Galactic diffuse molecular gas detected in absorption toward ALMA calibrator sources

as a compilation of

- Ando, R. et al. 2016, PASJ, 68, 6
- Ando, R. et al. 2018, submitted to ApJ

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Outline of this talk

Introduction

- Motivation to study diffuse gas

Detections of Galactic diffuse molecular gas

- Data analysis: ALMA calibrator sources
- Results
- Implication to the physical condition

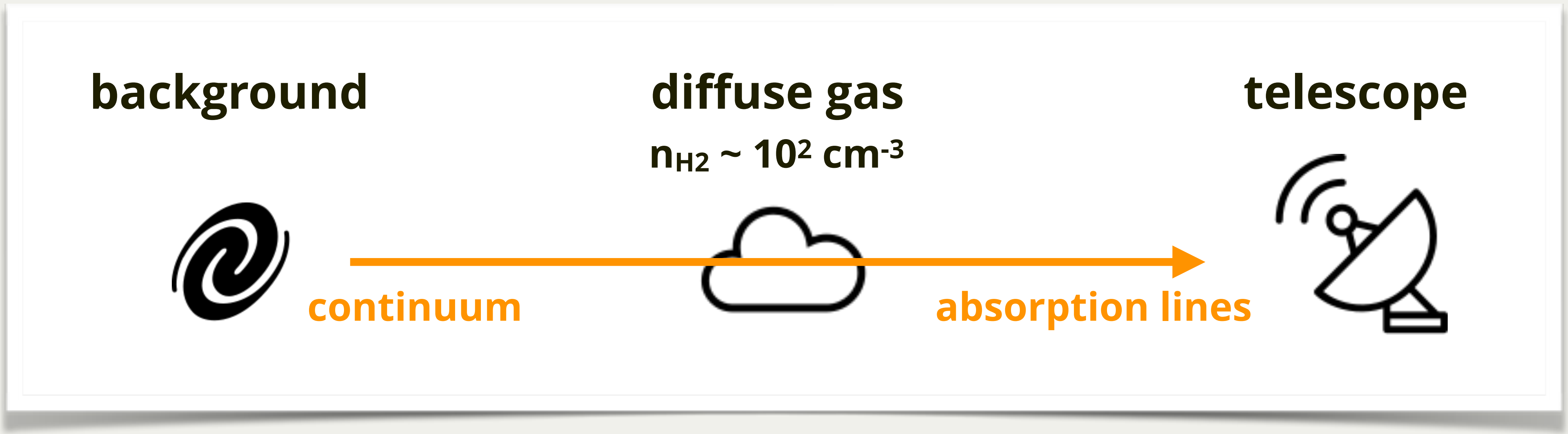
Excitation state of diffuse molecular gas

- Sensitive ALMA observations
- Results
- Relation to the extragalactic spectra

Summary

Motivation to study diffuse gas

Galactic molecular absorption system



ALMA Calibrator sources

- available in ALMA archive
- may include absorption systems?

Diffuse molecular ISM

- probed with **absorption lines** toward bright background sources
- important as an initial condition of dense molecular gas
- may contribute appreciably to, or even dominate, the total gas

Motivation to study diffuse gas

Molecular lines at millimeter wavelengths

- interstellar molecules: CO, HCN, HCO^+, CCH, CS, SO, ...
- rotational spectra of interstellar molecules
- ground state transitions (J = 1–0) in ALMA Band 3 ($\lambda \sim 3$ mm)

For example...

- determination of isotope ratio of fundamental elements
  e.g., Lucas & Liszt 1998
- probes of the molecular hydrogen column density
  e.g., Gerin+ 2018
- extending the molecular inventory
  e.g., Liszt+ 2014, 2015, 2018

This study: detection of absorption system toward ALMA calibrators
→ characterization of chemical and physical properties

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Data analysis: ALMA calibrator sources

ALMA archive

Selection criteria

- available in the ALMA archive prior to late 2014 (i.e., Cycle 0 data)
- continuum flux > 0.2 Jy at Band 3, 4, 7
- frequency resolution < 1 MHz

36 ALMA calibrator sources

analysis

4 Galactic absorption systems

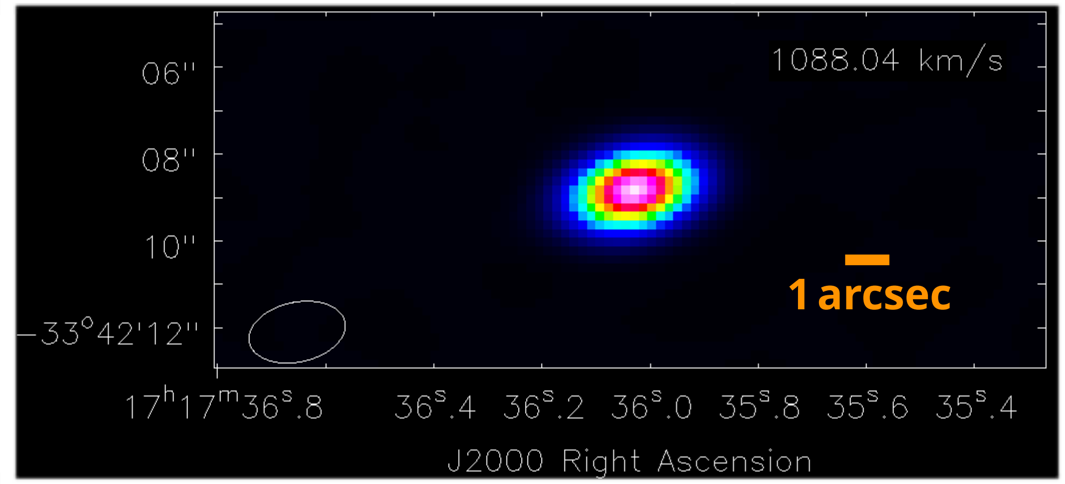
Object	Coordinates (*l*, *b*)	Band	Detected molecular species
J1717–337	(352.7, 2.4)	3	**c–C_3H_2, HCS^+, $H^{13}CN$, HCO, $H^{13}CO^+$, $HN^{13}C$, CCH, HCN, HCO^+, CS**
J1625–254	(352.1, 16.3)	3, 6	**c-C_3H_2, CCH, HCN, CO**
J1604–446	(335.2, 5.8)	3, 6, 7	**CS, CO**
NRAO530	(12.0, 10.8)	3, 6	**HCO**, $H^{13}CO^+$, SiO, CCH, HCN, HCO^+, CO

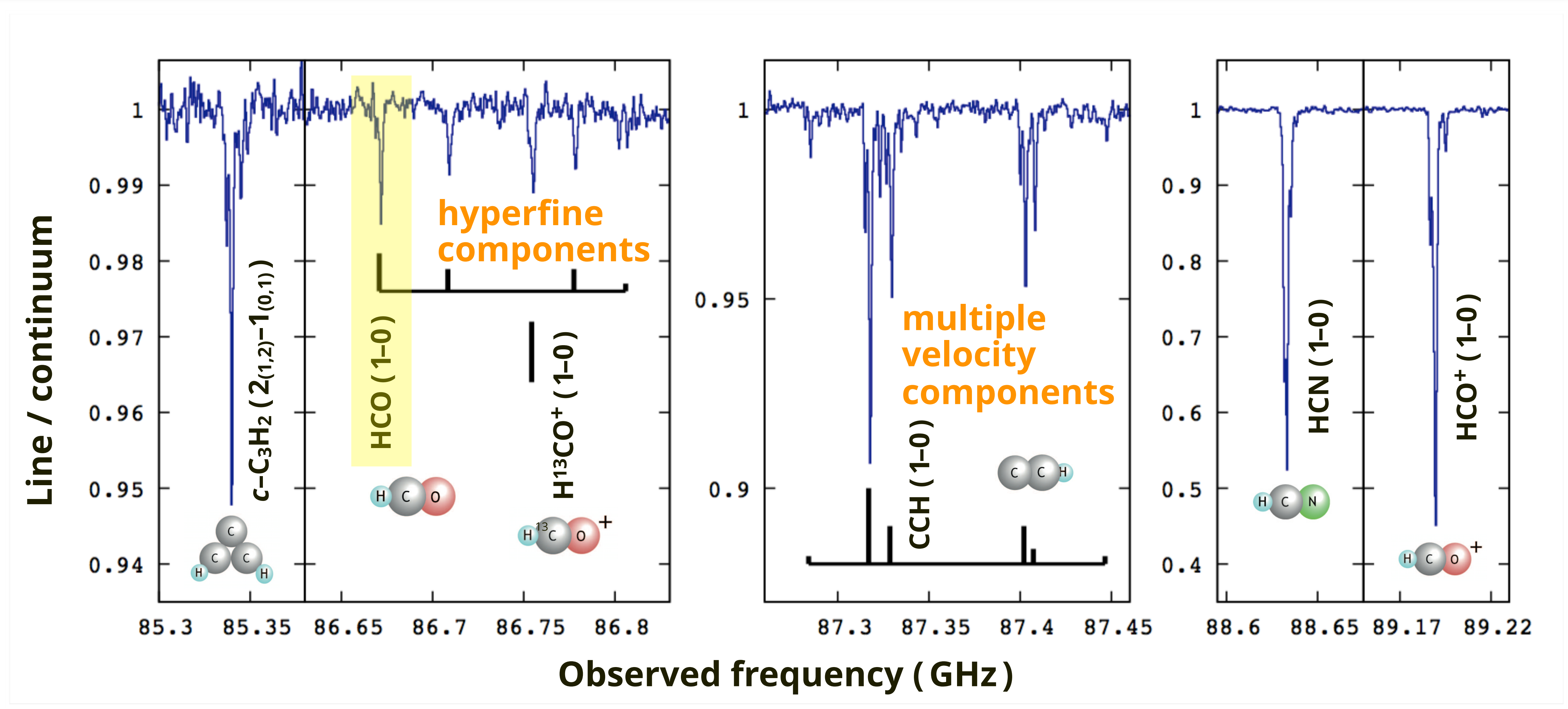
New detections !

Detections of Galactic diffuse gas: Results

Example: J1717–337

- newly detected molecular absorptions!
- multiple velocity components





Implication to the physical condition: HCO

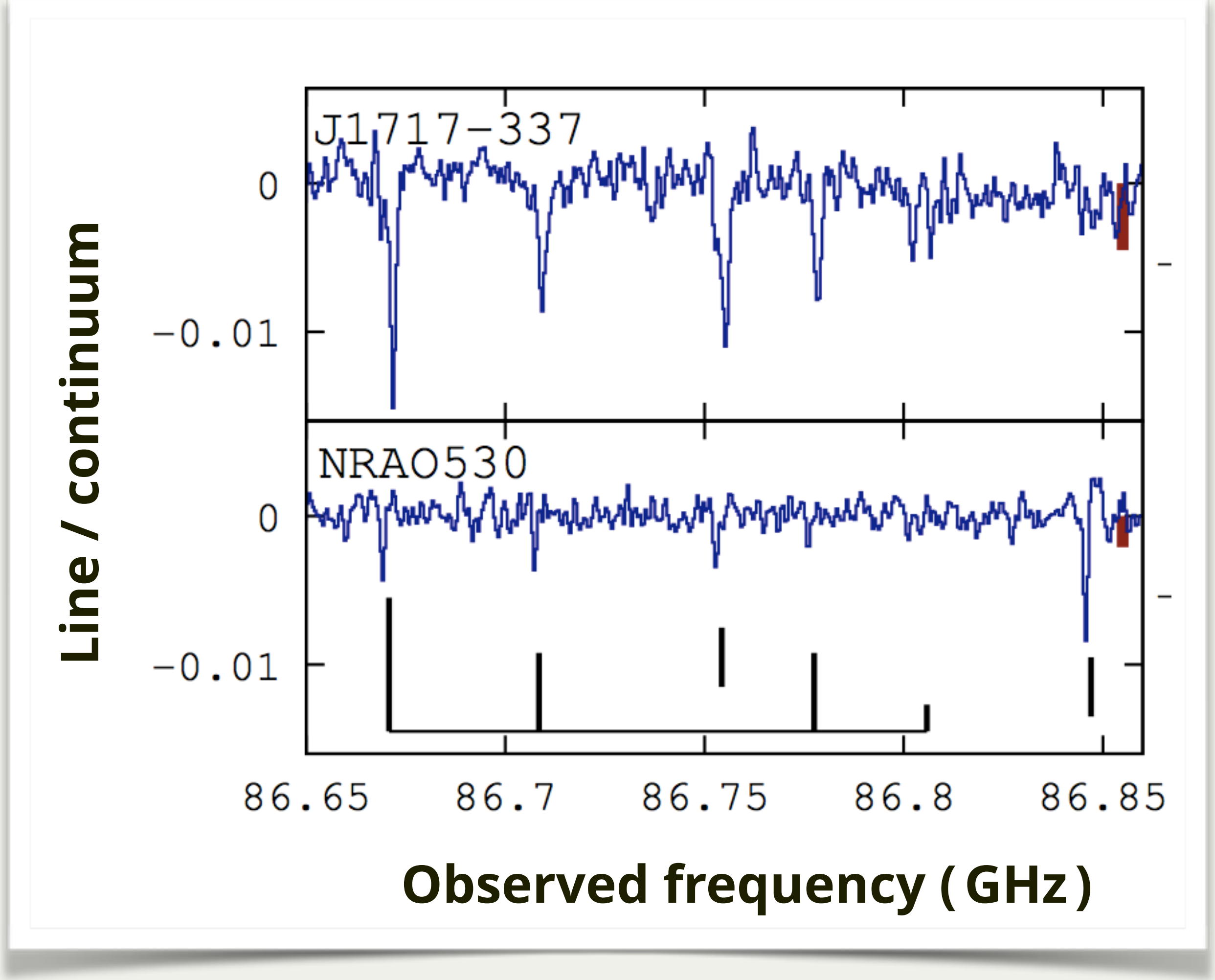
HCO absorption systems

- B0415+379 = 3C111
- B2200+420 = BL Lac
- W49

(Liszt+ 2014)

- **J1717–337**
- **NRAO530**

(Ando+ 2016)



HCO — Formyl radical

- Formation of HCO

$$O + CH_2 \rightarrow HCO + H$$

(Gerin+ 2009)

$$C^+ + H_2 \rightarrow CH_2^+ + h\nu$$

$$CH_2^+ + H_2 \rightarrow CH_3^+ + H$$

$$CH_3^+ + e^- \rightarrow CH_2 + H$$

(Schenewerk+ 1988)

environment where C^+ and H_2 coexist
= Photon dominated region (PDR)

HCO: as a PDR tracer

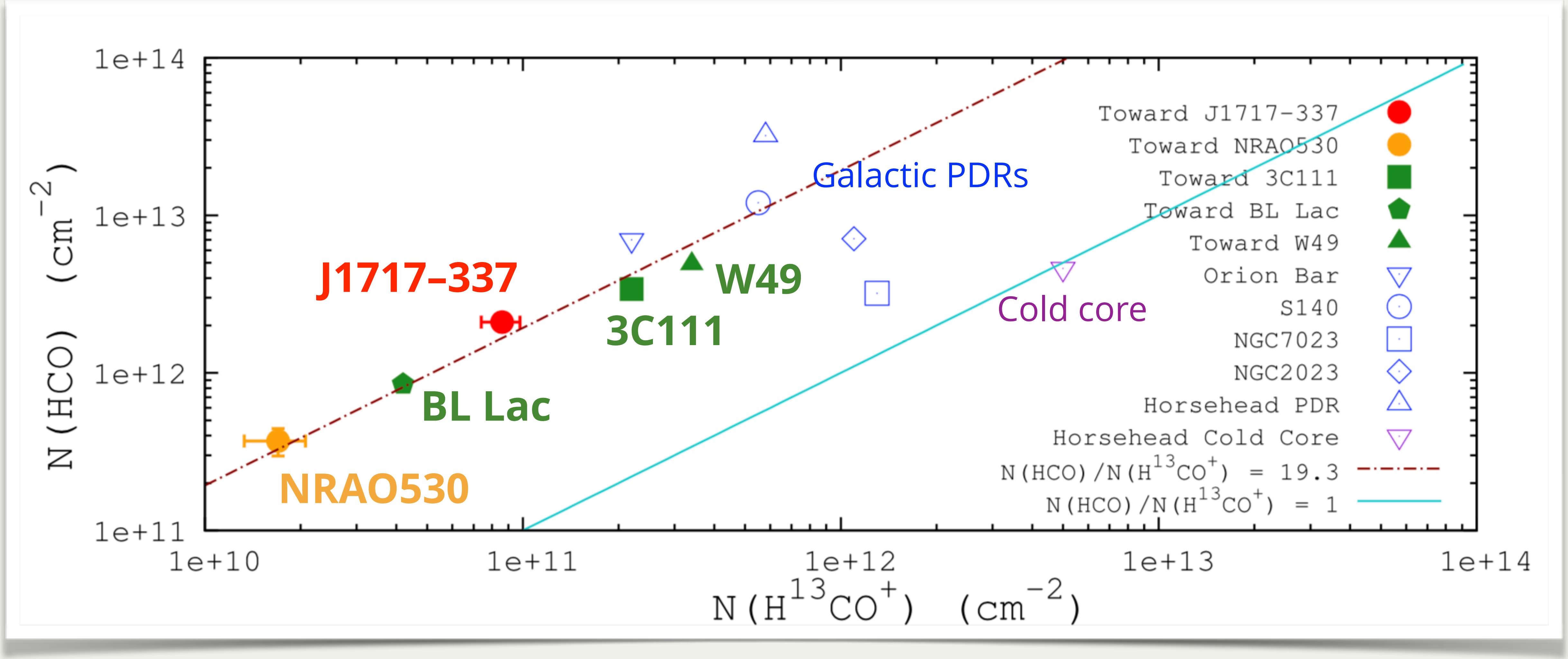
$HCO / H^{13}CO^+$ column density ratio

- $H^{13}CO^+$: as a total H2 column density

(Gerin+ 2009)

- high $HCO / H^{13}CO^+$ indicates the presence of **UV radiation field**

  → Galactic diffuse gas is in **PDR-like environment** !



Is diffuse molecular gas
REALLY
in equilibrium with CMB？

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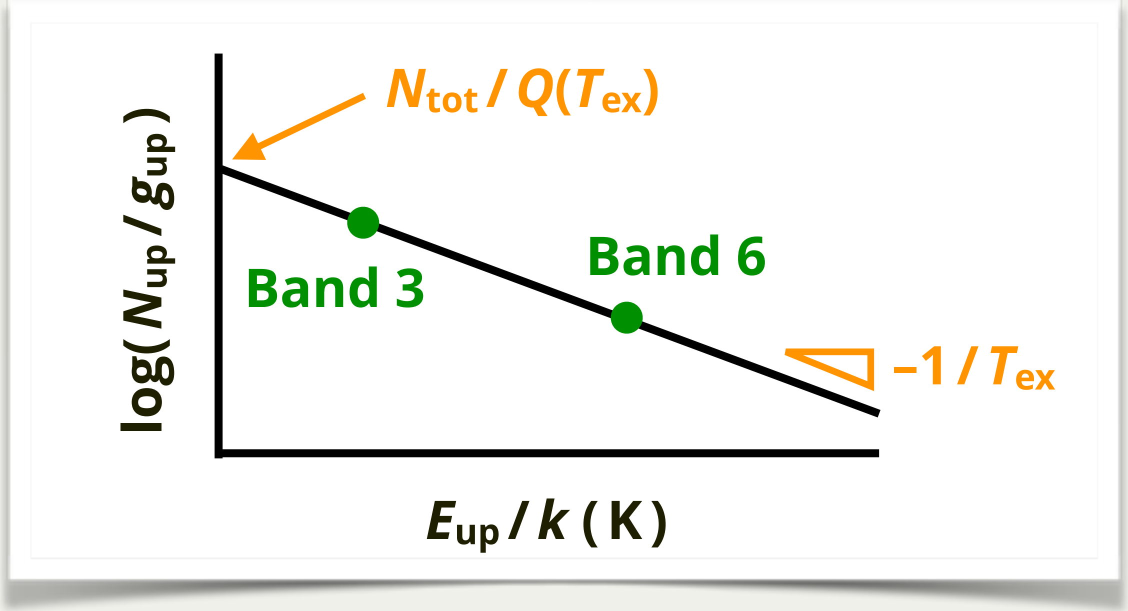
Excitation state of diffuse gas

Sensitive ALMA observations

- ALMA Cycle 3, 2015.1.00066.S (PI: Ando)
- Target systems: J1717–337, J1625–254, NRAO530
- **Band 6** (λ ~ 1.2 mm)
- Observing time: **3.2 hours** (on source ~ 0.4 hours / source)
- Target lines:

  higher-*J* transitions of C_2H, SiO, $H^{13}CO^+$, HCO, $H^{13}CN$, CS, *c*-C_3H_2

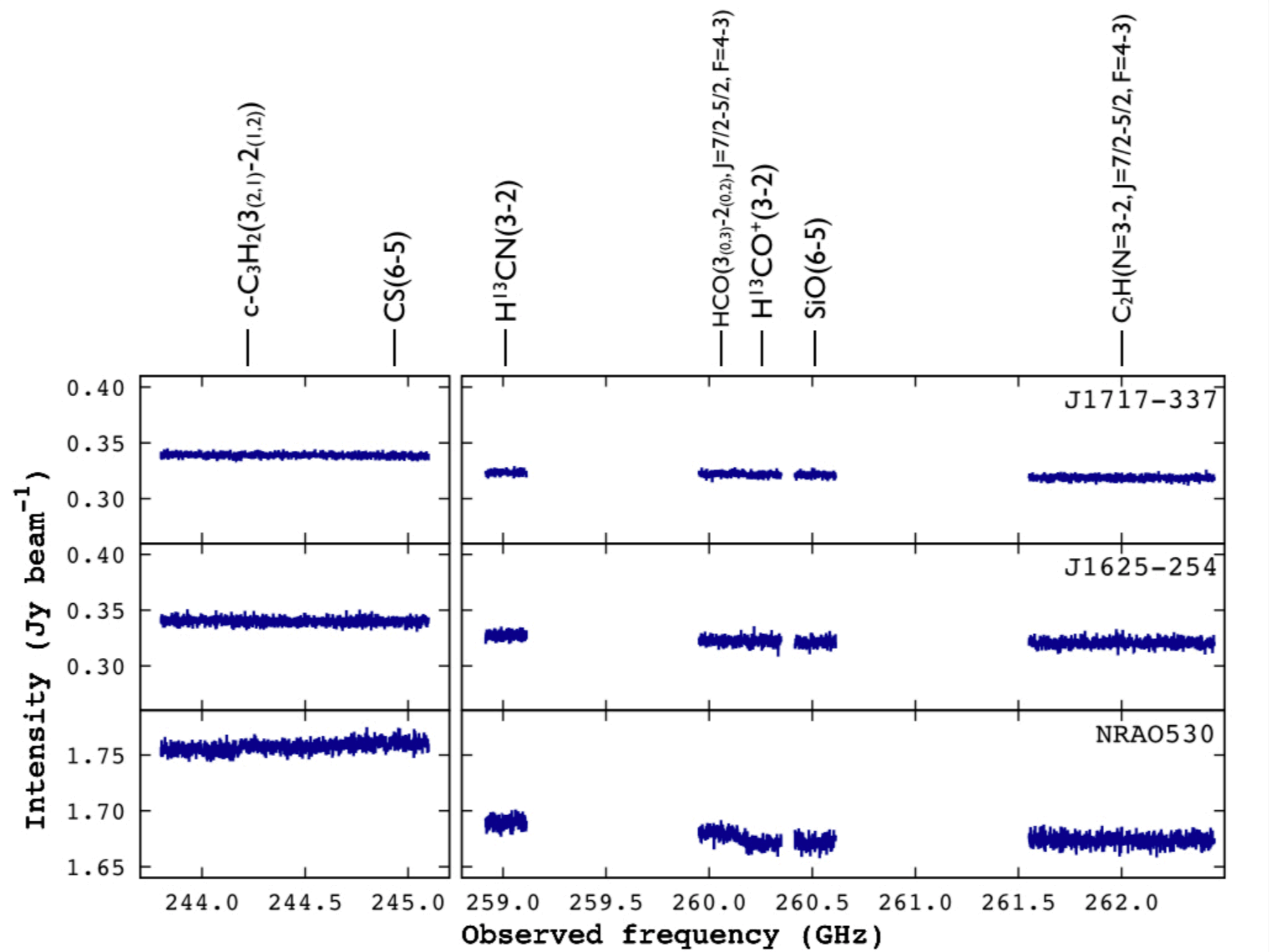
Multi-line analysis: rotation diagram



***J* = 1–0 (Band 3) & *J* = 3–2 (Band 6)**

- Excitation temperature
- Column density

Results: non-detection



Upper limits on the excitation temperatures

T_{ex} is lower than 10 K

- The excitation temperatures of multiple molecules are constrained.
- In spite of the PDR-like chemistry, the temperature is low.
- T_{ex} of common PDR tracer CCH is < 5 K in all three systems.

Excitation temperatures (K)

	J1717–337	J1625–254	NRAO530
HCO	< 8.7	< 15.0	—
$H^{13}CO^+$	< 9.6	< 10.8	—
$H^{13}CN$	< 8.2	—	—
CS	< 7.2	< 5.3	—
CCH	**< 4.3**	**< 4.4**	**< 4.6**
***c*–C_3H_2**	—	< 8.7	—
SiO	—	< 13.9	—

Is diffuse molecular gas REALLY in equilibrium with CMB ?

⬇

Yes, we confirmed the validity of the common assumption !

⬇

We can derive column densities without assumption.

“Diffuse gas is in equilibrium with CMB”

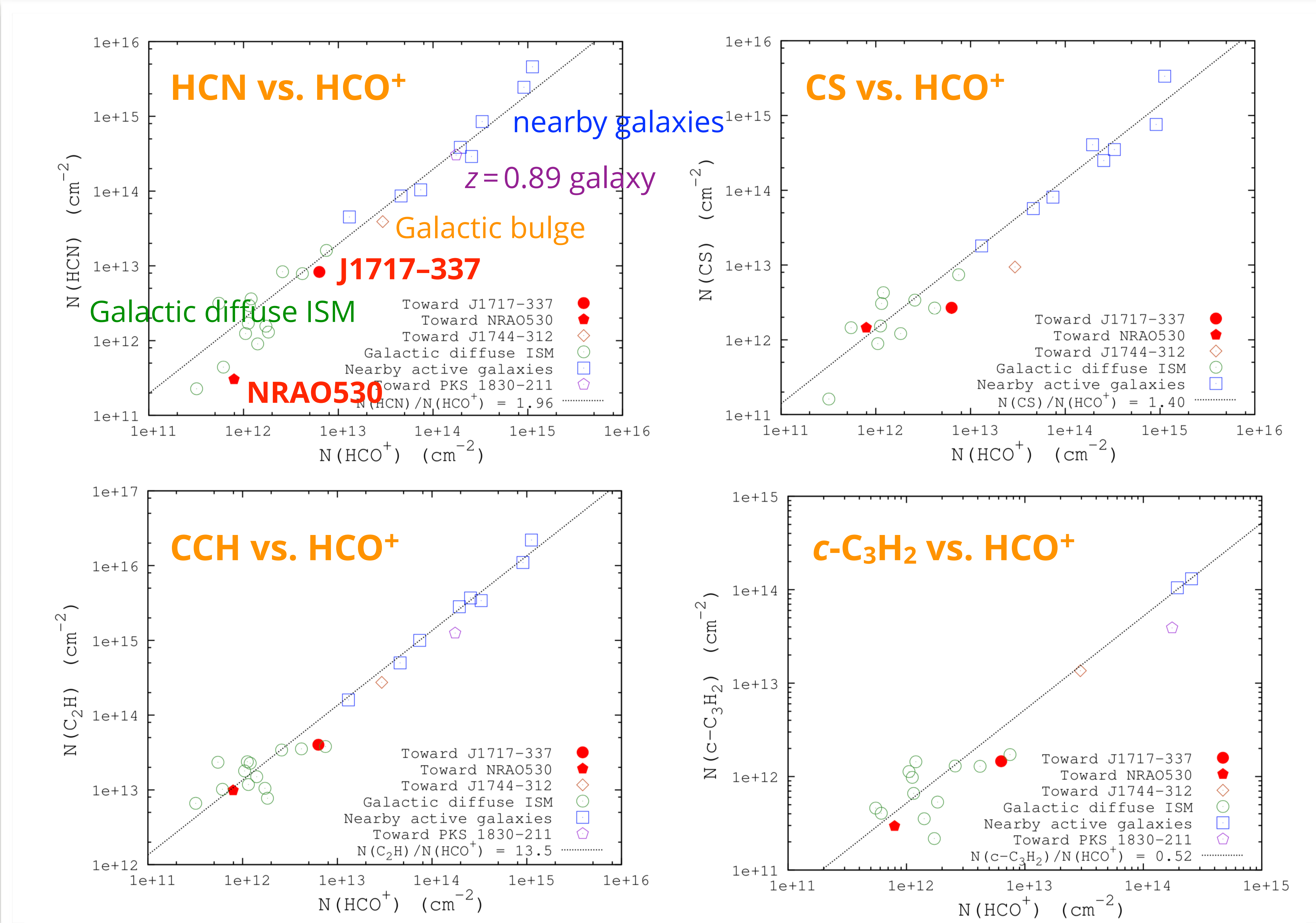
Abundances of molecules

- We assumed T_{ex} of from 2.73 K (= CMB) to the upper limit.
- The uncertainty is only a factor of several.
- Column densities in the literatures are not need to be corrected.

Column densities (cm^{-2})

	J1717–337	J1625–254	NRAO530
HCO	$(0.2-1.1)\times10^{13}$	$(0.4-7.3)\times10^{12}$	—
$H^{13}CO^+$	$(0.9-6.2)\times10^{11}$	$(0.2-1.5)\times10^{11}$	—
$H^{13}CN$	$(1.7-8.8)\times10^{11}$	—	—
CS	$(2.7-6.8)\times10^{12}$	$(1.5-2.4)\times10^{12}$	—
CCH	$(4.0-7.3)\times10^{13}$	$(1.0-1.9)\times10^{13}$	$(0.5-1.1)\times10^{14}$
c–C_3H_2	—	$(0.3-1.7)\times10^{12}$	—
SiO	—	$(0.1-1.0)\times10^{12}$	—

Comparison with other sources



Comparison with extragalactic sources

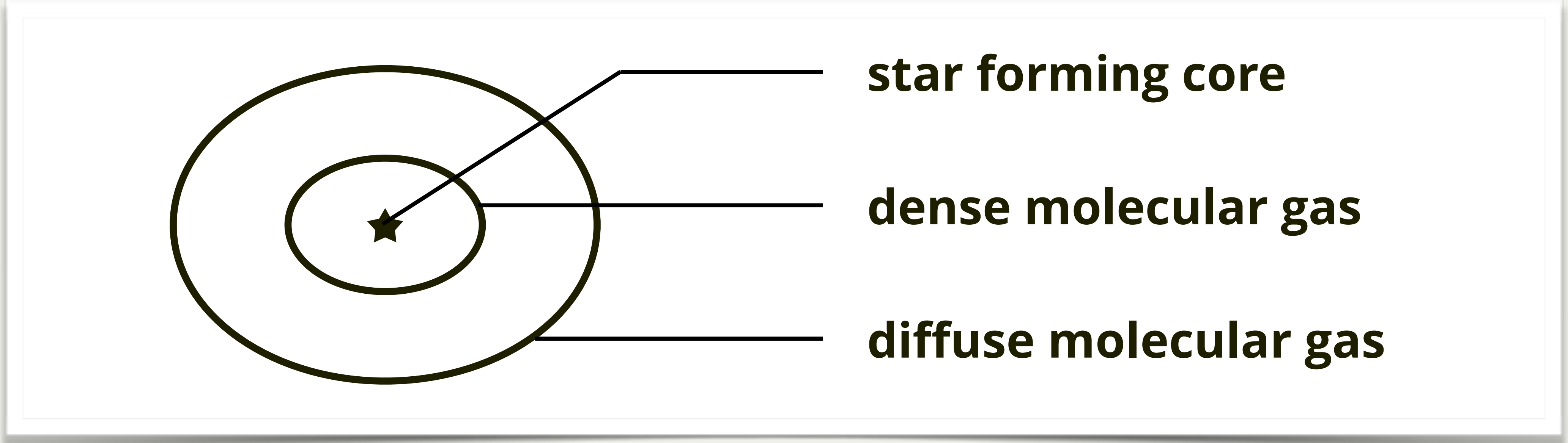
Similar to kpc-scale extragalactic molecular composition

- Recent molecular-cloud-scale (a few 10 pc-scale) imaging toward Galactic molecular clouds revealed that **emission from diffuse cloud peripheries** is not ignorable or dominant.

  (Nishimura+ 2017, Pety+ 2017, Watanabe+ 2017)

- We need to be aware that **"dense gas tracers"** are also in diffuse gas.
- To scrutinize nuclear activities, resolved observations are necessary.

Diffuse gas contributes to, or even dominate the cloud

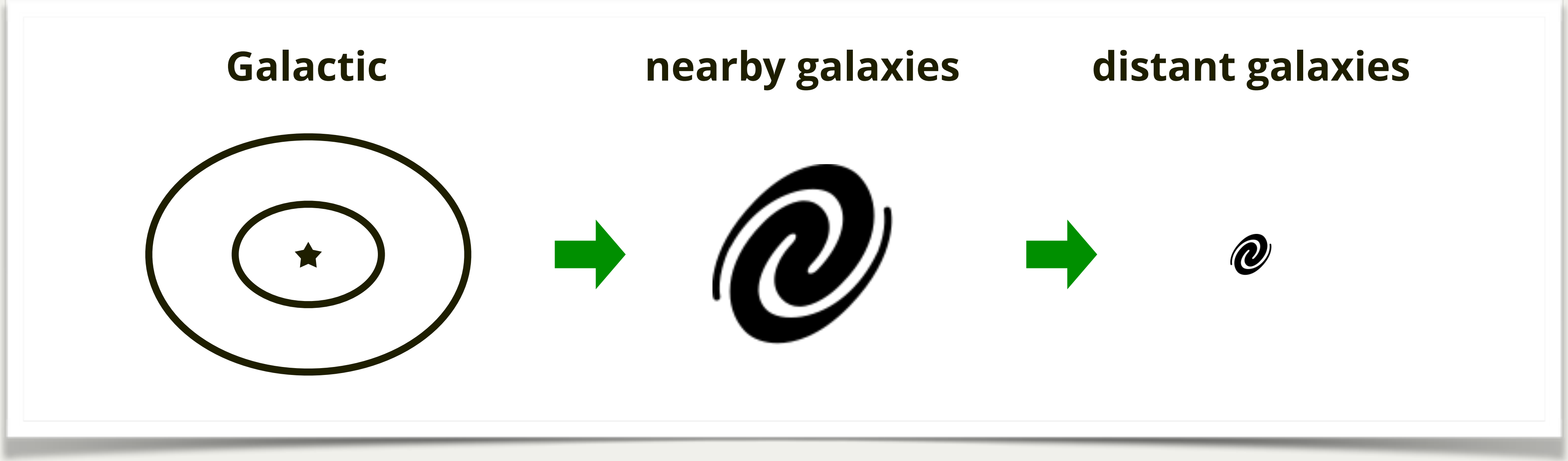


Future prospects

To increase the number of molecular absorption systems

- Galactic and high-redshift molecular absorption systems
- ALMA archive = a great treasure trove !

To use them as the cosmic "chemical" ladder



Summary

Chemical richness of Galactic diffuse gas is of great interest.

4 absorption systems / 36 candidates are detected.
HCO absorption lines toward 2 systems are newly detected.
Abundant HCO indicates **PDR-like chemistry** in diffuse gas.

To constrain the excitation state, **ALMA Band 6 observations** were conducted.
The excitation temperatures are found to be **<10 K.**
This result supports the widely accepted assumption
(i.e., diffuse gas is in equilibrium with CMB).

Similarity to the nearby galaxies observed at kpc-scale beam
reminds us the importance of spatially resolved observations.