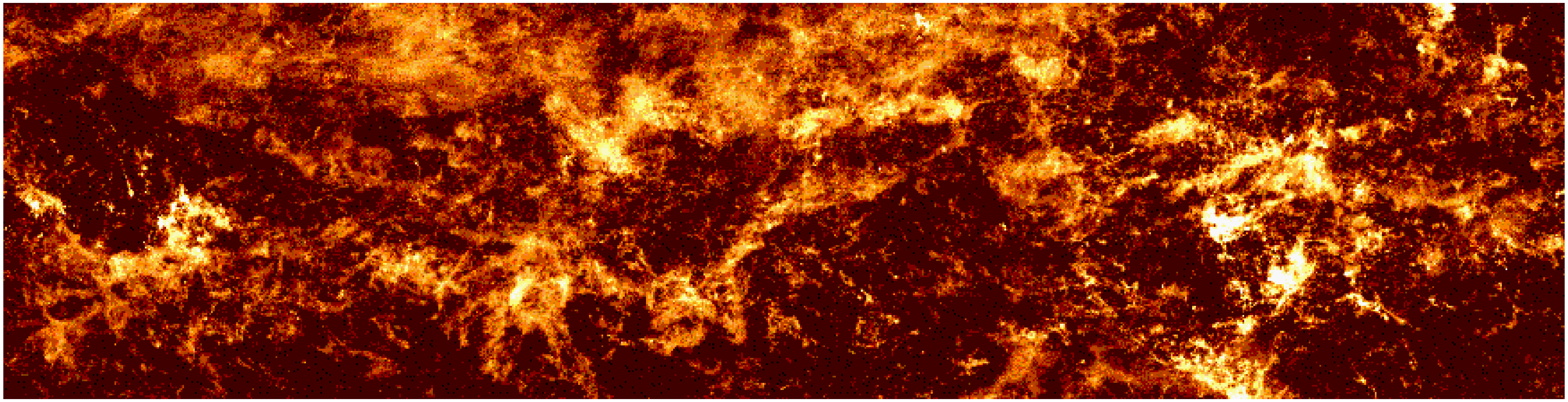
Molecular cloud surfaces: PDRs everywhere



Volker Ossenkopf,
Markus Röllig, Markus Cubick, Jürgen Stutzki

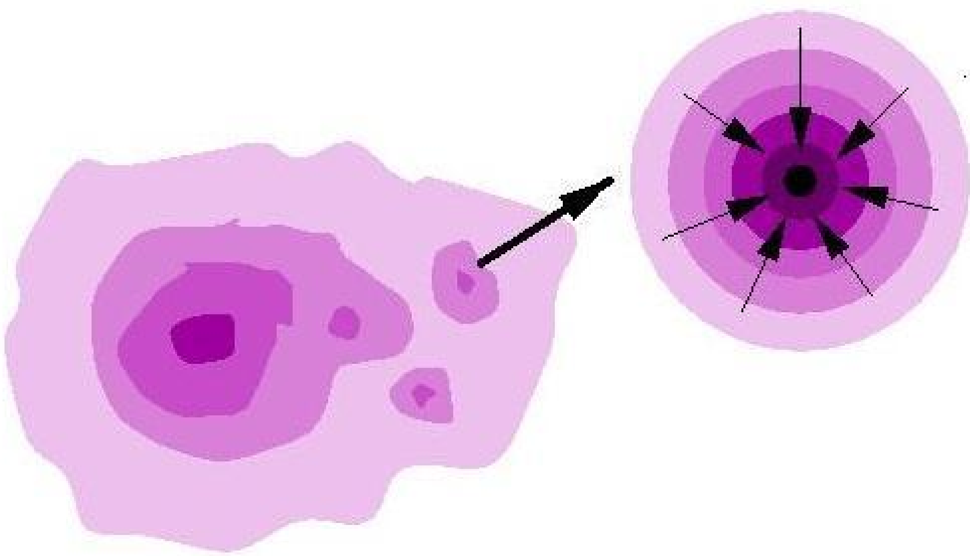
Overview

- What are molecular clouds?
  - The simple picture
    - Success
    - Failures
  - The fractal picture
    - Success
    - Failures
  - The dynamic picture
    - Success
    - Failures
- Ways forward

Disclaimer: $A_{\rm V} \lesssim 5$, i.e. cloud surfaces only, here

Molecular clouds

The simple picture

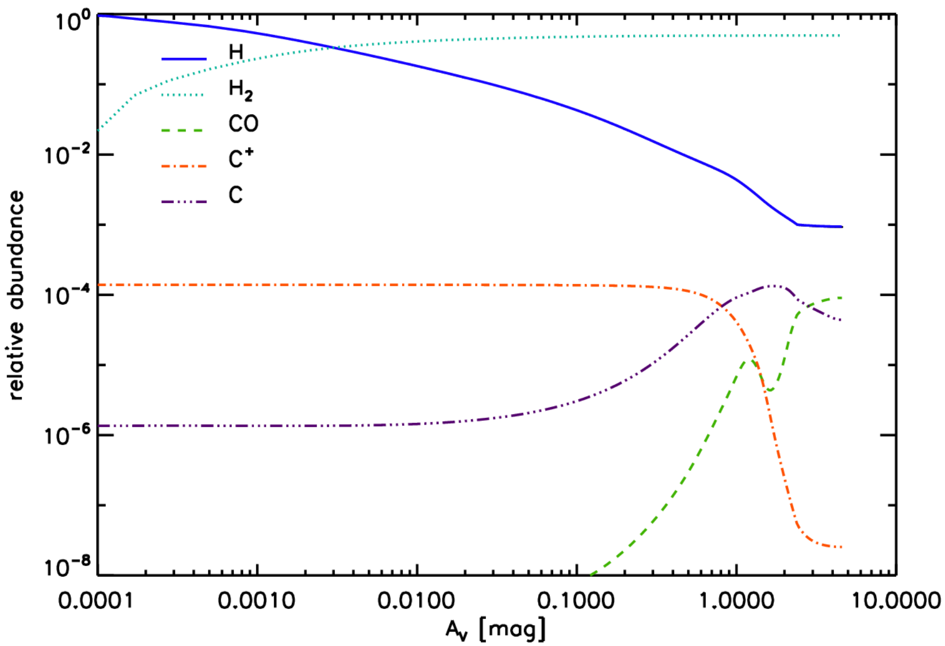


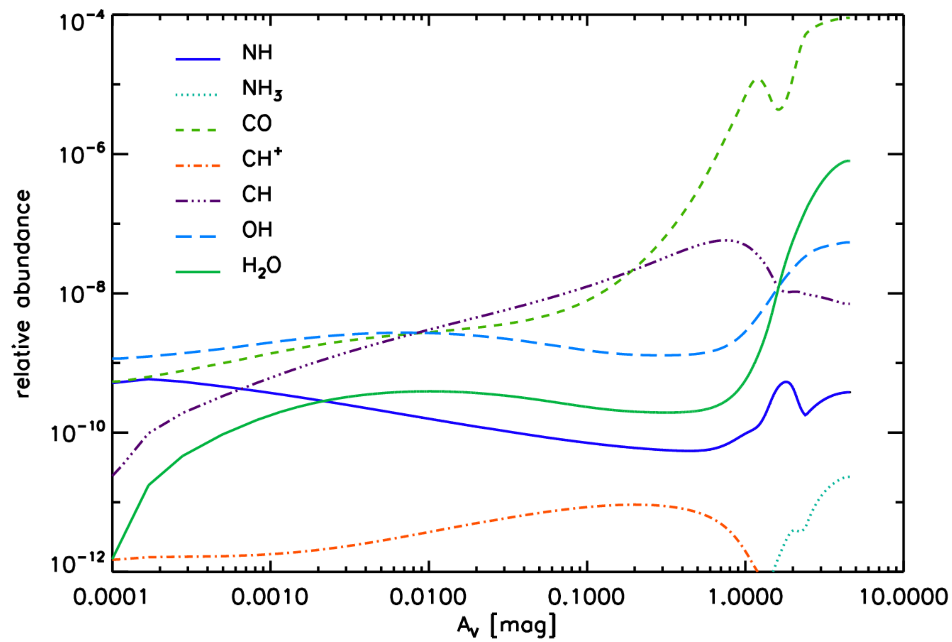
Hogerheijde et al. (1998)

- dense “blobs” of interstellar matter
- visible in CO
- in pressure- and virial equilibrium
- condensations form stars

Chemical structure

Density profile and external UV field produce chemical gradients:



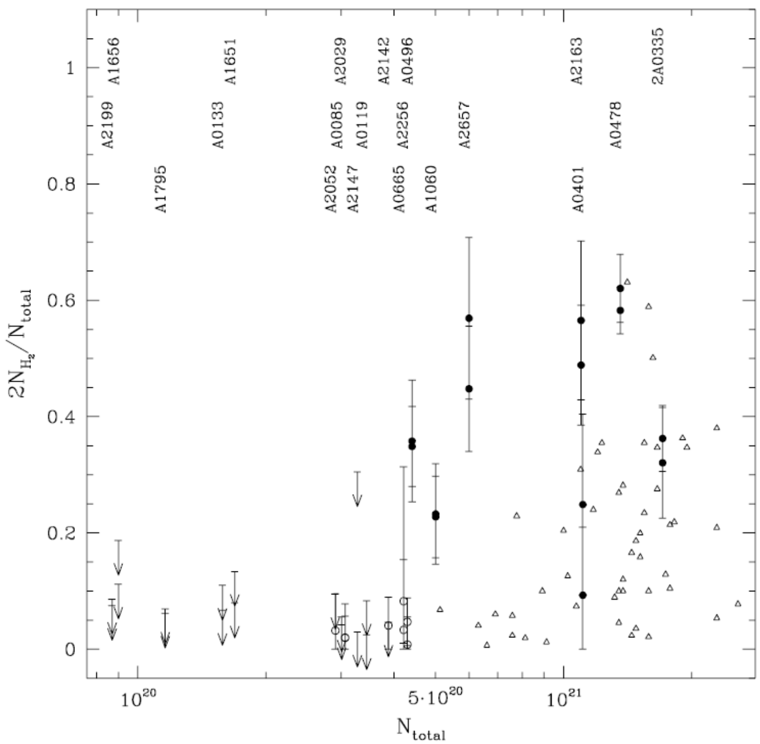


KOSMA-τ model of a cloud with $\chi = 1, M_{\rm tot} = 100 M_\odot, n = 500$ cm^{-3}

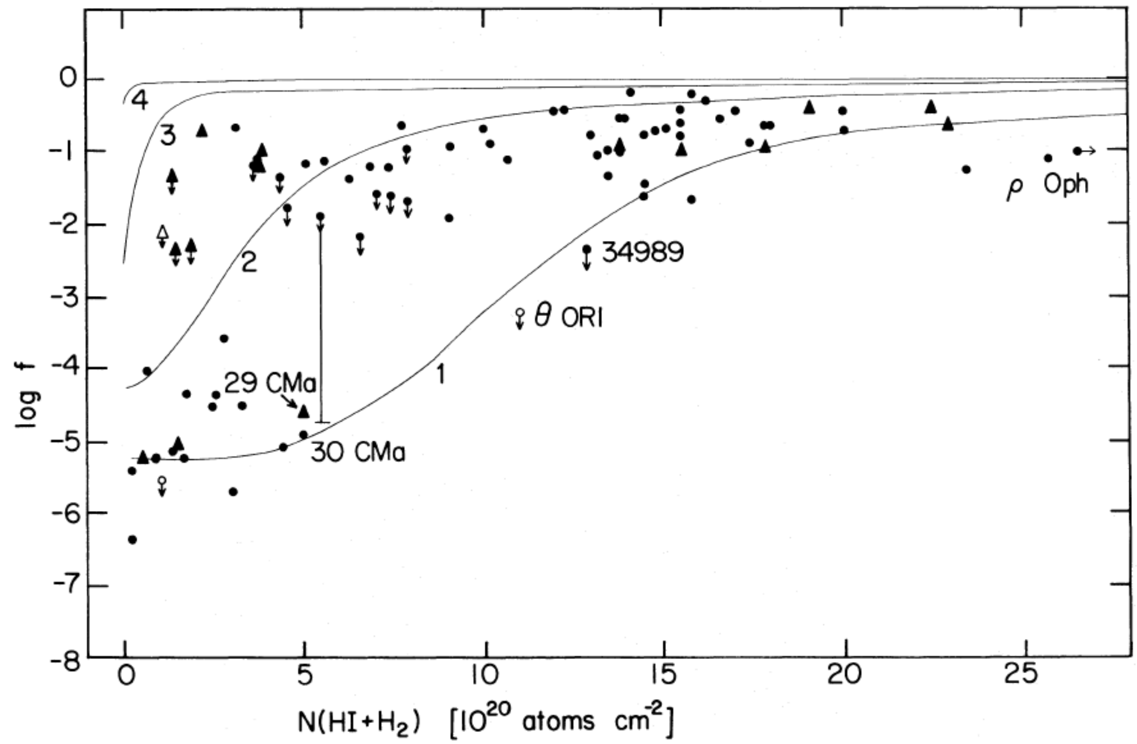
- There is no "molecular cloud". Each molecule sees a different size of the cloud.
- None of the mm/sub-mm tracers measures H_2. H_2 is molecular where many other molecules are dissociated.
- The region of strong chemical gradients is traced by [CI].

Success

H_2 fraction



Arabadjis & Bregman (1999): X-ray data

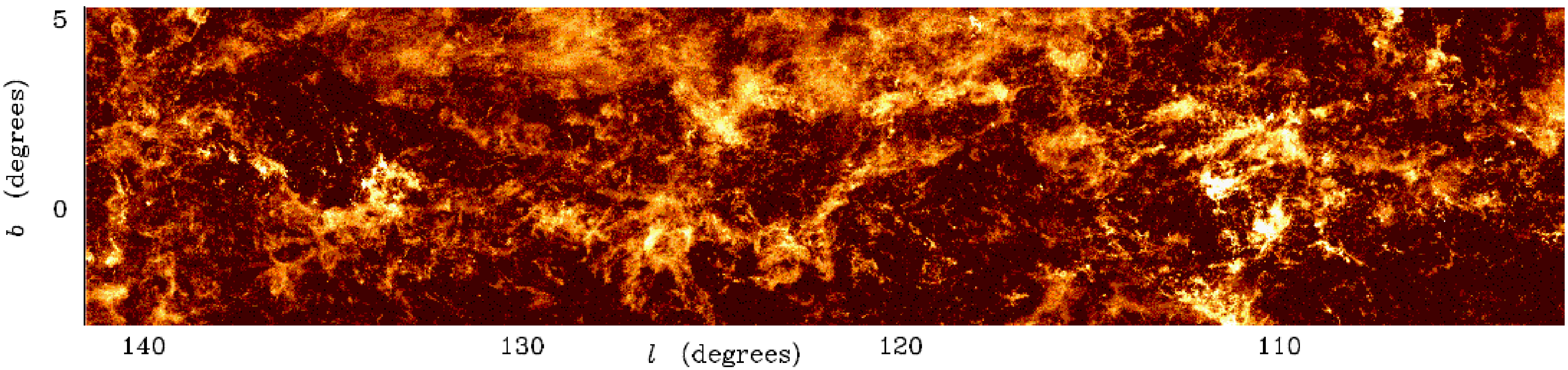


Savage et al. (1977): UV data

- up to 50 % of the CNM+WNM in solar neighbourhood is molecular (Savage 1977)
- f_{H_2} is a steep function of $N(H_{tot})$, with a critical column density at about $5\,10^{20}$ cm^{-2} (Savage et al. 1977, Liszt & Lucas 2001)

CO fraction

- CO is efficiently formed at $N(\mathrm{H_{tot}}) \gtrsim 2\,10^{21}$ cm^{-2} ($A_V \gtrsim 1$)
- $N(\mathrm{CO}) \propto N(\mathrm{H_2})^2$ (Liszt & Lucas 2001)

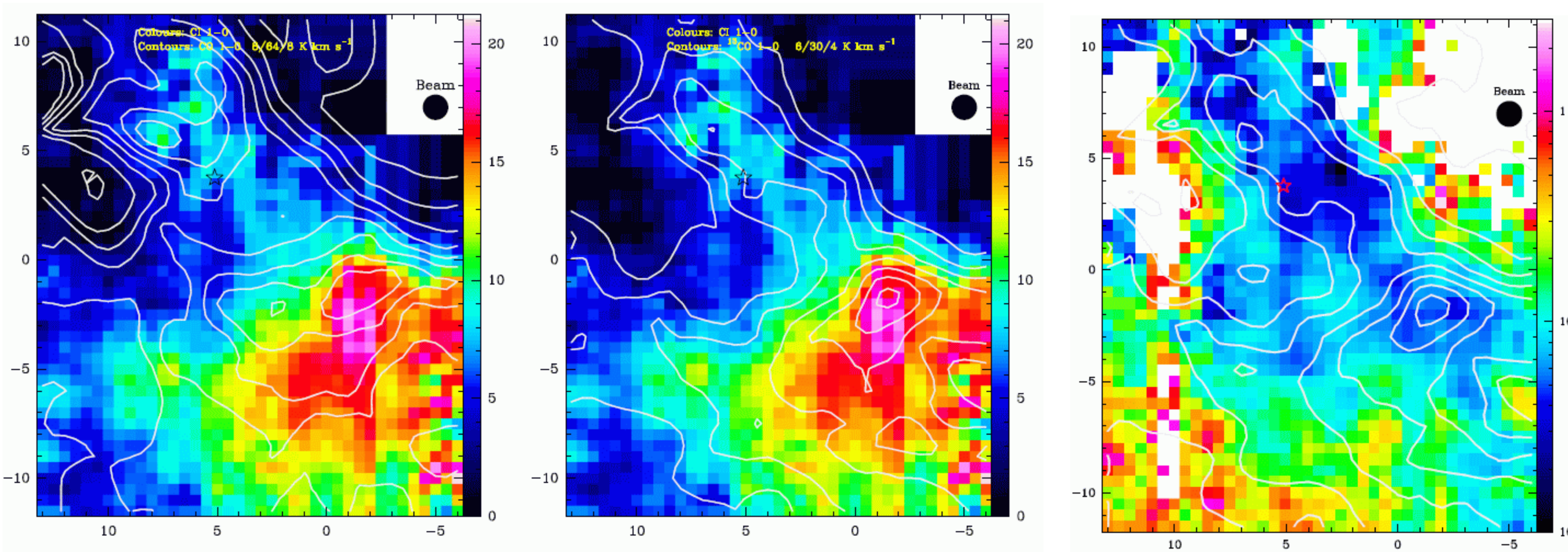


Heyer et al. (1998): FCRAO survey of the Outer Galaxy

22 % of the lines of sight through the Outer Galaxy show CO emission above a sensitivity limit of ≈ 2.4 K for the CO 1–0 line.

[CI] observations

[CI] should trace the transitional region where H_2 is molecular, and other molecules only start to form.

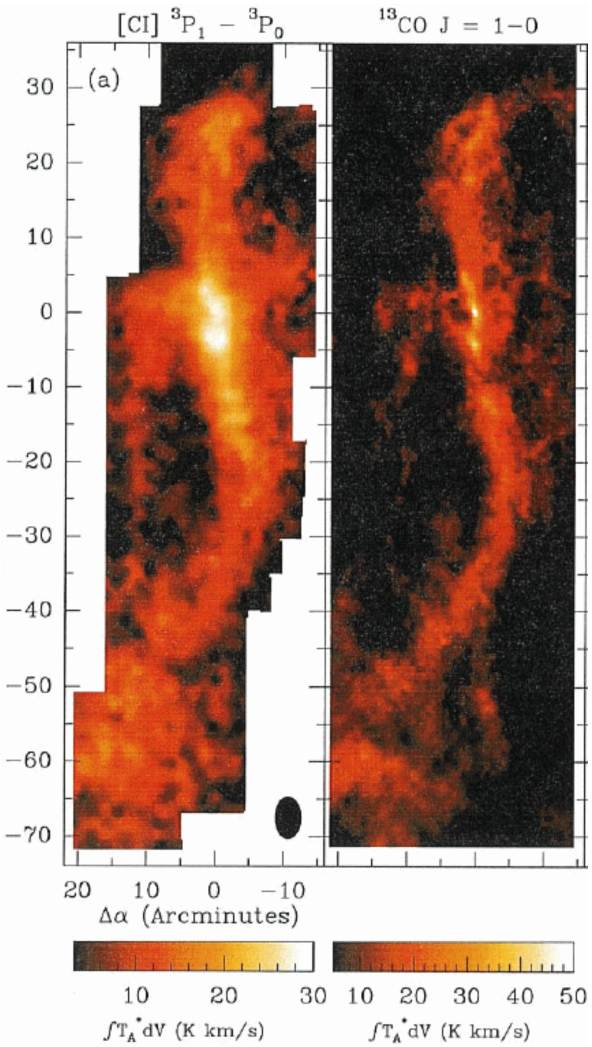


FCRAO and KOSMA observations of IC348 in CO 1-0 (left contours), ^{13}CO 1-0 (central contors) and [CI] (colors), right panel: [CI]/^{13}CO 1-0 line ratio, Sun et al. (2007)

- [CI] enhanced at the surface, but also strong in the cloud

[CI] observations

Observations at the somewhat larger scale:

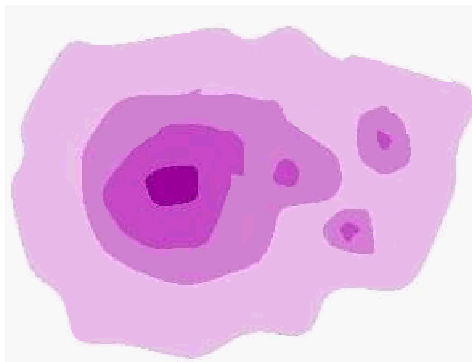


- [CI] is much more extended than CO, but also strong at the bulk of the material
- [CI] is often a molecular cloud volume tracer instead of a surface tracer

Orion A observations in CO and [CI], Plume et al. (2000)

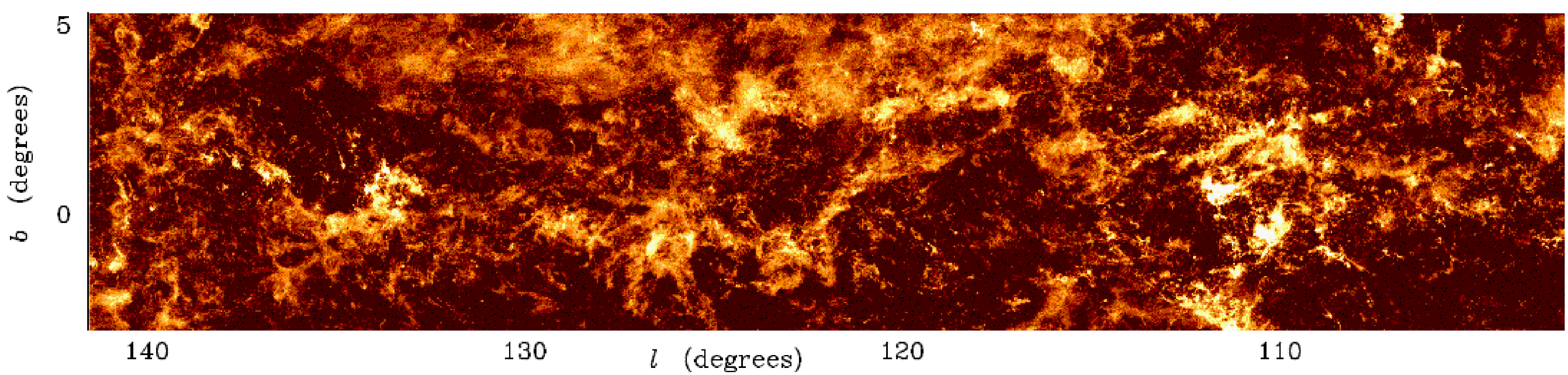
[C I] observations

Explanation:



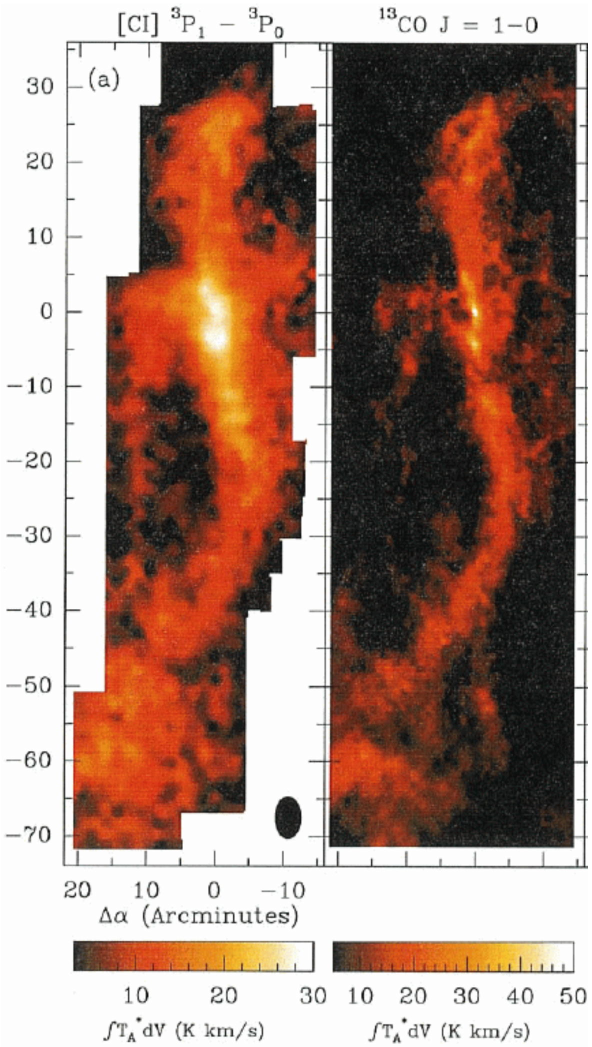
The clouds consist to a large part of surfaces

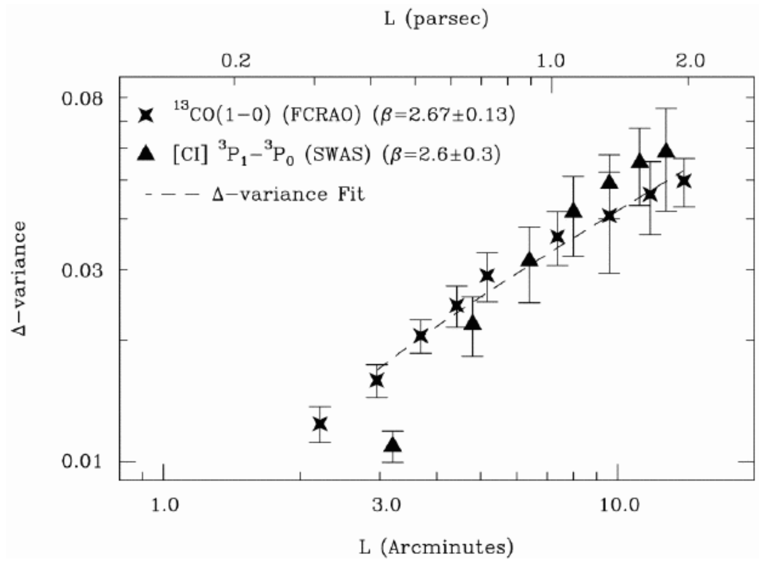
Clouds are not smooth, but complex, filamentary, fractal.



- fractal structures are created by a cascade of interstellar turbulence

The fractal picture





Δ-variance spectra of the Orion maps (Plume et al. 2000)

The Δ-variance spectrum measures the amount of structure on different size scales. A power-law indicates self-similar behaviour, i.e. an invariant scaling independent from the considered size.

- the turbulent structuring creates surfaces everywhere and at each scales
- UV radiation can deeply penetrate the clouds

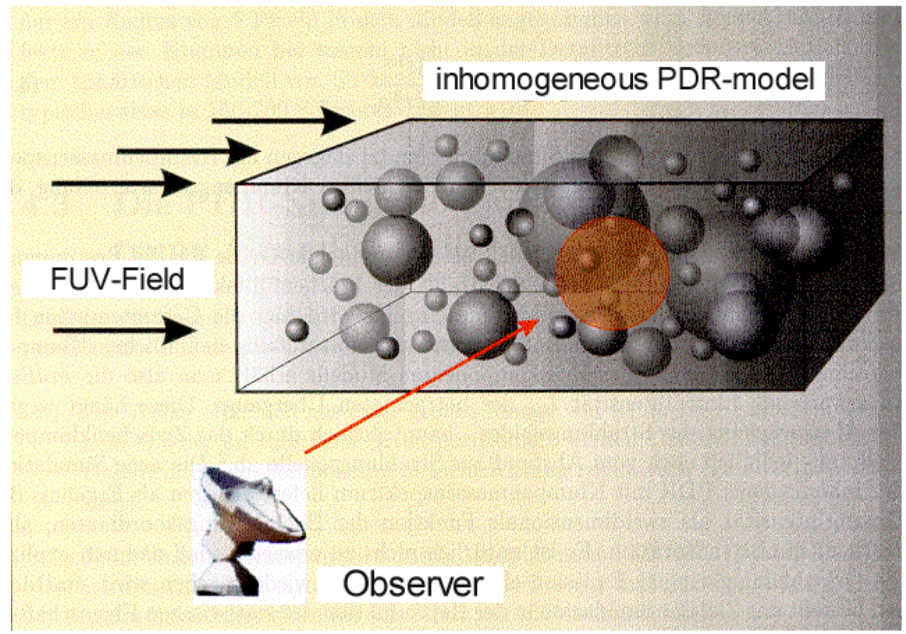
☞ PDRs everywhere

The fractal picture

The Δ-variance analysis shows a typical power-spectral index around $\beta \approx 2.7$ (Ossenkopf et al. 2002)

This can be represented by an ensemble of clumps with adapted mass-spectrum and mass-size relation (Stutzki et al. 1998, Heithausen et al. 1998):

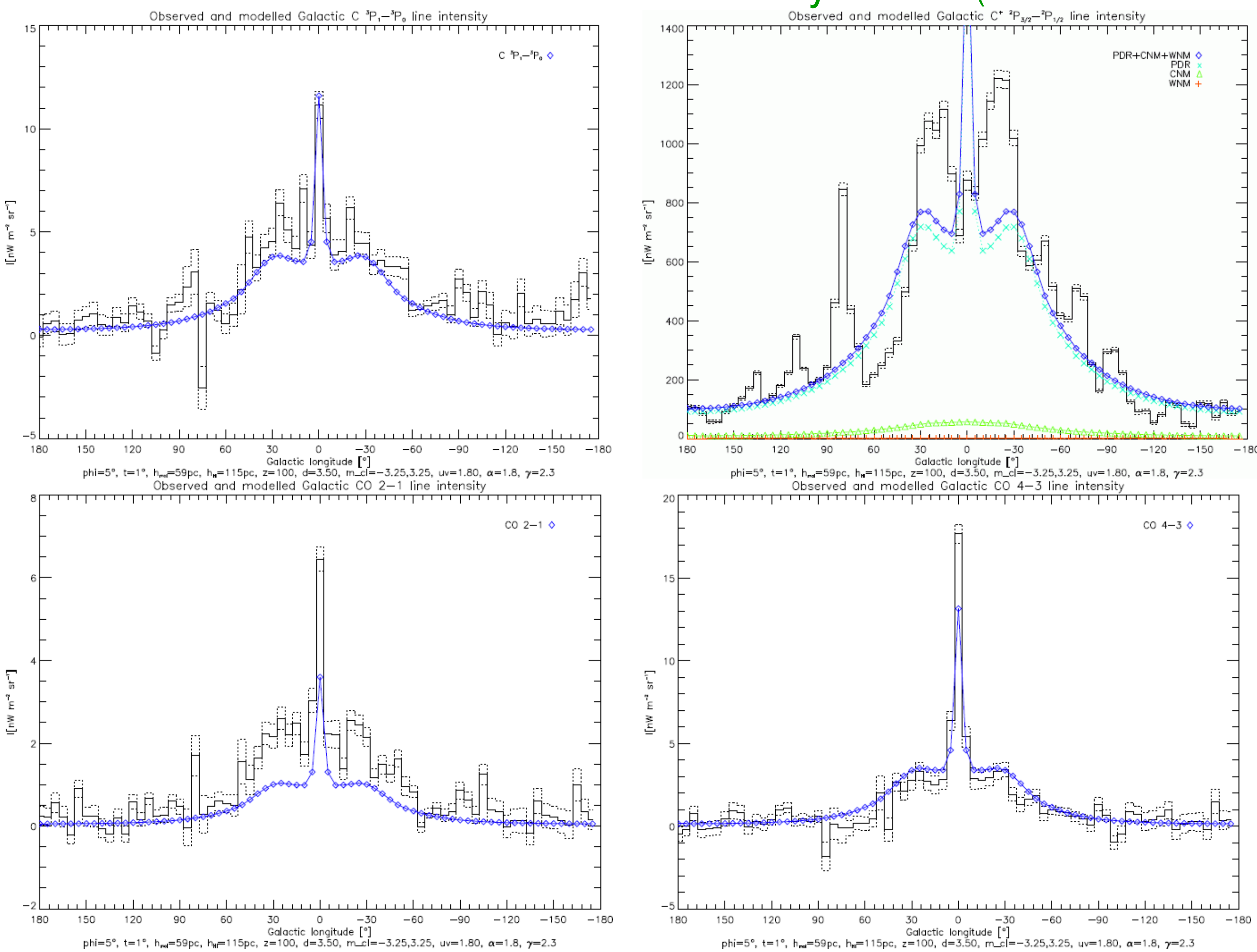
$$dN/dM \propto M^{-\alpha} \qquad \alpha = 1.8$$
$$M \propto R^{\gamma} \qquad \gamma = 2.3$$



Zielinsky et al. (2000)

The fractal picture

Explains Galactic FIR line emission as observed by COBE (Fixsen et al. 1999):

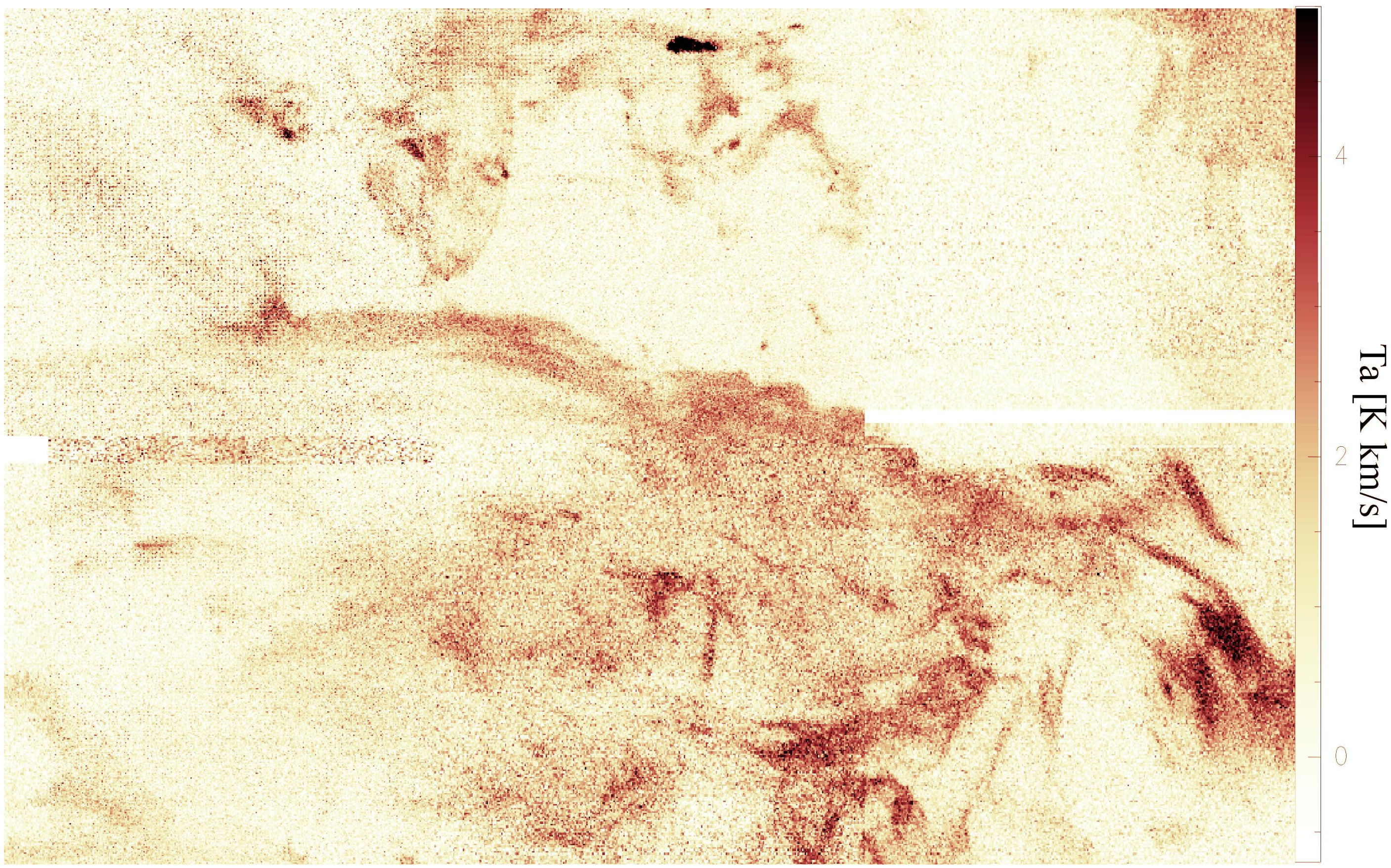


Cubick et al. (2007): clumpy PDR model using Galactic mass distribution of Wolfire et al. (2003)

Failures

CO at low column densities

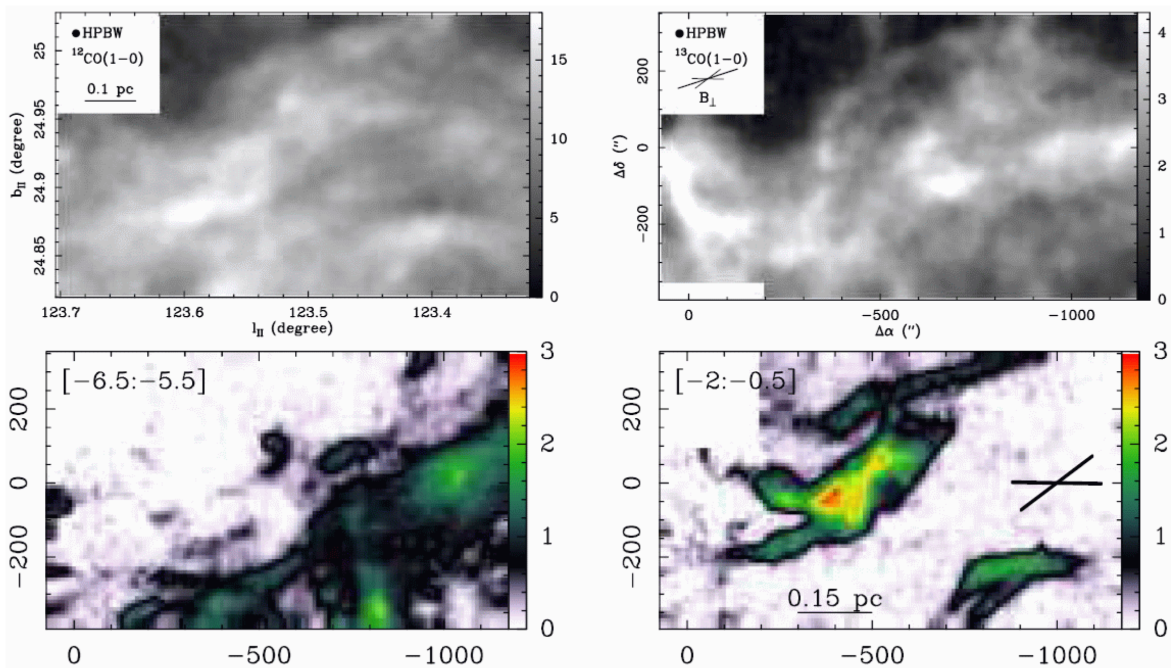
Wide spread filamentary ^{12}CO emission at a low column densities, $\int T dv \lesssim 2$ K km/s:



Schuster, Lefloch, Ungerechts, Thum, Gueth, Sterzik, Wiesemeyer, Hily-Blant (2004): 4.1-4.4 km/s

CO at low column densities

Detailed quantitative analysis by Hily-Blant & Falgarone (2006):



- filaments:
  - pure velocity structures
  - $D \approx 0.03$ pc, $\Delta v \approx 0.35$ km/s
  - $N(\mathrm{H_{tot}}) < 3\,10^{20}$ cm^{-3} ☞ $A_\mathrm{V} < 0.15$, $N_\mathrm{CO} \approx 10^{15}$ cm^{-3}
- overall line wing region:
  - total column corrsponds to $A_\mathrm{V} \lesssim 0.8$
  - gas is warmer and more diluted than average

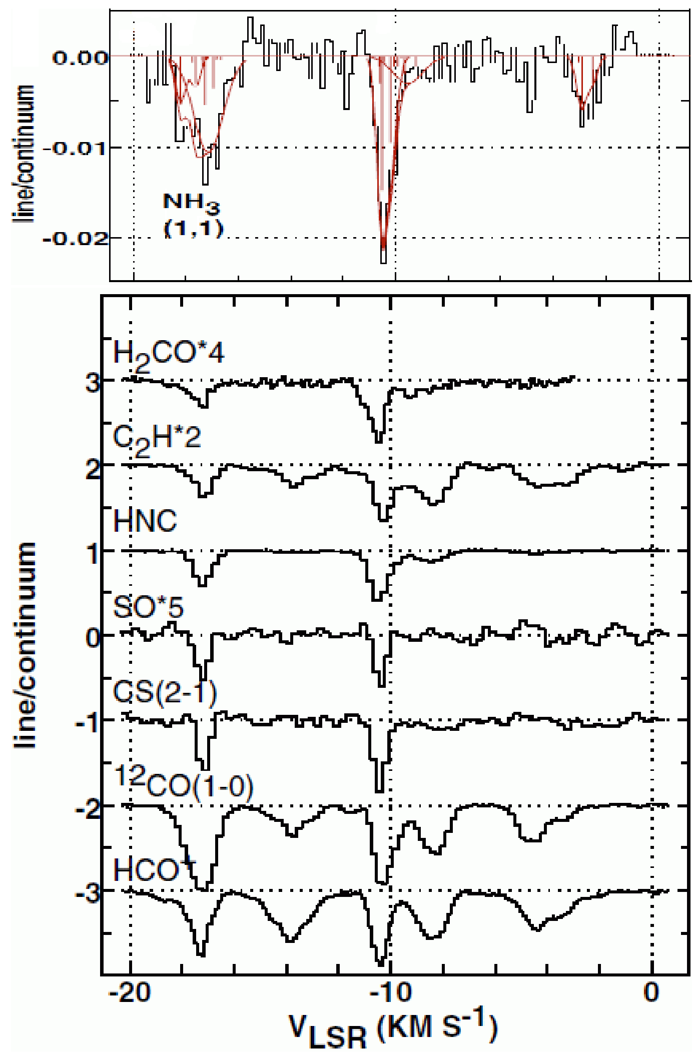
Molecules at low column densities

Classical example – ζ Oph
($A_V \approx 0.8$, $\chi \approx 3.5$):

	^{12}CO	^{13}CO
model	$\lesssim 2\,10^{14}$ cm^{-2}	$\lesssim 3\,10^{12}$ cm^{-2}
observations	$2\,10^{15}$ cm^{-2}	$4\,10^{13}$ cm^{-2}

(van Dishoeck & Black 1988)

Large quantities of CH^+, HCO^+, OH, CO, C_2H, NH_3, H_2CO, CN, CS, HCN, HNC, SO, C_3H_2, H_2O at low column densities. (Lucas and Liszt 2002, Liszt et al. 2006, Neufeld et al. 2003)



Absorption spectra towards B0355+508 (Liszt et al. 2006)

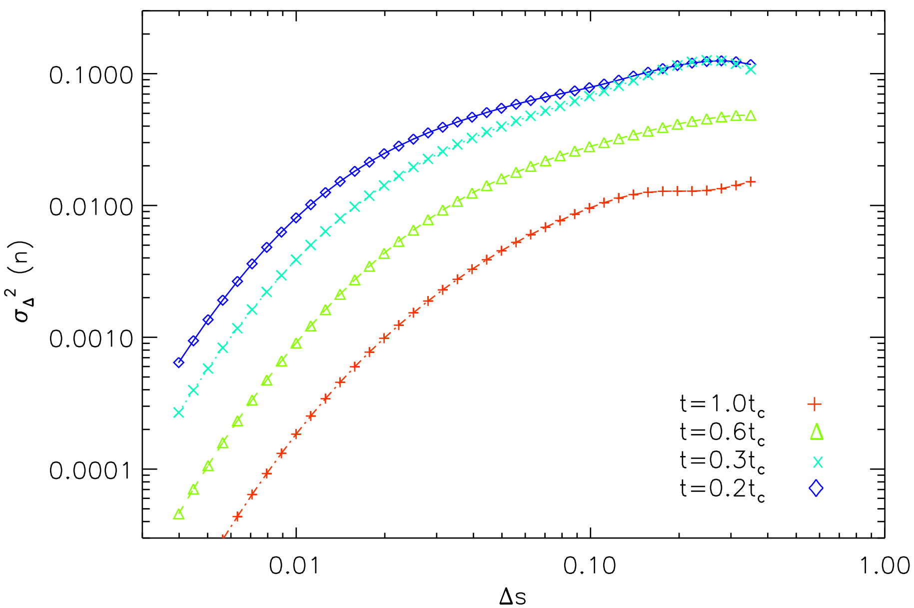
Similarities between dark cloud and diffuse cloud abundance patterns.

Static clouds with a turbulent structure?

- Turbulent motions stabilize against collapse, but also destroy the clouds.
- Molecular cloud lifetime $<$ crossing time (Falgarone et al. 2004)

Example:
$n_\mathrm{H} = 300\ \mathrm{cm}^{-3}$, $A_\mathrm{V} = 5 \Longrightarrow D = 10$ pc; with $v_\mathrm{turb} = 10$ km/s $\Longrightarrow \tau_\mathrm{cross} = 1$ Myr

Turbulent motions are rapidly damped (Mac Low & Klessen 2004):



Damping of turbulence leads to bending of structure cascade (Ossenkopf & Mac Low 2002). This is not observed ☞ large scale driving most be either permanent or recent.

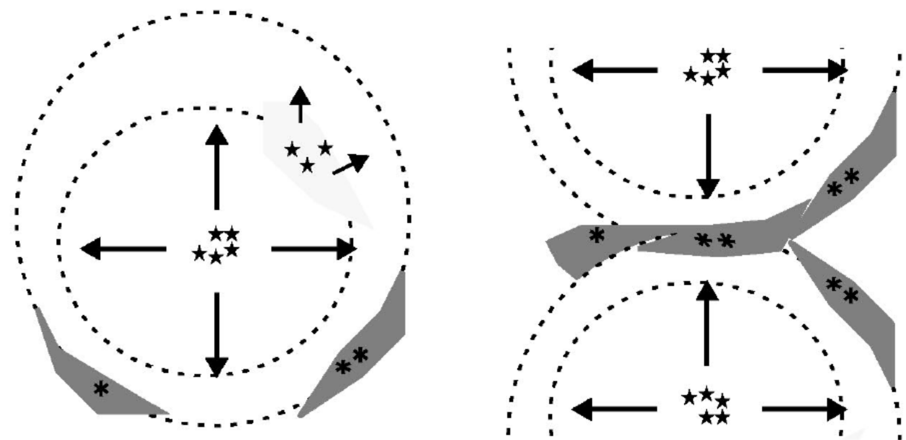
Molecular clouds are continuously restructured by ubiquitous turbulence.

The dynamic picture

- Turbulence in molecular clouds is large-scale driven (Ossenkopf & Mac Low 2002).
- Turbulent clouds are just high-density knots in large scale flows of atomic material (Brunt 2003)
- Clouds are essentially shock-dominated structures (Hartmann et al. 2001)

Implications:

- clouds are short lived (1 . . . 2 Myr)
- turbulent mass transport
- turbulent diffusion
- heating due to turbulence dissipation



Hartmann et al. (2001): triggering of molecular cloud and star formation by large scale flows, rapid dispersal of gas by newly formed stars

Problem:

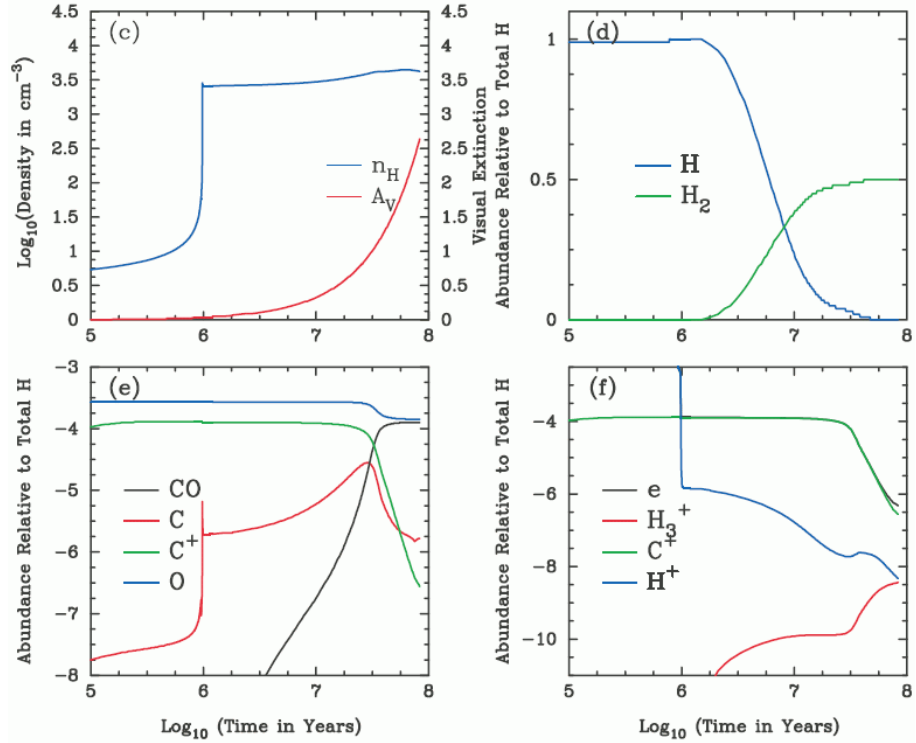
At standard H_2 formation rate, $\approx 10^9 \text{yr}/n_{\text{H}}[\text{cm}^{-3}]$, $\tau_{H_2}(300\ \text{cm}^{-3}) = 3\ \text{Myr} > \tau_{\text{cross}}$

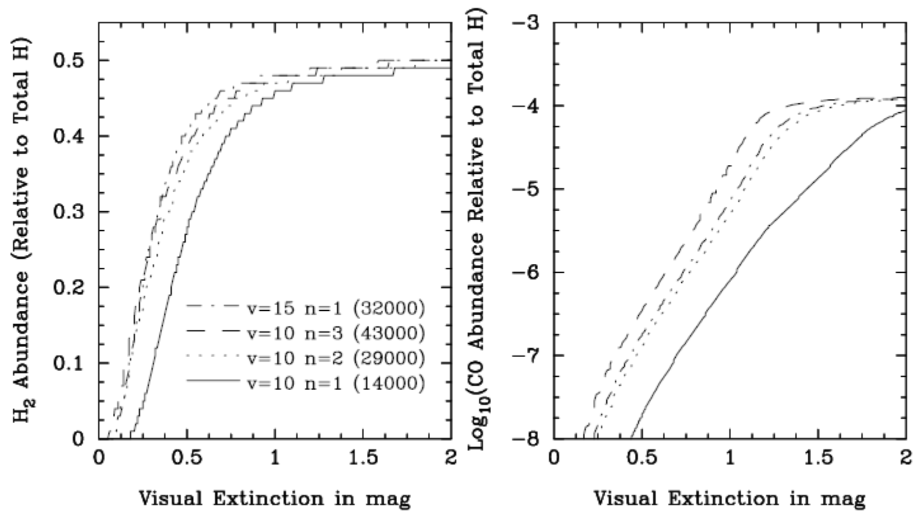
Fast H_2 formation

Solution: H_2 formation in short times at high densities created in shocks

Bergin et al. (2004):

- H_2 formation in a 1-D slow-velocity (10 km/s) shock in the atomic gas (1 cm^{-3}).
- H_2 is efficiently formed and self-shielded.
- CO forms for $A_V > 0.7$ on timescales of 10-20 Myr



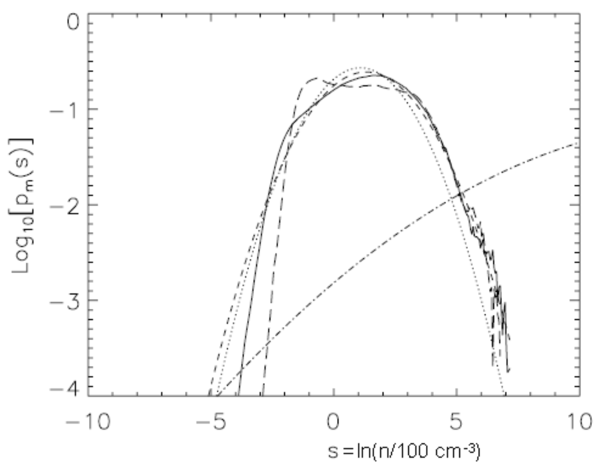


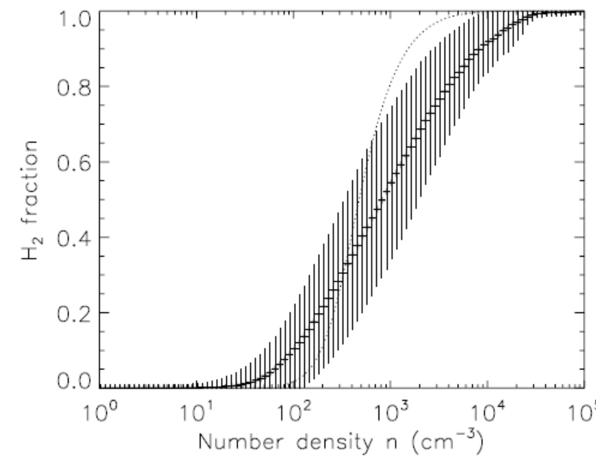
Fast H_2 formation

Distribution of the formed H_2 by turbulent advection:

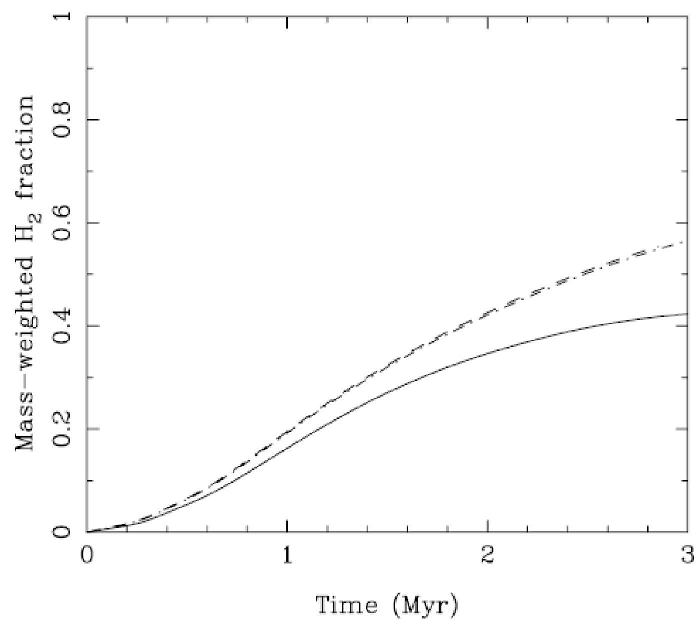
Glover & Mac Low (2007):

Turbulent cloud simulation including H_2 formation/self-shielding



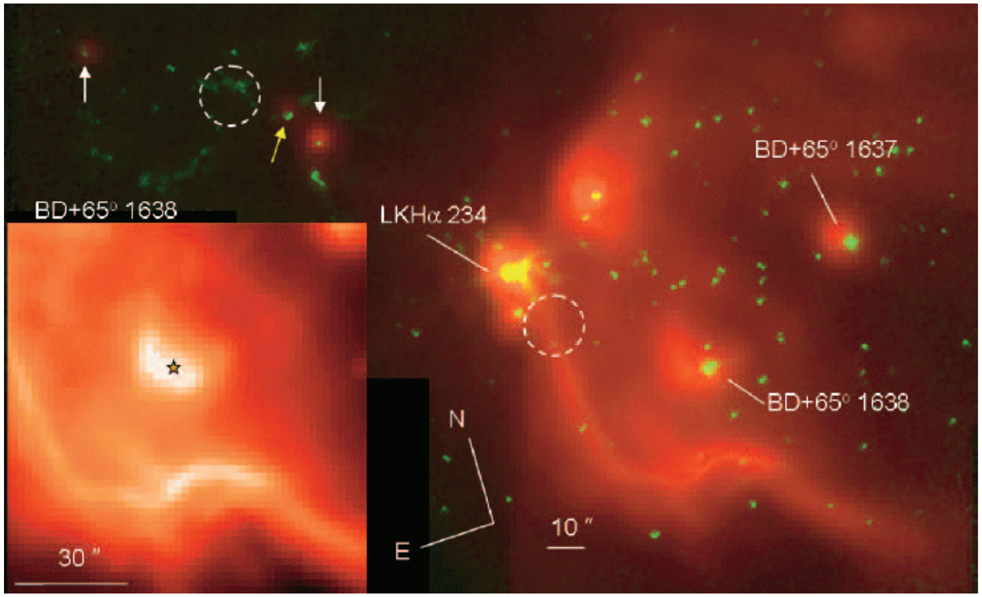


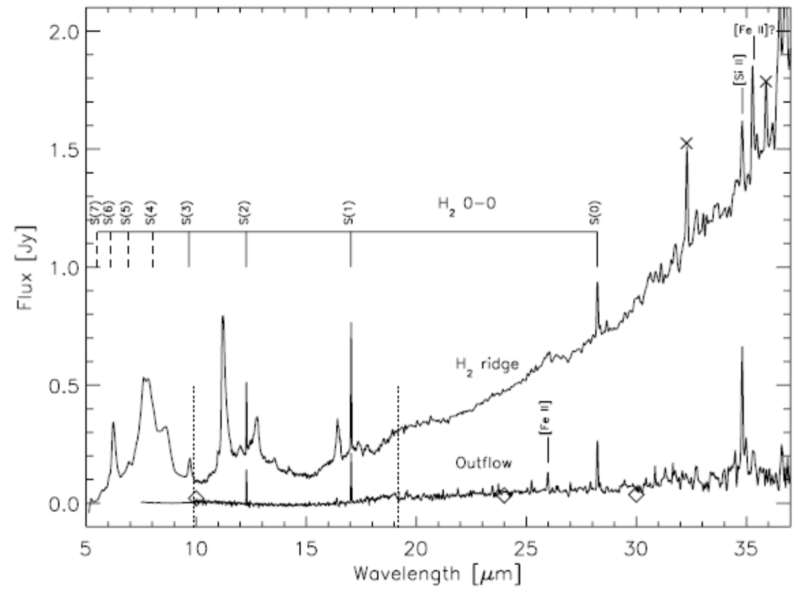
- wide density distribution
- fast H_2 formation at $n_H \gtrsim 300$ cm^{-3}
- turbulent redistribution of H_2 gas
- H_2 formation rate accelerates by a factor 3-5
- conversion of $\approx 40\%$ of the hydrogen into H_2 in the scale of 1-2 Myr



Hot H_2

Hot H_2 in PDRs and diffuse clouds:





Morris et al. (2004): NGC 7129: Excitation of H_2 rotational lines too high to be explained by UV pumping;
Falgarone et al. (2005): same conclusion for diffuse clouds

Solution:

- Chemistry driven by turbulent dissipation: ☞ talk by Edith Falgarone
- Chemistry driven by turbulent shocks: ☞ talk by Cesare Cecchi-Pestillini
- Chemistry driven by turbulent mixing at interfaces: ☞ talk by Maryvonne Gerin

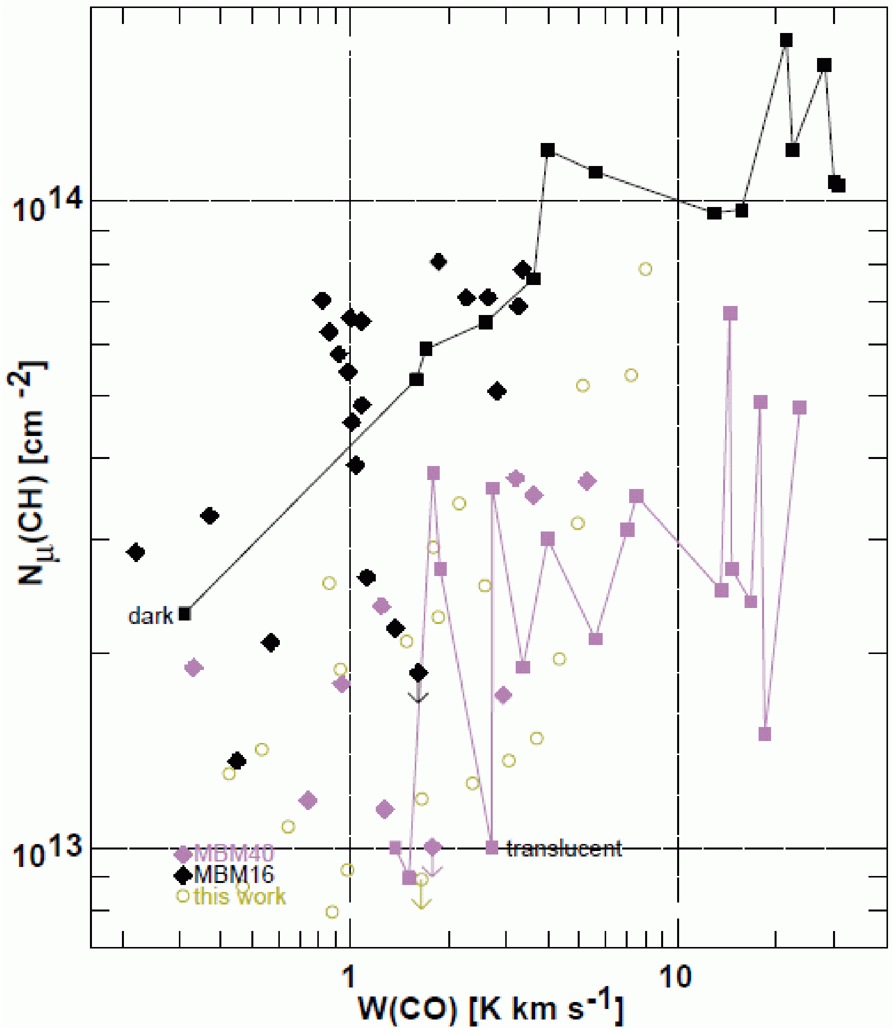
$\Longrightarrow$ warm H_2 + enhanced formation of HCO+, CH+, CH, H_3^+, OH, H_2O

Problems

- time-scales still too short for many chemical species

- f_{CH} is known to drop in dark clouds (see PDR models), but CH/CO is factor 3 larger in dark clouds

- for more problems ☞ see next talk

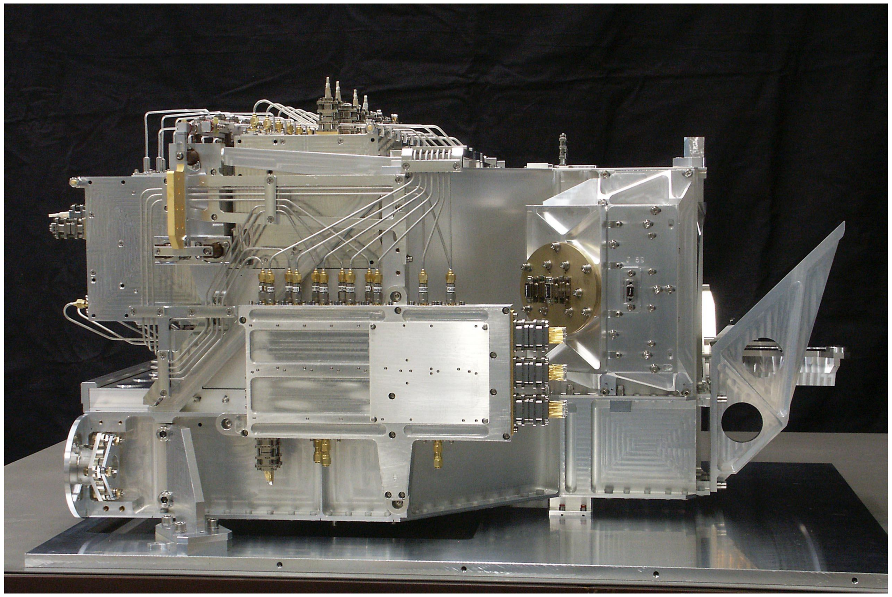


Liszt & Lucas (2002)

Ways forward

Observations

Herschel/HIFI:



- Continuous frequency coverage 480–1250 GHz and 1410-1910 GHz
- Spectral resolution 130 kHz–1.1 MHz
- Instantaneous bandwidth 4 GHz (2.4 GHz above 1410 GHz)
- Near-quantum noise limit sensitivity ($\approx 3h\nu/k$)
- Two polarizations simultaneously

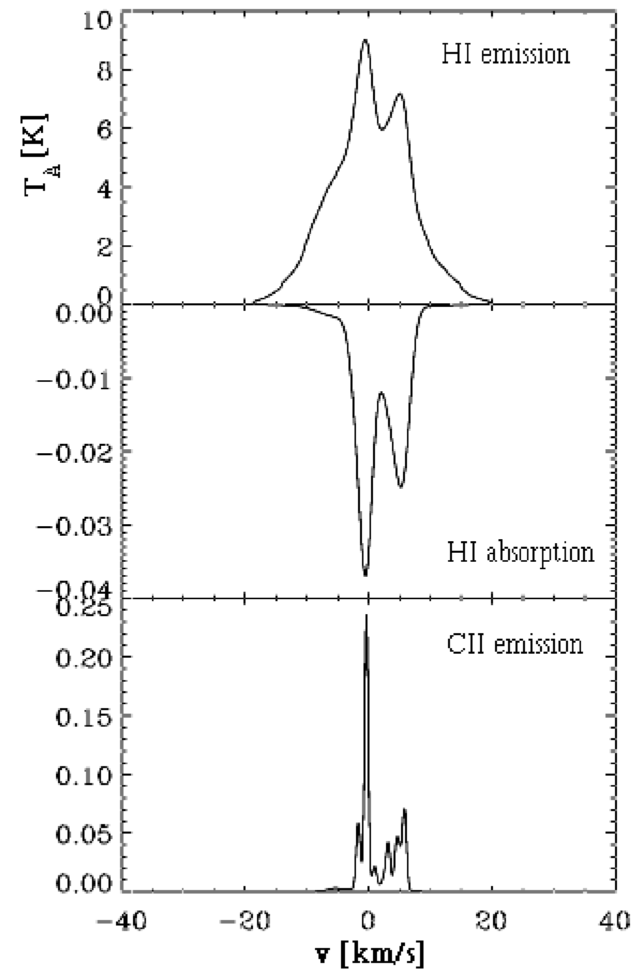
Observations

HIFI and PACS:

- provide a unique way to study the chemical inventory in dense interstellar clouds:
- observe ground-state transitions of key species: CH, NH, H_2O, OH (PACS), CH^+, NH^+, OH^+, H_3O^+

With the spectral resolution of HIFI we can

- resolve shock structures in turbulent velocity field
- study the dynamical structure of molecular clouds
- resolve the three-dimensional abundance distribution of species



Hennebelle & Perault (2000)

Deadline for open-time key project proposals: October 25, 2007

Conclusions

- a large fraction of the ISM gas is molecular
- most of that is only partially molecular
- H_2 seen at many different conditions, but a large fraction invisible in CO

- There is no simple answer to what a molecular cloud is.

  ☞ different molecules are found in different regions

  ☞ even for H_2, different thresholds for "molecular gas" need to be defined depending on the physical/chemical processes considered

- Clouds are turbulent. This implies
  - fractal structures ☞ surfaces everywhere ☞ PDRs everywhere
  - short lived clouds ☞ non-equilibrium chemistry
  - turbulent mixing, turbulent transport, turbulent dissipation

- Mapping observations of various tracers resolving the turbulent structure in space and velocity are needed.