Analytical Formulas of Molecular Ion Abundances and N_2H^+ Ring in Protoplanetary Disks

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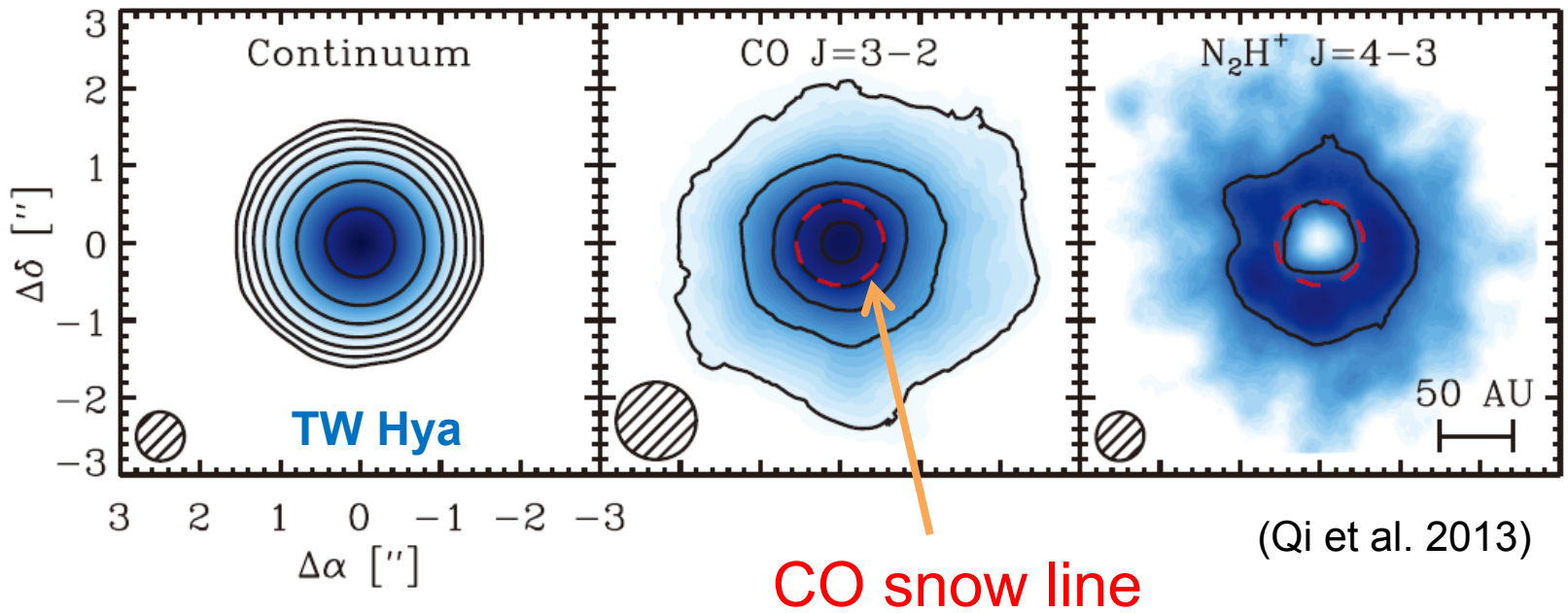
N_2H^+ ring



(Qi et al. 2013)

Anti-correlation of CO and N_2H^+

$$CO + N_2H^+ \rightarrow HCO^+ + N_2$$

➔ N_2H^+ ring as a probe of CO snow line

★But, the sublimation temperature of N_2 and CO are similar.
→ Why is N_2H^+ abundant outside CO (N_2) snow line？

This Work

1. Numerical calculation of disk chemistry

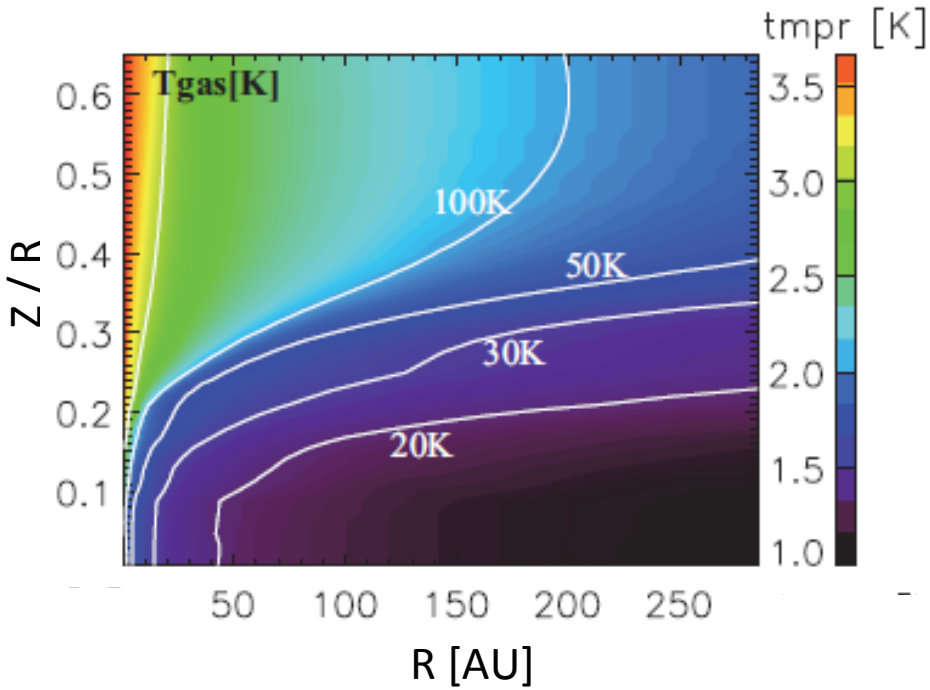
2. Derive analytical formulae of N_2H^+, HCO^+, H_3^+ abundances
   → Good agreement with numerical calculation

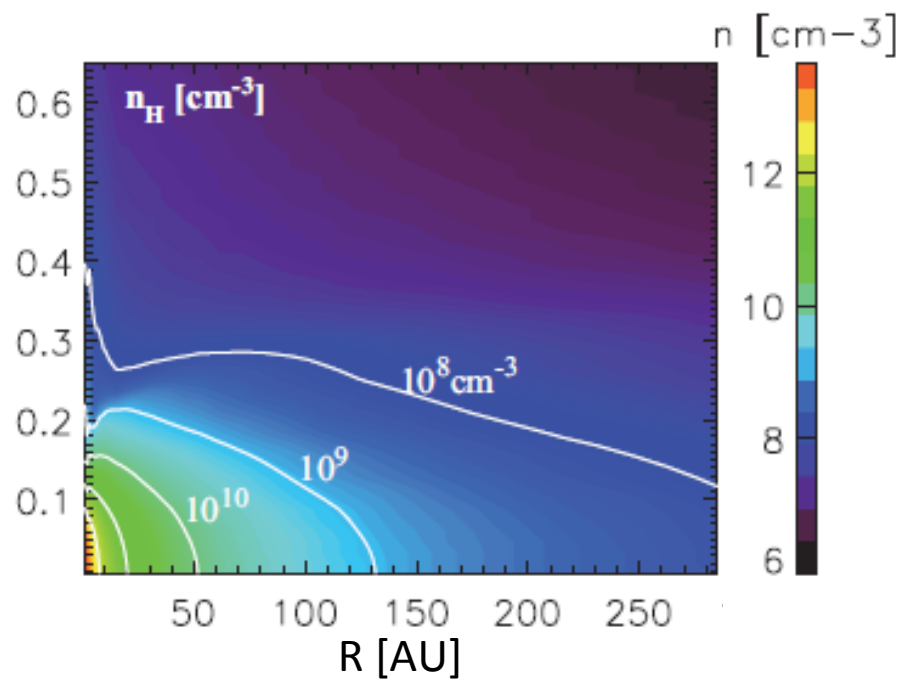
3. Dependence on ionization rate

Numerical calculation of disk chemistry

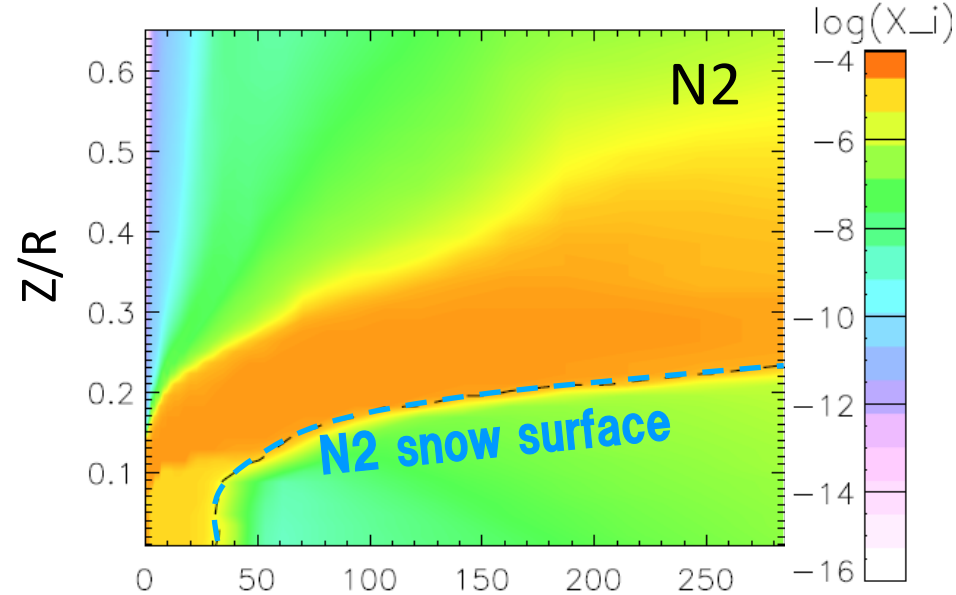
- T Tauri Disk model
  (Nomura et al. 2005; 2007)
  - M_{disk}=0.017M_{sun}
  - T_*=4000 K
  - L_X=10^{30} erg s^{-1}
  - L_{UV}=10^{31} erg s^{-1}

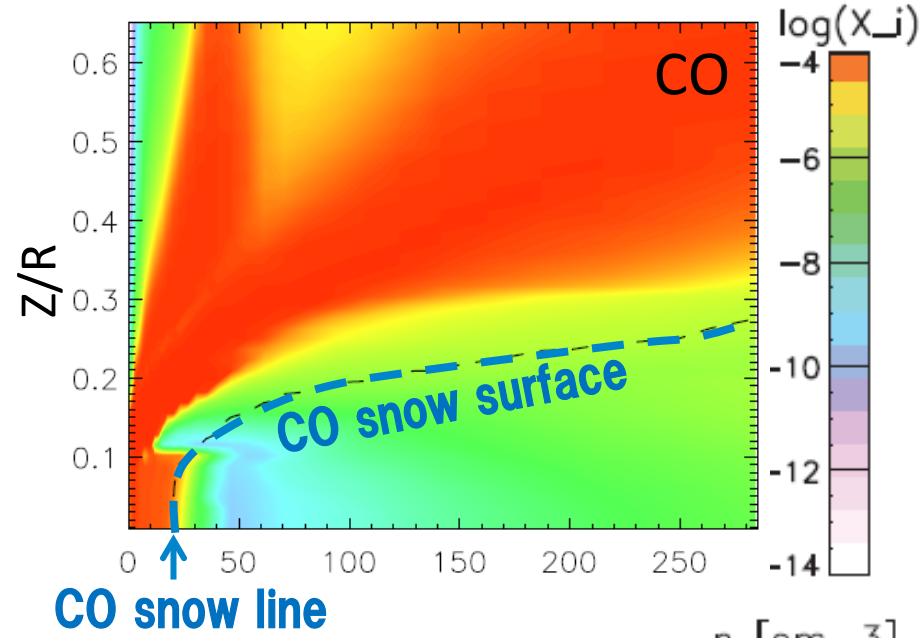
- Chemical model (Furuya &YA 2014)
  - Gas + Grain-surface reactions
  - shielding of H_2, HD, CO and N_2
  - Ionization { X-ray, cosmic-ray, radio-active }

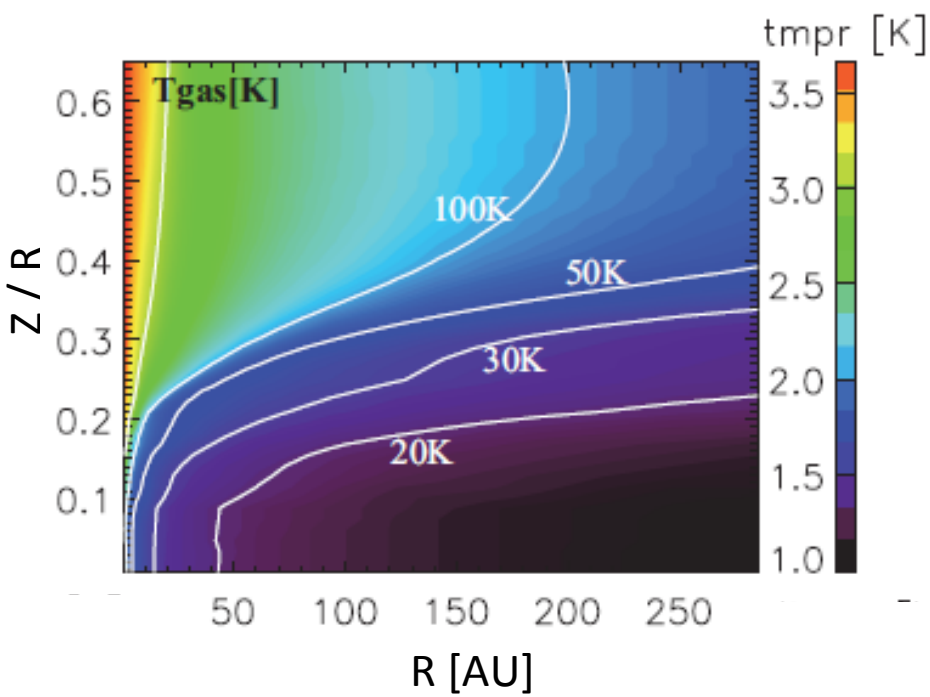


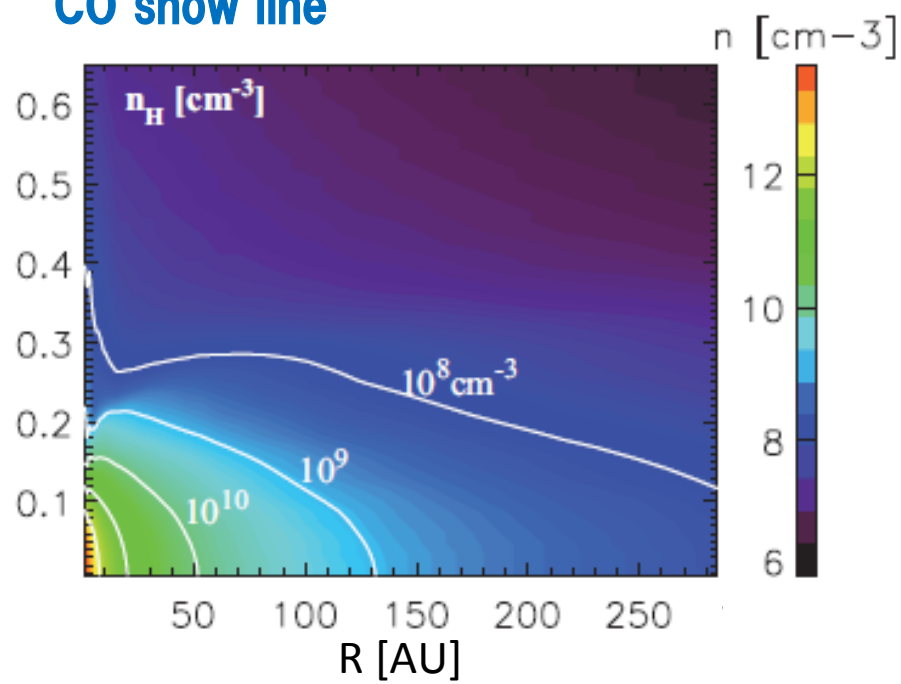


Numerical calculation of disk chemistry









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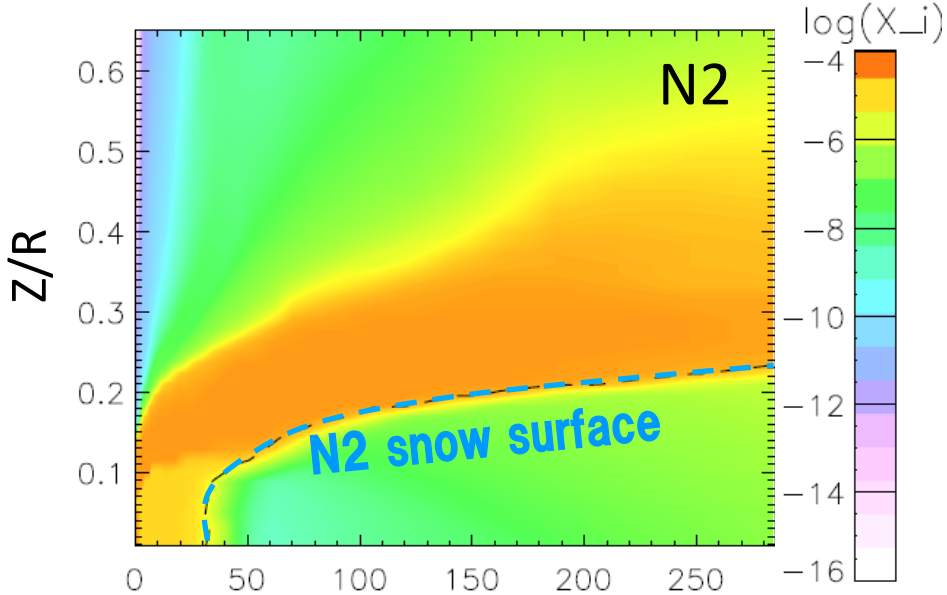
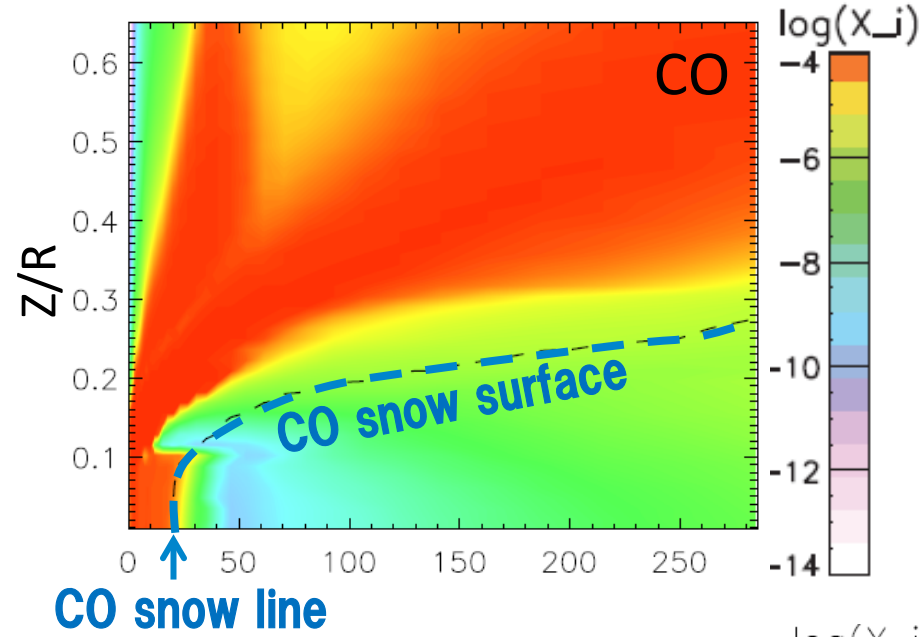
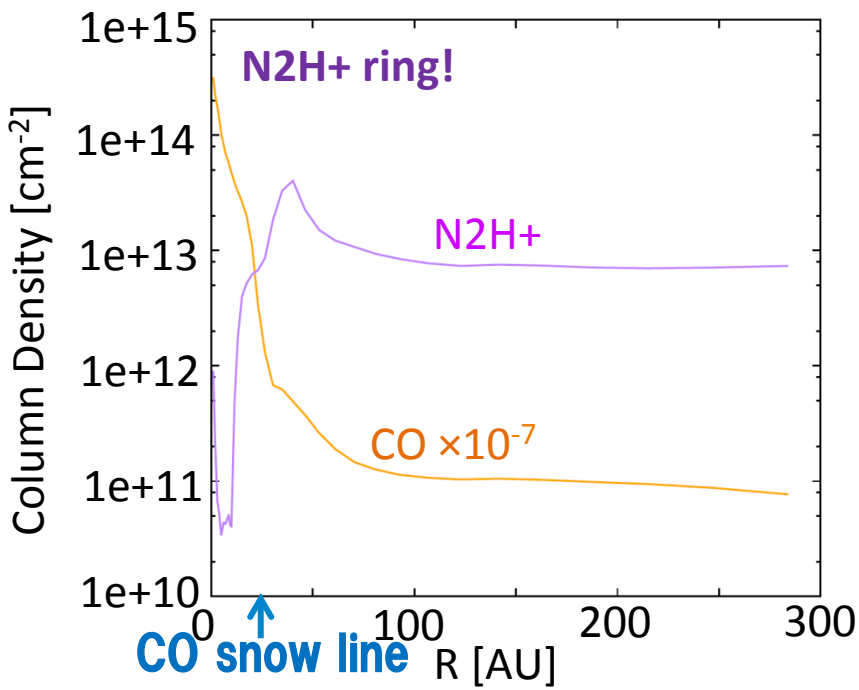
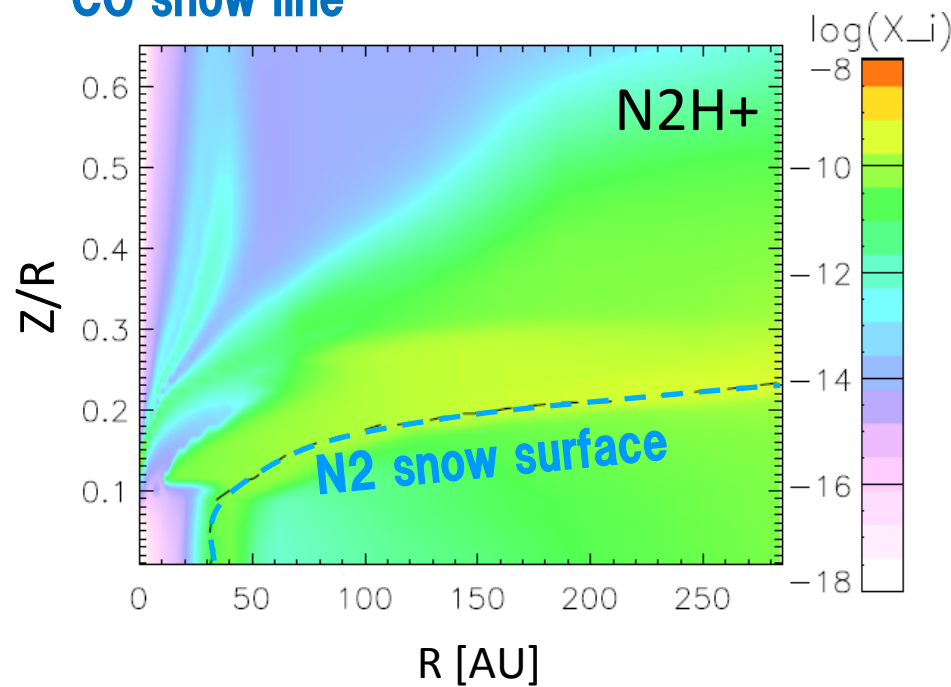








Numerical calculation of disk chemistry

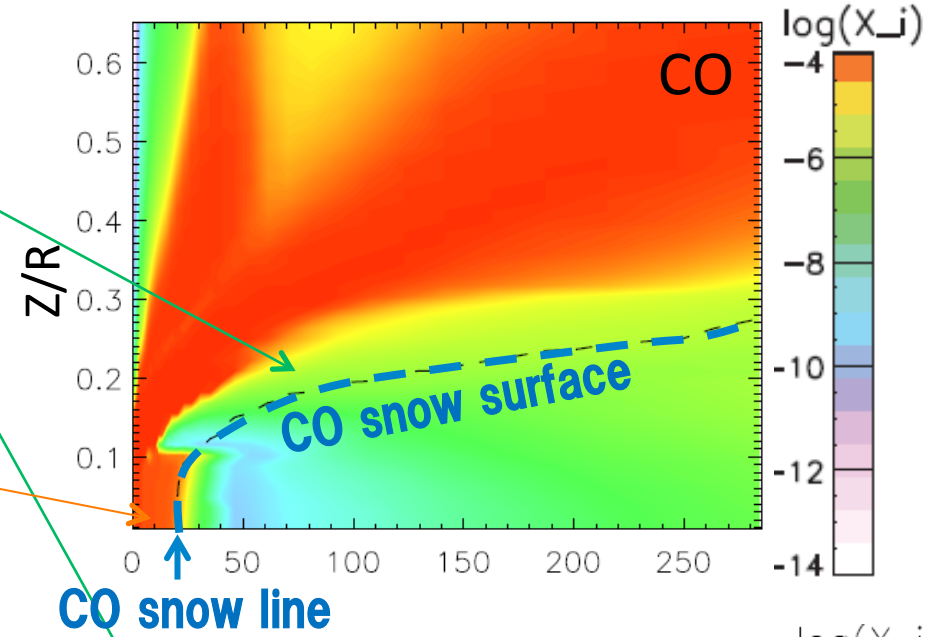
CO is depleted at T > T_{sub}

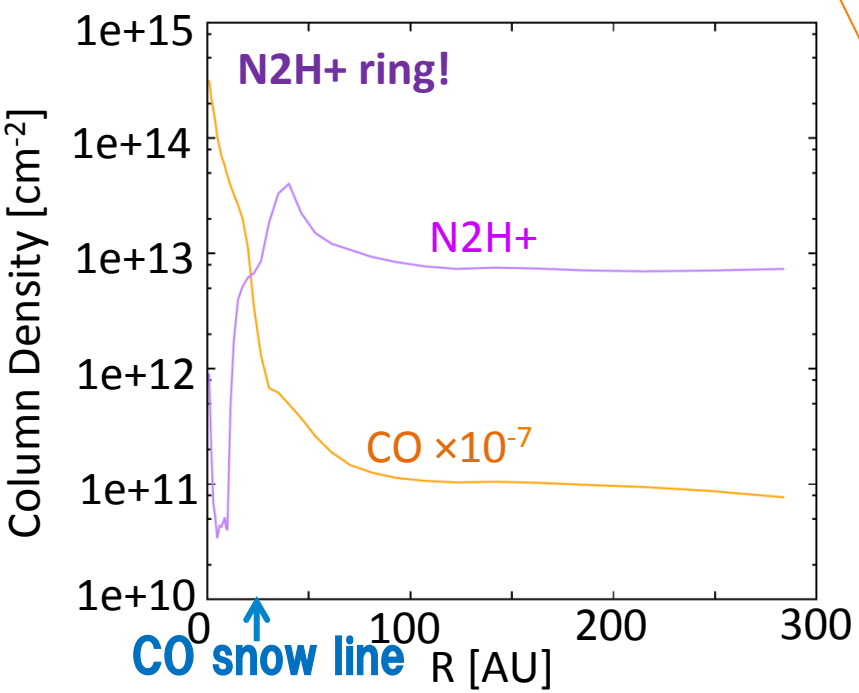
∵conversion to less volatile species

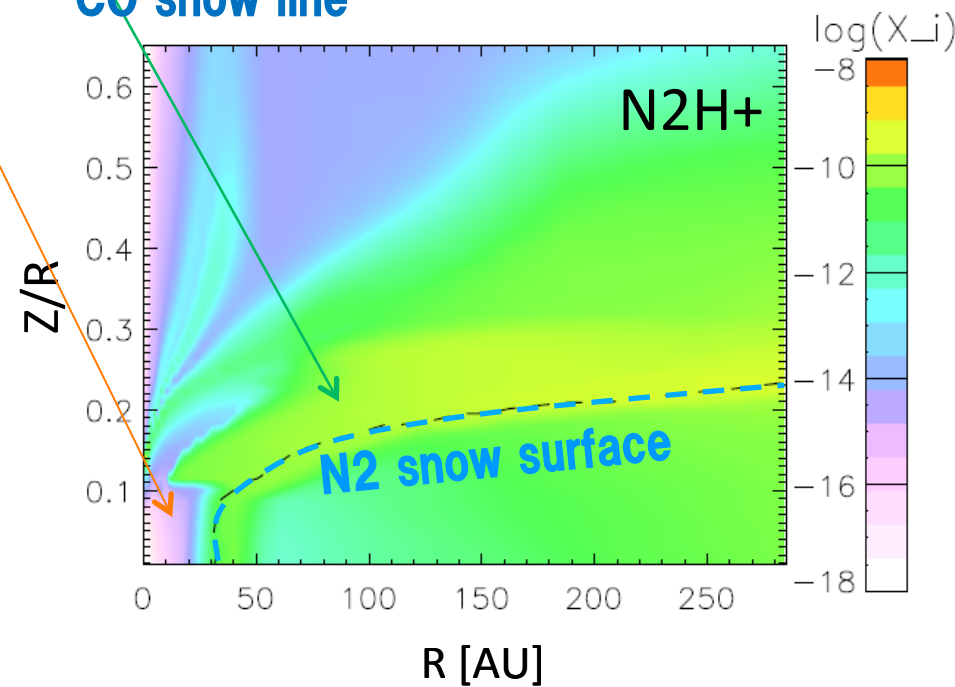
(Aikawa et al 1997; Favre et al 2013 ; Furuya &Aikawa 2014)

⇒ N_2H^+ is the major ion

CO is sublimated to destroy N_2H^+







Numerical calculation of disk chemistry

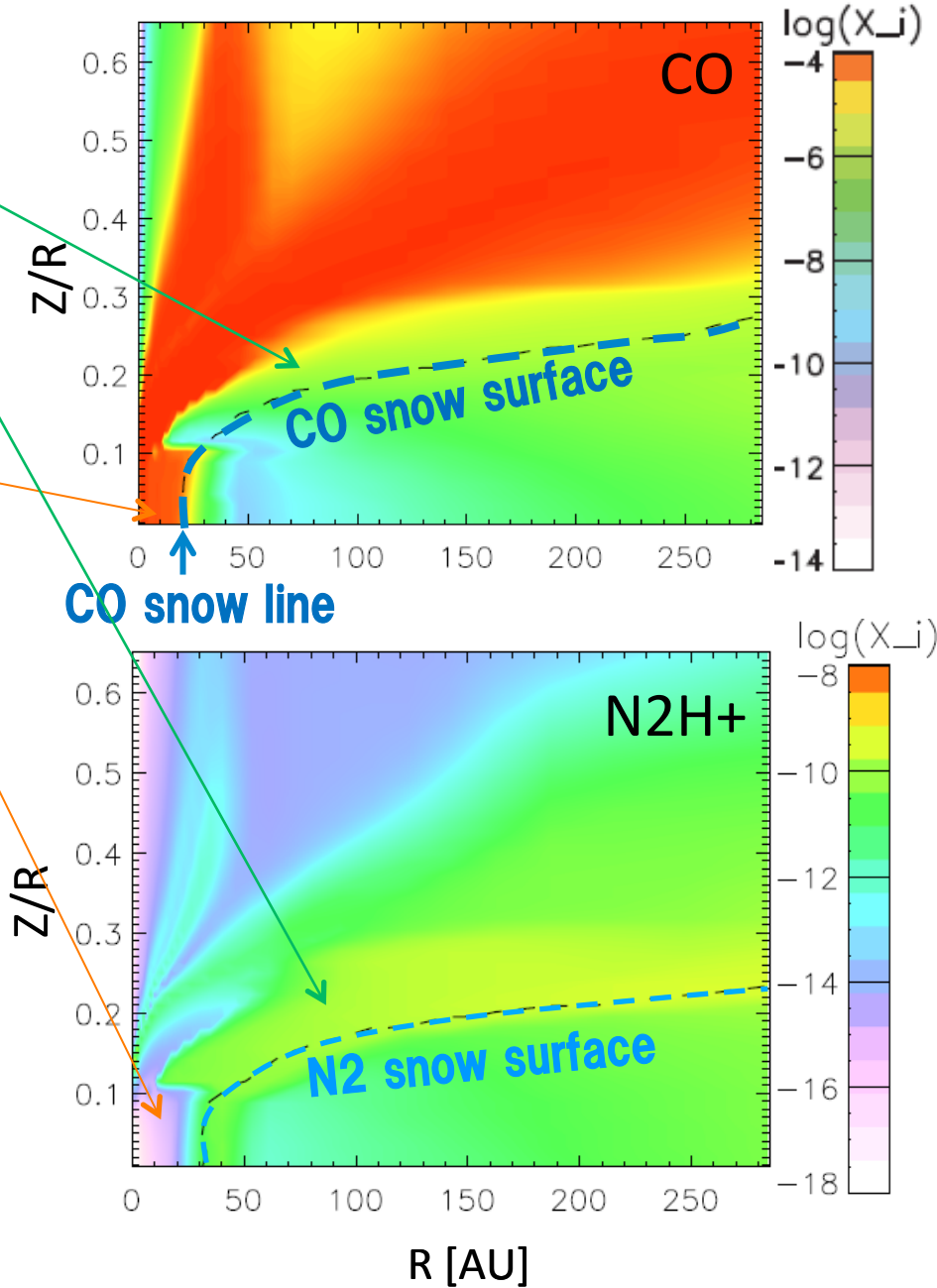
CO is depleted at T > T_{sub}
∵conversion to less volatile species
(Aikawa et al 1997; Favre et al 2013 ; Furuya &Aikawa 2014)
⇒ N_2H^+ is the major ion

CO is sublimated to destroy N_2H^+

N_2H^+ is abundant outside the CO snow line due to chem conv of CO

BUT, chem conv depends on
- ionization rate
- rates of grain surface reactions
- turbulence

No N2H+ ring w/o chem conv of CO?
need more simple & robust calculation to evaluate N2H+ distribution?



Analytical Formulas

Density, Temperature, ionization rate, CO&N2 abundances
⇒ N_2H^+, HCO^+, H_3^+, e abundances

ex $$x(\mathrm{N_2H^+}) = \frac{k_1 x(\mathrm{H_3^+}) x(\mathrm{N_2})}{k_2 x(\mathrm{e}) + k_3 x(\mathrm{CO})}$$

$$\begin{cases} H_3^+ + N_2 \rightarrow N_2H^+ + H_2 \\ N_2H^+ + e \rightarrow NH + N \text{ or } N_2 + H \\ N_2H^+ + CO \rightarrow N_2 + HCO+ \end{cases}$$

Analytical Formulas

Density, Temperature, ionization rate, CO&N2 abundances
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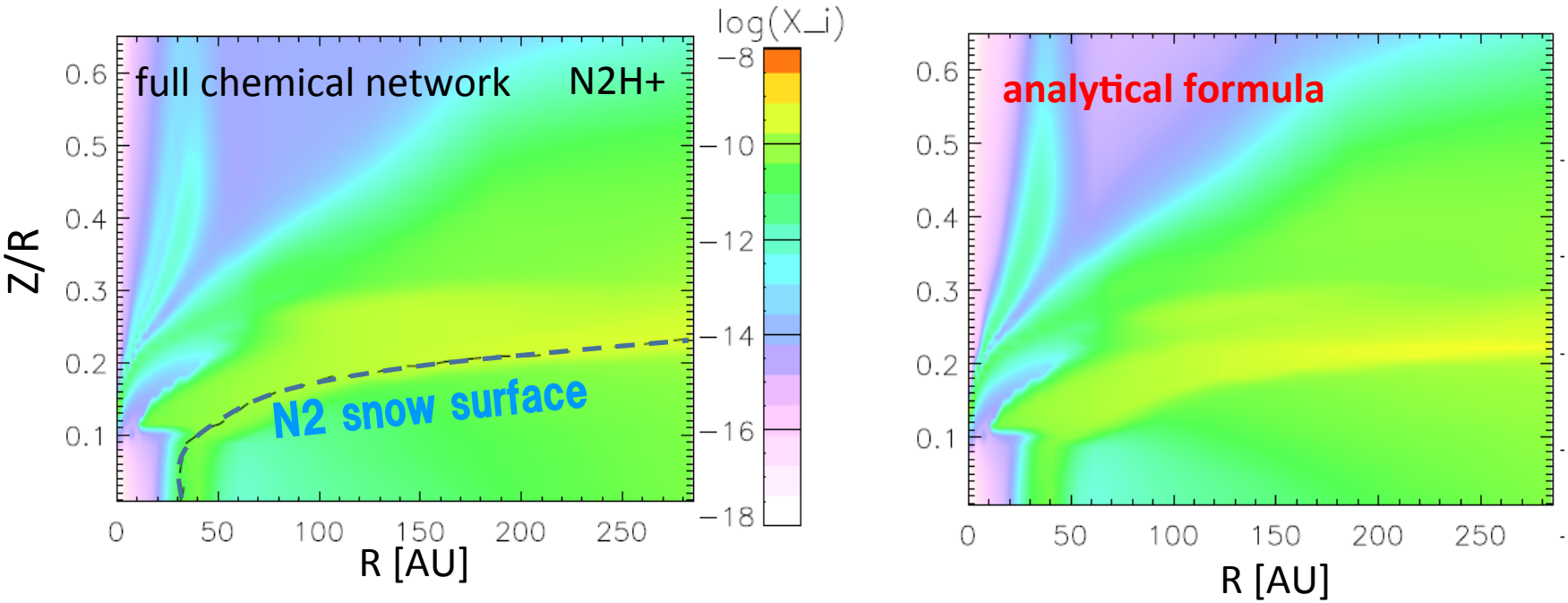


Analytical formulas agree well with the full network results.

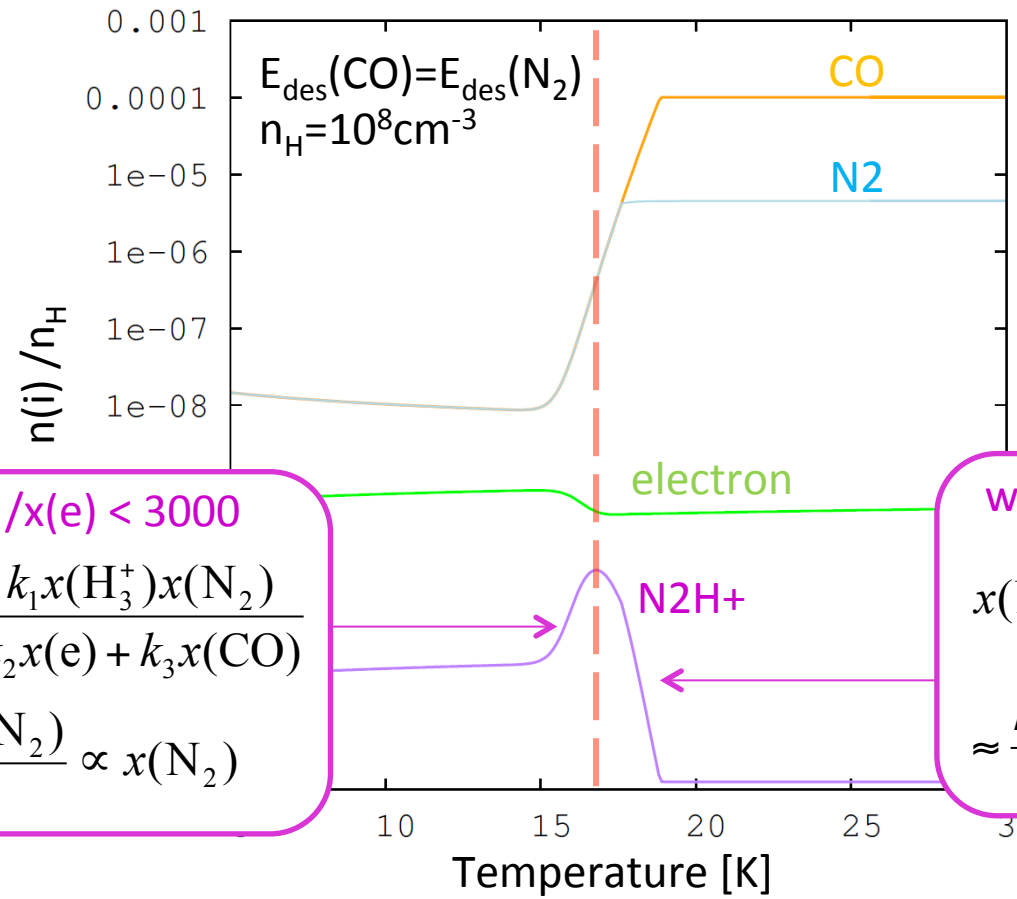
Analytical Model

If CO and N_2 abundances (gas + ice) are constant

$$S\pi a^2 v_{\rm th} n_{\rm COgas} n_{\rm dust} = \min[4\pi a^2 n_{\rm dust} N_{\rm site}, n_{\rm COice}]\left\{\nu \exp\left(-\frac{E_{\rm des}^{\rm CO}}{kT}\right) + \nu \tau_{\rm CR} C_{\rm Fe} \exp\left(-\frac{E_{\rm des}^{\rm CO}}{kT_{\rm max}}\right)\right\}$$

Adsorption onto grains

Desorption



when x(CO) /x(e) < 3000

$$x(N_2H^+) = \frac{k_1 x(H_3^+) x(N_2)}{k_2 x(e) + k_3 x(CO)} \approx \frac{k_1 x(H_3^+) x(N_2)}{k_2 x(e)} \propto x(N_2)$$

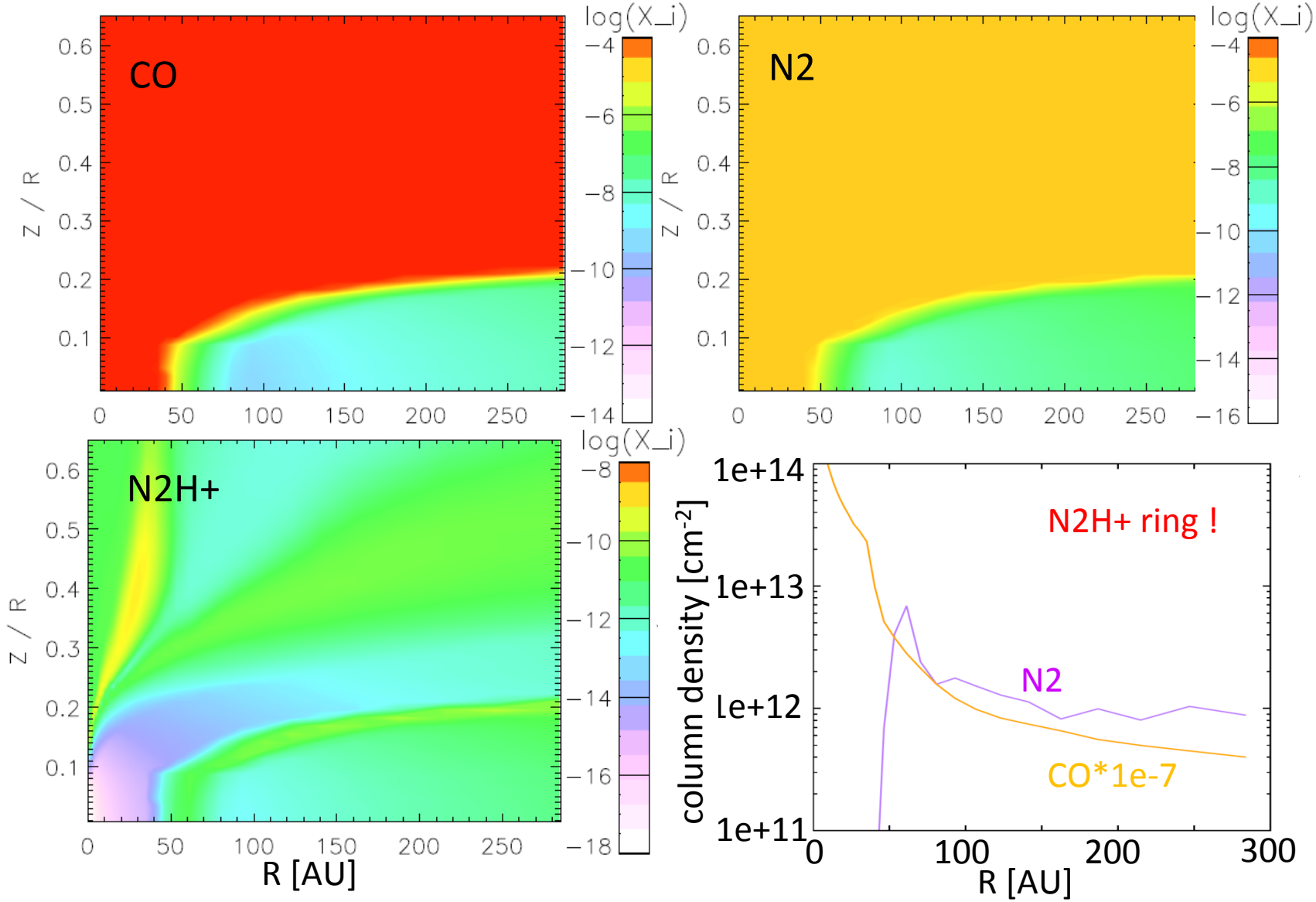
when x(CO) /x(e) > 3000

$$x(N_2H^+) = \frac{k_1 x(H_3^+) x(N_2)}{k_2 x(e) + k_3 x(CO)} \approx \frac{k_1 x(H_3^+) x(N_2)}{k_3 x(CO)} \propto \frac{x(N_2)}{x^2(CO)}$$

N_2H^+ abundance is maximized when x(CO)/x(e)~ 3000

Analytical Model

If CO and N_2 abundances (gas + ice) are constant



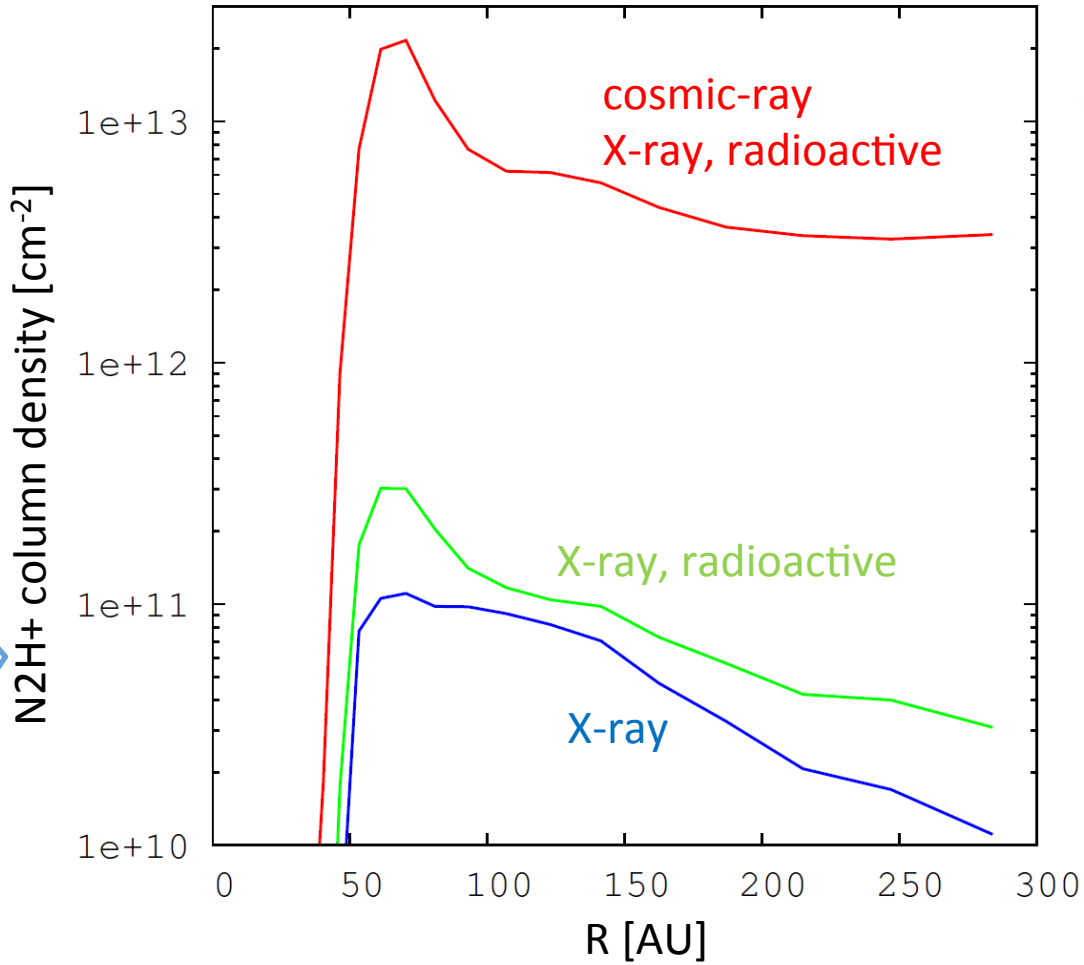
Dependence on ionization rate

Ionization source in disk:
- X-ray
- Cosmic Ray
- radioactive nuclei

Cosmic ray is the dominant ionization source in the midplane, but could be scattered by stellar winds.
(Glassgold et al. 1997; Aikawa et al. 1999; Cleevs et al. 2014)

Without cosmic-ray, N_2H^+ column declines by ~100

cf TW Hya (Qi et al. 2013)
N_2H^+ column at the ring inner edge
~ 4×10^{12} – 2×10^{15} cm^{-2}



Summary

1. Numerical calculation of disk chemistry
   - Outside the CO snow line, N_2H^+ is abundant in layers with CO conversion to less volatile species

2. Derive analytical formulae of N_2H^+, HCO^+, H_3^+ abundances
   - Good agreement with numerical calculation
   - N_2H^+ abundance is maximized when CO/e ~3000

3. Dependence on ionization rate
   - N_2H^+ column density declines by ~100 w/o cosmic-ray