The CO-H_2 conversion factor of diffuse ISM : Bright 12CO emission also traces diffuse gas

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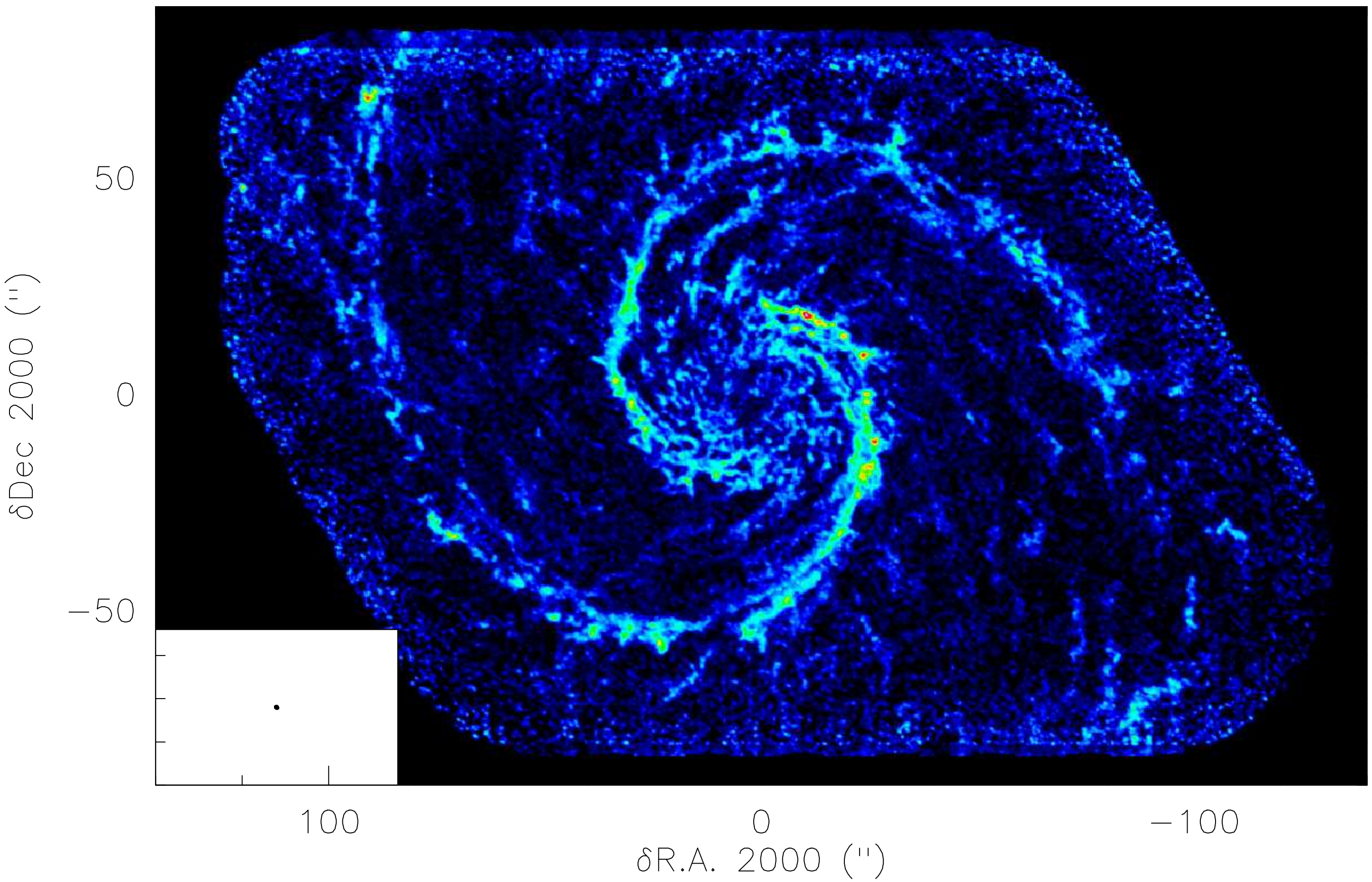
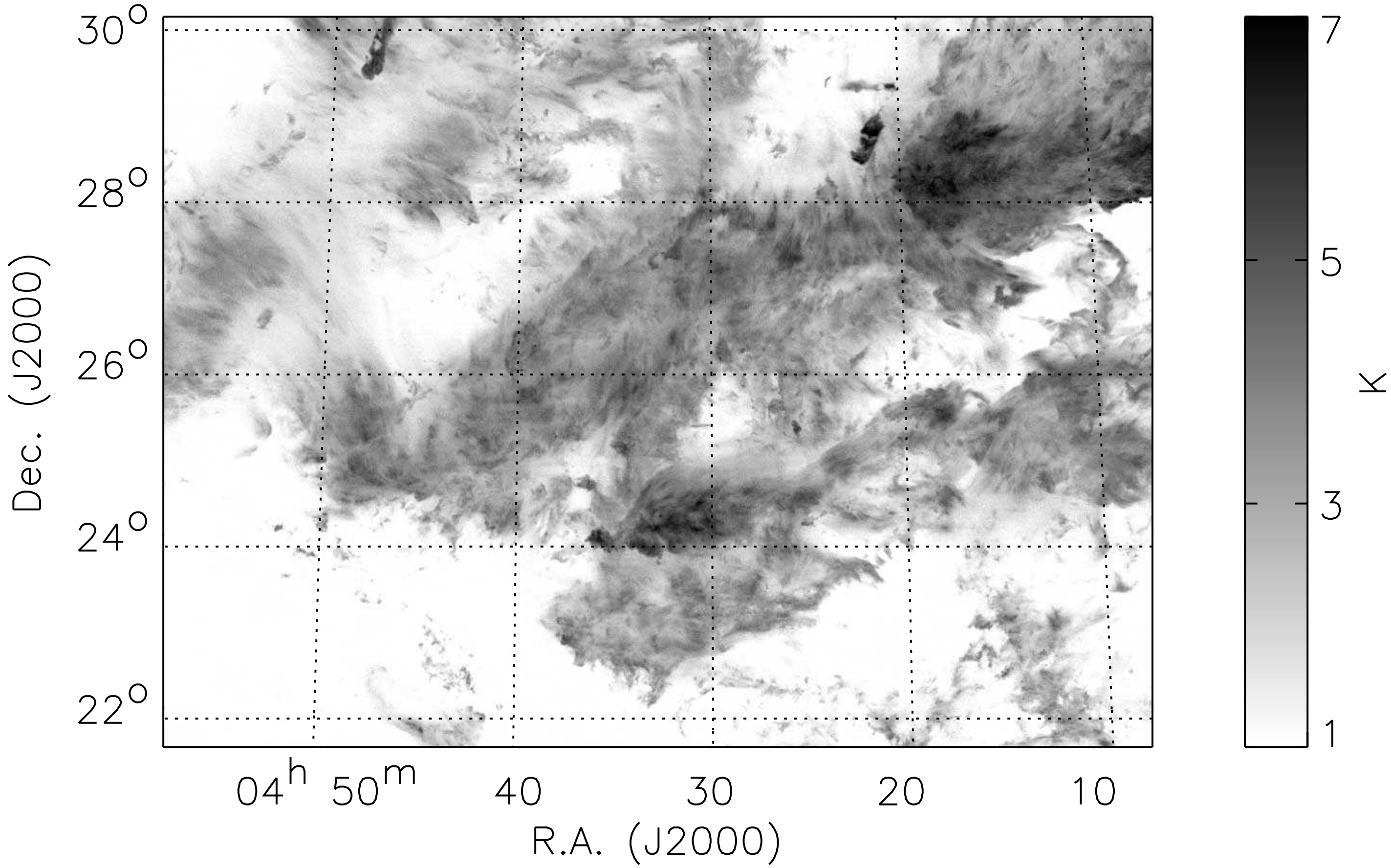
CO emission is often associated to cold (10-20 K), dense ($> 10^4\,\mathrm{cm}^{-3}$), strongly shielded, molecular gas (Carbon is locked in CO)

M51 as seen by PdBI+30m in ^{12}CO (J=1–0) (Schinnerer and the PAWS team)



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)



At beginning of the N_{H_2}/W_{CO} history (Young & Scoville 1982 and Liszt 1982), it was noted that diffuse and dense gas had similar ratio values.

Examples

A typical diffuse line of sight : ζOph

$N_{H_2} \simeq 5 \times 10^{20} H_2\,cm^{-2}$, and $W_{CO} = 1.5\,K\,km\,s^{-1}$

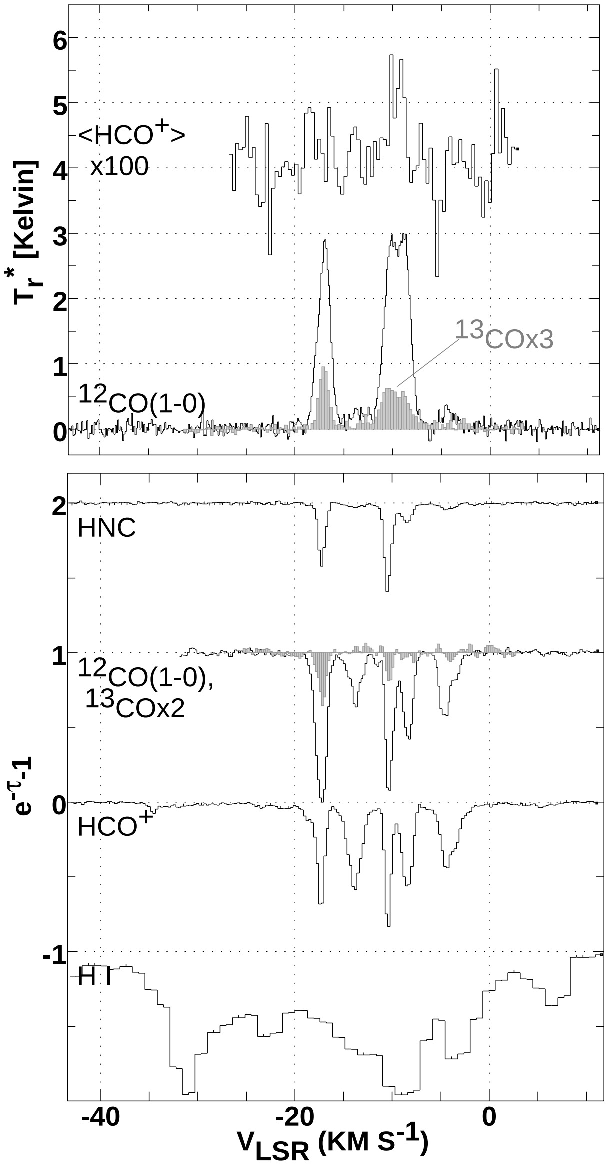
$\Rightarrow N_{H_2}/W_{CO} = 3.3 \times 10^{20} H_2\,cm^{-2}/(K\,km\,s^{-1})$

A typical dark cloud : Ori A

$N_{H_2} \simeq 2 \times 10^{23} H_2\,cm^{-2}$, and $W_{CO} = 450\,K\,km\,s^{-1}$

$\Rightarrow N_{H_2}/W_{CO} = 4.4 \times 10^{20} H_2\,cm^{-2}/(K\,km\,s^{-1})$

How to measure the mean N_{H_2}/W_{CO} conversion factor in diffuse gas?
1. Considering whole Galactic lines of sight



Absorption lines against extragalactic continuum background sources.

Here NRAO150 (pety et al. 2008)

Low CO column densities

$N_{CO} \lesssim 2 \times 10^{16}\,\text{cm}^{-3}$ ($\Rightarrow$ less than 7% of carbon in CO).

Either low extinction at $|b| \gtrsim 15 - 20°$.

Or multi-velocity components Total $A_V \sim 5\,\text{mag}$ but $A_V \lesssim 1\,\text{mag}$ per component.

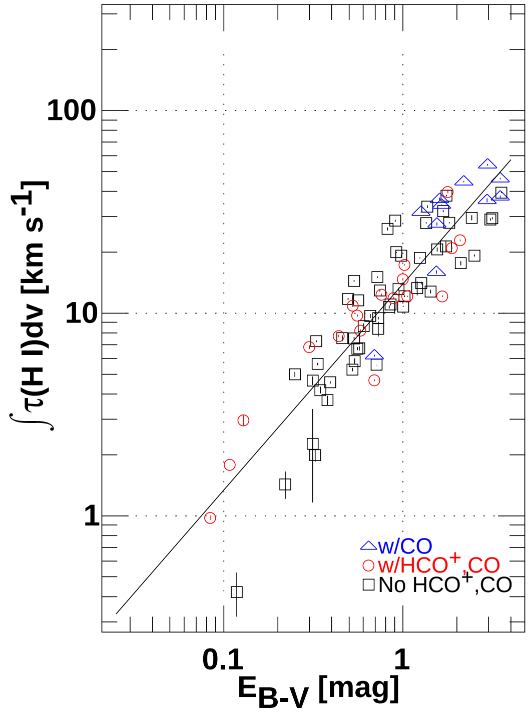
Total hydrogen column density from E_{B-V} extinction

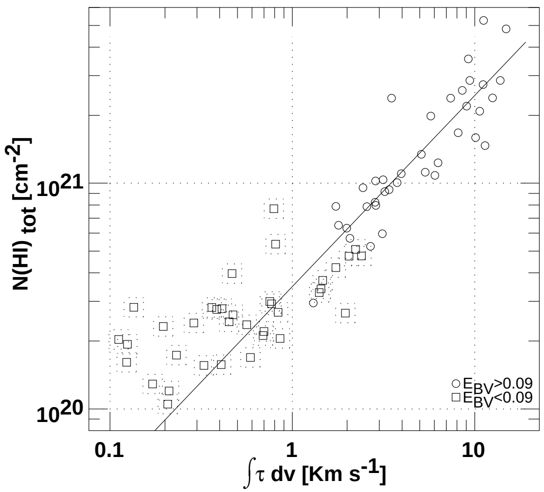
(Schlegel et al. 1998)

$N_H = N_{HI} + 2N_{H_2} = 5.8 \times 10^{21}\text{H}\,\text{cm}^{-2} E_{B-V}$

(Bohlin et al. 1978 and Rachford et al. 2009).

How to measure the mean N_{H_2}/W_{CO} conversion factor in diffuse gas ?
2. Estimating the atomic gas fraction via HI absorption





Methods $\langle f_{\rm HI}\rangle = \left\langle \frac{N_{HI}}{N_H} \right\rangle \sim \left\langle \frac{N_{HI}}{\int \tau_{\rm HI}\, dv} \right\rangle \times \left\langle \frac{\int \tau_{\rm HI}\, dv}{N_H} \right\rangle$ with

Top : $\left\langle \frac{\int \tau_{\rm HI}\, dv}{N_H} \right\rangle$ from the data.

Bottom : $\left\langle \frac{N_{HI}}{\int \tau_{\rm HI}\, dv} \right\rangle$ from Heiles & Troland (2003).

Remark HI absorbing gas is extremely well mixed in the interstellar gas because

Large difference in beam sizes

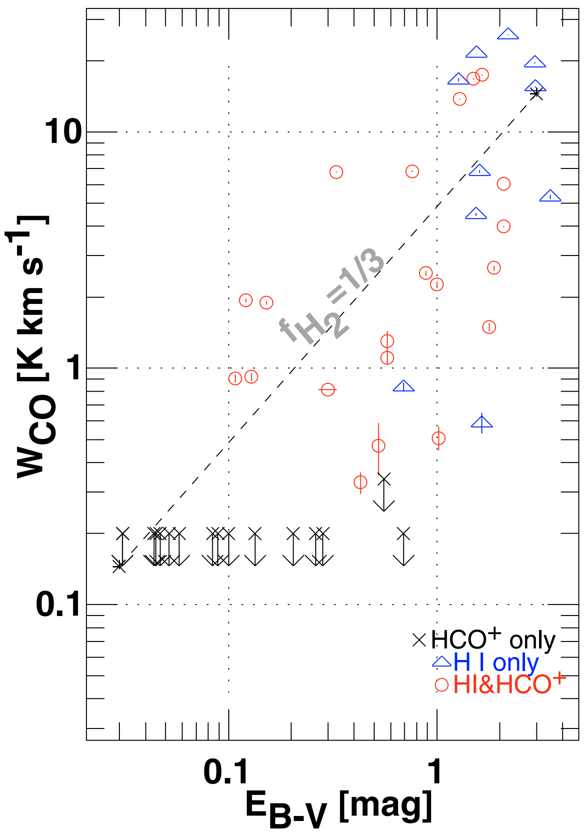
Reddening : 6′ ;

HI absorption : sub-arcsecond.

But tight correlation (correlation coefficient 0.9).

Results $\langle f_{\rm HI}\rangle = 0.65 \Rightarrow \langle f_{H_2}\rangle = 2N_{H_2}/N_H = 0.35.$

How to measure the mean N_{H_2}/W_{CO} conversion factor in diffuse gas ?
3. Measuring the CO luminosity



Comments

At low E_{B-V} (< 0.3 mag) **:** CO is not reliably detected
$\Rightarrow$ not counted.

At high W_{CO} (> 10 K) **:** Accumulation of several low-A_V components along the line of sight.

Computation of N_{H_2}/W_{CO}

$\langle W_{CO} \rangle = 4.4\,\mathrm{K\,km\,s^{-1}}$

$\langle E_{B-V} \rangle = 0.89$ mag

$\langle f_{H_2} \rangle = 0.35$

$\Rightarrow$ $N_{H_2}/W_{CO} = 2.04 \times 10^{20} H_2\,\mathrm{cm^{-2}}/(\mathrm{K\,km\,s^{-1}})$.

$\Rightarrow$ Same *mean* CO luminosity per H_2 in diffuse and dense gas !

Uncertainty In diffuse gas, $0.25 \le f_{H_2} \le 0.45$
$\Rightarrow$ 30% overall uncertainty on the method.

Why a common CO-H_2 conversion factor for diffuse and dense gas ?

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.

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).

LVG in 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).

Dense gas

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

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

Comparison with ISM models (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}.

How to discriminate diffuse from dense gas ?

^{12}CO alone can not be used ⇒ which other tracers ?

Usual way Molecules with higher dipole moments ?

Example HCO^+, CS, HCN.

Problem Difficult to detect.

A better way ? CO isotopologues, *i.e.* ^{12}CO and ^{13}CO (easier to detect).

Diffuse, warm gas $T_{^{12}CO}/T_{^{13}CO} \gtrsim 10-15$ (*e.g.* Liszt & Lucas 1998).

Dense, cold gas $T_{^{12}CO}/T_{^{13}CO} \lesssim 3-5$ (*e.g.* Burton & Gordon 1978).

What is the proportion of CO emission arising from diffuse gas in our Galaxy ?

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

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

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

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

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

Comparison with Galactic surveys of CO emission

Mean CO brightness per kpc $5\,\mathrm{K\,km\,s^{-1}/\,kpc}$ 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

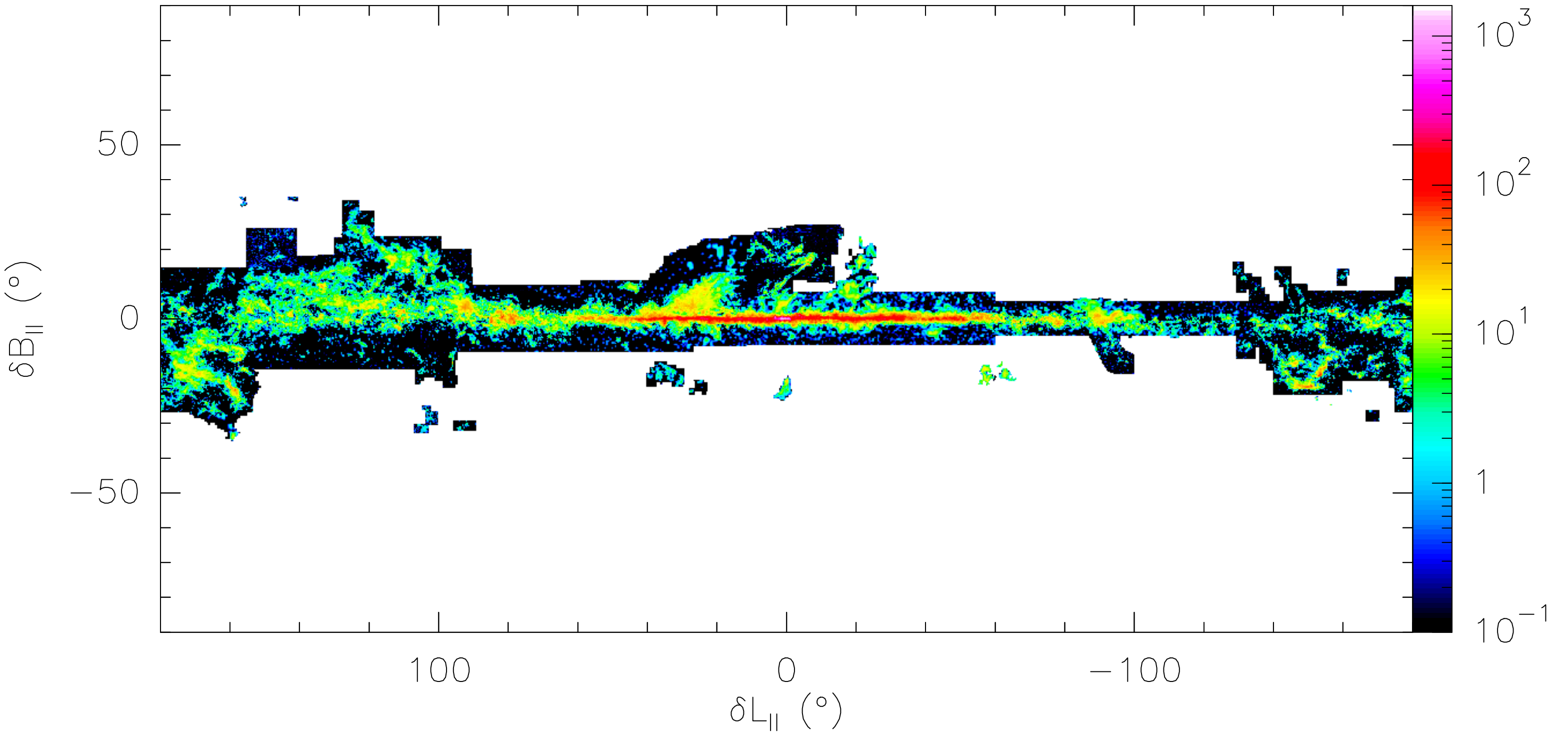
Local ISM geometry Bubble ;

Scatter from long mean free paths.

$\Rightarrow$ A large fraction of CO emission could come from diffuse gas.

Is the molecular diffuse gas a distinguishable component of the local CO emission near the Galactic plane ?

Dame, Hartman & Thaddeus



We still miss an all-sky survey of CO.

Interpreting a sky occupied by CO emission from diffuse gas

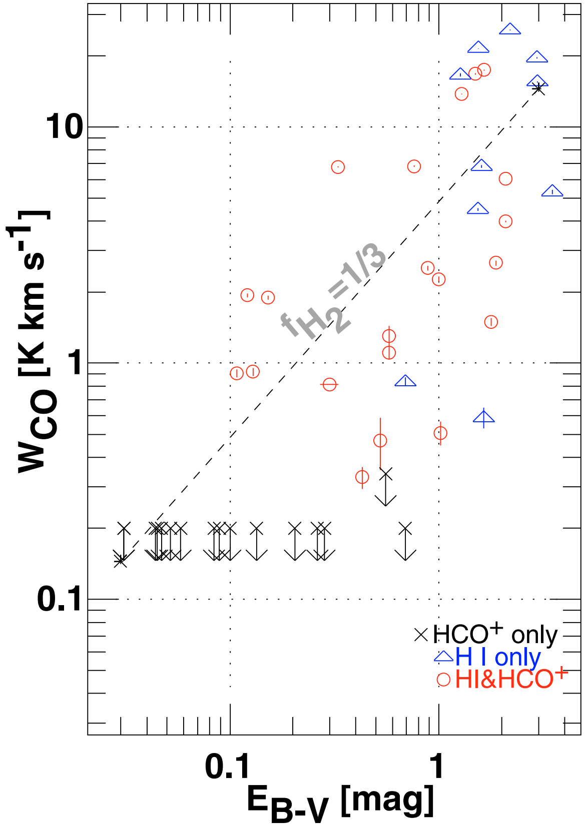
Correct mass estimates (for CO traced gas),

But different physical interpretation !

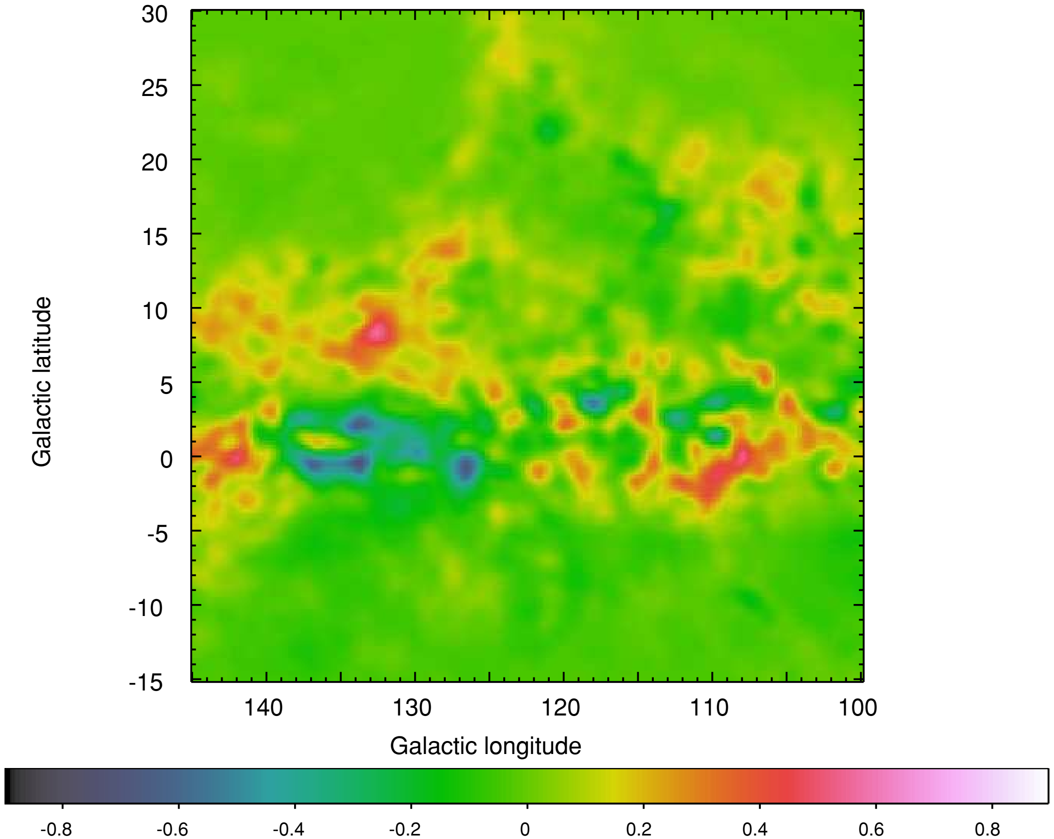
- **If dense gas :** small fraction of the ism volume, confined by ram or turbulent pressure, if not gravitationally bound, on the verge of forming star.
- **If diffuse gas :** warmer, low pressure medium filling a large fraction of the ism volume, contributed more to mid-IR dust or PAH emission, probably not gravitationally bound or about to form stars.

Liszt, Pety & Lucas, A&A, 518, A45

Diffuse vs Dark gas



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



Abdo et al. 2010 $E_{\rm B-V}$ residuals after subtraction of N(HI) and $W_{\rm CO}$ components ⇒ dark gas.