NRC · CNRC

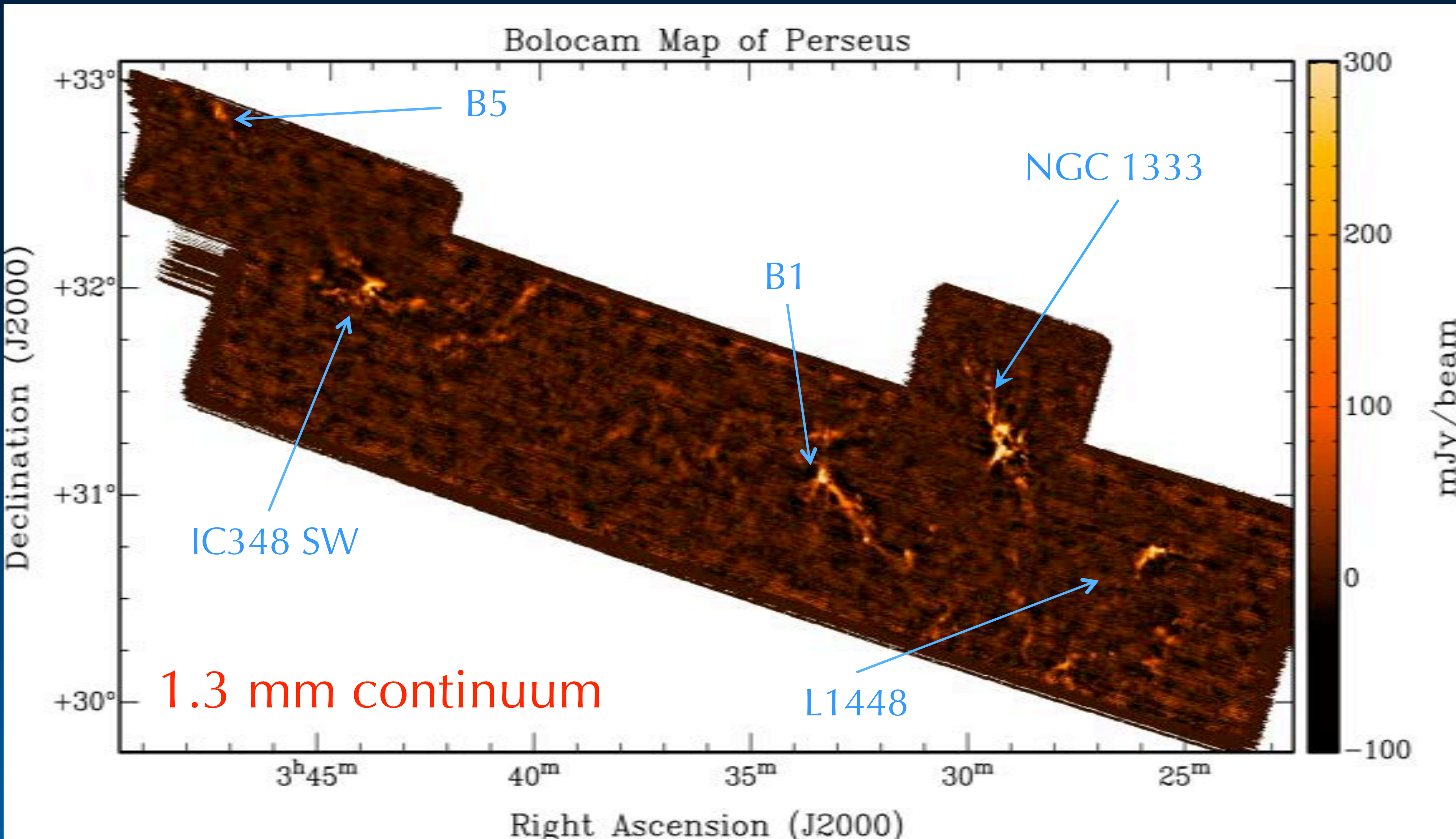
From Discovery to Innovation...

Herschel Observations of the Pre-Collapse Phase of Star Formation

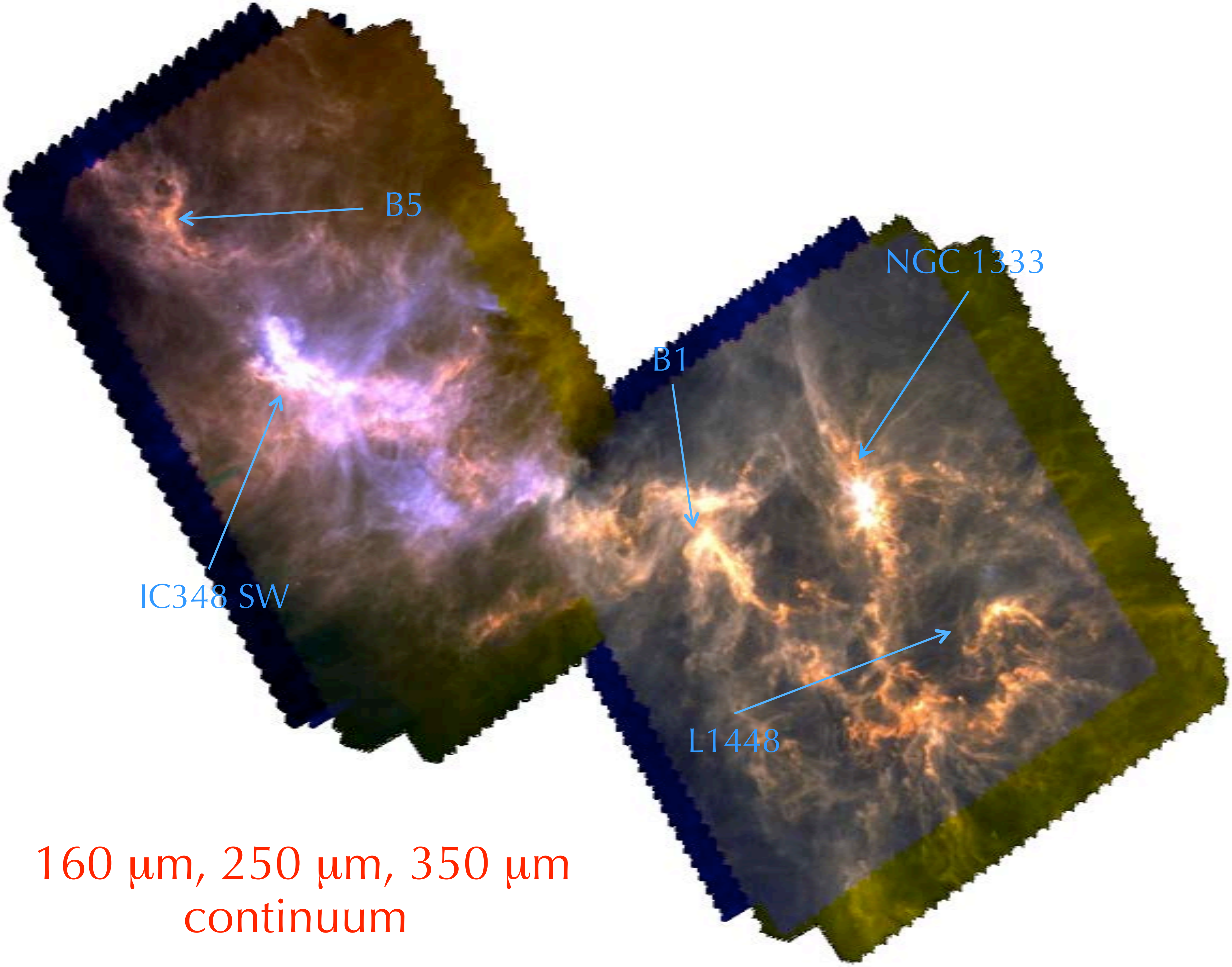
James Di Francesco

(thanks to Ph. André, F. Motte, N. Schneider, M. Juvela, M. Hennemann, N. Peretto, M. Nielbock, R. Launhardt, A. Stutz, S. Ragan, L. Wilcock, & S. Molinari)

Continuum Data of Nearby Clouds



Enoch et al. (2006)



160 μm, 250 μm, 350 μm
continuum

Herschel reveals the pre-collapse phase

PACS and **SPIRE** (esp. in parallel):

• probe thermal emission from cold dust at high resolution (~5″ - 36″)

• have wide dynamic range, probing link between diffuse and compact emission (cores)

• detect 70-500 μm, where cold cores are brightest, gives multi-λ data to constrain T_{dust}

• have high sensitivity for maps, yielding large samples

Herschel Star Formation Key Projects

- **Herschel Galactic Plane Survey** (***Hi-GAL***):
  - $|b| \le 1°$, 348° of *l* over 878 hours, SPIRE+PACS
  - PI: Sergio Molinari (IAPS-INAF)
- **Planck Cold Cores** (***PCC***):
  - 350 Planck clumps over ~151 hours, SPIRE+PACS
  - PI: Mika Juvela (U. of Helsinki)
- **Earliest Phases of Star Formation** (***EPoS***):
  - 60 cores over ~112 hours, SPIRE+PACS & PACS
  - PI: Oliver Krause (MPIA - Heidelberg)
- **Herschel OB Young Star Survey** (***HOBYS***):
  - 15 clouds (0.7-3 kpc) over 126 hours, SPIRE+PACS & PACS
  - PI: Fréderique Motte (CEA - Saclay)
- **Herschel Gould Belt Survey** (***GBS***):
  - 15 clouds (0.1-0.5 kpc) over 461 hours, SPIRE+PACS & PACS
  - PI: Philippe Andre (CEA - Saclay)

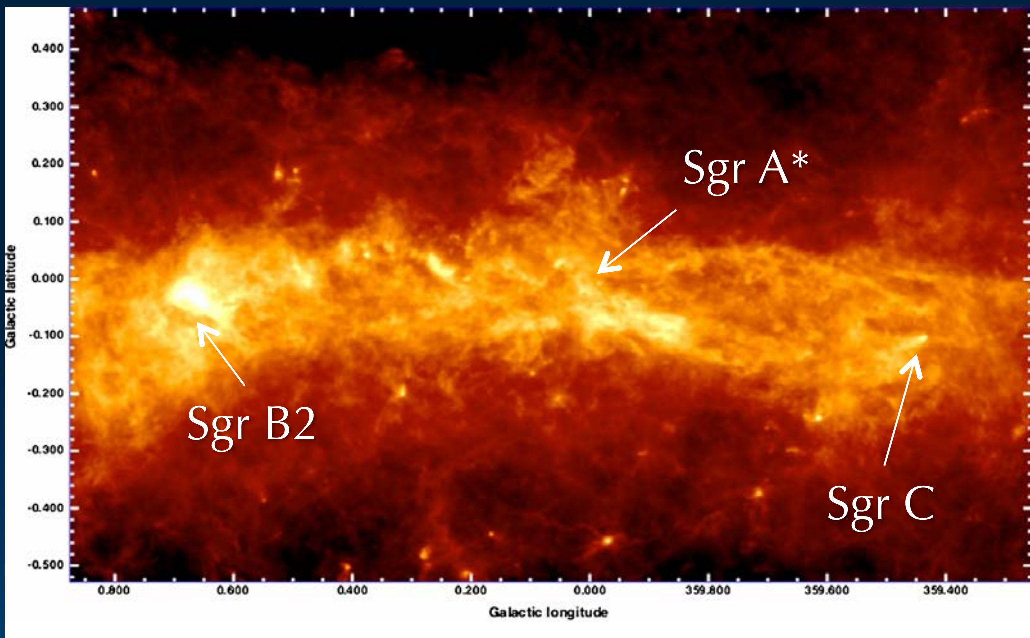
Talk Outline

We will review pre-collapse structures as revealed by *Herschel* in descending order of scale:

- *Clouds* (IRDCs): size > 10 pc, mass ~ 10^{4-6} $M_{\odot}$
  - Hi-GAL, EPoS
- ***Filaments***: size ~ 1-10 pc, mass ~ 10^{2-3} $M_{\odot}$
  - Hi-GAL, EPoS, PCC, HOBYS, GBS
- *Clumps*: size ~ 0.1-1 pc, mass ~ 10^{1-2} $M_{\odot}$
  - EPoS, PCC, HOBYS, GBS
- *Cores*: size < 0.1 pc, mass ~ $10^{-1 \text{ to } 1}$ $M_{\odot}$
  - EPoS, GBS

sorta adapted from Bergin & Tafalla (2007)

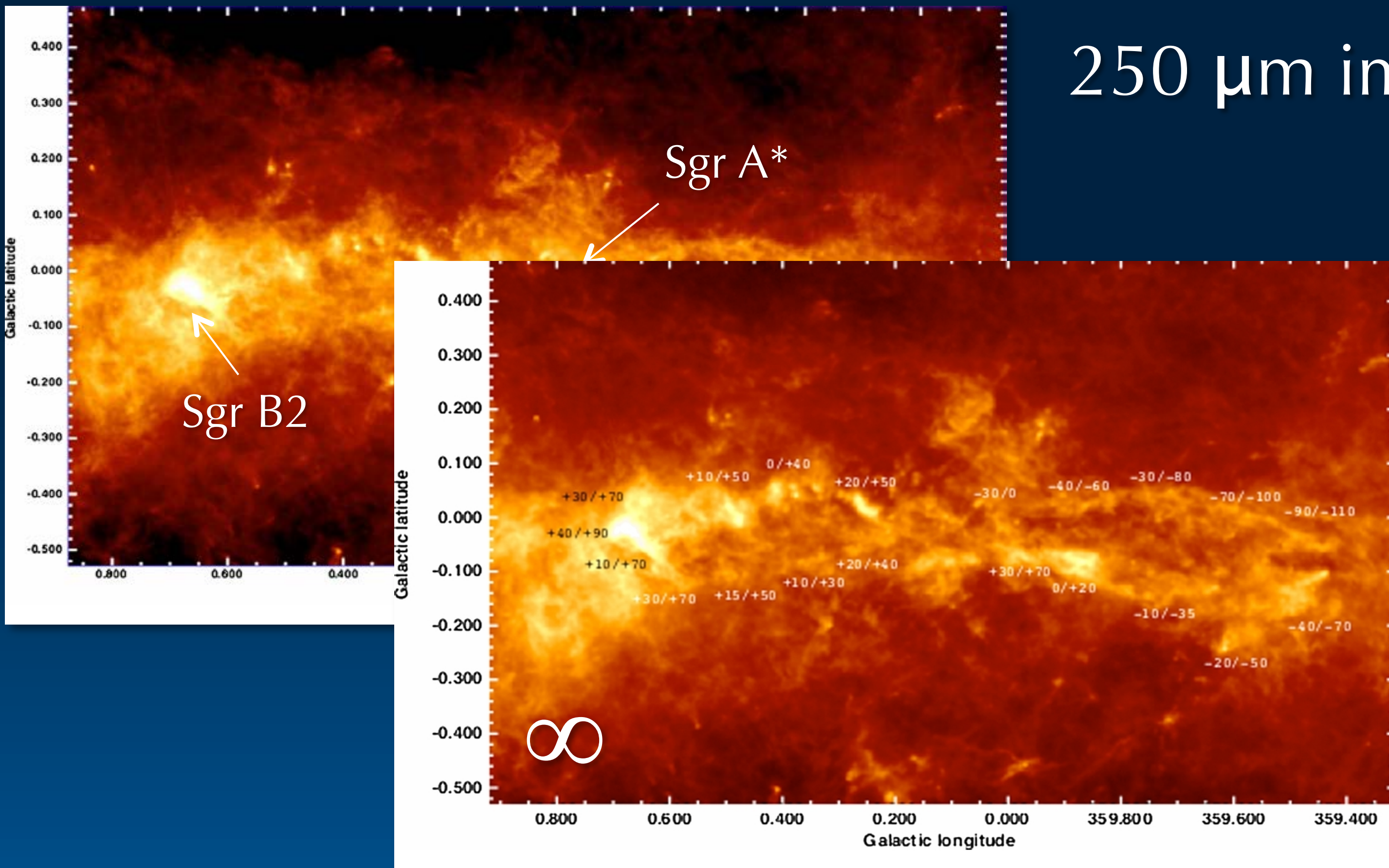
Clouds: An Elliptical Ring at Galactic Center



250 μm image

Molinari et al. (2011): Hi-GAL

Clouds: An Elliptical Ring at Galactic Center

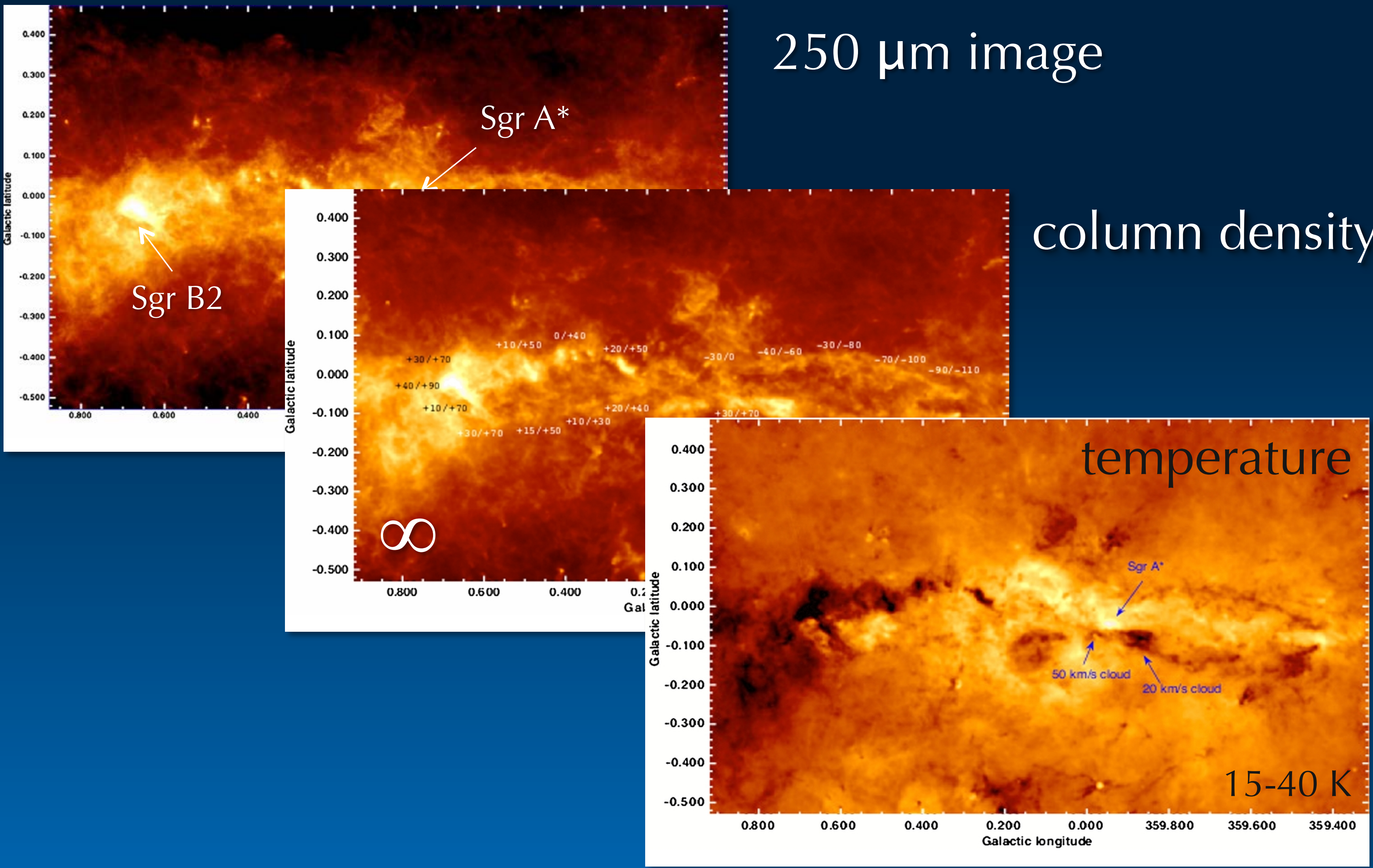


250 µm image

column density

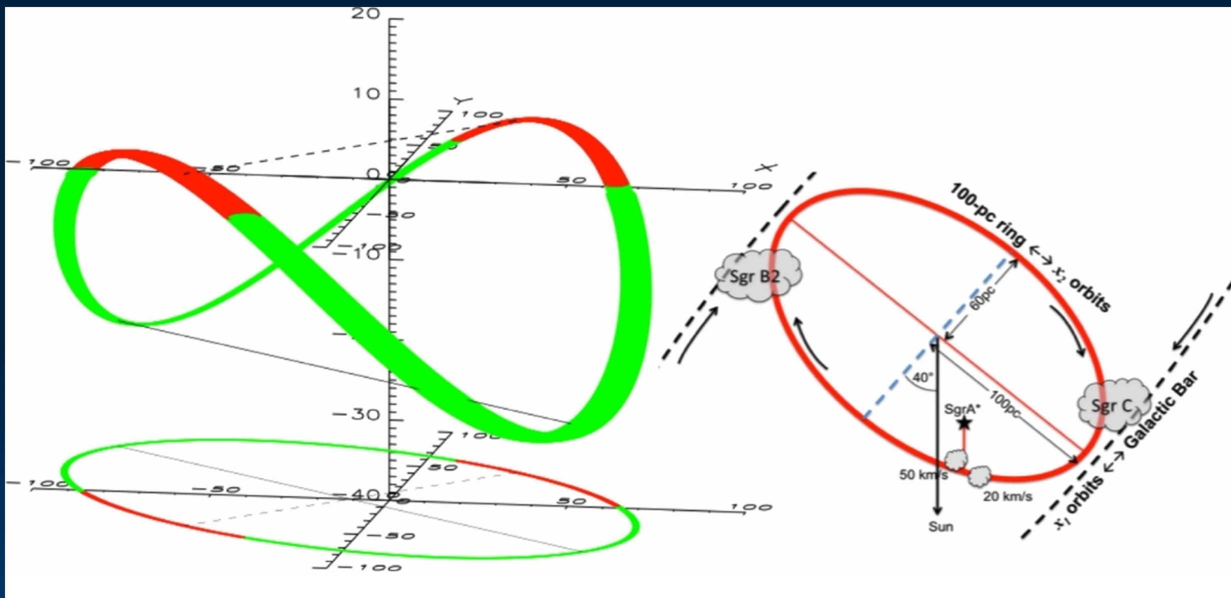
Molinari et al. (2011): Hi-GAL

Clouds: An Elliptical Ring at Galactic Center



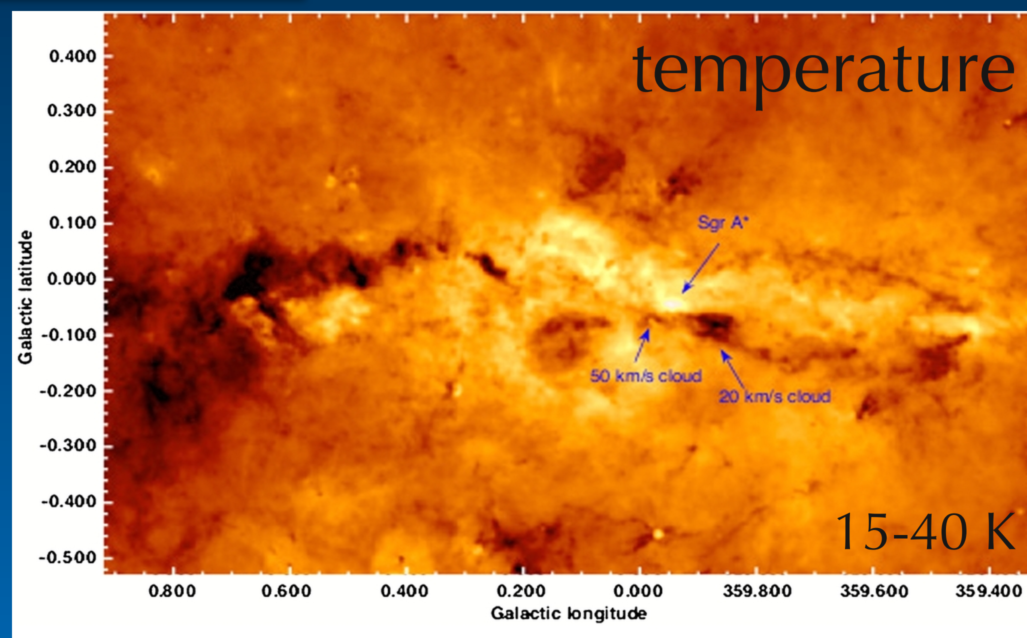
Molinari et al. (2011): Hi-GAL

Clouds: An Elliptical Ring at Galactic Center



Model:
200 pc x 120 pc ring,
mass ~ 3 x 10^7 $M_\odot$,
vertical frequency 2x
orbital frequency

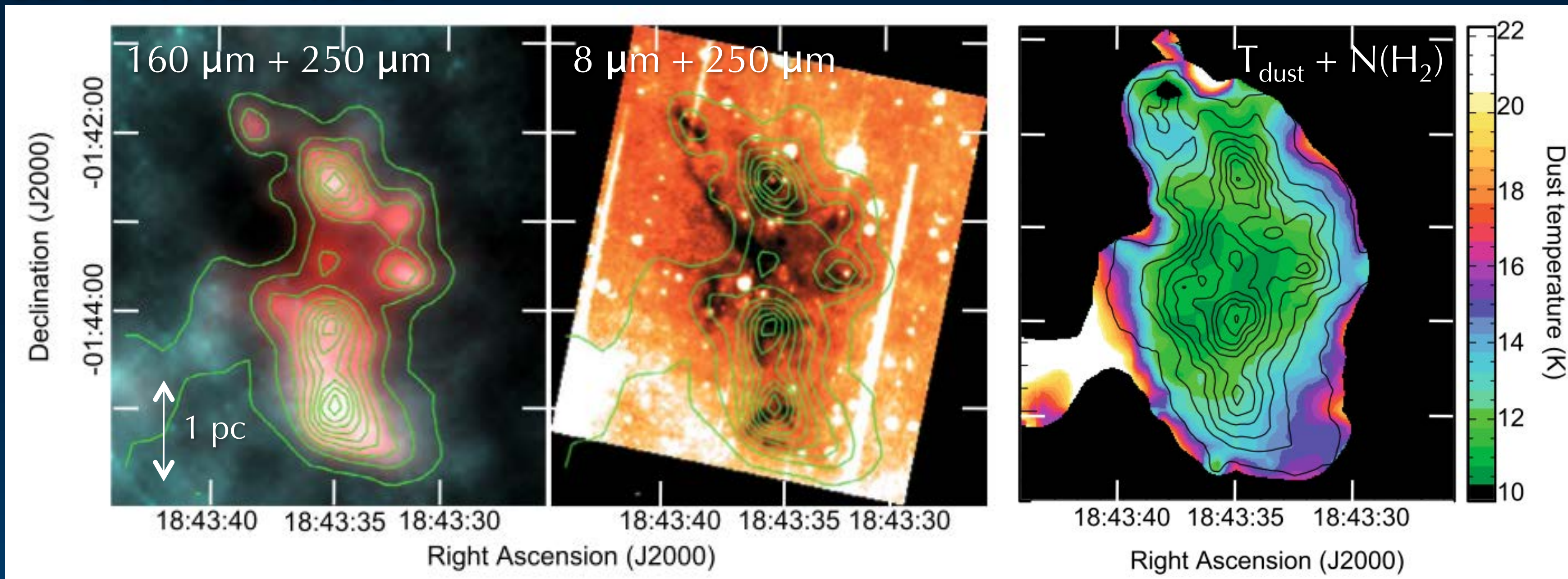
Cold dark clouds
seen against Galactic
background at 70 µm:
IRDCs



Molinari et al. (2011): Hi-GAL

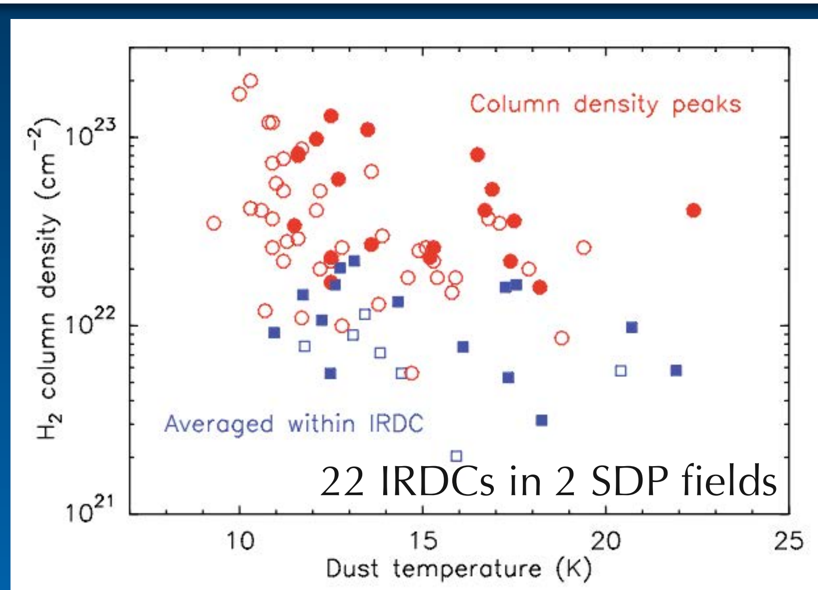
Clouds: Infrared Dark Clouds

SDC30.492+0.958



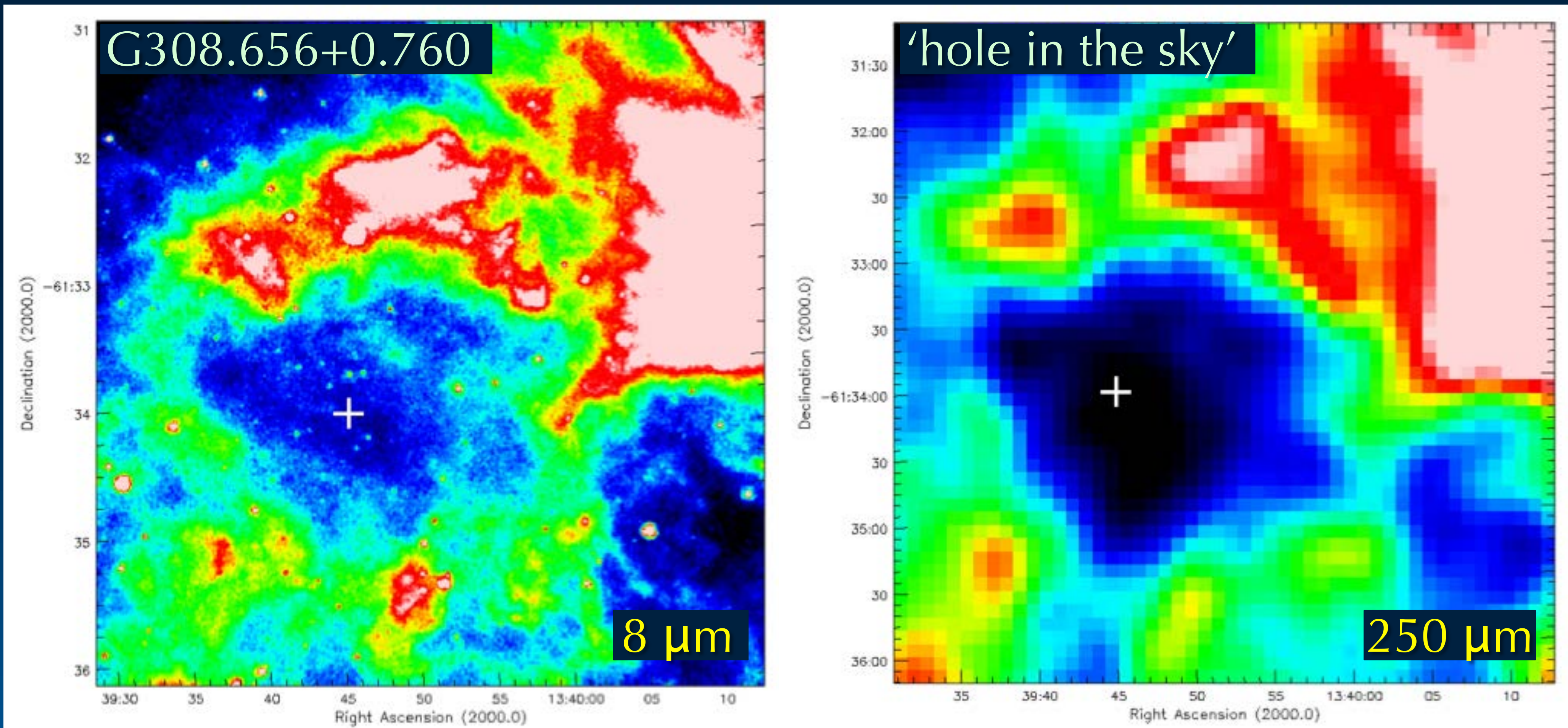
- Inverse correlation of mass-averaged LoS T_{dust} and $N(H_2)$

- watch for varying IRDC backgrounds!



Peretto et al. (2010); Hi-GAL (see Peretto & Bihr posters, also Battersby et al. 2011)

Clouds: Infrared Dark Clouds

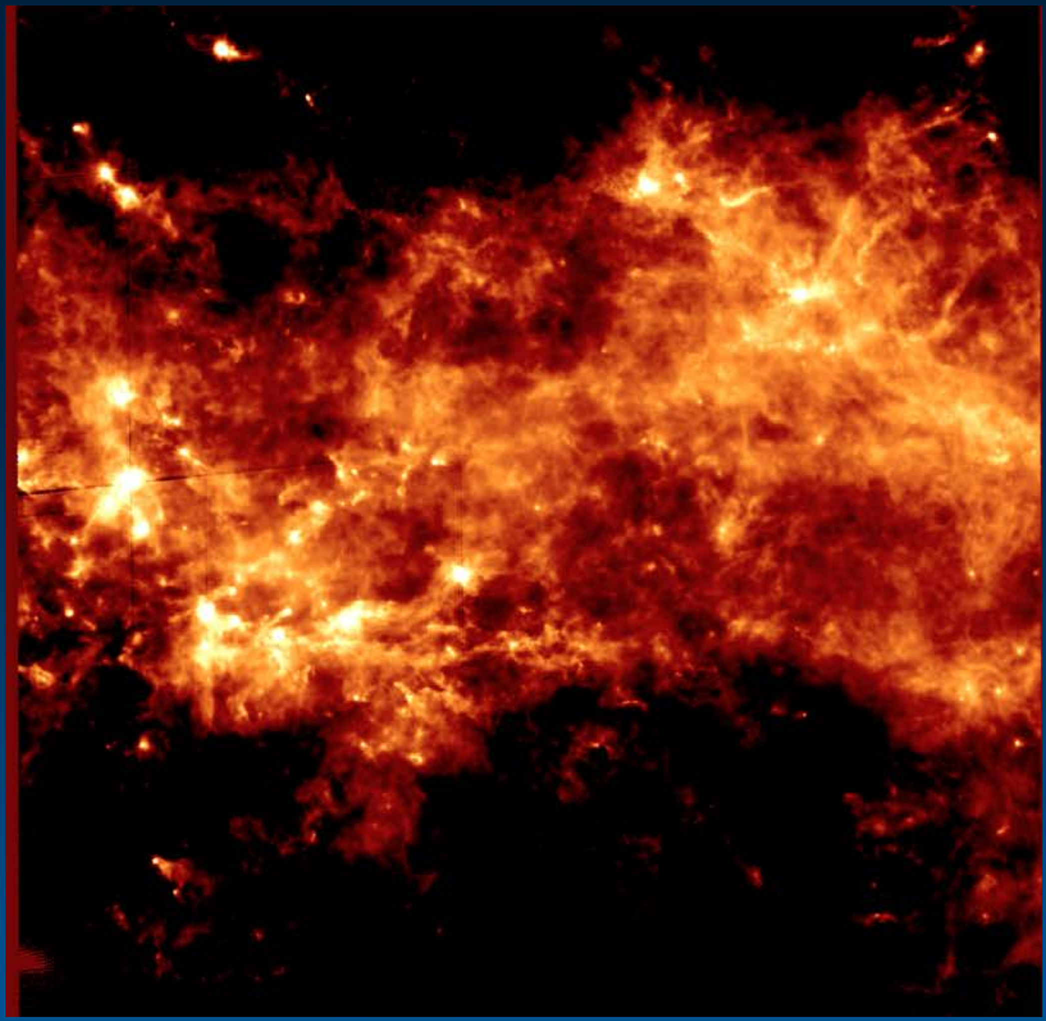


- of 3171 IRDCs, only 1205 (38%) show 250 μm emission
- IRDC population in Galaxy overestimated by 2-3x?

Wilcock et al. (2012); Hi-GAL

Filaments: Threading The Galaxy

l = 59° Hi-GAL field at 250 μm (SDP)



Molinari et al.; Elia et al.; Paradis et al. (2010); Hi-GAL

Filaments: Threading The Galaxy

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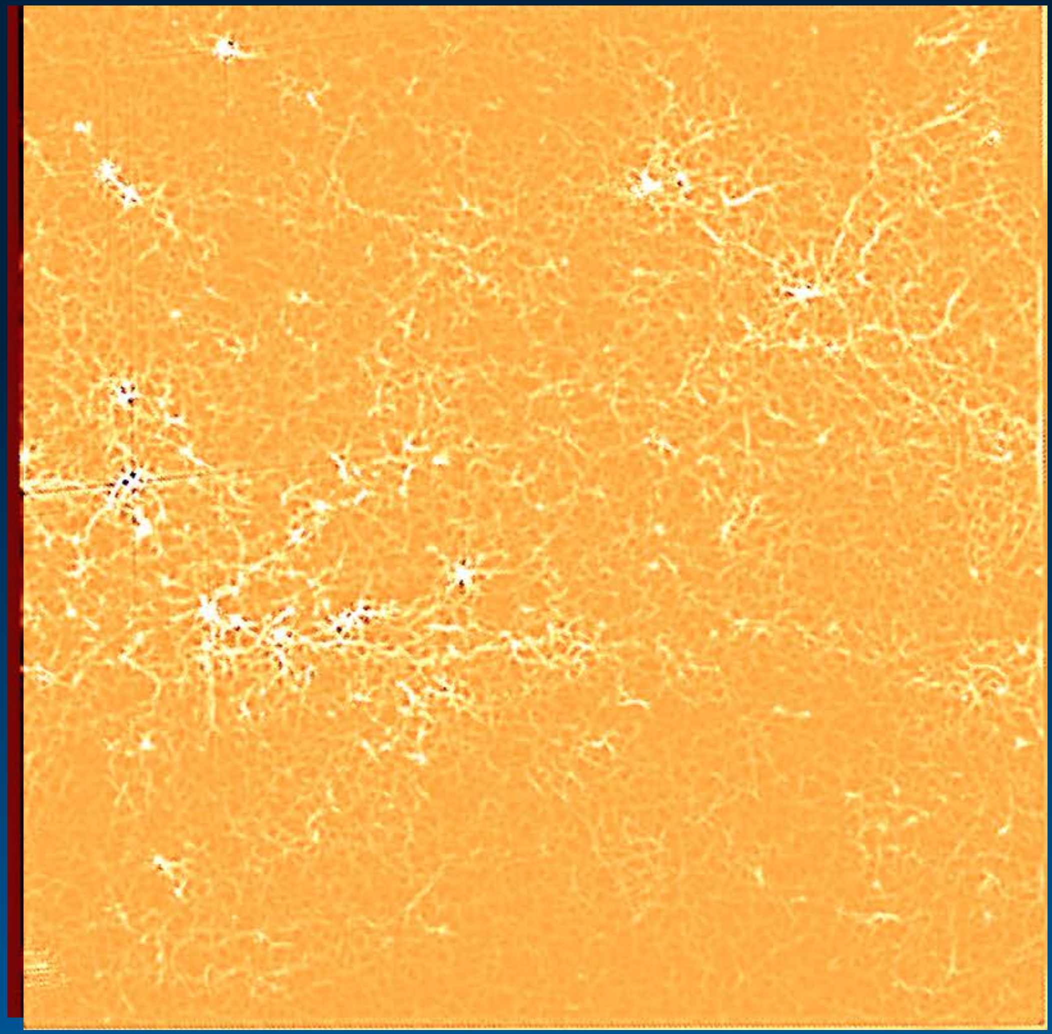

Multidirectional 2^{nd}-derivative image of field

Molinari et al.; Elia et al.; Paradis et al. (2010); Hi-GAL

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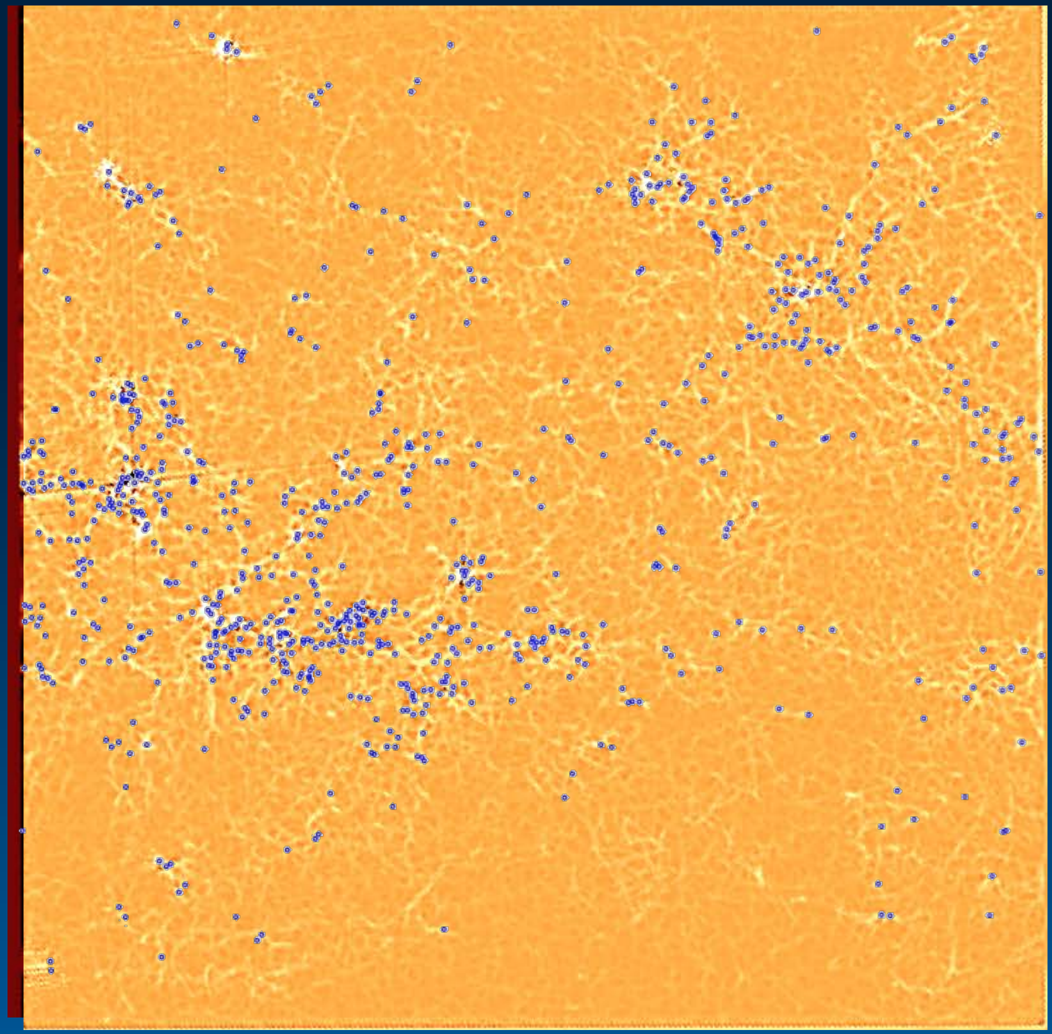


Multidirectional 2nd-derivative image of field

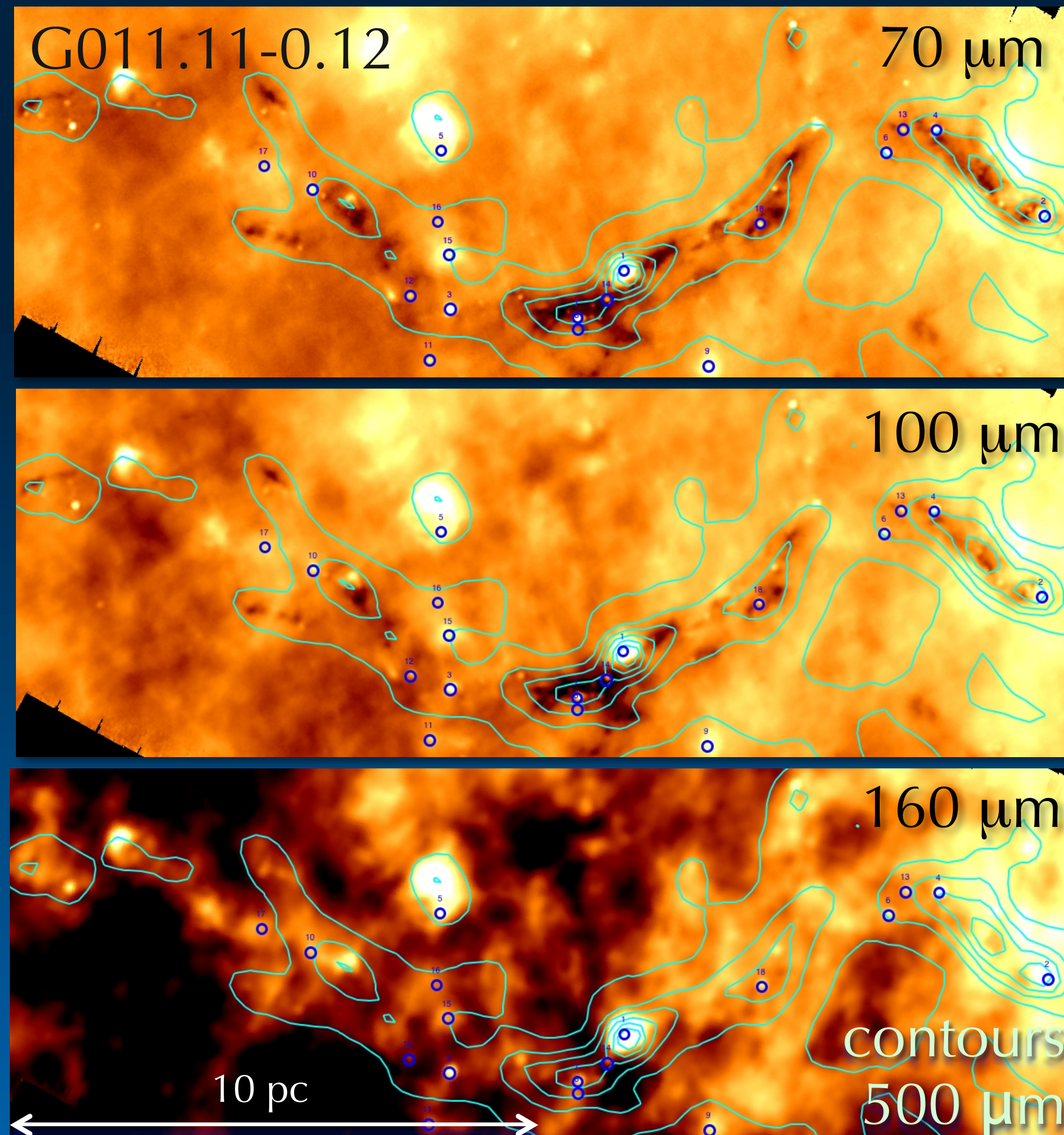
Overlay of 444 compact objects identified

- compact sources mostly seen associated with *filaments*
- A_V threshold = 1? (~**17 $M_\odot$/pc²** ≈ **10 $M_\odot$/pc²** ; Krumholtz et al. 2009)

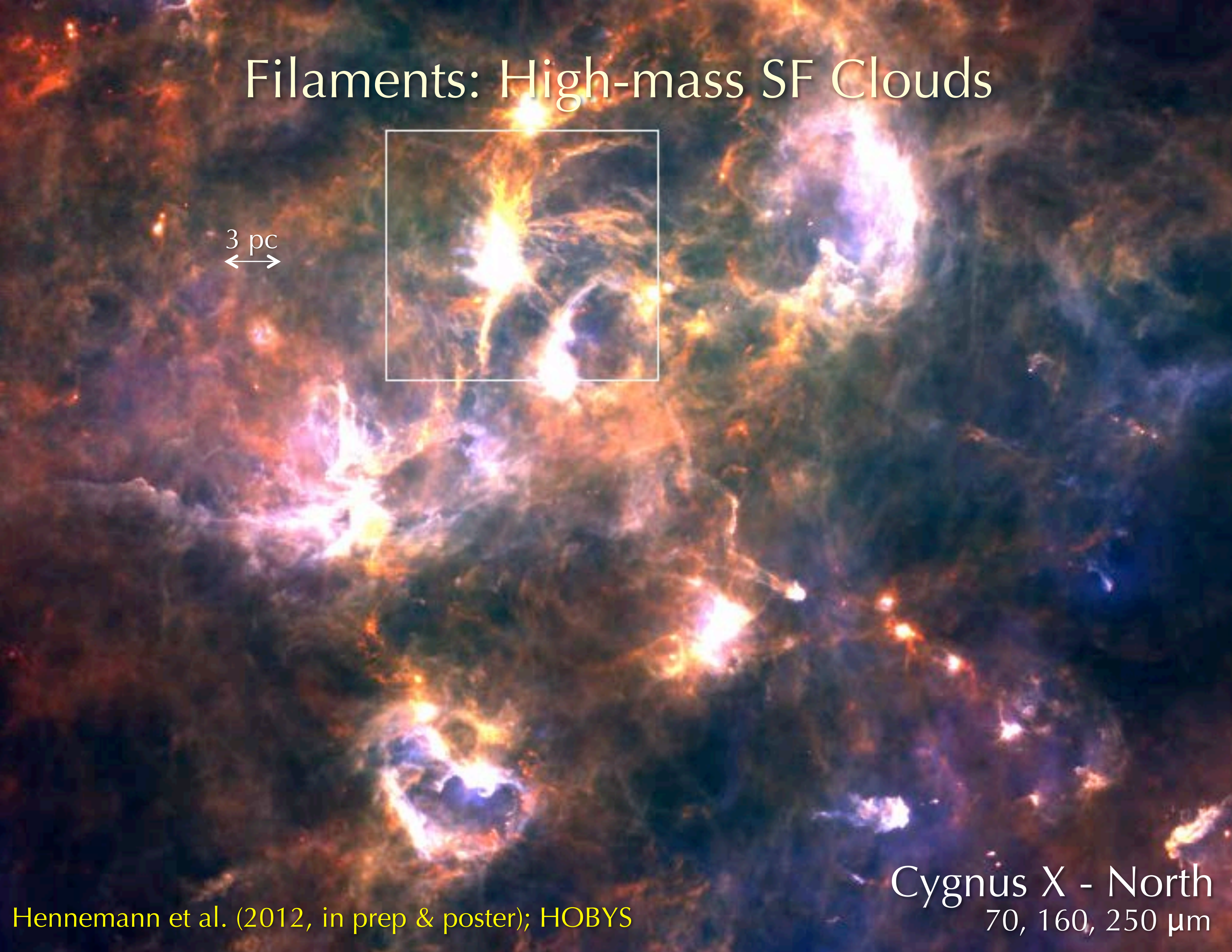
Molinari et al.; Elia et al.; Paradis et al. (2010); Hi-GAL

Filaments: Infrared Dark Clouds

- absorpt'n: short λ, emission: long λ
- 18 clumps/cores along filament
- $\langle M_c \rangle \sim 24\ M_\odot$; $\langle T_{dust} \rangle = 18\text{-}26$ K
- 2 clumps found with $M_c \sim 50\ M_\odot$
- $\langle D_{c\text{-}c} \rangle \sim 0.9$ pc, >> Jeans length

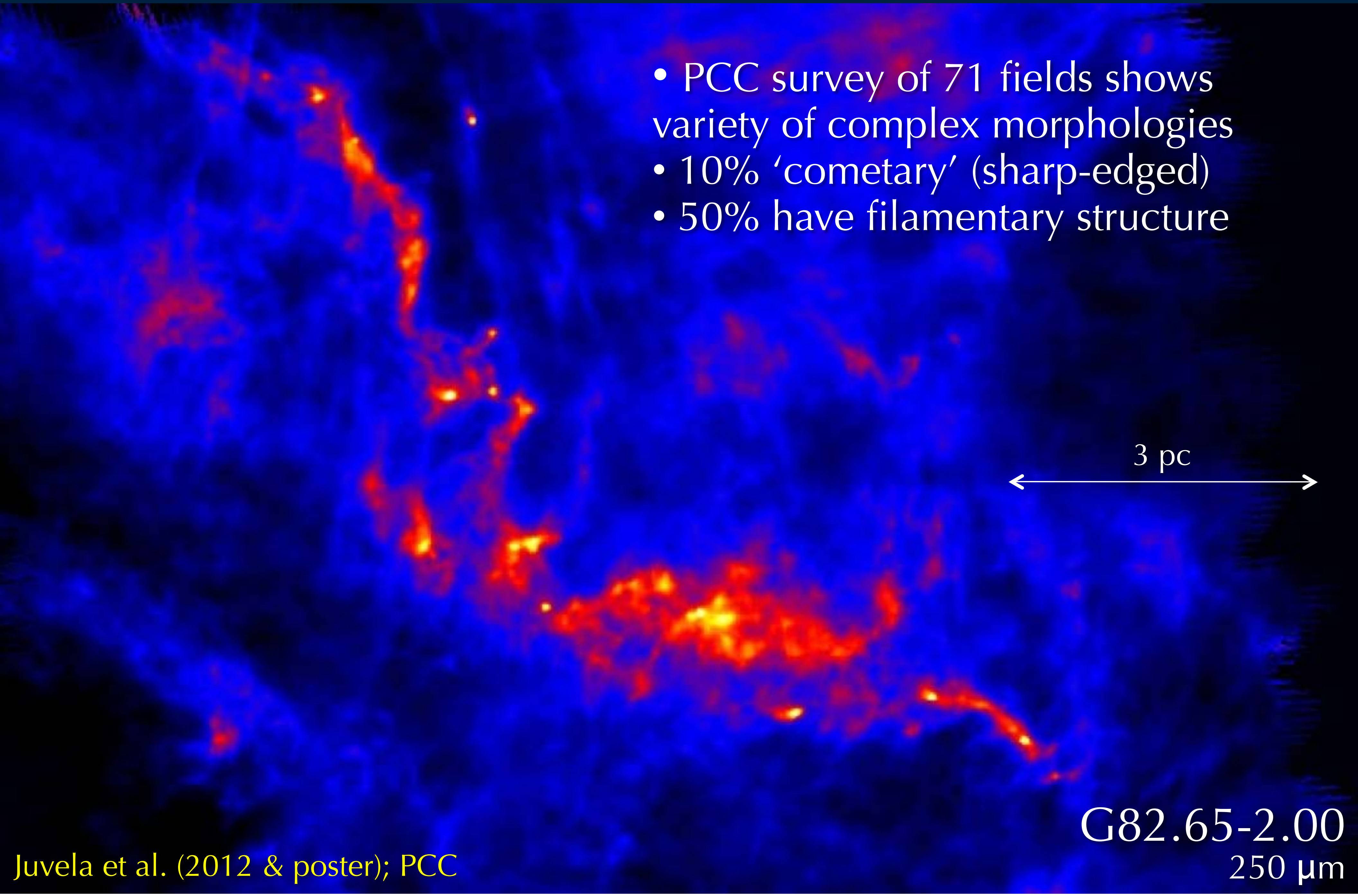


Henning et al. (2010); EPoS; see also Wilcock et al. (2011); Hi-GAL


Filaments: High-mass SF Clouds
3 pc
Cygnus X - North
70, 160, 250 μm
Hennemann et al. (2012, in prep & poster); HOBYS

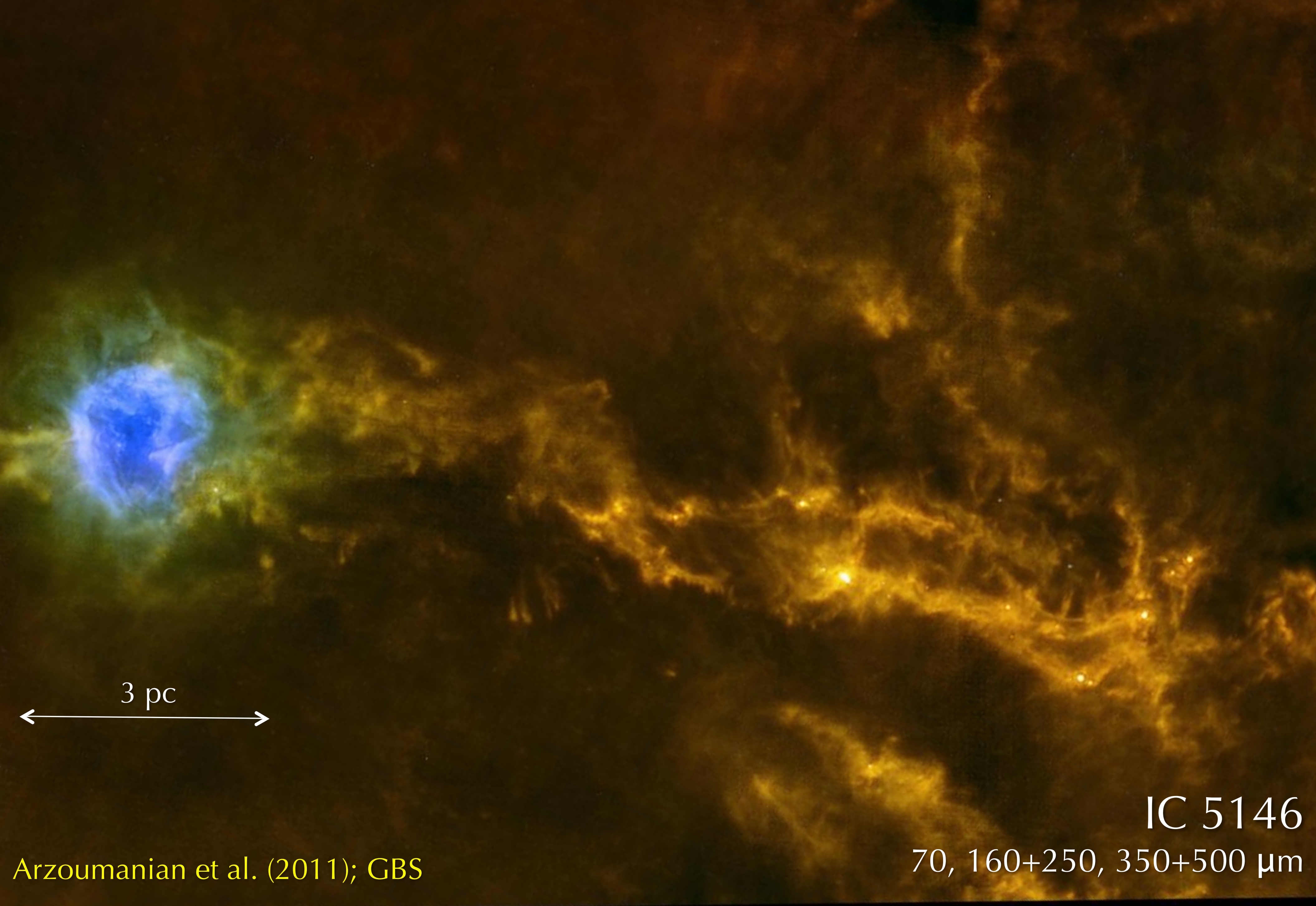
Filaments: Planck Cold 'Clumps'

• PCC survey of 71 fields shows variety of complex morphologies
• 10% 'cometary' (sharp-edged)
• 50% have filamentary structure



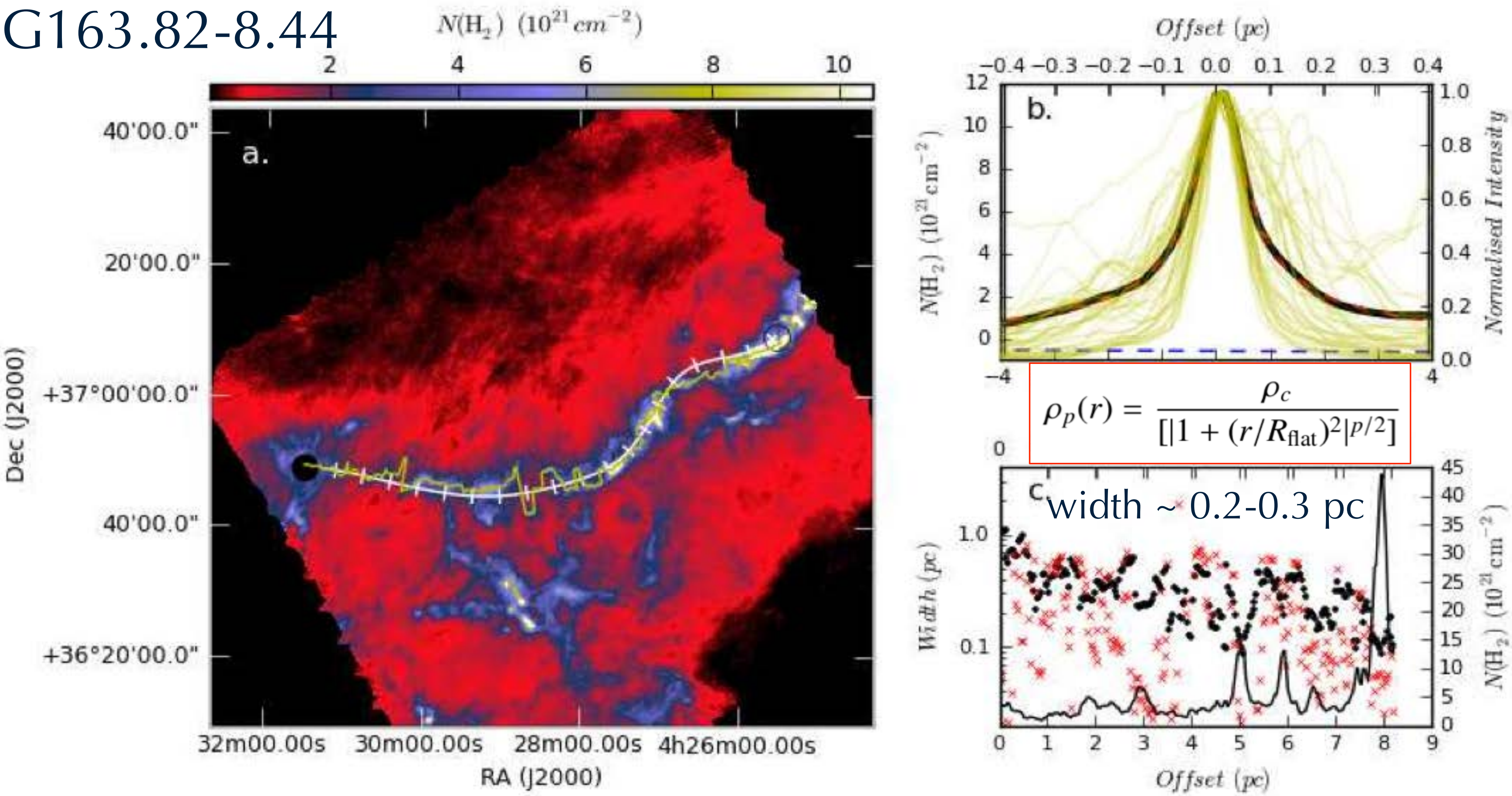
Juvela et al. (2012 & poster); PCC

Filaments: Low-mass SF Clouds



Filaments: Characterization

G163.82-8.44

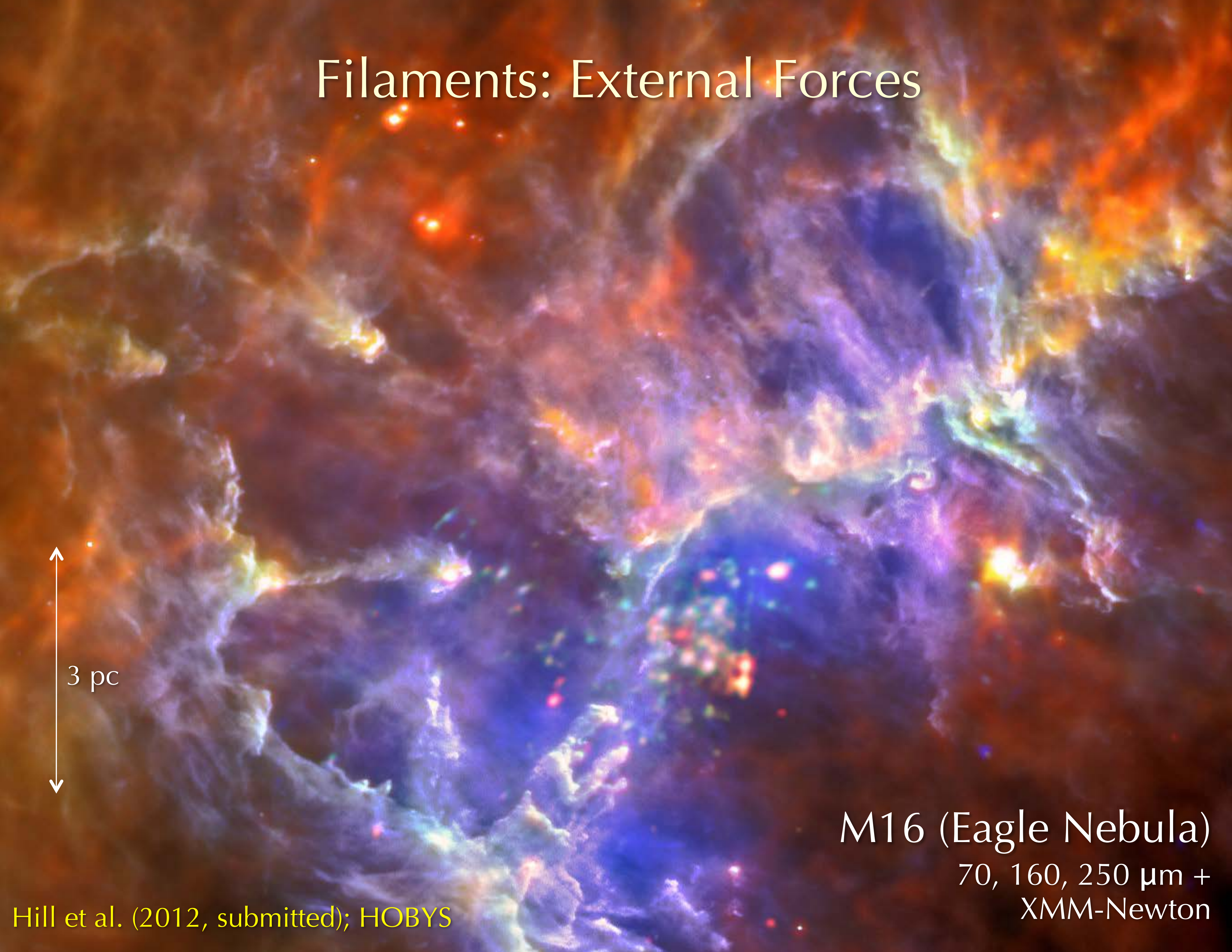


$$\rho_p(r) = \frac{\rho_c}{[|1 + (r/R_{\rm flat})^2|^{p/2}]}$$

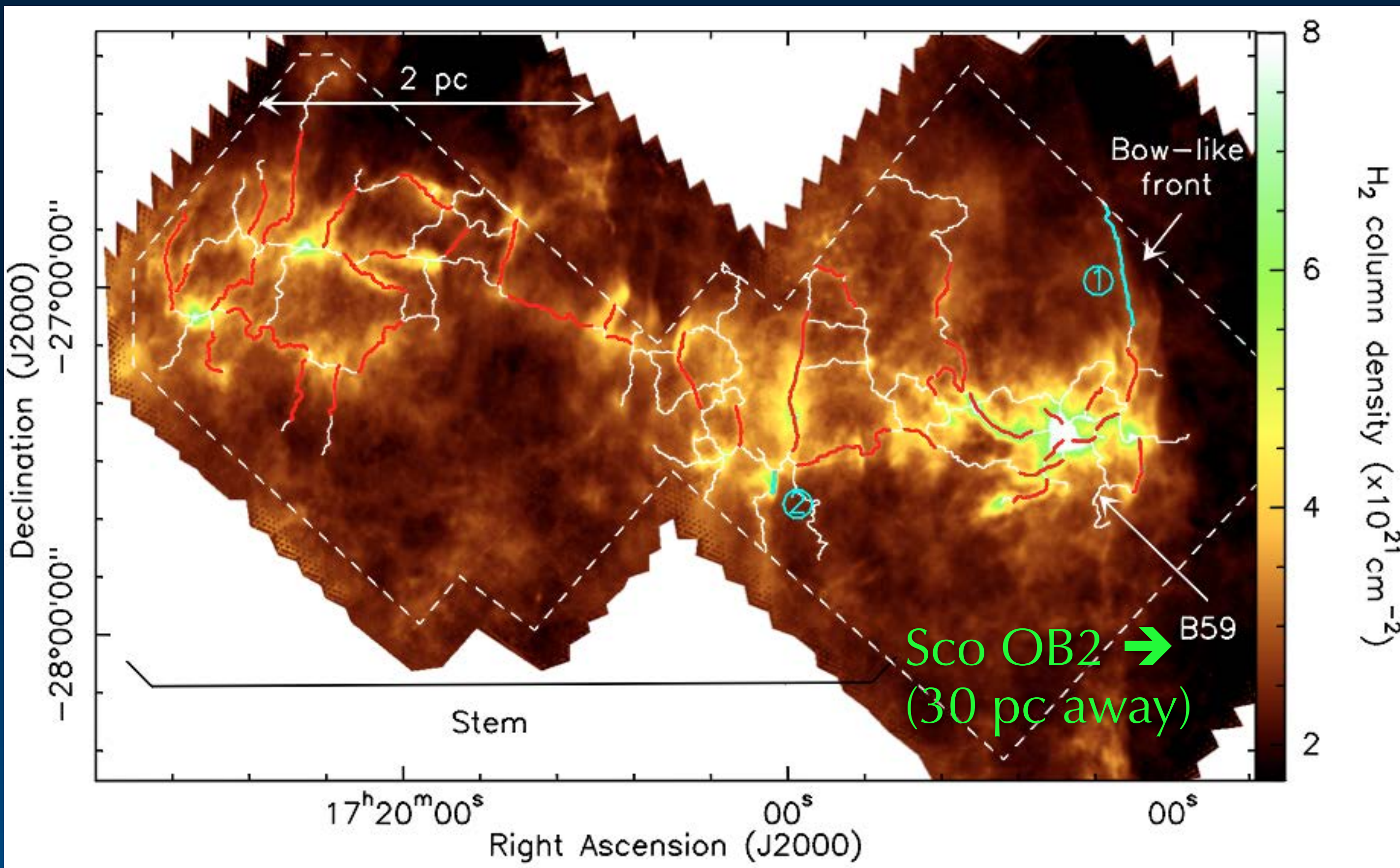
- hard to define: varying widths, backgrounds, projection and distances
- Plummer fits; *p* ~ 1.5 – 2 (cf. *p* = 4 isothermal cylinder; Ostriker 1964)

Juvela et al. (2012 & poster); PCC; see also Planck Collaboration XXII (2011

Filaments: External Forces



Filaments: Characterization

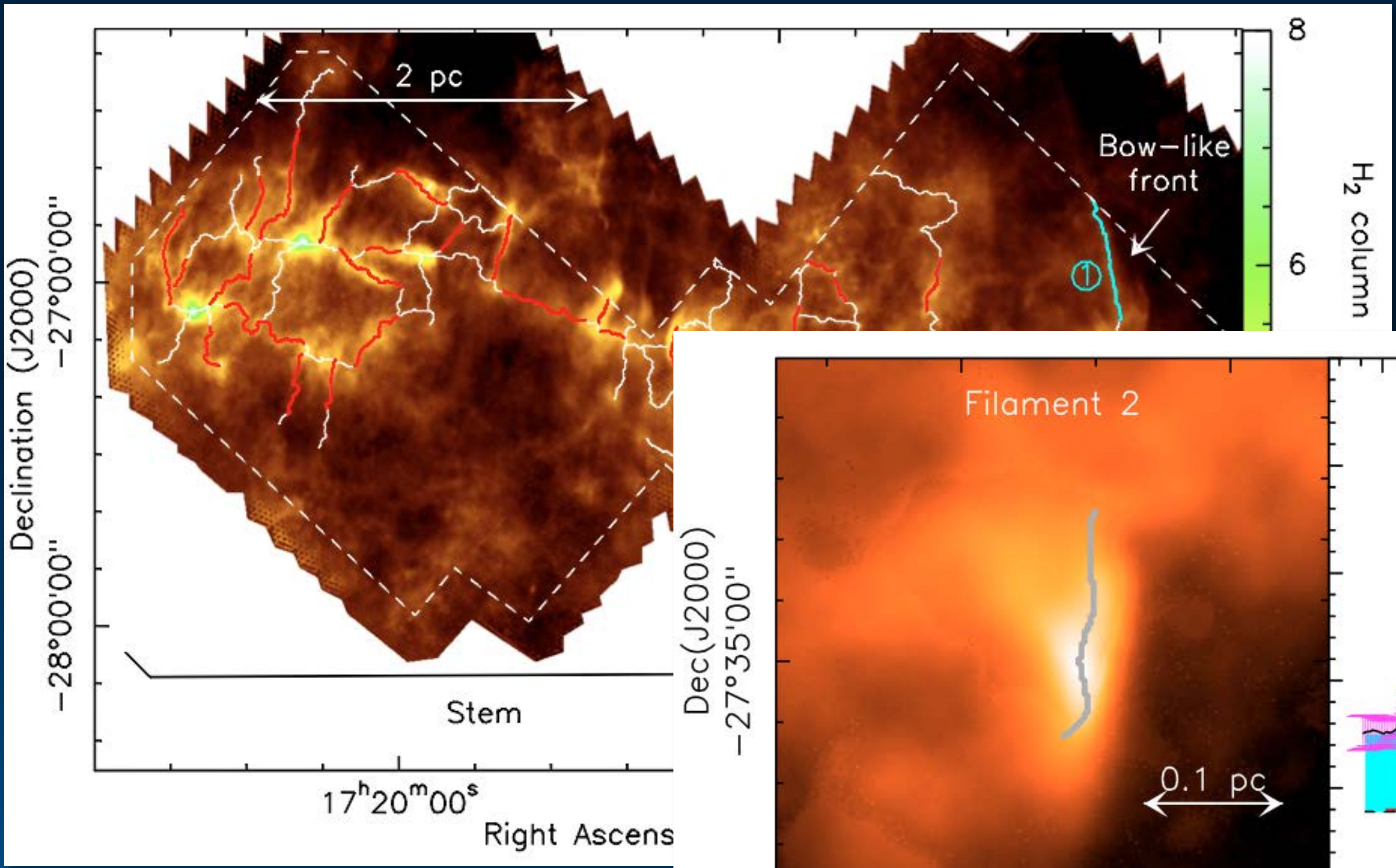


Pipe Nebula:
B59 + Stem

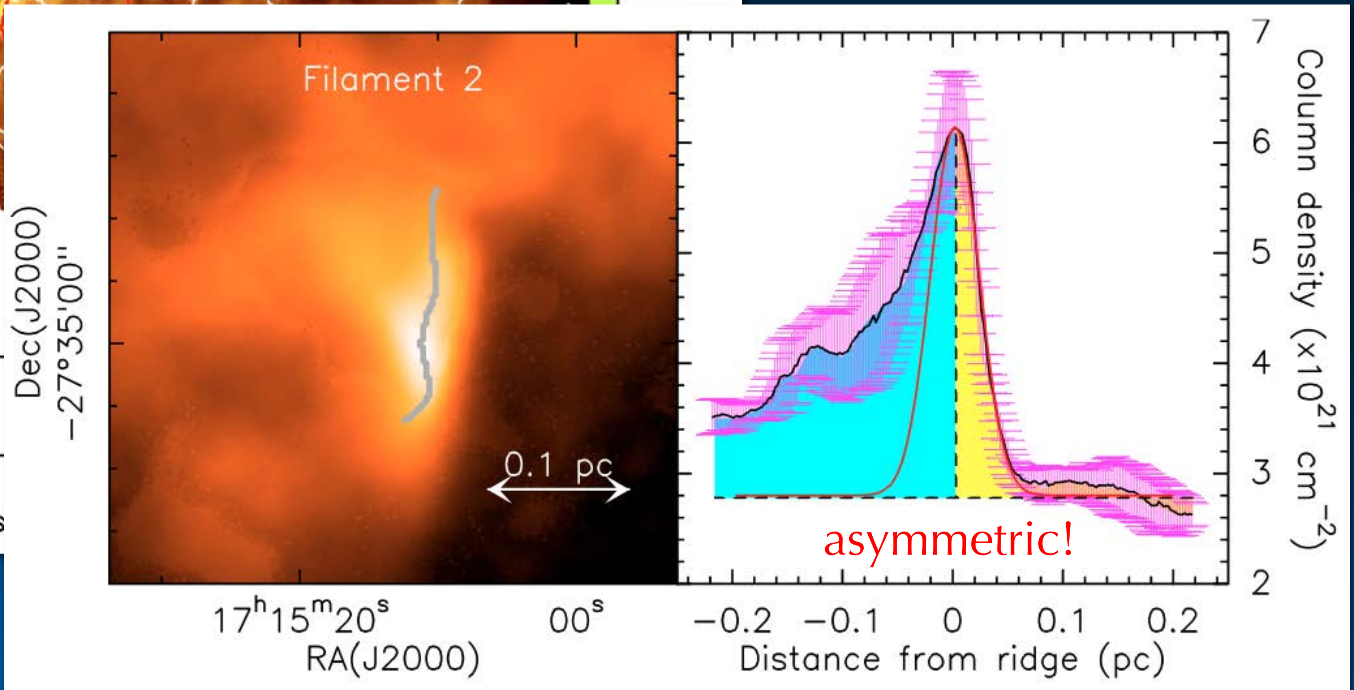
43 filaments detected by "DisPerSE" (Sousbie 2011)

Peretto et al. (2012); GBS

Filaments: Characterization



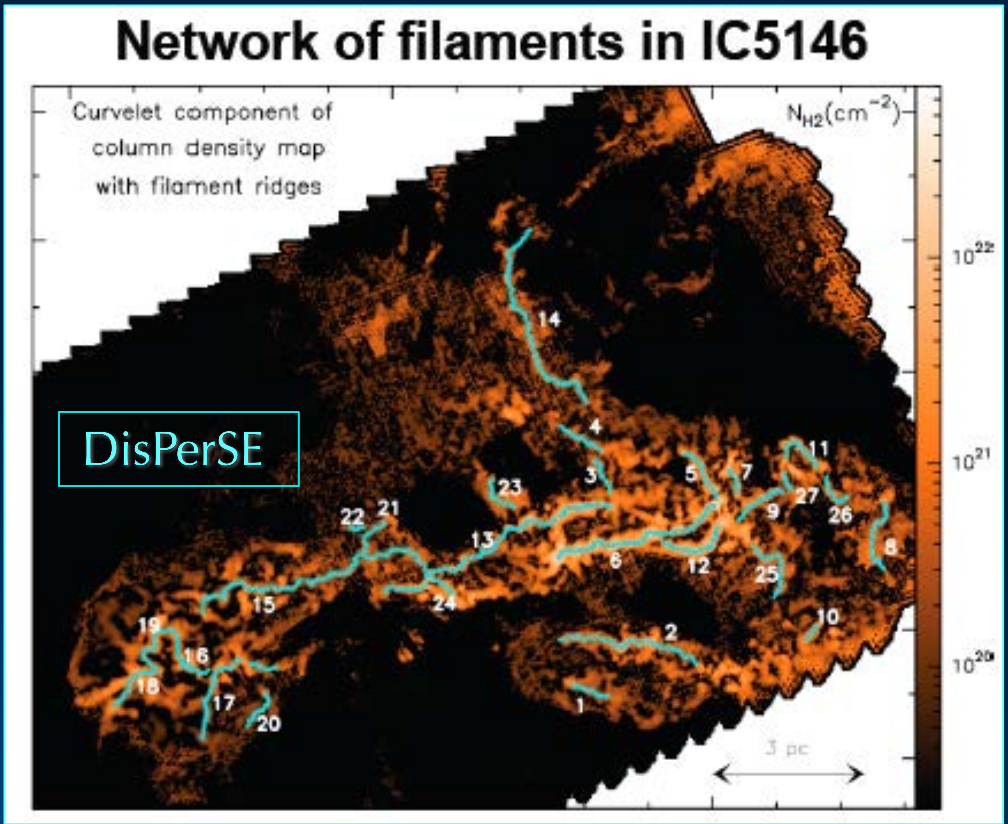
Pipe Nebula:
B59 + Stem

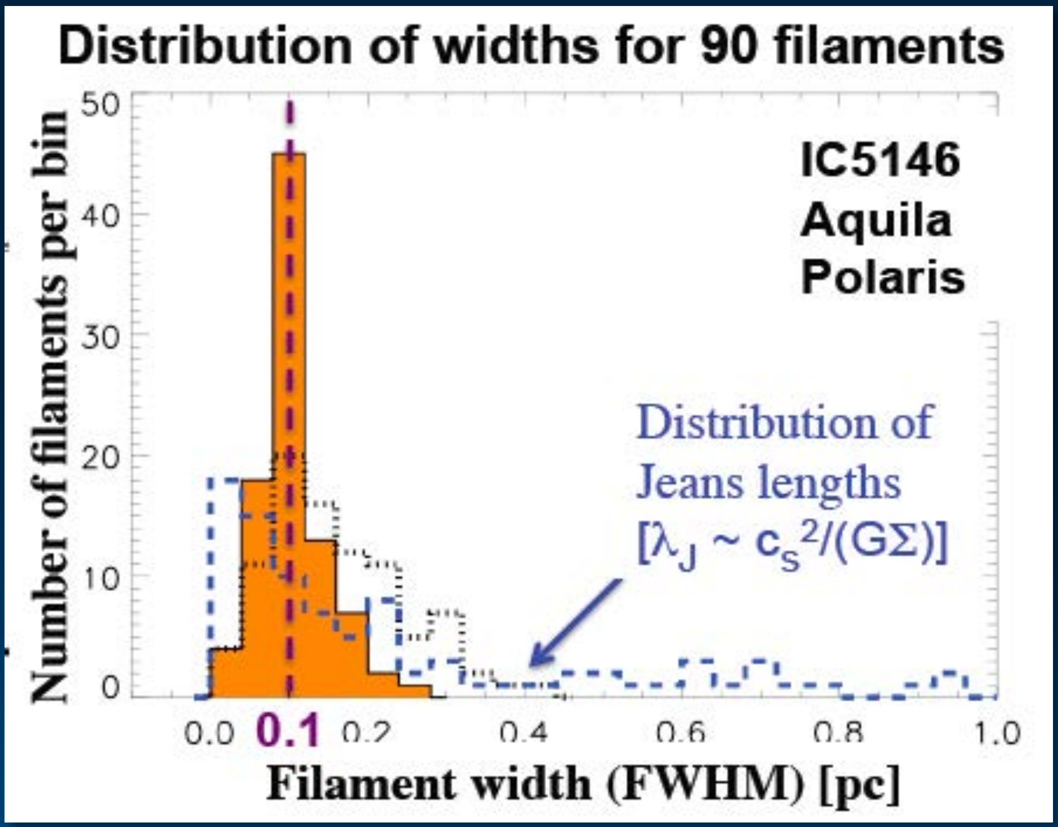


• some filaments may be affected (form?) by compression from feedback (winds, radiation from nearby luminous stars or clusters)

Peretto et al. (2012); GBS

Filaments: Constant Widths?





• central column densities vary over 2.5 orders of magnitude but widths vary little around ~0.1 pc (sonic scale), turbulent origins?

• filaments are ***hierarchical***, harder to define accurately with increasing distance (Juvela et al. 2012)

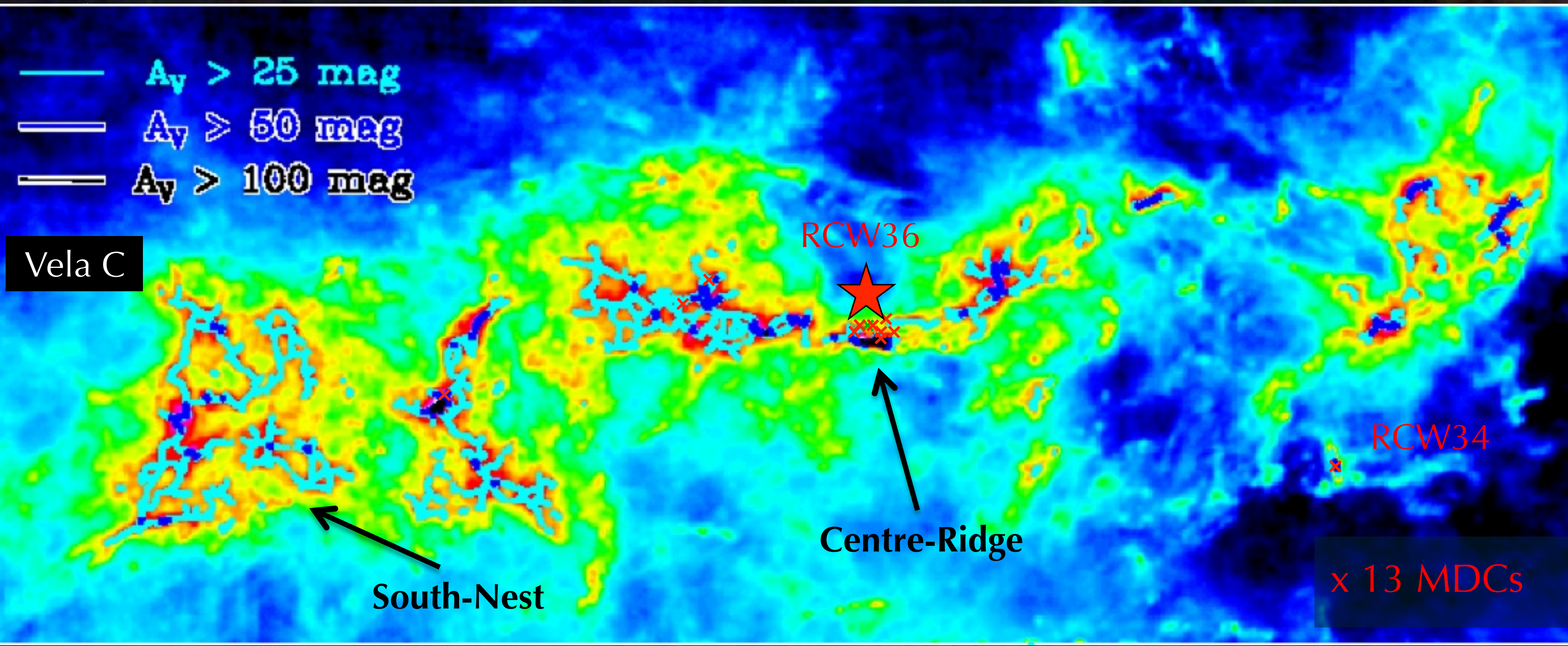
Arzoumanian et al. (2011); GBS

Filament Networks: Organization

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

Hill et al. (2011); HOBYS

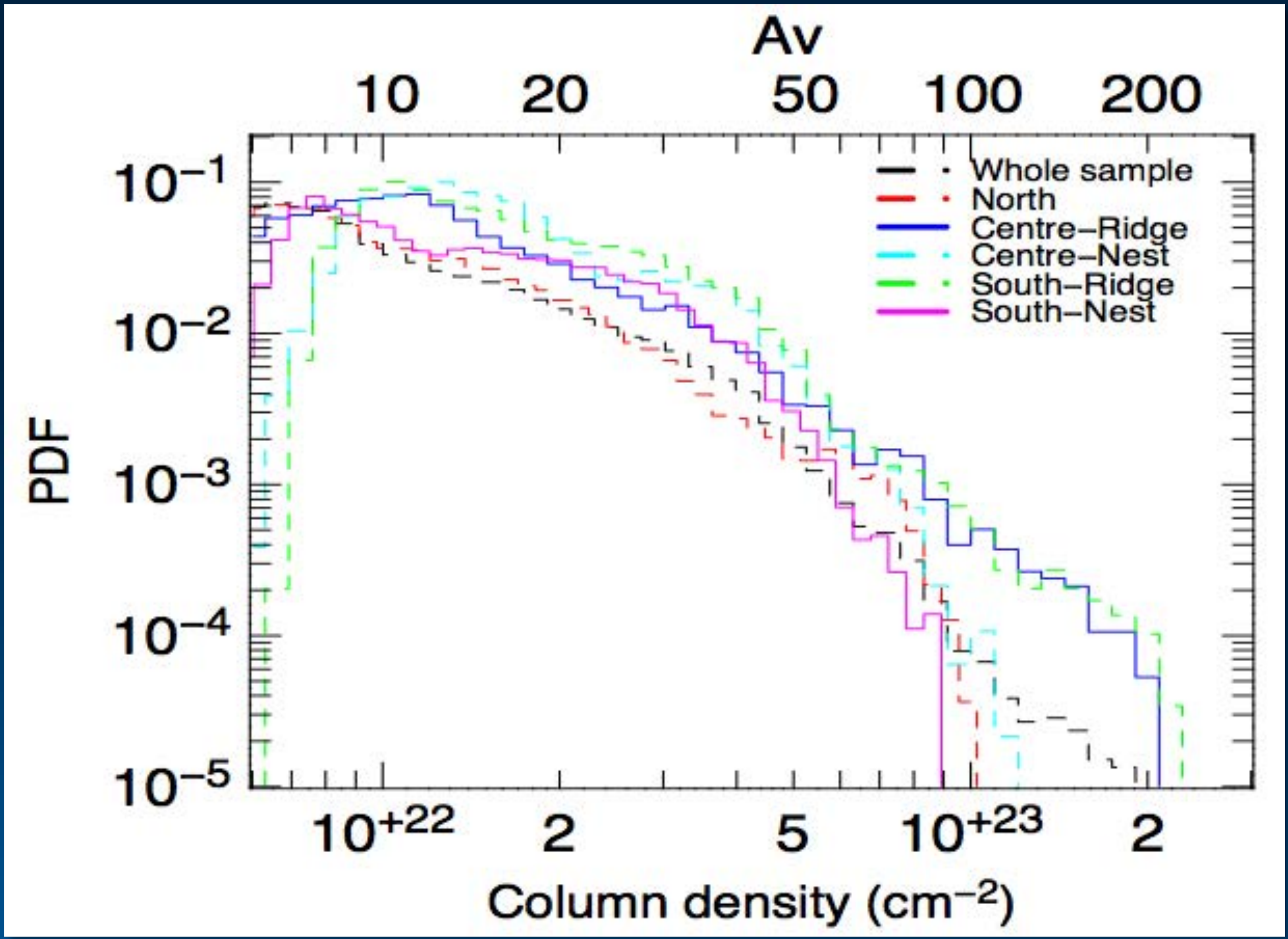
Filament Networks: Organization



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

Hill et al. (2011); Russeil poster; Minier et al., in prep.; HOBYS

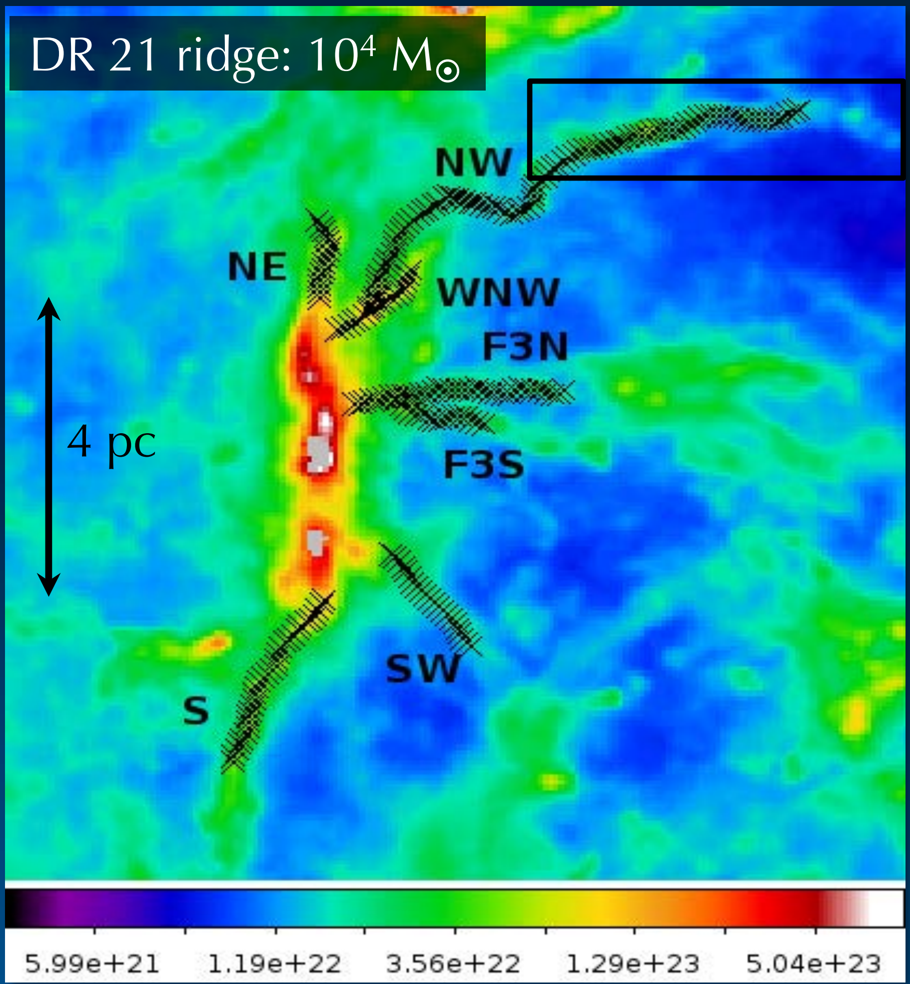
Filament Networks: PDFs

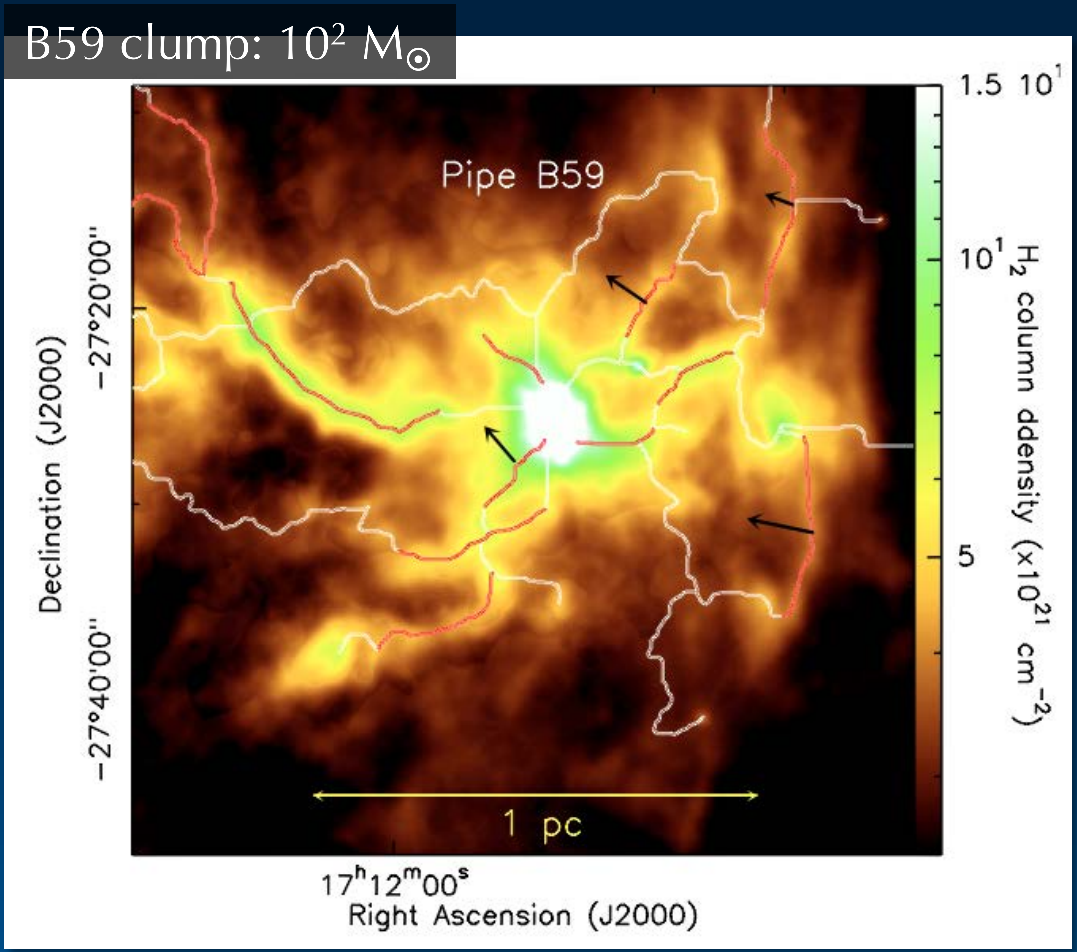


- PDFs are flatter in 'ridges' than in 'nests'
- predicted for coherent structures formed in large-scale flows (see Federrath et al. 2010; also Schneider et al. 2012)

Hill et al. (2012); HOBYS

Filament Networks: Mass Flow



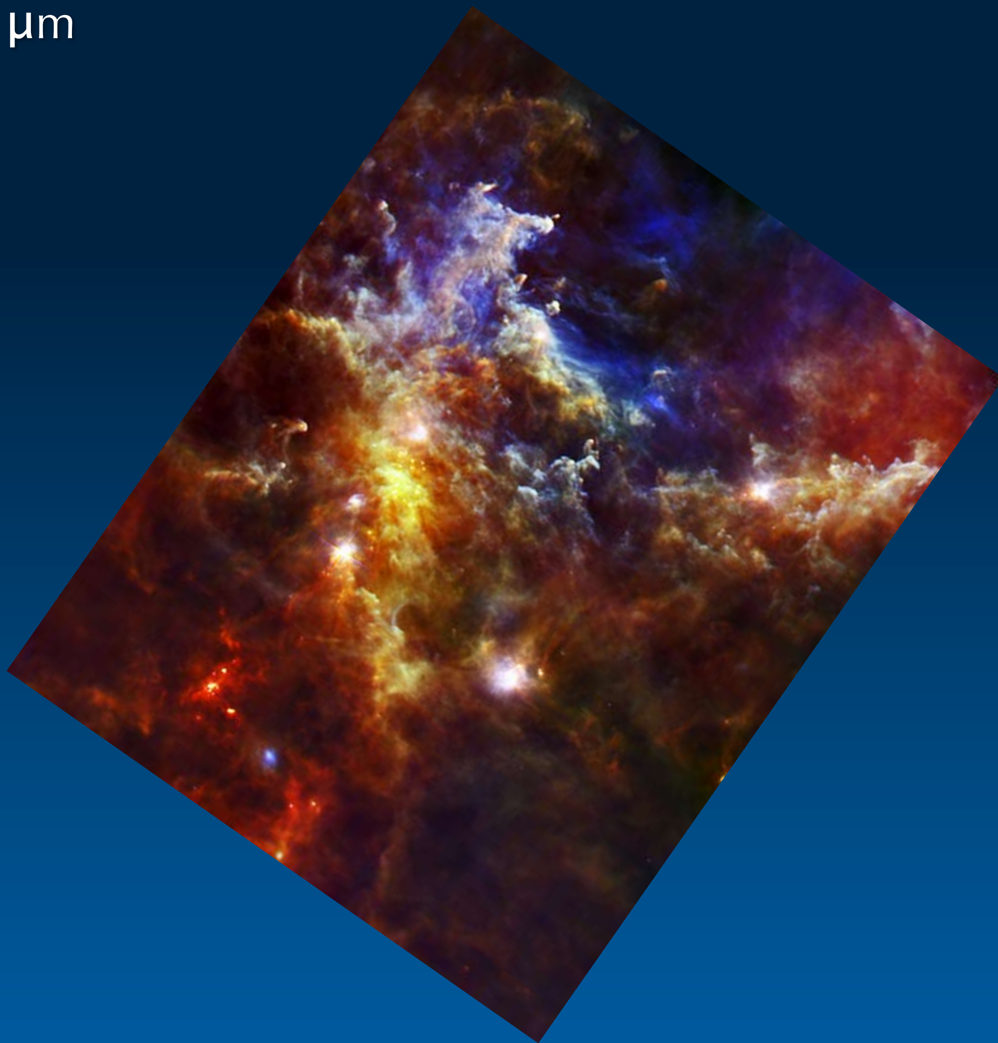


- ridges formed and fed by sub-filament merging (Schneider et al. 2010)
- sub-filaments also surround (feed?) dominant clump in Pipe Nebula

Hennemann et al. (2012 & poster), Marston et al., in prep.; HOBYS; Peretto et al. (2012); GBS

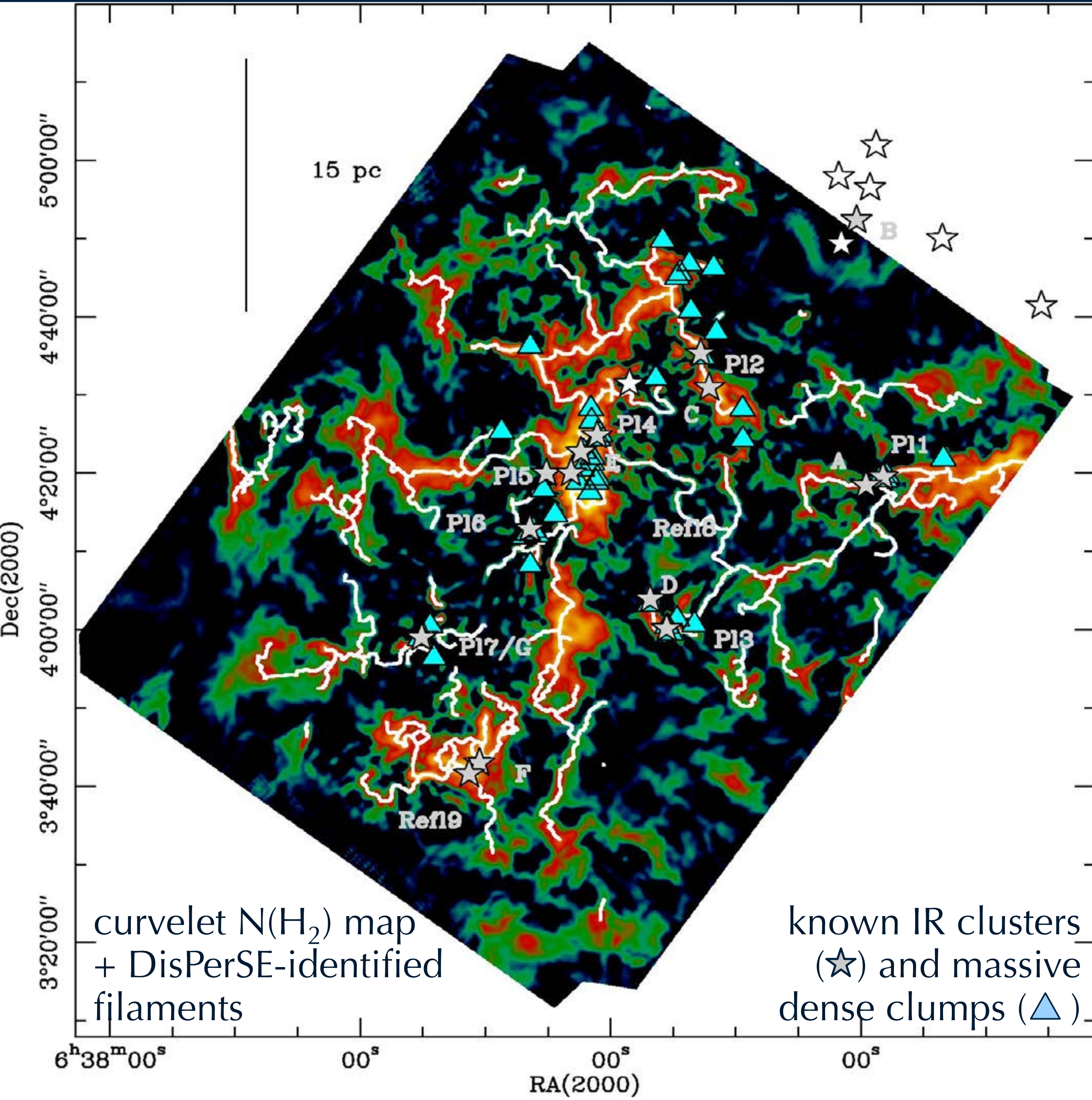
Filament Networks: Origins of Clumps

Rosette Molecular Cloud
70, 160, 250 μm



Schneider et al. (2012); HOBYS

Filament Networks: Origins of Clumps

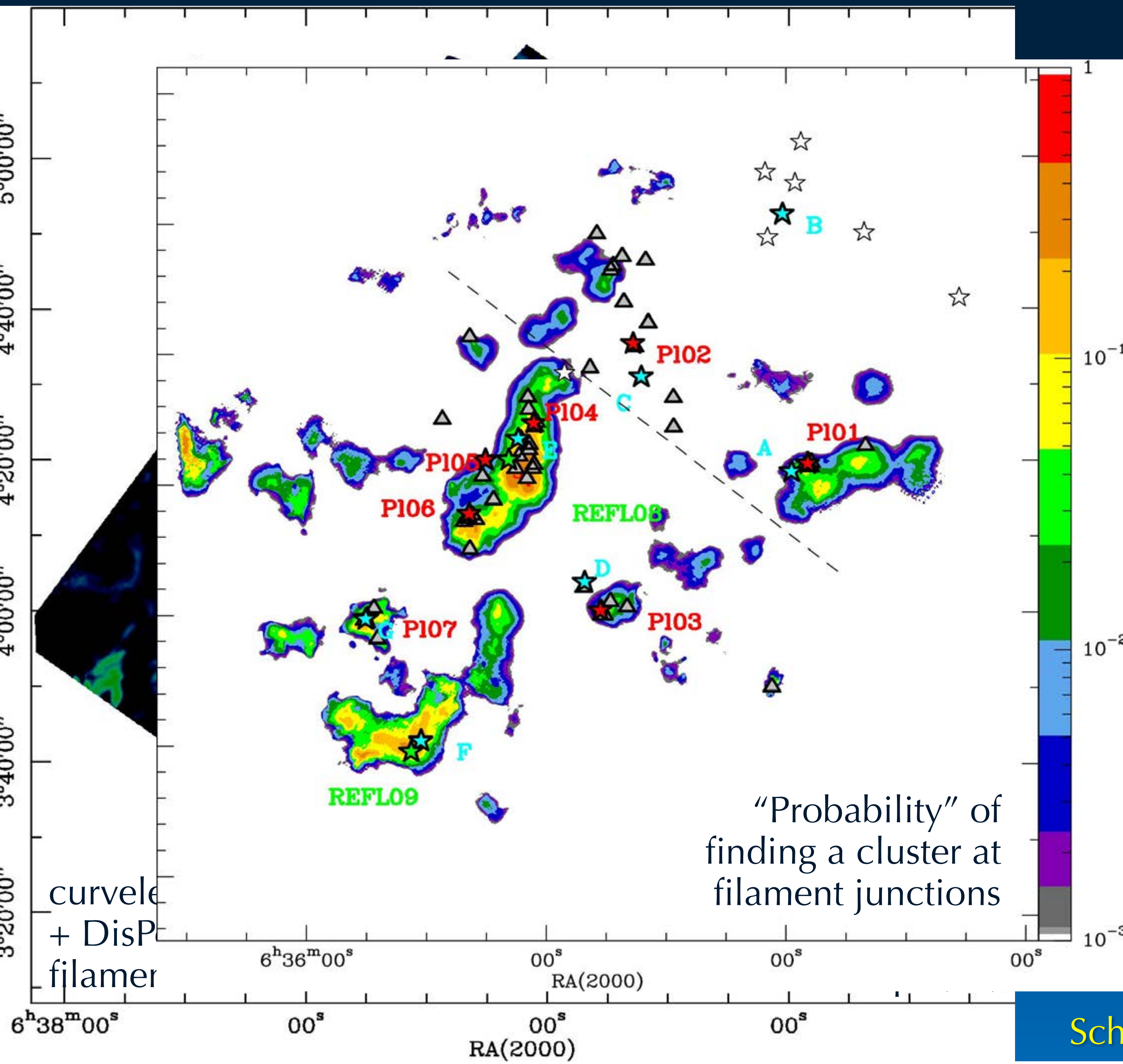


curvelet N(H_2) map + DisPerSE-identified filaments

known IR clusters (☆) and massive dense clumps (△)

Schneider et al. (2012); HOBYS

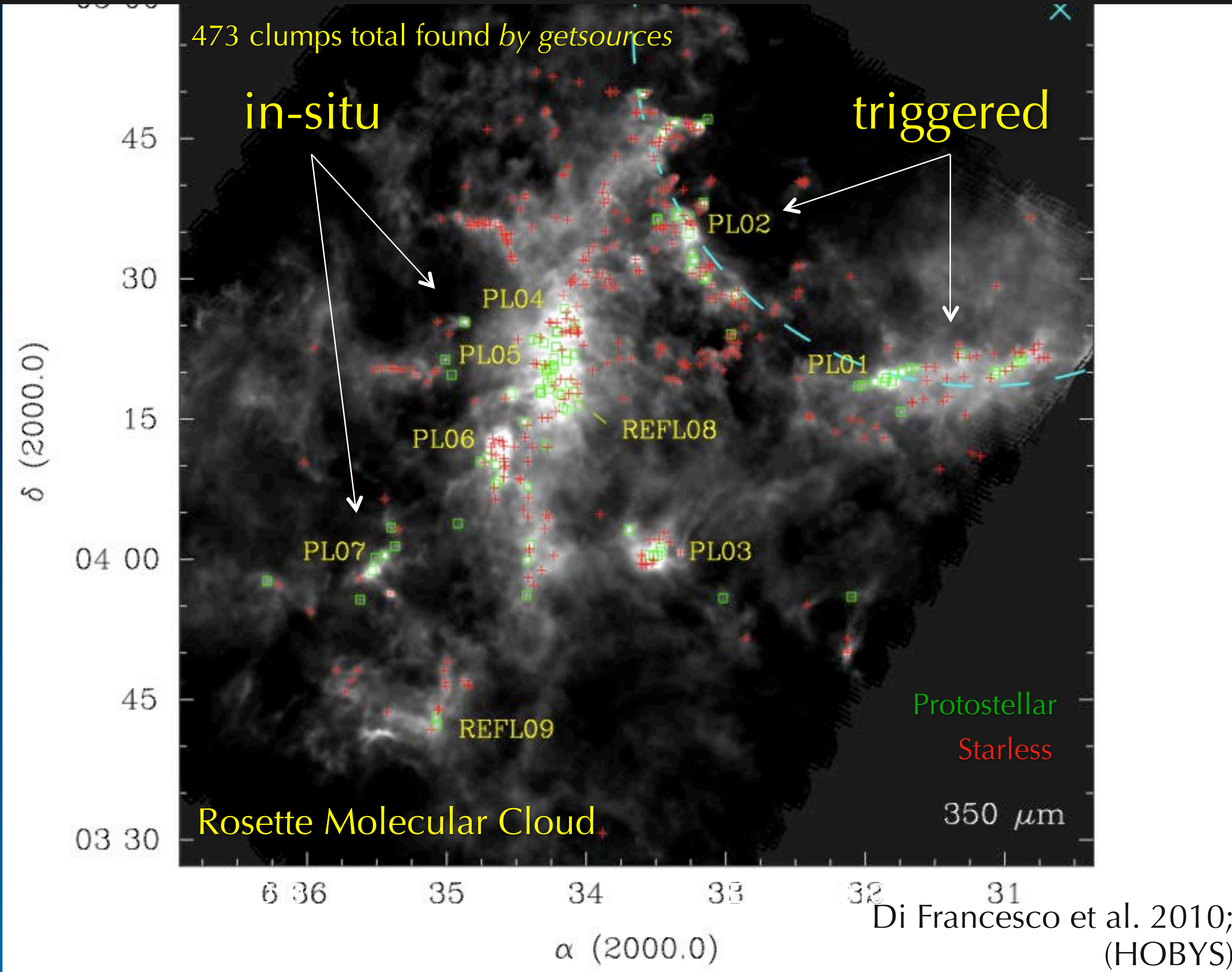
Filament Networks: Origins of Clumps



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

Schneider et al. (2012); HOBYS

Clumps

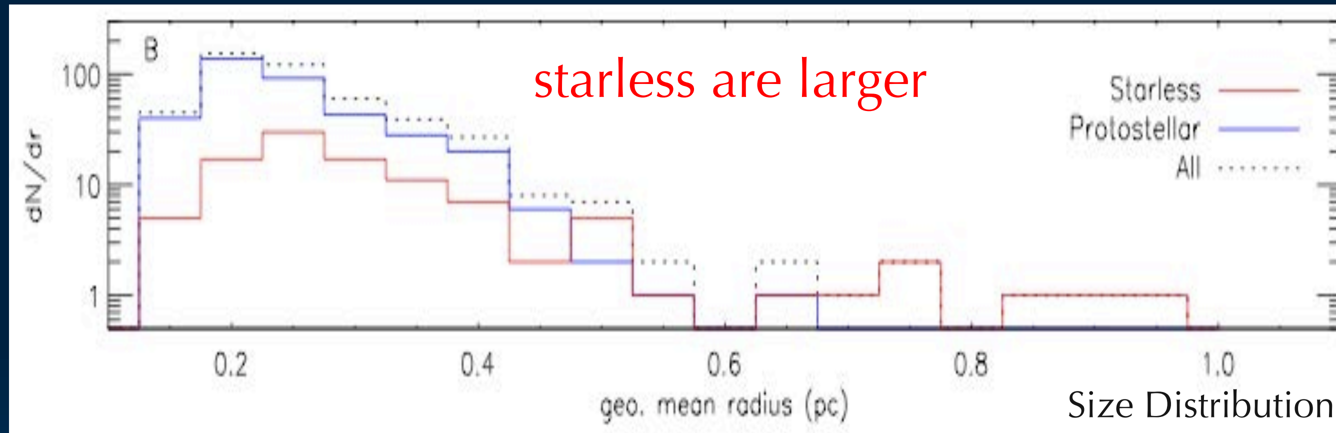


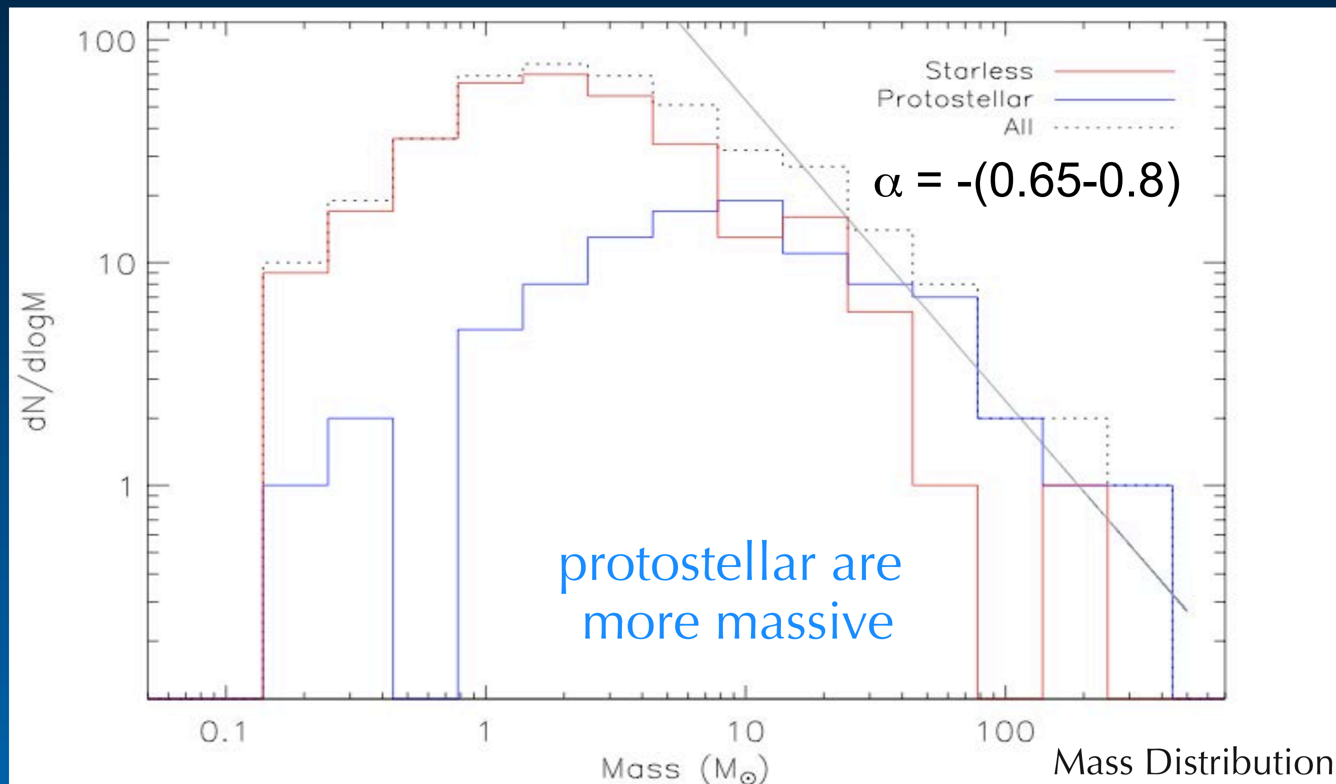
Di Francesco et al. 2010; (HOBYS)

Clumps: Characterization

RMC clumps have:

- Sizes: 0.15-1.0 pc
- Masses: 0.2-400 $M_\odot$
- Mass slope: 0.65-0.8, like CO clumps (see Dent et al. 2008)
- not Salpeter (1.35): due to clump crowding? Rosette at 1.6 kpc

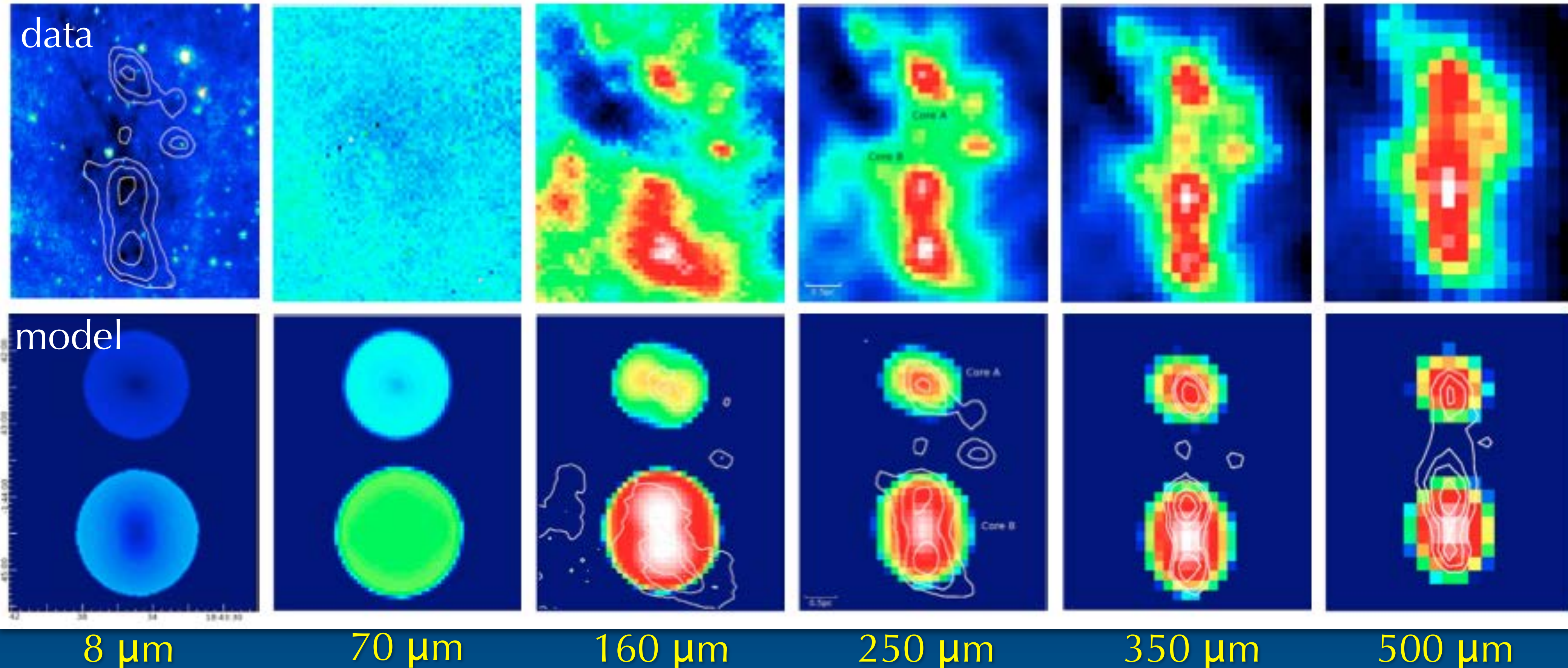




Di Francesco et al. (2010); HOBYS; Tackenberg poster; EPoS

Characterization of Clumps

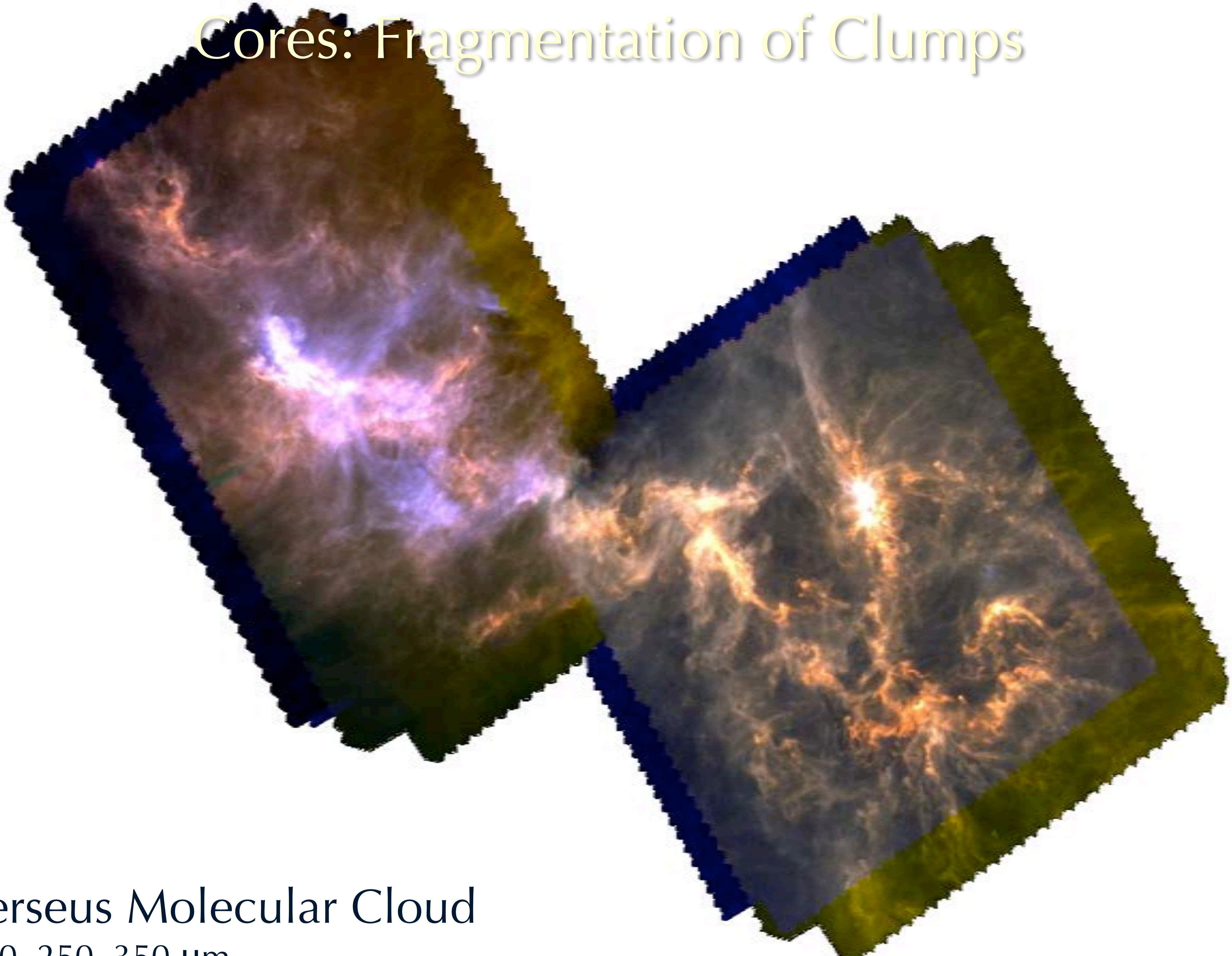
G030.50+00.95



- 6 clumps total; semi-major axes: 0.4-1.0 pc; masses: ~100-300 $M_\odot$
- single T_{dust} an oversimplification: T_{dust} = 10 K inside, T_{dust} = 20 K outside
- high-mass stars likely not to have yet formed

Wilcock et al. (2011); Hi-GAL

Cores: Fragmentation of Clumps

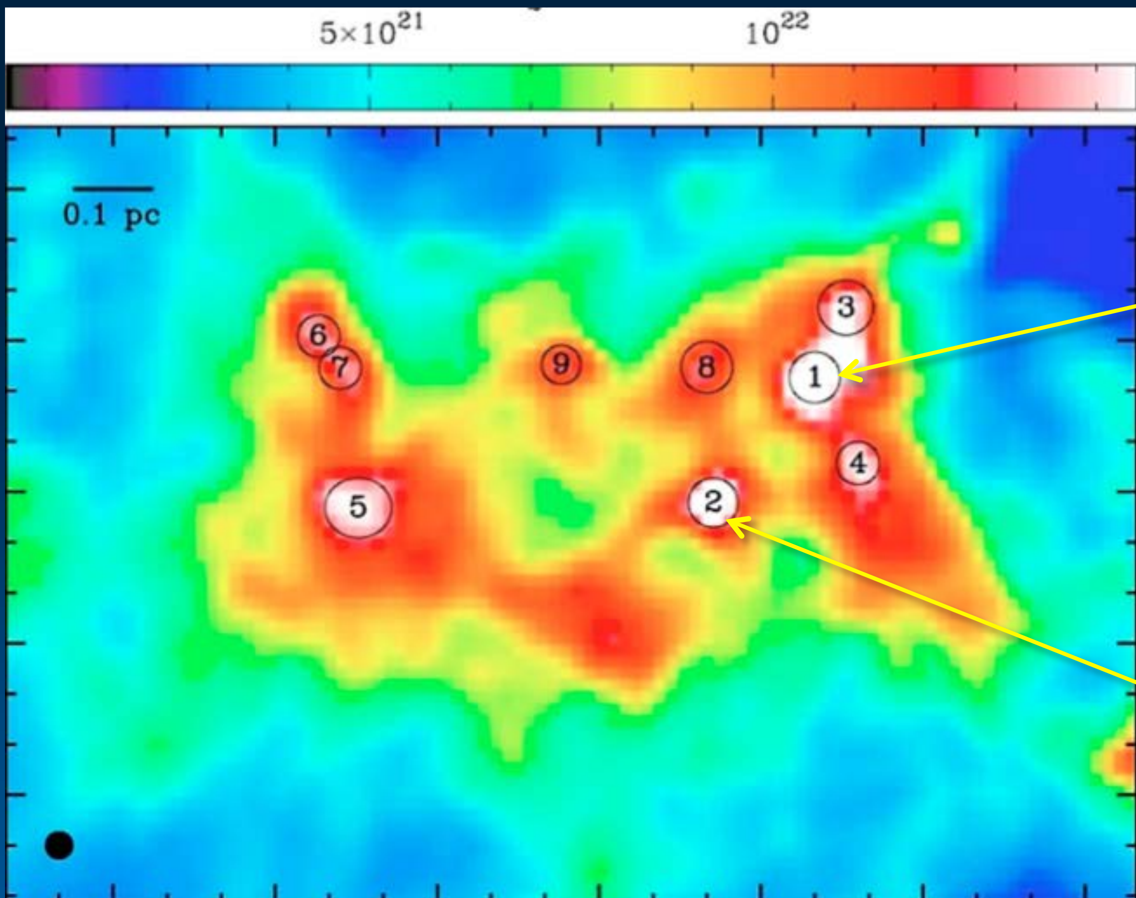


Perseus Molecular Cloud

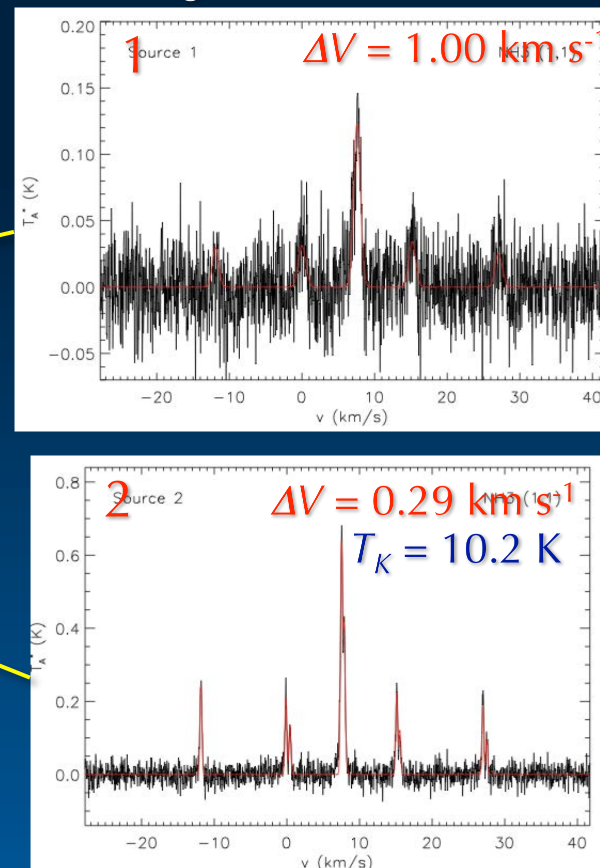
160, 250, 350 μm

Cores: Fragmentation of Clumps

Perseus B1-E: 100 $M_\odot$ clump with **no** YSOs



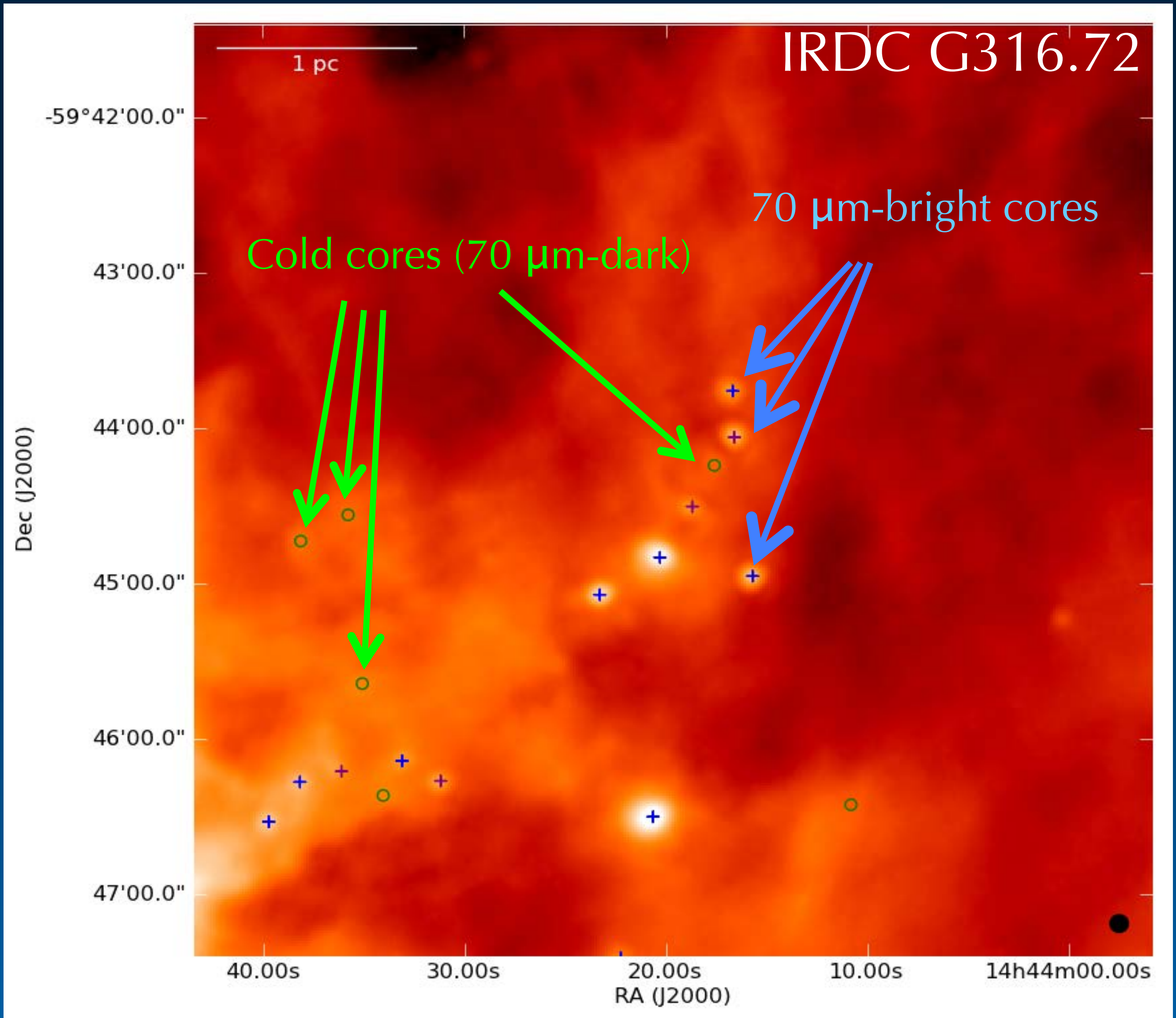
NH$_3$ GBT KFPA data



- Fragmenting into ~10 proto-cores, only #2 is quiescent and 'bound'
- Pristine example of core formation, need more kinematic data

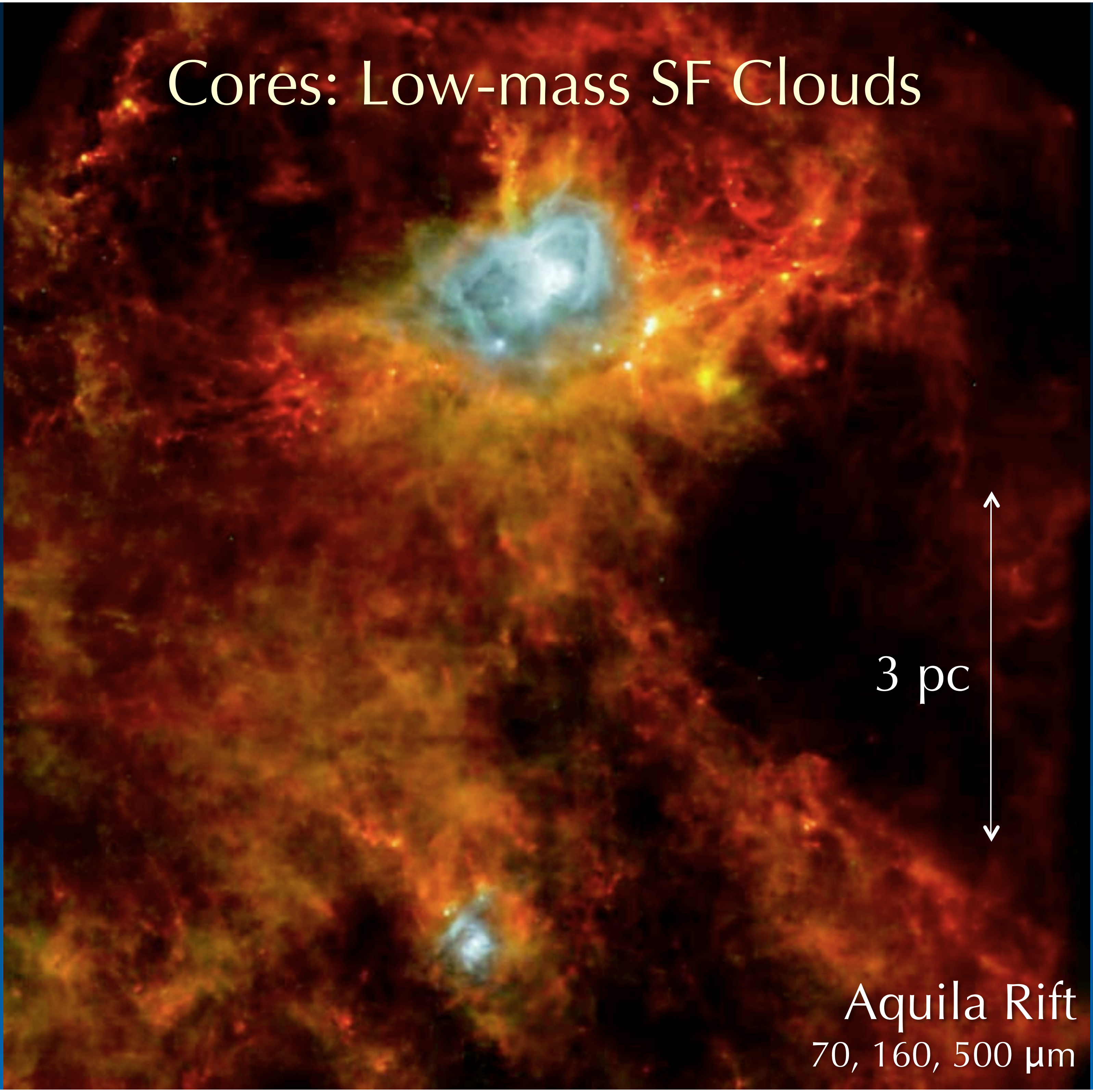
Sadavoy et al. (2012); GBS

Cores: Infrared Dark Clouds



- Mapping of 45 high-mass regions at all 6 PACS and SPIRE bands
- Population of 500 embedded cores (r ~ 0.05 - 0.15pc)
- $\langle T_{dust} \rangle \sim 20$ K
- Many stages seen; ~35% have no 24 µm counterpart

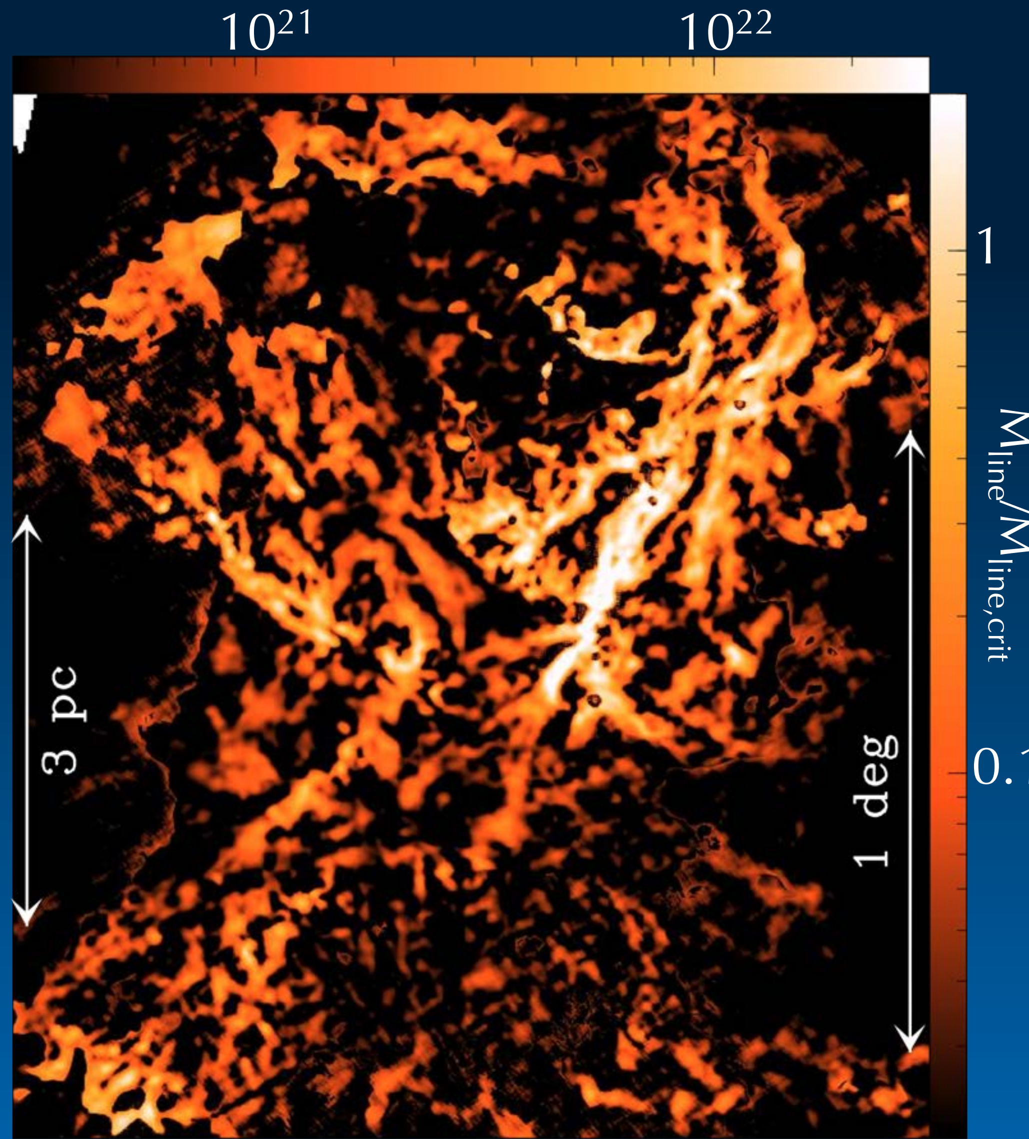
Ragan et al. (2012, submitted & poster); EPoS


Cores: Low-mass SF Clouds
3 pc
Aquila Rift
70, 160, 500 μm

Cores: Fragmentation of Filaments

- Filament stability depends on **mass per unit length** M_{line} (cf. Inutsuka & Miyama 1997)
- unstable if $M_{line} > M_{line,\ crit} = 2c_s^2/G \sim 15\ M_{\odot}/pc$ at 10 K
- networks of filaments form via **turbulence**
- filaments at $\boldsymbol{A_V > 6}$ are dense enough to fragment into cores (extinction threshold)

Curvelet component of column density map (H_2/cm^2)



André et al.; Könyves et al. (2010); Könyves, Spezzi, & Palmerim posters; GBS

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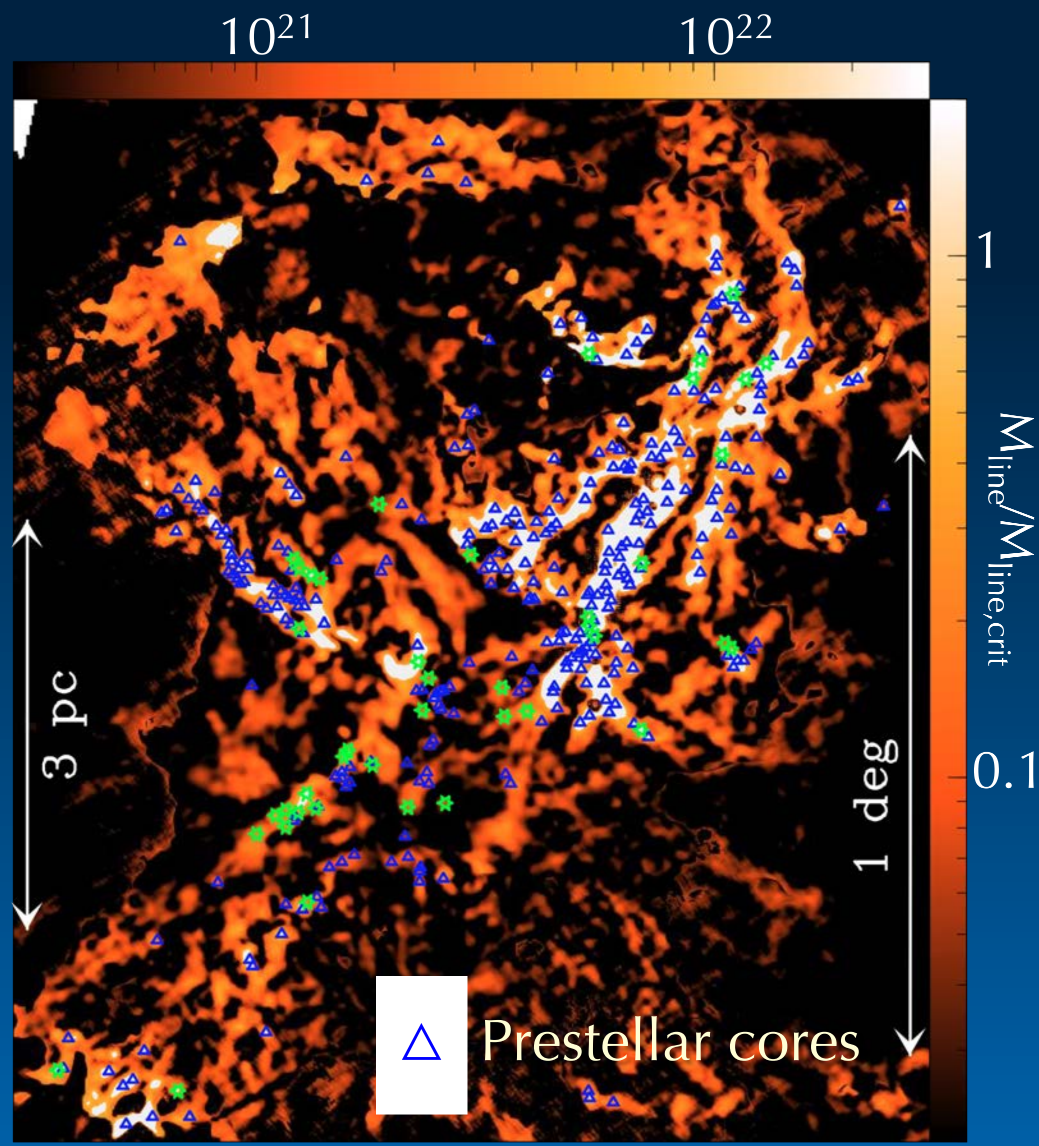

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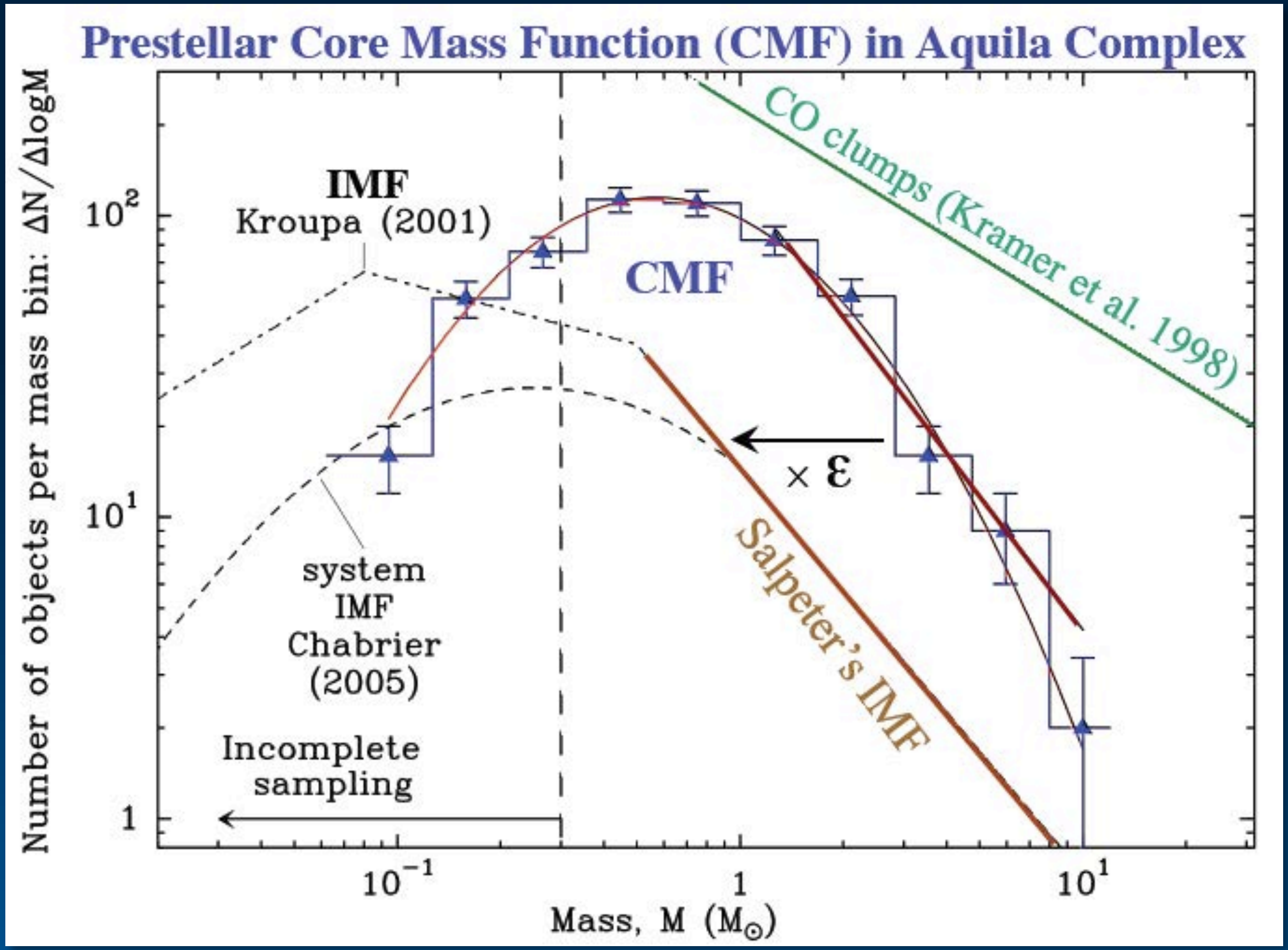
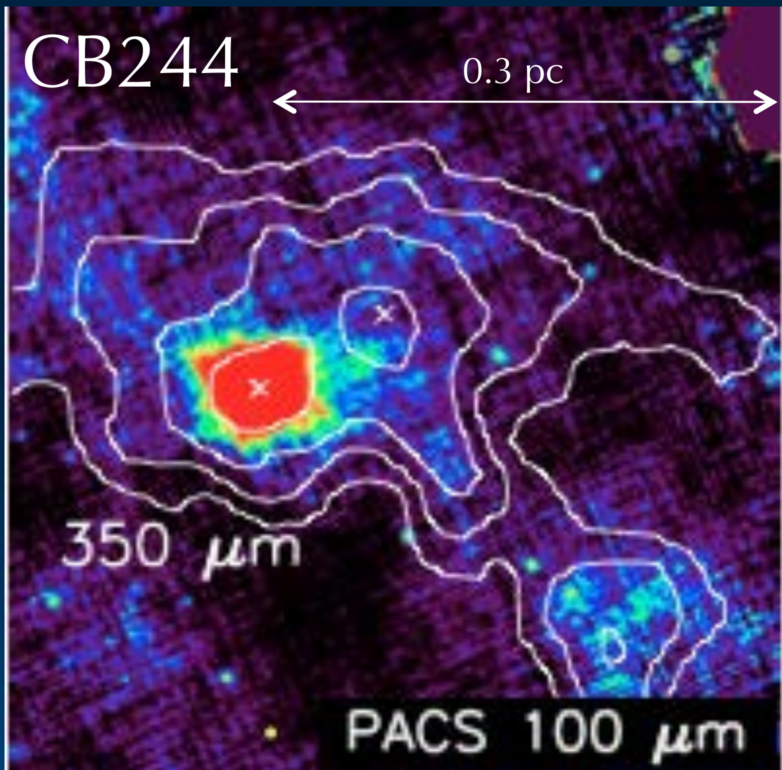
Cores: Mass Functions

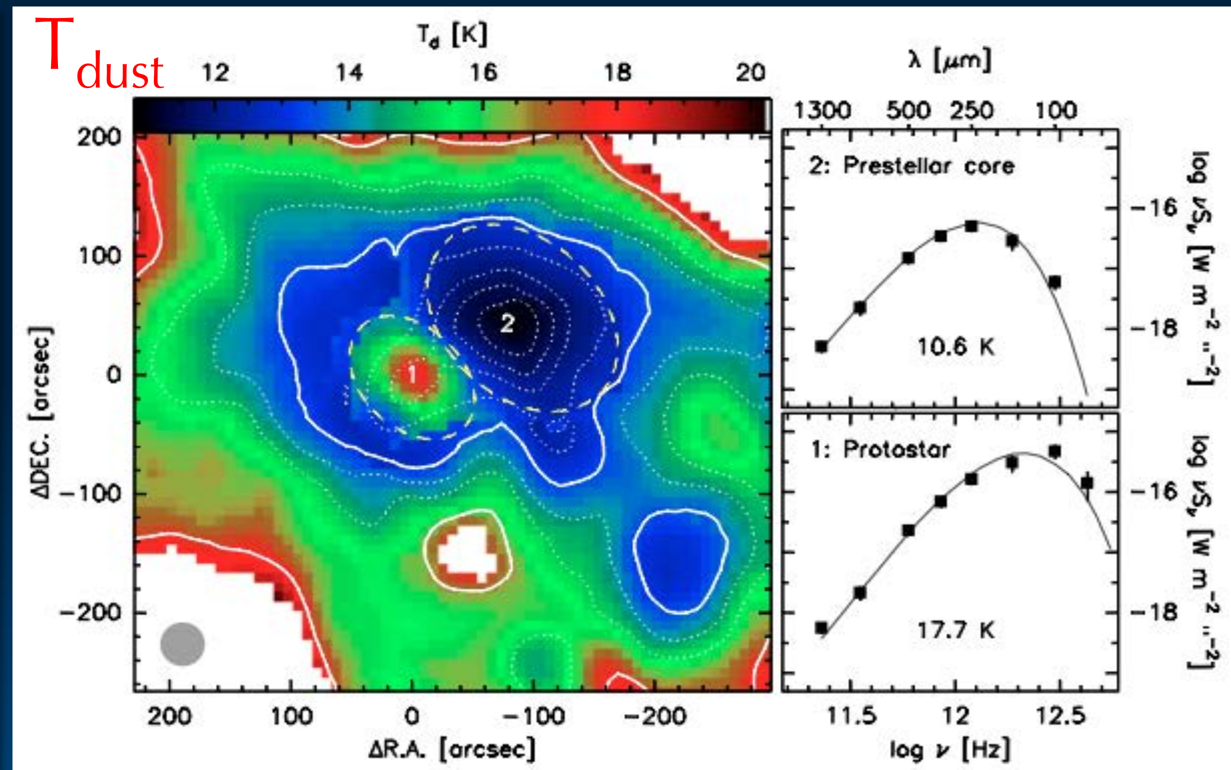


- shape of CMF very similar to IMF (ε ≈ 0.3)
- slope of high-mass end ≈ -1.5 ± 0.2 and Salpeter = -1.35
- consistent with "pre-collapse cloud fragmentation" picture

André et al. (2010); GBS

Cores: Thermal Structure

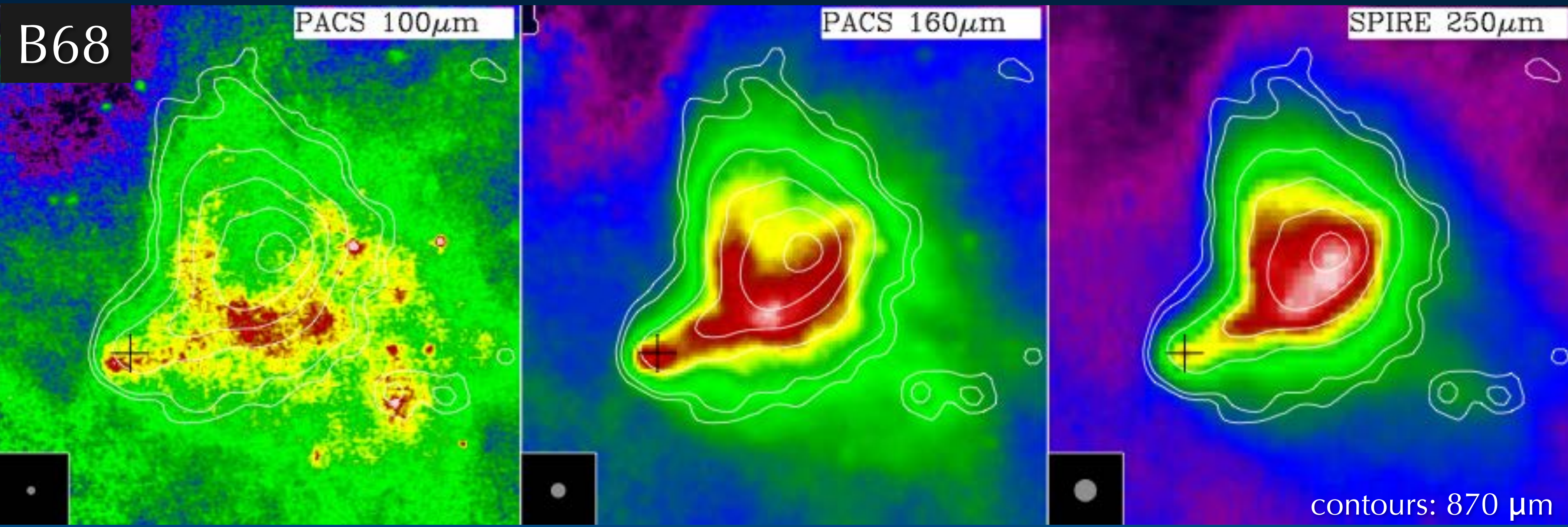




- very nice juxtaposition of different evolutionary stages
- LoS-averaged N_H and T_{dust} :
  - towards protostar: 17.7 K
  - towards starless core: 10.6 K
  - rises to ~17 K at core edge, where $N_H < 10^{21}$ cm^{-2}
- need higher dimensional modeling!

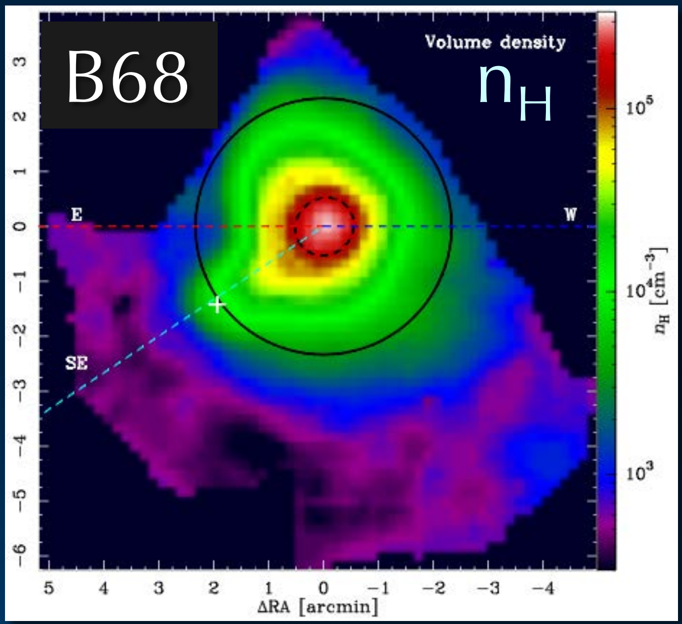
Stutz et al. (2010) also Launhardt poster; EPoS

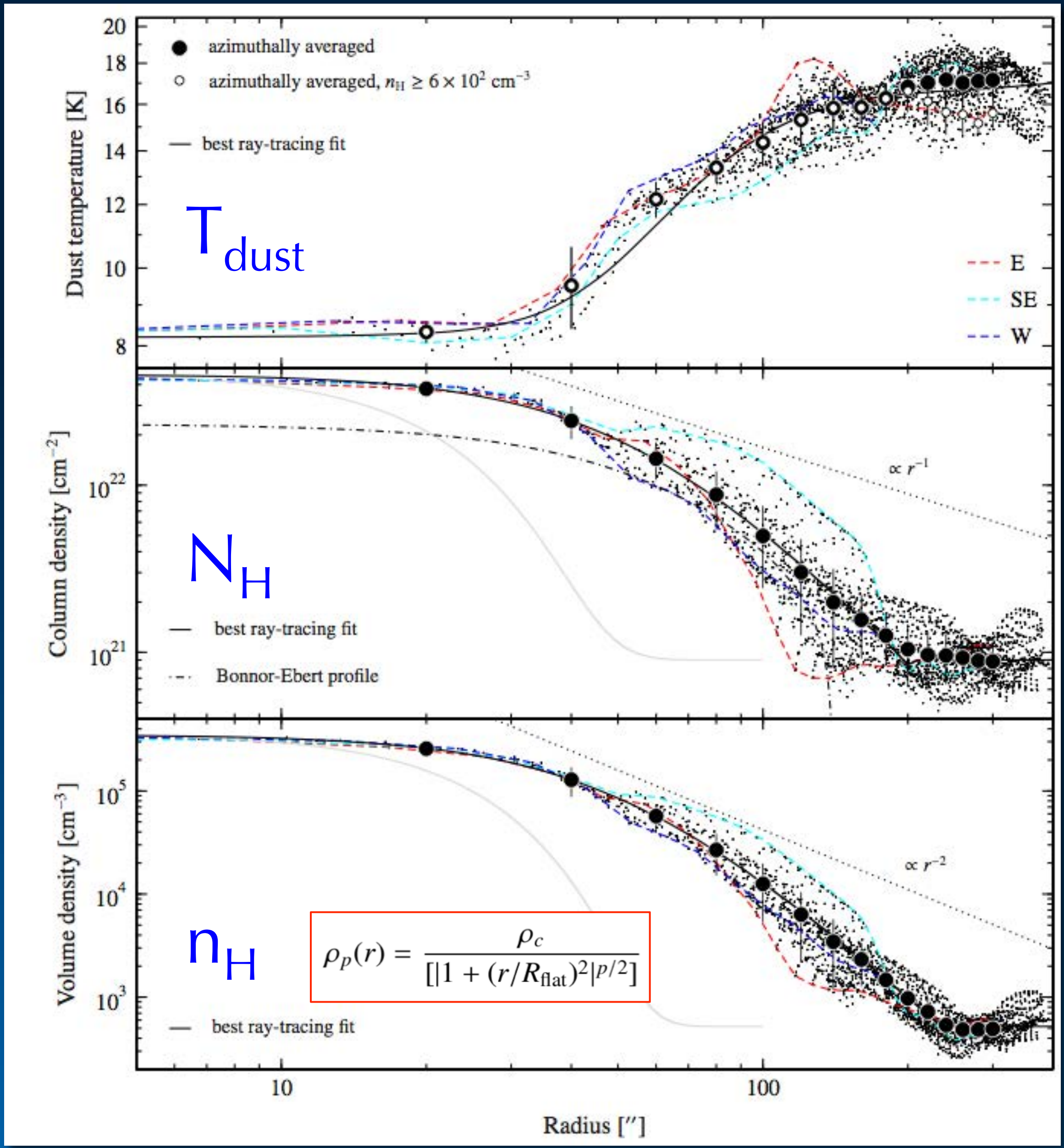
Cores: Thermal and Density Structures



Nielbock et al. (2012, submitted & poster); EPoS; see also Wilcock et al. (2011) ; Hi-GAL

Cores: Thermal and Density Structures



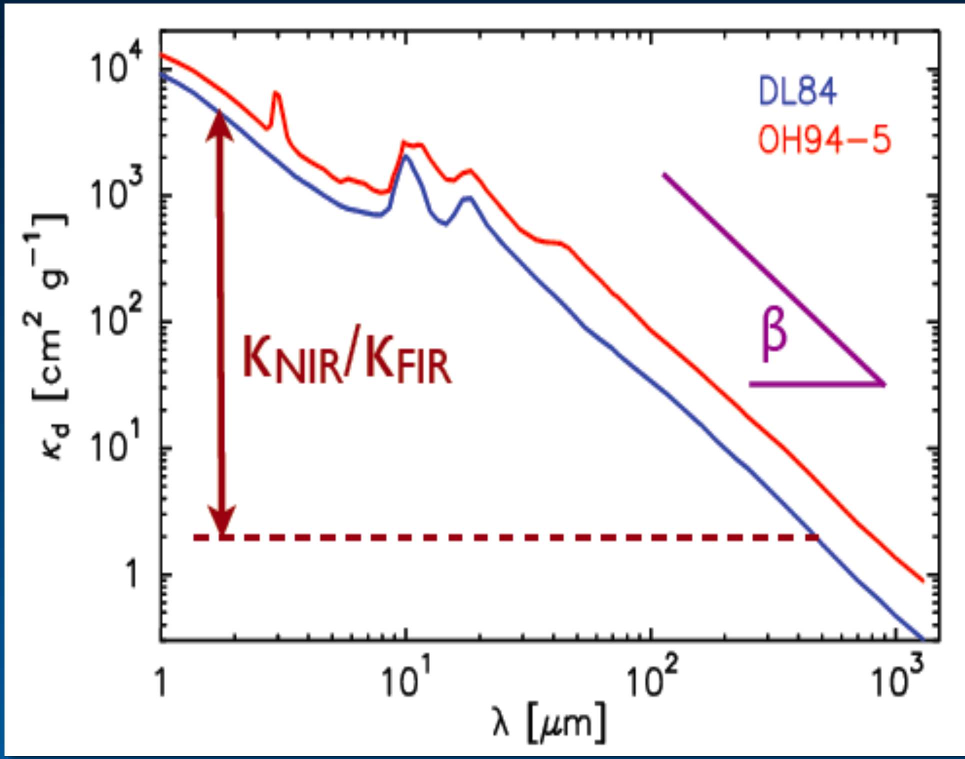


- 2D ray-tracing model
- Higher central density with "Plummer" profile (p = 4; Ostriker 1964)
- **not**: isothermal, axisymmetric, or externally heated isotropically!

Nielbock et al. (2012, submitted & poster); EPoS; see also Wilcock et al. (2011) ; Hi-GAL

What About β ?

$$\text{Mass} = S_\nu * d^2 / \boldsymbol{\kappa_\nu} * B_\nu(T_{dust})$$



Launhardt & Stutz + EPOS consortium (2010)

- $\kappa_\nu = \kappa_o(\nu/\nu_o)^\beta$
- β = 2.0 (Draine & Lee 1984; Ossenkopf & Henning 1994)
- β values found:
  - 1.6-2.3 (Peretto et al. Hi-GAL)
  - 1.8-2.6 (Paradis et al. Hi-GAL)
  - 1.9-2.2 (Juvela et al. PCC)
- possible degeneracy with T_{dust} ; increase of opacity with N_H
- need longer λ coverage along R-J SED tail to determine β:
  SCUBA-2, GISMO, MUSTANG
  (watch for spatial filtering!)

Summary

• *Herschel* is **revolutionizing** our knowledge of the pre-collapse phase, revealing cloud structures at high resolution without spatial filtering

• **filaments** are a key aspect of cloud structure, created through turbulence and responsible for cores, and clumps when filaments intersect

• molecular clouds become increasingly **cold** with column density, and hence density; T_{dust} = ~40 K ➔ ~8 K in core centers

• we have only scratched the surface of utilizing *Herschel* data; more sophisticated analysis coming

FIN