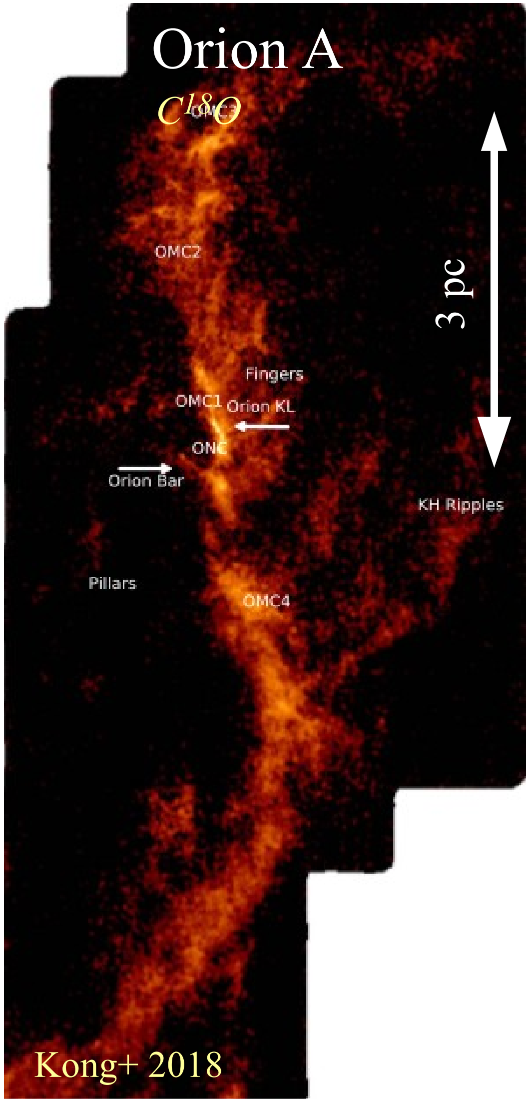

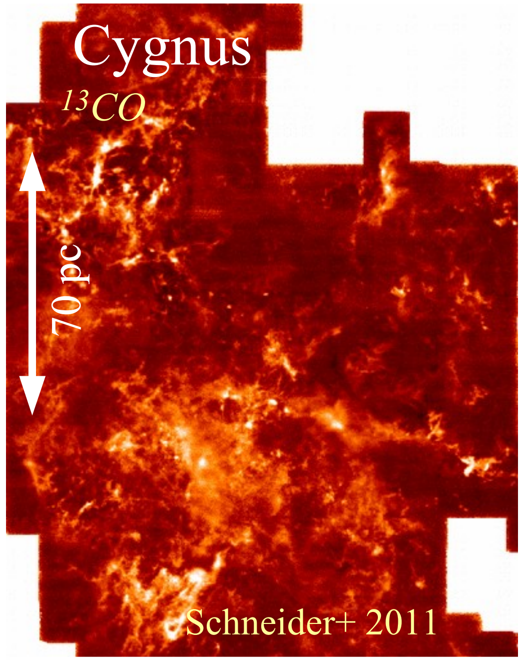

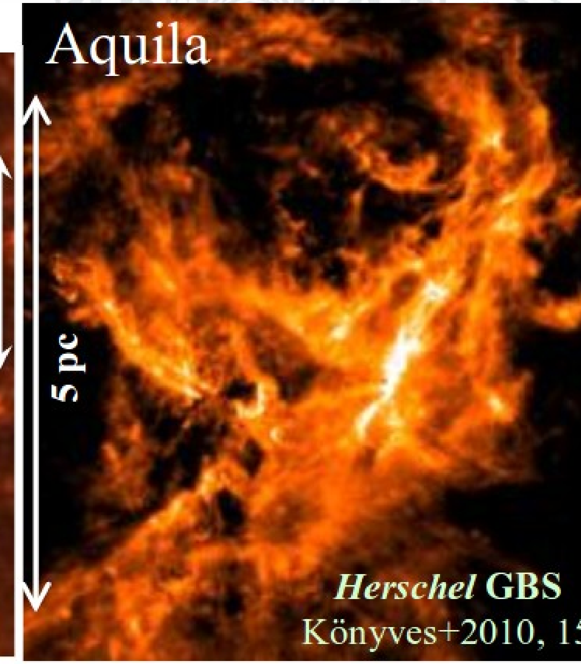

Measuring filaments through anisotropic wavelets

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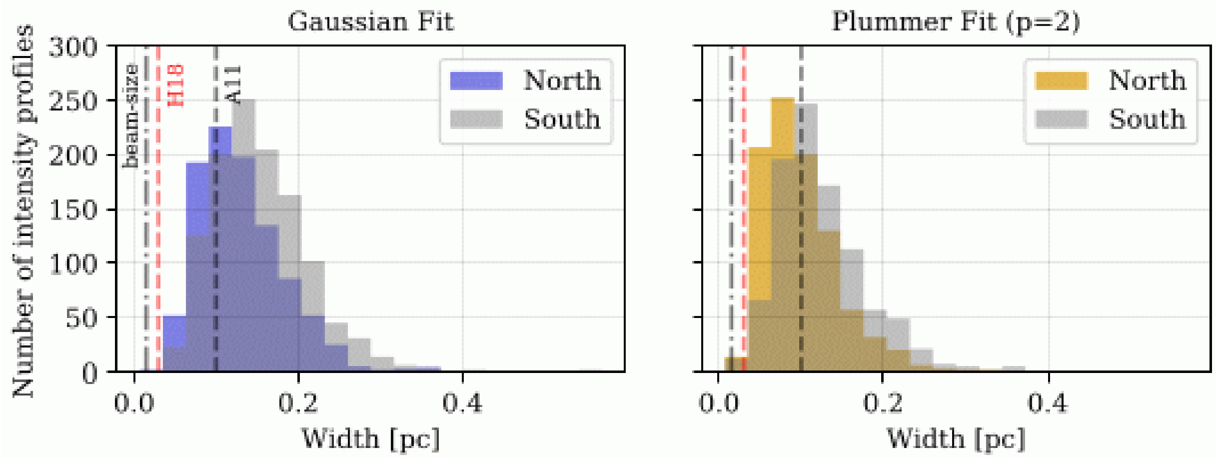
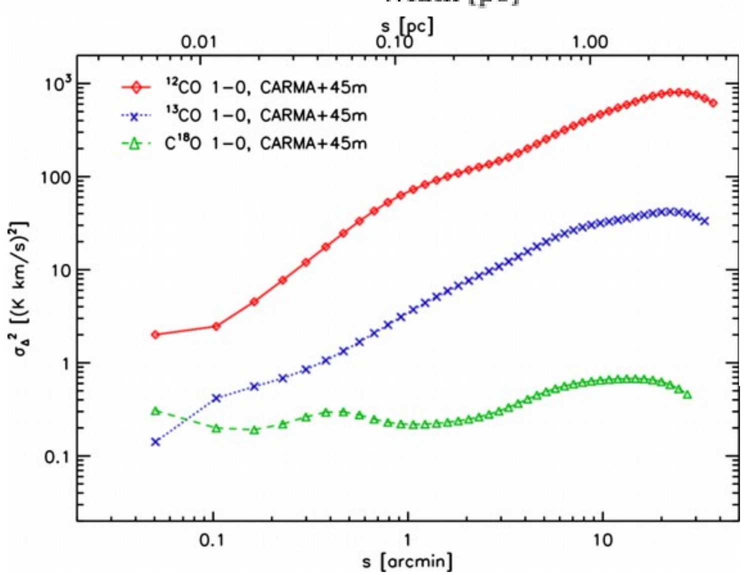
Is there a universal filament width of ~ 0.1pc?

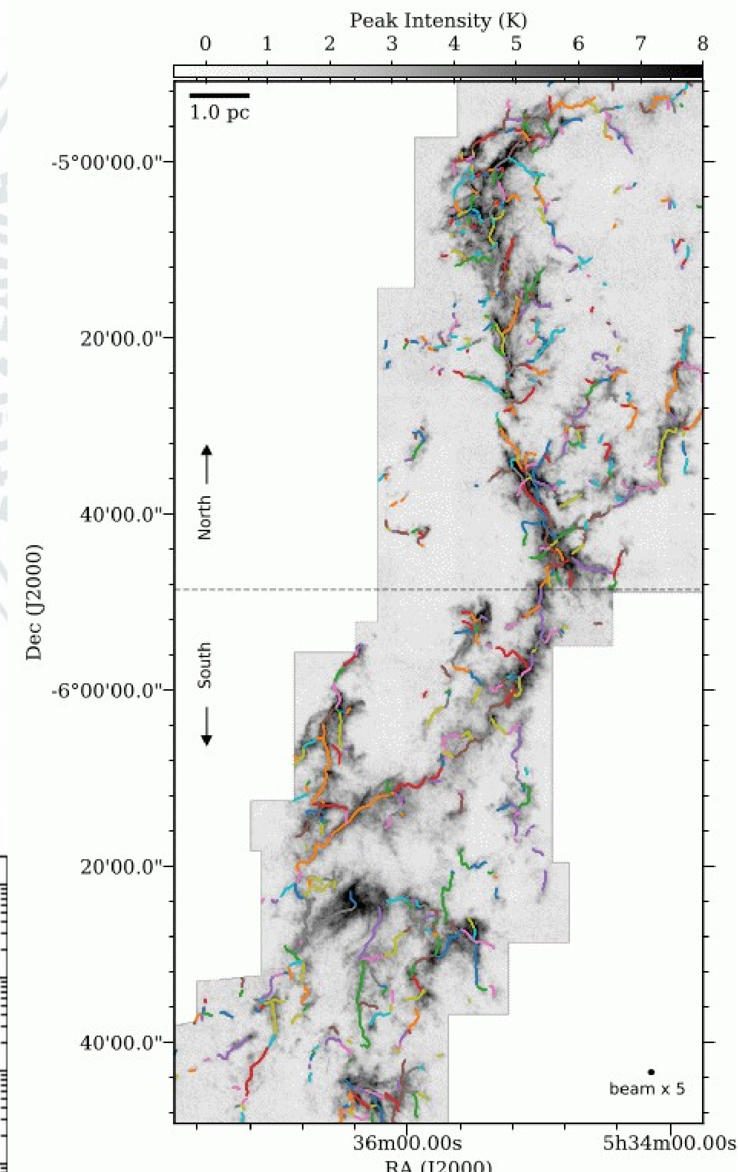
(Arzoumanian et al. 2011, 2018, Suri et al. 2018)

- DisPerSe + FilChap gives prominent scale
  - biased by “ruler parameters” (Panopoulou+ 2016)



- Power spectrum/ Δ-variance show no prominent scale
  - biased towards isotropic structures





→ **need for an unbiased filament measure**

Exploit inheritance from the Δ-variance

Use anisotropic wavelets for filaments

- Convolution of the map *f*(**x**): $W(s,\varphi,\mathbf{x}) = \frac{1}{s^{3/2}} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(\mathbf{x}) \psi_\varphi \left(\frac{\mathbf{x}' - \mathbf{x}}{s} \right) d\mathbf{x}'$

  with an anisotropic filter:

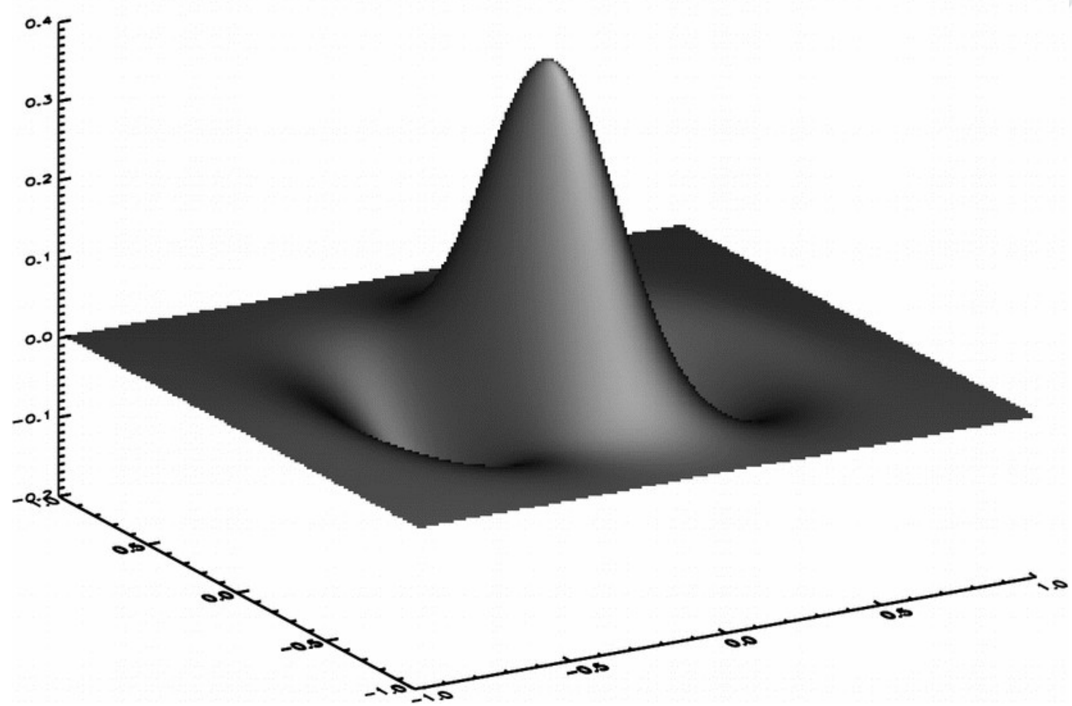
$$\psi_\varphi(\mathbf{x}) = \psi(x\cos\varphi - y\sin\varphi, x\sin\varphi + y\cos\varphi)$$

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

- Compute maps of isotropic and anisotropic wavelet coefficients as a function of the filter size *s*:

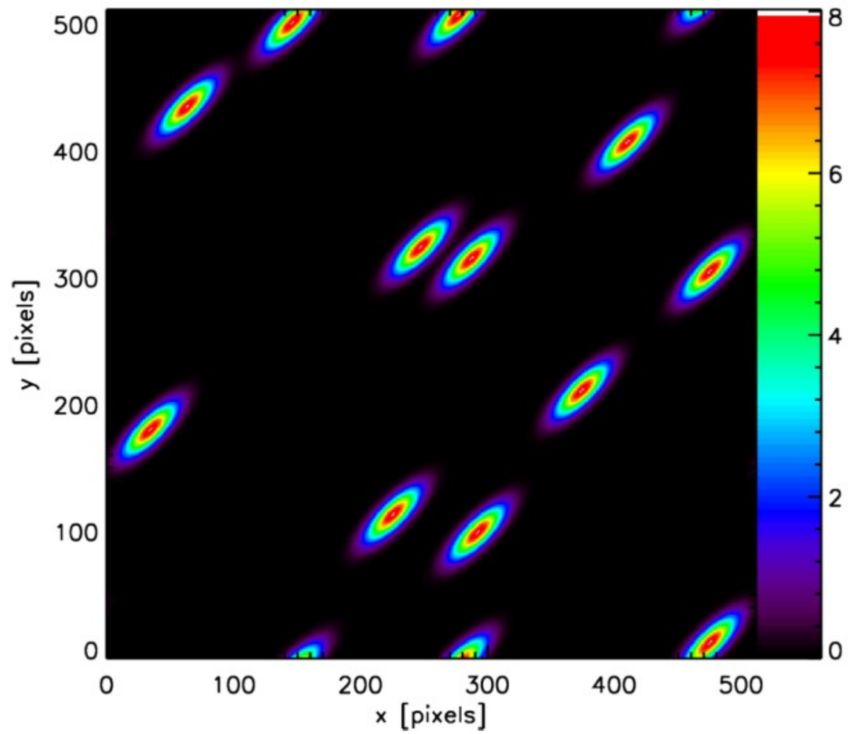
$$m^i(s,\mathbf{x}) = (2\pi)^{-1} \int_{-\pi}^{+\pi} |W(s,\varphi,\mathbf{x})|^2 d\varphi,$$

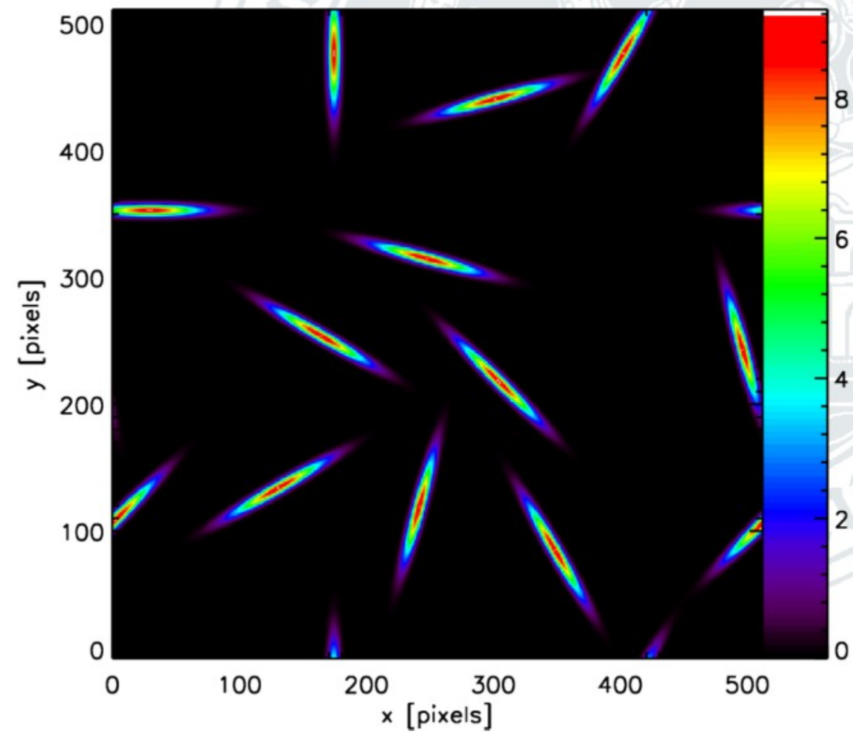
$$m^a(s,\mathbf{x}) = (2\pi)^{-1} \int_{-\pi}^{+\pi} |W(s,\varphi,\mathbf{x})|^2 e^{2\imath\varphi} d\varphi$$



Similar approach: Robitaille et al. (2014)

Example data sets used for calibration experiments



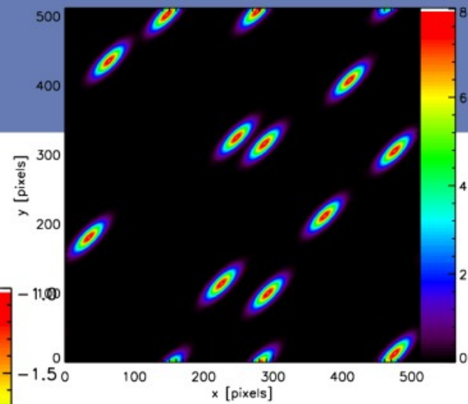


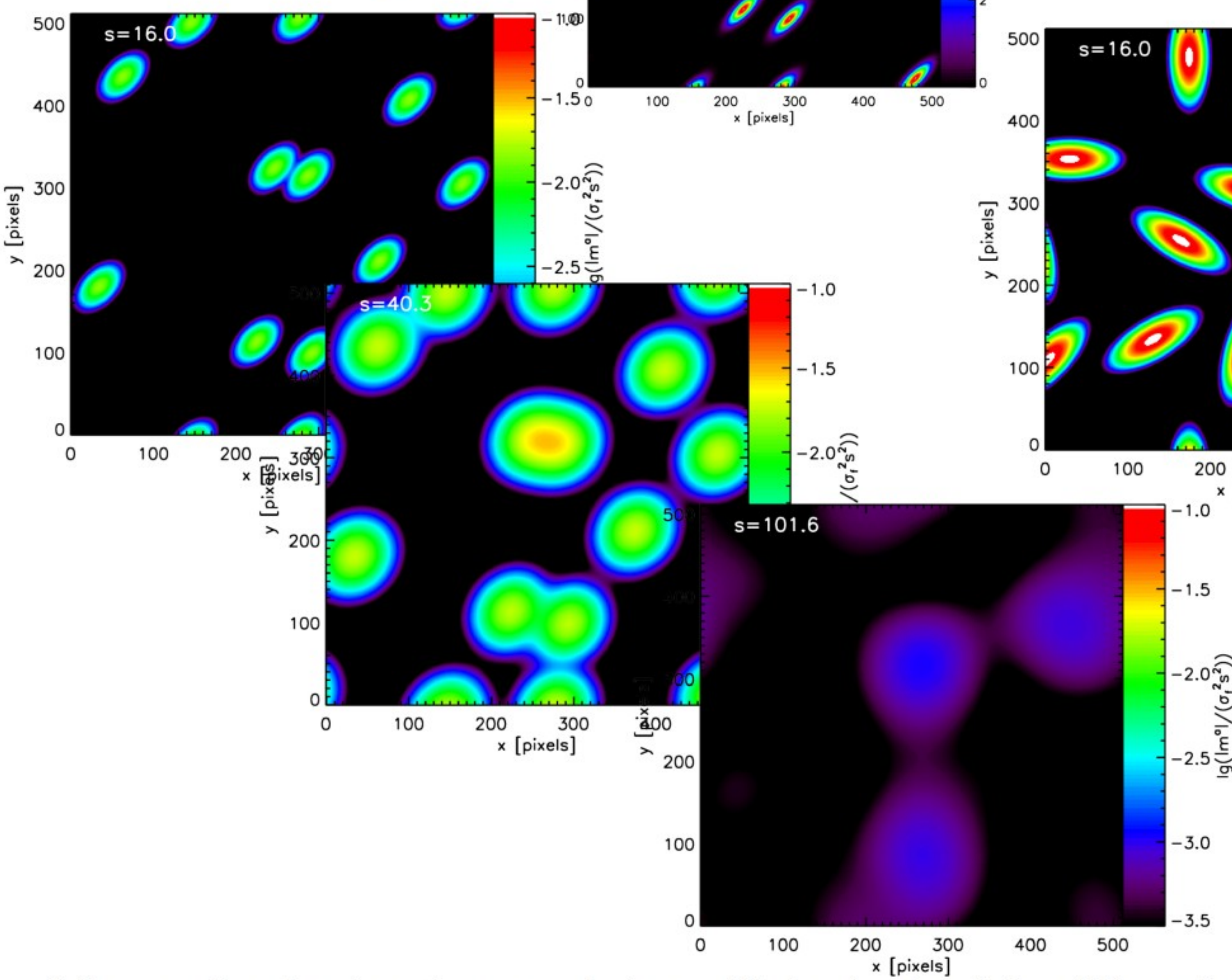
10 ellipses with axes ratios 3:1 and 9:1, aligned or uniformly distributed

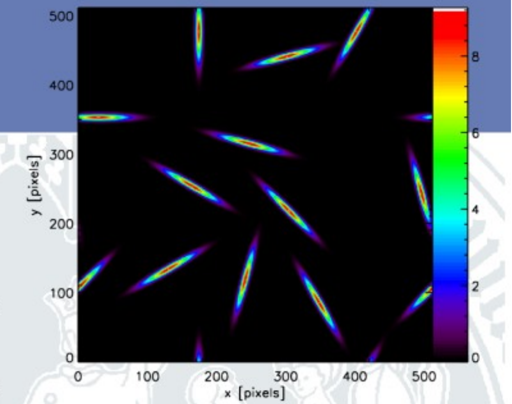
- Maps of isotropic and anisotropic coefficients with amplitude, angle and spatial distribution as a function of the wavelet scale *s*
  - 4D result

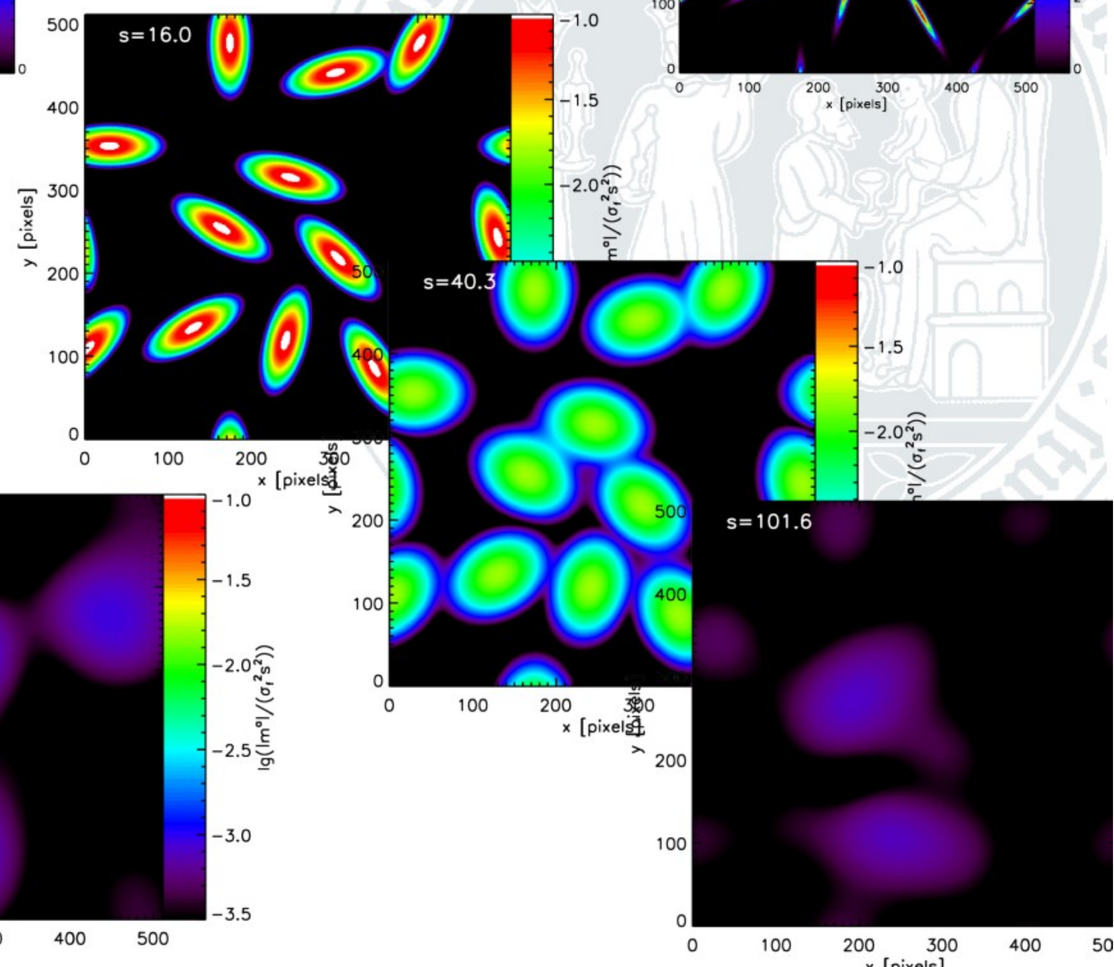
Calibration

Wavelet maps









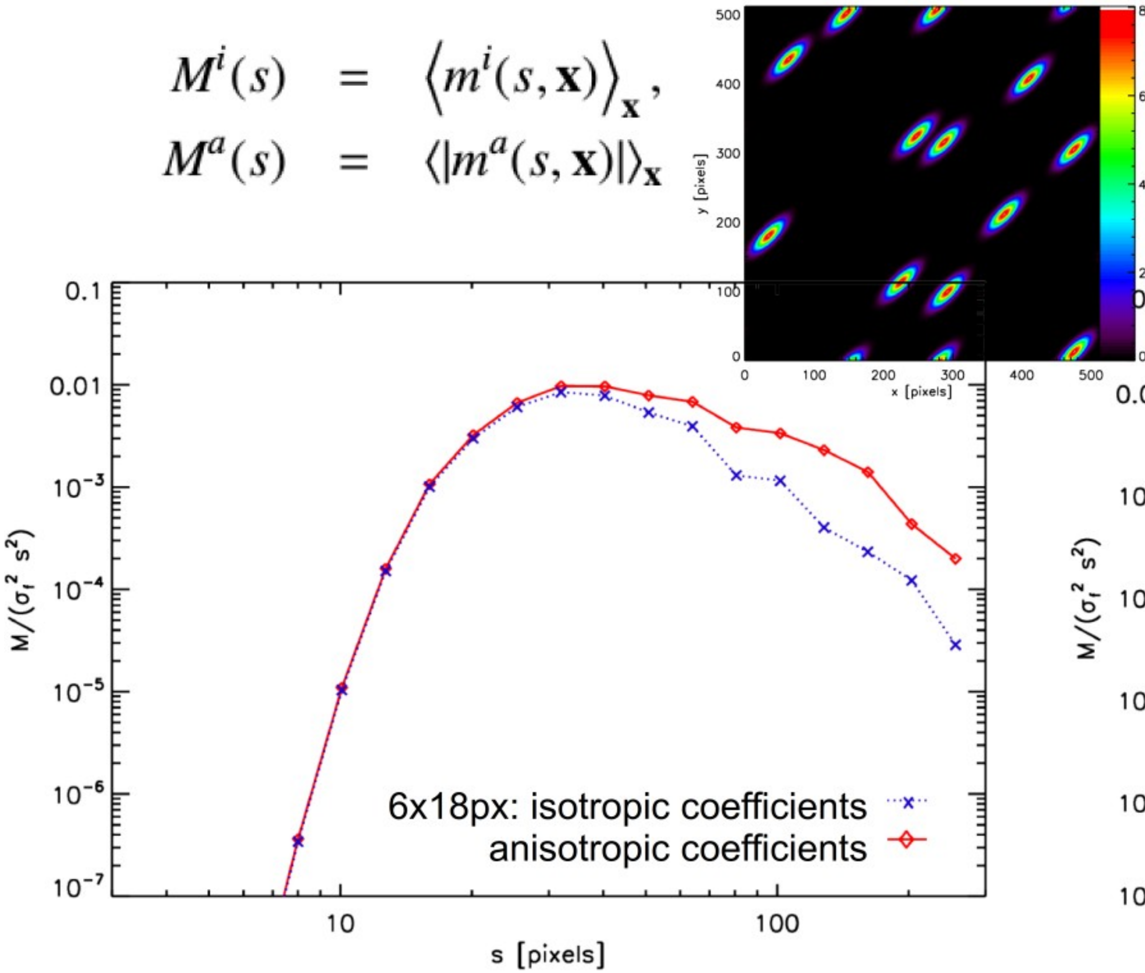
Maps of anisotropic wavelet coefficients (m^a) for filter sizes of 16, 40, 102 pixels

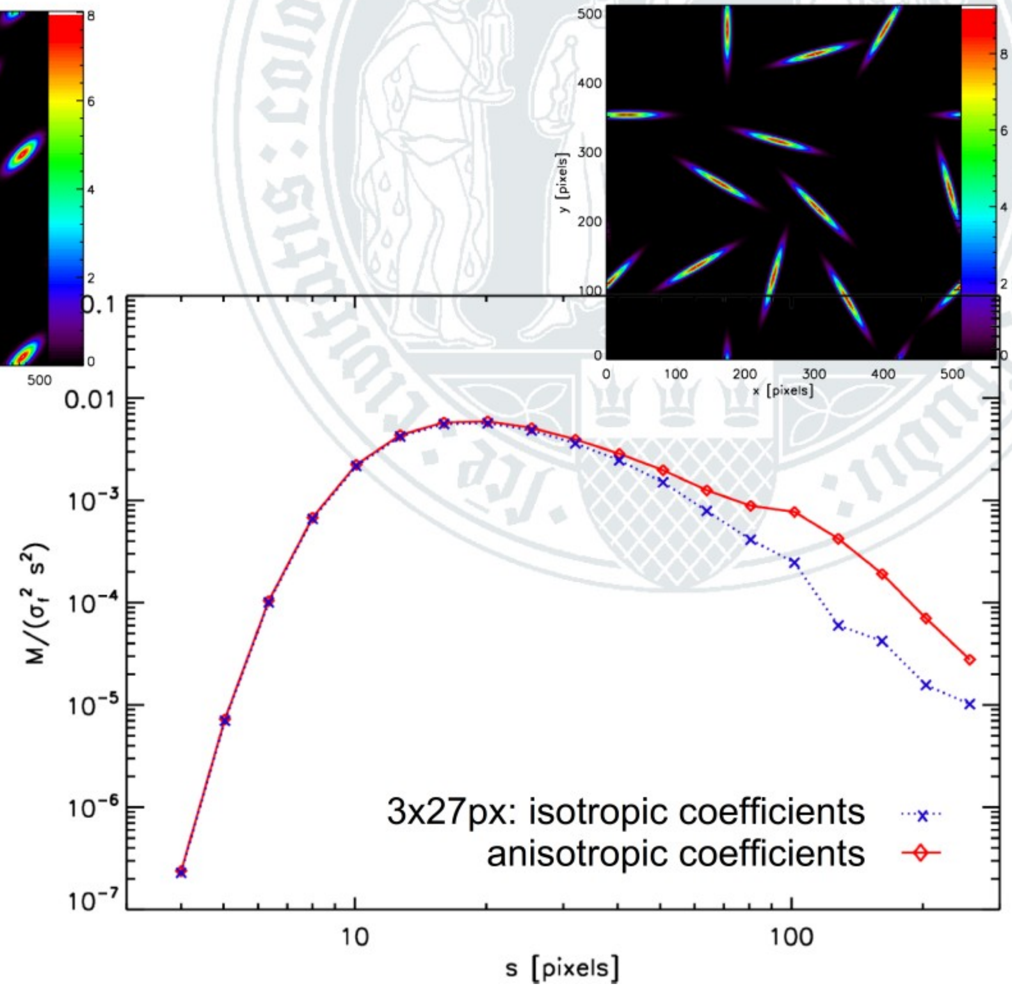
- Coefficients trace mainly the edges of the clumps
- Random anisotropic configurations from superposition at large *s*

From spatial averages

- Isotropic and anisotropic wavelet spectra as function of the filter size *s*:

$$M^i(s) = \left\langle m^i(s,\mathbf{x})\right\rangle_{\mathbf{x}},$$
$$M^a(s) = \langle |m^a(s,\mathbf{x})|\rangle_{\mathbf{x}}$$



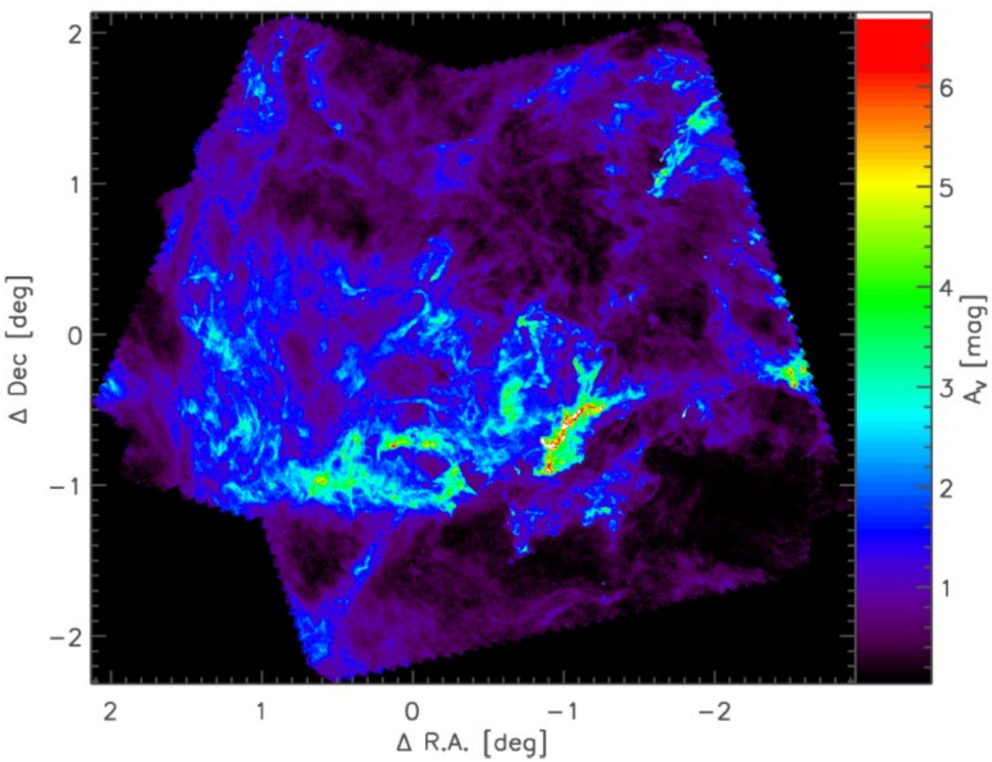


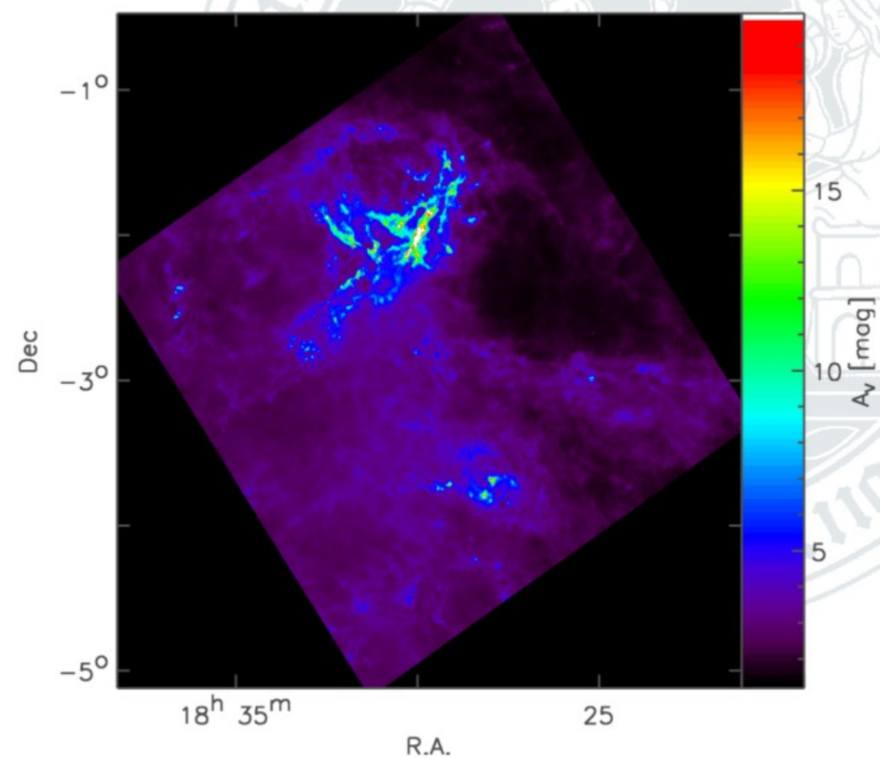
Normalized wavelet spectra (isotropic - M^i, anisotropic - M^a) compared to Fourier spectra

- Peak given by the width of the filaments: $s(M^i/s^2)_{\max} \approx 2.7\,\mathrm{FWHM}$

Application to observations

Observed column density maps from Herschel observations





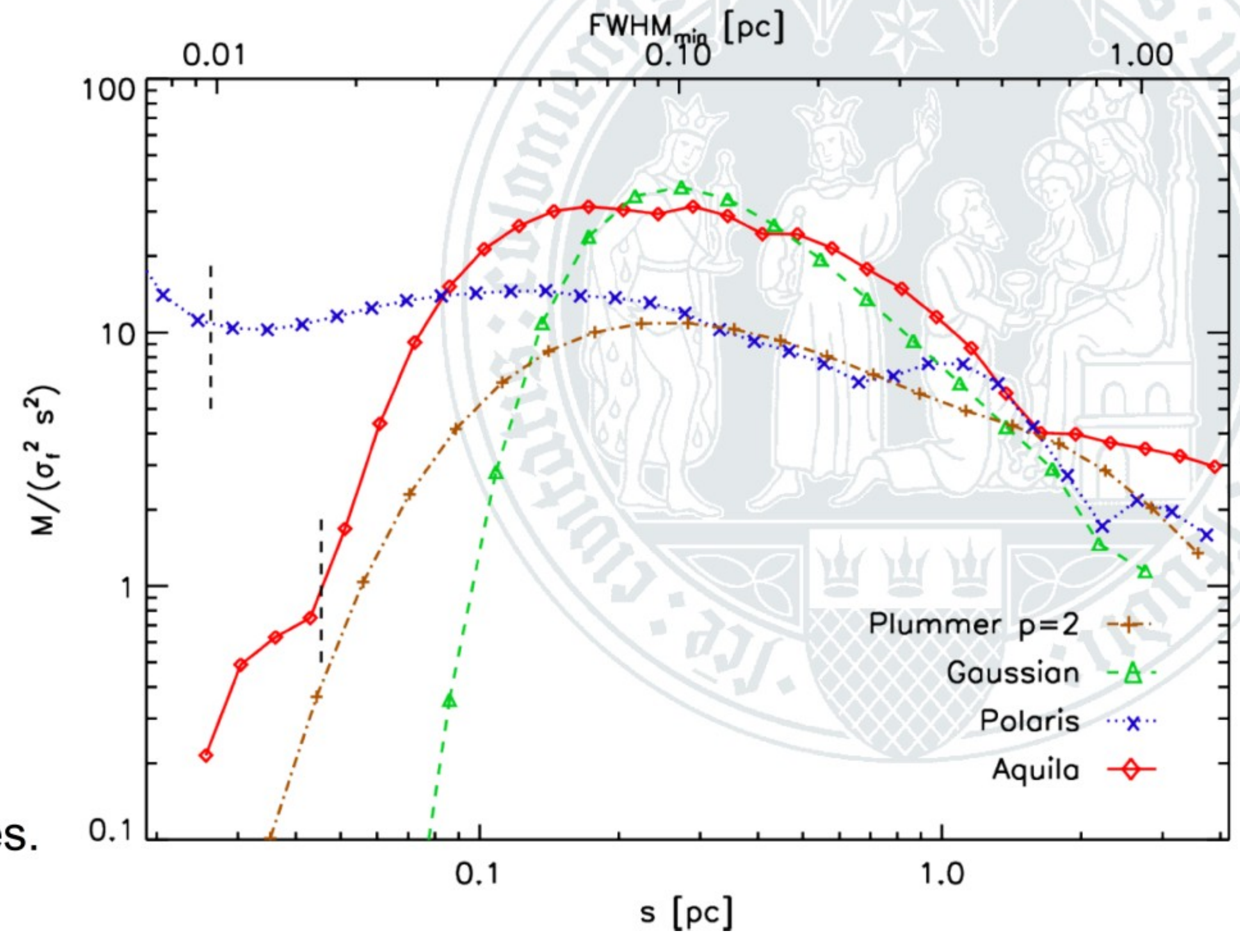
Filamentary dust maps of the Polaris (left) and Aquila (right) regions previously analysed by André et al. (2010) and Schneider et al. (2013).

- In spite of the different nature of the clouds André et al. (2010) find a common filament width of 0.1pc for both clouds.

Anisotropic wavelet analysis

Polaris and Aquila

Wavelet spectra for both regions:

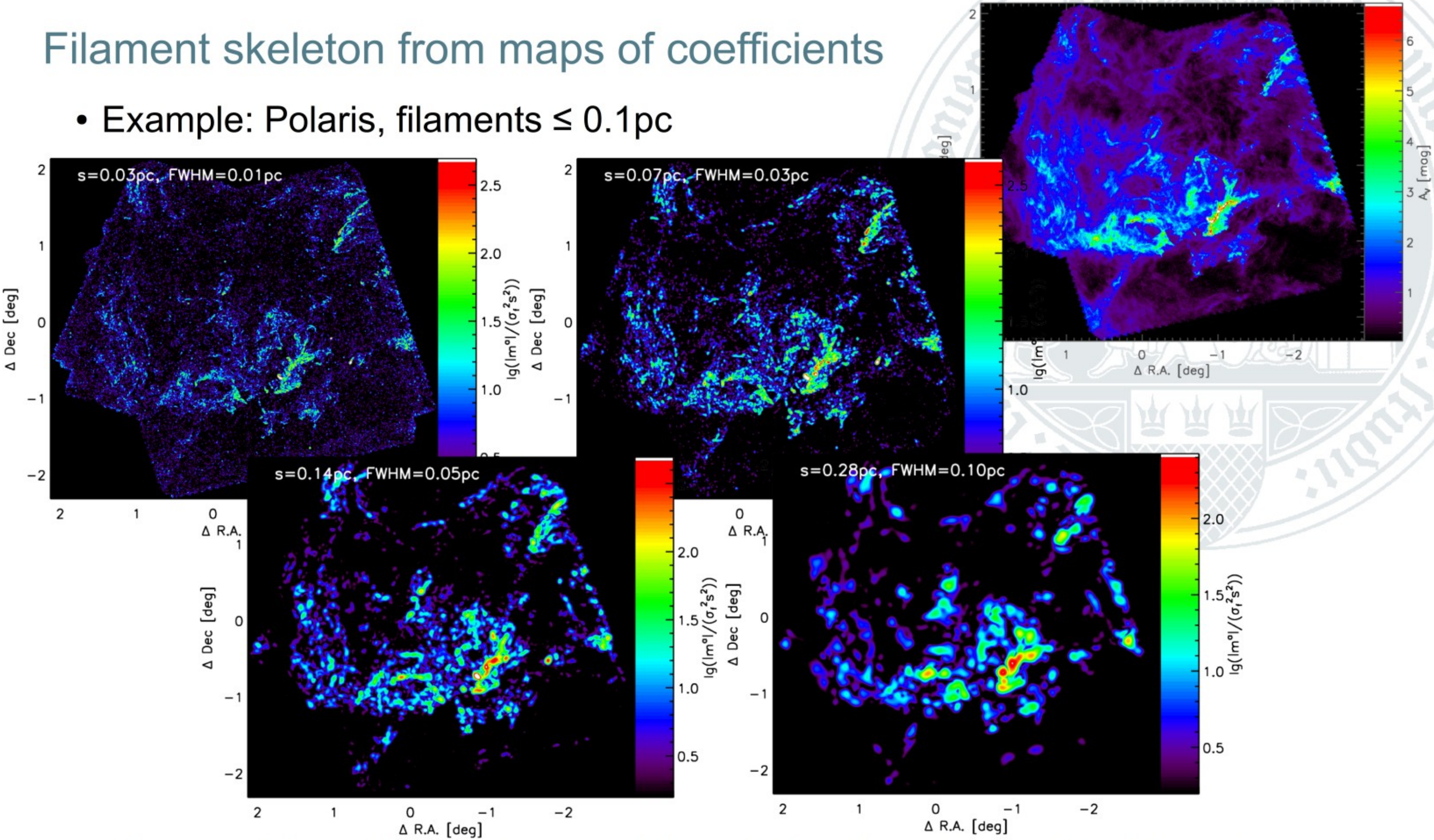


Comparison with the spectra of clumps with an axes ratio of 1:8. Dashed lines indicate the beam sizes.

- Polaris shows no characteristic size scale at small scales at all.
  - The drop at large scales matches Gaussian filaments with FWHM=0.4pc.
- Aquila is consistent with Gaussian filaments of FWHM=0.04...0.2pc or Plummer filaments of FWHM=0.07pc.

Filament skeleton from maps of coefficients

- Example: Polaris, filaments ≤ 0.1pc

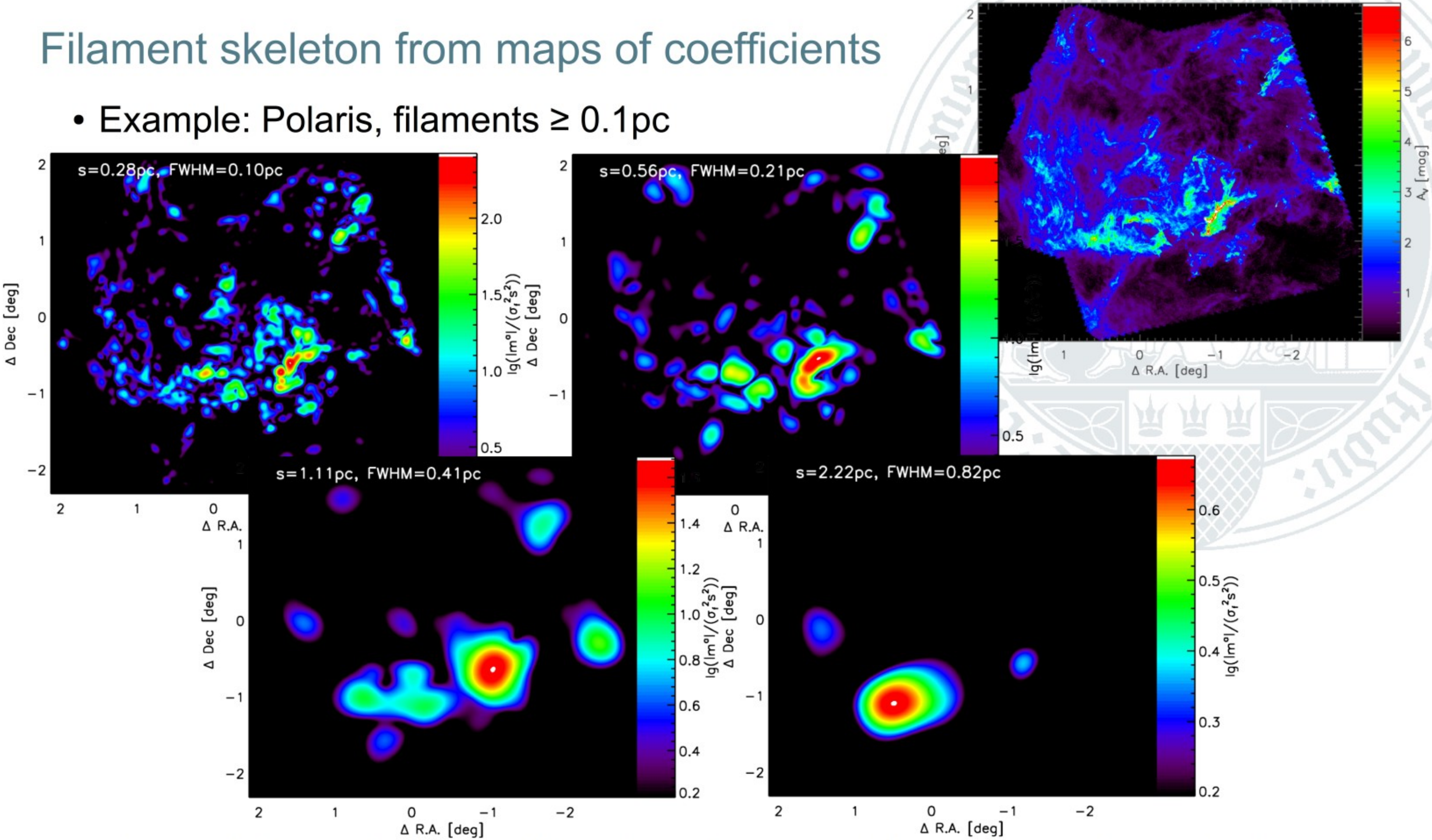


- The wavelet coefficients for small filters follow the spines of the filaments.
- They continue to break up into smaller structures.

What structures do we see at the different scales?

Filament skeleton from maps of coefficients

- Example: Polaris, filaments ≥ 0.1pc



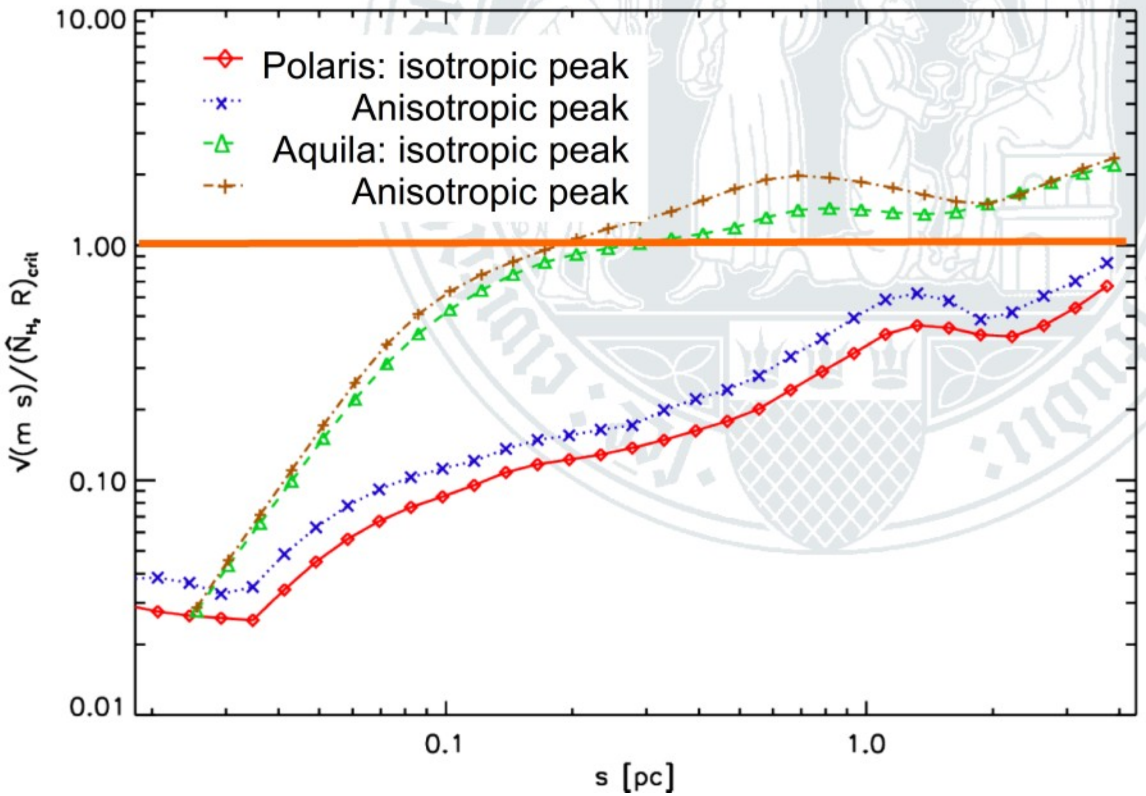
- The coefficients for larger filters trace larger and larger filamentary structures that are not necessarily correlated with those at small scales.

Gravitational stability against perturbations measured by wavelet coefficients

- Spherical and cylindrical collapse modes:

$$\sqrt{m^i s} > (\hat{N}R)_{\rm crit} = 2.07\frac{c_{\rm s}^2}{G\mu}$$

$$\sqrt{m^a s} > (\hat{N}R)_{\rm crit} = 1.27\frac{c_{\rm s}^2}{G\mu}$$



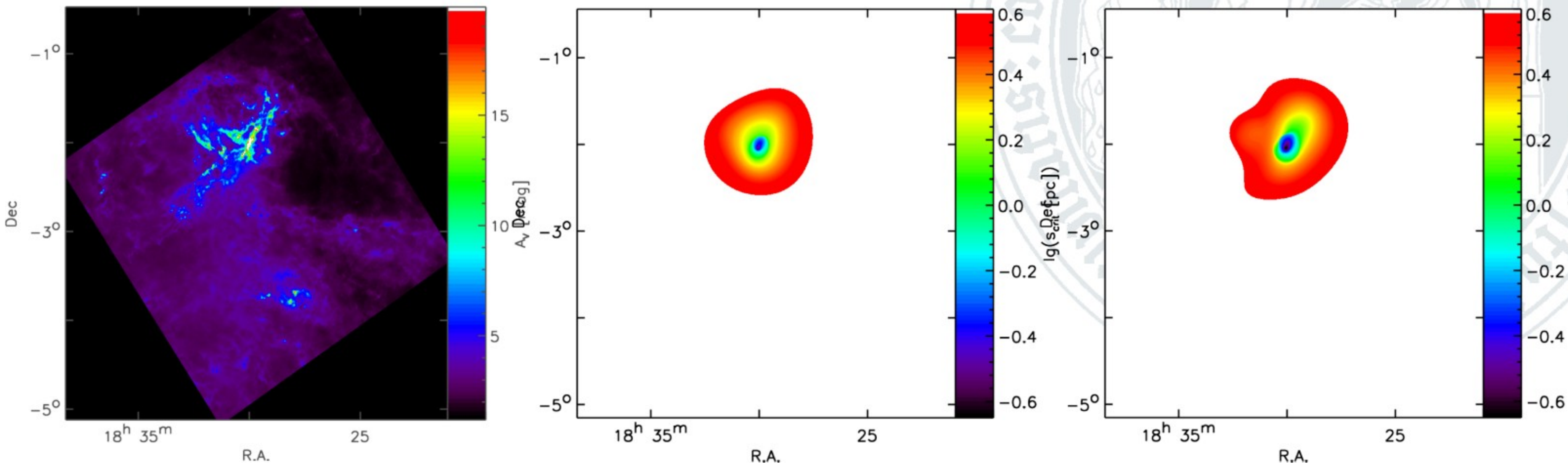
Gravitational mode spectrum for the dominating structures in the observed maps (15K molecular gas).

- Polaris stable
- Aquila unstable above 0.15pc. Cylindric modes “win” at all scales up to 2pc.

Gravitational stability

Spatial distribution from map of coefficients

- Scale of supercritical modes describes geometry of collapsing regions



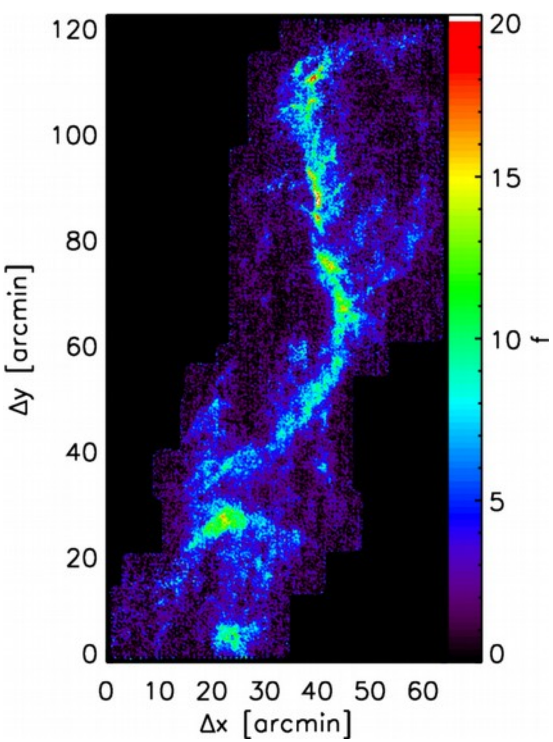
Minimum wavelet scale where stability criterion is exceeded for isotropic modes (left) and anisotropic modes (right) in the Aquila column density map.

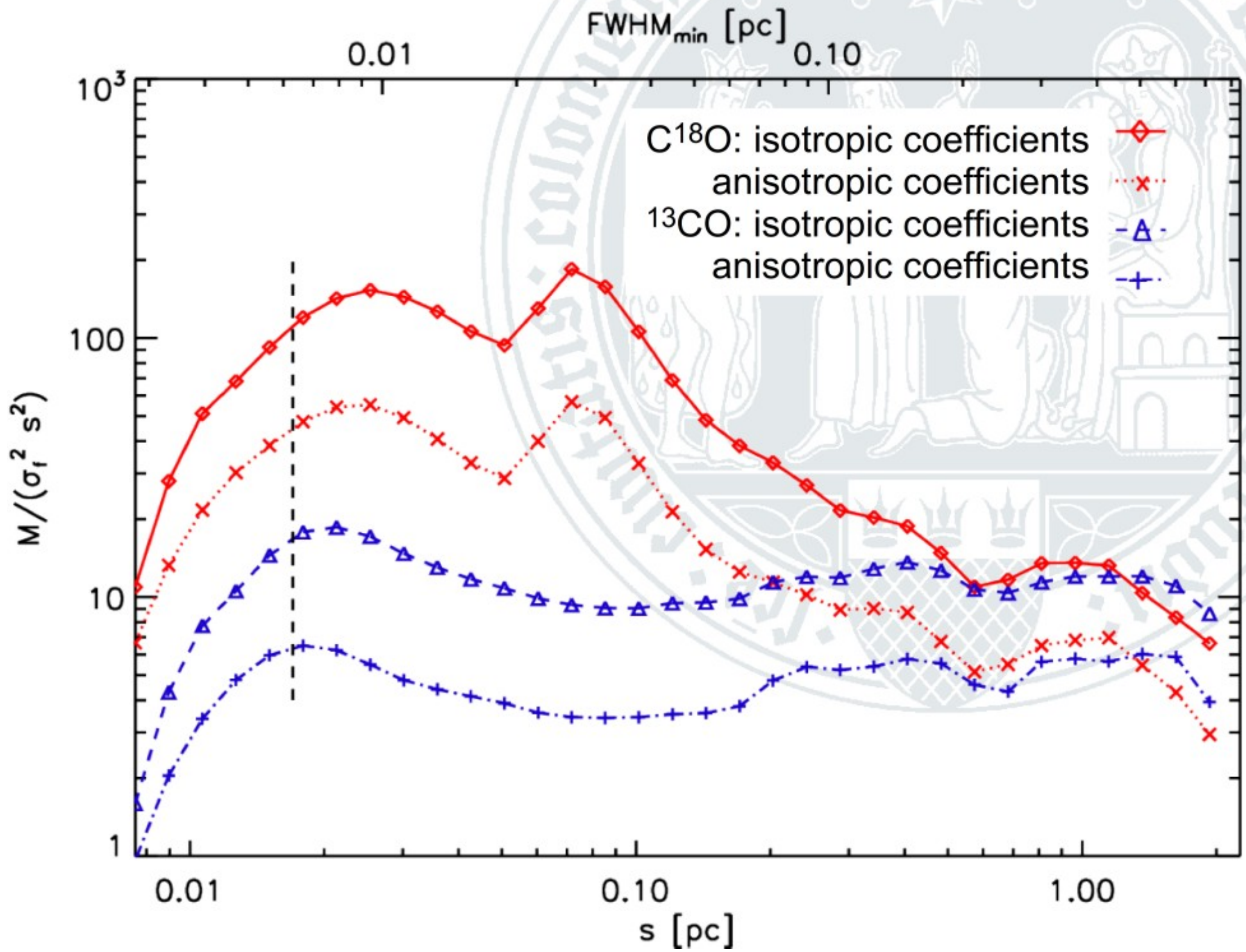
- Only the main Aquila filament will undergo quick collapse.
- Cylindrical collapse dominates along the main filament, isotropic collapse at its ends and in the extended environment of the filament.

Starting example

$C^{18}O$ 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

Summary

Anisotropic wavelets are an unbiased approach to measure filaments

- Full spectrum of filament widths from resolution to about 0.2 map size.

- Application to observed column density maps
  - No universal filament width of 0.1pc!
    - Polaris and Orion A show a mixture of filaments of all sizes and directions.
    - Aquila has a narrow size range. All filaments there are related to the main ridge providing a global anisotropy.
  - Spectra give relative importance of spherical and cylindrical collapse modes.
    - Cylindrical modes dominate on most scales
    - Collapse of the denser part expected for Aquila and Orion A. Polaris is stable.