Lecture 2: Molecular Clouds: Galactic Context and Observational Tracers

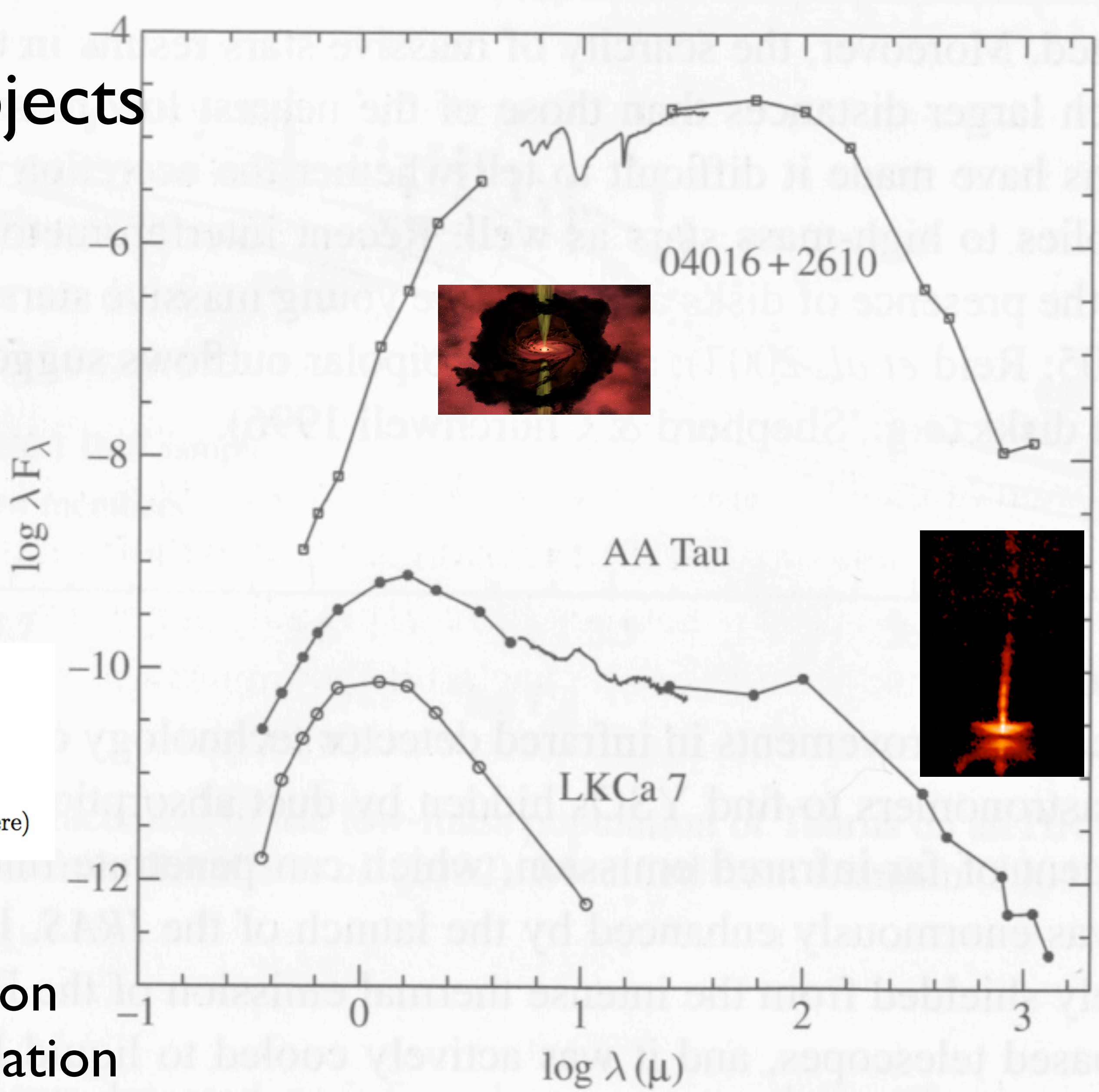
Corona Australis molecular cloud: Andrew Oreshko

Classification of Young Stellar Objects (YSOs)

Spectral Index

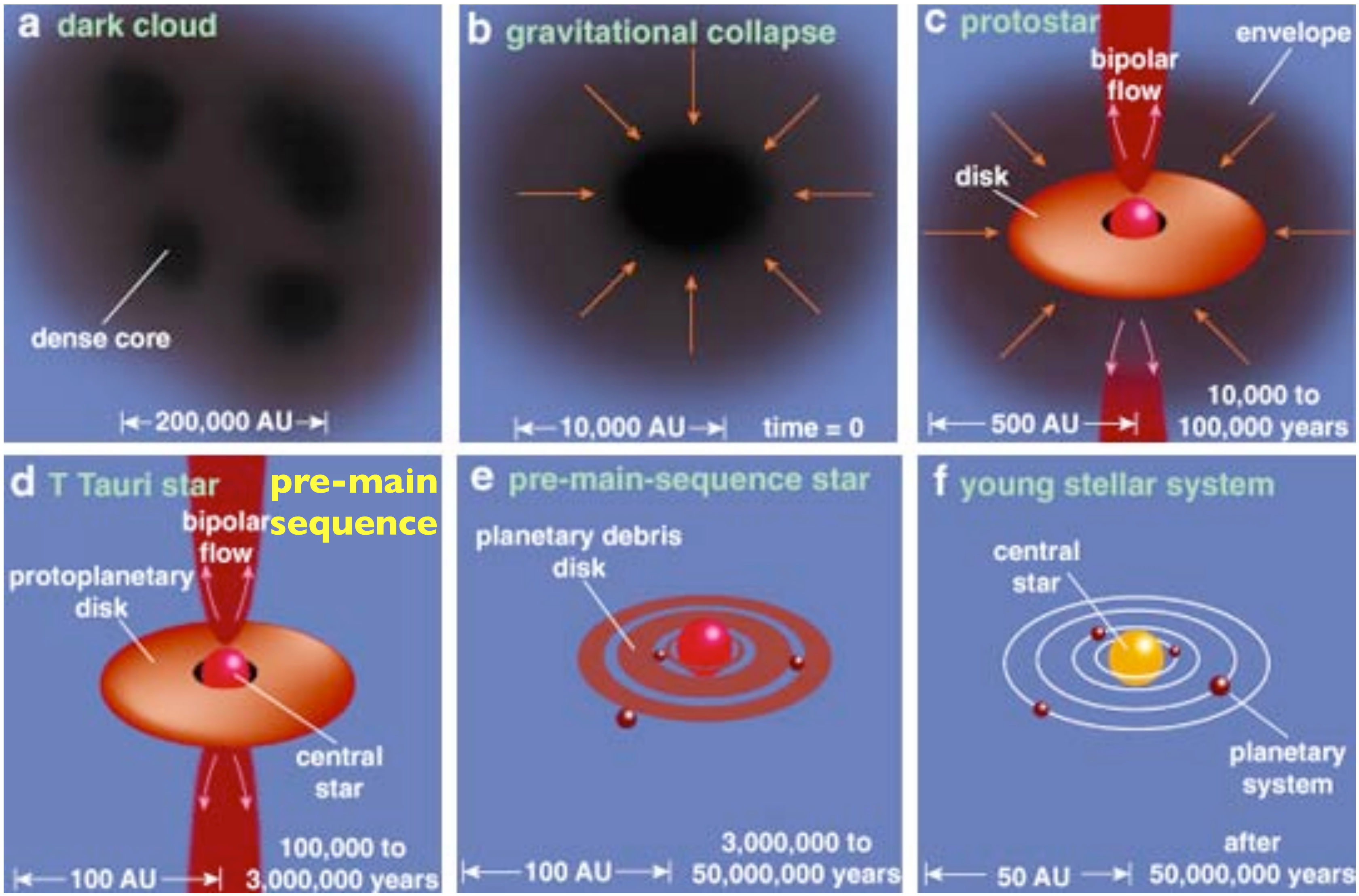
$$\alpha = \frac{dlog(\lambda F_\lambda)}{dlog(\lambda)}$$

- $\alpha > 0.3$ is a Class I source
- $-0.3 < \alpha < 0.3$ is a flat spectrum source
- $-3 < \alpha < -0.3$ is a Class II
- $\alpha = -3$ is a Class III object (pure photosphere)



Hartmann: Accretion Process in Star Formation

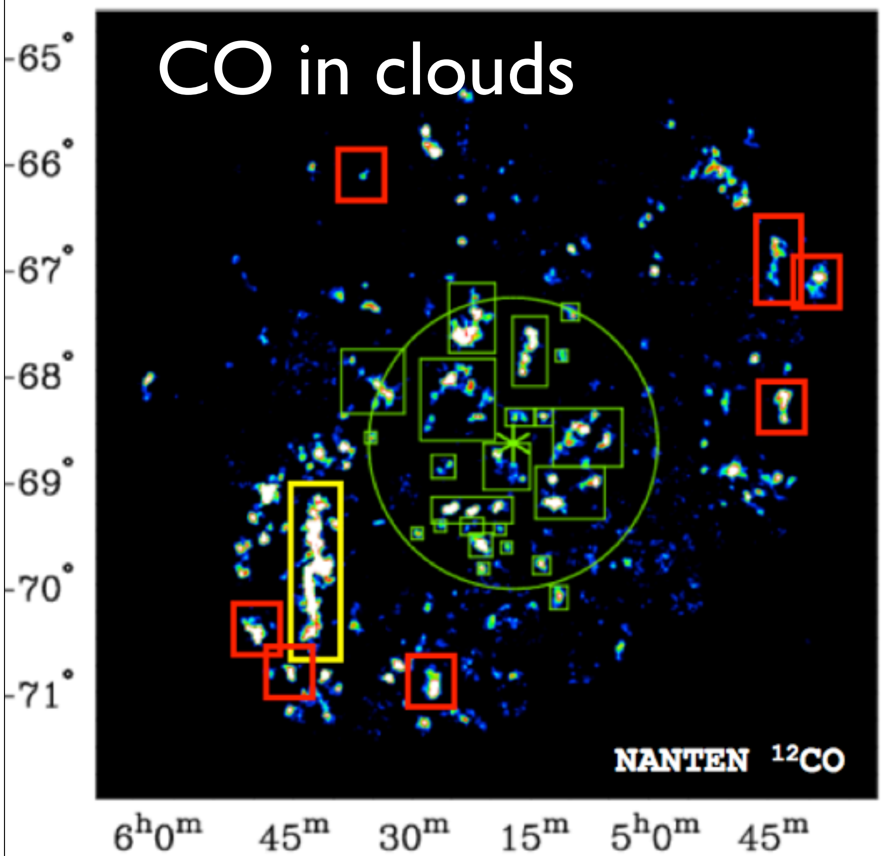
Stages of Star Formation

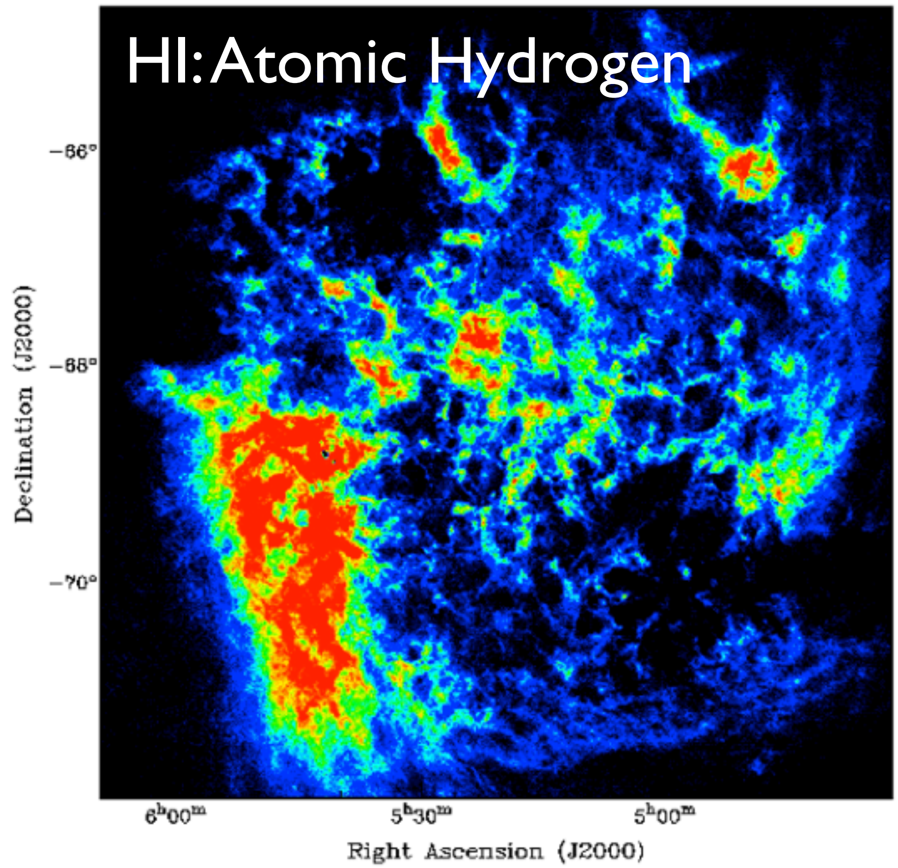


Molecular Clouds in a Galactic Context

CO and HI in the LMC

From slide from Annie Hughes





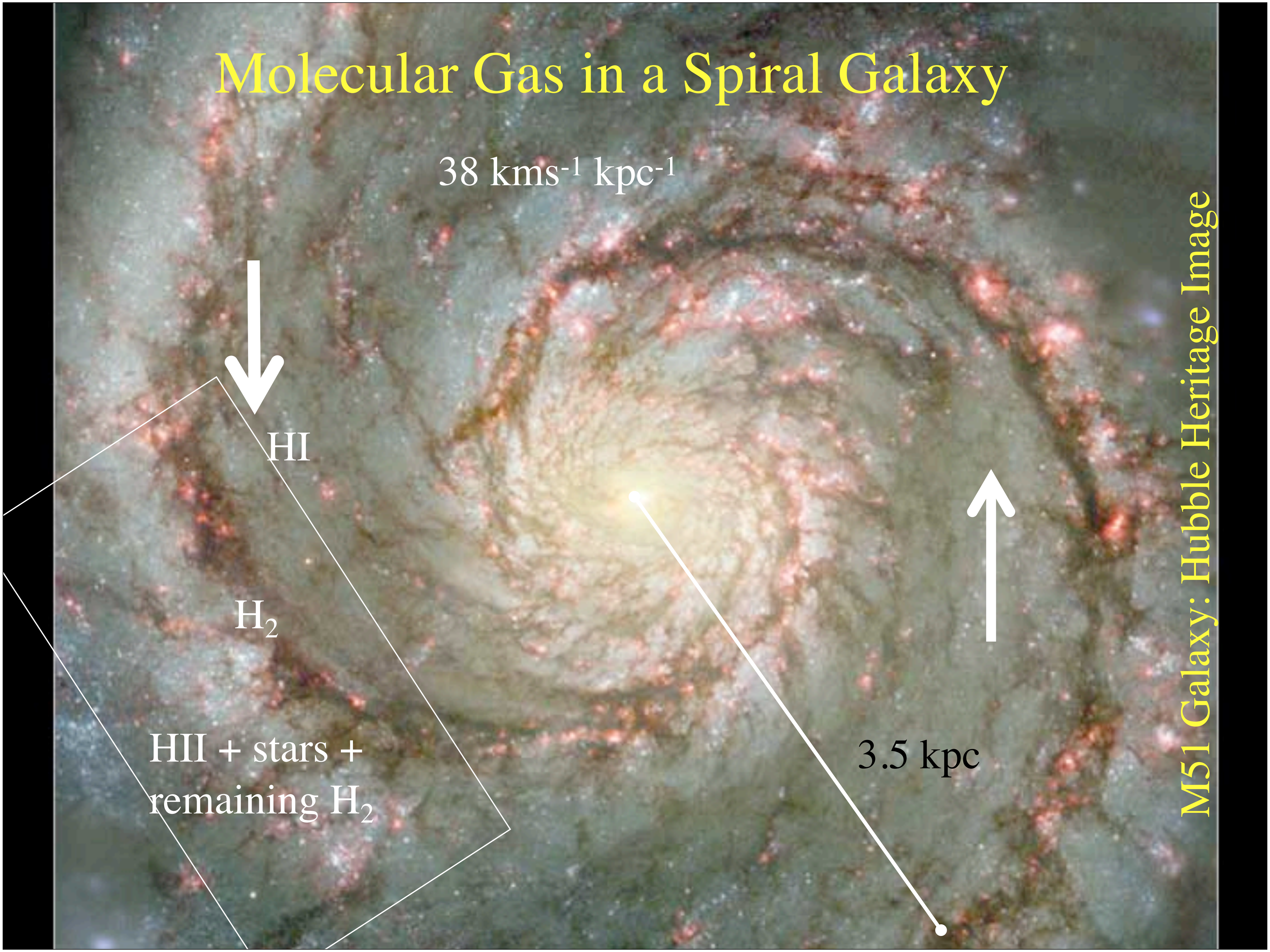
M_{mol} ~ 4-7 x 10^7 $M_\odot$ (Fukui ea. 1999)

Mopra: θ=35″ & Δv=0.1 km s^{-1}

M_{HI} ~ 4.8 x 10^8 $M_\odot$ (LSS ea. 2003)

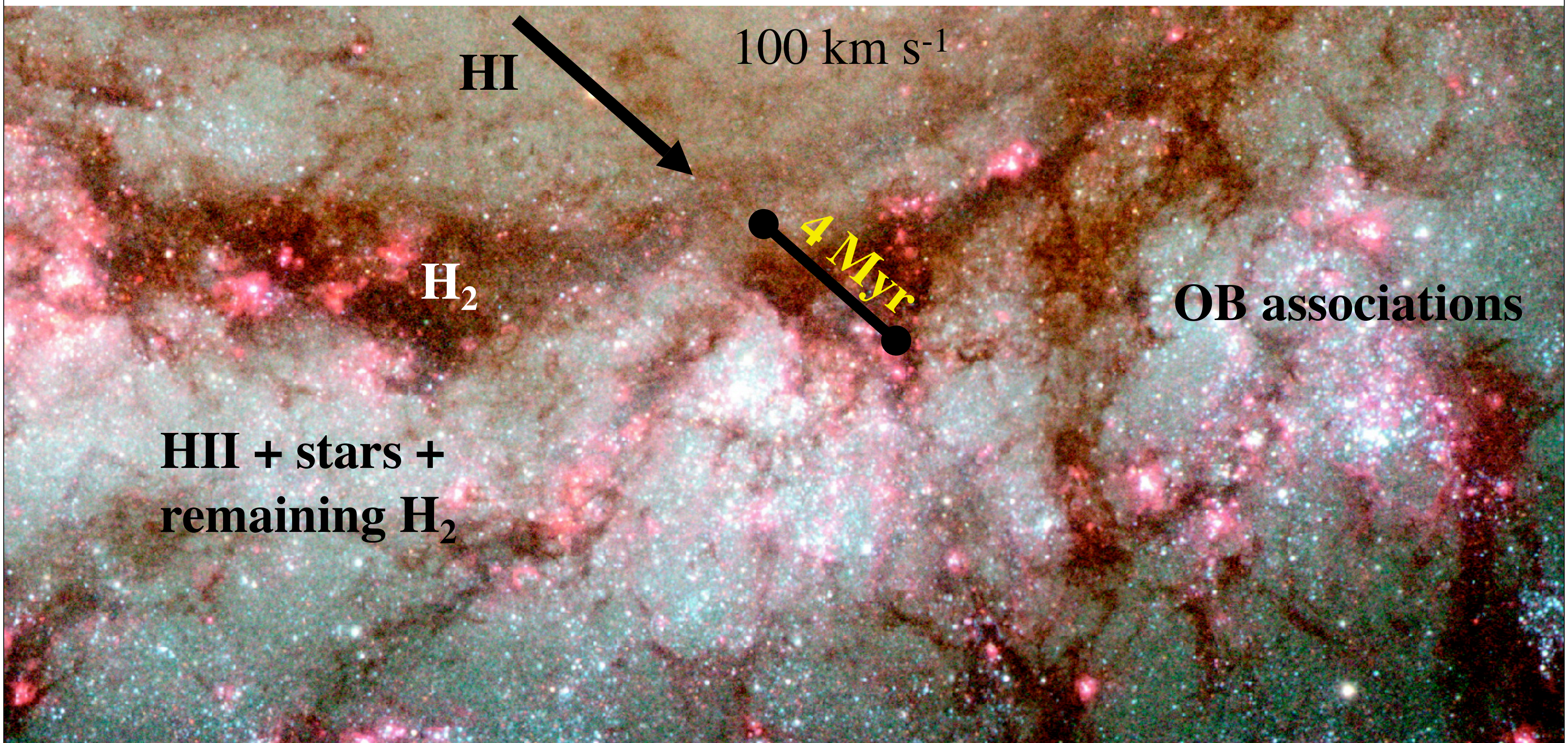
ATCA+PKS: θ=60″ & Δv=1.7 km s^{-1}

http://www.atnf.csiro.au/research/LVmeeting/magsys_pres/ahughes_MagCloudsWorkshop.pdf



Molecular Gas in a Spiral Galaxy
38 kms-1 kpc-1
HI
H2
HII + stars +
remaining H2
3.5 kpc
M51 Galaxy: Hubble Heritage Image

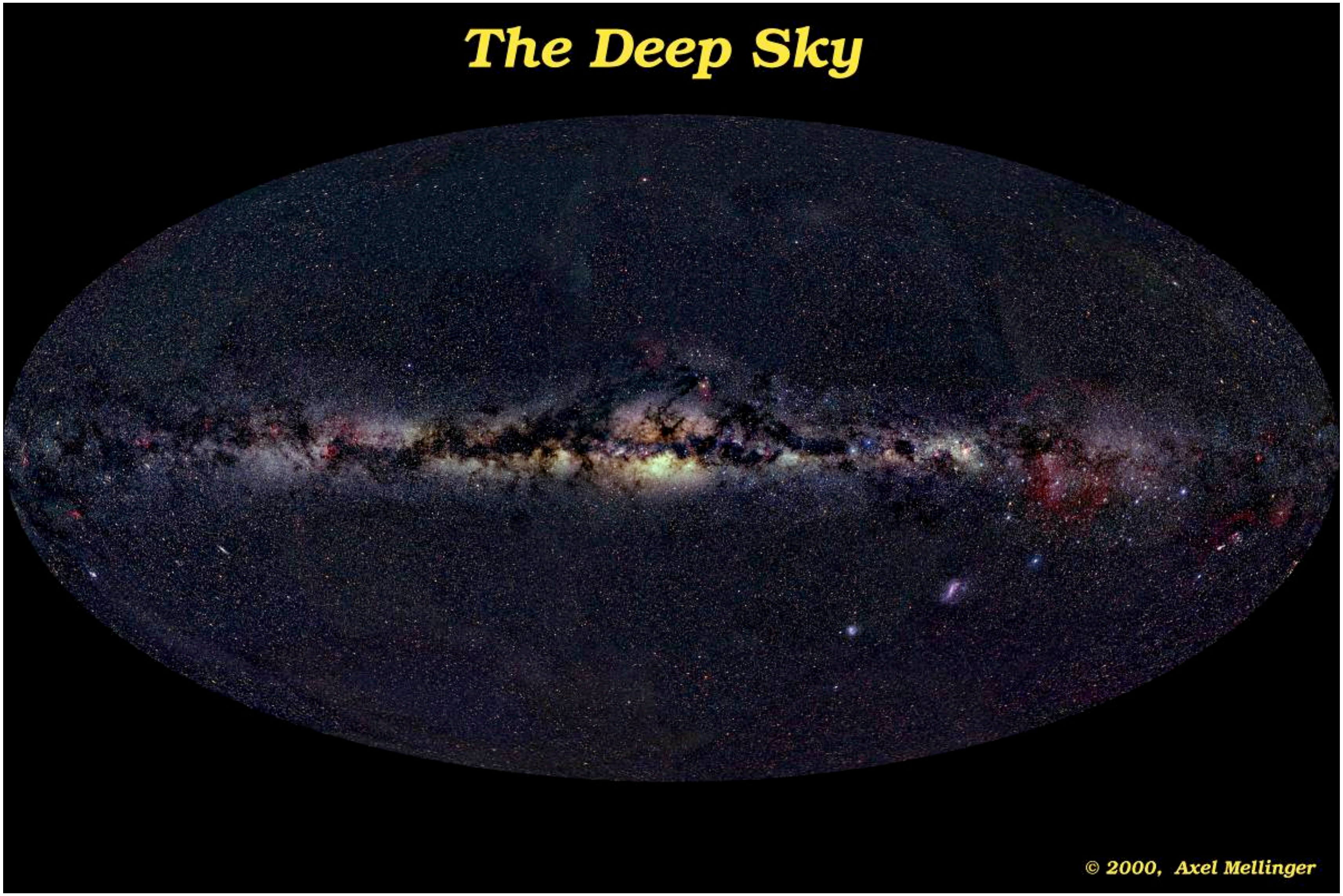
Spiral Arm Section of M51



3.40 x 1.65 kpc: Elmegreen 2007 ApJ, 668, 1064

Molecular Clouds in the Milky Way Galaxy

The Molecular Clouds in our Galaxy seen in Dust Extinction

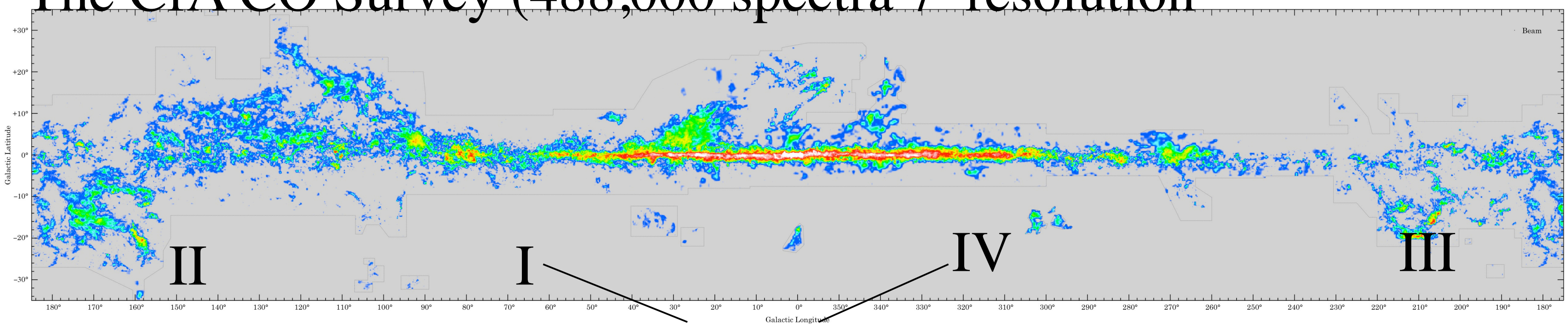


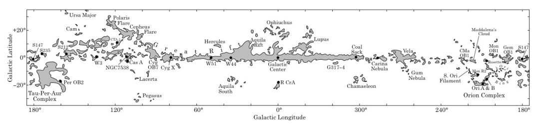
Molecular Clouds in our Galaxy seen in ^{12}CO (1-0)

Clouds are composed primarily out of H_2 and He. However, in cold clouds, these molecules don't emit. We map molecular with dust extinction and a variety of molecules that do emit such as CO (tracers).

The Galaxy in CO

The CfA CO Survey (488,000 spectra 7' resolution





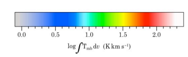
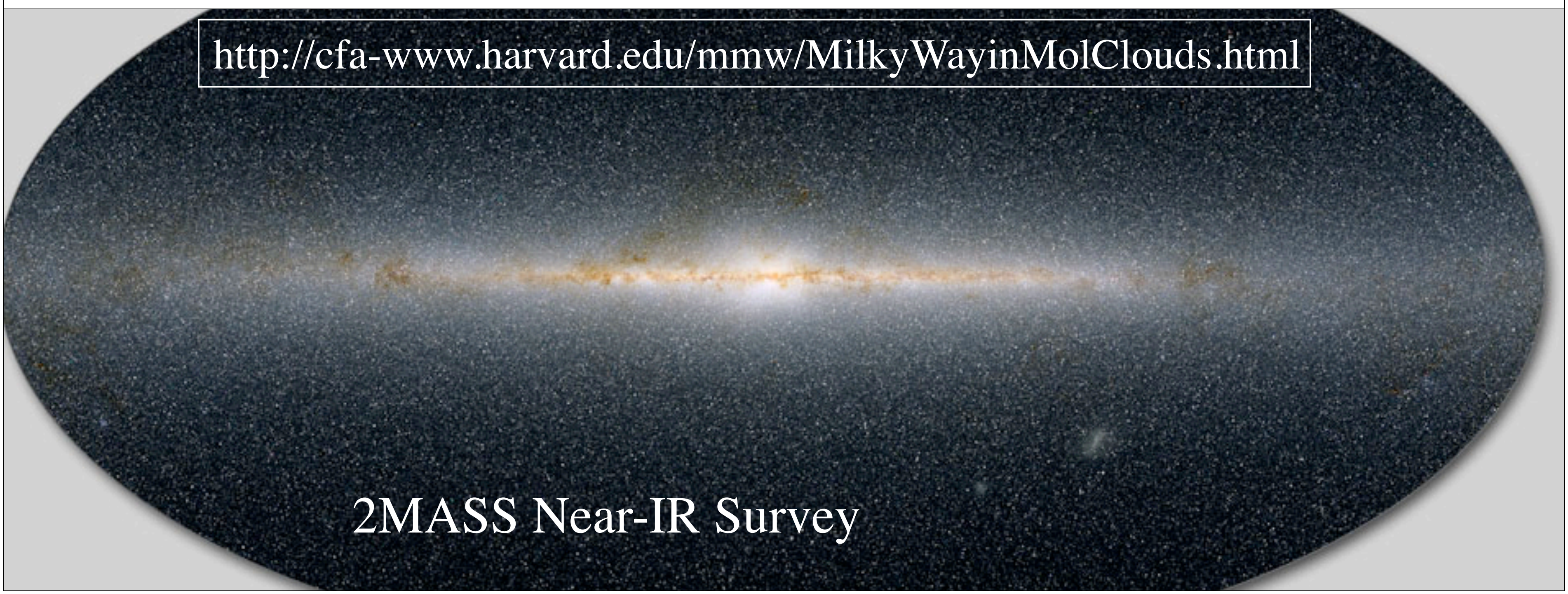
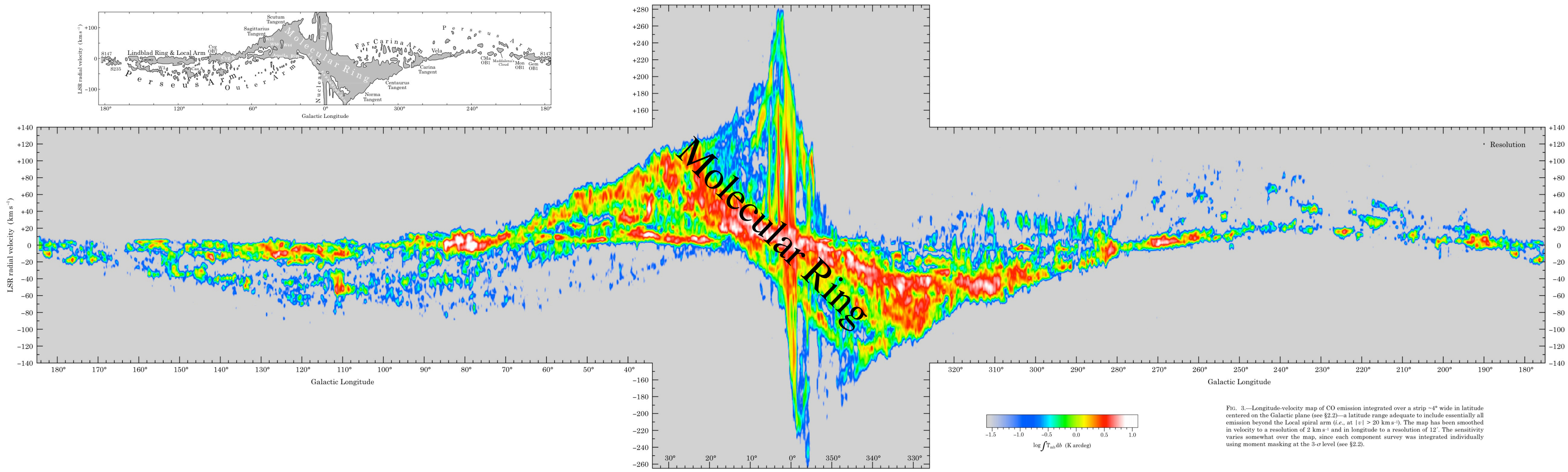
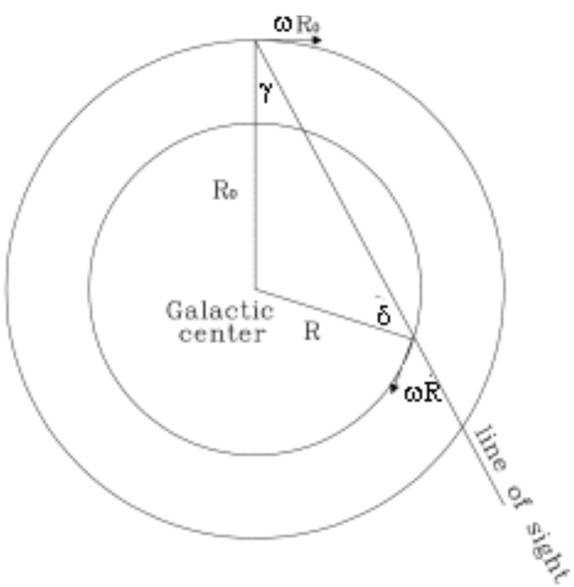


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey 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.



Determining Distances to Clouds





The line of sight velocity is

$V = wR\sin(\delta) - w_0 R_0 \sin(\gamma)$

Using identify of $R_0\sin(\gamma) = R\sin(\delta)$

$V = (w - w_0)R_0\sin(\gamma)$ or $w = V/(R_0\sin(\gamma)) - w_0$

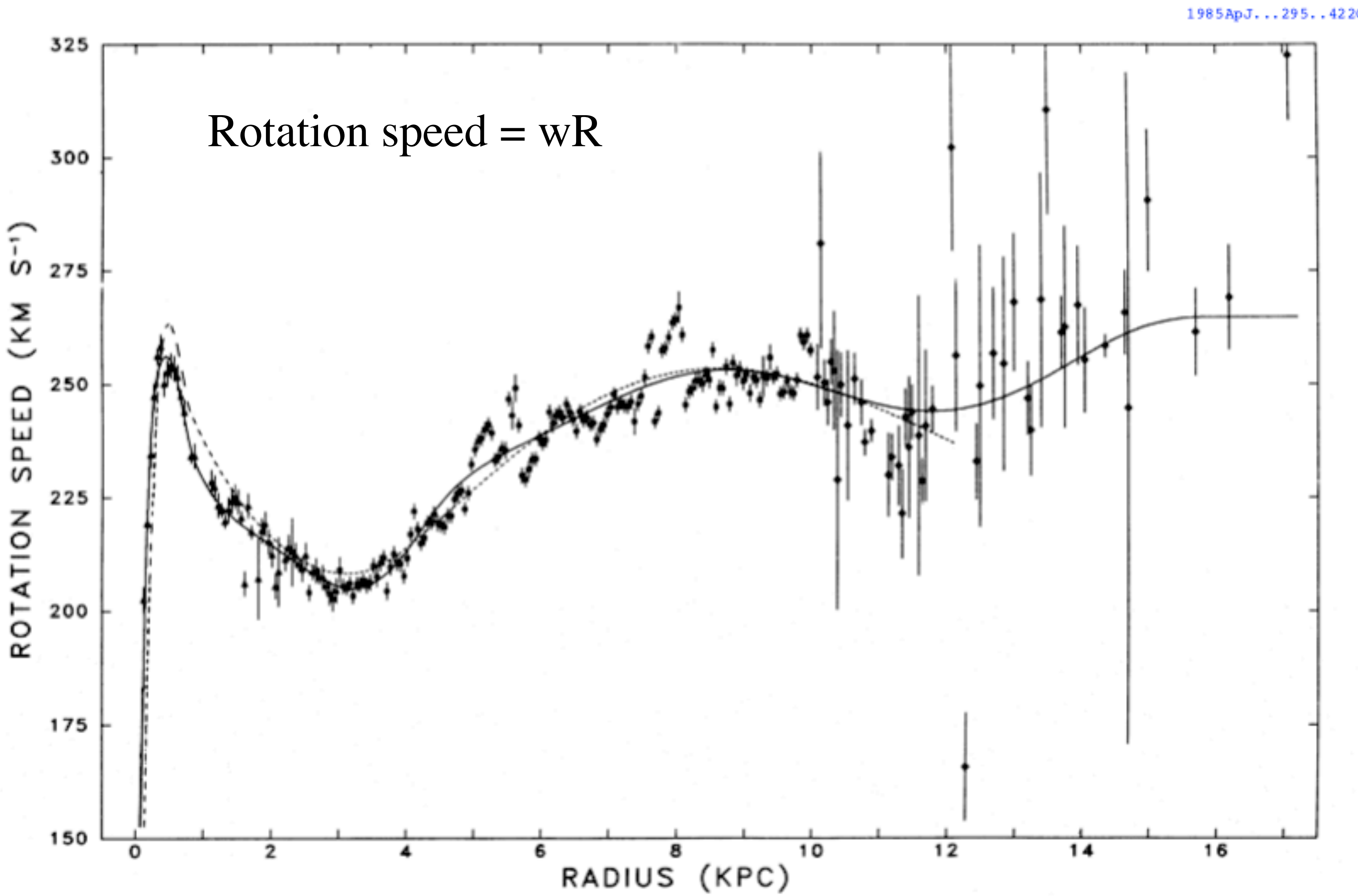
Given that $Rw \sim constant$

$w \sim 1/R$

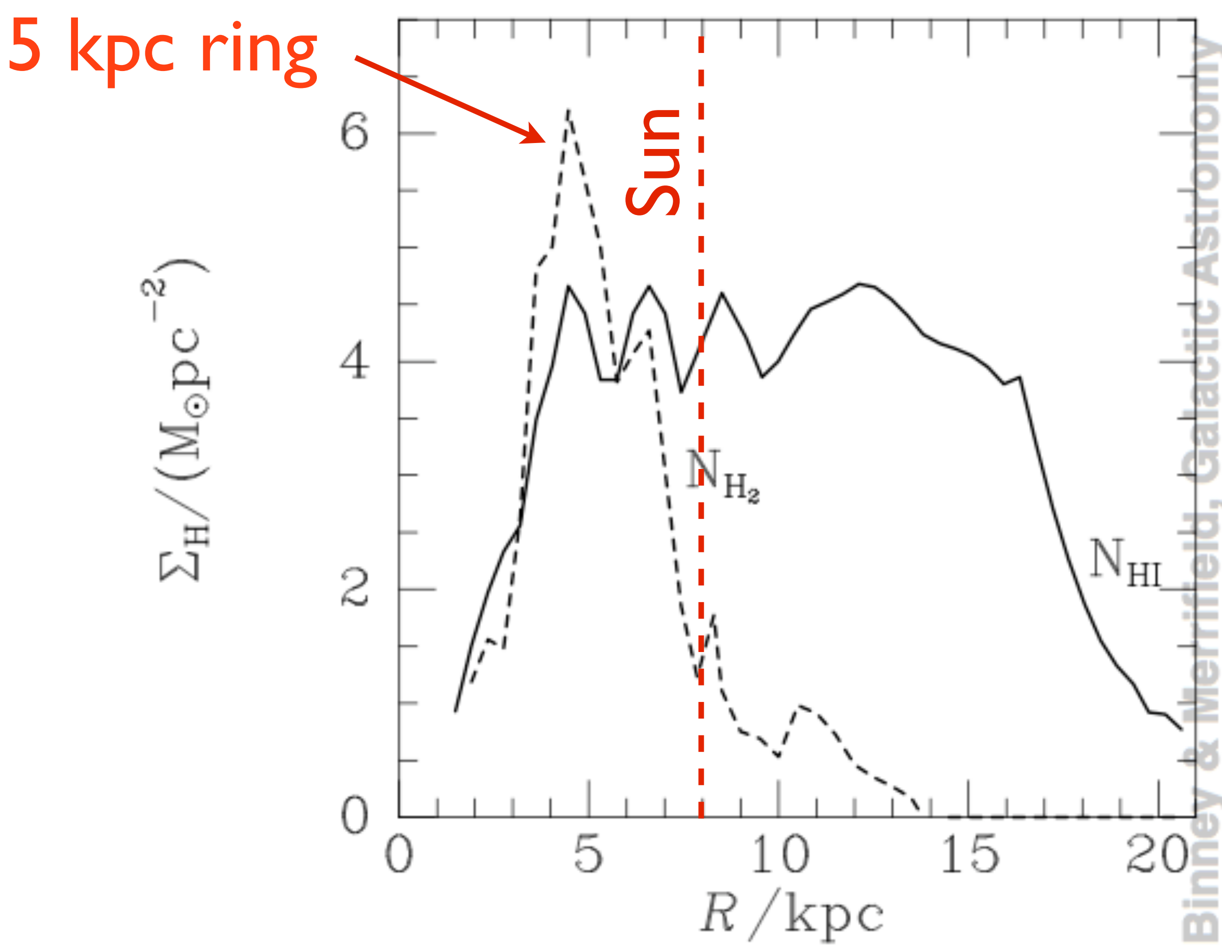
By solving for *w* we can determine two possible solutions for *R* in inner galaxy, one solution for *R* in outer galaxy.

http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotation.html

Galactic Rotation Curve: Clemens 1985 ApJ 295, 422



CO in our Galaxy



Using the rotation curve, we can map the distribution of molecular and atomic gas with galactic radius.

Surveys for Molecular Clouds

CfA Survey 1980-present, molecule: CO, 7' resolution, 7' sampling

U Mass/Stony Brook Survey 1981-1984, molecule: CO, 45" resolution, 180" sampling

Galactic Ring Survey, molecule ^{13}CO, 46" resolution 22" sampling http://www.bu.edu/galacticring/new_index.htm

Dobasi et al. Dark cloud Survey (using digital sky survey): http://darkclouds.u-gakugei.ac.jp/astronomer/astronomer.html

Giant Molecular Clouds

Most of the CO emission in the galaxy can be divided up into individual clouds with masses of 10^4-10^6 solar masses.

These are typically referred to as *Giant Molecular Clouds*.

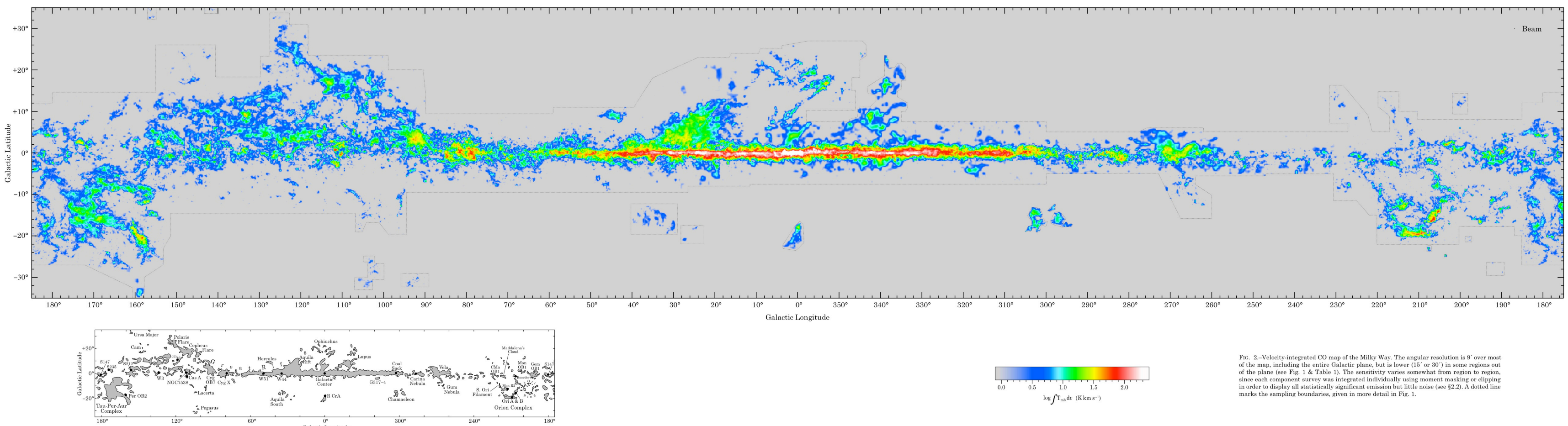
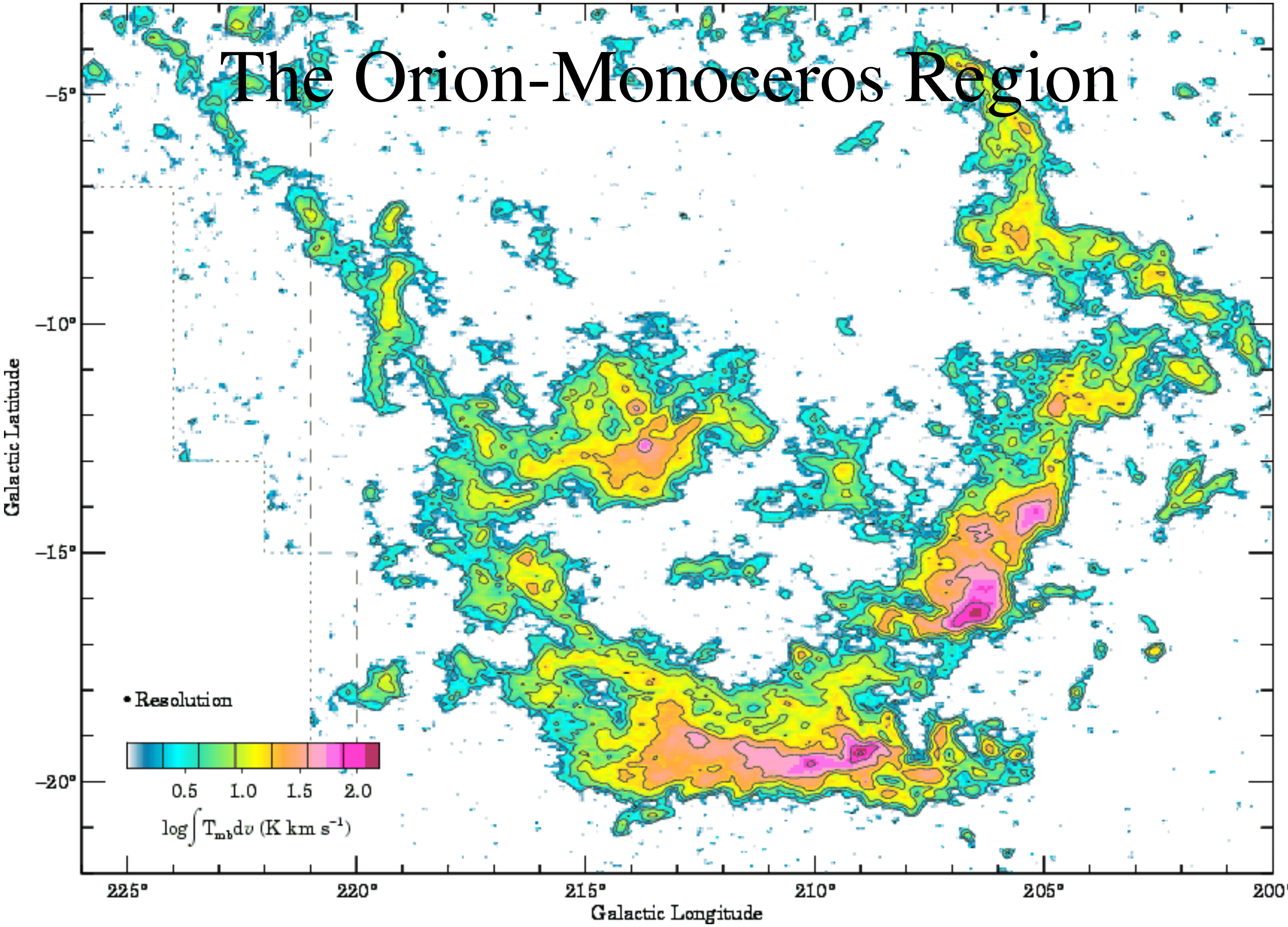
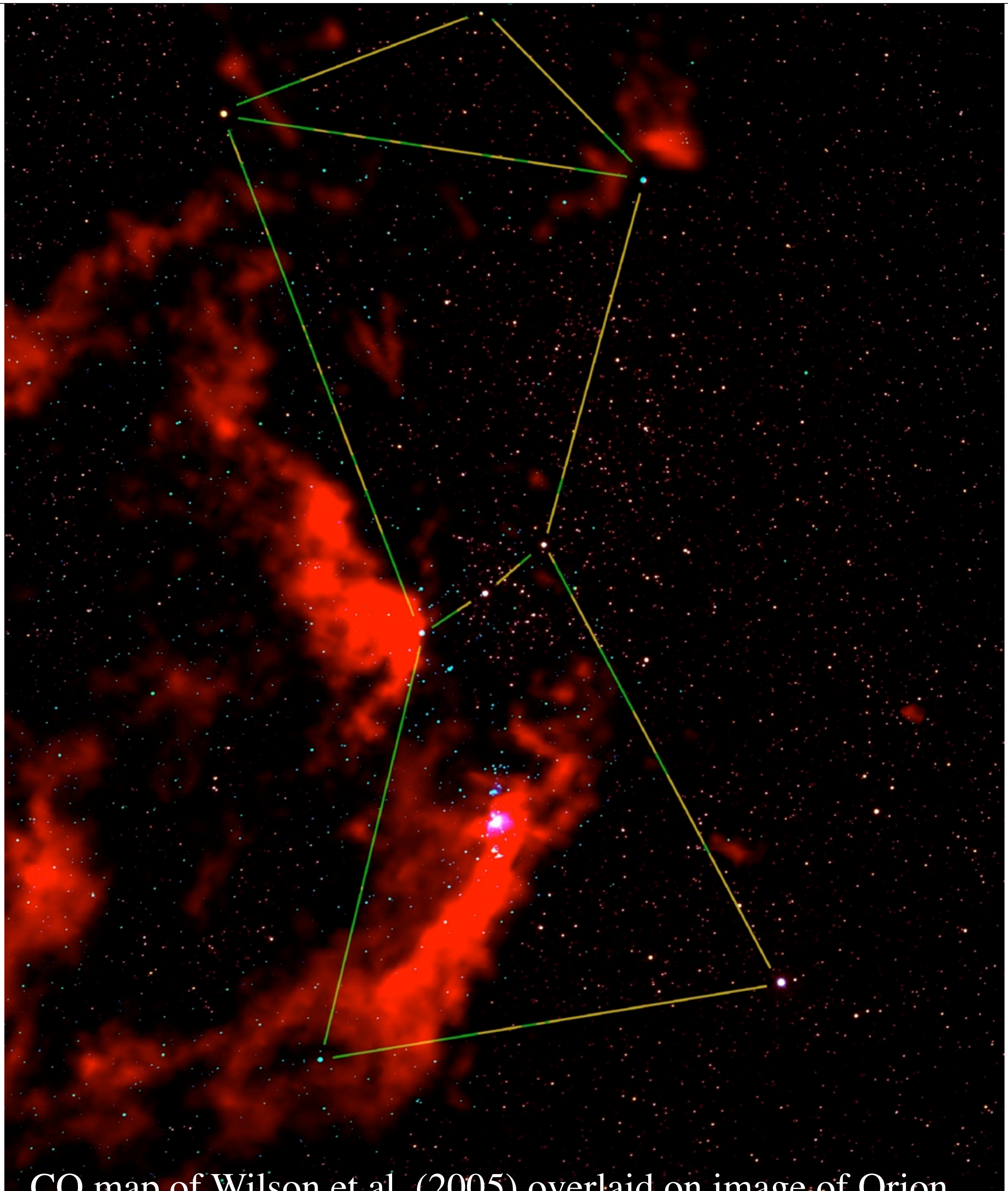


Fig. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey 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.

Giant Molecular Clouds



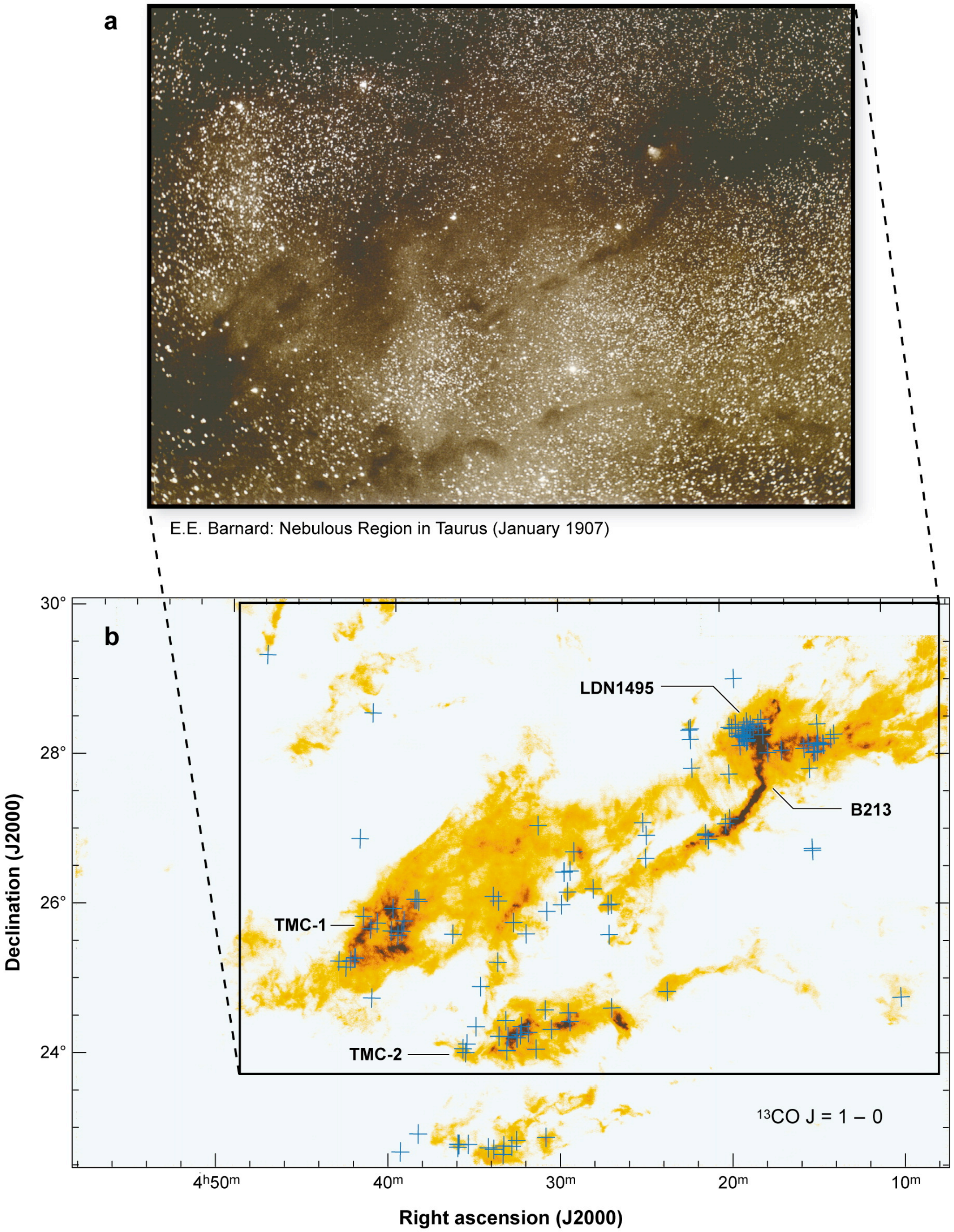
Wilson et al. 2005 A&A 430, 523



CO map of Wilson et al. (2005) overlaid on image of Orion

The Orion Giant Molecular Cloud Complex

Total mass 200,000 Msun



Molecular Cloud Complexes in the Milky Way: The Taurus Cloud

23,000 Solar Masses

Crosses: young stars and protostars

Smaller cloud forming primarily low mass stars.

Note: filamentary structure.

Bergin EA, Tafalla M. 2007.
Annu. Rev. Astron. Astrophys. 45:339–96

Map courtesy of P. Goldsmith, M . Heyer, G. Narayanan.

Molecular Clouds in the ‘hood

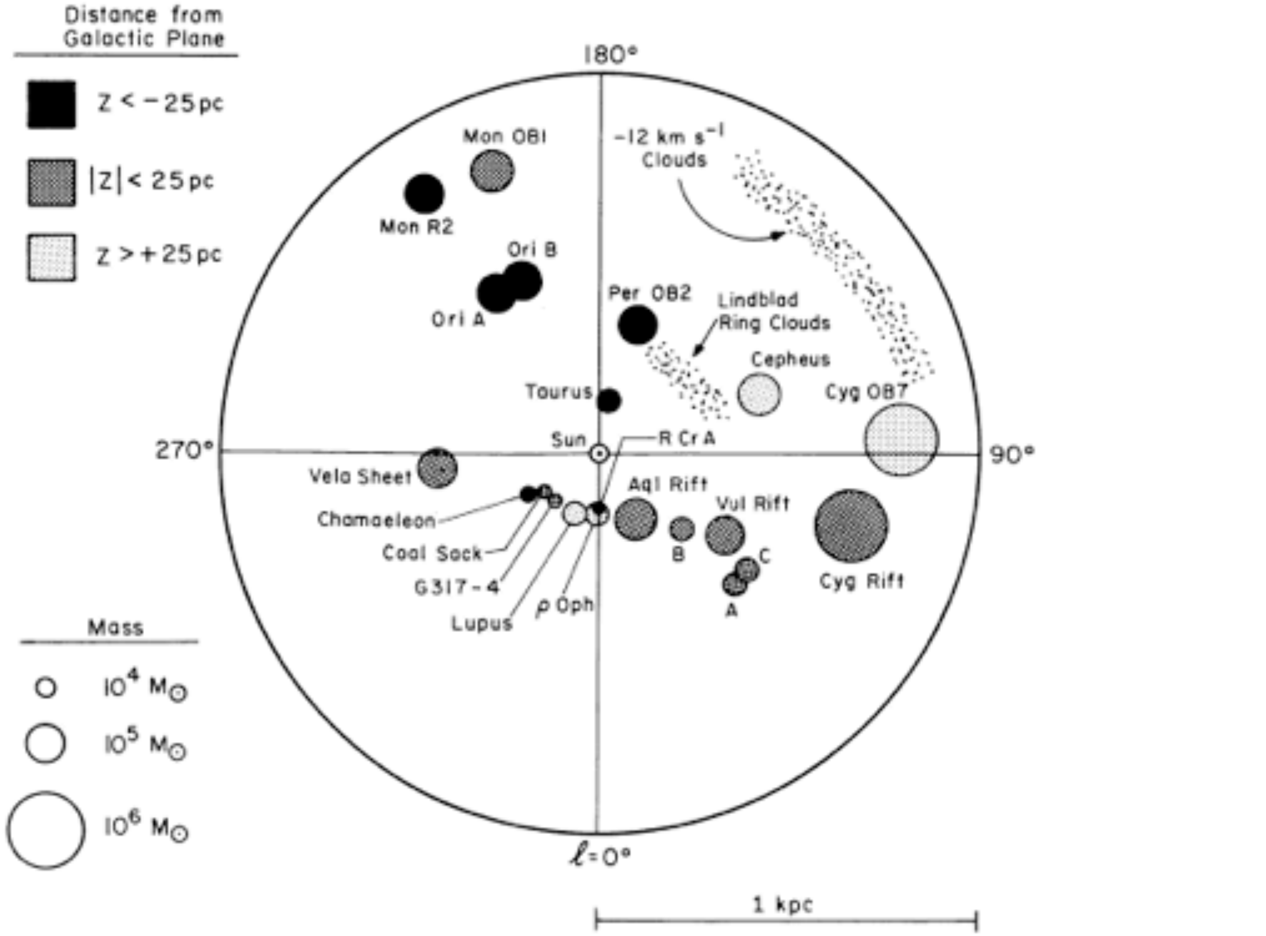


FIG. 7.—The distribution in the Galactic plane of molecular clouds within 1 kpc of the Sun (Table 2). The circle radii are proportional to the cube roots of the cloud masses and in most cases are close to the clouds' actual radii. The shading indicates distance from the Galactic plane.

The general regions of the " −12 km/s " and Lindblad Ring clouds are indicated but individual clouds are not shown. The widths of these regions in heliocentric distance are unknown; the widths shown are arbitrary.

Mapping Molecular Clouds

The Composition of Molecular Clouds

H_2
He (25% of mass)
dust (1% mass of mass)
CO (10^{-4} by number),
CS (~10^{-9} by number)
NH_3 (10^{-9} by number)
N_2H^+ (10^{-10} by number)

and many other molecules with low abundances.

Why molecular clouds cannot be mapped in H_2

Two reasons:

H_2 is a symmetric molecule without a permanent dipole moment. Dipole transitions are not permitted, so only electric quadrupole transitions are allowed.

Selection rules for electric dipole is $\Delta J=2$, thus the lowest rotational transition is the J=2 -> 0 transition.

Excitation energy of the J=2 is 510 K, typical cloud temperature is 30 K. In comparison, the first energy level of CO is 5.5 K

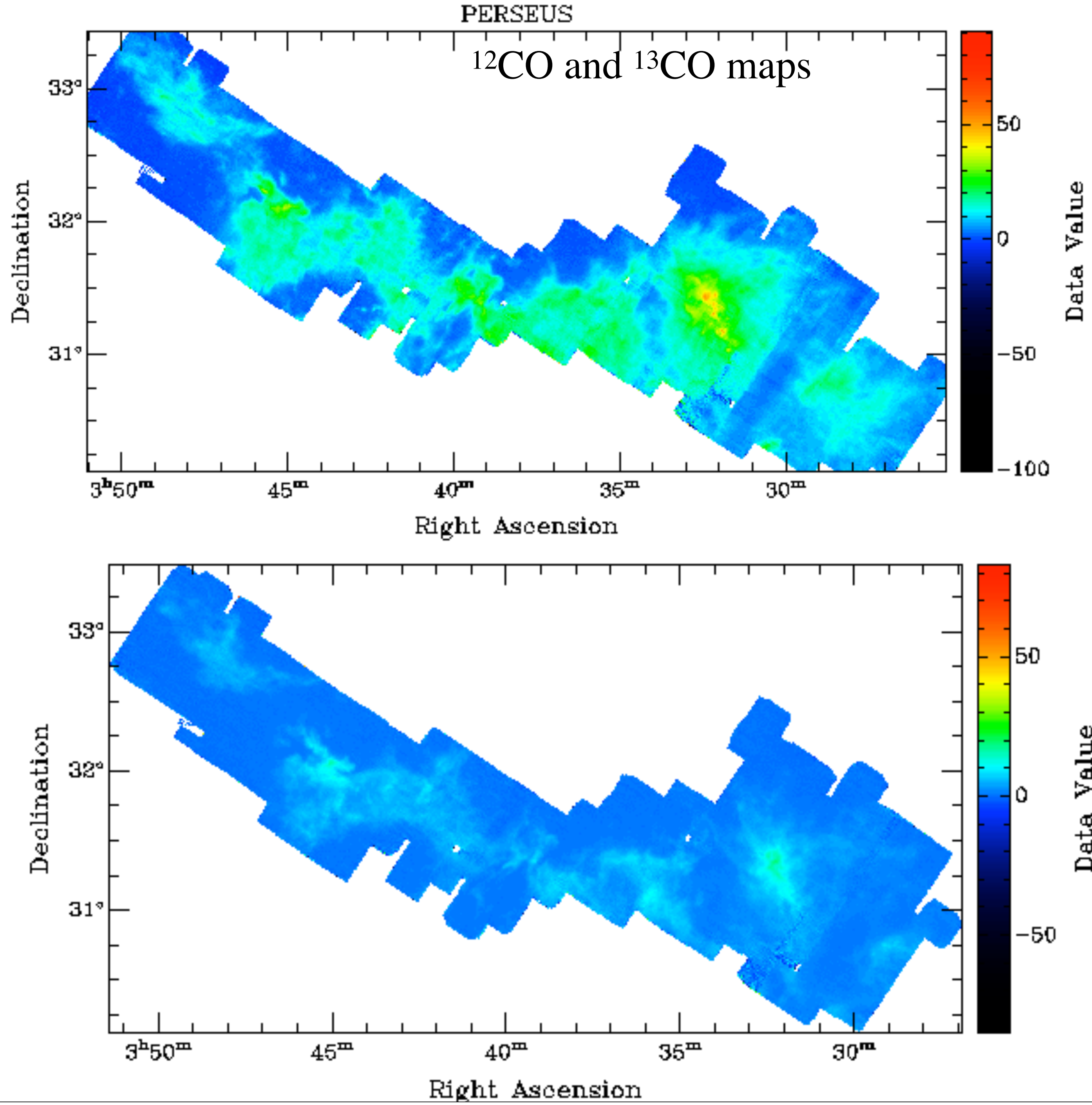
Quadrupole transitions are much weaker than dipole transitions:

H_2 (2 -> 0) $A_{20} = 2.54 \times 10^{-11}$ s^{-1}
CO (1-0) $A_{10} = 7.4 \times 10^{-8}$ s^{-1}

Mapping Molecular Clouds

- Combined ^{12}CO and ^{13}CO
- Extinction
- Thermal dust emission
- Virial theorem
- X-factor

http://www.cfa.harvard.edu/COMPLETE/data_html_pages/data.html



Calculating of CO Column Densities

$$B_\nu = \frac{2hv^3}{c^2}\frac{1}{e^{h\nu/kT}-1} \tag{1}$$

In the case $h\nu << kT$ then:

$$B_\nu = \frac{2\nu^2}{c^2}kT \tag{2}$$

Thus we can define brightness temperature as:

$$T_b = I_\nu \frac{c^2}{2\nu^2} \tag{3}$$

Given the equation of radiative transfer:

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu - B_\nu(T) \tag{4}$$

the solution is:

$$\frac{T_b(s)}{d\tau_\nu} = T_b - T(s) \tag{5}$$

which if you are observing a cloud of constant temperature T, the integral is:

$$T_b = T(1 - e^{-\tau_\nu}) \tag{6}$$

Calculating of CO Column Densities

$$T_A(\nu) \quad = \quad (\frac{T_o}{e^{T_o/T_{ex}} - 1} - \frac{T_o}{e^{T_o/T_{cmb}} - 1})(1 - e^{-\tau_\nu})$$

where $T_o = h\nu/k$.

$$T_{ex} = \frac{5.5}{ln(1 + \frac{5.5}{T_A + 0.82})}$$

← ^{12}CO is in optically thick limit: $\tau_\nu > 1$

^{13}CO is in optically thick limit: $\tau_\nu < 1$

$$N_{tot}(^{13}CO) = 2.6 \times 10^{14} \frac{1}{1 - e^{-5.3/T_{ex}}} \int T_A dv$$

From Genzel 1989

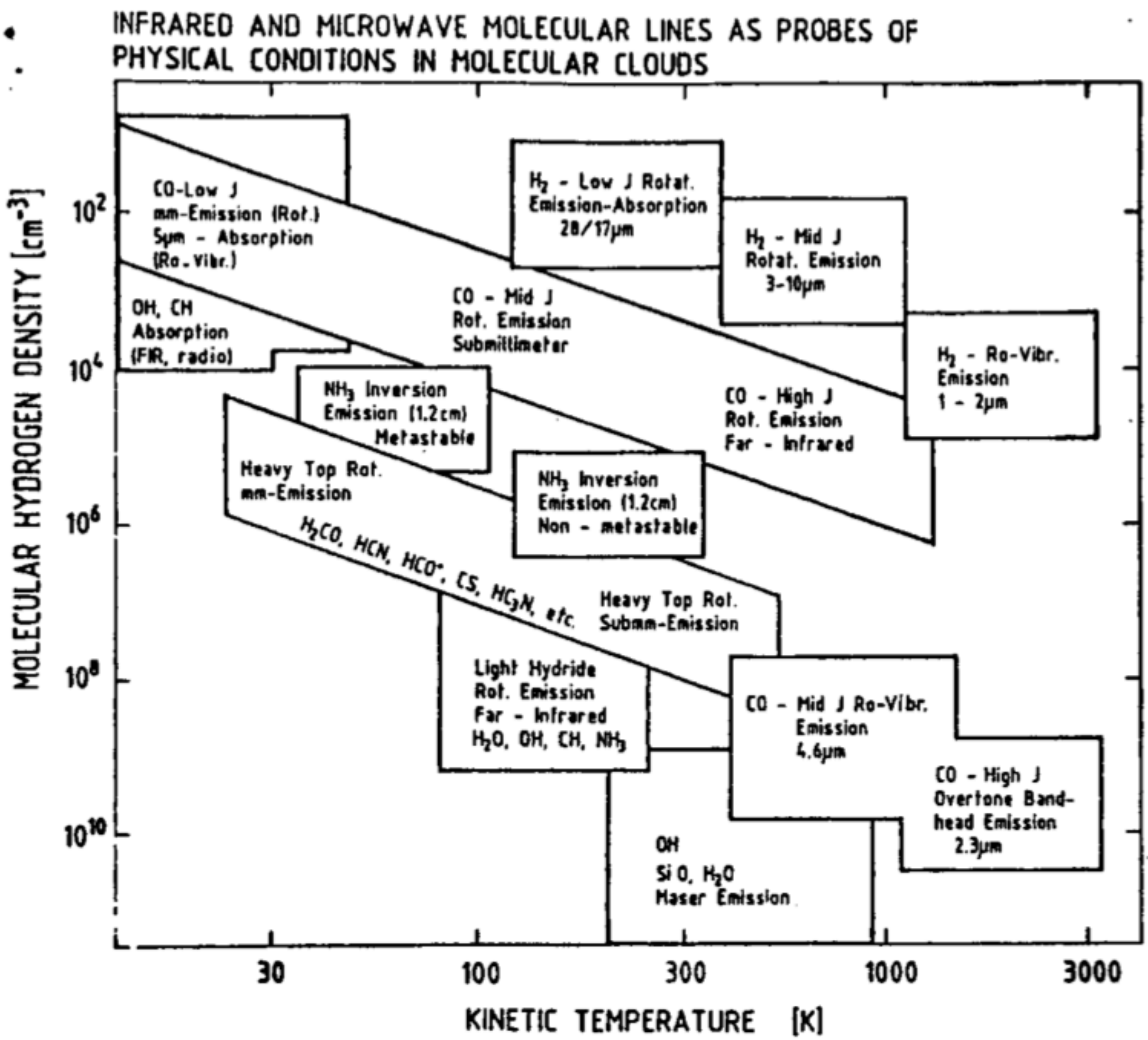
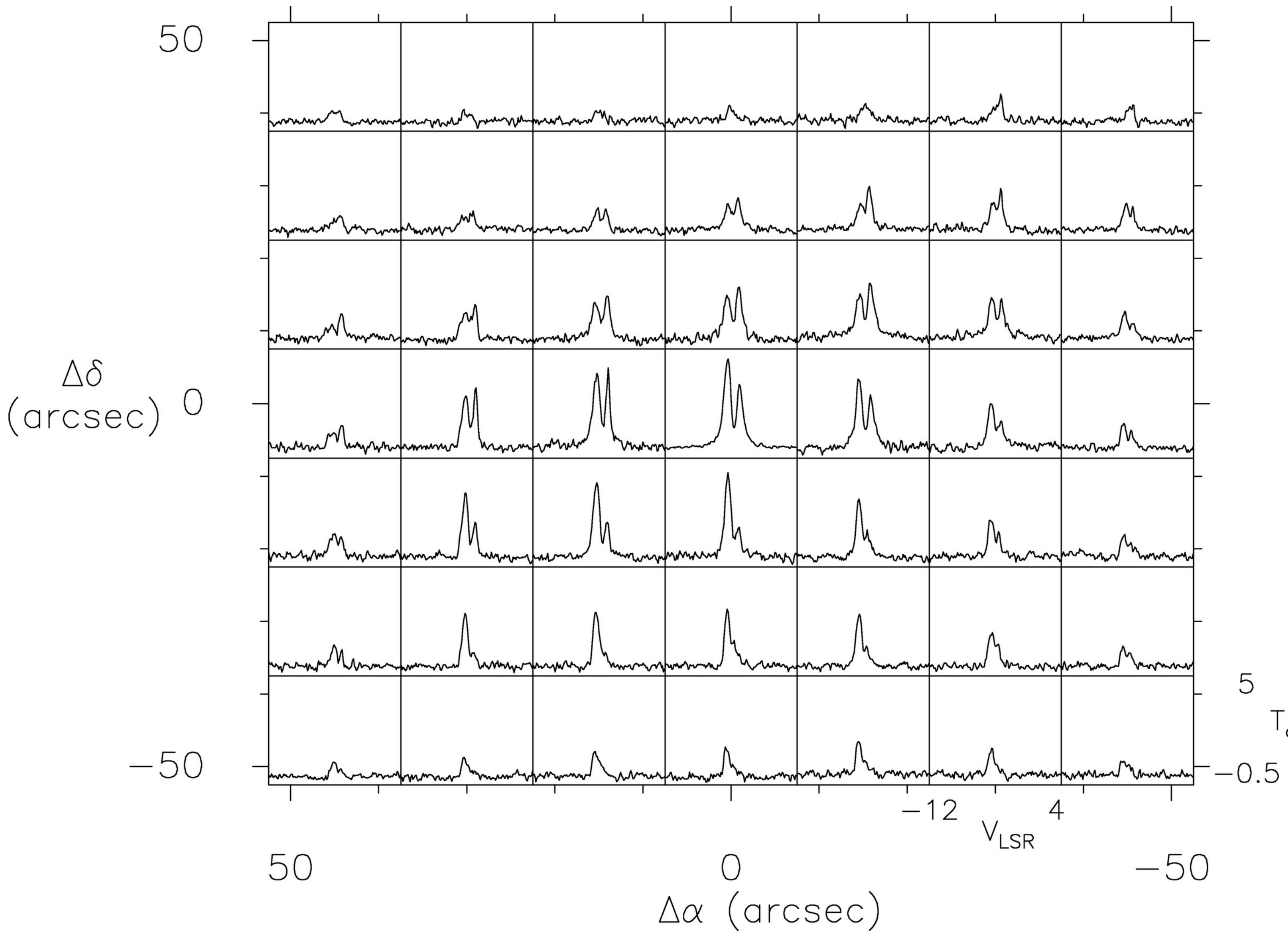
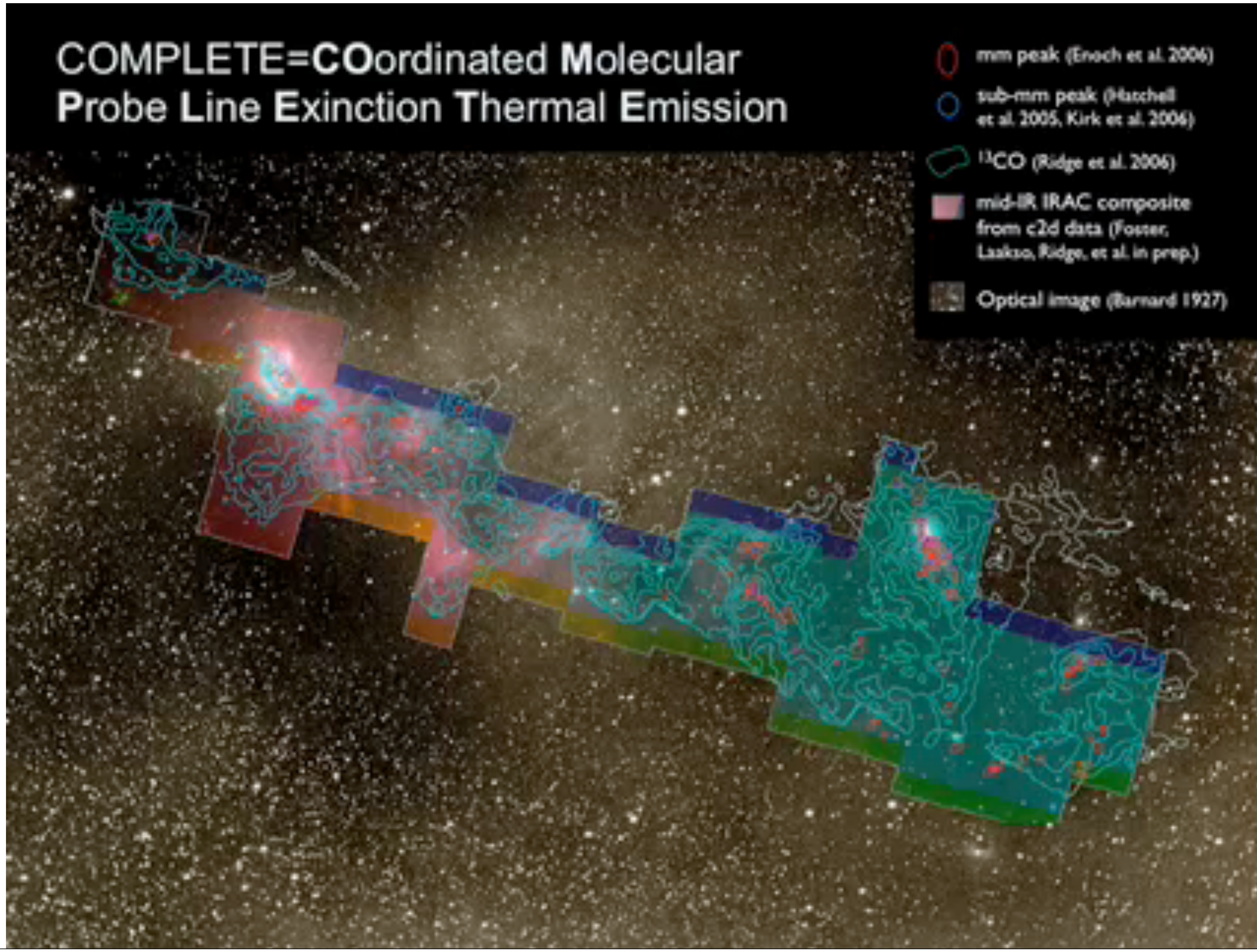


Fig. 8. Molecular lines as probes of physical conditions in interstellar clouds

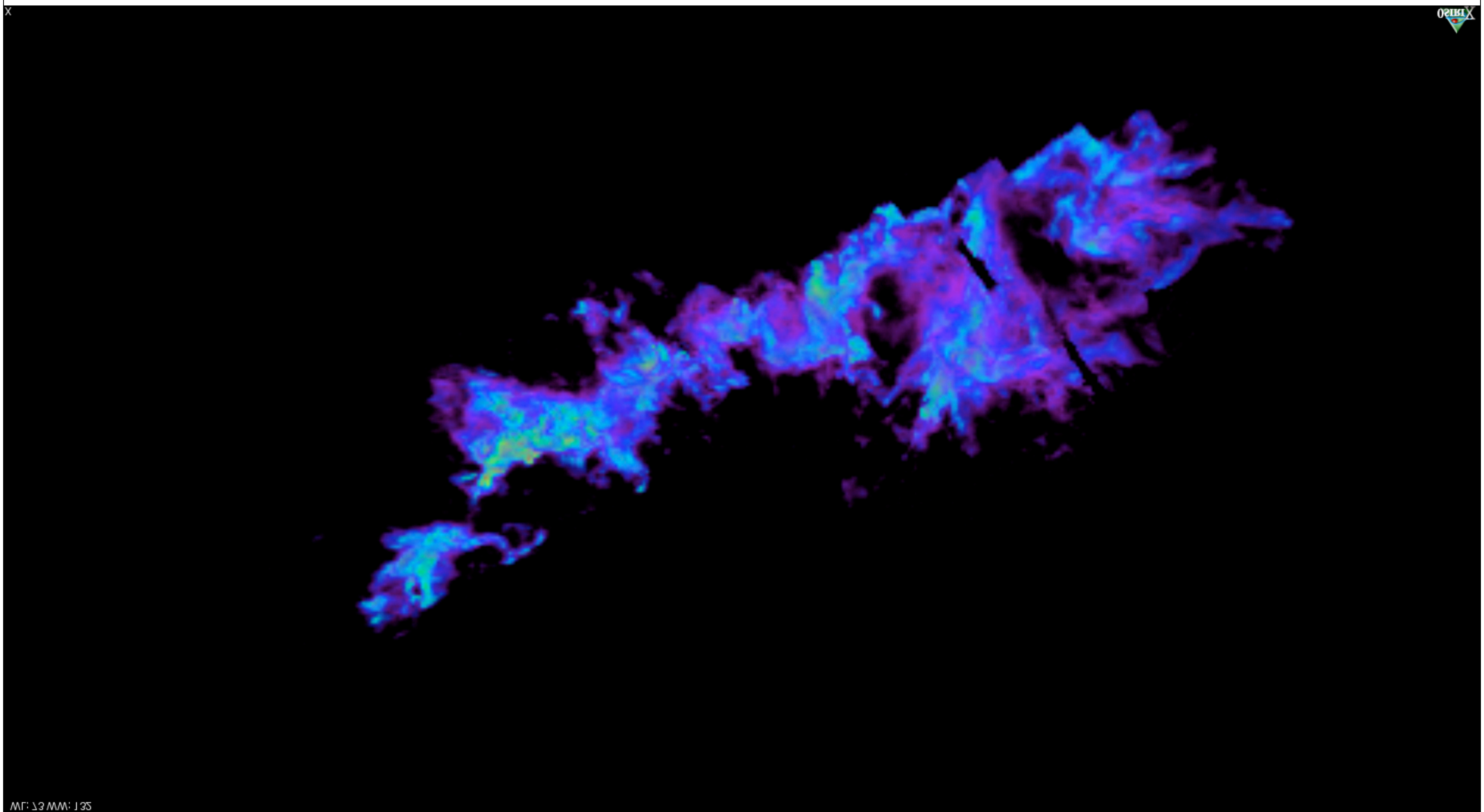
Advantages of Molecular Data: Velocity Information (a 3rd dimension)



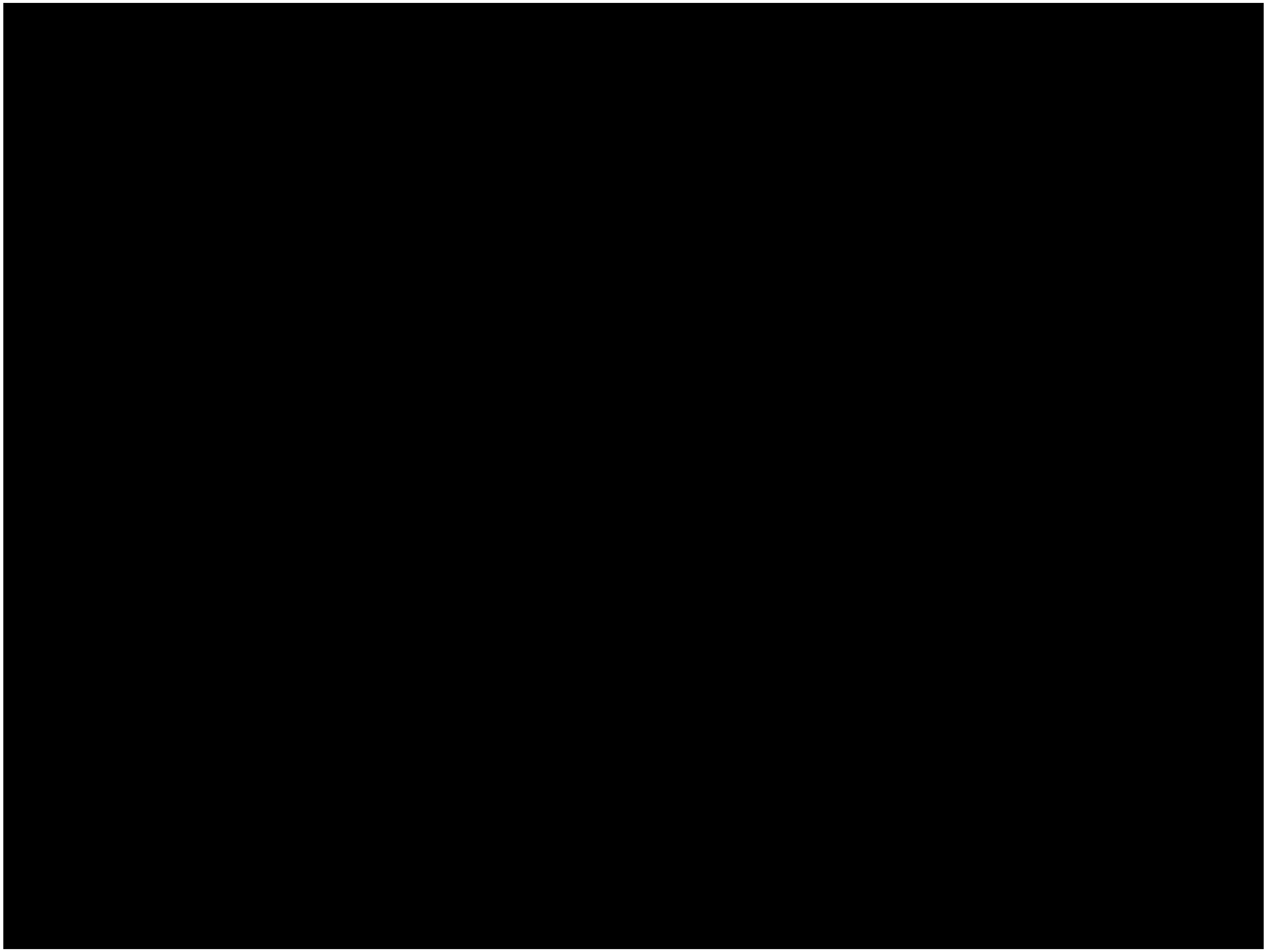
Structure of Clouds I: Data Cubes



Structure of Clouds I: Data Cubes

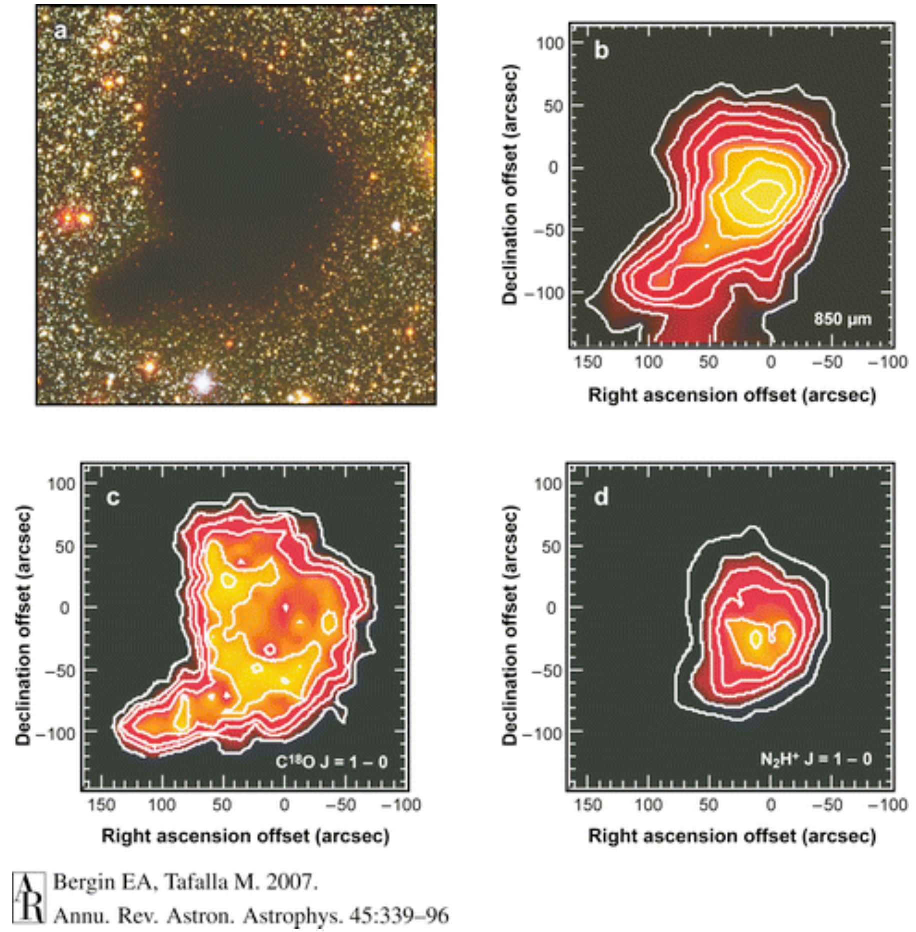


Structure of Clouds I: Data Cubes



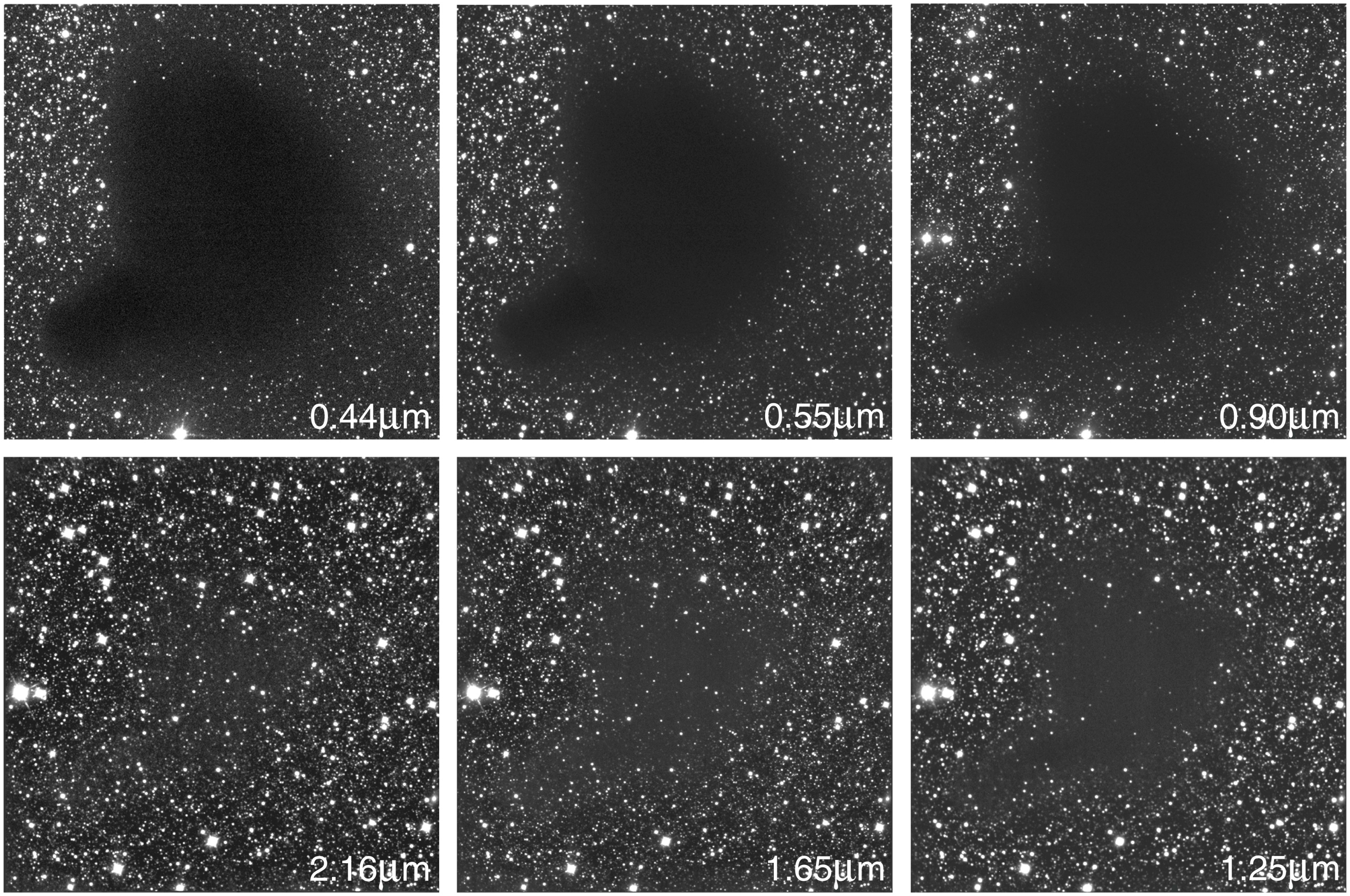
Problems with CO (and other molecules)

- Freeze out
- Chemistry
- Optical depth & excitation



Bergin et al. 2002

Extinction Mapping



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

ESO PR Photo 29b/99 (2 July 1999)

Extinction Mapping

$$F_\nu(app) = F_\nu(abs)(10pc/D)^2 e^{-\tau_\nu}$$

F_ν(app) is observed flux

F_ν(abs) is unattenuated flux observed at 10 pc

$$\begin{aligned}
m_\lambda &= -2.5log_{10}(F_\nu(app)/(F_\nu(Vega)) \\
&= -2.5log_{10}(F_\nu(abs)(10\ pc/D)^2 e^{-\tau_\nu}/(F_\nu(Vega)) \\
&= -2.5log_{10}(F_\nu(abs)(10\ pc/D)^2/(F_\nu(Vega)) - 2.5log_{10}(e^{-\tau_\nu}) \\
&= -2.5log_{10}(F_\nu(abs)(10\ pc/D)^2/(F_\nu(Vega)) + 1.09\tau_\nu \\
&= M_\lambda + A_\lambda + 5log(D/10\ pc)
\end{aligned}$$

Color Excess

$$m_{\lambda_1} - m_{\lambda_2} = M_{\lambda_1} - M_{\lambda_2} + A_{\lambda_1} - A_{\lambda_2}$$

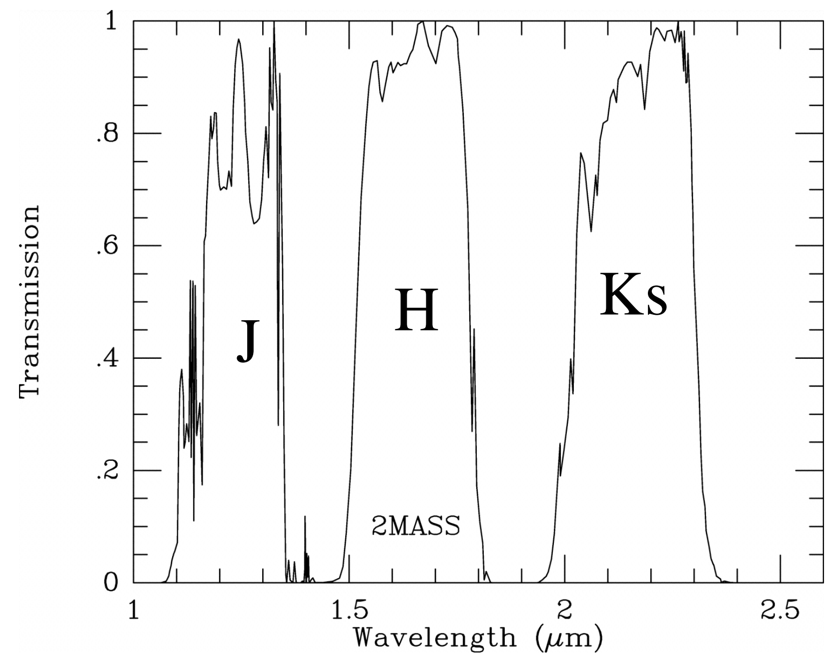
Observed color

Intrinsic color

Color Excess due to interstellar dust

For the near-IR H and K-bands, the color excess is given by:

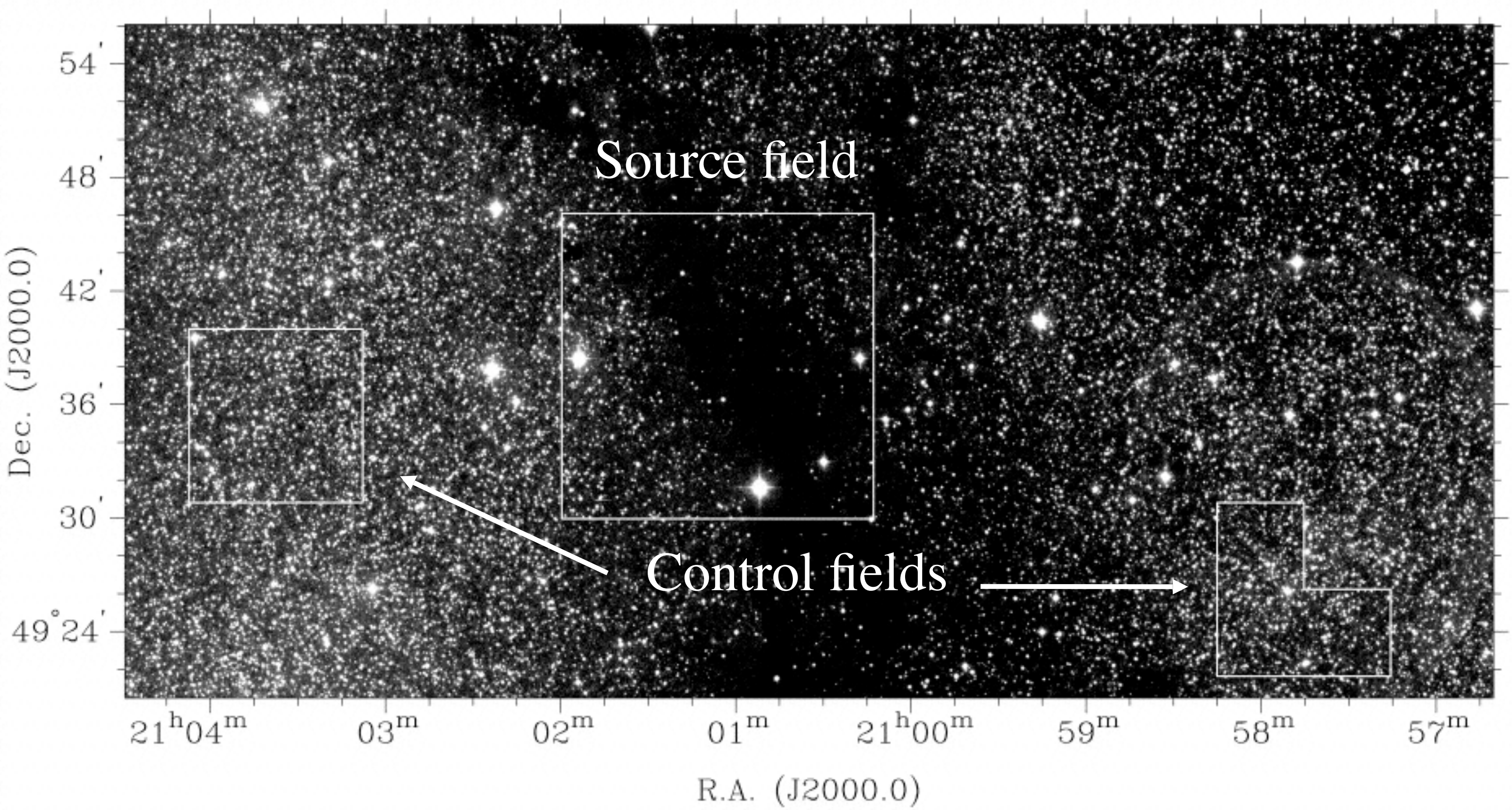
$$E(H-K) = (H-K)_{observed} - (H-K)_{intrinsic}$$



2MASS filters, Cohen et al. 2003, 126, 1090.

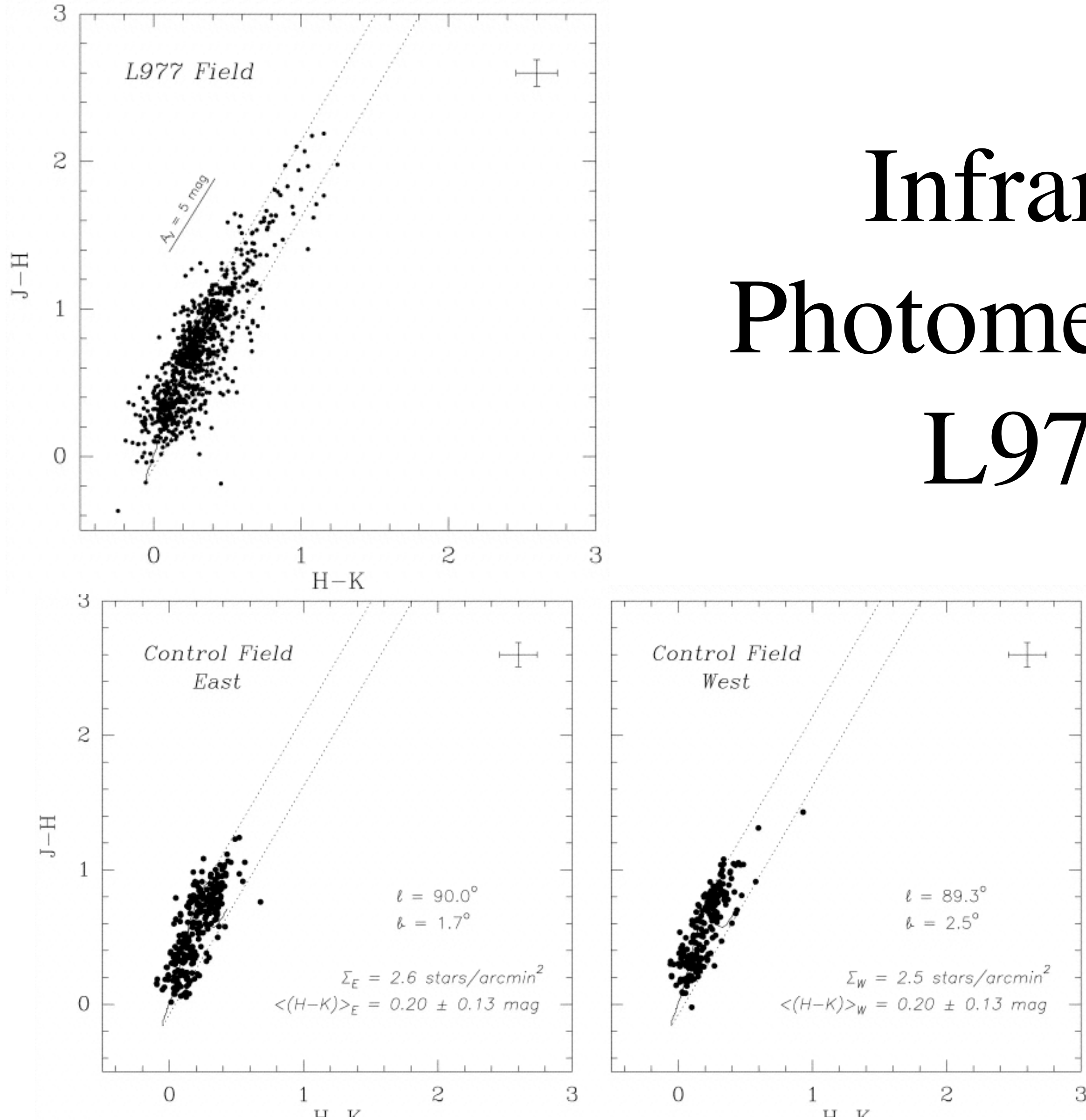
The Dark Cloud L977

Alves et al. 1998 ApJ 506, 292



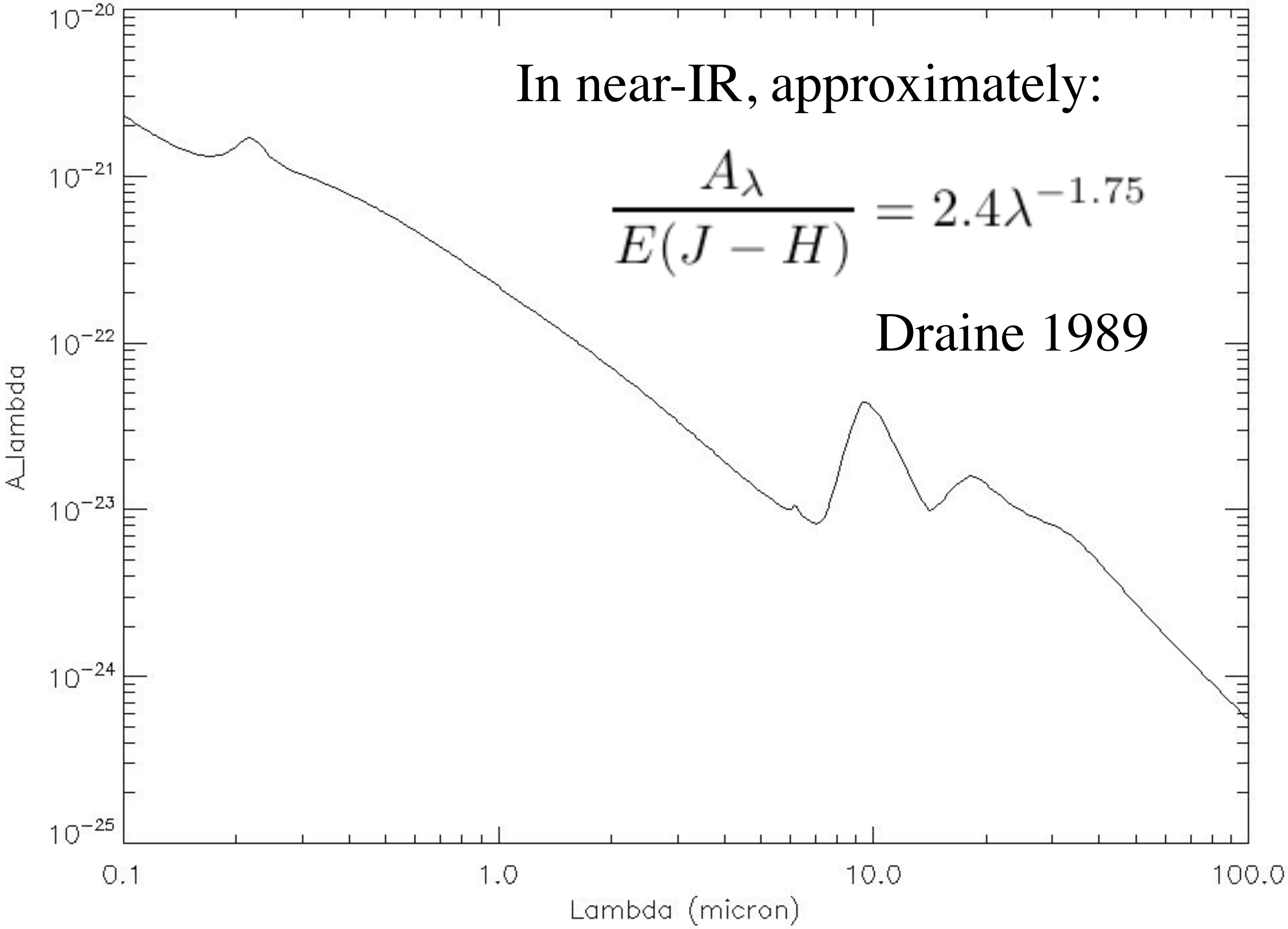
Visible light image

Infrared Photometry of L977



$$(H-K)_{intrinsic} = 0.20 \pm 0.13\ mag$$

The Interstellar Extinction Law from 0.1 to 100 μm



Weingartner & Draine (2001) $R_V = 3.1$

Converting From Color Excess to Column Density

$$E(H-K) = (H-K)_{observed} - (H-K)_{intrinsic}$$

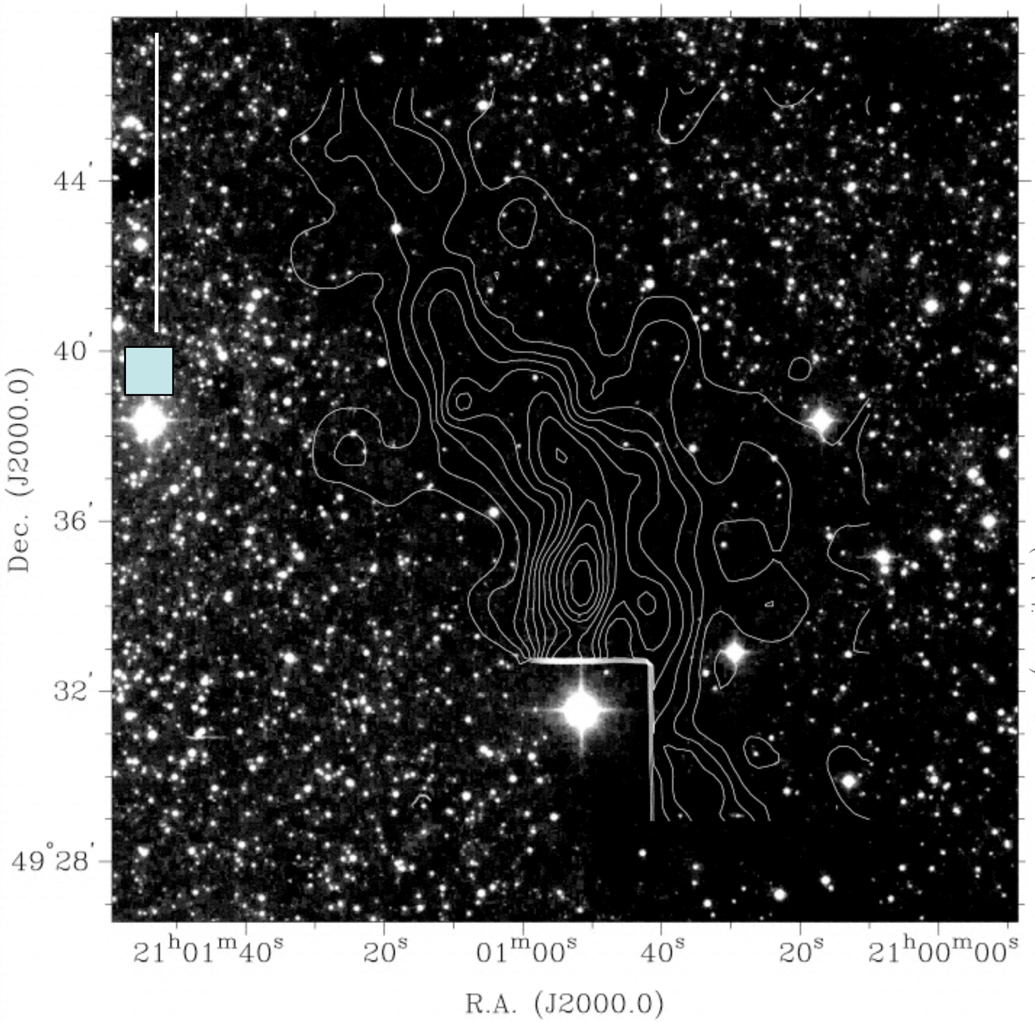
$$(H-K)_{intrinsic} = 0.20 \pm 0.13\ mag$$

$$A_V = 15.87E(H-K)$$

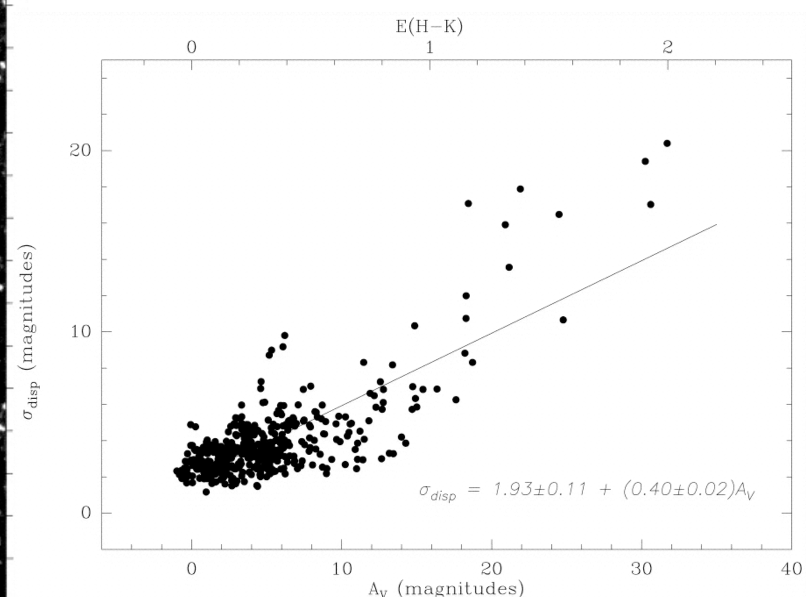
$$N(H_2) = 1 \times 10^{21}(A_V)cm^{-2}$$

Smoothing the Extinction Map

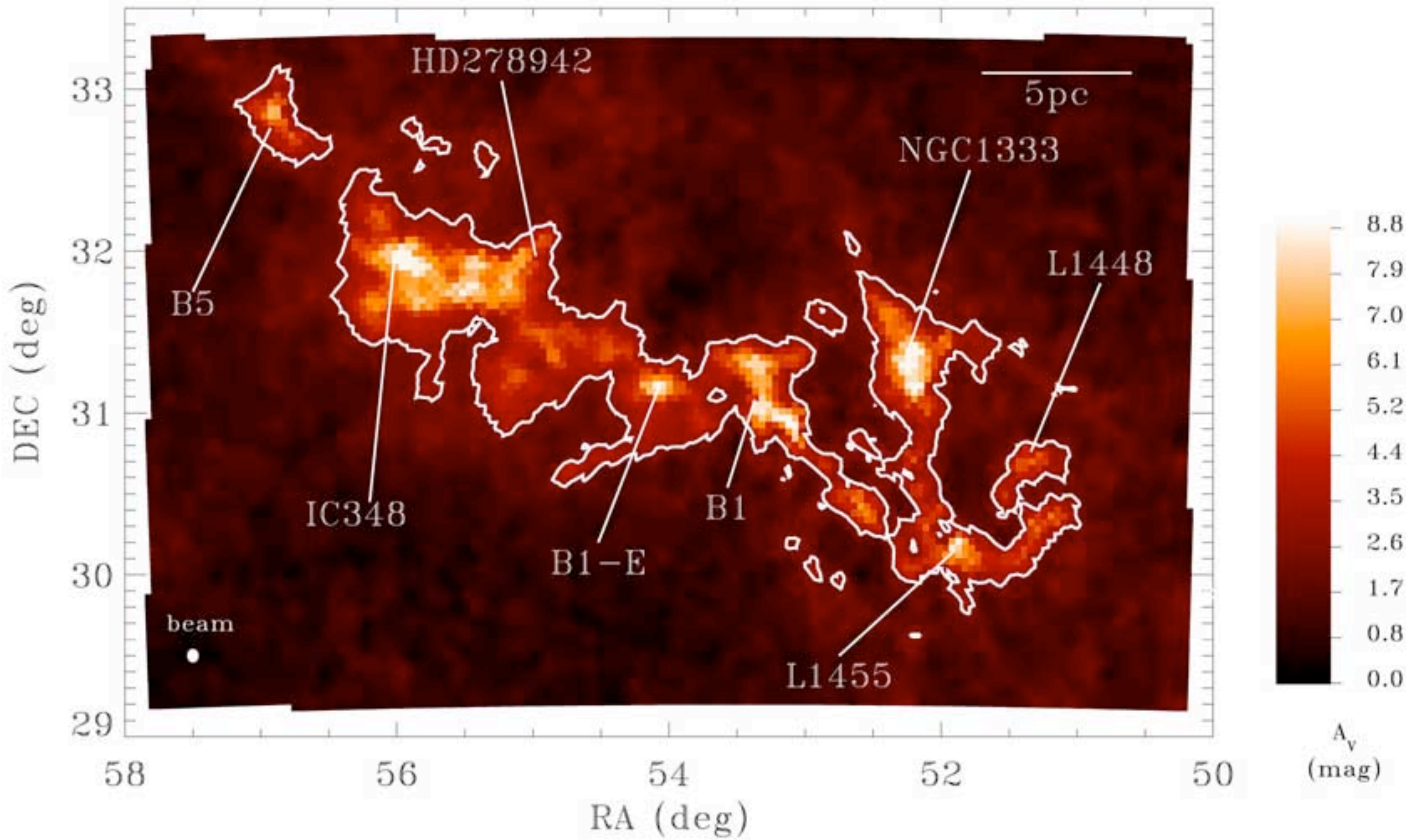
Smoothing box



Take mean extinction in 90”x90” squares placed every 45”

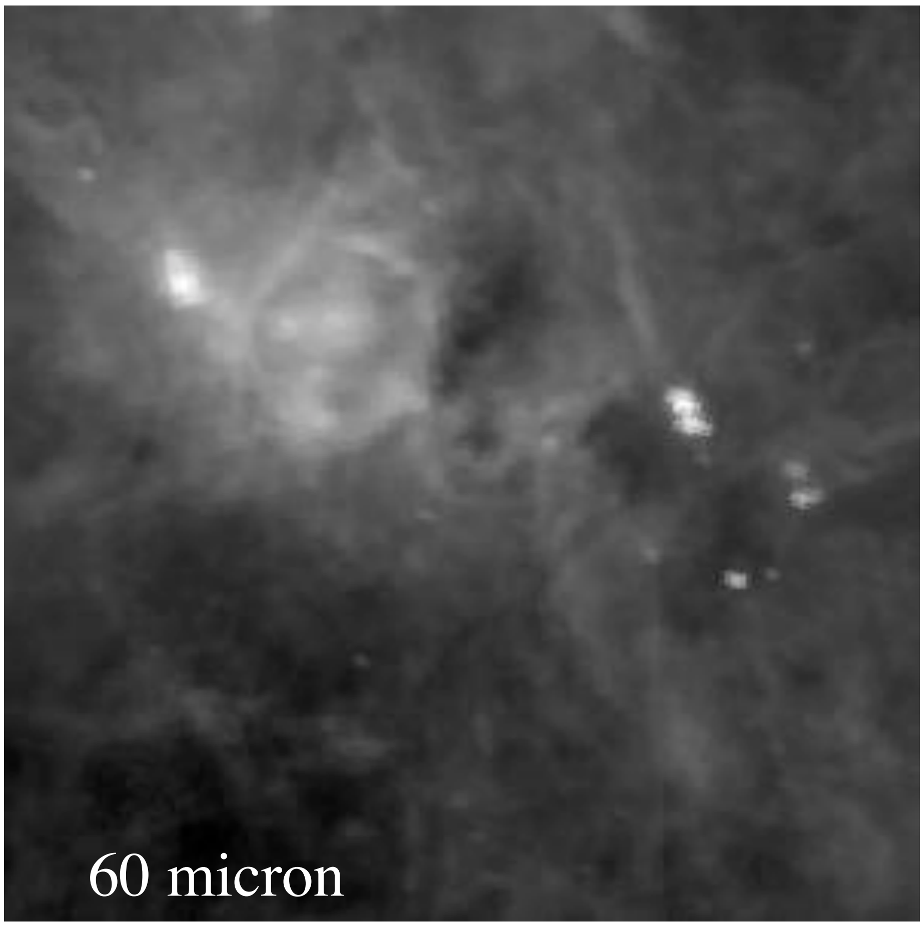


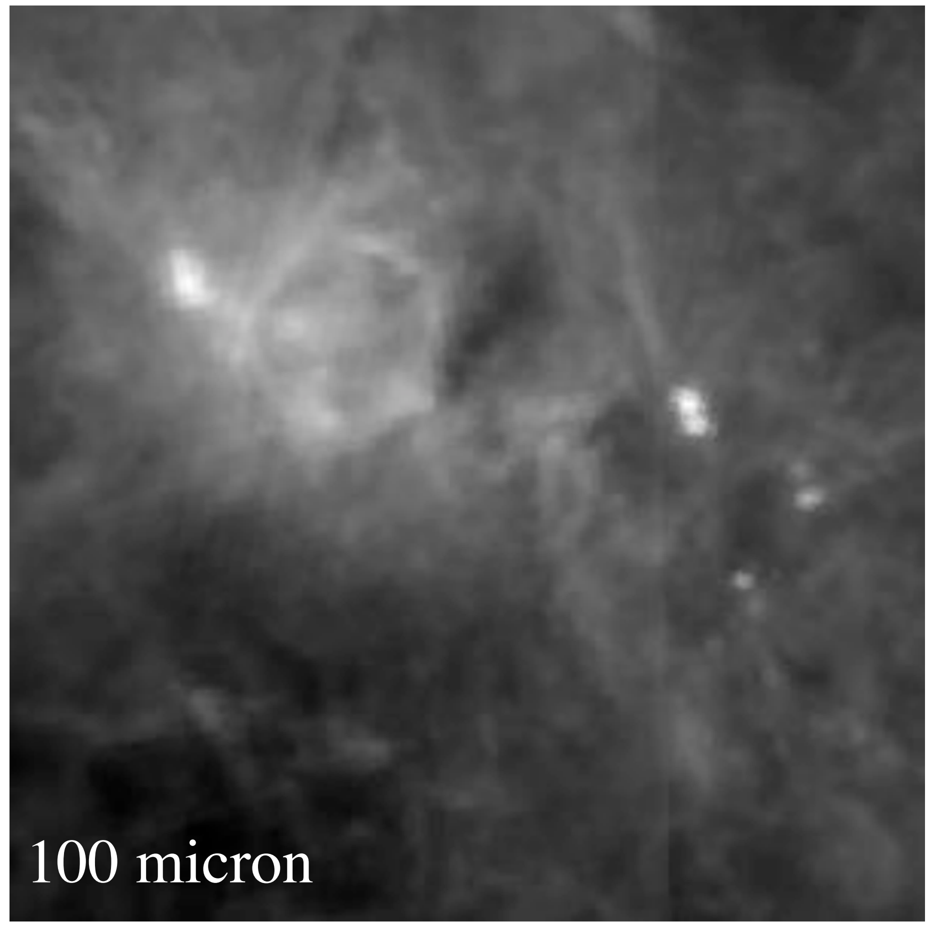
Extinction Map



http://www.cfa.harvard.edu/COMPLETE/data_html_pages/data.html

IRAS 60 and 100 micron images





Thermal Emission

In optically thin limit ($\tau_\nu << 1$):

$$\begin{aligned} I_\nu &= B_\nu(1 - e^{-\tau_\nu}) \\ &= \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}(1 - e^{-\tau_\nu}) \\ &= \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}\tau_\nu \end{aligned}$$

Use relationship:

$$\tau_\nu = \alpha\lambda^{-\beta}N_H$$

Where α and β are empirically determined.

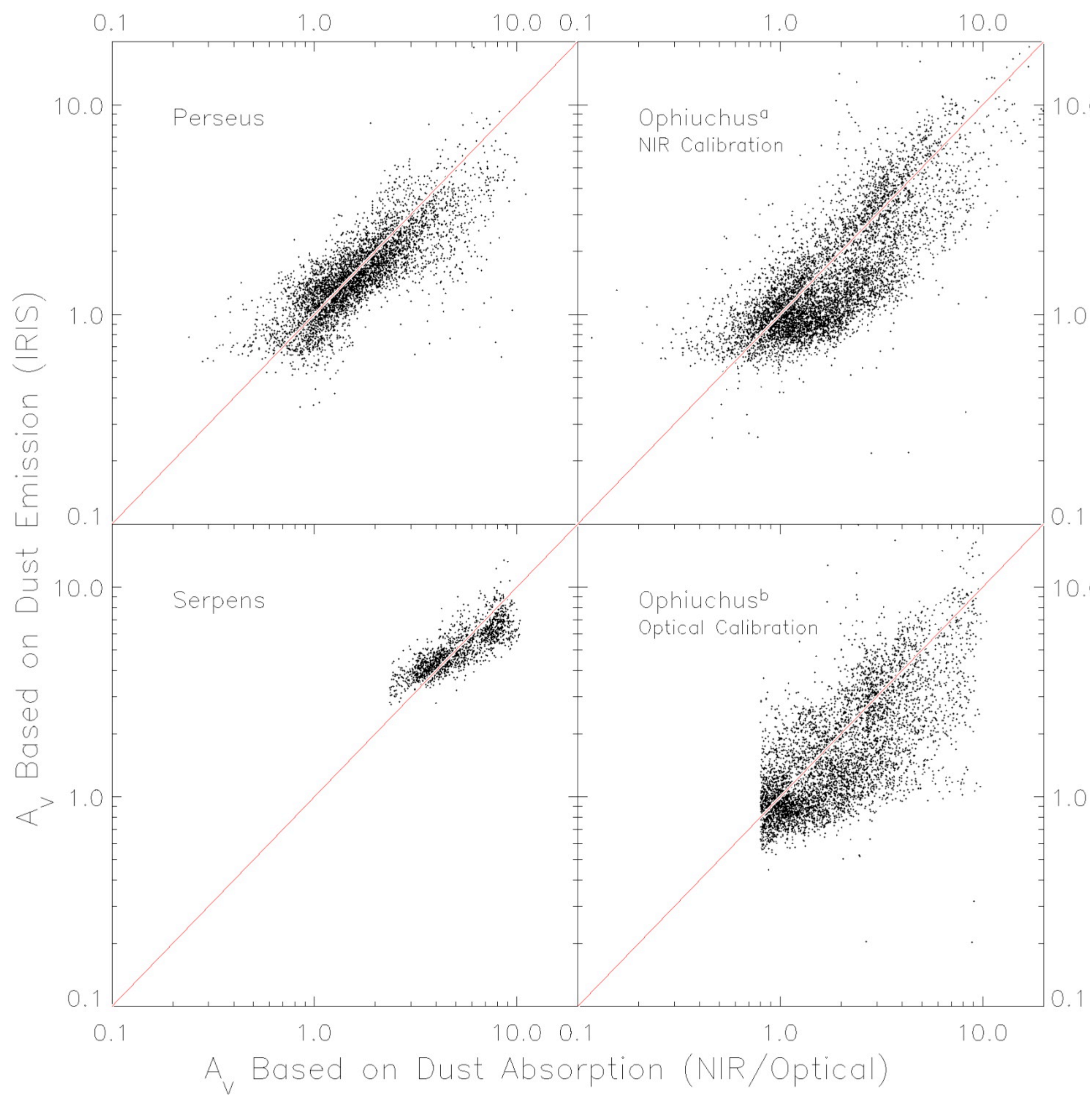
Thermal Emission (Con't)

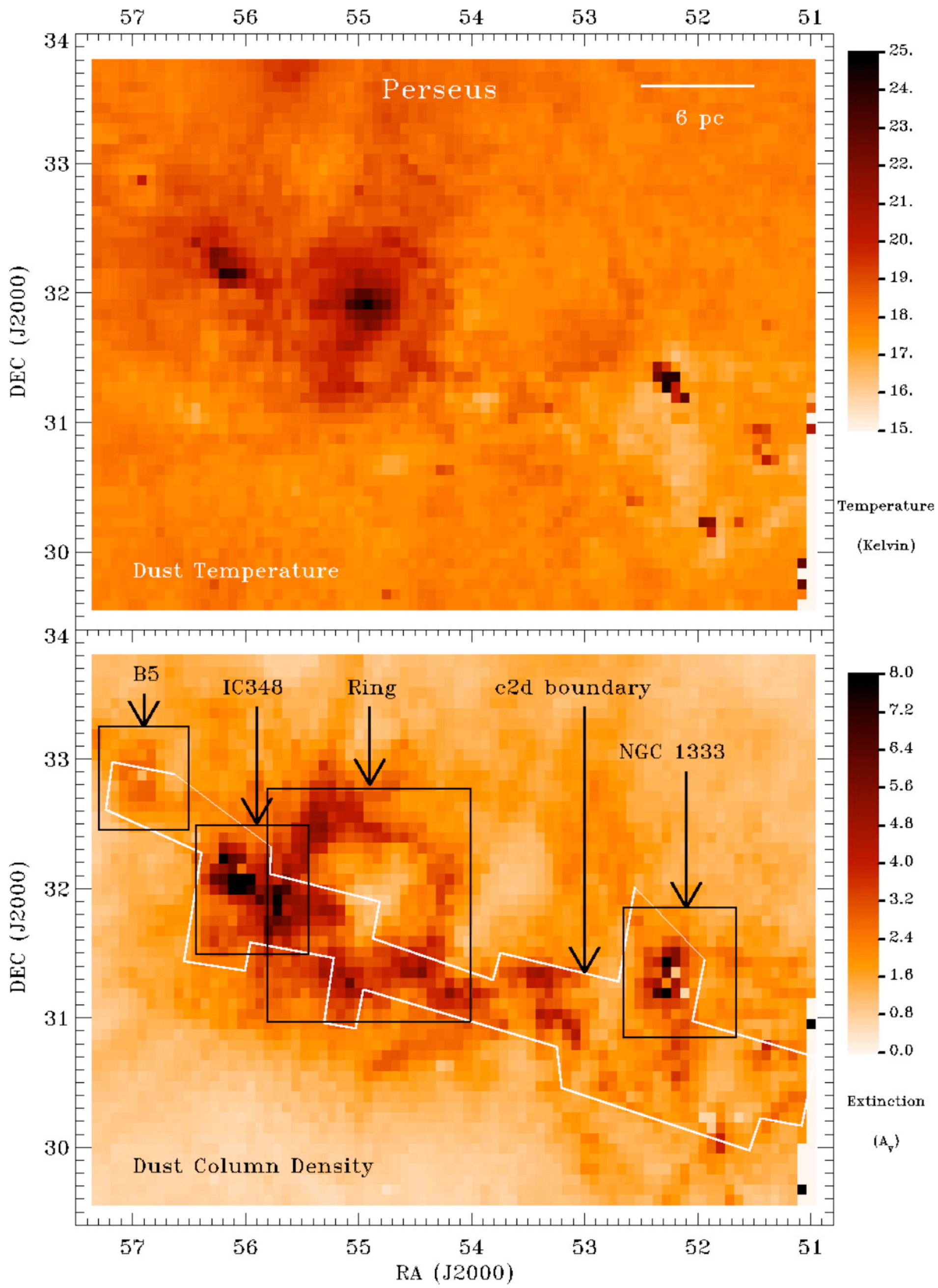
If you had a single grain size (Hillenbrand 1983):

$$\tau = \sigma^2 Q(\nu) N_{dust}$$

Given that we have a whole distribution of grain sizes, calibrate empirically:

$$A_V = X \tau_{100}$$





IRAS generated Temperature and Column Density Maps

Schnee et al 2005, 634, 442

Determining Cloud Mass With The Virial Theorem

Assume clouds are bound and in equilibrium

Virial theorem: $T = -1/2U$ (where T is K.E. and U is gravitational potential energy)

$T = 1/2\ M <v^2>$ where $<v^2>$ is the velocity dispersion of the cloud and can be derived from the linewidth.

For a spherical cloud with a uniform density:

$U = -3/5\ G\ M^2/R$ (you should be able to derive this!!!)

In this case we can derive a cloud mass:

$$1/2\ M<v^2> = 3/5\ GM^2/R \ \Rightarrow\ M = (5/(6G) <v^2> R)$$

This is typically written as:

$M[solar\ mass] = k_1 R[pc] \Delta V^2 [km\ s^{-1}]$

where ΔV is the Full Width at Half Maximum (FWHM) of the line and k_1 depends on the degree of central concentration. If $\rho(r)$ is the density as a function of radius:

$\rho(r)$ = constant, k_1= 210, $\rho(R) \sim 1/r$: k_1 = 190, $\rho(R) \sim 1/r^2$: k_2 = 126

Determining cloud masses in CO Surveys of our galaxy and others.

Statement of Problem:

1. Most surveys are done in CO because ^{13}CO line it too weak.
2. ^{12}CO line is optically thick - how can we measure masses?
3. We measure sizes of cloud, line widths and integrated ^{12}CO temperatures.

Determining Cloud Mass With the X-Factor

Measure for each pixel of cloud the quantity W_{CO}:

$$W_{CO} = \int T_{CO}\, dv \ [K\ km\ s^{-1}]$$

Then convert to column density:

$$N(H_2) = X\, W_{CO} \text{ where } X = 1.7 \times 10^{20}\ cm^{-2}/K\ km\ s^{-1}$$

X has been calculated empirically by comparing CO data, HI data, and maps of the 100 μm dust emission (Dame, Hartmann & Thaddeus 2001 ApJ, 547, 792).

This cannot be used to map accurately column density, but is reasonable for finding masses over molecular clouds.

$M = 2.7 m_H \int N(H_2) D^2 d\Omega$ where D is the distance, Ω is solid angle, and $2.7 m_H$ is the mass per hydrogen molecule.

End