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*From Discovery to Innovation...*

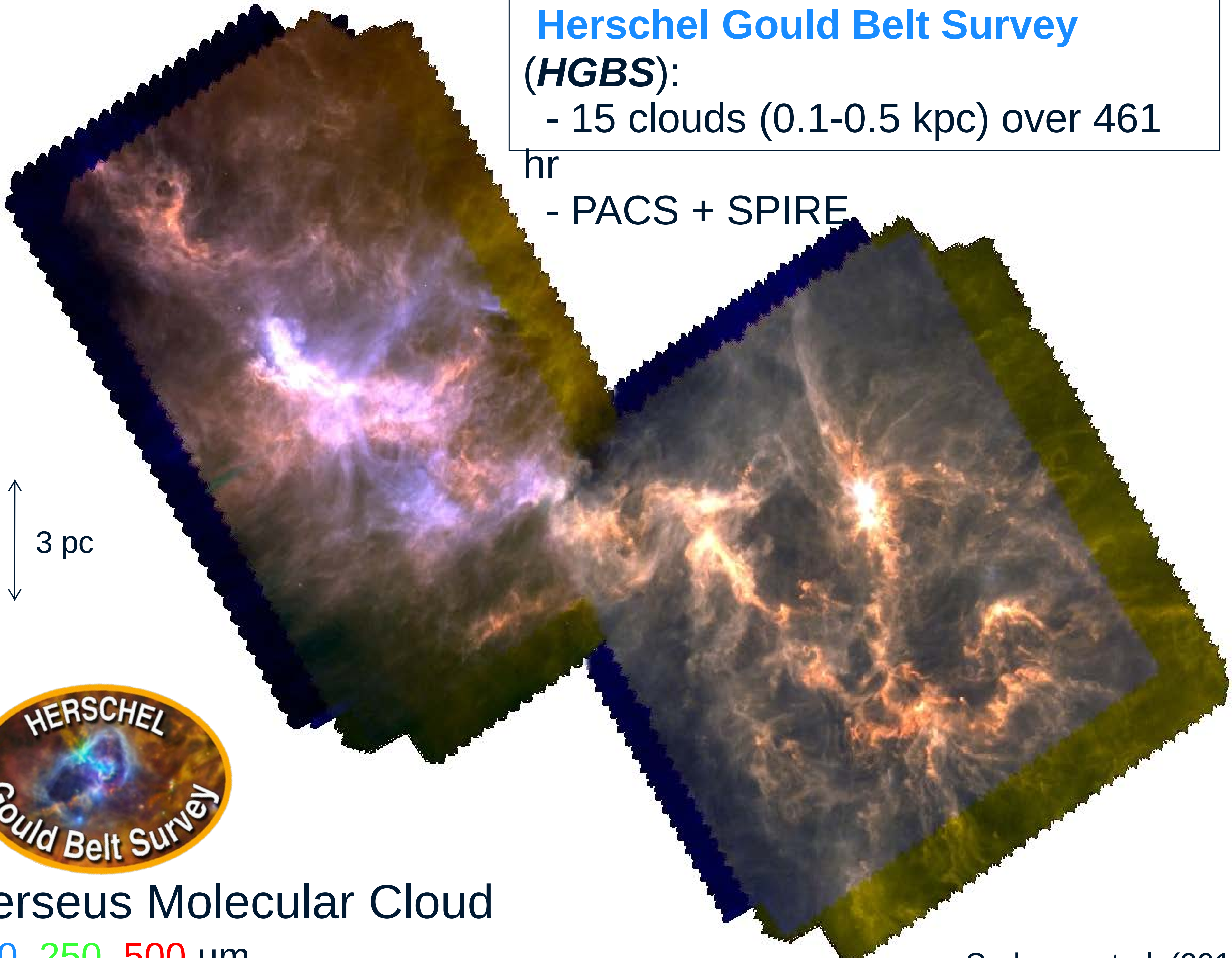
# Observed Relationships between Filaments and Star Formation


James Di Francesco

(Ph. André, J. Pineda, R. Pudritz, D. Ward-Thompson, S.Inutsuka & the Herschel GBS, JCMT GBS and HOBYS Teams

## Herschel Gould Belt Survey (*HGBS*):

- 15 clouds (0.1-0.5 kpc) over 461 hr
- PACS + SPIRE



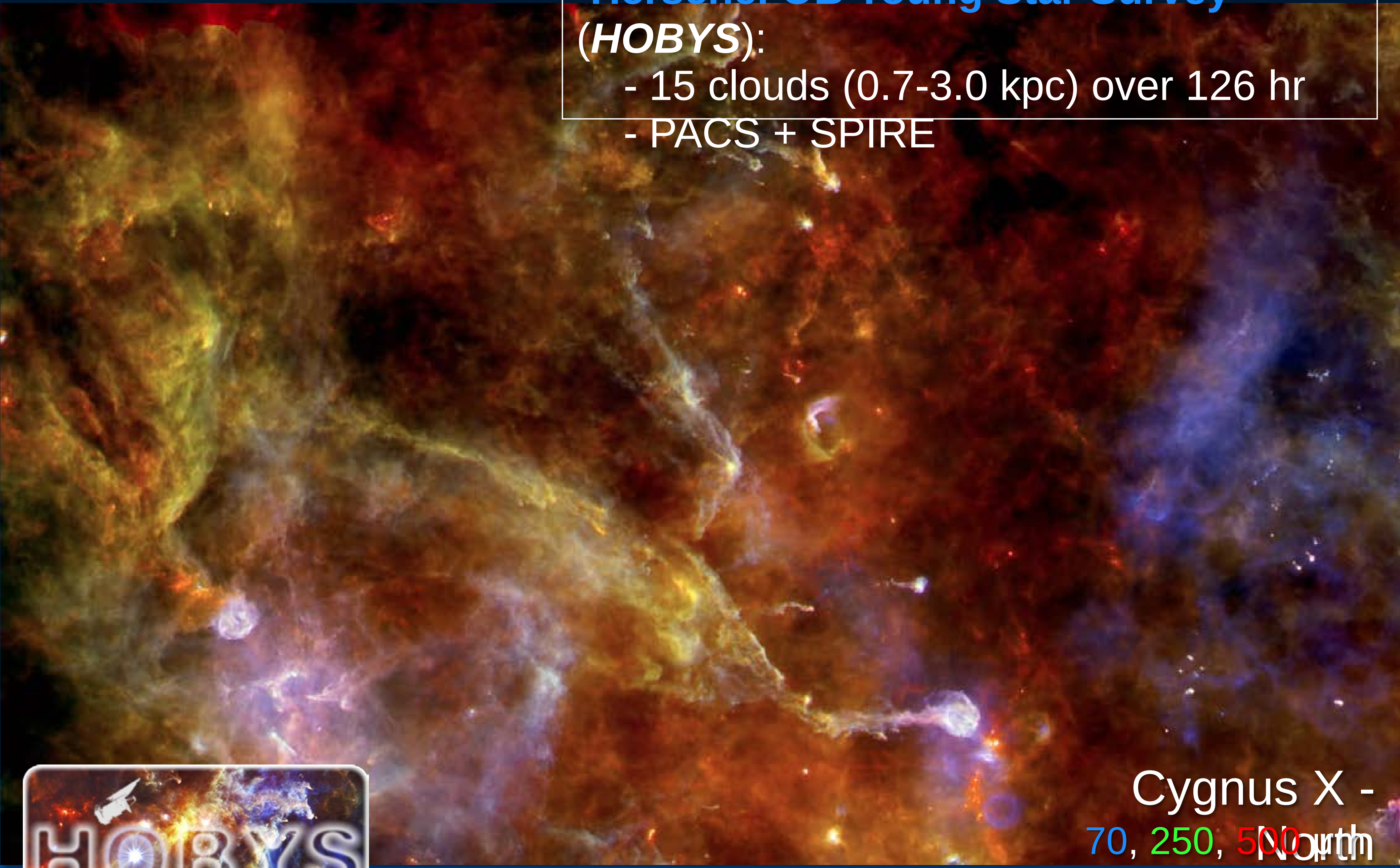

Perseus Molecular Cloud

160, 250, 500 μm

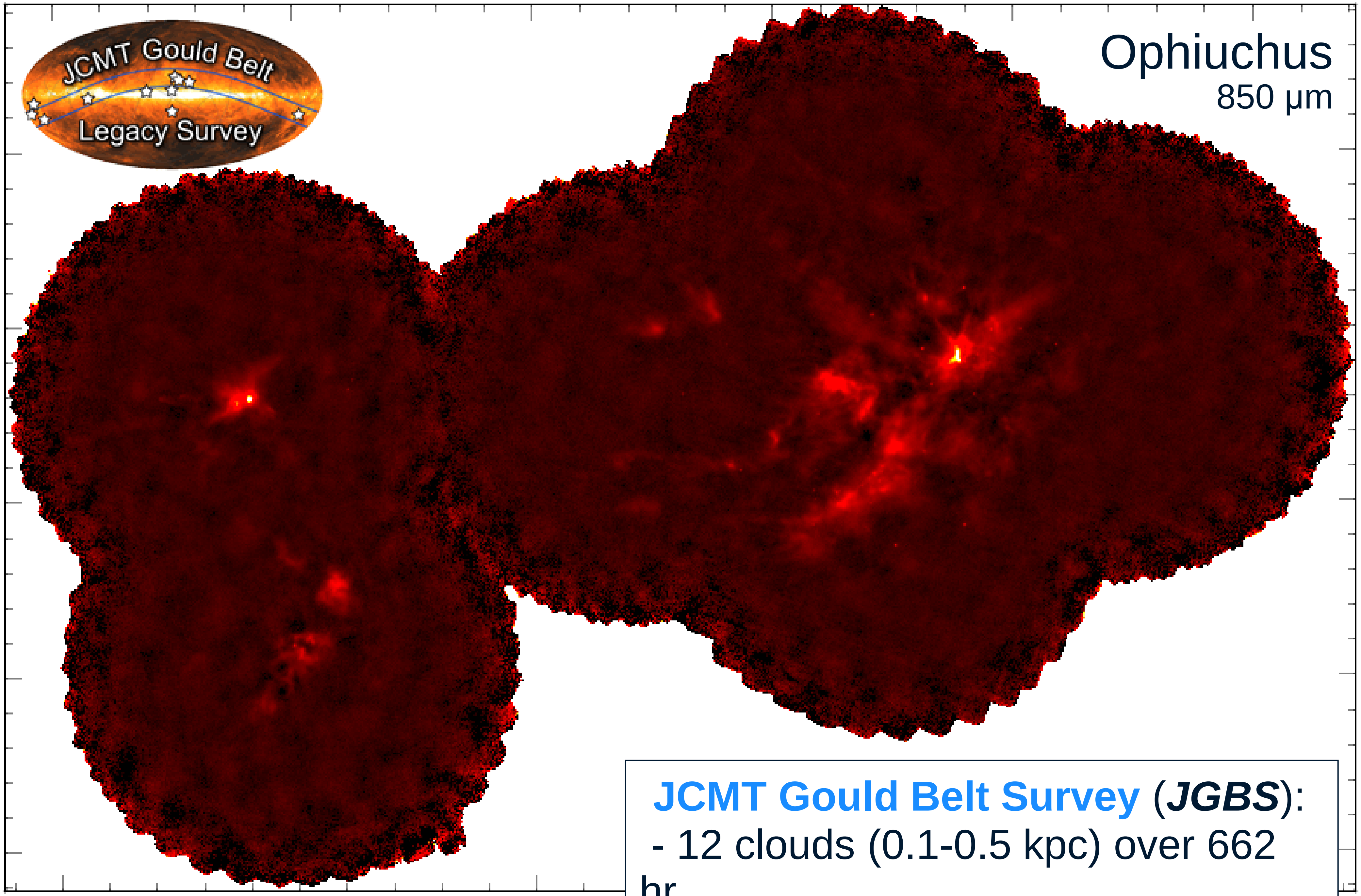
Sadavoy et al. (2014)

## Herschel OB Young Star Survey (***HOBYS***):

- 15 clouds (0.7-3.0 kpc) over 126 hr
- PACS + SPIRE




Hennemann et al. (2012)

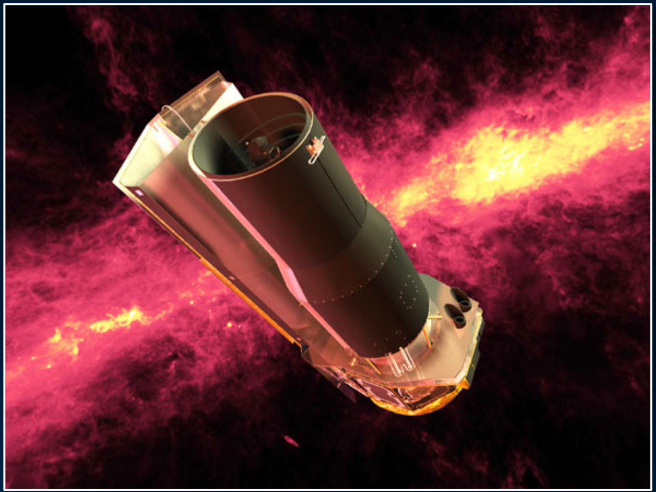



**JCMT Gould Belt Survey** (***JGBS***):

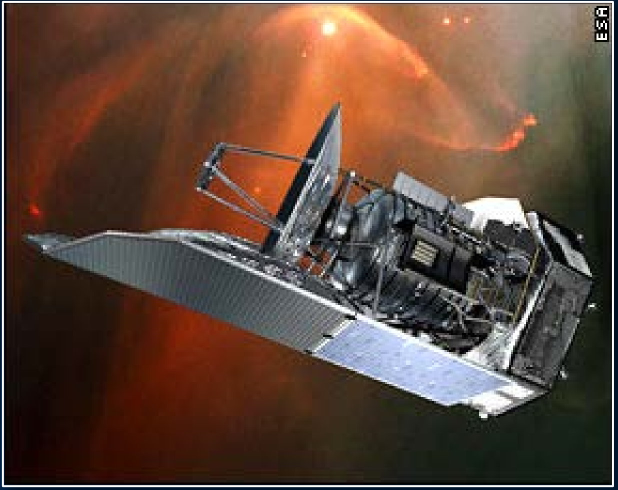
- 12 clouds (0.1-0.5 kpc) over 662 hr
- SCUBA-2 (ongoing!) + HARP

Image by R. Friesen; Pattle et al. (2014, in prep)

# Tracing YSOs, Cores and Filaments



Spitzer Space Telescope




Herschel Space Observatory

James Clerk Maxwell Telescope

Dust emission traces mass in clouds very well:

- **Spitzer** (3.6 – 8 μm, 24 – 160 μm) traced Class 0/I, II, III populations

- **Herschel** (70 μm – 500 μm) traced cores + filaments, $T_{dust}$ + $N(H_2)$

- **JCMT** (450 μm + 850 μm) traces cores + filaments, $\beta$, $T_{dust}$ + $N(H_2)$

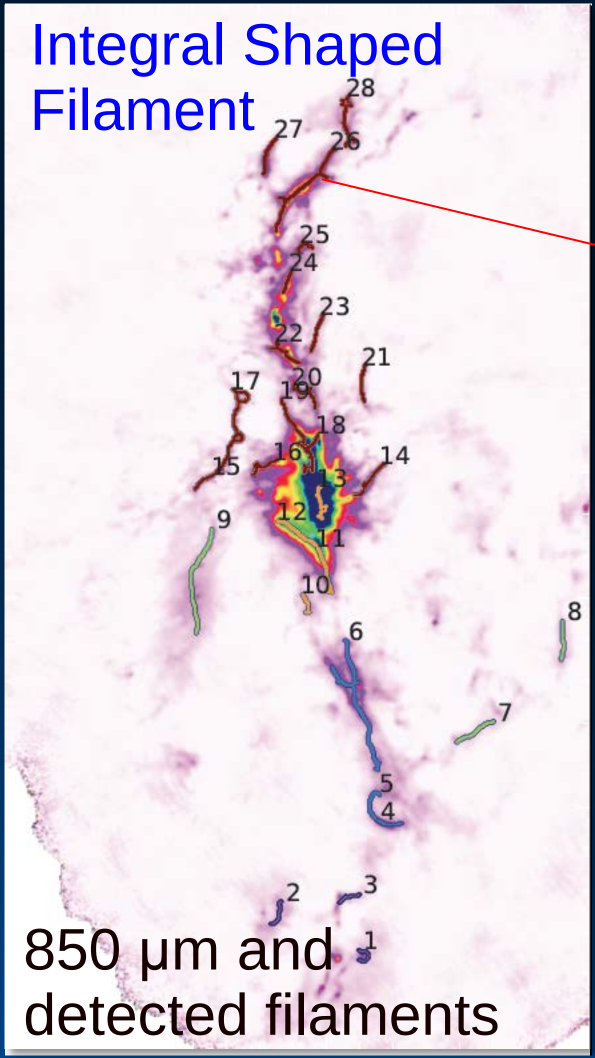
# YSO – Filament Spatial Correlations

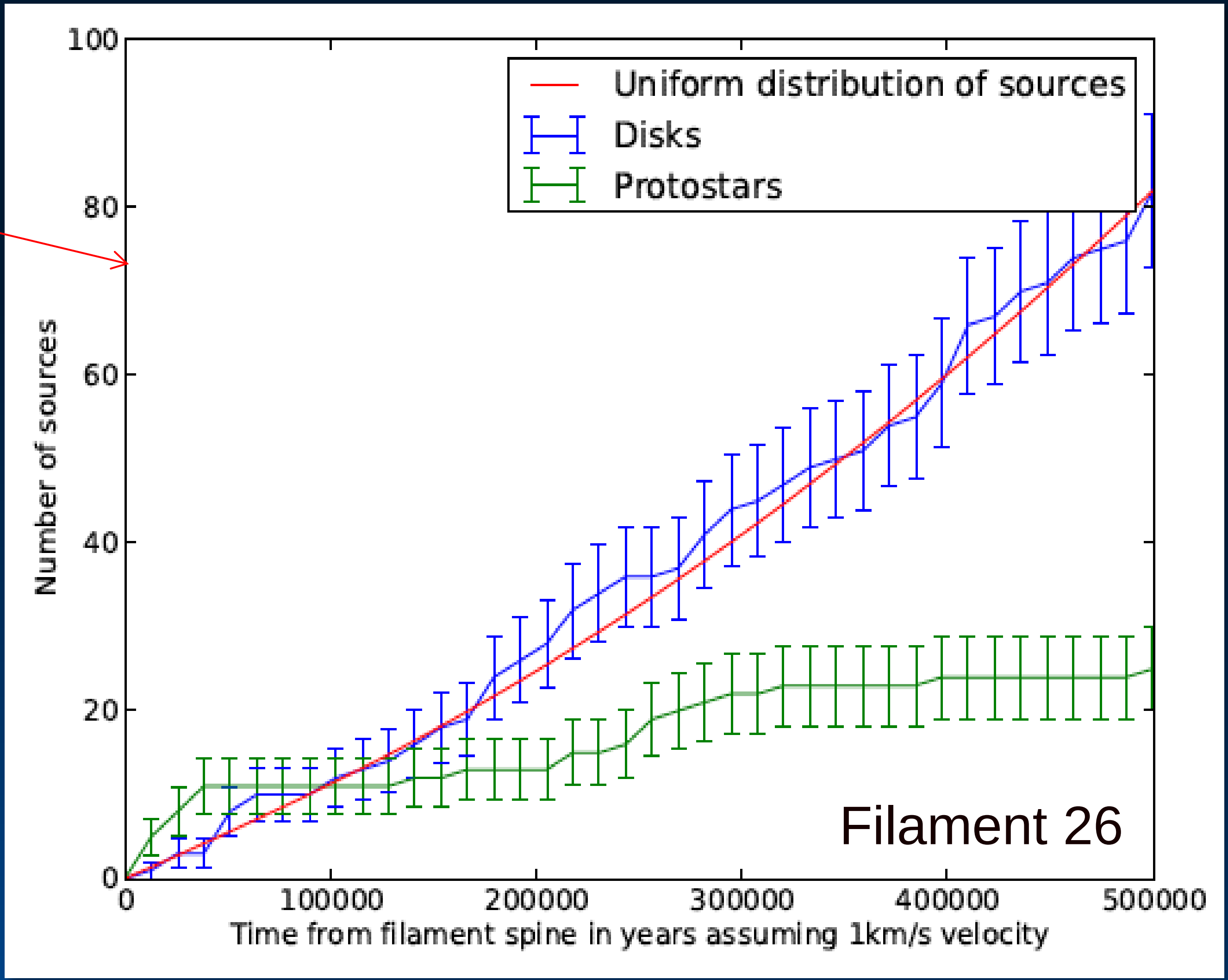

Image by J. Di Francesco

Are filaments spatially correlated with young stellar objects?

Direct comparisons of YSO and filament populations can provide answers…

# YSO – Filament Spatial Correlations

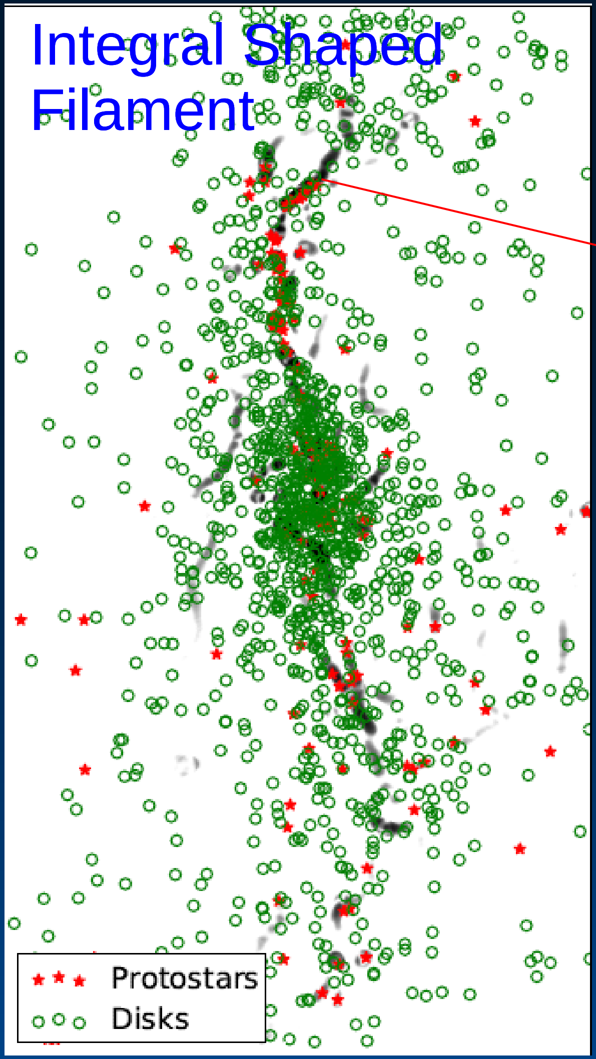


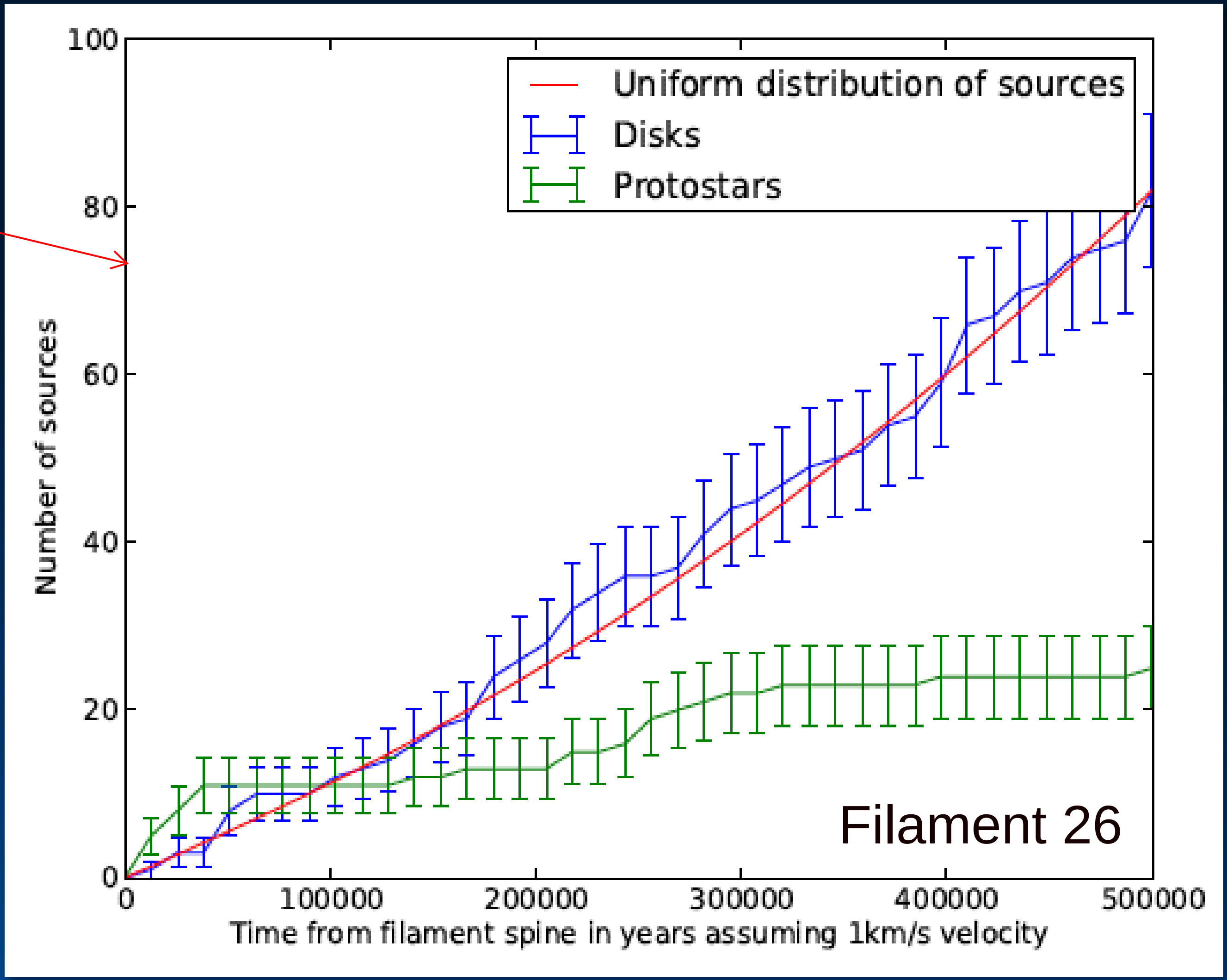




- filaments are far more spatially correlated with "protostars" (Class 0/I objects) than with "disks" (Class II objects)

Salji et al. (2014, submitted)

# YSO – Filament Spatial Correlations



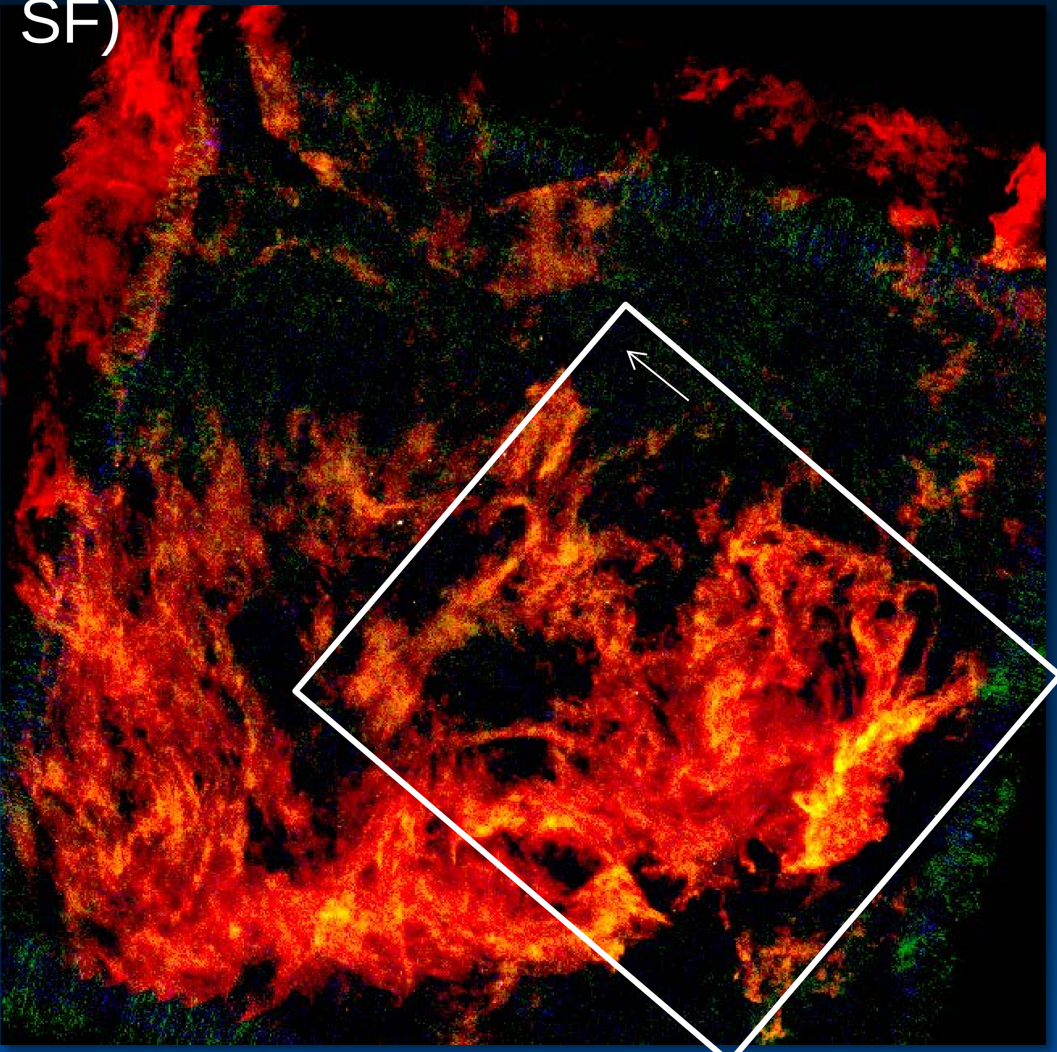




- filaments are far more spatially correlated with "protostars" (Class 0/I objects) than with "disks" (Class II objects)

Salji et al. (2014, submitted)

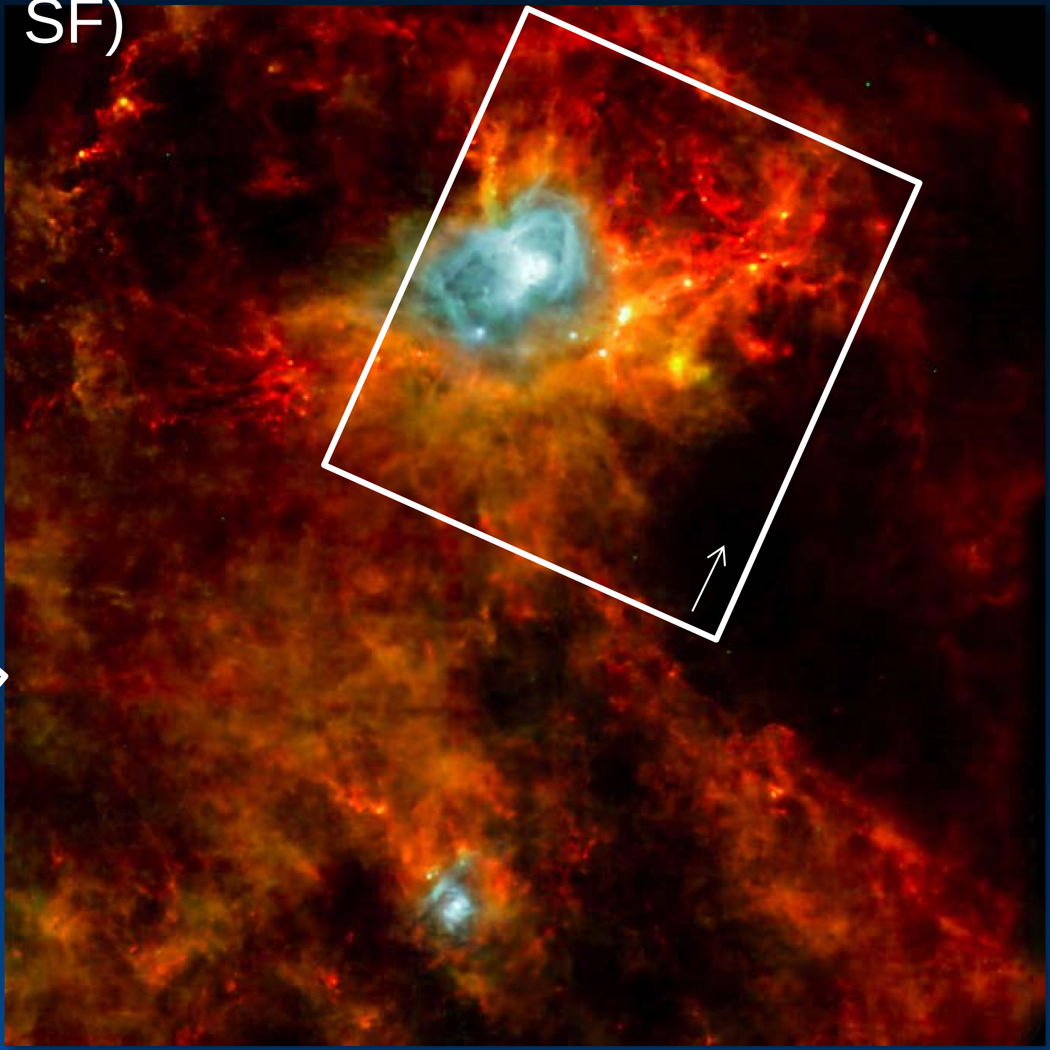
# YSO – Filament Spatial Correlations

Polaris Flare (no SF)



PACS + SPIRE: 160, 250, 500 µm

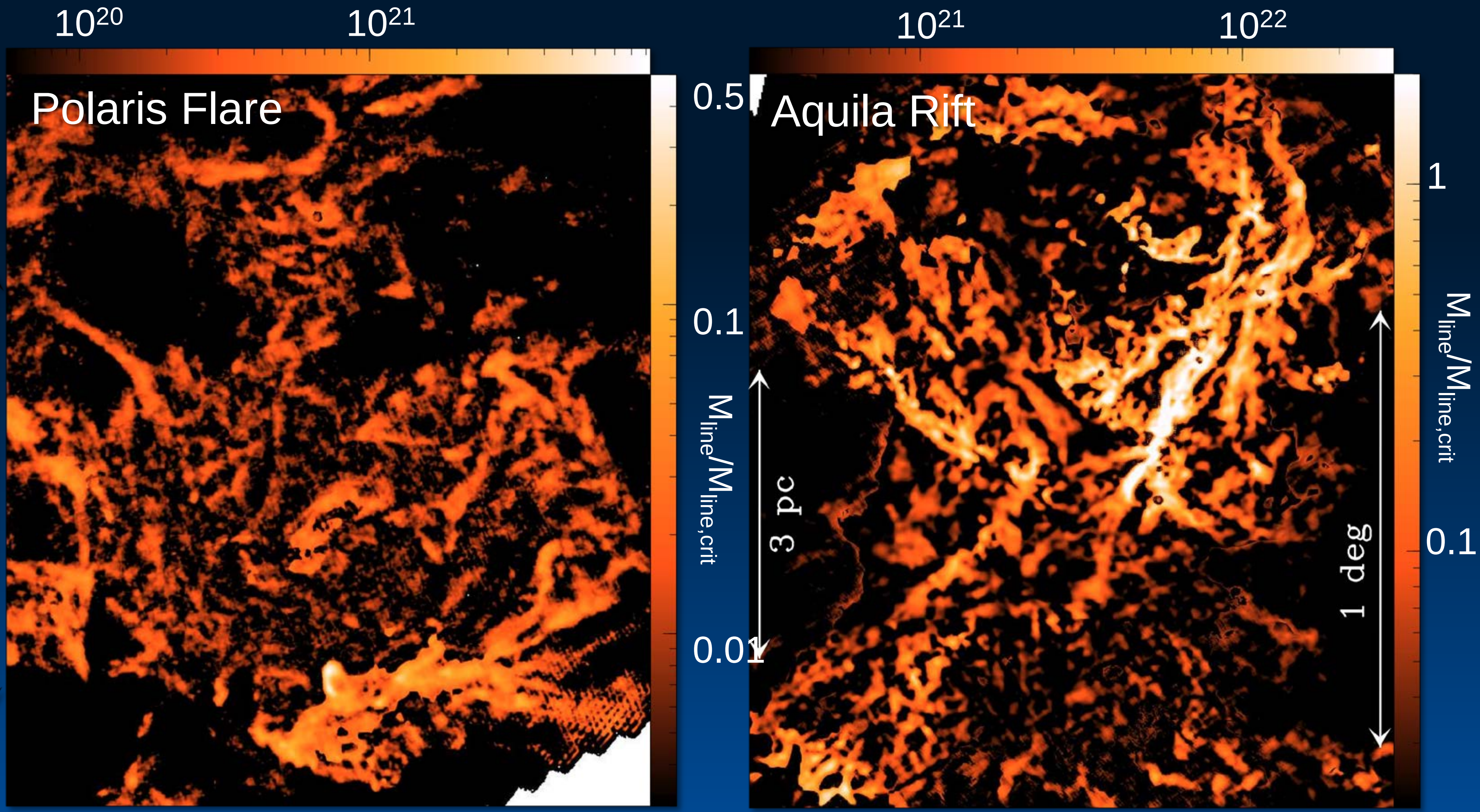
Aquila Rift (active SF)



PACS + SPIRE: 70, 160, 500 µm

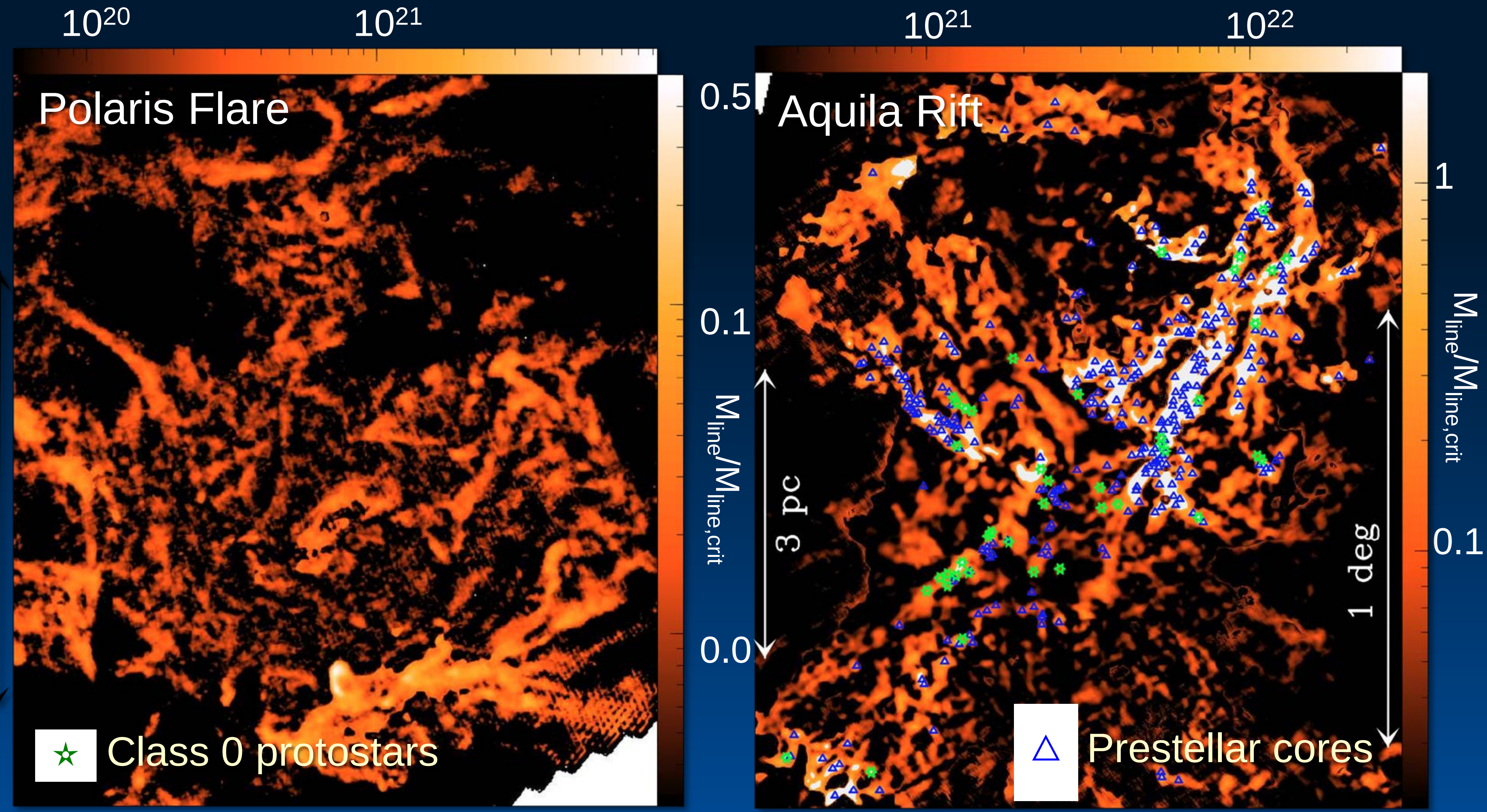
Ward-Thompson et al. (2010); Könyves et al. (2010)

# YSO – Filament Spatial Correlations




Mid-scale curvelet components of column density maps ($H_2/cm^2$)

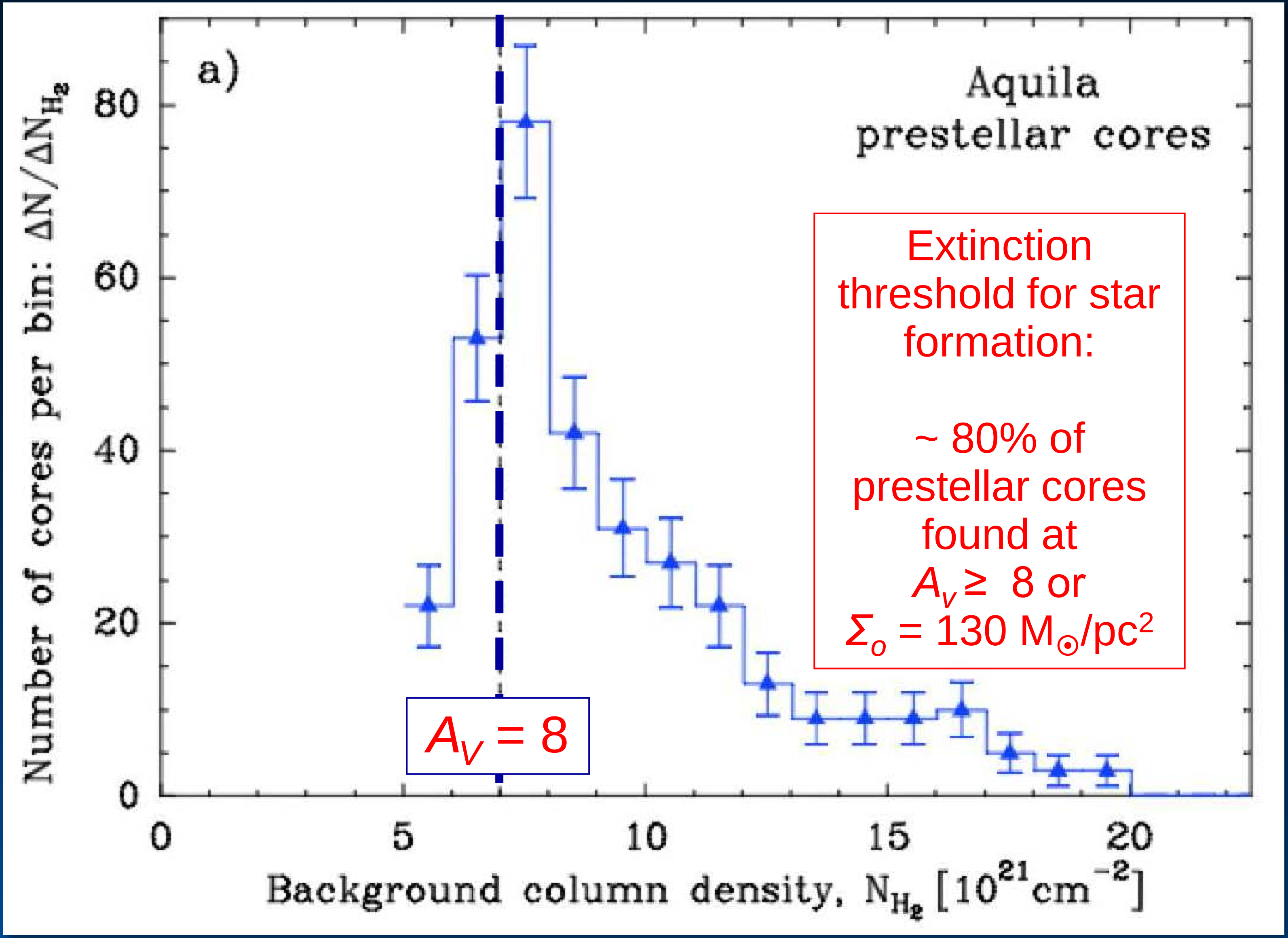
# YSO – Filament Spatial Correlations




>90% bound cores associated with *dense* filaments!

# Density Thresholds for SF in Filaments

Is there a density threshold for star formation ?




cf. Onishi et al. (1998; Taurus), Johnstone, Di Francesco & Kirk (2004; Ophiuchus)

André et al. (2014)

# Density Thresholds for SF in Filaments

- Core formation occurs primarily due to fragmentation of parent filaments

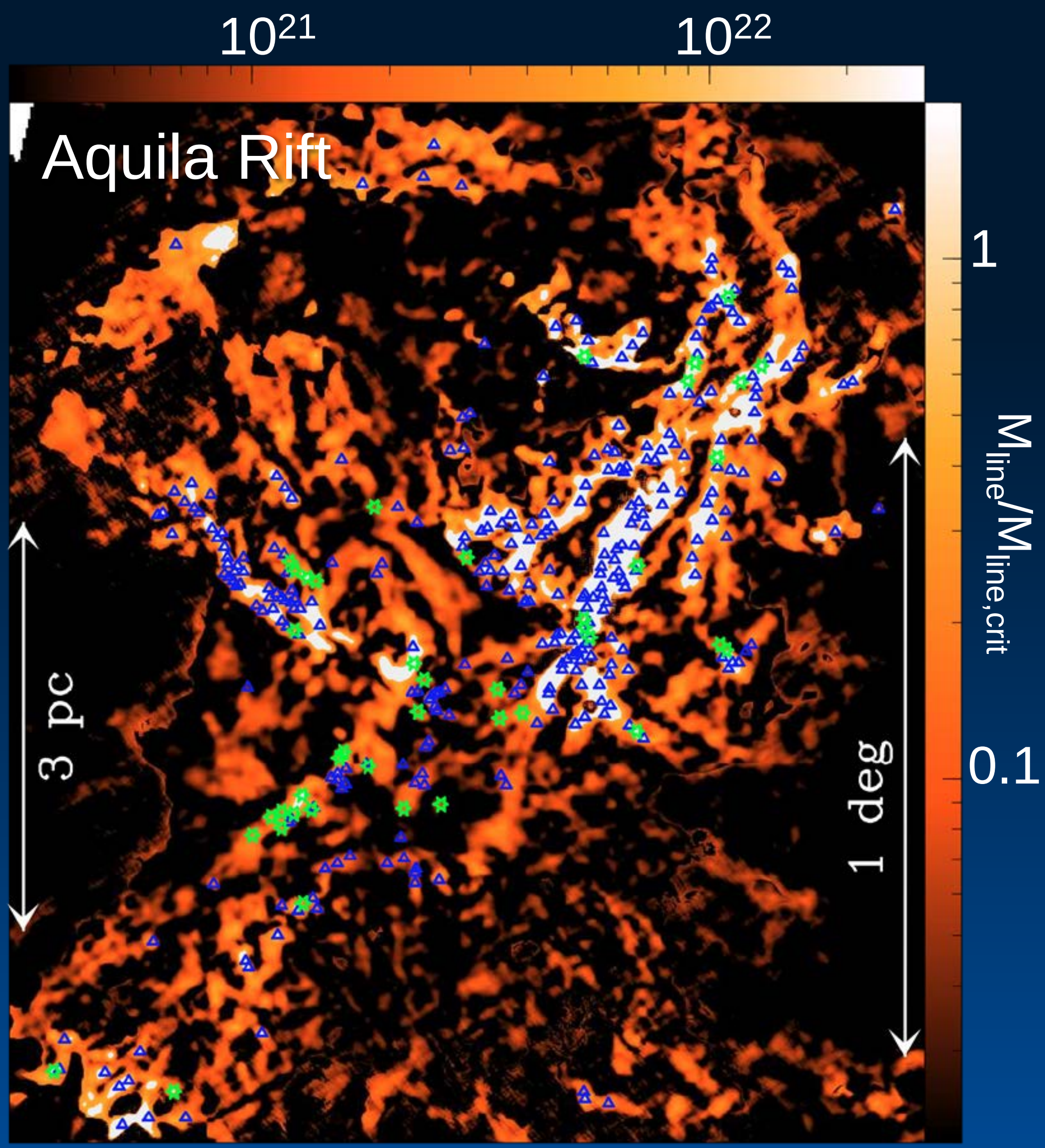
- **mass per unit length** $M_{line}$ of isothermal cylinder (Ostriker 1964; Inutsuka & Miyama 1997)

- cylinders unstable if:

$$\mathbf{M_{line} > M_{line,\,crit} = 2c_s^2/G}$$

$\sim 16\ M_\odot/\mathrm{pc}$ at 10 K

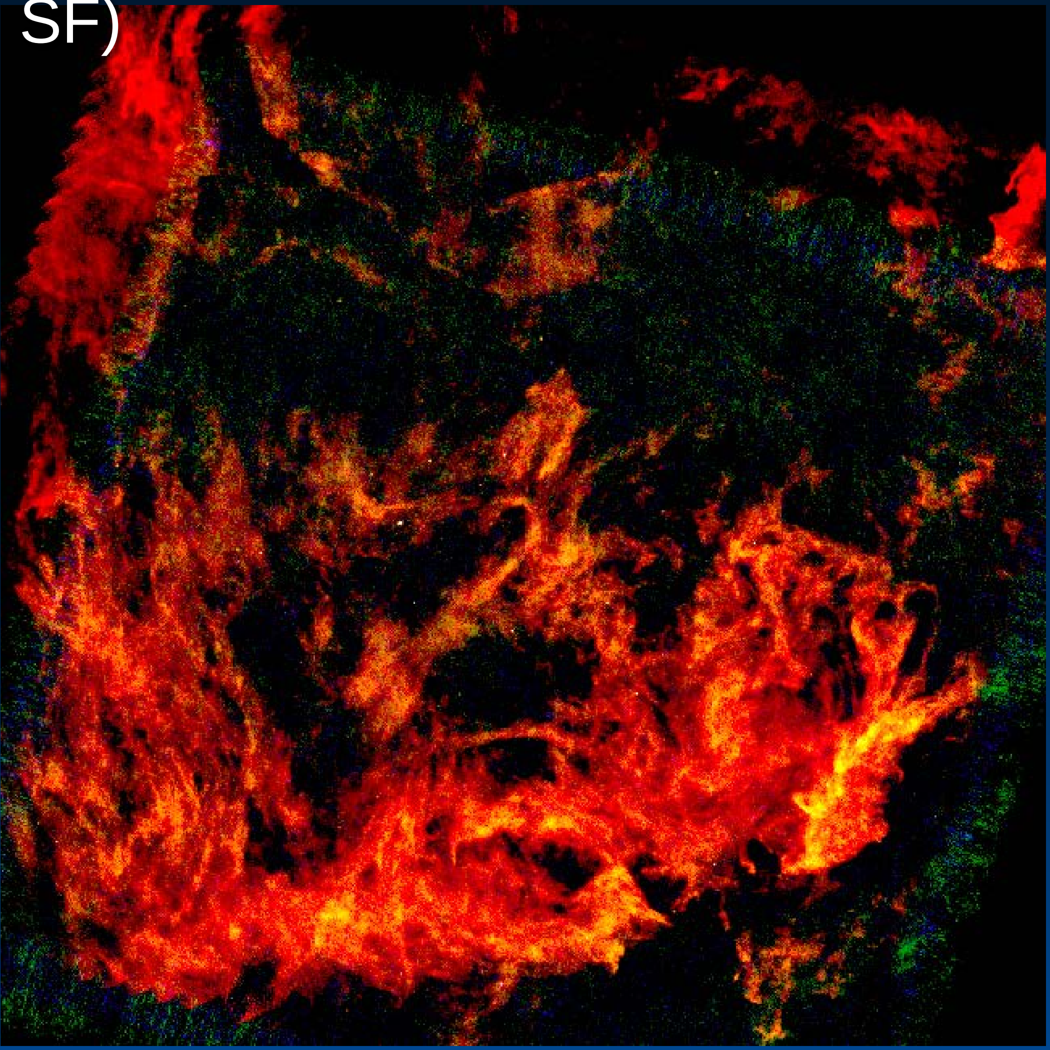
- if $\Sigma_o = 130\ M_\odot/\mathrm{pc}^2$, $W = 0.1$ pc, then $M_{line} \sim 13\ M_\odot/\mathrm{pc}$



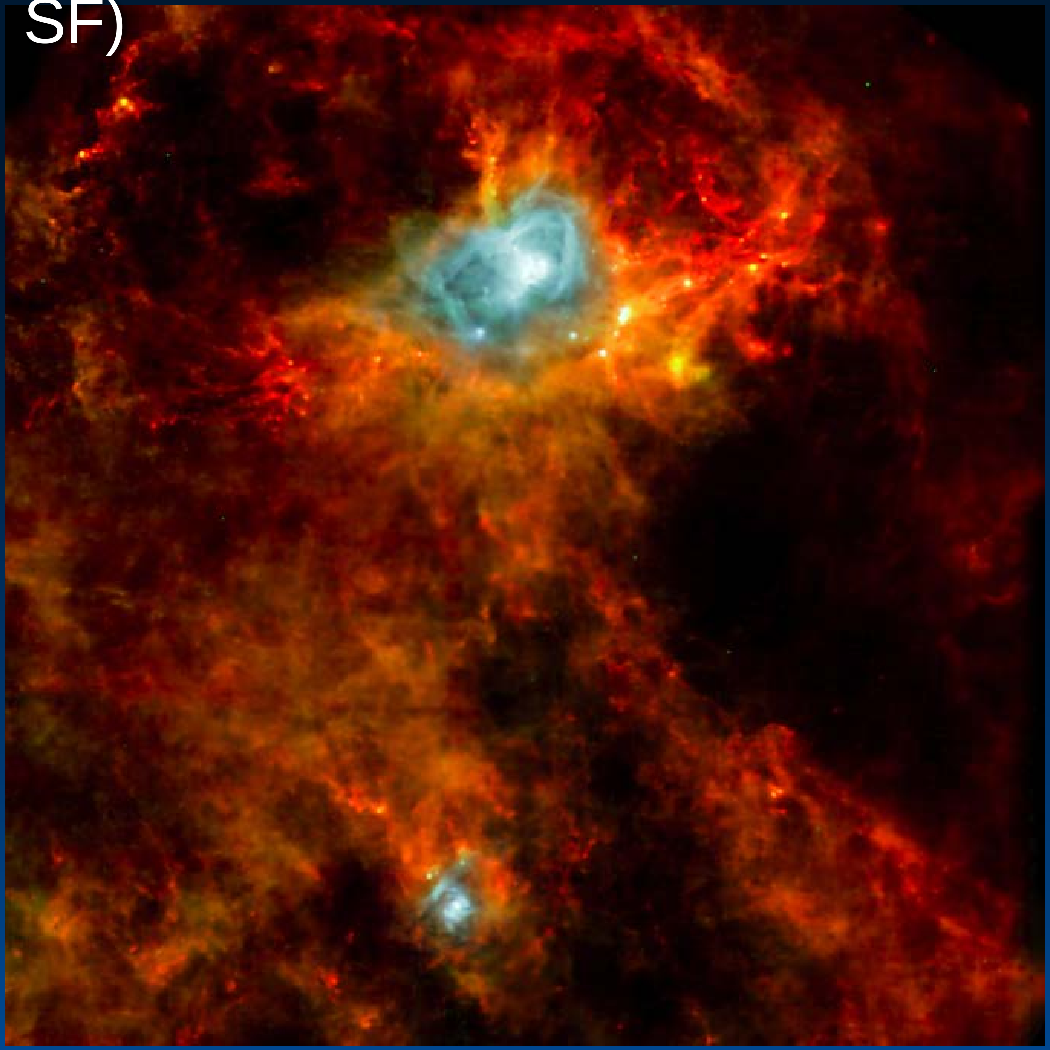

André et al. (2010)

# Density Thresholds for SF in Filaments

Polaris Flare (no SF)



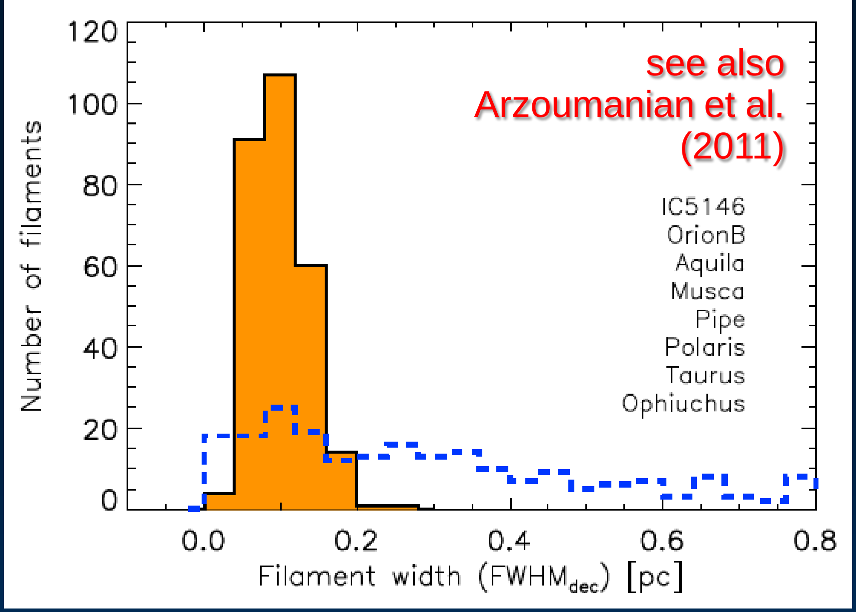
Aquila Rift (active SF)

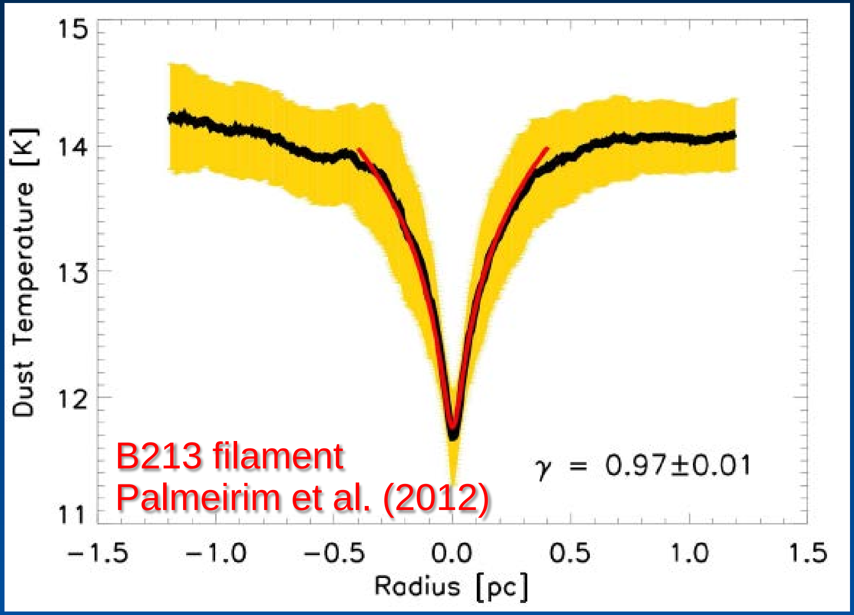


- Polaris: $A_V$ **> 1-2,** no supercritical

- Aquila: $A_V$ **> 8** filaments dense enough to fragment into cores

# Density Thresholds for SF in Filaments




"Threshold" boundary is smooth for three reasons:

1) Projection effects
   - filaments not all in plane of sky
   - leads to overestimate of $\Sigma_{obs}$ by $<1/\cos i>$ ~ 1.57

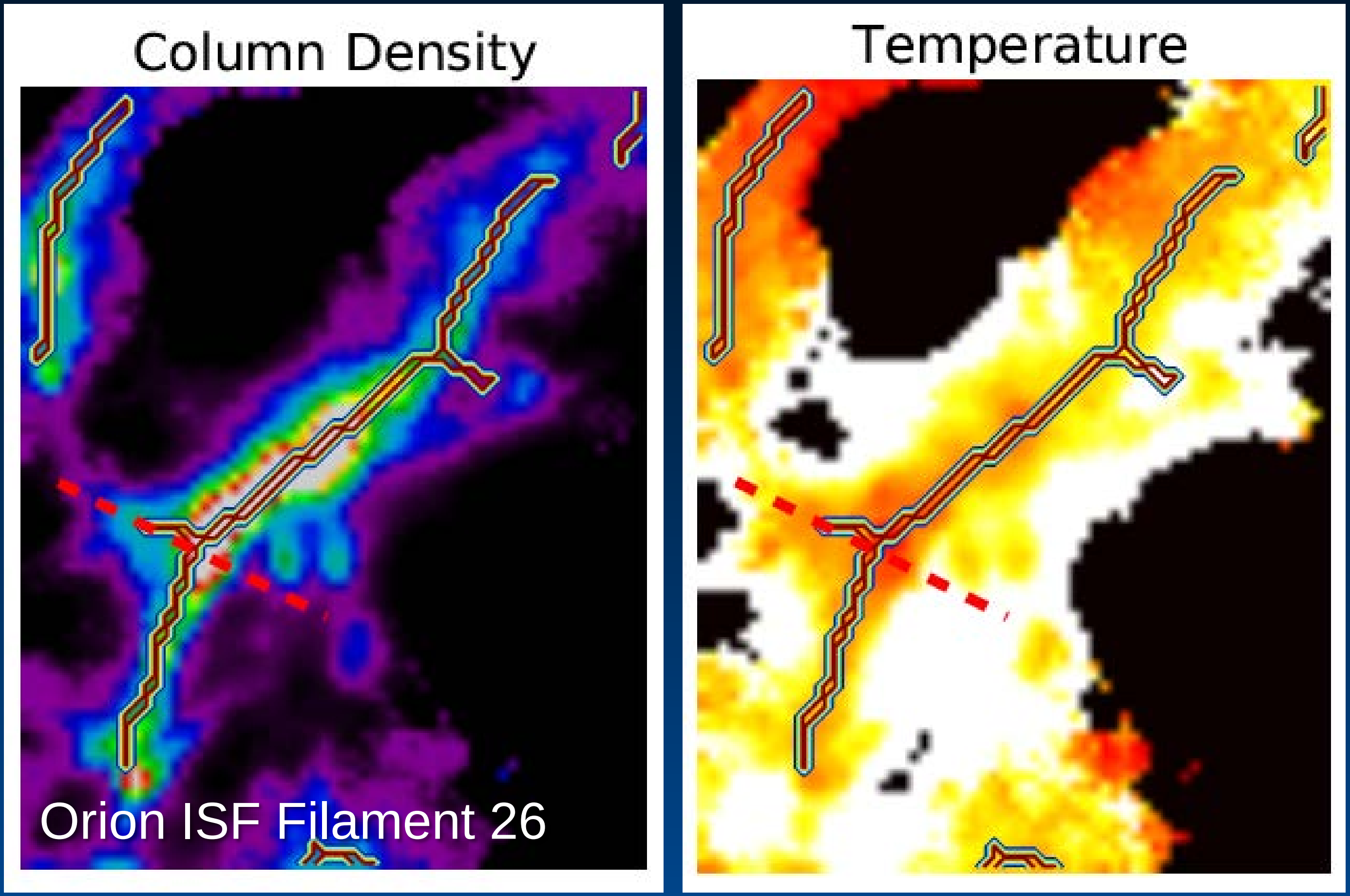
2) Factor ~2 variation around typical filament width of 0.1 pc

3) Filaments are not isothermal and have non-thermal components,
   - need $2\sigma_{tot}^2/G$ instead
   - observed threshold for filaments more like 16-32 $M_\odot$/pc

André et al. (2014)

# Density Thresholds for SF in Filaments

…but wait!  Contrary recent results?

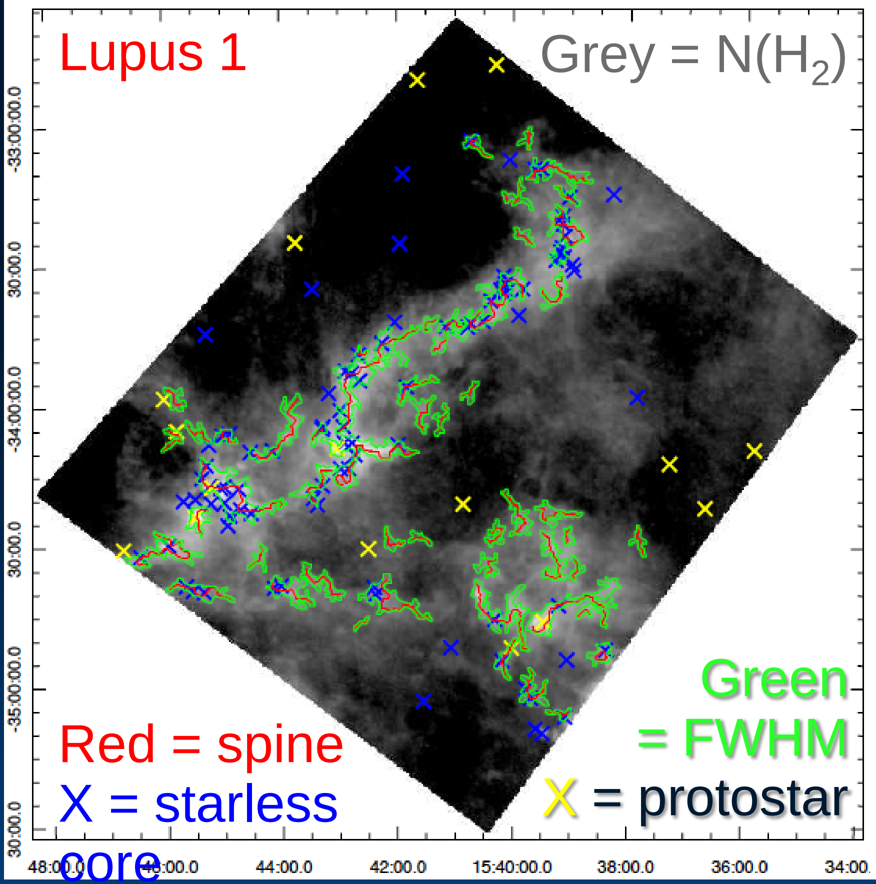


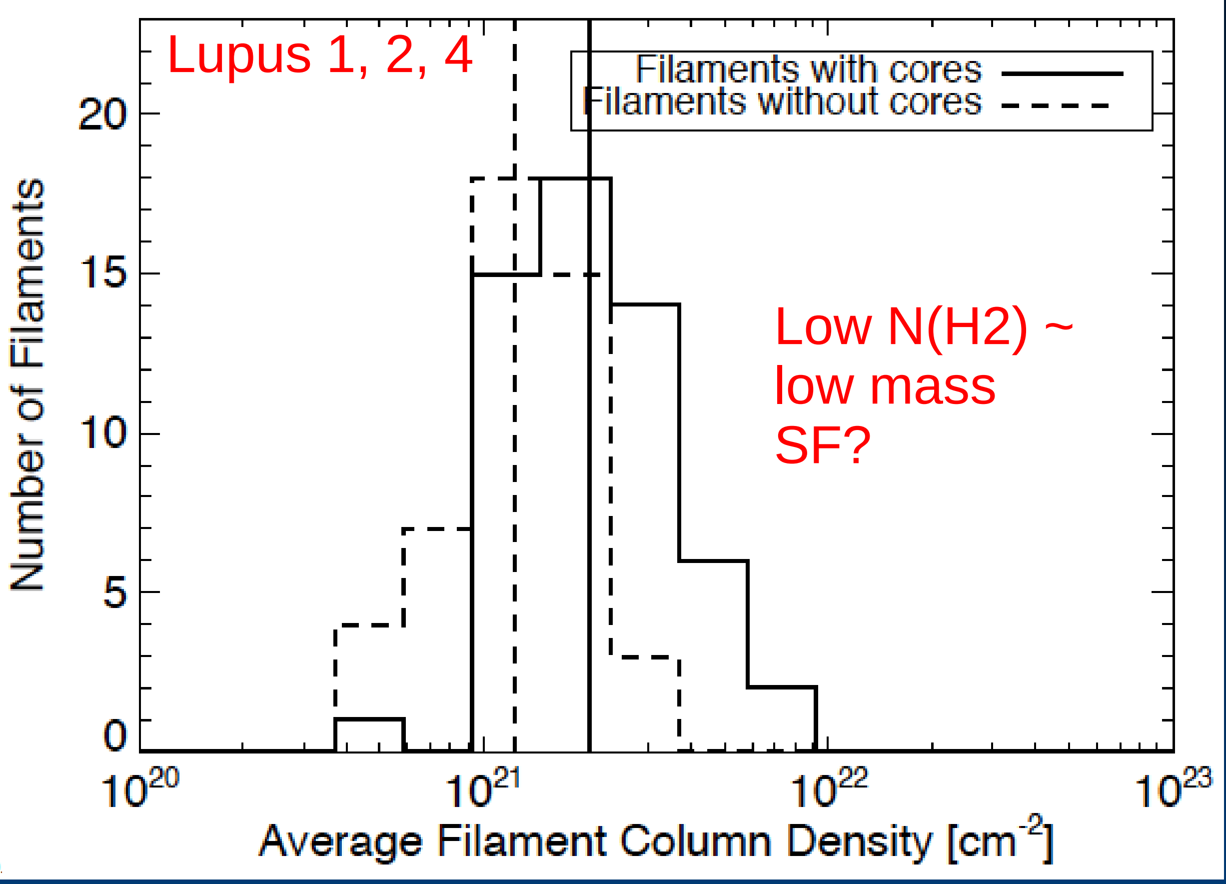

- Salji et al. (2014) used SCUBA-2 850 + 450 μm + HARP $C^{18}O$ 3-2 data to determine $M_{line}$ and critical $M_{line}$ of ~30 Orion ISF filaments
- find ~50% are ***sub-critical by a factors up to 10*** yet clearly have associated Class 0/I objects

Comparison with Herschel data needed!

Salji et al. (2014, submitted)

# Density Thresholds for SF in Filaments



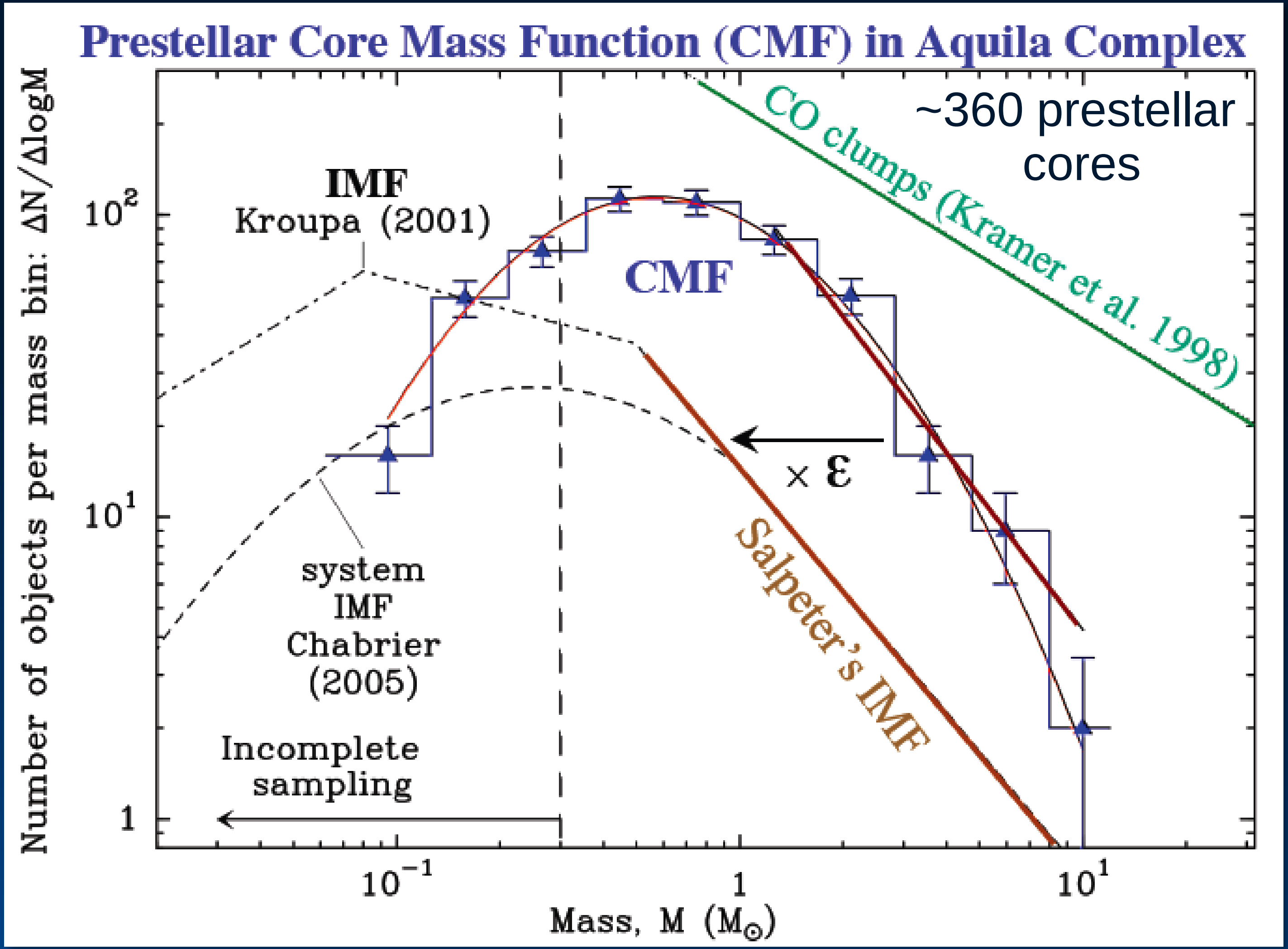




- "star-forming cores" are still seen in the "sub-critical" filaments
- only ***local*** super-criticality needed, average values can be misleading
- filaments still provide base environment for SF core mass growth

Benedettini et al. (2014, in preparation)

# Filaments Define the CMF

Is there a connection between filaments and the CMF?




- shape of CMF very similar to IMF ($\varepsilon \approx 0.3$)
- slope of high-mass end $\alpha \approx -1.5 \pm 0.2$ and Salpeter = -1.35

André et al. (2010); GBS

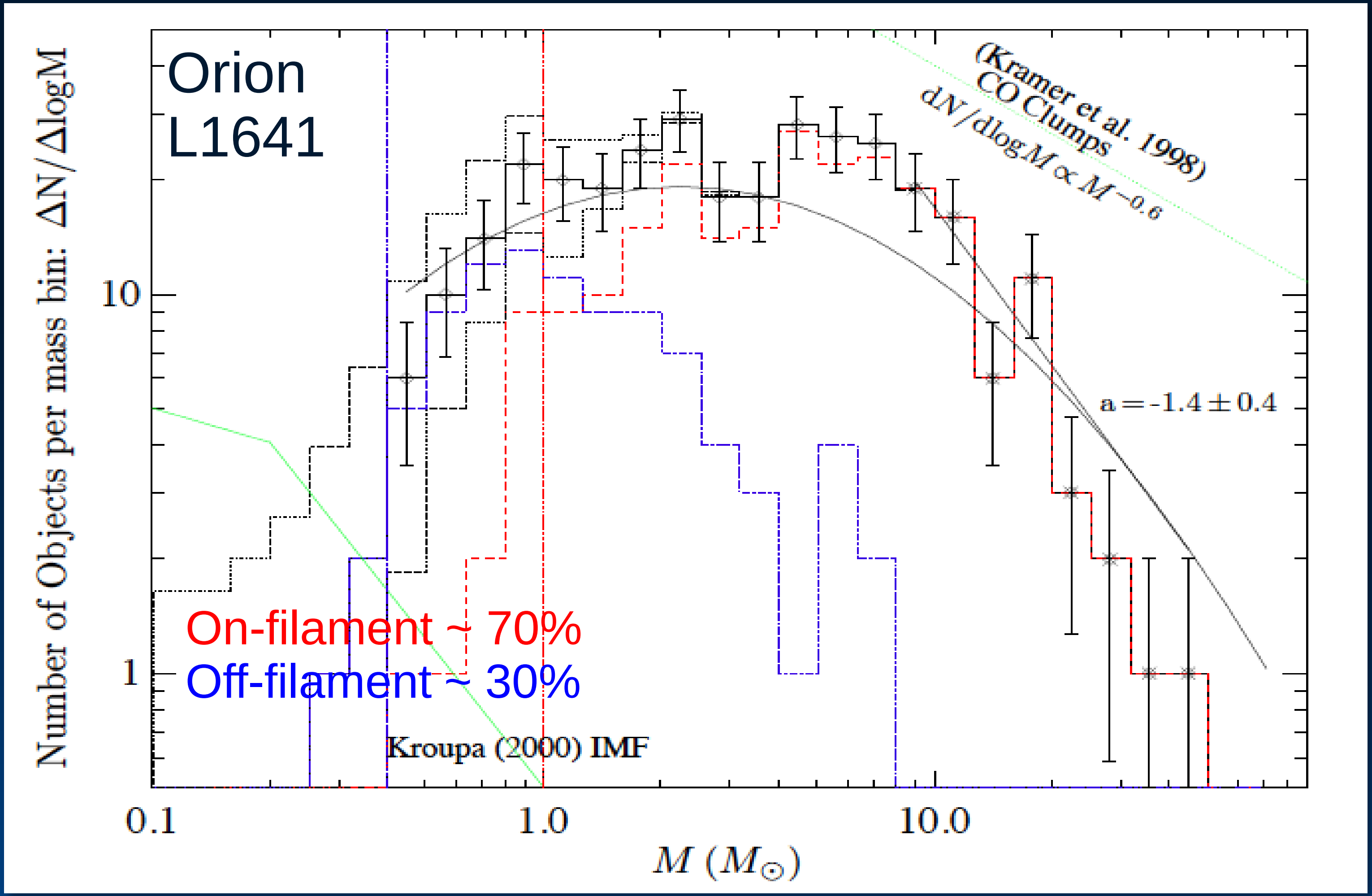
# Filaments Define the CMF

- isothermal cylinder on verge of global collapse: $M_{line} \sim 16\ M_\odot$/pc (at 10 K) and diameter ~ 0.1 pc
- segment of 0.1 pc length will have mass of $3 \times M_{BE} = 1.6\ M_\odot$ ; is *locally* unstable
- in filaments, local collapse favoured over global collapse (Pon et al. 2011), leading to **segmentation** into spherical cores

- in Aquila, CMF peak is $0.6\ M_\odot$, similar to local critical BE mass of $0.5\ M_\odot$
- gravitational fragmentation at the heart of the IMF (Larsen 1985) confirmed?

André et al. (2014; PPVI)

# Filaments Define the CMF




- high-mass end of the L1641 CMF comes from on-filament cores
- low-mass end comes from both on-filament and off-filament cores
- relationship between denser filaments and higher-mass stars?

Polychroni et al. (2013)

# Filaments Define the CMF

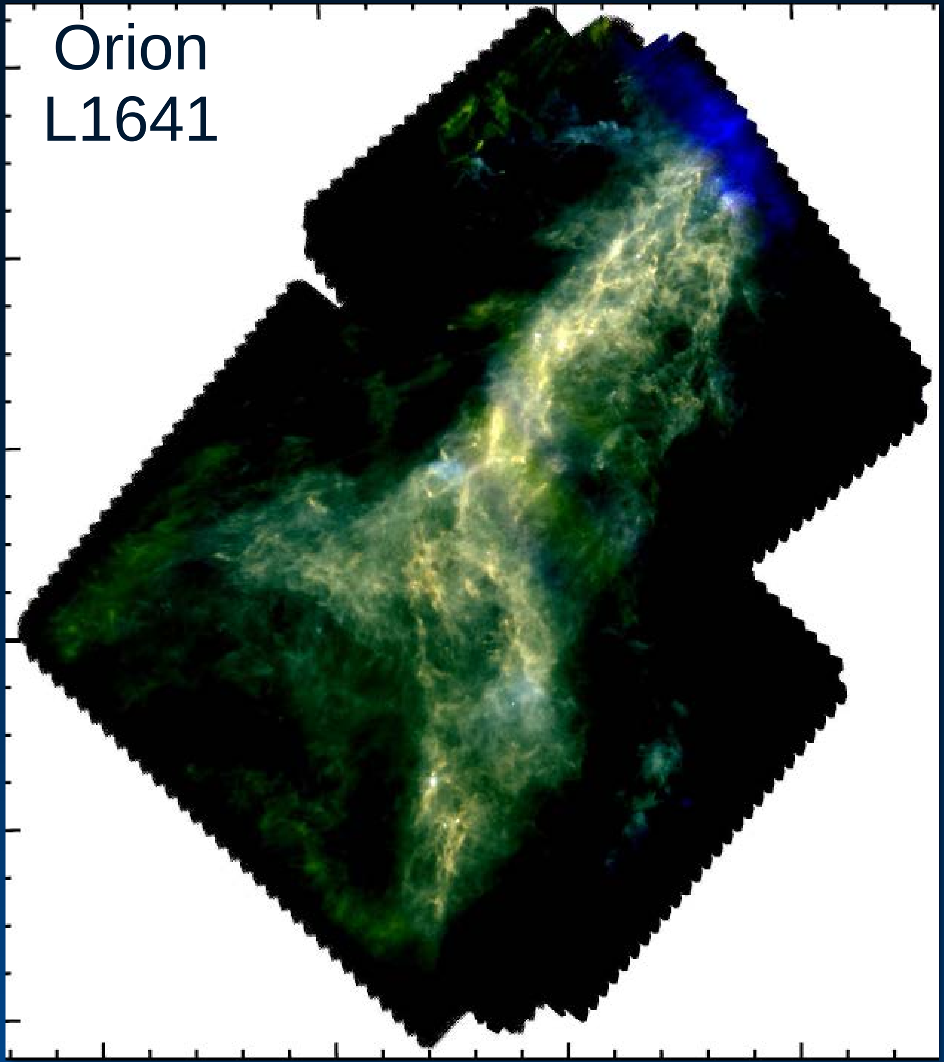
High-mass end of the CMF?

- power spectrum of initial density fluctuations (Inutsuka 2001):

  if $P(k) = |\delta_k|^2 \sim k^{-1.5}$, then
  $\alpha \sim 2.5$ ("Salpeter")

- filaments have power-law $M_{line}$ distribution (Arzoumanian et al.):

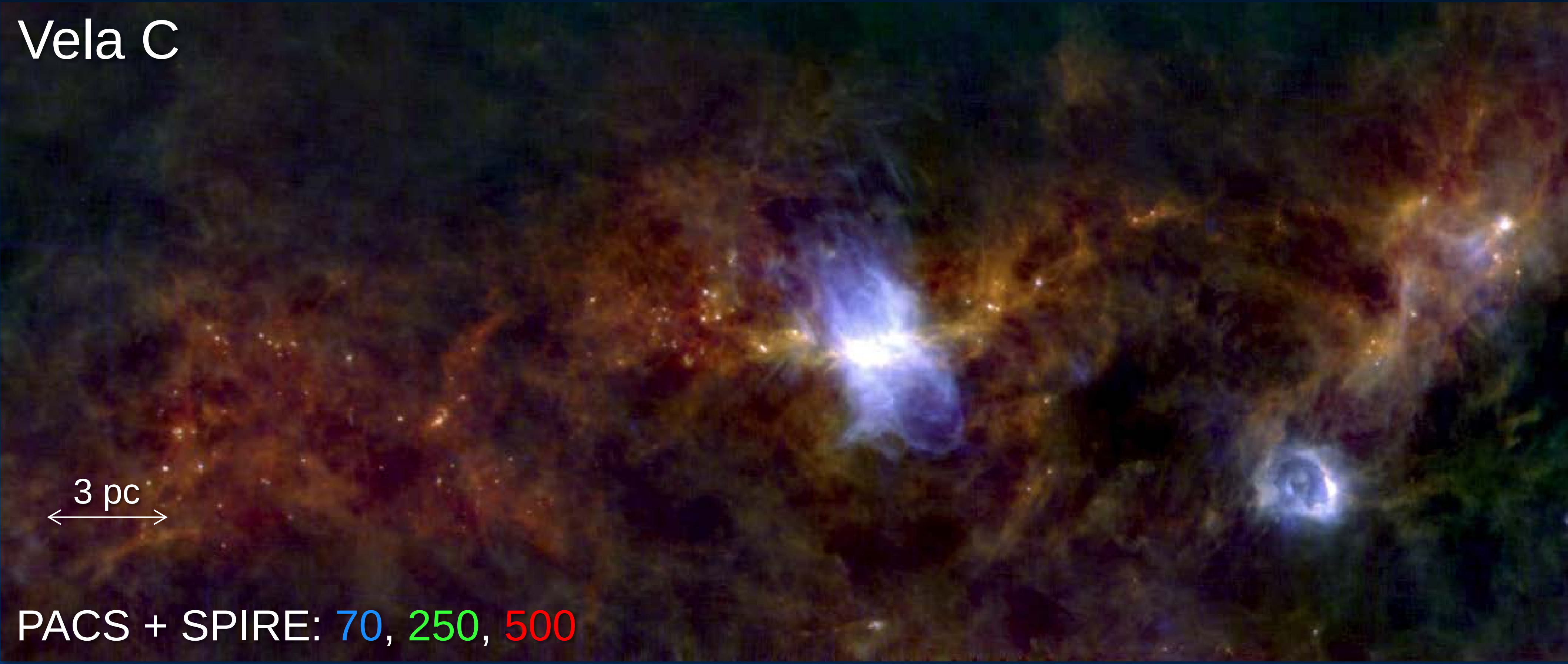
  if $dN/dlogM_{line} \sim M_{line}^{-1.2}$ above 20 $M_{\odot}$/pc, width ~ 0.1 pc, and $\sigma_{tot} \sim \Sigma^{0.5}$ (as observed), then
  $\alpha_{BE} \sim 1.2$ ("Salpeter")




PACS + SPIRE: 160, 250, 350 μm

André et al. (2014; PPVI)

# High-mass SF and Dense Filaments

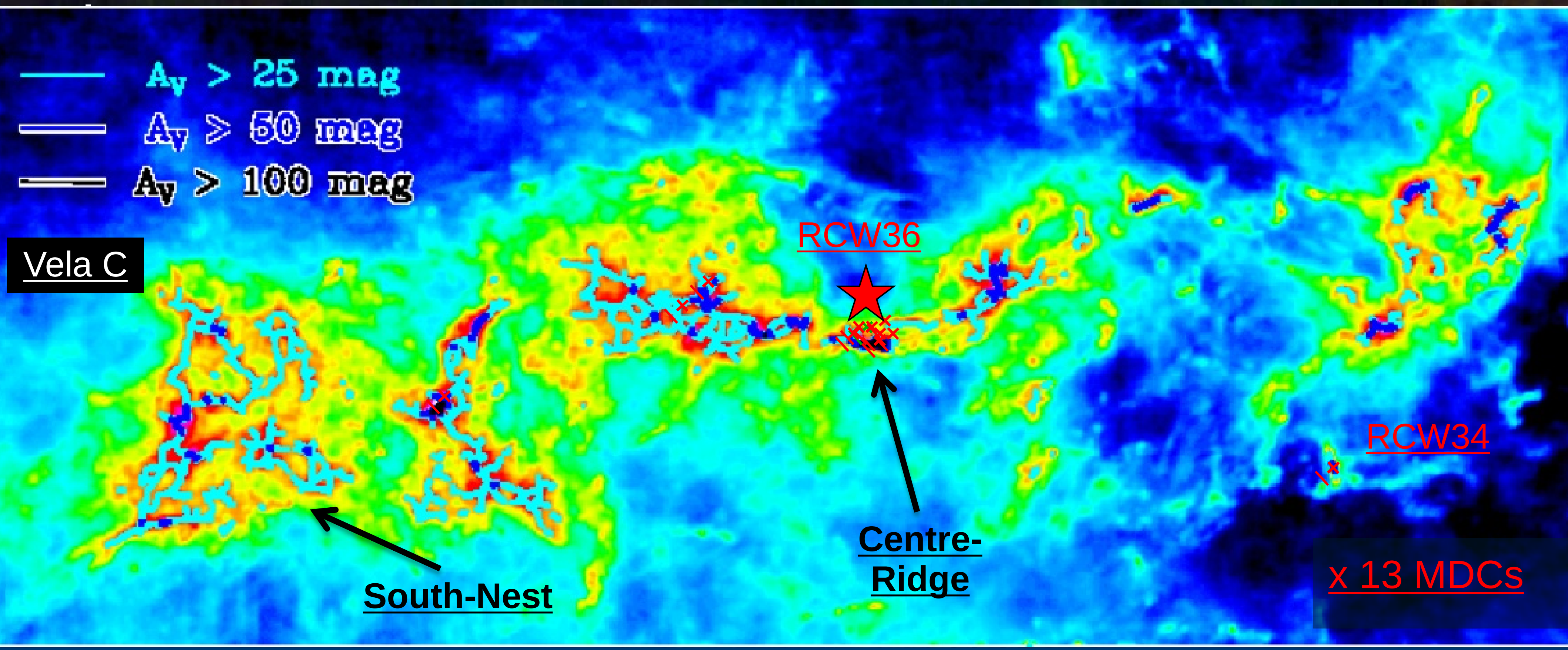


μm

- What is the connection between filaments and high-mass star formation?

Hill et al. (2011)

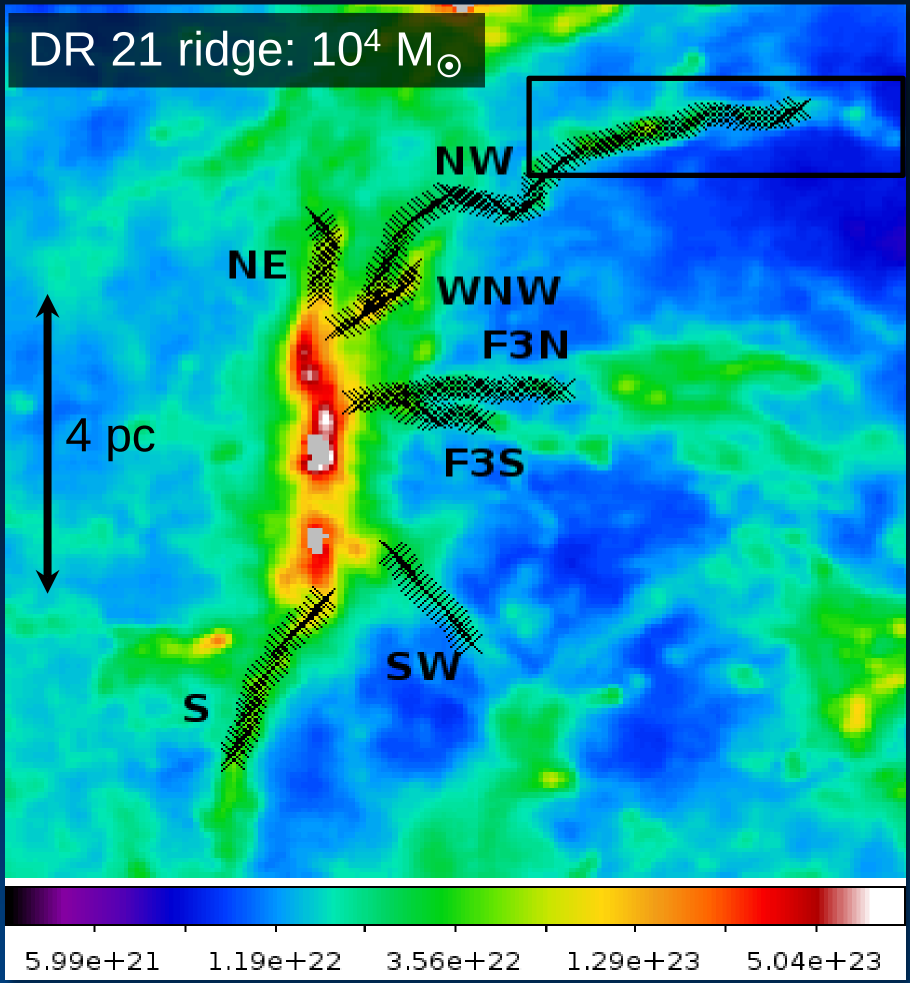
# High-mass SF and Dense Filaments

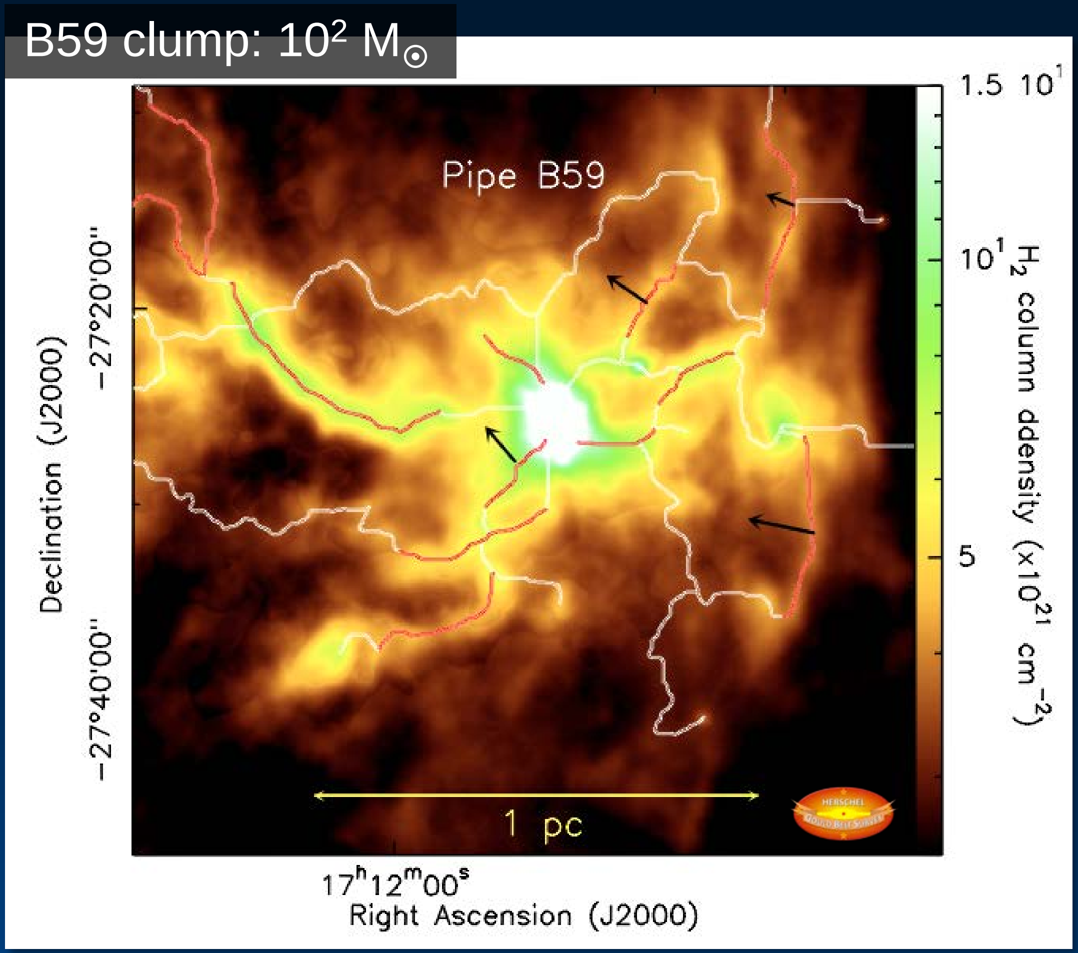



- disorganized networks ('nests') and dominating 'ridges' show relative importance of turbulence vs. gravity
- high-mass stars only found in '**ridges**' ; filaments of $A_V$ > 100

Hill et al. (2011); Minier et al. (2012)

# High-mass SF and Dense Filaments

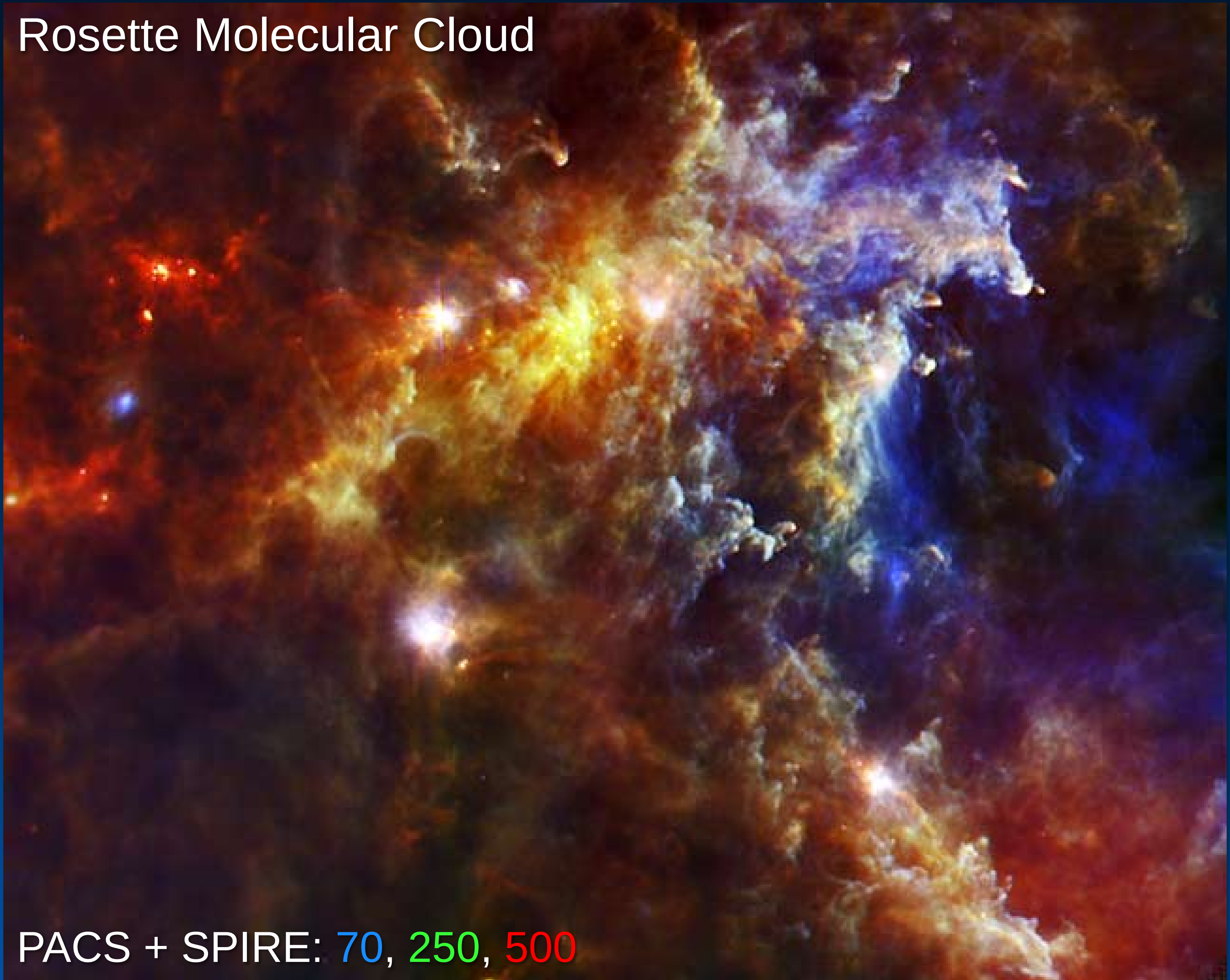



- ridges formed and fed by sub-filament merging
- sub-filaments also surround (feed?) dominant clump in Pipe Nebula

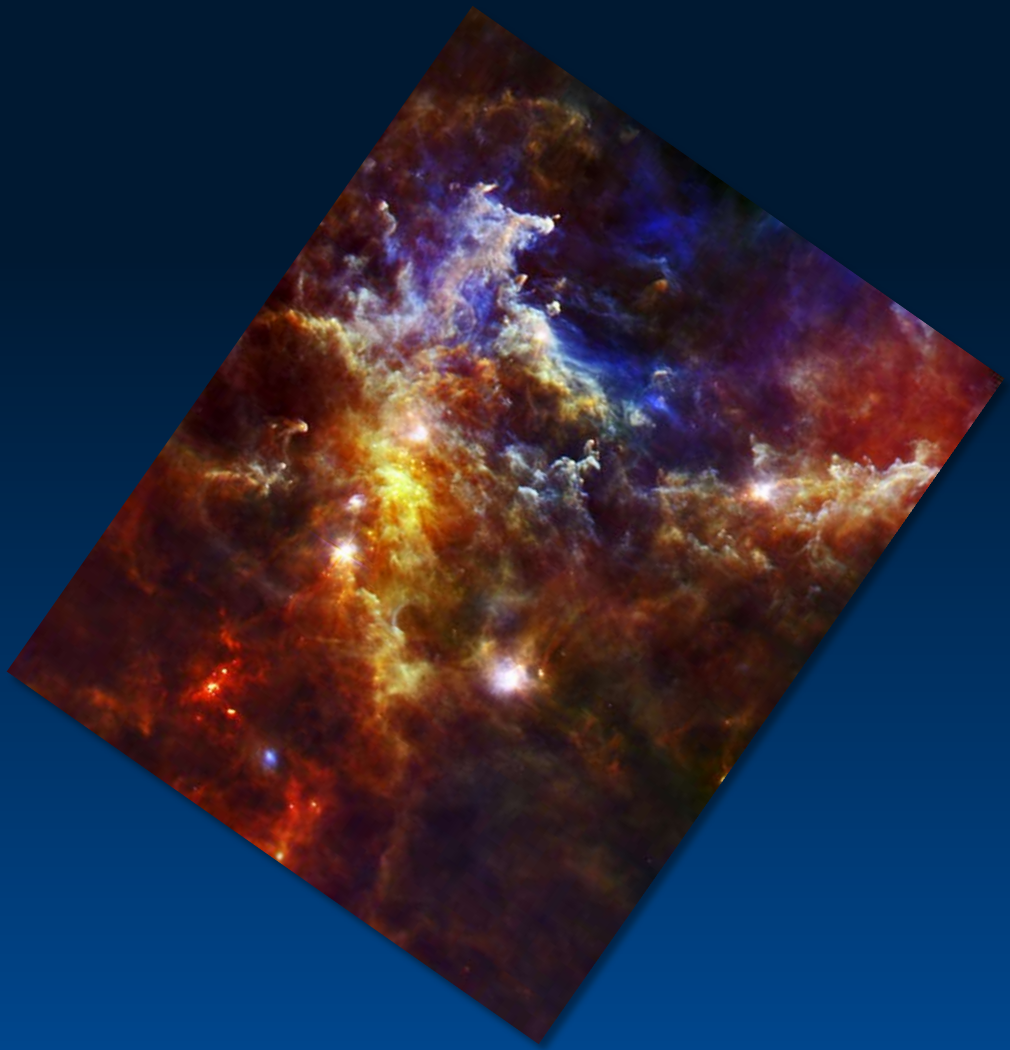
Hennemann et al. (2012), Schneider et al. (2010), Peretto et al. (2012)

# High-mass SF and Dense Filaments

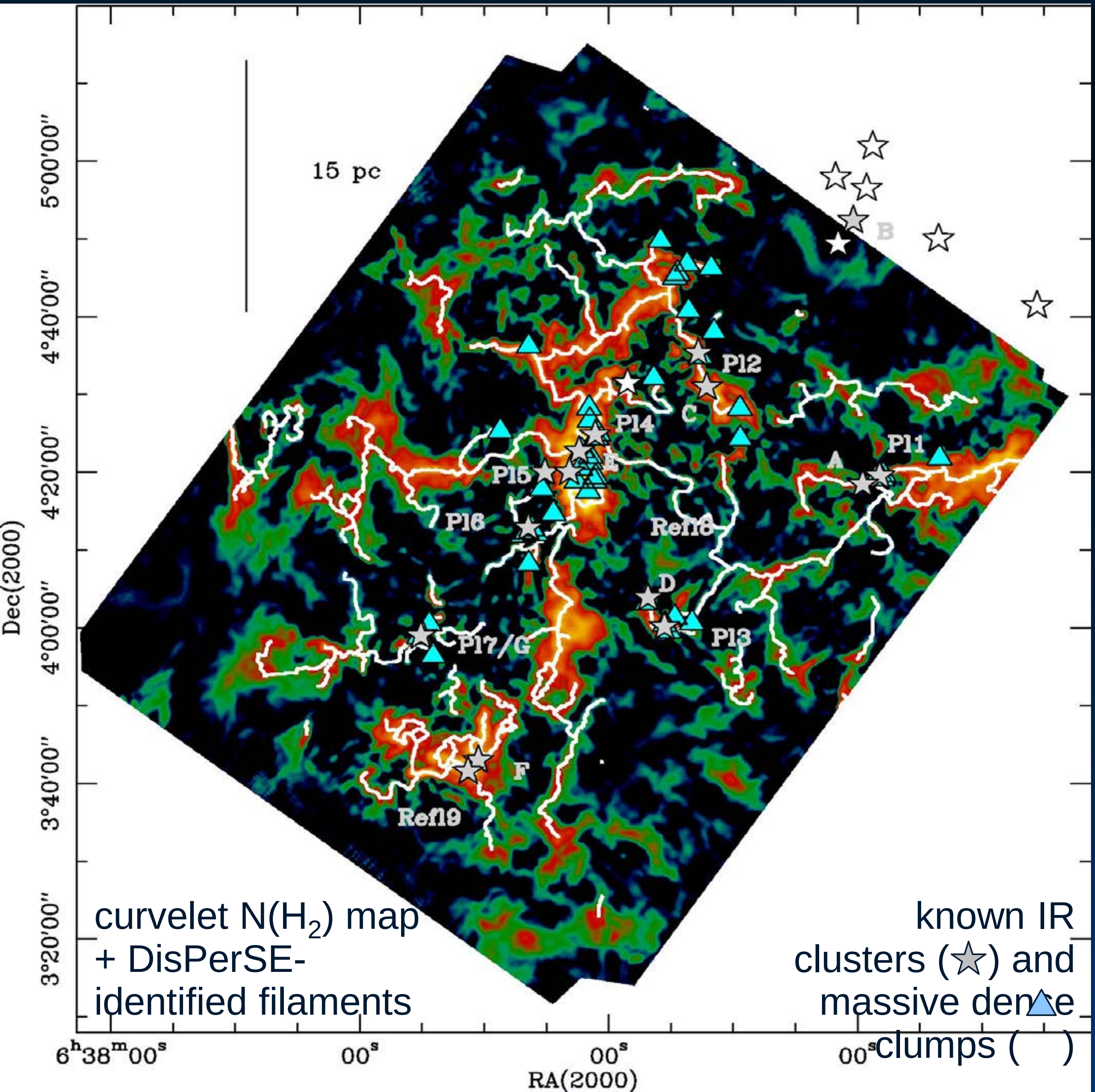



Schneider et al. (2012)

# High-mass SF and Dense Filaments



# High-mass SF and Dense Filaments




- massive clumps and IR clusters found at filament junctions
- mass flow into junction regions ➔ more clustered star formation?

Schneider et al. (2012)

# Summary

• the youngest protostars and pre-stellar cores are indeed spatially correlated with the filaments in nearby clouds

• the densest filaments ($A_V > 8$) primarily are able to produce the cores in molecular clouds that form stars

• filaments produce the higher mass cores that fill out the CMF, peak of CMF from gravitational fragmentation

• high-mass end of CMF may come from power spectrum of initial density perturbations or dense filament $M_{line}$ power law distribution

•high-mass stars form in clusters found either in ridges (very dense filaments) or at the dense junctions of filaments

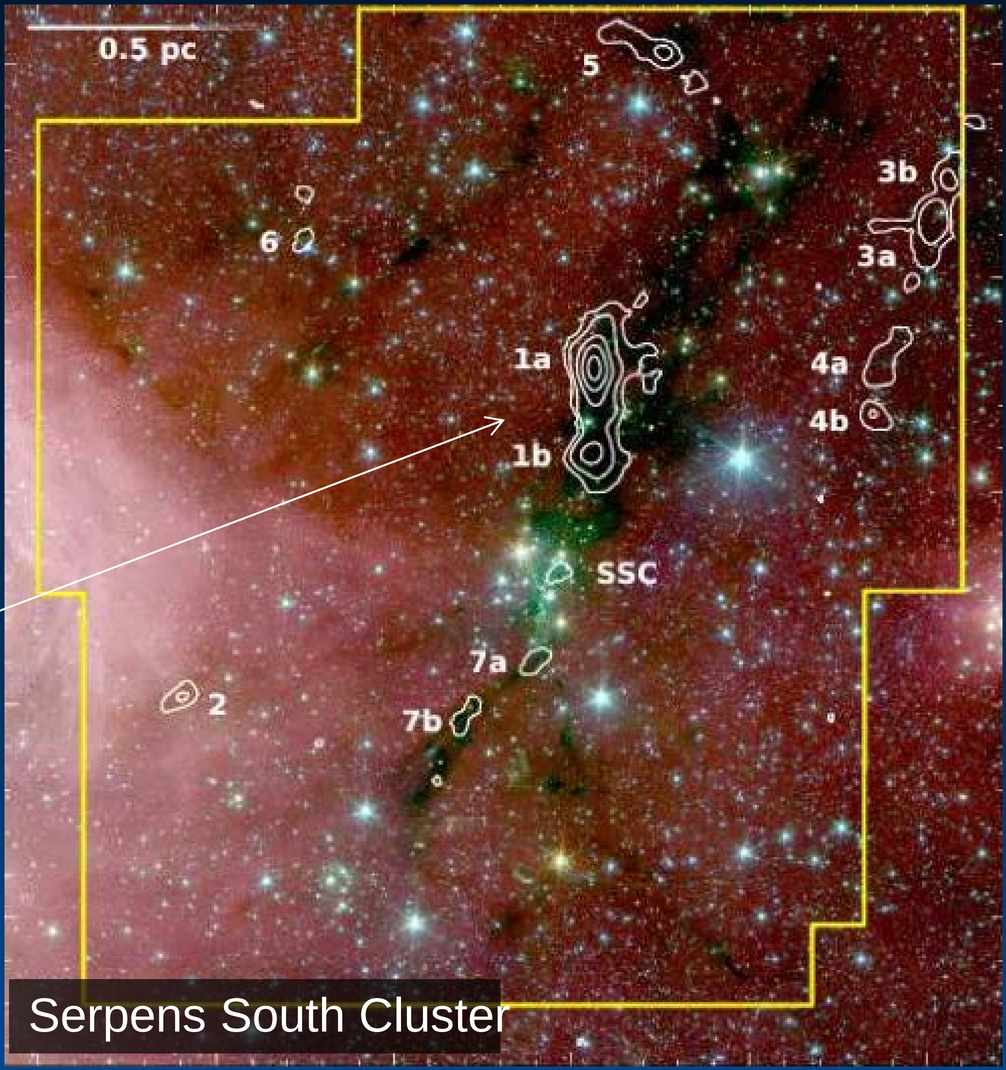
# The Future: Kinematic Studies

- with continuum studies (nearly) complete, need line studies to determine filament kinematics:

  - **$N_2H^+$** (Hacar & Tafalla 2013)

  - **$NH_3$** (Li et al. 2013; future GBT + JVLA survey?)
  - cyanopolyynes (eg., **$HC_7N$**; Friesen et al. 2013)
  - **CCS** (Swift et al. 2005)

  - **$C^{18}O$** (Buckle et al. 2012)
  - **$HCO^+$** / **HCN** (future JCMT survey?)



Friesen et al. (2013)