Filamentary Structures and Compact Objects in the Aquila and Polaris Clouds Observed by *Herschel*

Gould Belt GT KP

SPIRE SAG3

energie atomique • energies alternatives

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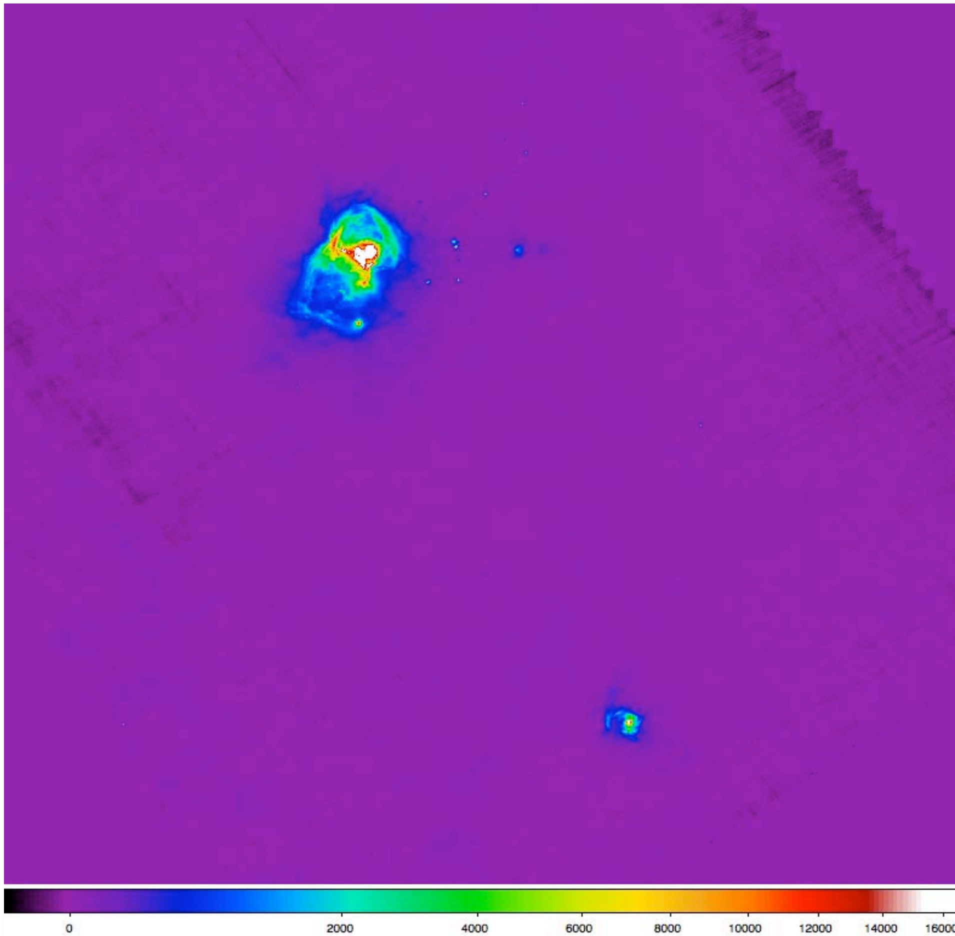
Herschel Science Demonstration

- Part of the large Gould Belt KP survey of the nearby star-forming regions
  - More results in talks by Philippe André, Vera Könyves, Sylvain Bontemps
- Aquila Rift and Polaris Flare fields (D ~260 pc and ~150 pc)
  - Cores in active star-forming region vs. high-latitude cirrus clouds
  - SPIRE/PACS parallel mode at 70, 160, 250, 350, 500 μm
  - Angular resolutions of ~8, 13, 18, 25, 37 arcsec
  - Fields ~3×3°, cross-scans at 60”/s

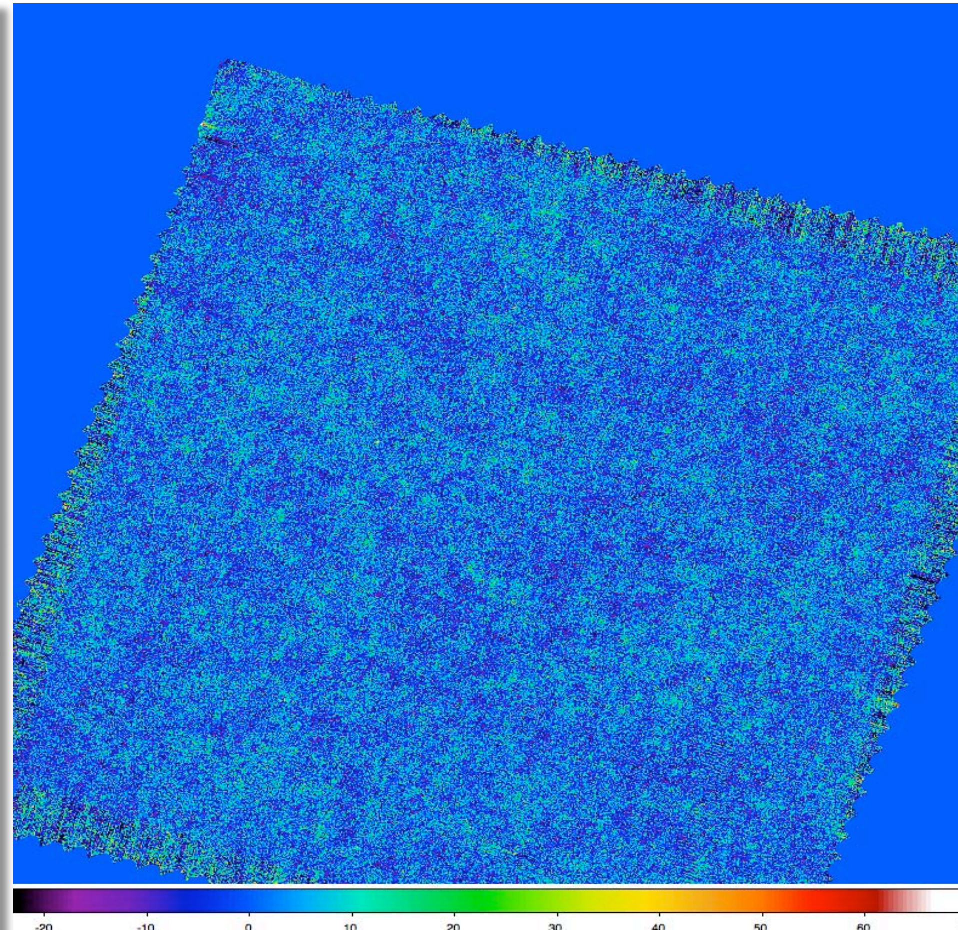
Herschel Images of the Aquila and Polaris Fields

Aquila and Polaris: PACS 70 μm

resolution ~8"



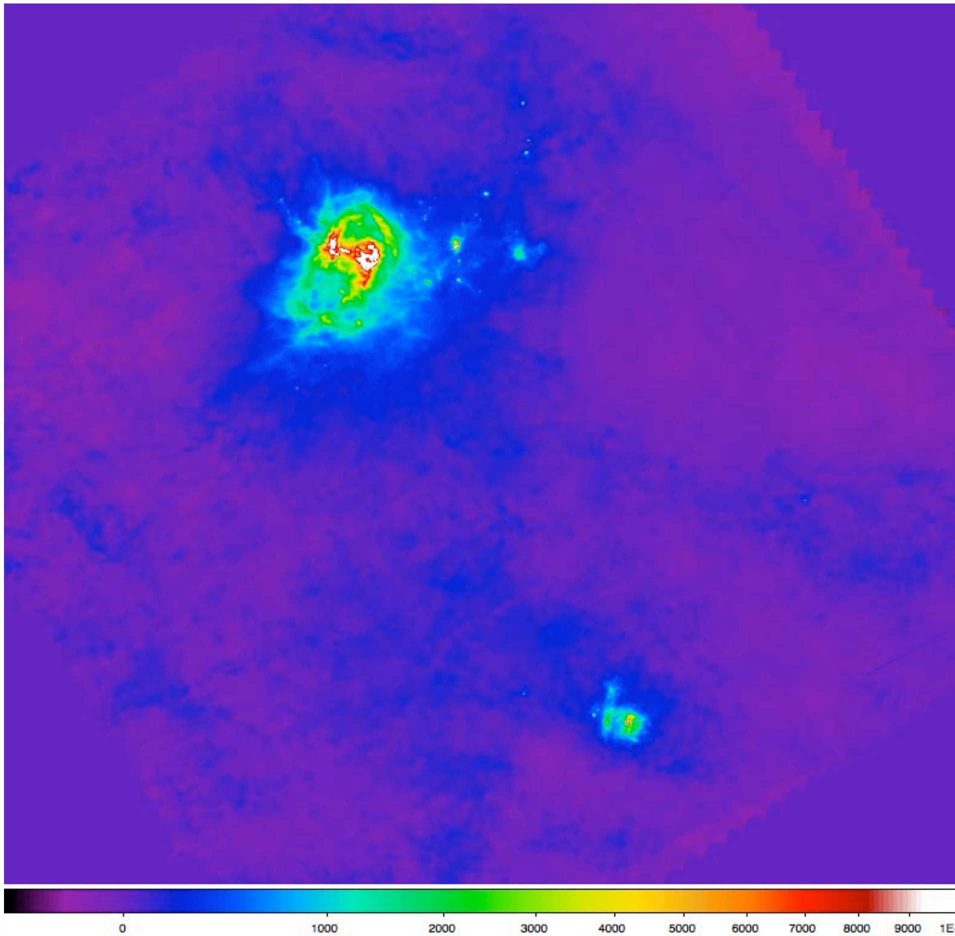
3.3°

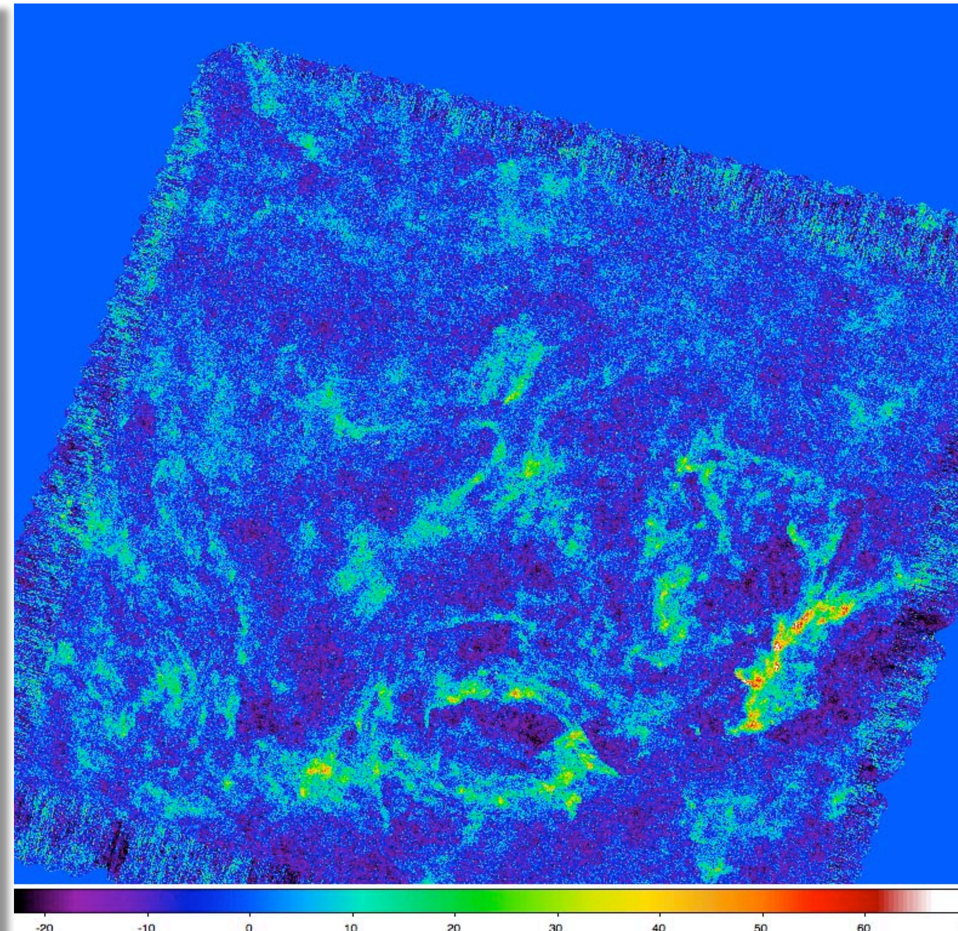


3.3°

Aquila and Polaris: PACS 160 μm

resolution ~13”



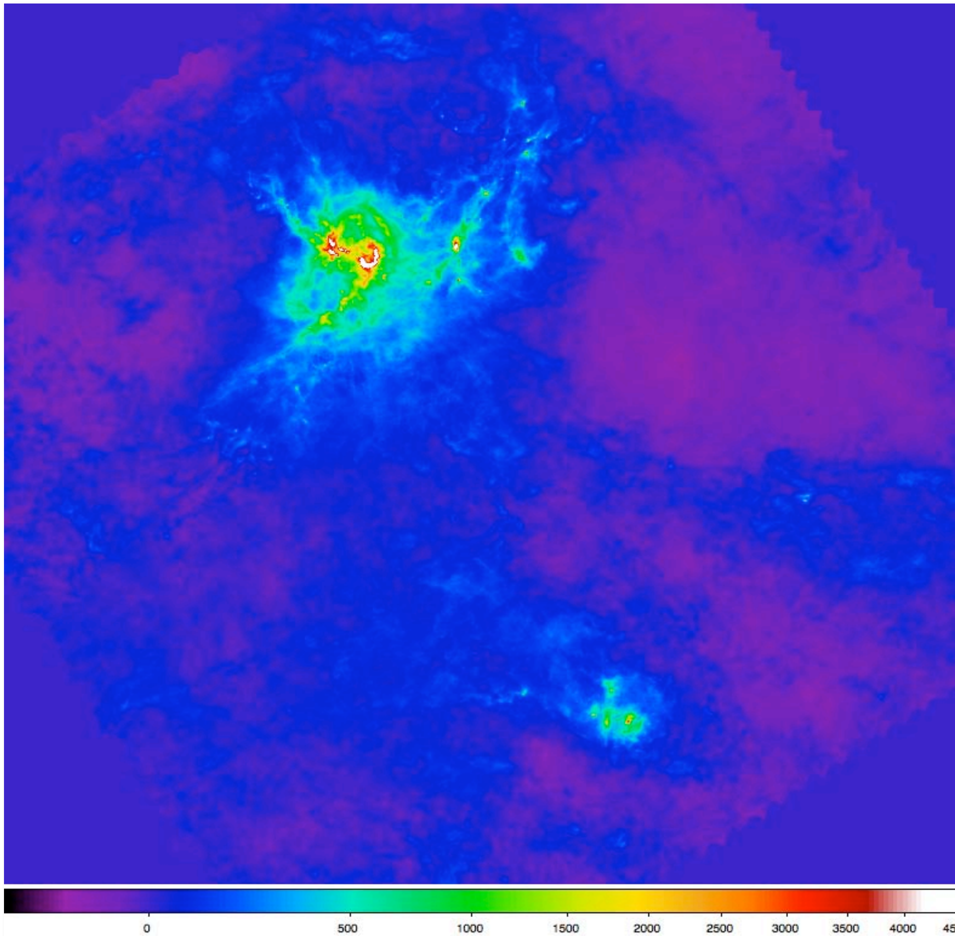


3.3°

3.3°

Aquila and Polaris: SPIRE 250 μm

resolution ~18"



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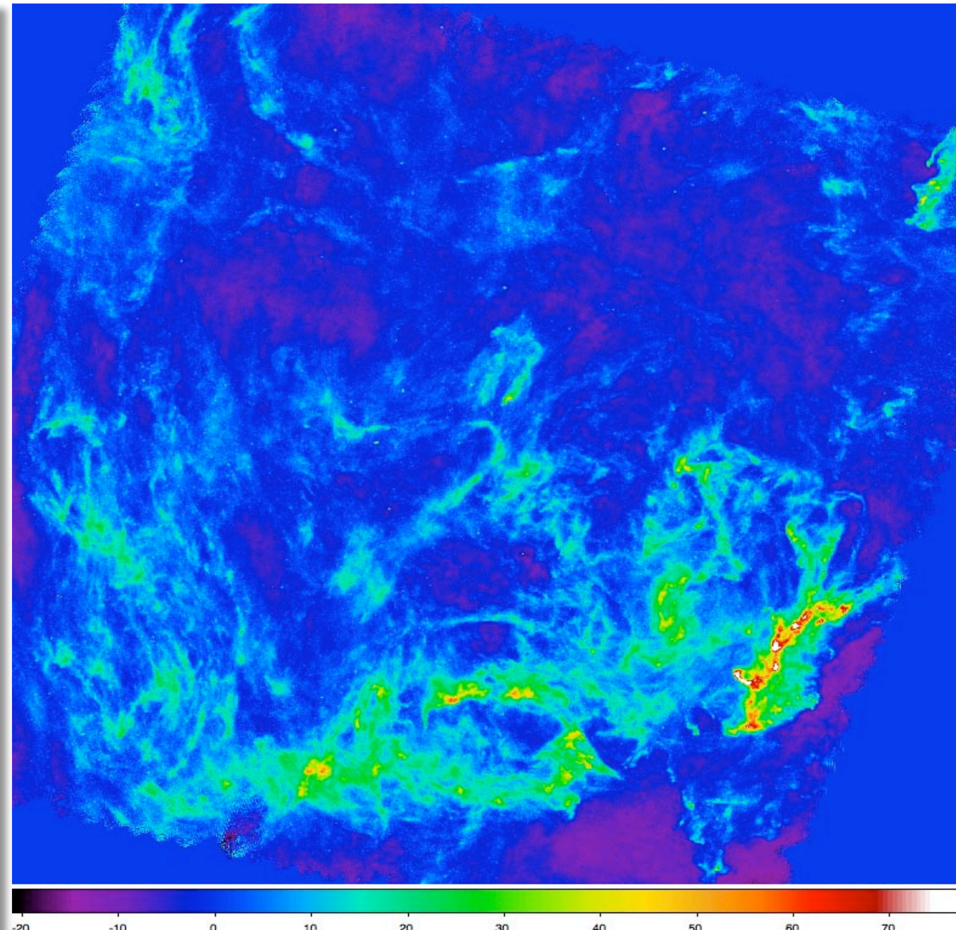

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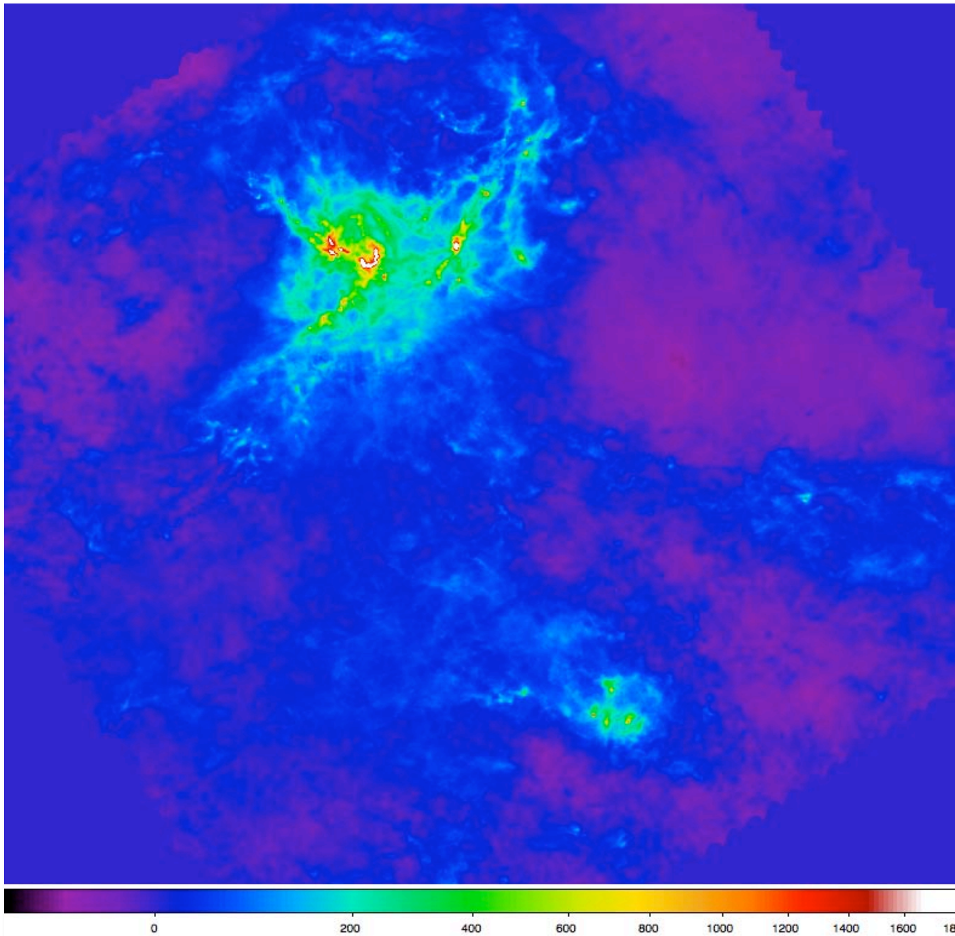
Aquila and Polaris: SPIRE 350 μm

resolution ~25”



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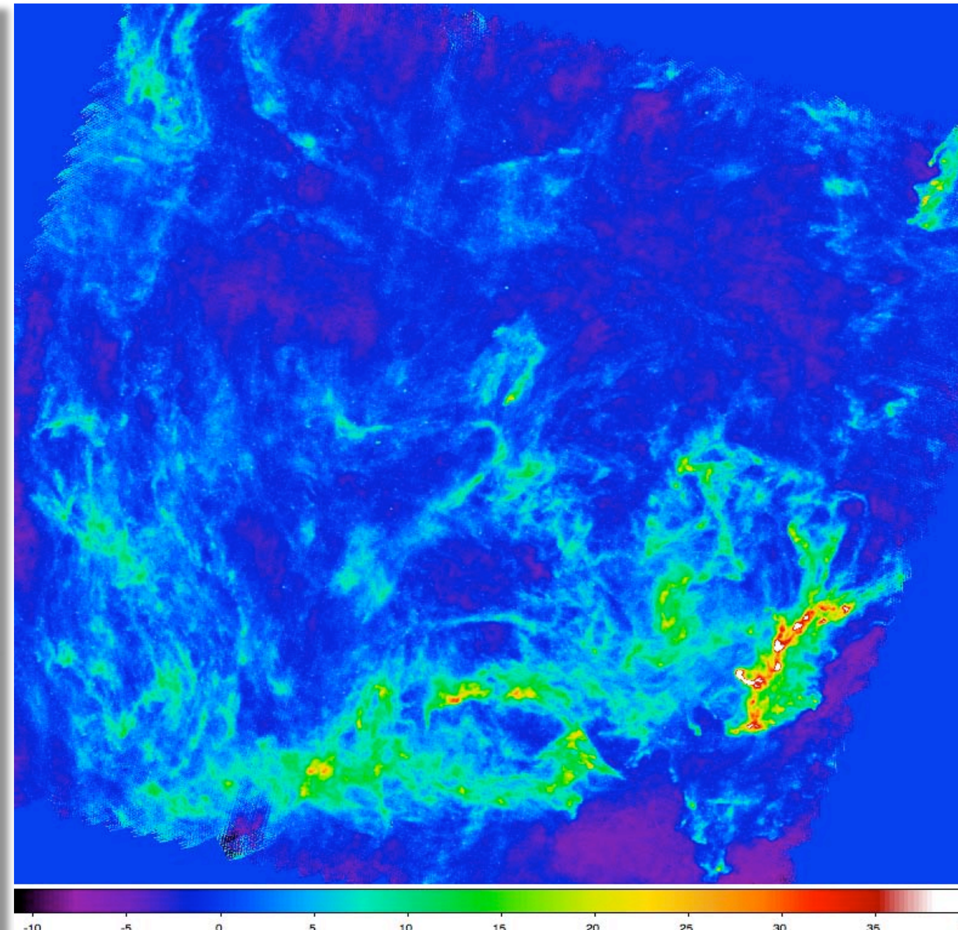

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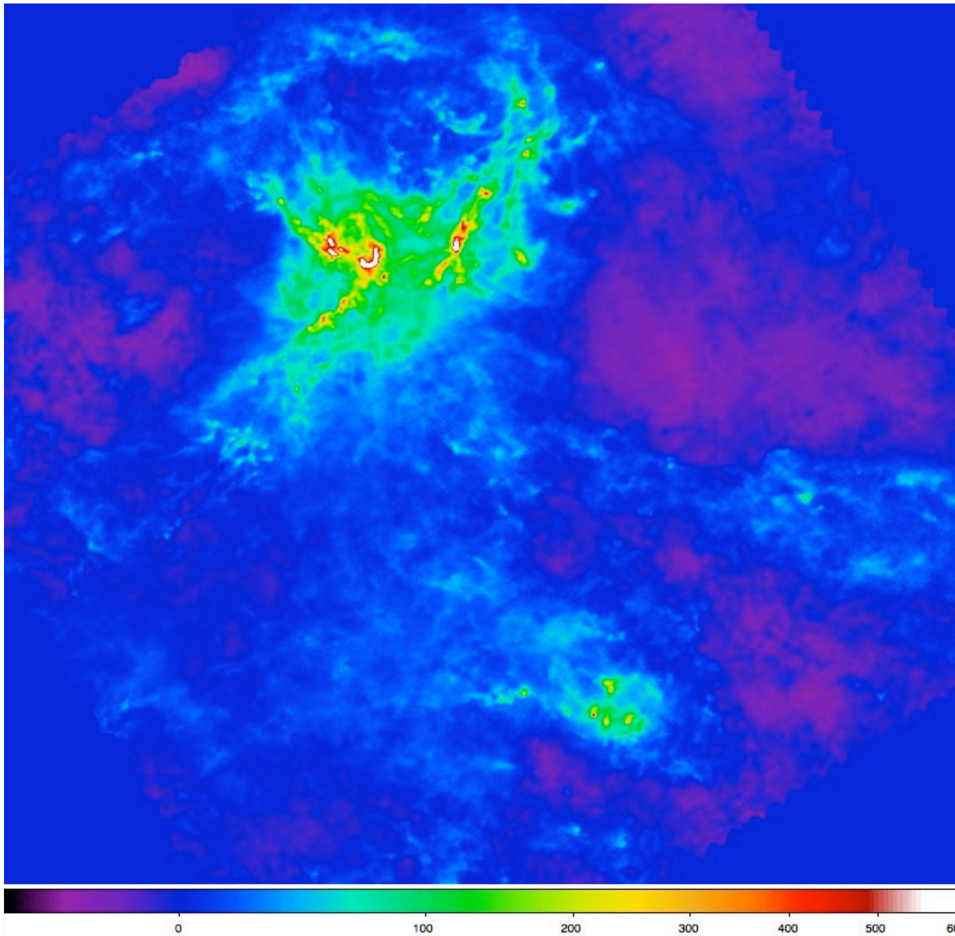
Aquila and Polaris: SPIRE 500 μm

resolution ~37”



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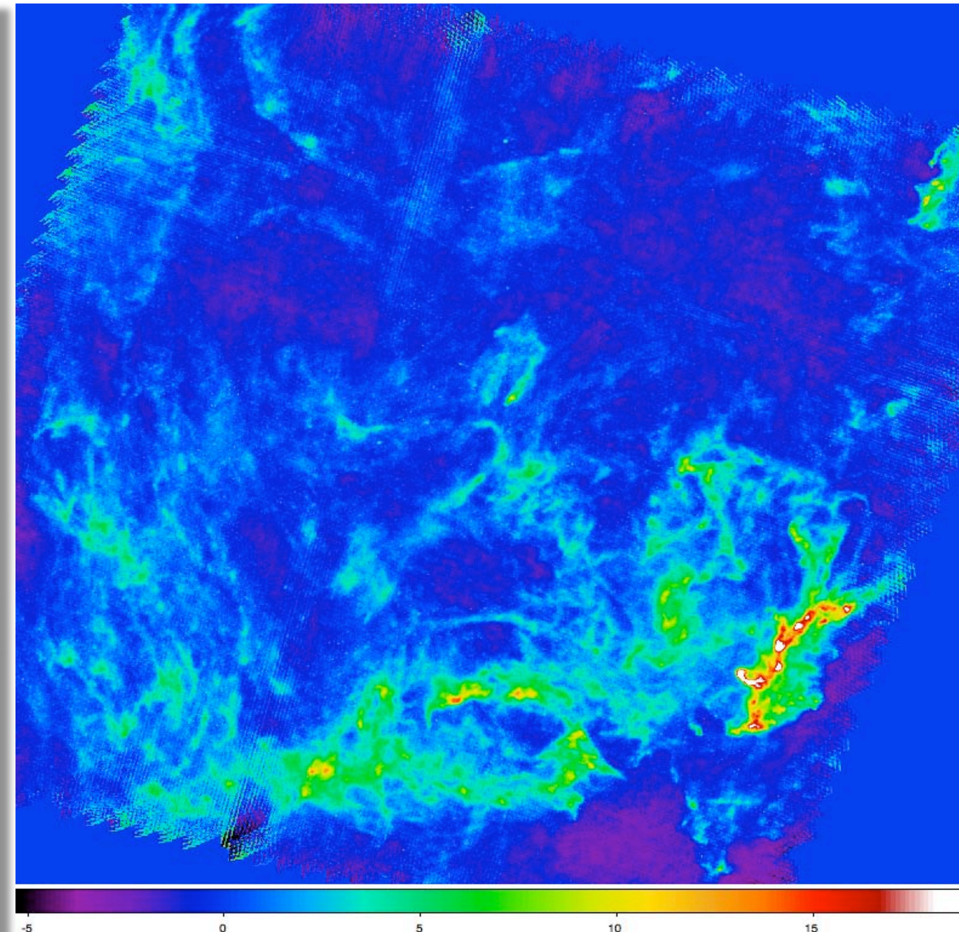

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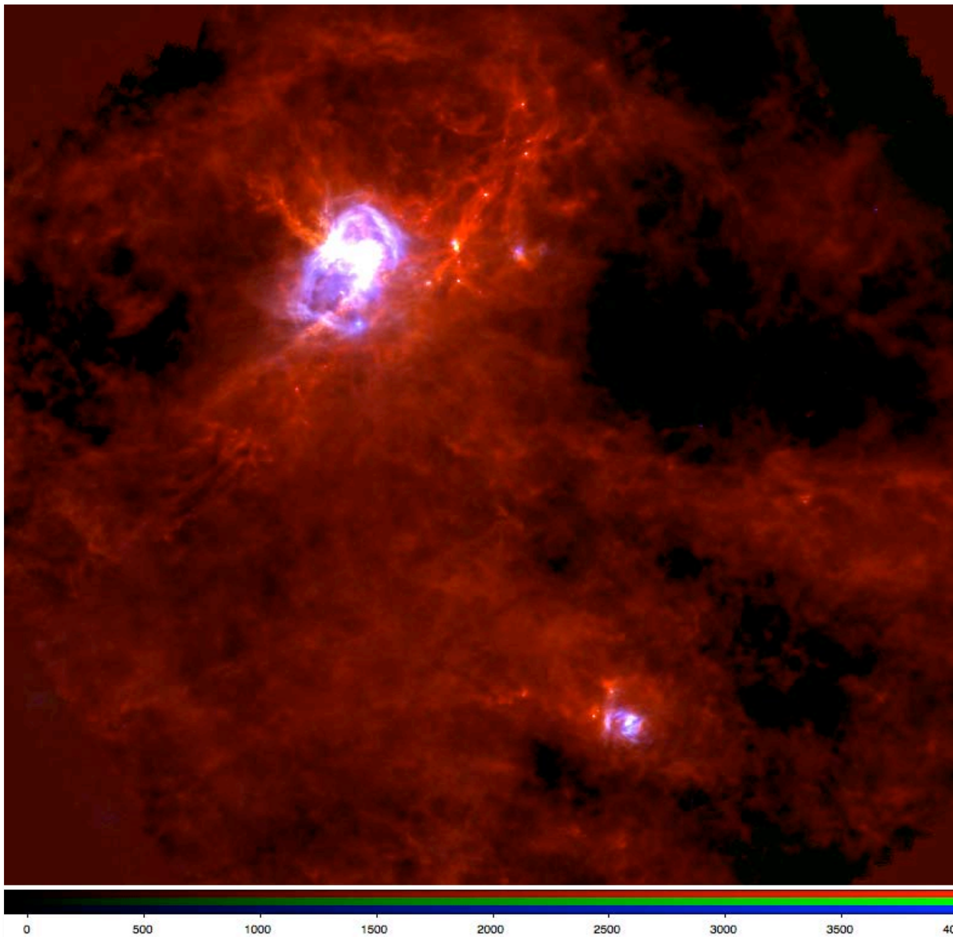
Aquila and Polaris: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



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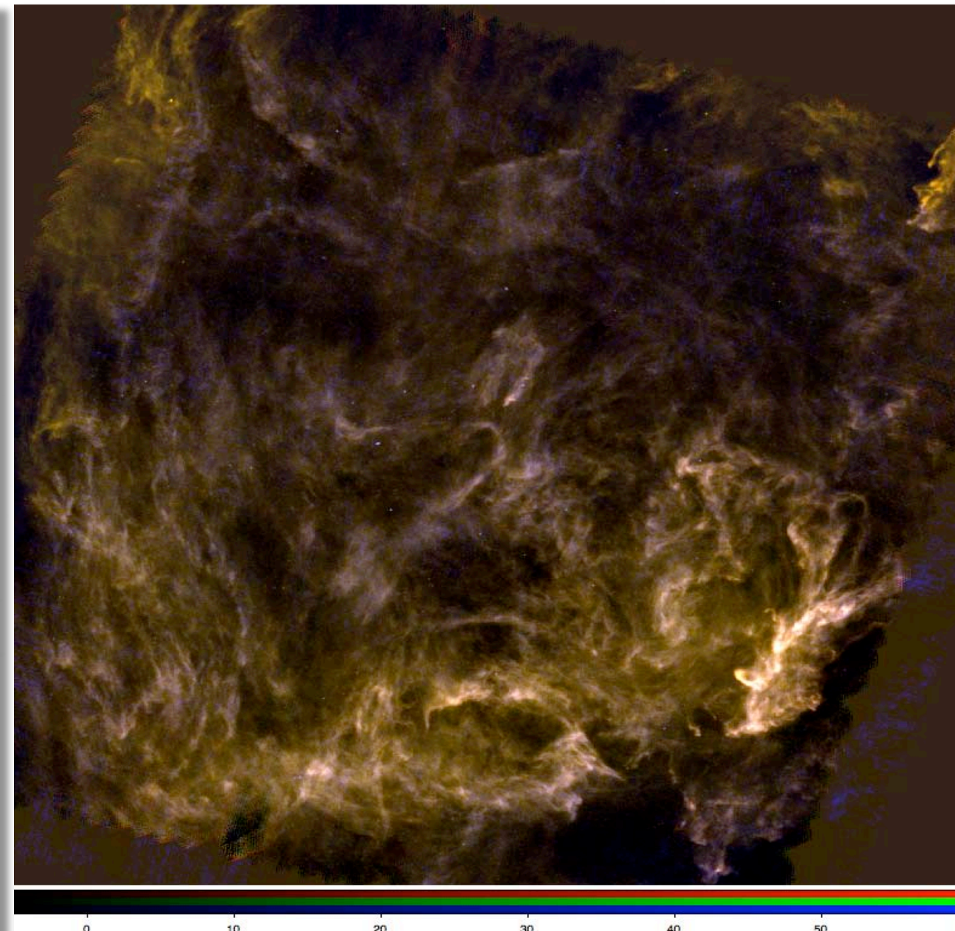

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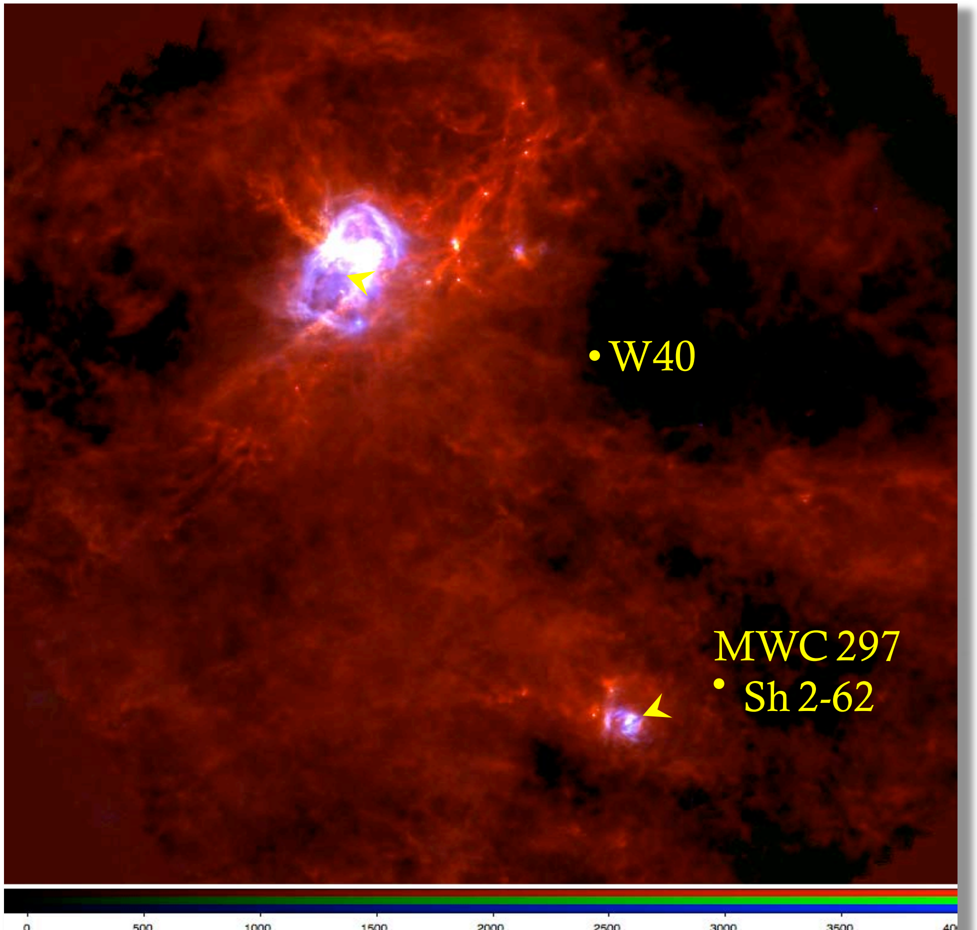
Aquila and Polaris: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



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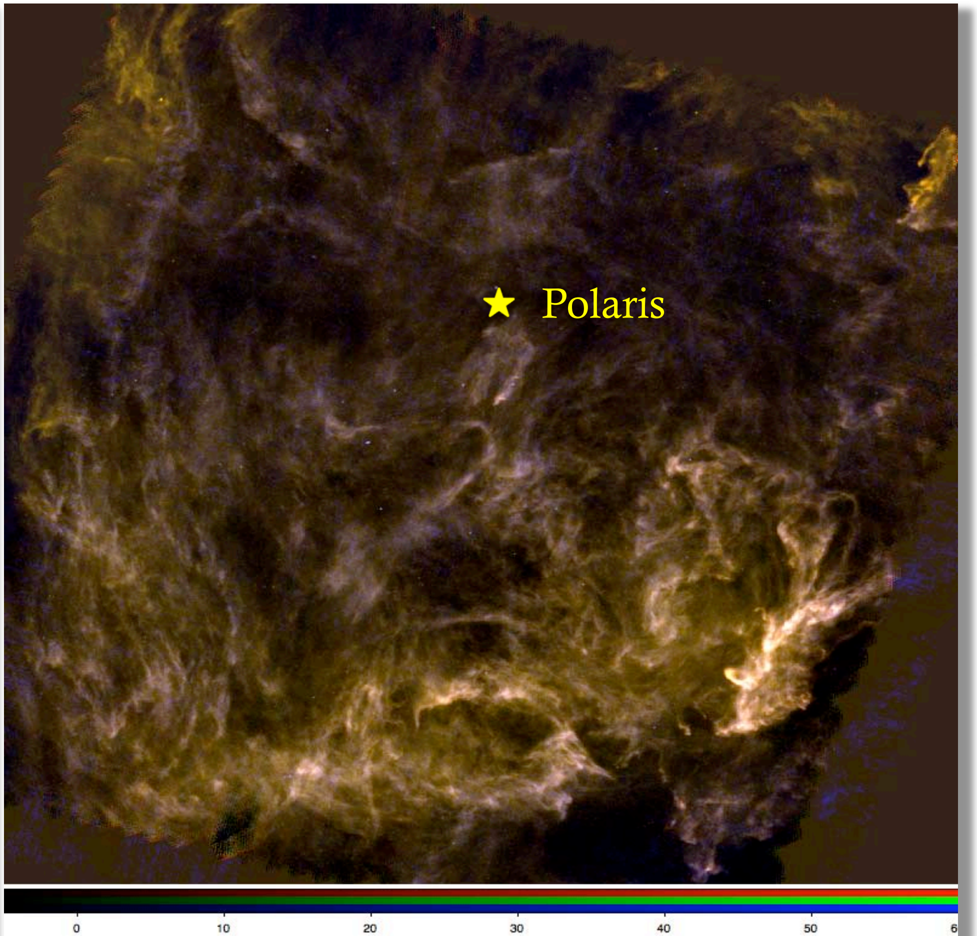

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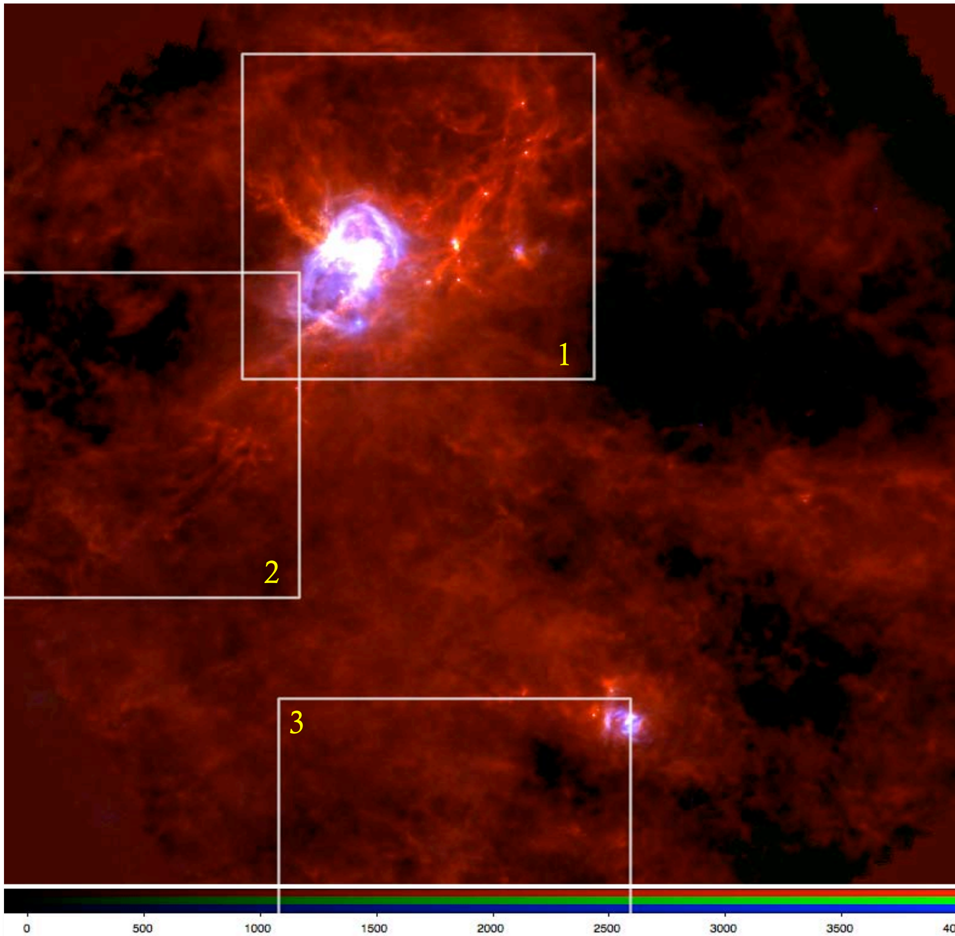
Aquila and Polaris: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



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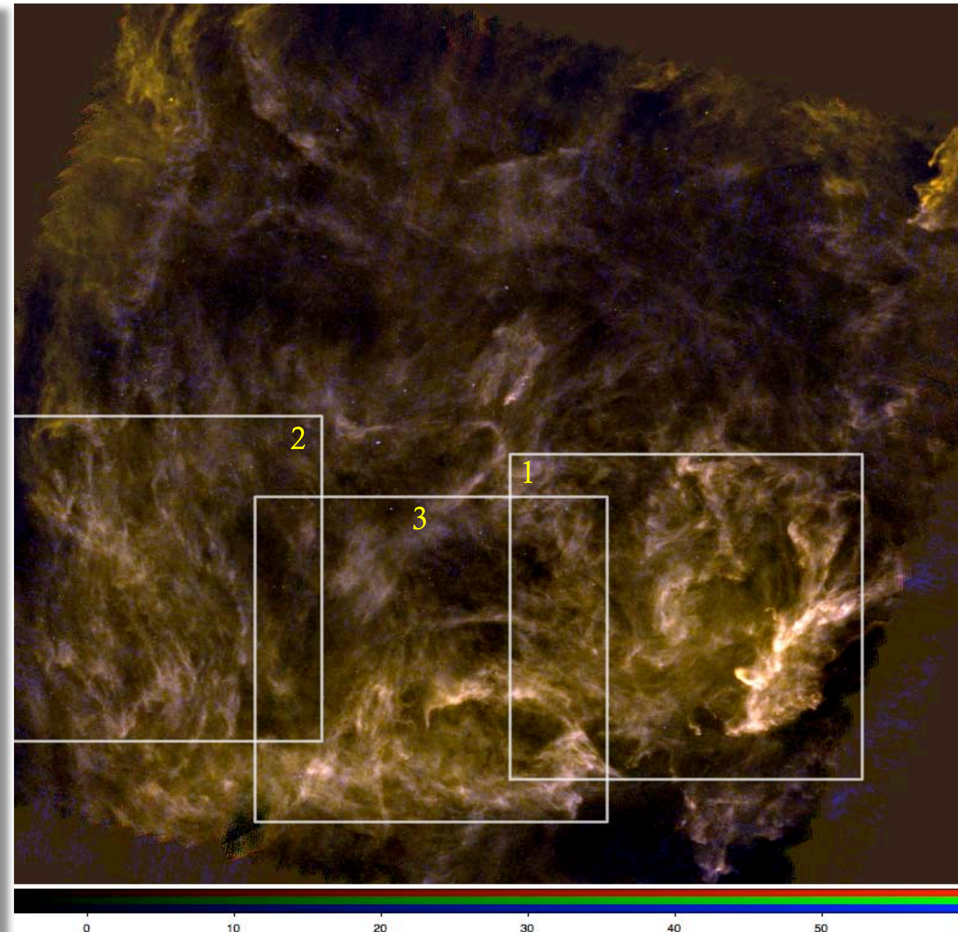


3.3°

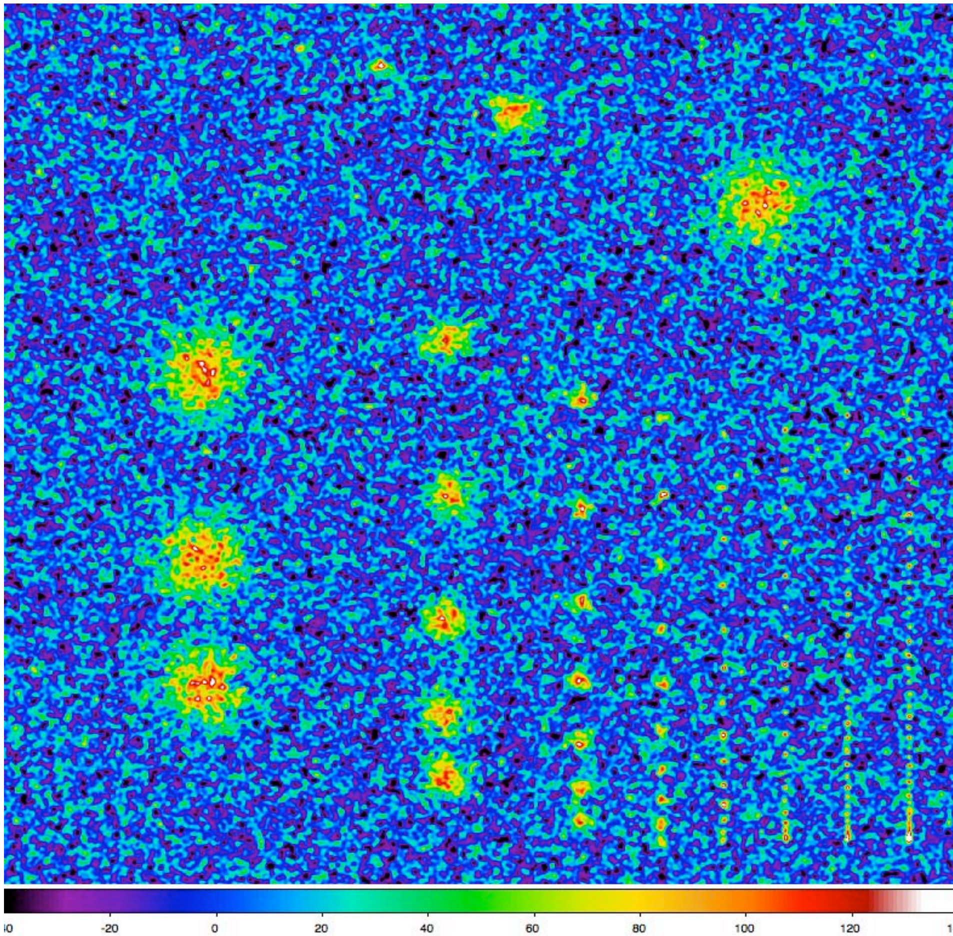
Extracting Sources

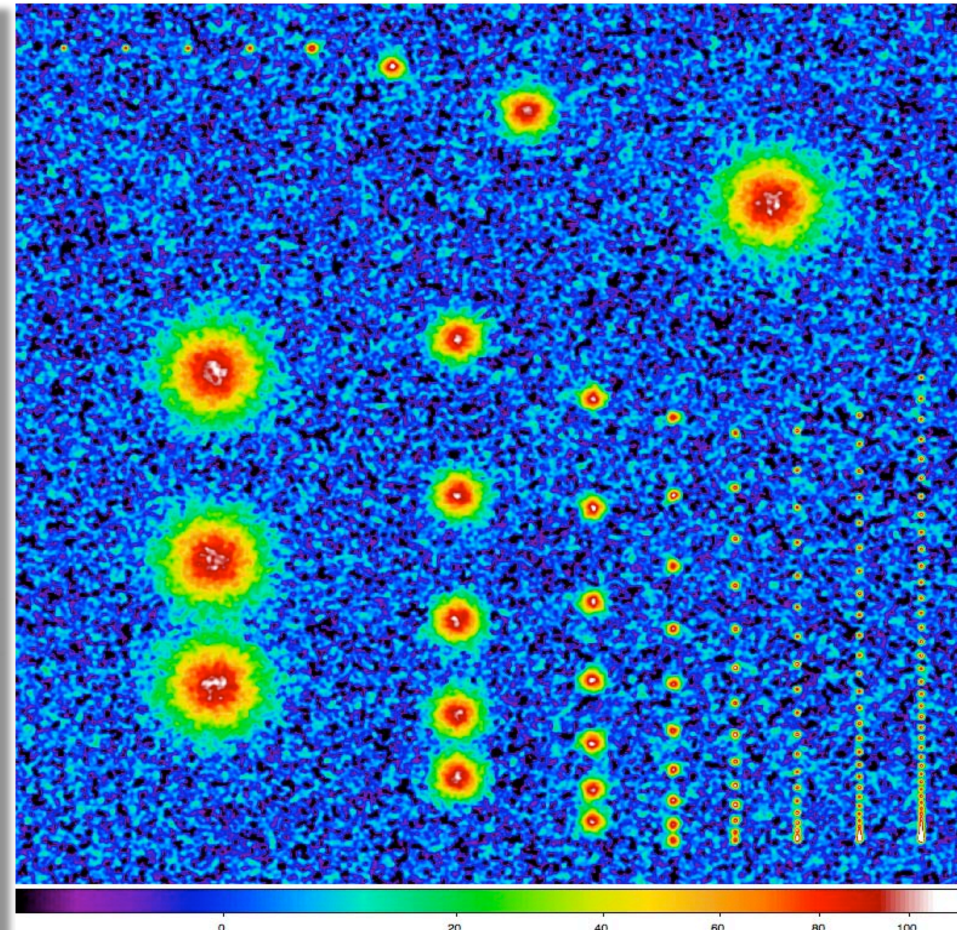
Multi-Scale, Multi-Wavelength Extraction

- New method and code *getsources* developed and used at CEA Saclay
  - No *multi-wavelength* extraction techniques existed for our *Herschel* projects
  - Must use higher resolution or sensitivity information across wavelengths
- Extensively verified at each step of its development
  - Multiple test images, simulated star-forming regions for *Herschel*
  - Star-forming regions NGC 2264, NGC 2068, W 43, Cyg X
- Benchmarked for the Gould Belt consortium, along with several other algorithms using simulated skies of various degree of complexity
  - *gaussclumps* (Stutzki & Guesten 1990)
  - *sextractor* (Bertin & Arnouts 1996)
  - *derivatives* (Molinari et al. 2010)
  - *reinhold* (CUPID software)
  - *clumpfind* (Williams et al. 1994)
  - *mre-gcl* (Motte et al. 2007)
  - *csar* (J. Kirk, private comm.)
  - *fellwalker* (CUPID software)

Benchmark 1: Simple Images

139 objects at 250 μm: effects of S/N, sizes, and separation



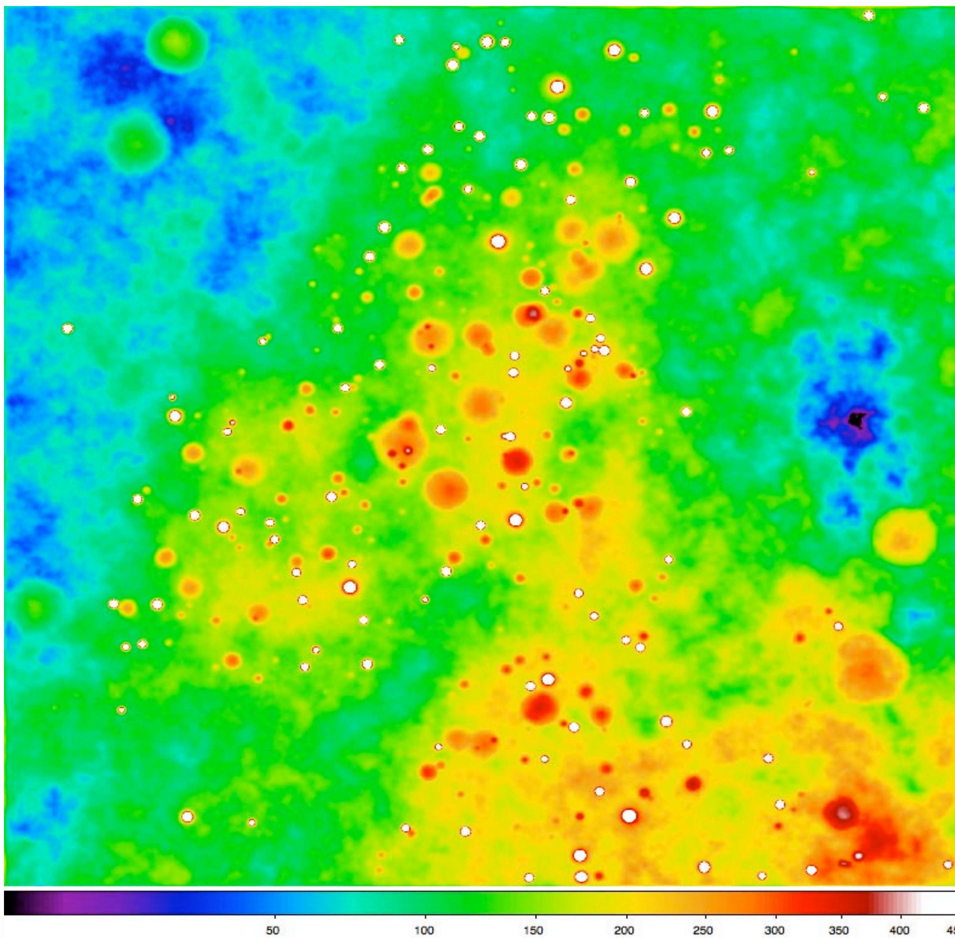


S/N = 5 1.0°

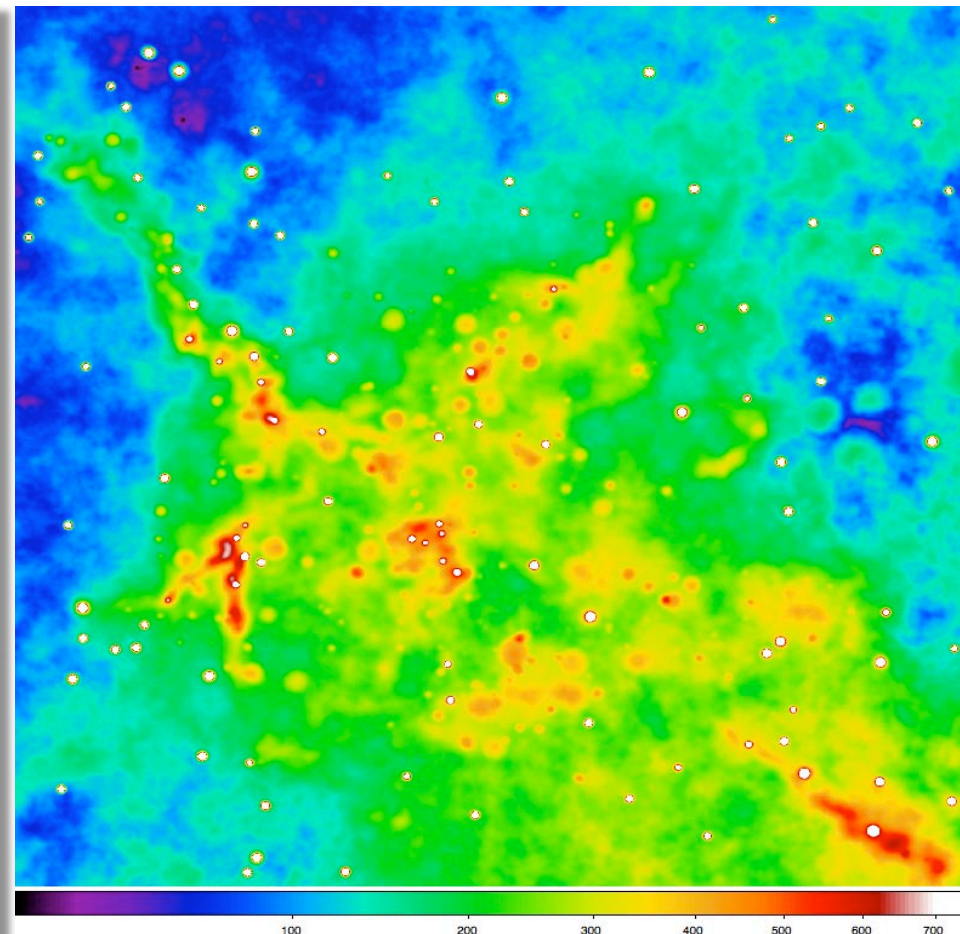
1.0° S/N = 20

Benchmarks 2 and 3: All *Herschel* Bands

350 cores and 100 protostars, shown at 350 μm



1.0°



background: Bate, Bonnell, & Bromm (2003)

Outline of the *getsources* Algorithm

- Cleaning: original observed images at each wavelength λ
  - Create a set of filtered "*single scales*" separated by a factor of ~1.05

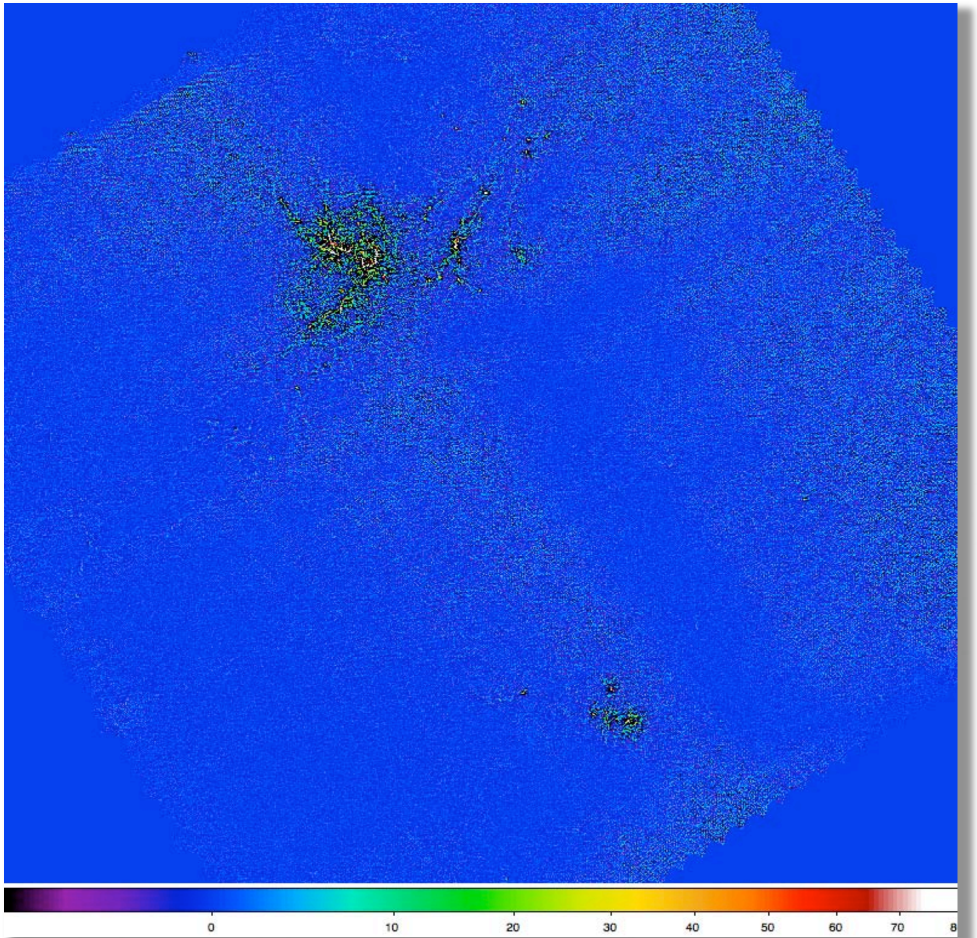
    successive unsharp masking: $I_j(\lambda) = G_{j-1} * I(\lambda) - G_j * I(\lambda), \quad j = 1, 2, \ldots, N$
  - Clean each of those scales of noise/background by iterating to $5\sigma_\lambda$ cut-offs
  - Re-normalize clean scales, sum up over all λ into *combined* detection images

- Detection: combined single-scale detection images, independent of λ
  - Track objects' appearance, "evolution", and disappearance: small to large scales
  - Find objects' positions, S/N, characteristic scales, and footprints

- Measurements: original observed images at each λ
  - Subtract background under the footprints and deblend overlapping objects
  - Measure their fluxes, sizes, and intensity profiles at each wavelength

Aquila and Polaris: SPIRE at 250 μm

single scale ~10”



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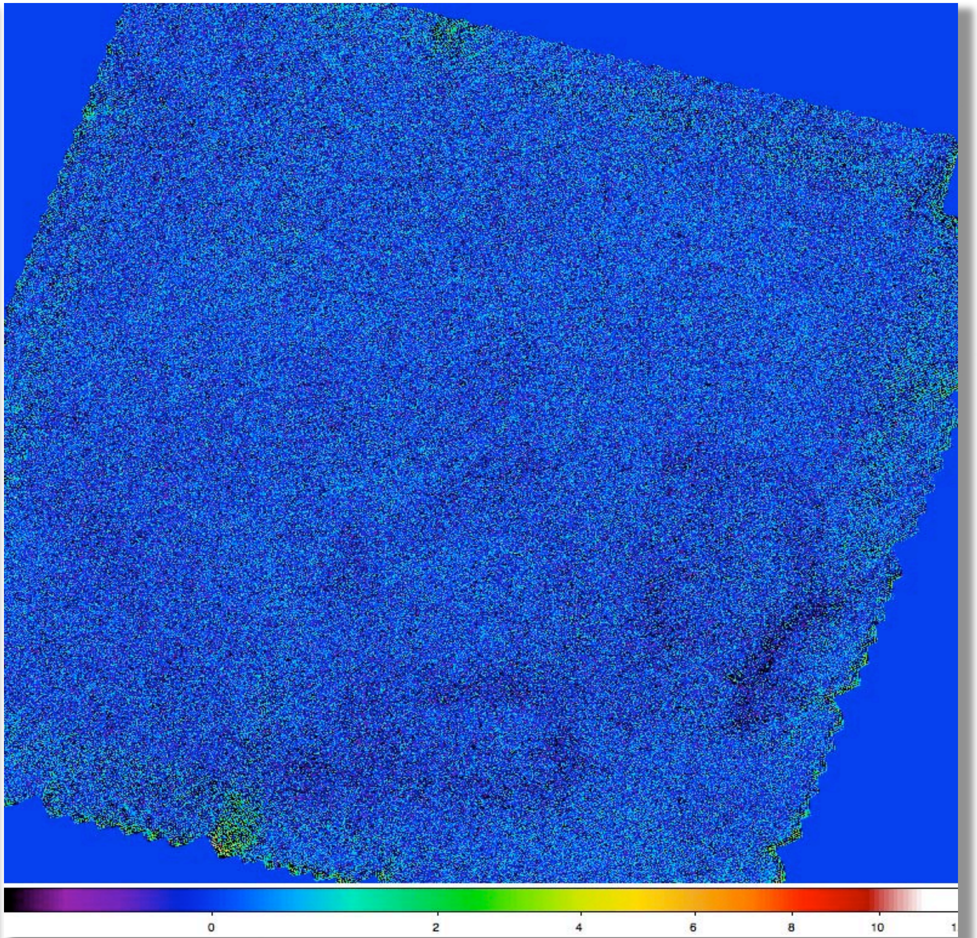
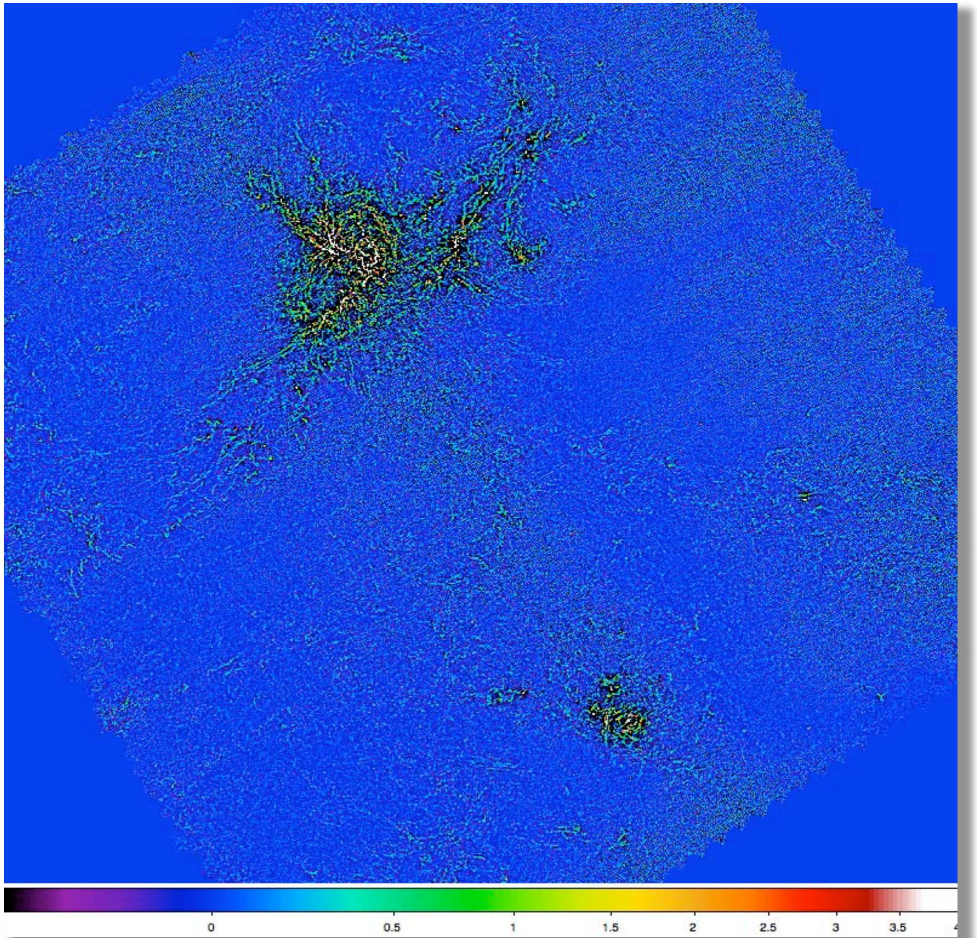


3.3°

Aquila and Polaris: SPIRE at 250 μm
single scale ~20"



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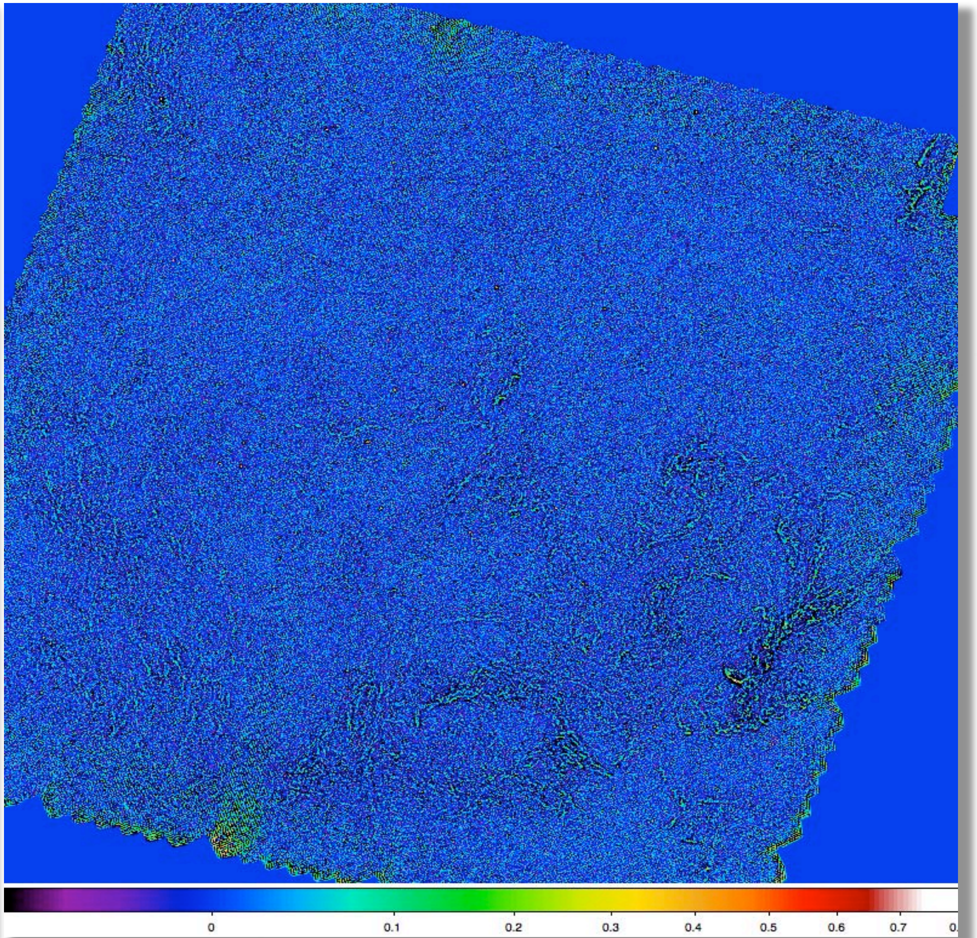
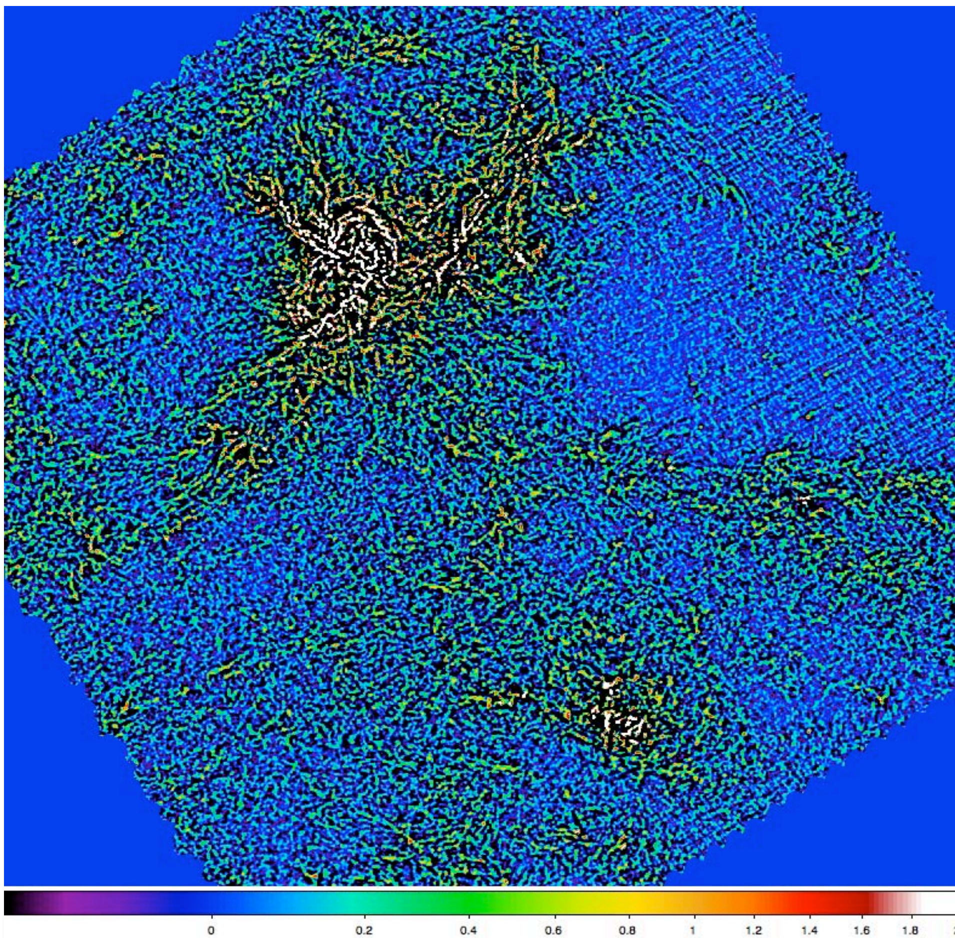


3.3°

Aquila and Polaris: SPIRE at 250 μm

single scale ~40”



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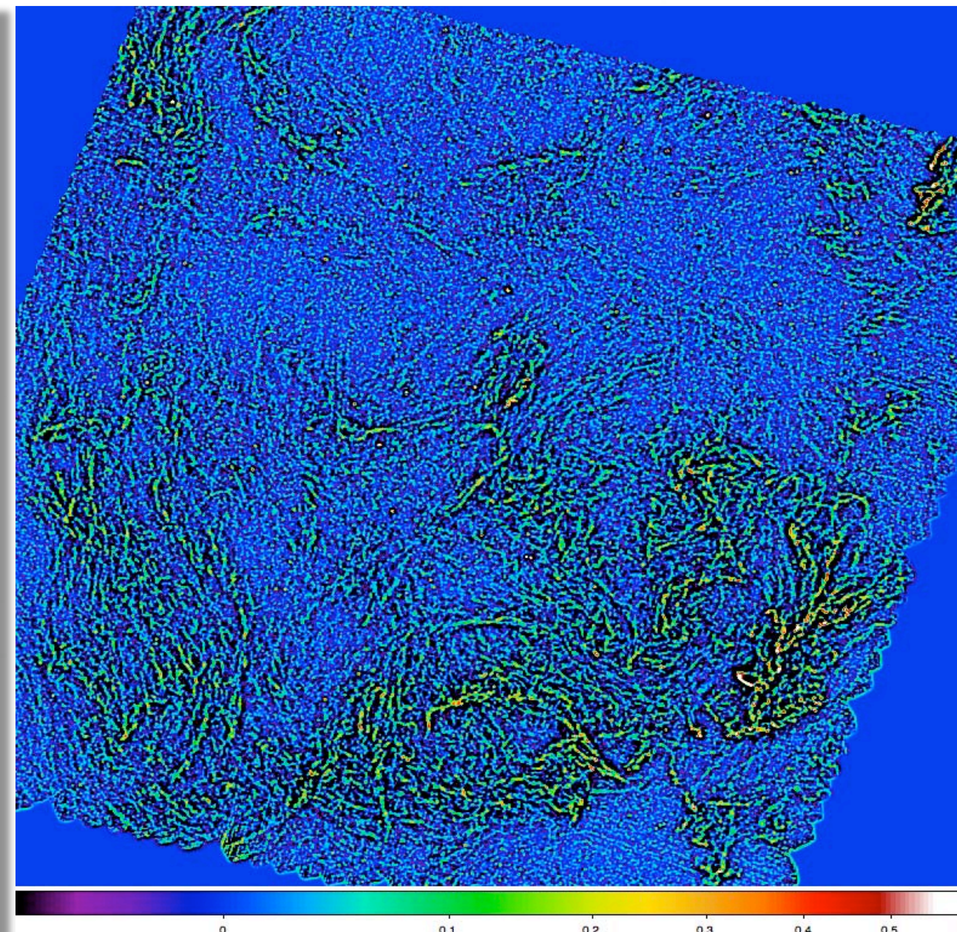
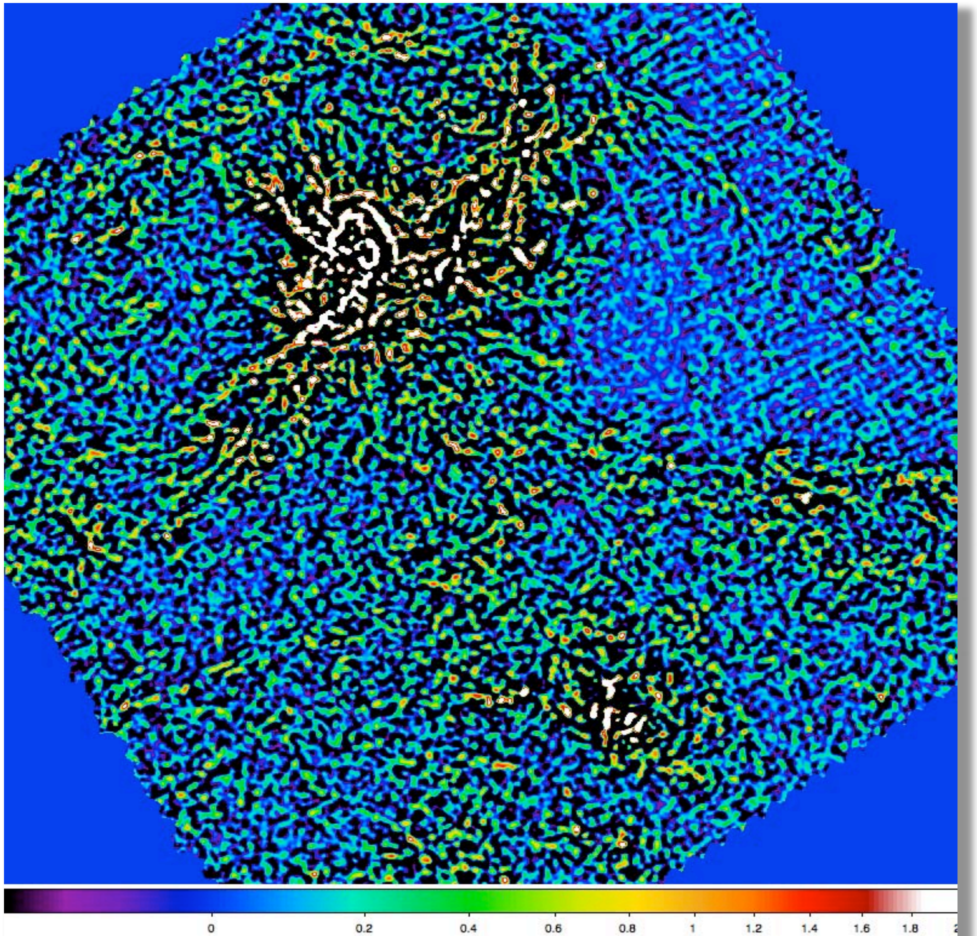


3.3°

Aquila and Polaris: SPIRE at 250 μm

single scale ~80”



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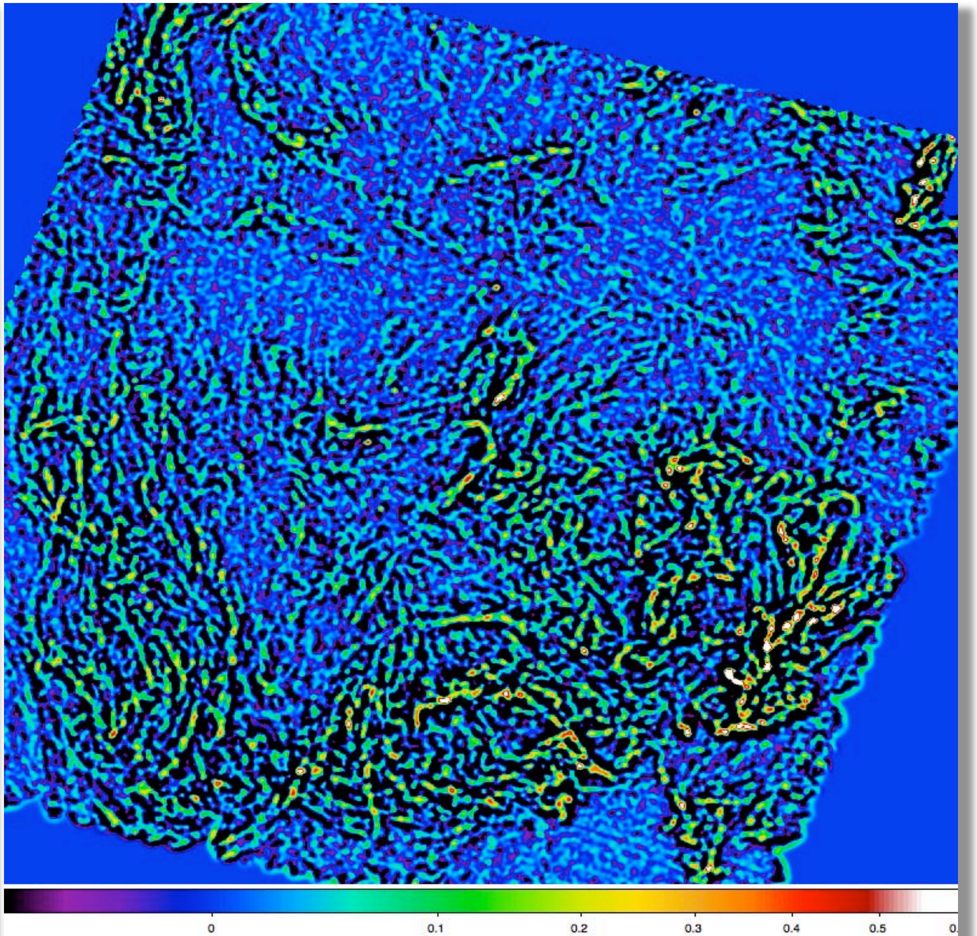
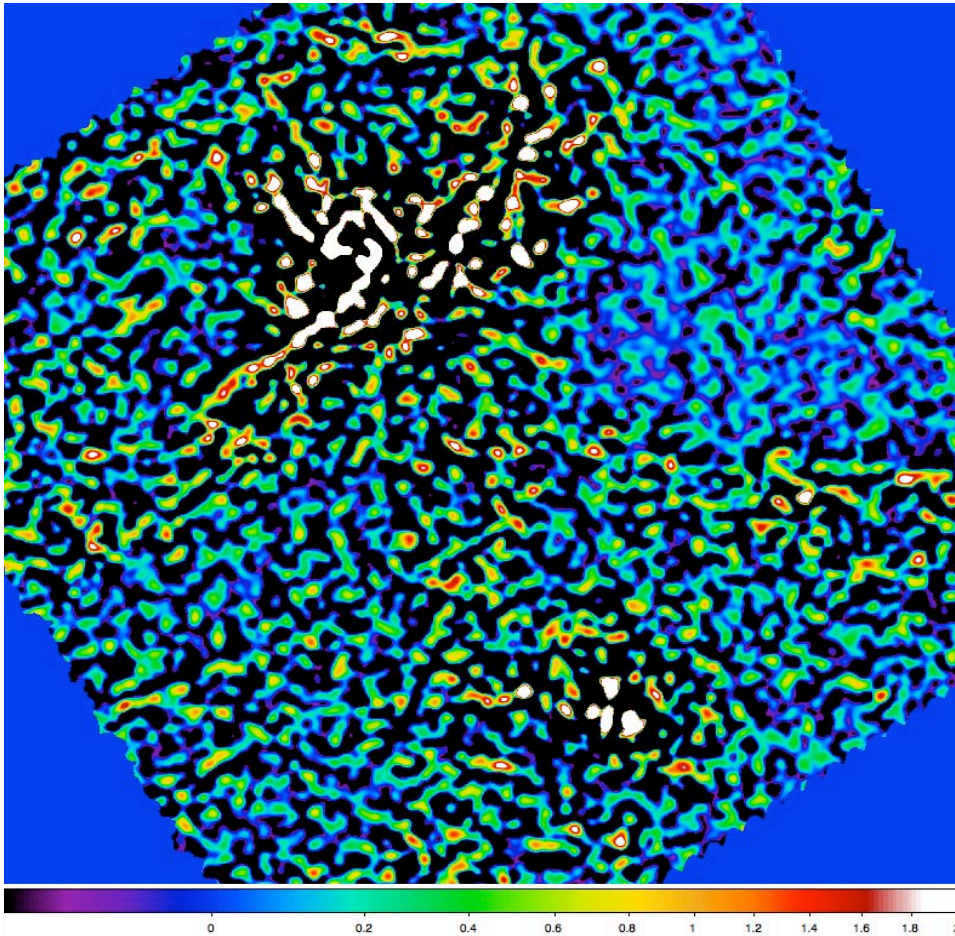


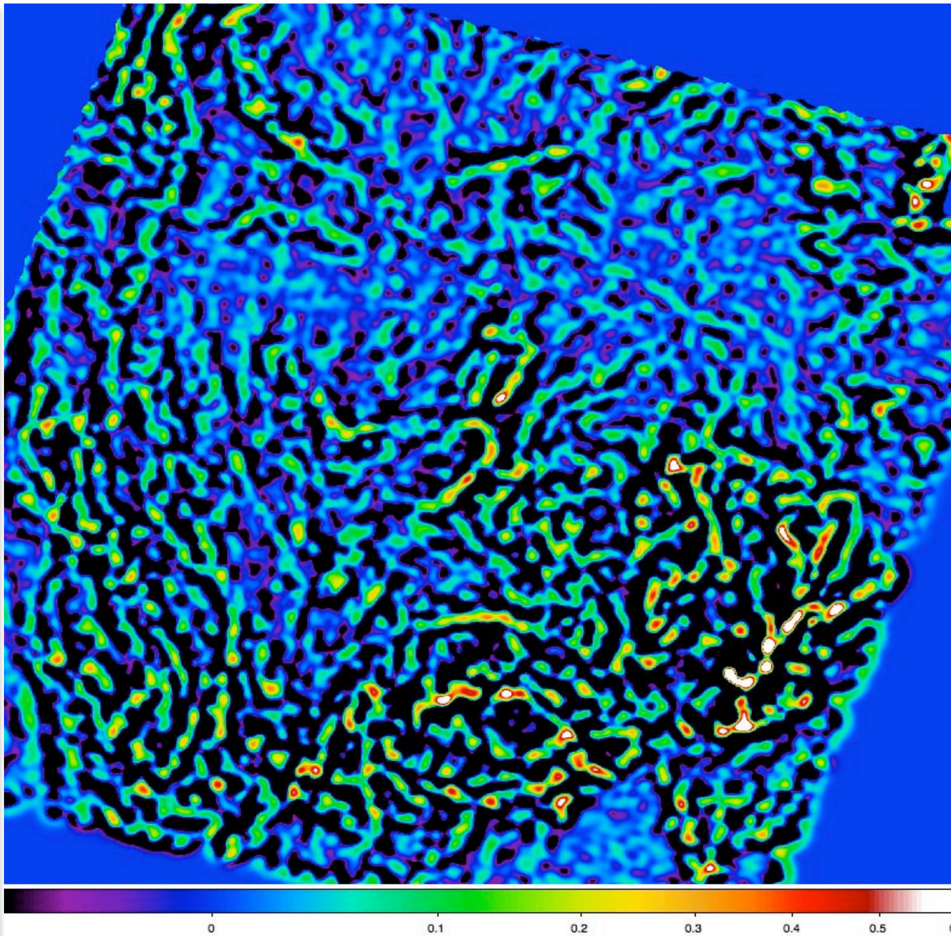
3.3°

Aquila and Polaris: SPIRE at 250 μm

single scale ~160”



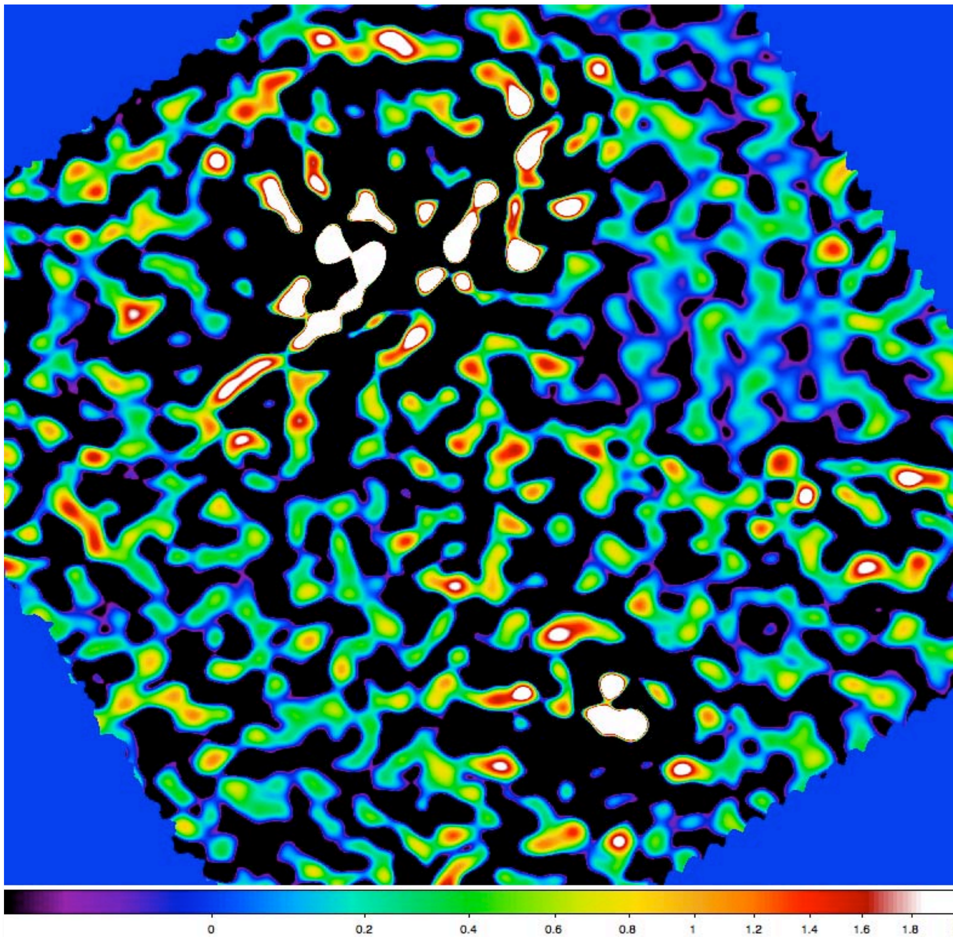
3.3°



3.3°

Aquila and Polaris: SPIRE at 250 μm

single scale ~320”



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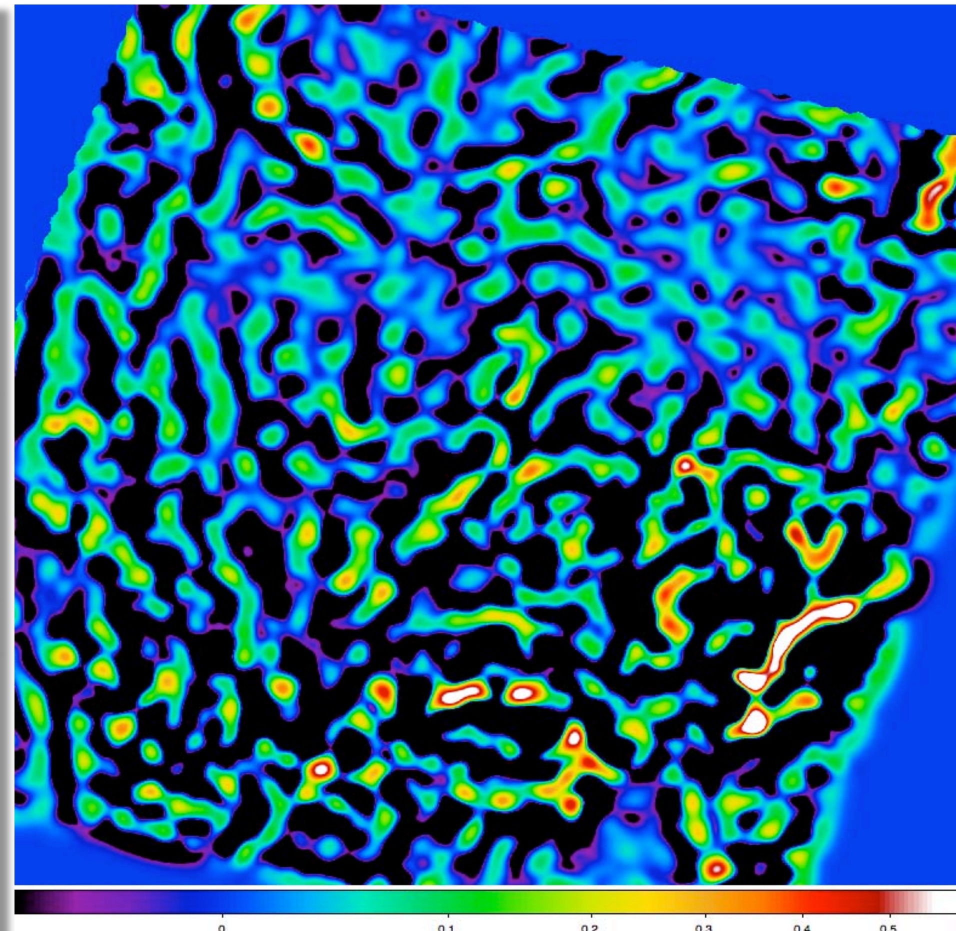
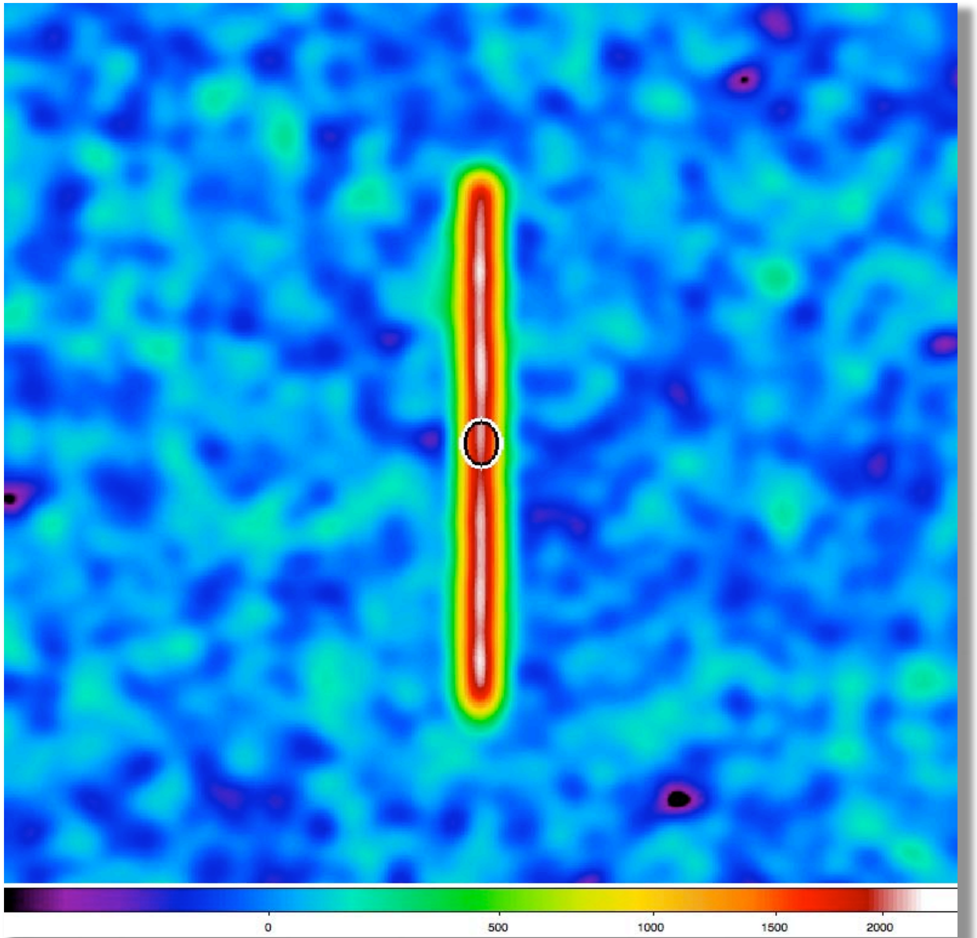


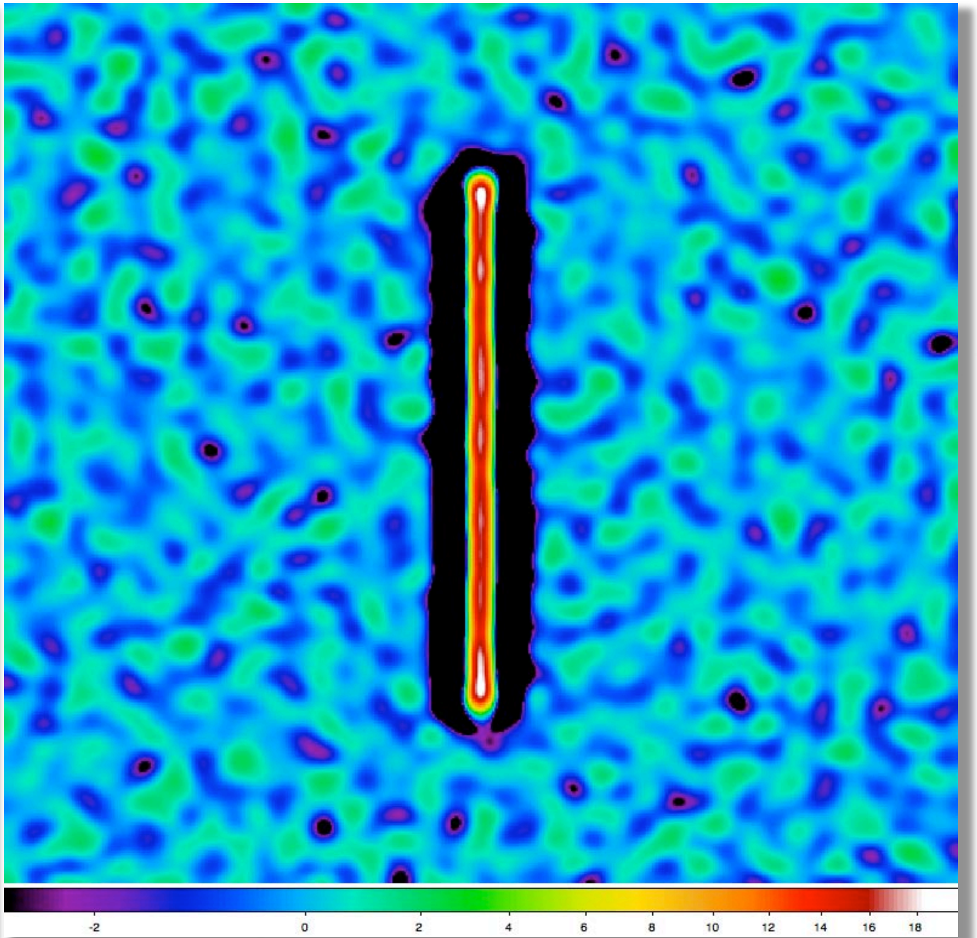
3.3°

Example of Test "Filaments": Cylinder

getsources does *not* break uniform filaments



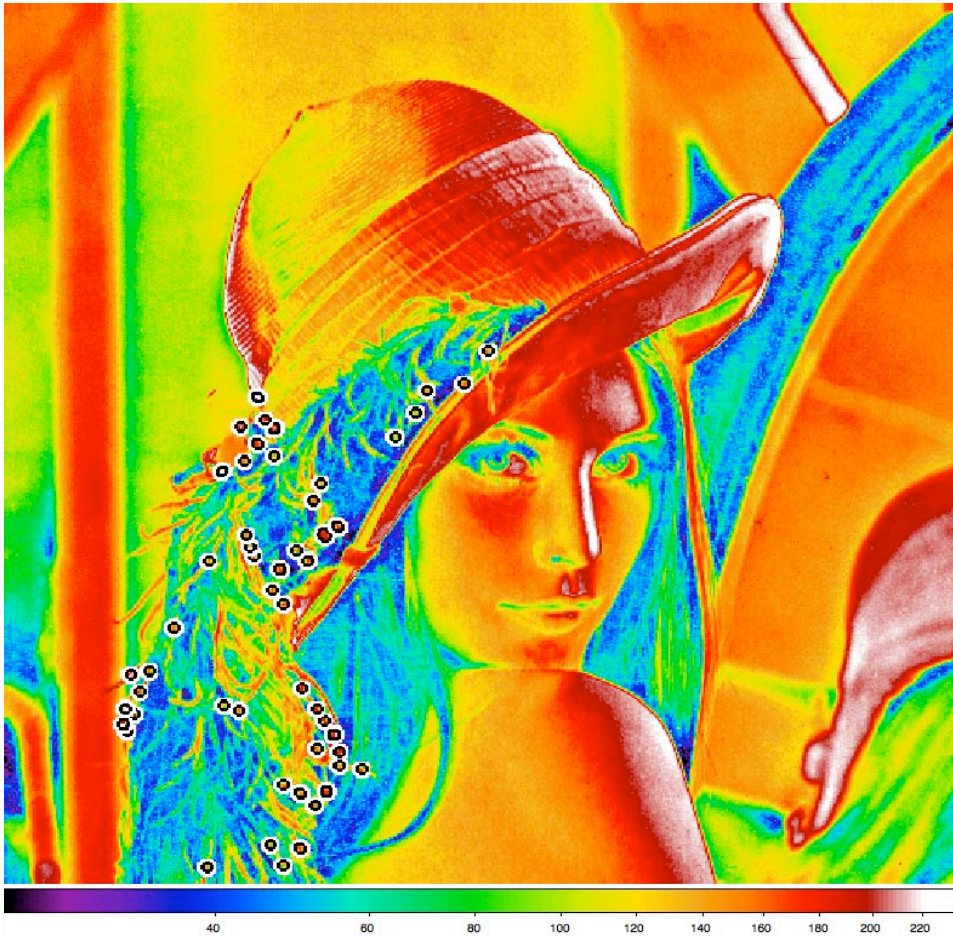
full image



single scale

Example of Test "Filaments": Lena

getsources finds significant peaks that *are present*



full image

single scale

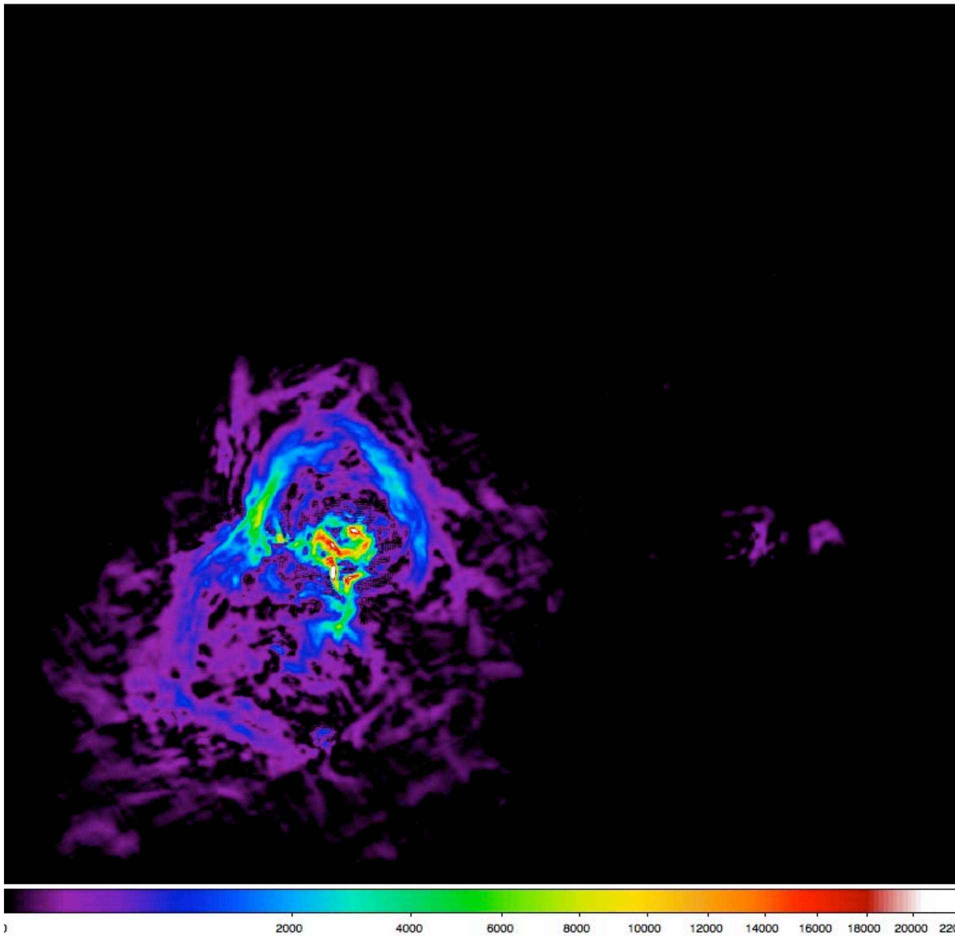
Extracting Filaments

Morphological Component Analysis

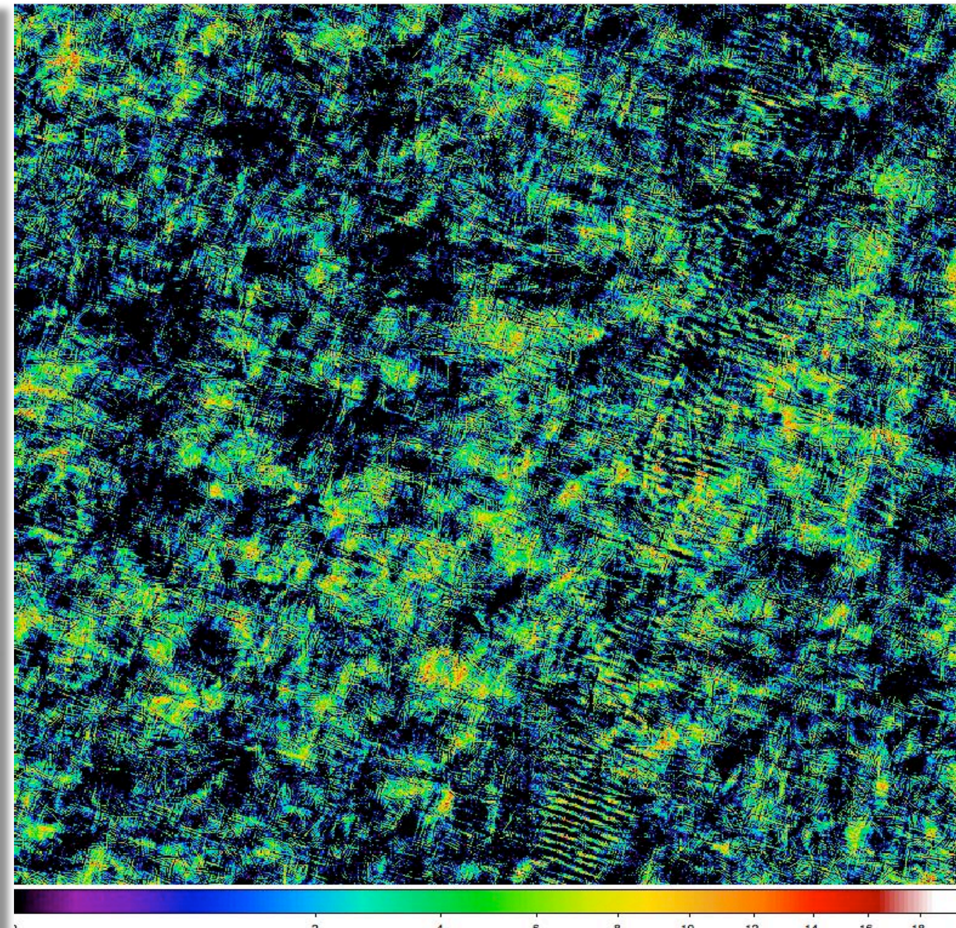
- The MCA method and code *cb_mca* developed by J.-L. Starck et al. (2004)
  - Decompose a signal into its morphological building blocks represented by the isotropic wavelets, ridgelets, or curvelets
- Applied the method to analyze large, complex *Herschel* images
  - Separate filamentary structures from the more isotropic structures
  - Decompose images alternating between the curvelet and wavelet transforms
  - Iterate until convergence in both wavelet and curvelet representations

Aquila and Polaris Sub-Fields 1: PACS 70 μm

curvelet components by *cb_mca*



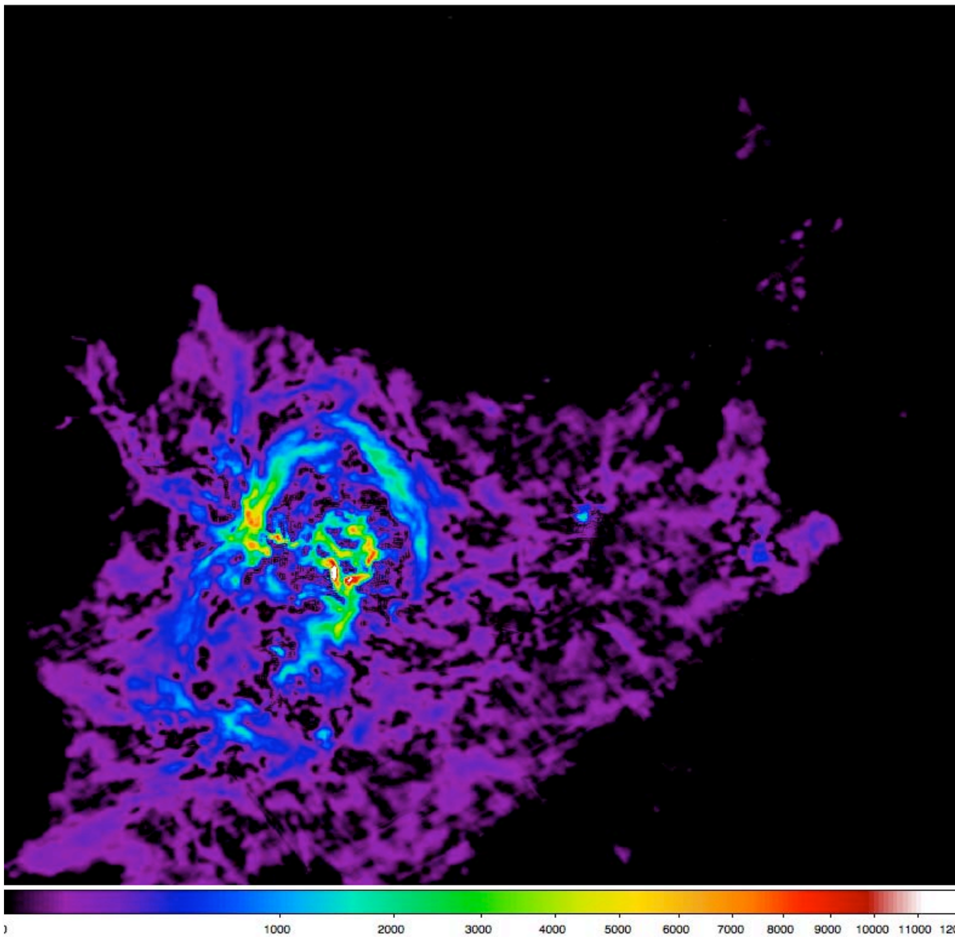
1.2°



1.2°

Aquila and Polaris Sub-Fields 1: PACS 160 μm

curvelet components by *cb_mca*



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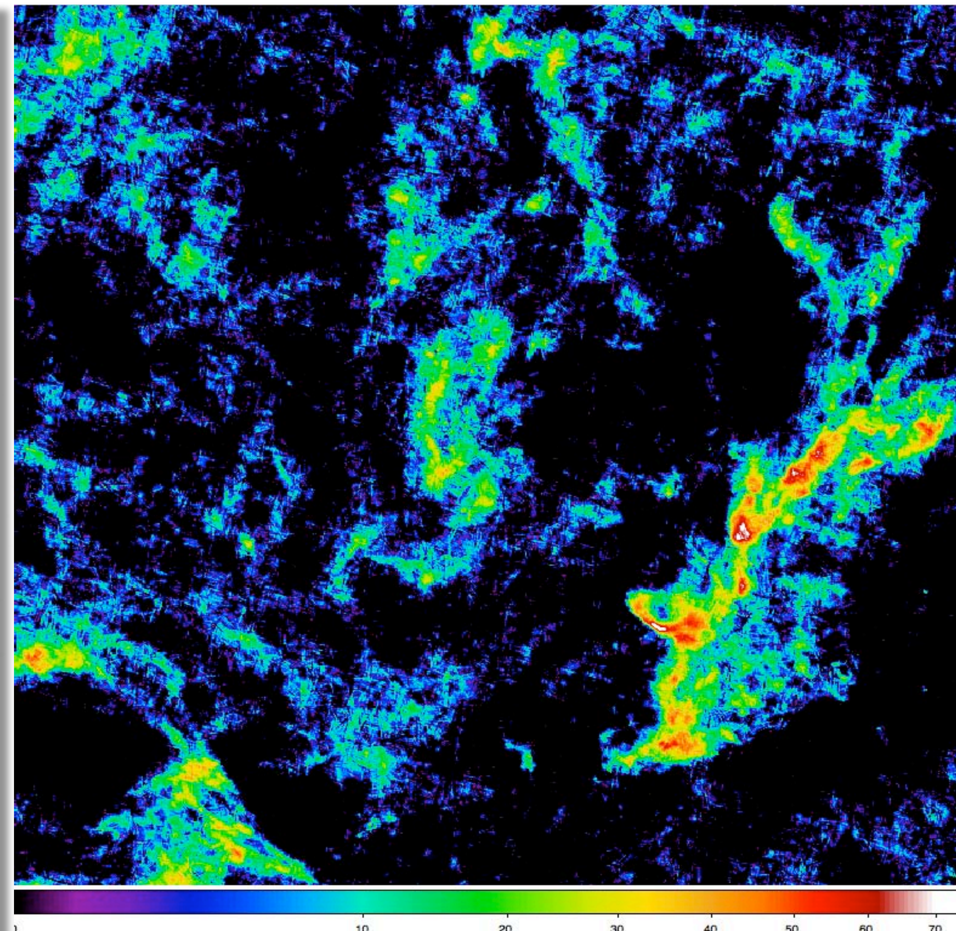
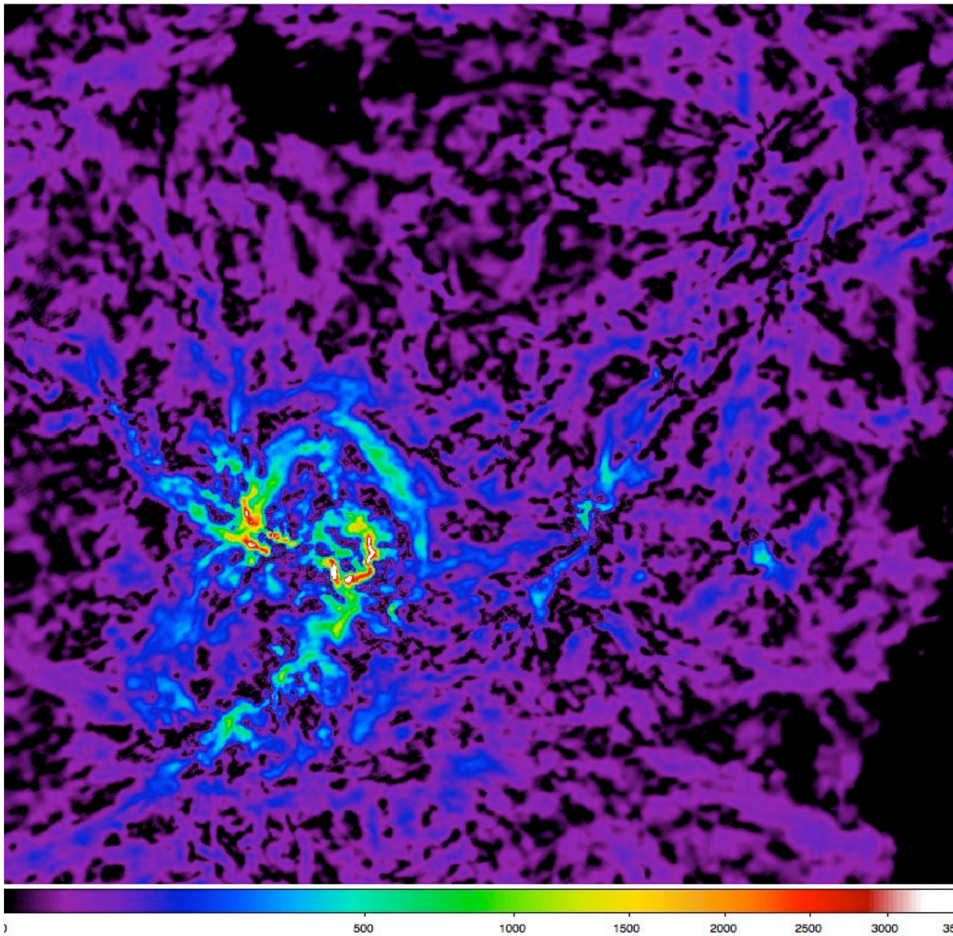


1.2°

Aquila and Polaris Sub-Fields 1: SPIRE 250 μm

curvelet components by *cb_mca*



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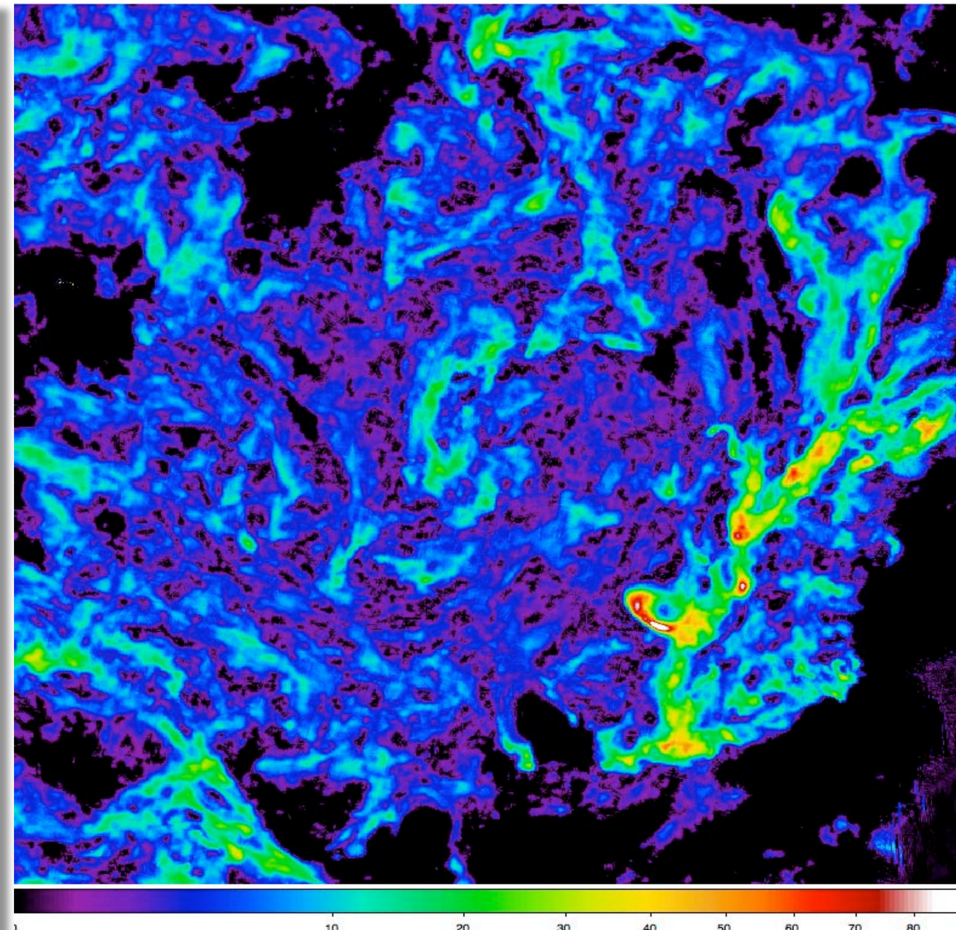
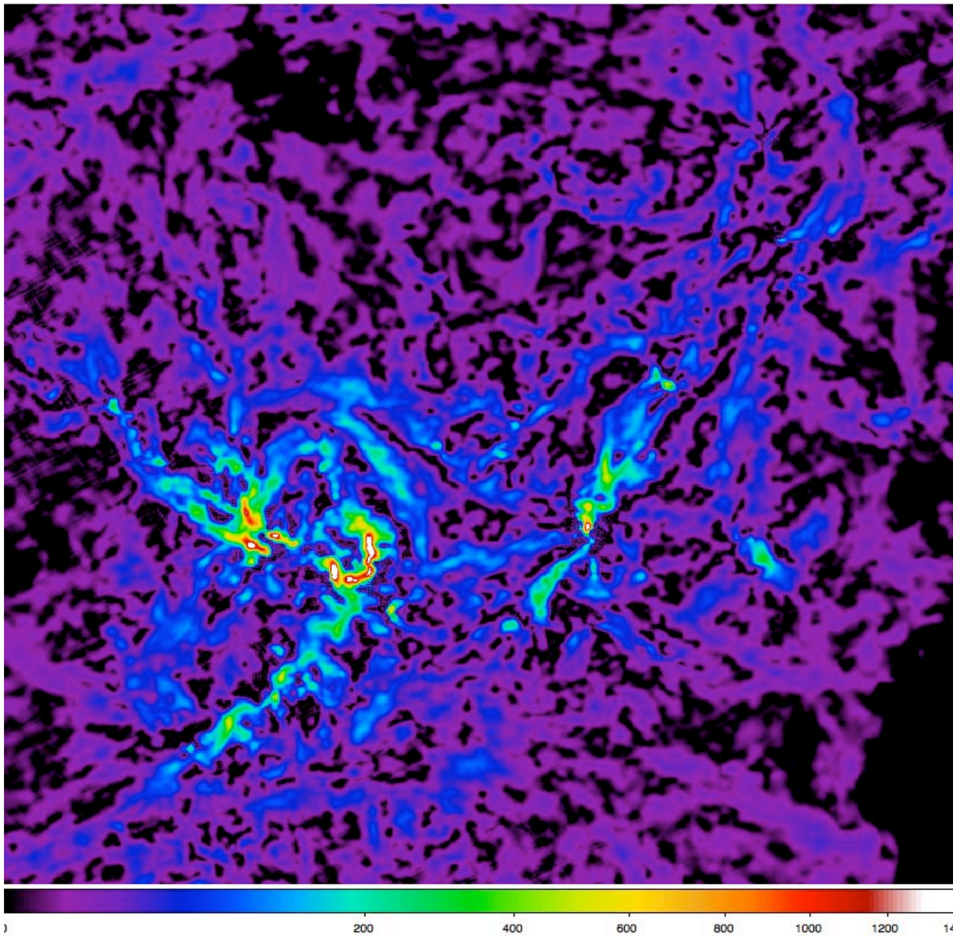


1.2°

Aquila and Polaris Sub-Fields 1: SPIRE 350 μm

curvelet components by *cb_mca*



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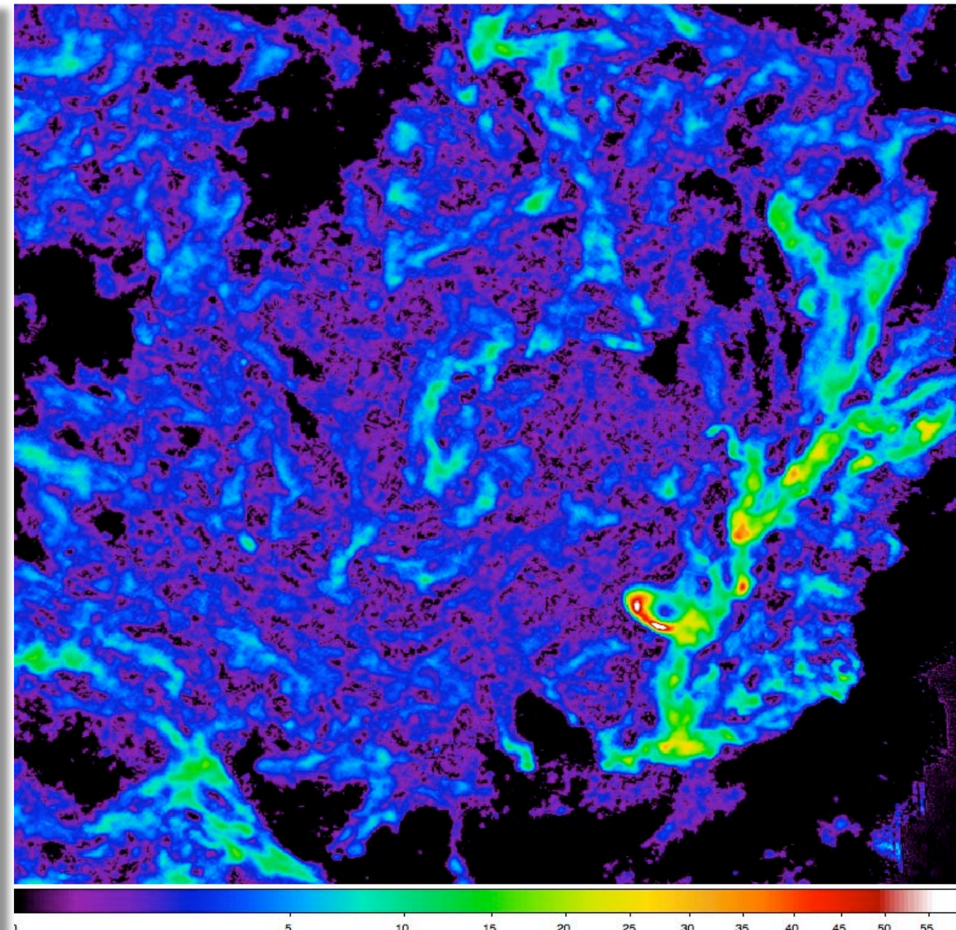
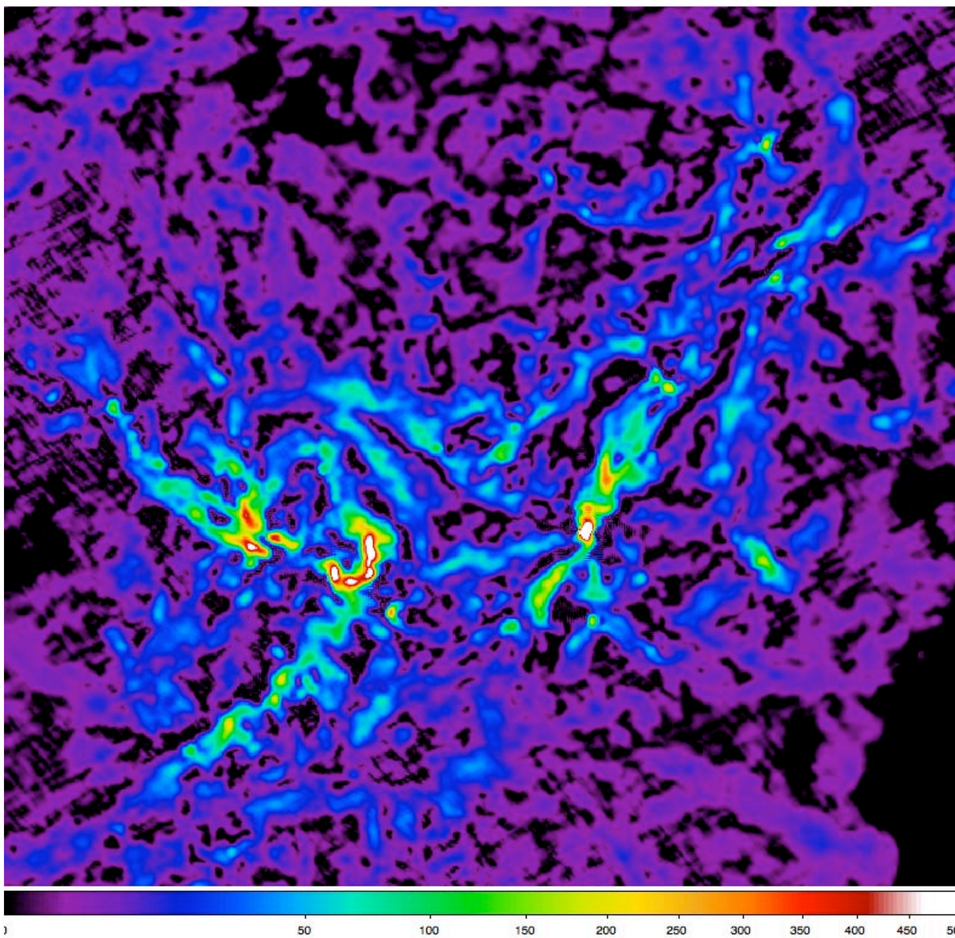


1.2°

Aquila and Polaris Sub-Fields 1: SPIRE 500 μm

curvelet components by *cb_mca*



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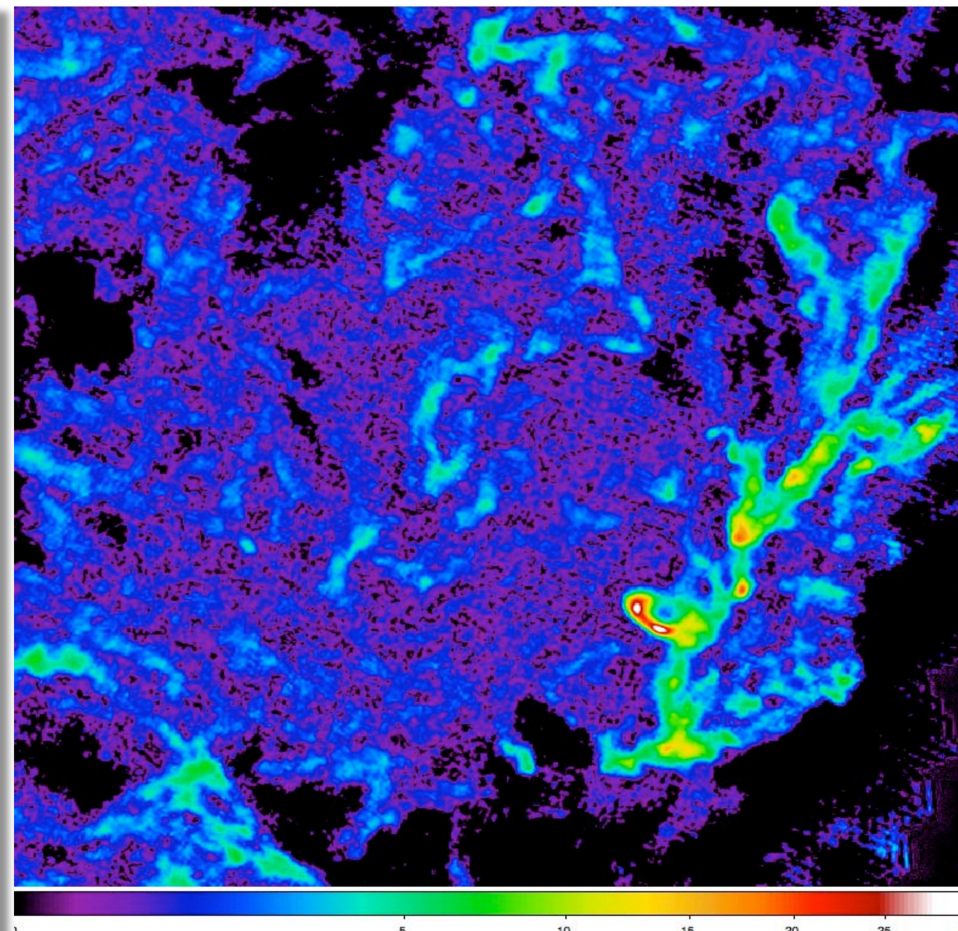
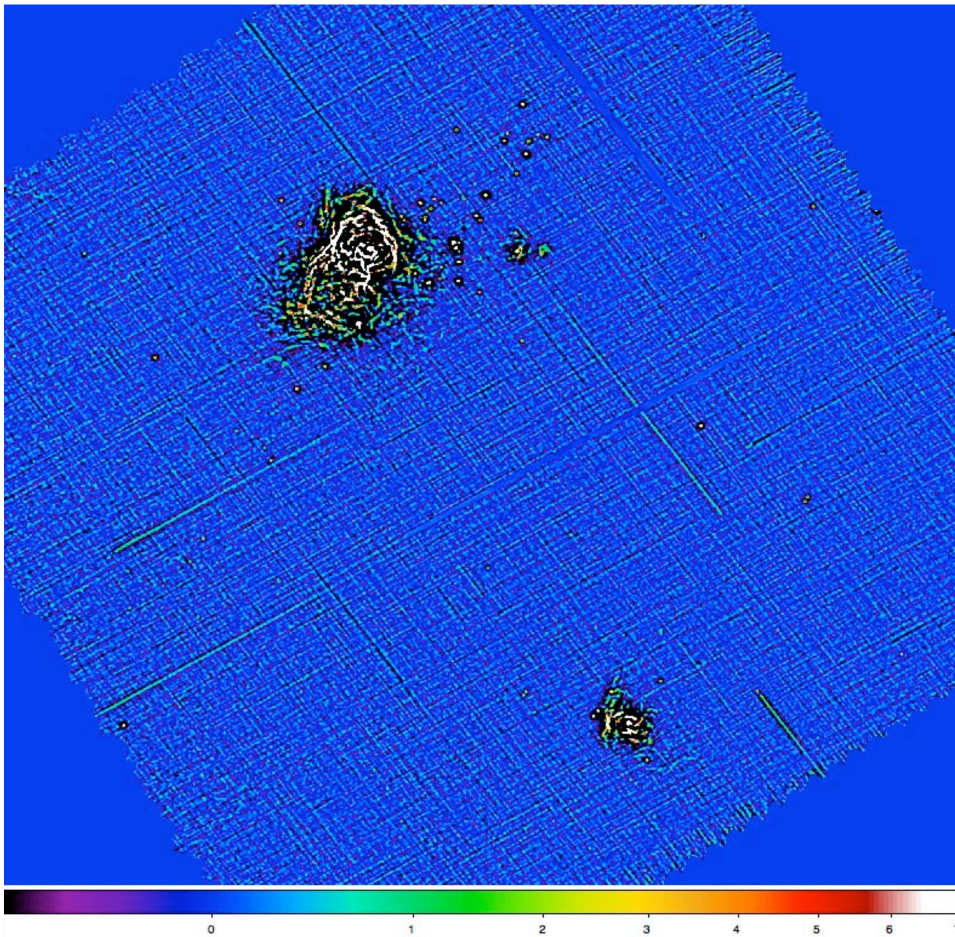


1.2°

Filamentary Structures at All *Herschel* Wavelengths

Aquila and Polaris: PACS 70 μm

single scales ~40” by *getsources*



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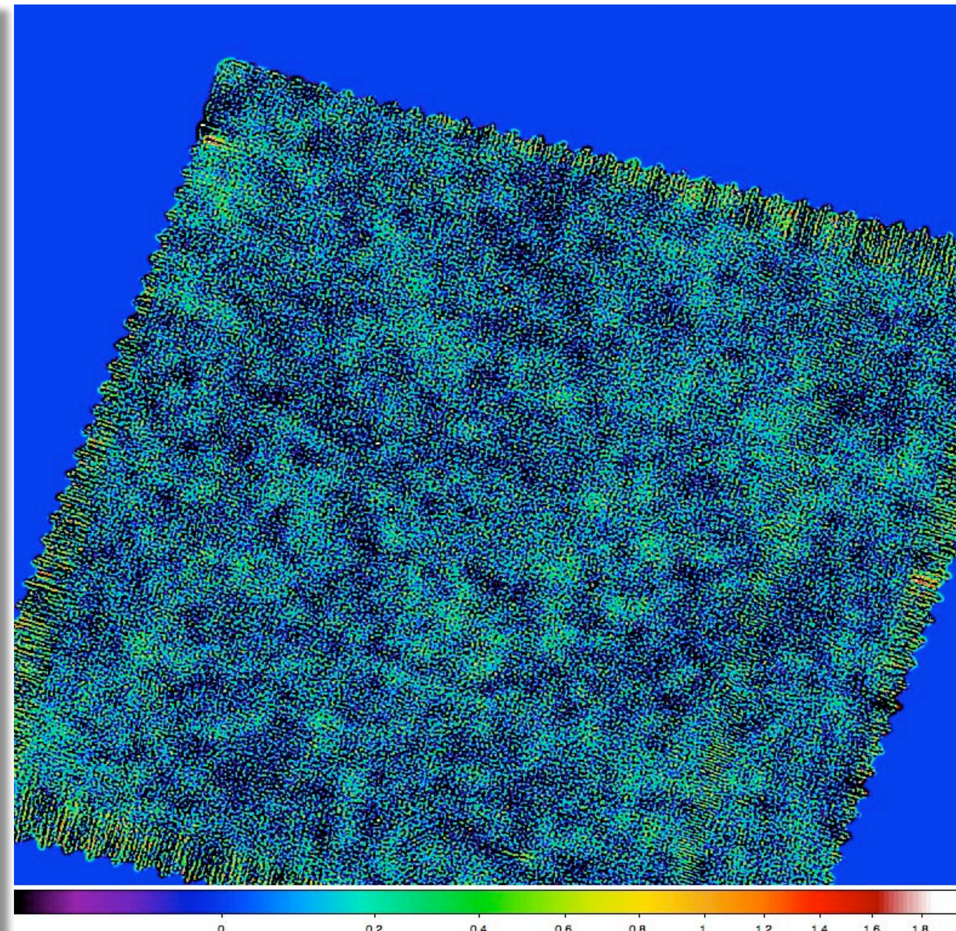
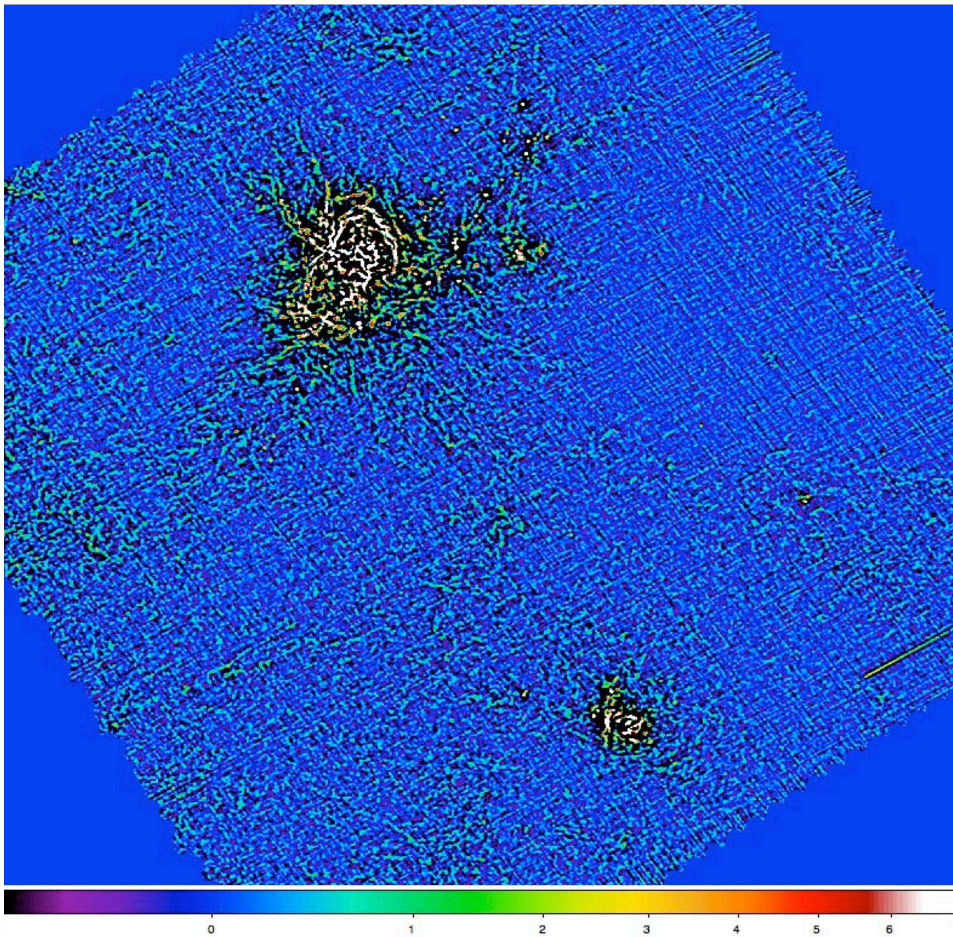
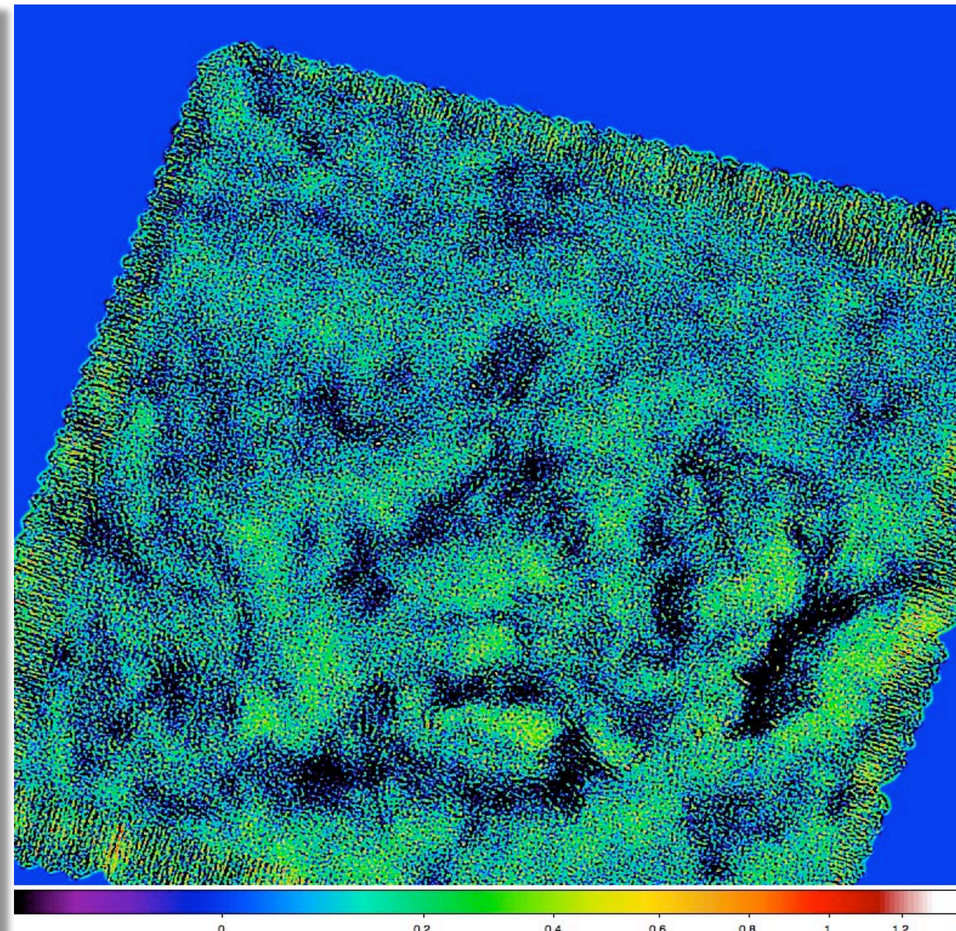


3.3°

Aquila and Polaris: PACS 160 μm
single scales ~40” by *getsources*



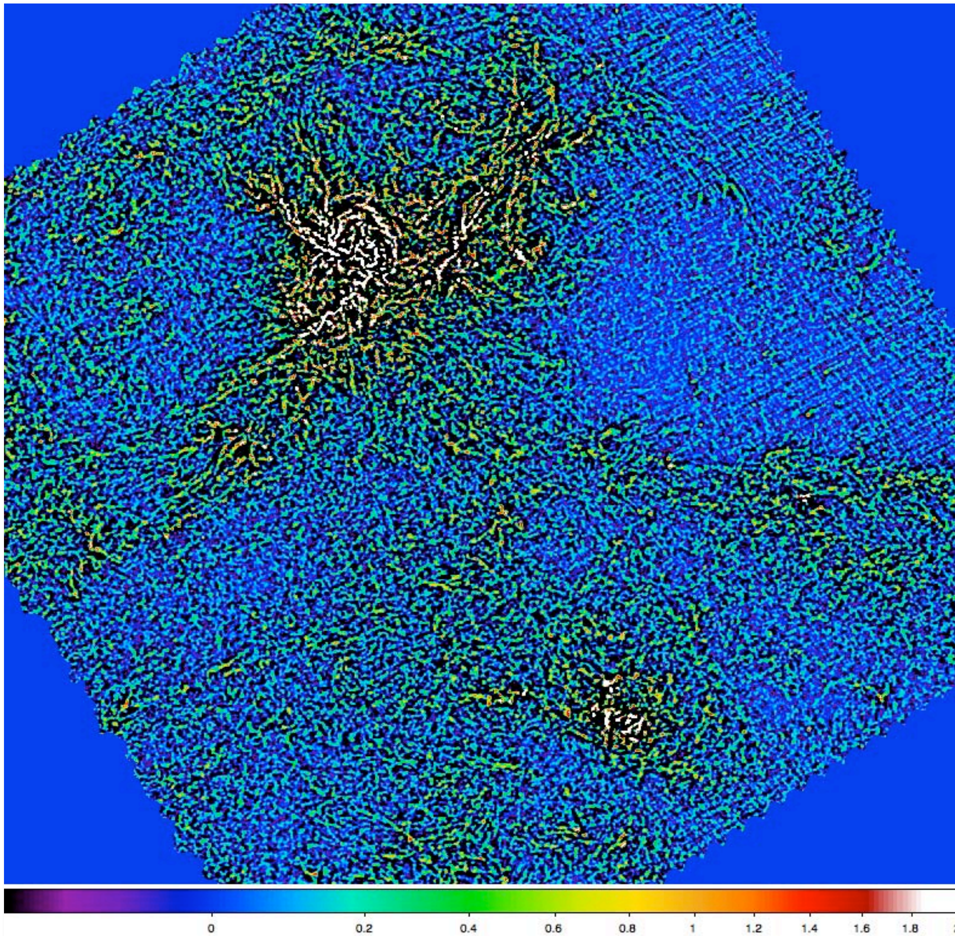
3.3°



3.3°

Aquila and Polaris: SPIRE 250 μm

single scales ~40" by *getsources*



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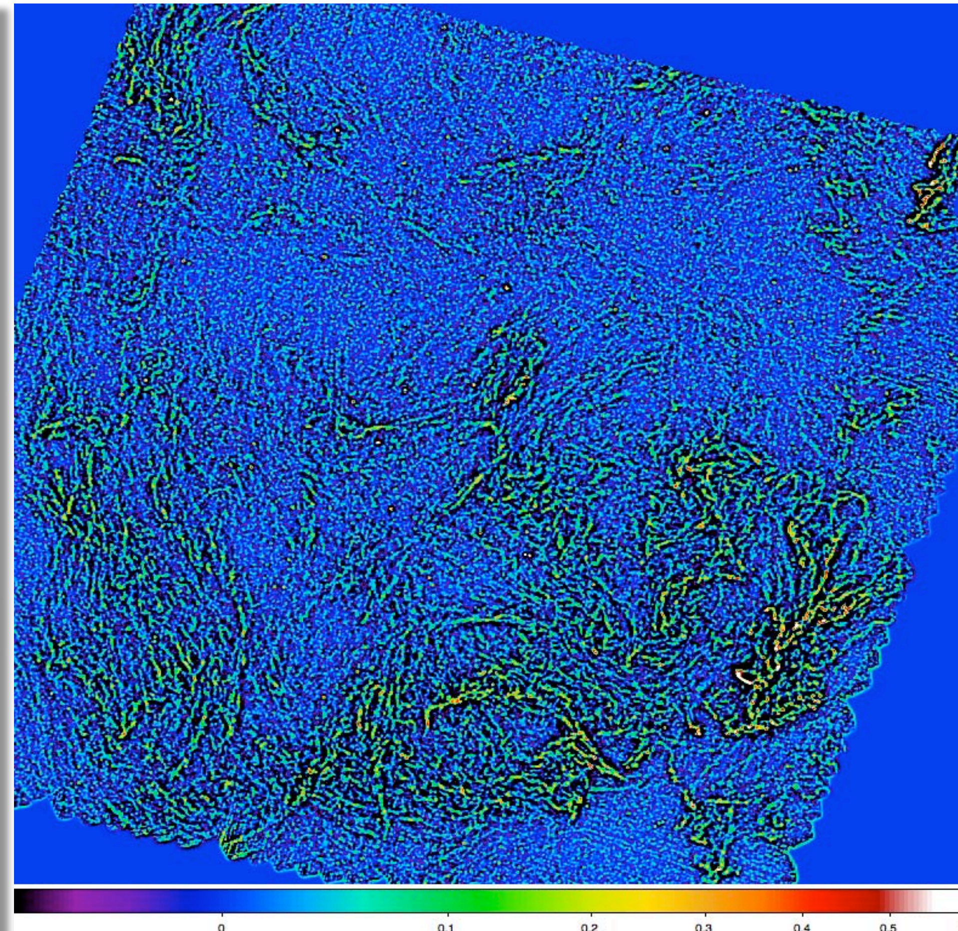
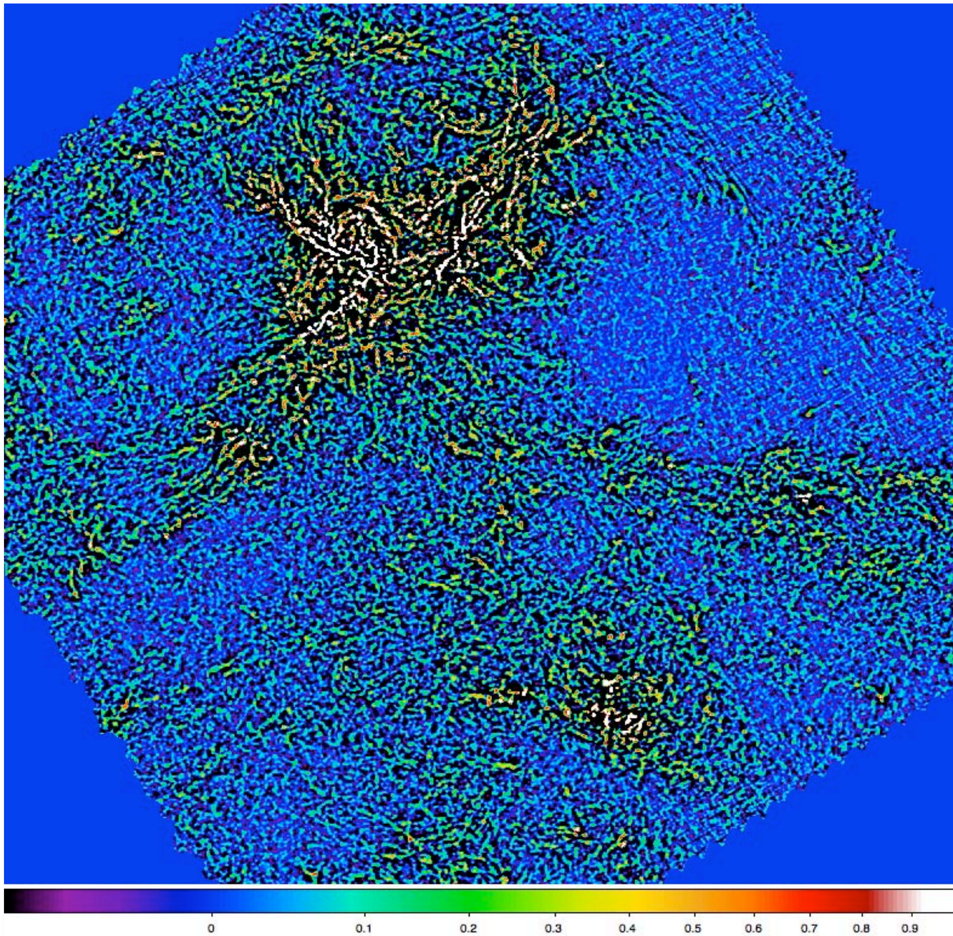


3.3°

Aquila and Polaris: SPIRE 350 μm

single scales ~40” by *getsources*



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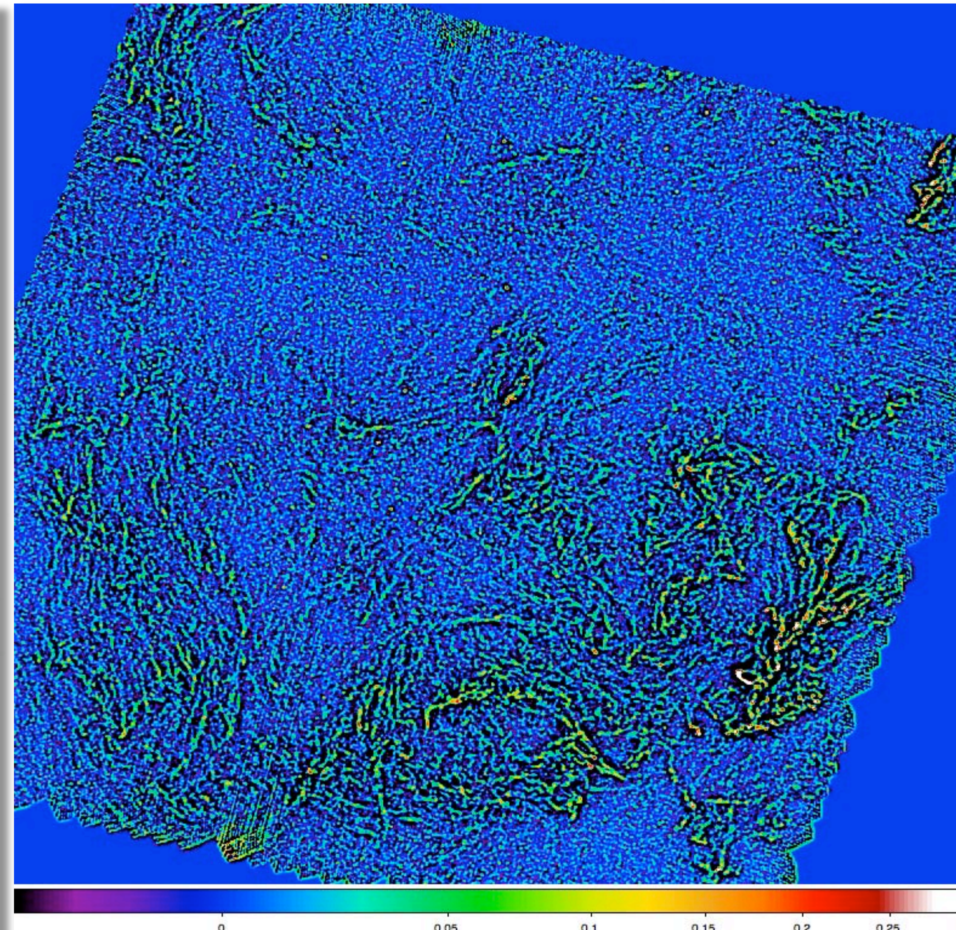
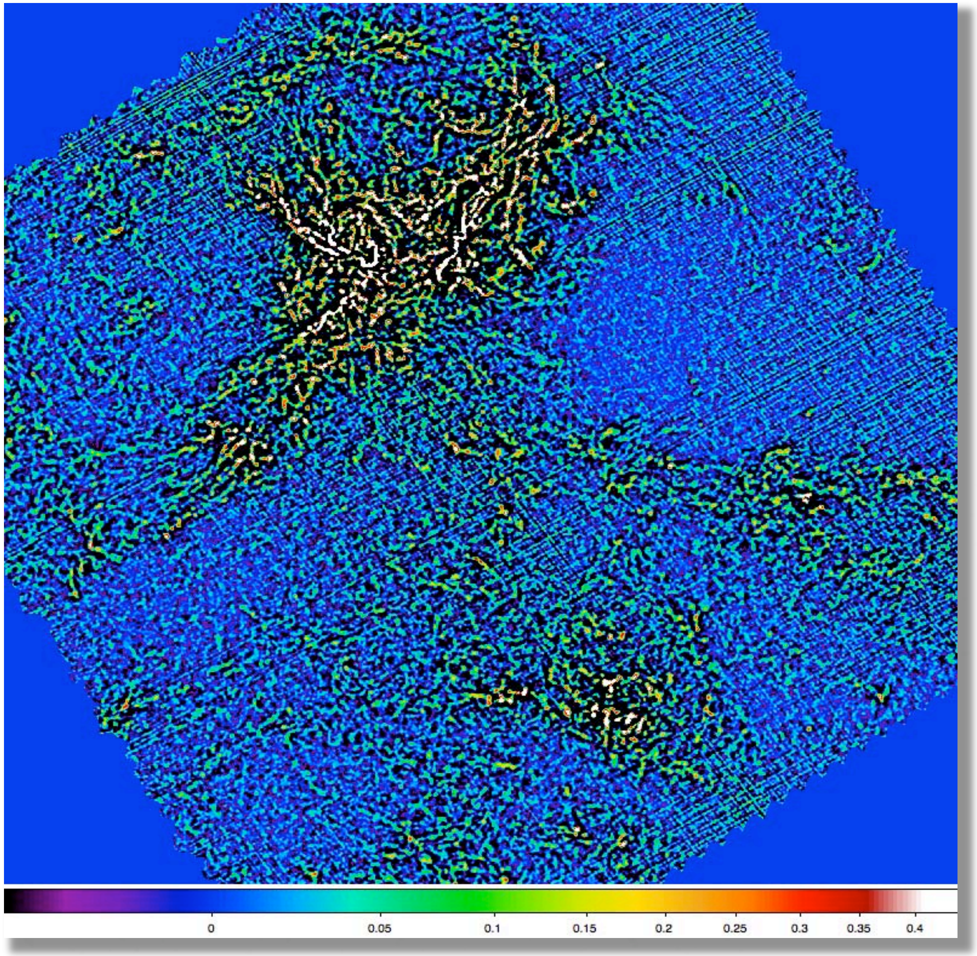


3.3°

Aquila and Polaris: SPIRE 500 μm

single scales ~40” by *getsources*



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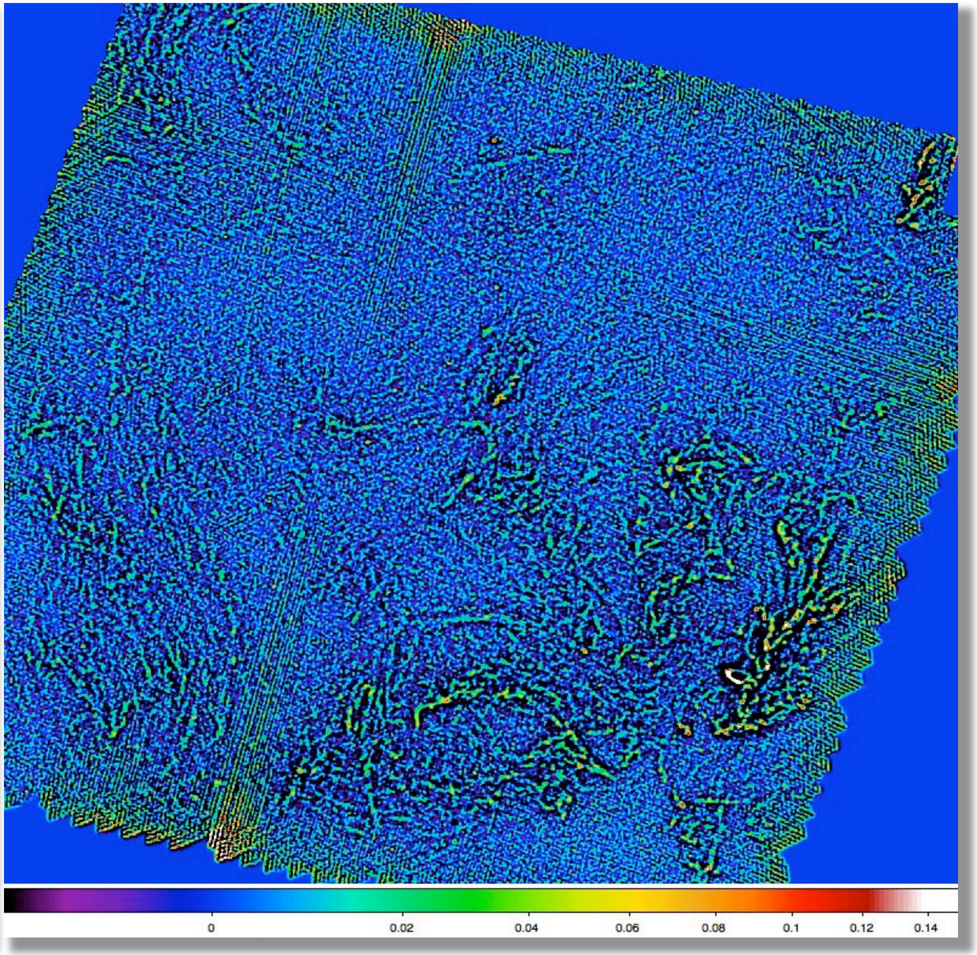
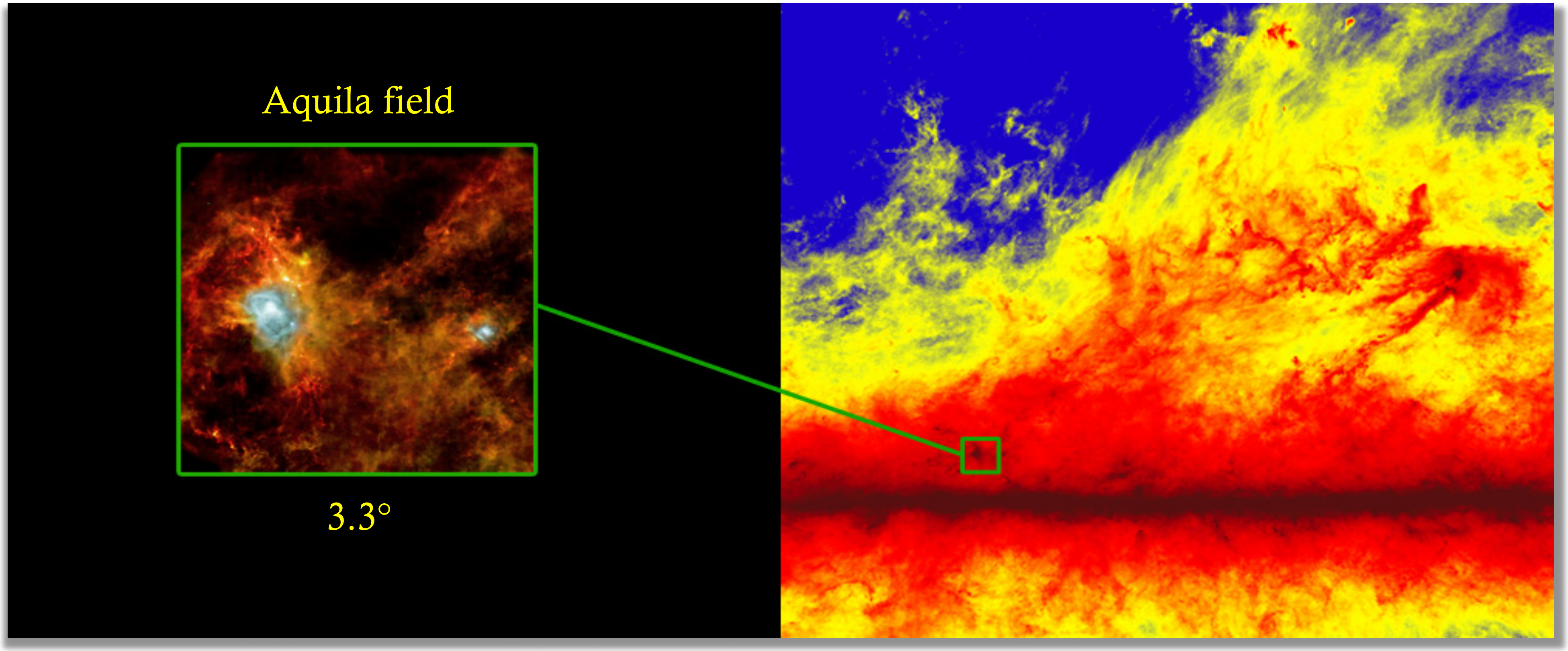


3.3°

Herschel SPIRE/PACS and *Planck* 350 μm

angular resolutions ~30" and 300"



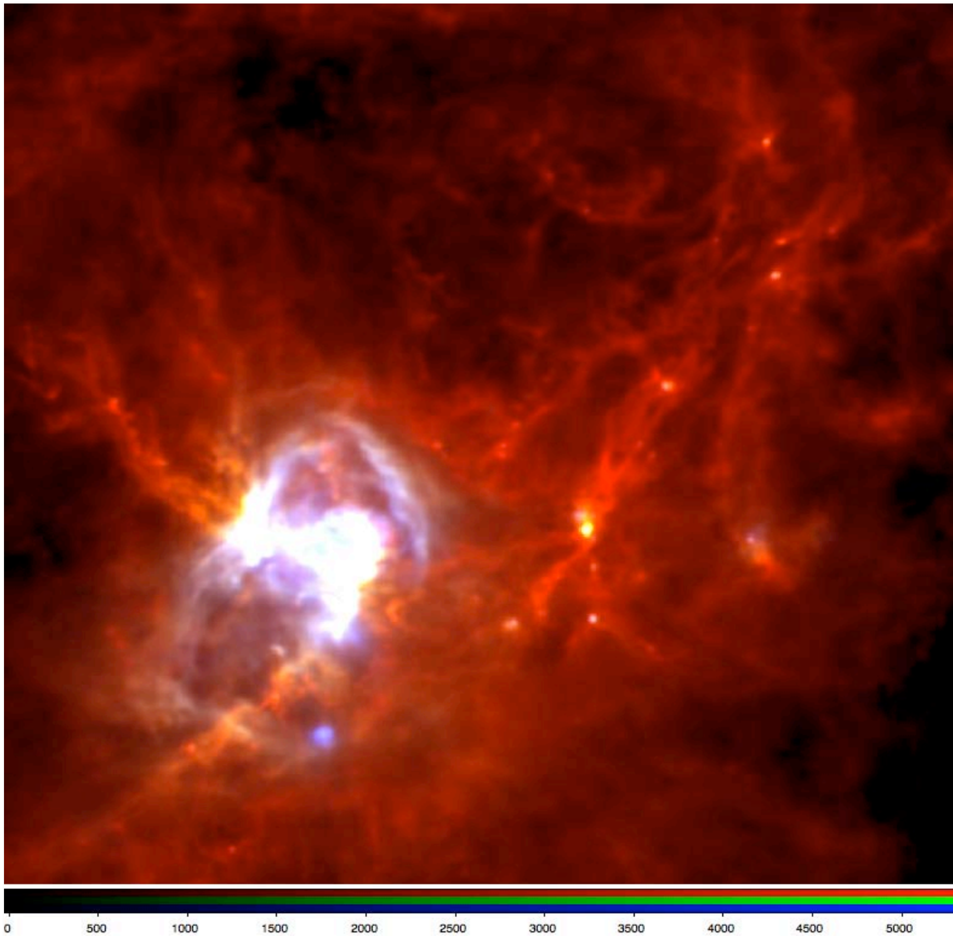
55°

Images: ESA, SPIRE, PACS, HFI Consortia, Gould Belt Key Project; http://www.esa.int/esa-mmg

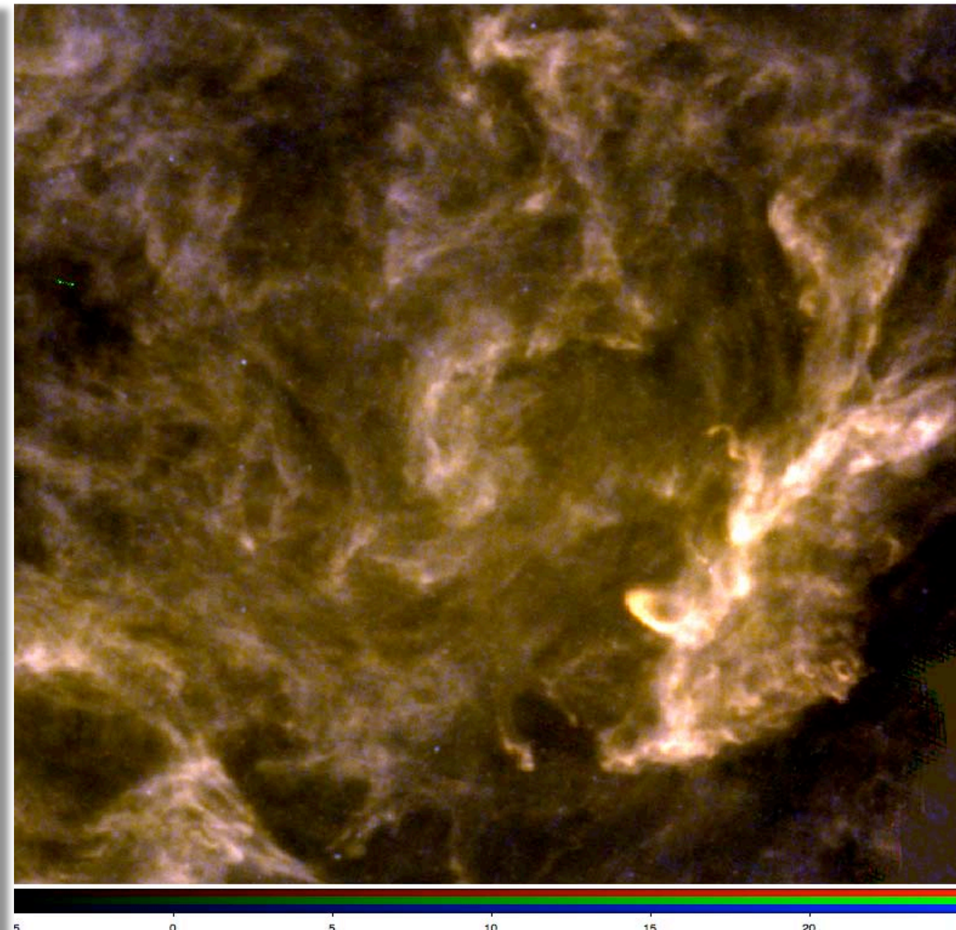
Intimate Physical Relationship of the Filaments and Cores

Aquila and Polaris Sub-Fields 1: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



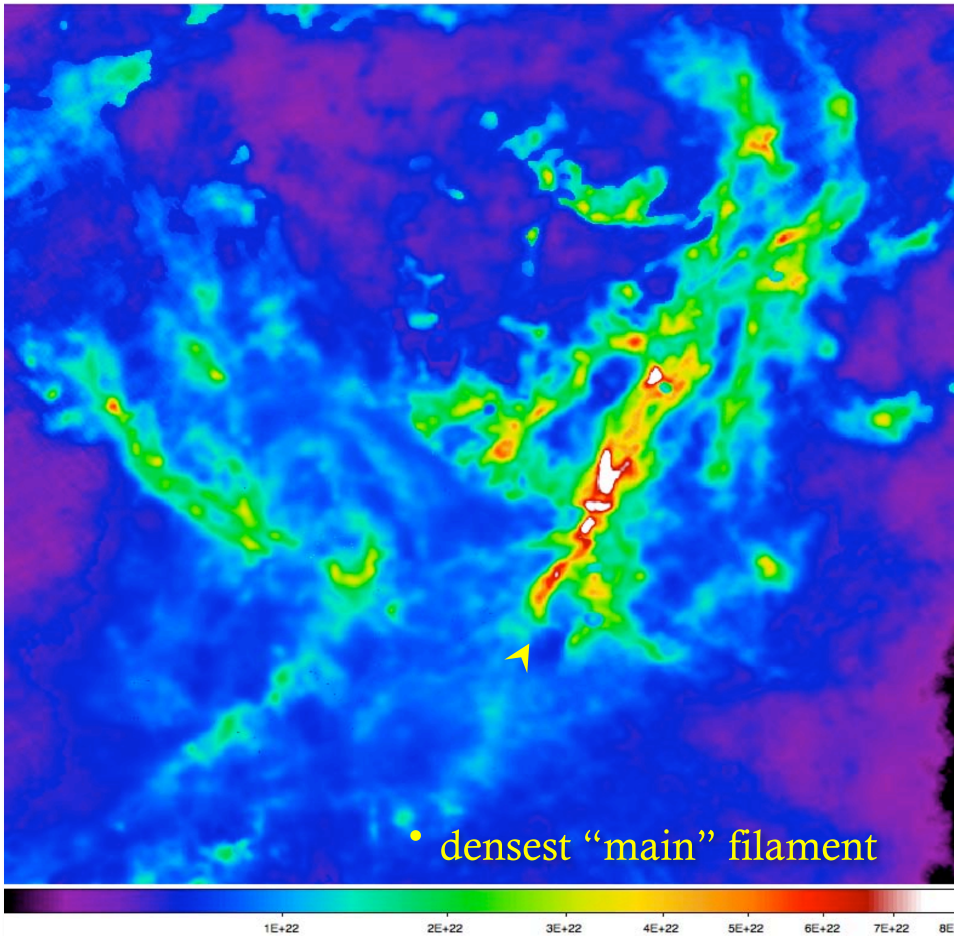
1.2°

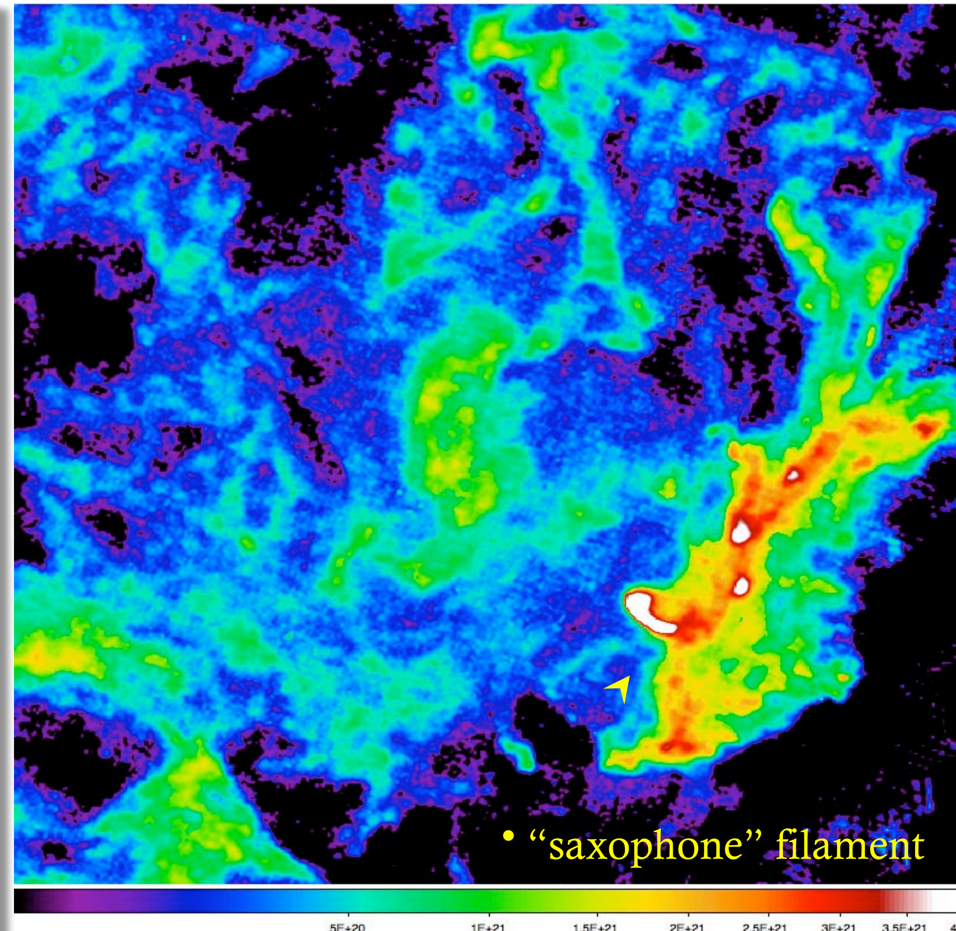


1.2°

Aquila and Polaris Sub-Fields 1: SPIRE/PACS

column densities $N(H_2)$

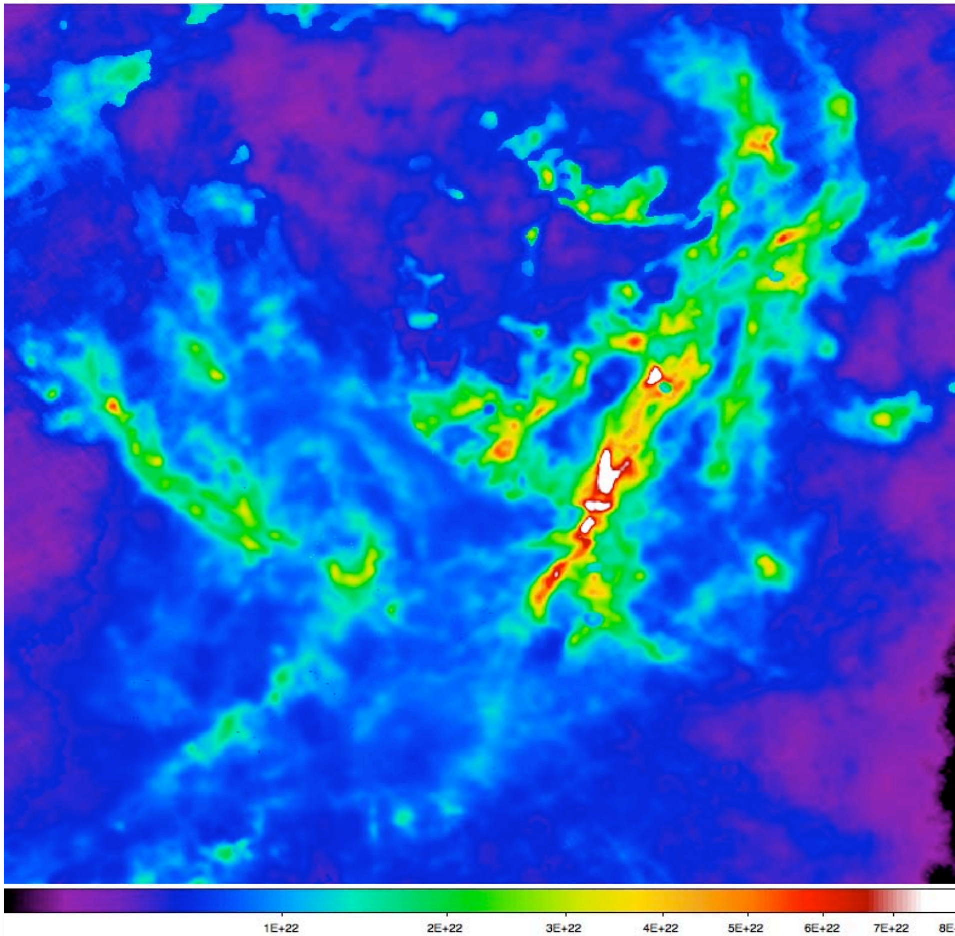


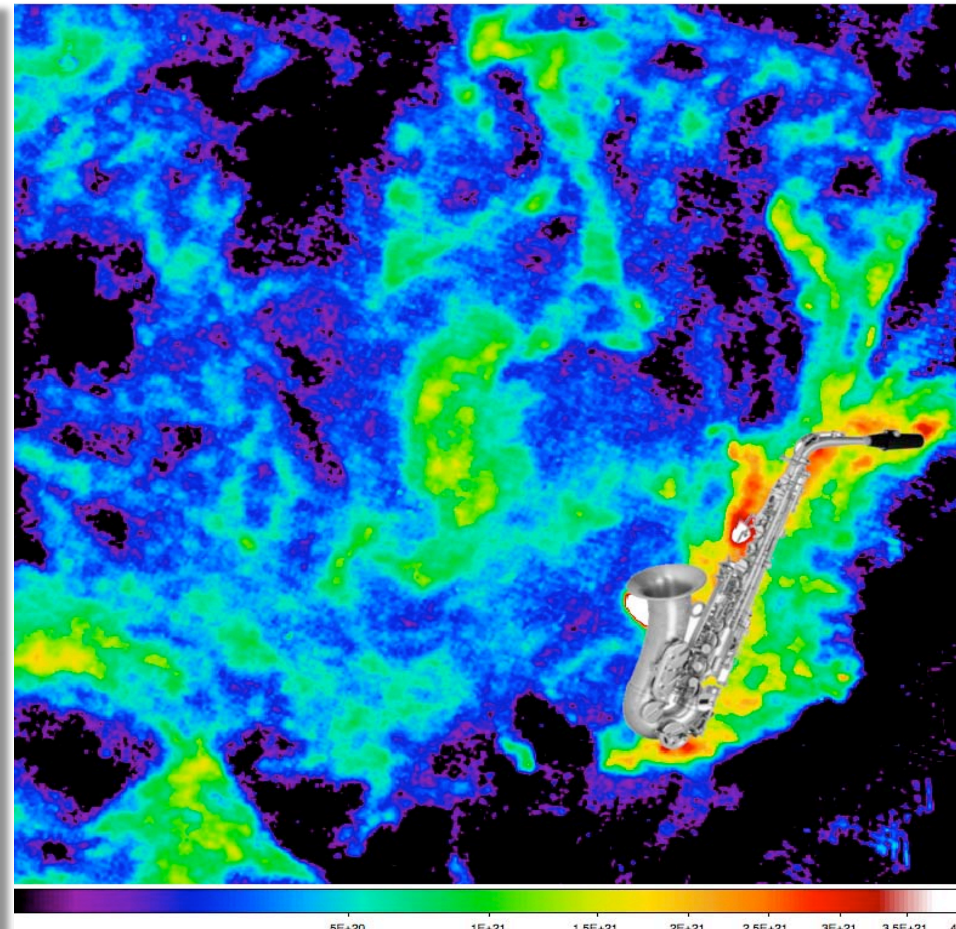


$<1.4\times10^{23}$ 1.2° 1.2° $<9\times10^{21}$

Aquila and Polaris Sub-Fields 1: SPIRE/PACS

column densities $N(H_2)$

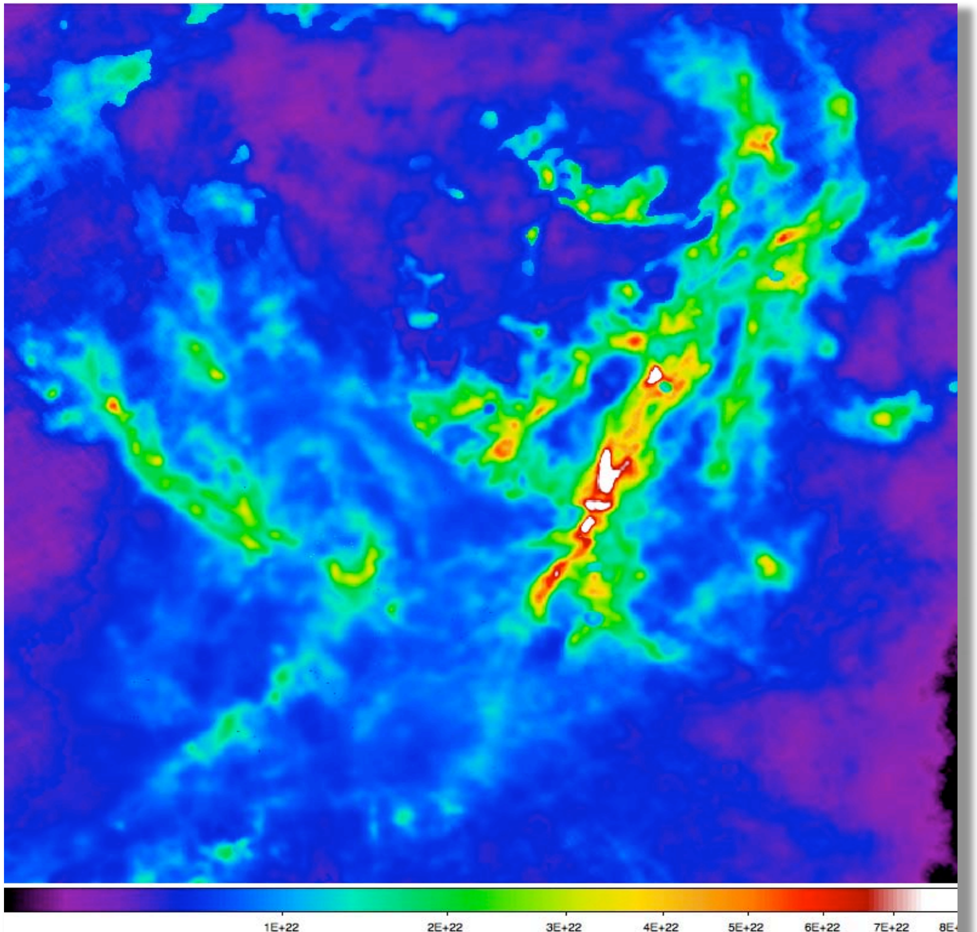


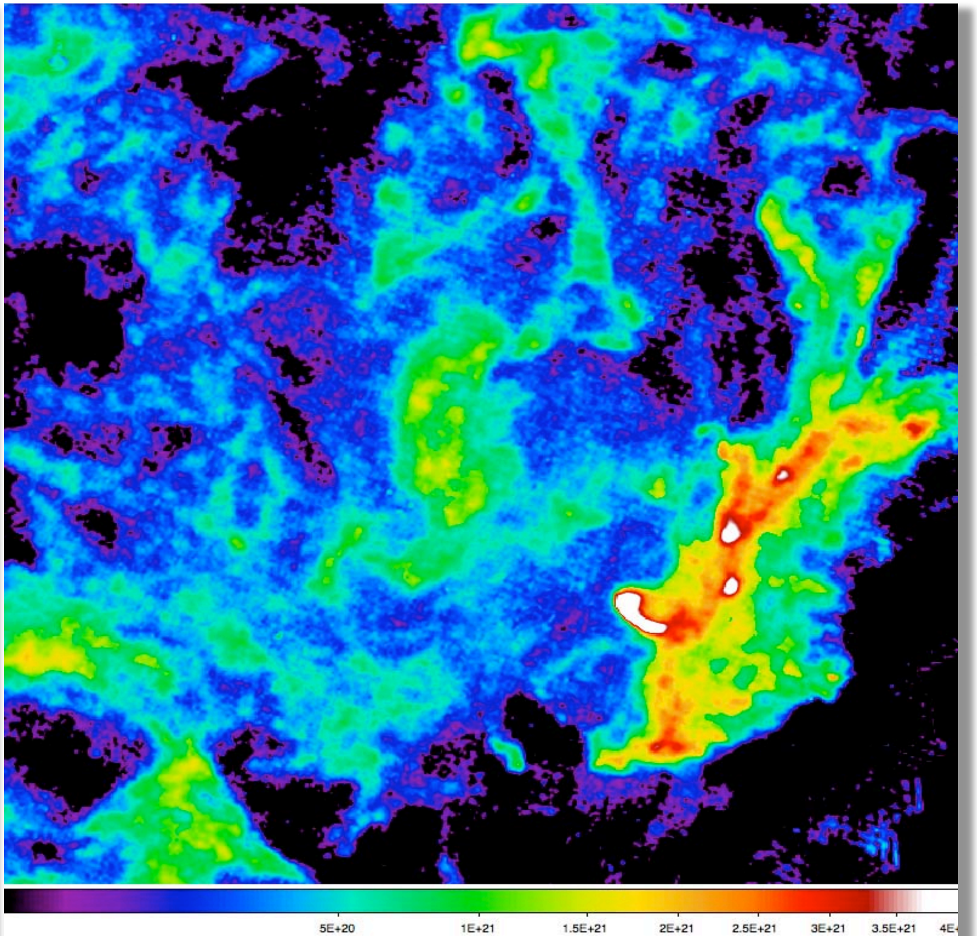


$<1.4\times10^{23}$ 1.2° 1.2° $<9\times10^{21}$

Aquila and Polaris Sub-Fields 1: SPIRE/PACS

column densities $N(H_2)$

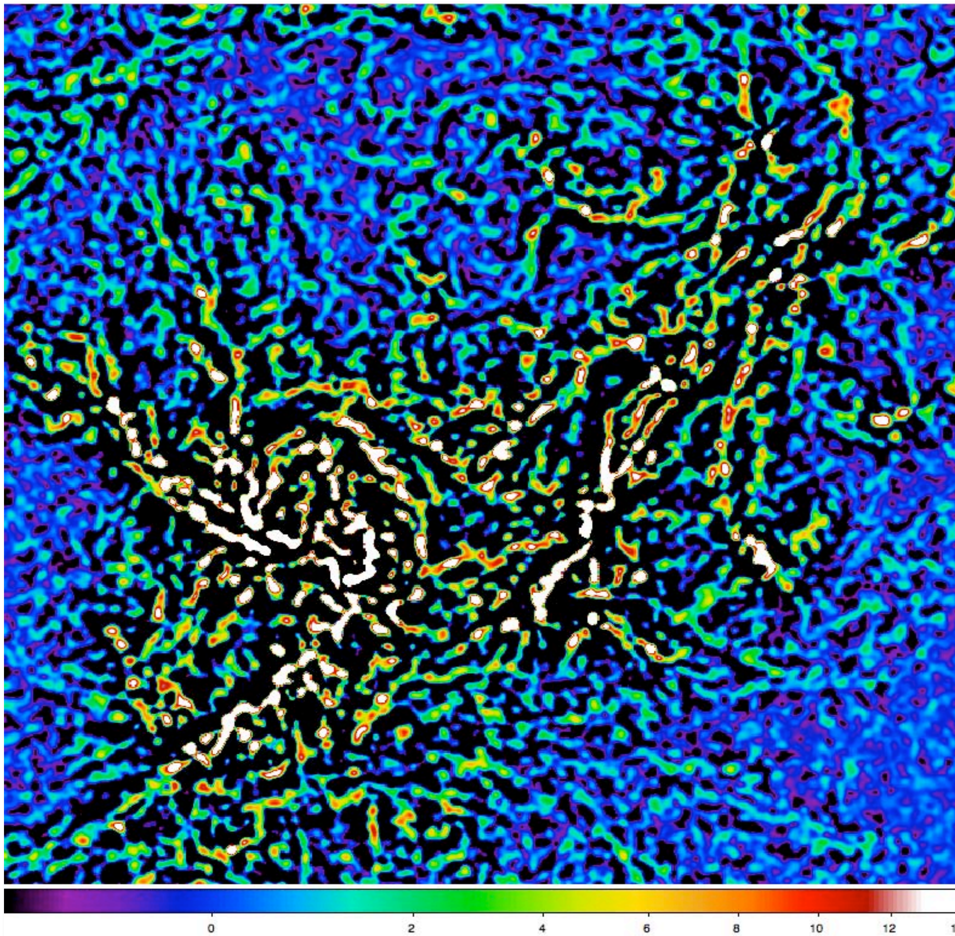




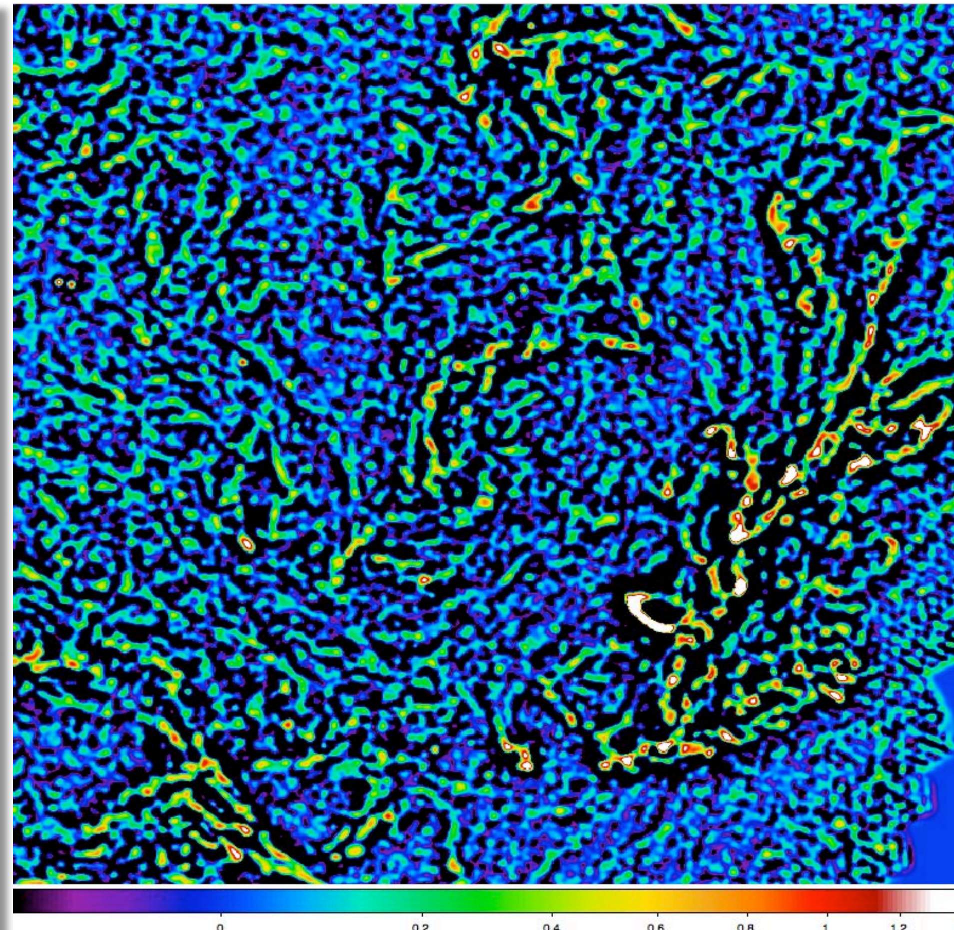
$<1.4\times10^{23}$ 1.2° 1.2° $<9\times10^{21}$

Aquila and Polaris Sub-Fields 1: SPIRE

single scales ~40”: high-contrast filaments and objects



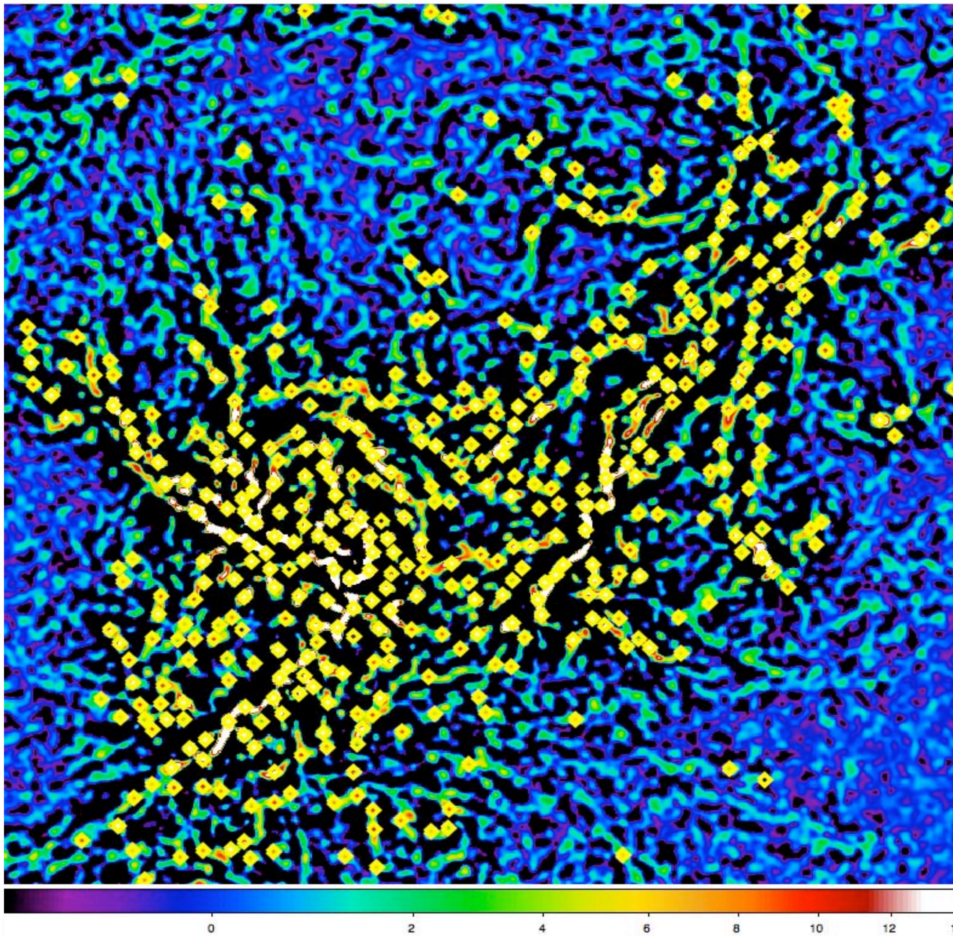
1.2°

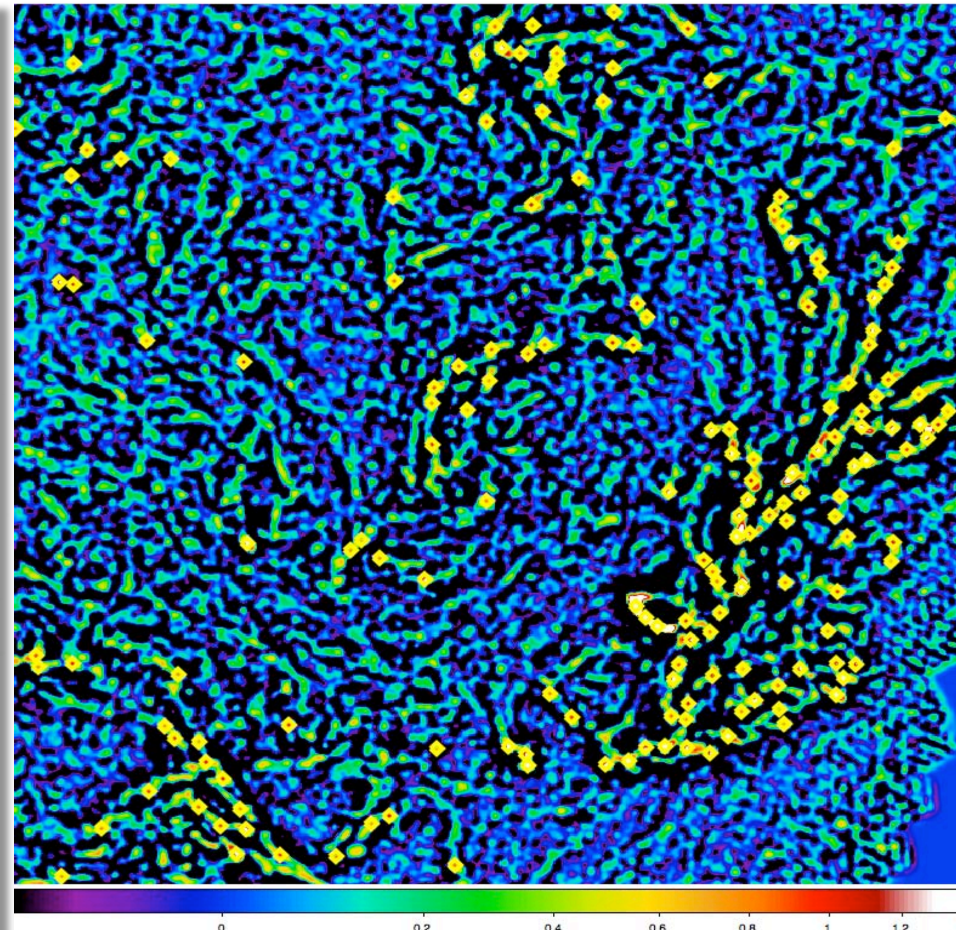


1.2°

Aquila and Polaris Sub-Fields 1: SPIRE

single scales ~40” + naive visual detection

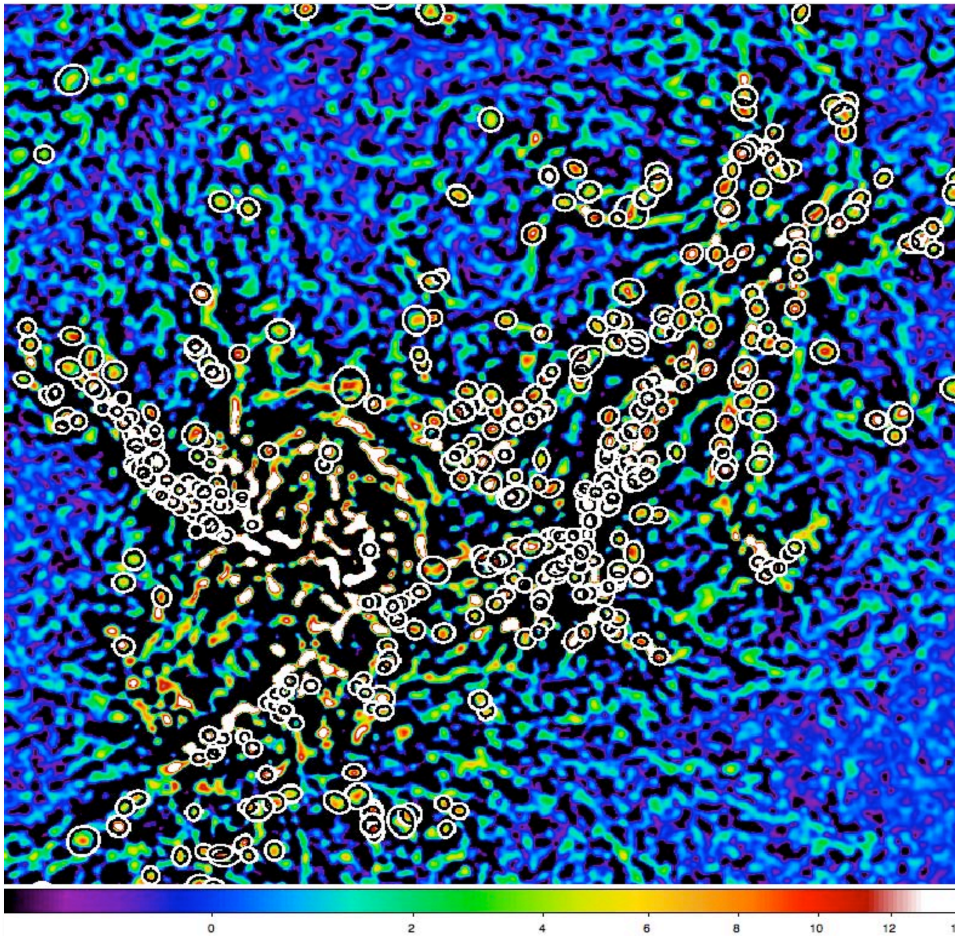


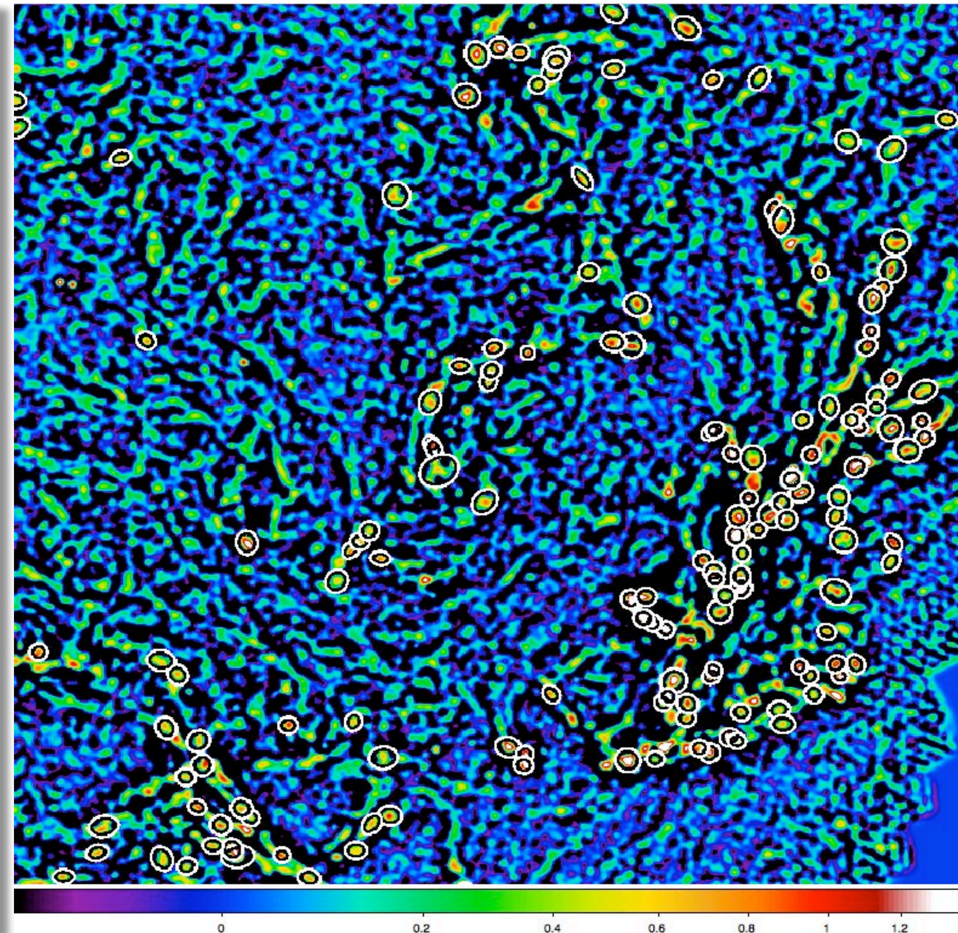


451 objects   1.2°   1.2°   168 objects

Aquila and Polaris Sub-Fields 1: SPIRE

single scales ~40” + starless cores by *getsources*

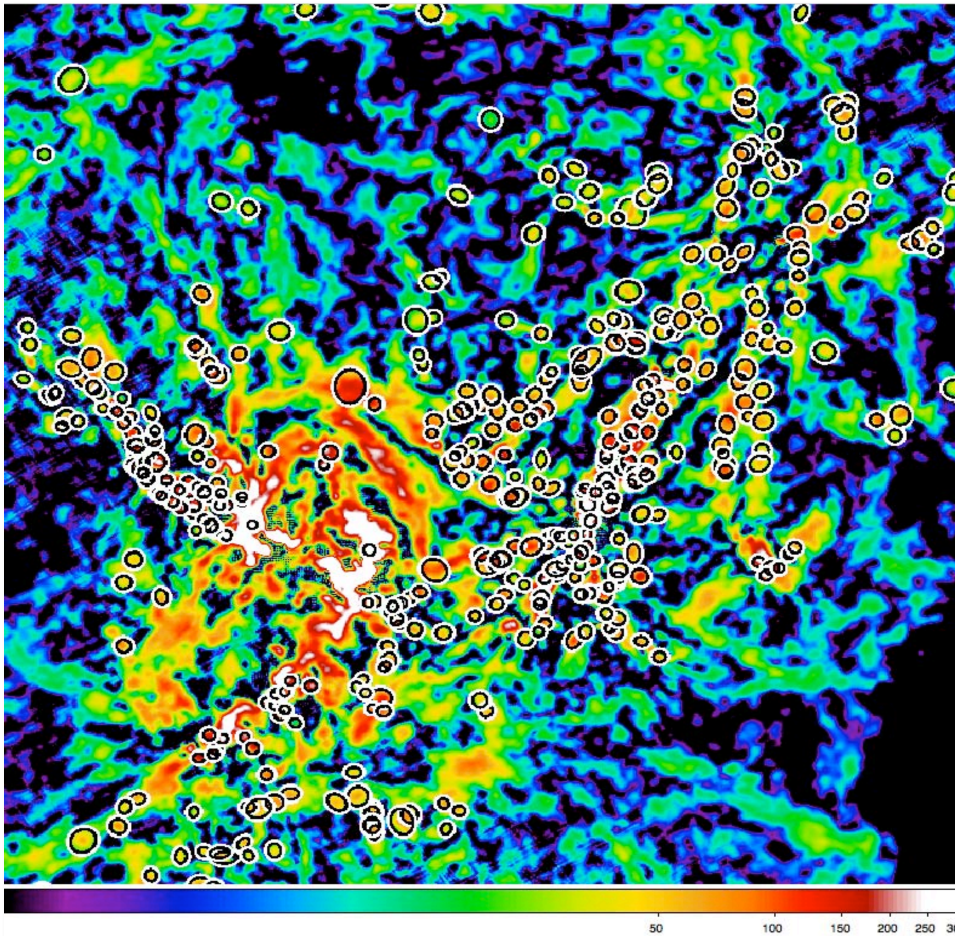


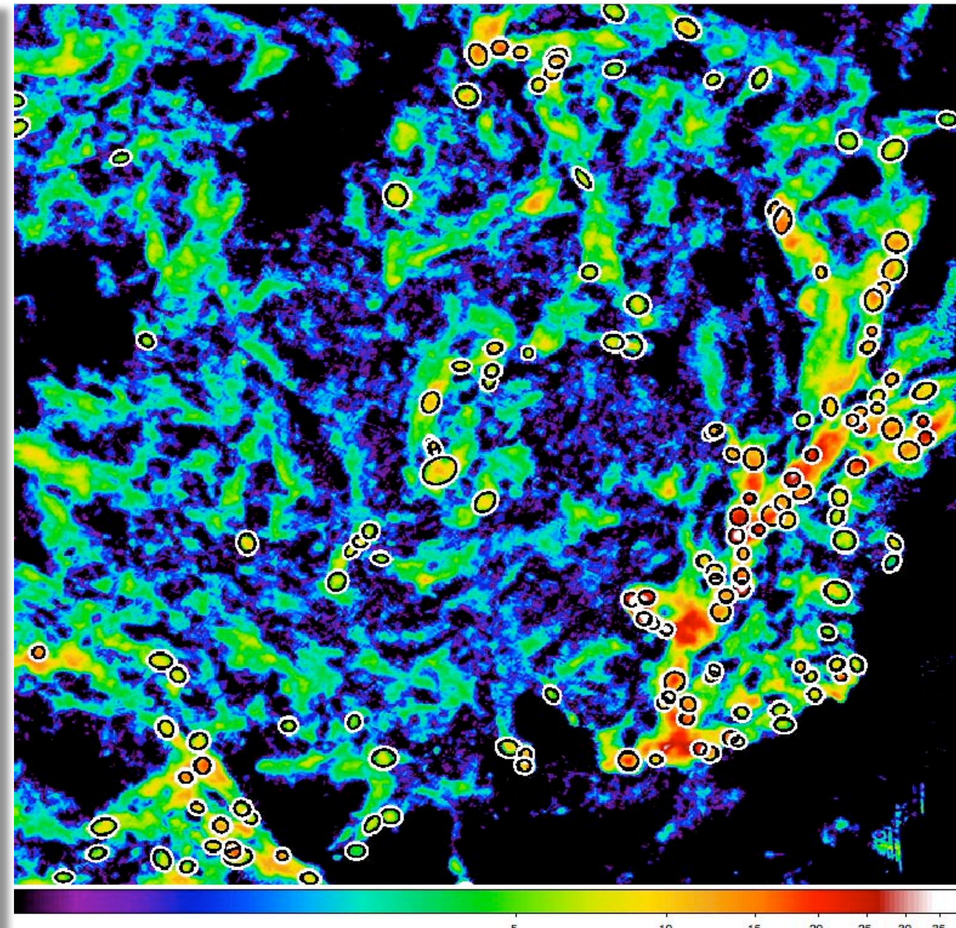


~400 cores 1.2° 1.2° ~160 cores

Aquila and Polaris Sub-Fields 1: SPIRE 350 μm

curvelet component by *cb_mca* + starless cores by *getsources*

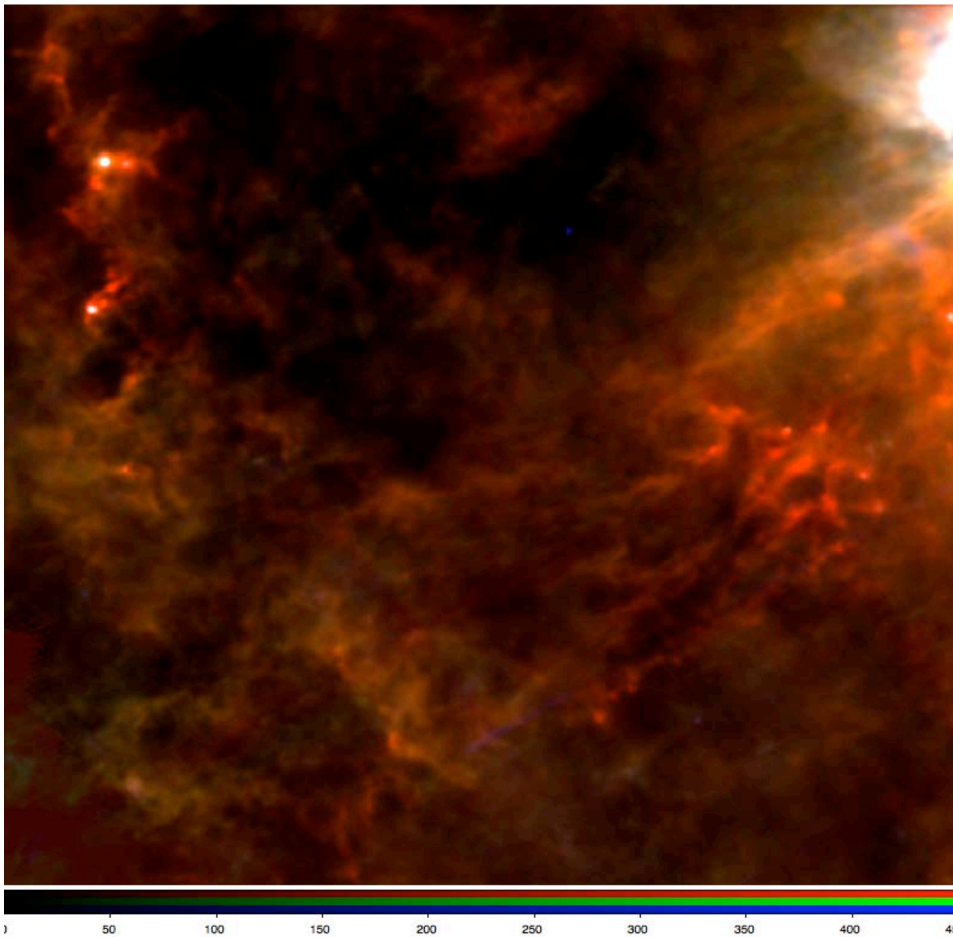




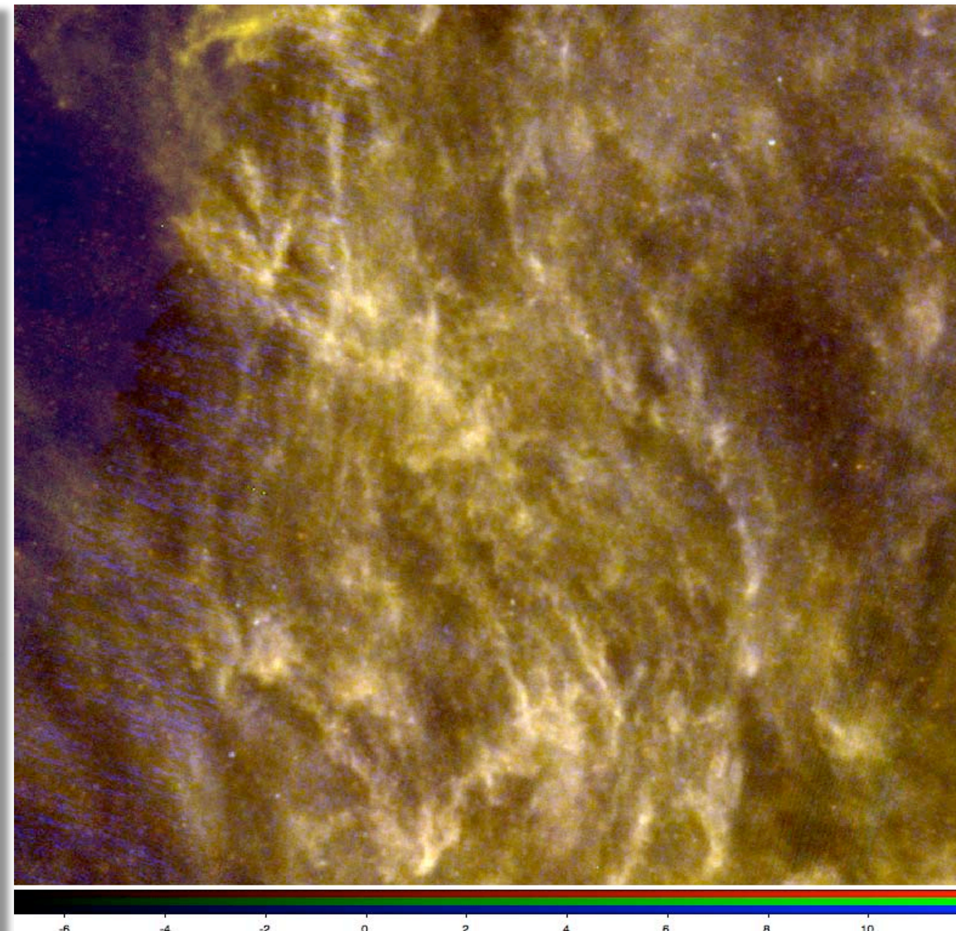
~400 cores 1.2° 1.2° ~160 cores

Aquila and Polaris Sub-Fields 2: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



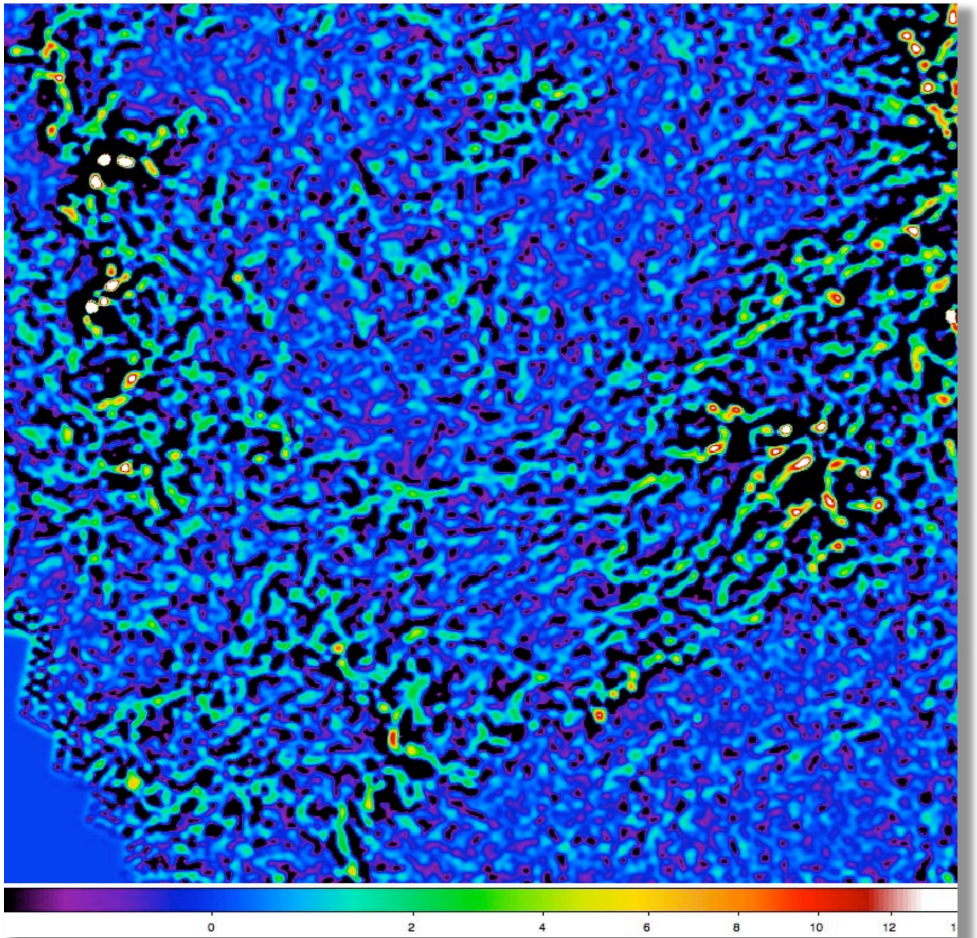
1.2°



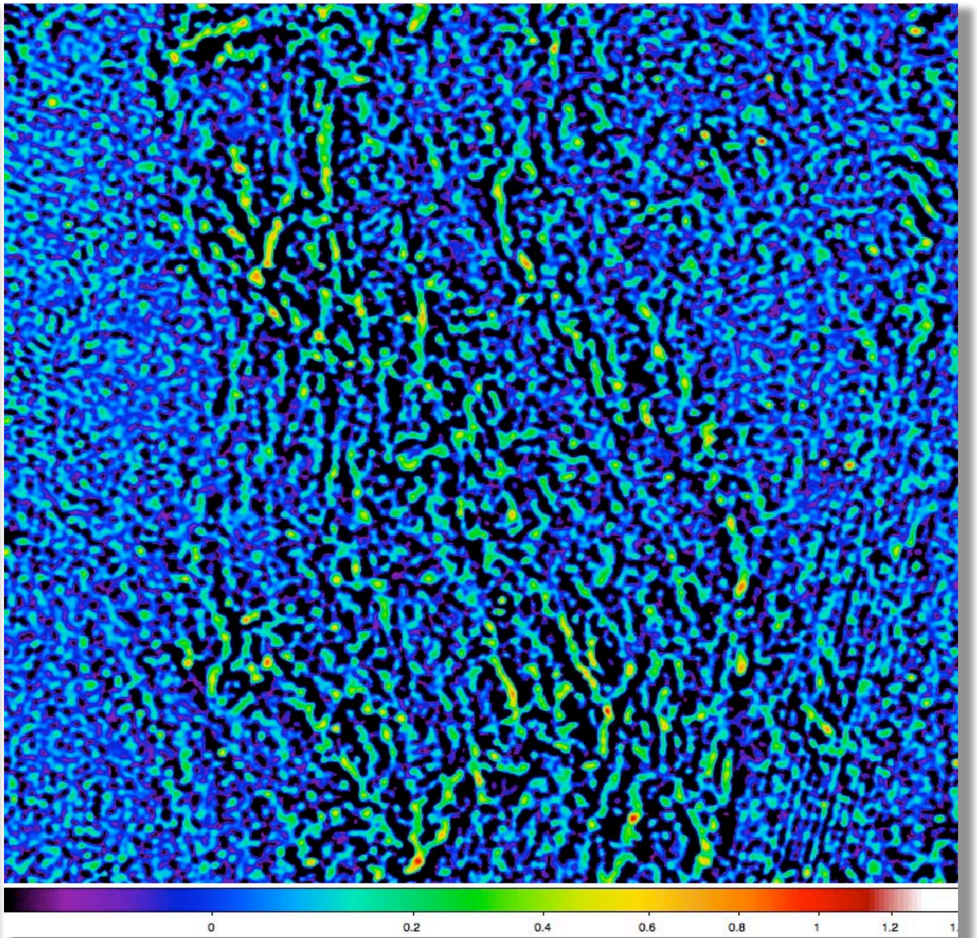
1.2°

Aquila and Polaris Sub-Fields 2: SPIRE

single scales ~40”: high-contrast filaments and objects



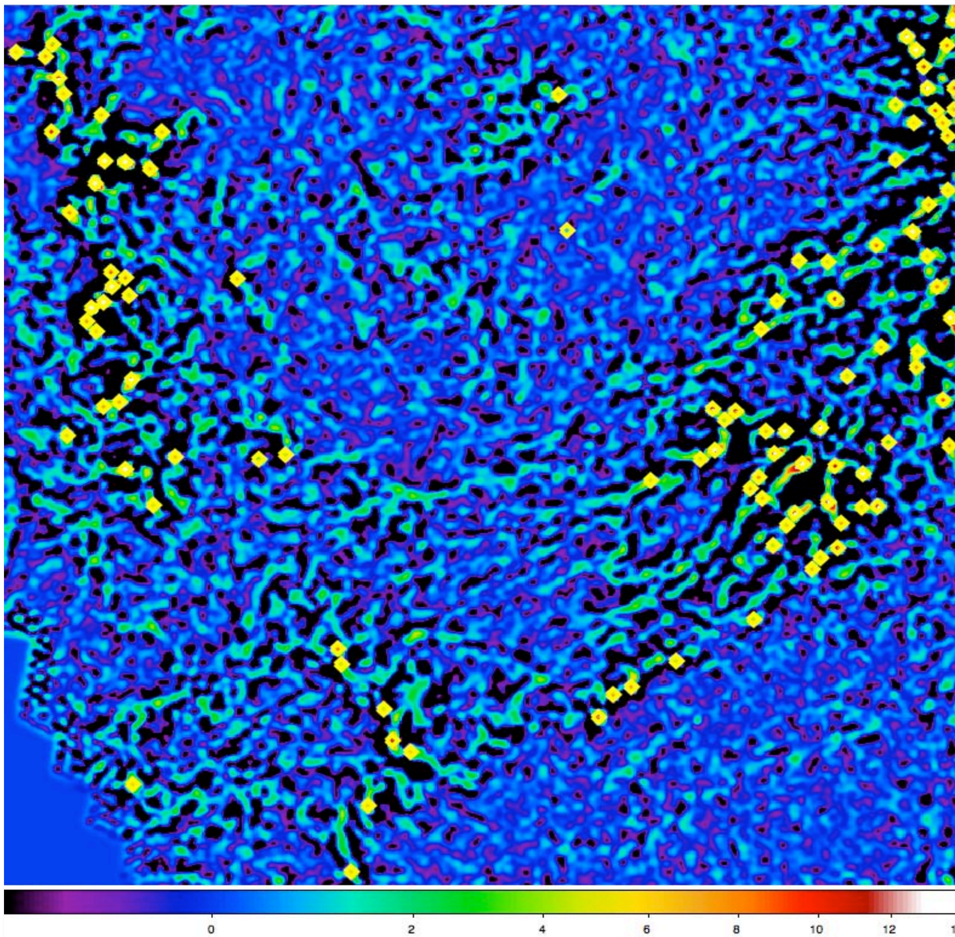
1.2°

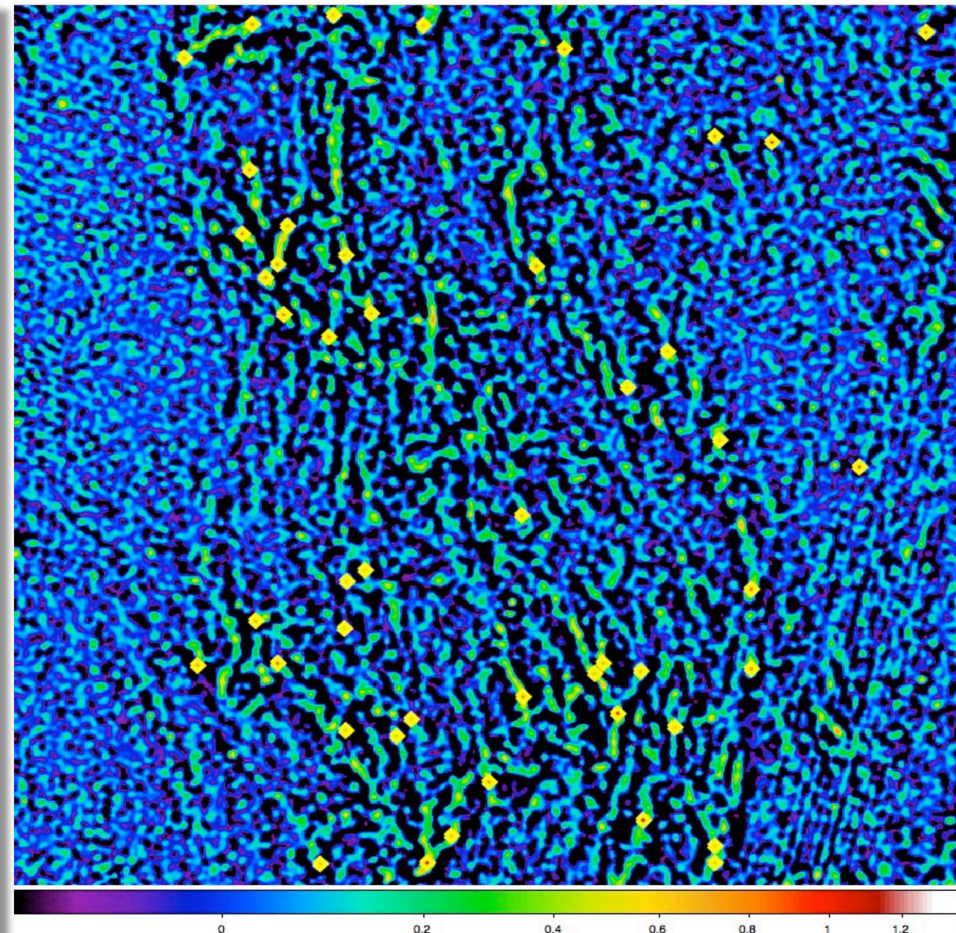


1.2°

Aquila and Polaris Sub-Fields 2: SPIRE

single scales ~40” + naive visual detection

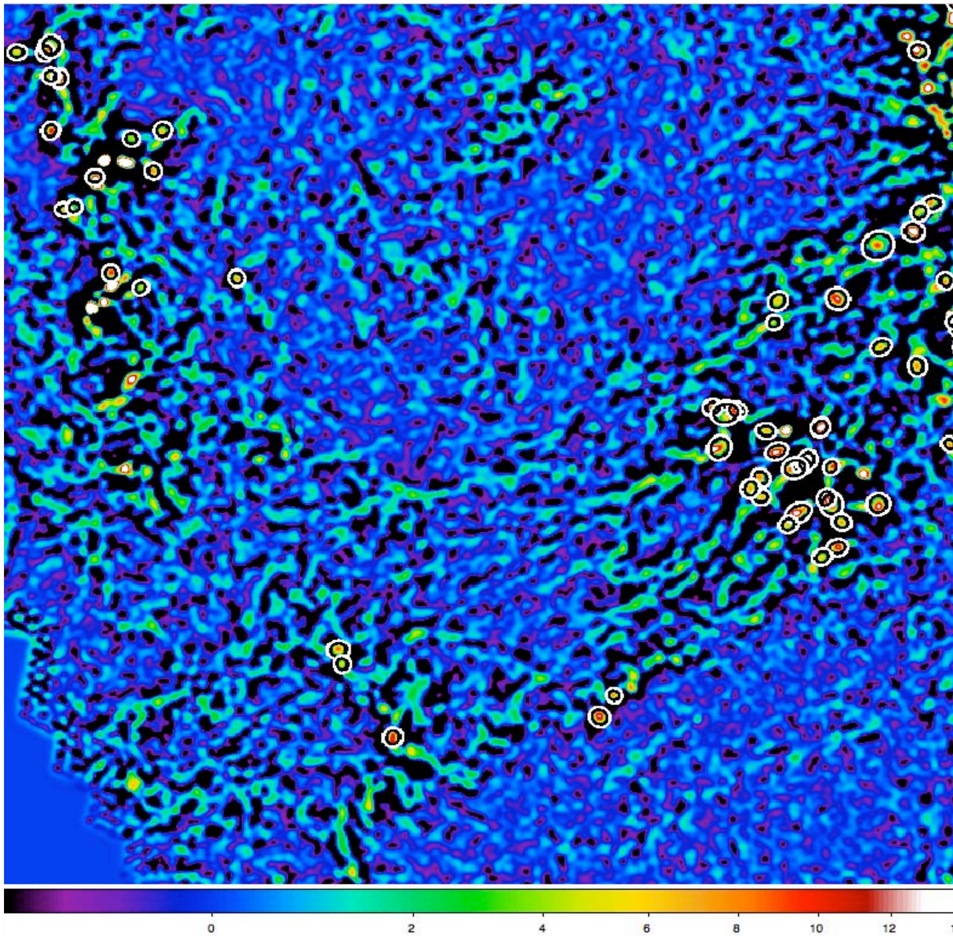


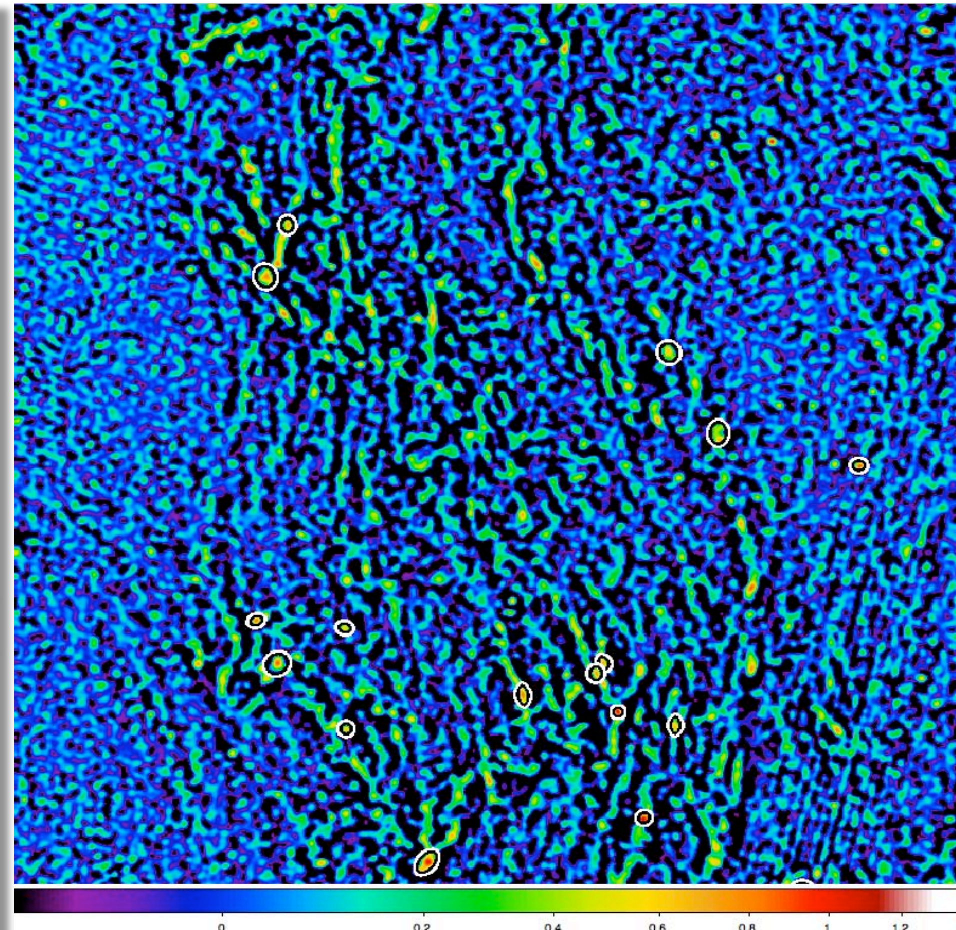


105 objects 1.2° 1.2° 47 objects

Aquila and Polaris Sub-Fields 2: SPIRE

single scales ~40” + starless cores by *getsources*

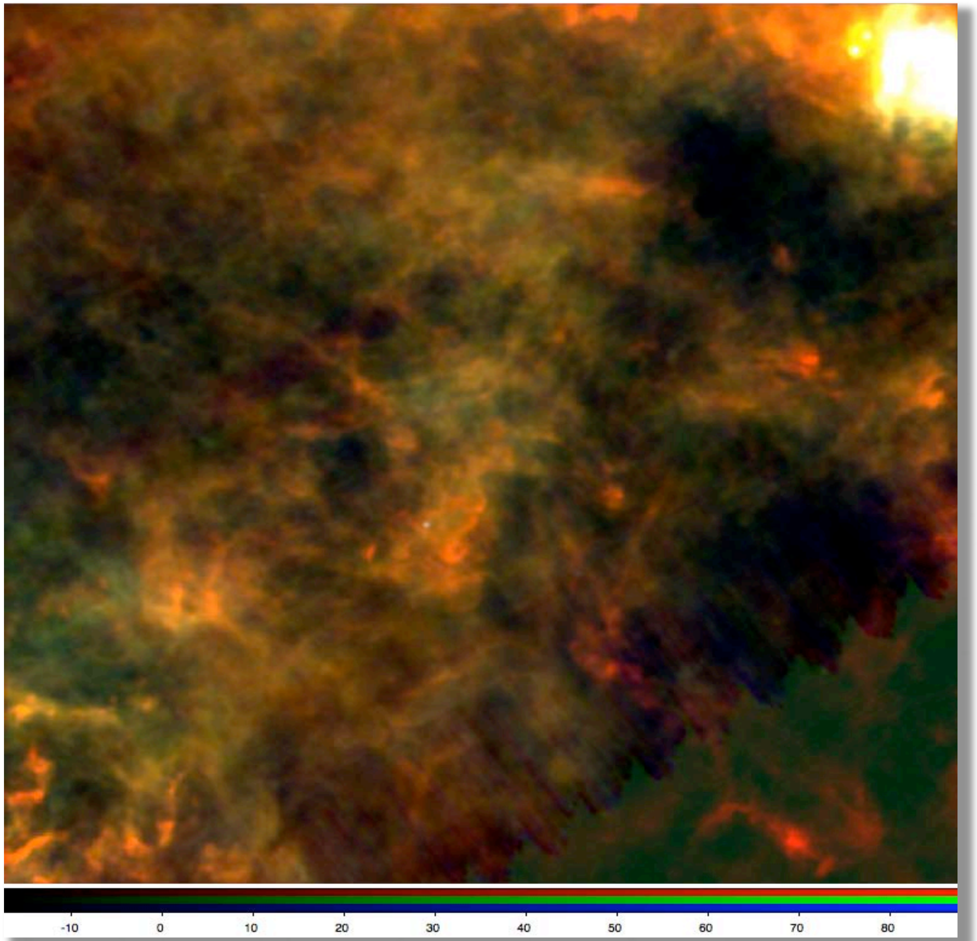




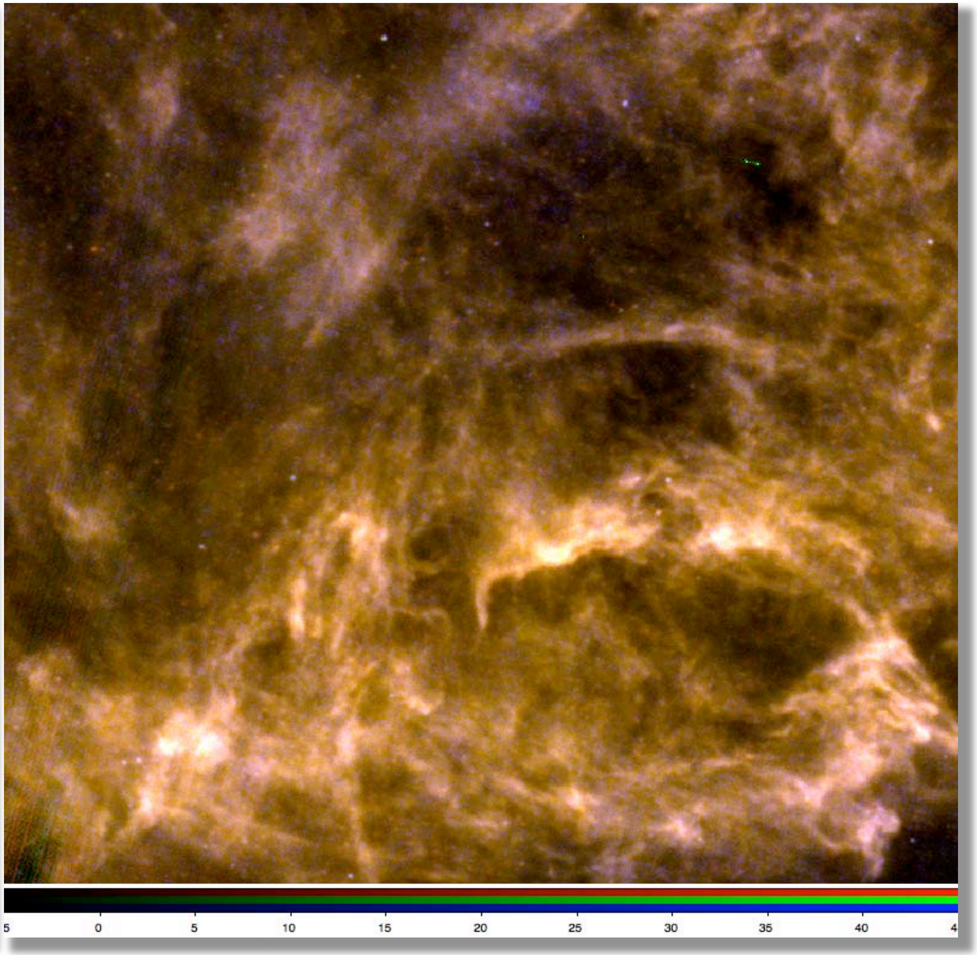
54 cores 1.2° 1.2° 17 cores

Aquila and Polaris Sub-Fields 3: SPIRE/PACS

RGB 350+160+70 μm and 350+250+160 μm



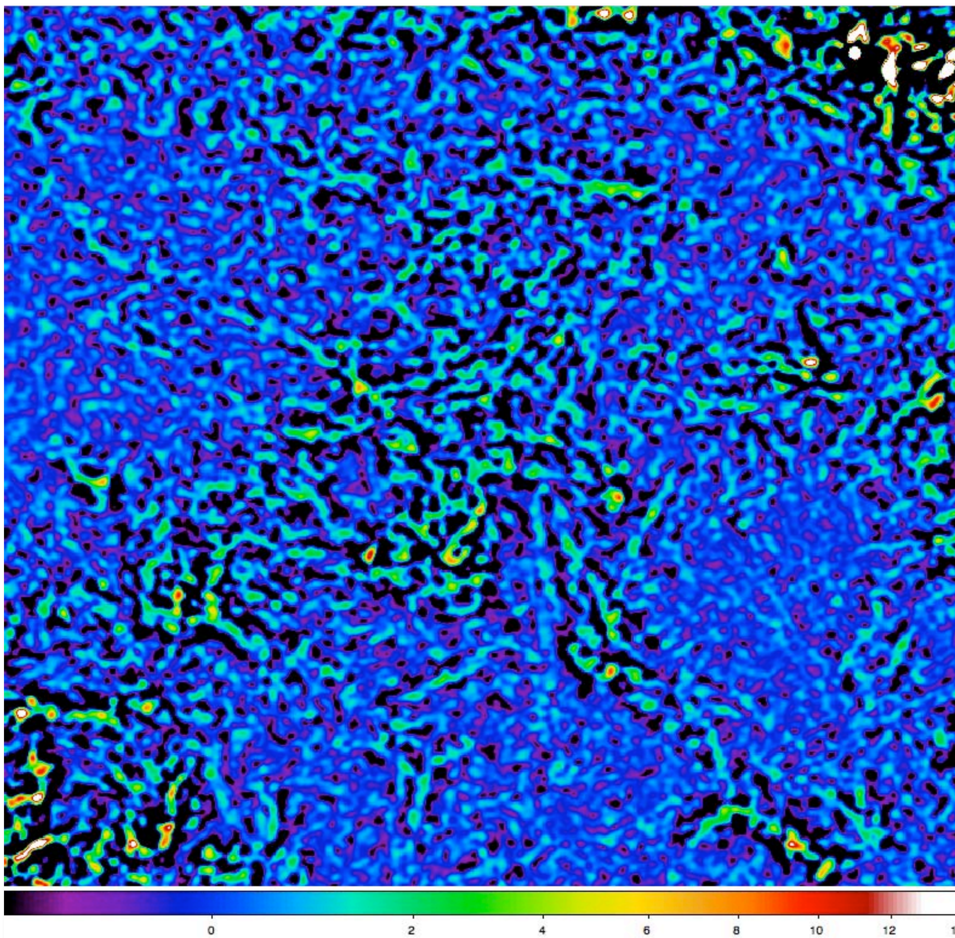
1.2°



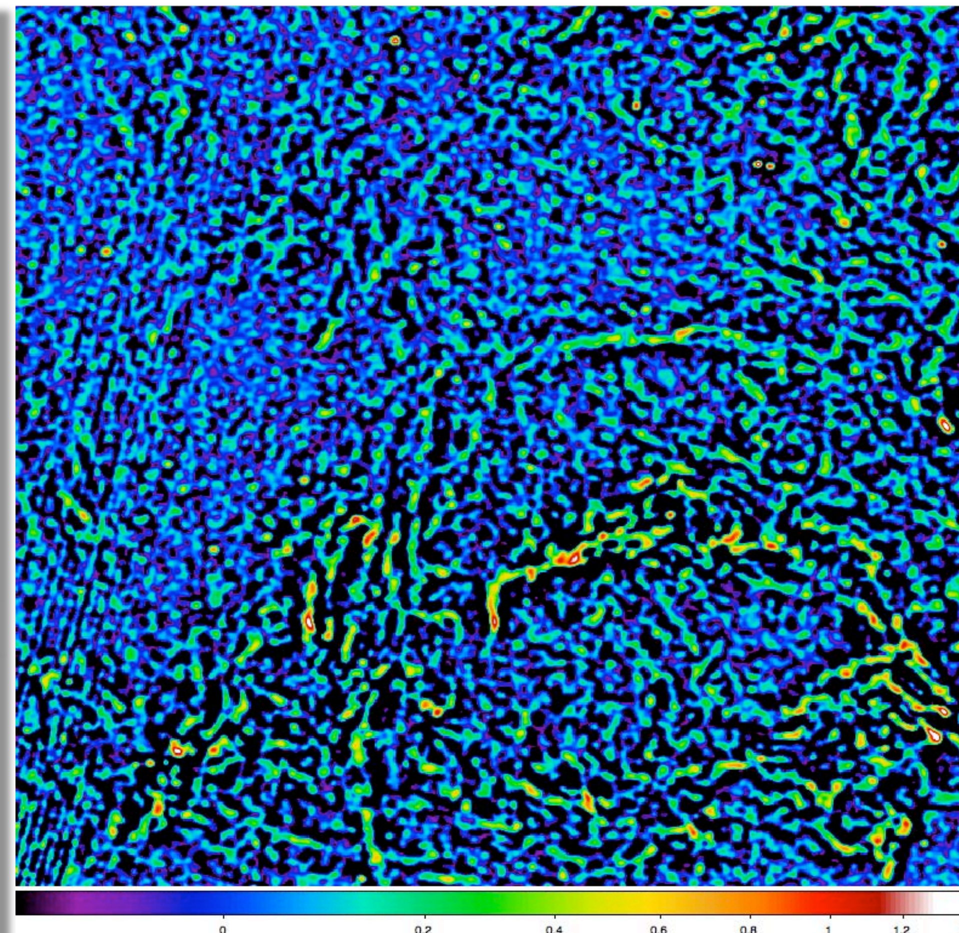
1.2°

Aquila and Polaris Sub-Fields 3: SPIRE

single scales ~40”: high-contrast filaments and objects



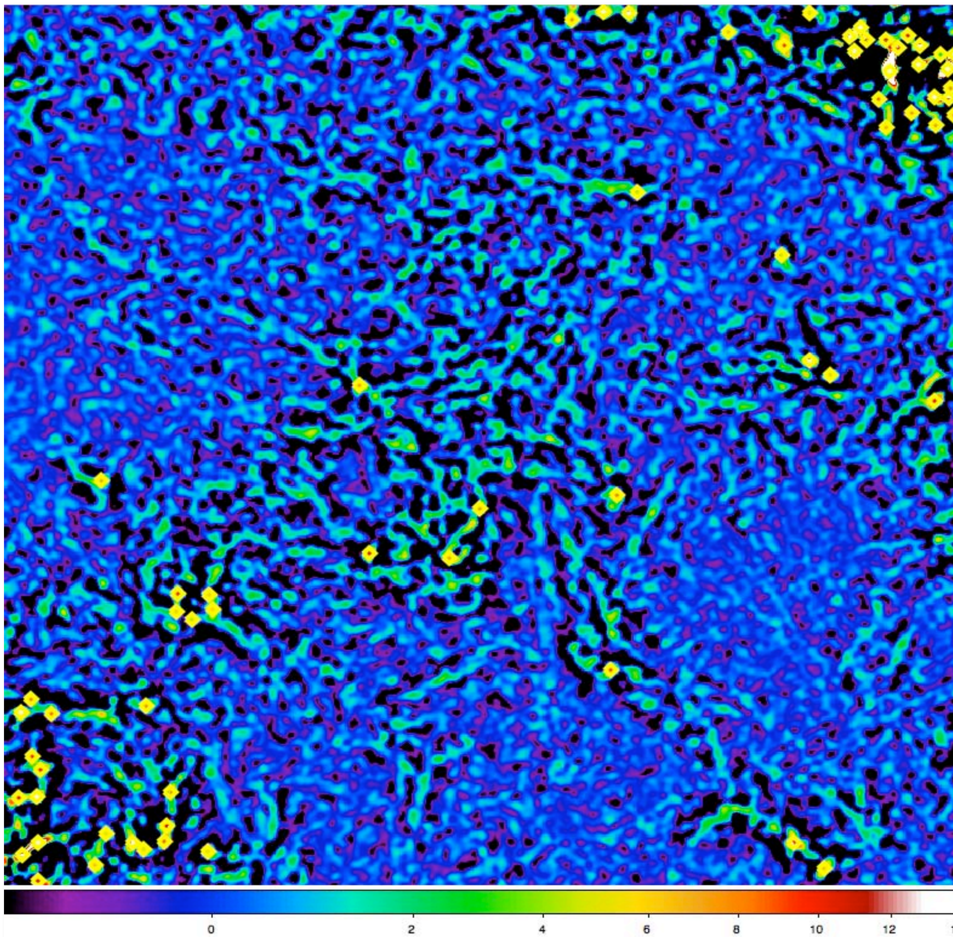
1.2°

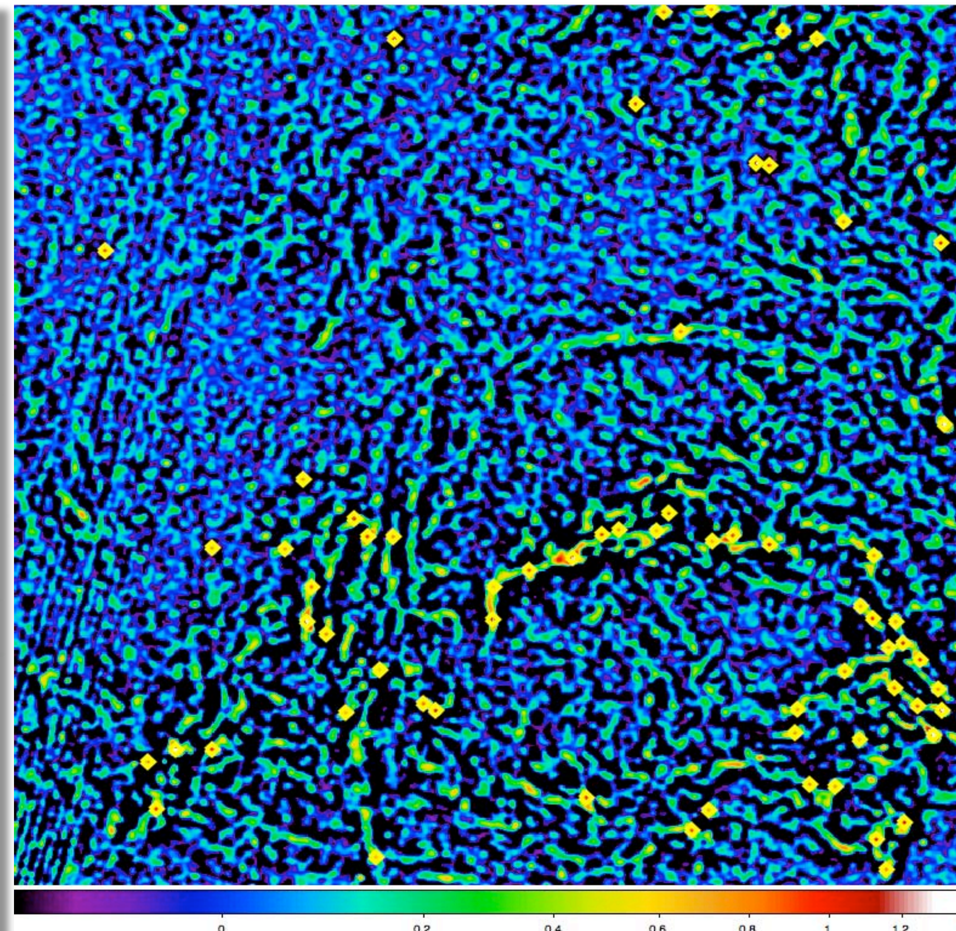


1.2°

Aquila and Polaris Sub-Fields 3: SPIRE

single scales ~40” + naive visual detection

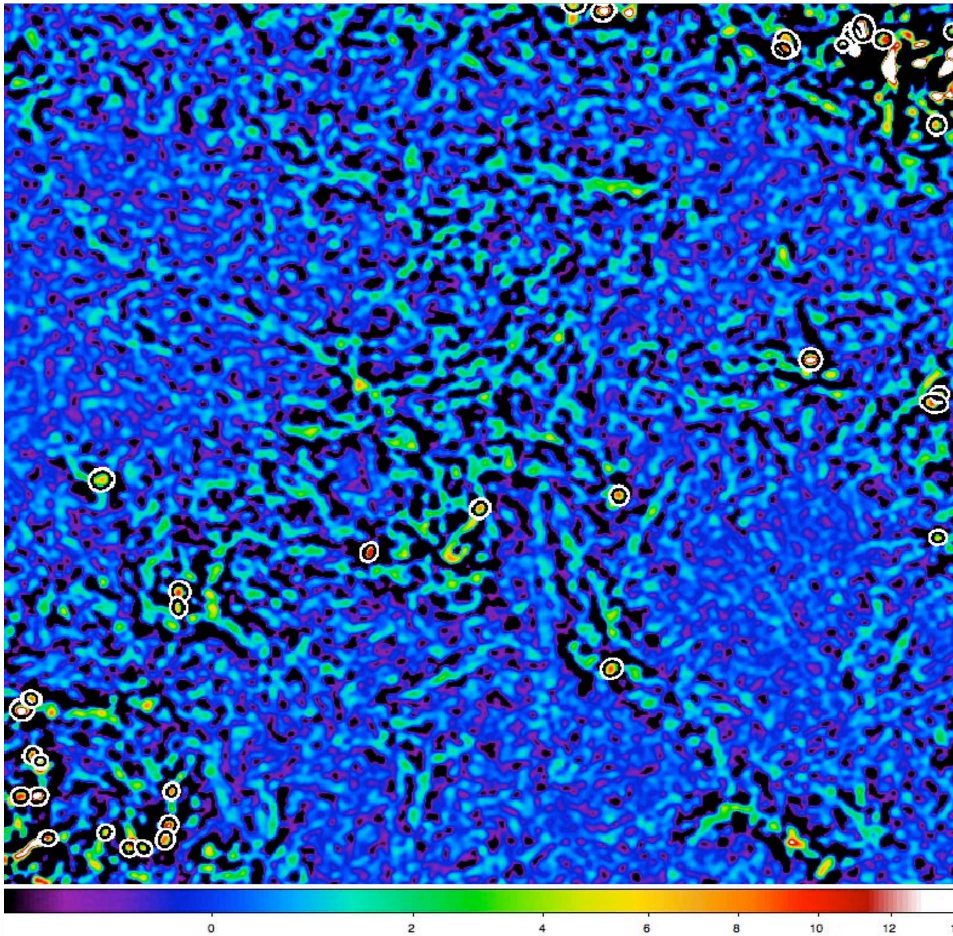


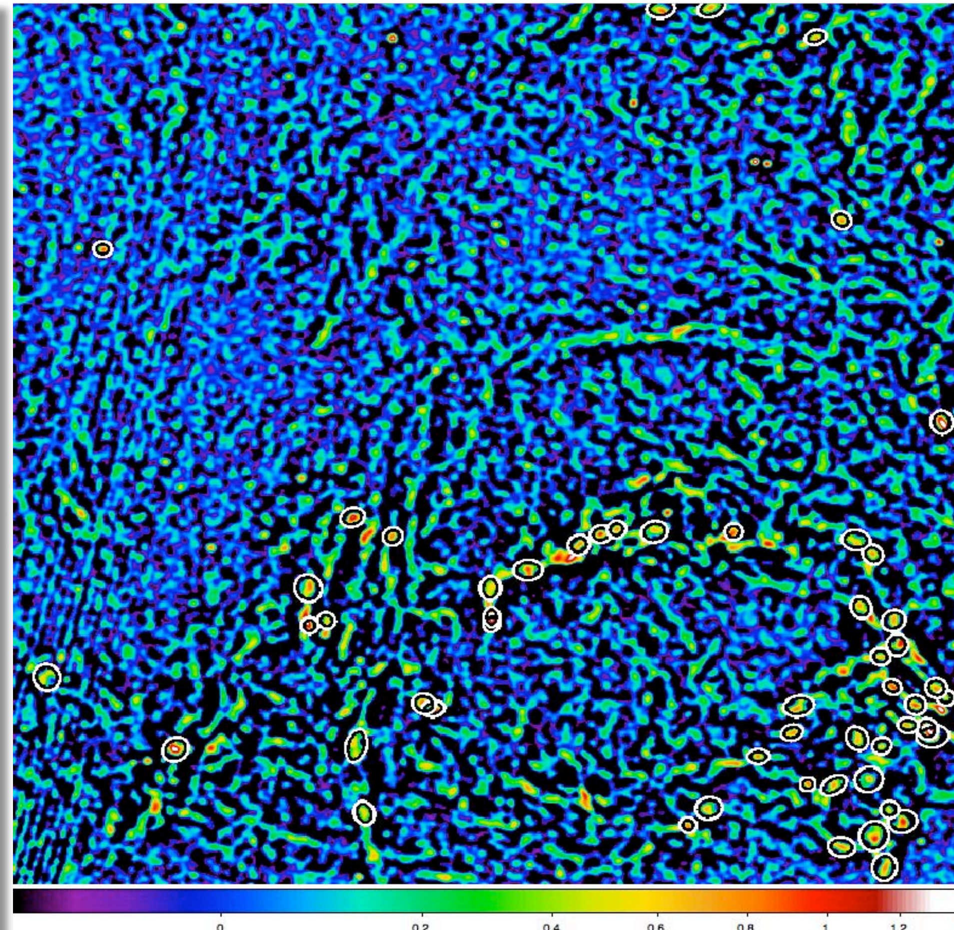


65 objects 1.2° 1.2° 66 objects

Aquila and Polaris Sub-Fields 3: SPIRE

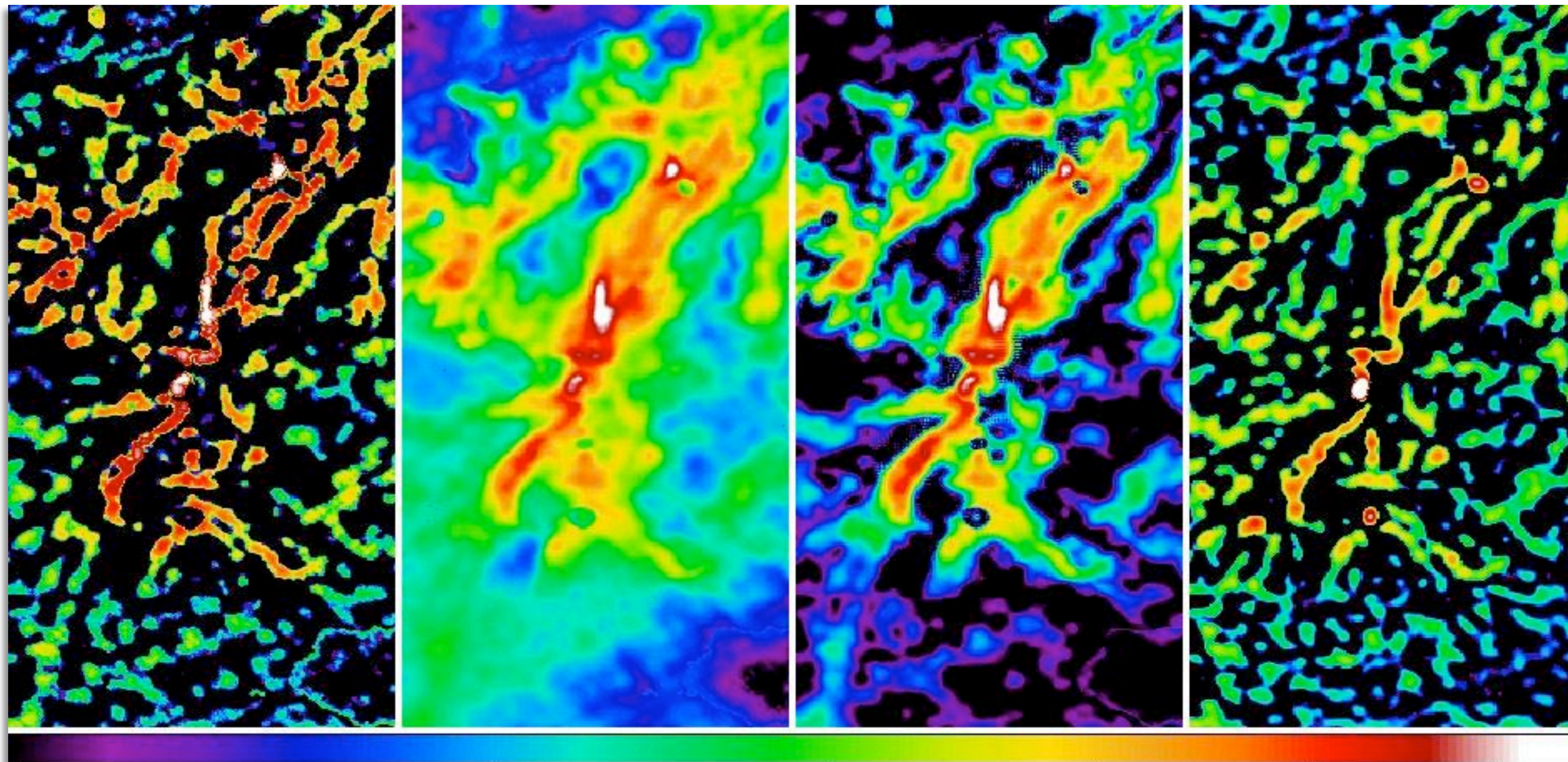
single scales ~40" + starless cores by *getsources*





34 cores 1.2° 1.2° 50 cores

Two Methods, Same Structures
column density, curvelet component, and single scale



curvelet log-scaled　　column density　　curvelet　　single scale ~40”

Filaments' Properties and Existing Models

Basic Properties of the Filaments

- Several well-behaved filaments in column density images, original images

Field	Colum H_2	Temper	<FWHM>deconv	Maximum length	Density
Aquila	$< 1.4\times10^{23}$	7.5-15 K	35"±12 ~9000 AU	~0.5 deg ~few pc	$\rho \sim r^{-1.5}$
Polaris	$< 9\times10^{21}$	10-15 K	60"±12 ~9000 AU	~0.5 deg ~few pc	$\rho \sim r^{-2}$

- Maps of the filaments' mass per unit length (talk by Ph. André):
  many Aquila filaments are gravitationally unstable, Polaris filaments are stable

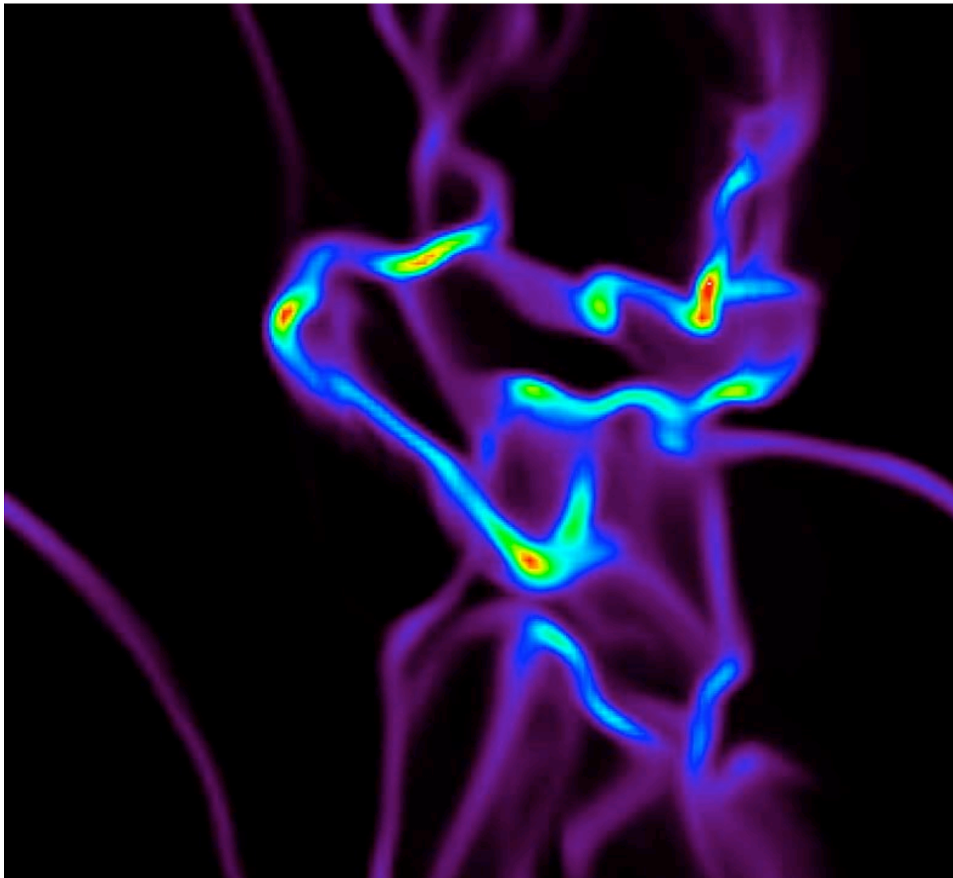
Formation of Filaments and Cores

a few selected models

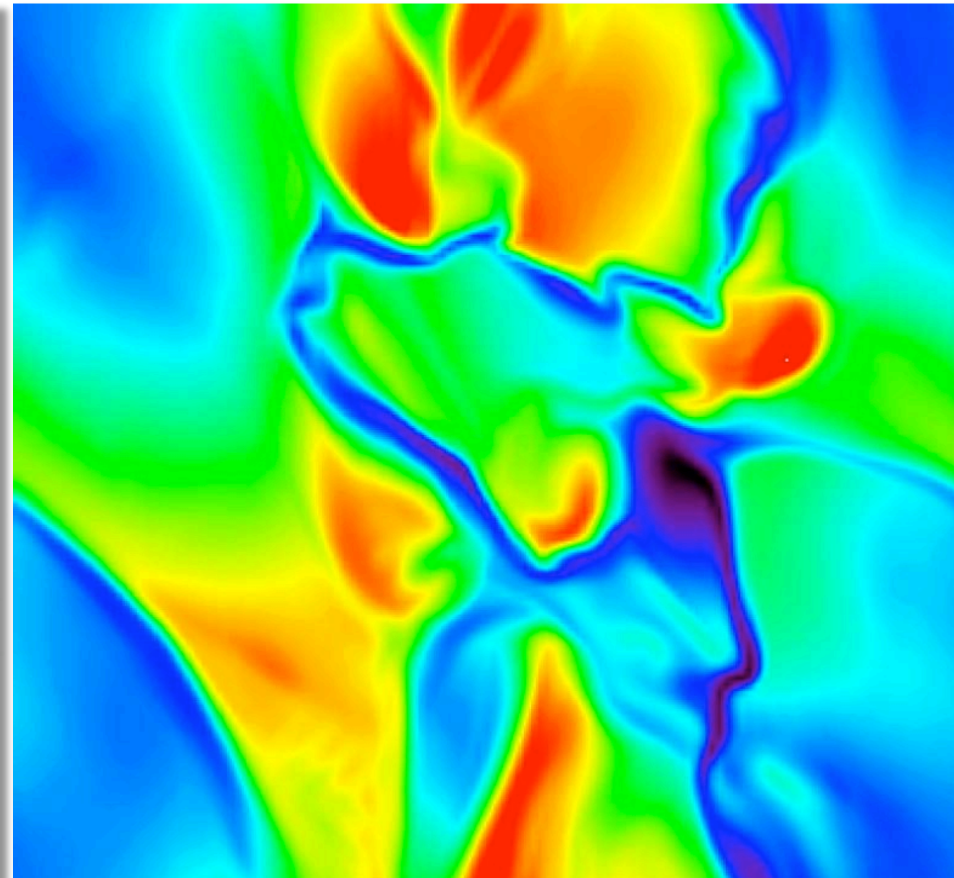
- MHD simulations of supersonic turbulent motions in weakly magnetized clouds (Padoan et al. 2001): complex system of shocks creating high-density sheets, filaments, and cores
- MHD simulations of turbulent, more strongly magnetized molecular clouds with ambipolar diffusion (Nakamura & Li 2008): sheets, filaments, and cores
- Observed profiles $\rho \sim r^{-1.5}$ and $\rho \sim r^{-2}$ are inconsistent with those of non-magnetic models of hydrostatic filaments, $\rho \sim r^{-4}$ (Ostriker 1964)
- Models of filaments with primarily toroidal or helical magnetic fields can account for profiles $\rho \sim r^{-1}$ to $\rho \sim r^{-2}$, in agreement with observations (Fiege & Pudritz 2000)

Turbulent Fragmentation, Padoan et al. (2001)

slices of the 3D density and velocity fields, Mach ~10



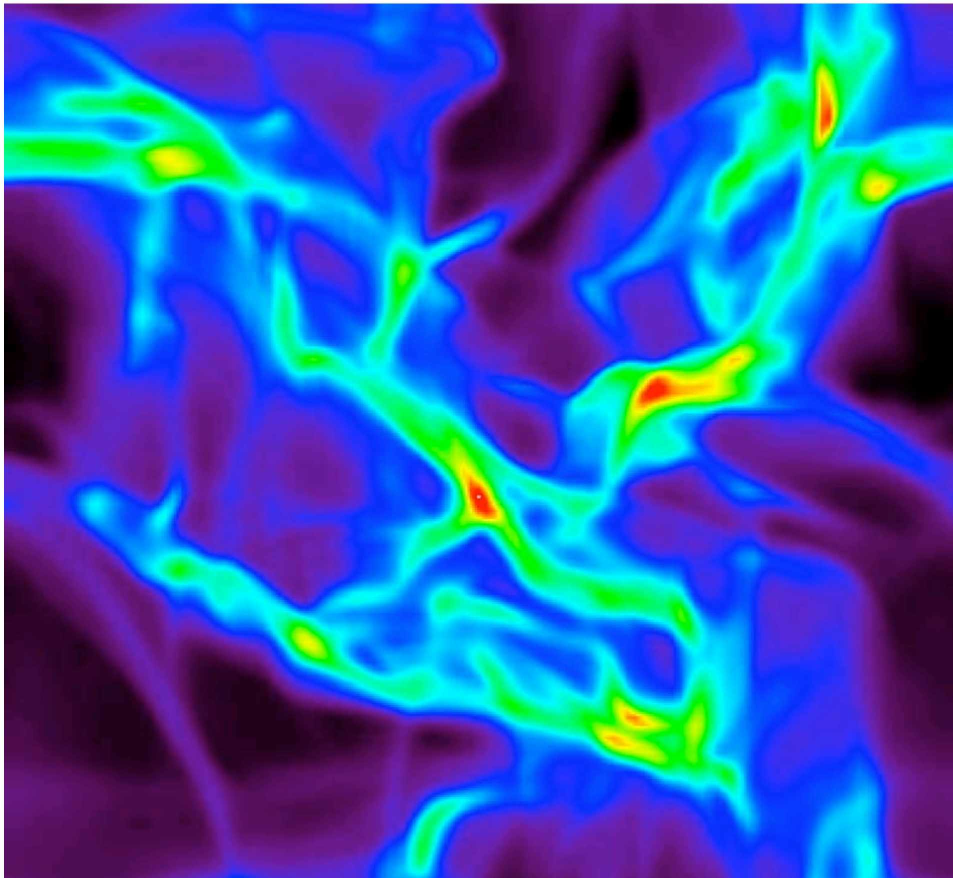
density



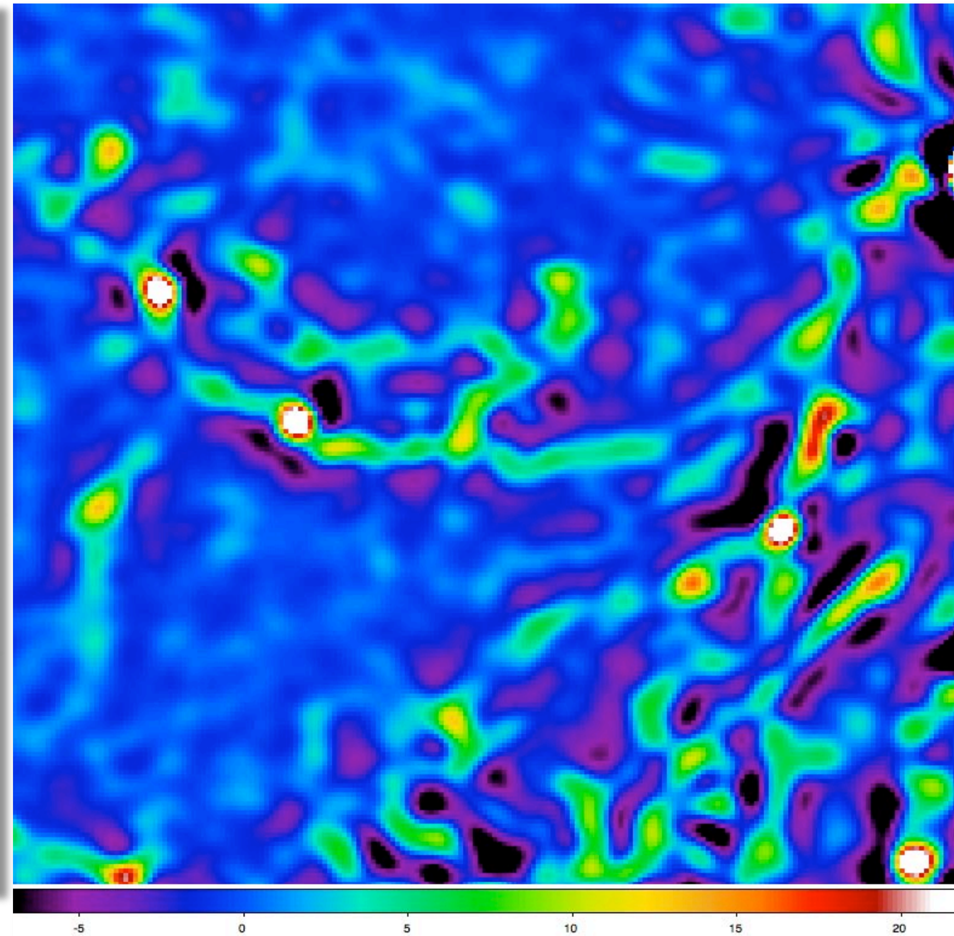
|velocity|

Turbulent Fragmentation, Padoan et al. (2001)

structural resemblance to the observed filaments



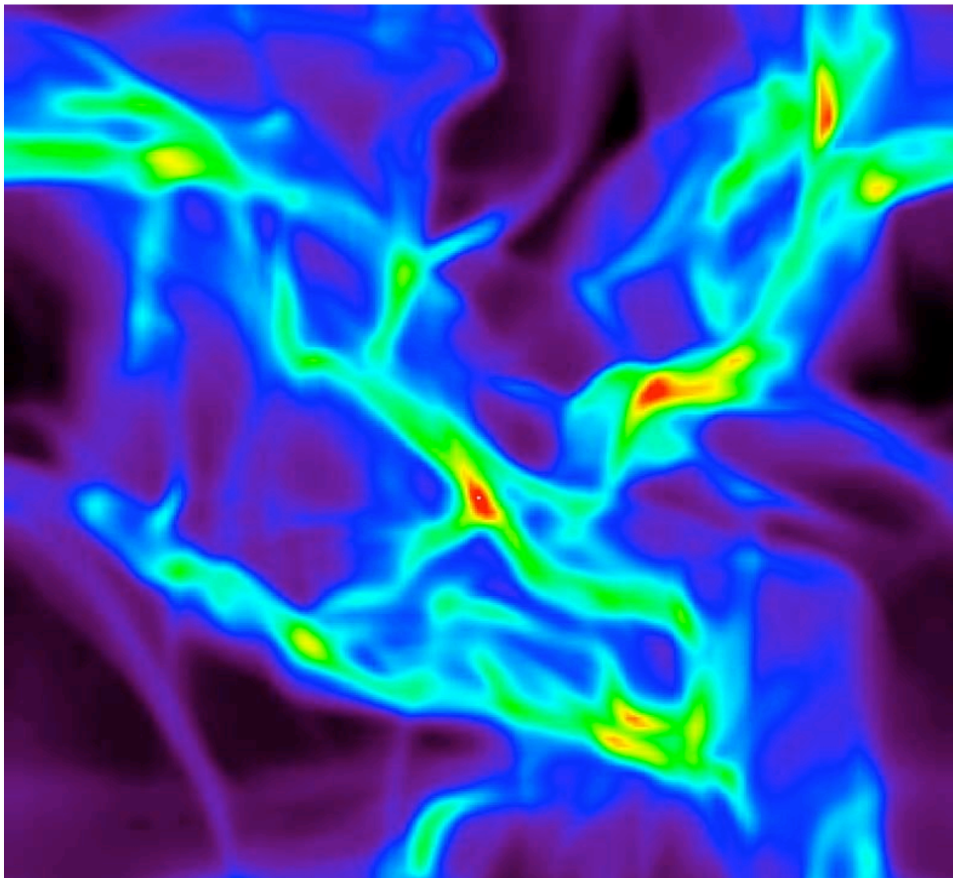
column density



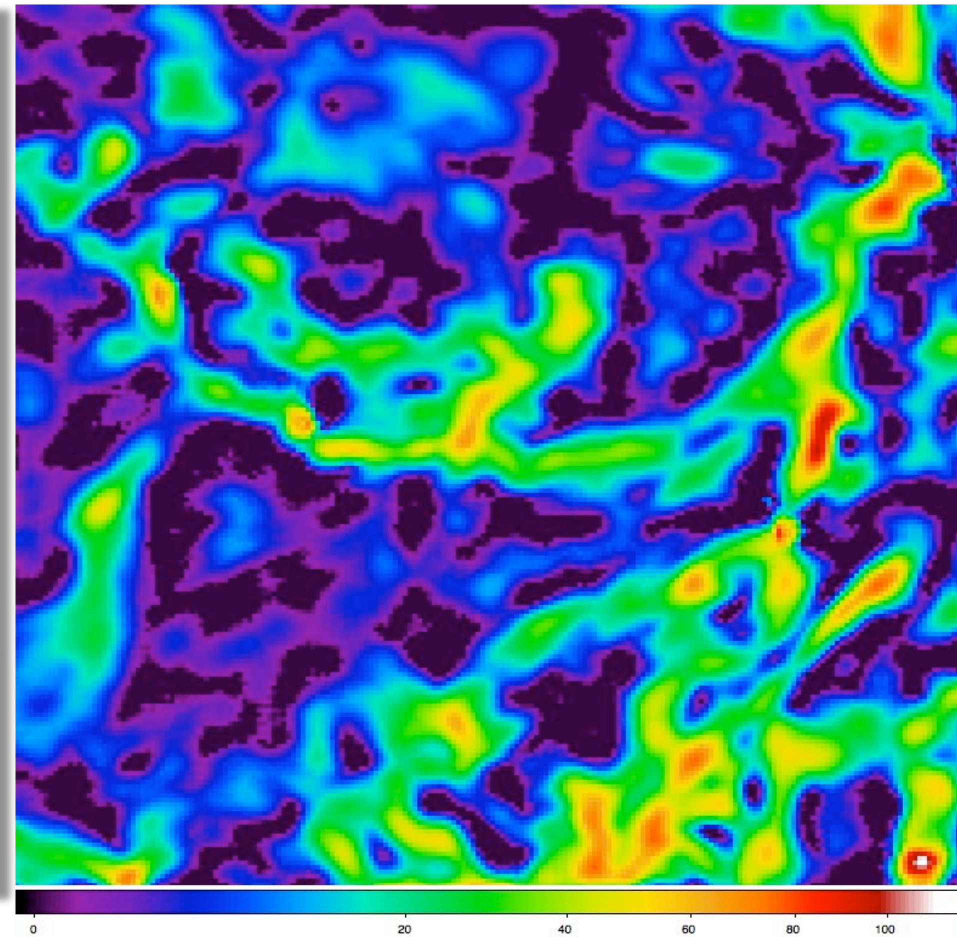
Aquila in SPIRE bands, single scale ~40”

Turbulent Fragmentation, Padoan et al. (2001)

structural resemblance to the observed filaments



column density



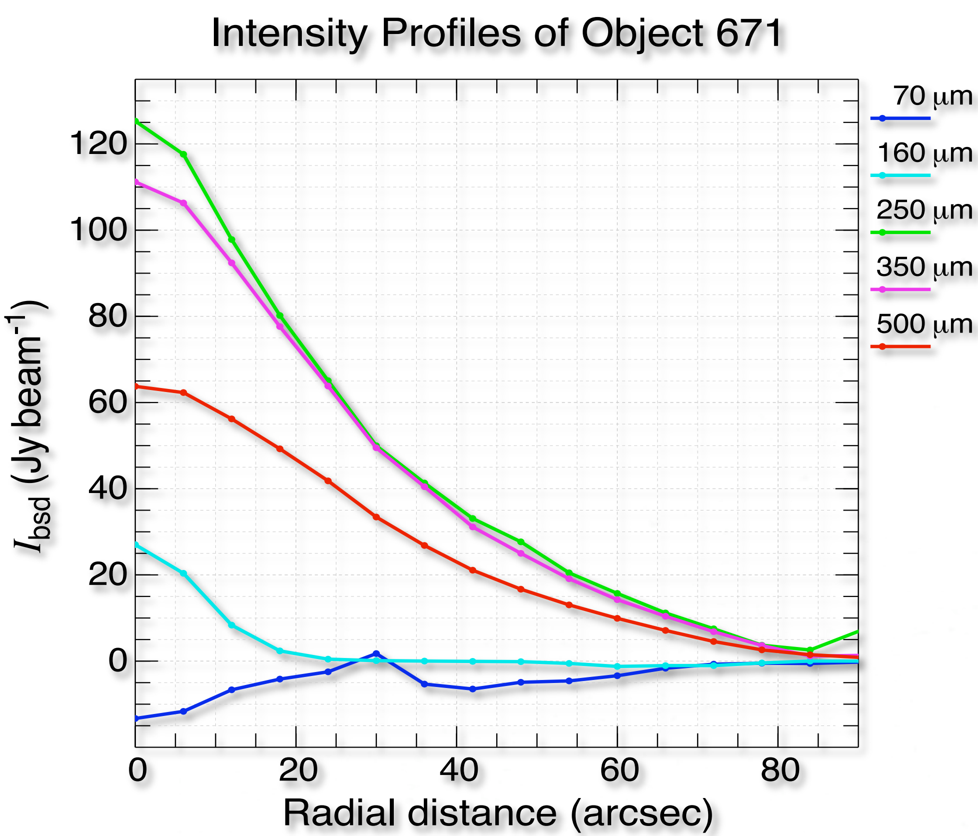
Aquila at 350 μm, curvelet component

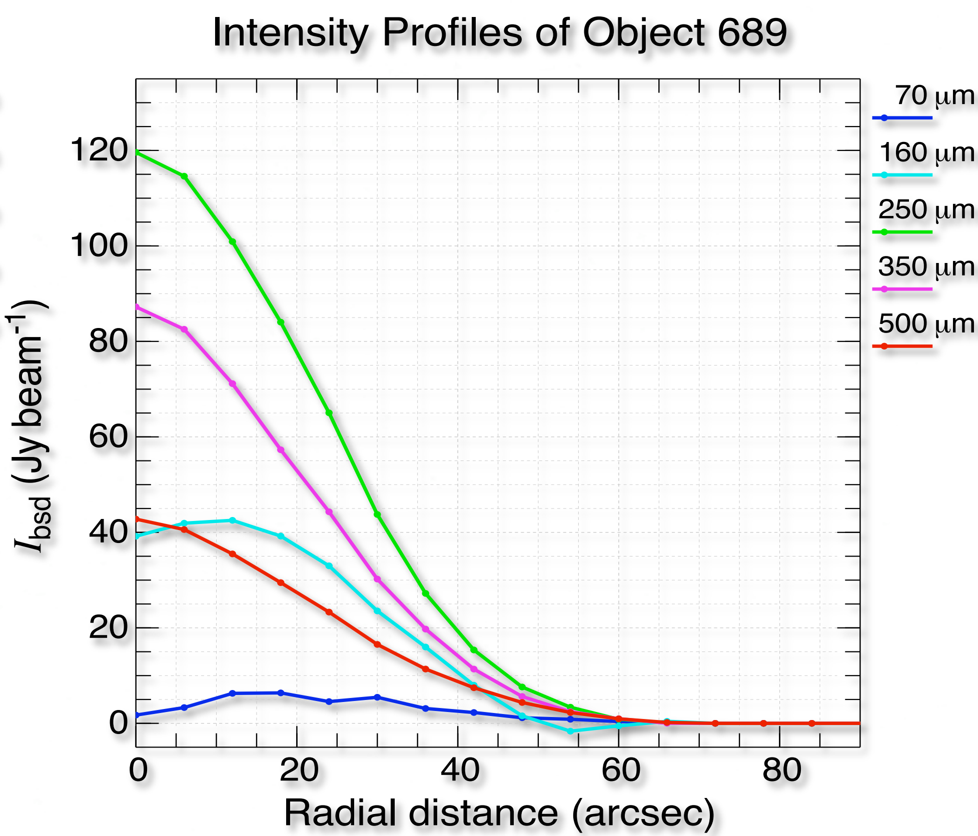
Conclusions

- Fascinating filamentary structures are *everywhere* – as deep as we can see with the sensitivity of our instruments
- All extracted objects (starless cores, prestellar cores, embedded protostars) are *physically* related to the filaments
- The observations suggest that, in general, prestellar cores *originate* in the fragmentation of complex filamentary networks
- To unravel the roles and relative importance of gravity, turbulence, and magnetic fields, we need to obtain additional *kinematic* information

Aquila: Profiles of Selected Objects

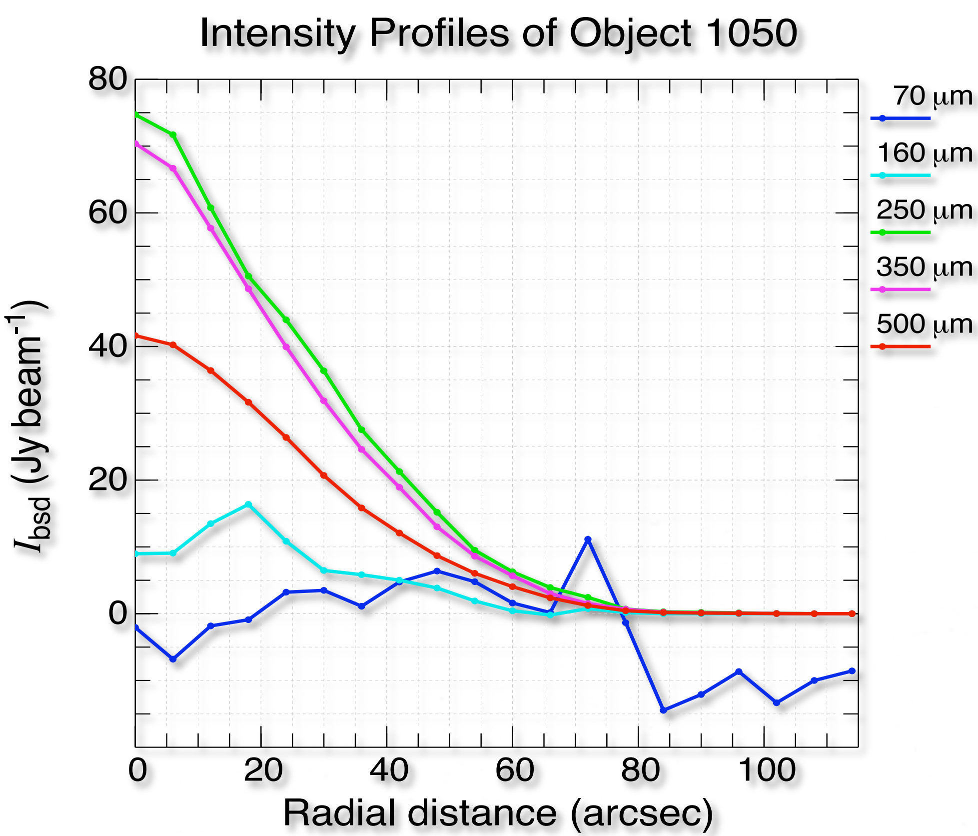
azimuthally-averaged intensities

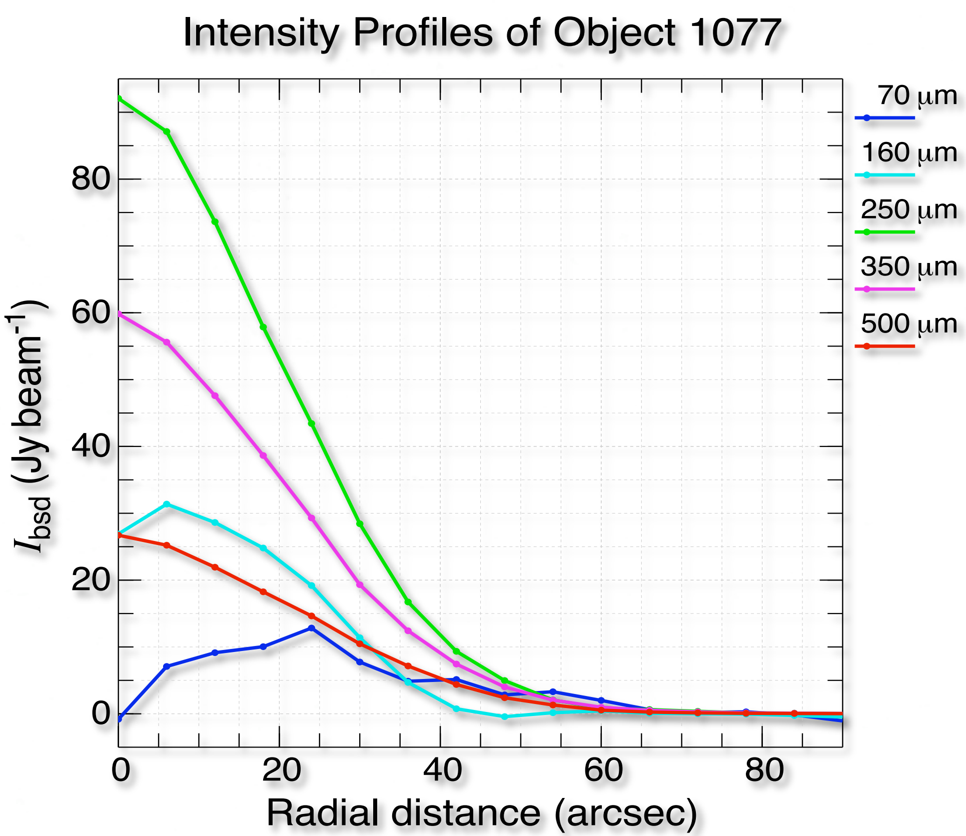




Aquila: Profiles of Selected Objects

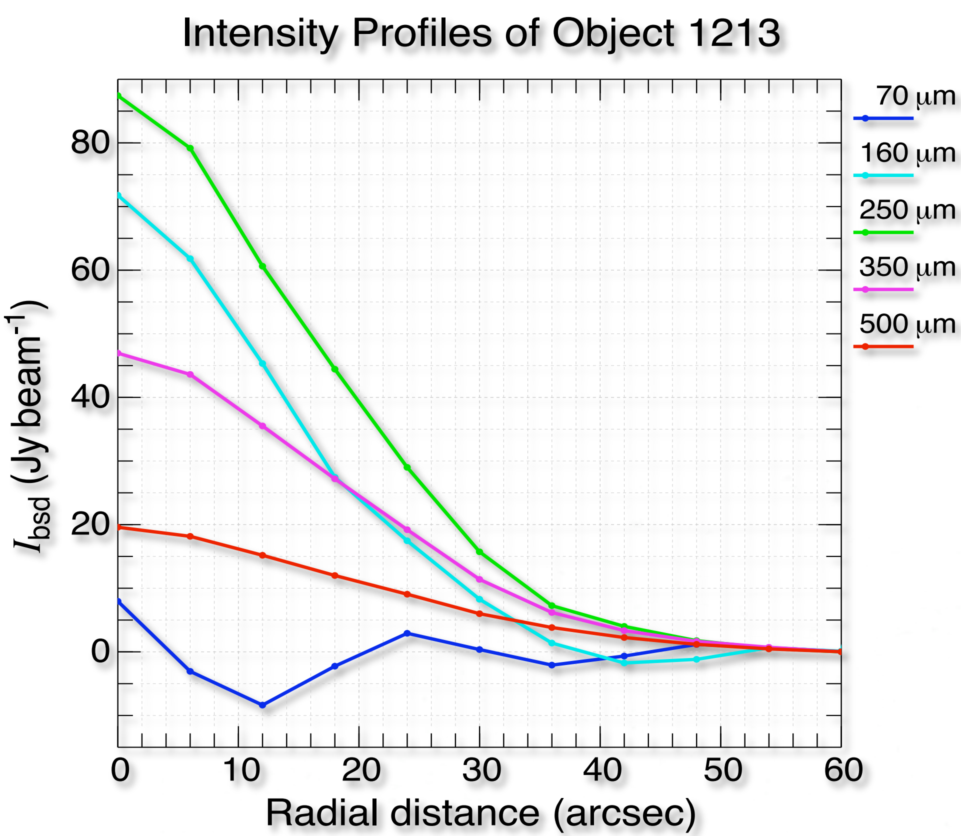
azimuthally-averaged intensities

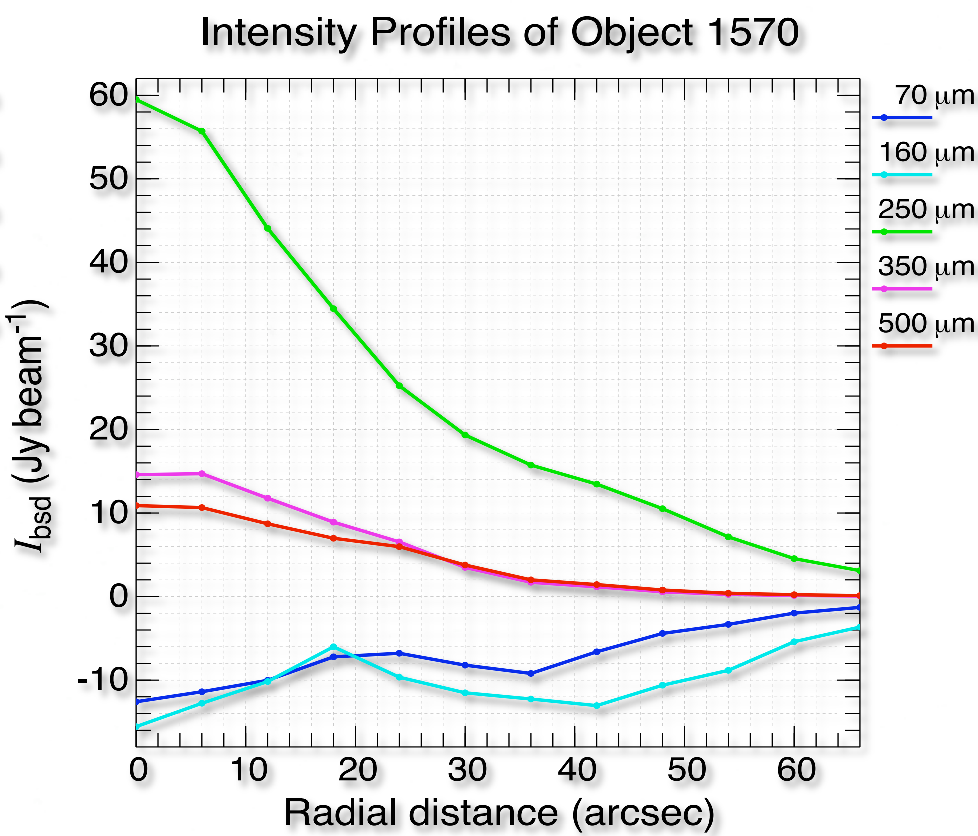




Aquila: Profiles of Selected Objects

azimuthally-averaged intensities





Aquila: Profiles of Selected Objects

azimuthally-averaged intensities