Molecular-Cloud-Scale Chemical Composition in Low-Metallicity Dwarf Galaxies

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Introduction

Low-Metallicity Dwarf Galaxies

- Observations of the LMC, IC10, and NGC6822
- Nitrogen-bearing species
- CCH and CH_3OH

Molecular-Cloud-Scale Chemical Composition: Galactic Cloud W3(OH)

- Why molecular-cloud-scale chemical composition?
- Contribution of cloud peripheries

Summary

Chemical Evolution

of the Universe

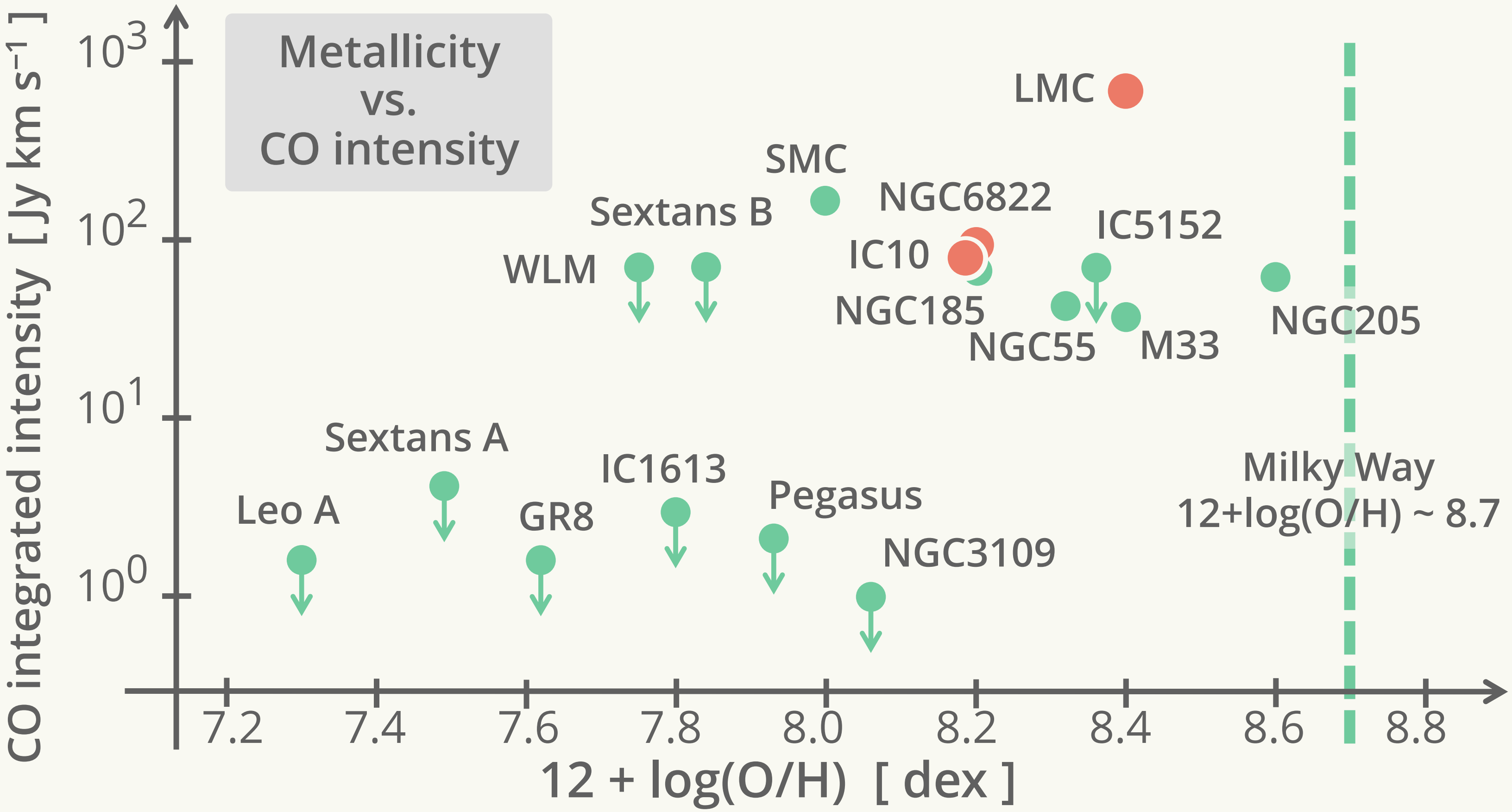
1. Enrichment of **metals** by nucleosynthesis and supernovae
2. Evolution of **molecular composition** in molecular clouds

heavy elements: C, N, O, ...

deficient in the early Universe

Dwarf Galaxies as a low-metallicity laboratory

- Majority of the Local Group
- Local approach to study galaxies in the early Universe



plotted based on Mateo 1998

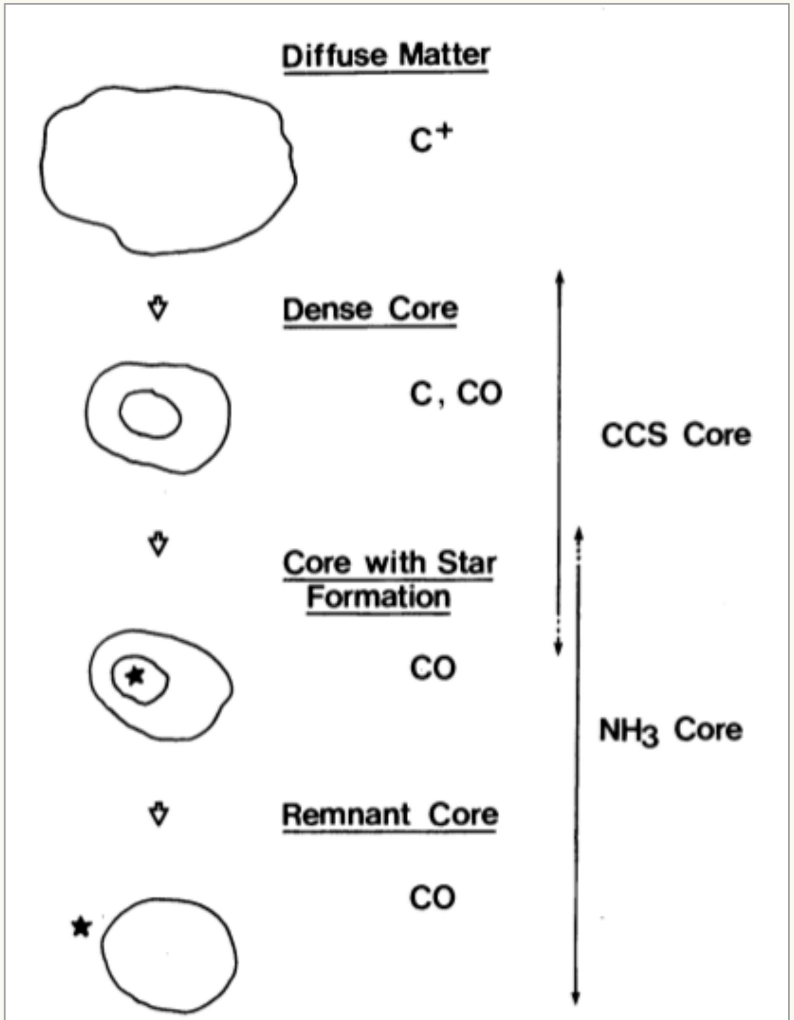
Chemical Evolution

of the Universe

1. Enrichment of **metals** by nucleosynthesis and supernovae
2. Evolution of **molecular composition** in molecular clouds

“chemical composition”
reflecting physical conditions

Chemical Evolution along **Star Formation**



Suzuki et al. 1992

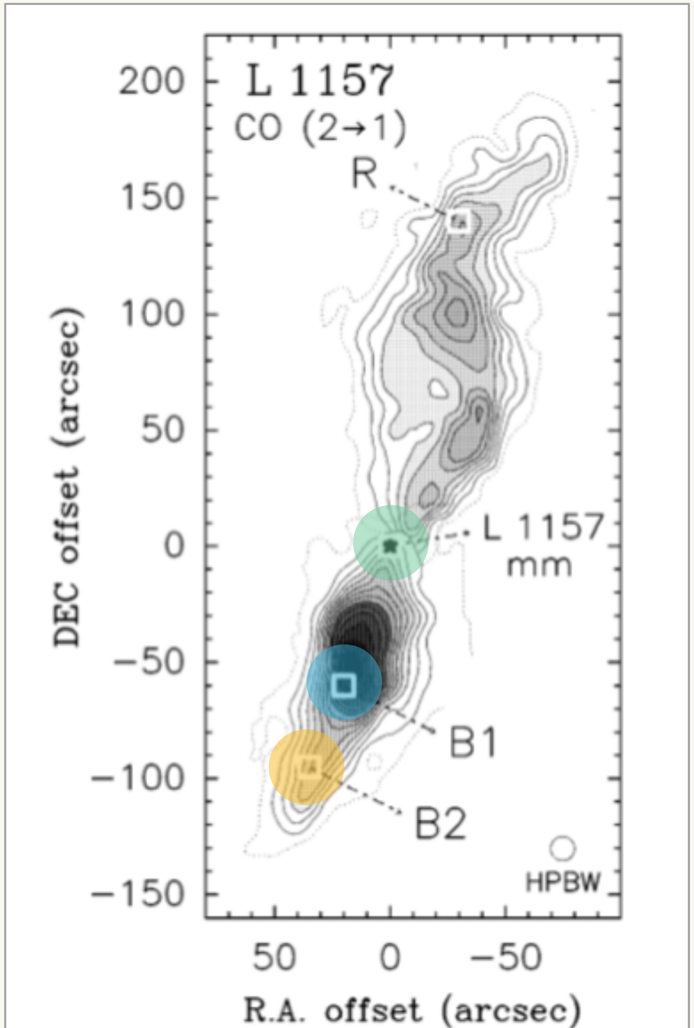
- Change of major form of carbon

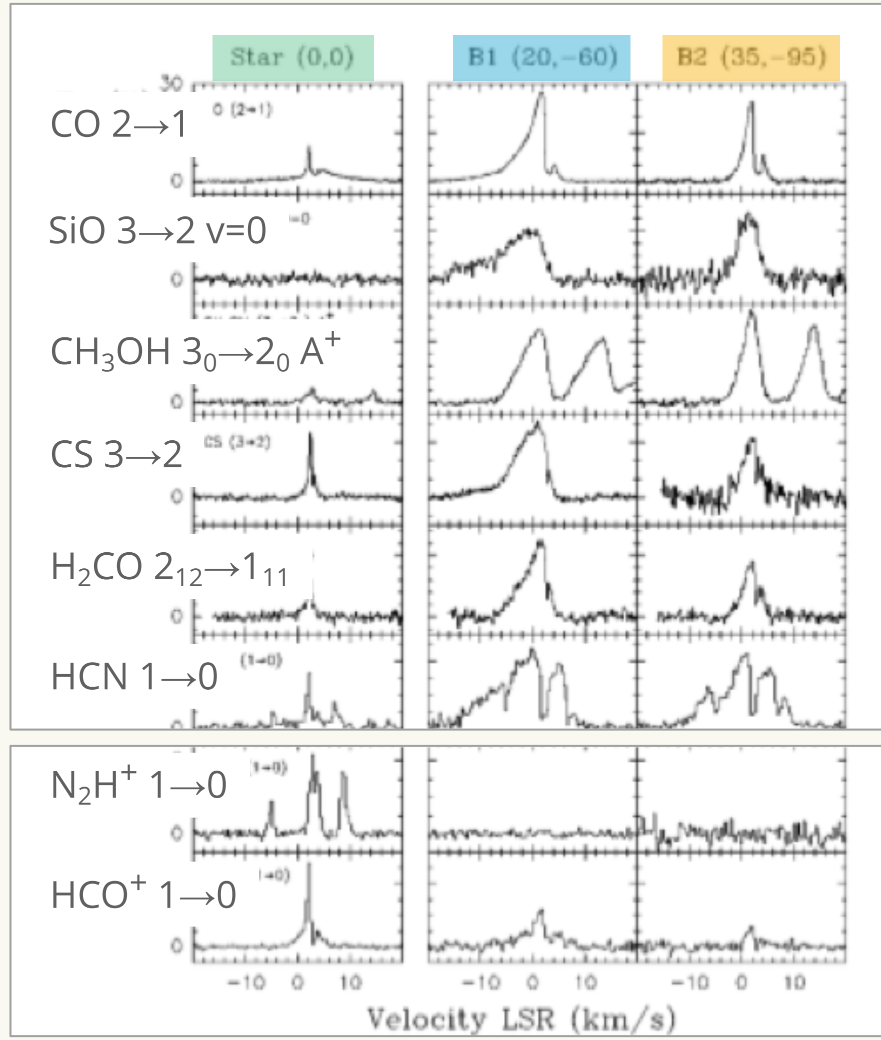
  C^+ — C — CO

- From unsaturated molecules to N-bearing molecules

  CCS — NH_3

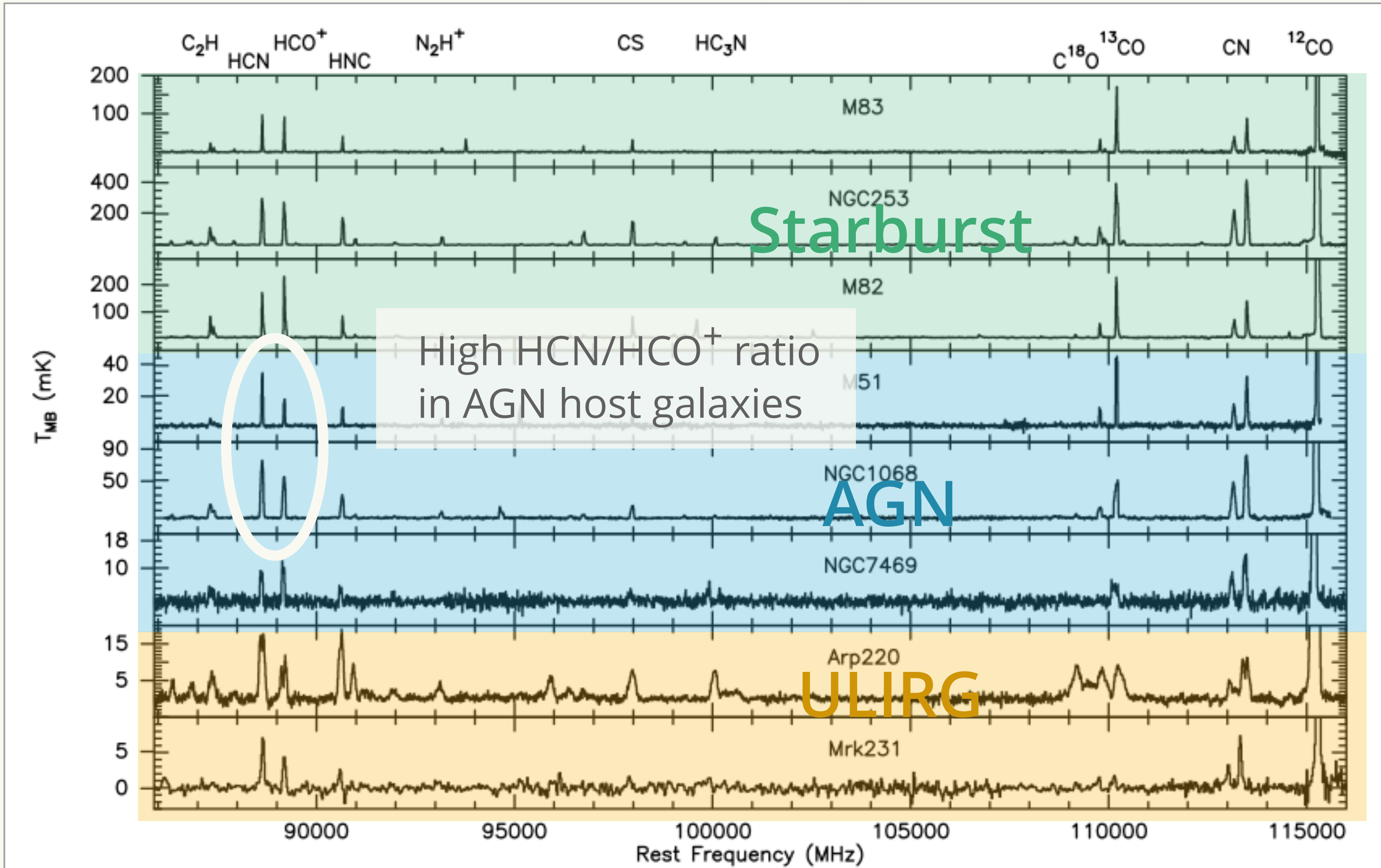
Molecules Reflecting **Physical Conditions**





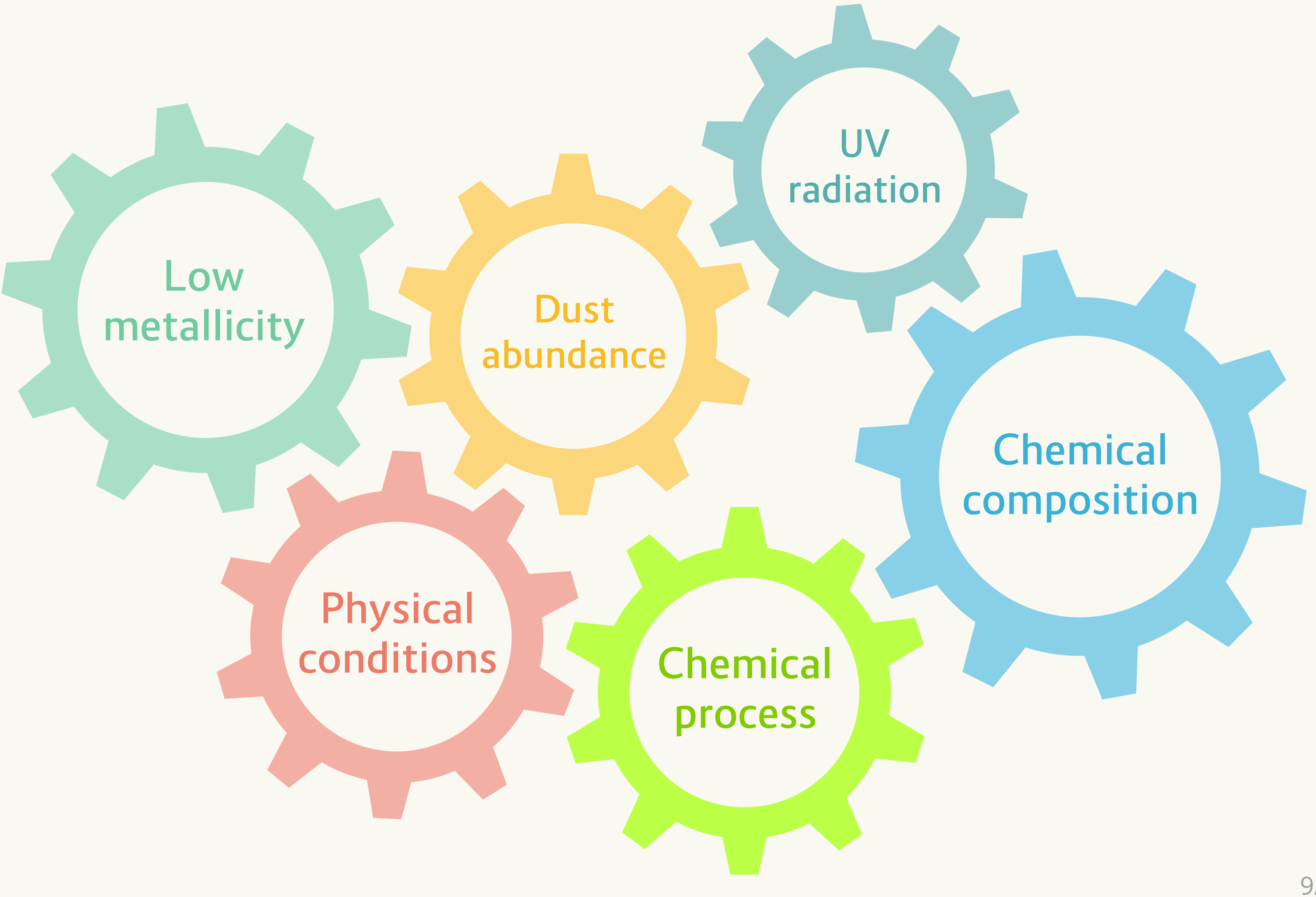
Bachiller & Pérez-Gutiérrez 1997

Extragalactic Astrochemistry



Aladro et al. 2015

Effect of Low-Metallicity on Molecular-cloud Chemical Composition



Low-metallicity dwarf galaxies

What is the characteristic chemical composition?

How does it differ from that in the metal-rich environment?

What physical and chemical process are responsible for it?

Elemental abundances

Nitrogen is significantly less abundant in dwarf galaxies.

Galaxy	$Z/Z_\odot$	O/H × 10^4	C/H × 10^4	N/H × 10^5	S/H × 10^5
LMC	1/3 – 1/2	2.40	0.79	0.87	1.02
IC10	1/5 – 1/3	1.58	0.46	0.63	0.75
NGC6822	1/5 – 1/3	1.35	0.68	0.52	0.41
Milky Way	1	7.41	4.47	9.12	1.70
M51	~ 1	6.31	3.98	15.85	1.59

LMC & MW: Dufour et al. 1982, M51: Bresolin et al. 2004, Garnett et al. 2004,
IC10: Magrini et al. 2009, Bolatto et al. 2000, Lequeux et al. 1979,
NGC6822: Esteban et al. 2014

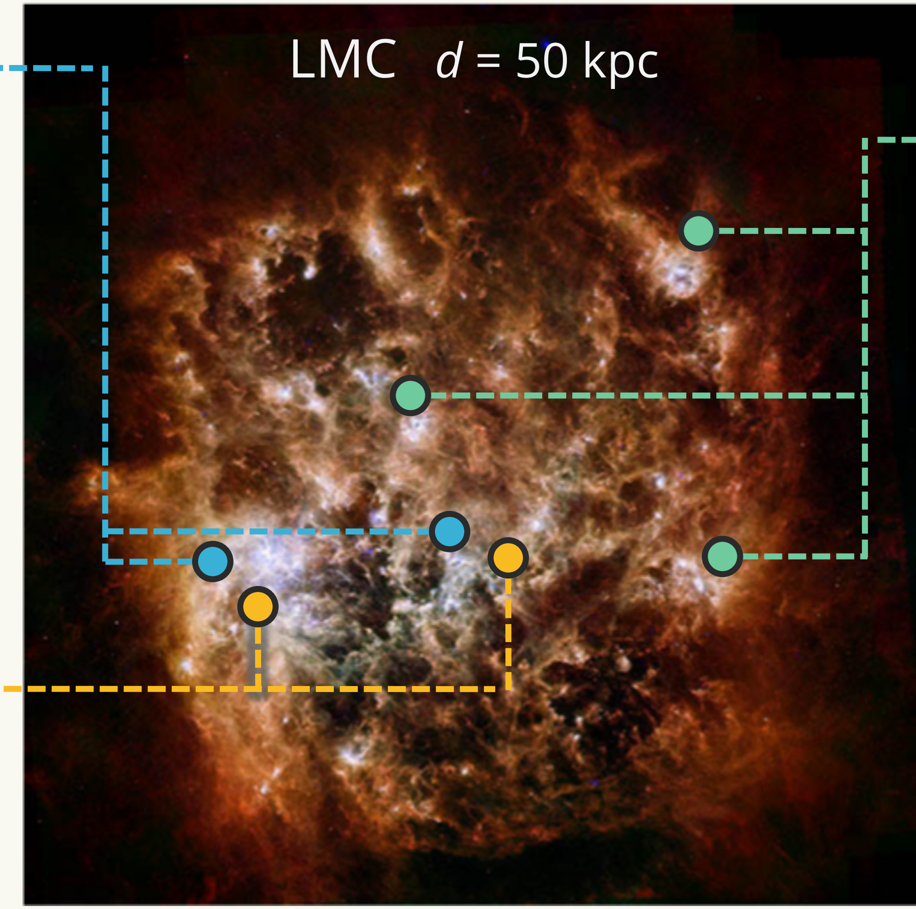
Target galaxy: **The Large Magellanic Cloud**

Quiescent clouds

- CO Peak 1
- NQC2

Star-forming clouds with H II region

- N113
- N159W



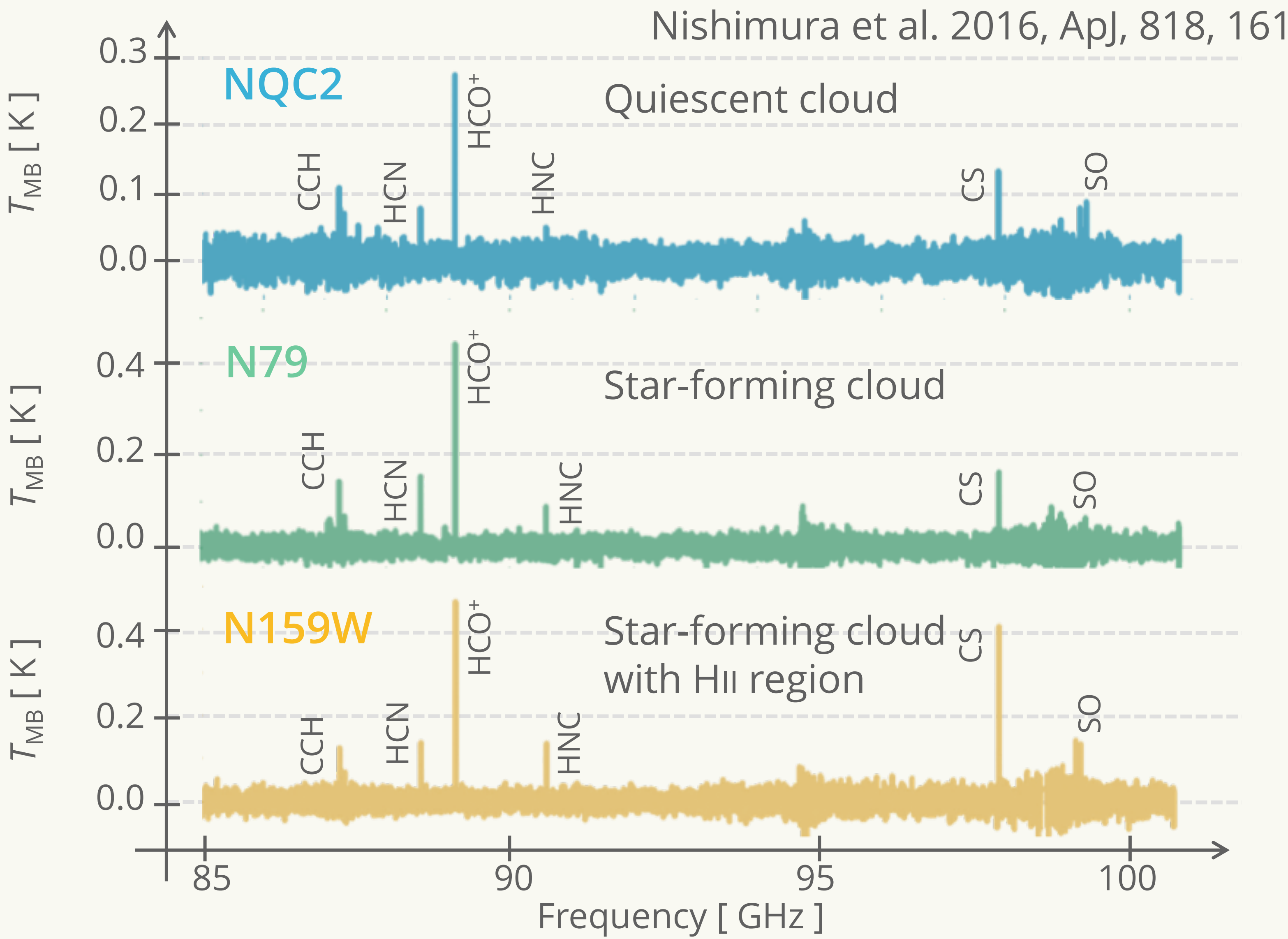
Spitzer/MIPS, *Herschel*-PACS, *Herschel*-SPIRE

Star-forming clouds

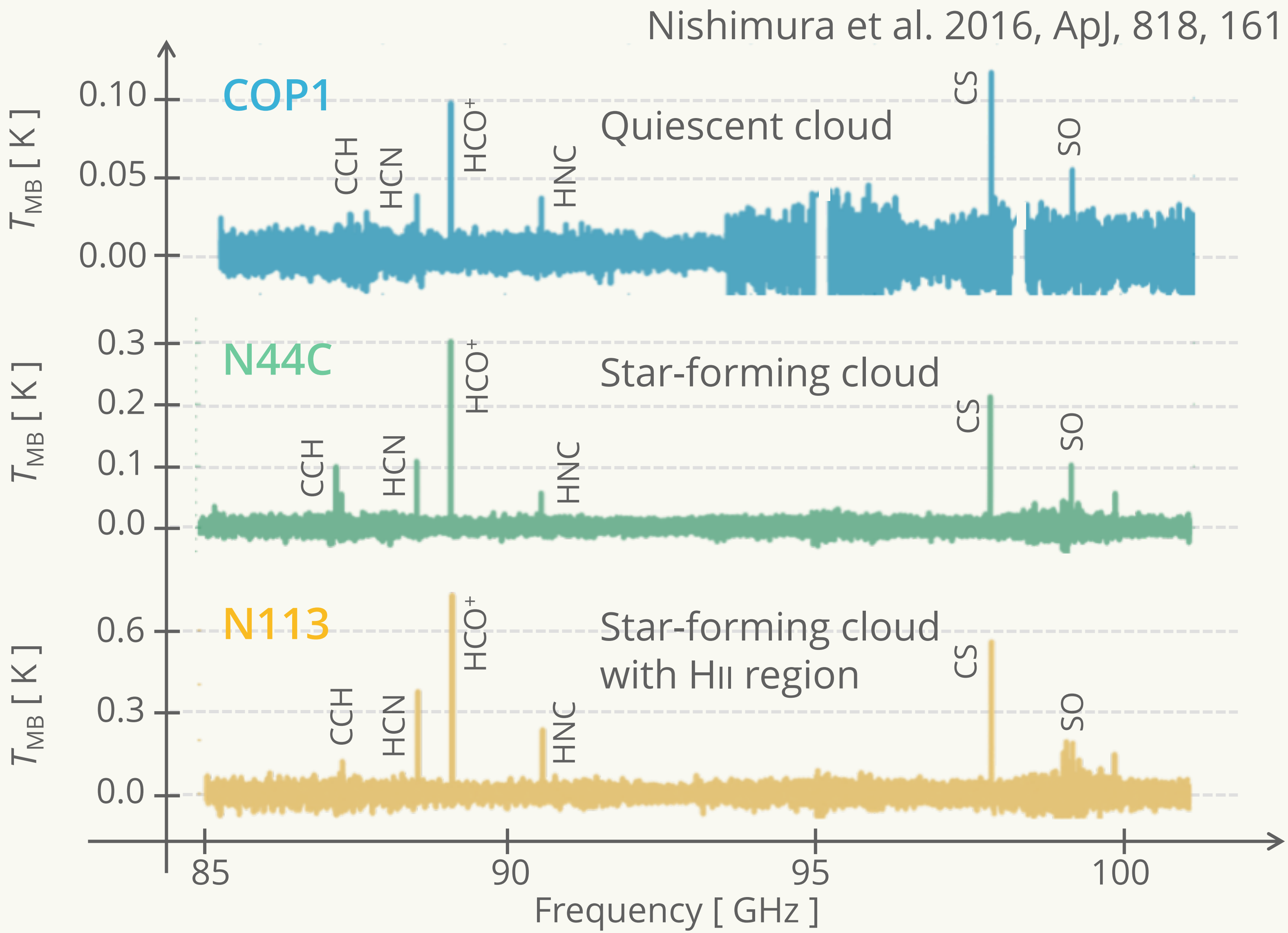
- N79
- N44C
- N11B

- 7 clouds
- 450 hours
- Mopra 22 m
- HPBW = 38″ ~ 10 pc

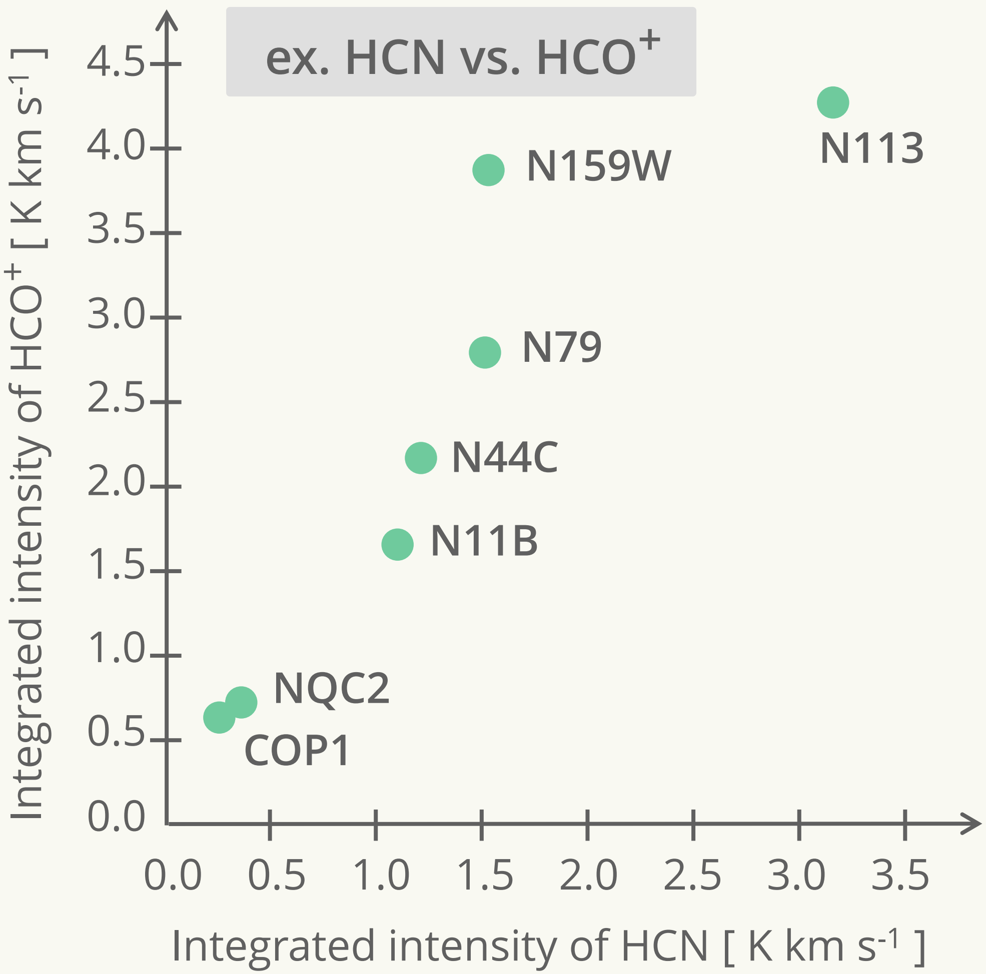
Similar spectral pattern



Similar spectral pattern



Resemblance of 7 clouds



Correlation coefficients of integrated intensity

$$c = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}}$$

x_i, y_i : integrated intensities

$\bar{x}, \bar{y}$: average of x_i, y_i

i : source #1-7

$HCN - HCO^+$

c = 0.908

Resemblance of 7 clouds

$$c = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}}$$

x_i, y_i : integrated intensities

$\bar{x}, \bar{y}$: average of x_i, y_i

i : source #1-7

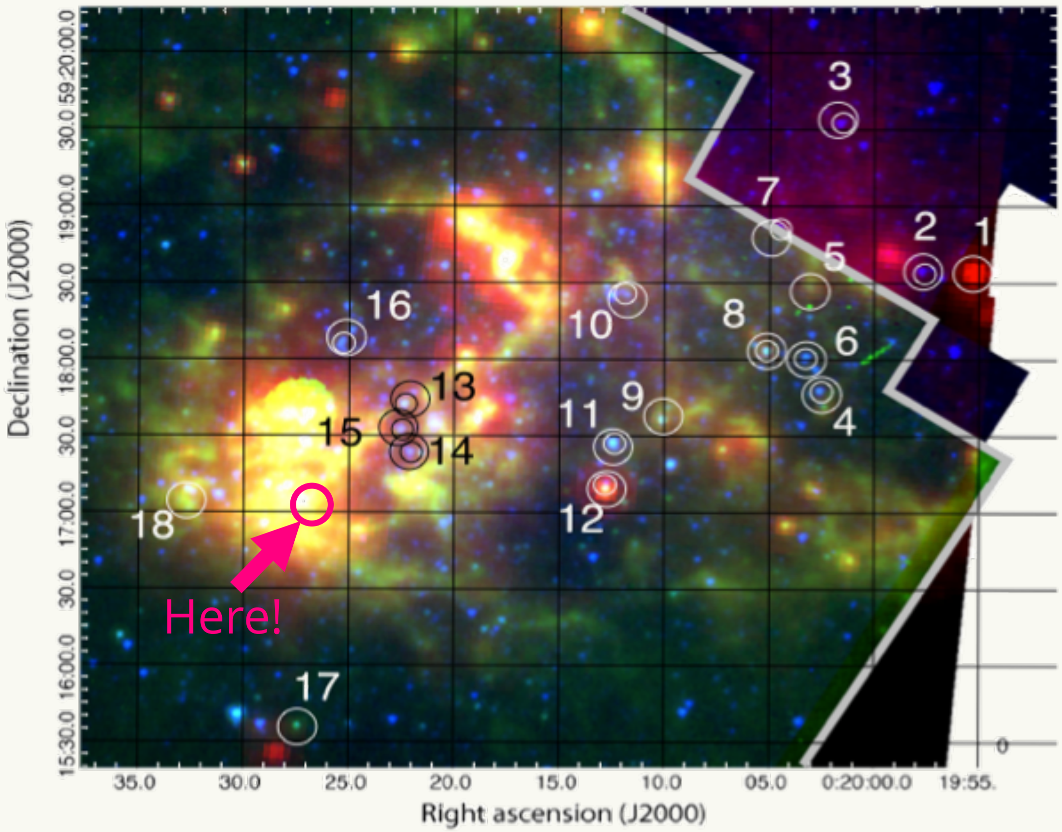
Correlation coefficients
of integrated intensity among 7 clouds

	CCH	HCN	HCO^+	HNC	CS	SO	^{13}CO
CCH	1.000						
HCN	0.974	1.000					
HCO^+	0.937	0.908	1.000				
HNC	0.901	0.912	0.928	1.000			
CS	0.862	0.845	0.925	0.963	1.000		
SO	0.895	0.870	0.948	0.983	0.985	1.000	
^{13}CO	0.555	0.549	0.691	0.824	0.812	0.845	1.000

high correlation

Another target galaxy: **IC10**

Spitzer MIPS [24 μm], IRAC [8.0, 3.6 μm]



Lebouteiller et al. 2012

We selected the CO-brightest cloud as a target.

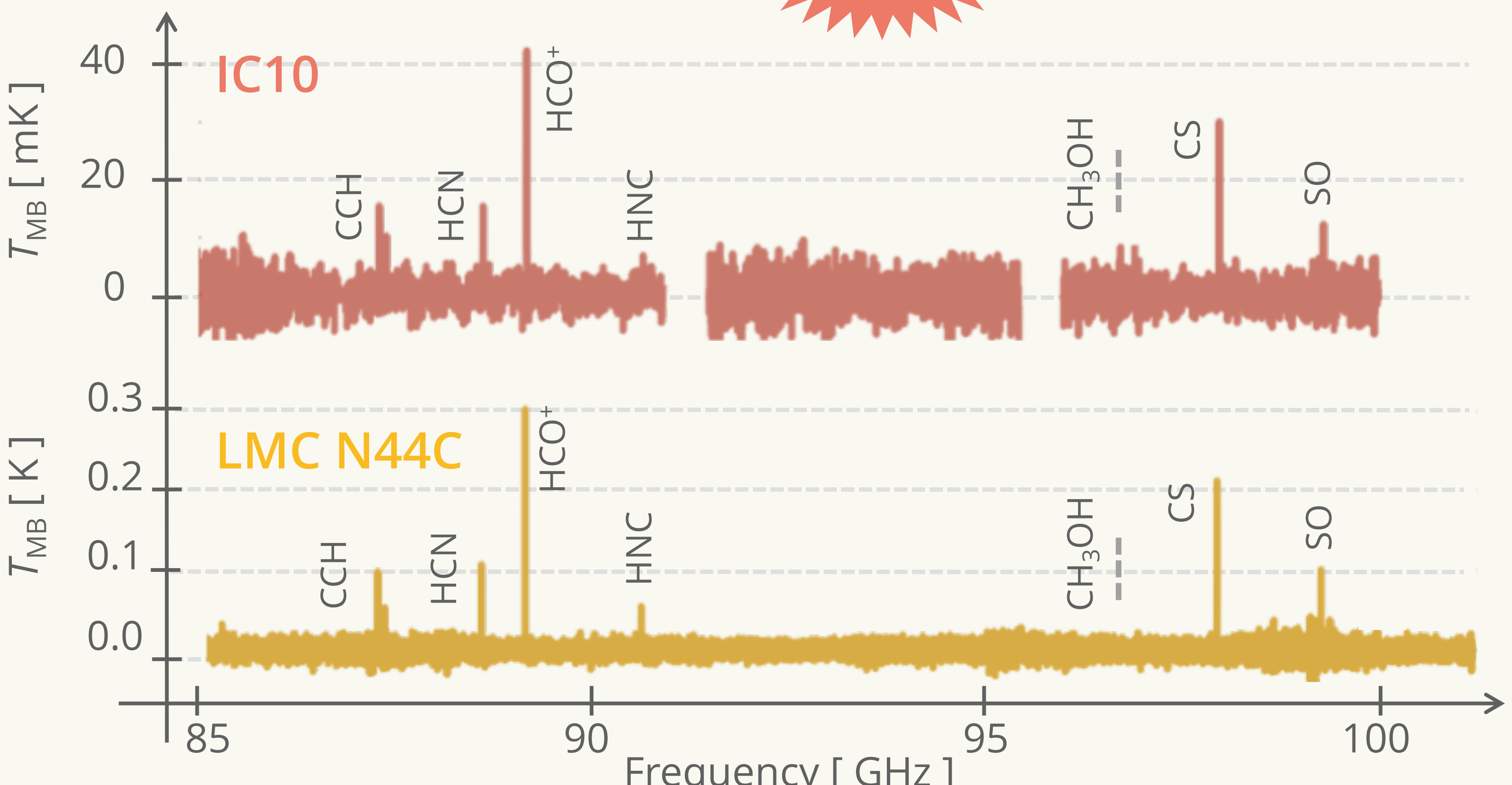
- CO 1-0
  Leroy et al. 2006
- CO 2-1 & 3-2
  Petitpas & Wilson 1998

- 1 GMC
- 55 hours
- NRO 45 m
- HPBW = 17″
  ~ 80 pc

Again **similar** spectral pattern

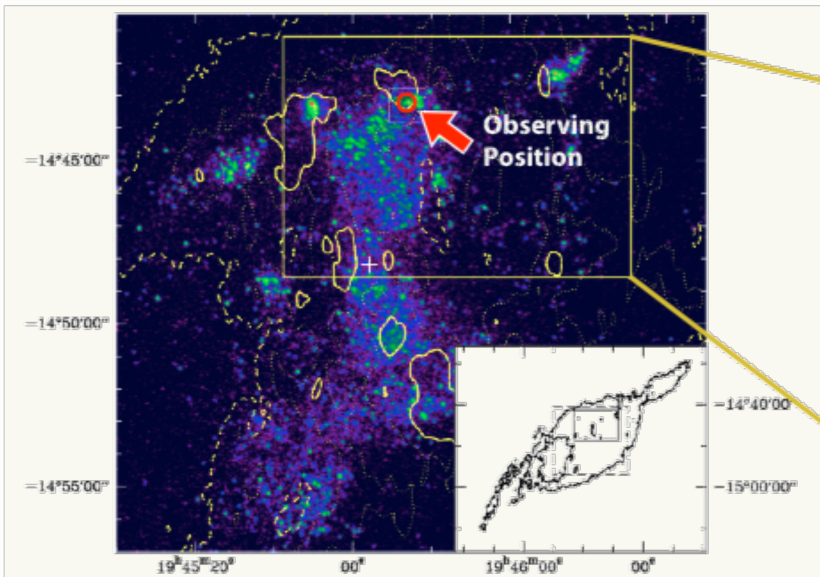
Nishimura et al. 2016, ApJ, 829, 94

Chemical composition of IC10 is **similar** to that of the LMC.

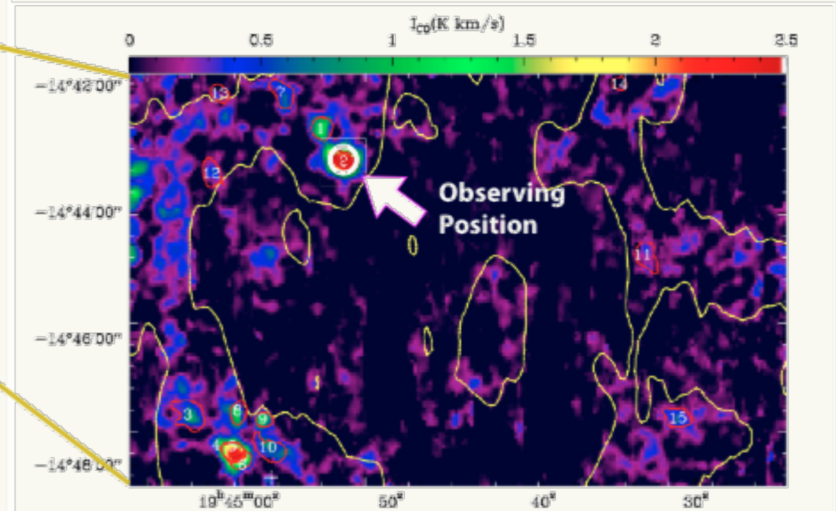


The other target galaxy: **NGC6822**

GALEX FUV image



CO (2-1) intensity map

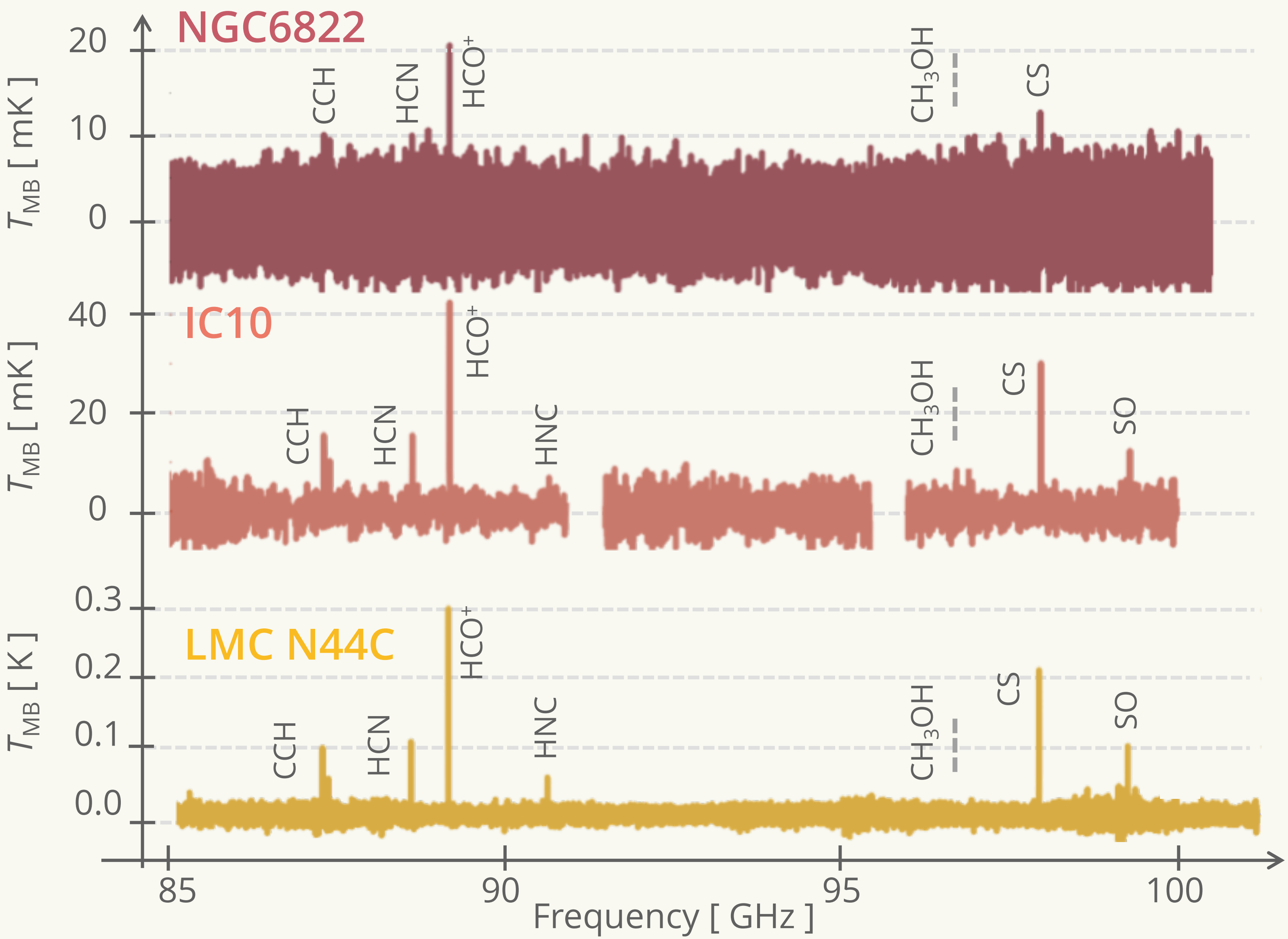


Gratier et al. 2010

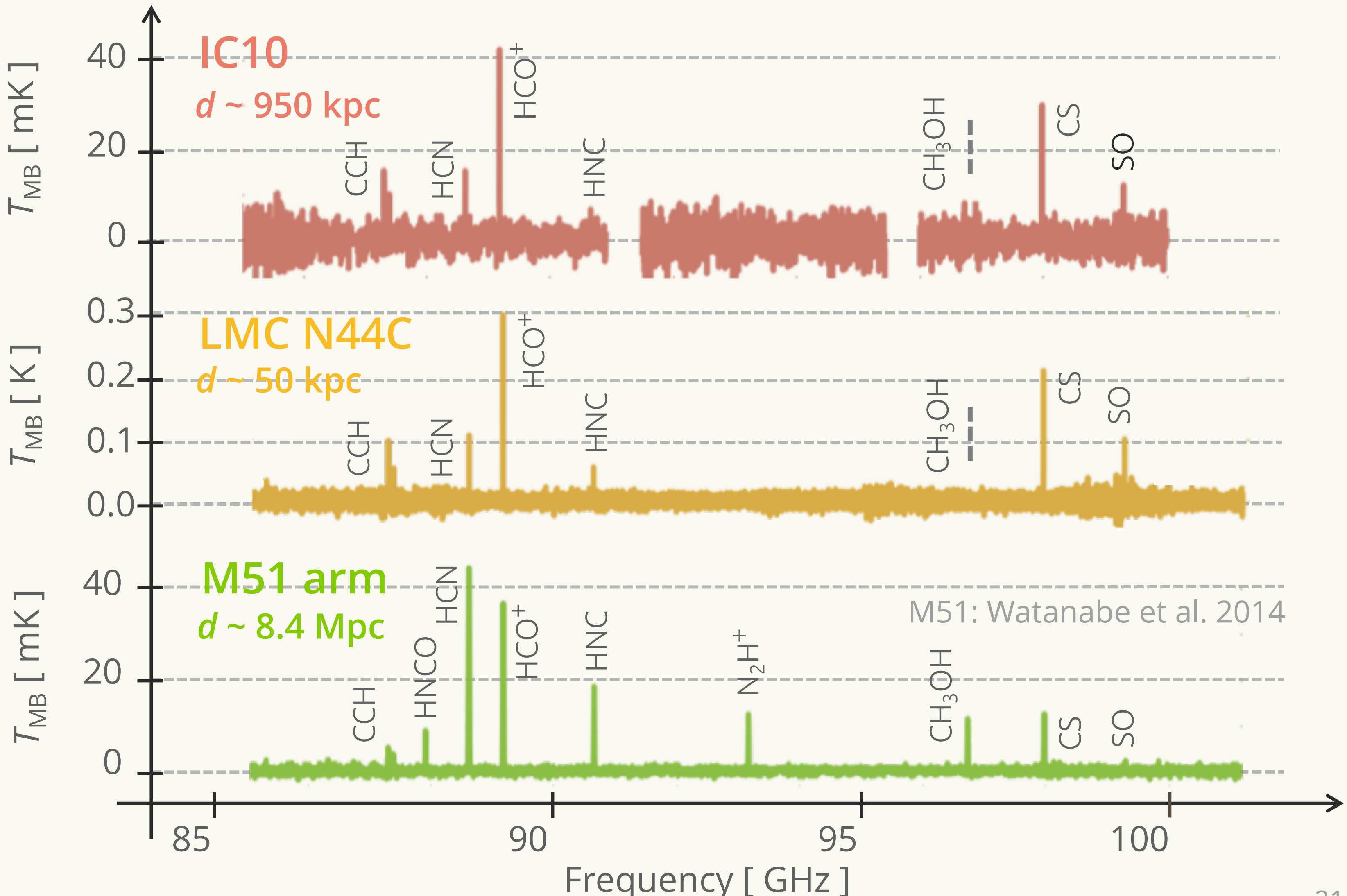
- The brightest HII region: Hubble V
- CO 2-1 & 3-2 multiline analysis
  by Petitpas & Wilson 1998

- 29 hours
- IRAM 30 m
- HPBW = 23″
  ~ 56 pc

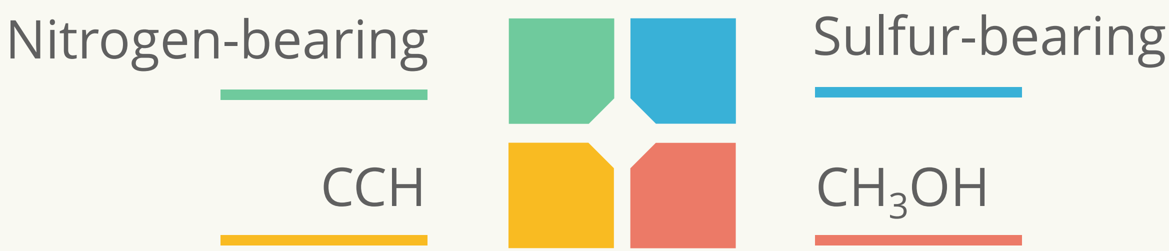
And again **similar** spectral pattern in **NGC6822**

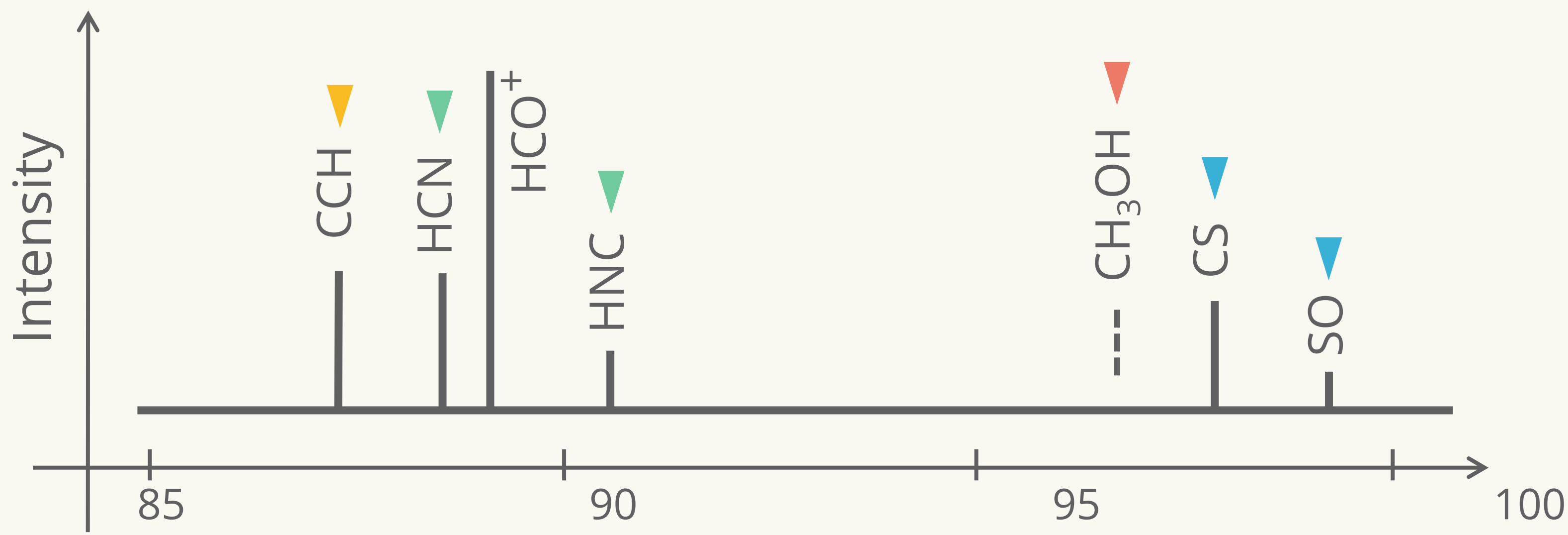


Metal-poor IC10/LMC and Metal-rich M51



Features of chemical composition
of low-metallicity **dwarf galaxies**





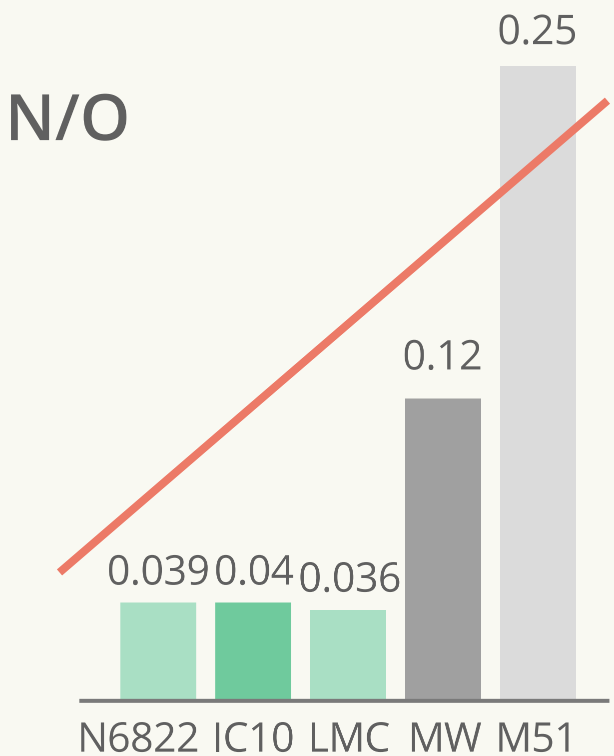
Direct impact: **Nitrogen**-bearing species

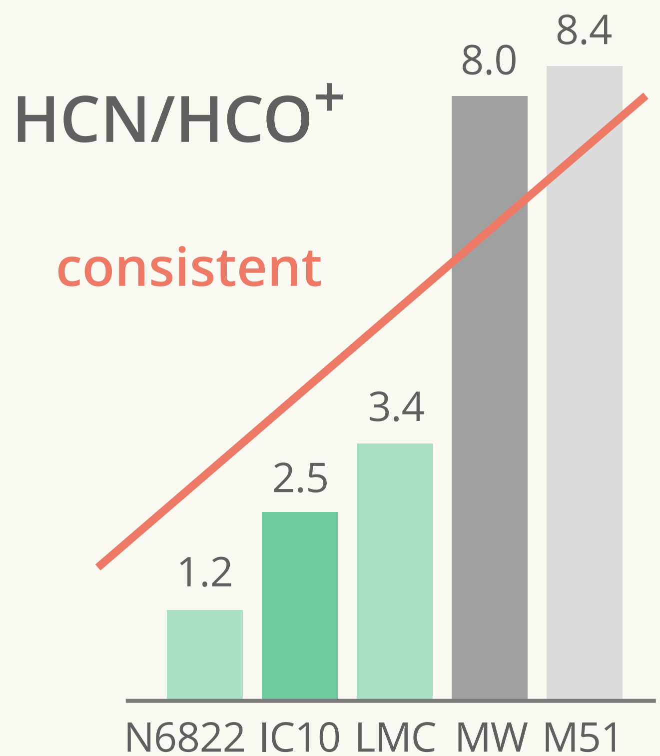
Abundance ratio	NGC6822	IC10	LMC		Milky Way	M51
N/O	0.039	0.04	0.036	<	0.12	0.25
HCN/HCO^+	1.2	2.5	3.4	<	8.0	8.4
HNC/HCO^+	< 0.3	0.4	0.8	<	3.4	1.6

IC10: Nishimura et al. 2016, ApJ, 829, 94, LMC: Nishimura et al. 2016, ApJ, 818, 161
MW: Turner et al. 1995a, 1995b, 1996, 1997, M51: Watanabe et al. 2014

Elemental abundances impact **chemical compositions**

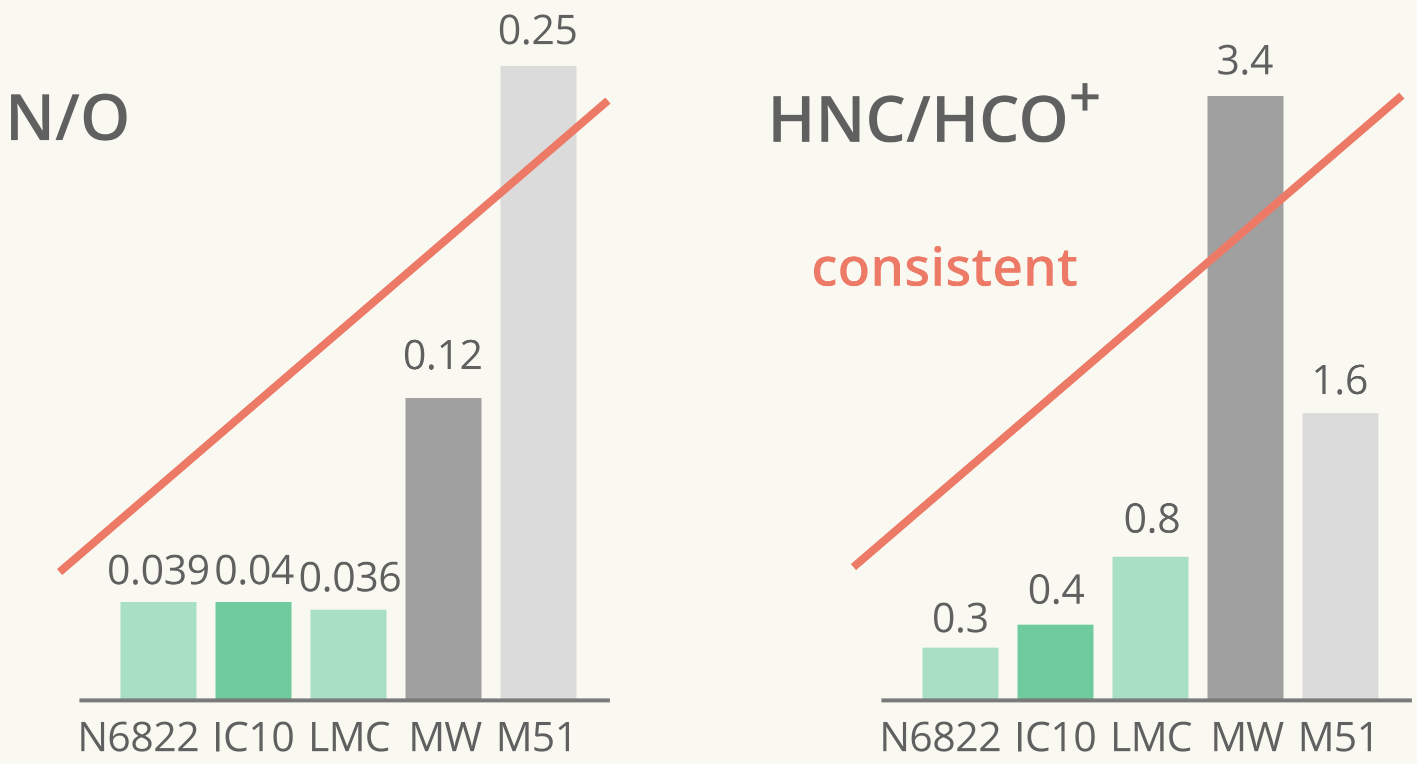
Direct impact: **Nitrogen**-bearing species





Elemental abundances → impact → **chemical compositions**

Direct impact: **Nitrogen**-bearing species



Elemental abundances impact **chemical compositions**

Relatively abundant **Sulfur**-bearing species

S/O ratio is NOT low in dwarf galaxies!

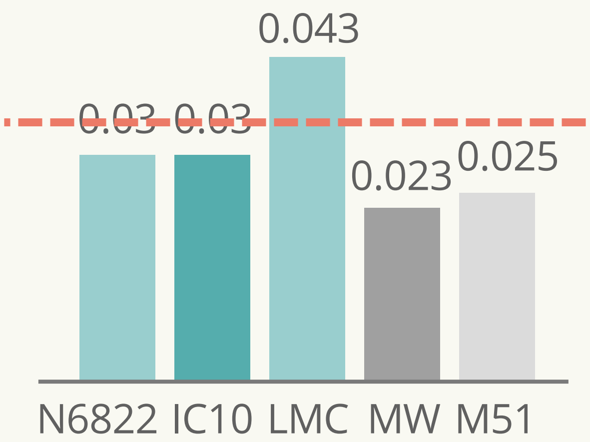
Abundance ratio	NGC6822	IC10	LMC	Milky Way	M51
S/O	0.03	0.03	0.043	0.023	0.025
CS/HCO^+	3.5	4.0	4.2	3.4	2.3

IC10: Nishimura et al. 2016, ApJ, 829, 94, LMC: Nishimura et al. 2016, ApJ, 818, 161
MW: Turner et al. 1995a, 1995b, 1996, 1997, M51: Watanabe et al. 2014

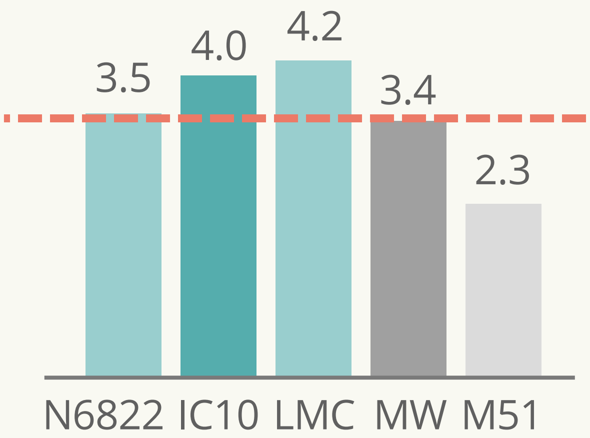
At least in HII region!
– In a molecular cloud, most of sulfur is depleted onto dust.

Relatively abundant **Sulfur**-bearing species

S/O

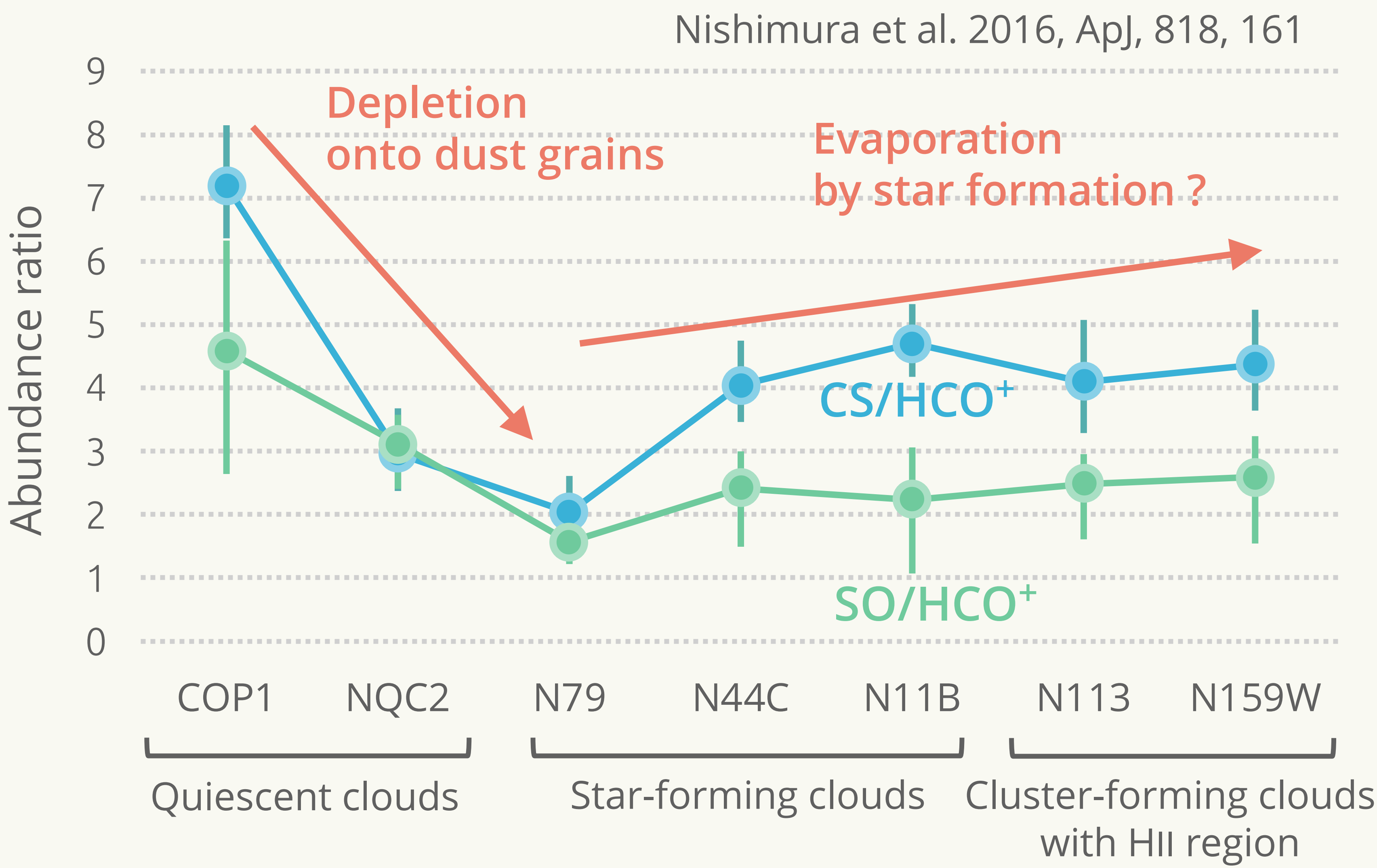


CS/HCO^+

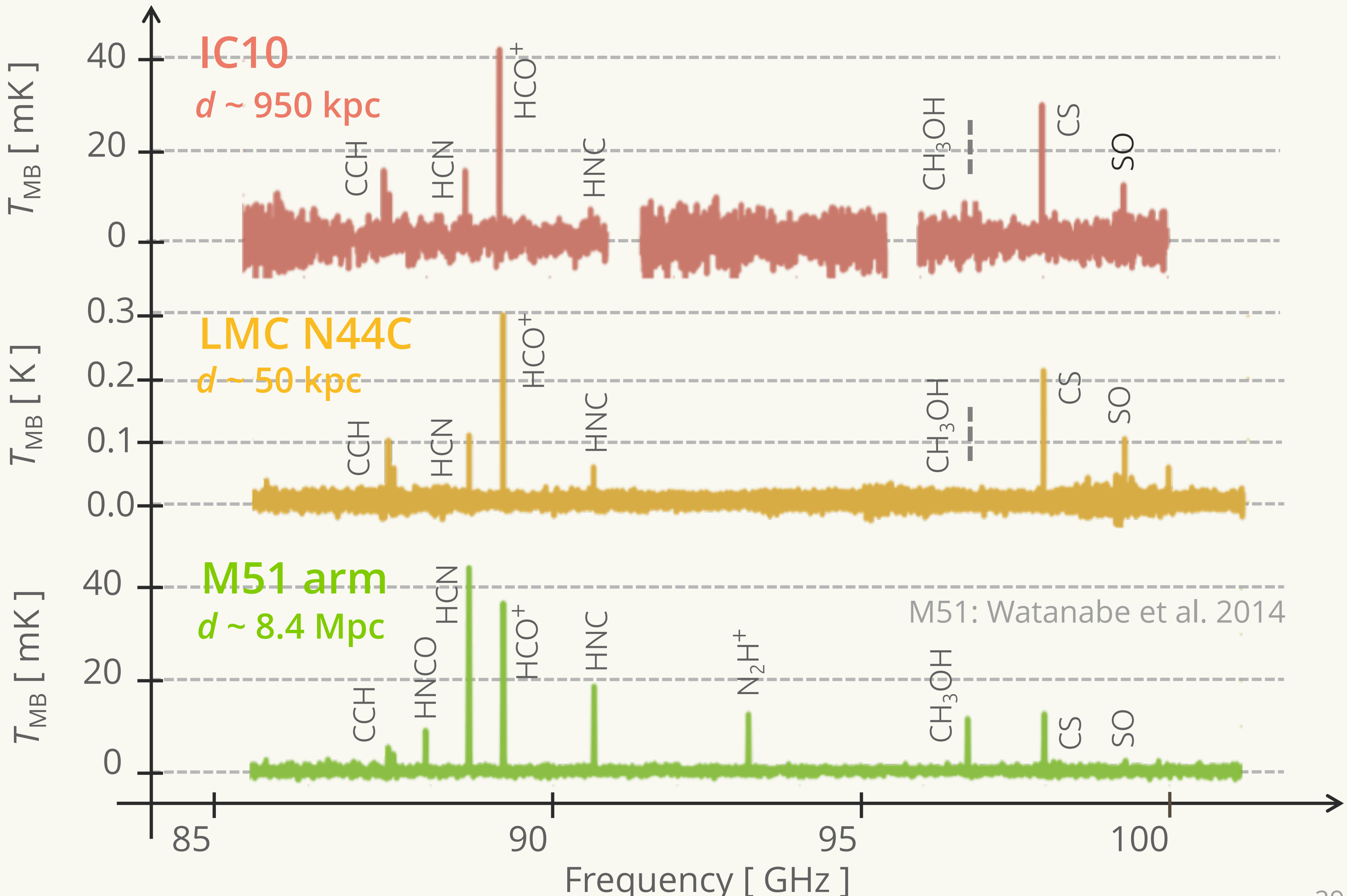


High S/O ratio + Lower abundance of dust ?

Variation of **Sulfur**-bearing species in the LMC



Metal-poor IC10/LMC and Metal-rich M51



Effect of UV: **Enhancement** of CCH

Not due to the difference of elemental abundances!

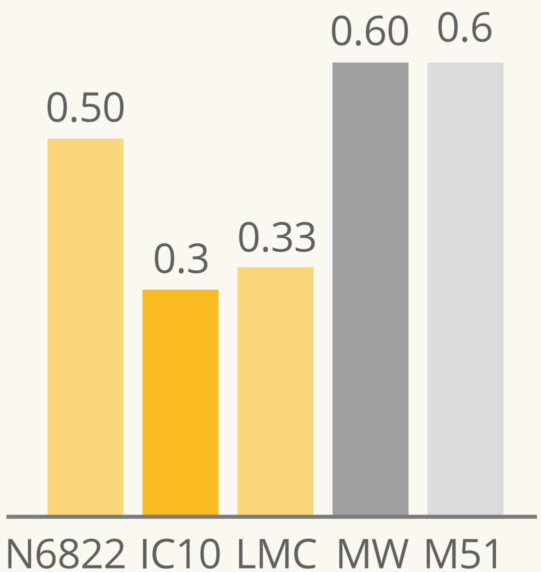
Abundance ratio	NGC6822	IC10	LMC		Milky Way	M51
C/O	0.5	0.3	0.33	$<$	0.60	0.6
CCH/HCO^+	16.7	17.5	13.9	$>$	5.3	9.1

IC10: Nishimura et al. 2016, ApJ, 829, 94, LMC: Nishimura et al. 2016, ApJ, 818, 161
MW: Turner et al. 1995a, 1995b, 1996, 1997, M51: Watanabe et al. 2014

Lower abundance of dust grains → extends → **PDR**

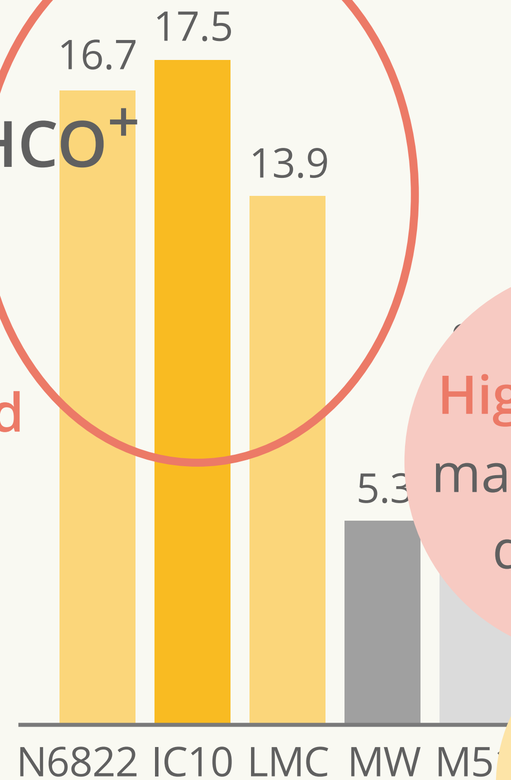
Effect of UV: **Enhancement** of CCH

C/O



CCH/HCO^+

Enhanced

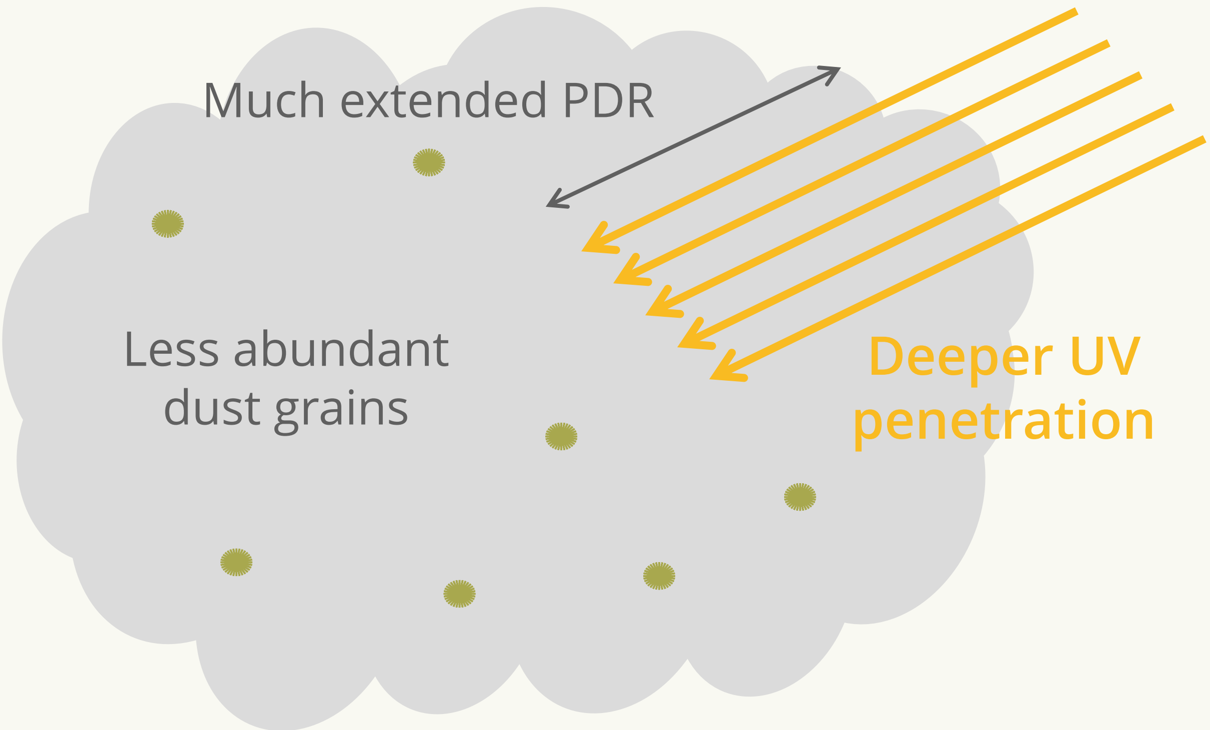


High *T* in PDR makes CH_3OH deficient.

CCH is enhanced in PDR.

Lower abundance of dust grains extends **PDR**

Effect of UV: **Enhancement** of CCH

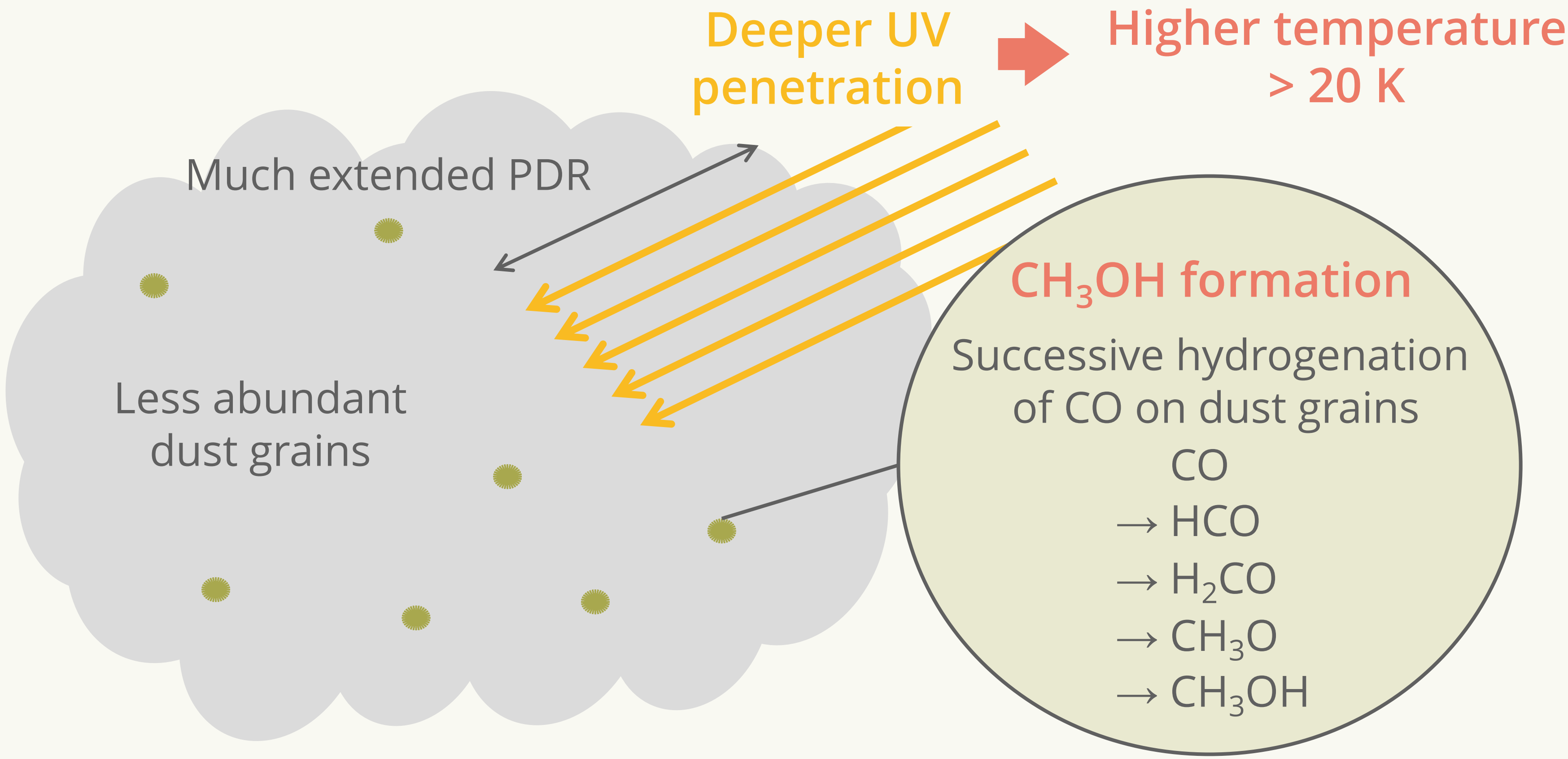


Extended PDR

- Less UV-shielding
- Photo-dissociation
  Photo-ionization
- Abundant C^+

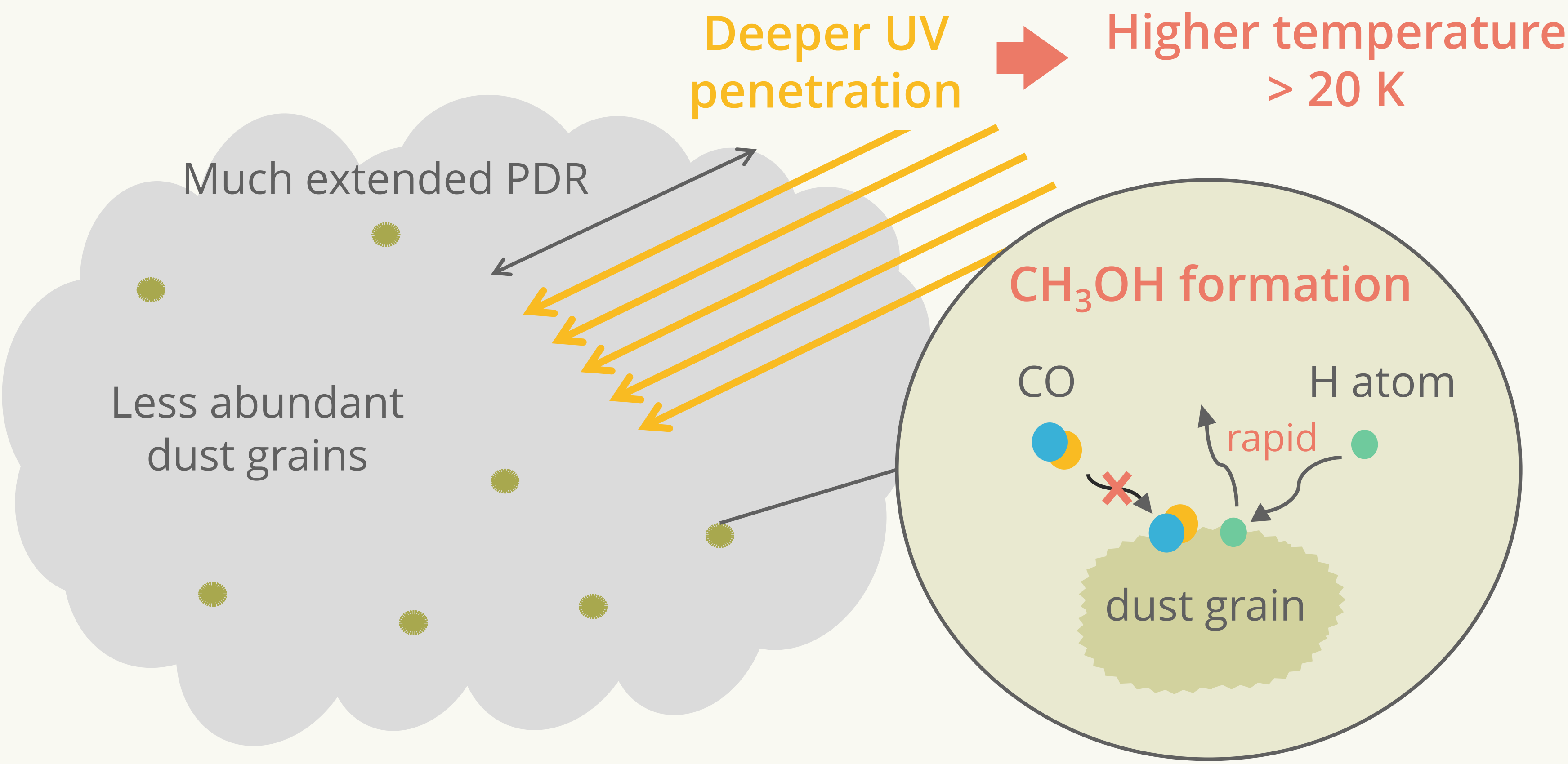
Lower abundance of dust grains → extends → **PDR**

Effect of UV: **Enhancement** of CCH



Lower abundance of dust grains → higher → **temperature** → decrease → **CH_3OH**

Effect of UV: **Enhancement** of CCH

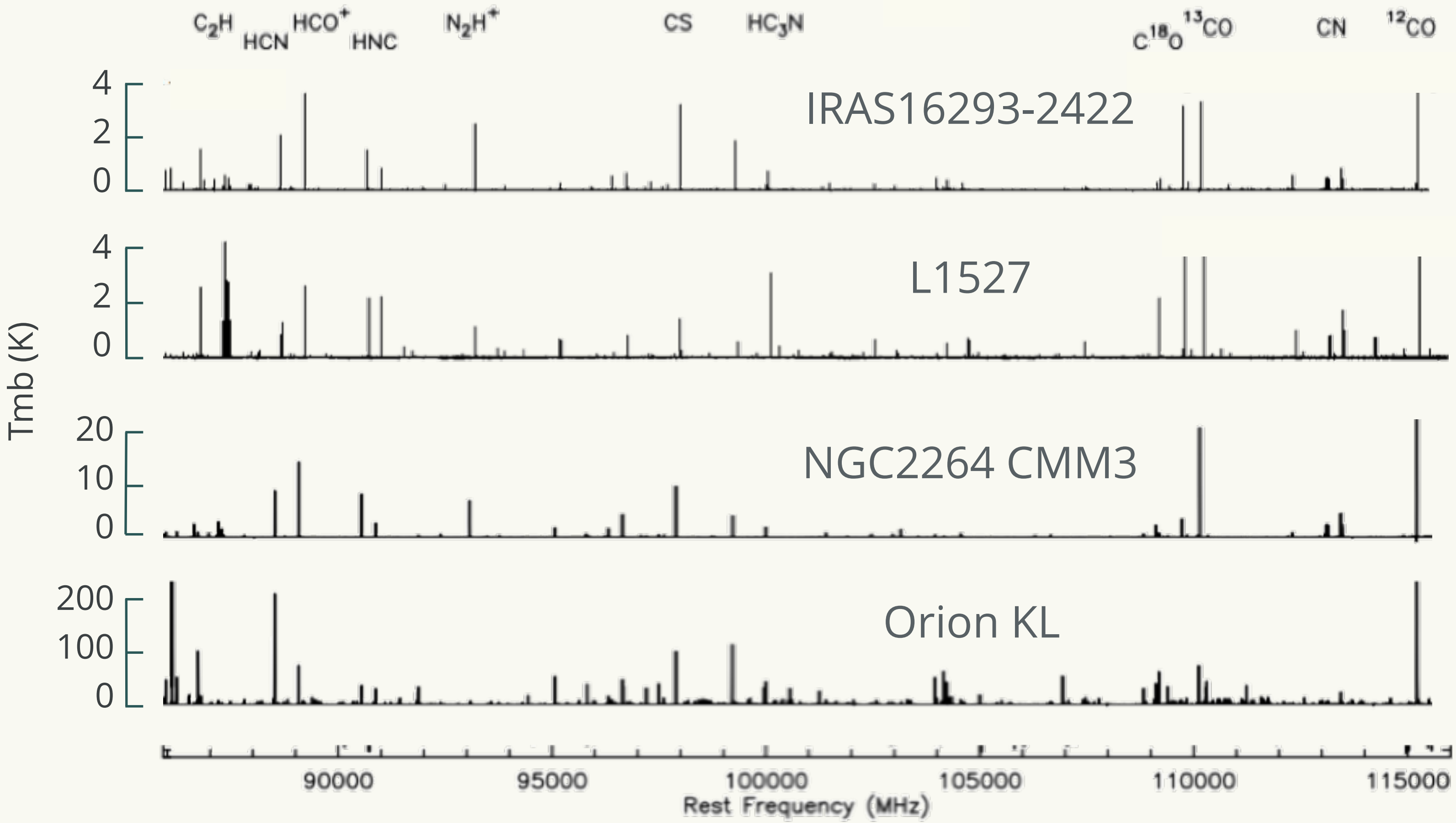


Lower abundance of dust grains → higher → **temperature** → decrease → **CH$_3$OH**

Molecular-cloud-scale chemical composition

Why molecular-cloud-scale chemical compositions are similar among molecular clouds?

Galactic star-forming regions



IRAS16293-2422: Caux et al. 2011,
L1527: Tokudome et al. 2013/Yoshida et al. in prep.
NGC2264 & Orion KL: Watanabe et al. 2015

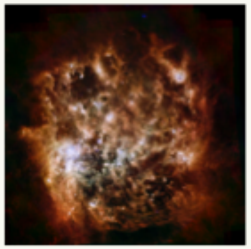
Galactic vs. Extragalactic

30″ 0.3″ resolution corresponds to…

Extragalactic

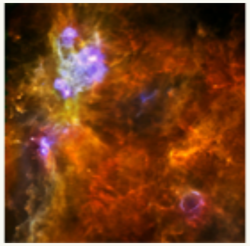
M51
D ~ 8.4 Mpc
12.6 pc

M83
D ~ 4.5 Mpc
6.75 pc



LMC
D ~ 50 kpc
0.075 pc

Galactic

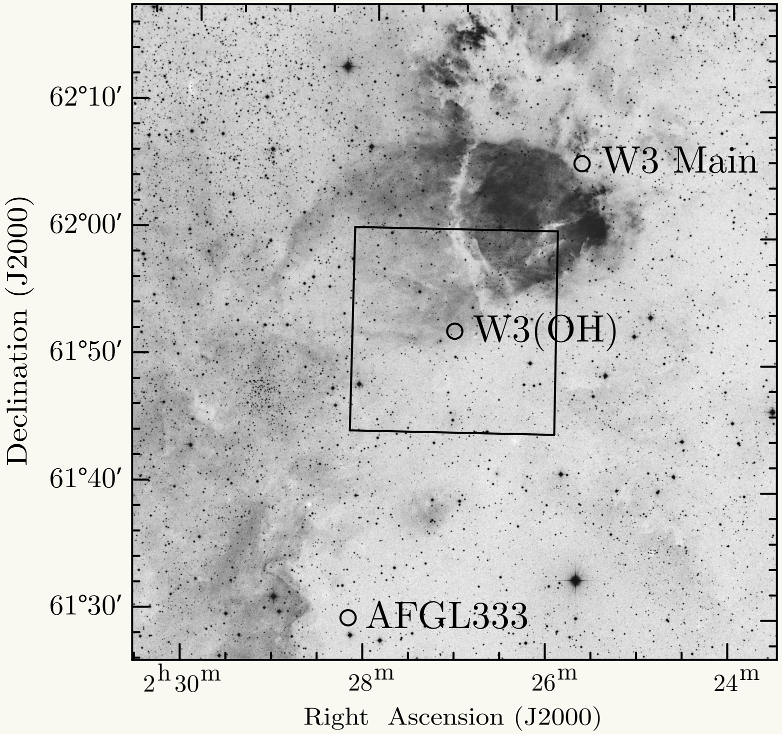


W3
D ~ 2 kpc
0.3 pc

Orion
D ~ 412 pc
0.06 pc

L1527
D ~ 140 pc
0.02 pc

Target and Observations

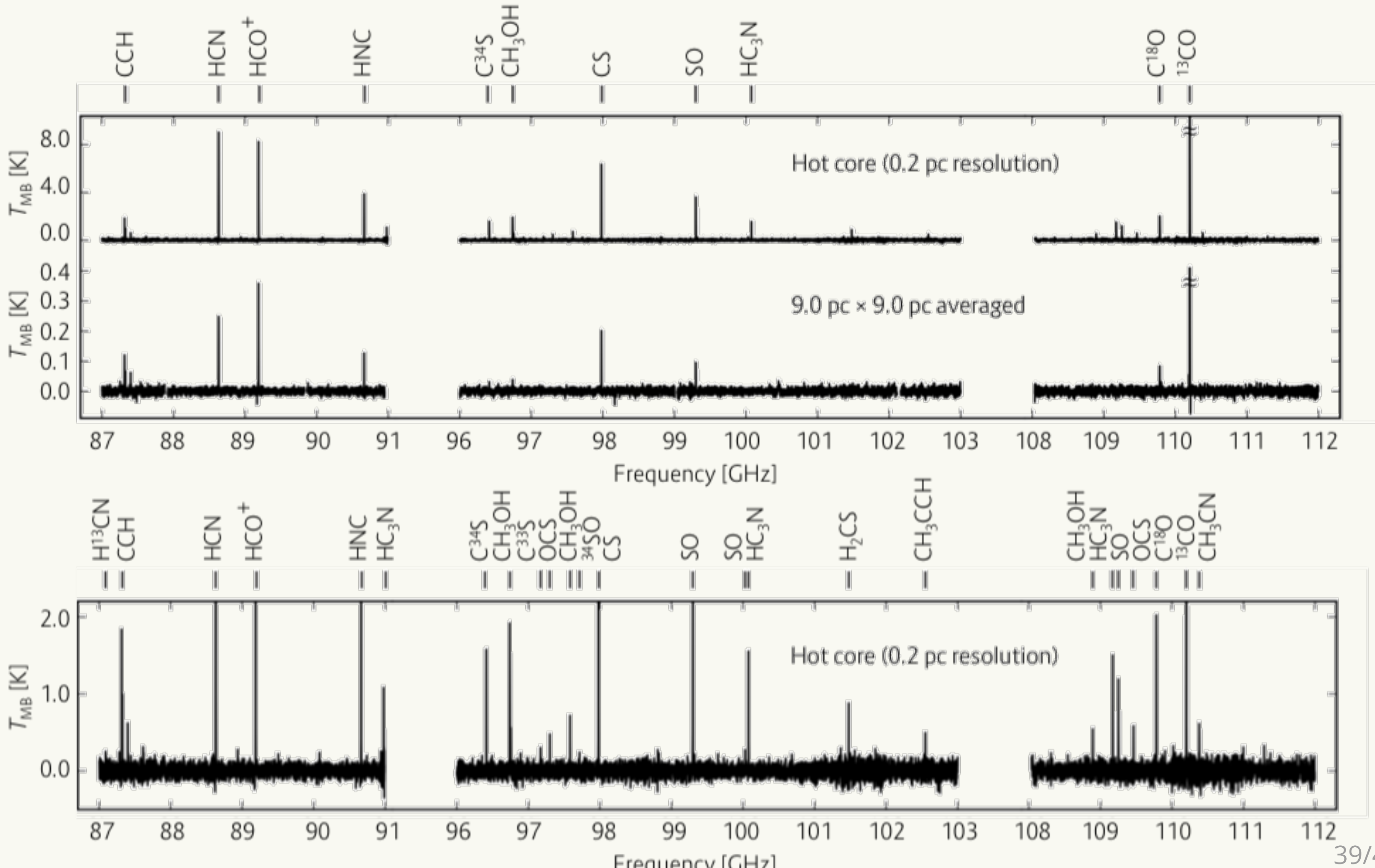


W3(OH): active star-forming region in the Perseus arm

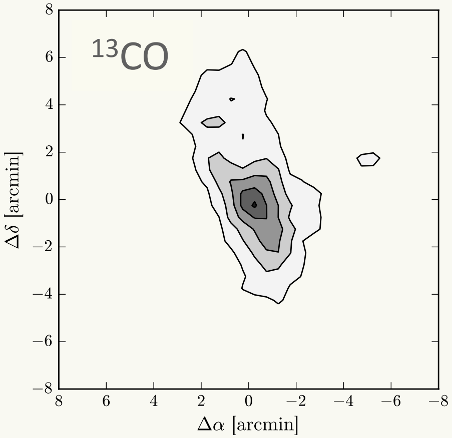
- NRO 45 m
- March 2015
- 3 mm (TZ/SAM45)
- On-The-Fly mode
- 16′ × 16′ (9 pc × 9 pc) area
- 20 hours in total

Results

W3(OH) hot core (0.2 pc resolution) / averaged over 9.0 pc × 9.0 pc area



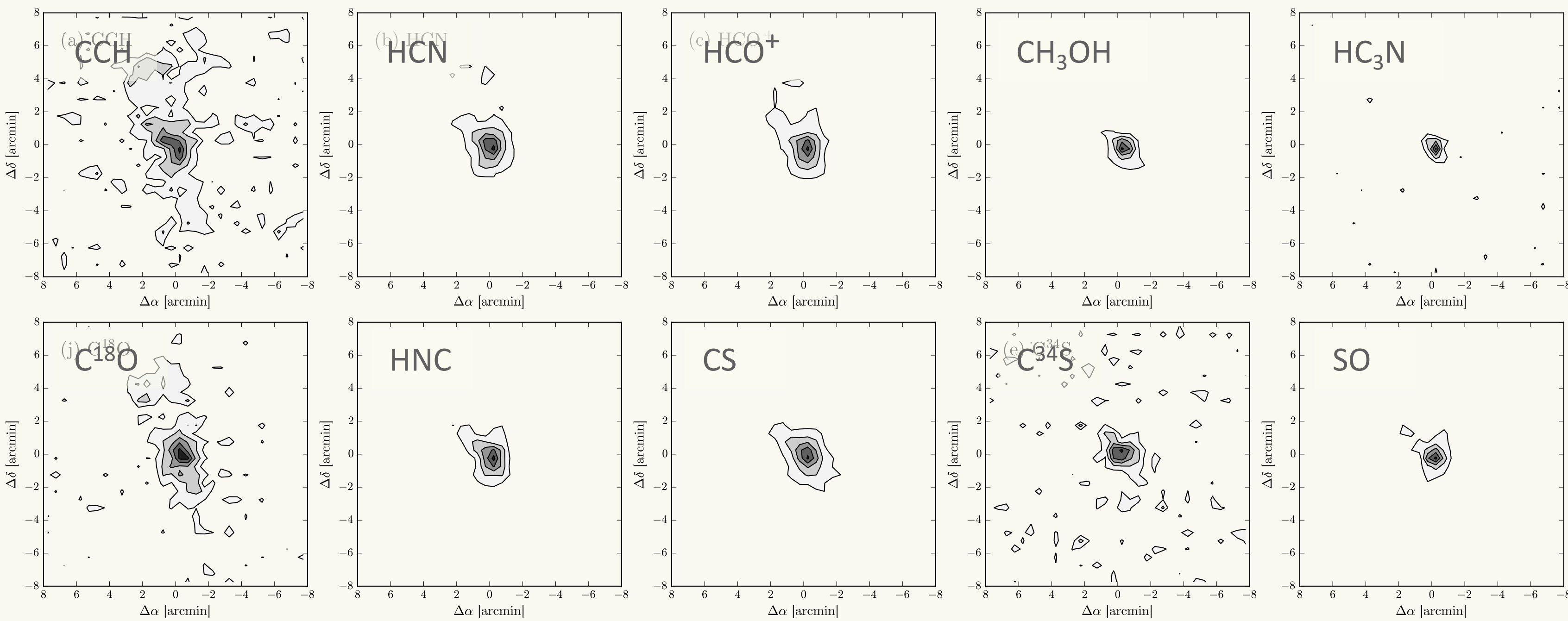
Integrated intensity map



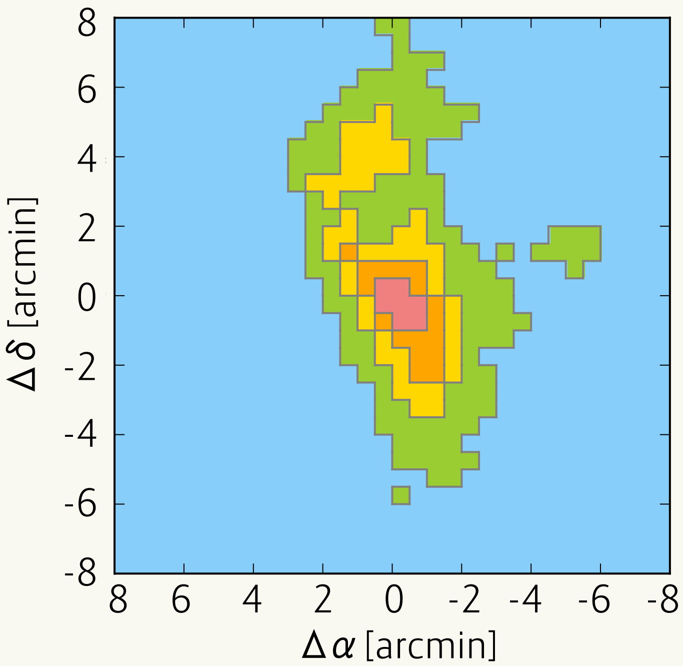
Integrated intensity maps of key molecules convolved to the 30’’ resolution.

Contour levels are (20%, 40%, 60%, 80%, 100%) of the peak integrated intensities.

Widespread ——— Concentrated



Classification of **5 sub-regions** according to ^{13}CO intensity

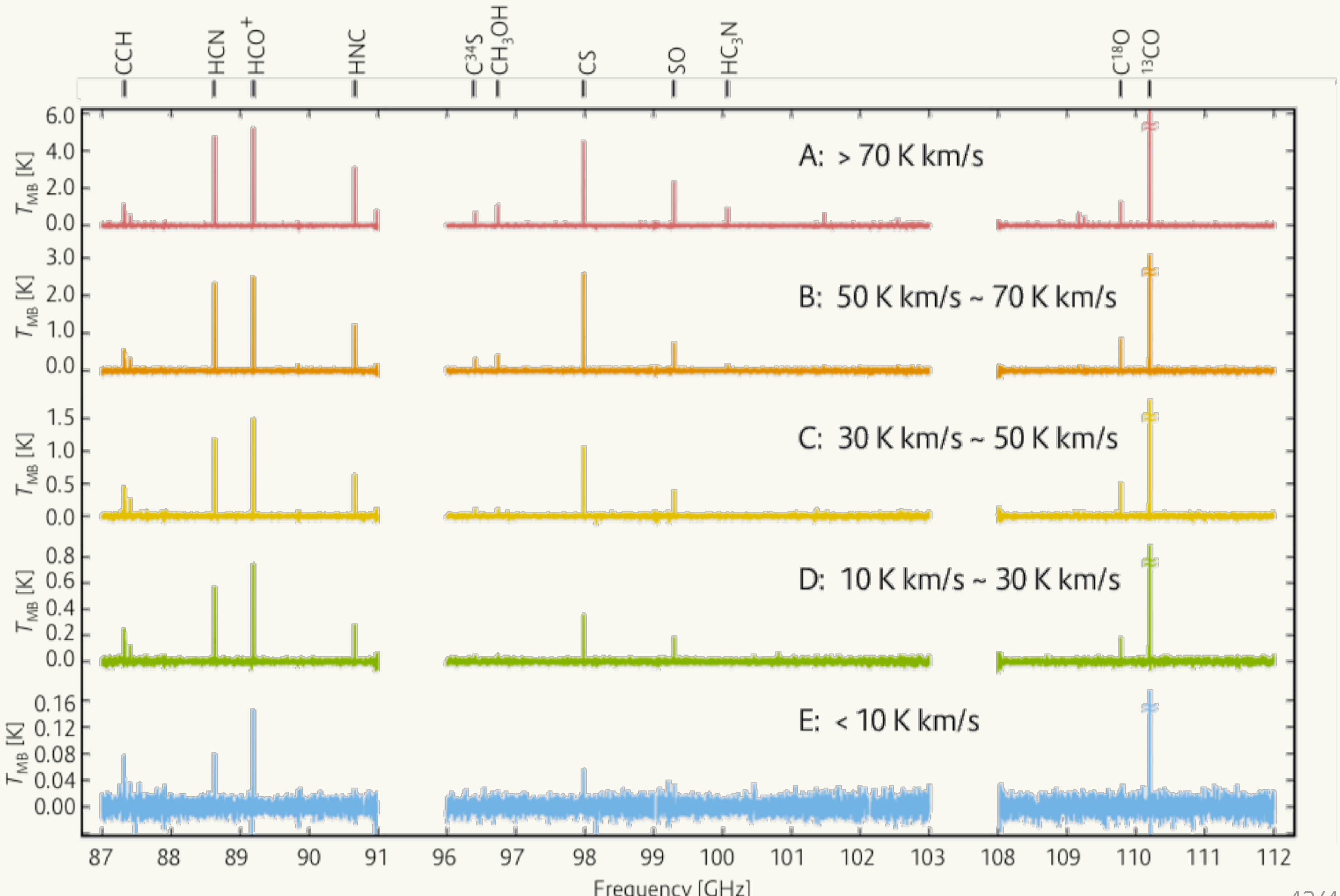


According to the integrated intensity of ^{13}CO, we classified the mapped area into 5 sub-regions.

Sub-region

- A : > 70 K km s^{-1}
- B : 50 K km s^{-1} ~ 70 K km s^{-1}
- C : 30 K km s^{-1} ~ 50 K km s^{-1}
- D : 10 K km s^{-1} ~ 30 K km s^{-1}
- E : < 10 K km s^{-1}

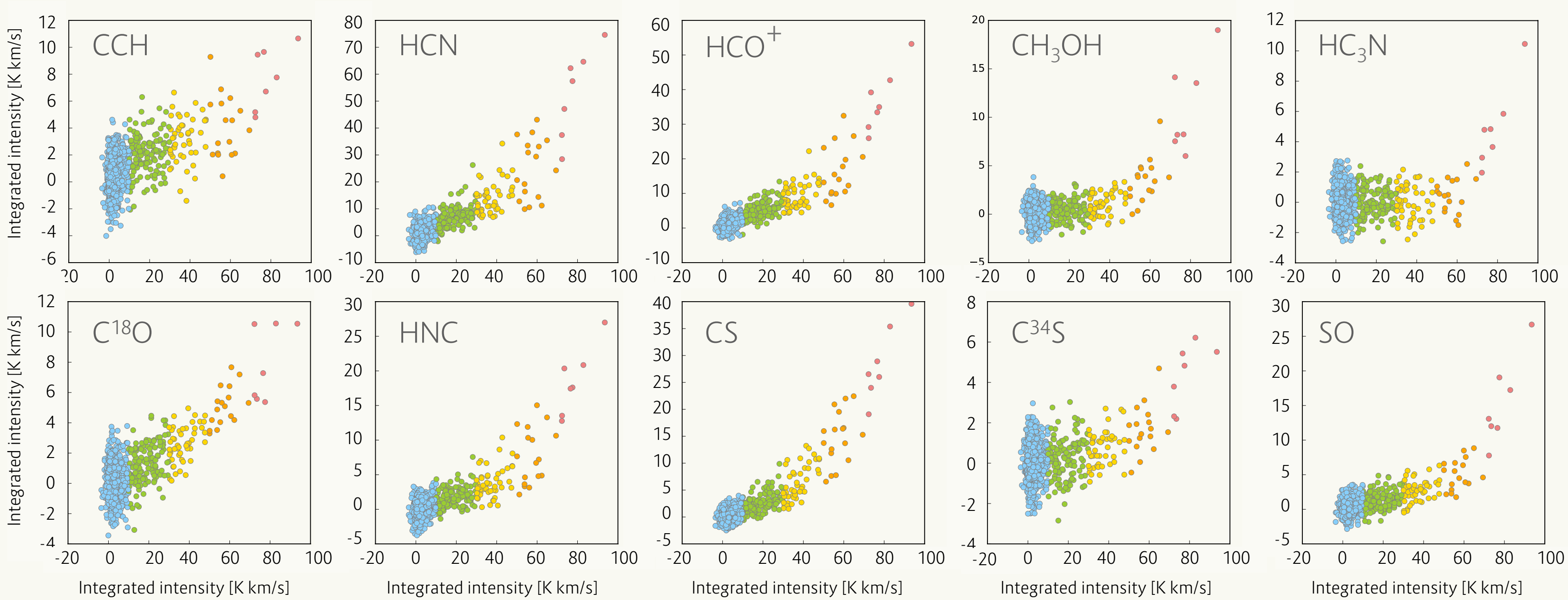
Discussion: **Averaged** spectra of each sub-region



Correlation between integrated intensity of ^{13}CO

x-axis: integrated intensity of ^{13}CO

y-axis: integrated intensity of a given molecule

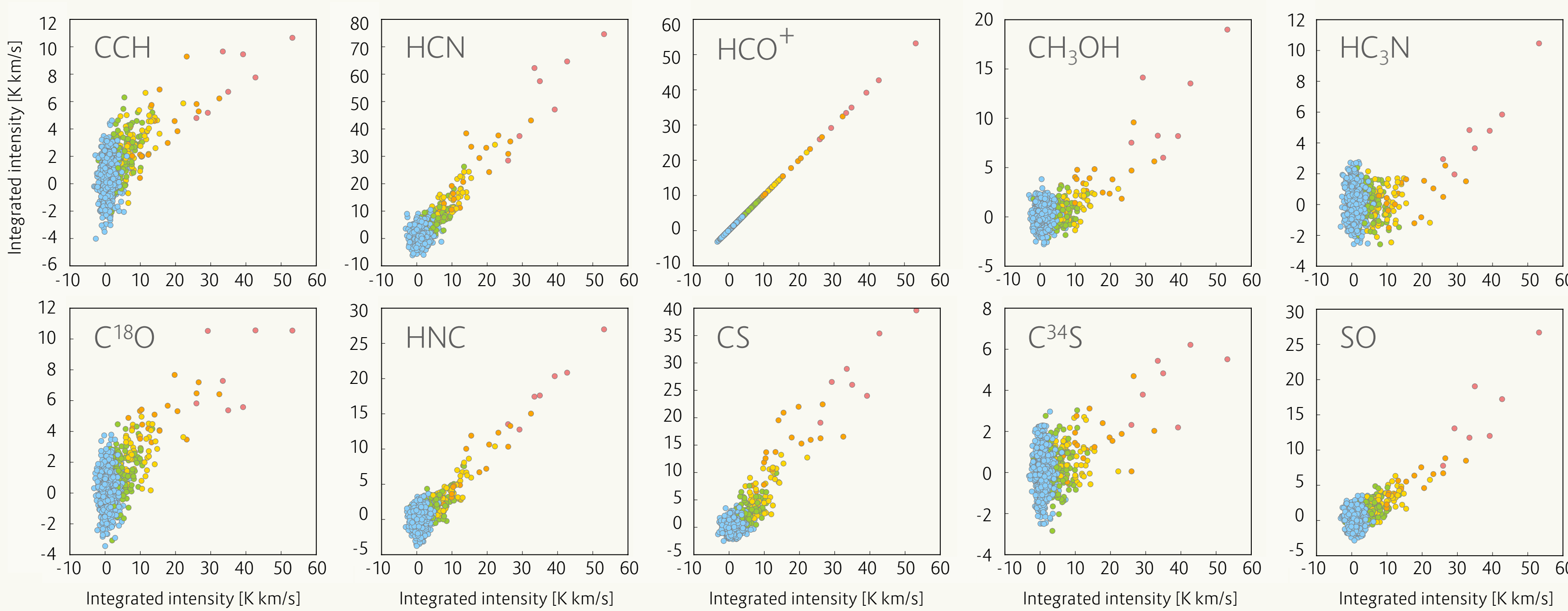


Different knee point!

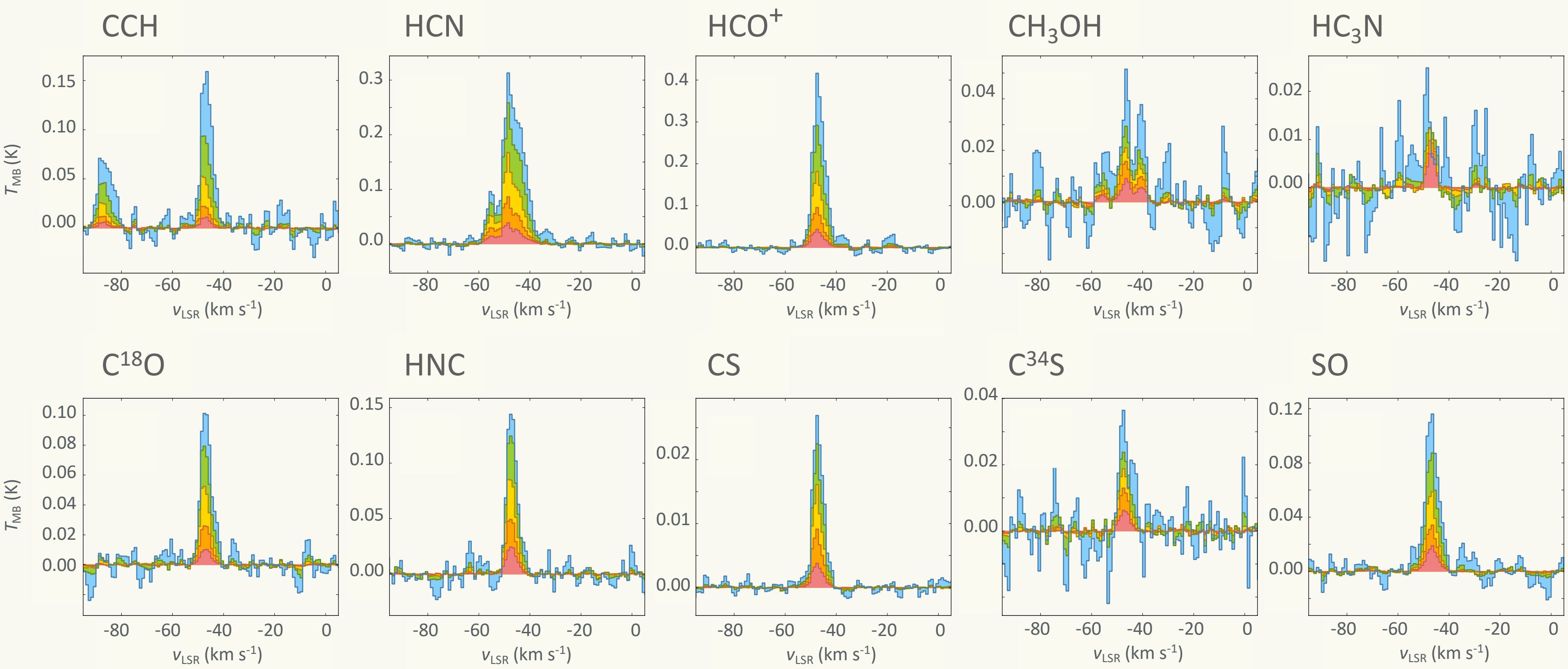
Correlation between integrated intensity of **HCO^+**

x-axis: integrated intensity of HCO^+

y-axis: integrated intensity of a given molecule



Fractional flux from each sub-region

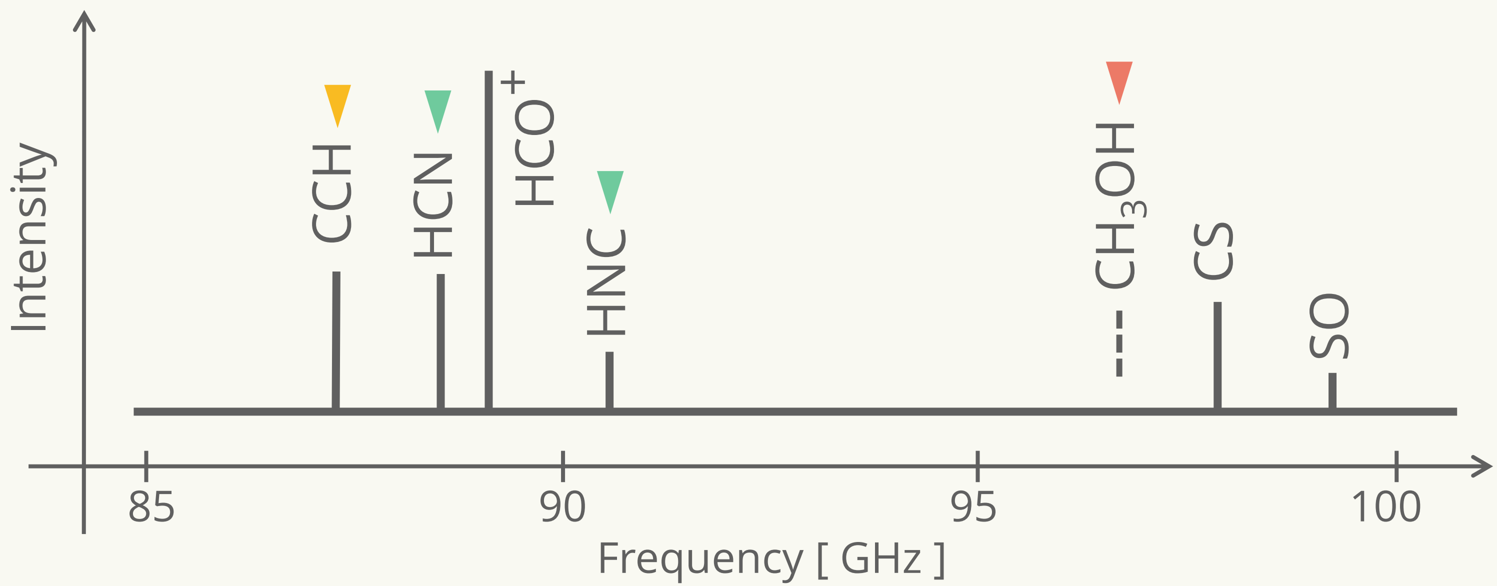


Contribution from the cloud peripheries is not small or dominant!

Summary

Characteristic features in low-metallicity galaxies

Elemental abundance	UV radiation & PDR	dust grains & UV radiation
↓	↓	↓
N- and S-species	**Enhanced CCH**	**Deficient CH_3OH**



Summary

Characteristic features in low-metallicity dwarf galaxies

Elemental abundance	UV radiation & PDR	dust grains & UV radiation
↓	↓	↓
N- and S-species	**Enhanced CCH**	**Deficient CH_3OH**

Diffuse part is a key to molecular-cloud-scale spectrum

We will conduct molecular-cloud-scale mapping observation of W3(OH)

in the 0.8 mm band with JCMT!

Molecular-cloud-scale mapping observation toward W3(OH) in the 0.8 mm band

PI: Yuri Nishimura

Background: Chemical diagnostics in extragalactic study

Thanks to the increased sensitivity and widened bandwidth of receicers, various molecular lines are now readily observed even toward external galaxies. Indeed, molecular line surveys have been conducted toward various kinds of galaxies, and have revealed their chemical compositions (e.g., Aladro et al. 2015). Chemical composition will be a powerful probe for star-forming activities in external galaxies, if we could link it to astrochemical concepts established in nearby star-forming regions in our Galaxy. Yet, comparison between extragalactic and Galactic observations is not straightforward. While we can readily resolve individual dense cores (< 0.1 pc) for Galactic sources, an available spatial resolution for extragalactic sources is a molecular-cloud scale (several ten pc) even with ALMA.

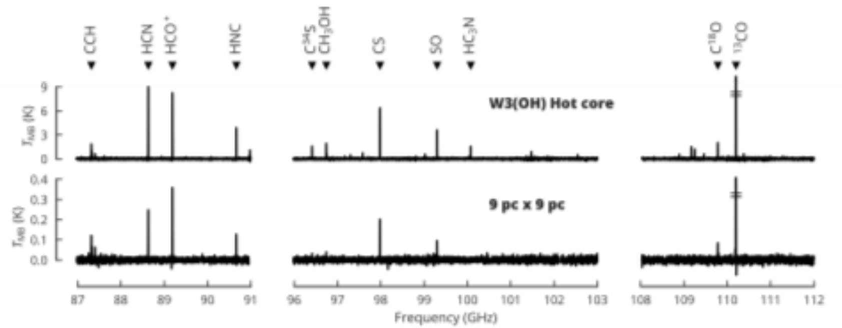


Fig. 1. Spectra observed toward the W3(OH) hot core and averaged over all the mapped area (9 pc $\times$ 9 pc).

Previous study: Molecular-cloud-scale observation of W3(OH) in the 3 mm band

To fill the spatial resolution gap between extragalactic and Galactic observations, a large-scale mapping observation toward Galactic clouds is useful. It provide us with a deep insight into the origin of the molecular-cloud-scale chemical composition, because we can study spatial distributions of molecules within a cloud. Hence, we have conducted a mapping line survey observation in the 3 mm band toward the Galactic high-mass star-forming region W3(OH) with NRO 45 m (Nishimura et al. 2017). The observation covers the $16' \times 16'$ area centered at the W3(OH) hot core, which corresponds to the linear size of 9 pc $\times$ 9 pc. Figure 1 shows the spectrum observed toward the W3(OH) hot core with a 0.15 pc beam and the spectrum averaged over all the mapped area (9 pc $\times$ 9 pc). The lines of CCH, HCN, HCO^+, HNC, CS, SO, $C^{18}O$, and ^{13}CO are strongly detected in the both spectra. However, intensity ratios of molecular lines between the hot core spectrum and the averaged spectrum are different from species to species.

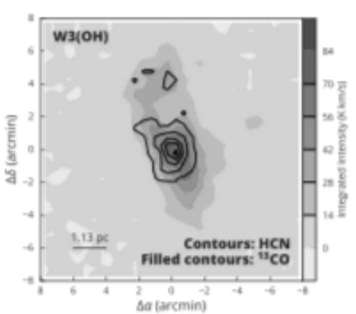


Fig. 2. Integrated intensity maps of the HCN line (contours) and the ^{13}CO line (filled contours) taken with NRO 45 m (Nishimura et al. 2017). The coordinates ($\Delta\alpha$, $\Delta\delta$) are the offsets from the W3(OH) hot core ($\alpha_{J2000} = 2^h27^m4.0^s$, $\delta_{J2000} = 61^\circ52'24.0''$).