デブリ円盤における一酸化炭素形成

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ALMAワークショップ：円盤から太陽系へ

CO in Debris Disks

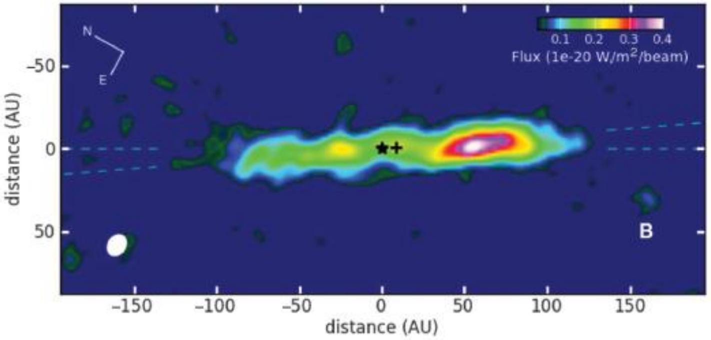
CO was detected in many debris disks.

- ✓ Around A-type stars

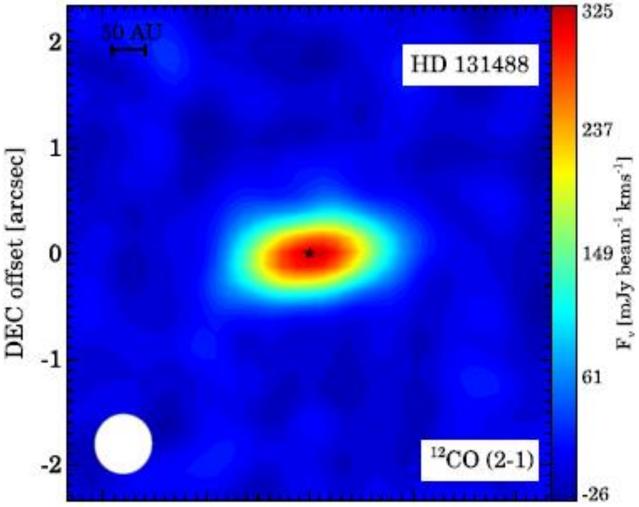
  49Cet (Zuckerman+ 1995), **HD 21997** (Moor+ 2011),
  β Pic (Dent+ 2014), **HD131835** (Moor+ 2015), **HD181327** (Marino+ 2016),
  HD110058, HD 138813, HD 146897, HD 156623 (Lieman-Sifry+ 2016),
  HD32297 (Greaves+ 2016), **Fomalhaut** (Matra+ 2017),
  HD121191, HD121617, HD131488 (Moor+ 2017)

- ✓ Around F and G-type stars

  HD146897



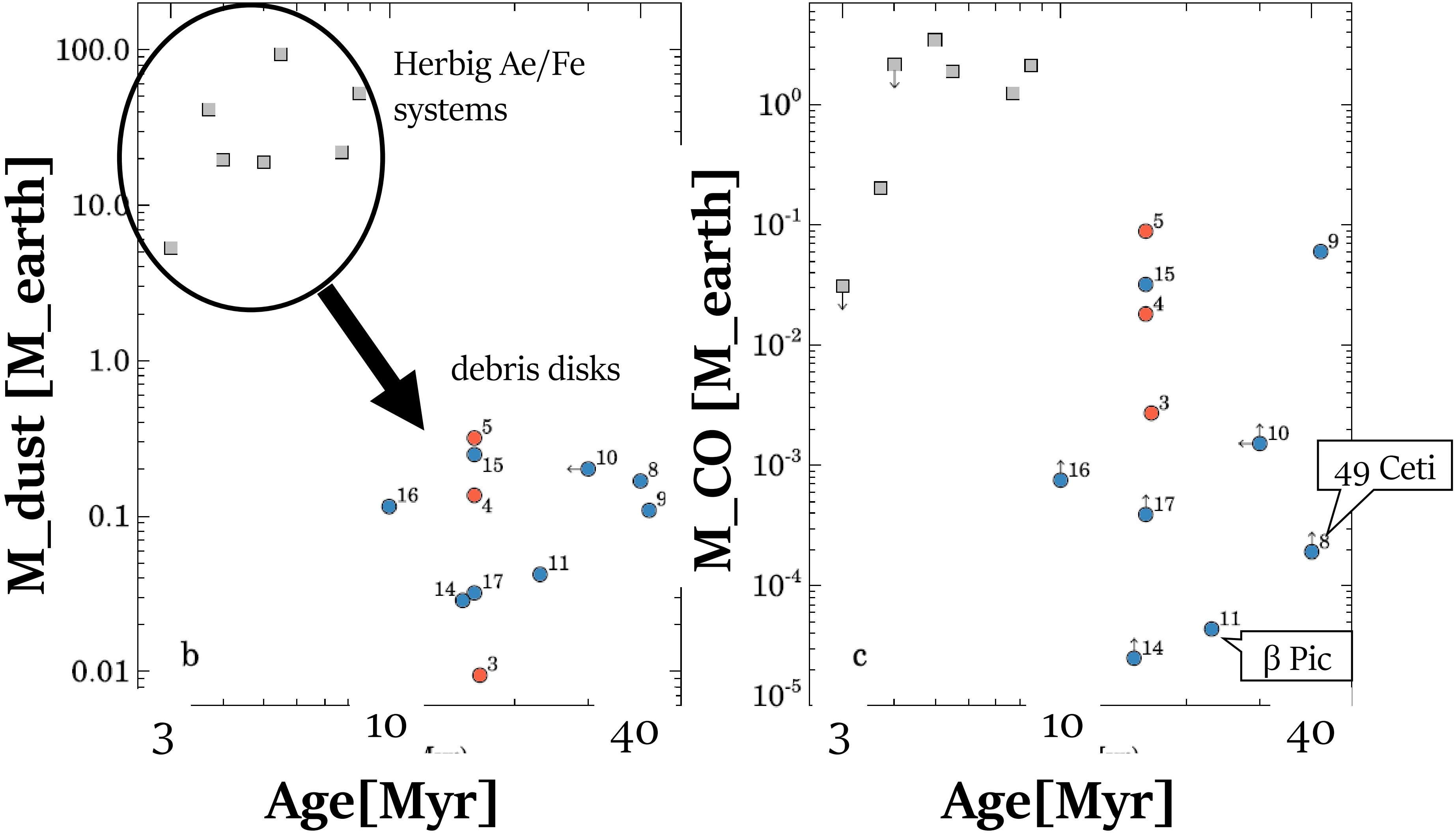
β Pic (Dent+ 2014)



HD131488 (Moor+ 2017)

Statistics

Moor+ 2017



Difference Between ISM and Debris Disks

	ISM	Debris Disks
Dust	**Size distribution：** MRN $n(a) \propto a^{-3.5} (a < 0.1\ \mu\text{m})$ **dust-to-gas mass ratio：0. 01**	**absence of small dusts (a<6μm)：** blown out by the radiative pressure. **dust-to-gas mass ratio：**?
Gas	**H-rich gas**	• **Primordial origin** the remnant of protoplanetary disks. → **H-rich gas** • **Secondary origin** vaporization by high velocity collision of dust grains → **H-poor gas**

Photo-dissociation of CO

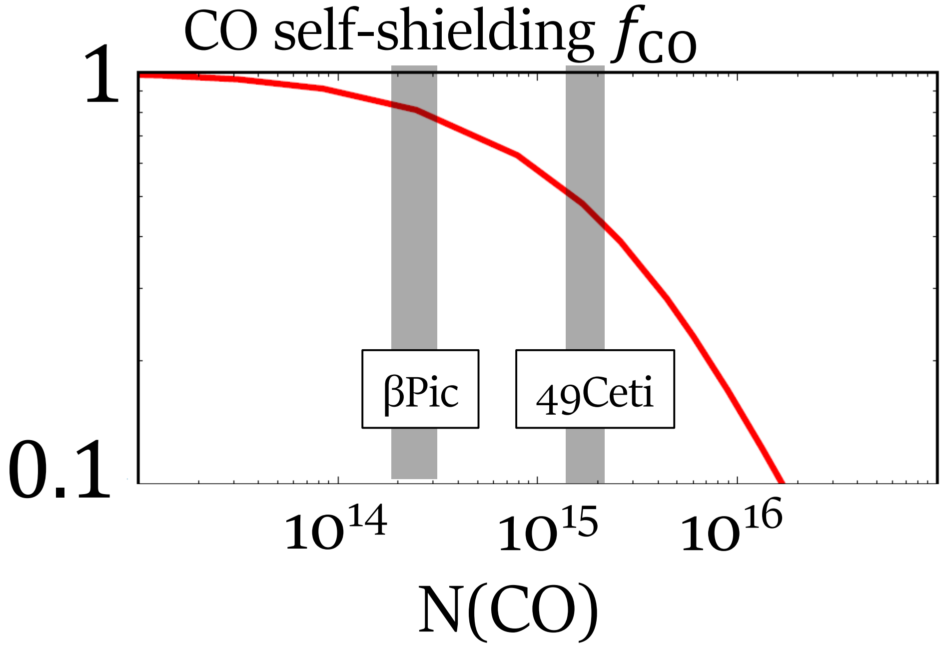
if there is no shielding effects,

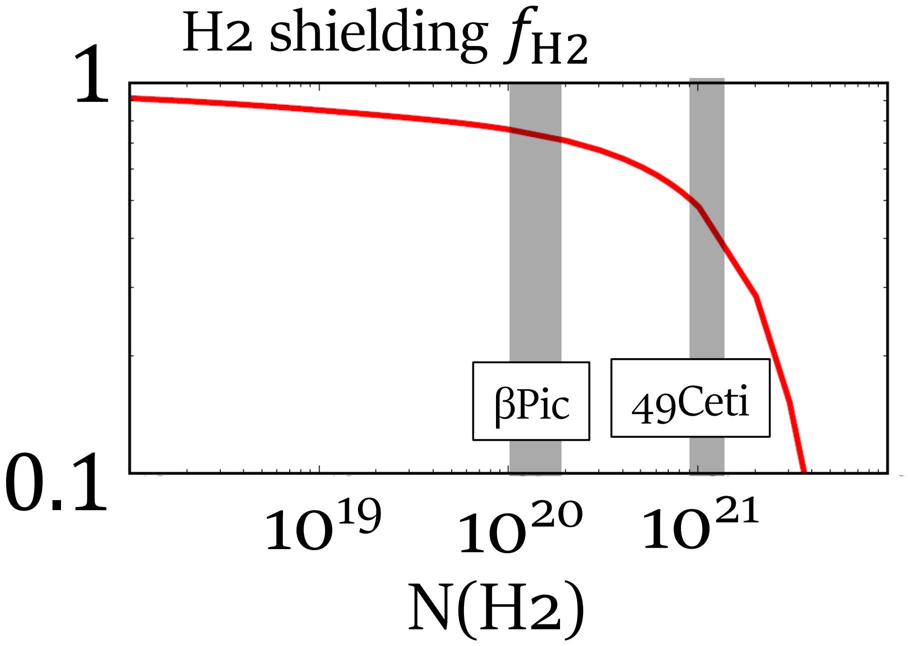
$$\Gamma_{\mathrm{CO,thin}} = 10^{-10} \left(\frac{F_{\mathrm{FUV}}}{1.2 \times 10^{7}} \right) s^{-1}$$

$$\Longrightarrow \; 300\, \chi^{-1}\, \mathrm{yr}^{-1}$$

$$\Gamma_{\mathrm{CO}} = \Gamma_{\mathrm{CO,thin}}\, f_{\mathrm{CO}} \times f_{\mathrm{H2}} \times f_{\mathrm{dust}}$$

van Deshoek and Black 1988,
Lee et al. 1996, Visser et al. 2009


CO self-shielding f_{CO}


H2 shielding f_{H2}

Shielding effect does not work significantly . → CO dissociates quickly.
→ Why CO exists in debris disks?

CO Chemistry in Debris Disks

- Kamp & Bertoldi 2000, Kamp & van Zedelhoff 2001
- Chemical equilibrium with respect to CO **keeping [C, O]/[H] constant.**

$$\boxed{\Gamma_{\mathrm{CO}} n_{\mathrm{CO}}} \quad \sim \quad \boxed{k n^{\alpha} \ (\alpha \geq 2)}$$

photo-dissociation rate

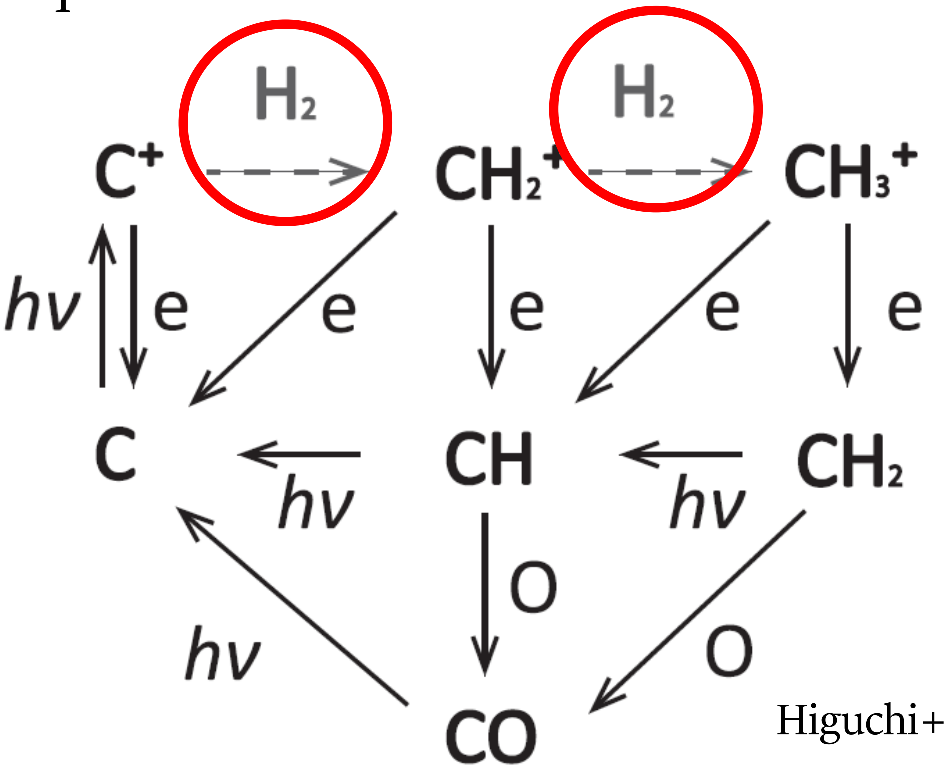
formation rate

$$\rightarrow \quad n_{\mathrm{CO}} \sim \frac{k n^{\alpha}}{\Gamma_{\mathrm{CO}}}$$

- To get a large amount of CO
  - ✓decreases Γ_{CO} : not effective
  - ✓increase the number density → enhance the formation rate
- For high density environment,
  even if the shielding does not work significantly, CO is reformed efficiently.

Dependence of CO Chemistry on H abundance

the CO chemistry requires H.



Higuchi+ 2017

How does the CO chemistry depend on [C, O]/[H]?

- **Can we guess the H2 mass from the CO fraction, CO/CI?**

Expected Volume Density

$h = c_s/\Omega$

$$n_{\rm C} = \frac{N_{\rm CI}}{\sqrt{2\pi}h} = 160\ {\rm cm^{-3}} \left(\frac{N_{\rm CI}}{3\times10^{16}\ {\rm cm^{-2}}}\right)\left(\frac{\rm T}{100\ {\rm K}}\right)^{-1/2}\left(\frac{R}{50\ {\rm AU}}\right)^{-3/2}$$

if C elemental abundance is the same as that in the ISM ($A_{\rm C} = 1.3\times10^{-4}$)

For β Pic,

$$n_{\rm H} = 10^6\ {\rm cm^{-3}}\left(\frac{A_{\rm C}}{1.3\times10^{-4}}\right)^{-1}\left(\frac{N_{\rm CI}}{3\times10^{16}\ {\rm cm^{-2}}}\right)\left(\frac{T}{100\ {\rm K}}\right)^{-0.5}\left(\frac{R}{50\ {\rm AU}}\right)^{-1.5}$$

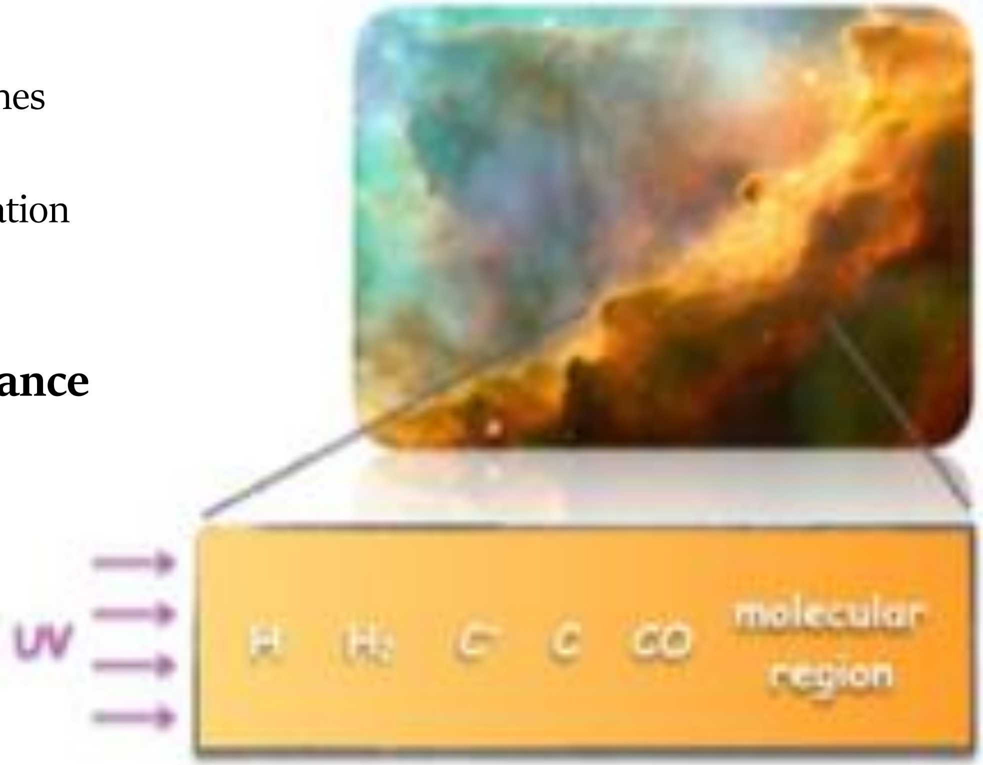
For 49 Ceti,

$$n_{\rm H} = 10^7\ {\rm cm^{-3}}\left(\frac{A_{\rm C}}{1.3\times10^{-4}}\right)^{-1}\left(\frac{N_{\rm CI}}{2\times10^{17}\ {\rm cm^{-2}}}\right)\left(\frac{T}{300\ {\rm K}}\right)^{-0.5}\left(\frac{R}{50\ {\rm AU}}\right)^{-1.5}$$

PDR Calculation

Meudon PDR code (Le Petit et al. 2006) developed for the ISM

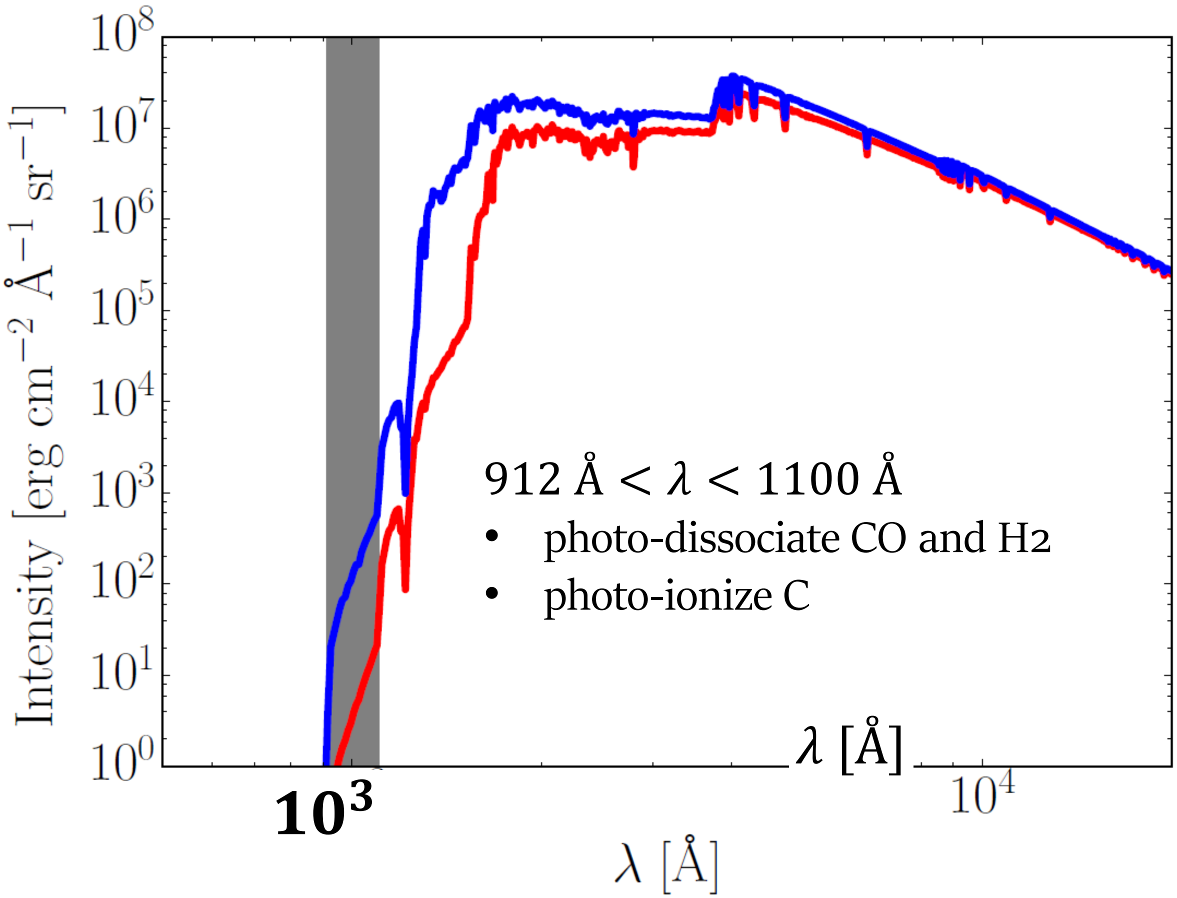
- **Radiative Transfer**
  - ✓Exact line transfer for UV photons Overlapping of H, H2, CO absorption lines is taken into account.
  - ✓UV radiation is decoupled from IR radiation
- **Chemistry**
  - ✓224 species, 2980 chemical reactions
- **Level populations and thermal balance**
- **Plane-parallel geometry**



Radiation Field

- Stellar radiation,

  ✓**A5V (β Pic, $T_{\rm eff} = 8250$ K)**, **A1V(49Ceti, $T_{\rm eff} = 9000$ K)**



912 Å < λ < 1100 Å
- photo-dissociate CO and H2
- photo-ionize C

photon number flux

$$F = \chi F_{\rm H}$$

$F_{\rm H} = 1.2 \times 10^7$ cm^{-2} s^{-1}
Habing constant (Habing 1968)

@50 AU

$\chi_{\beta \, \rm Pic} \sim 0.5$

$\chi_{\rm 49Ceti} \sim 24$

- interstellar radiation standard field (Habing 1965) → $\chi_{\rm ISRF} \sim 1$

Debris Disk in PDR

- radiation: the central star (A5V and A1V) (taken from Atlas)
  the interstellar standard radiation field
- Location: $r = 50$ AU
- Dust size distribution (mix of silicate and graphite)

$$a_{\rm min} = 1\mu{\rm m}, \quad a_{\rm max} = 10\mu{\rm m}, \quad n(a) \propto a^{-3.5}$$

$$\sigma_{\rm V} \sim 0.1\ \sigma_{\rm V,ISM}$$

the scale height $h \sim 5$ AU: $\tau_{\rm V} \sim 0.01$

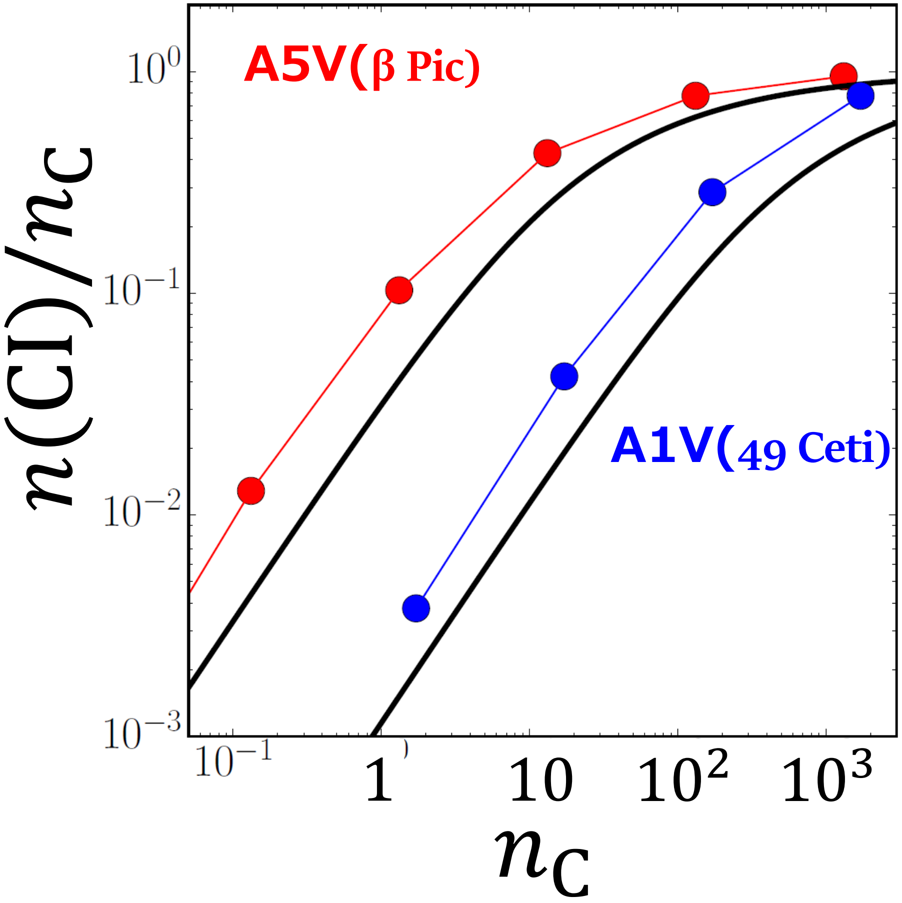
Parameters

- $n_{\rm H}$: Hydrogen nucleus number density (fiducial value: $10^6 {\rm cm}^{-3}$)
- $n_{\rm C}$: Carbon nucleus number density (fiducial value: $n_{\rm C0} = 10^6 \times A_{\rm C,ISM}$)
  - ✓O/C = 2.4 (fixed)
  - ✓dust to gas mass ratio = 0.01 (fixed)

Carbon Ionization Balance

$$\frac{n_{\mathrm{C}}}{n_{\mathrm{H}}} = 1.3 \times 10^{-4}$$

Kamp & Bertoldi (2000)



The C ionization balance depends only on n_{C} **but not on n_{H}**
(shielding by H2 and dust is not important)

(Kamp & Bertoldi 2000)

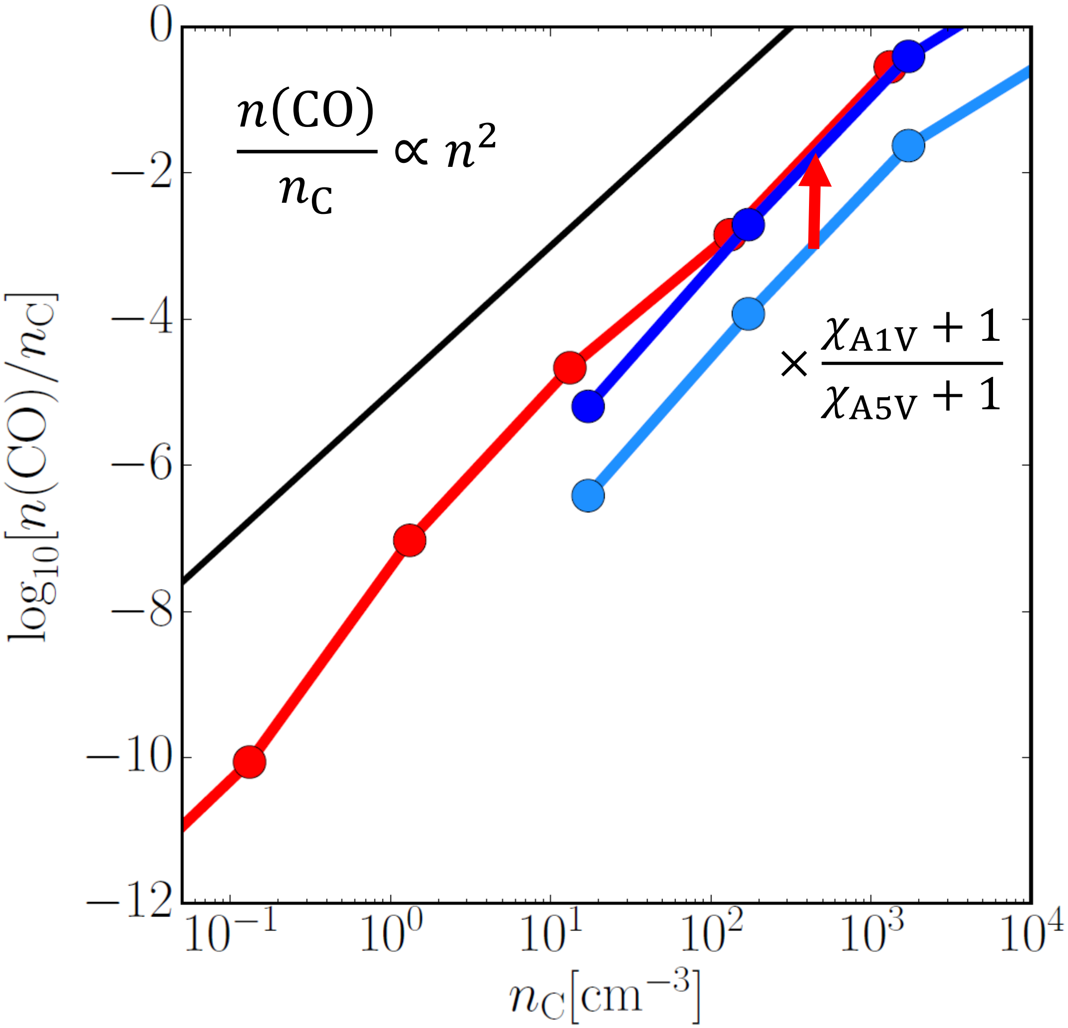
$$\mathrm{C} + \mathrm{h}\nu \rightarrow \mathrm{C}^{+}, \qquad \mathrm{C}^{+} + \mathrm{e} \rightarrow \mathrm{C}$$

$$\underset{\text{ionization}}{a_{\mathrm{C}} F_{\mathrm{FUV}} n(\mathrm{CI})} \sim \underset{\text{recombination}}{k_{\mathrm{rec}} n(\mathrm{C}^{+}) n(\mathrm{e})}$$

$$\Downarrow \qquad n(\mathrm{e}) \sim n(\mathrm{C}^{+})$$

$$\frac{n(\mathrm{CI})}{n_{\mathrm{C}}} = \mathrm{f}\left(\frac{F_{\mathrm{FUV}}}{n_{\mathrm{H}}}\right)$$

CO Fraction @ $\tau_V = 0.01$

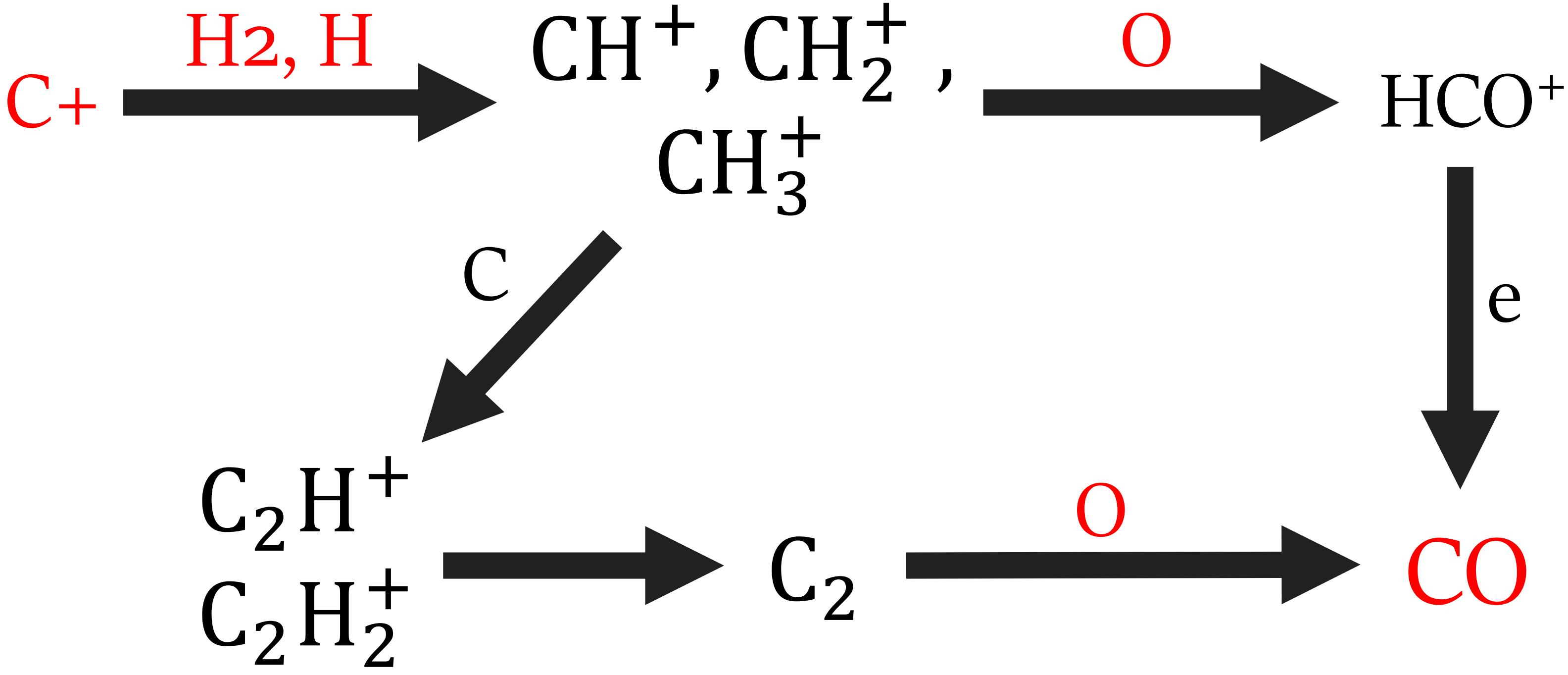


$$\frac{n_\mathrm{C}}{n_\mathrm{H}} = 1.3 \times 10^{-4}$$

$n(\mathrm{CO})$ strongly depends on n

$$\boldsymbol{n(\mathrm{CO}) \propto n^3 \times \chi^{-1}}$$

Main Route of CO Formation



$C+$ $\xrightarrow{H_2, H}$ CH^+, CH_2^+, CH_3^+ $\xrightarrow{O}$ HCO^+

CH^+, CH_2^+, CH_3^+ $\xrightarrow{C}$ C_2H^+, $C_2H_2^+$

C_2H^+, $C_2H_2^+$ $\rightarrow$ C_2 $\xrightarrow{O}$ CO

HCO^+ $\xrightarrow{e}$ CO

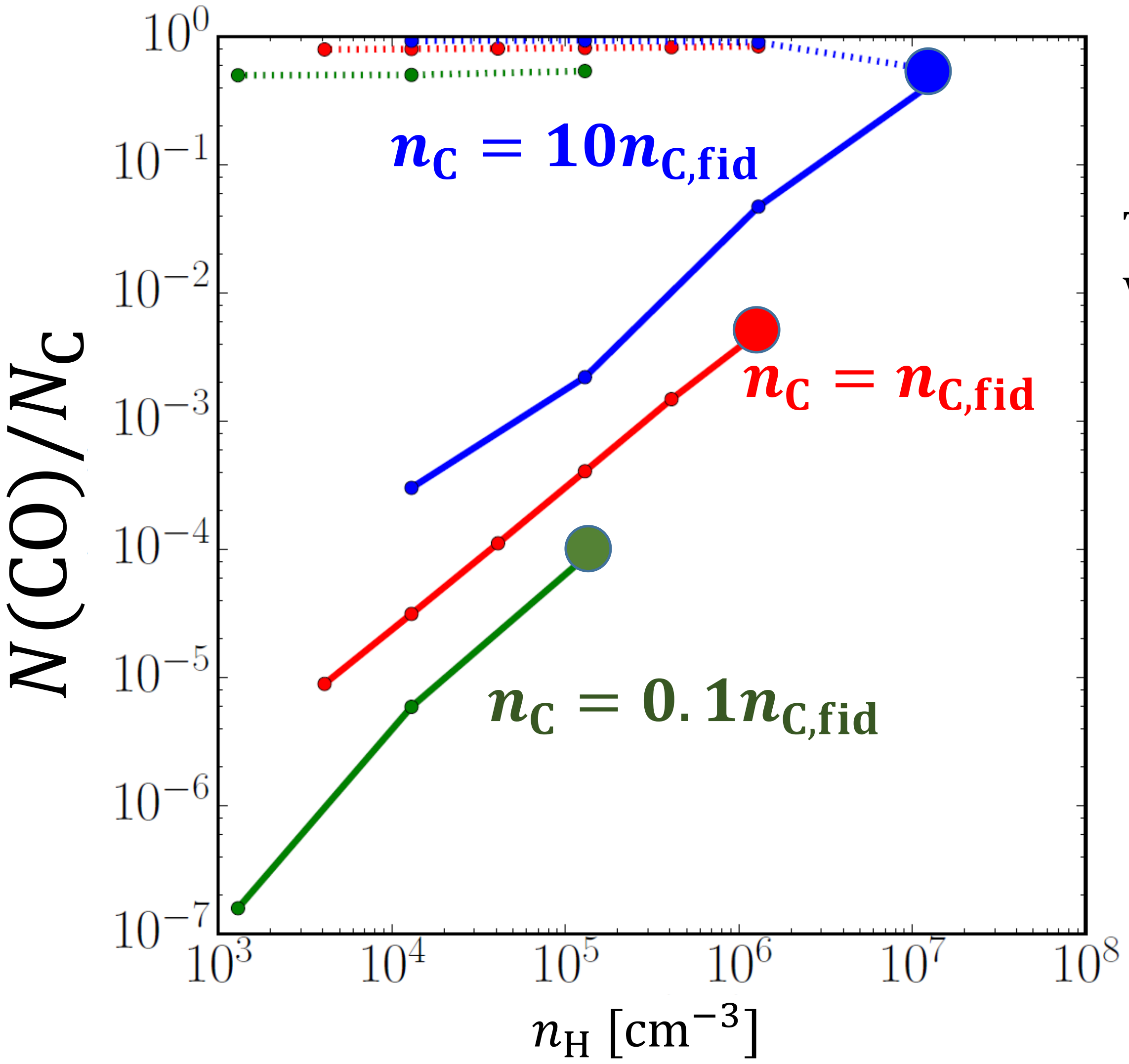
photo-dissociation rate

formation rate

$$\Gamma_{CO} n(CO) \sim k n(C^+) \times n(H_2) \times n(O)$$

$$\Rightarrow n(CO) \propto \boldsymbol{n_C^2 \times n_H \times \chi^{-1}}$$

$(n_\mathrm{H}, n_\mathrm{C})$-dependence of CO Column Density (A5V β Pic)



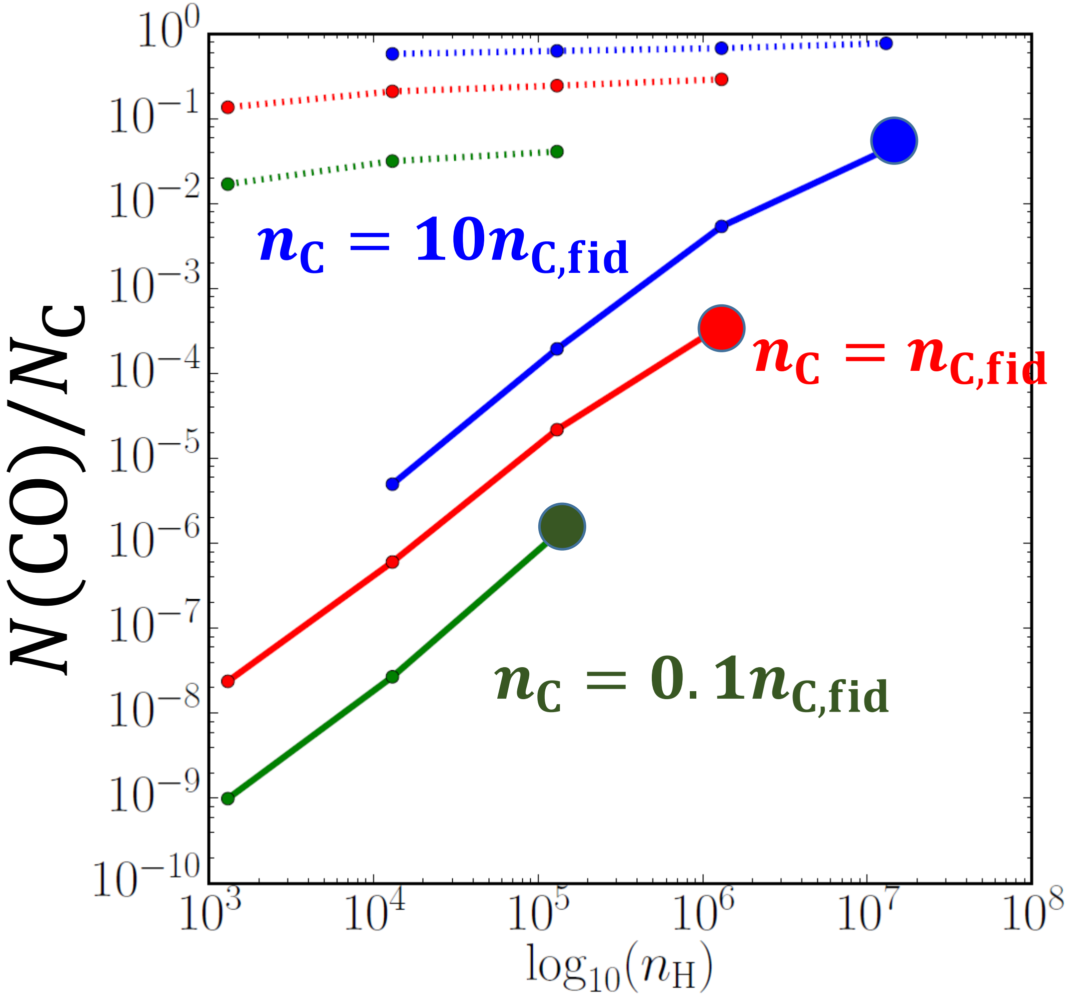
@ $\tau = 0.01$

The CO abundance increases with the hydrogen density.

$$\frac{N(\mathrm{CO})}{N_\mathrm{C}} \propto n_\mathrm{H} \times n_\mathrm{C}$$

n_H-dependence of CO Column Density (A1V 49Ceti)

@ $\tau = 0.01$

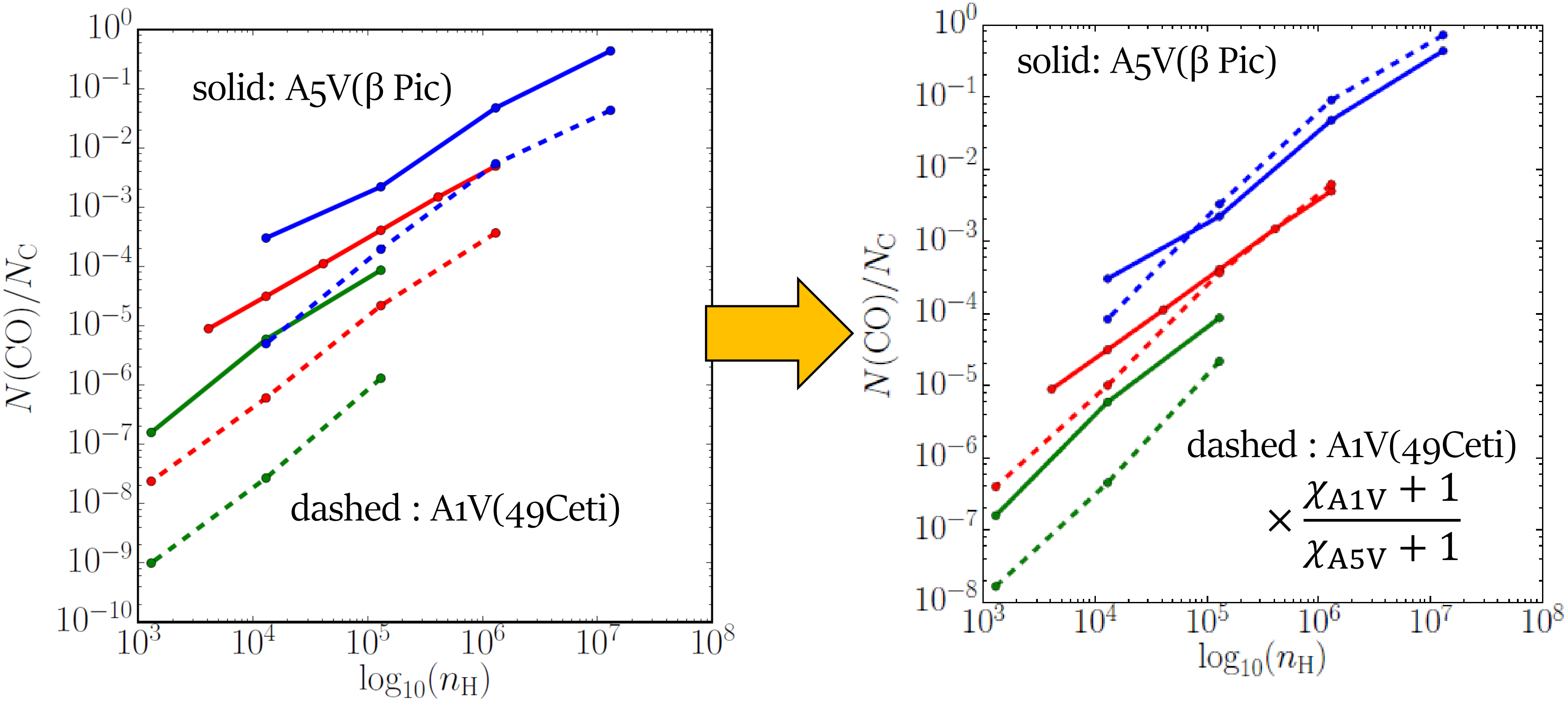


The CO abundance increases with the hydrogen density.

$$\frac{N(\mathrm{CO})}{N_\mathrm{C}} \propto n_\mathrm{H} \times n_\mathrm{C}$$

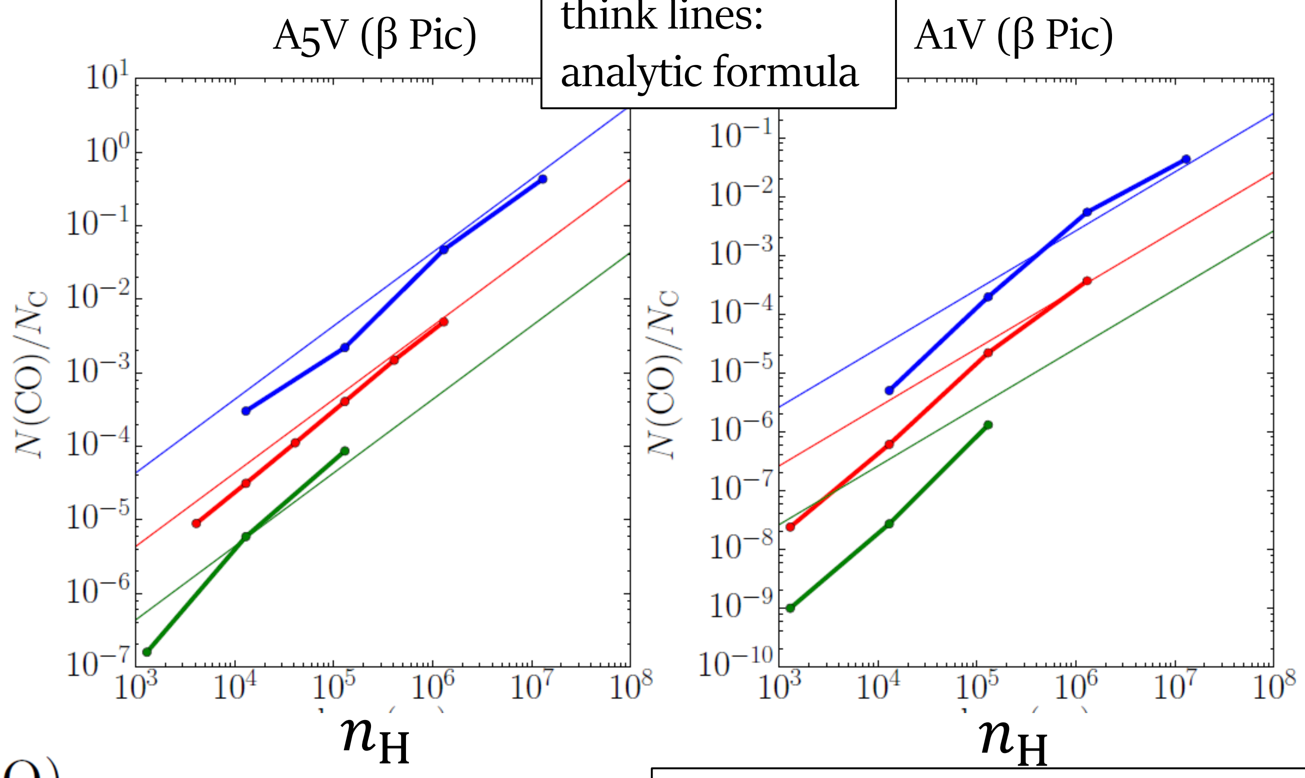
FUV Flux Dependence of CO Column Density

@ $\tau = 0.01$



$\dfrac{N(\mathrm{CO})}{N_\mathrm{C}} \propto n_\mathrm{H} \times n_\mathrm{C} \times \chi^{-1}$ is roughly satisfied except for low densities (the green lines).

Analytic Formula



think lines:
analytic formula

$$\frac{N(\mathrm{CO})}{N_\mathrm{C}} \sim 5 \times 10^{-11} n_\mathrm{H} n_\mathrm{C} \chi^{-1}$$

The analytic formula agrees with the results for higher densities.

$$\frac{N(\mathrm{CO})}{N_\mathrm{C}} \sim 7 \times 10^{-2} \left(\frac{n_\mathrm{H}}{10^{6}\ \mathrm{cm}^{-3}} \right)^{2} \left(\frac{\mathcal{A}_\mathrm{C}}{1.3 \times 10^{-4}} \right) \chi^{-1}$$

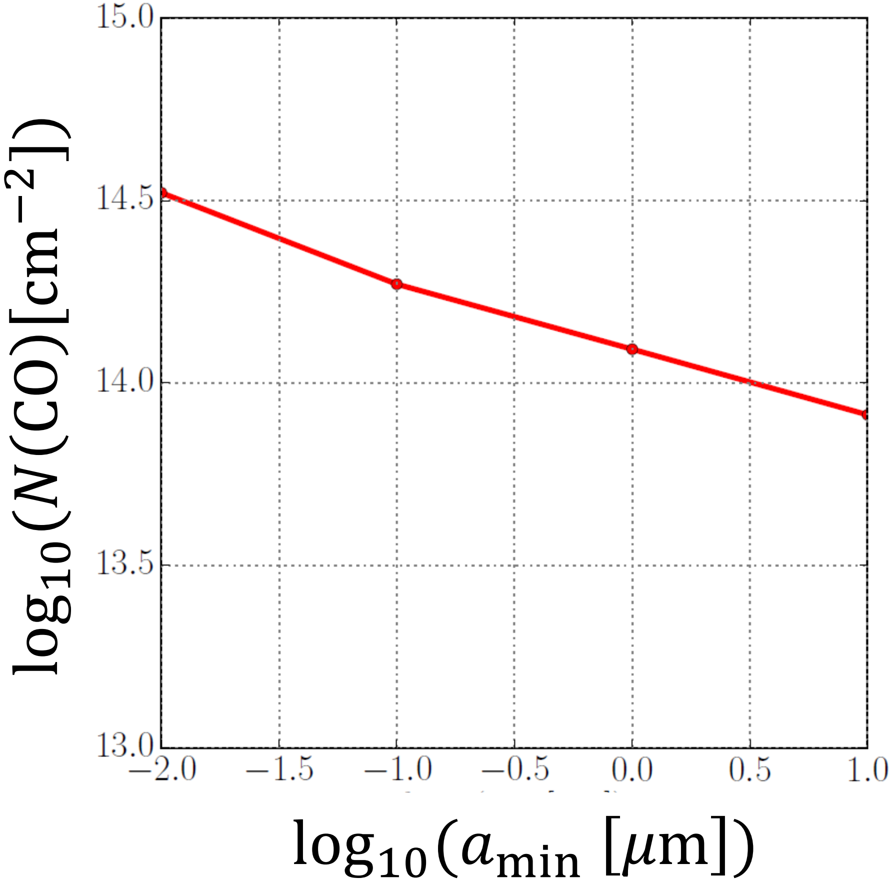
Compared with Observations

$$\frac{N(\mathrm{CO})}{N_\mathrm{C}} \sim 7 \times 10^{-2} \left(\frac{n_\mathrm{H}}{10^6 \ \mathrm{cm}^{-3}} \right)^2 \left(\frac{\mathcal{A}_\mathrm{C}}{1.3 \times 10^{-4}} \right) \chi^{-1}$$

- **β Pic**
  - ✓ Higuchi+ 2017 → $\frac{N(\mathrm{CO})}{N(\mathrm{CI})} \sim (2 \pm 0.5) \times 10^{-2}$
    if gas is the primordial origin, n_H should be larger than $10^{5-6}\ \mathrm{cm}^{-3}$.
  - ✓ there are several evidence for low H2 abundance.
    - ➢ Lecavelier des Etangs+2001: there are no absorption H2 lines in the stellar spectrum.
      → $N(\mathrm{H}_2) \leq 10^{18}\ \mathrm{cm}^{-2}$
    - ➢ Matra+2017 CO(3-2)/CO(2-1) line ratio depends on nH2.
      → $n(\mathrm{H}_2) < 10^3 - 10^4\ \mathrm{cm}^{-3}$
  - ✓ It is difficult to explain the large CO/CI ratio in the primordial origin.
- **49 Ceti**
  - ✓ Higuchi+ 2017→ $\frac{N(\mathrm{CO})}{N(\mathrm{CI})} \sim 0.01 - 0.04$
    if gas is the primordial origin, n_H should be larger than $10^{6-7}\ \mathrm{cm}^{-3}$.
  - ✓ So far, there is no constraint on H2
  - ✓ Roberge+ 2013: a simple chemical model cannot reproduce
    CO, C+, OI emissions simultaneously.

consistent with the scale height

Dependence of the CO column density on the minimum dust size



- The CO column density is almost independent of the minimum dust size.
  → dusts determine only A_V.

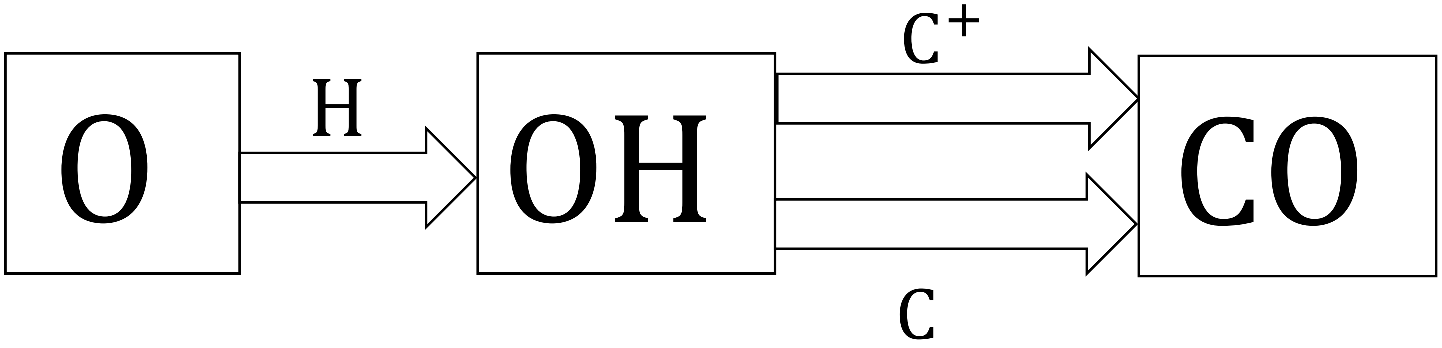
Summary

- We calculate the chemical and thermal equilibria with line and continuum radiative transfer in using the *Meudon* PDR code.
- We found that $n(\mathrm{CO}) \propto n_{\mathrm{C}}^{2} \times n_{\mathrm{H}} \times \chi^{-1}$

$$\frac{N(\mathrm{CO})}{N_{\mathrm{C}}} \sim 7 \times 10^{-2} \left(\frac{n_{\mathrm{H}}}{10^{6}\ \mathrm{cm}^{-3}} \right)^{2} \left(\frac{\mathcal{A}_{\mathrm{C}}}{1.3 \times 10^{-4}} \right) \chi^{-1}$$

✓ The CO fraction can be used to estimate n_{H} and N_{H2}.

CO Formation in Low Density Gas



O

H

OH

C+

C

CO

$$n_{\mathrm{CO}} = 9.6 \times 10^{-13} \left(n_{\mathrm{C}} + 17.4 n_{\mathrm{C+}}\right) n_{\mathrm{O}} \times n_{\mathrm{H}}$$