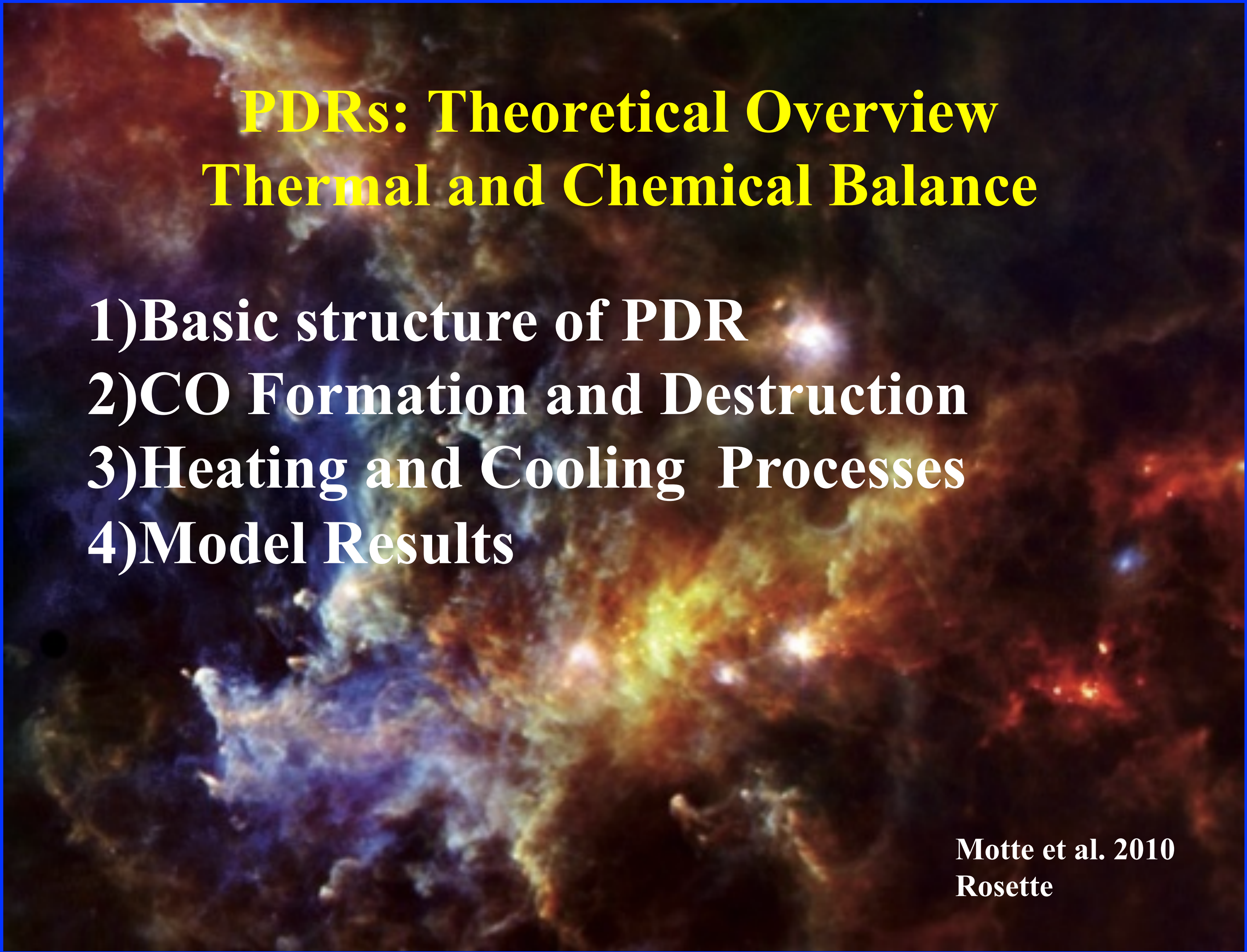
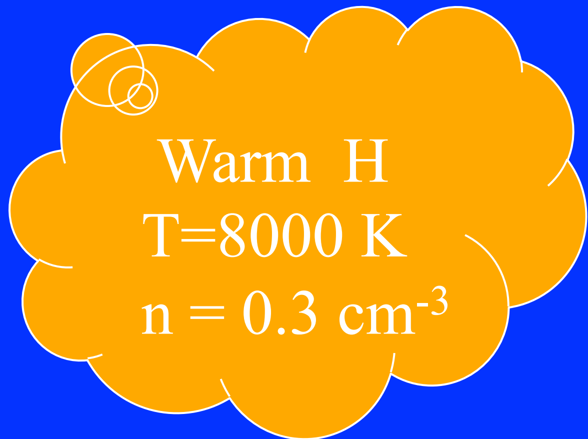
PDRs: Theoretical Overview
Thermal and Chemical Balance

1)Basic structure of PDR
2)CO Formation and Destruction
3)Heating and Cooling Processes
4)Model Results



Motte et al. 2010
Rosette

PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry

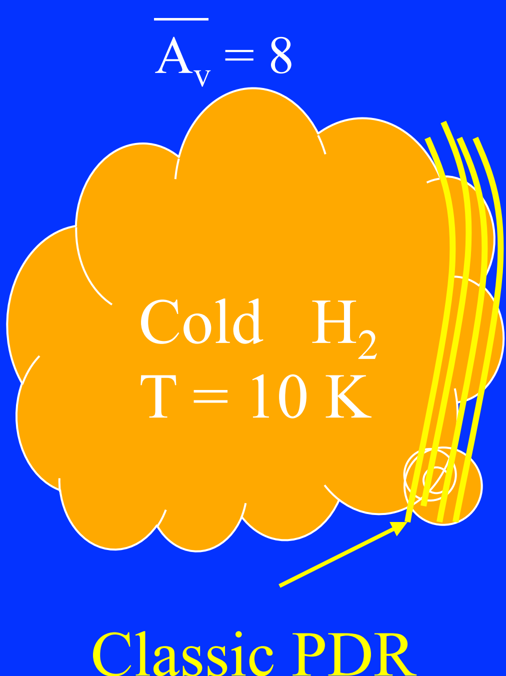


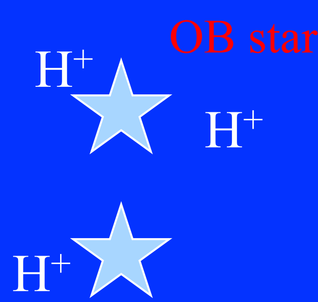
FUV: 6 eV – 13.6 eV

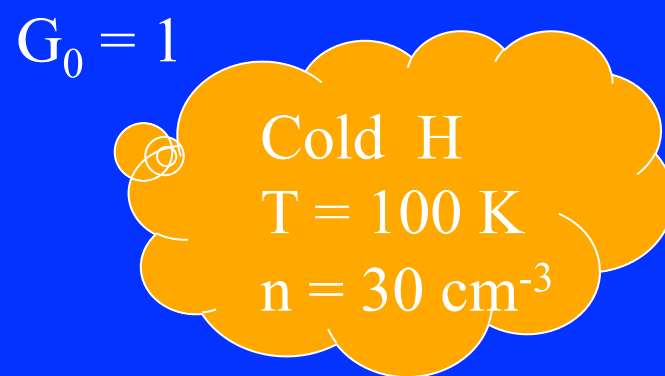
$G_0 = 1$ Interstellar field

G_0: Habing χ:Draine ~1.7 G_0

$G_0 = 10^5$ Orion trapezium

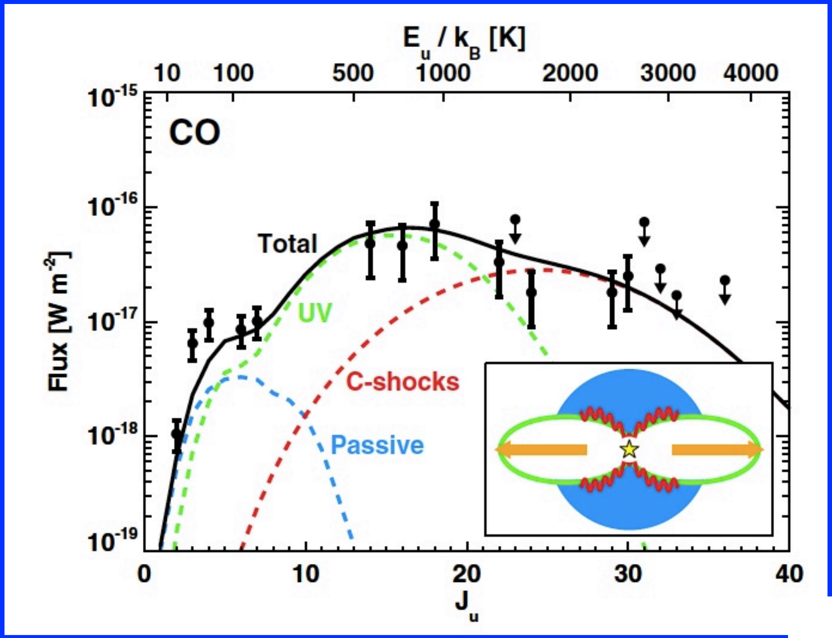






$P/k = nT = 10^3 - 10^4$ K cm^{-3}

$Av = 1 = 2 \times 10^{21}$ H cm^{-2}

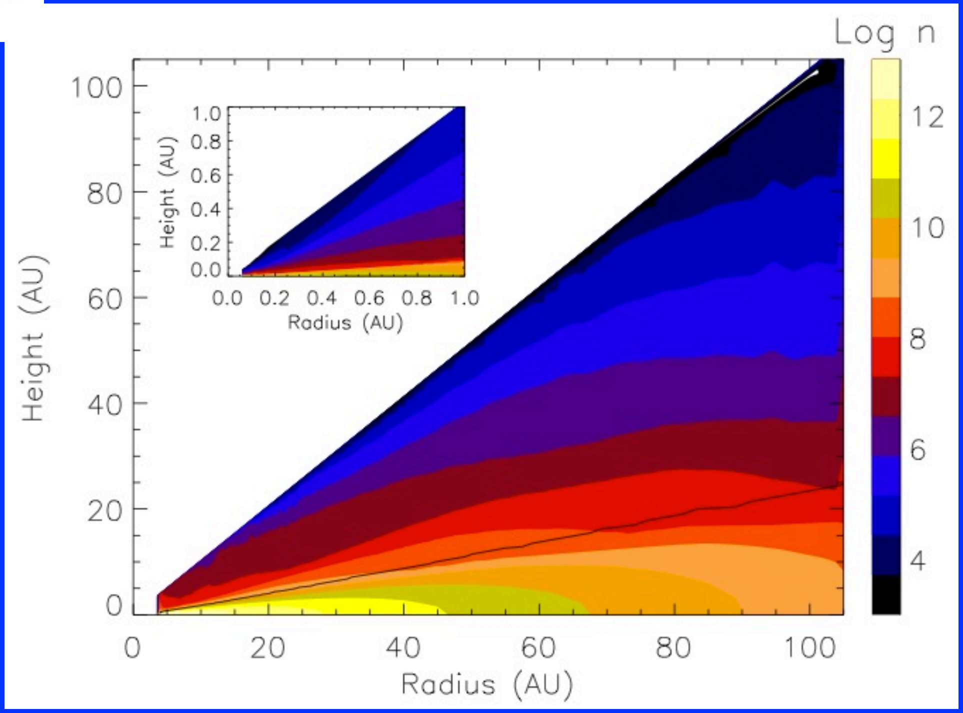


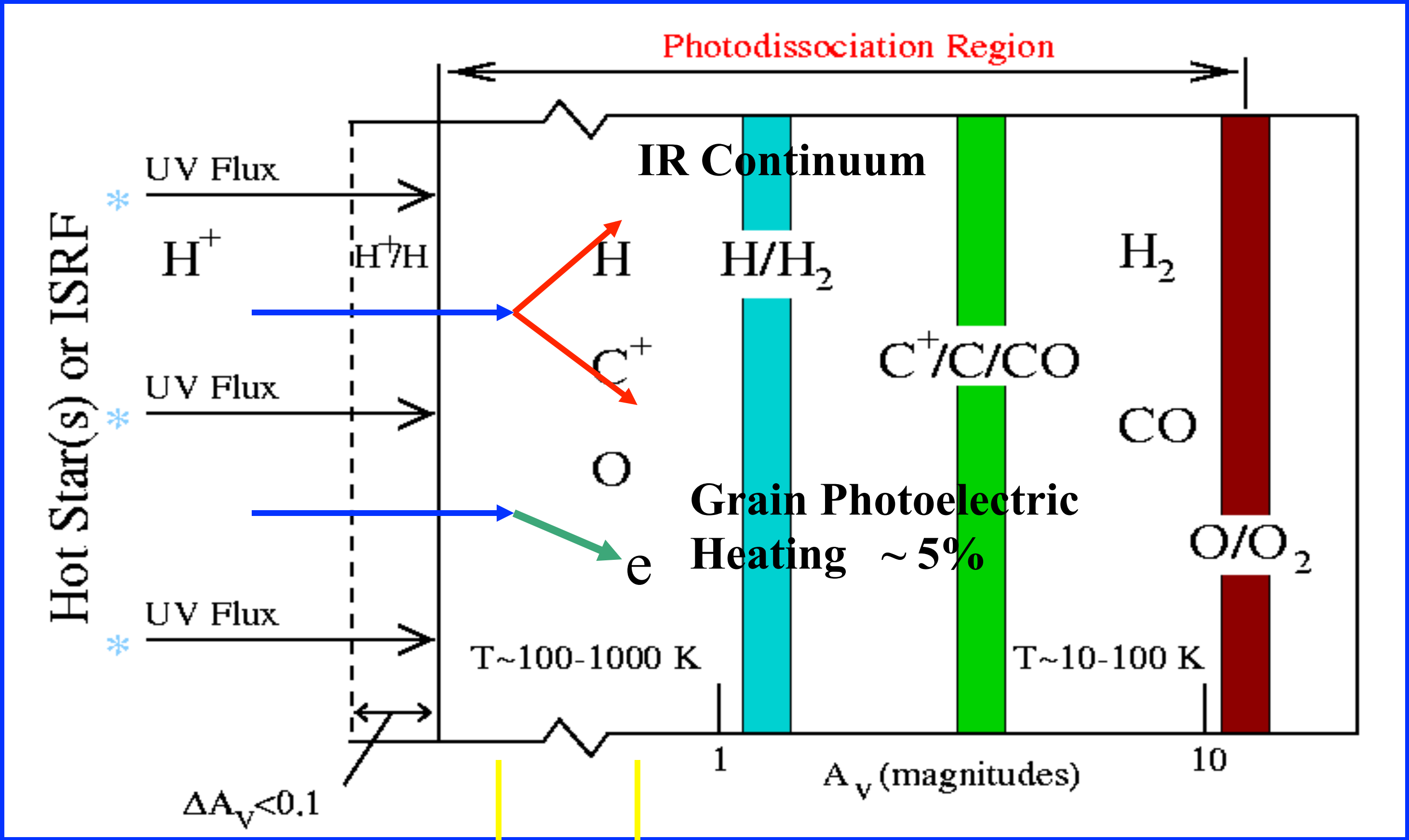
Protostellar Outflows

van Kempen et al. 2010
Visser et al. 2012
Herschel-Pacs HH46

Protostellar Disks

Gorti et al. 2011
Woitke et al. 2009
Bruderer et al. 2012
PDR disk heating, chemistry,
& structure





Diagnostics: C^+ 158 μm — Herschel

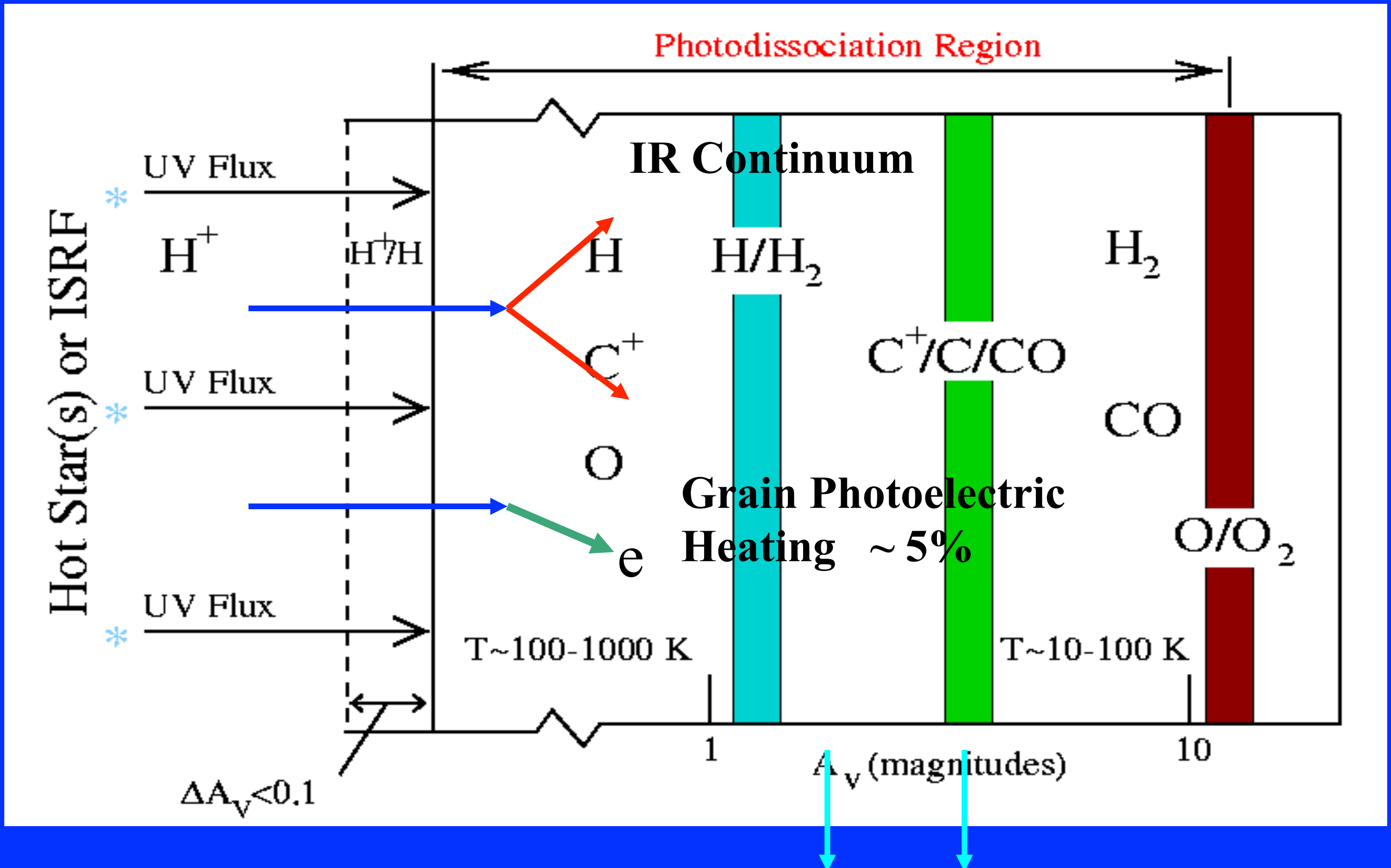
O 63 μm, 145 μm — Herschel

Si^+ 35 μm, Fe^+ 26 μm — Spitzer

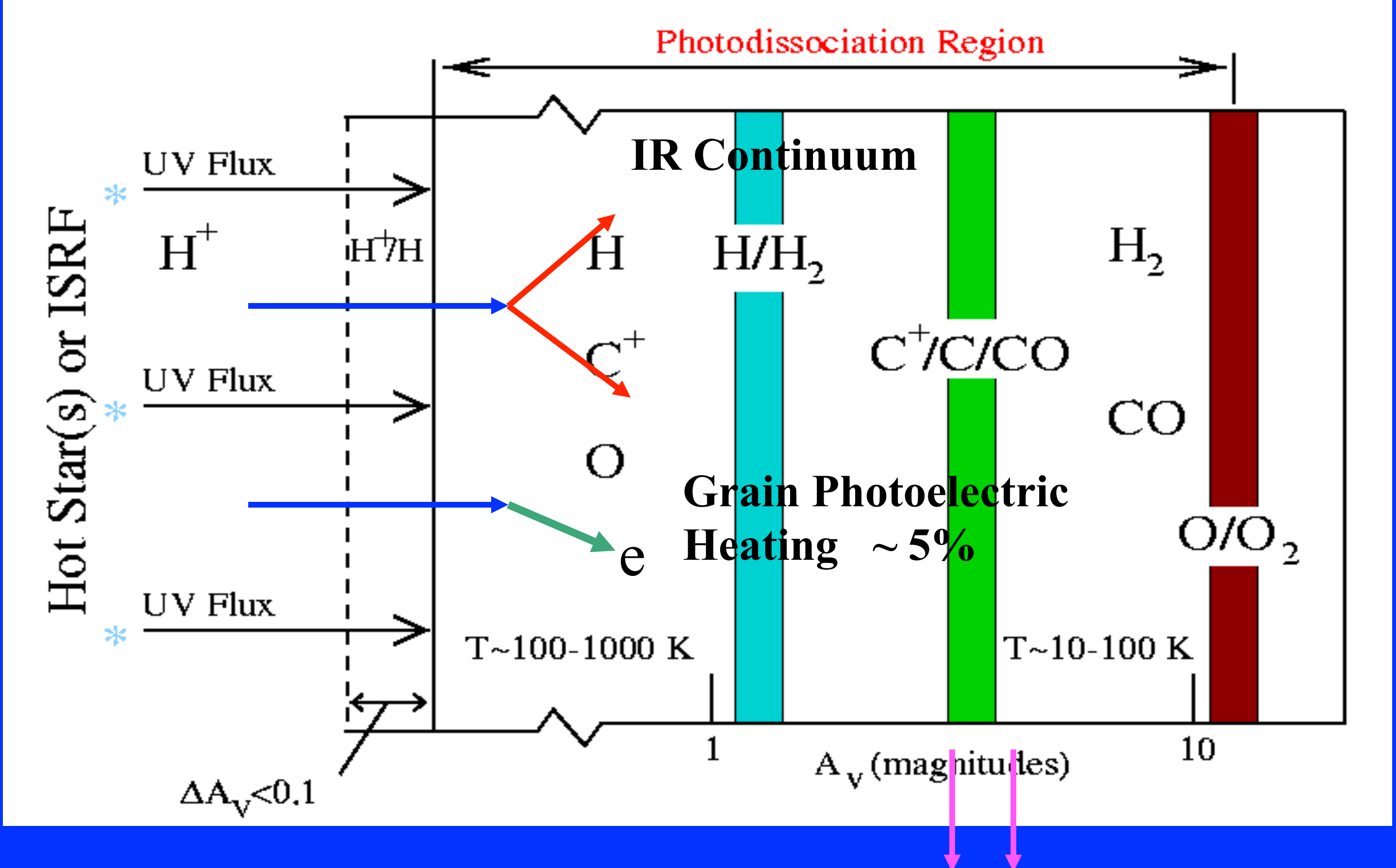
Dust Continuum — H, S

PAH 3.3, 6.2, 7.7, 8.6 — Spitzer

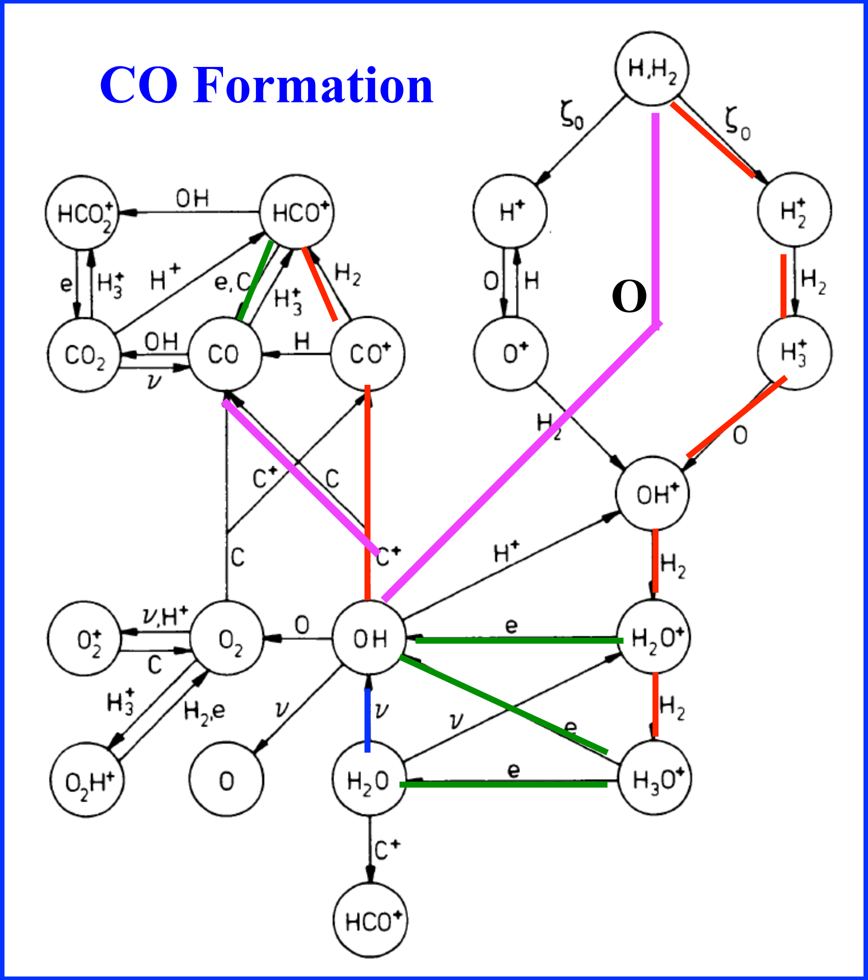
11.2 μm — Spitzer



Diagnostics: C^+ 158 µm, OI 63 µm H
C 609 µm, 370 µm H
H_2 0-0 S(2) 12.3 µm S
H_2O, H_2O^+, OH^+ H



Diagnostics: High –J CO **H**



van Dishoeck & Black 1986

CO Destruction

1)Photodissociation

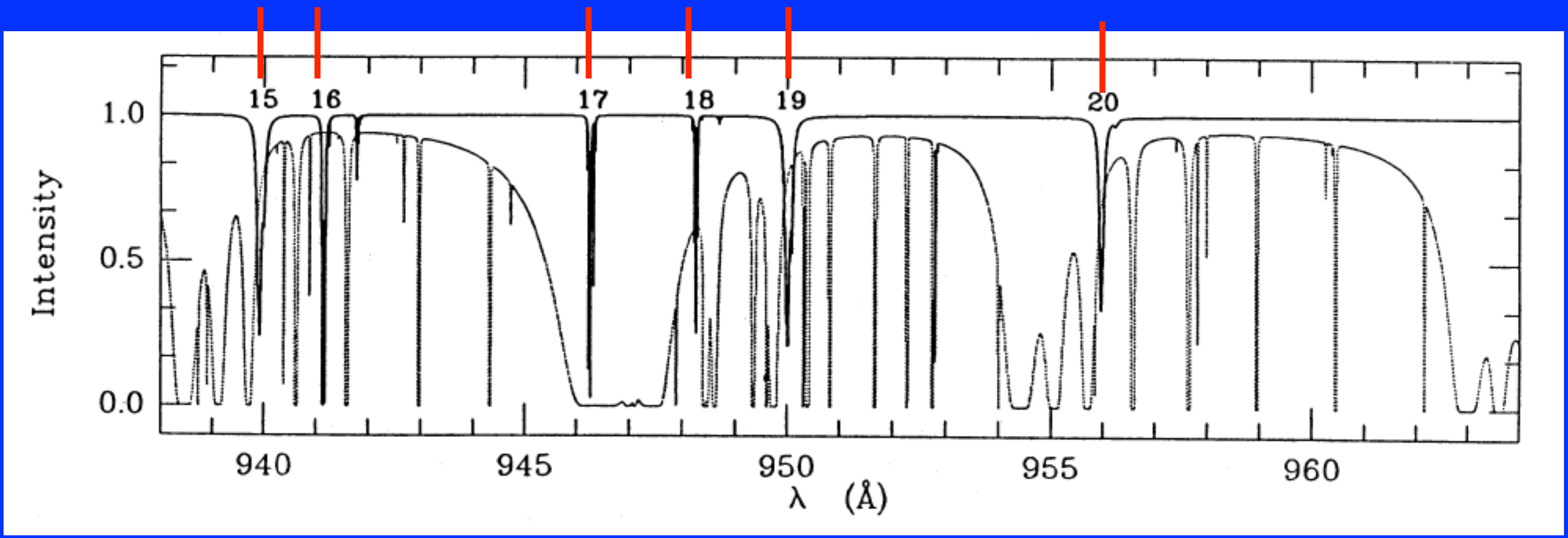
2)CO + H_3^+

3)CO + He^+

4)Freeze-out

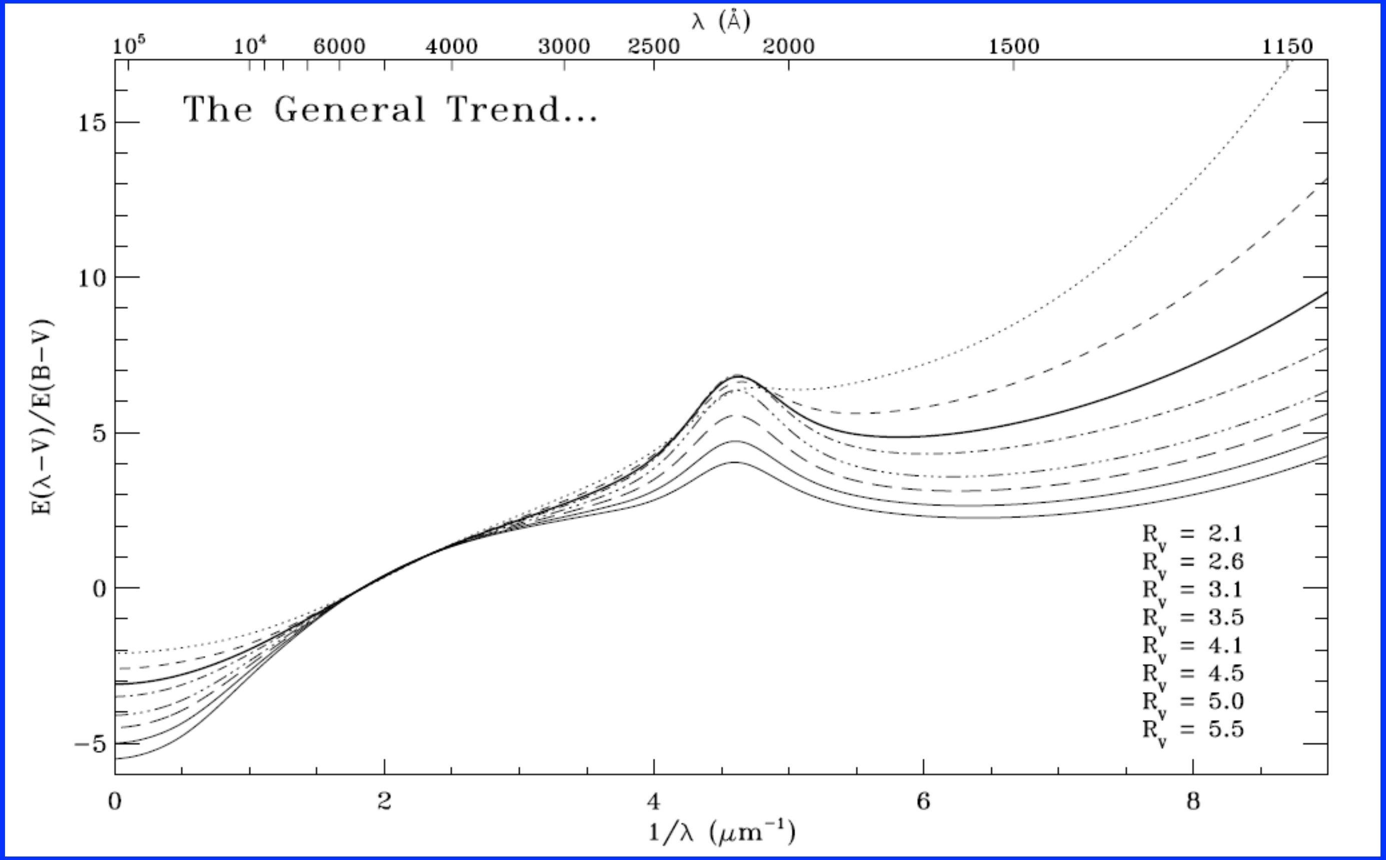
CO Photodissociation

1) Dissociates in lines
2) Wavelength < 1076 Å
3) Line overlap with H, H_2, CO
4) Self-Shielding



van Dishoeck & Black 1988
Visser, van Dishoeck, & Black 2009

Dust Extinction



Diffuse Gas

Dense Gas

CO →

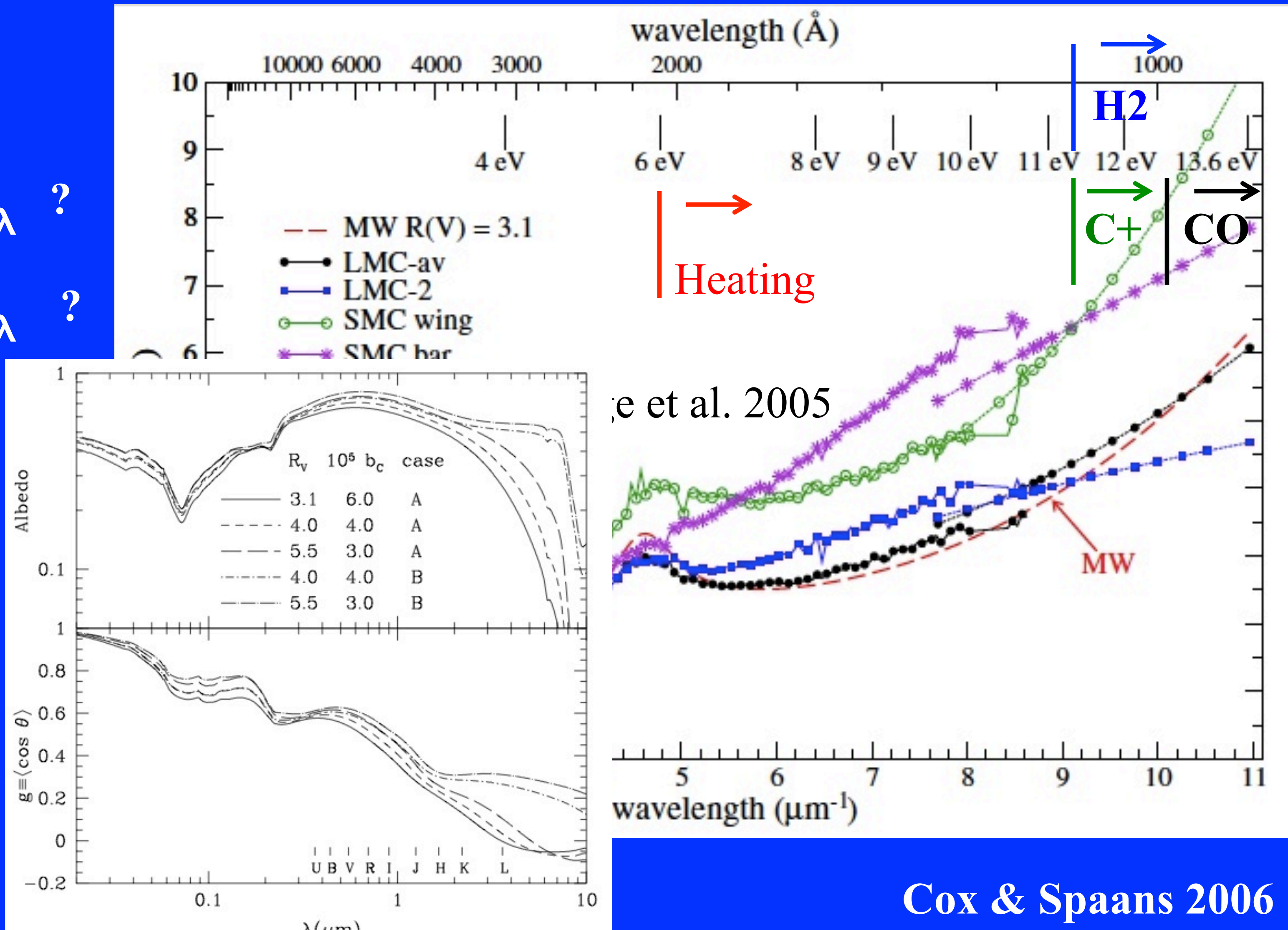
$$R \propto \exp(-\alpha A_\lambda)$$

Fitzpatrick 2004

Extinction Curves

ω_λ ?

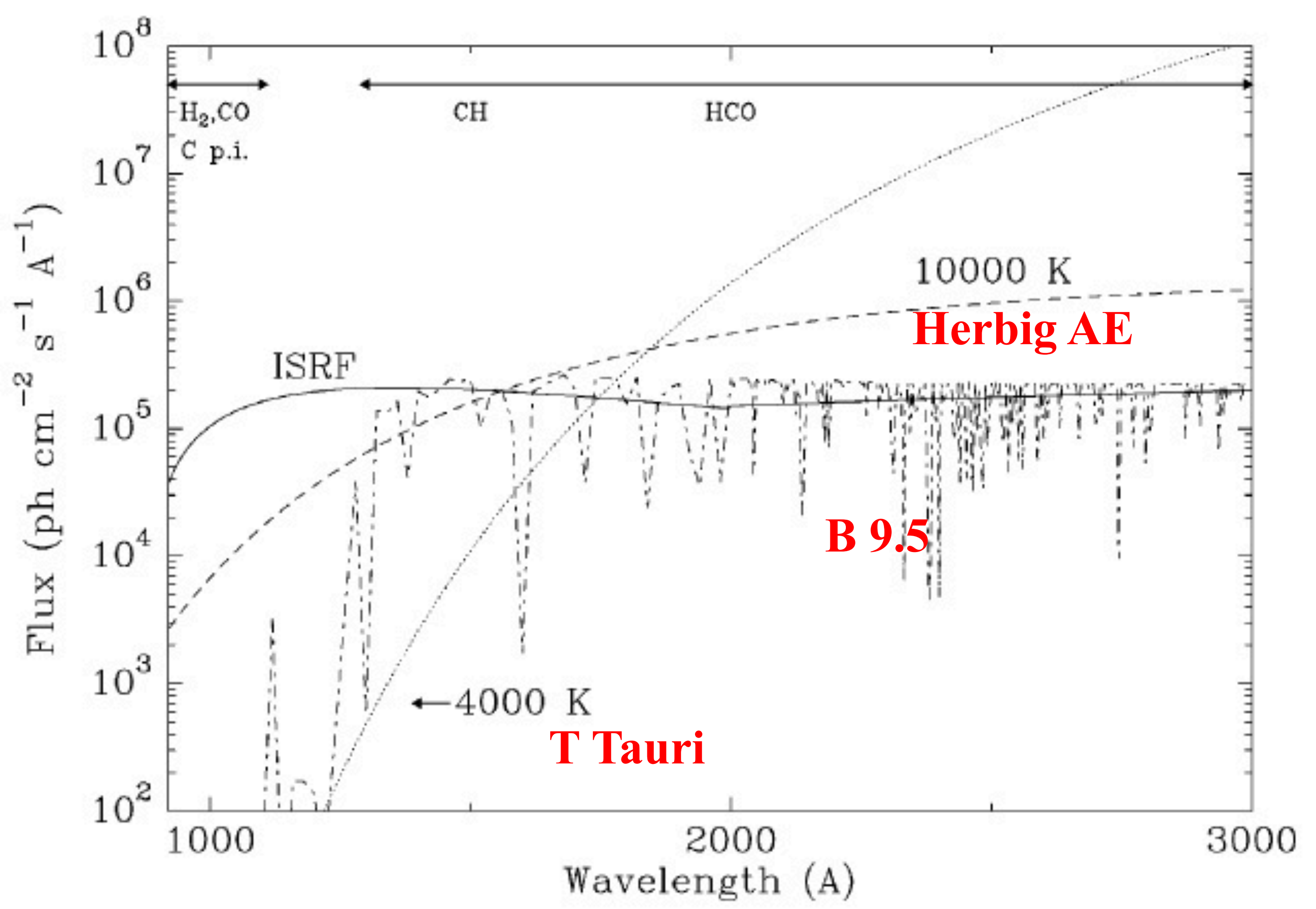
g_λ ?



Cox & Spaans 2006

Weingartner & Draine 2001

Radiation Field Hardness (FUV)



van Dishoeck, Jonkheid, van Hemert 2006
Bruderer et al. 2012

Table 2 Photodissociation rates for various radiation fields[ab]

$$k_{pd} = k^0_{pd} \exp(-\gamma A_V)$$

Species	$k^{\mathrm{o}}_{\mathrm{pd}}/\mathrm{s}^{-1}$ ISRF[c]	$k^{\mathrm{o}}_{\mathrm{pd}}/\mathrm{s}^{-1}$ 10 000 K[d]	$k^{\mathrm{o}}_{\mathrm{pd}}/\mathrm{s}^{-1}$ 4000 K[d]	γ ISRF	γ 10 000 K	γ 4000 K
O_2	7.9(−10)	4.9(−10)	4.5(−11)	2.13	2.05	1.97
O_2^+	3.5(−11)	3.6(−11)	1.0(−11)	2.02	1.92	1.90
HO_2	6.7(−10)	1.9(−9)	1.2(−8)	2.12	2.08	1.99
H_2O_2	9.5(−10)	4.3(−10)	1.4(−10)	2.28	2.07	1.97
O_3	1.9(−9)	5.4(−9)	1.5(−7)	1.85	1.69	1.57
CO	2.0(−10)	1.5(−11)	1.4(−15)	3.53	3.47	3.24
CO^+	1.0(−10)	2.2(−11)	1.2(−13)	2.52	2.43	2.32
CO_2	8.9(−10)	9.0(−11)	1.2(−12)	3.00	2.53	2.00
HCO	1.1(−9)	2.5(−9)	3.5(−6)	1.09	1.09	0.81
HCO^+	5.4(−12)	4.5(−13)	7.9(−17)	3.32	3.32	3.32

van Dishoeck, Jonkheid, van Hemert 2006

$$R = \chi k^0_{pd} \exp(-\gamma A_V)\Theta[N(\mathrm{H}_2), N(\mathrm{CO})]$$

Visser et al. 2009

A_V Conversion to N(H)

$$\mathrm{MW}: \mathrm{A_V} = \frac{N(H)}{1.9\mathrm{x}10^{21}\,\mathrm{cm}^{-2}} \qquad \propto Z'$$

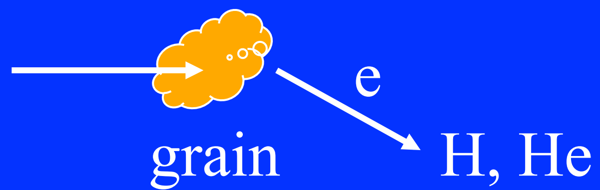
$$\mathrm{LMC\text{-}ave}: \mathrm{A_v} = \frac{N(H)}{3.3\mathrm{x}10^{21}\,\mathrm{cm}^{-2}} \qquad \propto \frac{Z'}{1.7}$$

$$\mathrm{LMC2}: \mathrm{A_v} = \frac{N(H)}{7.0\mathrm{x}10^{21}\,\mathrm{cm}^{-2}} \qquad \propto \frac{Z'}{3.7}$$

$$\mathrm{SMC\text{-}bar}: \mathrm{A_V} = \frac{N(H)}{1.3\mathrm{x}10^{22}\,\mathrm{cm}^{-2}} \qquad \propto \frac{Z'}{6.8}$$

Gordon et al. 2003

Grain Photoelectric Heating



Electron K.E. is a function of the grain charge.

Charge: Photoionization = Recombination

Photoionization α UV photon field [G_0]

Recombination α $n_e/T^{1/2}$

Photoionization/Recombination α $G_0T^{1/2}/n_e$

ε = Energy to Heating/Absorbed UV Photon Energy
= Heating Efficiency

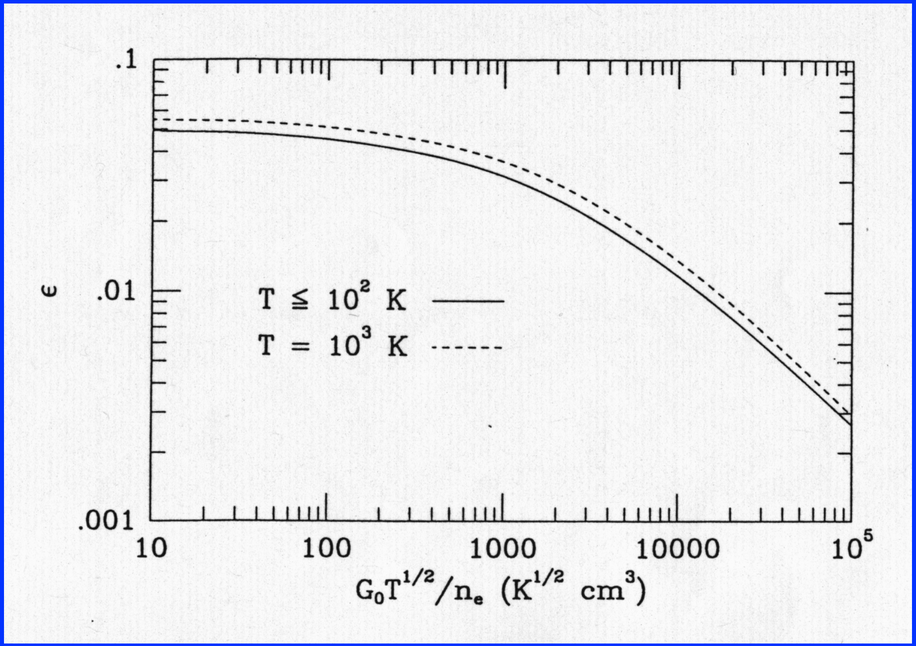
ε is a function of $G_0T^{1/2}/n_e$ (Photoionization/Recombination)

Bakes & Tielens (94)
Weingartner & Draine (01)

ε for a = 0.25 μm −> 5 Å

Neutral → Positive

Heating Efficiency



(Ionization/Recombination)

Few % -> Gas heating
Most -> IR continuum

1/2 Heating from smallest grain sizes < 15 Å

1) Yield increases as grain size decreases

2) Ionization/Recombination goes as (grain size)^2

$$n\Gamma = 1.3\text{x}10^{-24}\, n\varepsilon G_0 \;\; (\text{erg cm}^{-2}\ \text{s}^{-1})$$

$A_V = 2$

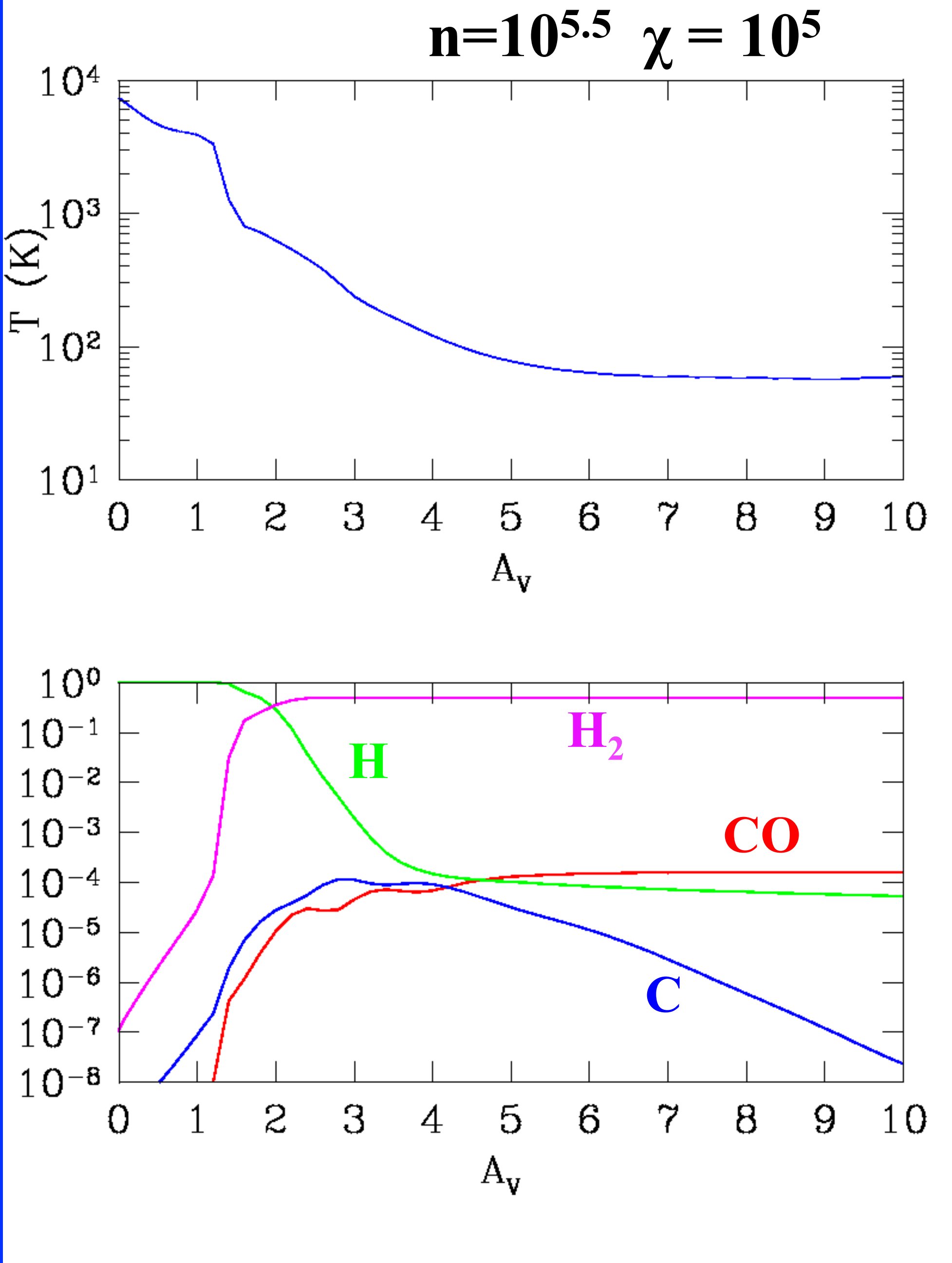
$H_2 + O$

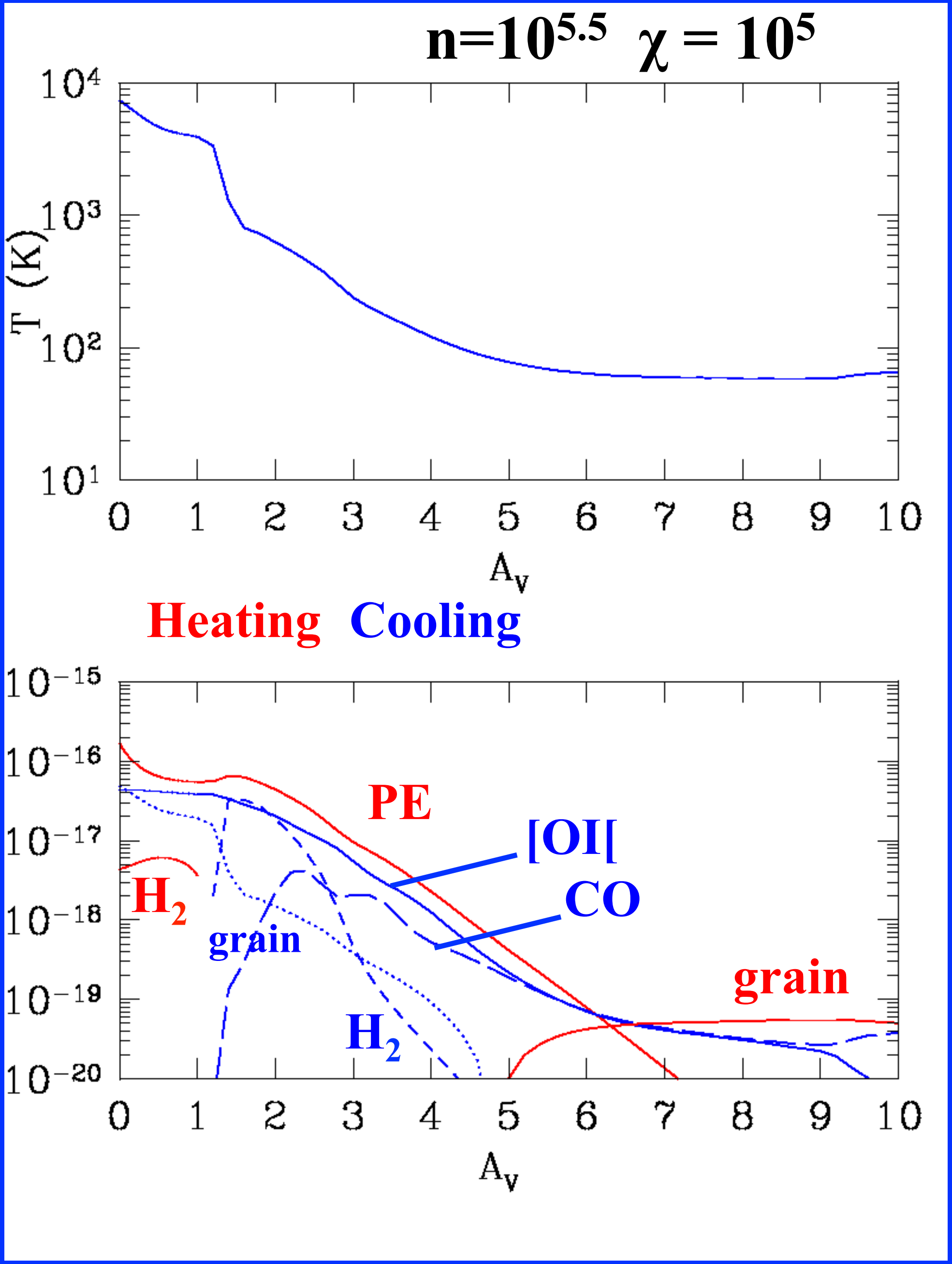
$CO + \gamma$

$A_V = 6$

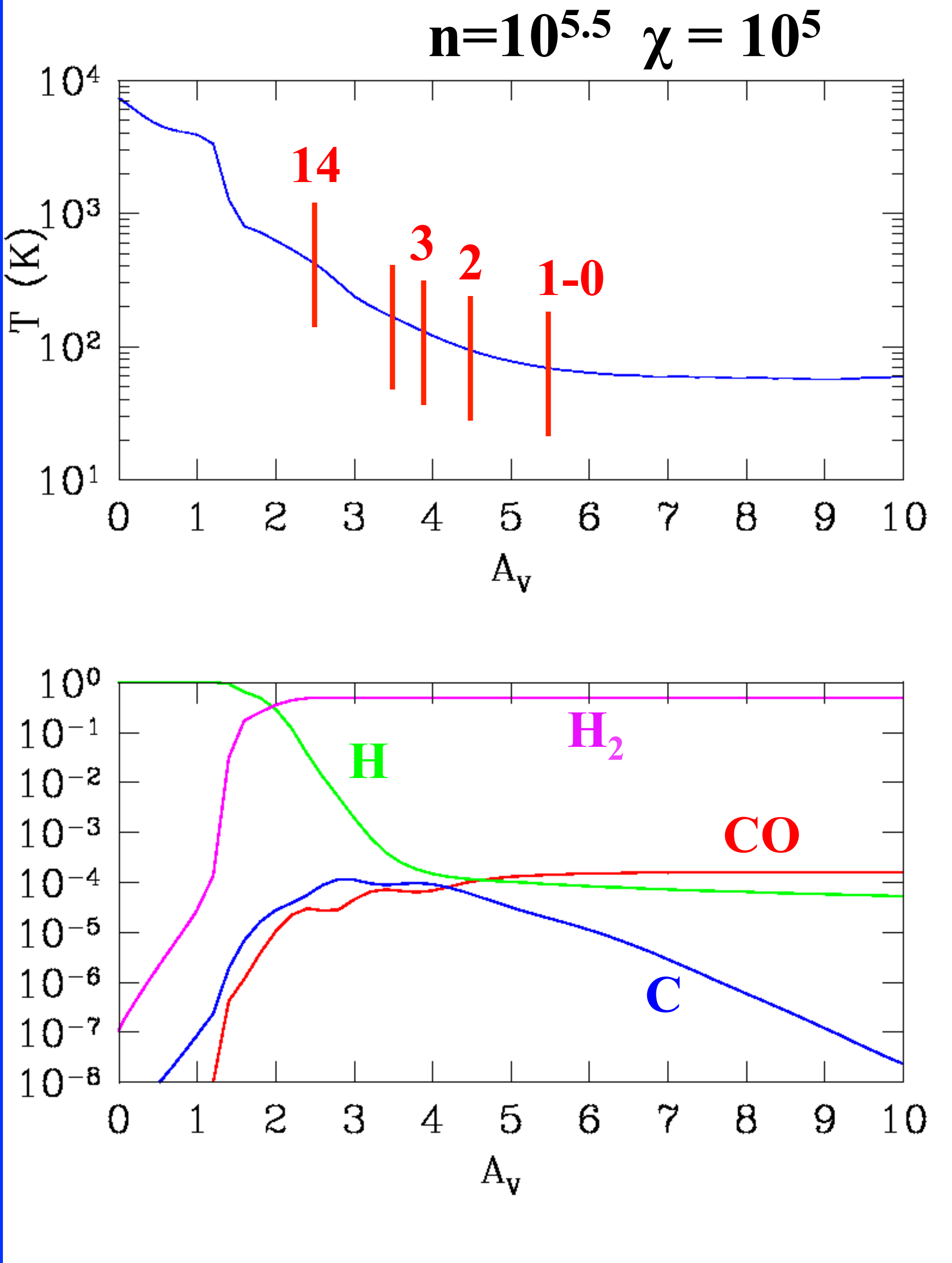
C.R. + H_2

$CO + H_3^+$
$CO + He^+$





n=10^5.5 χ = 10^5
T (K)
A_V
Heating Cooling
PE
[OI[
CO
H_2
grain
H_2
grain
A_V



n=10^5.5 χ = 10^5
T (K)
14
3
2
1-0
A_V
H
H_2
CO
C
A_V

1)Clumpy PDRs might increase the surface area of warm gas – Cubick et al. 2008, Dedes et al. 2010

2)High H_2 formation rates pull molecular gas to surface where T is higher – Le Bourlot et al. 2012

3)Ion–Recombination on PAHs – Hollenbach et al. 2012, Wolfire et al. 2003

4)Freeze out, surface chemistry, desorption – Öberg et al. 2009, Hollenbach et al. 2009, Cecchi-Pestellini et al. 2010