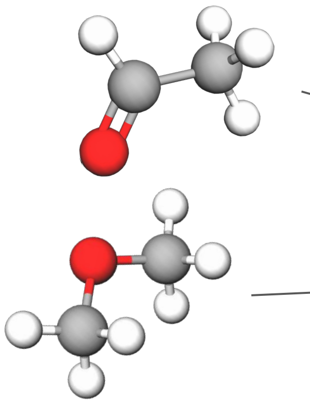
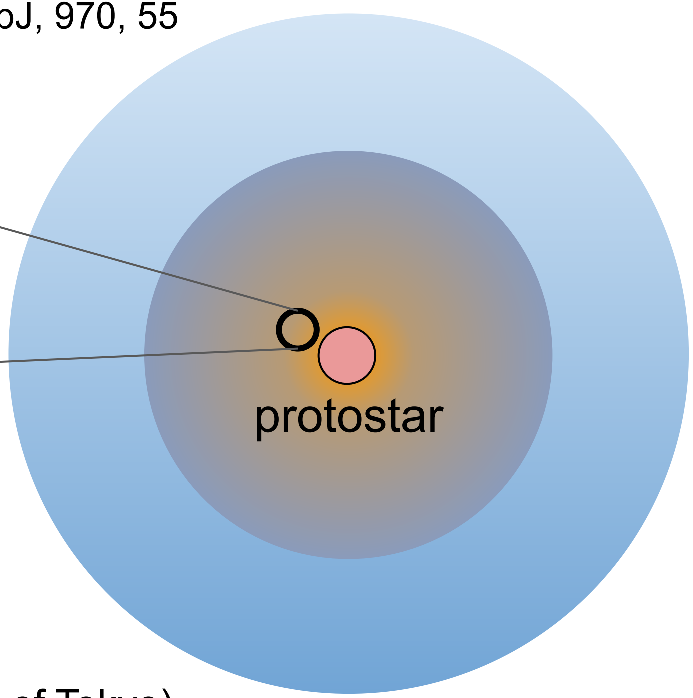
Carbon Isotope Fractionation of Complex Organic Molecules in Star-Forming Cores.

Ichimura et al. 2024, ApJ, 970, 55





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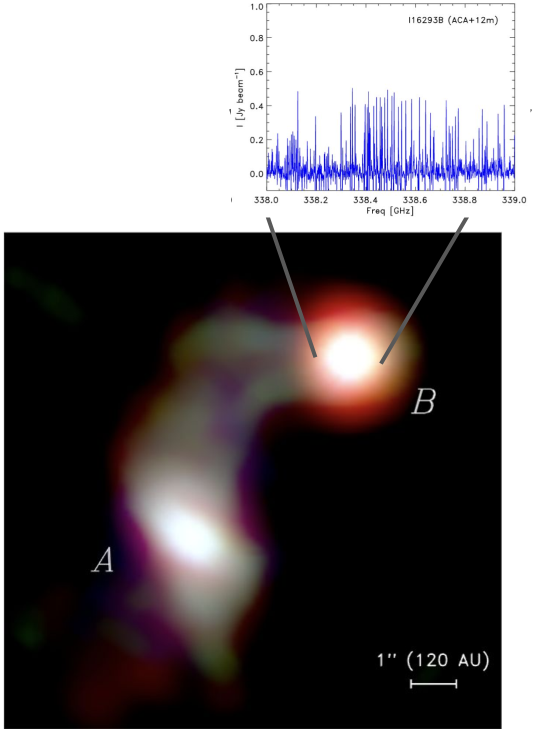
Hideko Nomura (NAOJ / SOKENDAI), Kenji Furuya (The Univ. of Tokyo)

CRs3 Oct 24, 2024

$^{12}C/^{13}C$ ratio of COMs toward IRAS 16293-2422B



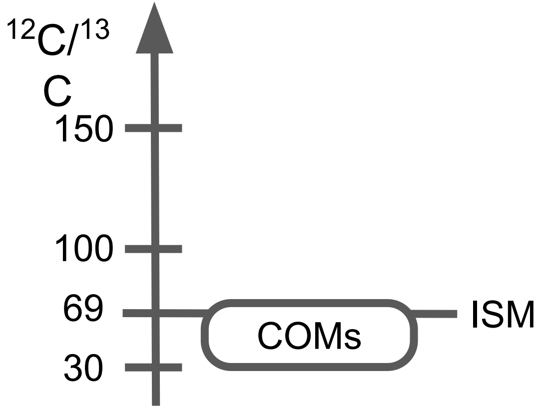
IRAS 16293-2422:
Jorgensen et al. 2016

ALMA PILS Survey of the Class 0 low-mass protostellar object IRAS 16293-2422B has detected several COMs (**C**omplex **O**rganic **M**olecules)

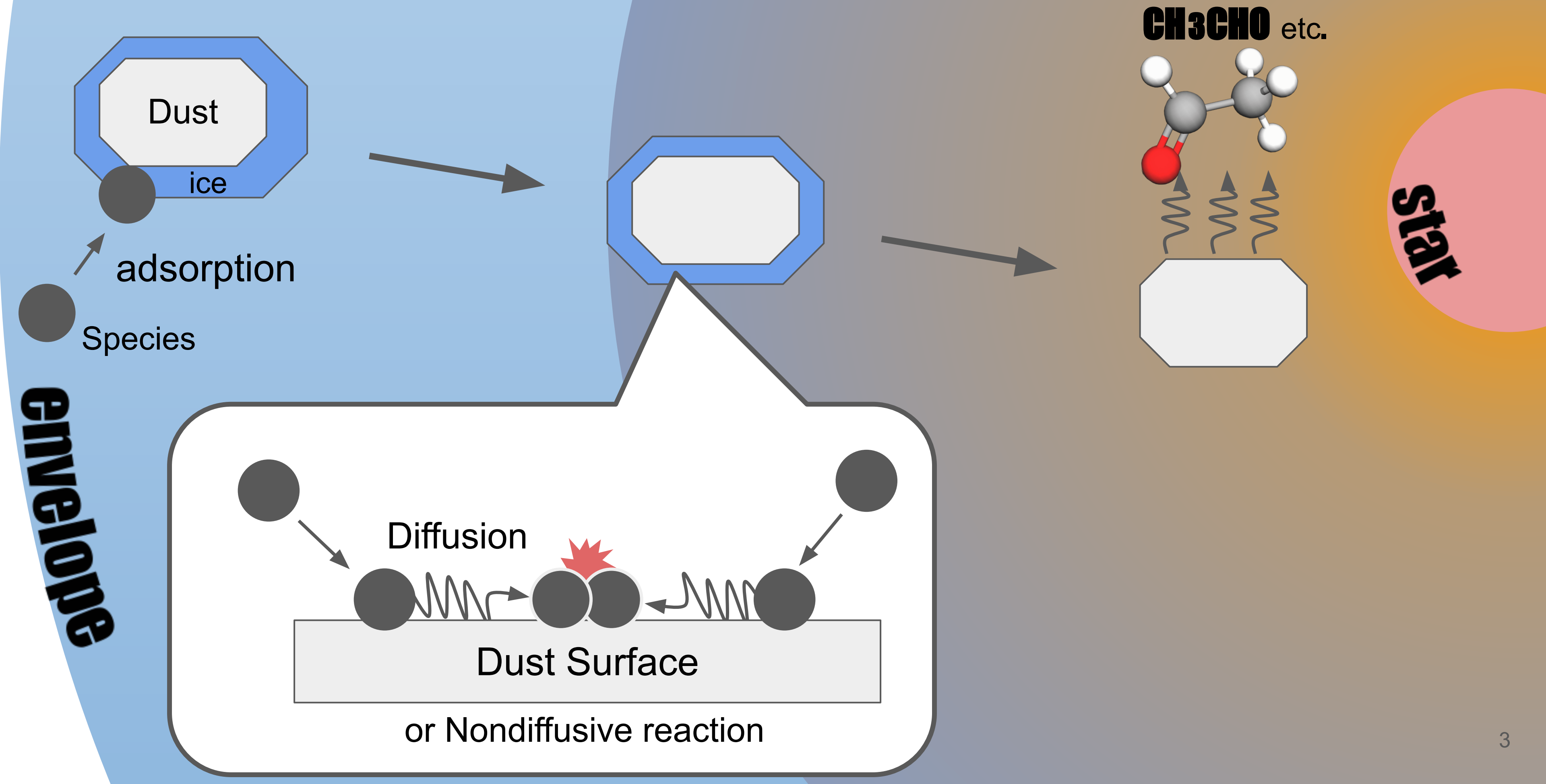
CH_2CO, CH_3CHO, HCOOH : $^{12}C/^{13}C$ = 69 (ISM)

CH_3OCH_3 : $^{12}C/^{13}C$ = 34

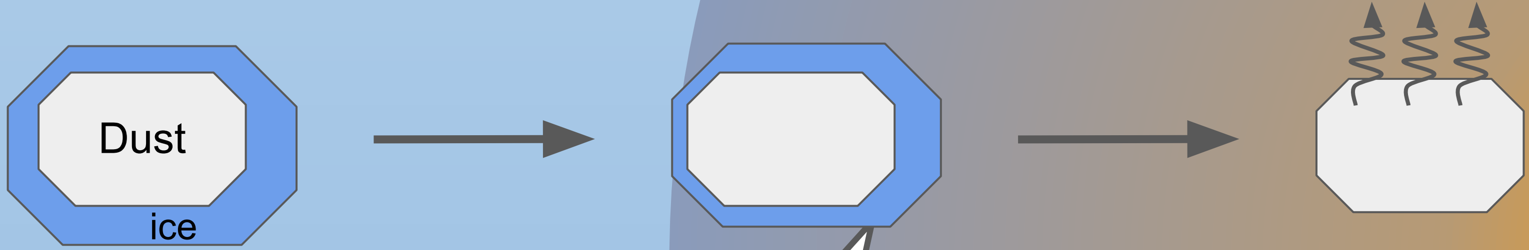
Jorgensen et al. 2018



COMs(Complex Organic Molecules) in a Star-Forming Core

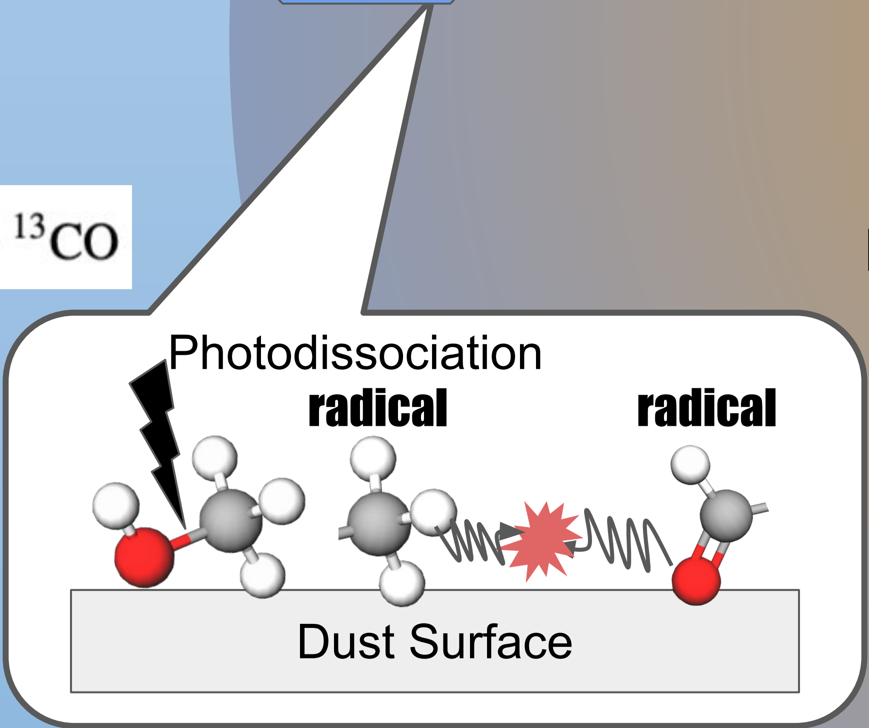


Effect of CR on Complex Organic Molecules



Change timescale of
ion-neutral reactions

$$^{13}C^{+} + CO \leftrightarrows C^{+} + ^{13}CO$$



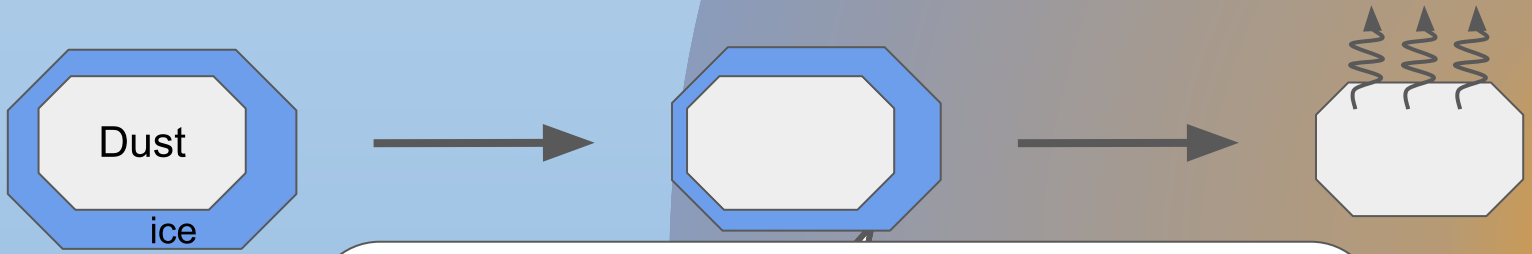
$$M \xrightarrow{H_3O^{+}} MH^{+}$$

$$NMH^{+} \xrightarrow[e]{} NM$$

star

envelope

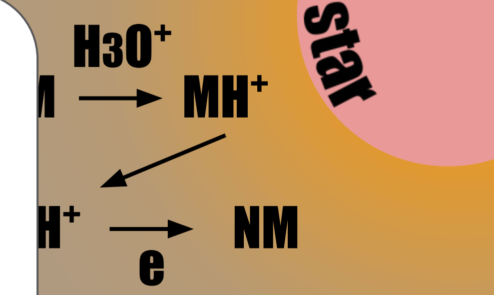
Effect of CR on Complex Organic Molecules

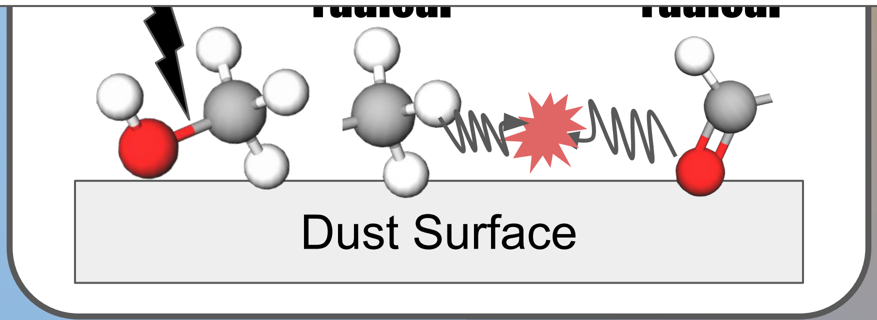


Change timescale
ion-neutral reacti

$^{13}C^{+} + CO \leftrightarrows$

$^{12}C/^{13}C$ of COMs could provide insights into their formation pathway





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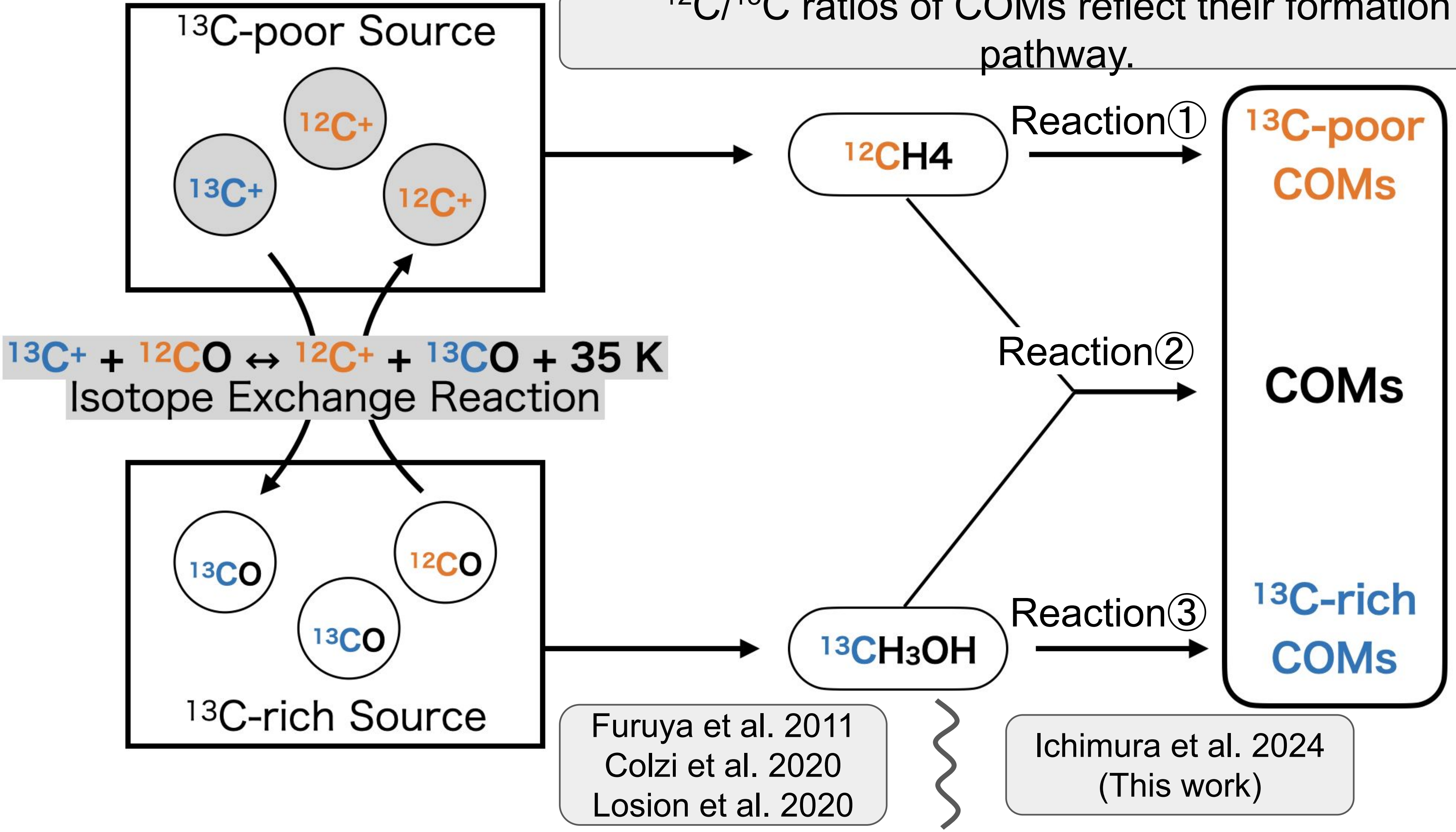
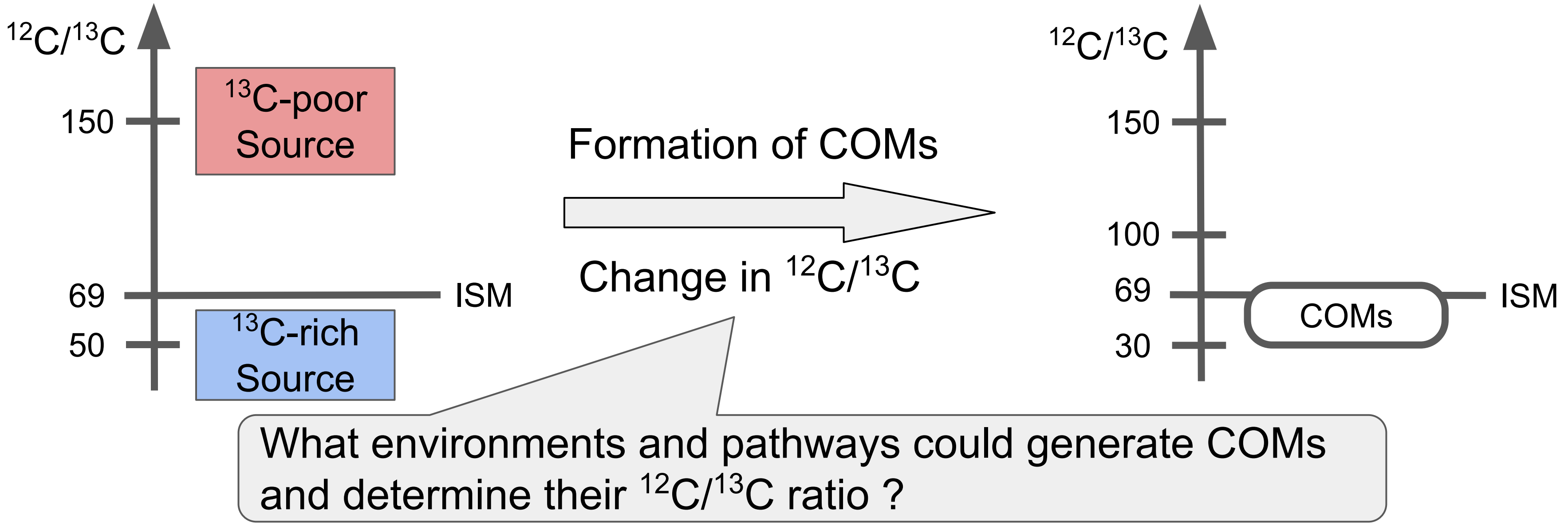
$^{12}C/^{13}C$ ratios of COMs reflect their formation pathway.



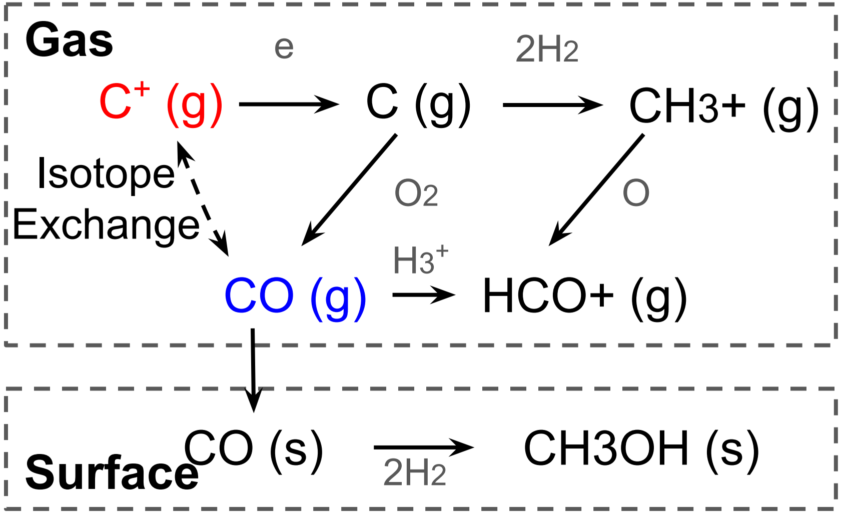
Aims

- Investigate the $^{12}C/^{13}C$ fractionations of COMs in a star-forming core.

- Discuss the chemical pathways occurring within these star-forming cores.



Astrochemical Model : Chemical Kinetics Model



- Rate equation approach.
- Based on gas-grain Model
  (Rokko; Furuya et al. 2015)
  Gas-phase reaction, adsorption, desorption, diffusion reaction on the grain surface
- Isotope exchange reactions
  (Roueff et al. 2015; Colzi et al. 2020; Loison et al. 2020)

Physical Model : Evolution of a Star-forming Core

Fluid Parcel

star

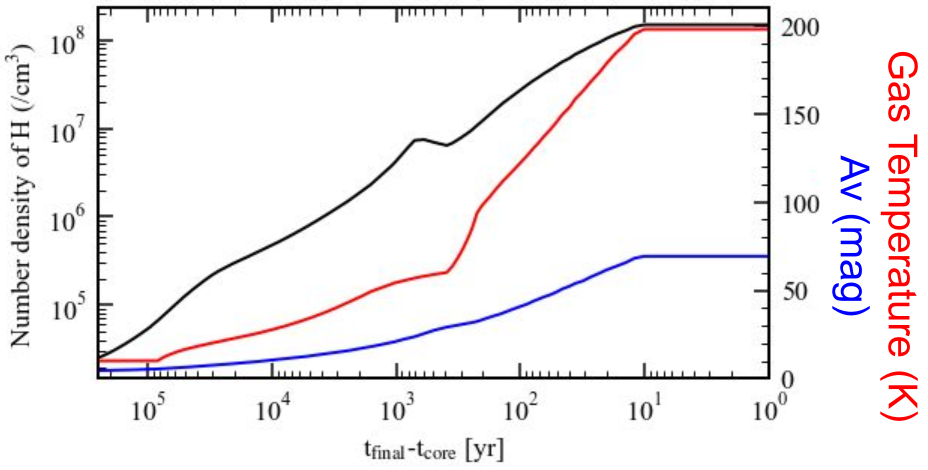
Prestellar Phase (10^6 yr) : Cold Phase

Gas & Dust temperature: 10 K
Number density of H: 2.28 x 10^4 (/cm^3)
Visual Extinction: 4.5 (mag)

envelope

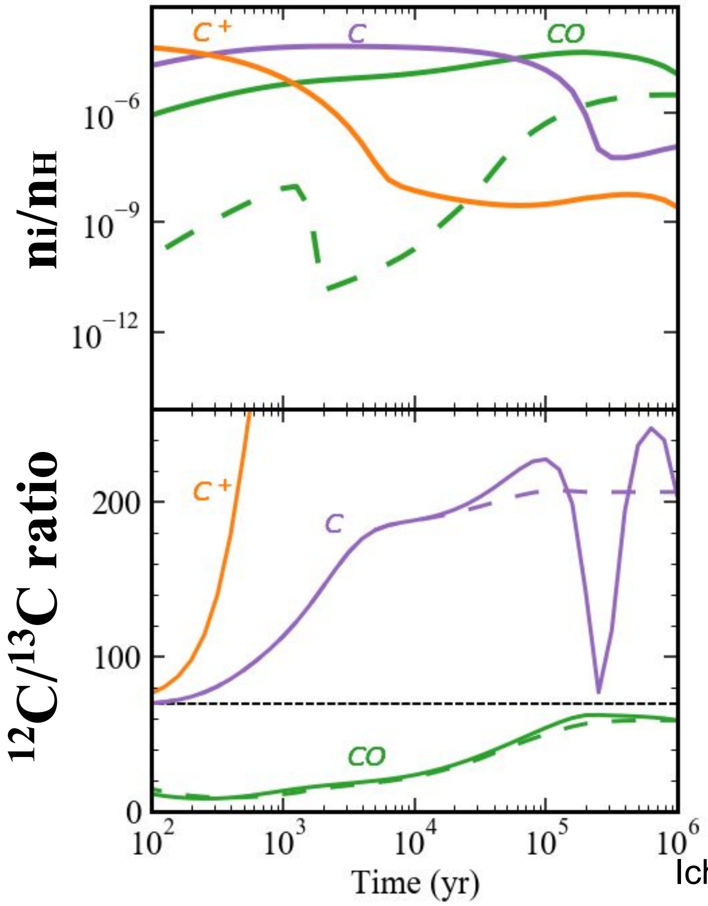
CR Ionization rate:
1.3 x 10^{-17} (s^{-1}) for the base model
H and L model (Padovani et al, 2018)

Protostellar Phase : Warm-up Phase



Radiation Hydrodynamic model;
Masunaga & Inutsuka 2000

Carbon Isotope Fractionation

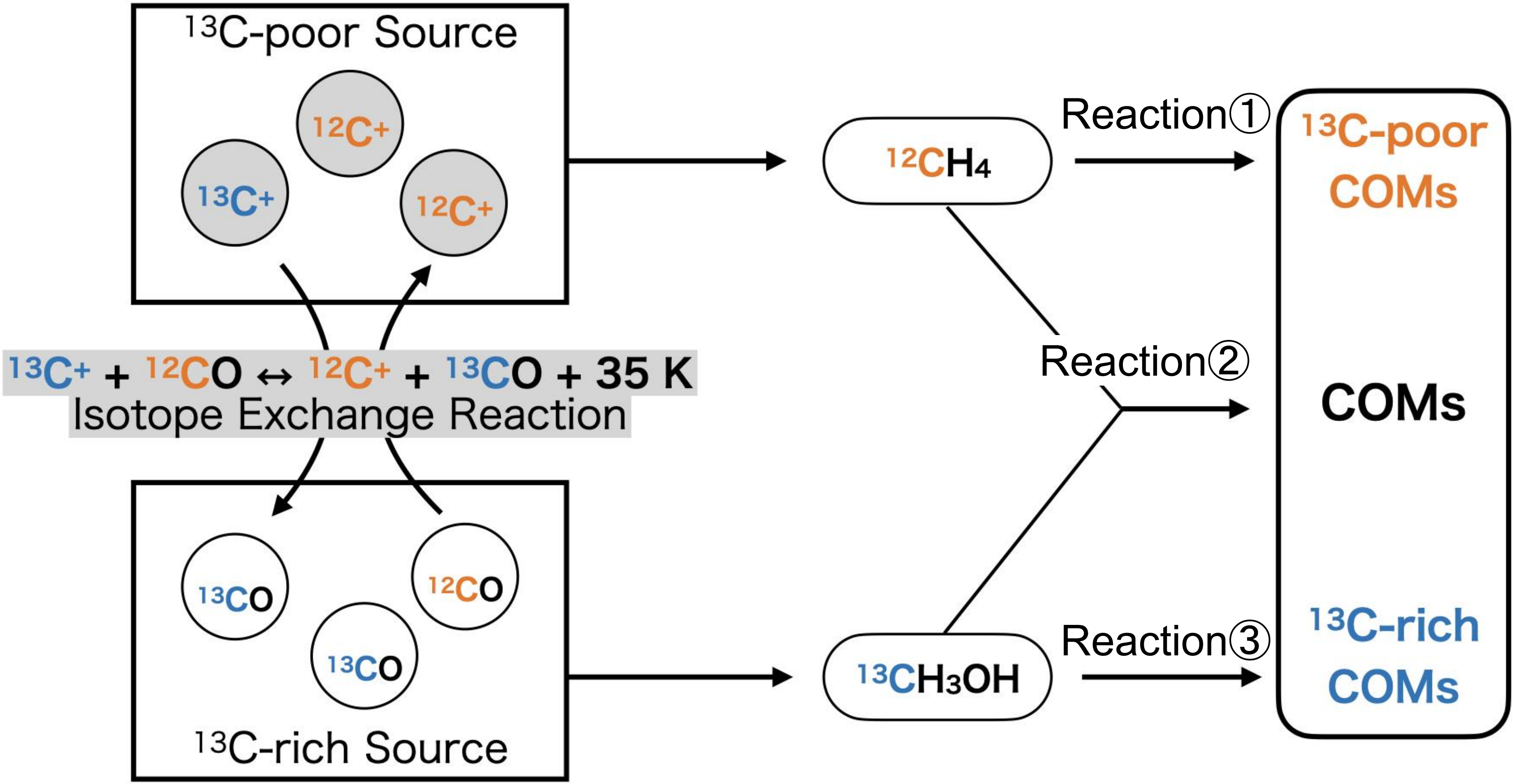


$$^{13}C^{+} + CO \leftrightarrows C^{+} + {}^{13}CO + \Delta E$$

- Isotope exchange reactions result in $^{12}C/^{13}C$ fractionation of C^+ and CO.
- This fractionation is constant with Colzi et al. (2020), Loison et al. (2020)
- The fractionation propagates into other molecules through chemical reactions.

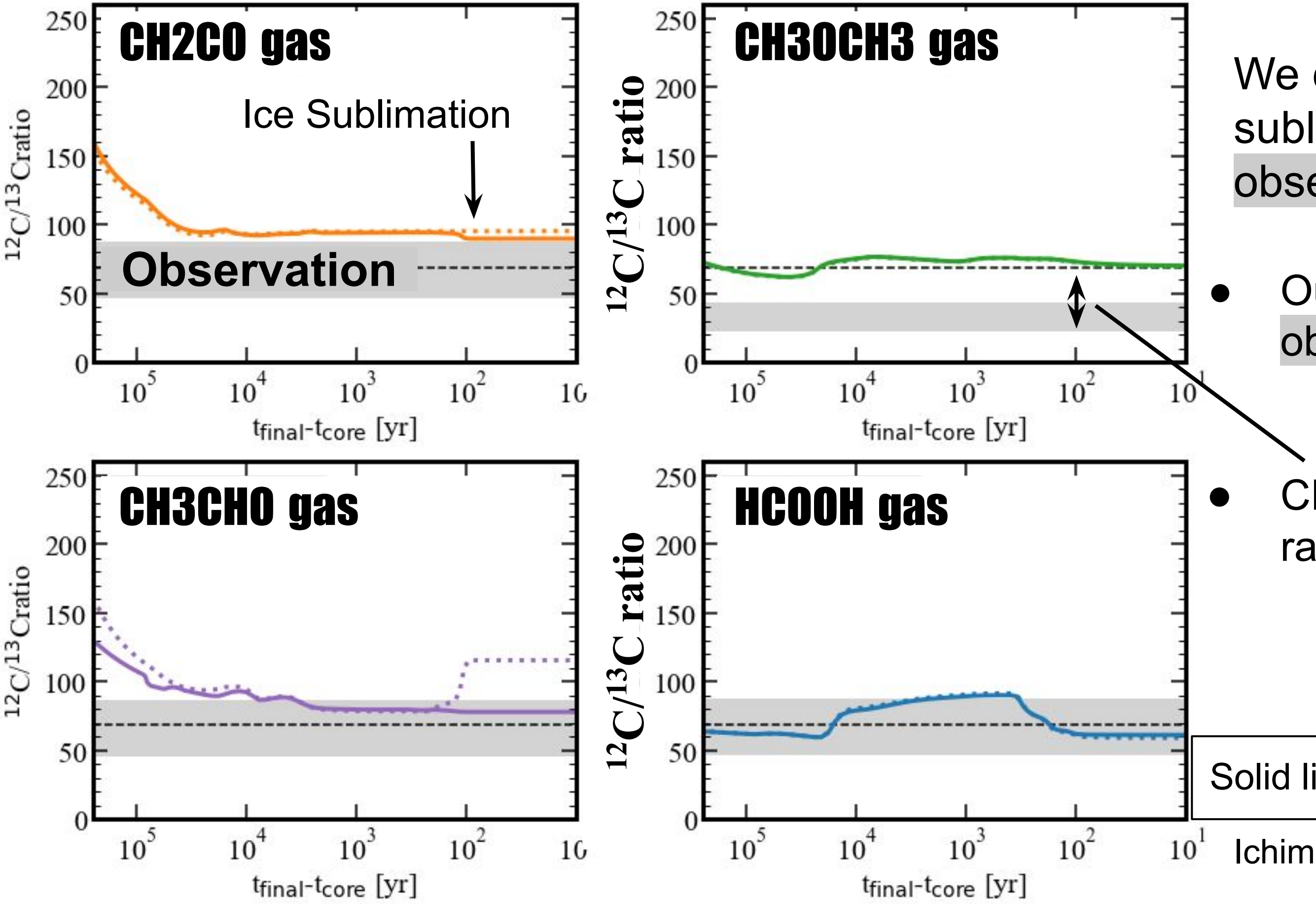
Dashed lines: Icy molecules
Solid lines : Gas molecules

Ichimura et al. 2024



13C-poor Source
12C+
13C+
12C+
13C+ + 12CO ↔ 12C+ + 13CO + 35 K
Isotope Exchange Reaction
13CO
12CO
13CO
13C-rich Source
12CH4
13CH3OH
Reaction①
Reaction②
Reaction③
13C-poor COMs
COMs
13C-rich COMs

Comparisons with Observations of IRAS16293-2422B



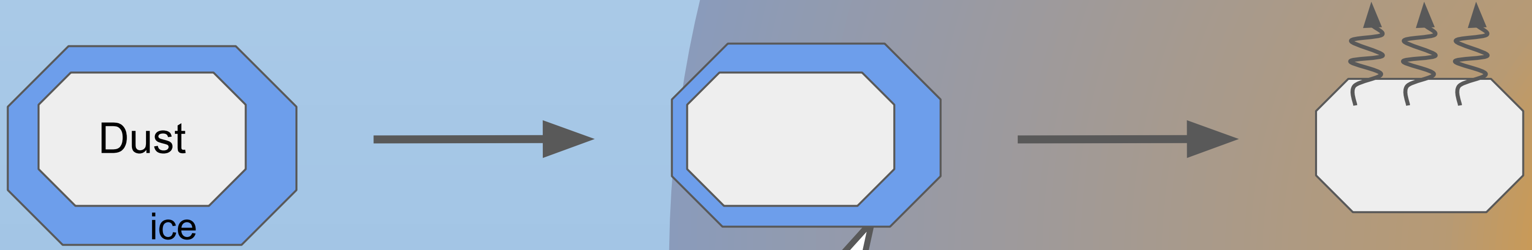
We compare $^{12}C/^{13}C$ ratios of sublimated molecules with observations

- Our results represent the observation of some molecules.
- CH_3OCH_3 has higher $^{12}C/^{13}C$ ratio than observation.

Solid line: Our Results

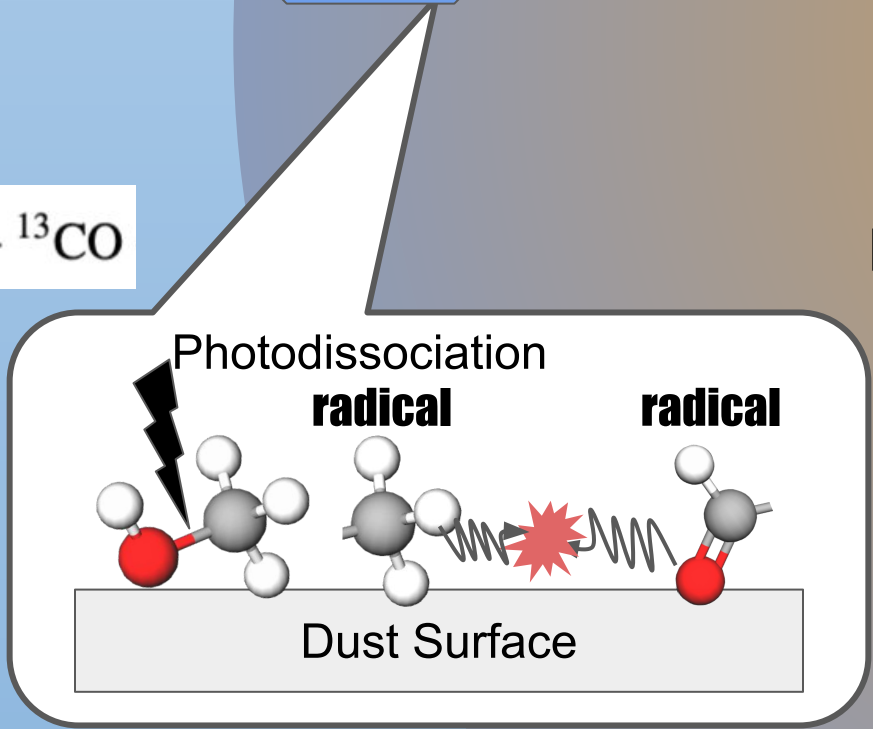
Ichimura et al. 2024

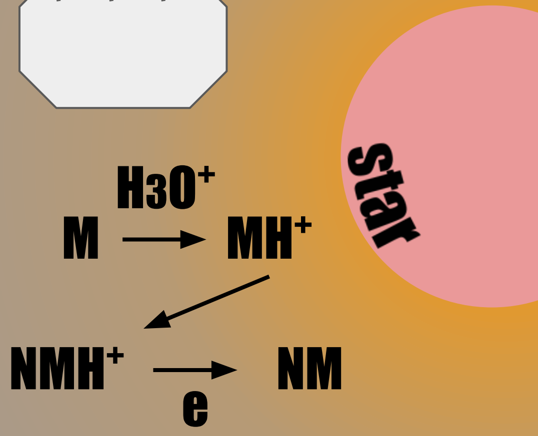
Effect of CR on Complex Organic Molecules



Change timescale of ion-neutral reactions

$$^{13}C^{+} + CO \leftrightharpoons C^{+} + {}^{13}CO$$





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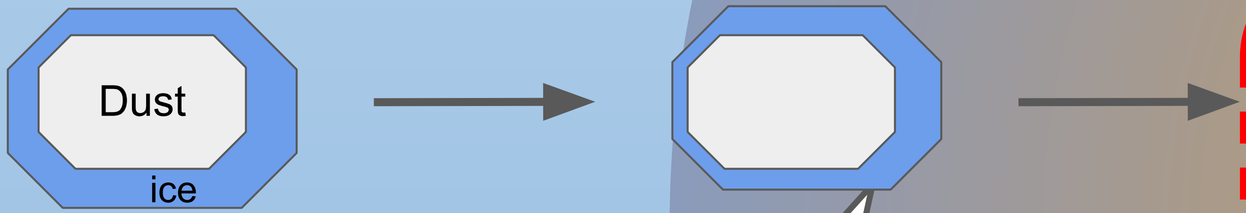
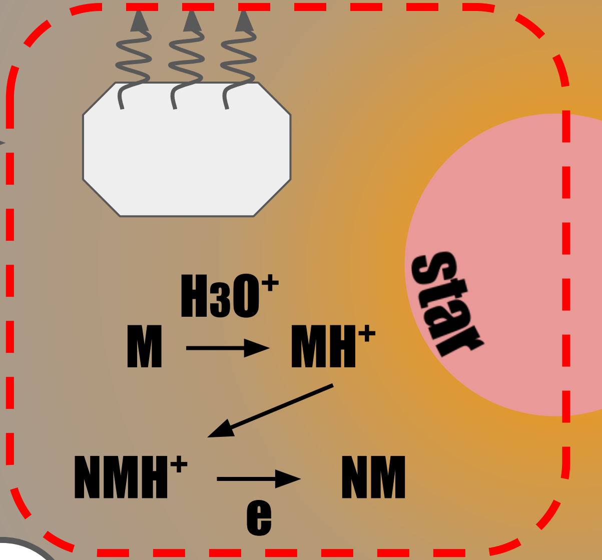
Effect of CR on Complex Organic Molecules





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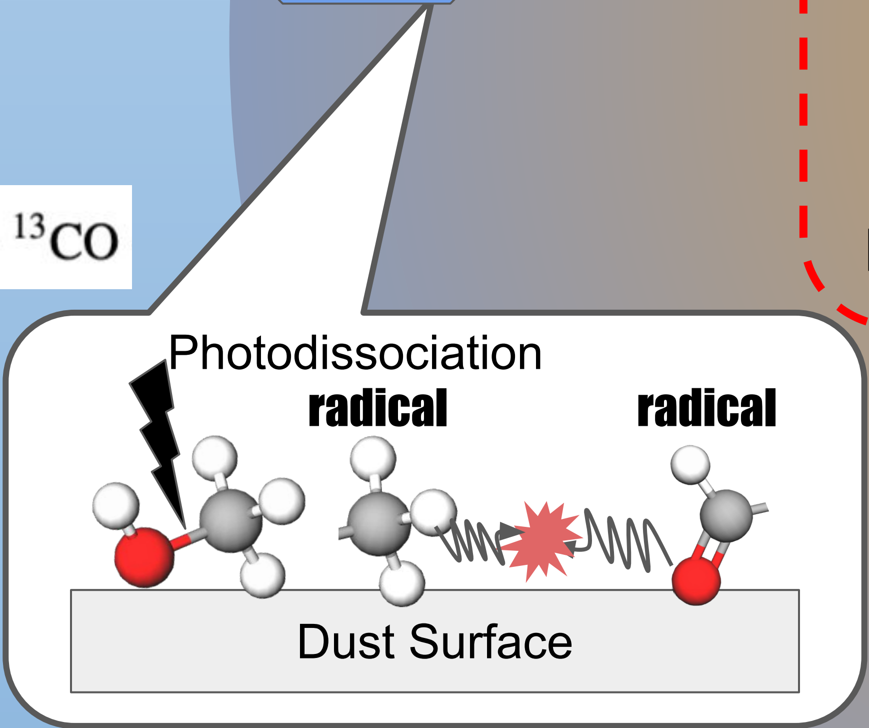

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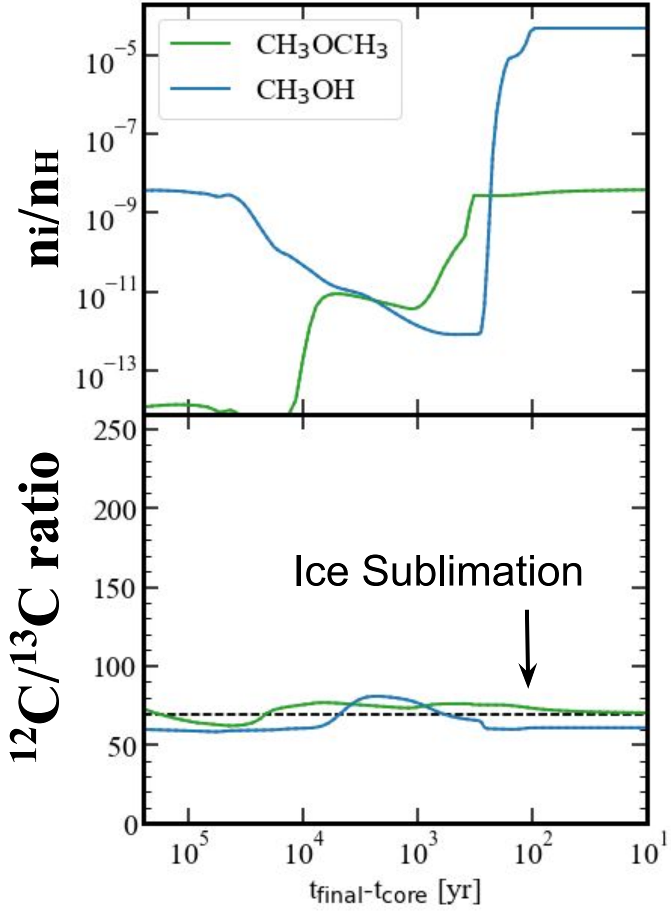
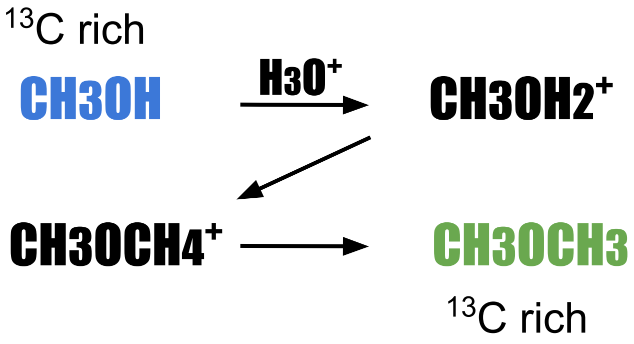
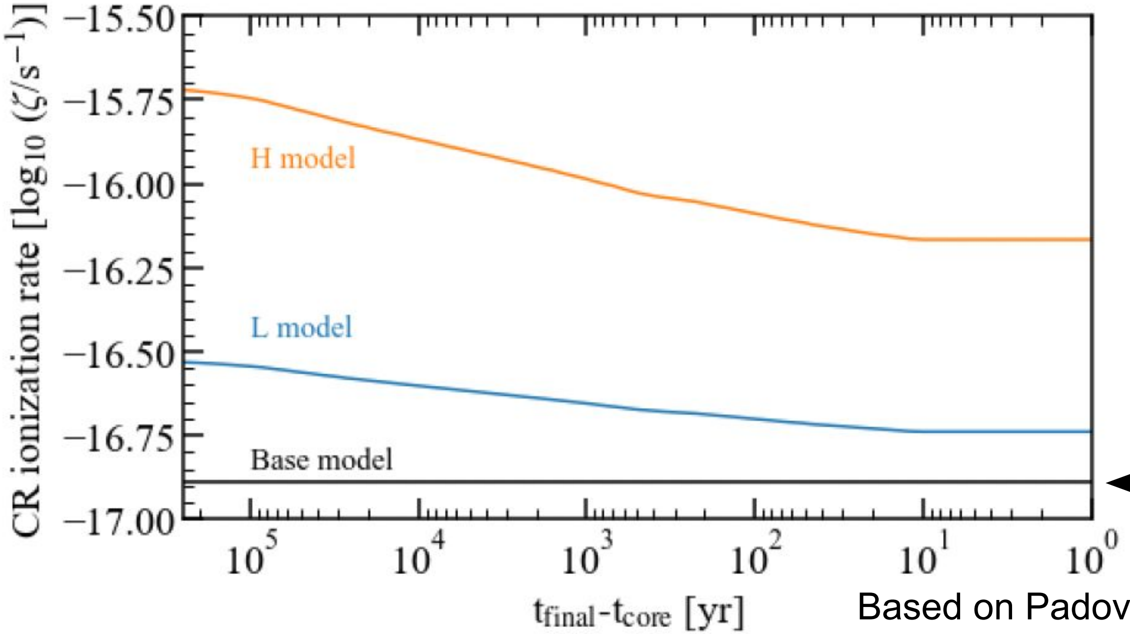
Effect of CR on chemistry of CH3OCH3



- The $^{12}C/^{13}C$ of sublimated **CH_3OCH_3** approaches to that of **CH_3OH** by Cosmic Ray ionization.
  (proton transfer induced by CR ionization)



CR ionization rate

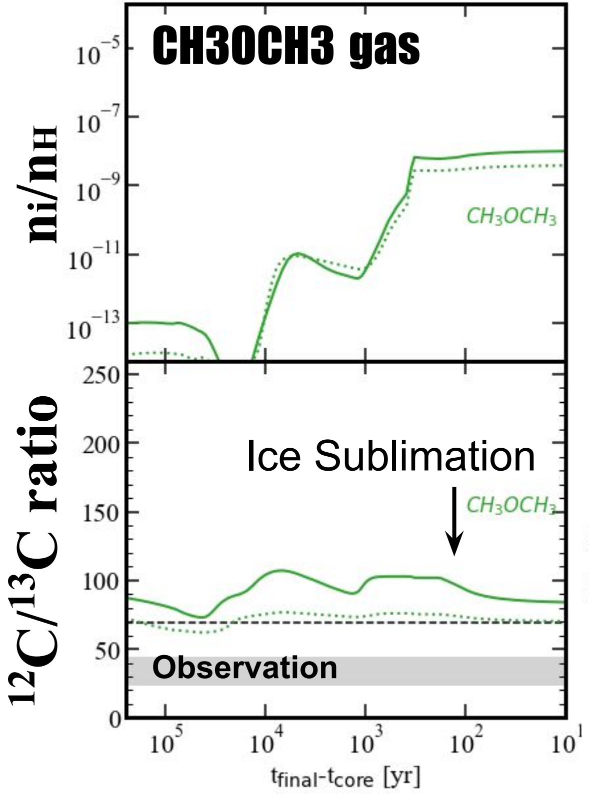


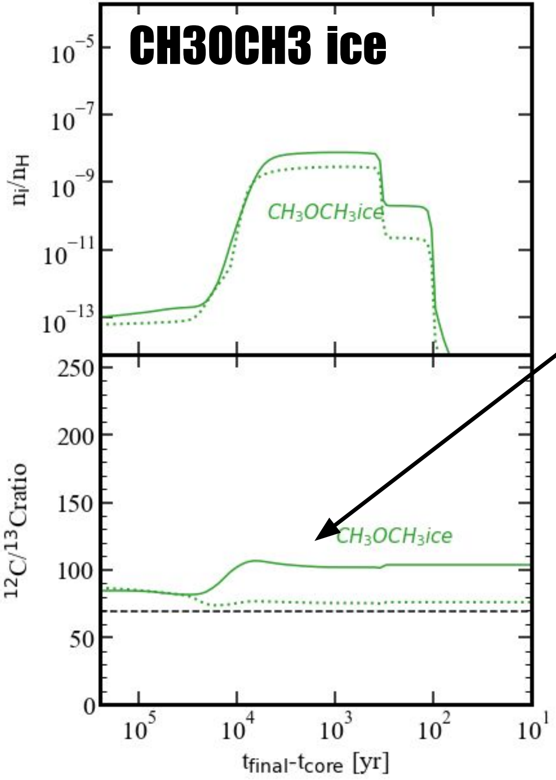
1.3×10^{-17} (s^{-1})
for the base model

Based on Padovani et al. 2018

- H (**H**igh CR ionization rate) model: comes from H_3^+ emission in diffuse clouds.
- L (**L**ow CR ionization rate) model: comes from the Voyager 1 data.

High Cosmic Rays Ionization Rates (H model)

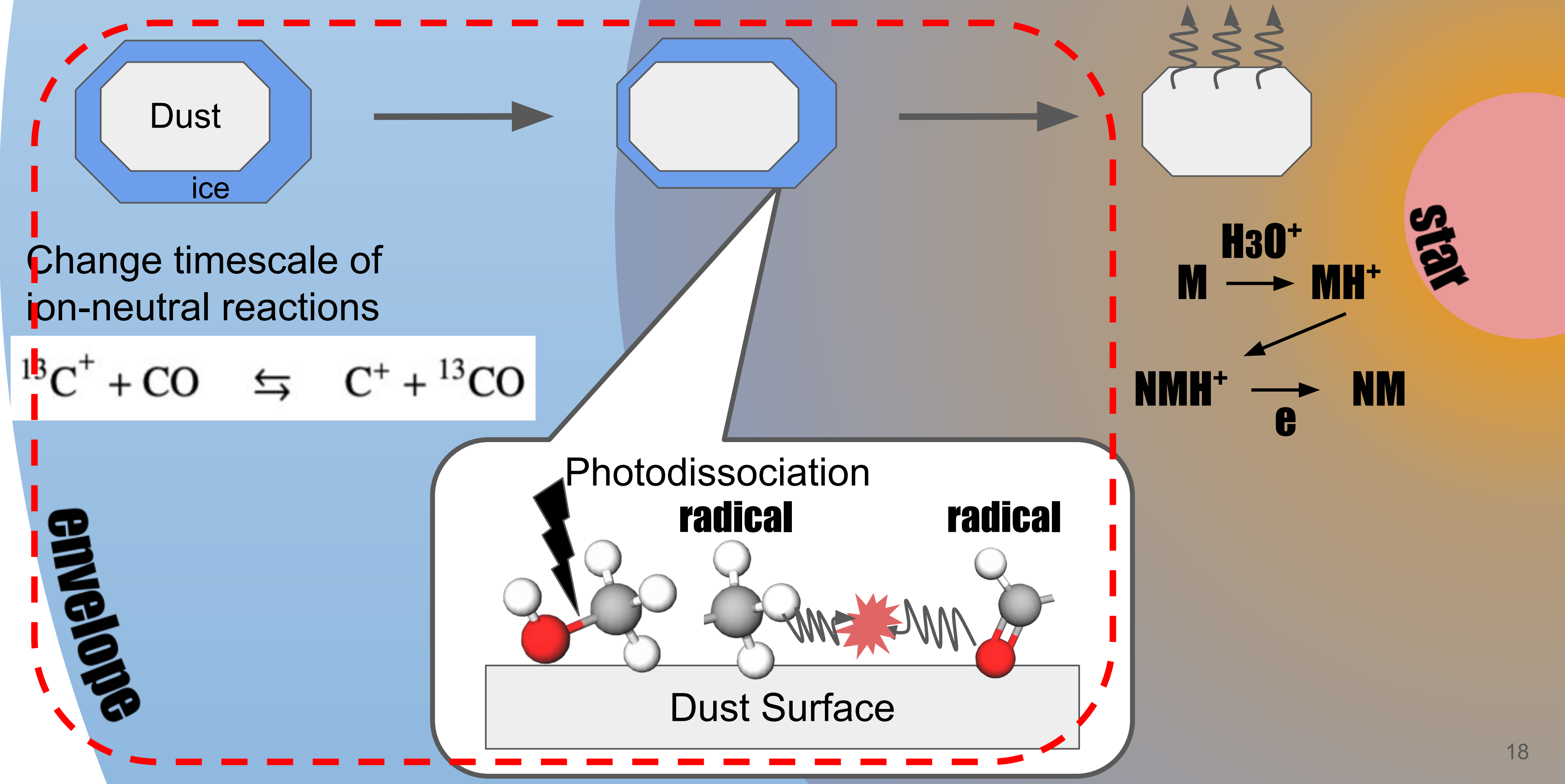




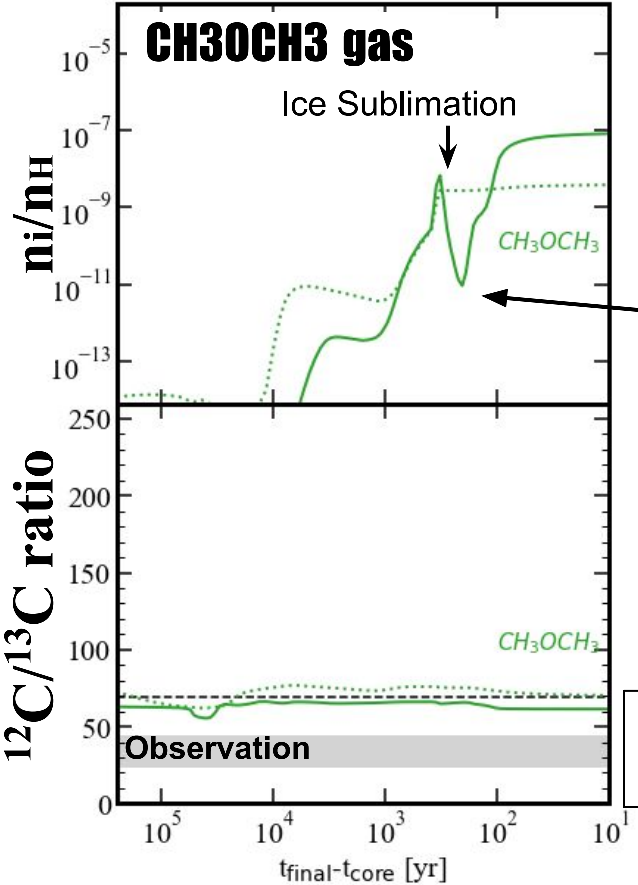
- The $^{12}C/^{13}C$ of sublimated CH_3OCH_3 quickly decrease.
- ^{13}C-poor CH_3OCH_3 ice is formed from ^{13}C-poor CH_3 radical.
- High CR ionization rates result in high $^{12}C/^{13}C$ in ice.

Dotted : the base model
Solid : H model

Effect of CR on Complex Organic Molecules



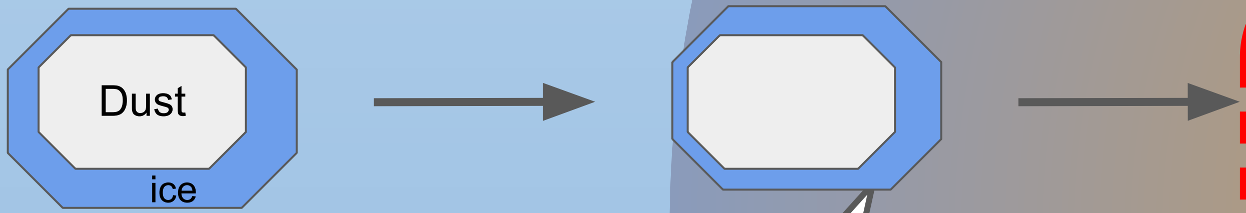
Cosmic Ray Acceleration after protostar formation



- CR acceleration after protostar formation
  CR ionization rate is increased from 1.3×10^{-17}/s to 1.3×10^{-14}/s after the protostar formation (Padovani et al., 2015, 2016).
- Sublimated CH_3OCH_3 is destroyed by CR.
- CH_3OCH_3 is newly formed from CH_3OH and has low $^{12}C/^{13}C$.
- The $^{12}C/^{13}C$ ratio of CH_3OCH_3 is still higher than the observation.

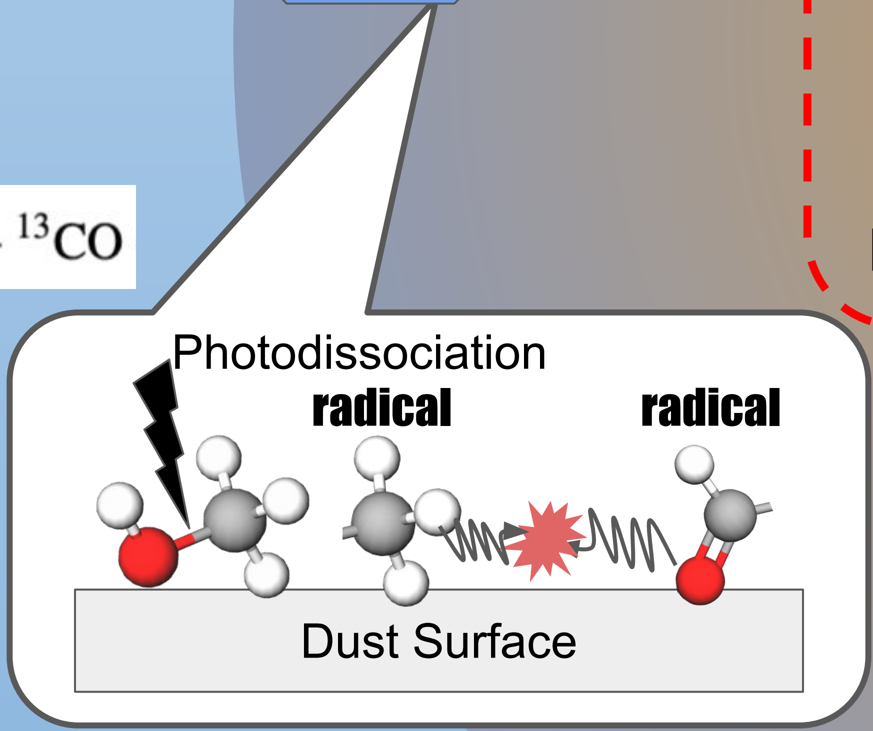
Dotted : the base model
Solid : CR acceleration model

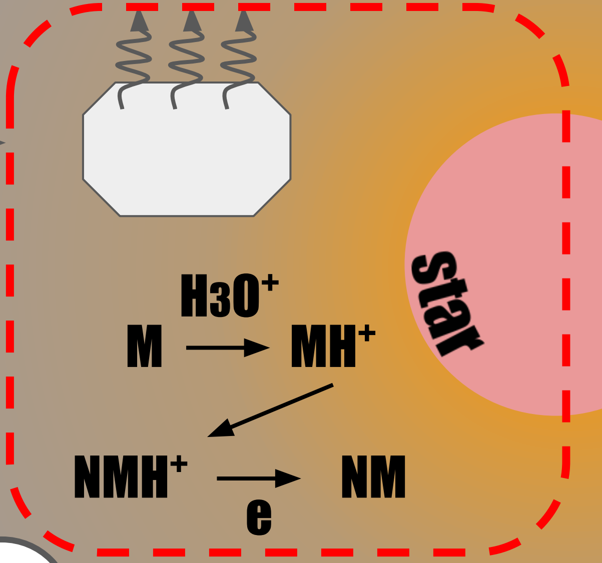
Effect of CR on Complex Organic Molecules



Change timescale of
ion-neutral reactions

$$^{13}\mathrm{C}^{+} + \mathrm{CO} \leftrightarrows \mathrm{C}^{+} + {}^{13}\mathrm{CO}$$





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Summary

- We investigate the carbon isotope fractionations of COMs in star-forming core.

- High Cosmic Ray ionization rate model cannot reproduce the observations of $^{12}C/^{13}C$ ratios of CH_3OCH_3

- Cosmic Ray acceleration after birth of protostar could make slightly low carbon isotope ratio of CH3OCH3.