Tracing the Physical Properties of Warm Molecular Gas Through Observations and Models of the Submillimeter CO Rotational Ladder

1. **Antonio Trovato**, University of Catania, Italy
2. **Vishalika Sharma,** University of Cologne, Germany
3. **Ilyse Clark**, UC San Diego, USA
4. **Esan Mouli Ghosh**, University of Groningen, The Netherlands
5. **Han-Tsung Lee**, University of Cologne, Germany
6. **Nicolas Brosseau**, Université de Franche-Comté, Besançon, France

PIs: Miriam G. Santa-Maria (OAN) & **Javier R. Goicoechea**, Astromol Department, IFF-CSIC, Spain

The Orion Bar PDR

d = 414pc

Metallicity $\sim Z_{\odot}$

Menten et al. 2007

O/B Stars

Hubble (Visible)

Credit: NASA & ESA

The Orion Bar PDR

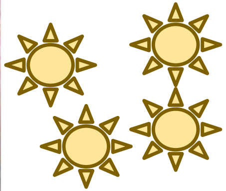
d = 414pc

Metallicity ~ $Z_{\odot}$

Menten et al. 2007

Goal: Characterize the physical conditions of the Orion Bar PDR, a local template for dense and highly irradiated PDRs

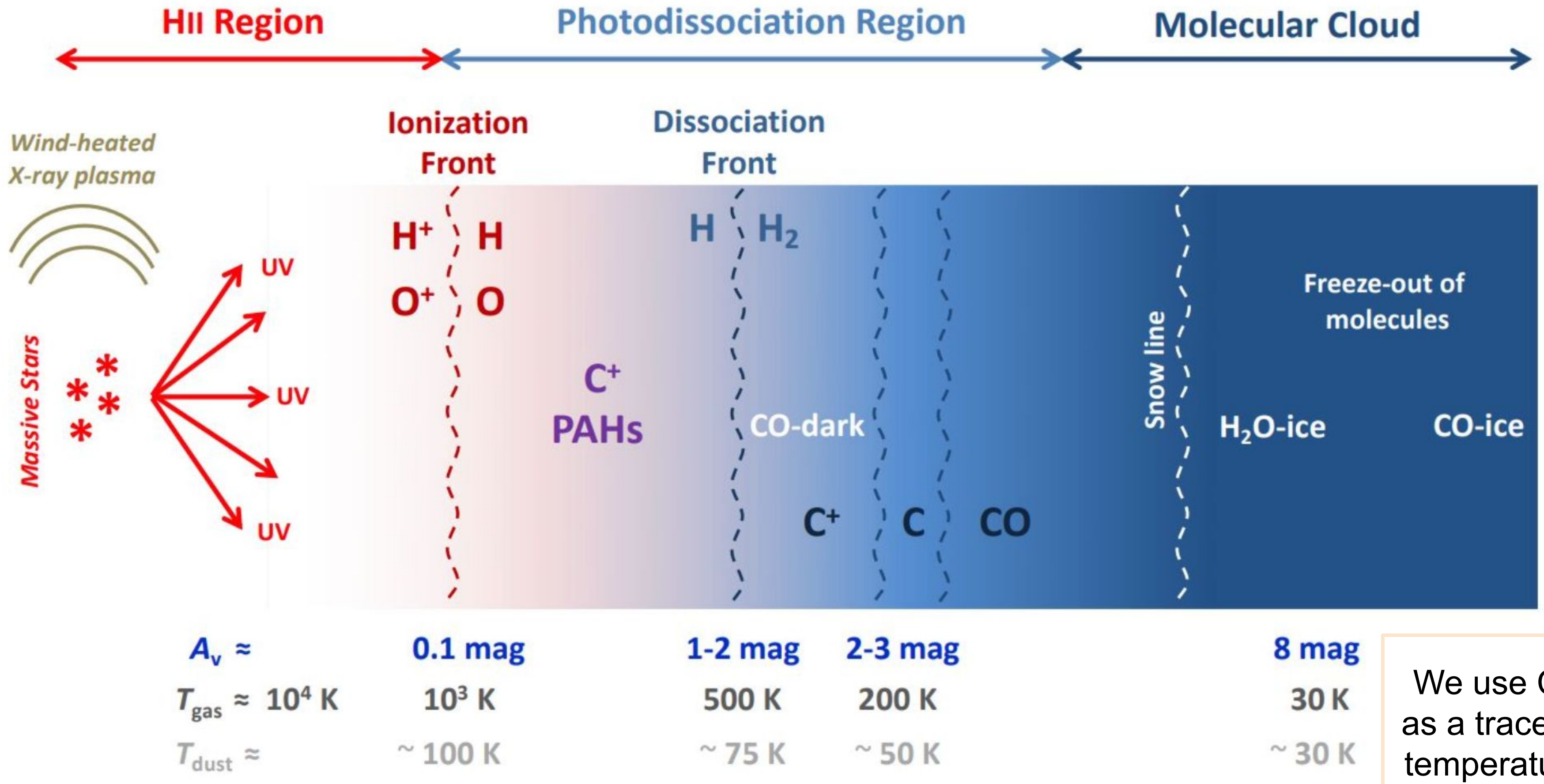
O/B Stars



JWST (Infrared)

Credit: NASA & ESA

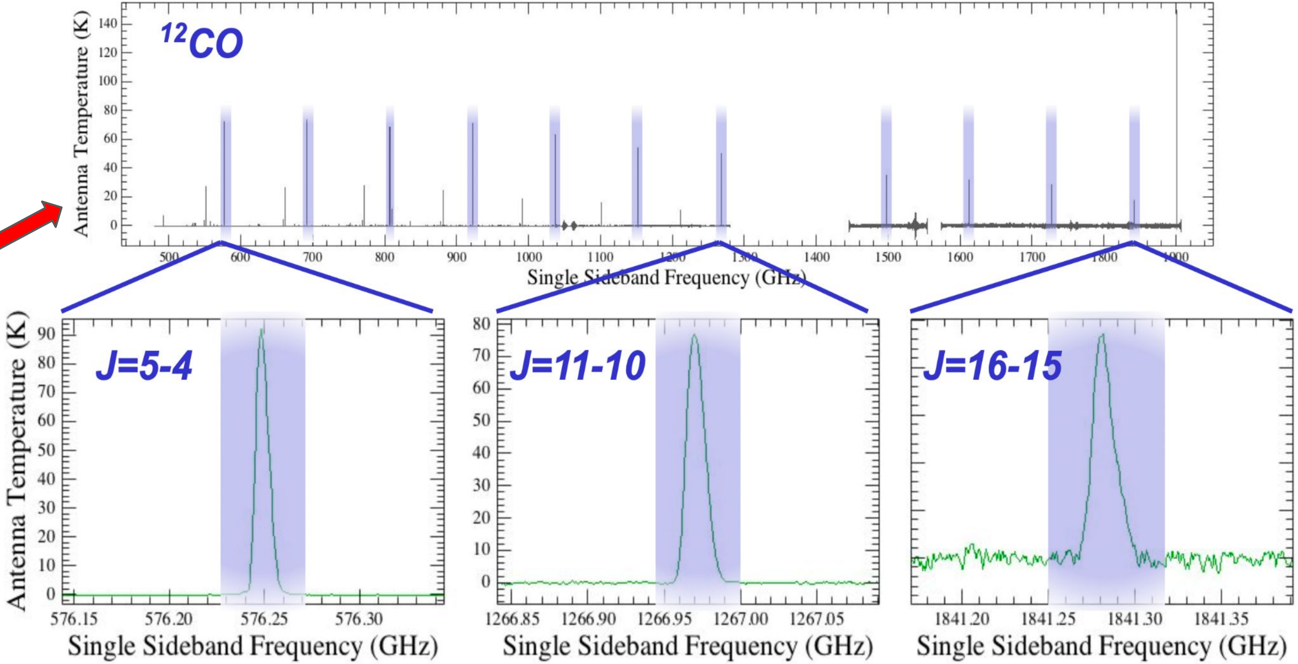
What is a Photodissociation Region (PDR)?



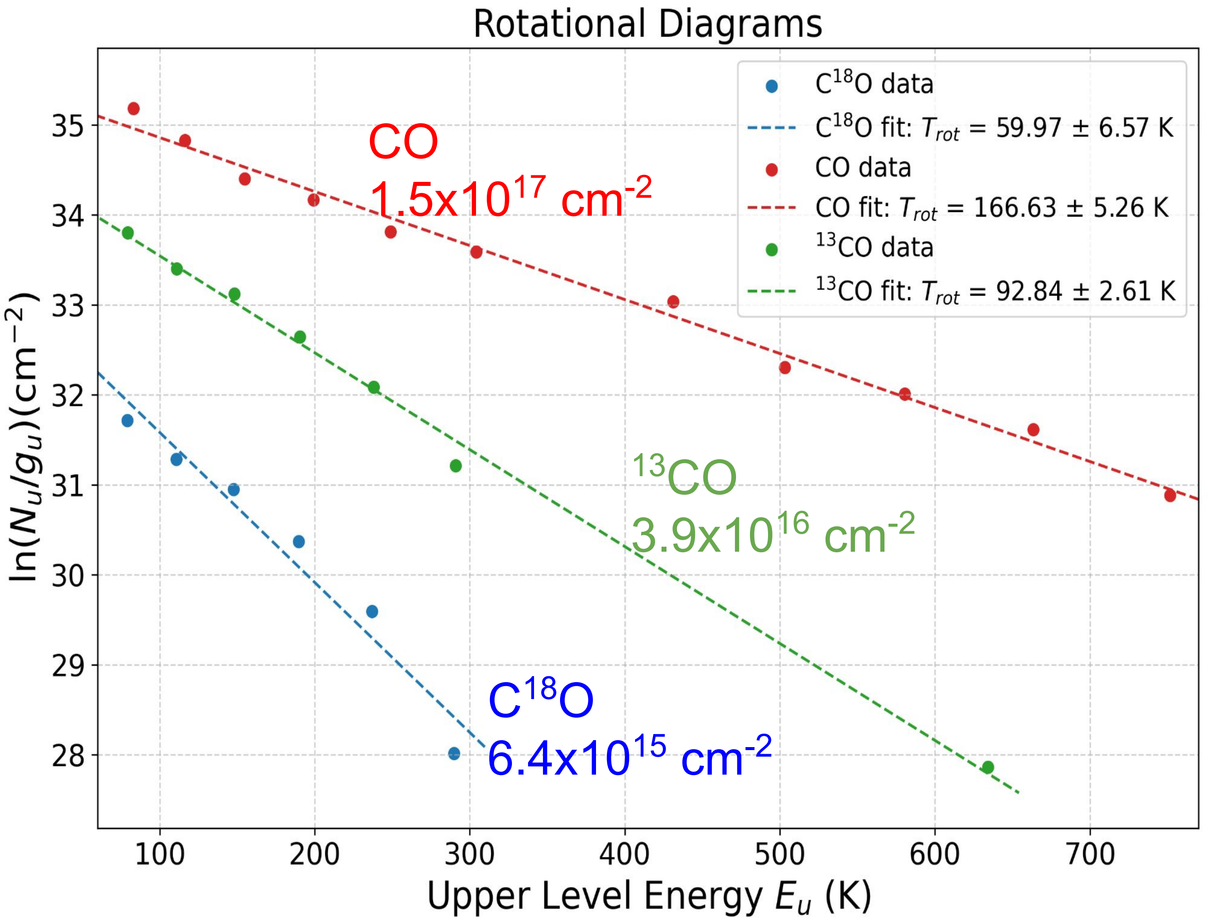
We use CO as a tracer of temperature!

Submillimeter observations with Herschel / HIFI

CO rotational ladder: from 500 GHz to 1900 GHz



Rotational diagram: powerful simple tool (LTE)



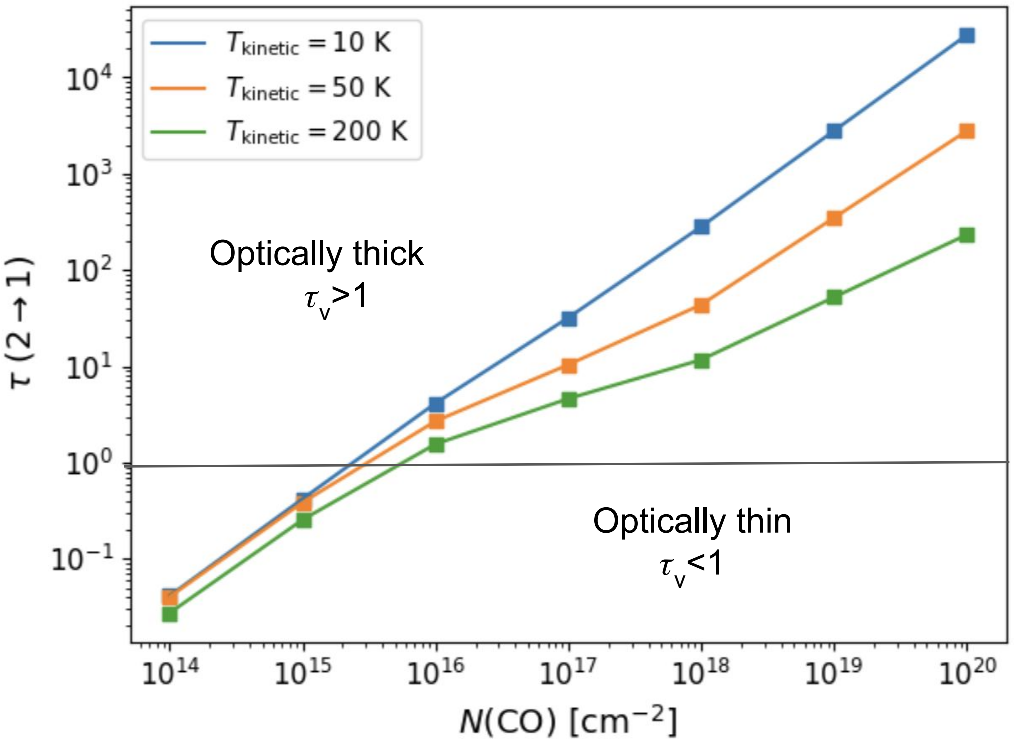
$$\ln\left(\frac{N_u}{g_u}\right) = -\frac{E_u}{kT_{\mathrm{rot}}} + \ln\left(\frac{N_{\mathrm{tot}}}{Q(T_{\mathrm{rot}})}\right)$$

$$\mathrm{T_{rot}} = -\frac{1}{\mathrm{slope}} \quad [\mathrm{K}]$$

$$\mathrm{N_{tot}} = Q(T_{\mathrm{rot}}) \cdot \exp(\mathrm{intercept}) \quad [\mathrm{cm}^{-2}]$$

Non-LTE Modelling (RADEX) - Example CO J=2→1

$\mathrm{n(H_2)}=10^3\ \mathrm{cm}^{-3}$



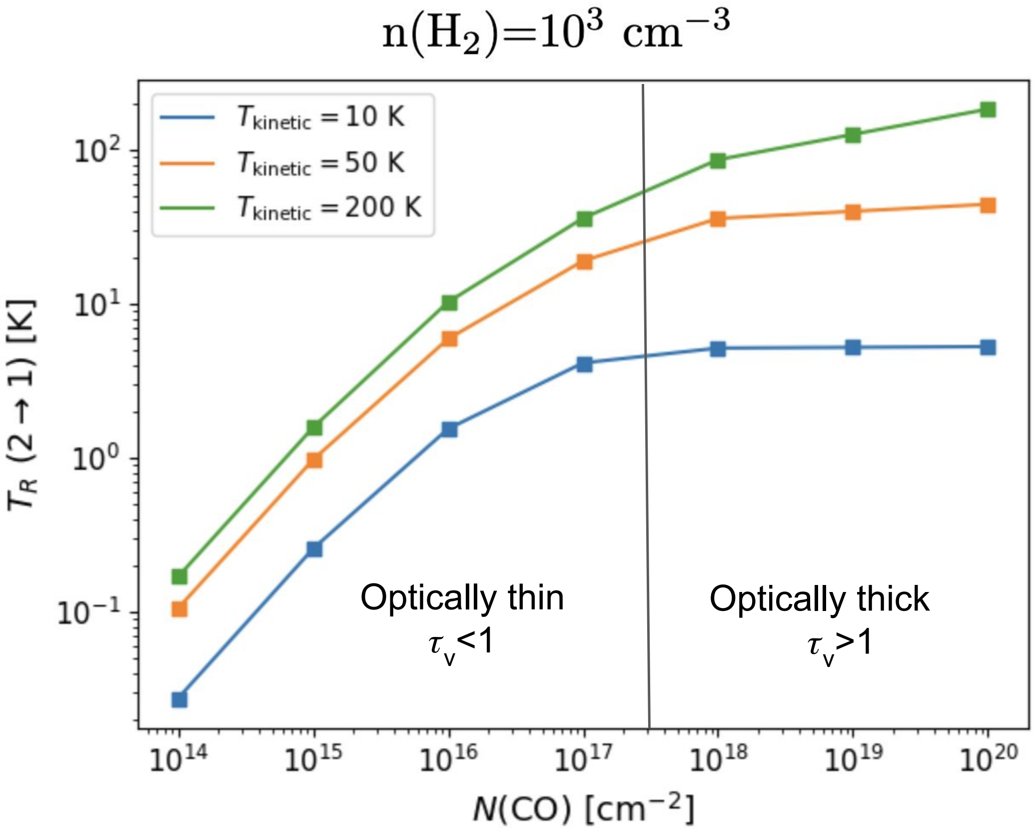
Line opacity (2→1) increases with column density N(CO)

$$\tau_\nu \sim N_u \sim N_{tot} e^{-E_i/kT}$$

Higher levels (J>2) populated at higher gas temperature ; $N_{u=2}$ decreases

RADEX (van der Tak et al 2007, *A&A*)

Non-LTE Modelling (RADEX) - Example CO J=2→1



$$T_R^{\mathrm{LINE}} = T_R - T_{\mathrm{bg}}^0 = \left(T_{\mathrm{ex}} - T_{\mathrm{bg}}^0\right) \cdot \left(1 - e^{-\tau_\nu}\right)$$

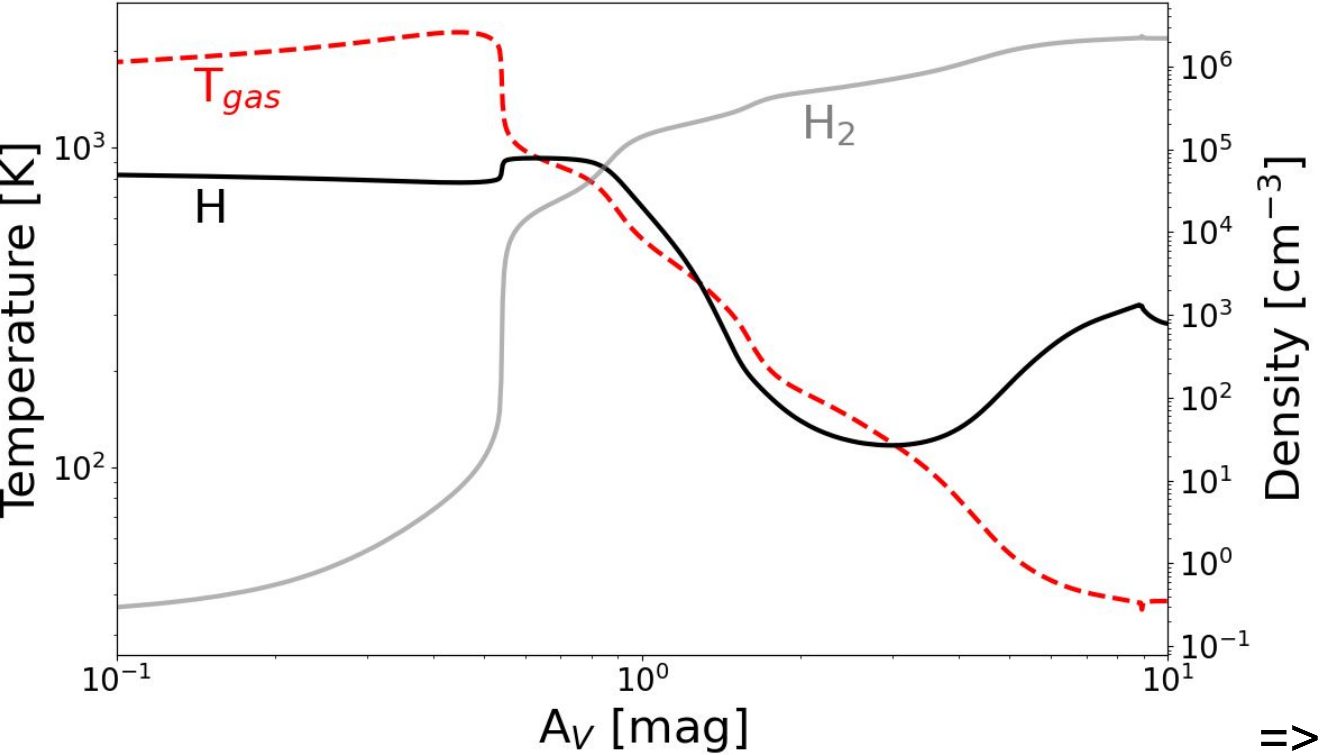
T_R increases with column density N(CO) in optically thin regime and saturates in optically thick regime

$$\tau_\nu \rightarrow 0 \quad \Rightarrow \quad T_R^{\mathrm{LINE}} \sim \left(T_{\mathrm{ex}} - T_{\mathrm{bg}}^0\right) \cdot \tau_\nu \sim T_{\mathrm{ex}} \cdot N$$

$$\tau_\nu \rightarrow \infty \quad \Rightarrow \quad T_R^{\mathrm{LINE}} \sim T_{\mathrm{ex}} - T_{\mathrm{bg}}^0 \sim T_{\mathrm{ex}}$$

RADEX (van der Tak et al 2007, *A&A)*

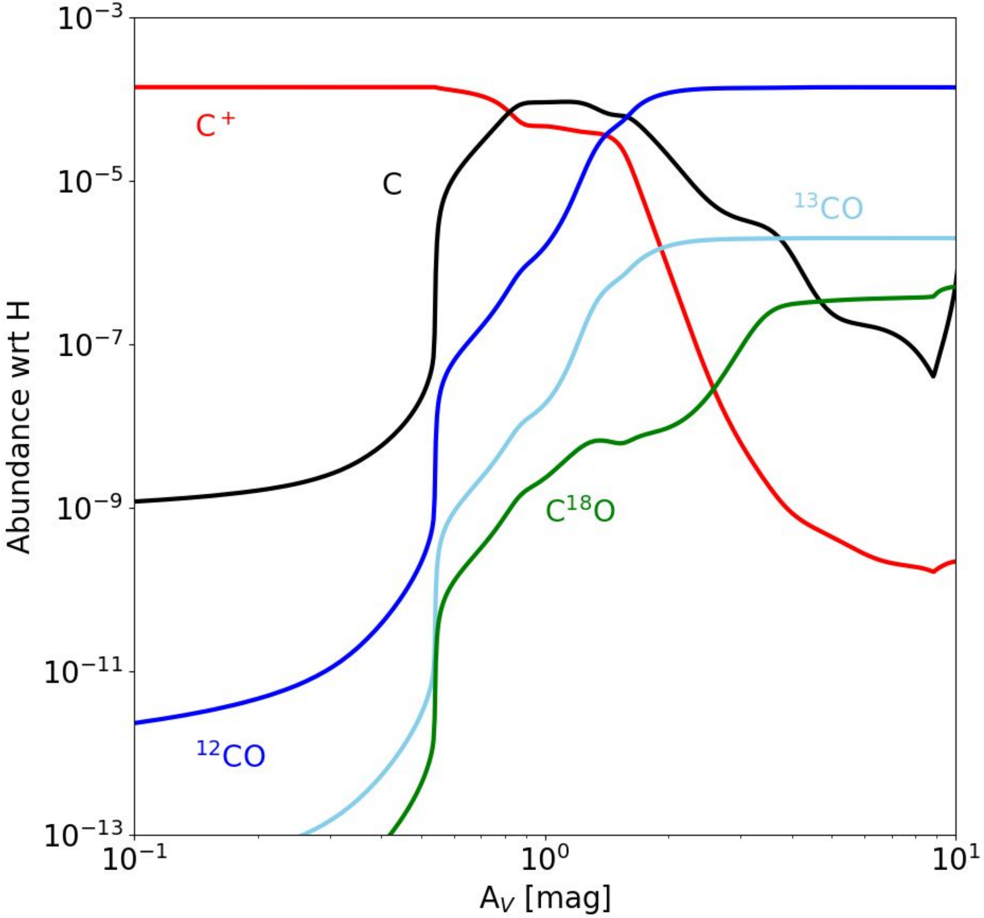
Meudon PDR model



Orion Bar:
$G_0 = 2x10^4$
$P_{th} = n_H \cdot T = 10^8$ K cm^{-3}
(isobaric)

=> **H to H_2 transition**

Meudon PDR model



Orion Bar:
$G_0 = 2x10^4$
$P_{th} = n_H \cdot T = 10^8$ K cm^{-3}
(isobaric)

C^+ to C to CO transition

Conclusions

- $N(^{12}CO)/N(^{13}CO) \sim 4 < 70$ (isotopic ratio in Orion) ➡ ^{12}CO emission $\tau \gg 1$
- $N(^{13}CO)/N(C^{18}O) \sim 7 \sim 7$ (isotopic ratio in Orion) ➡ ^{13}CO - $C^{18}O$ emission $\tau \ll 1$

RADEX MODELS:

gas physical conditions from CO @ 500-1900 GHz

$$T_{gas} \sim 200\ K$$

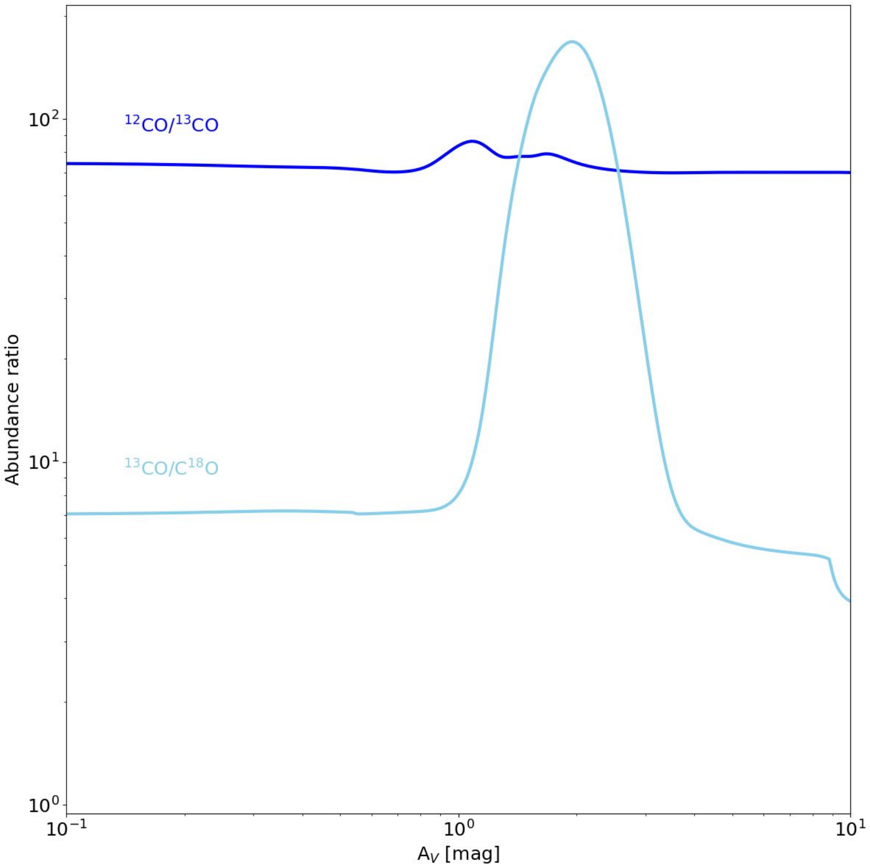
$$n_{H_2} \sim 10^{5-6}\ cm^{-3}$$

➡ gas is warm and dense In the Orion bar

CO ladder is an excellent tracer of warm and dense gas in high-mass Star-Forming regions

Thank you! Any question?

Meudon PDR model



$^{13}C^+ + {}^{12}CO \rightarrow {}^{12}C^+ + {}^{13}CO + 35\ K$