Physics 224
The Interstellar Medium

Lecture #16

Tracing Molecular Gas

H_2 is difficult to detect in cold, dense gas.
First rotational level requires $T > 100$ K to excite.

Need "tracers" for molecular gas:

- CO rotational emission
- dust extinction or emission
- other molecules rotational lines
- γ-rays

CO is the easiest -
bright & can be observed from the ground

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

column density of H_2

integrated intensity of CO line

$$N_{H2} = X_{CO}\ I_{CO}$$

X_{CO}: [$\mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}$]

molecular gas mass surface density

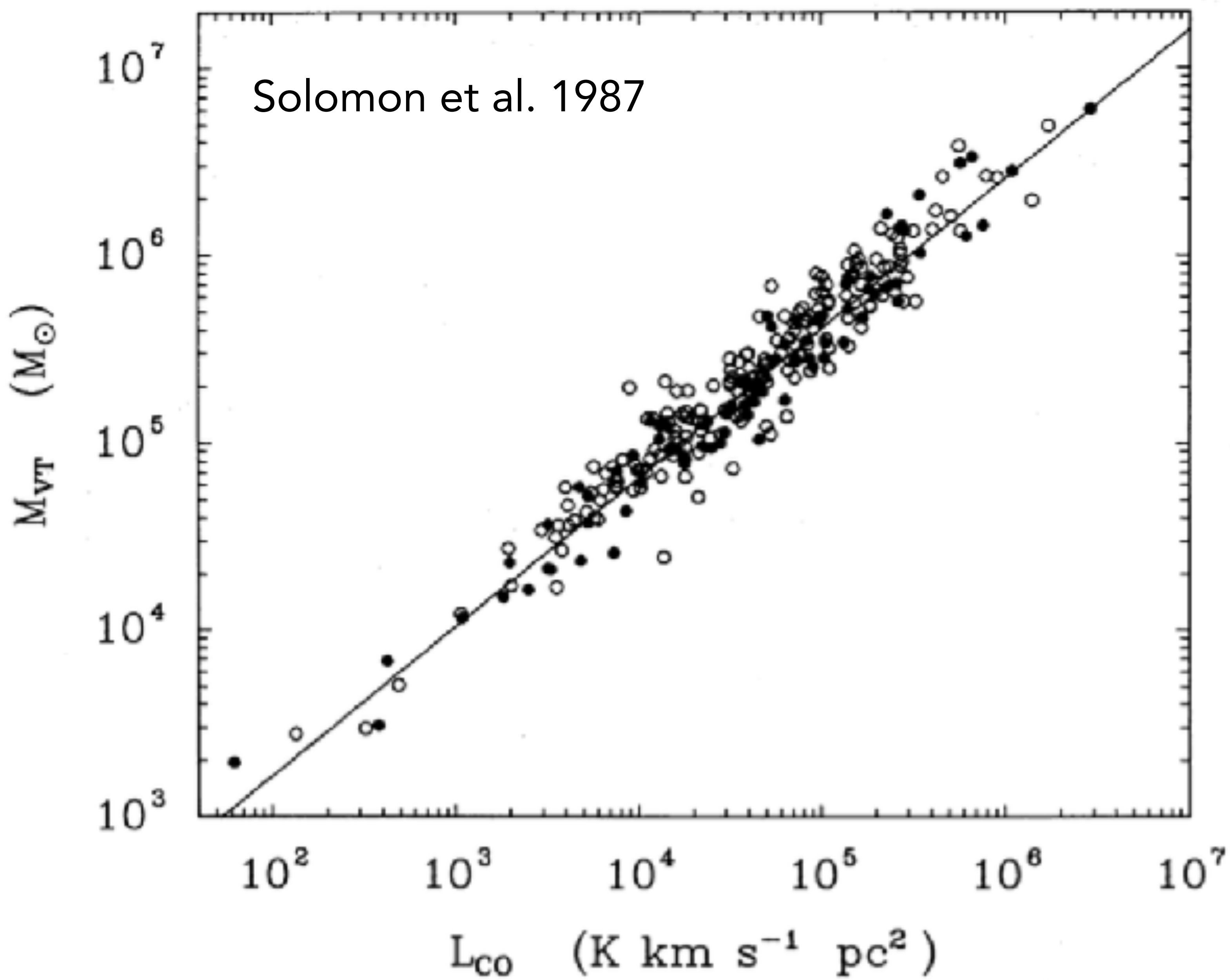
integrated intensity of CO line

$$\Sigma_{mol} = \alpha_{CO}\ I_{CO}$$

α_{CO}: [$\mathrm{M_\odot\ pc^{-2}\ (K\ km\ s^{-1})^{-1}}$]

Tracing Molecular Gas

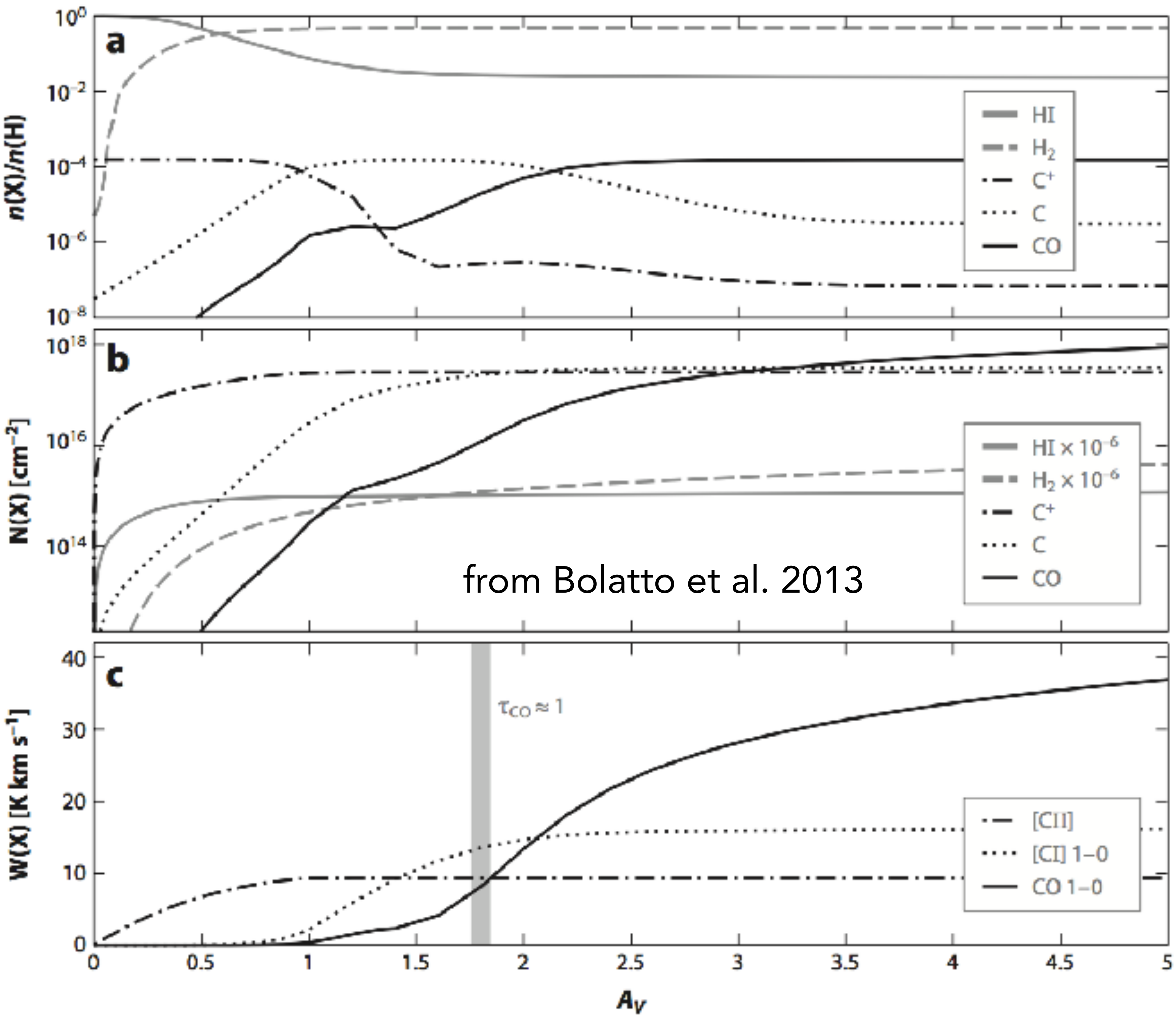
The CO-to-H_2 Conversion Factor



assuming clouds are in virial equilibrium you can use their velocity dispersion & sizes to calculate their mass

Correlation between CO luminosity & inferred mass led to first X_{CO} calibrations

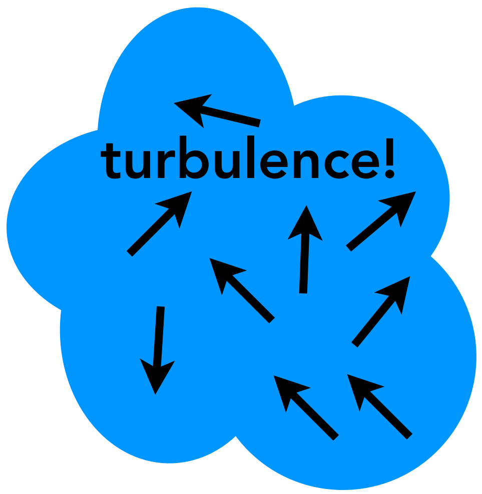
Tracing Molecular Gas



One key point: ^{12}CO low-J rotational emission is very optically thick!

How does an optically thick line tell you the mass?

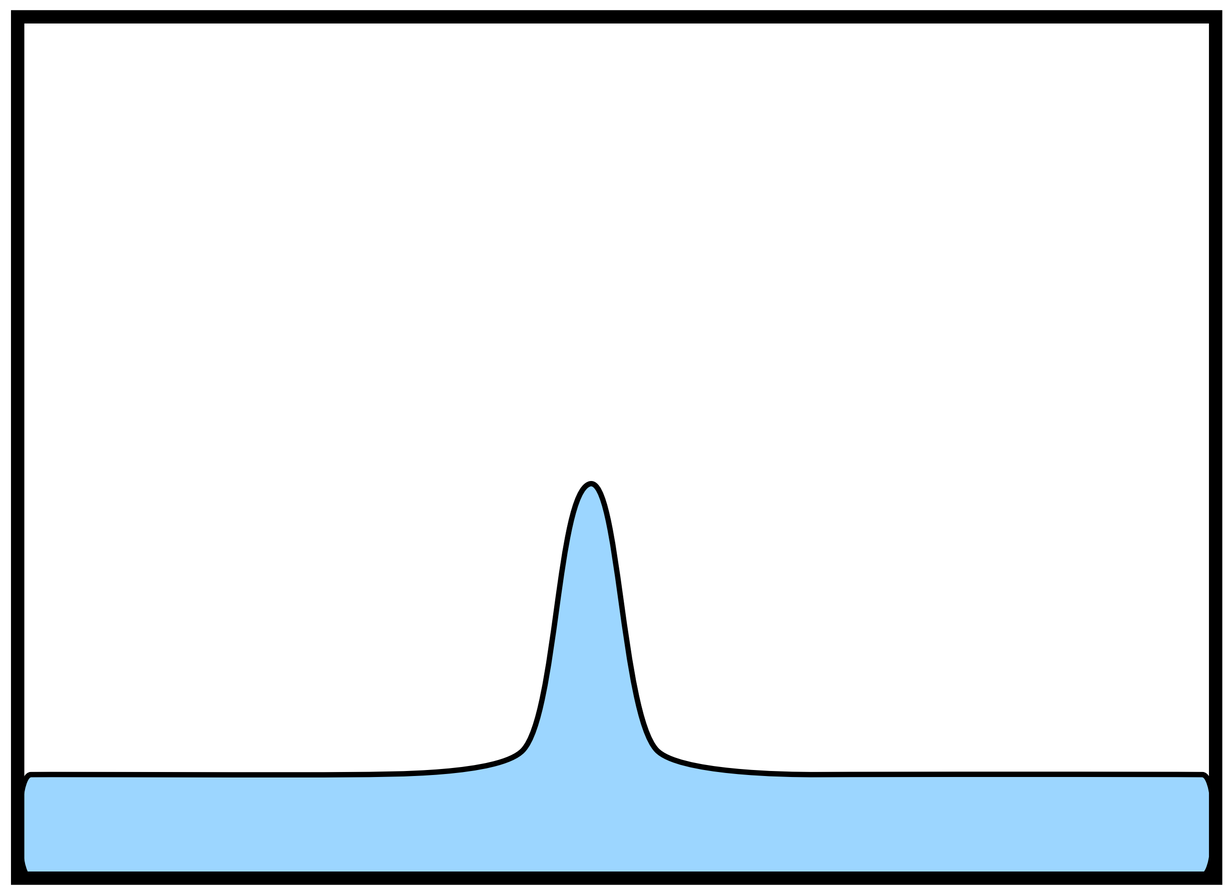
What Sets α_{CO}?



normal mol. cloud

Effects of molecular cloud properties on α_{CO}.

I_{CO}

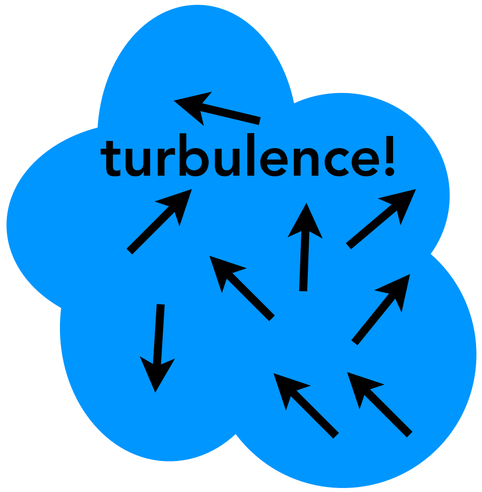


Velocity (km s^{-1})

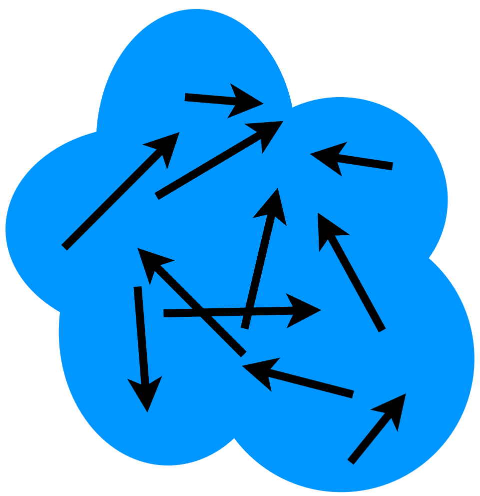
Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

What Sets α_{CO}?

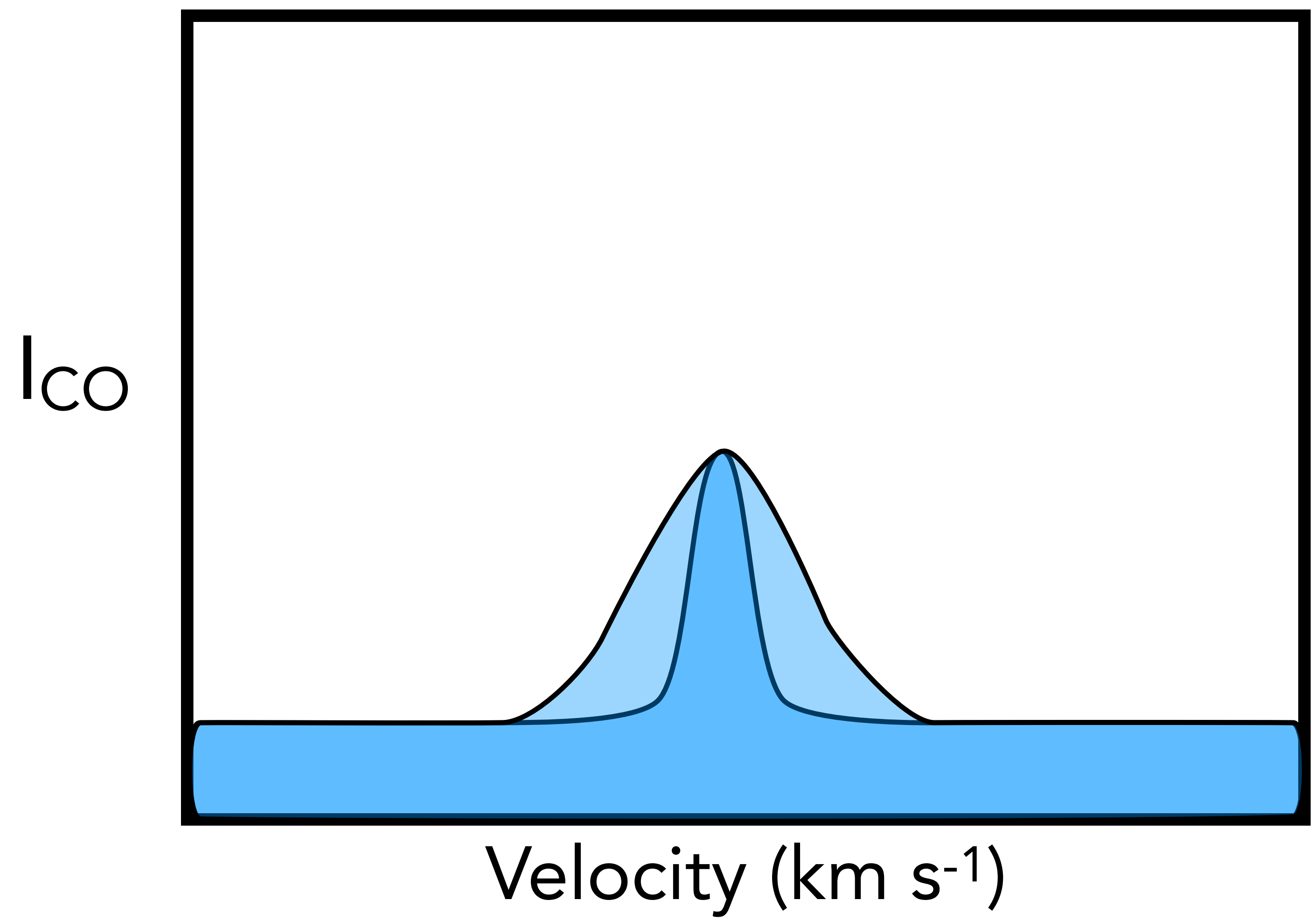


normal mol. cloud



more turbulence

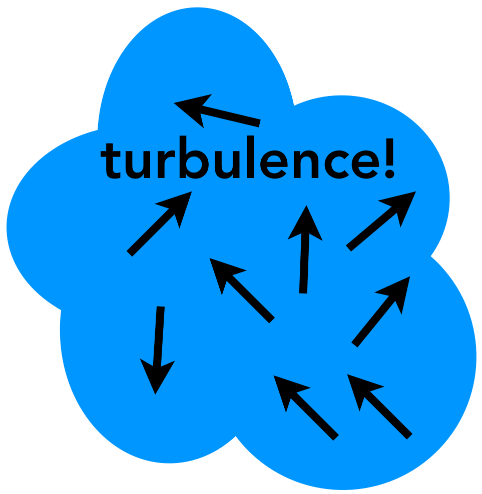
Effects of molecular cloud properties on α_{CO}.



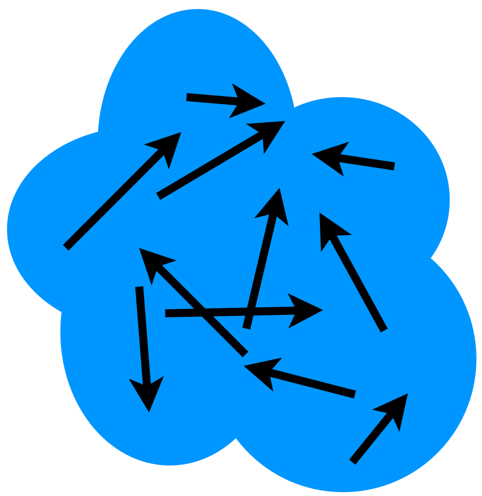
Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

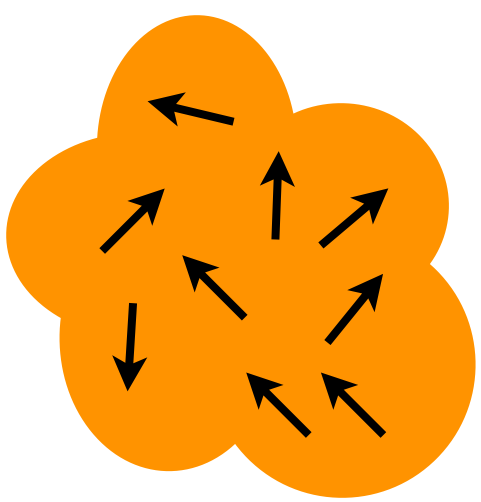
What Sets α_{CO}?



normal mol. cloud

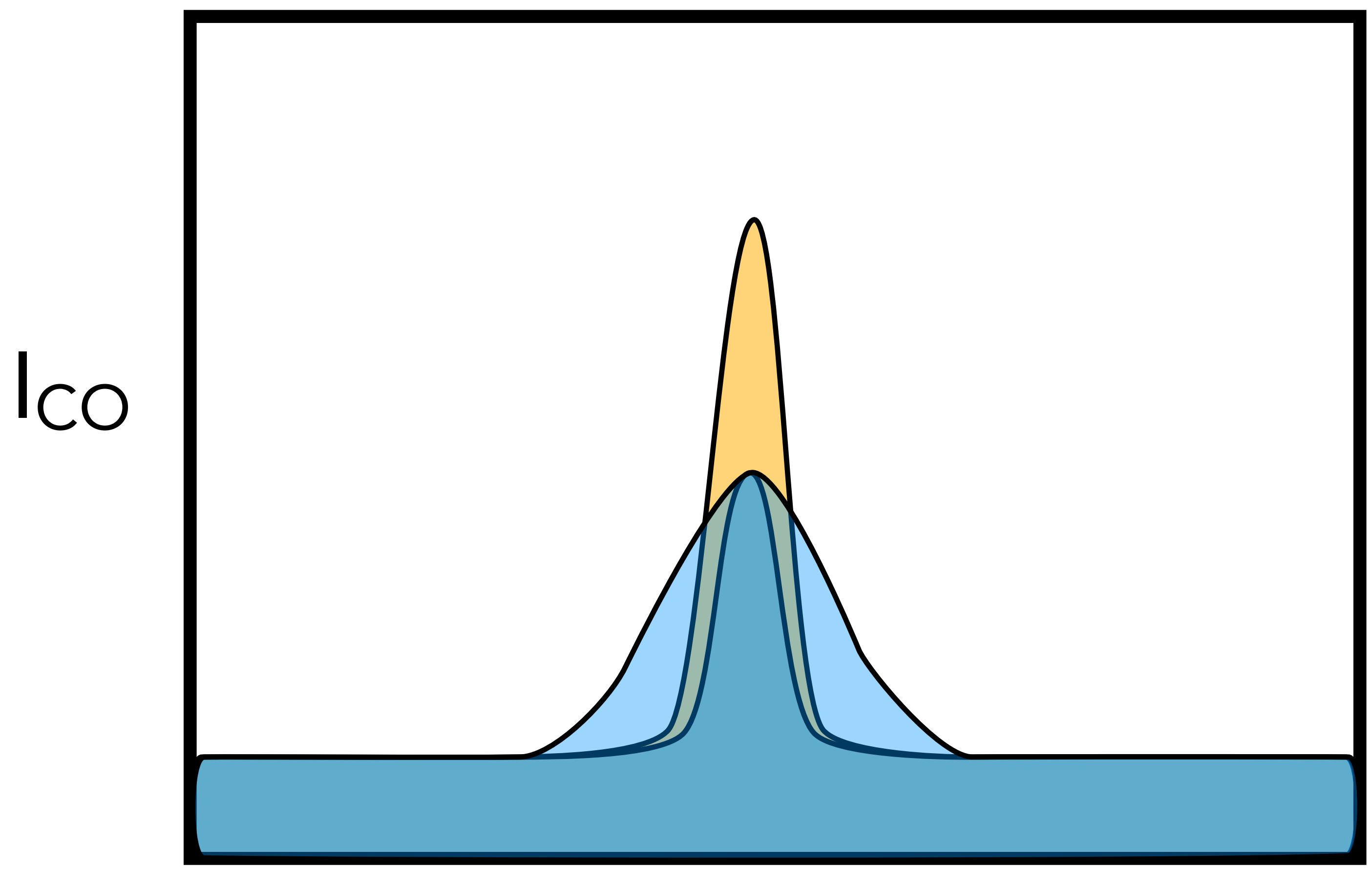


more turbulence



warmer gas

Effects of molecular cloud properties on α_{CO}.



Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

<u>X_{CO} works to first order because:</u>

1) turbulent velocity dispersion is correlated with the mass (& size) of cloud - *Larson's Laws*
2) clouds we see around us in the MW have pretty limited ranges of n,T

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

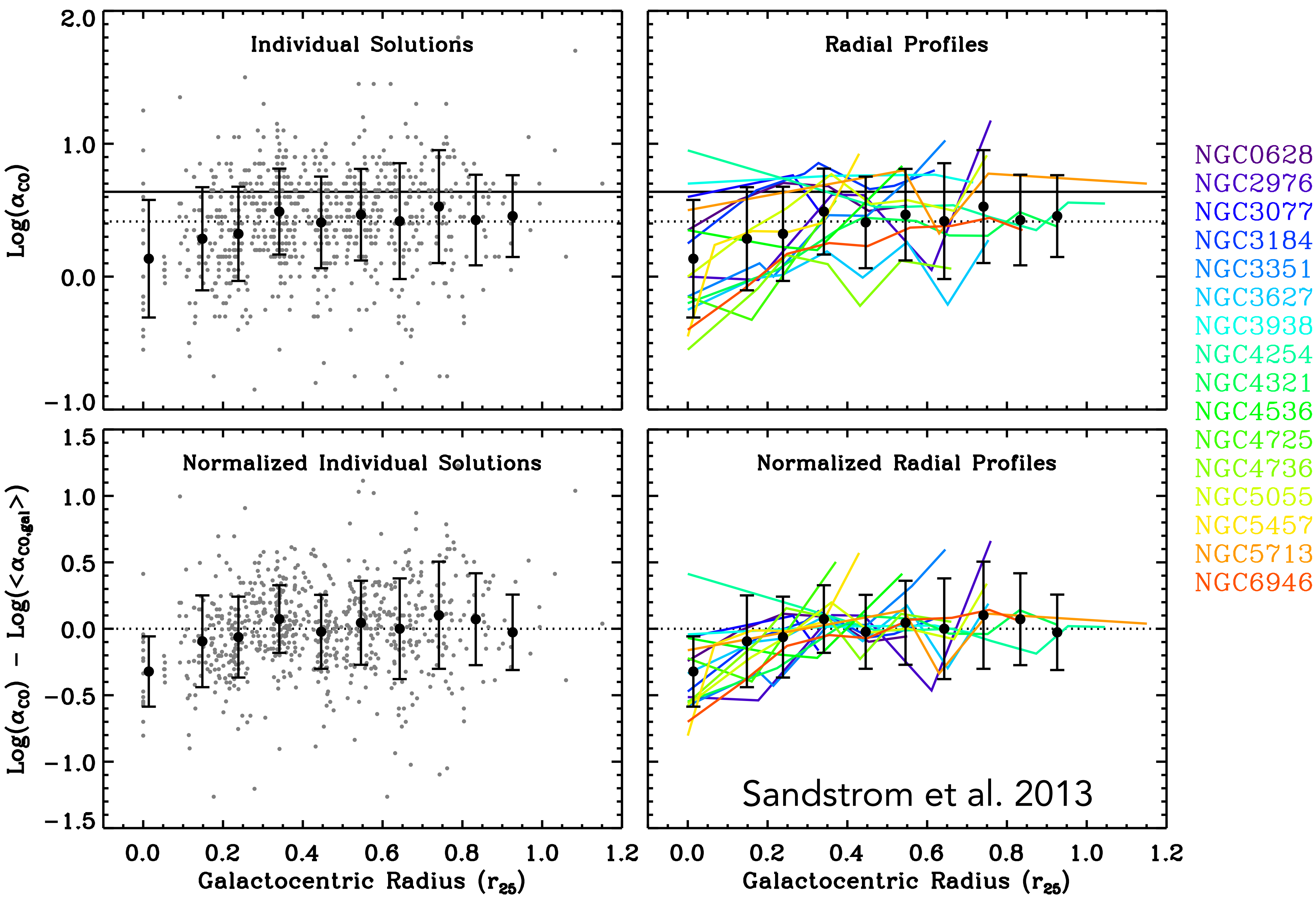
Table 1 Representative X_{CO} values in the Milky Way disk

from Bolatto et al. 2013

Method	$X_{CO}/10^{20}\mathrm{cm}^{-2}$ $(\mathrm{K\ km\ s}^{-1})^{-1}$	References
Virial	2.1	Solomon et al. (1987)
	2.8	Scoville et al. (1987)
Isotopologues	1.8	Goldsmith et al. (2008)
Extinction	1.8	Frerking, Langer & Wilson (1982)
	2.9–4.2	Lombardi, Alves & Lada (2006)
	0.9–3.0	Pineda, Caselli & Goodman (2008)
	2.1	Pineda et al. (2010b)
	1.7–2.3	Paradis et al. (2012)
Dust emission	1.8	Dame, Hartmann & Thaddeus (2001)
	2.5	Planck Collaboration XIX et al. (2011)
γ-rays	1.9	Strong & Mattox (1996)
	1.7	Grenier, Casandjian & Terrier (2005)
	0.9–1.9[a]	Abdo et al. (2010c)
	1.9–2.1[a]	Ackermann et al. (2011, 2012c)
	0.7–1.0[a]	Ackermann et al. (2012a,b)

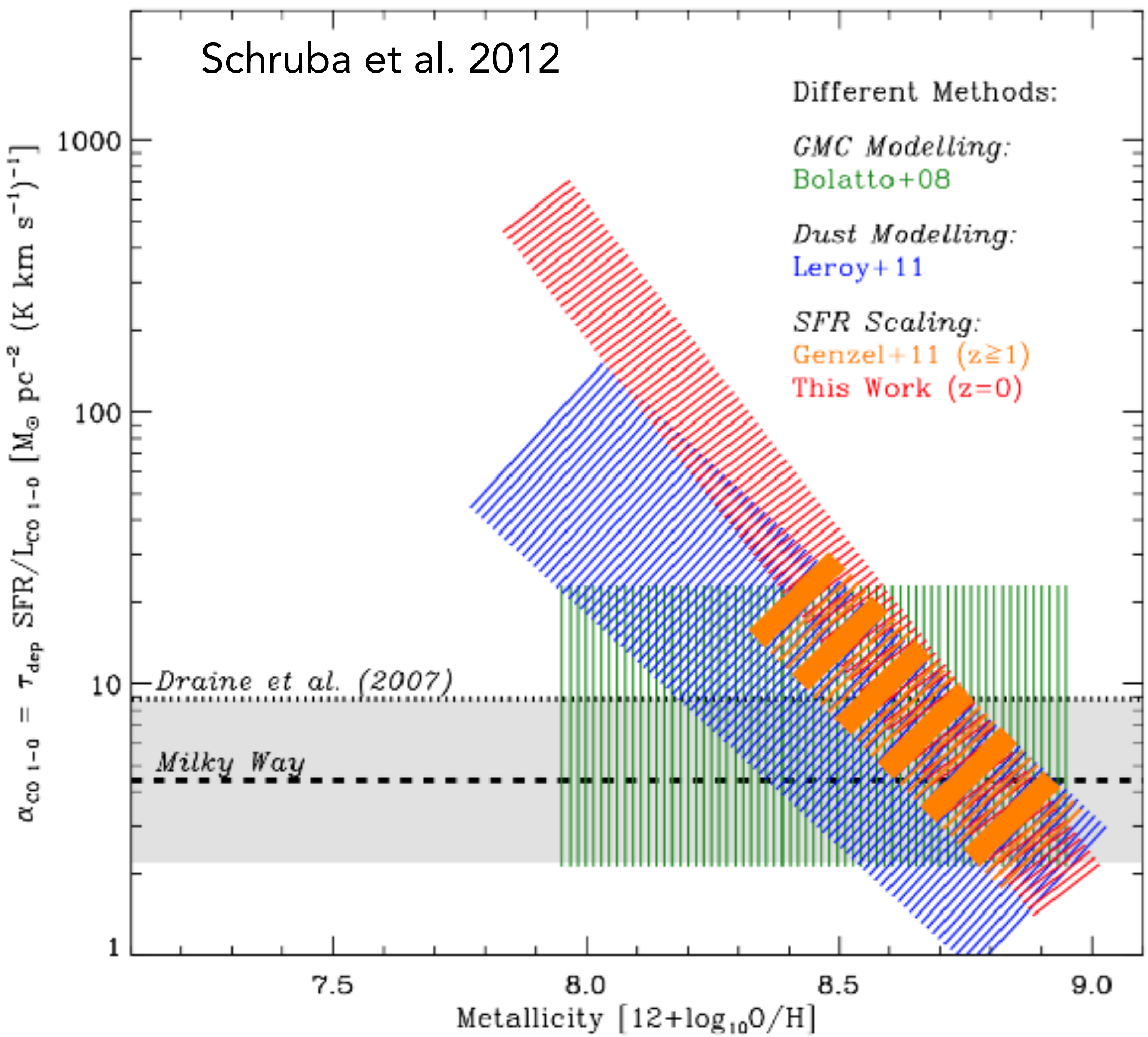
Tracing Molecular Gas

The CO-to-H_2 Conversion Factor



Tracing Molecular Gas

The CO-to-H_2 Conversion Factor



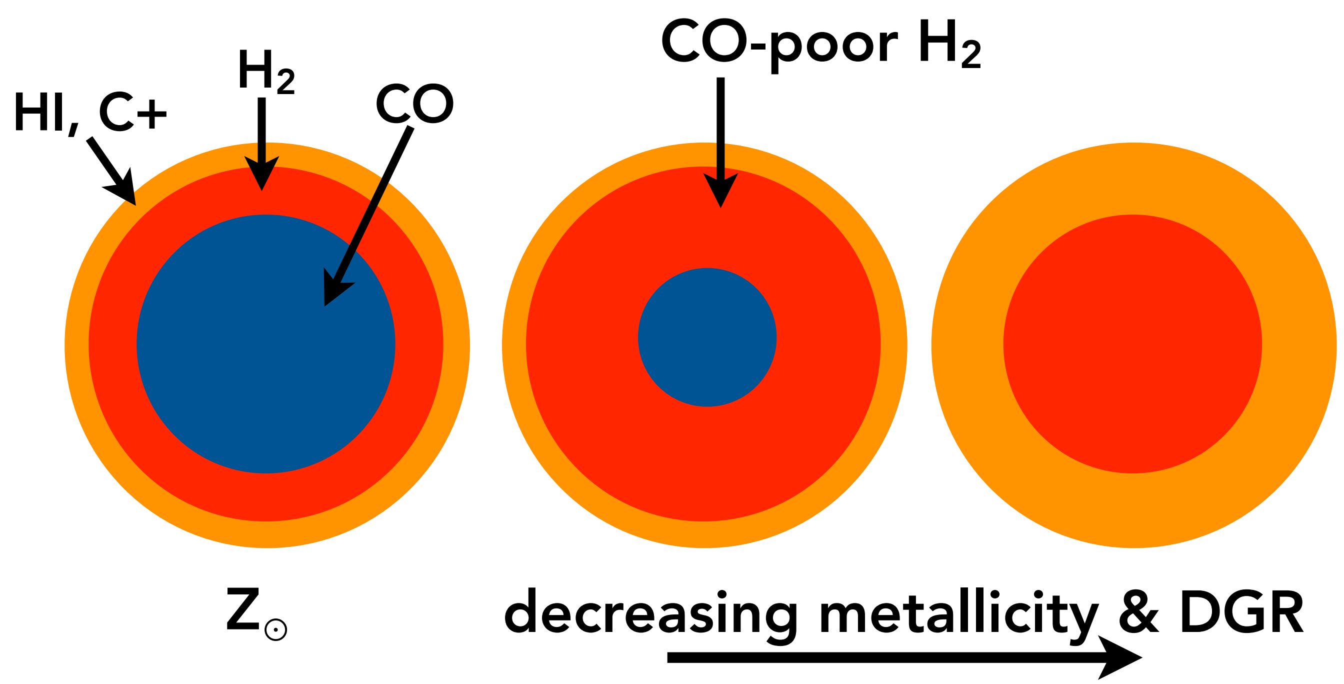
Things really fall apart at low metallicity!

$X_{CO} >> X_{CO,MW}$

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

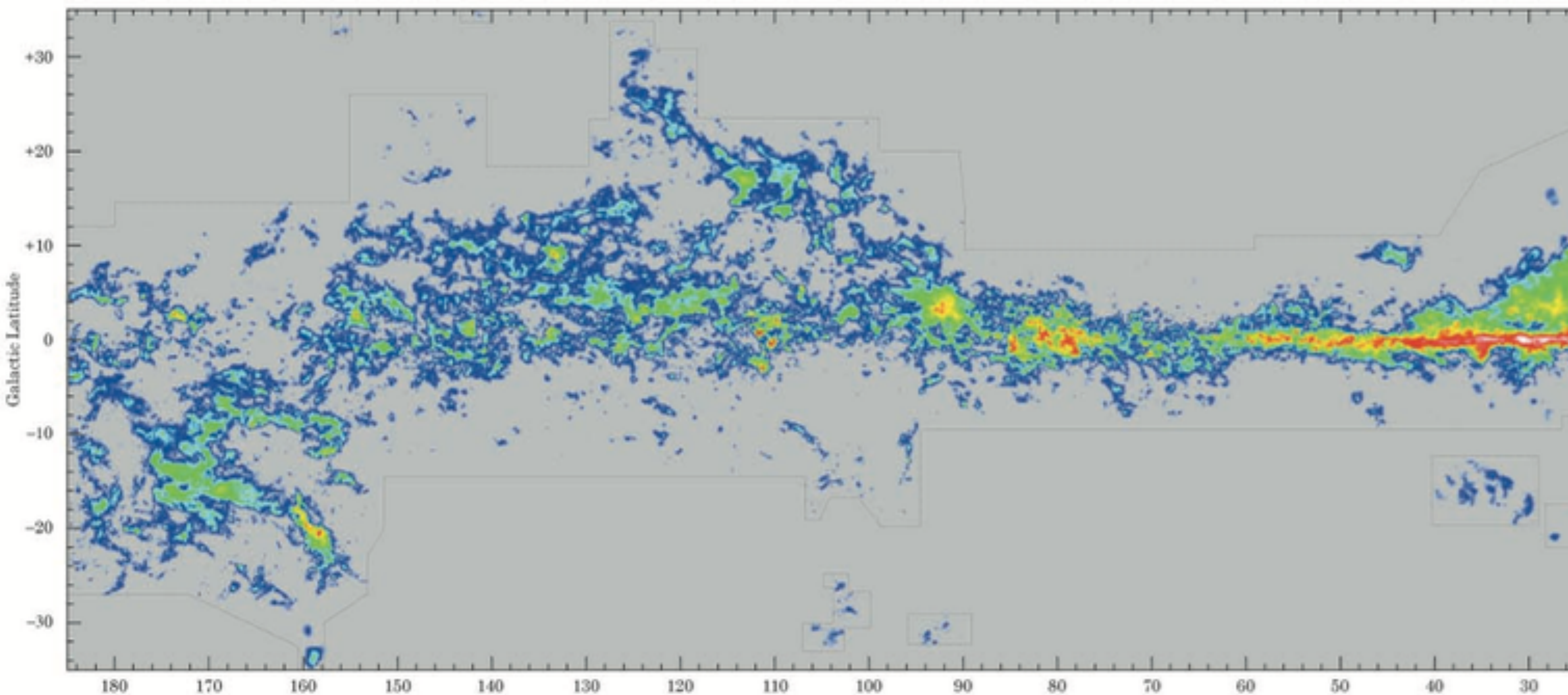
H_2 self-shields, but CO relies on dust,
when there is little dust, CO is photodissociated.



e.g. Maloney & Black 1988, Bolatto et al. 1999,
Wolfire et al. 2010, Glover & Mac Low 2011

Observations of Molecular Gas

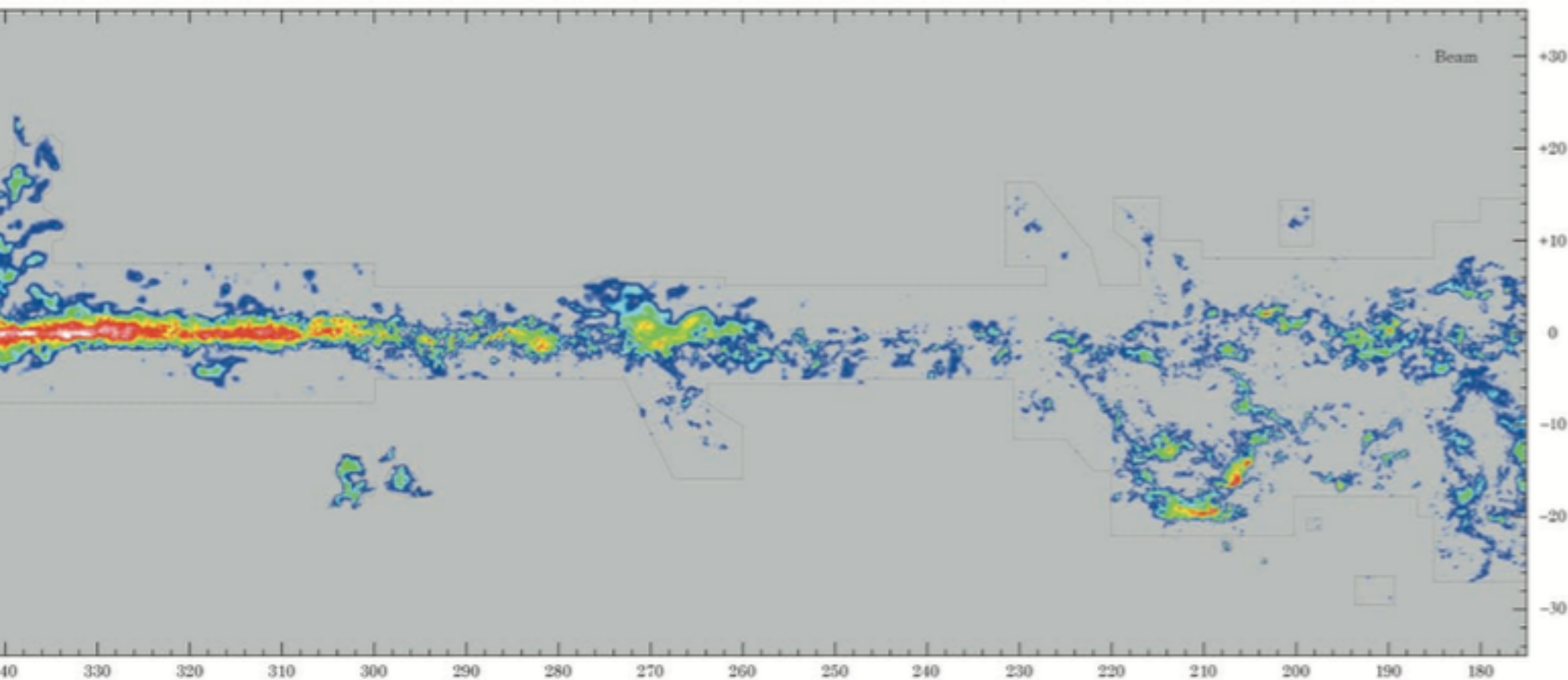
Distribution of Molecular Gas in the Milky Way:



Dame et al. 2001

Observations of Molecular Gas

Distribution of Molecular Gas in the Milky Way:

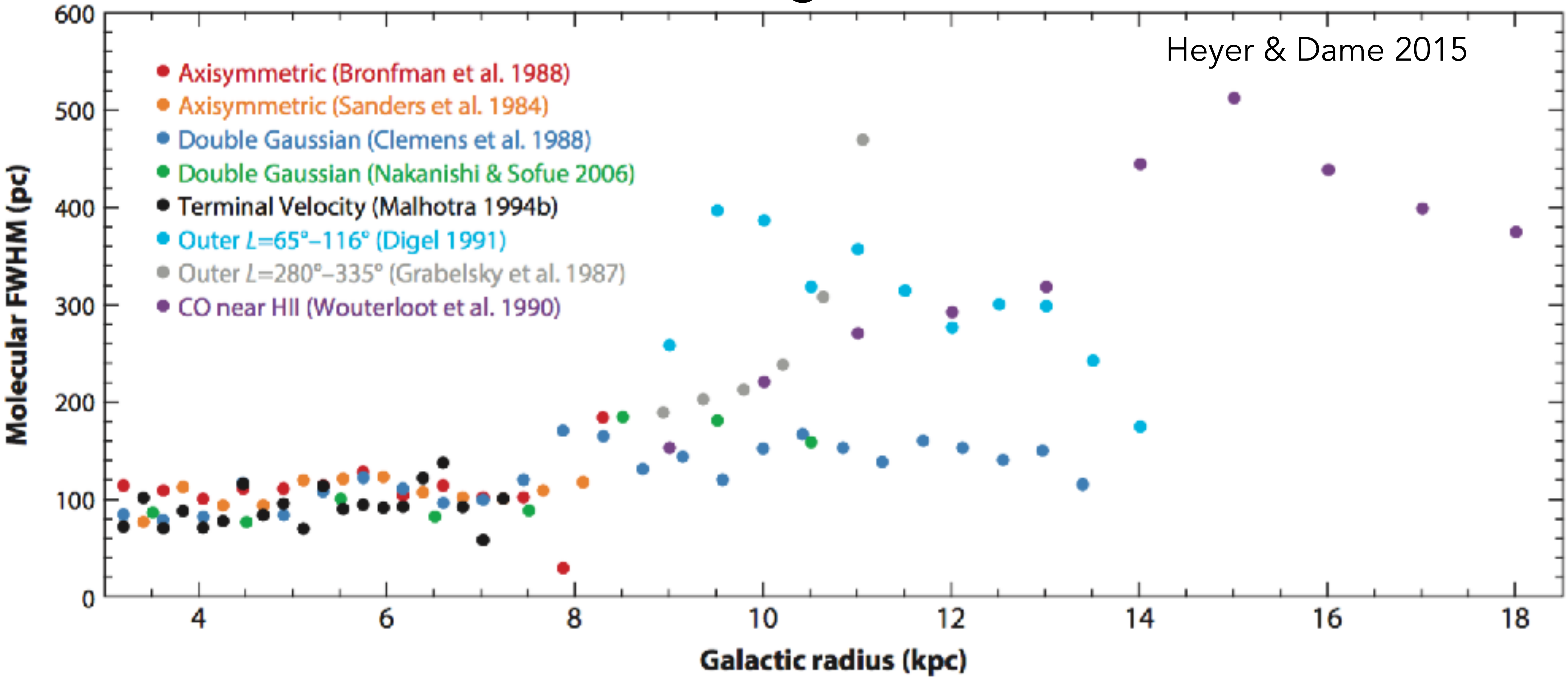


Dame et al. 2001

Observations of Molecular Gas

Distribution of Molecular Gas in the Milky Way:

Scale Height of CO

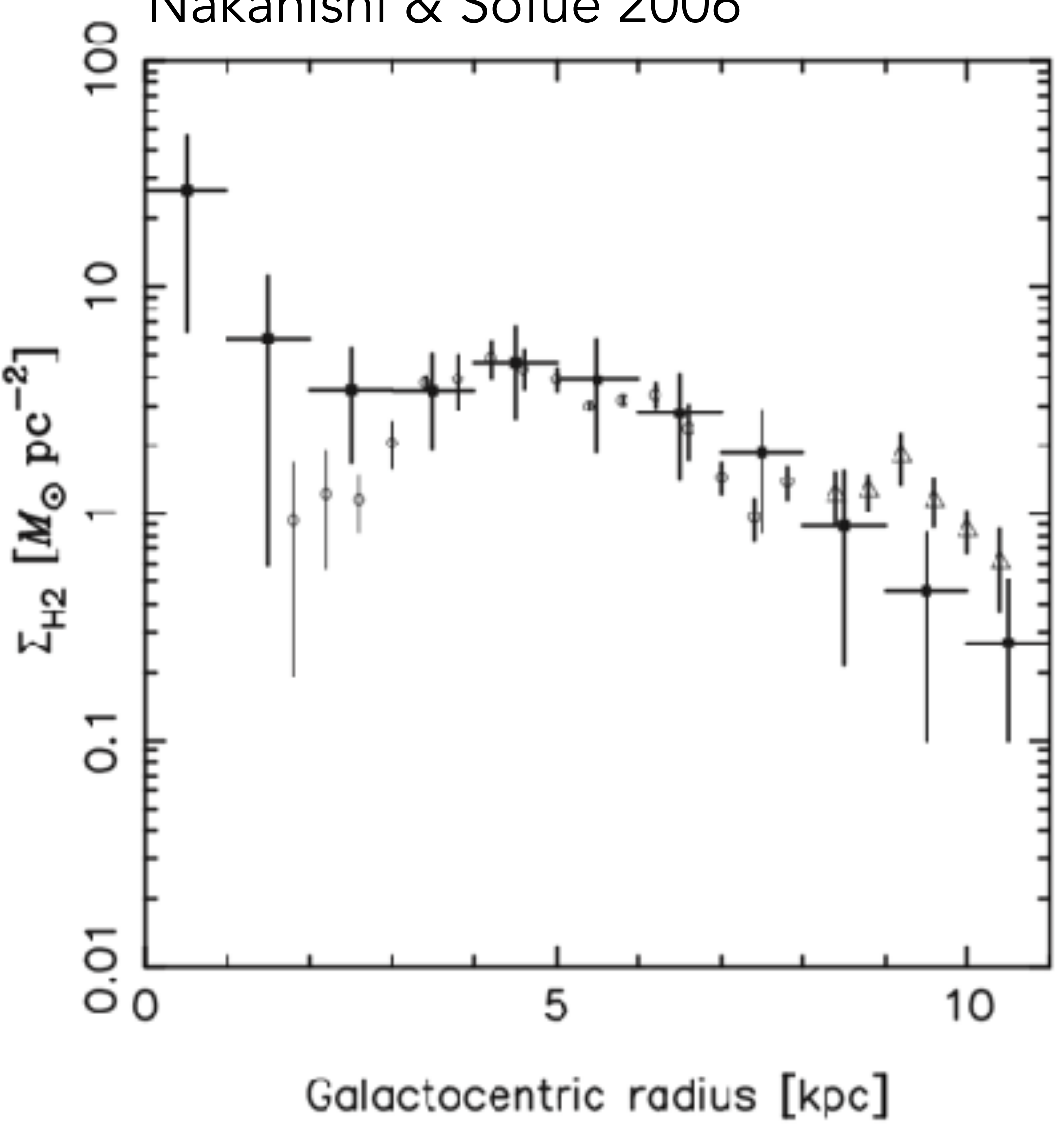


Observations of Molecular Gas

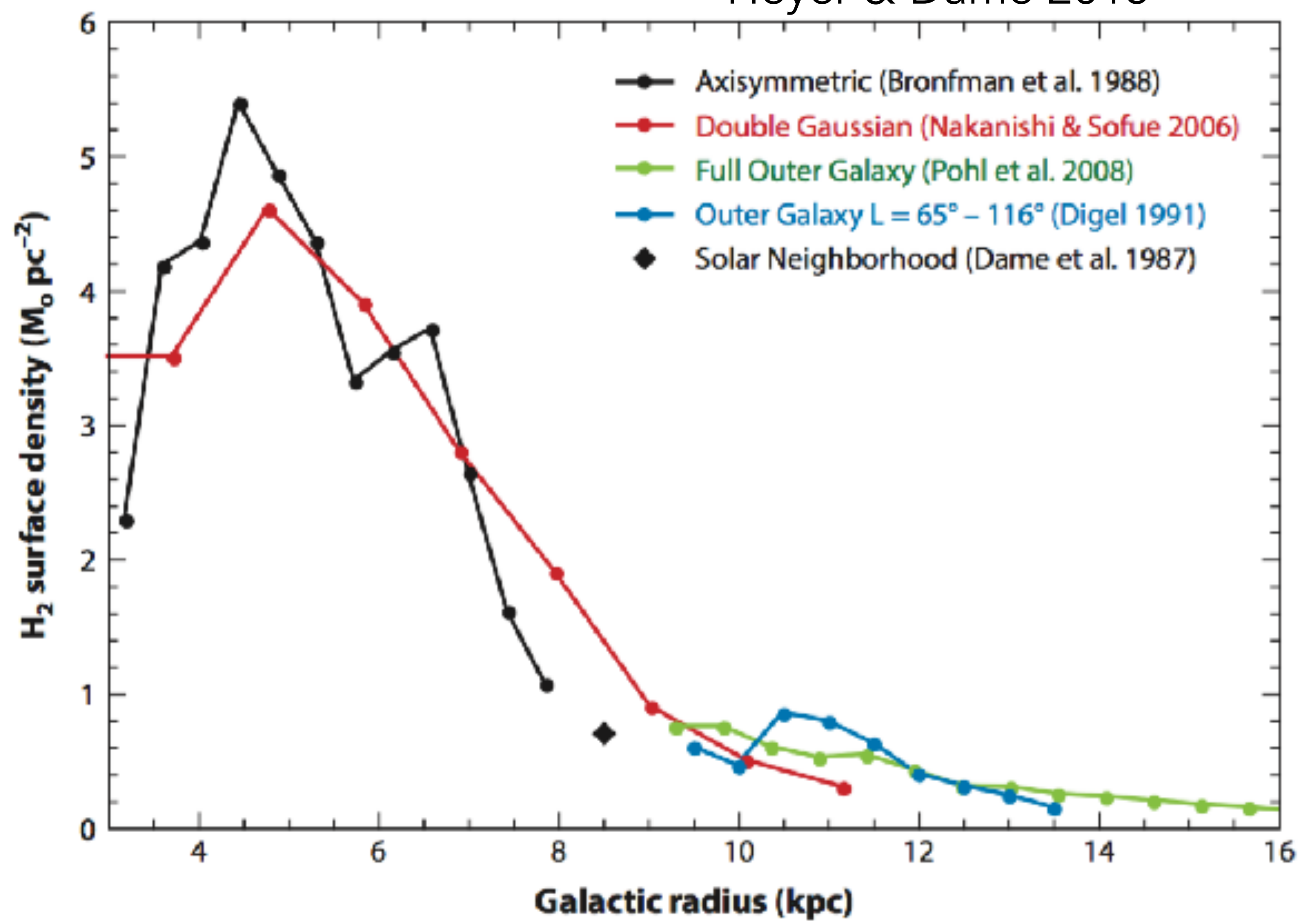
Distribution of Molecular Gas in the Milky Way:

Surface Density

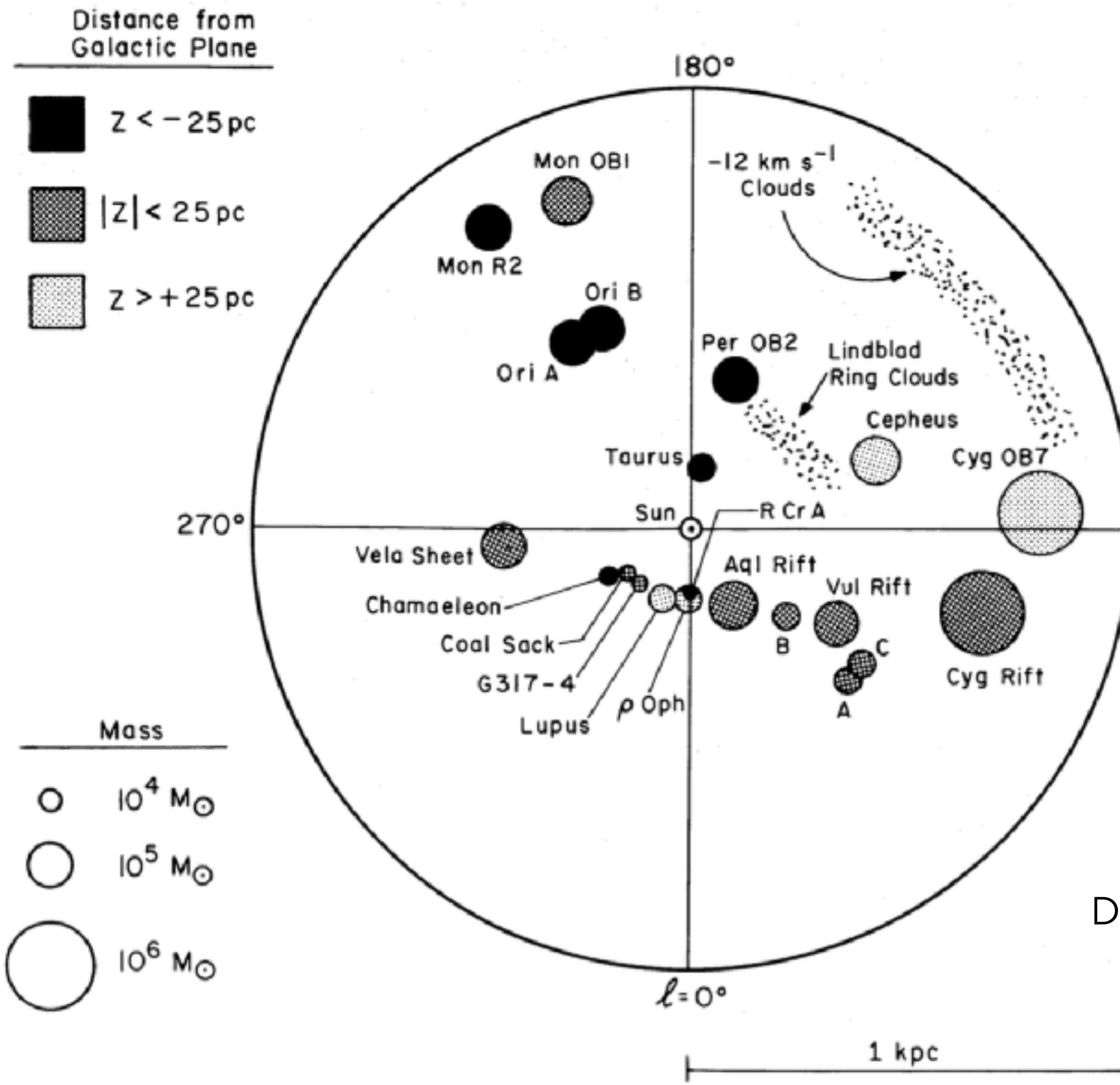
Nakanishi & Sofue 2006



Heyer & Dame 2015



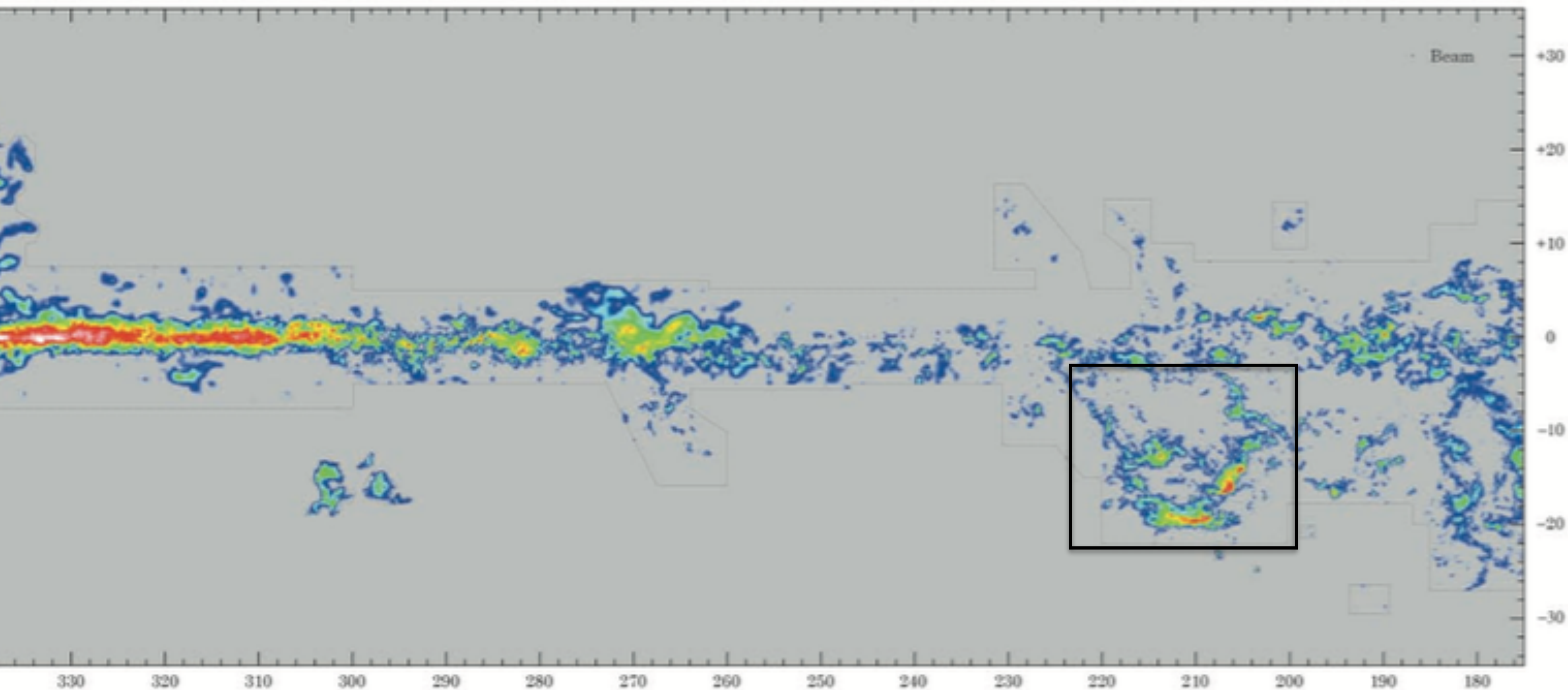
Observations of Molecular Gas



Dame et al. 1987

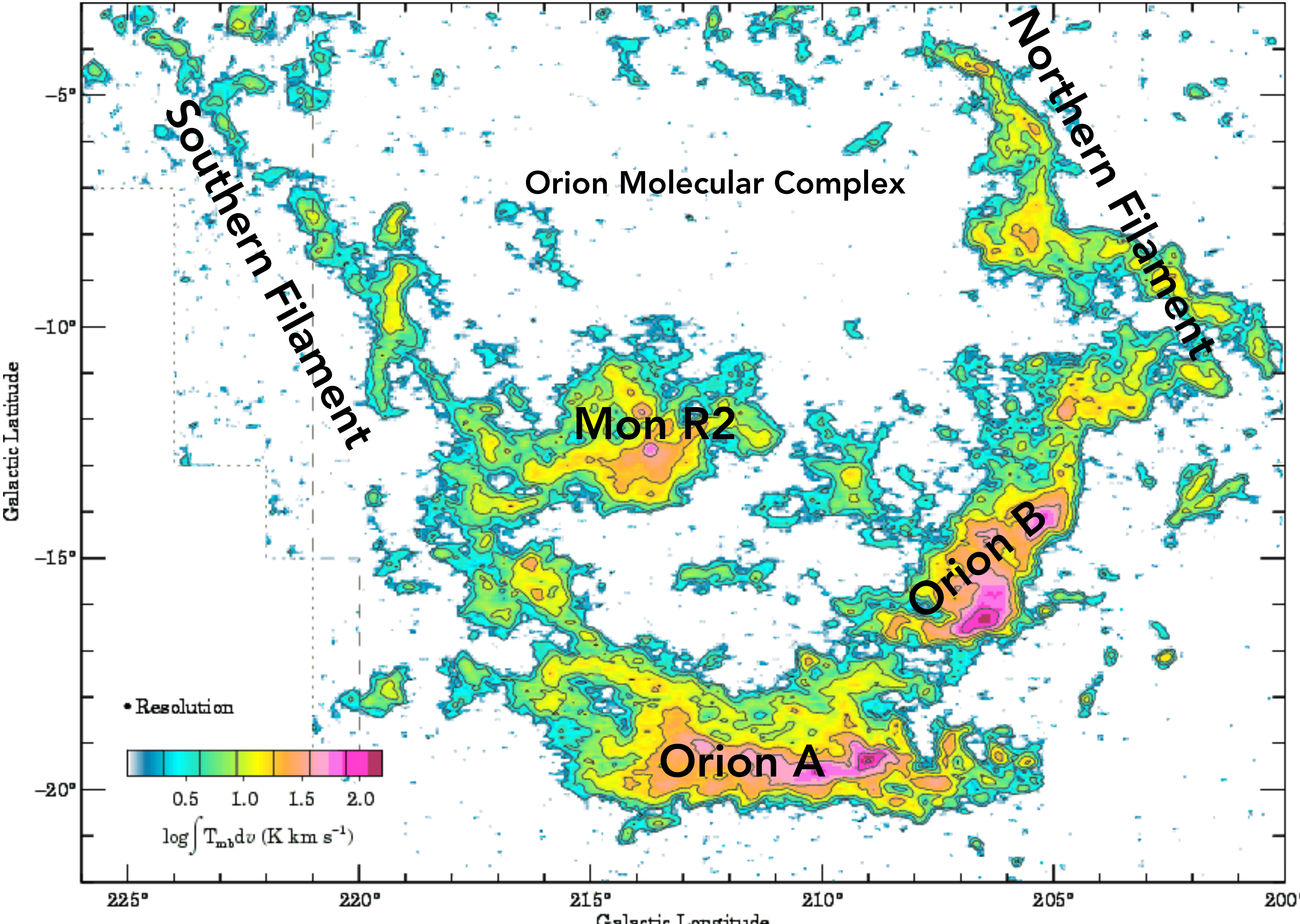
Observations of Molecular Gas

"Molecular Clouds"



Dame et al. 2001

Wilson et al. 2005



Molecular Clouds

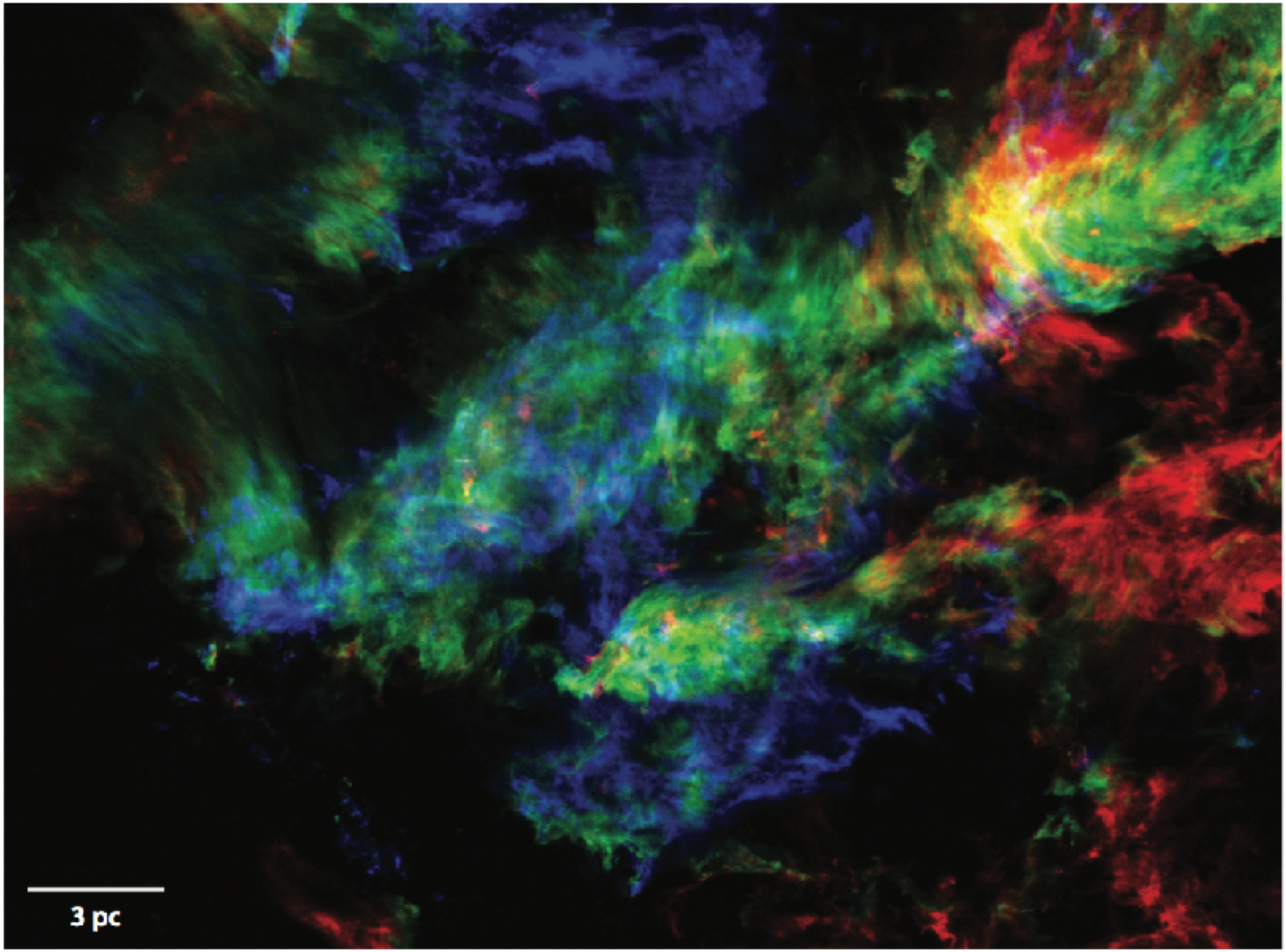
- Observational definition: Discrete regions of CO emission in position-position-velocity space.

MOPRA Galactic Plane Survey ^{12}CO ppv - Braiding et al. 2015

Molecular Clouds

- Observational definition: Discrete regions of CO emission in position-position-velocity space.

MOPRA Galactic Plane Survey ^{12}CO ppv - Braiding et al. 2015



Taurus Molecular cloud Heyer & Dame 2015

Figure 10

An image of ^{12}CO J = 1–0 emission from the Taurus molecular cloud integrated over v_{LSR} intervals 0–5 km s^{-1} (*blue*), 5–7.5 km s^{-1} (*green*), and 7.5–12 km s^{-1} (*red*), illustrating the intricate surface brightness distribution and complex velocity field of the Taurus cloud. The data are from Narayanan et al. (2008). Adapted from figure 12 of Goldsmith et al. (2008) and reproduced with permission from AAS.

Molecular Clouds

- Observational definition: Discrete regions of CO emission in position-position-velocity space.

<u>Giant Molecular Clouds (GMC):</u>

It is rather amazing that 15 yr since the identification of giant molecular clouds, there is no generally accepted definition of what a GMC is. There seems to be little disagreement about the classification of the largest clouds as GMCs, but an all inclusive definition of what a GMC is has proven elusive. A large part of the problem is that the various studies of the mass spectrum of molecular clouds indicate that the spectrum is well fit by a power law (see below) and there is consequently no natural size or mass scale for molecular clouds. What we call a GMC is therefore largely a question of taste. For the

Blitz 1993 - review for Protostars & Planets

Molecular Clouds

- Observational definition: Discrete regions of CO emission in position-position-velocity space.

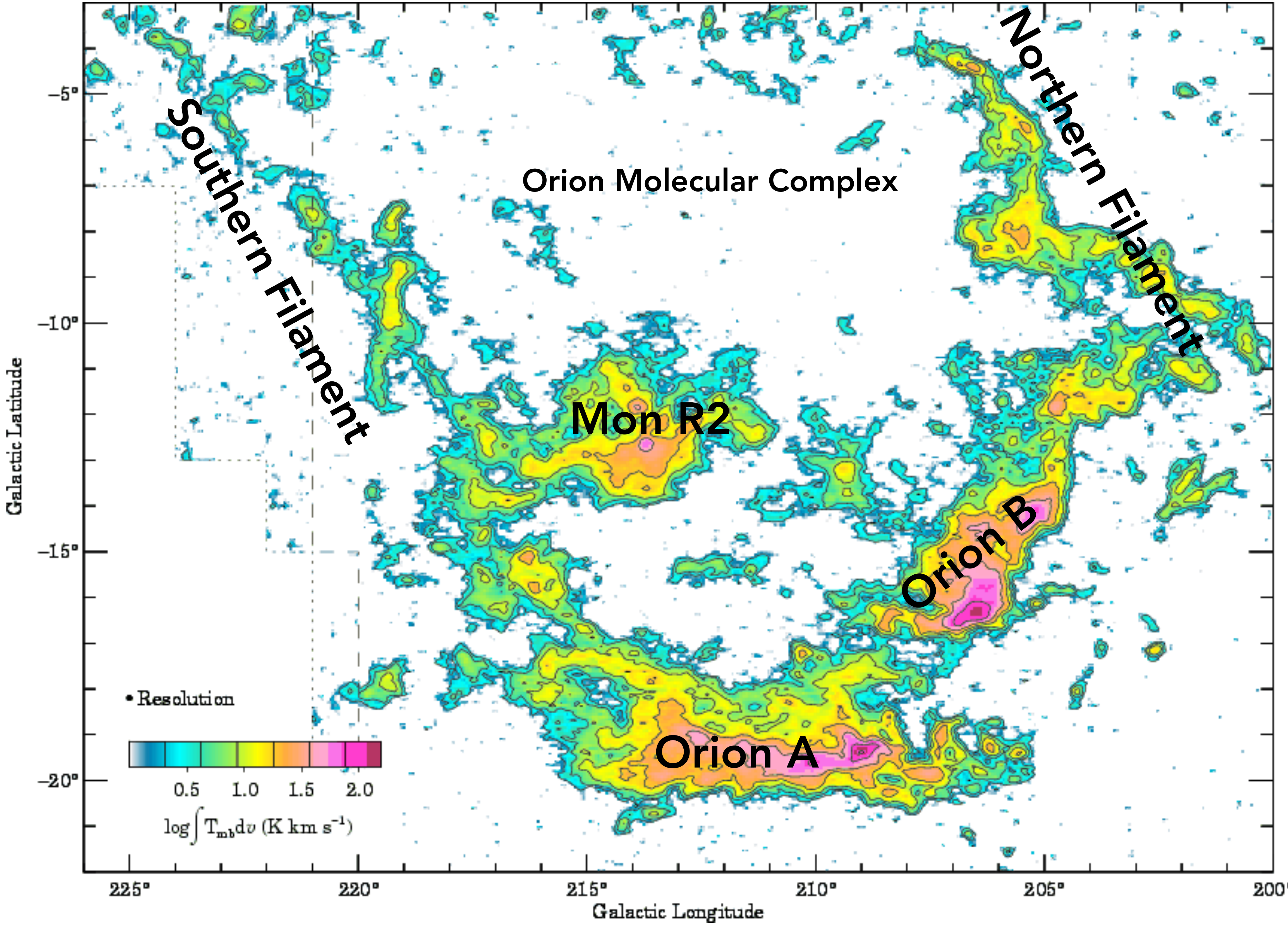
Giant Molecular Clouds (GMC):

Masses ~10^3 - 10^6 $M_\odot$

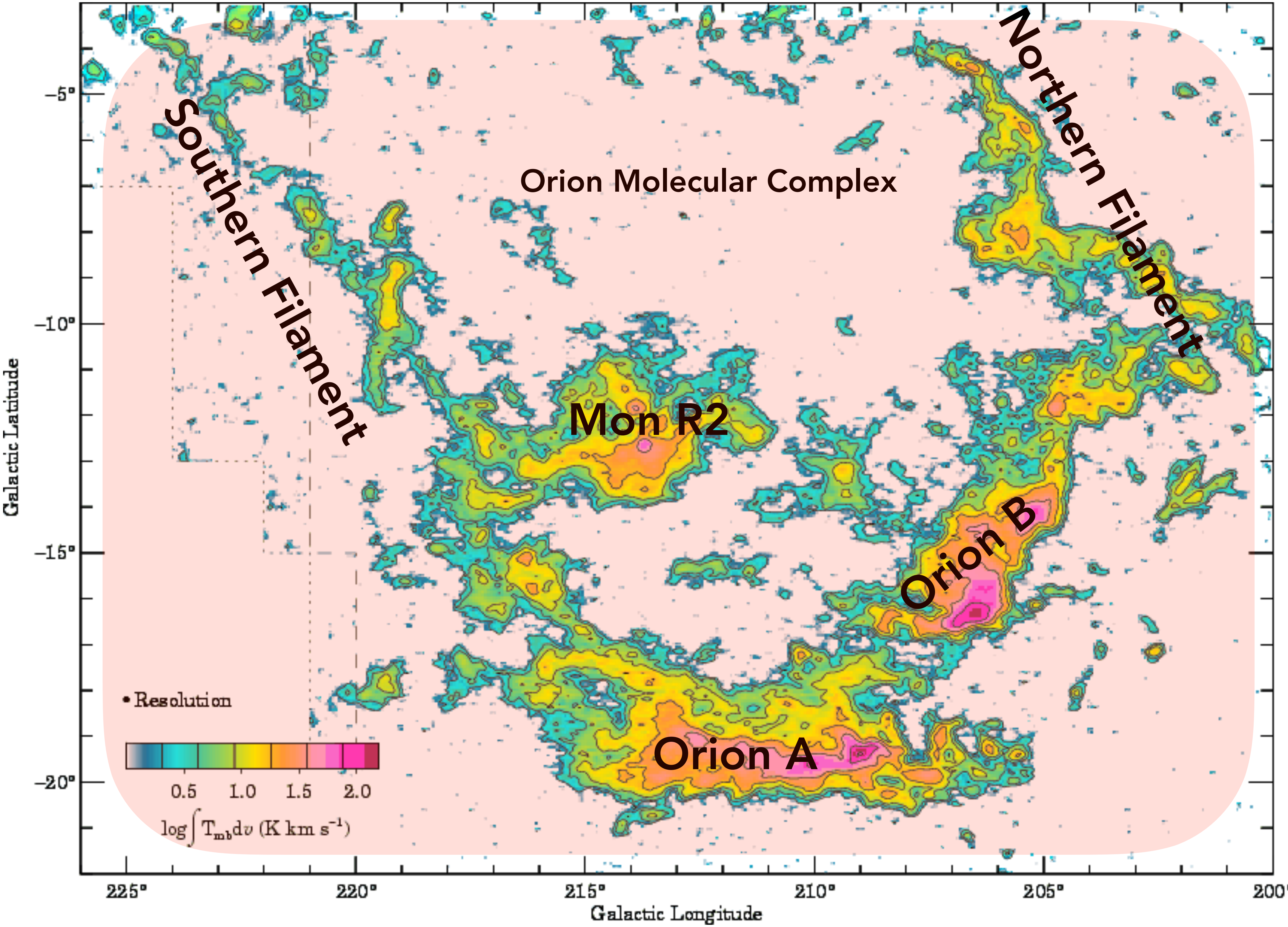
Size ~ 10^1 - 10^2 pc

GMC is the largest unit, it can have substructure & more than one can be clustered together in a "GMC complex".

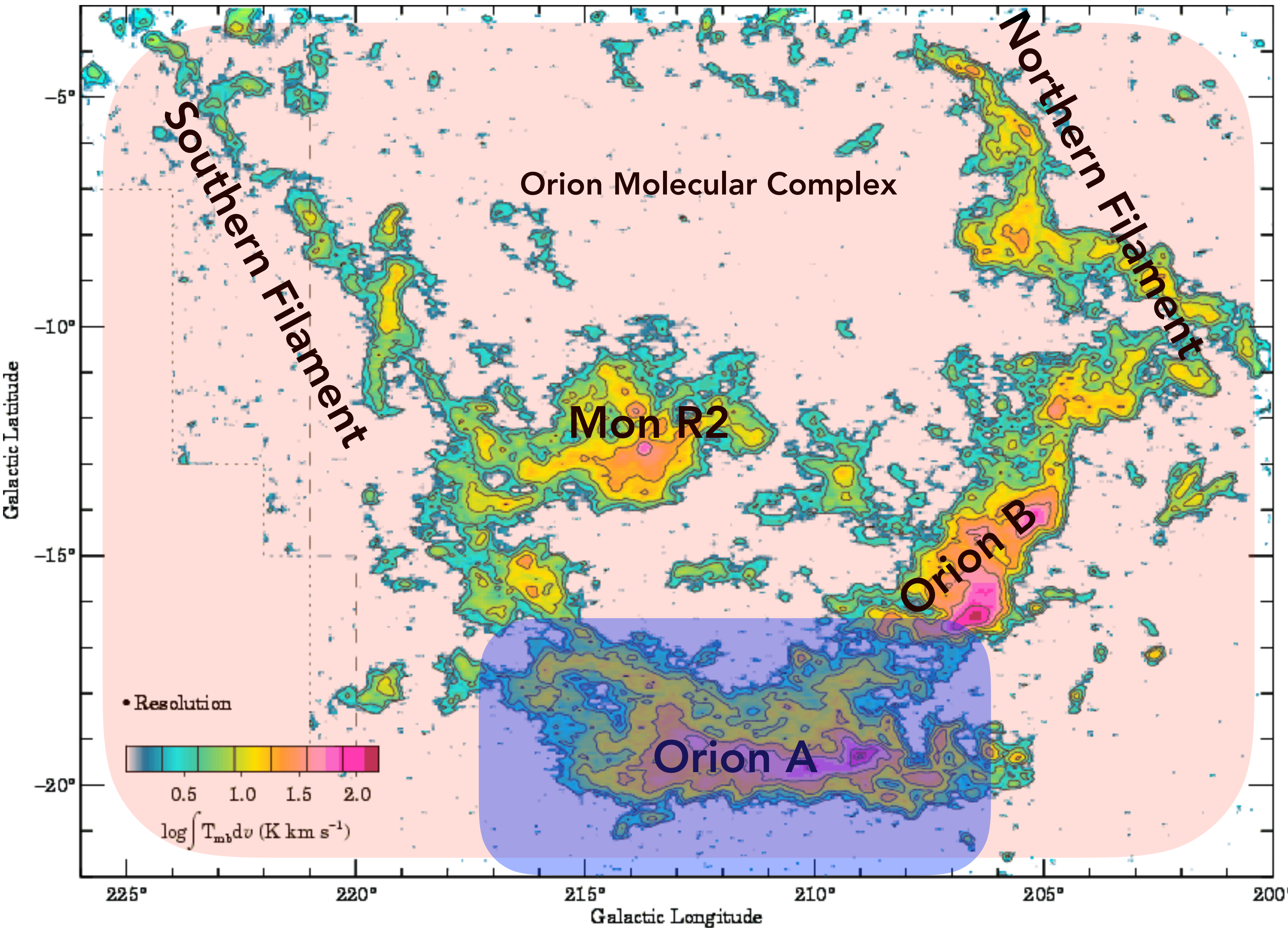
Wilson et al. 2005



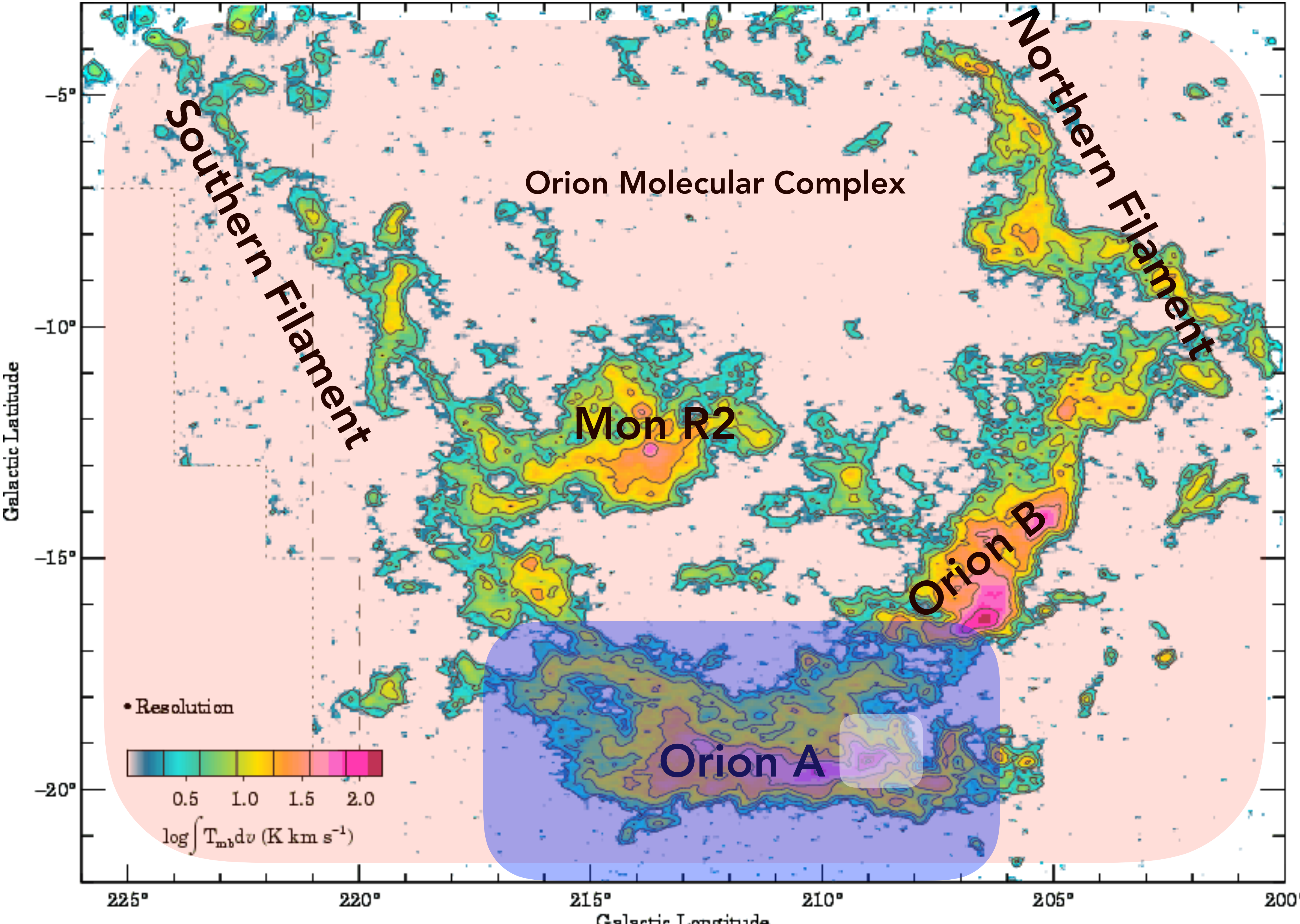
Wilson et al. 2005



Wilson et al. 2005



Wilson et al. 2005



Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

Describes force balance in a fluid element (or cloud), including gravity, fluid flows, pressure, B-fields.

Neglects viscosity and resistivity (deal with big scales where these are unimportant).

see Krumholz “Notes on Star Formation” for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

2nd derivative of
moment of Inertia of cloud $I = \int_V \rho r^2 \, dV$

negative if cloud is collapsing, positive if expanding

see Krumholz "Notes on Star Formation" for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

total kinetic plus thermal energy of the cloud

$$\mathcal{T} = \int_V \left(\frac{1}{2}\rho v^2 + \frac{3}{2}P\right) dV$$

see Krumholz “Notes on Star Formation” for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

confining pressure on the cloud's surface

$$\mathcal{T}_S = \int_S \mathbf{r} \cdot \mathbf{\Pi} \cdot d\mathbf{S}$$

fluid pressure tensor

$$\mathbf{\Pi} \equiv \rho \mathbf{v}\mathbf{v} + P\mathbf{I}$$

see Krumholz "Notes on Star Formation" for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

difference in magnetic pressure in cloud interior vs magnetic pressure plus tension at cloud surface

$$\mathcal{B} = \frac{1}{8\pi}\int_V B^2\, dV + \int_S \mathbf{r} \cdot \mathbf{T}_M \cdot d\mathbf{S}$$

see Krumholz “Notes on Star Formation” for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

gravitational energy of the cloud

$$\mathcal{W} = -\int_V \rho \mathbf{r} \cdot \nabla \phi \, dV$$

see Krumholz “Notes on Star Formation” for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

rate of change of momentum flux
across cloud surface

see Krumholz "Notes on Star Formation" for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

in equilibrium, with no B-field and negligible surface forces

$$2\mathcal{T} = -\mathcal{W}$$

can define "virial parameter":

$$\alpha_{\mathrm{vir}} = \frac{2\mathcal{T}}{|\mathcal{W}|}$$

see Krumholz "Notes on Star Formation" for a very clear derivation

Some Fluid Dynamics Background

The Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

in equilibrium, with no B-field and negligible surface forces

$$\mathcal{T} \sim \frac{1}{2} M \sigma^2$$

$$\mathcal{W} \sim \frac{GM^2}{R}$$

$$\alpha_{\mathrm{vir}} \sim k \frac{R\sigma^2}{GM}$$

order unity constant that depends on density distribution

see Krumholz "Notes on Star Formation" for a very clear derivation

Some Fluid Dynamics Background

Gravitational Collapse

$\alpha_{vir} \sim 1$ is the dividing line between stability and collapse

assume isothermal cloud, with only thermal pressure:

$$\mathcal{T} = \frac{3}{2} M c_s^2$$

$$\mathcal{W} = -a \frac{GM^2}{R}$$

order unity constant that depends on density distribution

collapsing cloud with $\alpha_{\mathrm{vir}} \gtrsim 1$

$$M c_s^2 \gtrsim \frac{GM^2}{R}$$

Some Fluid Dynamics Background

Gravitational Collapse

rewrite in terms of density and length scale:

$$R_J \lesssim \frac{c_s}{\sqrt{G\rho}}$$

"Jean's Length"

Some Fluid Dynamics Background

Gravitational Collapse

another order-of-magnitude derivation:

$$t_{\rm ff} = \frac{1}{\sqrt{G\rho}} \simeq (2\ {\rm Myr})\left(\frac{n}{10^3\ {\rm cm}^{-3}}\right)^{-1/2}$$

$$t_{sound} = \frac{R}{c_s} \simeq (5\times10^5\ {\rm yr})\left(\frac{R}{0.1\ {\rm pc}}\right)\left(\frac{c_s}{0.2\ {\rm km\ s}^{-1}}\right)^{-1}$$

Region unstable to collapse when:

$$t_{\rm ff} < t_{sound}$$

$$R_J = \frac{c_s}{\sqrt{G\rho}} \simeq (0.4\ {\rm pc})\left(\frac{c_s}{0.2\ {\rm km\ s}^{-1}}\right)\left(\frac{n}{10^3\ {\rm cm}^{-3}}\right)^{-1/2}$$

Some Fluid Dynamics Background

Gravitational Collapse

Jean's Mass:

$$M_J = \left(\frac{4\pi}{3}\right)\rho R_J^3 = \left(\frac{\pi}{6}\right)\frac{c_s^3}{G^{3/2}\rho^{1/2}} \simeq (2\,\mathrm{M}_\odot)\left(\frac{c_s}{0.2\ \mathrm{km\ s^{-1}}}\right)^3\left(\frac{n}{10^3\ \mathrm{cm^{-3}}}\right)^{-1/2}$$