# $^{13}$C fractionation in PDRs

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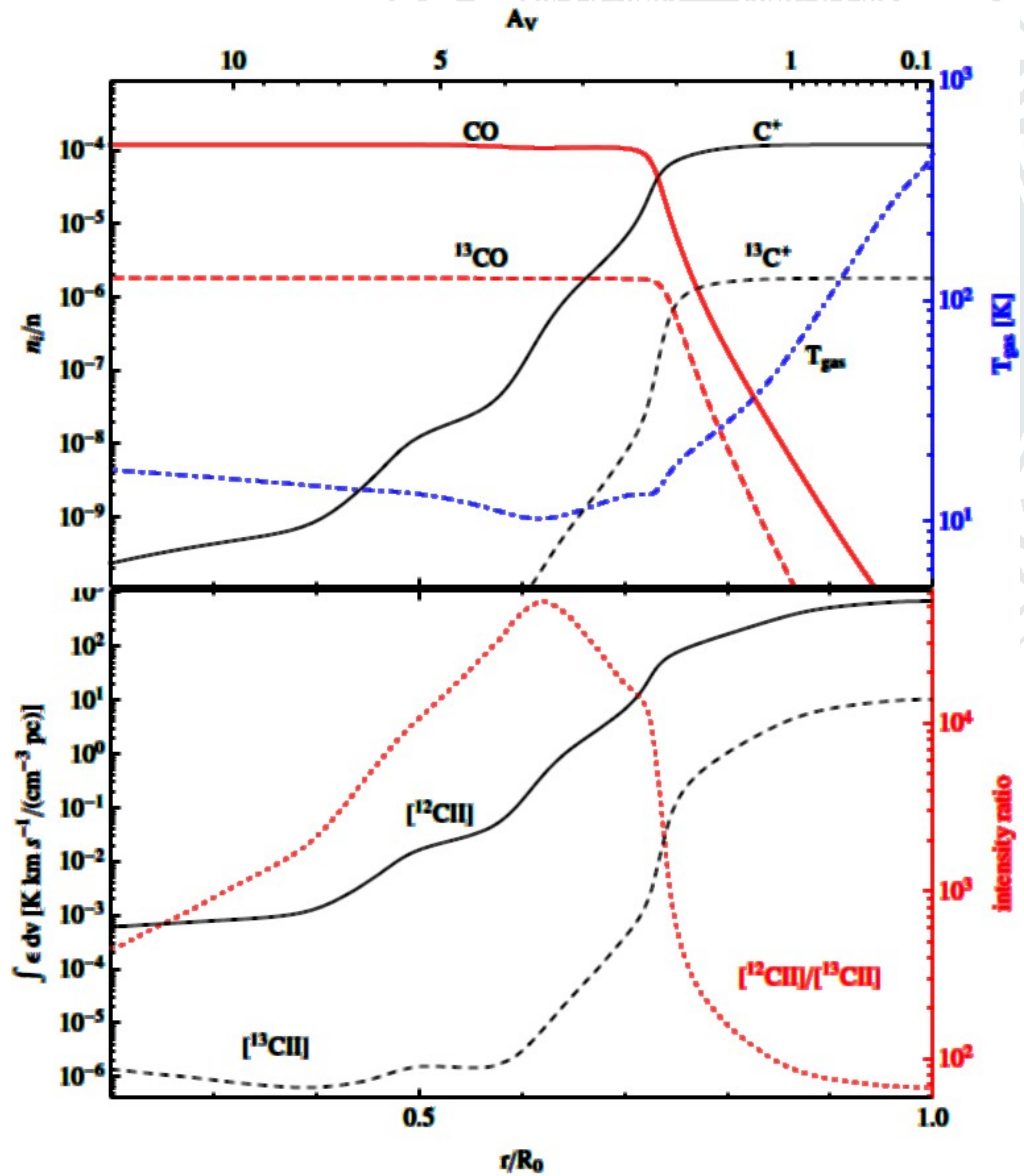
- Fractionation reaction

$$^{13}C^{+} + CO \rightleftharpoons C^{+} + {}^{13}CO + 34.8\,K$$

drives a different chemistry for $^{12}$C and $^{13}$C

- Relevant for photo-dissociation regions (PDRs) with significant fraction of $C^{+}$

- $^{12}C^{+}/^{13}C^{+}$ can be enhanced by factor > 100

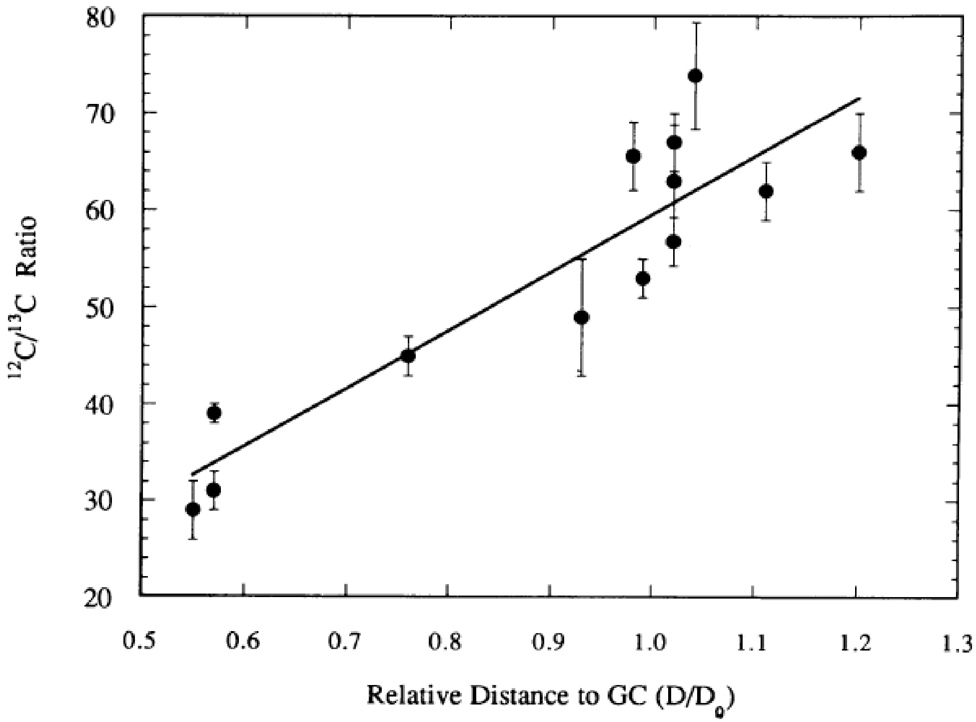



*Chemical structure of a $100M_{\odot}$ PDR for $\chi=1000\chi_0$*

# Input: the elemental ratio

- Optically thin $C^{18}O$ and $^{13}C^{18}O$ should directly measure the elemental abundance ratio
  (Langer & Penzias 1990, 1993, Keene et al. 1998)

- Dependence on Galactocentric radius:

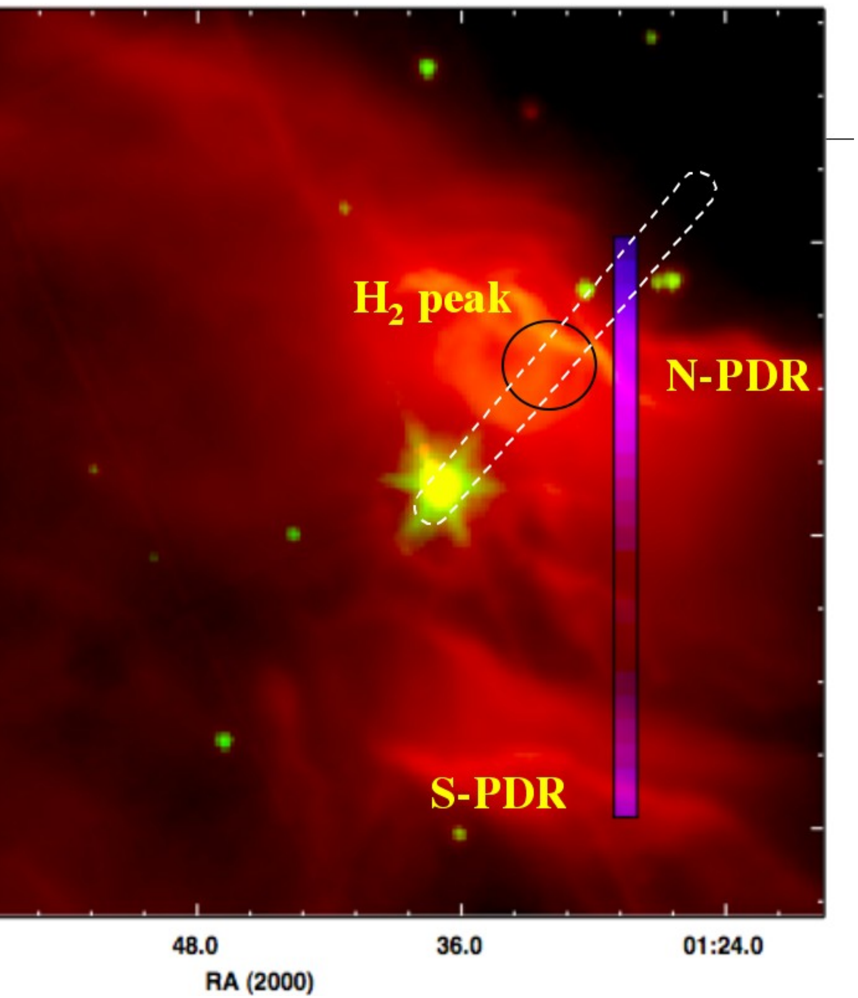



Langer & Penzias (1993)

- Average at solar Galactocentric radii: *ER* = $^{12}C/^{13}C \approx 60$

# Observational test of fractionation

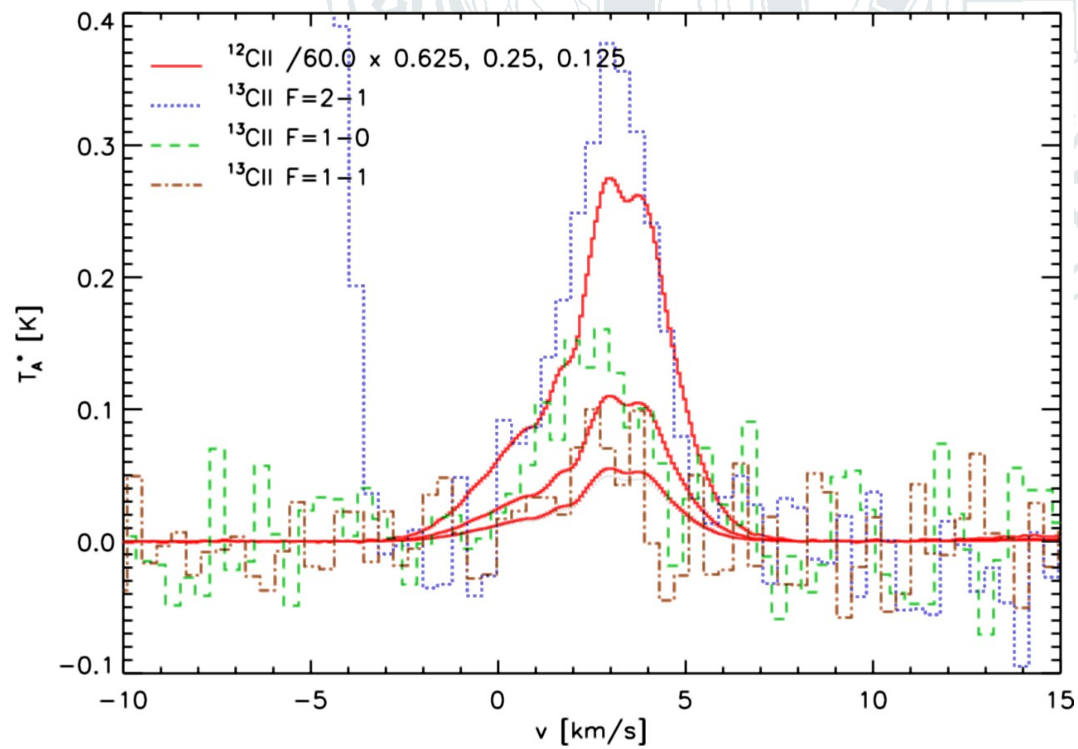
## [CII]/[$^{13}$CII] in NGC7023




*Spitzer IRAC (Joblin et al. 2008)*
*Observations at northern point*

HIFI observations of $C^+$ and $^{13}C^+$ at 158µm:

- Intensity ratio: [$^{12}$CII]/[$^{13}$CII]=51

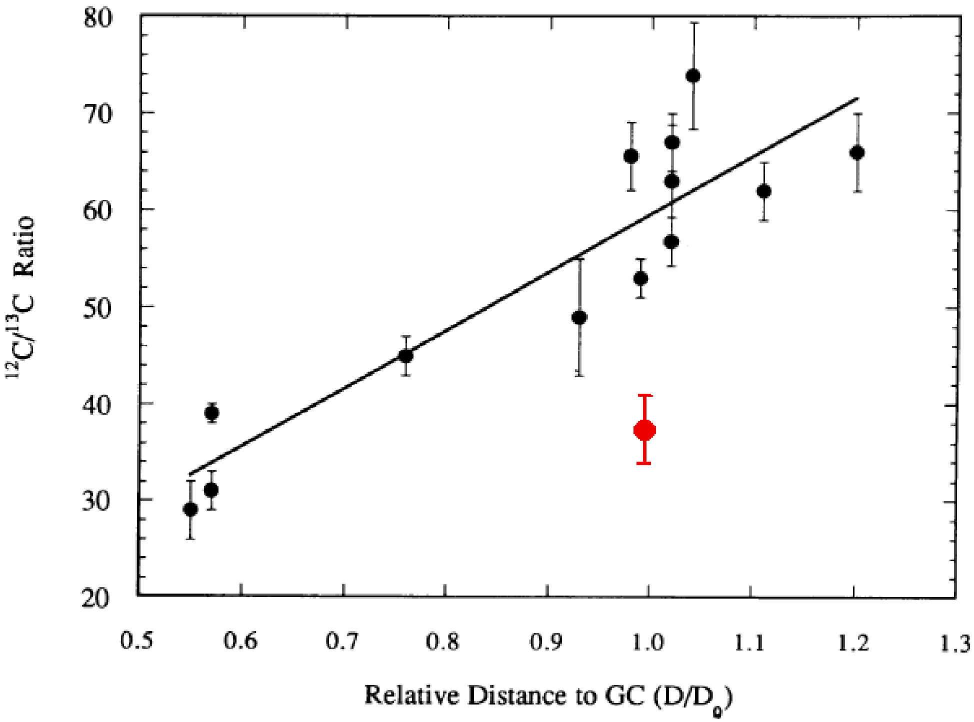


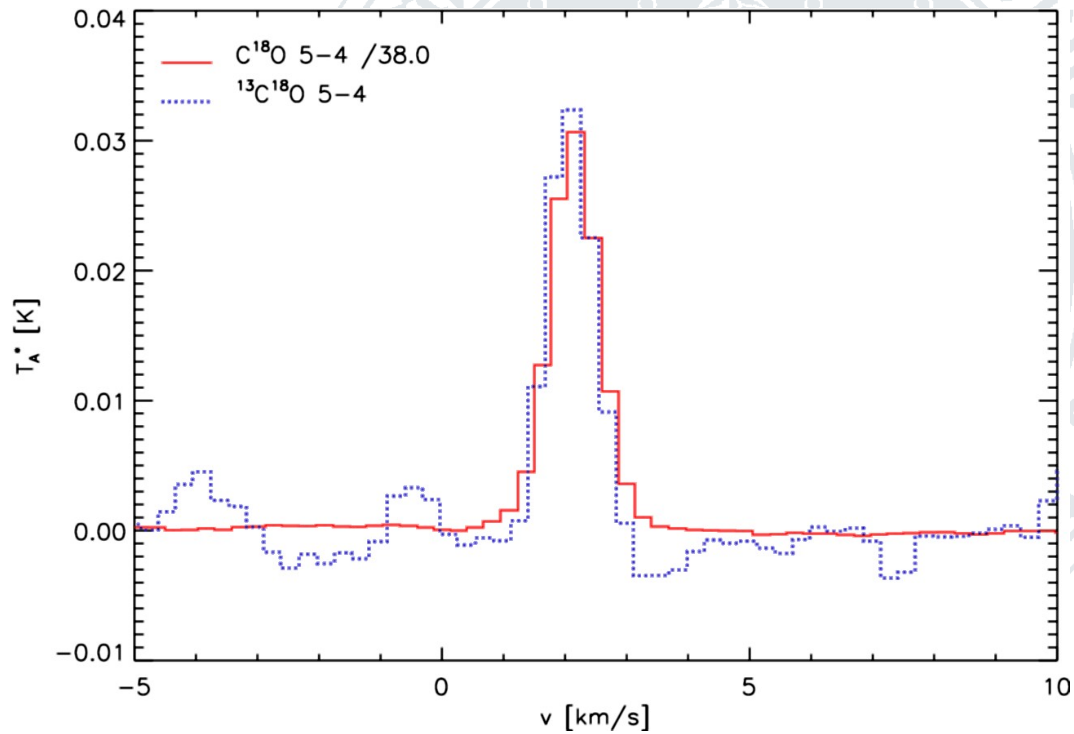

*[$^{13}$CII] hyperfine components compared to [CII] scaled by normal HF ratio and FR=60 for optically thin emission (Ossenkopf et al. 2013)*

# Testing the elemental ratio

## $^{13}C^{18}O$ / $C^{18}O$:

- Perfect match of the *J*=5-4 lines for a ratio of 38 !



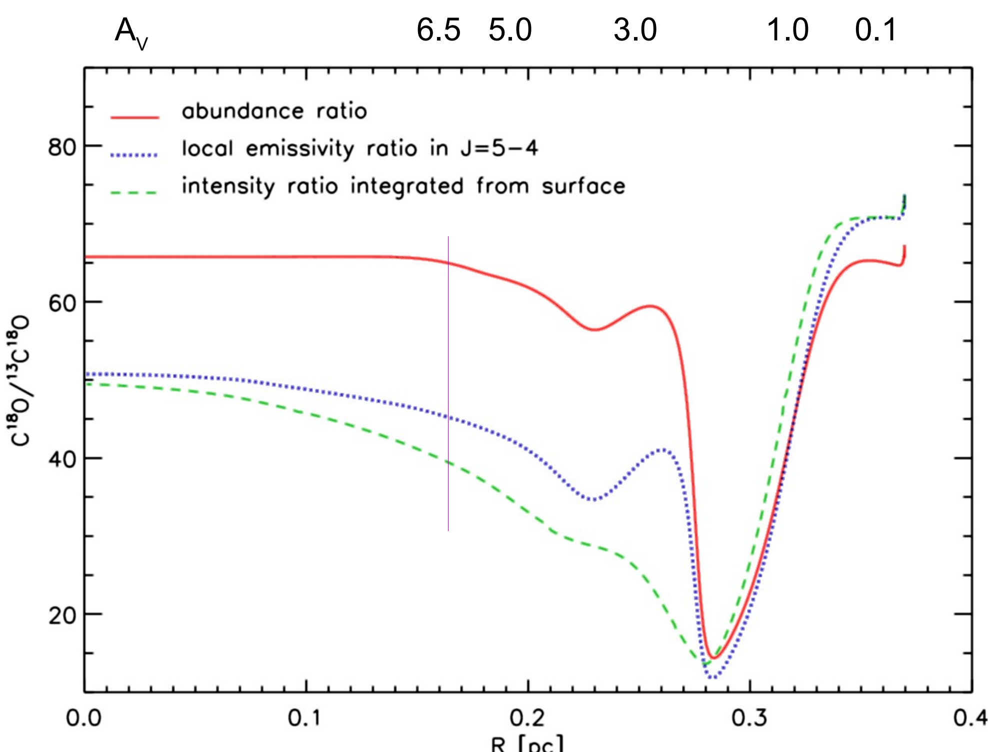

*The new point for NGC 7023 falls way off the "standard" curve (Langer & Penzias 1993)*

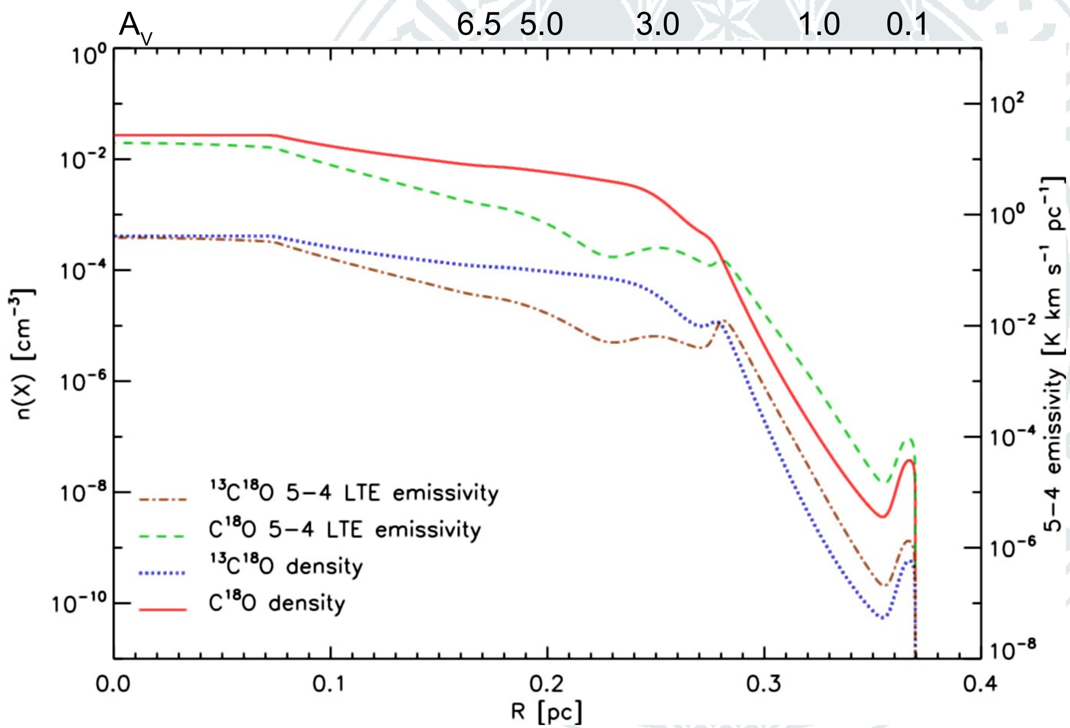
Temporary conclusion:

- Elemental ratio lower than derived before
- Weak fractionation in $C^+$

**If $C^+$ is affected by fractionation, $C^{18}O$ should be affected too!**

- Model: $^{13}C^{18}O$ enhanced relative to $C^{18}O$ at $A_V \approx$ 1..5
- At those depths the gas is warm → combined effects of fractionation and excitation




*Abundance and J=5-4 emissivity of $^{13}C^{18}O$ and $C^{18}O$ in the $100M_\odot$ PDR*

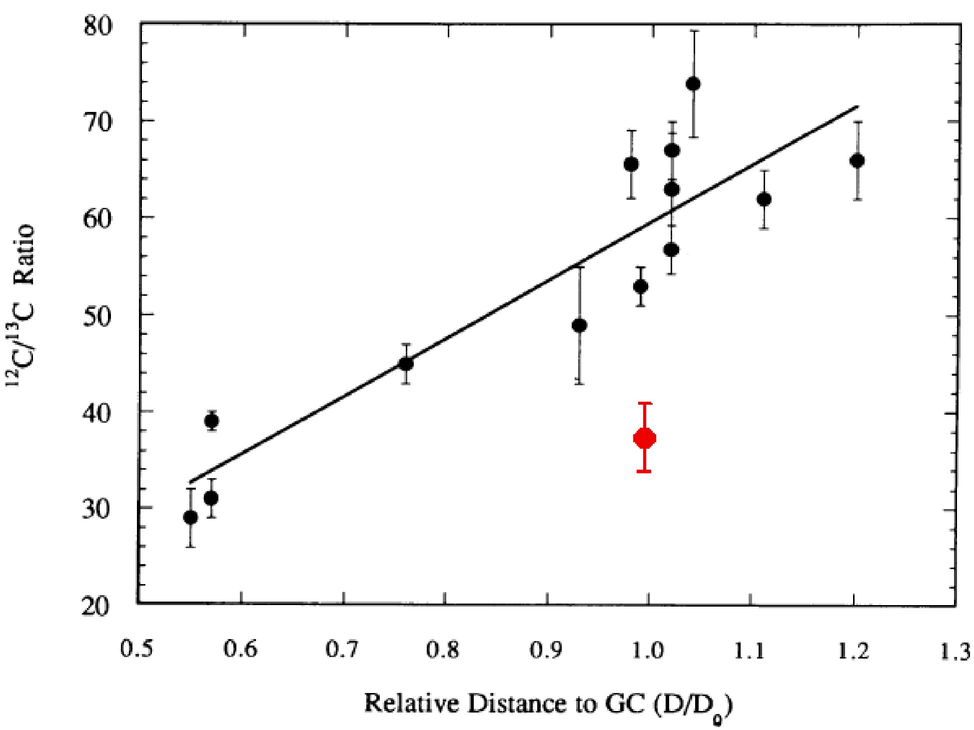
For the $A_V$= 6.5 of NGC7023, we get an emissivity ratio of 39 for a standard abundance ratio $C/^{13}C$=67.

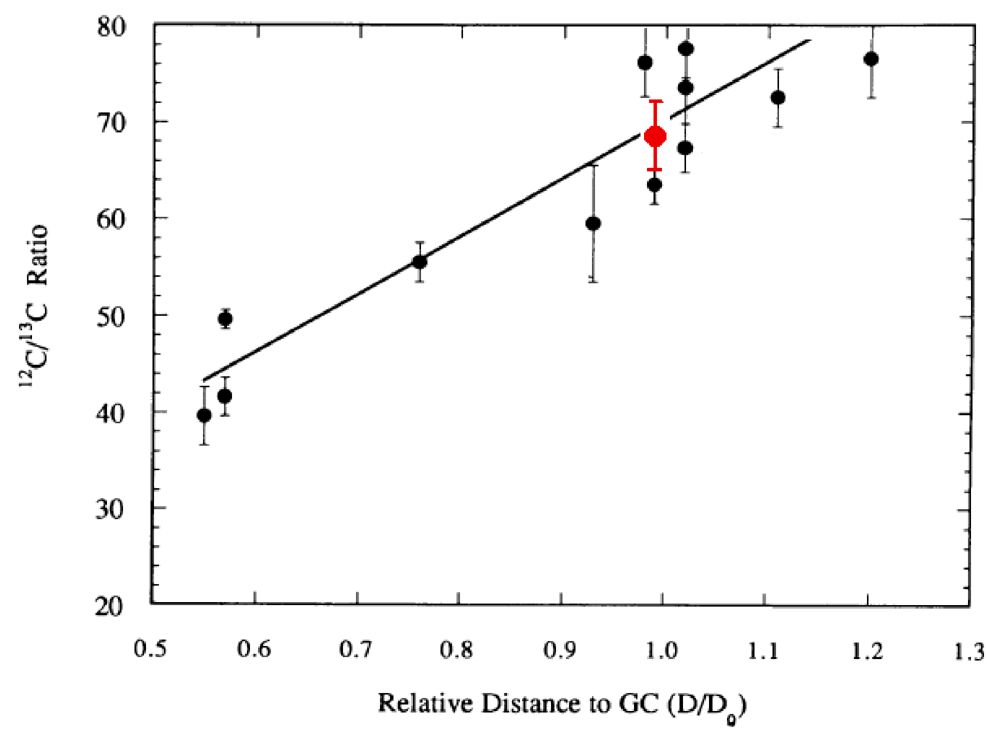
# Recalibrating the elemental abundances

All previous analyses based on J=1-0 and J=2-1 are also affected

**→ Model abundances wrong by 10-20%**

Correcting Langer & Penzias (1993) for fractionation gives consistent picture:




New average at solar Galactocentric radii: $ER = {}^{12}C/{}^{13}C \approx 67$

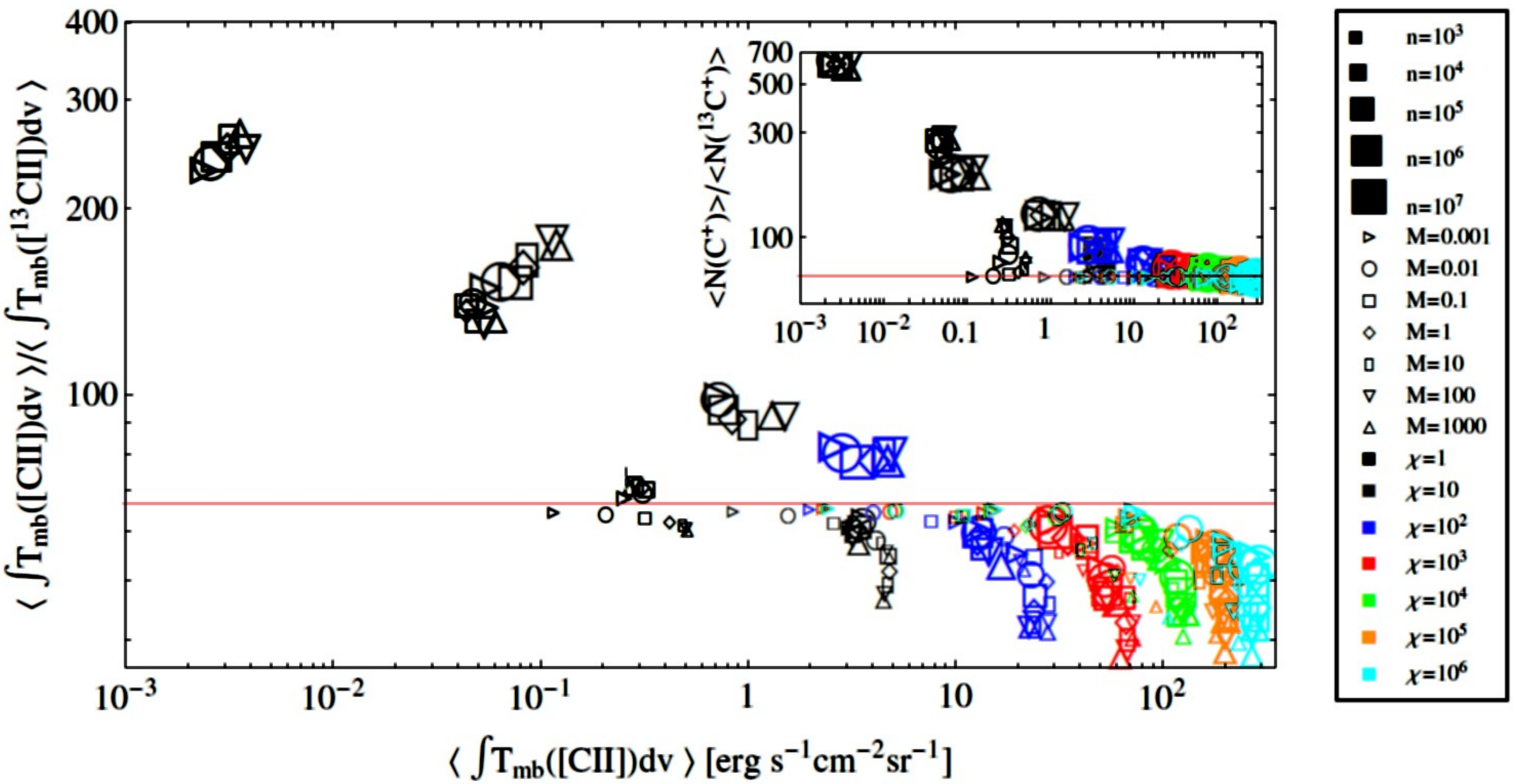
# Why is [CII]/[$^{13}$CII] then < 67?

- Intensity ratio rather governed by the optical depth of the [CII] line

$$\frac{IR_\nu}{FR} = \frac{1 - \exp(-\tau_{[CII]})}{\tau_{[CII]}}$$

- Intensity ratios < 67 through $\tau_{[CII]}$:
  - NGC7023: $\tau_{center} \approx 0.6$

- Directly measuring C$^+$ fractionation is very hard




*Integrated [CII]/[$^{13}$CII] intensity ratio for spherical PDRs*

# How to decide about fractionation?

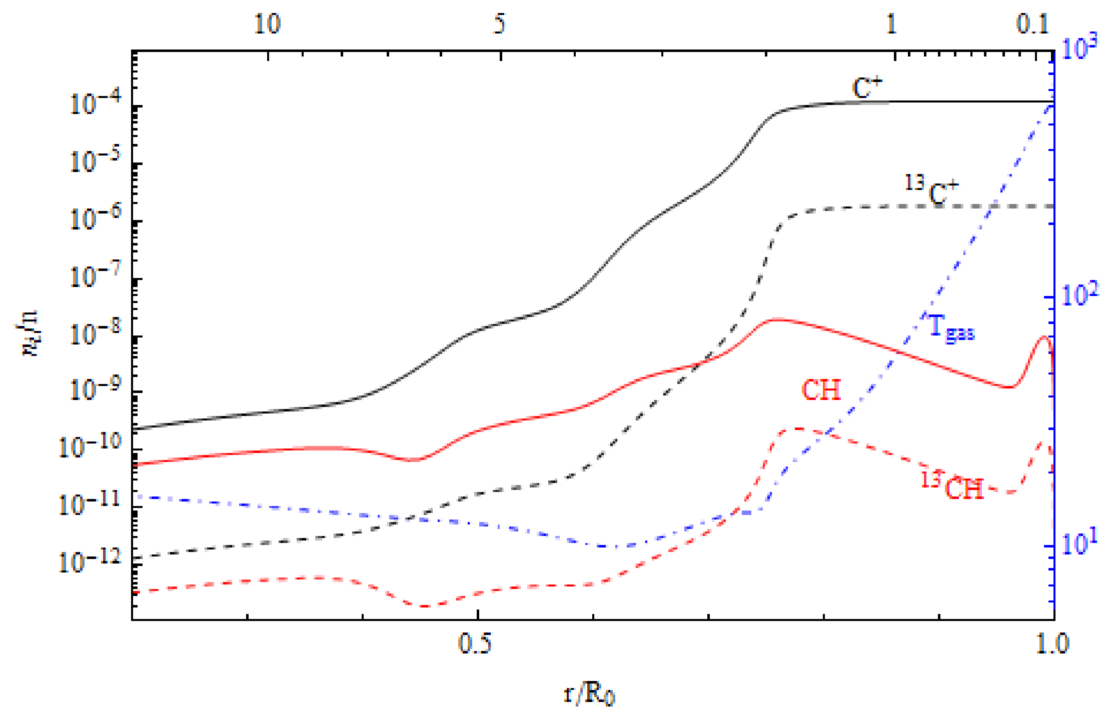
Which scenario holds?

- *ER*=38, no fractionation
- *ER*=67, $C^+$, $^{13}C^{18}O$ fractionated

Other species also affected!

- Chain of species produced from $C^+$
- CH inherits $C^+$ fractionation

$^{12}CH/^{13}CH$ enhanced



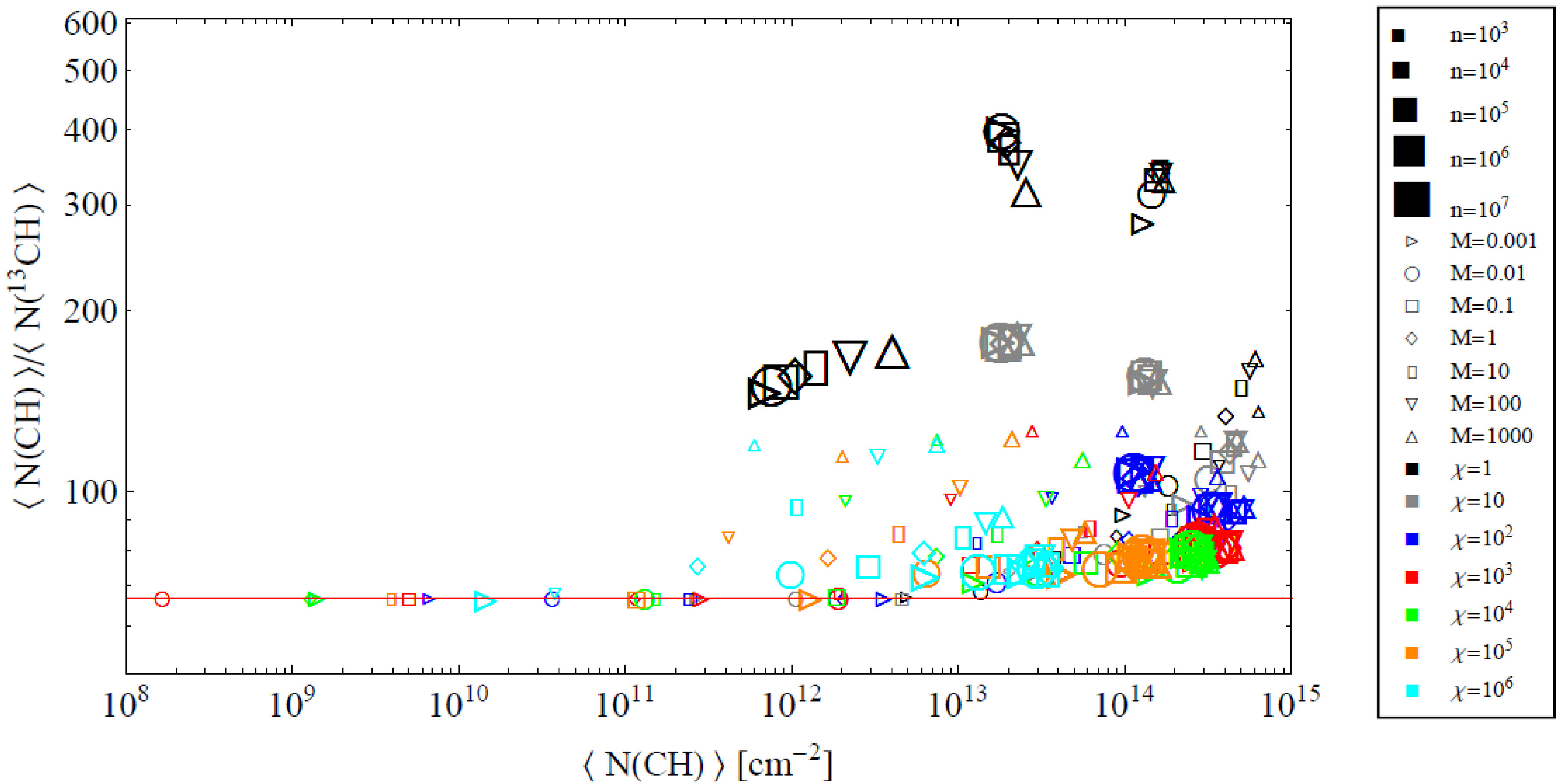

*Chemical structure of the 100$M_\odot$ PDR in $C^+$, $^{13}C^+$, CH, and $^{13}CH$*

*Same effect also in Roueff et al. (2015) for time-dependent model*

- CH fractionation is strong where CH is abundant!

# CH fractionation

$^{13}$CH abundance:



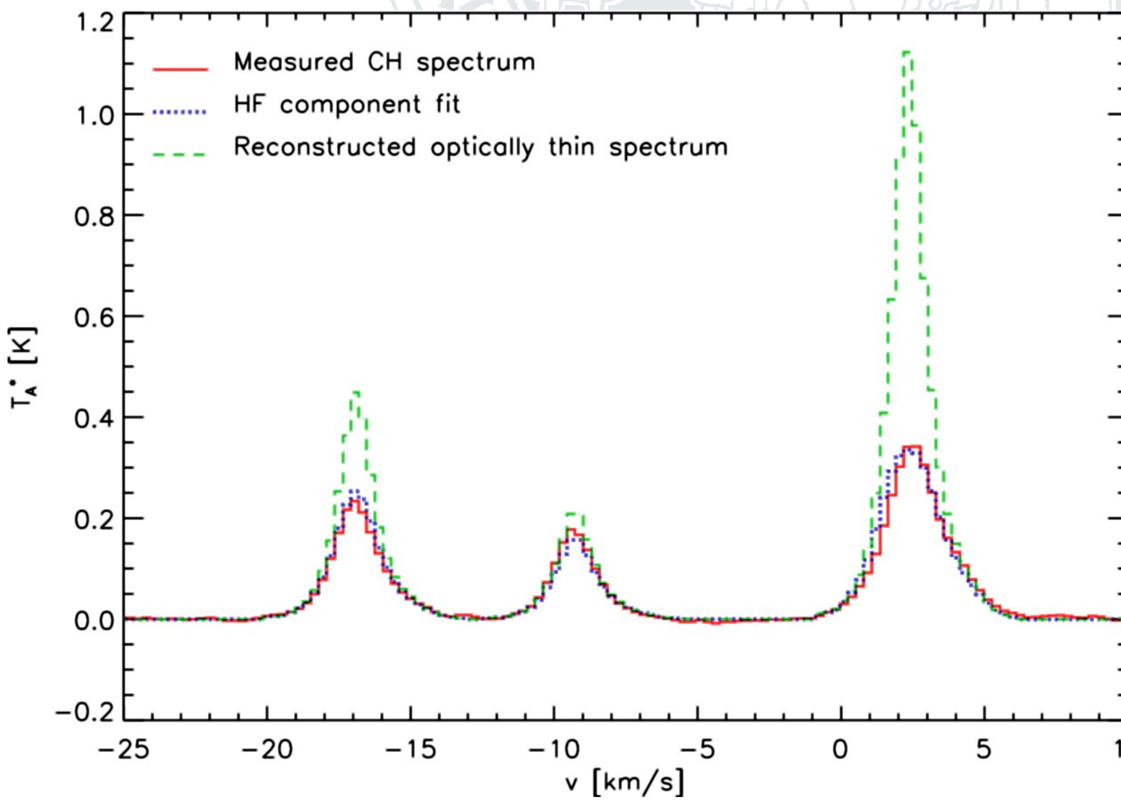

*Integrated CH/$^{13}$CH column density ratios for spherical PDRs*

- All models with high CH column density also show high fractionation
- CH is the ideal fractionation tracer.

# Measuring CH and $^{13}$CH

## Observation

- 536 GHz ground state line
- CH is also partially optically thick
- But: line split into multiple HF components
  - Can be used to correct for optical depth by simultaneously fitting all three components

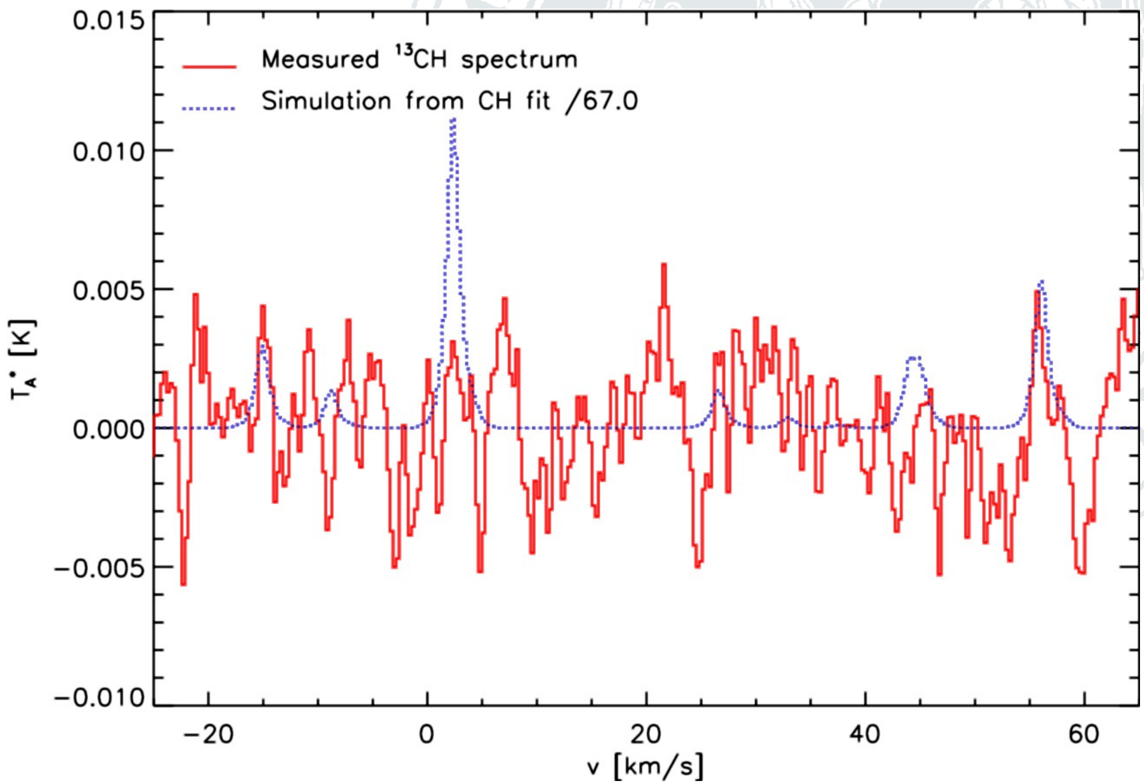



- Fit good, but not perfect.
  - Possible uncertainty in line frequencies (?)

WADI

τ-corrected CH profile measures total CH abundance:

- Allows to simulate the $^{13}CH$ profile for a given abundance ratio
- But: **Non-detection**
- Way forward: Can we constrain the $^{13}CH$ column from the non-detection?



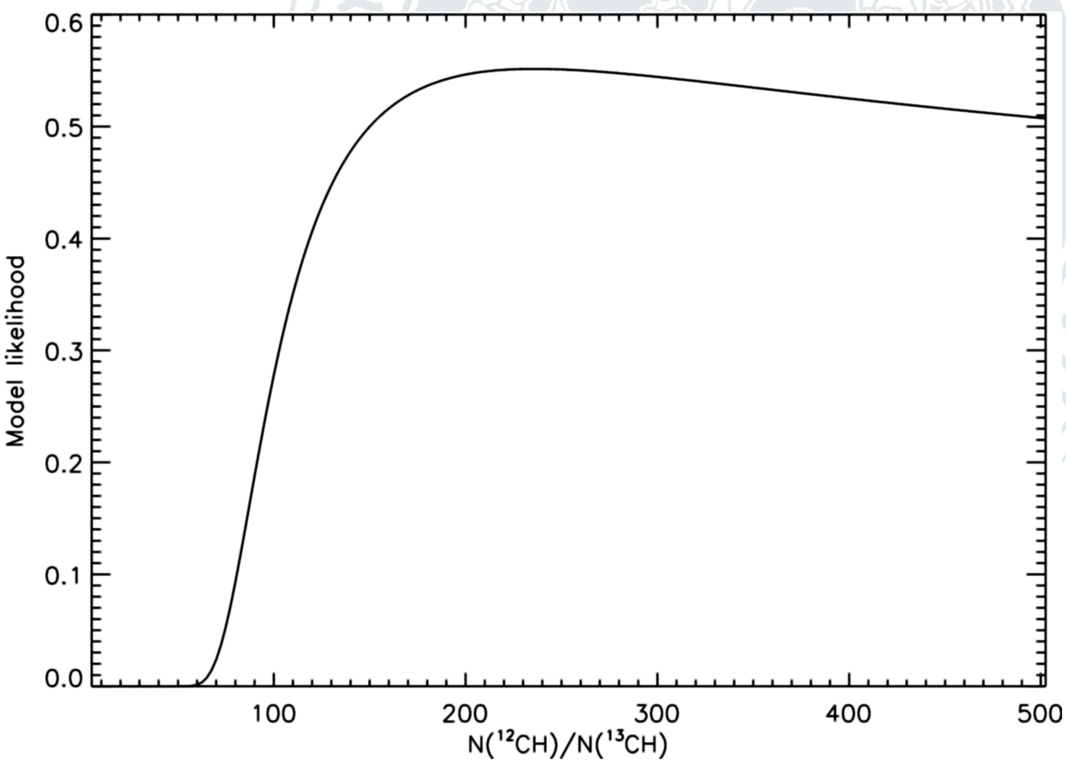

*$^{13}CH$ 536GHz spectrum simulated from the measured CH spectrum, corrected for optical depth, and abundance ratio of 67 and the different hyperfine ratios*

# Exploit the non-detection

Quantify non-detection through statistical likelihood:

- Compute likelihood of measured spectrum for $^{13}CH$ models computed for different $CH/^{13}CH$ abundances
- Model with $CH/^{13}CH > 200$ has maximum likelihood
- Models with $CH/^{13}CH < 67$ can be excluded with 99% confidence
- Models with $CH/^{13}CH < 107$ can be excluded with 67% confidence

**→ Fractionation by factor 1.5**




*Likelihood of model match to observed spectrum as a function of the $CH/^{13}CH$ abundance ratio*

# Conclusions

- Detecting $^{13}C^+$ with HIFI or GREAT is easy
- ➢ But: For most PDRs [CII] is optically thick
  - [CII]/[$^{13}$CII] dominated by opt. depth, not chemical fractionation

- $C^{18}O/^{13}C^{18}O$ always assumed to trace the elemental ratio
- ➢ But: Is also affected by chemical fractionation
  - Matches NGC 7023 observations for the standard the C/$^{13}$C=67 ratio.

- $^{13}$CH should be best fractionation tracer
- ➢ But: Detecting $^{13}$CH is very hard
  - Non-detection proves slight fractionation (factor 1.5).

**→ Clear observational proof of $^{13}$C fractionation (C$^{18}$O and CH).**