Physics 224
The Interstellar Medium

Lecture #15: Chemistry, Observations of Molecular Gas

Outline

- Part I: Molecular Gas Chemistry
- Part II: Tracing Molecular Gas
- Part III: Observations of Molecular Gas

Chemistry in Molecular Gas

Key Elements of Gas Phase Chemistry in Dense Clouds:

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Chemistry in Molecular Gas

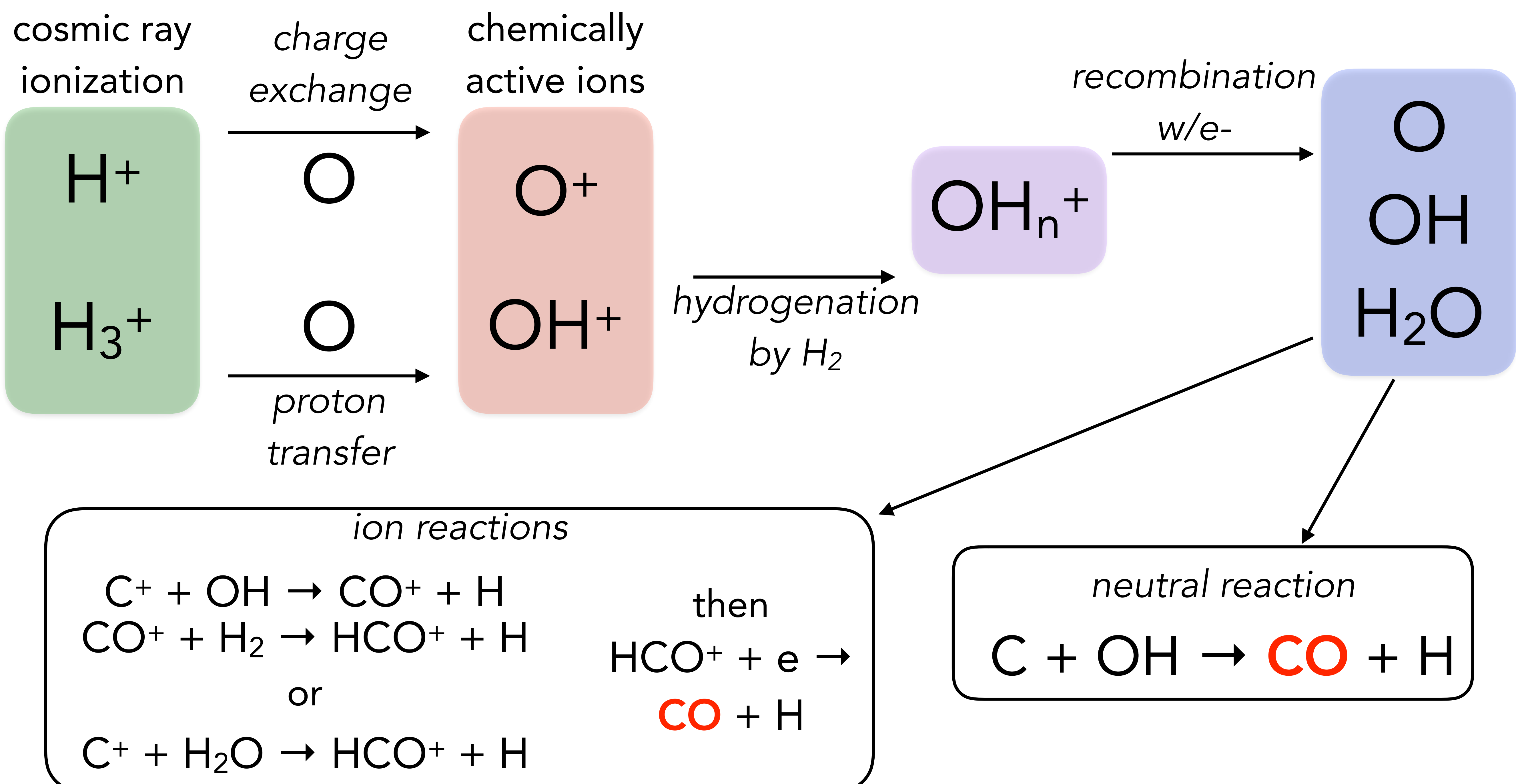
Some key gas phase reaction types:

Type	Example	Notes	typical rate coefficient (k)
Neutral-Radical	$O + H_2 \rightarrow OH + H$	some have thermal activation barriers	~10^{-10} cm^3 s^{-1}
Ion-Molecule	$H^+ + O \rightarrow O^+ + H$ $O^+ + H_2 \rightarrow OH^+ + H$ $H_3^+ + O \rightarrow OH^+ + H_2$	<- charge exchange <- H abstraction <- proton transfer	~10^{-9} cm^3 s^{-1}
Radiative Association	$H + H^+ \rightarrow H_2^+ + h\nu$	only important if other pathways lacking	very low
Photodissociation	$h\nu + OH \rightarrow O + H$	always important	~10^{-10} cm^3 s^{-1}
Dissociative Recombination	$e + H_3^+ \rightarrow$ 3H, $H_2 + H$ (branching 3:1)	always important	~10^{-7} cm^3 s^{-1}

info from A. Glassgold Ay216 at Berkeley

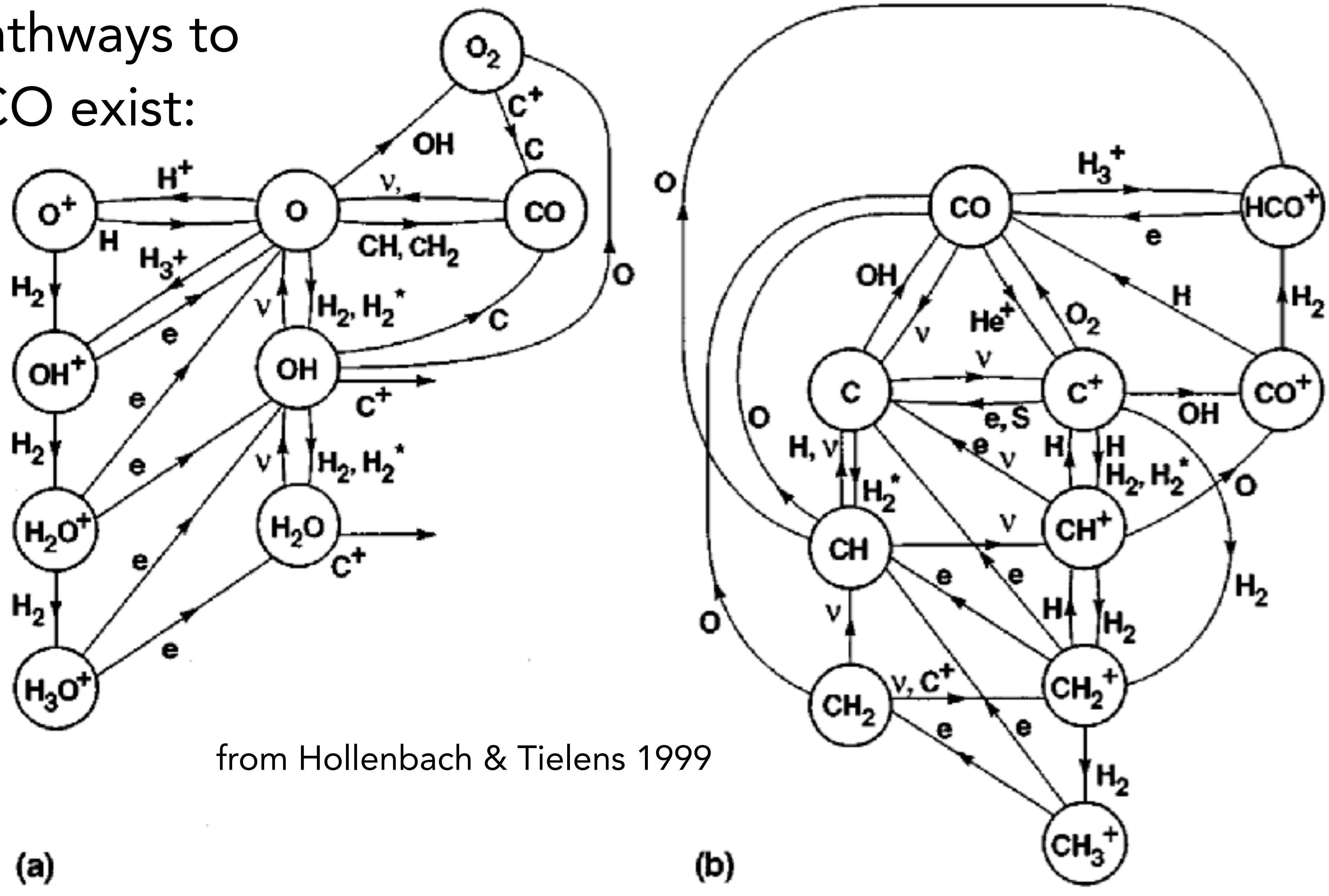
Chemistry in Molecular Gas

Carbon Monoxide - most abundant molecule after H_2



Chemistry in Molecular Gas

Many pathways to form CO exist:

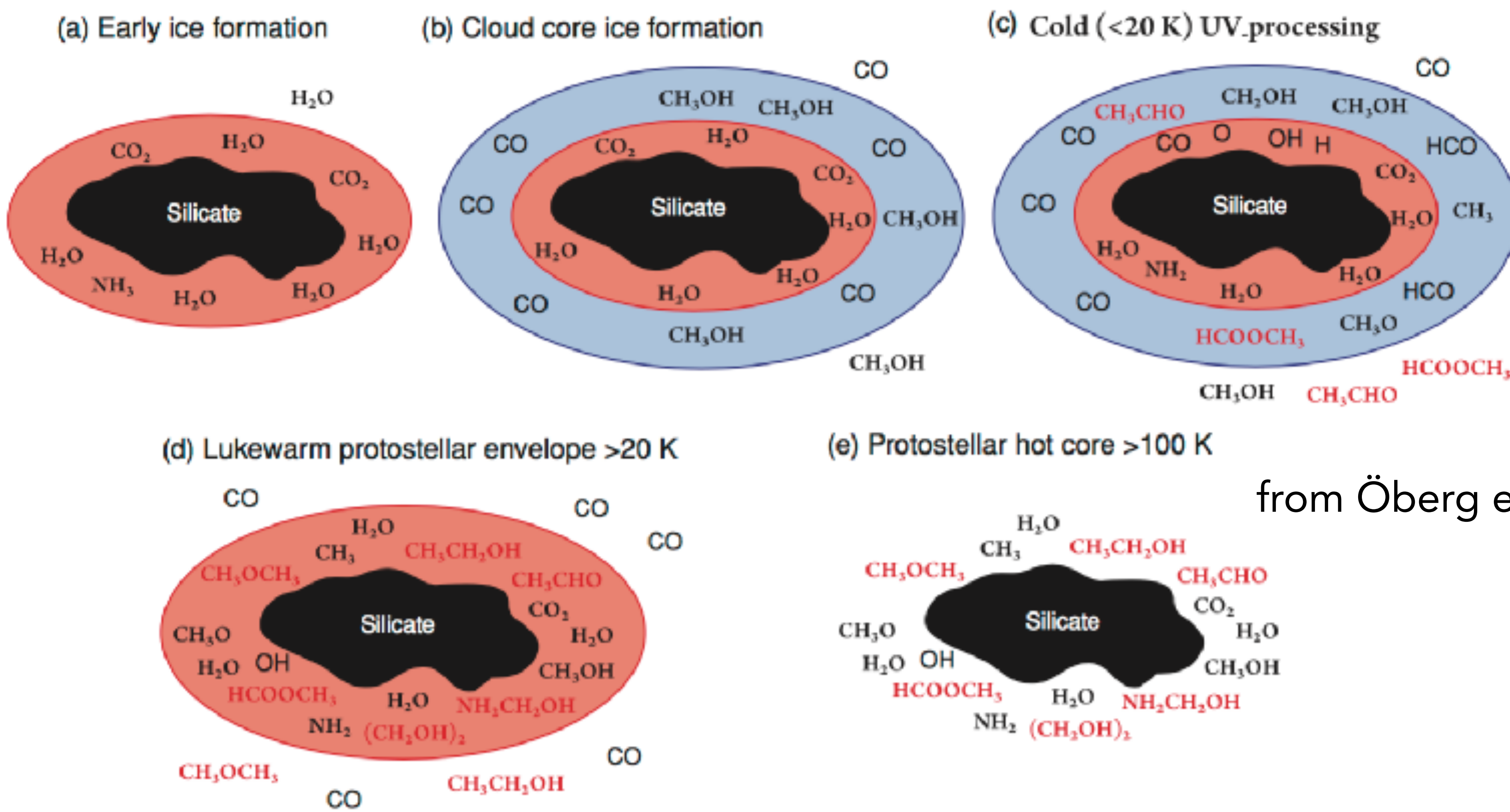


from Hollenbach & Tielens 1999

Chemistry in Molecular Gas

In dense parts of clouds

CO can "freeze out" to form ice on grains.

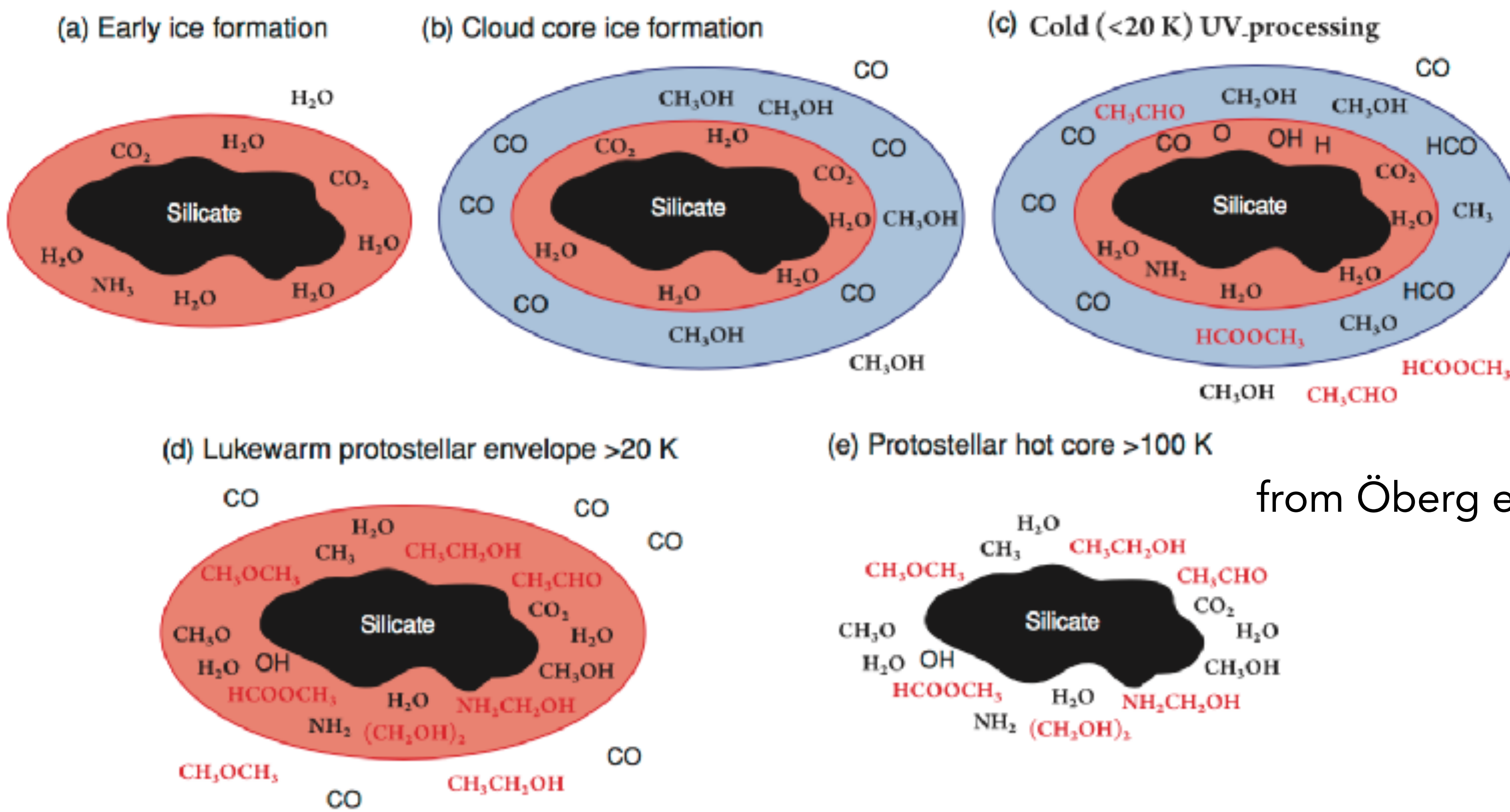


from Öberg et al. 2010

Figure 7. Suggested evolution of ices during star formation. Pink indicates an H_2O-dominated ice and blue a CO-dominated ice. At each cold stage a small amount of the ice is released non-thermally. Early during cloud formation (a) an H_2O-rich ice forms. Once a critical density and temperature is reached CO freezes out catastrophically (b), providing reactants for CH_3OH ice formation. Far away from the protostar (c), photoprocessing of the CO-rich ice results in the production of, e.g., $HCOOCH_3$. Closer to the protostar (d), following sublimation of CO, other complex molecules become abundant. Finally, all ice desorb thermally close to the protostar >100 K (e).

Chemistry in Molecular Gas

Grain surface chemistry + Ice mantle chemistry can lead to complex molecules!



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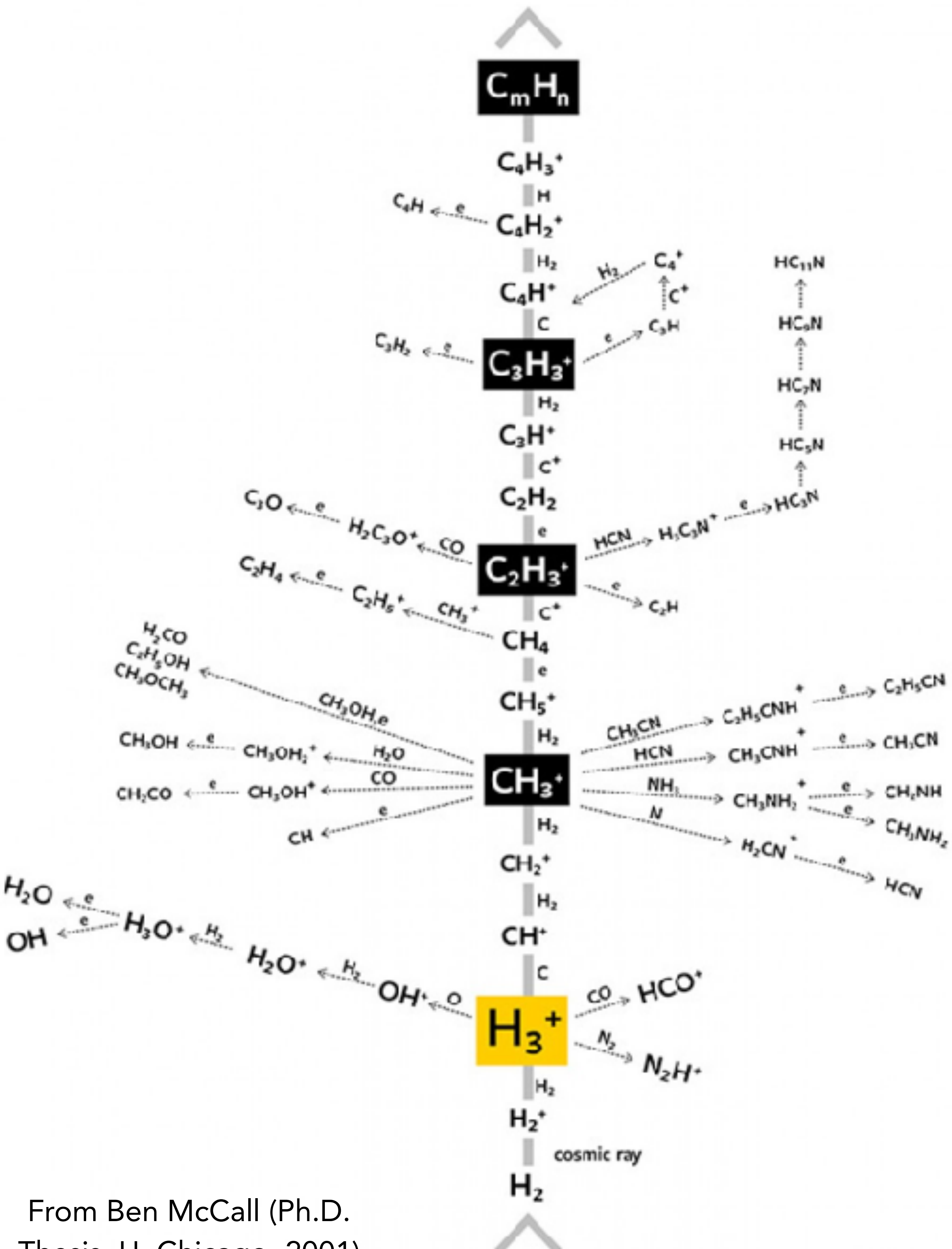

From Ben McCall (Ph.D. Thesis, U. Chicago, 2001)

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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

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

molecular gas mass surface density → integrated intensity of CO line

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

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

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

Tracing Molecular Gas

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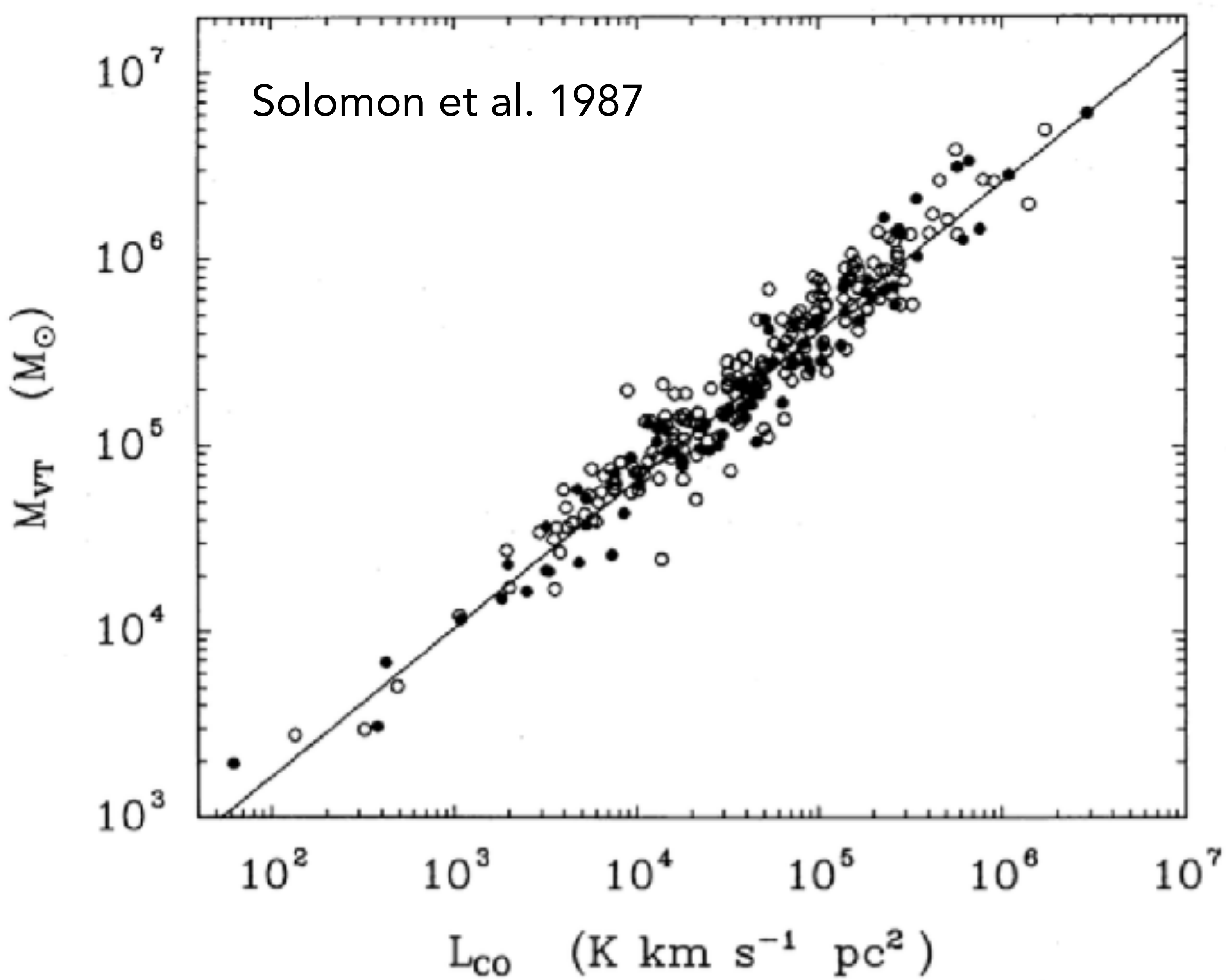
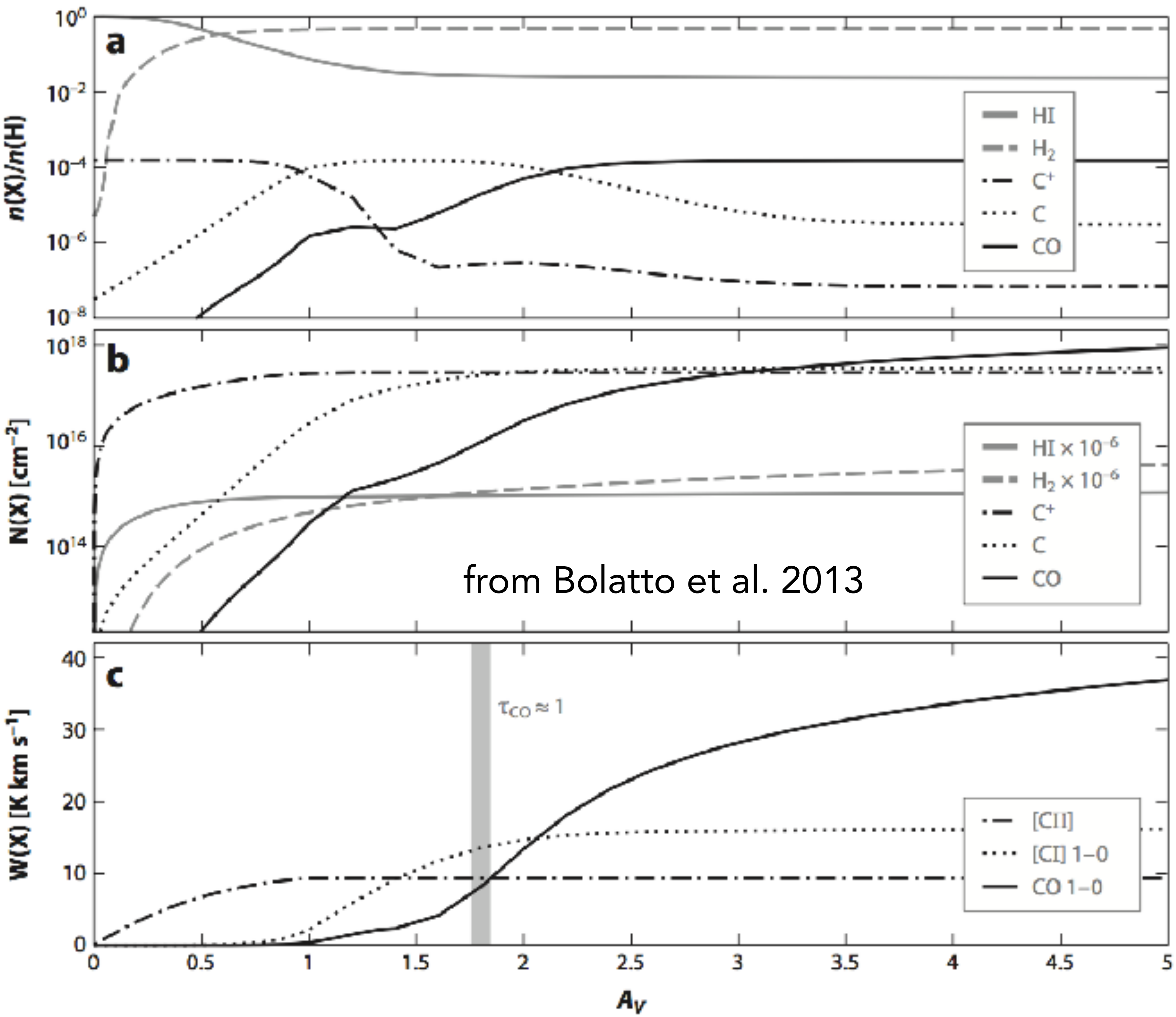


assuming clouds
are in virial equilibrium
you can use their
velocity dispersion &
sizes to calculate
their mass

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

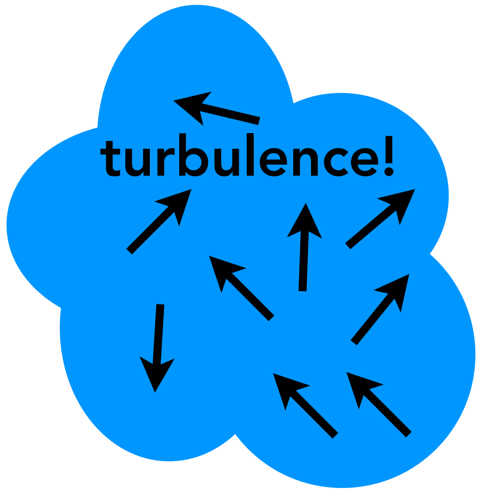
Tracing Molecular Gas



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

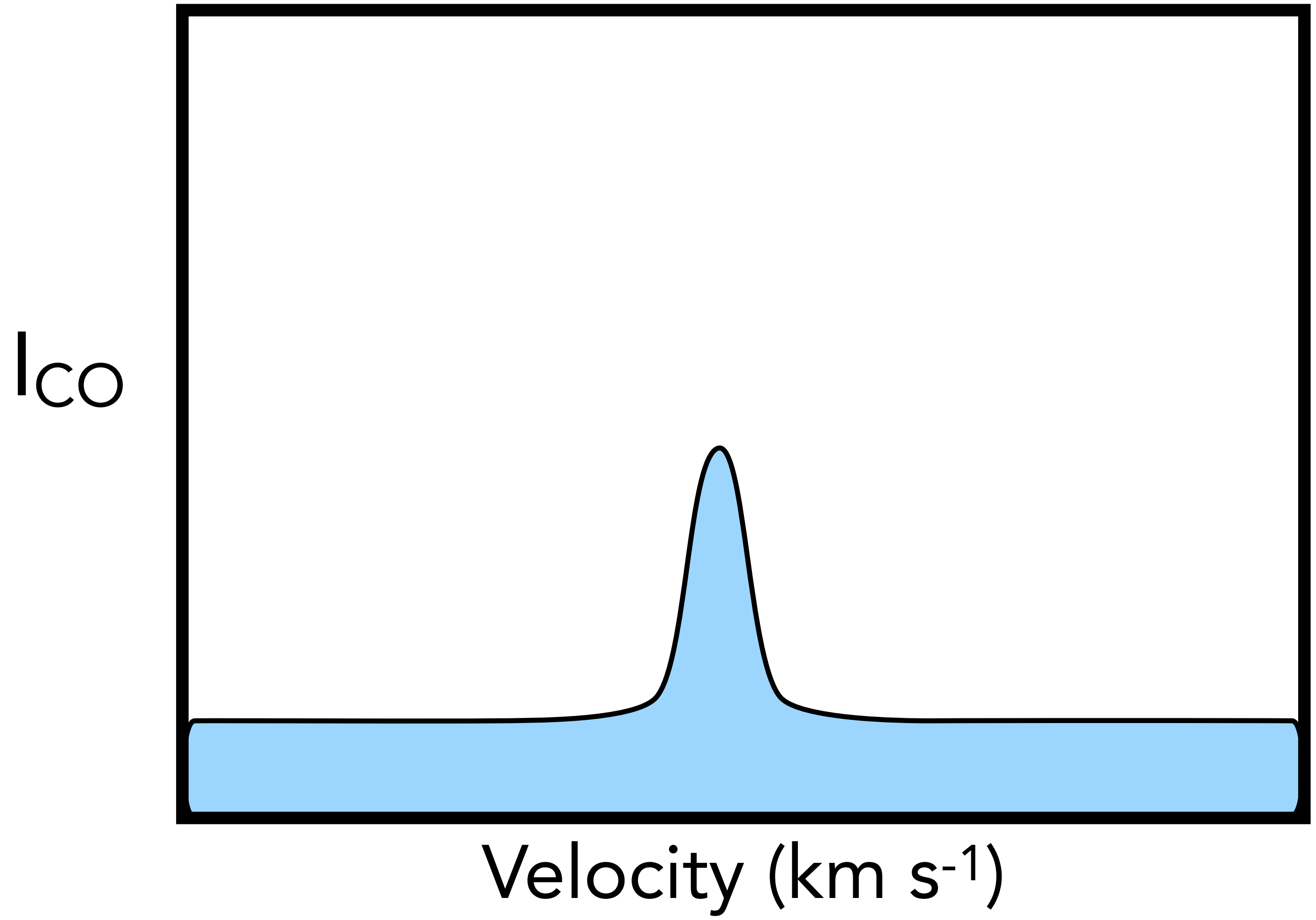
How does an optically thick line tell you the mass?

What Sets α_{CO}?



normal mol. cloud

Effects of molecular cloud properties on α_{CO}.



Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

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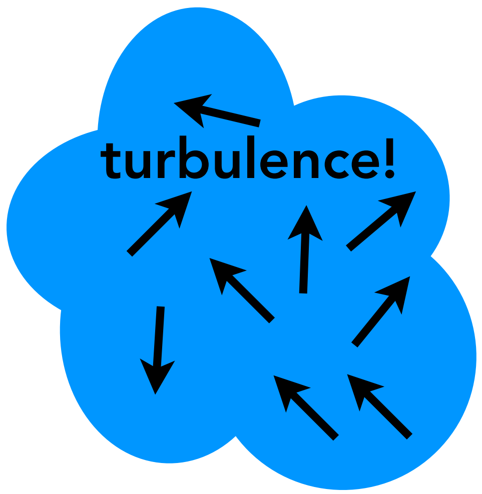

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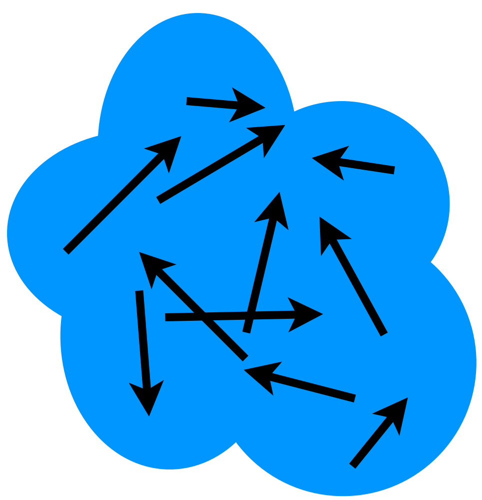
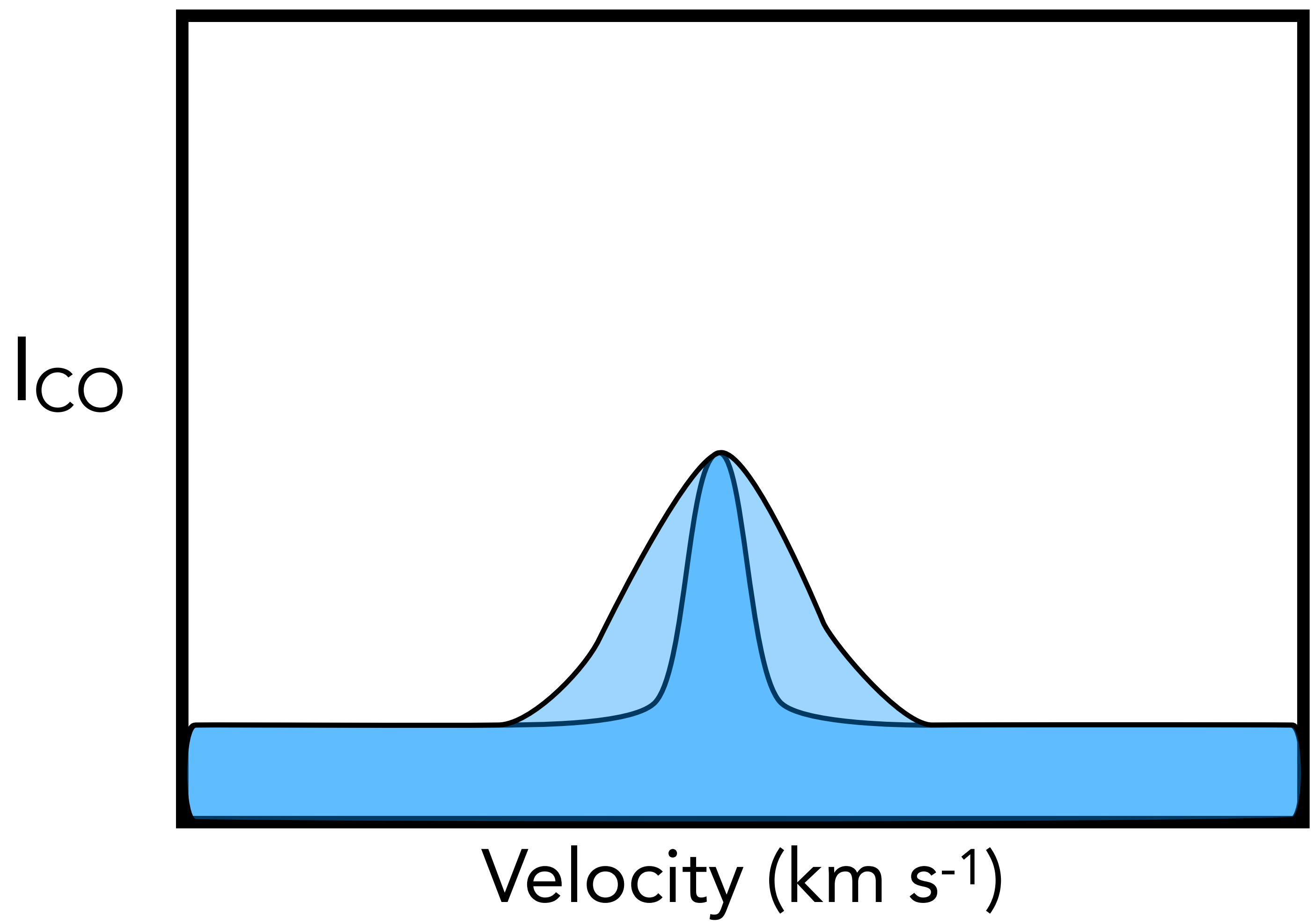


more turbulence

Effects of molecular cloud properties on α_{CO}.



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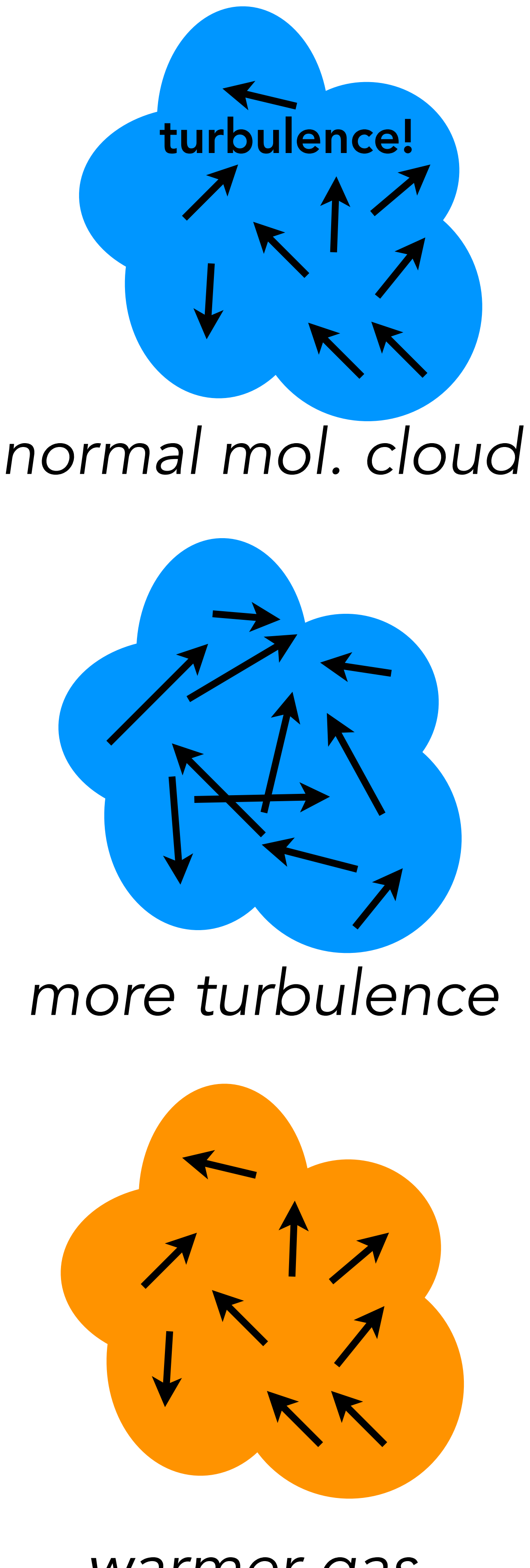

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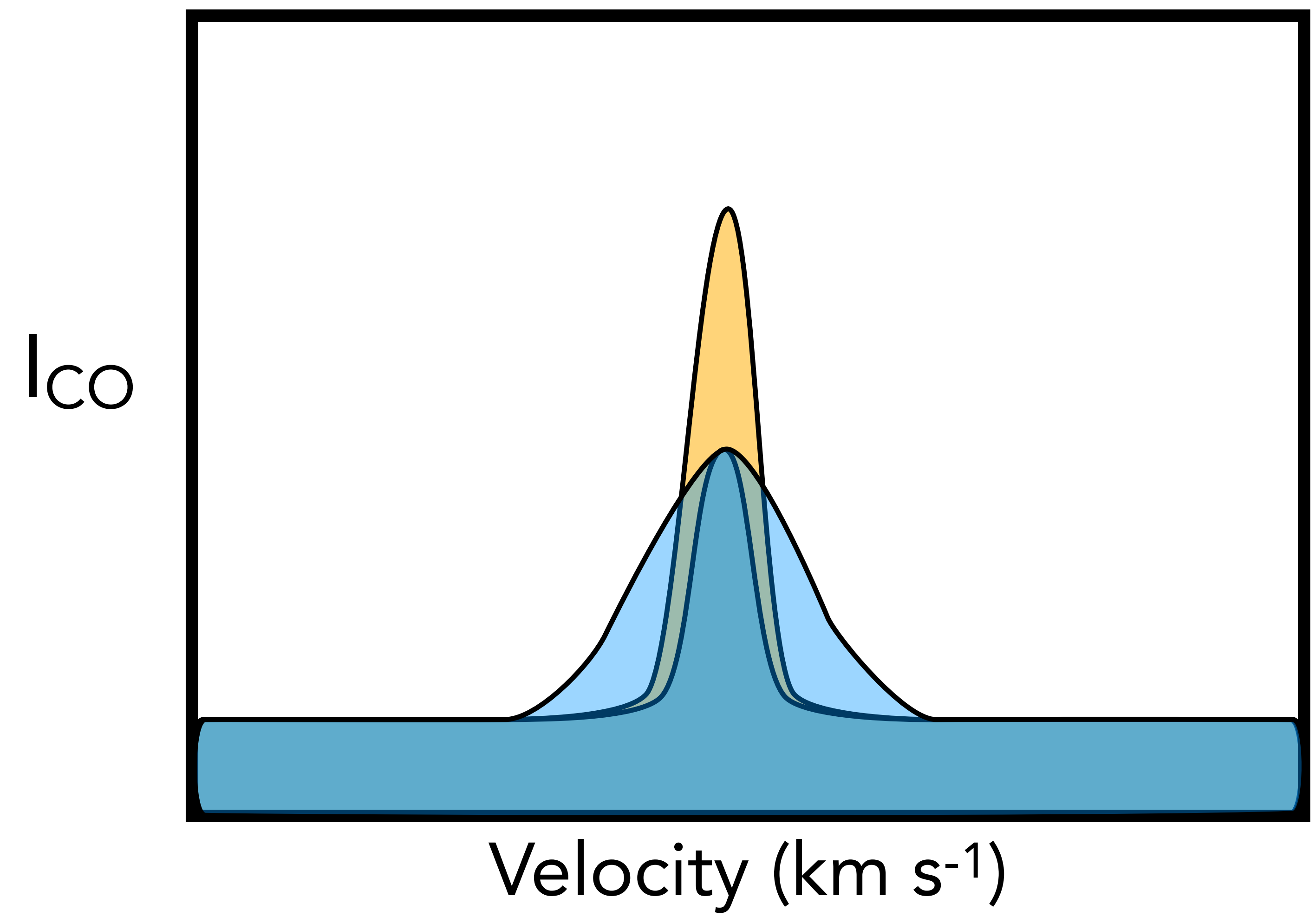

Peak brightness = excitation temperature of CO

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	$X_{CO}/10^{20}cm^{-2}$ $(K\ km\ s^{-1})^{-1}$	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

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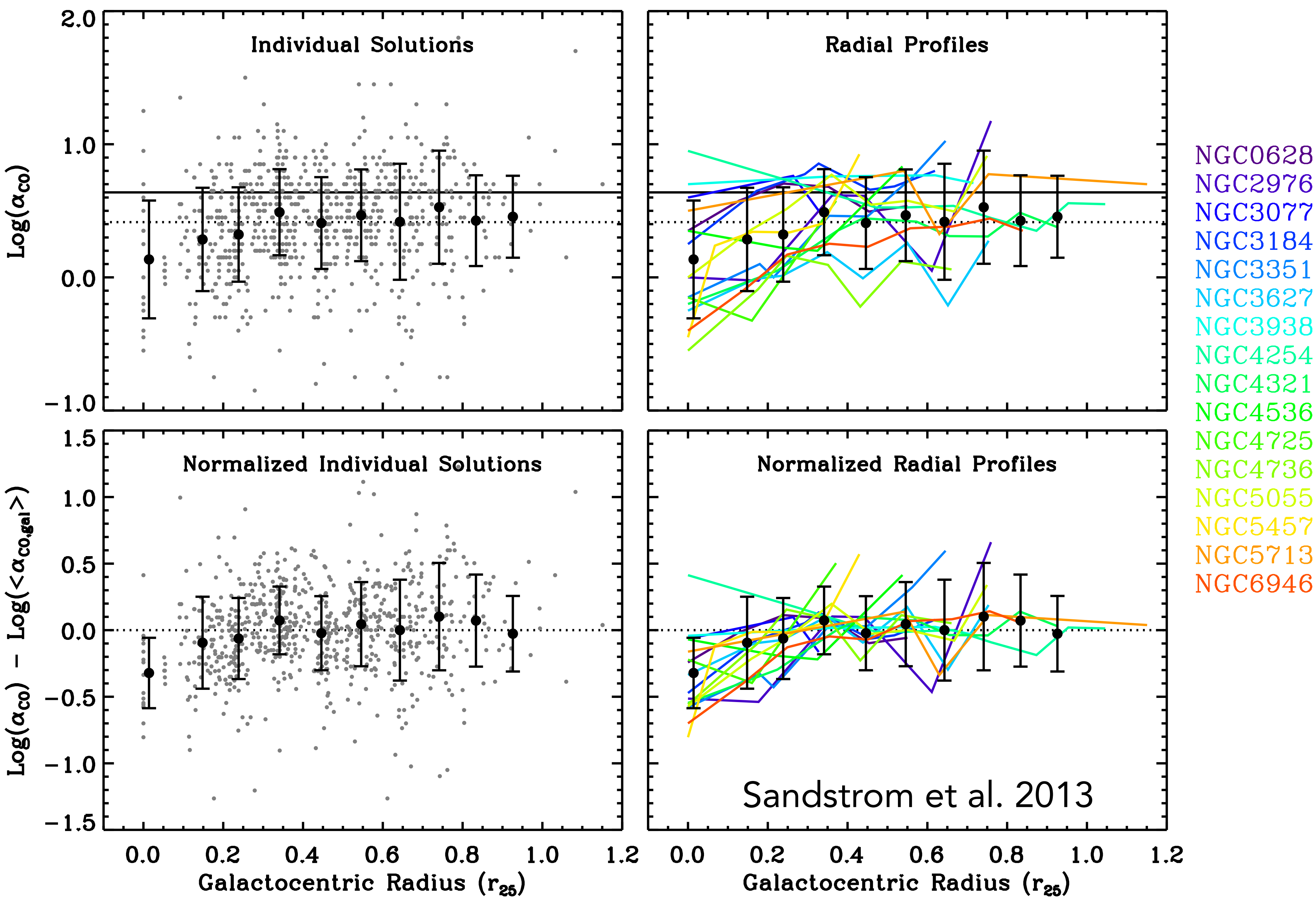

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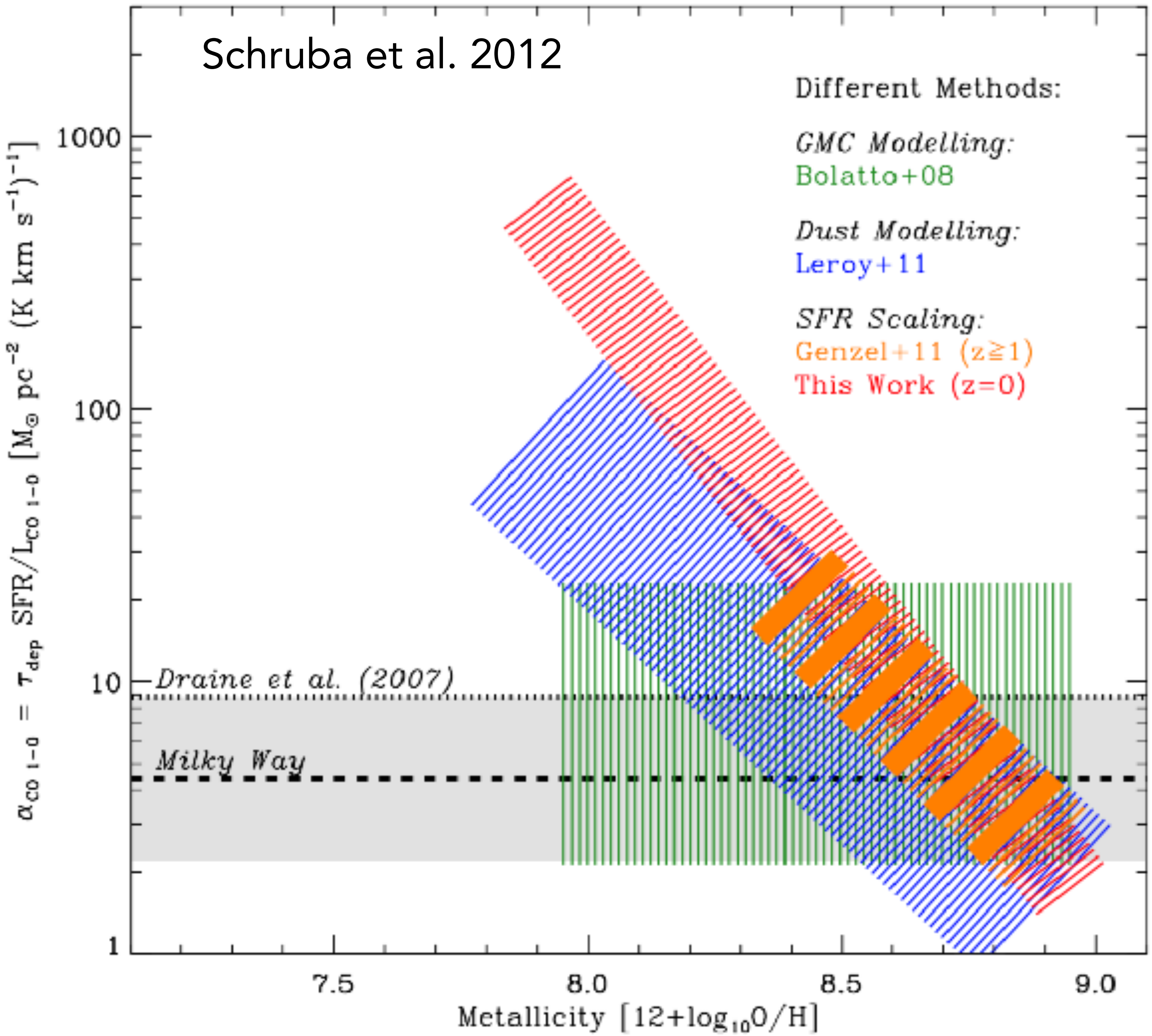


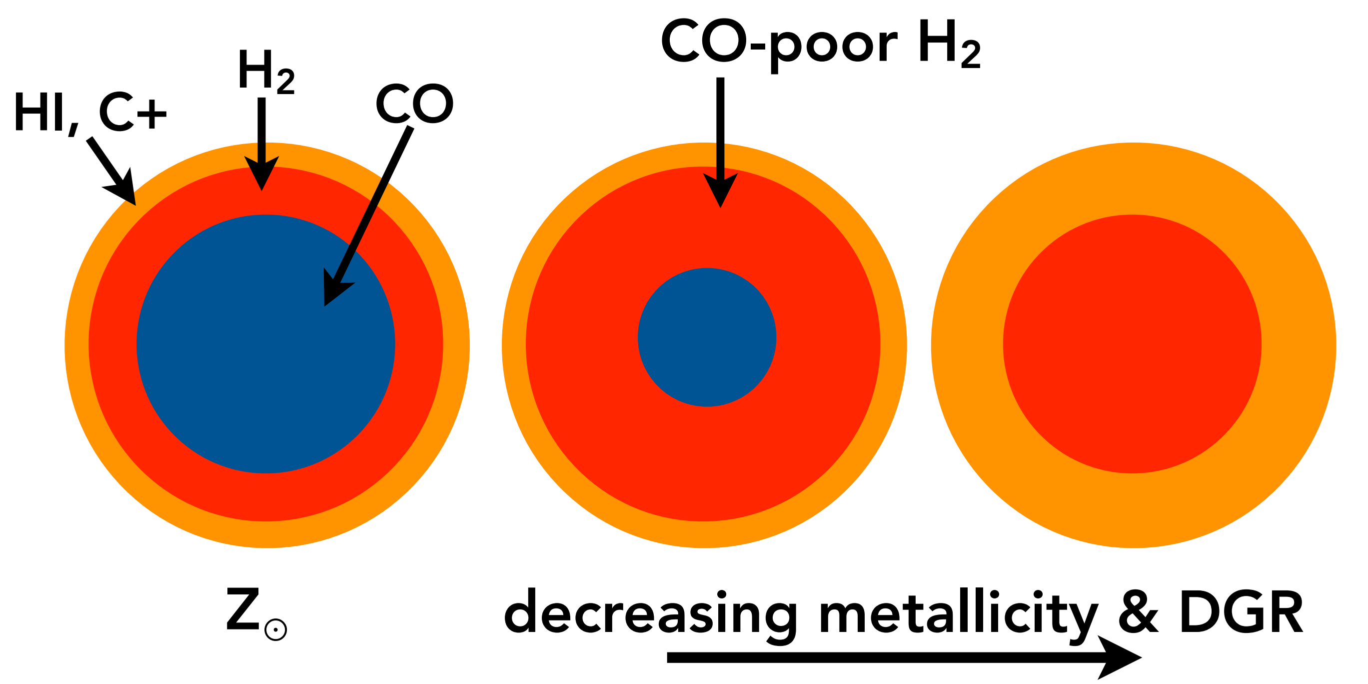
Things really fall apart at low metallicity!

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

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.

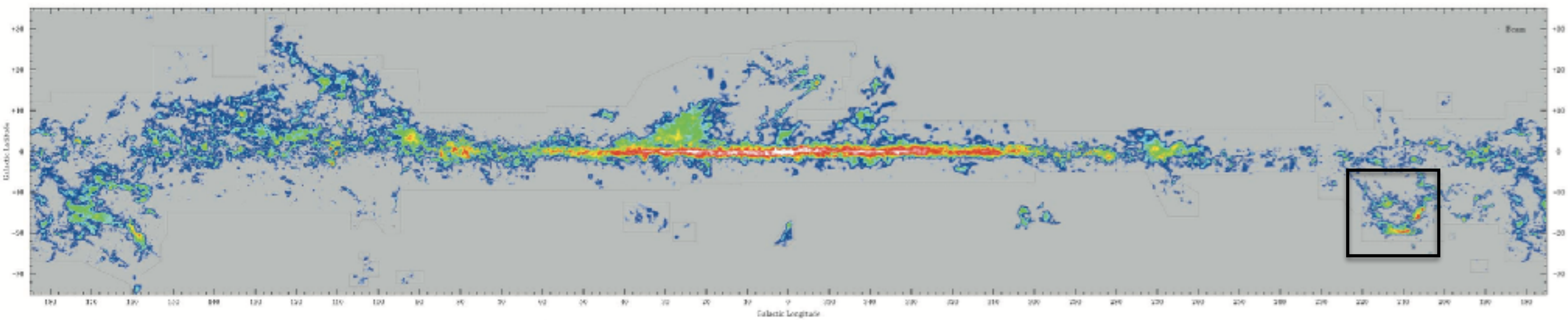


e.g. Maloney & Black 1988, Bolatto et al. 1999,
Wolfire et al. 2010, Glover & Mac Low 2011

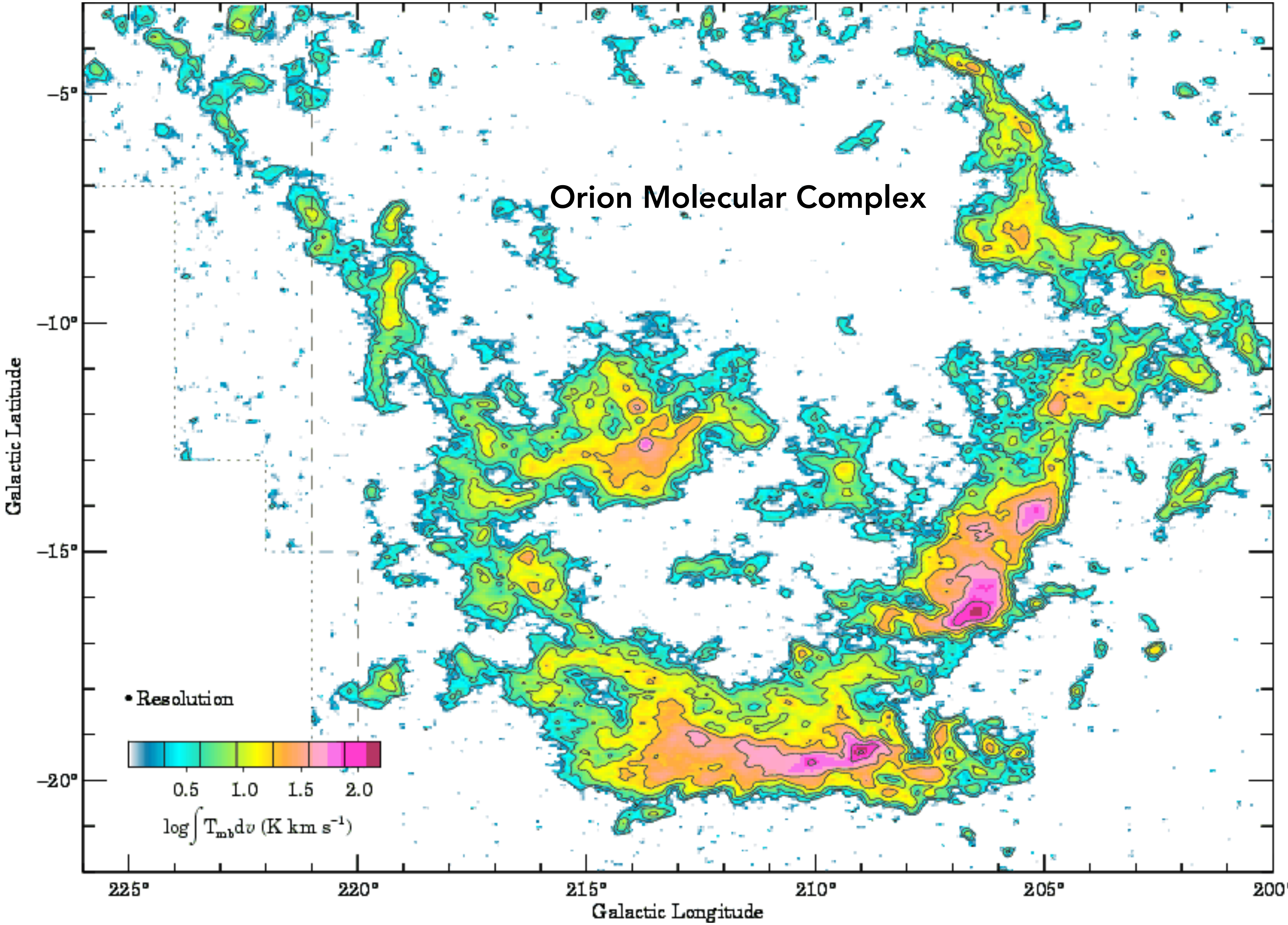
Observations of Molecular Gas

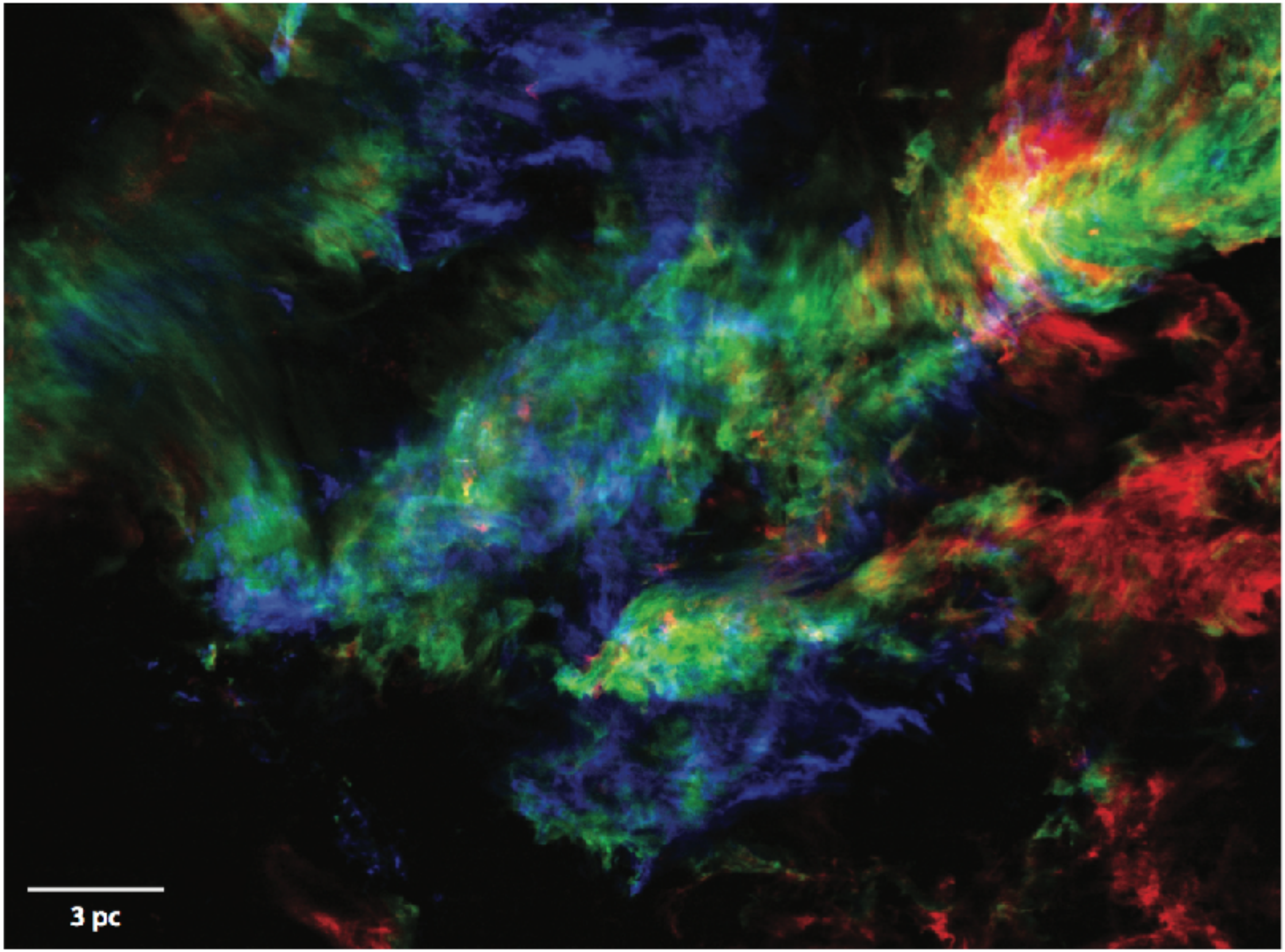
What are “clouds”?

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

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<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