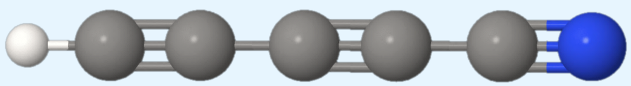
Formation Mechanisms of Cyanopolyynes and Chemical Evolution in the High-Mass Star-Forming Regions



$HC_{2n+1}N$ (n = 1,2,3,..)

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Fumitaka Nakamura (NAOJ), Yusuke Miyamoto, Tetsuhiro Minamidani,
Hiroyuki Kaneko (NRO), T. K. Sridharan (CfA),

Kazuhito Dobashi, Tomomi Shimoikura (Tokyo Gakugei Univ.)

Self Introduction

B.S. Department of Environmental Science, Faculty of Science, Toho University
(Supervisor; Hiroyuki Ozeki) 2013 Mar
"Laboratory spectroscopy, Spectroscopic identification of CH_2IBr"

M.S. Department of Environmental Science, Faculty of Science, Toho University
/Nobeyama Radio Observatory 2015 Mar
"Observations of the ^{13}C isotopologues of HC_5N"

2015 Apr. – present SOKENDAI/Nobeyama Radio Observatory
(Supervisors; Masao Saito, Tomoya Hirota)
2017 Apr. - JSPS Fellowship (DC2)

Research Interest : Astrochemistry, Star/Planet Formation

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1. Introduction
   - ✧ Massive Star Formation Process
   - ✧ Astrochemistry & Carbon-Chain Chemistry in Low-Mass Star-Forming Regions
   - ✧ Chemistry in High-Mass Star-Forming Regions
2. Motivation of This Dissertation
3. Observations, Results & Discussions
   - ✧ Long Cyanopolyynes around MYSOs
   - ✧ Formation Mechanism of Cyanopolyynes in G28.28-0.36
   - ✧ Chemical Evolution in the High-Mass Star-Forming Regions
4. Summary

Publications Related to Dissertation

1. K. Taniguchi, H. Ozeki, M. Saito *et al.*, *ApJ*, **817**, 147 (2016)
2. K. Taniguchi, M. Saito, & H. Ozeki, *ApJ*, **830**, 106 (2016)
3. K. Taniguchi, M. Saito, T. Hirota, *et al.*, *ApJ*, **844**, 68 (2017)
4. K. Taniguchi, H. Ozeki, & M. Saito, *ApJ*, **846**, 46 (2017)
5. K. Taniguchi & M. Saito, *PASJ*, **69**, L7 (2017)
6. K. Taniguchi, M. Saito, T. K. Sridharan, & T. Minamidani, accepted by *ApJ*

2 papers are under preparation.

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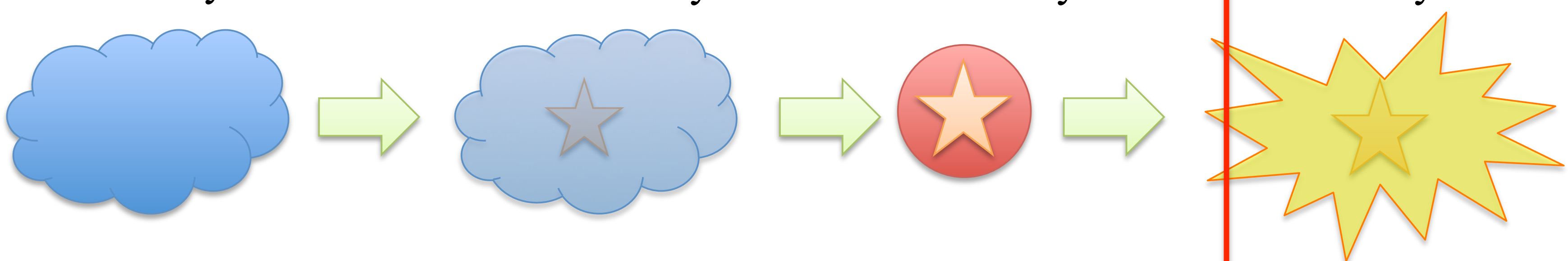
Massive Star Formation Process

overlapped

High-Mass Starless Core (HMSC)	High-Mass Protostellar Object (HMPO)	Hot Core	Ultracompact HII region (UCHII)
$n \sim 10^4$-10^5 cm^{-3}, $T \sim 15$ K	$n \sim 10^6$ cm^{-3}, $T \sim 50$ K	$n > 10^7$ cm^{-3}, $T > 100$ K, 0.1 pc	$n \sim 10^4$ cm^{-3}, $T \sim 100$ - 200 K
Without 8.3 μm emission, With 1.2 mm emission	With 8.3 μm emission, Without 3.6 cm emission	6.7 GHz CH_3OH maser	With cm emission
$\sim 10^4$ yr	$\sim 6 \times 10^4$ yr	$\sim 4 \times 10^4$ yr	$\sim 10^4$ yr



Gerner et al. (2014)

Still poorly understood due to observational difficulties
(far, small sample, born in cluster)

Astrochemistry & Carbon-Chain Molecules

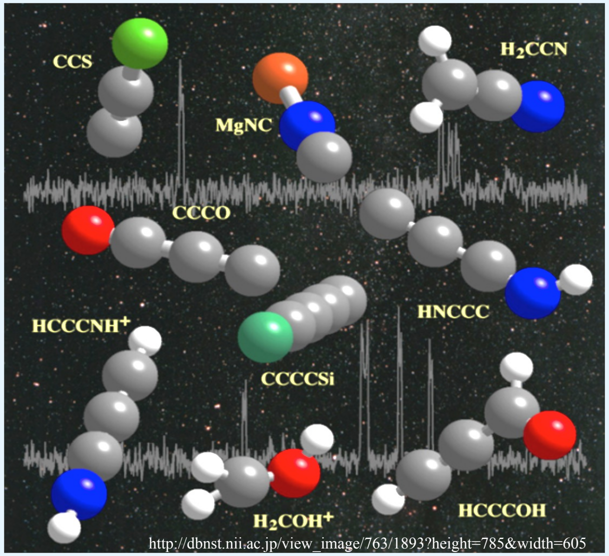
Chemical composition : a good diagnostic tool for
physical conditions & evolutionary stages

Carbon : Contained in ~75% molecules detected in the Universe

Carbon-chain molecules :

✓ ~ 40% of 200 interstellar molecules

✓ Provide useful information about star formation process from the foremost stage (e.g., chemical evolution)



Carbon-chain molecules
= Important for star formation

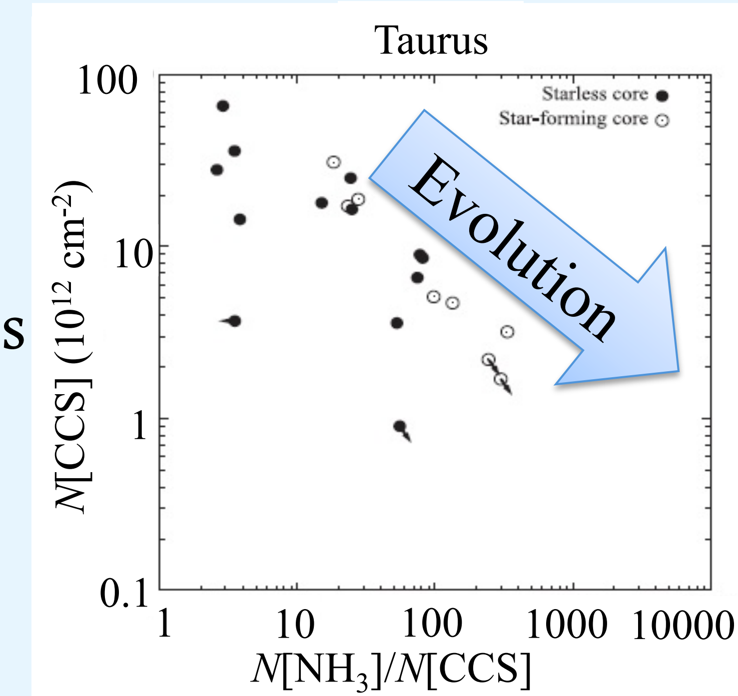
Confirmed only in low-mass star-forming regions

The Carbon-Chain Chemistry in Low-Mass Star-Forming Regions (SFRs)

1. Chemical Evolutional Indicator
(e.g., Suzuki et al., 1992, Hirota et al., 2009)

- Abundant in young starless cores
- Deficient in evolved star-forming cores

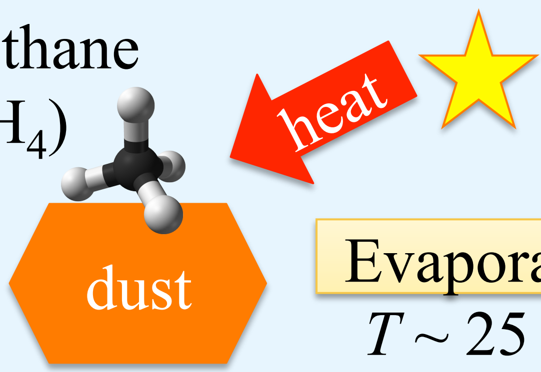
They are formed by the gas-phase ion-molecule reactions containing C and C^+



T. Hirota *et al*. (2009)

2. Warm Carbon Chain Chemistry
(e.g., L1527; Sakai et al., 2008)

Methane (CH_4)



Evaporation $T \sim 25$ K
(Yamamoto *et al*., 1983)

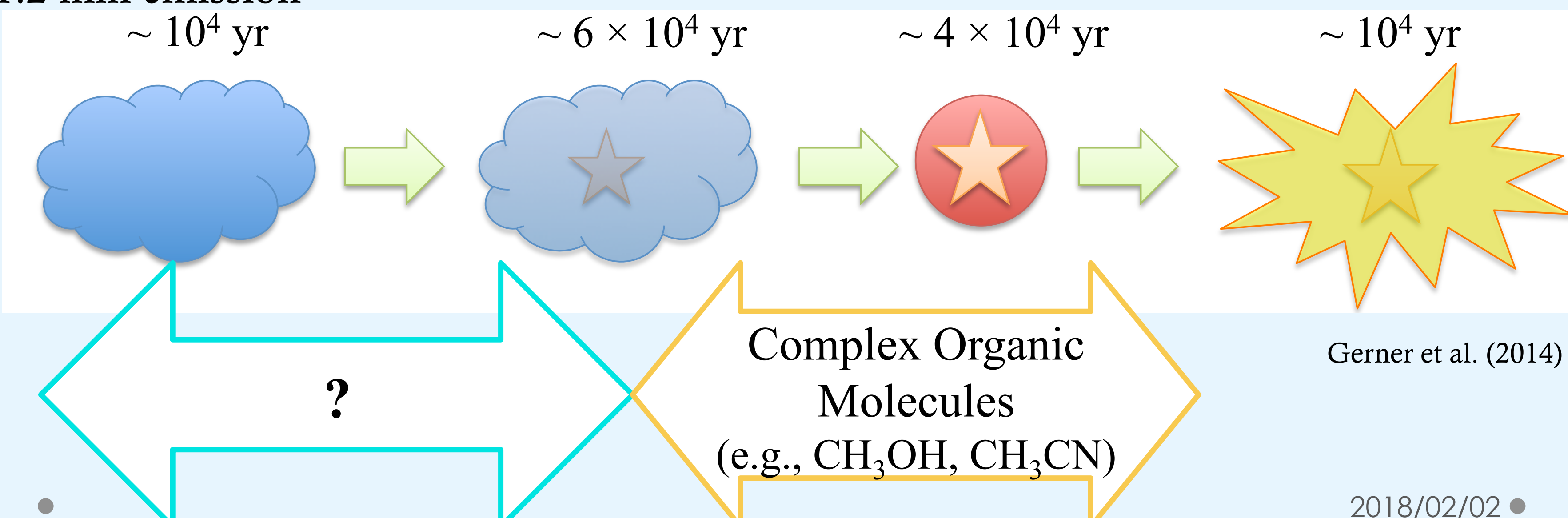
Gas-phase reactions

$CH_4 + C^+$ → Carbon-chain molecules

Chemistry in High-Mass SFRs

overlapped

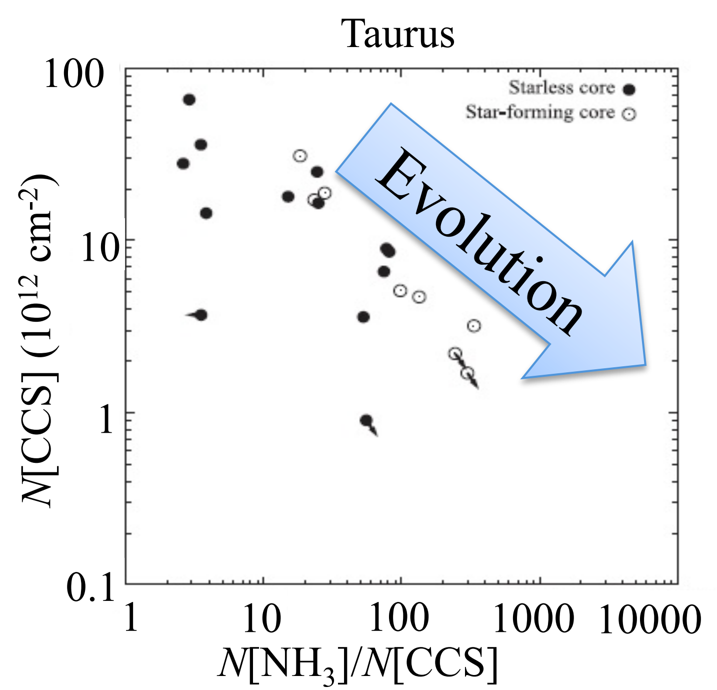
High-Mass Starless Core (HMSC)	High-Mass Protostellar Object (HMPO)	Hot Core	Ultracompact HII region (UCHII)
$n \sim 10^4$-10^5 cm^{-3}, $T \sim 15$ K	$n \sim 10^6$ cm^{-3}, $T \sim 50$ K	$n > 10^7$ cm^{-3}, $T > 100$ K, 0.1 pc	$n \sim 10^4$ cm^{-3}, $T \sim 100$ - 200 K
Without 8.3 μm emission, With 1.2 mm emission	With 8.3 μm emission, Without 3.6 cm emission	6.7 GHz CH_3OH maser	With cm emission



Gerner et al. (2014)

Chemical Evolution in High-Mass Star-Forming Regions

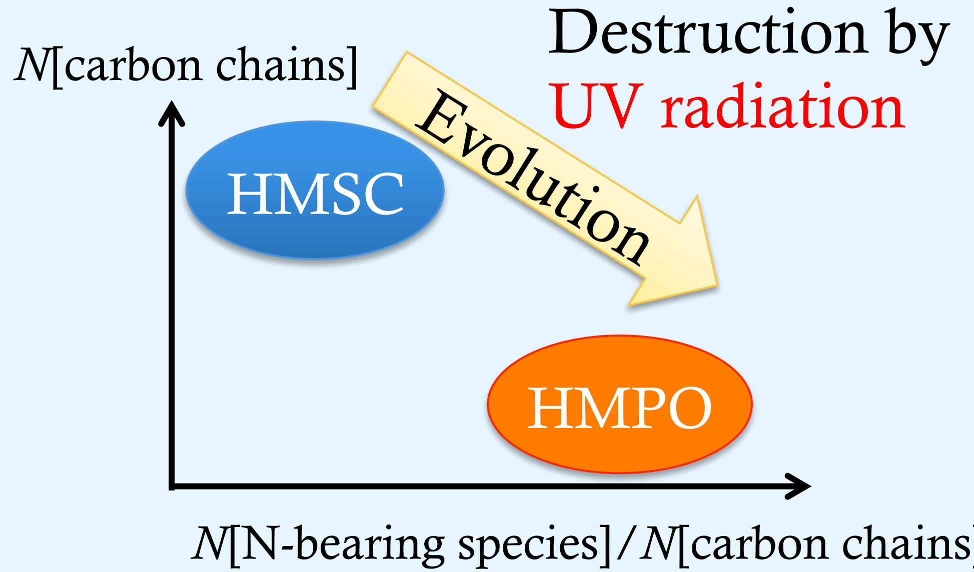
Low-Mass Star-Forming Regions



T. Hirota *et al.* (2009)

How about High-Mass Star-Forming Regions?

Expectation; Similar to that in low-mass star-forming regions



Previous Researches on Cyanopolyynes in Hot Cores

Survey observation of HC_5N (J = 12-11; E_u = 10.0 K)
toward hot cores associated with 6.7 GHz CH_3OH maser

(Green *et al.*, 2014)

Detection Rate = 44% (35/79)
(may be ambient cold gas component)

Beam size = 0.95' (0.7 pc at *d* = 3 kpc)

c.f. Typical hot core size ~ 0.1 pc

➡ Their observations are not enough to confirm that HC_5N exists in hot cores

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Motivation & Goal of This Dissertation

Goal : Understand chemical properties of carbon-chain molecules in the high-mass star-forming regions with evolution

1. Are carbon-chain molecules associated with and/or formed around massive young stellar objects (MYSOs)?
   If they are formed, how are they formed?

Yes: Cyanopolyynes are formed from CH_4/C_2H_2

2. Do carbon-chain molecules have relationship with evolution of massive stars?

Probably Yes: ($N(N_2H^+)/N(HC_3N)$)

Focus on cyanopolyyne series ($HC_{2n+1}N$; n=1,2,3,…)

↑

Survive in the hot gas (T ~ 80 K) (Hassel *et al.*, 2011)

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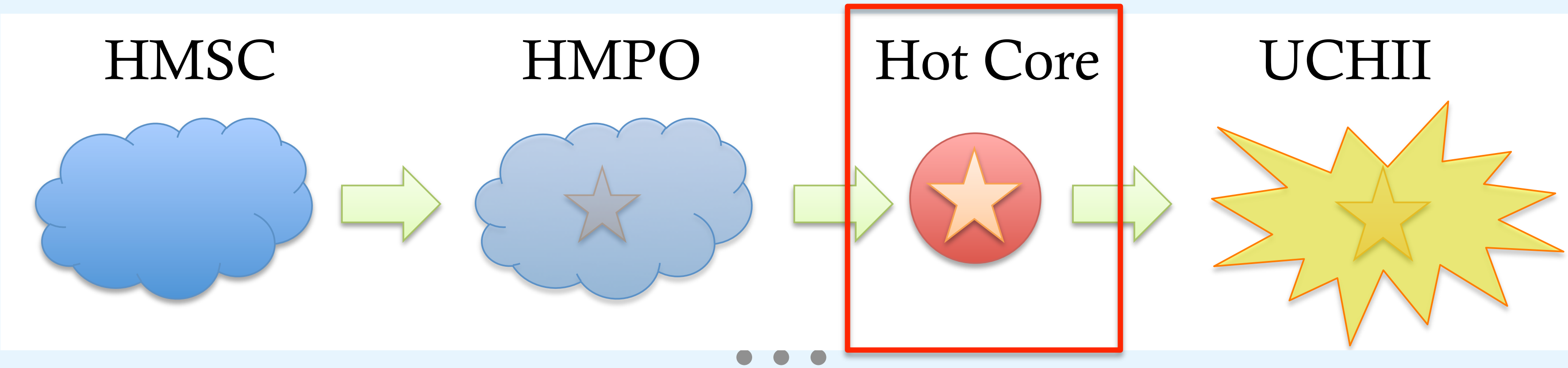
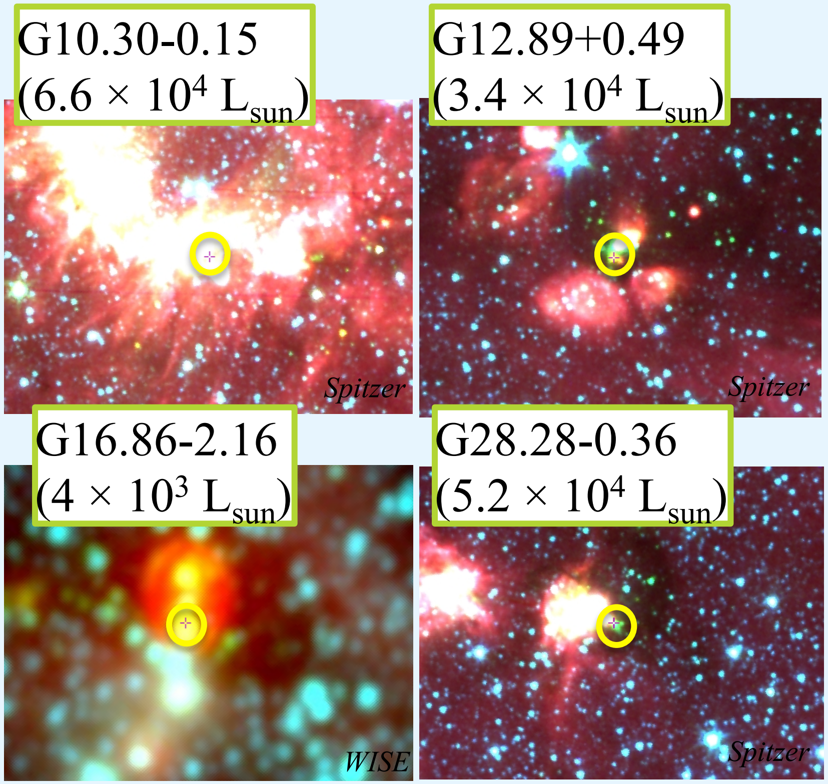
Long Cyanopolyynes around Massive Young Stellar Objects

Clear whether long cyanopolyynes exist in the warm gas around MYSOs



- ✓ Confirm warm component of HC_5N
- ✓ Detection of HC_7N
- ✓ A possibility of the chemical differentiation among MYSOs

Observational Details



Source Selection

Selected from HC_5N-detected source list by Green et al. (2014) applying the following criteria:

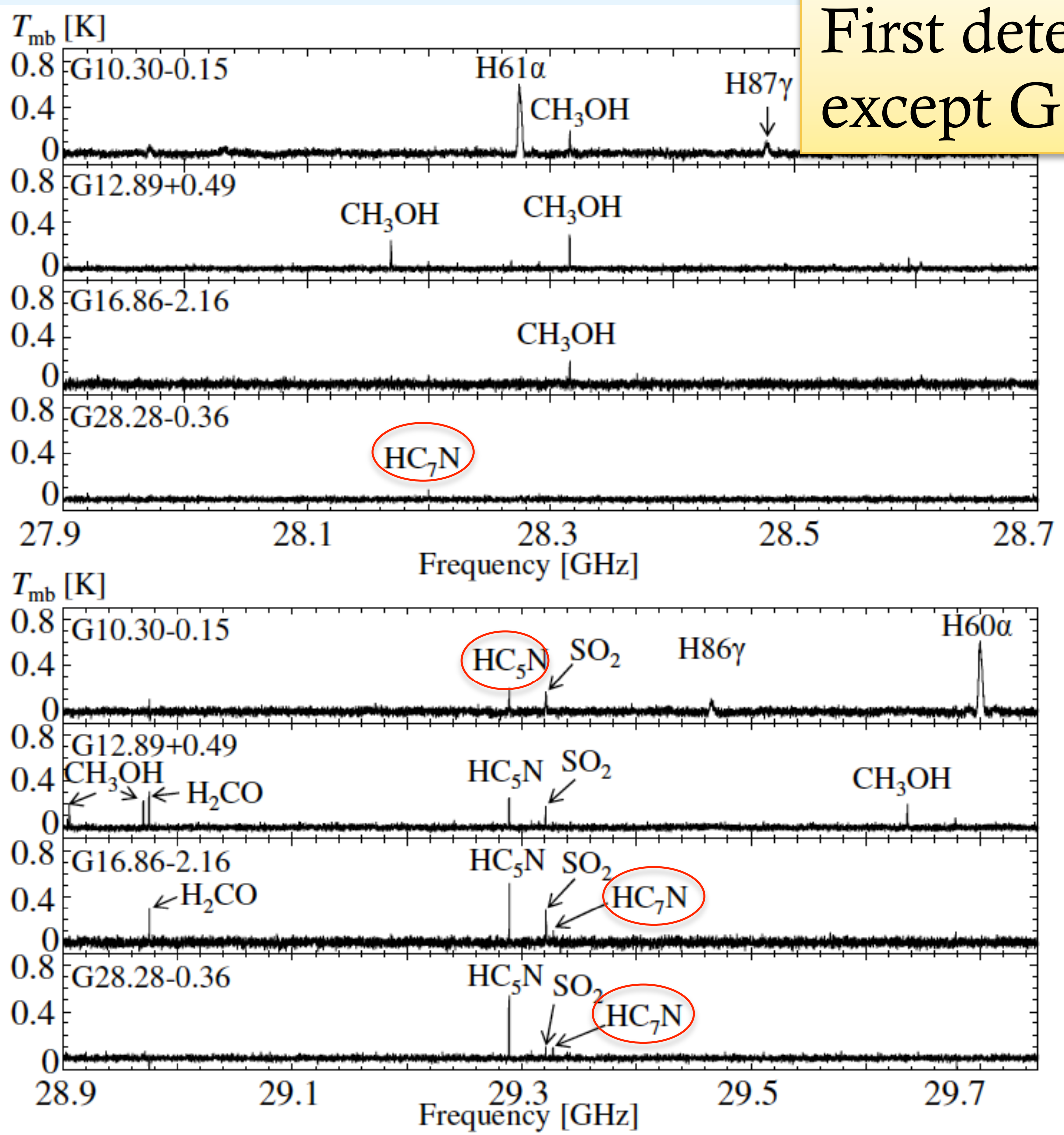
1. Decl. > -21°
2. D < 3 kpc
3. CH_3CN (hot core tracer) was detected (Purcell et al., 2006)

In order to detect HC_7N, observations in the 27-29 GHz is suitable

→ GBT

In order to derive T_{rot} of HC_5N accurately, we need data with a wide frequency range → NRO

Spectra Obtained with the GBT

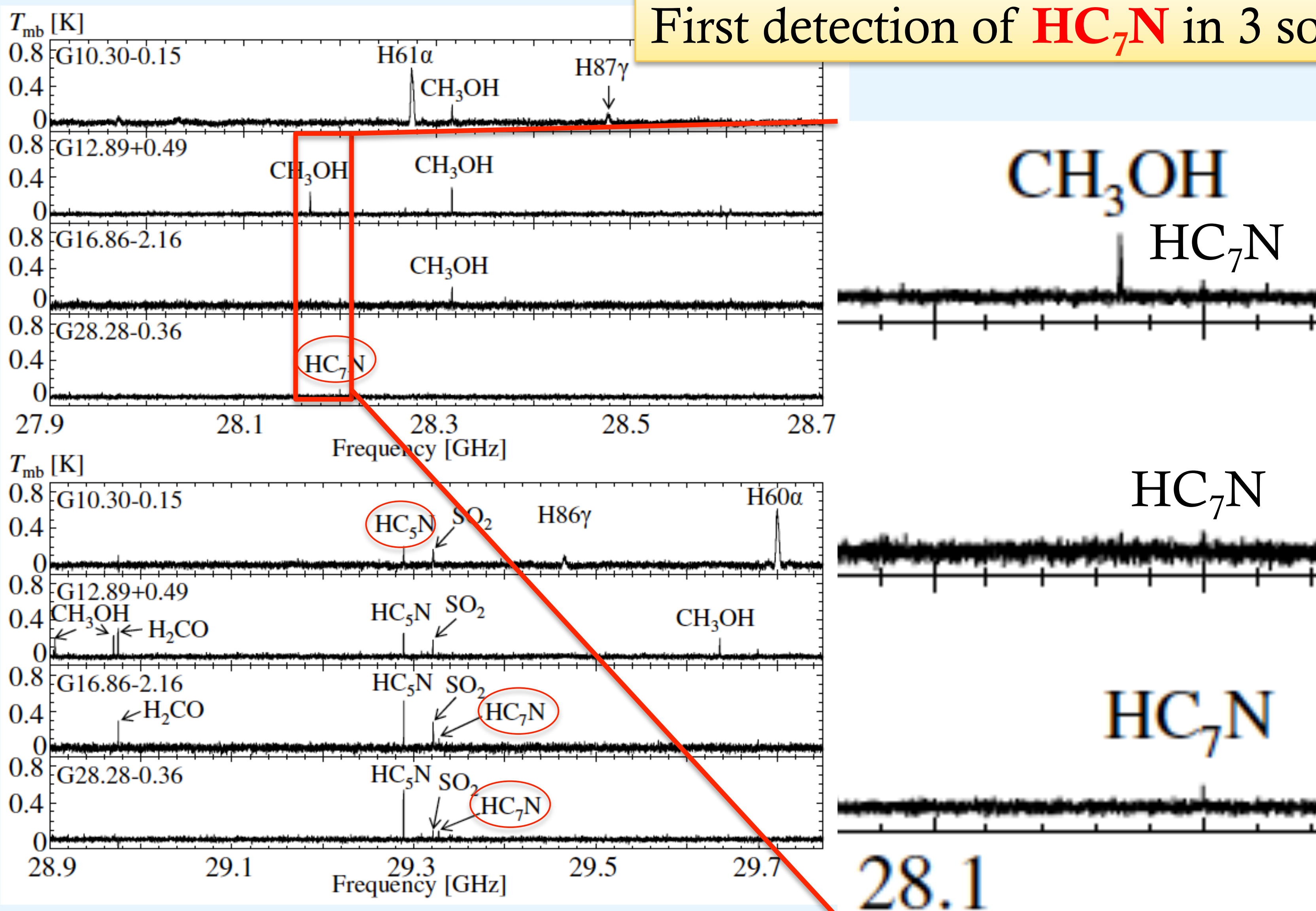


First detection of **HC_7N** in 3 sources, except G10.30-0.15

Rich in long cyanopolyynes

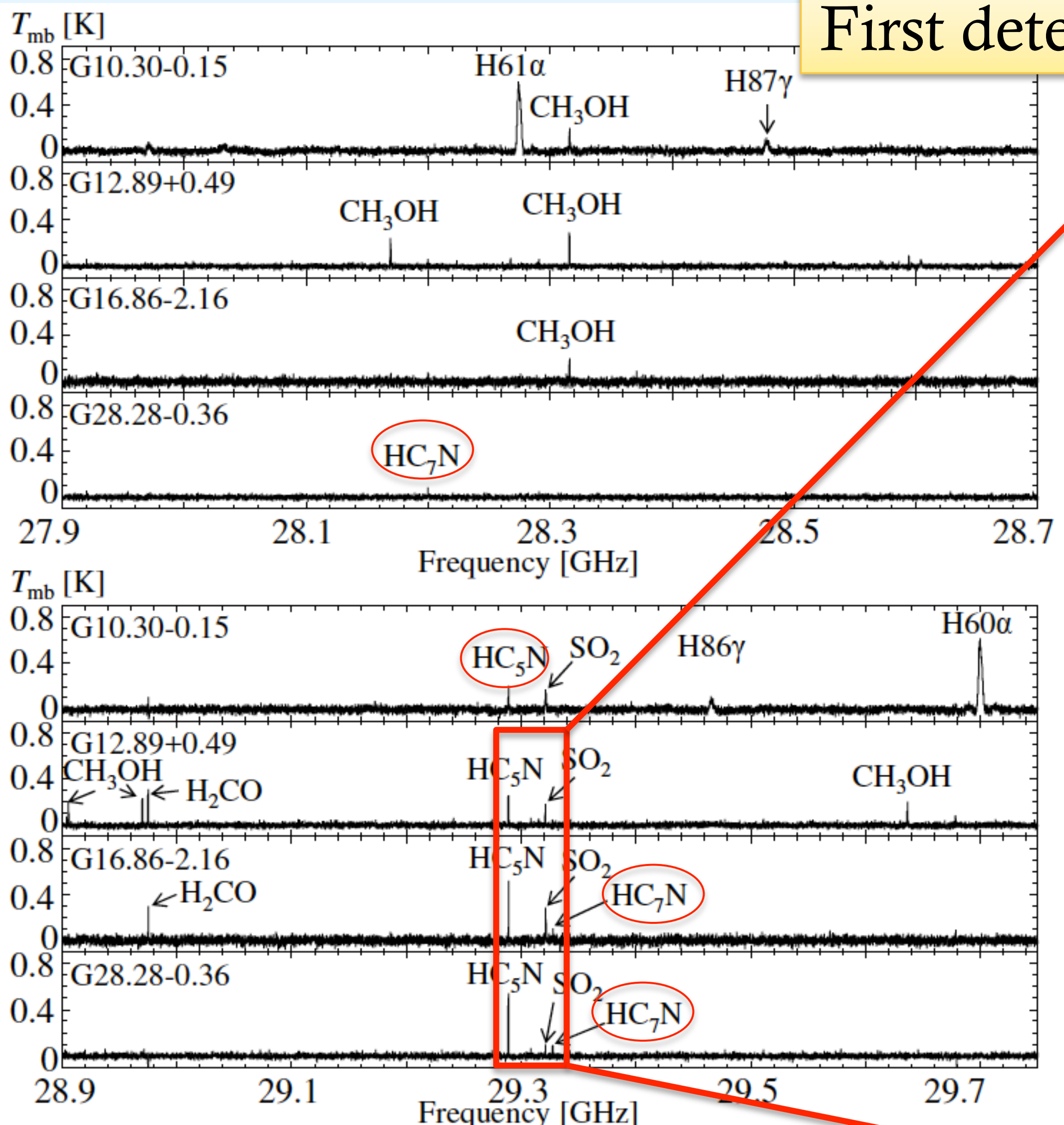
Spectra Obtained with the GBT

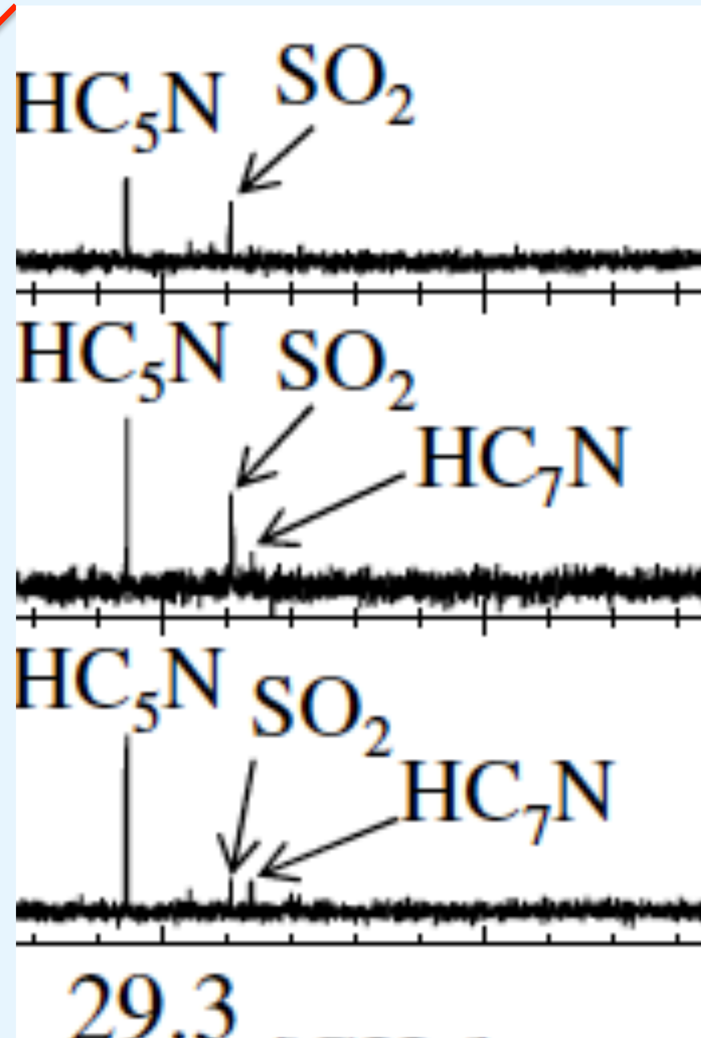
First detection of **HC_7N** in 3 sources



Spectra Obtained with the GBT

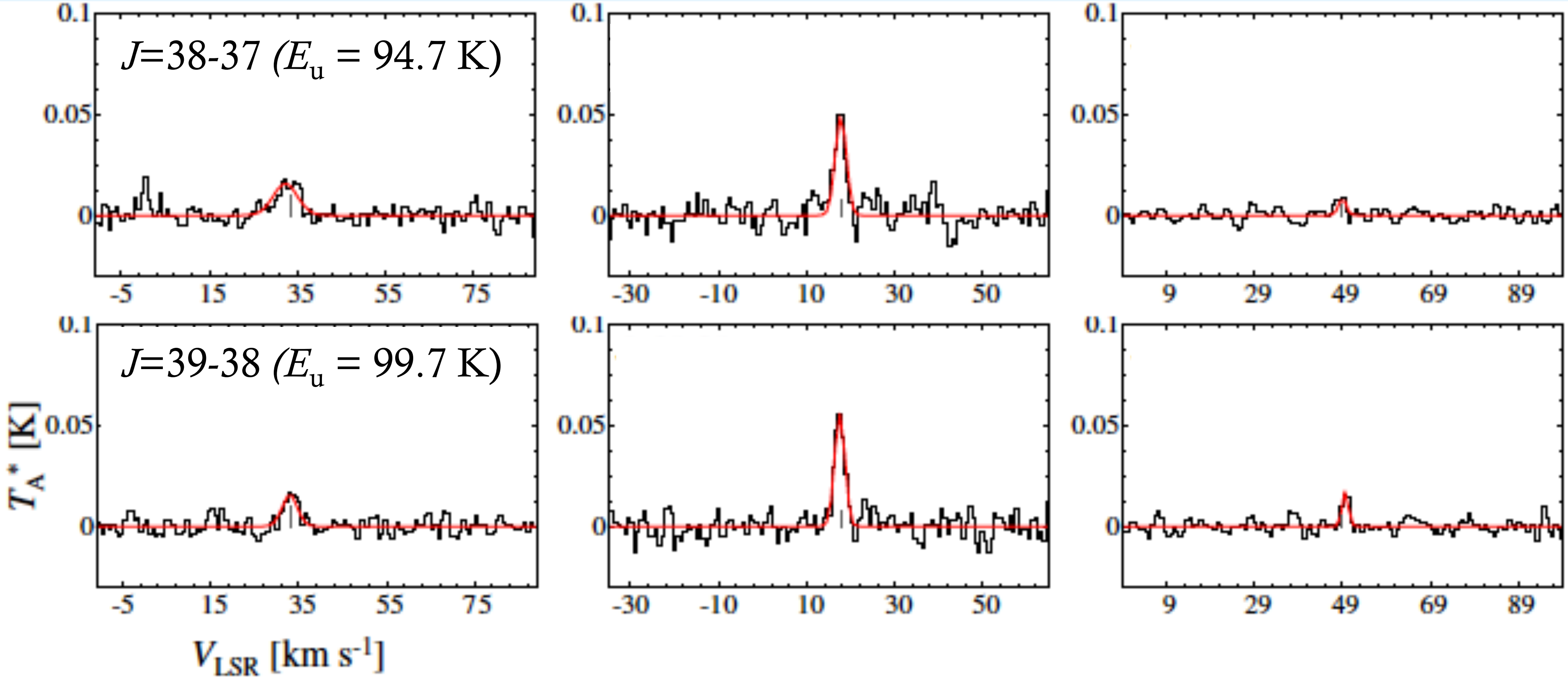
First detection of **HC_7N** in 3 sources





Spectra of HC_5N with the Nobeyama

G12.89+0.49 G16.86-2.16 G28.28-0.36



T_{rot} > 16 K (18 ± 2 K)

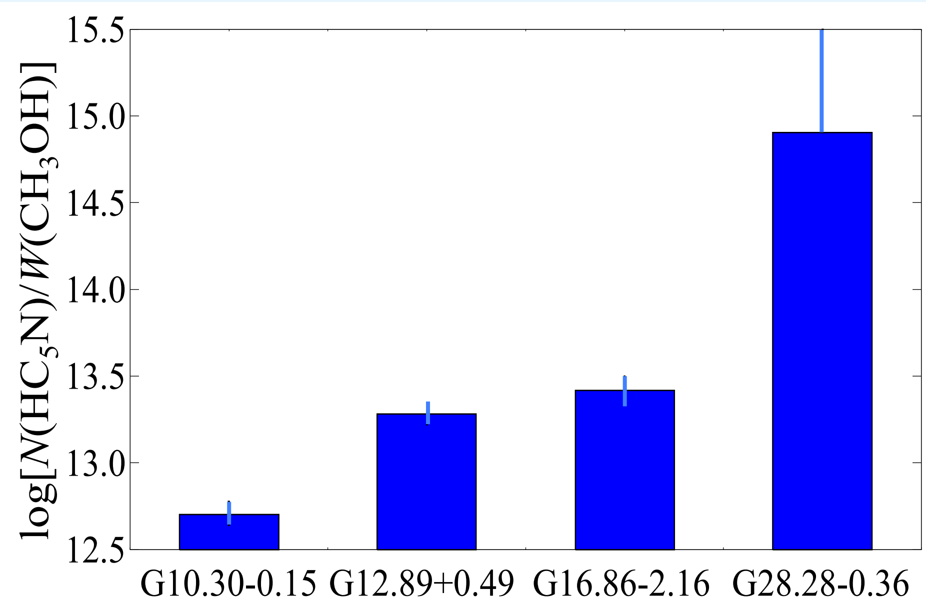
T_{rot} > 15 K (17 ± 2 K)

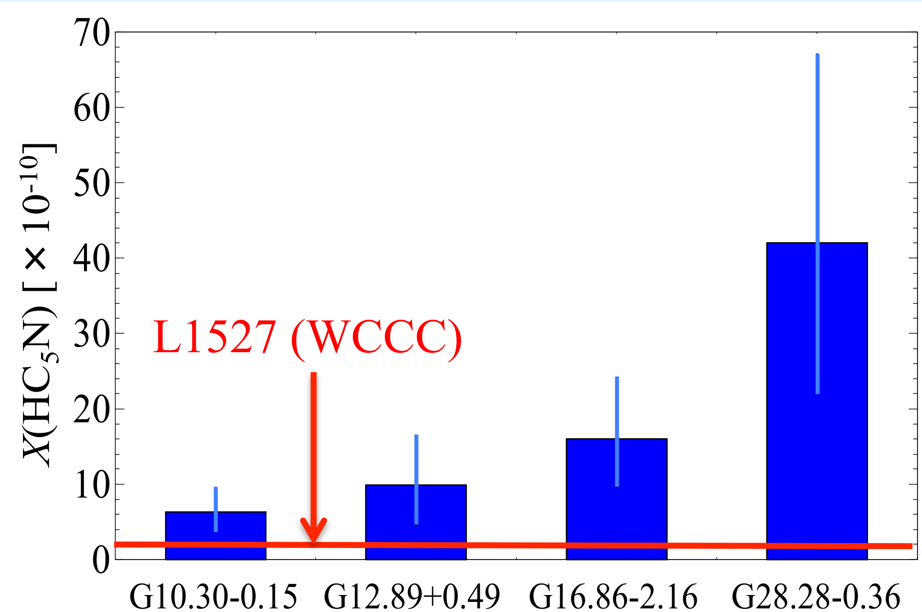
T_{rot} > 12 K (13.8 ± 1.5 K)

c.f. Typical T_{rot}
Dark cloud; 5-8 K (Suzuki et al., 1992)
WCCC; 12-15 K (Sakai et al., 2008)

Warm component of HC_5N

Chemical Differentiation among High-Mass Star-Forming Cores

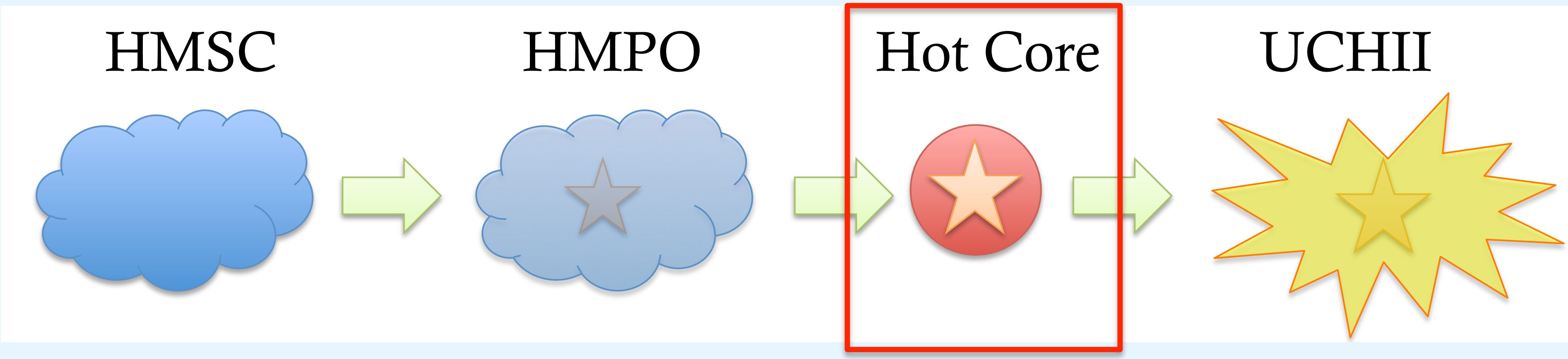




Chemical differentiation among four target MYSOs

Carbon-chain molecules are efficiently formed around MYSOs

Summary of This Subsection

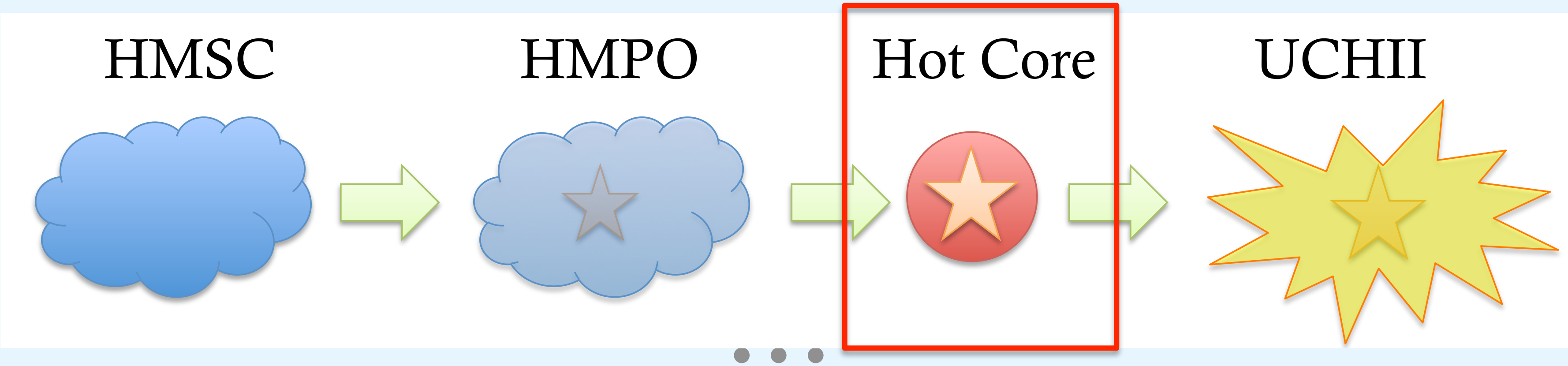


HC_5N exists in the warm gas around MYSOs abundantly

Are carbon-chain molecules formed at the hot core position?

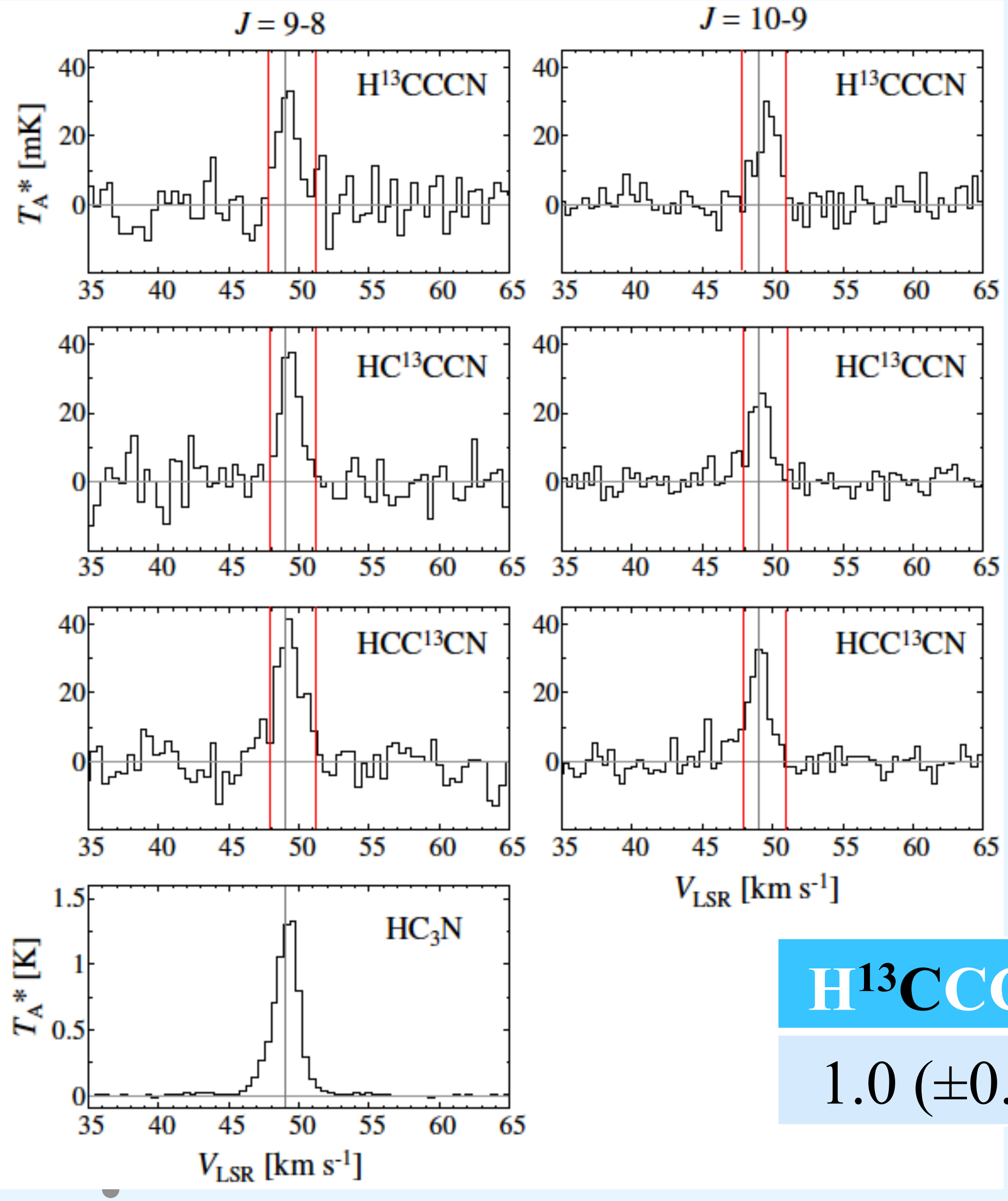
Formation Mechanism of Cyanopolyynes in G28.28-0.36

Investigate possible triggers of cyanopolyyne formation in this hot core



- ✓ Determination of main formation mechanism of HC_3N from its ^{13}C isotopic fractionation
- ✓ Spatial distributions of cyanopolyynes

Spectra of ^{13}C Isotopologues of HC_3N with the Nobeyama



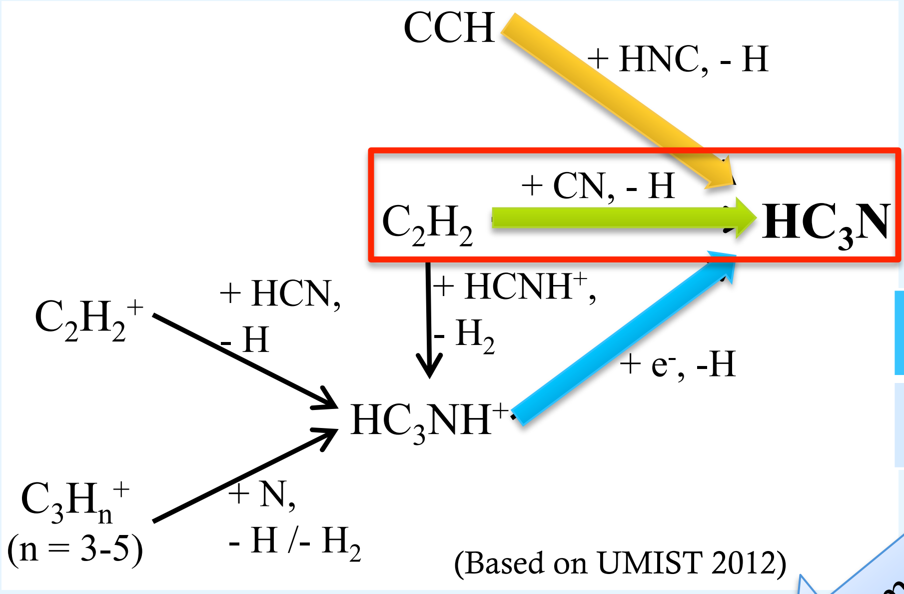
J = 9-8 in the 82 GHz band (E_u = 19.6 K)

J = 10-9 in the 91 GHz band (E_u = 24.0 K)

Integrated Intensity Ratios (J = 9-8 transition)

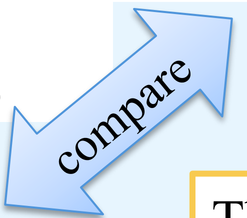
$H^{13}CCCN$	$HC^{13}CCN$	$HCC^{13}CN$
1.0 (±0.2)	1.00	1.47 (±0.17)

Possible Formation Pathways of HC_3N



Observational results

$H^{13}CCCN$	$HC^{13}CCN$	$HCC^{13}CN$
1.0 (±0.2)	1.00	1.47 (±0.17)



Expected fractionation patterns of each formation pathway

The main formation pathway of HC_3N in G28.28-0.36 is "C_2H_2 + CN"

Pathway 1 CCH + HNC
$[H^{13}CCCN]:[HC^{13}CCN]:[HCC^{13}CN]$ = **x : 1 : y** x > 1

Pathway 2 C_2H_2 + CN
$[H^{13}CCCN]:[HC^{13}CCN]:[HCC^{13}CN]$ = **1 : 1 : z**

Pathway 3 HC_3NH^+ + e
$[H^{13}CCCN]:[HC^{13}CCN]:[HCC^{13}CN]$ ~ **1 : 1 : 1**

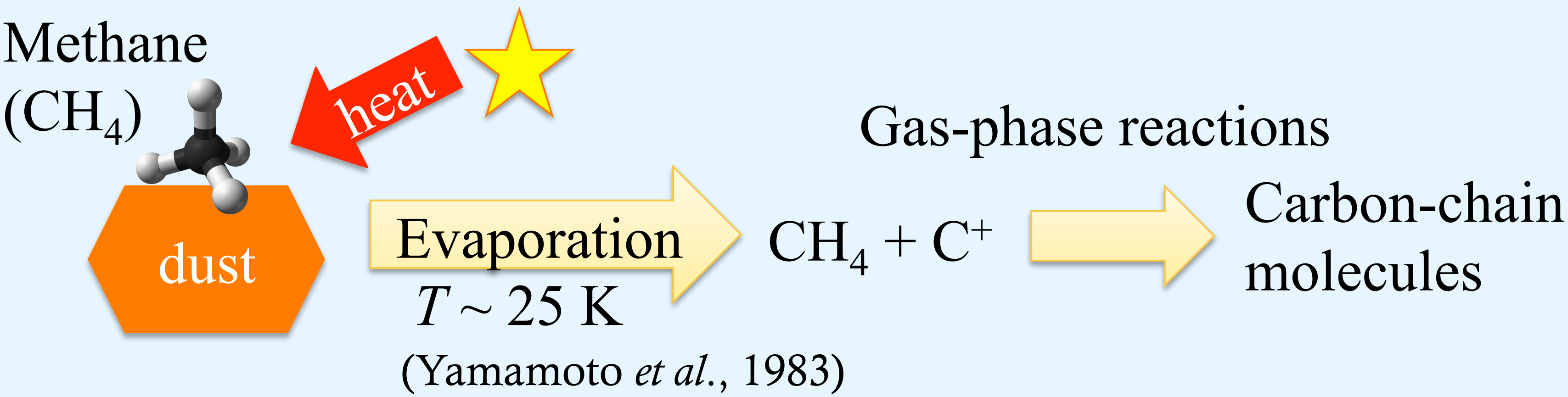
Comparisons with 450 μm Warm Dust Emission

Long cyanopolyynes exist at the hot core region

I'm sorry that I cannot upload figures in this slide, because the paper is under preparation.

Possible Formation Mechanisms in the G28.28-0.36 Hot Core I

Warm Carbon Chain Chemistry (CH_4-origin chemistry)



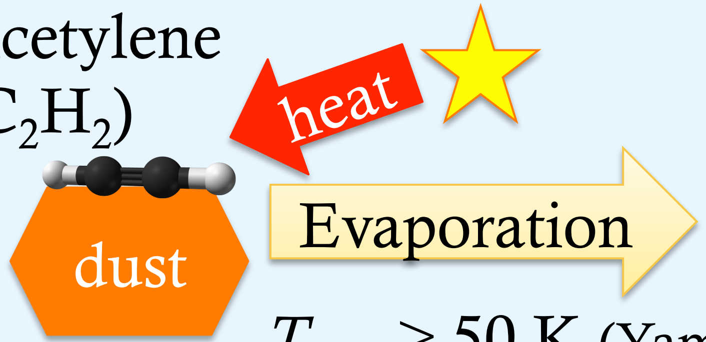
$X(HC_5N)$
G28.28-0.36 >> L1527 (× 20)

WCCC mechanism is not enough to reproduce the observed $X(HC_5N)$ in G28.28-0.36

Possible Formation Mechanisms in the G28.28-0.36 Hot Core II

Chapman's Mechanism (C_2H_2-origin chemistry) (Chapman *et al*. 2009)

Acetylene (C_2H_2)



$C_2H_2 + CN \rightarrow HC_3N$ etc.

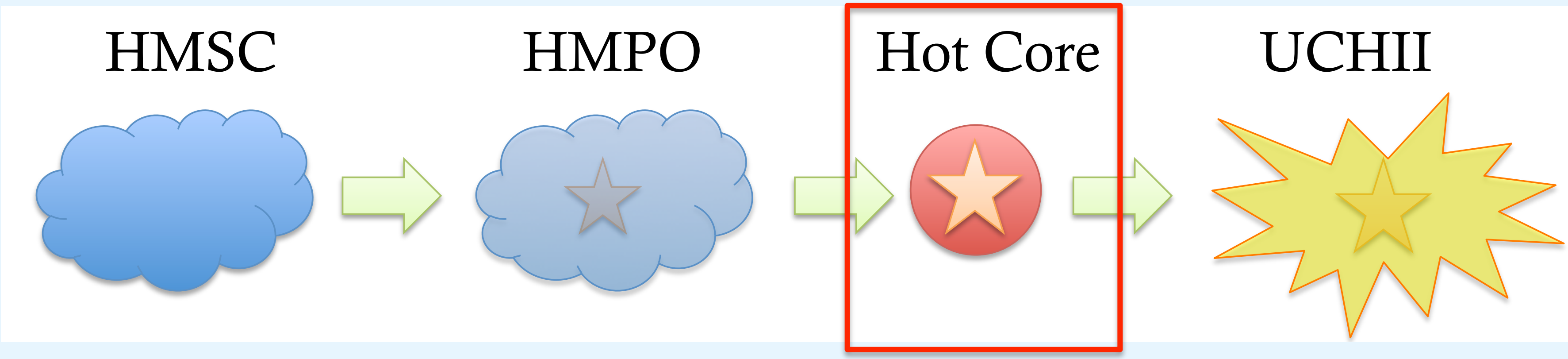
$T_{dust} \geq 50$ K (Yamamoto *et al*., 1983)

Previous observations support this model

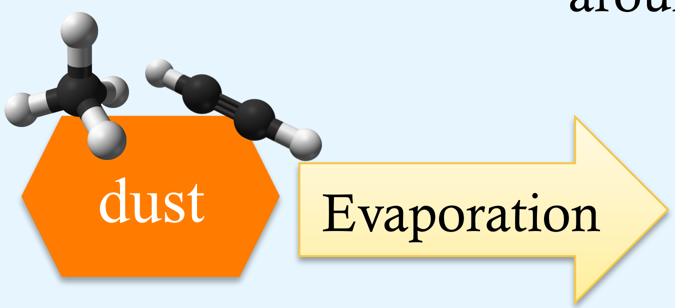
- ✓ C_2H_2 abundances in the gas phase in hot cores are high
- ✓ C_2H_2 is thought to be evaporated from grain mantles

(Lahuis & van Dishoeck, 2000)

Summary of This Subsection



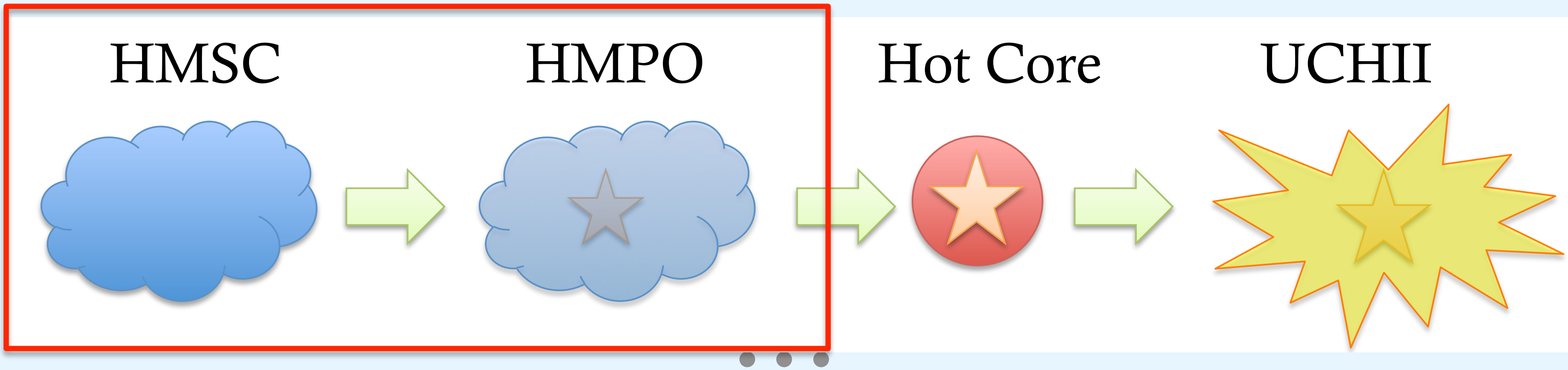
HC_5N exists in the warm gas around MYSOs abundantly



Cyanopolyynes are formed in the warm gas

Chemical Evolution in the High-Mass Star-Forming Regions

Investigate more common characteristics of HC_3N in the early high-mass star-forming regions



- ✓ $N(HC_3N)$ vs. L/M ratio
- ✓ Chemical evolutional indicator, $N(N_2H^+)/N(HC_3N)$ ratio

Observational Details

Source Selection

Selected from HMSC list (Sridharan et al., 2005) & HMPO list (Sridharan et al., 2002) applying the following criteria:

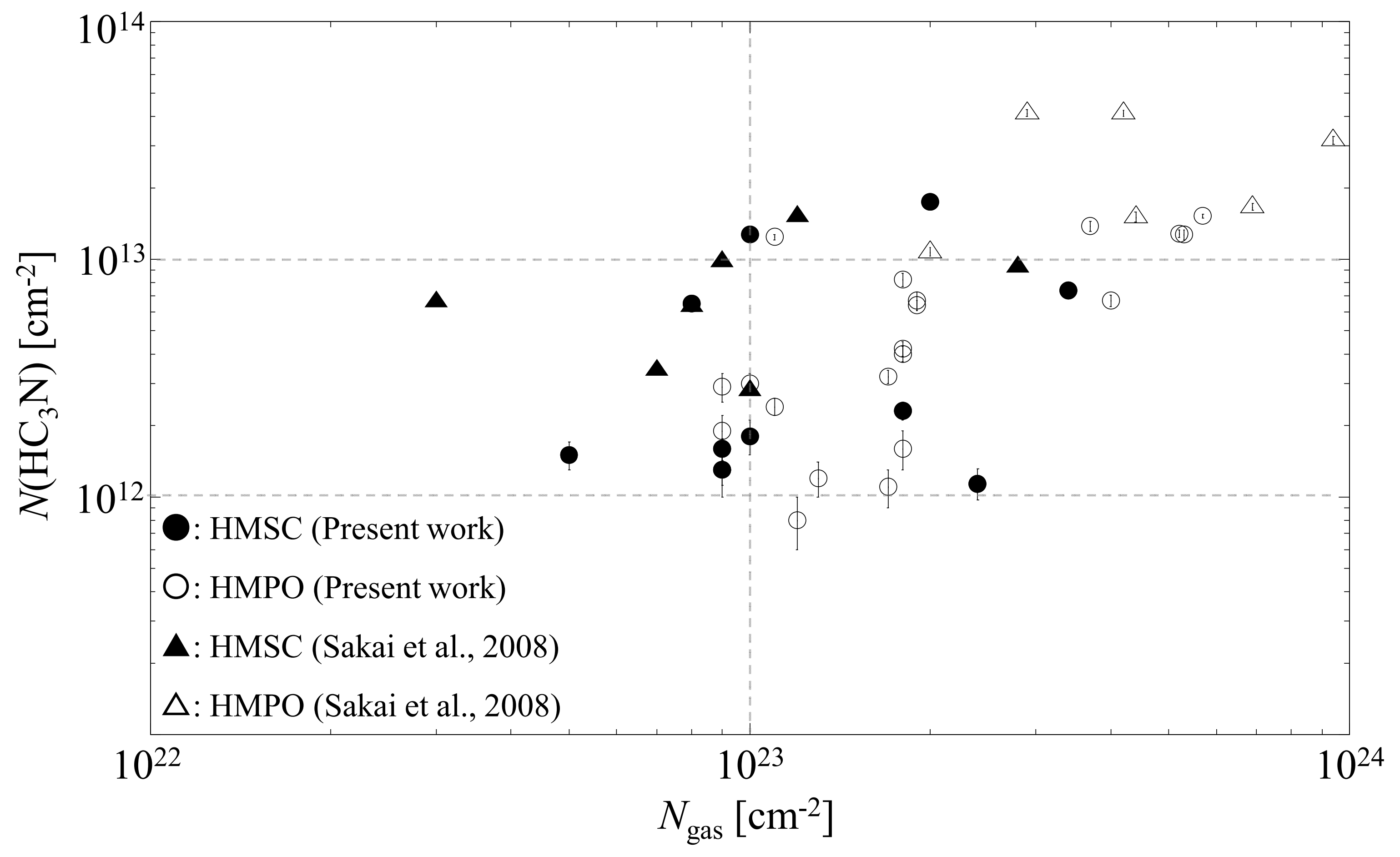
1. Decl. > -6° for HMSCs & +6° for HMPOs
2. NH_3 has been detected
3. HMPOs located in the same region as the observed HMSCs

Species & Line Selection

HC_3N : High detection rate & surely excited even in HMSCs

N_2H^+ : T_{ex} and N can be derived from its hyperfine splitting & D isotopologues

Correlation between $N(HC_3N)$ and $N(H_2)$



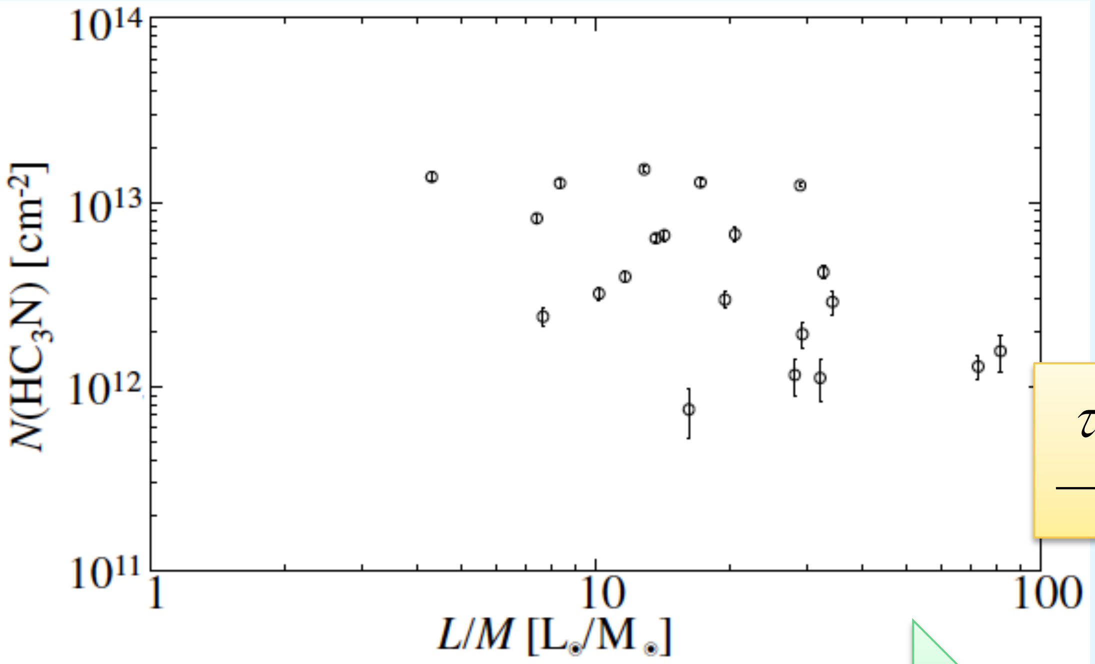
Kendall's tau correlation coefficient (τ)
HMSC : +0.16 (p = 38.4 %) → Independent
HMPO : +0.63 ($p = 5 \times 10^{-4}$%) → Positive correlation

HC_3N exists in dense gas in HMPOs

Relationship between Physics & Chemistry in HMPOs

Luminosity-to-mass ratio (L/M) : physical evolutional indicator

(Sridharan *et al.*, 2002)



τ = -0.34 (p = 31 %)
→ Weak negative correlation

Physical evolution

HC_3N is destroyed by stellar activities (e.g., UV radiation)

Chemical Evolutional Indicator

$N(\mathrm{HC_3N})$ increases
$N(\mathrm{N_2H^+})$ slightly decreases

I'm sorry that I cannot upload the figure in this slide, because the paper is under preparation.

Interpretation of Chemical Evolutional Indicator

Increasing $N(HC_3N)$

- WCCC (CH_4-origin) mechanism
- Chapman's (C_2H_2-origin) mechanism
- $T_{sub}(CH_4) = 25$ K
- $T_{sub}(C_2H_2) = 50$ K

(Yamamoto *et al.*, 1983)

Decreasing $N(N_2H^+)$

- $N_2H^+ + CO \rightarrow N_2 + HCO^+$
- $T_{sub}(CO) = 20$ K

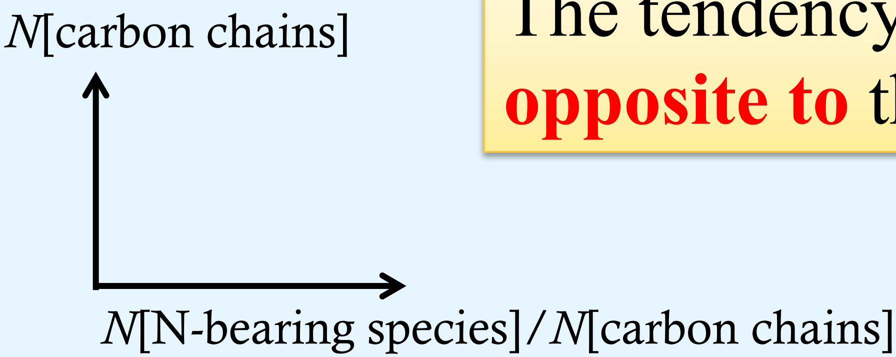
(Yamamoto *et al.*, 1983)

$T_{dust} \sim 50 - 200$ K (HMPOs)

(Sridharan *et al.*, 2002)

CH_4, C_2H_2, and CO can evaporate into the gas phase

High-Mass SFR vs. Low-Mass SFR



The tendency in the high-mass SFR is **opposite to** the low-mass SFR

Temperature

High-mass SFR

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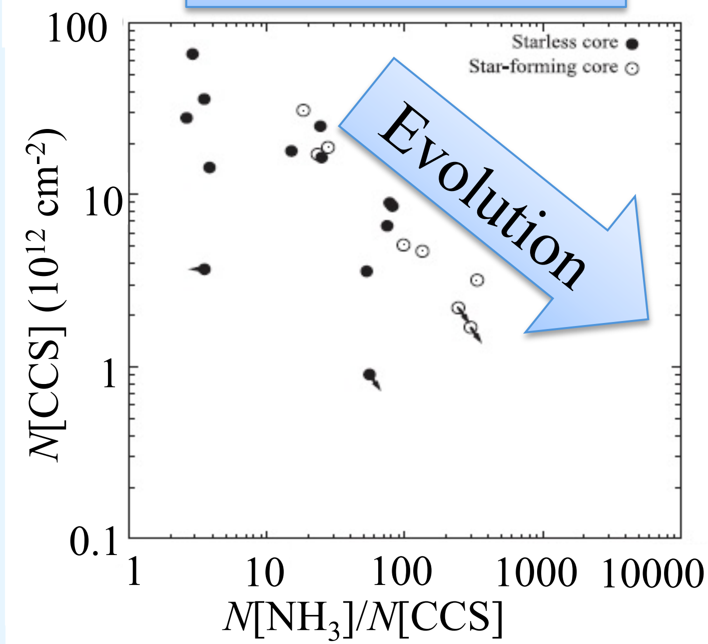
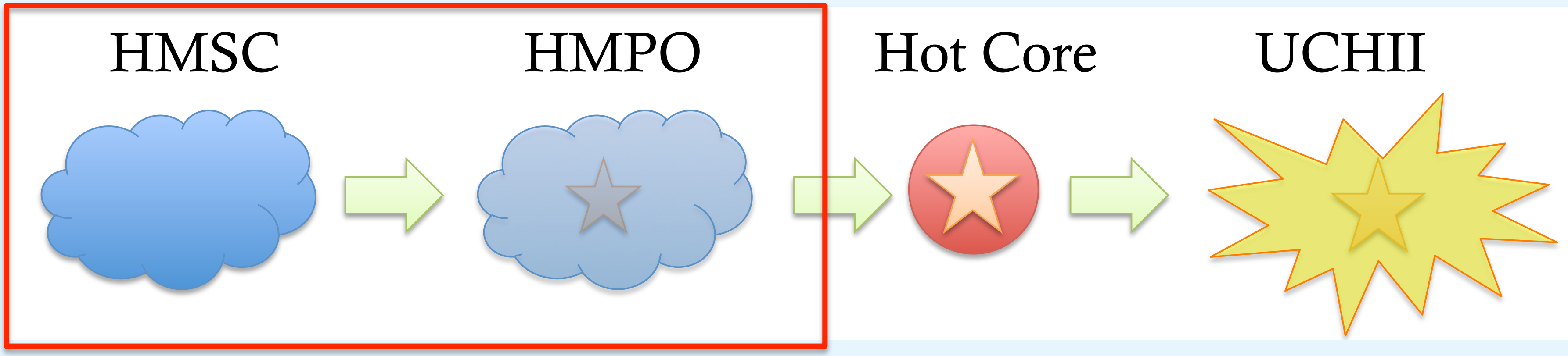
Low-mass SFR



T. Hirota *et al*. (2009)

Summary of This Subsection



1. $N(N_2H^+)/N(HC_3N)$ ratio decreases from HMSCs to HMPOs

2. HC_3N is formed in the warm dense gas around YSOs

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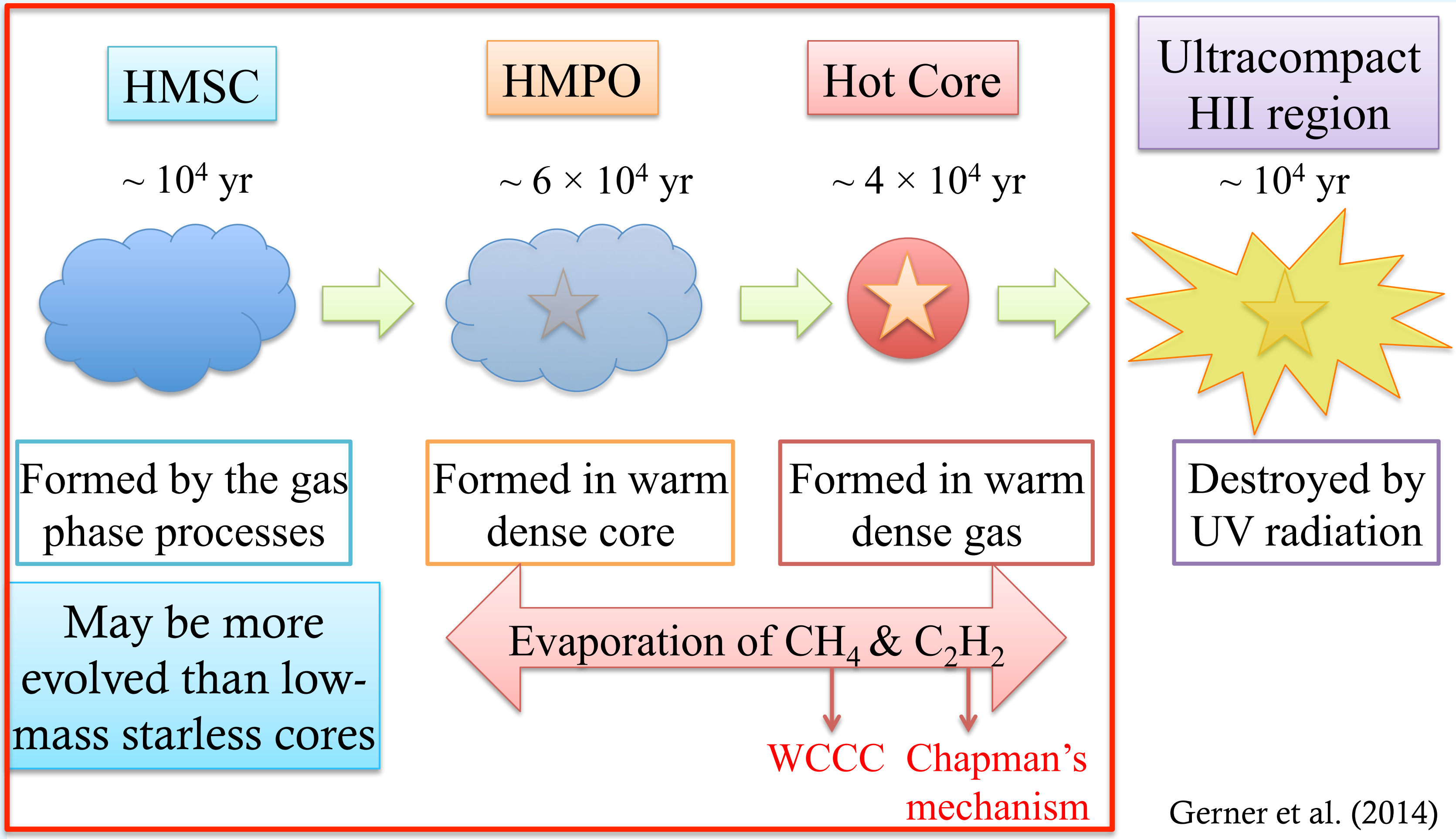
Summary of the Cyanopolyyne Chemistry in High-Mass Star-Forming Regions



Summary

1. Are carbon-chain molecules associated with and/or formed around massive young stellar objects (MYSOs)?
   If they are formed, how are they formed?

Yes : Cyanopolyynes are formed from CH_4 and/or C_2H_2 evaporated from grain mantles around MYSOs.

2. Do carbon-chain molecules have relationship with evolution of massive stars?

Probably Yes : The $N(N_2H^+)/N(HC_3N)$ ratio decreases from HMSCs to HMPOs.

Observations of cyanopolyynes
= a good tool for investigation of
massive star formation process successively

Thank you very much for your attention