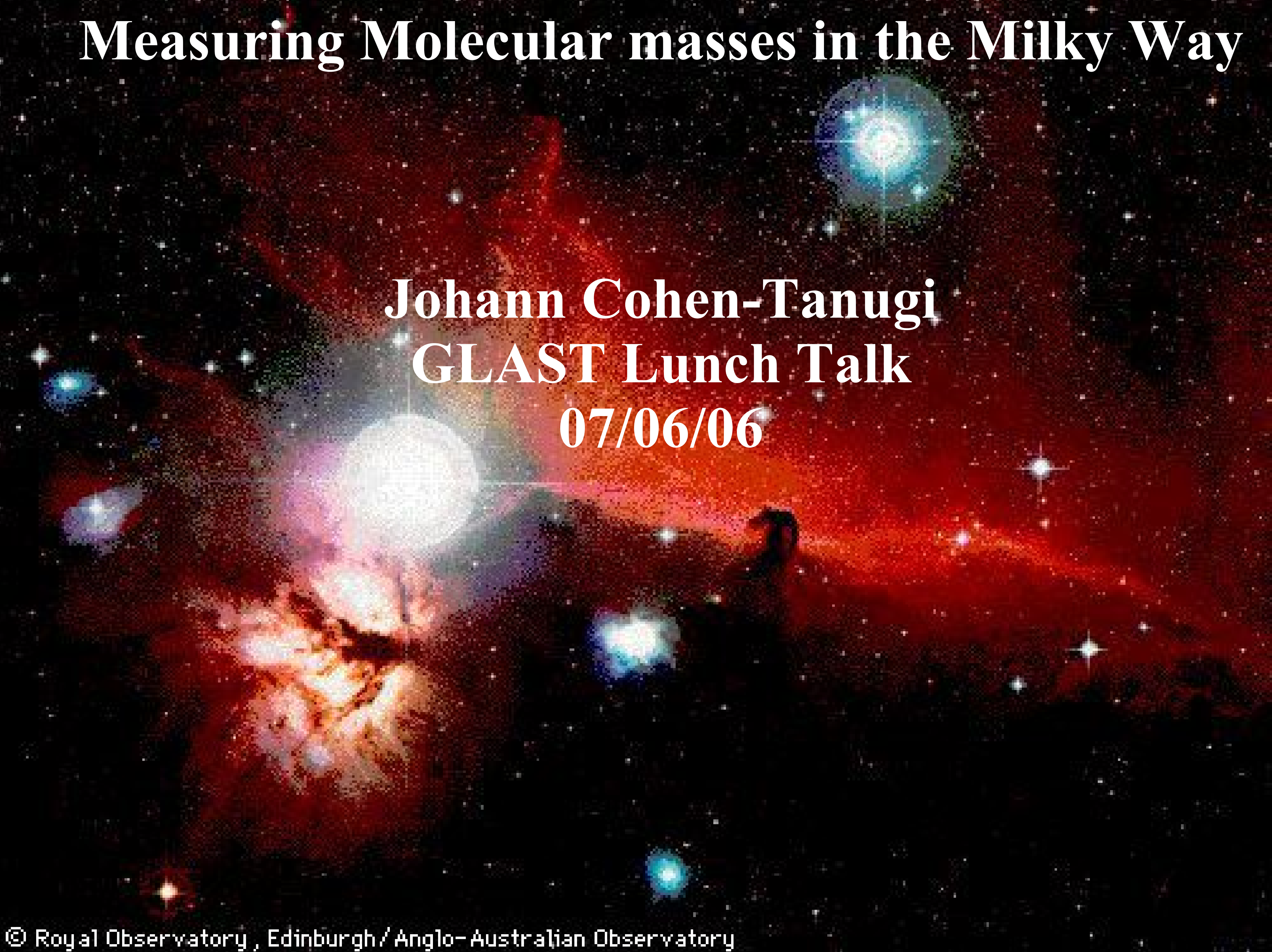
Measuring Molecular masses in the Milky Way

Johann Cohen-Tanugi

GLAST Lunch Talk

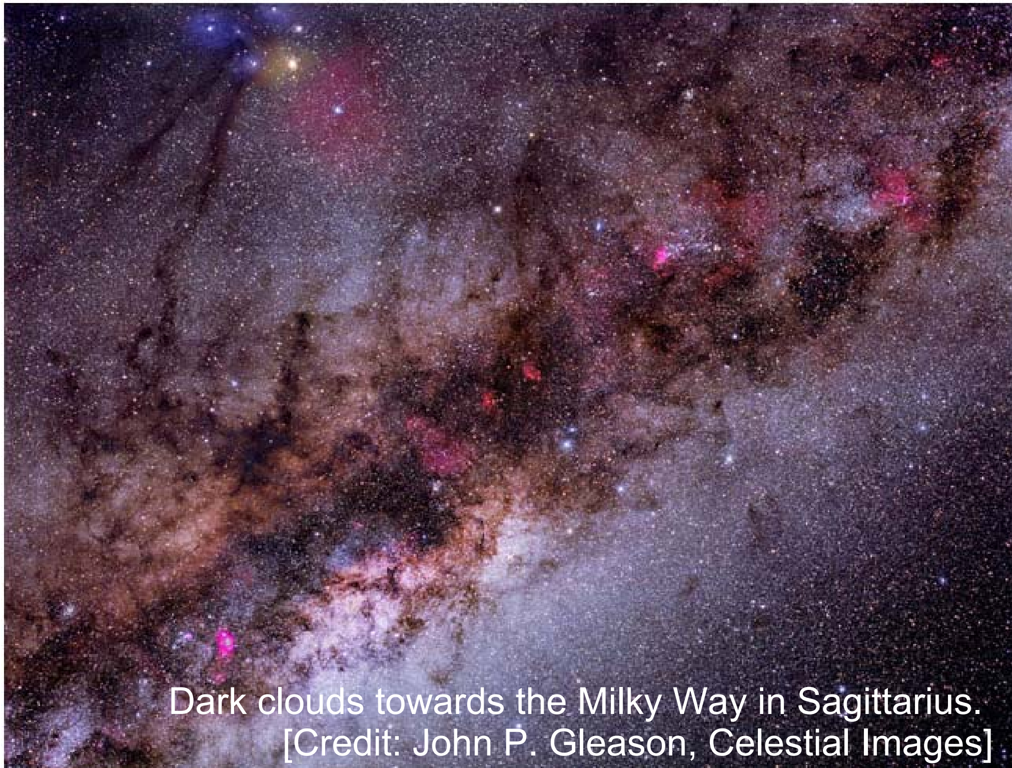
07/06/06



What are molecular clouds?

Interstellar regions that are cold, dense, and big enough to allow the formation of molecules and shield them from dissociating radiation from nearby stars.

- T~10-50K range, density>10^3cm^{-3}
- ~50% of the mass of the ISM, in ~1% of its volume
- H_2 by far dominant, followed by HI, He, and CO



Dark clouds towards the Milky Way in Sagittarius.
[Credit: John P. Gleason, Celestial Images]

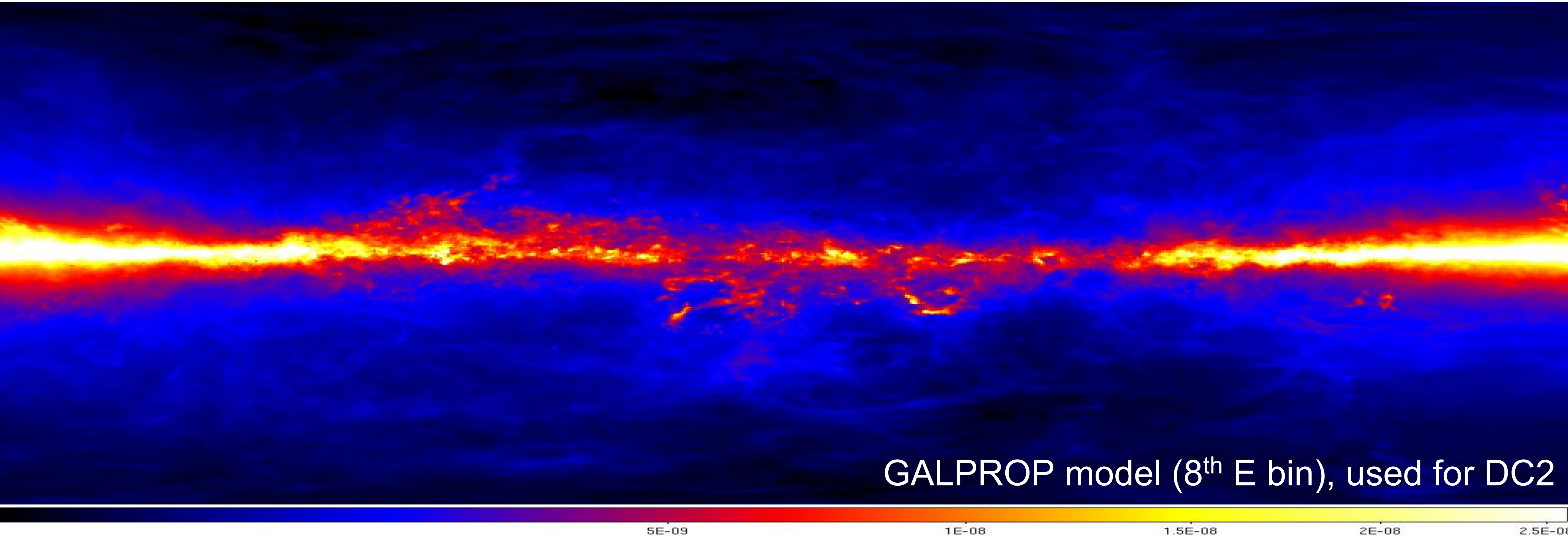
Other features :

- region of star formation (for the largest : Giant Molecular Clouds)
- preferentially in the arms of a galaxy
- contains dust (optical absorber)
- highly turbulent, and very clumpy

Why do I ruin your lunch break with them?

- **The galactic diffuse emission that the LAT will see comes predominantly from cosmic ray-molecular cloud interactions (enhanced p-p emission)**

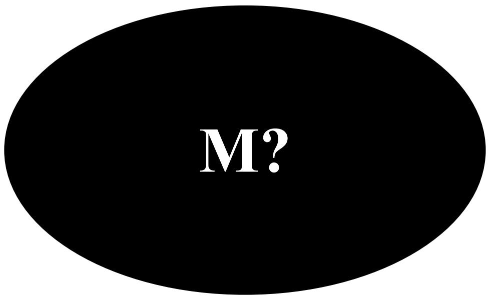
We need to know where the clouds are to model the expected diffuse map



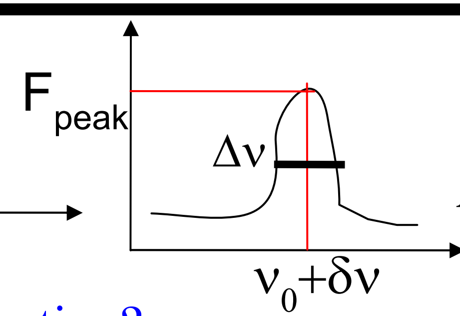
GALPROP model (8th E bin), used for DC2

- **GLAST can actually add information to the understanding of molecular clouds, as we will see later**

What to do with a line feature?



optical depth?
chemical distribution?
equilibrium state?



Doppler effect along the line of sight : $\delta\nu=\beta\nu_0$ where $\beta=\langle v\rangle/c$.
At worse, $\delta\nu/\nu_0 \sim 10^{-4}$ No problem...
With a galactic velocity curve → distance estimate to the cloud

- Galactic radial distribution from CO emission is worth another talk...
- ν_0, transition rates, etc..., are 'lab' constants.
- Usage is to express everything in velocity and not frequency : the width of the line is key to understanding the 'state' of the cloud :
  - dominated by Doppler broadening (thermal, collisional, and/or turbulent)
- The rule of the game : extract M (or $N(H_2)$) from the line profile and intensity :
  - Cloud opaque? Then the line observation does not probe the whole cloud....
  - Collision rate << radiative emission ? Then the emitting component is not thermalized... (concept of critical density, see later)

Tricky business...

How to go home early : Virial Analysis

- **Assume that :**
  - **the gas motions of a cloud are confined solely by its gravitational attraction**
  - **A spherical mass distribution with a density profile $\propto \rho^{-n}$**

$$M_{vir} = \frac{5-2n}{3-n}\,\frac{R\,\square^{2}}{G}$$

with $\sigma^2 = \langle v^2 \rangle$ **DONE!**

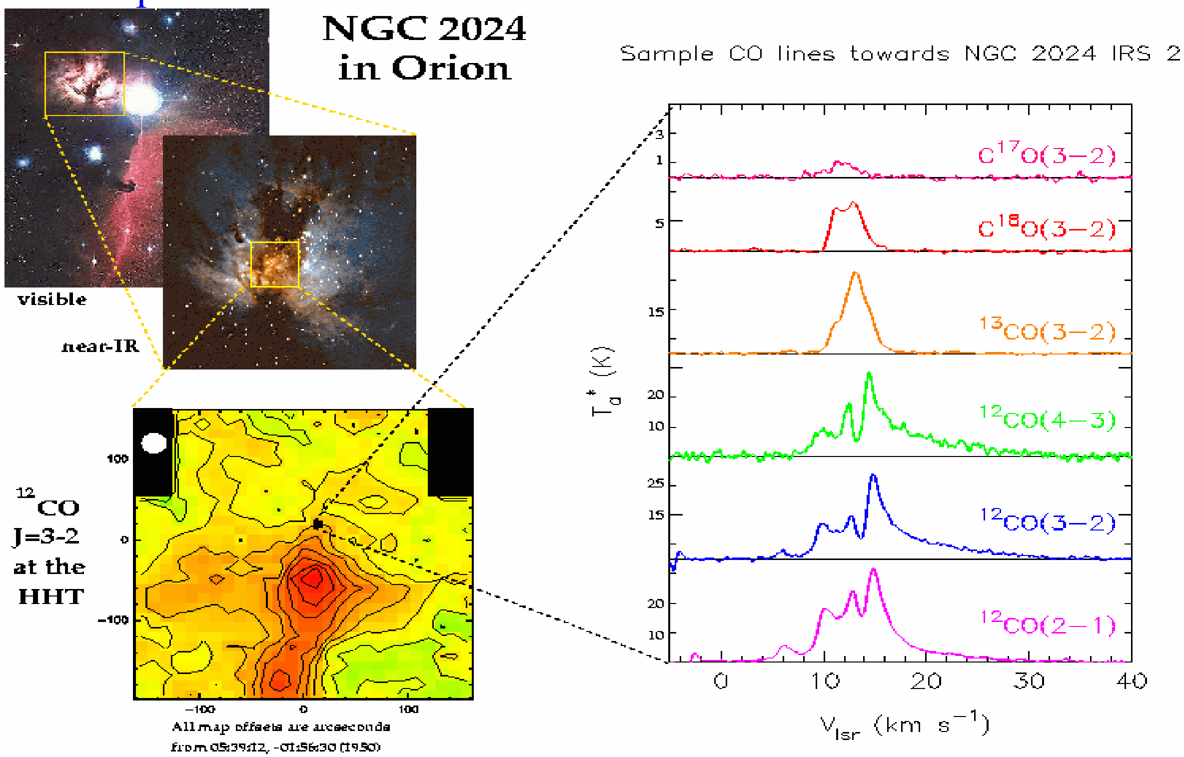
Not quite...

- **Cloud support : magnetic force, turbulence, thermal motions?**
  - **thermal velocities << observed velocities → turbulent field (or self-gravity)**
- **Star formation region : internal photon fields, etc...**
  - **MCs formed from atomic clouds, triggered by an event that compresses the atomic gas and increases the visual extinction, thus increasing formation rate and decreasing destruction rate of H_2 → hardly a sterile static blob of self-gravitating stuff...**
- **Still, for the largest clouds (GMC), might be a more reasonable hypothesis.... Anyway, you need lines to get R and σ^2!**

...and the most conspicuous is the CO rotational line...

Observations of the CO line

from http://loke.as.arizona.edu/~ckulesa/research/submm.html



- **Studies of GMCs in the solar neighborhood have shown a linear relationship between CO luminosity and the mass of the GMC, using a Viral Analysis.**
- **Typical (early) values of this ratio:**
  $X = \sim 2\ 10^{20}\ cm^{-2}\ s^{-1}\ (K\ km\ s^{-1})^{-1}$

- **Radio convention : express intensity in Brightness Temperature** $T_B \equiv \frac{c^2}{2h\nu^2} I_\nu$
  - **Source in LTE in the Raleigh-Jeans regime : T_B=T (removes the ν-dependence)**
- **Define $I_{CO} = \int T_B dv$**
- **By definition $X = N(H_2)/I_{CO}$ (or $X = M(H_2)/L_{CO}$)**
- **If we want to estimate H_2 mass distribution from X and I_{CO}, we need to understand what I_{CO} measures and how X varies**

CO observations of the Milky Way (Dame et al. 2001)

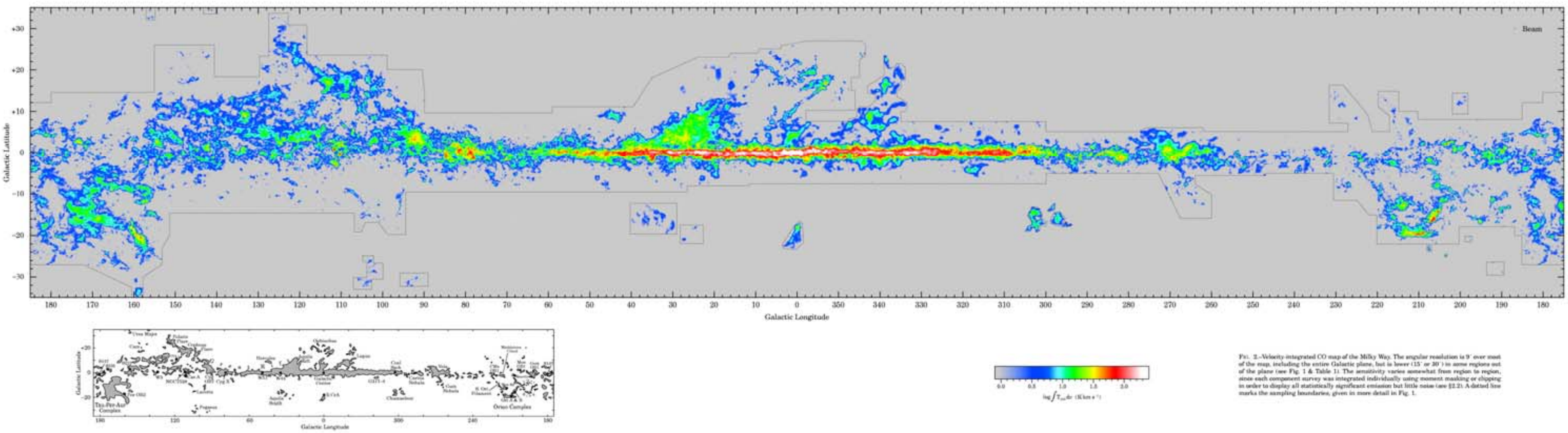


FIG. 2.—Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

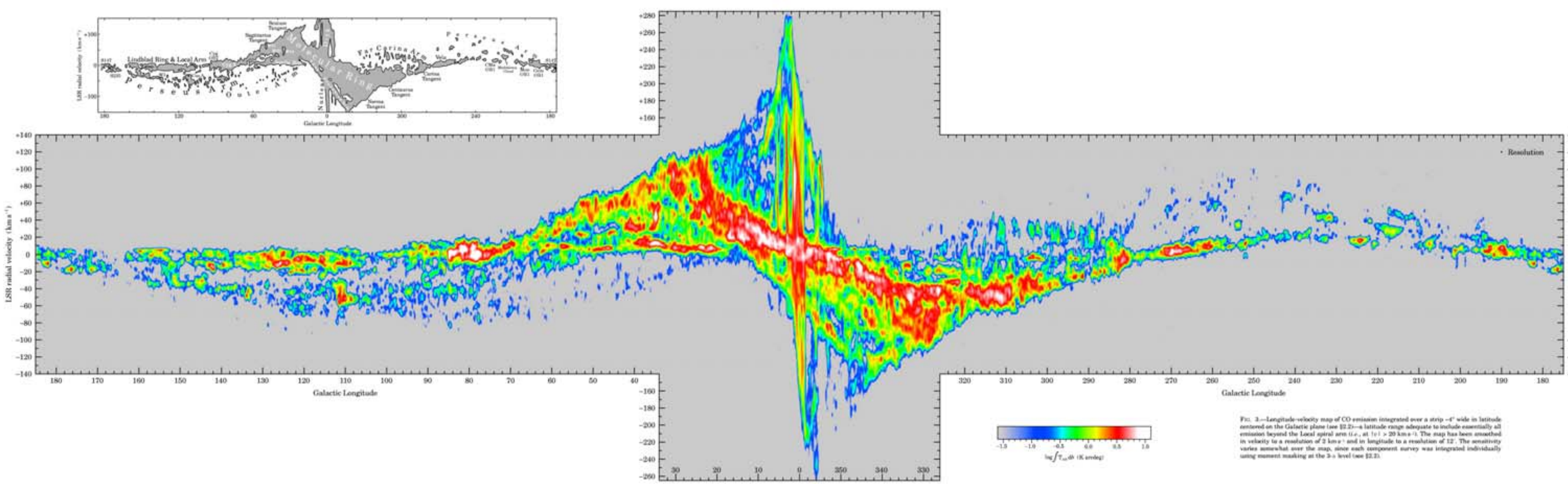
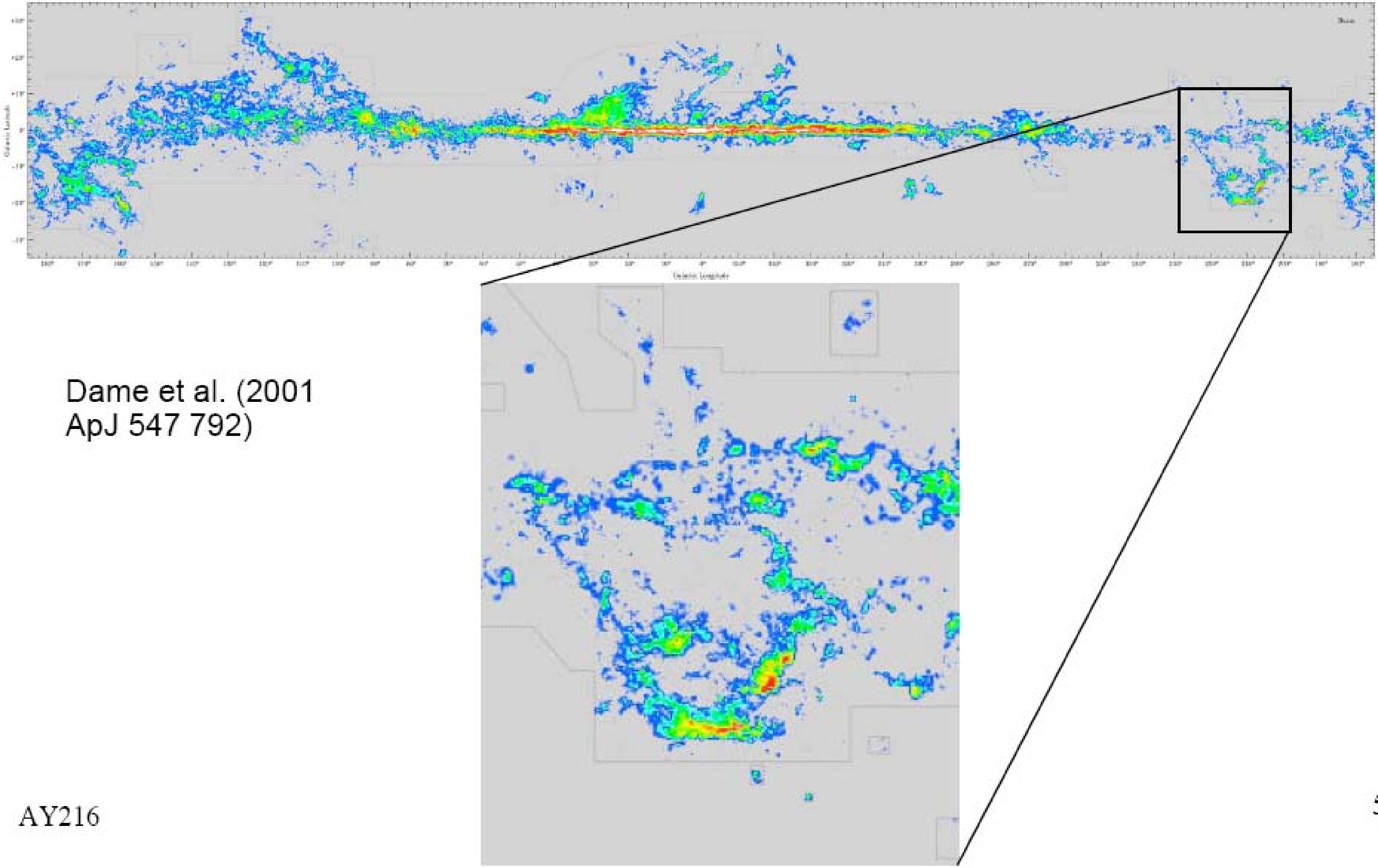


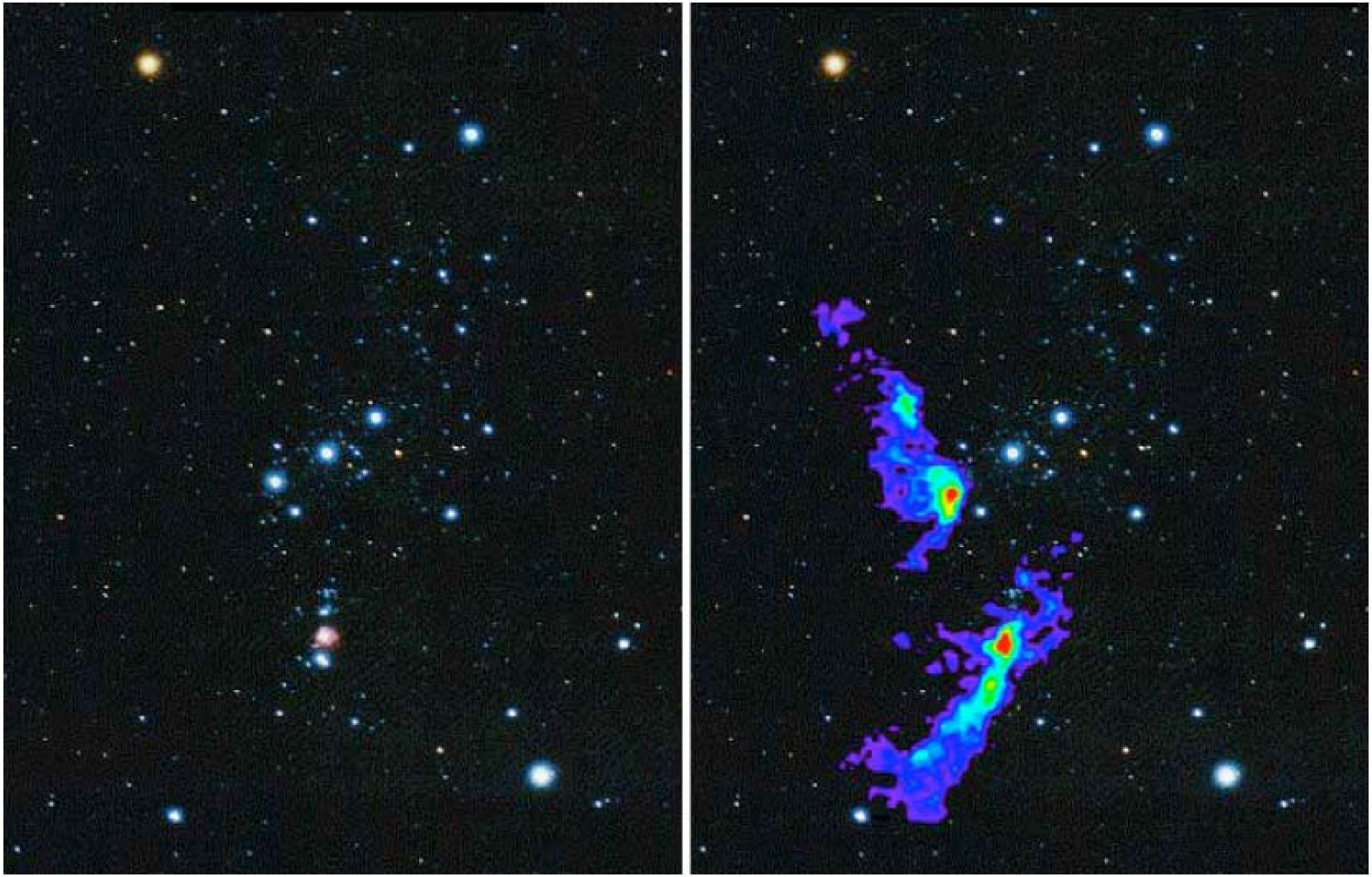
FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (i.e., at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-σ level (see §2.2).

Local GMCs Orion A & B

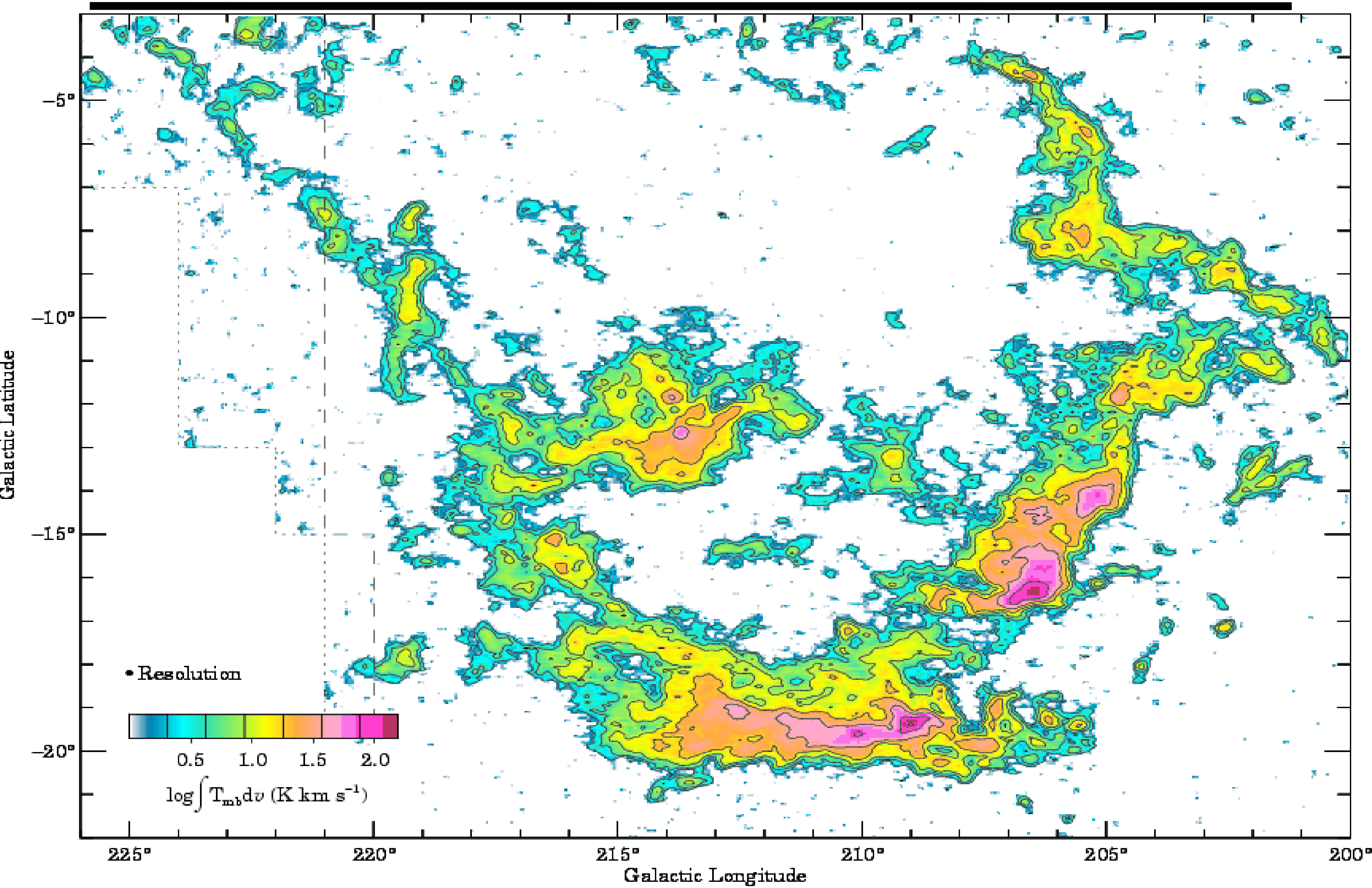


Dame et al. (2001
ApJ 547 792)

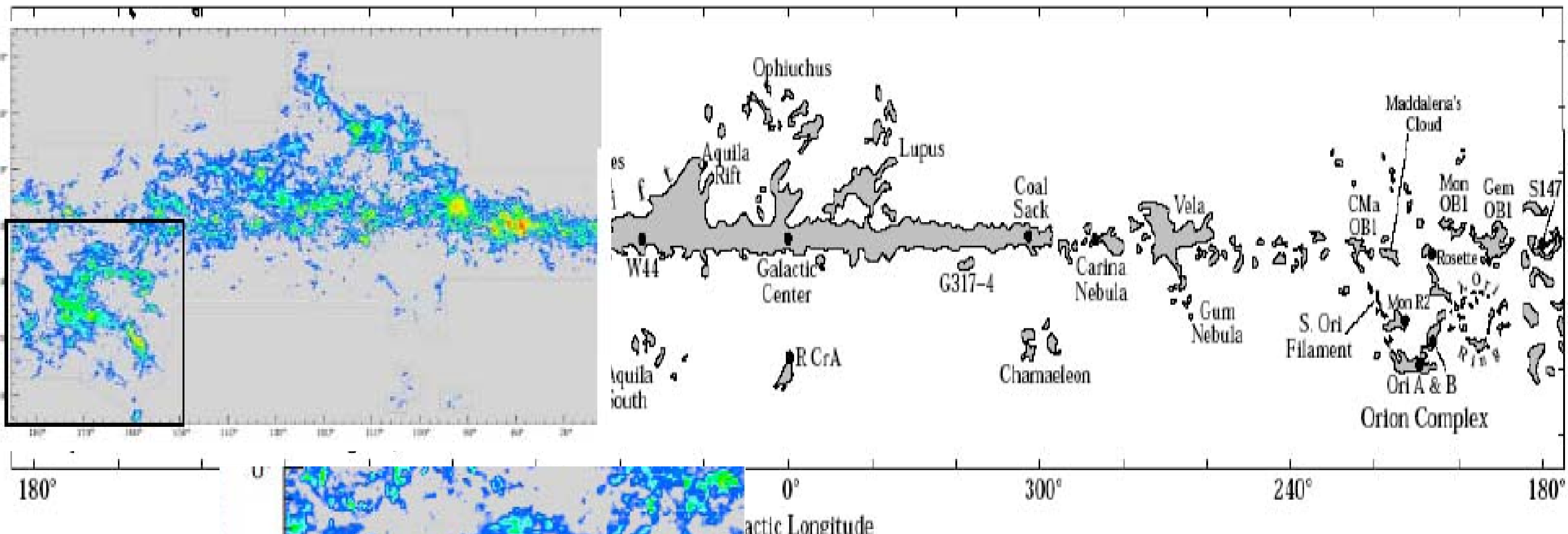
Orion in CO

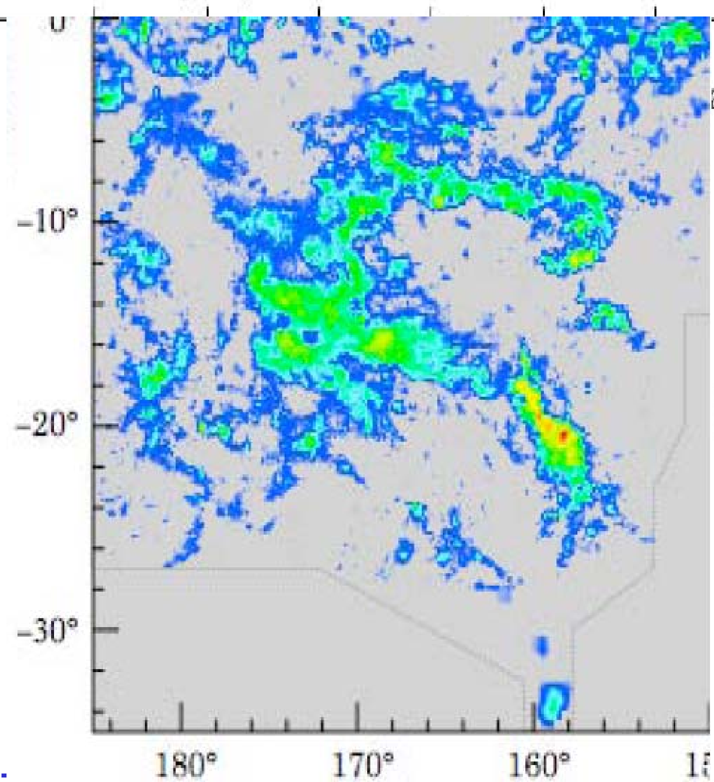


Orion again, from Wilson et al., A&A 430, 523-539 (2005)



Taurus - Perseus - Auriga





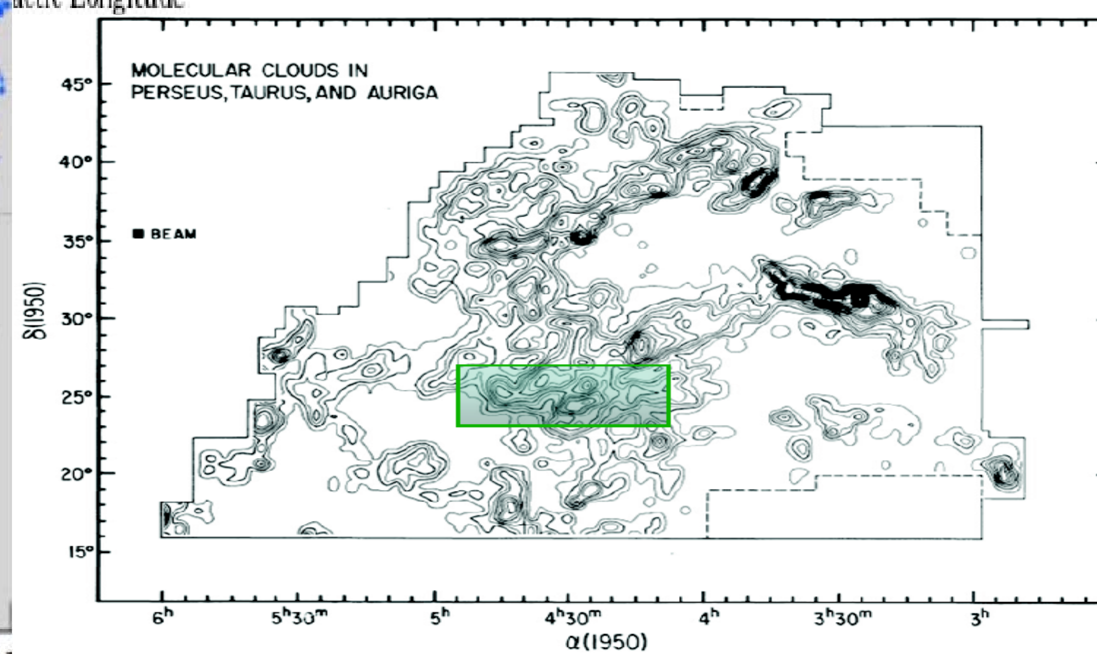
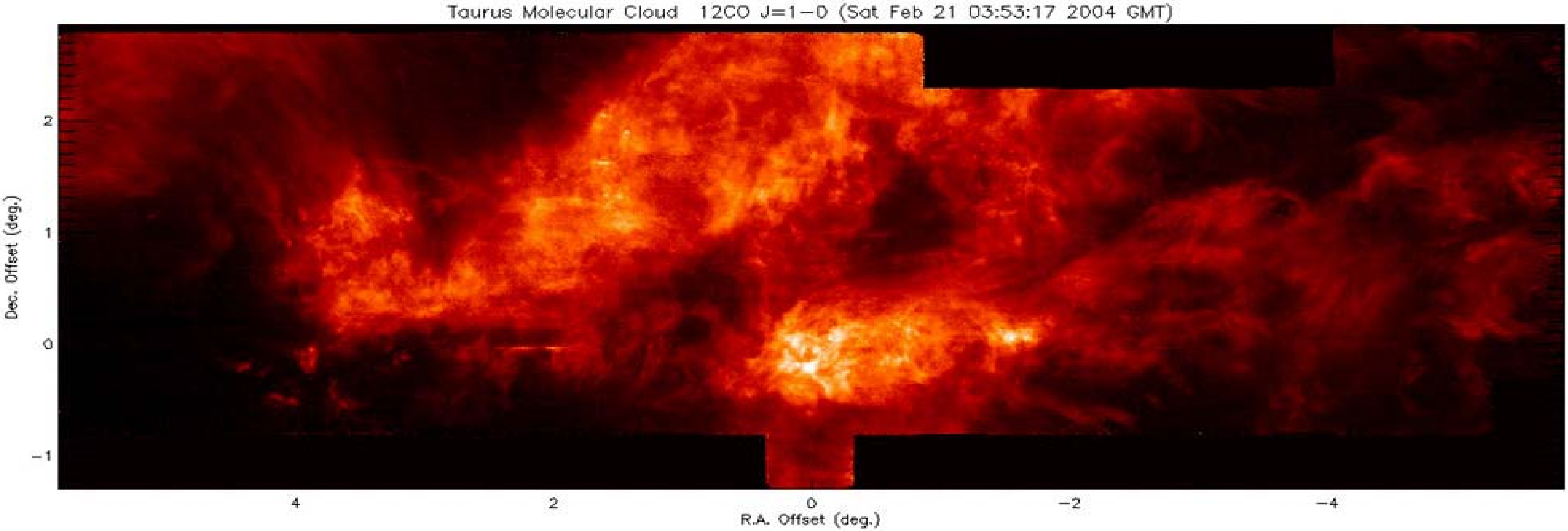
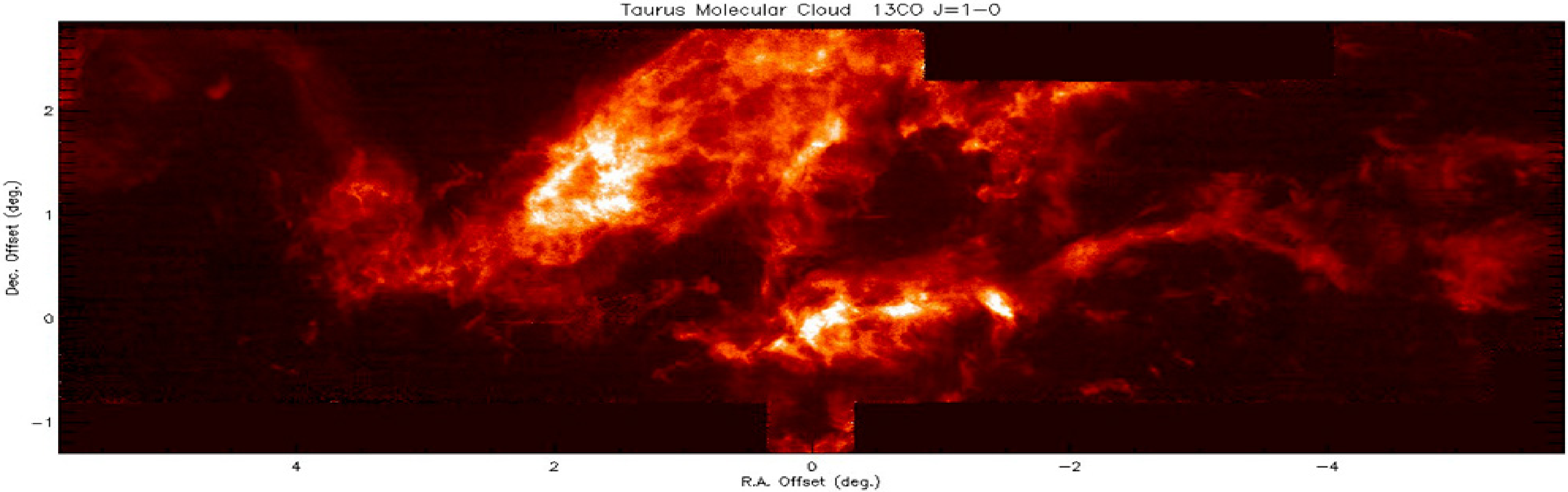


FIG. 1.—Velocity-integrated intensity of CO emission, W_{CO}. The lowest contour is 0.5 K km s^{-1}, and the separation between contours is 1.5 K km s^{-1}. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of $4^m \times 1°$.

TMC in ^{12}CO and ^{13}CO FCRAO 14 m (HPBW 50'')





Rotational Transitions

- **Rotational line emission :**
  - **quantify the angular momentum in the usual way :** $L^2 = J \square J \square 1 \square\square^2$
  - **Semi classical rigid rotator :** $I = \square m_i r_i^2$

$$E_j = \frac{M^2}{2\mathrm{I}} \quad \square \quad \square E_j = \frac{\square^2 J}{I}$$

  - **In order to have a reasonable transition rate, the molecule needs to have a permanent dipole moment**

- **Einstein A coefficient ~ probability of de-excitation per unit time :**

$$A^{-1}_{J \square 1, J} \sim \frac{E}{P} = \frac{\square\square_0}{\frac{2e^2 \ddot{x}^2}{3c^3}} \quad \square \quad A_{J \square 1, J} \sim \frac{2\mathrm{d}^2 \square_0^3}{3 \square c^3}$$

where d is the transition dipole moment (actually depends on J) and we use an oscillator model

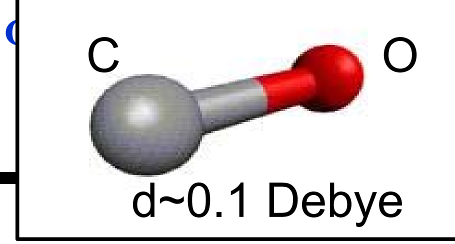
rotational transitions with H_2

- H_2 has three drawbacks :
  - no permanent dipole moment : rate is very weak (quadrupole term in the perturbation analysis : $\mu \approx 3.10^{-6}$ Debye)
  - transition levels widely spaced : weak emissivity and needs warm medium (>~70K) observed in IR -> not well suited to study cold dense MCs
  - selection rules due to non-discernability apply : $\Delta J=2$ (ortho/para)

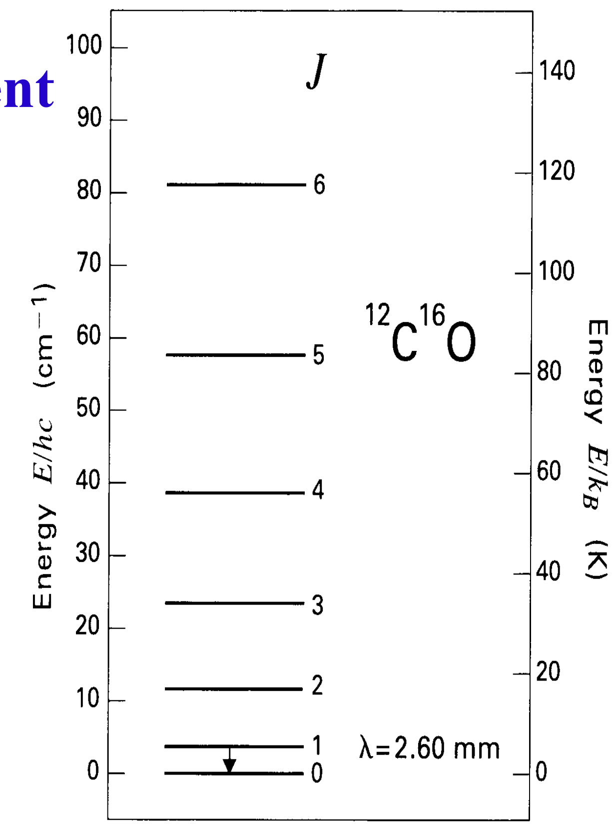
Species	Transition	ν (GHz)	E_u (K)	A (s^{-1})	n_{cr}(cm^{-3})
$^1H_2$	2-0	10,623.8	510	2.9×10^{-11}	10
	3-1	17,598.8	1015	4.8×10^{-10}	300

- <u>Quadrupole transitions</u> : ISO observations of H_2 rotation lines at 28.2 and 17.0 µm
  - in a few extragalactic star forming regions
  - in the NGC 891 galaxy (Valentijn and P.P van der Werf 1999)
  - in 6 other galaxies (Dale et al. 2005)
- Punch Line : most of the unseen mass in such galaxies would be H_2, aka.... baryonic (topic for another GLAST lunch?)

The CO proxy

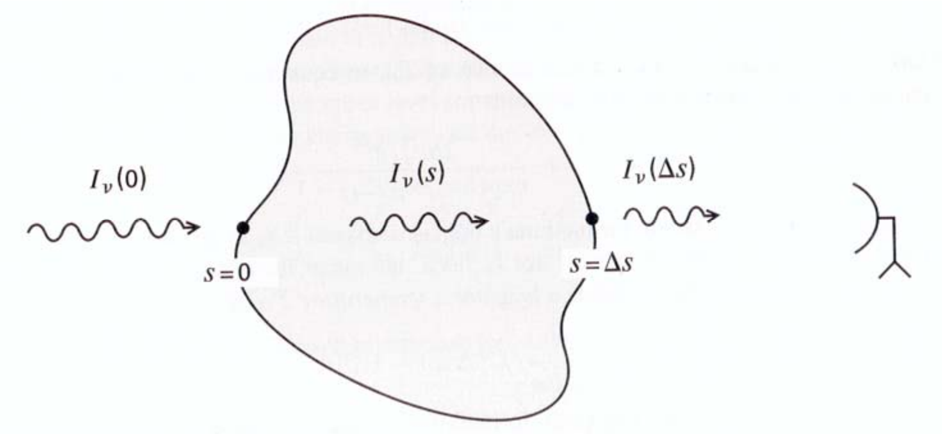


- **In principle a good tracer of H_2**
  - **Forms through gas phase reaction catalyzed by dust... like H_2**
  - **In MCs excitations are mainly due collisions with H_2 → strong correlation of excitation transitions with quantity of H_2 around?**
- **Pros :**
  - **First level at 4.8 10^{-4}eV (5.5K)**
    - **Raleigh-Jeans approx still OK for 1st transition**
  - **most abundant after H_2**
    - **Strong binding energy of 11.1 eV helps to prevent much further destruction (self-shielding)**
  - **High emission rate (A) (actually not so good)**
  - **N_{cr} still ~OK to apply Boltzmann law**



Species	Transition	ν (GHz)	E_u (K)	A (s^{-1})	n_{cr}(cm^{-3})
$^{12}C^{16}O$	1-0	115.271	5.5	7.2×10^{-8}	1100
	2-1	230.538	16.6	6.9×10^{-7}	6700
	3-2	345.795	33.2	2.5×10^{-6}	21,000

Radiation Transfer (I)



Radiative Transfer Equation

$$dI_\nu = -\kappa_\nu I_\nu ds + \epsilon_\nu ds = I_\nu d\tau_\nu - S_\nu$$

with

$d\tau_\nu = -\kappa_\nu ds$ Optical depth

$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu}$ Source function

Assuming a constant source function : $I_\nu(\tau_\nu) = S_\nu(1 - e^{-\tau_\nu}) + I_\nu(0)e^{-\tau_\nu}$

For a uniform cloud in LTE :

$$S_\nu \equiv B_\nu(T) = \frac{2h\nu^3}{c^2}\left(e^{\frac{h\nu}{kT}} - 1\right)^{-1} \sim \frac{2k\nu^2}{c^2}T$$ in Raleigh-Jeans limit (hν « kT)

Optically thick limit : $T_B \sim T$ → line intensity measures the Temperature
Optically thin limit : $T_B \sim \tau_\nu T$ → line intensity measures the molecule N_{col}

If not in LTE, still can define the excitation temperature T_{ex} : $\frac{n_{J+1}}{n_J} = \frac{g_{J+1}}{g_J} e^{-\frac{\Delta E}{k_B T_{ex}}}$

If the 2 levels are in equilibrium, we also have $S_\nu = B_\nu(T_{ex})$ and the radiative transfer equation becomes

→ Replace T by T_{ex}

$$\Delta T_B = (1 - e^{-\tau})(T_{ex} - T(0))$$

Collisional excitations

- Consider a system (CO) with 2 levels u and l spaced by $\Delta E_{ul}=h\nu$.
  - assume that transitions are triggered by a collision partner (H_2) of volume density n
  - γ_{ul} : u→l rate per second per CO per H_2. Likewise γ_{lu}.
  - A_{ul} : rate of spontaneous de-excitation
- Detailed balance for a steady state situation : $n_l(\gamma_{lu} n) = n_u(\gamma_{ul} n + A_{ul})$

⇒

$$n_{tot}\,\gamma_{lu} = n_u\,\gamma_{ul}\left[1+\frac{\gamma_{lu}}{\gamma_{ul}}+\frac{n_{crit}}{n}\right] \quad where \quad n_{tot}=n_u+n_l\,,\; n_{crit}=\frac{A_{ul}}{\gamma_{ul}}$$

- n_{crit} **indicates at what density collisions can keep up with spontaneous radiative processes**

$$n \gg n_{crit} \Rightarrow n_l\,\gamma_{lu} \approx n_u\,\gamma_{ul} \quad which\ means\ that\ populations\ u,l\ are\ thermalized\ at\ T_{kin}\ \ such\ that\ \frac{n_u}{n_l}=\frac{g_u}{g_l}e^{-\frac{h\nu}{kT_{kin}}}$$

$$n \ll n_{crit} \Rightarrow n_l\,\gamma_{lu} \approx n_u\,\gamma_{ul}\frac{n_{crit}}{n} \Rightarrow \frac{n_u}{n_l} \sim \left(\frac{n}{n_{crit}}\right)\left(\frac{n_u}{n_l}\right)_{thermal}$$

The spontaneous radiation is faster than collisions, and each collision l→u leads to photon emission. The population is sub-thermal.

The CO Proxy : Caveats ... and a hand-waving way out

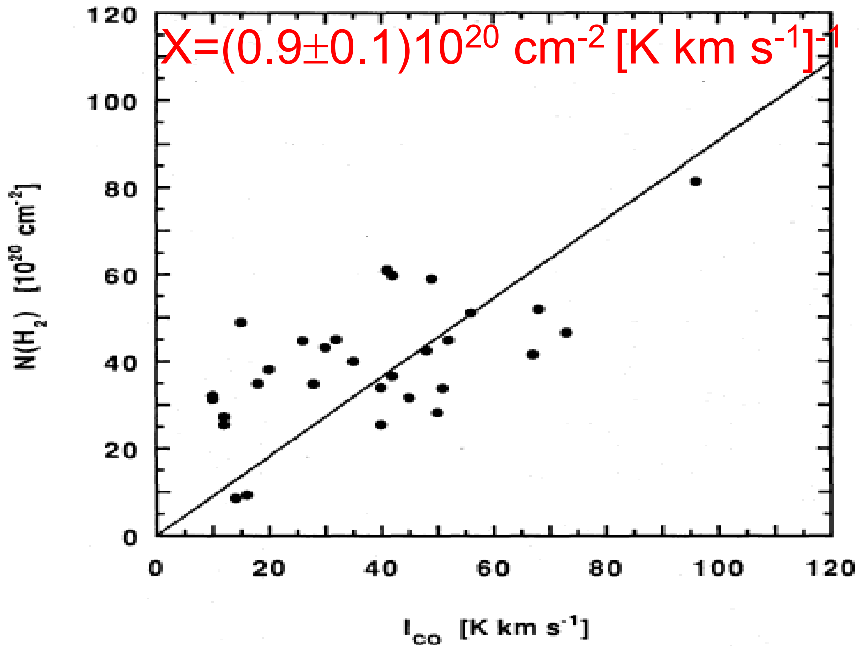
- low abundance of CO is mitigated by high Einstein A parameter :
  - The line is optically thick in most MCs situations
  - Need to resort to higher transitions (→ warmer medium) or isotope molecules (like ^{13}CO) → a new mass ratio to determine!
- lifetime of rotationally excited levels relatively short : unless gas density and collision frequency are high, the Boltzmann state distribution might not hold.
- Still, on can hope that I_{CO}□💣✱ ♓■ ♋●● ♍♋♦♏♦ ☎➚❒❑❍ 👌♓■■♏⌧🕮💣✱♏❒❒♓➚♓♏●♎◗💻

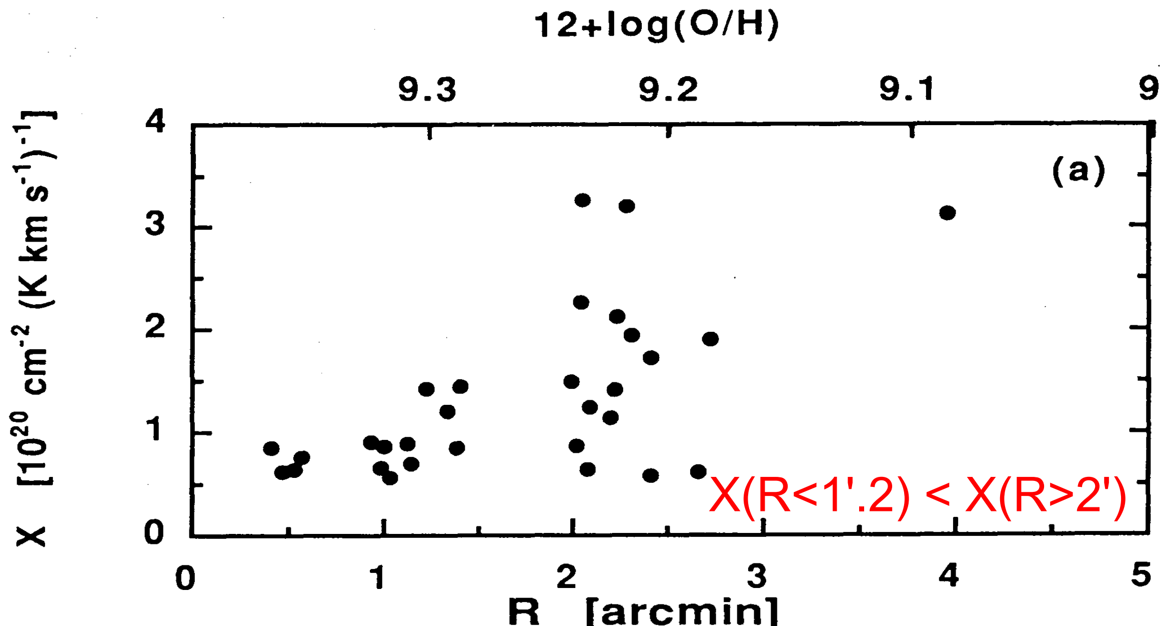
- Start with the observation that clouds are clumpy/filamentary;
- Model the MC as a sphere with many cloudlets inside;
- Each cloudlet will contribute the same amount to I_{CO}
- Unless there is significant shadowing (behind the thick portion of a cloudlet there is another one with a velocity that differs from the first by less than ~2x the velocity width of the line), then counts the number of clouds in the beam area.
- If the clouds are all the same, I_{CO}□ #cloudlets □ M
- With a Virial analysis, I_{CO}□ M even if shadowing is important.

More refined simulations by Wolfire, Hollenbach and Tielens (1993) seem to point to the same direction.....

Determining X : dust extinction (Nakai and Kuno 1995)

- From Van der Hulst et al. (1988) :
  - Visual extinction A_V from HII regions
    - by comparing radio and Hα fluxes
    - corrected by Nakai, Kuno to depend on radius
  - N(HI) from Rots et al. (1990) (VLA HI maps)
  - $N(HI+H_2)/E(B-V)$ and $A_V/E(B-V)$ assumed
  - → $N(H_2)$ as a function of A_V and N(HI)
- CO data from Nakai et al (1994)
  - → X from 30 regions where analysis above c





Determining X : gamma ray measurements (Strong et al. 1988)

- General Idea : γ–ray emission intensity $Q_\gamma \propto q_\gamma N$

  where q_γ = local cosmic ray flux and N = density of the ISM

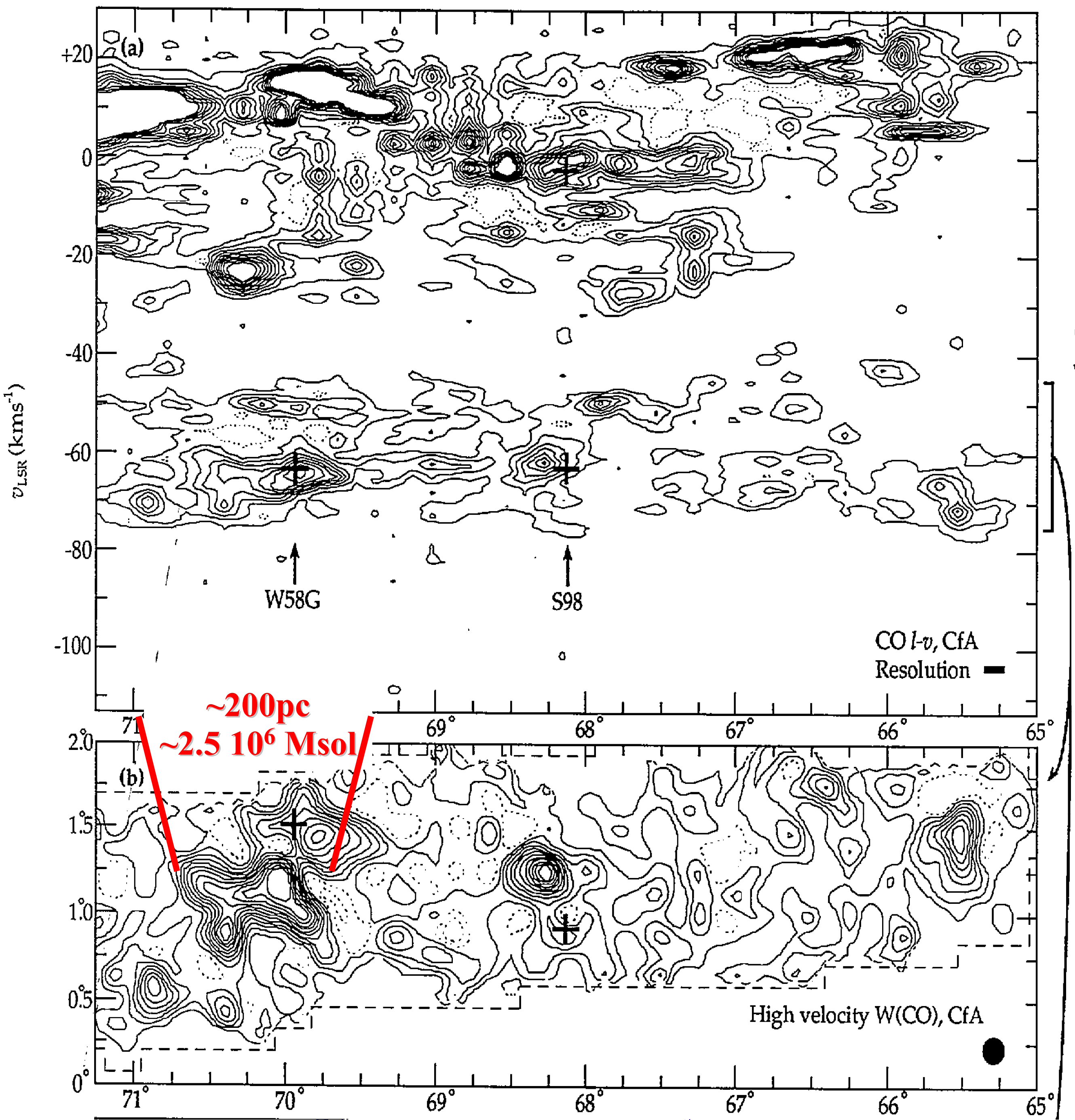
  → infer N from estimated q_γ and measured Q_γ
- Estimate X among other parameters with a fit to COS B data :
  - CO intensity map from Dame et al. (1987)
  - axisymmetric galactic model with 6 rings
  - 4 energy ranges

4 point sources removed

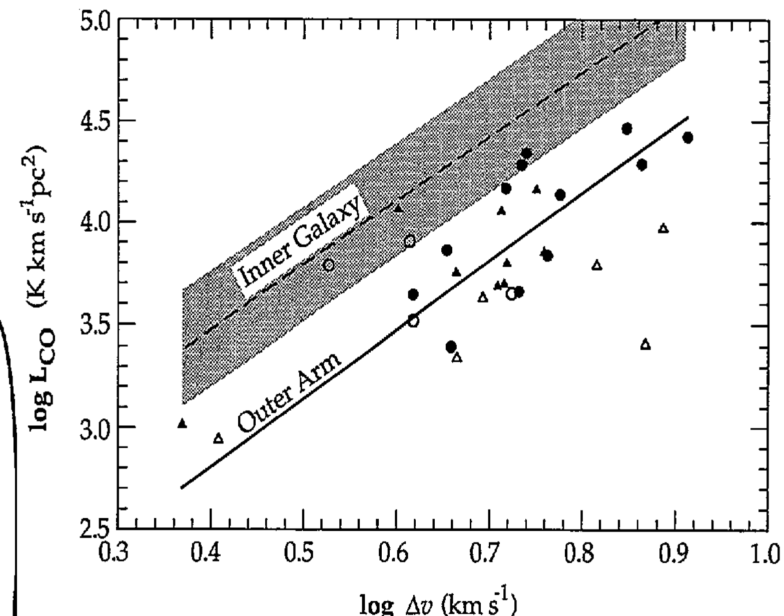
$$I_\gamma = \sum_i \frac{q_i}{4\pi}(\tilde{N}_{\mathrm{H\,I},i} + 2Y\tilde{W}_{\mathrm{CO},i}) + f_{\mathrm{IC}}\tilde{I}_{\mathrm{IC}} + I_{\mathrm{B}}^{0} + \sum_k f_k I_k ,$$

  - Free parameters (for each energy range) : $q_{i,i=1-6}$, Y, f_{IC}, I_{B}^{0} and $f_{k,k=1-4}$
  - Y is X in the approximation that the ring representation
- Best fit result :
  - X=(2.3±0.3) 10^{20}
  - No strong hint at radial dependence for X
  - $q_\gamma(R_i)$ seems to decrease by a factor 2 from center to outer regions.

Value of X : Looking at the outer Galaxy (Digel et al. 1990)



Low CO luminosity observed in outer arm of the MW (12kpc)
- **low metallicity?**
- **low T?**



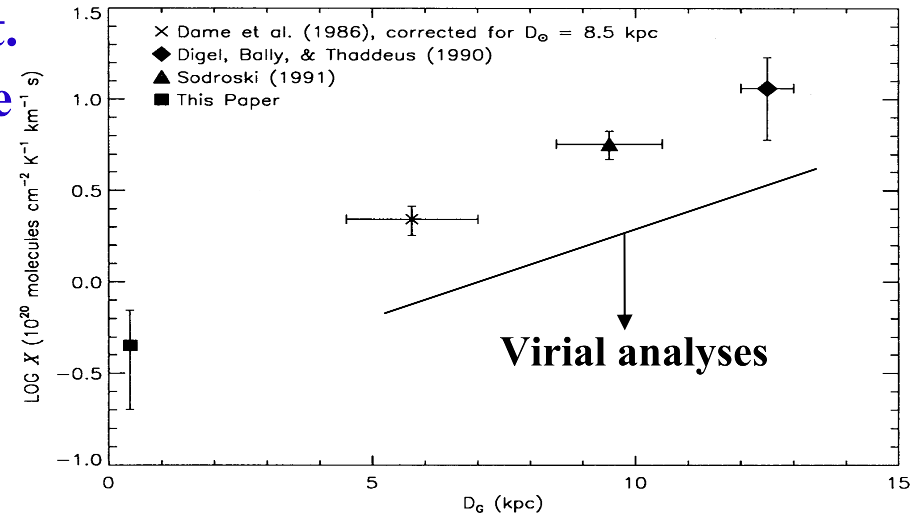
Mass calibrations of these MCs
- **Virial analysis**
- **$L_{co}/\Delta v$ relationship**

gives same conclusion :

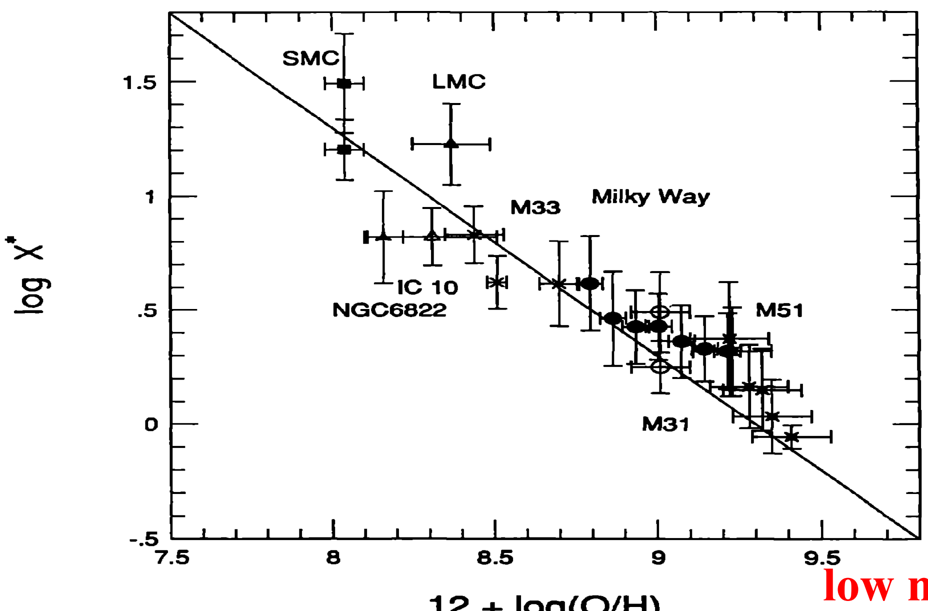
The X ratio in the outer arm clouds is 4±2 times in the inner galaxy value (2.3 10^{20})

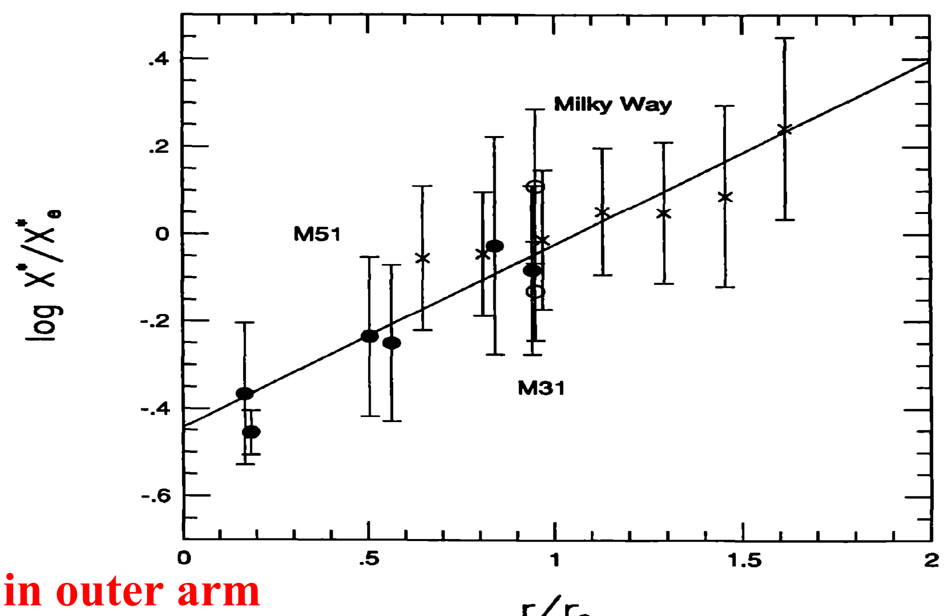
Value of X : Global Evolution with galactic radius

- **Sodroski et al. (1995) analysis of the vicinity of the GC (central 400 pc):**
  - Use DIRBE 140 and 240 um obs. to trace dust.
  - Use independent means to estimate large scale variation of the gas to dust mass ratio
  - Combine to CO observations (Dame et al.) to get large scale variation of the latter
  - 'obsoleted' by Schegel, Finkbeiner, & Davis (1998, ApJ, 500, 525)



- **Arimoto, Sofue and Sutjimoto (1996) :**
- assume that the relative C/O ratio propto metal abundance = 12+log(O/H)
  - Use of Virial analyses + O/H ratio in literature : $\log (X^*/X^*_e) = 0.39(r/r_e-1)$

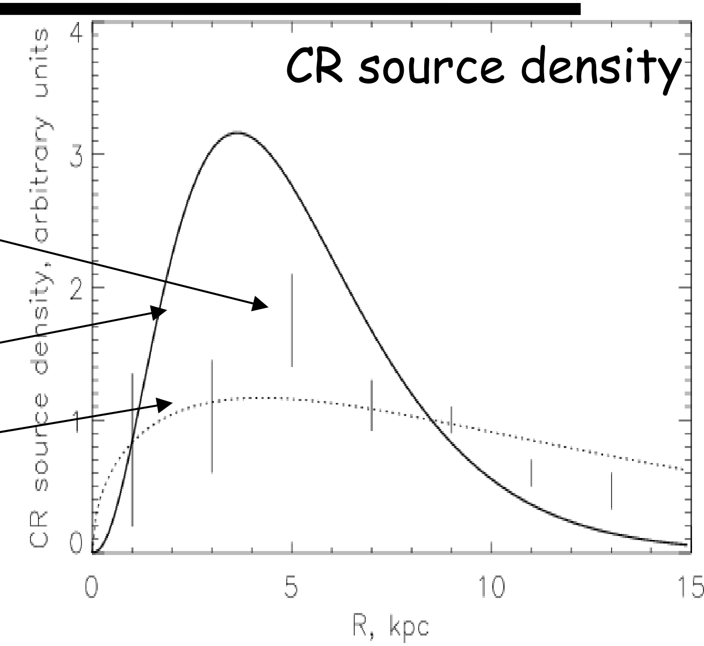


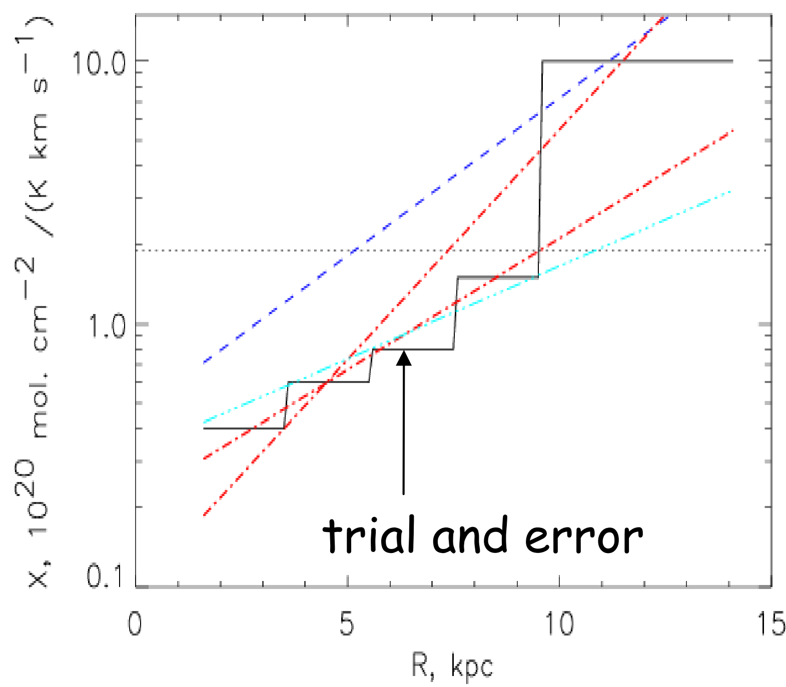


low metallicity in outer arm

Radial dependence of the X factor (Strong et al. 2004)

- Effect of X on expected gamma ray diffuse models :
  - SNR pop. studies: concentration in inner galaxy
  - Pulsar pop. studies : idem (with better stat.)
  - COSB, EGRET using HI and CO survey : emissivity per atom does not show much gradient! Uncomfortable for the SNR/Cosmic ray paradigm
- One way out : increase X at large radius! Then for a measured W_{co}, more H_2 expected at large radius → higher emissivity with comparatively fewer CRs...
- Paper preliminary results seem to indeed give a better fit, with a more “acceptable” CR source density as input....
- GLAST : more data→full fit of X(R)?





Conclusions

- Correct use of X factor and/or CO line emission depends on correct estimates of several parameters :
  - CO gas excitation temperature
  - Cloud temperature
  - Cloud equilibrium state
  - level populations
  - ....
- Different lines and probably information from other phases of the cloud (HI notably) are clearly needed
- Spatial distribution is yet another topic to get right.....