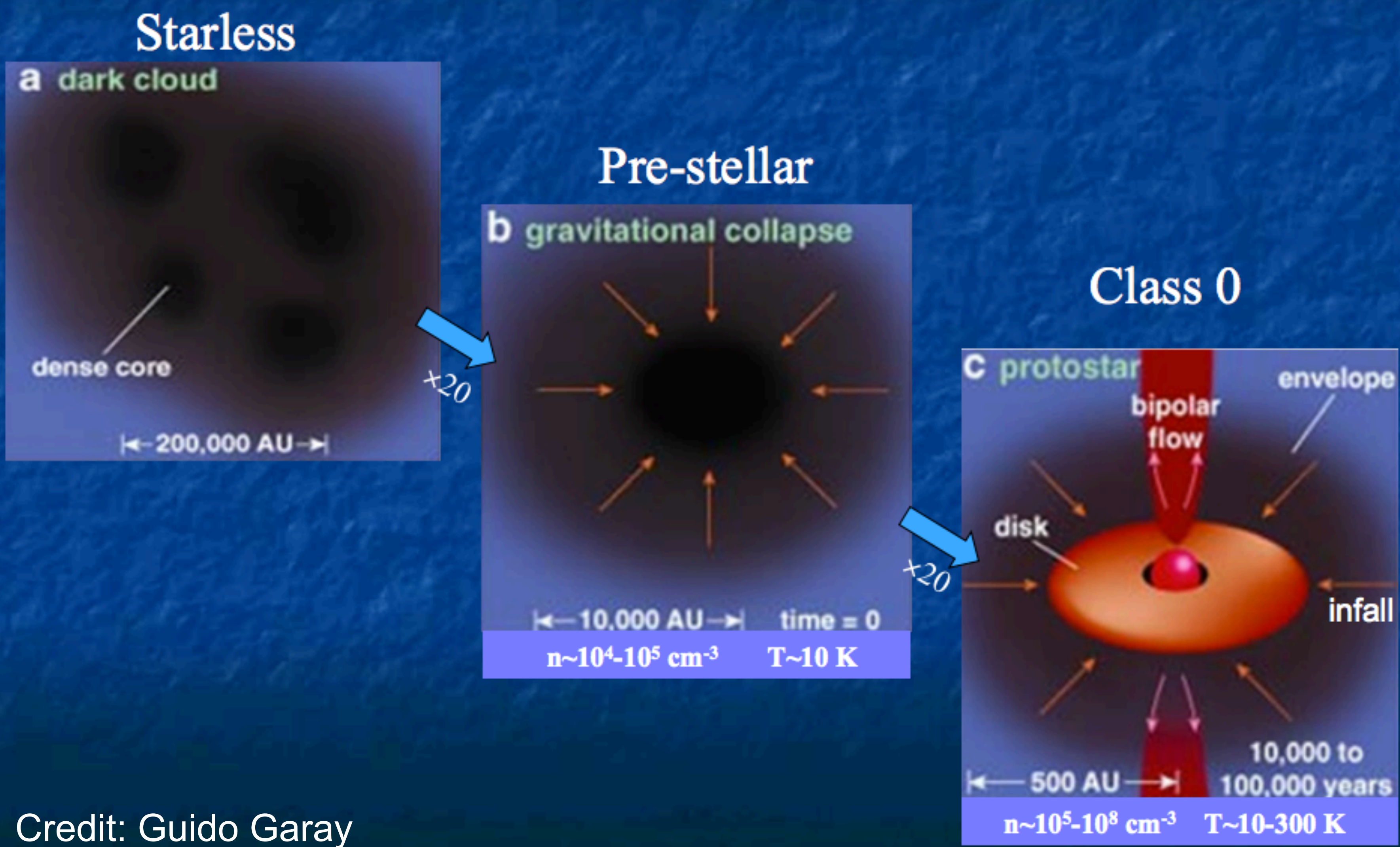
RIDGES: HOW TO FORM A HIGH MASS STAR

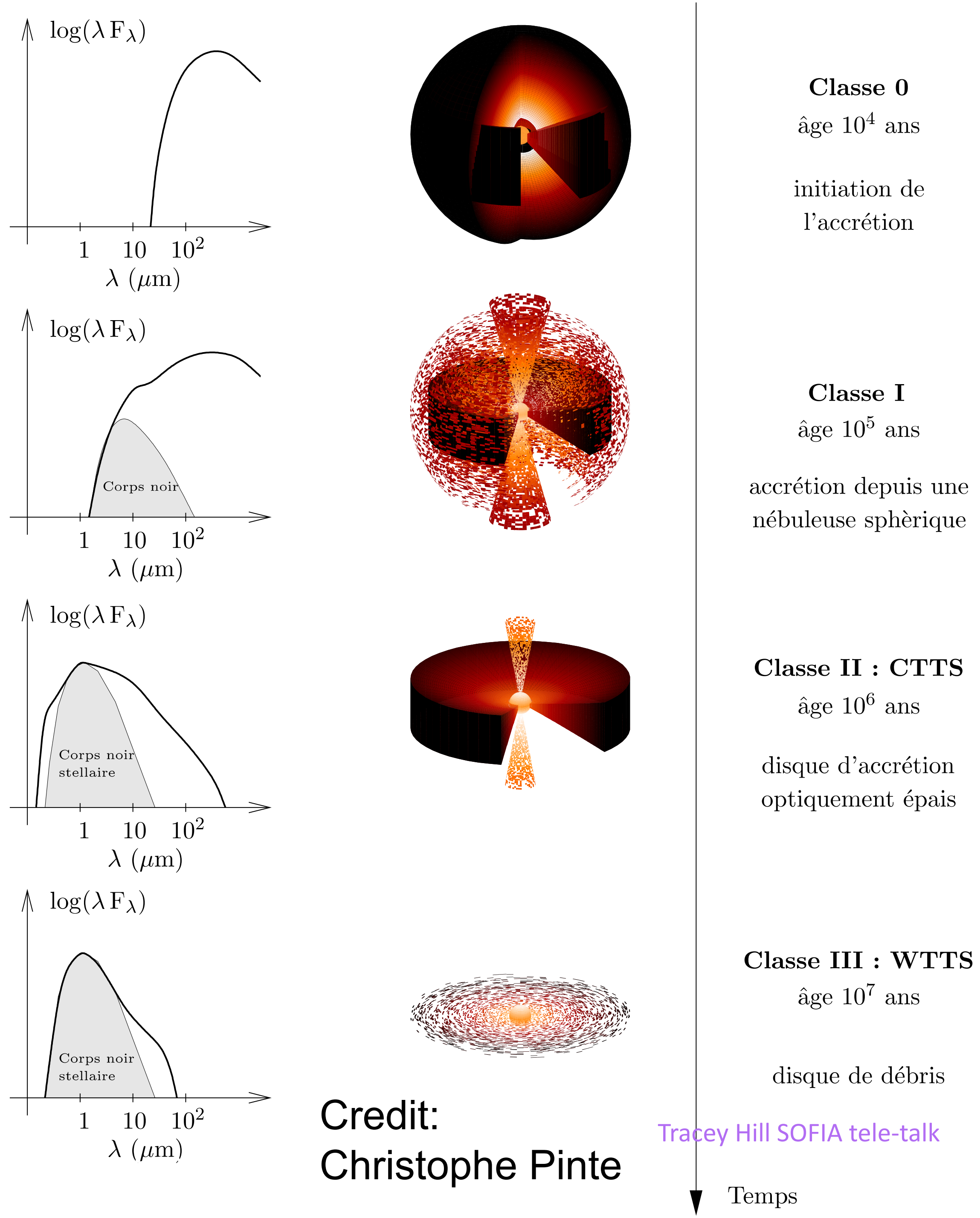
SOFIA Tele-Talk 3-26-2014

Tracey Hill
Joint ALMA Observatory

Standard evolutionary scenario of low-mass star formation ($M < 8\ M_\odot$)



Credit: Guido Garay

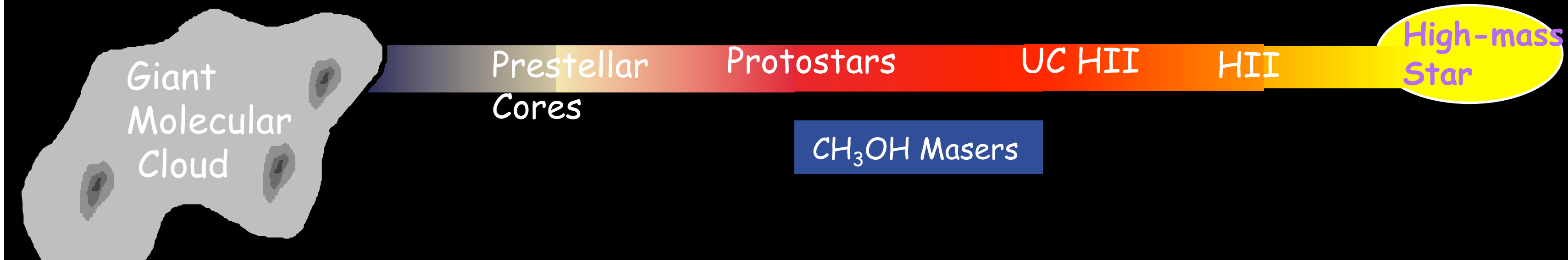


Credit:
Christophe Pinte

Low mass stars

- Formation scenario well understood
  - See Shu, Adams & Lizano 1987, Andre et al., 2000

High-mass star formation



Open Questions:

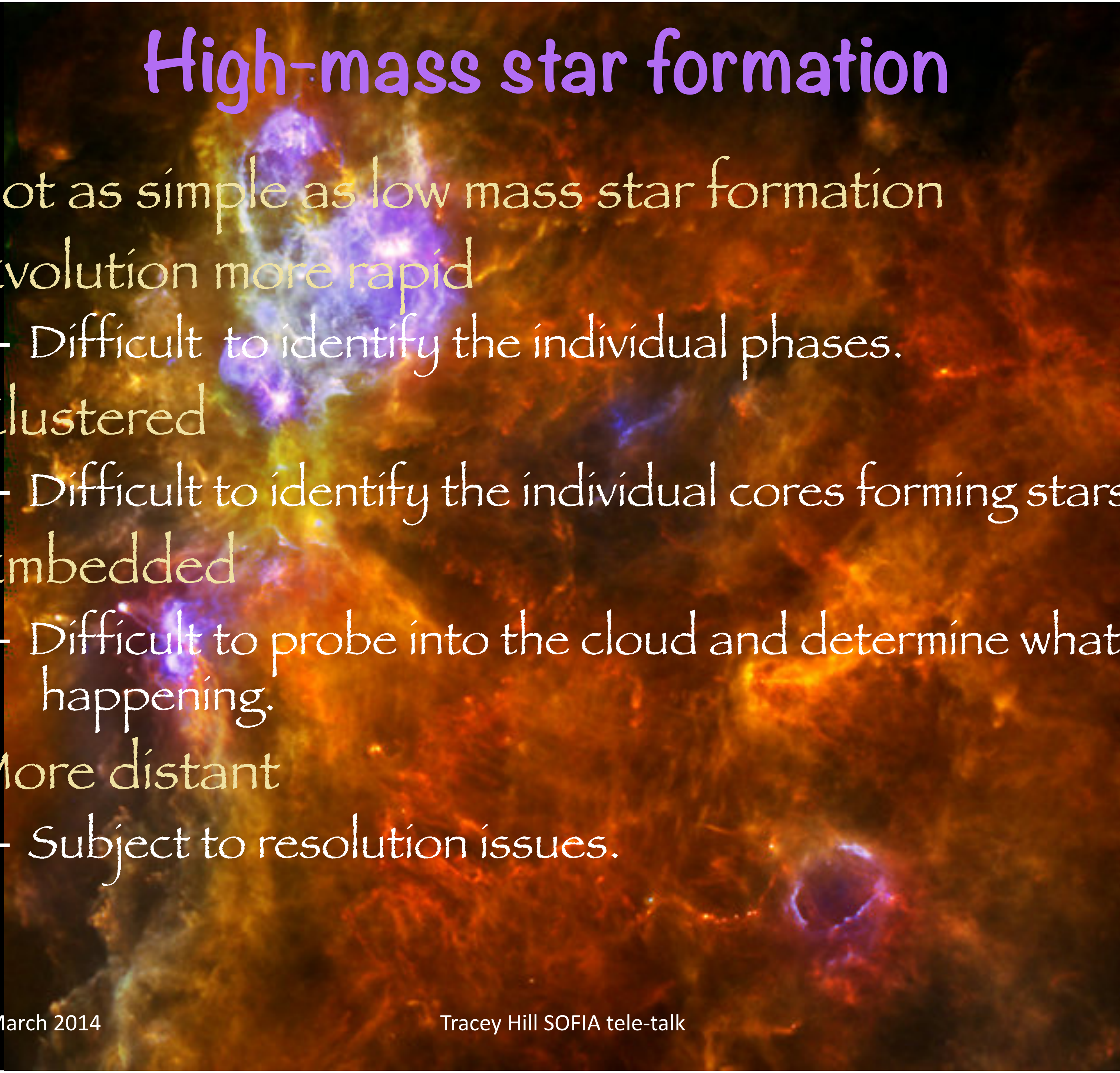
How do High Mass (OB > 8M$_\odot$) stars form?

- Quasi-static vs dynamic scenario
- powerful gas (competitive) accretion vs coalescence

- Scaled up low mass star formation? (e.g. André et al.)
- What are the signposts of high-mass star formation?
- What are the initial conditions (density, temperature, kinematics) for high-mass star formation?
- High mass stars are pivotal to studies of external galaxies.
  - Star Formation Rate & Star Formation Efficiency.

High-mass star formation

- Not as simple as low mass star formation
- Evolution more rapid
  - Difficult to identify the individual phases.
- Clustered
  - Difficult to identify the individual cores forming stars
- Embedded
  - Difficult to probe into the cloud and determine what is happening.
- More distant
  - Subject to resolution issues.



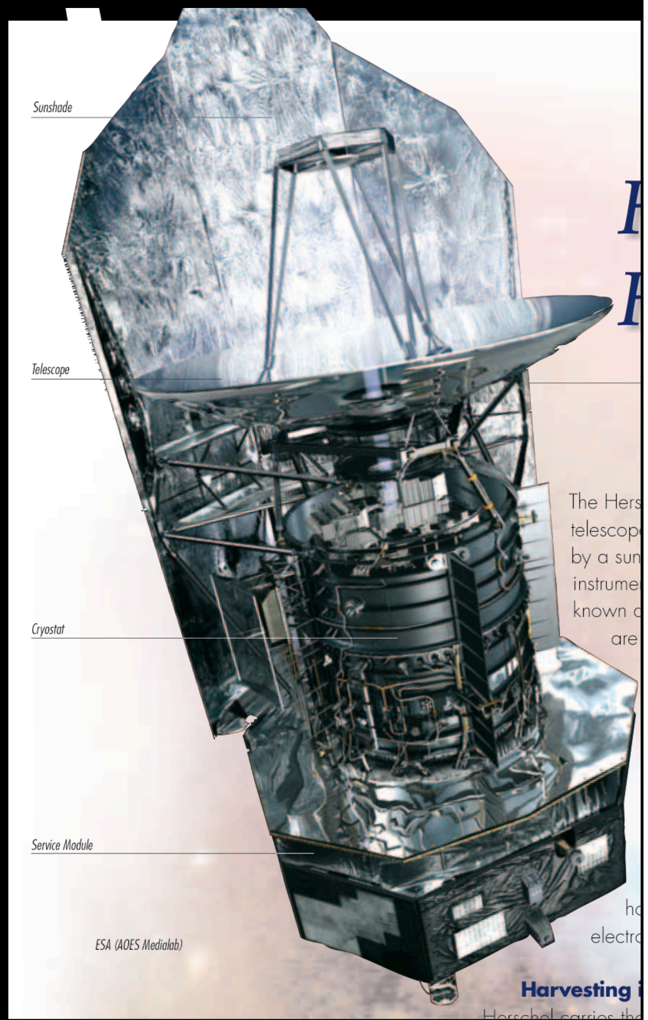
W3 HOBYS, Rivera-Ingraham et al.

Observational constraints provided by Herschel

- Evolutionary sequence of massive YSOs before HII region develops
- Identifying single protostars
  - Brogan et al. 2009; Bontemps et al. 2010; Zhang et al. 2010; …
- Lifetimes and kinematics in High mass star forming regions (Large statistical samples)
  - Short prestellar and protostellar lifetimes (e.g. Motte et al. 2007)
  - Global infall and converging flows (e.g. Schneider et al. 2010; Csengeri et al. 2010)
  - Molecular cloud formation through converging flows (Hill et al., 2011, Nguyen-Luong et al. 2011)

Herschel

- Built by ESA – with sig. cont. NASA
- Largest single mirror launched: 3.5m
- Passively cooled telescope. < 2K
- Orbits at the Lagrangian L2 point
- FIR – submm observing
- Launched 14 May, 2009.
  - 15th July performance verif. commences.
  - 12th Sept. – science demonstration
  - 18 October, 2009: Routine Phase Observations
- 3 instruments: PACS, SPIRE, HIFI
  - Herschel ceased operations in April 2013.



Star-forming regions are filamentary

The Astrophysical Journal, 700:1609–1625, 2009 August 1 doi:10.1088/0004-637X/700/2/1609

FILAMENTARY STRUCTURE OF STAR-FORMING COMPLEXES

Philip C. Myers
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; pmyers@cfa.harvard.edu
Received 2009 March 14; accepted 2009 June 3; published 2009 July 15

ABSTRACT

The nearest young stellar groups are associated with "hubs" of column density exceeding 10^{22} cm^{-2}, according to recent observations. These hubs radiate multiple "filaments" of parsec length, having lower column density and fewer stars. Systems with many filaments tend to have parallel filaments with similar spacing. Such "hub–filament structure" is associated with all of the nine young stellar groups within 300 pc, forming low-mass stars. Similar properties are seen in infrared dark clouds forming more massive stars. In a new model, an initial clump in a uniform medium is compressed into a self-gravitating, modulated layer. The outer layer resembles the modulated equilibrium of Schmid-Burgk with nearly parallel filaments. The filaments converge onto the compressed clump, which collapses to form stars with high efficiency. The initial medium and condensations have densities similar to those in nearby star-forming clouds and clumps. The predicted structures resemble observed hub–filament systems in their size, shape, and column density, and in the appearance of their filaments. These results suggest that HFS associated with young stellar groups may arise from compression of clumpy gas in molecular clouds.

Key words: ISM: clouds – stars: formation

Online-only material: color figures

Figure 7. NGC 1333 in the west part of Perseus, in a deep optical image (nightskyphotography.com), showing the embedded cluster and five filamentary extensions. The scale bar indicates 1 pc.

(A color version of this figure is available in the online journal.)

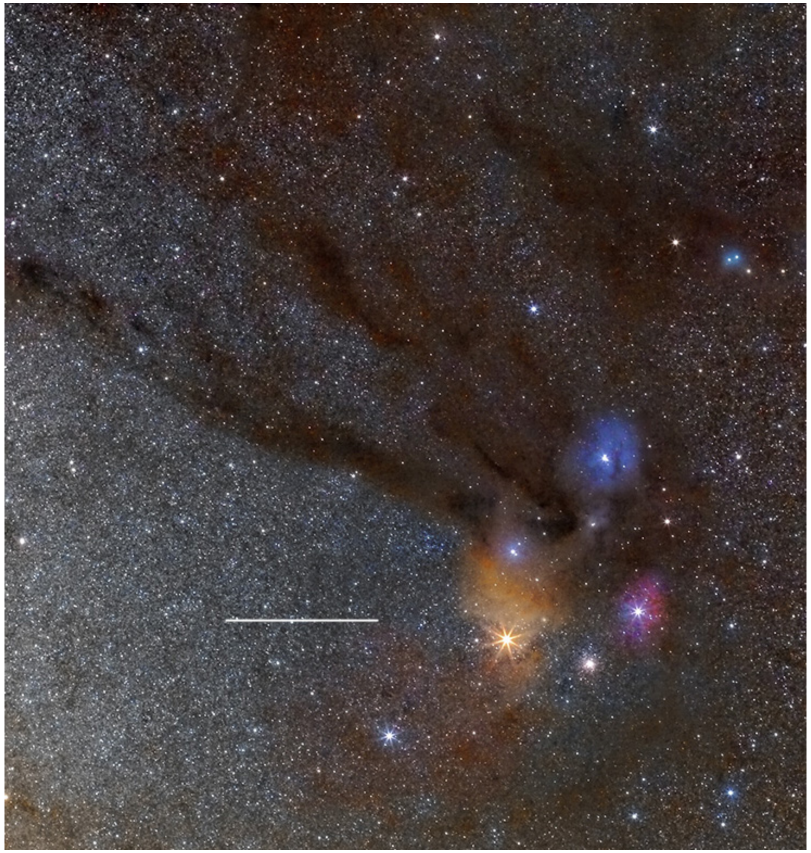
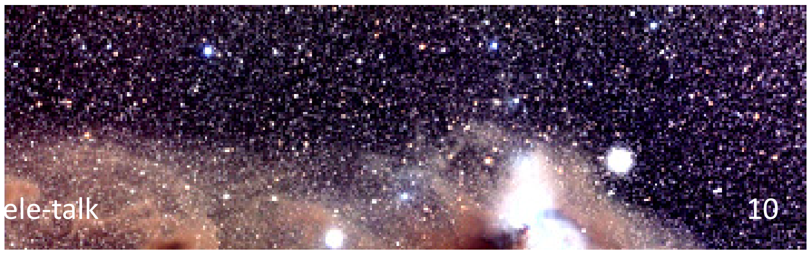


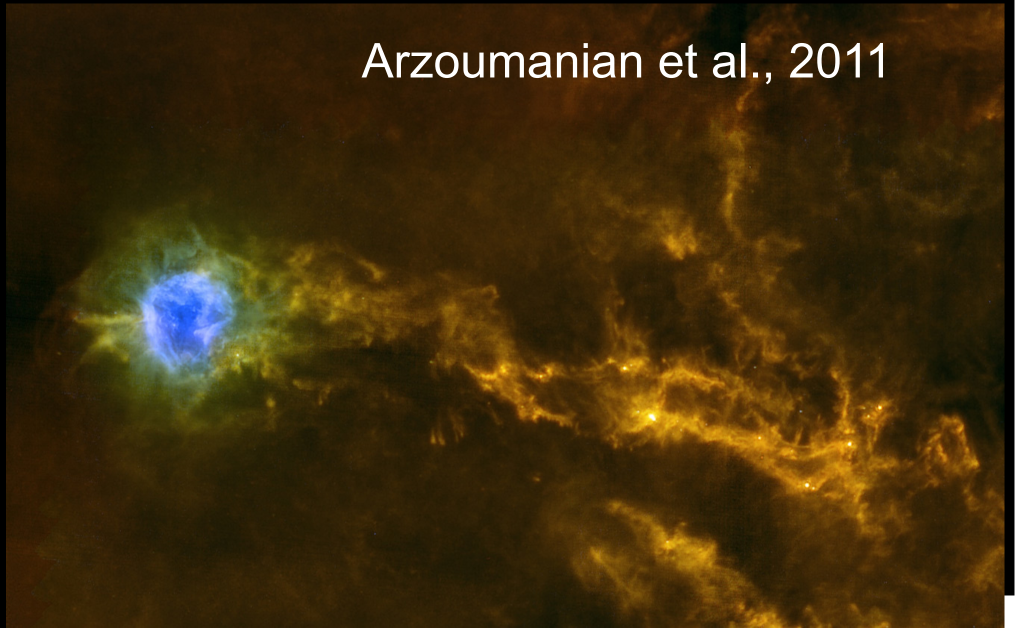
Figure 8. Ophiuchus complex in a deep optical image (astromodelismo.es), showing the embedded cluster and four nearly parallel filaments extending to the NE, two curving filaments to the south, and a neighbor filament offset to the NW. The scale bar indicates 5 pc.

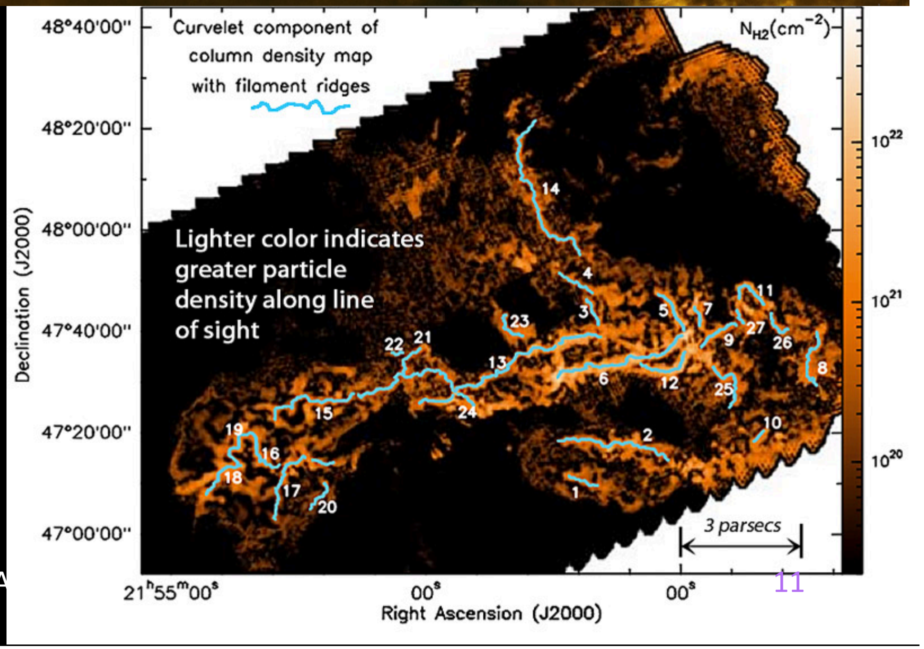
(A color version of this figure is available in the online journal.)



Herschel & Filaments

- Filaments known before
- Herschel showed us just how prolific filaments are.
  - See Andre et al., 2010, 2011
  - See Arzoumanian et al., 2011
- Star-forming cores are located within interstellar filaments.
- Low-mass filaments have a characteristic width ~ 0.1pc

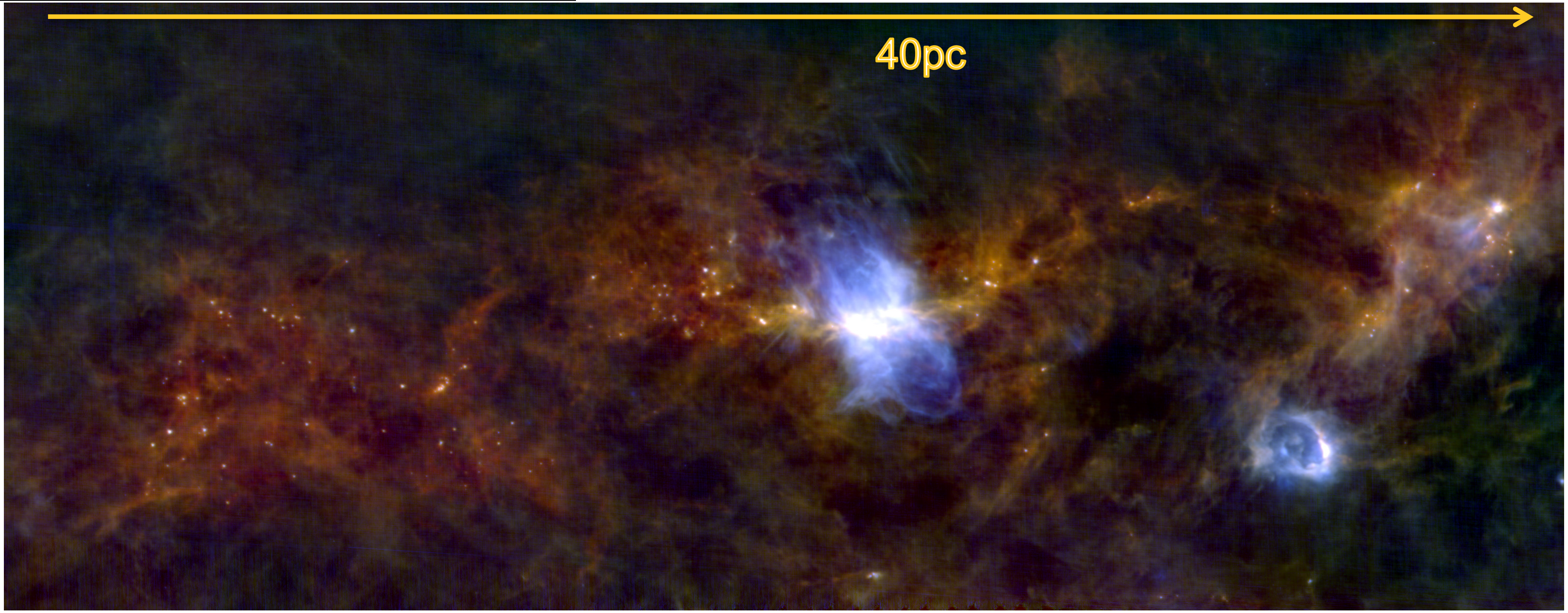




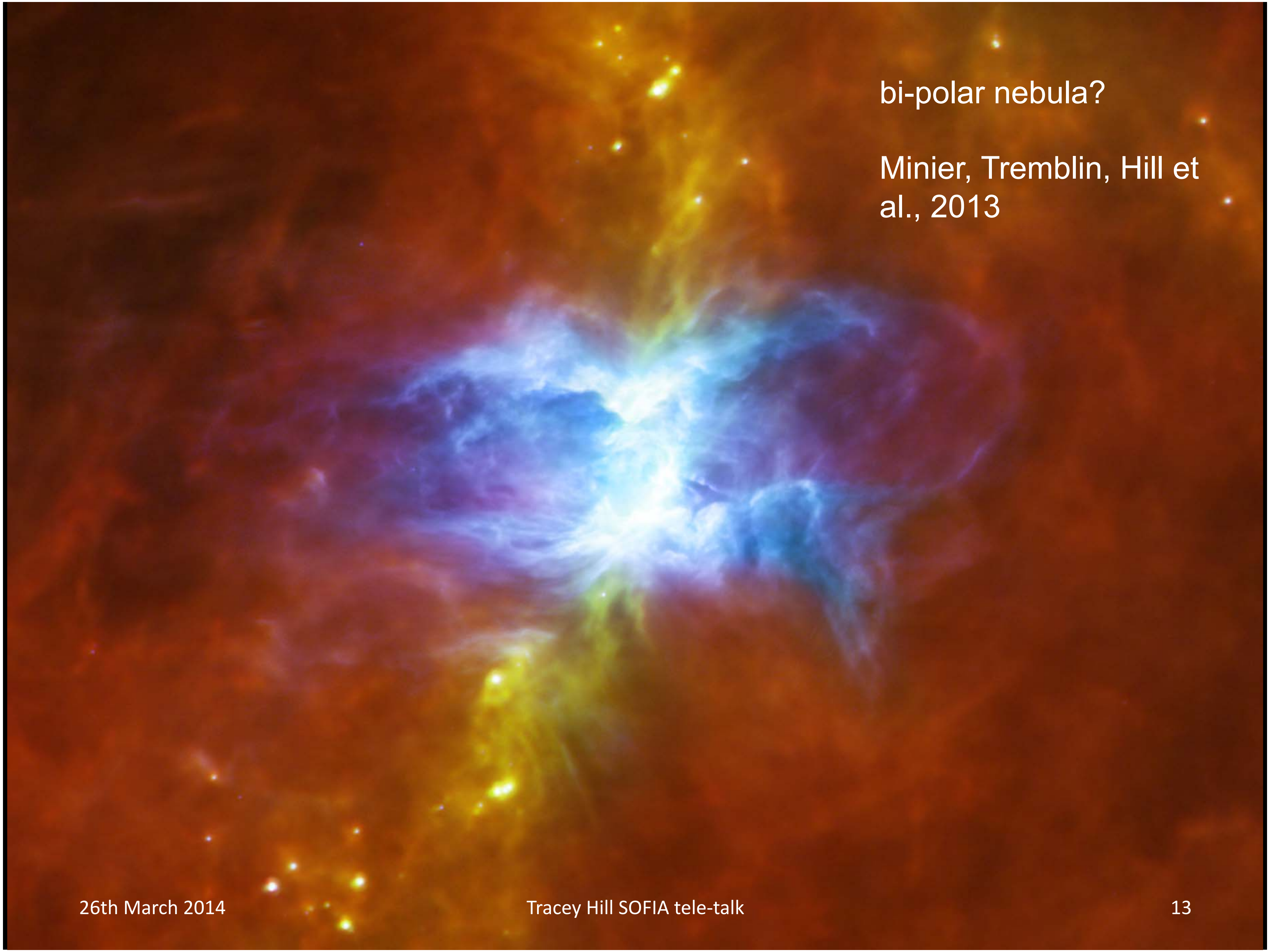
VELA C

(Hill, Motte, Didelon et al. 2011)

70um, 160μm,250μm



- May 18, 2010, 700pc, Parallel scan-mode, 3 deg^2
- Sources extracted with getsources (multi-wavelength, multi-resolution) sources extraction algorithm (Men' shchikov et al., 2012)
- Conservative S:N, gives 13 high-mass sources – 14-70$M_\odot$
- ~ 0.04 pc, these sources correspond to protostellar or prestellar cores, i.e., the direct progenitors of individual high-mass stars.

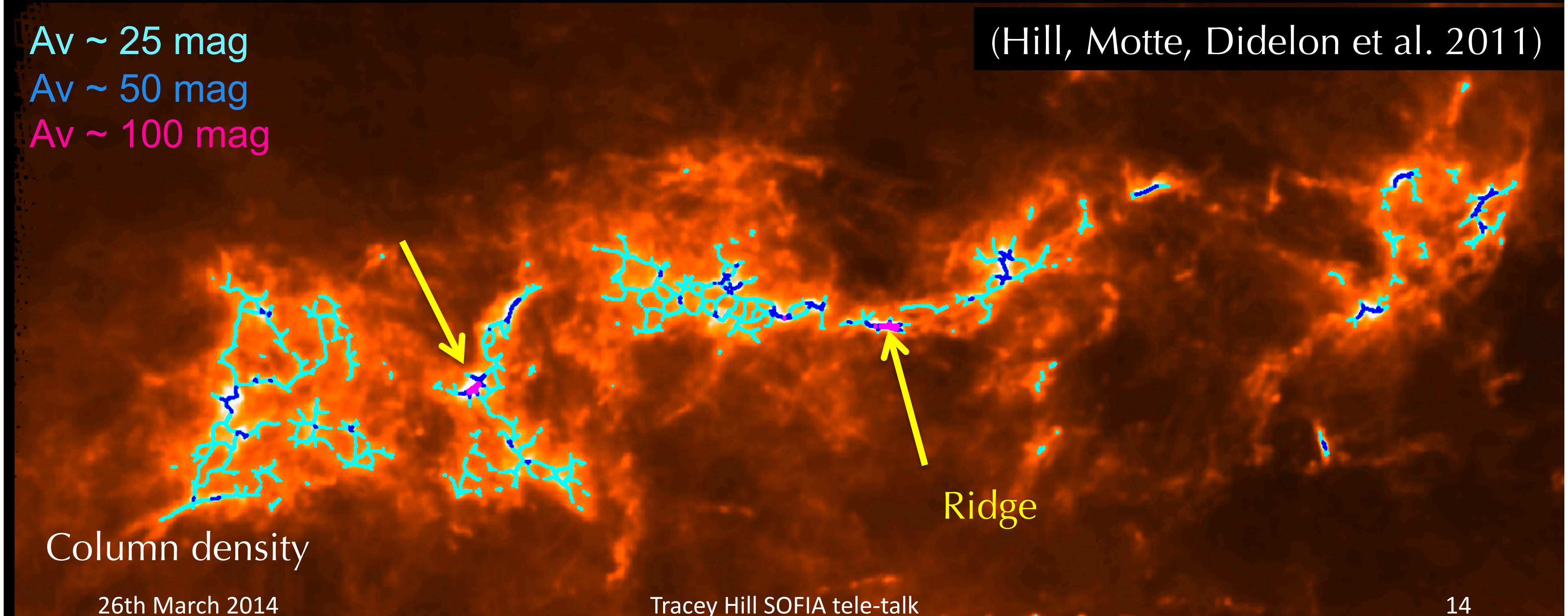


bi-polar nebula?

Minier, Tremblin, Hill et al., 2013

Identifying Filaments & RIDGES

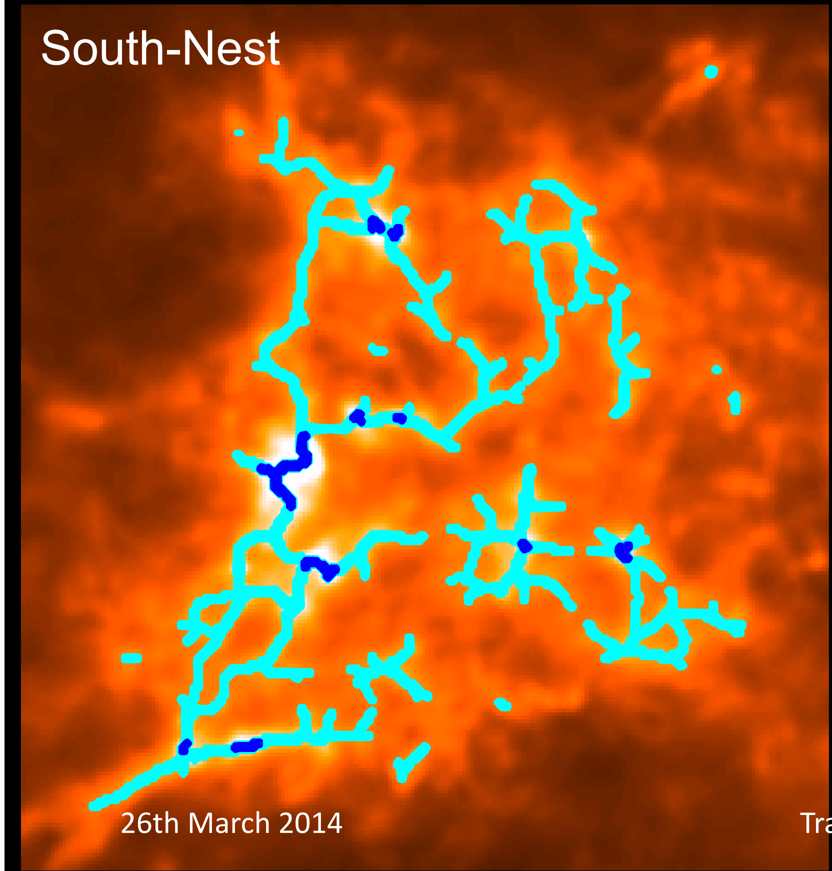
- Dust temperature and column density from greybody fits (37")
- Census of filaments: DisPerSE (Sousbie 2011)
- Above Av > 50 mag all filaments identified have supercritical masses per unit length and are thus likely forming stars

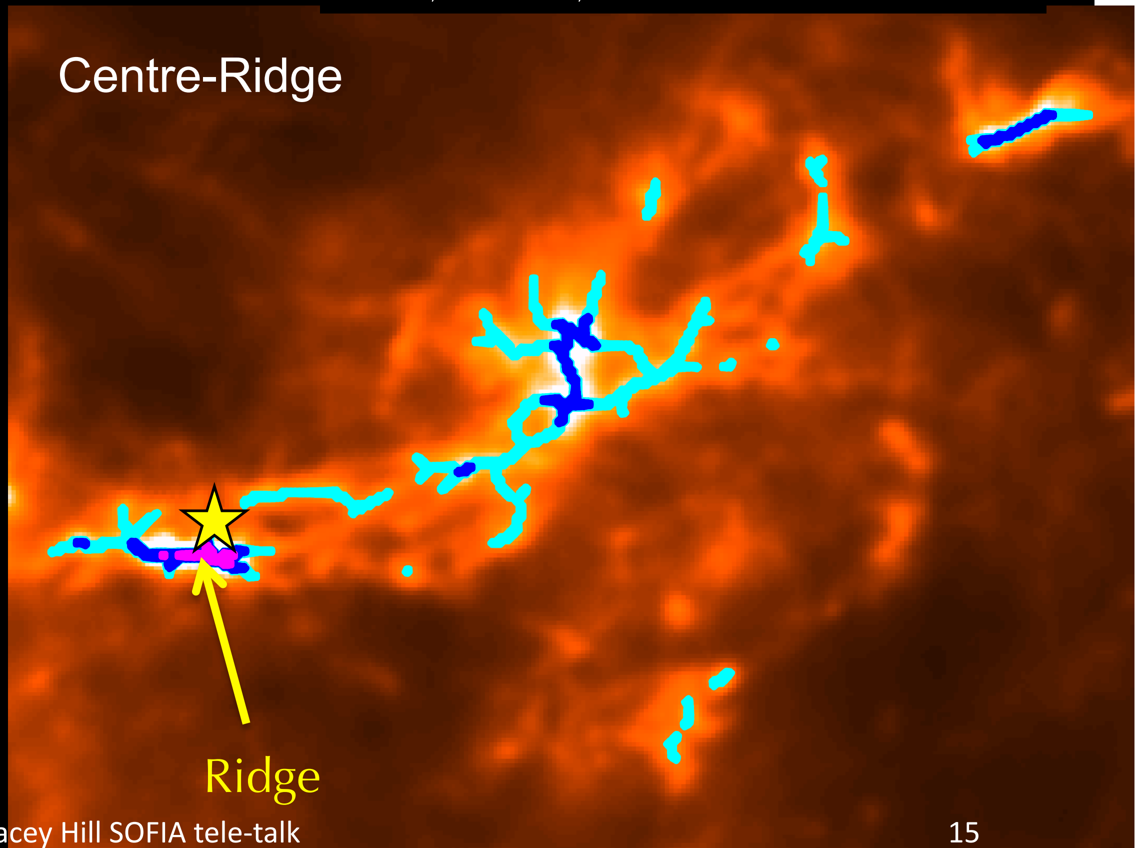


Cloud structure in Sub-regions

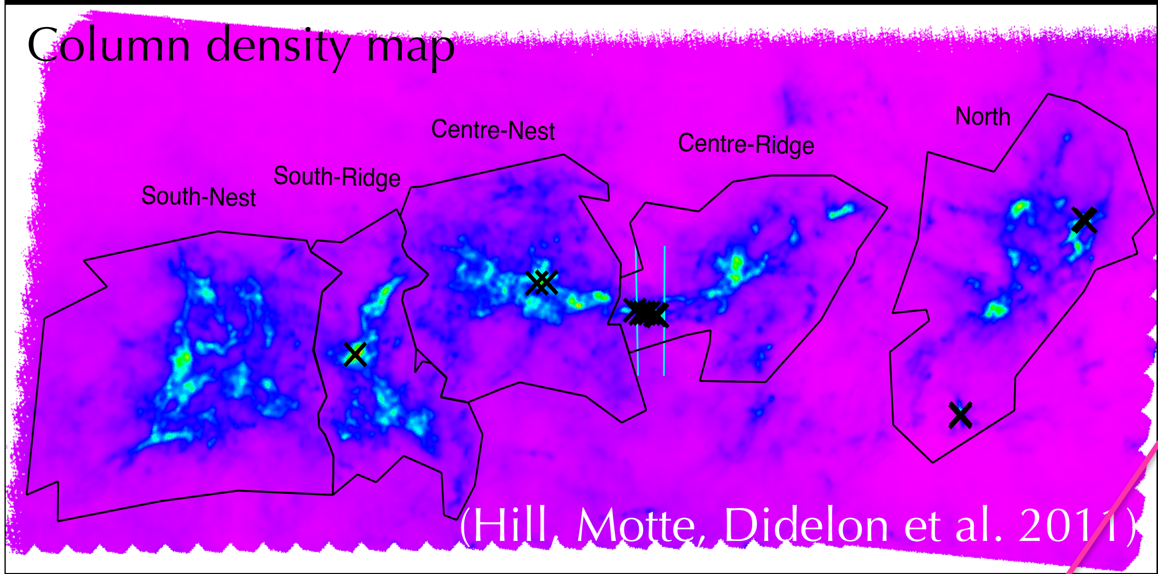
- Disorganised network of filaments vs single dominating ridge.
- High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), wide (>0.3 pc) filaments present in specific regions.

(Hill, Motte, Didelon et al. 2011)

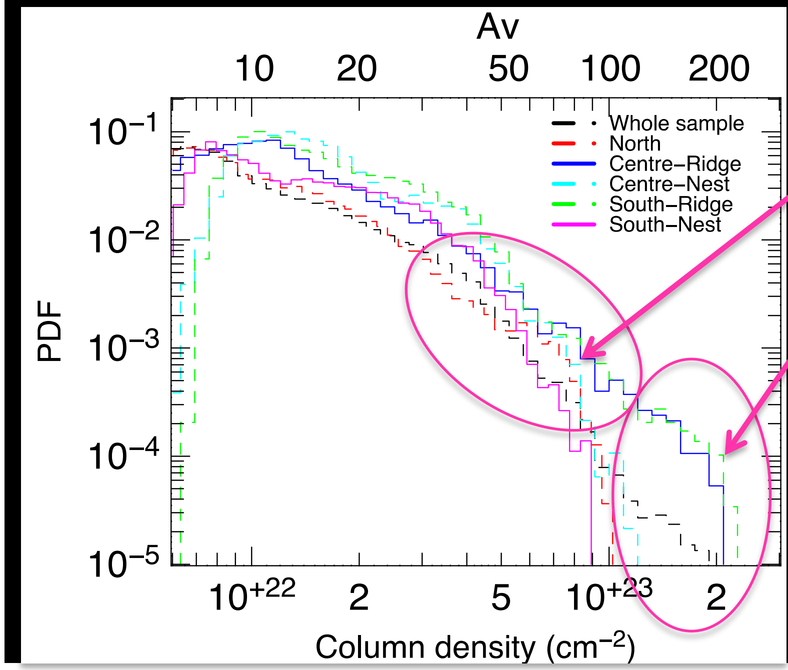




Gravity vs Turbulence



- At Av~ 7 mag, Vela C segregates into 5 sub-regions of similar mass
- CR has a high CD tail
  – May suggest gravity rather than turbulence is shaping the cloud.

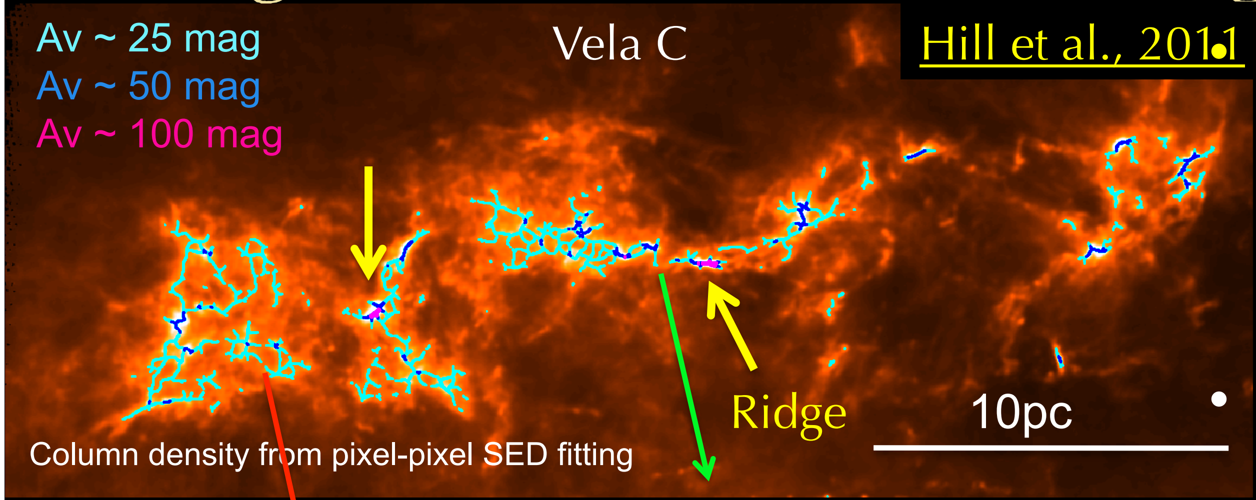


- Flatter PDF (CR) observed for coherent structures created via constructive large-scale flows in some numerical simulations (Federrath et al., 2010)

- **The Ridge is dominated by gravity and large-scale converging flows.**

Cloud Structure   Environment

- Disorganised network of filaments vs single dominating ridge.



TOOLS: Probability Distribution Functions (PDFs), multi-scale analysis

- PDF:
  - May suggest that gravity rather than turbulence is shaping the cloud.
  - Flatter PDF observed for coherent structures created via constructive large-scale flows in some numerical simulations (Federrath et al., 2010)

South- Nest

Forming low mass stars, and analysis suggests region is more turbulent.

The Ridge is comprised of high-mass stars.

dominated by gravity and large-scale converging flows.

Is this difference systematic?

P-ArTéMiS observations

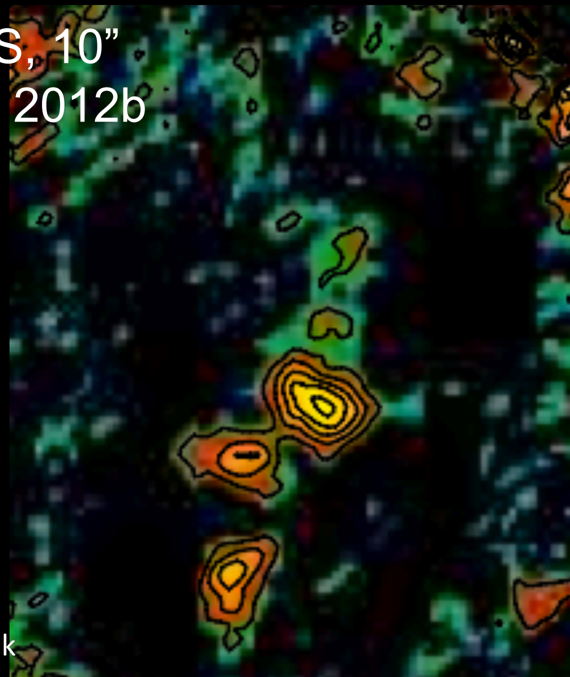
- A new submm bolometer on APEX
- Observations at 450µm,
  - Taken May 2009
- Prototype for ArTéMiS
  - Developed by CEA/Saclay
  - PI instrument
  - Commissioning late 2013
  - Revamped early 2014
  - Offered this ESO call (Mar 27) –obs late 2014.
- Greek mythology : was one of the most widely venerated of the Ancient Greek deities. Daughter of Zeus and Leto, sister of Apollo

70, 160, 250µm

Herschel, 18”
Hill et al., 2011

~4pc

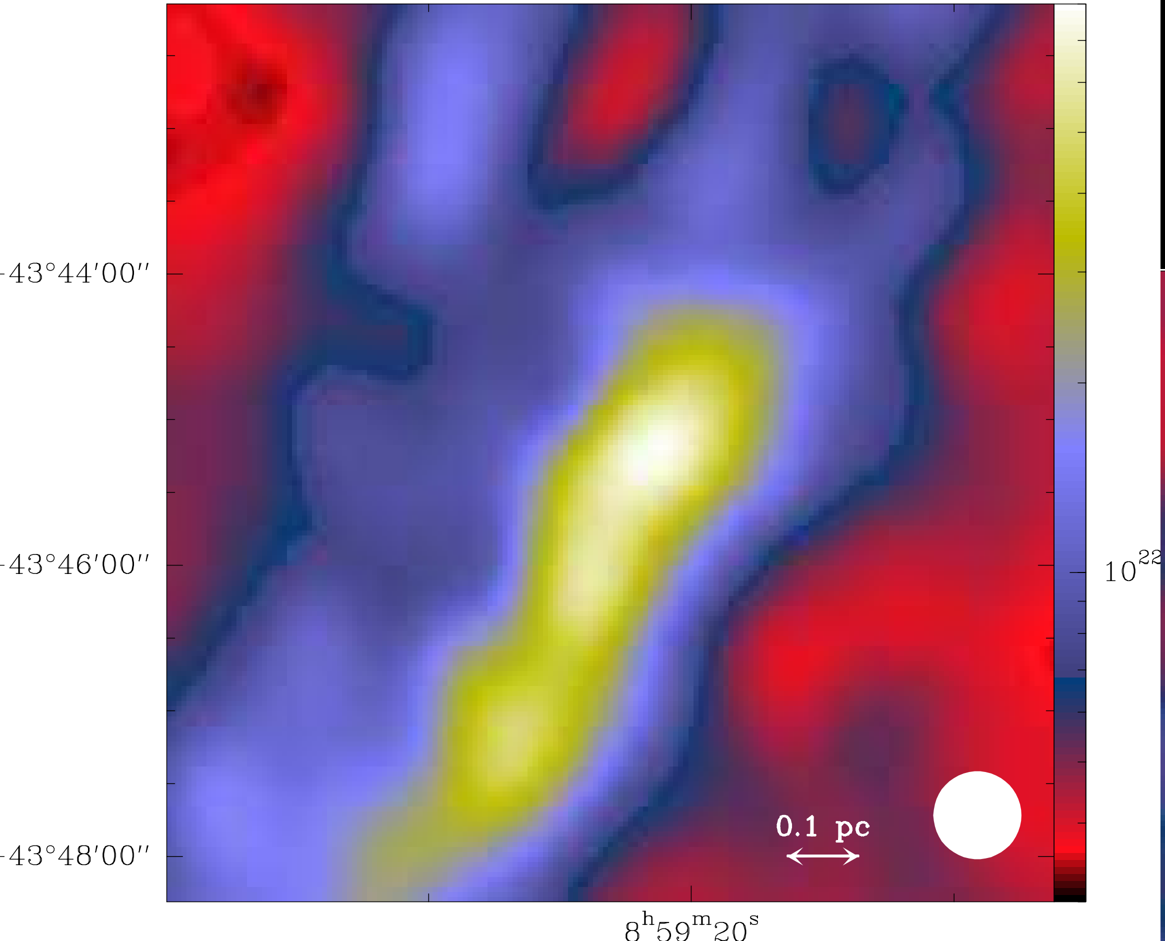
P-ArTéMiS, 10”
Hill, et al., 2012b



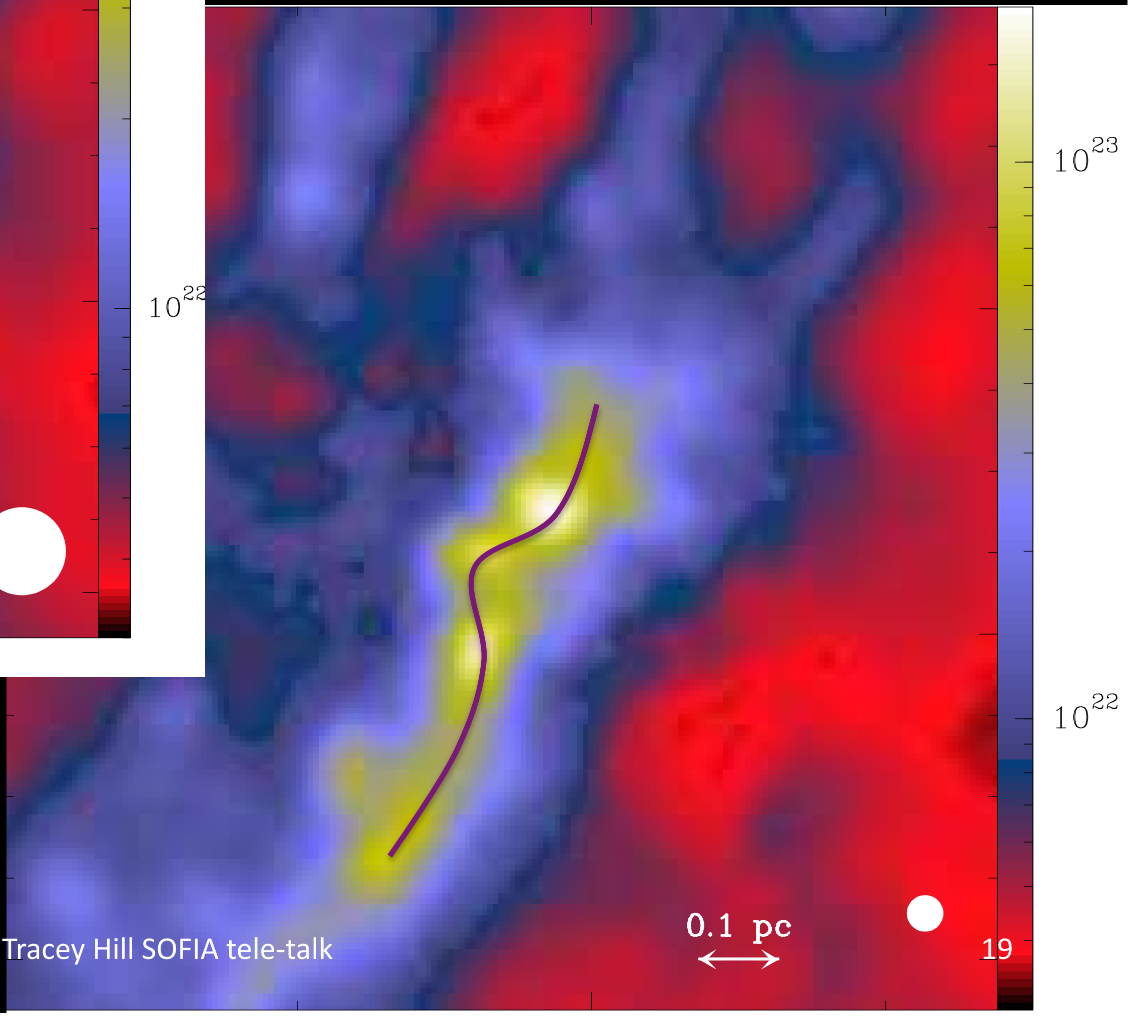
450µm

~4pc

Higher CD maps

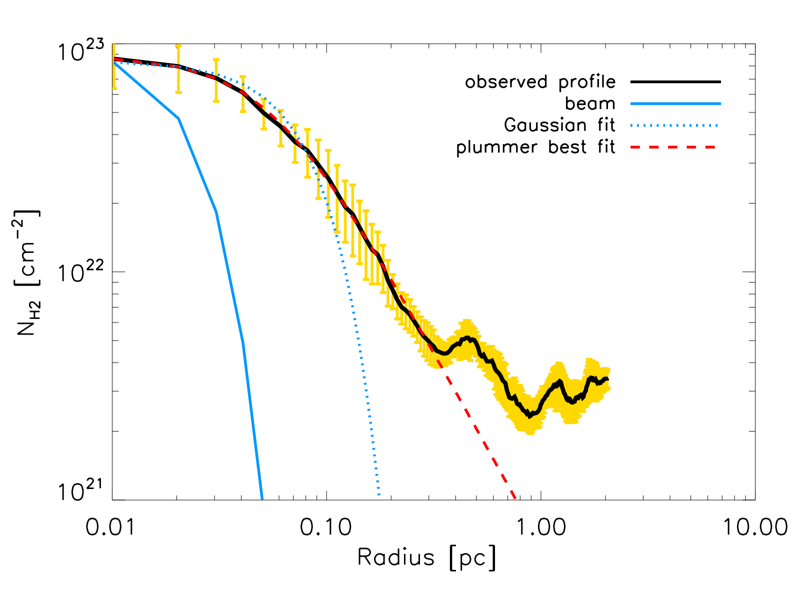


Herschel, 36”
Hill, Motte, Didelon et al., 2011

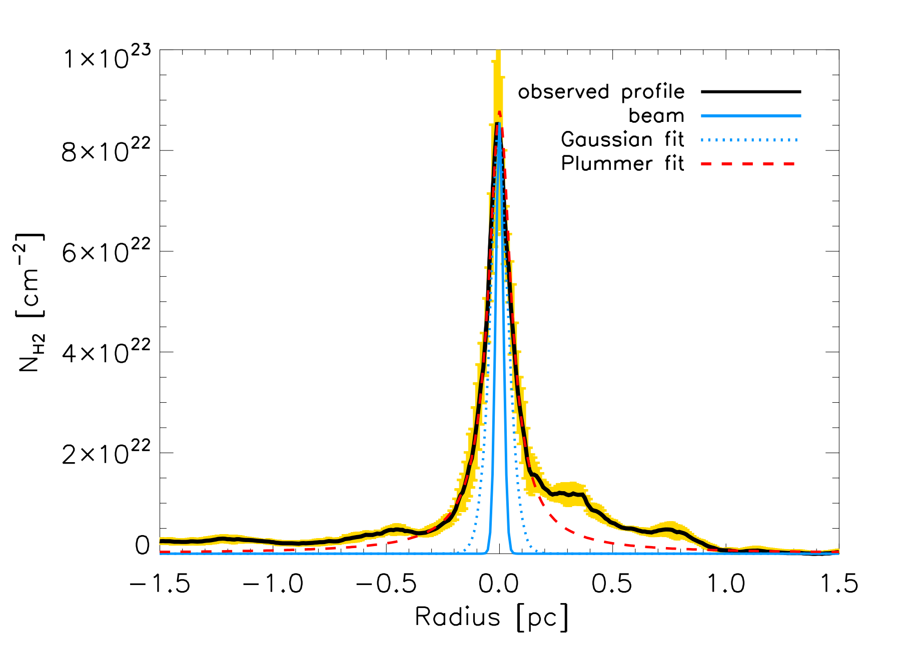


P-ArTéMiS + Herschel,11.5”
Hill, André, Arzoumanian et al., 2012

Parameters of the Vela C Ridge

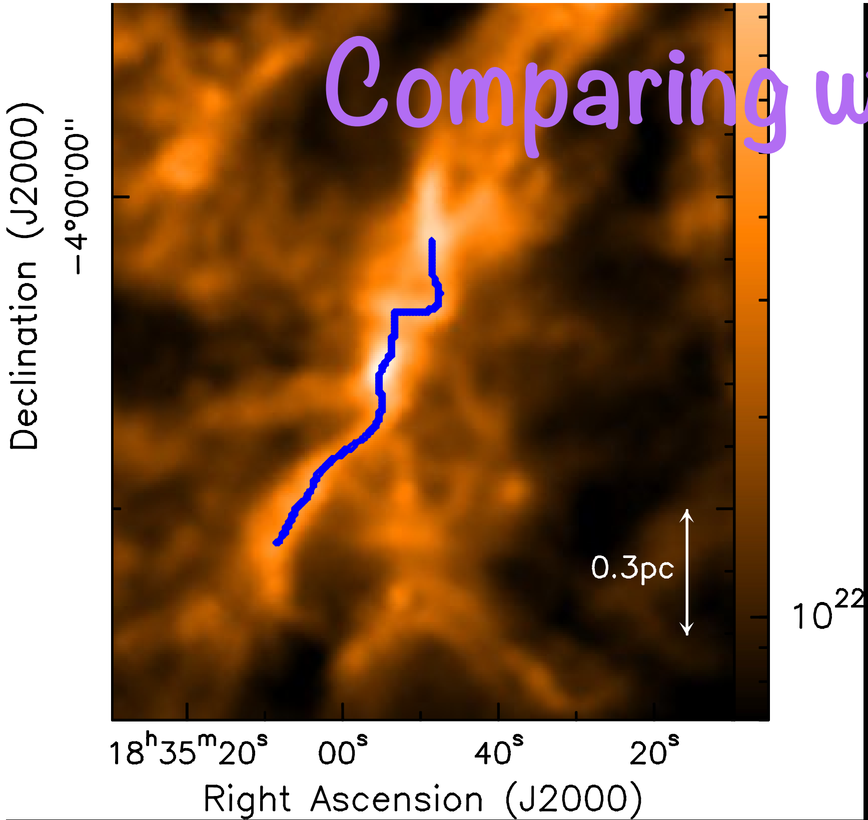


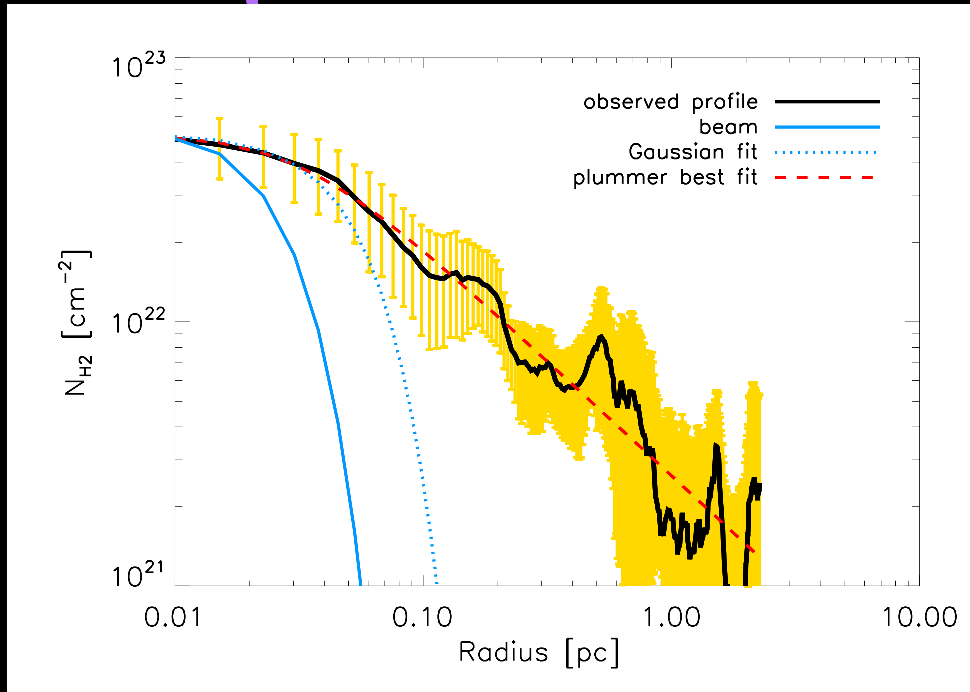
Plummer fit parameters:
P=2.7 +/- 0.2
Rflat = 0.05



- 0.4pc outer width
  - Consistent with Hill et al., 2011
- Inner width of 0.12pc
  - Consistent with characteristic filament width (Arzoumanian et al., 2011)
- Mline ≈ 320$M_\odot$/pc

Comparing with Serpens South





- Spatial res. on sky: 0.05pc at 260pc (0.04pc at 700pc)
- Outer width – ~0.4pc (~0.4pc)
- Inner width ~ 0.1 +/- 0.05 pc (0.12pc)
- Mline= = 290M$_\odot$/pc (320)
- Jeans Length = 0.005pc (0.003pc)
- Central Col. den 5.6 x 10^{22}cm^{-2} (8.6 x 10^{22}cm^{-2})

Threshold for high-mass stars?

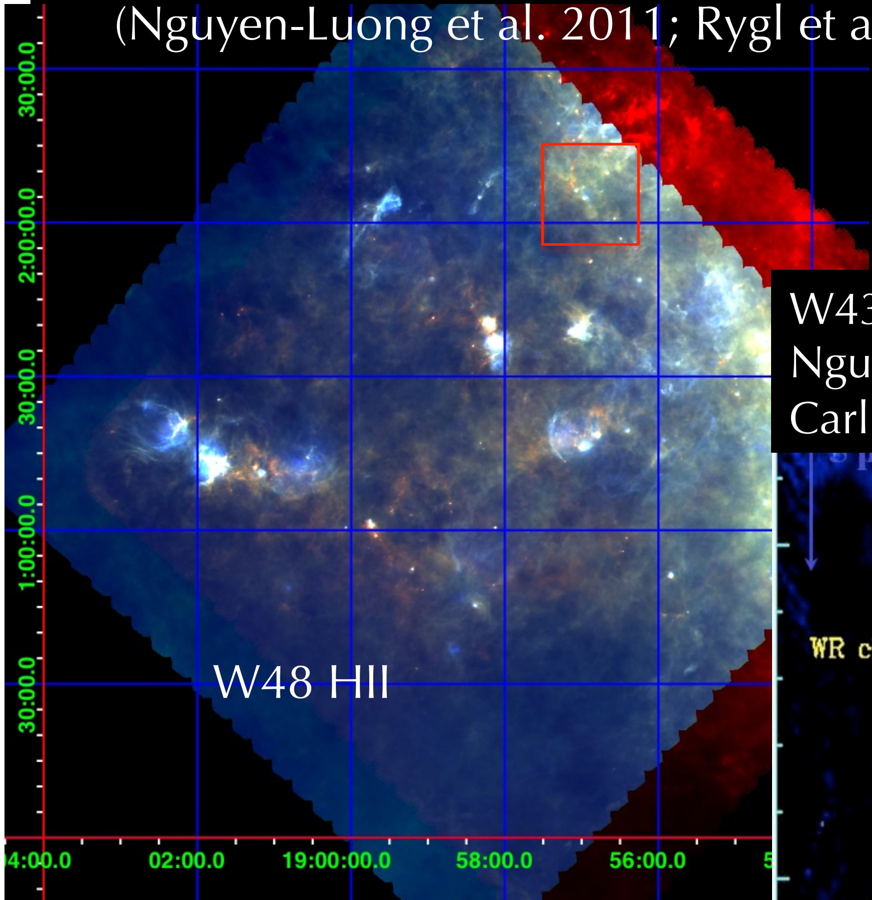
- Observational predictions:
  - Need a minimum reservoir to form a HM star.
  - E.g. Evans 2008, Lada et al., 2010
- Theoretical predictions
  - Krumholz & McKee 2008
    - Min. col. dens. (> 1 g/ cm^{-2} or N_{H_2}~ 3 x 10^{23} cm^{-2})
    - Below this threshold cores will fragment.
- Comparison of Vela C and Serpens South.
  - Little difference in CD.
  - Both are supercritical (will! form stars)
  - Vela C – 7 high mass clumps (Hill et al., 2011)
  - Serpens South has a number of Class 0 objects. Vela C does not.
  - Similar characteristics (e.g. inner filament width, outer width, Mline)
- Observational data does not support a threshold between low and high-mass stars (in CD)
  - Need to compare more regions.

Hill, André, Arzoumanian et al., 2012b

Other HOBYS Ridges

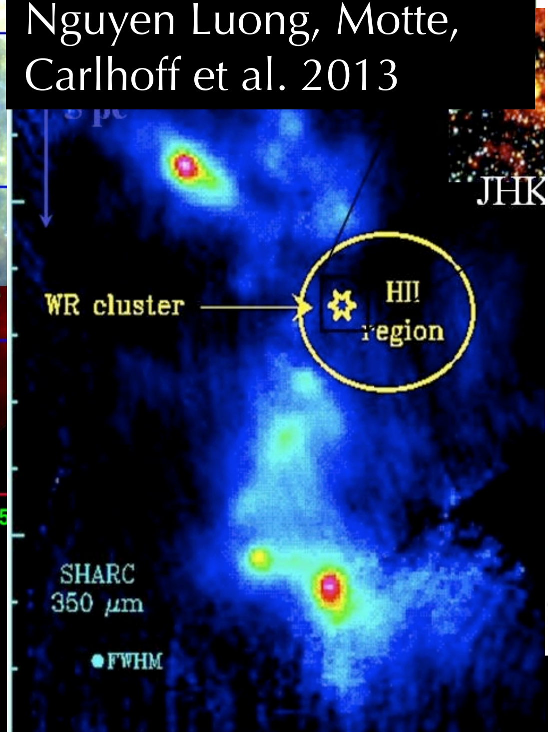
IRDC G035.39-00.33, A RIDGE IN W48

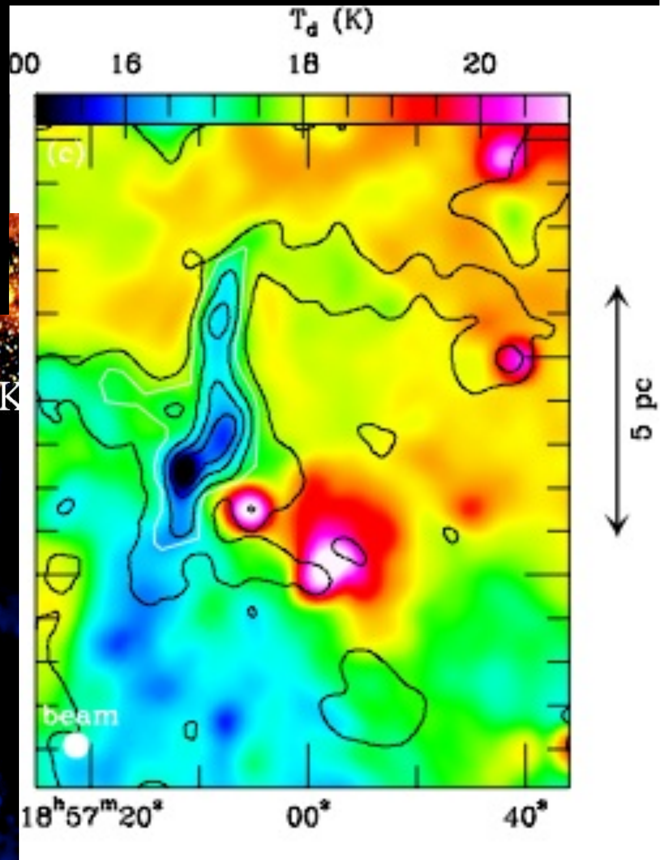
(Nguyen-Luong et al. 2011; Rygl et al. 2013.)



70µm, 160µm, 250µm

W43-MM1, MM2 ridges: Nguyen Luong, Motte, Carlhoff et al. 2013



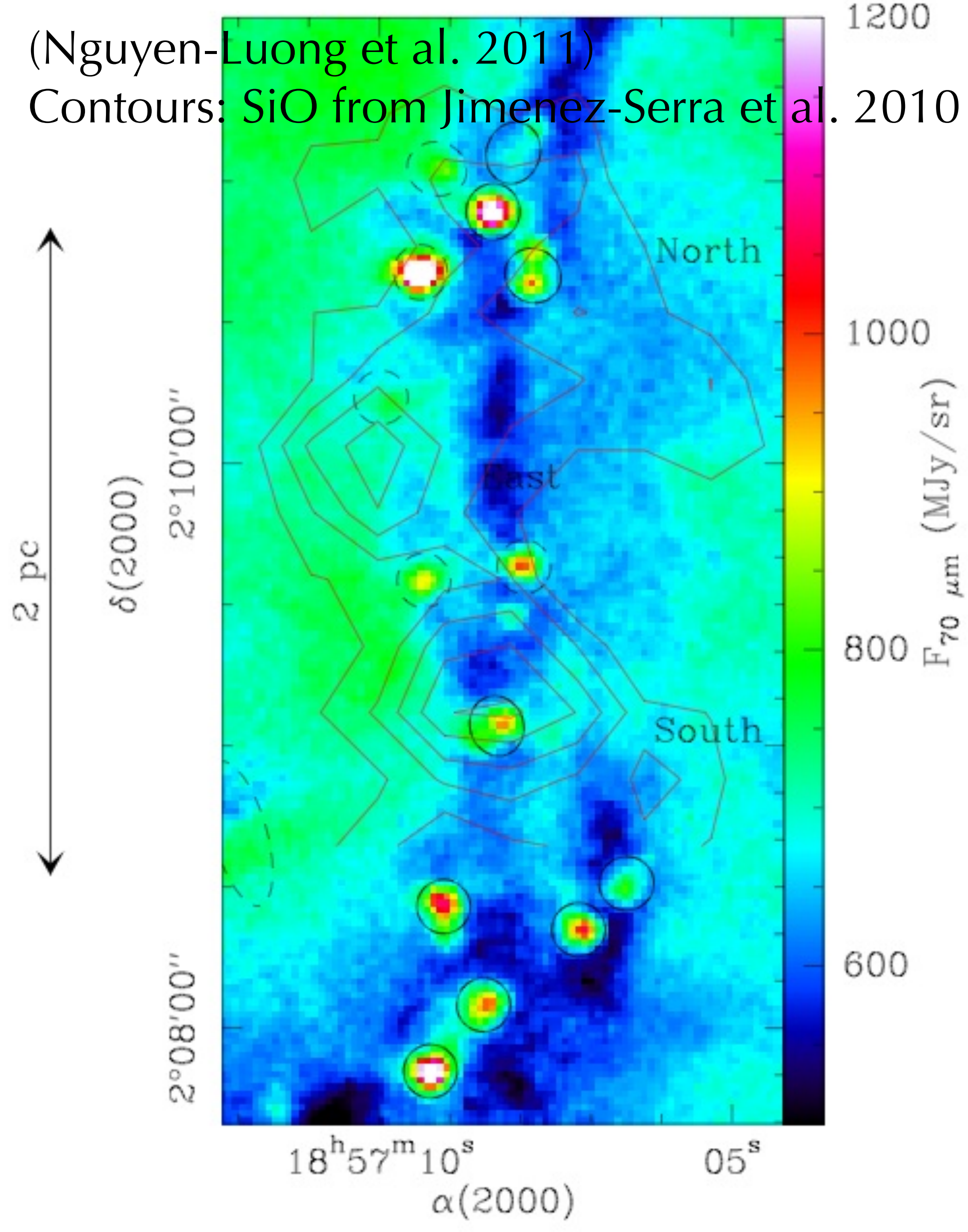


Density contours

- W48, 3kpc, $1\times10^6 M_\odot$, ~1.5-8 10^{22}cm^{-2}, 16K

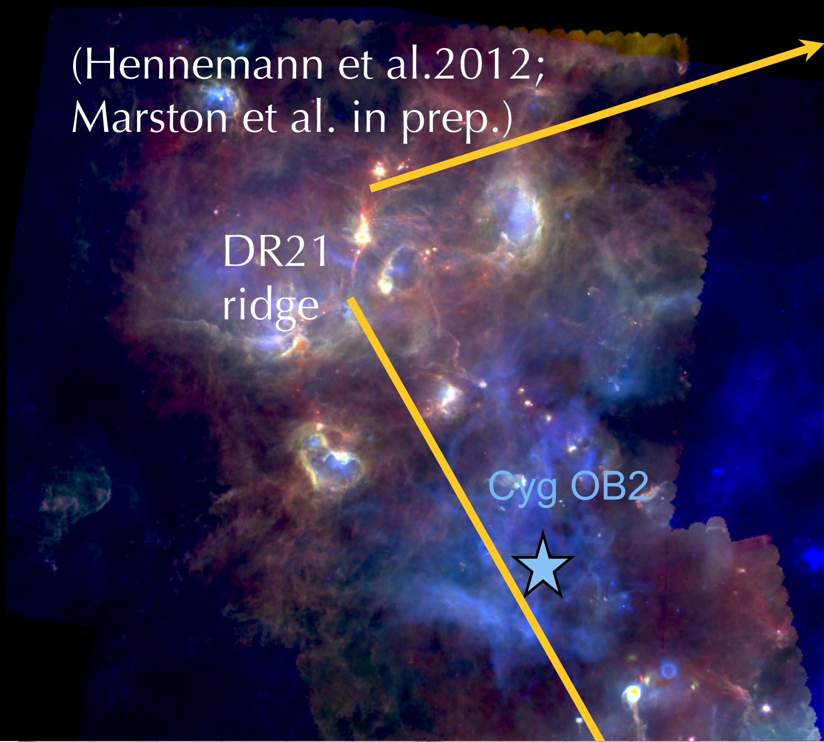
High-mass star formation in G0.35.39-00.33

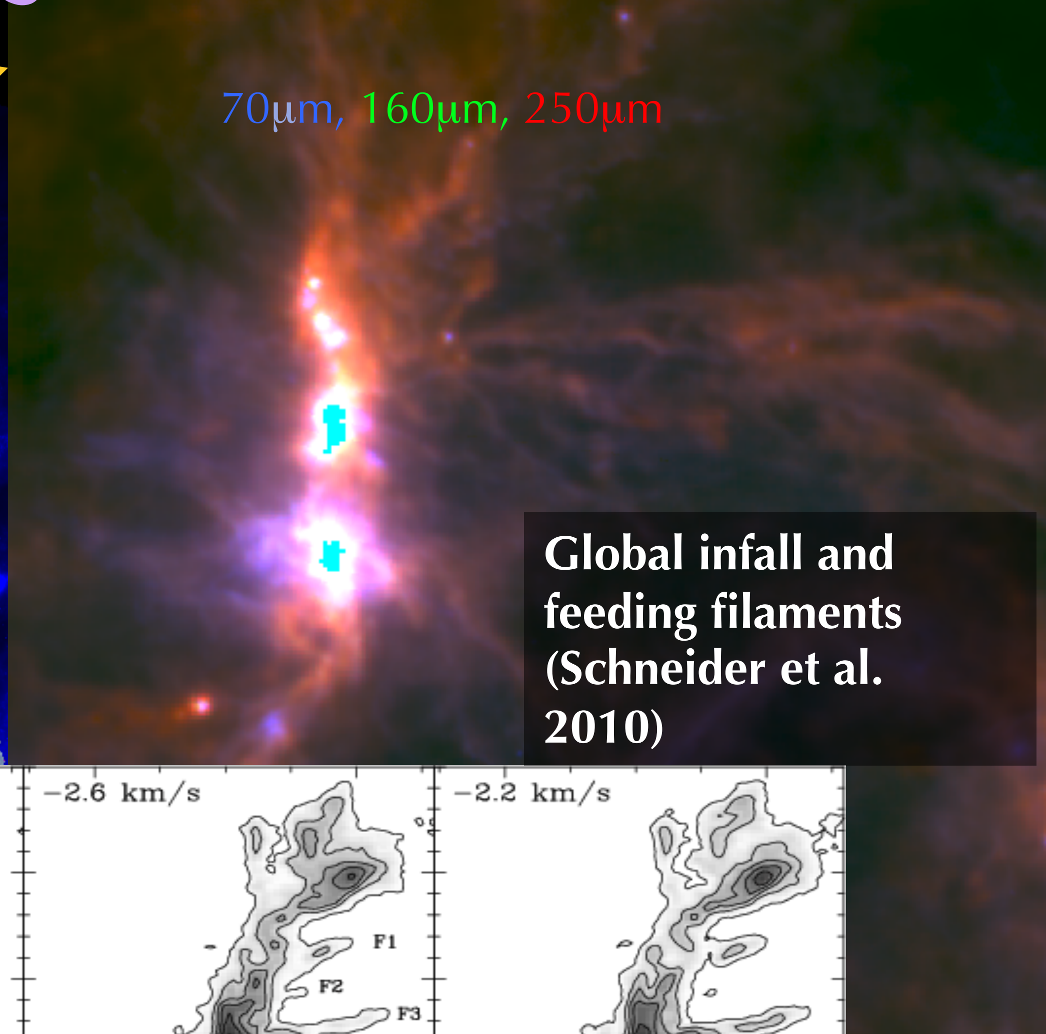
(Nguyen-Luong et al. 2011)
Contours: SiO from Jimenez-Serra et al. 2010

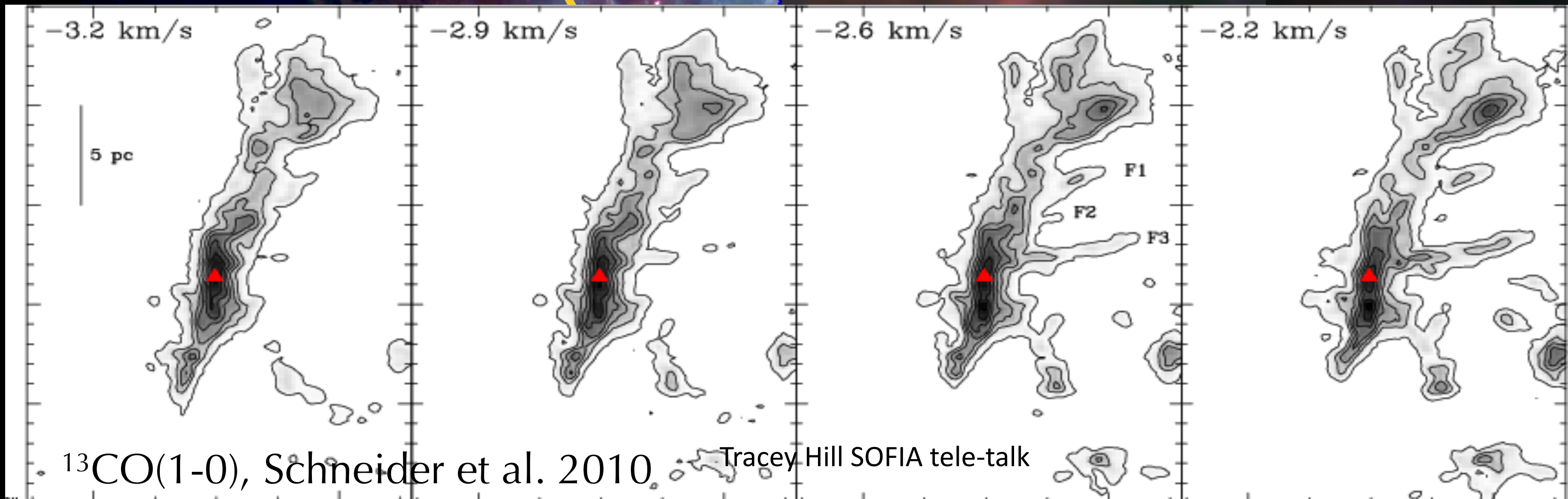


- From the Herschel column density map, IRDC mass = 4000M$_\odot$
- Greybody fitting
  - A cluster of 9 MDC, (0.1-0.2pc, 30-1000M$_\odot$) harbouring class 0 objects
- Part of the SiO may be tracing low velocity shocks assoc. with converging flows.
- A burst of star formation (SFE ~15%) after the fast cloud formation?

DR21, fed by sub-filaments?







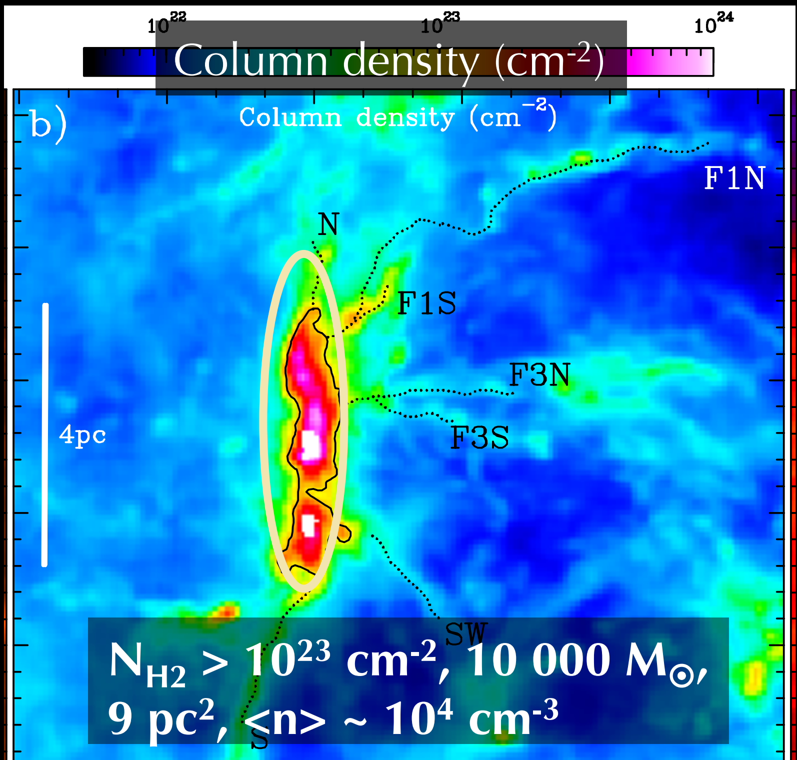
^{13}CO(1-0), Schneider et al. 2010

Most ridges should form by cloud global collapse

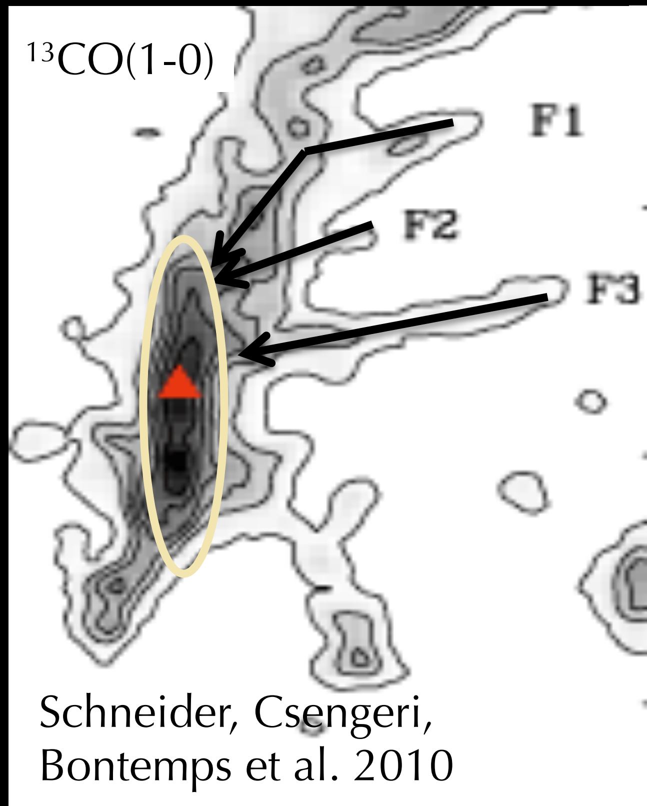
- Forced-fall (pressure-driven infall) of the DR21 ridge further fed by filaments.

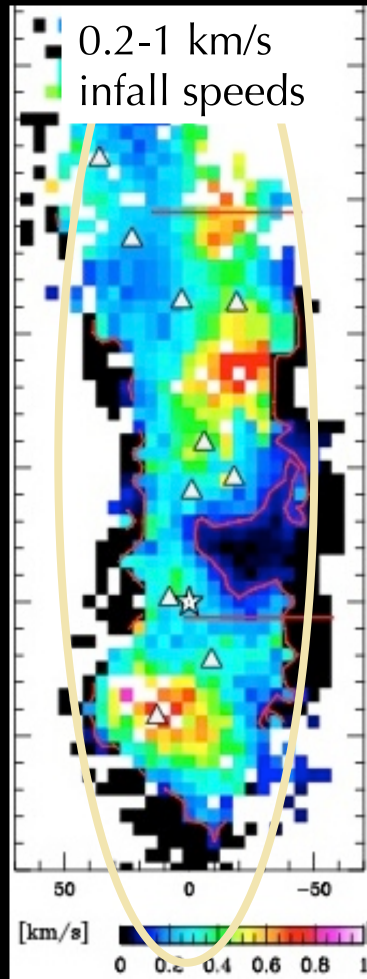
Gas flows along sub-filaments

Global infall



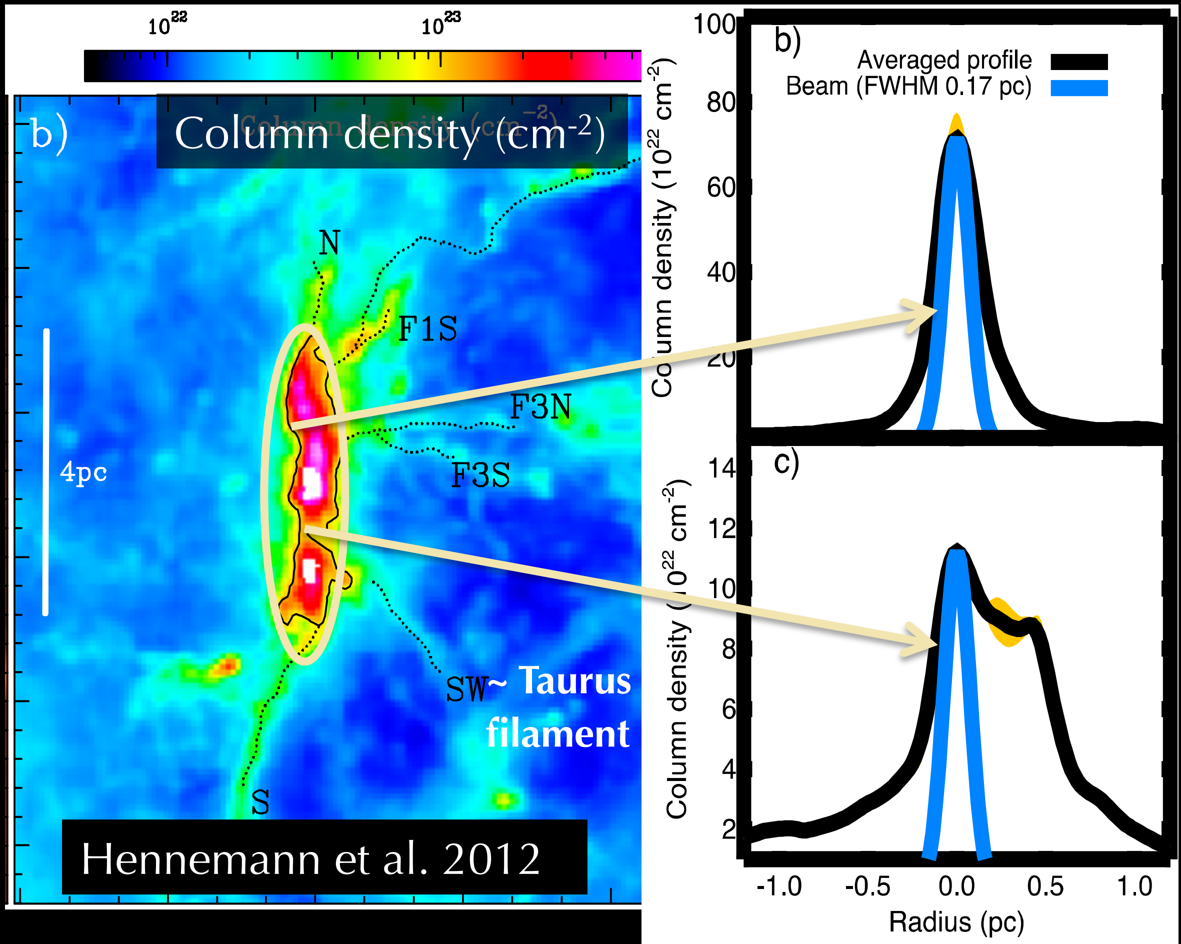
Hennemann, Motte, Schneider et al. 2012





- Similar kinematics and SiO shocks for the W43-MM1 & MM2 ridges (Nguyen Luong et al. 2013; Louvet et al. in prep.)

The DR21 ridge, formed by merging of super-critical filaments?



Steps toward SF in ridges:

1. MHD tubulent shocks build-up filaments that gently accrete from their surrounding.

2. Gravity braids filaments in a collapsing clump attracting more filaments.

3. Stars and filaments simultaneously form. Protostar accretion is non-local & aspherical.

⇒Prestellar cores may not exist in such environment

See Csengeri et al. 2011a-b for gas inflow shears in DR21 cores

See also Henshaw et al. 2013; Louvet et al. in prep. for other ridges

Ridges are extreme clumps forming clusters of high-mass stars

- ~50% of high-mass protostars are forming in clusters within high-density elongated clumps

⇒ Ridge definition : 5-10 pc^3 above 10^4-10^5 cm^{-3}

For convenience, we use the 100 A_v level to identify ridges but it is not a physical threshold

- Surrounding gas concentrates toward ridges at high column-density (seen e.g. with PDF studies)

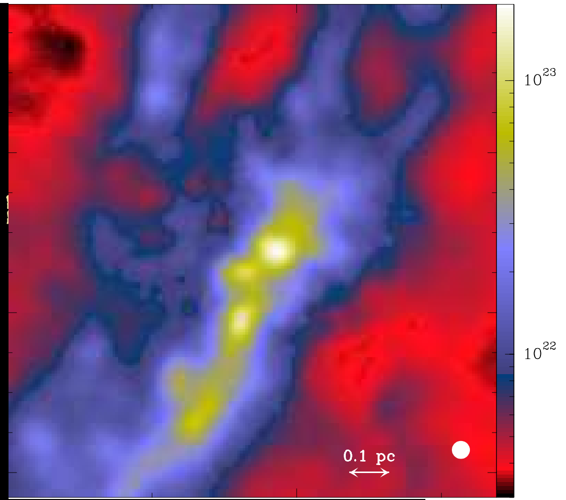
➢ Vela C ridge (Hill, Motte, Didelon et al. 2011)

➢ DR21 ridge in Cygnus X (Hennemann, Motte, Schneider et al. 2012)

➢ IRDC G035.39-00.33 ridge (Nguyen Luong, Motte, Hennemann et al. 2011a)

➢ W43-MM1, MM2 ridges (Nguyen Luong, Motte, Carlhoff et al. 2013)

RIDGES



- Many HOBYS (and HI-GAL) regions contain
  - The preferential sites of high-mass star formation
  - Not seen in low mass star forming regions!
- How do ridges differ from filaments?
  - Width, density, temperature, tracers of converging flows (e.g. SiO)
  - Star formation content.
  - Evidence of mini-star bursts in ridges (e.g. White, Hill et al., in prep, Nguyen Luong et al., 2011)
  - High star formation efficiency?
- How are ridges built up
  - Converging flows? (Hill, Motte et al., 2011)
  - Filament mergers? (Hennemann et al., 2012)
- Planning a large studywith the ALMA , ATCA & PdBI
  - A census and chracterisation of ridges.

SOFIA observations

- 24 & 35um imaging off the DR21 ridge
- To model the SEDs of the sources in the ridge
  - 35um is vital to complete SED coverage.
  - 24um to compare with Spitzer
    - (which was also saturated towards most of this region)
    - Better resolution than Spitzer.
  - To complement that of Herschel, and existing PdBI observations (1 and 3mm).
- To constrain the Lbol, temperature, and Menv
  - Estimate the evolutionary status of the cores.
- Comparable resolution to Hershel.

SOFIA

- Represents the transition of cold dust (submm/FIR) to the emission from a potential protostar forming inside the core.
- At 24/35um, attenuation from dust remains low.
  - Allowing to probe embedded objects.
  - unlike shorter wavelengths.
- DR21 studied in great detail by our group.
  - One of richest and most active regions of SF in Galaxy.
  - Ideal place to characterise high-mass stars, at their earliest stages
  - Excellent example of a ridge.
    - Can study core dynamics within the ridge.