Physics 224
The Interstellar Medium

Lecture #17: More molecular clouds!

Outline

- Part I: Virial Equation, Bonnor-Ebert Mass, Magnetic Sub-/Super-critical Clouds
- Part II: Molecular Gas Chemistry
- Part III: Tracing Molecular Gas
- Part IV: Observations of Molecular Gas

Chemistry in Molecular Gas

List of molecules that have been detected in the ISM:

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	C_3 *	c-C_3H	C_5 *	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{60} *
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	C_{70} *
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$?	C_{60}^+ *
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH^+	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	CH_4 *	CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO	CH_3NCO 2015	H_2NCH_2CN	CH_3CH_2SH (?)				
SiC	H_2O	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H *							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4 *	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3 *	HC(O)CN								
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								

http://www.astro.uni-koeln.de/cdms/molecules

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KCl	HNC	H_2CO	H_2NCN	*l*-HC_4N
NH	HNO	H_2CN	HNC_3	*c*-H_2C_3O
NO	MgCN	H_2CS	SiH_4 *	H_2CCNH (?)
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-
NaCl	N_2H^+	*c*-SiC_3	C_4H^-	HNCHCN
OH	N_2O	CH_3 *	HC(O)CN	
PN	NaCN	C_3N^-	HNCNH	
SO	OCS	PH_3	CH_3O	
SO^+	SO_2	HCNO	NH_4^+	
SiN	*c*-SiC_2	HOCN	H_2NCO^+ (?)	
SiO	CO_2 *	HSCN	$NCCNH^+$ 2015	
SiS	NH_2	H_2O_2		
CS	H_3^+ (*)	C_3H^+		
HF	SiCN	HMgNC		
HD	AlNC	HCCO 2015		
FeO ?	SiNC			
O_2	HCP			
CF^+	CCP			
SiH ?	AlOH			
PO	H_2O^+			
AlO	H_2Cl^+			
OH^+	KCN			
CN^-	FeCN			
SH^+	HO_2			
SH	TiO_2			
HCl^+	C_2N			
TiO	Si_2C 2015			
ArH^+				
NO^+ ?				

http://www.astro.uni-koeln.de/cdms/molecules

Chemistry in Molecular Gas

Abundance of molecules is set by rates of formation & destruction.

Formation

- gas-phase reactions
  - neutral-neutral
  - ion-neutral
  - radiative association
- grain surface reactions

Destruction

- photoionization
- photodissociation
- incorporation into other molecular species

Dense gas, shielded from UV, but still with ions & dust is ideal for chemistry.

Chemistry in Molecular Gas

Snow & McCall 2006

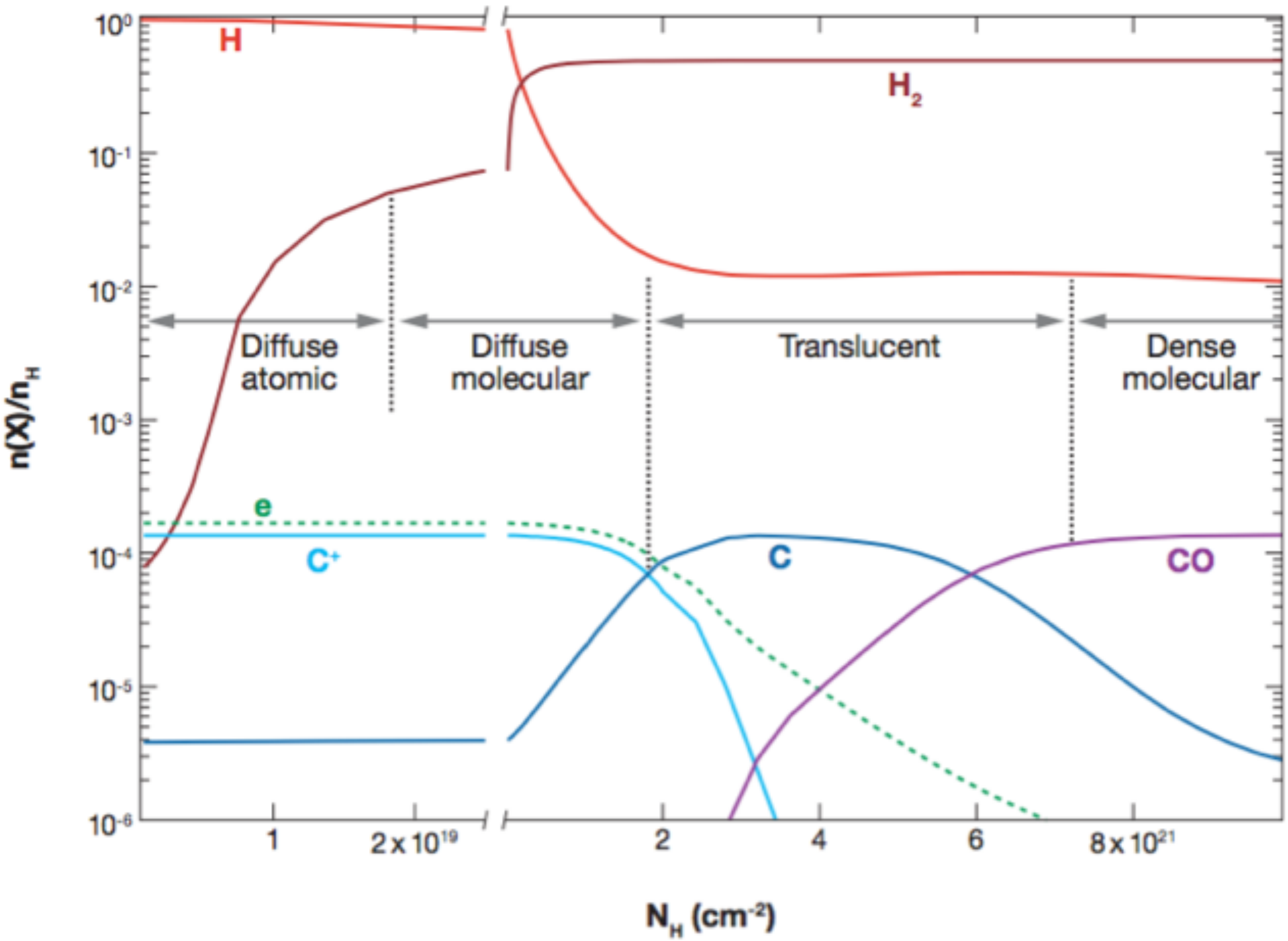

Figure 1

Results from photodissociation region model [with $n_H = 100\ cm^{-3}$ and $\chi_{UV} = 1$] from Neufeld et al. (2005), illustrating the revised definitions of cloud types.

Chemistry happens in diffuse phases,

(& is very interesting - intermittent turbulent dissipation, shattering of dust grains, grain surface reactions, etc)

…but things really get going when H_2 forms.

Chemistry in Molecular Gas

Astrochemistry is really interesting!

The time scale to reach steady state in the interstellar medium is longer than the dynamical time scale of the physical condition evolution in most regions; as a consequence, the chemical composition depends on the initial conditions (initial chemical composition). For example, under dense cloud conditions (typical temperature of 10 K, density of a few 10^4 cm^{-3}, and a visual extinction A_V of 30 magnitudes[104]), the typical time to reach the steady state for a reservoir molecule such as CO is approximately 10^9 yr if both gas-phase chemistry and gas–grain interactions are considered, whereas the typical lifetime of such objects is 10^7 yr or shorter.[105,106] Since most chemical models of dense clouds do not take into account the formation of the cloud itself, the computed chemical composition depends on the initial conditions.

Agundez & Wakelam 2013 - arXiv:1310.3651

Chemistry is not in thermochemical equilibrium - governed by “chemical kinetics”.

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Chemistry in Molecular Gas

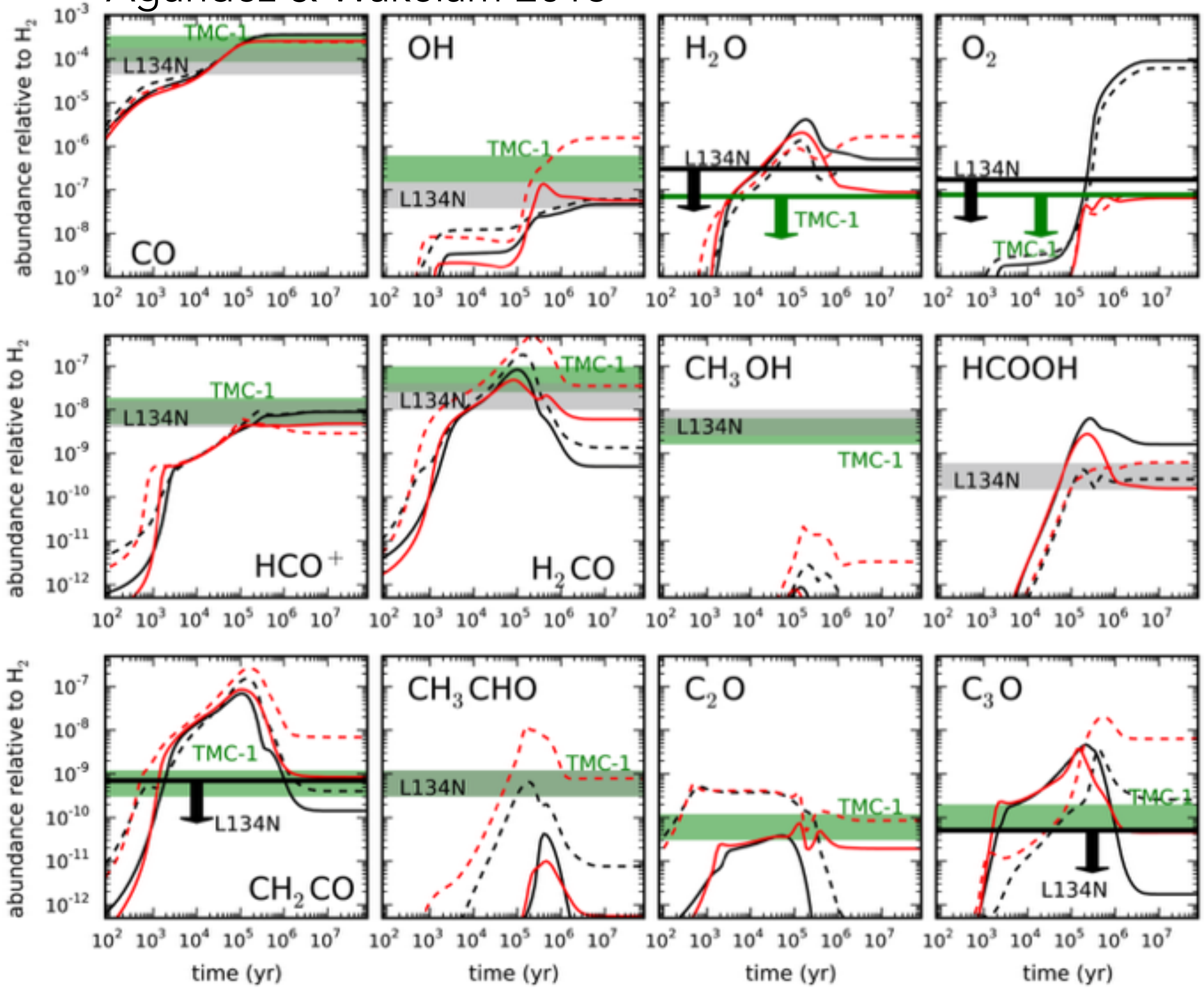
<u>Evidence of non-equlibrium chemistry:</u>

CO is the most abundant molecule after H_2

Chemical equilibrium models at T=10 K would predict most carbon in CH_4 and most oxygen in H_2O.

Chemistry in Molecular Gas

Agundez & Wakelam 2013



Chemistry in Molecular Gas

Key Elements of Gas Phase Chemistry in Dense Clouds:

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4. Exothermic reactions with no activation barrier are strongly preferred due to low temperatures. **Ion-neutral reactions** are the most efficient path in these conditions - drive chemical networks.

Chemistry in Molecular Gas

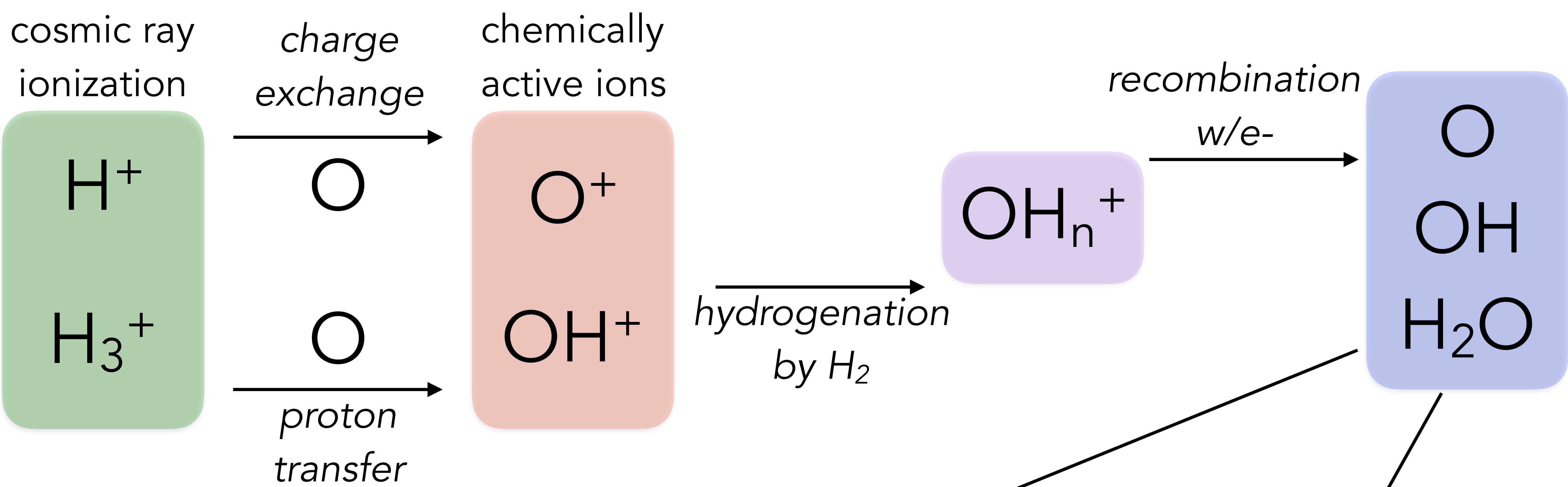
Some key gas phase reaction types:

Type	Example	Notes	typical rate coefficient (k)
Neutral-Radical	$O + H_2 \rightarrow OH + H$	some have thermal activation barriers	$\sim 10^{-10}$ 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	$\sim 10^{-9}$ 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	$\sim 10^{-10}$ cm^3 s^{-1}
Dissociative Recombination	$e + H_3^+ \rightarrow 3H, H_2 + H$ (branching 3:1)	always important	$\sim 10^{-7}$ cm^3 s^{-1}

info from A. Glassgold Ay216 at Berkeley

Chemistry in Molecular Gas

Carbon Monoxide - most abundant molecule after H_2



ion reactions

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

or

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

then

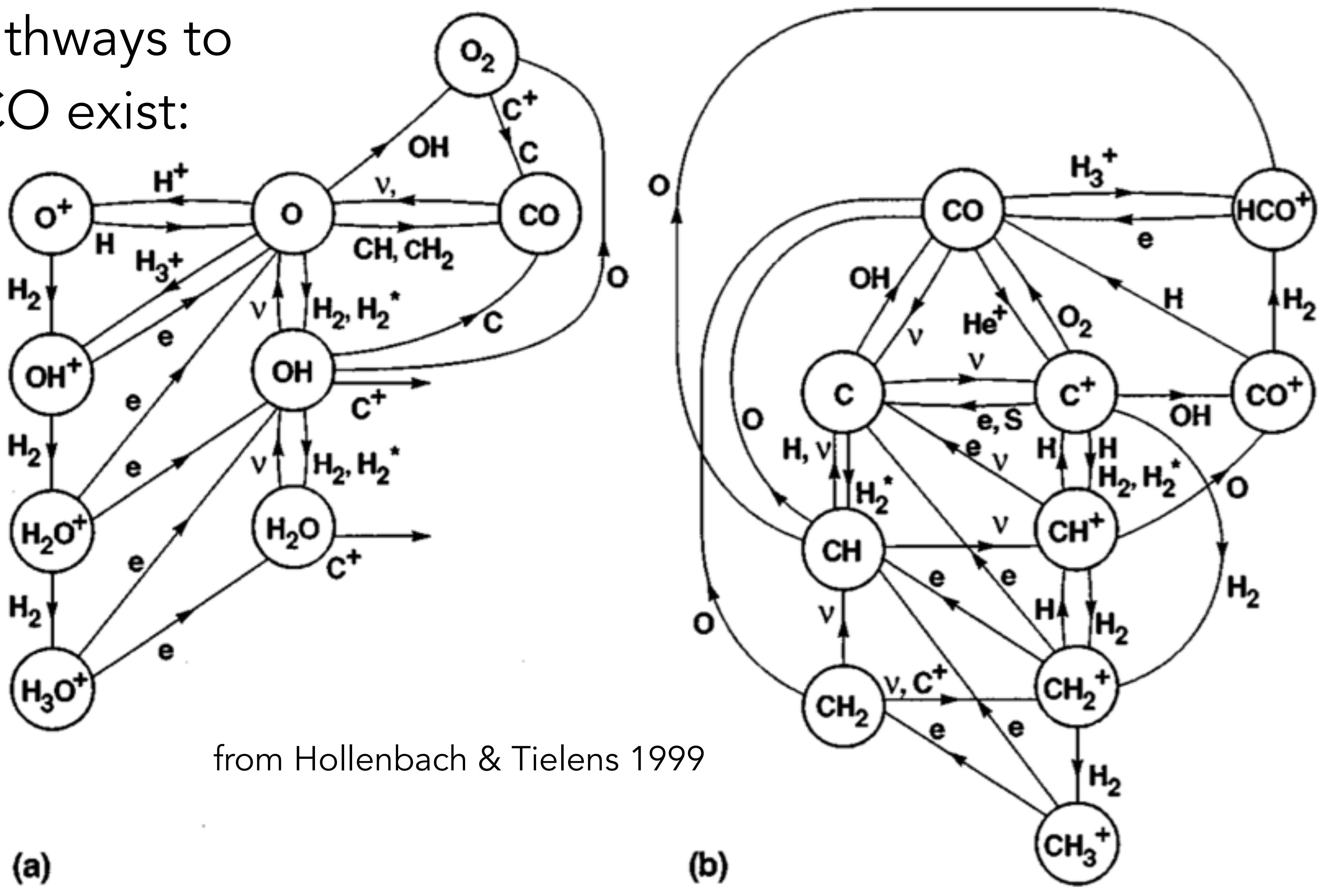
$$HCO^+ + e \rightarrow CO + H$$

neutral reaction

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

Chemistry in Molecular Gas

Many pathways to form CO exist:

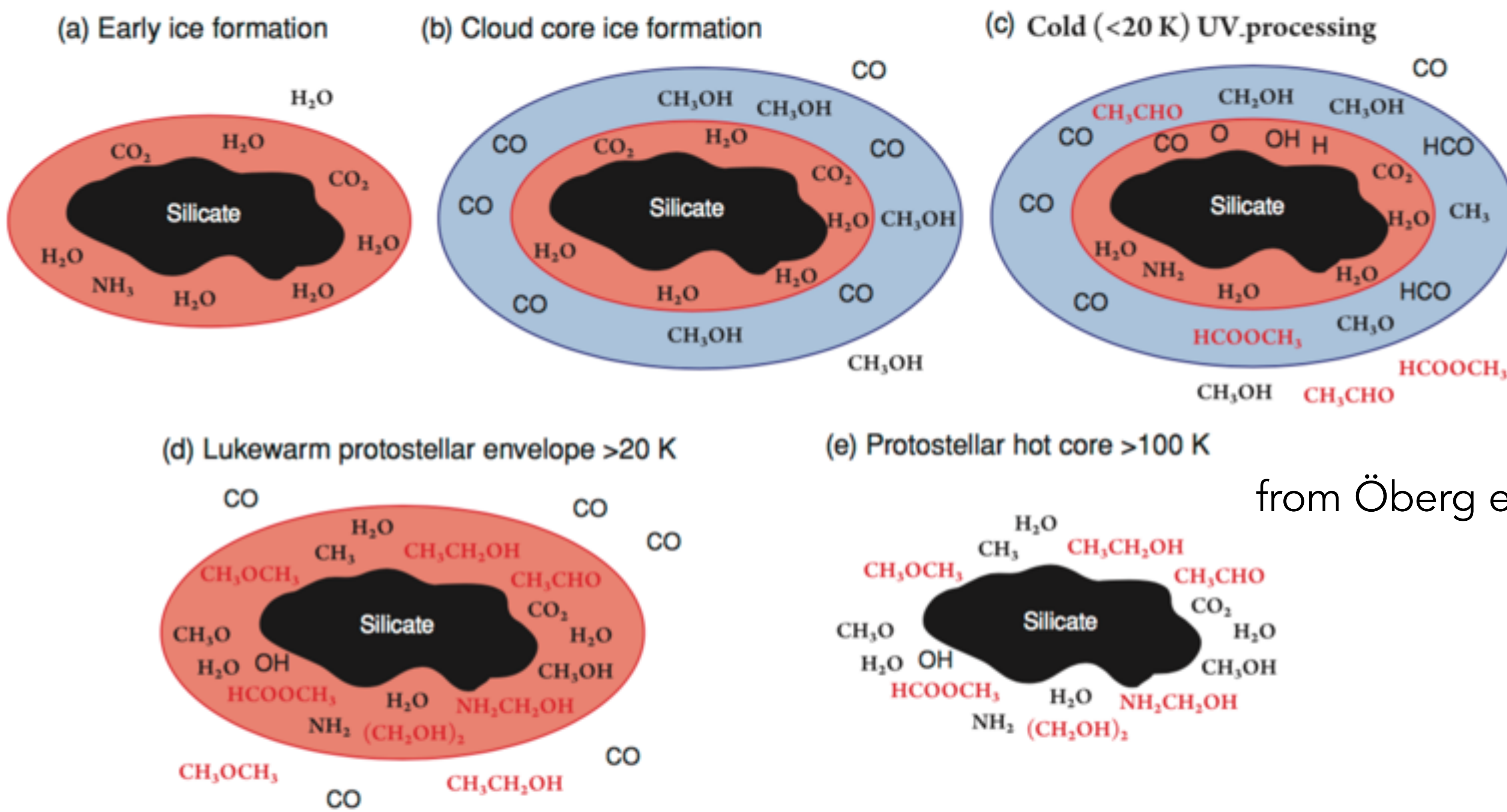


from Hollenbach & Tielens 1999

Chemistry in Molecular Gas

In dense parts of clouds

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

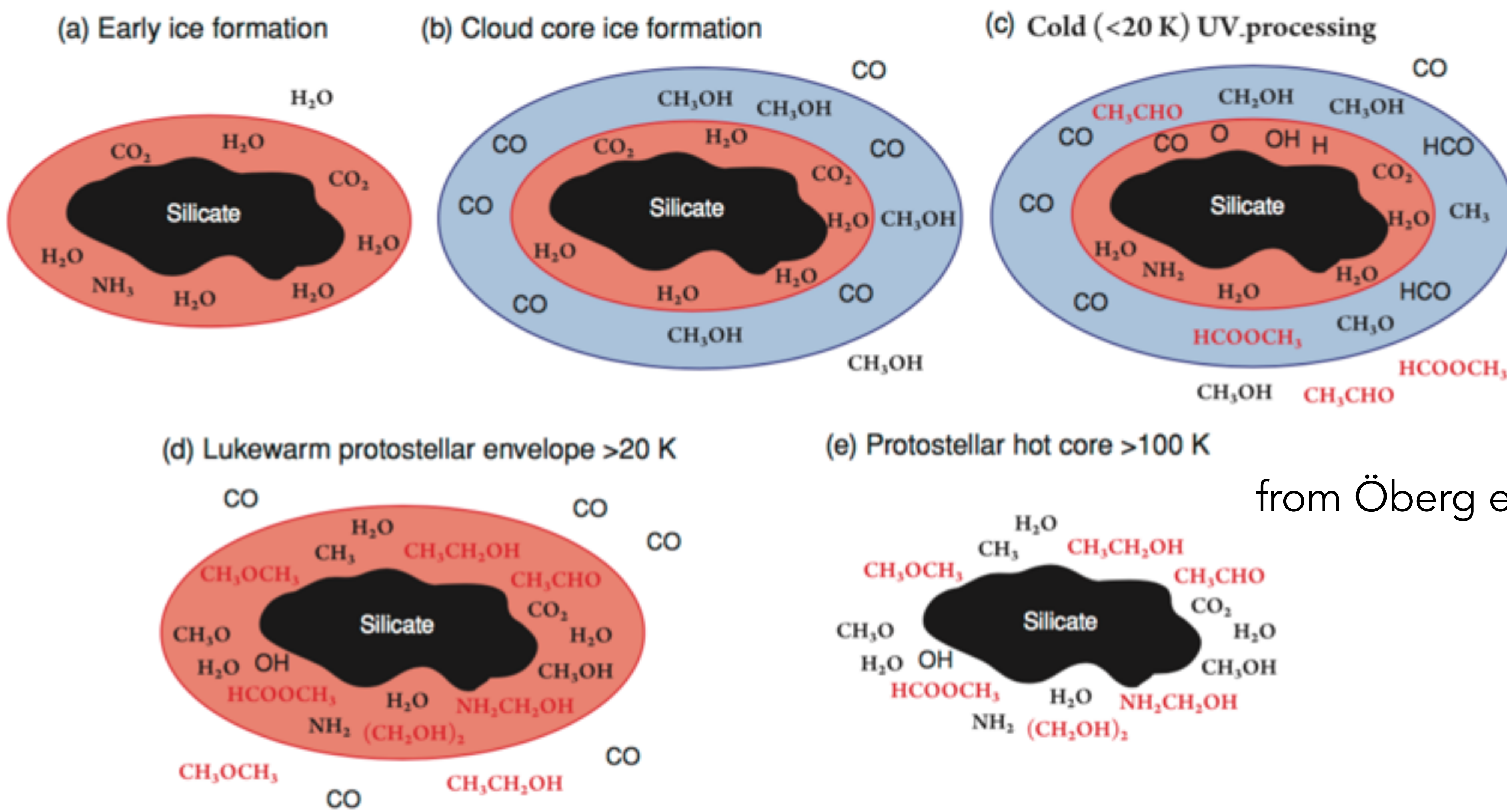


from Öberg et al. 2010

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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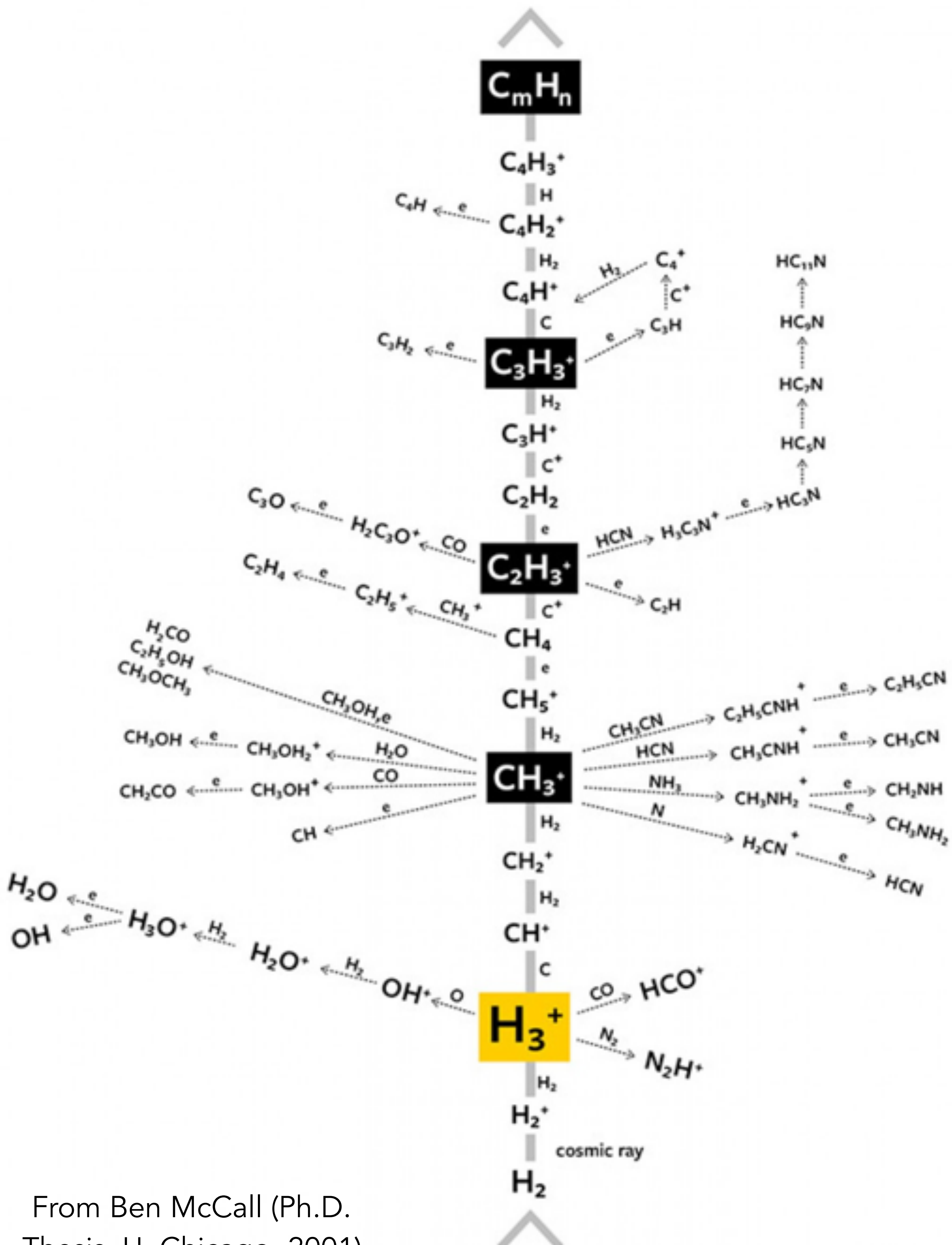

From Ben McCall (Ph.D. Thesis, U. Chicago, 2001)

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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 → N_{H2}

integrated intensity of CO line → I_{CO}

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

molecular gas mass surface density → Σ_{mol}

integrated intensity of CO line → I_{CO}

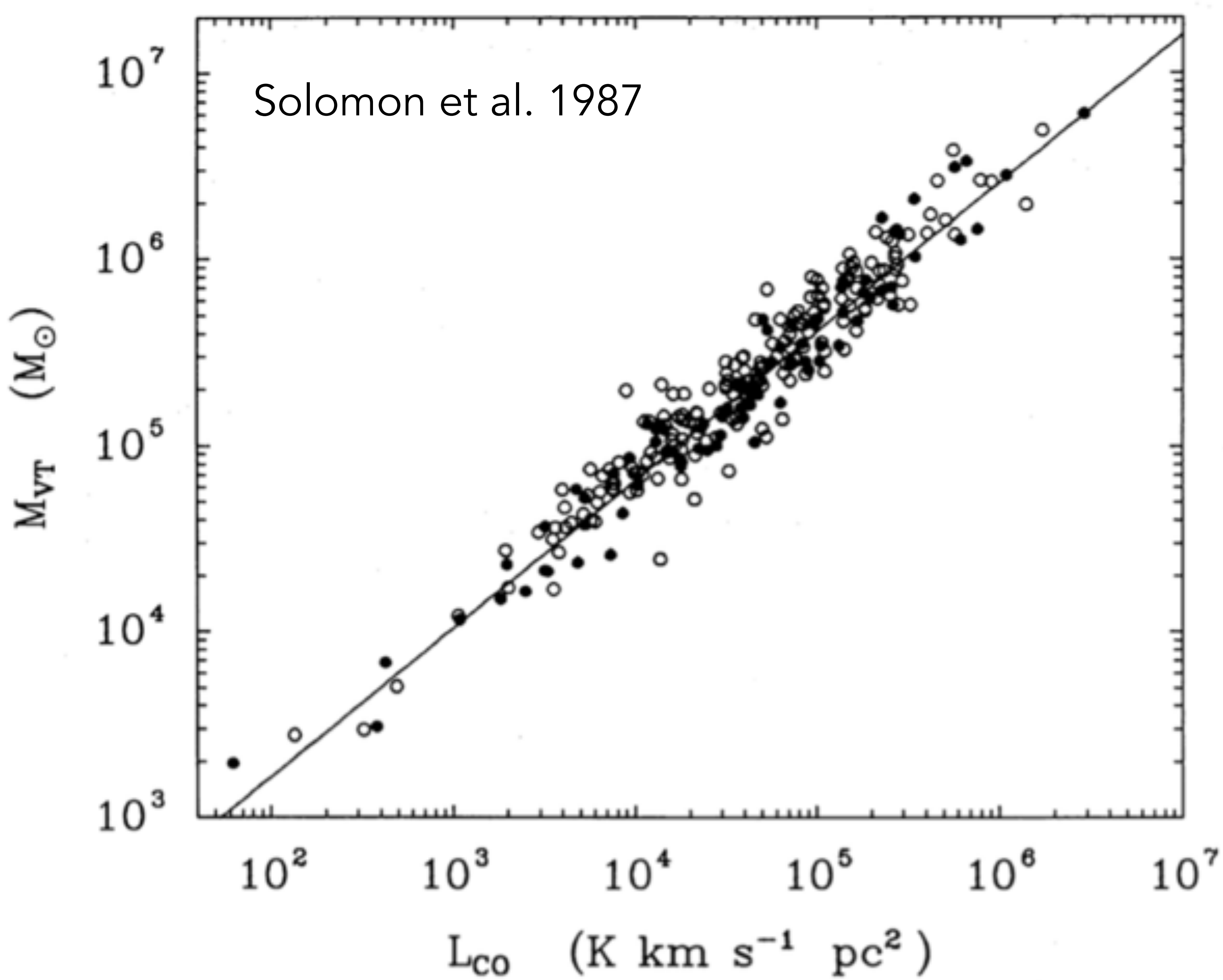
$$\Sigma_{mol} = \alpha_{CO}\, I_{CO}$$

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

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

Tracing Molecular Gas

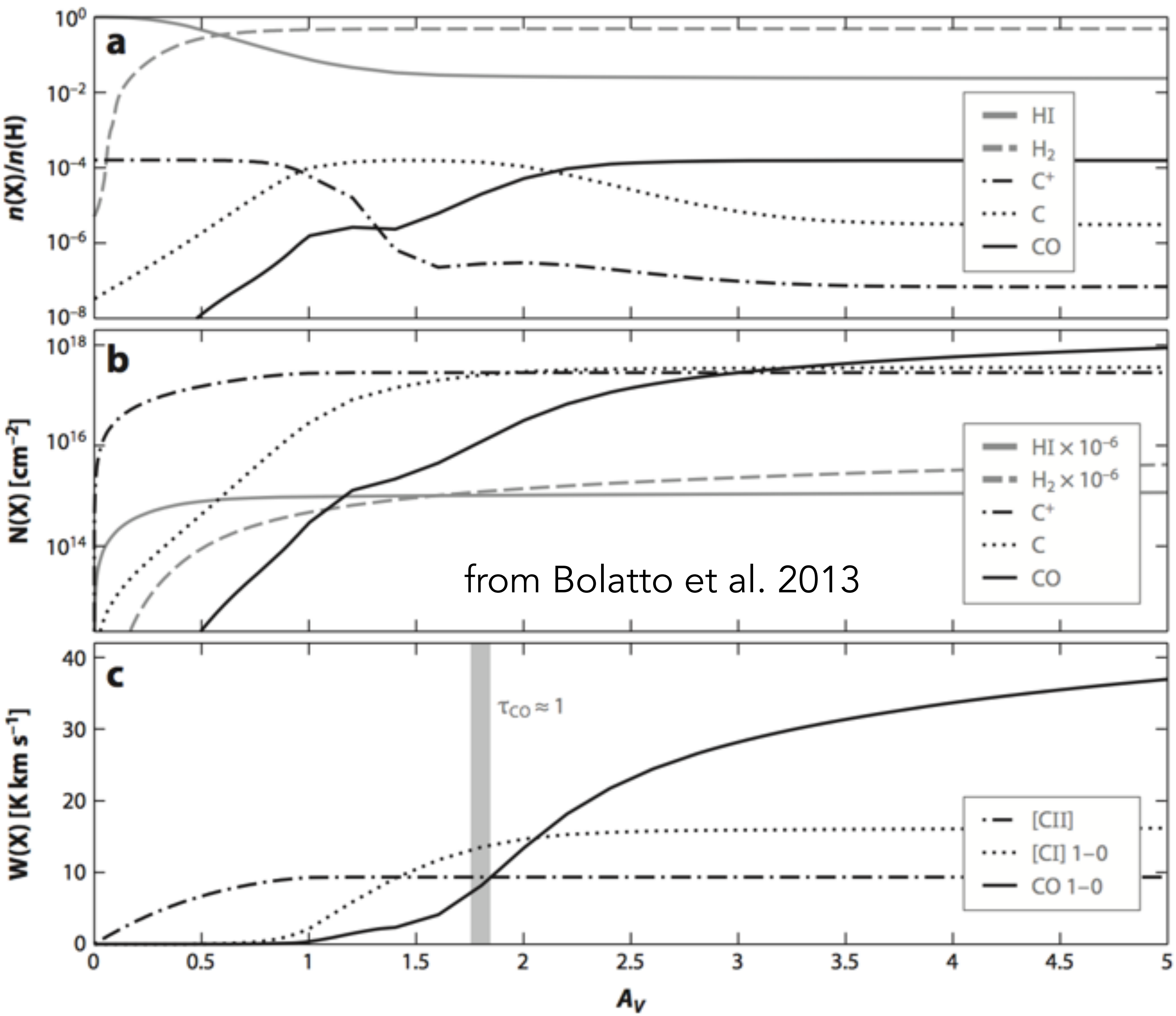
The CO-to-H_2 Conversion Factor



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

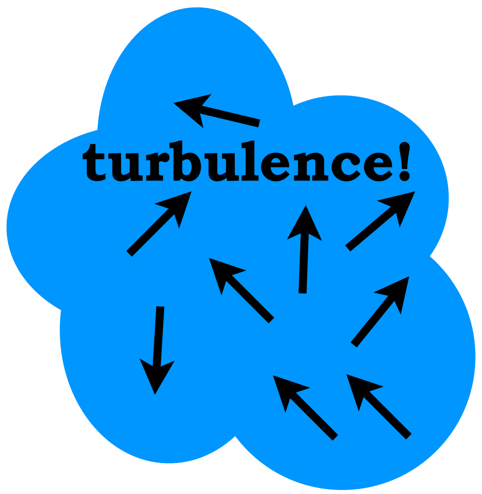


from Bolatto et al. 2013

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

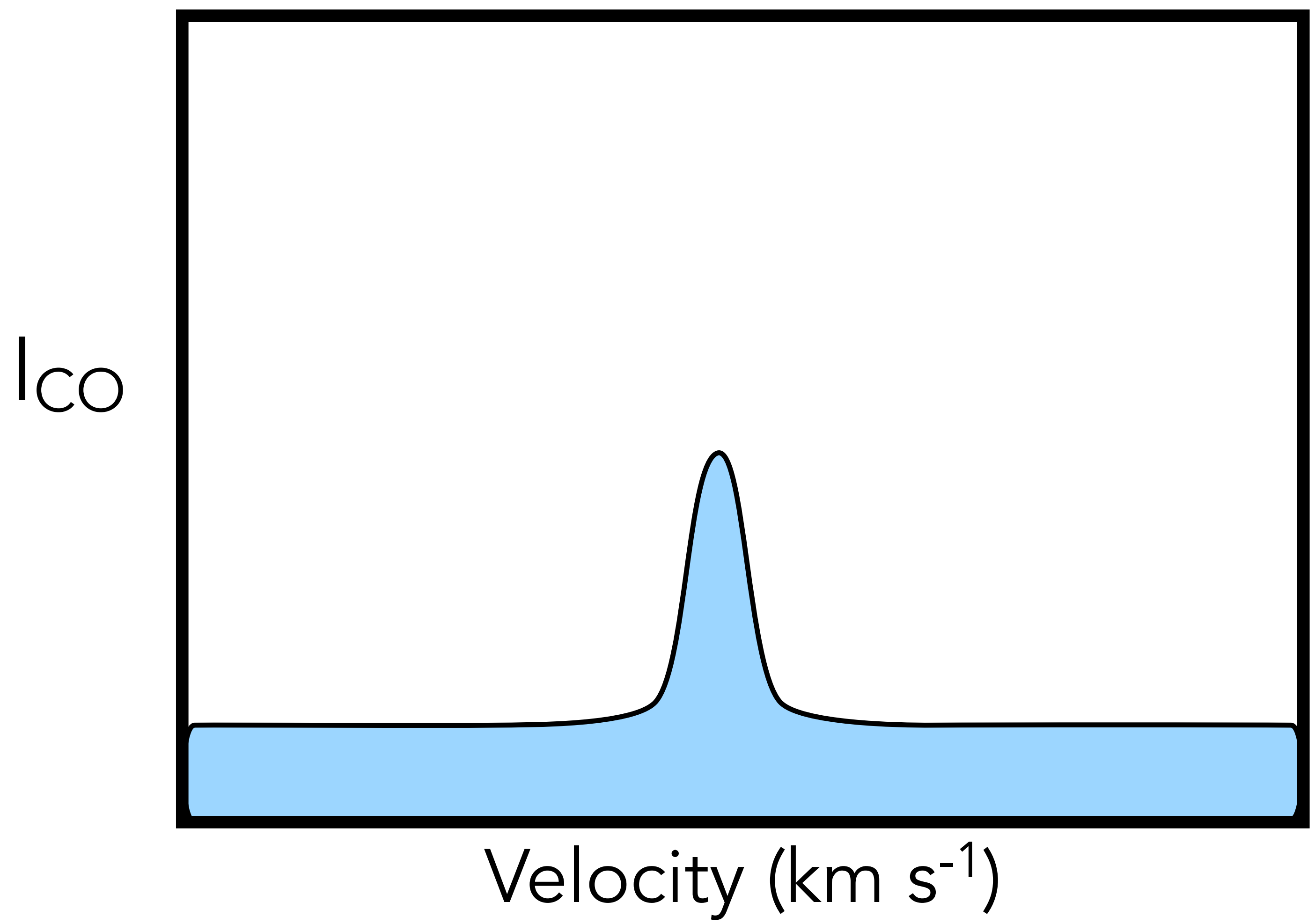
How does an optically thick line tell you the mass?

What Sets α_{CO}?



normal mol. cloud

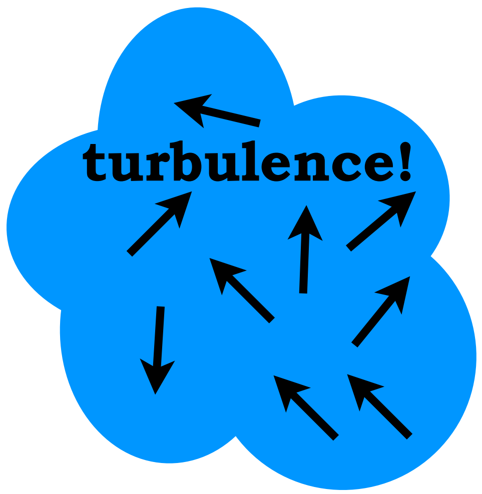
Effects of molecular cloud properties on α_{CO}.



Peak brightness = excitation temperature of CO

line width = turbulent velocity dispersion

What Sets α_{CO}?



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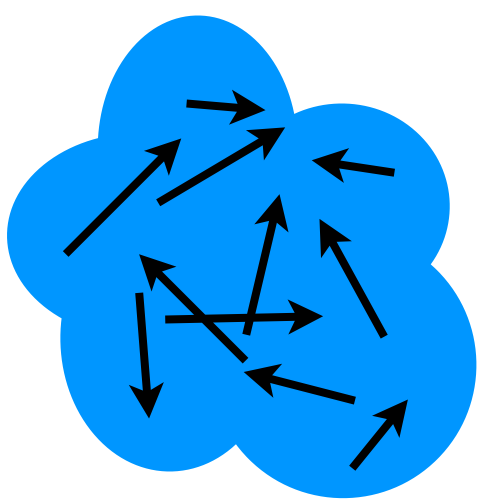
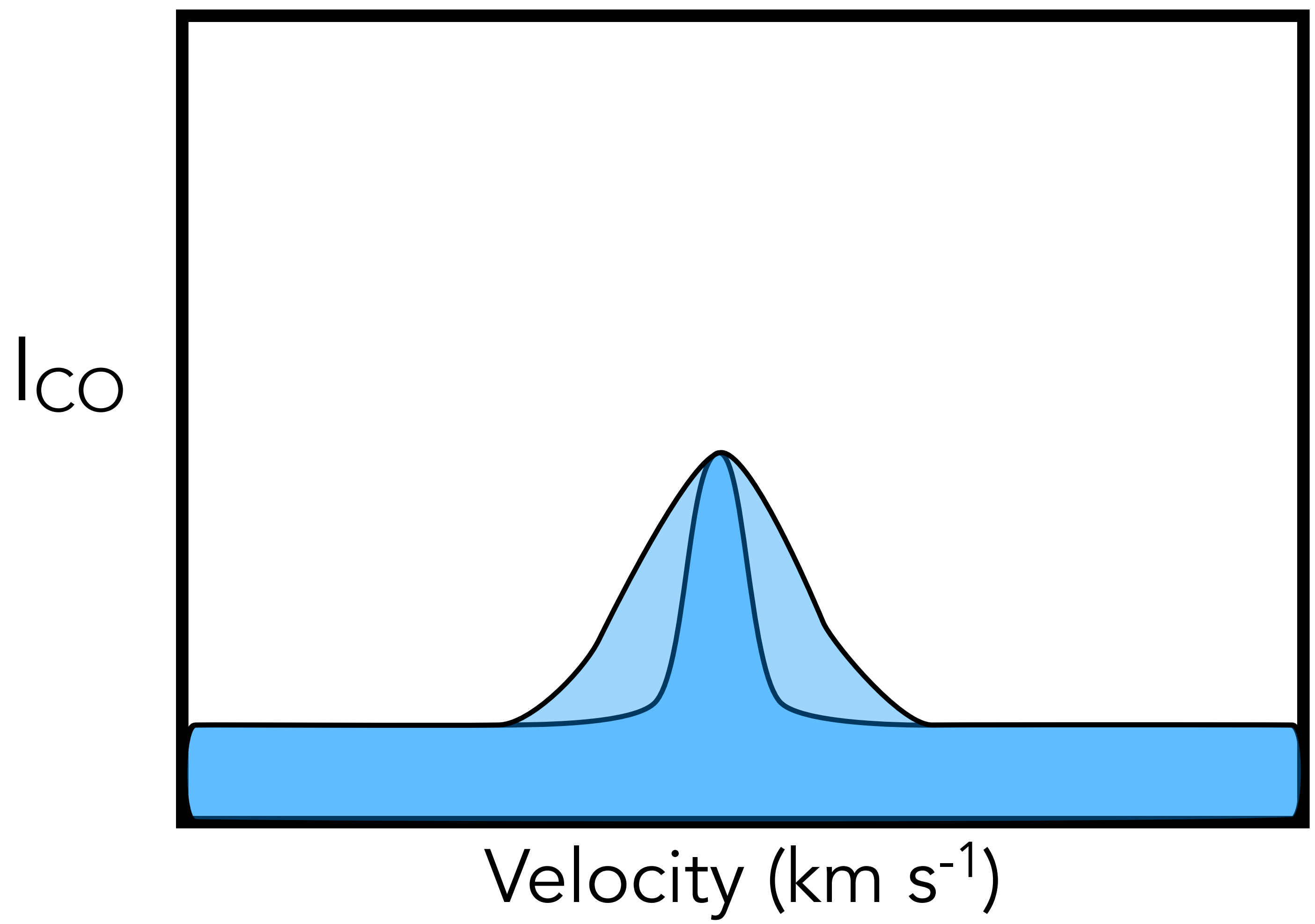


more turbulence

Effects of molecular cloud properties on α_{CO}.



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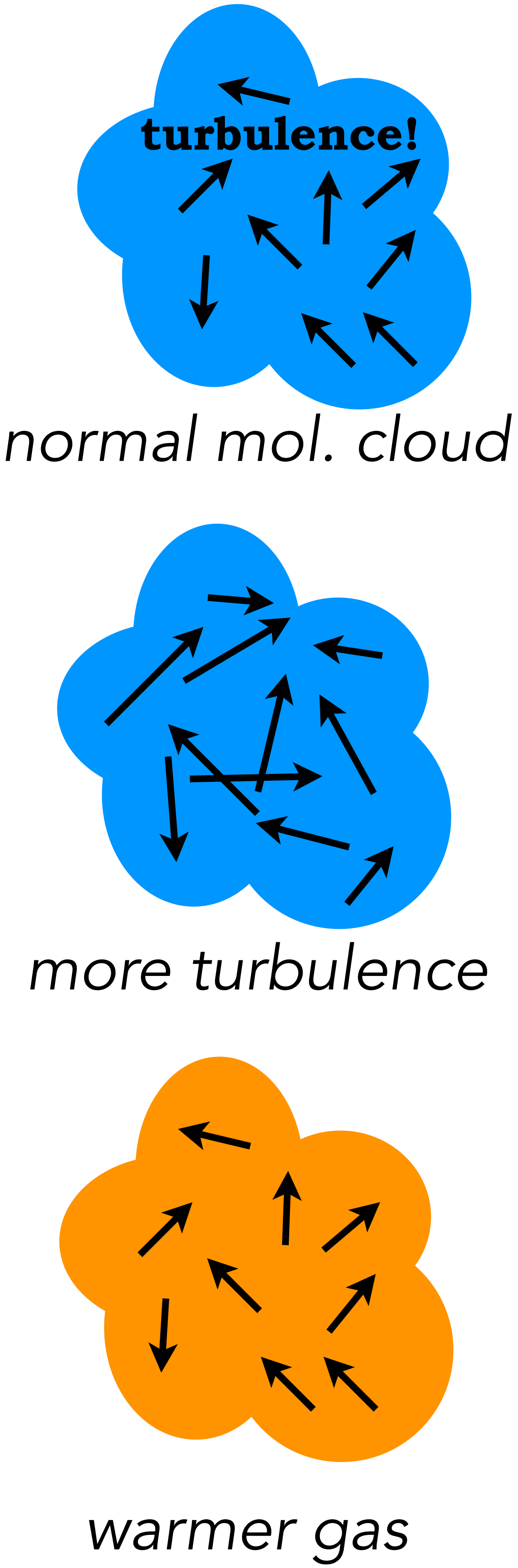

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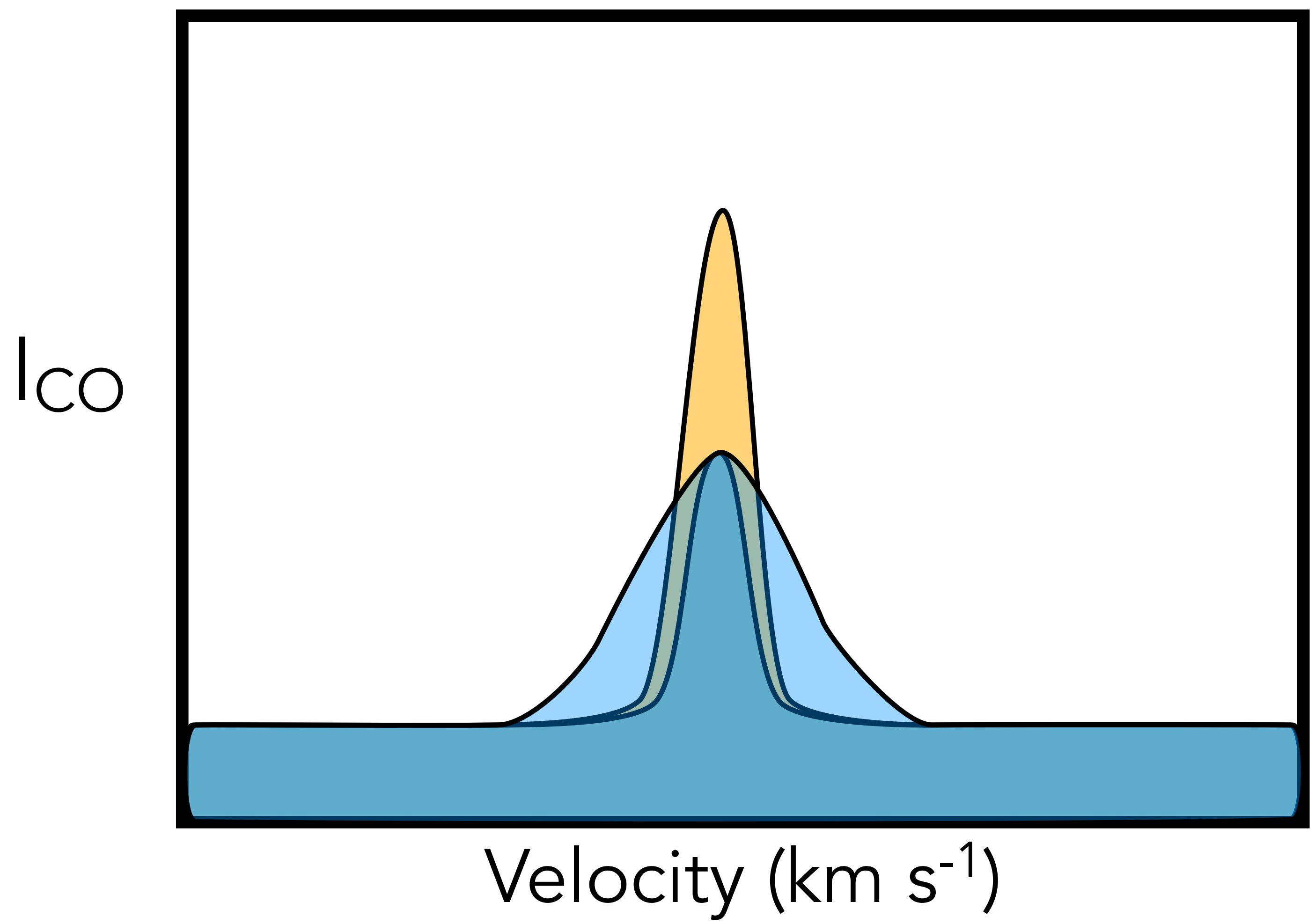

Peak brightness = excitation temperature of CO

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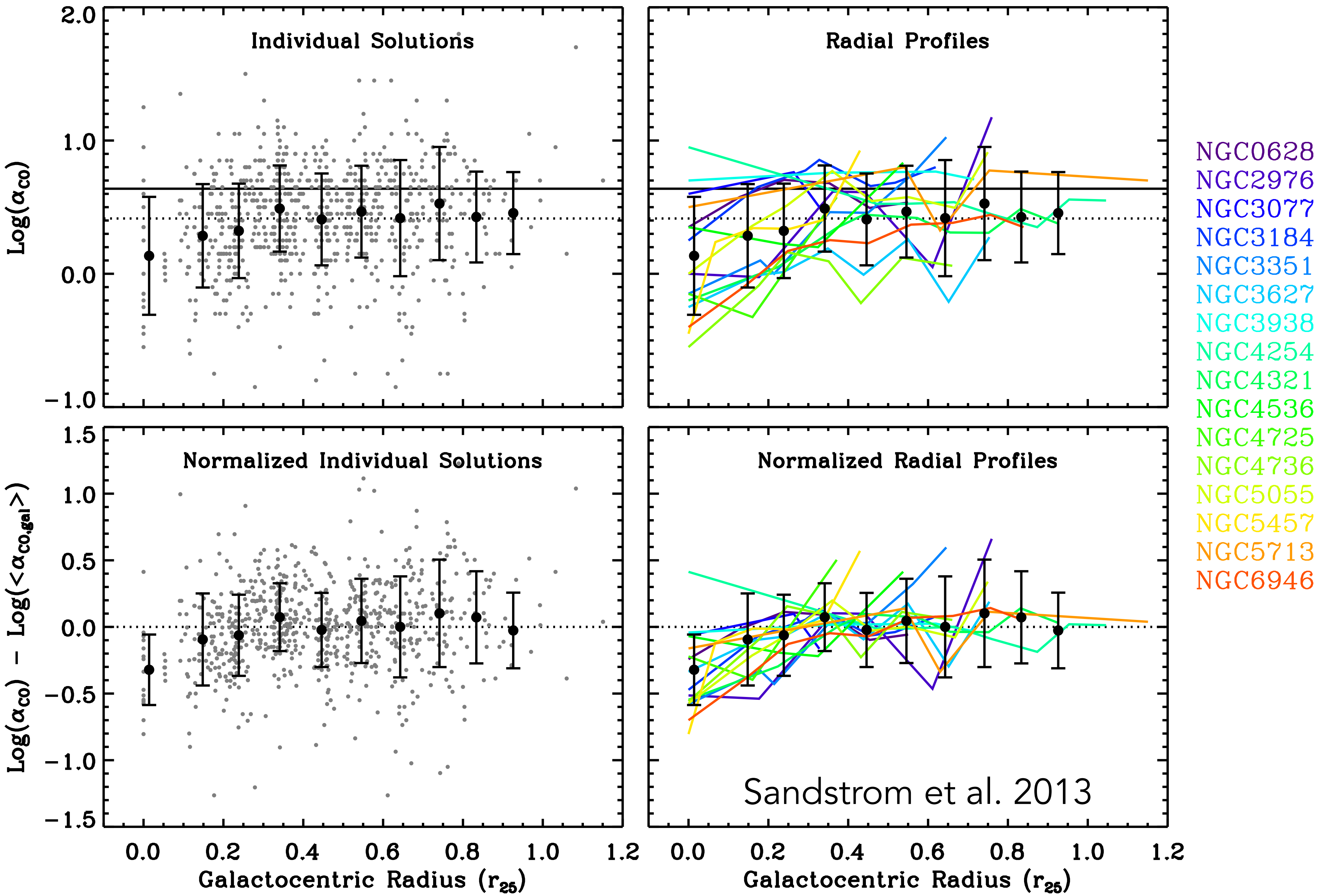

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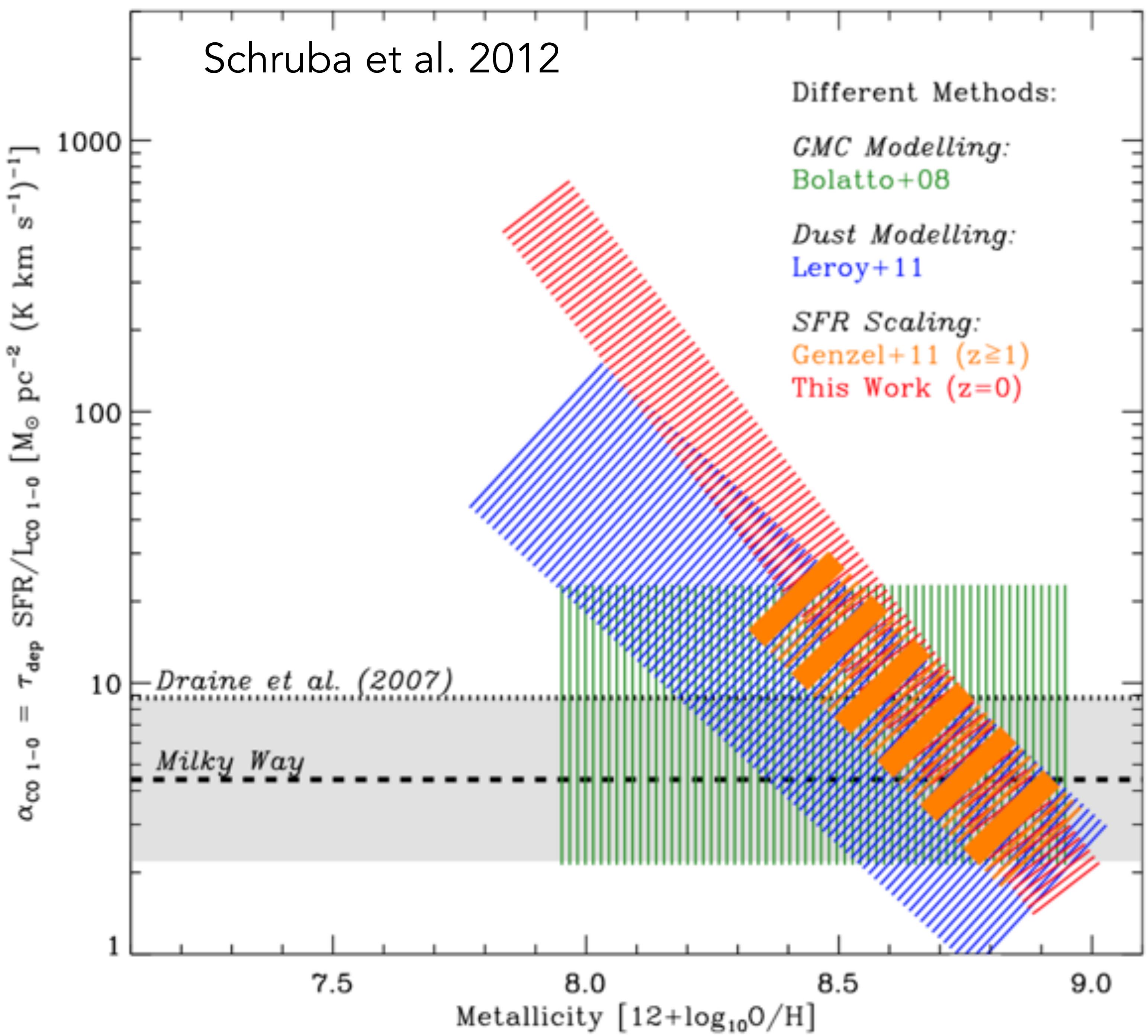


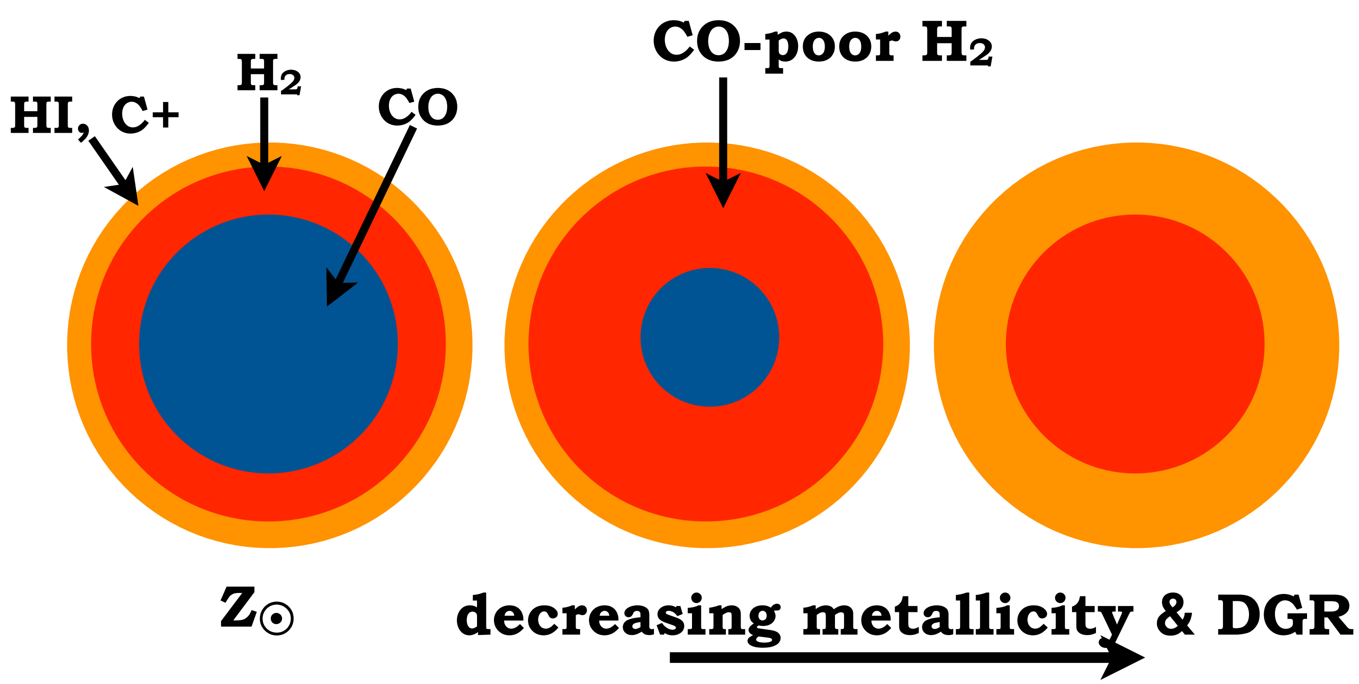
Things really fall apart at low metallicity!

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

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.

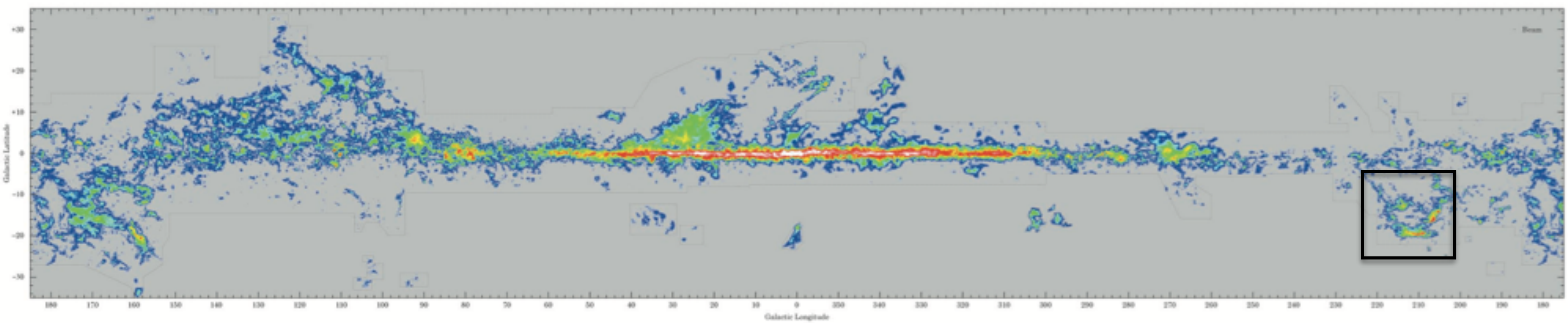


e.g. Maloney & Black 1988, Bolatto et al. 1999,
Wolfire et al. 2010, Glover & Mac Low 2011

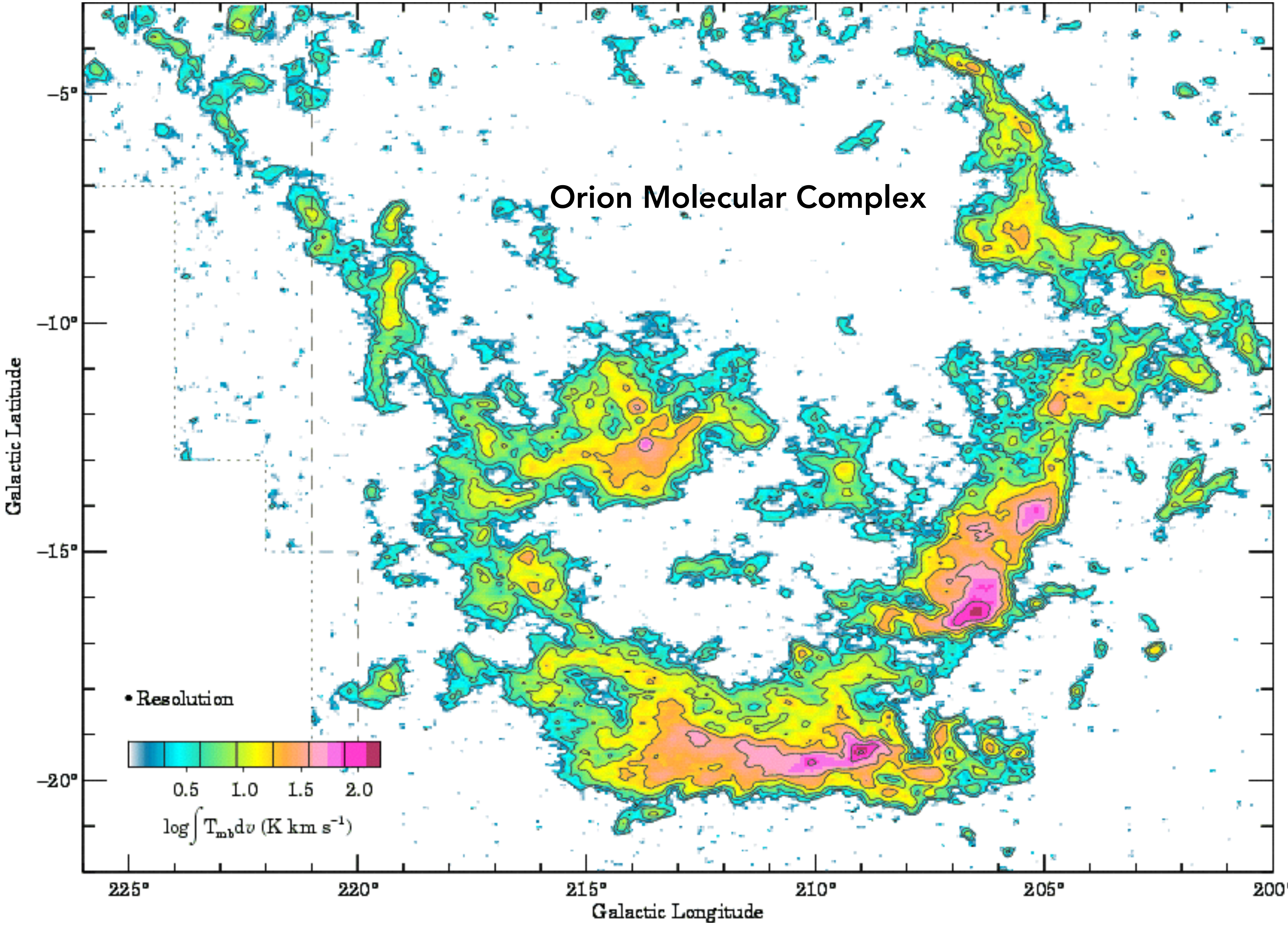
Observations of Molecular Gas

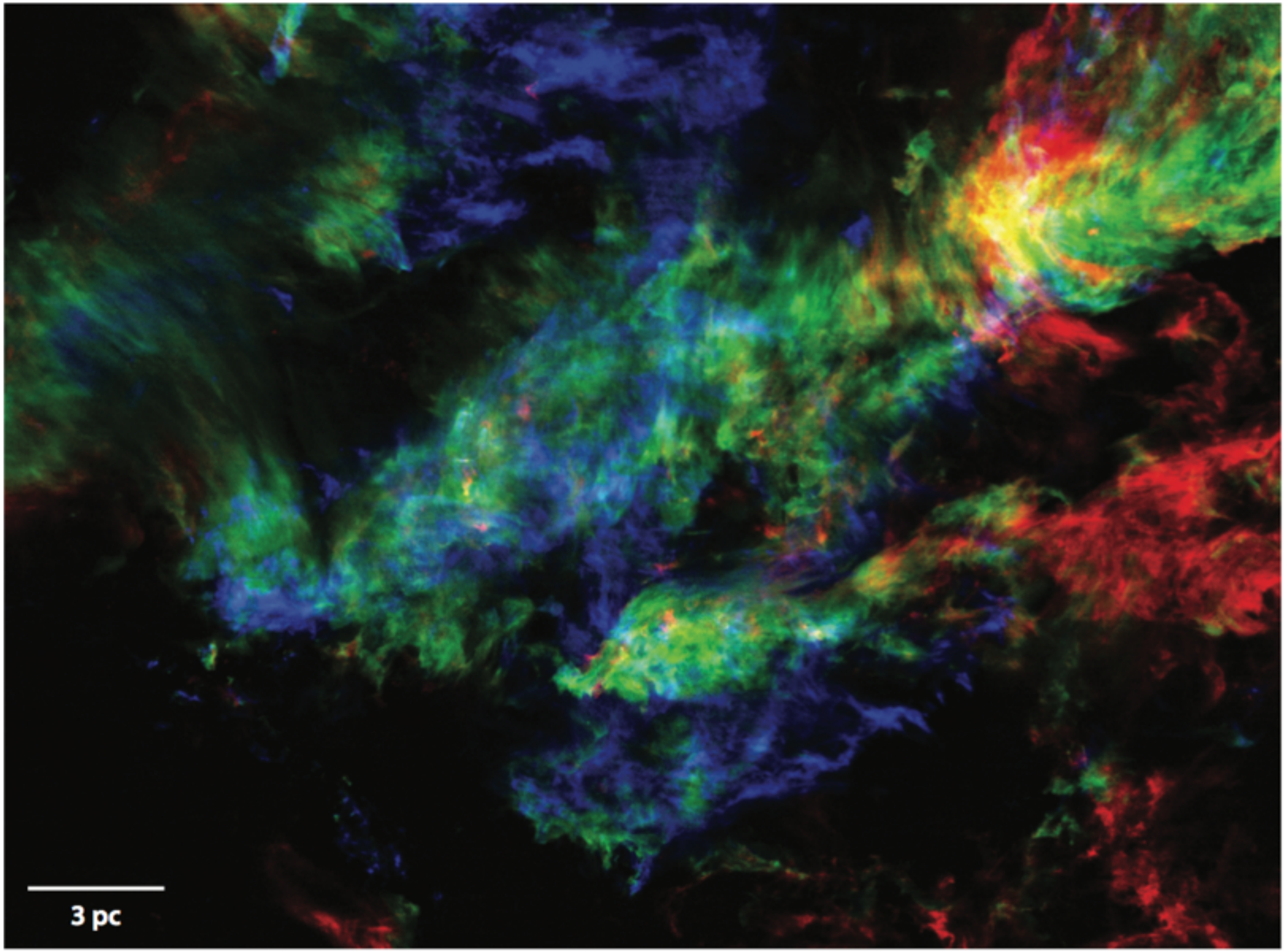
What are “clouds”?

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.