Excitation of the C^+ 158 μm Transition

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Early History of Observations of [CII] 158 μm Fine Structure Transition

DETECTION OF THE 157 MICRON (1910 GHz) [C II] EMISSION LINE FROM THE INTERSTELLAR GAS COMPLEXES NGC 2024 AND M42

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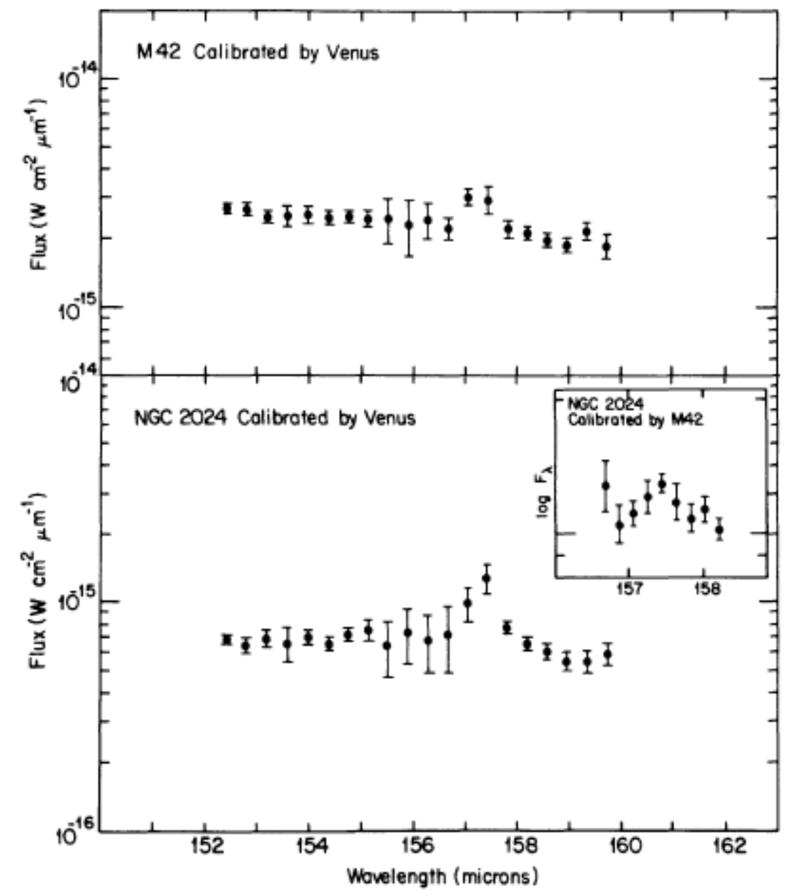
We have obtained the first observations of the 157 μm [C II] cooling line. On the assumption that the 157 μm [C II] radiation emanates from the same region as 63 μm [O I] radiation, i.e., from neutral H I layers surrounding the H II domain, we can derive approximate gas temperatures. Optical depth effects in the 157 μm line may be significant but have not been taken into account in our calculations because our data base is still too restricted.



GIANT [C II] HALOS AROUND H II REGIONS

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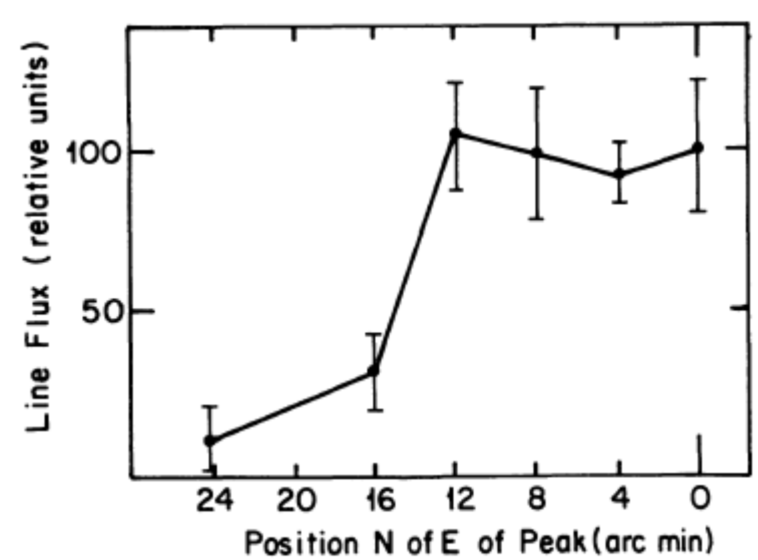
The arguments presented by Russell *et al.* (1980) show that most of the [C II] 157 μm emission from M42 and NGC 2024 does not arise from within the ionized gas. This conclusion can be shown to apply also to M17, where much of the carbon within the H II region will be doubly ionized. We therefore assume that the 157 μm emission is excited collisionally in a predominantly neutral medium.

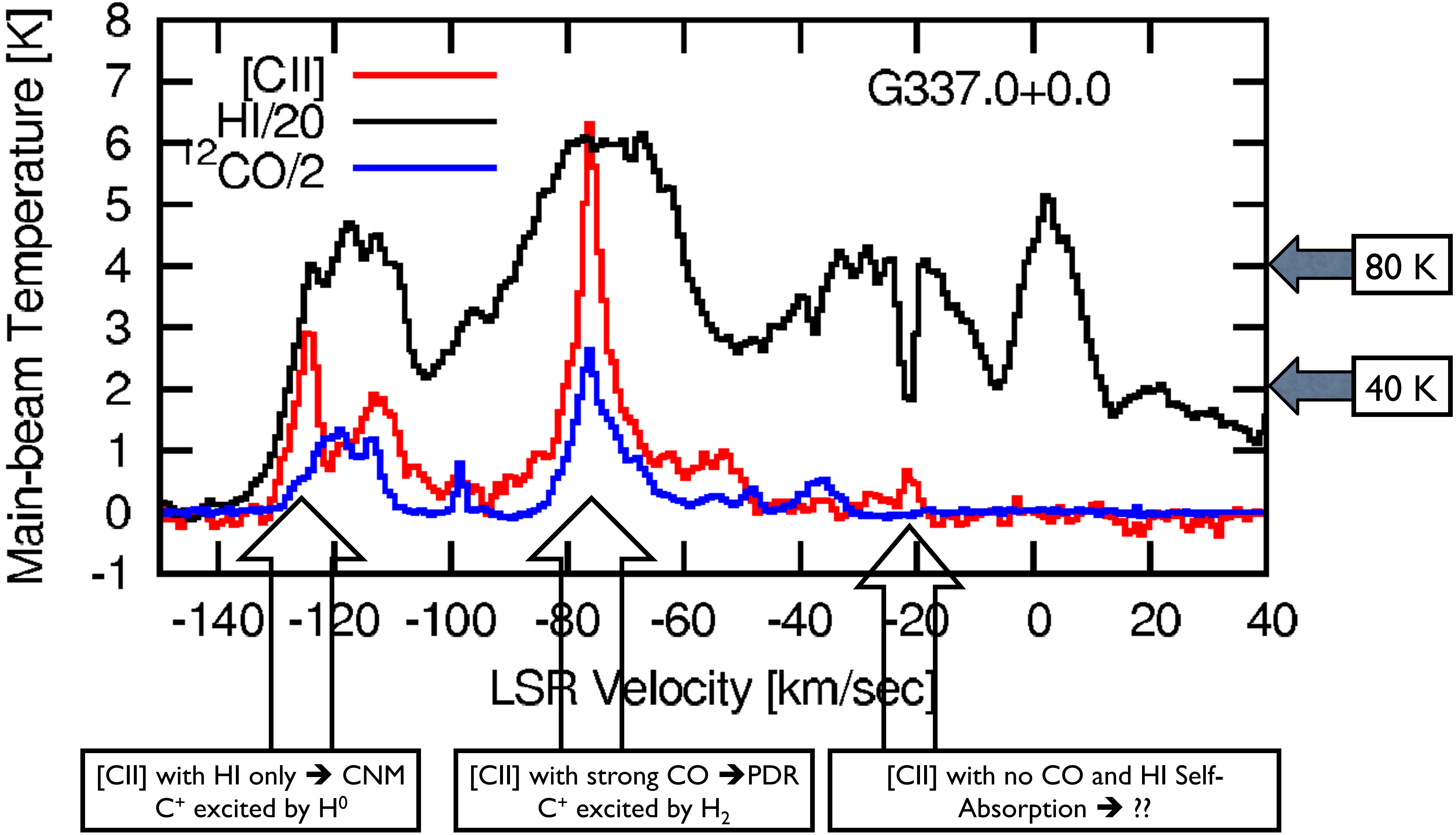


Why is C+ Important?

- C+ is the dominant ionization state of carbon in neutral atomic gas (WNM/CNM) and in the outer layers of molecular clouds (PDRs)
- Possibly good tracer of “CO-dark H_2 gas”
- Under conditions in much of the neutral ISM, the C^+ fine structure line is the dominant gas coolant; this is evident in infrared spectra of galaxies where L_{CII} ~ 1% of L_{IR}
- C^+ is also emitted from ionized gas (WIM and HII regions)

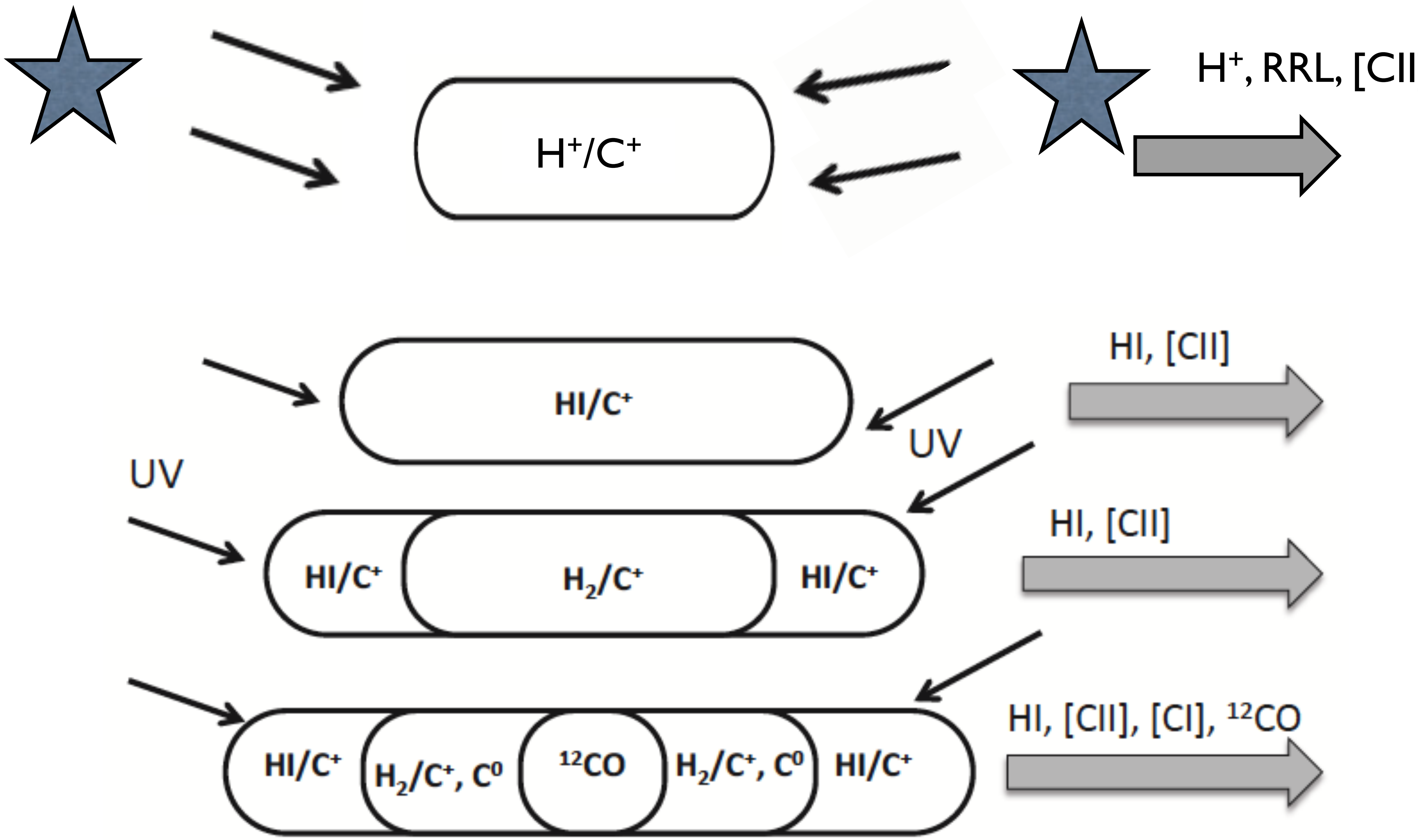
GOT C+ Survey of Milky Way (W. Langer PI)
(b = 0° and strips to ±1°)

Variety of spectra; to interpret you need CO and HI (at least)



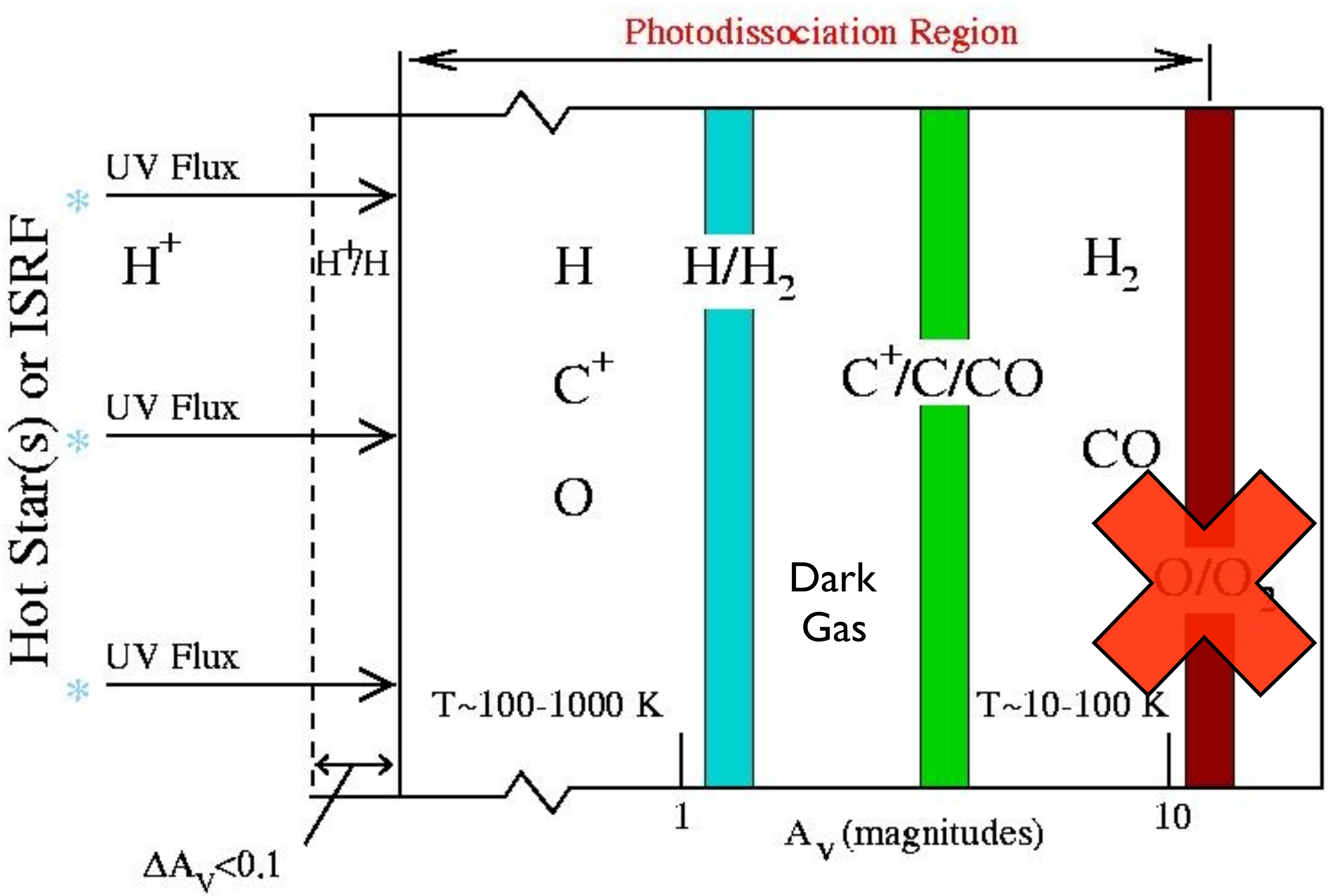
Where is [CII] Emission Produced?

Carbon is ionized by photons with hν>11.3 eV



Langer et al. (2013)

PDR Schematic



e H H_2

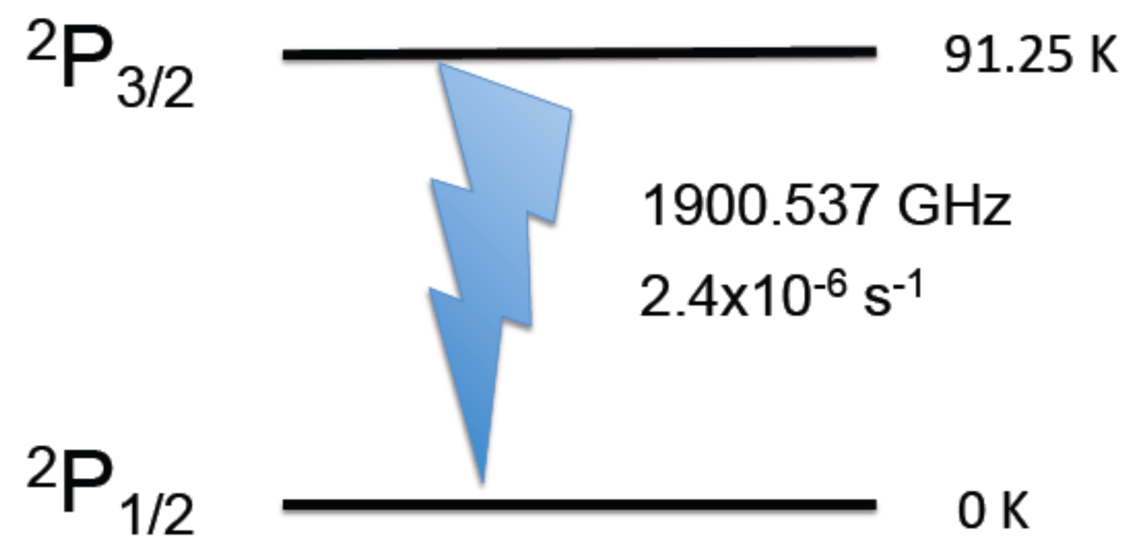
What do we need to know to model CII Emission?

- C^+ atomic parameters (A-value, energy levels)
- Physical conditions (density, temperature)
- Collision partners/collisions rates

Solve equations of statistical equilibrium for two-level system, taking into account geometry, temperature gradients, velocity fields, background radiation, etc.

C^+ Fine Structure Level Parameters

- $^{12}C^+$ has nuclear spin 0 so there is only a pair of levels with J = 3/2 and J = 1/2
- $A_{ul} = 2.4 \times 10^{-6}$ s^{-1}
- $\Delta E/k = 91.25$ K
- f = 1900.537 GHz ($^{12}C^+$)
- $\lambda = 157.75$ μm ($^{12}C^+$)



- $^{13}C^+$ has I = ½ so that $^2P_{1/2}$ is split into F = 0 and F = 1, while $^2P_{3/2}$ level is split into F = 1 and F = 2 ➔ 3 HFS transitions

Transition F' –F''	Freq (GHz)#	Δv (km/s)* Relative to $^{12}C^+$	Relative Intensity**
2 – 1	1900.466	-11.2	0.625
1 – 1	1900.136	-63.2	0.250
1 – 0	1900.950	+65.2	0.125

#Cooksy et al. (1986)
*Stacey et al. (1991)
**Ossenkopf et al. (2013)

Collisional Excitation of C^+

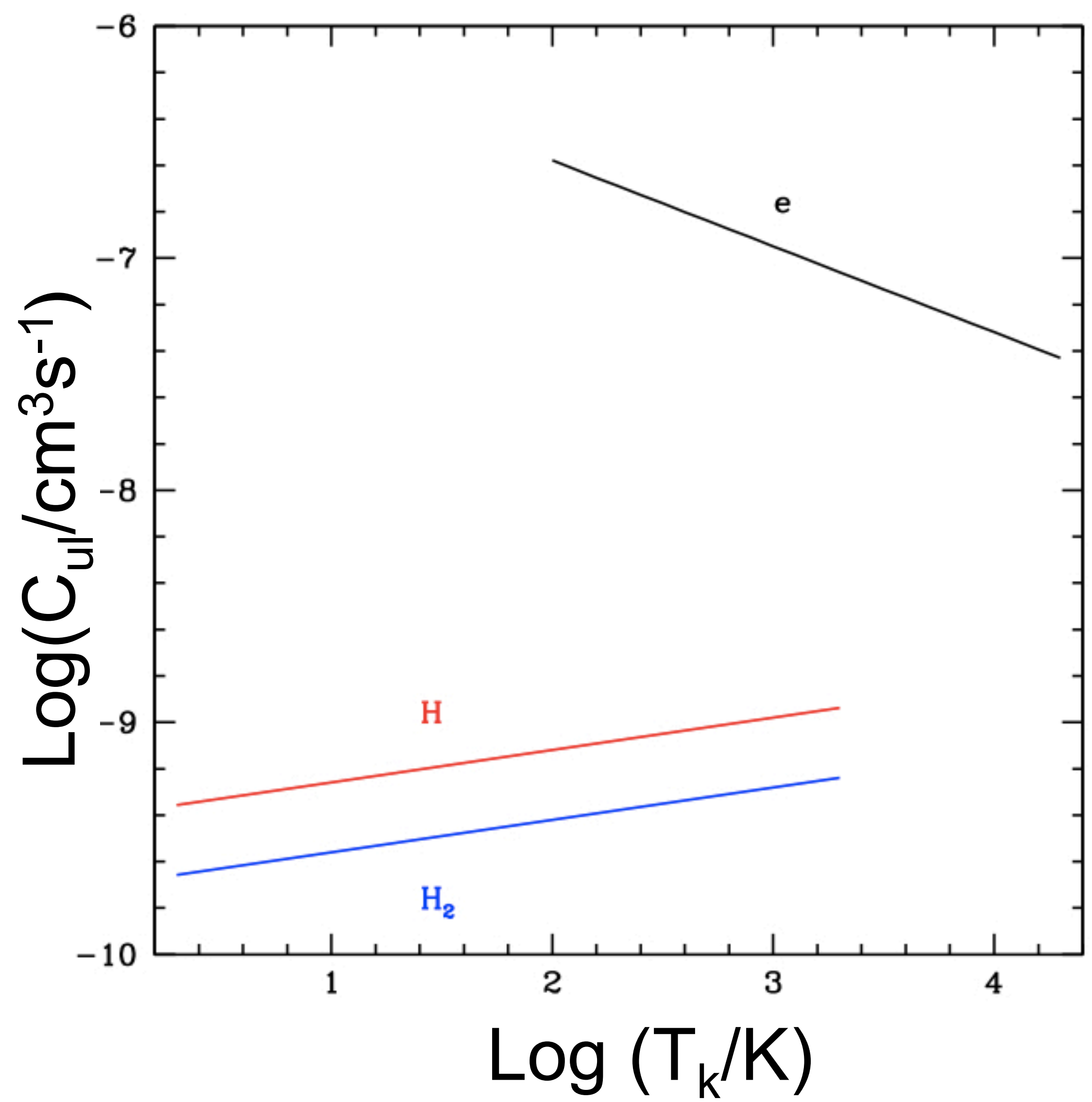
Depending on the region, the C^+ fine-structure transition may be excited by collisions with electrons (HII/WIM), H atoms (CNM/ atomic clouds), or H_2 (translucent clouds/ "CO-dark H_2 gas"/PDRs)

A convenient parameter is the collisional deexcitation rate coefficient $\mathbf{R_{ul}}$ ($cm^3\ s^{-1}$) Depends on the collider and kinetic temperature, T_k

e^- : $R_{ul} = 8.7\times10^{-8}(T_k/2000)^{-0.37}$
[Blum & Pradhan '91]

H^0 : $R_{ul} = 7.6\times10^{-10}(T_k/100)^{0.14}$
[Launay & Roueff '77, Barinovs '05]

H_2: $R_{ul} = 3.8\times10^{-10}(T_k/100)^{0.14}$
[Chu & Dalgarno '75, Flower 1990]



Critical Densities for C^+

$C_{ul} = R_{ul}$*colliding particle density

Collisional deexcitation rate @ critical density = Spontaneous decay rate

$$n_c = A_{ul}/R_{ul}$$

Critical Densities for [C II] 158 μm Fine Structure Line (cm^{-3})

Temperature	Collision Partner		
(K)	e^-	H^0	H_2
20	5	3800	7600
100	9	3000	6100
500	16	2400	4800
1000	20	2200	4400
8000	44	1600	3300

Goldsmith et al. (2012) based on other references

C^+ will not necessarily be in LTE

Calculating Excitation

Two levels so only a single rate equation

$$n_u(A_{ul} + B_{ul}U + C_{ul}) = n_l(B_{lu}U + C_{lu})$$

Excitation temperature

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-92K/T_{ex}}$$

Definitions

$$K = e^{92K/T_{kin}} \quad G = \frac{1}{e^{92K/T_{bg}} - 1}$$

Use escape probability and LVG model to define effective decay rate

$$X = \frac{C_{ul}}{\beta A_{ul}}$$

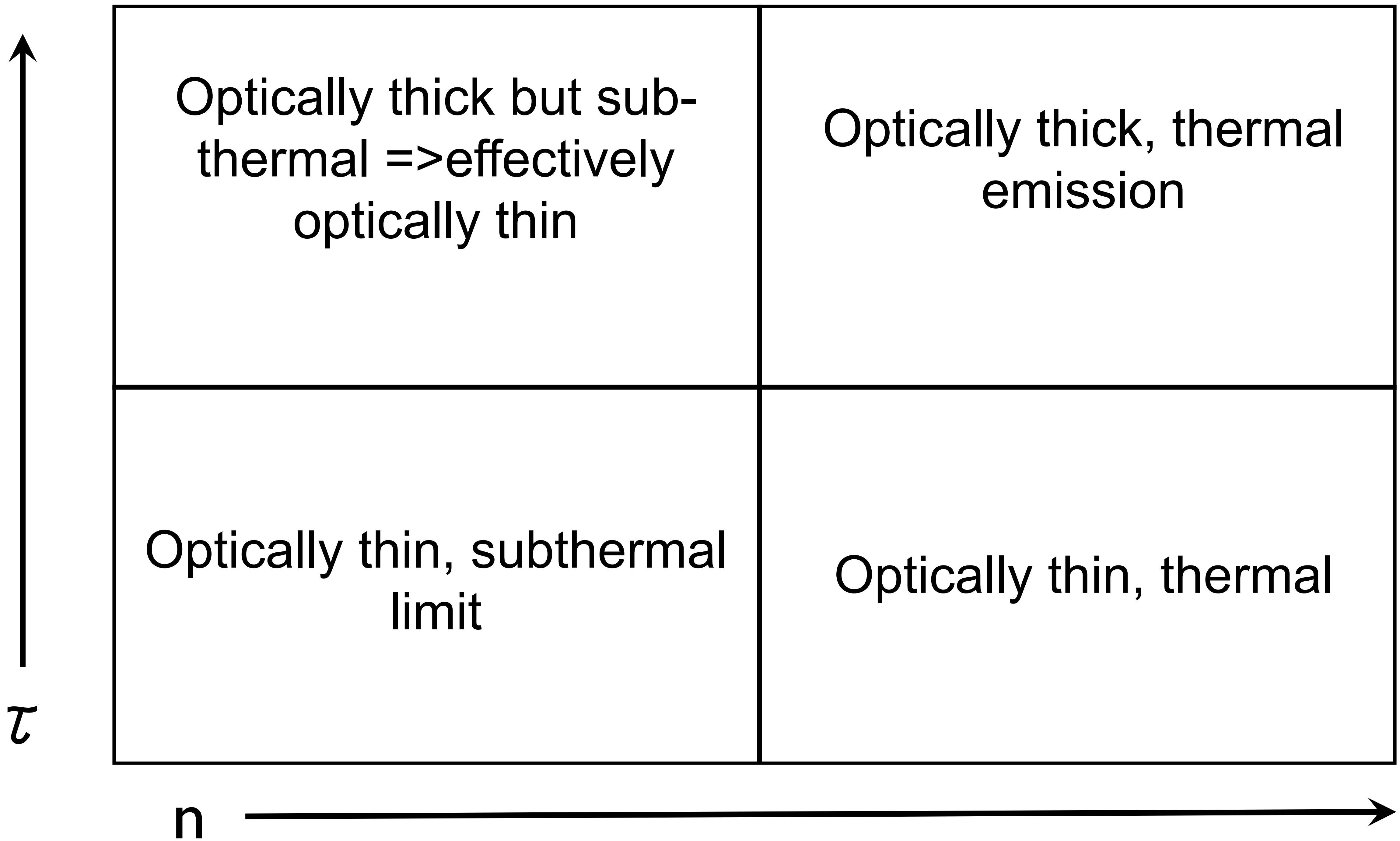
Solution for T_{ex}

$$e^{92K/T_{ex}} = K \frac{X + 1 + G}{X + GK}$$

$$For\, X \rightarrow 0\ (low\, density), T_{ex} \rightarrow T_{bg}$$

$$For\, X \gg 1\ (high\, density), T_{ex} \rightarrow T_{kin}$$

Characterization of Emission Regimes



Emission Regimes: Dependence on N(C^+)

τ ↑

$T_A \propto C_{lu}(n,T_{kin})N(C^+)$ Effectively Optically Thin (EOT)	$T_A \propto 92/(e^{92/T_{kin}} - 1)$ Optically Thick, Thermalized
$T_A \propto C_{lu}(n,T_{kin})N(C^+)$ Optically Thin, Subthermal	$T_A \propto N(C^+)/(2 + e^{92/T_{kin}})$ Optically Thin, Thermalized

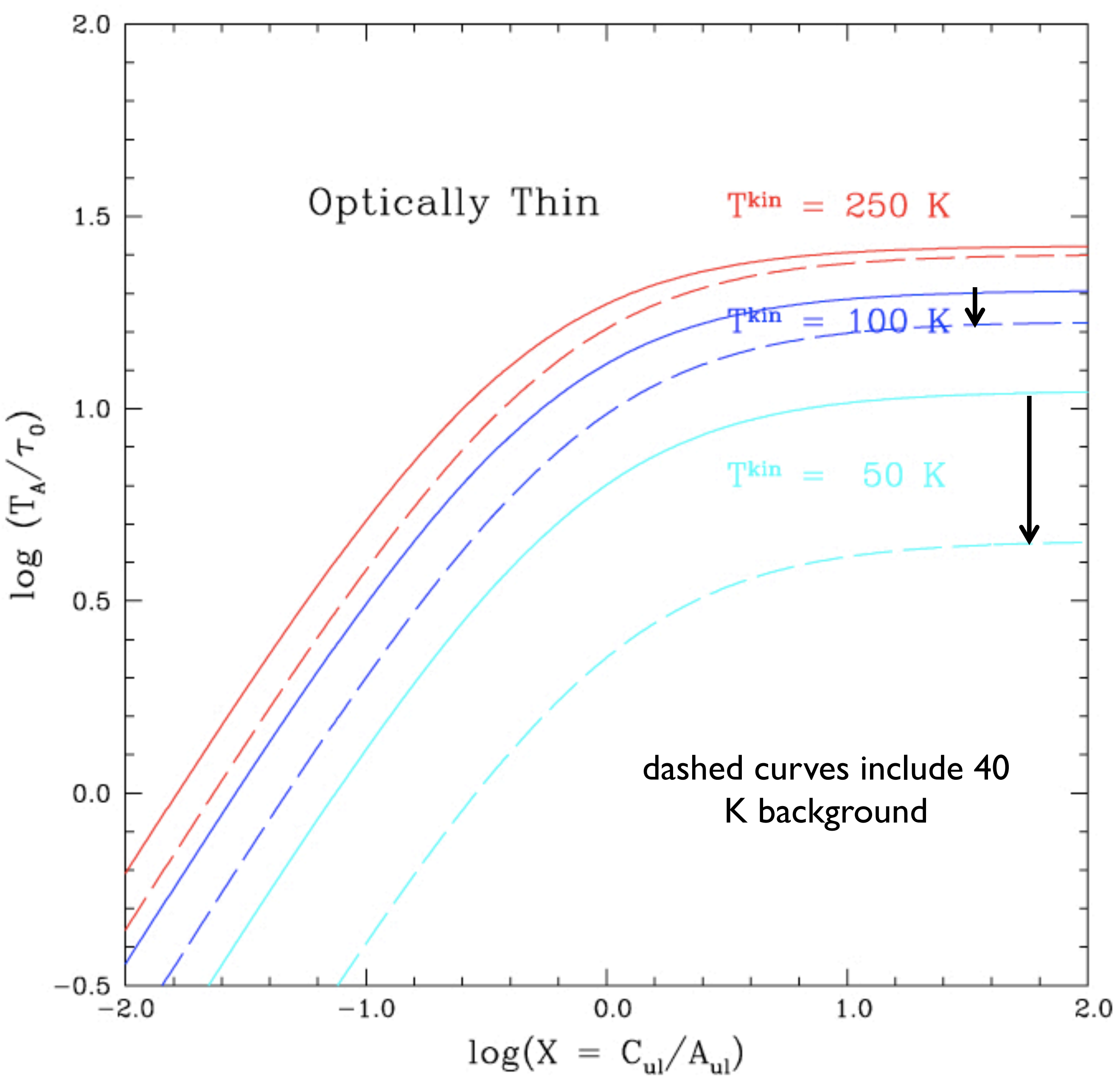
n →

Optically Thin Emission

- Optically thin emission *per unit column density* as a function collision rate for several T^{kin} & background temperatures

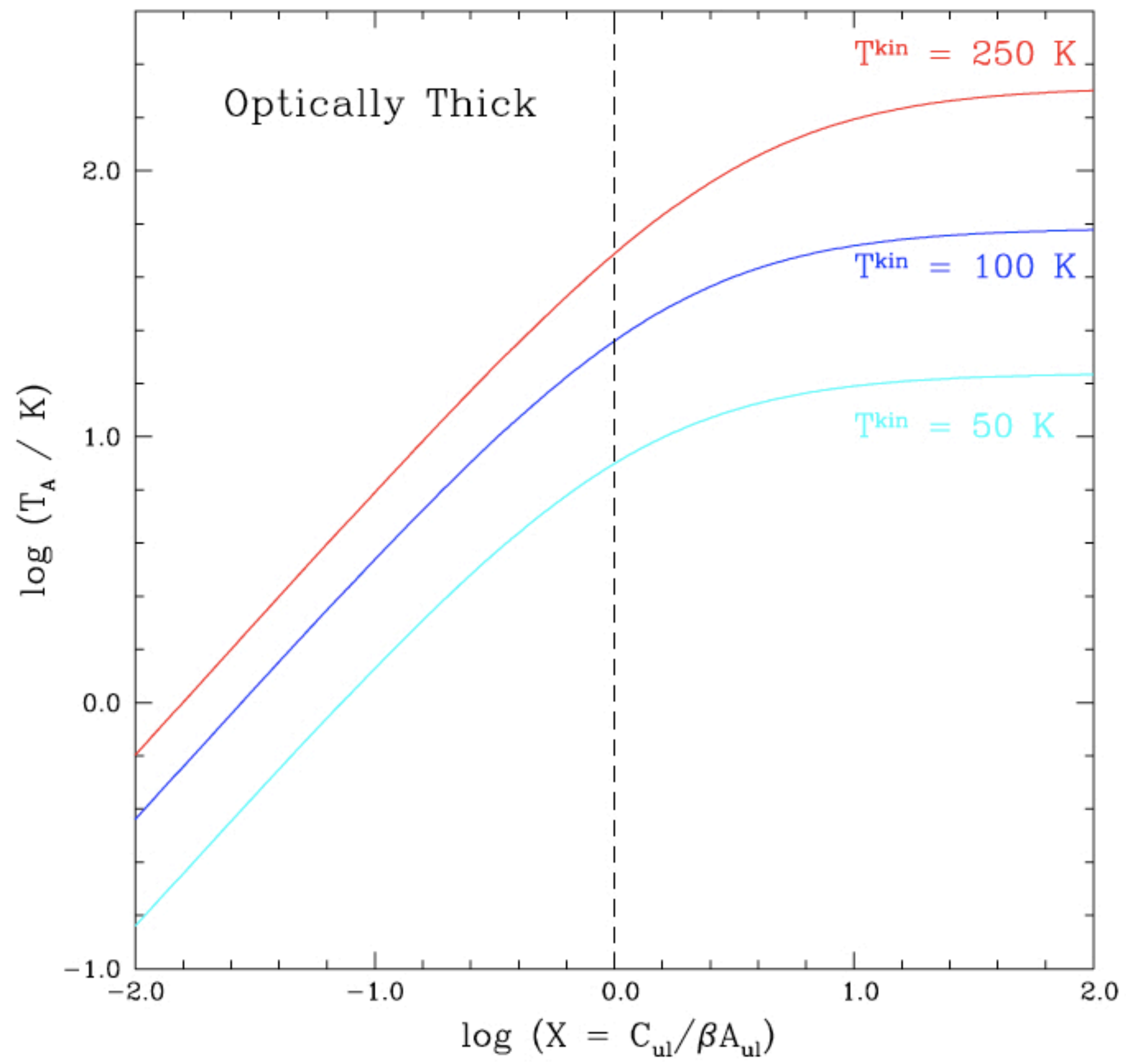
- Subthermal and thermalized régimes are evident

- Background *reduces* the value of T_A
  This is not likely to be a major factor for Galactic observations but could be for Era of Reonization C^+ observations; T_{CMB} ~ 30 K



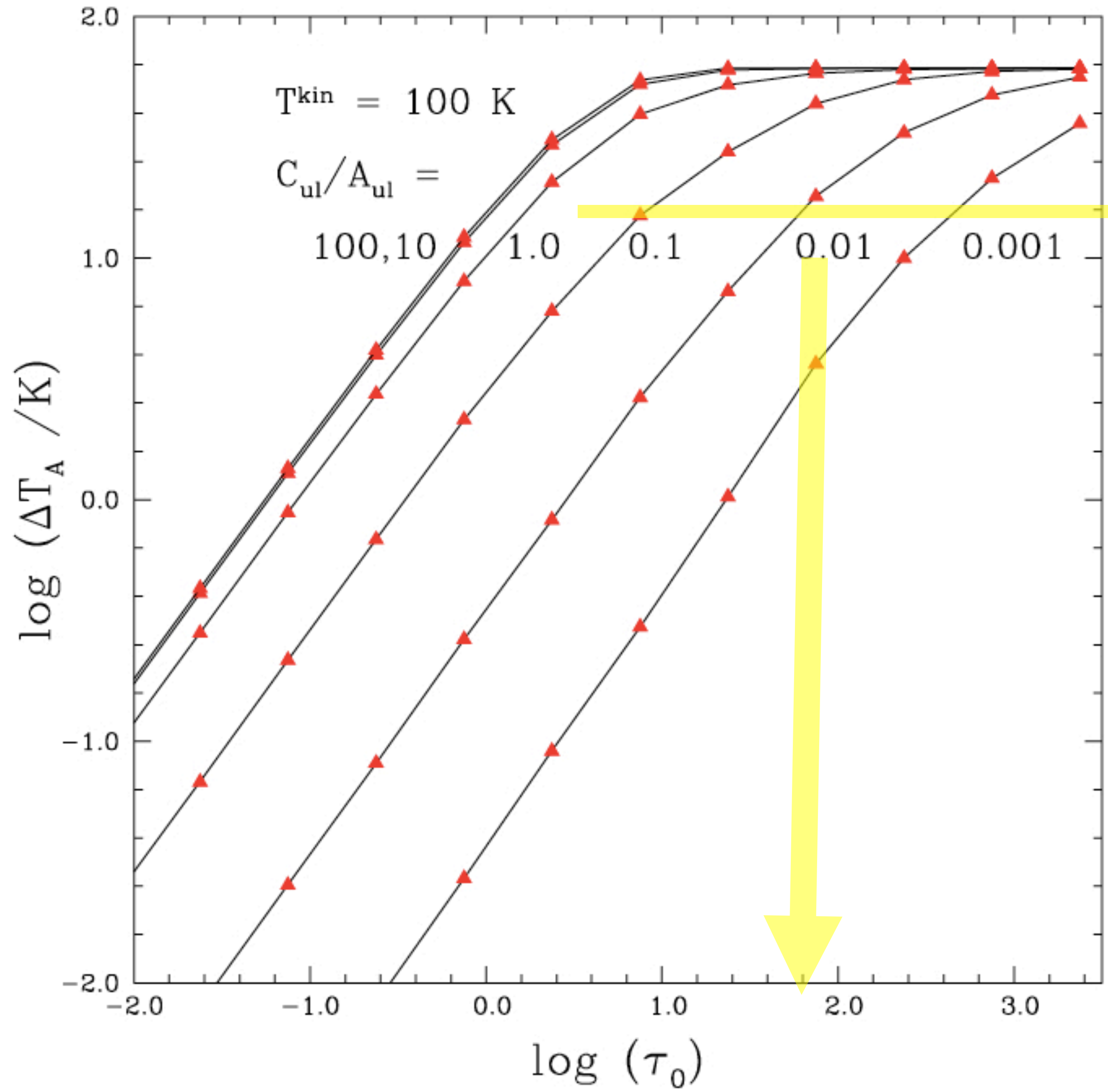
Optically Thick Emission

- As long as $X = C/\beta A < 1$, T_A is proportional to optical depth, even though the transition is optically thick
- For $X >> 1$, T_A reaches T_B of the kinetic temperature



T_A as Function of $N(C^+)$ for Different Densities

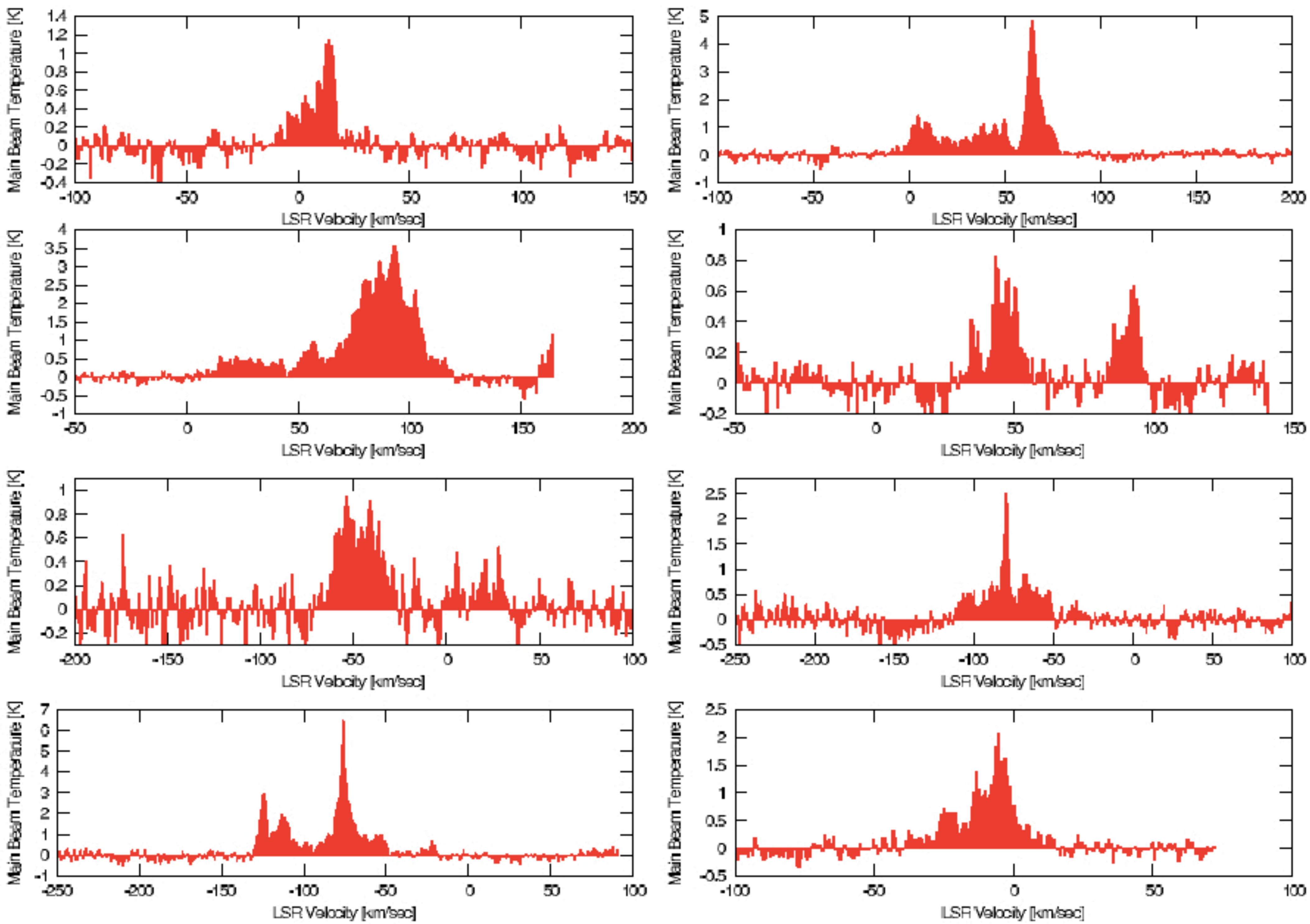
- Effectively optically-thin (i.e. $T_A \propto N(C^+)$) as long as line is “weak”, with $T_A < T_B(T_{kin})/4$
- Where: in the CNM, where $n/n_{cr} \sim 10^{-2}$; τ < many
- Where: in “moderate” PDRs where $n/n_{cr} \sim 0.1\text{-}0.5$; τ < few



$$\tau_0 \sim N_{17}[C^+]/\delta v\,(km/s)$$

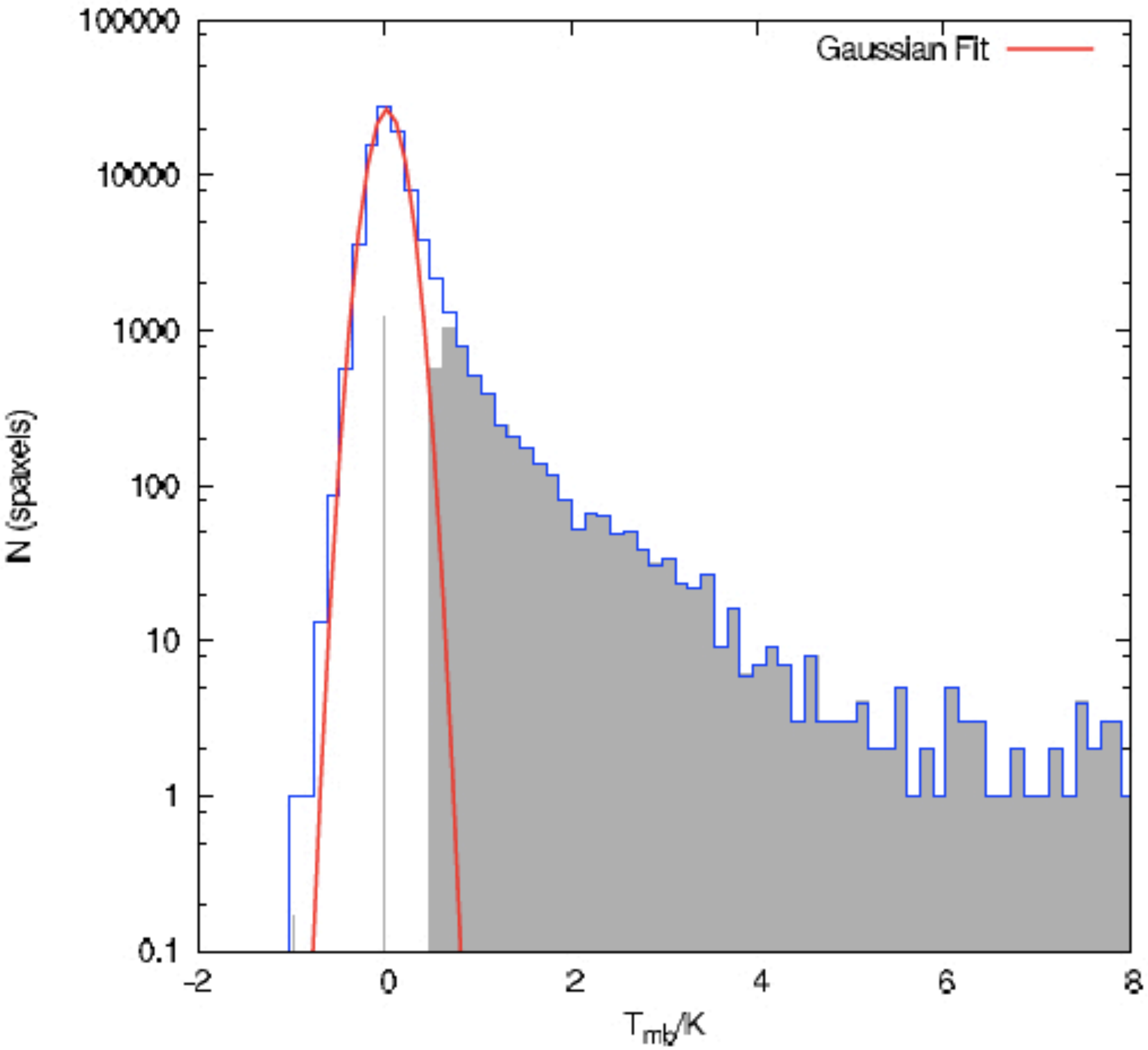
No-Excitation Optical Depth **α** Col.Dens./Line Width

GOT C^+ Observations: Lines are Generally Weak



Distribution of Antenna Temperatures from GOT C^+

- Red curve indicates radiometer noise
- 99% of spaxels have $T_A \leq 5$ K
- In the absence of severe beam dilution, these are all in the thin or effectively-thin limit



Summary and Implications

- Most [CII] emission is optically thin or in the effectively optically thin (EOT) limit, simplifying analysis of emission
- Velocity resolved emission from the Galactic plane traces all (or nearly all) the C^+ column density
- Averaged over an entire galaxy, [CII] traces the mass of the CNM + PDRs in some combination which needs to be unraveled to analyze star formation in external galaxies
- You need to know **n** rather well to model [CII] emission accurately
- **T** is less critical given expected conditions in [CII]-emitting regions, but cold gas could be relatively easy to miss – a possible concern