Physics 224
The Interstellar Medium

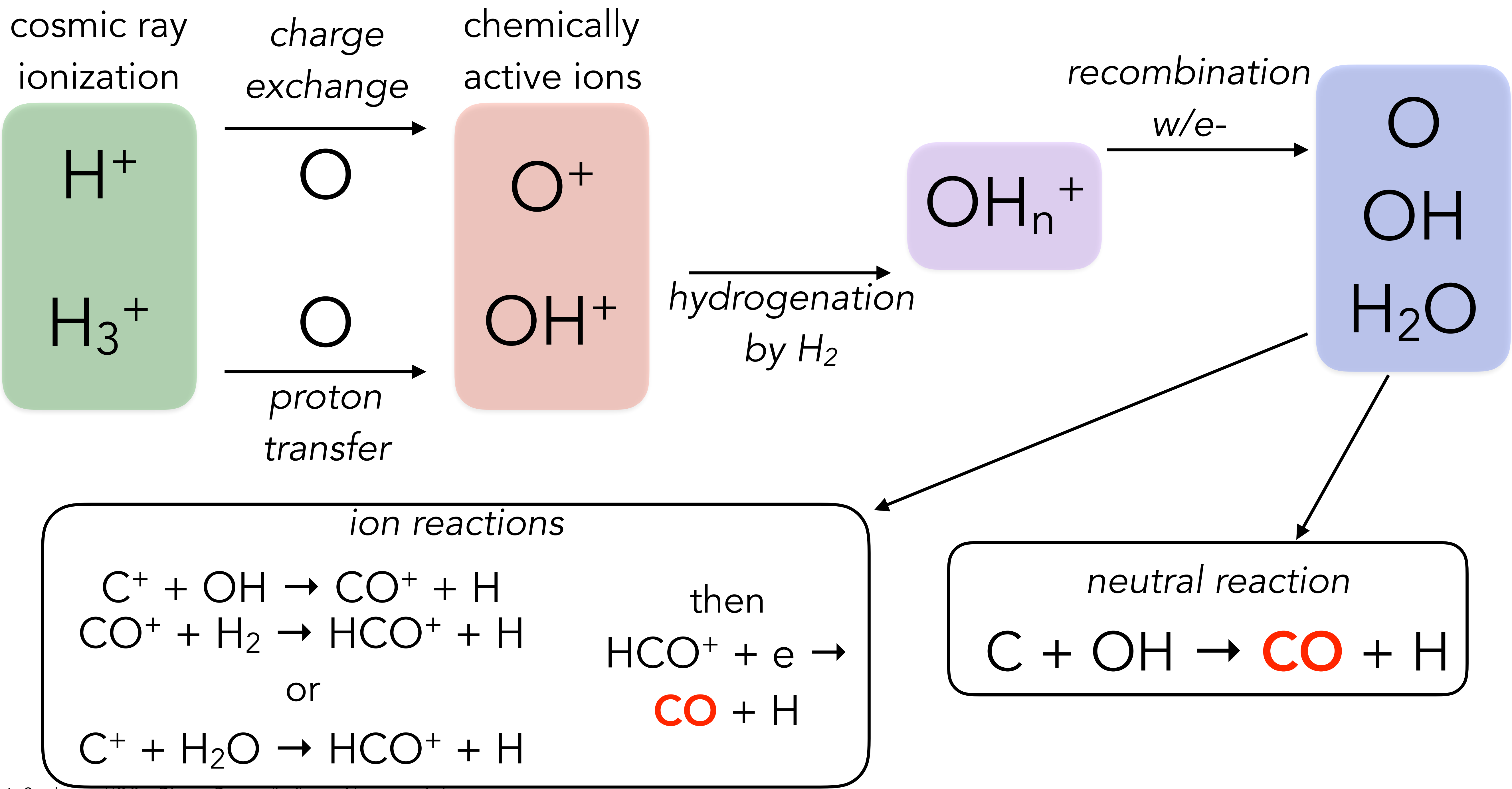
Lecture #18: Molecular clouds, B-fields, Star Formation

Outline

- Part I: Tracing Molecular Gas
- Part II: Observations of Molecular Gas
- Part III: Magnetic Fields
- Part IV: Star Formation

Chemistry in Molecular Gas

Carbon Monoxide - most abundant molecule after H_2



cosmic ray ionization

H^+

H_3^+

charge exchange

O

O

proton transfer

chemically active ions

O^+

OH^+

hydrogenation by H_2

OH_n^+

recombination w/e-

O

OH

H_2O

ion reactions

$C^+ + OH \rightarrow CO^+ + H$

$CO^+ + H_2 \rightarrow HCO^+ + H$

or

$C^+ + H_2O \rightarrow HCO^+ + H$

then

$HCO^+ + e \rightarrow$ **CO** $+ H$

neutral reaction

$C + OH \rightarrow$ **CO** $+ H$

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

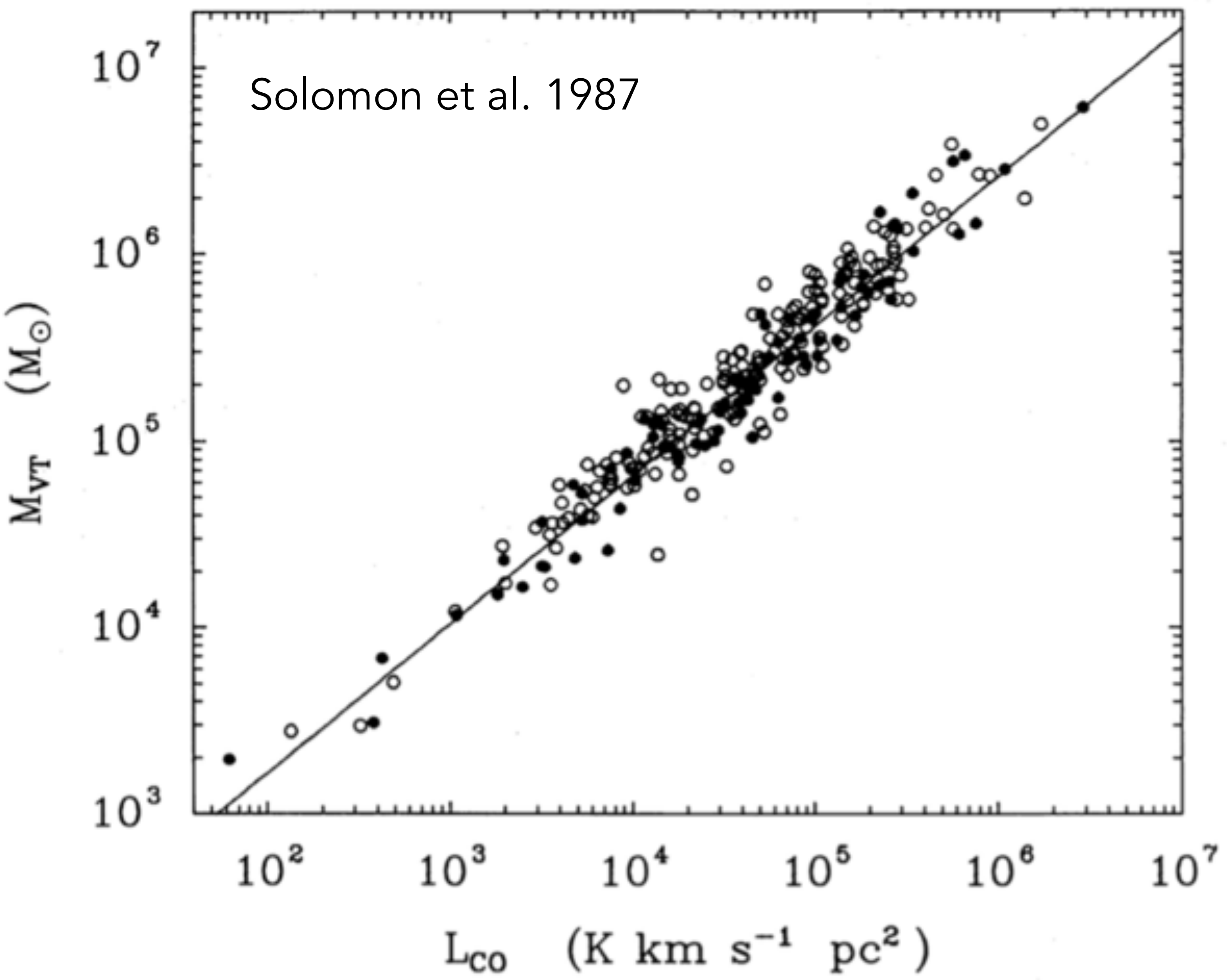
integrated intensity of CO line

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

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

Tracing Molecular Gas

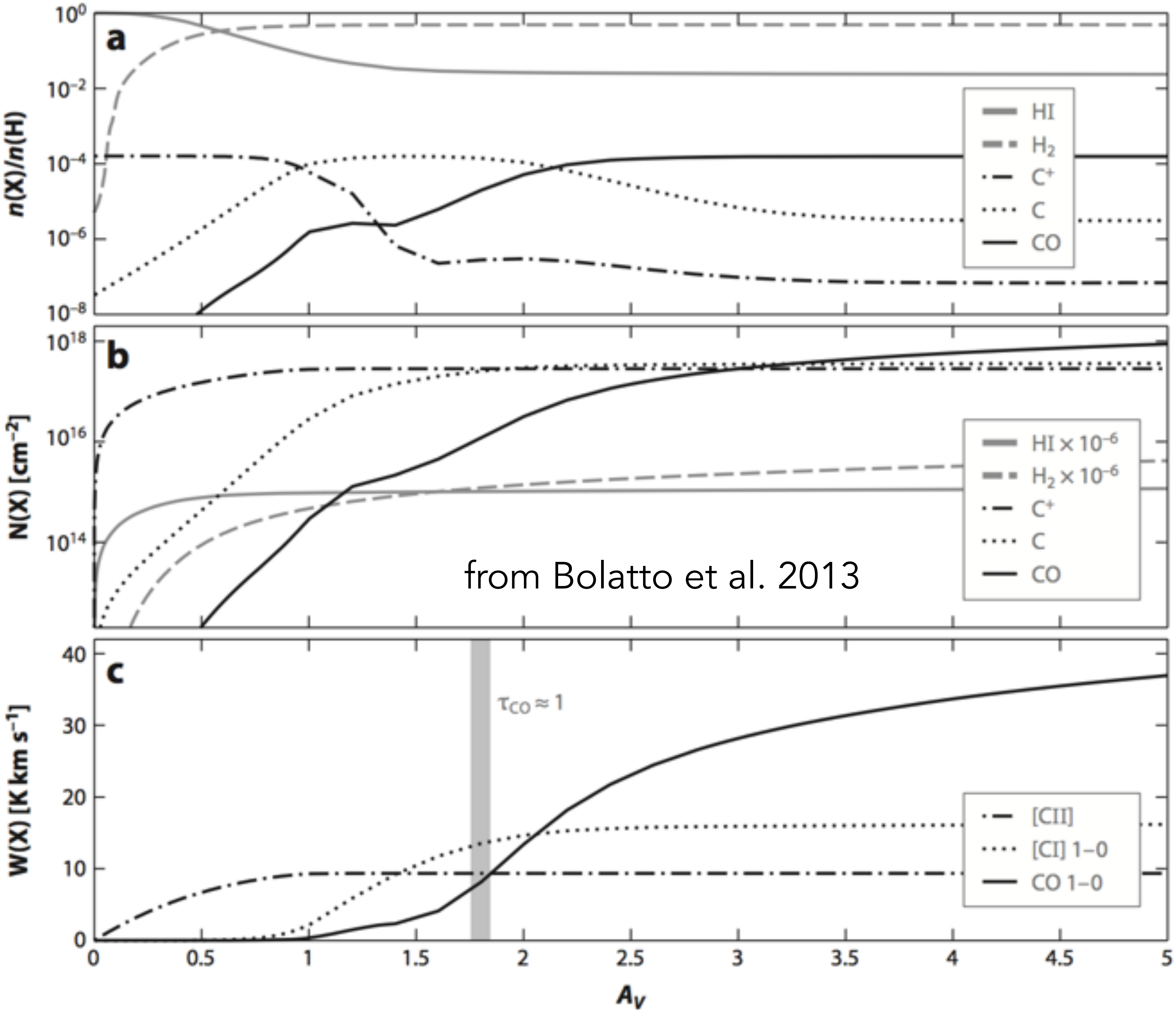
The CO-to-H_2 Conversion Factor



assuming clouds
are in virial equilibrium
(w/no B-field, pressure,etc)
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

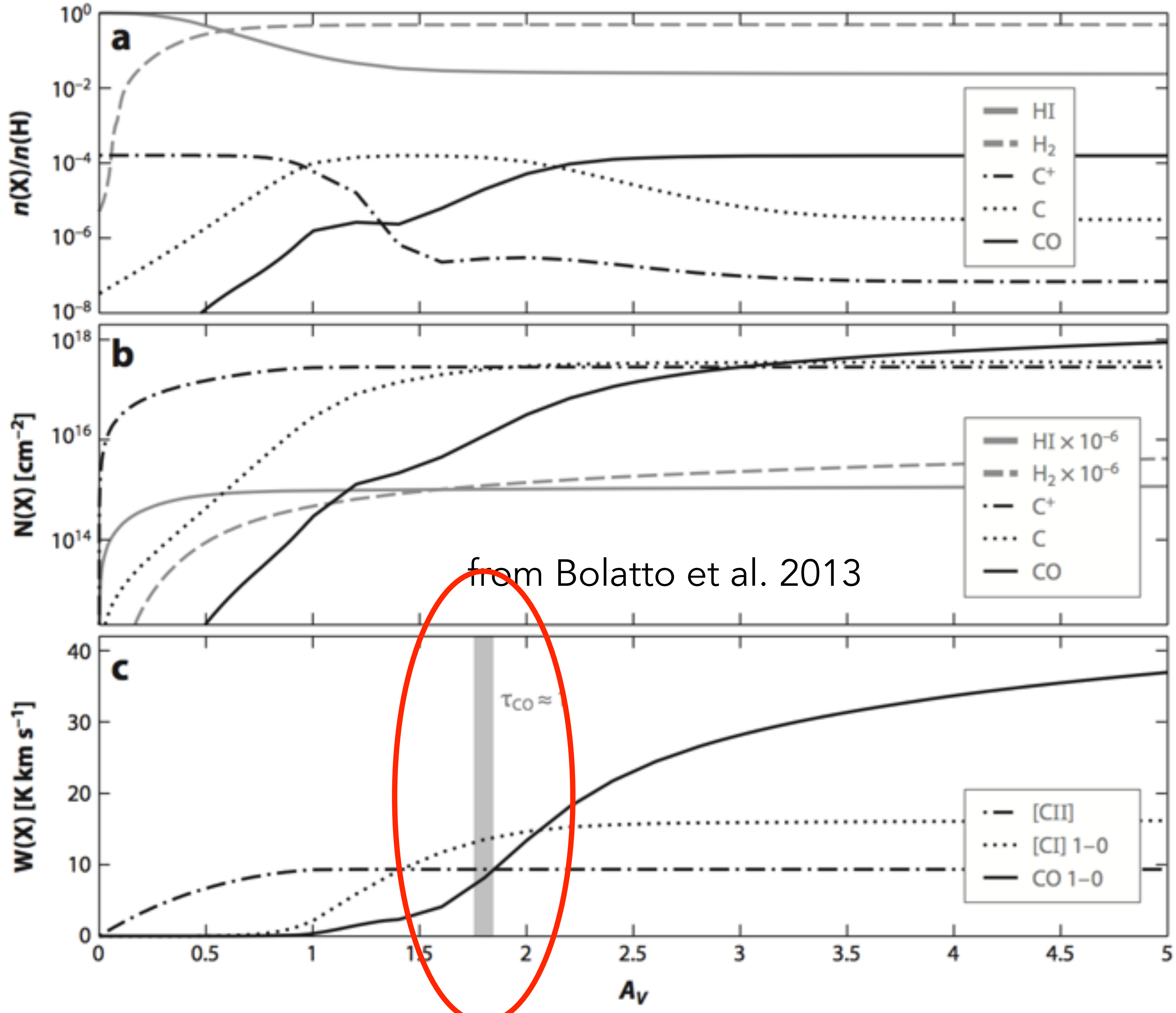


from Bolatto et al. 2013

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

How does an optically thick line tell you the mass?

Tracing Molecular Gas



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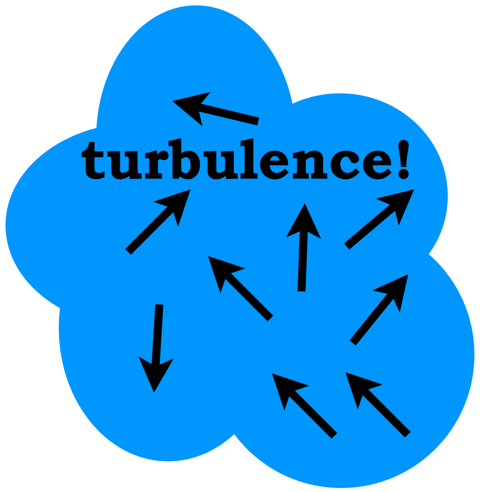
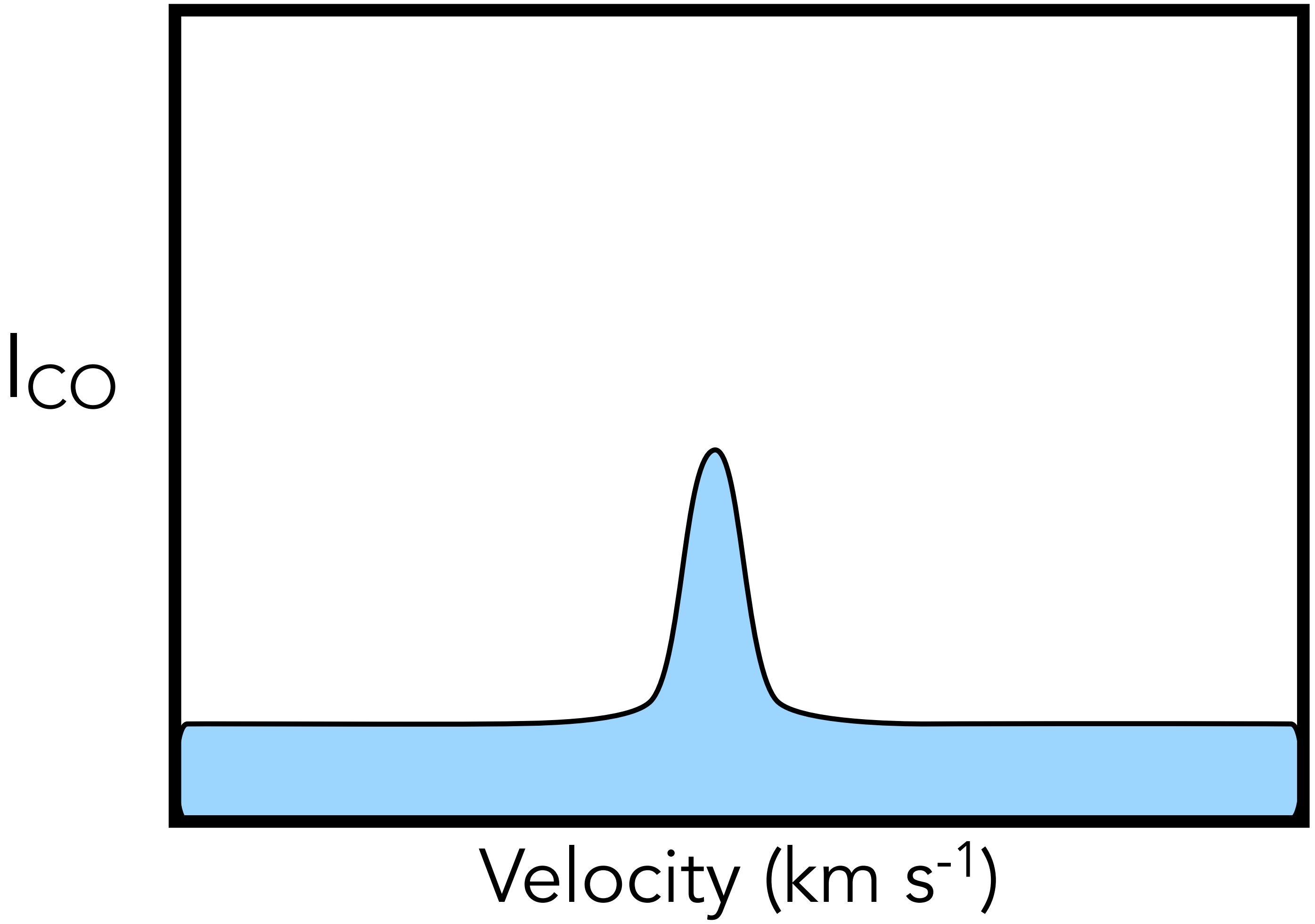
What Sets X_{CO}?



normal mol. cloud

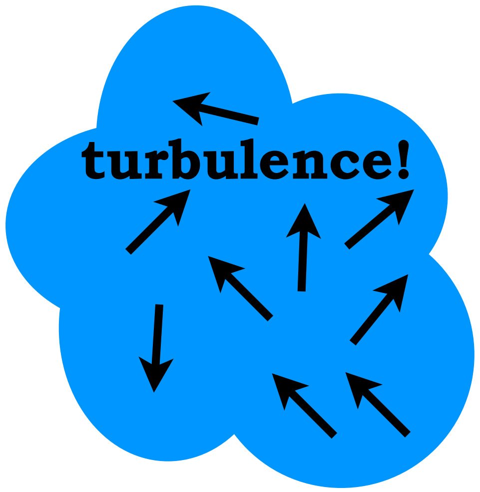
Effects of molecular cloud properties on X_{CO}.



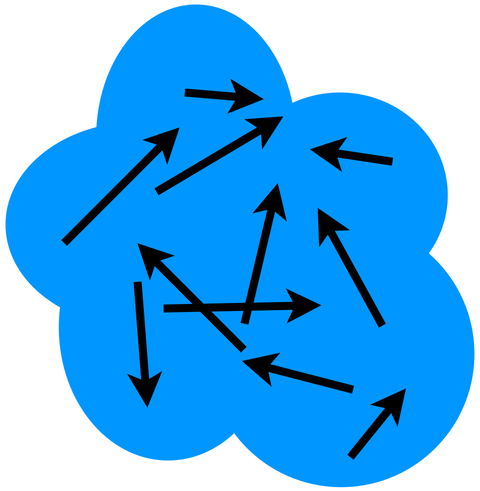
Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

What Sets X_{CO}?

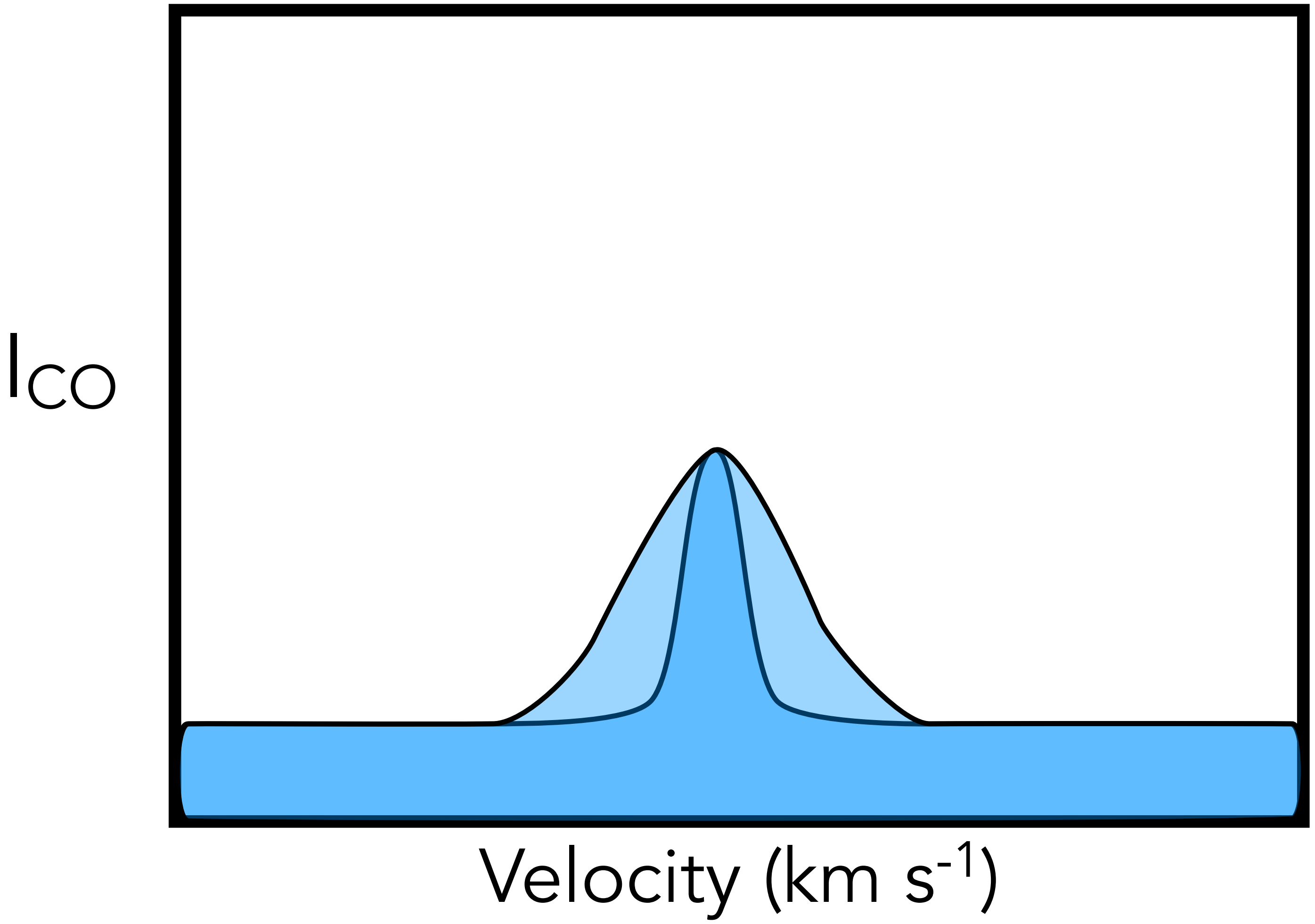


normal mol. cloud



more turbulence

Effects of molecular cloud properties on X_{CO}.



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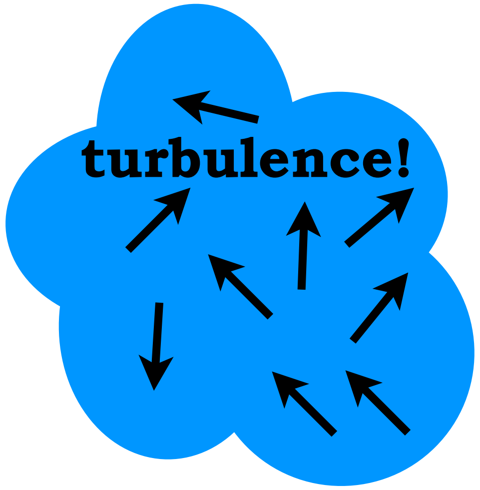

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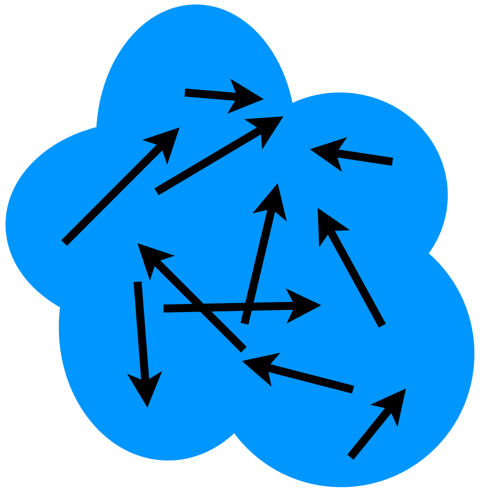

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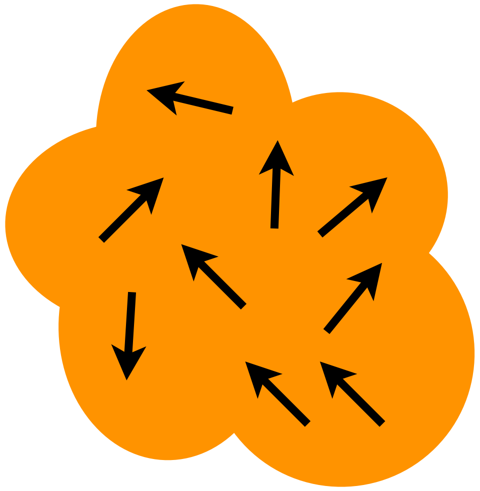
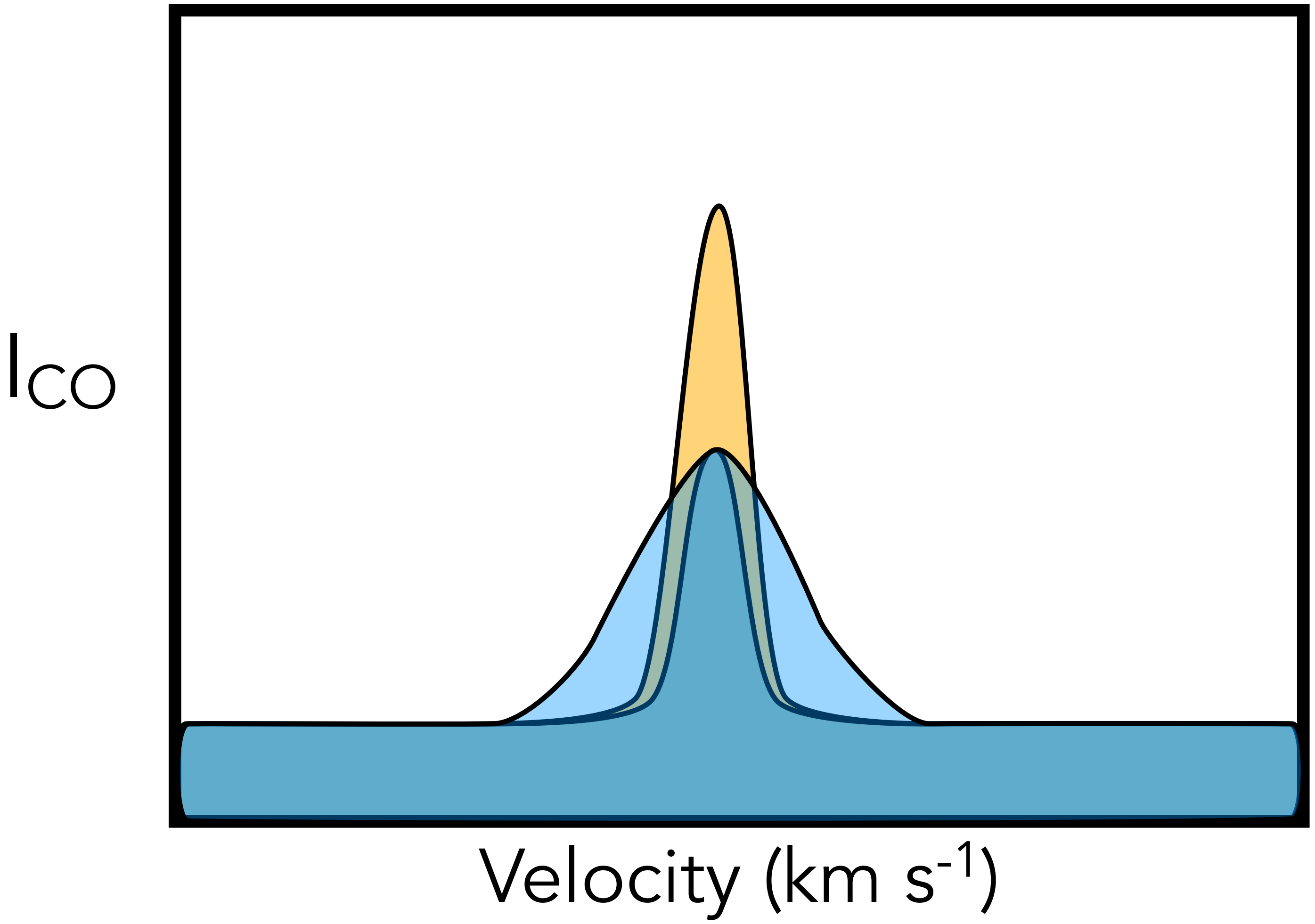


warmer gas

Effects of molecular cloud properties on X_{CO}.



Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

X_{CO} works to first order because:

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

from Bolatto et al. 2013

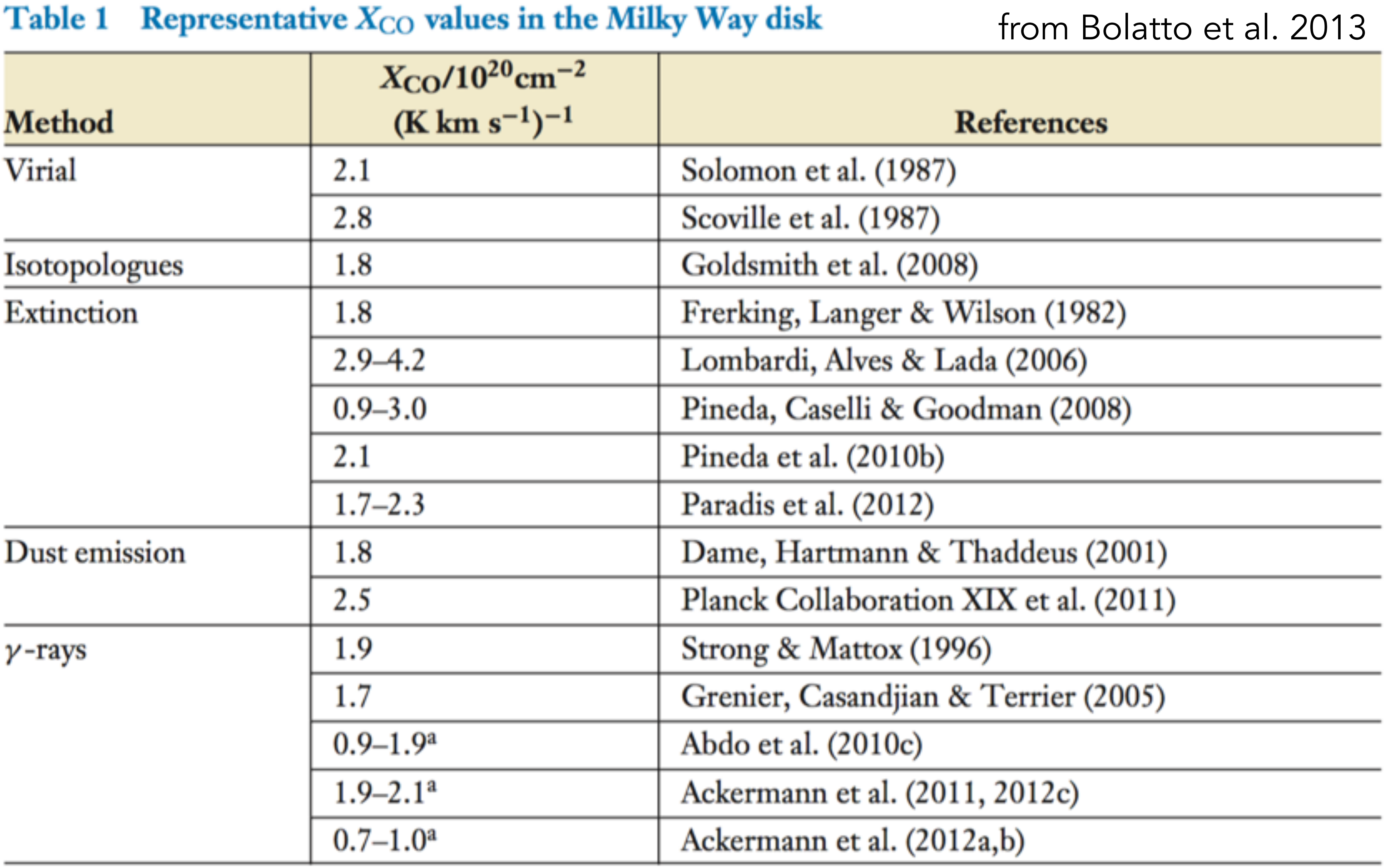
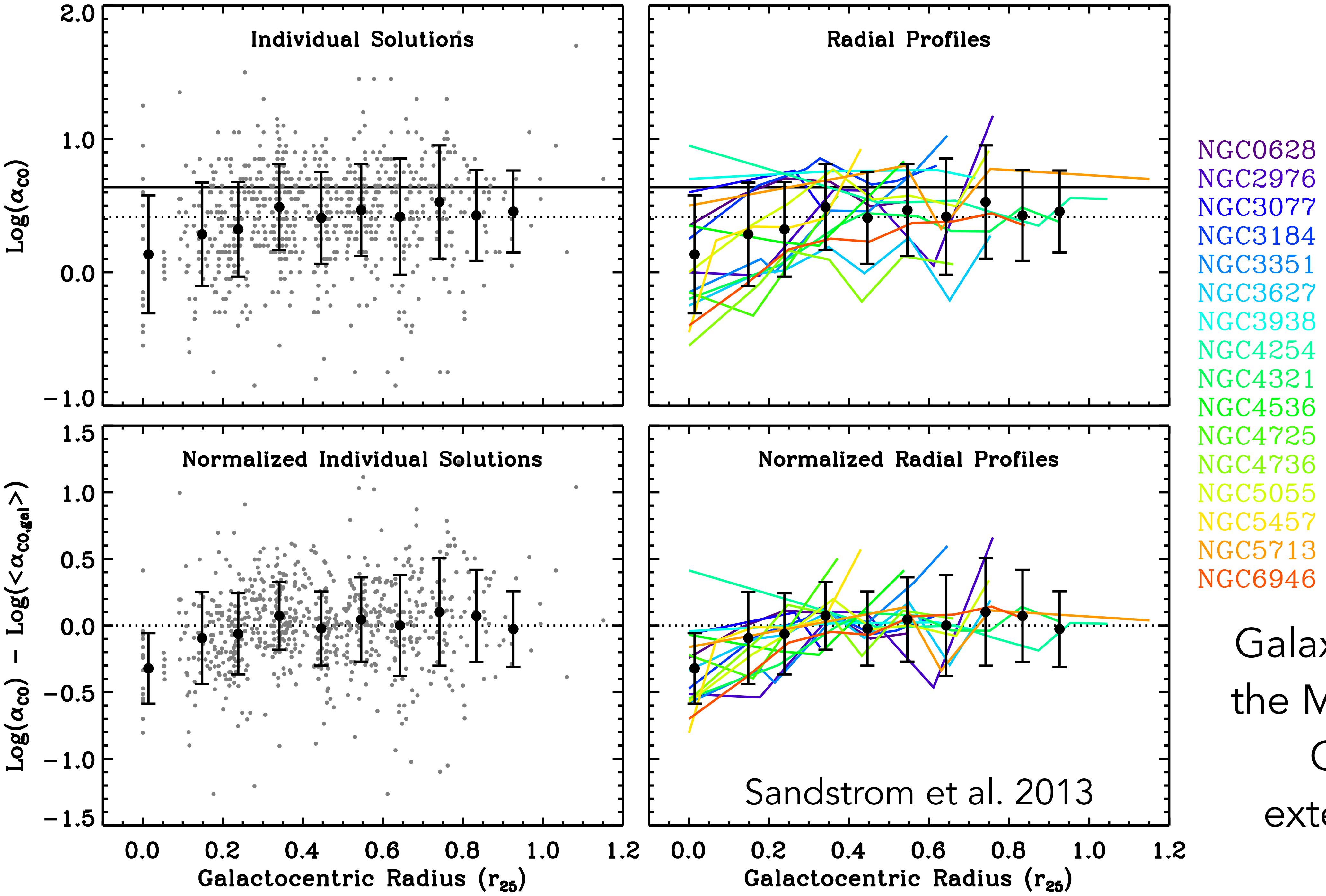


Table 1 Representative X_{CO} values in the Milky Way disk

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

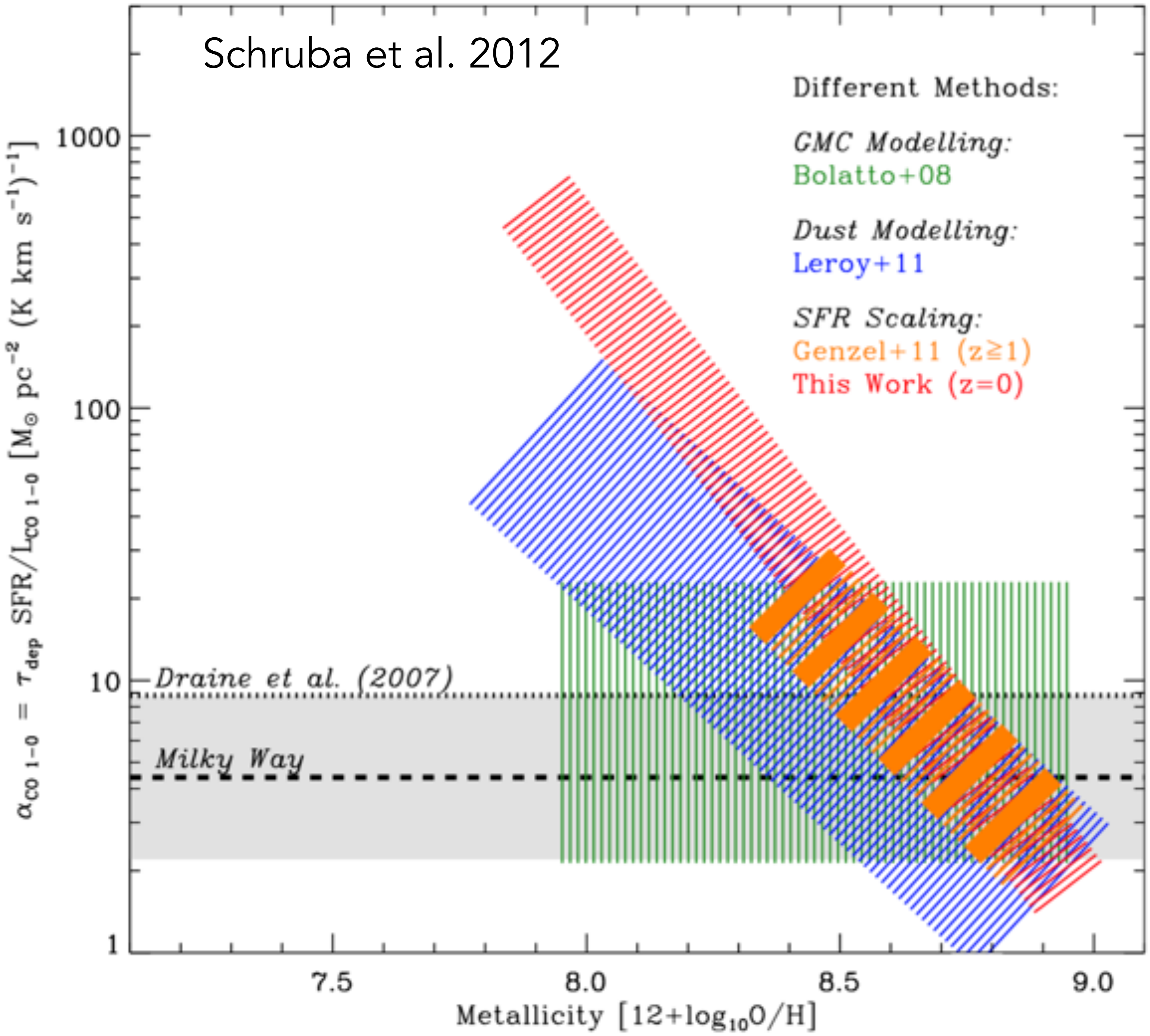


Sandstrom et al. 2013

Galaxy centers including the MW, have lower X_{CO}. Consequence of external pressure? Or hotter gas?

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor



Schruba et al. 2012

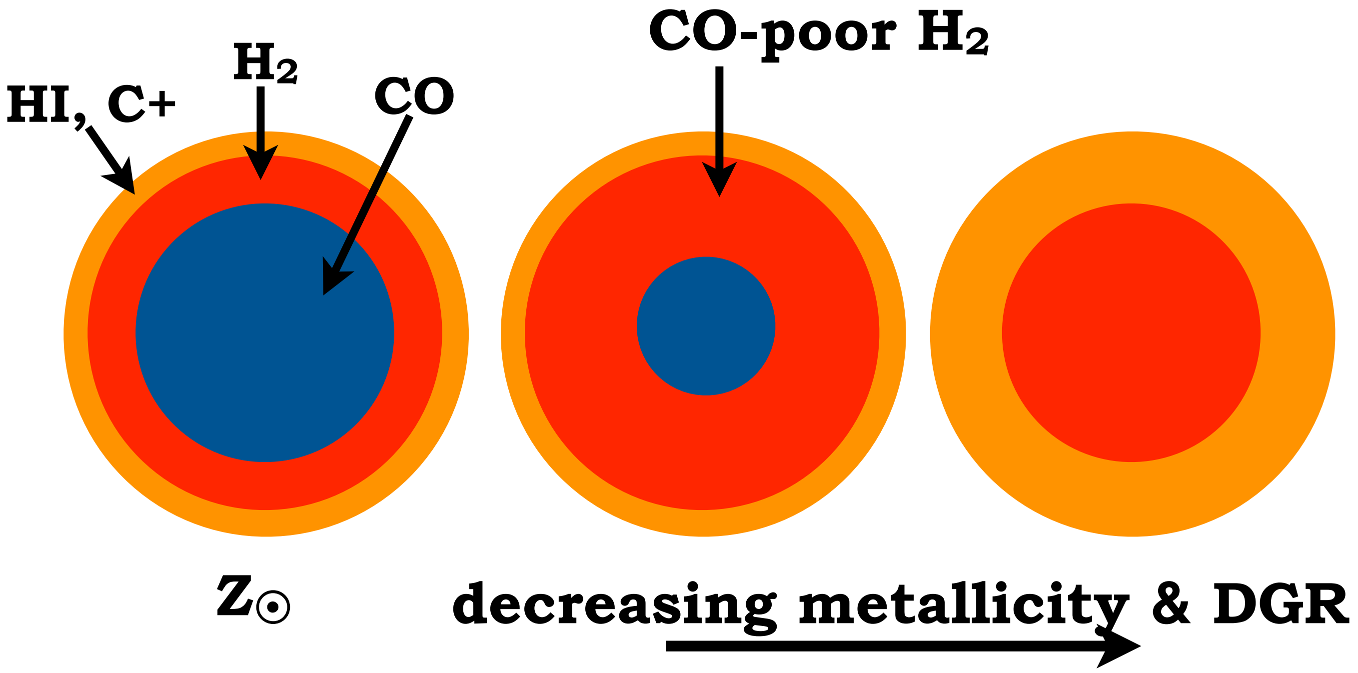
Things really fall apart at low metallicity!

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

Tracing Molecular Gas

The CO-to-H_2 Conversion Factor

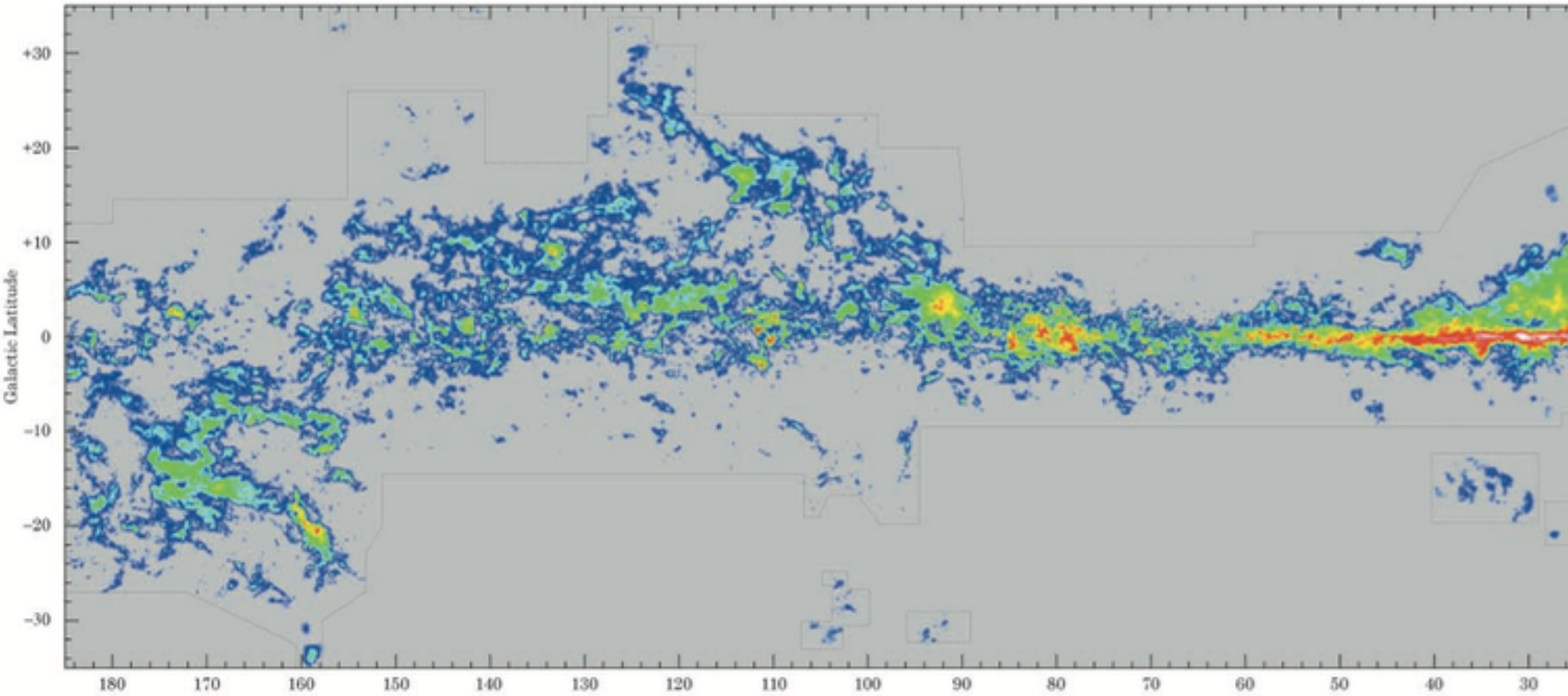
H_2 self-shields, but CO relies on dust,
when there is little dust, CO is photodissociated.



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

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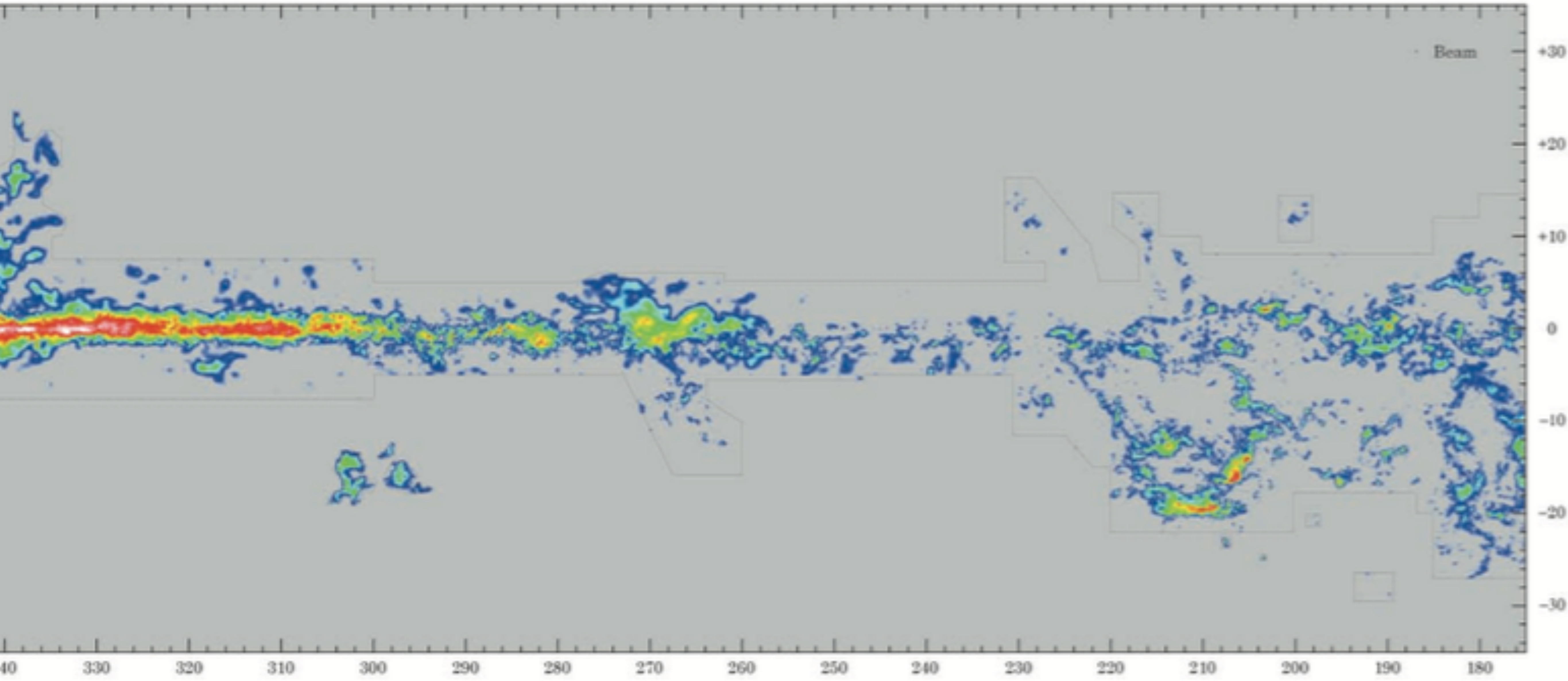
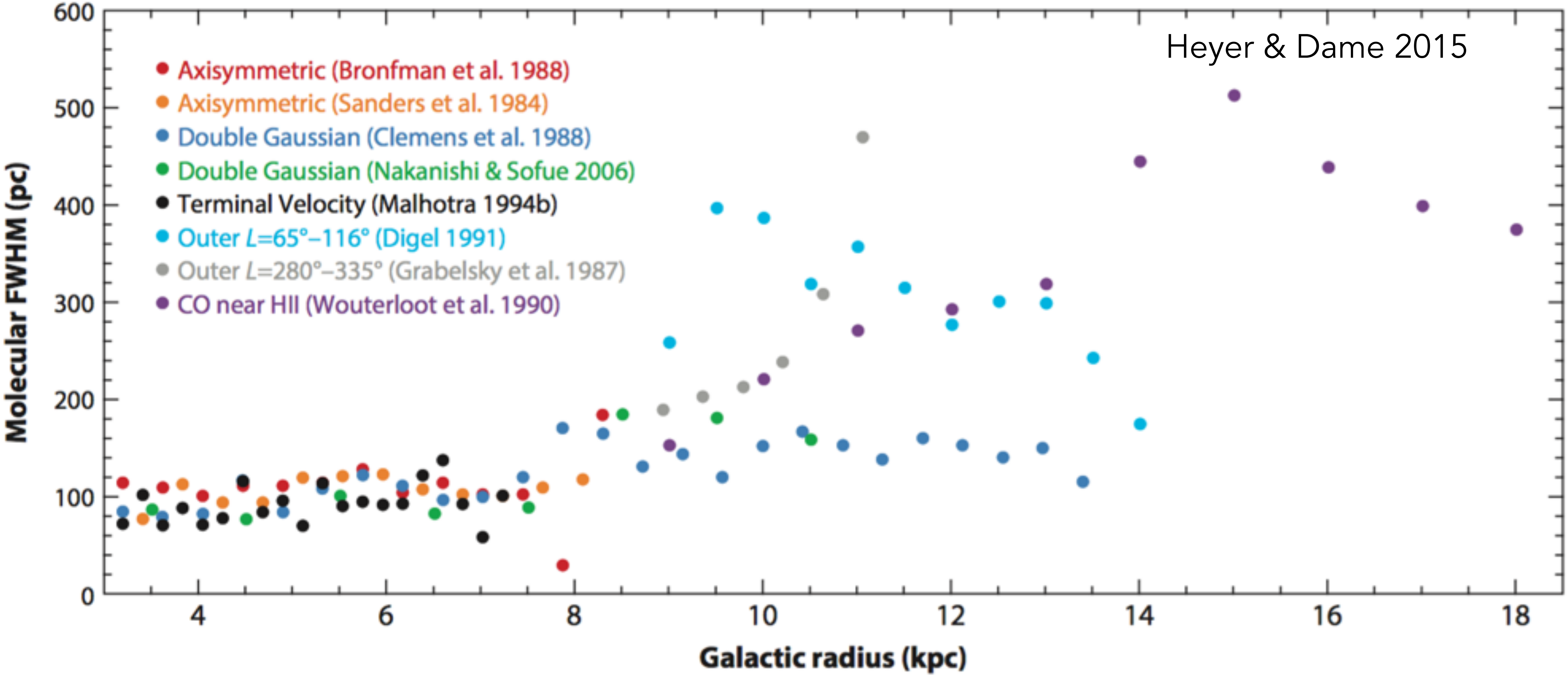


Dame et al. 2001

Observations of Molecular Gas

Distribution of Molecular Gas in the Milky Way:

Scale Height of CO

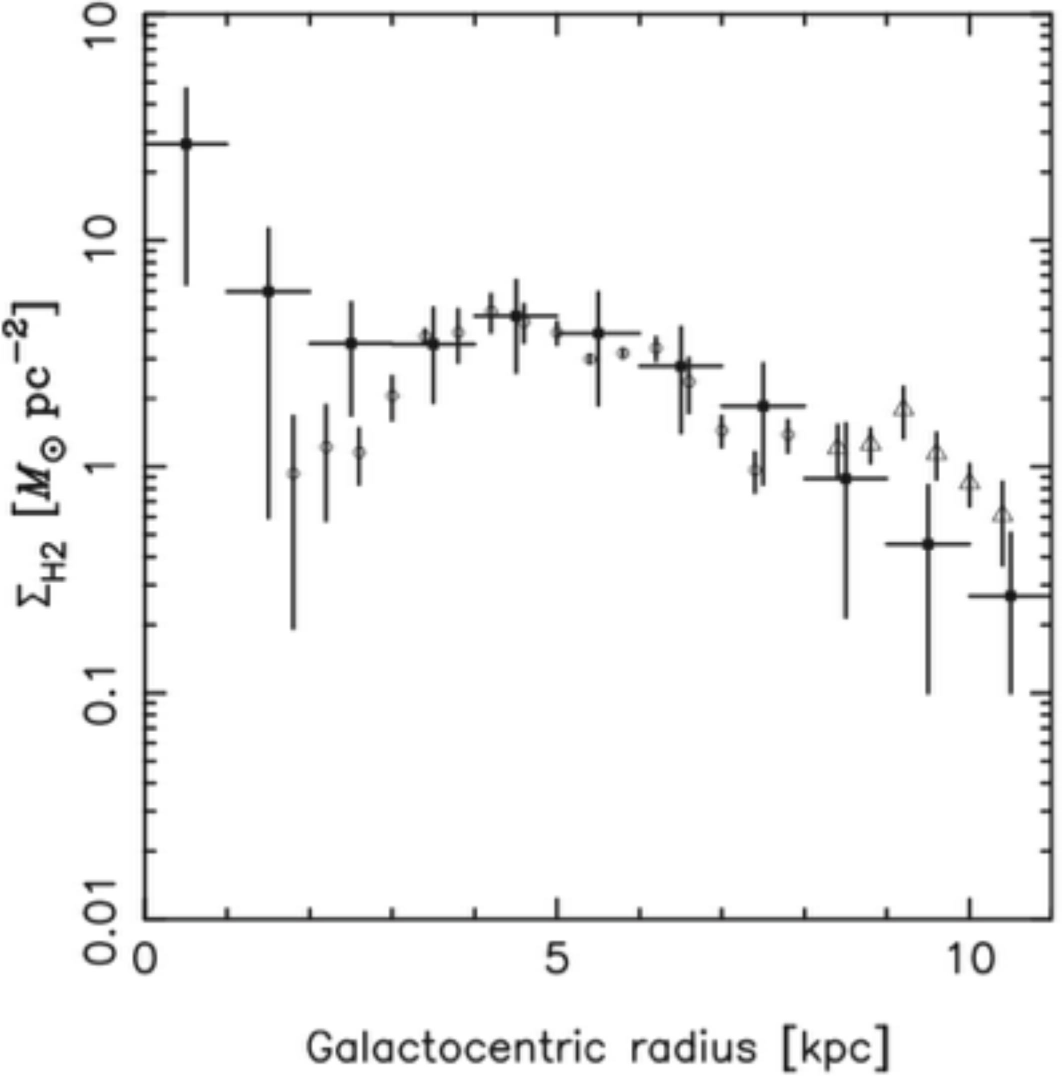


Observations of Molecular Gas

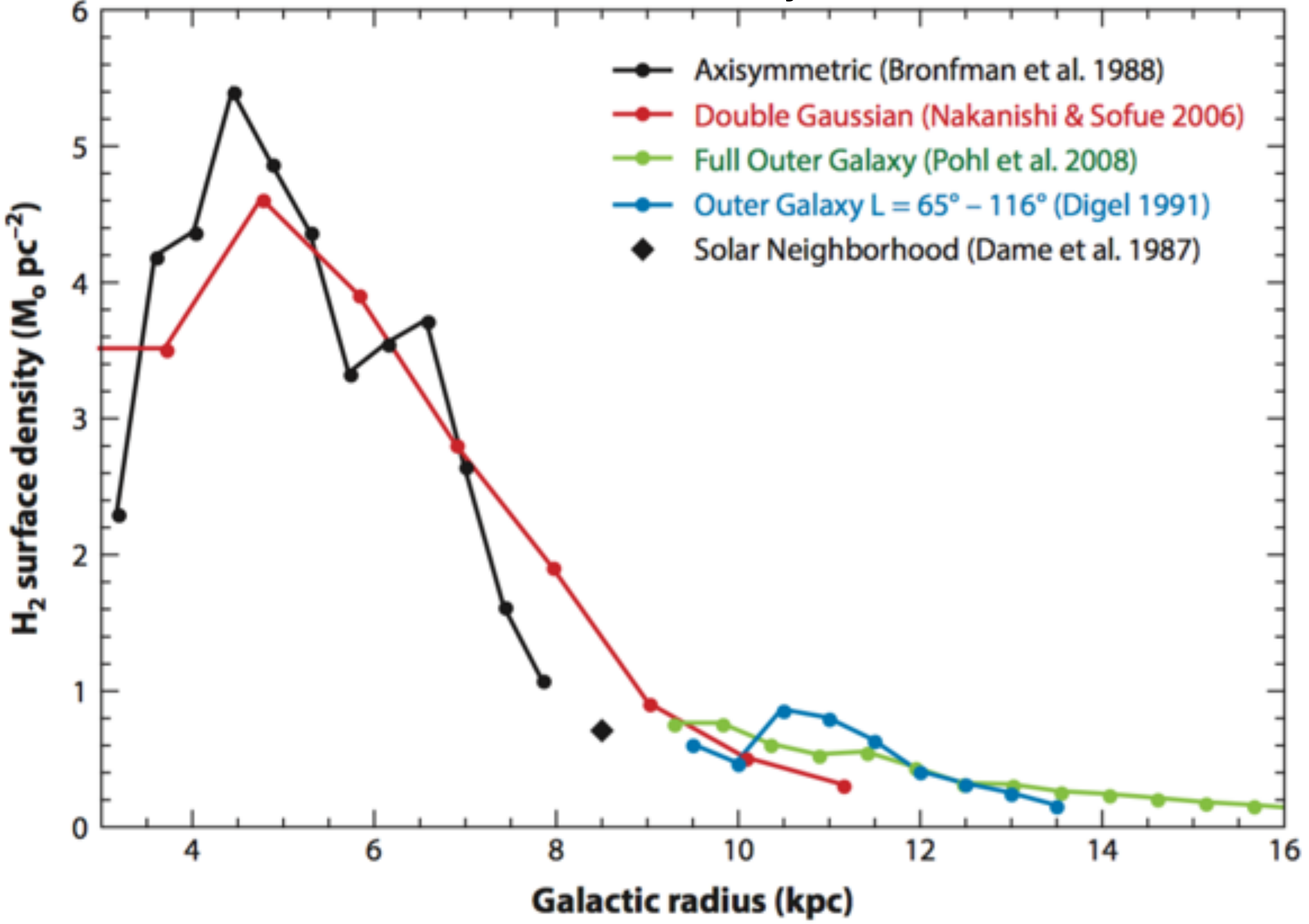
Distribution of Molecular Gas in the Milky Way:

Surface Density

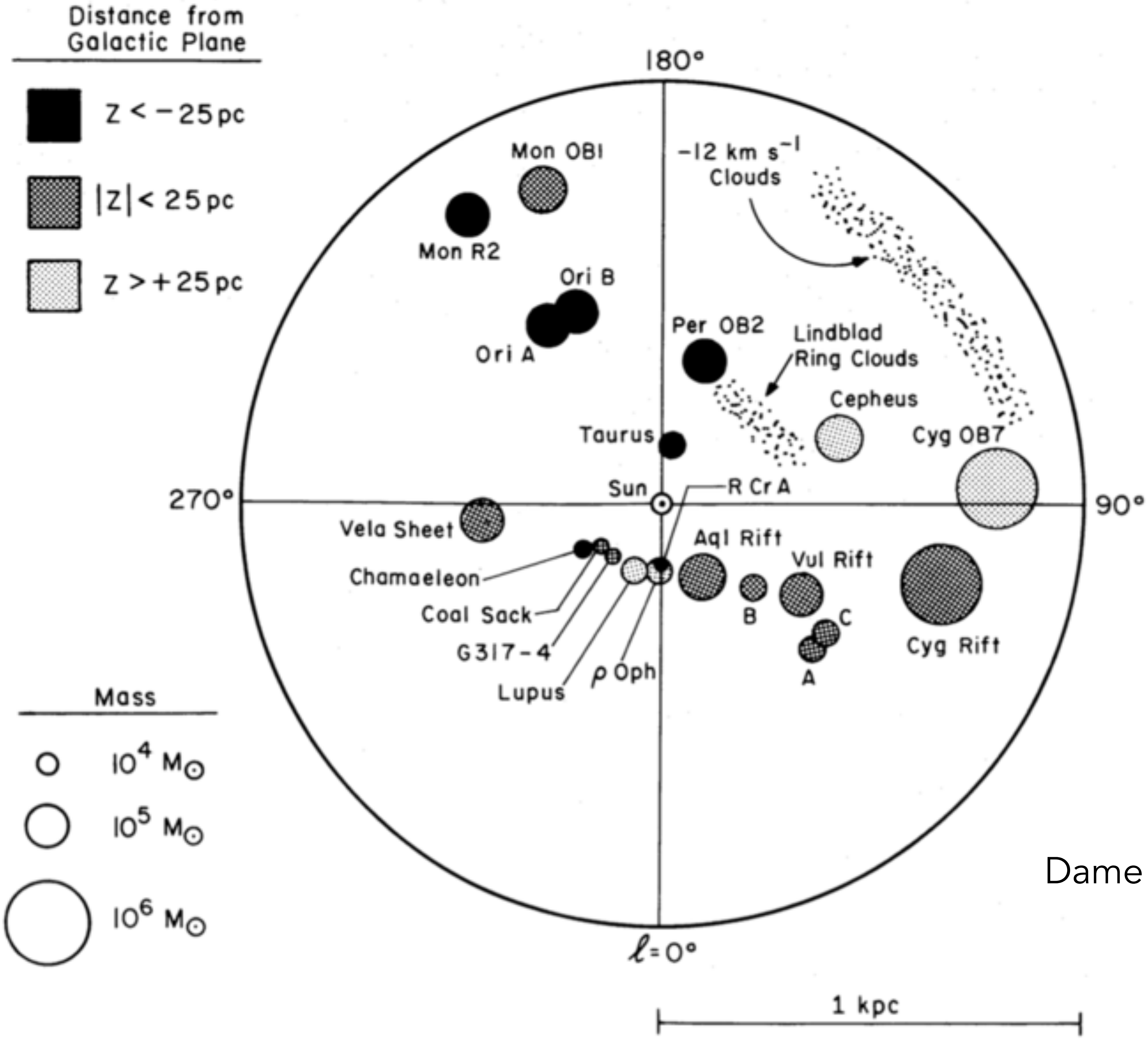
Nakanishi & Sofue 2006



Heyer & Dame 2015



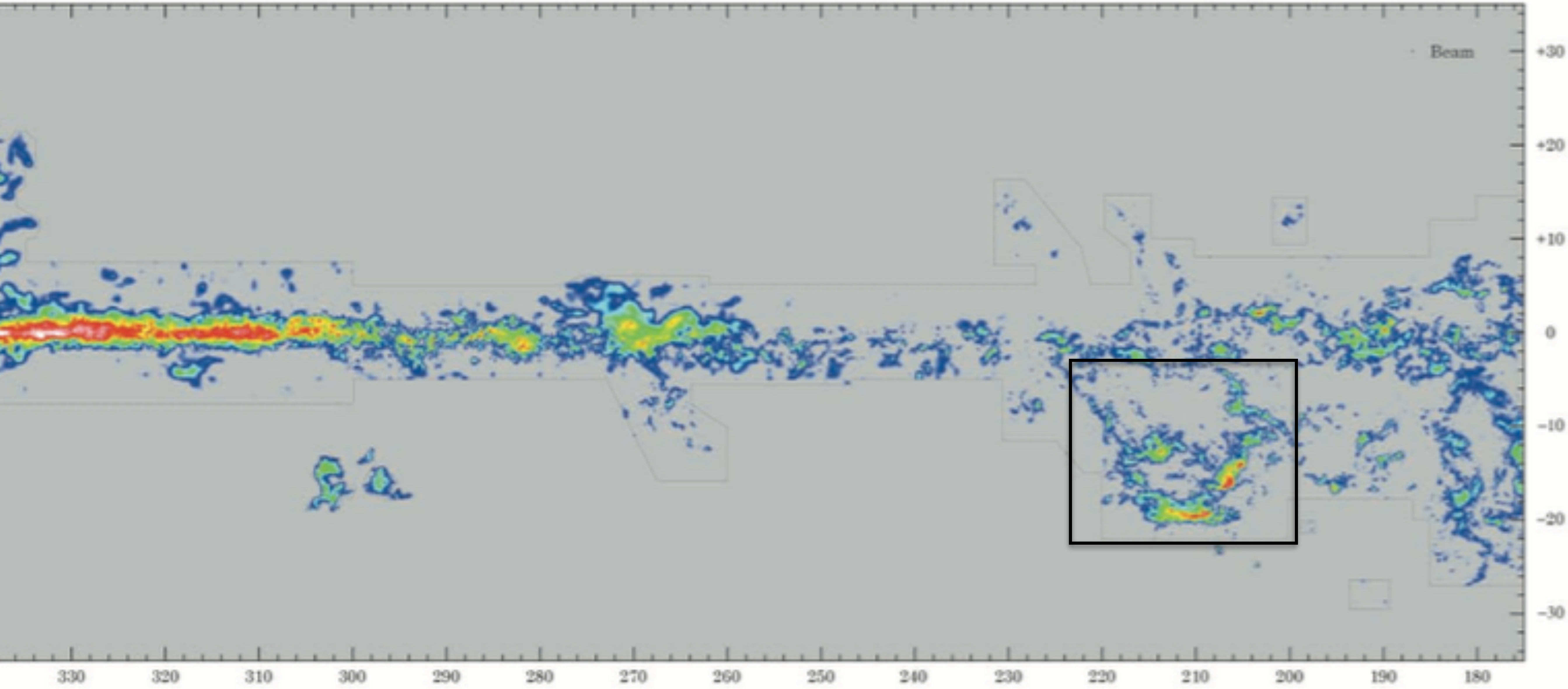
Observations of Molecular Gas



Dame et al. 1987

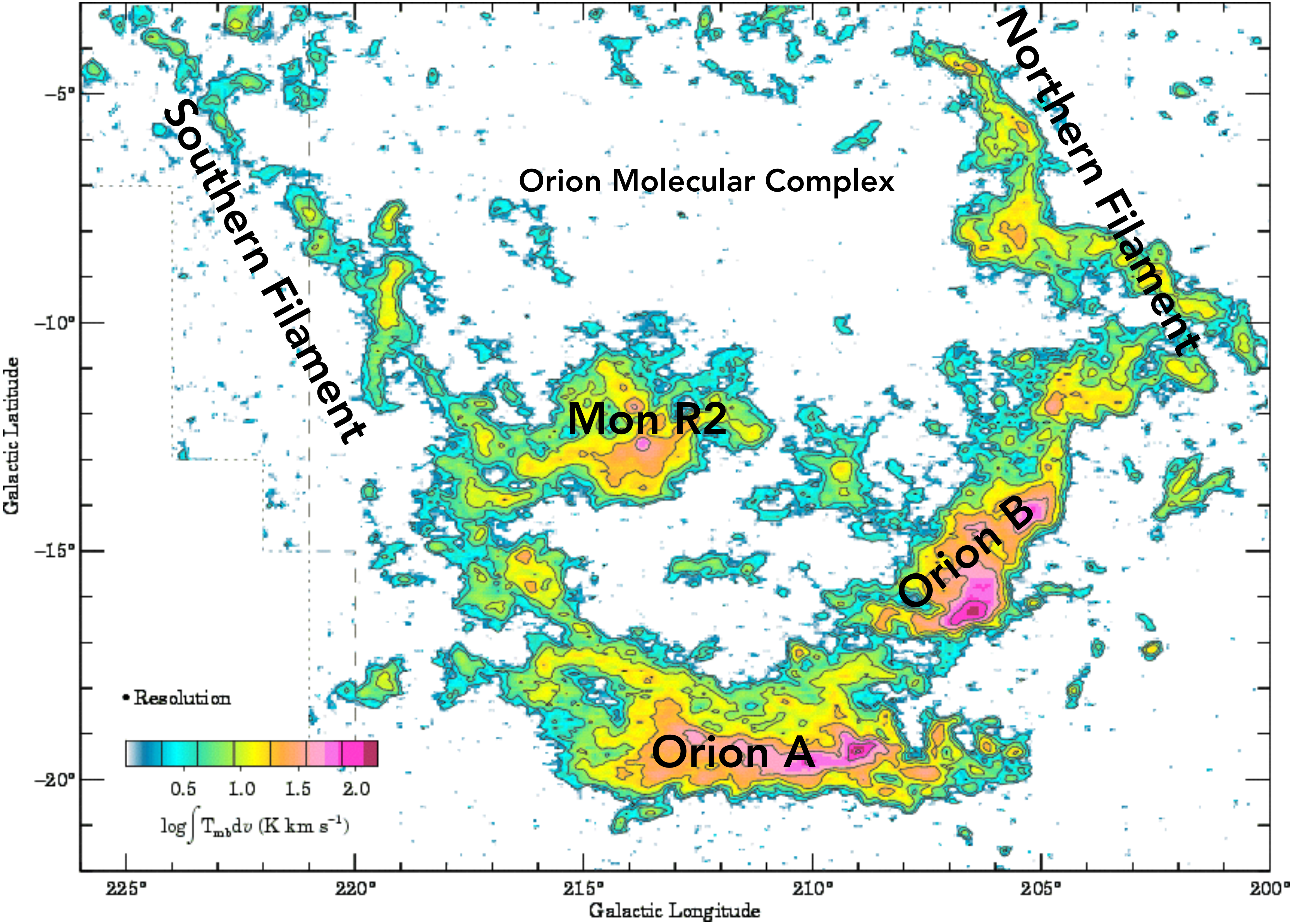
Observations of Molecular Gas

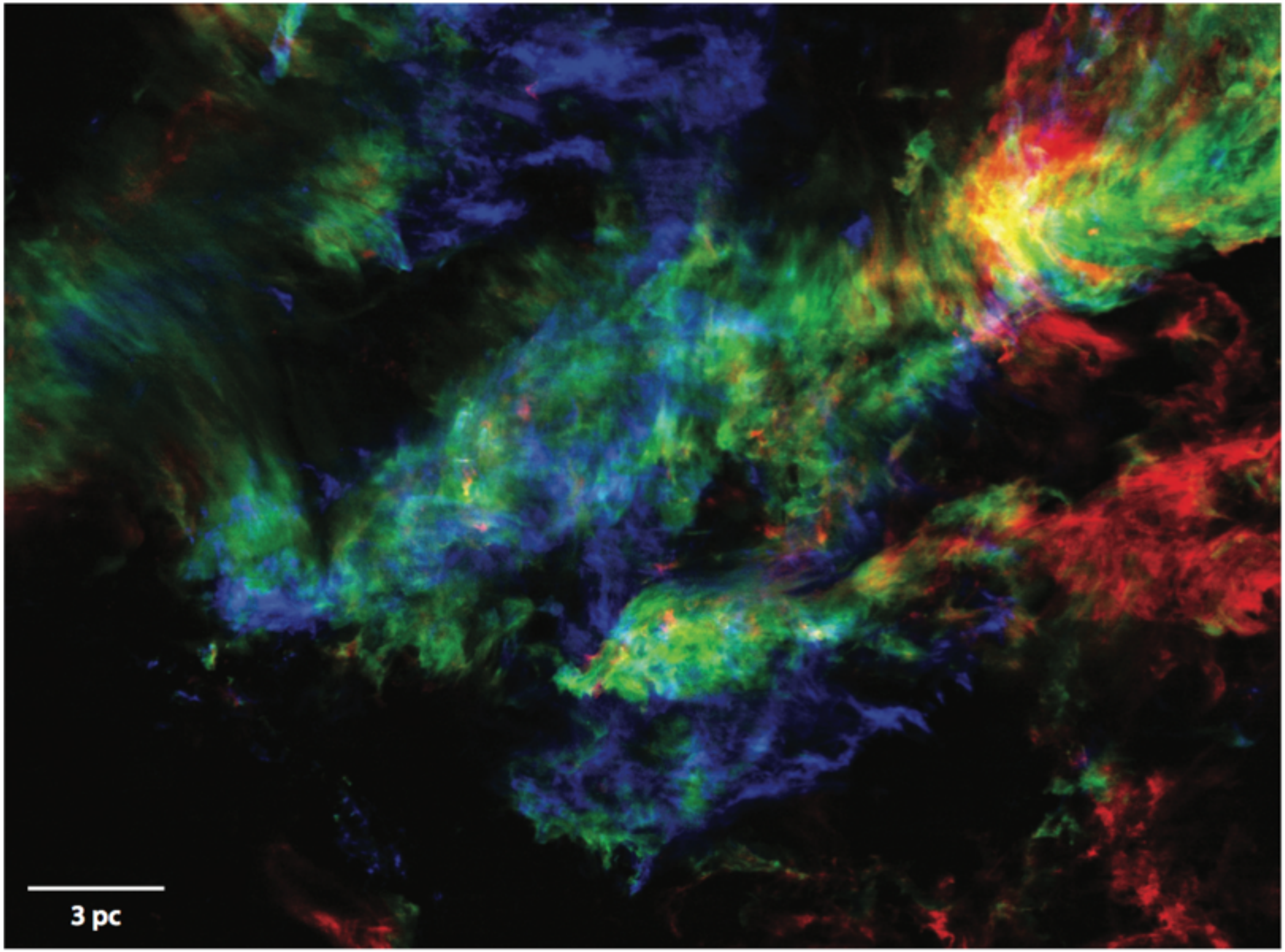
"Molecular Clouds"



Dame et al. 2001

Wilson et al. 2005





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.

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

Molecular Clouds

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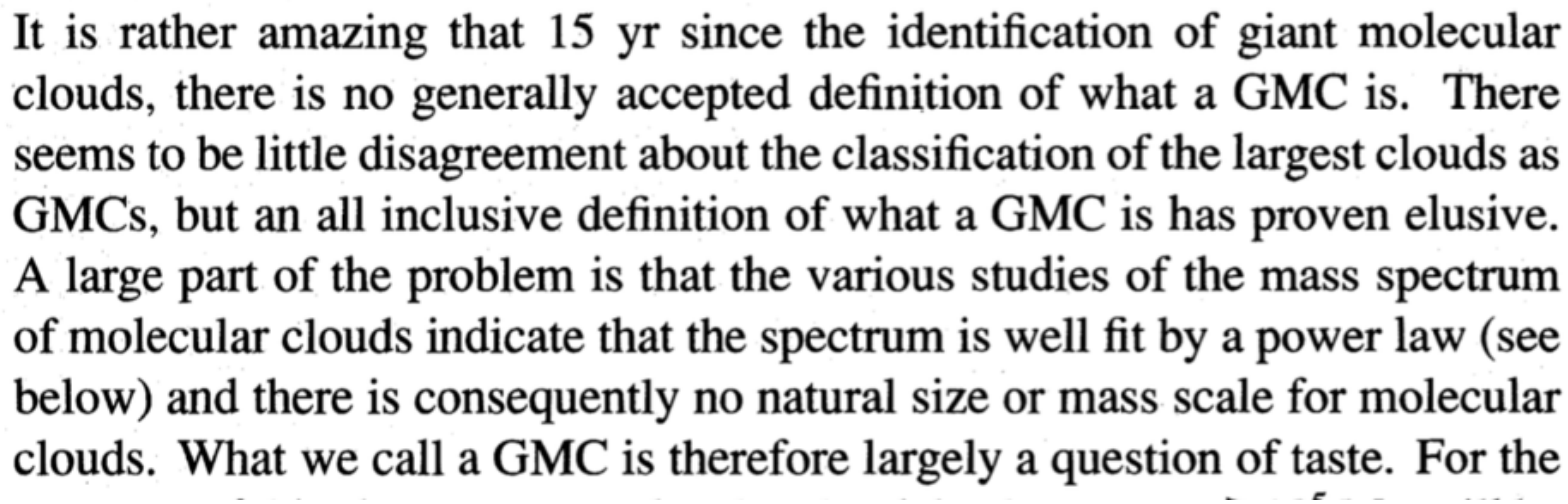
Giant Molecular Clouds (GMC):



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.

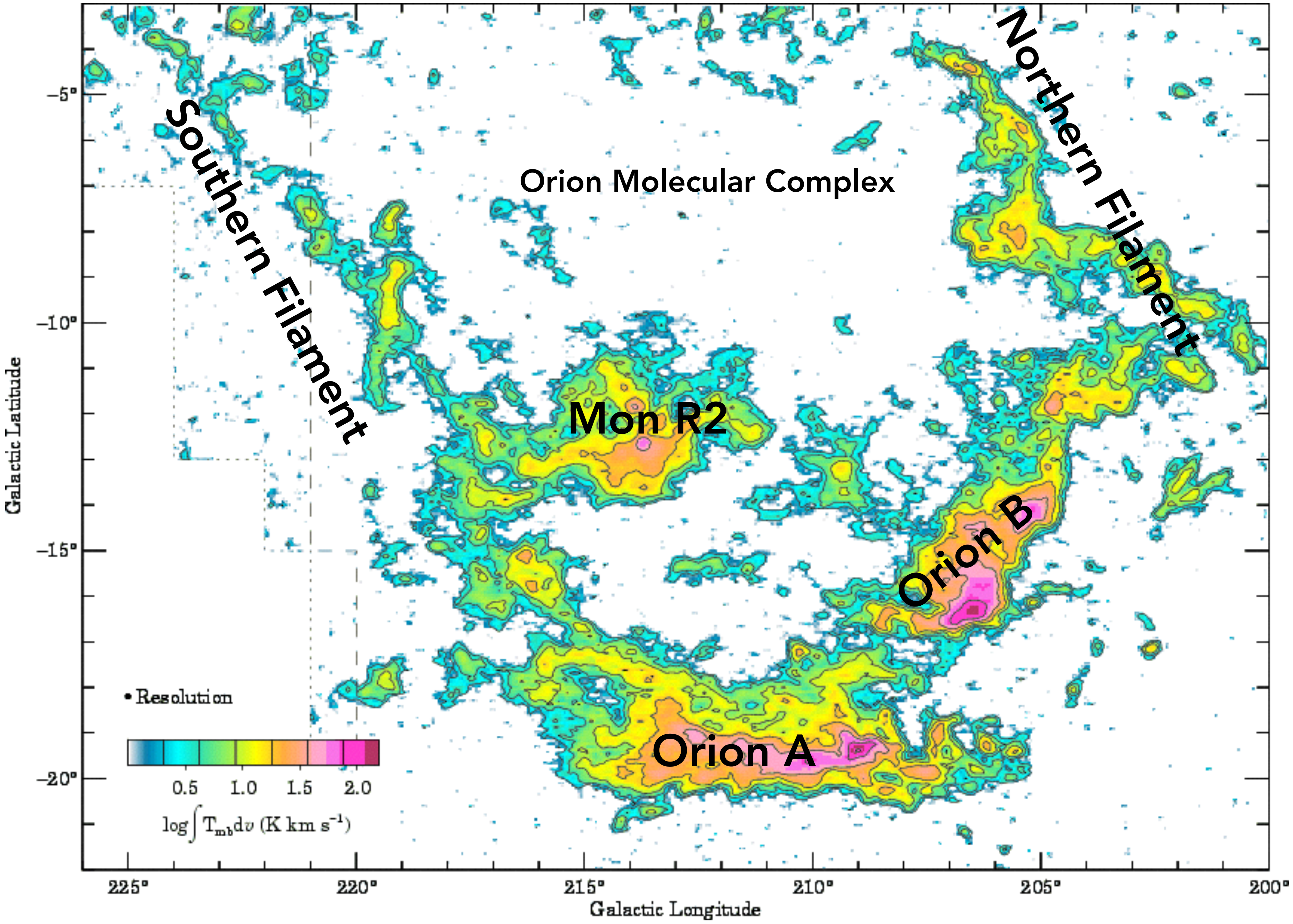
Giant Molecular Clouds (GMC):

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

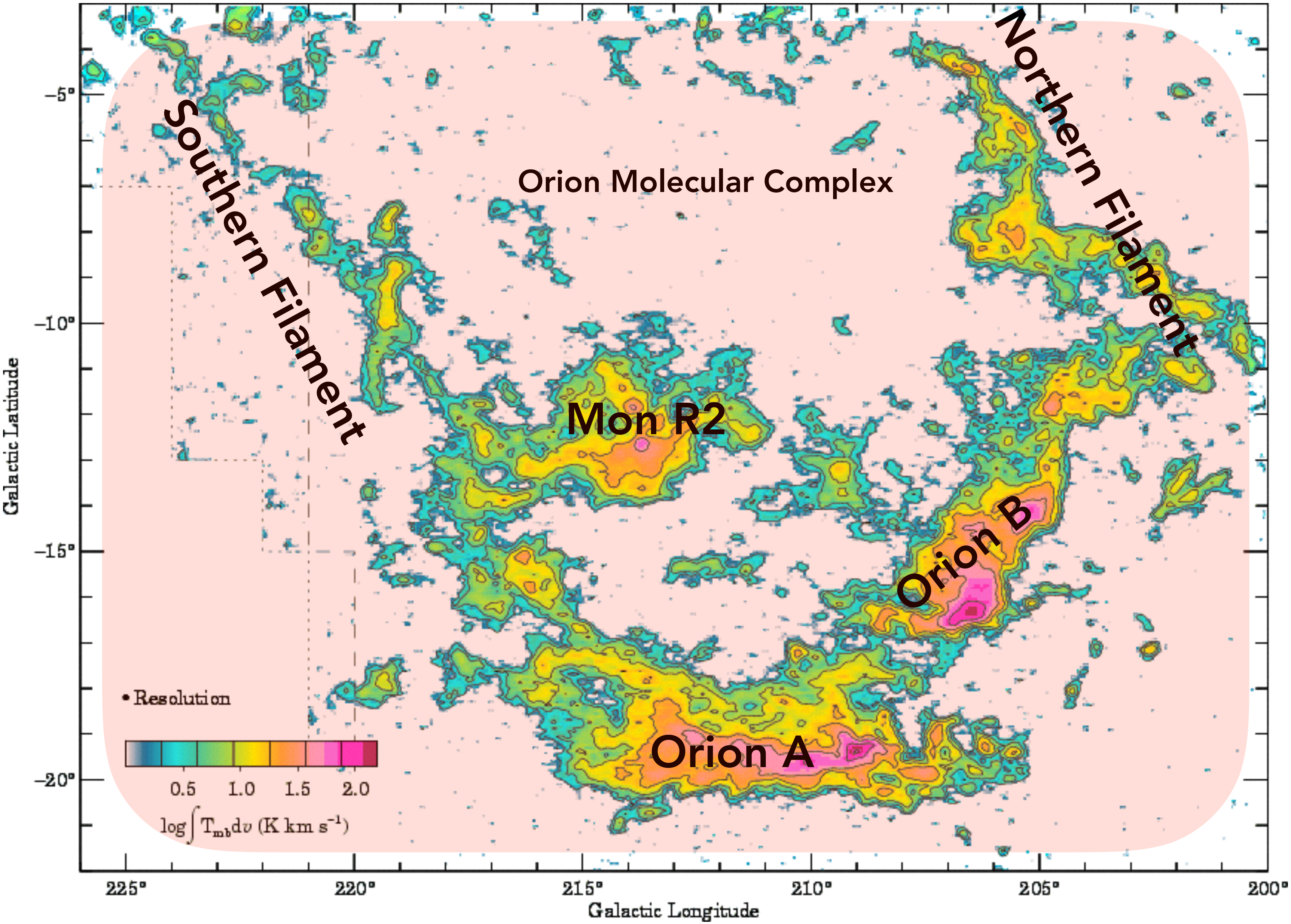
Size ~ 10^1 - 10^2 pc

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

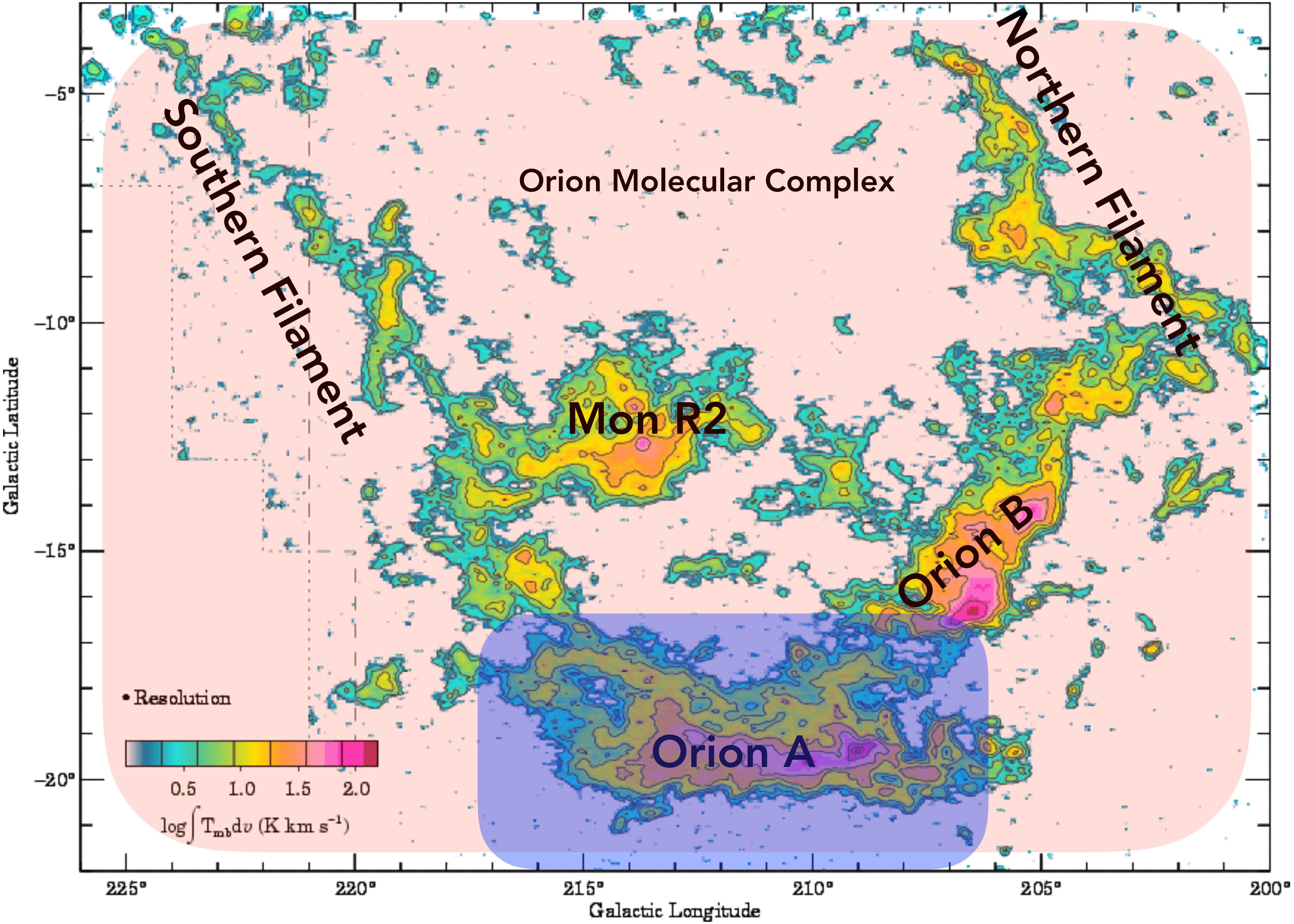
Wilson et al. 2005



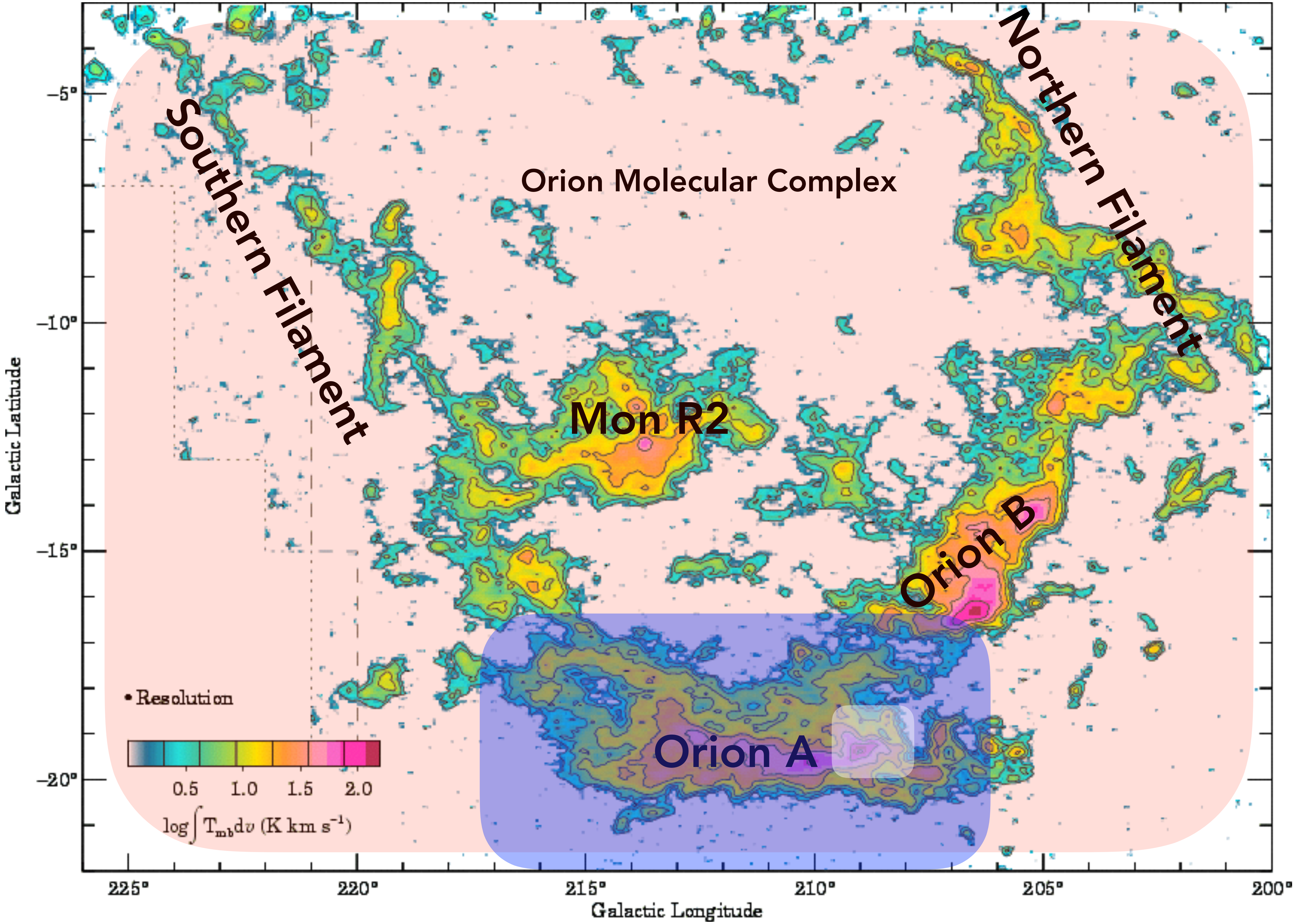
Wilson et al. 2005



Wilson et al. 2005



Wilson et al. 2005



Molecular Clouds

Observed Characteristics

- Self-Gravity
- Turbulence
- Substructure
- Magnetic Fields
- Mass Spectrum
- Lifetimes
- Star Formation

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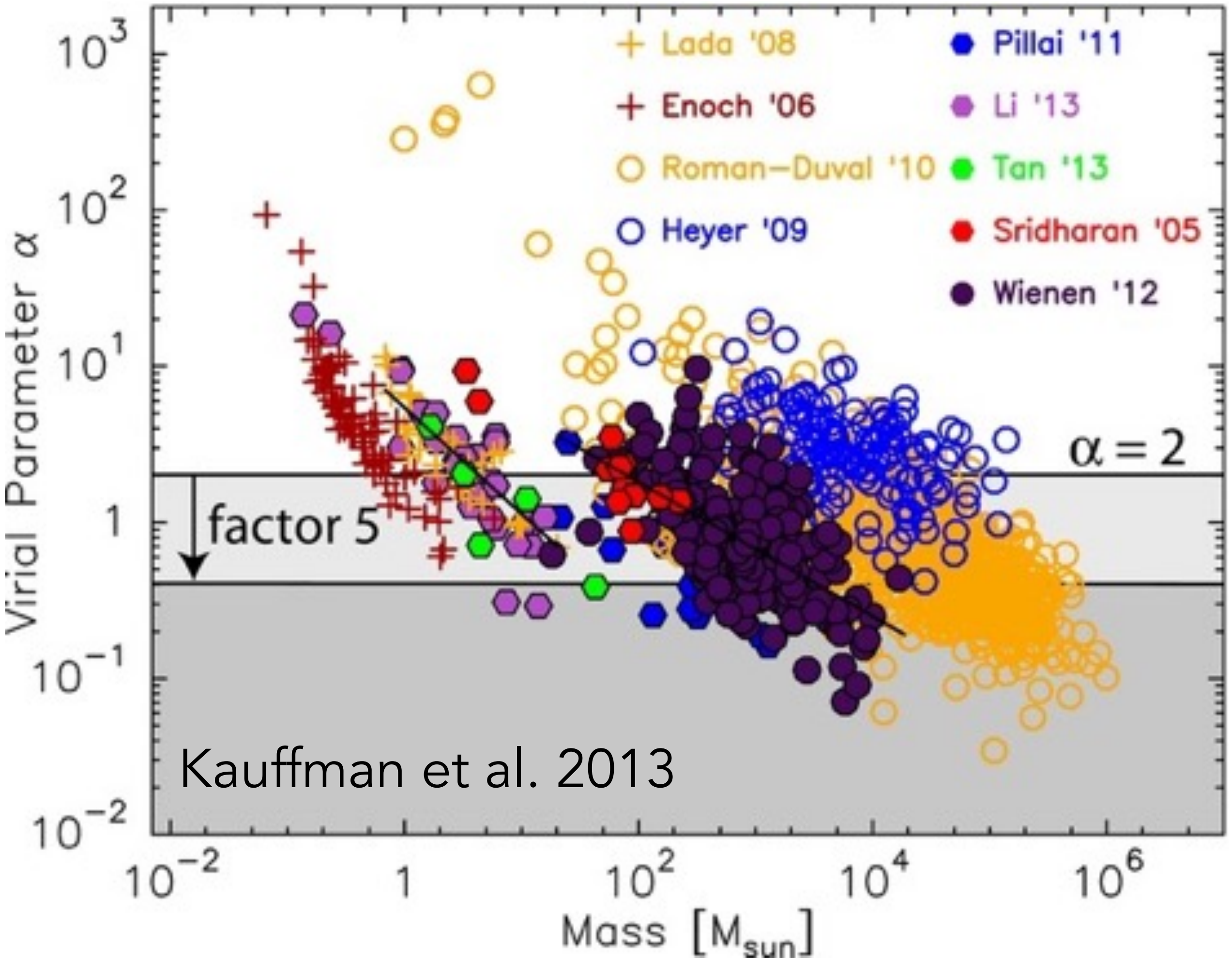
Continuing controversy over whether GMCs are gravitationally bound.
Regardless, $\alpha_{vir} = 5\sigma_v R/GM$ ~ order unity



Kauffman et al. 2013

Molecular Clouds

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Also note that GMCs are "over-pressurized" wrt diffuse ISM:

WNM/CNM: P ~ 3800 cm^{-3} K

GMC (T=10, n=10^4): P ~ 10^5 cm^{-3} K

Without self-gravity, GMCs would be transient.

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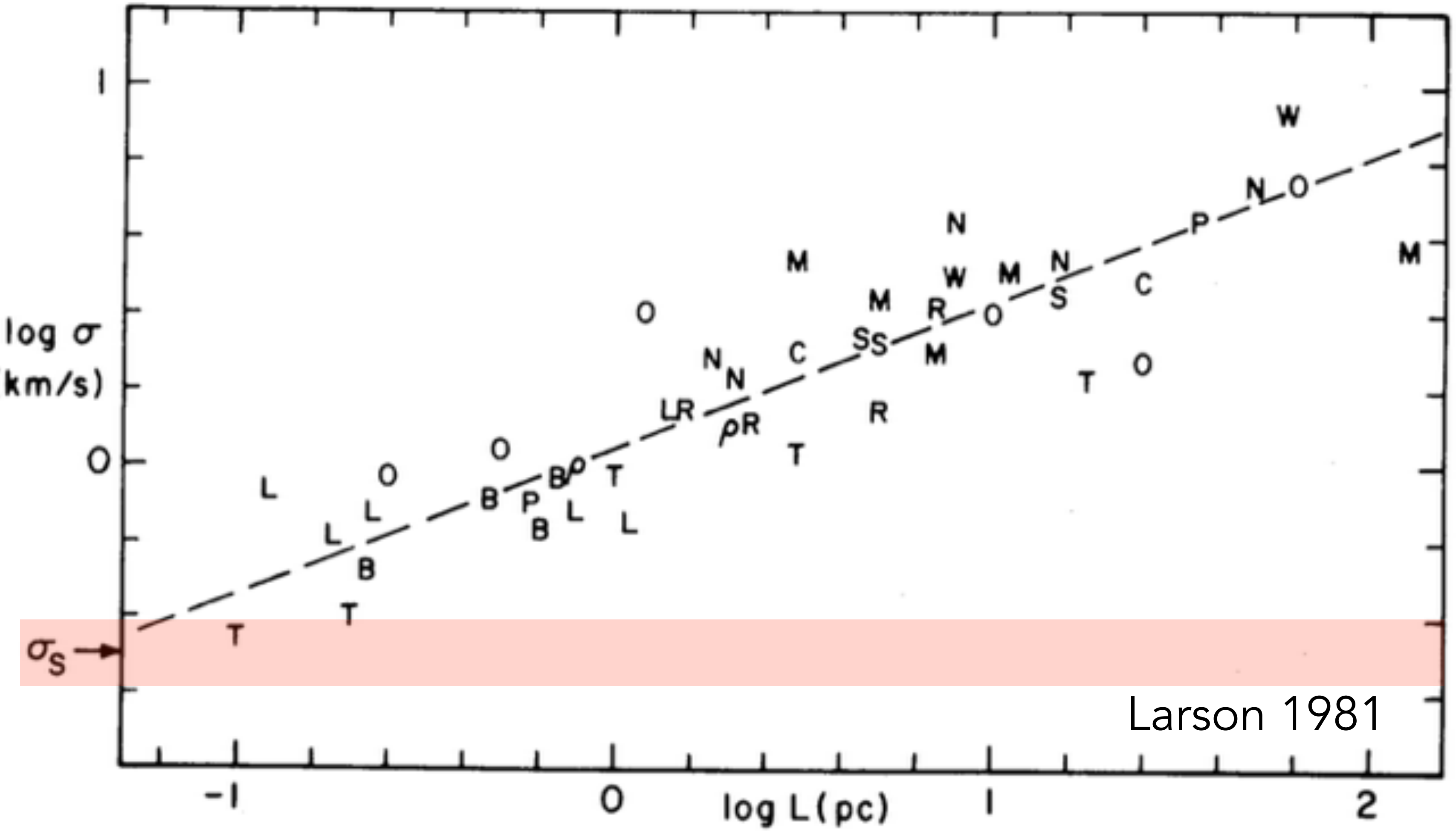

Larson 1981

Velocity dispersion is >> sound speed, supersonic turbulence provides support against gravity.

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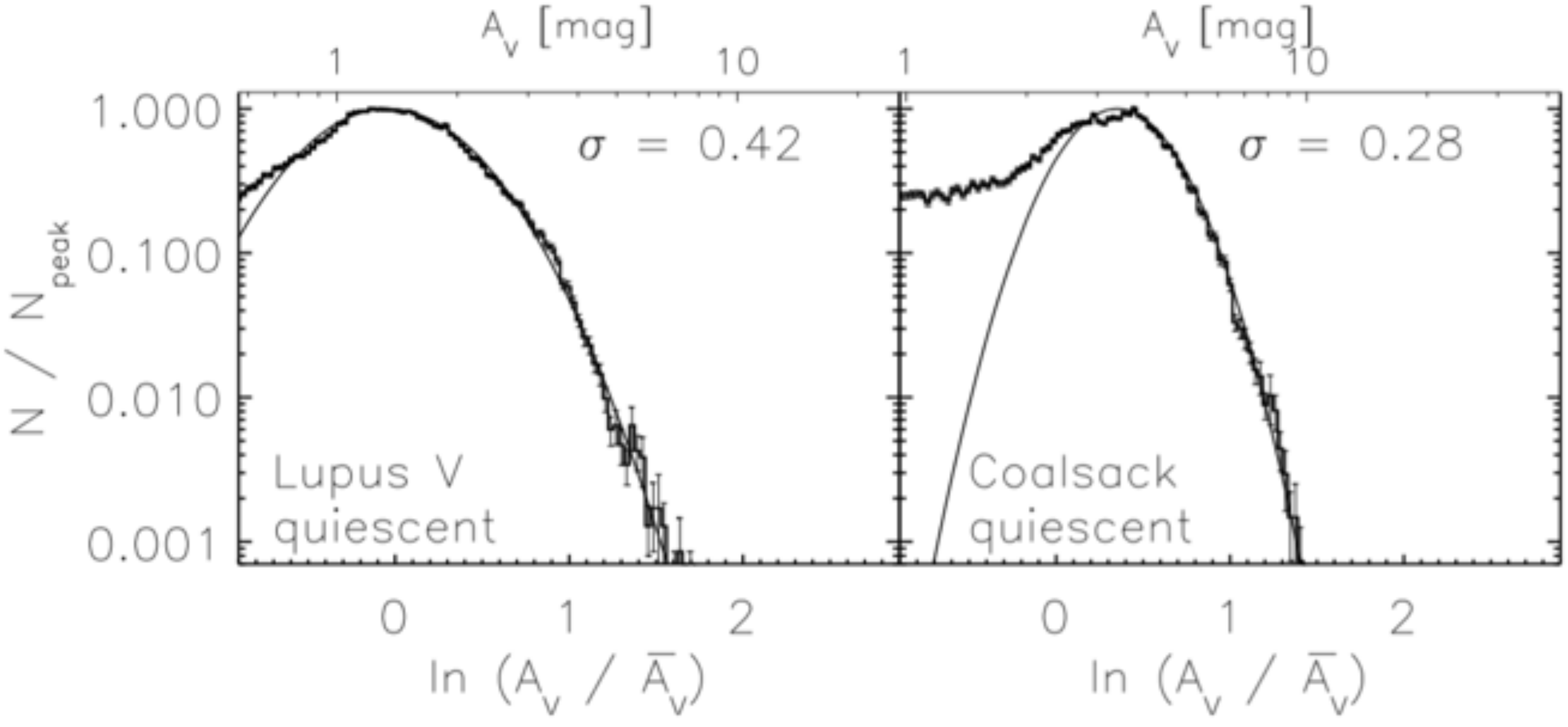

Kainulainen et al. 2009

Log-Normal PDF of column density observed in molecular clouds.

Molecular Clouds

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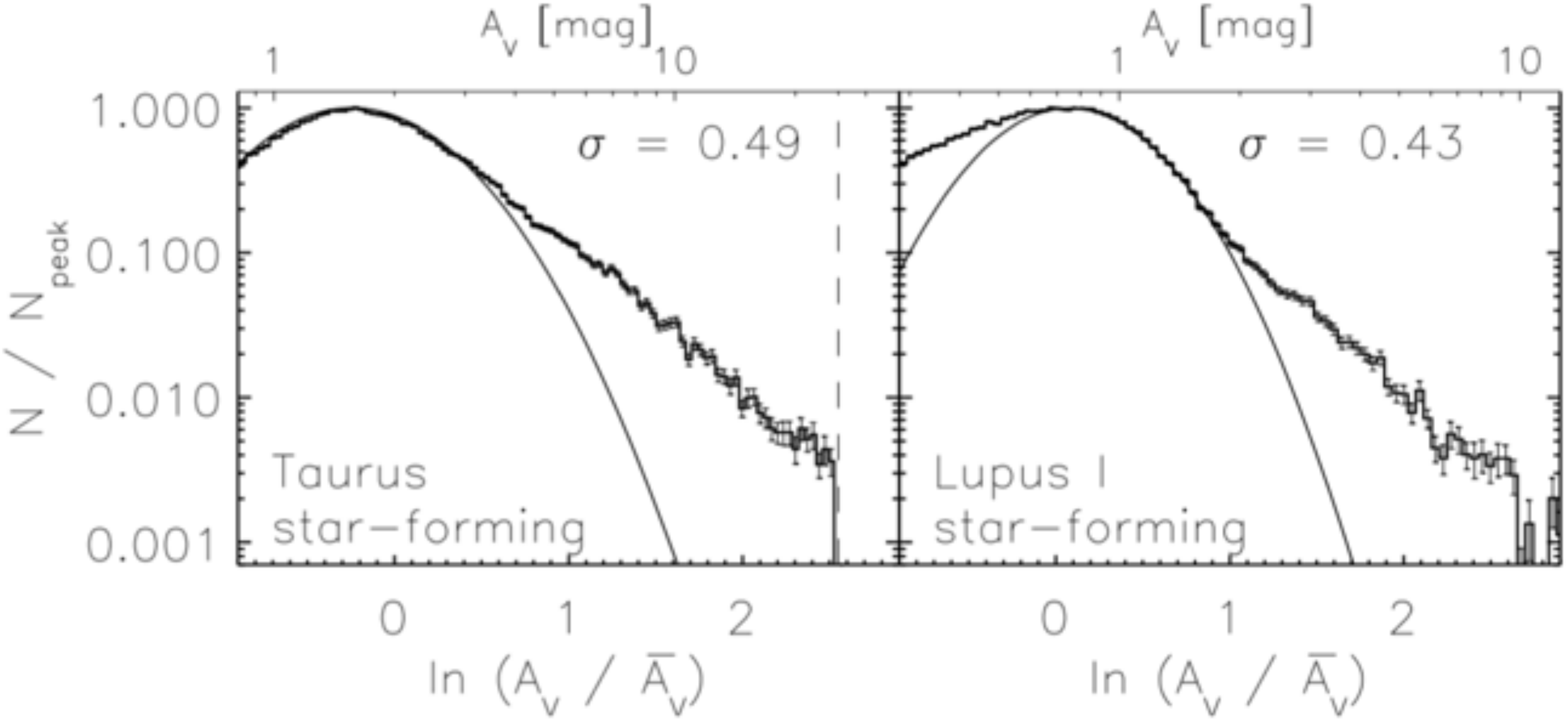

Kainulainen et al. 2009

Actively star-forming clouds show power-law tail at high column.

Molecular Clouds

Observed Characteristics

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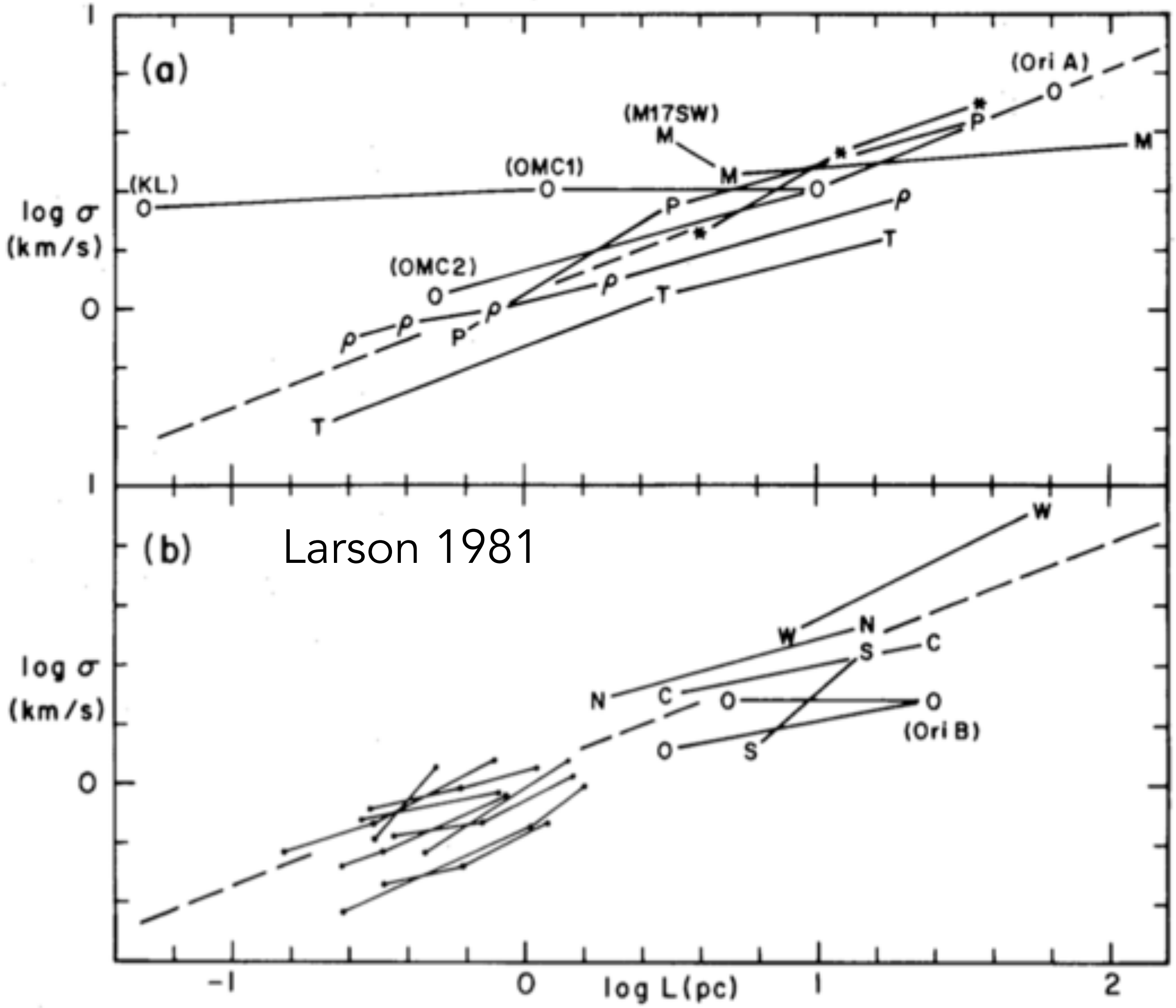
Sub-structures show scaling of L, σ_v, M.



Larson 1981

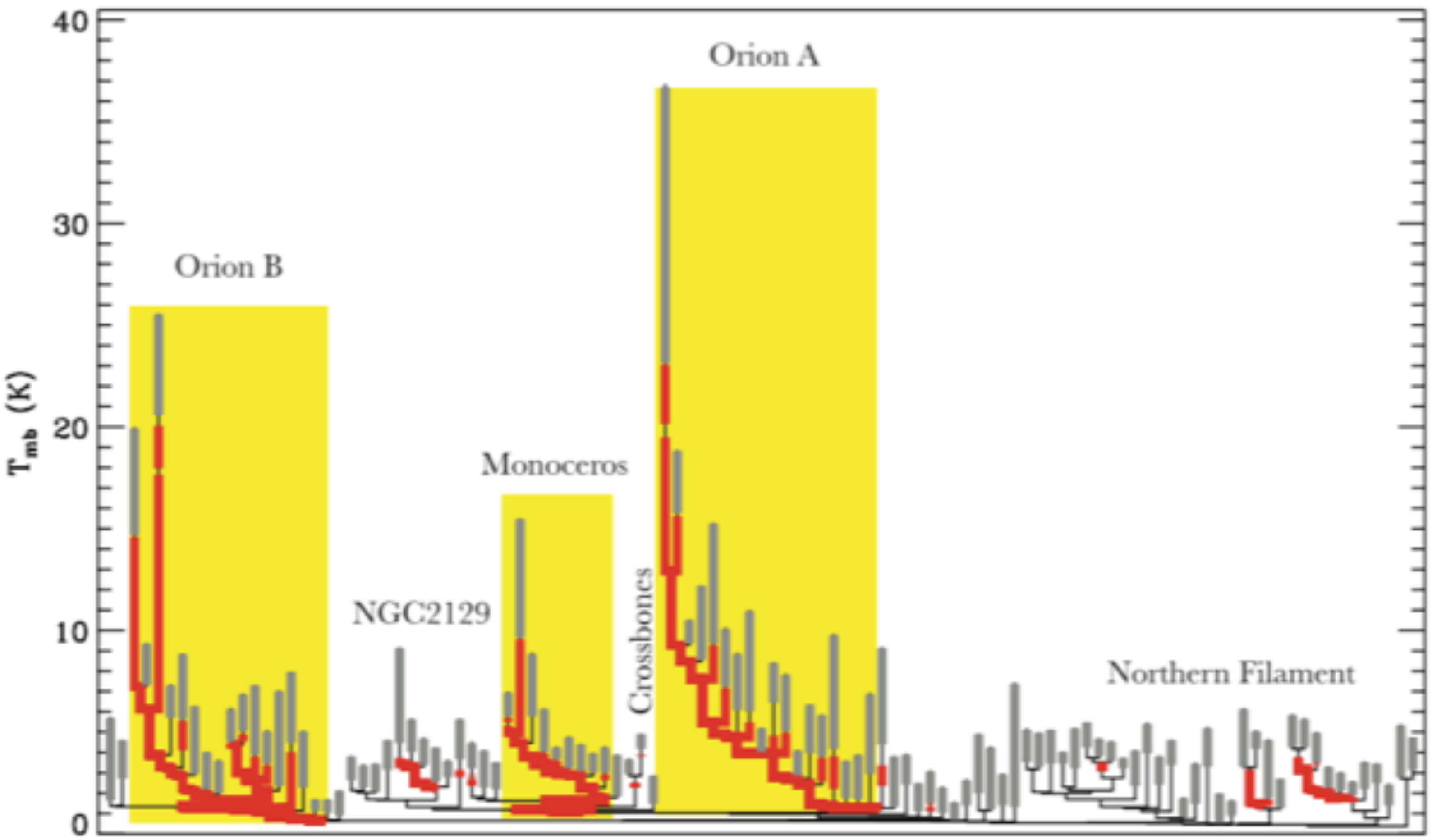
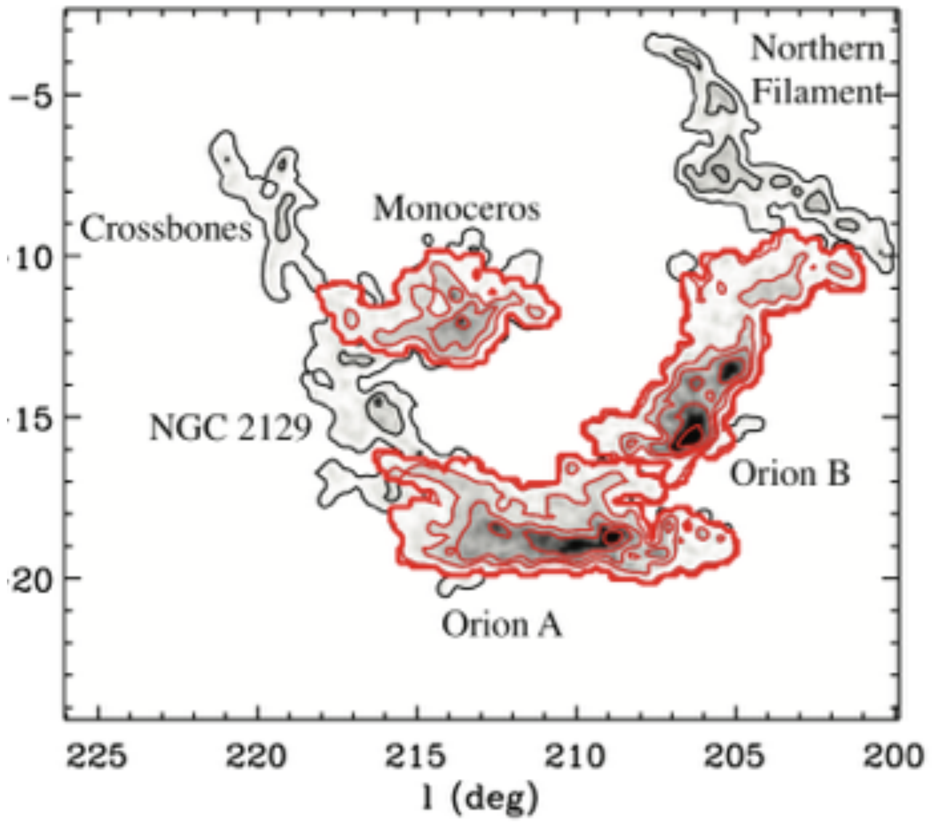
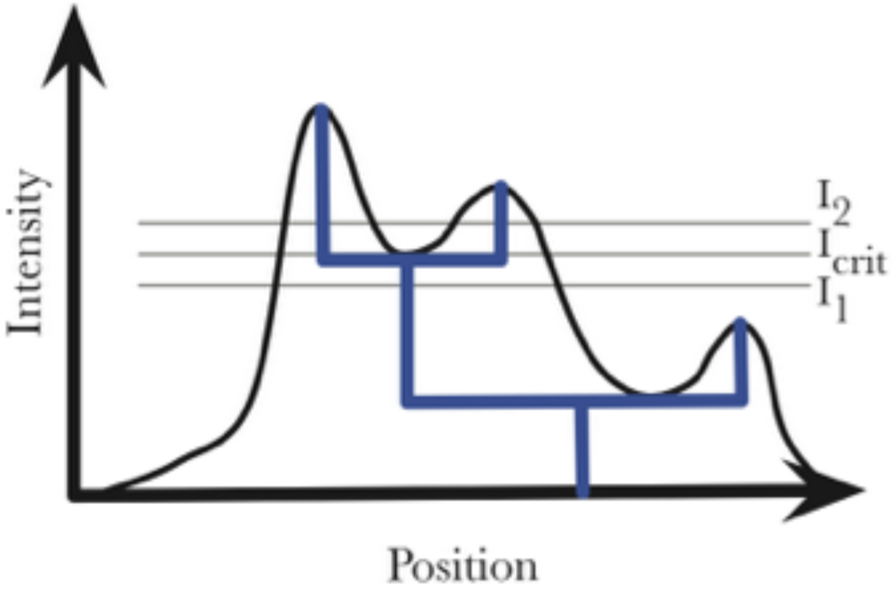


FIG. 15.—Dendrogram of the Orion-Monoceros region. Branches of the dendrogram corresponding to self-gravitating structures are highlighted in red. Regions where the quality of the data prohibit accurate estimation of the virial parameter are shown in gray. The GMCs within the data cube are identified as the largest scale objects that are self-gravitating but not bound to each other. Regions of the dendrogram corresponding to specific objects are labeled and the sections of the dendrogram corresponding to GMCs are shaded in yellow.





Ways to quantify substructure in GMCs: dendrograms (Rosolowsky et al. 2008)