分子輝線から銀河を理解するための
“分子雲”の星間化学

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About Me

- 西村 優里（にしむら ゆり）
- March 2017: PhD in physics (Supervisor: Prof. Yamamoto)
  @ Dept. of Physics, The University of Tokyo (Hongo)
- April 2017~: Postdoc (ALMA Research Fellow, Prof. Kohno)
  @ Institute of Astronomy, The University of Tokyo (Mitaka)
- Recent research interests:
  - Molecular cloud properties and star formation in nearby galaxies
  - Molecular and atomic lines in high-redshift galaxies
  - ISM cycle / metallicity evolution of galaxies
  - AGNs / starbursts / (U)LIRGs / the Galactic Center
  - Astrochemistry in general

Astrochemistry

Line Diagnostics — HCN/HCO^+ ?

Line Survey toward a Spiral Arm of M51

Large Magellanic Cloud

IC10, NGC6822

Molecular-Cloud-Scale Chemistry

W3(OH)

Bridge the Gap

Take Home Messages +α

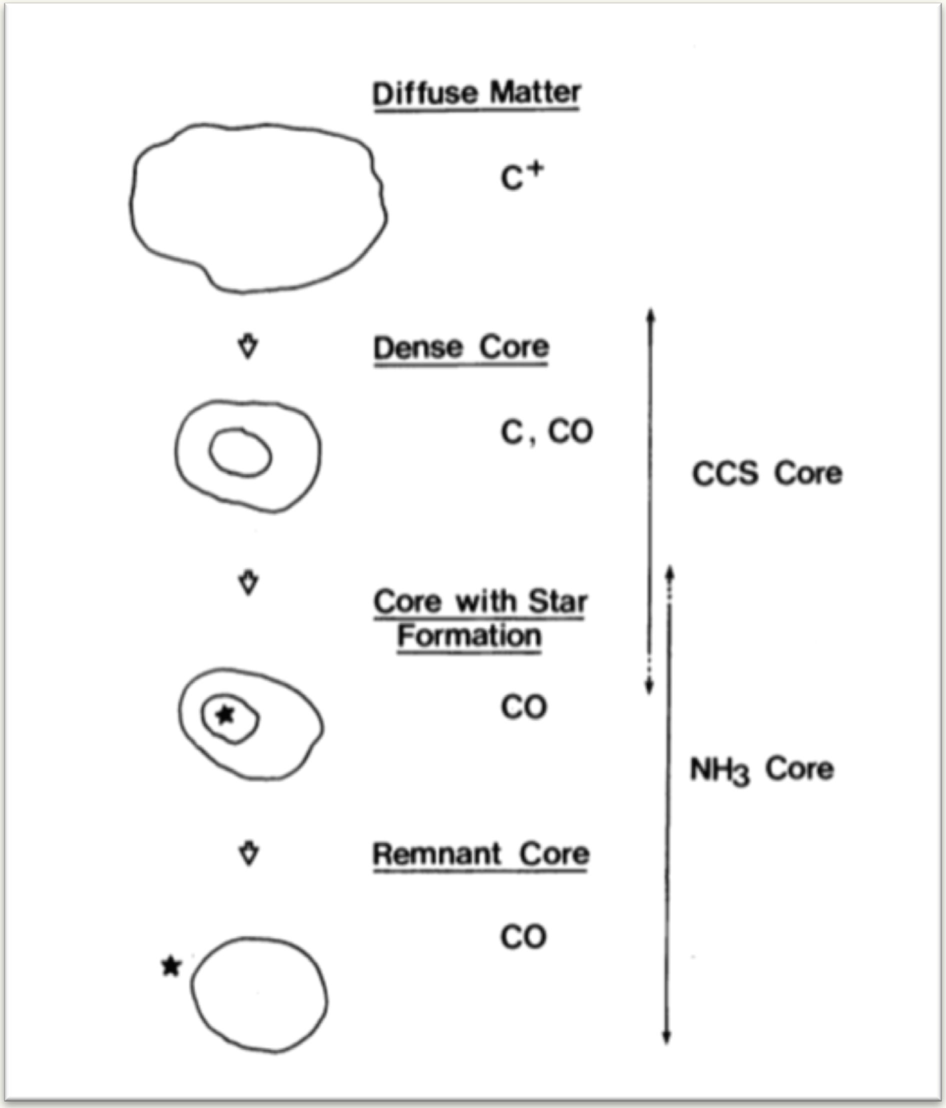
Astrochemistry

Chemical Evolution

Two different concepts according to the context

- Enrichment of heavy elements or metals by stellar nucleosynthesis and supernovae
- Evolution of molecular composition along star formation processes

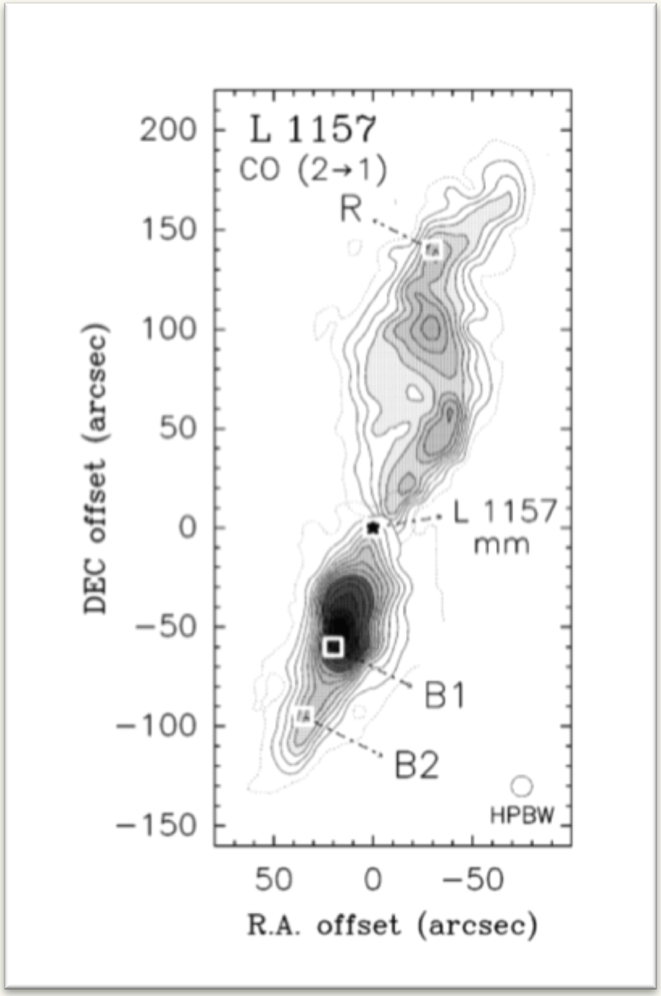
Astrochemistry: Evolution of Molecular Composition



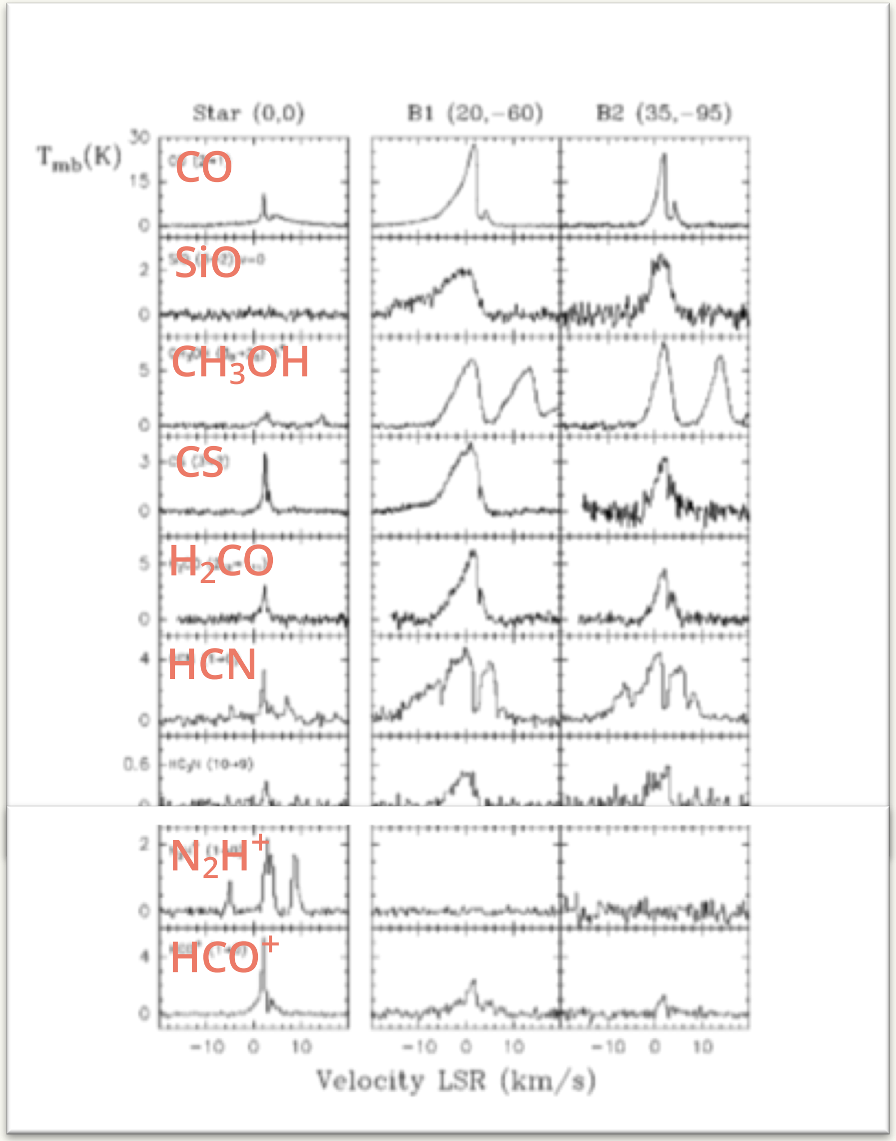
- Systematic change of major form of carbon:
  ionized carbon [CII]
  ↓
  atomic carbon [CI]
  ↓
  carbon monoxide CO
- Unsaturated organic molecules (carbon chain)
  ↓
  Nitrogen-bearing species

Suzuki et al. 1992

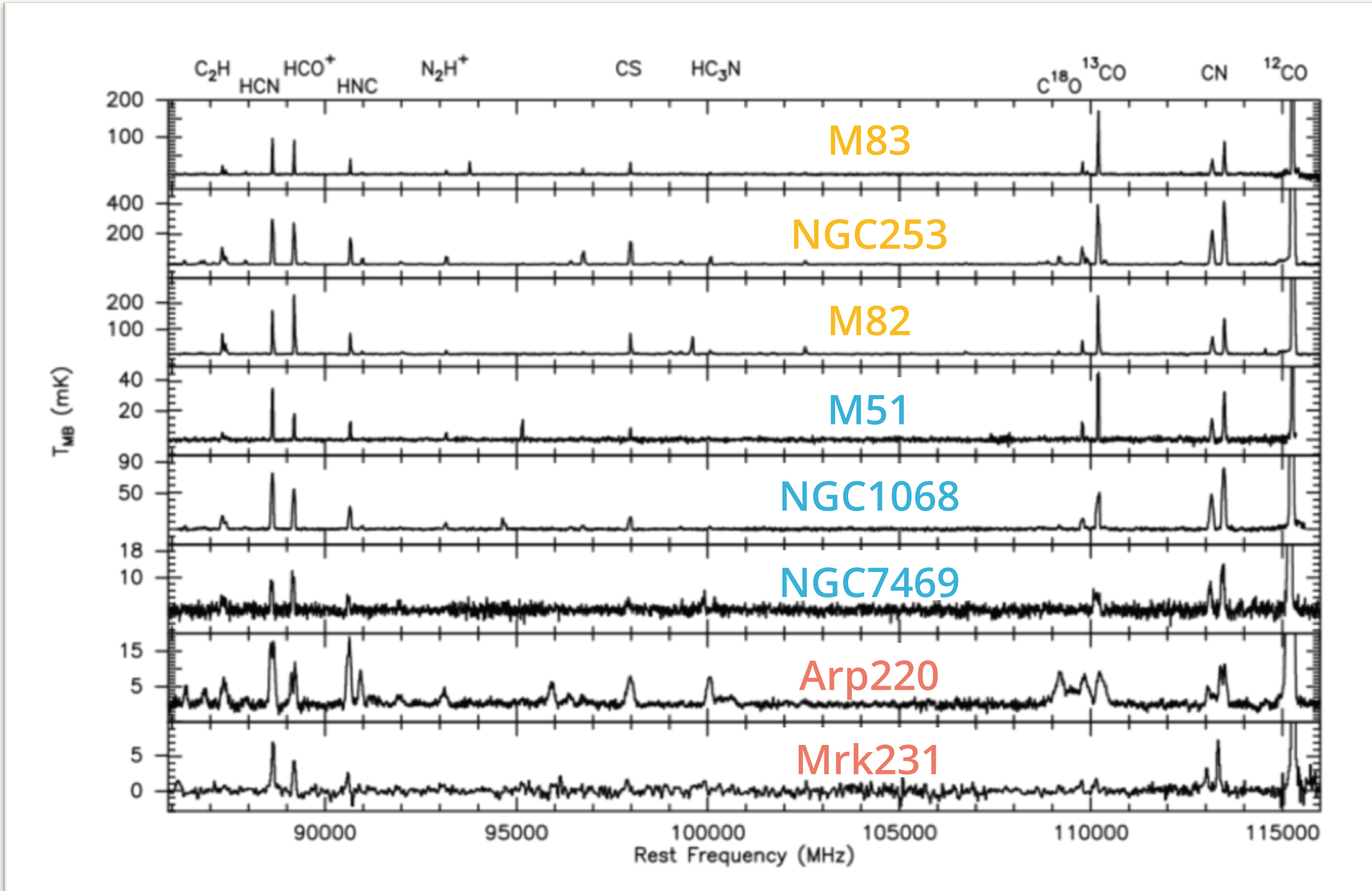
Astrochemistry: Dependency on Physical Environments



Bachiller & Pérez Gutiérrez 1997



Astrochemistry: Now Applied to External Galaxies

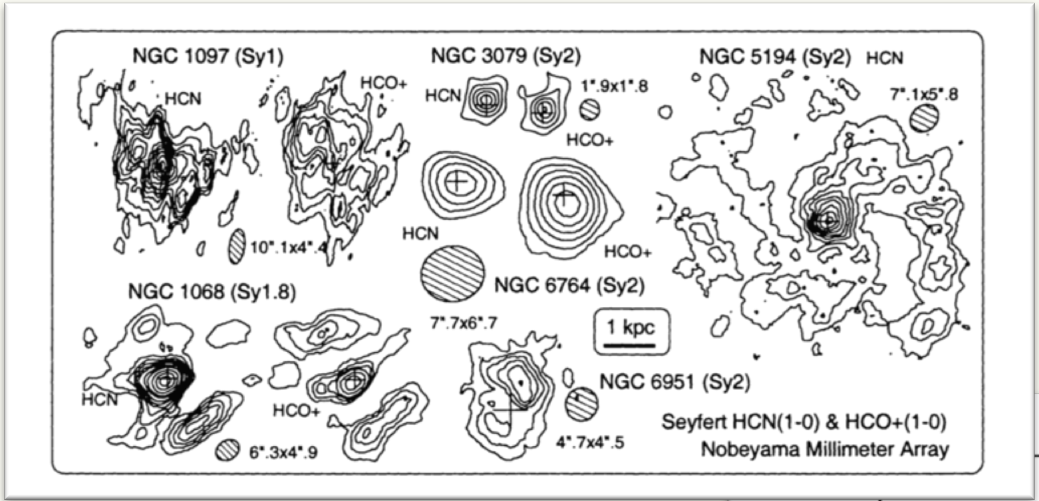


Aladro et al. 2015

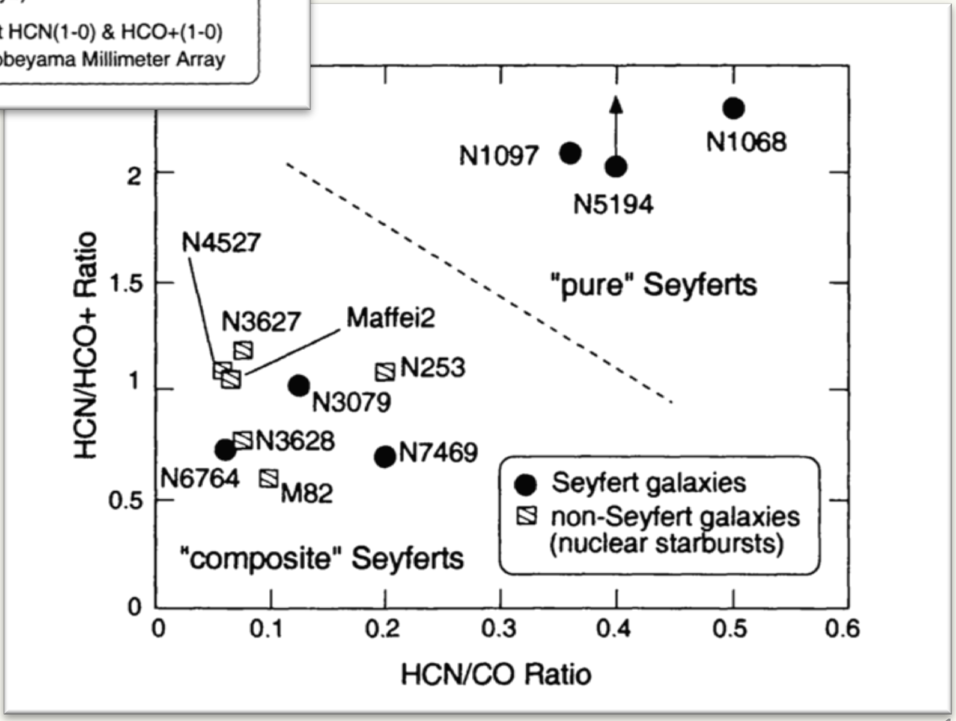
Line Diagnostics

— HCN/HCO^+ ?

HCN/HCO$^+$: As a Diagnostic Tool of (Obscured) AGN ?

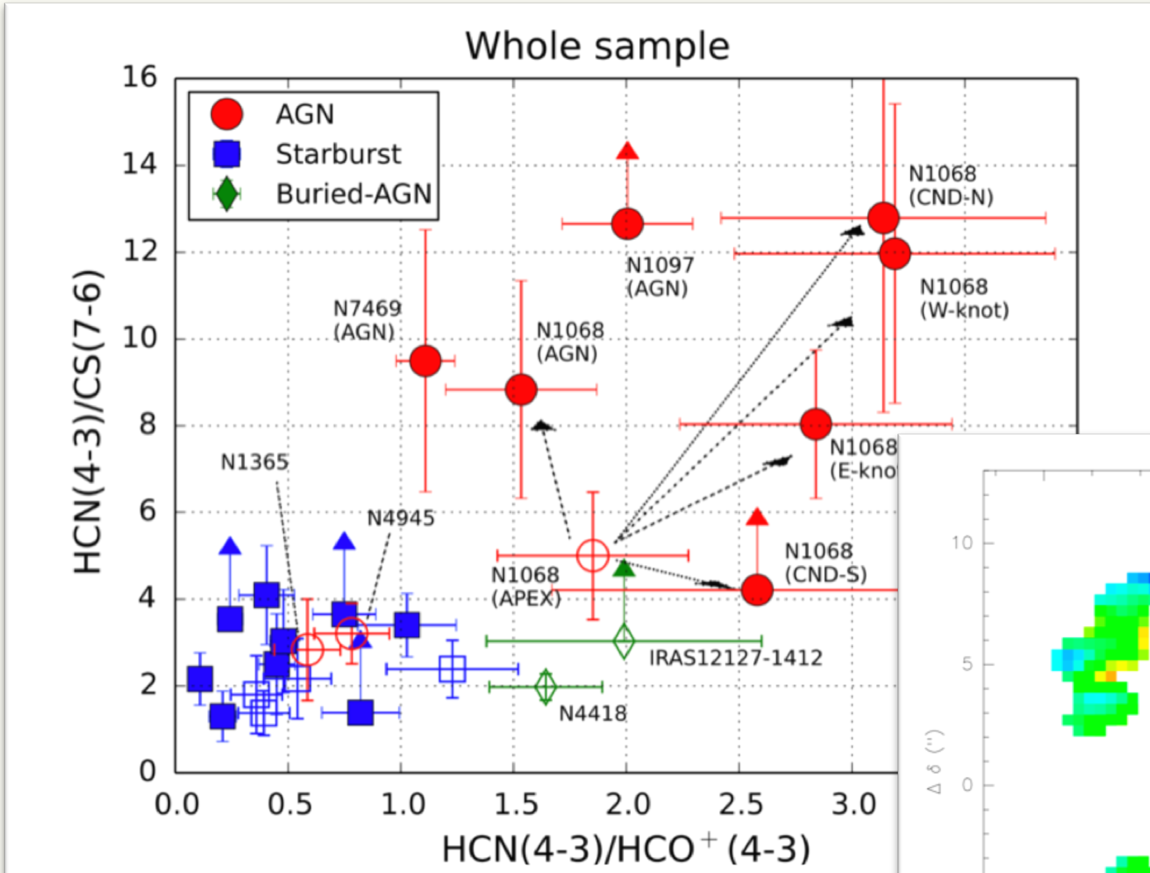


Kohno et al. 2001



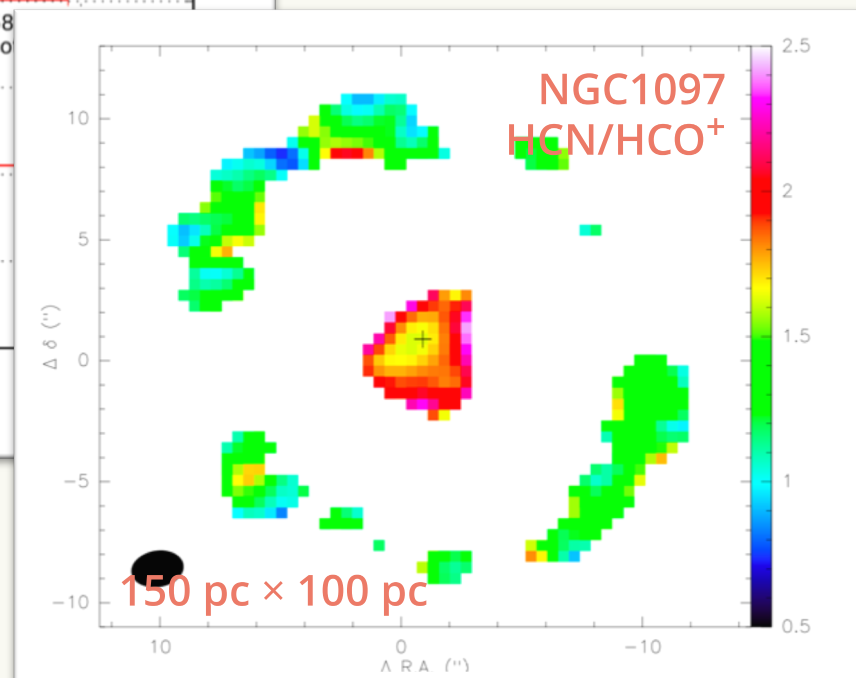
- Due to X-ray radiation?
  (e.g., Meijerink et al. 2007)
- Mechanical heating?
  (e.g., Harada et al. 2010)

HCN/HCO$^+$: Still Being Debated...



Izumi et al. 2017

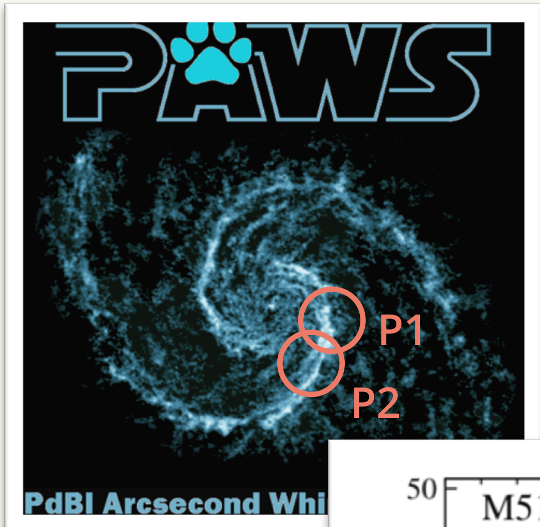
- Mechanical heating?
- More to come...
  (Taniguchi et al. in prep.)



Martín et al. 2015

Line Survey toward a Spiral Arm of M51

M51: Not Only Centers But Also **Spiral Arm**



PAWS: **CO 1–0 mapping**

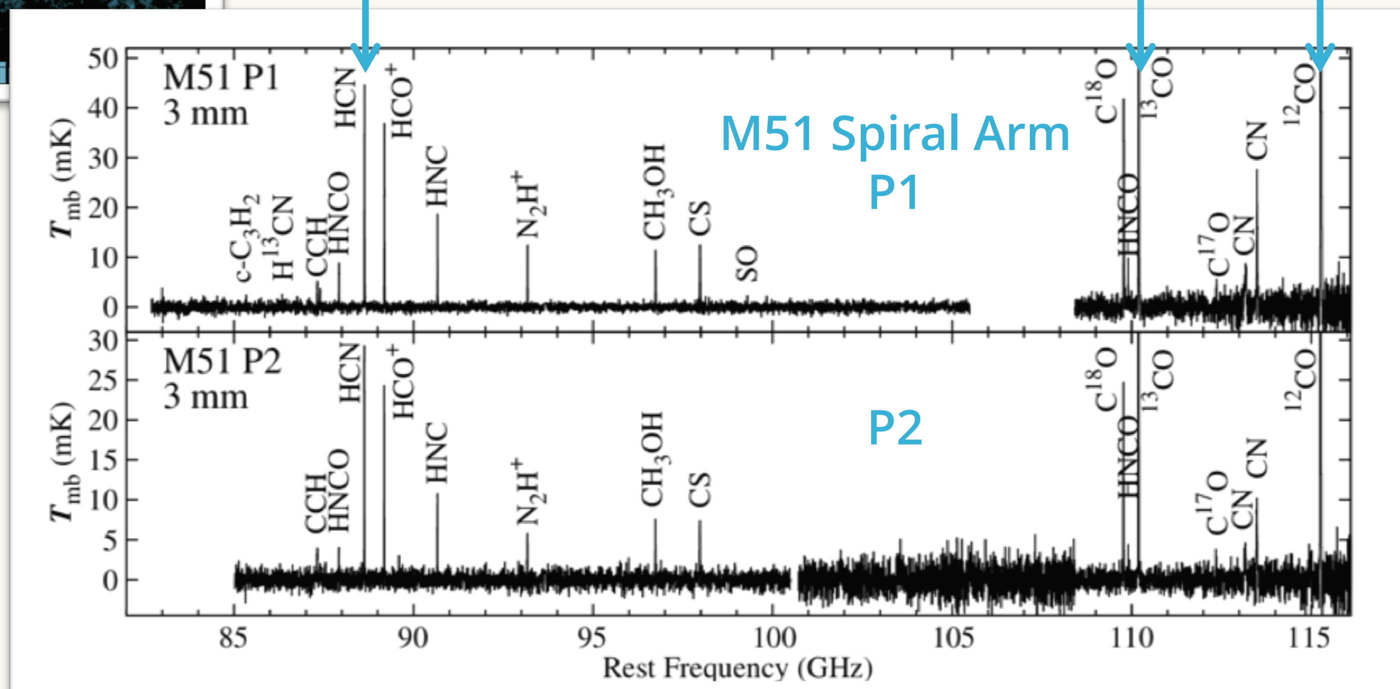
e.g., Schinnerer et al. 2013

HCN 1–0
45 mK

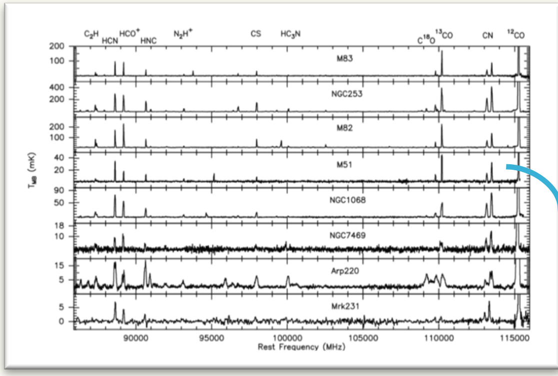
^{13}CO 1–0
158 mK

CO 1–0
1.4 K

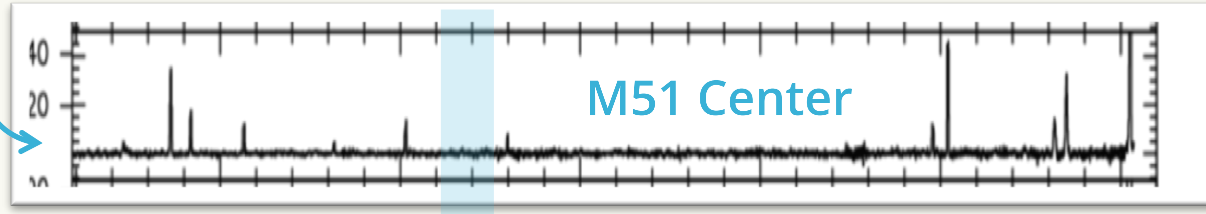
Watanabe et al. 2014



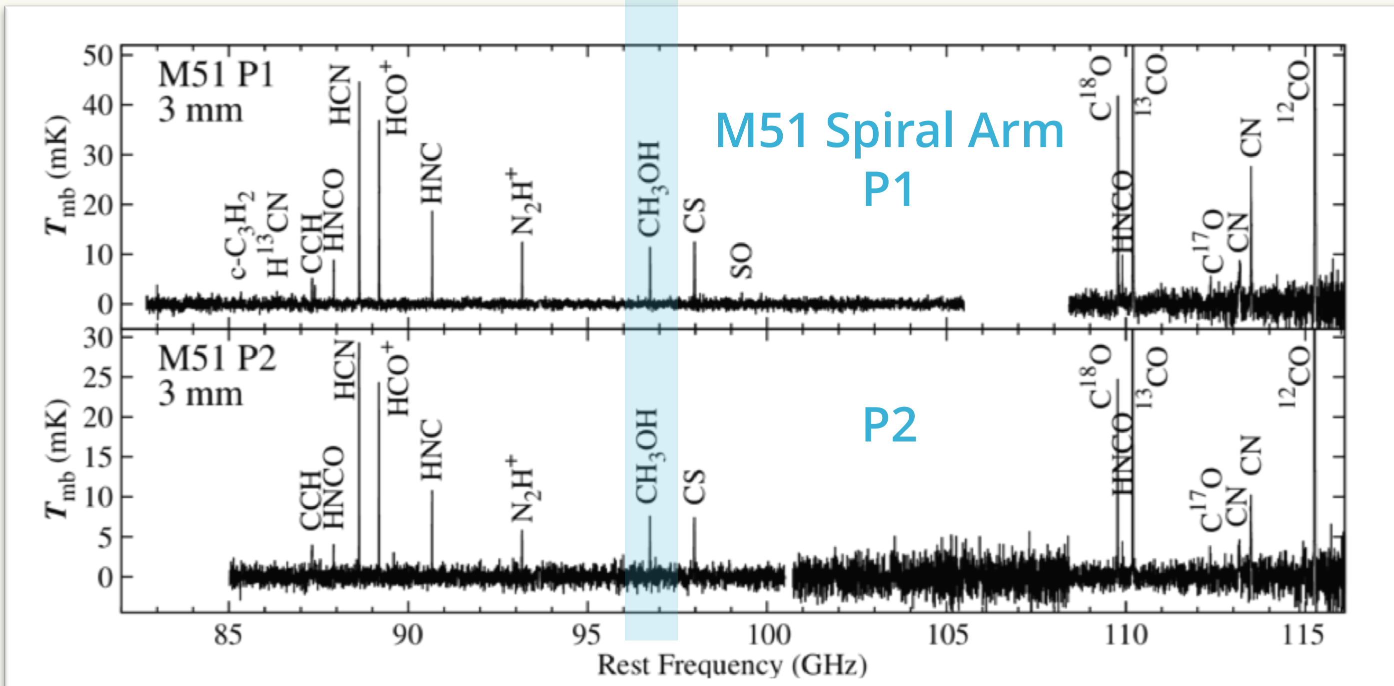
M51: CH_3OH Tells Something



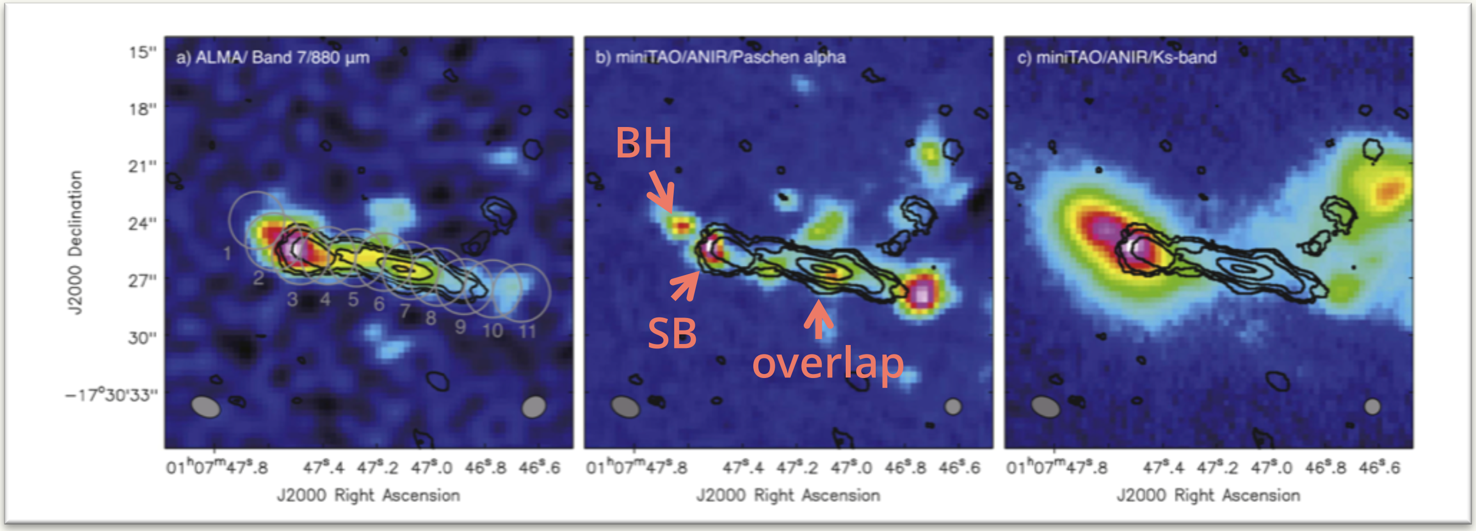
Aladro et al. 2015



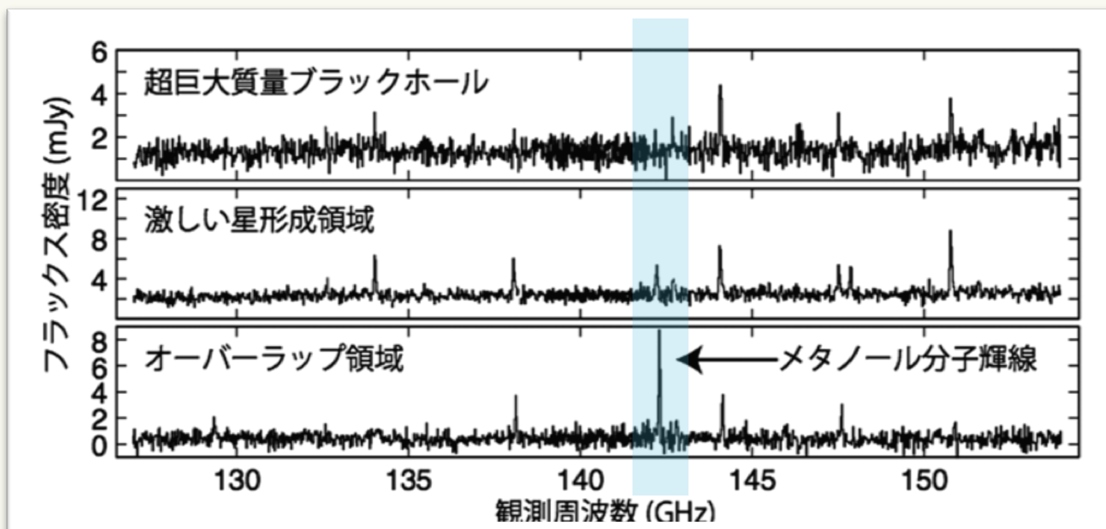
Watanabe et al. 2014



CH_3OH Tells Something: Merger VV114



Saito et al. 2017

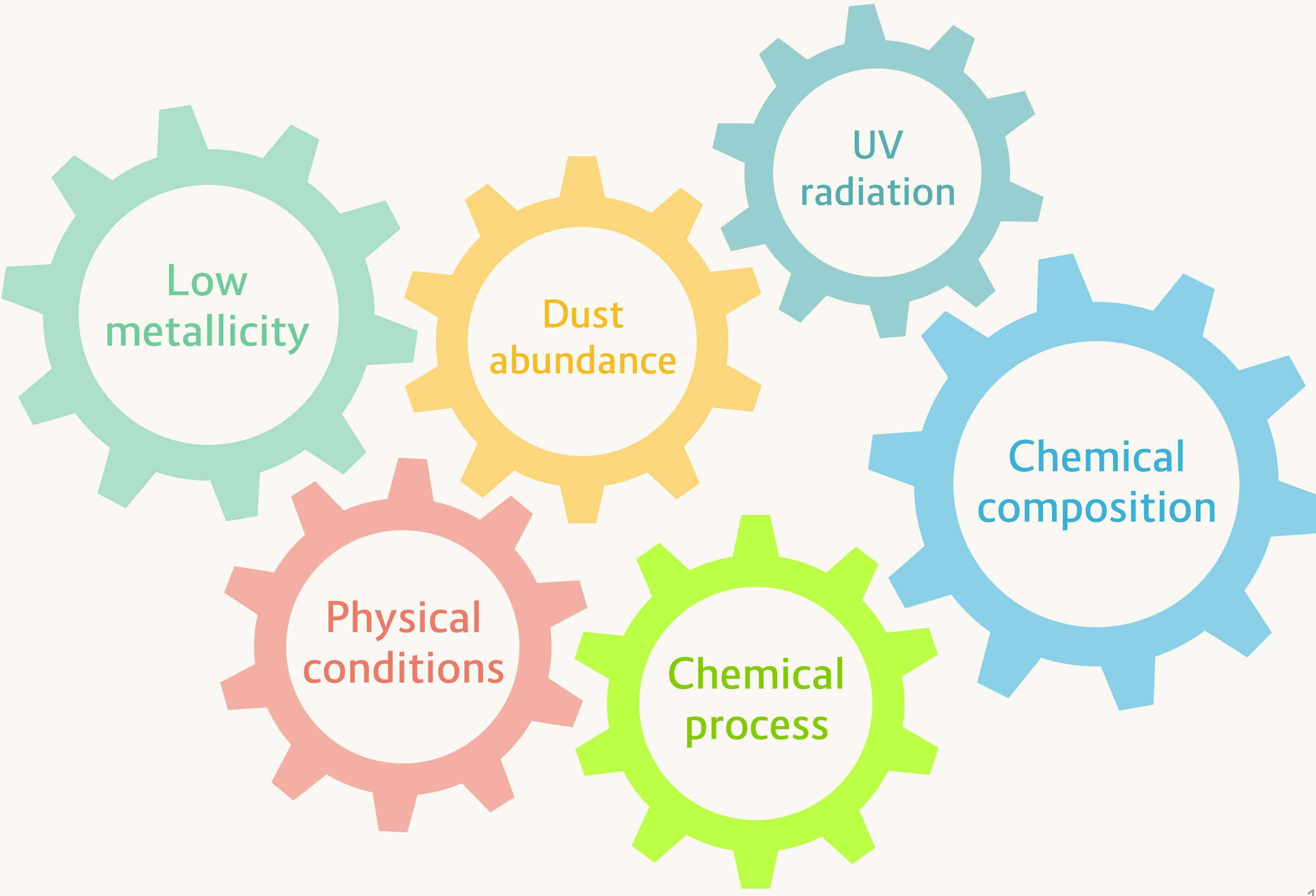


斉藤 2017

天文月報 2017年6月号

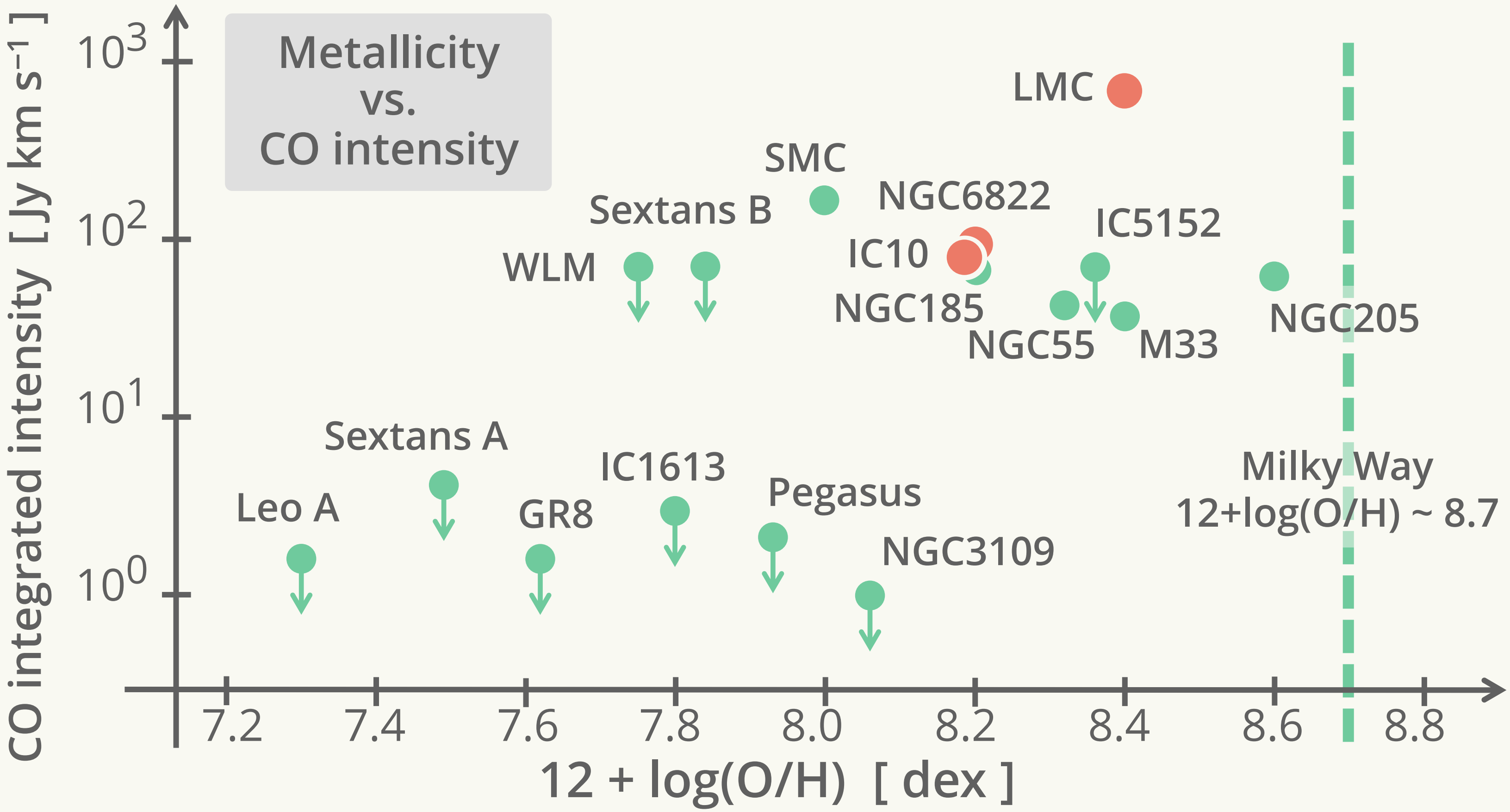
Low-Metallicity Dwarf Galaxies: LMC, IC10, NGC6822

Effect of Low-Metallicity on Molecular-cloud Chemical Composition



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

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

x $\frac{1}{3}$ x $\frac{1}{10}$

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

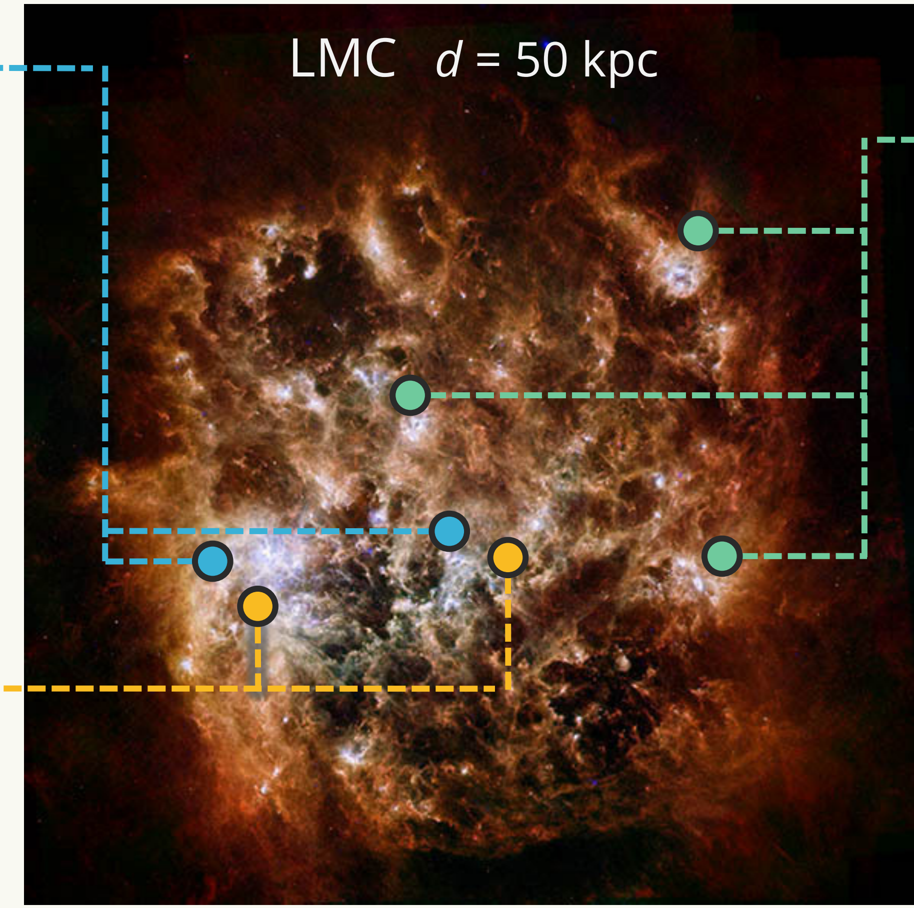
Target galaxy: **The Large Magellanic Cloud**

Quiescent clouds

- CO Peak 1
- NQC2

Star-forming clouds with HII region

- N113
- N159W



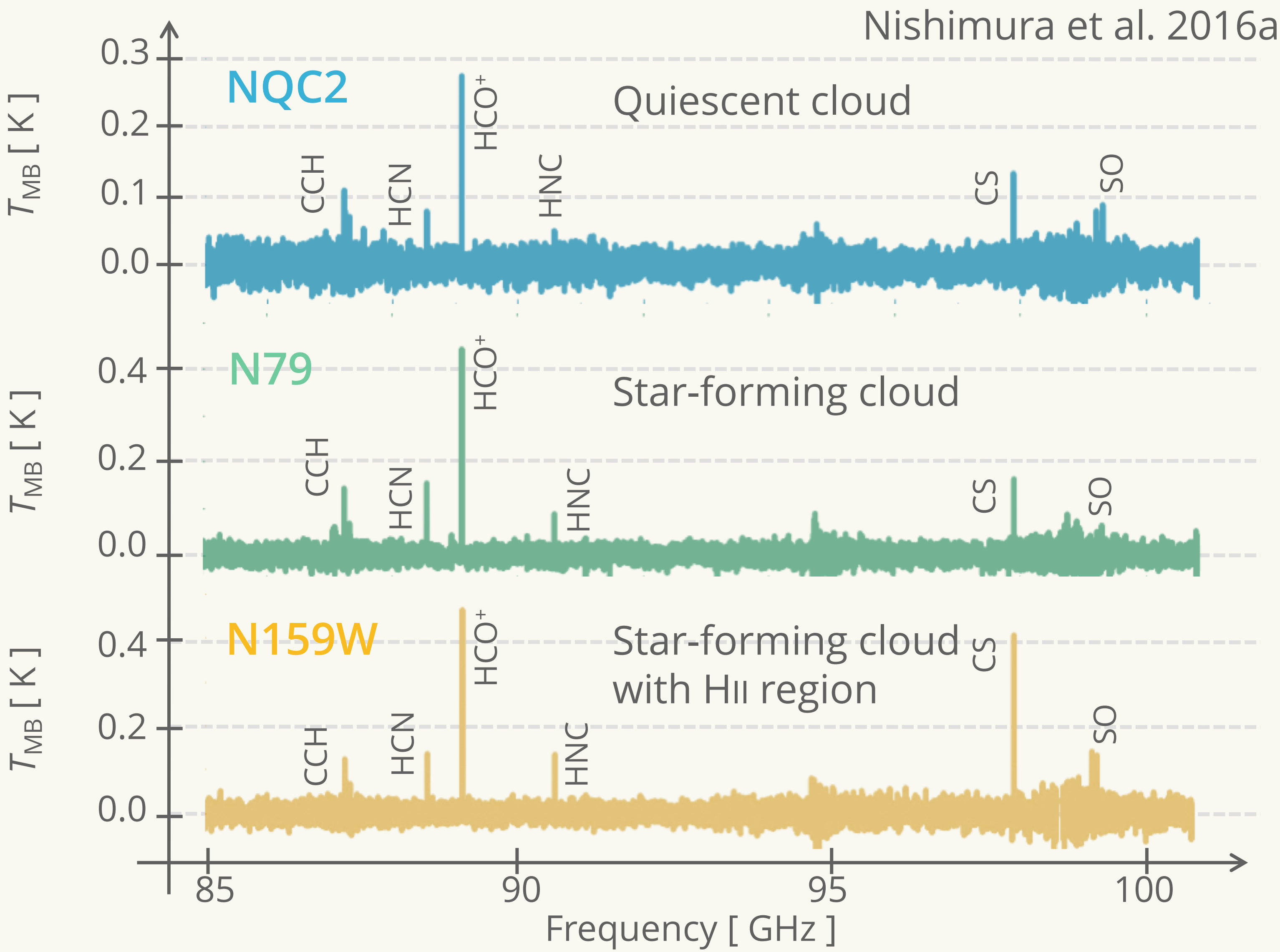
Spitzer/MIPS, *Herschel*-PACS, *Herschel*-SPIRE

Star-forming clouds

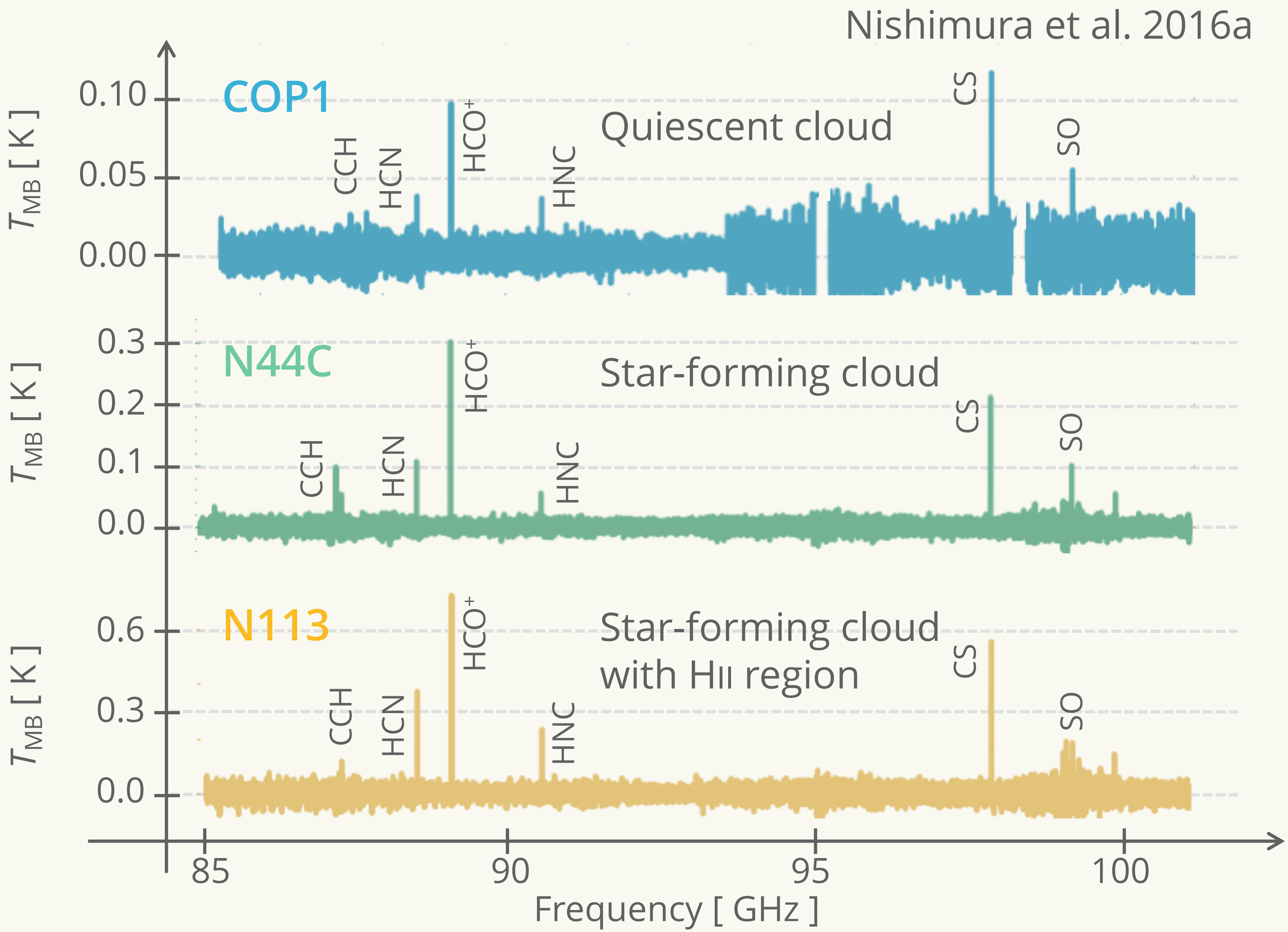
- N79
- N44C
- N11B

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

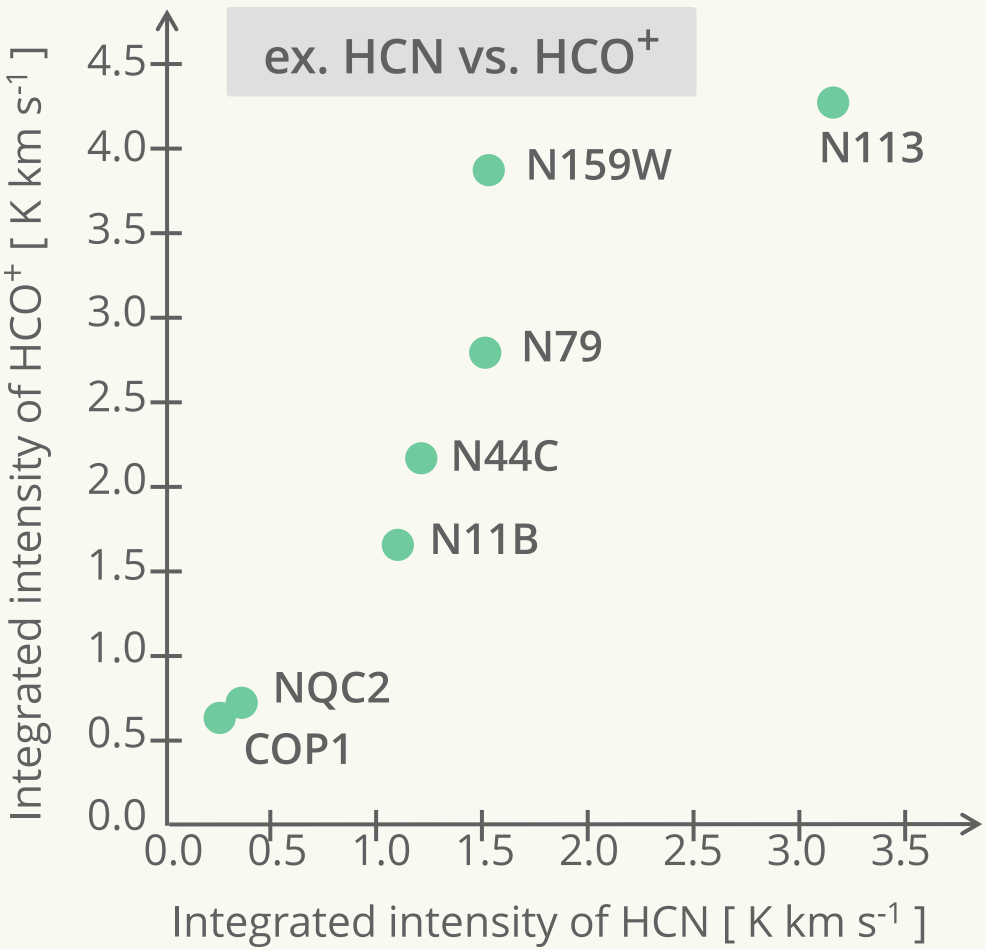
Similar spectral pattern



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

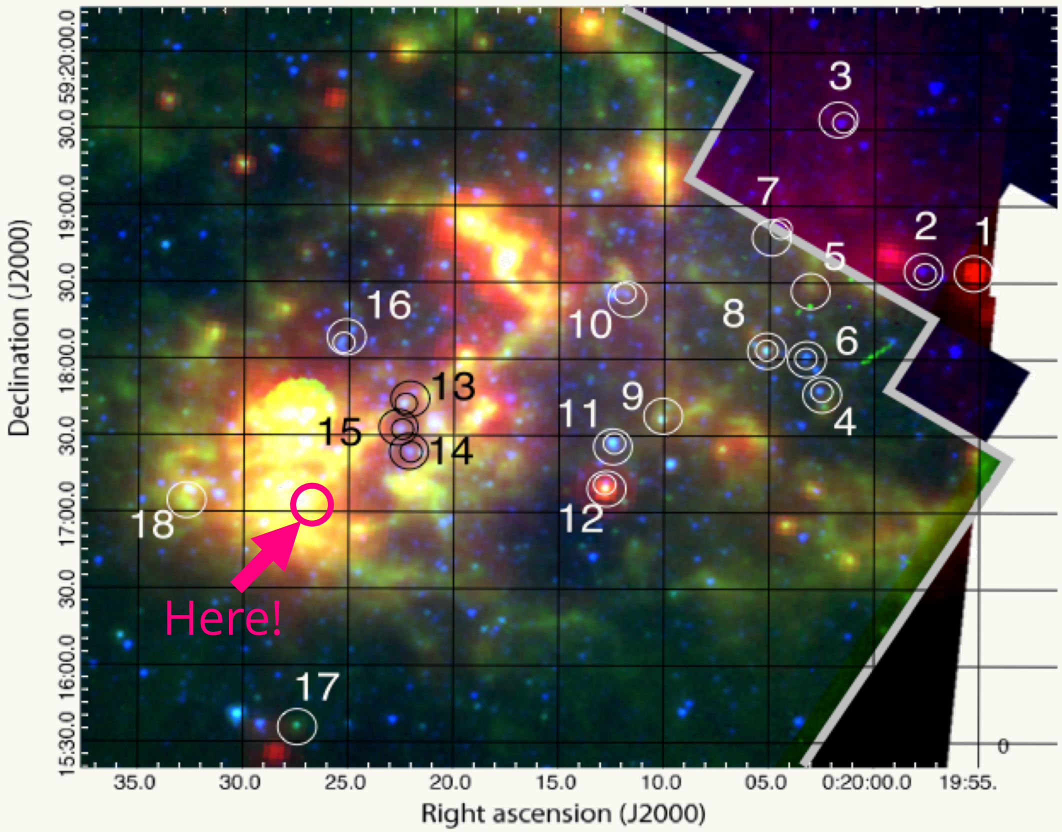
Correlation coefficients
of integrated intensity among 7 clouds

	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.

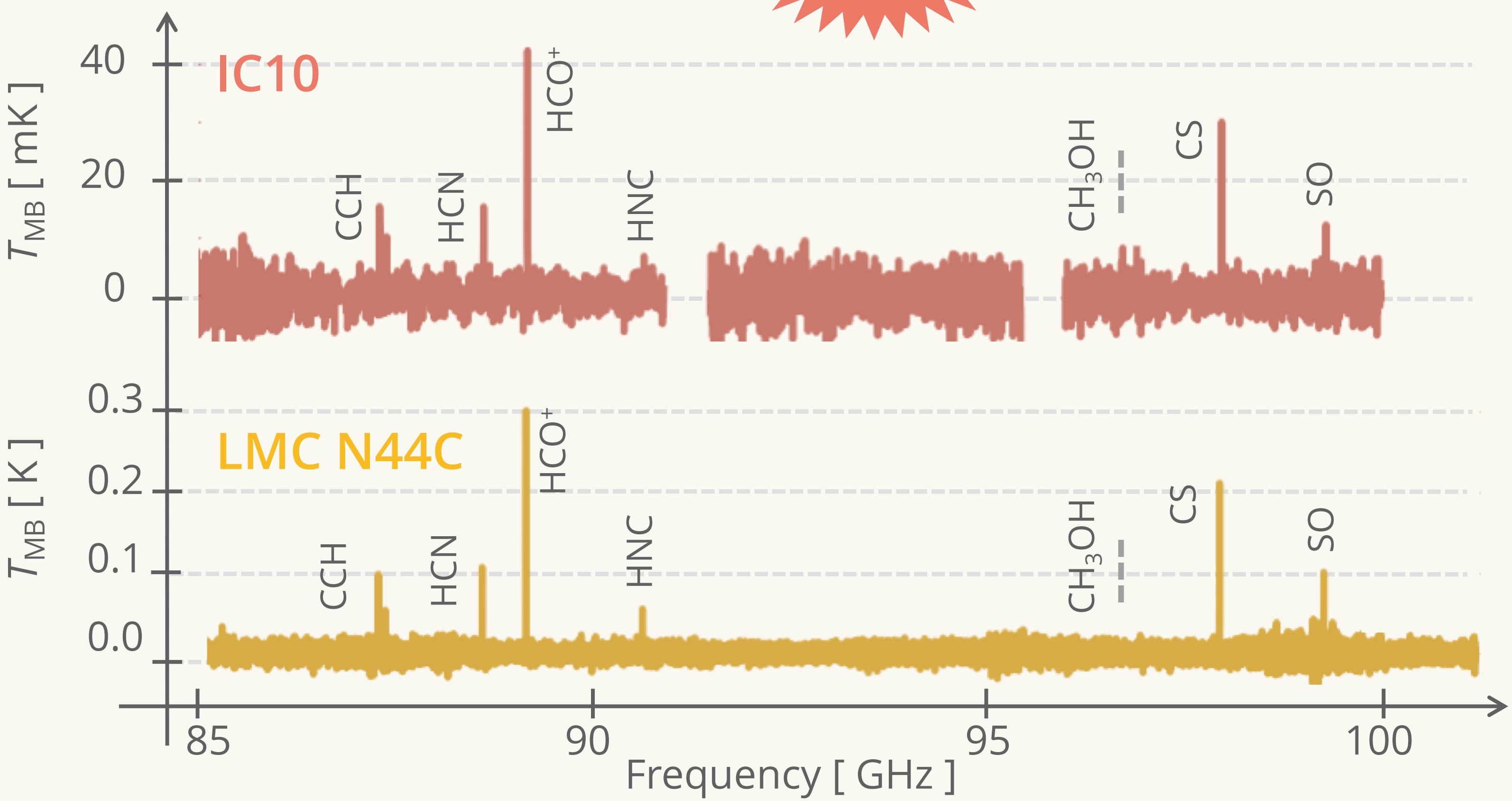
- CO 1-0
  Leroy et al. 2006
- CO 2-1 & 3-2
  Petitpas & Wilson 1998

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

Again **similar** spectral pattern

Nishimura et al. 2016b

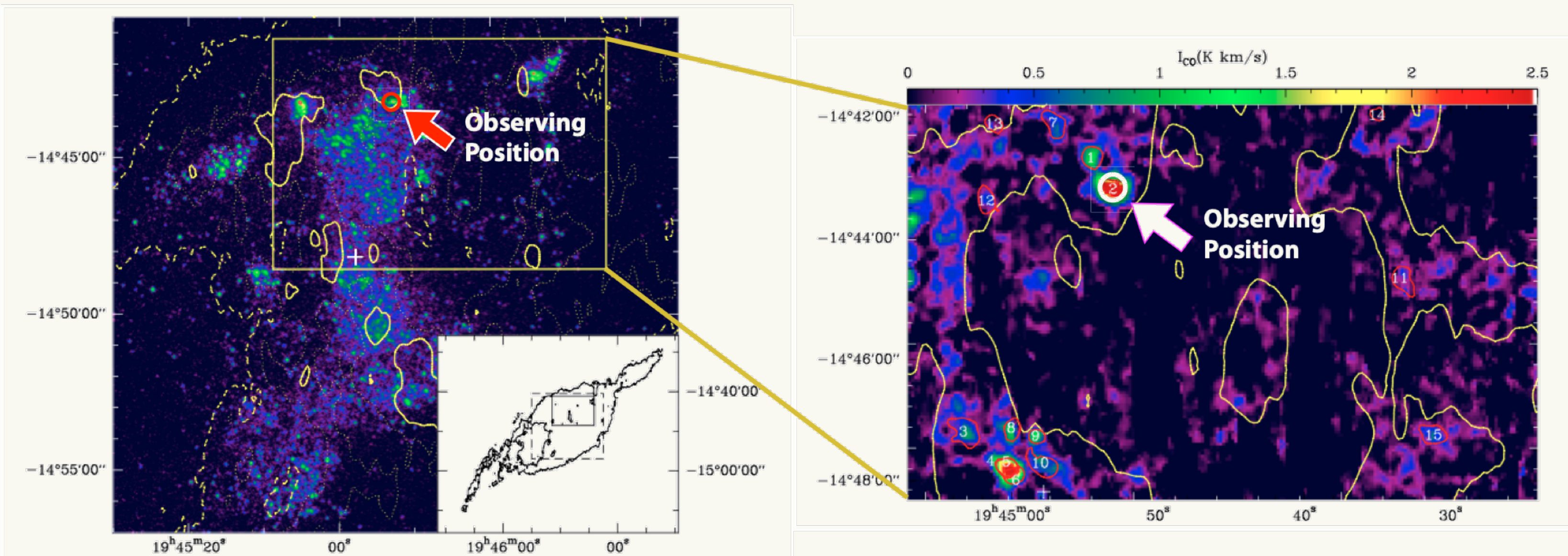
Chemical composition of IC10 is **similar** to that of the LMC.



The other target galaxy: **NGC6822**

GALEX FUV image

CO (2-1) intensity map

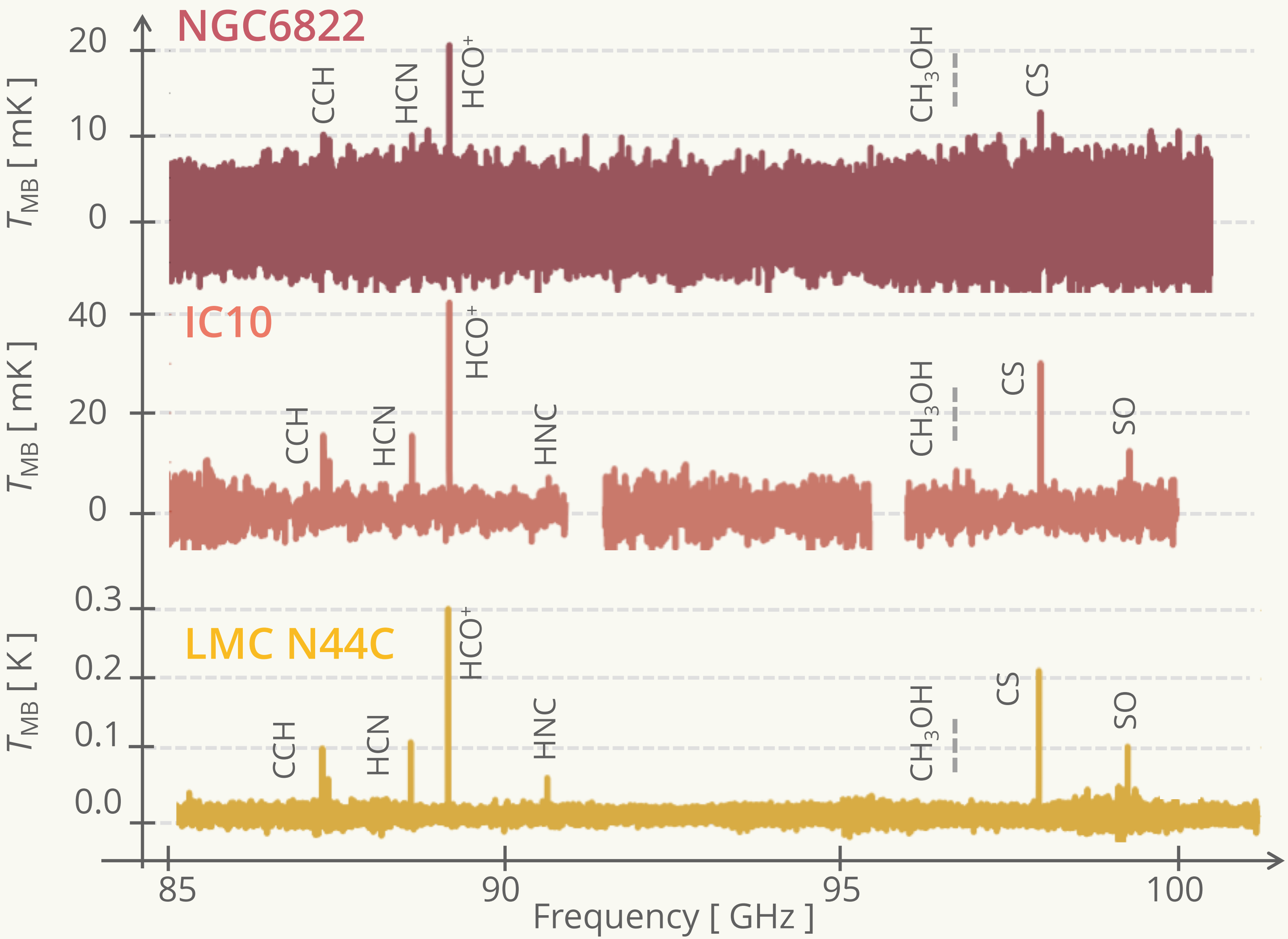


Gratier et al. 2010

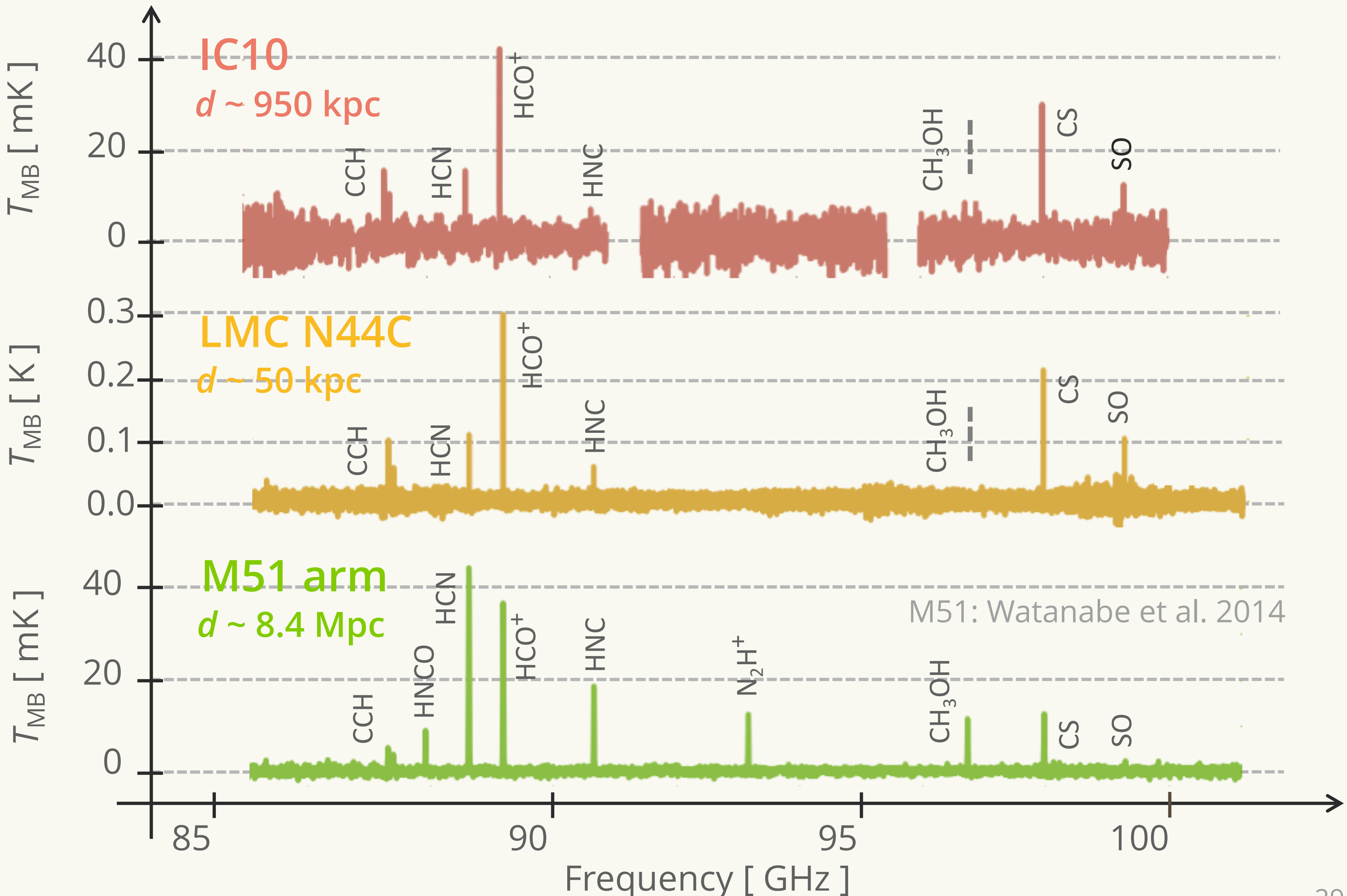
- The brightest HII region: Hubble V
- CO 2-1 & 3-2 multiline analysis by Petitpas & Wilson 1998

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

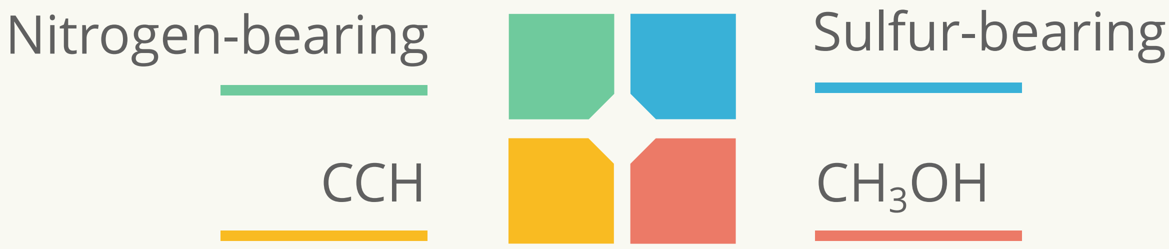
And again **similar** spectral pattern in **NGC6822**

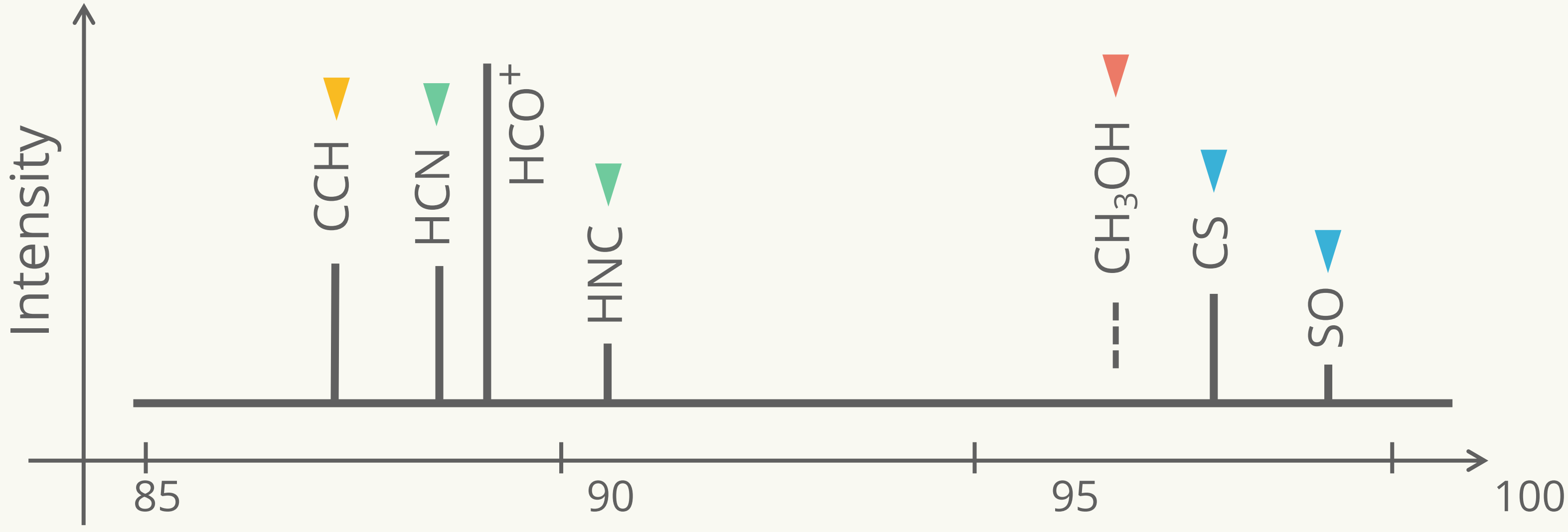


Metal-poor IC10/LMC and Metal-rich M51



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





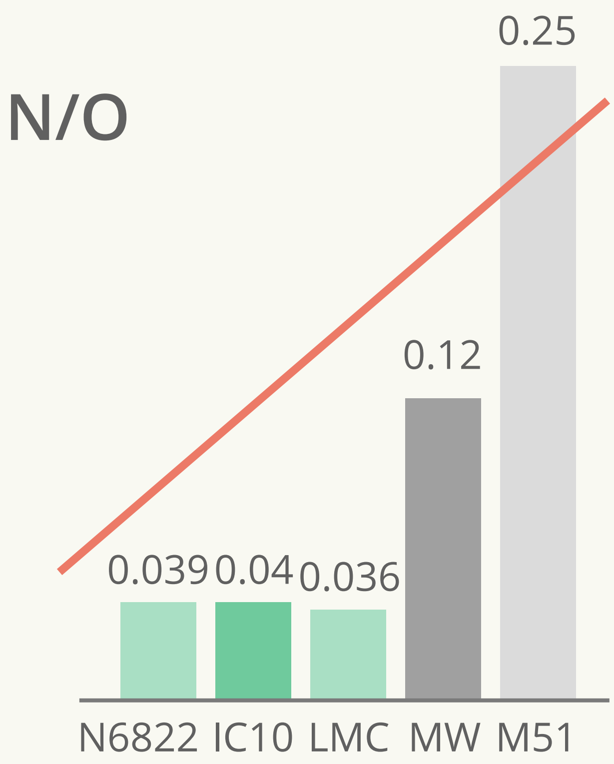
Direct impact: **Nitrogen**-bearing species

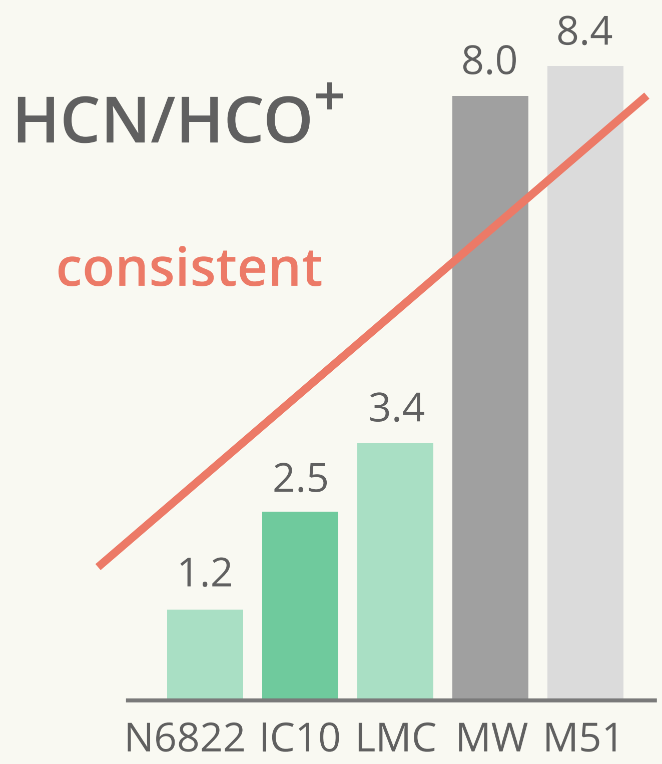
Abundance ratio	NGC6822	IC10	LMC		Milky Way	M51
N/O	0.039	0.04	0.036	<	0.12	0.25
HCN/HCO^+	1.2	2.5	3.4	<	8.0	8.4
HNC/HCO^+	< 0.3	0.4	0.8	<	3.4	1.6

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**

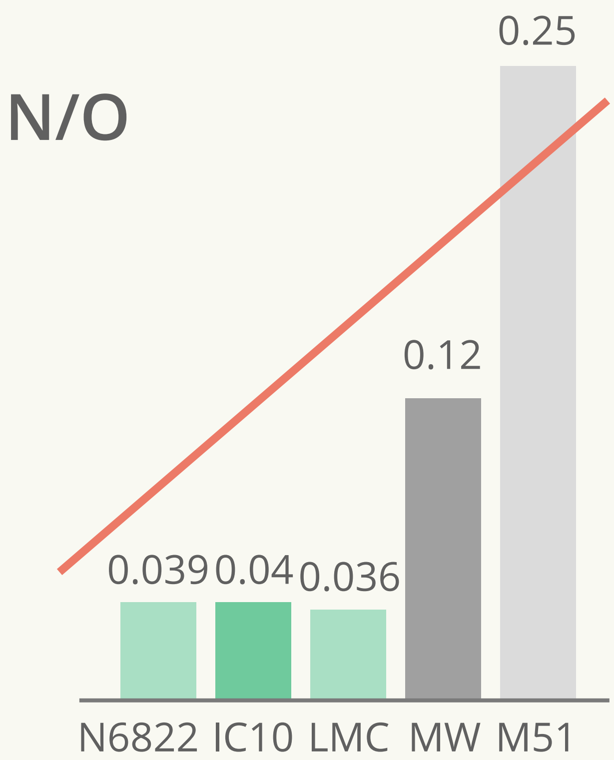
Direct impact: **Nitrogen**-bearing species

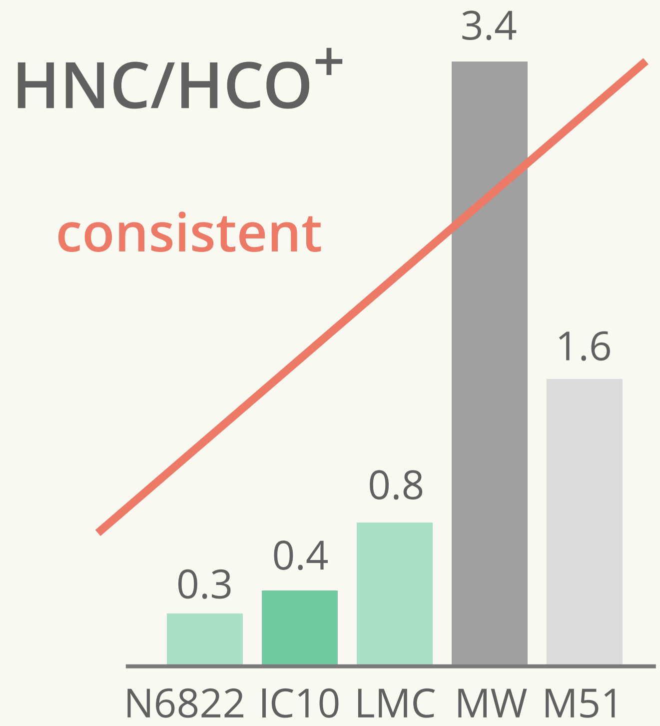




Elemental abundances impact **chemical compositions**

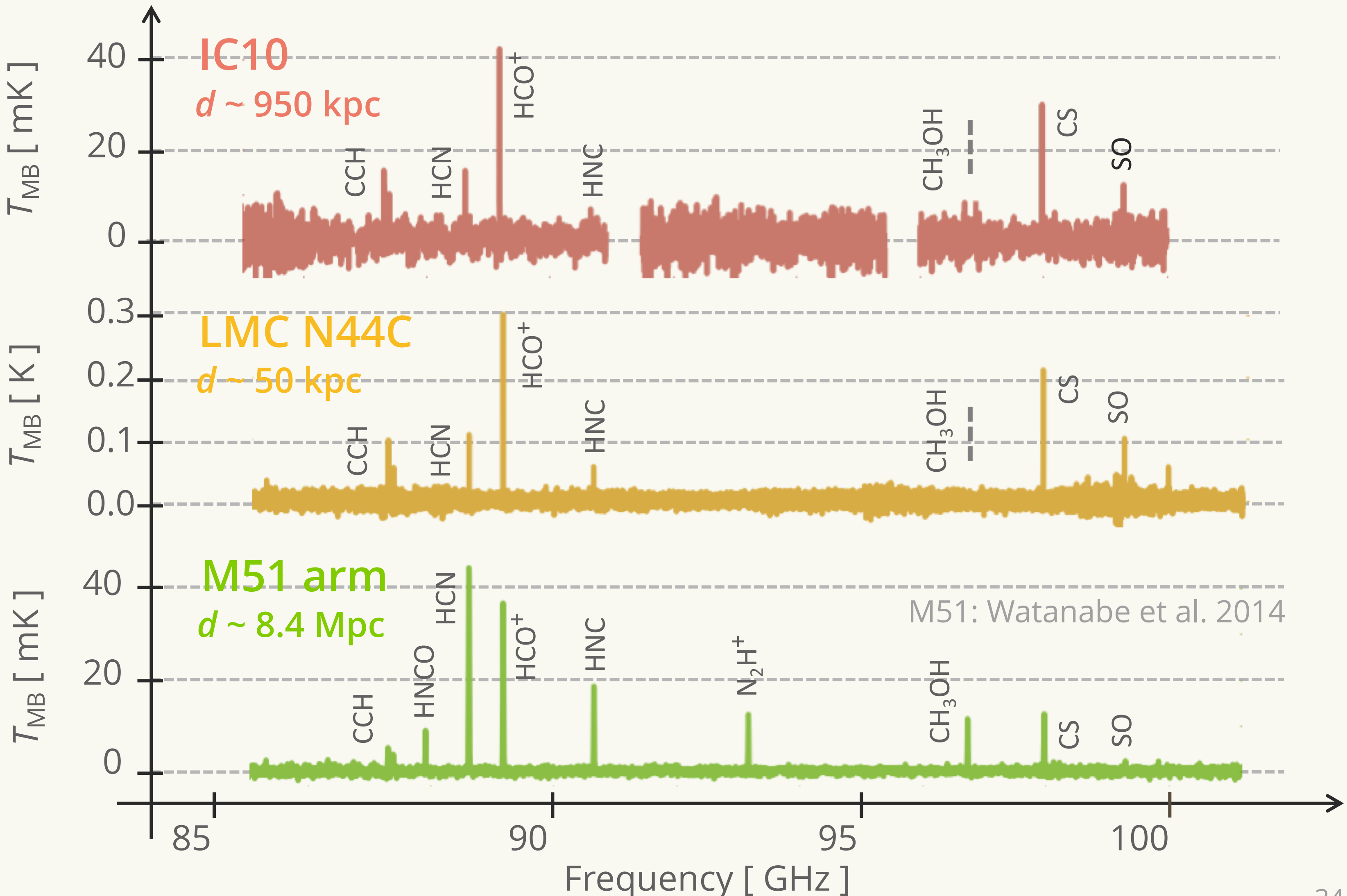
Direct impact: **Nitrogen**-bearing species





Elemental abundances → impact → **chemical compositions**

Metal-poor IC10/LMC and Metal-rich M51



Effect of UV: **Enhancement** of CCH

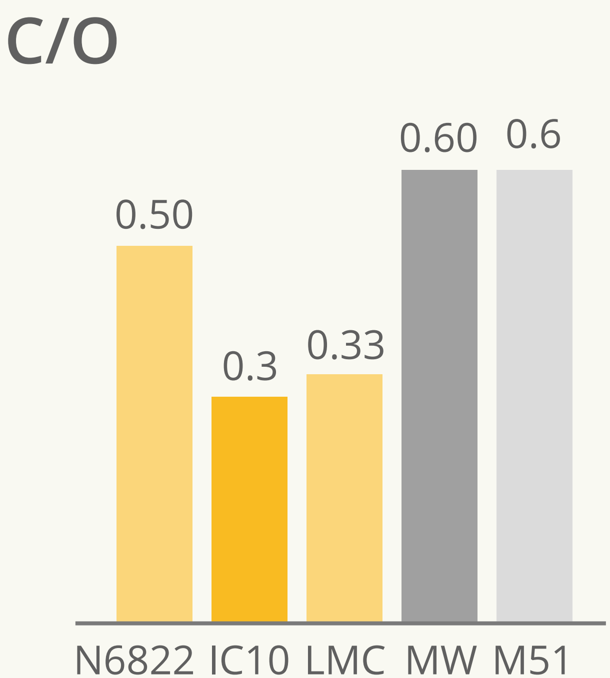
Not due to the difference of elemental abundances!

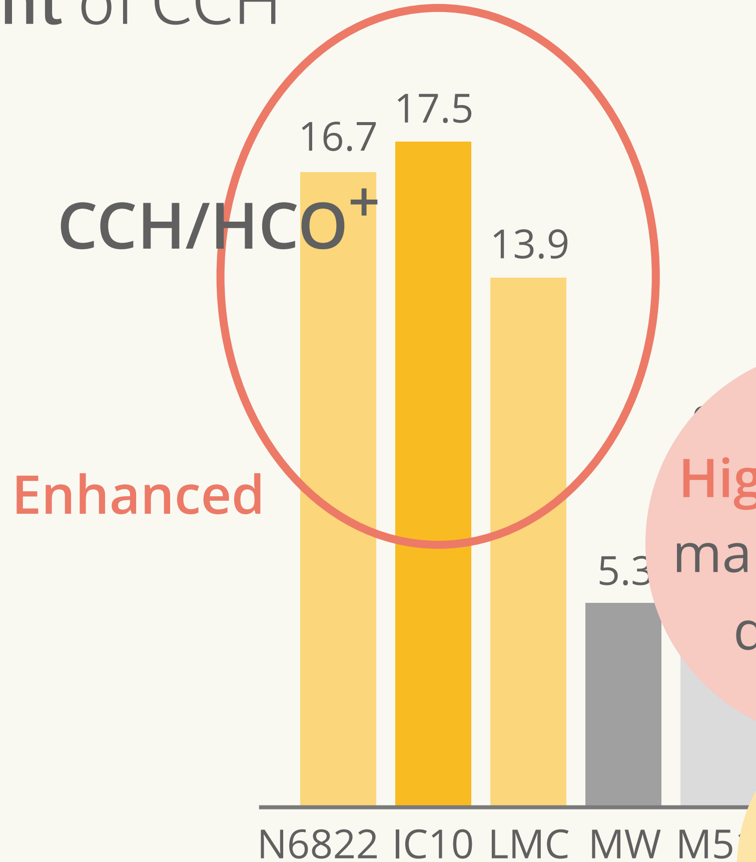
Abundance ratio	NGC6822	IC10	LMC		Milky Way	M51
C/O	0.5	0.3	0.33	$<$	0.60	0.6
CCH/HCO^+	16.7	17.5	13.9	$>$	5.3	9.1

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



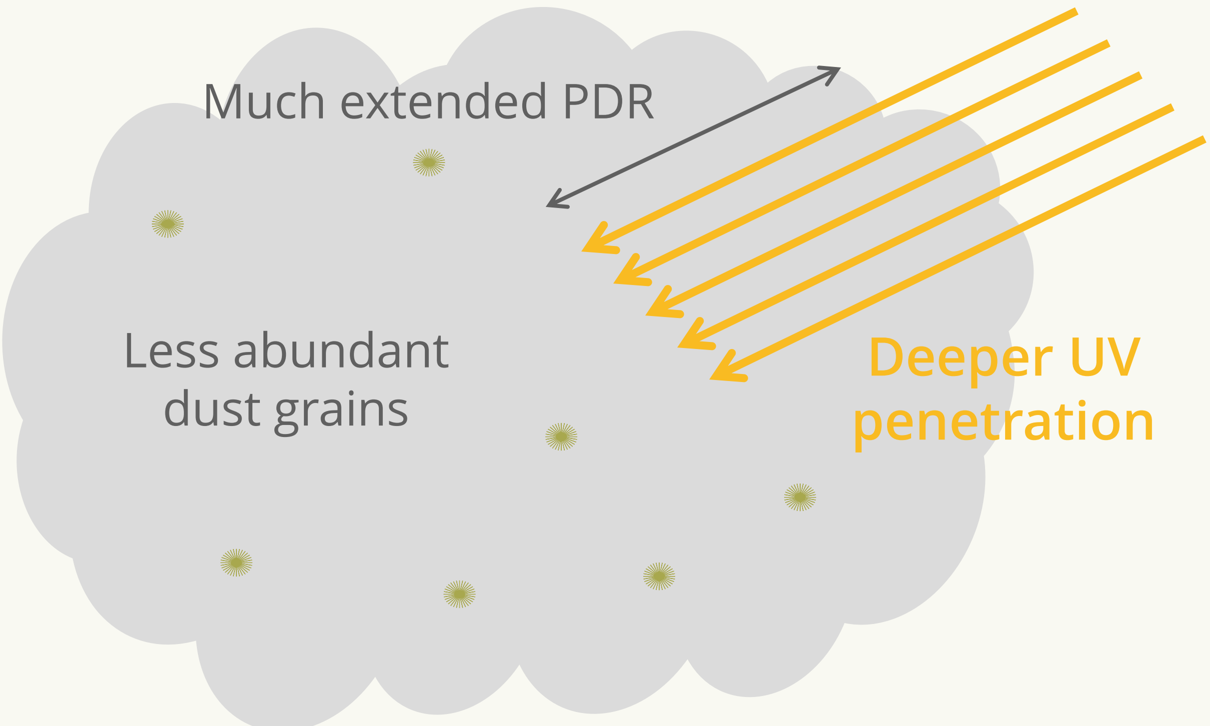


High *T* in PDR makes CH_3OH deficient.

CCH is enhanced in **PDR**.

Lower abundance of dust grains extends **PDR**

Effect of UV: **Enhancement** of CCH

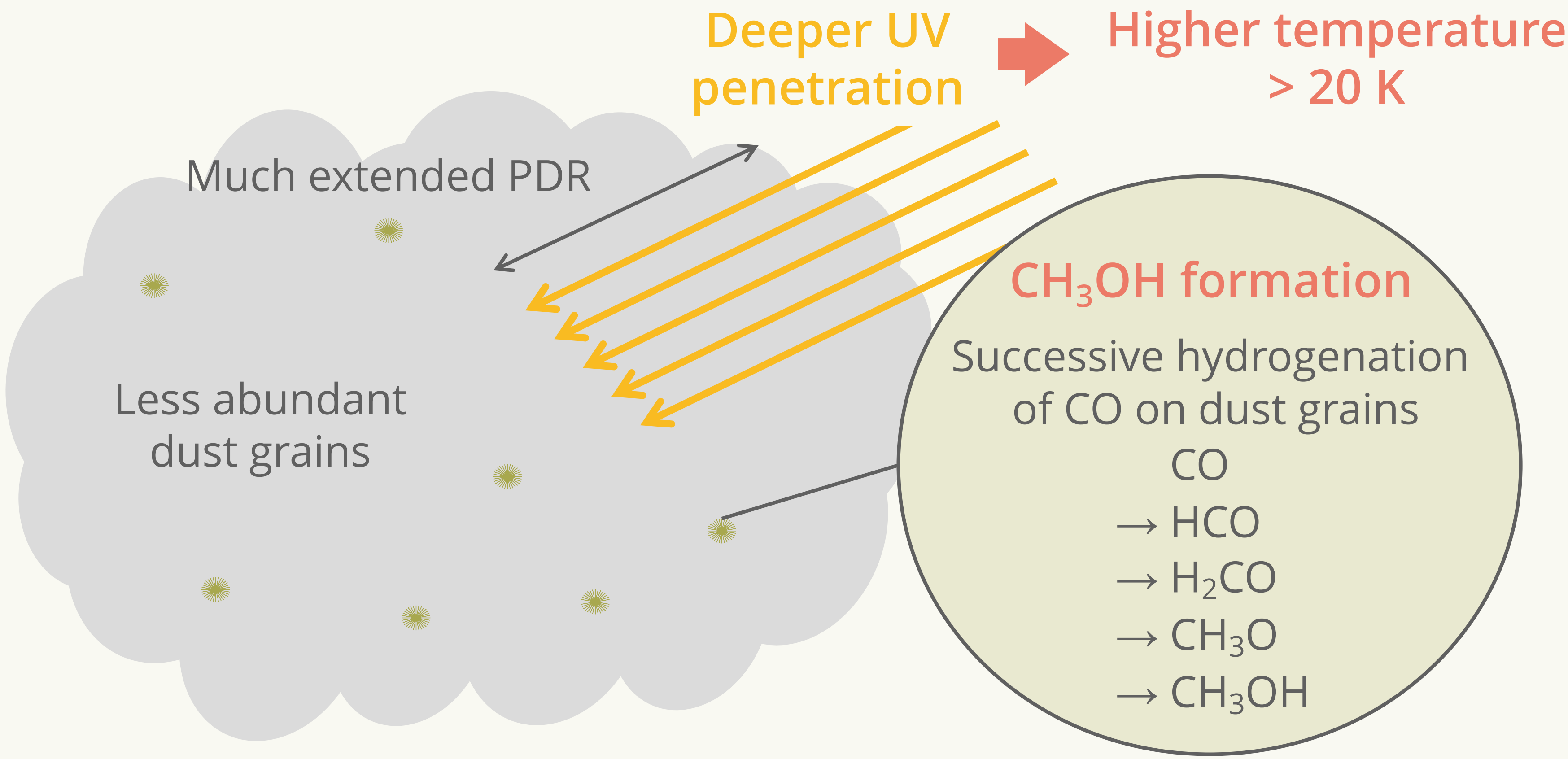


Extended PDR

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

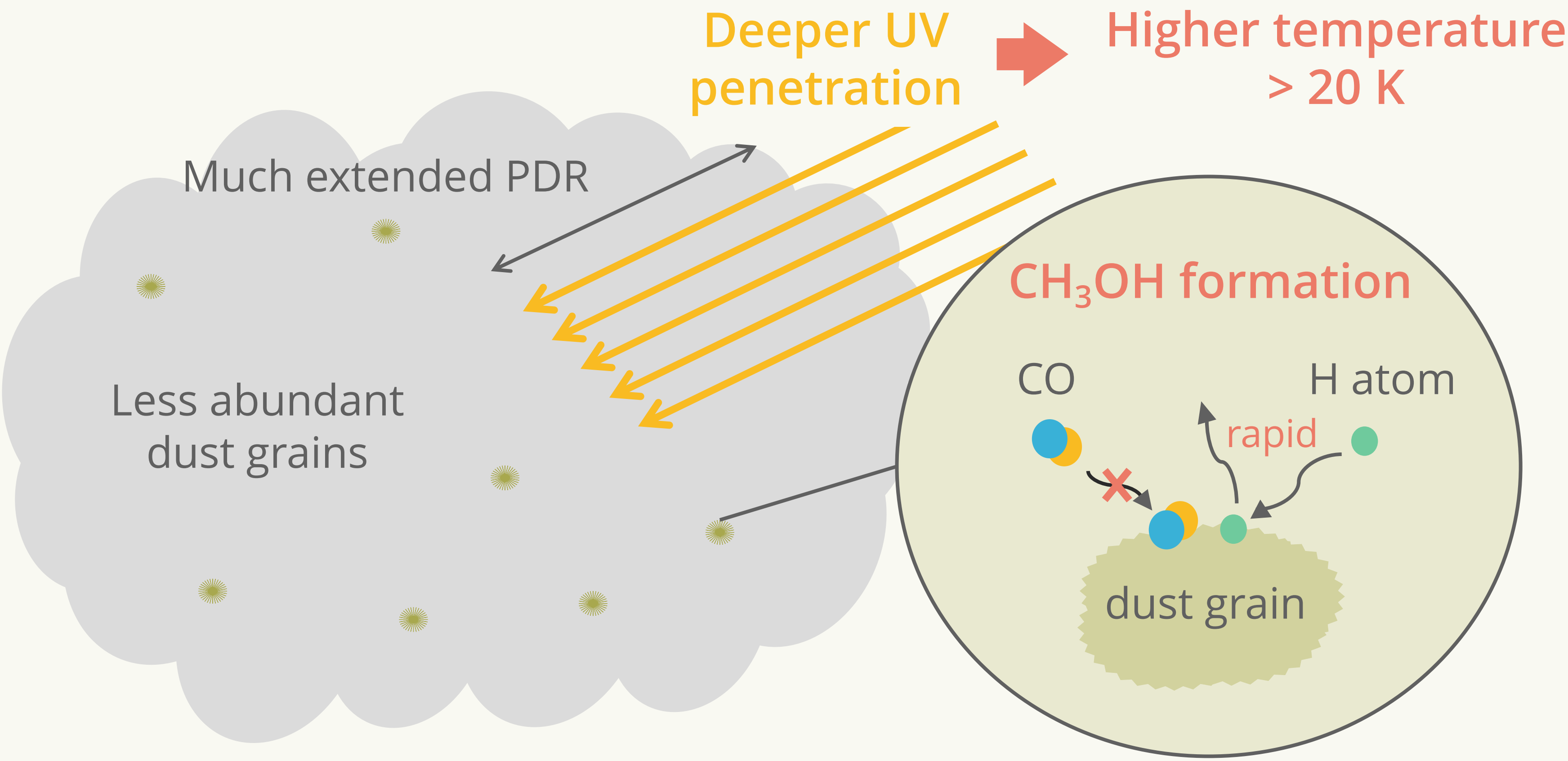
Lower abundance of dust grains → extends → **PDR**

Effect of UV: **Enhancement** of CCH



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

Effect of UV: **Enhancement** of CCH

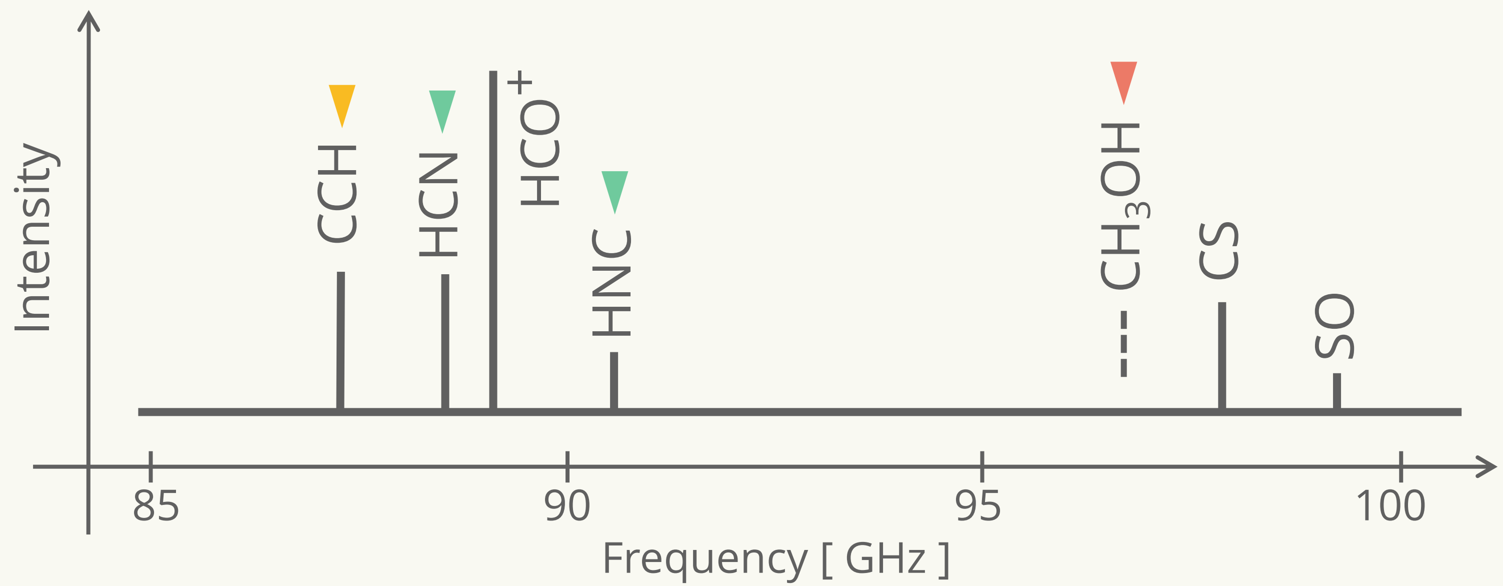


Lower abundance of dust grains → higher → temperature → decrease → CH$_3$OH

Summary 1

Characteristic features in low-metallicity galaxies

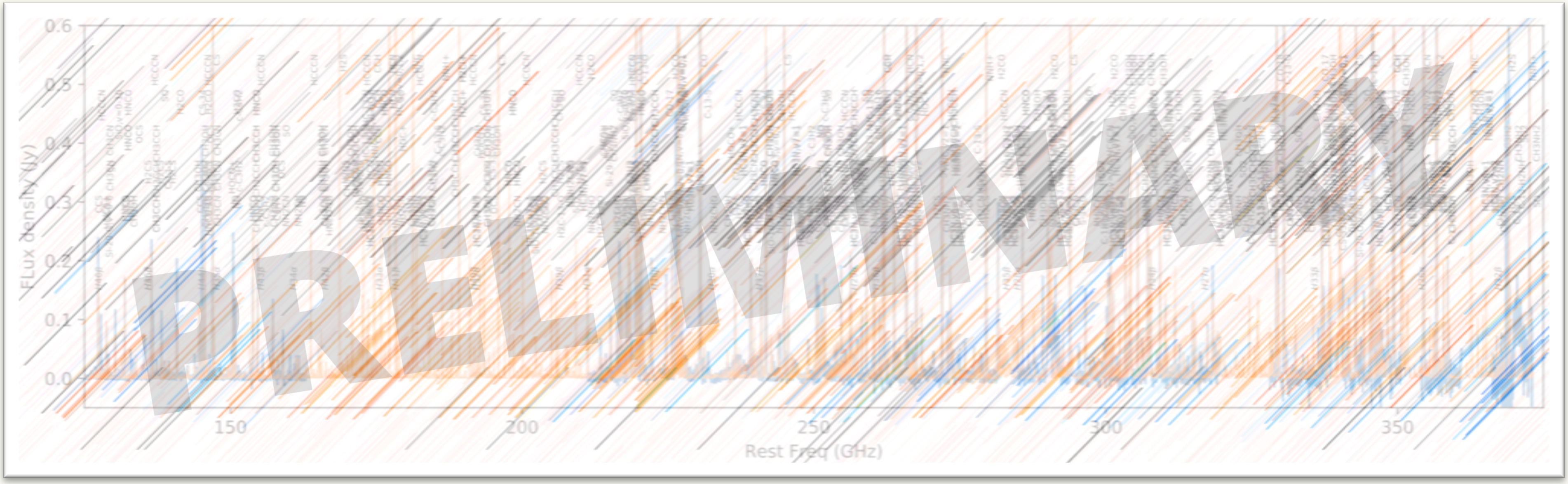
Elemental abundance	UV radiation & PDR	dust grains & UV radiation
↓	↓	↓
N-bearing species	**Enhanced CCH**	**Deficient CH_3OH**



ALCHEMI

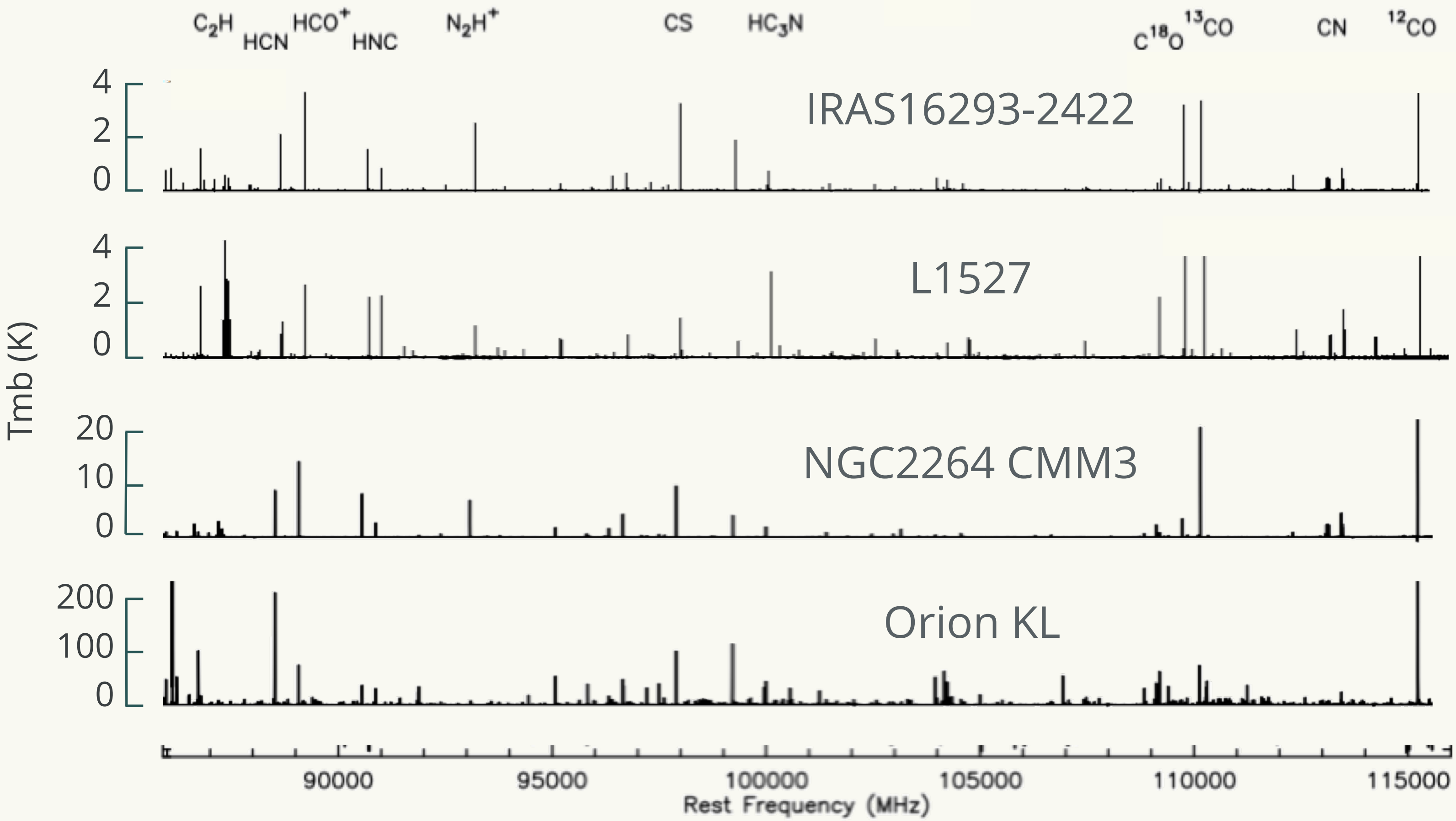
ALMA large program (2017.1.00161.L) targeting at NGC253

The **AL**MA **C**omprehensive **H**igh-resolution **E**xtragalactic **M**olecular **I**nventory



Molecular-Cloud-Scale Chemistry

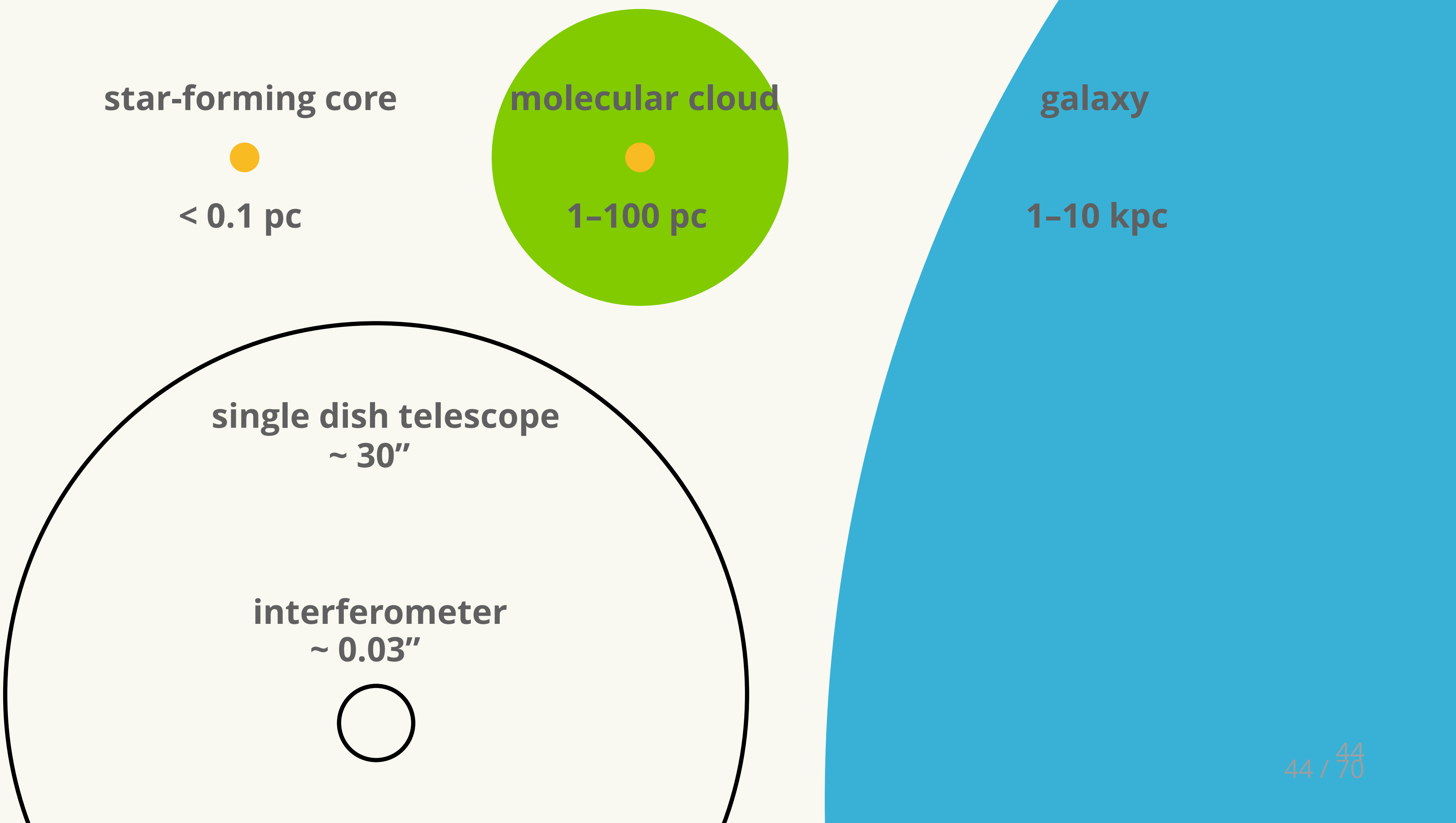
Galactic star-forming regions



IRAS16293-2422: Caux et al. 2011,
L1527: Tokudome et al. 2013 / Yoshida et al. 2018
NGC2264 & Orion KL: Watanabe et al. 2015

“Molecular Cloud Scale”

Attainable spatial resolution for nearby galaxies = a few 10–100 pc



Galactic vs. Extragalactic

30″ 0.3″ resolution corresponds to…

Extragalactic

M51

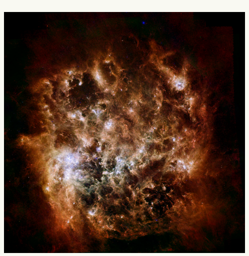
D ~ 8.4 Mpc

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

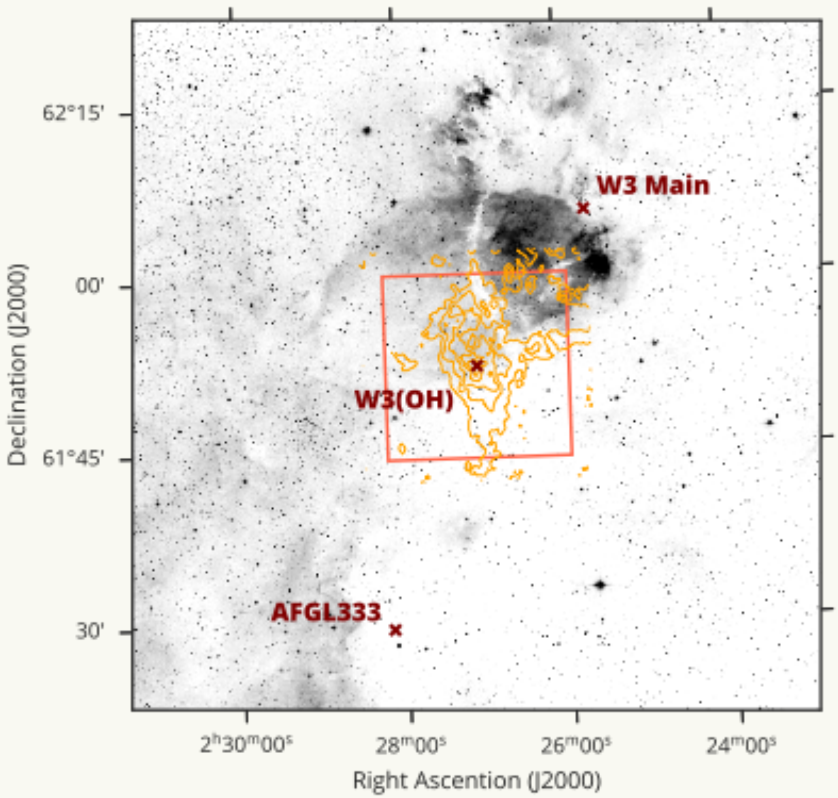
0.06 pc

L1527

D ~ 140 pc

0.02 pc

W3(OH) Observations in the 3 mm band



W3(OH):

active star-forming region

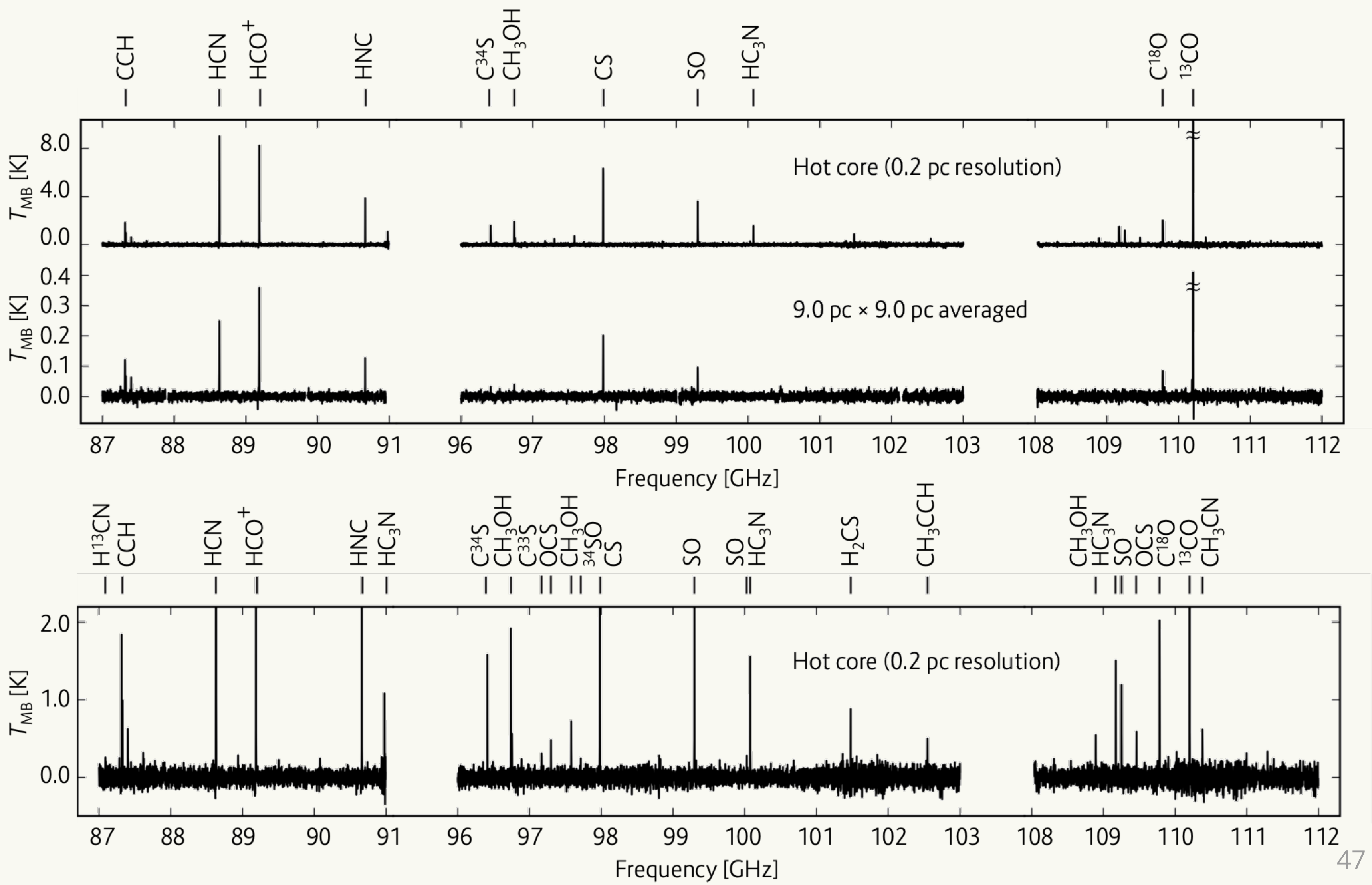
in the Perseus arm

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

Nishimura et al. 2017

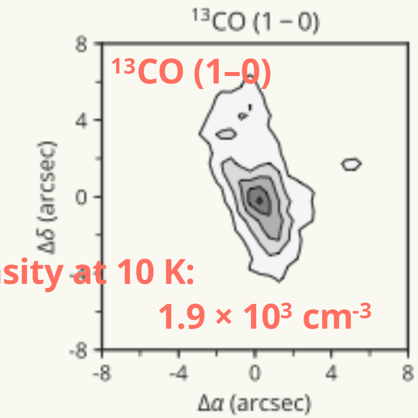
Results

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

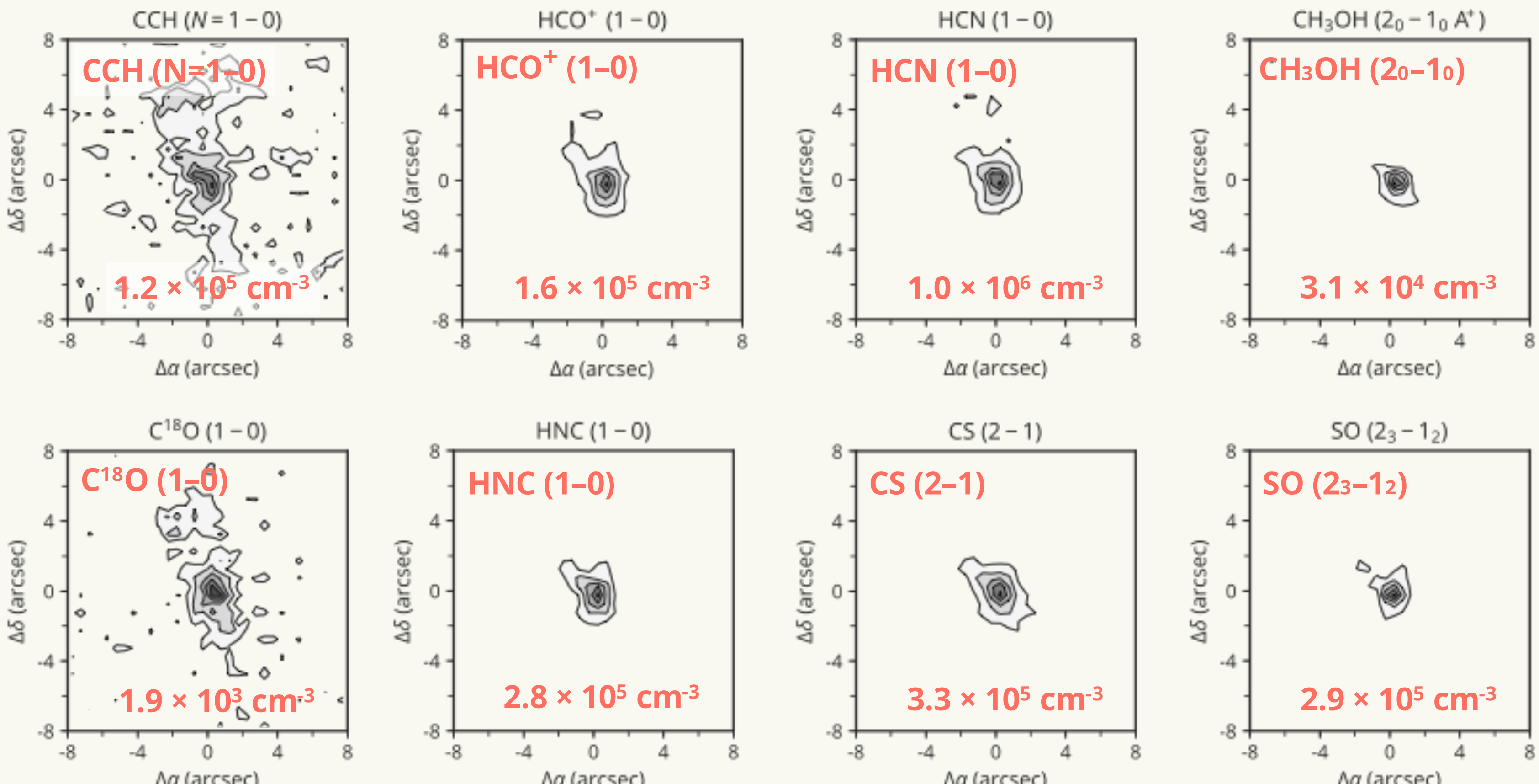


Integrated intensity map: 3 mm

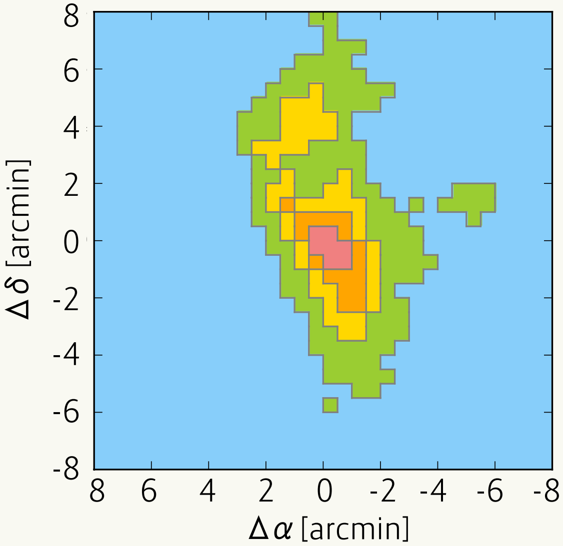
Integrated intensity maps of key molecules convolved to the 30” resolution.



Contour levels: (20%, 40%, 60%, 80%, 100%) of peak intensity



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



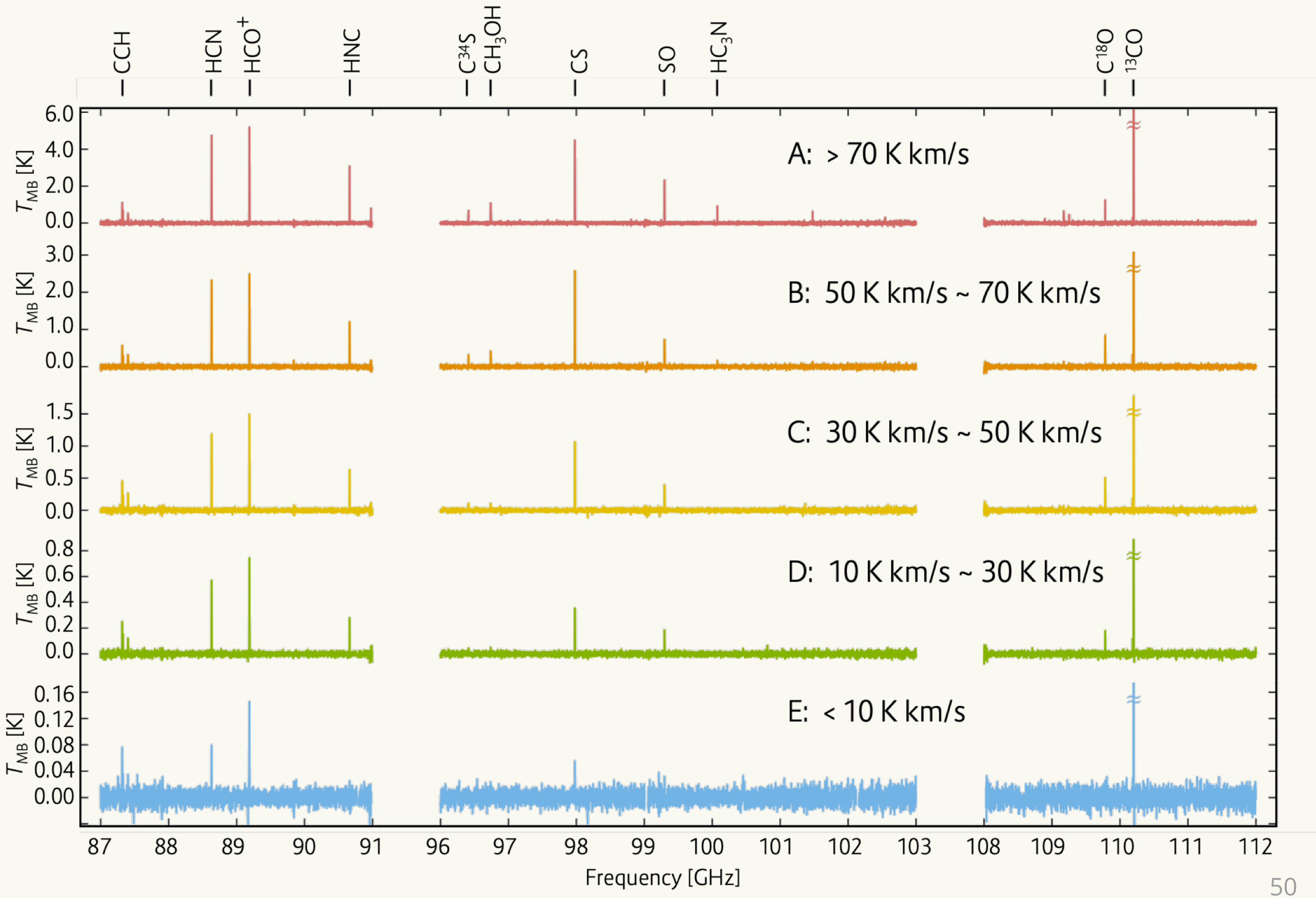
According to the integrated intensity of ^{13}CO, we classified the mapped area into 5 subregions.

Subregions

- A: > 70 K km s^{-1}
  > 8.4 × 10^{23} cm^{-2} / > 3.8 × 10^{5} cm^{-3}
- B: 50–70 K km s^{-1}
  (6.0–8.4) × 10^{23} cm^{-2} / (2.4–3.8) × 10^{5} cm^{-3}
- C: 30–50 K km s^{-1}
  (3.6–6.0) × 10^{23} cm^{-2} / (1.0–2.4) × 10^{5} cm^{-3}
- D: 10–30 K km s^{-1}
  (1.2–3.6) × 10^{23} cm^{-2} / (3.7–10.2) × 10^{4} cm^{-3}
- E: < 10 K km s^{-1}
  < 1.2 × 10^{23} cm^{-2} / < 5.0 × 10^{3} cm^{-3}

assuming X_{CO} = 2 × 10^{20} cm^{-2}/(K km^{-1}), ^{12}CO/^{13}CO = 60

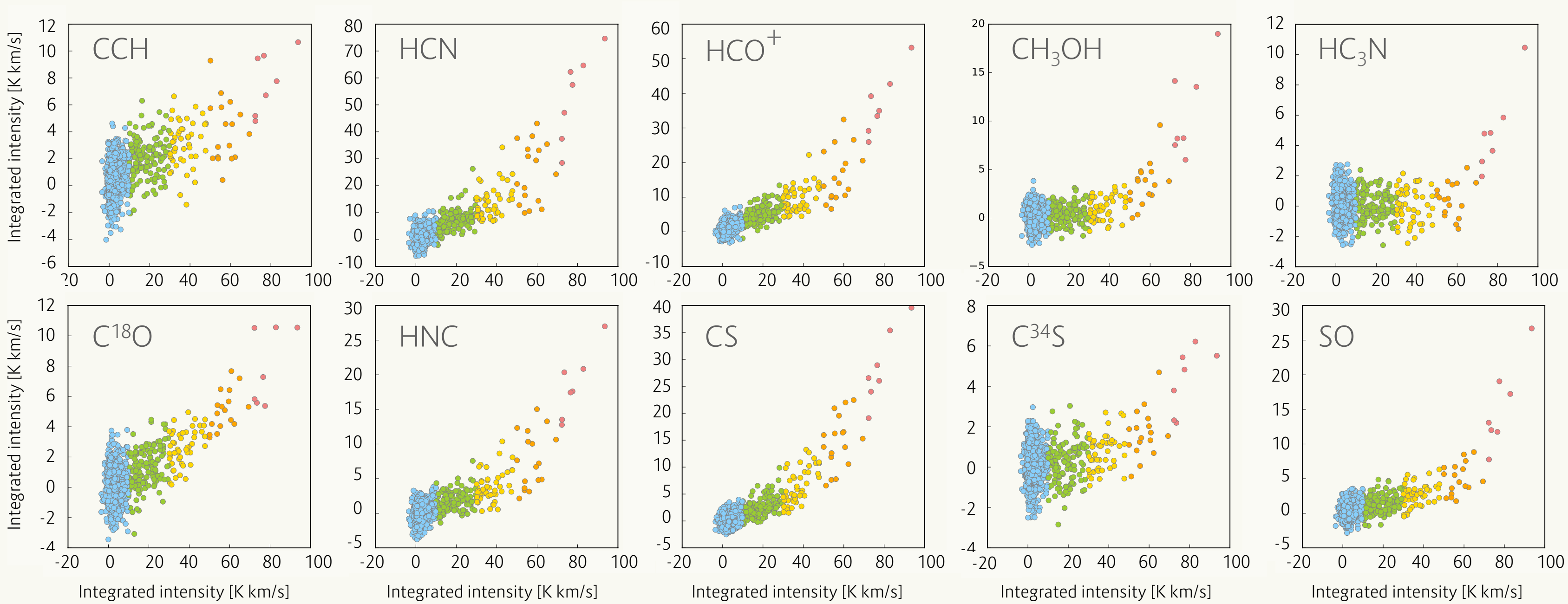
Discussion: **Averaged** spectra of each sub-region



Correlation between integrated intensity of ^{13}CO: 3 mm

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

y-axis: integrated intensity of a given molecule

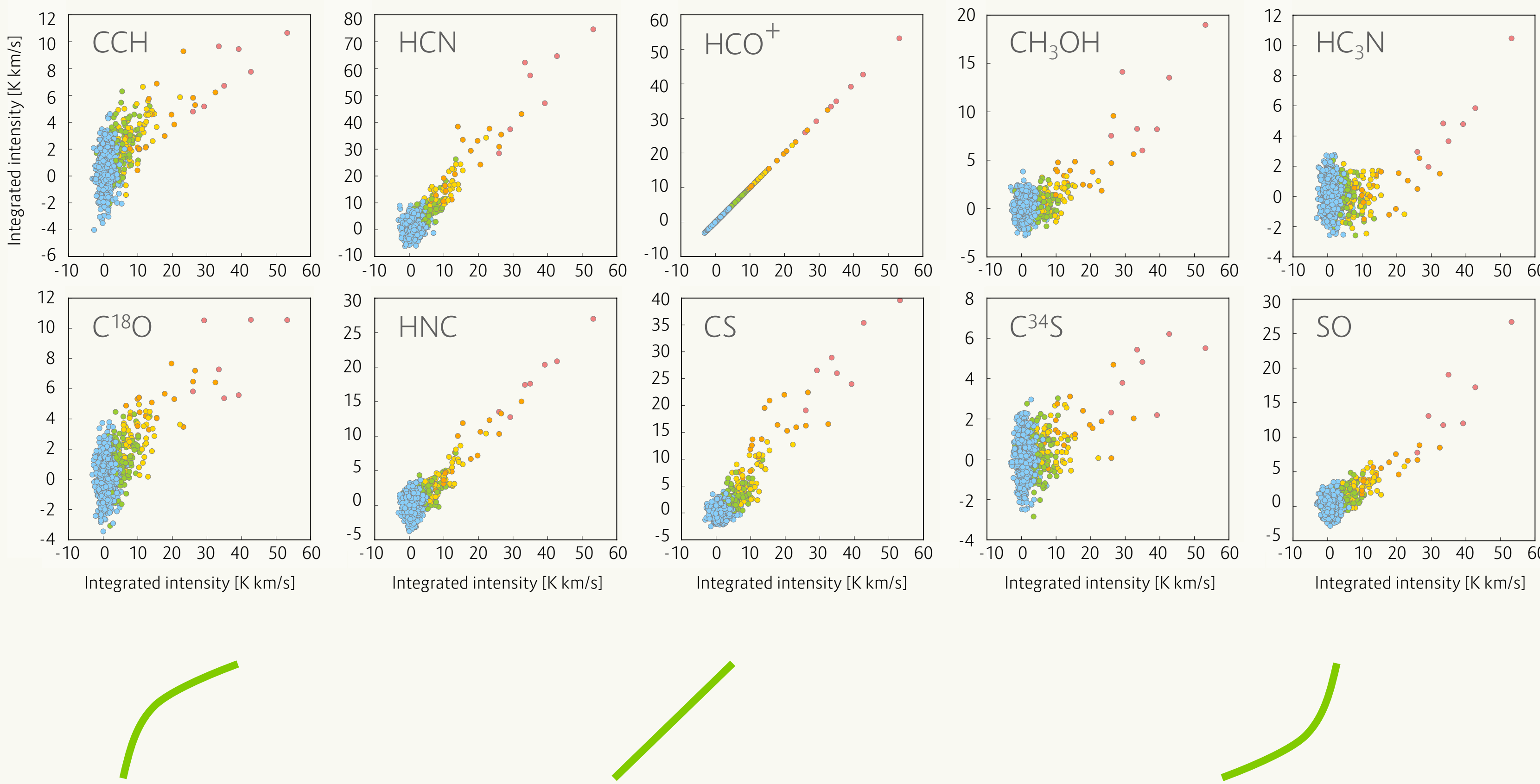


Different knee point!

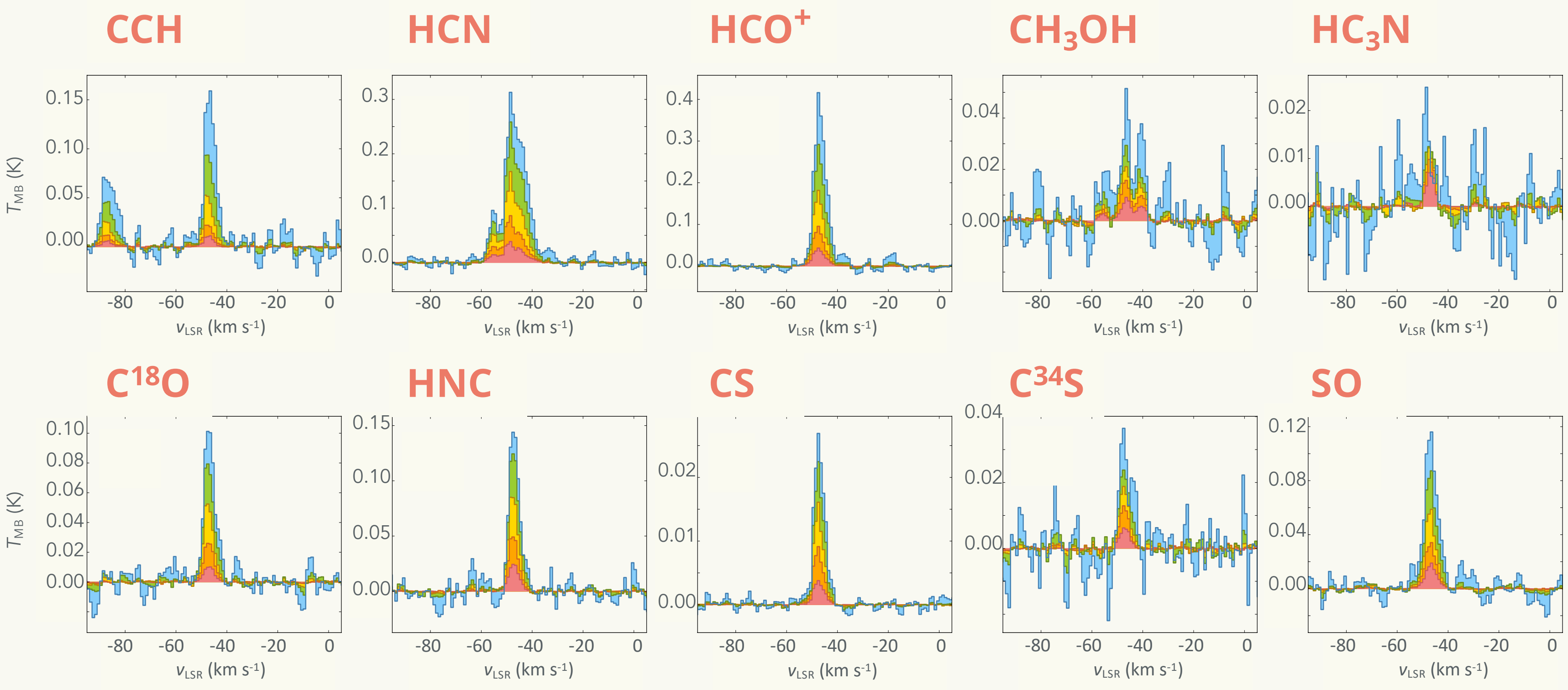
Correlation between integrated intensity of **HCO^+**

x-axis: integrated intensity of HCO^+

y-axis: integrated intensity of a given molecule



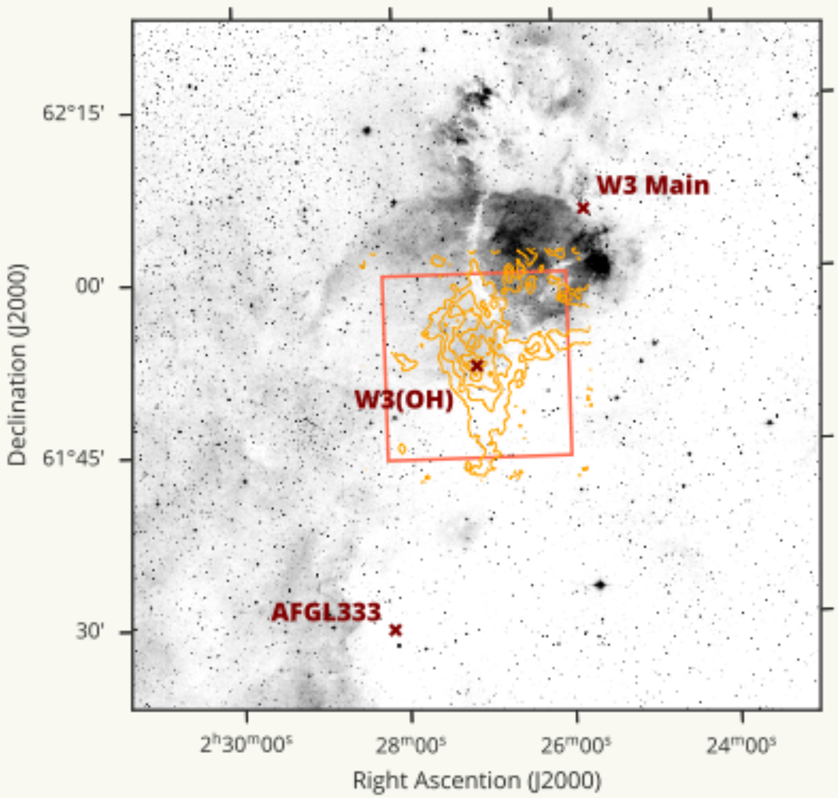
Fractional flux from each sub-region: 3 mm



Contribution from the cloud peripheries is not small or dominant!

Higher-*J* transitions: 0.8 mm observations with JCMT

R band image / CO 3-2



Are the higher-J transitions spatially more closely correlated with dense star-forming gas?

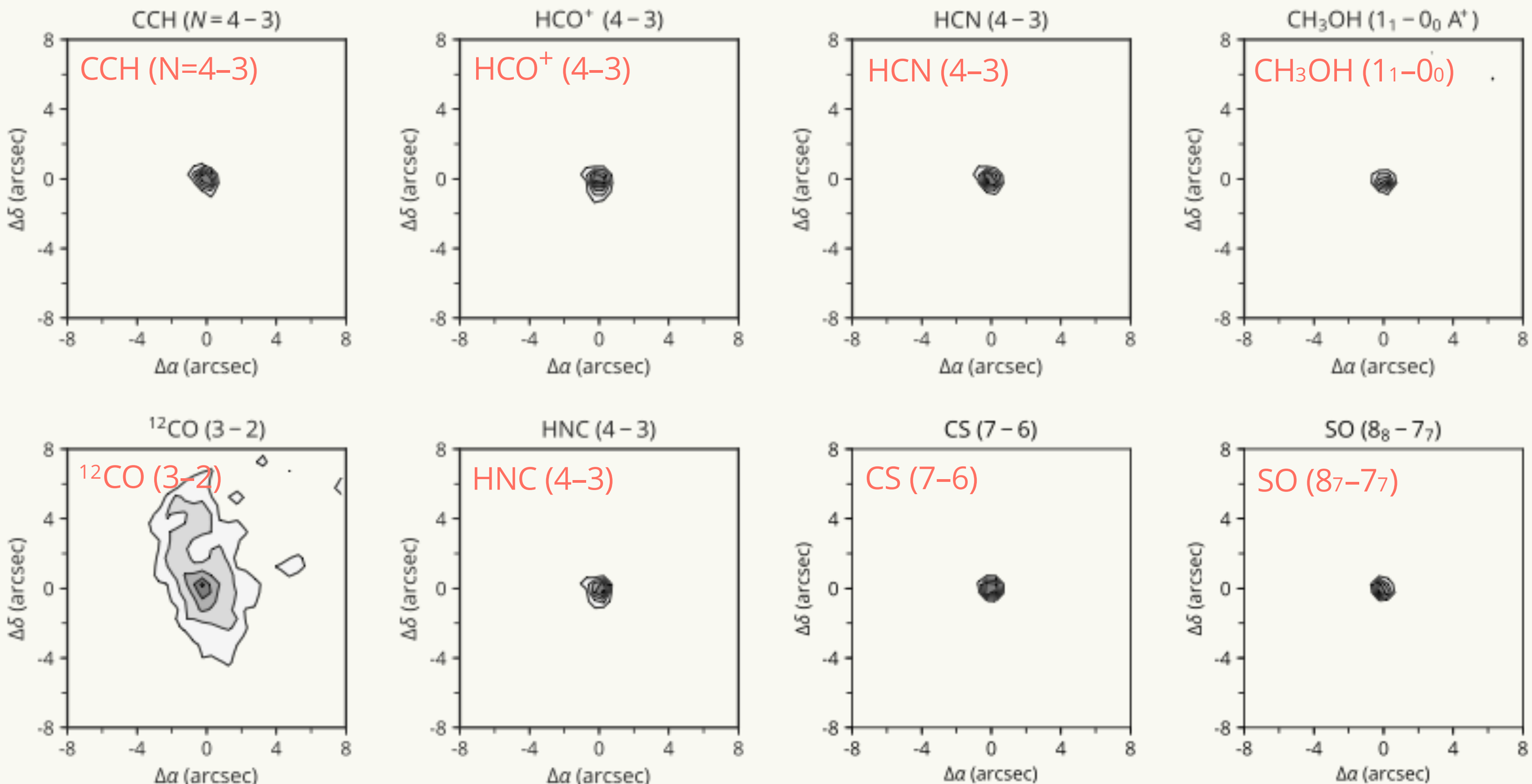
- JCMT 15 m telescope
- February -- December 2018
- On-The-Fly mapping mode
- Same region as the 3 mm band

  16′ × 16′ (9 pc × 9 pc) area
- 20 hours in total

Integrated intensity map: 0.8 mm

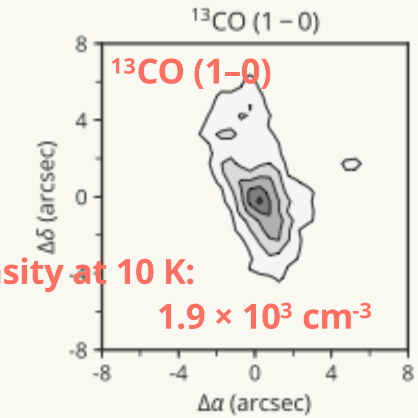
Distribution of the higher-*J* transition lines are generally more compact than that of lower-*J* transition lines.

Contour levels: (20%, 40%, 60%, 80%, 100%) of peak intensity

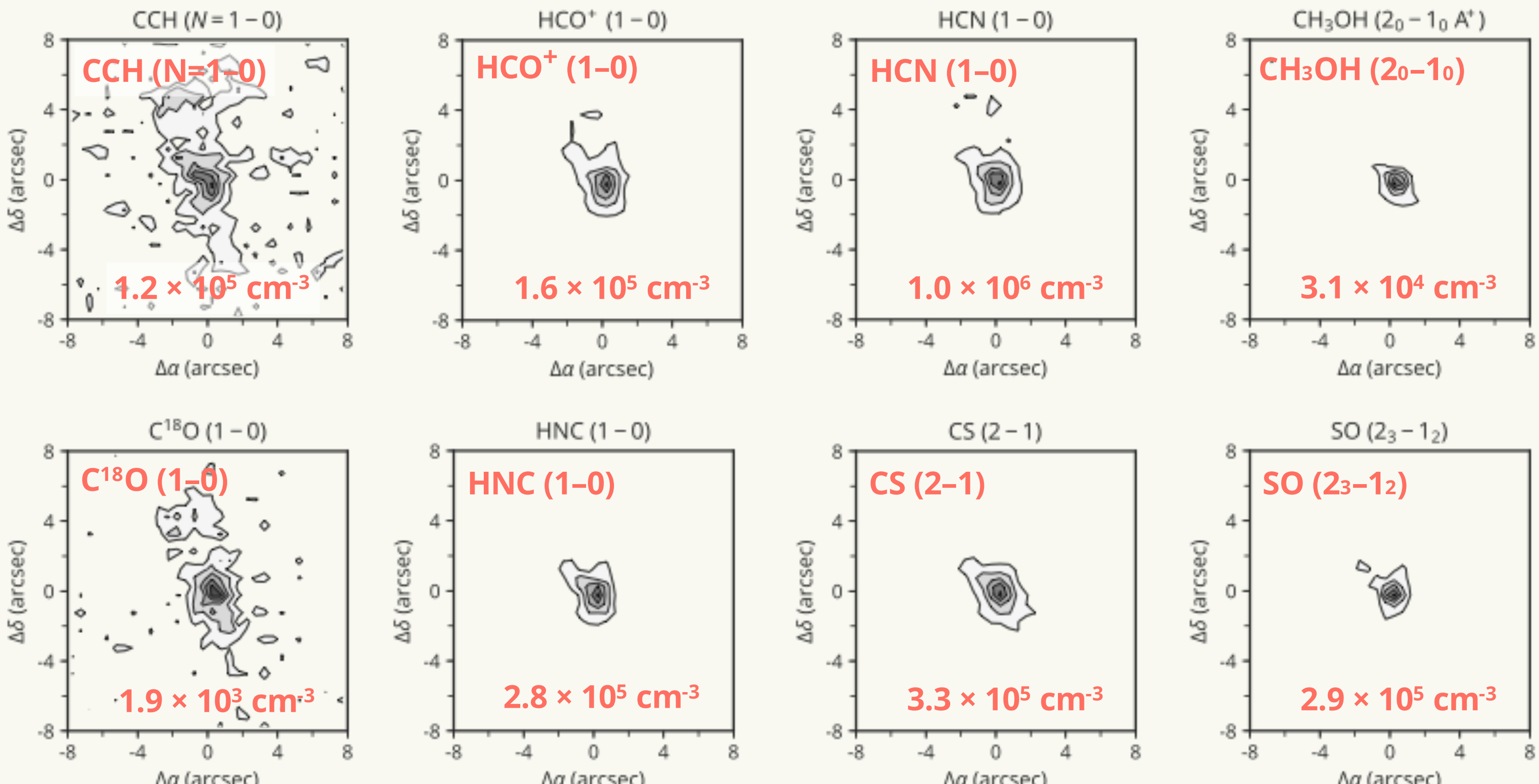


Integrated intensity map: 3 mm

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

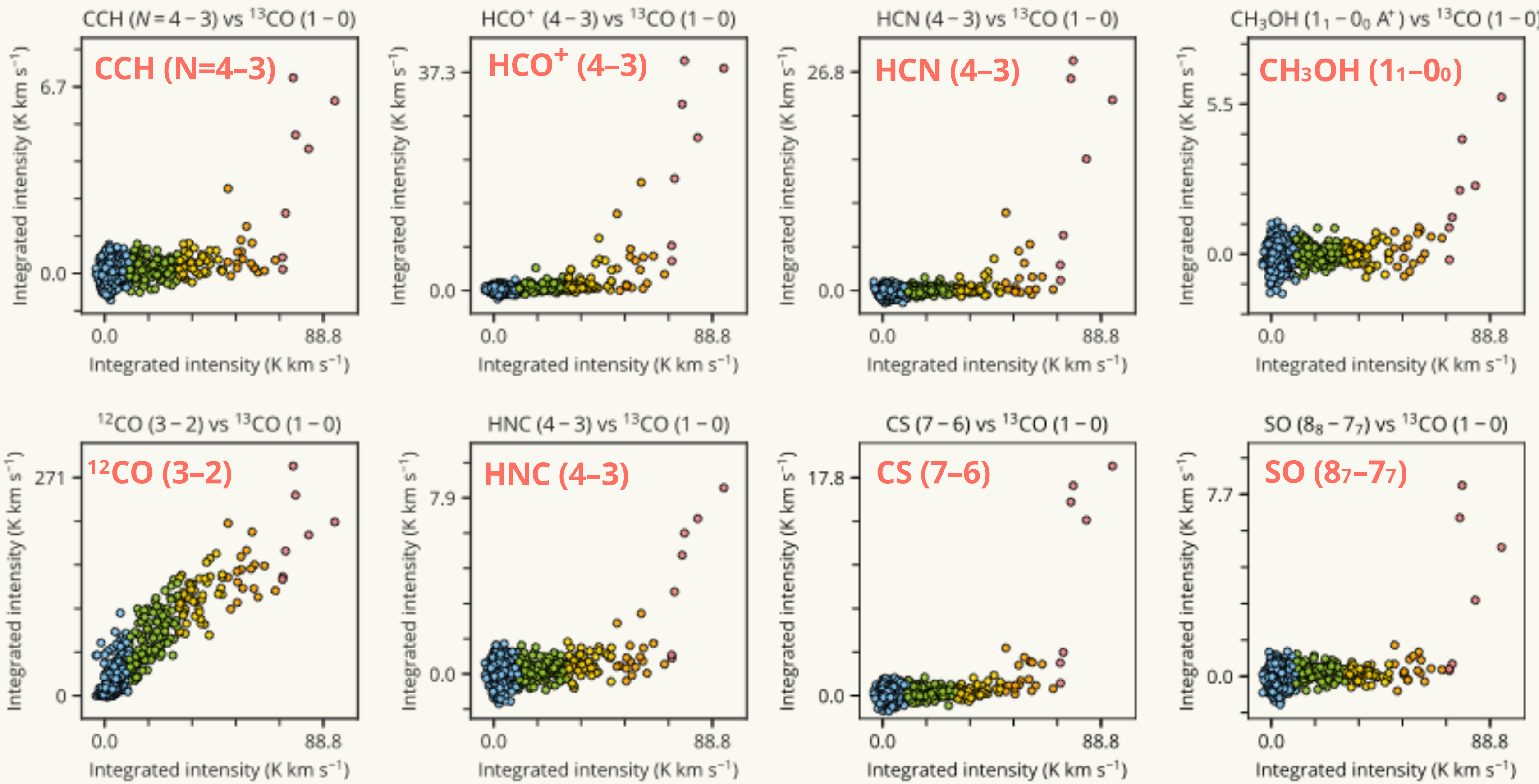


Contour levels: (20%, 40%, 60%, 80%, 100%) of peak intensity



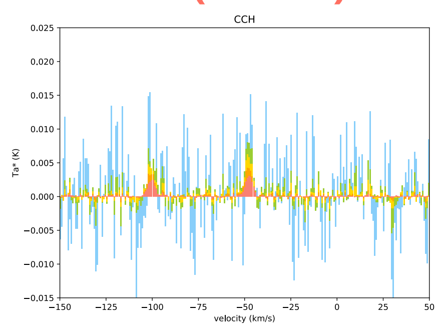
Correlation between integrated intensity of ^{13}CO: 0.8 mm

x-axis: integrated intensity of ^{13}CO (1−0)
y-axis: integrated intensity of a given molecule

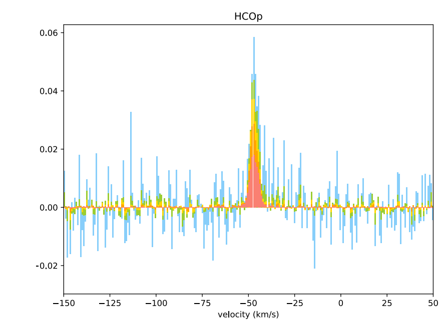


Fractional flux from each sub-region: **0.8 mm**

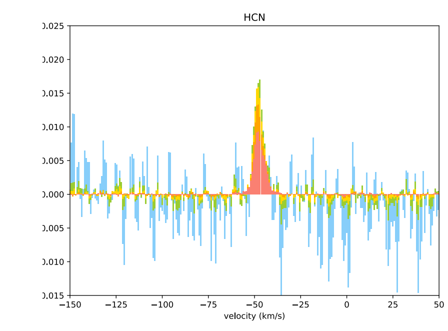
CCH (*N*=4–3)



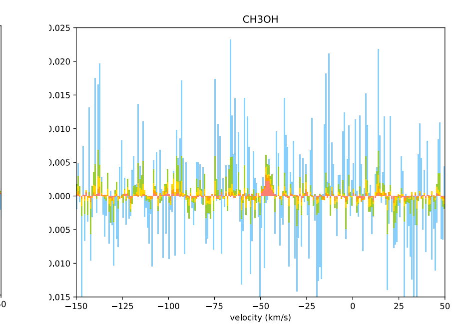
HCO^+ (4–3)



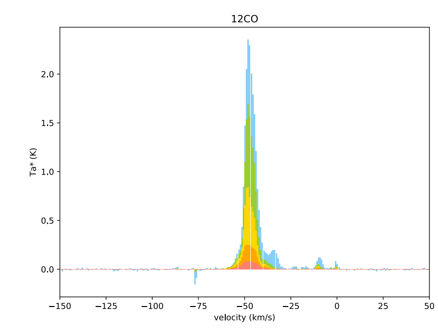
HCN (4–3)



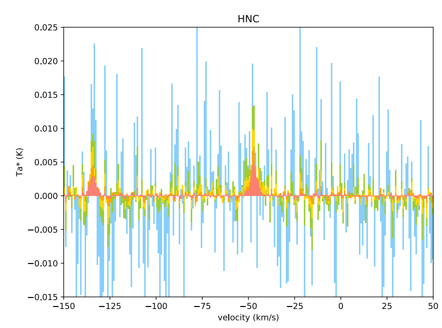
CH_3OH (1_1–0_0)



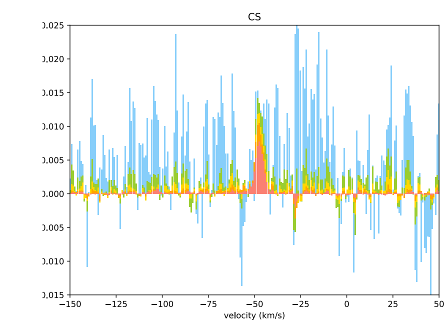
^{12}CO (3–2)



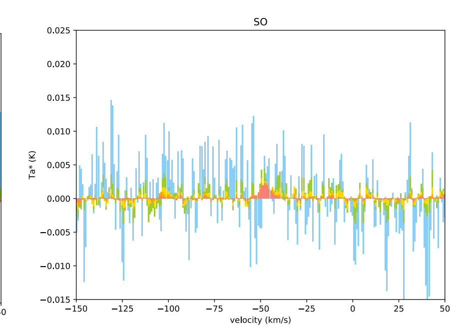
HNC (4–3)



CS (7–6)



SO (8_7–7_7)

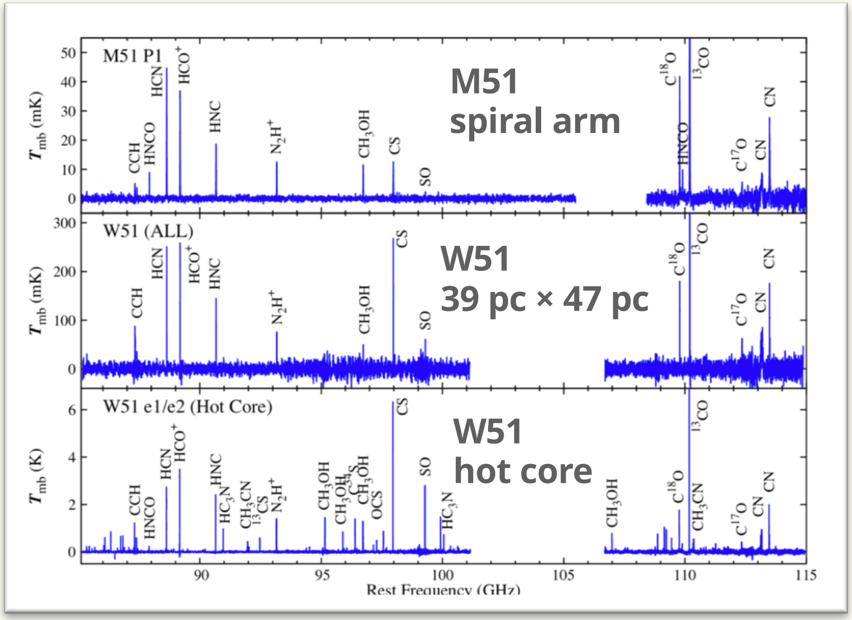


Summary 2

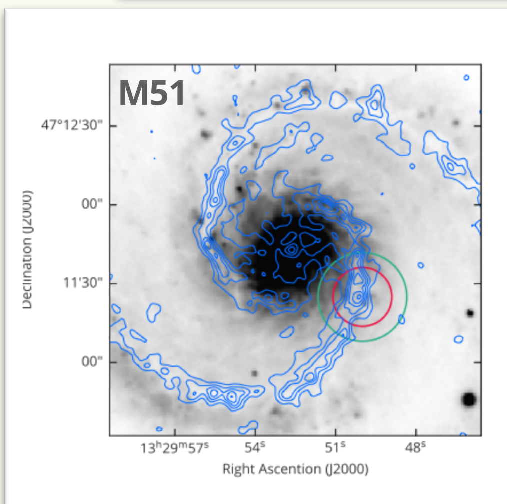
- We have conducted multi-line imaging toward a Galactic molecular cloud W3(OH) in the 3 mm & 0.8 mm band.
- For the lower-J transition lines in the **3 mm** band, it is indicated that the gas in diffuse or translucent regime actually contributes to **a larger fraction of the total line emission** from the 9.0 pc square region.
- In contrast to the lower-J transition lines in the 3 mm band, the higher-J transition lines in the **0.8 mm** band trace **almost exclusively high density**, except for the 12CO (3-2) line.
- In multi-transition analysis of ”high density tracers”, the difference of the emitting regions between low-J and high-J transitions should be taken into account.

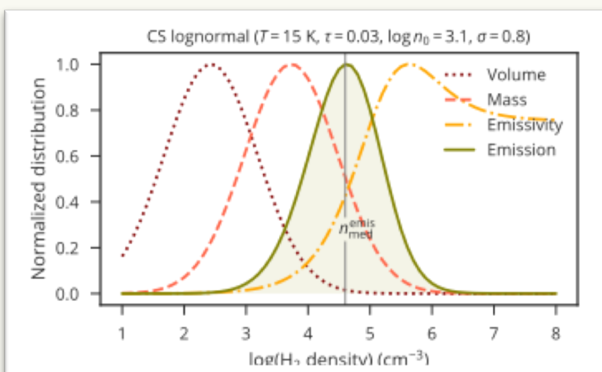
Bridge the Gap between Galactic and Extragalactic

Bridge the Gap between Galactic and Extragalactic



Watanabe et al. 2017





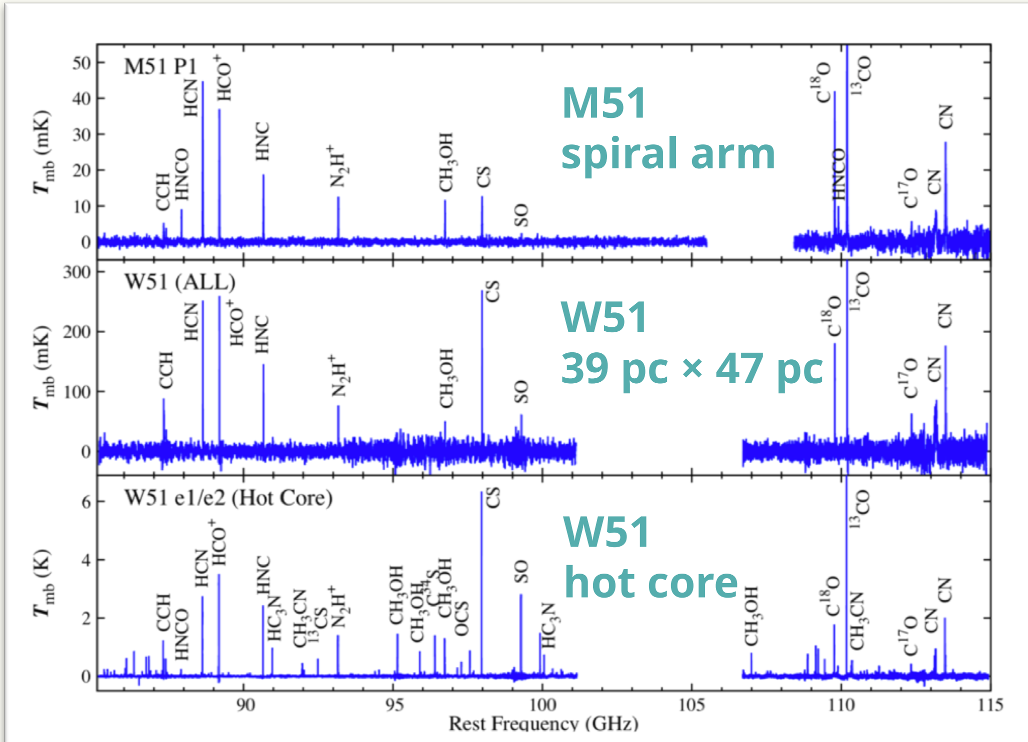
Nishimura et al. 2019

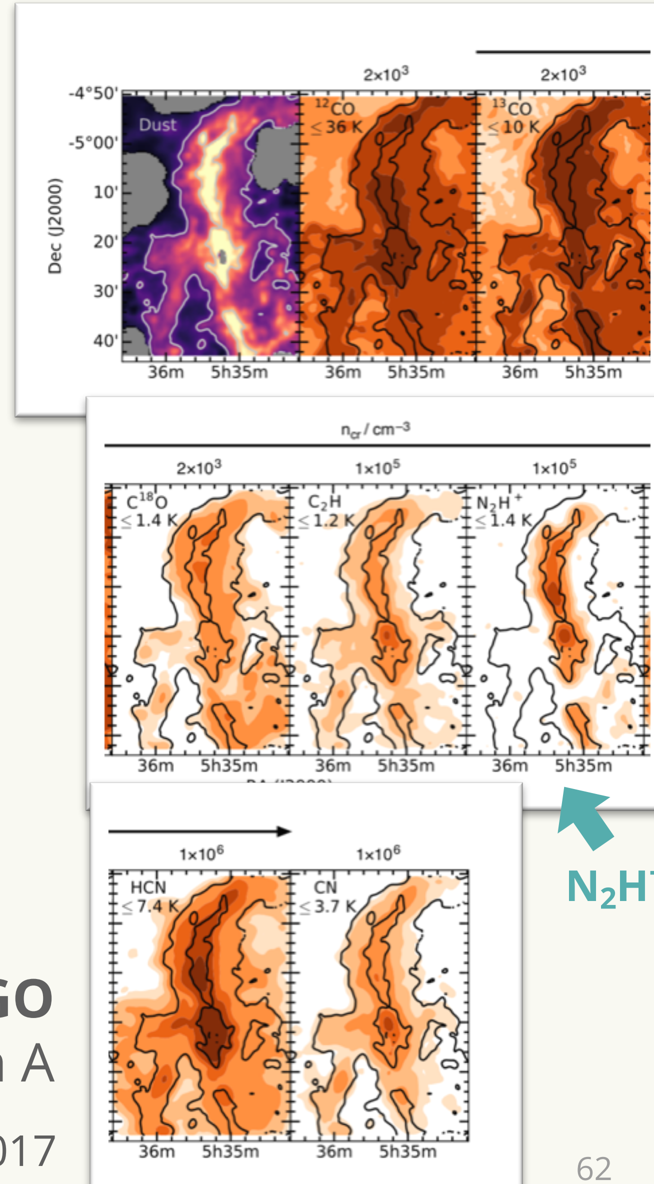
- Measuring the gas density by multi-transition analysis
  - Watanabe et al. 2014
  - Nishimura et al. 2019
- Making large-scale maps of Galactic molecular clouds
  - Nishimura et al. 2017 **W3(OH)**
    Nishimura et al. in prep.
  - Watanabe et al. 2017 **W51**
  - Pety et al. 2017 **Orion B**
  - Kauffmann et al. 2017 **Orion A**
  - Yoshimura et al. in prep. **W41**

Line Mapping of Galactic Molecular Clouds

W51 vs. M51

Watanabe et al. 2017





N_2H^+

See also

Orion B

Pety et al. 2017

N_2H^+ could be “densest” gas tracer?

LEGO

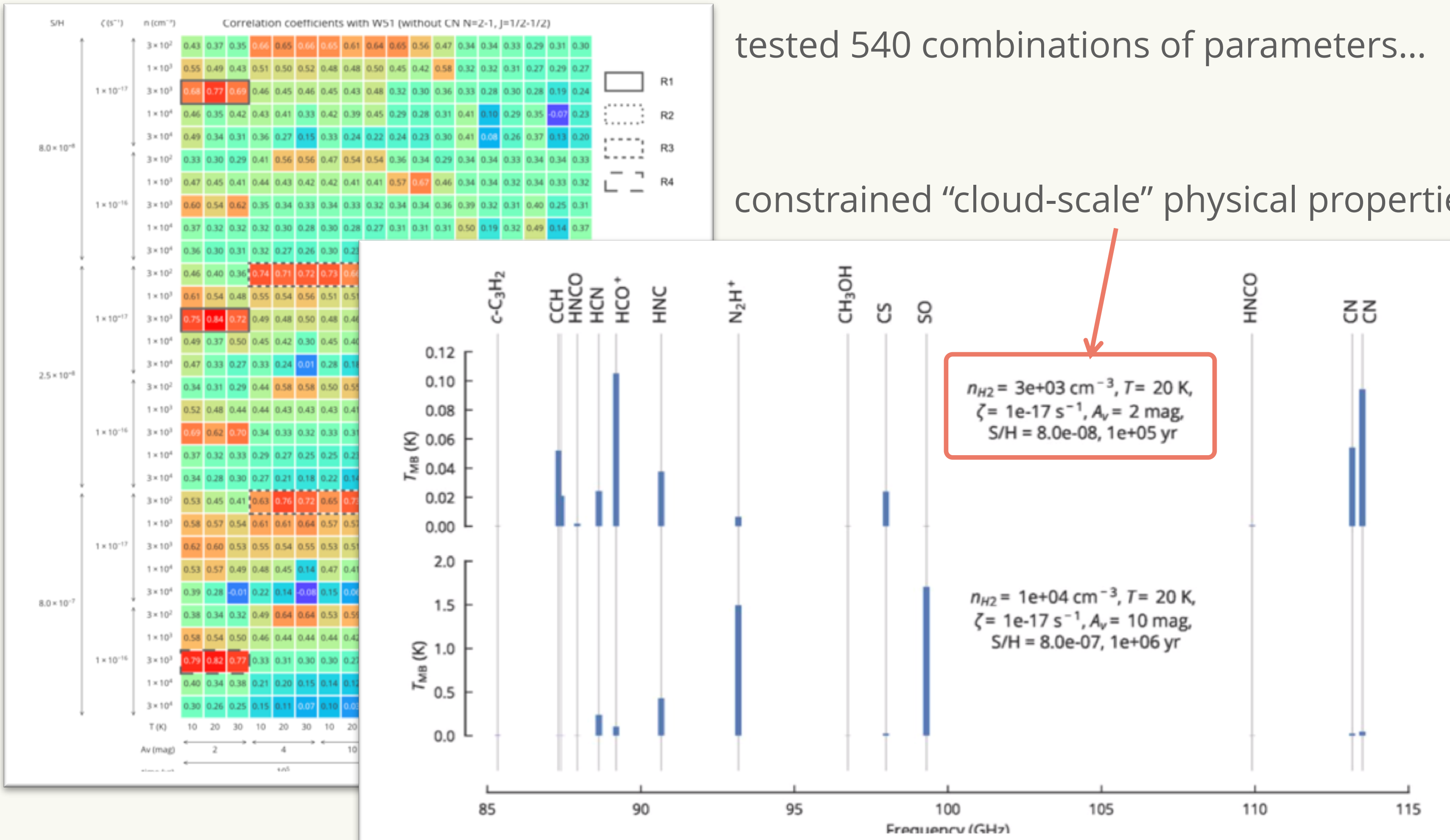
Orion A

Kauffmann et al. 2017

To Constrain Physical Properties

Chemical modeling

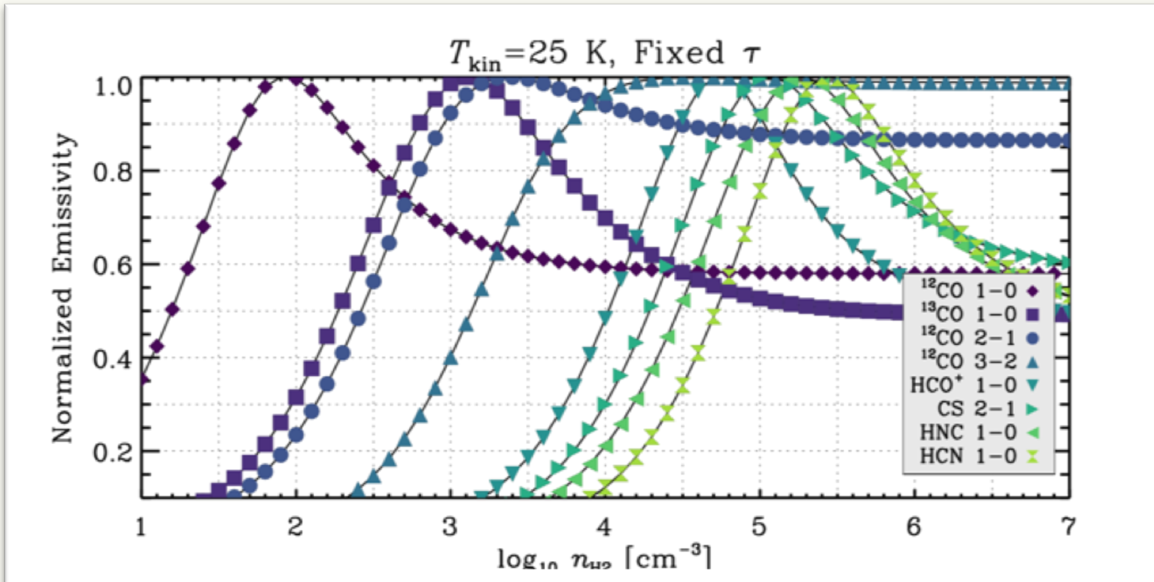
Harada et al. 2019



tested 540 combinations of parameters…

constrained “cloud-scale” physical properties

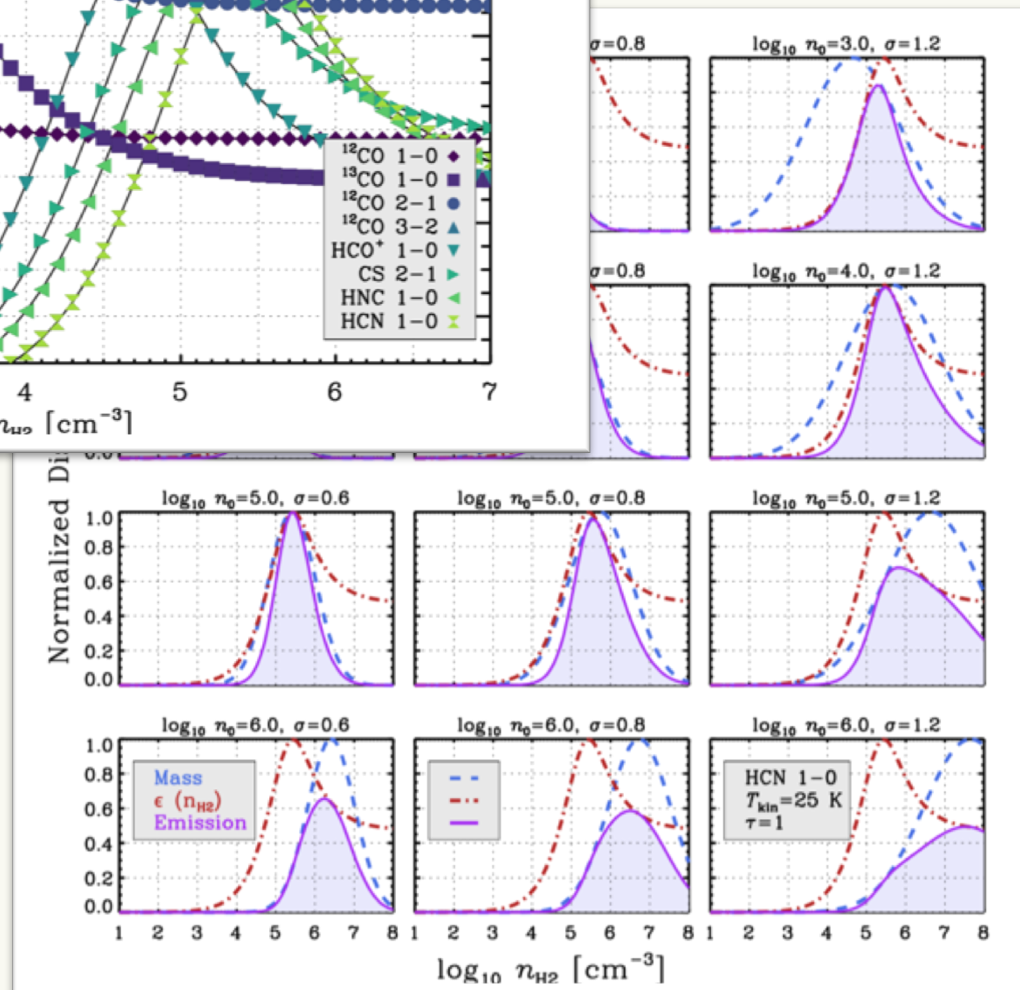
To Probe Density Distribution



Emissivity

Density (cm^{-3})

Leroy et al. 2017

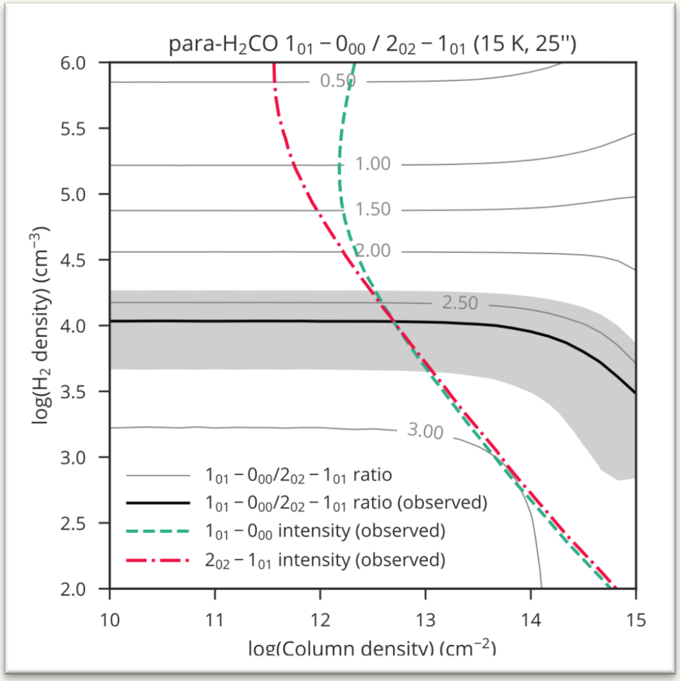


All these simulations
are using **RADEX**
(code for non-LTE analysis)

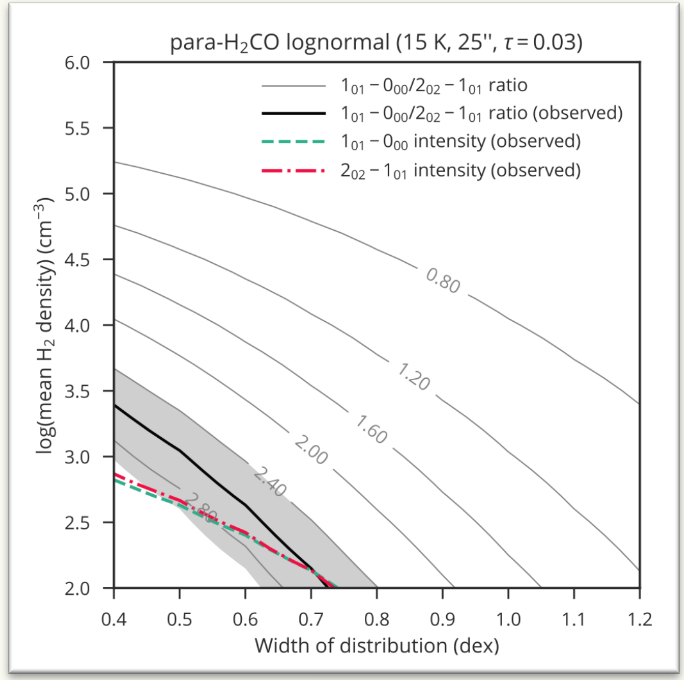
van der Tak et al. 2007

Application for **Observations**

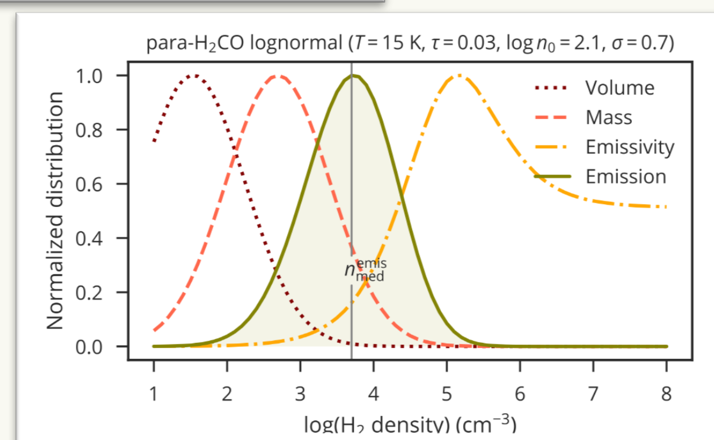
Nishimura et al. 2019



Harada-like approach



Conducted non-LTE analysis using **RADEX** to reproduce observed intensity of **H_2CO** and **CS**

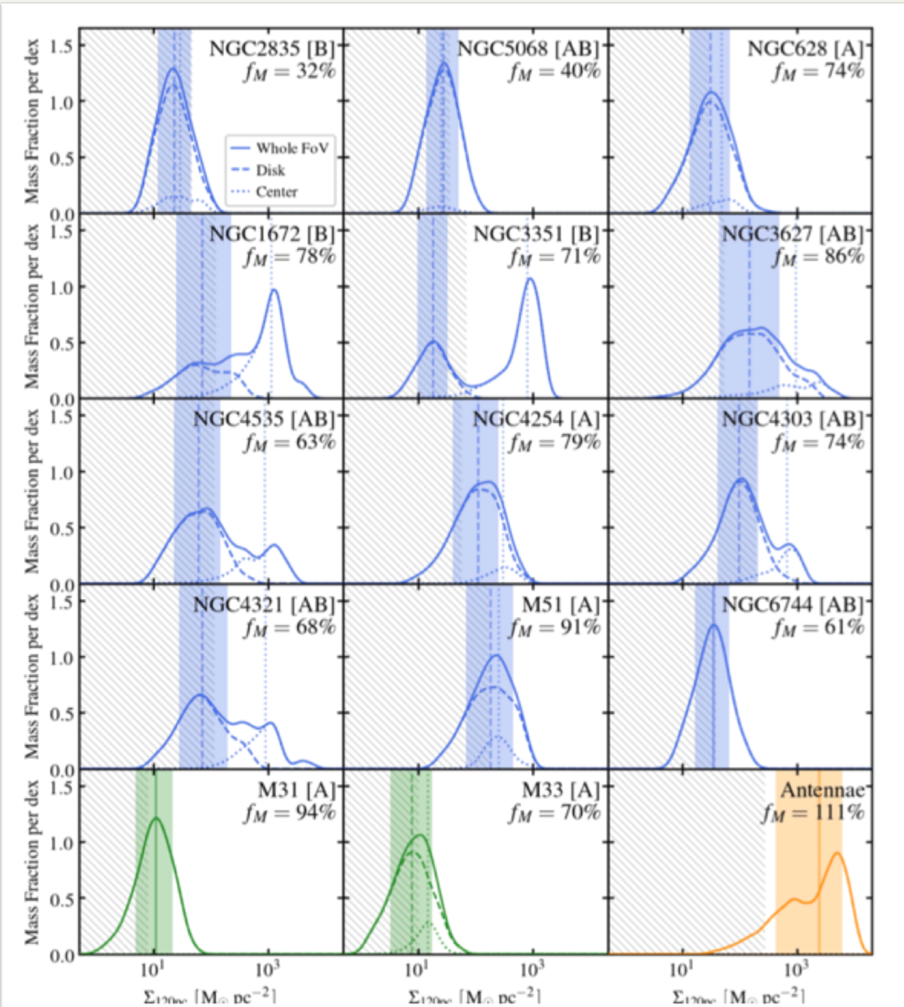


Leroy-like approach

and More Observations

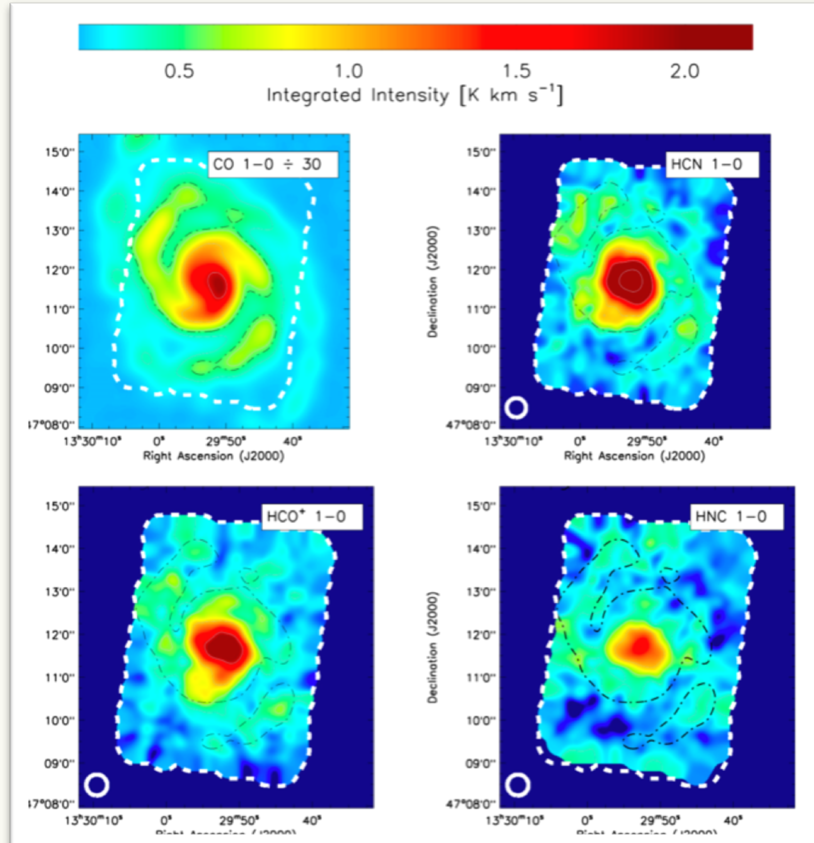
PHANGS

Sun et al. 2018



EMPIRE

Bigiel et al. 2016



will allow us to explore ISM conditions in different galactic environments

Take Home Messages

Take Home Messages

キャリア：就職

- いろんな自己実現の方法あり
- 科学に携わる職業はアカデミックだけではない

キャリア：ポスドク

- 何を大事に職を選ぶか自分の基準を考えておく：
  Duty workの質・量 / 勤務地 / アドバイザー・メンター
- いろんなグループのいろんなやり方を見るのは勉強になる
- 他人の研究をリスペクトする、コラボレーターを大切に

Take Home Messages

研究

- 研究しながら勉強する（勉強は永遠に終わらない）
- 自分の研究の軸を大切に持っておく
- オリジナリティは大事、でもタコツボ化しないように！
  “Big Question”と繋がっていることはもっと大事
- 「両足をいっぺんに浮かせると転ぶ」
  片足は持ちネタ、もう片足は新しいチャレンジ、くらいのバランス
- うまくいかなかった経験は肥やしになるので、簡単に腐らない
- （特に書くとき）構成、言葉づかい、図表をよく吟味する

Special thanks to...

Yuri Aikawa

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Kotaro Kohno

Nami Sakai

Takashi Shimonishi

Satoshi Yamamoto

Yoshimasa Watanabe