Isotopic Fractionation of C^+

M. Röllig & V. Ossenkopf

A&A 550, A56 (2013)

Isotopic fractionation reaction

- Fractionation reactions with different back and forth reaction rates channel isotopes into some preferred isotopologues.
- Whenever the chemistry of one of the involved species is dominated by the respective fractionation reaction, that species will show considerable fractionation, i.e., a deviation from the elemental abundance ratio (ER).

$$^{13}C^{+} + CO \rightleftharpoons C^{+} + {}^{13}CO + \Delta E = 35\,K$$

$$HCO^{+} + {}^{13}CO \rightleftharpoons H{}^{13}CO^{+} + CO + \Delta E = 9\ K$$

Isotopic fractionation reaction

- Fractionation reactions with different back and forth reaction rates channel isotopes into some preferred isotopologues.
- Whenever the chemistry of one of the involved species is dominated by the respective fractionation reaction, that species will show considerable fractionation, i.e., a deviation from the elemental abundance ratio (ER).

$$^{13}C^{+} + CO \rightleftharpoons C^{+} + {}^{13}CO + \Delta E = 35\,K$$

$k_{\rightarrow}$ fast → / slow ← $k_{\leftarrow} = k_{\rightarrow} \times e^{(-35K/T)}$

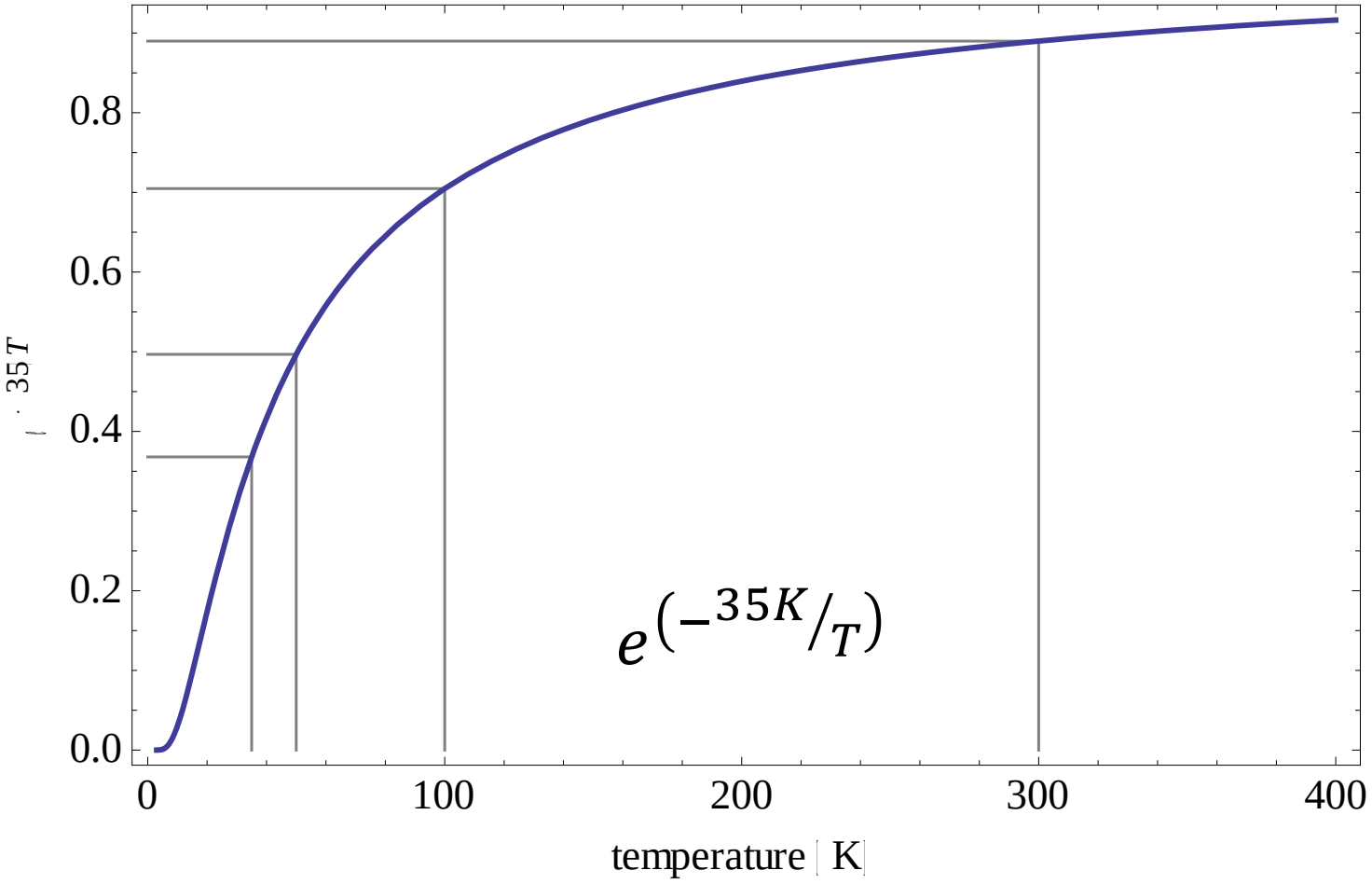
CO vs. C^+

$$^{13}C^+ + CO \rightleftharpoons C^+ + {}^{13}CO + \Delta E = 35\,K$$

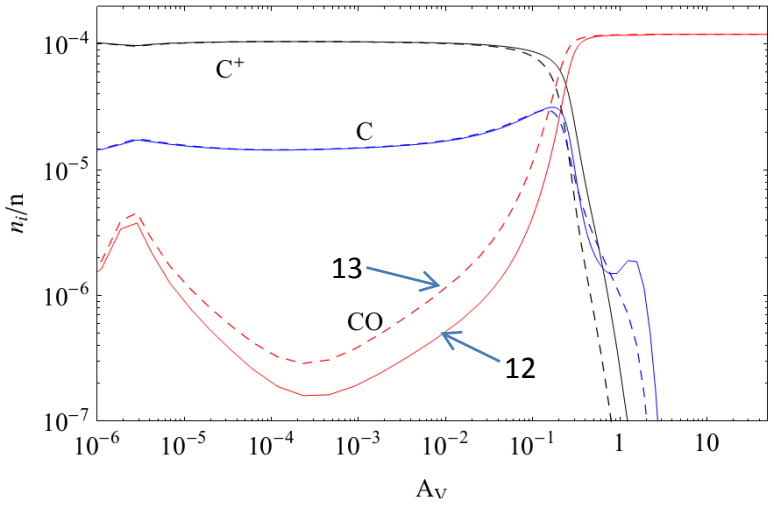
- The fractionation reaction will always try to enhance $^{12}C^+/^{13}C^+$ and $^{13}CO/^{12}CO$
- Isotope selective photodissociation of CO is a competing process trying to diminish $^{13}CO/^{12}CO$.
- There is no isotope selective destruction process of C+ that could reduce $^{12}C^+/^{13}C^+$

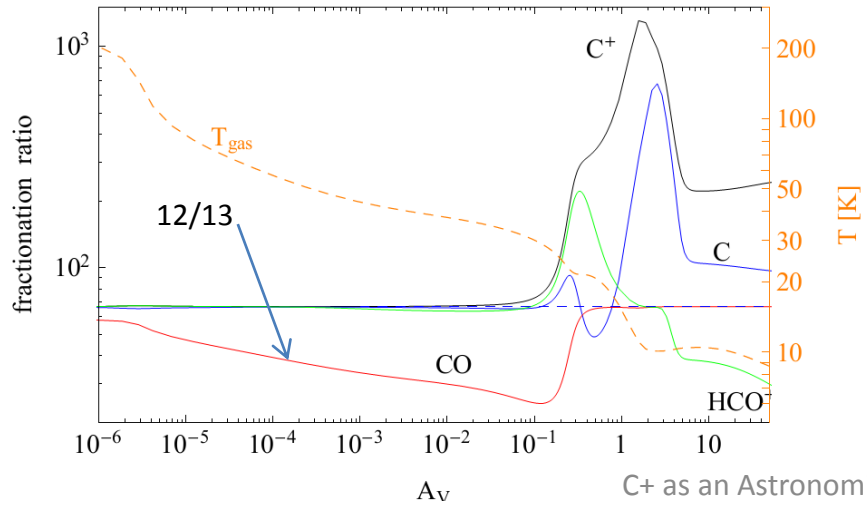
→ $^{12}C^+/^{13}C^+$ will always be enhanced relative to the elemental ratio (ER)

NOT only a low-T effect



C⁺ fractionation





Standard behavior of carbon isotopologues in PDRs:

- C⁺ fractionation ratio (FR) is always ≥ ER
- C⁺ FR ≈ ER at low A_V
- C⁺ FR increases significantly with A_V

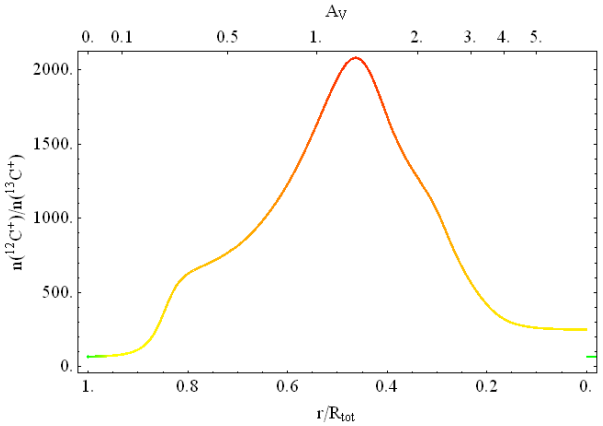
$$^{13}C^+ + CO \rightleftharpoons C^+ + {}^{13}CO + \Delta E = 35\,K$$

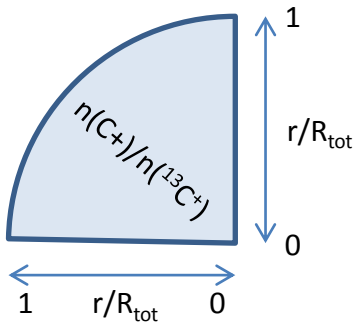
$$R_{\rightarrow} = n(^{13}C^+) \times n(CO) \times k_{\rightarrow}$$

C⁺ fractionation needs cool, shielded C⁺ gas (weak column density effect)

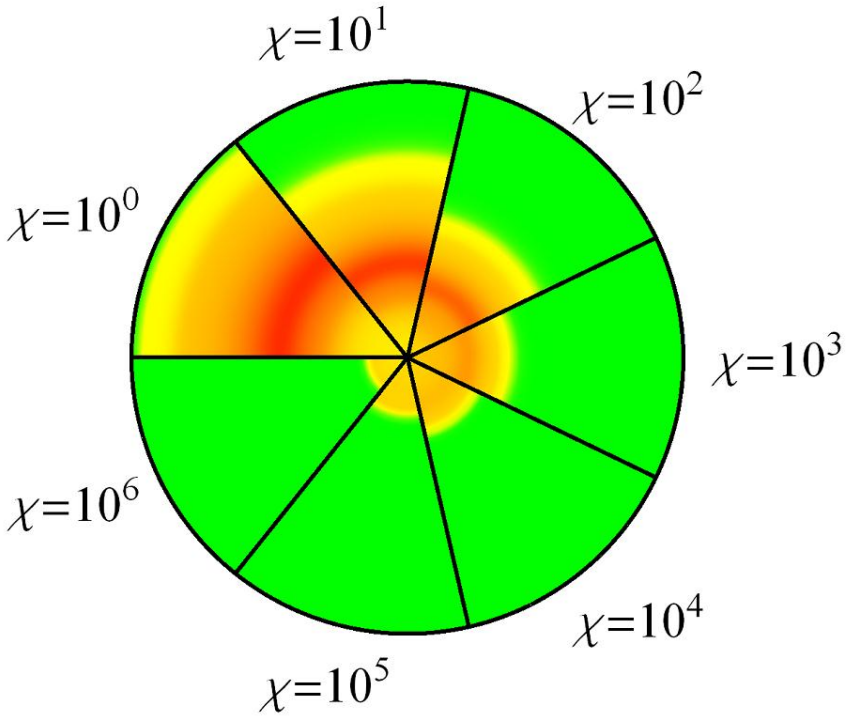
C^+ Fractionation ratio

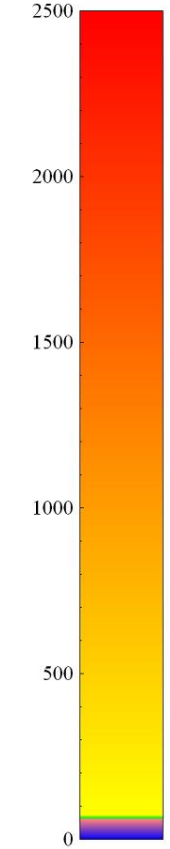
$n=10^4\ cm^{-3}, M=10^0\ M_\odot$





Each segment corresponds to a seperate clump model



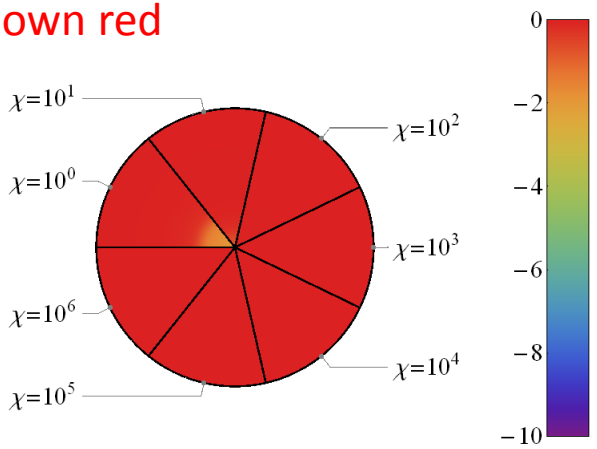


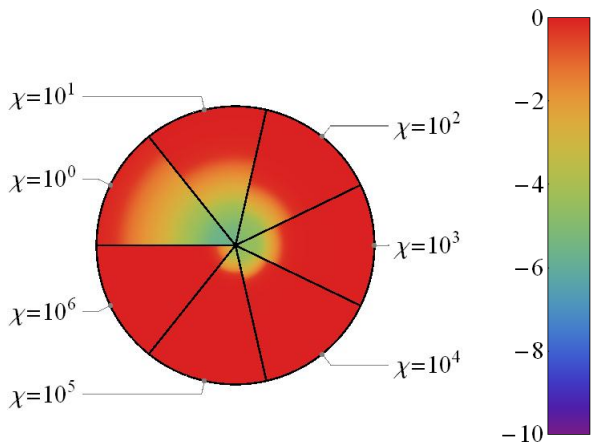
What clump volume is filled by C^+?

$$\frac{n(C^+)}{n(C^+) + n(C) + n(CO)}$$

C^+ gas is shown red

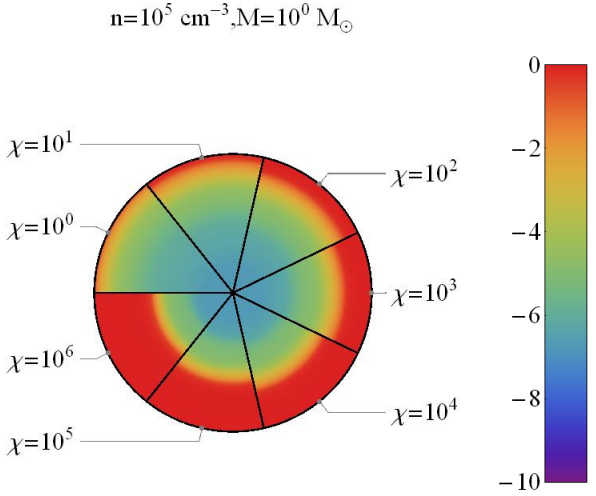
$n=10^3$

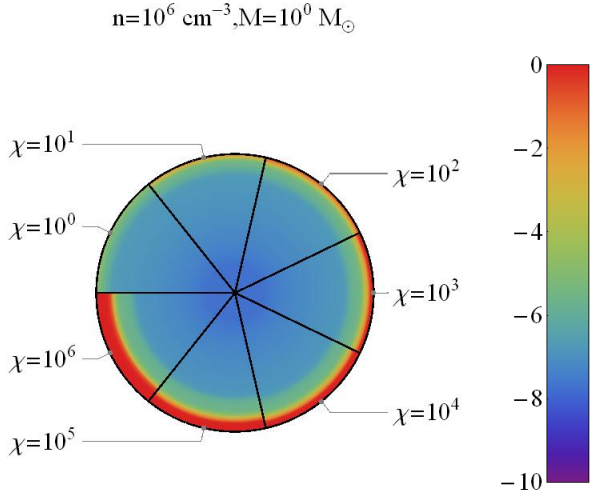




$n=10^4$

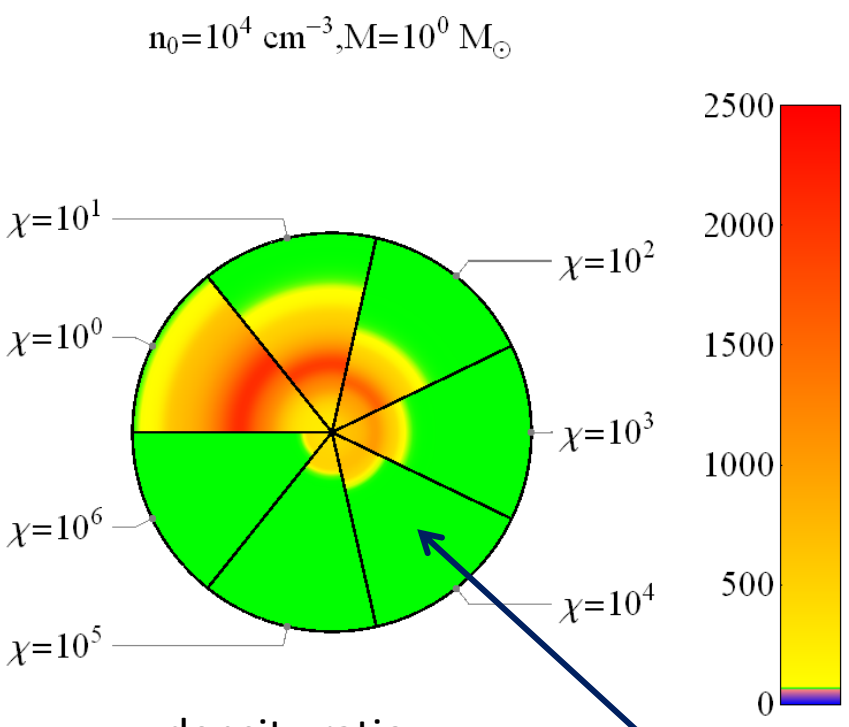
$n=10^5$



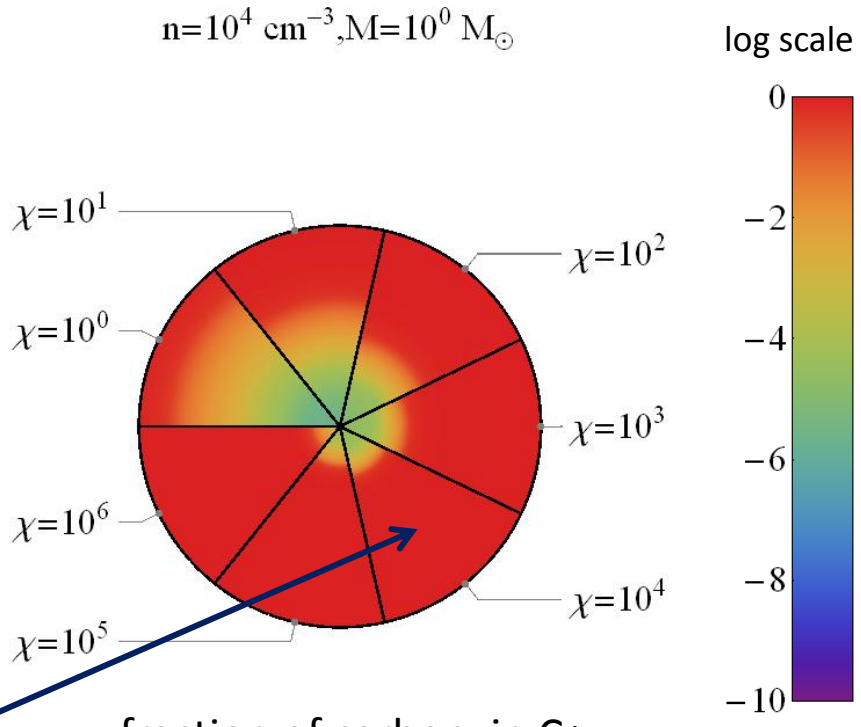


$n=10^6$

Volume effect of fractionation



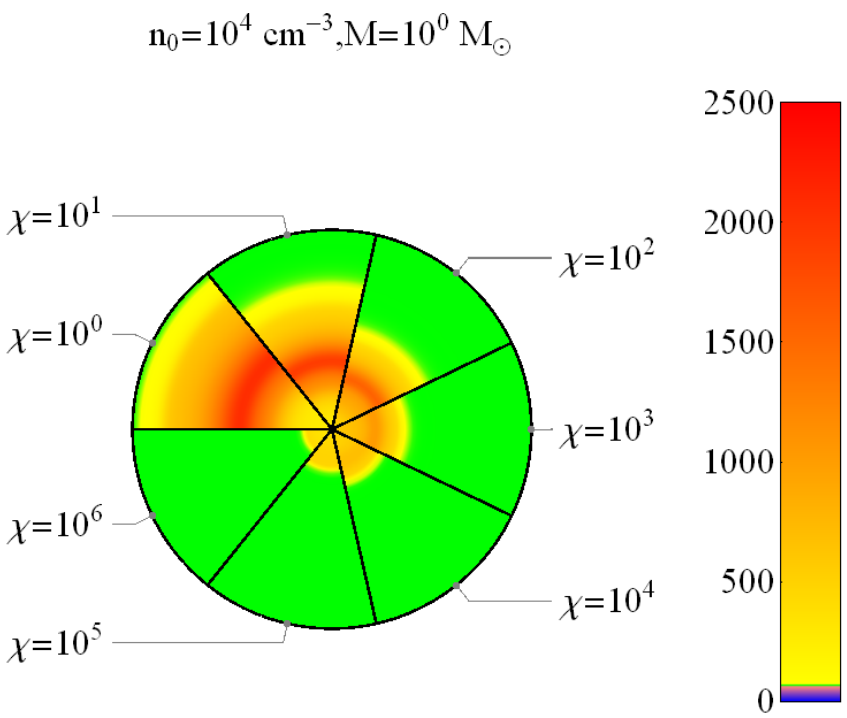
density ratio



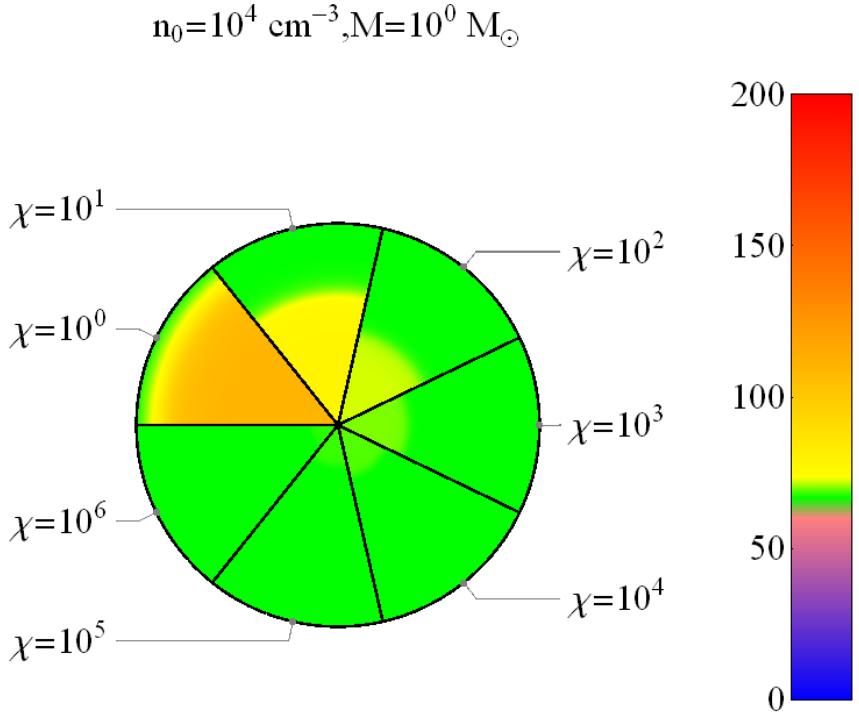
fraction of carbon in C+

Majority of C^+ gas not fractionated

Column density effect



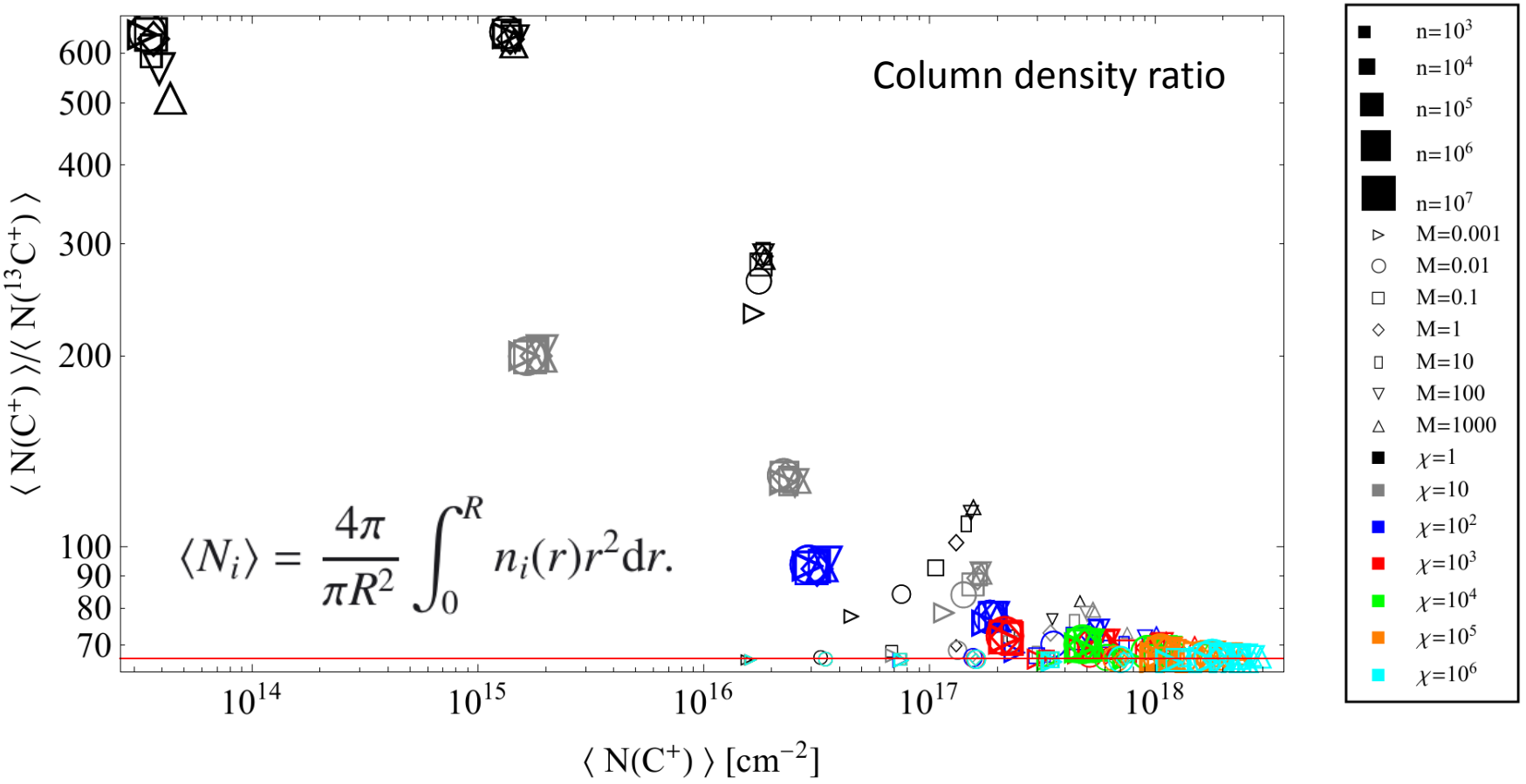
density ratio



column density ratio

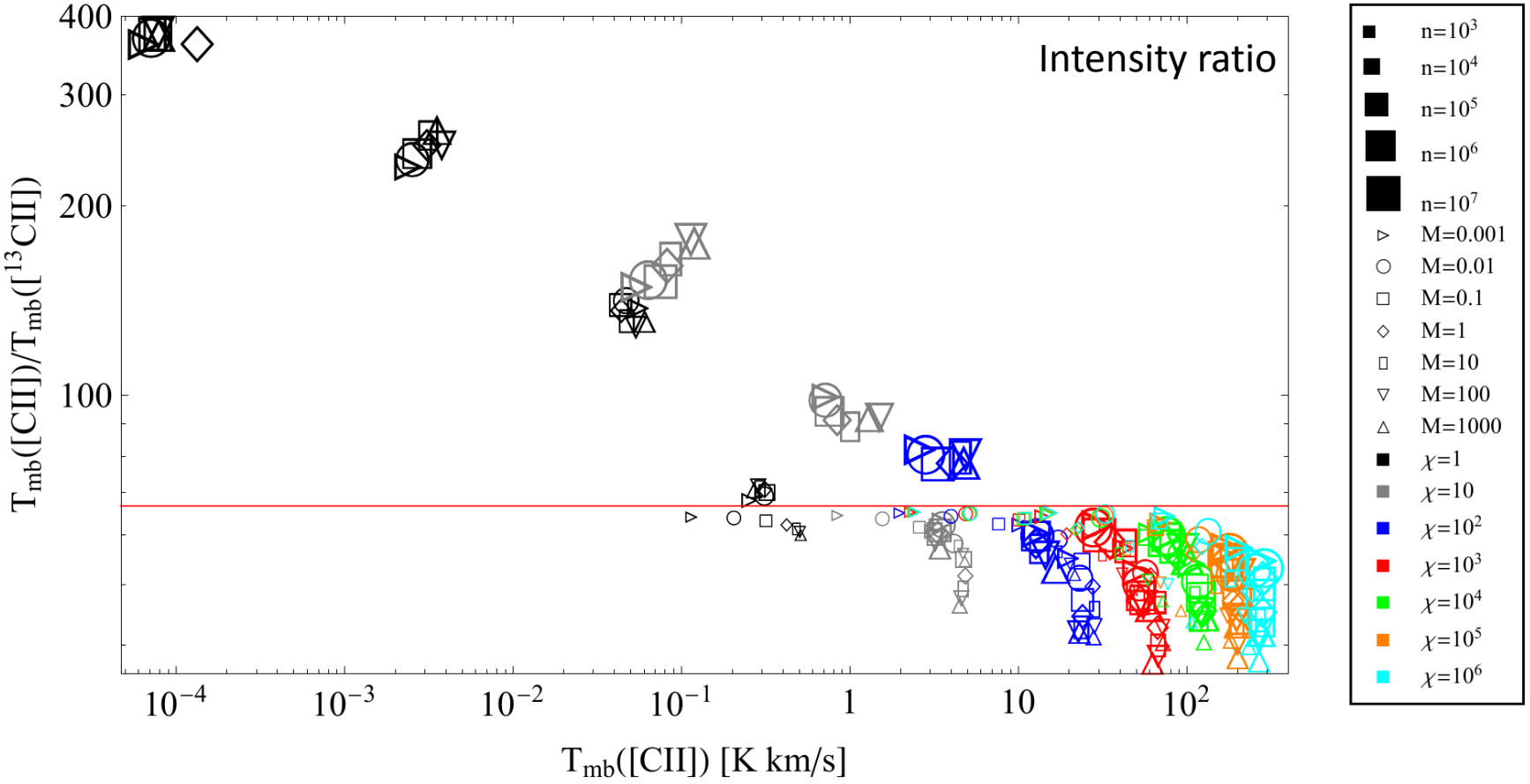
$C^+/^{13}C^+$ column density ratios

C^+ fractionation needs cool, shielded C^+ gas (weak column density effect)

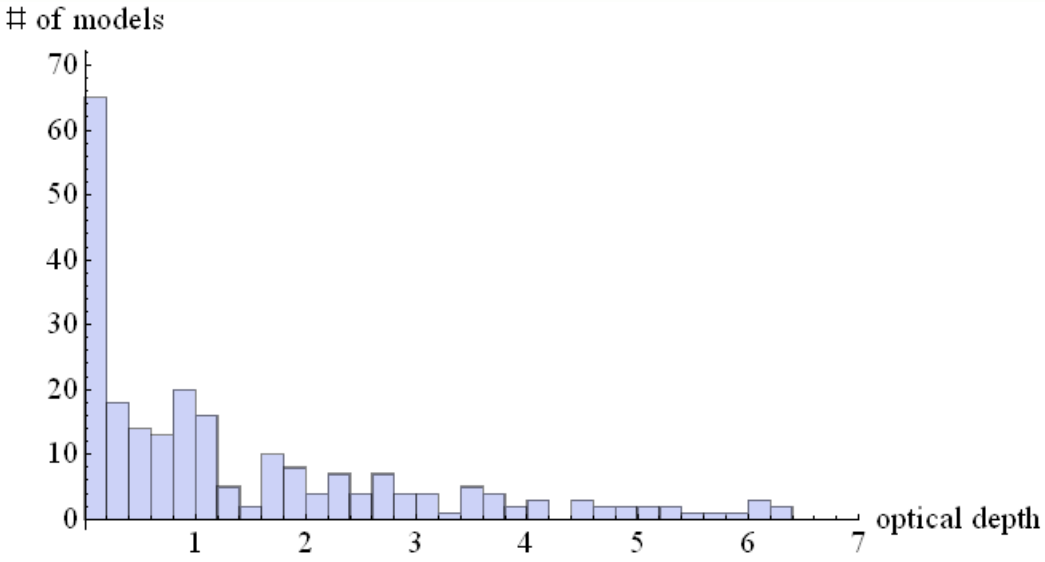


$C^+/^{13}C^+$ intensity ratios

Optical depth effects will lead to a FR < ER



[CII] optical depths

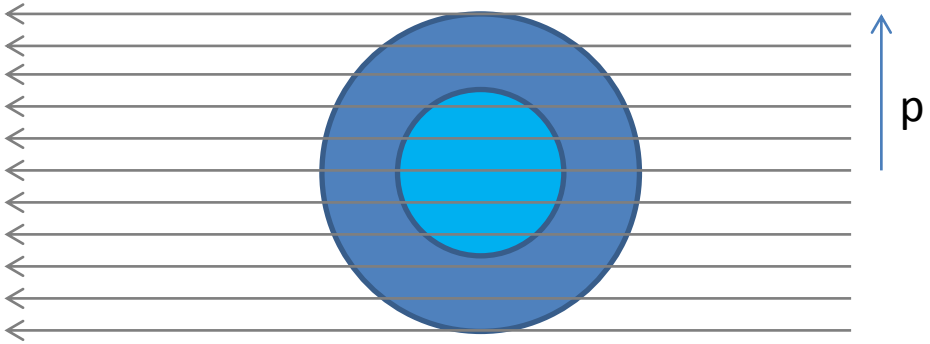


Parameter grid

n = 10^3-10^7 cm^{-3}

M = 10^{-3}-10^3 $M_\odot$

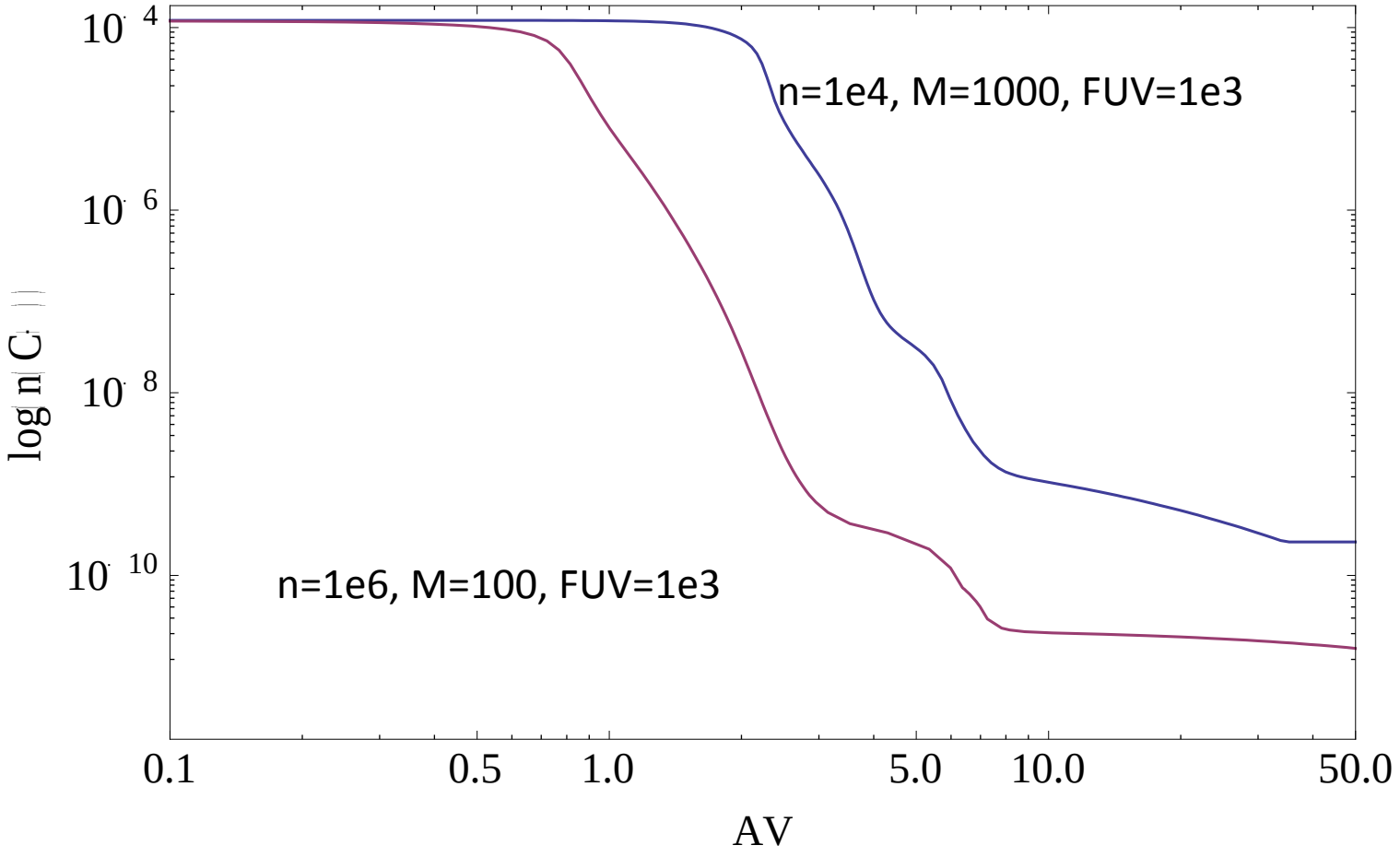
FUV = 1-10^6



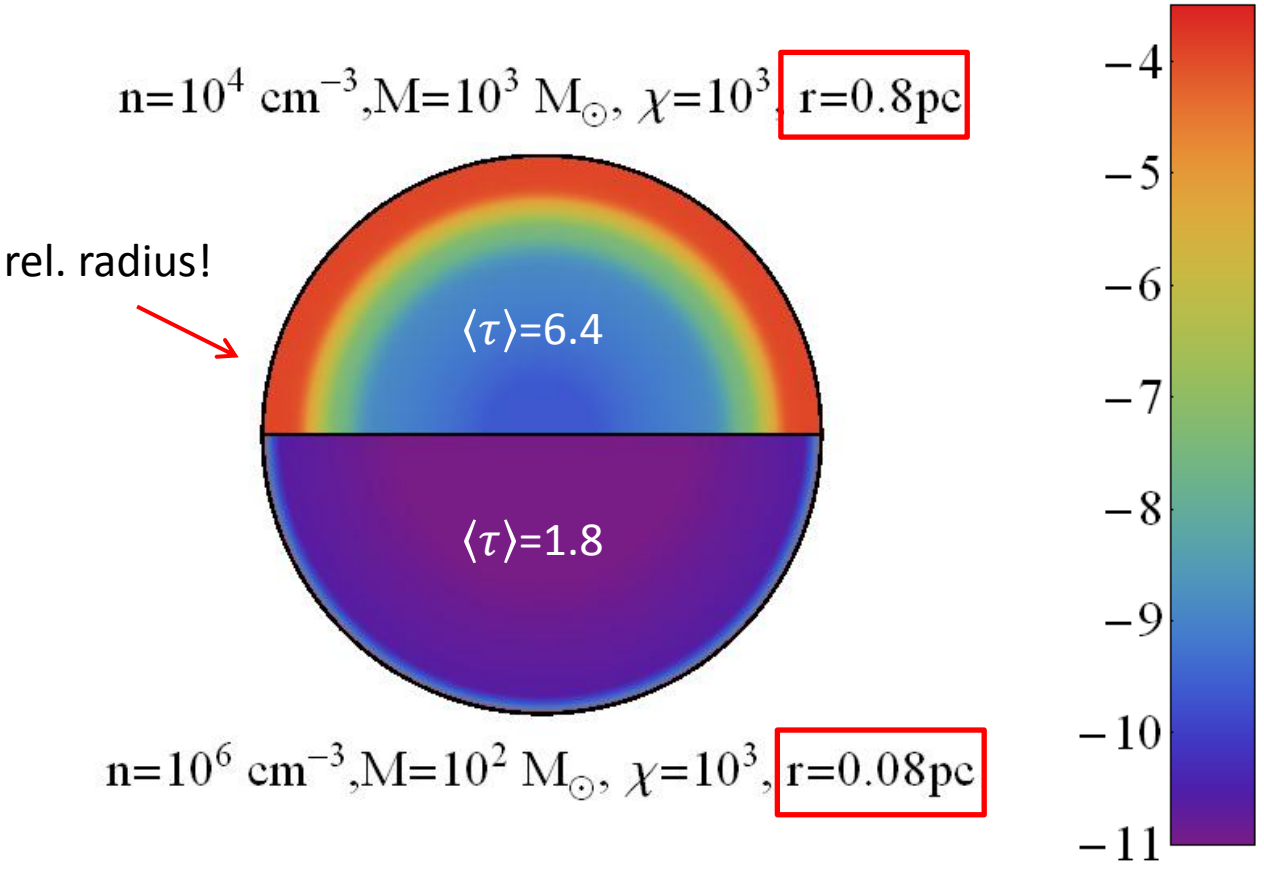
clump averaged optical depths will be (somewhat) higher than simple, plane-parallel figures

$$\langle \tau \rangle = \frac{4\pi}{\pi R^2} \int_0^R \tau(p) p dp$$

A_V versus spatial dimension

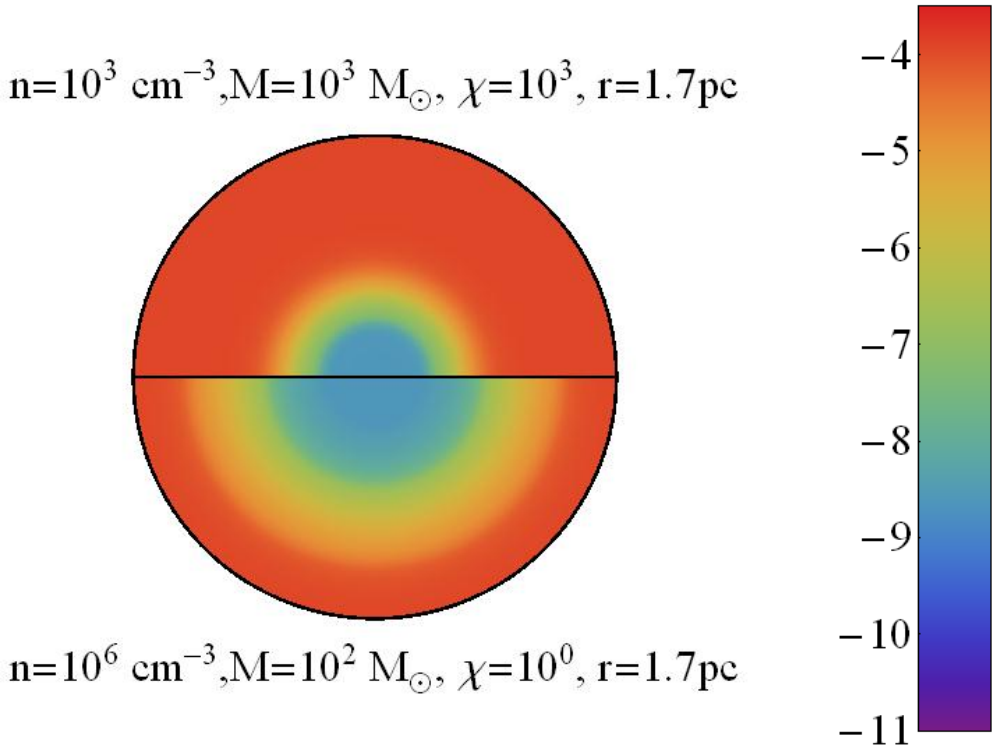


A_V versus spatial dimension



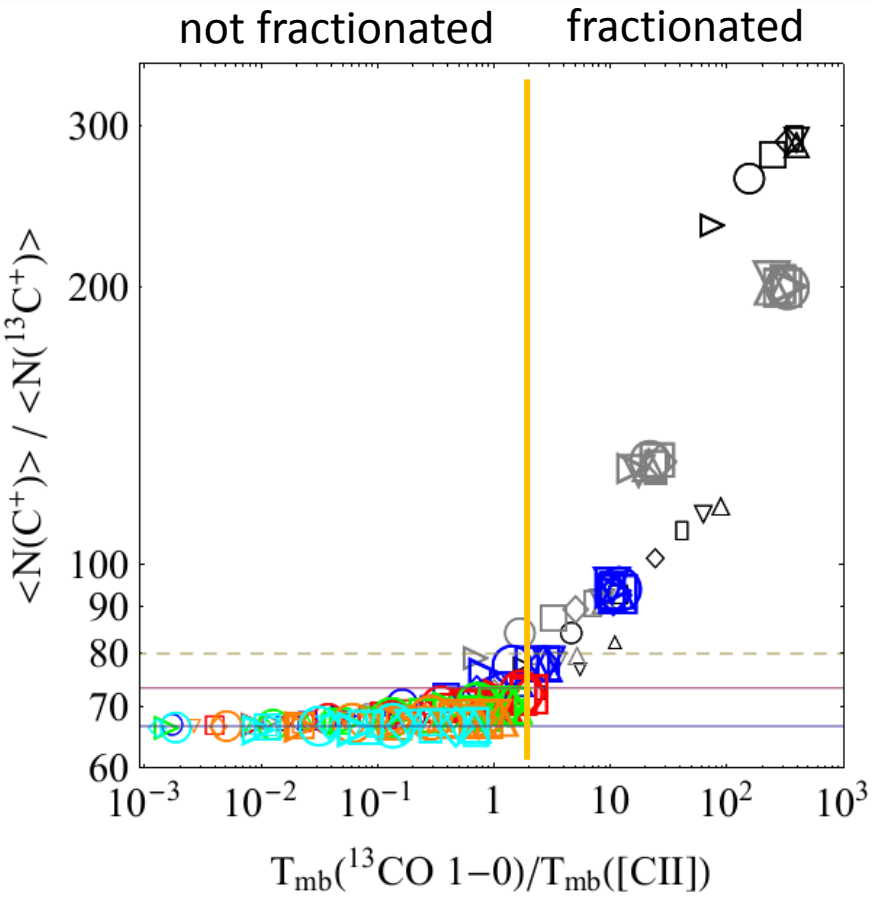
A_V versus spatial dimension

rel C^+ density



low FUV PDR still has a large C^+ volume

C^+ fractionation diagnostics



Diagnostic line ratios to detect column density fractionation of C^+:

A line ratio of ^{13}CO (1-0)/ [CII] > 2 indicates a fractionated **C^+** column.

No fractionation expected for FUV > 100

Summary

- Any fractionation of C^+ will always be in favor of $^{12}C^+$.
- Considerable C^+ fractionation will only occur in cool, shielded C^+ gas.
- Clumps with FUV illumination of χ>100 will show negligible C^+ fractionation.
- Optical thickness effects will give $T_{mb}([CII])/T_{mb}([^{13}CII]) < ER$.