The dynamics of photon-dominated regions (PDRs)

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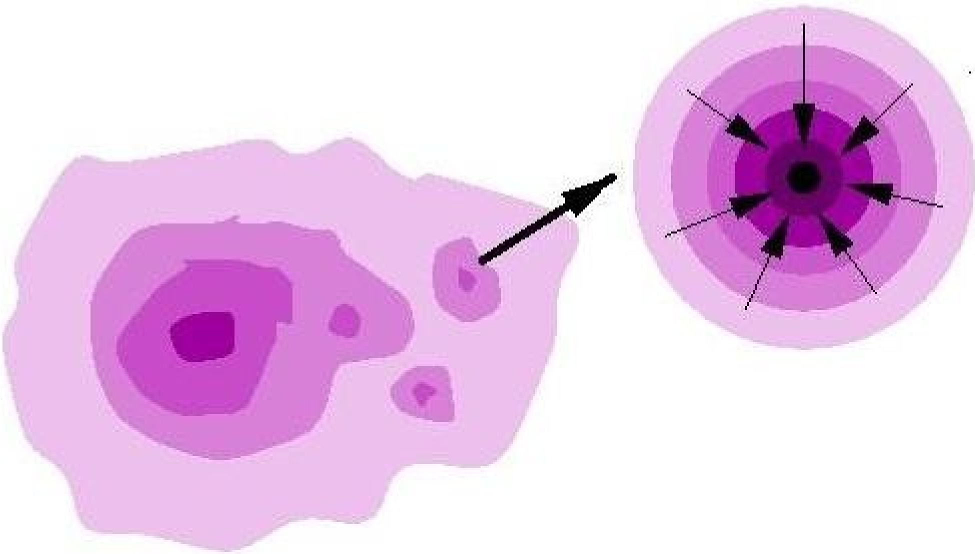
Main question: What happens here?

- Impact of winds and radiation from young stars on their environment?
  - density
  - temperature
  - velocity field

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

Do they **trigger** or **prevent** further star formation?

How is star-formation triggered?



Collapse of clumps in dense clouds

Jeans-criterion:

$$M > M_J = 2.1\, M_O \sqrt{\frac{T^3[K]}{n_H[cm^{-3}]}}$$

Hogerheijde et al. (1998)

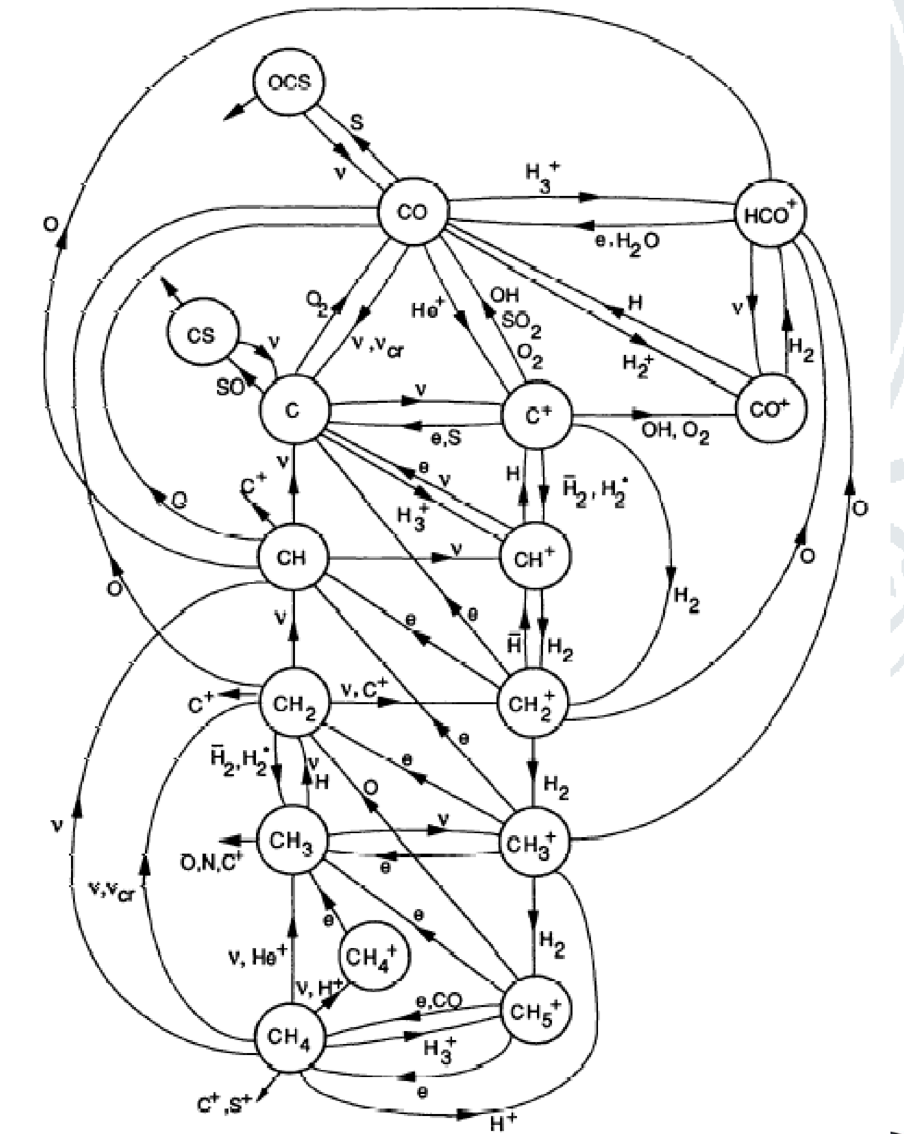
- Temperature counts
  - Determined by heating and cooling processes → Chemistry

Chemistry

The chemical network

- Reactions driven by UV photons
  - → **Photon-dominated regions (PDRs)**

- Solution of the network provides abundance of cooling and heating agents
  - Main cooling: C^+, O, CO, H_2, dust
  - Main heating: PAHs, small dust grains



Carbon network (Sternberg & Dalgarno 1995)

Is star-formation triggered?

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

- UV radiation heats the gas
  - ➔ temperature increase
    → prevents SF

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

➔ Science topics:
- ➔ **chemistry,**
- ➔ **energy balance,**
- ➔ **dynamics.**

of the interaction regions

Overview

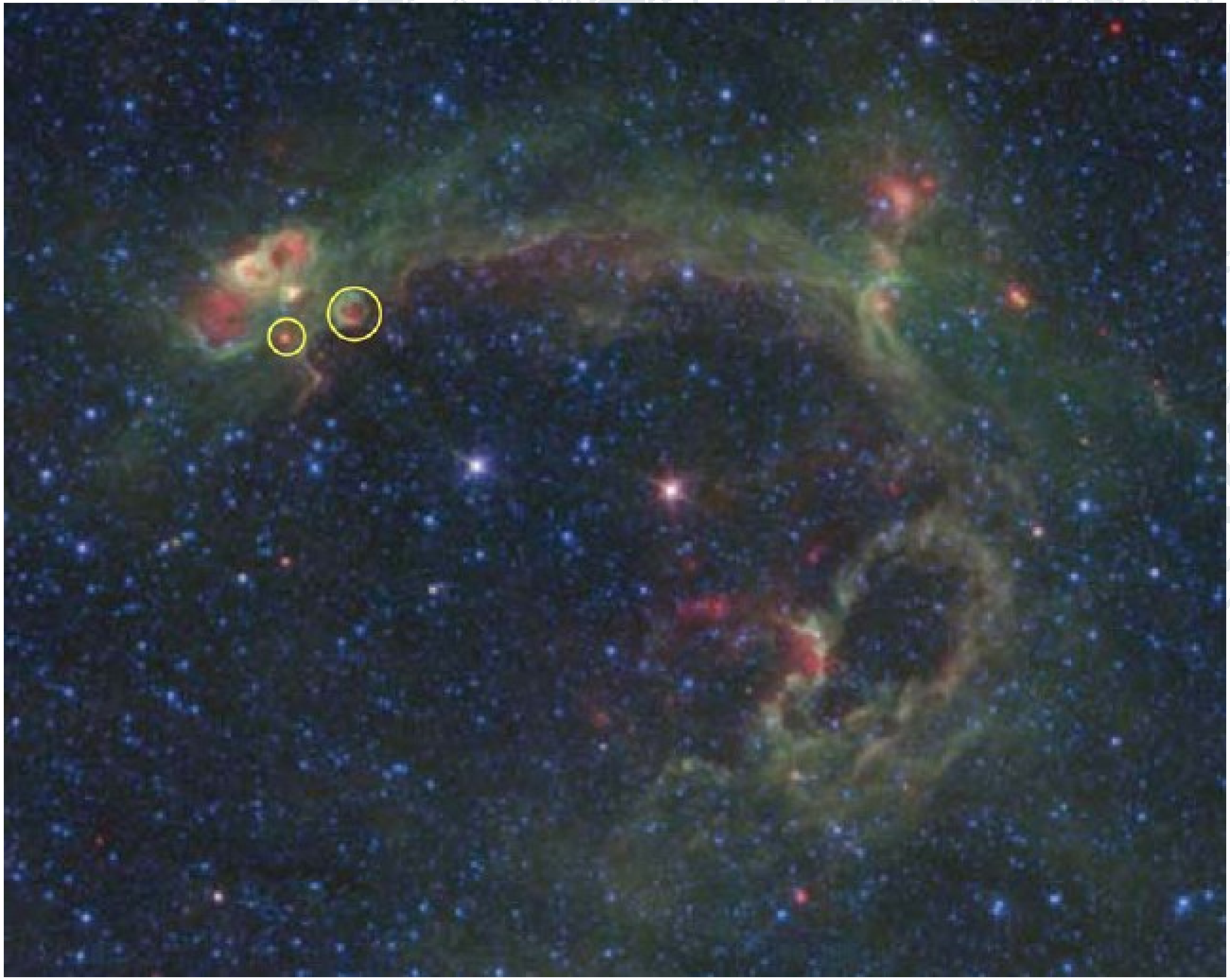
- Arguments for induced SF
  - Observational evidence: Sequential Star-formation
  - Theory: What do we expect?

- Verification
  - Induced collapse in individual sources?
    - Observation of velocity structures
  - Globally significant triggered star-formation?
    - Statistics of SF activity depending on radiative interaction

Observational evidence

Star-formation around “Spitzer bubbles”:

- YSOs at the rim of UV-illuminated “PAH rings”

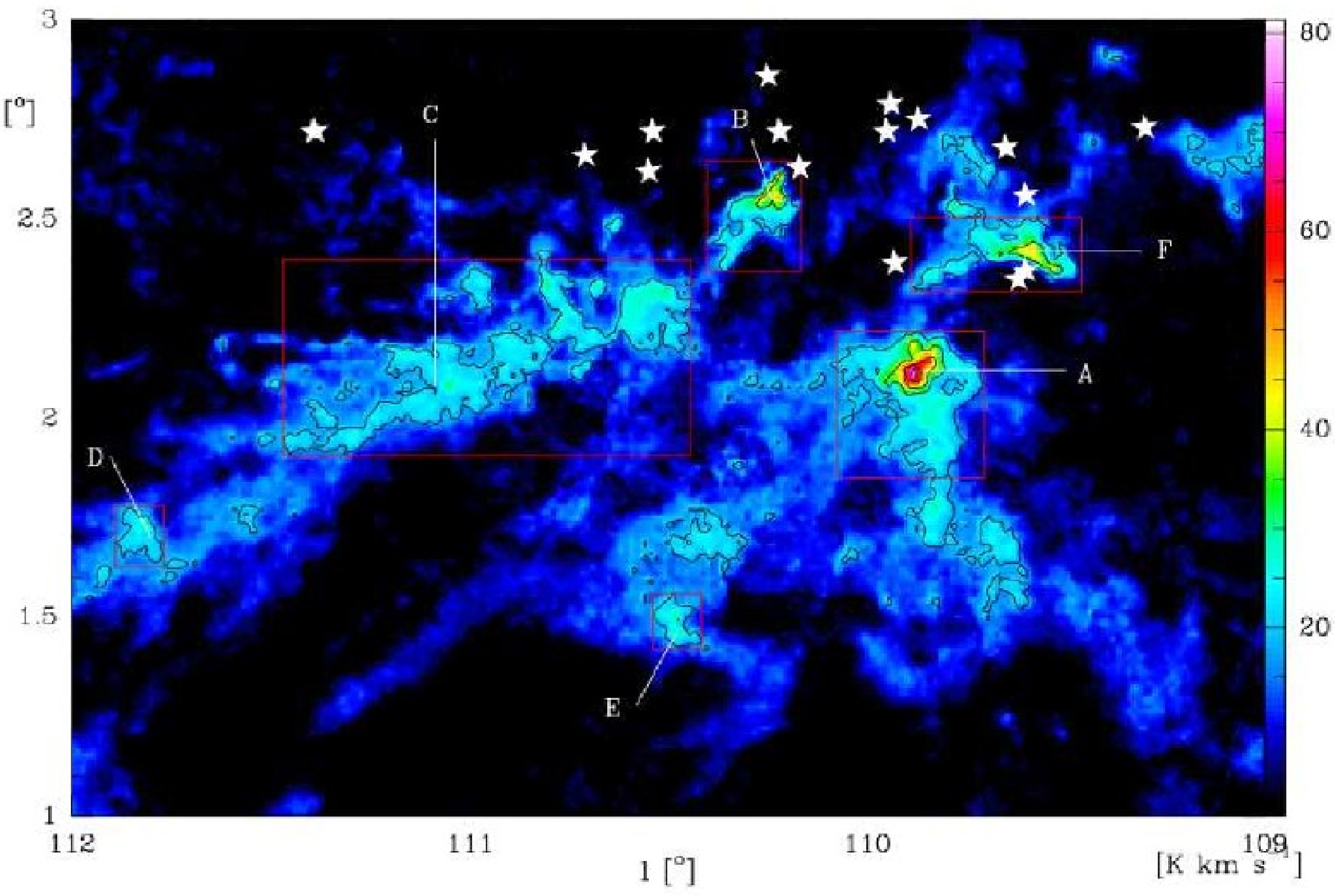


N109 (Thompson et al. 2012)

Observational evidence

Sequential star formation:

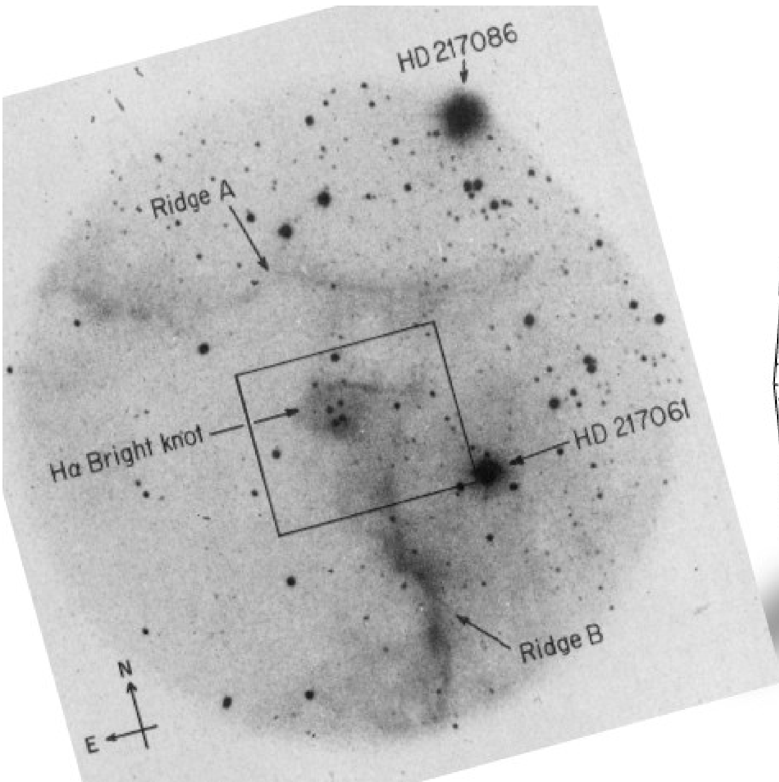
- Example: Cep B
- Age gradient of stars towards Cep B

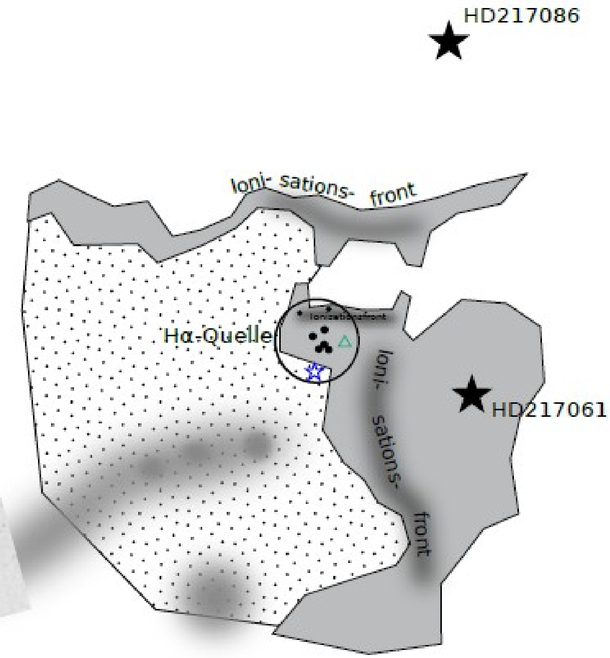


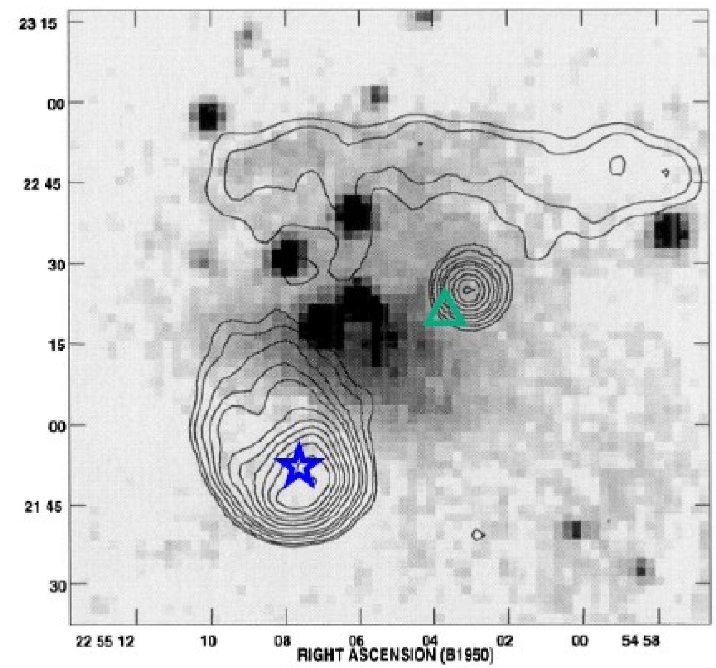
Large-scale structure of the Cepheus molecular cloud (CO 1-0, Sun et al. 2006)

Observational evidence

Sequential star-formation in Cep B:







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

2 embedded HII regions (Testi et al. 1995)

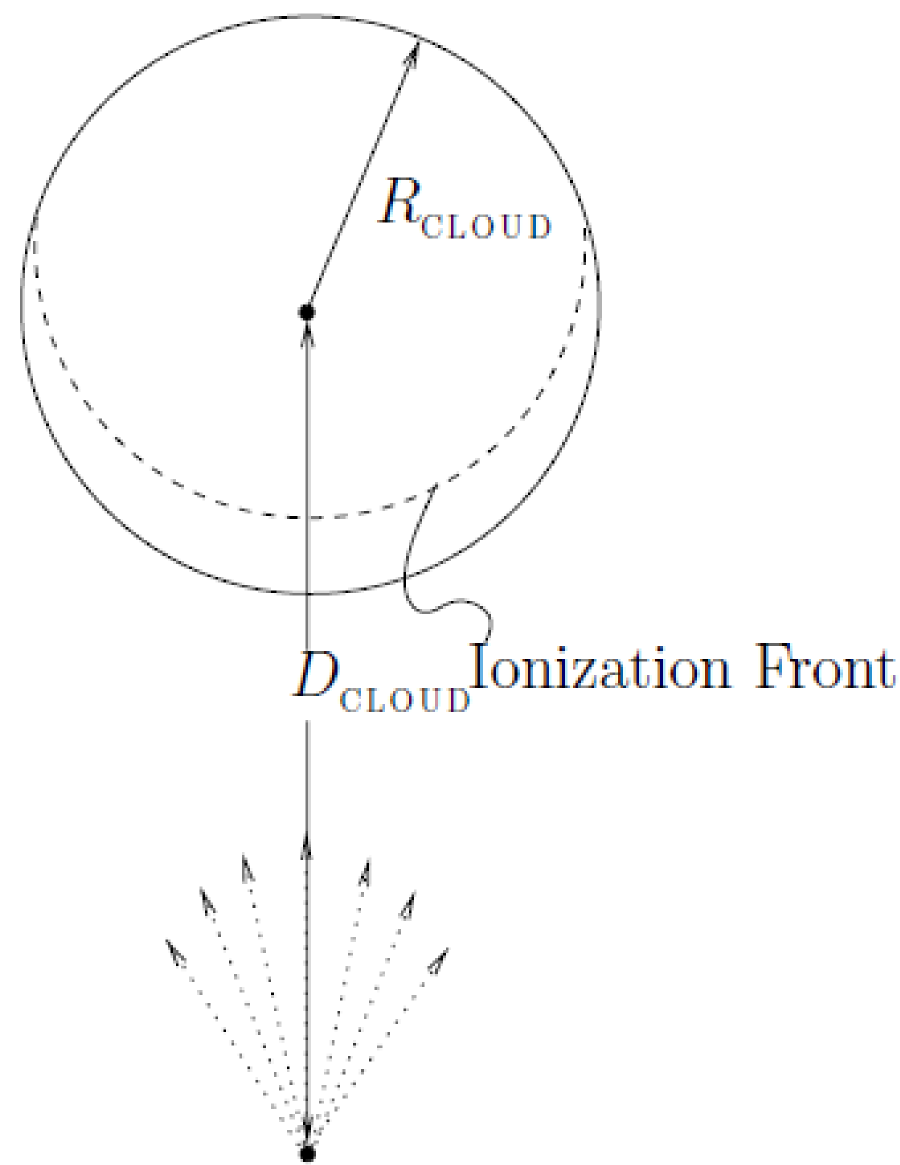
What do we expect?

Theory:

- Radiation pressure
- Thermal pressure of heated gas

→

- Ionization and photo-chemistry
- Compression of clouds
- Dispersion

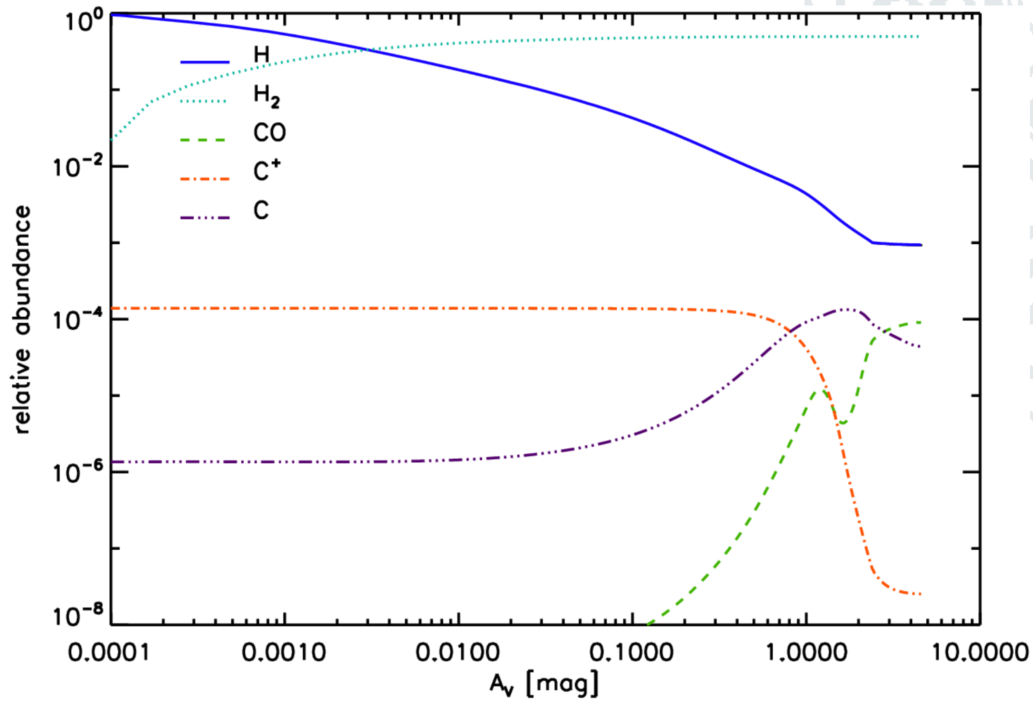


Schematic picture of pillar formation (Bisbas et al. 2011)

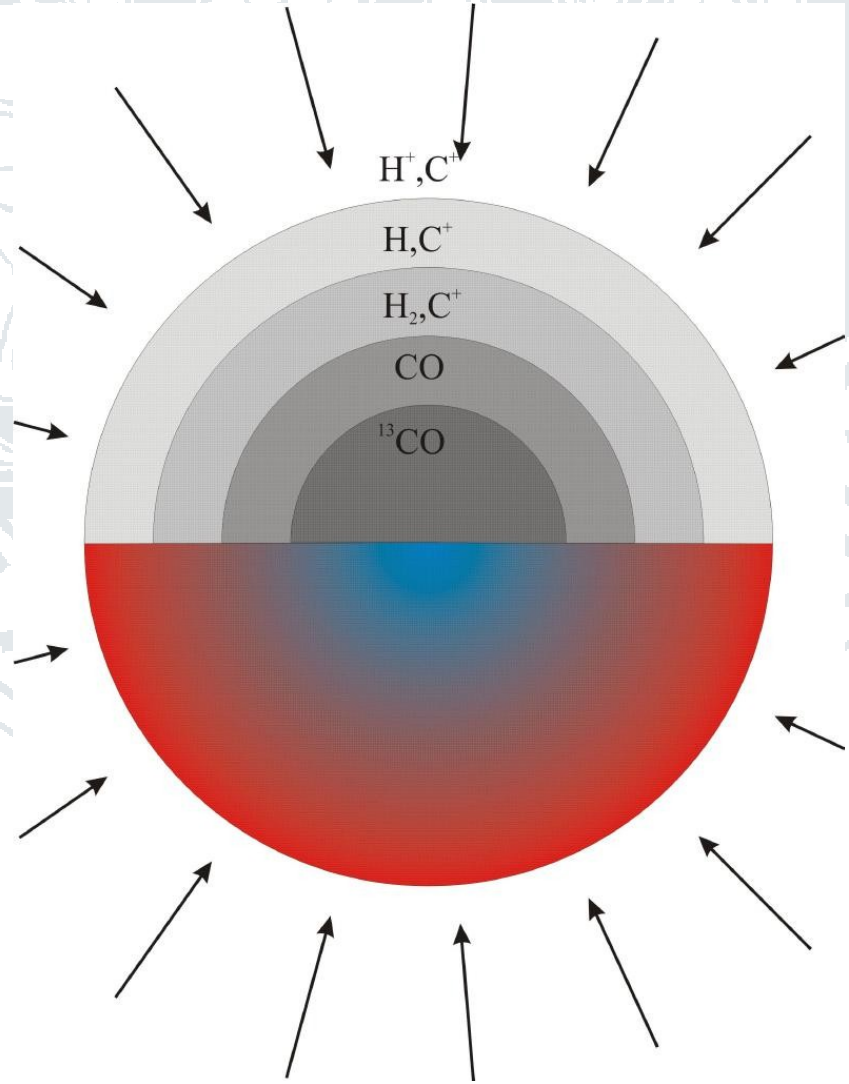
What do we expect?

Chemical structure:

- Layering of species as a function of UV field



Abundance of selected species as a function of optical depth from the cloud surface (KOSMA-τ model with χ = 1, M_{tot} = 100$M_{\odot}$,n = 500cm^{-3})

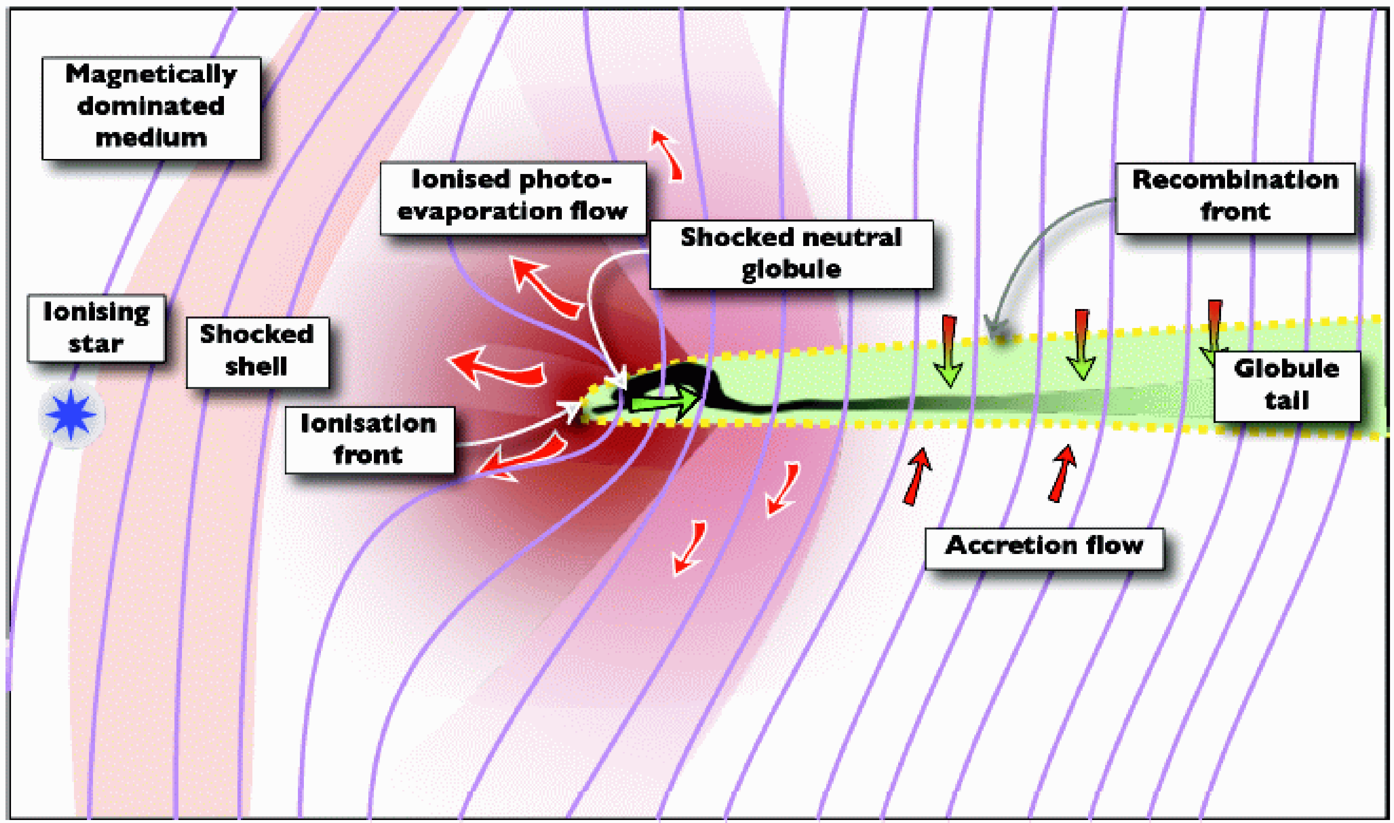


What do we expect?

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**



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

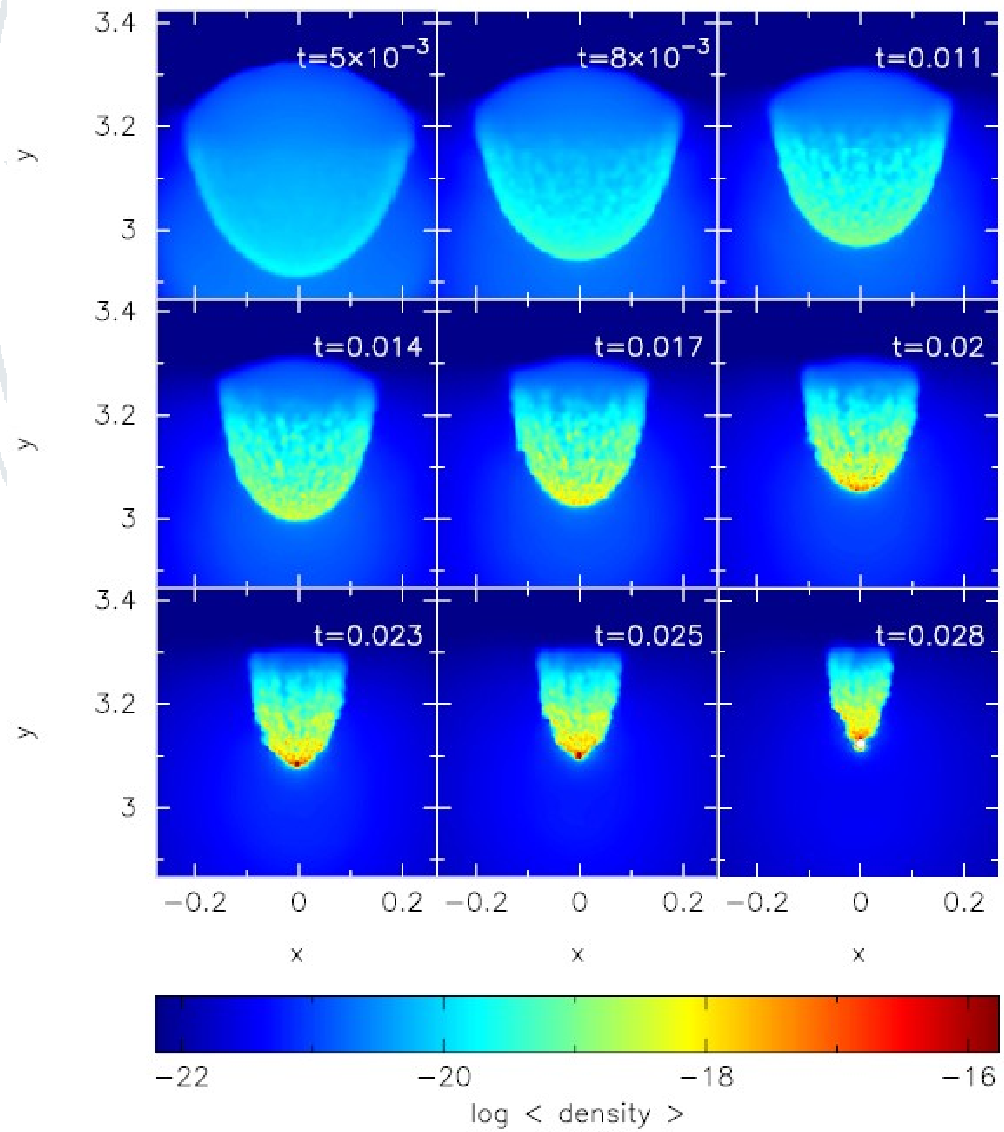
What do we expect?

SPH simulations:

- Dispersion and compression
  - Outcome very sensitive to initial parameters
  - Total dispersion frequent

Unknowns:

- Advection flows
- Impact of turbulence

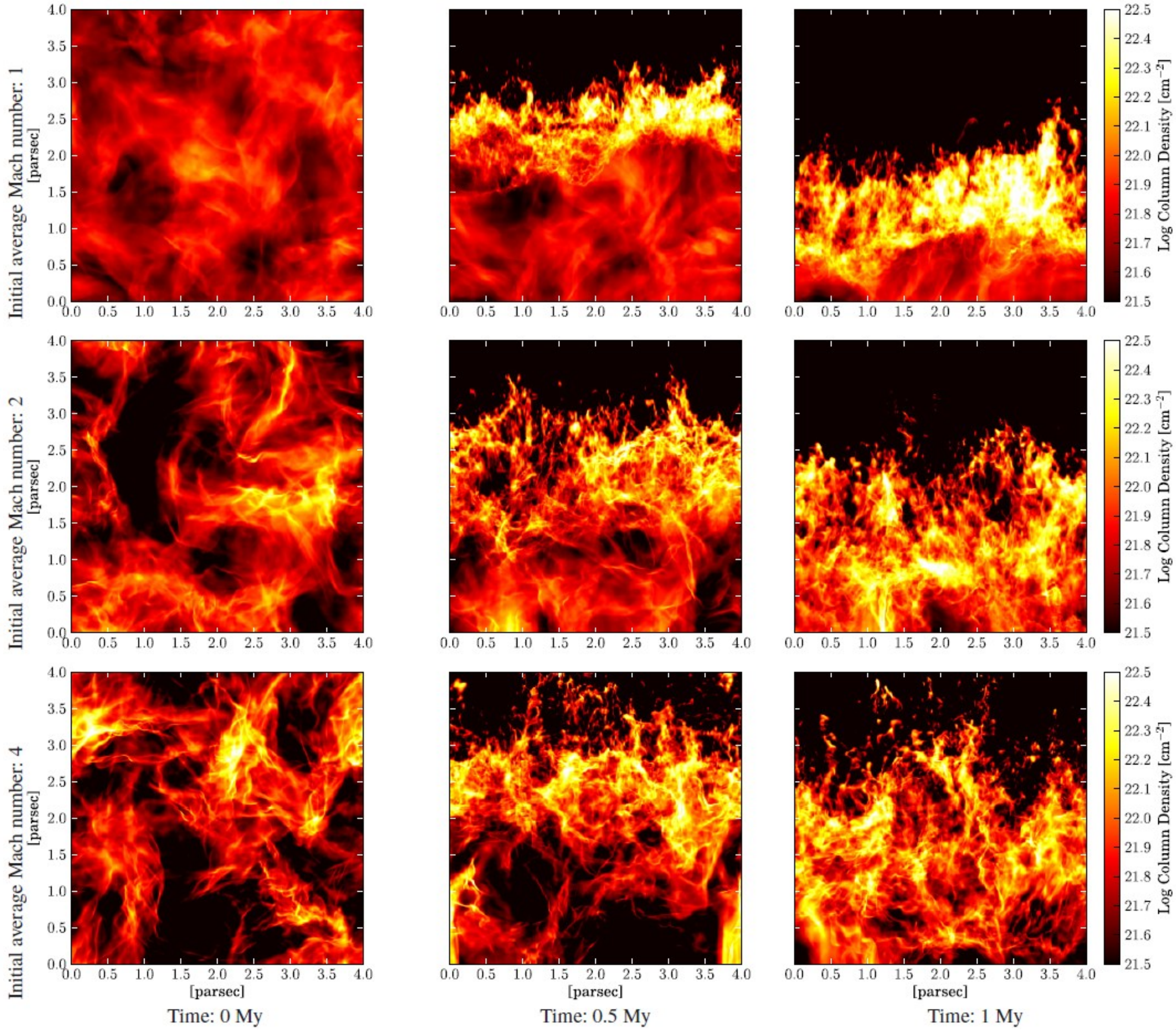


Column density evolution in a globule towards pillar formation (Bisbas et al. 2011)

What do we expect?

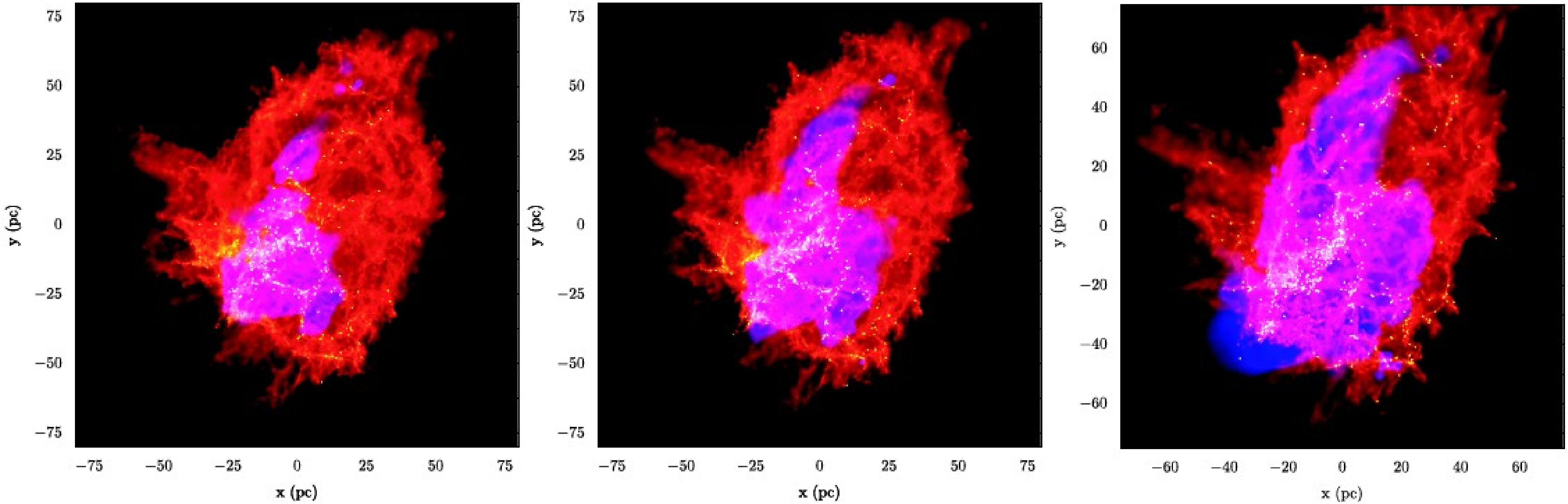
Turbulence simulations:

- Turbulent ram pressure can prevent pillar formation



HERACLES simulation
Tremblin 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

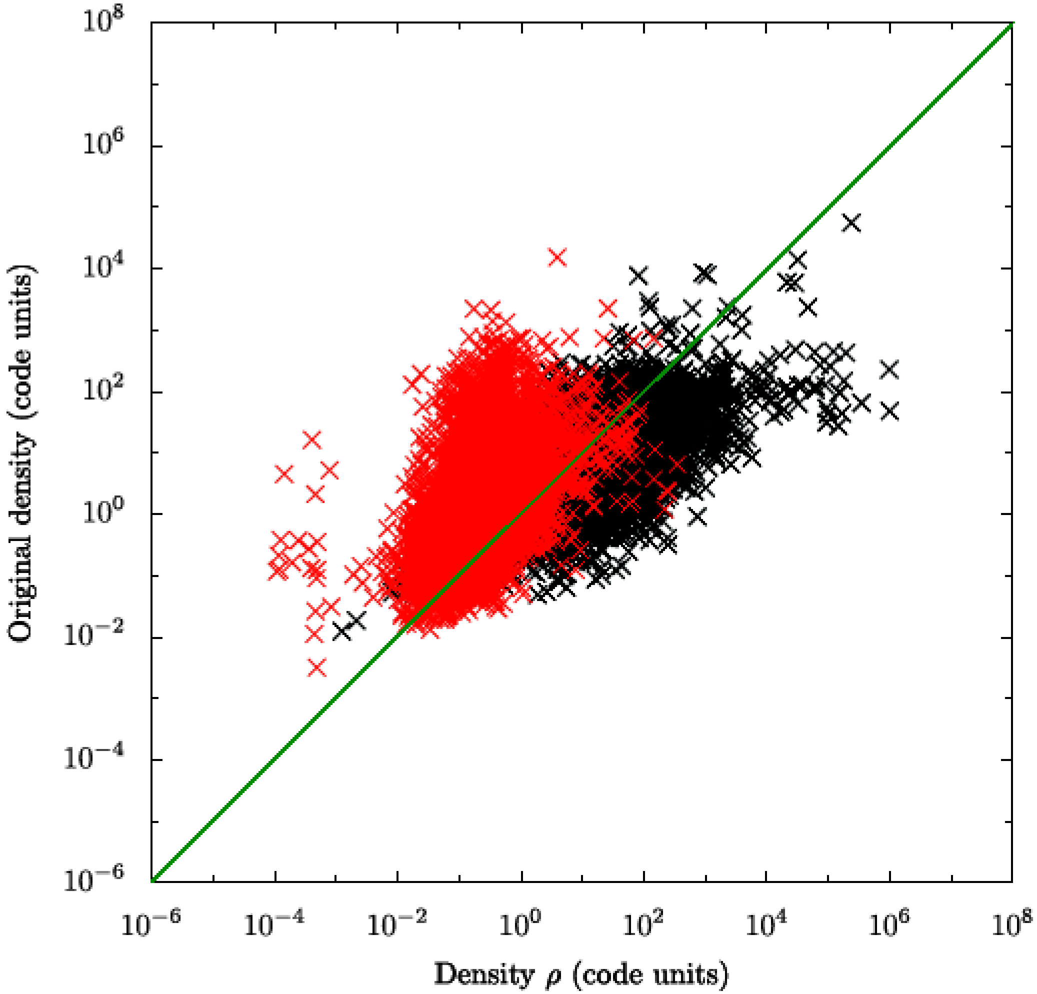
Dale & Bonnell (2006)

Is the process statistically significant?

Simulation of density evolution in SPH model:

- Neutral material (black), ionized (red)

Dale & Bonnell (2006)



→ Radiative impact leads to slightly enhanced dispersion

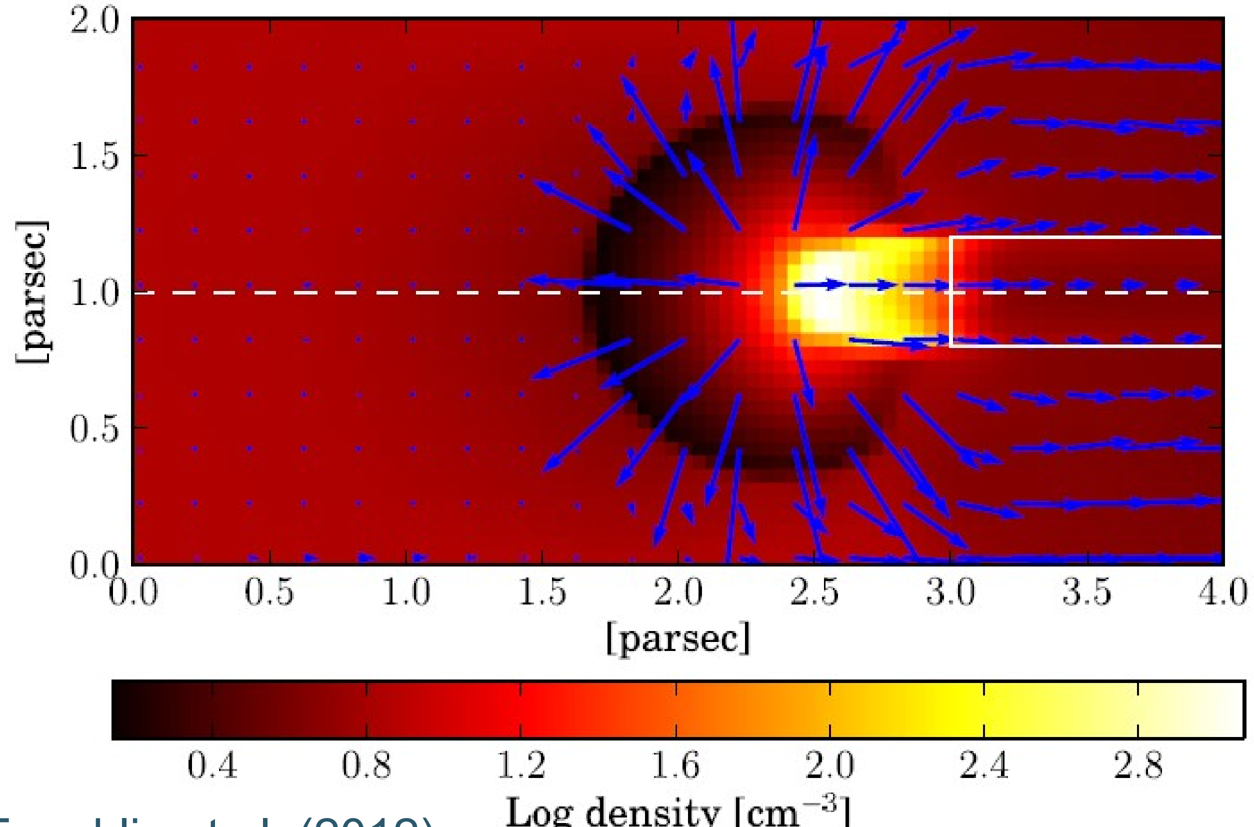
But:

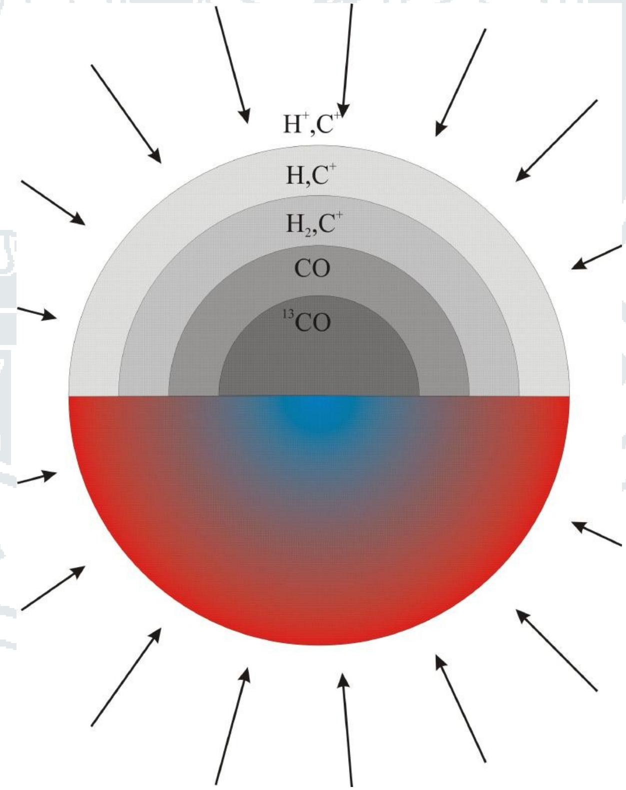
- resolution of simulations insufficient
- Chemistry neglected
- Many other deficiencies

Observational verification

Look for characteristic velocity flow patterns of triggered collapse

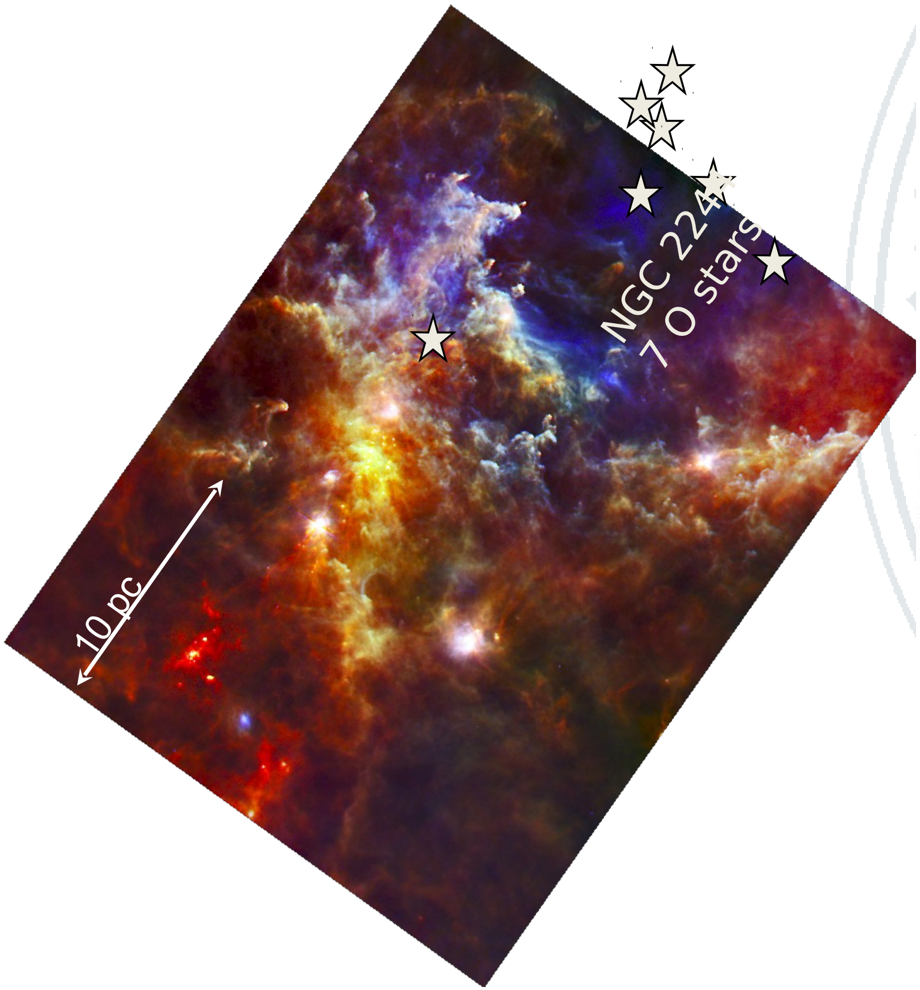
- Chemical structure has to be taken into account when observing any gas tracer

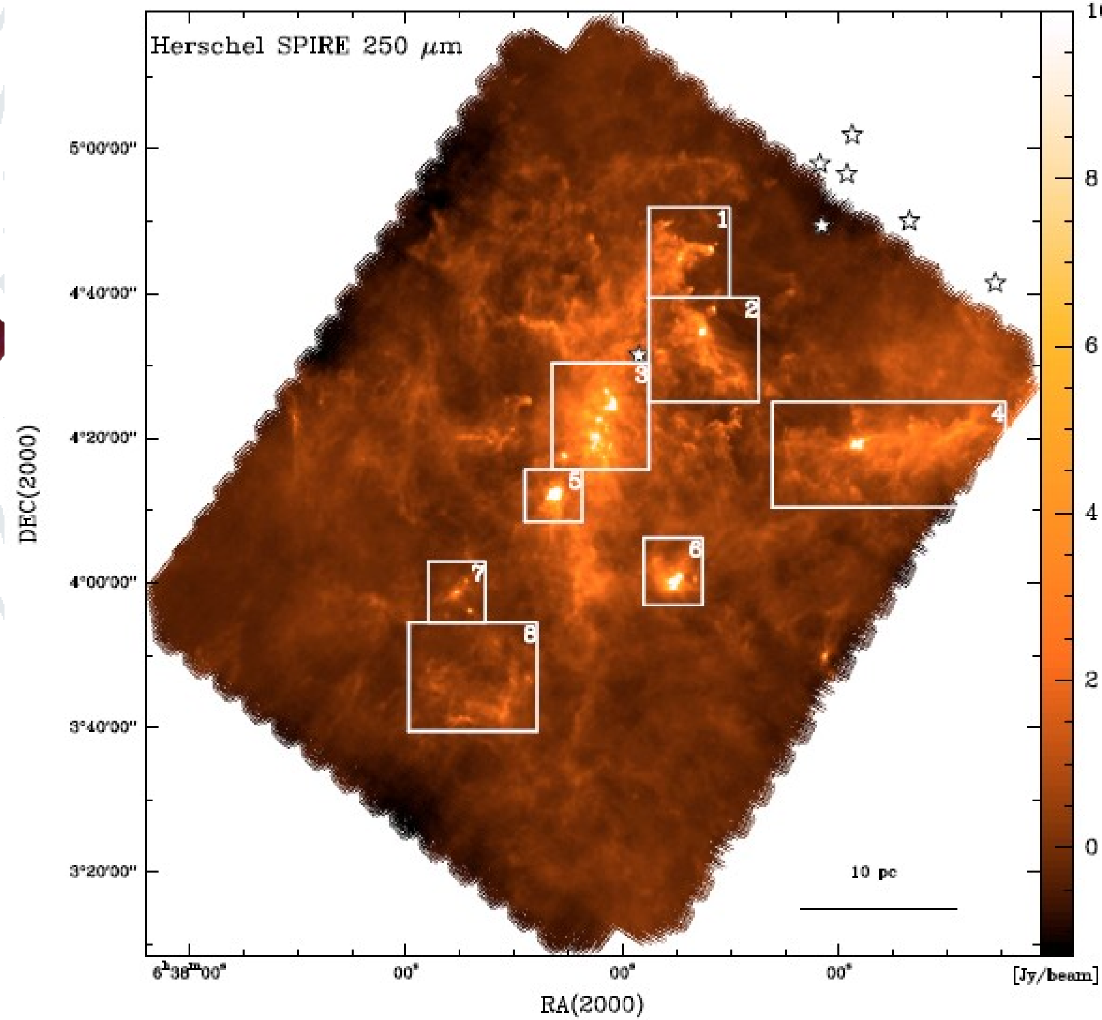




Tremblin et al. (2012)

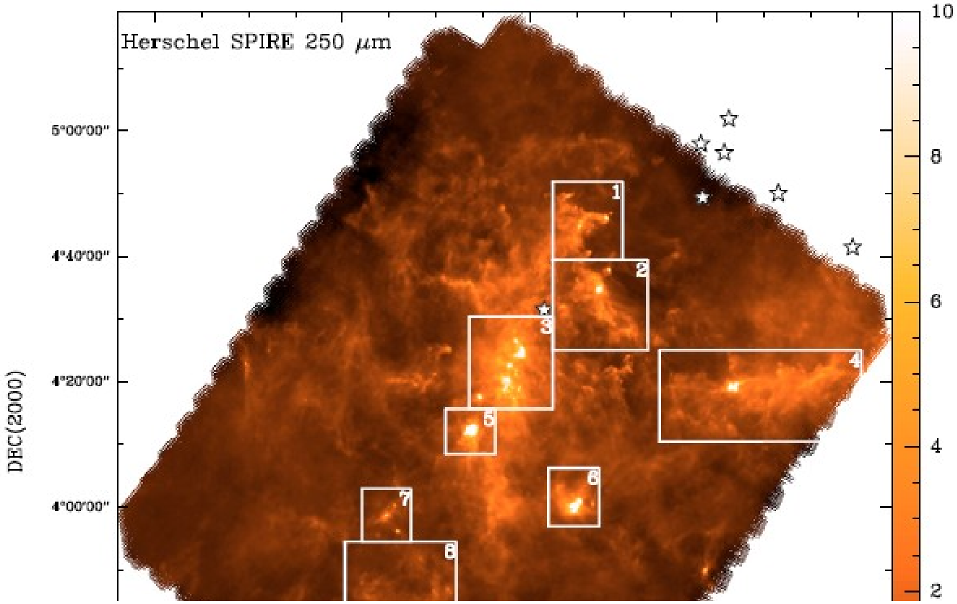
Example 1: Rosette





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

Investigation of individual pillars: Region 1+2

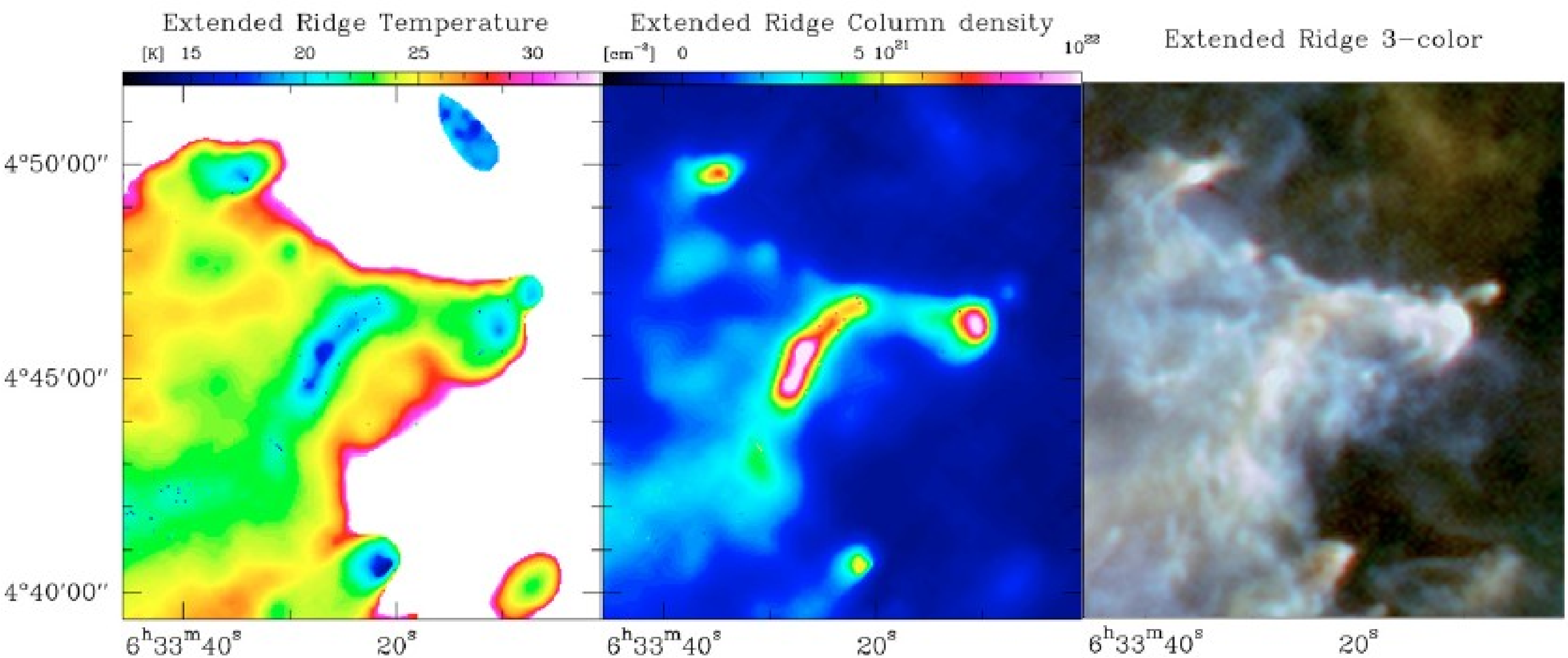


Rosette

Region 1 - high resolution:

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

(Schneider et al. 2010)

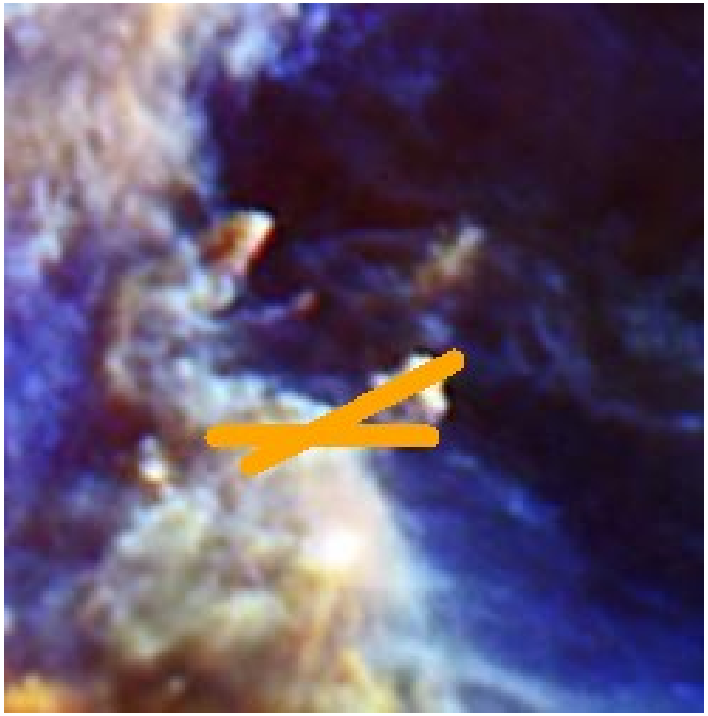


Rosette

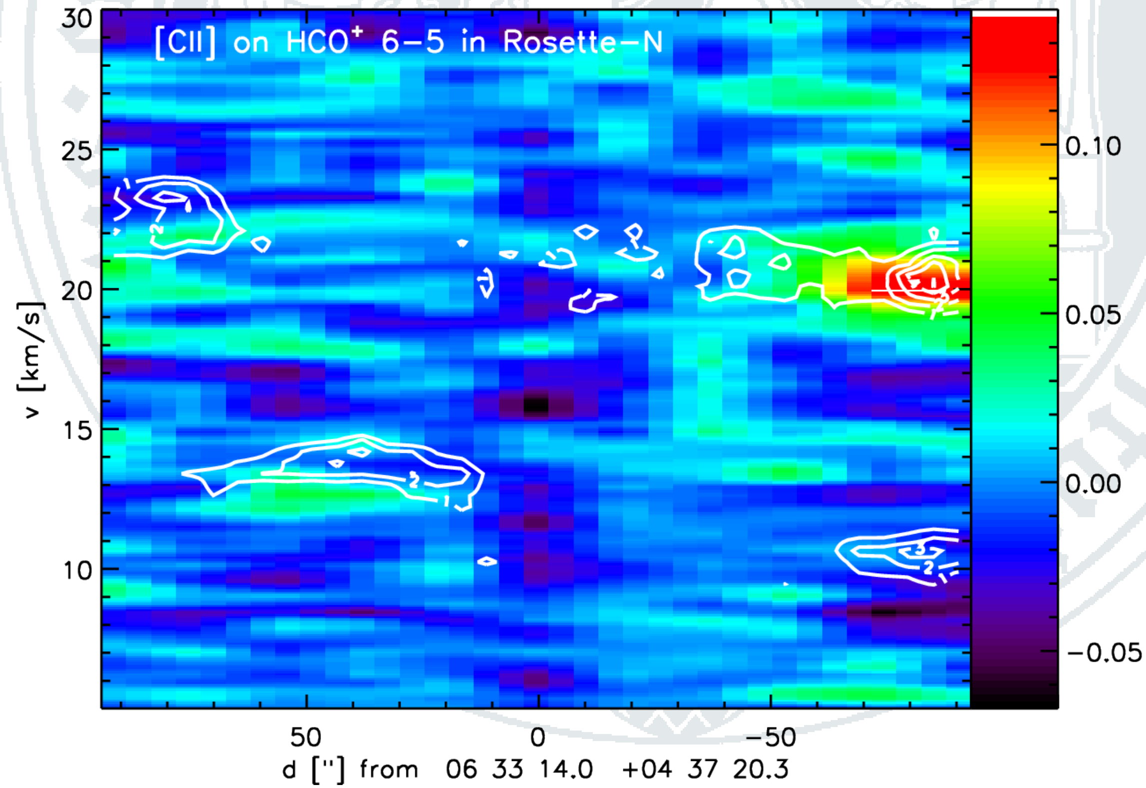
Cuts through pillars to trace velocity structure:

- **Position-velocity diagrams**

2 interfaces:



[CII] (contour) on HCO^+ 6-5 (color)



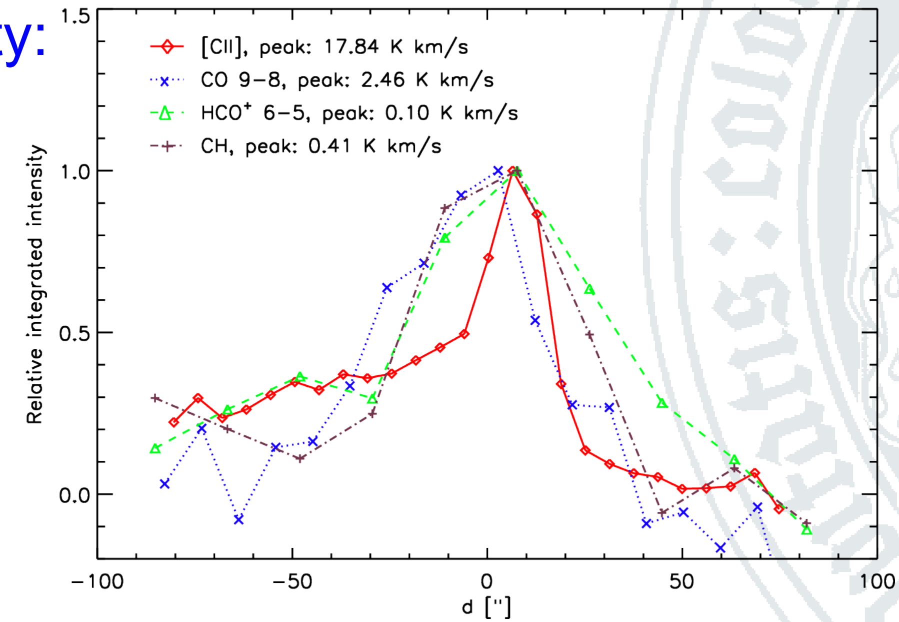
2 separate velocity components, i.e. 4 instead of 2 surfaces

- No significant detection of systematic flows in Rosette

Typical systematics

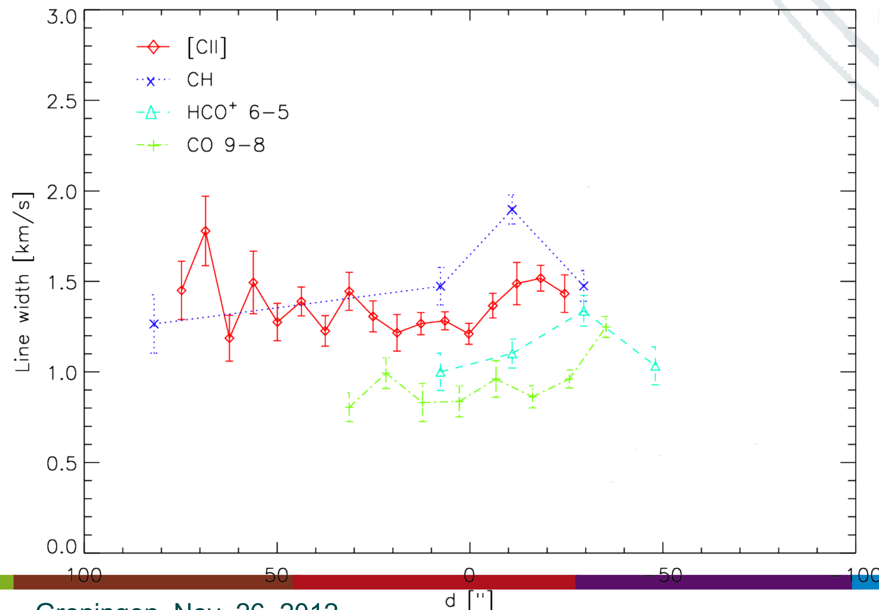
Interpretation of line profiles

Intensity:



- Stratified chemical structure
- Layering $C^+ \rightarrow HCO^+ \rightarrow CO$
- CH very extended
- C^+ in sharp surface layer but with long tail

Width:

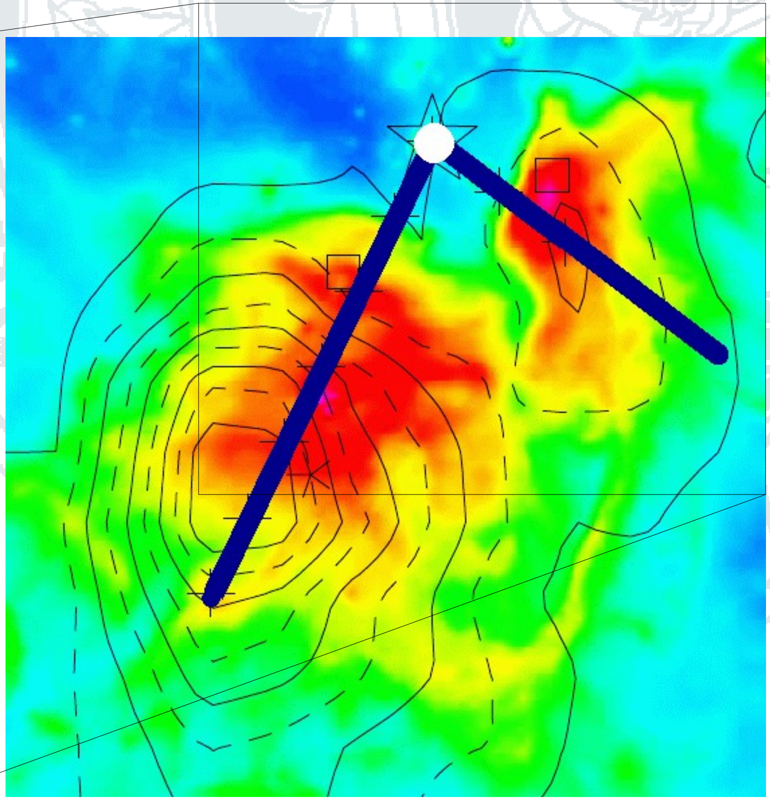


- Confirmation of expected pressure “jump” at interface
- [CII] wider than molecules
  - stronger coupling to radiation pressure
- Wider width of CH mysterious

Example 2: NGC3603

- Position-velocity cuts across the PDR interfaces

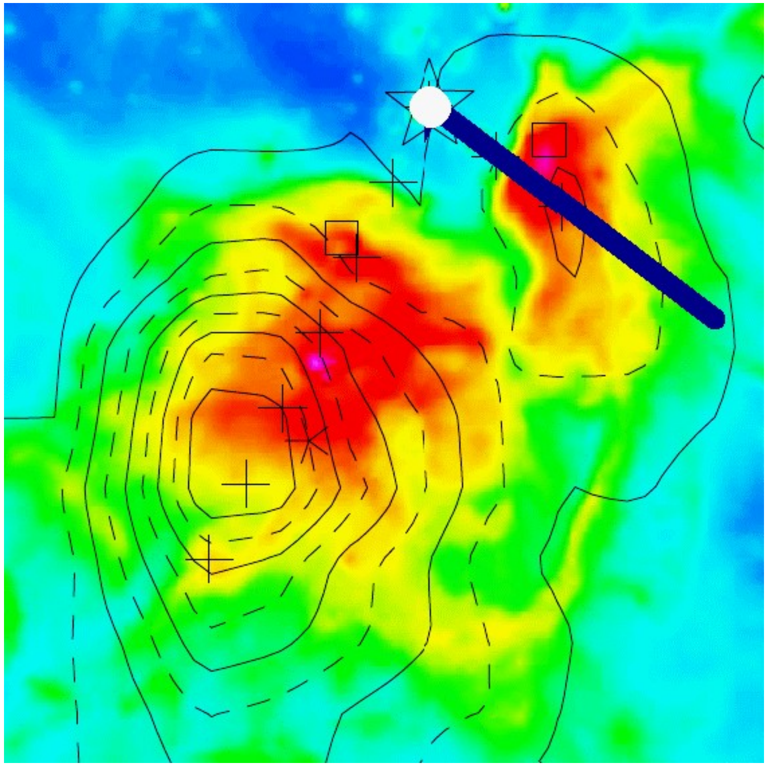
Pillars at PDR fronts (HST, Brandner et al. 2000)



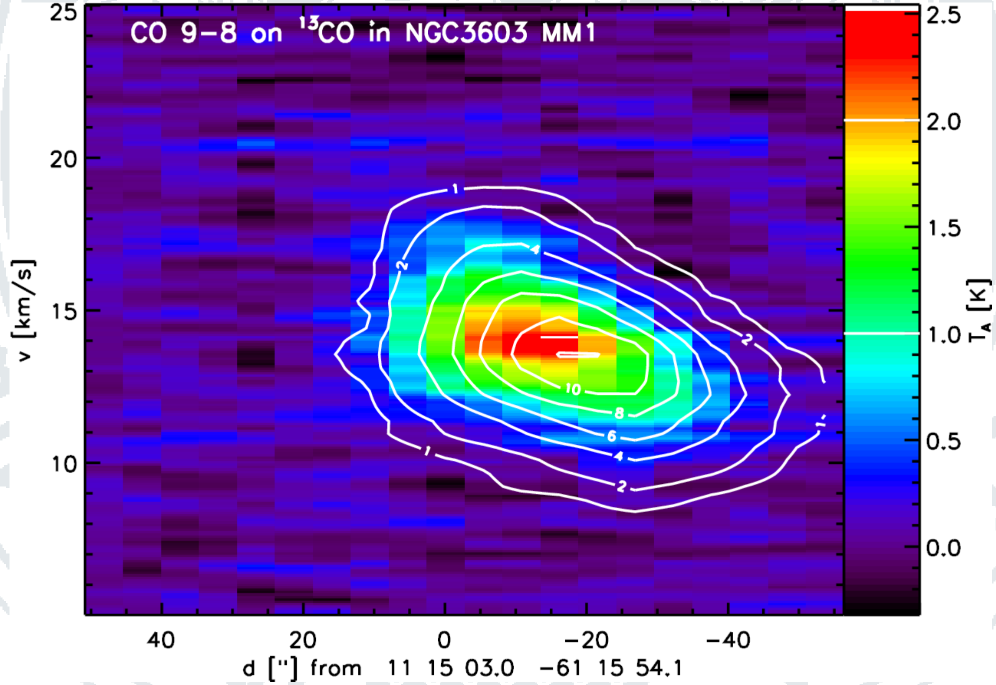
Observed cuts overlaid on Spitzer 8µm (color) and CO 4-3 (contours)

NGC3603 MM1

Velocity structure from p-v diagrams:



Observed cuts in NGC3603 overlaid on Spitzer 8µm



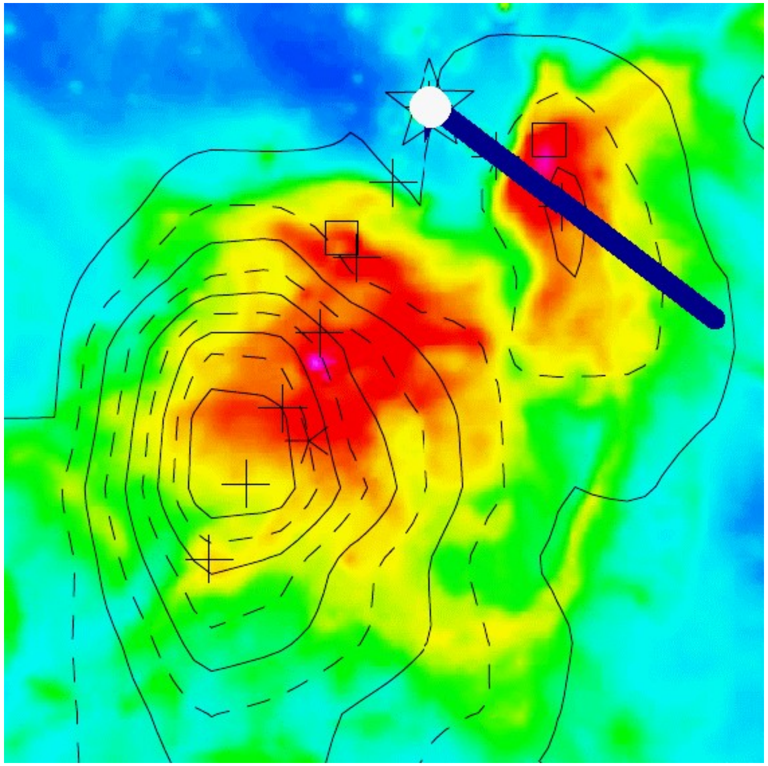
p-v diagram: ^{13}CO 10-9 (colors) + CO 9-8 (contours).

Velocity gradient across the core

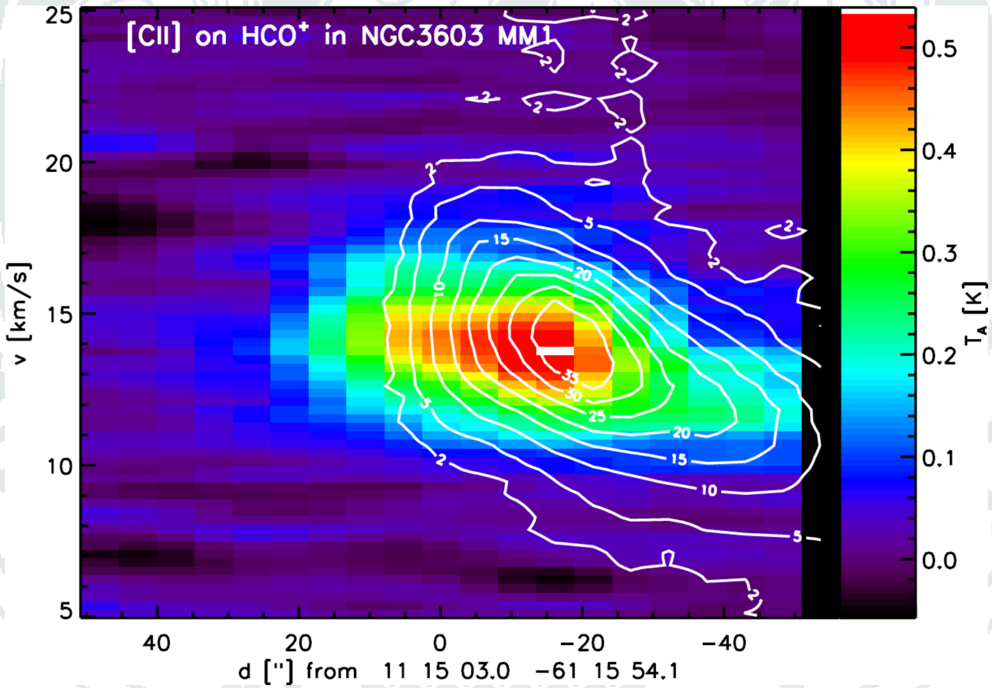
- Compression ?
- Dispersion ?
- Rotation ?

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).

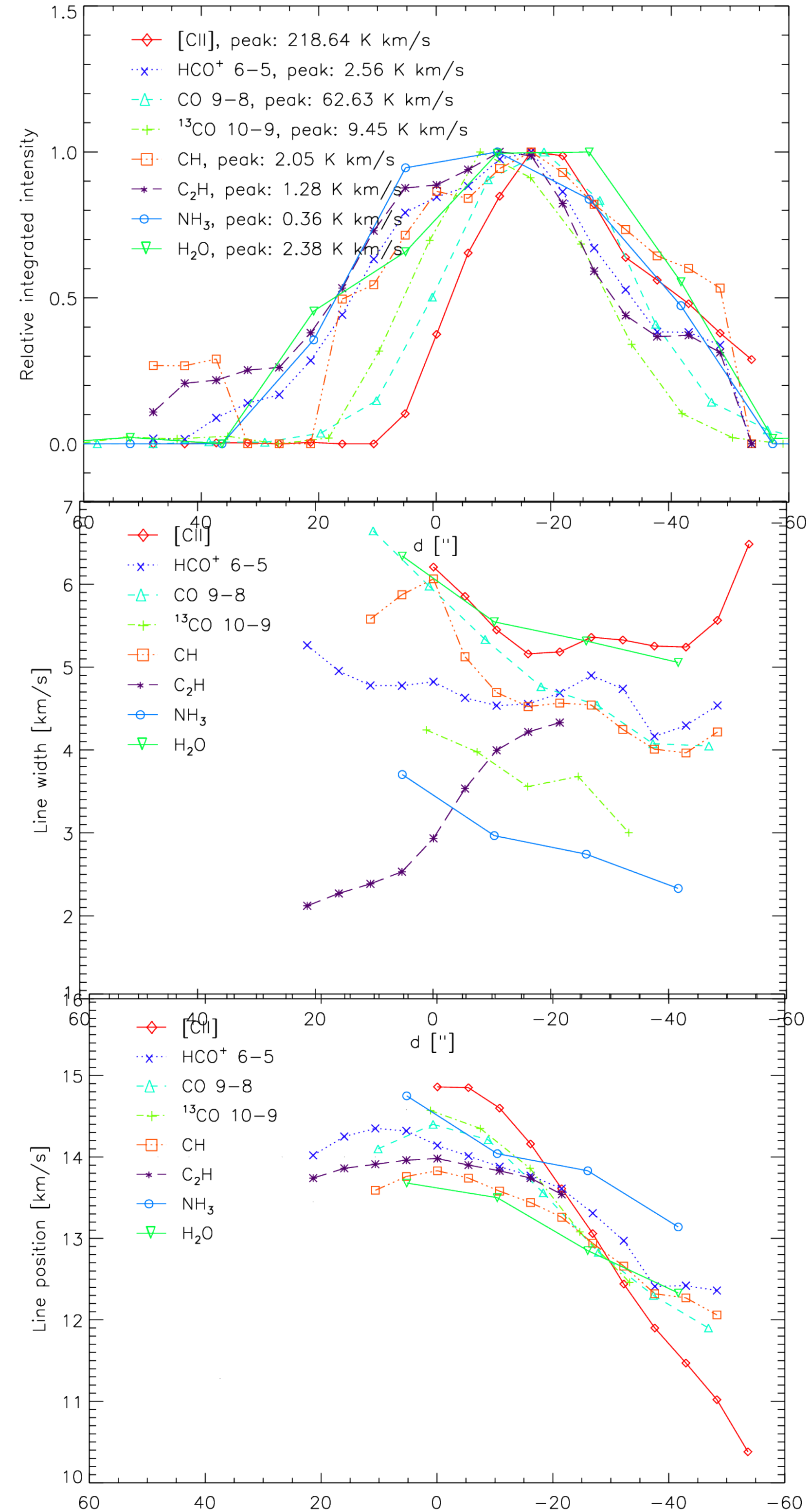
- All lines broadened towards UV source
  - pressure gradient confirmed
- [CII] shows a long turbulent tail of material “behind” the core

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

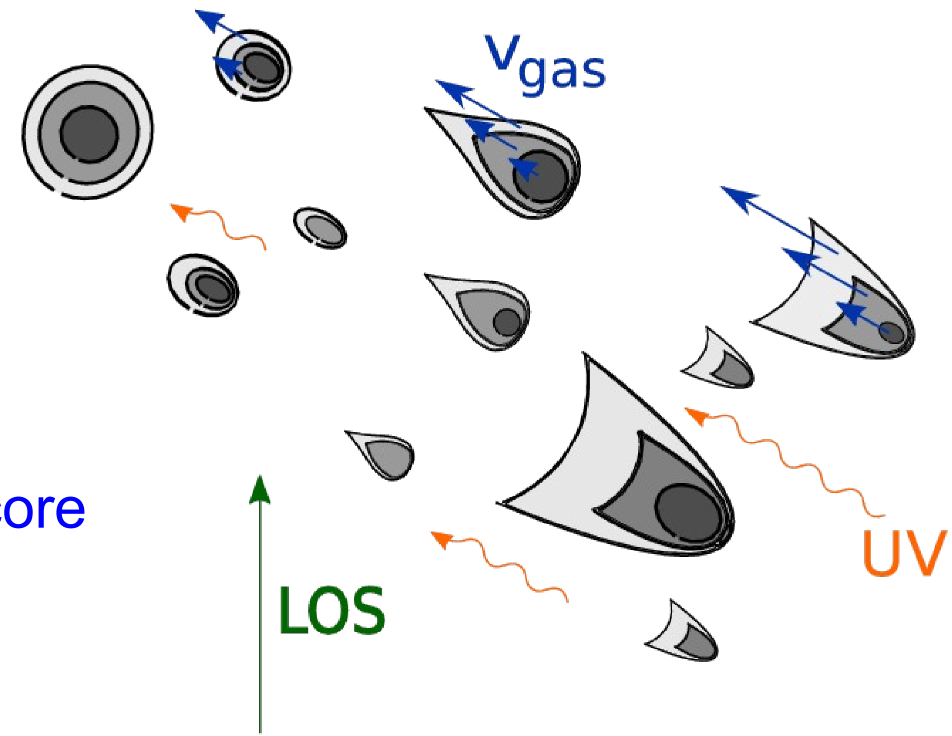
→ C^+ must be blown from the surface into a clumpy medium

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

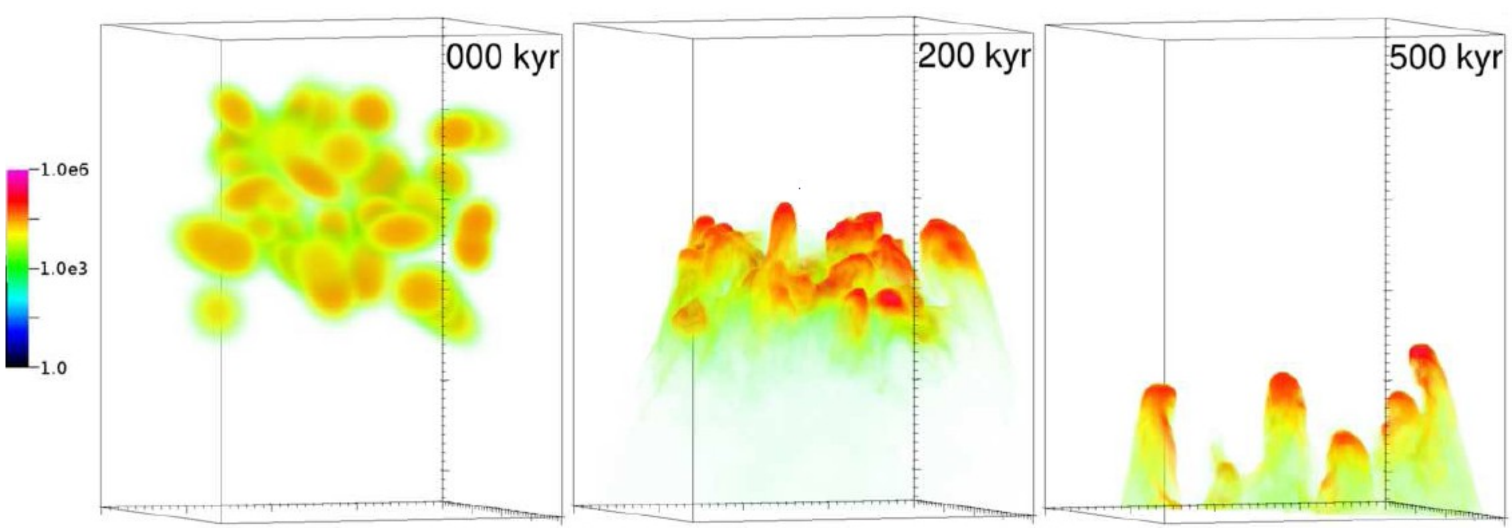


Interpretation

- 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)

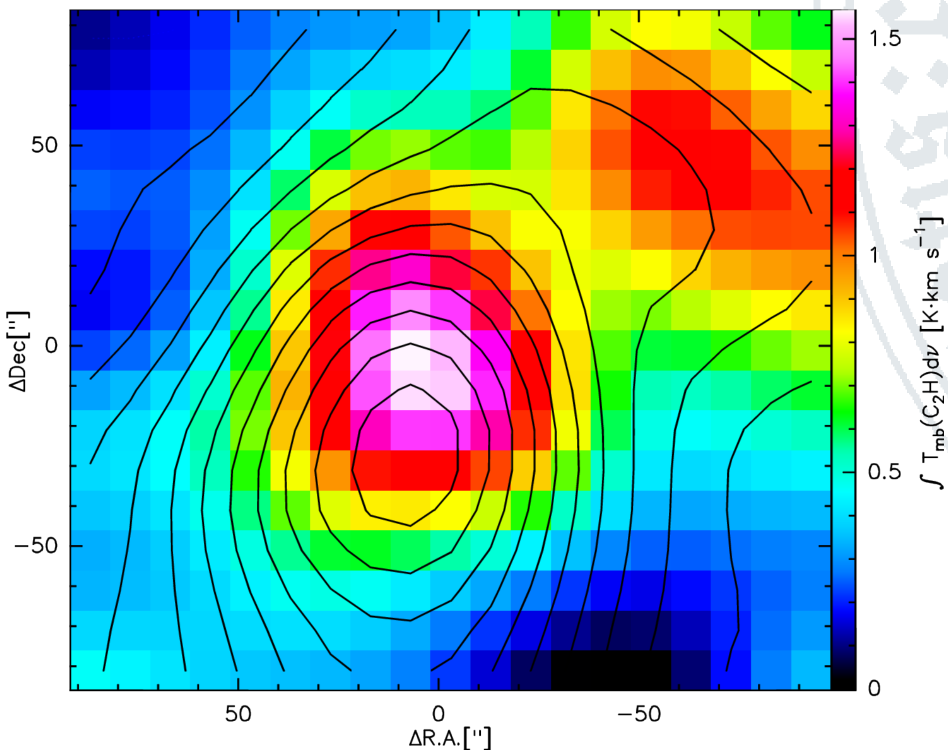


→ Pillar formation

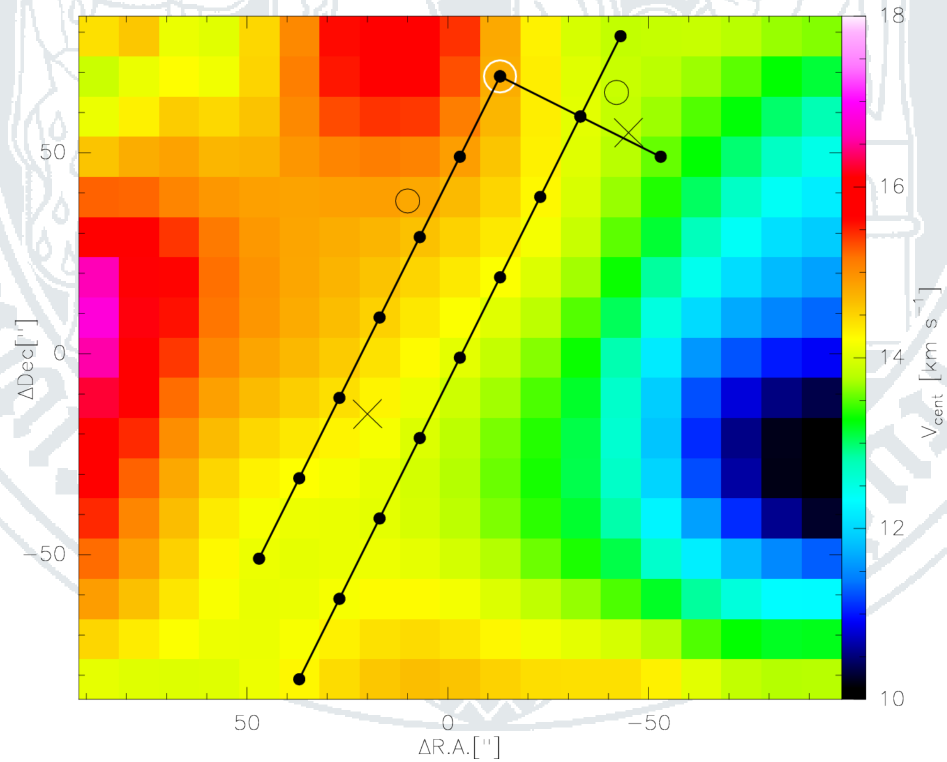
But …

New full mapping observations:

Gradient is not radially symmetric around stellar cluster!



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



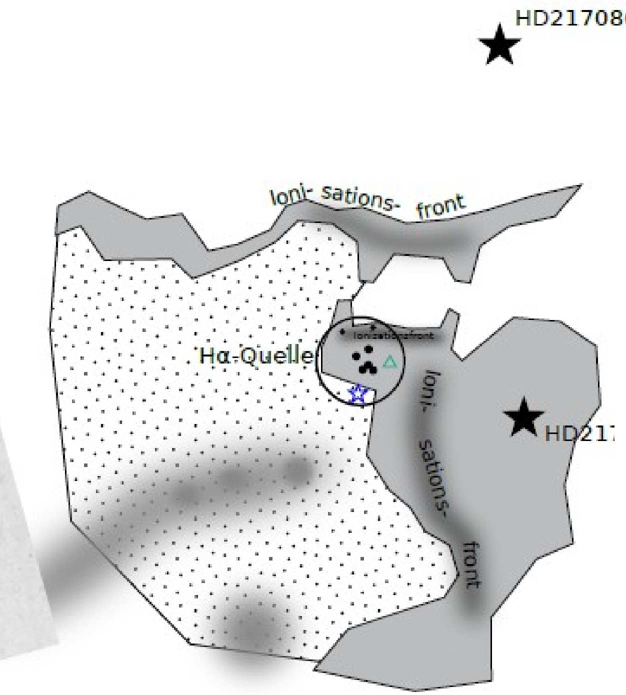
CH line centroid map

→ probably rather large scale systematic shear

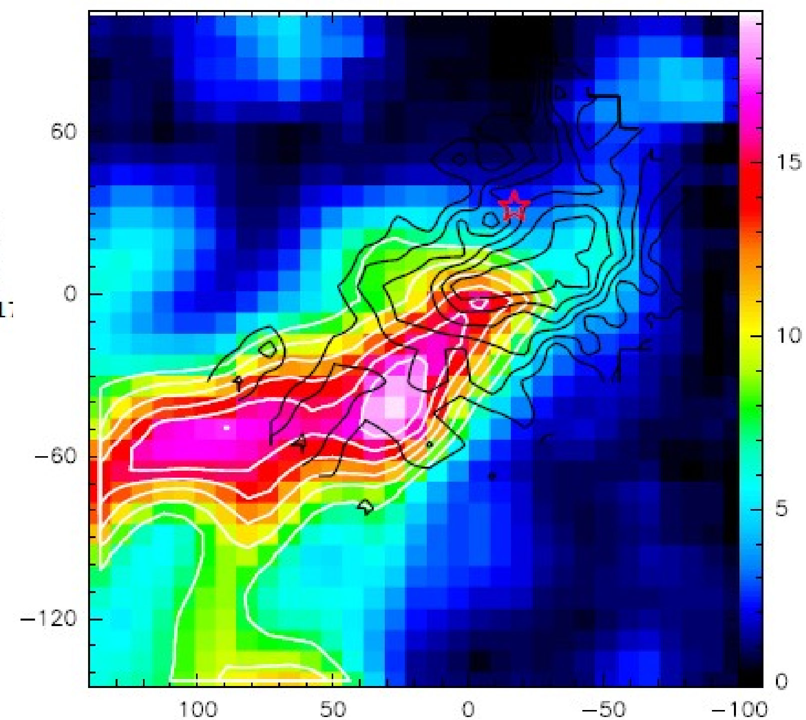
- **Again no holy grail**

Example 3: Cep B

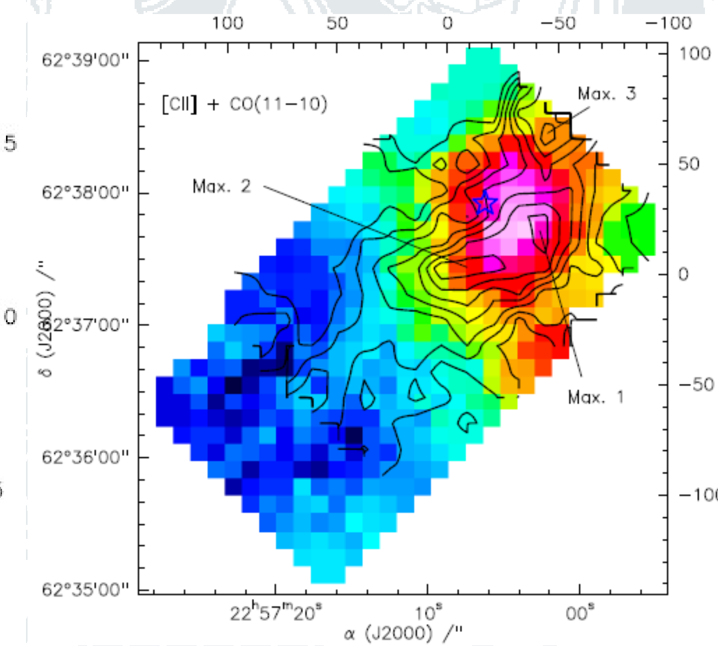
SOFIA observations:



(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)

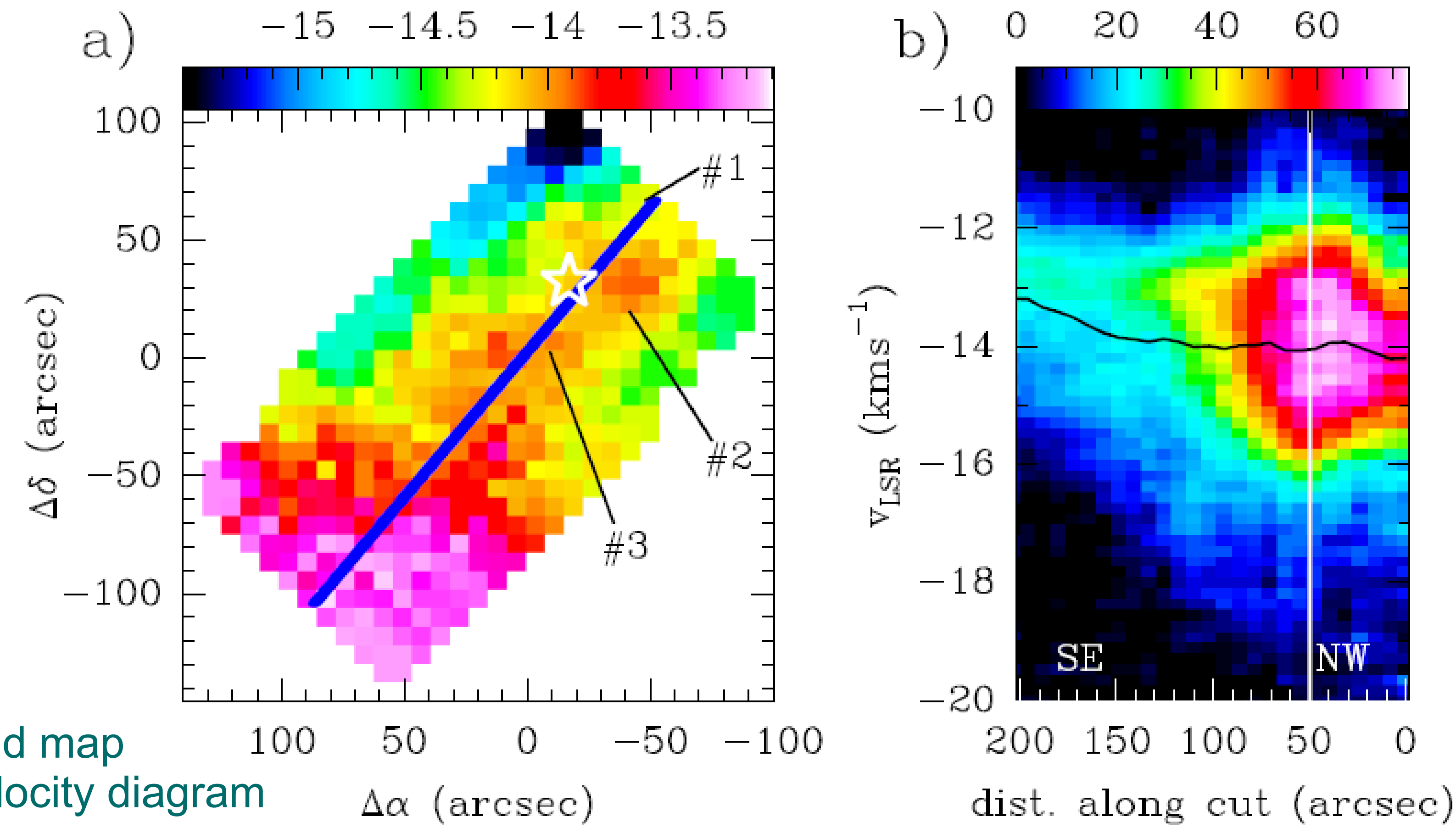
Embedded UC-HII-region • heats surrounding gas

• induces photon-dominated chemistry → trigger of SF?

Example: Cep B

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

→ Study velocity structure

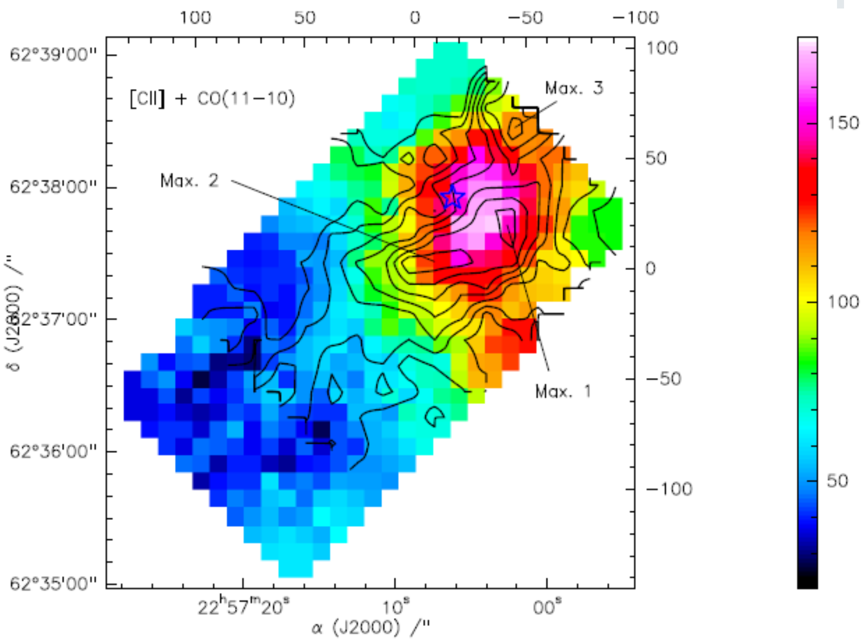


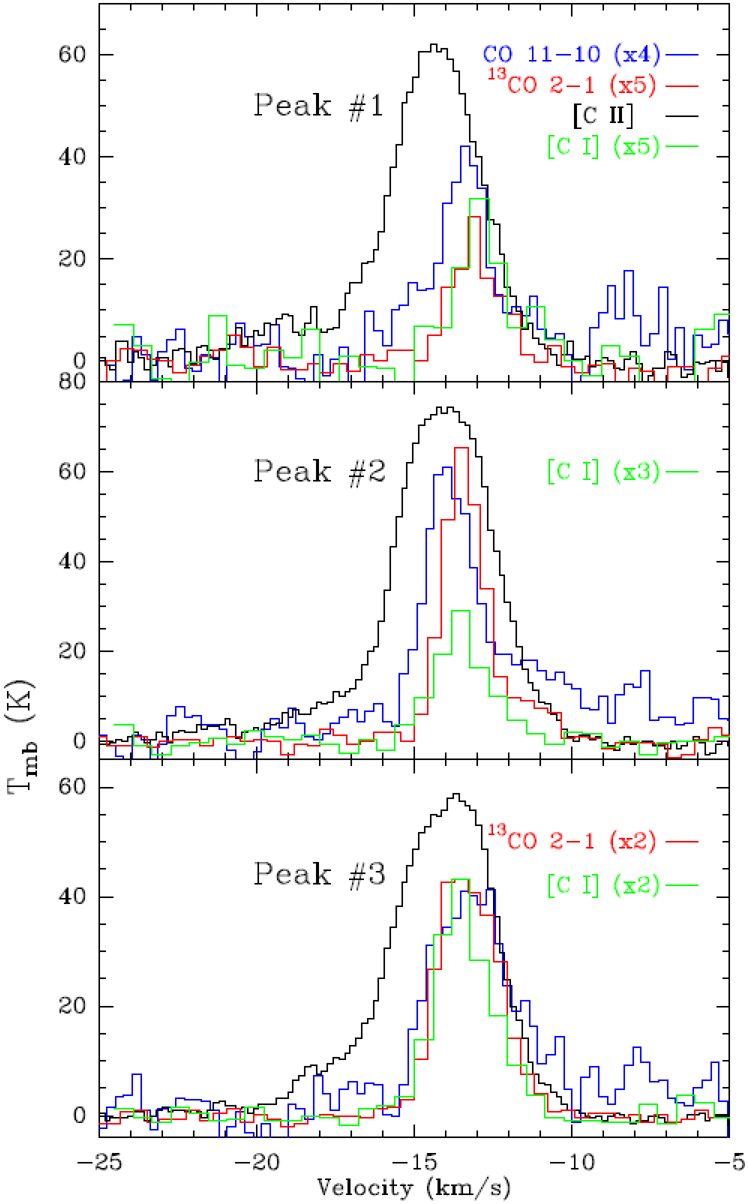
[CII] line centroid map and position-velocity diagram

- 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

Inventory of individual PDR dynamics

- Low-density gas is dynamically affected by UV radiation
- Acceleration through radiation pressure
  - Significant dispersion of gas traced
- Pressure jump at the surface confirmed
  - No clear detection of radiative core compression yet
  - No evaporation flows!
  - No indication of turbulent stirring through radiation
- The layering of species in PDRs is quantitatively understood
  - Line width sequence: [CII]/CH^+ - CH – other molecules
  - Stronger coupling of interclump gas tracers to radiation pressure
- UV creates local heating and velocity gradients but is irrelevant for large-scale collapse

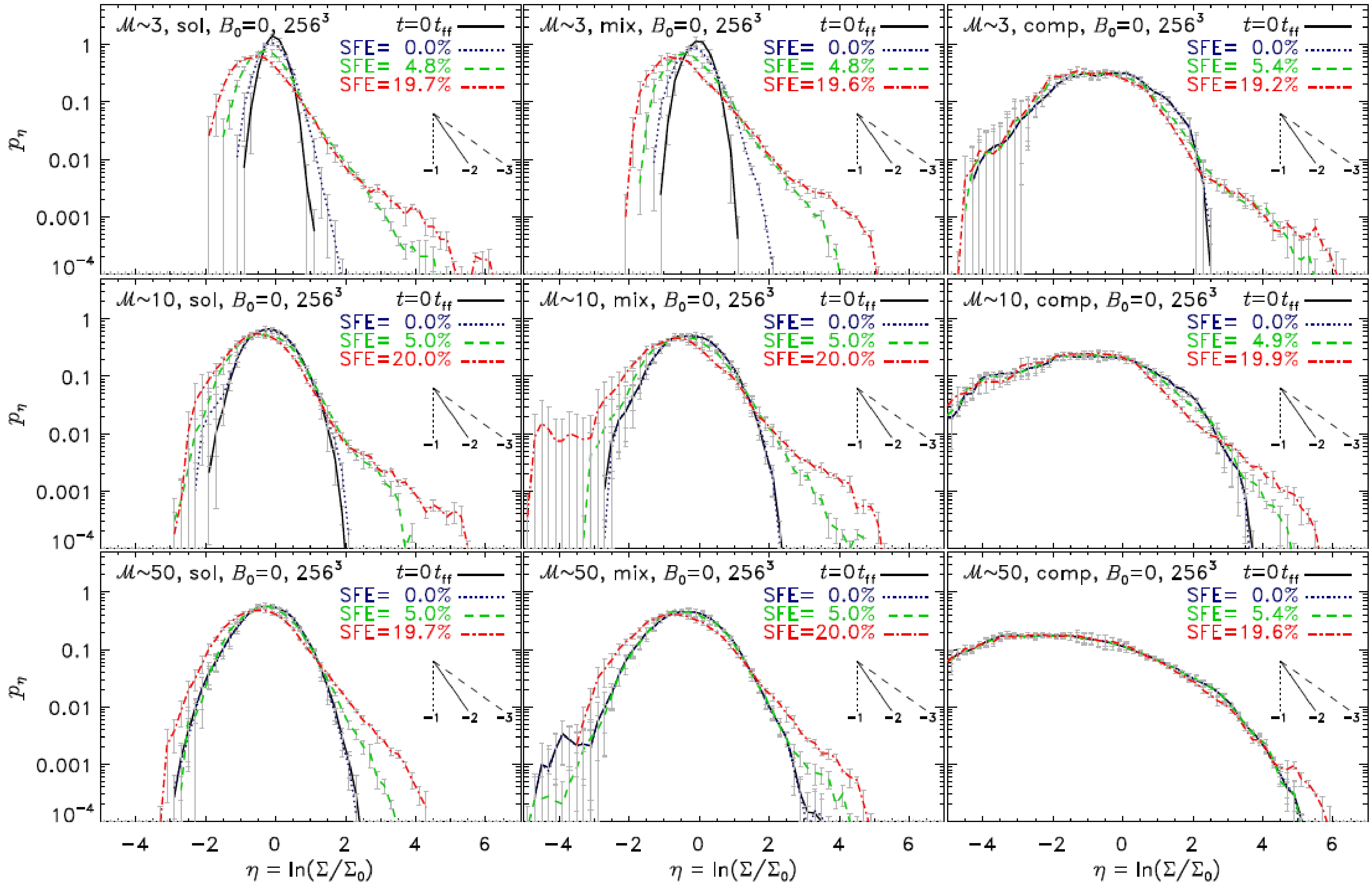
Statistical approach

Is there more star-formation at high radiation fields?

- **How do we trace the spatial distribution of star-formation?**
  - Look for high densities
    - Column density PDFs
  - Look for small structures
    - Δ-variance
    - Velocity fields

Column density PDFs

High column density excess from gravitational collapse:



Progressing time steps in a large-scale driven turbulence simulation including gravity (Federrath & Klessen 2012): log-normal distribution + high-density tail from collapse at late stages

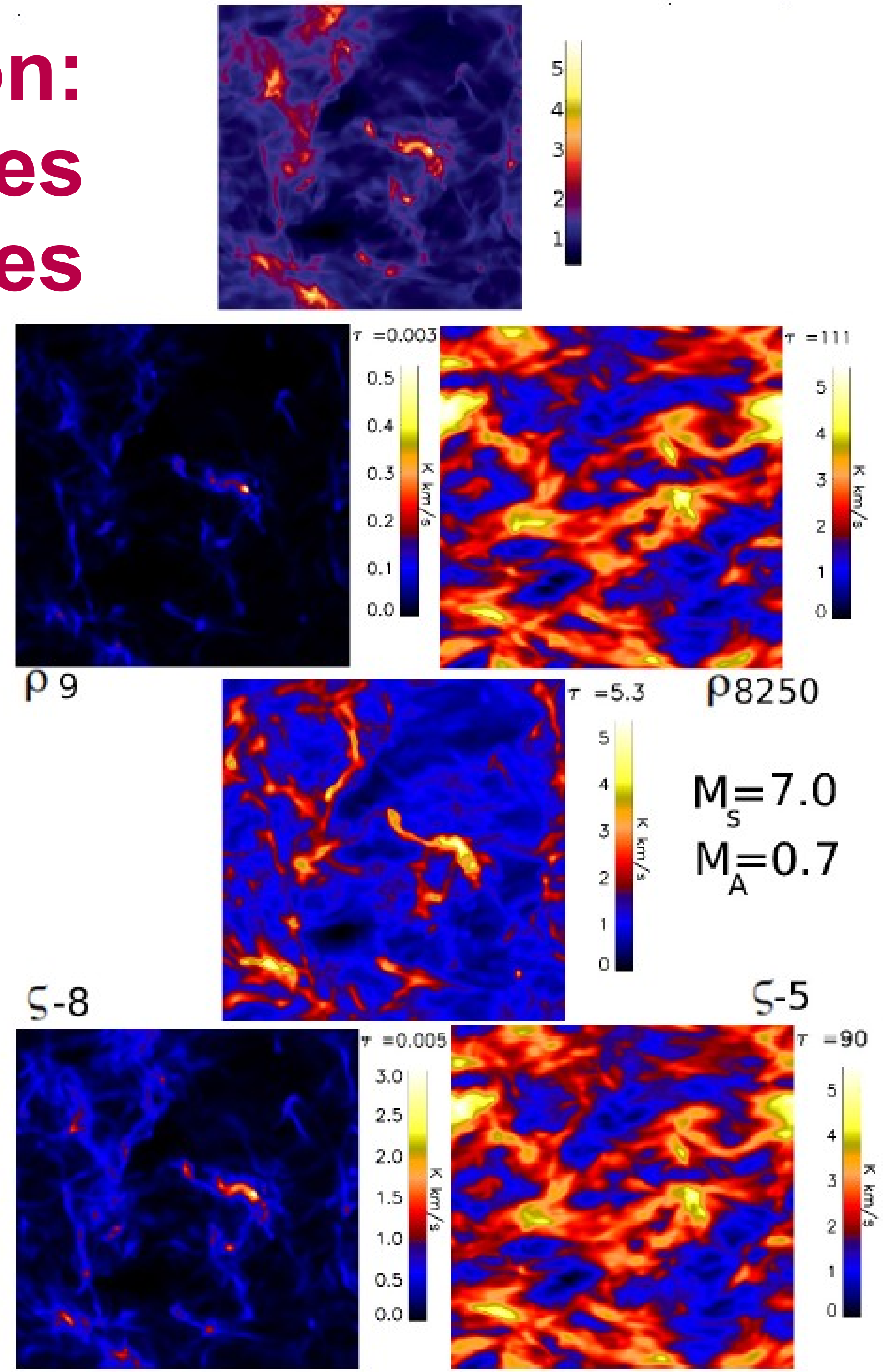
Complication: measure column densities through radio lines

Radiative transfer effects:

Full 3-D line radiative transfer (Ossenkopf 2002)

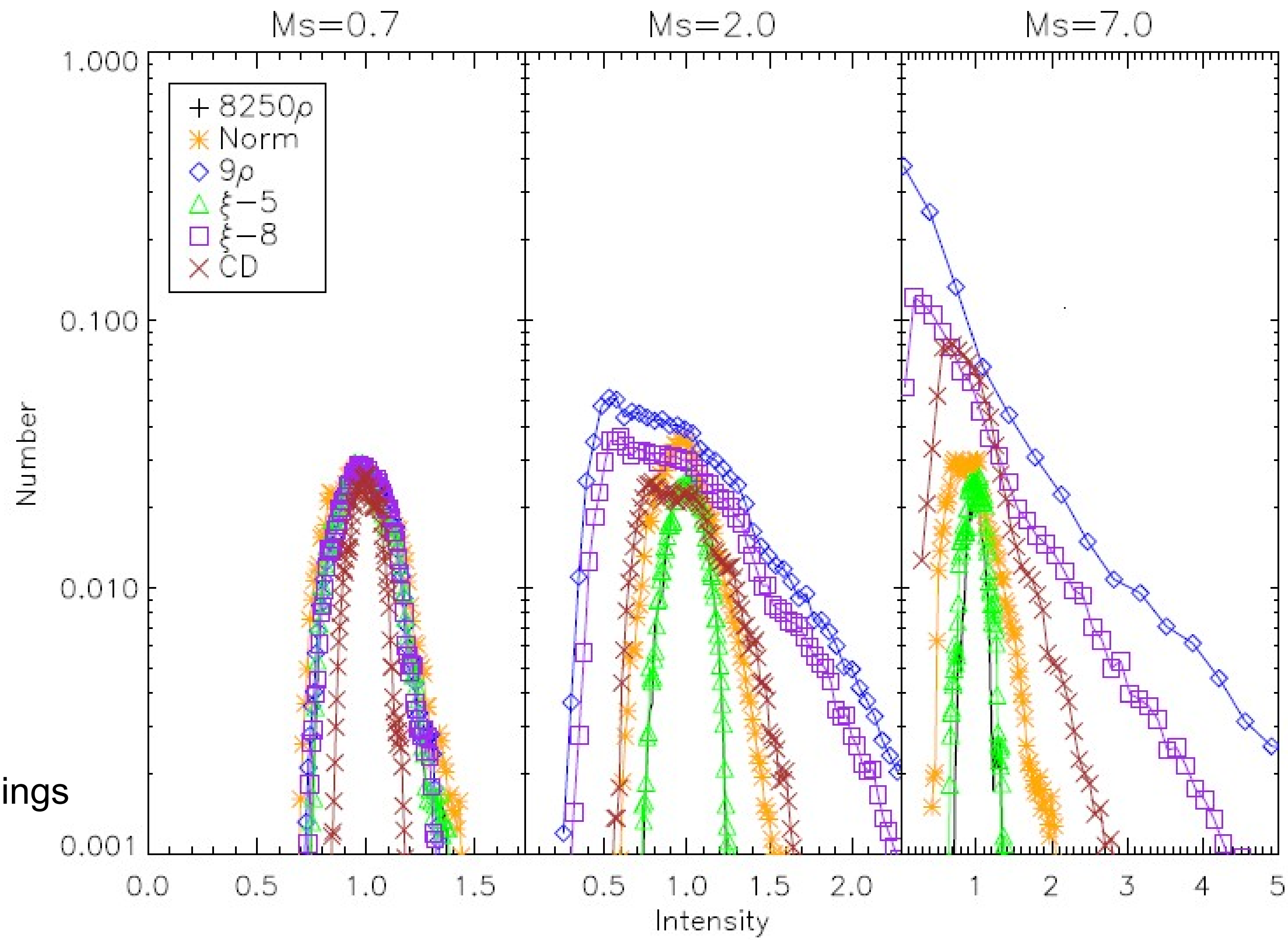
Simulated ^{13}CO 2-1 maps from a large-scale driven MHD turbulence simulation assuming different density and abundance scalings (Burkhart et al. 2013)

- At low densities and optical depths the molecule is hardly excited; at high optical depths the variation of the velocity structure along the line of sight dominates the integrated line intensities.



Radiative transfer effects

Impact on column density PDFs:



PDFs of integrated ^{13}CO 2-1 intensities using different density and abundance scalings (Burkhart et al. 2013).

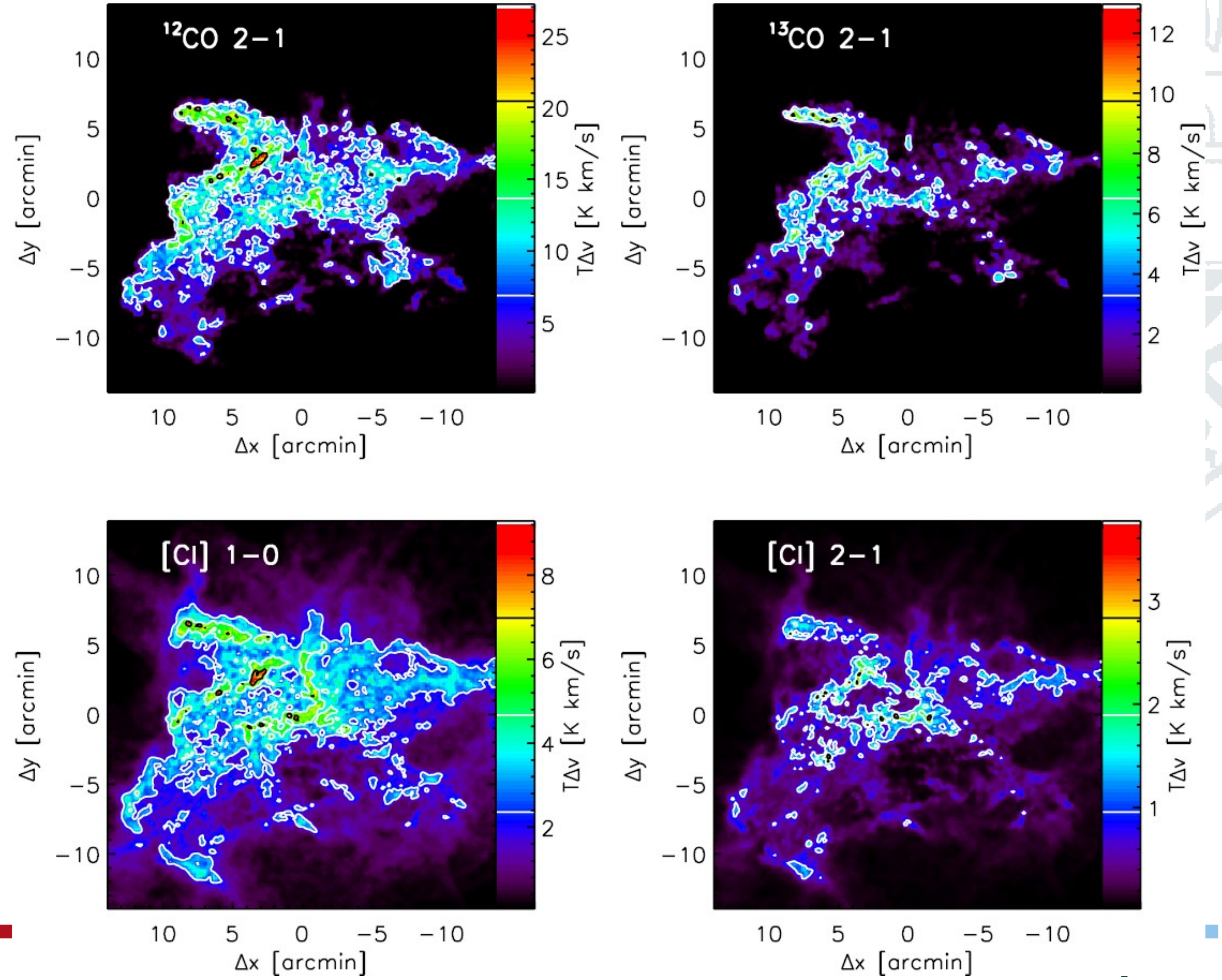
- At low Mach number (weakly driven turbulence) the lines trace column density
- At higher Mach number velocity structure and excitation dominate the line-PDFs

More complications

Non-equlibrium chemistry

→ Phase transition from atomic to molecular carbon

- full MHD model coupled with small chemical network and escape probability radiative transfer (Glover 2010, Shetty et al. 2011)

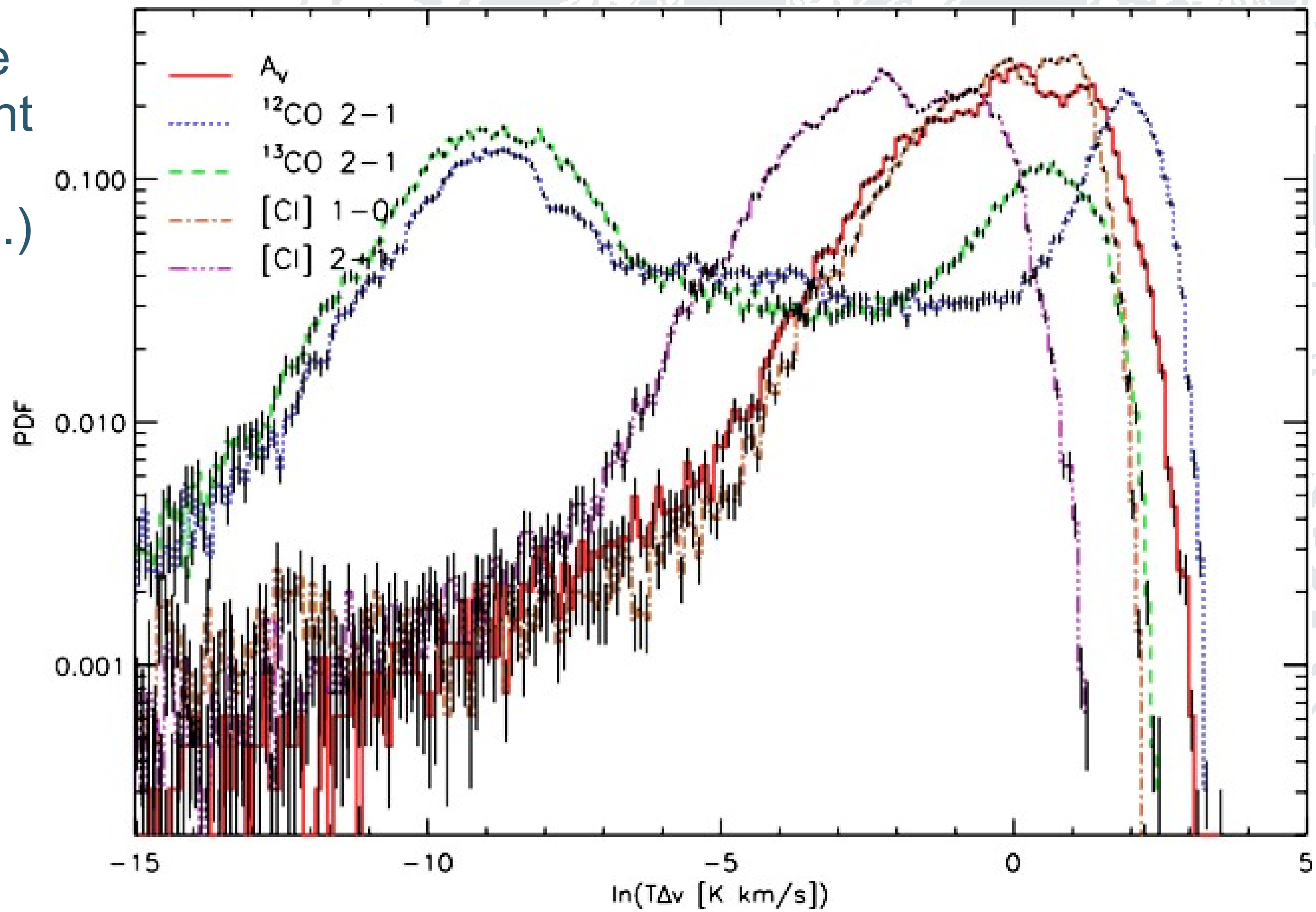


GADGET simulation of chemical structure in irradiated, turbulent molecular cloud (Molina et al, in prep.)

With phase-transitions

Phase transition from atomic to molecular carbon

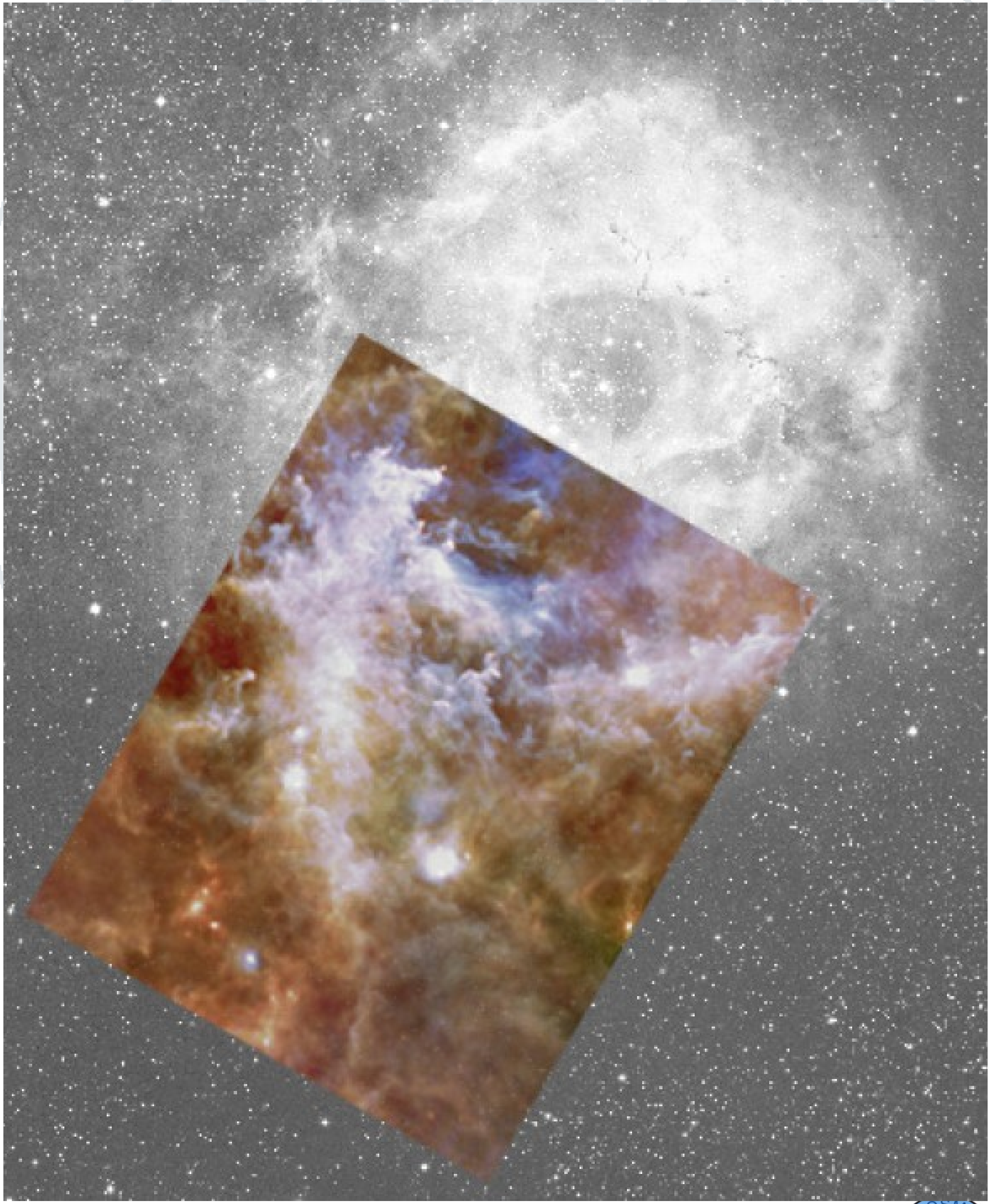
- GADGET simulation of chemical structure in irradiated, turbulent molecular cloud (Molina et al, in prep.)



- None of the typical molecular line tracers measures the true column density PDF
- The [CI] 809GHz line is best representing the global column density PDF

Column density PDFs

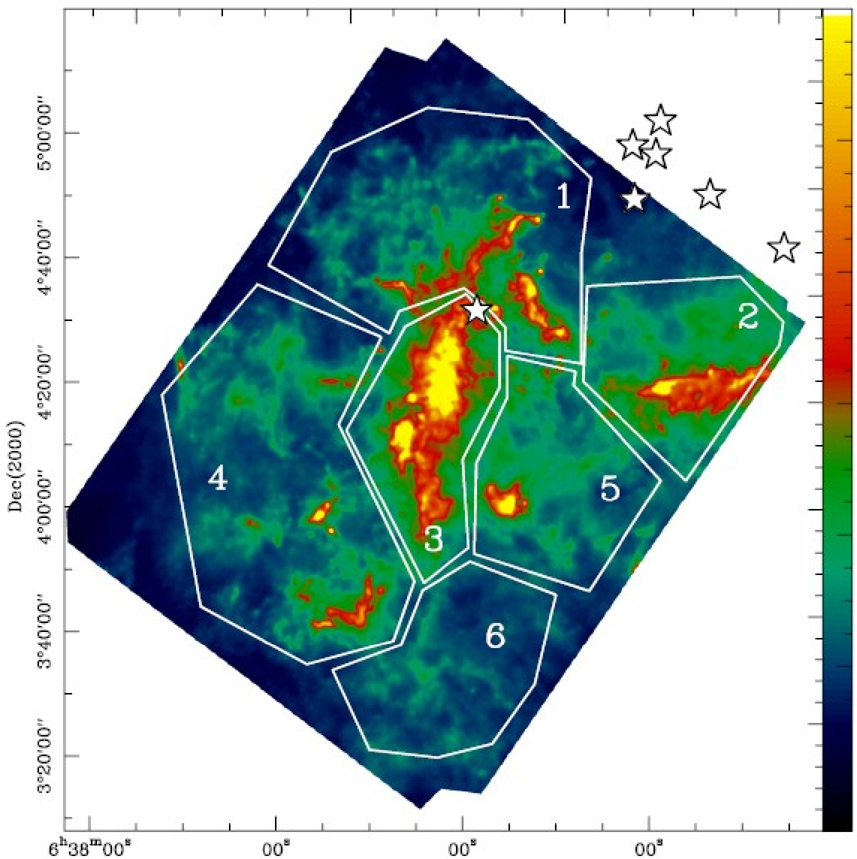
Rosette:

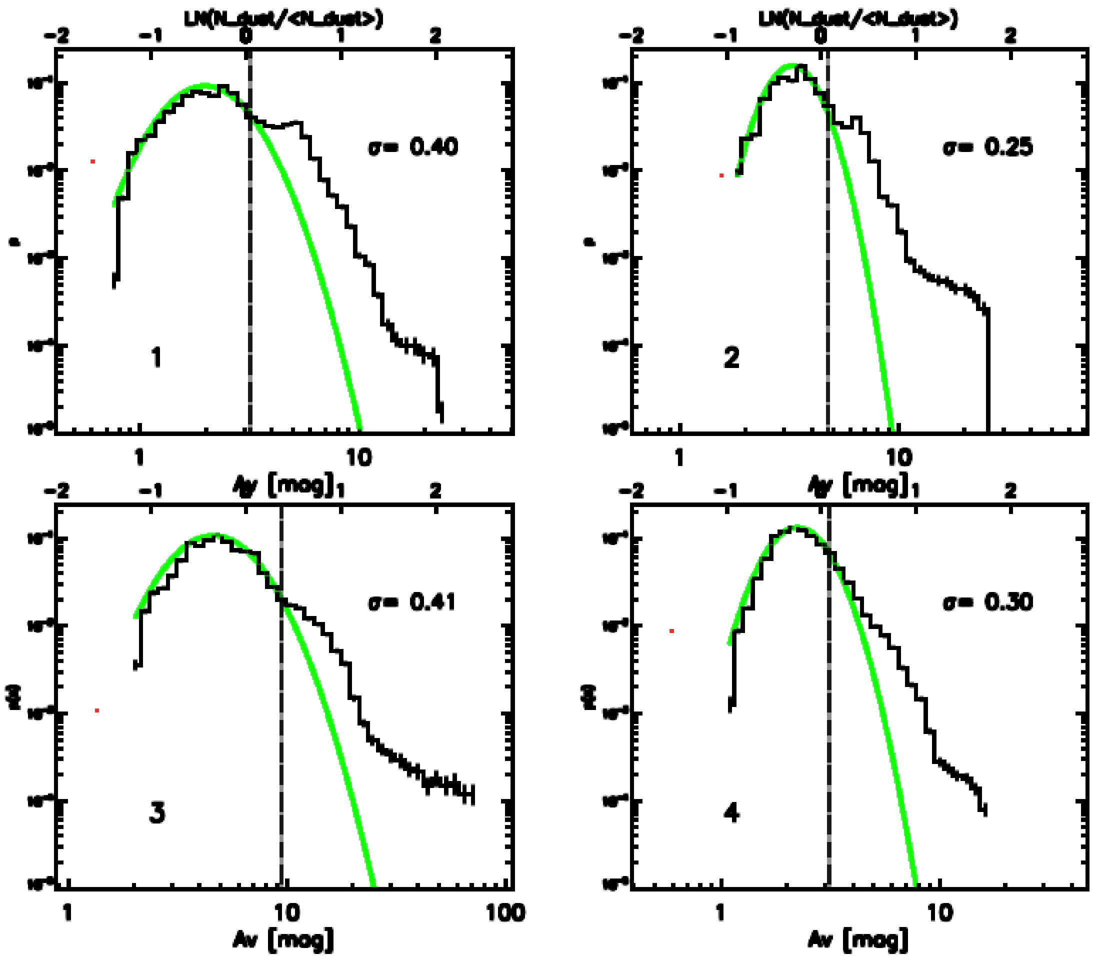


Extinction map from Herschel observations (Motte et al. 2010, Schneider et al. 2011)

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)

Trace SF by measuring the spatial scaling

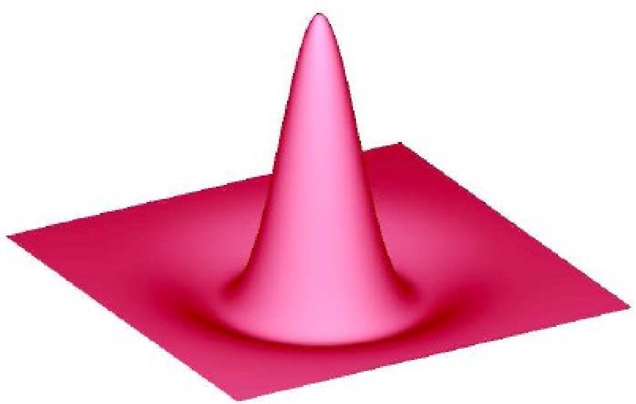
Measure the spatial density and velocity structure of interstellar clouds

Δ-variance: Probe the amount of structural variation on a scale l:

- Filter the structure by a radially symmetric wavelet $\odot_l(\vec{r})$ with a length scale l
- Compute the total variance in the convolved image depending on filter size l

$$\sigma_\Delta^2(l) = \left\langle \left(f(\vec{r}) * \odot_l(\vec{r}) \right)^2 \right\rangle_{\vec{r}}$$

French hat Δ-variance wavelet



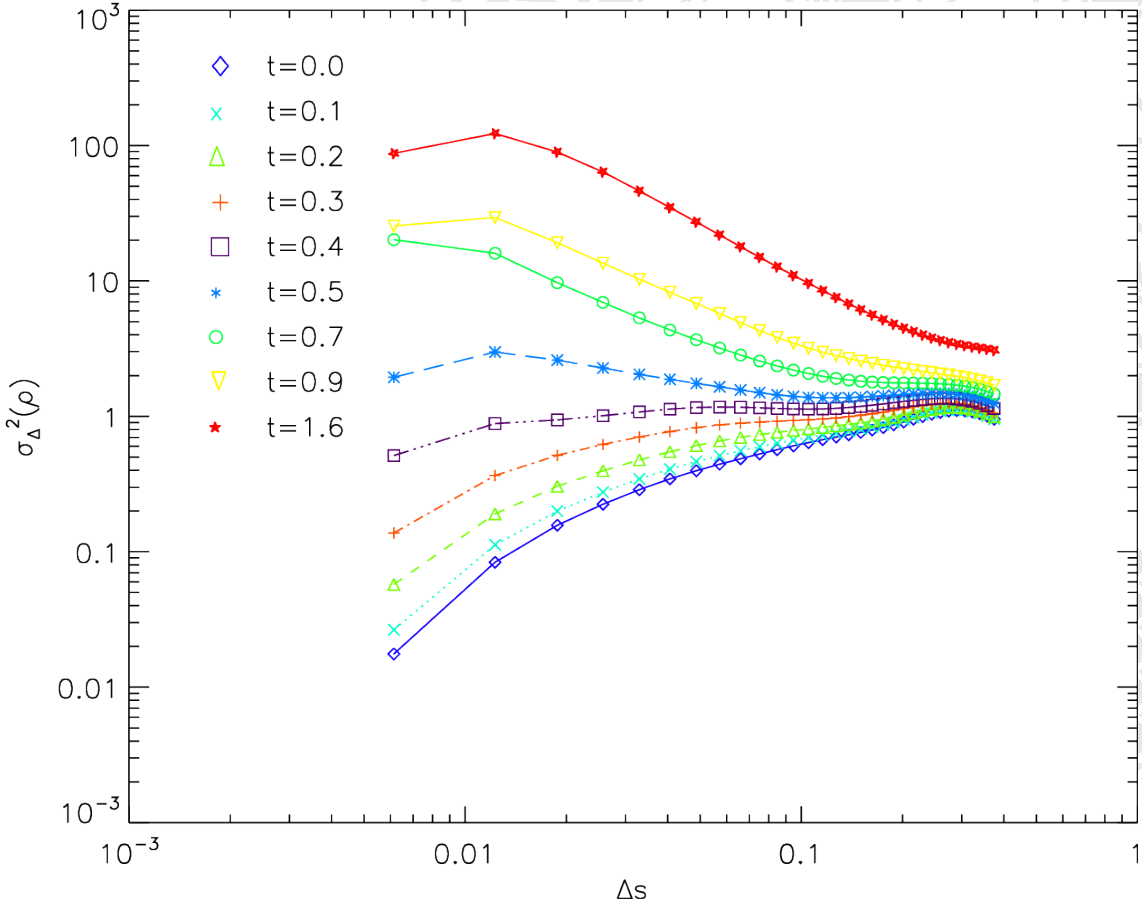
Mexican hat Δ-variance wavelet

Stutzki et al. (1998), Ossenkopf, Krips, Stutzki (2008a,b)

Trace SF by measuring the spatial scaling

Impact of gravitational collapse on Δ-variance spectrum:

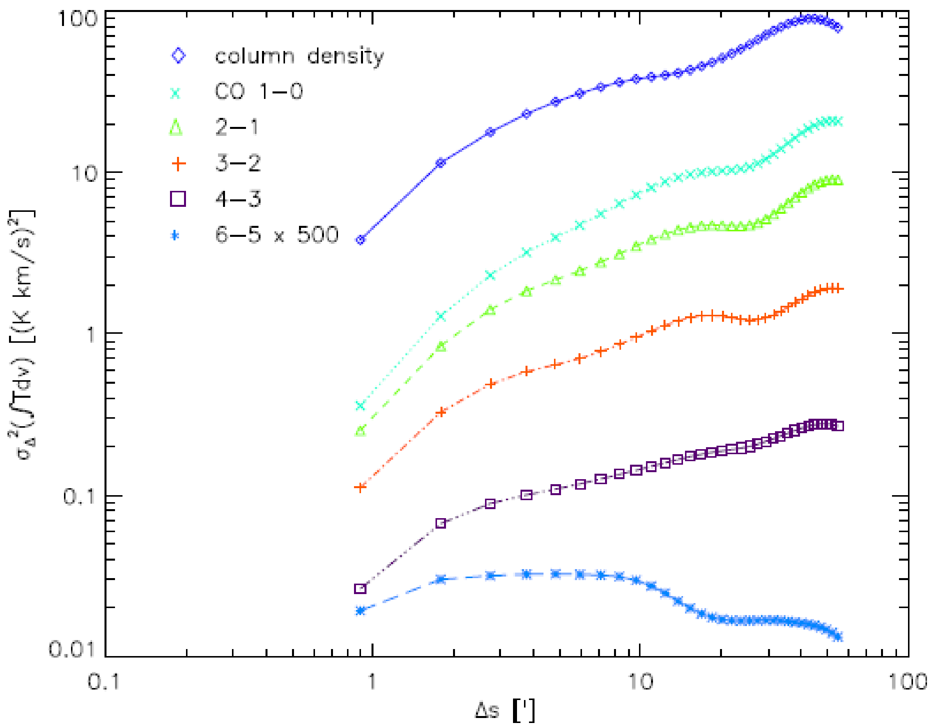
- Relative increase of small-scale structures



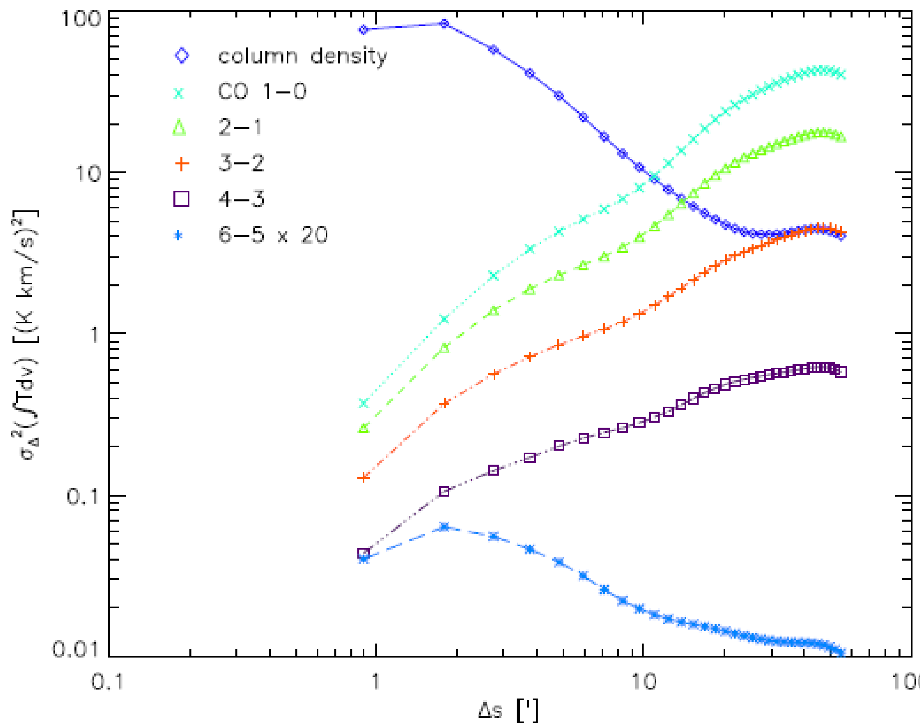
Evolution of the Δ-variance of the column density maps of a collapsing turbulent molecular cloud (SPH simulation, Ossenkopf et al. 2001)

Radiative transfer effects

•



Δ-variance spectra for maps of a large-scale driven turbulence model (MacLow et al. 1998, Ossenkopf 2002)



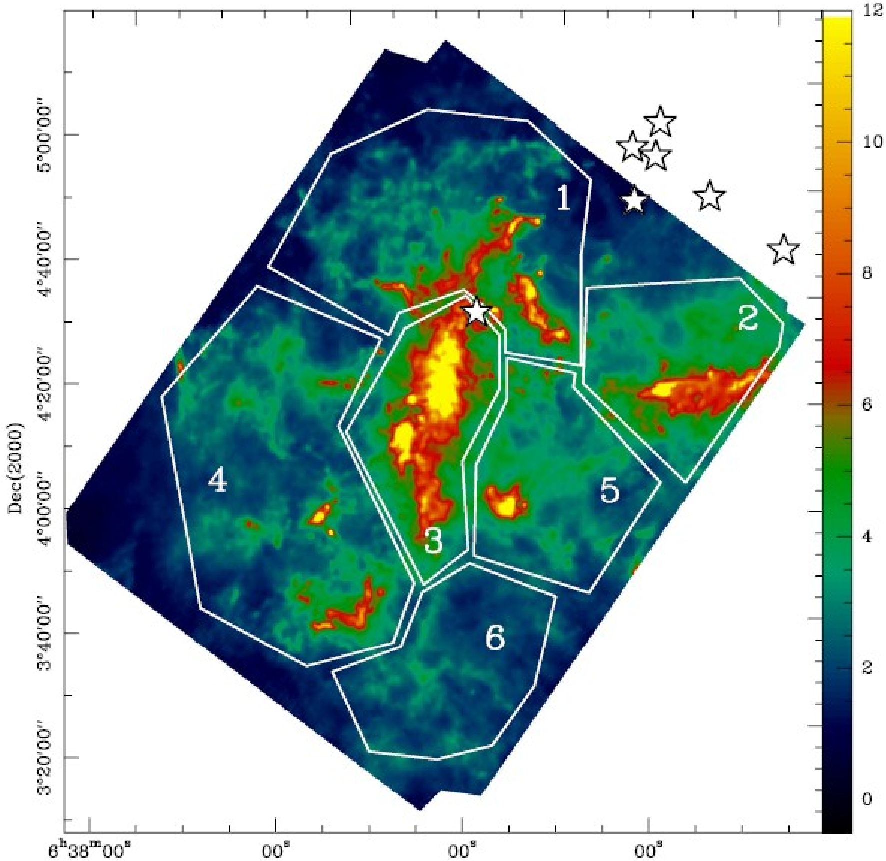
Δ-variance spectra for maps of a gravitationally collapsed model (Klessen et al. 2001, Ossenkopf 2002)

- The low-J CO transitions always trace the large scale distribution only.
- High-J transitions "see" the dense clumps

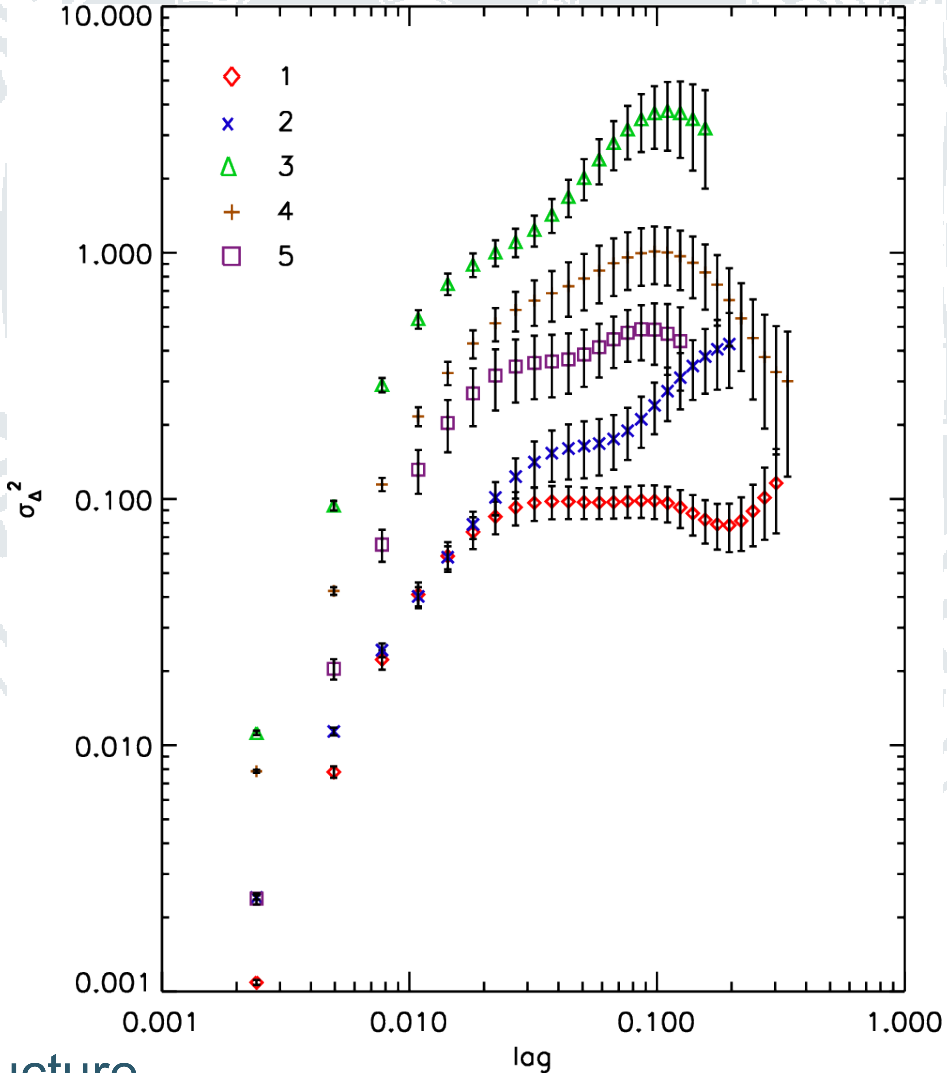
→ **no diagnostics of true density structure or gravitationally collapse state**

Δ-variance spectra

Column densities in Rosette:

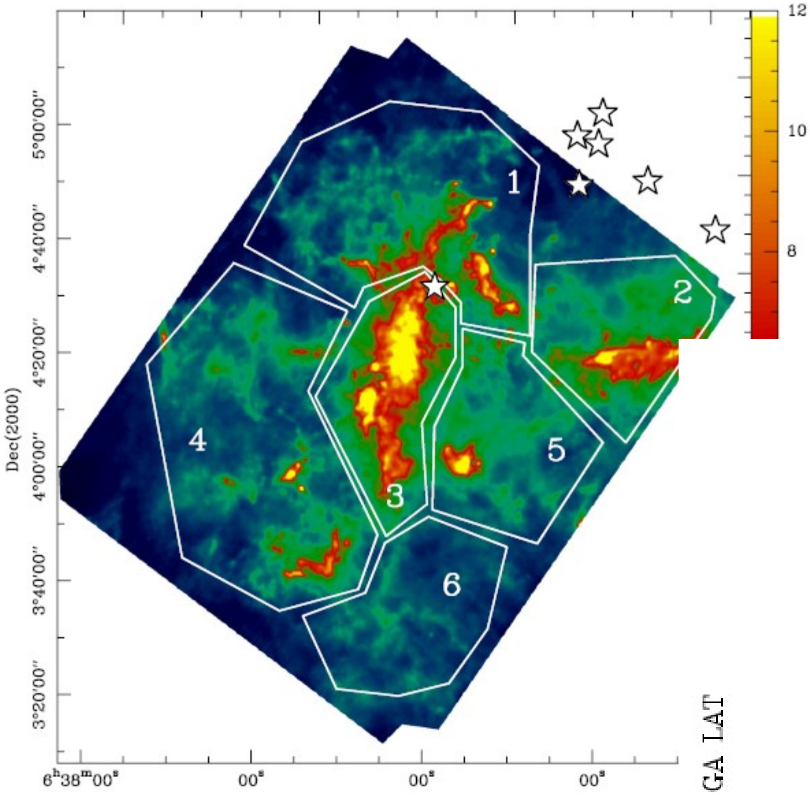


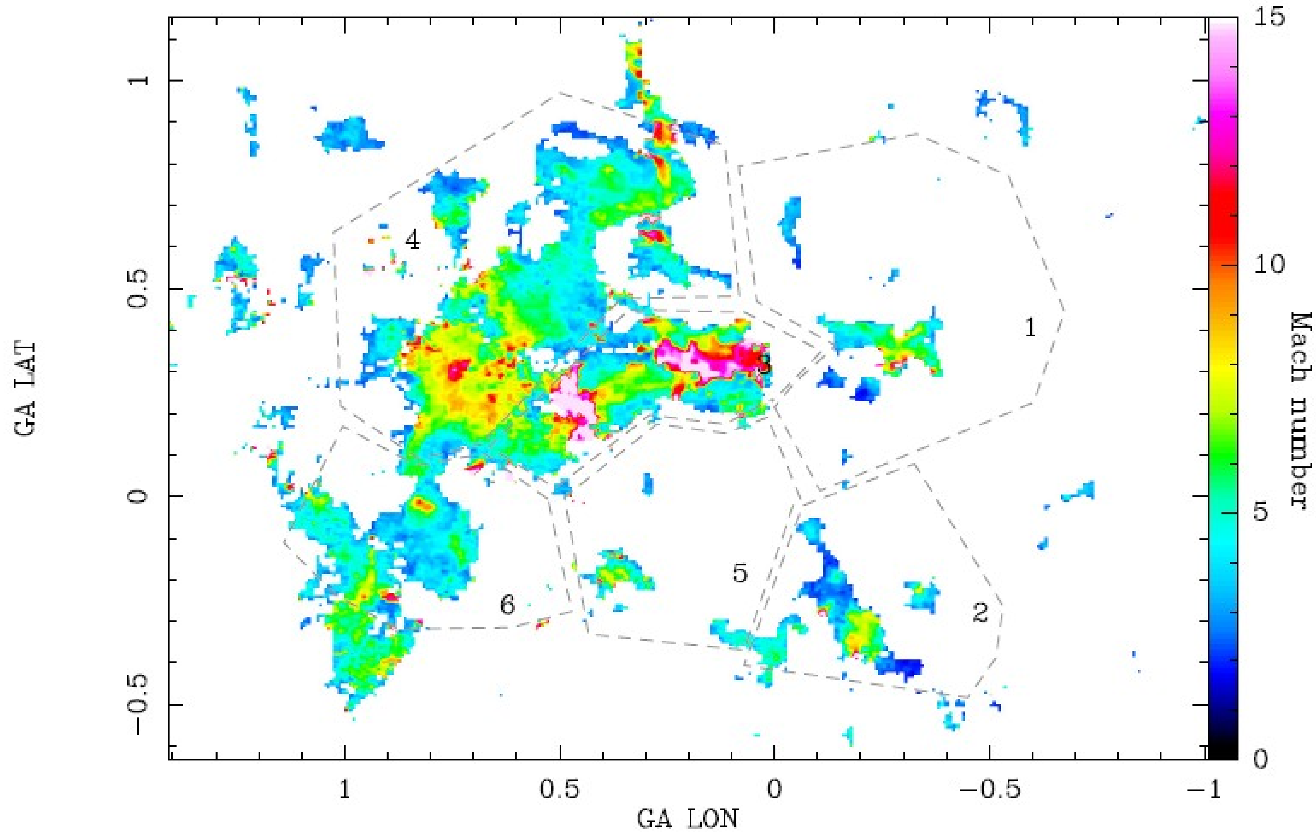
(Schneider et al. 2011)



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

The velocity structure





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

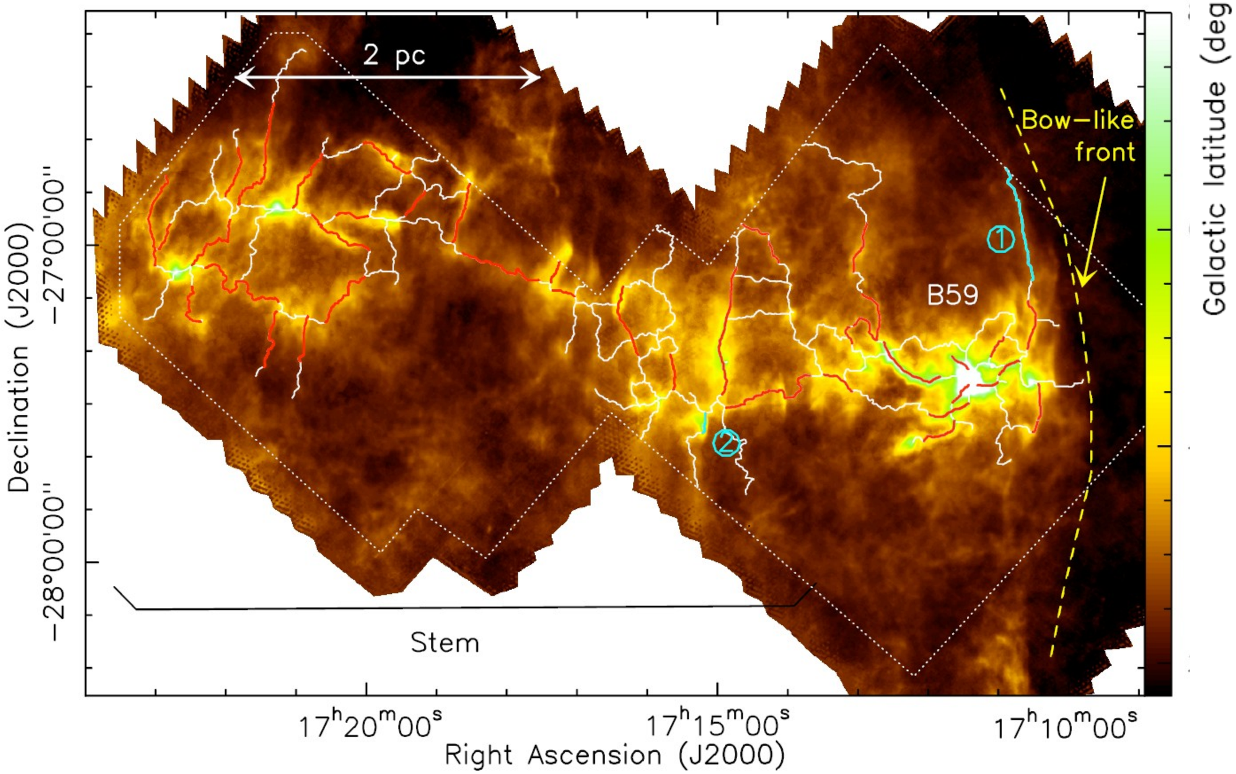
- Very localized line broadening at PDR surface
  - Affects little gas volume
- Main line broadening from ongoing SF activity in center region

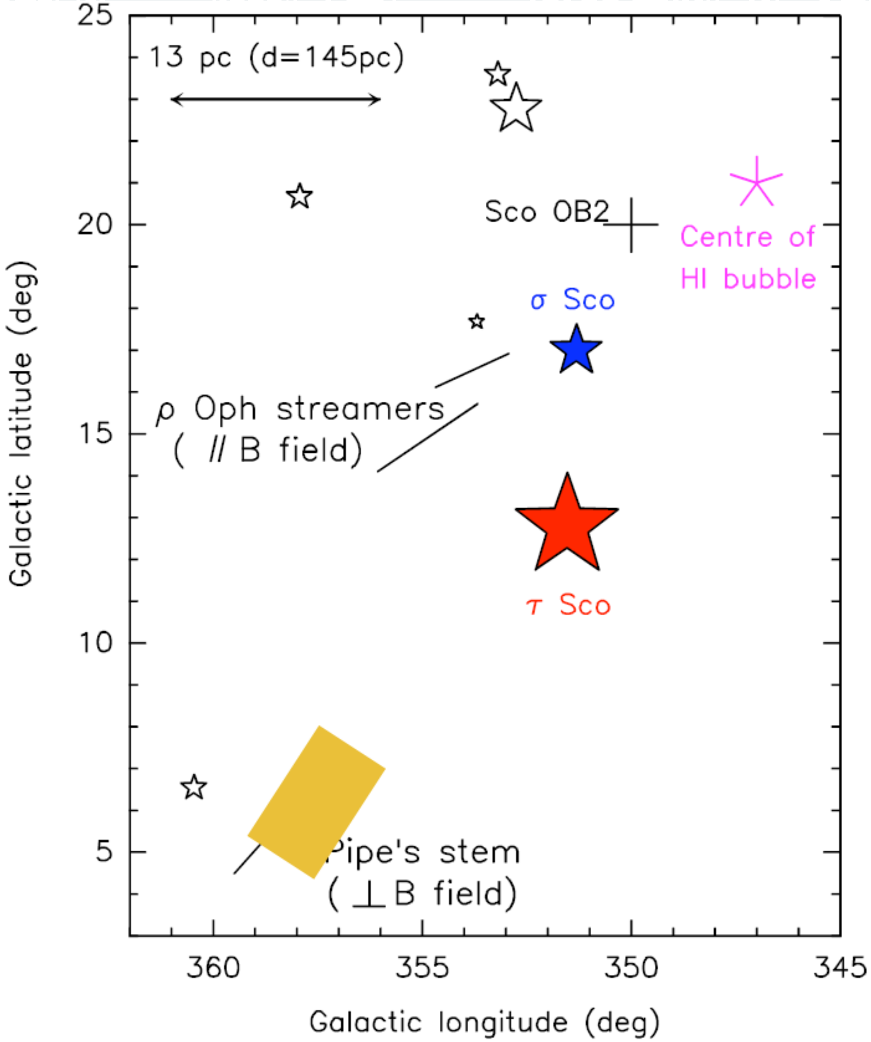
More cases?

Pipe Nebula:

Star formation along filaments

- Dominated by B-field direction, not radiation field!





SF in filaments in the Pipe Nebula: Peretto et al. (2012)

Summary

- UV creates local heating and streams but no large-scale collapse
- Significant dispersion of gas
- Triggered SF can occur at the expanding interfaces of HII regions in case of favourable conditions
  - But: Pillar formation rarely means star-formation triggering ?

- **Statistically, there is 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
  - Must not be mistaken for mutual triggering in SF sequence

➢ Role of magnetic field to be explored