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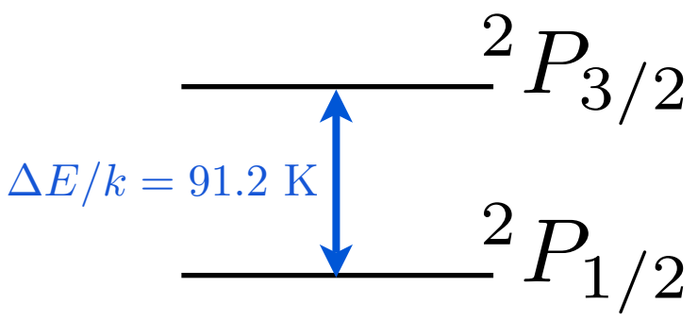
The Meudon PDR code on complex ISM structures

F. Levrier
P. Hennebelle, E. Falgarone, M. Gerin
(LERMA - ENS)

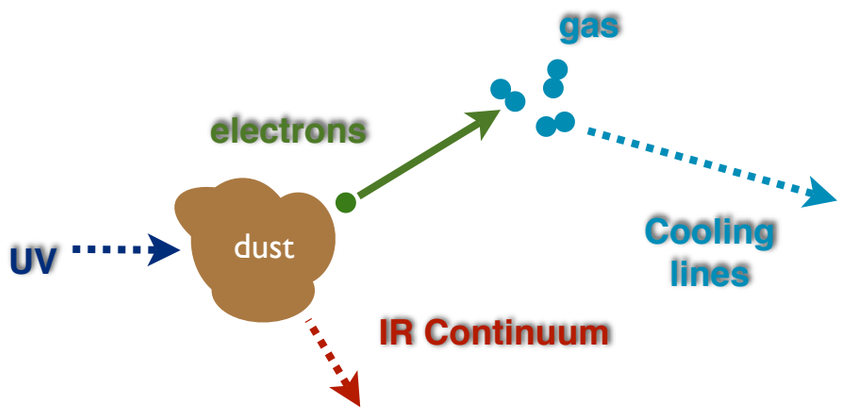
F. Le Petit
(LUTH - Observatoire de Paris)

J. R. Goicoechea
(CAB)

A case study : The [CII] 158 µm line



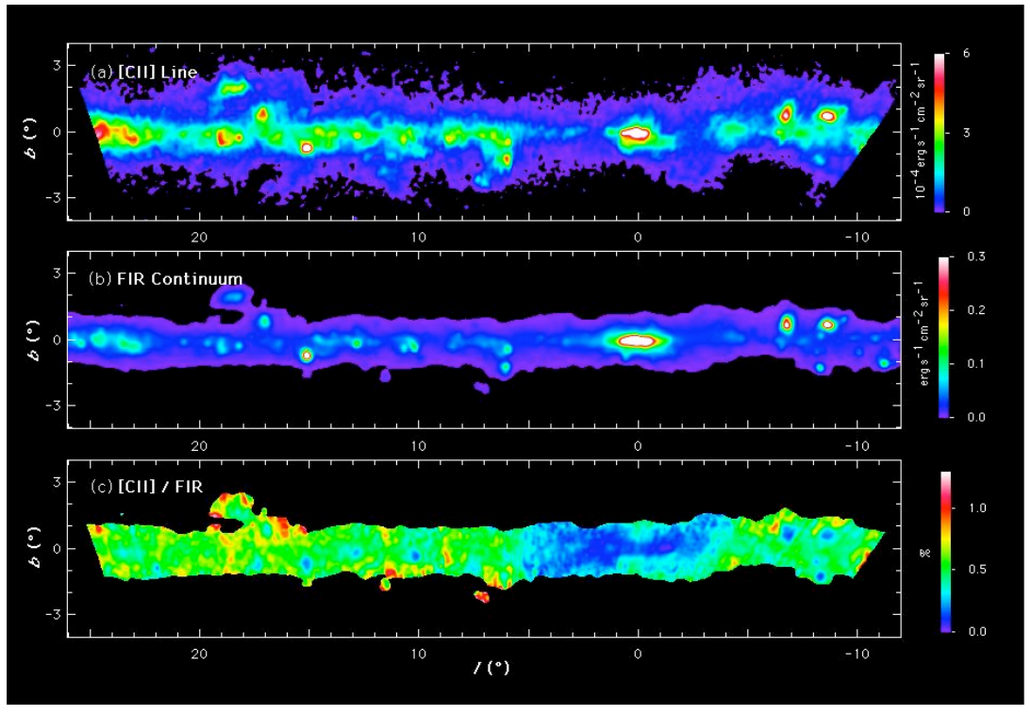
Fine structure of the ground state of C+



UV to IR energy transfer via photoelectric effect

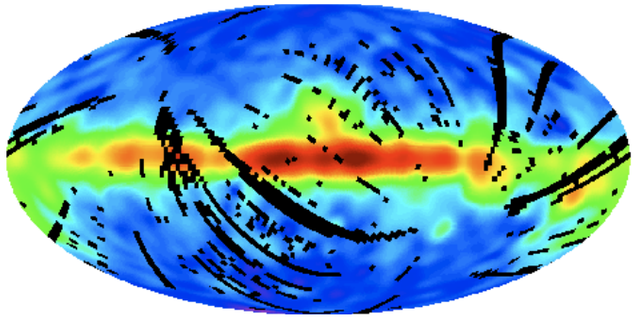
SPICA / SAFARI (Joint JAXA / ESA)

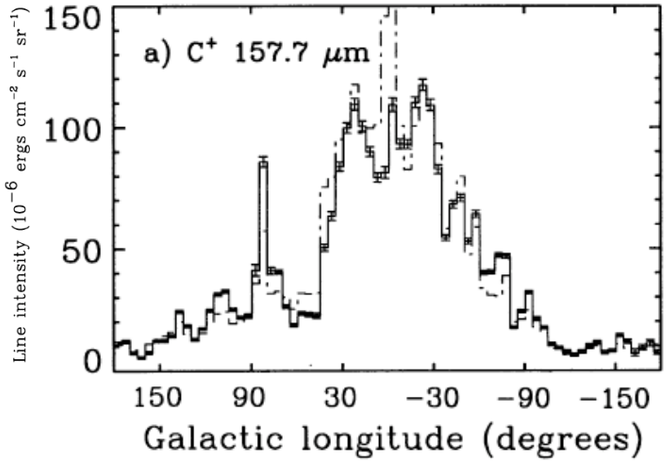
- Carbon ionization potential : 11.3 eV
- One of the dominant cooling lines of interstellar gas
- Early stages of star formation
- 0.3% of the bolometric FIR emission of the Galaxy *(Wright et al. 91)*
- Seen "everywhere"

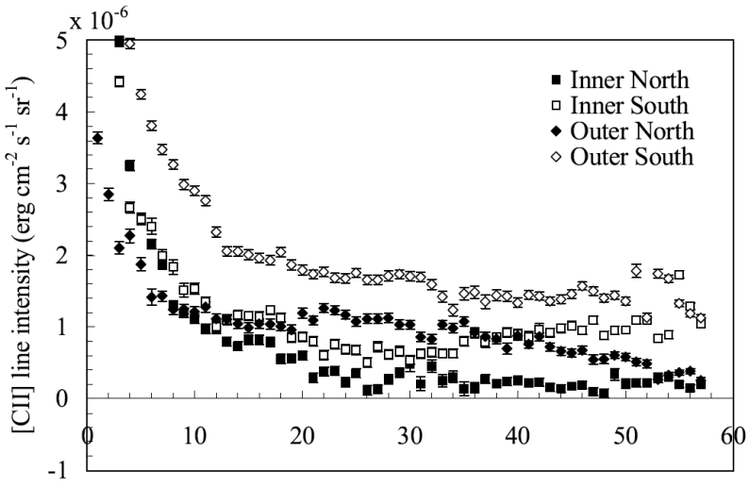


Nakagawa et al. 98 (BICE)

Bennett et al. 94 (COBE / FIRAS)







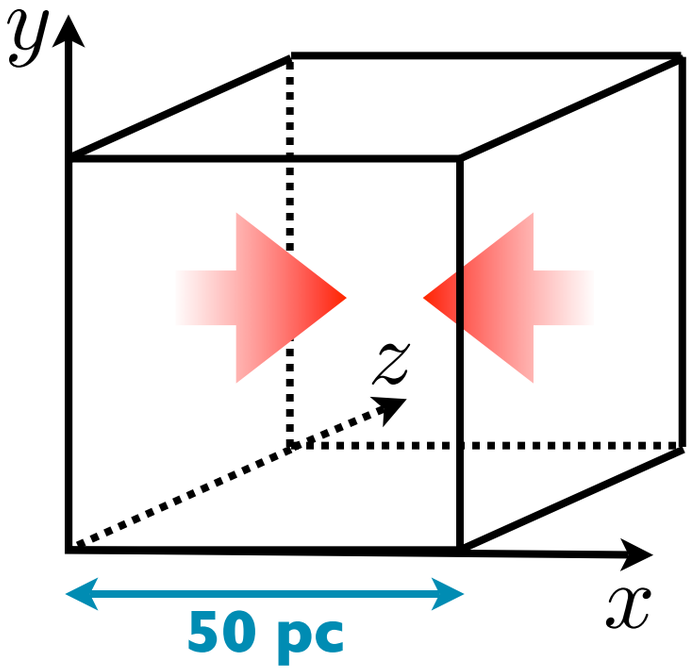
Makiuti et al. 2002 (FILM / IRTS)

A very crude method

- Sample lines of sight in the MHD simulation cubes
- Extract "clouds" by applying a simple density threshold
- Use these as input density profiles in the Meudon PDR code
- Derive 158 μm line intensity vs. HI column density
- Estimate Total gas vs HI relationship
- Build line emission map from simulated cube
- Estimate time required to map the sky area covered by the sim

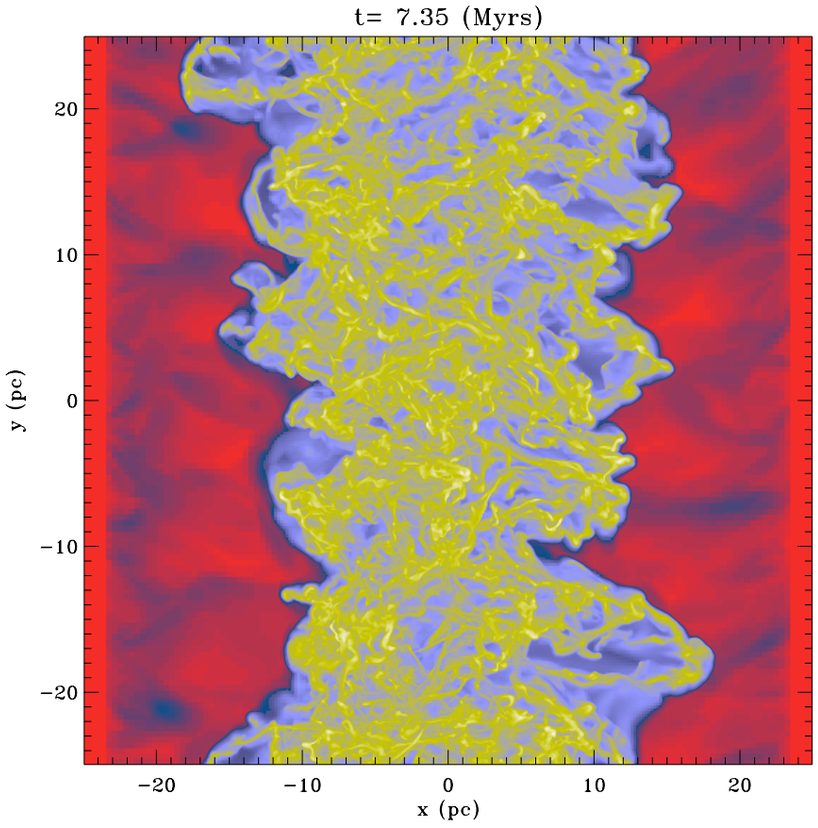
Compressible MHD turbulence simulations

Hennebelle et al. 2008

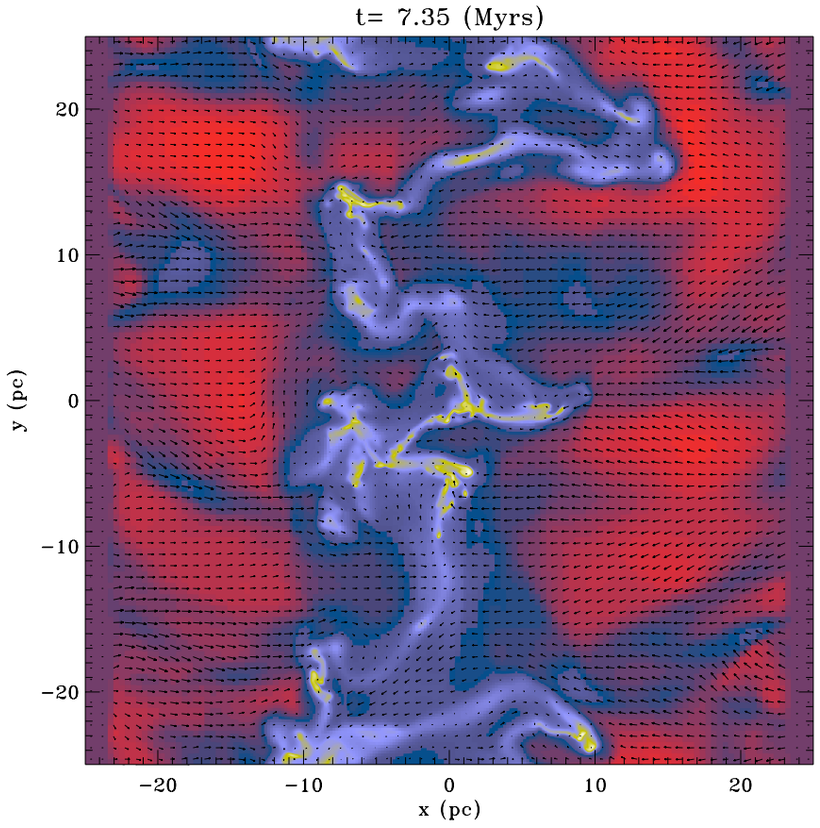


- RAMSES code (Teysier 2002, Fromang et al. 2006)
- Adaptive Mesh Refinement with up to 14 levels
- Converging flows of warm (10,000 K) atomic gas
- Periodic boundary conditions on remaining 4 sides
- Includes magnetic field, atomic cooling and self-gravity consistently
- Covers scales 0.05 pc - 50 pc
- Heavy computation : ~30,000 CPU hours ; 10 to 100 GB

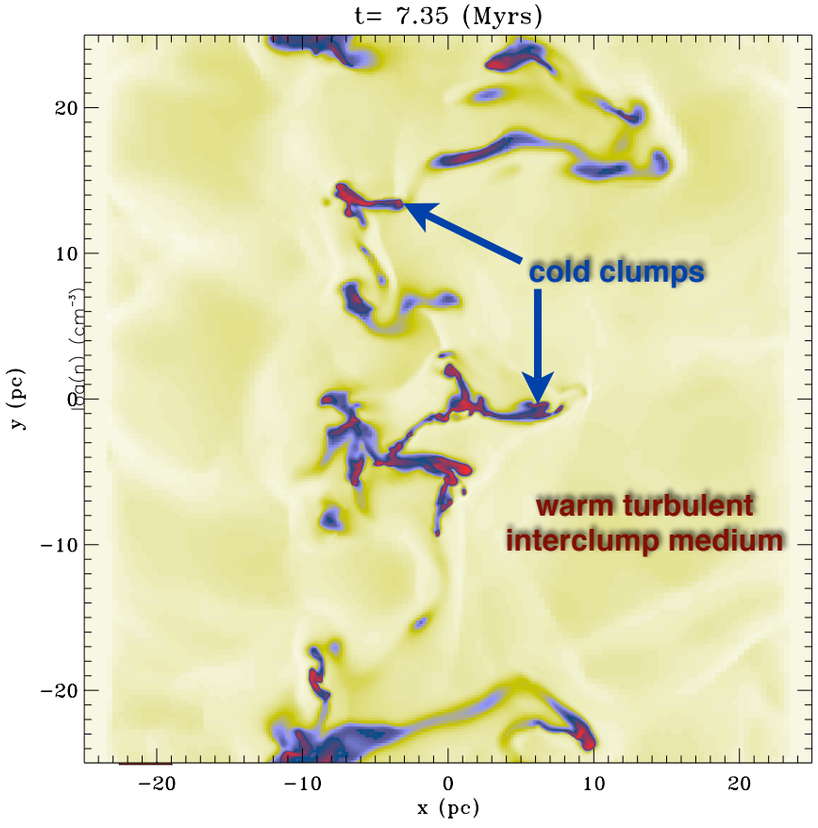
X-Y column density



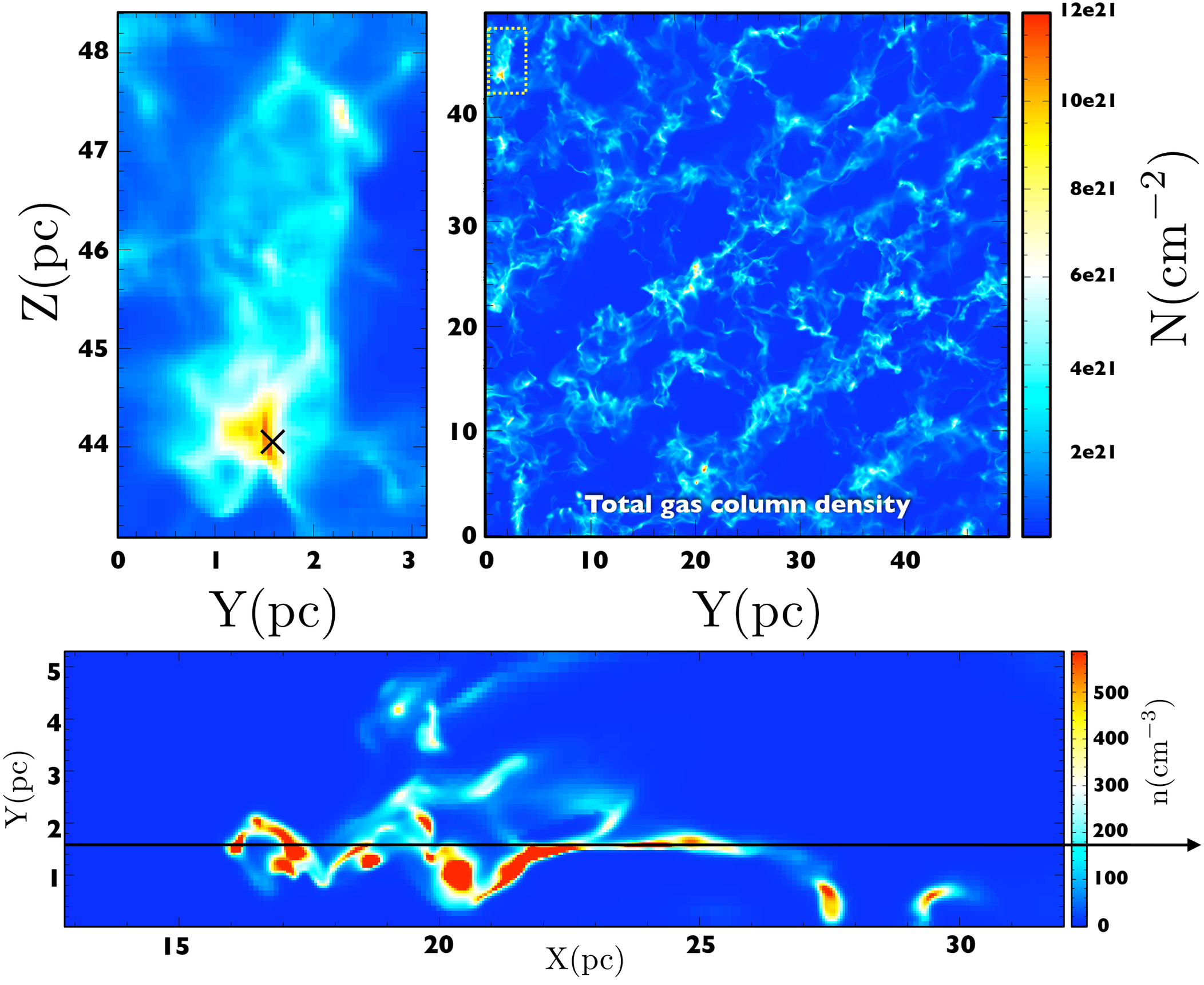
X-Y density cut



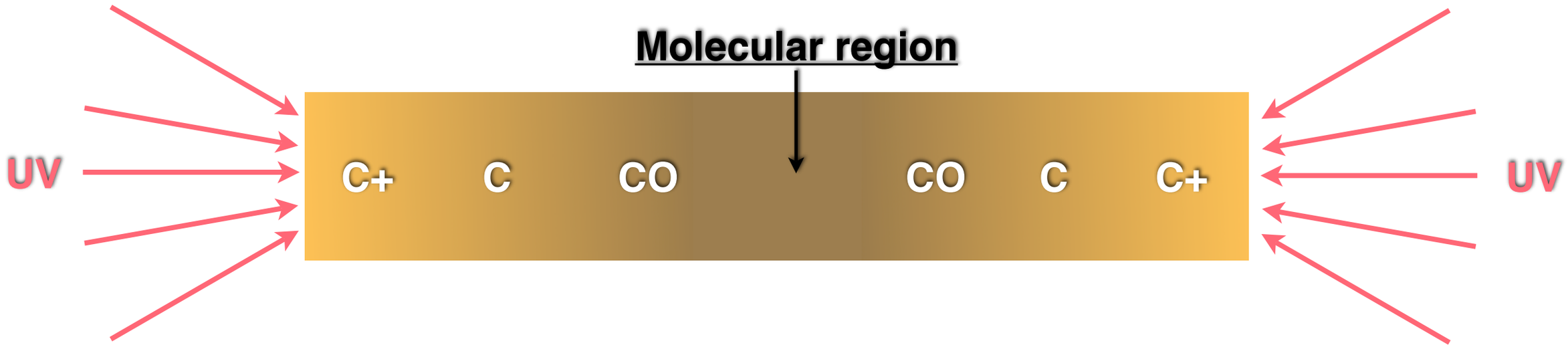
X-Y temperature cut



Density structures along the line of sight



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
- Statistical equilibrium of level populations
  - Radiative and collisional excitations and de-excitations
  - Photodissociation
- Thermal balance:
  - Photoelectric effect
  - Chemistry
  - Cosmic rays
  - Atomic and molecular cooling

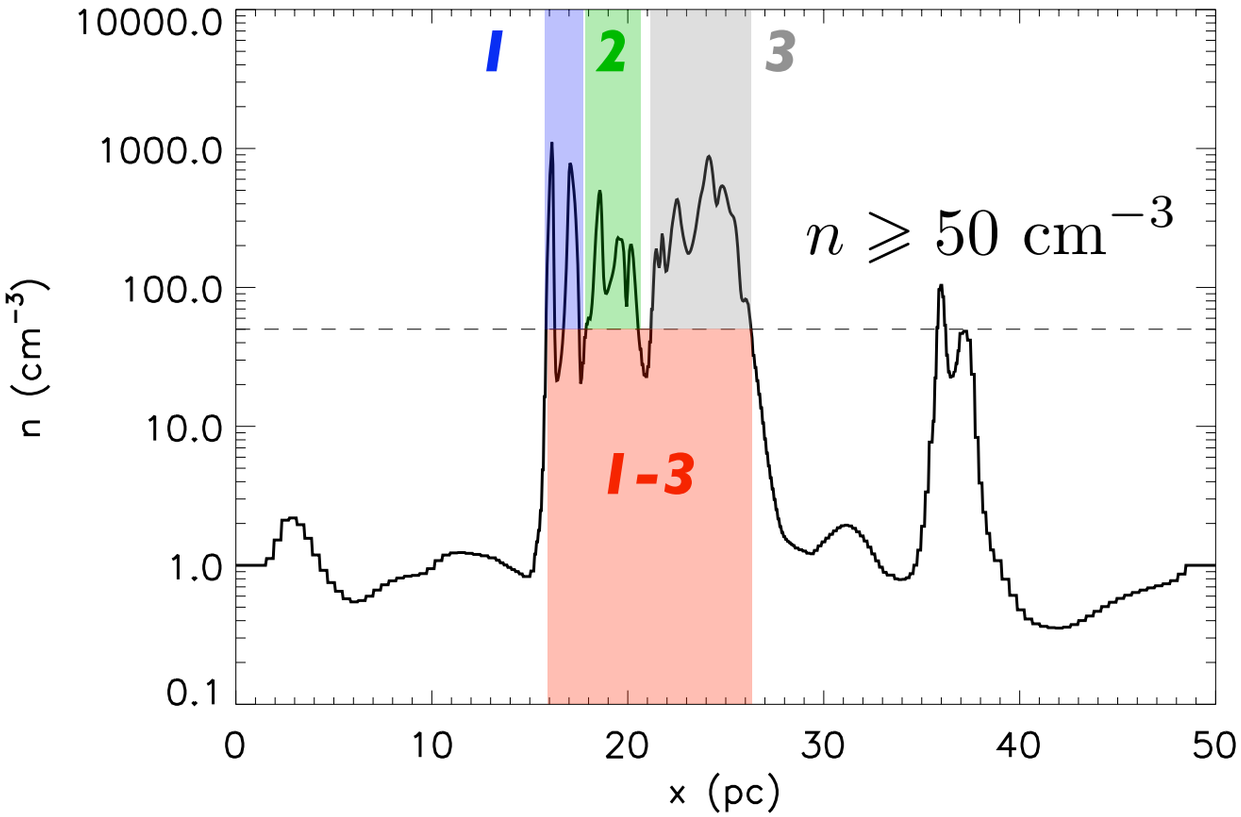
Outputs :

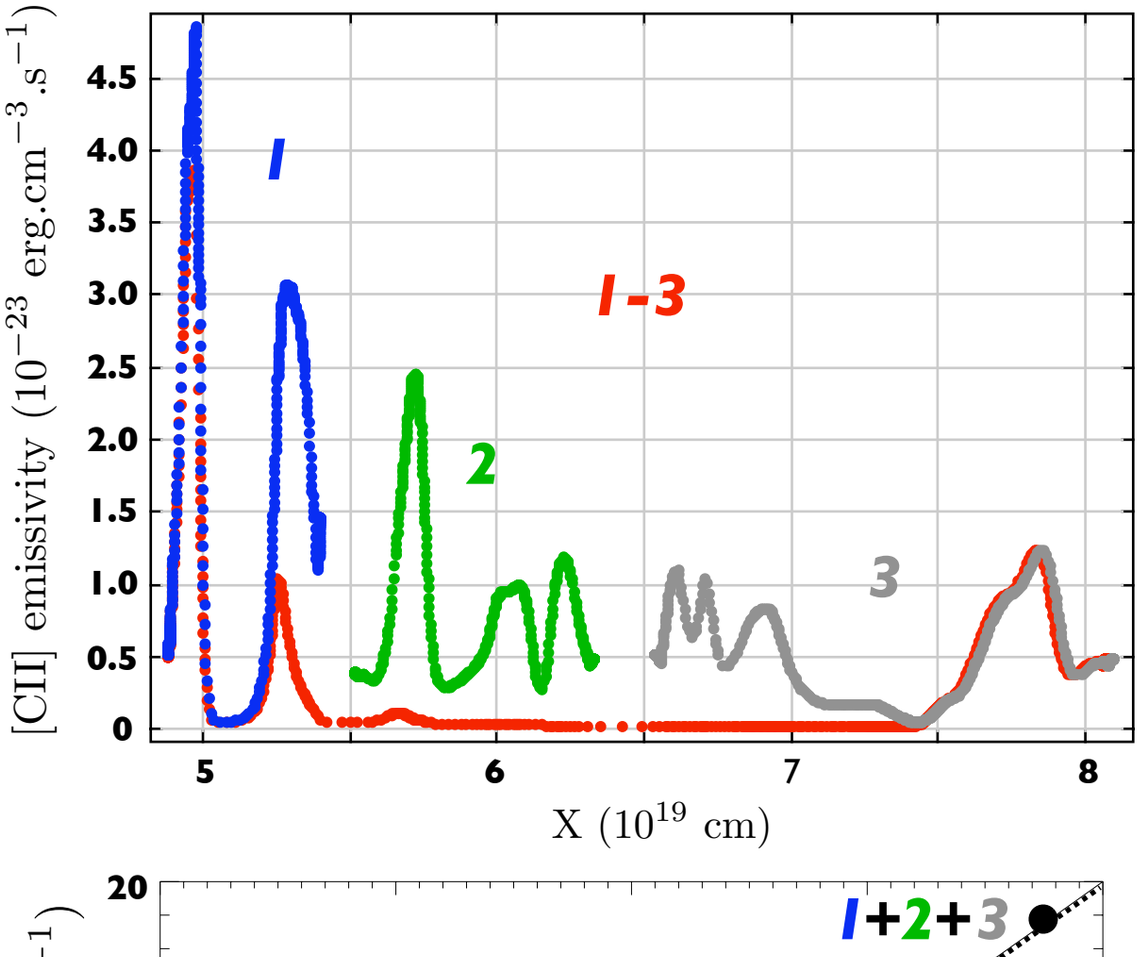
- Local quantities :
  - Abundance and excitation of species
  - Temperature of gas and duts
  - Detailed heating and cooling rates
  - Energy density
  - Gas and grain temperatures
  - Chemical reaction rates
- Integrated quantities on the line of sight :
  - Species column densities
  - Line intensities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

J. Le Bourlot
F. Le Petit
E. Roueff
M. Gonzalez-Garcia
J. R. Goicoechea
P. Hily-Blant
S. Guilloteau
C. Joblin
G. Pineau des Forêts
[...]

http://pdr.obspm.fr/

Simulation results





HI column density

$$N_1 + N_2 + N_3 = 3.70\ 10^{20}\mathrm{cm}^{-2}$$

$$N_{1-3} = 1.70\ 10^{20}\mathrm{cm}^{-2}$$

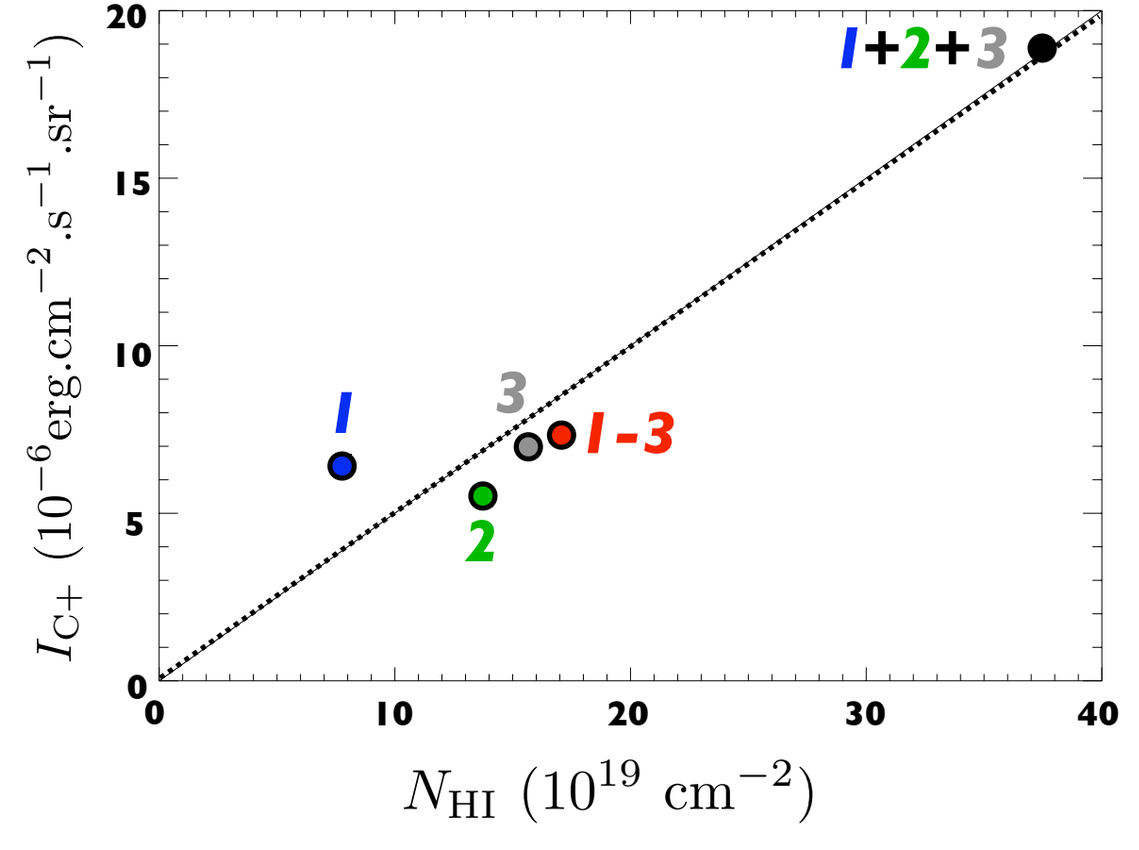
Integrated emissivity of the [CII] line

$$I_1 + I_2 + I_3 = 1.88\ 10^{-5}\mathrm{erg.cm}^{-2}.\mathrm{s}^{-1}.\mathrm{sr}^{-1}$$

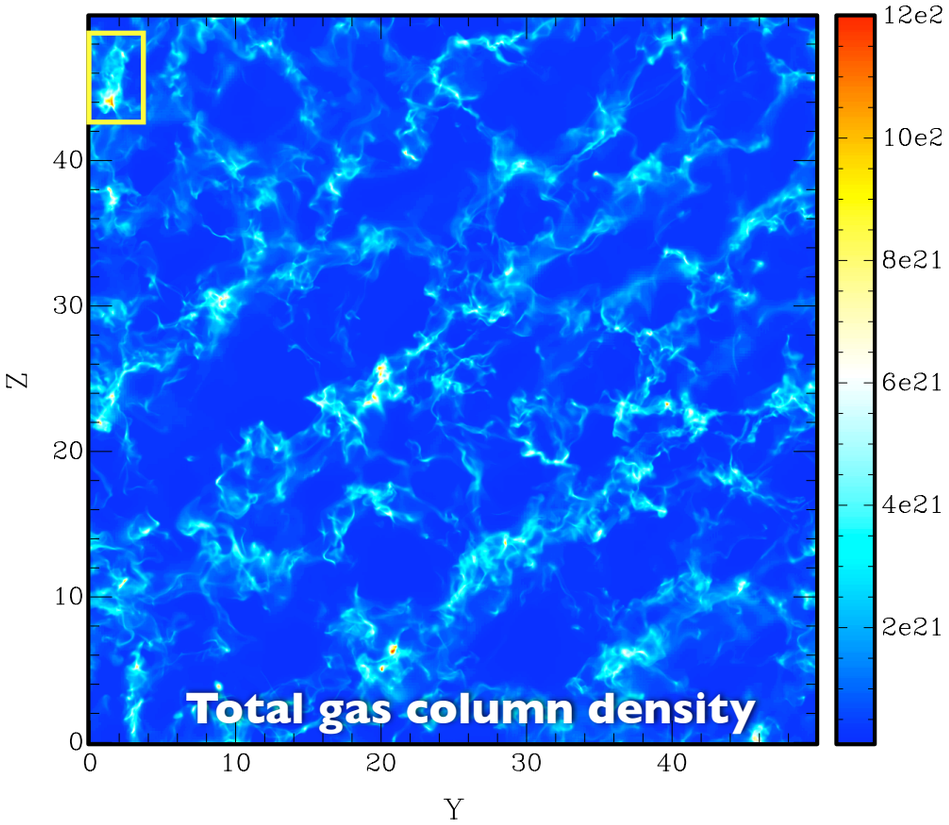
$$I_{1-3} = 7.21\ 10^{-6}\mathrm{erg.cm}^{-2}.\mathrm{s}^{-1}.\mathrm{sr}^{-1}$$

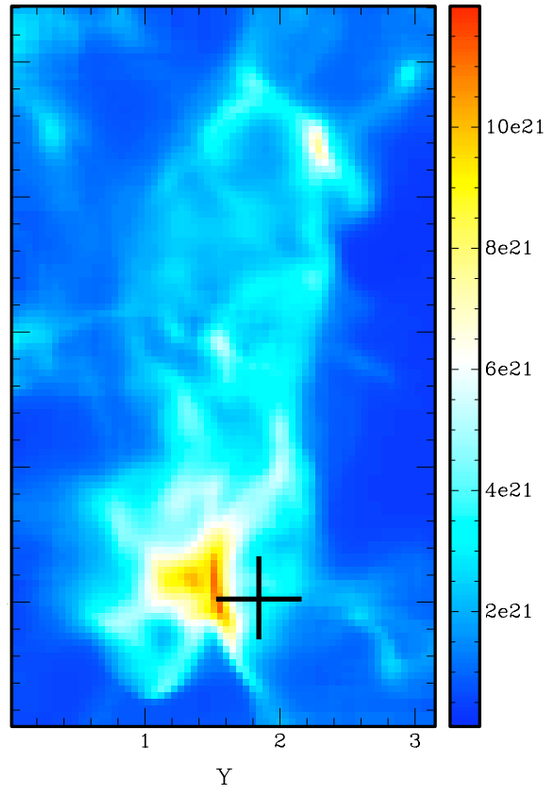
$$\frac{I_{C+}}{10^{-6}\mathrm{erg.cm}^{-2}.\mathrm{s}^{-1}.\mathrm{sr}^{-1}} \simeq 0.5 \times \frac{N_{\mathrm{HI}}}{10^{19}\mathrm{cm}^{-2}}$$

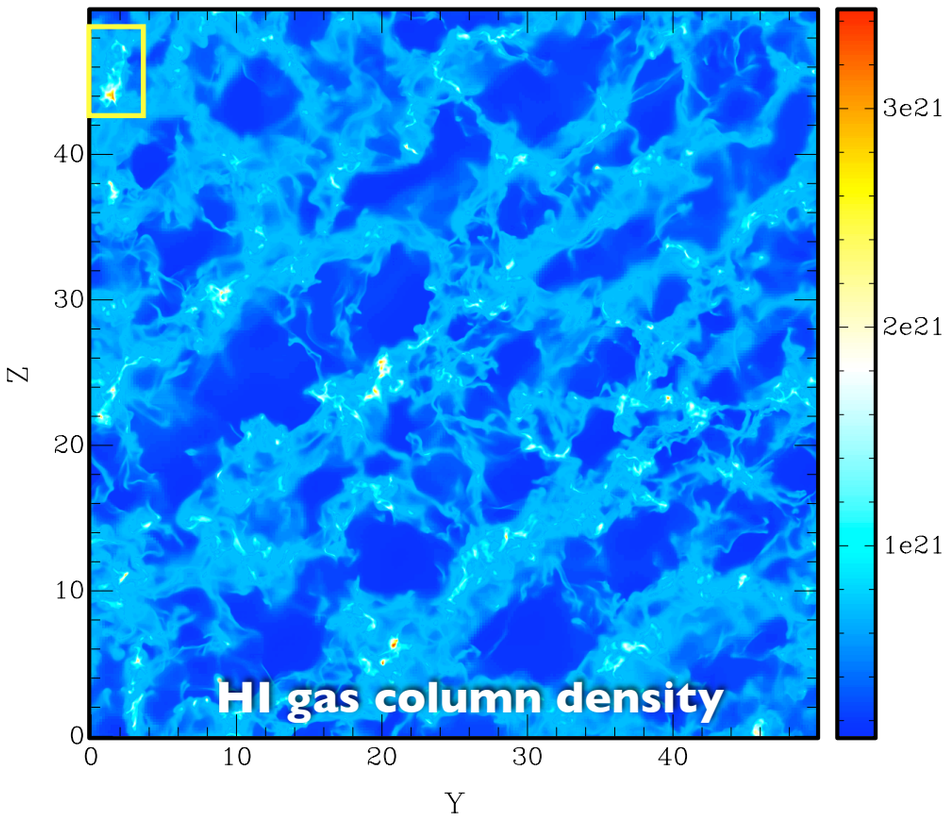
(See Bennett et al. 94)

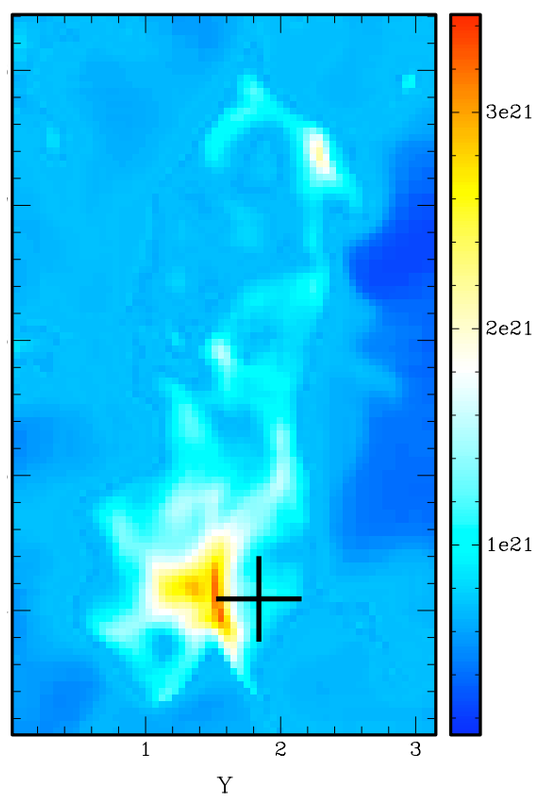


Total gas to HI conversion

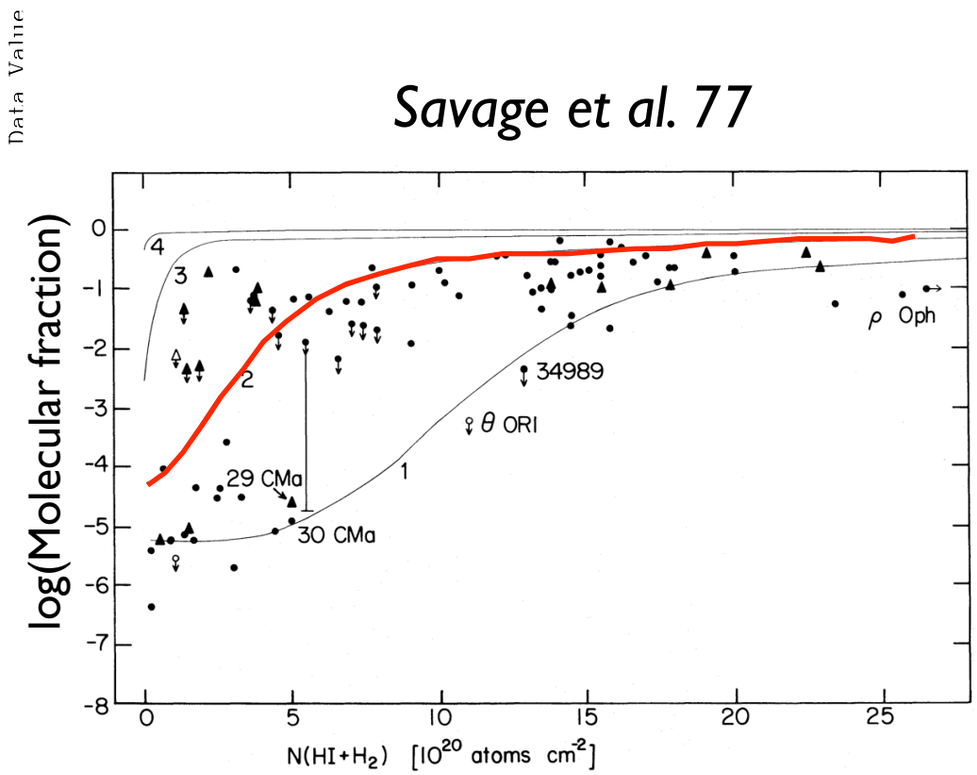








Savage et al. 77

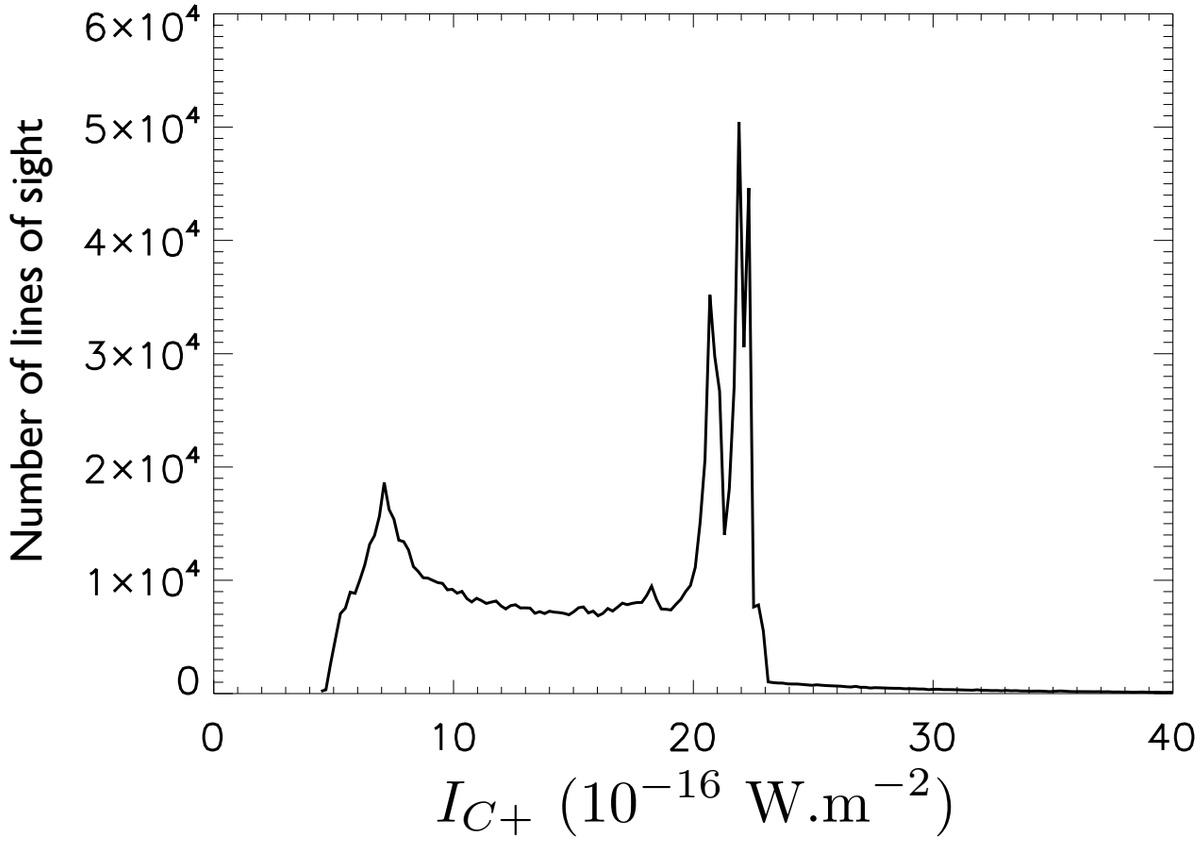


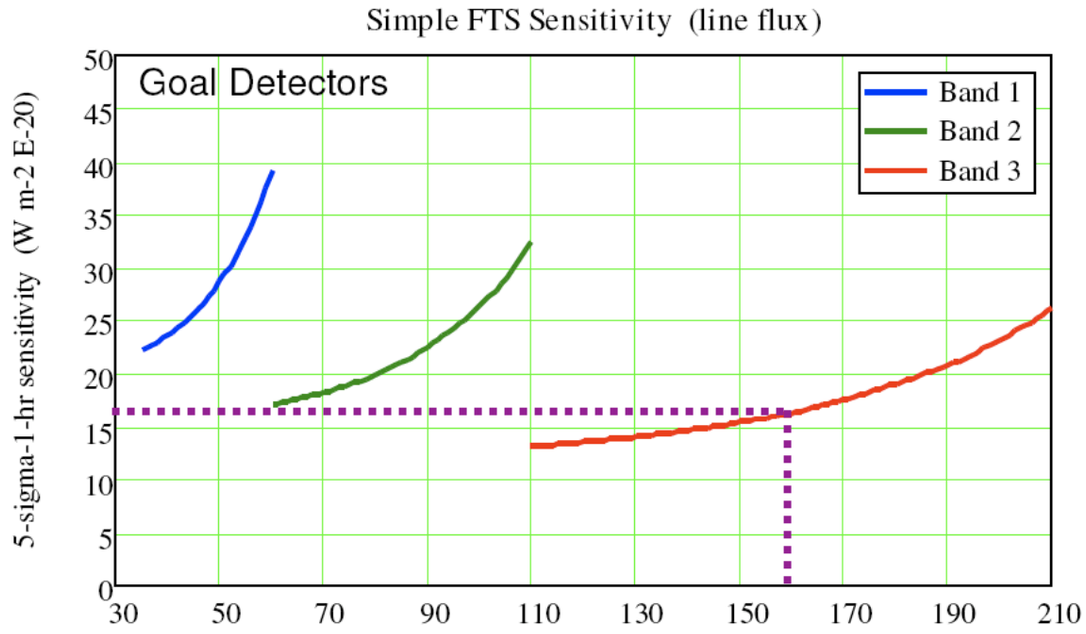
Total gas column density

$$\langle N_{\rm tot} \rangle = 8.1\ 10^{20}\ {\rm cm}^{-2}$$

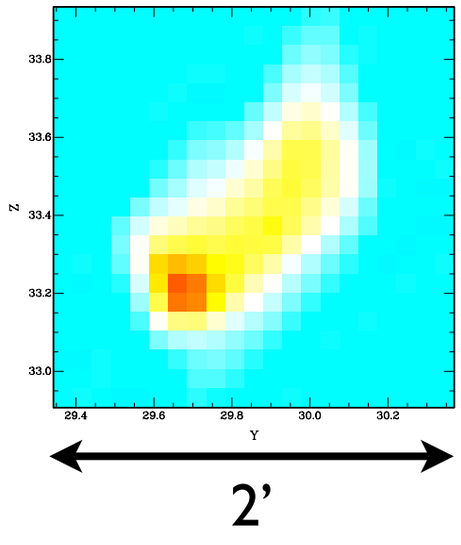
$$\langle N_{\rm HI} \rangle = 6.8\ 10^{20}\ {\rm cm}^{-2}$$

SAFARI mapping speed





5-sigma, 1-hour sensitivity : $1.6\ 10^{-19}$ W.m^{-2}



- Say the cloud is 1.75 kpc away, 1.6° across
- Pixel size is 5.75" (ie that of the SAFARI FPA pixels)
- FPA is 20x20 (FOV=2'x2')
- 2600 pointings needing between 1 and 24 seconds
- Total mapping time : 4.5 hours without overheads

Conclusions

SAFARI will be able to map the [CII] emission over large areas in a short time

STAR FORMAT (Astronet)

- Simulation results databases :
  - MHD simulations
  - Dense cores
  - PDR calculations
- Code interplay and publication :
  - MHD codes (RAMSES, FLASH)
  - Meudon PDR code
  - Radiative transfer code (PHOENIX)
- Observational diagnostics :
  - Statistical analysis tools
  - Instrumental simulations (ALMA)

Hennebelle
Klessen
Banerjee
Dullemond
Falgarone
Glover
Hauschildt
Le Bourlot
Le Petit
Lesaffre
Levrier
.....

→ First approach towards integrating MHD and PDR codes

- Heavy computations : a few hours per "clump"
- Convergence issues in low density regions
- Geometry issue : requires 2D/3D PDR code

Grid computation

Code development

Interaction with observers