Characterizing the HI → H_2 transition: Bright ^{12}CO (J=1–0) emission also traces diffuse gas

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Diffuse cloud named MBM 54 (Copyright: Ignacio de la Cueva Torregrosa)

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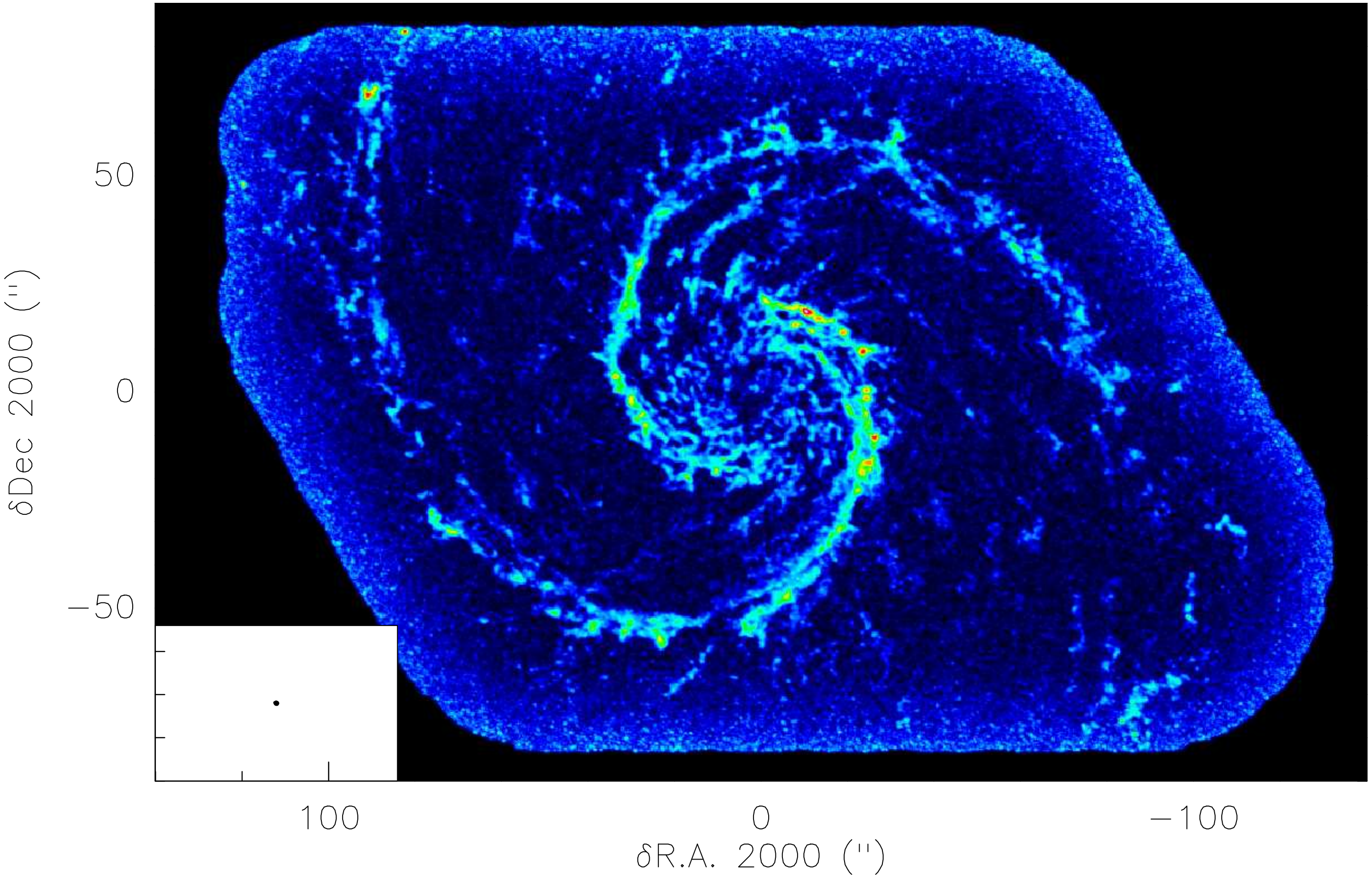
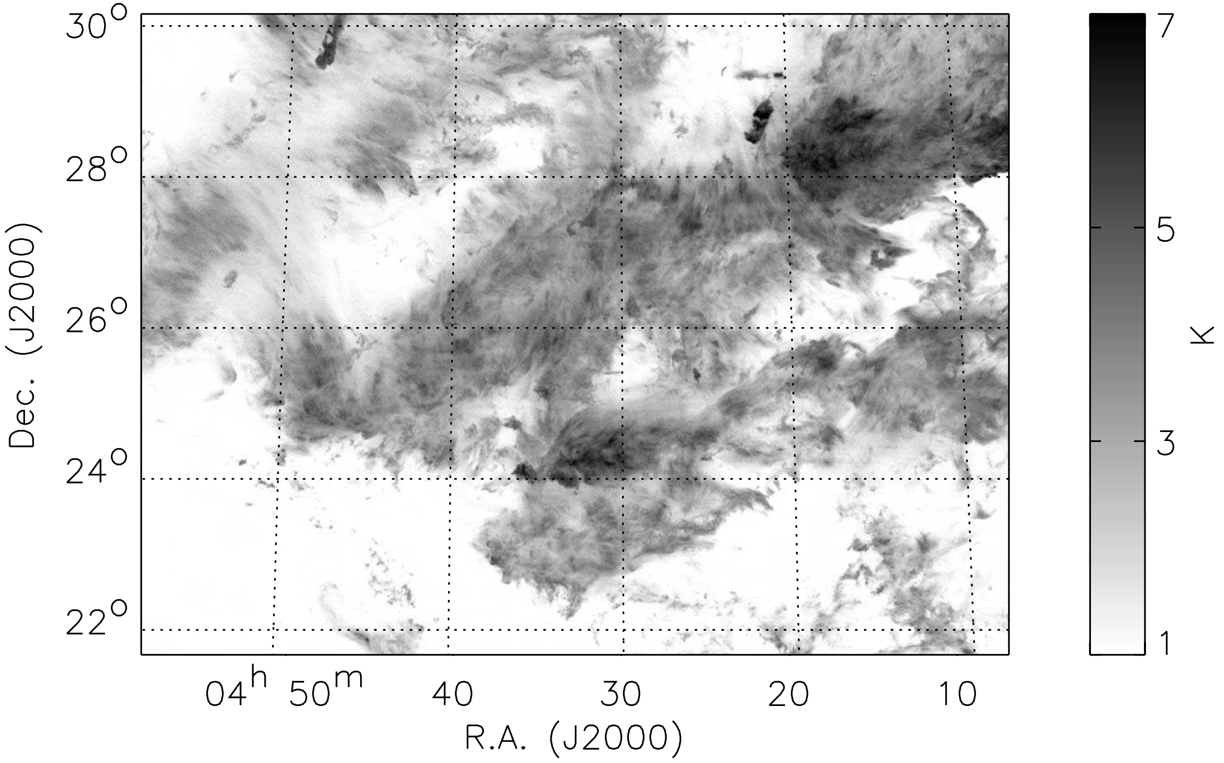
CO emission is often associated to cold (10-20 K), dense ($> 10^4\,\mathrm{cm}^{-3}$), strongly shielded, molecular gas (Carbon is locked in CO)

M51 as seen by PdBI+30m in ^{12}CO (J=1–0)
(PAWS collaboration, PI: Schinnerer)



However, about half the CO emission in Taurus comes from warm (50-100 K), low density (100-500 cm^{-3}), weakly shielded, diffuse gas (carbon is mostly locked in C^+).

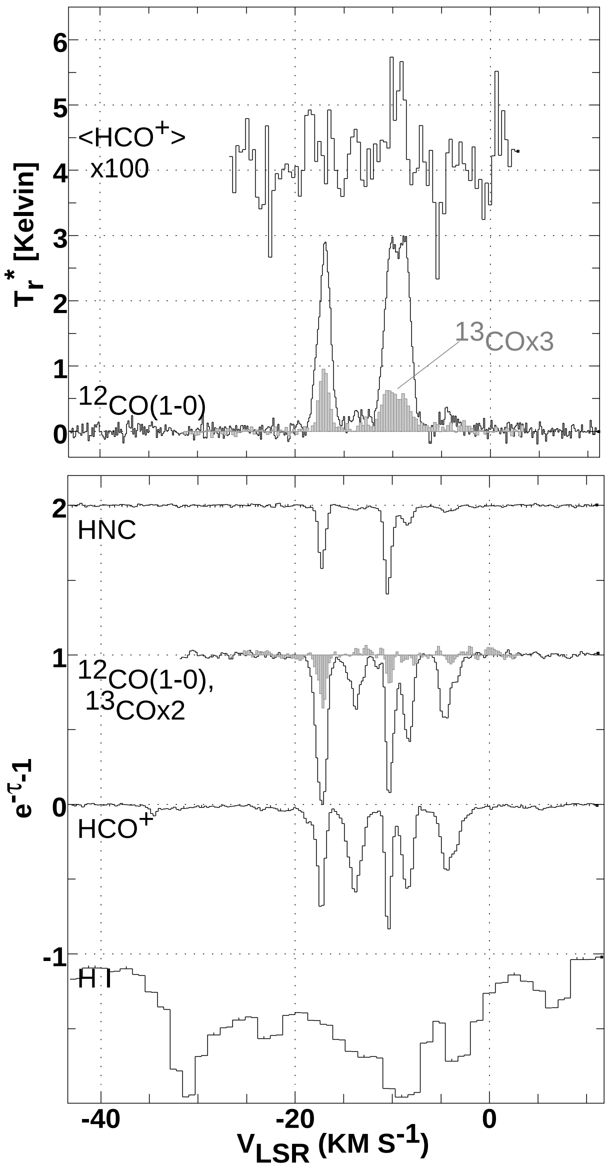
Taurus as seen by FCRAO-14m (Goldsmith et al. 2008, Pineda et al. 2010)



Question Values of $X_{\mathrm{CO}} = \mathrm{N}_{\mathrm{H}_2}/\mathrm{W}_{\mathrm{CO}}$?

Context Study of far and near galaxies (*e.g.* Leroy et al. 2011).

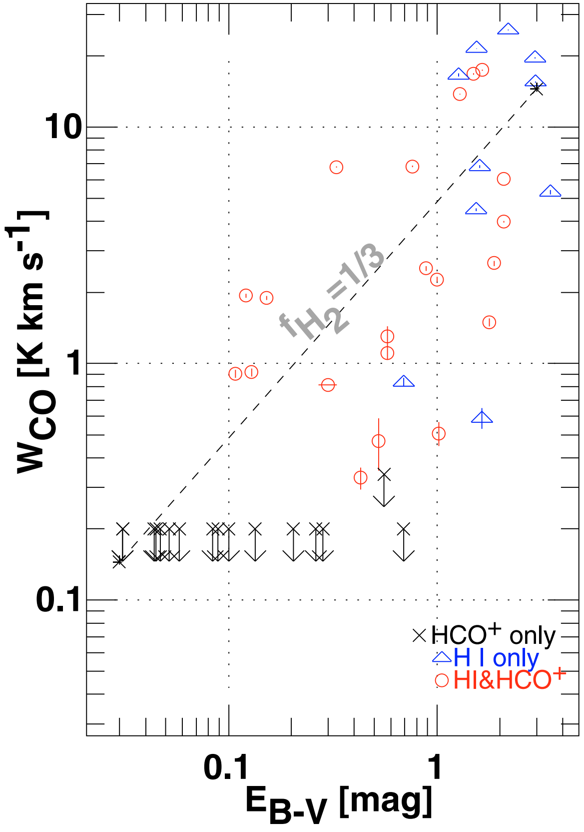
Measuring the mean N_{H_2}/W_{CO} conversion factor in diffuse gas (Liszt, Pety & Lucas, 2010, *A&A*)



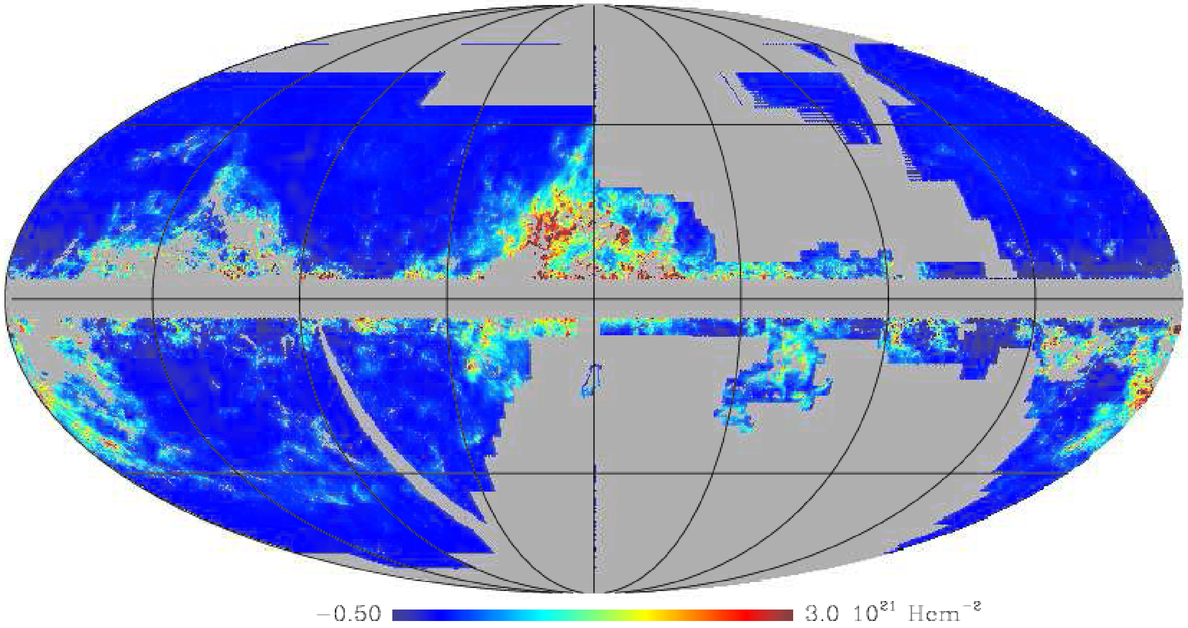
1. Considering whole Galactic lines of sight both in emission and in absorption against extragalactic continuum background sources (Here NRAO150, pety et al. 2008).
   Either low extinction at $|b| \gtrsim 15-20°$.
   Or multi-velocity components Total $A_V \sim 5$ mag
   but $A_V \lesssim 1$ mag per component.
   In all cases, low CO column densities per component
   $N_{CO} \leq 2\times 10^{16}\,\mathrm{cm}^{-3}$ ($\Rightarrow$ less than 7% of carbon in CO).
2. Total hydrogen column density from E_{B-V} extinction
   $N_H = N_{HI} + 2N_{H_2} = 5.8\times 10^{21}\,\mathrm{H\,cm}^{-2} E_{B-V}$
   (Schlegel et al. 1998 + Bohlin et al. 1978 and Rachford et al. 2009) $\Rightarrow \langle E_{B-V}\rangle = 0.89$ mag.
3. Estimating the atomic gas fraction via HI absorption
   Methods $\langle f_{HI}\rangle = \left\langle \frac{N_{HI}}{N_H} \right\rangle \sim \left\langle \frac{N_{HI}}{\int \tau_{HI}\,dv} \right\rangle \times \left\langle \frac{\int \tau_{HI}\,dv}{N_H} \right\rangle$ with
   Results $\langle f_{HI}\rangle = 0.65 \Rightarrow \langle f_{H_2}\rangle = 2N_{H_2}/N_H = 0.35$.
4. Measuring the CO luminosity $\Rightarrow \langle W_{CO}\rangle = 4.4\,\mathrm{K\,km\,s^{-1}}$.

$\Rightarrow \left\langle N_{H_2}/W_{CO} \right\rangle = 2.04\times 10^{20}\,\mathrm{H_2\,cm^{-2}/(K\,km\,s^{-1})}$, *i.e.*, same *mean* CO luminosity per H_2 in diffuse and dense gas!

Diffuse vs CO dark gas
(Liszt, Pety & Lucas, 2010, *A&A*)

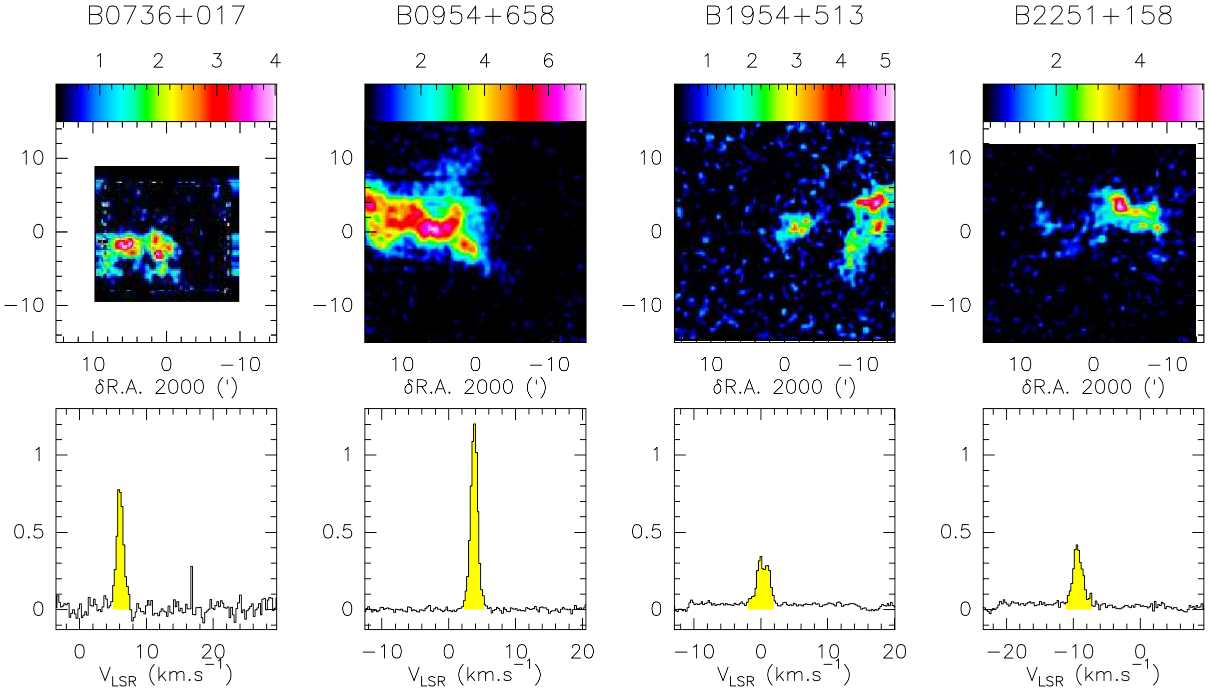


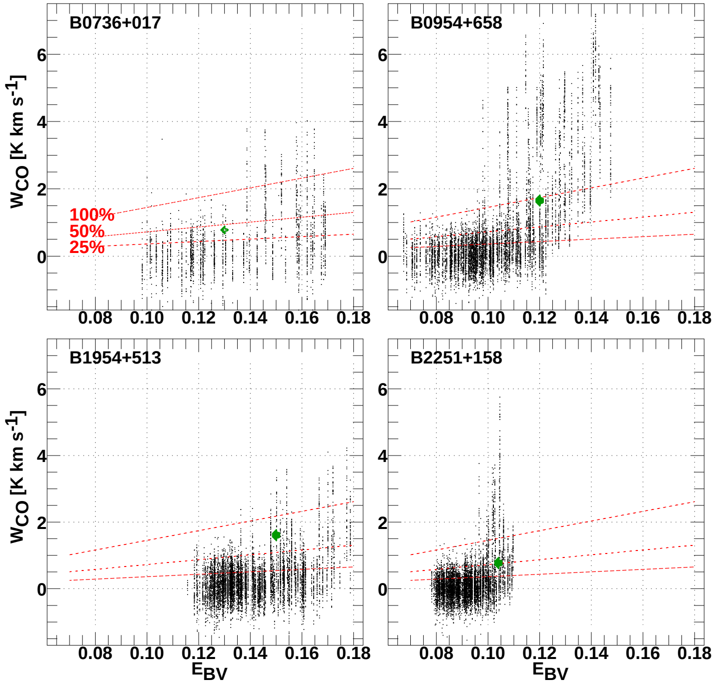
This work At low E_{B-V} (< 0.3 mag): CO is not reliably detected ⇒ not counted.



Fermi collaboration 2010, Planck collaboration 2011 E_{B-V} residuals after subtraction of N(HI) and W_{CO} components ⇒ CO dark gas.

CO dark and CO bright gas:
Imaging in emission diffuse gas regions at high Galactic latitudes
(Liszt, & Pety, 2012, *A&A*)





Diffuse gas $A_V < 1$.

Bright CO **(3 to 6 $\mathrm{K\,km\,s^{-1}}$) covers 20% of the surface**

Problem

Standard $W_{CO}/N(H_2) = 2 \times 10^{20}\,\mathrm{cm^{-2}\,H_2\,(km\,s^{-1})^{-1}}$ + Standard $N(H)/E_{B-V} = 5.8 \times 10^{21}\,\mathrm{cm^{-2}\,mag^{-1}}$

$\Rightarrow W_{CO} = 14.5 f_{H_2}\, E_{B-V}\ \mathrm{K\,km\,s^{-1}}$

$E_{B-V} = 0.1$ mag and $W_{CO} \gtrsim 1\,\mathrm{K\,km\,s^{-1}}$, $\Rightarrow f_{H_2} > 1$!

Solution As soon as detected, CO is overluminous by a factor 4-5.

Intermediate summary

These On average, same X_{CO} values for diffuse and dense gas:
$X_{\mathrm{CO}} \equiv \mathrm{N}_{\mathrm{H}_2}/\mathrm{W}_{\mathrm{CO}} = 2.04 \times 10^{20} \mathrm{H}_2\,\mathrm{cm}^{-2}/(\,\mathrm{K\,km\,s}^{-1})$.

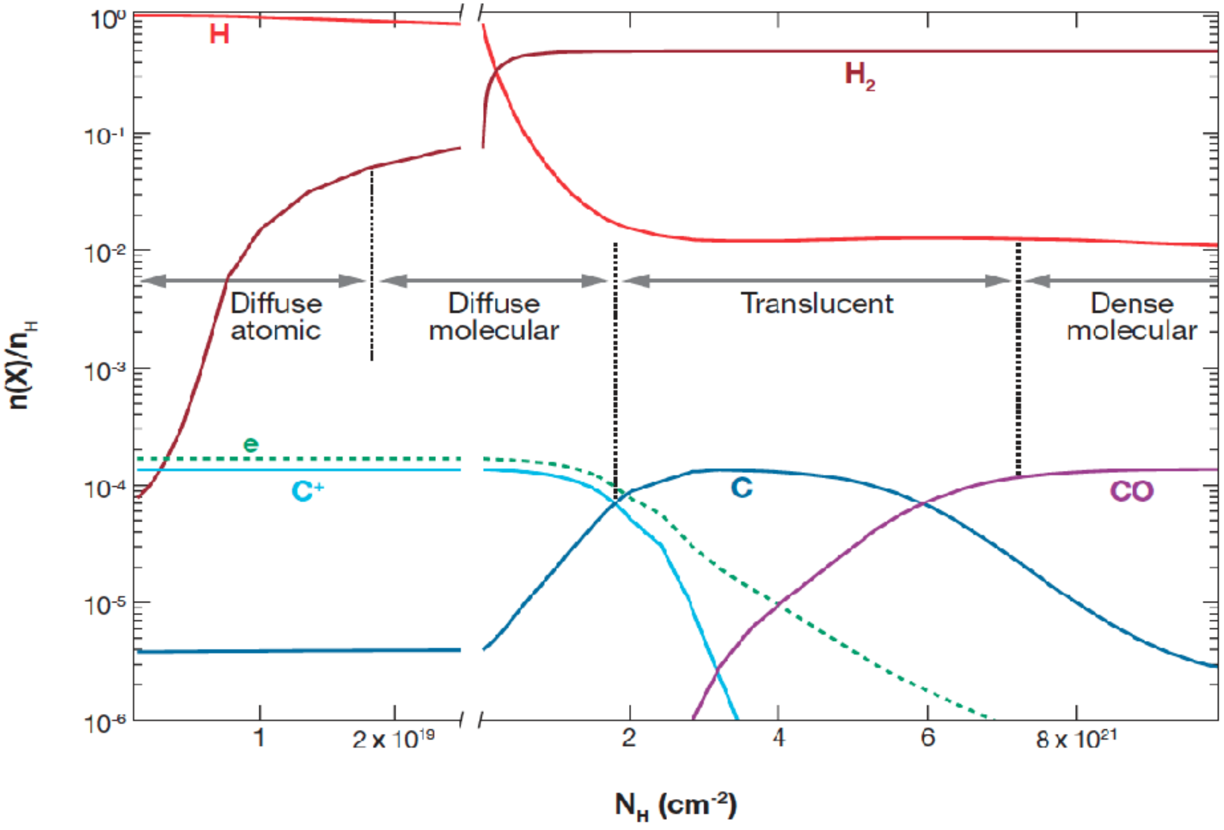
Antithese Locally (*i.e.* at small spatial scale), X_{CO} widely varies: Not only molecular gas untraced by CO (CO dark gas), but also molecular gas where CO is overly bright!

Synthese In diffuse regions, CO easily detectable in emission (*i.e.*, $\mathrm{W}_{\mathrm{CO}} \geq 1\,\mathrm{K\,km\,s}^{-1}$)

1. covers only 20% of the sky;
2. is overluminous by 4-5 compared to the standard X_{CO} factor.

⇒ On average, both effects cancel.

Translucent clouds: 1. Definition



Snow & Mc Call, ARAA, 2006
from Neufeld et al. 2005.

Diffuse clouds $A_v \lesssim 1$ and carbon in C^+.

Translucent clouds $2 \leq A_v \leq 5$ and carbon in C.

Dark clouds $6 \leq A_v$ and carbon in CO.

$\Rightarrow$ Translucent clouds are naively expected to have larger X_{CO} factors.

Translucent clouds: 2. Observational example
(Gratier, Pety et al., in prep)

IC 405 aka flame nebula

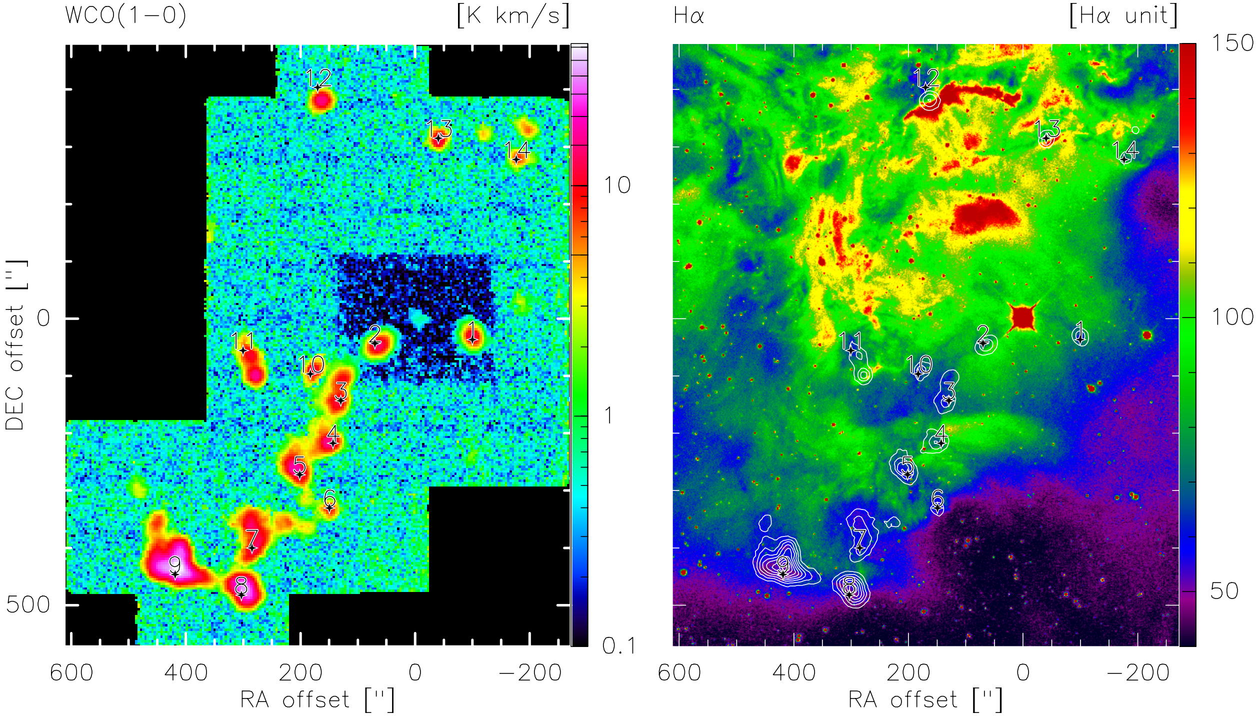
Diffuse gas not detected in CO in the Dame and/or Planck surveys.

HD 34078 Fastest O9.5V runaway star in the sky (Distance: 530 pc ⇒ $V = 120\,\mathrm{km\,s^{-1}}$).

Interaction ⇒ Sets of bright (∼ 10 K), small ($\lesssim 10''$) CO clumps in the foreground of the Hα emission.

Typical A_V from Hα emission:

3-5 ⇒ These clumps are characterized by a standard N_{H_2}/W_{CO} factor!



⇒ Translucent CO clumps!

Why a common CO-H_2 conversion factor for diffuse and dense gas? The change of radiative transfer regime compensates the change in chemistry (Liszt, Pety & Lucas, 2010, *A&A*)

Decomposition of the conversion factor $\frac{N_{H_2}}{W_{CO}} = \left(\frac{N_{H_2}}{N_{CO}}\right)\left(\frac{N_{CO}}{W_{CO}}\right)$ with

N_{H_2}/N_{CO}**:** CO chemistry;

N_{CO}/W_{CO}**:** Cloud structure and radiative transfer.

Dense gas

All the carbon is locked in CO $\langle N_{CO}/N_{H_2}\rangle = 10^{-4}$.
Consequence: $N_{H_2}/W_{CO} = \text{cst} \Rightarrow W_{CO} \propto N_{CO}$.

Why $W_{CO} \propto N_{CO}$**?** A bulk effect in a turbulent medium?

Diffuse gas

More than 90% of the carbon is locked in C^+
$\langle N_{CO}/N_{H_2}\rangle = 3 \times 10^{-6}$ (Burgh et al. 2007).

Subthermally excited gas (Goldreich & Kwan 1974)

- W_{CO}/N_{CO} much larger because of weak CO excitation in warm gas (60-100 K);
- $W_{CO} \propto N_{CO}$ until the opacity is so large that the transition approaches thermalization.

$\Rightarrow N_{CO}/W_{CO} \simeq 10^{15}\,\mathrm{CO\,cm^{-2}/(K\,km\,s^{-1})}$ (Liszt 2007).

Comparison with ISM models (Glover et al. 2011, Shetty et al. 2011)

Dense gas OK.

Diffuse gas Correct radiative transfer but wrong chemistry.
$\Rightarrow$ up to 4 orders of magnitude difference in N_{H_2}/W_{CO}.

A CO map of diffuse gas is an image of the complex CO chemistry
⇒ Only indirectly and at large spatial scale, CO traces the underlying mass distribution (Liszt, & Pety, 2012, *A&A*)

Subthermal excitation ⇒ $W_{CO} \propto N_{CO}$ (Goldreich & Kwan 1974).

Chemistry of CO in diffuse gas not yet fully understood

- Through $HCO^+ + e^- \rightarrow H + CO$.
  The electronic dissociation gives the right amount of CO if the abundance of HCO^+ with respect to H_2 is fixed to 10^{-9}. Liszt & Lucas, A&A, 2000, 355, 333, Liszt, A&A 2007, 476, 291, Visser, van Dishoeck, Black, A&A 2009, 503, 323: This rules of thumb can be used in models.

- What is not yet fully understood The formation of HCO^+ requires much more energy than present in the diffuse gas... (One possible solution: Turbulent intermittency, see Falgarone et al. papers).

A large fraction of CO emission could come from diffuse gas in our Galaxy (Liszt, Pety & Lucas, 2010, *A&A*)

Aim Estimating the luminosity of diffuse molecular gas perpendicular to the Galactic plane from the CO absorption data.

Hypothese Plane-parallel, stratified gas layer.

Two computations

1. **Direct** $\langle W_{\mathrm{CO}_\perp} \rangle = 2\,\langle \mathrm{W_{CO}}(b)\,\sin|b| \rangle$ with b the galactic latitude;

   Result $\langle W_{\mathrm{CO}_\perp} \rangle = 0.84\,\mathrm{K\,km\,s^{-1}}$.

2. **Mean luminosity** $\langle \mathrm{W_{CO}} \rangle = 4.6\,\mathrm{K\,km\,s^{-1}}$;

   Mean number of galactic half-width along integration path $\langle 1/\sin|b| \rangle = 19.8$;

   Result $2\,\langle \mathrm{W_{CO}}(b) \rangle \,/\, \langle 1/\sin|b| \rangle = 0.47\,\mathrm{K\,km\,s^{-1}}$.

Comparison with Galactic surveys of CO emission

Mean CO brightness per kpc $5\,\mathrm{K\,km\,s^{-1}}/\,\mathrm{kpc}$ at $R_\odot = 8\,\mathrm{kpc}$ (Burton & Gordon 1978).

Vertical height 0.150 kpc (for a single Gaussian vertical distribution of dispersion 60 pc, Cox 2005).

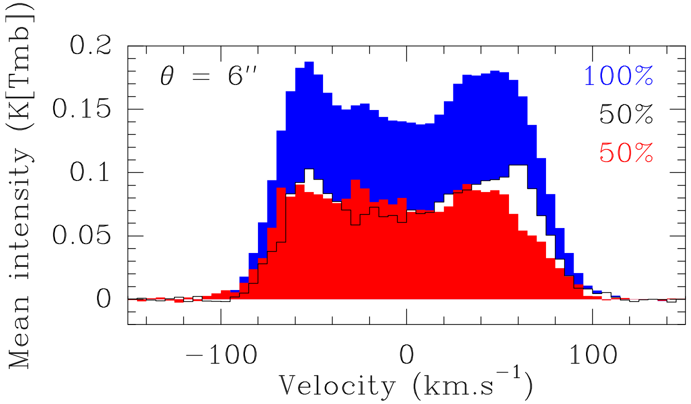
Result $\langle W_{\mathrm{CO}_\perp} \rangle = 0.75\,\mathrm{K\,km\,s^{-1}}$.

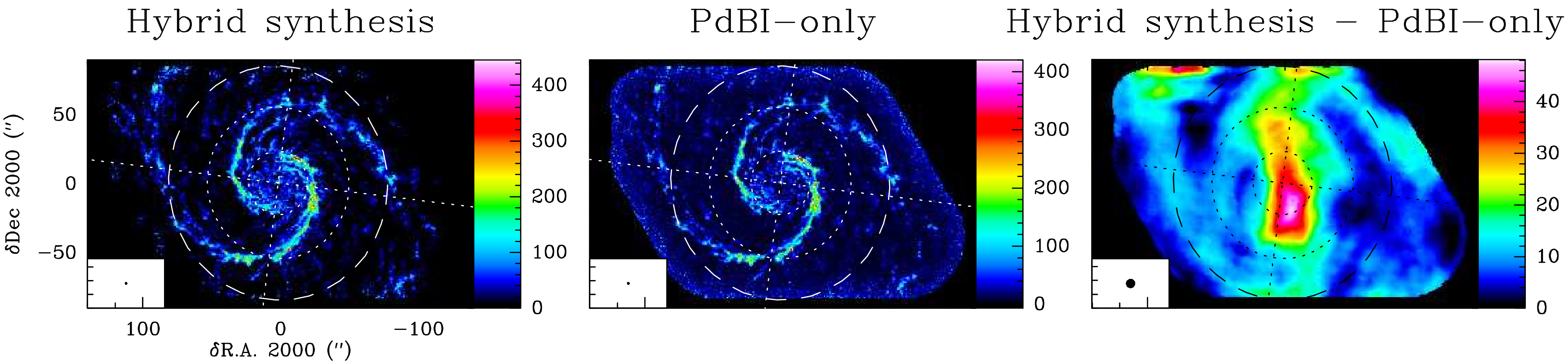
Potential difficulties

Local ISM geometry Bubble;

Scatter from long mean free paths.

A CO diffuse thick disk in M51: $\sim 50\%$ of the flux is resolved at scales $\geq 36'' \sim 1.3\,\mathrm{kpc}$ (PAWS collaboration, Pety et al., arXiv:1304.1396)





Integrated emission $[\mathrm{K.km.s^{-1}}]$

PdBI-only component

- **Bright** From 2 to 16 K with a median of 2.5 K.
- **Compact** It fills only $\sim 2\%$ of the surface.

Filtered component

- **Faint** From 0.07 to 1.36 K with a median of 0.14 K.
- **Extended** It fills $\sim 30\%$ of the surface.

A CO diffuse thick disk in M51:
A dense and diffuse components of very different vertical scale heights, which probably mix in the galactic plane.
(PAWS collaboration, Pety et al., arXiv:1304.1396)

Relative linewidths

Fact The filtered component has a velocity dispersion at least twice as large as the compact component.

Interpretation **(using Koyama & Ostriker 2009)** The extended component has a Gaussian scale height ($\sim 200\,$pc) typically 5 times as large as the compact component one ($\sim 40\,$pc). The Galaxy scale height is 57 pc (Ferriere 2001, Cox 2005).

Consequence The extended component average density ($1\mathrm{H_2\ cm^{-3}}$) is one order of magnitude lower than the compact component one ($10\mathrm{H_2\ cm^{-3}}$). The Galaxy average density is $0.29\mathrm{H_2\ cm^{-3}}$ (Ferriere 2001, Cox 2005).

Interpreting a sky occupied by CO emission from diffuse gas

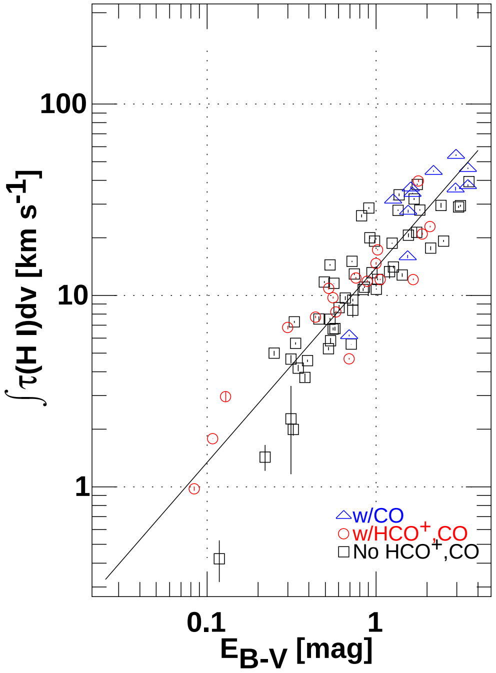
Correct mass estimates (for CO traced gas), The dark molecular gas (as evidenced by FERMI and PLANCK) is compensated by overly bright CO gas as soon as detected.

But different physical interpretation!

If dense gas: small fraction of the ism volume, confined by ram or turbulent pressure, if not gravitationally bound, on the verge of forming star.

If diffuse gas: warmer, low pressure medium filling a large fraction of the ism volume, contributes more to mid-IR dust or PAH emission, probably not gravitationally bound or about to form stars.

How do molecular and atomic gas mix?
(Liszt, Pety & Lucas, 2010, *A&A*)



Large difference in beam sizes

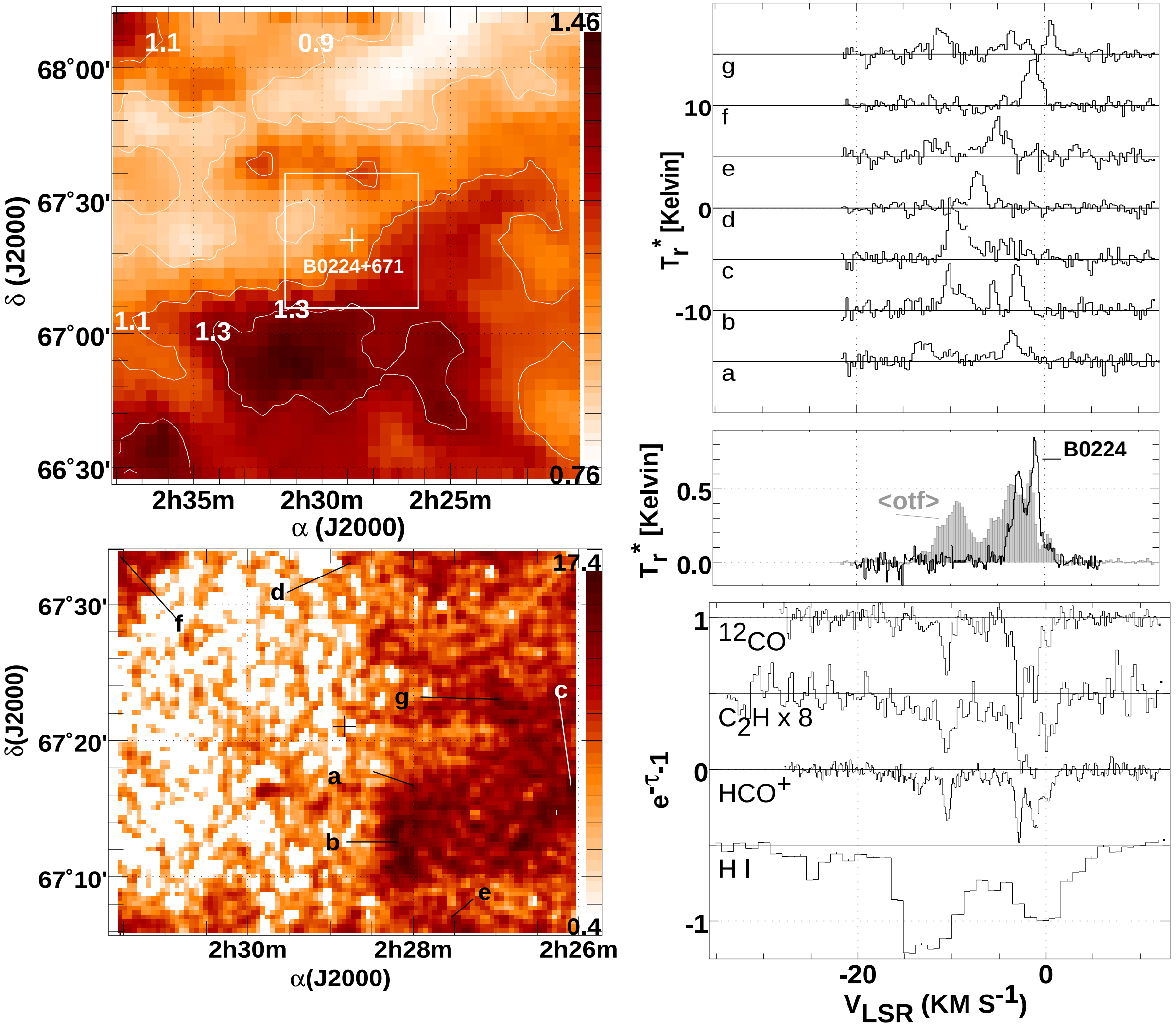
Reddening: 6′;

HI absorption: sub-arcsecond.

But tight correlation (correlation coefficient 0.9).

⇒ excellent mixing!

How do molecular and atomic gas mix? (Liszt & Pety, 2012, *A&A*)



- The ^{12}CO (J=1–0) emission spectra at distances as large as 15′ fills the velocity range of the absorption spectrum measured at an angular resolution of 1″.
- This was already emphasized in the analysis of turbulent simulations (Pety & Falgarone, 2000, *A&A*).