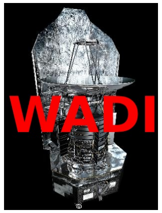
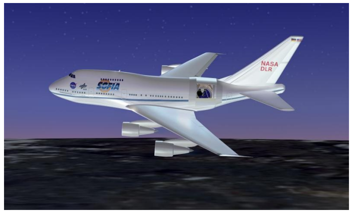




The role of radiative triggering for star-formation

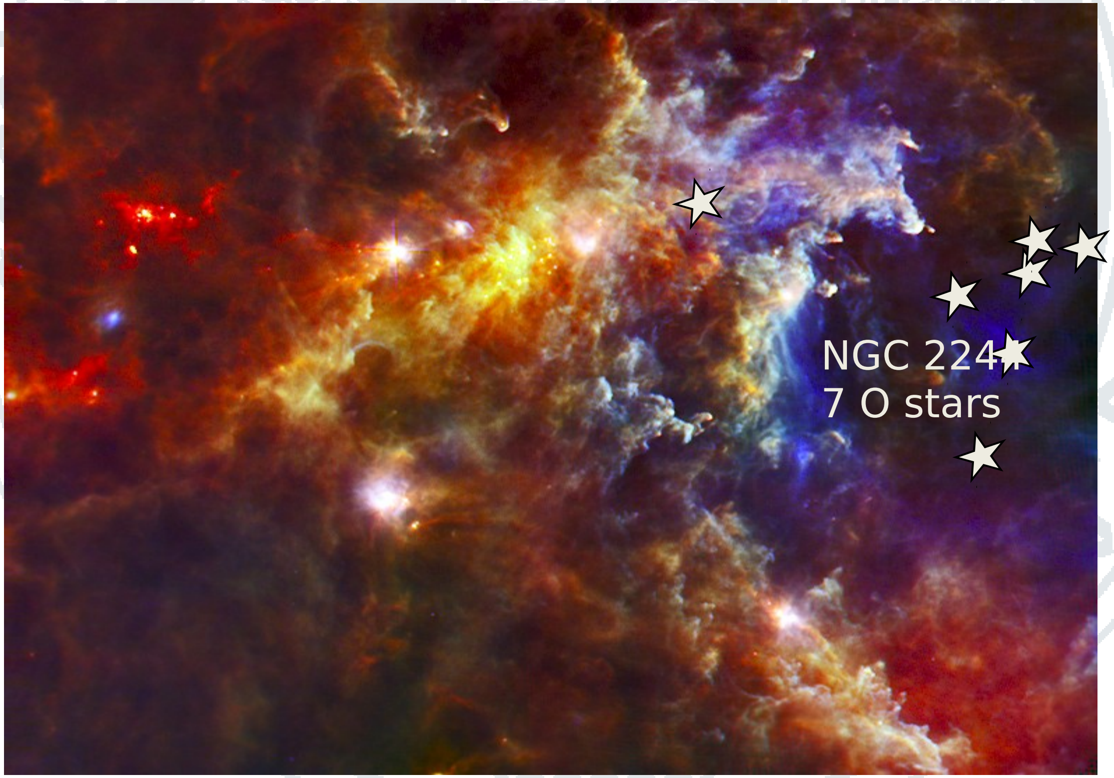
V. Ossenkopf, *M. Röllig, N. Schneider, P. Pilleri, B. Mookerjea, Z. Makai, Y. Okada*

Is star-formation significantly triggered?

- dynamic impact from winds and outflows
  - → dispersion → prevents SF
  - → compression → triggers SF

- UV radiation heats the gas
  - → temperature/pressure increase → prevents SF

- UV radiation dissociates the gas
  - → change of chemical structure
  - → remove cooling agents → prevents SF
  - → create cooling agents → triggers SF



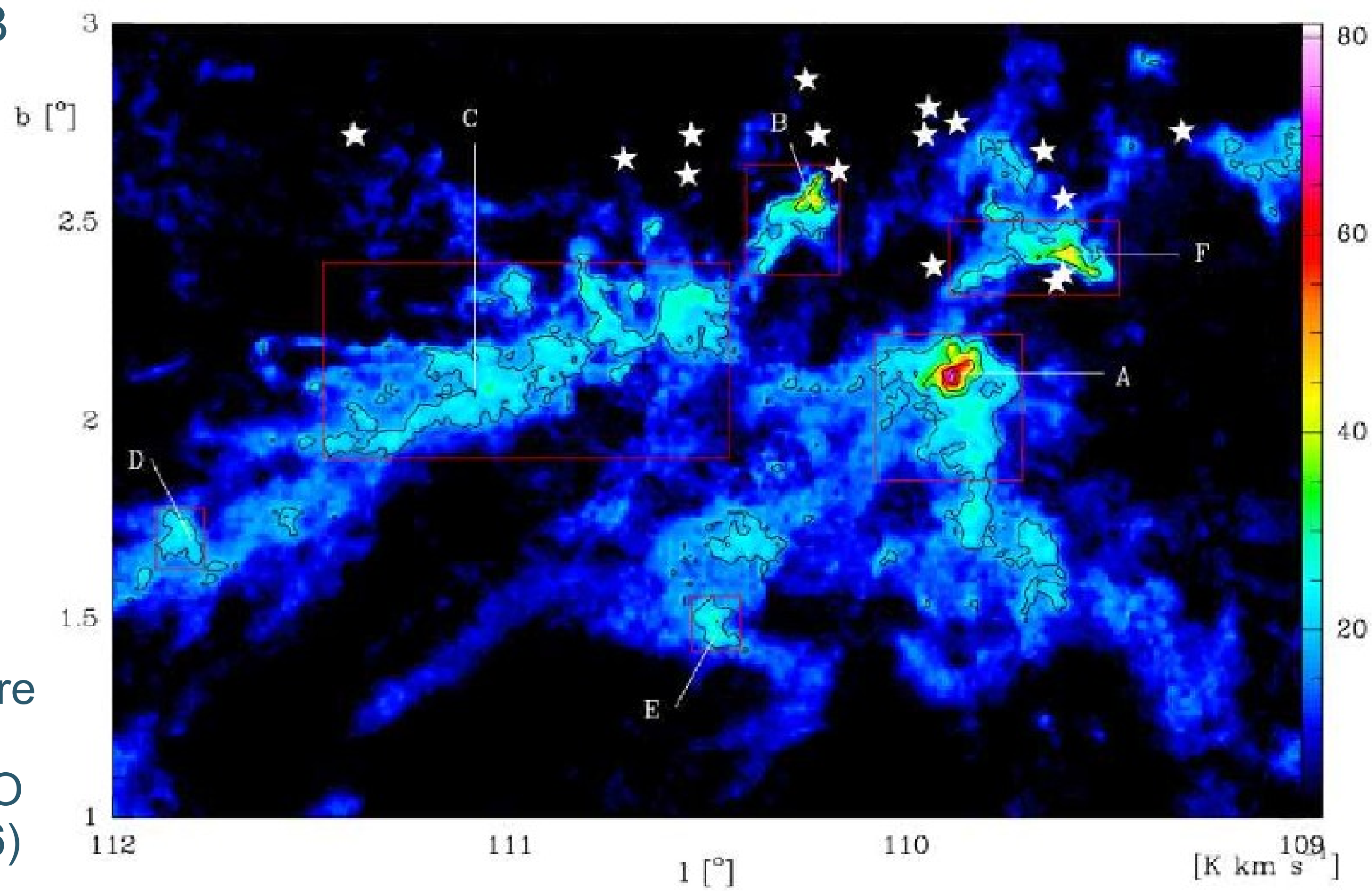
Pillars in Rosette (HOBYS team: Motte et al. 2010)

Total net effect ?

Observational evidence

Clear indication of sequential star formation:

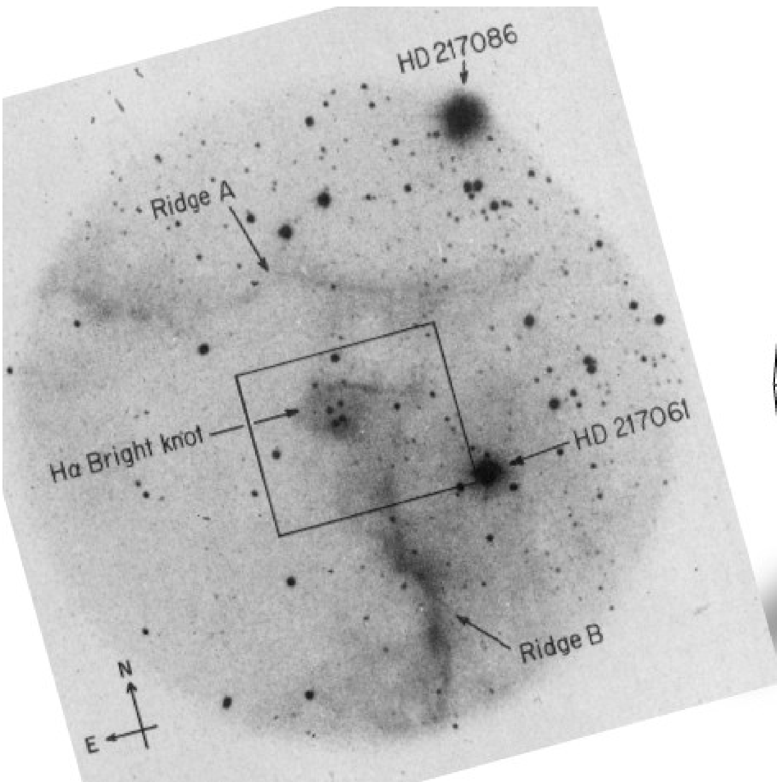
- Example: Cep B
- Age gradient of stars towards Cep B

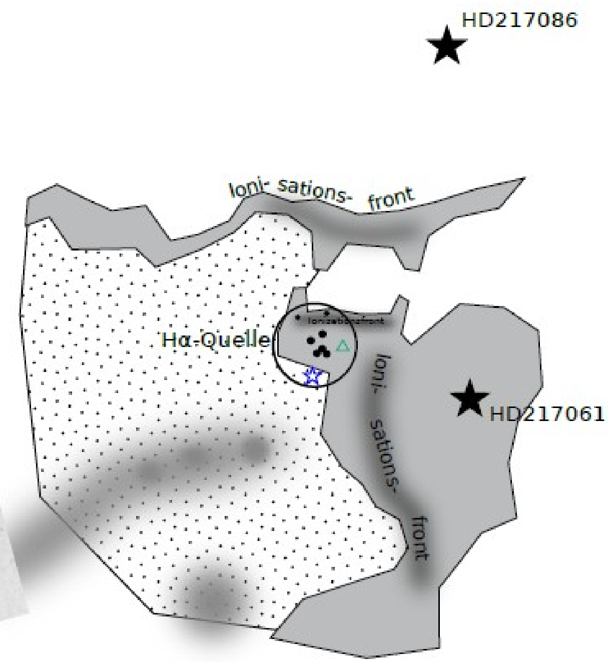


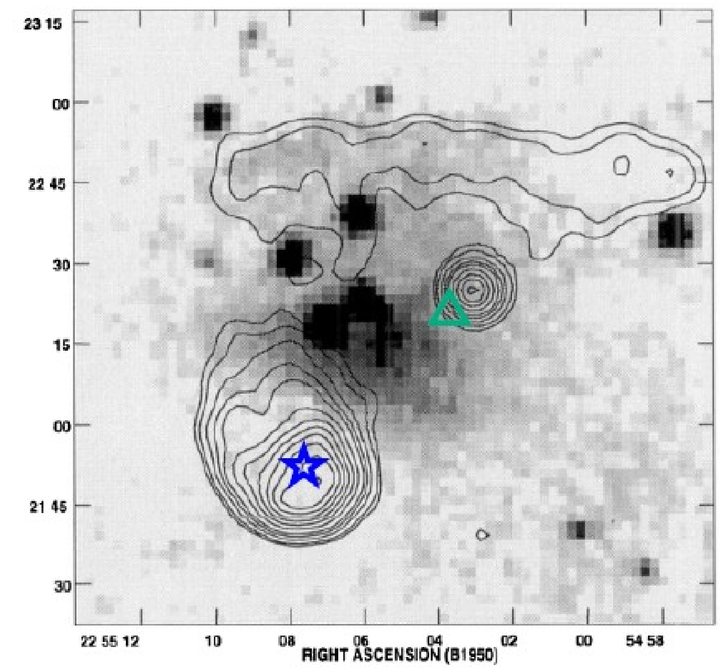
Large-scale structure of the Cepheus molecular cloud (CO 1-0, Sun et al. 2006)

Observational evidence

Sequential star-formation in Cep B:







Cep B structure (Moreno-Corral et al. 1993)

2 embedded HII regions (Testi et al. 1995)

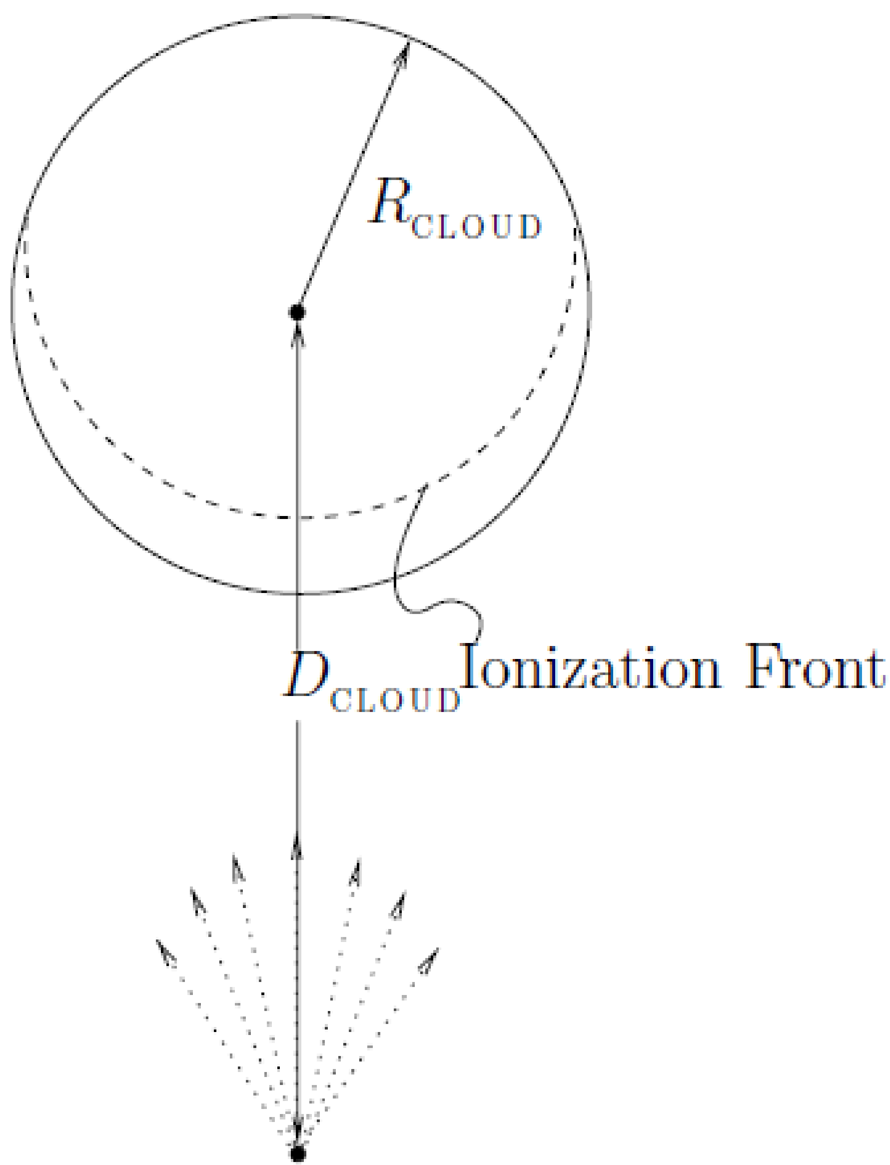
Radiative impact: what do we expect?

Theory:

- Radiation pressure
- Thermal pressure of heated gas

  →

  - Ionization and photo-chemistry
    → Photon-dominated regions (PDRs)
  - Compression of clouds
  - Dispersion



Schematic picture of pillar formation (Bisbas et al. 2011)

Radiative impact: what do we expect?

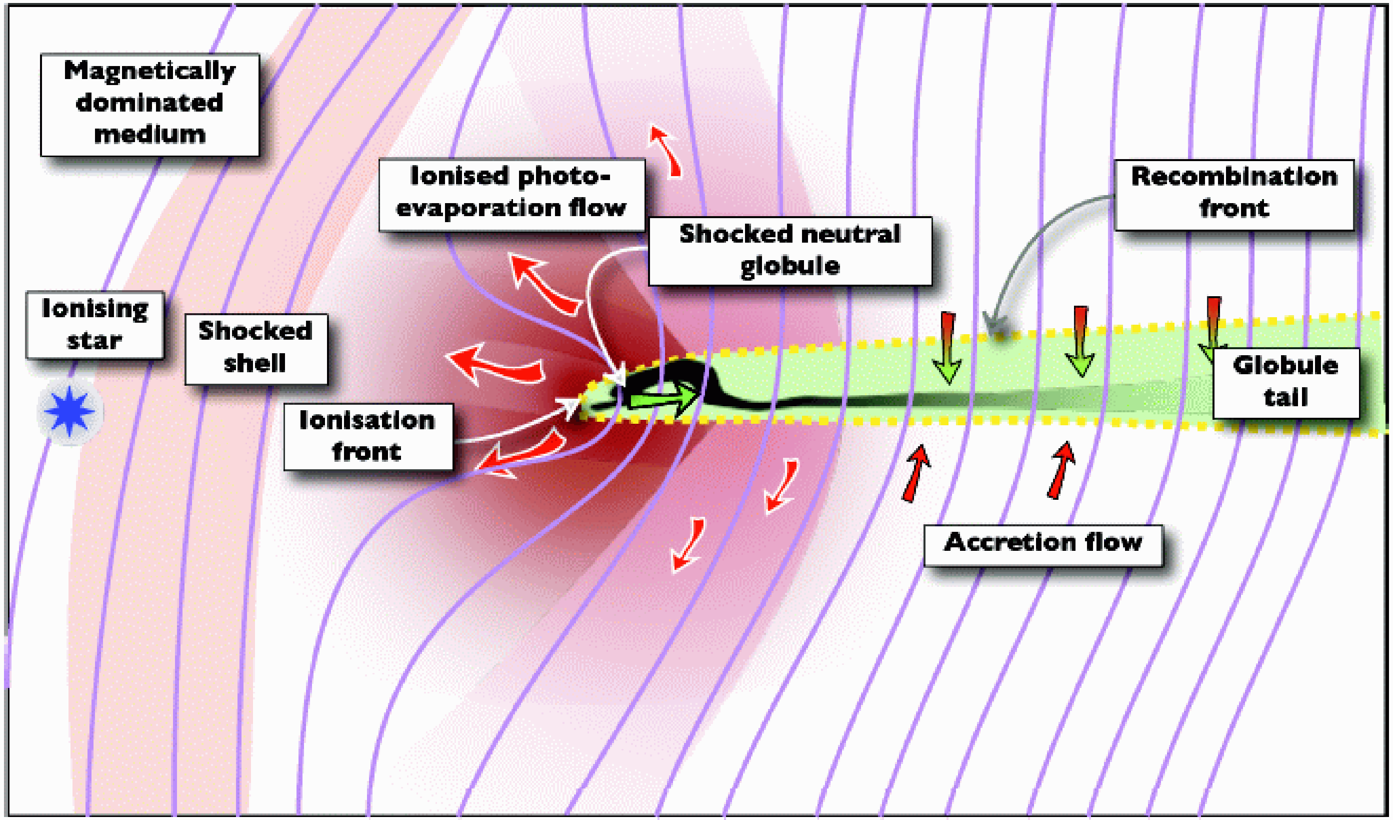
Dynamics:

- Photo-evaporation of PDRs → flow of ionized material
- High pressure zone at PDR surface → cloud compression
  → shock fronts
- Ionization front "eats" into molecular cloud

→ **pillar formation**

Unknowns:

- *Advection flows*
- *Impact of turbulence*

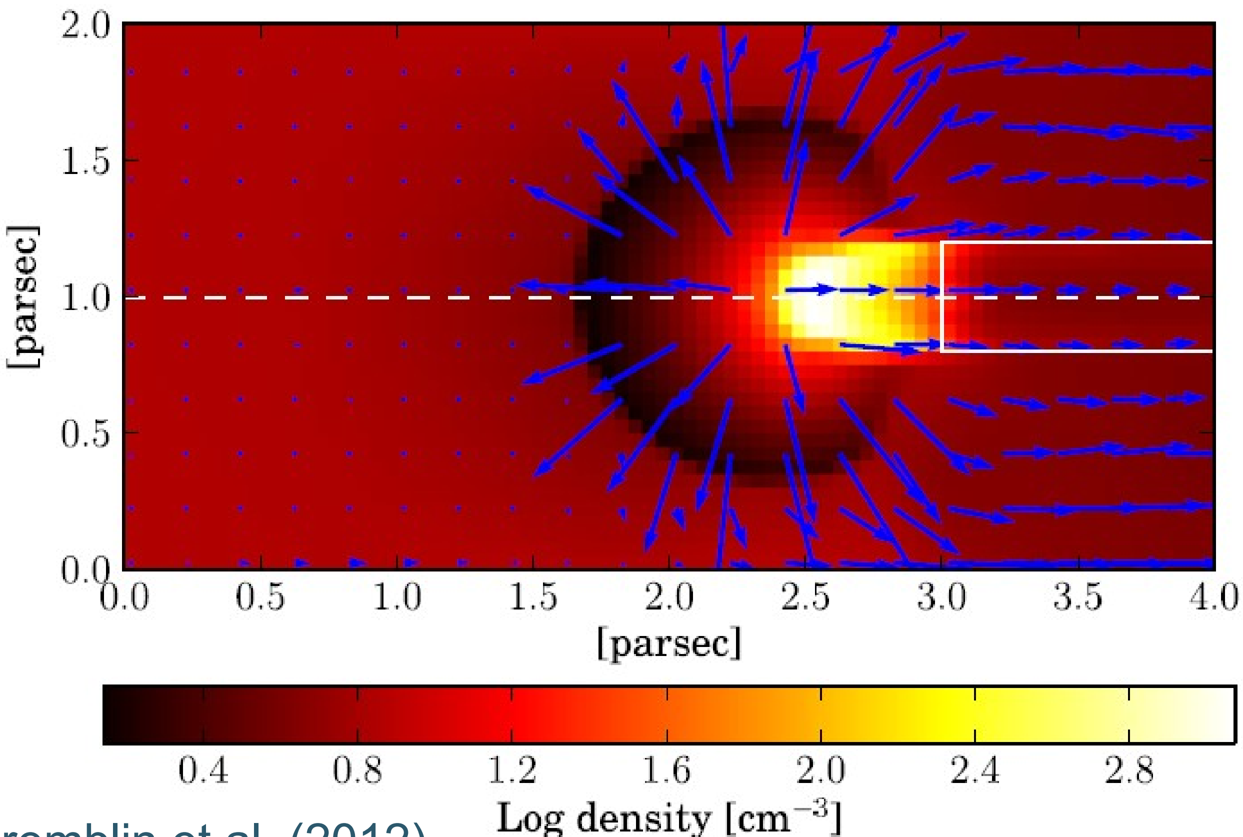


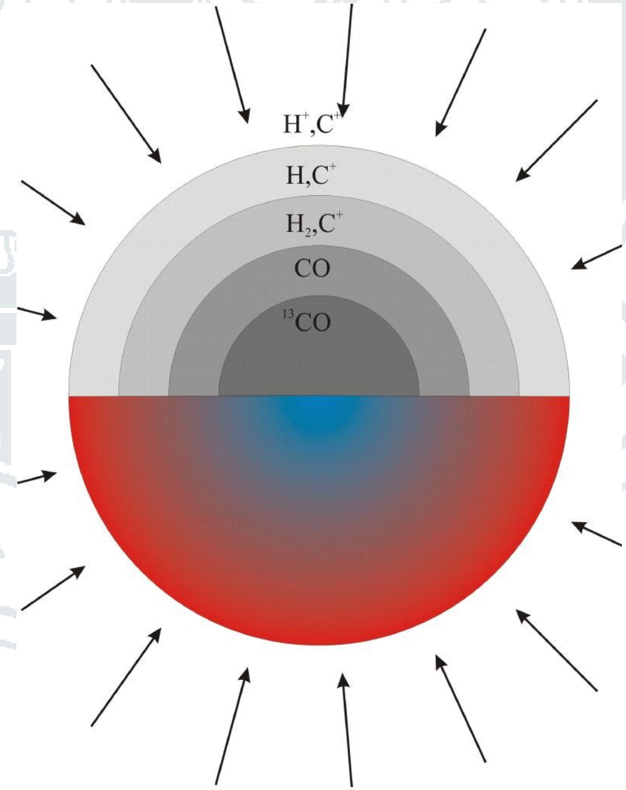
3-D MHD model by Henney et al. (2009)

Observational verification

Look for characteristic velocity flow patterns of triggered collapse

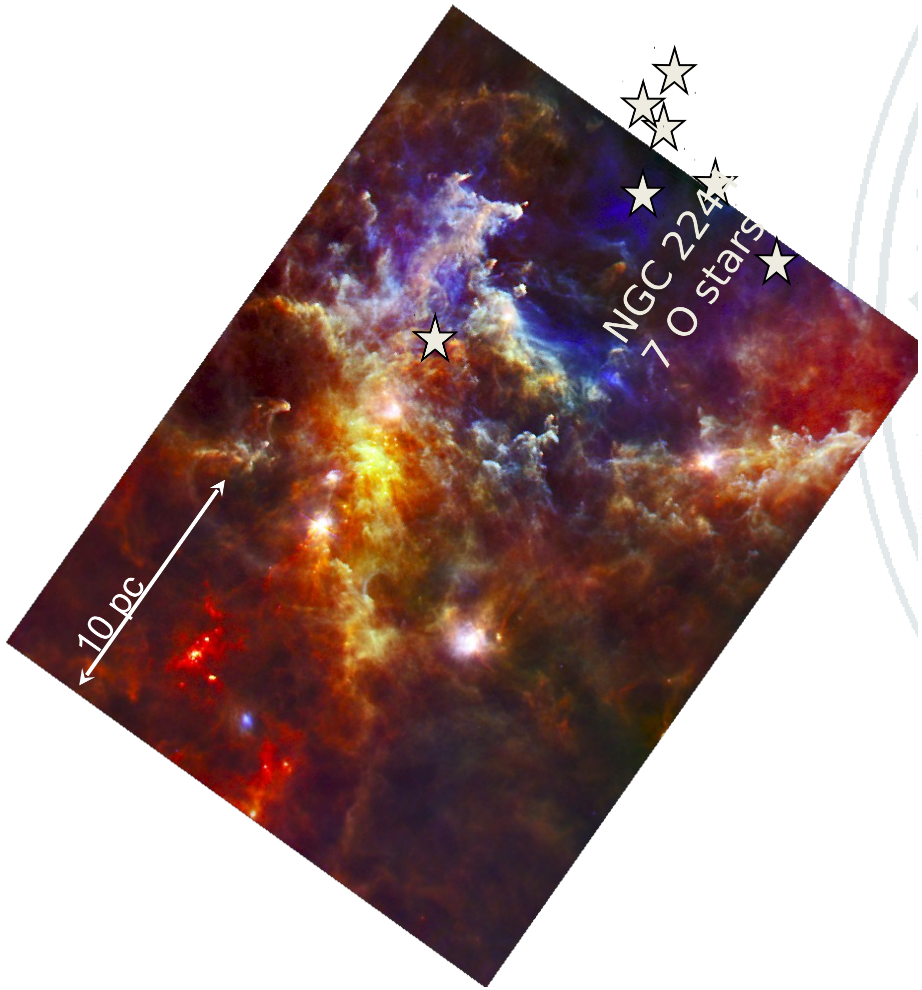
- Chemical structure has to be taken into account, but can be exploited

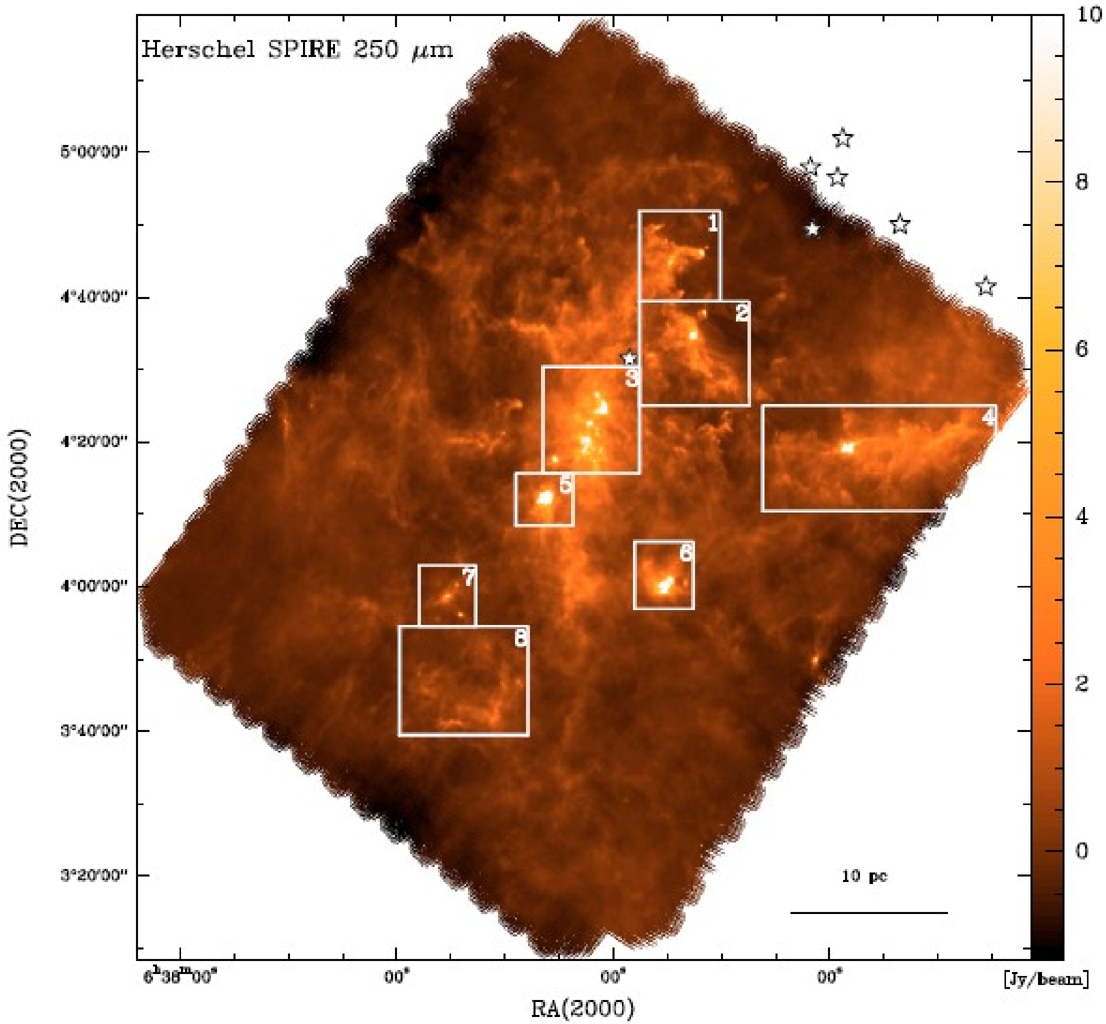




Tremblin et al. (2012)

Example 1: Rosette

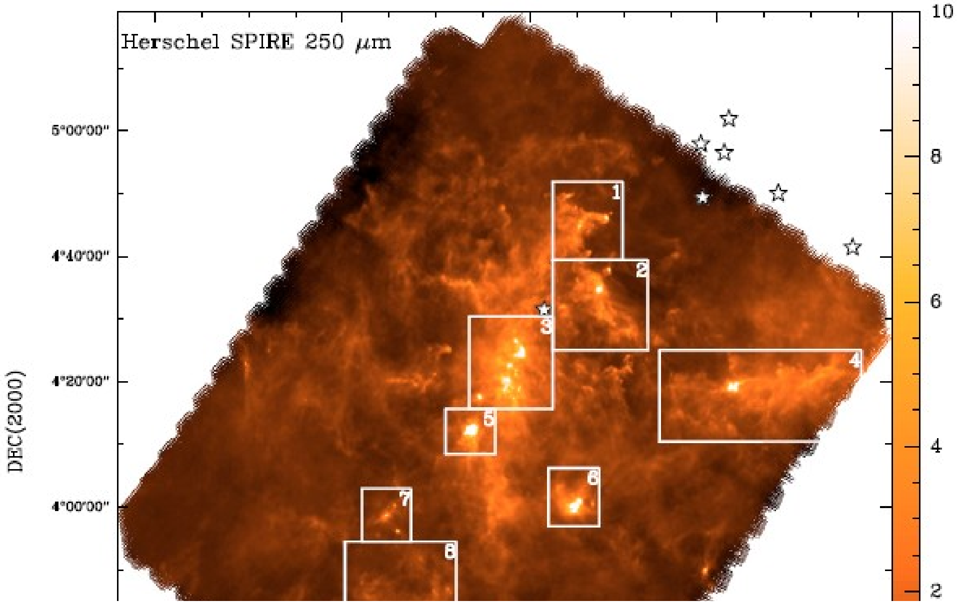




PACS/SPIRE map of Rosette
(Motte et al. 2010, Schneider et al. 2010)

Investigation of individual pillars: Region 1+2

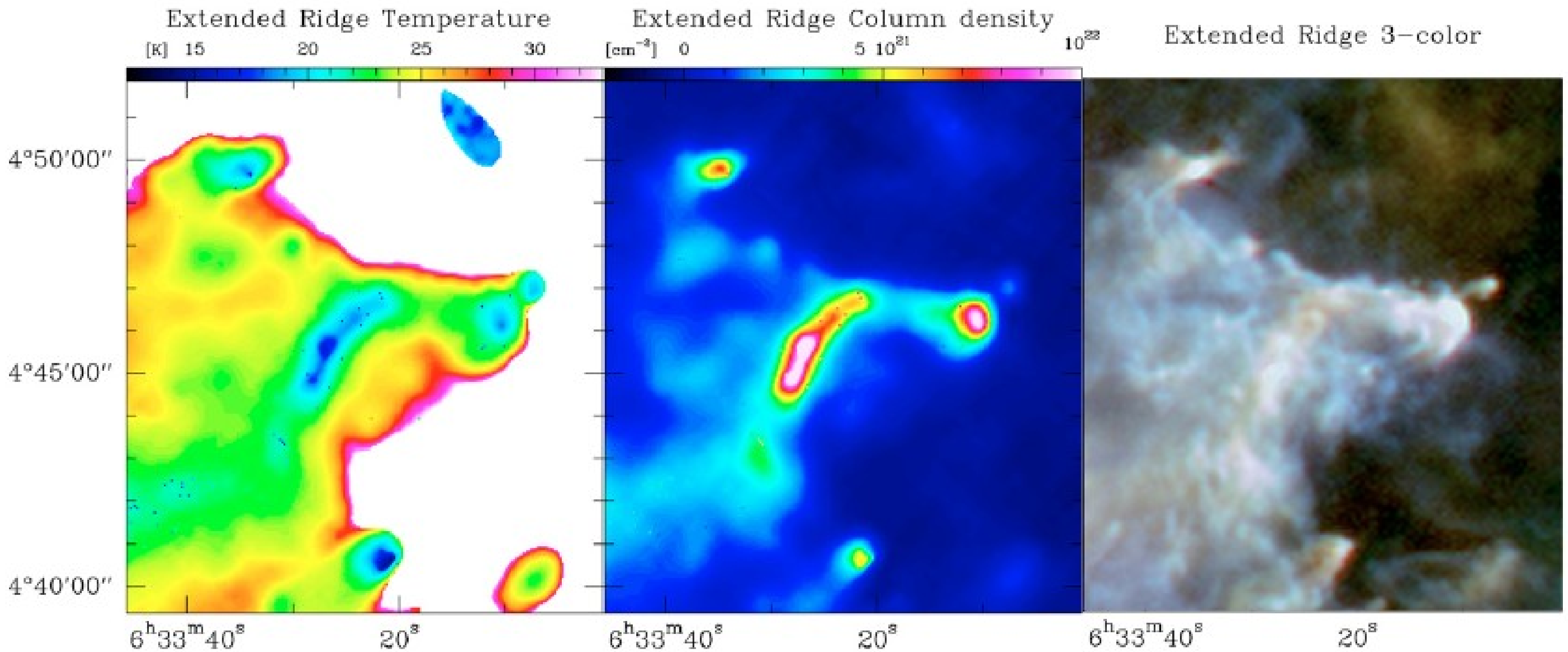
Rosette



Region 1 - high resolution:

- High density pillars
  - Temperature low from better cooling, heating only at surface
  - No SF in pillars

(Schneider et al. 2010)

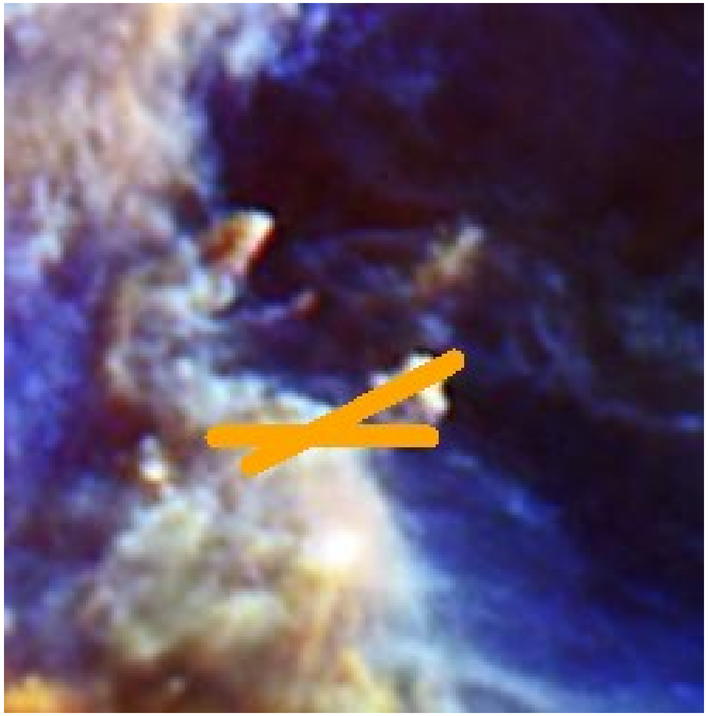


Rosette

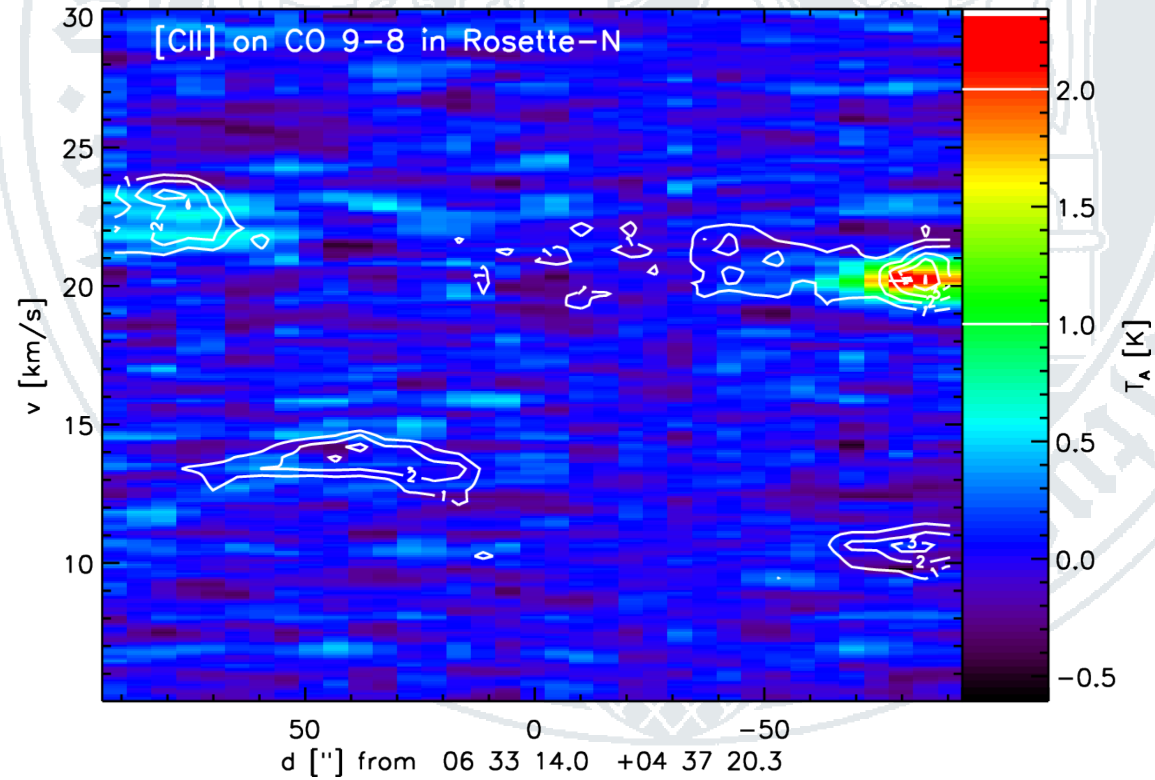
Region 1+2 - cuts through pillars to trace velocity structure:

- **Position-velocity diagrams**

2 interfaces:



[CII] (contour) on CO 9-8 (color)

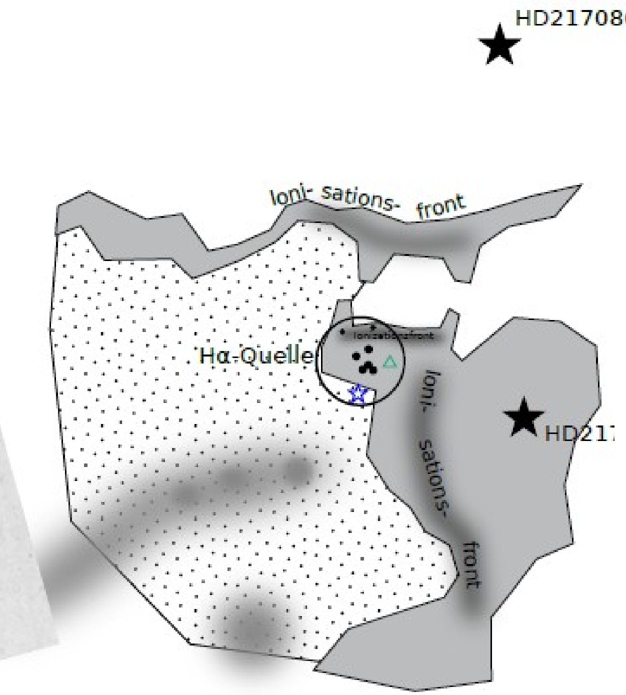


2 separate velocity components, i.e. 4 instead of 2 surfaces

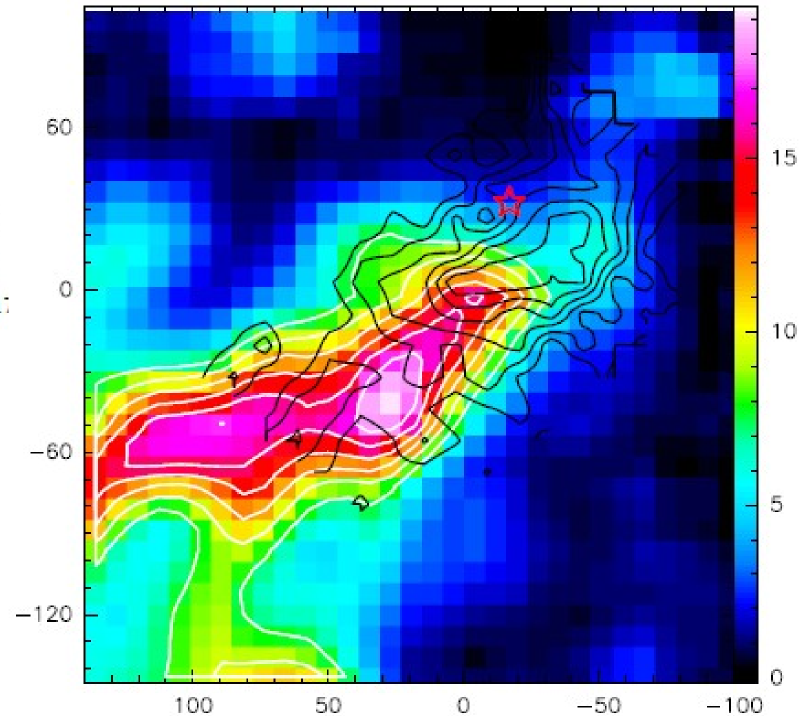
- CO only from dense gas
- No detection of a systematic flow

Example 2: Cep B

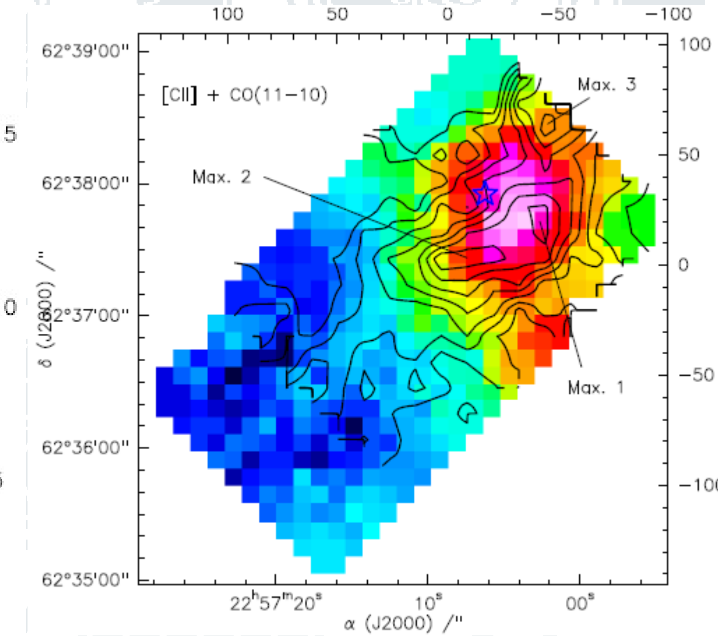
SOFIA observations:



(Moreno-Corral et al. 1993)



CO 11-10 (black contours) over ^{13}CO 1-0 (colors)
(Mookerjea et al. 2012)



CO 11-10 (black contours) over [CII] (colors)

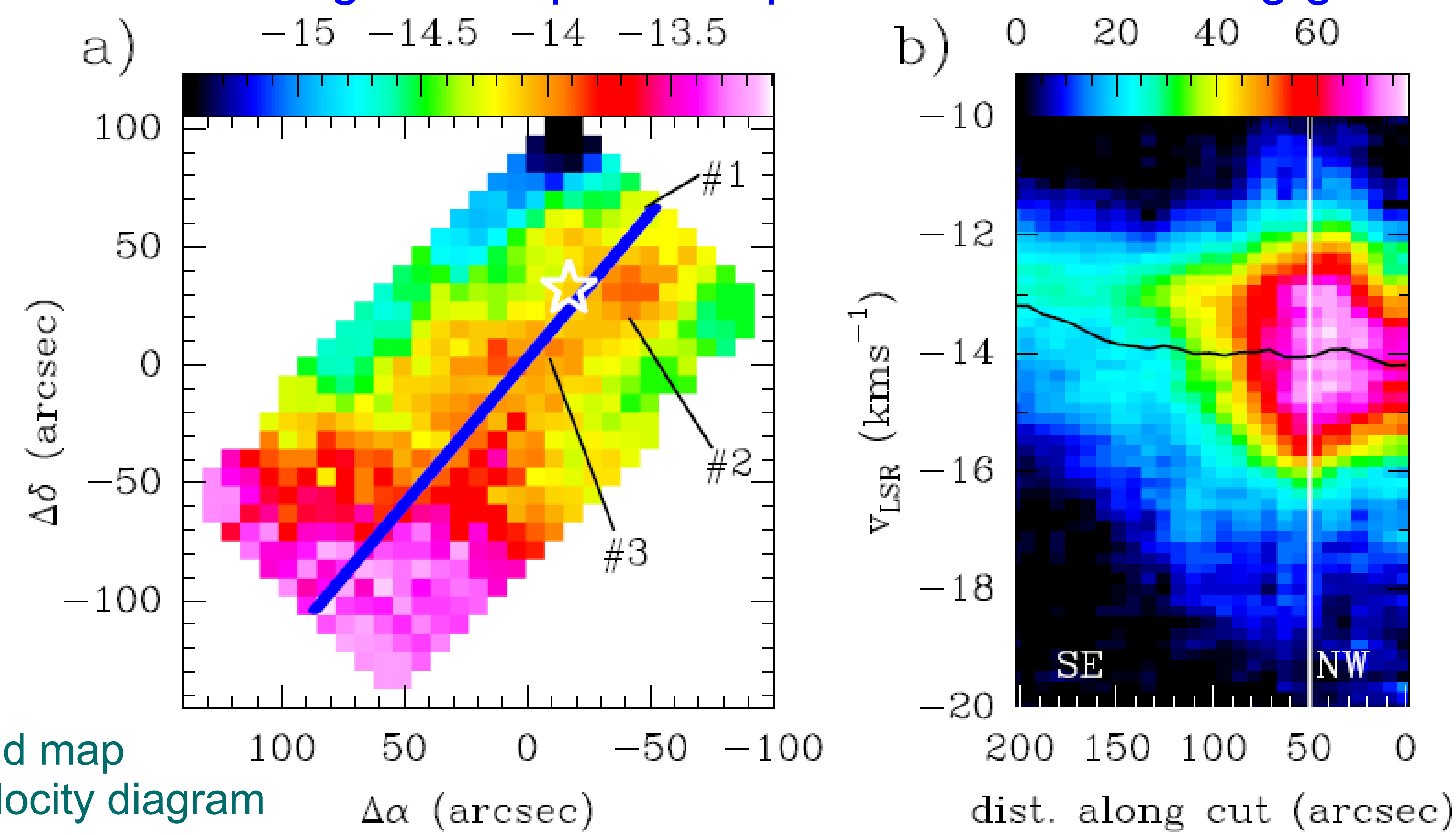
Embedded UC-HII-region • heats surrounding gas

• induces photon-dominated chemistry → trigger of SF?

Example: Cep B

Does the embedded HII-region compress/disperse the surrounding gas?

→ Study velocity structure

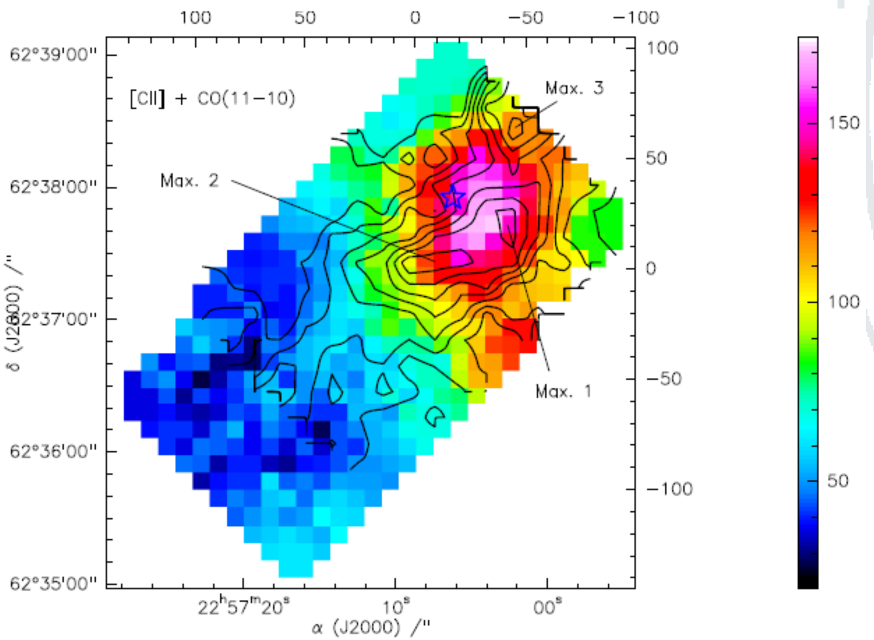


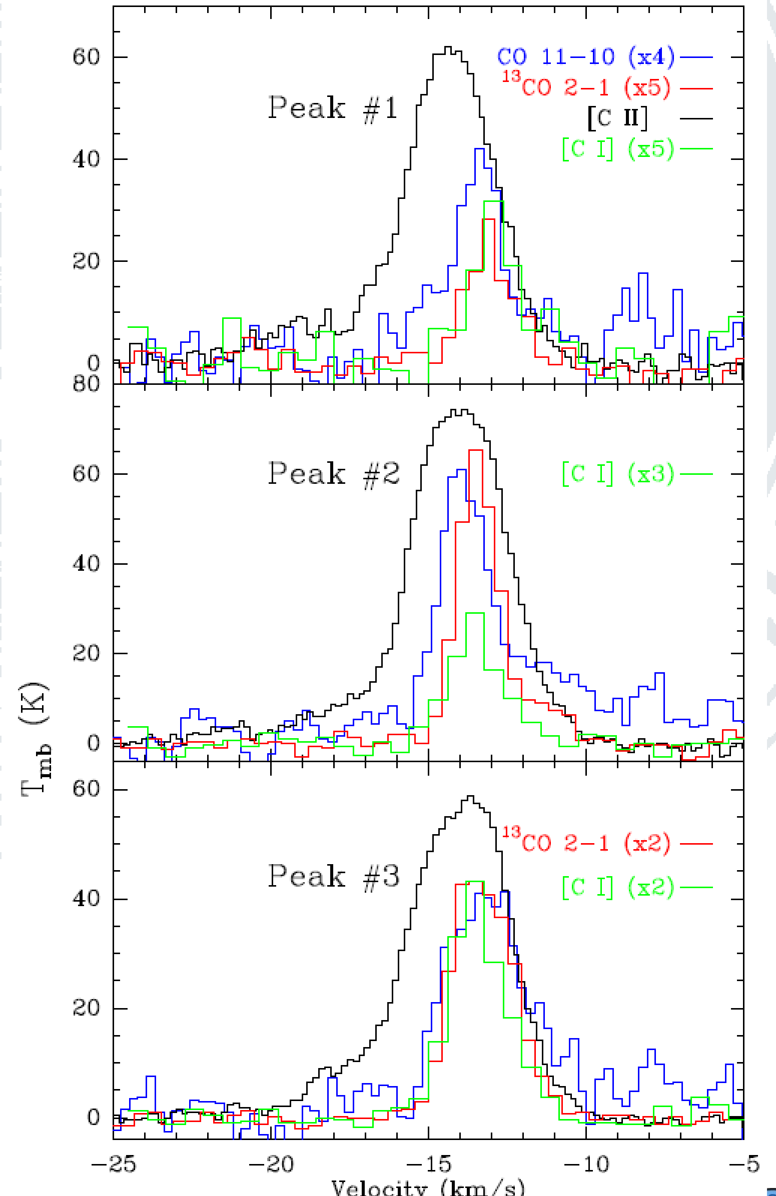
[CII] line centroid map and position-velocity diagram

- Global velocity gradient changed around HII region
- No large-scale impact

Example: Cep B

Velocity structure:





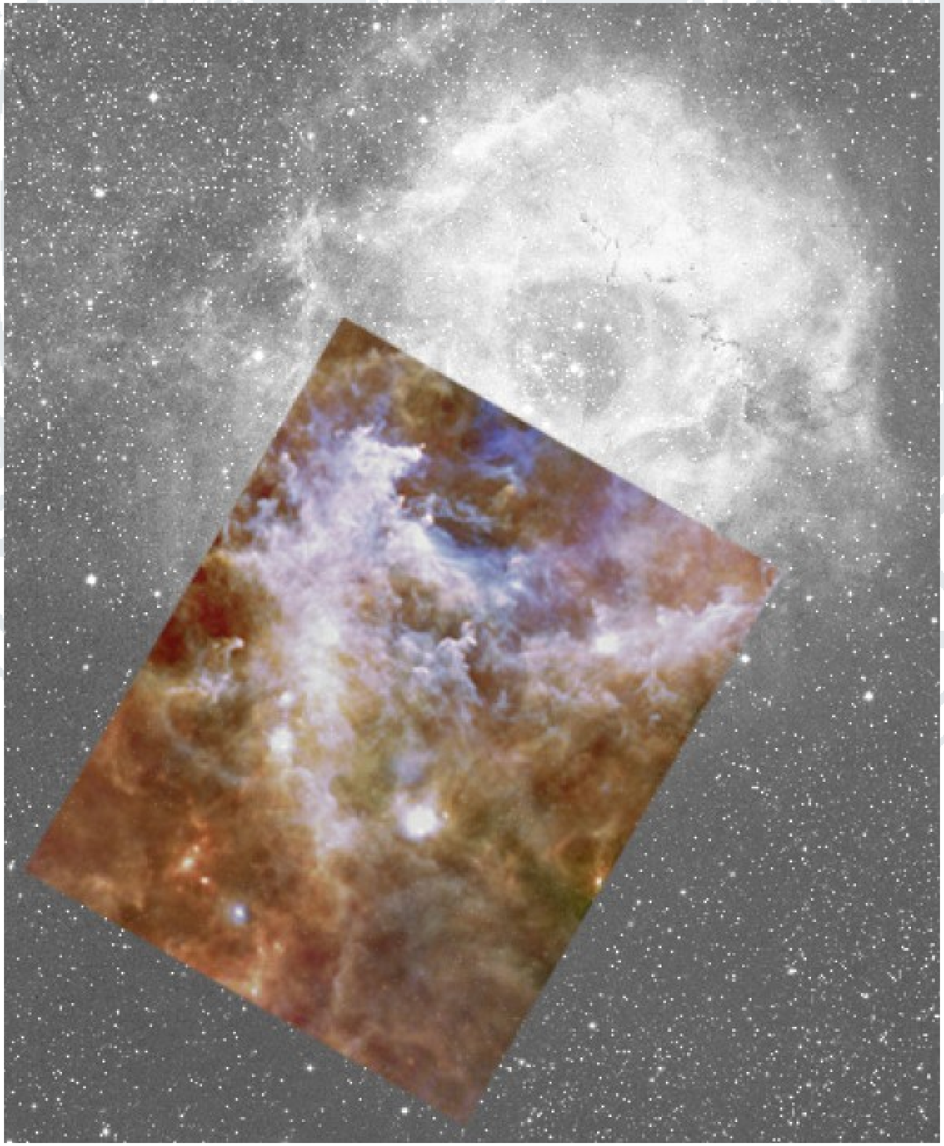
- Blue wing only in [CII]
- Ablating wind from S155 external HII region
- Dense gas **not** affected by radiation

Statistical approach

Is there more star-formation at high radiation fields?

➔ How to trace the spatial distribution of star-formation?

- ➔ Look for high densities
  - ➔ Column density PDFs
- ➔ Look for small structures
  - ➔ Δ-variance
- ➔ Infall/outflow signatures
  - ➔ Velocity structure analysis

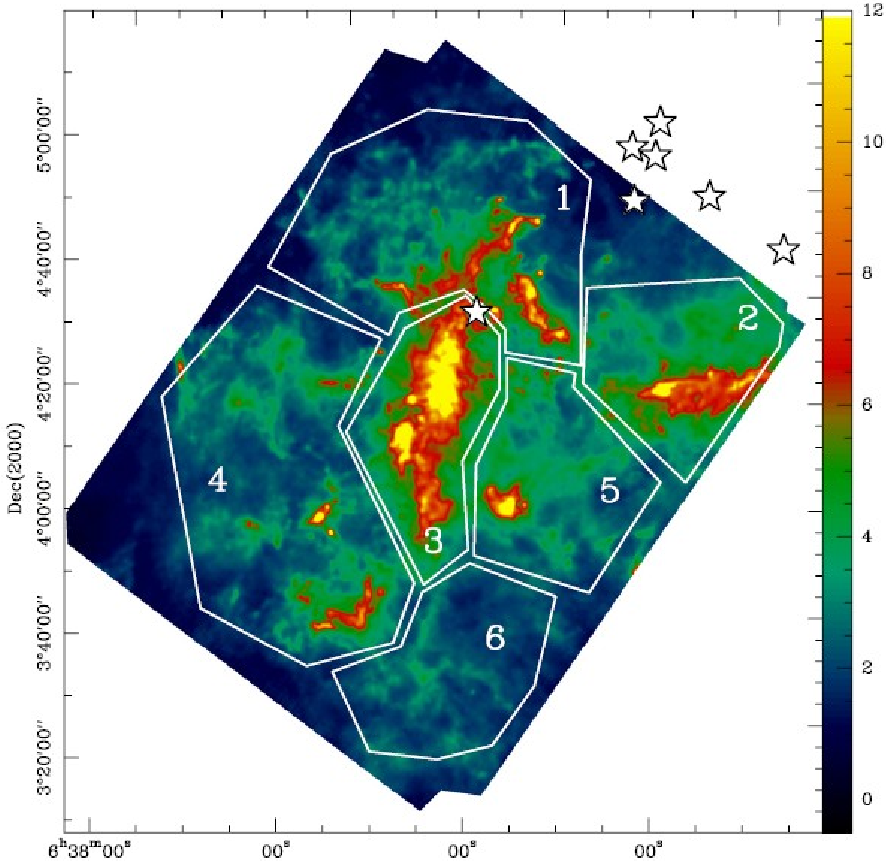


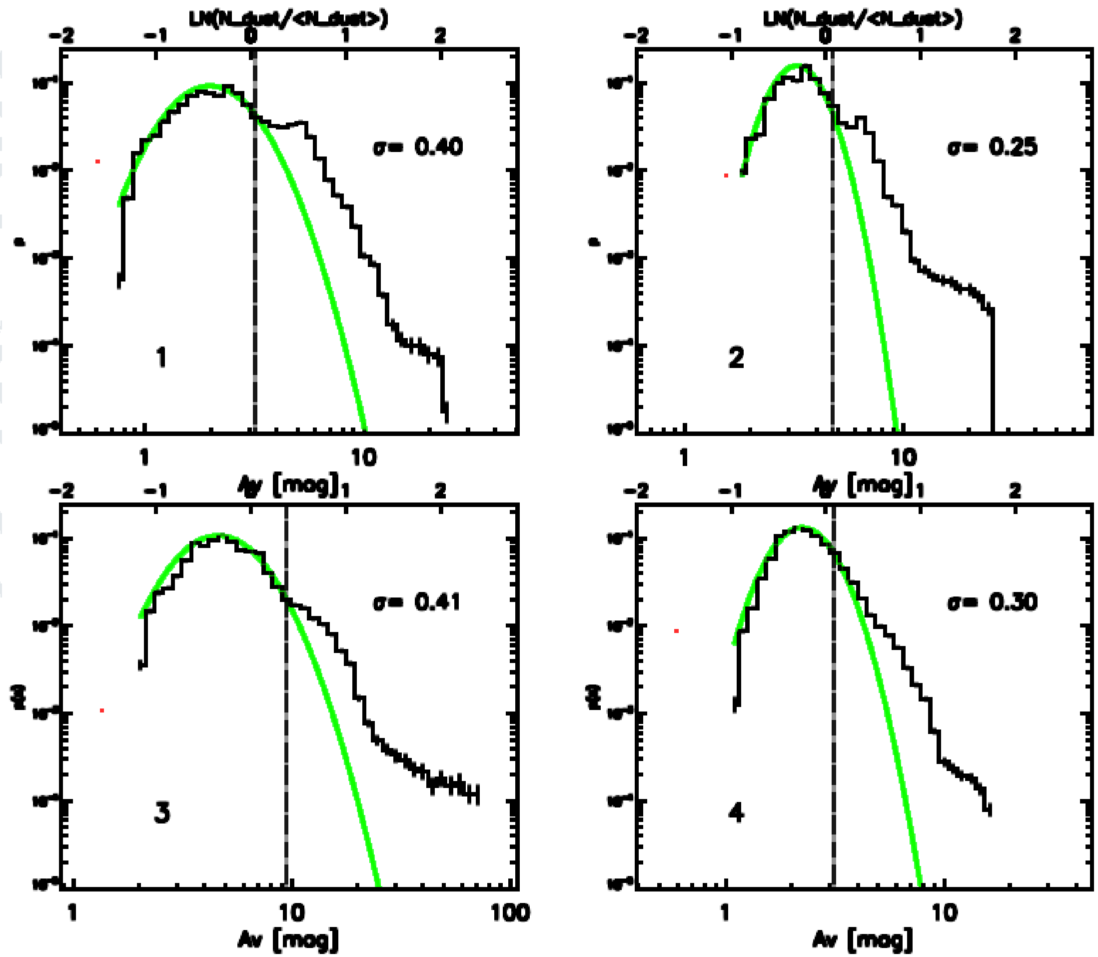
Rosette:

Extinction map from Herschel observations
(Motte et al. 2010, Schneider et al. 2011)

Column density PDFs

Rosette:





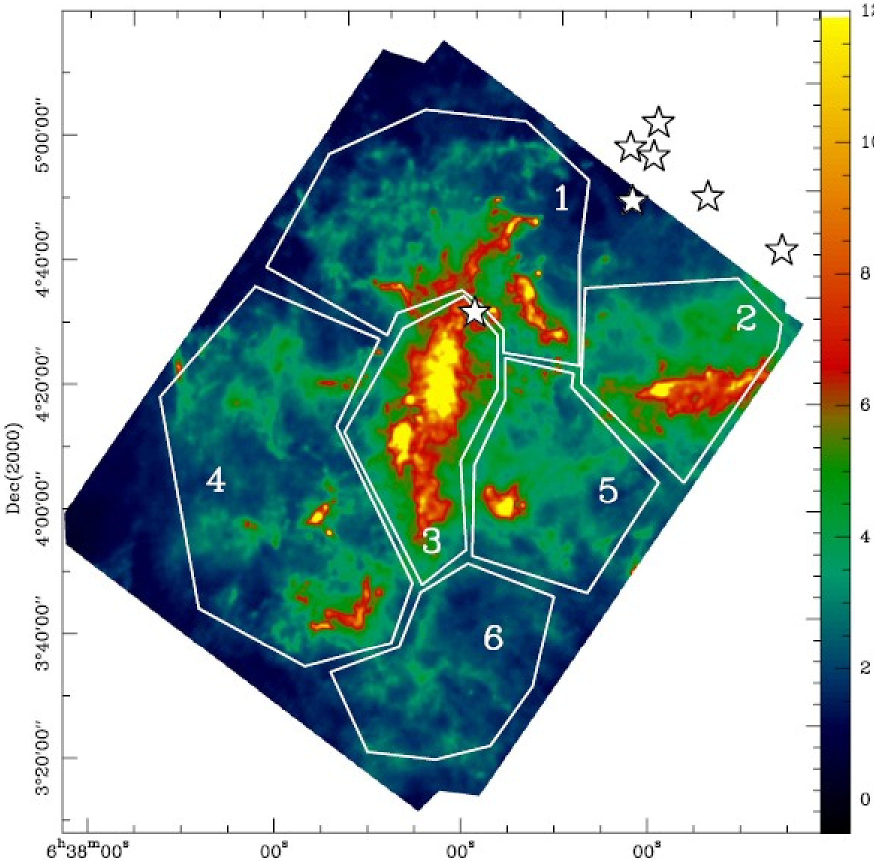
(Schneider et al. 2011)

High column density excess from gravitational collapse

- strongest in center region (3),
- weaker in PDR regions (1) and (2)

Analysis of significant scales

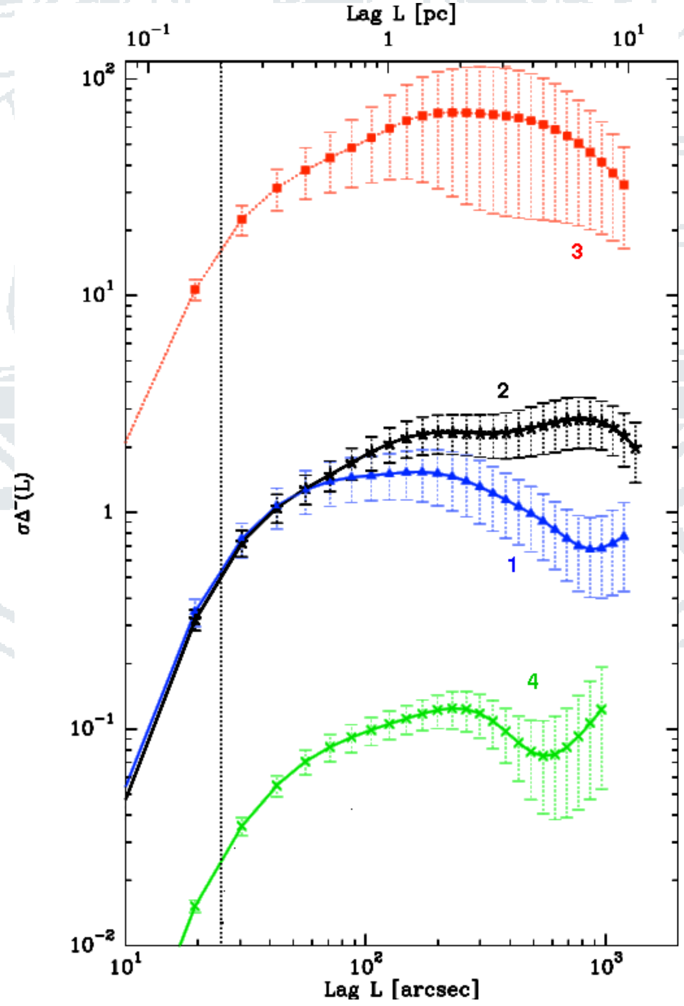
Column densities in Rosette:



(Schneider et al. 2011)

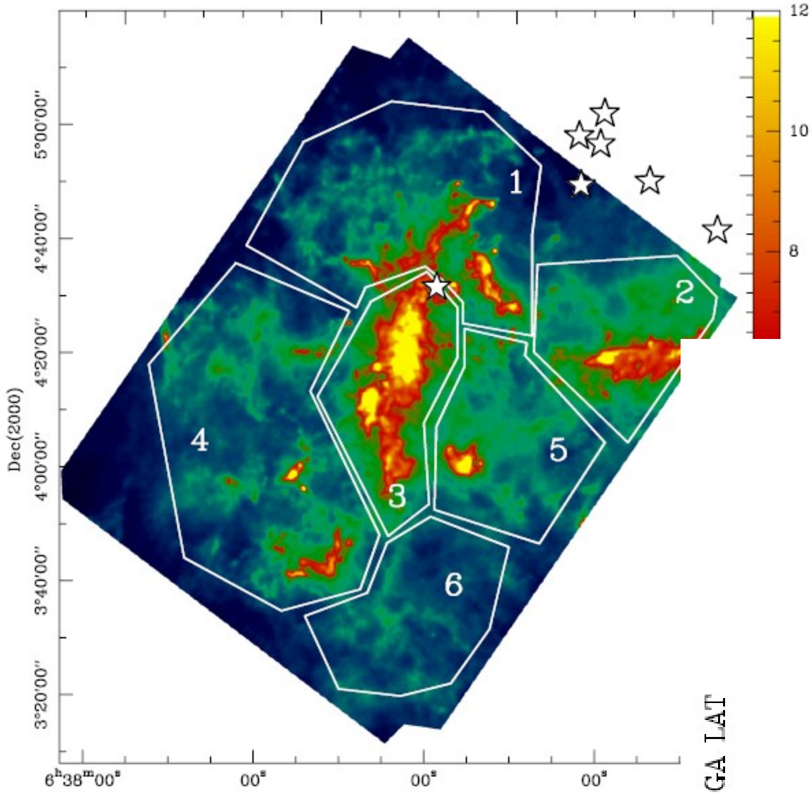
Δ-variance spectra:

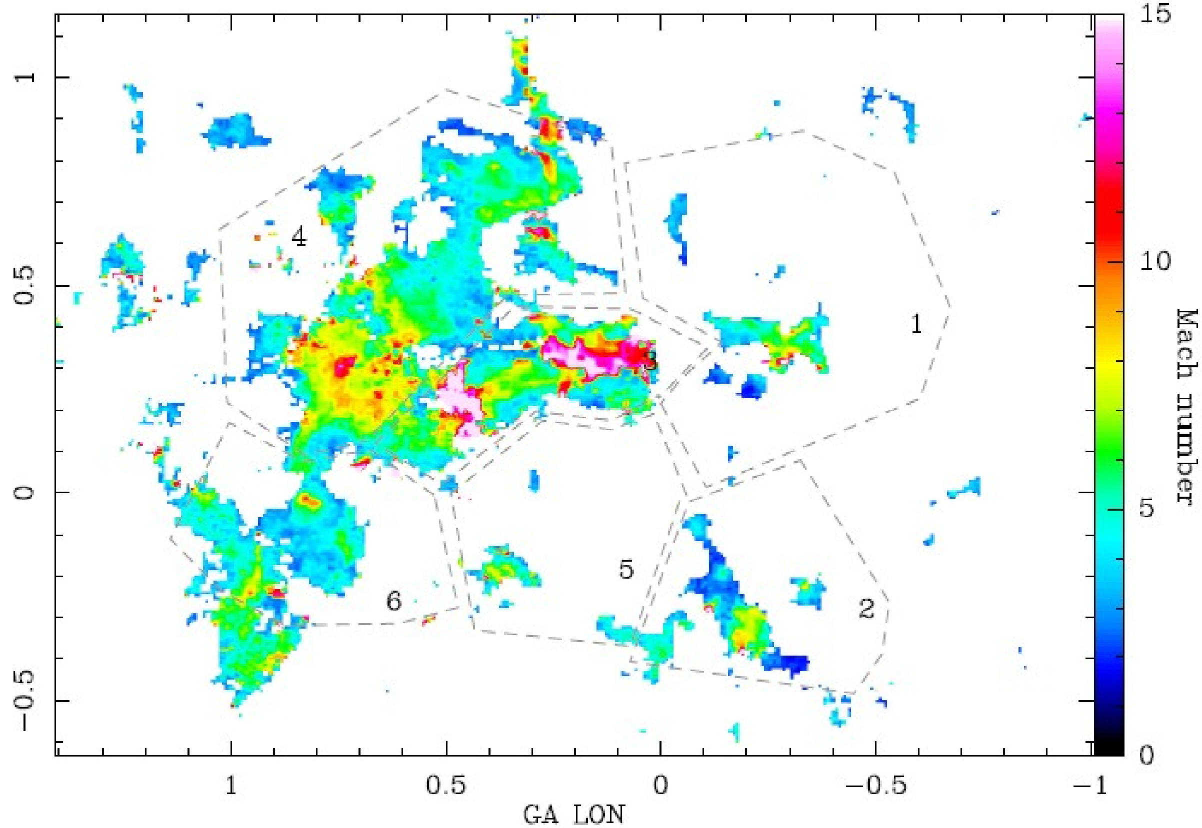
- Gravitational collapse enhances small-scale structures



- Main ridge in center forms dominant structure
- No small-scale enhancement at PDR interfaces

The velocity structure





Mach number derived from local velocity dispersion (Csengeri et al. 2013)

- Very localized line broadening at PDR surface
  - Affects little gas volume
- Main line broadening from ongoing SF activity in center region

Summary

- The layering of species in PDRs is quantitatively understood
- Pressure jump at the surface confirmed
  - But no detection of radiative core compression
- UV creates local heating and streams
  - Low-density gas is dynamically affected by UV radiation
  - But no large-scale collapse
  - Significant dispersion of gas
- Triggered SF around HII regions only in favourable conditions
  - Pillar formation rarely means star-formation triggering

- **Statistically, we find no significant radiative triggering of star-formation on global scales.**

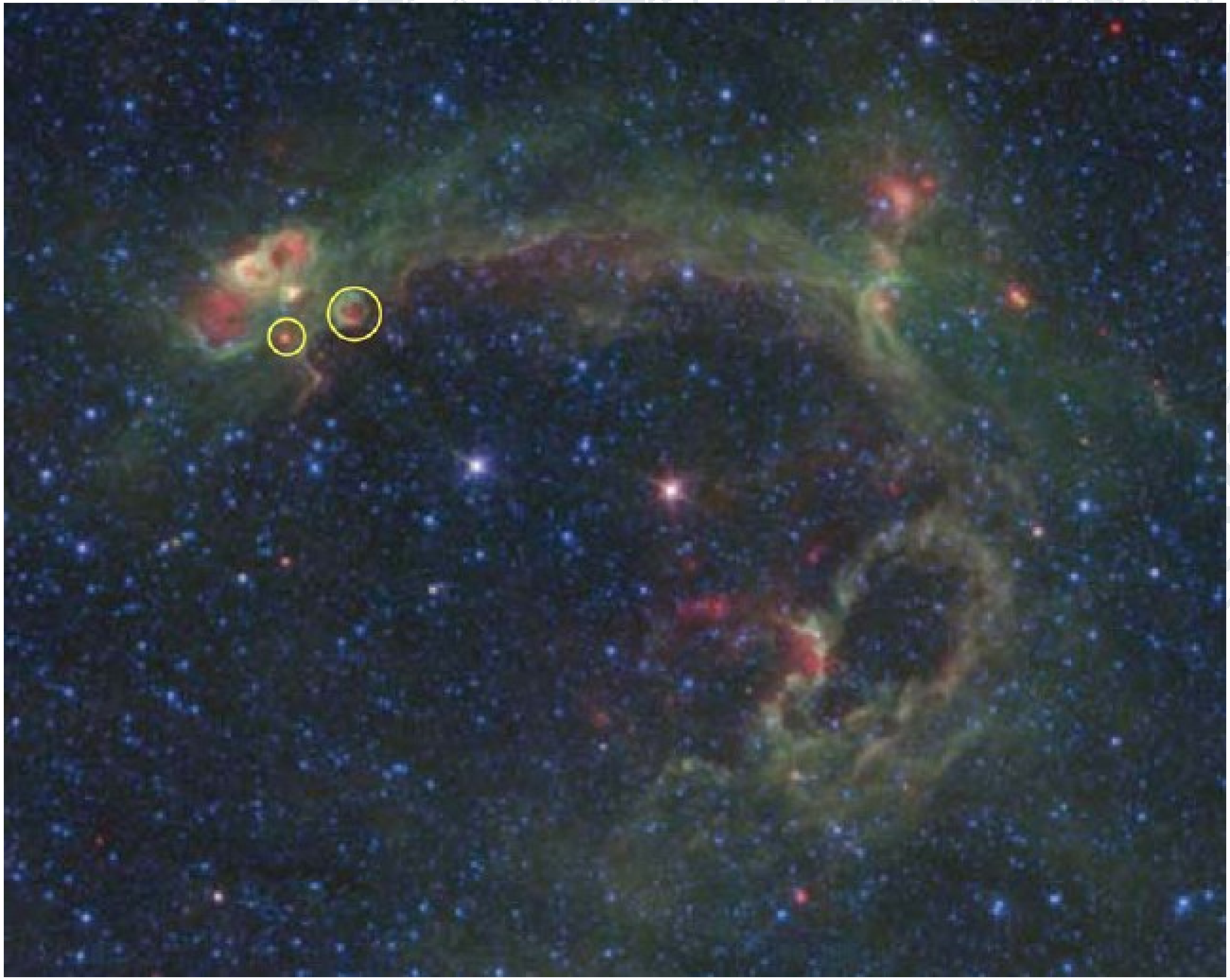
- In contrast, sequential star formation is common.
  - Natural outcome of filament formation in titled colliding flows

Appendices

Observational evidence

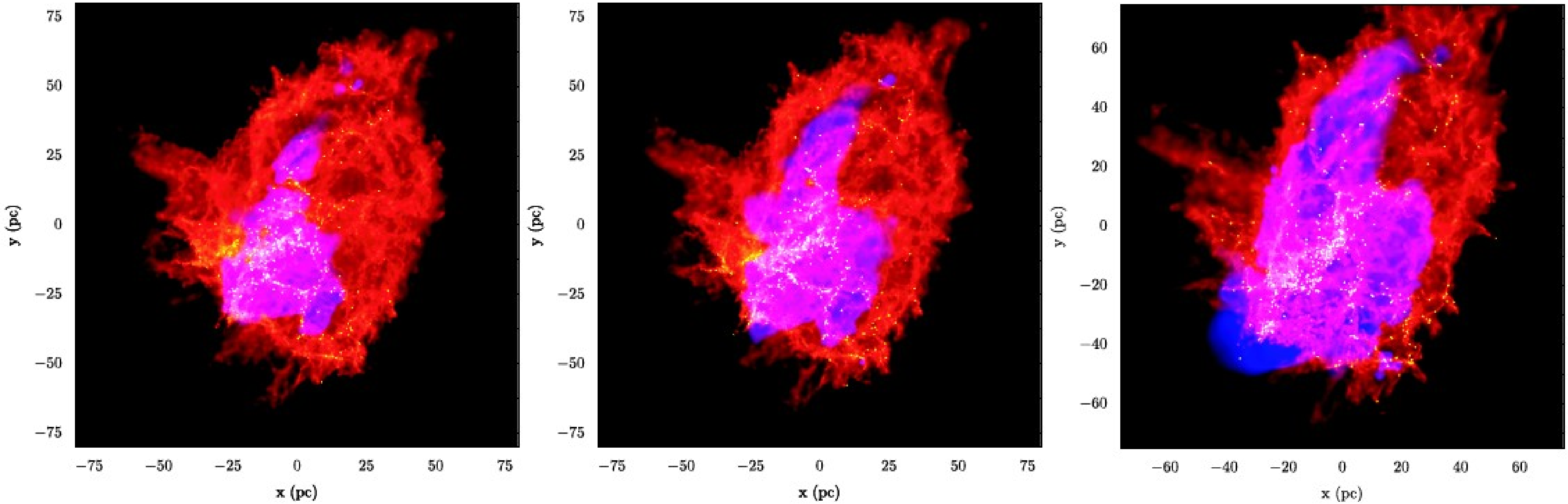
Star-formation around "Spitzer bubbles":

- YSOs at the rim of UV-illuminated "PAH rings"



N109 (Thompson et al. 2012)

Is the process statistically significant?



Simulation of density evolution in SPH model:

- Neutral material (red), ionized (blue)
- 3 steps: 0.66 Ma, 1.08 Ma, 2.18 Ma

Dale & Bonnell (2006)

Radiative impact → slightly enhanced dispersion

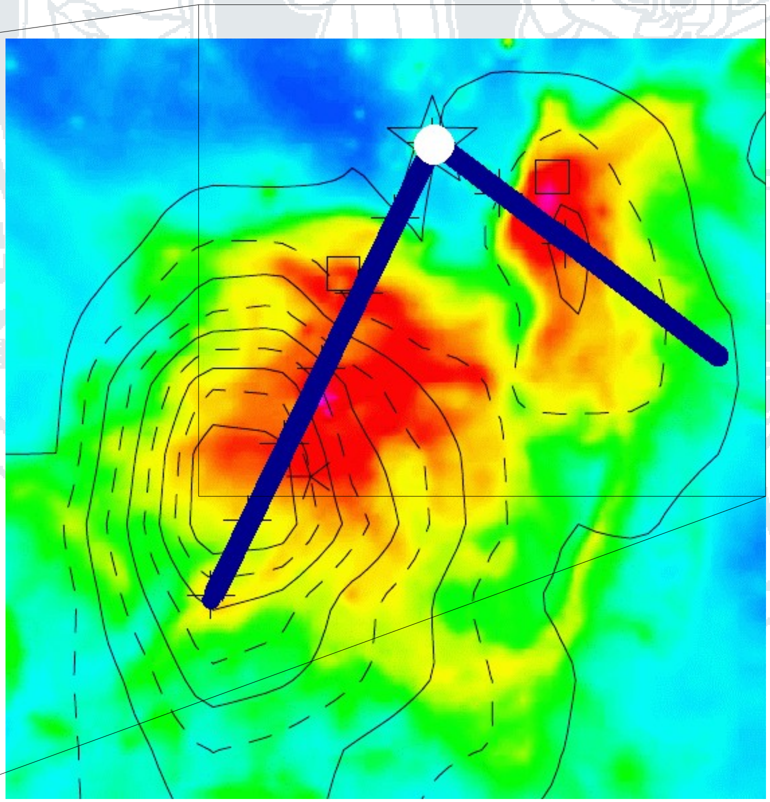
But:

- Resolution insufficient
- Chemistry neglected

Example 2: NGC3603

- Position-velocity cuts across the PDR interfaces

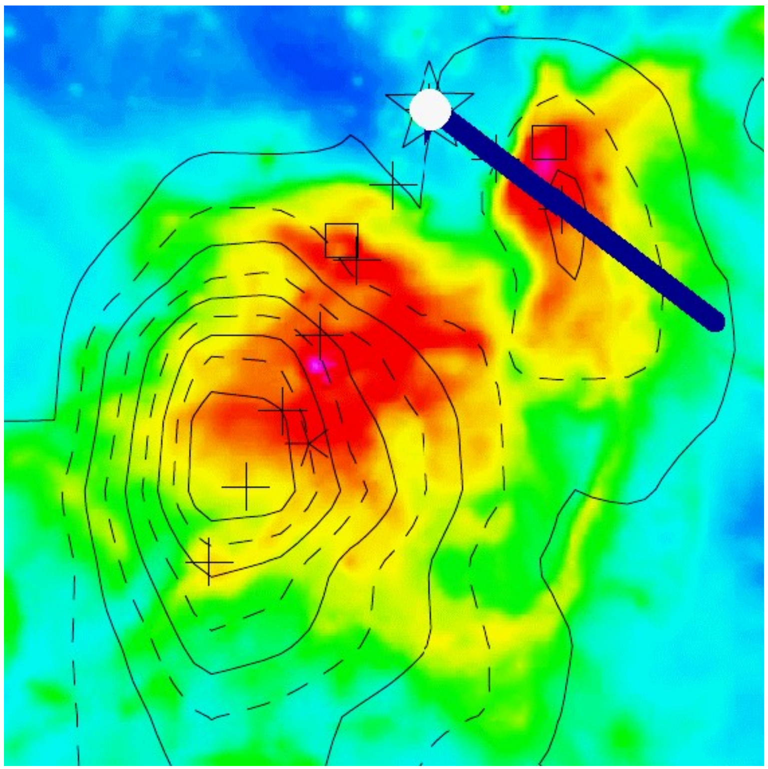
Pillars at PDR fronts (HST, Brandner et al. 2000)



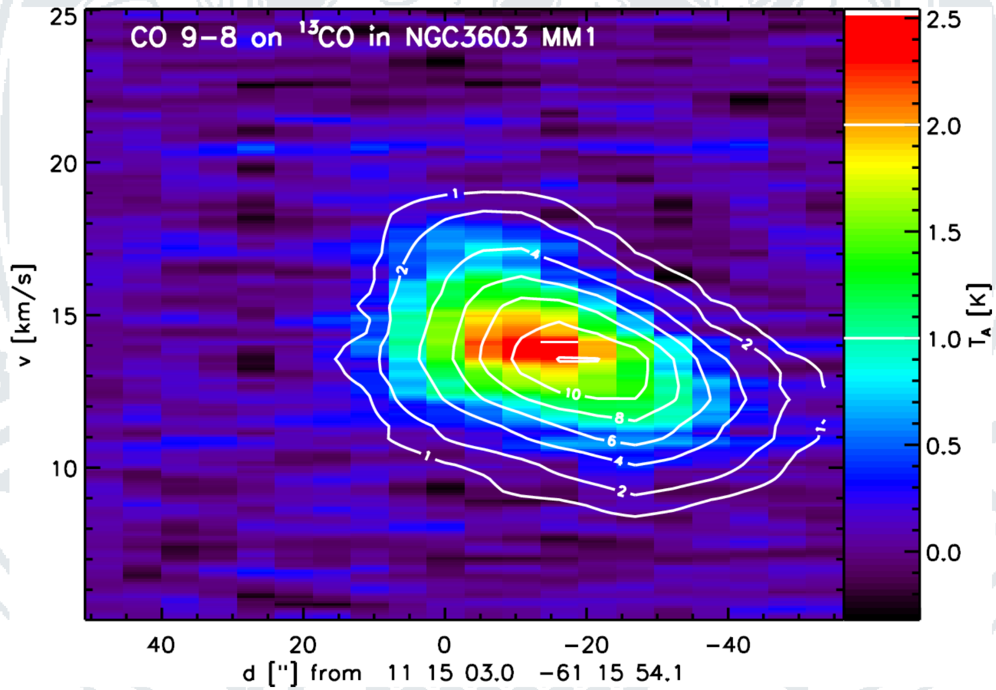
Observed cuts overlaid on Spitzer 8µm (color) and CO 4-3 (contours)

NGC3603 MM1

Velocity structure from p-v diagrams:



Observed cuts in NGC3603 overlaid on Spitzer 8µm



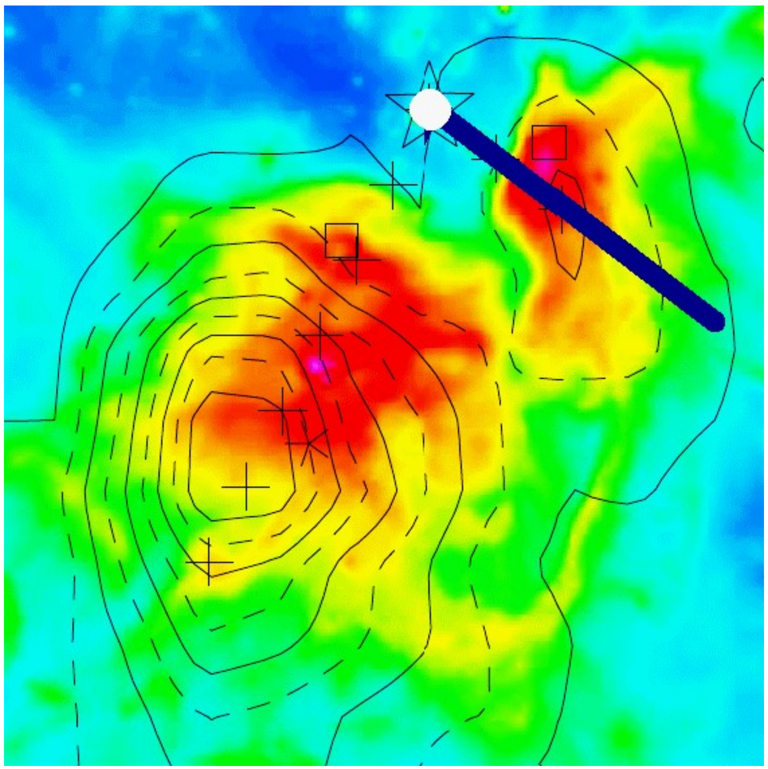
p-v diagram: ^{13}CO 10-9 (colors) + CO 9-8 (contours).

Velocity gradient across the core

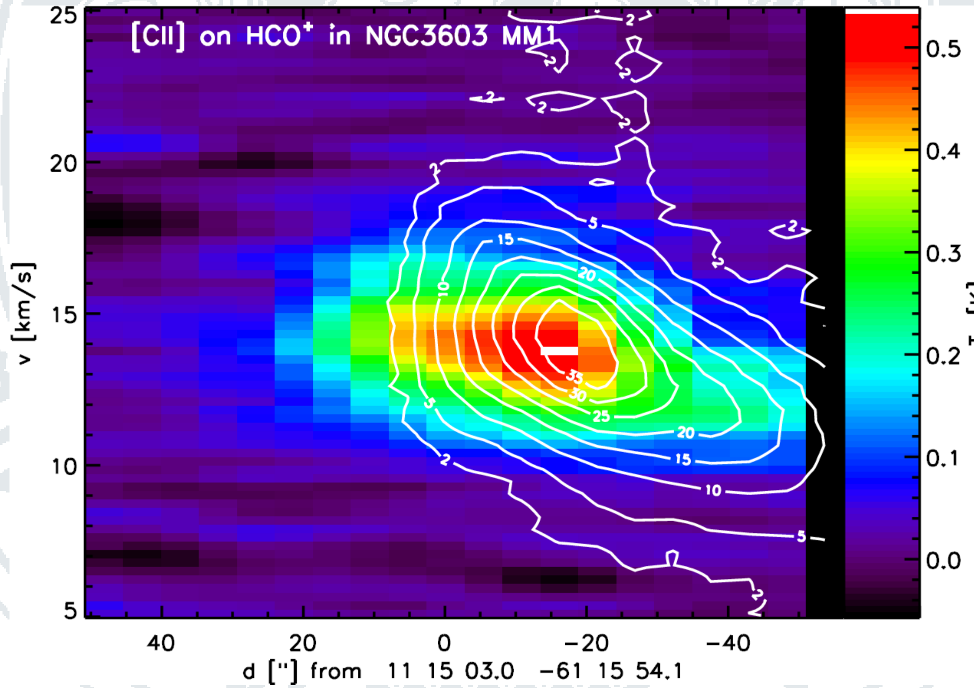
- Compression ?
- Dispersion ?
- Rotation ?

NGC3603 MM1

Velocity structure from p-v diagrams:



Observed cuts in NGC3603 overlaid on Spitzer 8µm



p-v diagram: HCO^+ 6-5 (colors) + [CII] (contours).

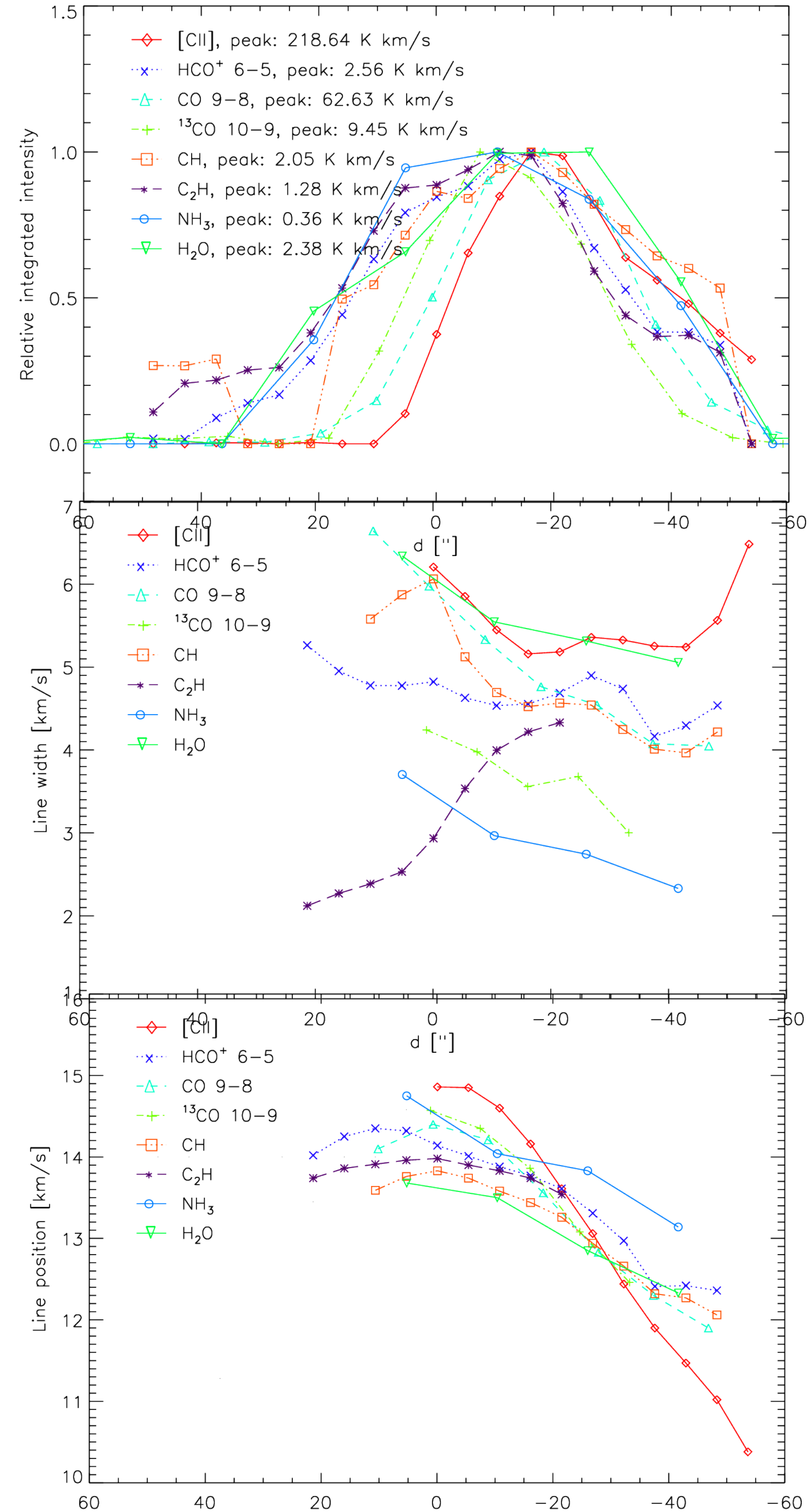
- All lines broadened towards UV source
  - pressure gradient confirmed
- [CII] shows a long turbulent tail of material “behind” the core

NGC3603 MM1

- Chemical layering partially inverted!
  - [CII] peaks deeper in the core than CO and ^{13}CO
- [CII] is red-shifted relative to molecular tracers at interface
- Stronger velocity gradient in [CII] than in molecules

→ C^+ must be blown from the surface into a clumpy medium

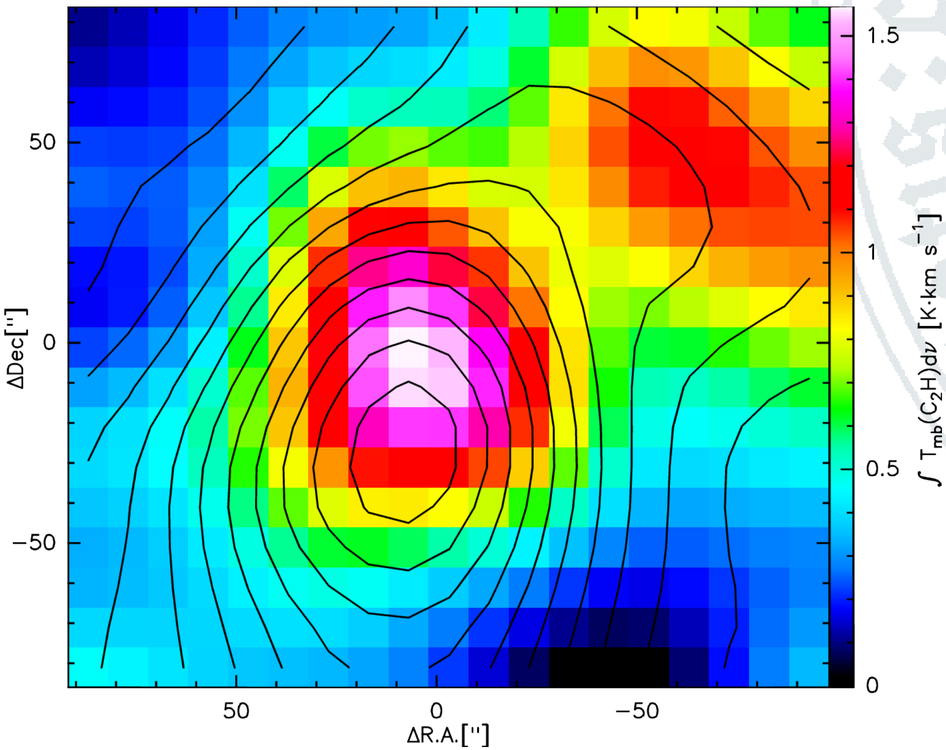
- Redshifted profiles → affected material sits behind the cluster
- The 4km/s gradient along the core measures compression!
  - Triggered SF?



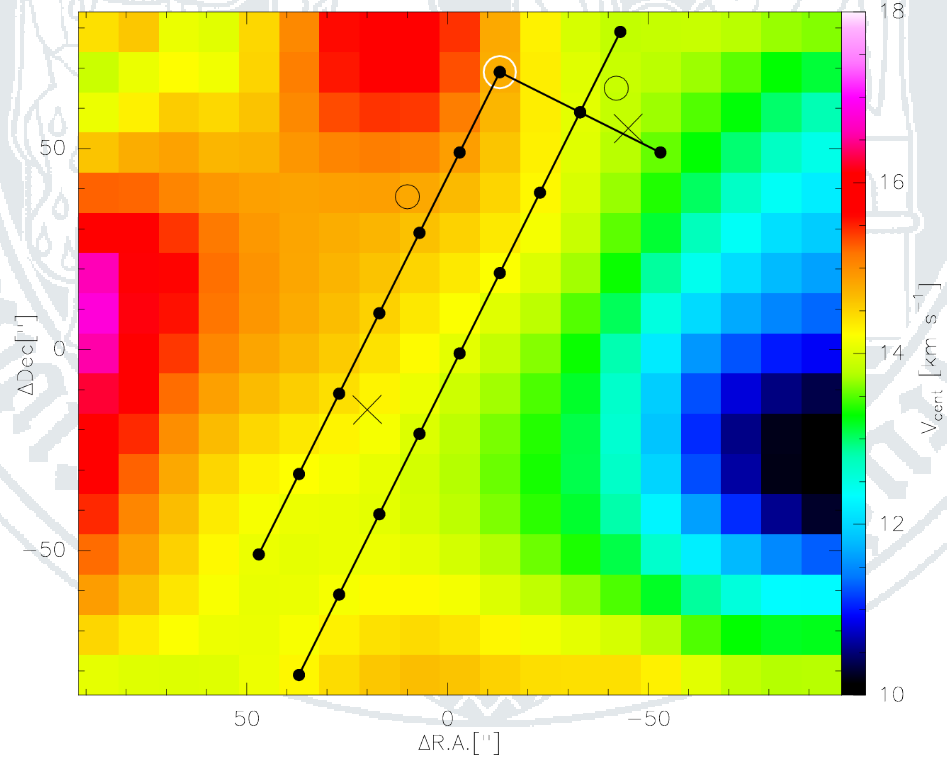
New full mapping observations:

But …

Gradient is not radially symmetric around stellar cluster!



Integrated line intensities of C2H (colors), CH (contours)



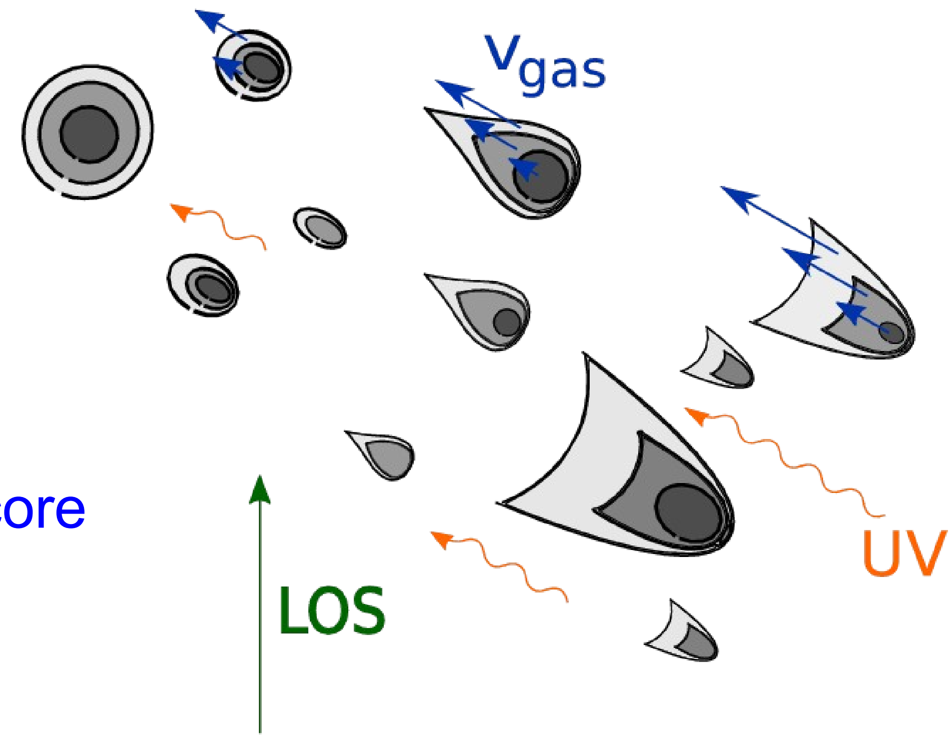
CH line centroid map

→ probably rather large scale systematic shear

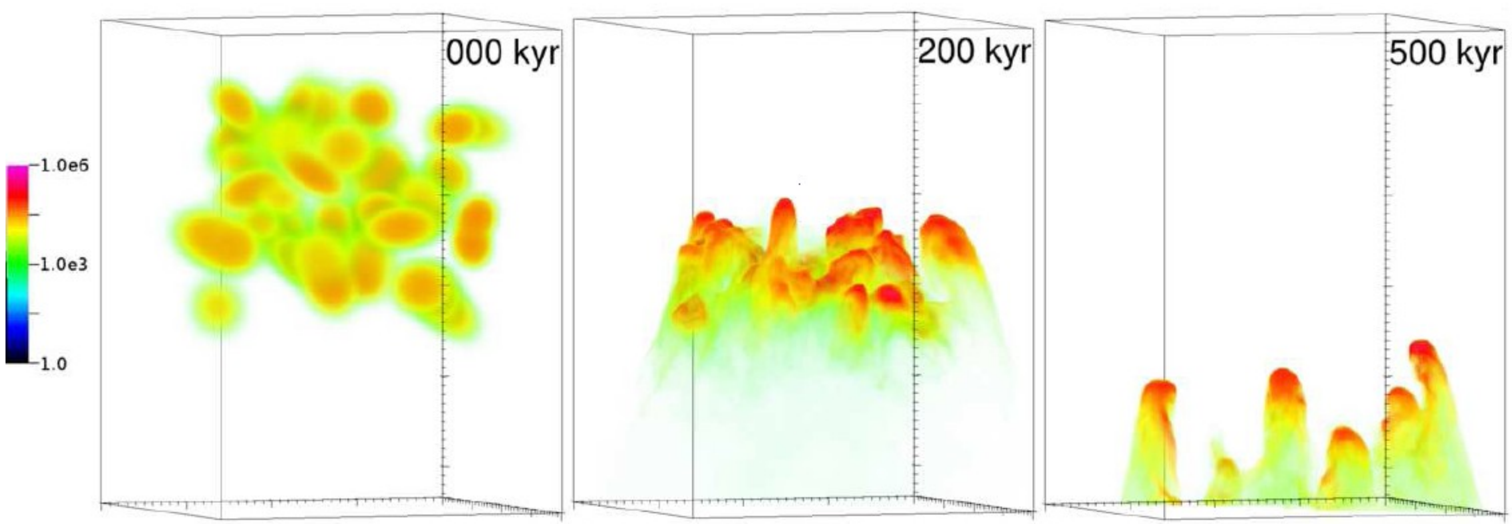
- **Again no holy grail**

Interpretation

- Clumps → cometary clumps
- Evaporation flow towards cluster suppressed
- Material is "blown" into the cloud
- Compression and dispersion of the core



Compare: Mackey & Lim (MNRAS 2011)



→ **Pillar formation**

Driving mechanism

- Comparison to radiation pressure:

$\rightarrow \quad \chi = 2 \times 10^{4} \chi_{D} \qquad a_{rad} = 3.2 \times 10^{17} \frac{\mathrm{km/s}}{\mathrm{a}} \times \frac{\mathrm{cm}^{-2}}{N}$

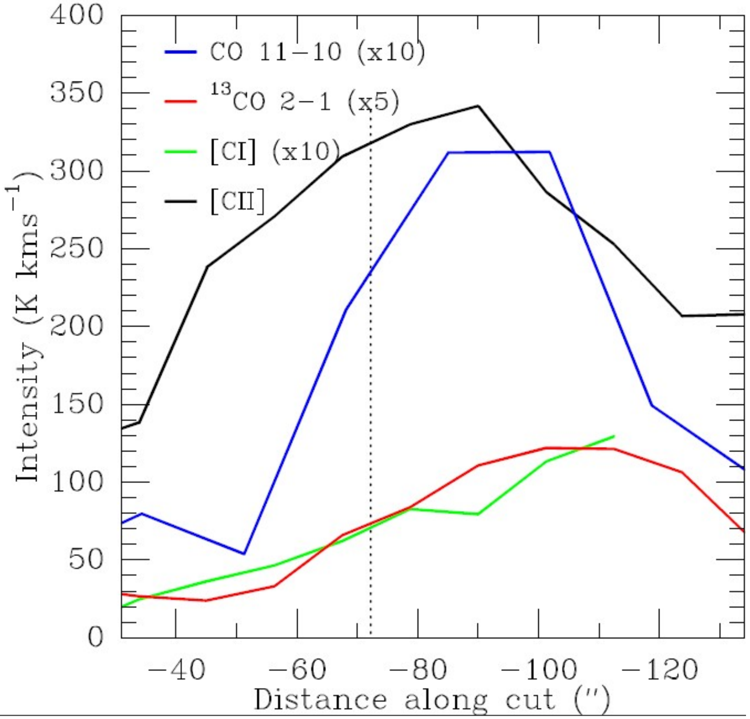
$\rightarrow \quad N = \frac{700\, M_{O}}{\pi\, (0.4\mathrm{pc})^{2}} = 1.7 \times 10^{23}\,\mathrm{cm}^{-2} \qquad v = 20\,\mathrm{km/s}$ after 1Ma

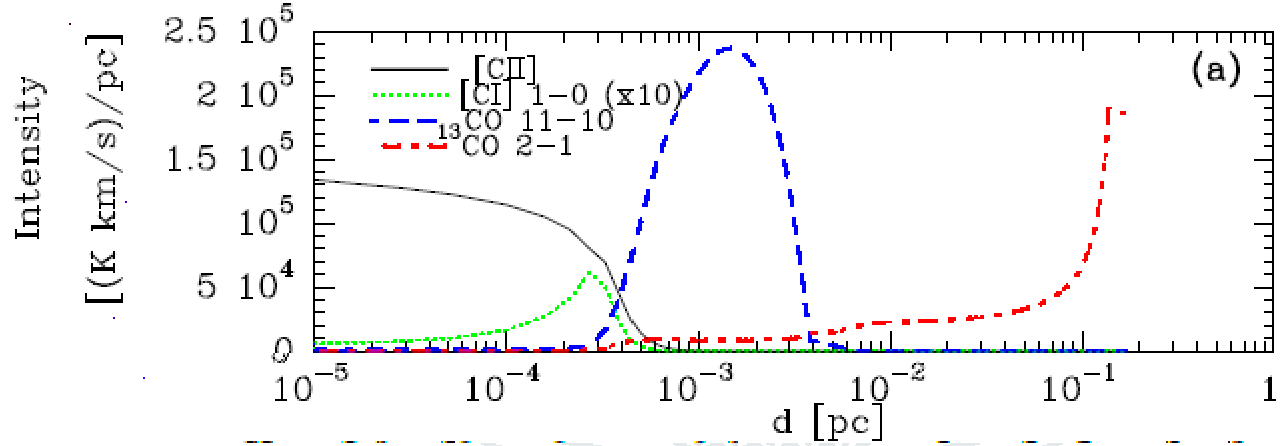
- Additional momentum must have dispersed more gas that is no longer present in the core
- Other pressure contributions only add up

- Signs of evaporation flows hidden in compression pattern

Example: Cep B

From PDR models, we expect a stratified chemical structure with C^+ and first hydrides at the surface, hot CO and atomic carbon at intermediate layers and cold CO and complex molecules deeper in the cloud.

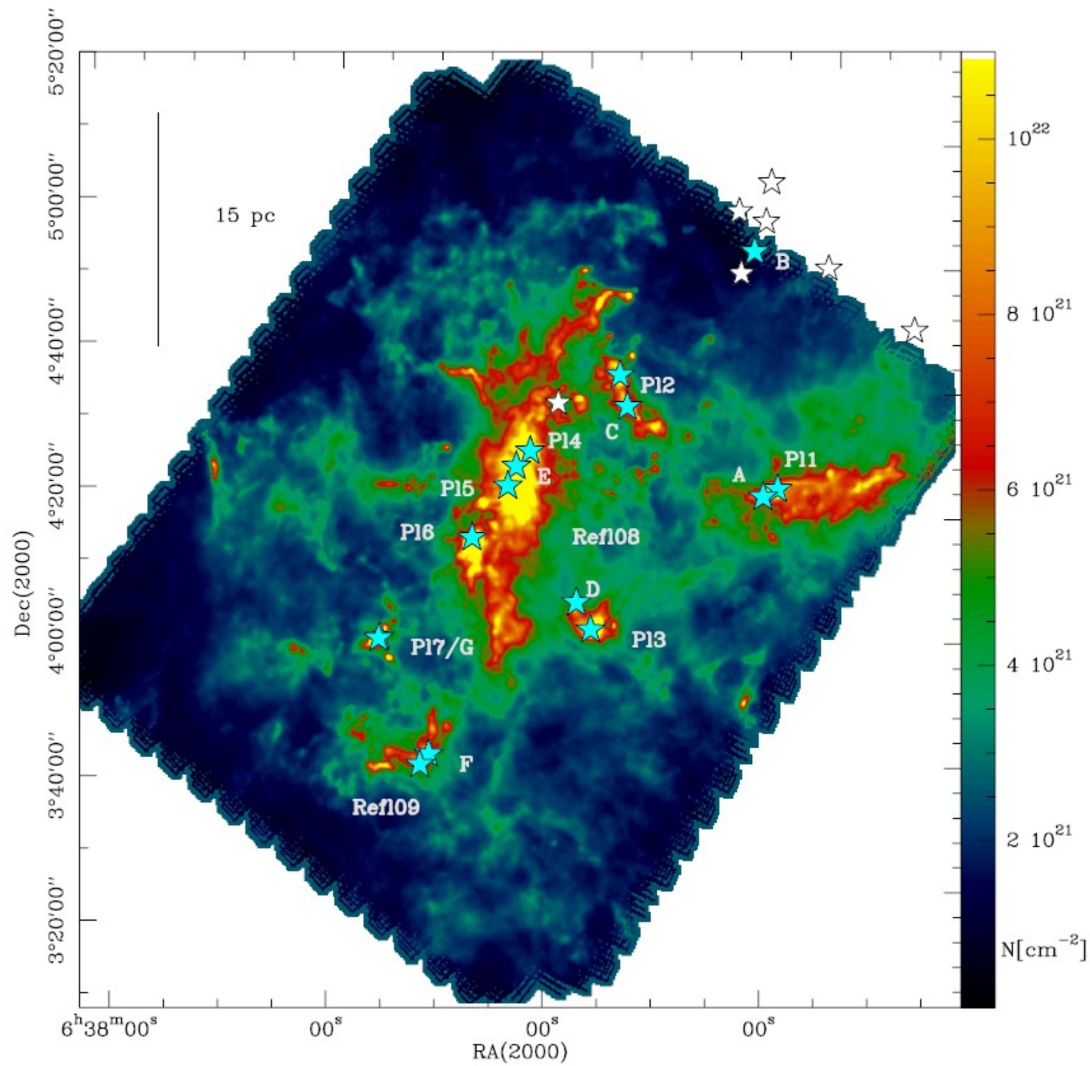




Comparison of observed chemical layering with PDR model.

Column density PDFs

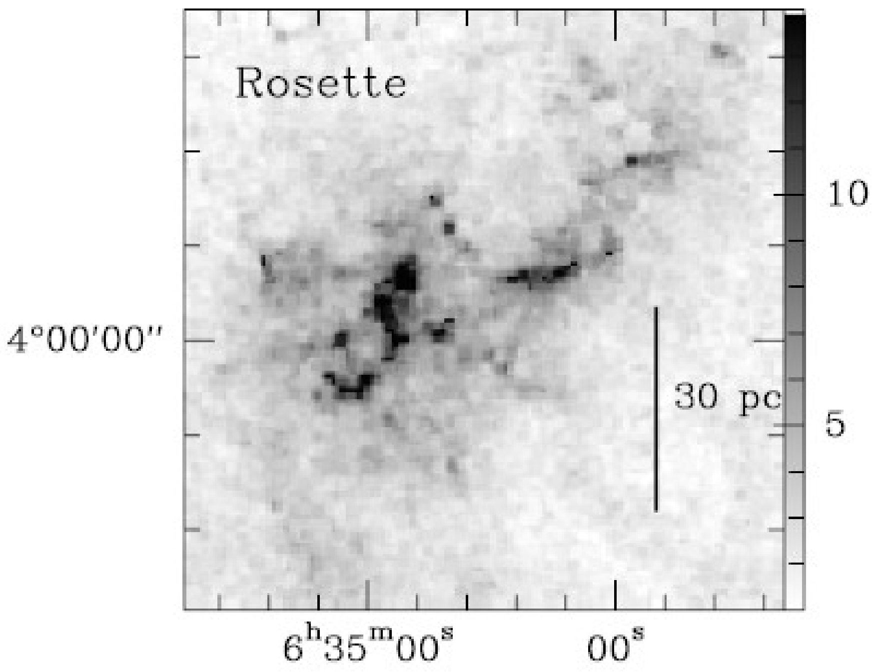
- High column density excess from gravitational collapse strongest in center region (3), not in PDR regions (1) and (2)
- Direct counting also confirms stronger SF in center.

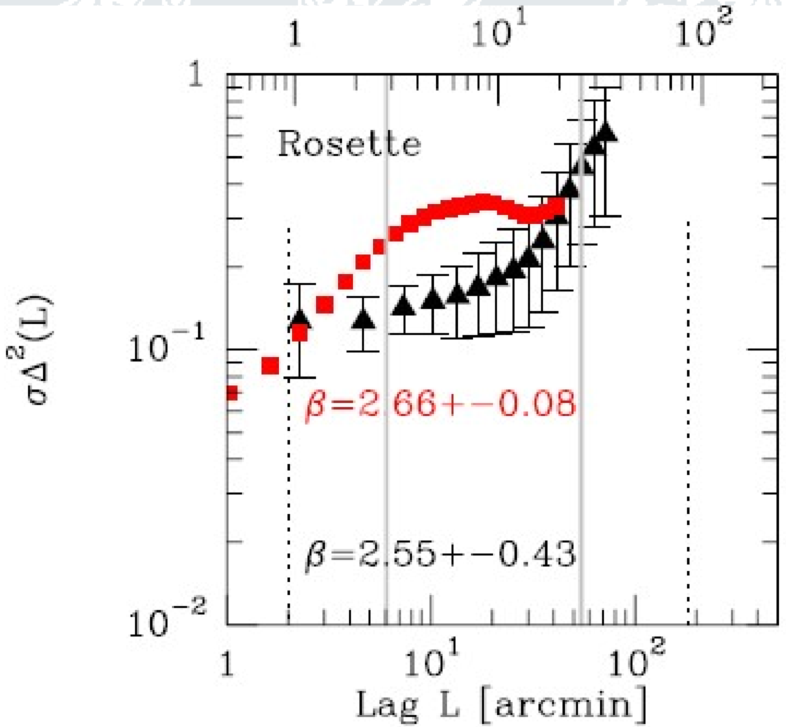


(Schneider et al. 2011)

Complication: Lines vs. continuum

Comparison of the dust extinction (2MASS) with the ^{13}CO 1-0 emission map:





- The dust distribution follows a self-similar relation up to the size of the whole region

→ Prominent scale in ^{13}CO due to

- Velocity structure?
- Chemical transition from atomic to molecular gas ?
- Line radiative transfer effects ?