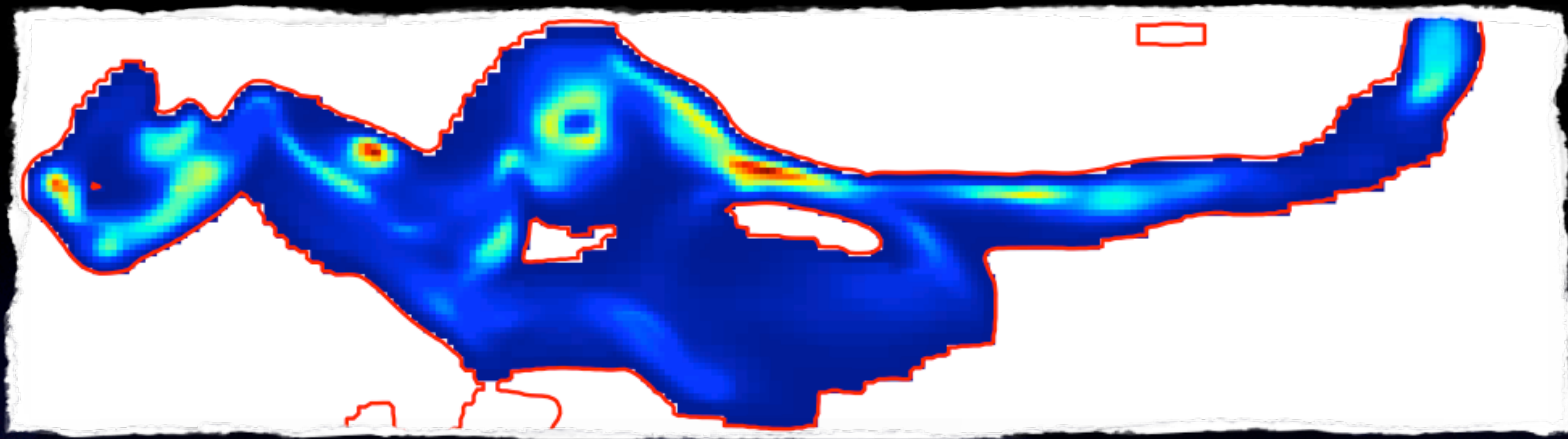
STAR FORMAT meeting, Paris, 09-10 June 2011



Applying the Meudon PDR code on dense structures from MHD simulations of the ISM

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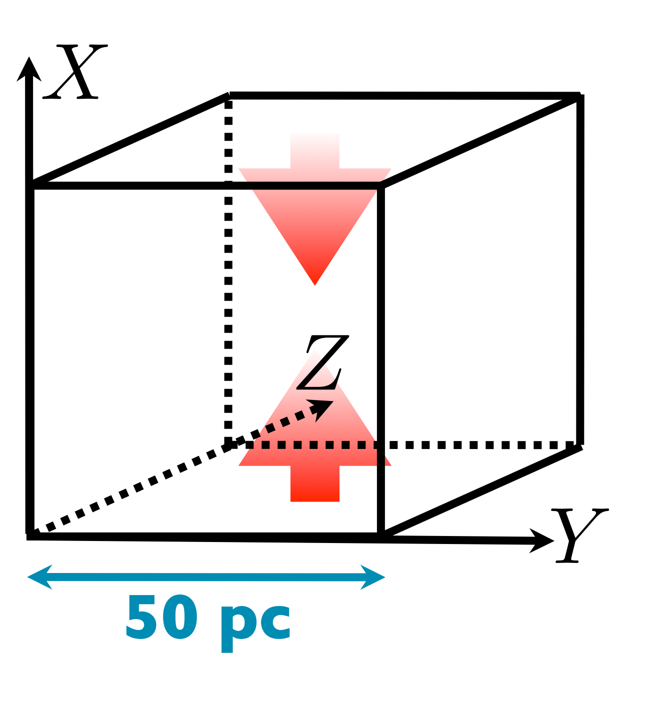
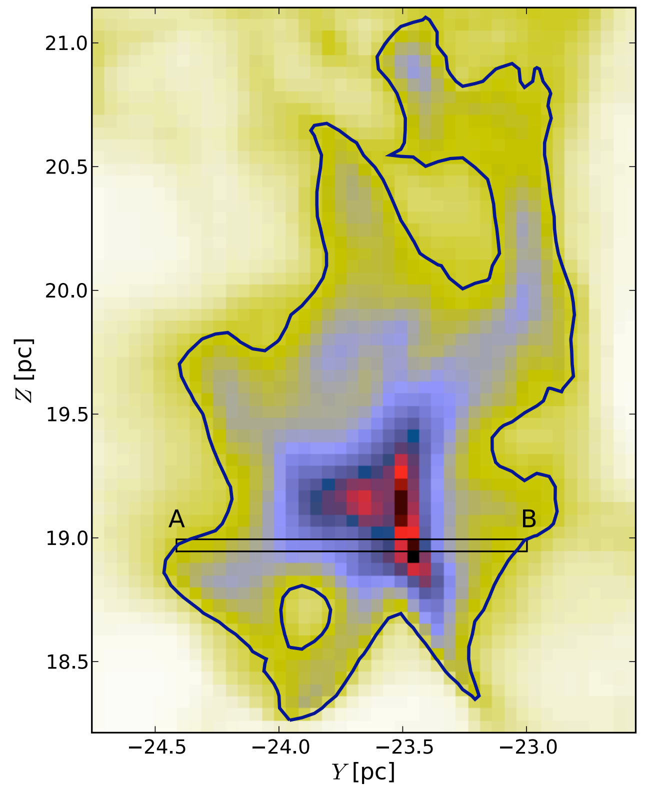
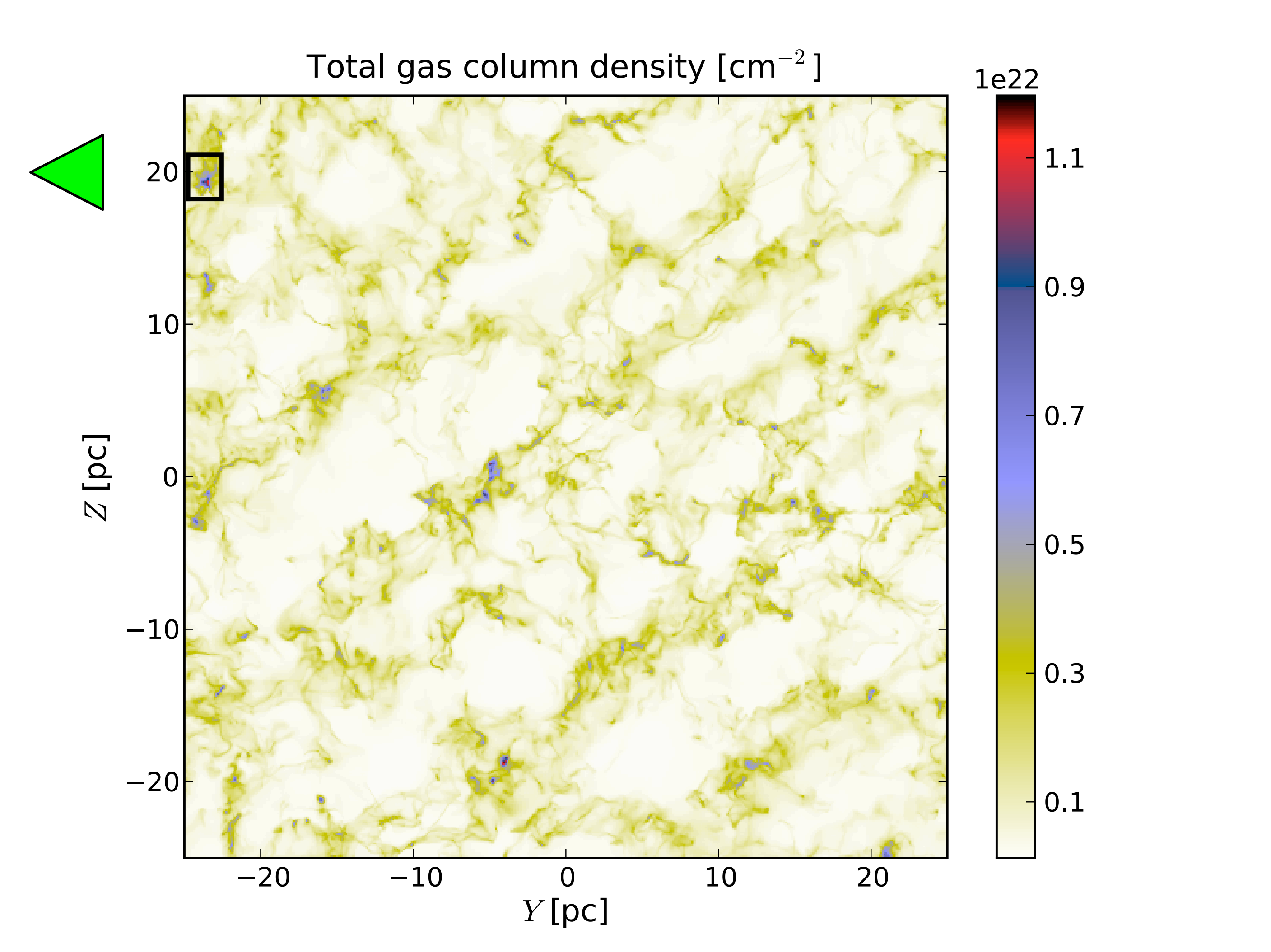
MHD simulation of the ISM

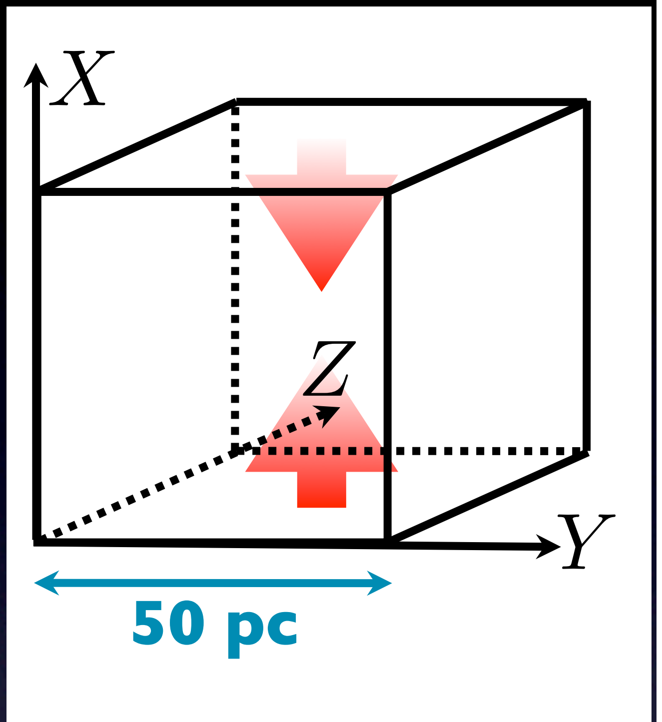
- RAMSES code (Teysier 2002, Fromang et al. 2006)
- Adaptive Mesh Refinement with up to 14 levels
- Converging flows of warm (10,000 K) neutral atomic gas
- Periodic boundary conditions on remaining 4 sides
- Includes magnetic field, atomic cooling and self-gravity
- Covers scales 0.05 pc - 50 pc
- ~30,000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

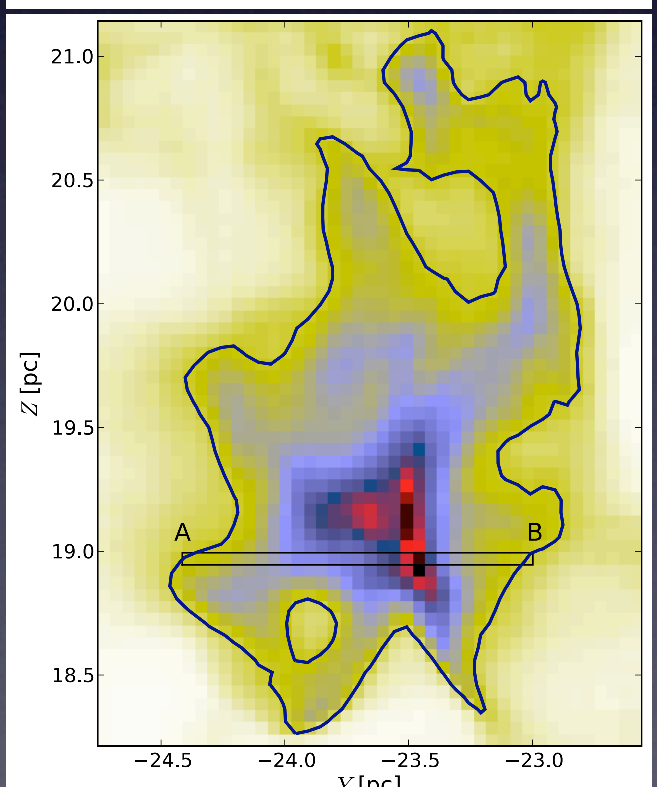


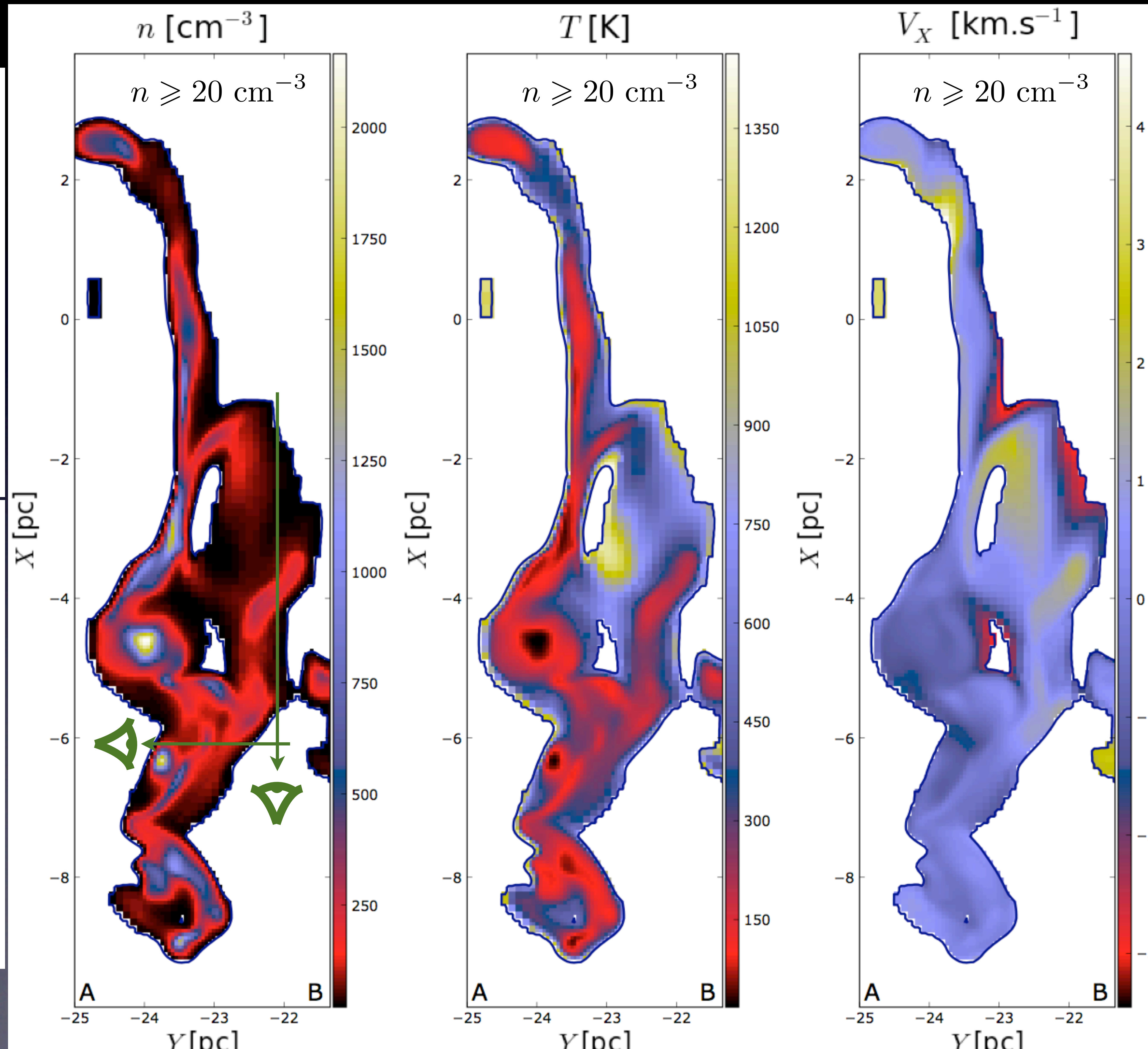




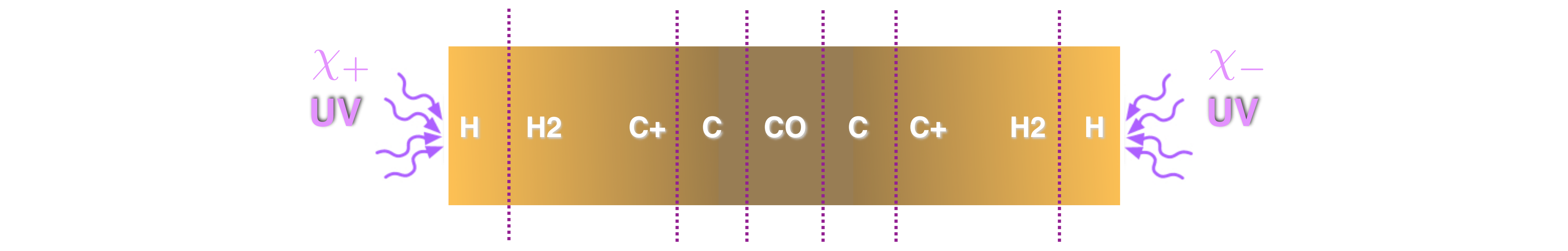
Density, temperature and line-of-sight velocity cuts in the XY plane of the MHD simulation (mean direction of the flow along the vertical axis), showing only where density exceeds the threshold of 20 cm^{-3}







The Meudon PDR code



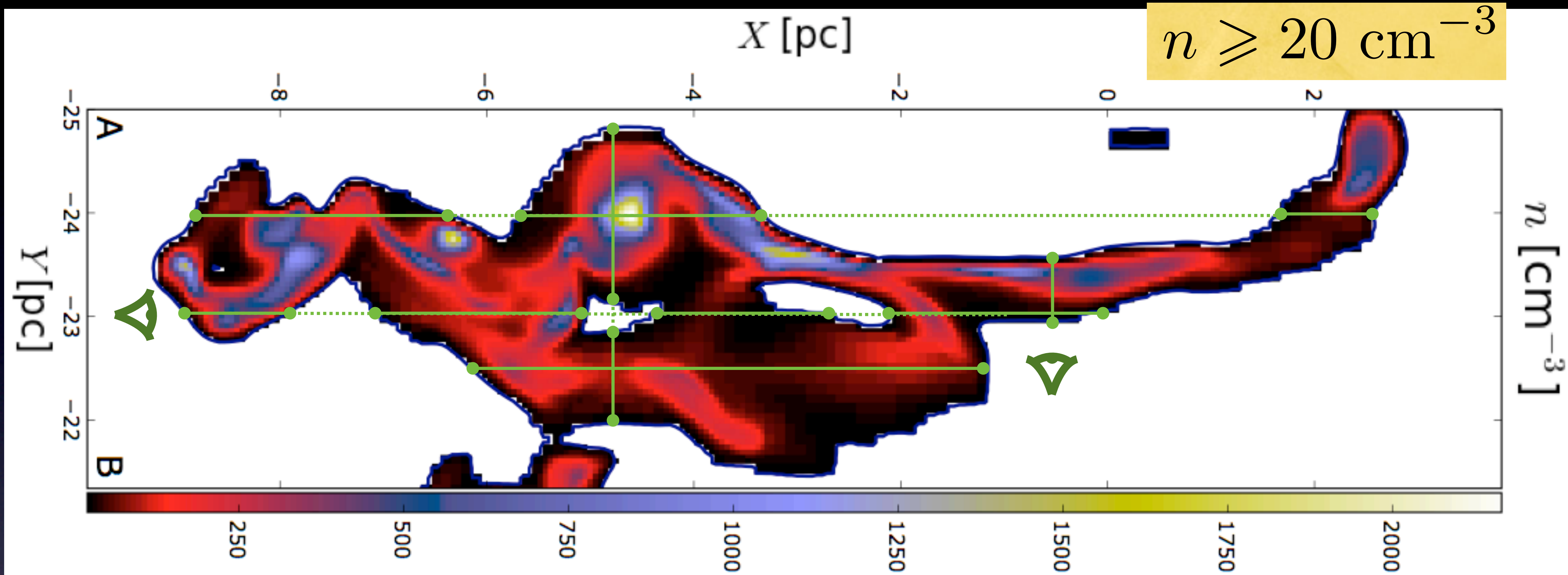
Stationary 1D model, including :

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

Outputs :

- **Local quantities :**
  - Abundance and excitation of species
  - Temperature of gas and dust
  - Detailed heating and cooling rates
  - Energy density
- **Integrated quantities on the LOS**
  - Species column densities
  - Line intensities
  - Absorption of the radiation field
  - Spectra

"Overcoming the shadows"



$F(X,Y)_{\parallel X}$

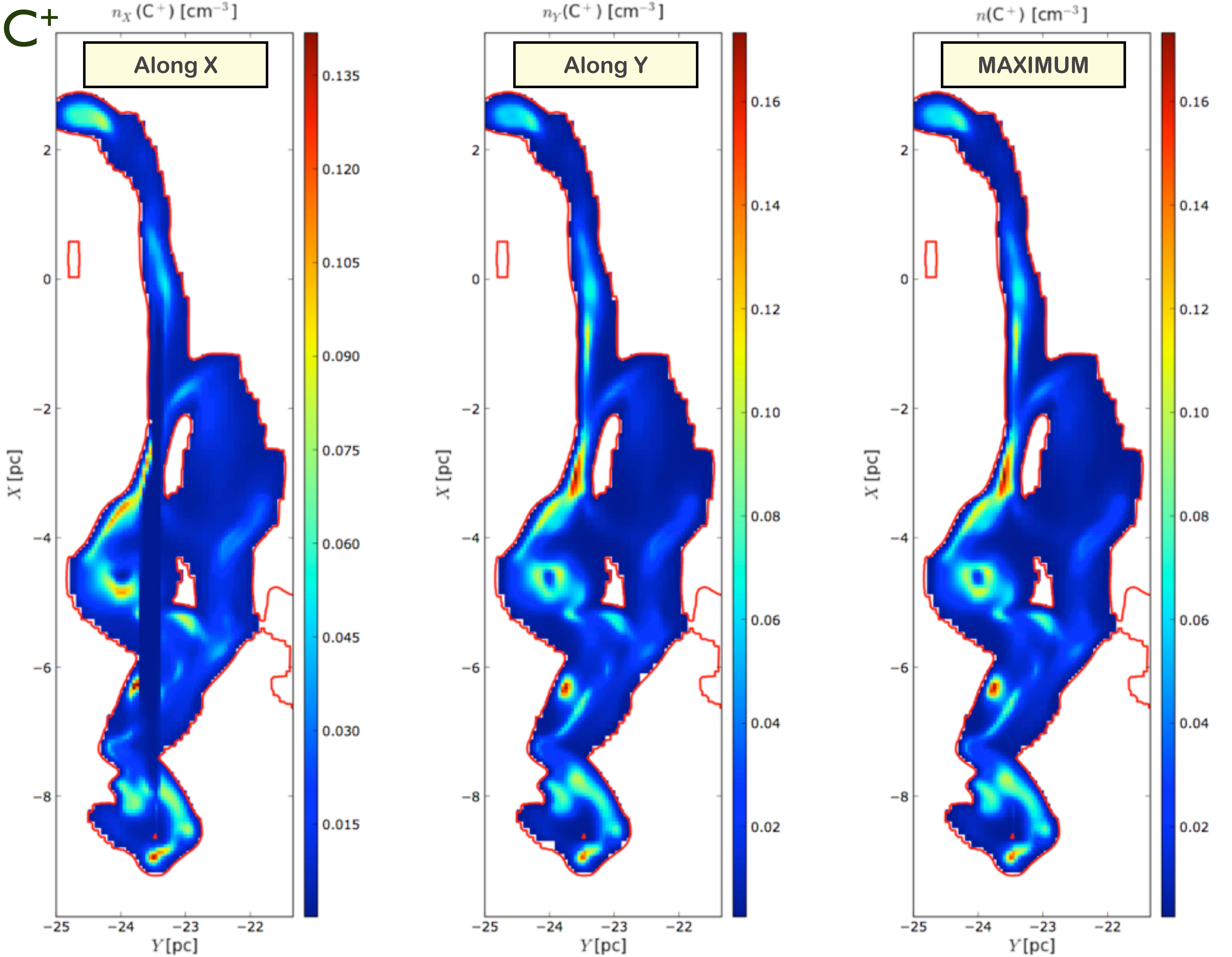
$F(X,Y)_{\parallel Y}$

min

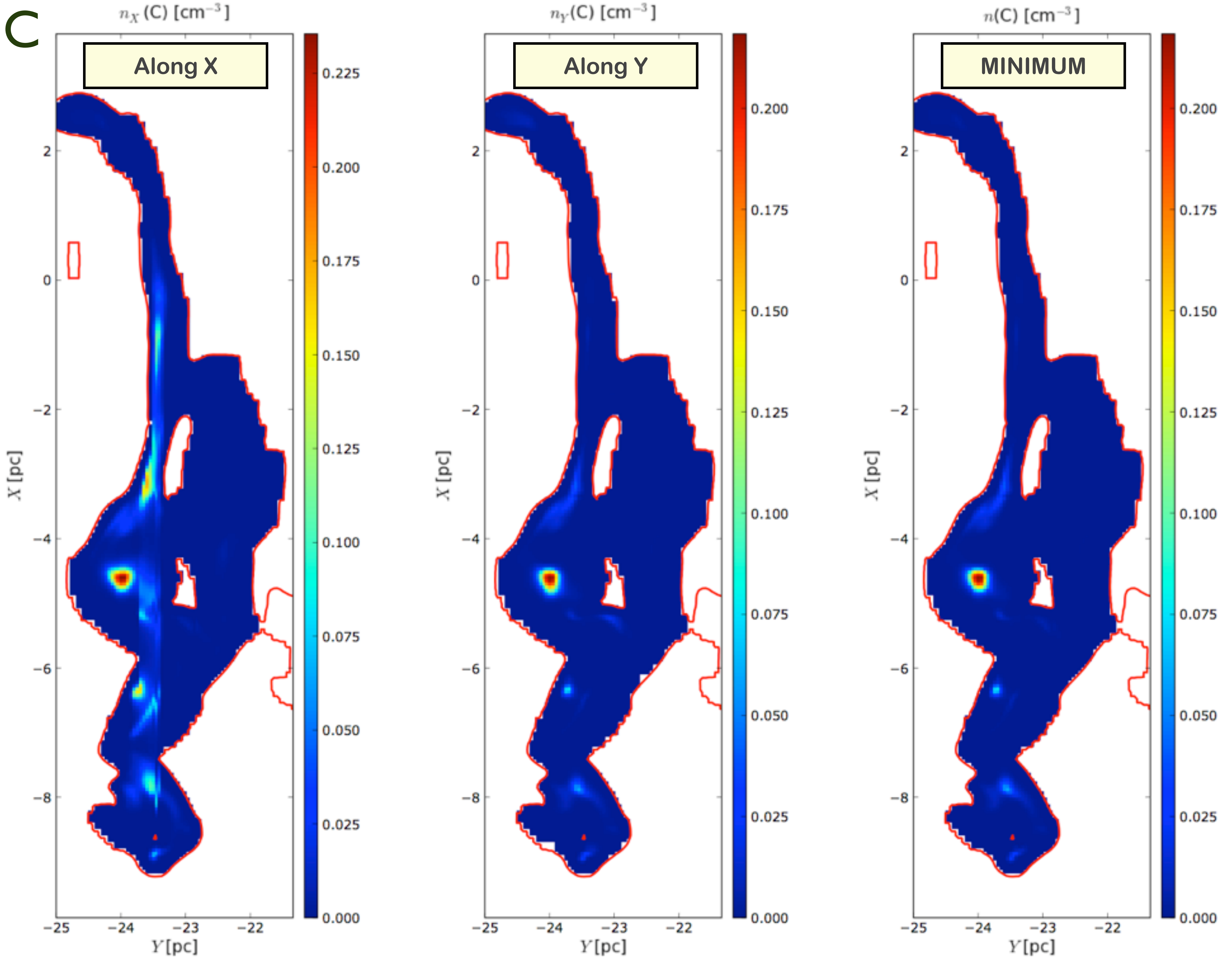
max

mean

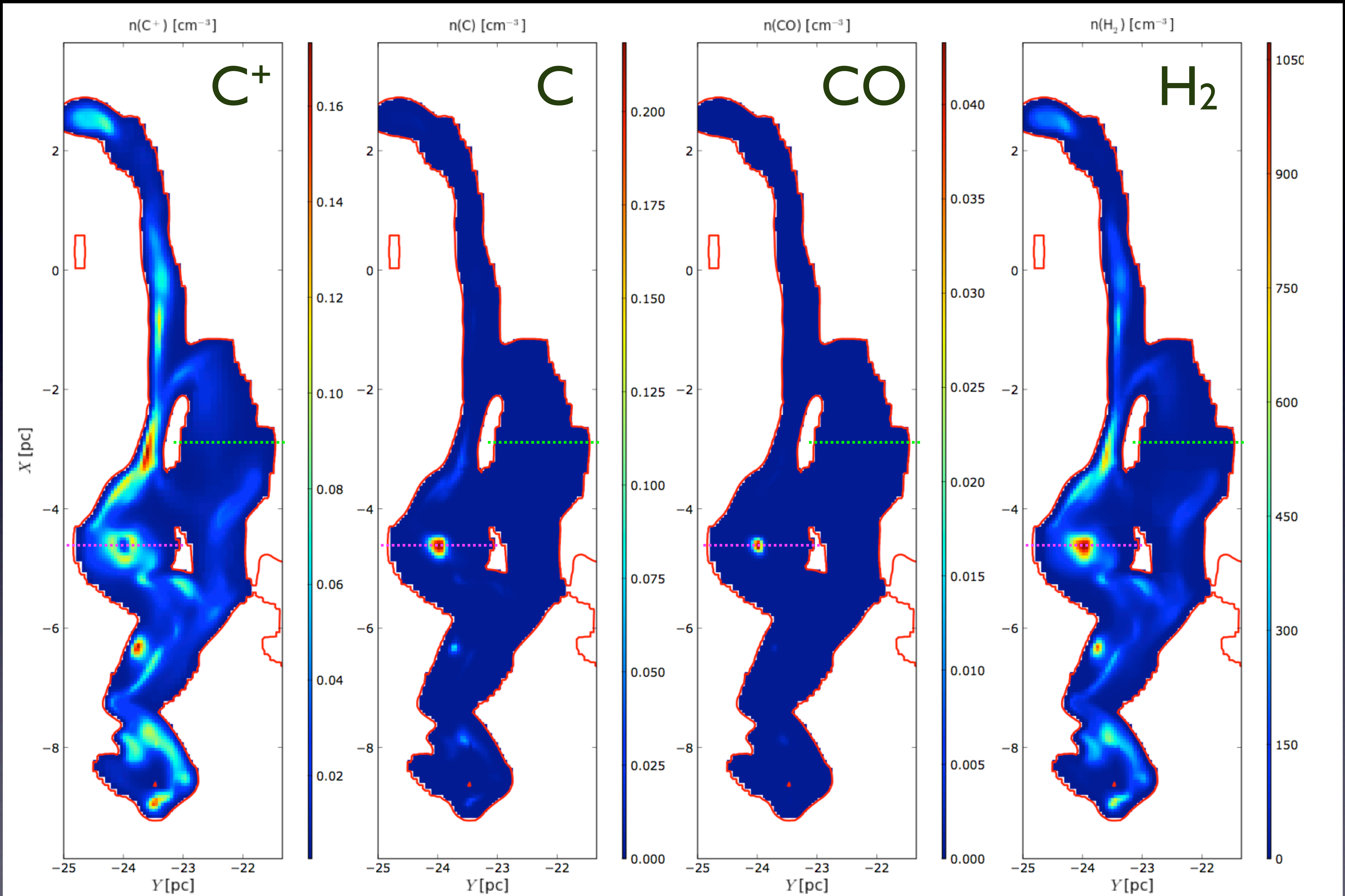
$\rightarrow F(X,Y)$



C+
n_X(C+) [cm-3]
Along X
n_Y(C+) [cm-3]
Along Y
n(C+) [cm-3]
MAXIMUM
X [pc]
Y [pc]


C
n_X(C) [cm^{-3}]
Along X
n_Y(C) [cm^{-3}]
Along Y
n(C) [cm^{-3}]
MINIMUM
X [pc]
Y [pc]

Volume densities of C^+, C, CO and H_2

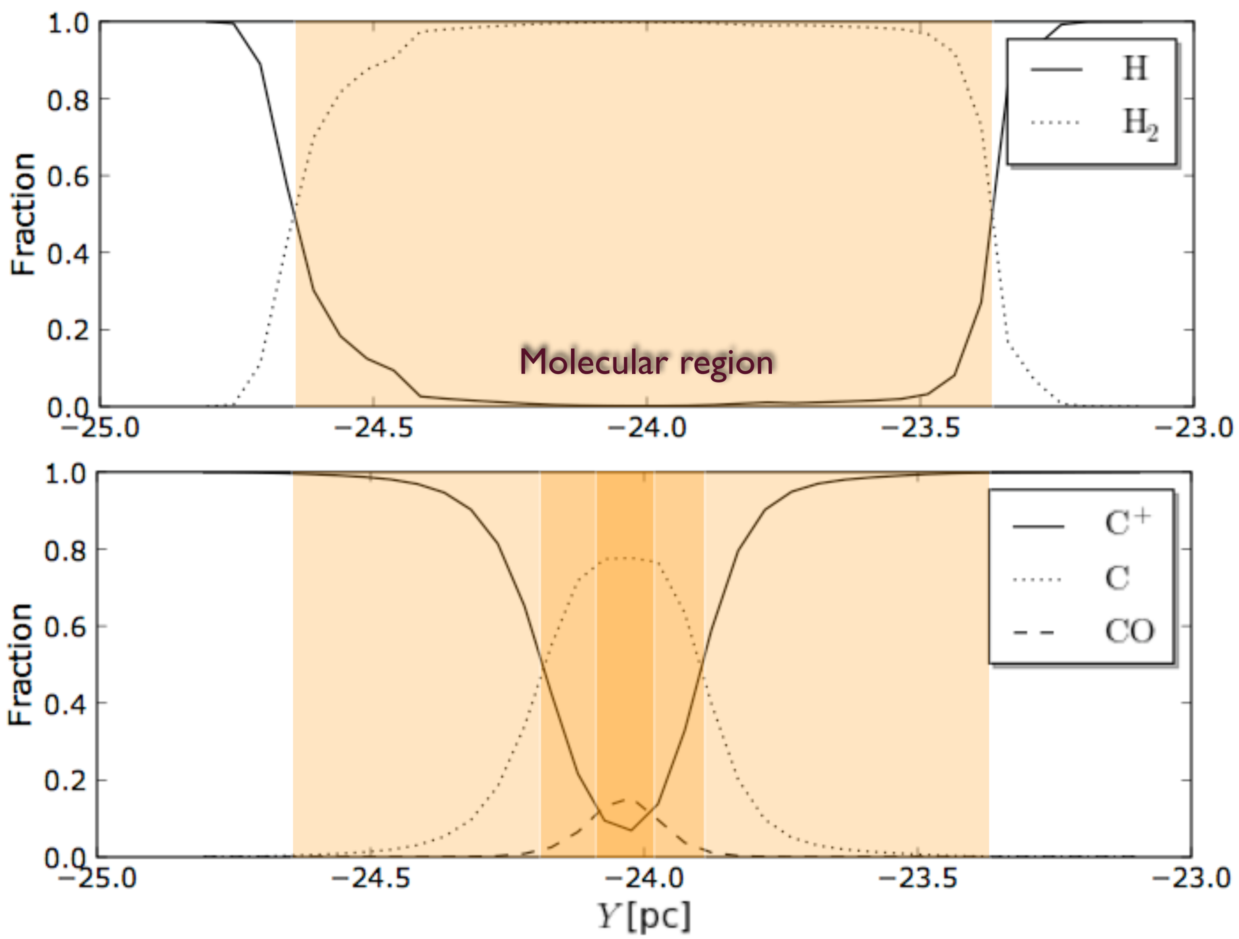


“Dark” molecular gas

Fractions in volume densities

H_2 : $\frac{2n(\mathrm{H_2})}{2n(\mathrm{H_2})+n(\mathrm{H})}$ H : $\frac{n(\mathrm{H})}{2n(\mathrm{H_2})+n(\mathrm{H})}$ CO : $\frac{n(\mathrm{CO})}{n(\mathrm{C^+})+n(\mathrm{C})+n(\mathrm{CO})}$ C : $\frac{n(\mathrm{C})}{n(\mathrm{C^+})+n(\mathrm{C})+n(\mathrm{CO})}$ C^+ : $\frac{n(\mathrm{C^+})}{n(\mathrm{C^+})+n(\mathrm{C})+n(\mathrm{CO})}$

Through the cloudlet



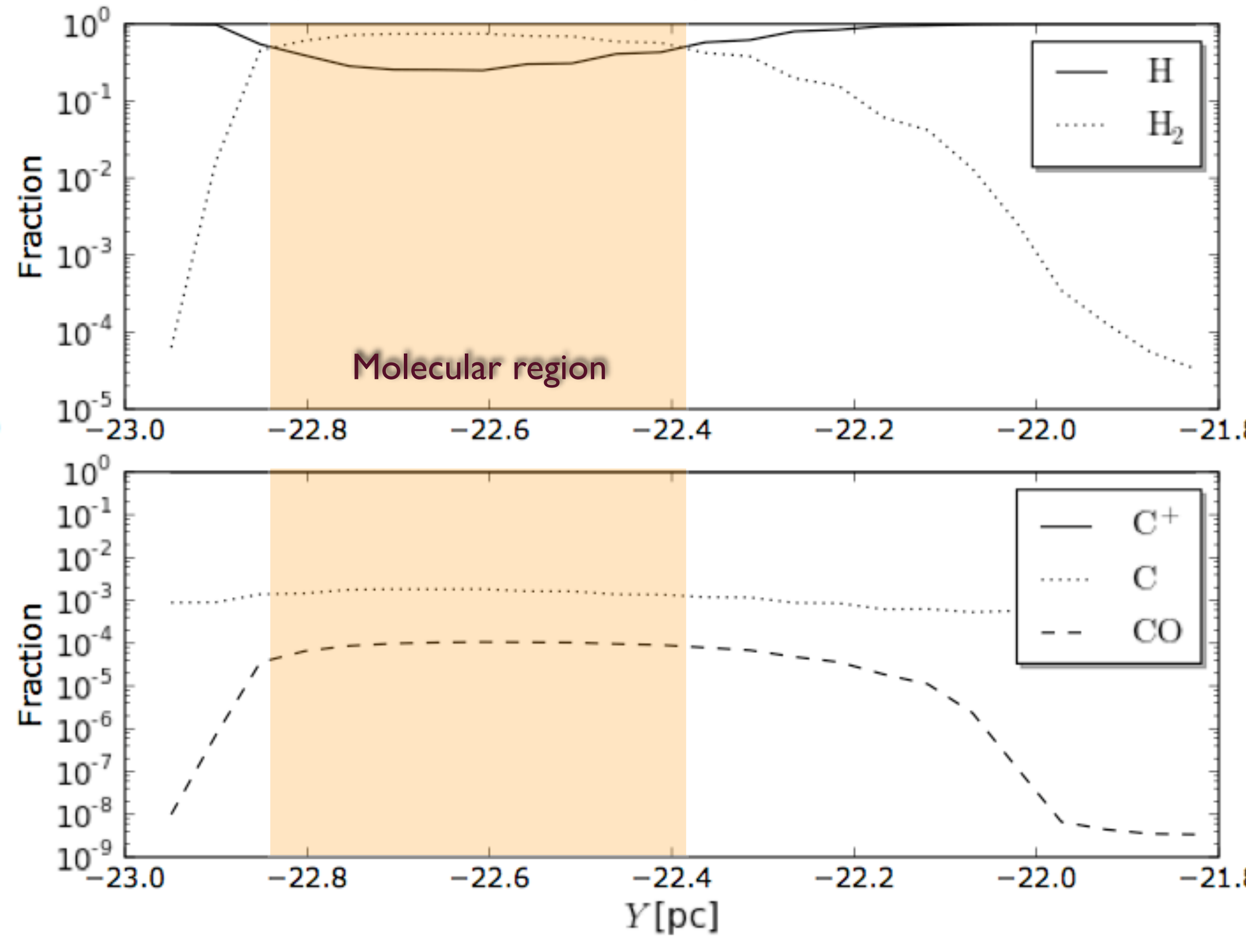
Mass fraction in the molecular region : 98%

... of which traced by C+ : 48%

... of which traced by C : 47%

... of which traced by CO : 5%

Through the diffuse region



Mass fraction in the molecular region : 70%

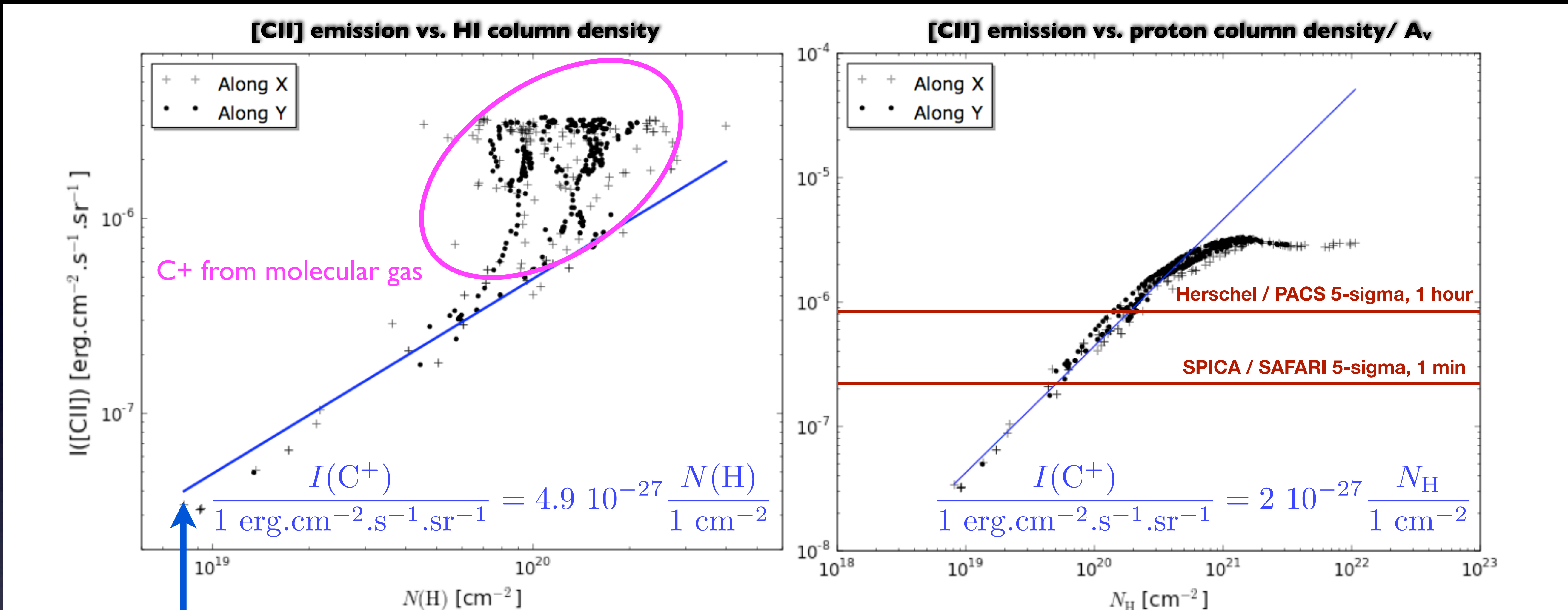
... of which traced by C+ : 99.8%

... of which traced by C : 0.16%

... of which traced by CO : 0.01%

Significantly higher than Wolfire et al. 2010 : $\tau_{\mathrm{CO}} \lesssim 1$

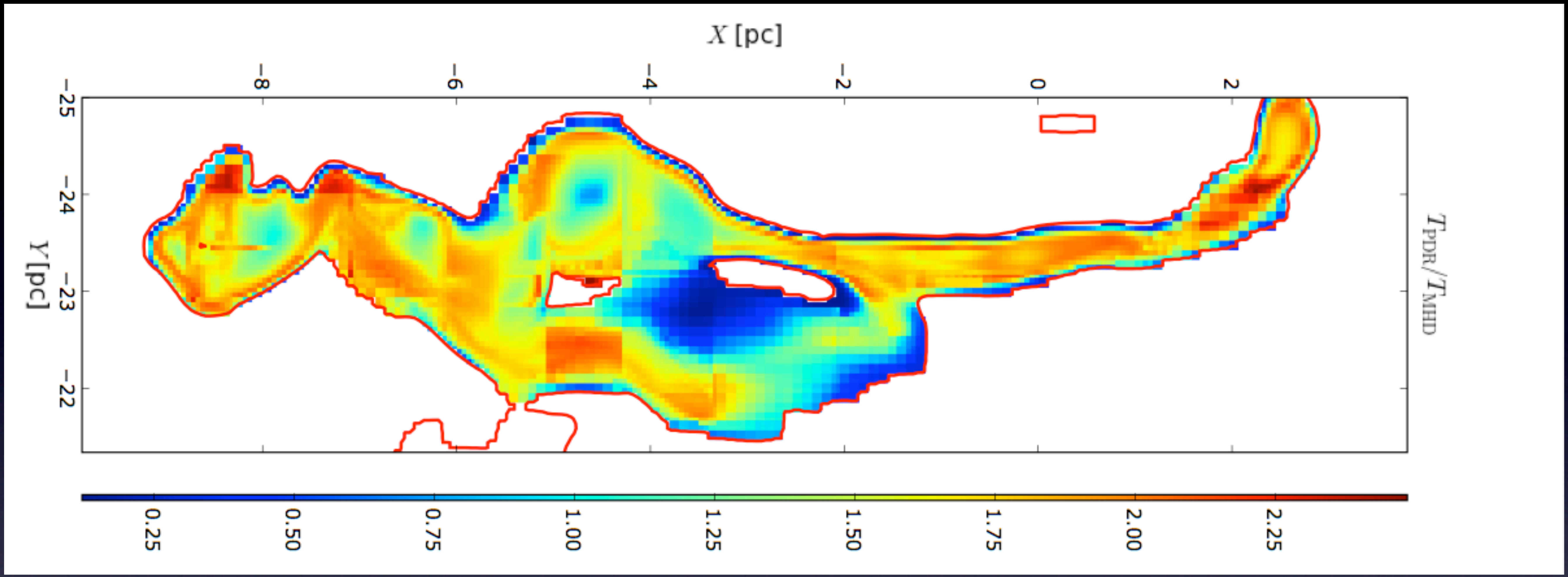
[CII] 158µm emission



From correlations at high galactic latitude :

- **I([CII]) - I_{FIR} (Ingalls et al. 2002)**
- **I_{FIR} - N(H) (Boulanger & Pérault 1988)**

PDR vs MHD temperatures

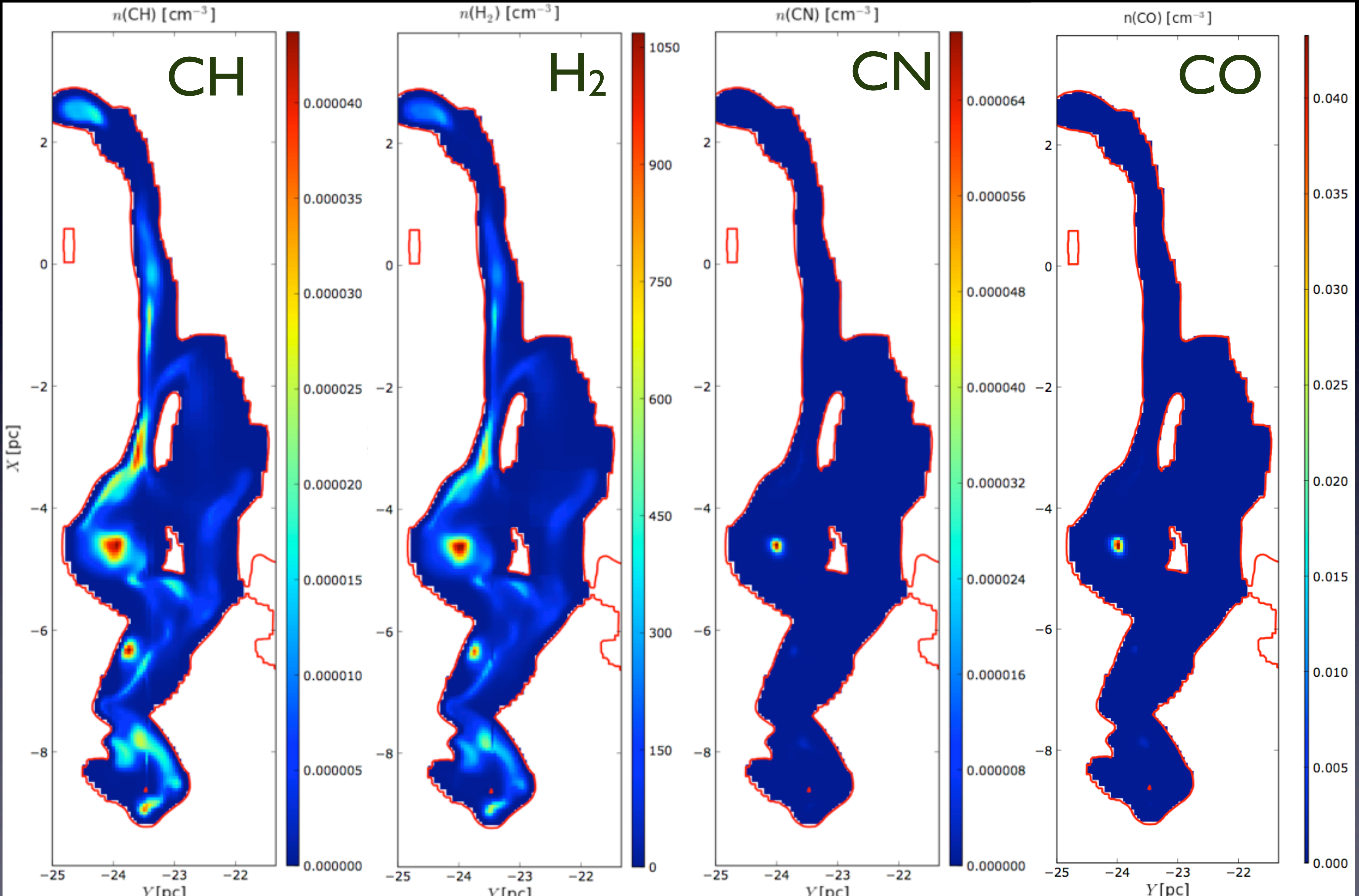


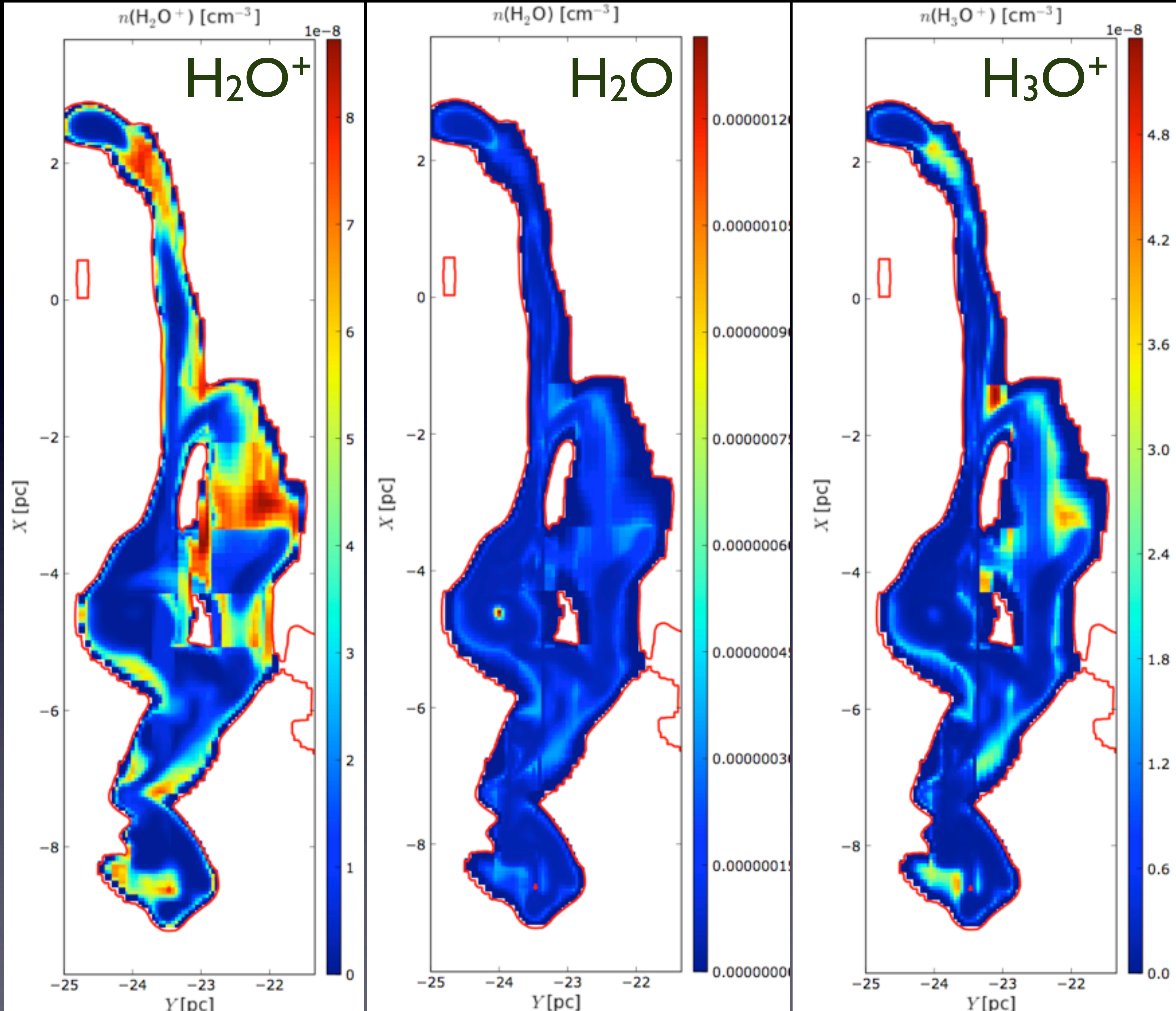
$$0.25 \leqslant \frac{T_{\rm PDR}}{T_{\rm MHD}} \leqslant 2.5$$

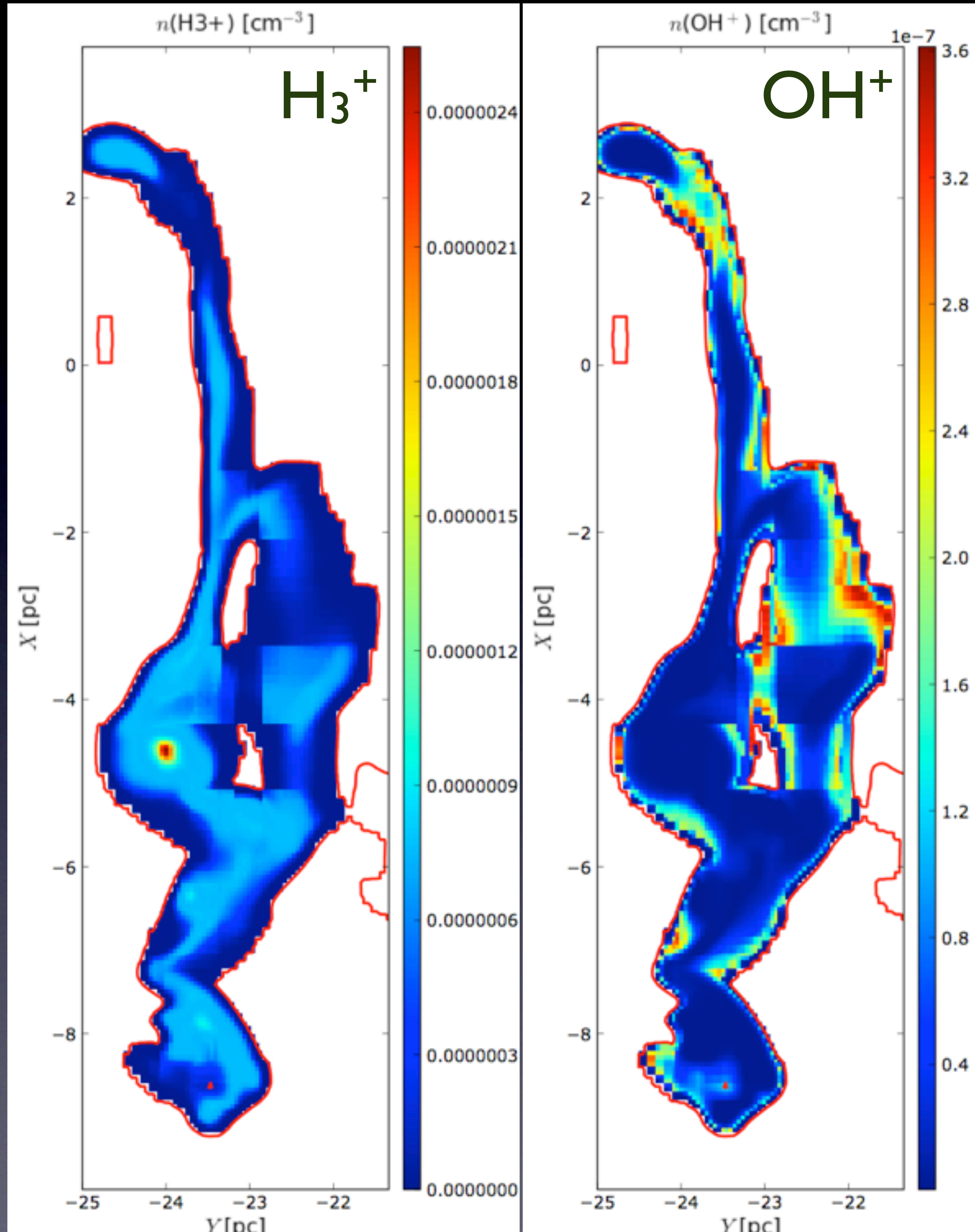
This agreement is somewhat of a surprise, given the differences between the codes :

- Different cooling functions
- Steady-state versus dynamical
- 1D versus 3D

CH and CN densities



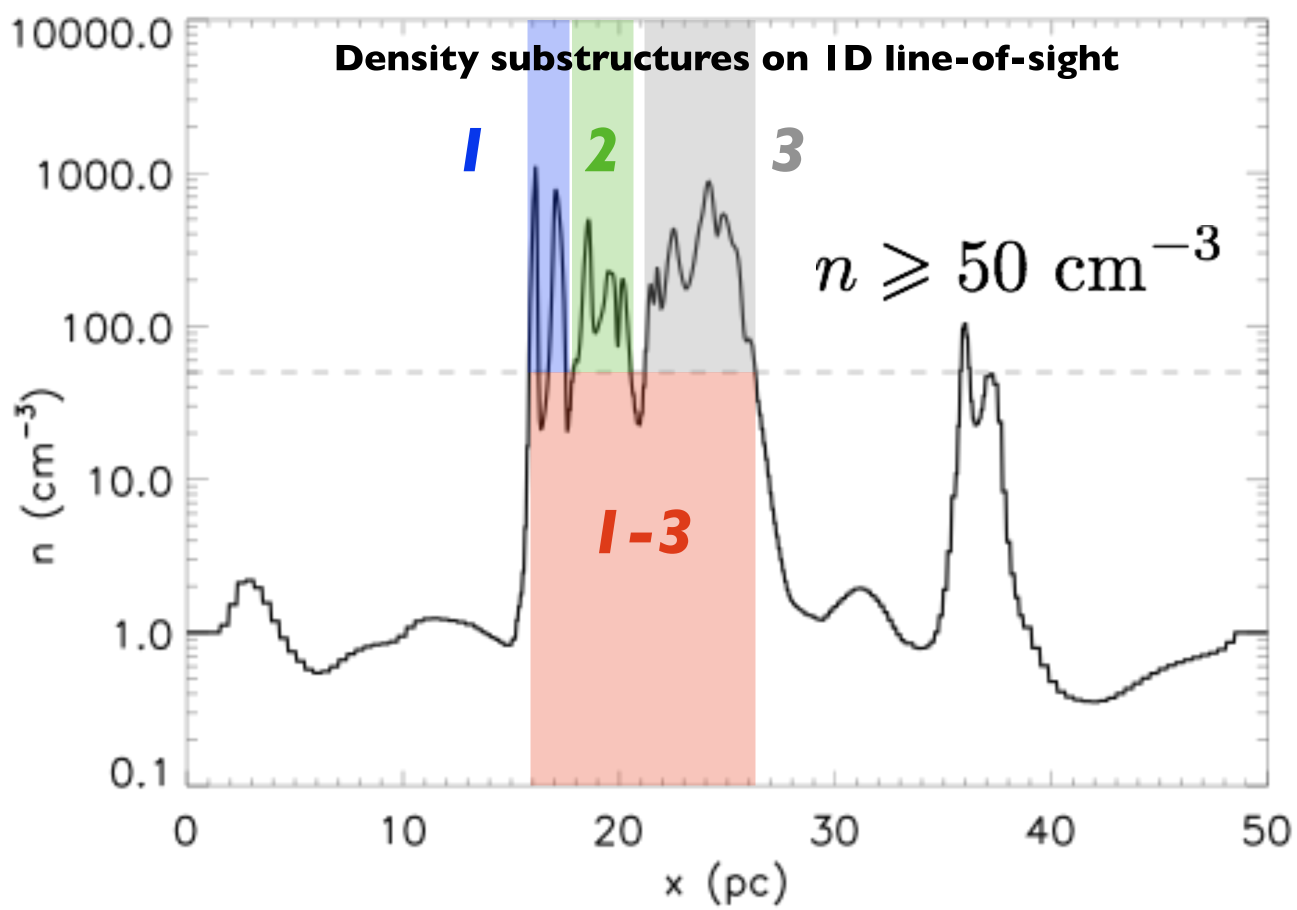

$n(H_2O^+)$ [cm^{-3}]
H_2O^+
$n(H_2O)$ [cm^{-3}]
H_2O
$n(H_3O^+)$ [cm^{-3}]
H_3O^+
X [pc]
Y [pc]
1e-8

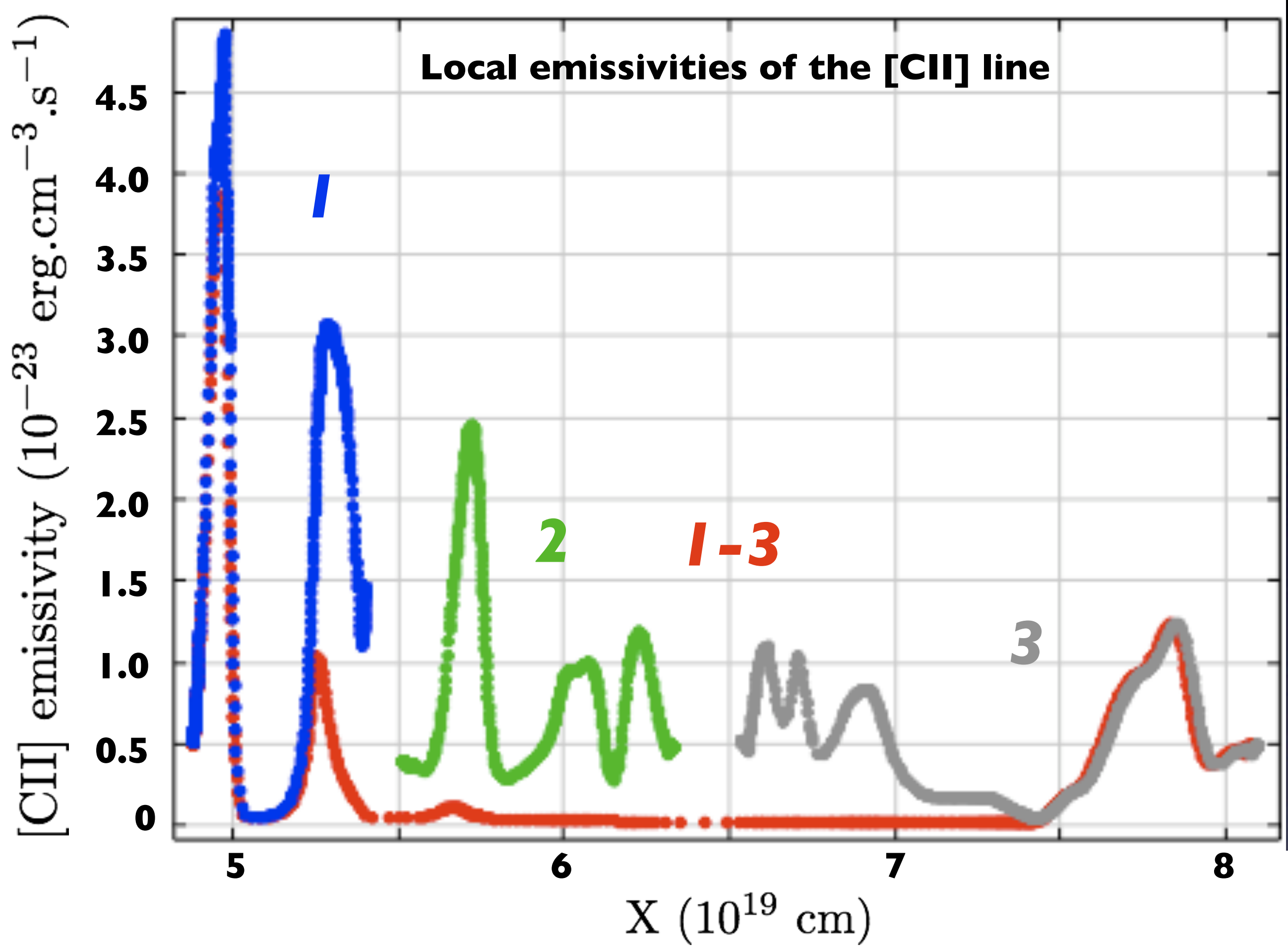


n(H3+) [cm^-3]
H3+
0.0000024
0.0000021
0.0000018
0.0000015
0.0000012
0.0000009
0.0000006
0.0000003
0.0000000
X [pc]
Y [pc]
n(OH+) [cm^-3]
OH+
1e-7
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
X [pc]
Y [pc]

Developments on the way...

- "Fractal" nature of actual ISM clouds and simulated density structures
- PDR code 1D - overestimates shielding : local illumination and C+ content might be much higher
- Application of the code to substructures, all with $\chi = 1$ on both sides





Integrated intensity of the [CII] line

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

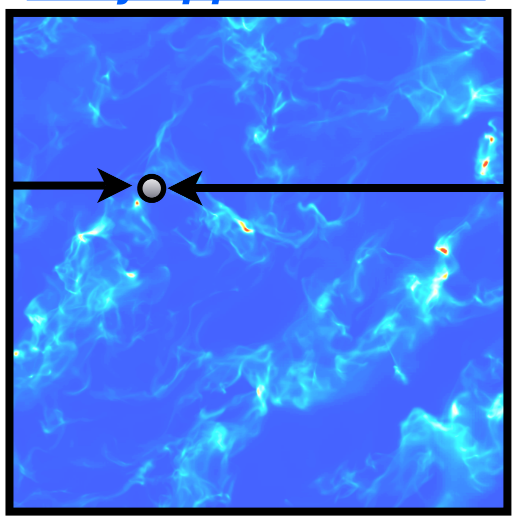
$$I_1 + I_2 + I_3 = 1.88\ 10^{-5} \mathrm{erg.cm^{-2}.s^{-1}.sr^{-1}}$$

Developments on the way...

Local UV field from extinctions in many directions

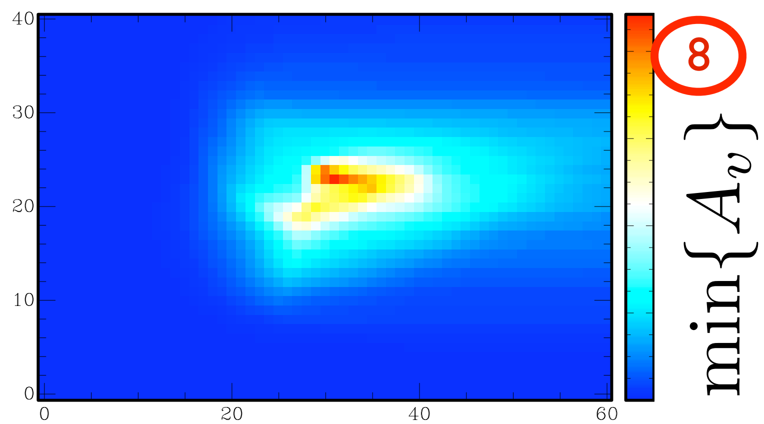
$$\chi \propto \langle \exp(-\alpha A_v) \rangle$$

2-ray approximation

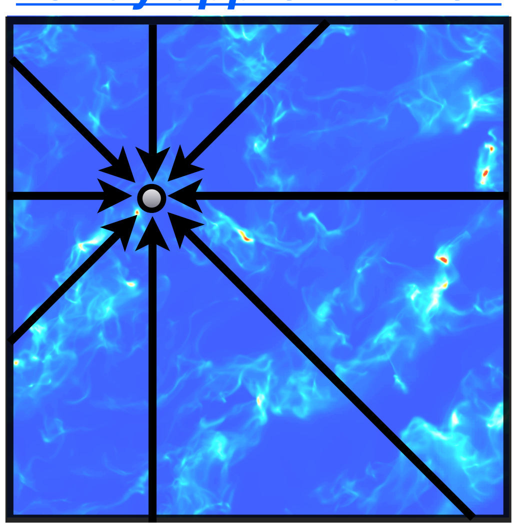


(1D : same as PDR code)

Minimum extinction for a 2D cut

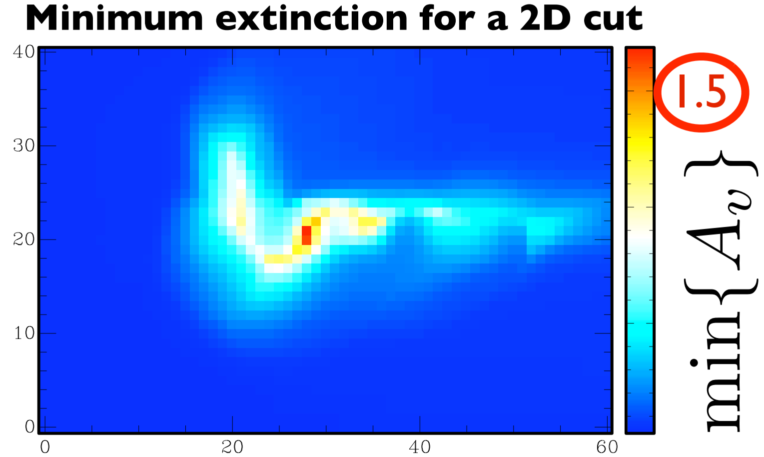


18-ray approximation

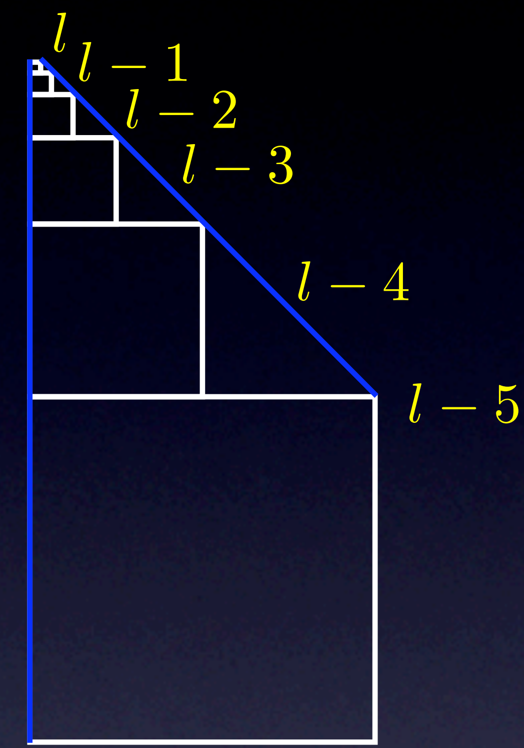


(in each of XY, XZ, YZ planes)

Minimum extinction for a 2D cut



- Extinction computation scheme in an AMR grid (W. Valdivia)



- Properly 3D PDR code (C. Pinto)
- RAMSES to PDR pipeline