Observing turbulence in chemical phase transitions

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The start – building on the heritage of the Δ-variance

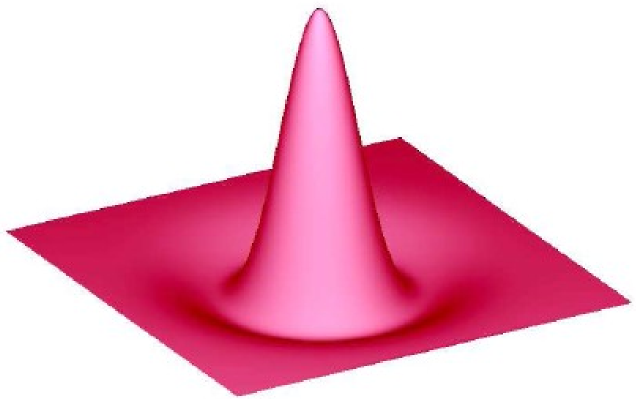
Measure the spatial density and velocity structure of interstellar clouds

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 (2008)

The Δ-variance

The Δ-variance is related to the power spectrum:

$$\sigma_\Delta^2(l) = \int_0^\infty P(|\vec{k}|)\,\left|\tilde{\odot}_l(|\vec{k}|)\right|^2 |\vec{k}|\, d|\vec{k}|$$

☞ Fixed relation between exponents of Δ-variance spectrum and power spectrum:

$\alpha = \beta - E$ (in E dimensions).

$$\alpha = \beta - 2 \quad \text{in } 2-\text{D}$$
$$\alpha = \beta - 3 \quad \text{in } 3-\text{D}$$

But computation can use significance/weighting function *w(**r**)*:

$$G_{l,\text{core}}(\boldsymbol{r}) = f_\text{padded}(\boldsymbol{r}) * \underset{l,\text{core}}{\odot}(\boldsymbol{r}')$$
$$G_{l,\text{ann}}(\boldsymbol{r}) = f_\text{padded}(\boldsymbol{r}) * \underset{l,\text{ann}}{\odot}(\boldsymbol{r}')$$
$$W_{l,\text{core}}(\boldsymbol{r}) = w(\boldsymbol{r}) * \underset{l,\text{core}}{\odot}(\boldsymbol{r}')$$
$$W_{l,\text{ann}}(\boldsymbol{r}) = w(\boldsymbol{r}) * \underset{l,\text{ann}}{\odot}(\boldsymbol{r}')$$

→

$$\sigma_\Delta^2(l) = \frac{\sum_\text{map} (F_1(\boldsymbol{r}) - \langle F_1 \rangle)^2 W_{l,\text{tot}}(\boldsymbol{r})}{\sum_\text{map} W_{l,\text{tot}}(\boldsymbol{r})}$$

with

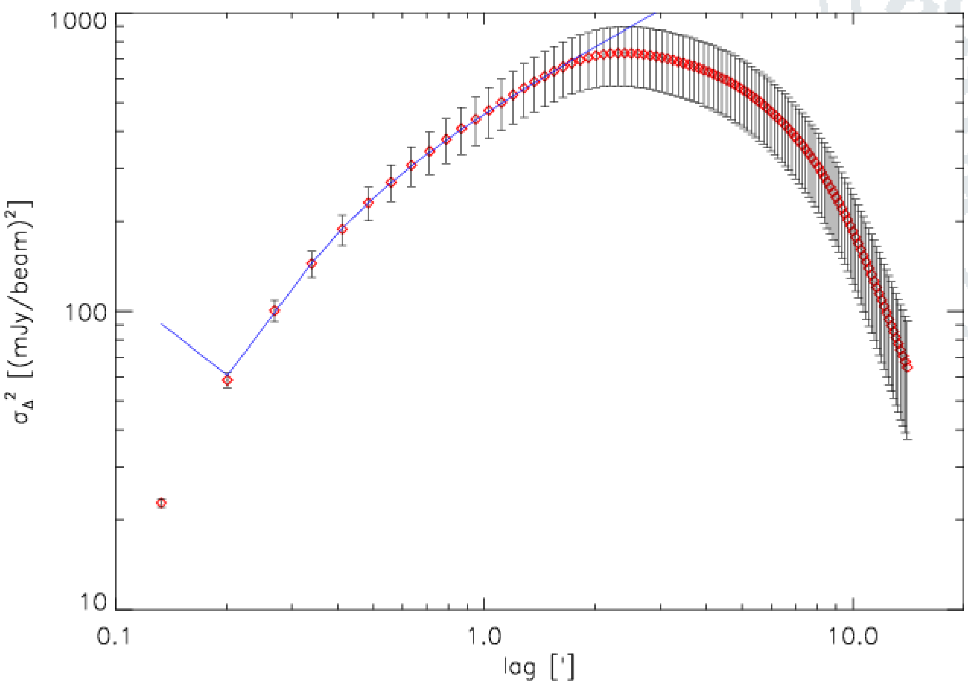
$$F_1(\boldsymbol{r}) = \frac{G_{l,\text{core}}(\boldsymbol{r})}{W_{l,\text{core}}(\boldsymbol{r})} - \frac{G_{l,\text{ann}}(\boldsymbol{r})}{W_{l,\text{ann}}(\boldsymbol{r})}$$

$$W_{l,\text{tot}}(\boldsymbol{r}) = W_{l,\text{core}}(\boldsymbol{r}) W_{l,\text{ann}}(\boldsymbol{r})$$

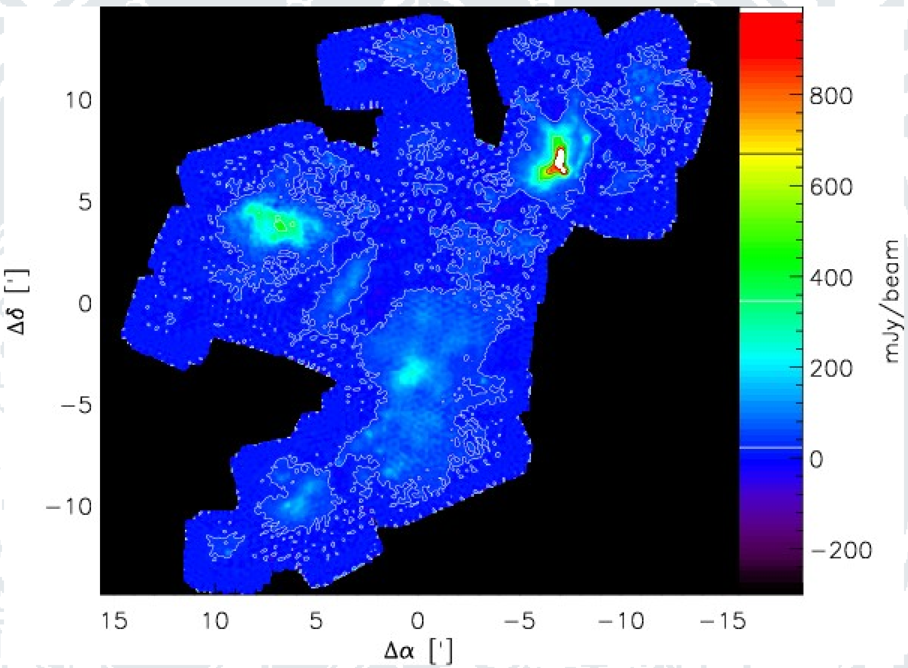
The Δ-variance

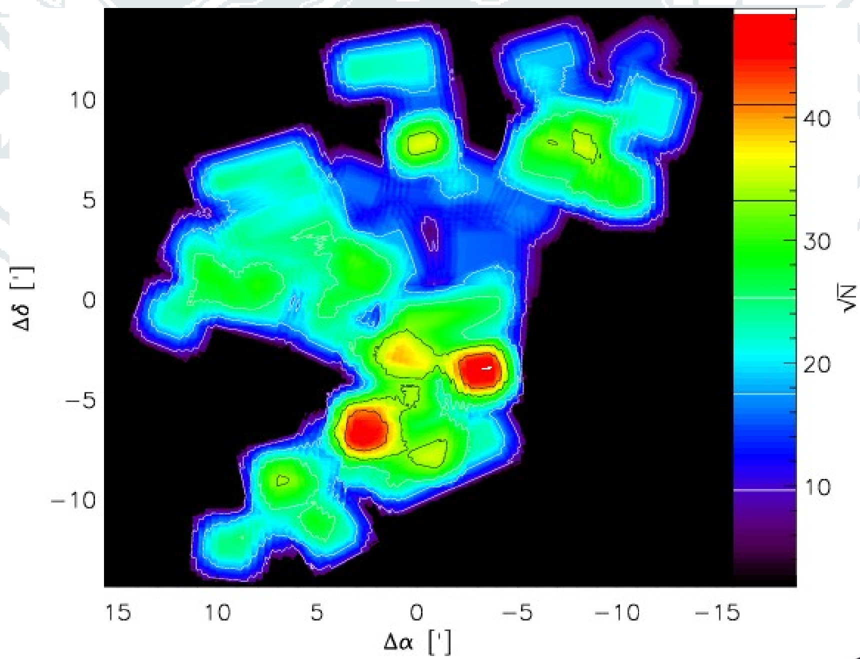
Use of the weighting function pre-requisite to deal with real observational data:

- Include effect of variable noise across the map
- Avoid edge-effects from finite map size



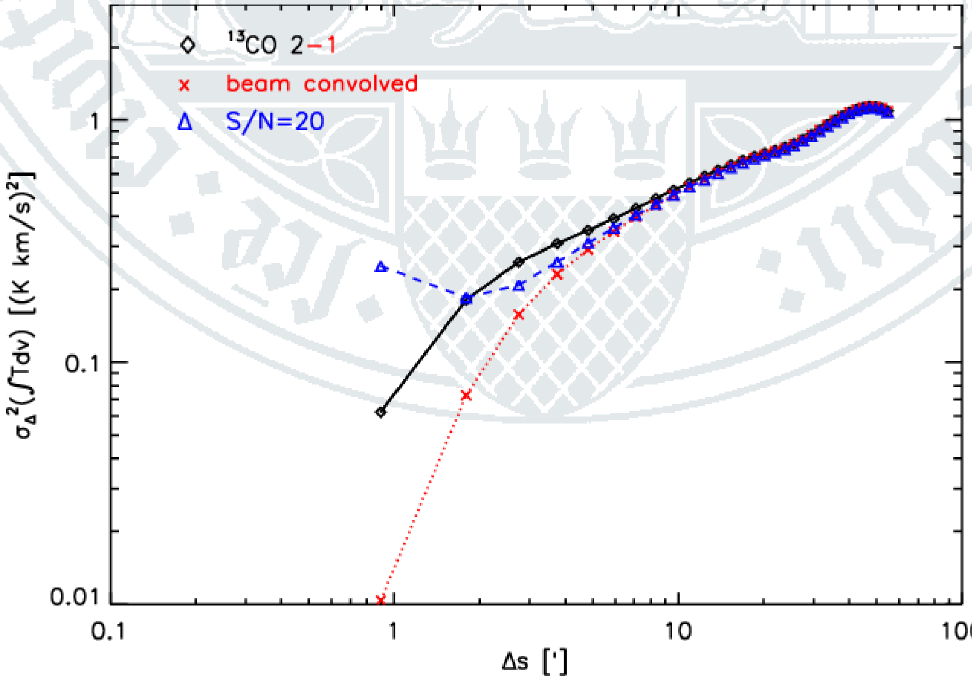
Δ-variance spectrum of 1.2 mm dust continuum map of ρ Oph by Motte et al. (1998) including irregular boundaries and a variable noise





Main advantages of the Δ-variance

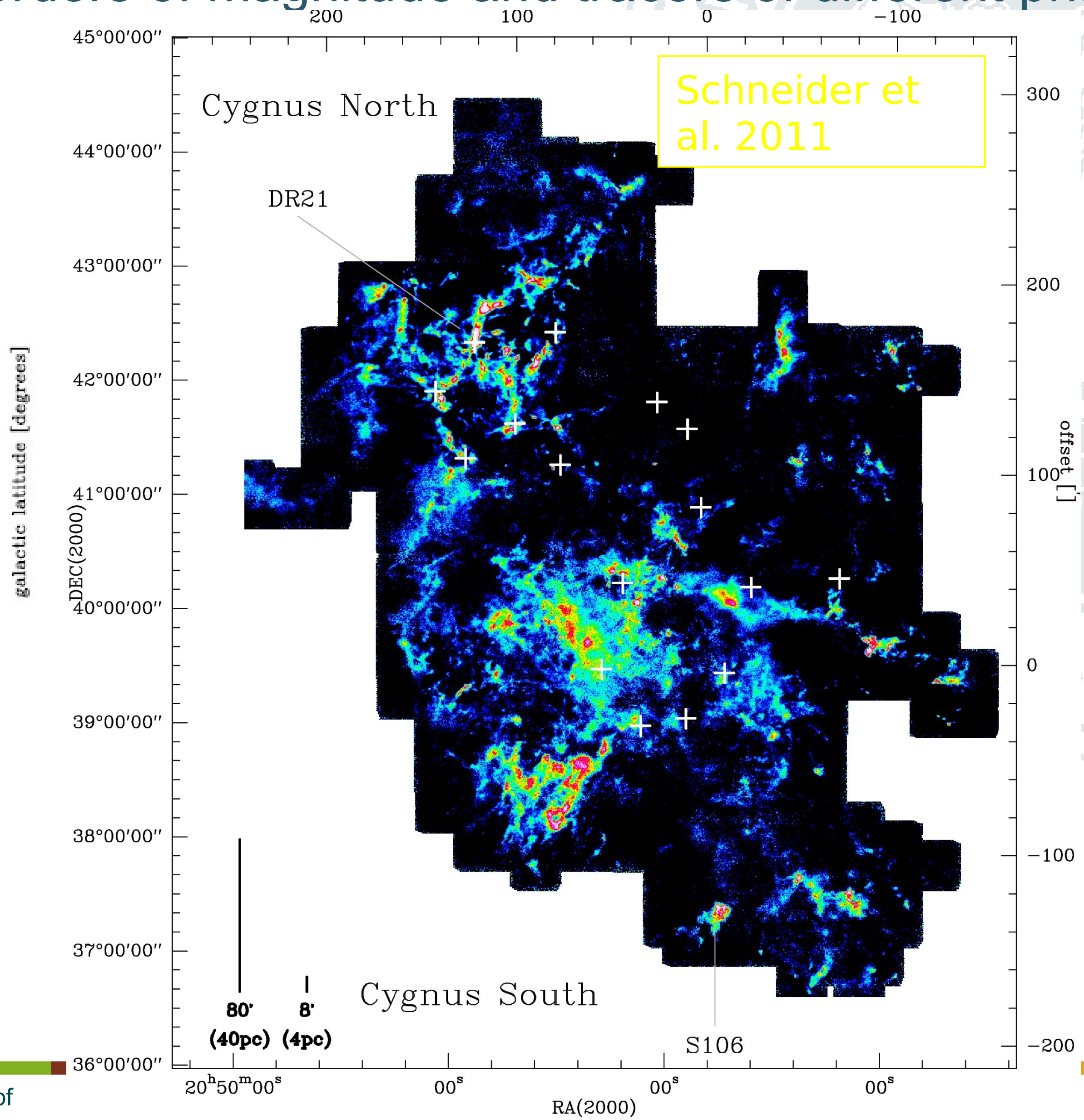
- Insensitive to
  - edge effects,
  - finite map sizes,
  - truncation of emission in the mapped area,
  - irregular boundaries
- Inclusion of information on reliability of every individual data point
- Analytic description of impact observational artifacts
  - from telescope beam smearing
  - instrumental noise.
- Extends usable dynamic range.



Impact of finite telescope beam and the typical S/N of observed data on the Δ-variance spectrum of a simulated, fully sampled ^{13}CO 2-1 map from an HD turbulence simulation.

Applications

Measure spatial scaling relations over a dynamic range covering more than three orders of magnitude and tracers of different phases of the ISM.



Cygnus X region as seen at 8 μm by MSX overlaid with FCRAO ^{13}CO 1→0 emission as black contours.

Eventually measured ^{13}CO 1→0 map tracing the molecular gas

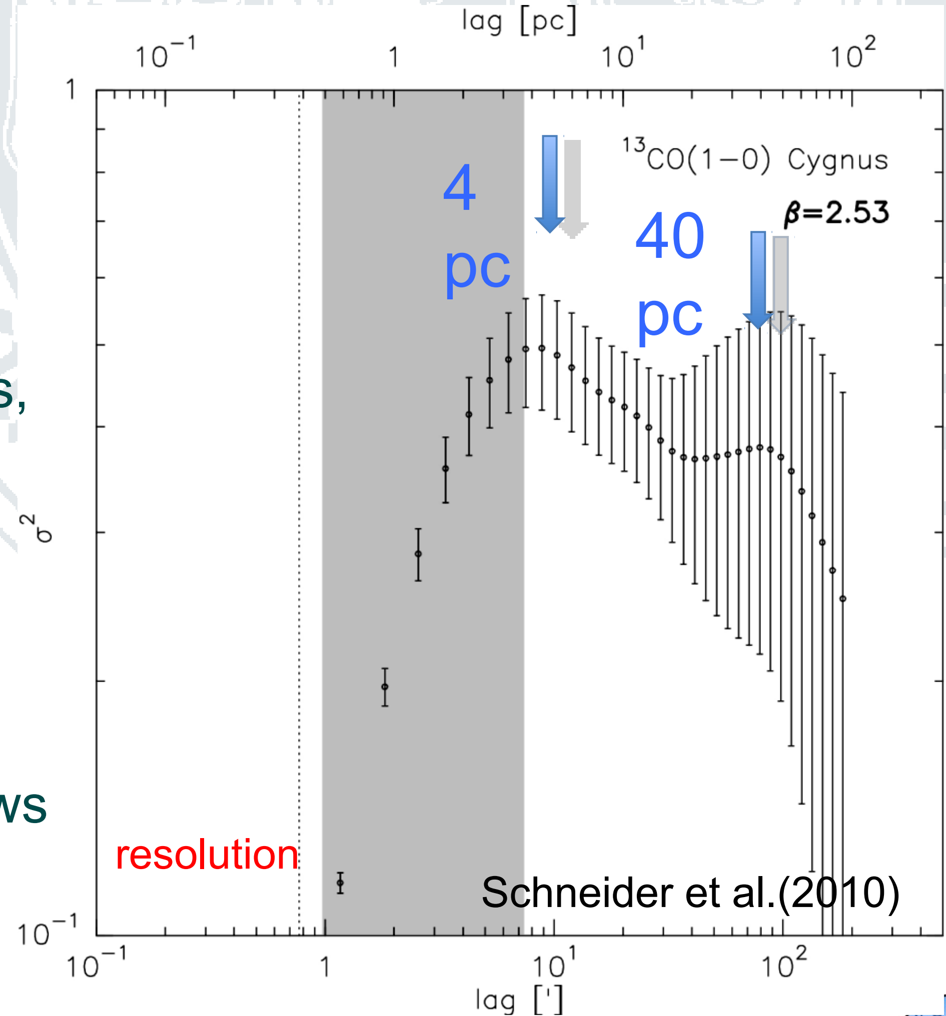
Applications

Characteristic scales:

- Self-similarity only in very small dynamic range
  - β measured from resolution limit to first dominant scale

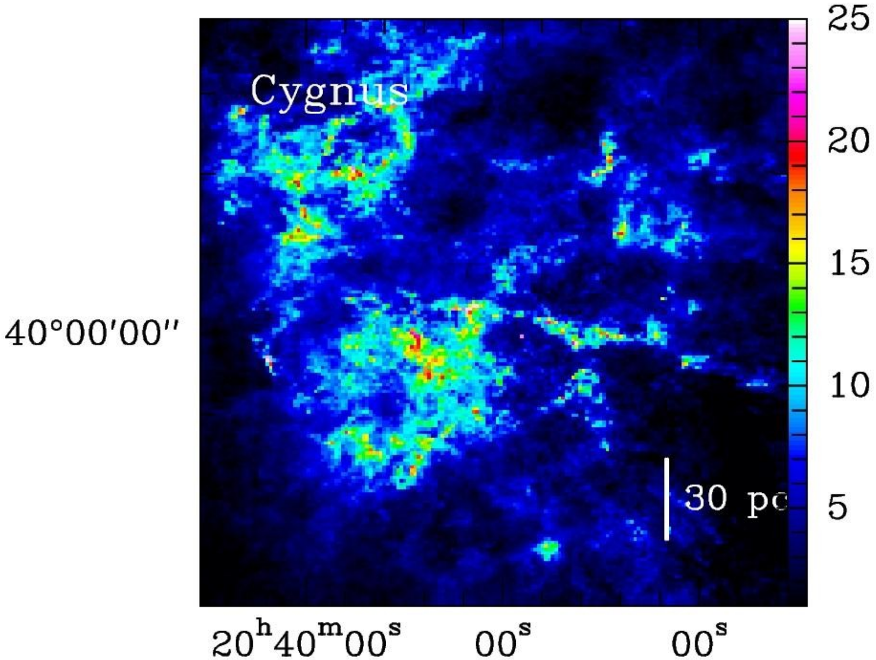
Origin of characteristic scales:

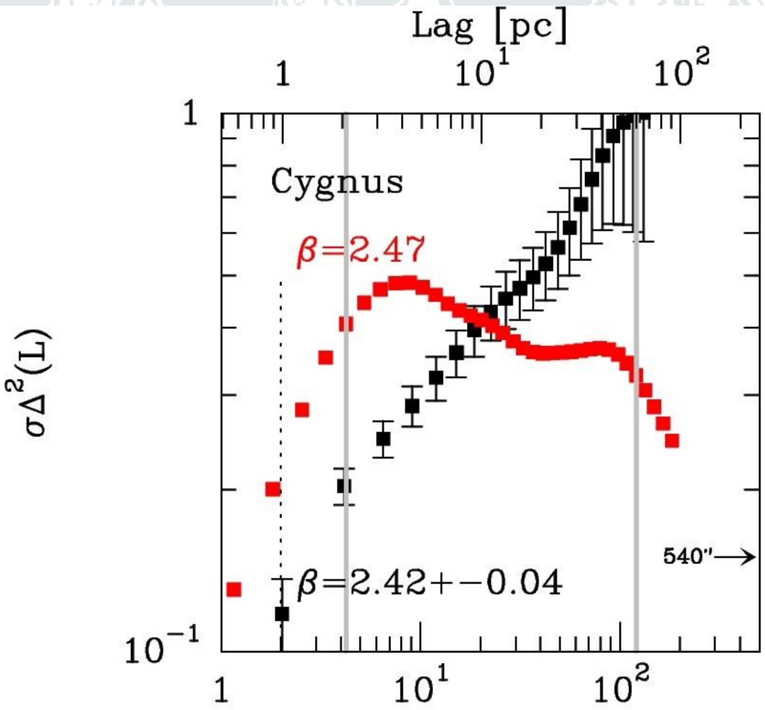
- geometry (e.g. length/width of filaments)
  - Typical width of filaments is 0.1 pc,
    - corresponds to the sonic scale
- energy injection scales due to SNR shells, outflows, HII-regions ...
  - 4 pc could be the scale where the systematic velocity from a SN shock turns into turbulence
- tracer turns optical thick
  - peak in the Δ-variance spectrum shows
  - the ^{13}CO „photosphere“
  - at column densities > 10^{22} cm^{-2}



Dust and molecules

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





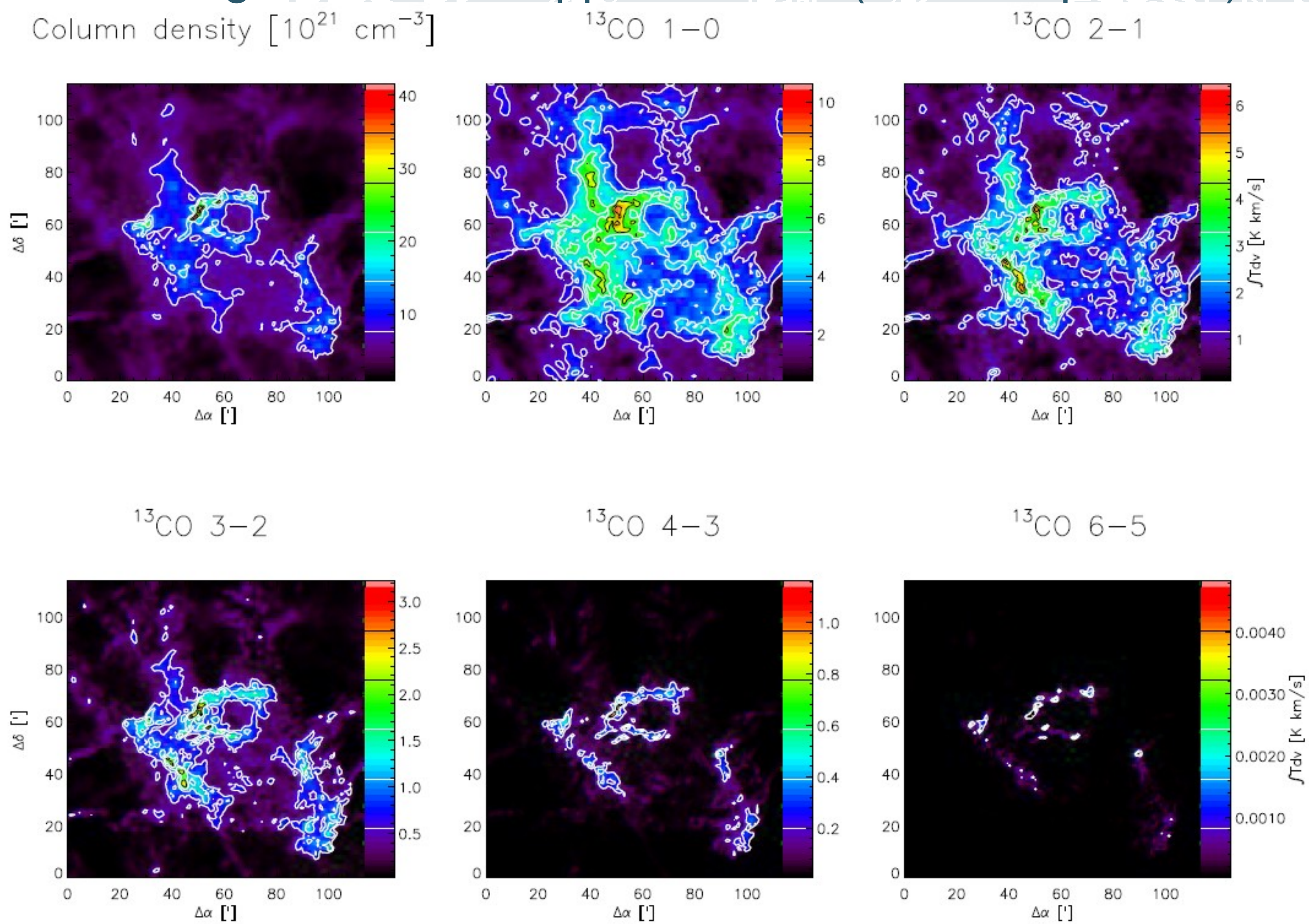
- The dust distribution follows a self-similar relation up to the size of the whole region

→ Prominent scales in ^{13}CO due to

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

Radiative transfer effects

Full 3-D line radiative transfer using a two scale-approximation (Ossenkopf 2002):

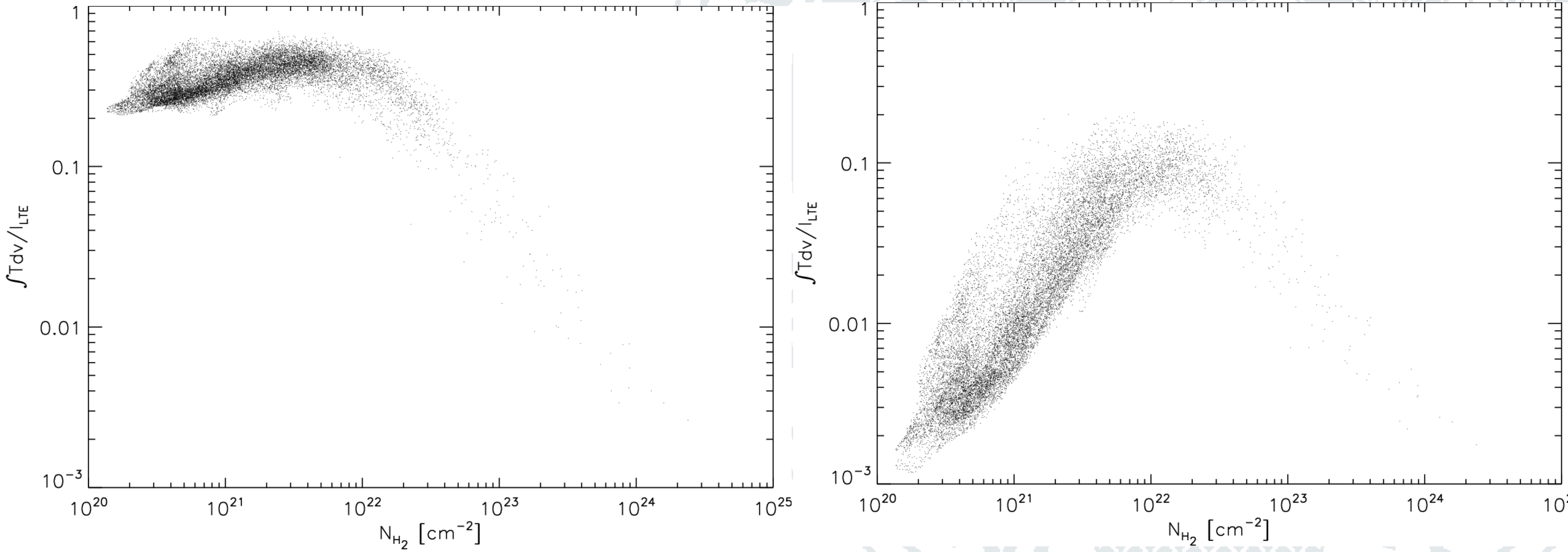


Column density and ^{13}CO mapsin different transitions for a large-scale driven hydrodynamic turbulence model (Heitsch et al. 2001).

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

The X factor

Radiative transfer results in a variable conversion from column density to ^{13}CO brightness for every pixel:



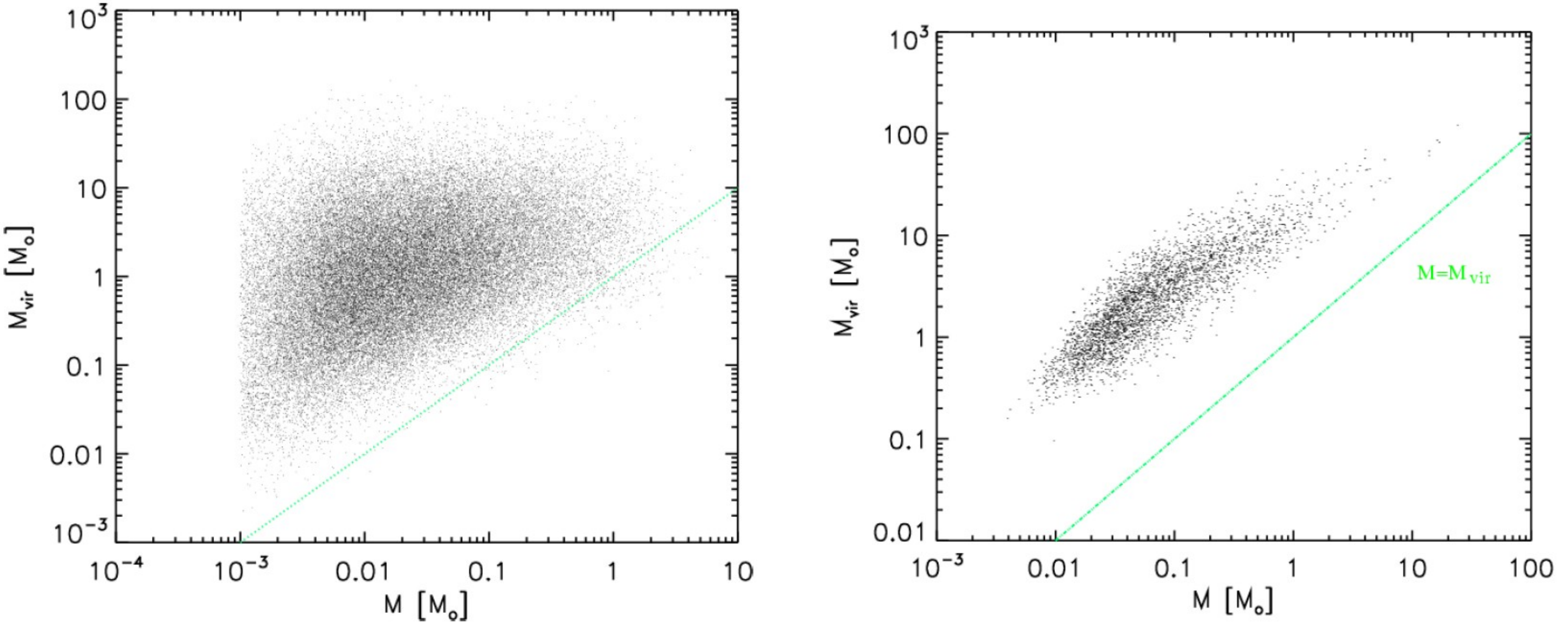
Integrated intensity of the ^{13}CO 1-0 (left) and 3-2 (right) transitions relative to the line-of-sight integrated LTE emissivity as a function of the column density in a collapsing large-scale turbulence model.

- Low-*J* lines turn optically thick above 10^{22} cm^{-2}
- Higher-*J* lines are sub-thermally excited at low densities

→ **Molecular lines are sensitive to a narrow density interval only**

Side effect: pseudo-virialization

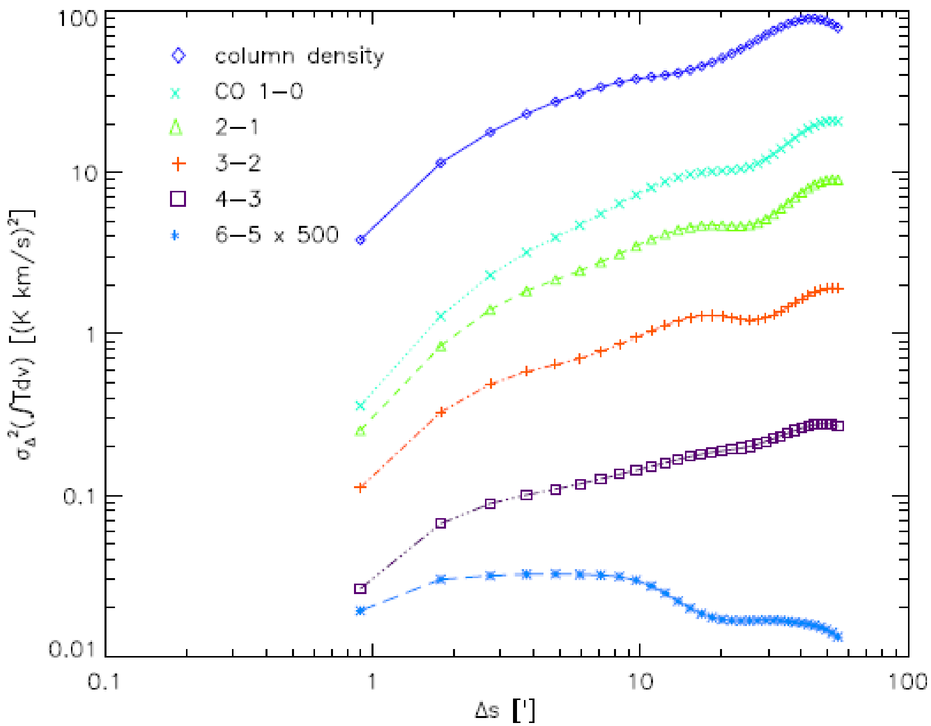
Result of a GAUSSCLUMPS decomposition of the original 3-D density cubes and the simulated position-velocity cubes:



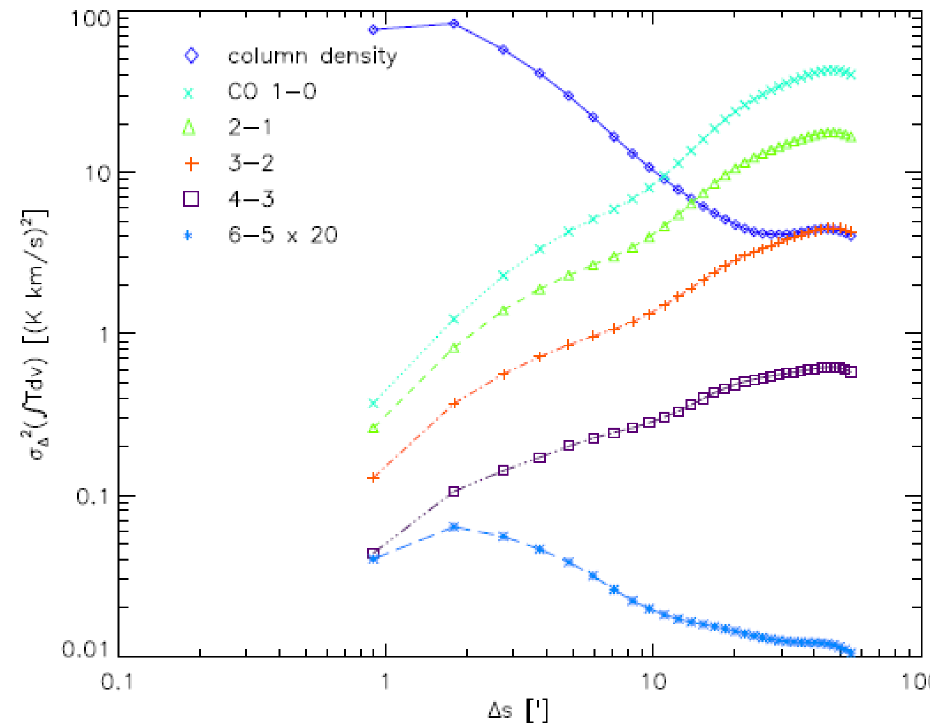
Virial mass versus actual mass for the clumps found in the original density structure and versus the mass obtained from the corresponding ^{13}CO 1-0 intensities in the computed line map assuming an LTE conversion factor.

The column density truncation by optical depth effects creates clumps that artificially follow a virial-equilibrium relation.

Δ-variance spectra



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**

The velocity structure

The Δ-variance can be applied in the same way to velocities

- Velocity channel analysis (VCA, see Sun et al. 2006)
- Centroid maps

Centroids contain the convolved information about density and velocity variations:

The Δ-variance spectrum is dominated by two terms:

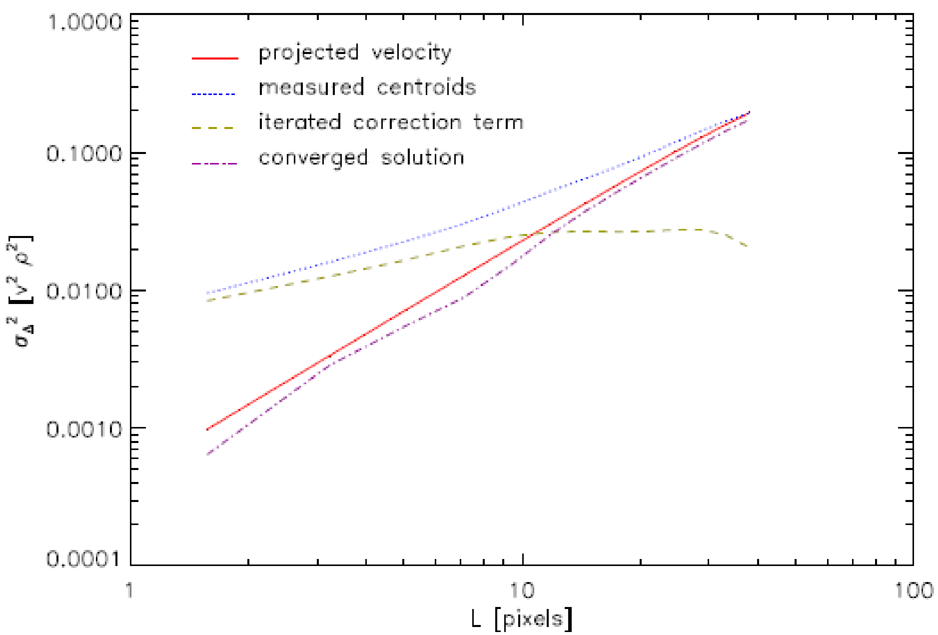
$$\sigma^2_{\Delta,v_c} \propto \rho_0^2 \left\langle \int dz\, \delta v(\vec{x}) \times \int dz\, \delta v(\vec{x}+\vec{l}) \right\rangle_{\vec{x}} + \left\langle \int dz\, \delta\rho(\vec{x})\delta v(\vec{x}) \times \int dz\, \delta\rho(\vec{x}+\vec{l})\delta v(\vec{x}+\vec{l}) \right\rangle_{\vec{x}}$$

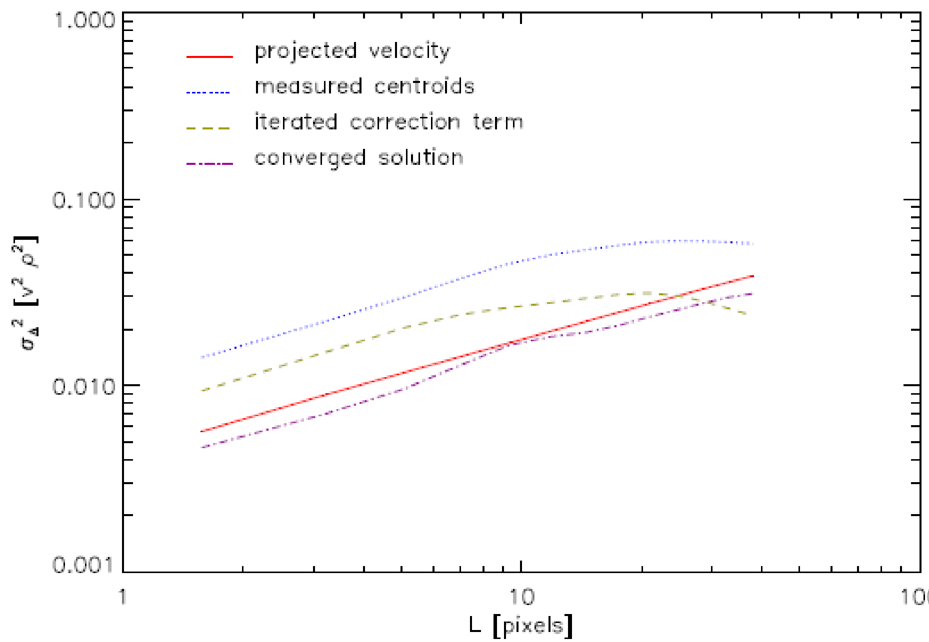
There is no direct match between line centroid scaling and the properties of the underlying turbulent velocity field.

The velocity structure

When assuming 3-D isotropy, deconvolution of the true velocity spectrum is possible when knowing

- the centroid spectrum
- the projected density spectrum
- the average density



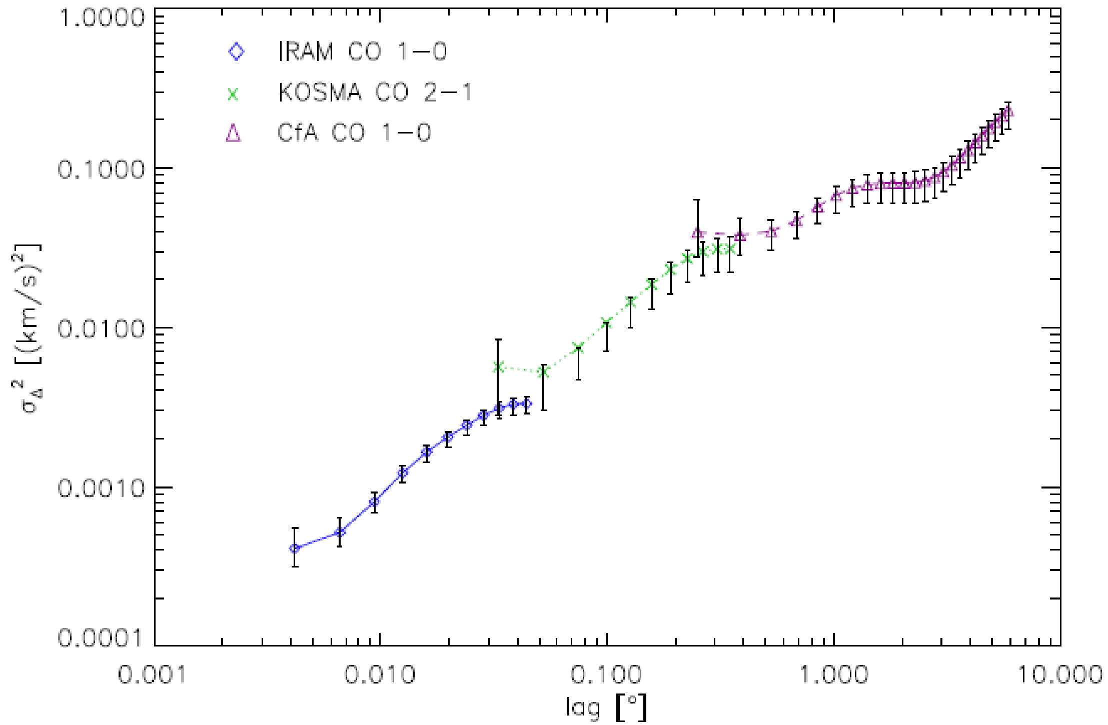


The dash-dot line demonstrates the reconstruction of the underlying velocity scaling from the centroid map. Left: $\beta_{\text{density}} = 2.6$, $\beta_{\text{velocity}} = 3.7$, right: $\beta_{\text{density}} = 3.7$, $\beta_{\text{velocity}} = 2.6$, $\langle\rho\rangle = 1/4\sigma$.

Ossenkopf, Esquivel, Lazarian, Stutzki (2006)

The velocity structure

Application:

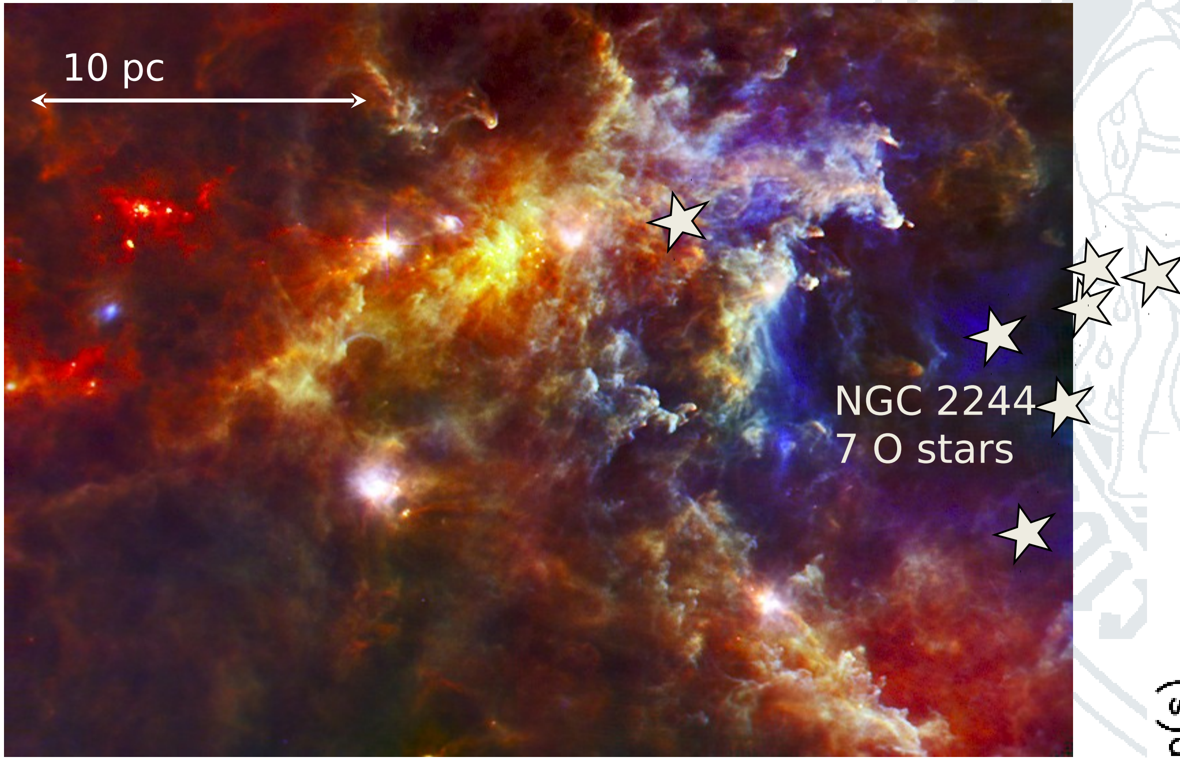


Centroid velocity Δ-variance spectra for nested maps of CO observations in the Polaris Flare

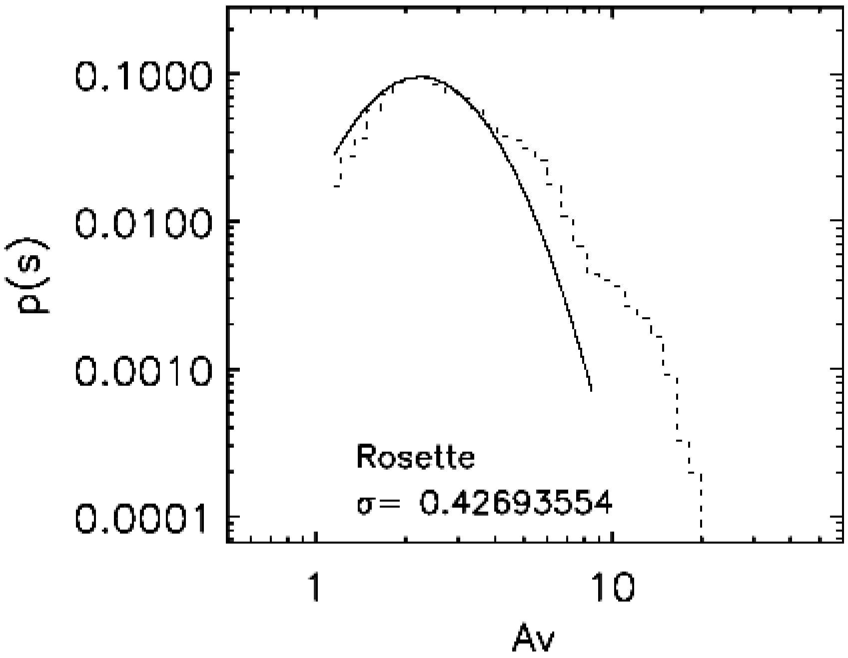
- Universal power law from 0.03 pc to 3 pc
  - deviation from self-similarity around 5 pc (3°).
- $\beta_{centroid}$ = 2.8 . . . 3.2 ≈ $\beta_{vel\text{-}3D}$ -1 matches HD simulations with $\beta_{vel\text{-}3D}$ = 3.9 . . . 4.2

Measuring densities

Column densities in Rosette:



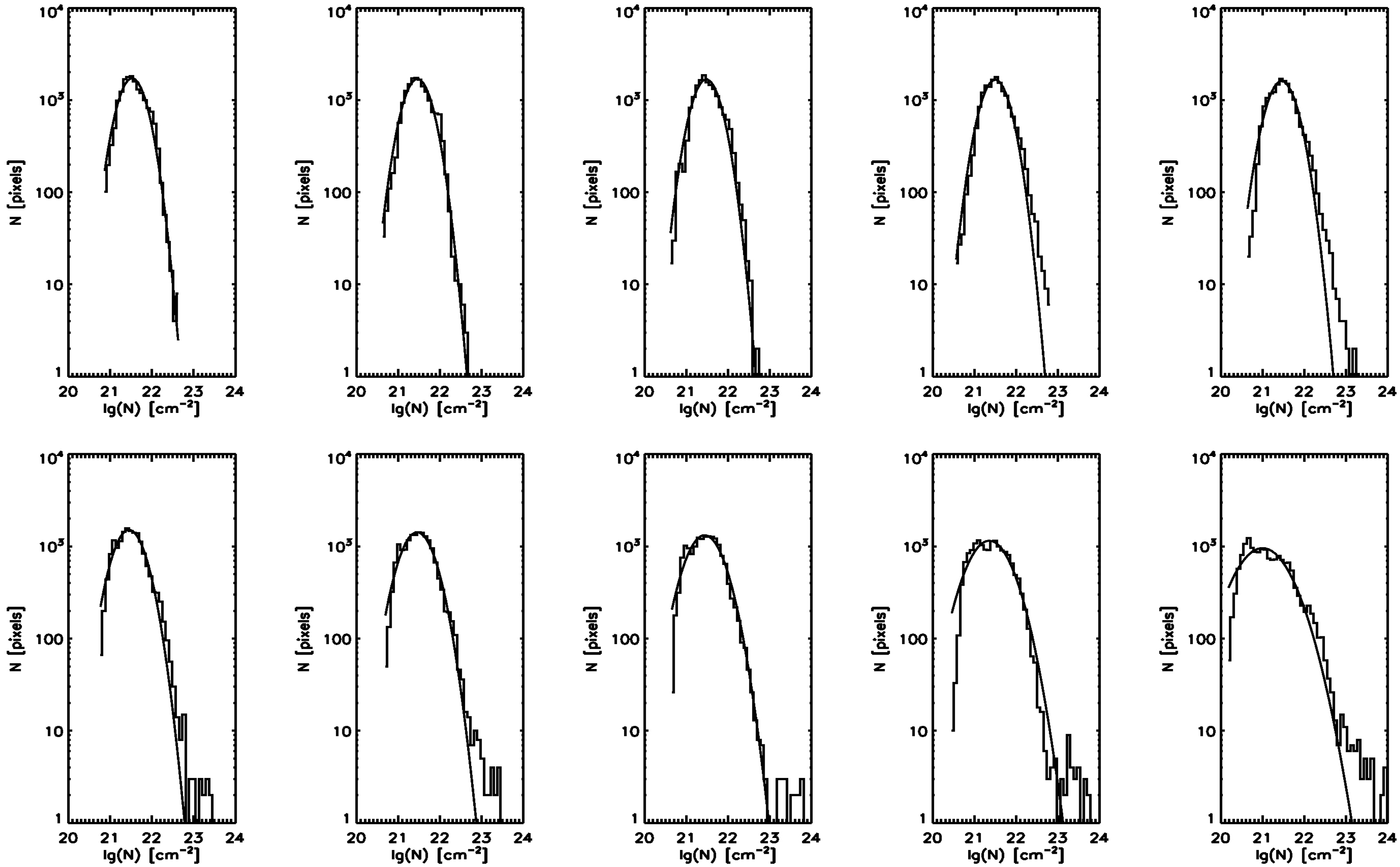
Herschel observations
(Motte et al. 2010, Schneider et al. 2011)



The column density PDF shows a high density excess that may trace gravitational collapse.

Density PDFs

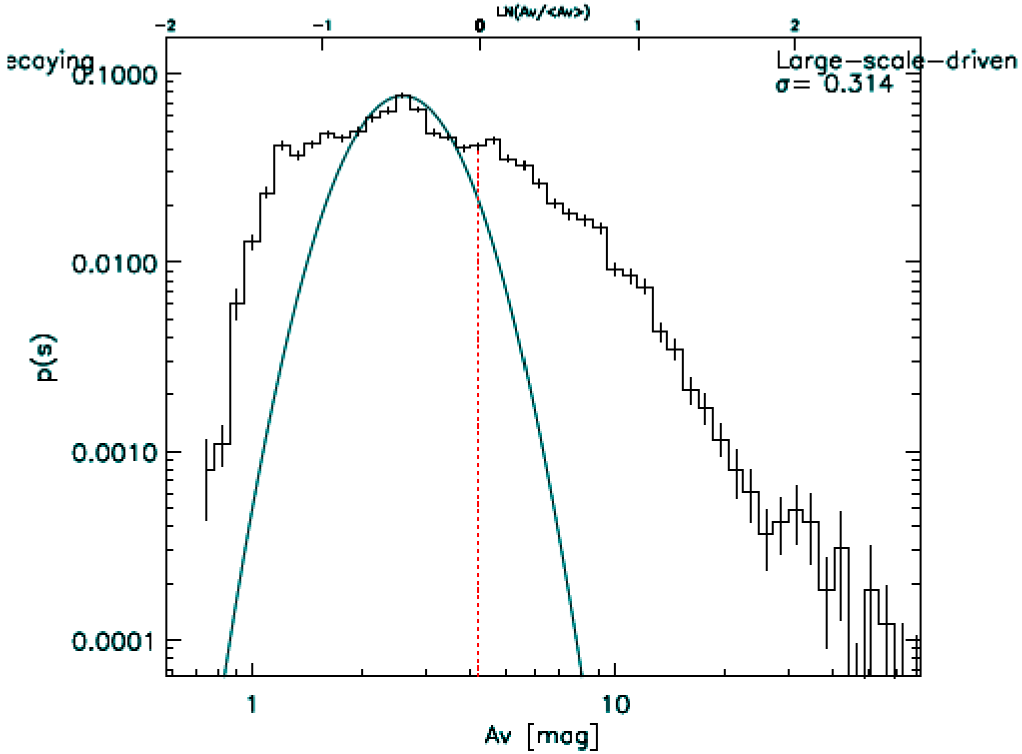
High column density excess from gravitational collapse:



Progressing time steps in a large-scale driven turbulence simulation including gravity (Ossenkopf, Klessen, Heitsch 2001): deviation from a log-normal distribution at late stages

Density PDFs

High column density excess from gravitational collapse:



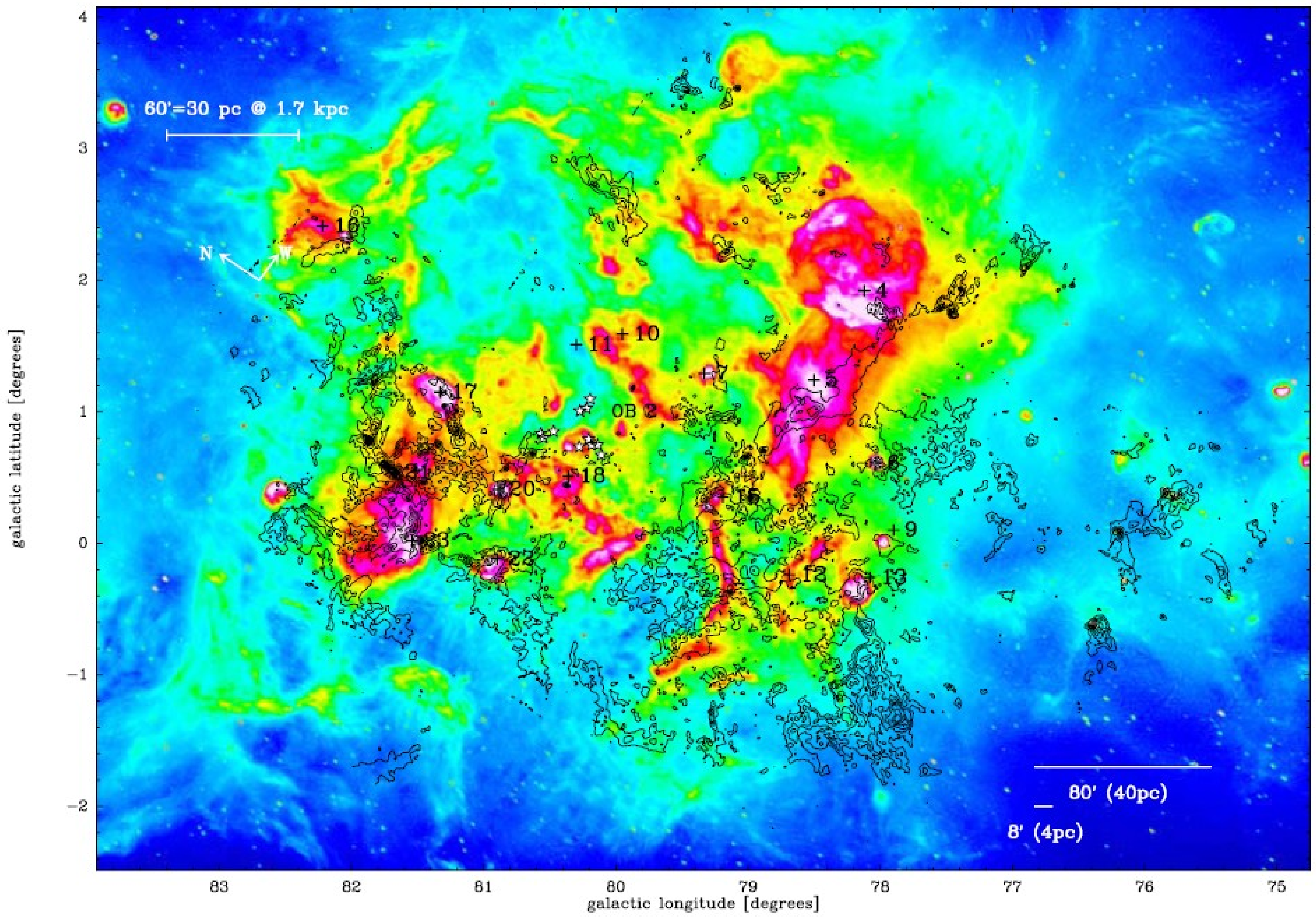
Time-average over all steps: Strong high-density excess in agreement with observations (Csengeri et al. in prep.)

Different evolutionary steps of gravitational collapse provide a natural explanation for non-log-normal density PDFs.

The future (2012-2014)

Understand the interplay of the different chemical and physical phase transitions with the turbulent structure.

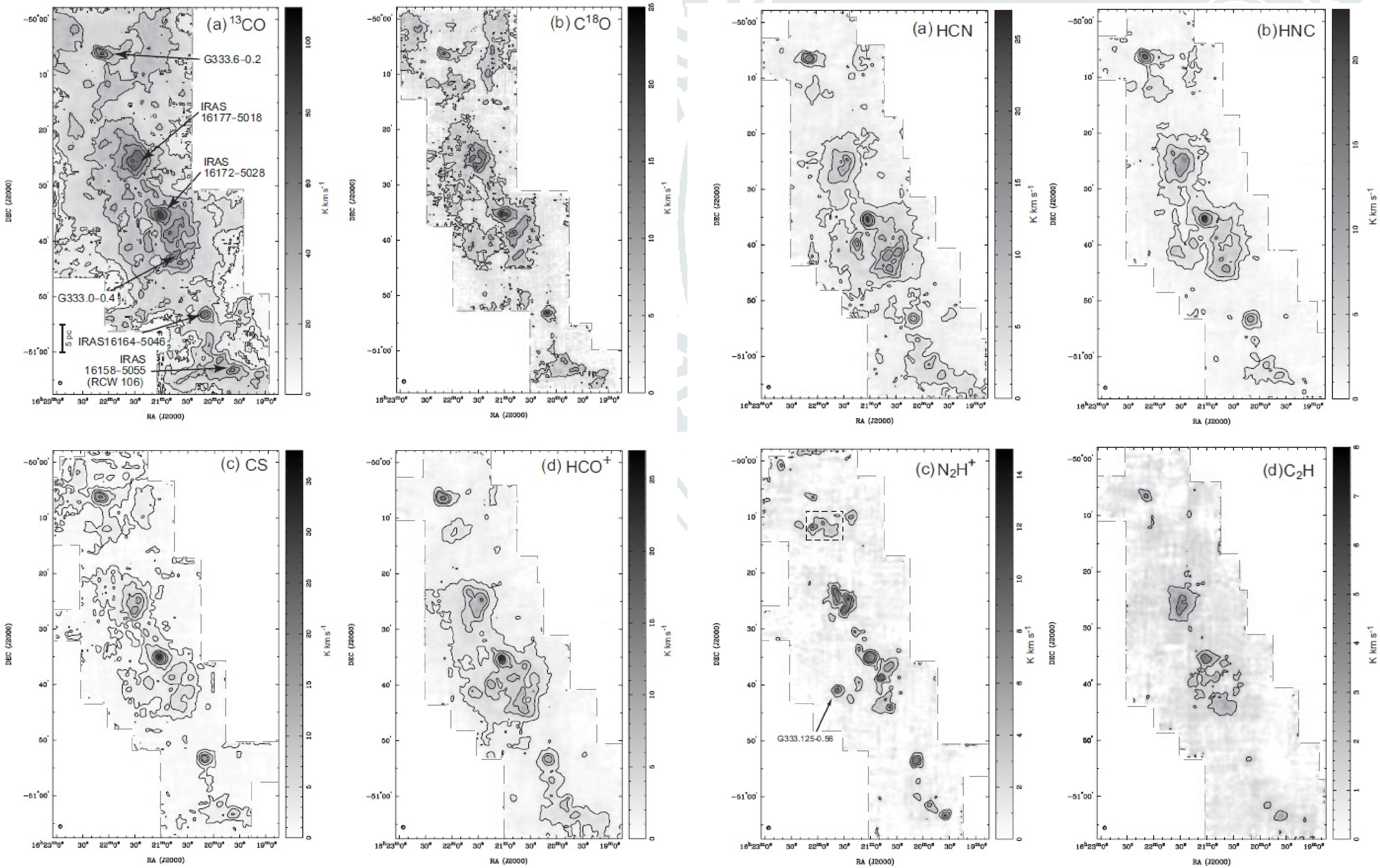
Compare structure seen in different tracers:



Cygnus X region as seen at 8 µm by MSX overlaid with FCRAO ^{13}CO $1\rightarrow0$ emission as black contours.

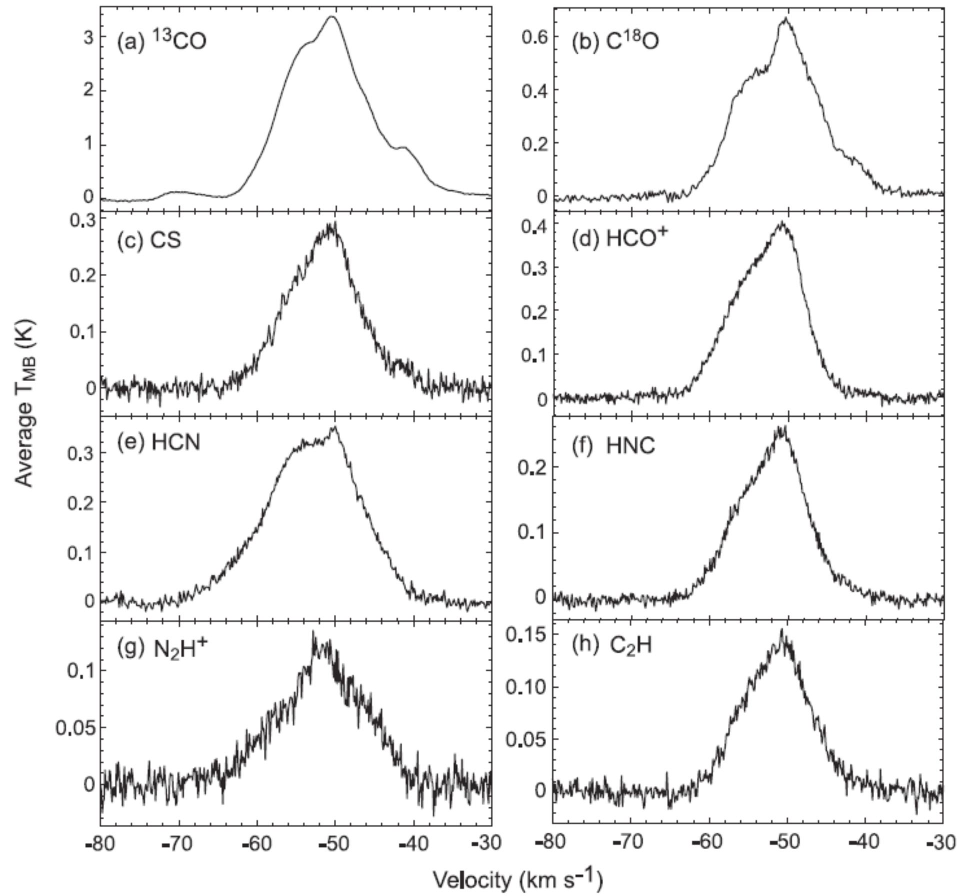
21cm radio continuum overlaid ^{13}CO $1\rightarrow0$ emission as black contours.

G333 seen in different molecular tracers



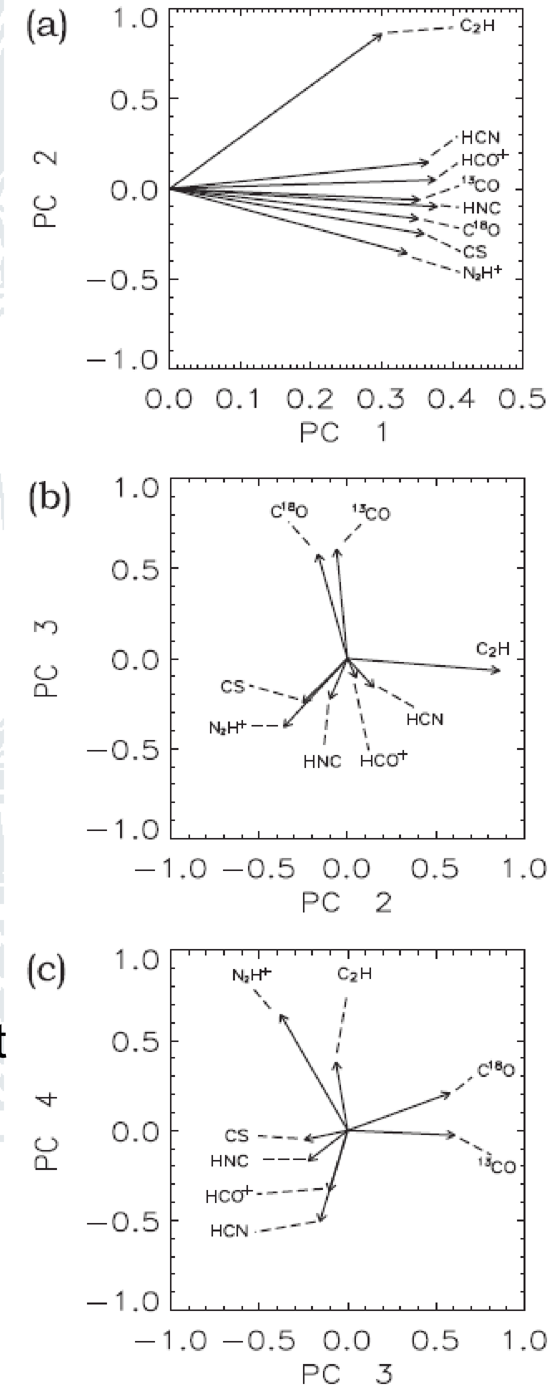
G333 seen in different molecular tracers

- Different density and velocity structure seen in different molecules



Average line profiles in for the 8 species

- **Excitation effects**
- **Chemistry**

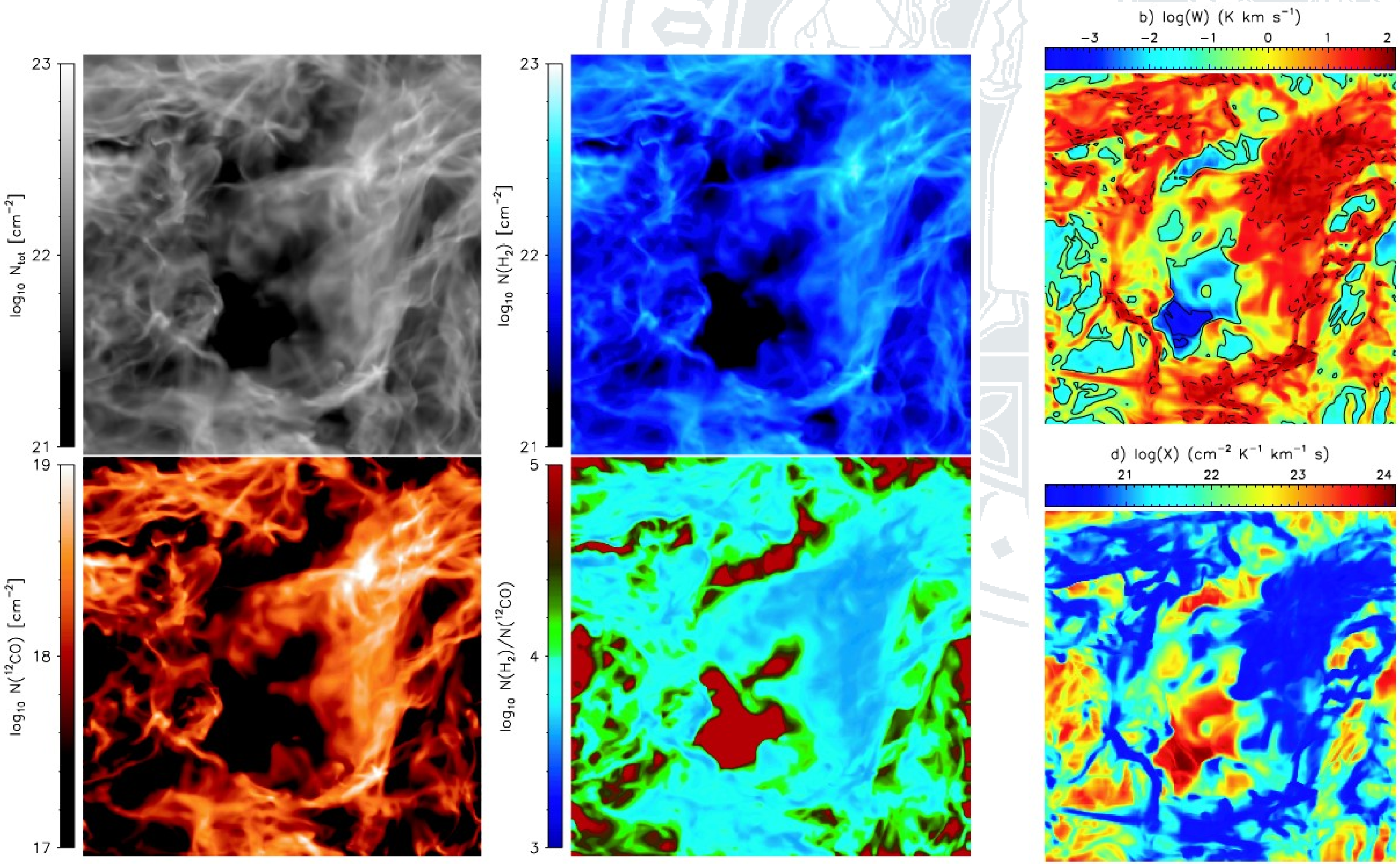


Principal component analysis for the individual maps. At smaller scales the spatial correlation drops. C$_2$H deviates first.(Lo et al. 2009)

Phase transition from atomic to molecular carbon

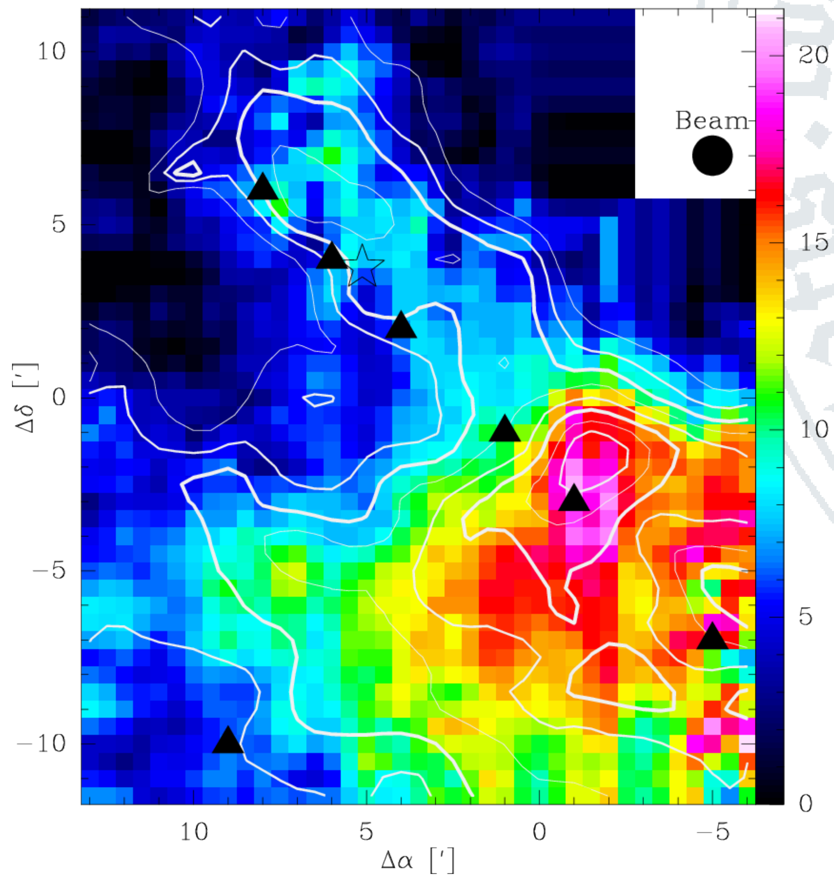
State of the art provided by simulations of Simon Glover

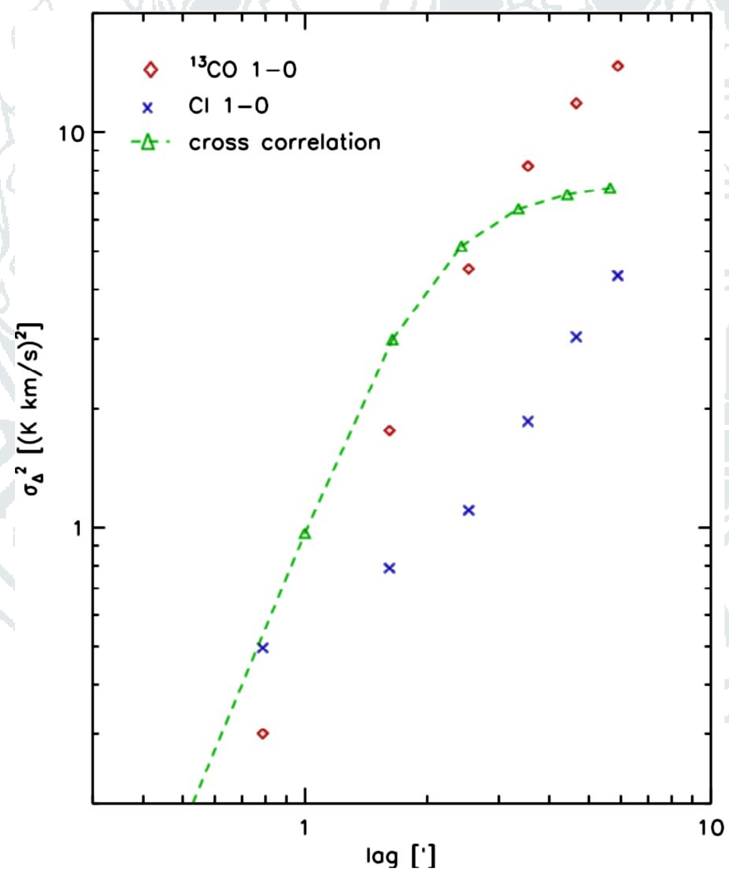
- full MHD model coupled with small chemical network and escape probability radiative transfer (Glover 2010, Shetty et al. 2011)



How to compare species?

Idea: Re-use the power of the Δ-variance, but do not measure the variation in one tracer, but the difference between two maps as a function of the scale (similar to Rainer's wavelet cross correlation)





IC348: CI in colors and ^{13}CO 1-0 in contours (Sun et al. 2006). Right panel: Δ-variance spectra of the two maps and the cross correlation variance spectrum.

The saturation shows a characteristic chemical correlation scale of 2-3'.

The plan (2012-2014)

- Compare statistical properties of observed maps in various tracers with simulated observations from turbulence models
- Measure the spatial correlation and systematic variation between different tracers
  - Δ-variance spectra and spatial correlation analysis,
  - Non-sperical wavelets in Δ-variance
  - PDFs of intensities, velocities and increments
  - Structure functions of variable order
  - Principal component analysis
  - Clump decomposition
  - Bispectrum
- Identify observable tracers and statistical tools sensitive to different aspects of cloud structures
  - chemical structure
  - dynamical, and energetic state
- Measure observational bias introduced by the limitations of today's observational technology
- Determine scales of numerical artifacts in models

Main goals

Quantify the impact of physical and chemical processes in the structure formation:

- phase transition from atomic to molecular gas at cloud boundaries
- formation of essential cooling species (C^+,O)
- local energy balance and deviations from LTE
- impact of optically thick cooling lines
- dynamical instabilities driven by ram pressure
- turbulent heating and mixing
- radiation pressure from the ISRF