Master course: Astrochemistry I:

Lecture 4: Chemistry in quiescent clouds

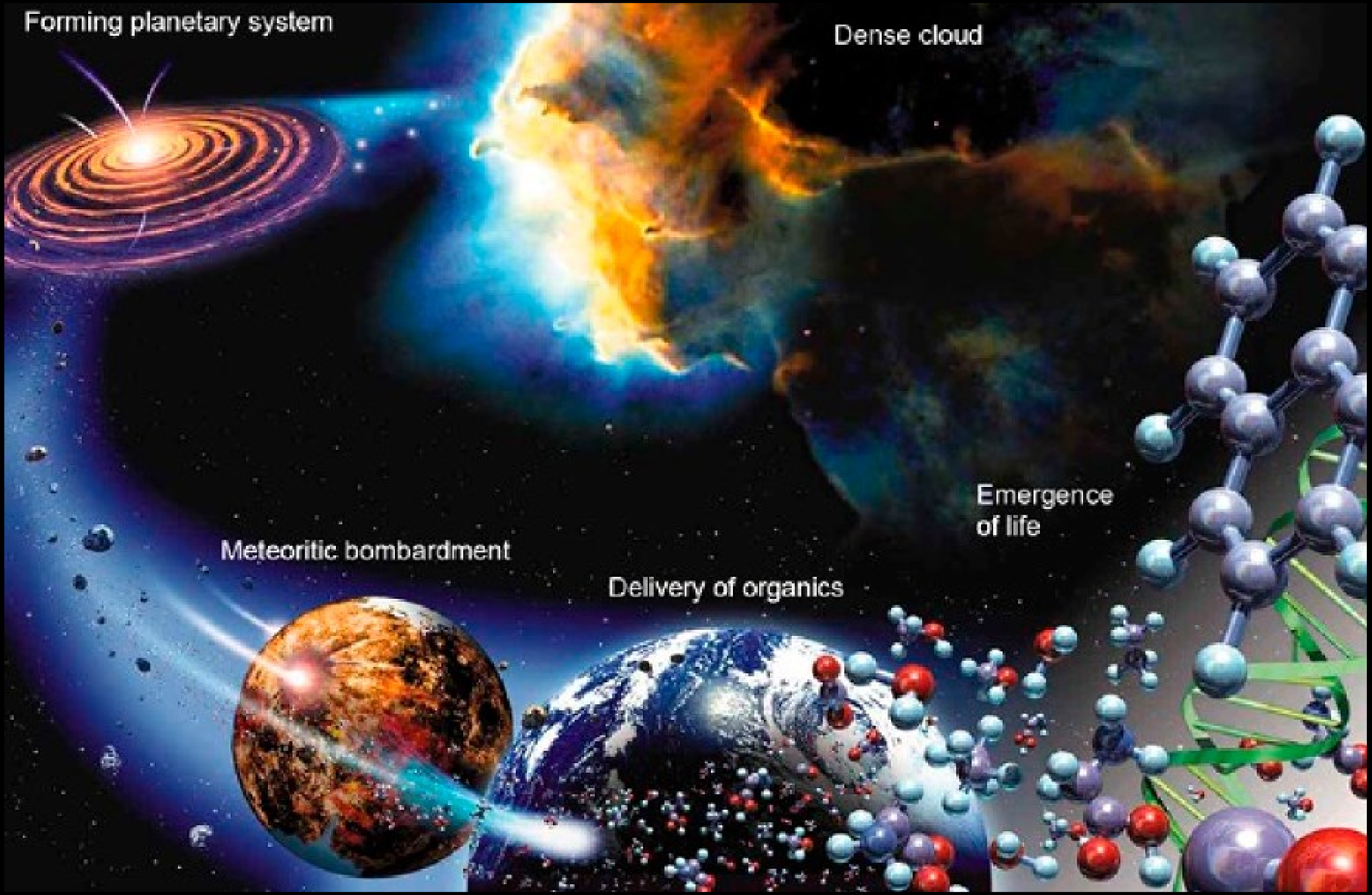
Reading list:

van Dishoeck (1998)
In MA II

Snow & McCall
(2006)

Gerin et al. (2016)
ARA&A

Tielens Chap. 9



Dr. Helgi Rafn Hrodmarsson – UPEC – 2026-2027

Outline

A. Diffuse and translucent clouds

- Introduction
- Physical structure
- Gas-phase chemistry networks
- Steady-state models: $H \rightarrow H_2$, $C^+ \rightarrow CO$

B. Photon-dominated regions (PDRs)

- Introduction
- Chemical structure

A. Diffuse and translucent clouds

4.1 Introduction

- Diffuse clouds with $A_V \approx 1$ mag are the best testing ground for basic interstellar chemistry because
  - ~~Only~~ **Mostly** ‘simplest’ diatomic molecules found
  - Gas-phase elemental abundances directly measured
  - H and H_2 directly measured
  - UV penetrates => short timescales => chemical equilibrium
  - No embedded / hidden energy sources
- Models first considered by Kramers & ter Haar (1946) and Bates / Spitzer (1951). Subsequent models include ion-molecule network developed by Herbst & Klemperer (1973)

Questions

- To what extent can ion-molecule gas-phase chemistry reproduce observed abundances?
- What is the role of shocks and turbulence?
- What is the role of grains in the formation of molecules other than H_2?
- What is the relation between diffuse and dense clouds?
- => study also ***translucent**** clouds with A_V = 1-5 mag

* Term coined by van Dishoeck & Black (1989)

Observations diffuse clouds

VIS + UV absorption lines

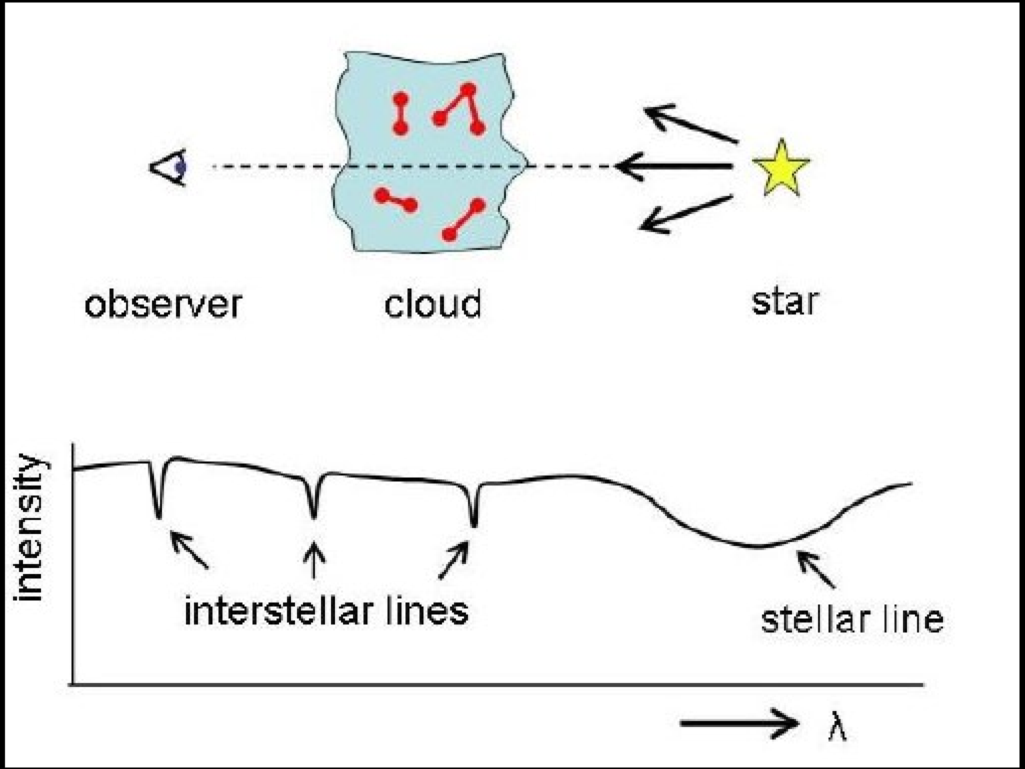
- Many atomic lines => depletion of elements C, O, N, …
- Chemistry sensitive to C/O ratio
- Few molecular lines detected
  - H_2, HD
  - CH, CH^+, C_2, C_3
  - OH, OH^+, CO
  - NH, CN, HCl
- Not detected at optical wavelengths:
  - H_2O, H_2O^+, C_4, …
  - MgH, NaH, SH^+

Millimeter/far-IR absorption and emission lines

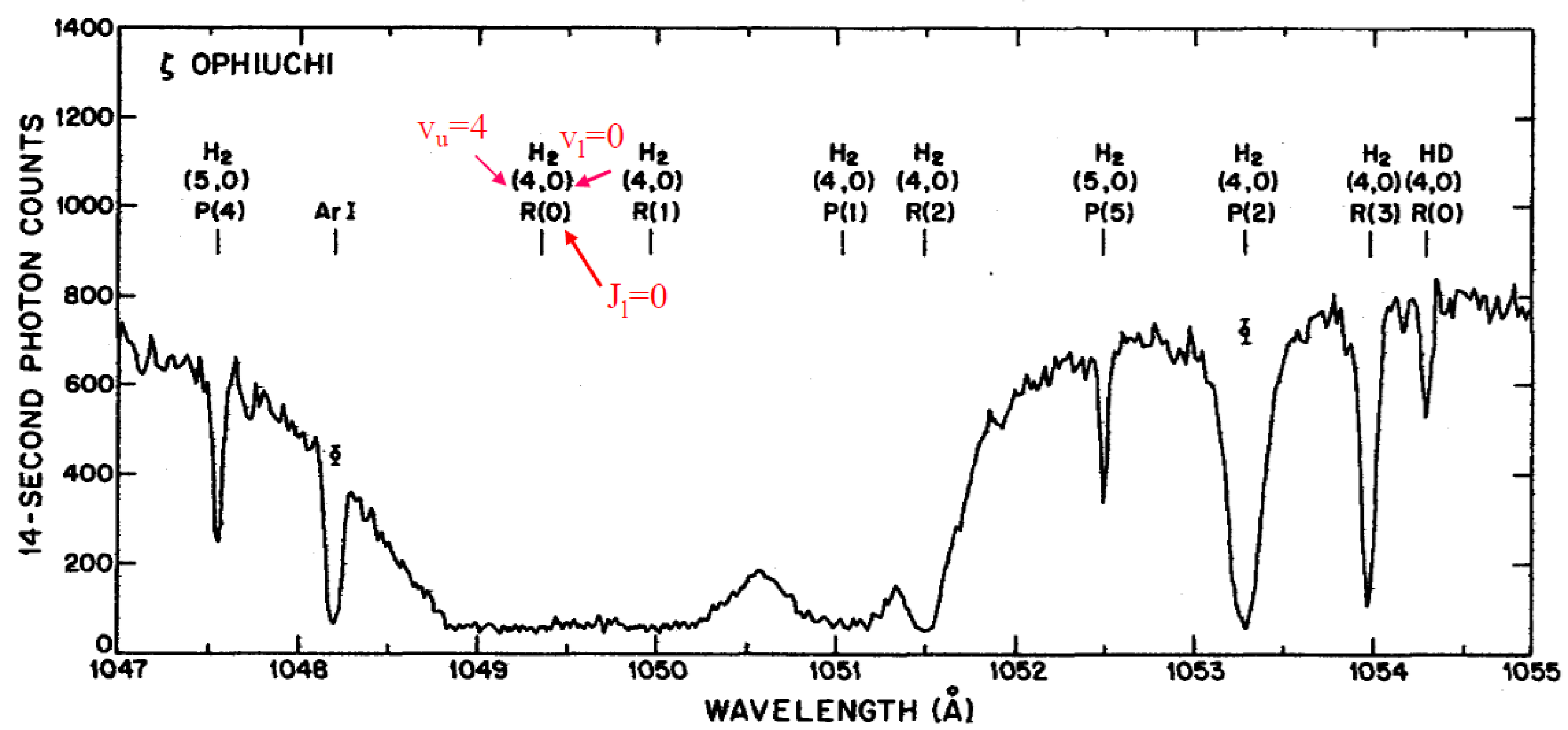
- Weak emission, many absorption lines

Observations of diffuse clouds

- Observed primarily by absorption lines at visible (since 1900‘s) and UV wavelengths (since 1970‘s: *Copernicus, FUSE*)
- Classical example: line-of-sight toward ζ Oph
- Spectra show sharp interstellar lines super-imposed on broad stellar lines



Interstellar H_2 lines toward ζ Ophiuchi



Federman et al. 1995 Copernicus satellite

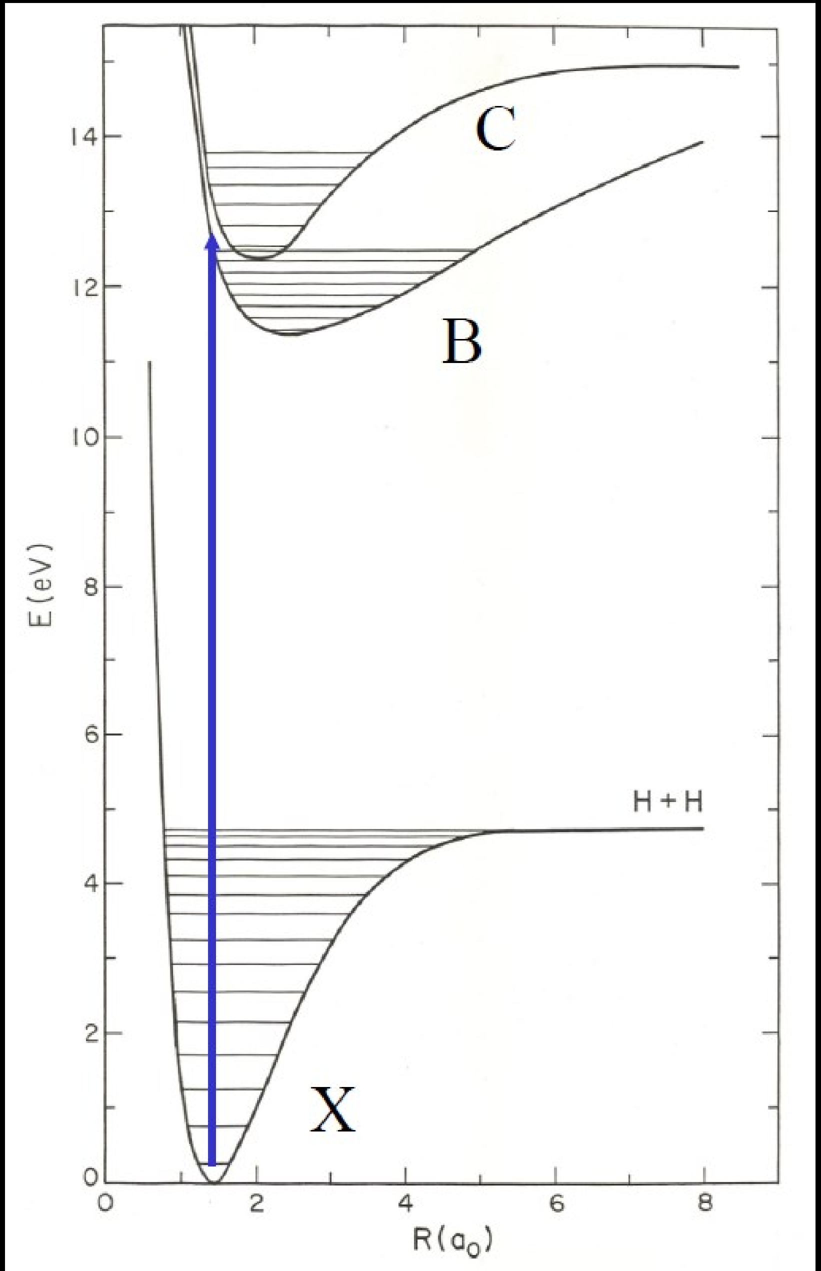
$\Delta J = J_u - J_l = +1$: R-branch

$\Delta J = J_u - J_l = -1$: P-branch

R(0): $J_u = 1 - J_l = 0$

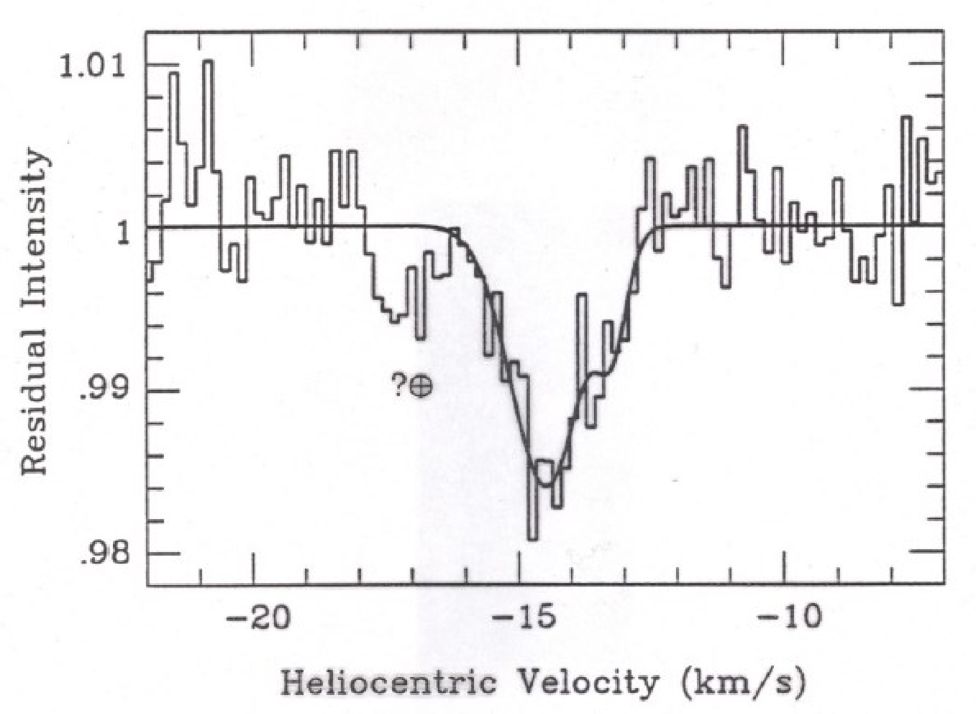
H_2 absorption

B-X: Lyman system
C-X: Werner system



$\Delta J = J_u - J_l = +1$: R-branch
$\Delta J = J_u - J_l = -1$: P-branch

Example: NH toward ζ Ophiuchi



Crawford & Williams 1997

- Ultra high resolution observations R = 800000
- Two component fit:
  - v = -14.5 km s – 1, *b* = 0.91 ± 0.15 => $T < 750$ K
  - v = -13.2 km s – 1, *b* = 0.33 ± 0.13 => $T < 100$ K
- Upper limits on *T* from line width exclude $N + H_2 \rightarrow NH + H$ reaction

Lines are narrow (except CH^+) → excludes strong shocks!

Typical abundances (ζ Oph, ζ Per)

- CH ≈ 2×10^{13} cm^{-2} => x(CH) = N(CH)/N(H_2) ≈ 4×10^{-8}
- OH ≈ 4×10^{13} cm^{-2} => x(OH) ≈ 8×10^{-8}
- NH ≈ 9×10^{11} cm^{-2} => x(NH) ≈ 2×10^{-9}
- CO ≈ 10^{14}–10^{15} cm^{-2} => x(CO) ≈ 2×10^{-7}–2×10^{-6}
- CH^+ ≈ 10^{12}–10^{13} cm^{-2} => x(CH^+) ≈ 2×10^{-9}–2×10^{-8}

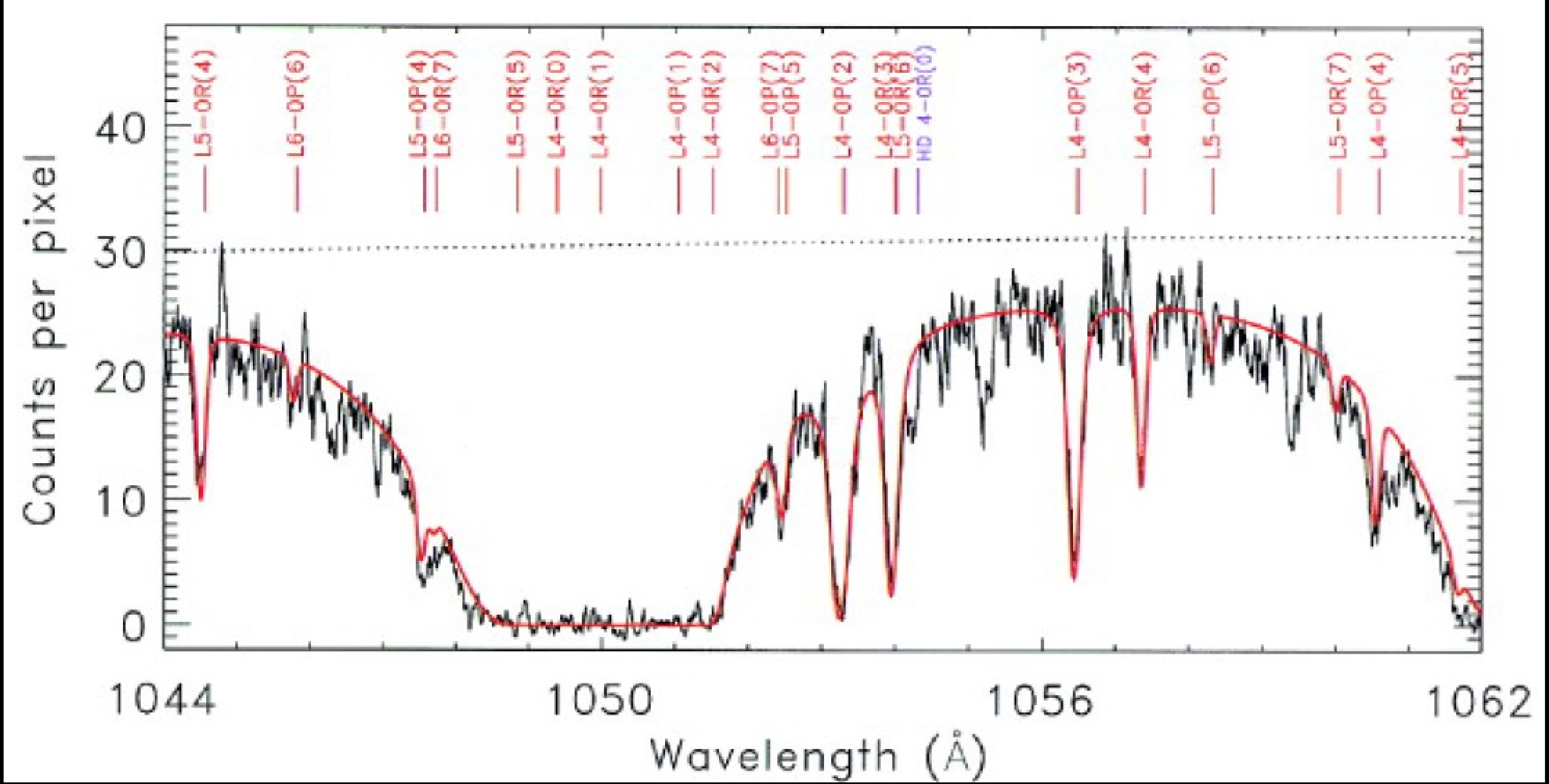
- The fact that the observed column densities of CH, OH >> NH indicates that grain surface chemistry is not dominant for carbon- and oxygen chemistry in diffuse clouds

Translucent clouds

- Can be isolated clouds, edges of dark clouds or GMCs, high-latitude clouds.
- Visible absorption lines of CH^+, CH, CN, C_2, …
- UV absorption lines with FUSE => H_2, HD, CO
  - Only for some clouds
- Clouds thick enough for mm emission => CO and very weak [C I], CS, CN, HCO^+, … ***‘CO dark gas’***
- mm absorption lines against background quasars => surprisingly large column densities of HCO^+, HCN, …
- Infrared absorption => threshold for ice mantle formation at $A_V \geq 3$ mag

UV spectroscopy: FUSE

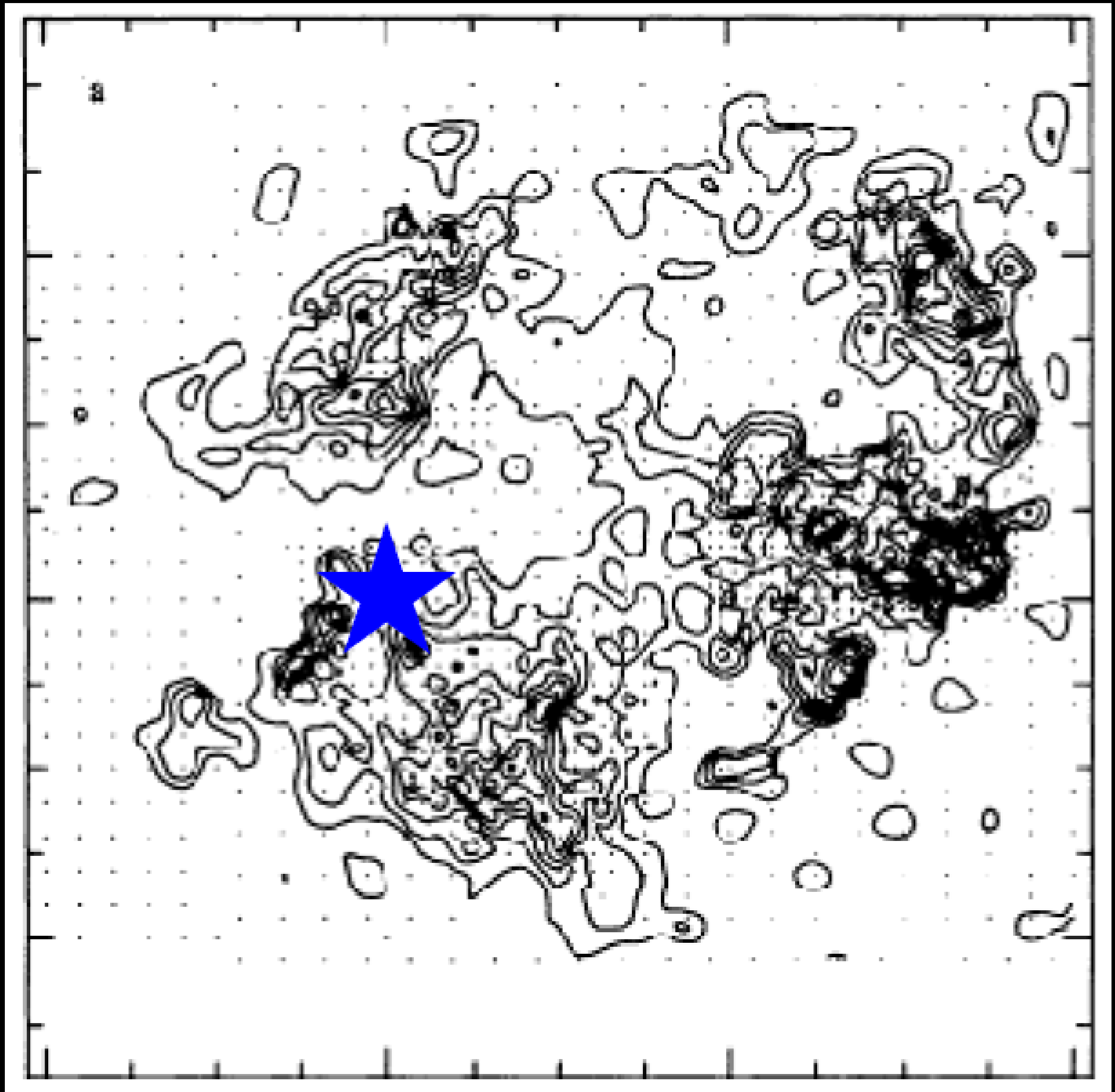
HD 73882



Snow et al. (2000)

FUSE spectrum toward HD 73882 translucent cloud showing H_2 and HD lines

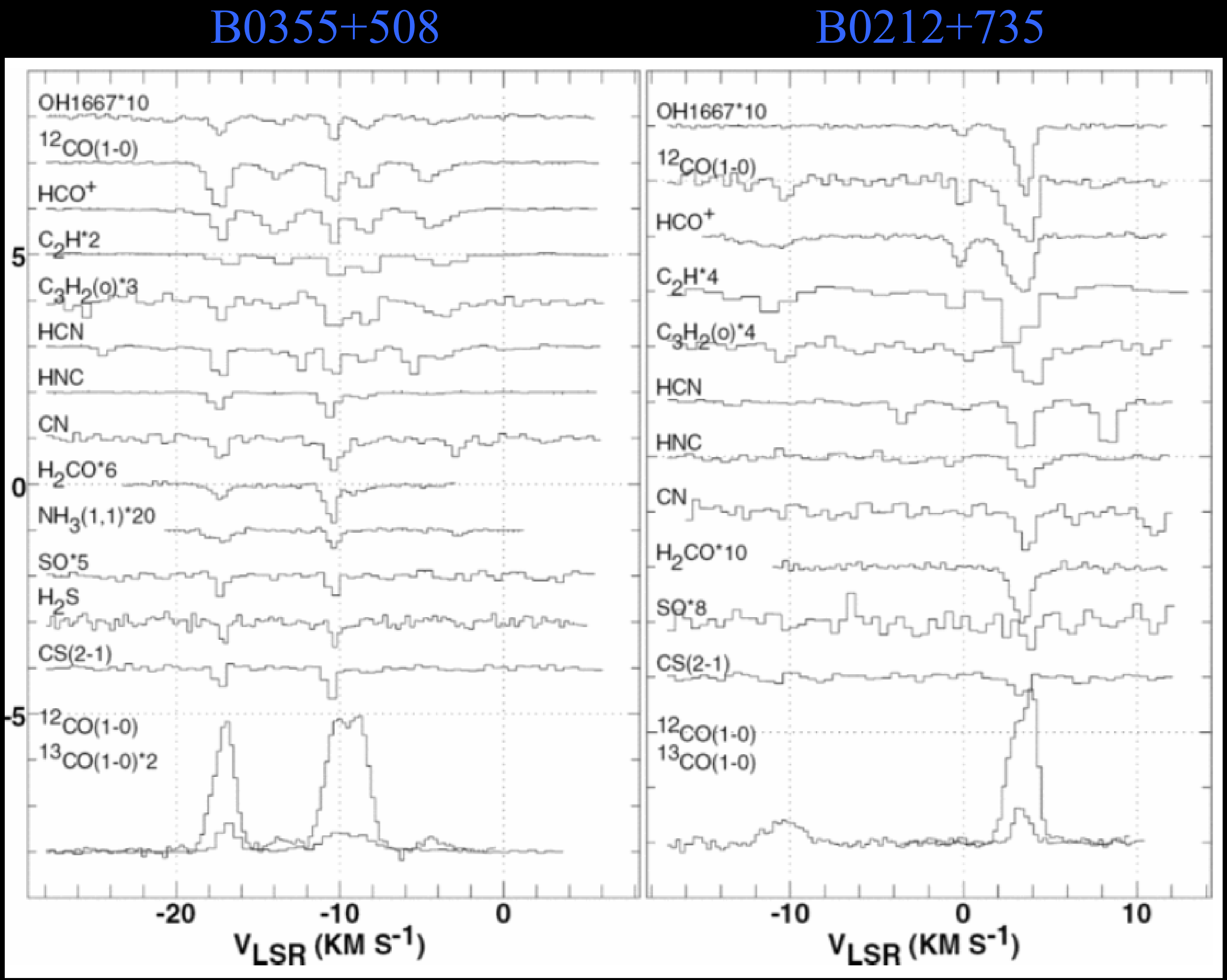
High latitude cloud toward HD 210121



CO J = 1–0 map

Gredel et al. (1992)

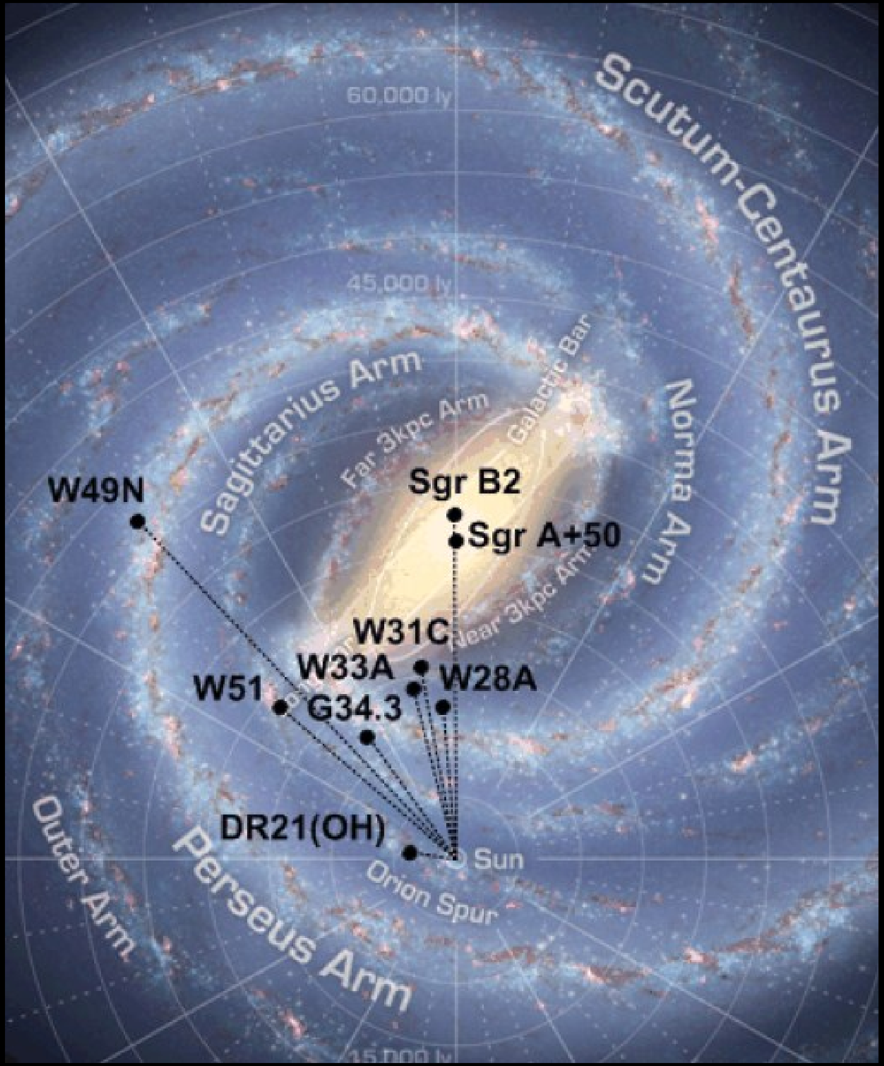
mm absorption lines: quasars



Lucas & Liszt ‘94-05
Hogerheijde et al. 1995
Liszt 2005, IAU 231

Far-infrared absorption

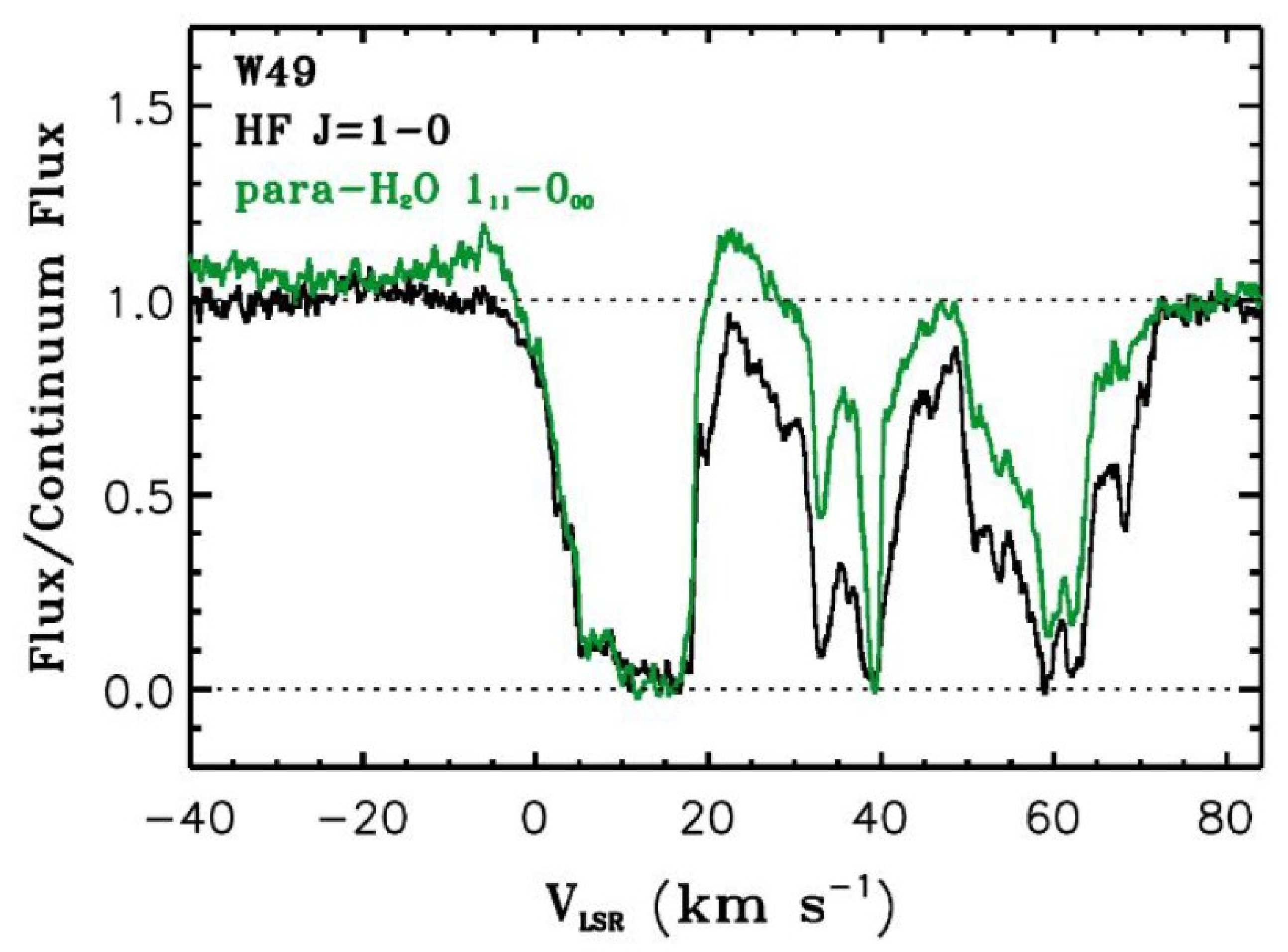
- Absorption against bright far-IR continuum
- Clouds A_V ~ few mag
- Hydrides have their lowest transitions at higher frequencies (sub-mm/far-IR wavelengths) because of lower mass than CO
- All molecules in ground state → simple analysis



Gerin et al. 2016, ARA&A

PRISMAS survey

Far-IR absorption lines: HF and H_2O



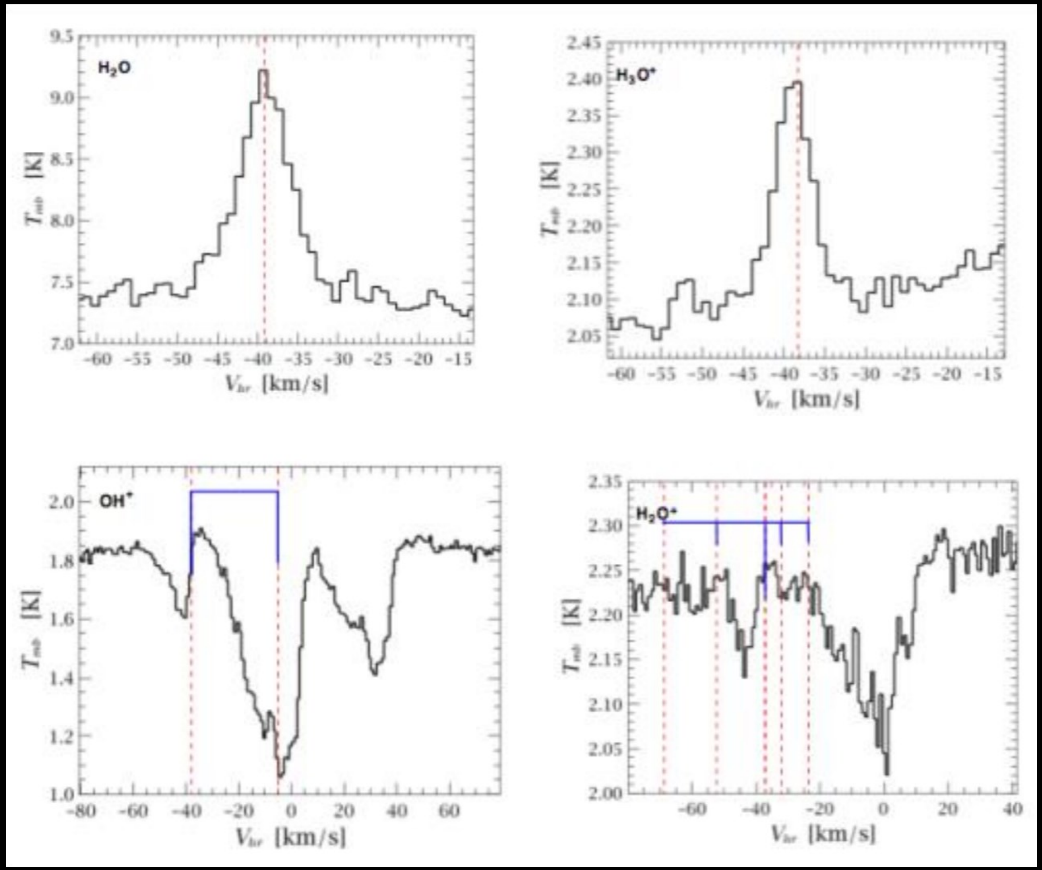
Herschel-HIFI

Gerin et al. 2016

- Diffuse and translucent clouds along the line of sight
- HF as tracer of H_2 column density because of simple chemistry
- Constant H_2O/H_2 abundance of 5×10^{-8}

Herschel surprise: H_2O^+ widespread

- Points to an ISM phase with high H/H_2 (see exercise on ArH^+)



Benz, Bruderer et al. 2010
Gerin et al. 2010
Ossenkopf et al. 2010
Wyrowski et al. 2010

- Also observed: OH^+, CH^+, SH^+, HCl^+, H_2Cl^+, ArH^+, OH, H_2O, CH, NH, HF, SH, HCl

4.2 Physical structure: diagnostics

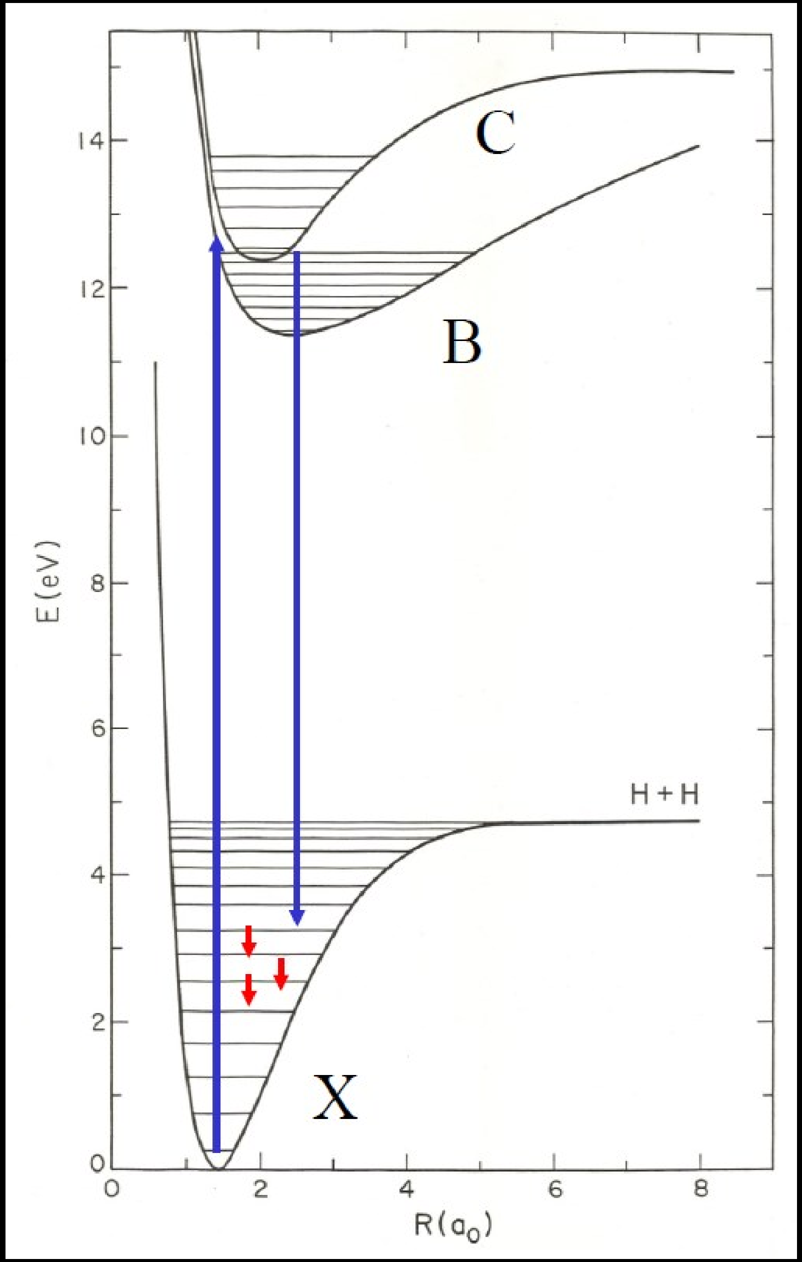
Species	**Probes**	**Diffuse clouds**	**Translucent clouds**
H_2 low J	T	+	-
H_2 high J, v>0	I_{UV}, formation	+	-
C_2 low J	T	+	+
C_2 high J	I_R/n_H	+	+
C, C^+, O(J)	n_H, T	+	-
CO low	n_H, T	+	+
CN J	n(e)	+	+
HCO^+, ...	n(e), n_H	-	+

a. Rotational excitation of H_2

- H_2 lines out of $J = 0–7$ detected with Copernicus + FUSE
- Population distribution non-thermal
  - Low *J*: excitation dominated by collisions

    => ***sensitive to*** T ***and*** n_H
    - Abundance H^+ large enough that ortho/para exchange rapid and J=1/J=0 gives T_{kin}
  - High *J*: energy levels lie very high (> 1000 K) => not populated by collisions at T = 40-80 K => populated by optical pumping process through B → X and C → X systems
  - => ***proportional to interstellar radiation field*** I_{UV}
    - Formation process may play a small role as well
- I_{UV} is scaling factor w.r.t. general interstellar radiation field (ISRF) in 6 – 13.6 eV range (also called G_0)

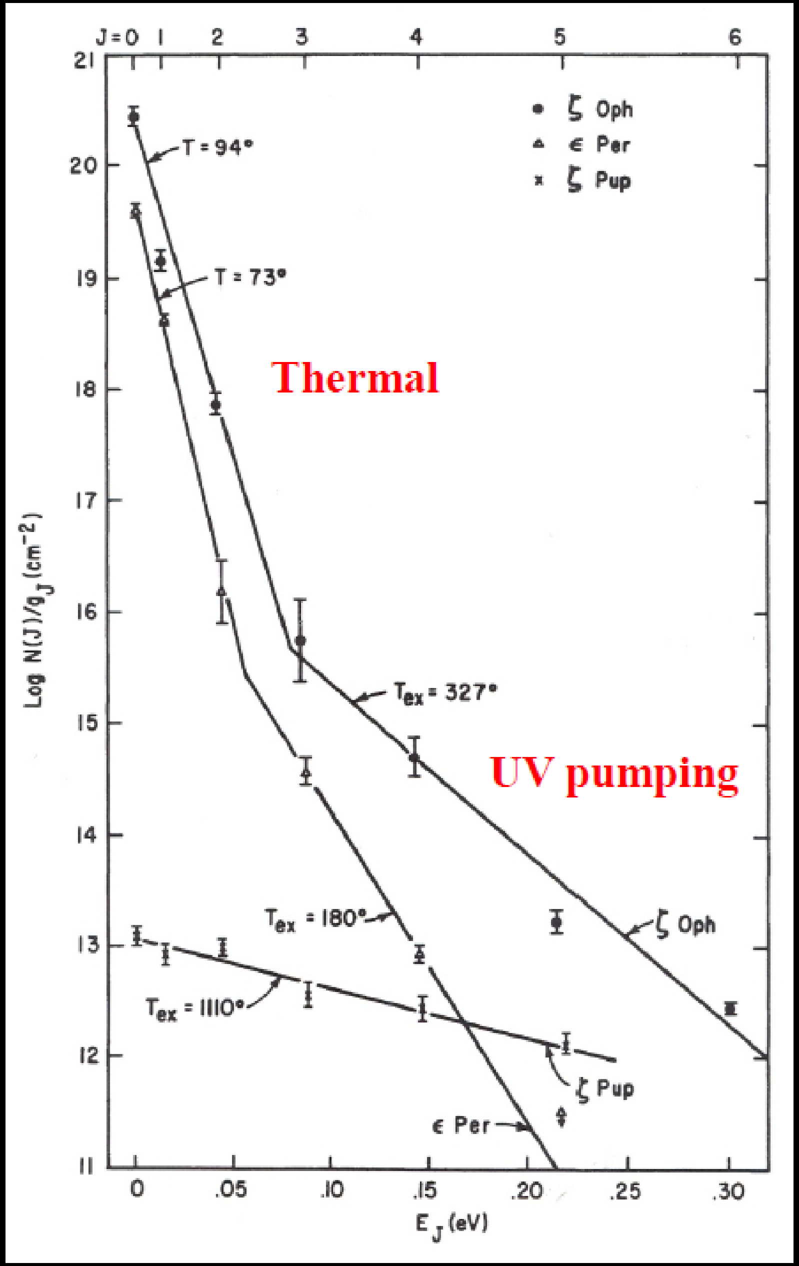
H_2 excitation



B-X: Lyman system
C-X: Werner system

Observed H_2 rotational excitation

$\ln N_J/g_J$



Thermal

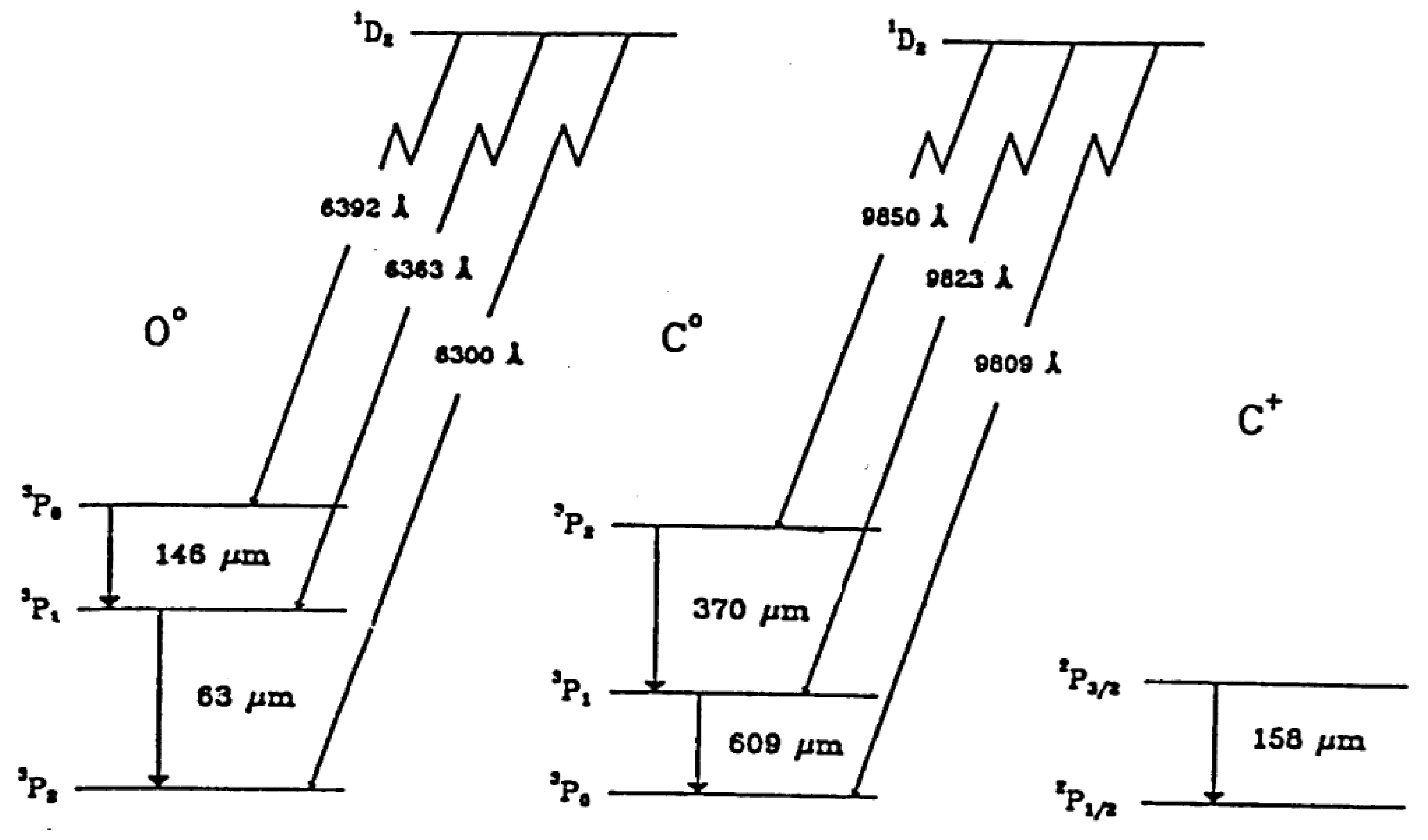
UV pumping

Diffuse clouds

b. Other diagnostics

- C_2: similar to H_2, but pumping by radiation around 1 μm => **sensitive to I_R, T, and n_H**
- CO rotational excitation
  - Small dipole moment => lowest levels can be populated by collisions even at low densities => **sensitive to T and n_H**
- C, C^+, O fine-structure excitation
  - Fine-structure populations determined by collisions => **sensitive to T and n_H**

O I, C I, and C II fine structure lines



Results physical parameters

- Diffuse clouds

  Edge **Center**

  - n_H: 100 → 500 cm^{-3} gradient?
  - T: 100-200 → 25-40 K
  - I_{UV}: 1-2 x ISRF → decrease depending on λ
- Translucent clouds
  - C_2: $T \approx$ 15-40 K; $n_H \approx$ 500-5000 cm^{-3}
  - CO: if $T \geq$ 15 K => $n_H \approx$ 1000 cm^{-3}
  - CN: $n(e) \approx$ 0.02-0.1 cm^{-3} => $n_H \approx$ 500-5000 cm^{-3}
  - No constraints on I_{UV} for translucent clouds
  - CO maps reveal inhomogeneous / ‘clumpy’ structure

Bottom line: diffuse cloud densities a few hundred cm^{-3},
translucent cloud densities a few thousand cm^{-3}

4.3 Chemistry networks

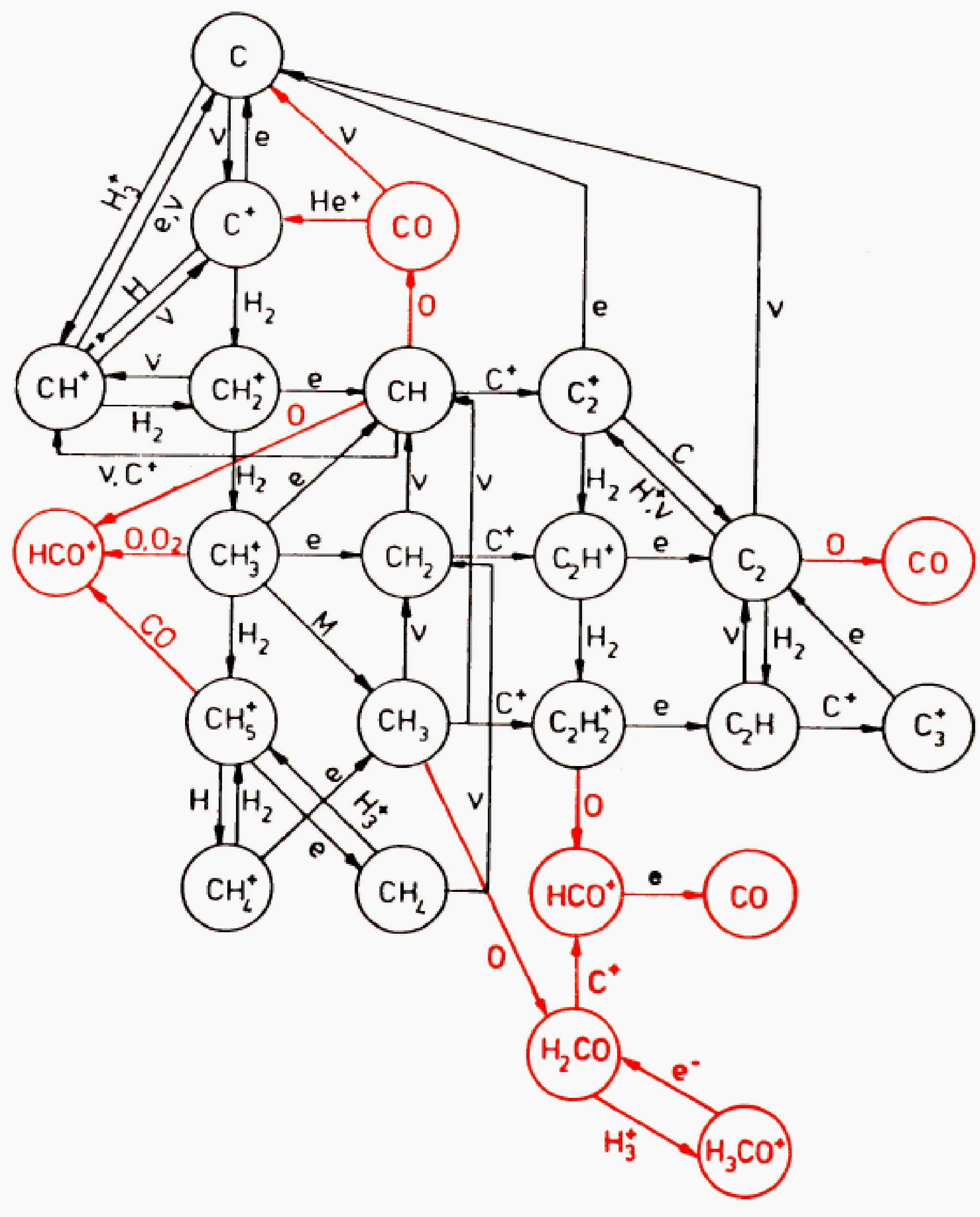
- Formation of bonds k (cm^3 s^{-1})
    - Radiative association: $\sim 10^{-17} - 10^{-14}$
    - Grain surface: $\sim 10^{-17}$
- Destruction of bonds
    - Photodissociation: $\sim 10^{-10} - 10^{-8}$
    - Dissociative recombination: $\sim 10^{-7} - 10^{-6}$
- Rearrangement of bonds
    - Ion-molecule reactions: $\sim 10^{-9} - 10^{-8}$
    - Neutral-neutral reactions: $\sim 10^{-10} - 10^{-9}$

- Hydrogen is dominant element => if species can react with H or H_2, it will be the dominant route

Carbon chemistry

- Need to have ions and molecules to start ion-molecule chemistry
- I.E. of C < 13.6 eV => Carbon mostly C^+
- $C^+ + H_2 \rightarrow CH_2^+ + h\nu$ possible at low T (initiating reaction)
- Once CH_2^+ formed, rapid ion-molecule reactions lead to CH, C_2, …
- $C^+ + H_2 \nrightarrow CH^+ + H$ endothermic by 0.4 eV

Carbon chemistry and its coupling with oxygen



Vertical

Down: H_2

Up: photon *ν*

Horizontal

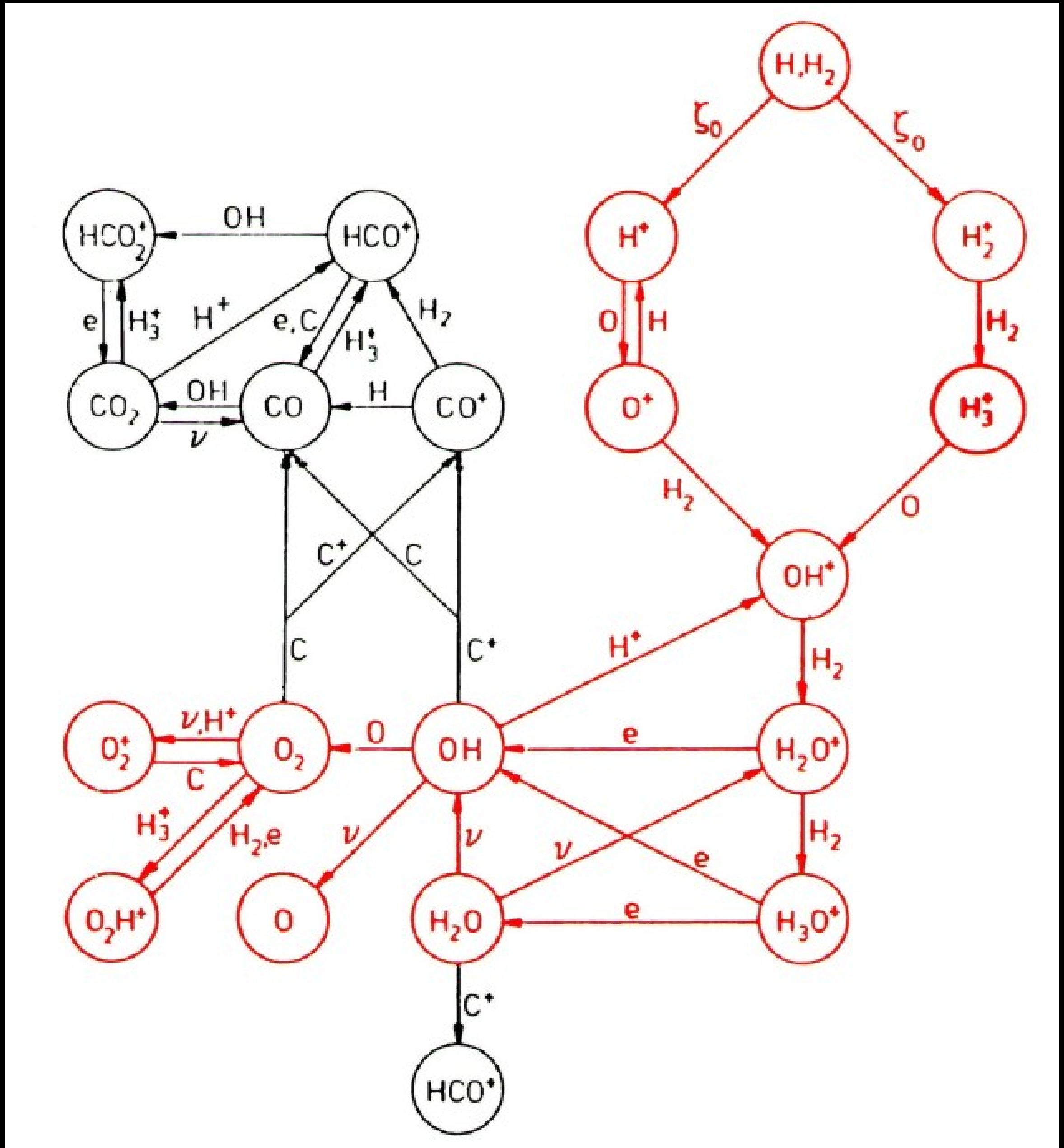
Ion: *e*

Neutral: C^+

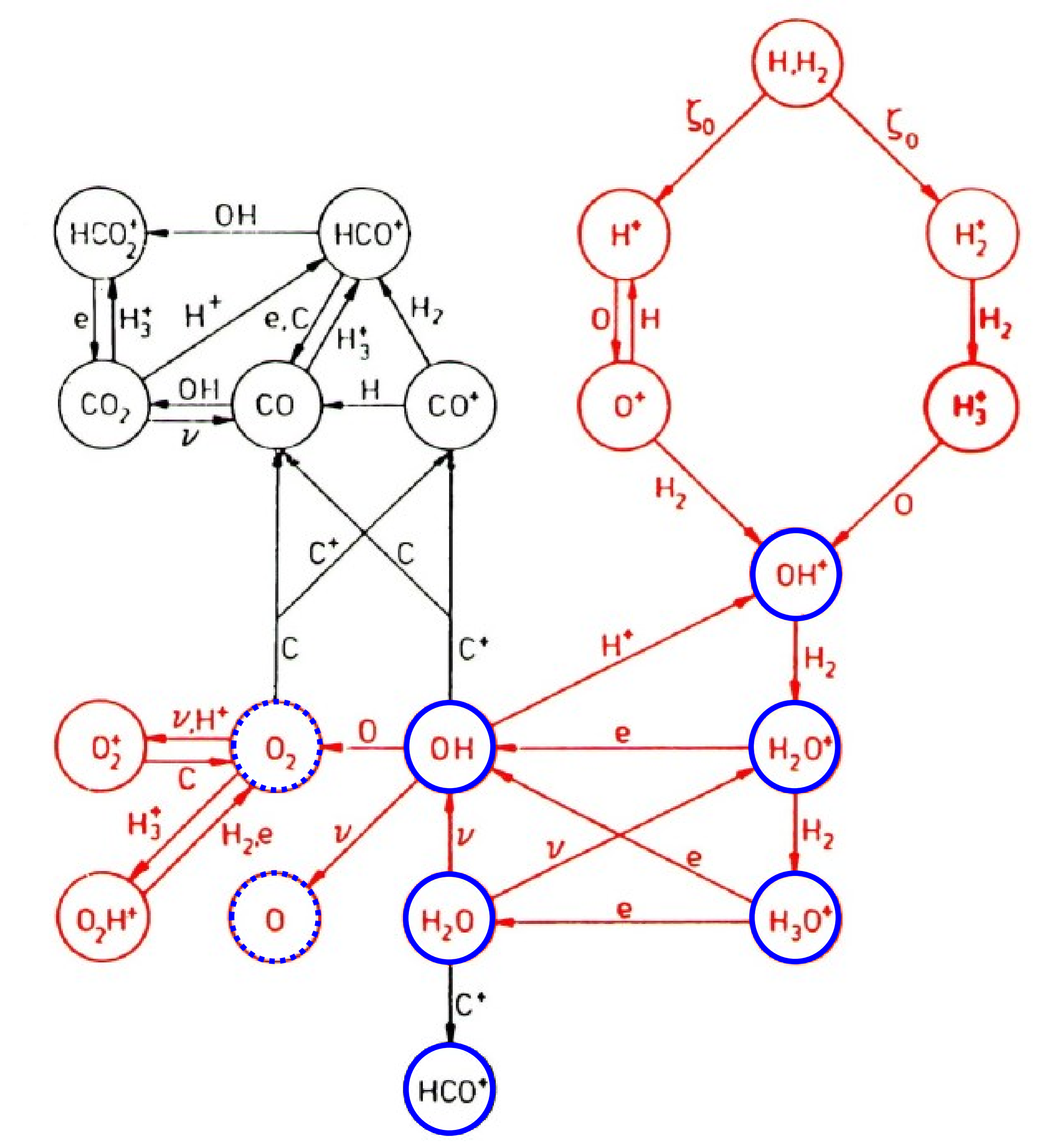
Oxygen chemistry

- I.E. of O > 13.6 eV => Oxygen mostly neutral O
- Ionization provided by cosmic rays
  - H_2 or H + C.R. → H_2^+ or H^+ + C.R. + e^-
  - $H_2^+ + H_2 \rightarrow H_3^+ + H$ (very fast)
- H^+ or H_3^+ can react with oxygen
  - $H^+ + O \leftrightarrow H + O^+$ $\Delta E = 227$ K; $O^+ + H_2 \rightarrow OH^+ + H_2$
  - $H_3^+ + O \rightarrow OH^+ + H_2$
- Once OH^+ formed, rapid ion-molecule reactions lead to OH, H_2O and CO
- Note that OH abundance is proportional to cosmic ray ionization rate ζ_{CR} => can use observed OH abundance to determine ζ_{CR}

Oxygen chemistry and its coupling with carbon



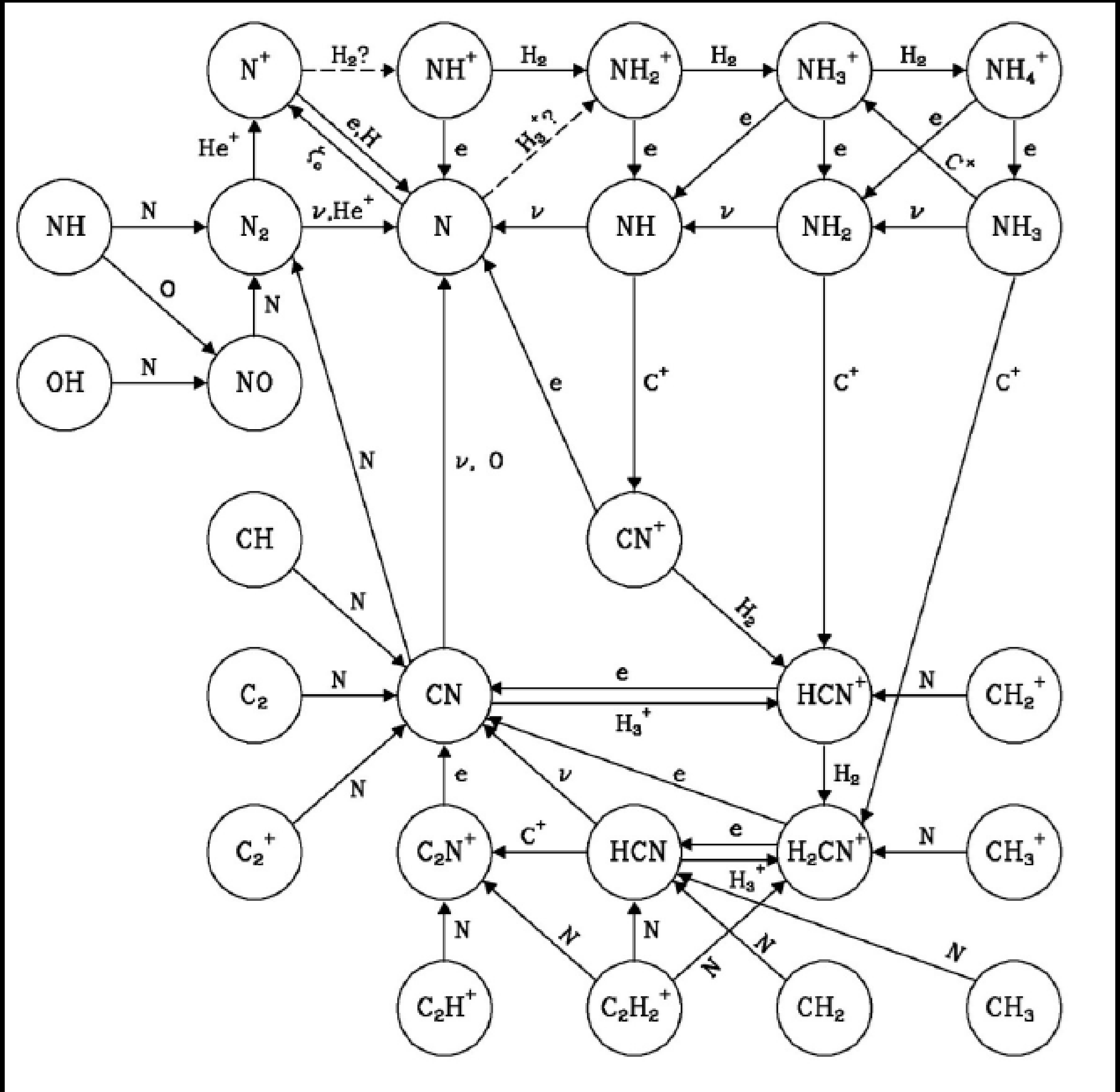
All key species in oxygen chemistry detected!



Nitrogen chemistry

- I.E. of N > 13.6 eV => Nitrogen mostly neutral N
- Nitrogen chemistry initiated by
  - $N + H_3^+ \rightarrow NH_2^+ + H$? Energy barrier?
  - $N^+ + H_2 \rightarrow NH^+ + H$? Small barrier ~100 K
- Link with carbon chemistry
  - $CH, C_2 + N \rightarrow CN + H, C$
  - $CH_3^+ + N \rightarrow H_2CN^+ + H$
  - $H_2CN^+ + e^- \rightarrow$ HCN or HNC + H

Nitrogen chemistry



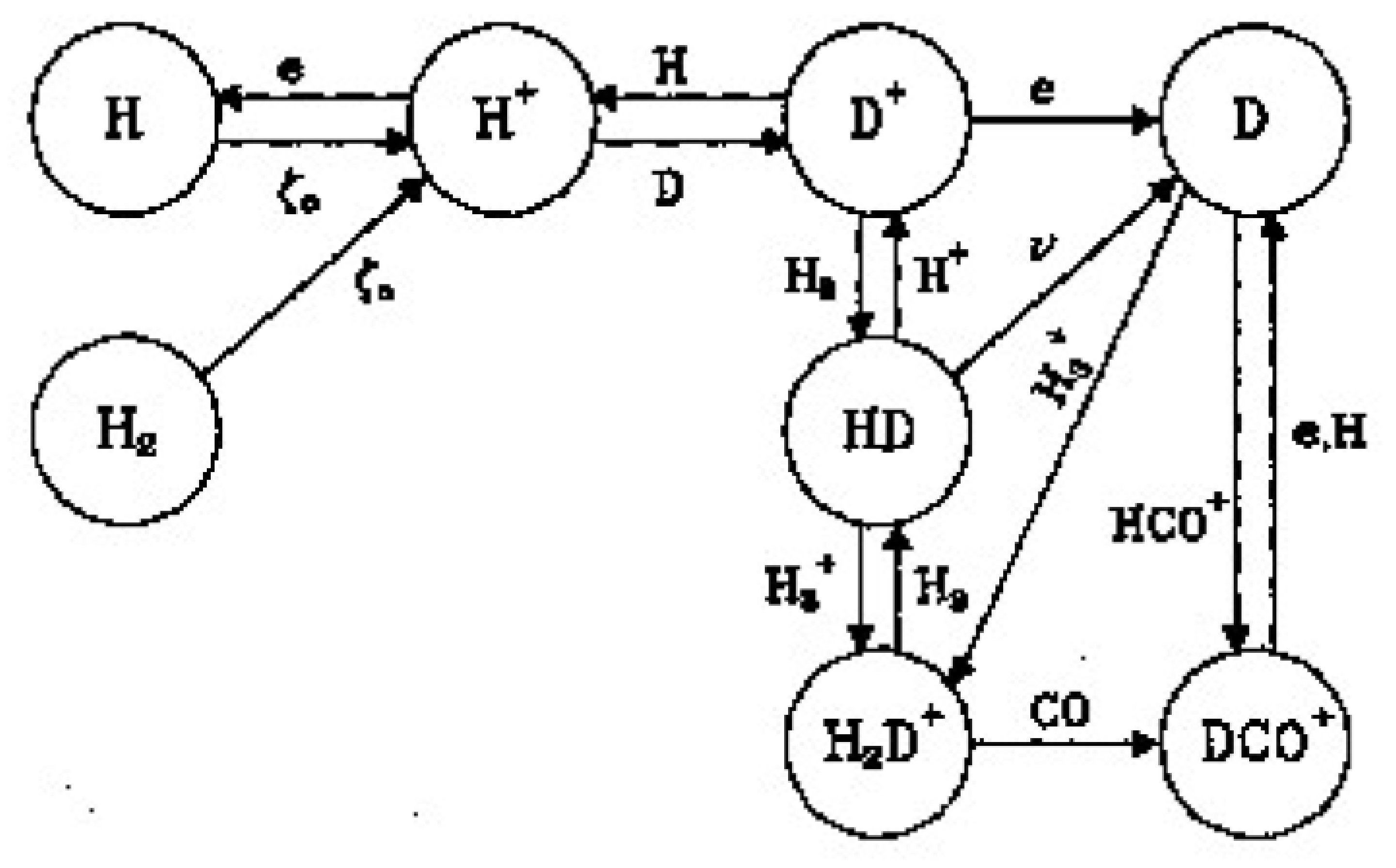
Deuterium chemistry

- HD formed mostly by rapid gas-phase reactions (not on grains), in contrast with H_2
  - $H^+ + D \leftrightarrow H + D^+$
  - $D^+ + H_2 \rightarrow HD + H^+$
- HD more rapidly destroyed by photodissociation than H_2, because column densities too small for self-shielding

=> Both formation and destruction up 10^5–10^6 times faster;

Result: overall $HD/H_2 \sim 10^{-6}$–10^{-5} vs $[D]/[H] = 1.5 \times 10^{-5}$

Deuterium chemistry



4.4 Steady-state models

- Because photorates change with depth into cloud, models of diffuse clouds need to be depth-dependent.
- Most reaction are fast (except H_2 formation) => steady-state usually a good assumption: $\mathrm{d}n_\mathrm{i}/\mathrm{d}t = 0$

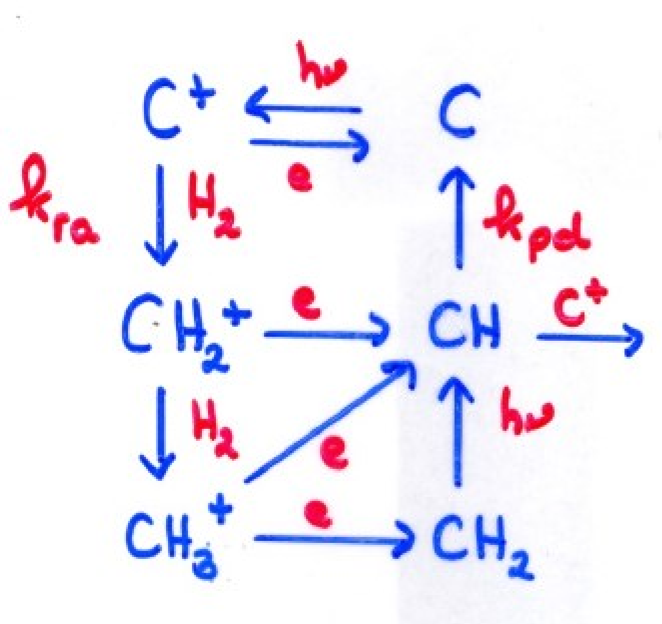
density $n_i(z) = \frac{formation\ rate}{destruction\ rate}$ $\mathrm{cm^{-3}}$

Column density $N_i = \int n_i(z)dz$ $\mathrm{cm^{-2}}$

Parameters

- Geometry: plane parallel
- Elemental abundances: C, O, N, S, Fe, Mg, ….
  - Often constrained by observations
- Density structure: $n_{\mathrm{H}}(\mathrm{z})$
  - Constrained by observations
- Temperature structure: $T(\mathrm{z})$
  - Constrained by observations or by solving thermal balance
- Incident radiation field: I_{UV} x standard field, plus grain absorption + scattering parameters
  - Constrained by observations
  - $I_{\mathrm{UV}} = I_0\ 10^{-0.4\mathrm{A_v}}$ (definition of $\mathrm{A_V}$)
  - $I_{\mathrm{UV}}(\lambda) = I_0 \exp(-\tau_d(\lambda))$ $\tau_d(\lambda) = n_d C_{ext}(\lambda) L$
- Cosmic ray ionization rate: ζ (s^{-1})

Example: CH



$$n(\mathrm{CH}) \propto \frac{n(\mathrm{C}^{+})n(\mathrm{H}_2)k_{ra}}{k_{pd}}$$

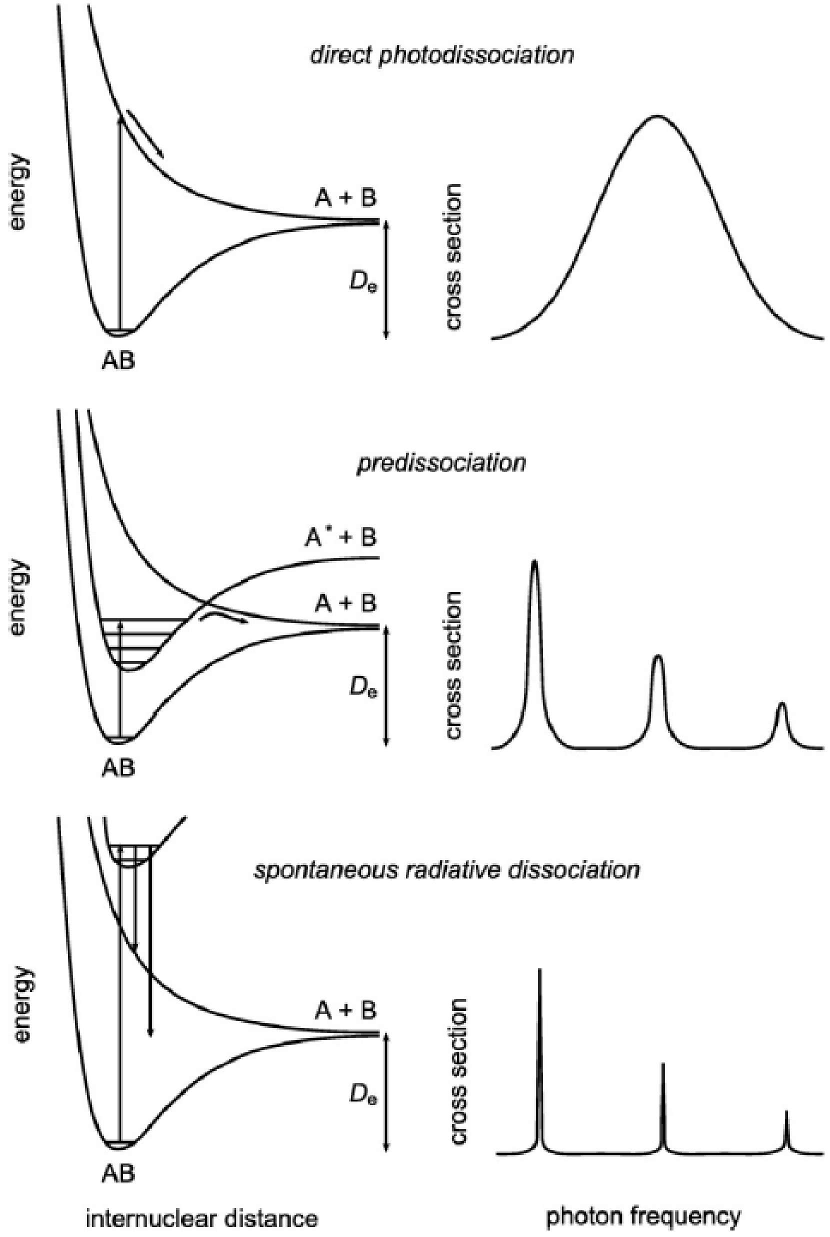
- All rates well known (within factor 2) => possible to fit observed CH column densities
  - Cannot claim that *all* CH is formed by this scheme; up to 50% could result from other processes
- Test: can a consistent model be made that reproduces all observational data with same set of physical conditions and molecular parameters?

Comprehensive models

- Comprehensive models attempted by several groups, e.g., Black & Dalgarno (1977), van Dishoeck & Black (1986), Meudon group (Roueff et al.), UMIST (Millar et al.), ...

- Chemistry governed by H → H_2 and C^+ → C → CO transitions
- Because of self-shielding, these transitions are sharp as functions of depth into cloud

Recall photodissociation Lecture 1



Direct p.d.

Ex: H_2^+, OH, H_2O

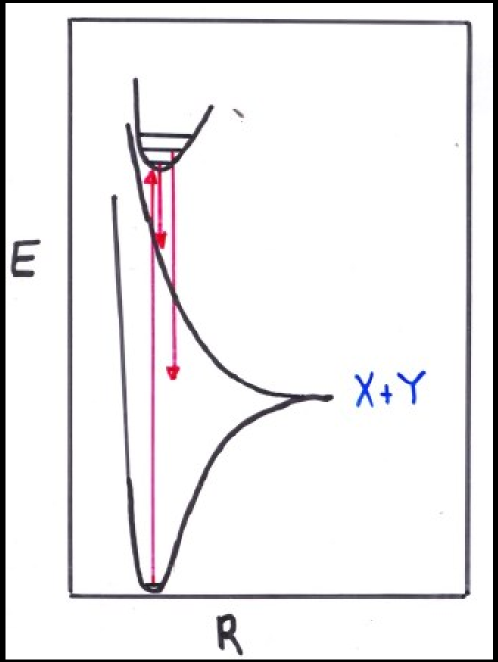
Predissociation

Ex: CO

Spontaneous radiative dissociation

Ex: H_2

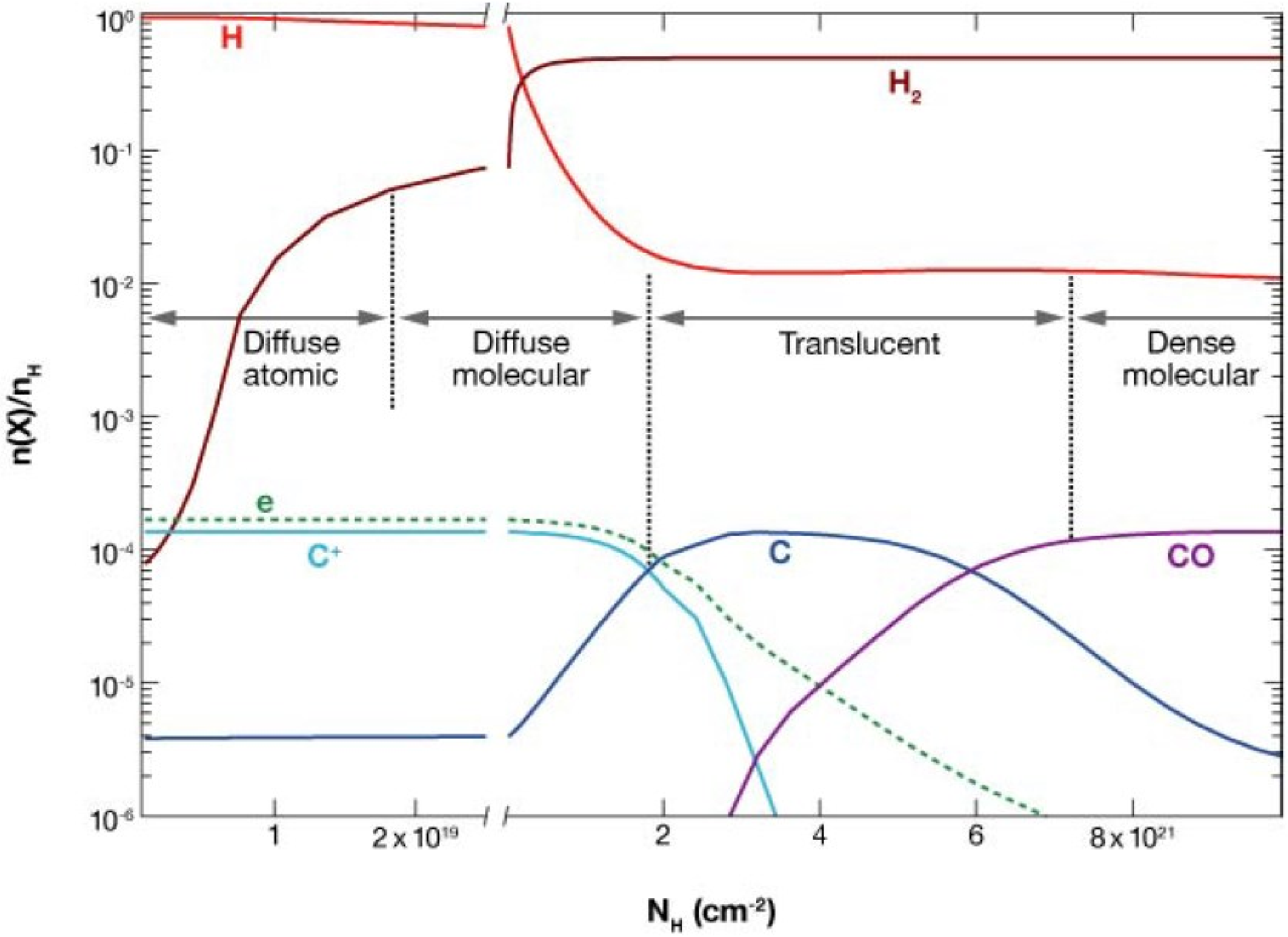
Photodissociation: self-shielding



Spontaneous radiation dissociation
Ex: H_2

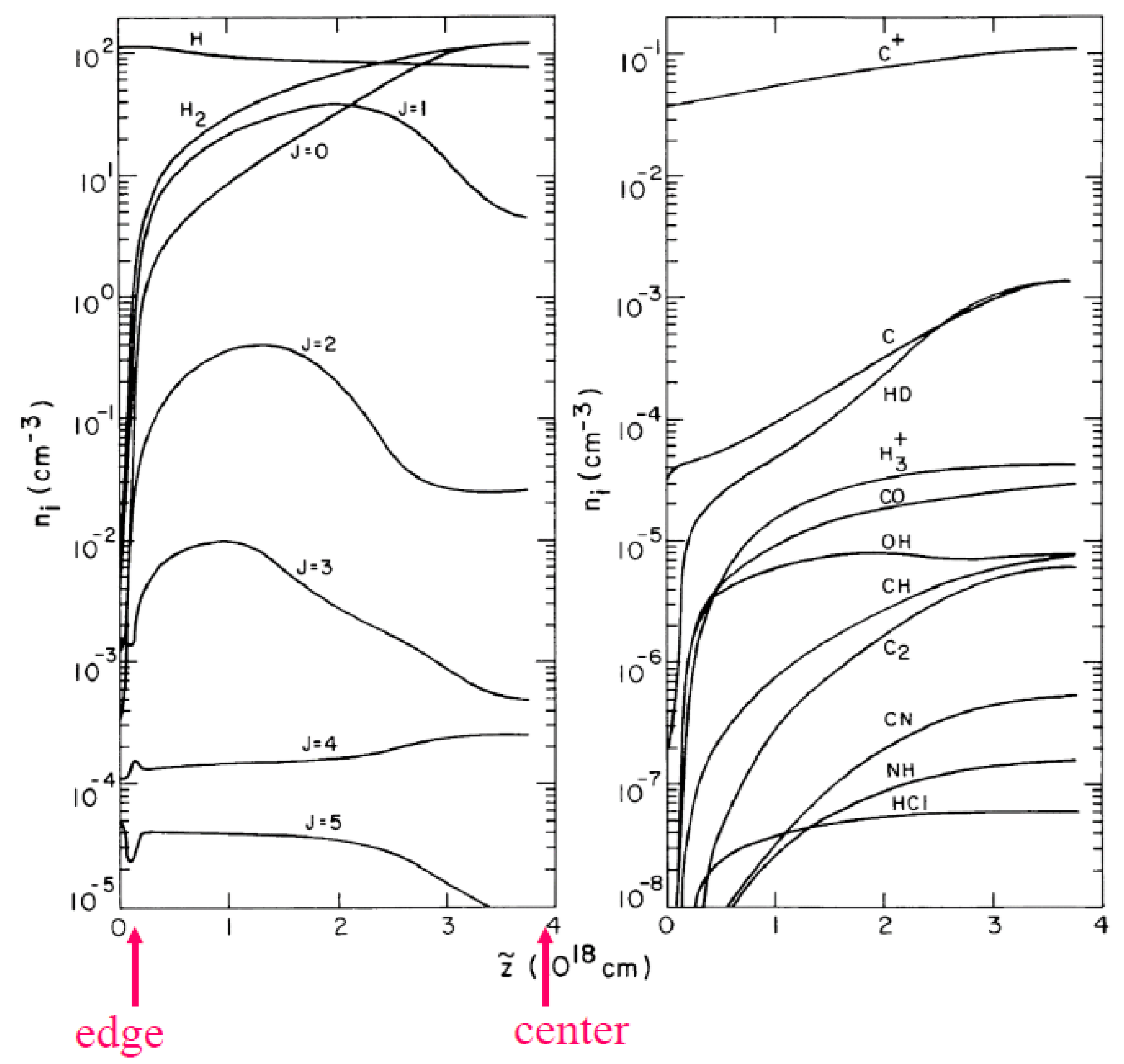
- Photodissociation of both H_2 and CO occurs by line absorption => lines can become optically thick => ***self-shielding*** inside clouds
  - Molecules lying at the edge of the cloud absorb all available photons at that wavelength, so that molecules lying deeper in the cloud are protected: ***sharp*** transition!

Types of molecular clouds



Snow TP, McCall BJ. 2006.
Annu. Rev. Astron. Astrophys. 44:367–414

Depth dependence of major species
ζ Per cloud



Note: overall density increases slightly with depth

van Dishoeck & Black (1986)

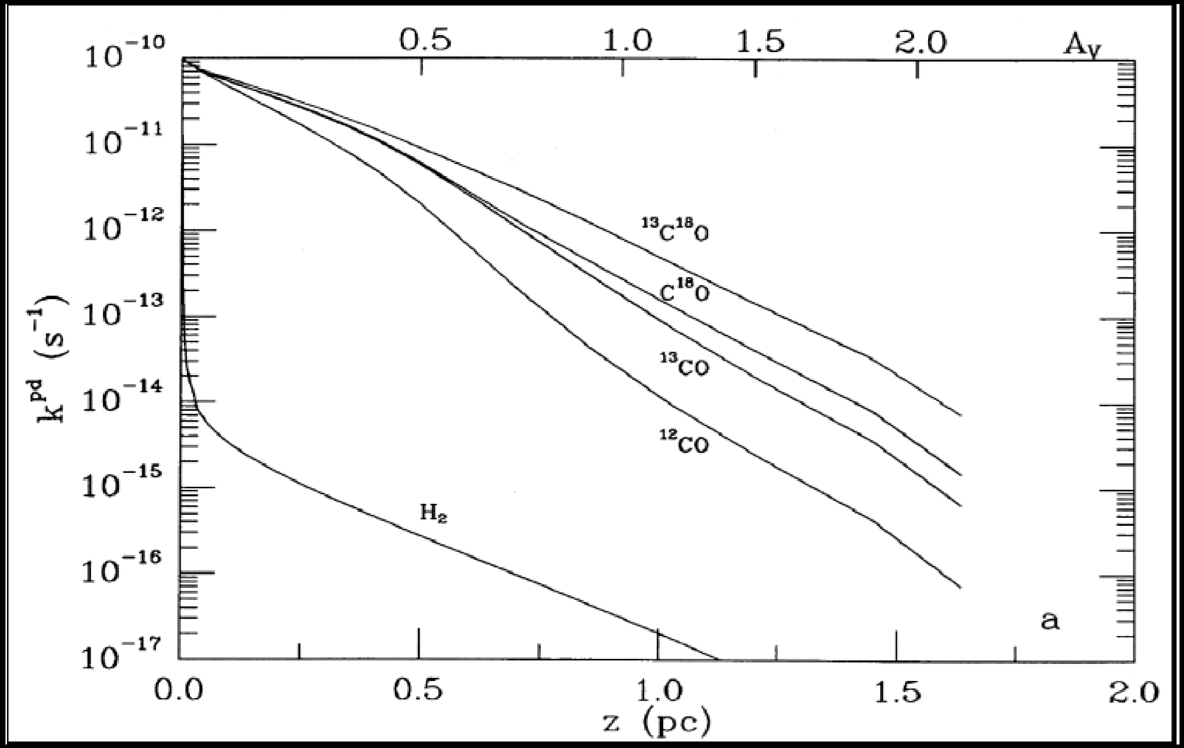
CO formation and destruction

- CO is most abundant molecule after H_2 and is easily observed through (sub-)mm lines
  - Good tracer of H_2
- At edge of cloud, most carbon is C^+
- Transition: $C^+ \rightarrow C \rightarrow CO$ with increasing depth
- CO is very stable ($D_e = 11.09$ eV ↔ 1118 Å)
- => can only be dissociated at 912 Å $< \lambda <$ 1118 Å

CO photodissociation

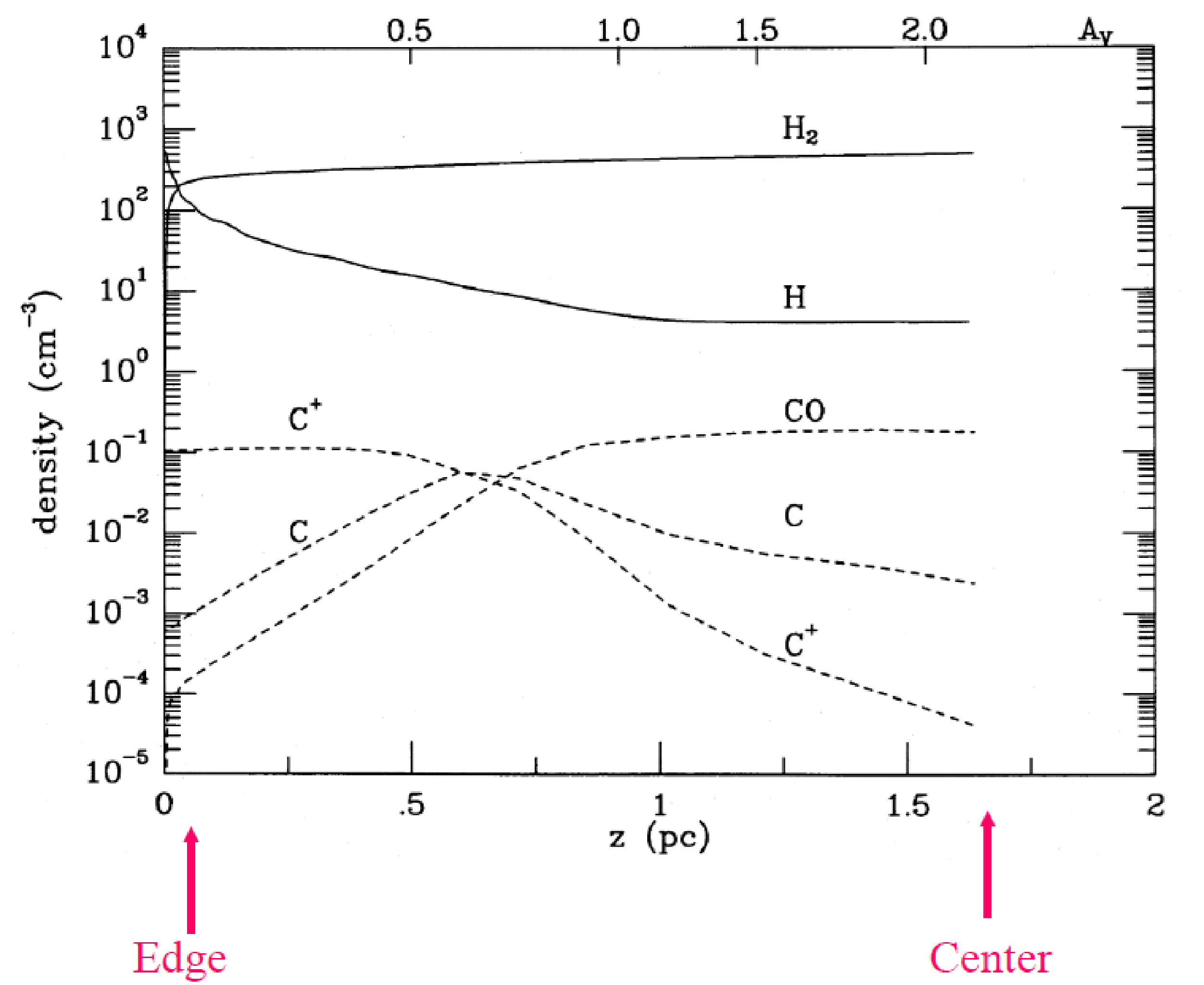
- Like H_2, CO has no direct dissociation channels => dissociation through line absorption (pre-dissociation) =>
  - Self-shielding, but at greater depth than H_2 because of lower abundance
  - Mutual shielding of CO by H_2
  - Mutual shielding of ^{13}CO by ^{12}CO
  - Attenuation by dust
  - => complicated UV radiative transfer!
- Note that H_2 and CO photodissociation and C photoionization all occur in the same λ range (912 – 1100 Å)
  - Important to know shape of UV radiation field at short λ
- At $A_V \approx$ 1-2 mag, CO / H_2 increases from 10^{-7} to 10^{-4}

Self-shielding of CO and H_2 Photodissociation rates



- Decrease of CO p.d. rate with depth is less steep than that of H_2 because of larger competition with dust for UV photons
- CO self-shielding starts at $N(\mathrm{CO}) \approx 10^{15}$ cm^{-2}

Densities of major species in translucent cloud



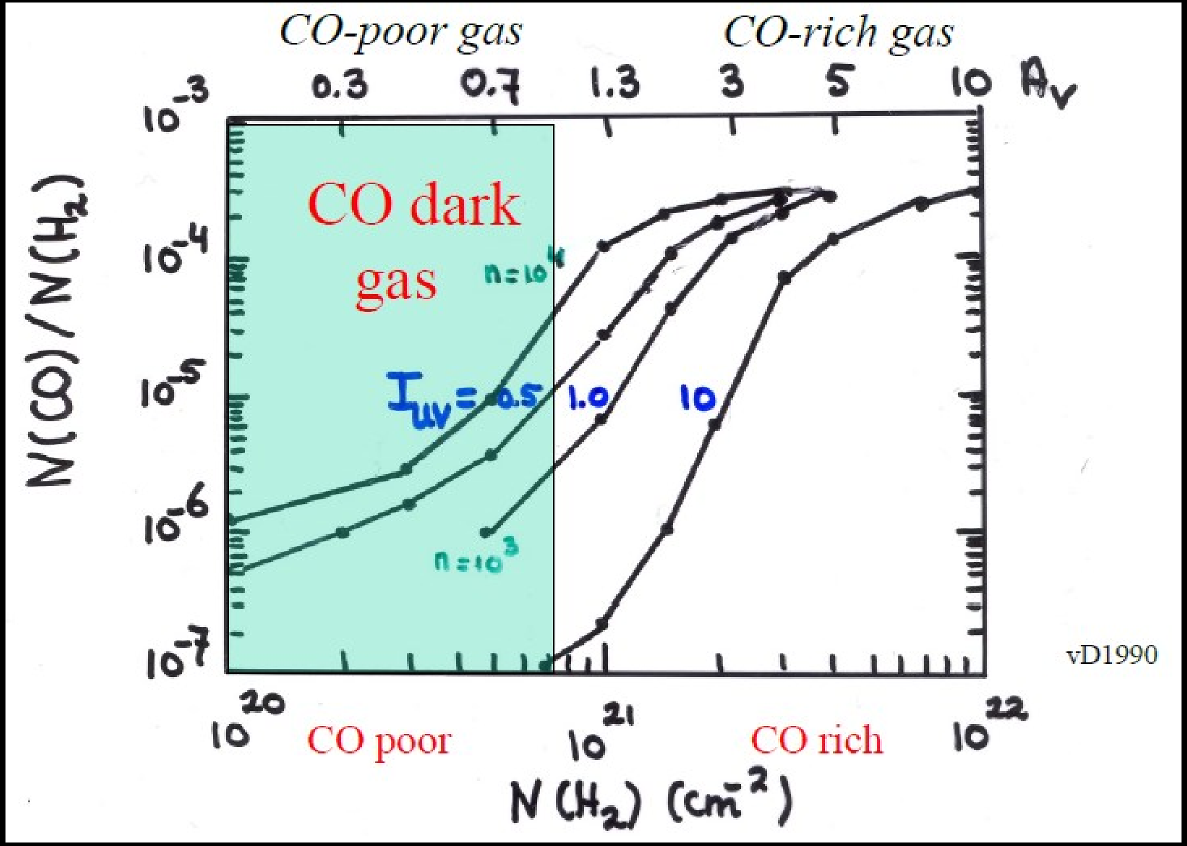
$T = 15$ K

$n_H = 1500$ cm^{-3}

$I_{UV} = 1$

- Only column densities are observed => integrate over z

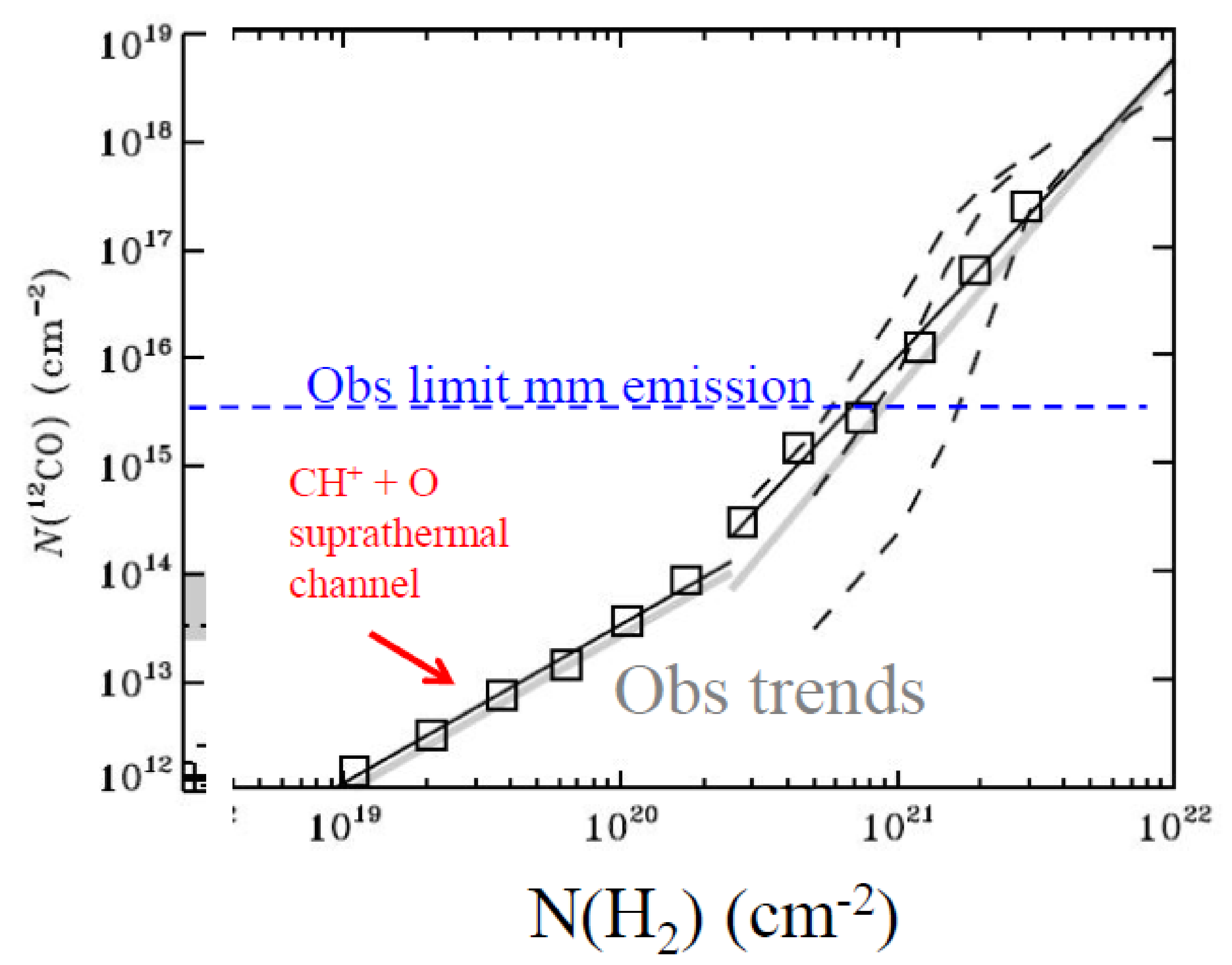
Column densities with N_H or A_V



→ Increase in CO/H_2 at A_V = 1-2 mag from 10^{-7} to 10^{-4}

- Exact location and sharpness transition depend on
  - I_{UV}, n_H, elemental abundances
  - Presence of PAHs, chemistry details (S), ζ, grain details, geometry,…

CO vs H_2 column density



Visser et al. 2009
Sheffer et al. 2008

- At low A_V, formation of CH^+ through superthermal chemistry of $C^+ + H_2$ needs to be invoked to fit observations of CO in diffuse clouds.

Model successes

- Column densities of CH, C_2, C_3, CN, OH, HCl OK within a factor of 2
- Constraints on ζ and [D]/[H]
    - $\zeta = (7 \pm 3) \times 10^{-17}\ s^{-1}$ (but see below H_3^+, OH^+)
    - $[D]/[H] \approx (1\text{-}2) \times 10^{-15}$

Model failures

- CH^+ too low by a factor of 100
- NH too low by a factor of 20
- Polyatomic molecules HCO^+, HCN, CH_3, ... too low by a factor of 100

Possible remedies

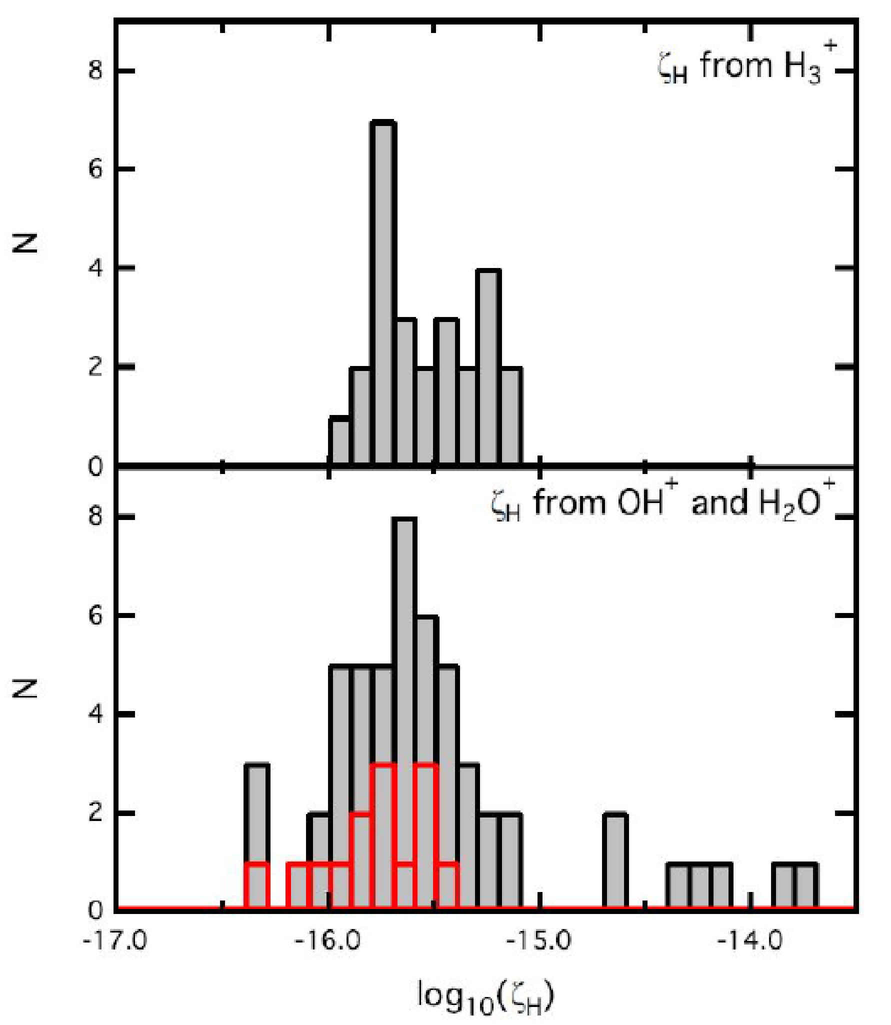
- Weak shocks or turbulence
  - CH^+: see Lecture 5
  - HCO^+, HCN, CO, CH_3 enhanced if CH^+ enhanced
- Surface chemistry
  - NH, CH_3?
- Cloud structure: clumpy, high H/H_2, ...
  - CO
  - OH^+, H_2O^+, ArH^+

H_3^+ as a tracer of ζ

- Large column densities of $\sim 10^{14}$ cm^{-2} found in several diffuse clouds (Galactic center, ζ Per, others)
  - $n(H_3^+) = (\zeta/k_{DR})n(H_2)/n(e)$
  - $N(H_3^+) = n(H_3^+)L$ $\quad L$ = path length
  - $n(e)/n(H_2) \approx N(e)/N(H_2) \approx N(C^+)/N(H_2) \approx 3.8 \text{ x } 10^{-4}$ observed ζ Per
  - $k_{DR} = 2.6 \text{ x } 10^{-7}$ cm^3 s^{-1} from exp
  - $N_H = \underset{\overset{\uparrow}{\text{obs}}}{1.6 \text{ x } 10^{21}}$ cm^{-2}, $\langle n_H \rangle = \underset{\overset{\uparrow}{\text{obs}}}{250}$ cm^{-3} $= > L = 2.1$ pc
- **$\zeta = 1 \text{ x } 10^{-15}$ s^{-1}**, factor of 10-20 larger than „canonical value‘
- Survey gives range of 10^{-16}–10^{-15} s^{-1} for number of sources

McCall et al. 2003
Le Petit et al. 2004
Indriolo et al. 2007

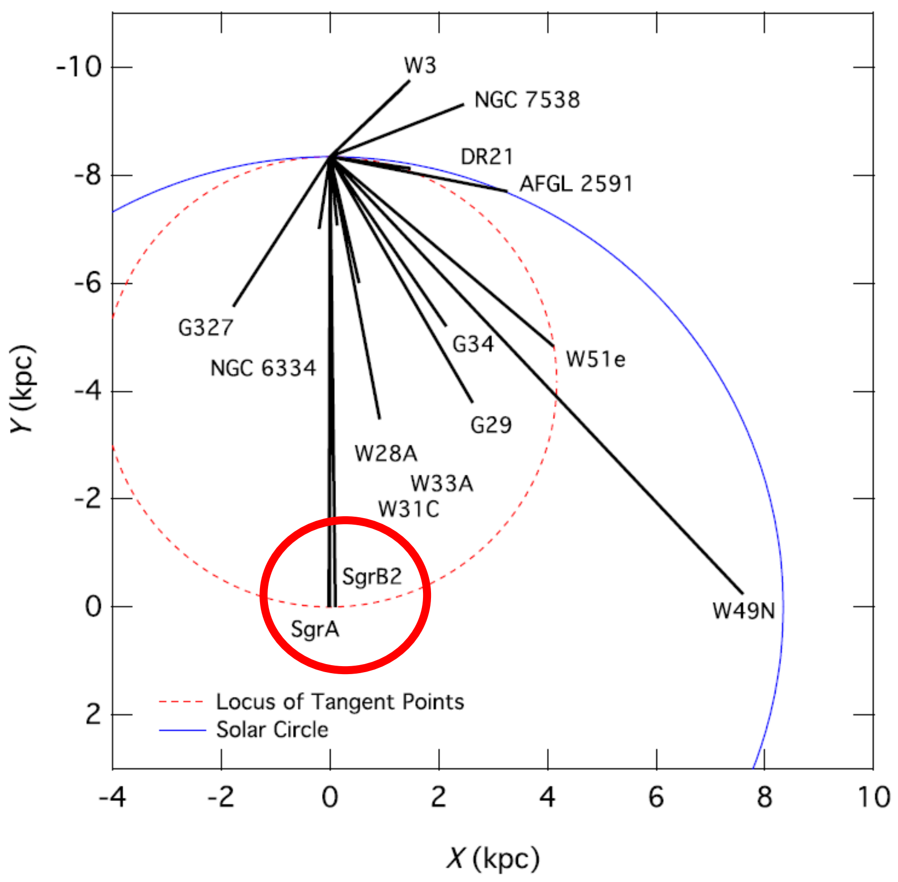
Cosmic ray ionization rate

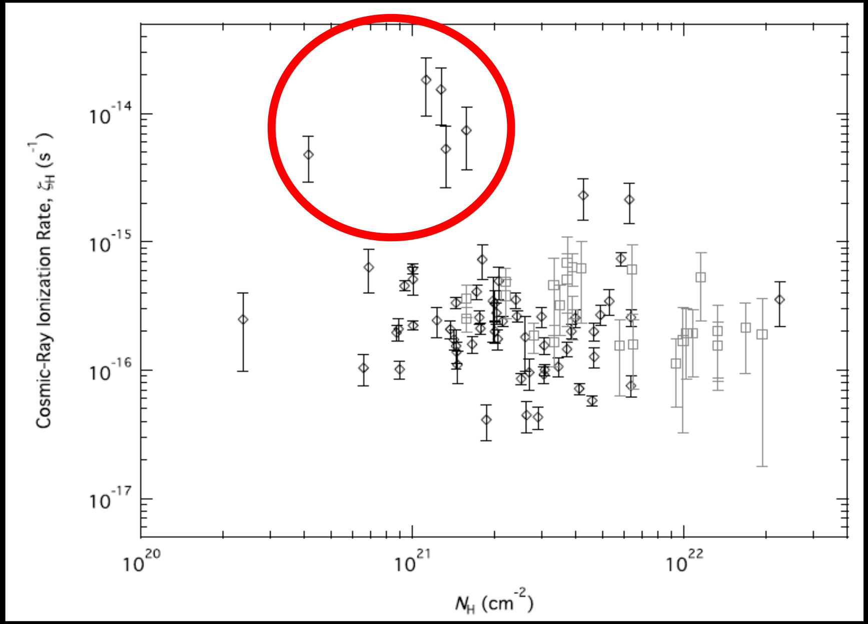


Indriolo et al. 2015
Neufeld et al. 2017

- Use both H_3^+ and OH^+, H_2O^+ as probes

Cosmic ray ionization rate





ξ_{CR} 1-2 orders of magnitude larger toward the Galactic center compared to the Galactic disk.

Indriolo et al. 2015
Neufeld et al. 2017

Photon dominated regions (PDRs)

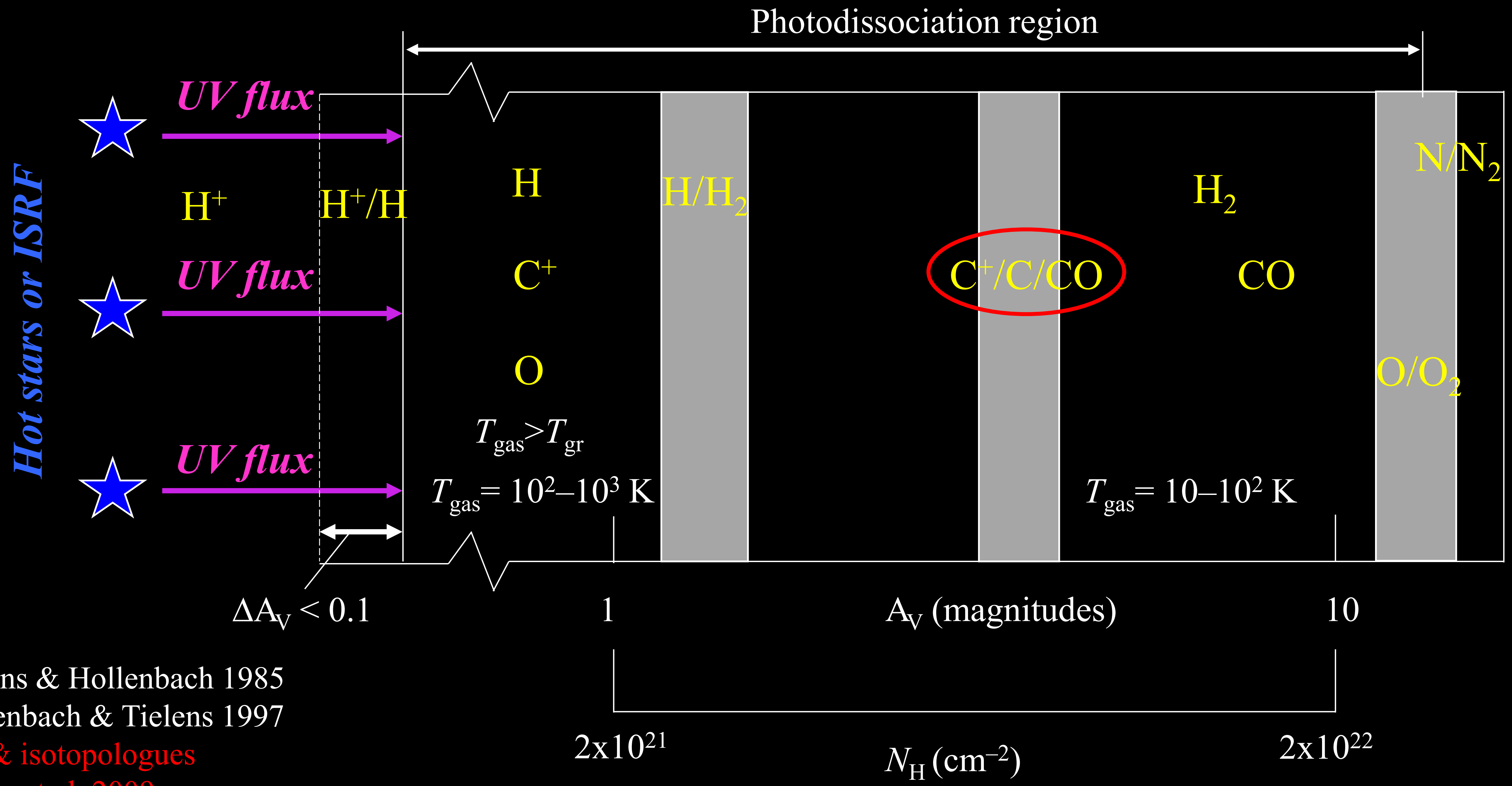
- Diffuse and translucent clouds are examples of PDRs, i.e., clouds in which UV photons control the physical and chemical state of the cloud
- Traditionally, PDRs are dense molecular clouds located close to an OB star, in which the UV radiation field is enhanced by a factor of 10^5 w.r.t. average interstellar radiation field (ISRF)
  - Example: Orion Bar
- PDRs show very strong atomic fine-structure lines
  - E.g. [C II] 158 μm, [C I] 610 μm, [O I] 63 μm
- And submillimeter lines of molecules
  - E.g. CO 7-6, HCO^+ 4-3
- And strong H_2 mid- and near-IR lines

Tielens chapter 9
Tielens & Hollenbach 1997

Horsehead nebula as PDR

AAT

PDR structure



Photodissociation region

Hot stars or ISRF

UV flux

UV flux

UV flux

H^+

H^+/H

H

C^+

O

H/H_2

$C^+/C/CO$

H_2

CO

N/N_2

O/O_2

$T_{gas} > T_{gr}$

$T_{gas} = 10^2$–10^3 K

$T_{gas} = 10$–10^2 K

$\Delta A_V < 0.1$

1

A_V (magnitudes)

10

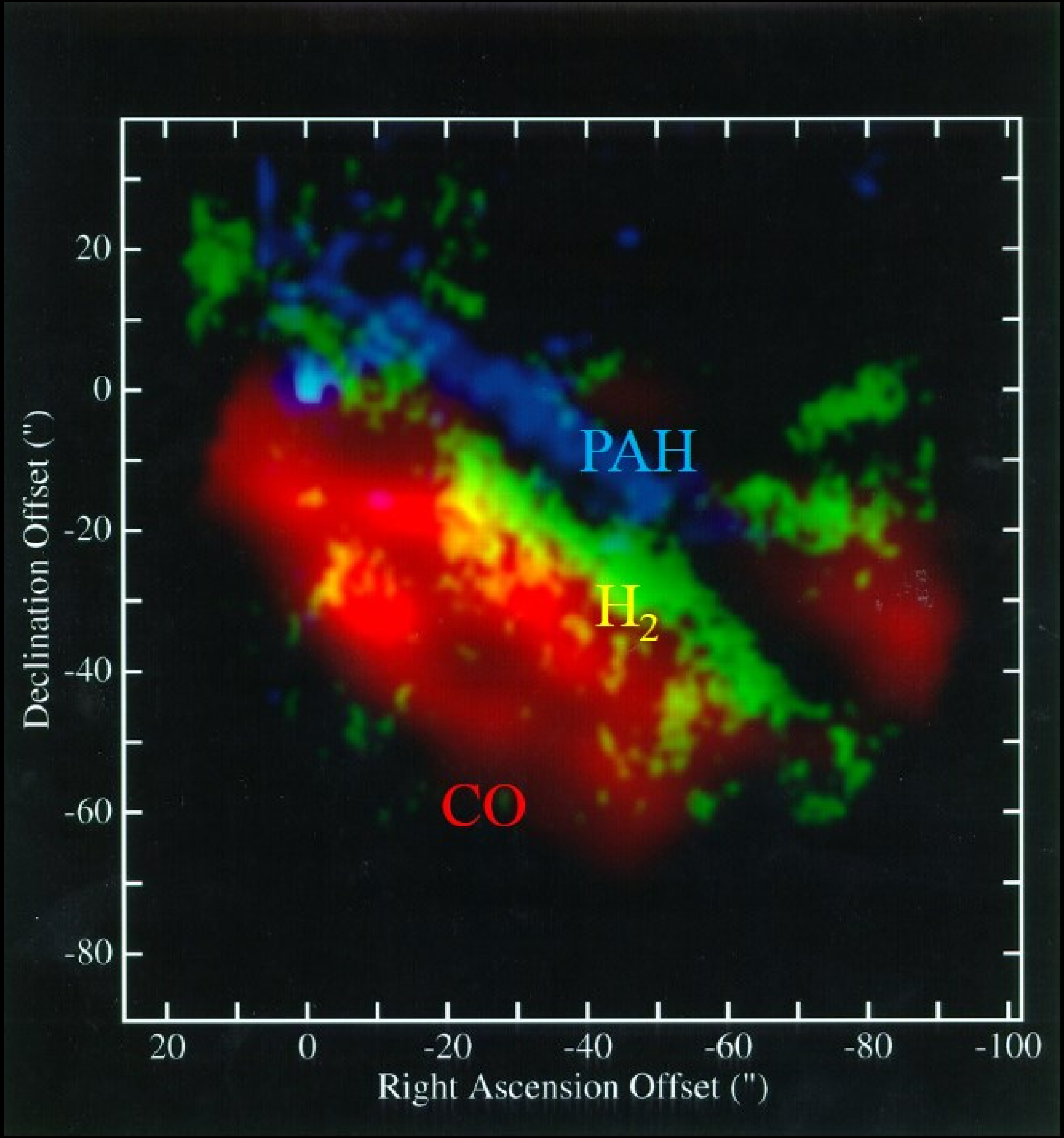
$2x10^{21}$

N_H (cm^{-2})

$2x10^{22}$

Tielens & Hollenbach 1985
Hollenbach & Tielens 1997
CO & isotopologues
Visser et al. 2009

Orion bar PDR



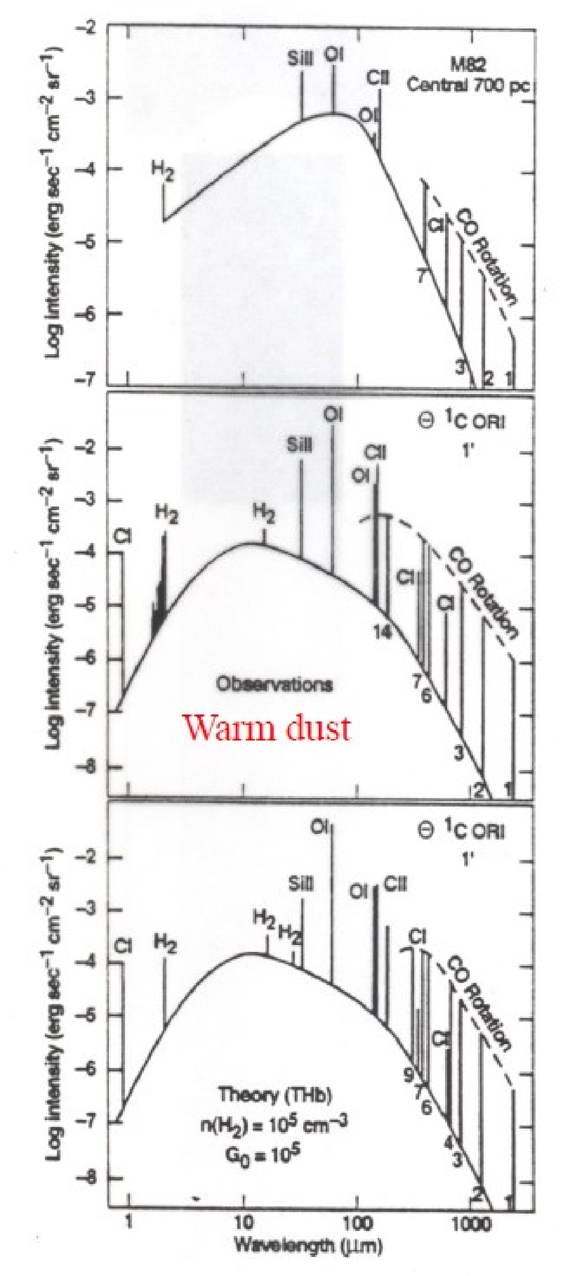
Yellow: H_2 v = 1-0
Blue: PAH
Red: CO

(0,0) = Θ^2 A Ori

Note layered structure!

Tielens et al. 1993

Global PDR emission



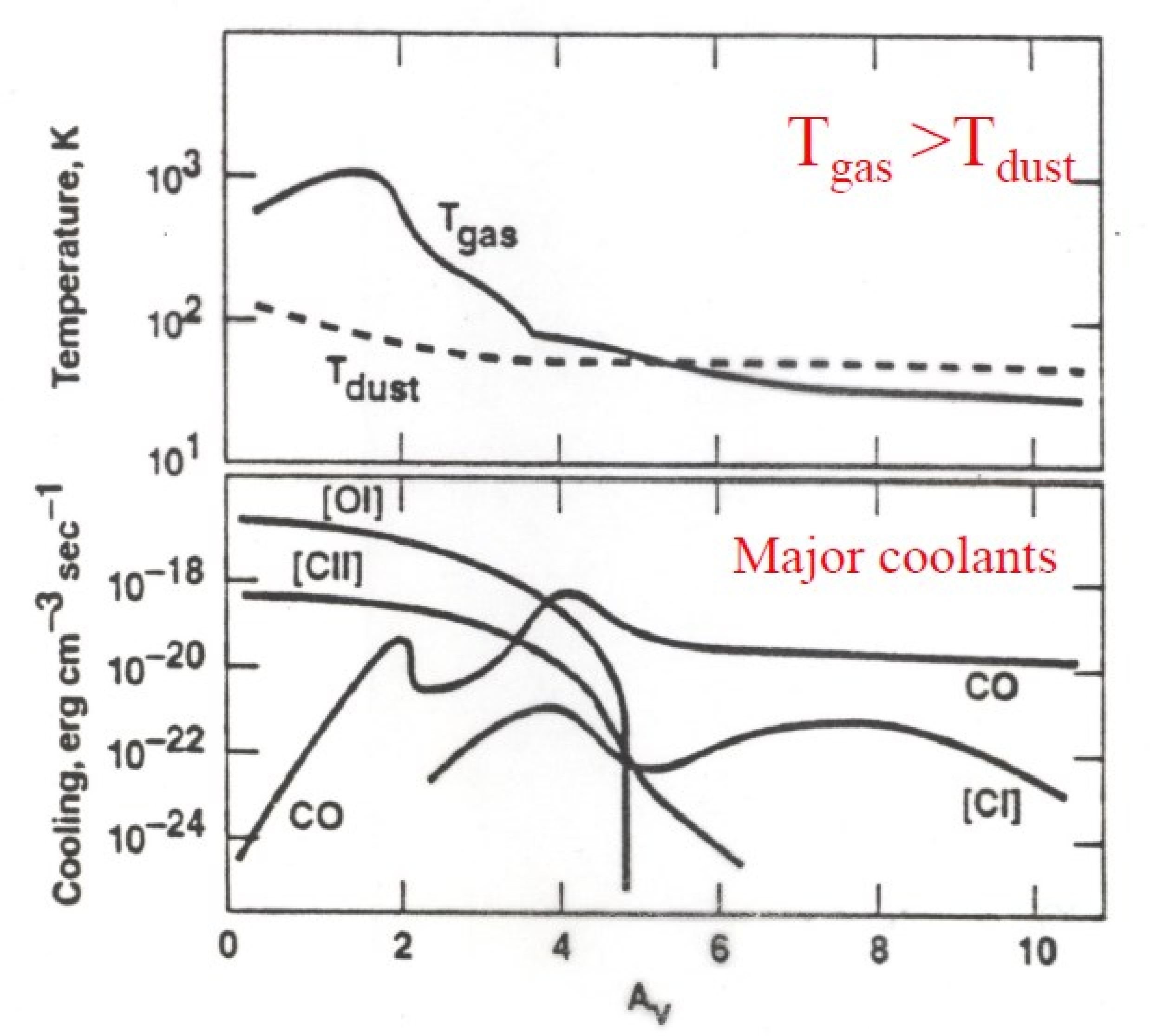
M82 galaxy

Orion

Dense PDR model

Genzel et al. 1989

Orion PDR physical structure



$n_H = 10^5$ cm^{-3}

$I_{UV} = 10^5$

Tielens & Hollenbach 1985

4.5 PDR chemistry

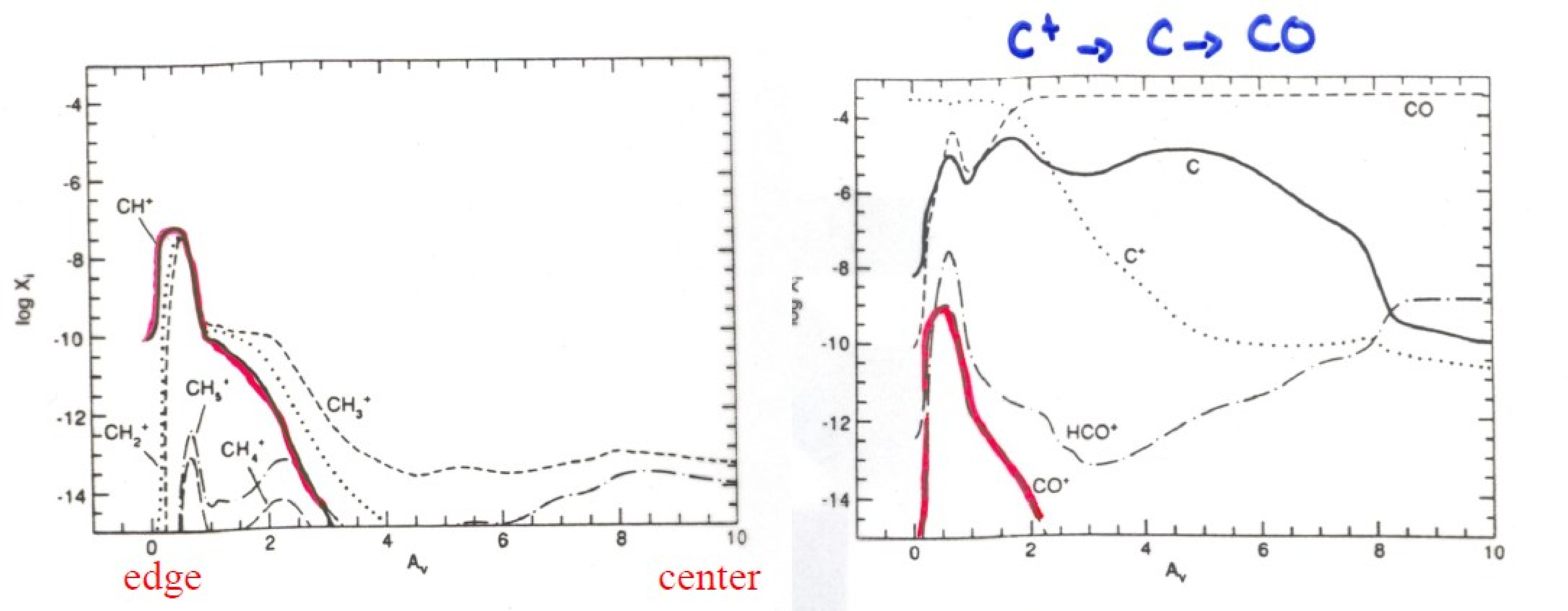
- General PDRs physics → Astrochem 2
  - Heating: photoelectric effect on grains
  - Cooling: [C II], [O I], CO
- Consider here chemistry
  - Orion Bar: $n_H = 10^6$ cm^{-3}, $I_{UV} = 10^5$
- Main chemical characteristics linked to transition atomic → molecular form
  - $H \rightarrow H_2$
  - $C^+ \rightarrow C \rightarrow CO$
  - $O \rightarrow O_2$

Note: these conditions are also representative of surface layers of protoplanetary disks.

Orion

- **$H \rightarrow H_2$ transition layer:** $A_V < 0.5$ mag
  - Because of high I_{UV}, $T > 1000$ K => endoergic reactions
    - $O + H_2 \rightarrow OH + H$
    - $C^+ + H_2 \rightarrow CH^+ + H$
    - $N + H_2 \rightarrow NH + H$
    - $S + H_2 \rightarrow SH + H$
- Large abundance of OH leads to other species
- Note that CO^+ prominent in PDRs.

Orion PDR



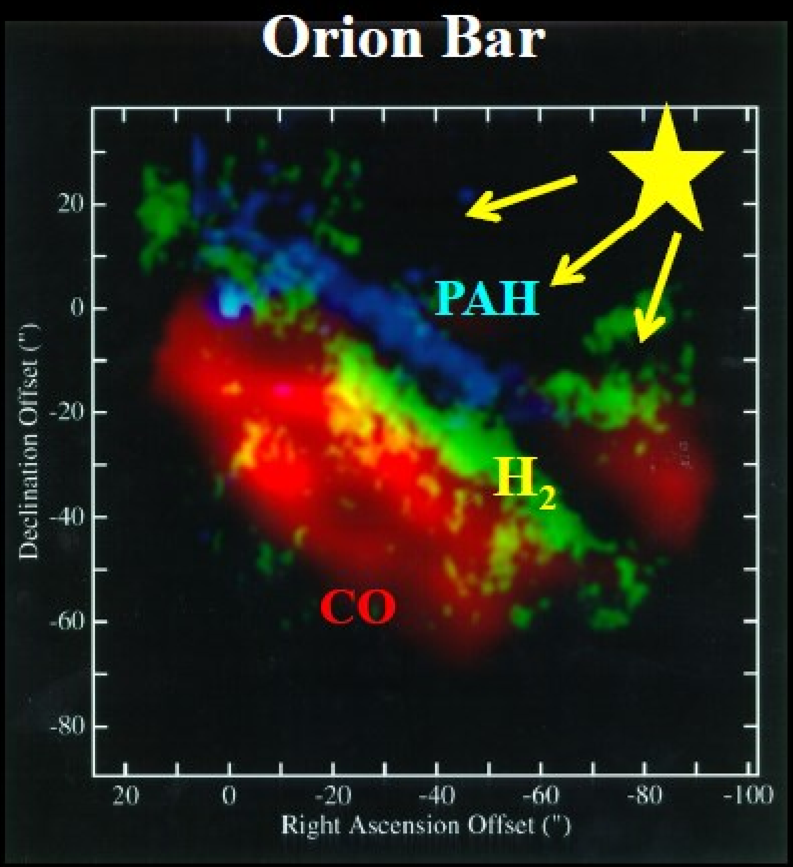
PDR tracers: CH$^+$, CO$^+$

Sternberg & Dalgarno 1995

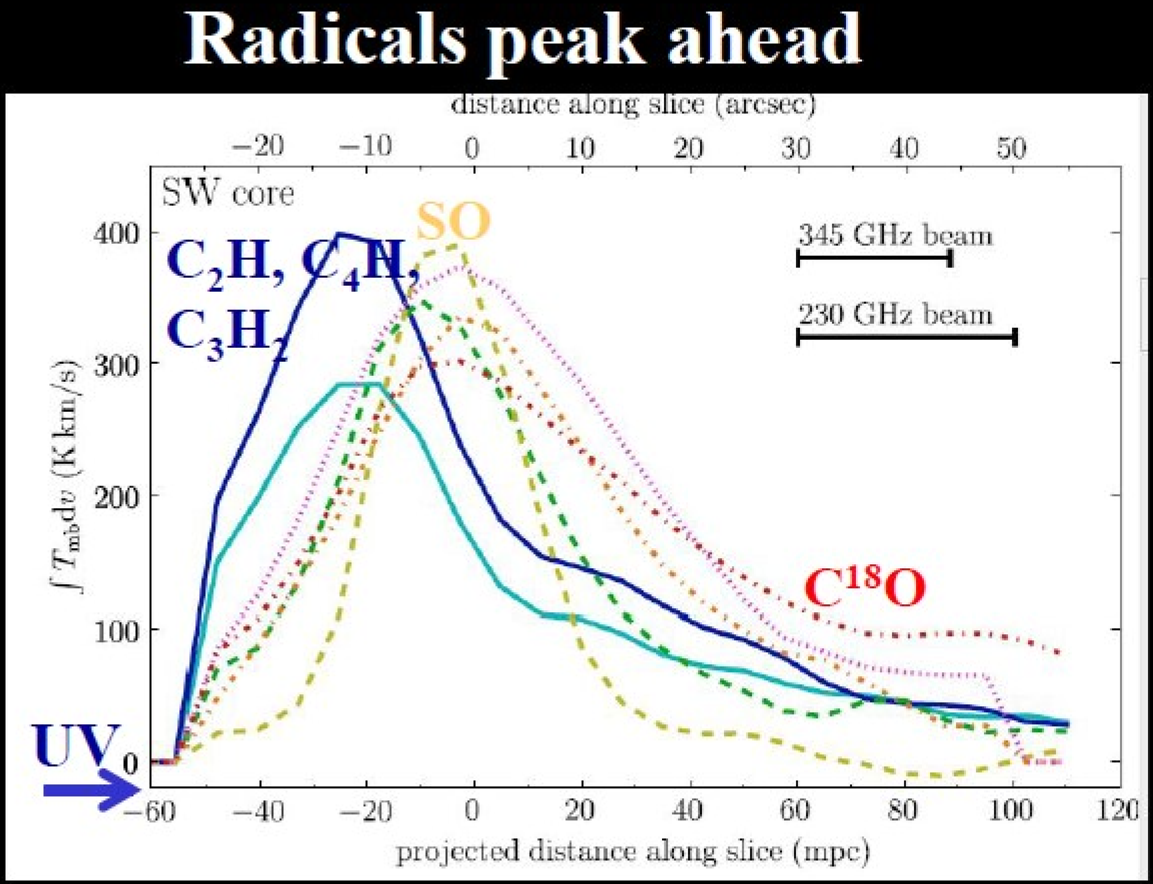
Orion PDR chemistry

- **C^+, S^+ zones:** A_V = 0.7-1.7 mag; 1.7-3.7 mag
  - *T* ~ few hundred K => form CH^+ through $C^+ + H_2{}^*$ reaction
  - Ion-molecule reactions lead to CH, C_2H, CN, ...
  - $C^+ + S \rightarrow C + S^+$ maintains S^+
- **Si^+, S zones:** A_V = 3.7-7 mag
  - Charge transfer with Si^+ maintains S^+ and S
  - Reactions with O important; CS and SO formed
- **Dark cloud chemistry**

Layered PDR structure



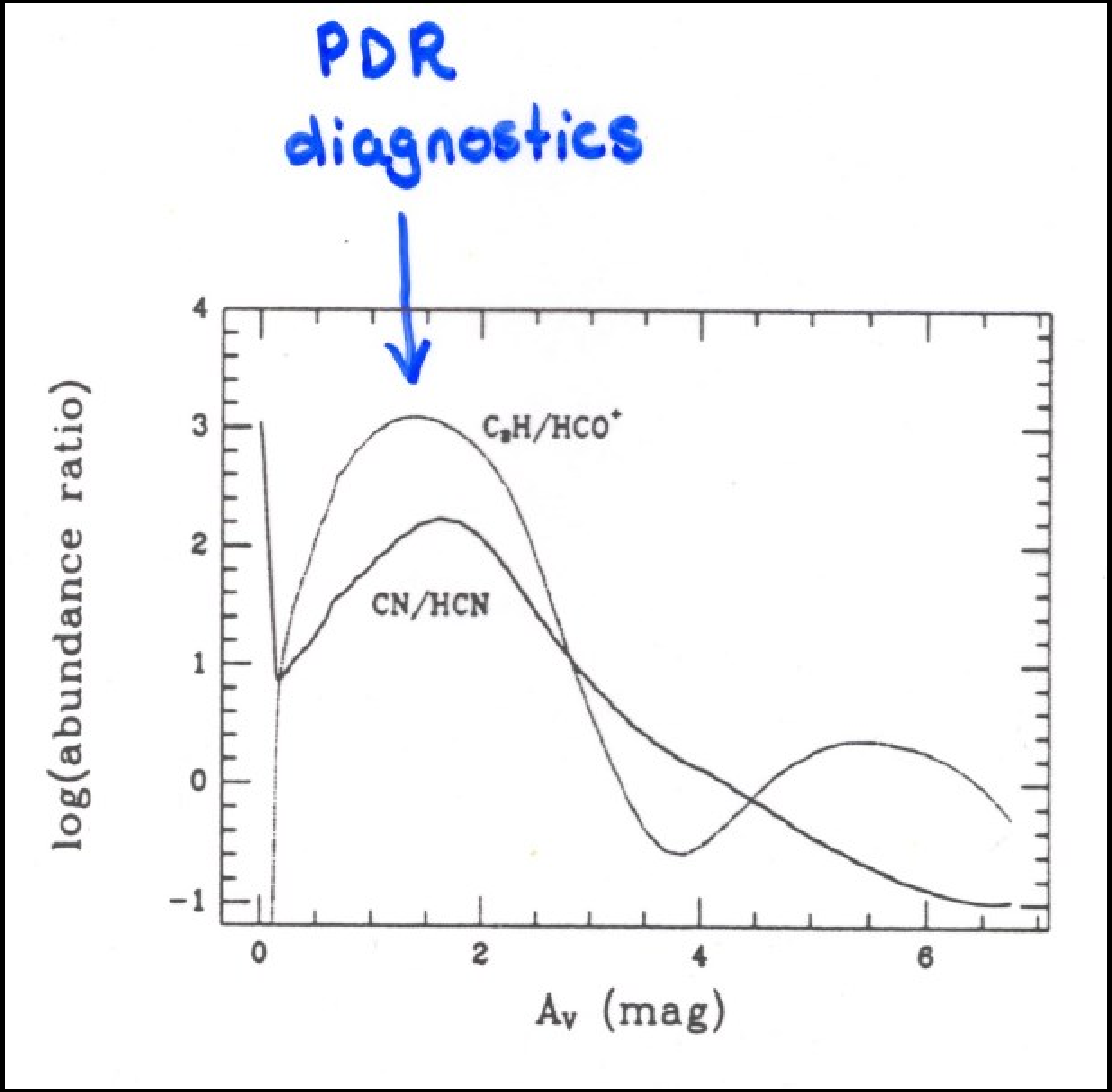
Tielens et al. 1993



Hogerheijde et al. 1995, van der Wiel et al. 2009

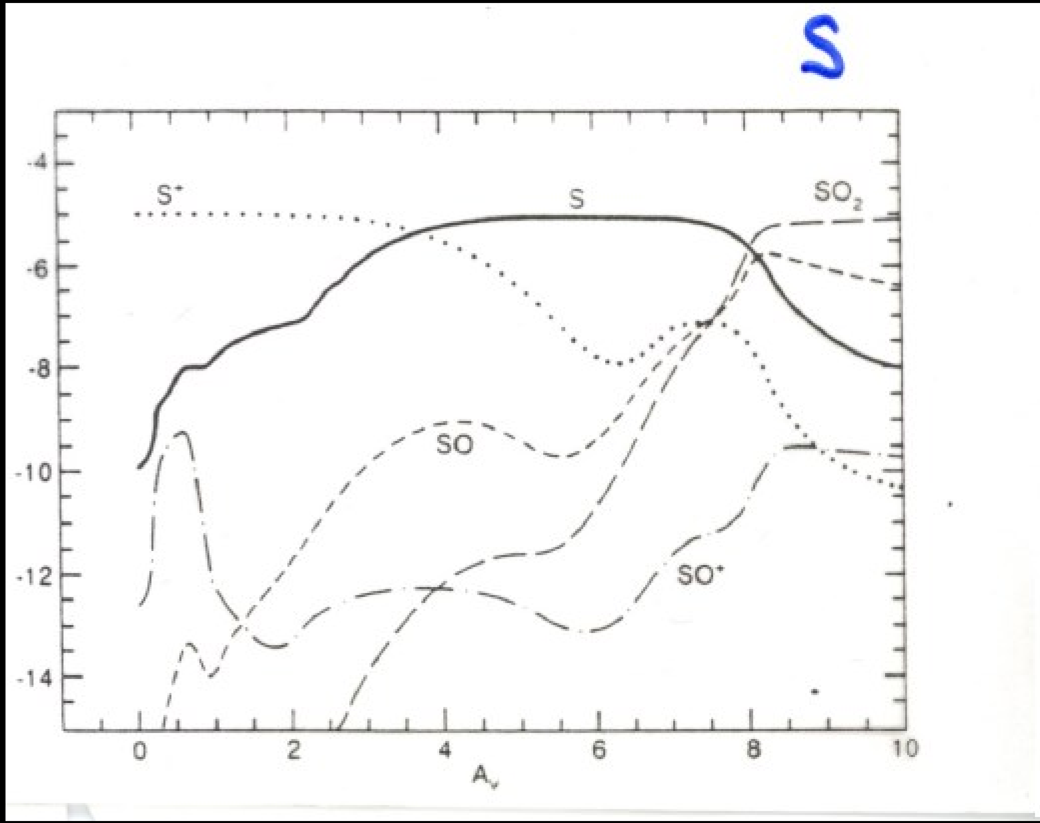
- Radicals C_2H, CN peak at $C^+ \rightarrow C$ transition
- Stable HCN, CO peak deeper into cloud

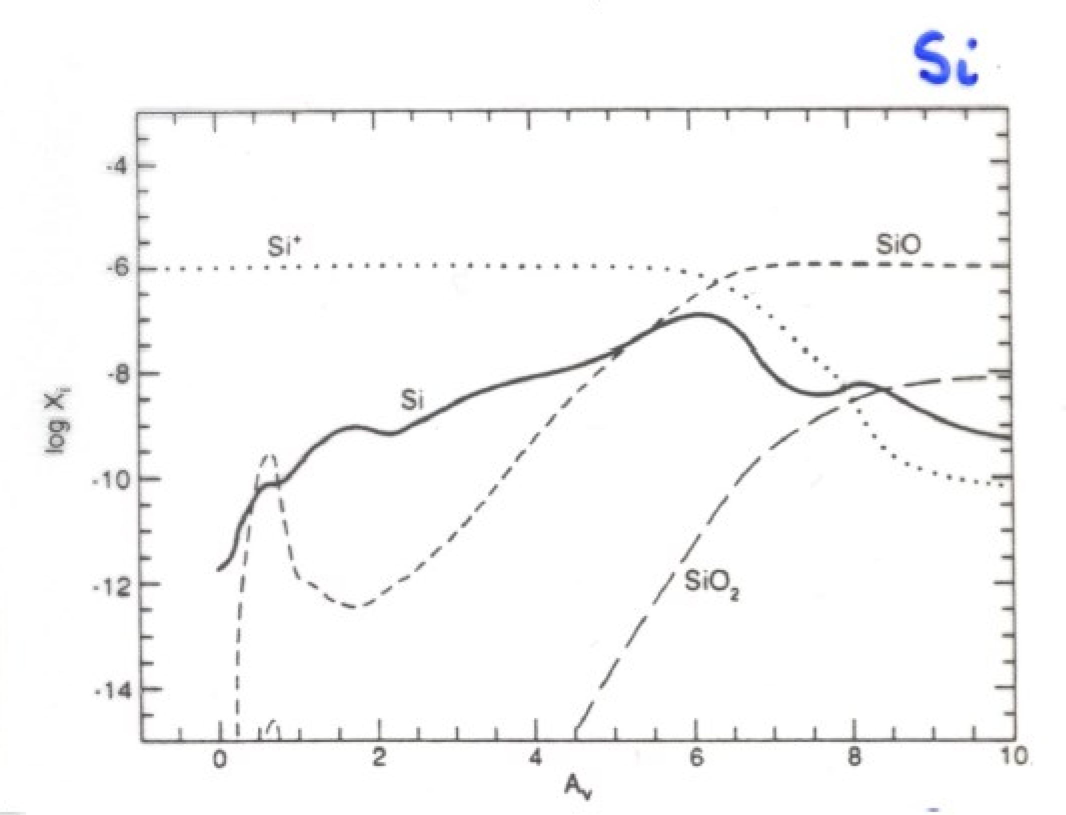
PDR diagnostics: CN/HCN



Jansen et al. 1995

Orion chemistry

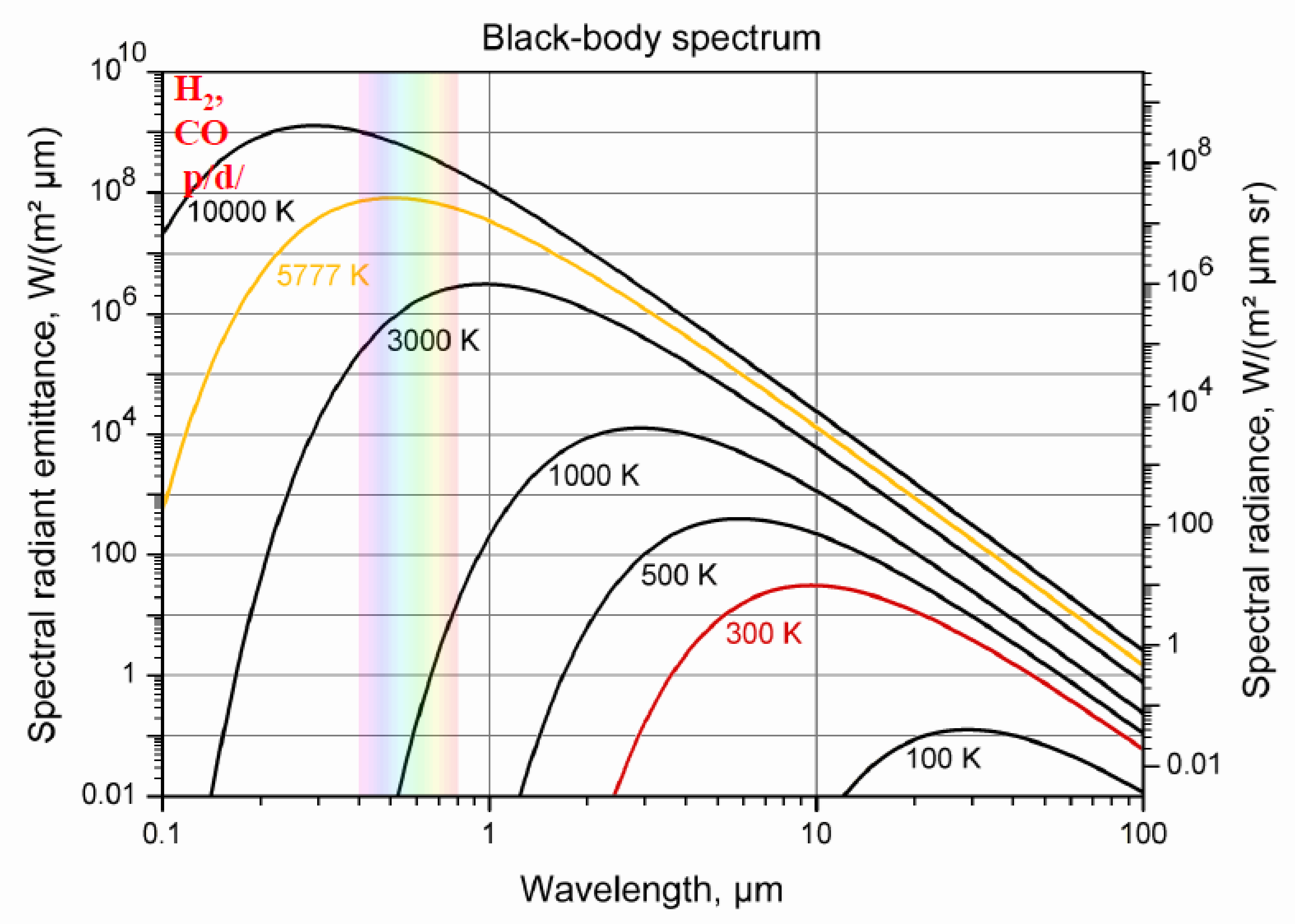




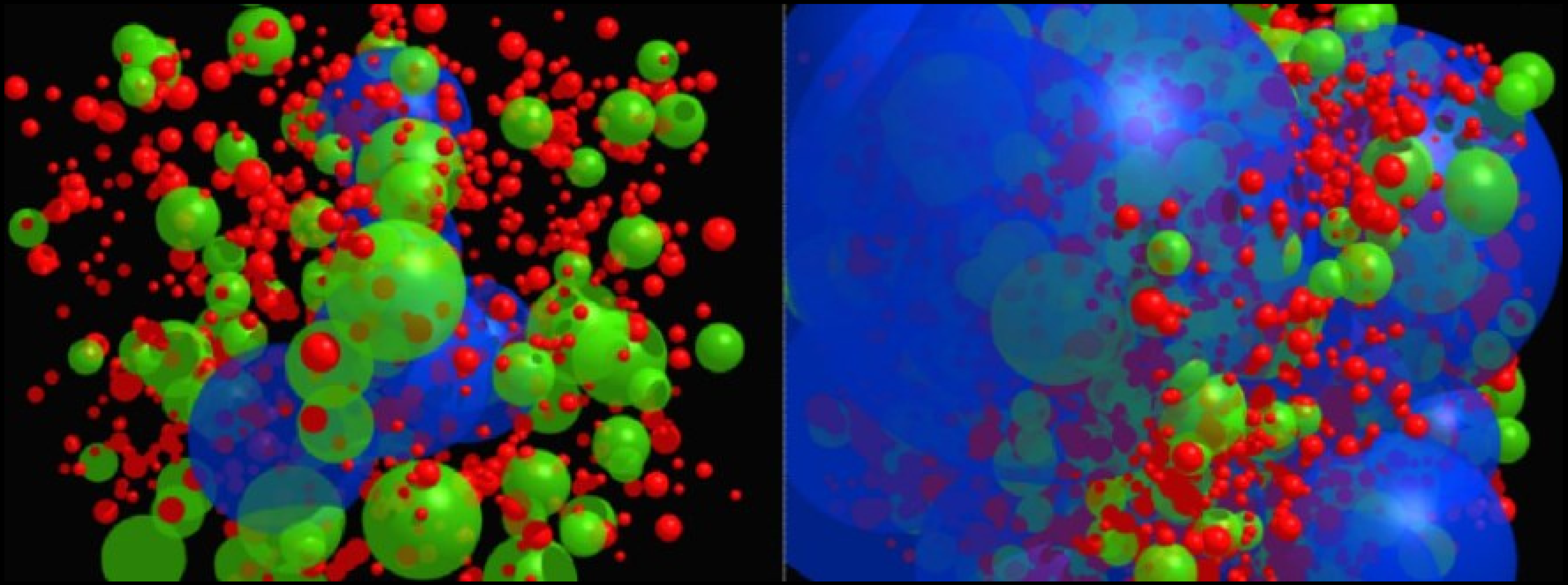
Beyond the standard model

- Cool PDRs
  - Clouds exposed to A, F, ... Stars with T_{eff} = 6000-10000 K => fewer photons between 11 and 13.6 eV to dissociate H_2 and CO
- Metal poor PDRs
  - Regions with C, O, ... depleted by factors > 4. Large gas/dust ratios (ex: LMC, SMC)
- Inhomogeneous, clumpy PDRs
  - Regions with large density contrasts and small filling factors clumps
- Time-dependent PDRs
  - Regions with evolving radiation field (e.g., planetary nebulae) or flowing gas (e.g., expanding H II region)
- XDRs
  - Regions exposed to X-rays, which ionize H, He, and multiply ionized atoms (e.g., S^{2+}). Penetrate farther into cloud than UV

Cool radiation fields



Clumpy molecular clouds



Stutzki et al. 1998, Stutzki 2009

- **Do molecular clouds indeed have such a structure?**
- **Adds additional parameters to models**

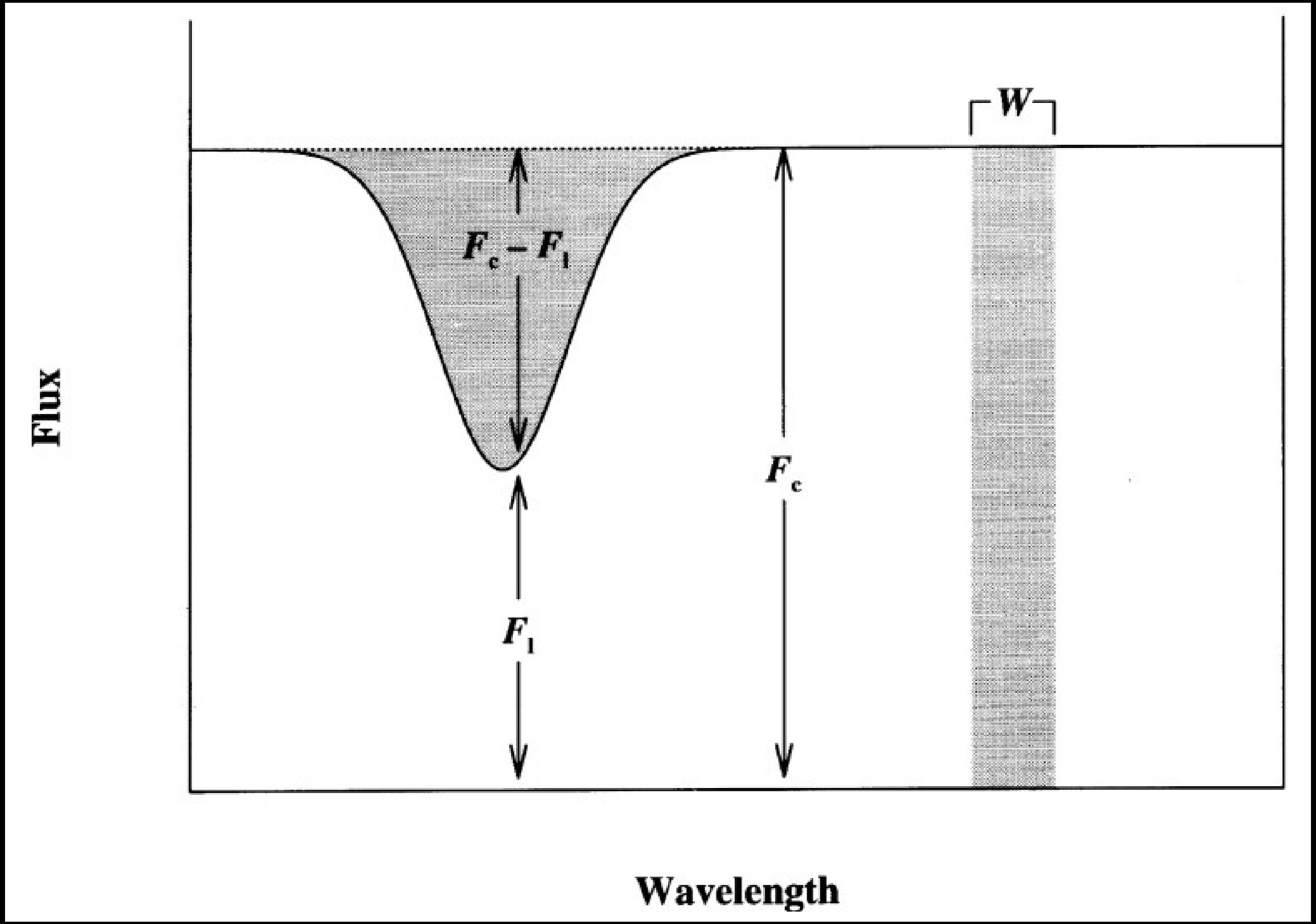
Summary Lecture 4

- Diffuse and translucent clouds are unique laboratories for testing gas-phase chemistry
- Data and insight from mm+FIR absorptions
  - Herschel, ALMA
- Several successes, but also some problems
  - Sometimes physics rather than chemistry not understood (e.g., turbulence)!
- Structure of diffuse and translucent clouds as well as dense PDRs controlled by $H \rightarrow H_2$, and $C^+ \rightarrow C \rightarrow CO$ transitions

Appendix: equivalent width of spectral lines

- In practice, resolution at optical wavelengths often insufficient to resolve line => measure only line strength or equivalent width
- Definition of equivalent width of line:
- $W_\nu = \int_{-\infty}^{+\infty} (1 - e^{-\tau_\nu}) d\nu = \int_{-\infty}^{+\infty} \left[\frac{I_\nu(0) - I_\nu}{I_\nu(0)}\right] d\nu$ [Hz]
- W_ν is the width of a rectangular profile from 0 to $I_\nu(0)$ that has the same are as actual line
- W_ν measures line strength, but units are Hz
- In wavelength units: $W_\lambda = \frac{d\lambda}{d\nu} W_\nu = \frac{\lambda^2}{c} W_\nu$ [cm]

Schematic drawing of equivalent width of line



Column density: $N \propto W/f$ if line optically thin with f= oscillator strength