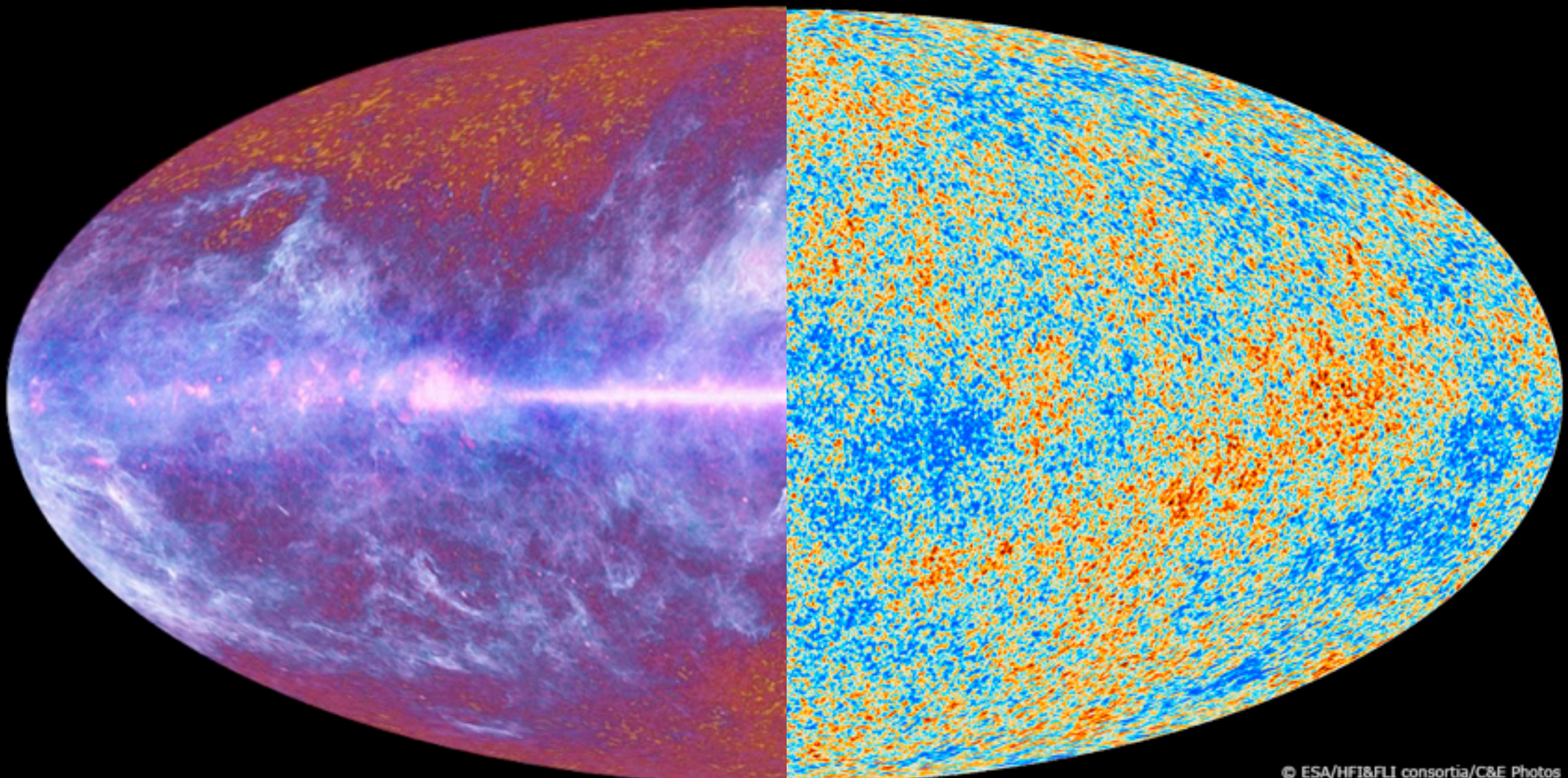
The ISM for cosmologists



F. Levrier

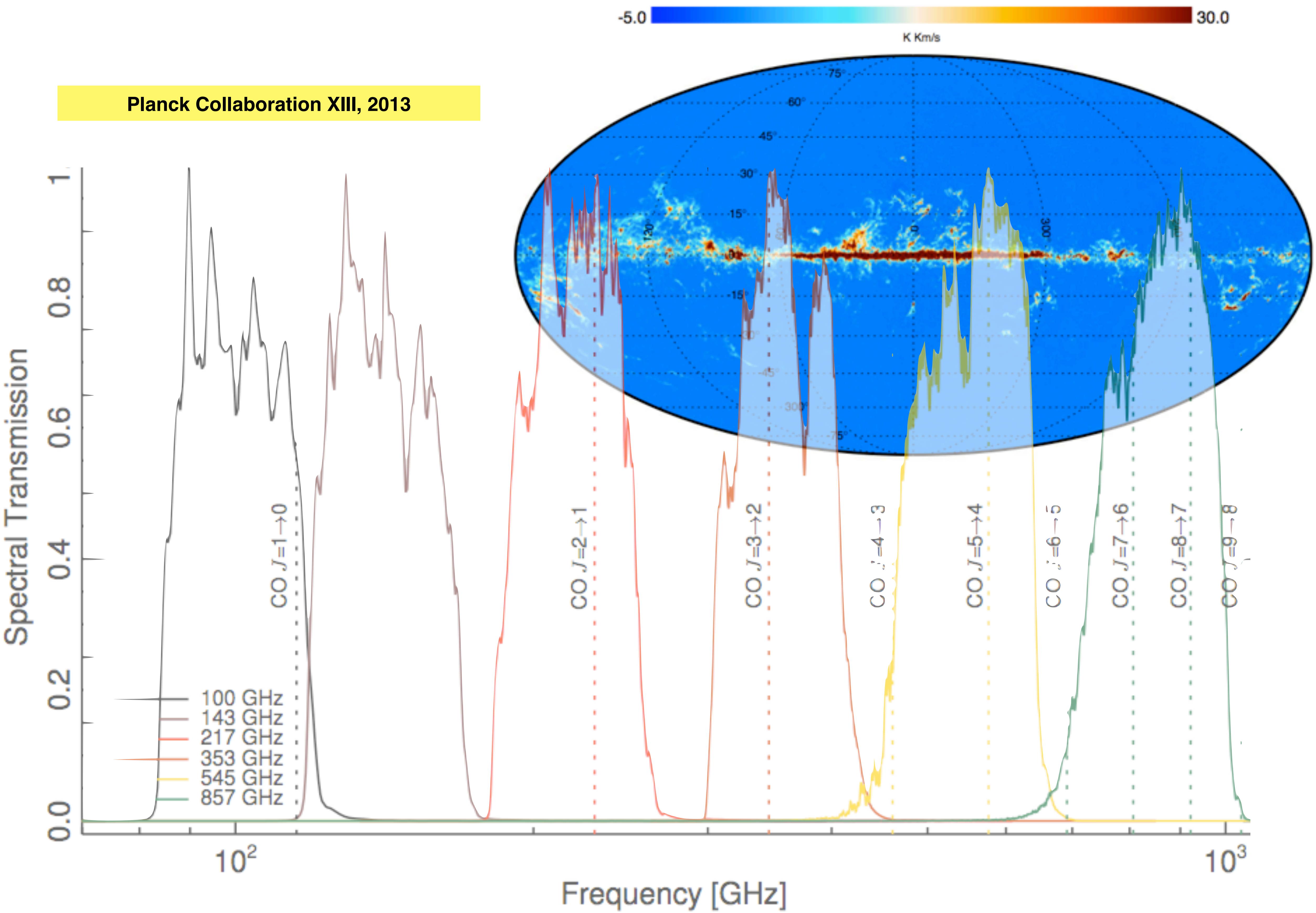
LRA - LERMA / ENS / Observatoire de Paris

l'Observatoire de Paris
LERMA
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

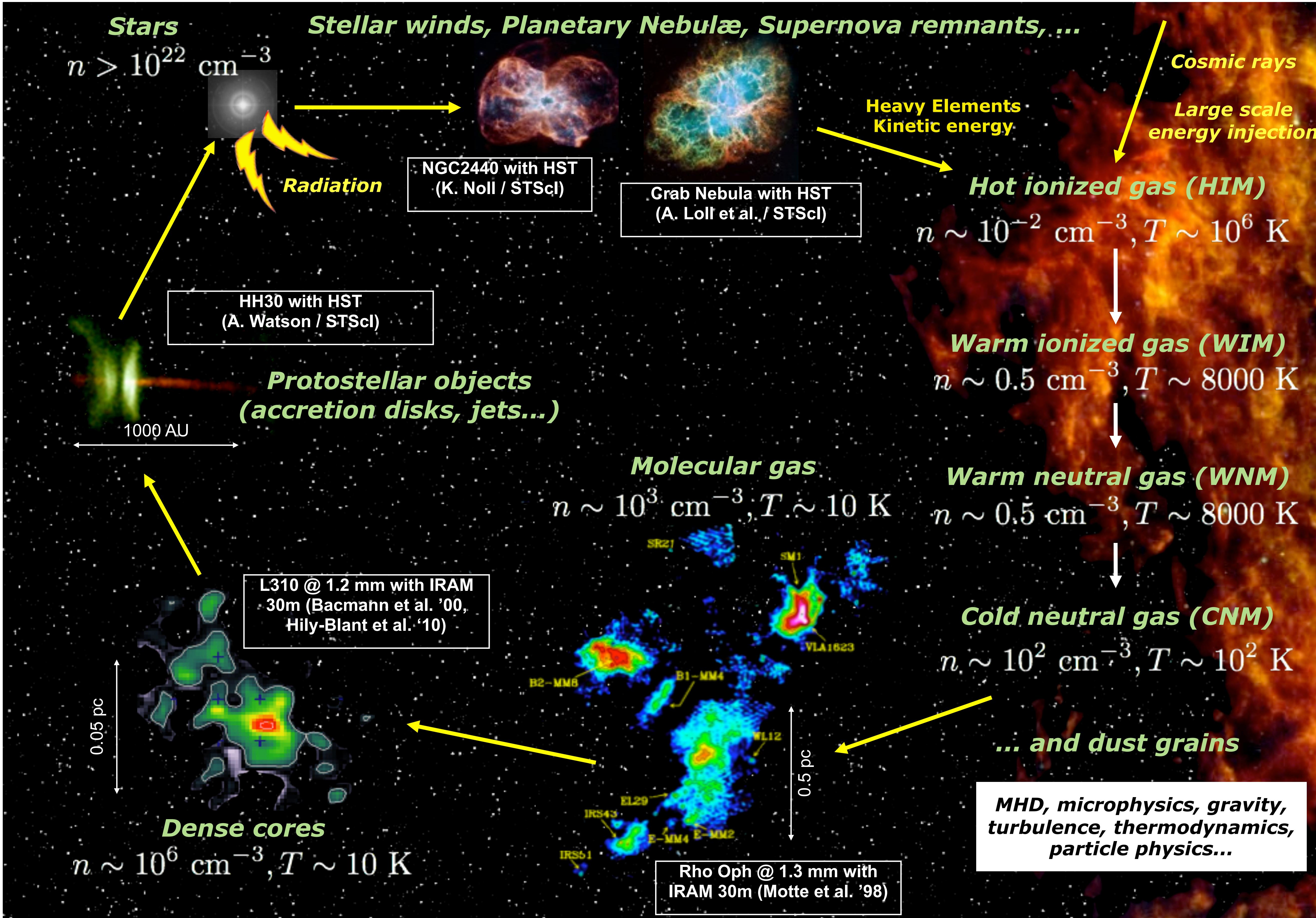
The nature and role of galactic winds through cosmic time - Lyon - 28/10/2013

CO gas in Planck data

Planck Collaboration XIII, 2013



The cycle of interstellar matter



Turbulence in the interstellar medium ?

THE EVOLUTION OF GALAXIES AND STARS

C. F. VON WEIZSÄCKER
Max Planck Institut, Göttingen
Received May 17, 1951

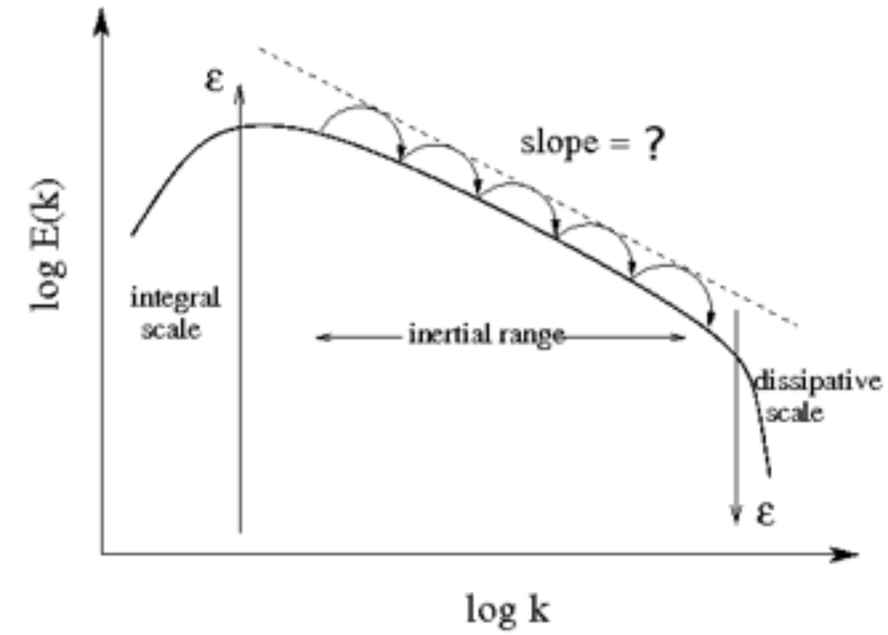
ABSTRACT

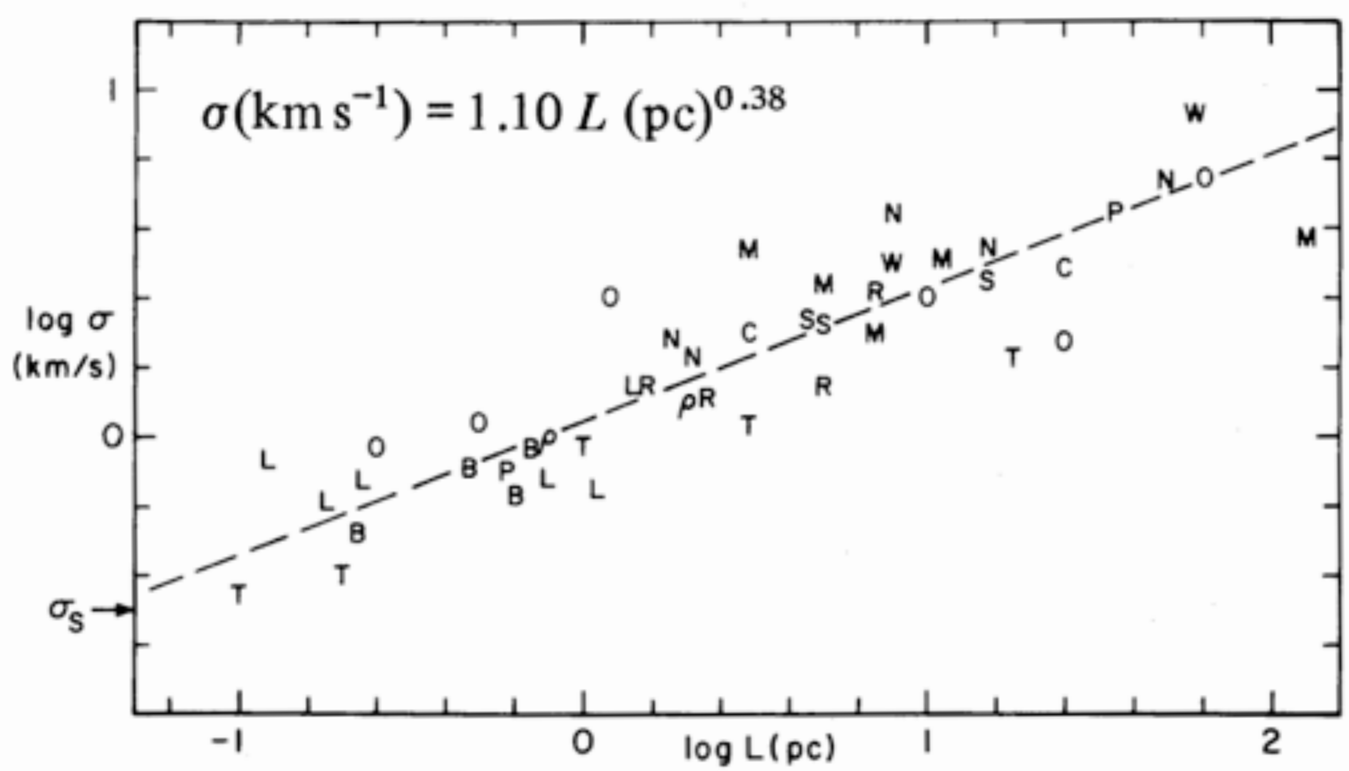
I. Aims of the theory.—A hydrodynamical scheme of evolution is proposed, confined to events after the time when the average density in the universe was comparable to the density inside a galaxy at our time.

II. Hydrodynamical conditions.—Gas in cosmic space is moving according to hydrodynamics, mostly in a turbulent and compressible manner. Dust is carried with the gas, probably by magnetic coupling. Star systems cannot be described hydrodynamically and hence do not show turbulence and supersonic compressibility.

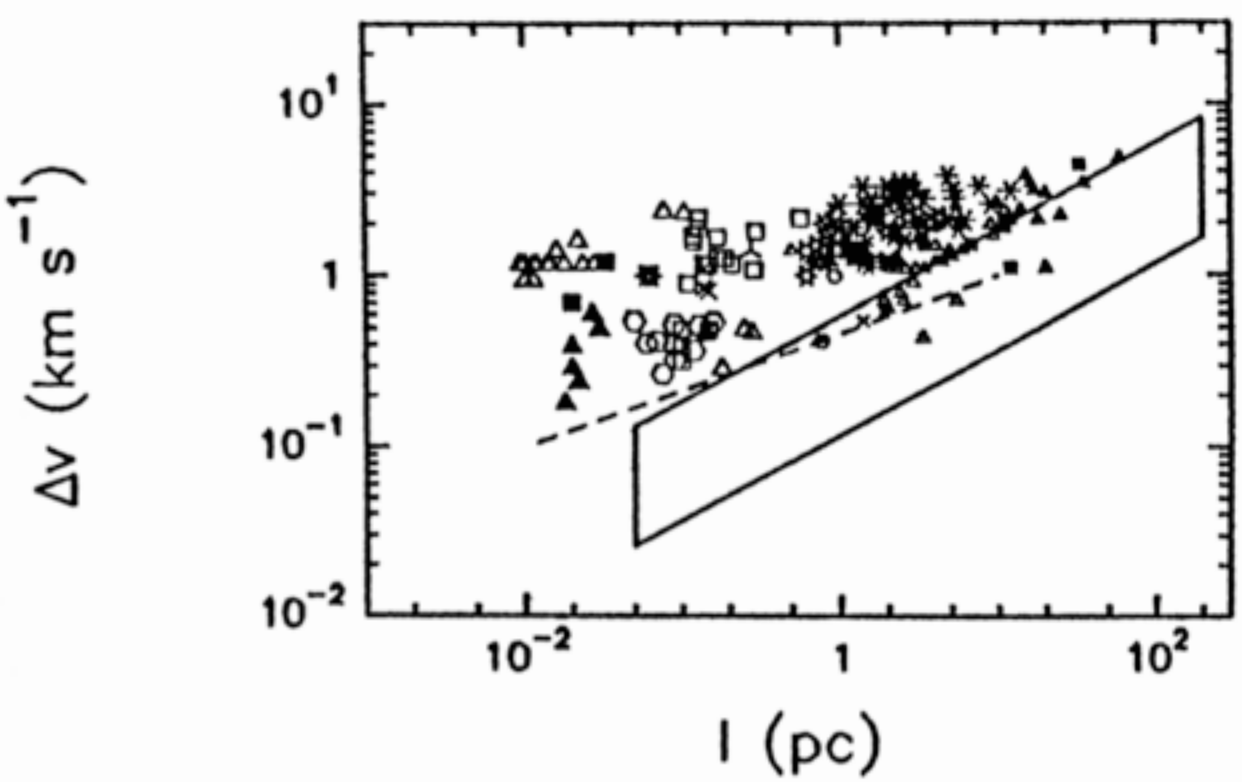
III. The spectral law of incompressible turbulence.—The relative velocity of two points at a distance l is proportional to $l^{1/3}$. This is deduced from the picture of a hierarchy of eddies.

IV. Compressibility and interstellar clouds.—A hierarchy of clouds is considered.





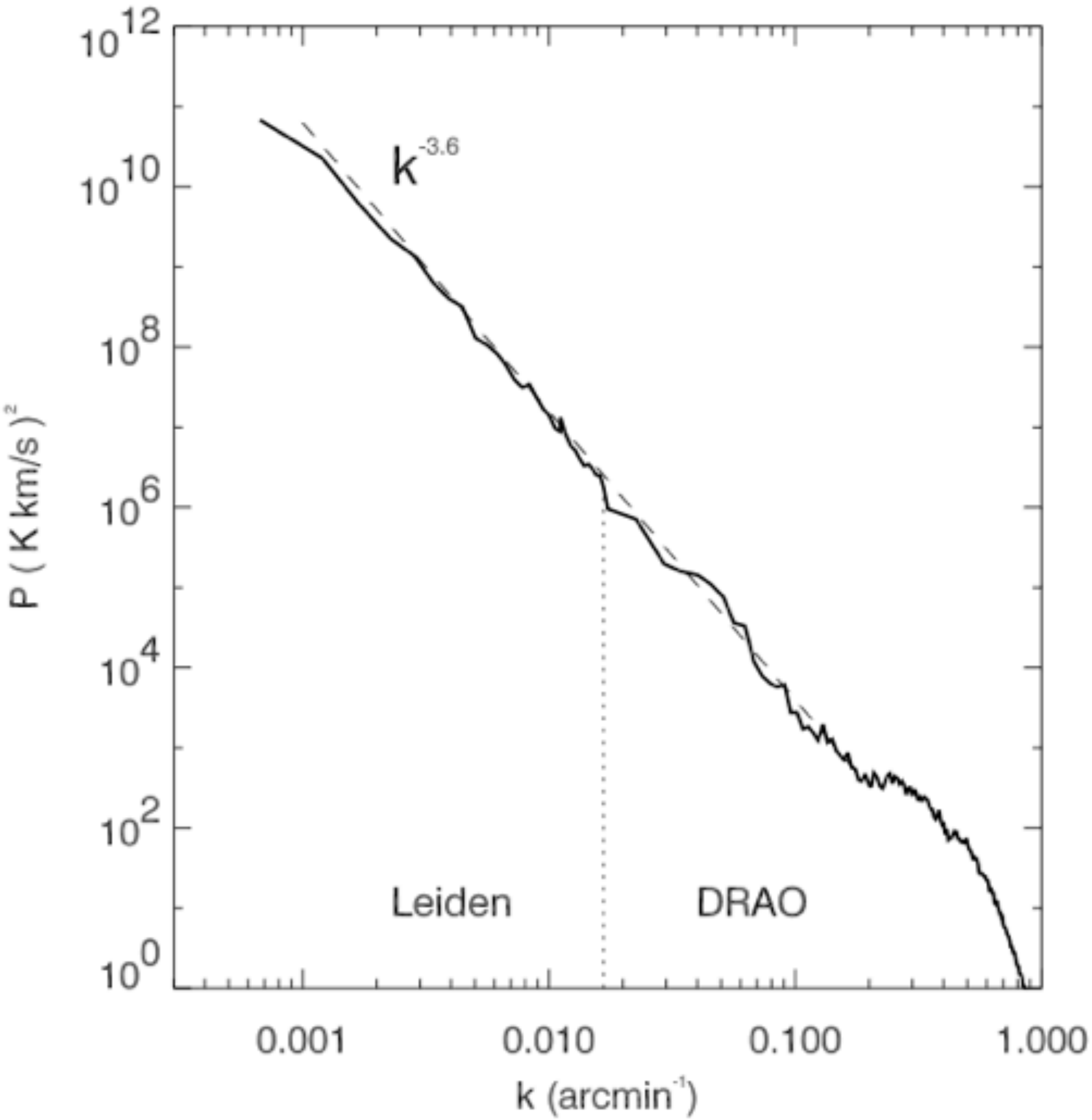
Larson, 1981



Falgarone, 1997

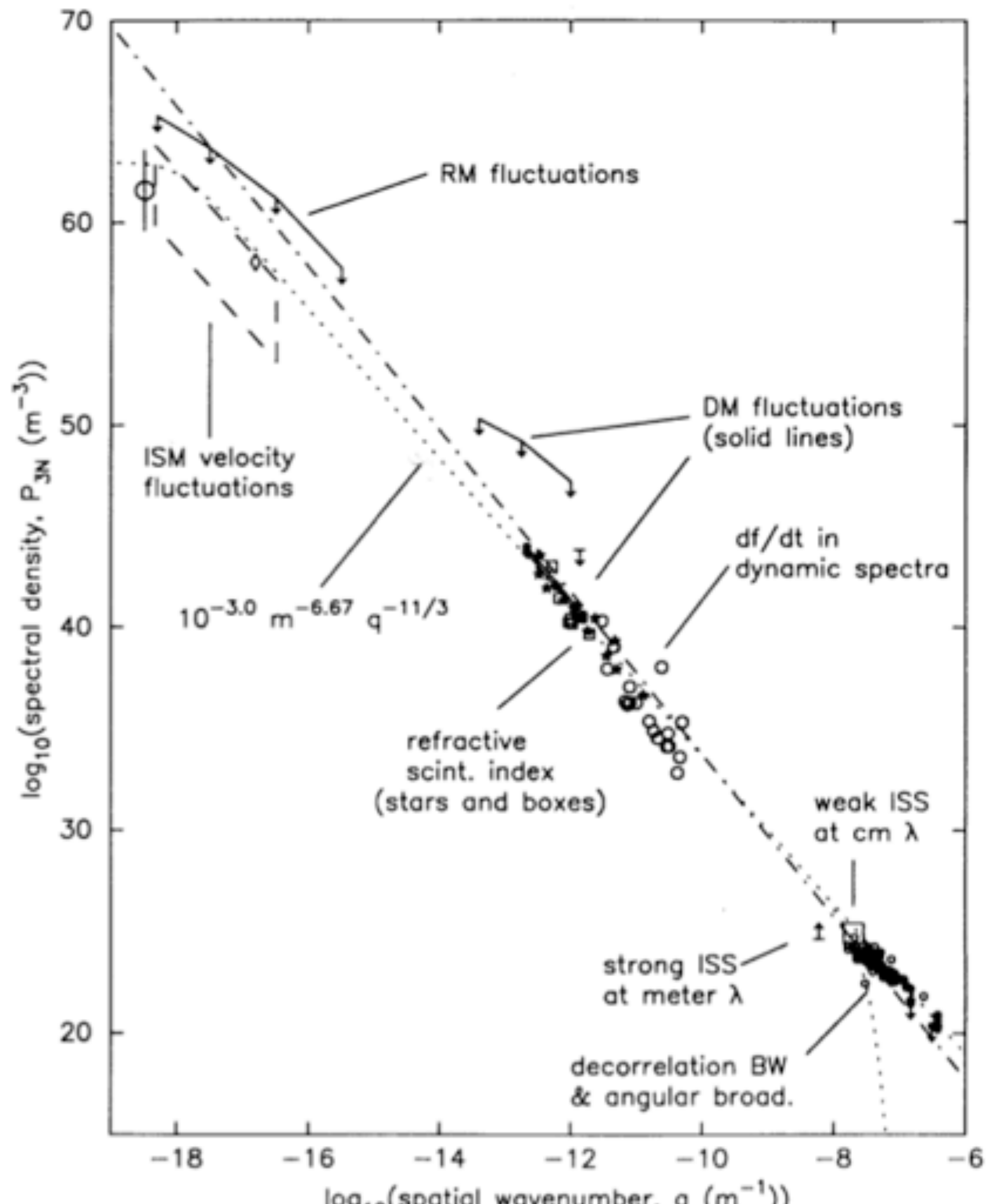
Power spectra in various phases

HI gas in Ursa Major



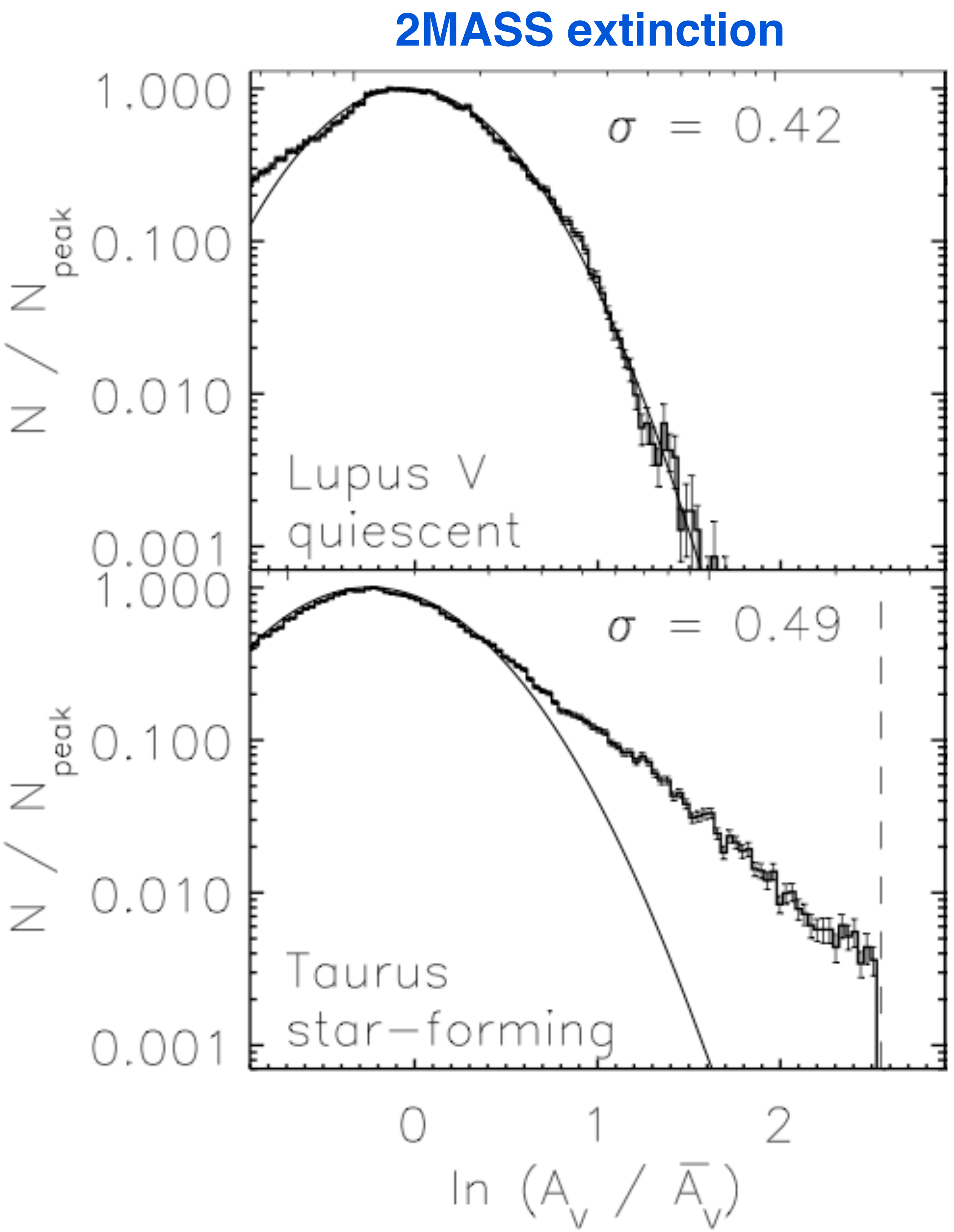
Miville-Deschênes et al., 2003

Electron density in local ISM



Armstrong et al., 1995

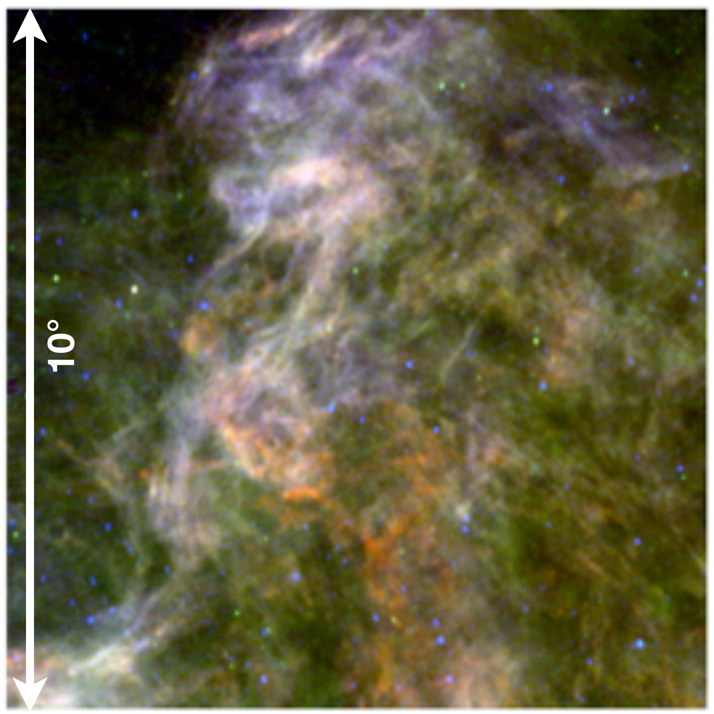
Starforming and non-starforming clouds



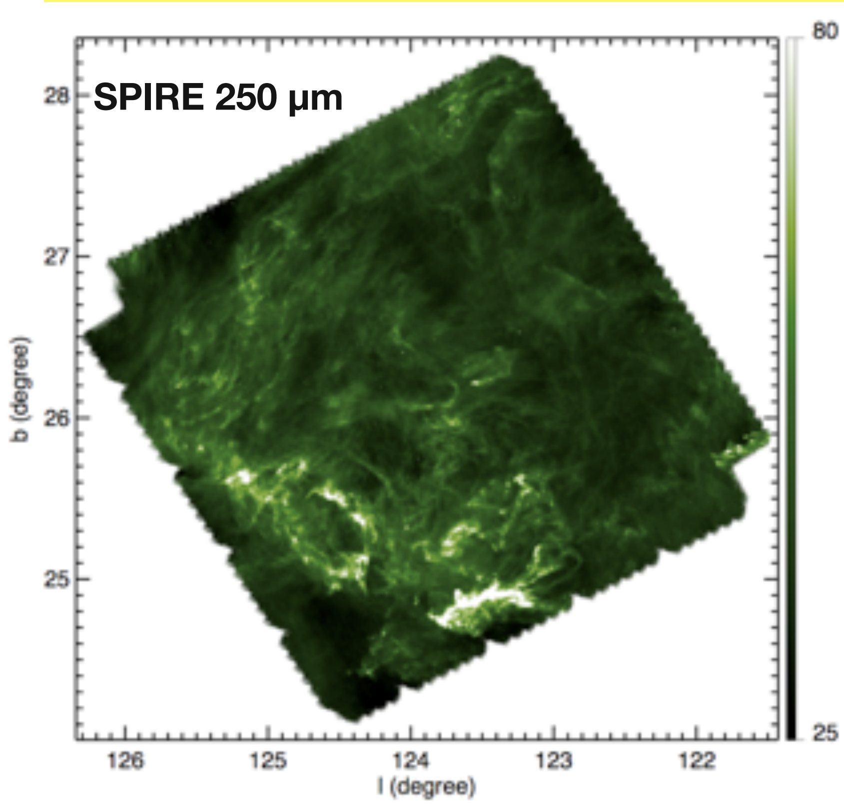
Kainulainen et al., 2009

Filamentary structures at many scales

IRIS 25+60+100µm

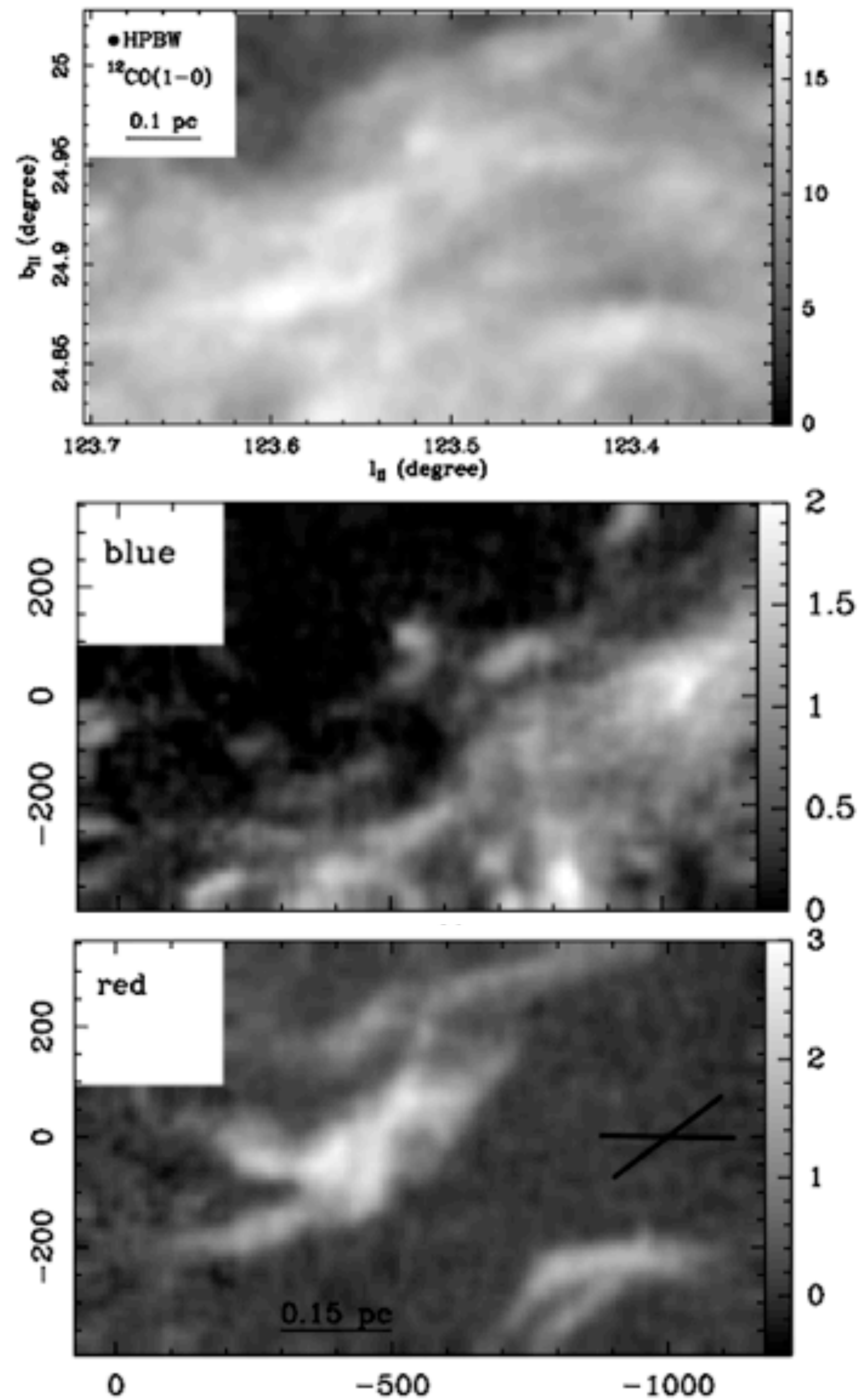


Miville-Deschênes & Lagache, 2005



Miville-Deschênes et al., 2010

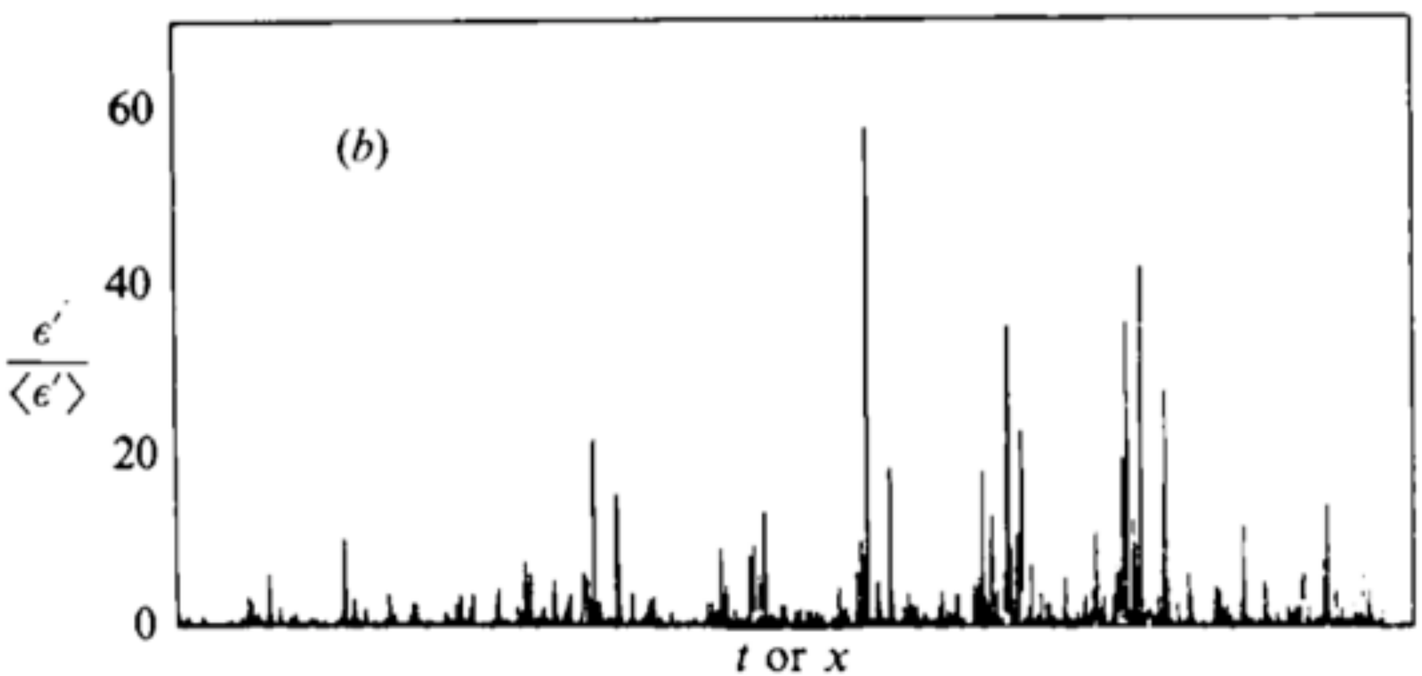
Dust and CO gas in the Polaris Flare



Hily-Blant et al., 2007

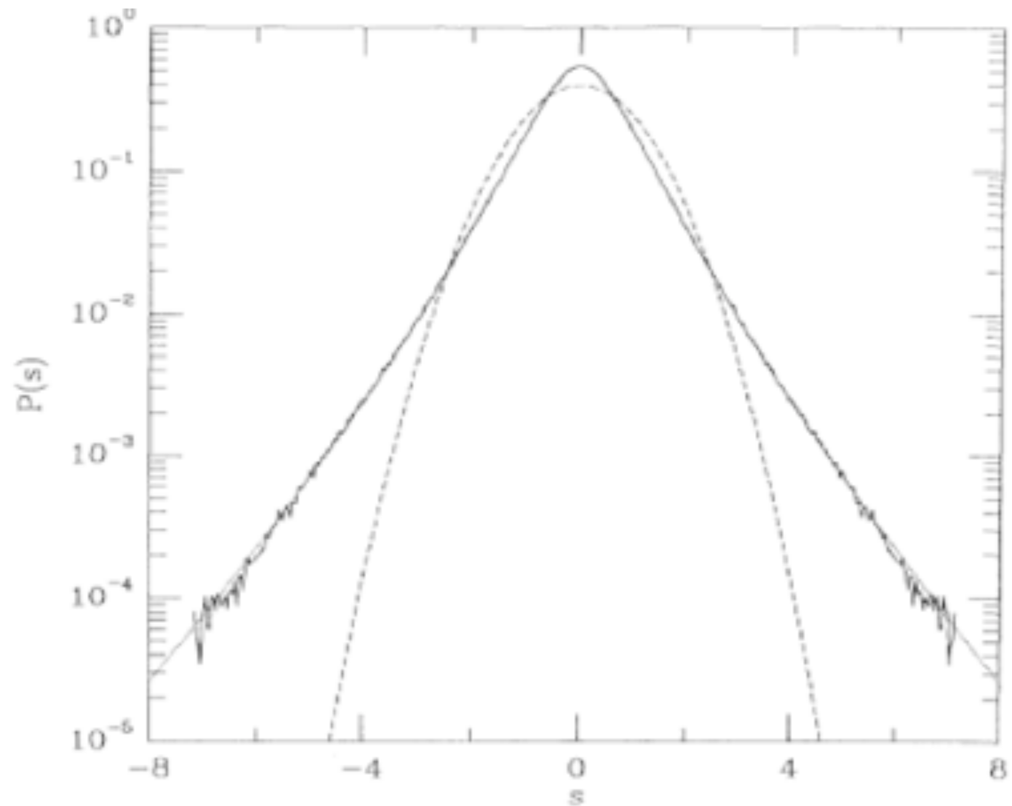
Intermittent dissipation of turbulence

Temporal series of the dissipation rate



Meneveau & Sreenivasan, 1991

Experimental PDF of velocity increments

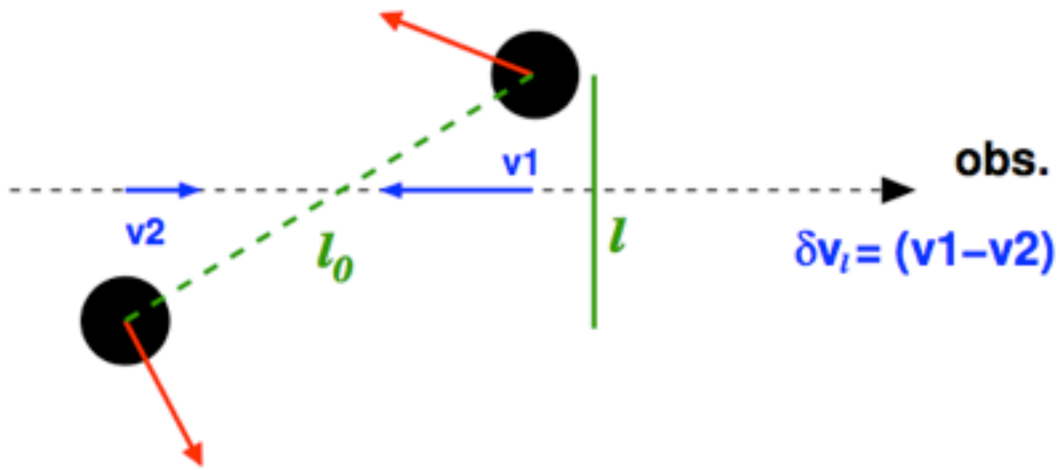


She 1991, Belin et al., 1996

Viscous dissipation rate $$\langle \epsilon_d \rangle = \nu \left| \nabla \times \boldsymbol{v} \right|^2$$

Problem : we cannot trace the vorticity ! $$v_z(x, y)$$

Centroid Velocity Increments

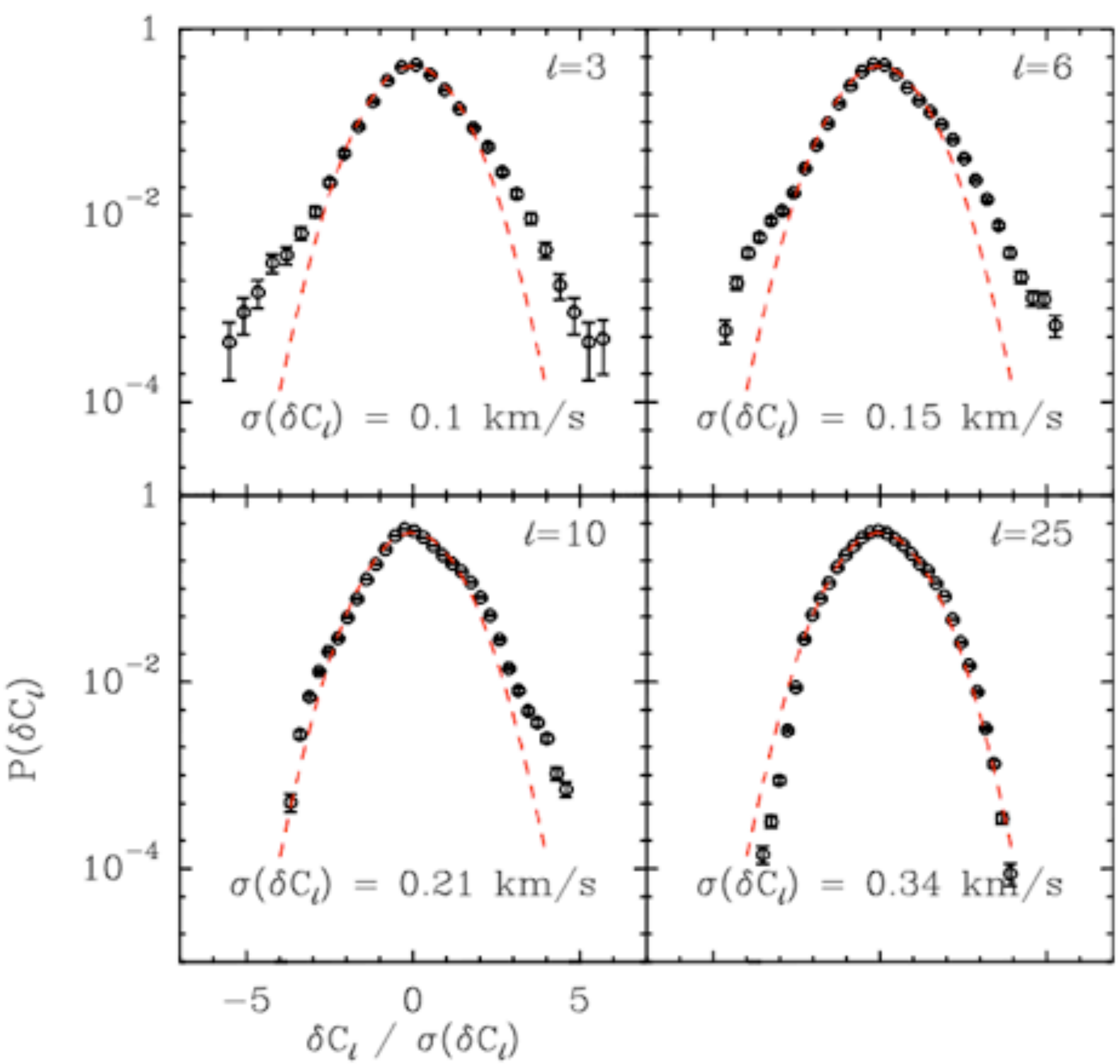


Line centroid velocity:

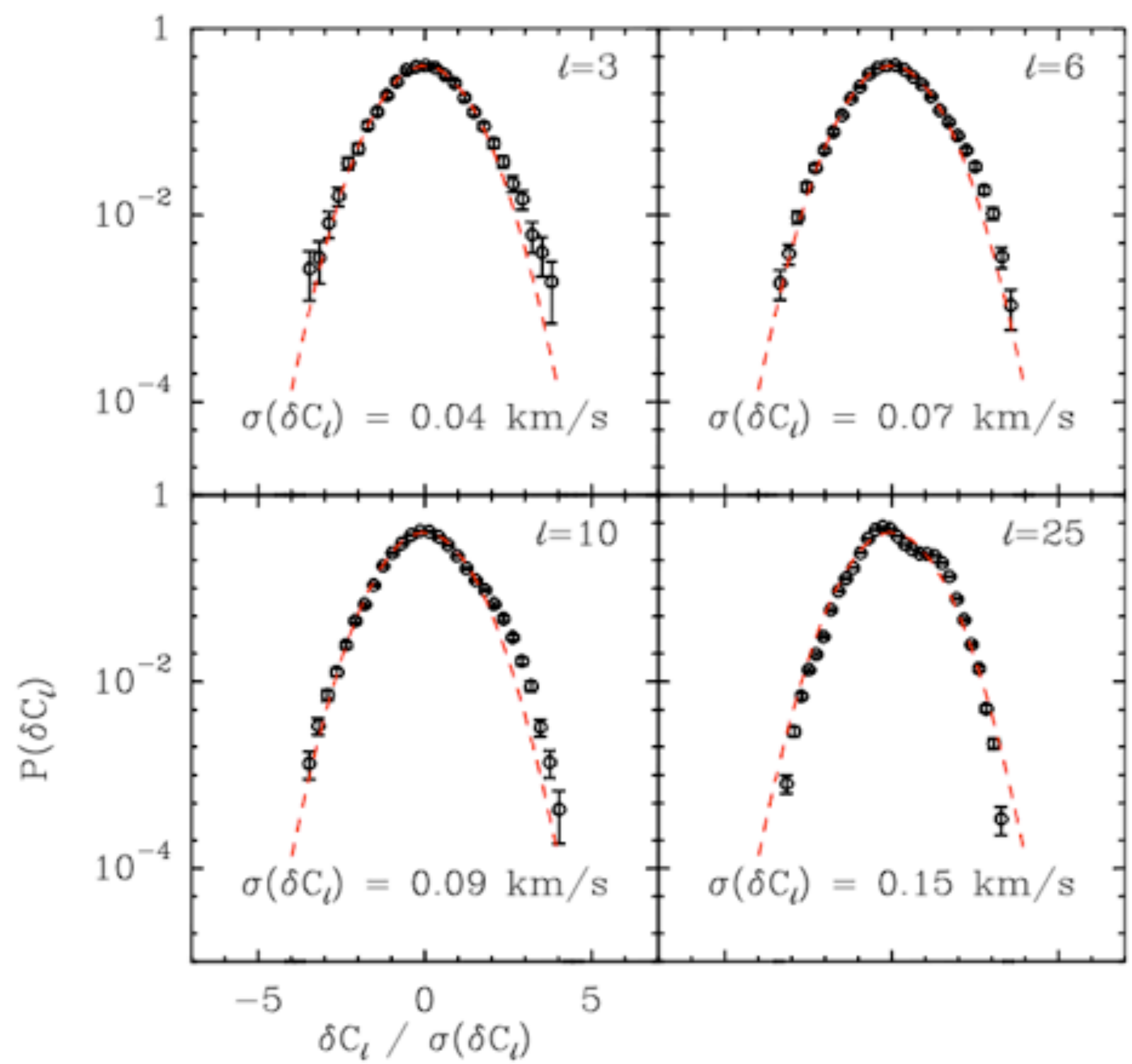
$$C(\mathbf{r}) = \int T(\mathbf{r}, v_x) v_x dv_x / \int T(\mathbf{r}, v_x) dv_x$$

Miesch & Scalo 1999, Pety & Falgarone 2003, Levrier 2004

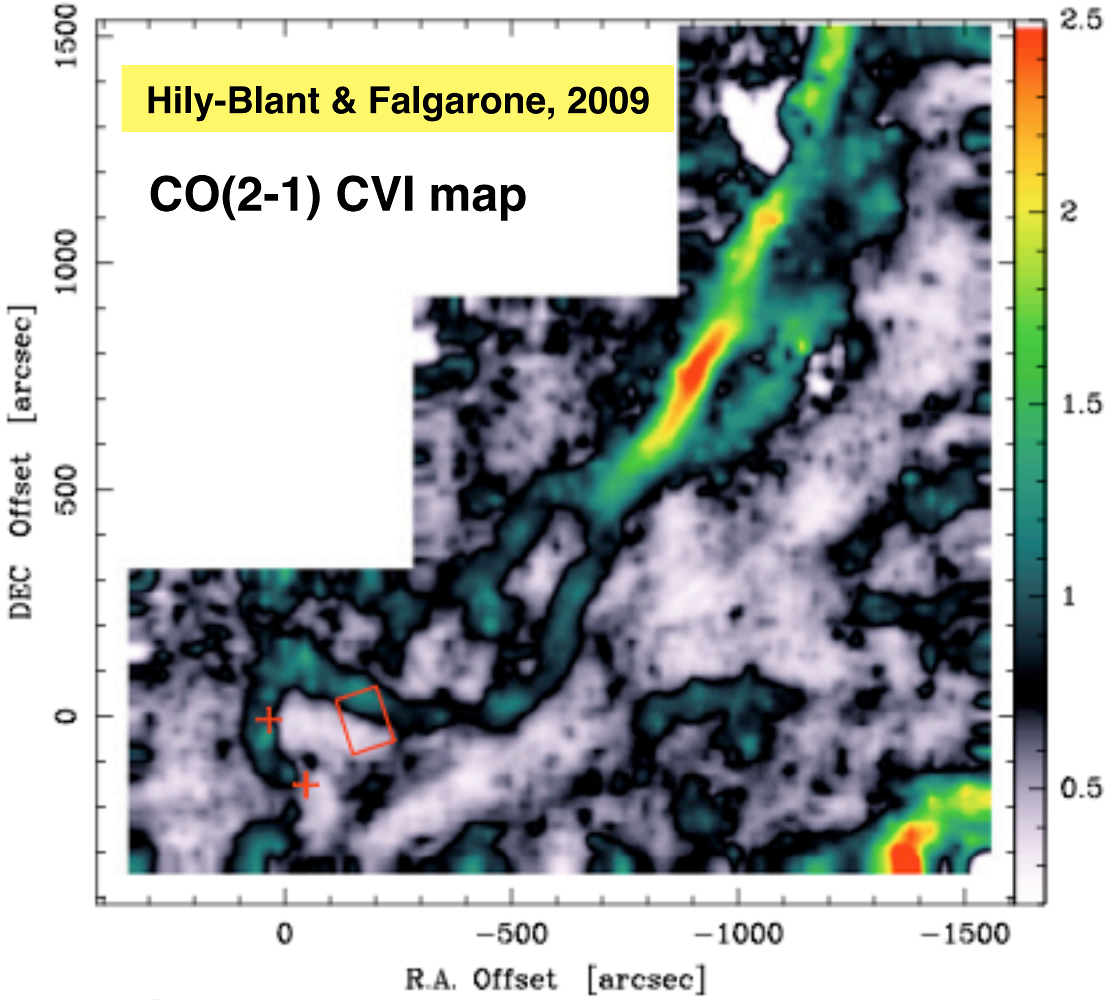
Polaris

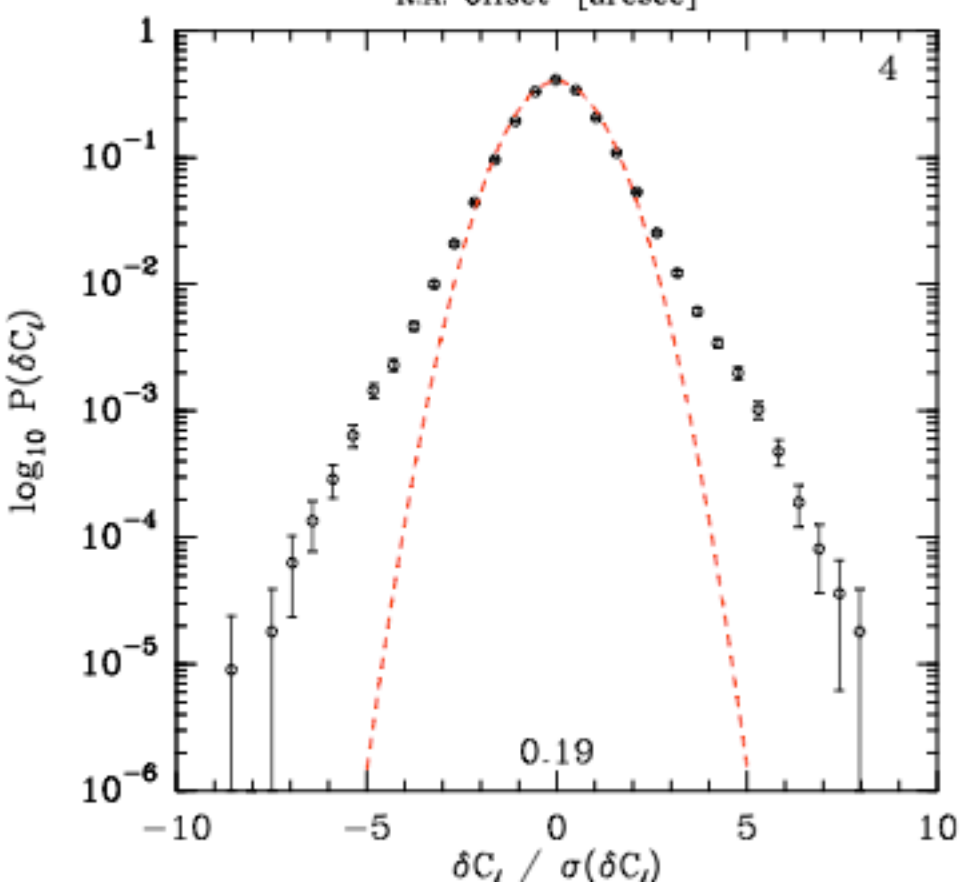


Taurus

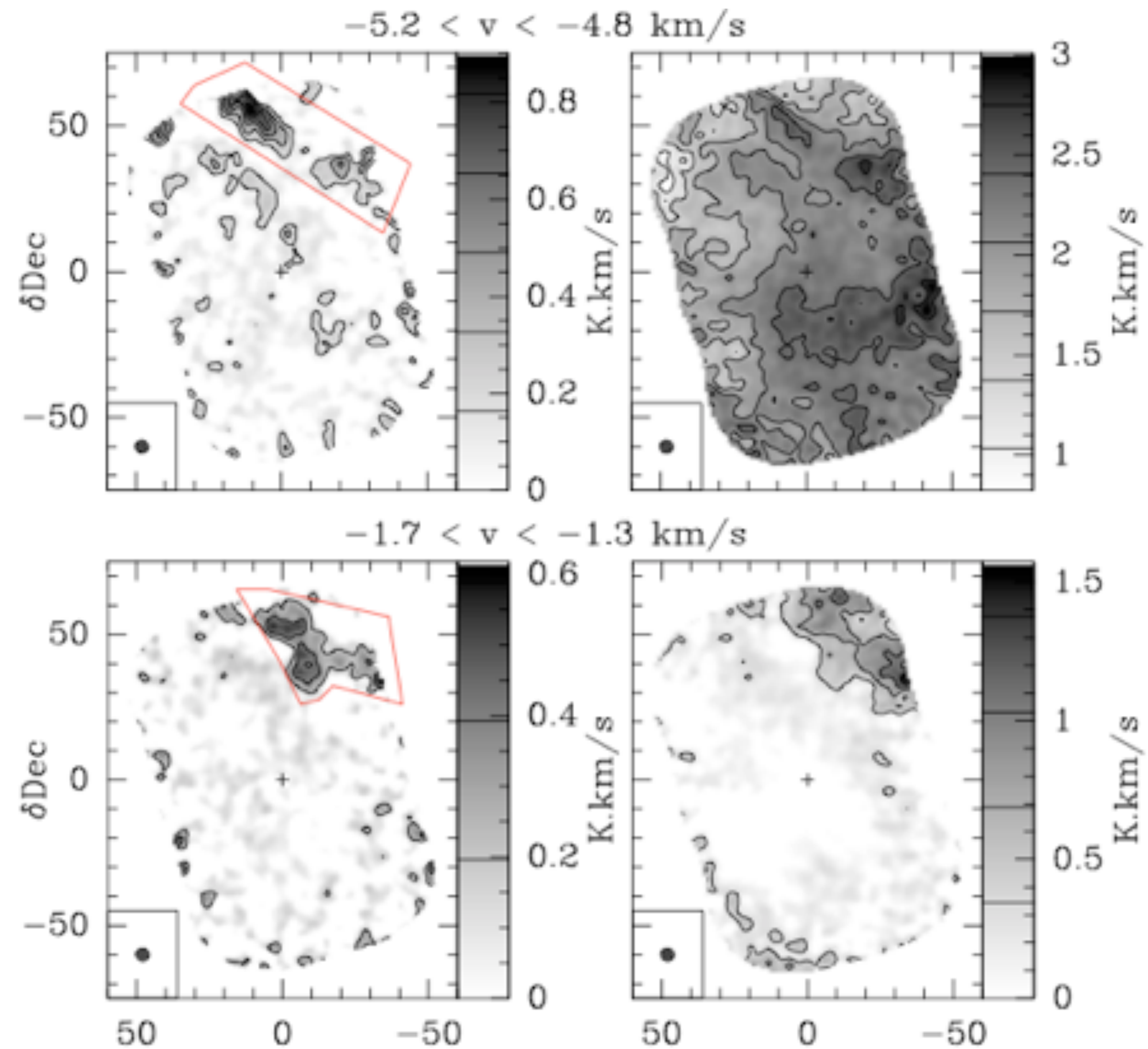


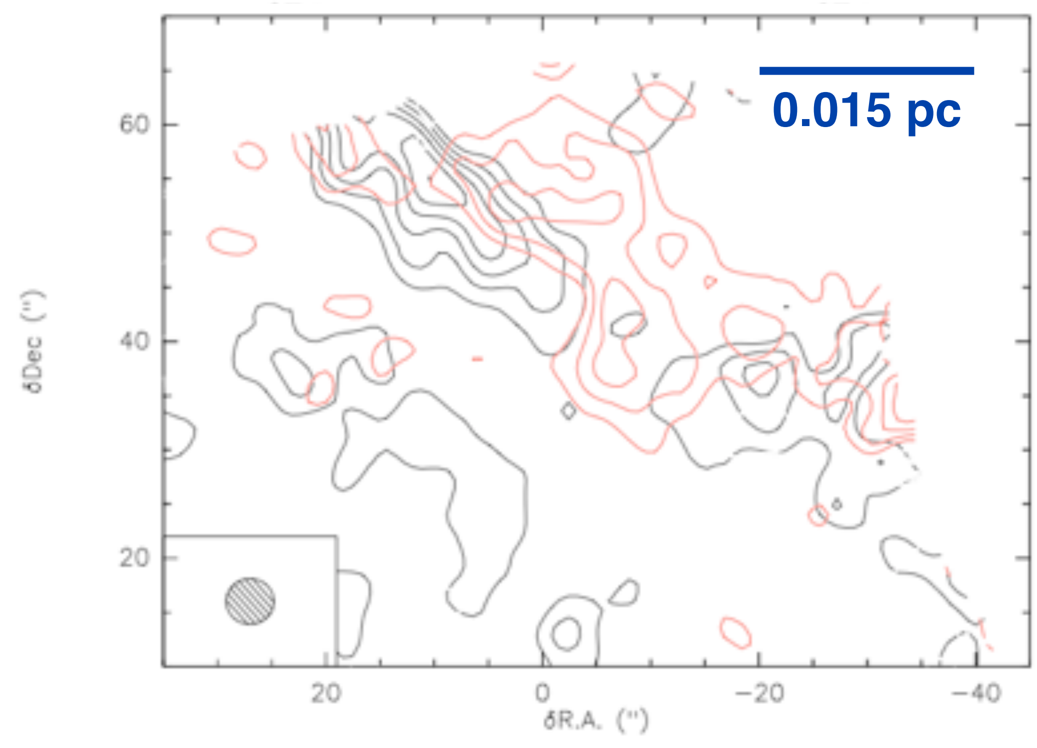
Loci of extreme CVI





Falgarone, Pety & Hily-Blant, 2009





The molecular universe

About 200 species detected in the ISM

OUT OF THIS WORLD

A wealth of molecules is found in interstellar clouds

2 atoms
H_2, AlF, AlCl, C_2, CH, CH^+, CN, CO, CO^+, CP, CSi, HCl, KCl, NH, NO, NS, NaCl, OH, PN, SO, SO^+, SiN, SiO, SiS, CS, HF, SH, FeO

3 atoms
C_3, C_2H, C_2O, C_2S, CH_2, HCN, HCO, HCO^+, HCS^+, HOC^+, H_2O, H_2S, HNC, HNO, MgCN, MgNC, N_2H^+, N_2O, NaCN, OCS, SO_2, c-SiC_2, CO_2, NH_2, H_3^+, SiCN, AlNC

4 atoms
c-C_3H, l-C_3H, C_3N, C_3O, C_3S, C_2H_2, HCCN, $HCNH^+$, HNCO, HNCS, $HOCO^+$, H_2CO, H_2CN, H_2CS, H_3O^+, NH_3, SiC_3

5 atoms
C_5, C_4H, C_4Si, l-C_3H_2, c-C_3H_2, CH_2CN, CH_4, HC_3N, HC_2NC, HCOOH, H_2CHN, H_2C_2O, H_2NCN, HNC_3, SiH_4, H_2COH^+

6 atoms
C_5H, l-H_2C_4, C_2H_4, CH_3CN, CH_3NC, CH_3OH, CH_3SH, HC_3NH^+, HC_2CHO, NH_2CHO, C_5N

7 atoms
C_6H, CH_2CHCN, CH_3C_2H, HC_5N, $HCOCH_3$, NH_2CH_3, c-C_2H_4O, CH_2CHOH

8 atoms
CH_3C_3N, $HCOOCH_3$, CH_3COOH, C_7H, CH_2OHCHO

9 atoms
CH_3C_4H, CH_3CH_2CN, $(CH_3)_2O$, CH_3CH_2OH, HC_7N, C_8H

10 atoms
CH_3C_5N, $(CH_3)_2CO$, NH_2CH_2COOH

11 atoms
HC_9N

13 atoms
$HC_{11}N$

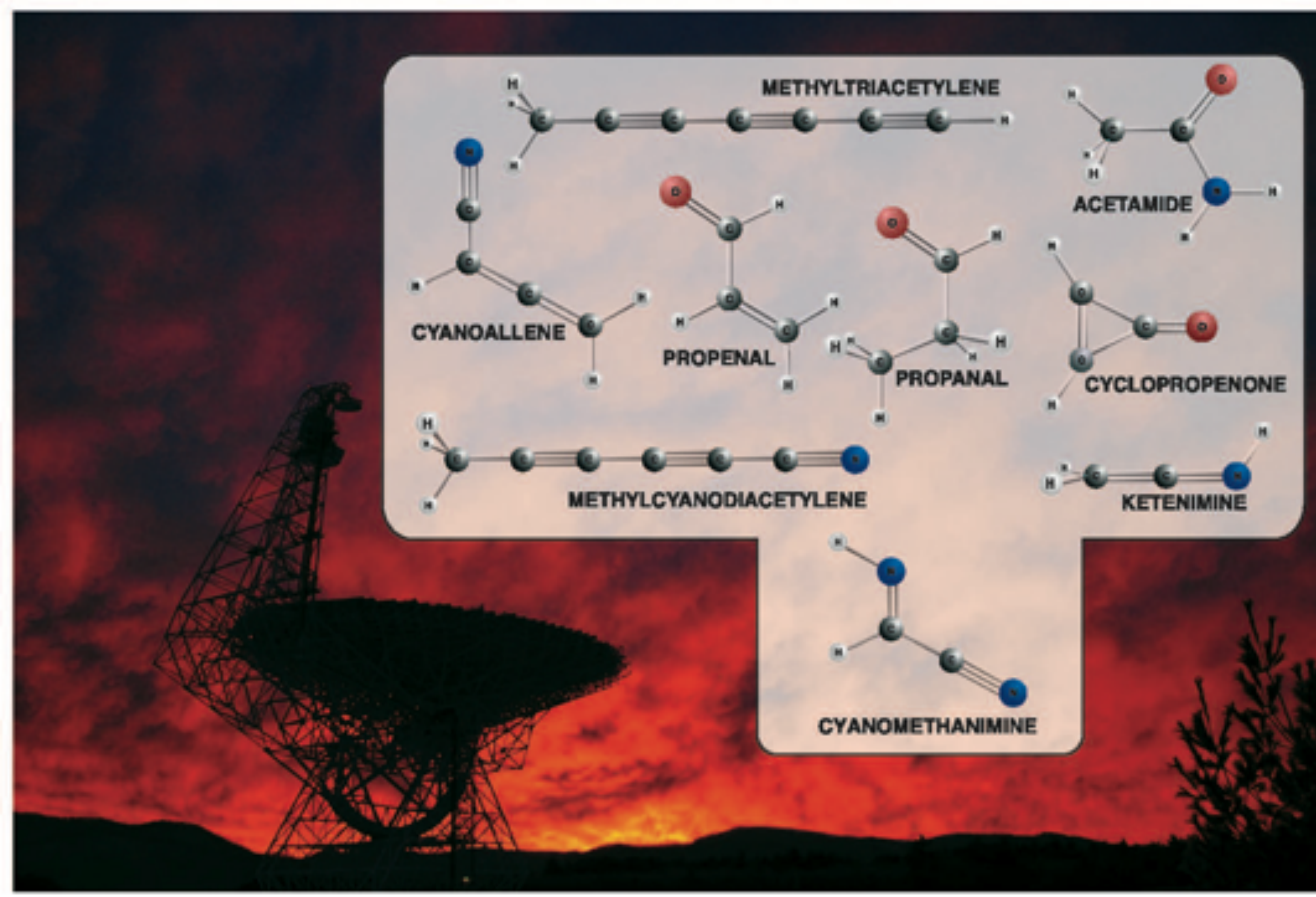
NOTE: Evidence suggests that much larger molecules such as polycyclic aromatic hydrocarbons and fullerenes are also present.
SOURCE: National Radio Astronomy Observatory

Among them hydrides

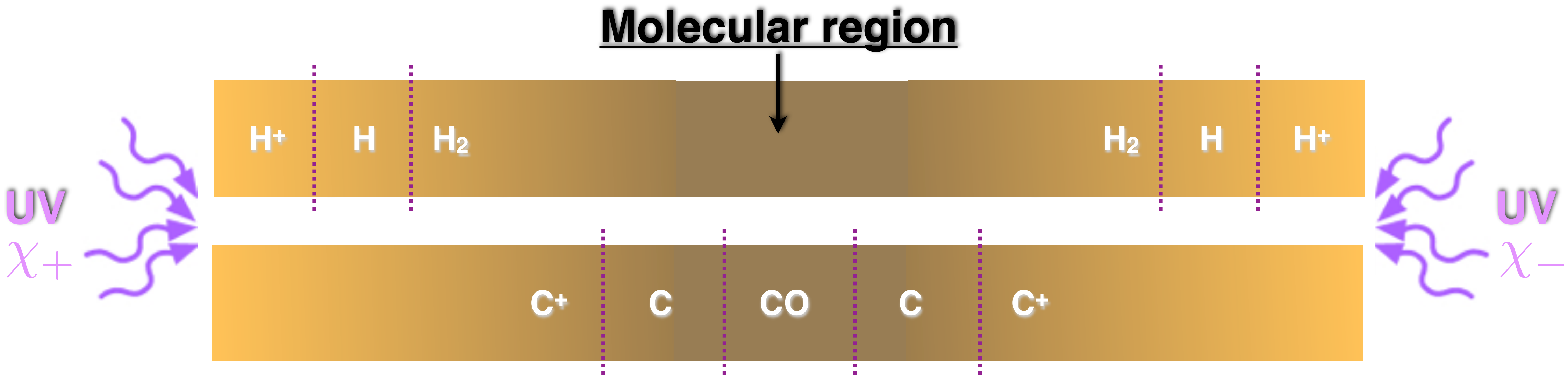
OH^+	H_2O^+	ND	HCl^+	H_2Cl^+	SH	OD

Gerin et al. (2010), Neufeld et al. (2010), De Luca et al. (2012), Neufeld et al. (2012), Lis et al. (2010), Parise et al. (2012), Bacmann et al. (2010)

- One heavy atom (C,N,O,S,F,Cl) plus a number of H
- Tracers of physical and chemical processes
- First building blocks of the molecular ISM



The Meudon PDR code



Stationary 1D model, including :

- UV radiative transfer:
  - Absorption in molecular lines
  - Absorption in the continuum (dust)
  - 10000's of lines
- Chemistry :
  - Several hundred chemical species
  - Network of sevral thousand chemical reactions
  - Photoionization
  - Cosmic ray ionization
- Statistical equilibrium of level populations
  - Radiative and collisional excitations and de-excitations
  - Photodissociation
- Thermal balance:
  - Photoelectric effect
  - Chemistry
  - Cosmic rays
  - Atomic and molecular cooling

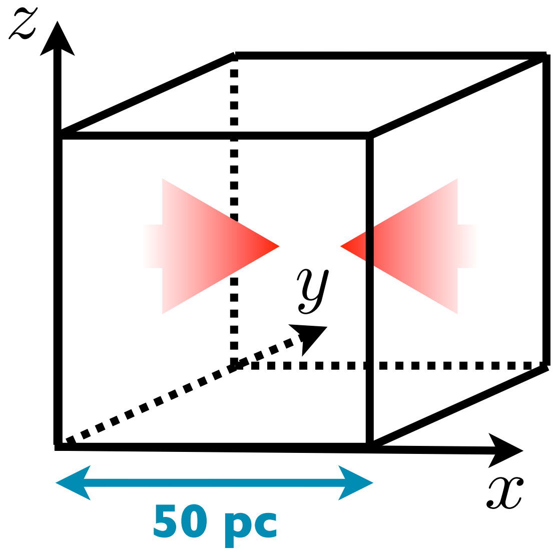
Outputs :

- Local quantities :
  - Abundance and excitation of species
  - Temperature of gas and duts
  - Detailed heating and cooling rates
  - Energy density
  - Gas and grain temperatures
  - Chemical reaction rates
- Integrated quantities on the line of sight :
  - Species column densities
  - Line intensities
  - Absorption of the radiation field
  - Spectra

Le Bourlot et al. 1999
Le Petit et al. 2006
Goicoechea & Le Bourlot 2007
Gonzalez-Garcia et al. 2008

http://pdr.obspm.fr/

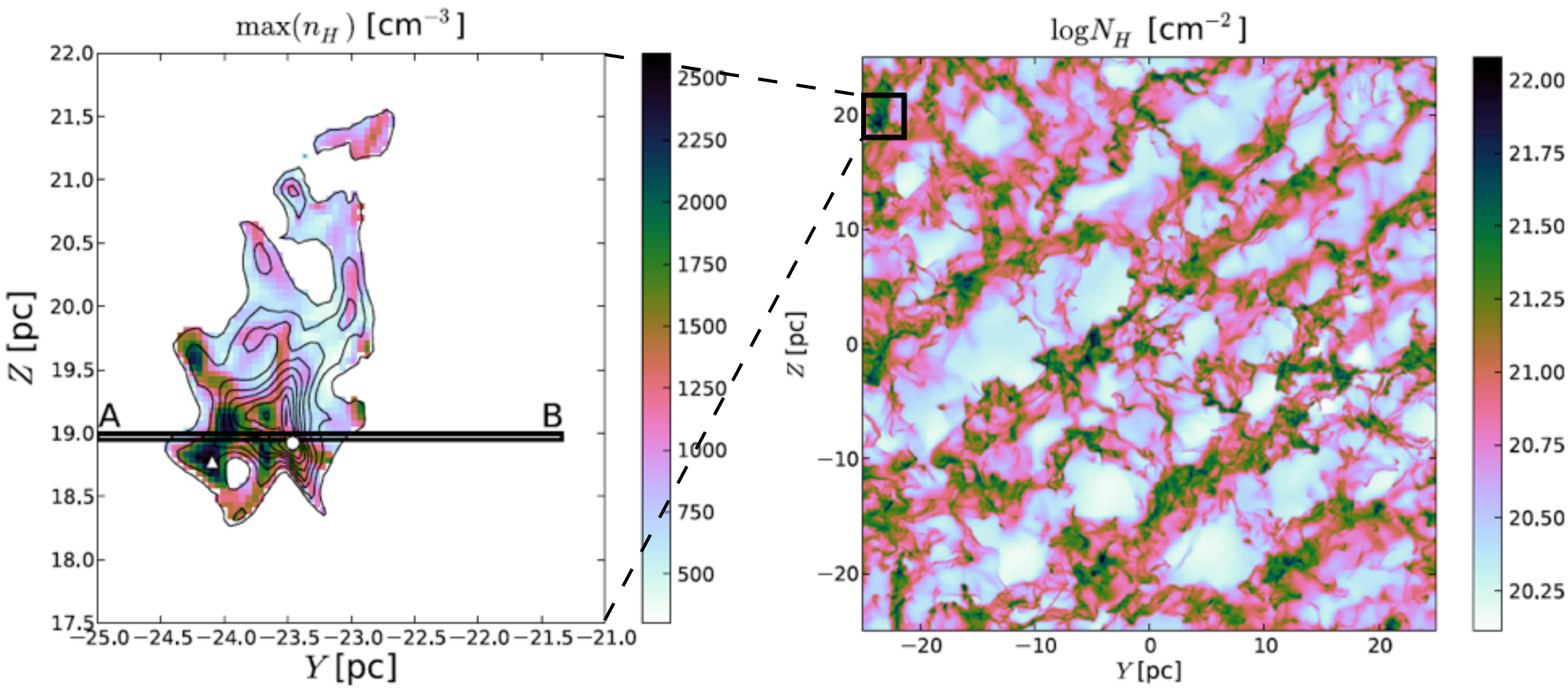
Compressible MHD turbulence simulation

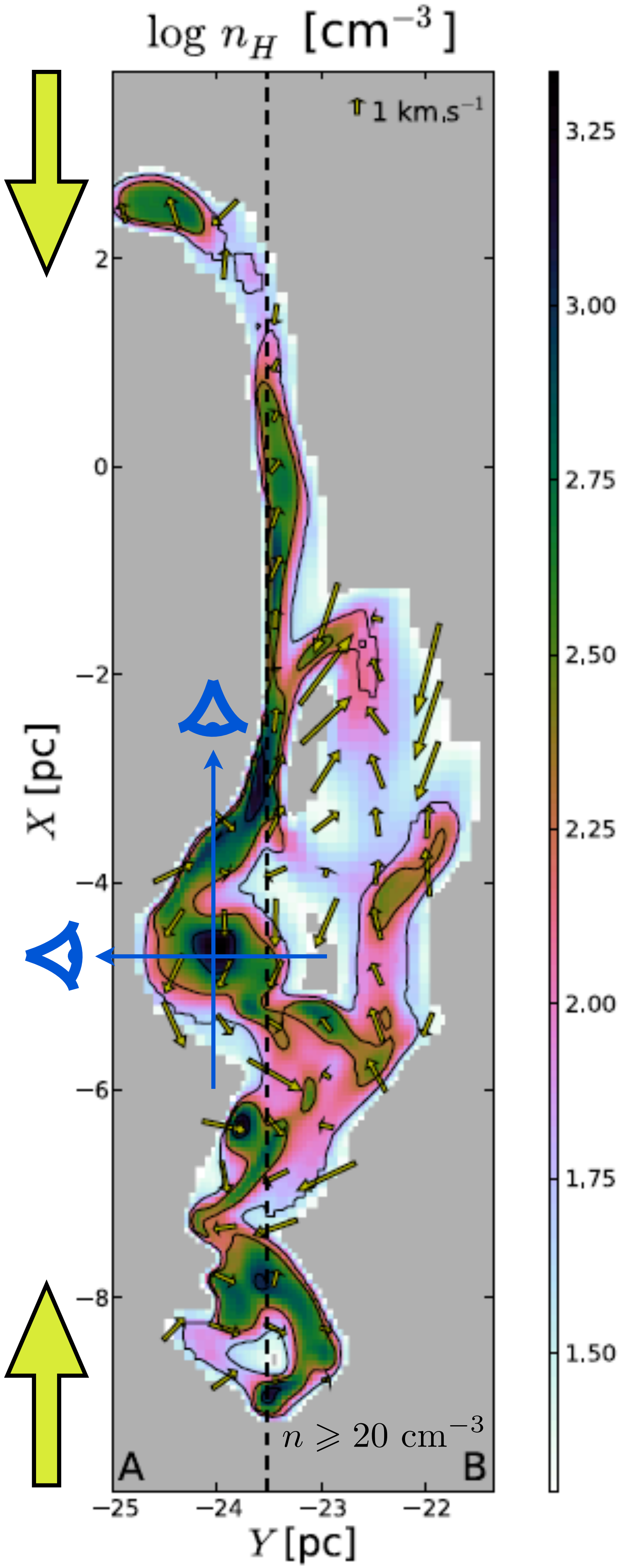


- RAMSES code (Teysier 2002, Fromang et al. 2006)
- Adaptive Mesh Refinement with up to 14 levels
- Converging flows of warm (8,000 K) atomic gas
- Periodic boundary conditions on remaining 4 sides
- Includes magnetic field, atomic cooling and self-gravity consistently
- Covers scales 0.05 pc - 50 pc

Hennebelle et al. 2008

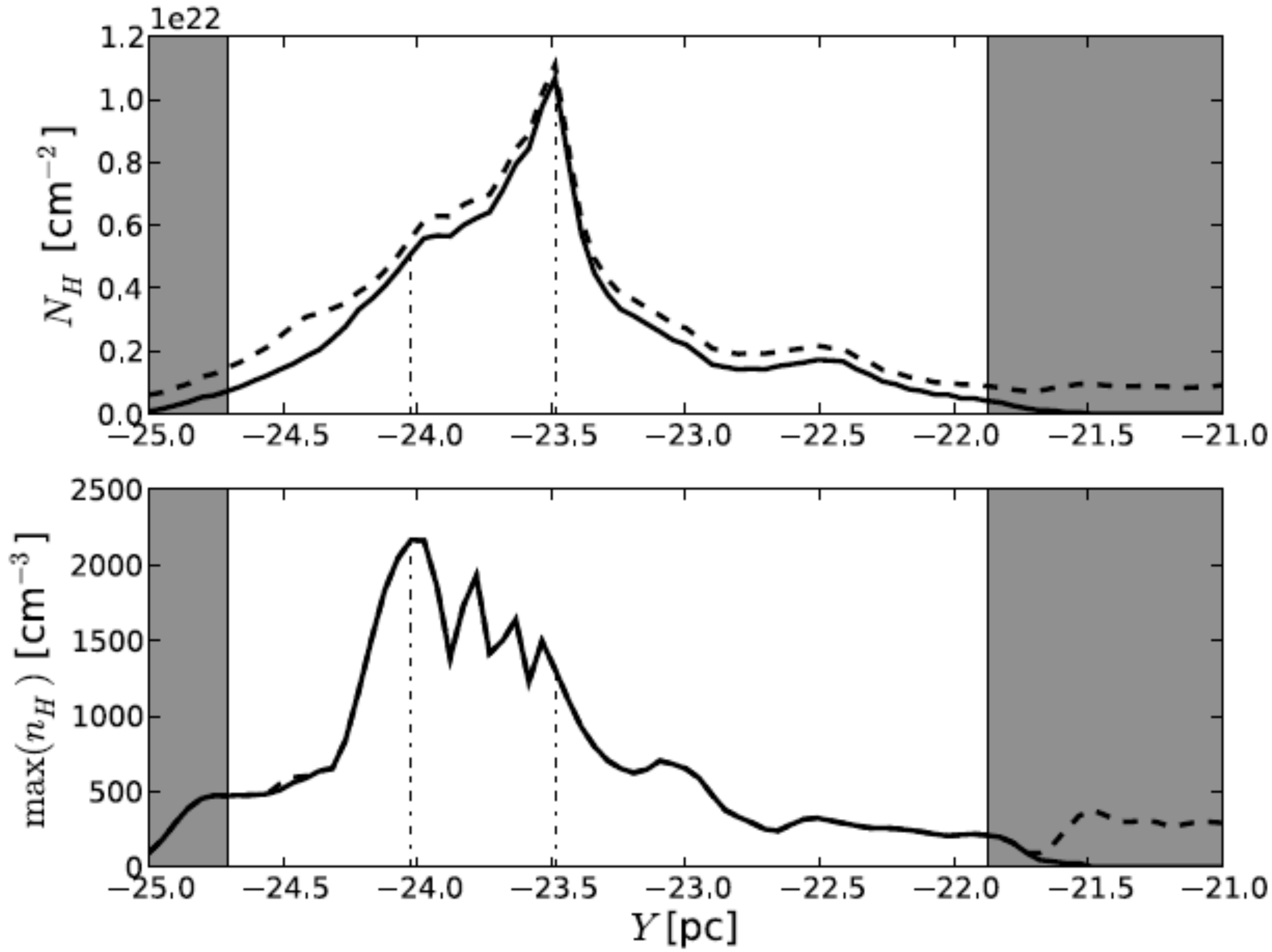
Levrier et al. 2012





Structures along the line of sight

Central ~14 pc cover most of the mass in this 2D slice



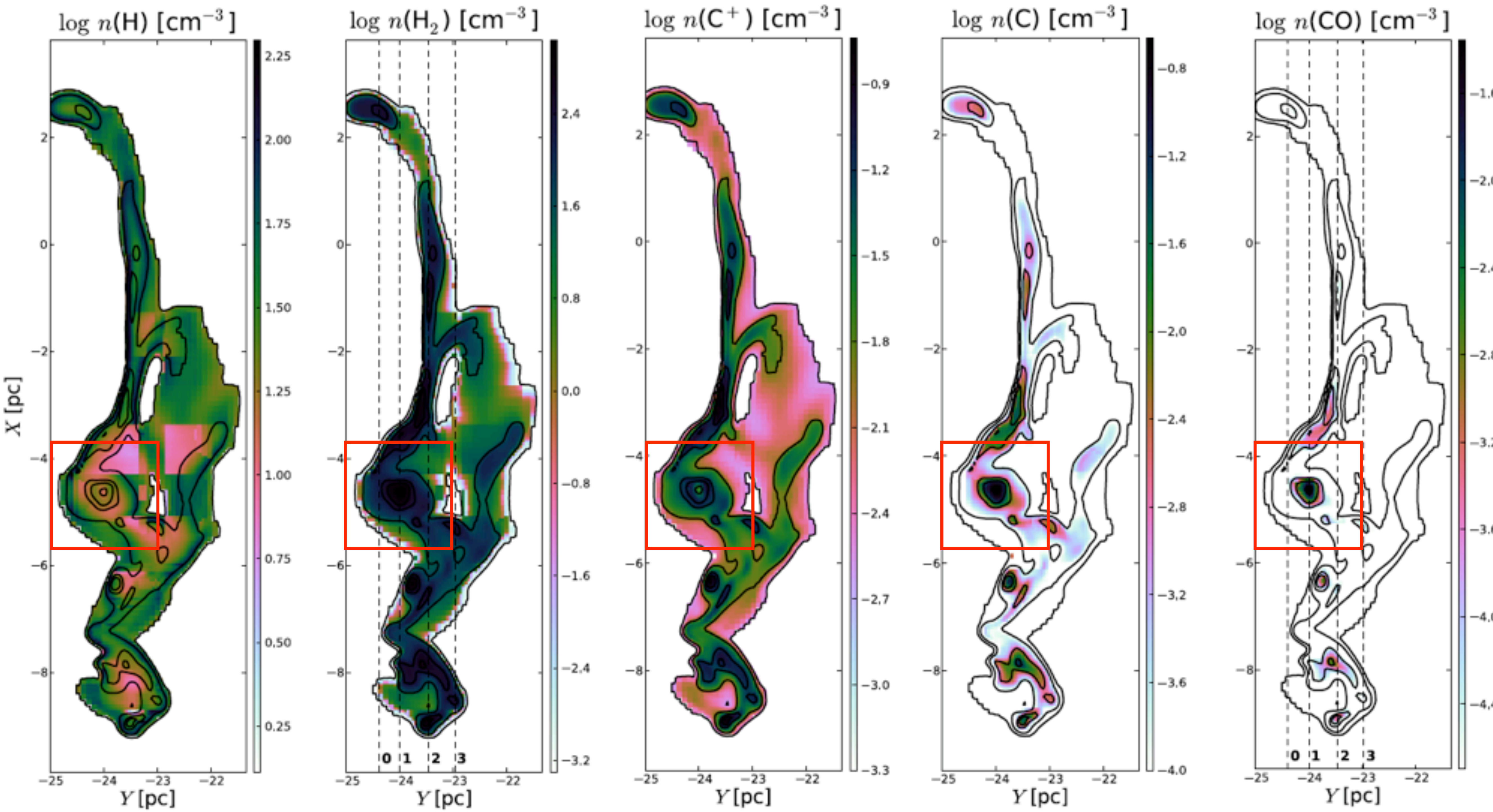
PDR code run on 1D density profiles above 20 cm^{-3} extracted along lines of sight either parallel to X or Y.

Outputs (temperature, chemical abundances) combined in 2D arrays.

Levrier et al. 2012

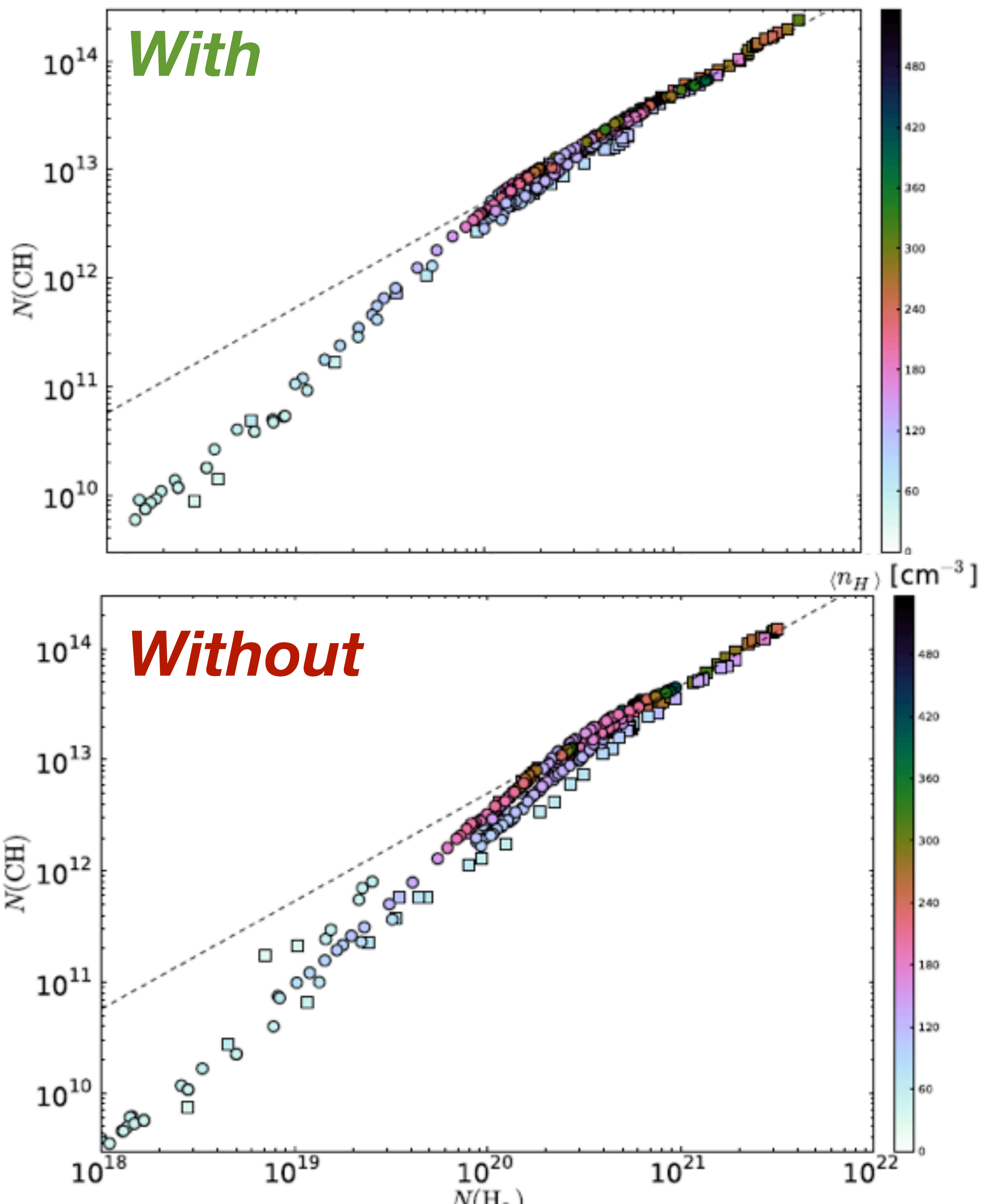
Main H and C bearers in the MHD/PDR simulation

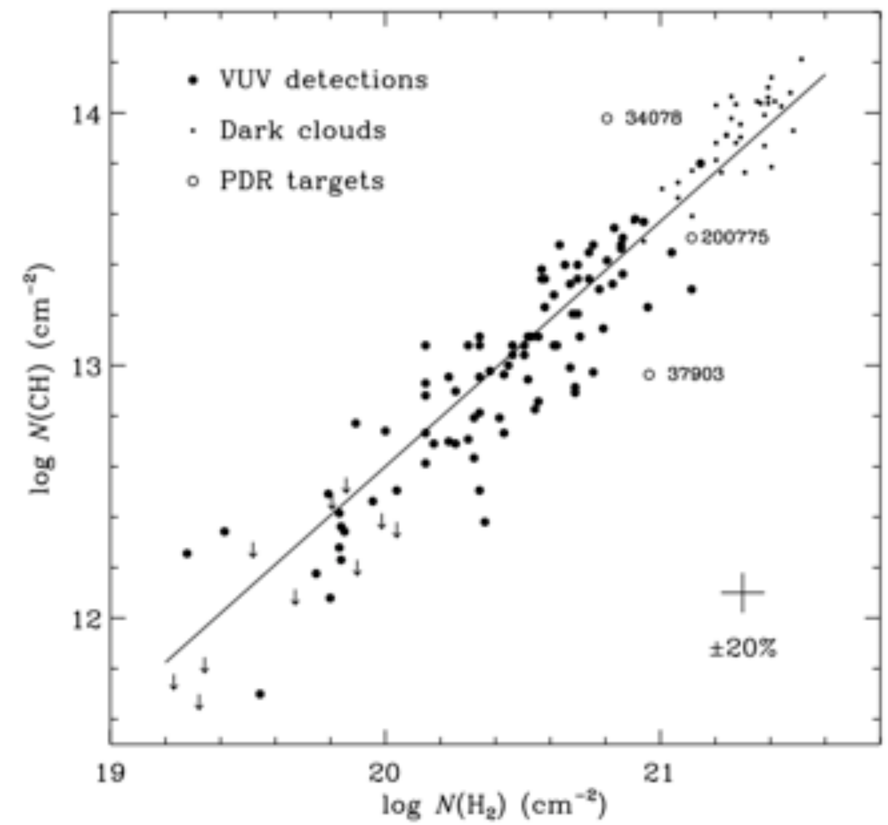
Levrier et al. 2012



- C^+ closely follows the total gas density, except in the densest regions.
- CO only in the densest regions

Density fluctuations vs. Uniform density : CH





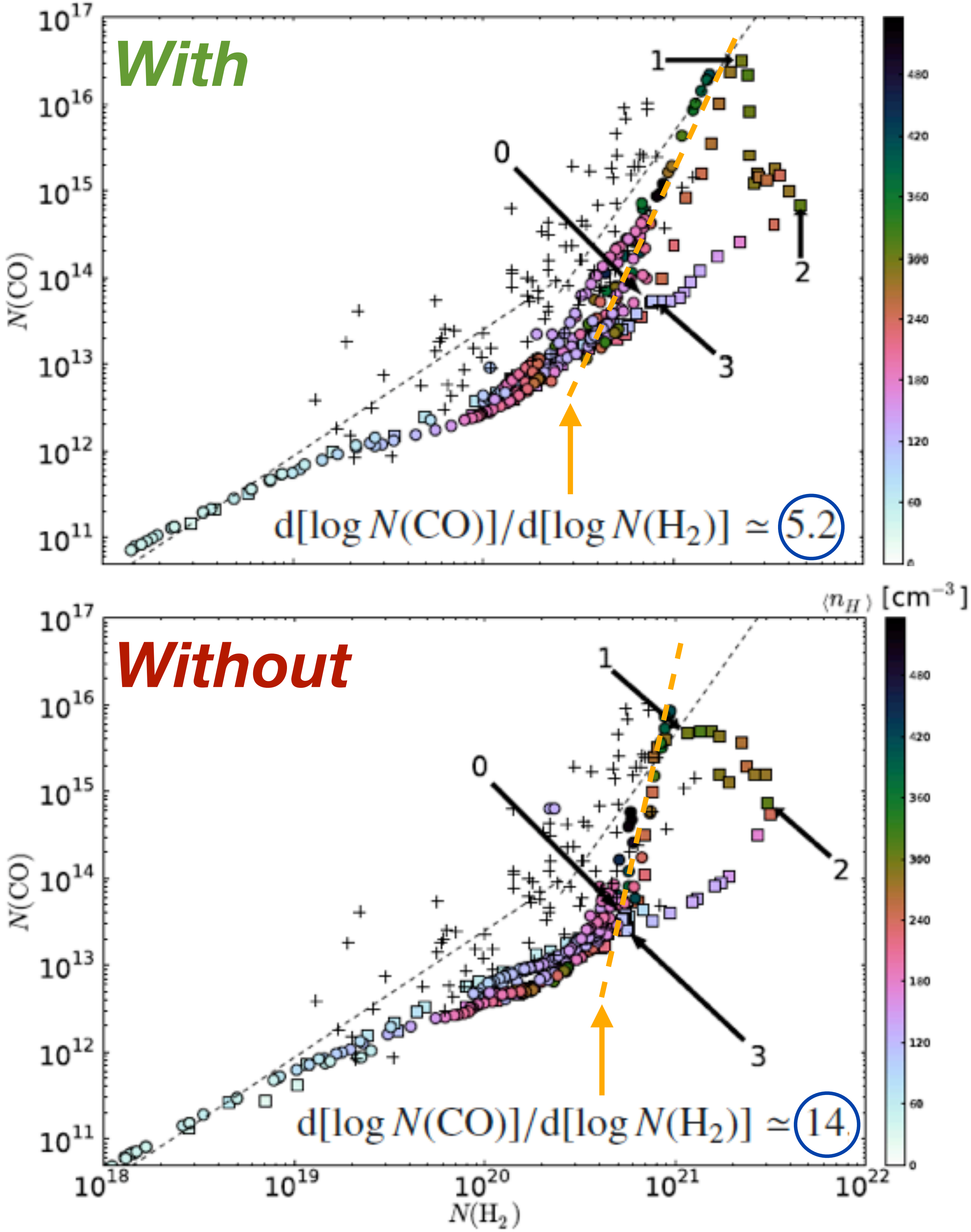
Observational fit

$$\mathrm{d}\left[\log N\left(\mathrm{CH}\right)\right]/\mathrm{d}\left[\log N\left(\mathrm{H}_2\right)\right] \simeq 1.09 \pm 0.19$$

Sheffer et al. 2008

- Maximum column densities are about twice as low in the uniform models
- CO vs CH column densities correlation agrees better with observations

Density fluctuations vs. Uniform density : CO



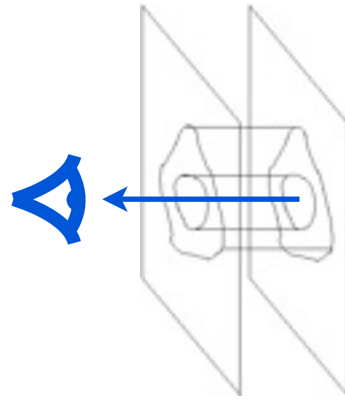
Observational fit

$$d[\log N(CO)]/d[\log N(H_2)] \simeq 3.07 \pm 0.73$$

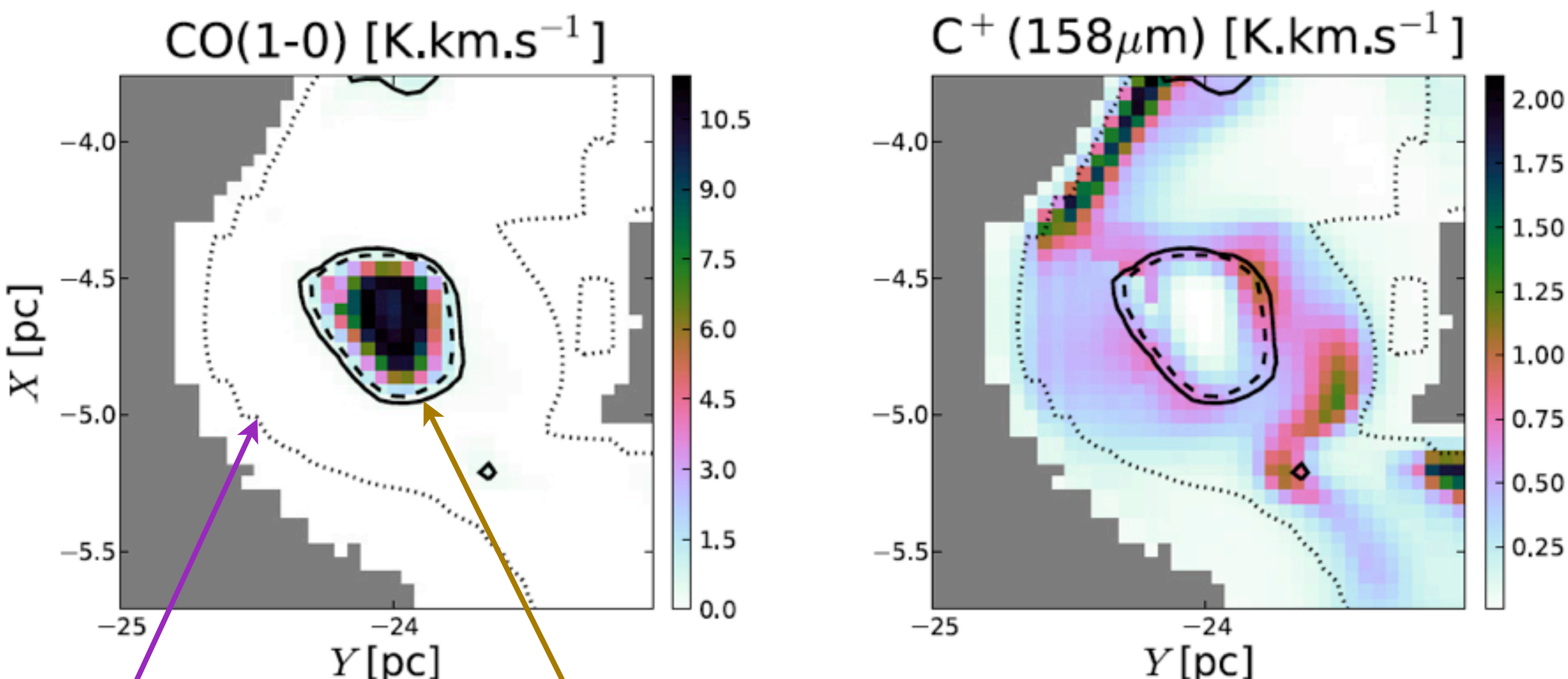
Sheffer et al. 2008

- Maximum column densities are about 3 times as low in the uniform models
- CO vs H_2 column densities correlate better

Simulated observations in CO and C$^+$



Radiative transfer with RADEX (LVG approximation)



$\boxed{f_{\mathrm{H_2}} = 1/2}$

$\boxed{W_{\mathrm{CO}} = 0.4 \text{ K.km.s}^{-1}}$

$\sigma_{\mathrm{CII}} = 0.1 - 0.2 \text{ K.km.s}^{-1}$

Levrier et al. 2012

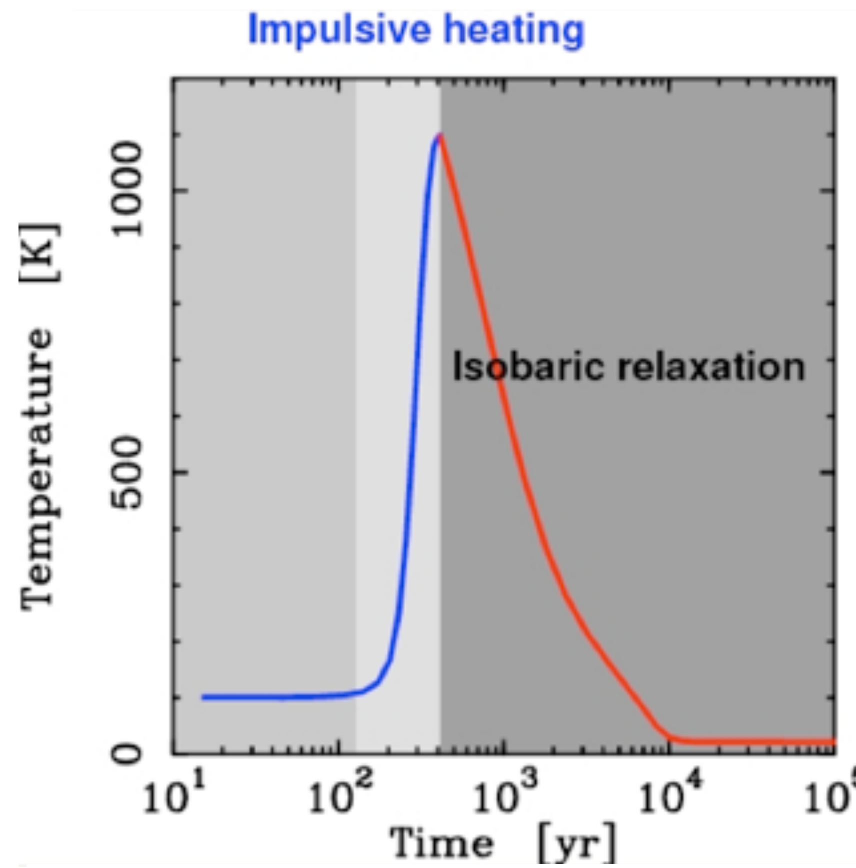
Velusamy et al. 2010

The TDR model

Magnetized modified Burgers vortex

$$\omega_z(r) = \omega_0 \cdot e^{-\frac{a}{4\nu\beta}\left[1-e^{-\beta r^2}\right]}$$

a : Turbulent rate of strain



Joulain et al., 1998
Godard et al., 2009

Magnetized vortices:
~ 50 AU
~ 100 years lifetime

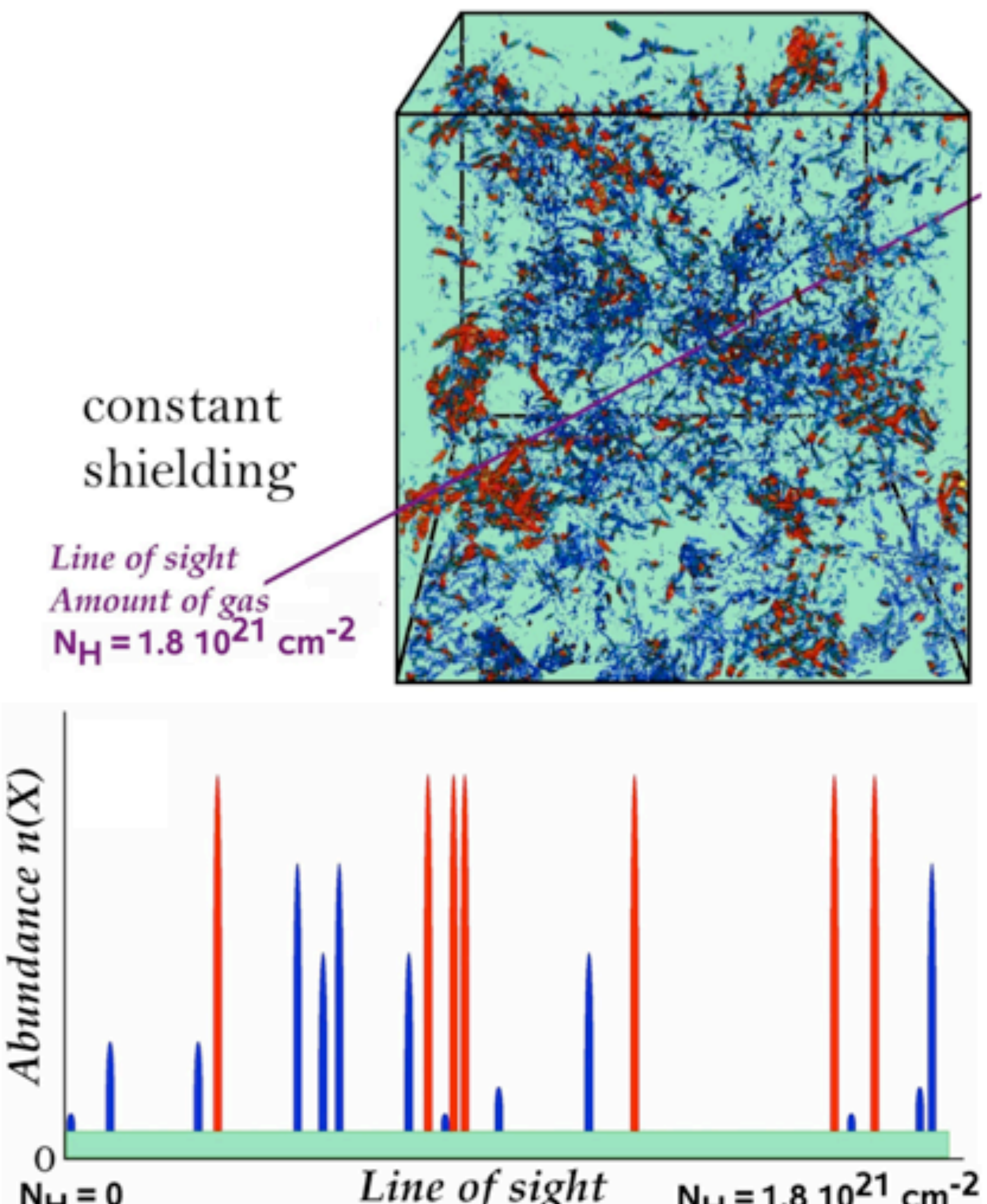
Dissipation leads to warm chemistry

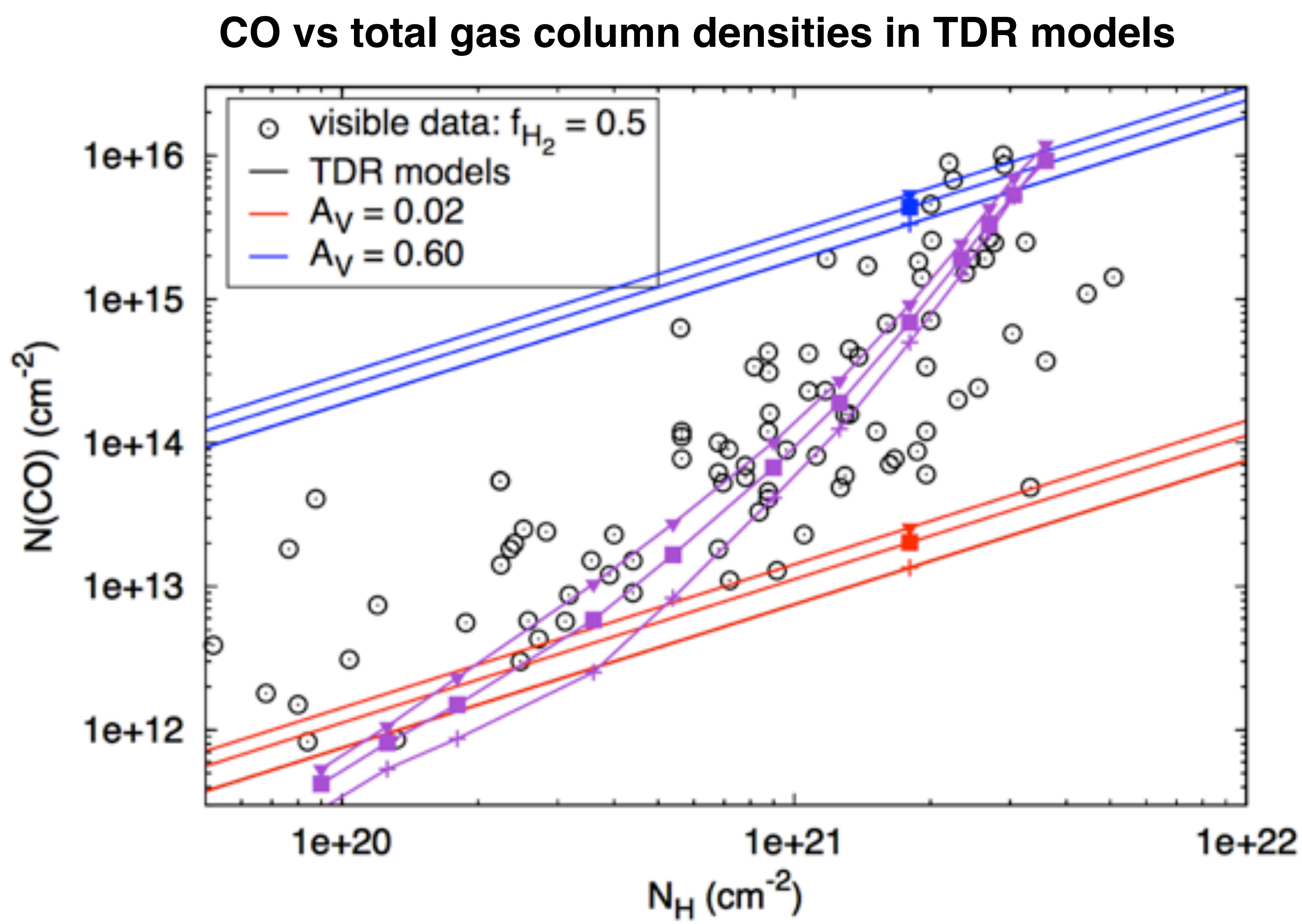
Thermal and chemical relaxation last up to 4.10⁴ years

Free parameters $a \; ; \; n_{\rm H} \; ; \; A_{\rm V}$

3 phases : active and relaxing vortices, ambient medium

Chemical enrichment by turbulent dissipation

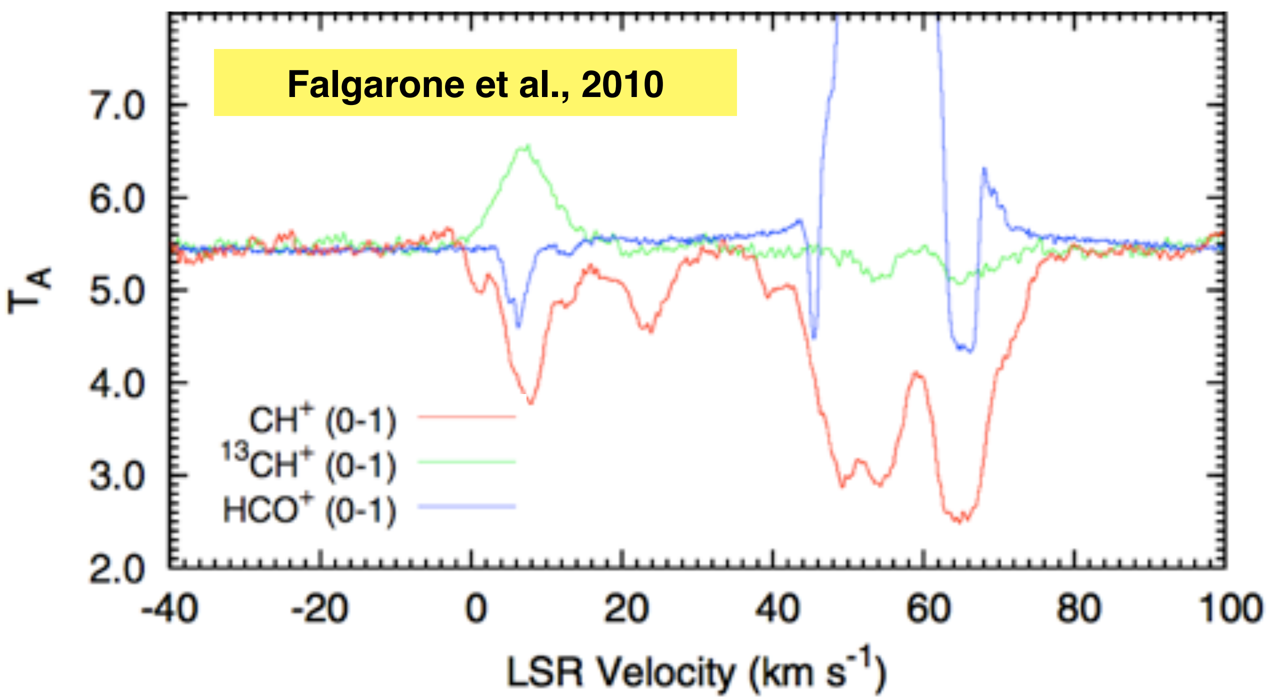




Godard et al. in prep

The CH^+ puzzle solved ?

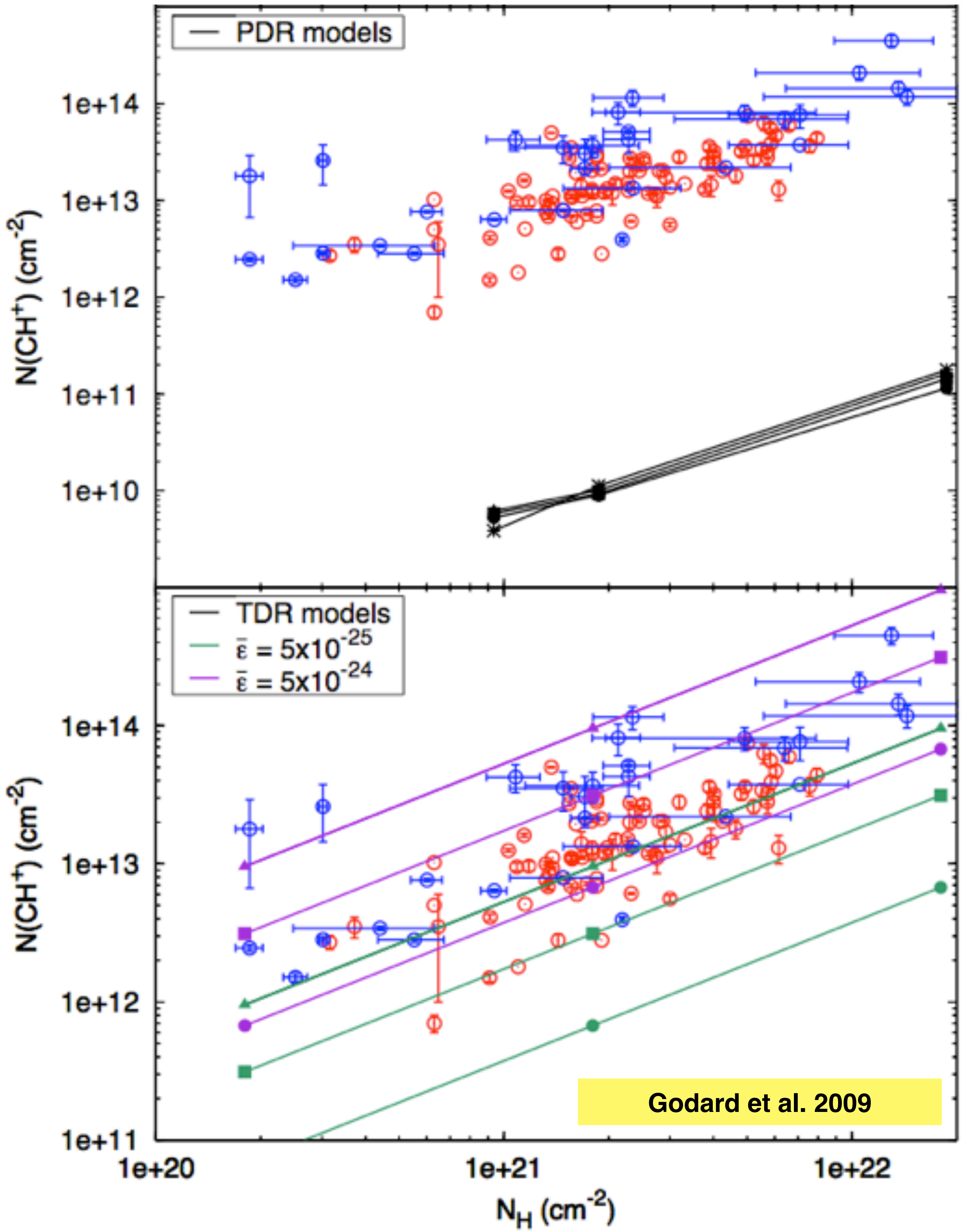
CH^+ absorption towards massive SF regions



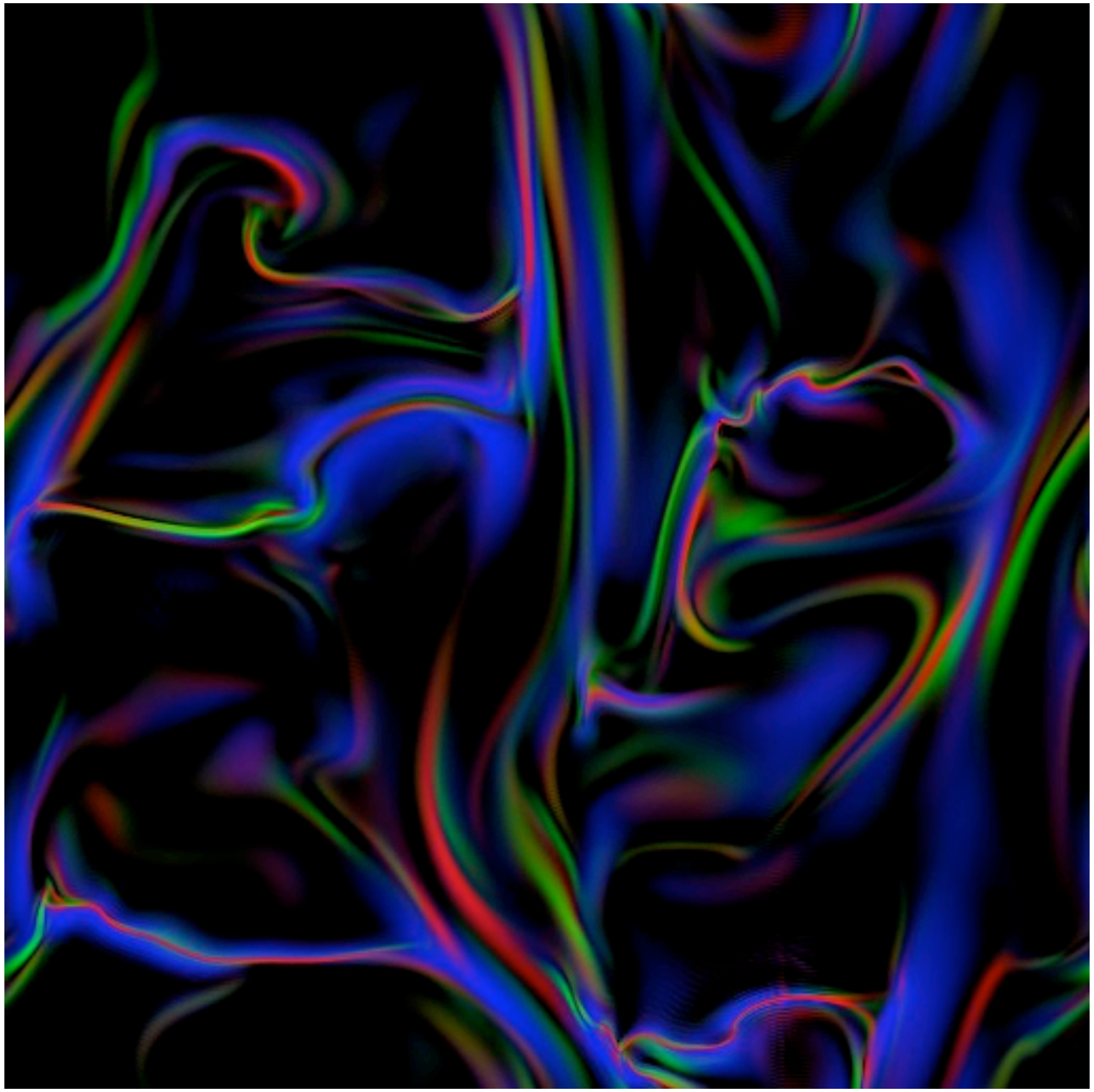
$$C^+ + H_2 \rightarrow CH^+ + H$$

HIGHLY ENDOTHERMIC (E/k=4640 K)

CH^+ abundances in PDR and TDR models



Dissipation processes



2D cut through a 512^3 incompressible turbulence simulation with the ANK code

- Viscous heating
- Ohmic heating
- Ambipolar diffusion heating

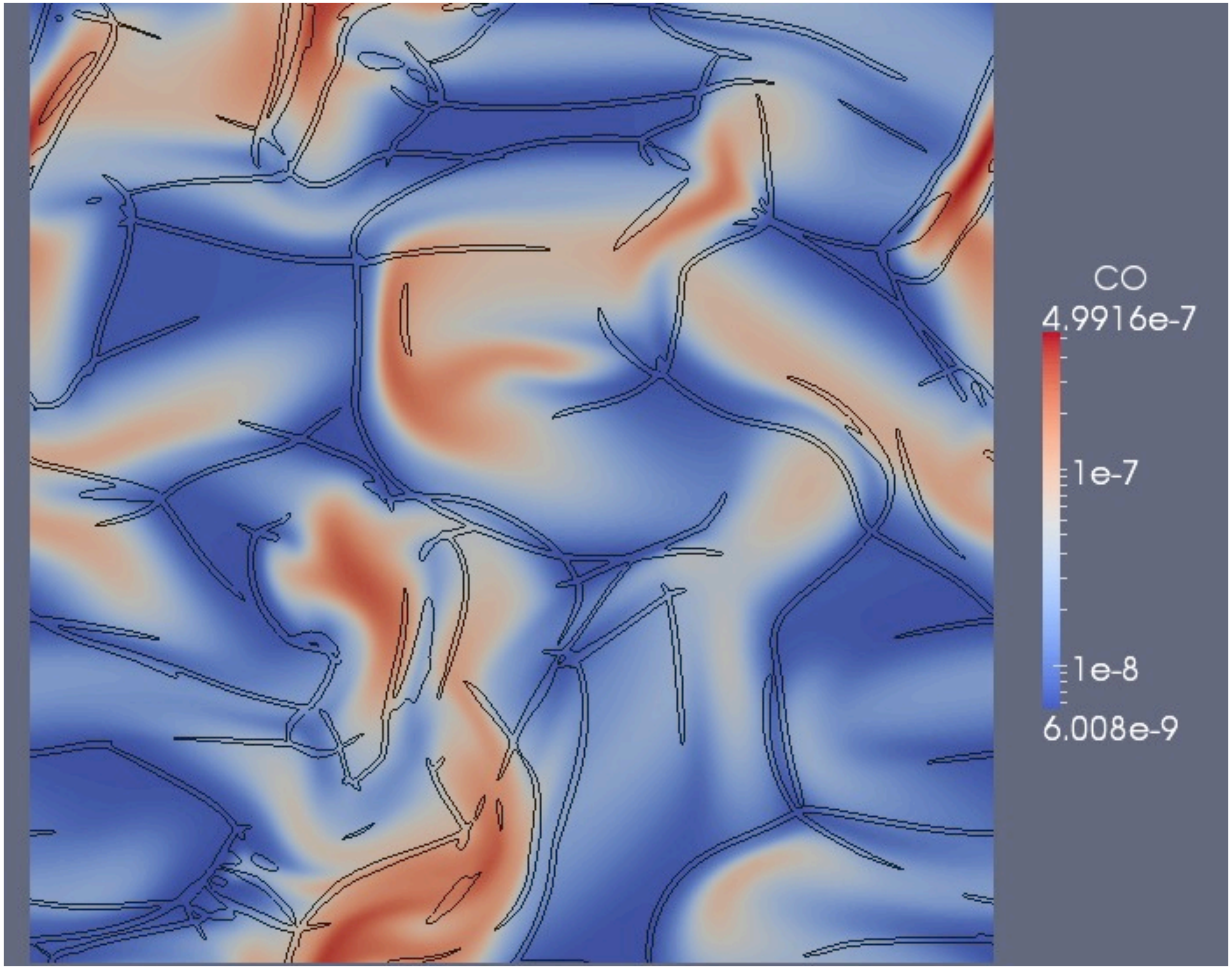
Momferratos, Lesaffre, Falgarone, in prep.

Chemical enrichment in the wakes of shocks

<u>**2D decaying turbulence simulation with chemical coupling**</u>

- Colour scale : CO abundances

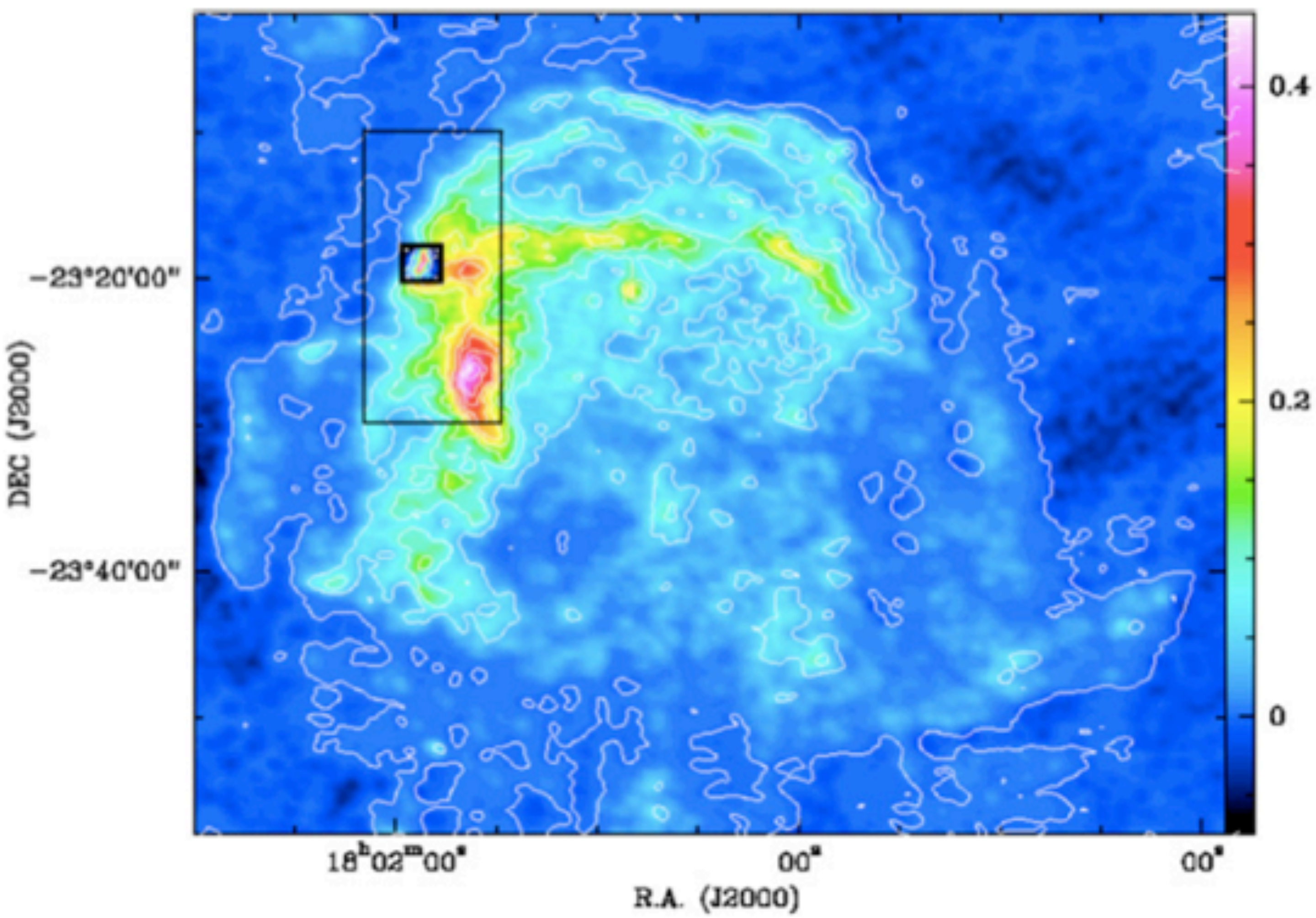
- Contours : Regions of high viscous heating



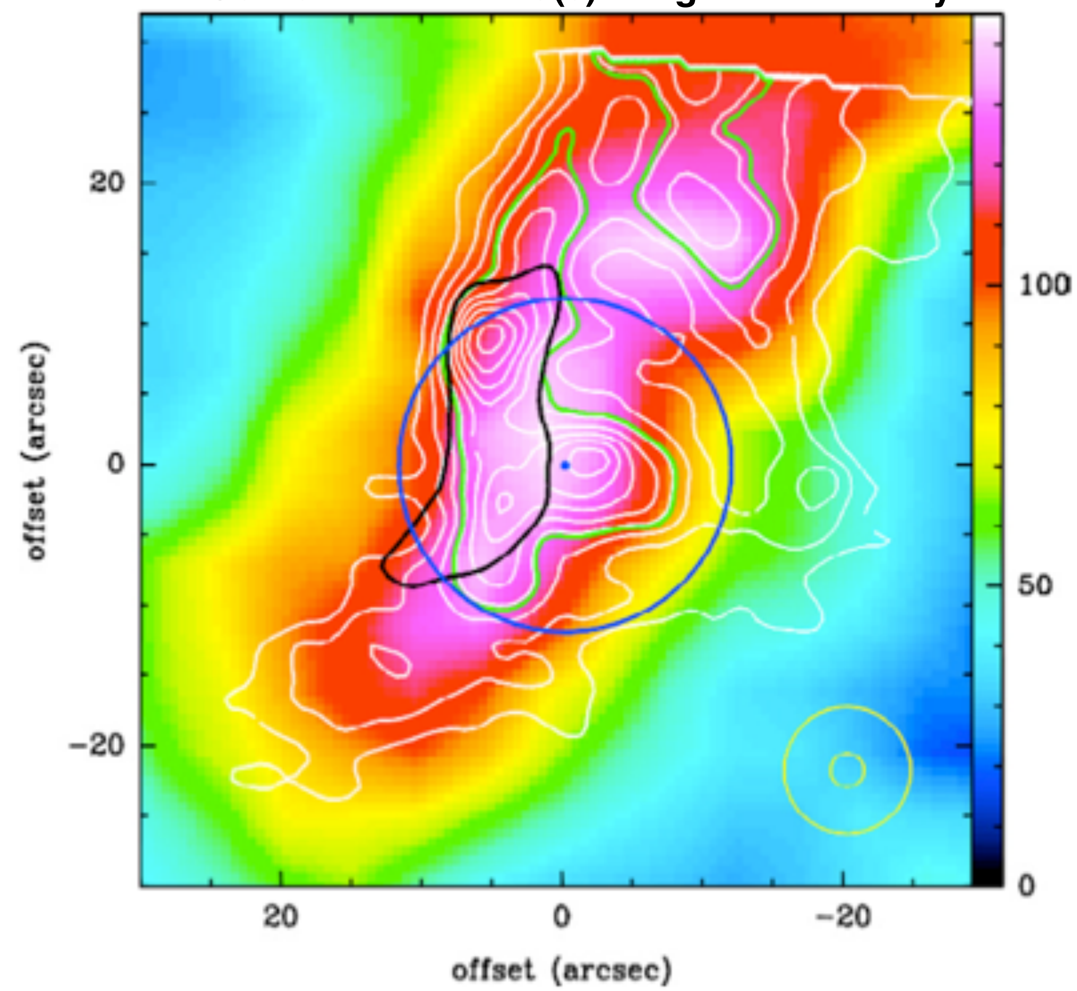
Lesaffre et al., in prep

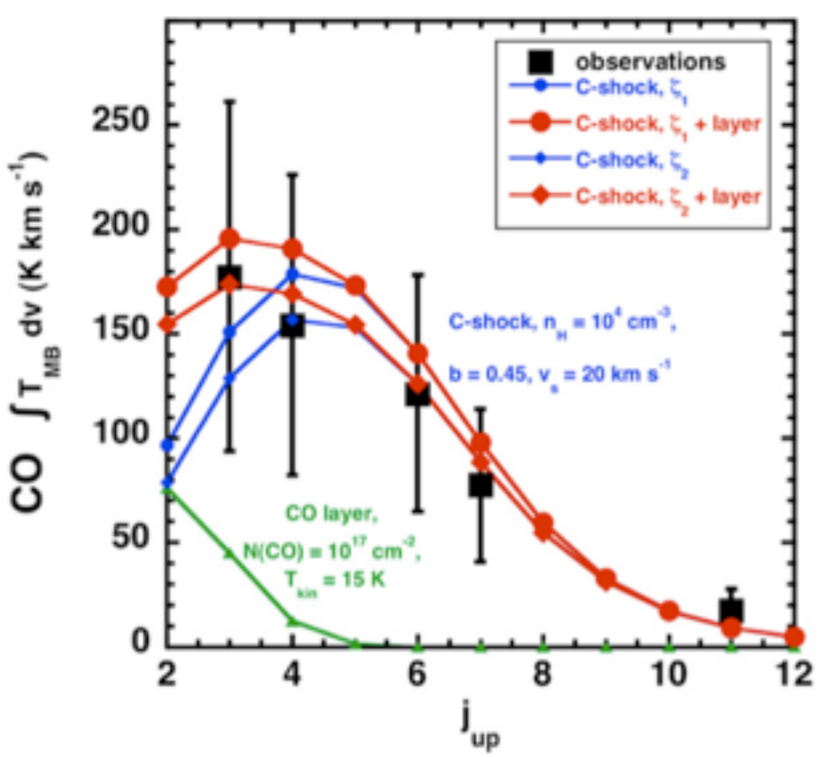
Shocks in SNR : W28F

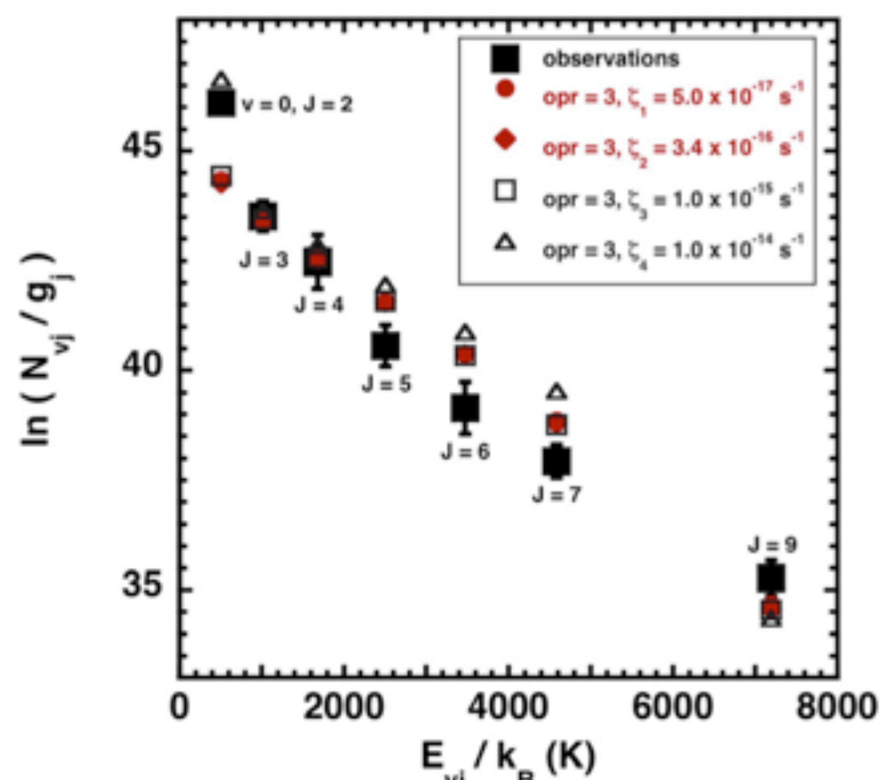
Radio continuum (327 MHz)



- Colour scale : CO(6-5) integrated intensity
- Contours : H2 0-0 S(5) integrated intensity







Gusdorf et al., 2009

Conclusions

- **Observations provide kinematical and chemical clues of the small-scale (mpc) dissipation of ISM turbulence**

- **This dissipation may be in the form of vortices or low-velocity shocks**

- **What is the impact of cosmic rays as another source of energy for chemistry ? How do they propagate in the fractal ISM ?**

- **What is the role of the magnetic field in the formation of dense self-gravitating filaments and ultimately dense cores and stars ?**

- **What is the interaction between the magnetic field and structures of intense velocity shears at small scales ?**

- **How can we properly model the turbulent cascade when it requires some 10^7 grid points per dimension ?**