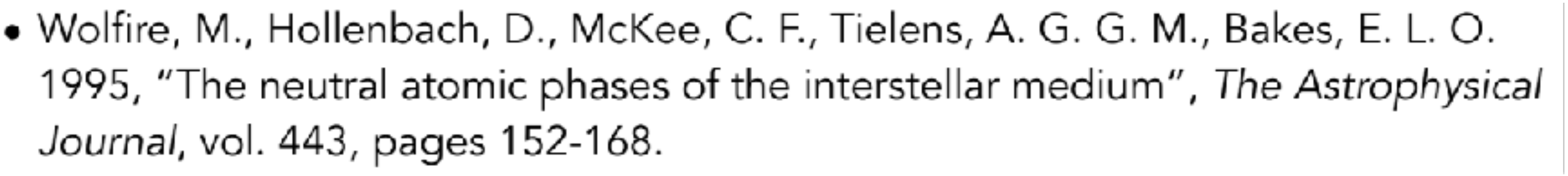
Physics 224
The Interstellar Medium

Lecture #15

a brief note on proposal formatting

You should attempt to use the proposal template
for the type of proposal you are submitting.

Your bibliography should include the following
information for work thing you cite:



- Wolfire, M., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., Bakes, E. L. O. 1995, “The neutral atomic phases of the interstellar medium”, *The Astrophysical Journal*, vol. 443, pages 152-168.

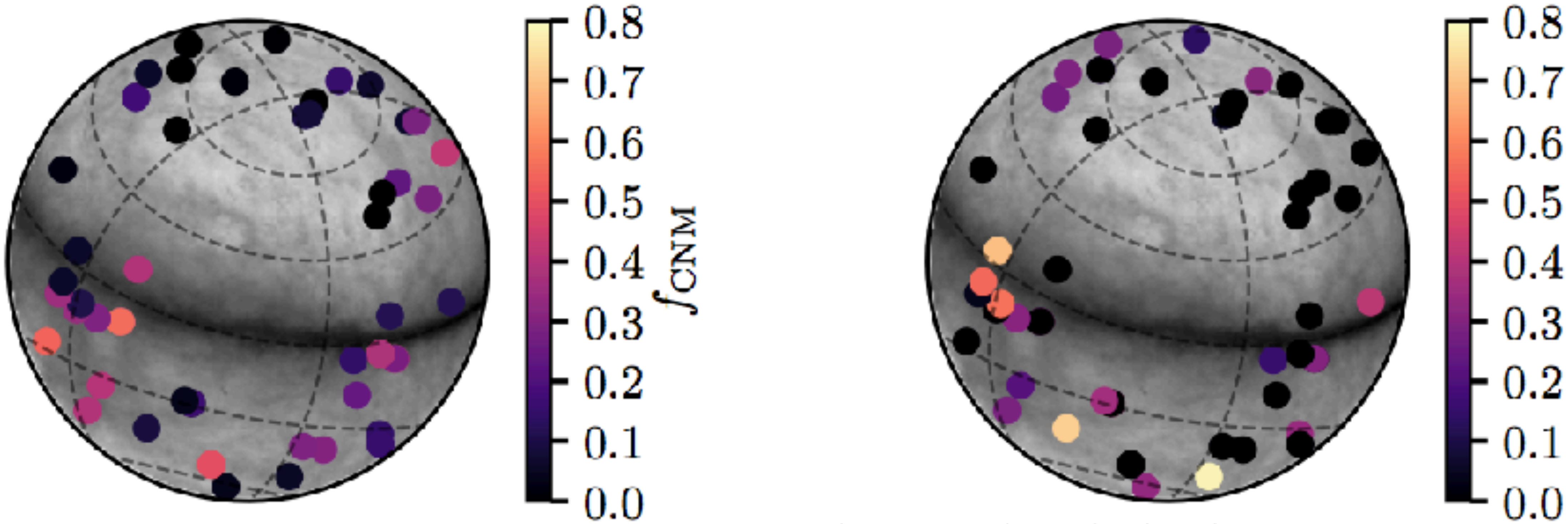
authors, year, title, journal, volume, pages

in latex, I recommend using natbib - good practice!

Observed HI Spin Temperature

Best recent constraints for the Milky Way:
28% CNM, 20% unstable, 52% WNM by mass

VLA 21SPONGE Survey - Murray et al. 2018

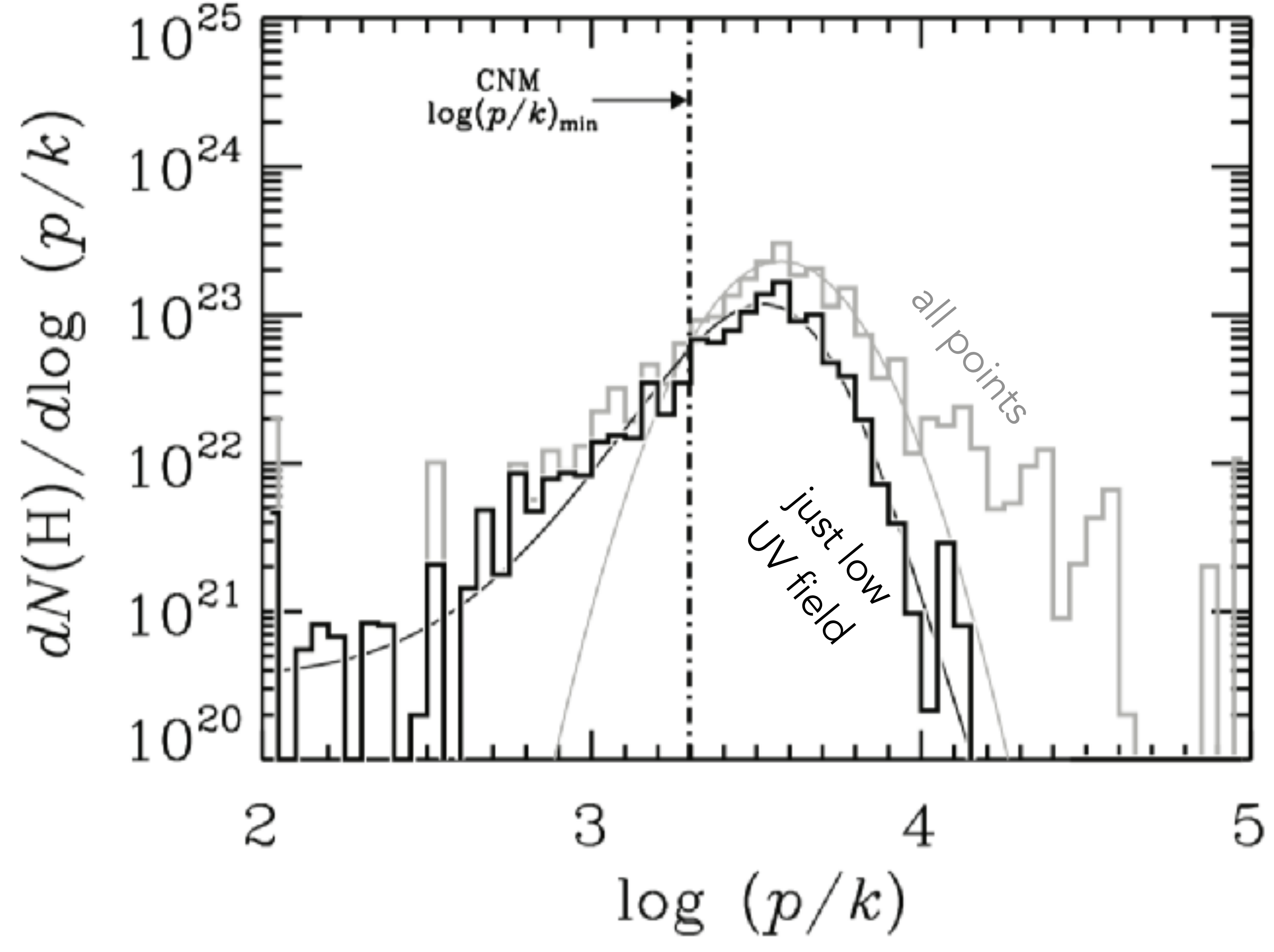


EBHIS survey & 21SPONGE targets

also: WNM is hotter than equilibrium models predict.

Thermal Pressure from [CI]

Jenkins & Tripp 2001, 2011

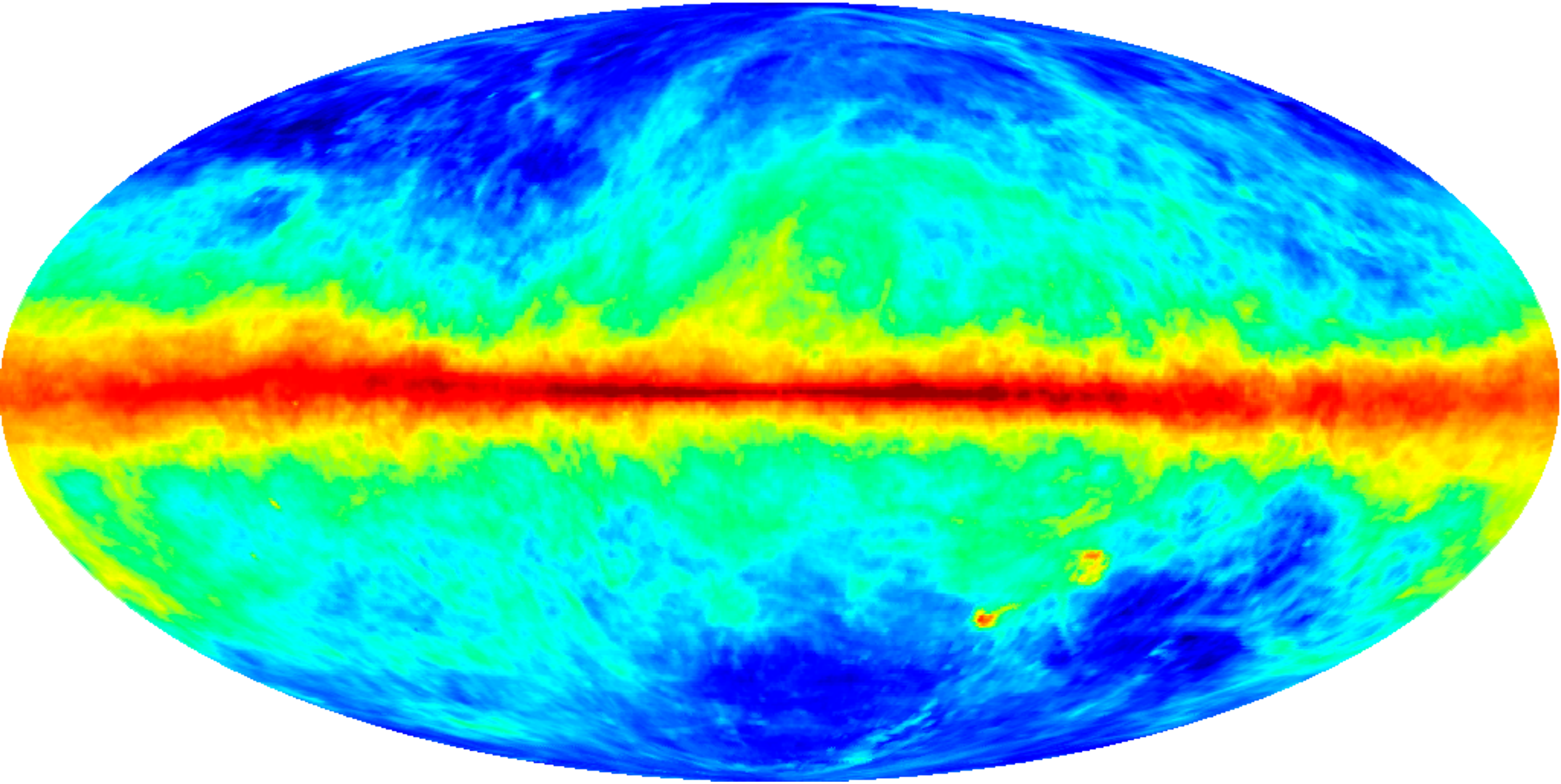


Most gas is at pressures that agree with the FGH picture, but there are tails of low & high pressure that are probably related to turbulence.

Is the FGH model a good representation of the ISM?

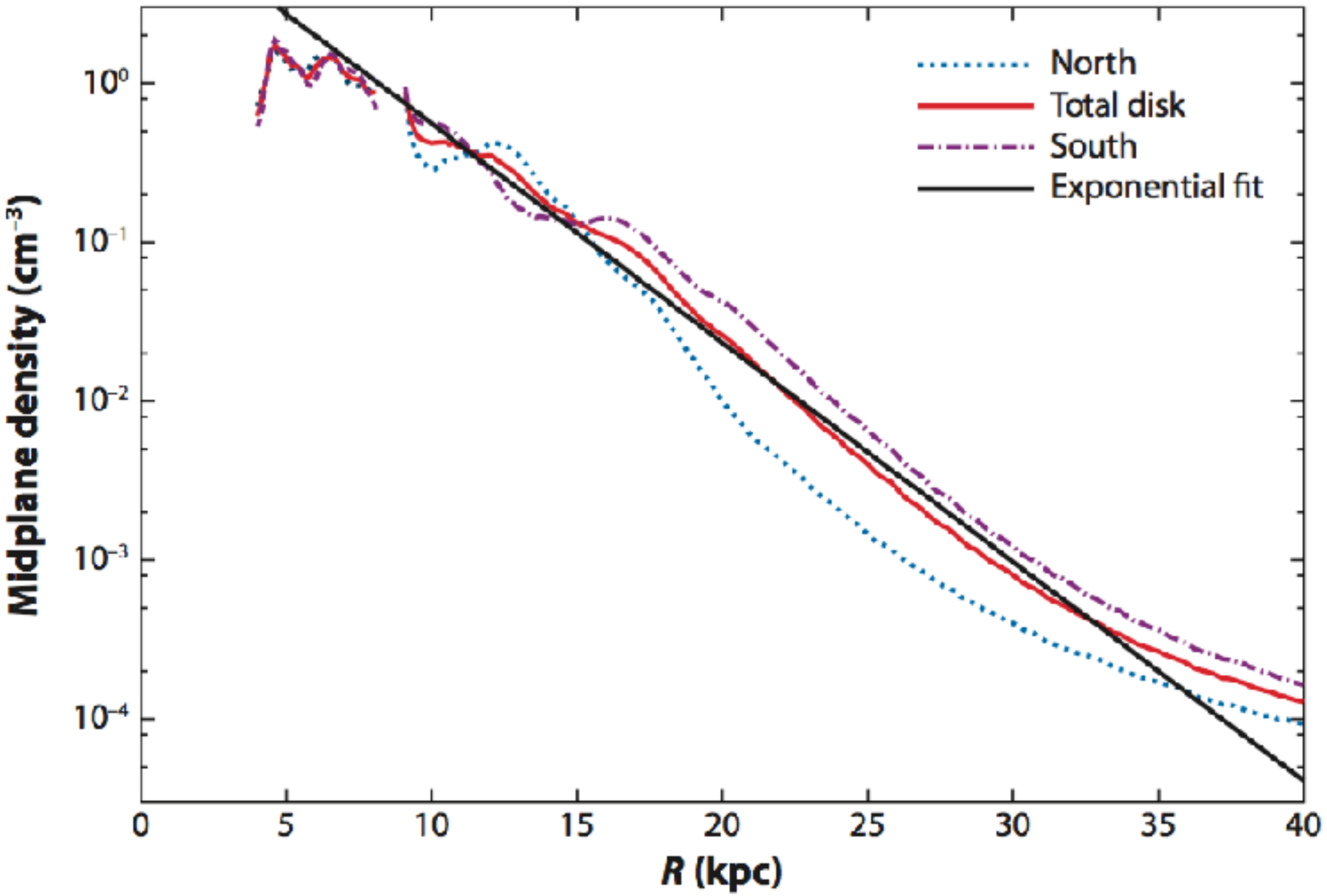
Maybe.

All-Sky Map of N(HI) from the Leiden-Argentine-Bonn Survey (Kalberla et al. 2005)



Distribution of HI in the MW

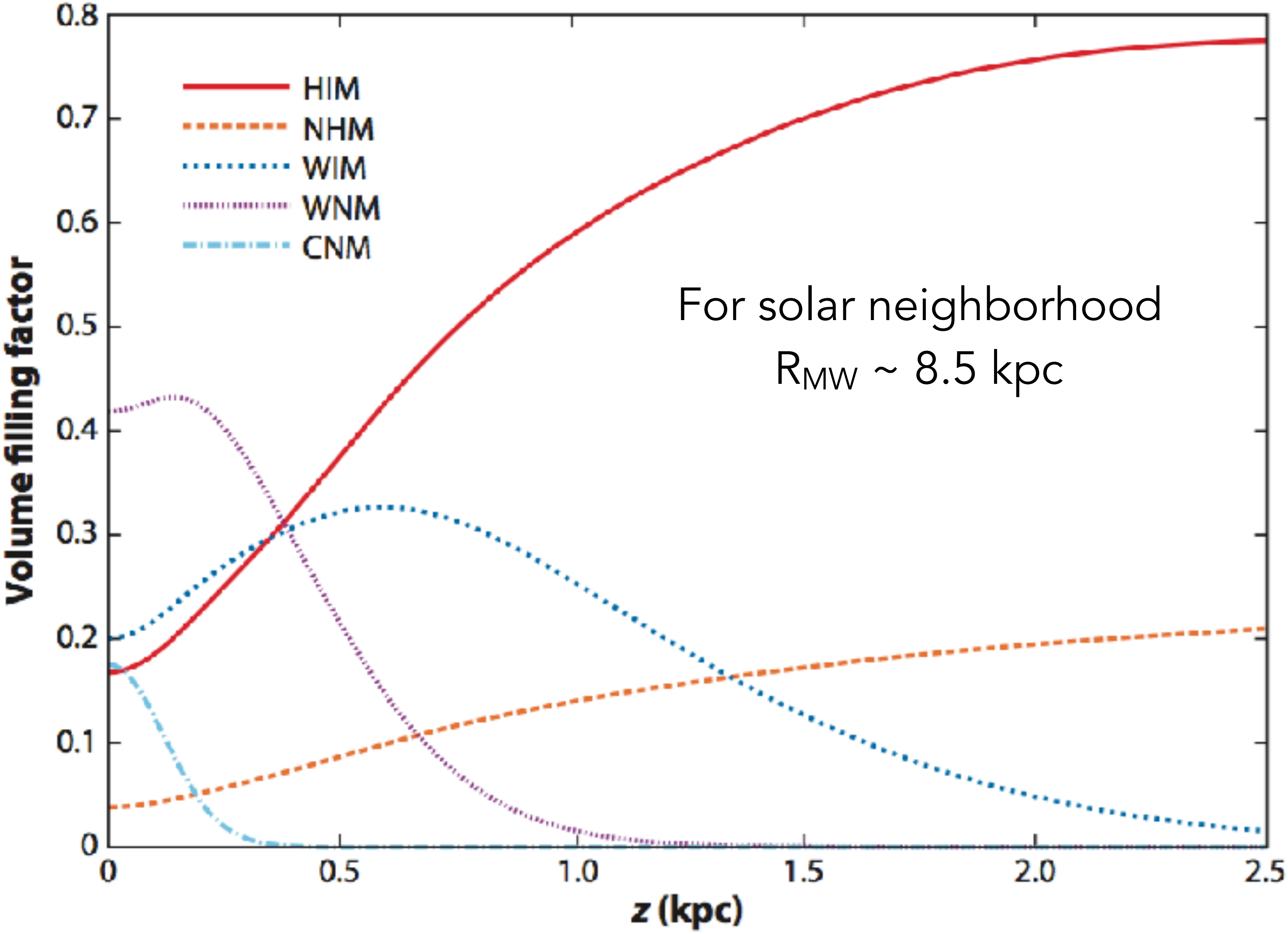
Kalberla & Kerp 2009, ARA&A



distance from Galactic center

Distribution of HI in the MW

Kalberla & Kerp 2009, ARA&A

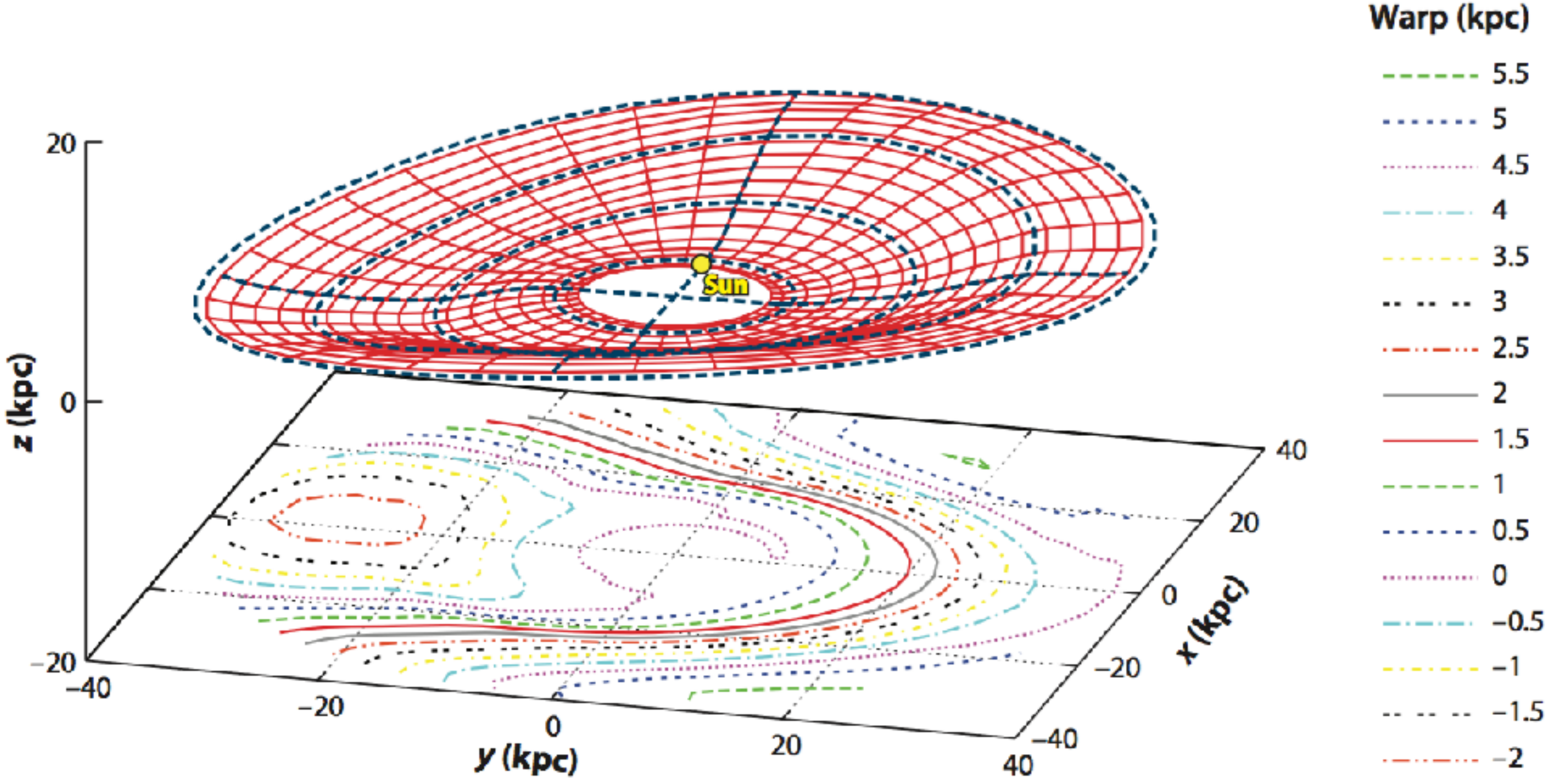


For solar neighborhood
R_{MW} ~ 8.5 kpc

height above Galactic midplane

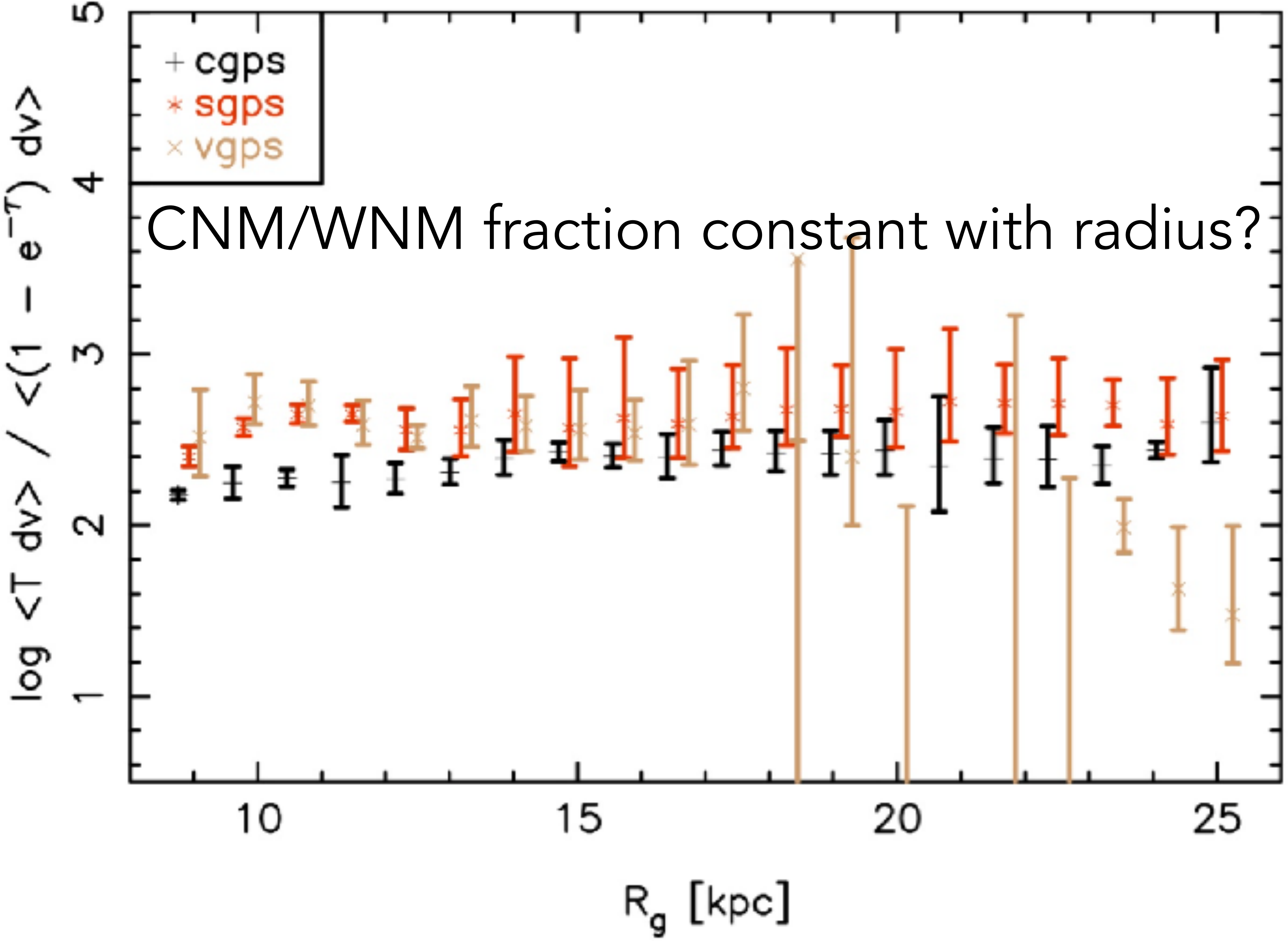
Distribution of HI in the MW

Kalberla & Kerp 2009, ARA&A



Distribution of HI in the MW

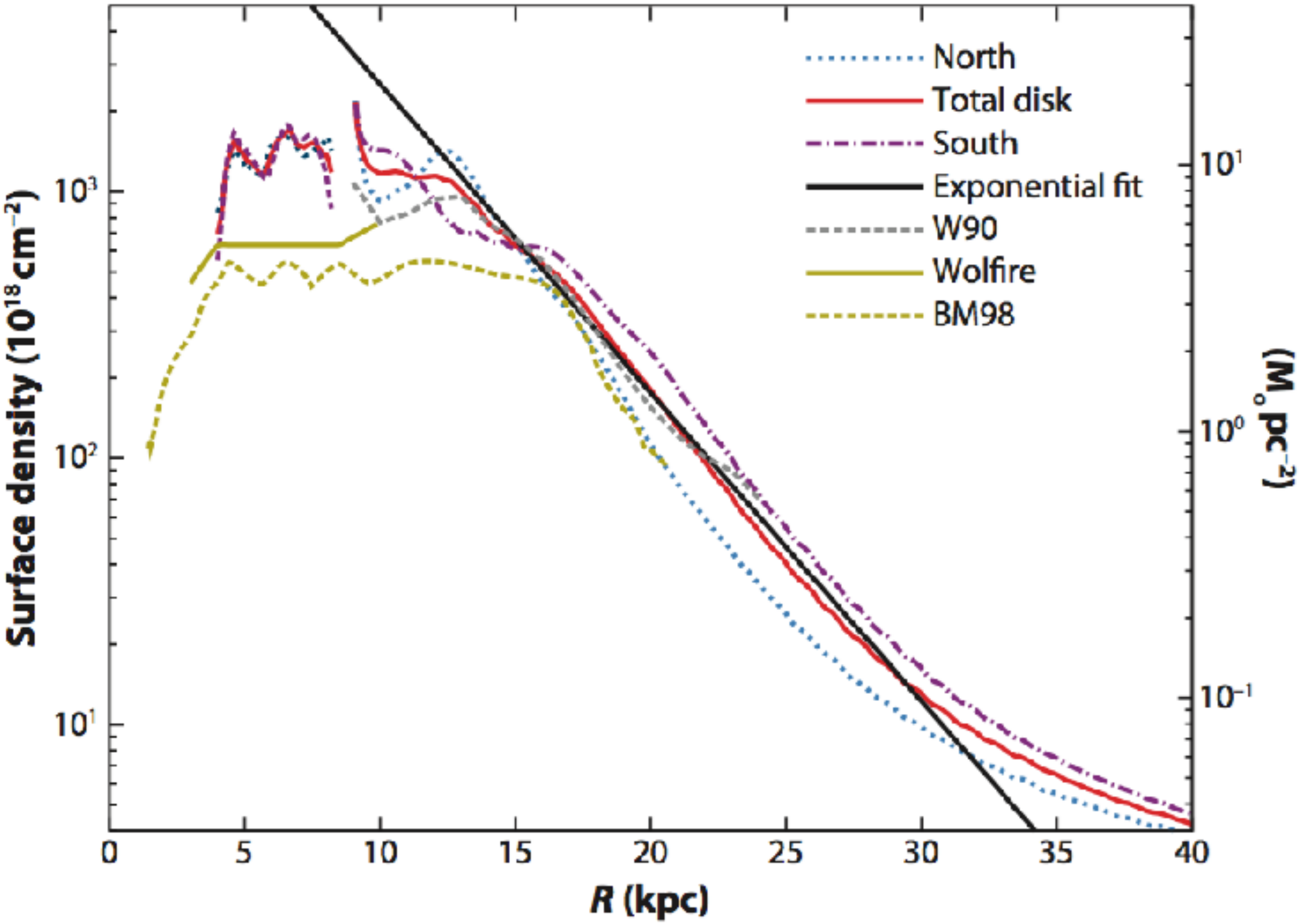
Dickey et al. 2009



CNM/WNM fraction constant with radius?

Distribution of HI in the MW

Kalberla & Kerp 2009, ARA&A



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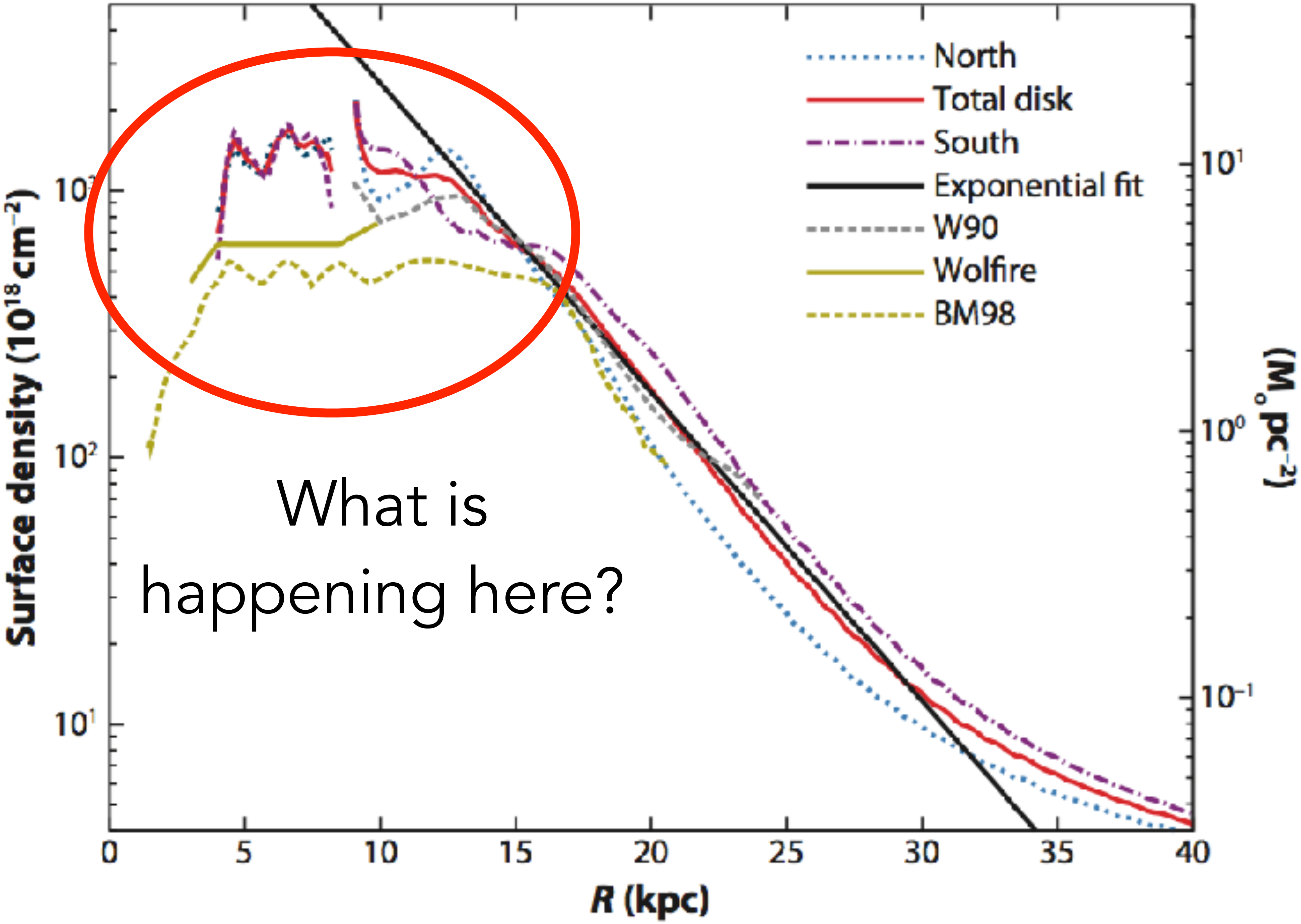
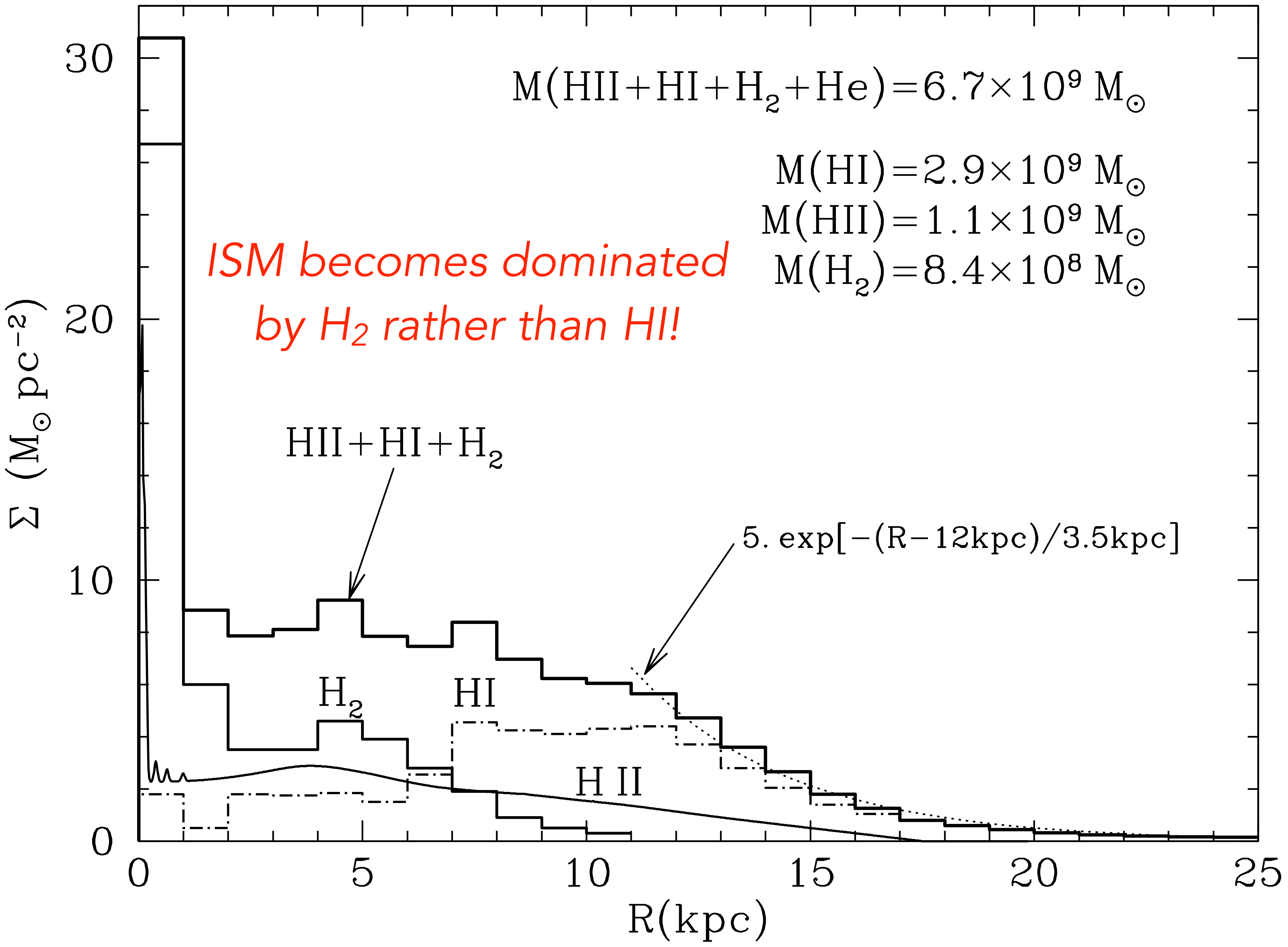


What is happening here?

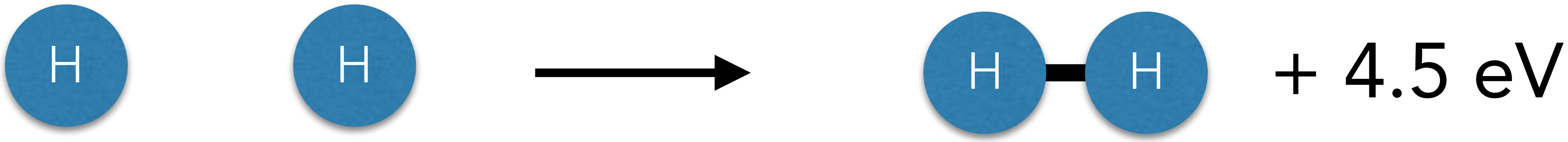
Distribution of HI in the MW



ISM becomes dominated by H_2 rather than HI!

Forming H_2

Formation of H_2 by gas-phase reactions is slow



+ 4.5 eV

no effective way to carry away 4.5 eV worth of binding energy when two H bond, no dipole moment

negligible rate for this reaction

Forming H_2

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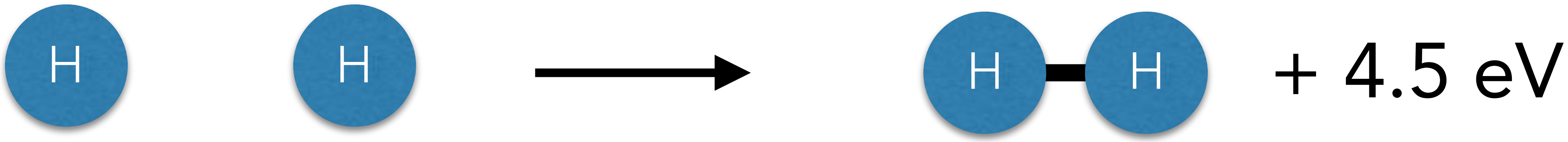

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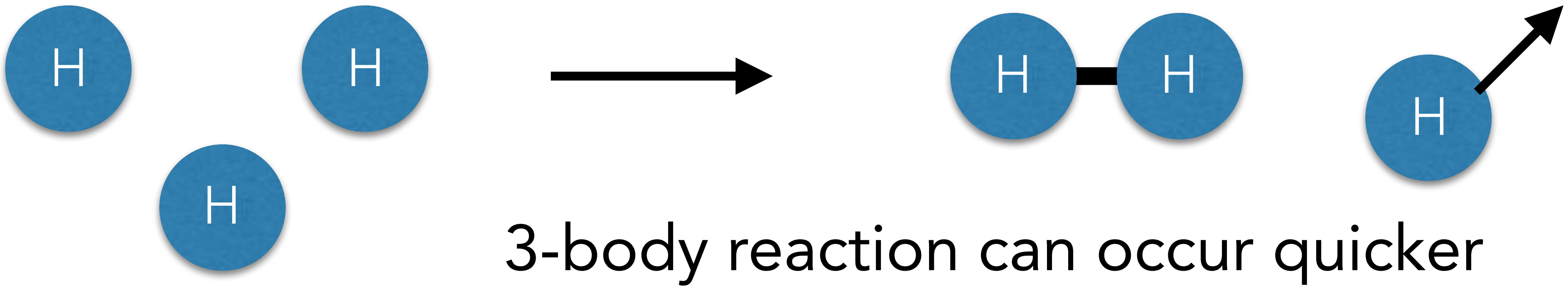


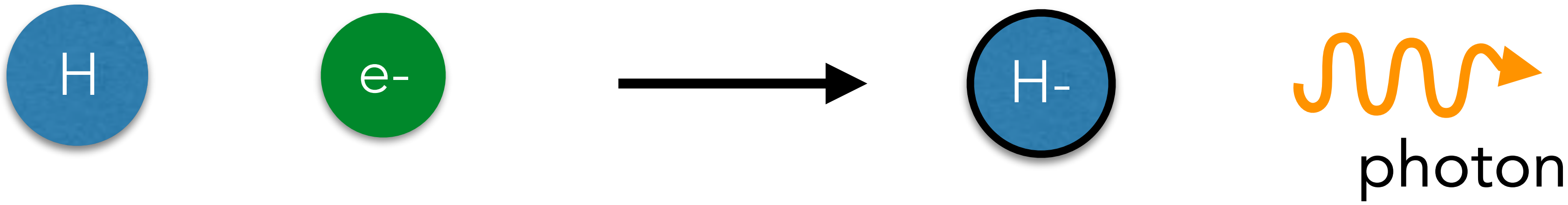
3-body reaction can occur quicker
but this is still very slow

Forming H_2

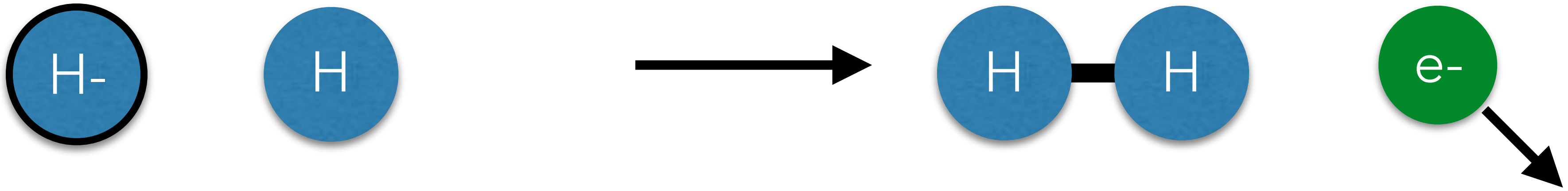
Formation of H_2 by gas-phase reactions is slow

Fastest gas-phase route is "associative attachment"

First:

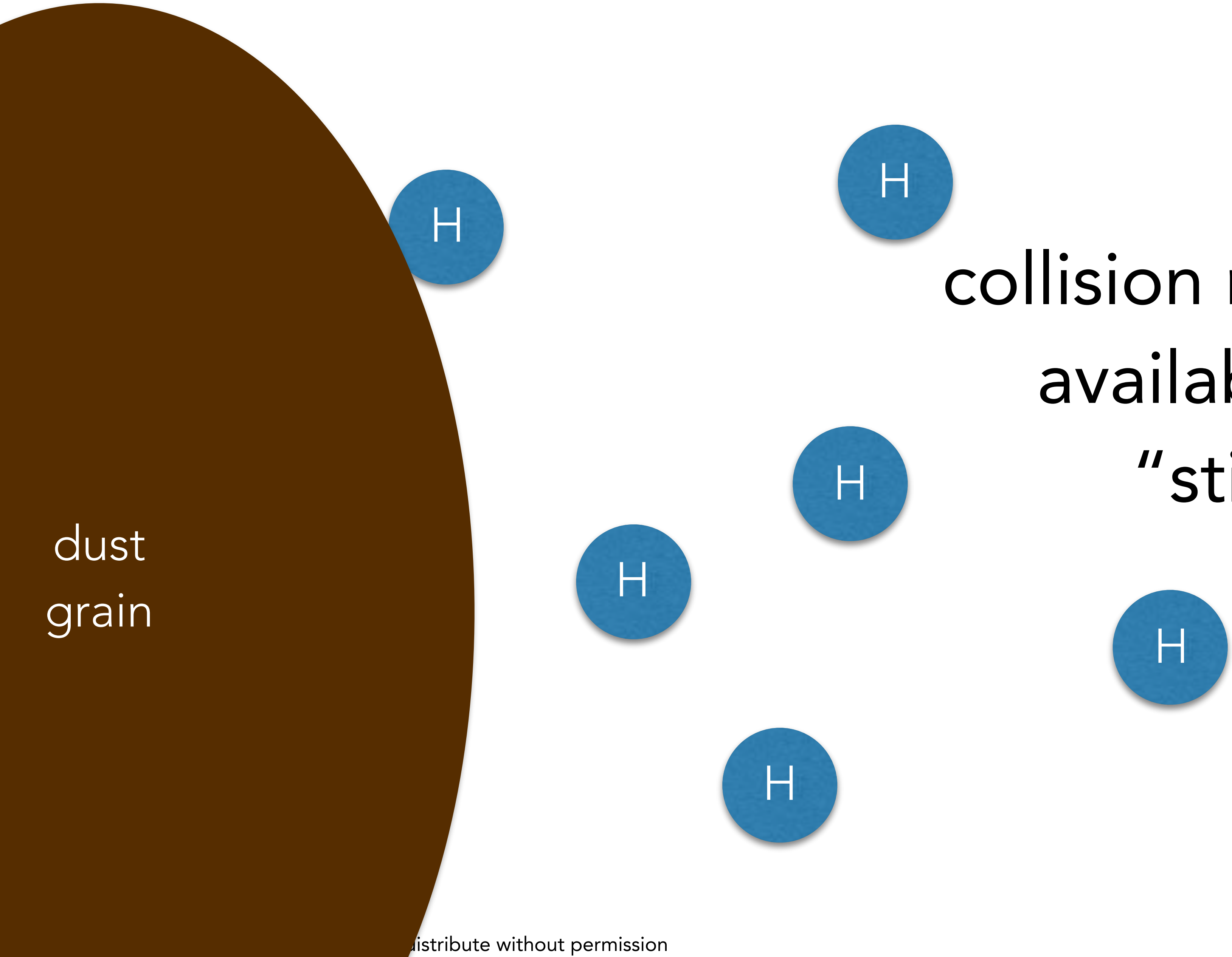


Then:



Forming H_2

Grain Surface H_2 formation is much faster if there is dust.



Depends on:

collision rate of H with grain (n,T)

available grain surface area

“sticking” probability

Forming H_2

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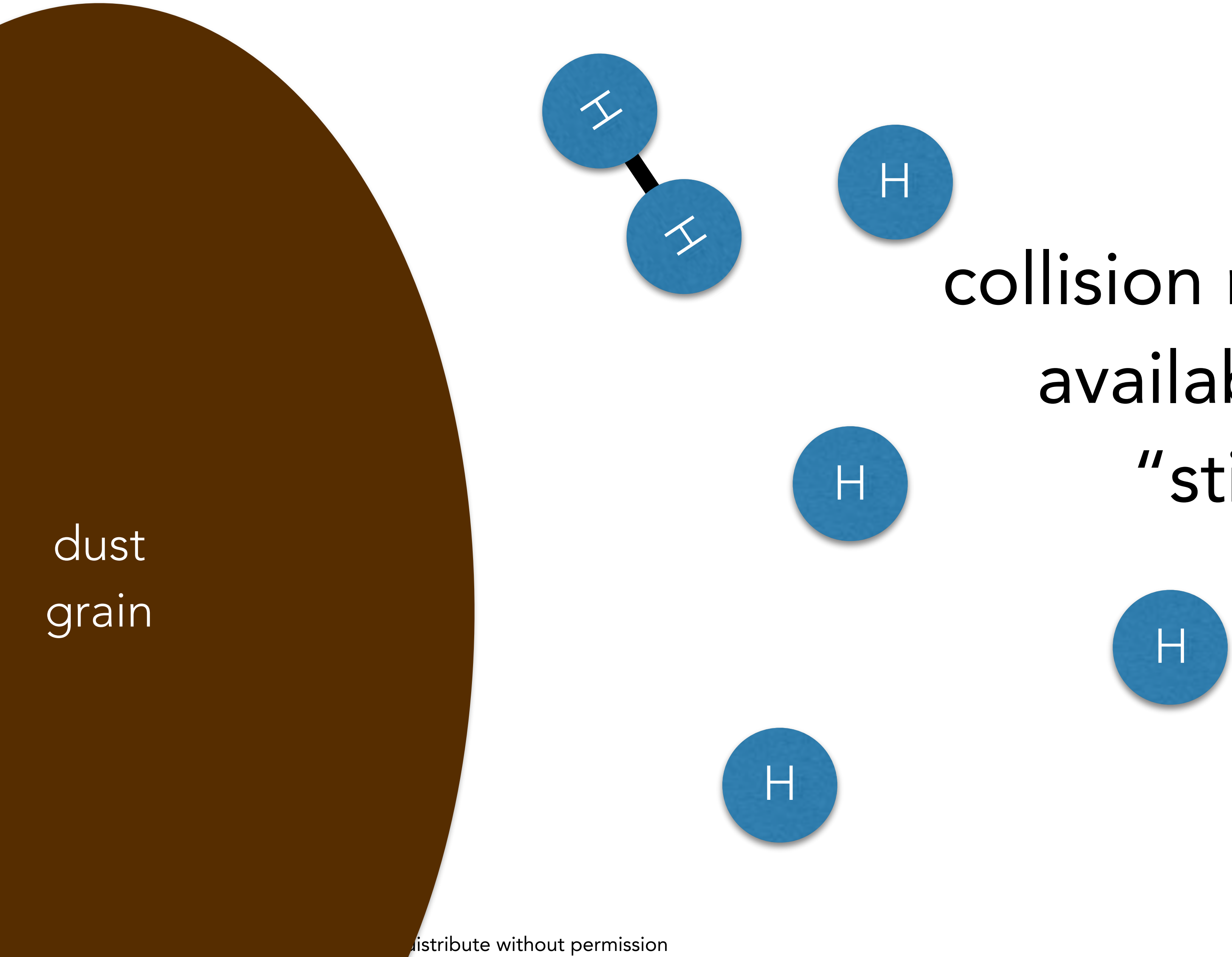

Depends on:
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"sticking" probability

Forming H_2

Grain Surface H_2 formation is much faster if there is dust.

$$\left(\frac{dn(\mathrm{H_2})}{dt}\right)_{\mathrm{gr}} = R_{\mathrm{gr}}\ n_H\ n(H)$$

density of
H atoms

total density
of hydrogen in
any form

Forming H_2

Grain Surface H_2 formation is much faster if there is dust.

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density of
H atoms

total density
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any form

$$R_{\mathrm{gr}} = \frac{1}{2}\left(\frac{8kT}{\pi m_H}\right)^{1/2} \langle \epsilon_{\mathrm{gr}} \rangle \Sigma_{\mathrm{gr}}$$

v_{thermal}

average “sticking”
coeff for grain pop

Forming H_2

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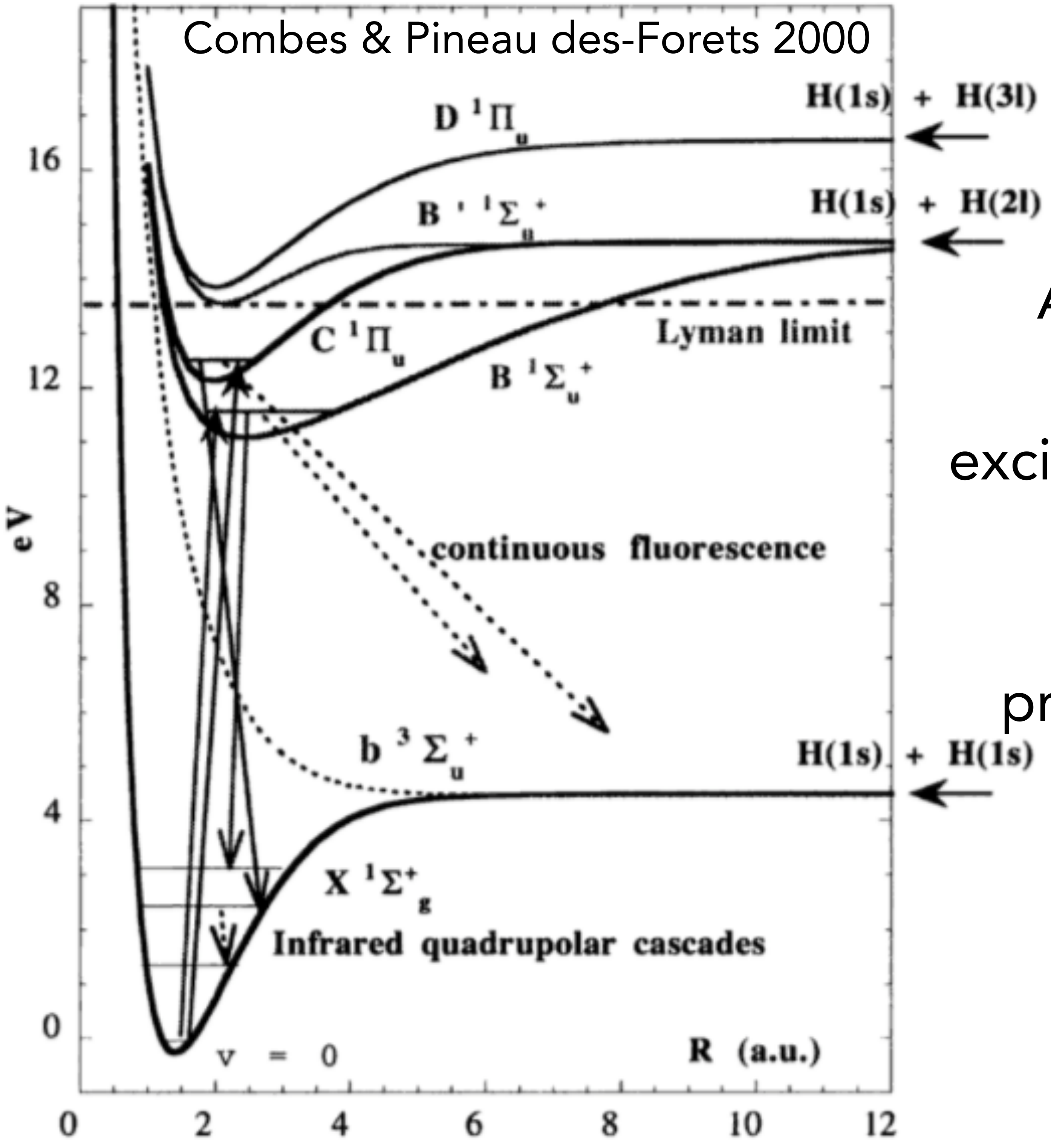
v_{thermal}

average “sticking”
coeff for grain pop

Grain surface area

$$\Sigma_{\mathrm{gr}} \equiv \frac{1}{n_H}\int \pi a^2 \frac{dn_{\mathrm{gr}}}{da}\, da$$

Photodissociation of H_2


Combes & Pineau des-Forets 2000

After H_2 absorbs a UV photon from ground to one of the excited levels (Lyman-Werner bands) has ~85% probability of radiative decay, ~15% probability of photo-dissociating

Lyman band = ground -> B
Werner band = ground -> C

Photodissociation of H_2

$$\varsigma_{\rm diss} = \boxed{\sum_u \varsigma_{l\rightarrow u}}\, p_{{\rm diss},u}$$

dissociation rate

sum of rates for transitions from ground state to excited states

probability of photo-dissociation from upper state

Photodissociation of H_2

$$\varsigma_{\rm diss} = \boxed{\sum_u \varsigma_{l\rightarrow u}}\ p_{{\rm diss},u}$$

dissociation rate

sum of rates for transitions from ground state to excited states

probability of photo-dissociation from upper state

depends on quantum mechanics and radiation field intensity at relevant wavelengths

H_2 Abundance

In steady state:

photo-dissociation

$$\zeta_{\rm diss} n(H_2) = R_{\rm gr} n_H n(H)$$

formation on dust grains

For CNM conditions this is pretty small:

$$\frac{n(H_2)}{n_H} \approx 1.8 \times 10^{-5} \left(\frac{n(H)}{30{\rm cm}^{-3}}\right) \left(\frac{R_{\rm gr}}{3 \times 10^{-17}{\rm cm}^3{\rm s}^{-1}}\right) \left(\frac{\zeta_{\rm diss}}{5 \times 10^{-11}{\rm s}^{-1}}\right)^{-1}$$

But we have left out an important component: shielding

H_2 Abundance

Sternberg et al. 2014

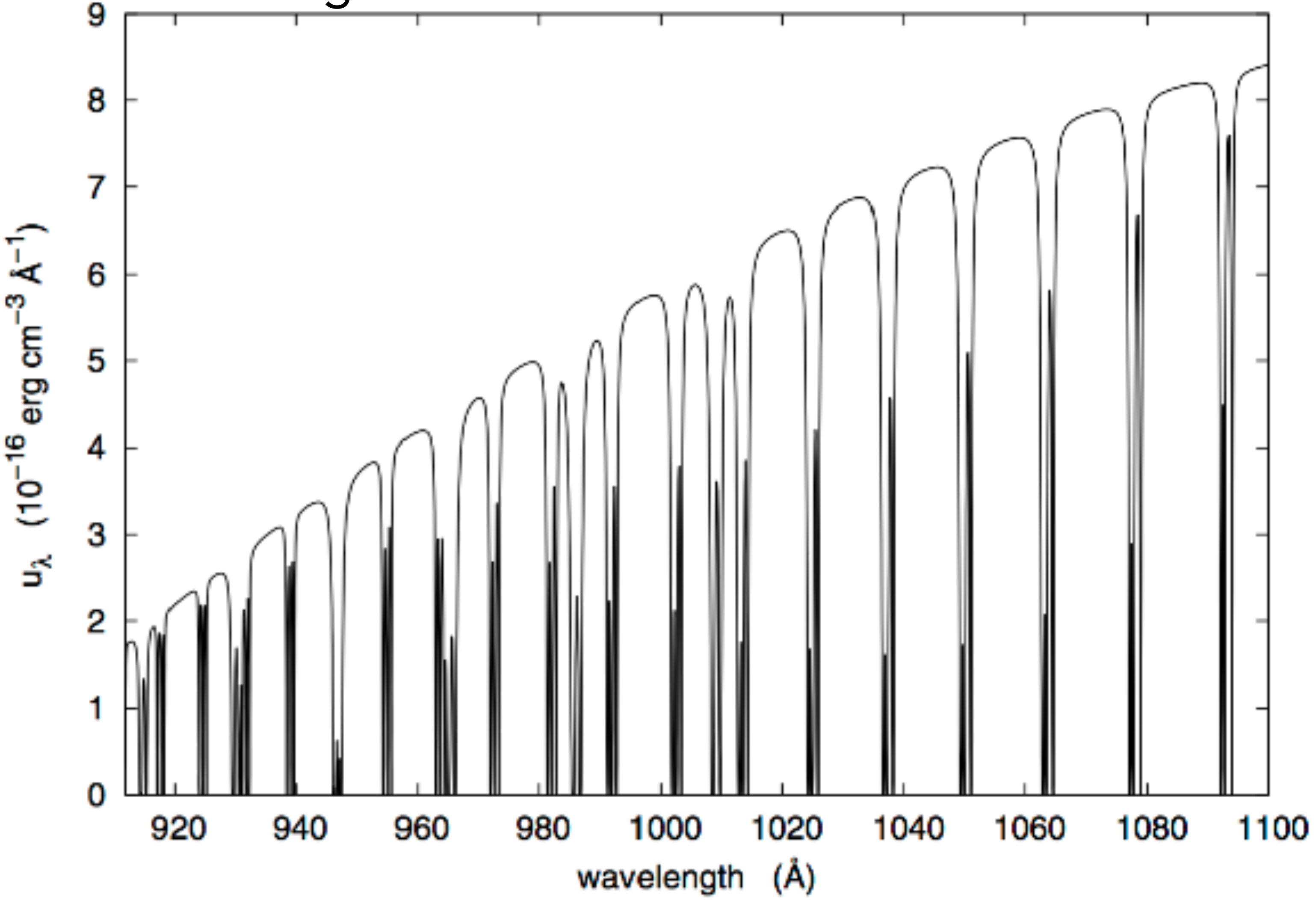
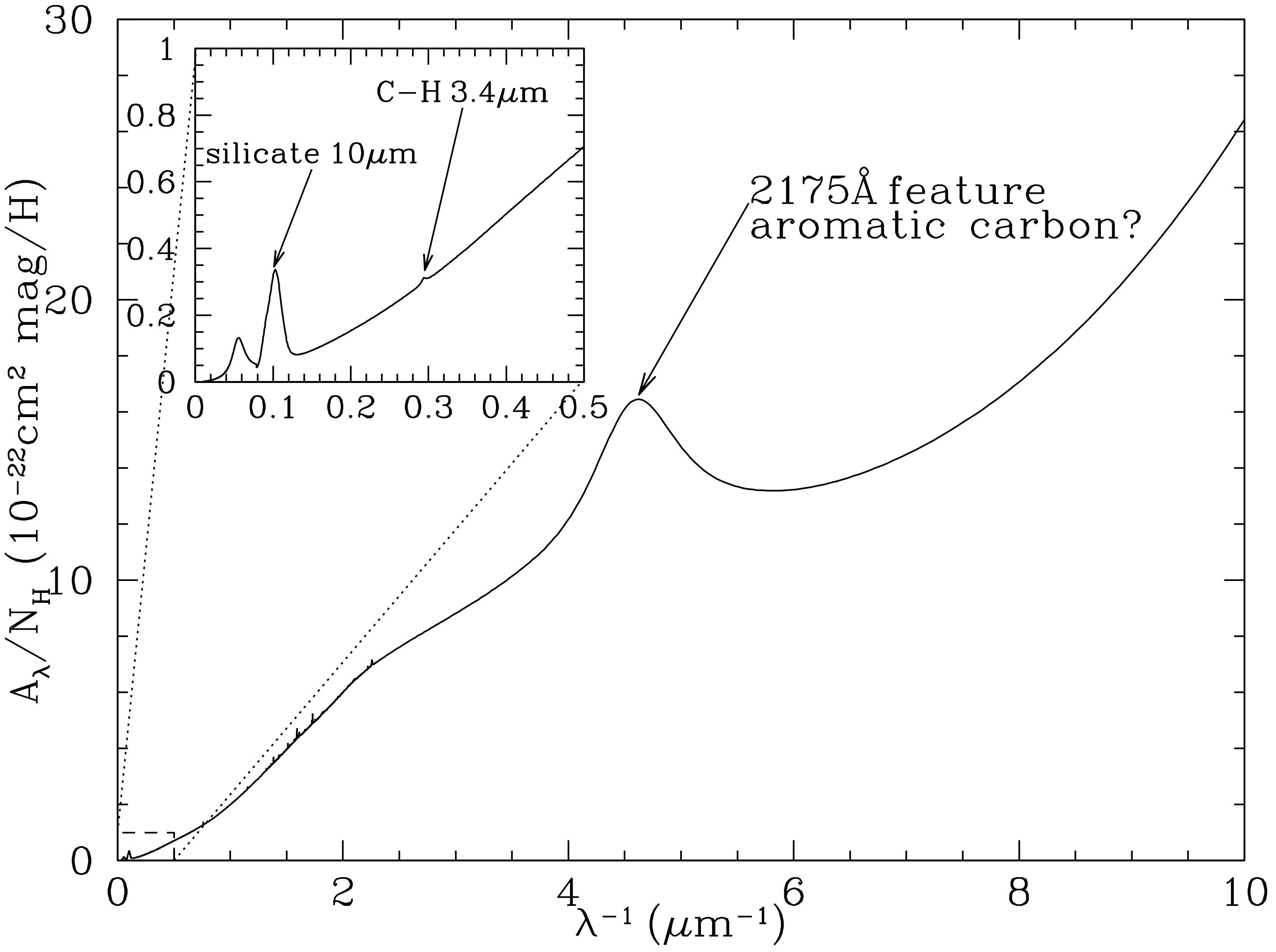


Figure 2. Absorbed far-UV spectrum showing partially overlapping Lyman–Werner band absorption lines, for beamed radiation into a cloud, at a total hydrogen gas column density of 3.74×10^{20} cm^{-2}, for a free-space radiation intensity $I_{\mathrm{UV}} = 35.5$, gas density $n = 10^3$ cm^{-3}, and metallicity $Z' = 1$ $(\alpha G/2 = 1)$.

H_2 Lyman-Werner bands can become optically thick and shield interior H_2 from being dissociated.

H_2 Abundance



At UV wavelengths even small A_V corresponds to substantial amounts of UV extinction.

H_2 Abundance

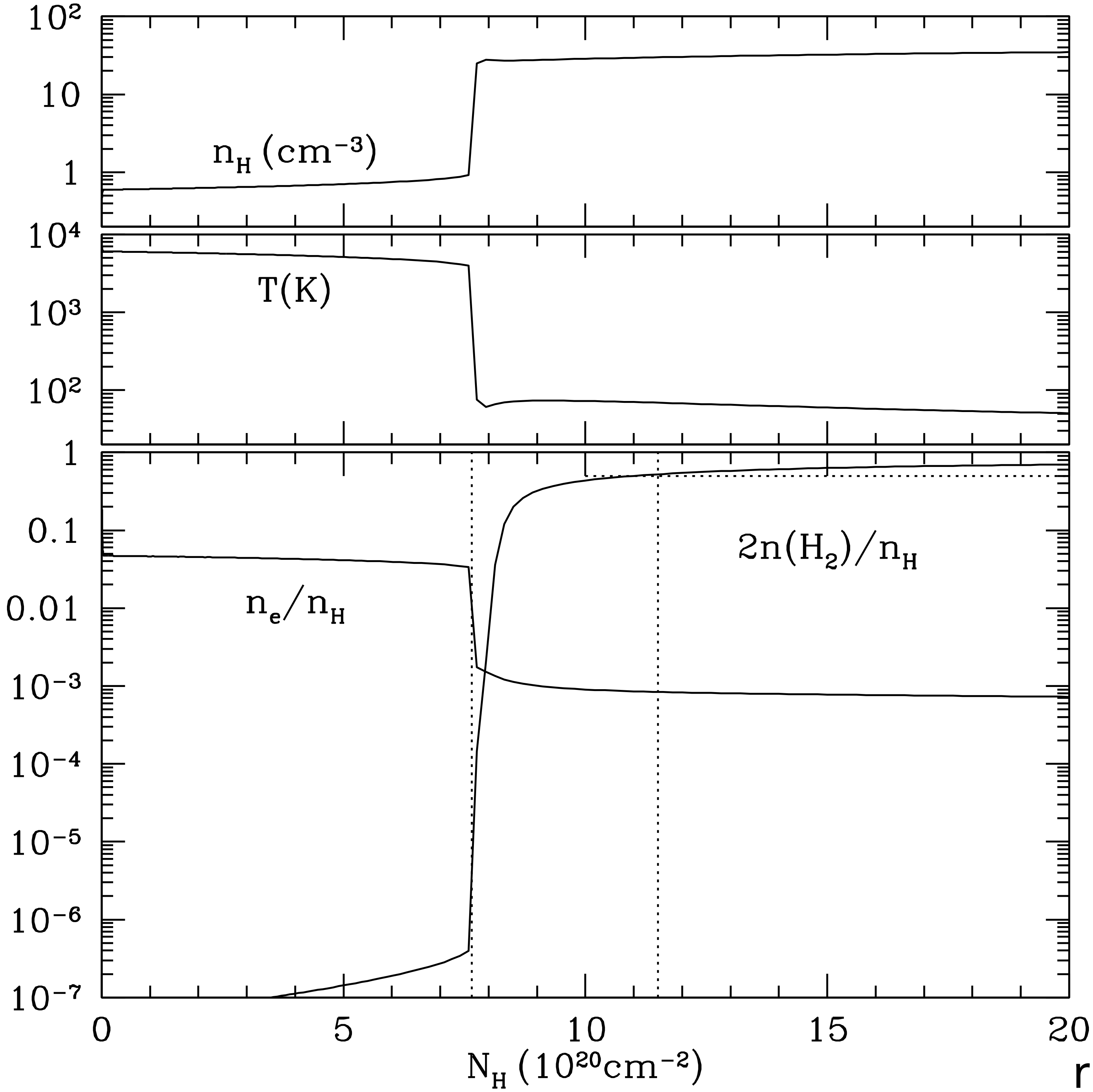
$$\varsigma_{\rm diss} \approx \varsigma_{\rm diss,0}\ f_{\rm shield}\ e^{-\tau_{d,1000}}$$

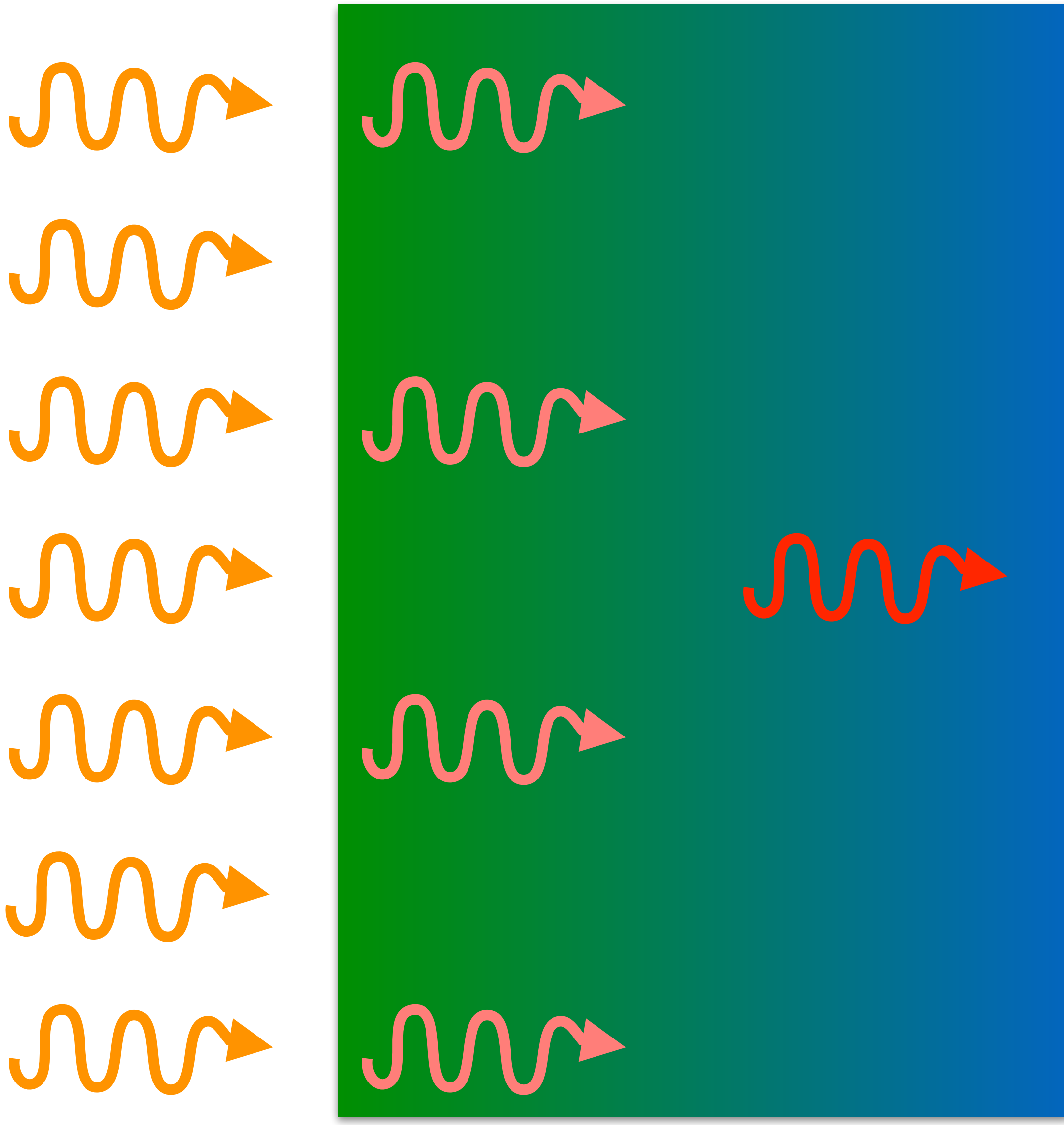
dissociation rate
with no shielding

self-shielding
factor

dust extinction
at 1000 Å

H_2 Abundance



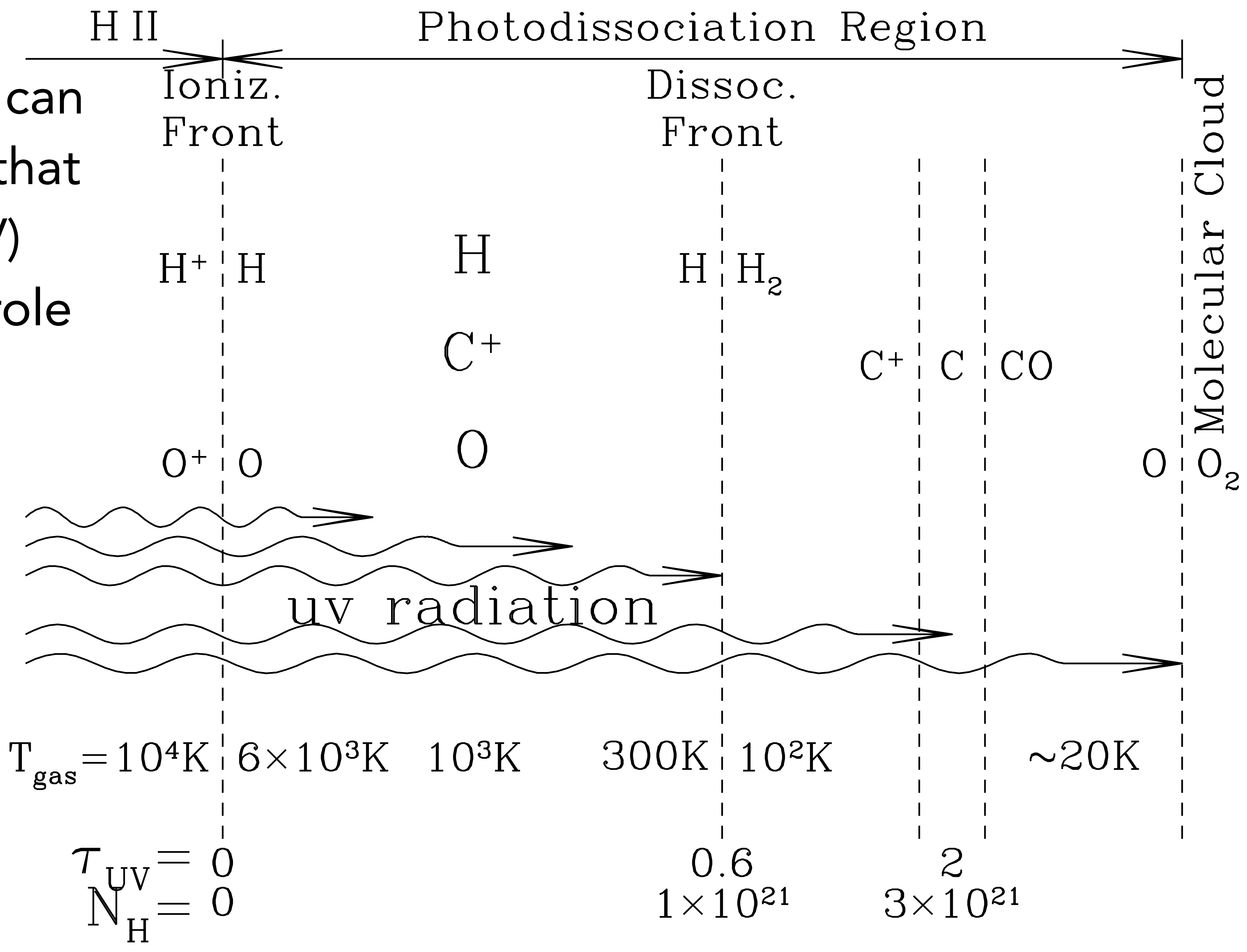


external radiation field

plane-parallel distribution of gas

Photodissociation Regions

Very general term, can refer to anywhere that far-UV (<13.6 eV) photons play key role in chemistry, ionization, etc.



Photodissociation Regions

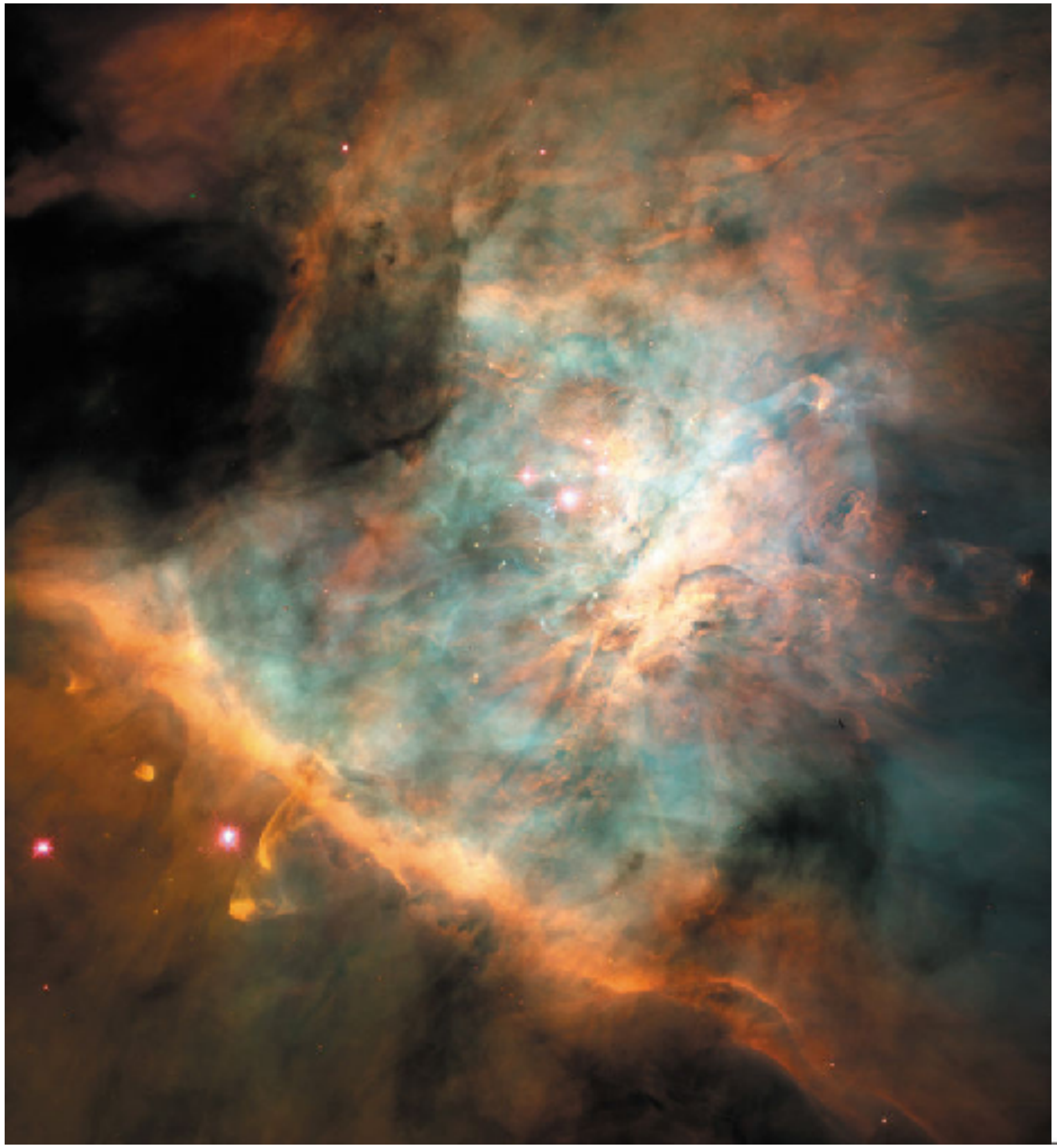


Image: NASA/C. R. O'Dell & S. K. Wong (Rice Univ.)

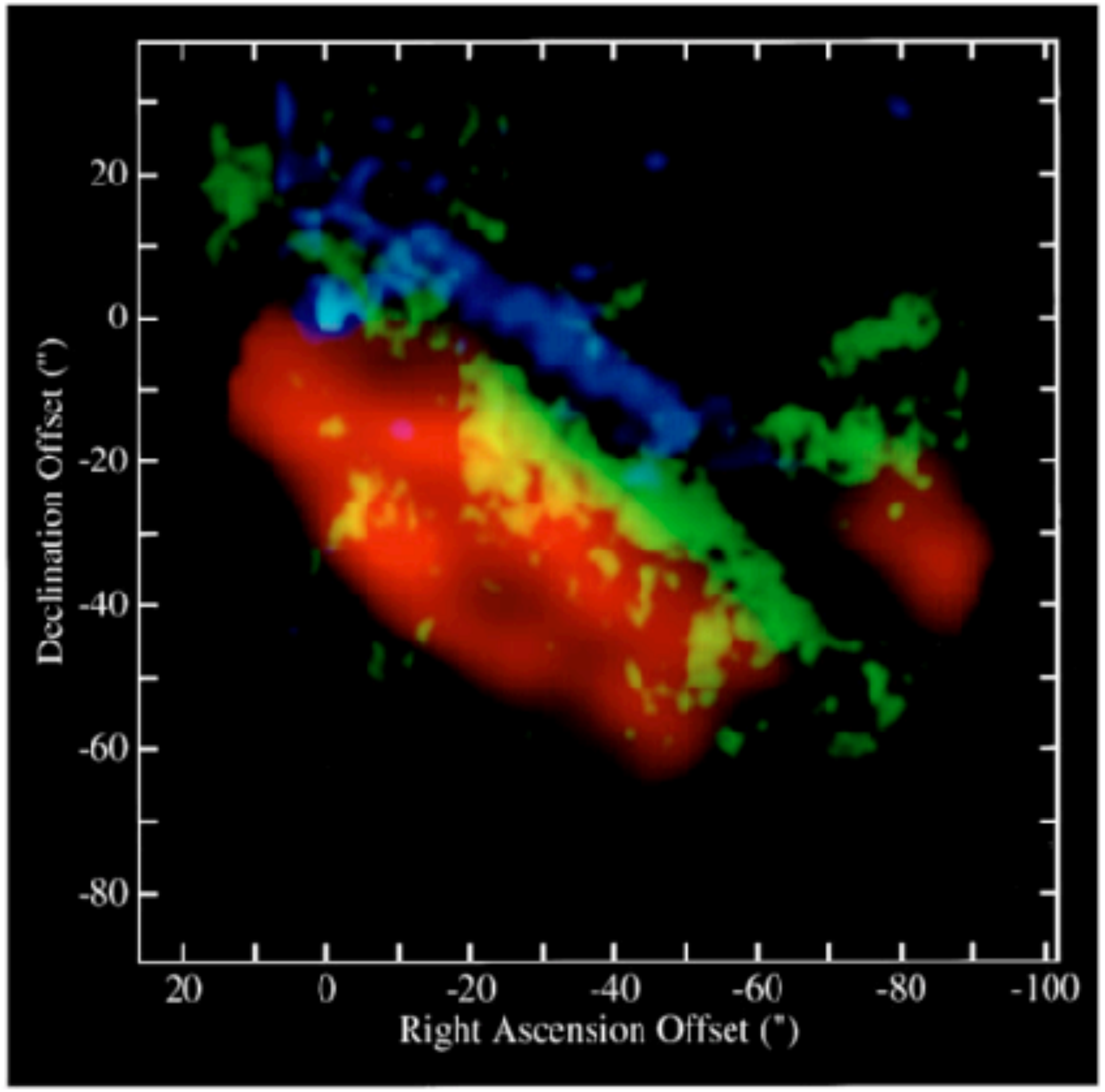
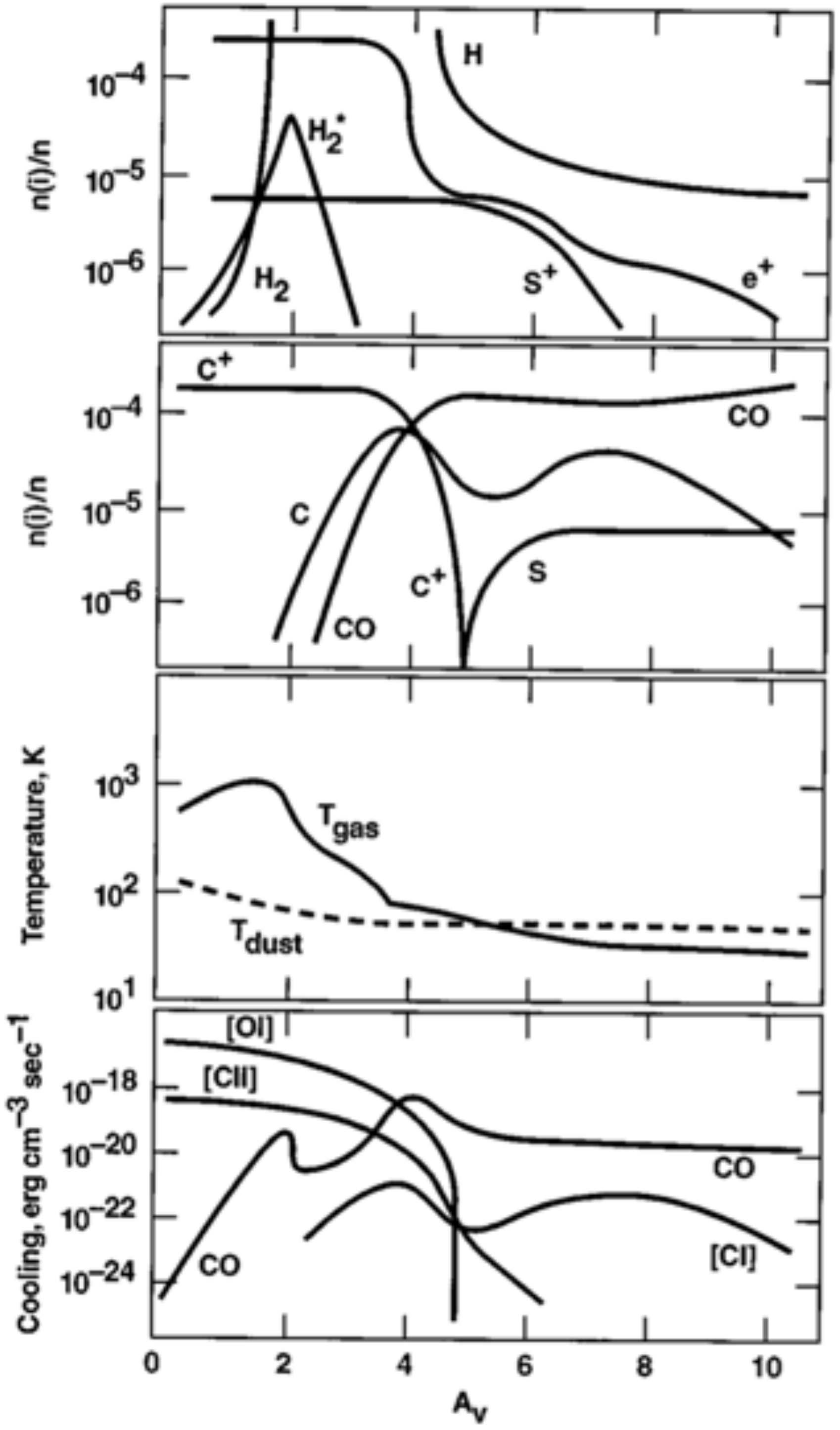
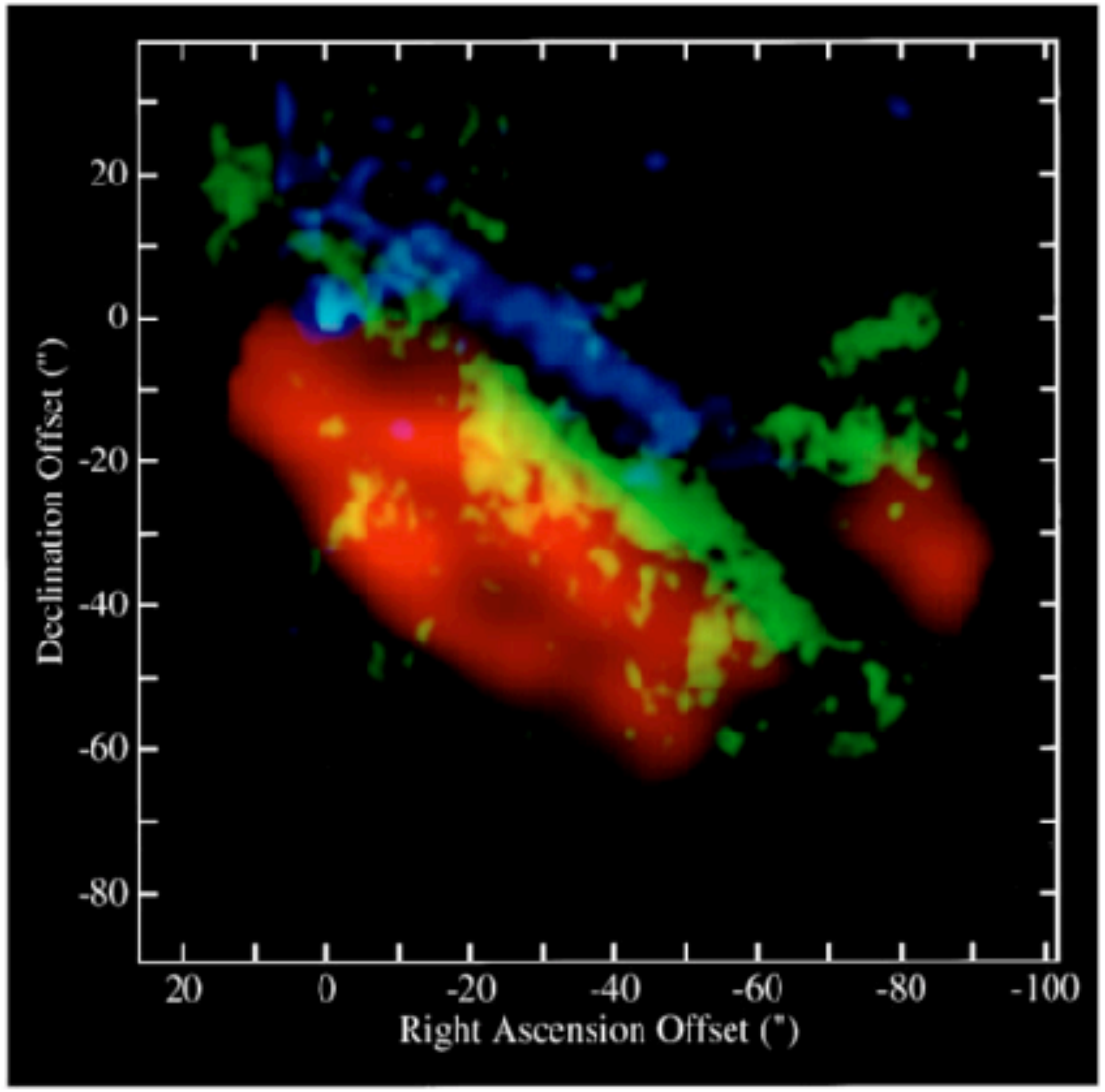


FIG. 2. (Color) The Orion Bar region mapped in the 3.3-μm PAH feature (blue), H_2 1-0 S(1) emission (yellow), and CO $J=1-0$ emission (red; Tielens *et al.*, 1993). The (0,0) position corresponds to the (unrelated) star θ^2 A Ori. The illuminating source, θ^1 C Ori, and the ionized gas are located to the northwest (upper right). For all three tracers, the emission is concentrated in a bar parallel to but displaced to the southeast from the ionization front. The PDR is seen edge on; a separation of ≃ 10" is seen between the PAH emission and the H_2 emission, and between the H_2 emission and the CO emission, as predicted by PDR models (see text).

Hollenbach & Tielens 1999 Review

Photodissociation Regions





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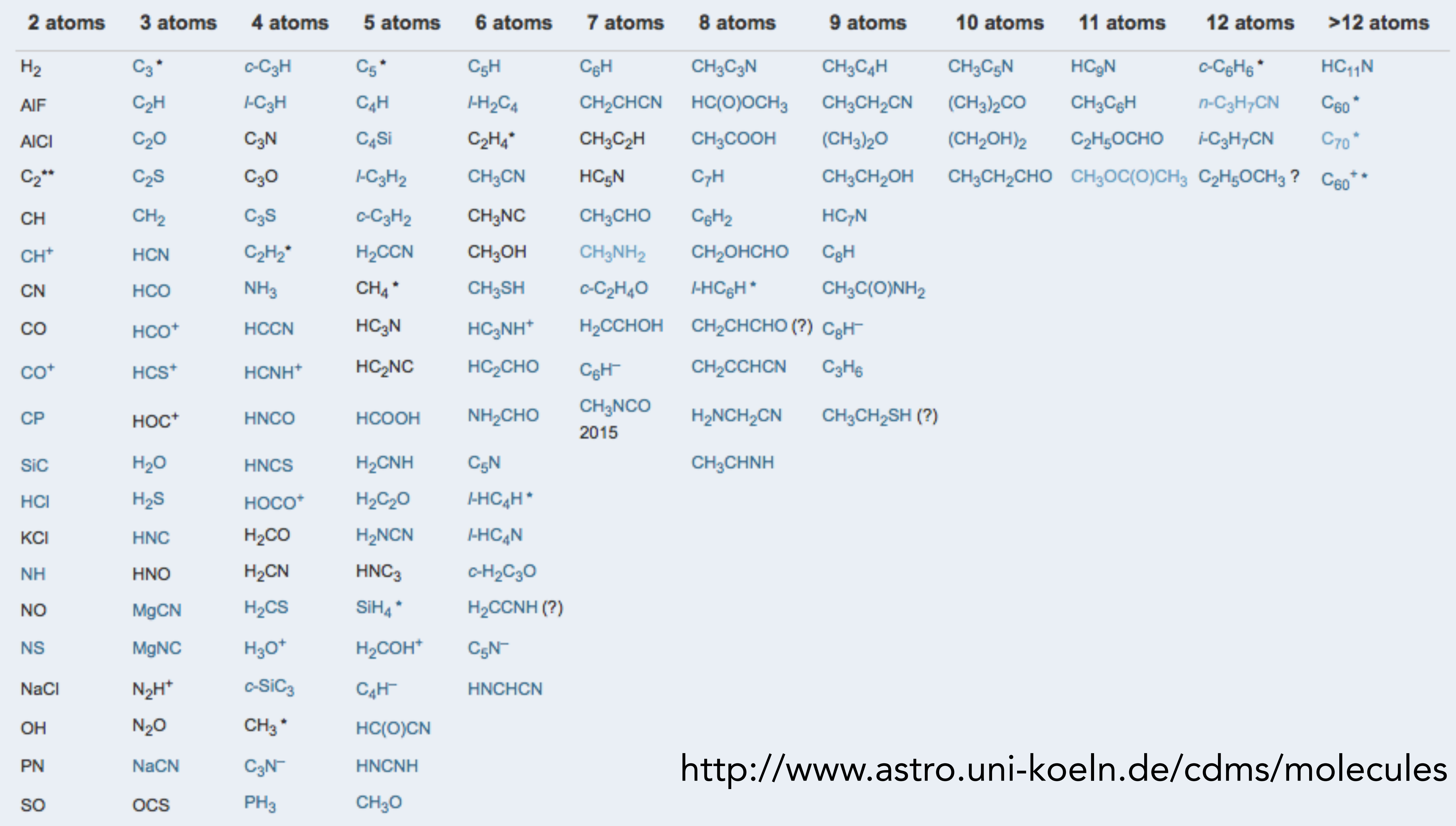
Hollenbach & Tielens 1999 Review

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	$C_3{}^{*}$	$c\text{-}C_3H$	$C_5{}^{*}$	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	$c\text{-}C_6H_6{}^{*}$	$HC_{11}N$
AlF	C_2H	$l\text{-}C_3H$	C_4H	$l\text{-}H_2C_4$	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$n\text{-}C_3H_7CN$	$C_{60}{}^{*}$
AlCl	C_2O	C_3N	C_4Si	$C_2H_4{}^{*}$	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	$i\text{-}C_3H_7CN$	$C_{70}{}^{*}$
$C_2{}^{**}$	C_2S	C_3O	$l\text{-}C_3H_2$	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	$c\text{-}C_3H_2$	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	$c\text{-}C_2H_4O$	$l\text{-}HC_6H{}^{*}$	$CH_3C(O)NH_2$				
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	$l\text{-}HC_4H{}^{*}$							
KCl	HNC	H_2CO	H_2NCN	$l\text{-}HC_4N$							
NH	HNO	H_2CN	HNC_3	$c\text{-}H_2C_3O$							
NO	MgCN	H_2CS	$SiH_4{}^{*}$	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	$c\text{-}SiC_3$	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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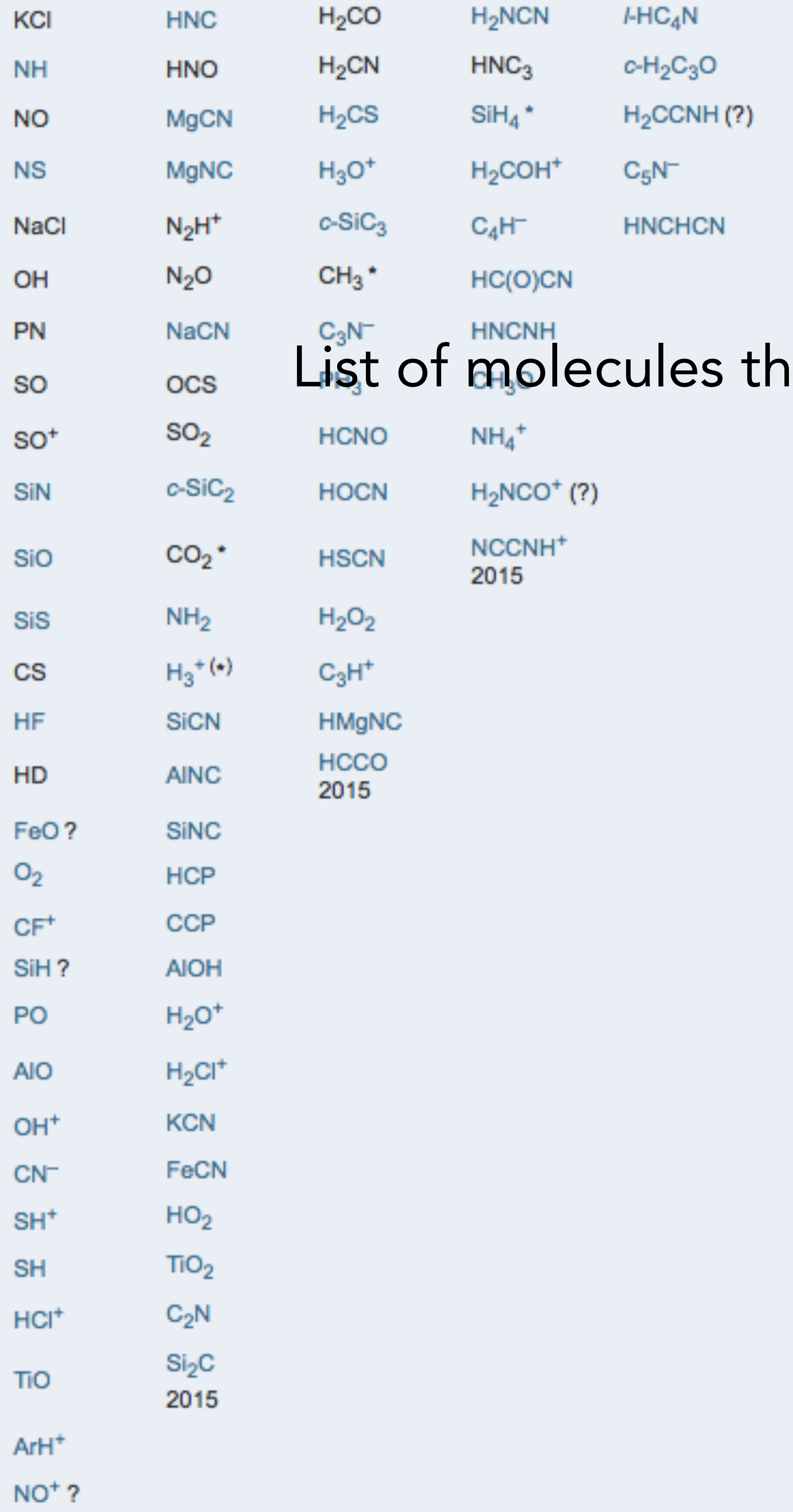

KCl
NH
NO
NS
NaCl
OH
PN
SO
SO^+
SiN
SiO
SiS
CS
HF
HD
FeO ?
O_2
CF^+
SiH ?
PO
AlO
OH^+
CN^-
SH^+
SH
HCl^+
TiO
ArH^+
NO^+ ?

HNC
HNO
MgCN
MgNC
N_2H^+
N_2O
NaCN
OCS
SO_2
c-SiC_2
CO_2 *
NH_2
H_3^+ (*)
SiCN
AlNC
SiNC
HCP
CCP
AlOH
H_2O^+
H_2Cl^+
KCN
FeCN
HO_2
TiO_2
C_2N
Si_2C
2015

H_2CO
H_2CN
H_2CS
H_3O^+
c-SiC_3
CH_3 *
C_3N^-
PH_3
HCNO
HOCN
HSCN
H_2O_2
C_3H^+
HMgNC
HCCO
2015

H_2NCN
HNC_3
SiH_4 *
H_2COH^+
C_4H^-
HC(O)CN
HNCNH
CH_3O
NH_4^+
H_2NCO^+ (?)
$NCCNH^+$
2015

l-HC_4N
c-H_2C_3O
H_2CCNH (?)
C_5N^-
HNCHCN

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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

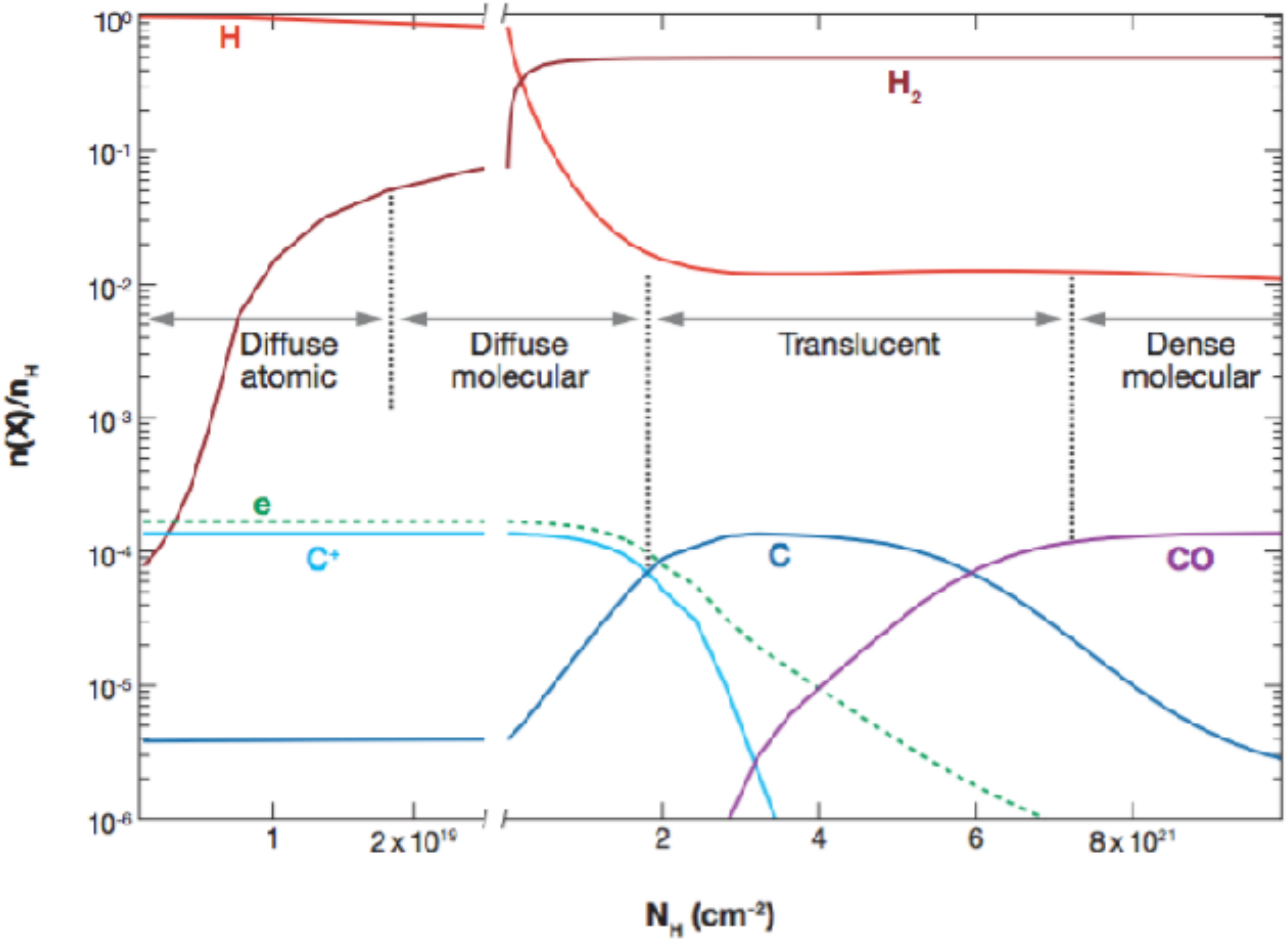


Figure 1

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.

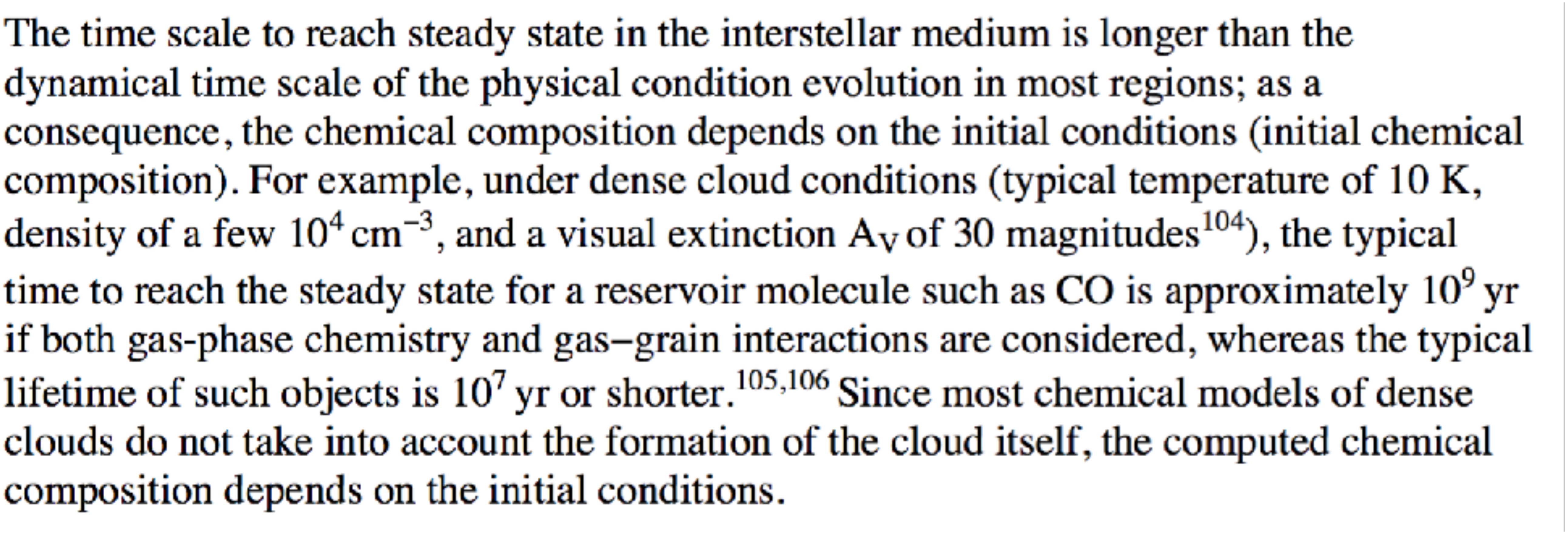
Chemistry happens in diffuse phases,

(& 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”.

Chemistry in Molecular Gas

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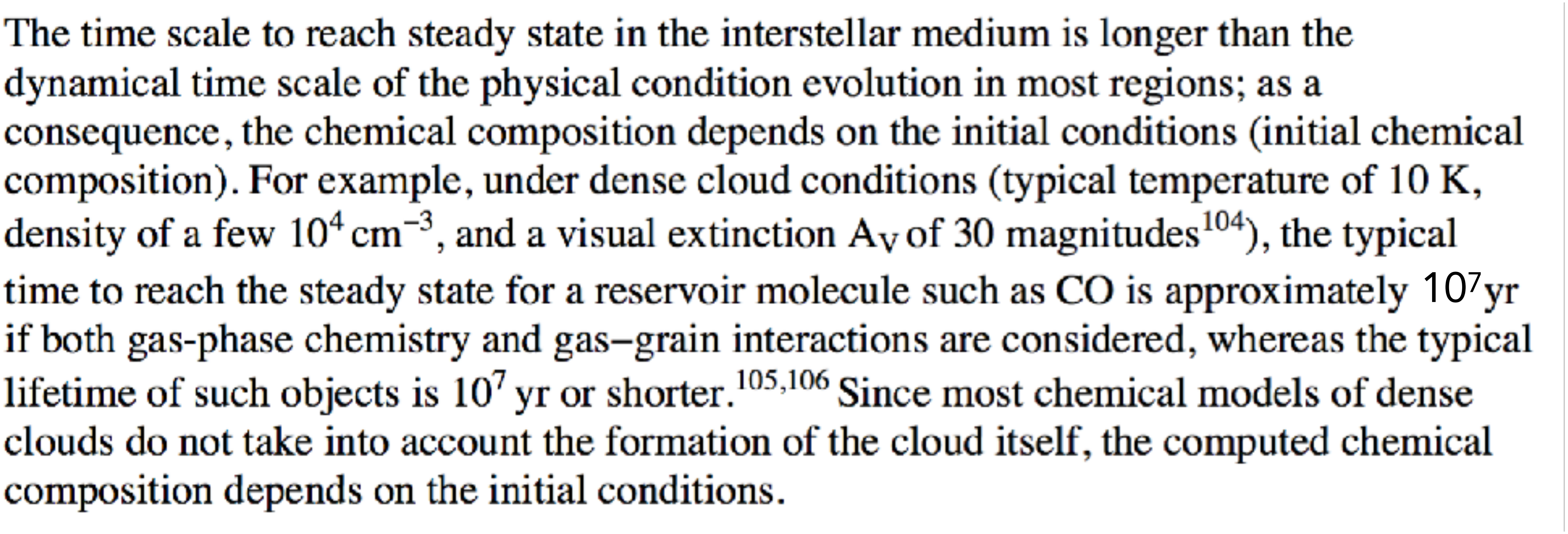

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Chemistry in Molecular Gas

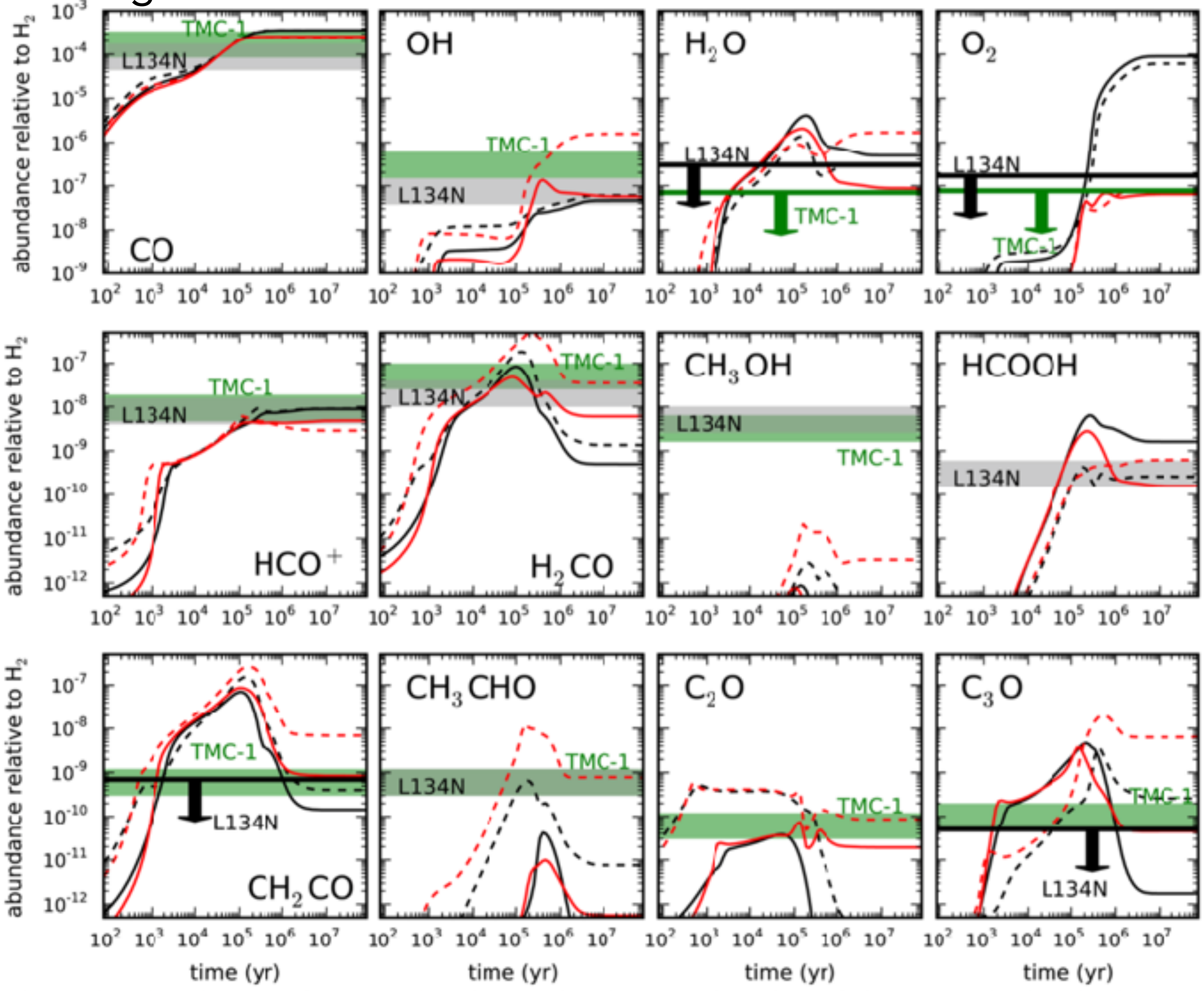
Evidence of non-equlibrium chemistry:

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

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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	$\sim 10^{-10}$ 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

cosmic ray
ionization

H^+

H_3^+

Chemistry in Molecular Gas

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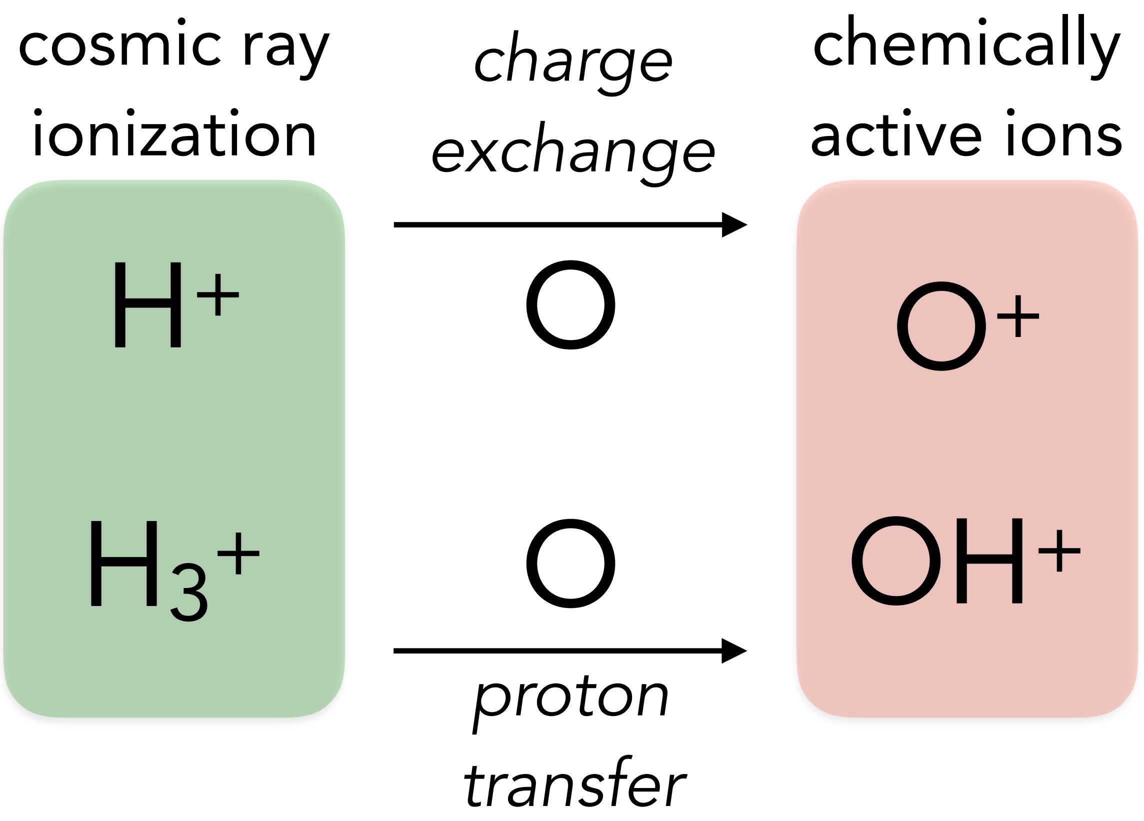

cosmic ray ionization

charge exchange

chemically active ions

$H^+ \xrightarrow{O} O^+$

$H_3^+ \xrightarrow{O} OH^+$

proton transfer

Chemistry in Molecular Gas

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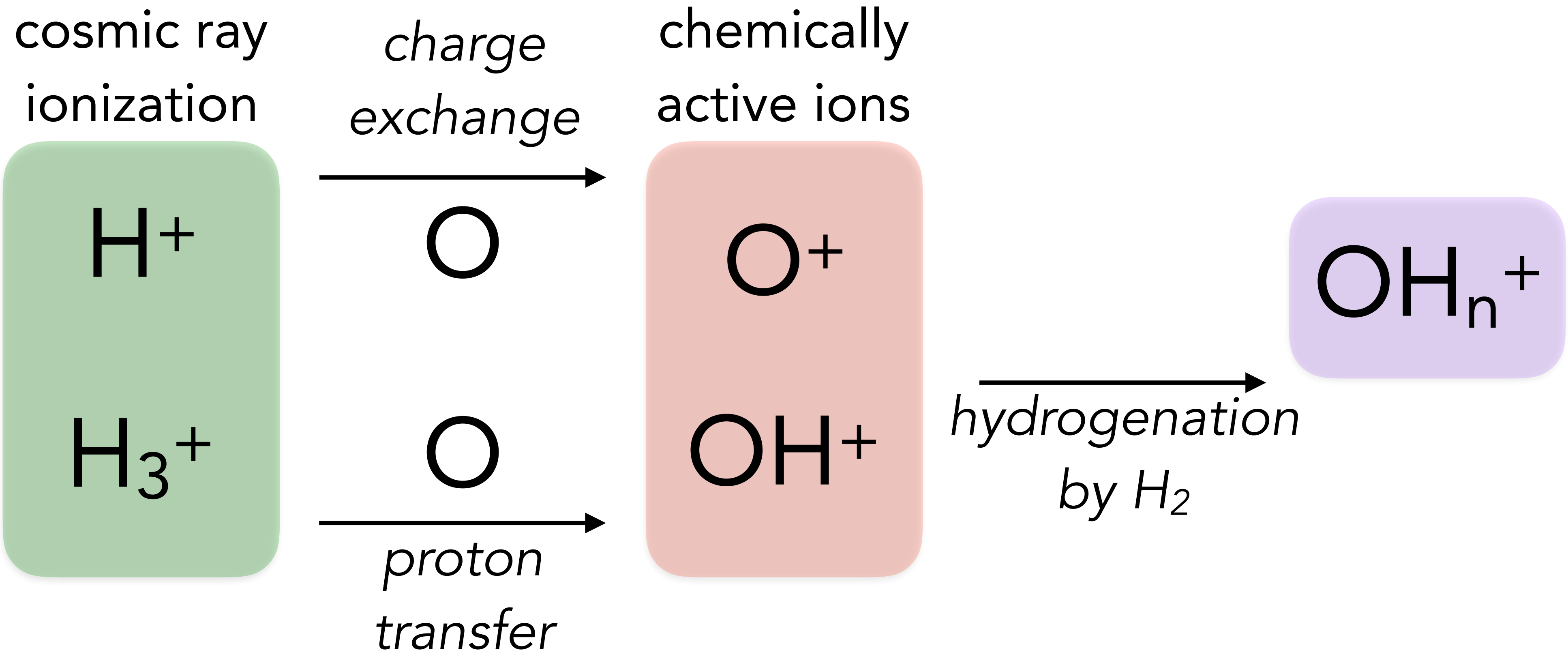

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O^+

OH^+

hydrogenation by H_2

OH_n^+

Chemistry in Molecular Gas

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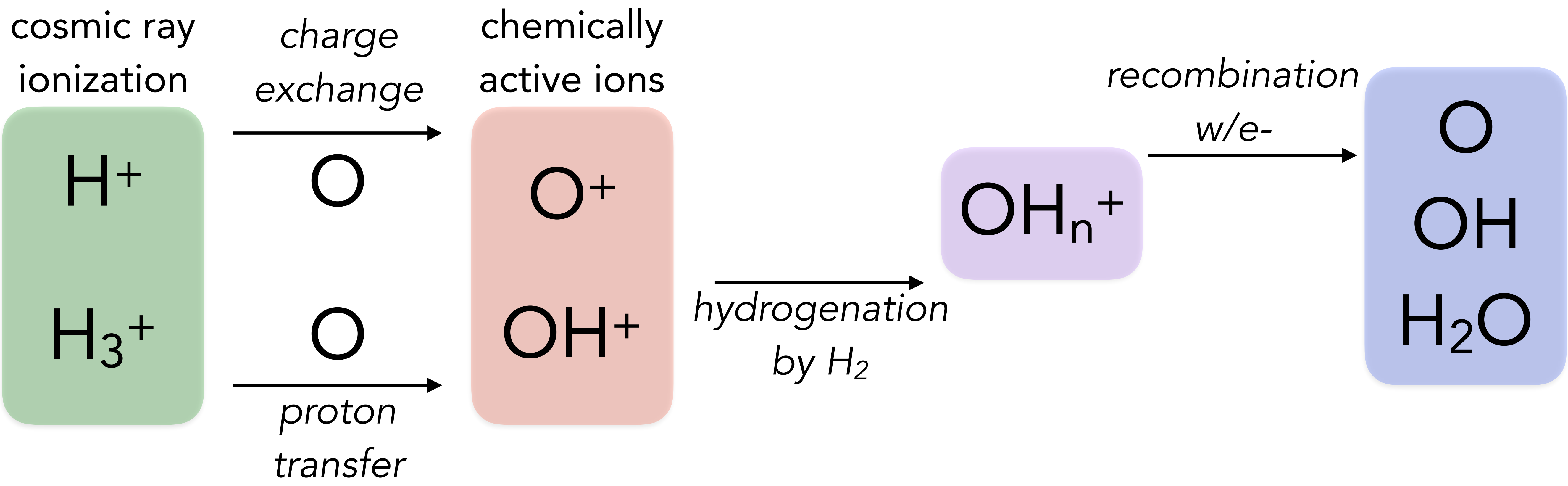

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proton transfer

chemically active ions

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hydrogenation by H_2

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recombination w/e-

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H_2O

Chemistry in Molecular Gas

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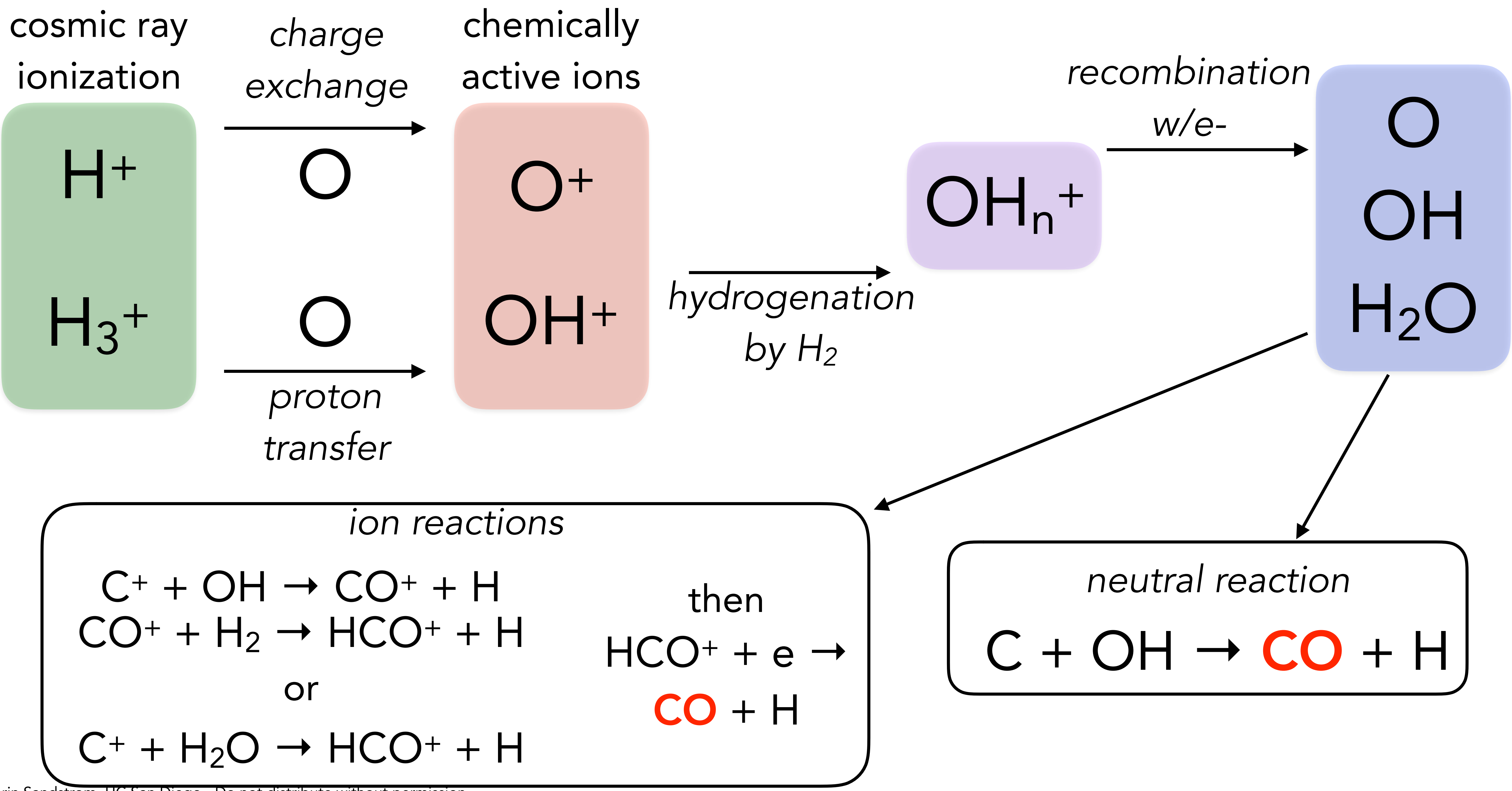

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ion reactions

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

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

or

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

then

$HCO^+ + e \rightarrow$

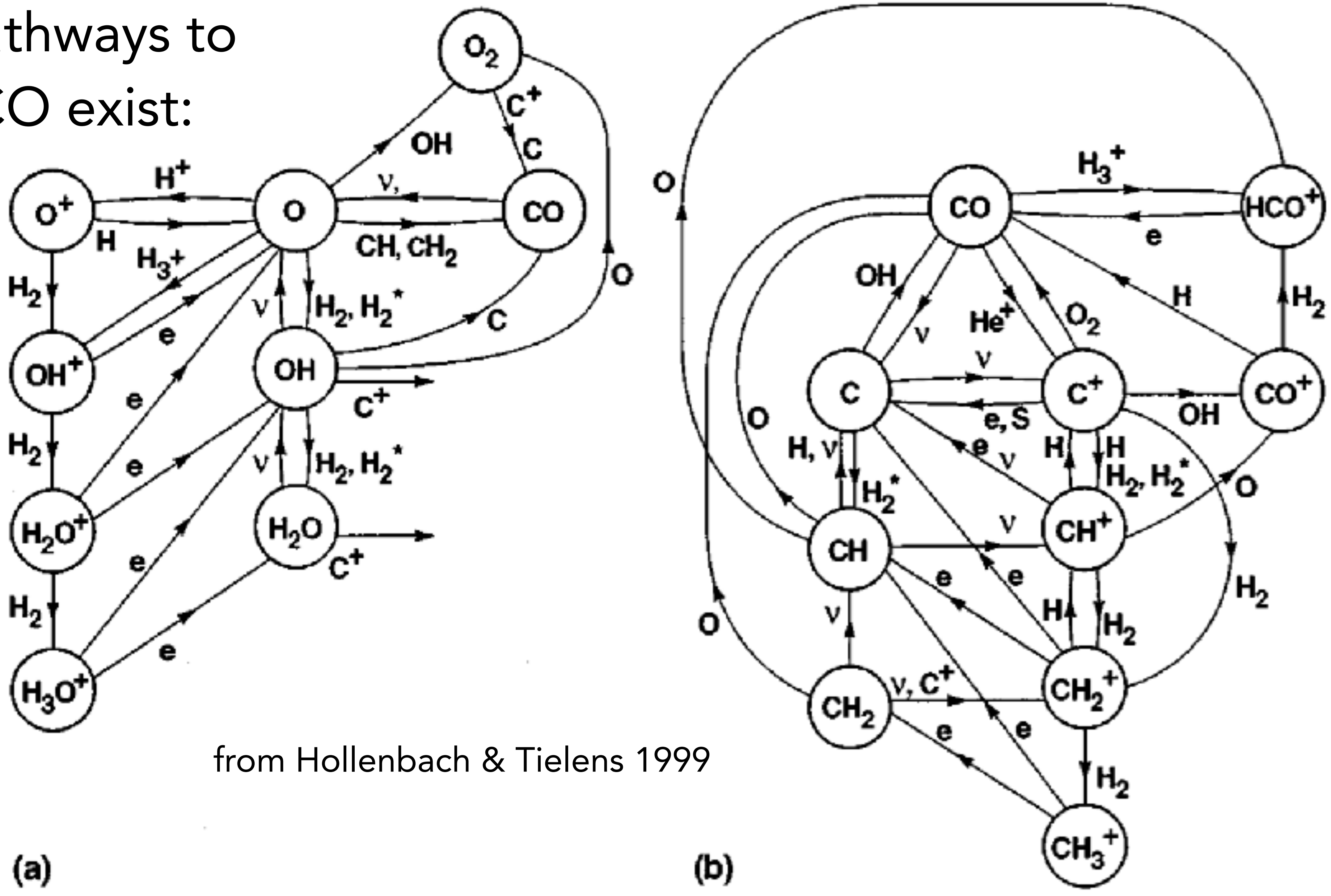
$CO + H$

neutral reaction

$C + OH \rightarrow CO + H$

Chemistry in Molecular Gas

Many pathways to form CO exist:

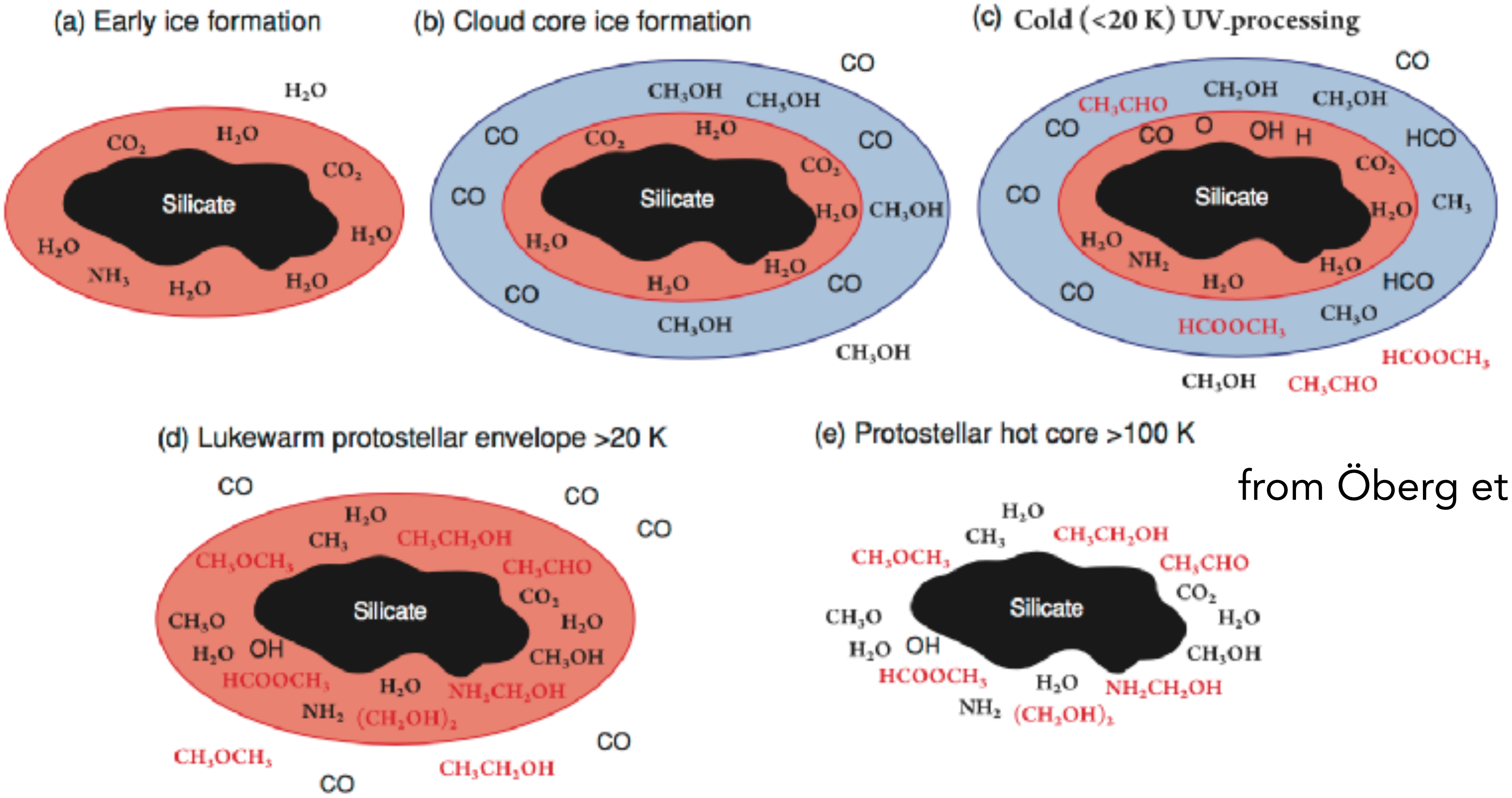


from Hollenbach & Tielens 1999

Chemistry in Molecular Gas

In dense parts of clouds

CO can “freeze out” to form ice on grains.

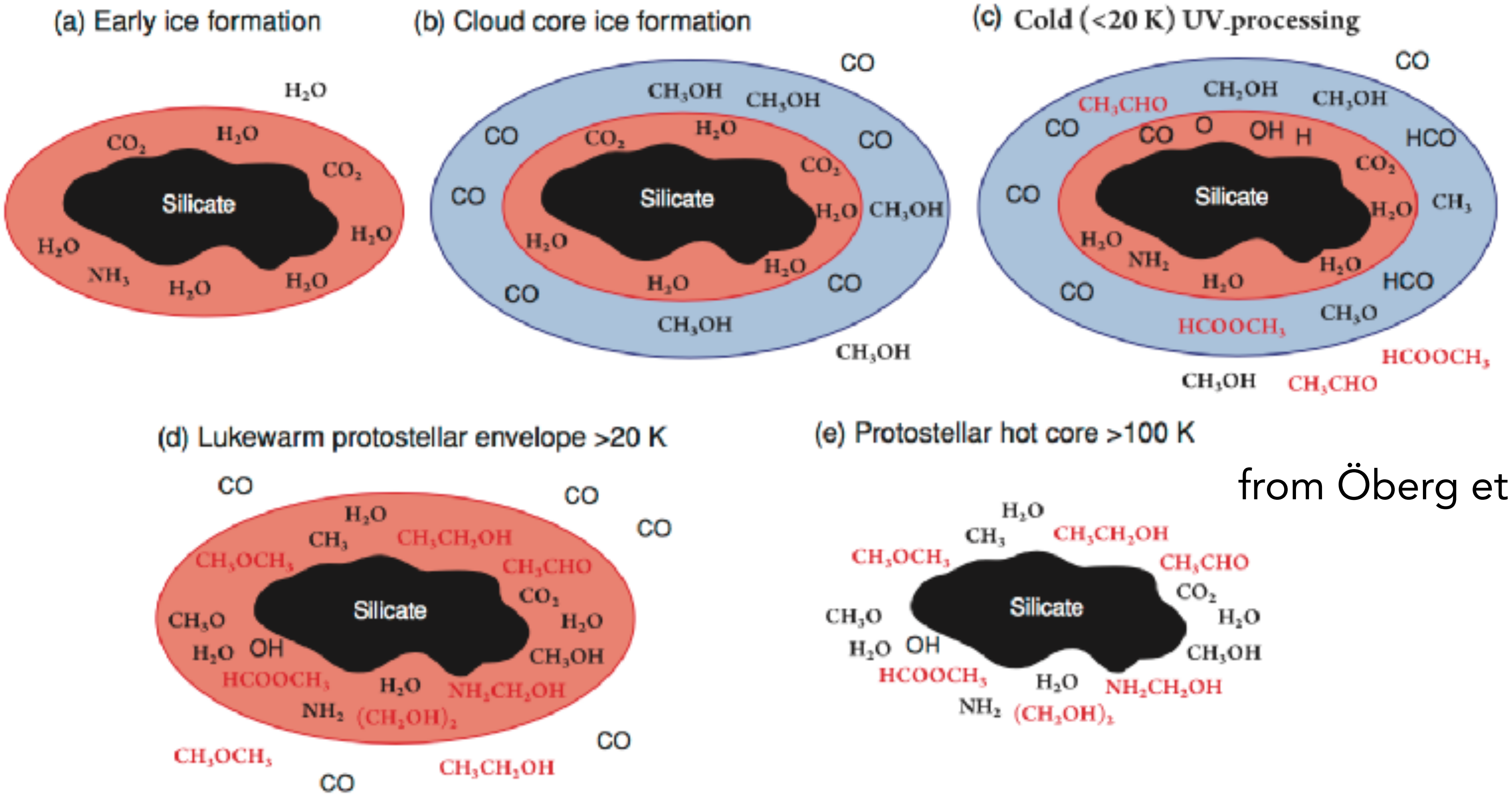


from Öberg et al. 2010

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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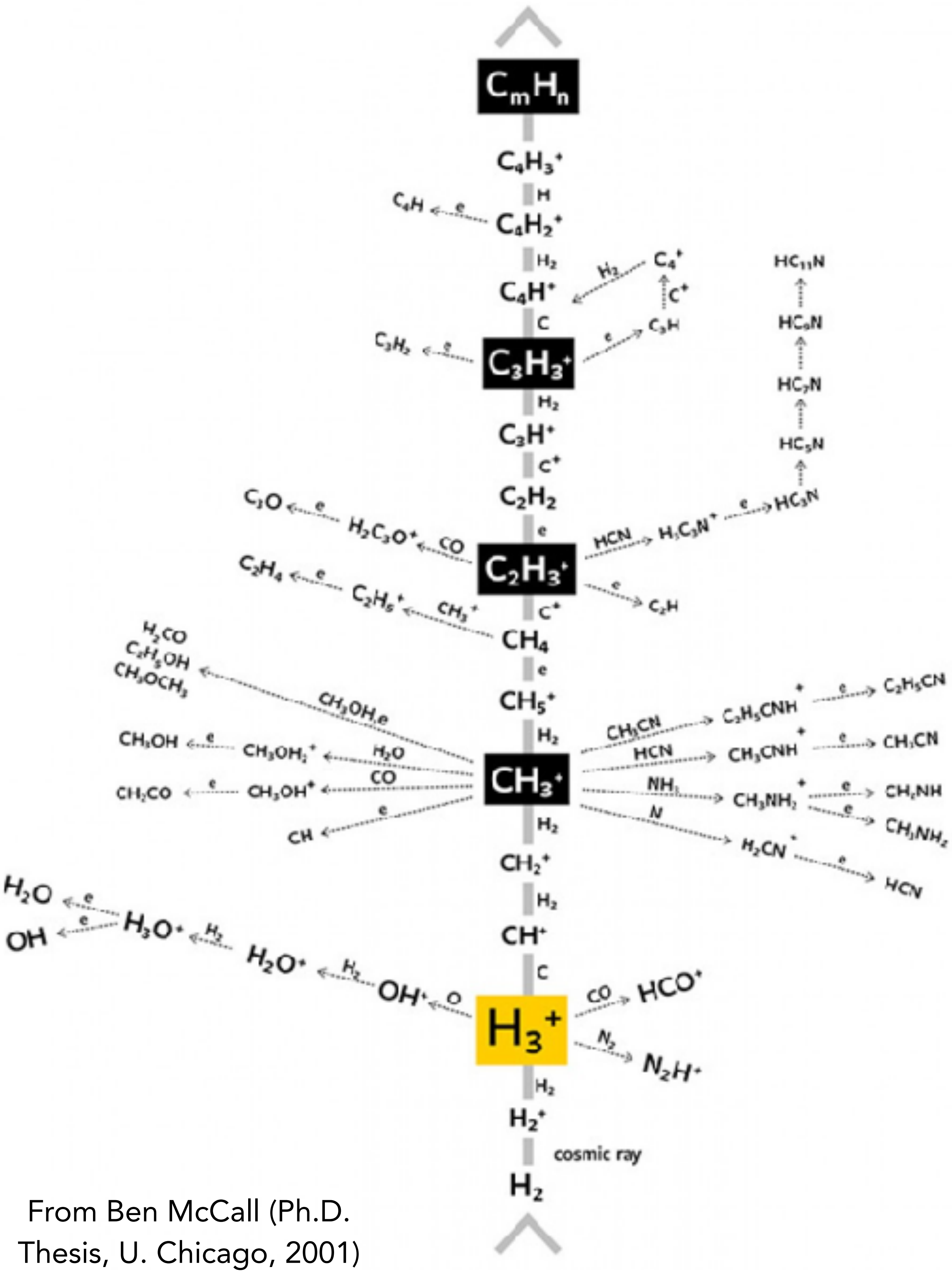

From Ben McCall (Ph.D. Thesis, U. Chicago, 2001)

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