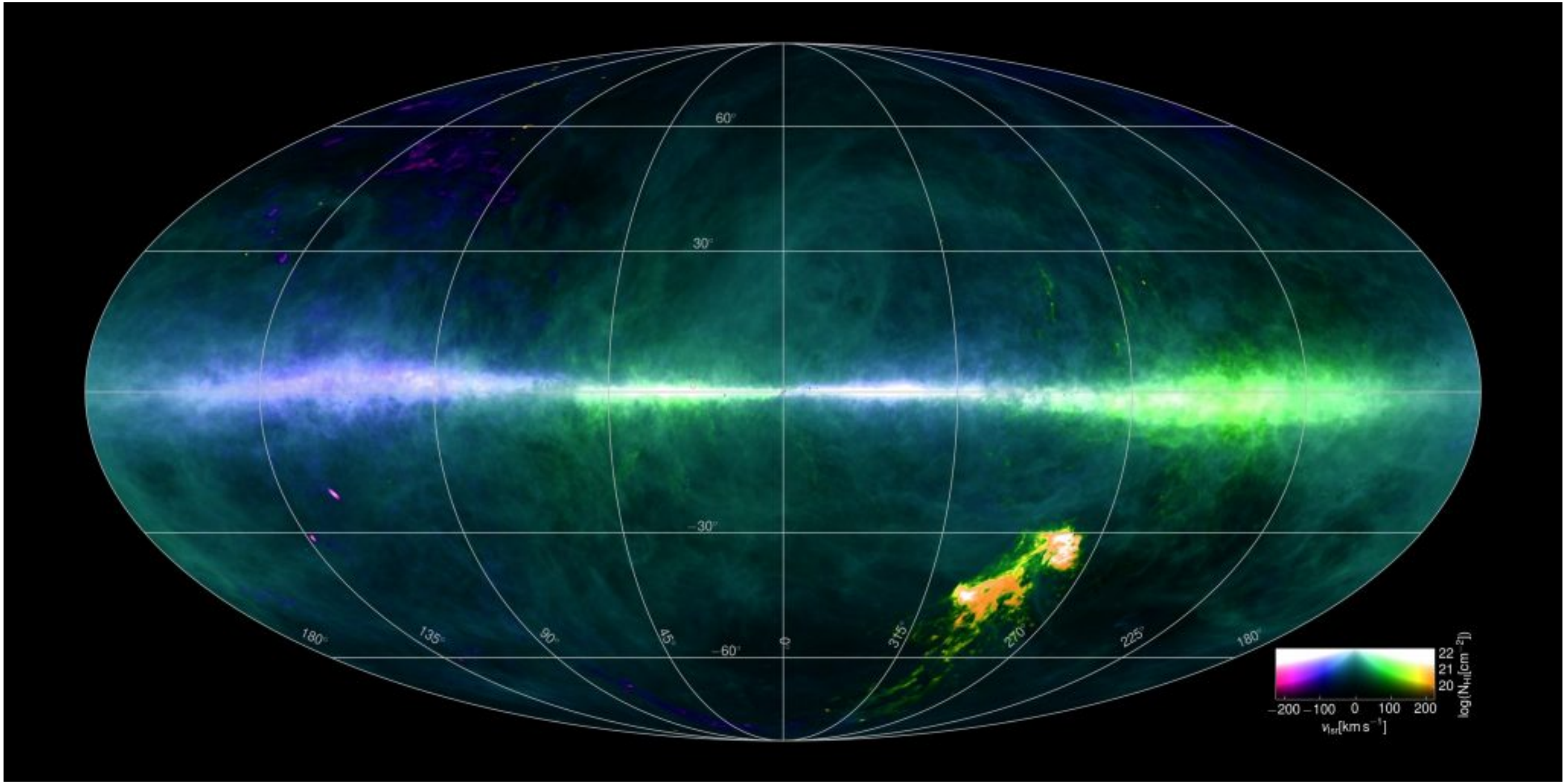
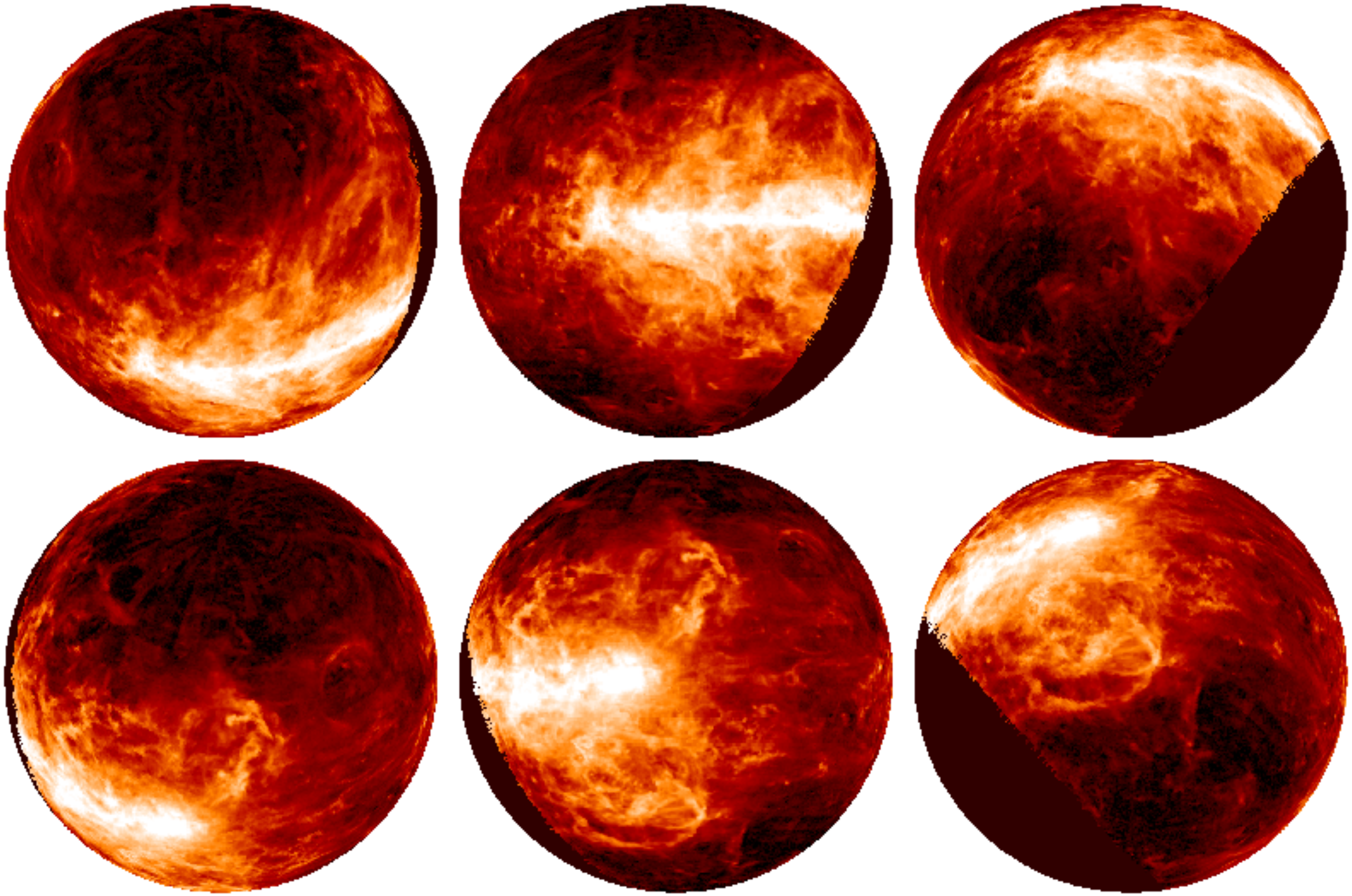
Galactic distribution HI



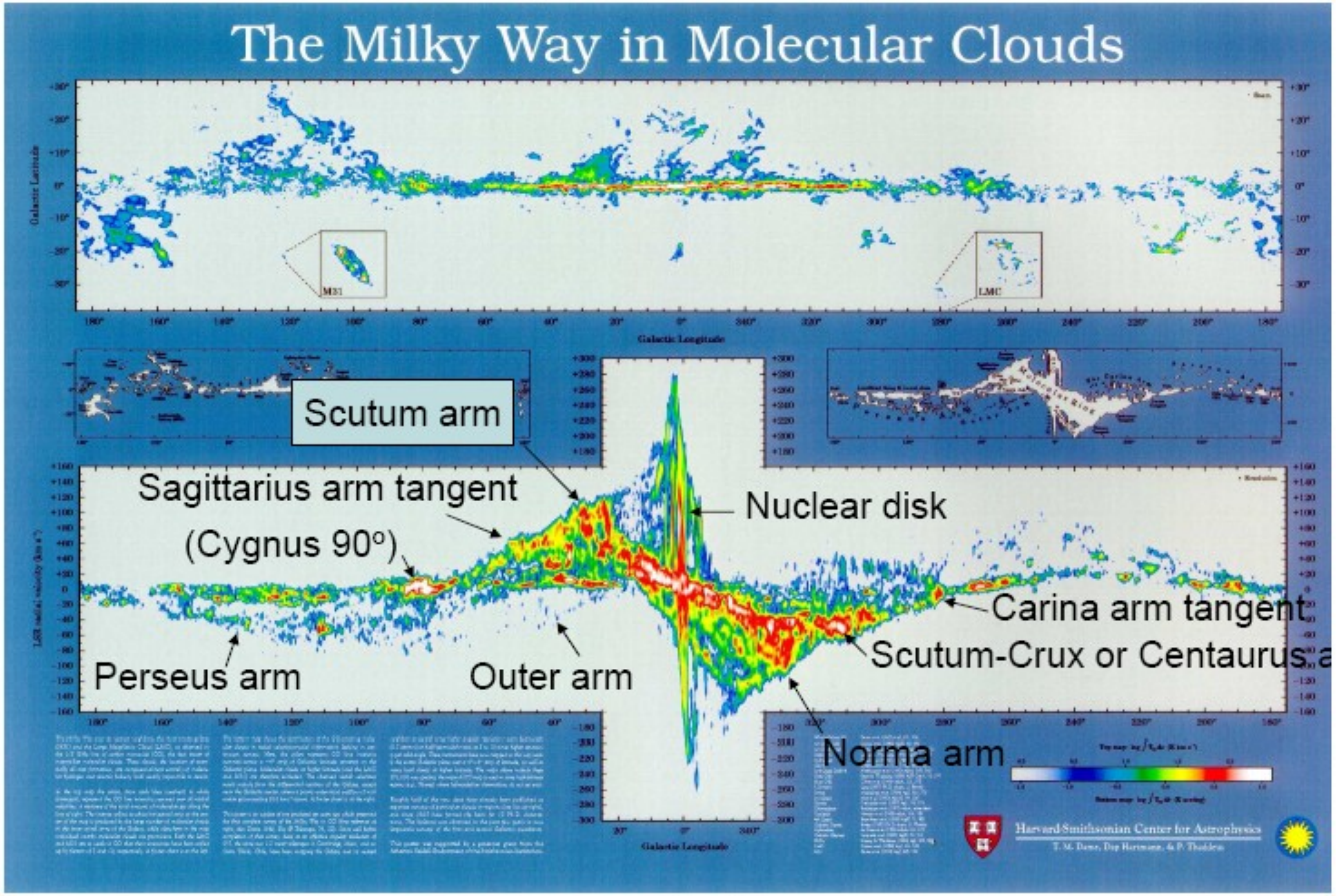
HI4PI collaboration: Effelsberg 100-m + Parkes 64-m

Resolution: 16.2 arcmin; rms: 43 mK.   Full spatial sampling.

LAB: Galactic distribution HI

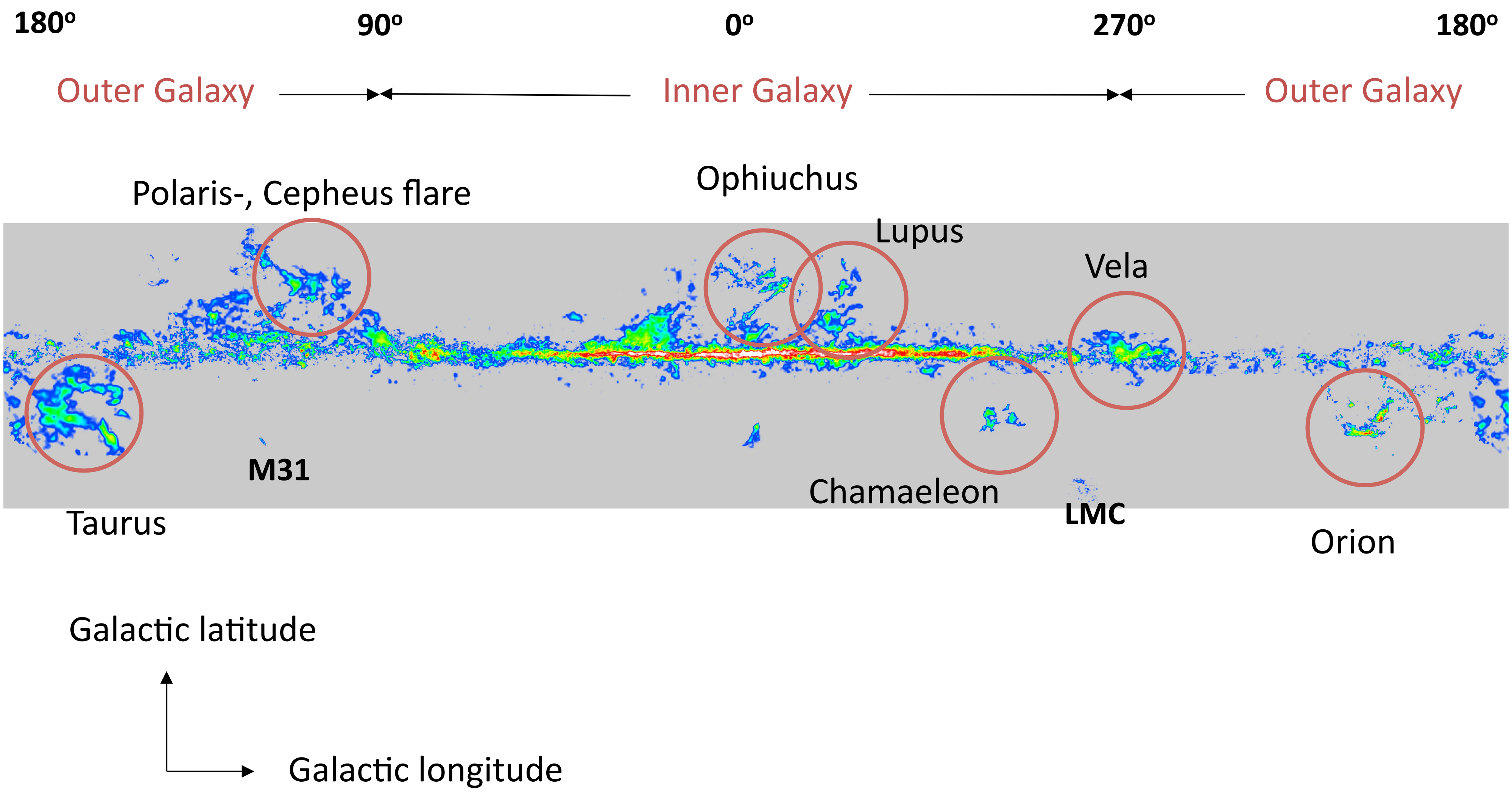


Hartmann & Burton 1994



Largest SF Regions: CFA CO survey of the Milky Way

Galactic distribution CO



Dame, Hartmann & Thaddeus 2001

CO, not H_2

ISM composed essentially of hydrogen:

HI: 21-cm line

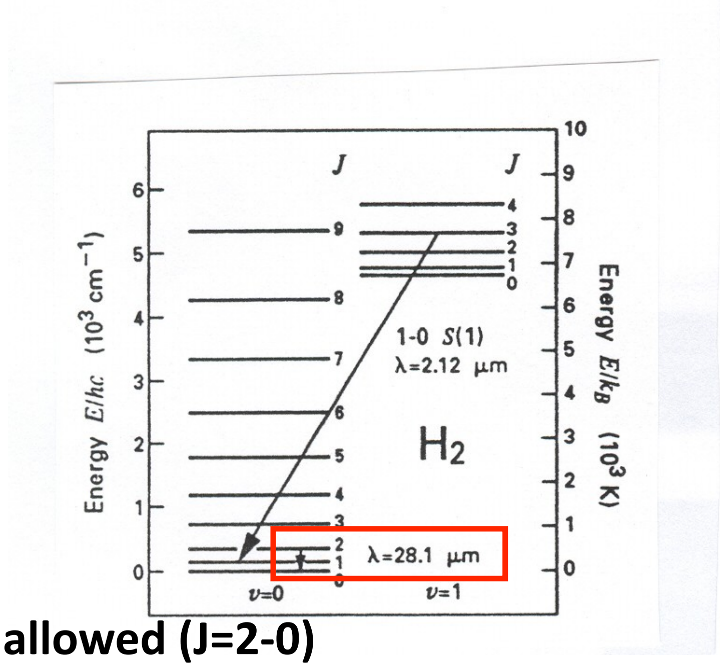
H_2: symmetric molecule ⇒ no radio emission

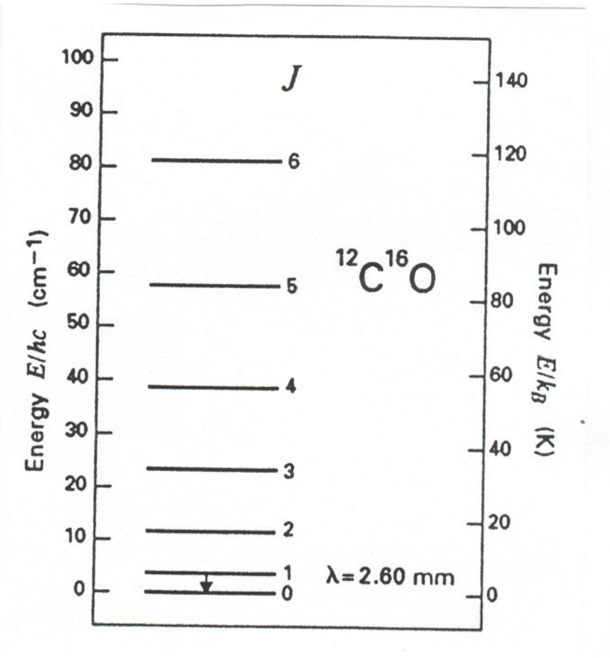
- UV absorption lines
- IR emission lines

CO: most abundant after H_2 : $[H_2]/[CO] \sim 1 \times 10^{-4}$.

- excited by collisions with H_2
- easily observed rotational transitions at (sub-)mm wavelengths
- $n(H_2) \geq$ a few $\times\ 10^3\ cm^{-3}$

Observing molecular clouds at large



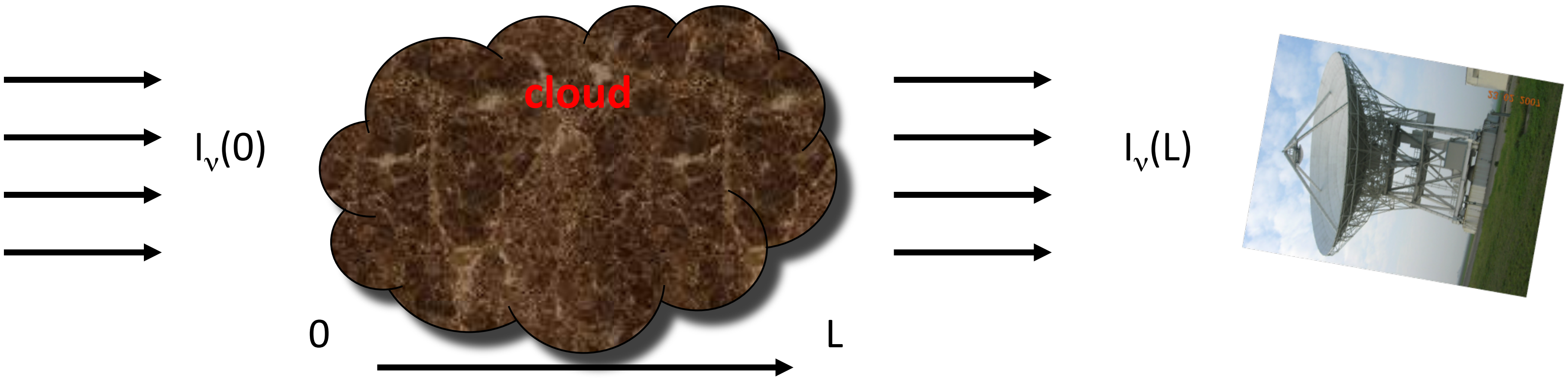


Lowest allowed (J=2-0)
ΔE = 510 K

H_2 smallest diatomic molecule: widely-spaced energy levels
Even lowest excited rot. levels too far above ground state
to be easily populated at normal molecular cloud T.
no dipole moment, hence quadrupole radiation (slow)

CO: more closely-spaced energy levels; easily populated also at
low T

Radiation transport



$I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1- e^{-\tau_\nu})$ $B_\nu(T) = \dfrac{2h\nu^3}{c^2}\dfrac{1}{(e^{h\nu/kT}-1)}$: Planck function

Define $T_A(\nu) \equiv \dfrac{I_\nu c^2}{2k\nu^2}$, $T_A(0) = T_{bg}$, and define $J_\nu(T) = \dfrac{h\nu}{k}\dfrac{1}{(e^{h\nu/kT}-1)}$

Then: $T_A = J(T_{ex})(1- e^{-\tau_\nu}) + J(T_{bg})e^{-\tau_\nu}$ → **Detection equation**

In practice one measures $\Delta T_A = T_A - T_{bg}$ (ON-OFF) $= (T_{ex} - T_{bg})(1- e^{-\tau_\nu})$

1) $\tau_\nu \ll 1$: $\Delta T_A \approx T\tau_\nu$ measure column density. All photons escape.
2) $\tau_\nu \gg 1$: $\Delta T_A \approx T$ measure kinetic temperature, but independent of col. dens.
Only photons at cloud surface ($\tau_\nu \leq 1$) escape.

T_{ex} , τ, and column density in LTE

For an optically thick line, e.g. CO(1-0): $\tau_\nu \gg 1$; the detection equation yields:

$T_{ex} = (h\nu/k)\ \ln^{-1}(h\nu/k\ [T_A + J(T_{bg})\ ]^{-1} + 1)$
$\quad = 5.532\ \ln^{-1}(5.532[T_A + 0.818\ ]^{-1} + 1)$

For an optically thin line, e.g. ^{13}CO(1-0): $\tau_\nu \ll 1$; it follows that:

$\tau_\nu = -\ln[1 - T_A/(J(T_{ex})\ - J(T_{bg})\ )]^{-1}$

Column density – derived from transition between levels J and J-1.
Detection equation: $T_A = J(T_{ex})\ (1- e^{-\tau_\nu}\ ) + J(T_{bg})\ e^{-\tau_\nu}$ and $\tau_\nu \ll 1$, solve for τ_ν .
From definition of T_{ex} , the definitions of the Einstein-coefficients, the equation for the absorption coefficient, and the definition of τ

$$N_{tot} = \left(\frac{3h}{8\pi^3\mu^2}\right)\left(\frac{Z}{J}\right)e^{\frac{h\nu}{kT_{ex}}}\left[1 - e^{-\frac{h\nu}{kT_{ex}}}\right]^{-1}\left[J(T_{ex}) - J(T_{bg})\right]\int T_A dv$$

with Z the partition function (linking N_1 to N_{tot}).

or: $N_{tot} = f(T_{ex}) \int T_A\, dv$

Total column density

$$N_{tot} = f(T_{ex}) \int T_A \, dv$$

For $^{13}CO(1\text{-}0)$ and $C^{18}O(1\text{-}0)$ and $T_{ex} \approx 5 - 20$ K:

$$f(T_{ex}) \approx (1.1 \pm 0.2) \times 10^{15}\ \mathrm{cm}^{-2} / (\mathrm{Kkm/s})$$

Hence:

$N_{tot} = (1.1 \pm 0.2) \times 10^{15} \int T_A \, dv\ \mathrm{cm}^{-2} \Rightarrow$ Mass!

If $\tau_\nu \leq 2$ then correction factor $\tau_0 / [1 - \exp(-\tau_0)]$, with τ_0 the opt. depth at line center $\tau_0 = -\ln(1-1/R)$ and $R = T_A(^{12}CO) / T_A(^{13}CO)$.

Therefore:

$$N_{tot} = (1.1 \pm 0.2) \times 10^{15} \times \tau_0 / [1 - \exp(-\tau_0)] \times \int T_A \, dv\ \mathrm{cm}^{-2}$$

Mass follows via abundances: $N(^{12}CO)/N(^{13}CO) \sim 90$ and $N(^{12}CO)/N(H_2) \sim 1 \times 10^{-4}$

Deriving $N(H_2)$, total mass

1. Lines (Planck & Boltzmann)

Detection eqn., LTE, $\tau(^{12}CO) \gg 1$ ($\Rightarrow T_{ex}$), $\tau(^{13}CO) \ll 1$

$N(^{13}CO) = f(\tau_{13}, T_{ex}, \Delta v_{13}) + [H_2]/[^{13}CO] = \ldots \Rightarrow N(H_2)_{LTE}$

$^{12}C/H$, $^{12}C/^{13}C$ gradients $\Rightarrow [H_2]/[^{13}CO] = f(R)$

Non-LTE transitions: LVG model (full radiation transport eqns.)

2. Virial theorem

Cloud radius (r), linewidth (Δv), assumptions about density distribution. For spherical cloud, $n \propto r^{-2} \Rightarrow M_{vir} = 126\, r\, \Delta v^2$

Exclude non-bound motions (e.g. outflows); actual density distribution?

3. Dust continuum

$M = (gS_\nu d^2)/\kappa_\nu B(T_{dust})$

κ_ν, T-structure, gas-to-dust ratio (g) uncertain

4. Extinction mapping $N(HI) + 2N(H_2) \approx 1.9 \times 10^{21}\ cm^{-2} A_V$, I_{CO} or $N(^{13}CO)$

5. Lines (empirical)

$N(H_2)/\int T(^{12}CO)\, dv \equiv X \Rightarrow N(H_2)_{Wco}$

X = constant or $f(R)$?

$$N(H_2) = X_{CO}\, W_{CO} \quad \text{with } W_{CO} = \int T(^{12}CO)\, dv$$

In Milky Way $X_{CO} = 2 \times 10^{20}$ (K kms^{-1})$^{-1}$ cm^{-2} with 30% uncertainty (Bolatto+ 2013 ARAA)

$$M = \pi R^2 \times N(H_2) \times m(H_2) \times \text{He-corr} = \pi R^2 X_{CO} W_{CO} \times m(H_2) \times \text{He-corr} =$$
$$= [\, X_{CO} \times m(H_2) \times \text{He-corr}\,] \times L_{CO}$$

$M_{mol} = \alpha_{CO}\, L_{CO}$ with $L_{CO} = \pi R^2 W_{CO}$, in K km s^{-1} pc^2

…. Plugging in values, pc^2 -> cm^2, g -> $M_\odot$ ….

=> **$M(M_\odot) = 4.3\, L_{CO}$** for the galactic value of X_{CO}

The value of $\boldsymbol{X_{CO}}$ is determined by calibrating empirical N or M with other methods.

Original derivation of $\boldsymbol{X_{CO}}$ was by using diffuse γ-ray emission (Lebrun+ 1983)

Based on fact that diffuse γ-ray emission is mostly due to collisions between cosmic rays and the ISM: $I_\gamma = \varepsilon_\gamma [N(HI) + 2 X_{CO} W_{CO}]$ (Bloemen 1989)
compare maps of diffuse γ-emission, HI and CO to find $\boldsymbol{X_{CO}}$.

Values for other types of galaxies

- Normal galaxies: $\boldsymbol{X_{CO}} \approx 2 \times 10^{20}$ with factor 2 uncertainty

  Increases sharply in systems with metallicity ca. 0.5 solar
  Often smaller in central regions, as in MW

* Starbursts and other luminous galaxies: $\boldsymbol{X_{CO}} \approx 0.4 \times 10^{20}$ with factor 3 uncertainty

  Antennae-values: see Zhu, Seaquist & Kuno 2003 ApJ 588, 243
  Mtot ~ 2×10^9 $M_\odot$

  See also Herrera+ 2012 A&A 538, L9 for ALMA data (3-2 instead of 1-0!)
  or Espada+ 2012 ApJL 760, L25 ALMA CO(2-1): derives Σ ($M_\odot$ pc^{-2}), uses units like Jy kms^{-1} $arcsec^{-2}$!

* At high redshifts:

  In massive merger-driven starbursts such as SMGs, most consistent with low $\boldsymbol{X_{CO}}$ (cf. local ULIRGs)
  In blue-sequence galaxy disks, likely higher $\boldsymbol{X_{CO}}$ (cf. local disks)