DNC/HNC Ratio in Molecular Clumps

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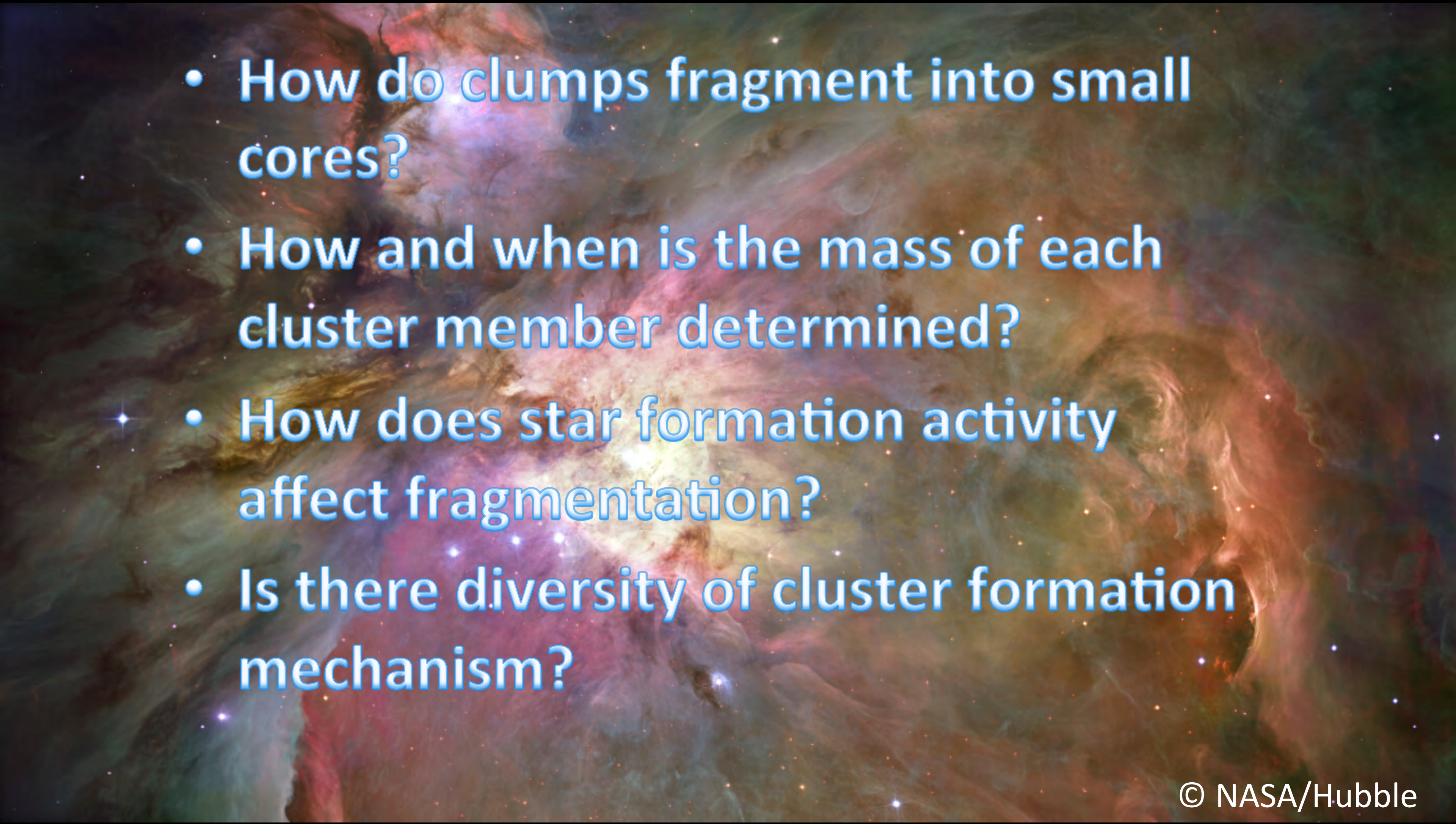
Cluster formation

- Most of stars (~90 %) are born in clusters (Lada & Lada 2003).



- How do clumps fragment into small cores?
- How and when is the mass of each cluster member determined?
- How does star formation activity affect fragmentation?
- Is there diversity of cluster formation mechanism?

Deuterium Fractionation

- Molecules are highly deuterated in molecular clouds.

$$H_3^+ + HD \rightleftharpoons H_2D^+ + H_2 + 230\ K$$

$$CH_3^+ + HD \rightleftharpoons CH_2D^+ + H_2 + 370\ K$$

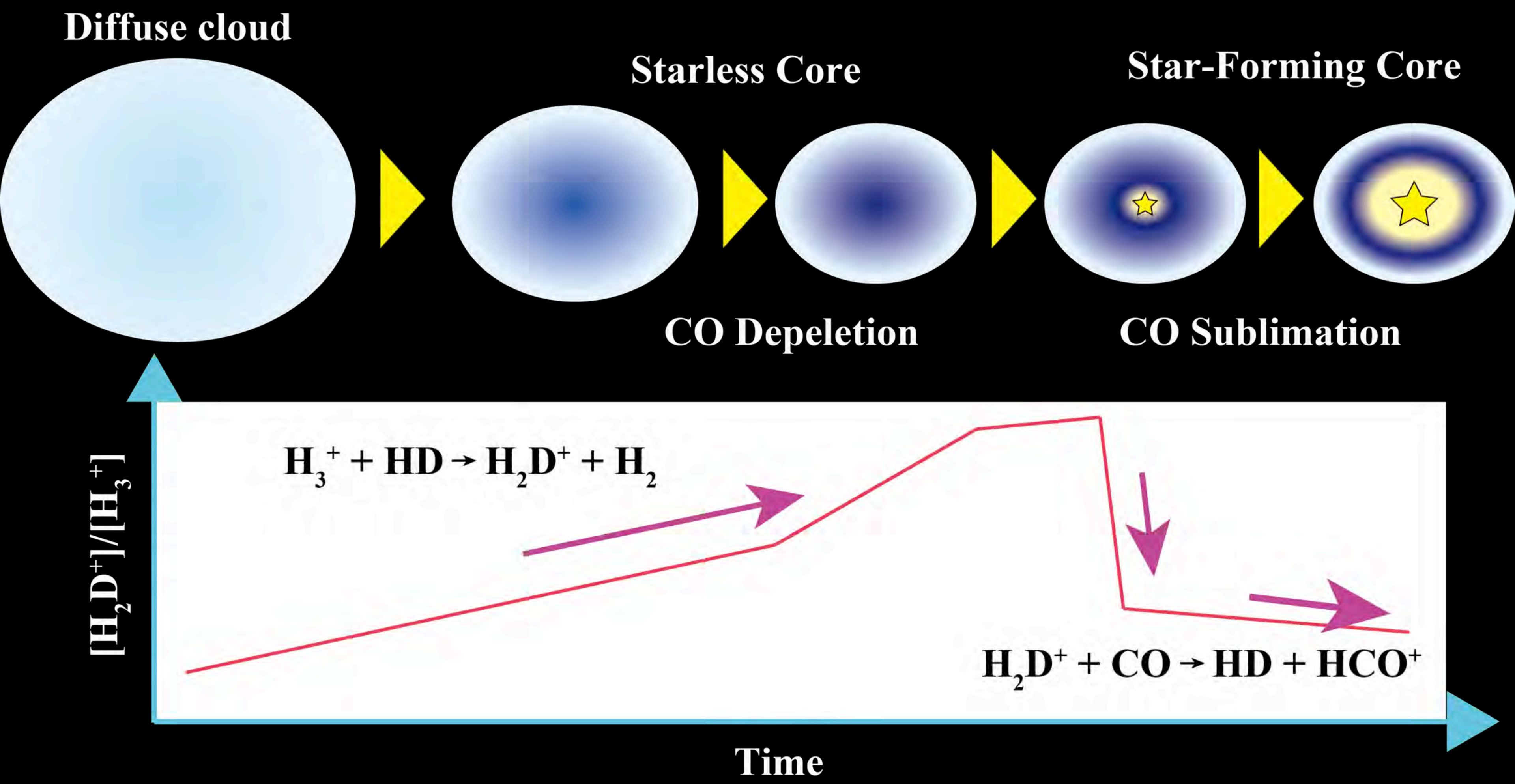
$$C_2H_2^+ + HD \rightleftharpoons C_2HD^+ + H_2 + 550\ K$$

- CO depletion (< ~20 K).

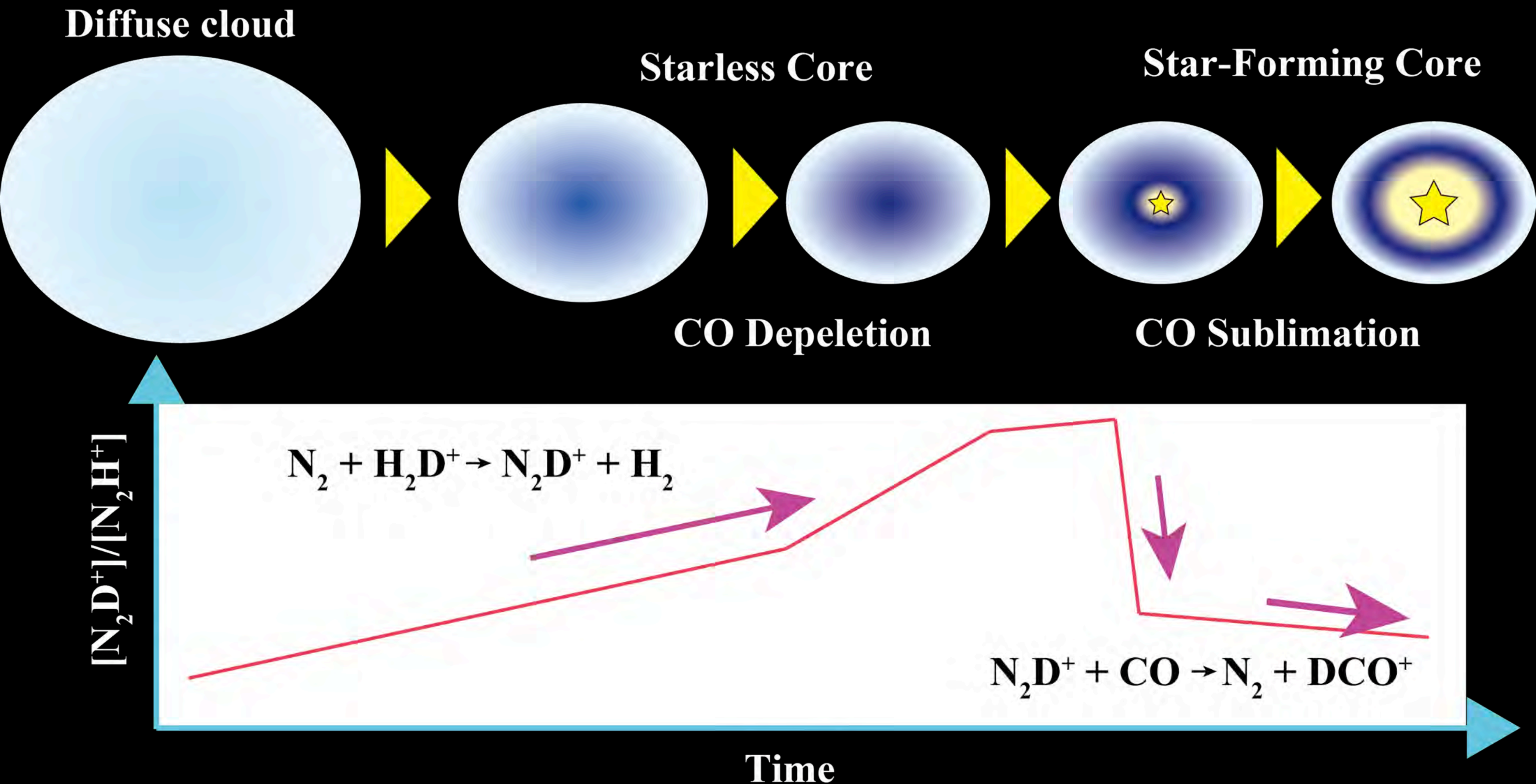
$$H_2D^+ + CO \not\rightarrow HCO^+ + HD$$

Deuterium Fractionation

H_2D^+/H_3^+

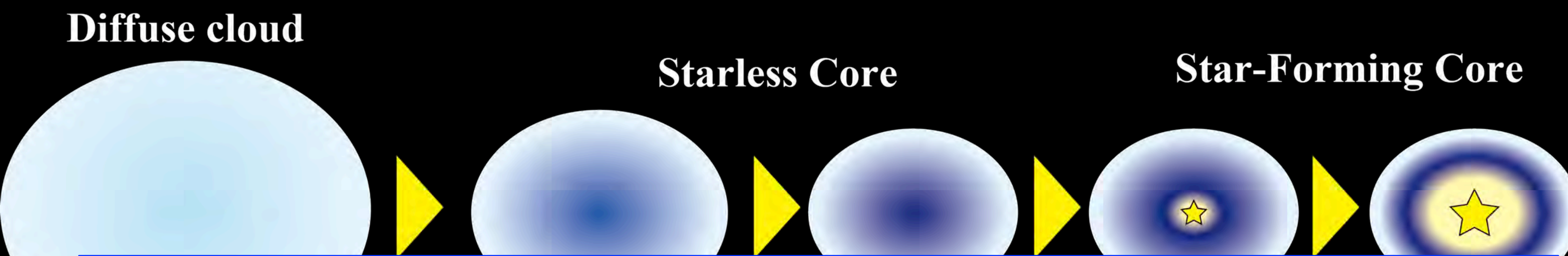


Deuterium Fractionation
N_2D^+/N_2H^+

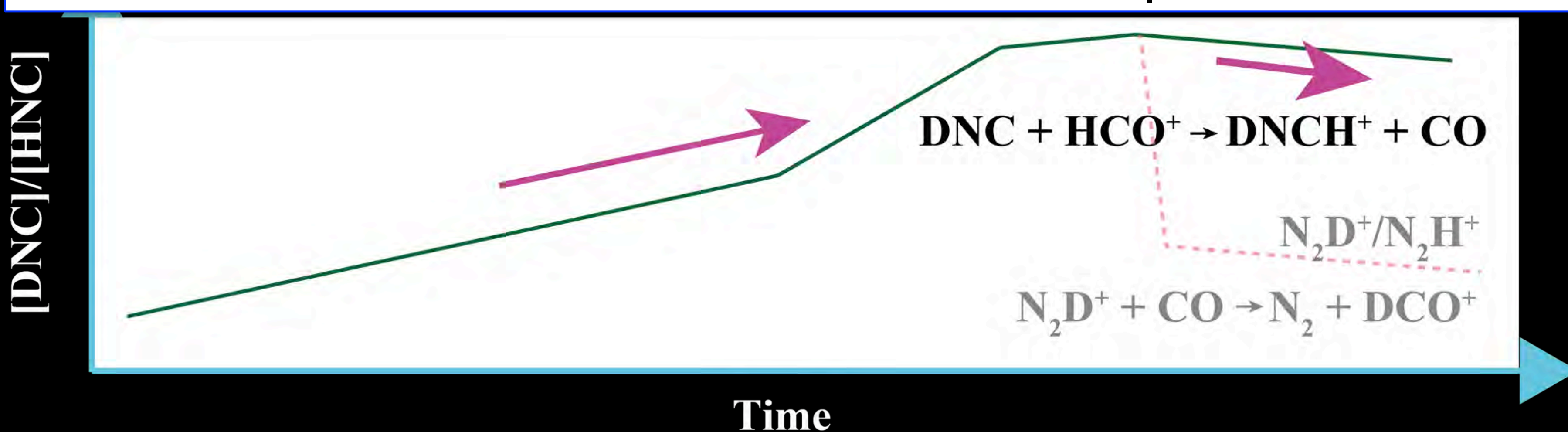


N_2D^+/N_2H^+, as well as H_2D^+/H_3^+, is sensitive to the "current" temperature.

Deuterium Fractionation
DNC/HNC



DNC/HNC ratio of star-forming regions may have information of their cold starless phase.



DNC/HNC ratio does not rapidly decrease after the onset of star formation.

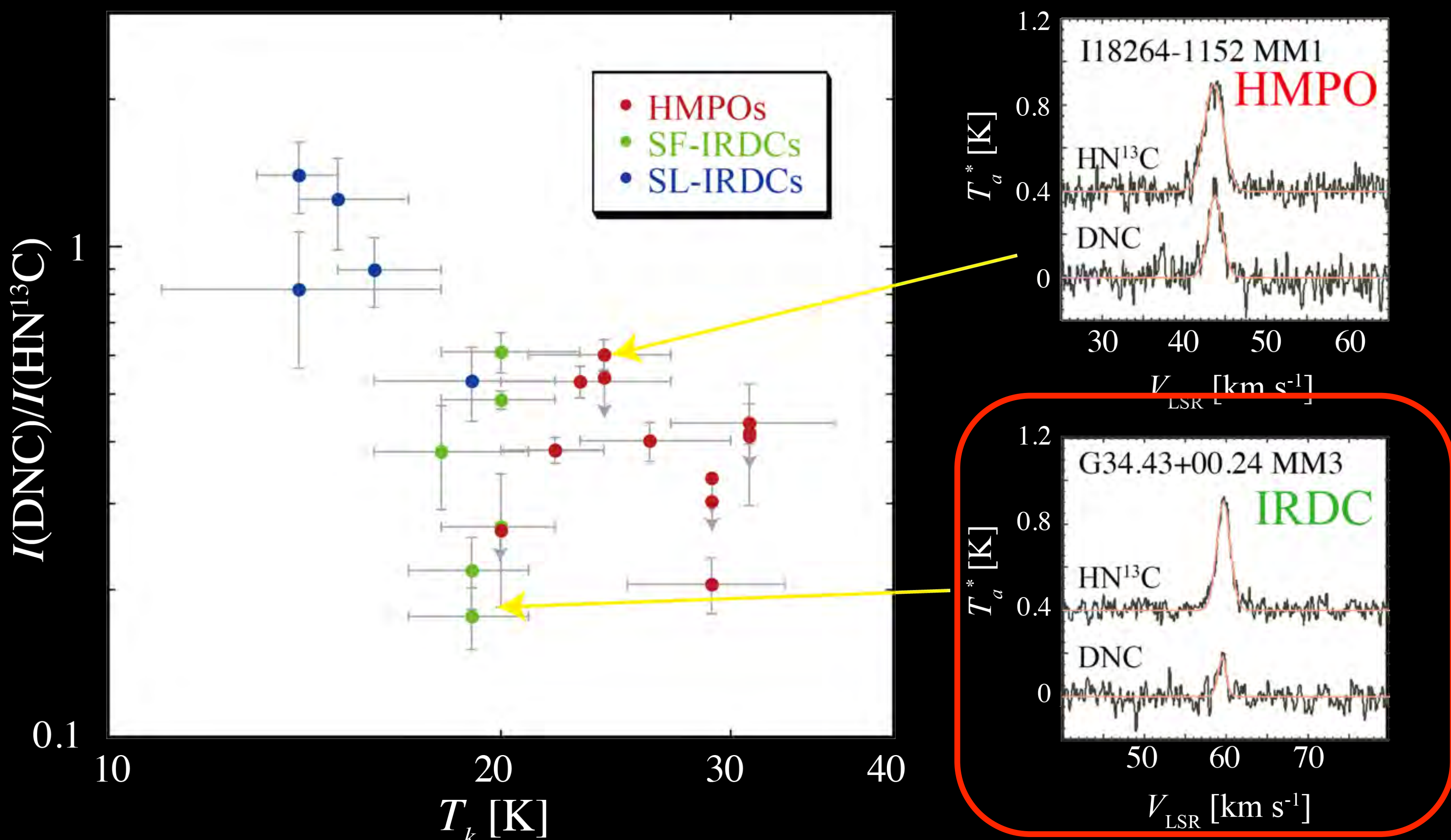
Single-dish Survey of DNC/HNC toward Molecular Clumps

- Nobeyama 45 m
  - DNC J=1-0 (76 GHz)
  - $HN^{13}C$ J=1-0 (87 GHz)
    - Beam size ~20”

- Targets
  - IRDCs: starless (24 μm dark) & star-forming (24 μm source)
    - Rathborne et al. 2006;Sridharan et al. 2005; Beuther et al. 2002
  - HMPOs
    - Sridharan et al. 2002; Beuther et al. 2002

Survey of DNC/HNC with NRO 45 m

(Sakai et al. 2012, ApJ)



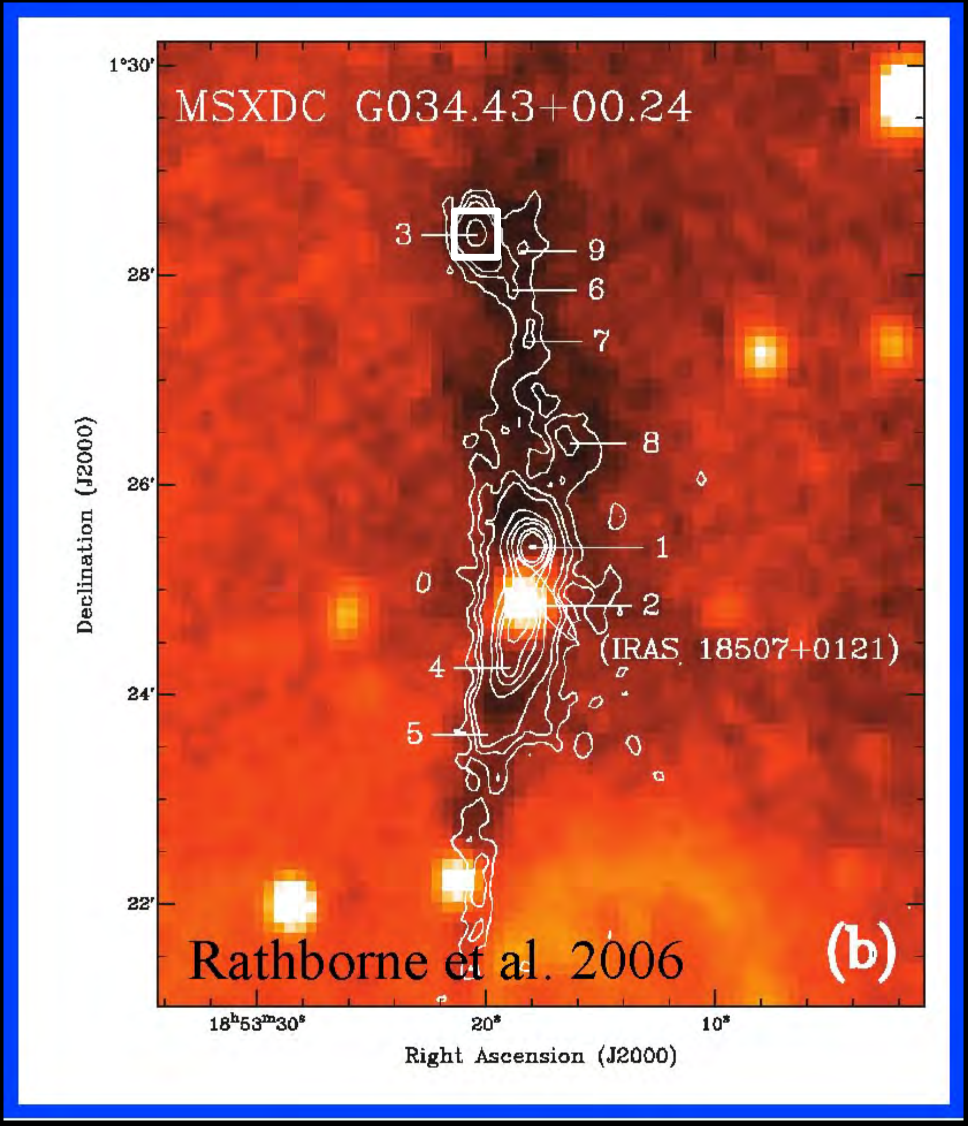
- IRDCs < HMPO

G34.43+00.24 MM3

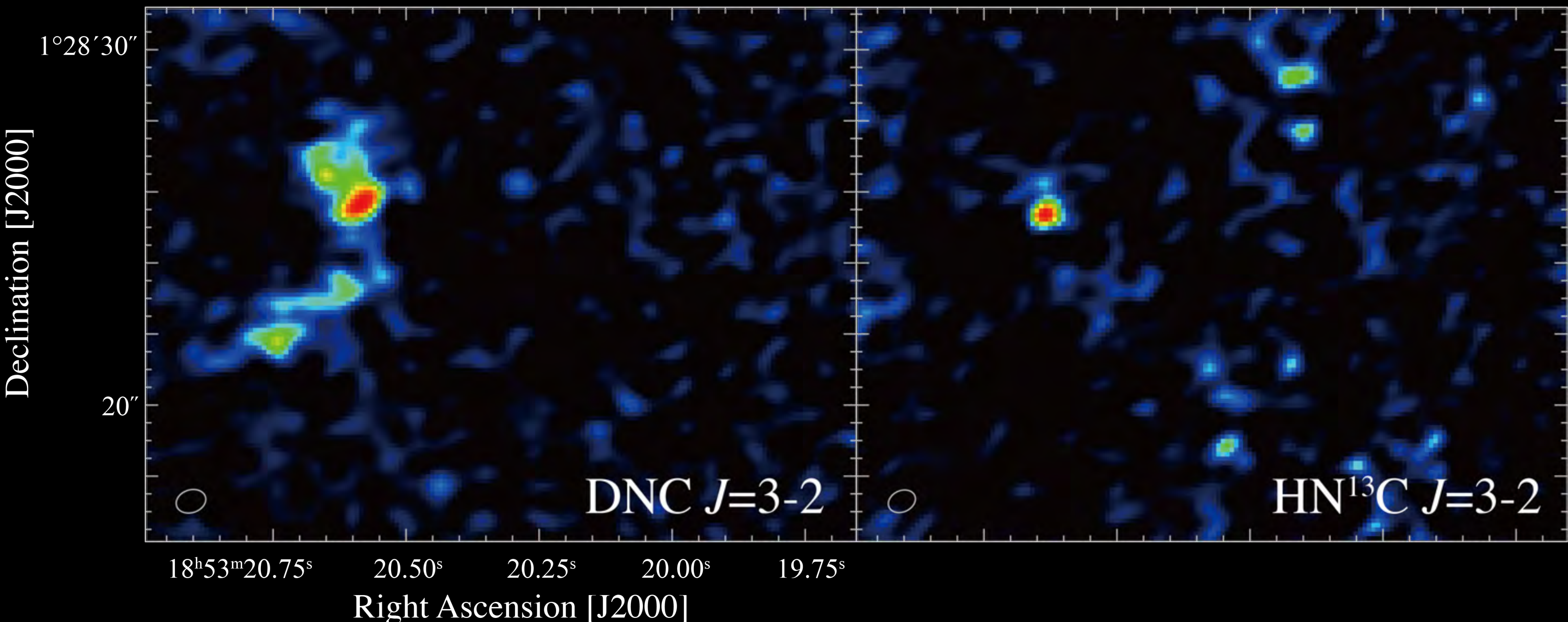
- The third most massive clump in G34.43+00.24 (Rathborne et al. 2006)
- Distance
  - 1.56 kpc (VLBI: Kurayama et al. 2011)
  - 3-4 kpc (kinetic distance or extinction; Foster et al. 2012)
- Mass
  - ~30 M_{sun} (D=1.56 kpc)
  - ~171 M_{sun} (D=3.7 kpc)
    - Rathborne et al. 2010

- ALMA cycle 0
  - Band 6 and Band 7
  - Antenna
    - 23-26
  - Beam size: ~0.8”

Garay et al. 2004; Rathborne et al. 2005, 2006; Sanhueza et al. 2010 ; Ashley Barnes’s talk

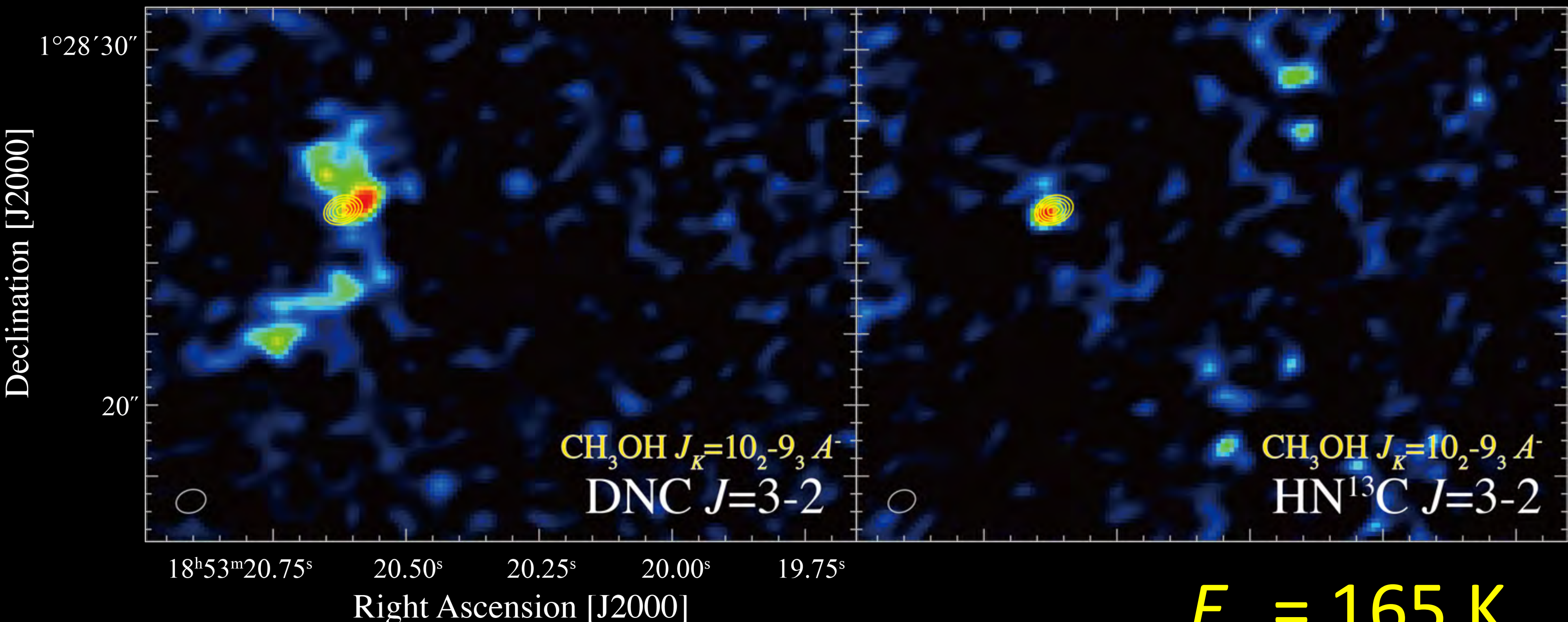


Results
DNC and $HN^{13}C$



- The DNC emission is more extended than the $HN^{13}C$ emission.

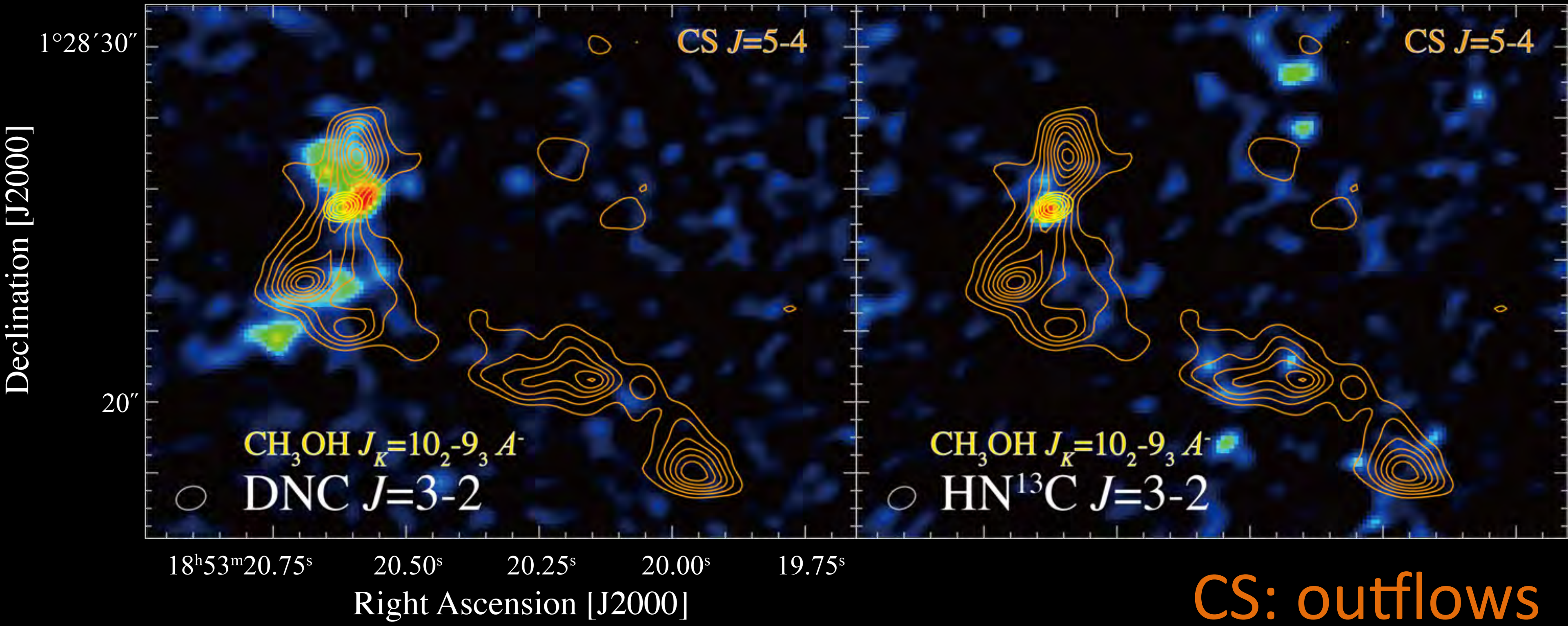
Results
DNC, $HN^{13}C$ and CH_3OH



E_u = 165 K

- $HN^{13}C$ -> Hot core
- DNC -> Extended around the hot core

Results
DNC, $HN^{13}C$, CH_3OH and CS

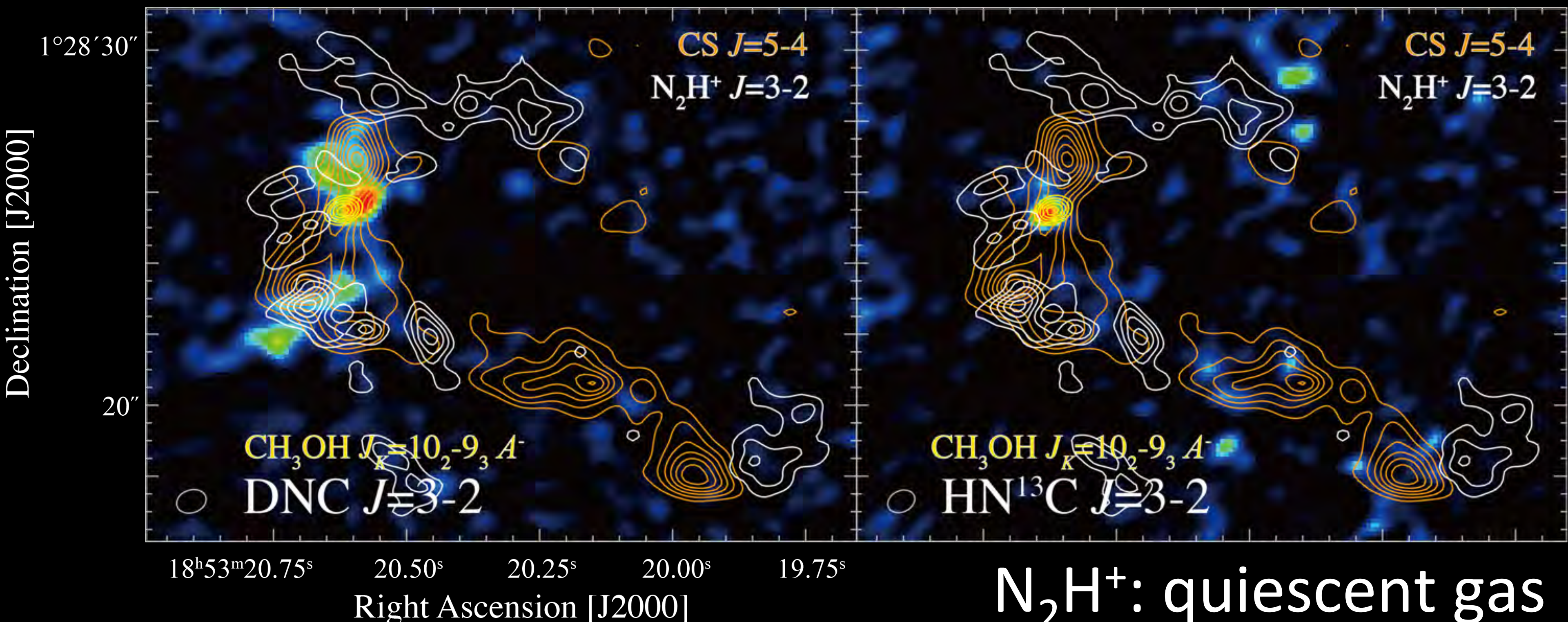


CS: outflows

- The DNC peaks are offset from the CS peaks.
  - Shock chemistry does not affect to the formation of DNC.

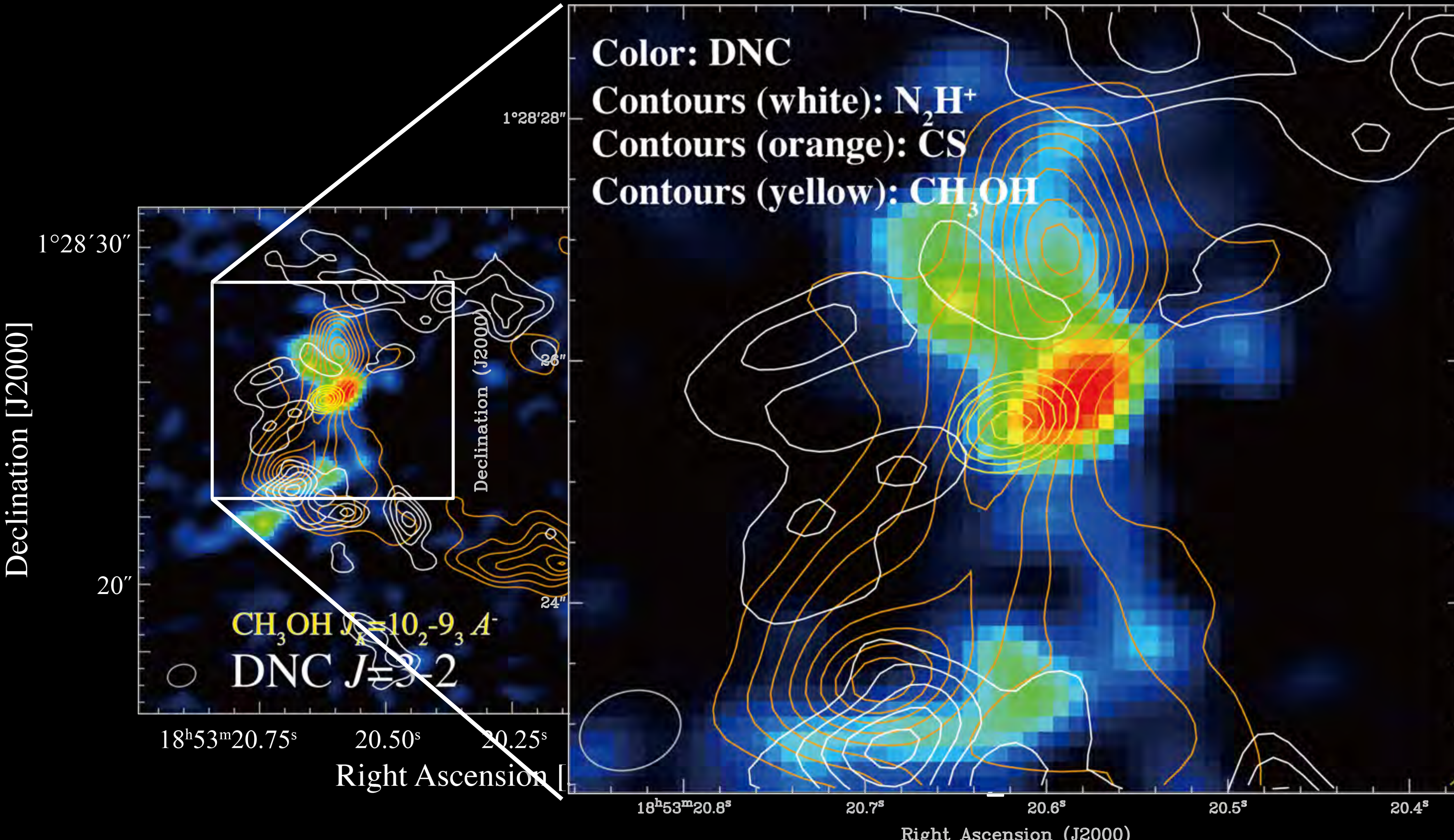
Results

DNC, $HN^{13}C$, CH_3OH, CS and N_2H^+



N_2H^+: quiescent gas

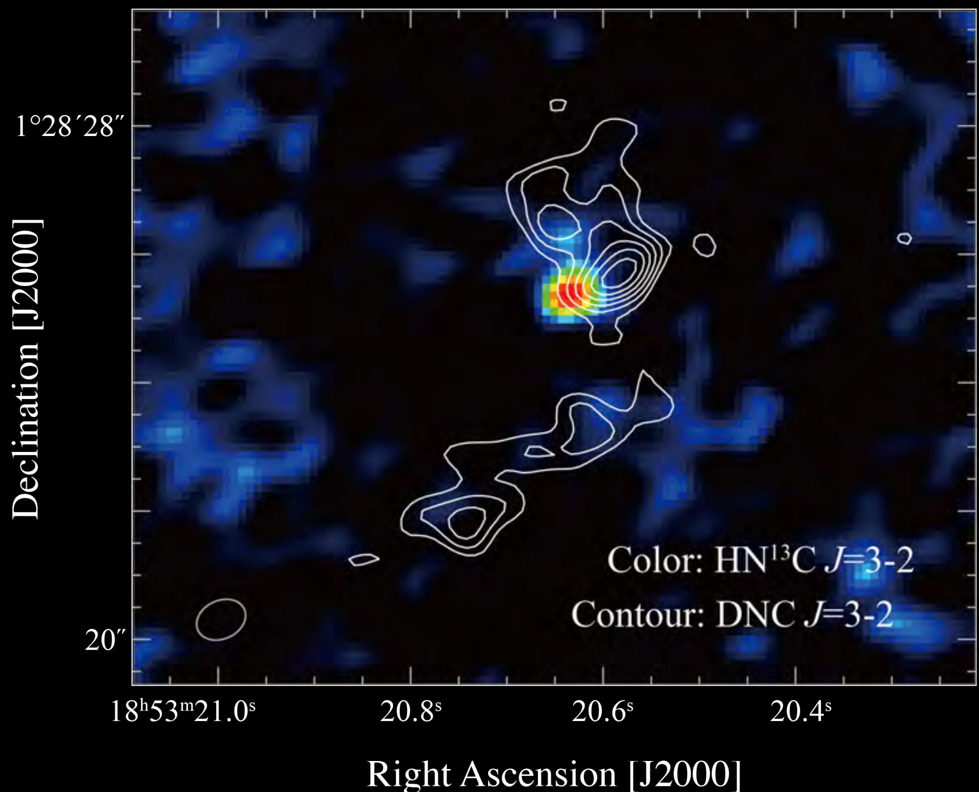
- No N_2H^+ emission near the hot core.
  - $N_2H^+ + CO \rightarrow HCO^+ + H_2$

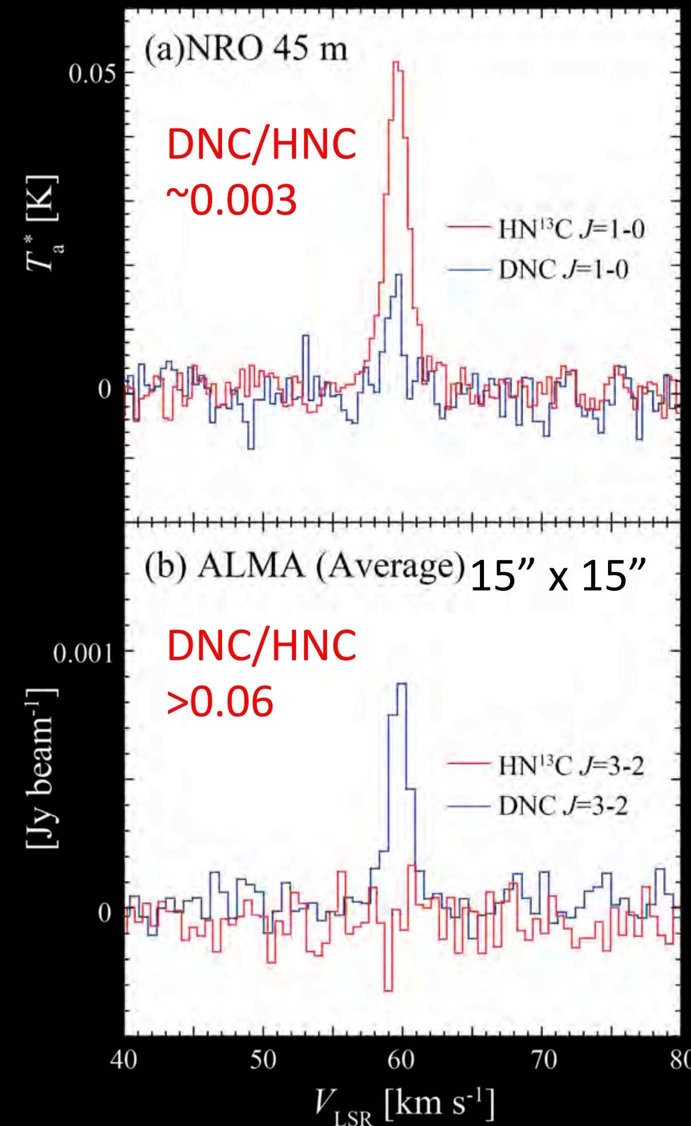


- No N_2H^+ emission
  - N_2H^+ + CO -> HCO

DNC emission can trace warm (>20 K) regions.

Difference between single-dish and ALMA observations

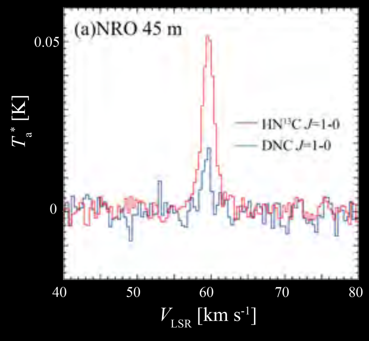


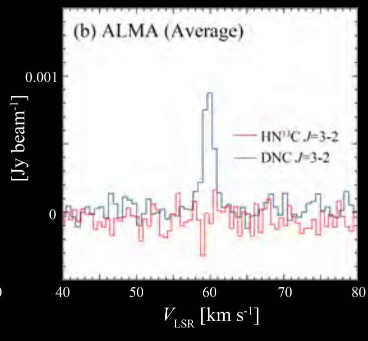


- The DNC emission is stronger than the $HN^{13}C$ emission.
  - Apparently inconsistent with the single-dish results.

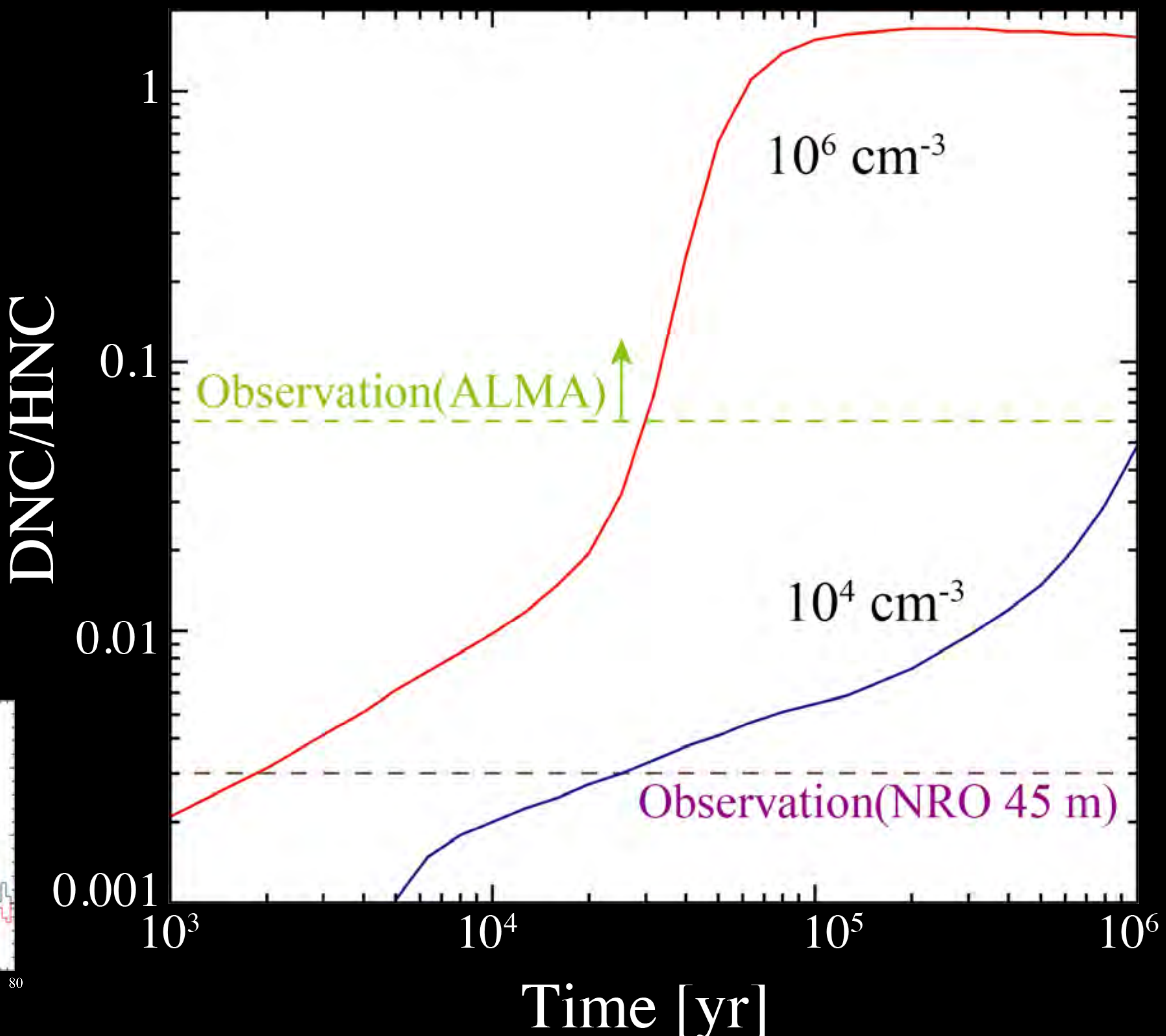
Difference in Critical Density

- NRO 45 m
  - DNC & HN^{13}C *J*=1-0
    - n_{cr} ~ 10^5 cm^{-3}
- ALMA
  - DNC & HN^{13}C *J*=3-2
    - n_{cr} ~ 10^7 cm^{-3}



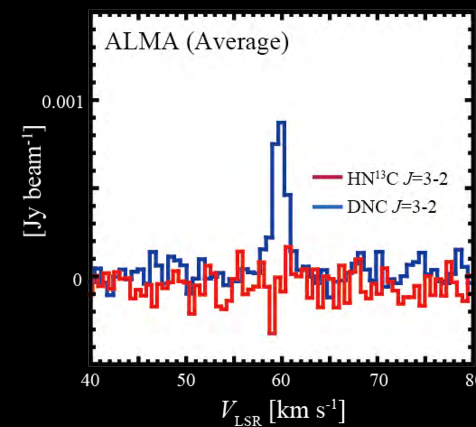


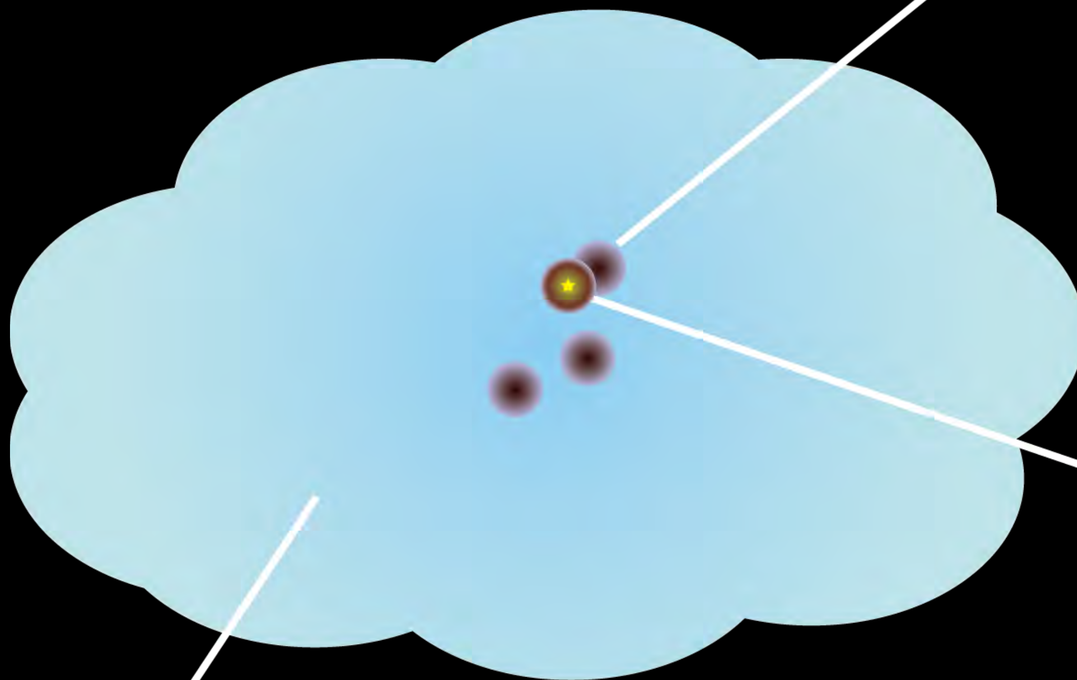
Model Calculation Results



Summary: DNC/HNC in G34.43+00.24 MM3

High Density Regions (~10^{6-7} cm^{-3})
DNC/HNC (>0.03)



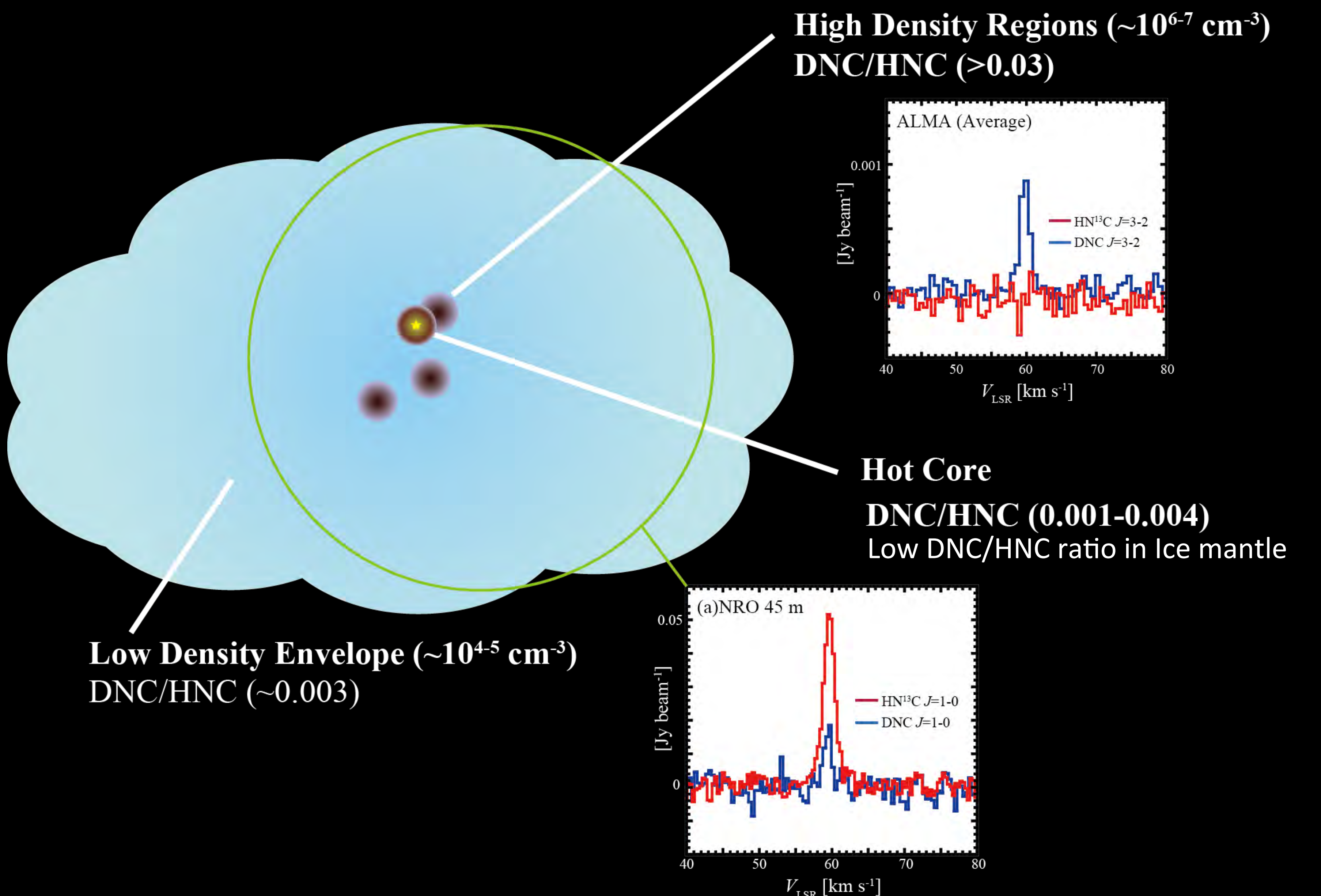


Hot Core

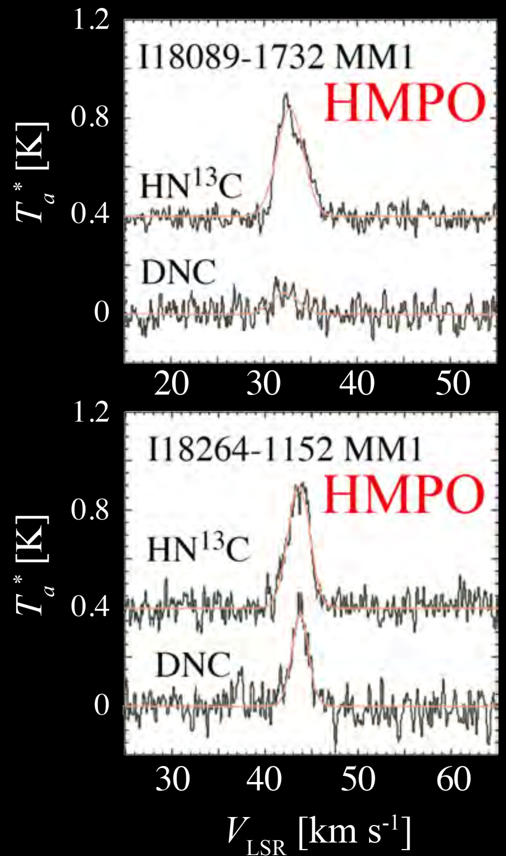
DNC/HNC (0.001-0.004)
Low DNC/HNC ratio in Ice mantle

Low Density Envelope (~10^{4-5} cm^{-3})
DNC/HNC (~0.003)

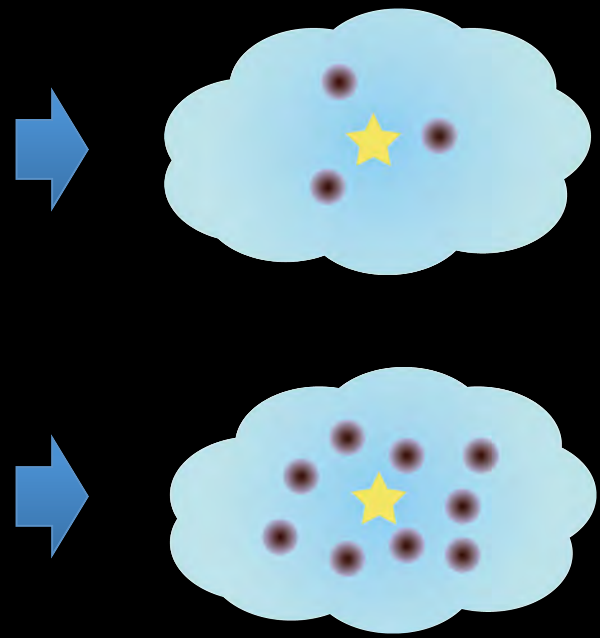
Summary: DNC/HNC in G34.43+00.24 MM3



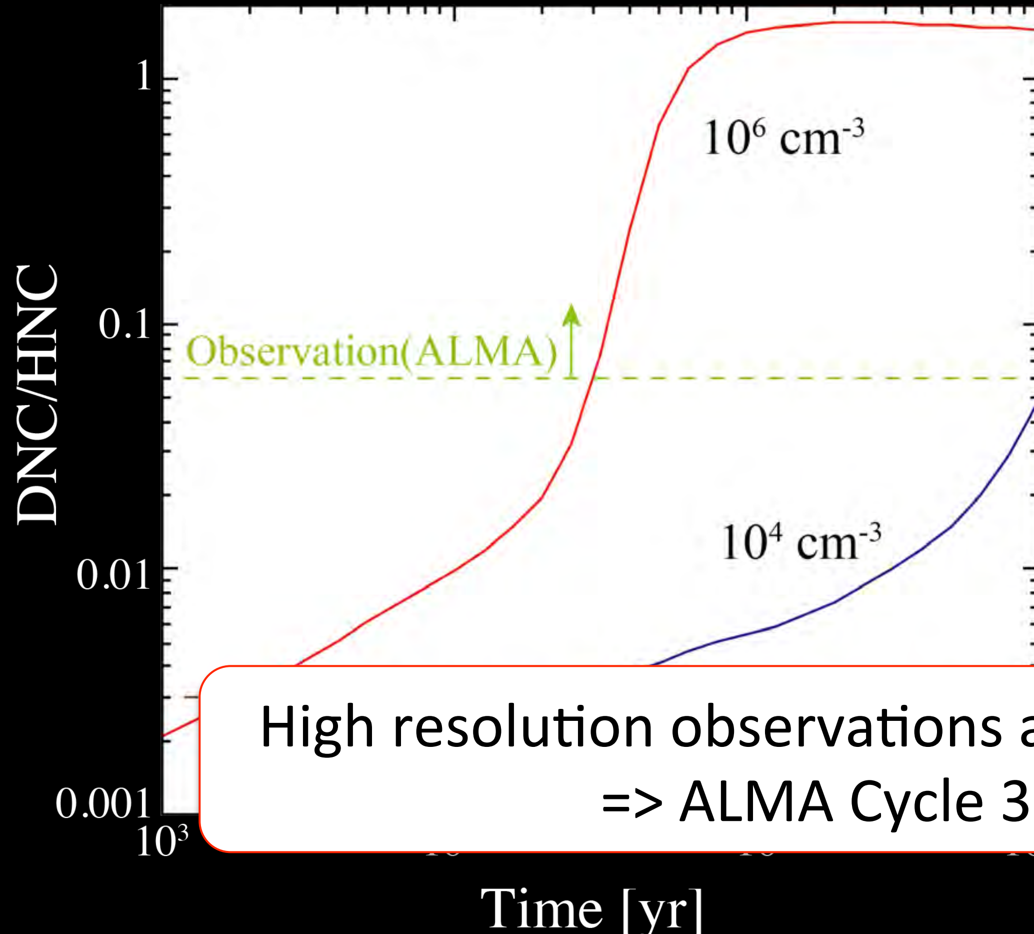
Origin of Diversity of DNC/HNC



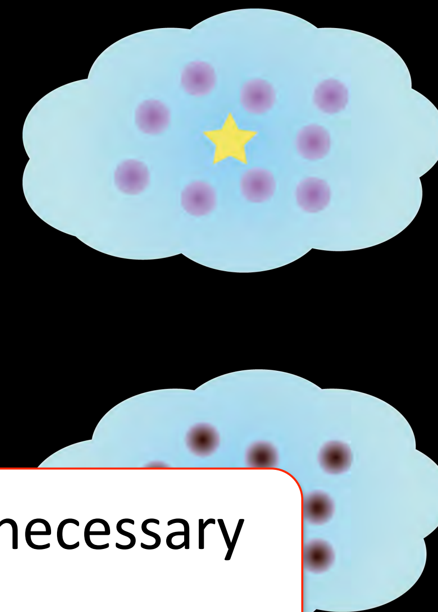
Filling factor of dense regions



Origin of Diversity of DNC/HNC



Timescale of
cold phase

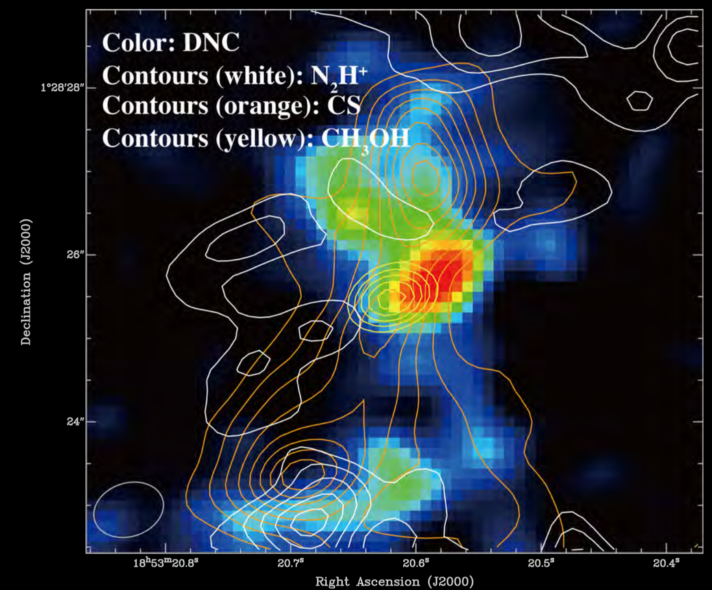


High resolution observations are necessary
=> ALMA Cycle 3

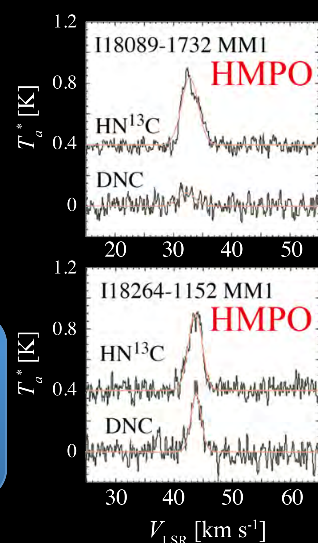
- In any cases, different DNC/HNC ratio suggests different history of the cluster formation.

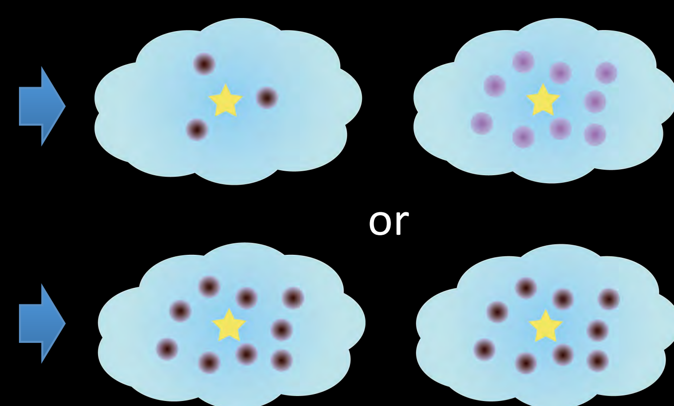
Summary

- DNC/HNC
  - can be high in warm regions.
  - depends on density.
    - Multi-transition line observations
      -> ALMA Band 2 (70 GHz-band)



- Diversity of DNC/HNC
  - Diversity of cluster formation?



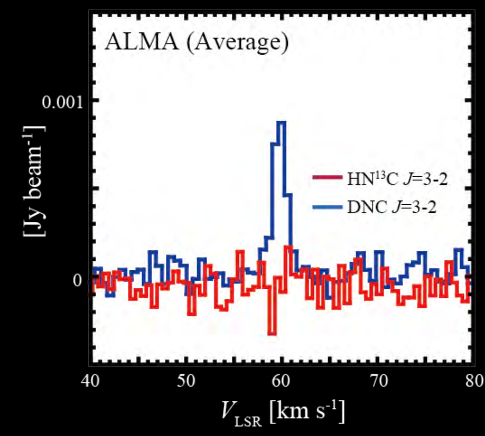


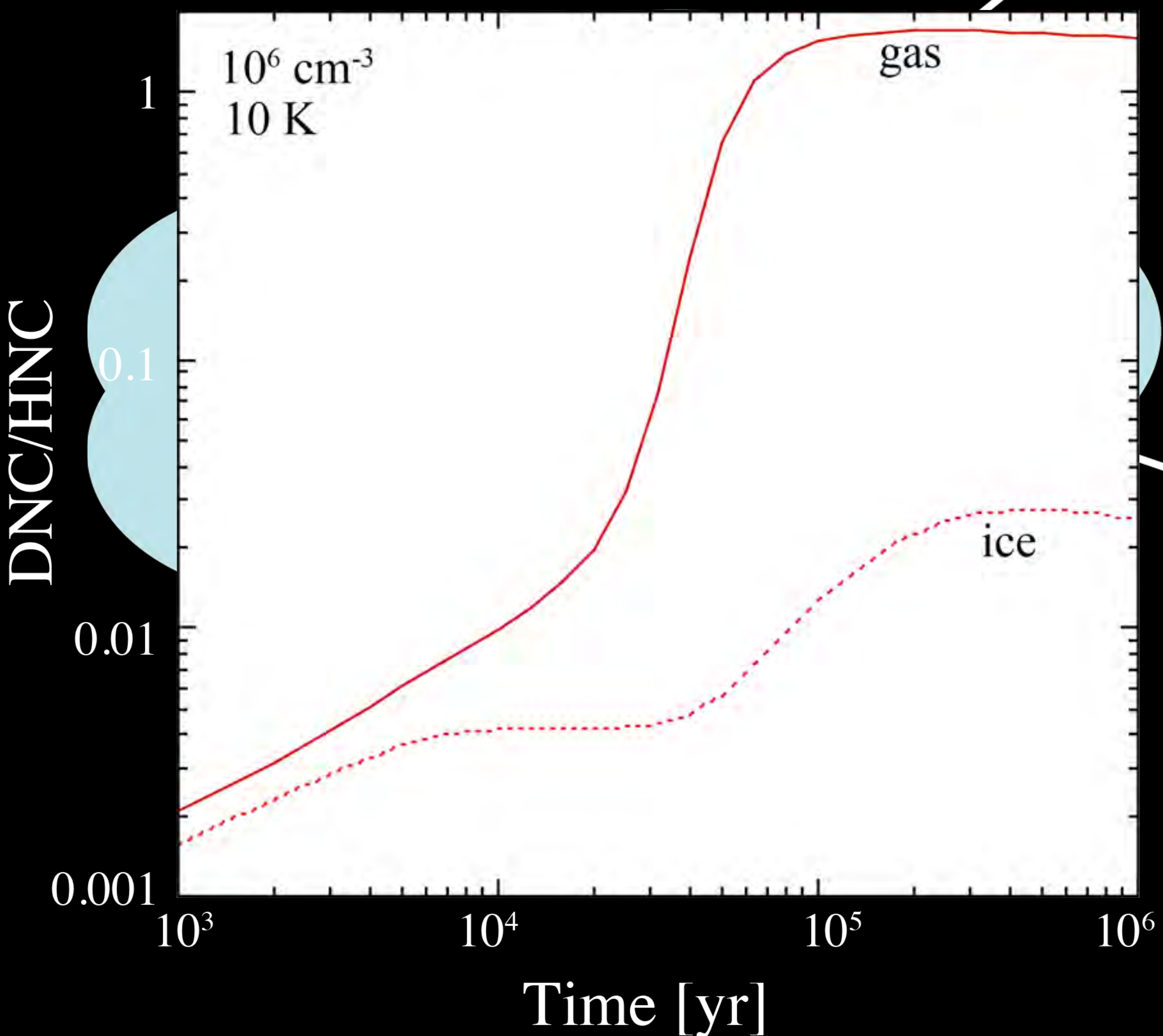
High resolution observations are crucial.

Sakai et al. 2015, ApJ, accepted

Summary: DNC/HNC in G34.43+00.24 MM3

High Density Regions (~$10^{6\text{-}7}$ cm^{-3})
DNC/HNC (>0.03)

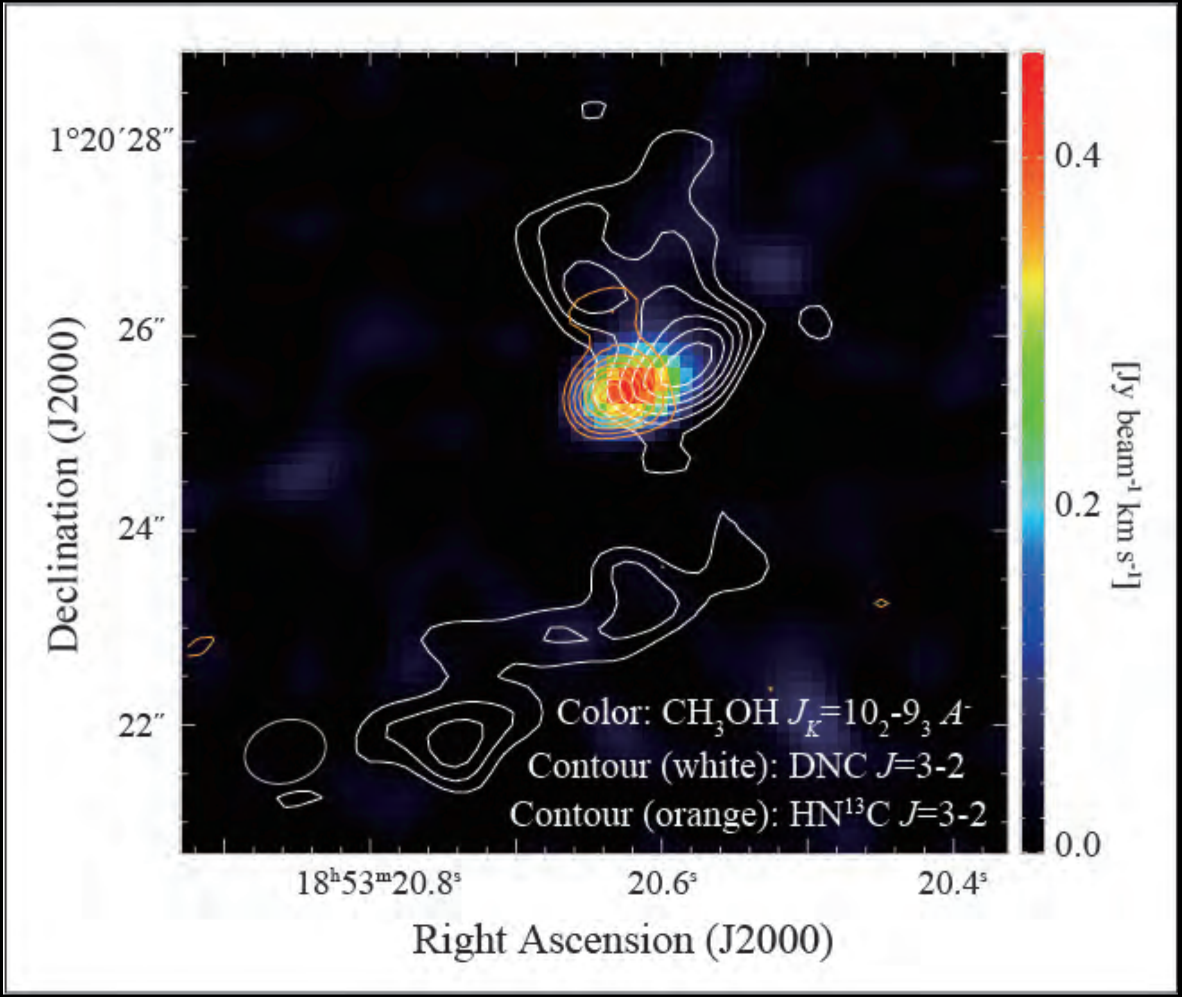




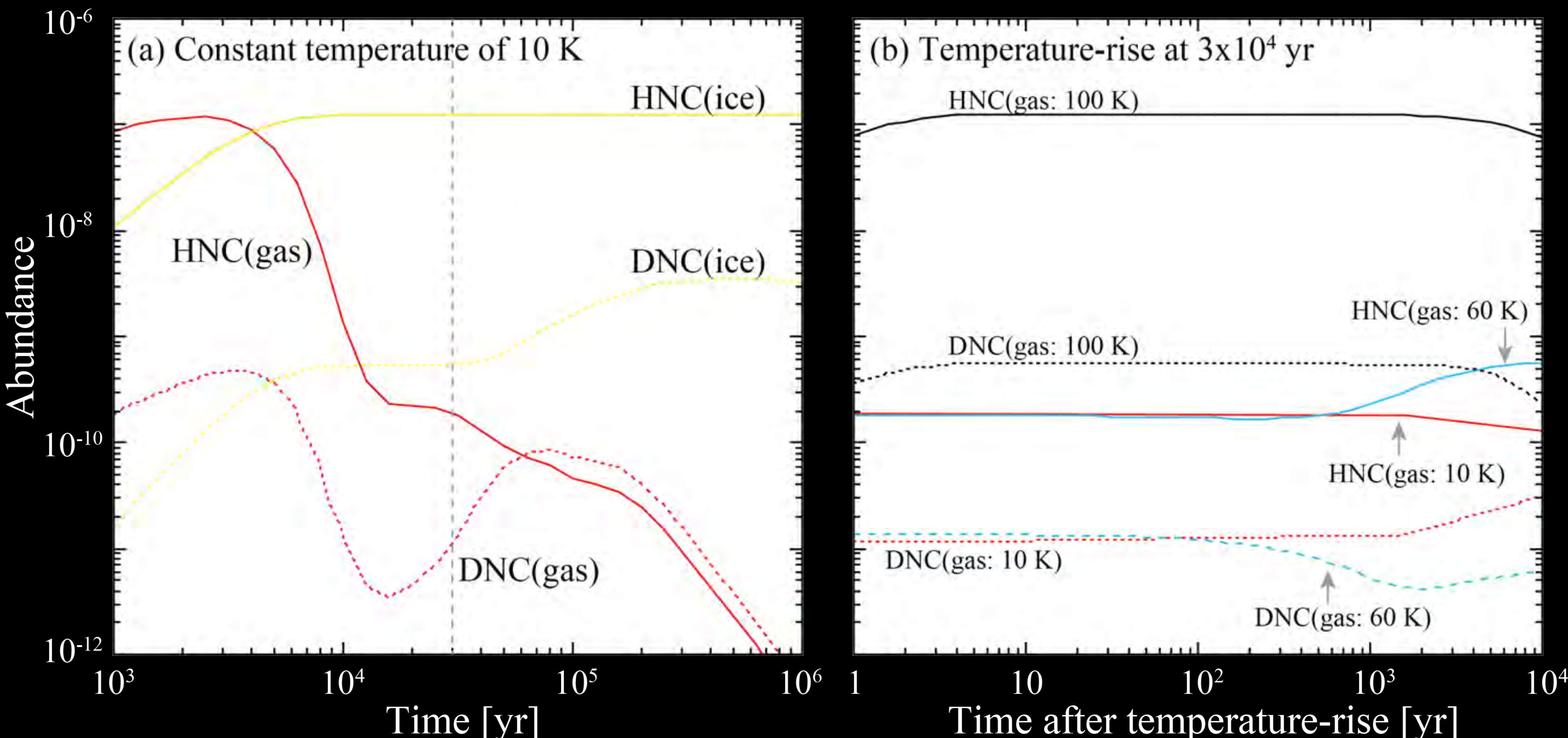
Hot Core
DNC/HNC (0.001-0.004)

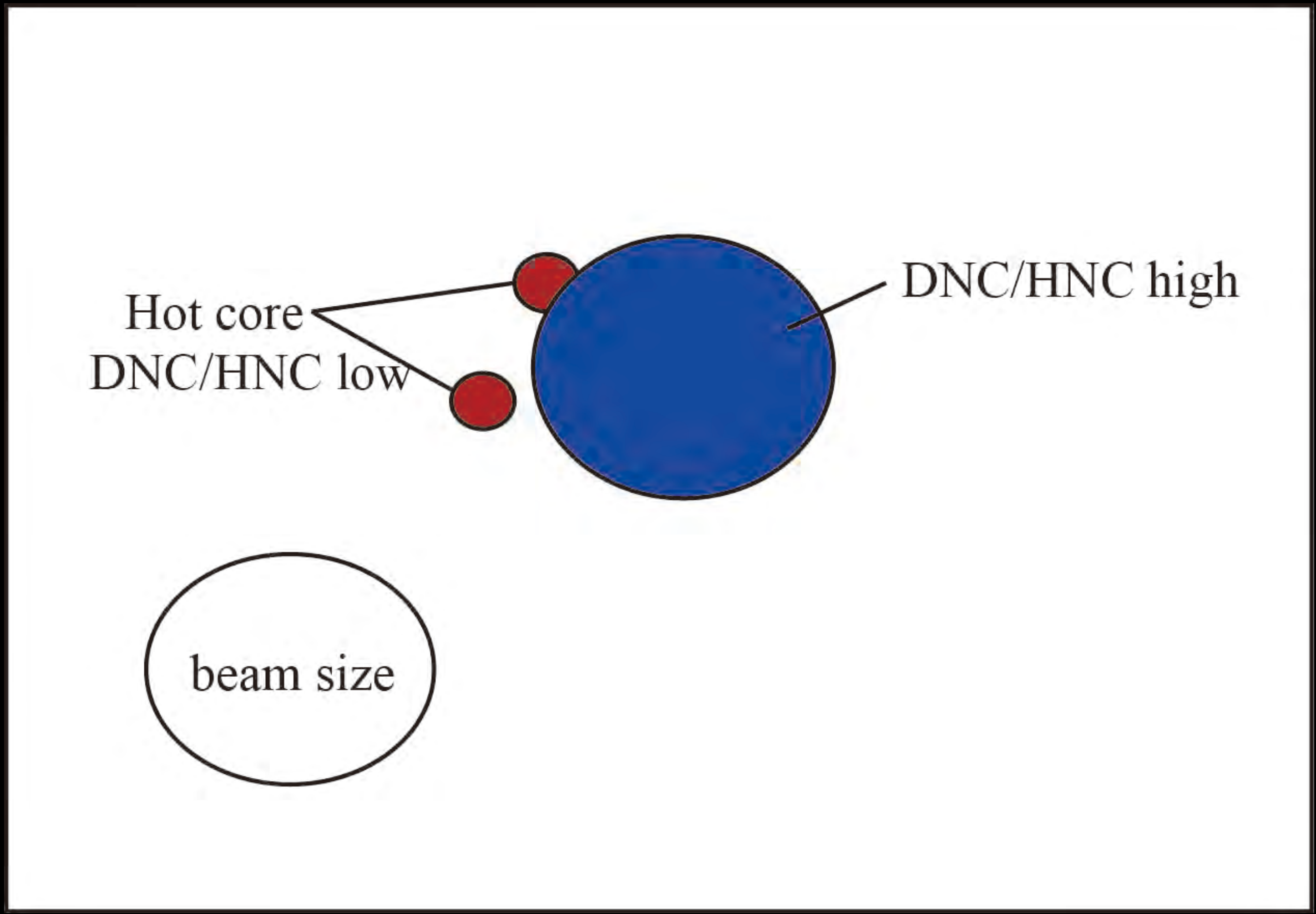
DNC/HNC toward the Hot Core

- $HN^{13}C$
  - Hot core (> 90 K)
- DNC
  - Offset from the hot core



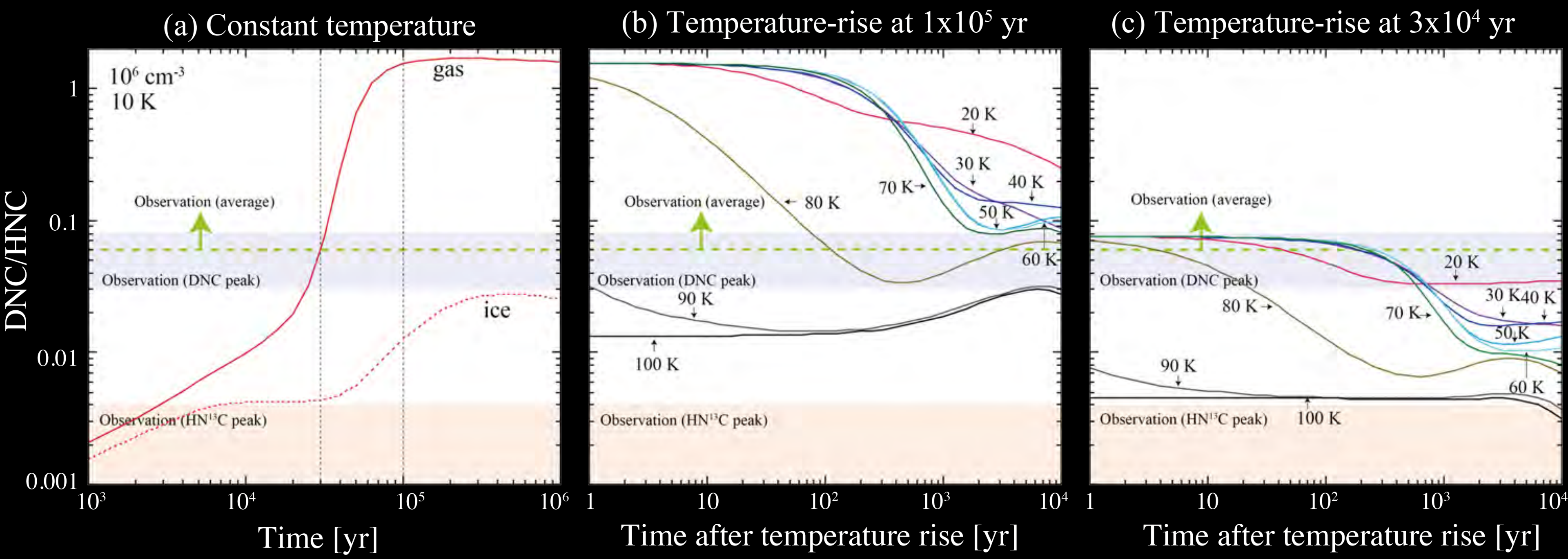
Chemical Model Calculations



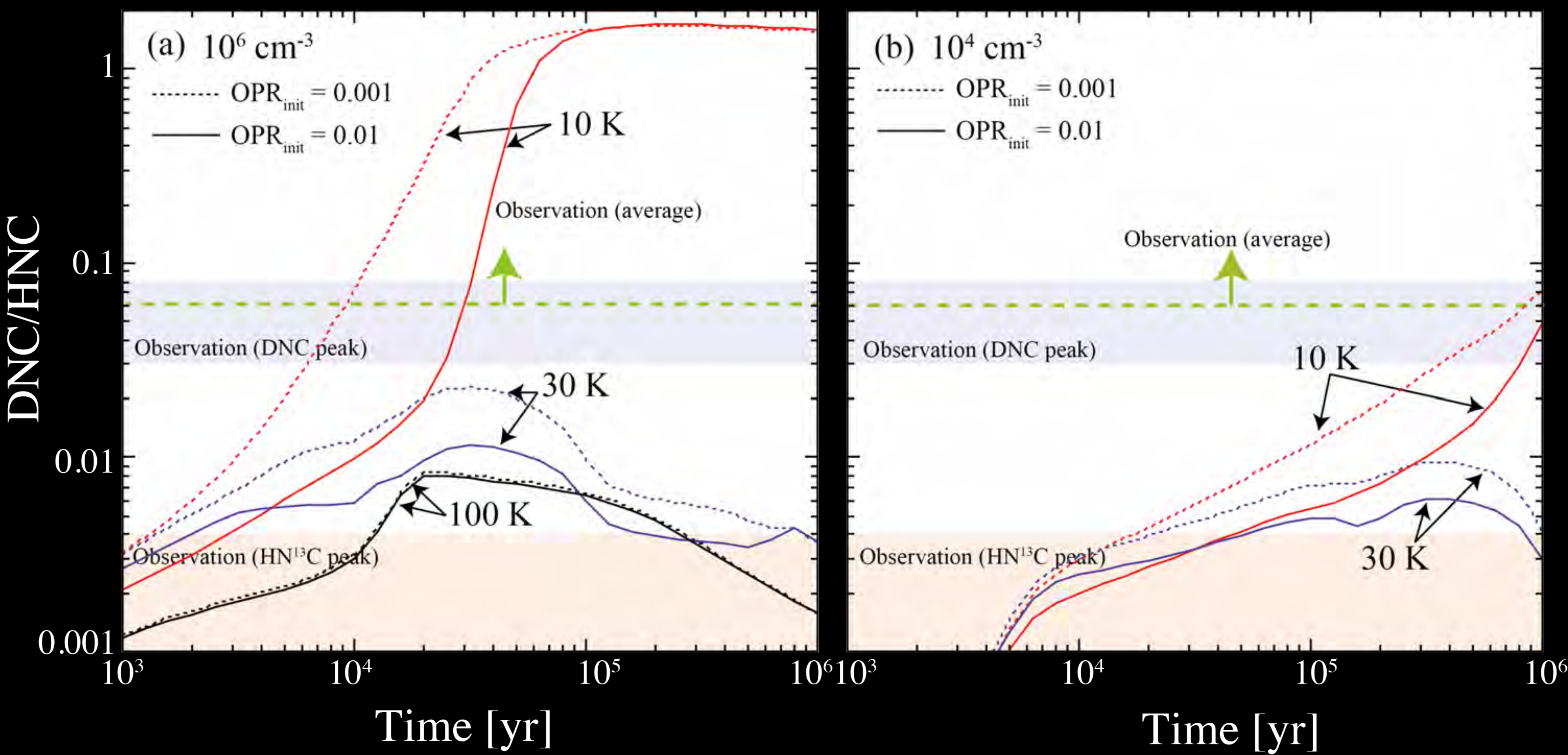

Hot core
DNC/HNC low
DNC/HNC high
beam size

Chemical Model Calculations

- Temperature rises from 10 K to a given temperature at a given time.



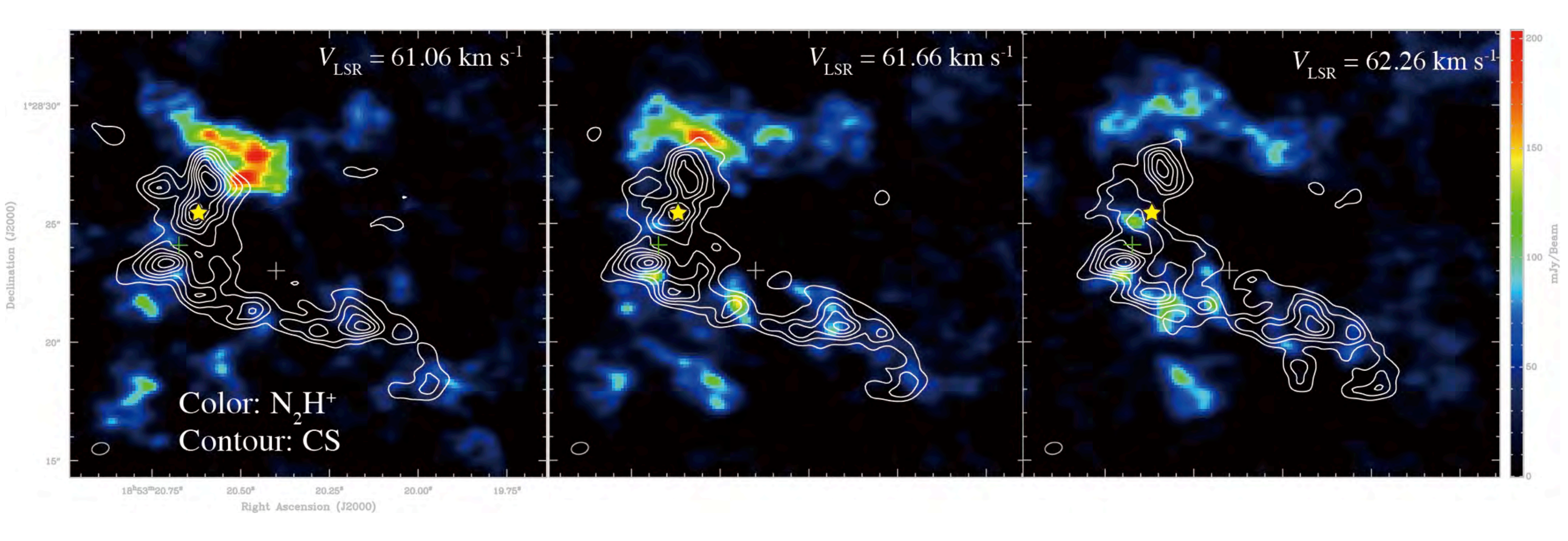
o/p ratio



(a) 10^6 cm^-3
OPR_init = 0.001
OPR_init = 0.01
10 K
Observation (average)
Observation (DNC peak)
30 K
100 K
Observation (HN^13C peak)
(b) 10^4 cm^-3
OPR_init = 0.001
OPR_init = 0.01
Observation (average)
Observation (DNC peak)
10 K
30 K
Observation (HN^13C peak)
DNC/HNC
1
0.1
0.01
0.001
10^3
10^4
10^5
10^6
Time [yr]
Time [yr]

Interaction between the Outflow and Ambient Gas

- Channel maps of N_2H^+ J=3-2 and CS J=5-4

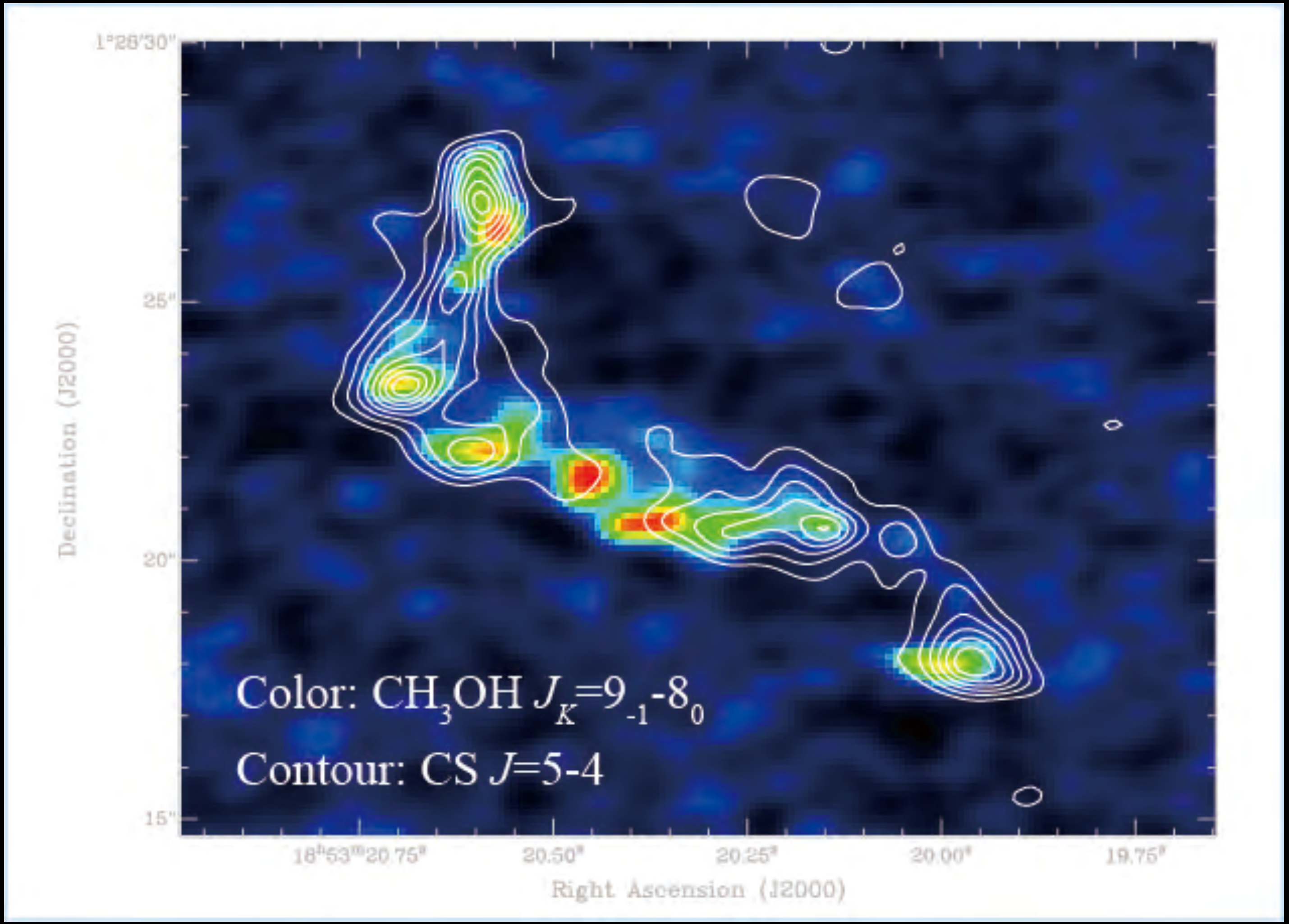


- The outflow is penetrating into cold gas
- The outflow should be very young.

278 GHz Class I Methanol Masers

(Yanagida, Sakai, Hirota et al. 2014, ApJL)

- CH_3OH J_K=9_{-1}-8_0: shock excited maser



Results: Keck