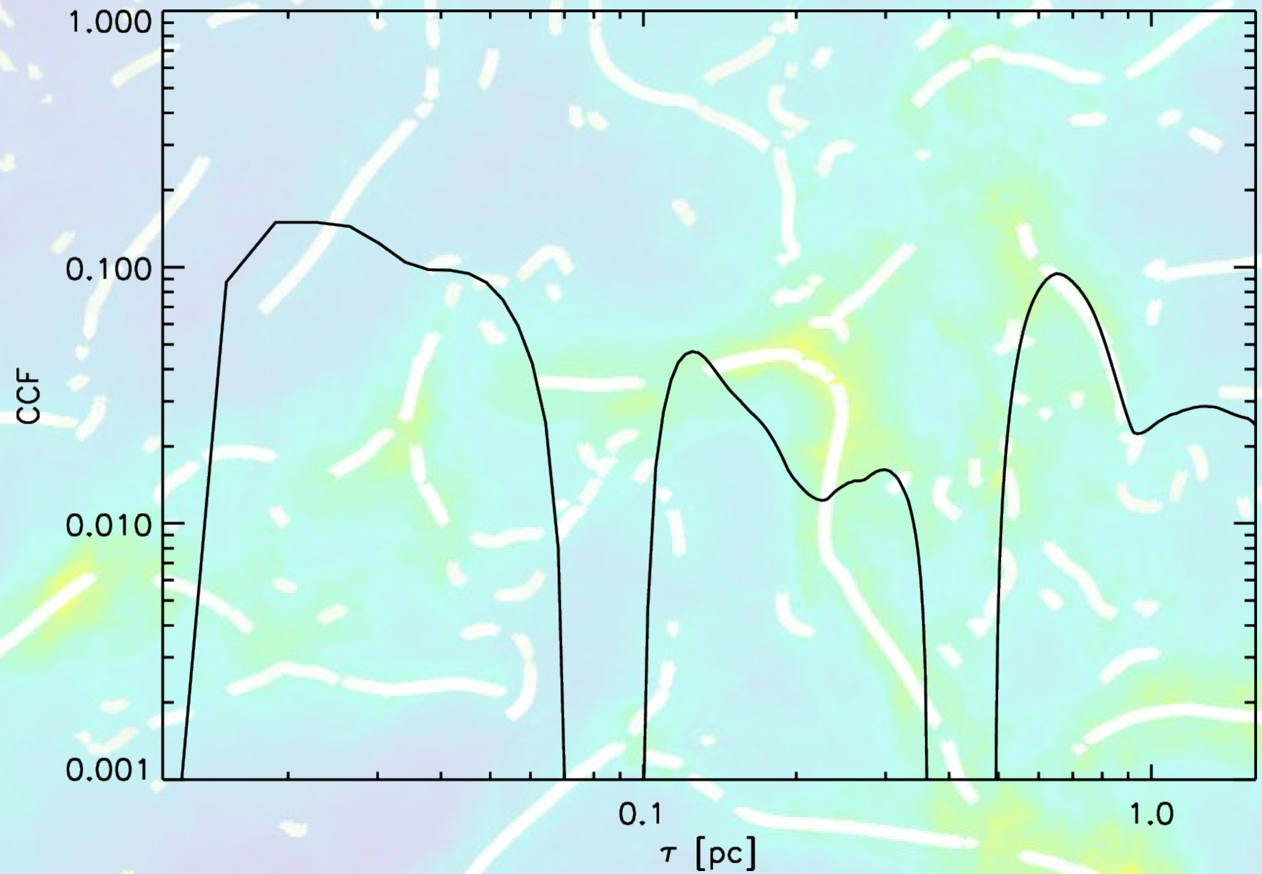


Line-integrated $C^{18}O$ 1-0 map



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(10048^3 pixels, Federrath 2020)

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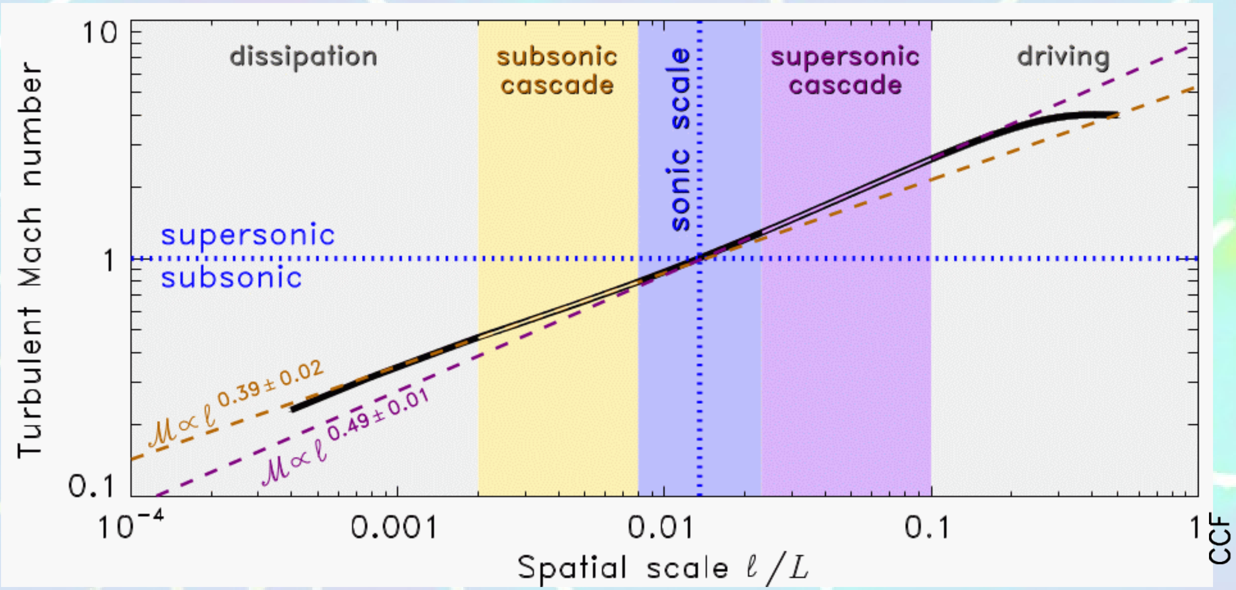
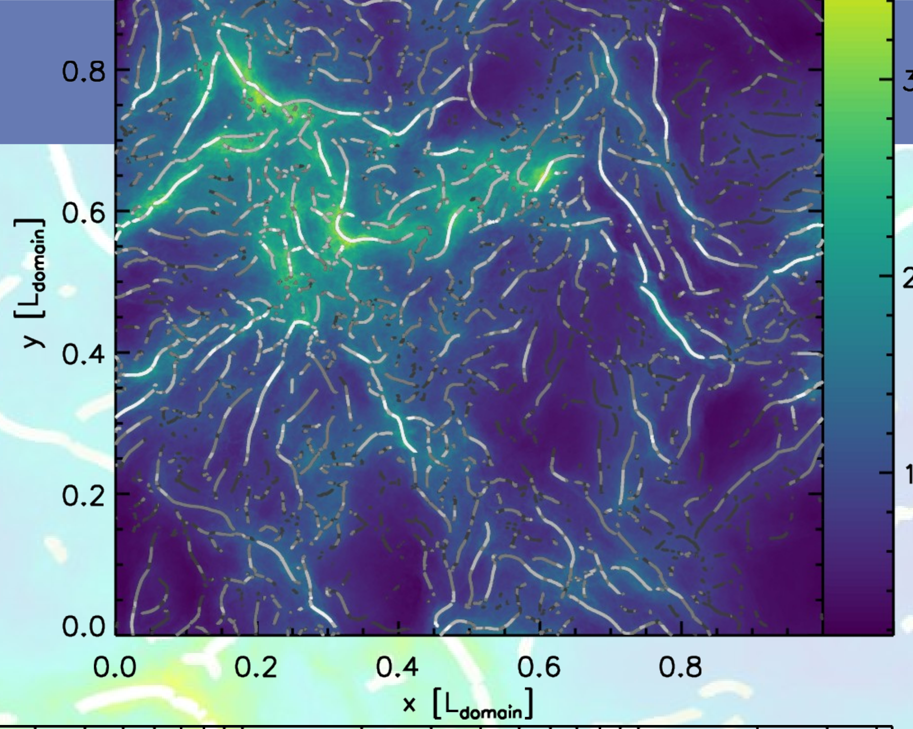
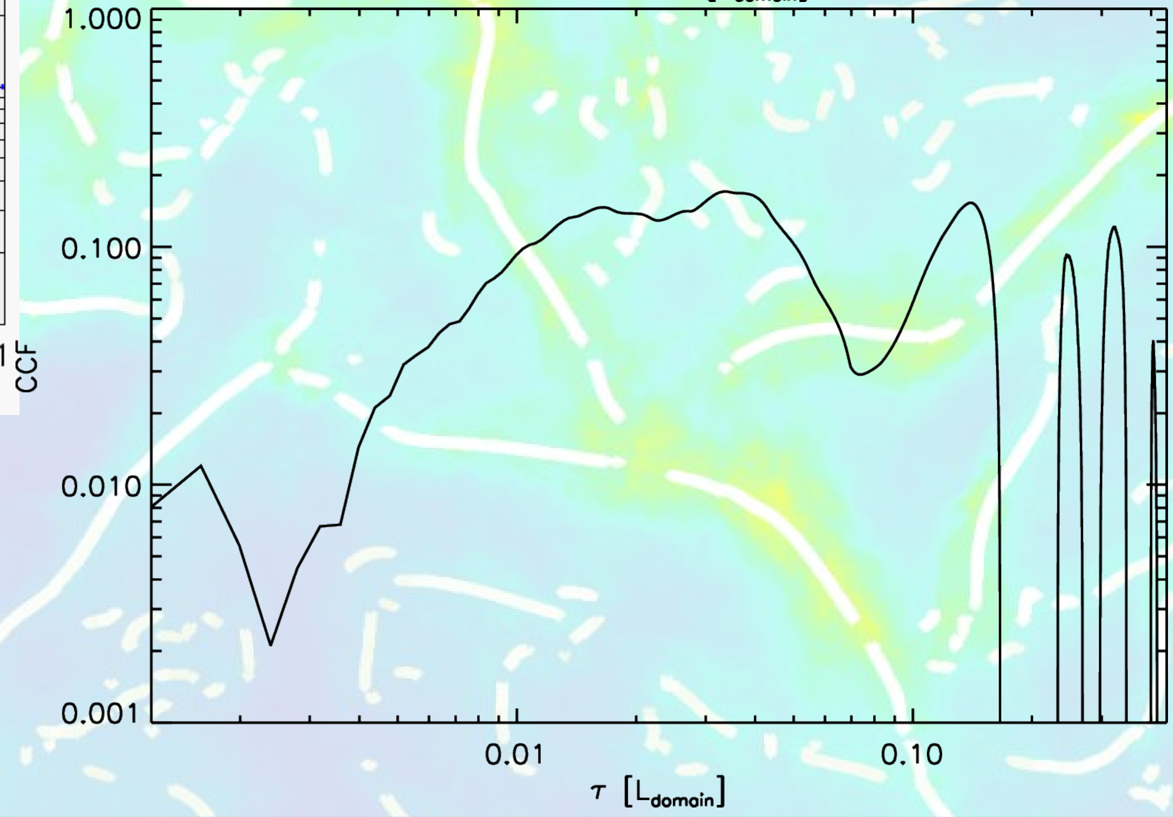




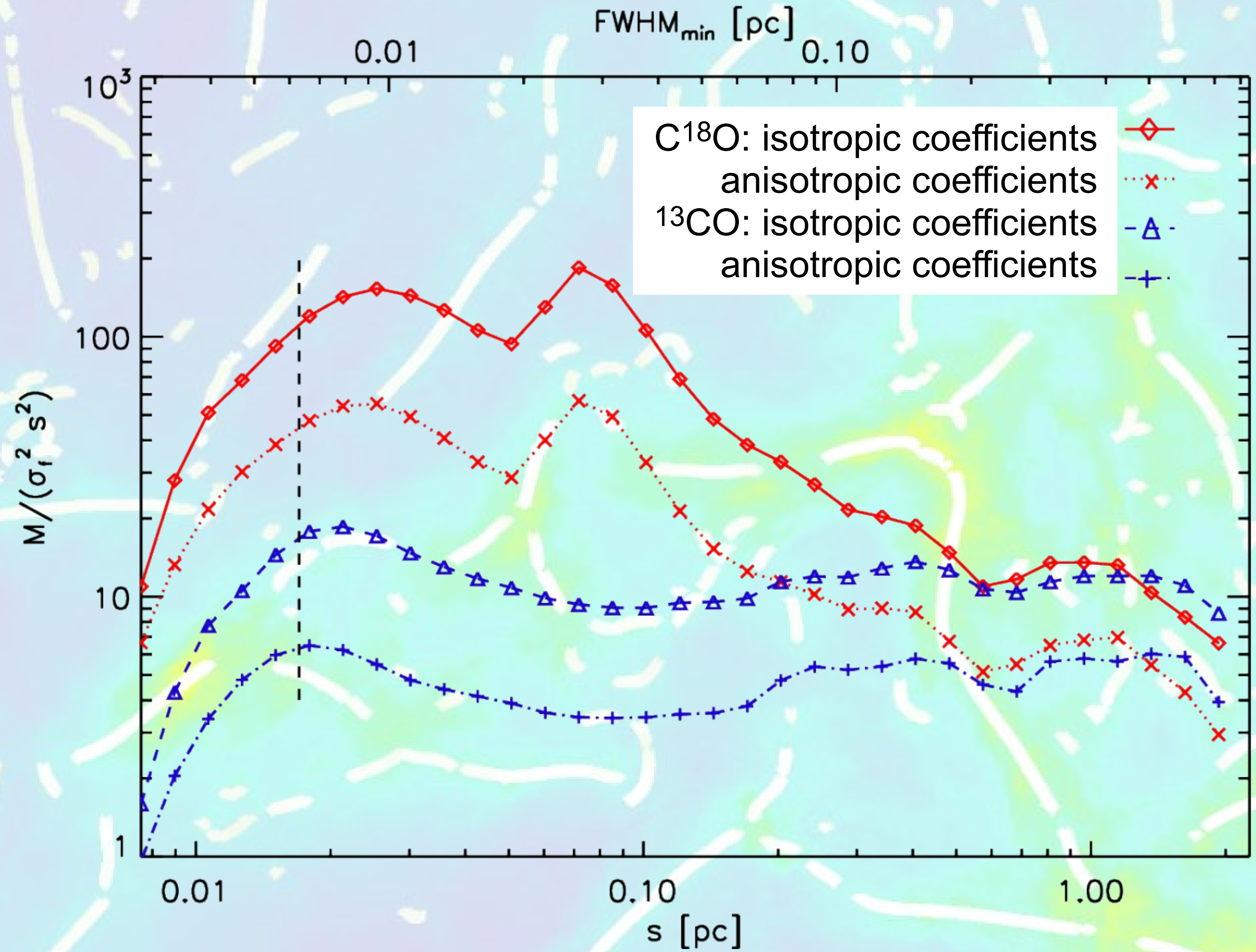


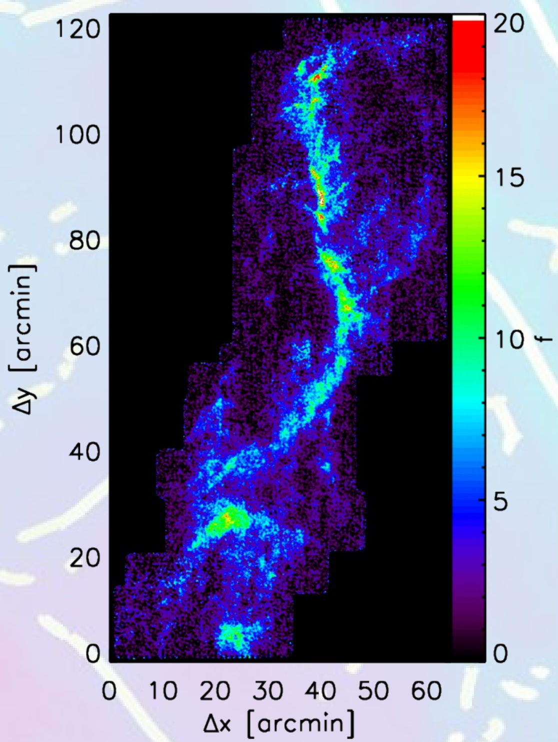
- Confirmed, but very broad distribution
  - Scale not really pronounced

Anisotropic wavelet spectra

C^{18}O in Orion A:

- No prominent width around 0.1pc
- Peak at 0.009pc given by resolution limit
- isotropic peak at FWHM= 0.03pc artifact in C^{18}O data

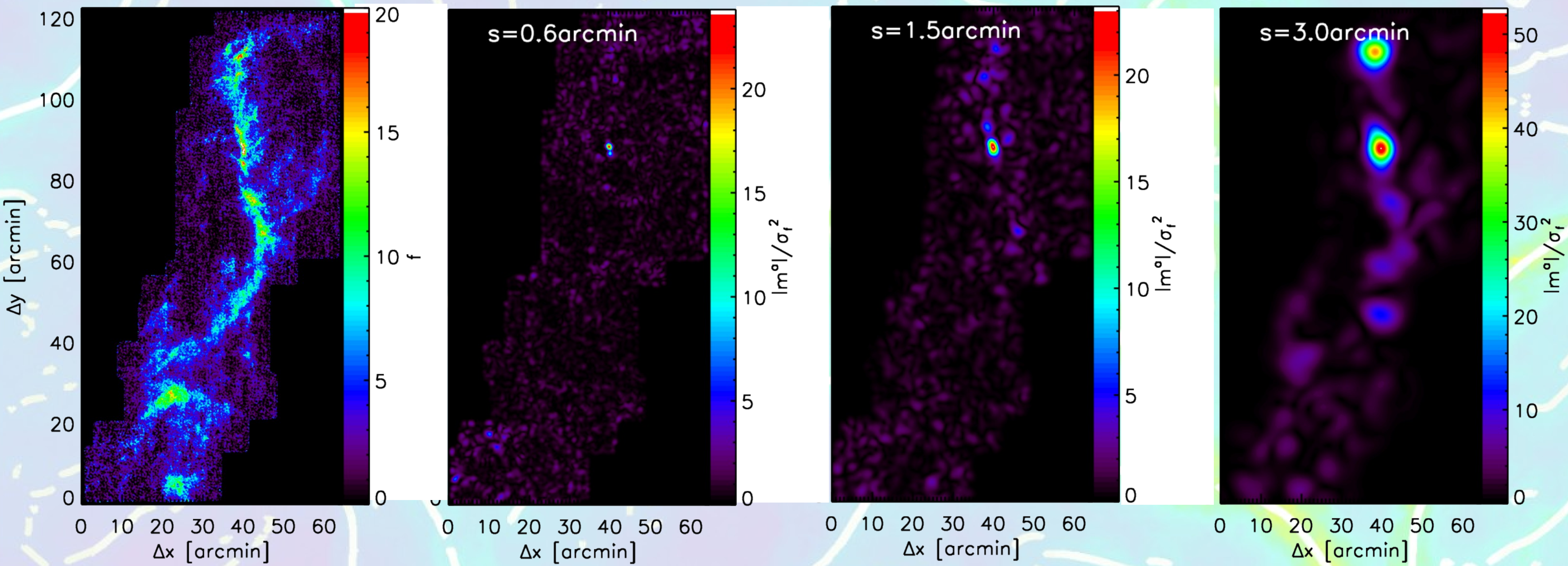




- ^{13}CO data even show a perfectly flat spectrum
- No characteristic filament width at all

Location of filaments

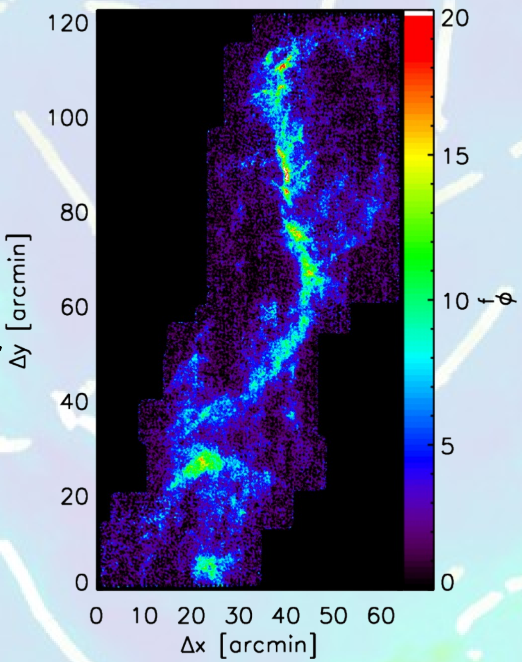
- Traced by maps of wavelet coefficients and degree of anisotropy

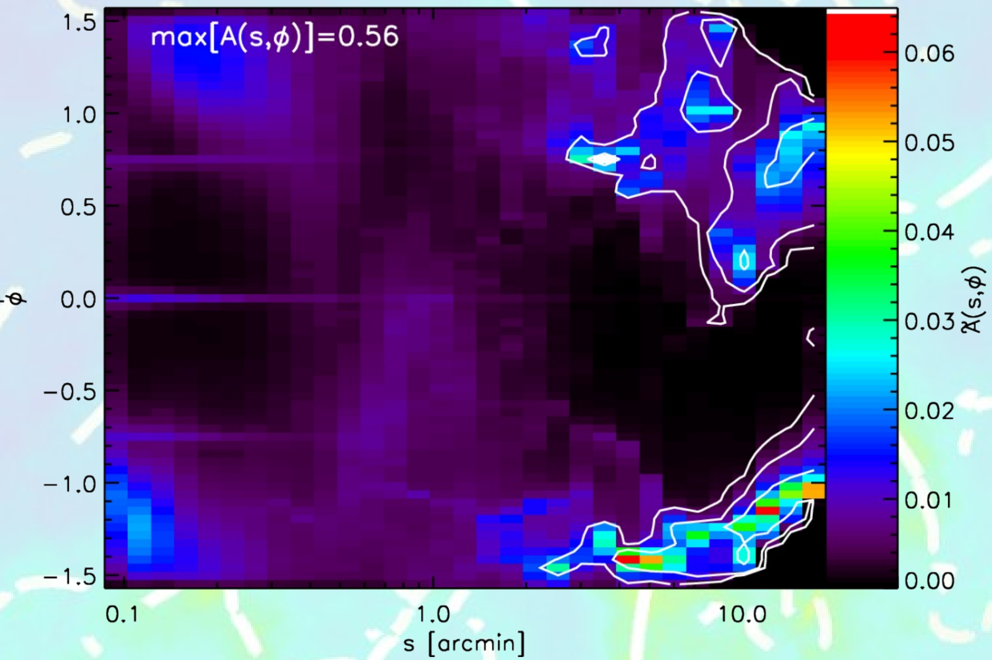


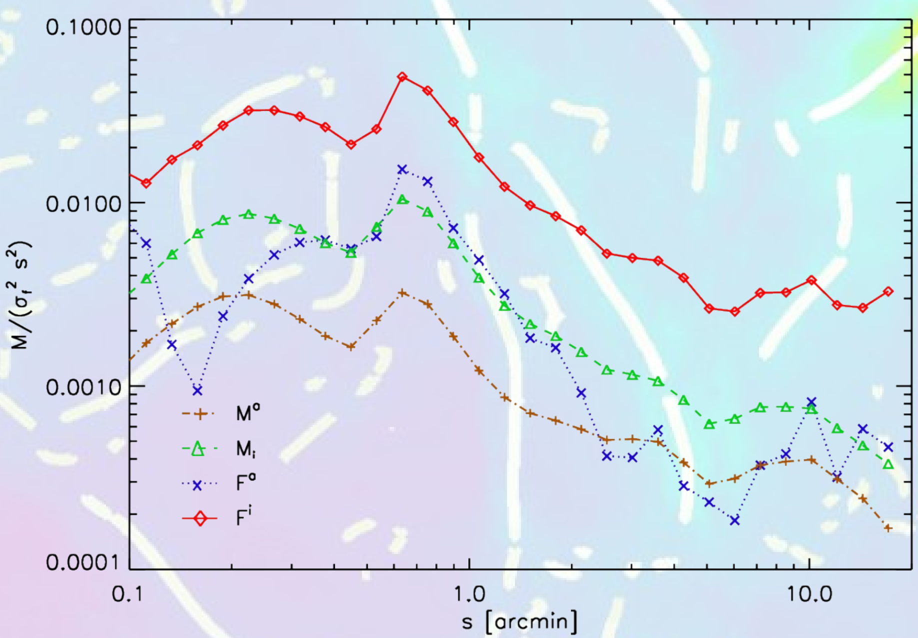
Anisotropic wavelet analysis

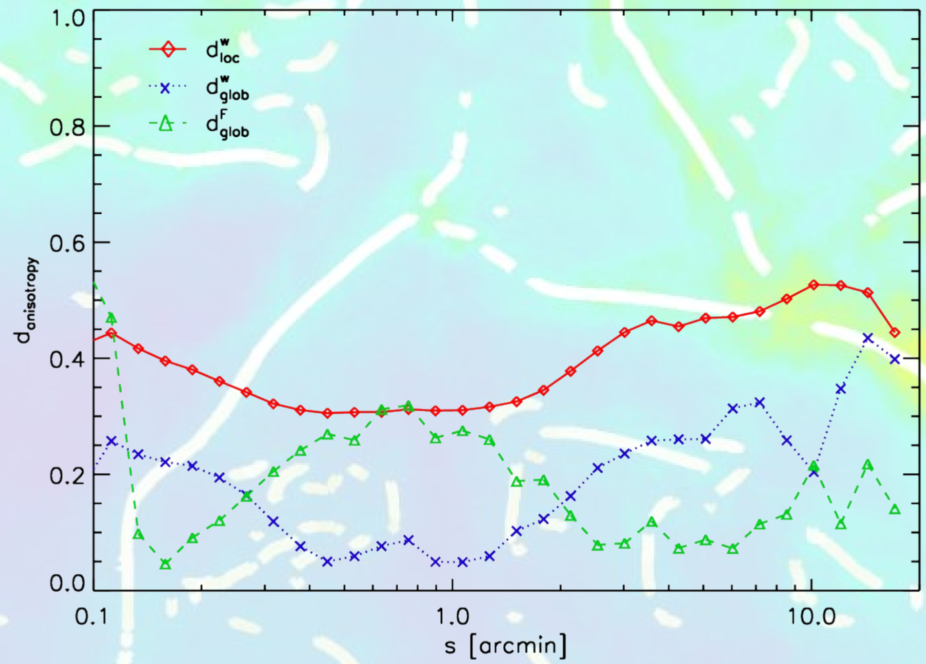
$C^{18}O$:

- Small-scale excess
- Prominent feature at 0.07pc seen in wavelet and Fourier coefficients





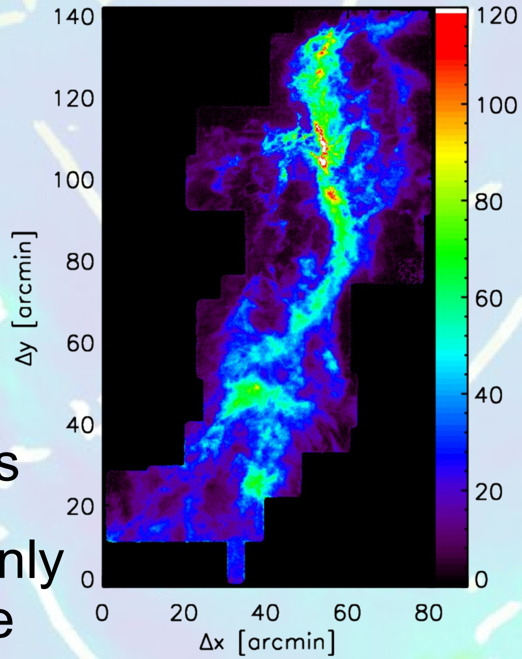


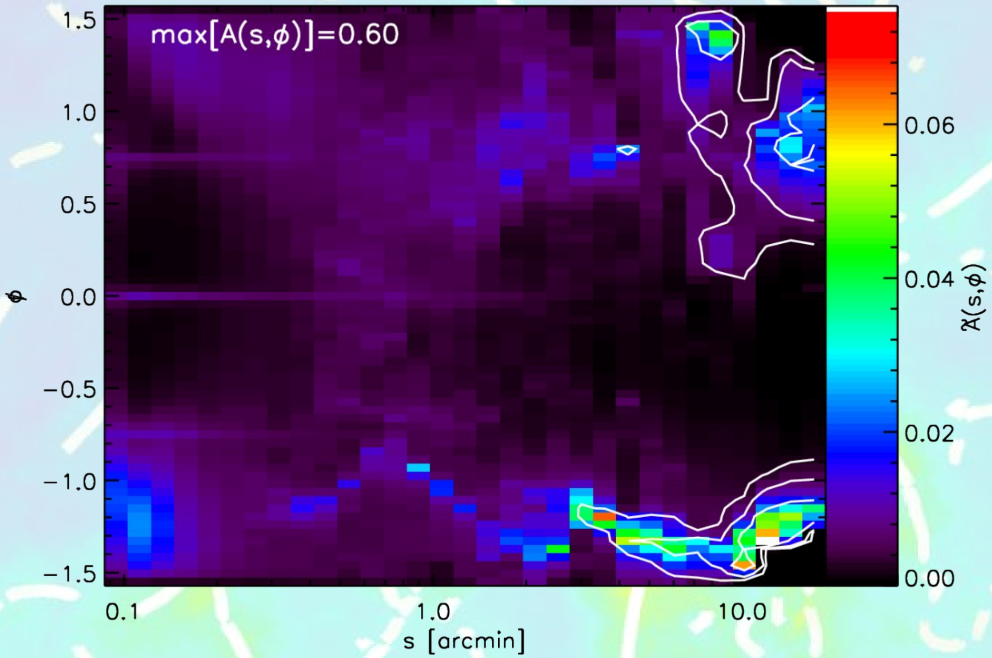


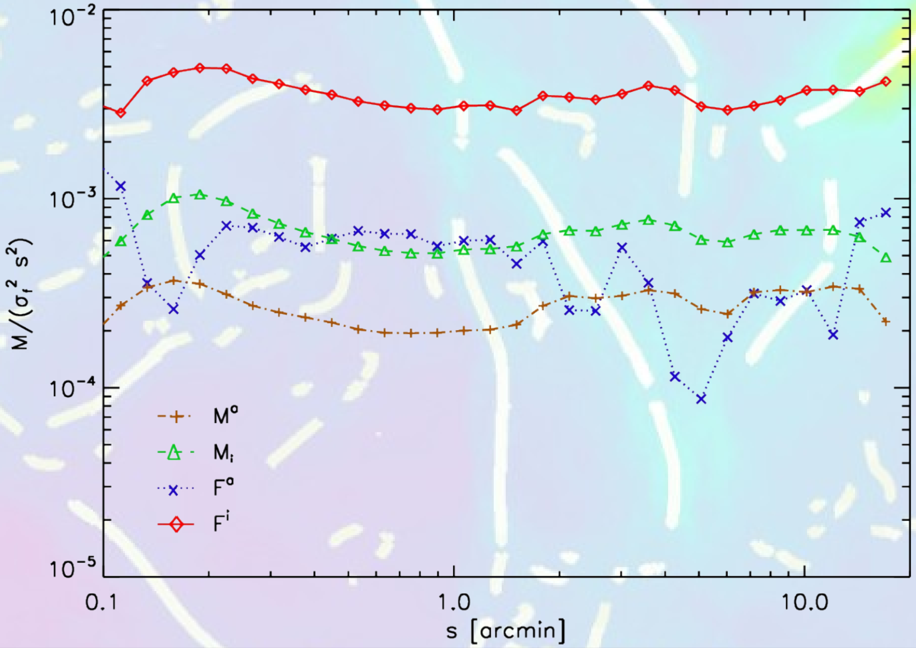
Anisotropic wavelet analysis

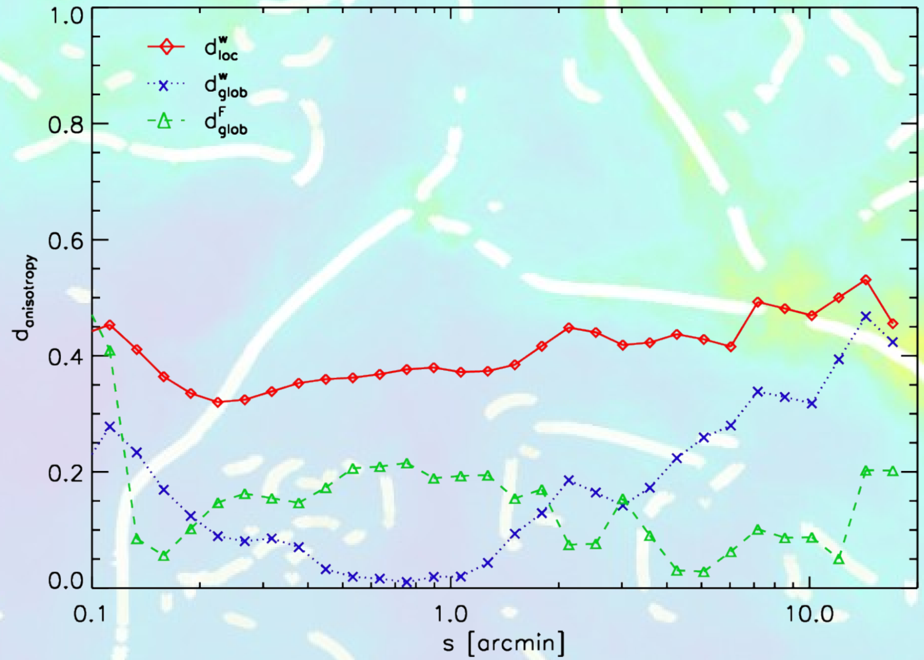
^{13}CO:

- Spectra close to power law, β=3
- No prominent scales
- Minor edge artifacts
- Global alignment only on very large scale

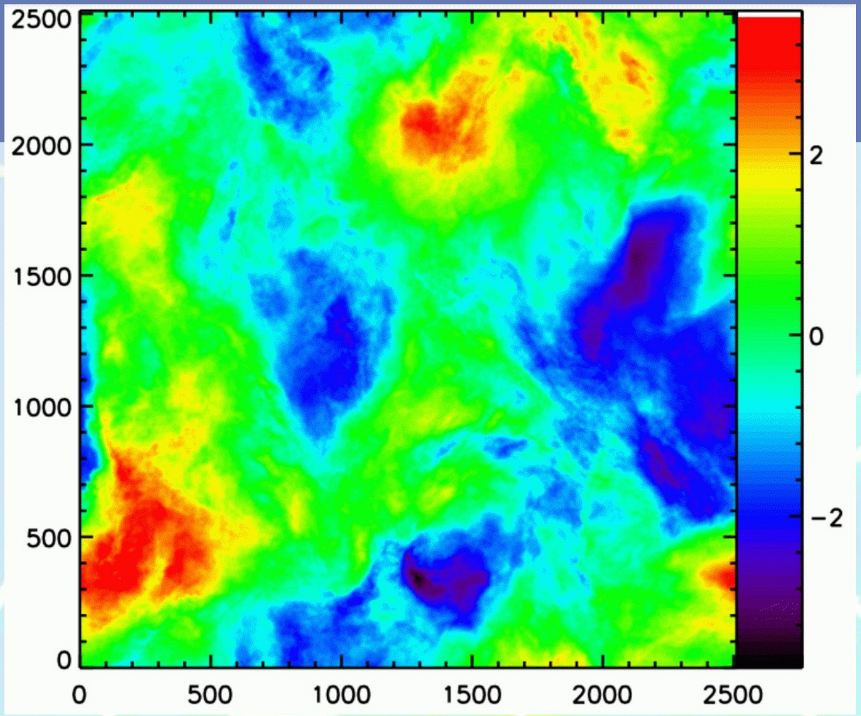








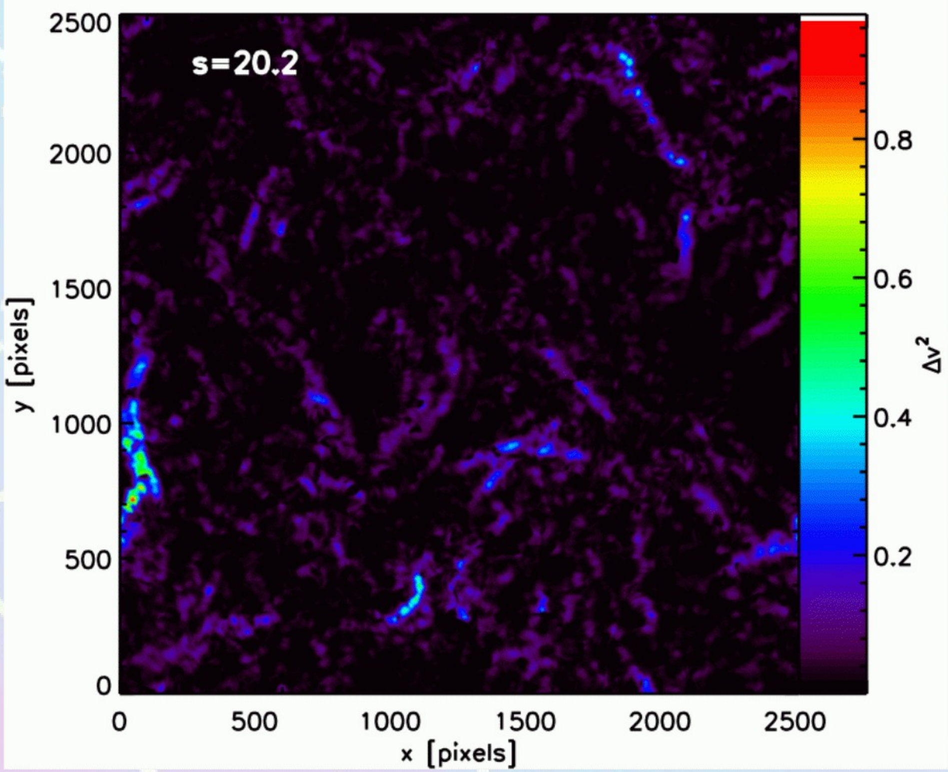
Application to High-res simulations

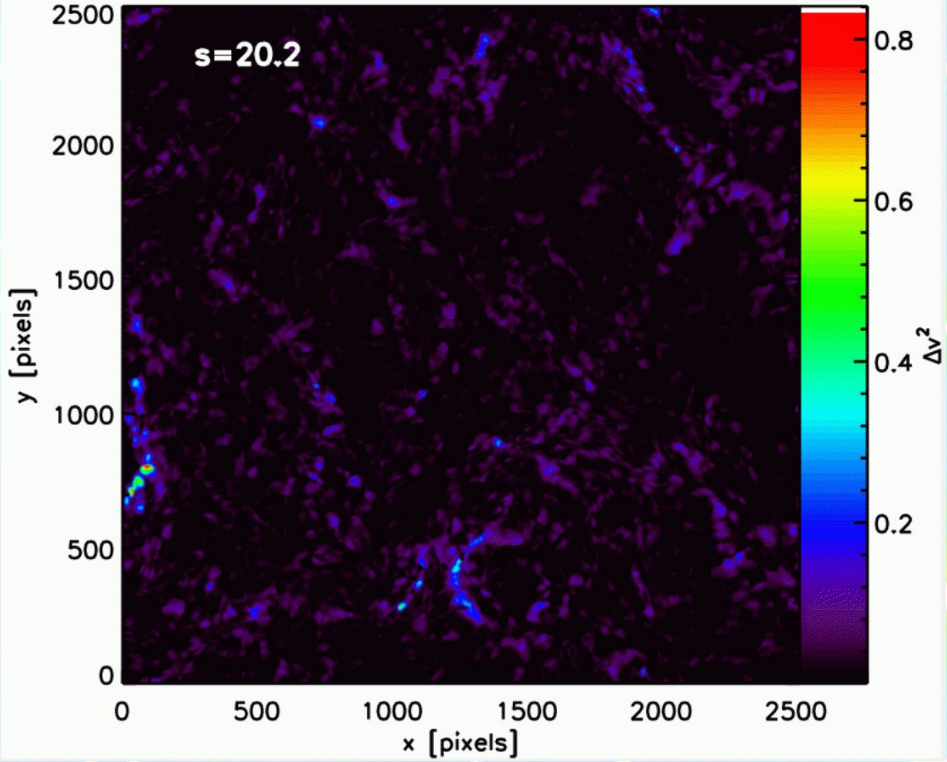


Combine:

Measure velocity variation perpendicular and parallel to filament directions identified in column density (scale dependent):

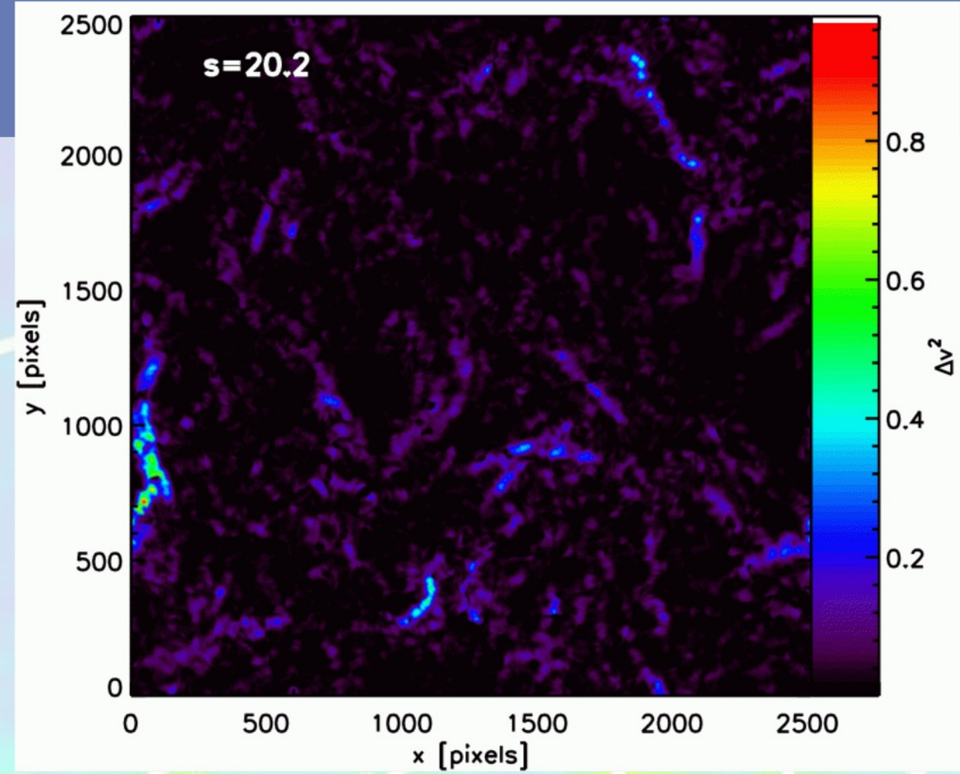
- "Magical" appearance of filaments in velocity structure knowledge





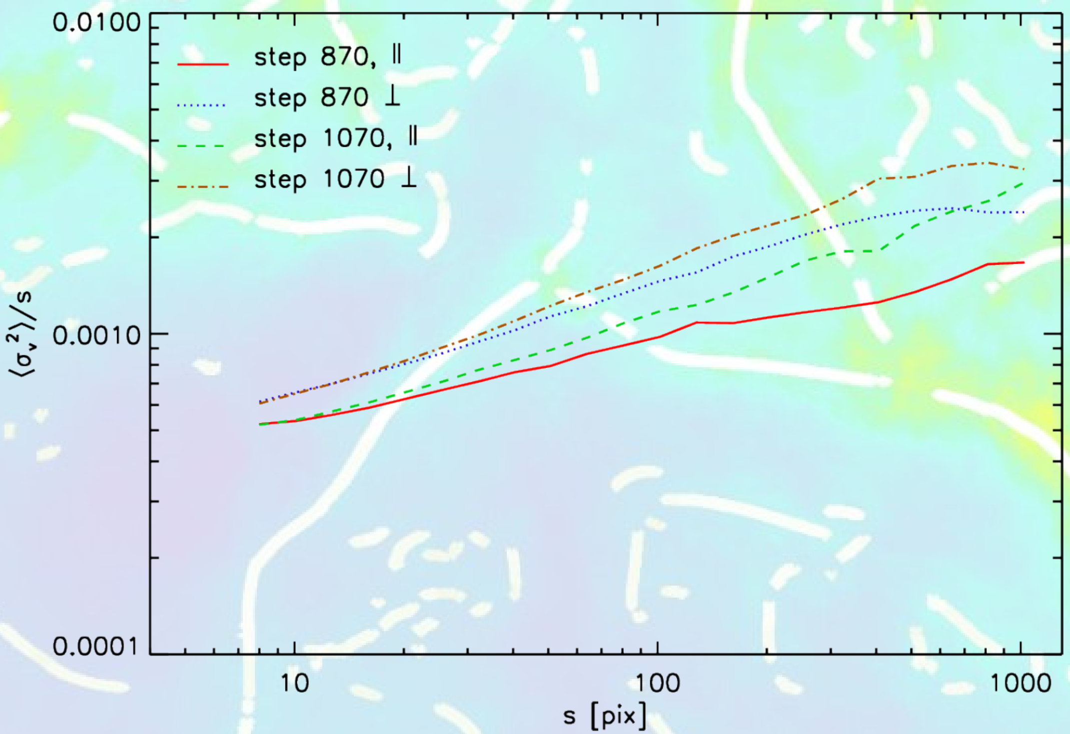
Velocity dispersions over 20 pixels perpendicular and parallel to column density filaments

Application to High-res simulations



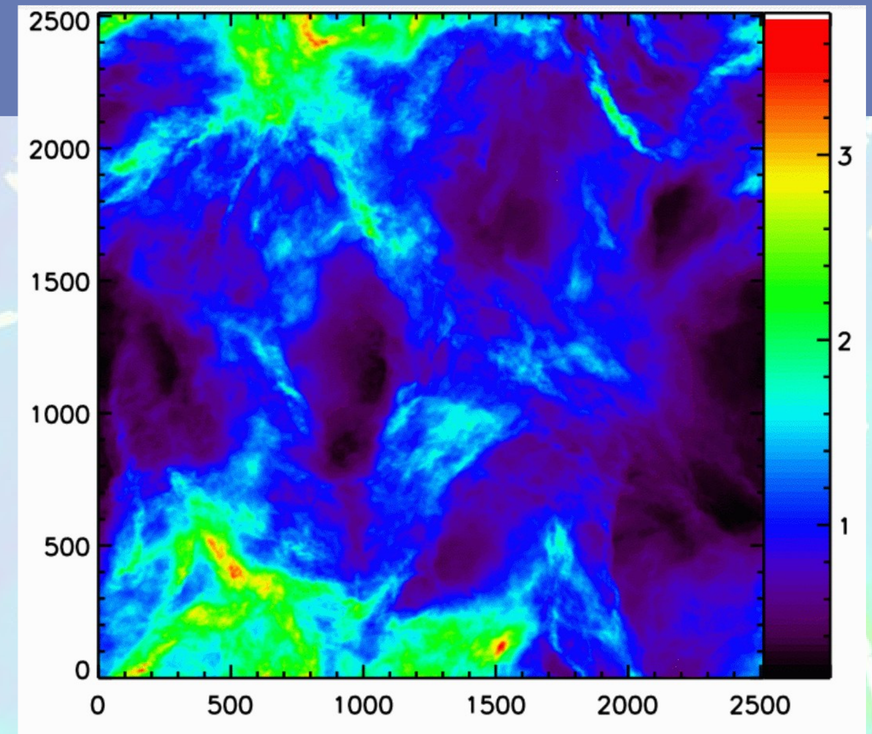
Combination:

- "Magical" appearance of filaments in velocity structure knowledge
  - Filaments are shocks
  - Velocity filaments well correlated with density filaments without using the density information (only angle)
- Perpendicular gradient twice as high as parallel gradient
  - Most filaments must stem from compressive motions



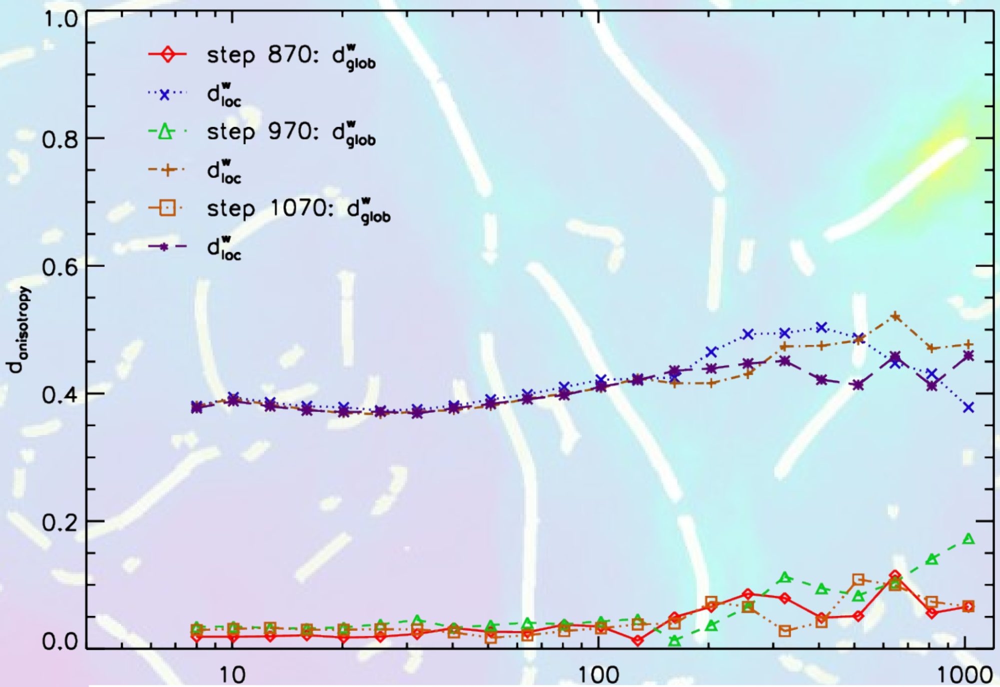
Spectrum of velocity dispersion parallel and perpendicular to the density filament direction

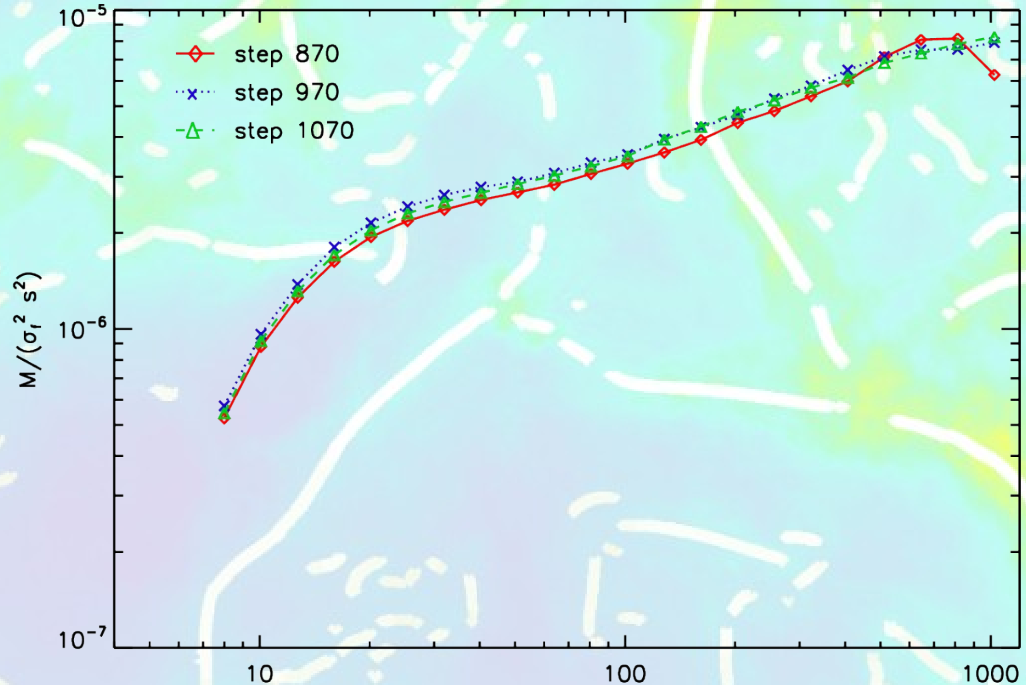
Application to High-res simulations



Wavelet analysis:

- Small kink at sonic scale also seen in column density structure
- Significant local degree of anisotropy from filaments at all scales
  - Small increase at sonic scale





Column density, degrees of anisotropy, and anisotropic wavelet spectrum