分子雲スケールの星間分子組成

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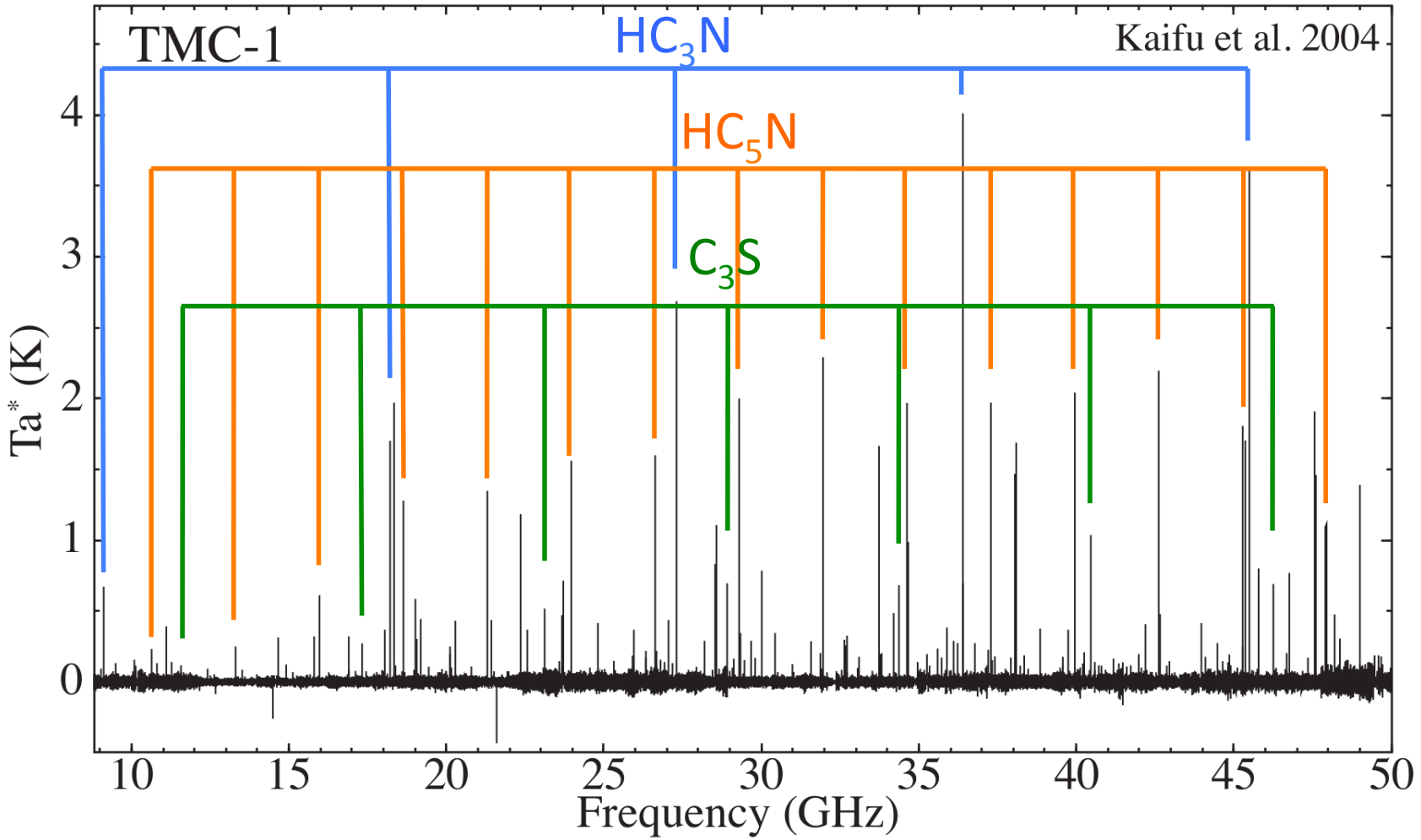
Summary

Interstellar Molecules



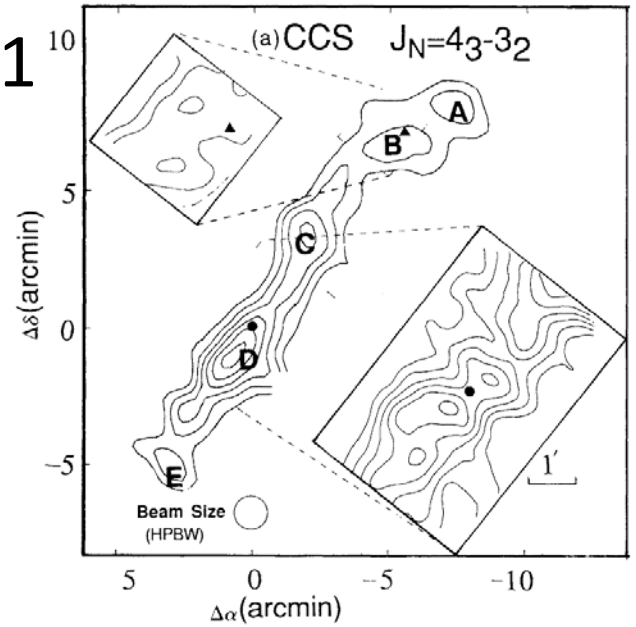
More than 190 species have been identified.

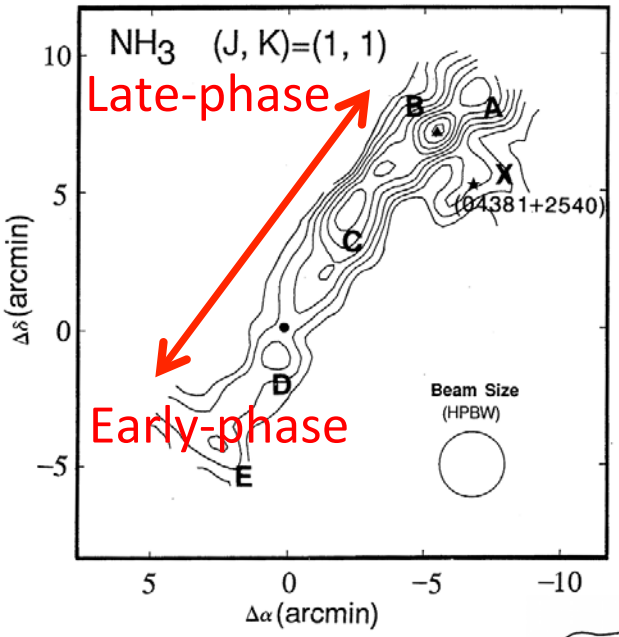
Target Sources in the Milky Way (MW)

- Dark molecular cloud cores
- Star-forming regions
- Late type stars (AGB stars)

Chemical Evolution of Molecular Cloud Cores

TMC-1





Hirashita et al. 1992

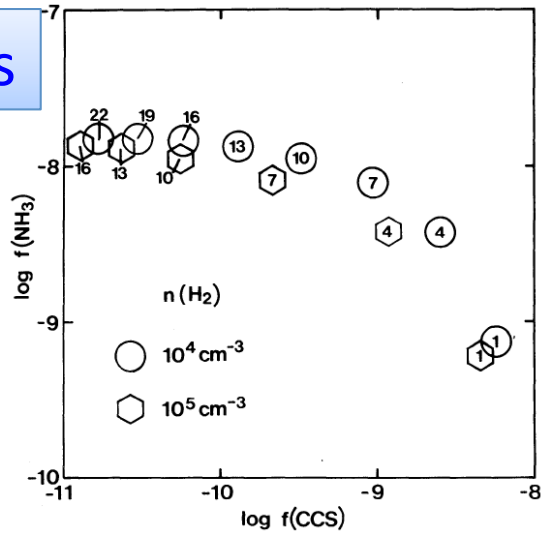
Chemical difference among cores

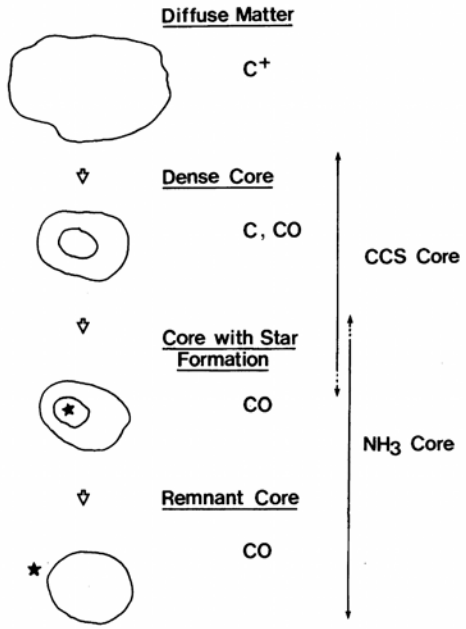
Starless Cores: high CCS, low NH_3

Protostars : low CCS, high NH_3

Successful chemical modeling

Chemical evolution



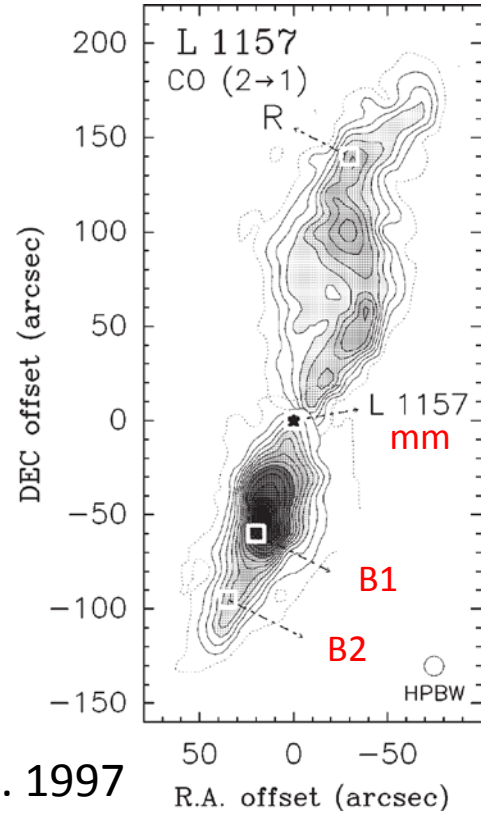


Suzuki et al. 1992

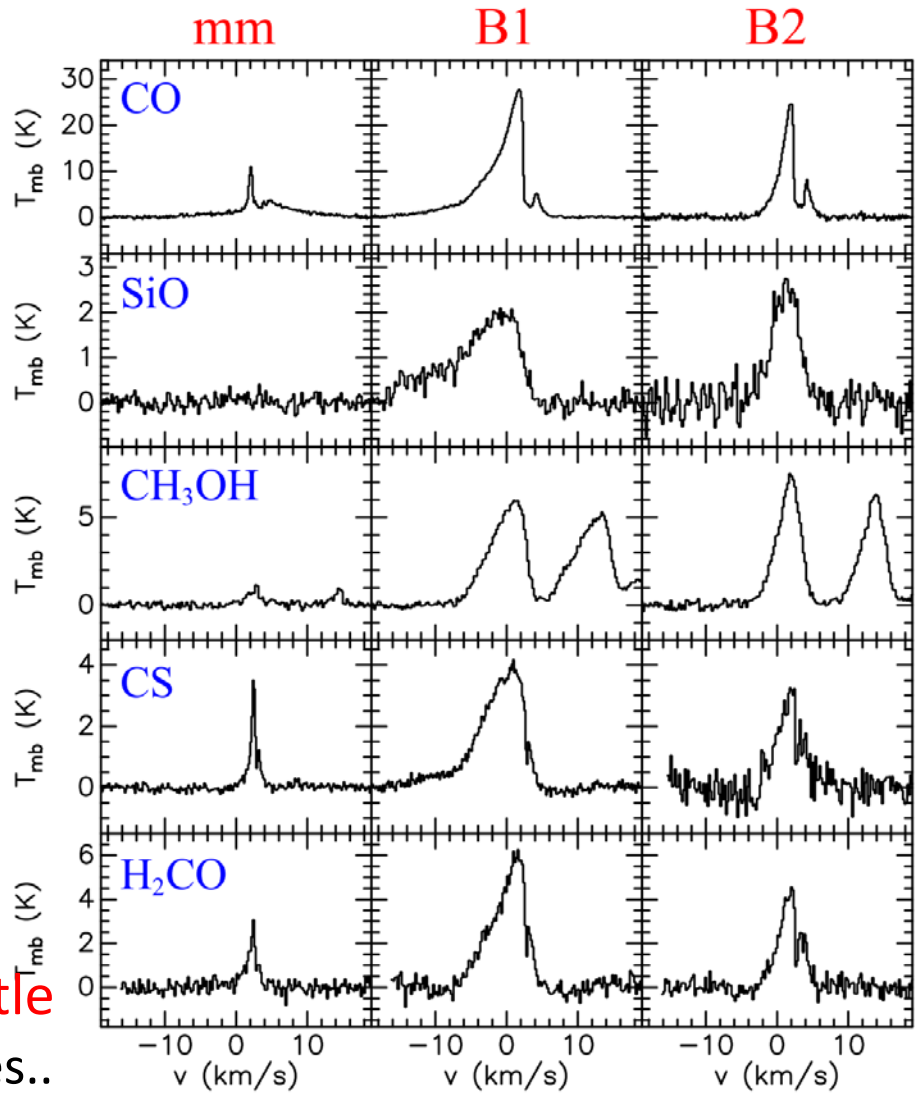
Chemistry as a Diagnostic Tool of Physical Condition

Characteristic chemistry in { shocked region / photodissociation region (PDR)

e.g.: Outflow-shock in L1157



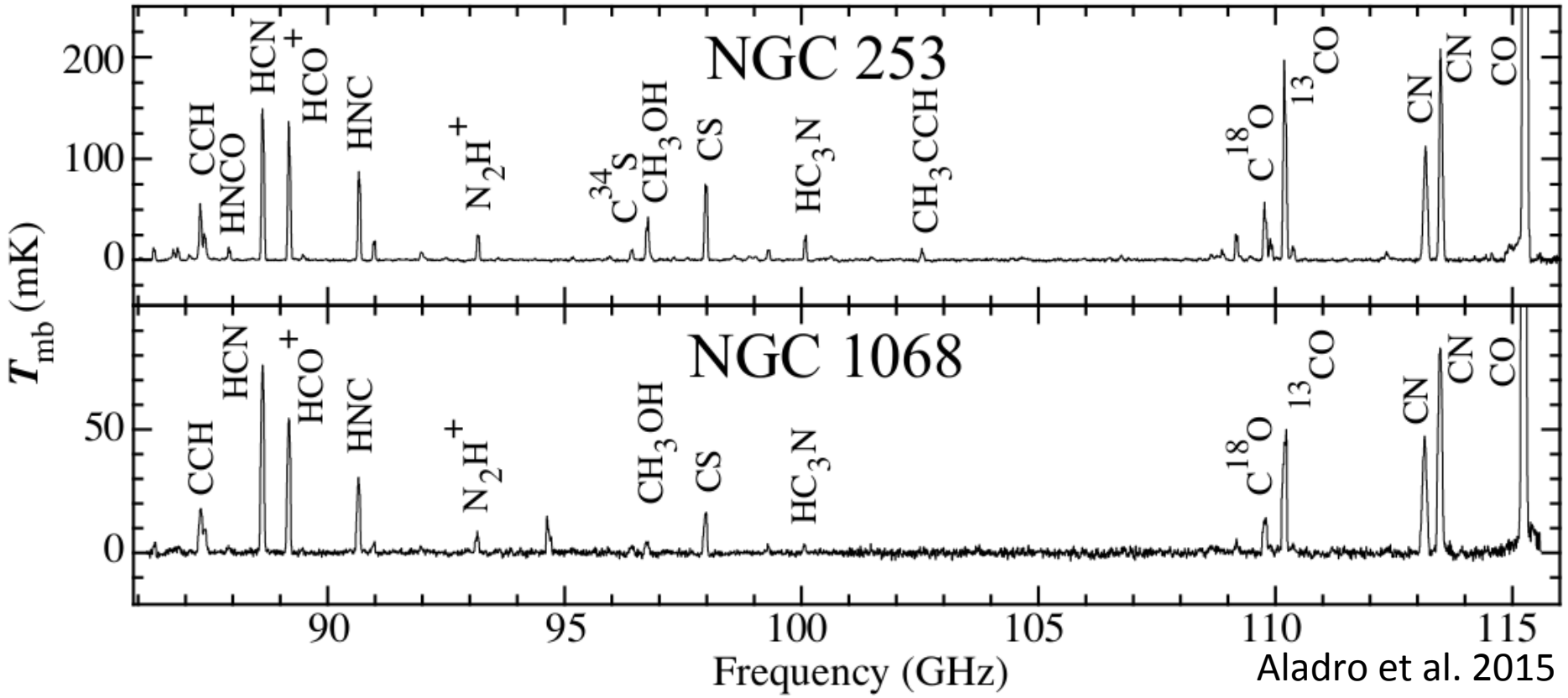
Bachillar et al. 1997



Evaporation of molecules from grain mantle

e.g.: CH_3OH, SiO, complex organic molecules..

Chemical Studies in External Galaxies



Aladro et al. 2015

Target Sources

Starburst: NGC 253, M82 ..

AGN: NGC1068, NGC 1096, ..

LIRG/ULIRG: Arp220, NGC 4418, ..

Spectral line surveys

Chemical diagnostics

- Nuclear activities
- HCN/HCO^+ : XDR?

Interstellar Molecules in External Galaxies

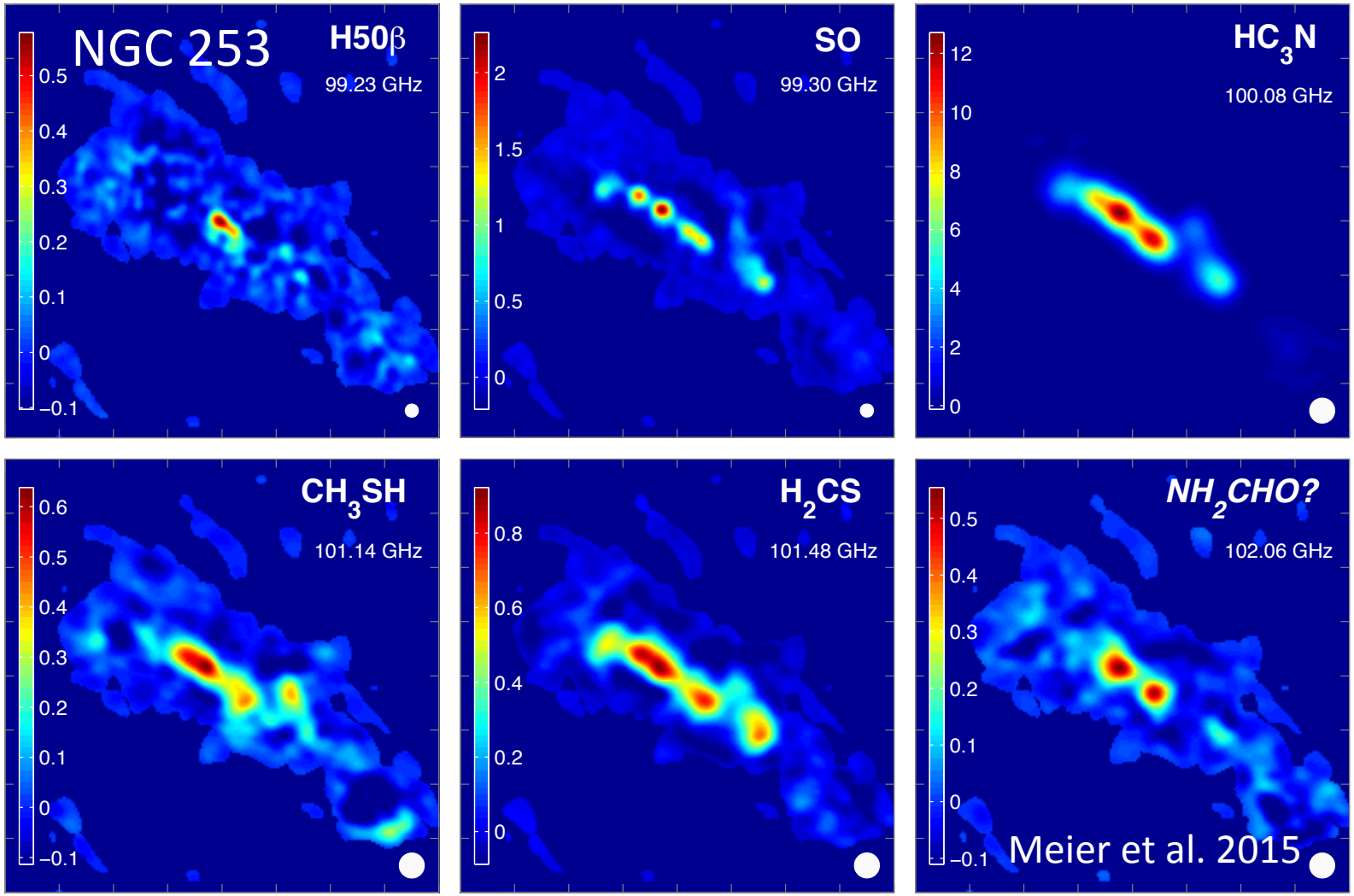
2 atoms		3 atoms		4 atoms	5 atoms	6 atoms	>7 atoms
H_2	NO	H_2O	HOC^+	HNCO	*c*-C_3H_2	CH_3OH	CH_3CCH
OH	NS	HCN	CCS	C_2H_2	HC_3N	CH_3CN	CH_3NH_2
CH	NH	HCO^+	H_2O^+	H_2CS	CH_2NH	HC_4H	HC_6H
CH^+	OH^+	CCH	HCS^+	$HOCO^+$	NH_2CN	$HC(O)NH_2$	*c*-C_6H_6
CS	HF	HNC	H_2CO	c-C_3H	*l*-C_3H_2		
CN	SO^+	N_2H^+	NH_3	H_3O^+	H_2CCN		
SO	ArH^+	HCO	SO_2	*l*-C_3H	H_2CCO		
SiO	CF^+	OCS			C_4H		
CO^+		H_2S					

From The Cologne Database for Molecular Spectroscopy
http://www.astro.uni-koeln.de/cdms/

59 molecular species have been identified in external galaxies

c.f. more than 190 species in MW

Chemical Studies with ALMA



Beam: 2-4” (35 – 70 pc)

High resolution imaging with ALMA

Detailed study of chemistry in nuclear regions

Chemistry of External Galaxies

Diagnostic tool of nuclear activities (AGN & Starburst)

Chemical compositions ⟺ Peculiar physical conditions

- PDR, XDR, Shocks...

Can astrochemical concepts established in the MW be applied to the studies in external galaxies?

Large scale difference

- Galactic observations: smaller than > 0.1 pc
- Extagalactic observations: > 1 kpc – 10 pc

A few order of magnitude...

Chemistry of Molecular Cloud-Scale Gas

For interpretation of extragalactic astrochemistry..

Chemical composition of 'starndard molecular clouds'

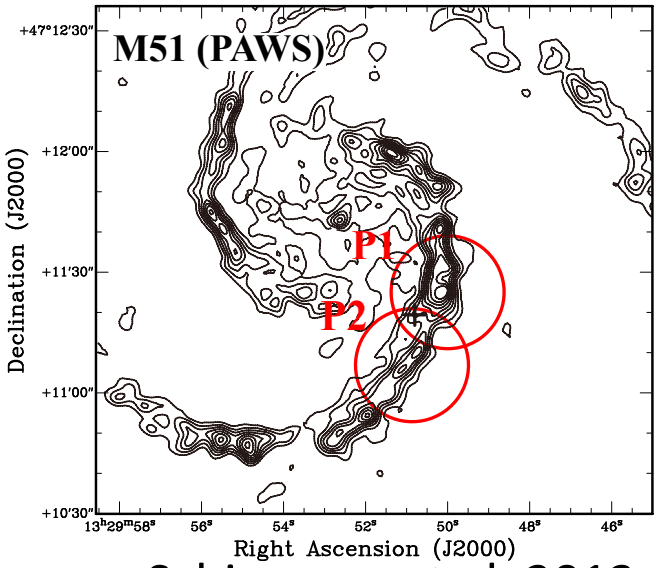
- e.g.: Giant molecular cloud (GMC) in a spiral arm

Effect of star formation

Effect of galactic-scale dynamics

Effect of metallicity

Spectral Line Survey of M 51



Schinnerer et al. 2013

IRAM 30m

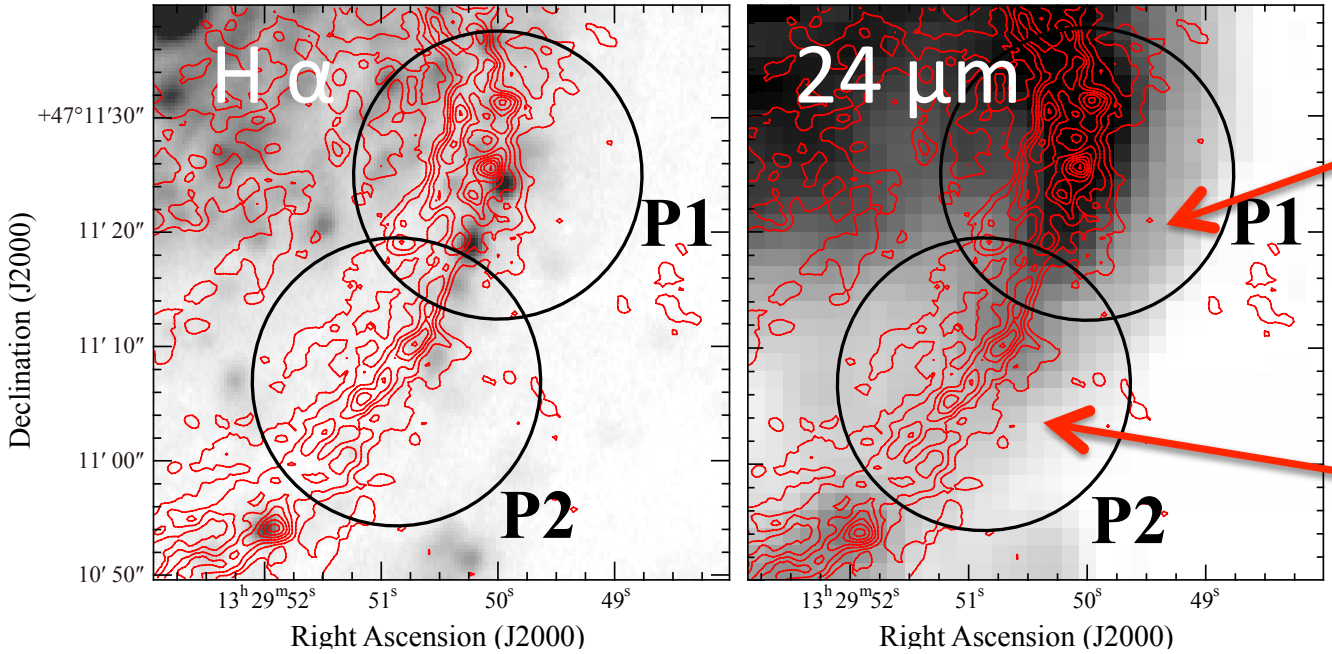
Date : Dec. 2011, Aug. 2012

Frequency : 83 – 116 GHz

130 – 148 GHz

Resolution : 30” – 17” (~ 1 kpc)

d : ~ 8.4 Mpc (Feldmeier et al. 1997)



P1

SFR: 0.055 $M_\odot$ yr^{-1}

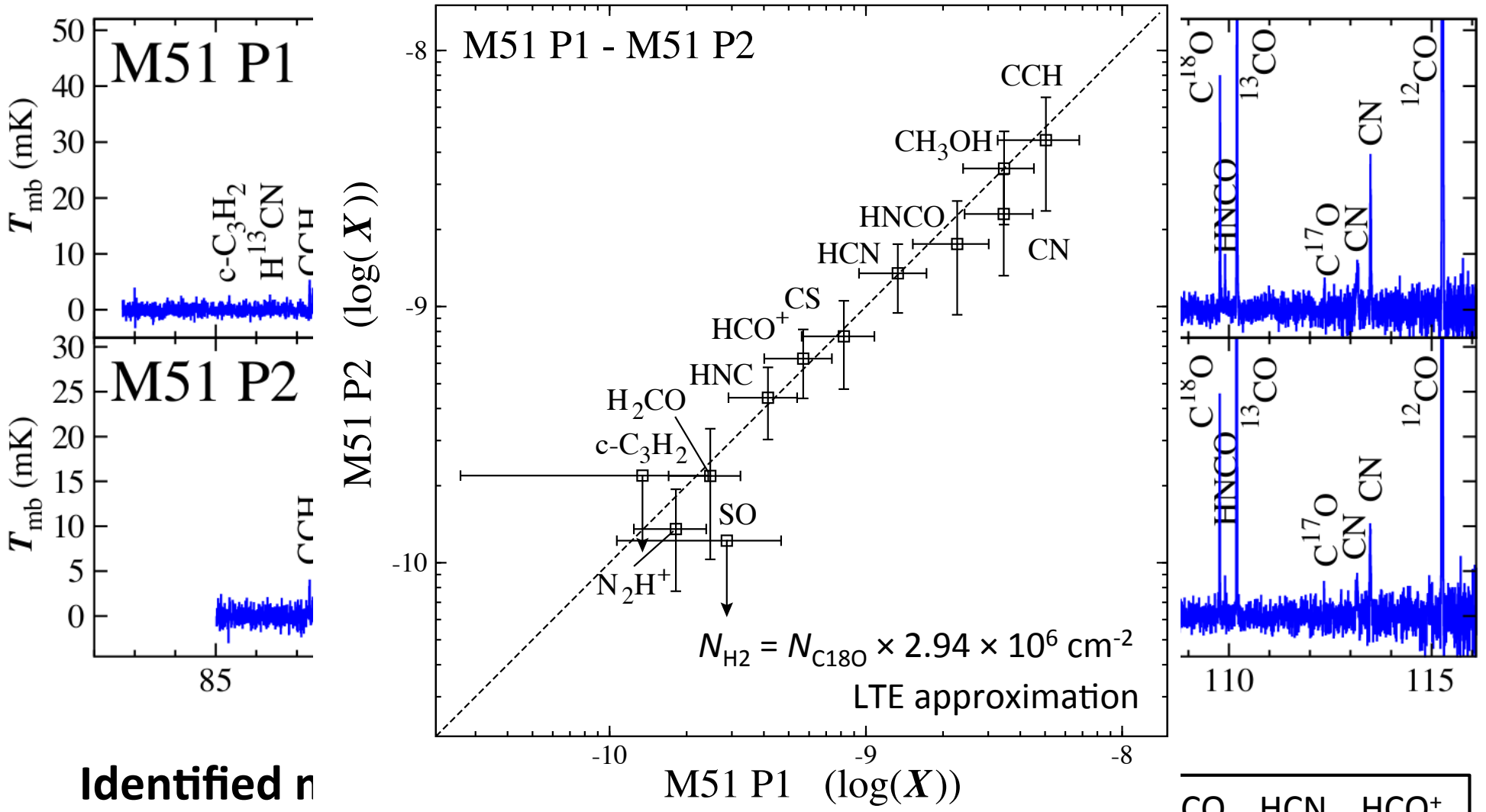
SFE: 4.5 x 10^{-10} yr^{-1}

P2

SFR: 0.022 $M_\odot$ yr^{-1}

SFE: 2.9 x 10^{-10} yr^{-1}

Comparison between Positions 1 and 2

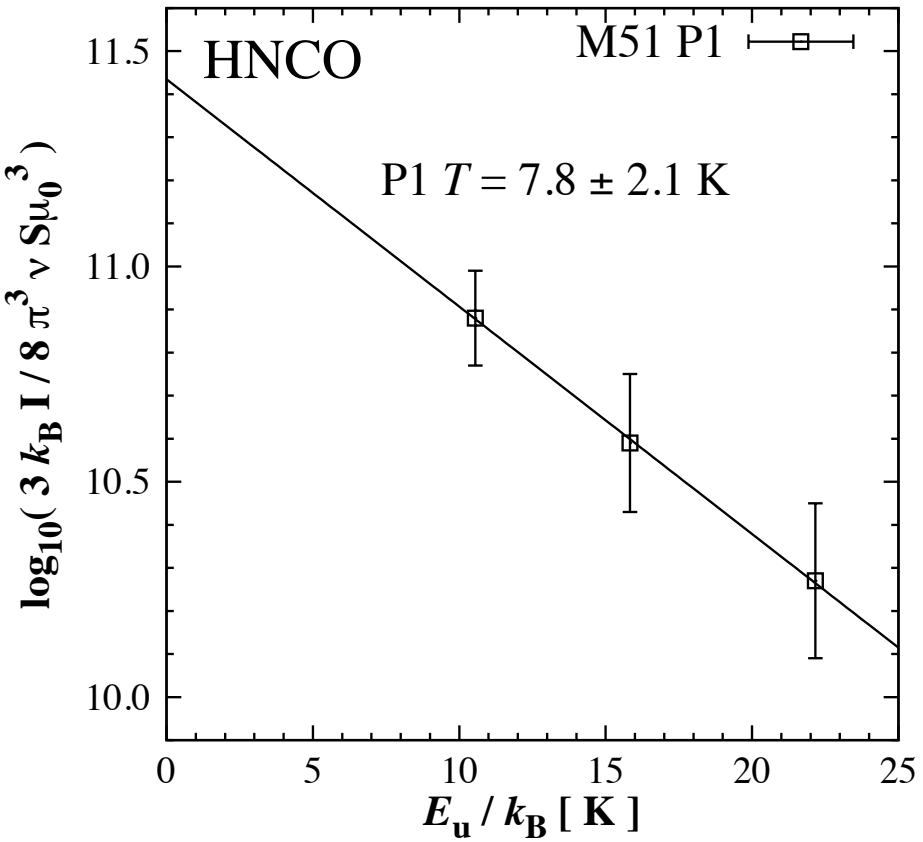


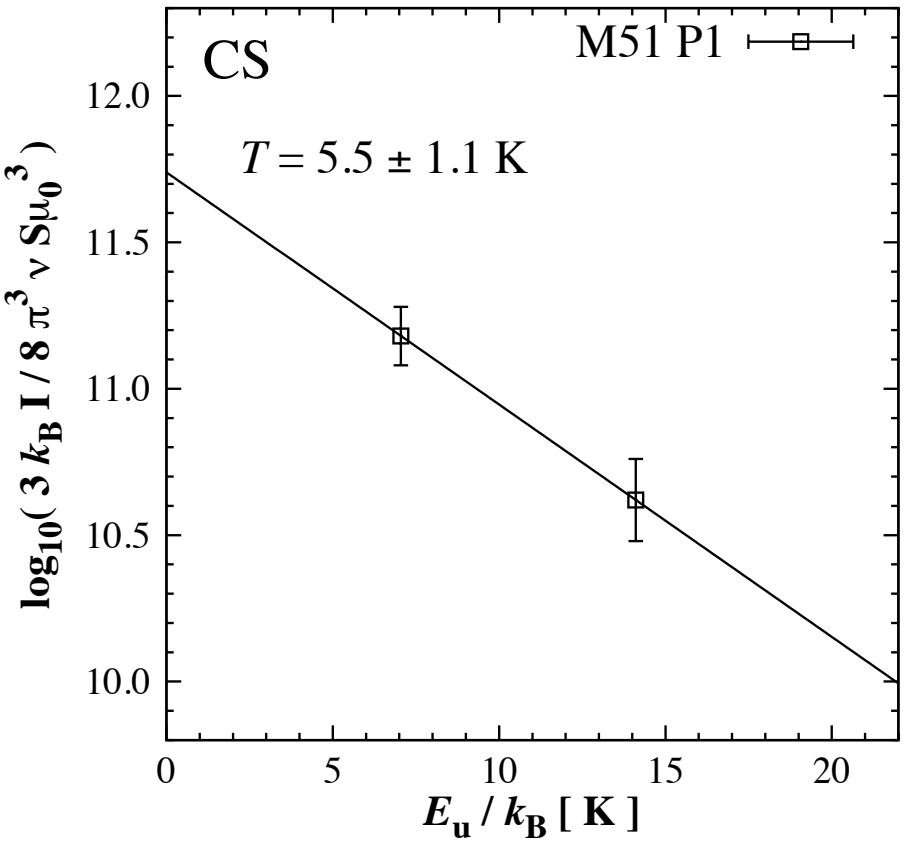
Identified m

- 13 molecular species
- 6 isotopologues

CO	HCN	HCO^+				
HNC	N_2H^+	$C^{34}S$	CH_3OH	CS	SO	$C^{18}O$
^{13}CO	$C^{17}O$	CN	^{12}CO	H_2CO		

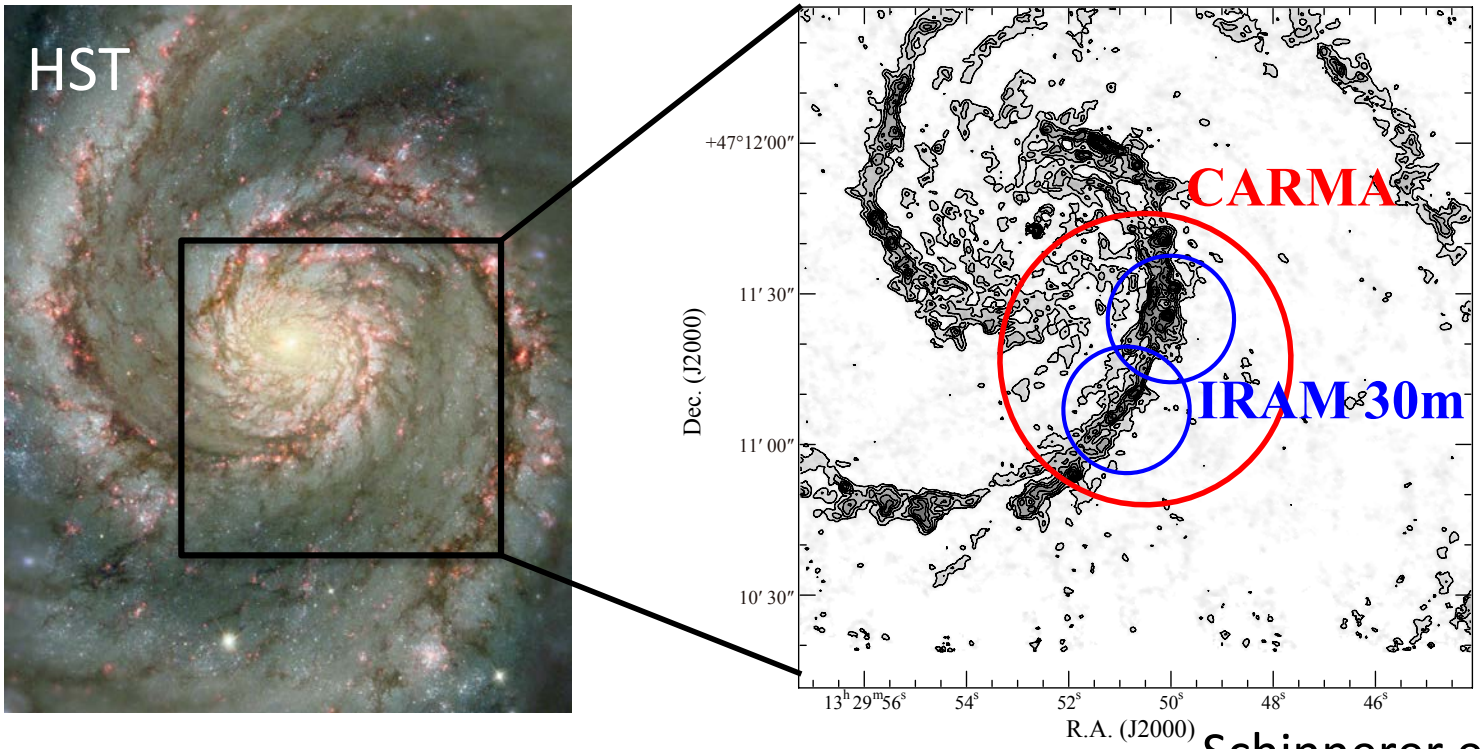
Rotation Temperatures





- Low rotational temperatures (< 10 K) of CH_3OH, HNCO and CS
- H_2CO observation (1-0, 2-1) => H_2 density of 10^4 cm^{-3} (Nishimura et al.)
- Detected molecules reside in quiescent diffuse cold molecular gas

Insight into 100 pc Scale



Schinnerer et al. 2013

Date : May – Jul. 2014

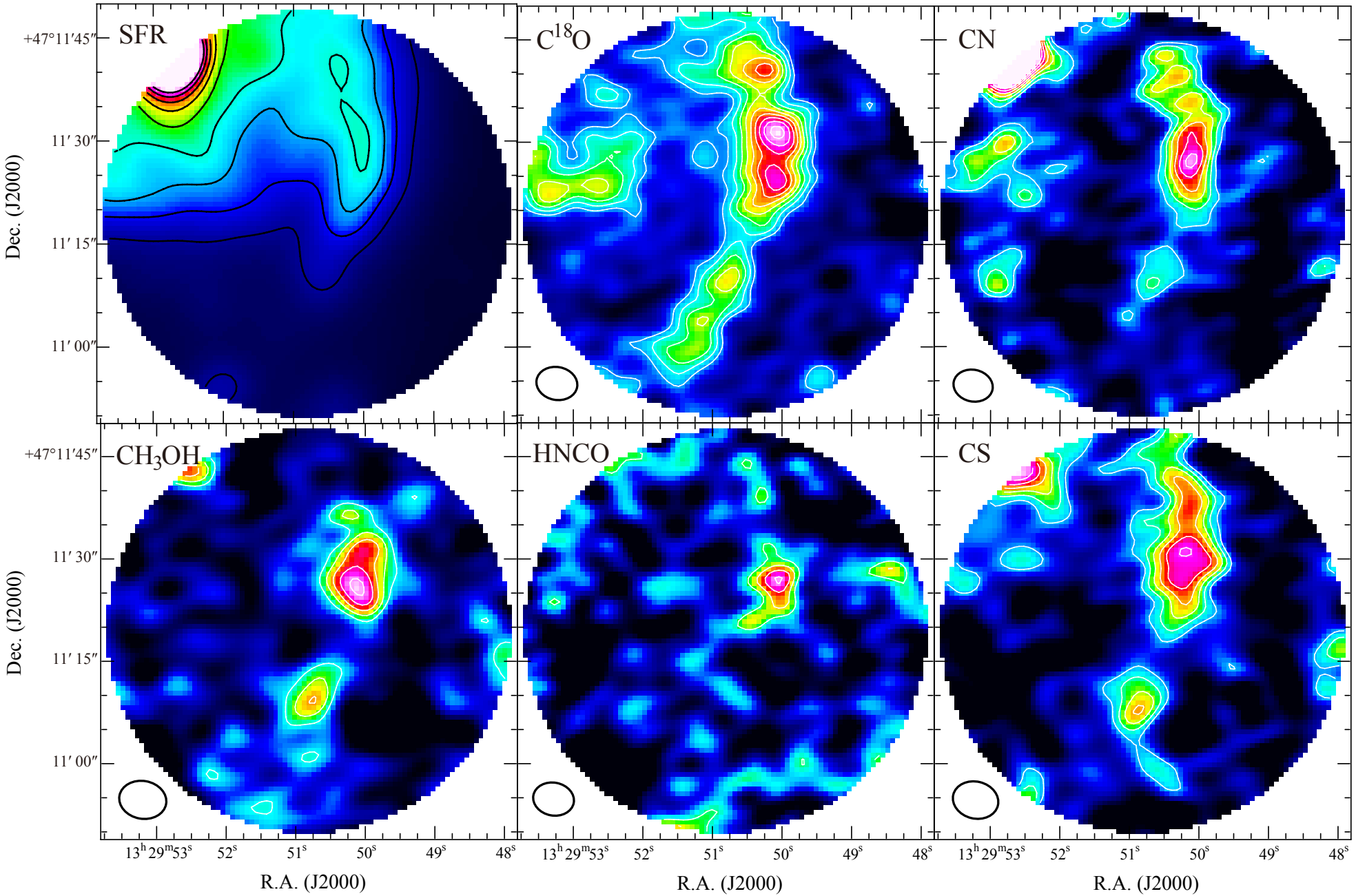
Configuration: D + E (Baseline: 2 – 55 k λ)

FoV : ~ 60”

Resolution: ~ 5–7” (~300 pc)

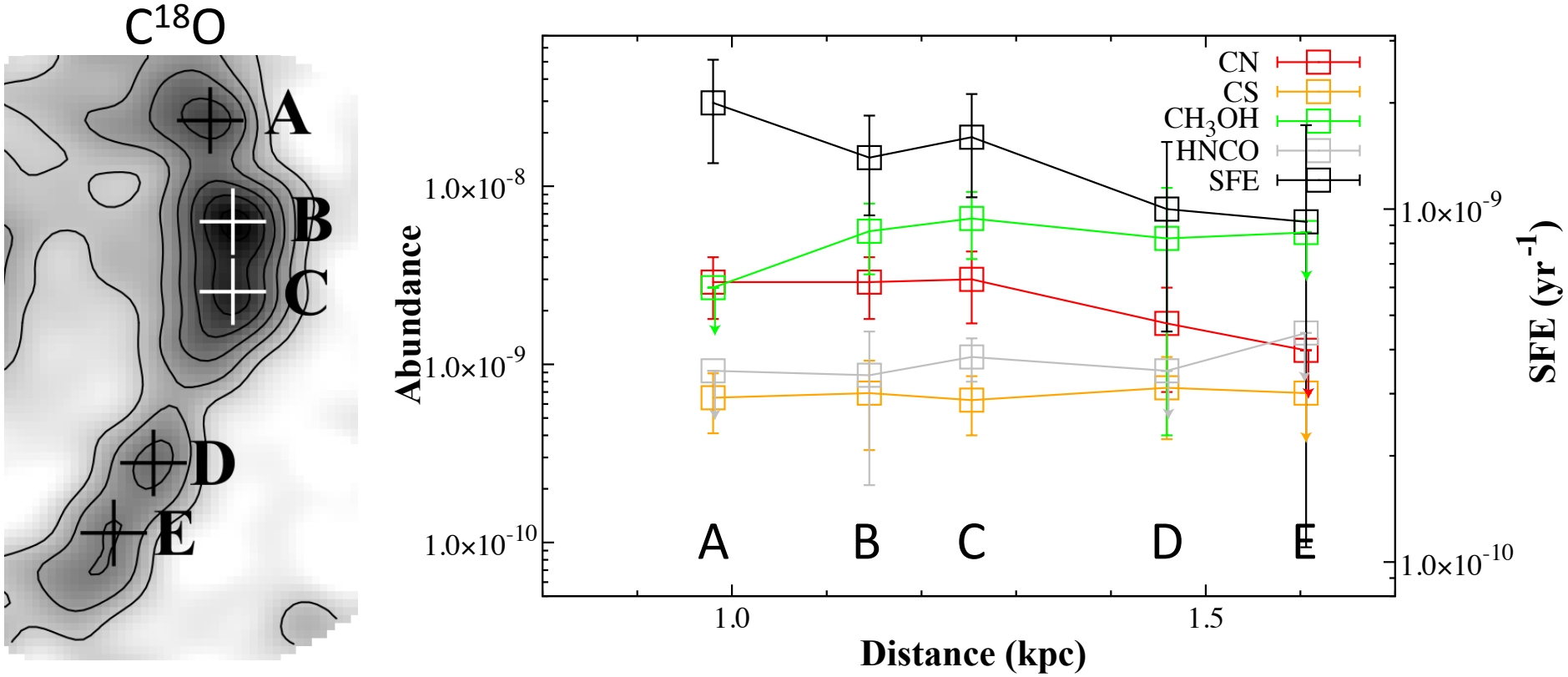
Band : 3 mm CH_3OH, CS, $C^{18}O$, HNCO, ^{13}CO, CN

Integrated intensity maps



Watanabe et al. 2016, ApJ

Position-to-Position Chemical Composition



Almost similar chemical compositions

Meaning of Large-Scale Chemical Composition

- Maybe reflects quiescent, cold, and diffuse molecular clouds
- How to confirm it….?

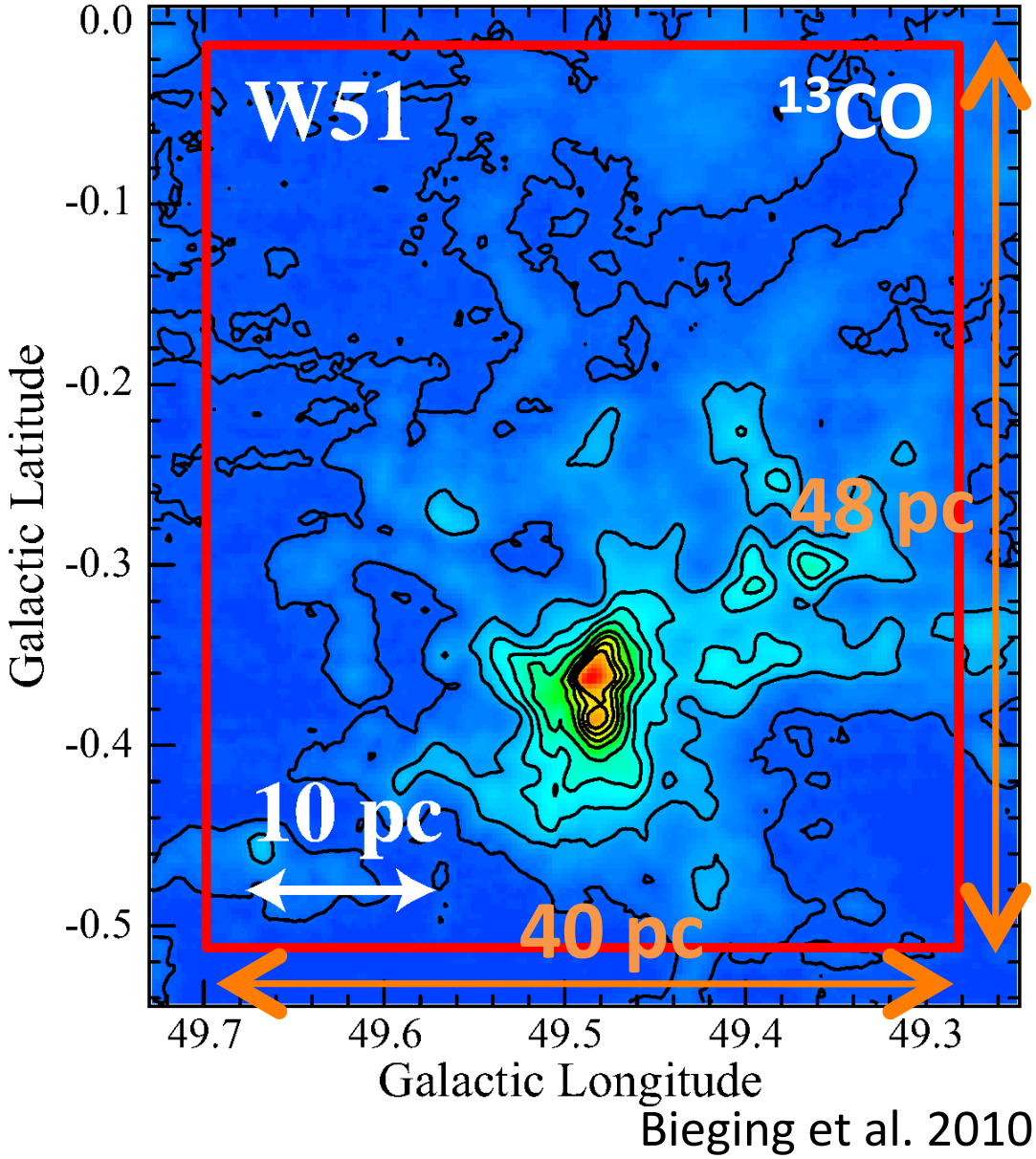
Our Strategy:

Mapping spectral line survey of representative Galactic molecular clouds

→ Averaged spectrum over a large area

→ Representative area in GMC

Mapping Spectral Line Survey toward W51



Bieging et al. 2010

Distance: 5.4 kpc

- 5’ = 8 pc

(Sato et al. 2010)

the most vigorous recent star formation in the Galaxy

<u>Observation with Mopra</u>

Date: Oct. 2013 – Sep. 2014

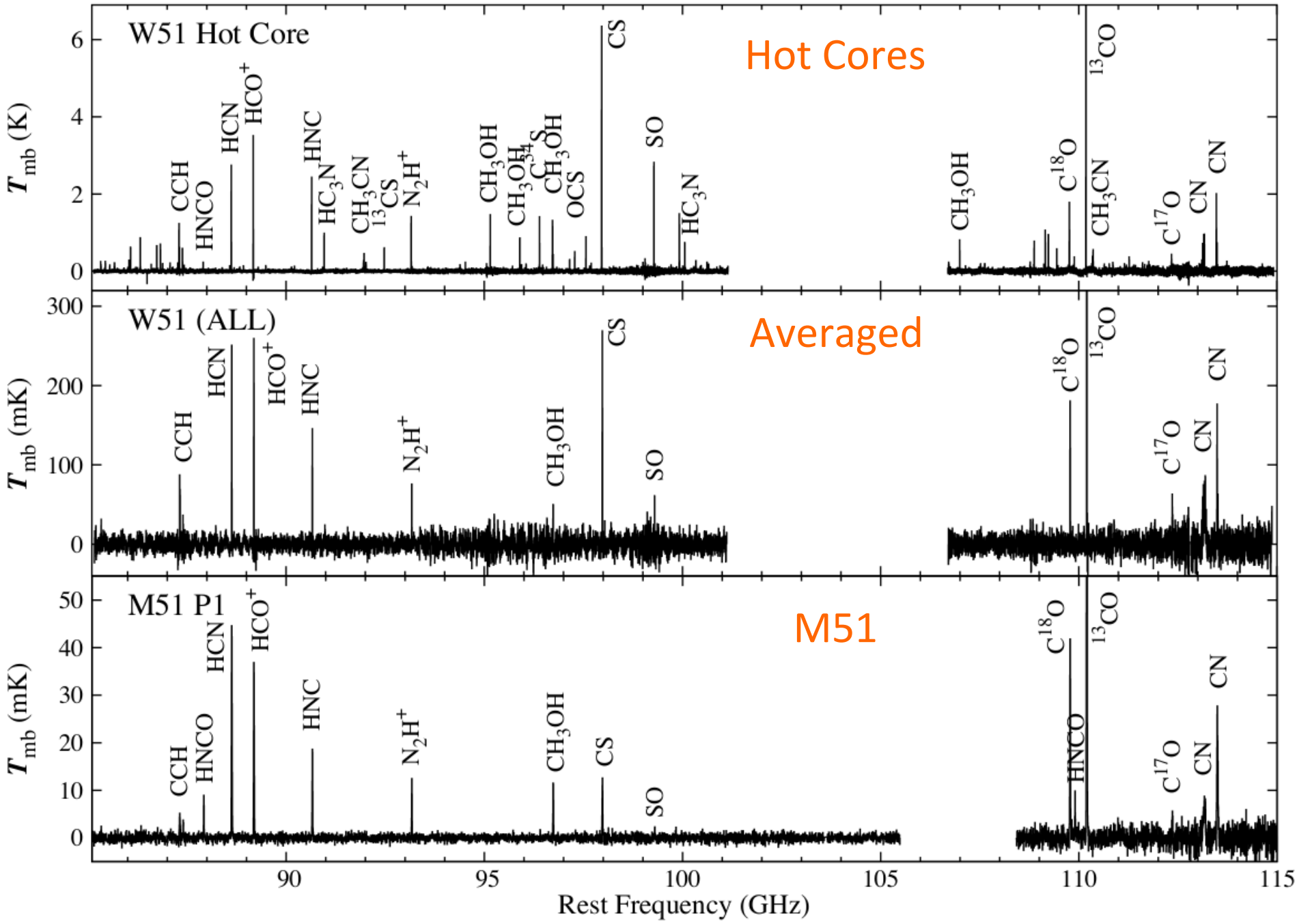
Obs. Mode : OTF

- 30’ x 25’
- **~40 pc x ~48 pc**

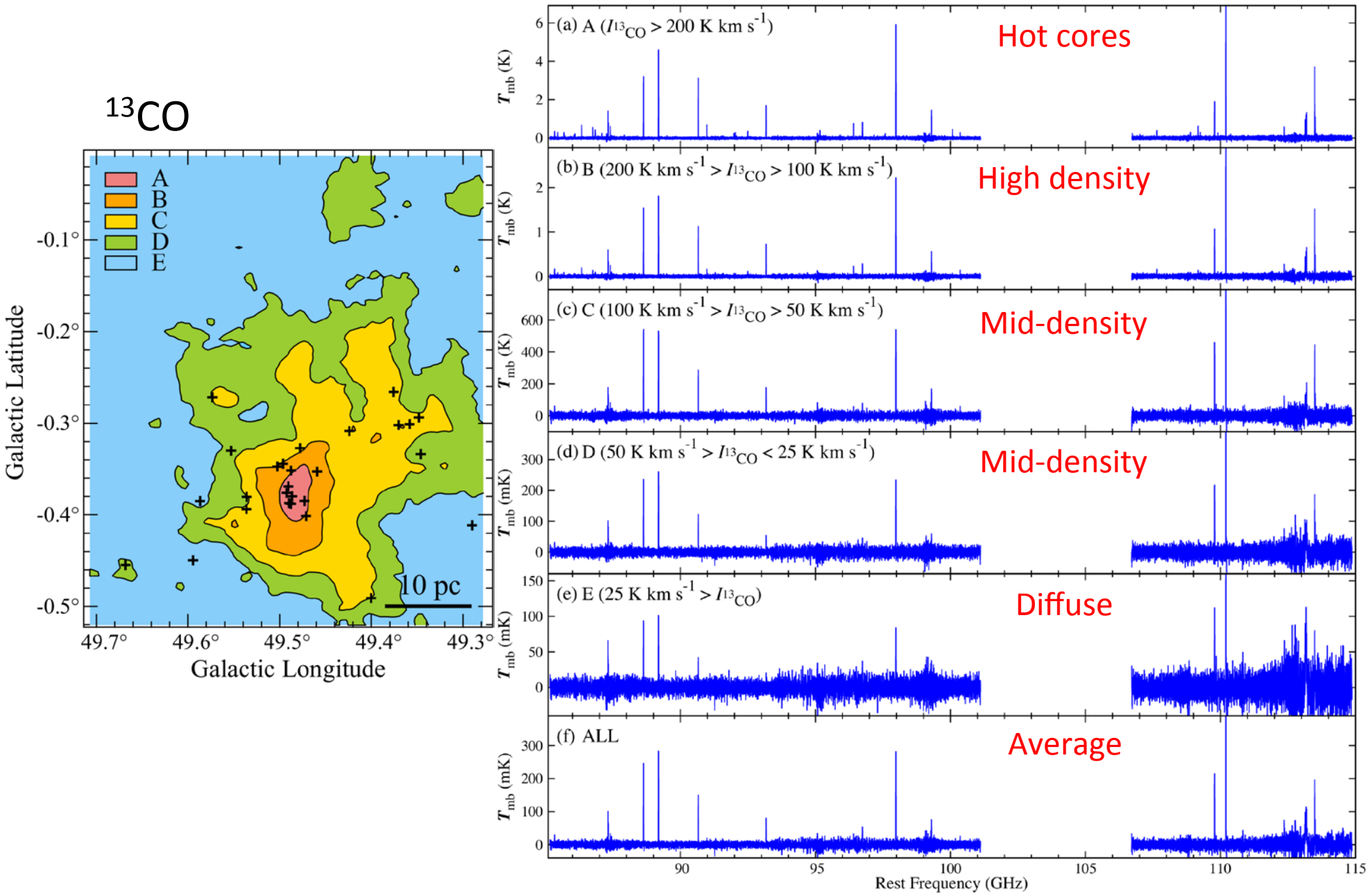
Frequency Range: 84 – 103 GHz

106 - 114GHz

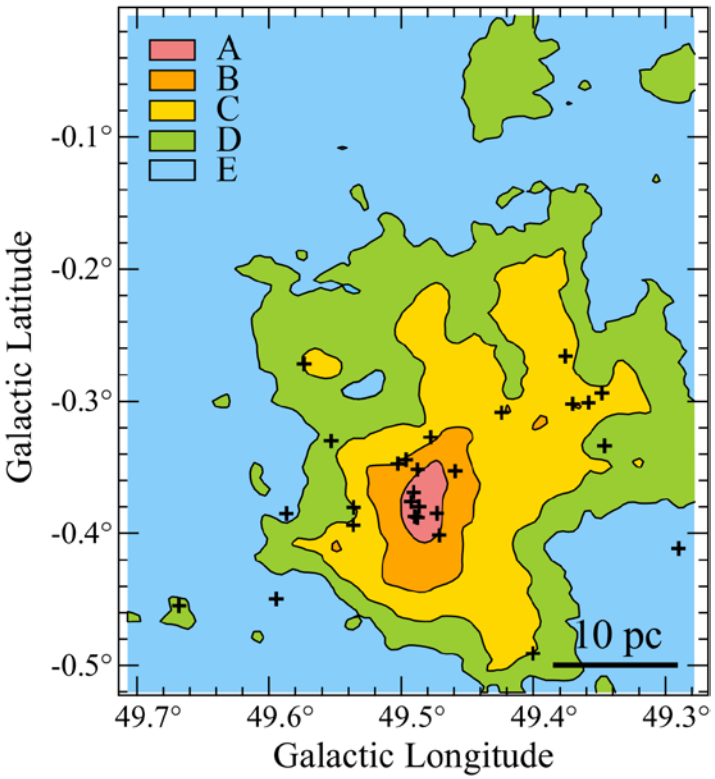
Averaged Spectra of W51



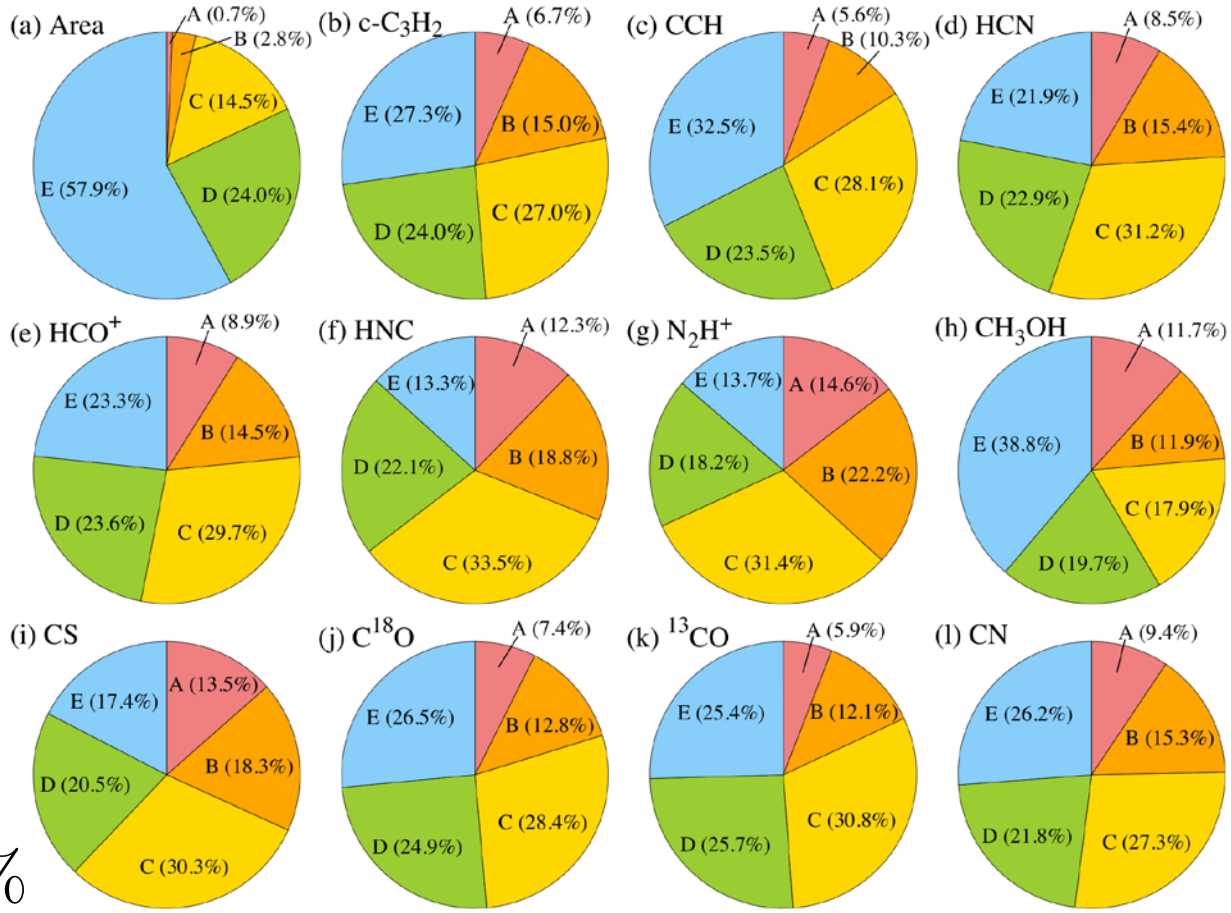
Contribution of Extended Molecular Gas in W51



Contribution of Extended Molecular Gas in W51



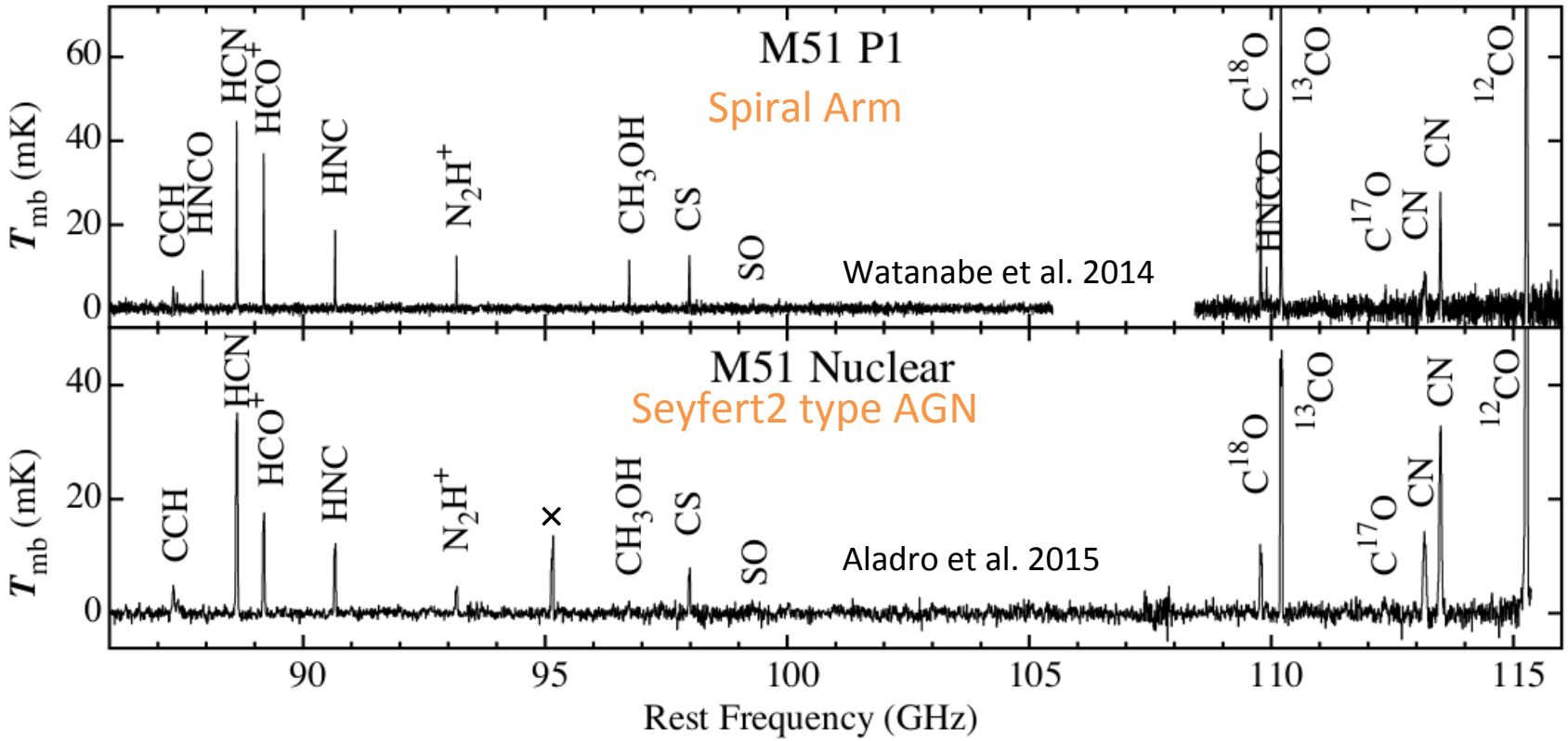
$$\frac{\int_{\mathrm{S}} I_{\mathrm{mol.}} dxdy}{\int_{\mathrm{ALL}} I_{\mathrm{mol.}} dxdy} \times 100\,\%$$



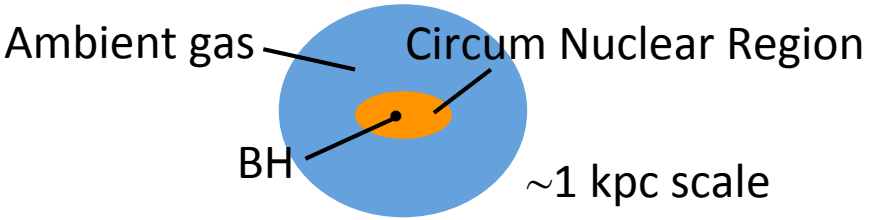
Most flux comes from the regions C,D, and E.

Local SF activities are smeared out by extended gas.

Smeared-Out by Extended Molecular Gas



AGN/Starburst Observation

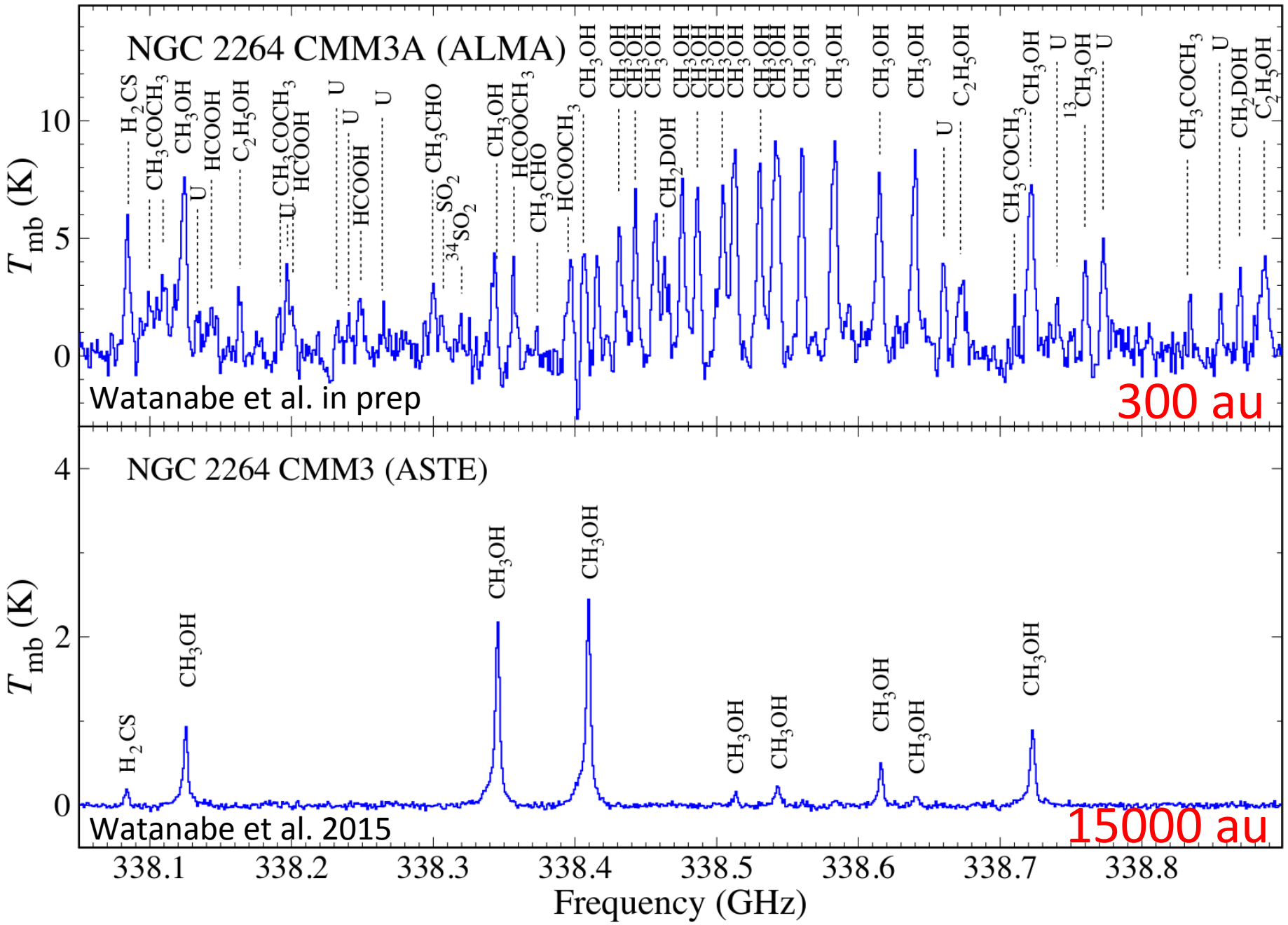


Observation in the 3 mm band

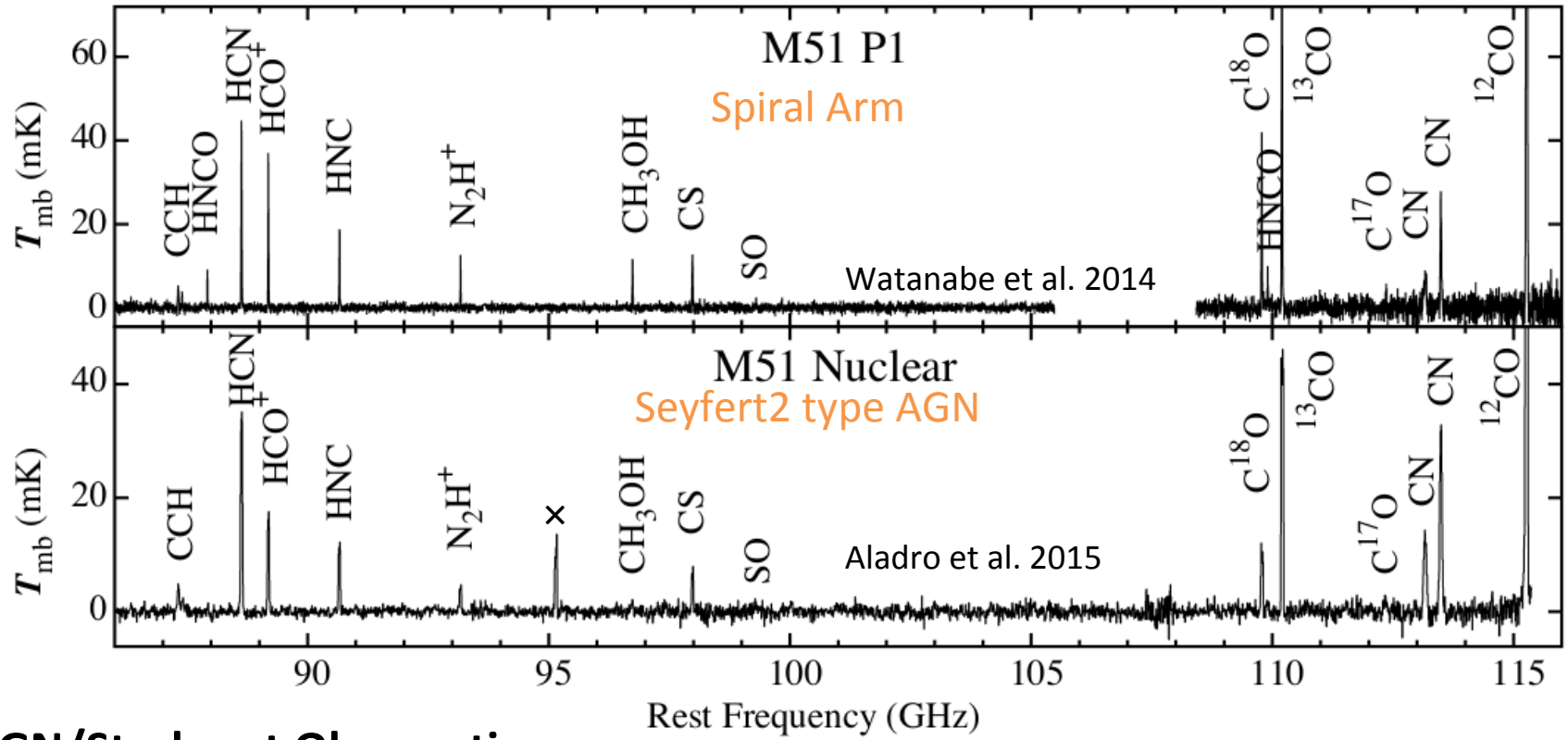
No effect of SF/Nuclear activities

Tracing chemical composition of cloud itself

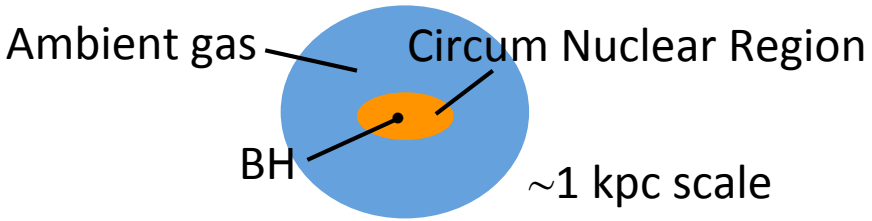
Expanded Spectrum toward NGC 2264 CMM3A



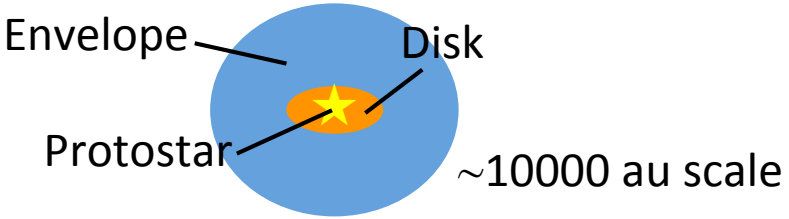
Smeared-Out by Extended Molecular Gas



AGN/Starburst Observation



Galactic observation



Observation in the 3 mm band

No effect of SF/Nuclear activities

Tracing chemical composition of cloud itself

We can compare GMCs in different Galaxies.

Chemistry of Molecular Cloud-Scale Gas

For interpretation of extragalactic astrochemistry..

Chemical composition of 'Starndard molecular clouds'

- e.g.: Giant molecular cloud (GMC) in a spiral arm

Effect of star formation ⇒ No

Effect of galactic-scale dynamics

Effect of metallicity

Large-Scale Shocks in Bar

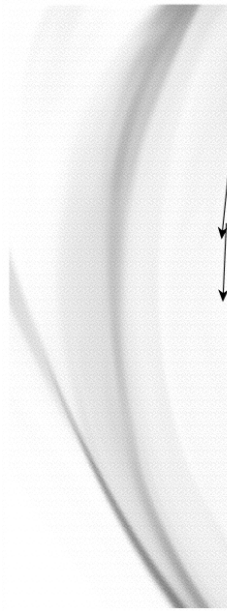
Strong shear/shocks in bar

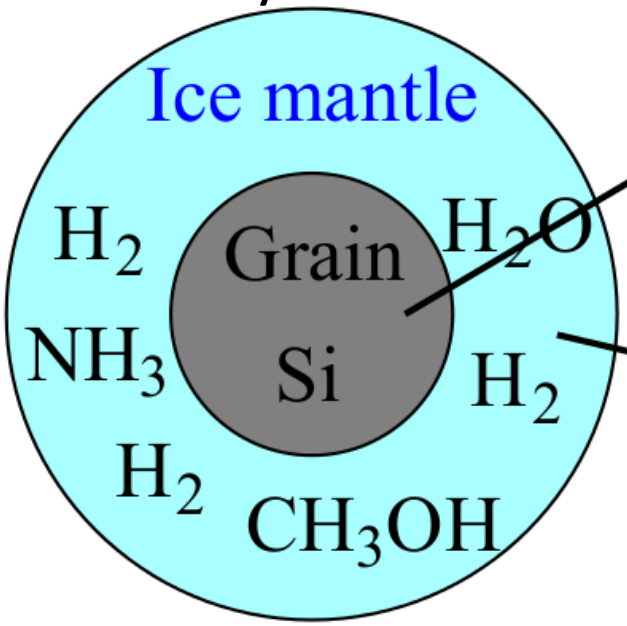
- Non-circular motion in bar potential

e.g. William et al. (1979) 、Athanassoula (1992)

Detection of shock tracers in bar (Meier & Turner, Usero et al.)

Good target to study effect of GMC-scale shock



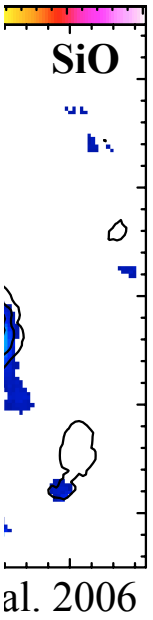


SiO

$V_{shock} > 15 - 20$ km s^{-1}

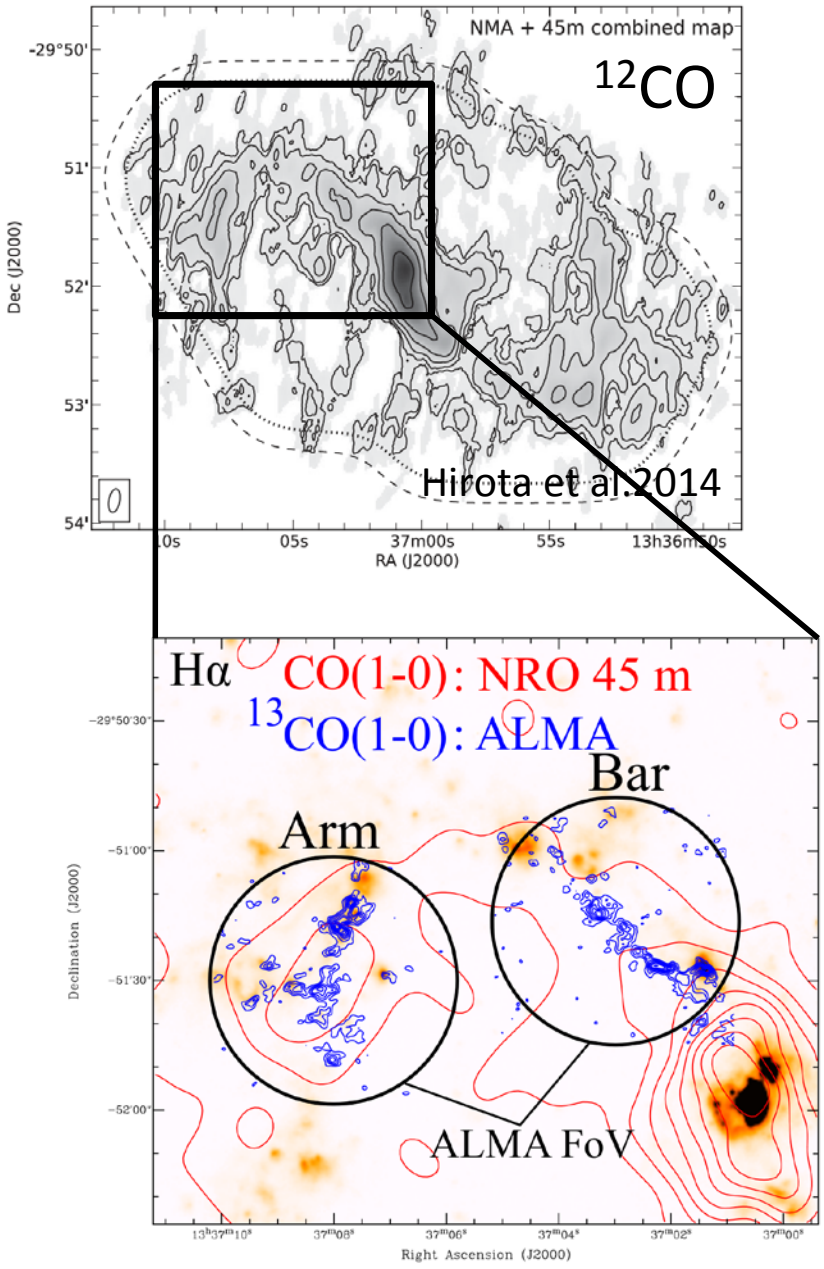
CH_3OH

$V_{shock} < 10 - 15$ km s^{-1}



al. 2006

Observations of M83 with ALMA



M83

Distance: 4.5 Mpc

Many CO observations

(e.g. Lundgeren et al. 2004, Muraoka et al. 2009, Hirota et al. 2014)

Shocks in the bar (Onderechen 1985)

Low star formation efficiency in the bar

(Handa et al. 1990, Hirota et al. 2014)

- Due to strong shear?

(Nimori et al. 2013, Fujimoto et al. 2014)

ALMA cycle-2, Band3

85.7 – 88.1 GHz, 88.0 – 91.5 GHz

96.1 – 99.6 GHz, 108.4 – 111.7 GHz

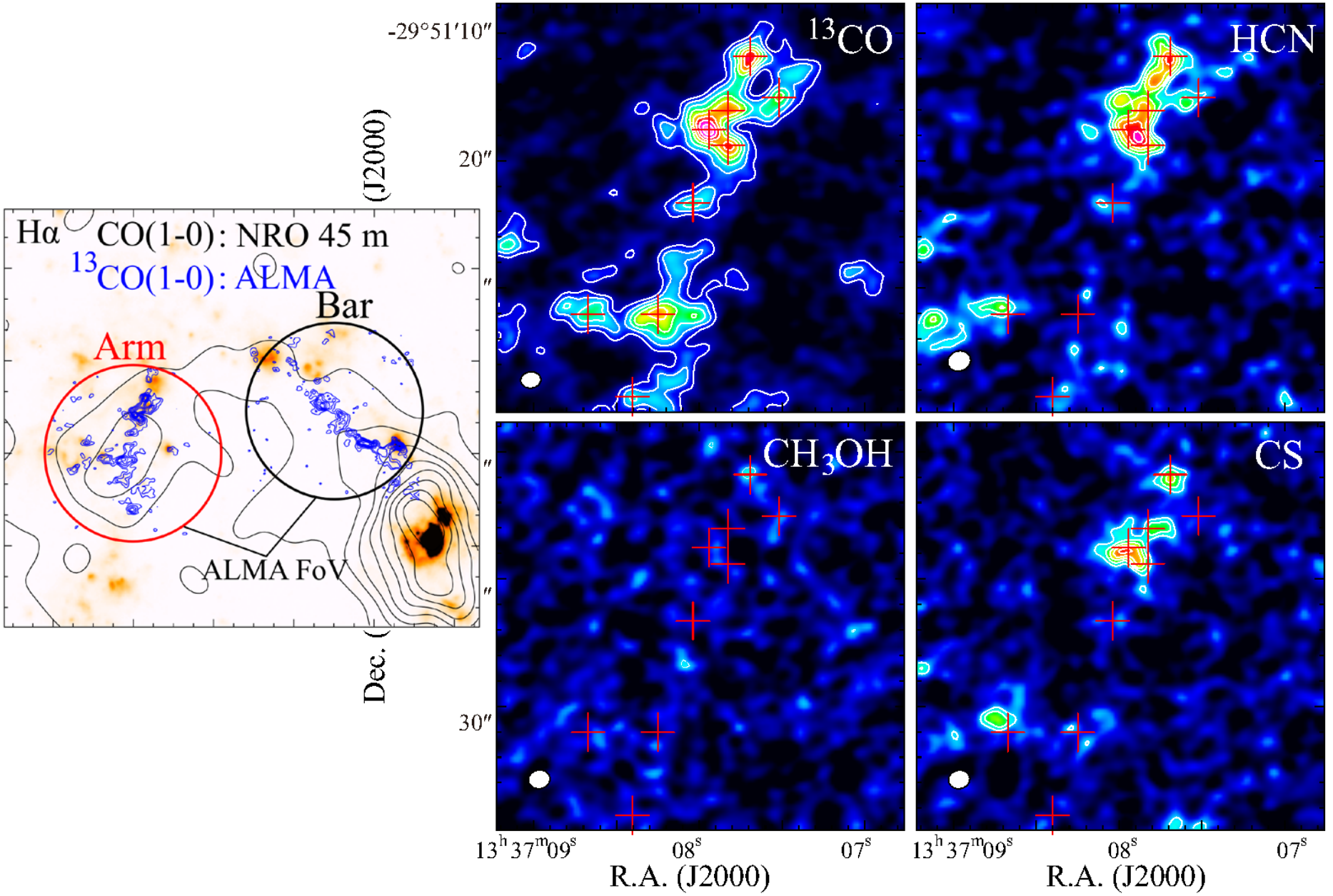
Beam Size

1.92” – 1.59” (~ 35 pc @ 4.5 Mpc)

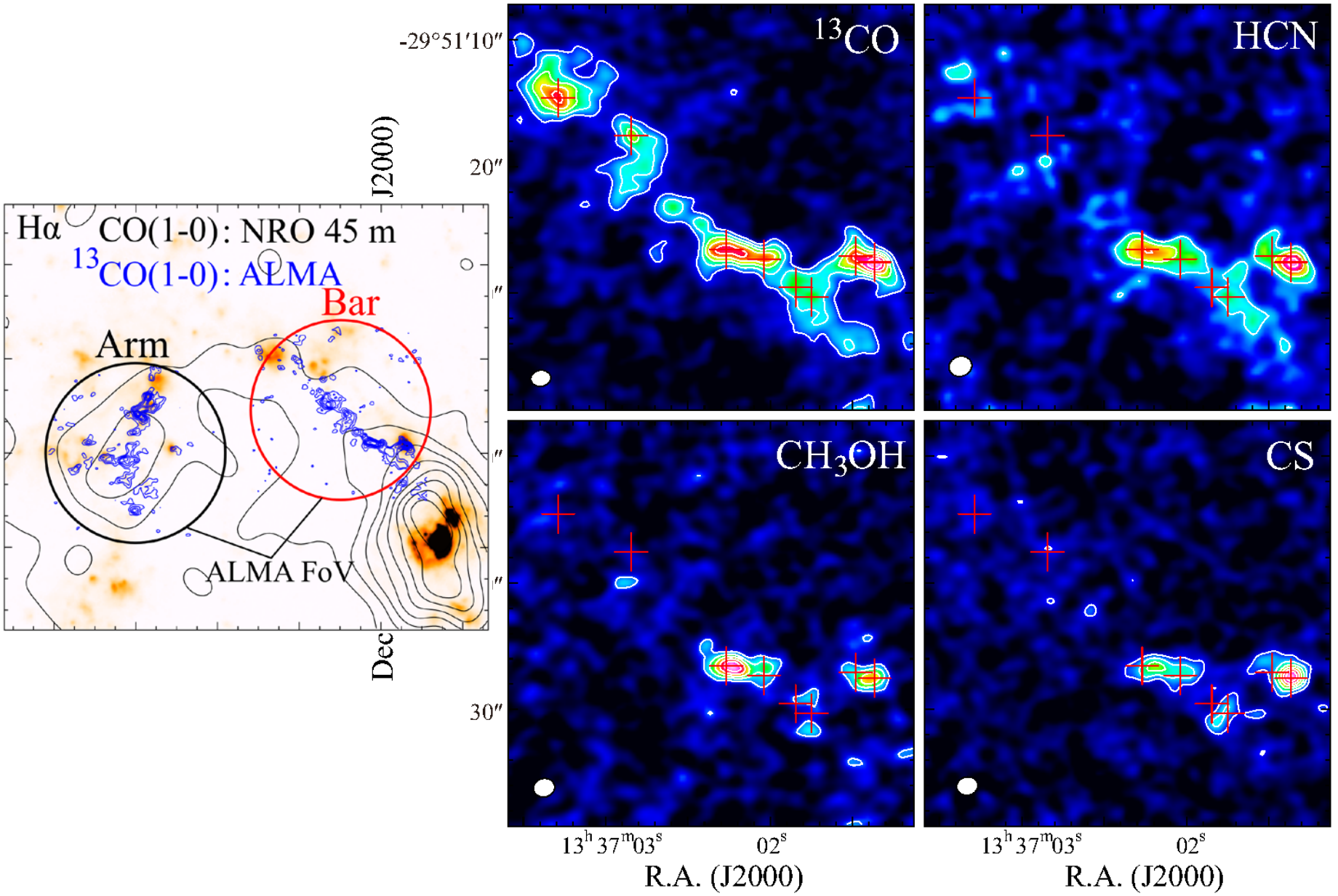
Sensitivity

1.4 – 0.6 mJy/beam in 5 km/s

Distributions of Molecules in the Arm

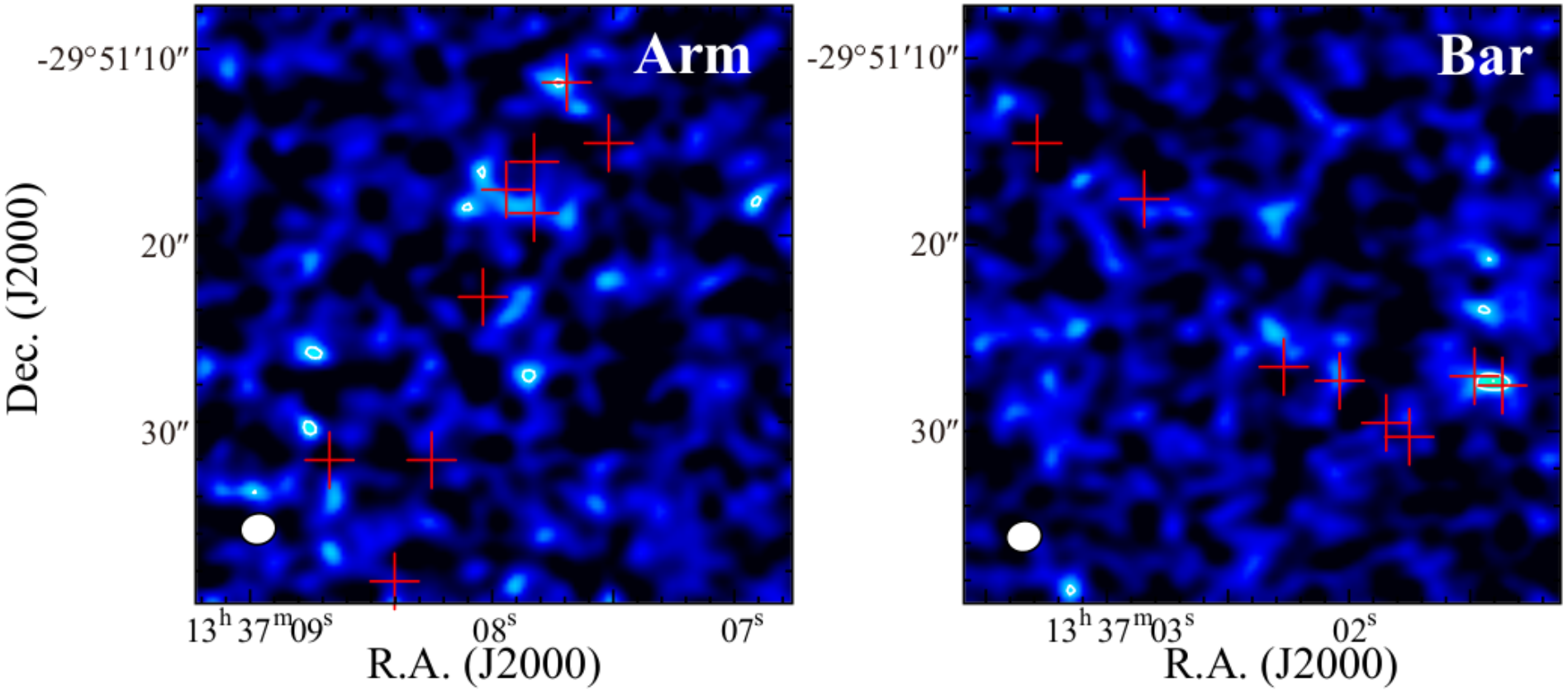


Distributions of Molecules in the Bar



Other Molecules: $C^{18}O$, HCO^+, HNC, HNCO, CCH

Non-detection of SiO



No SiO detection in both Arm and Bar

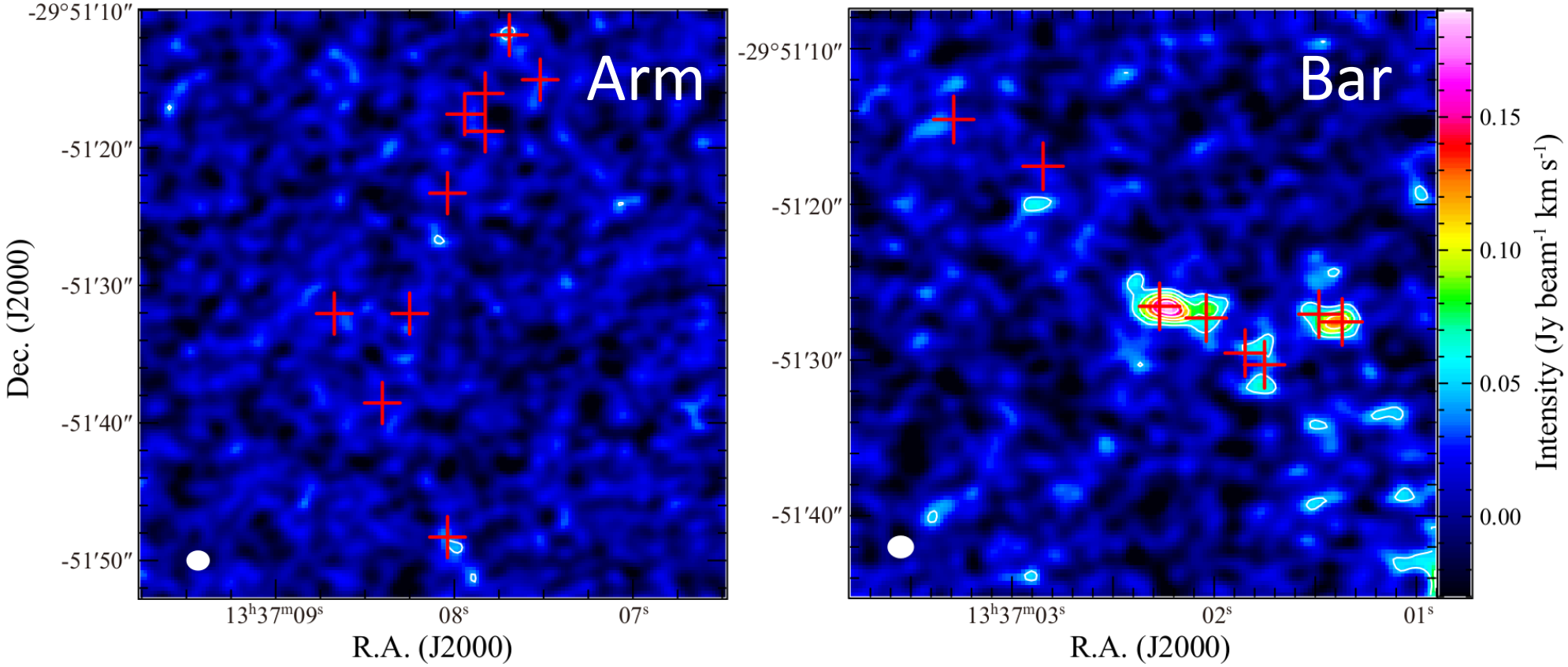
Upper limit of SiO abundance in Bar:

$X_{SiO} < 5 \times 10^{-10}$ (T = 10 K)

c.f.: $X_{SiO} = 1 - 4 \times 10^{-9}$ in Bar of IC 342 (Usero et al. 2006)

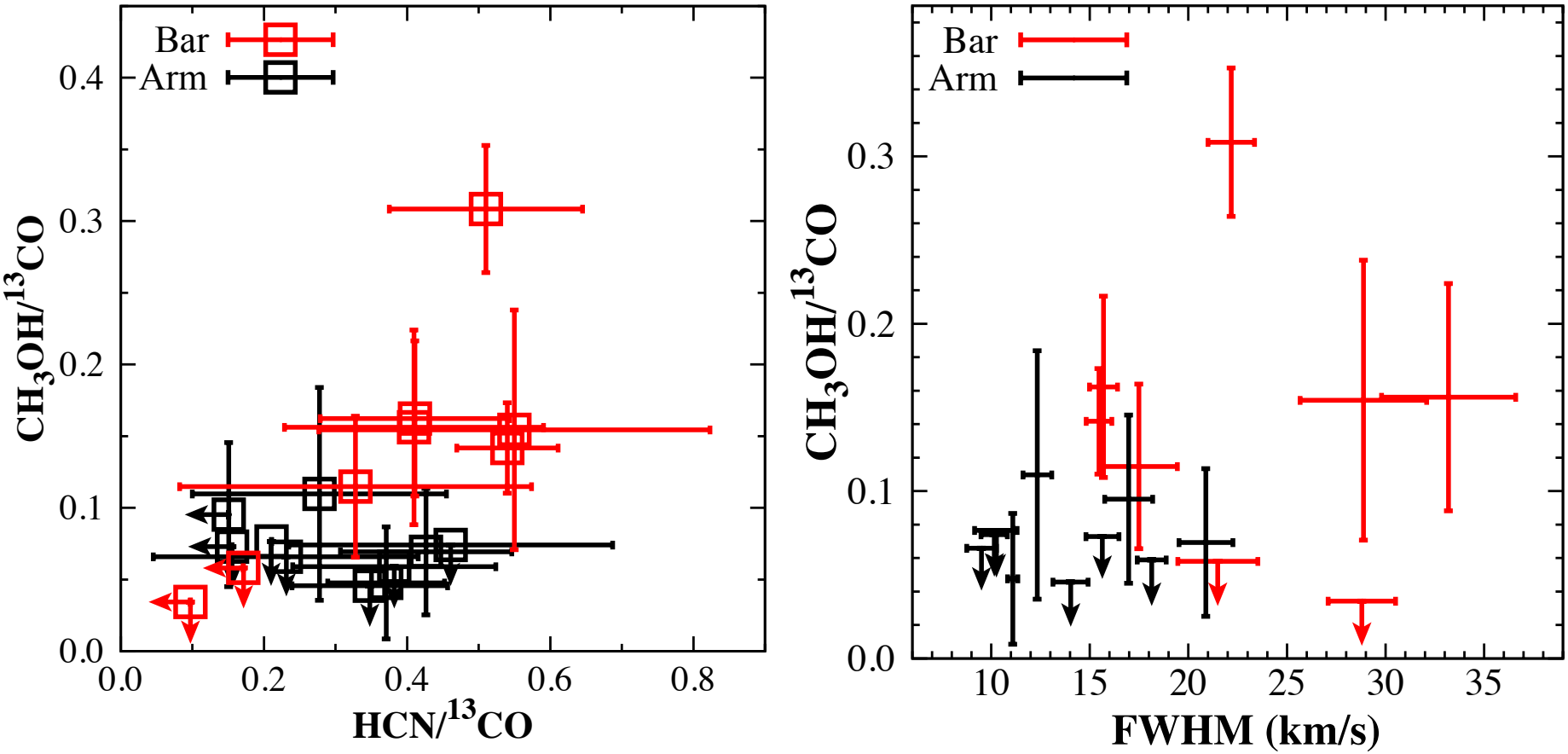
Weaker shock in bar of M83 than IC342?

Distribution of CH_3OH in Arm and Bar



Strong CH_3OH emission in the bar,
while very weak in the arm

$CH_3OH/^{13}CO$ Ratios in the Arm and the Bar



Higher $CH_3OH/^{13}CO$ ratio in the bar

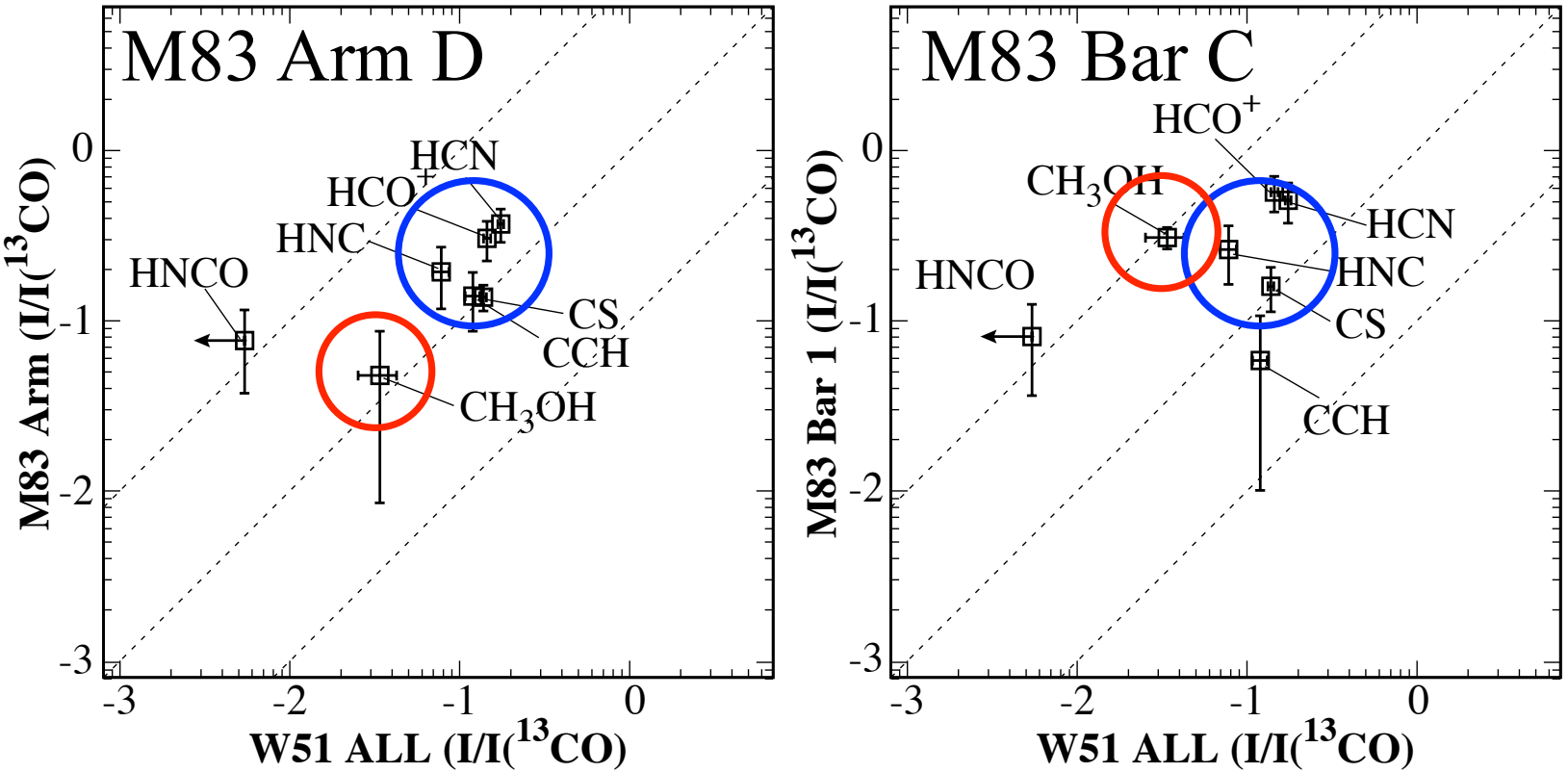
Bar: 0.17 ± 0.06, Arm: 0.08 ± 0.05

(c.f. $CH_3OH/^{13}CO$ = 0.069 +/- 0.007 in Arm of M51)

Broader linewidth in the bar

Stronger shear/shocks in bar than spiral arm?

Chemical Composition of GMC-Scale Gas



Comparison of chemical compositions between M83 and W51

- Similar size: M83 (~35 pc), W51 (~50 pc)
- Similar chemical composition in a spiral arm of M83
  - Except for HNCO
- CH_3OH is slightly enhanced in a bar of M83

Chemistry of Molecular Cloud-Scale Gas

For interpretation of extragalactic astrochemistry..

Chemical composition of 'Starndard molecular clouds'

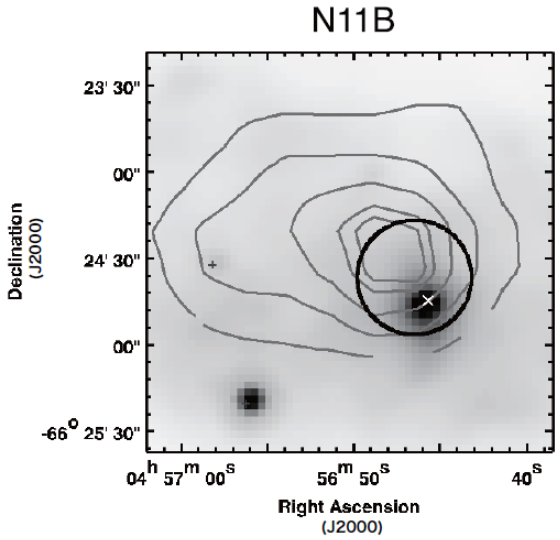
- e.g.: Giant molecular cloud (GMC) in a spiral arm

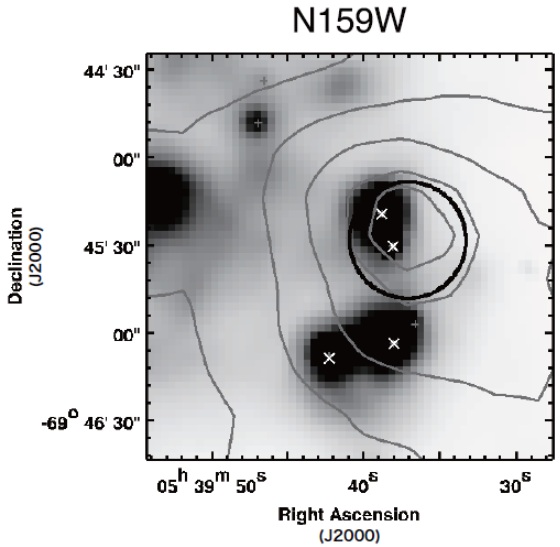
Effect of star formation ⇒ No

Effect of galactic-scale dynamics ⇒ Maybe yes

Effect of metallicity

Effect of Metallicity (PI: Nishimura, Y.)
Spectral Line Survey toward the LMC





Disntance: 50 kpc (38" = 9.2 pc)

Low metal abundance

- A half of solar abundance (Westerlund, B.E., 1990)

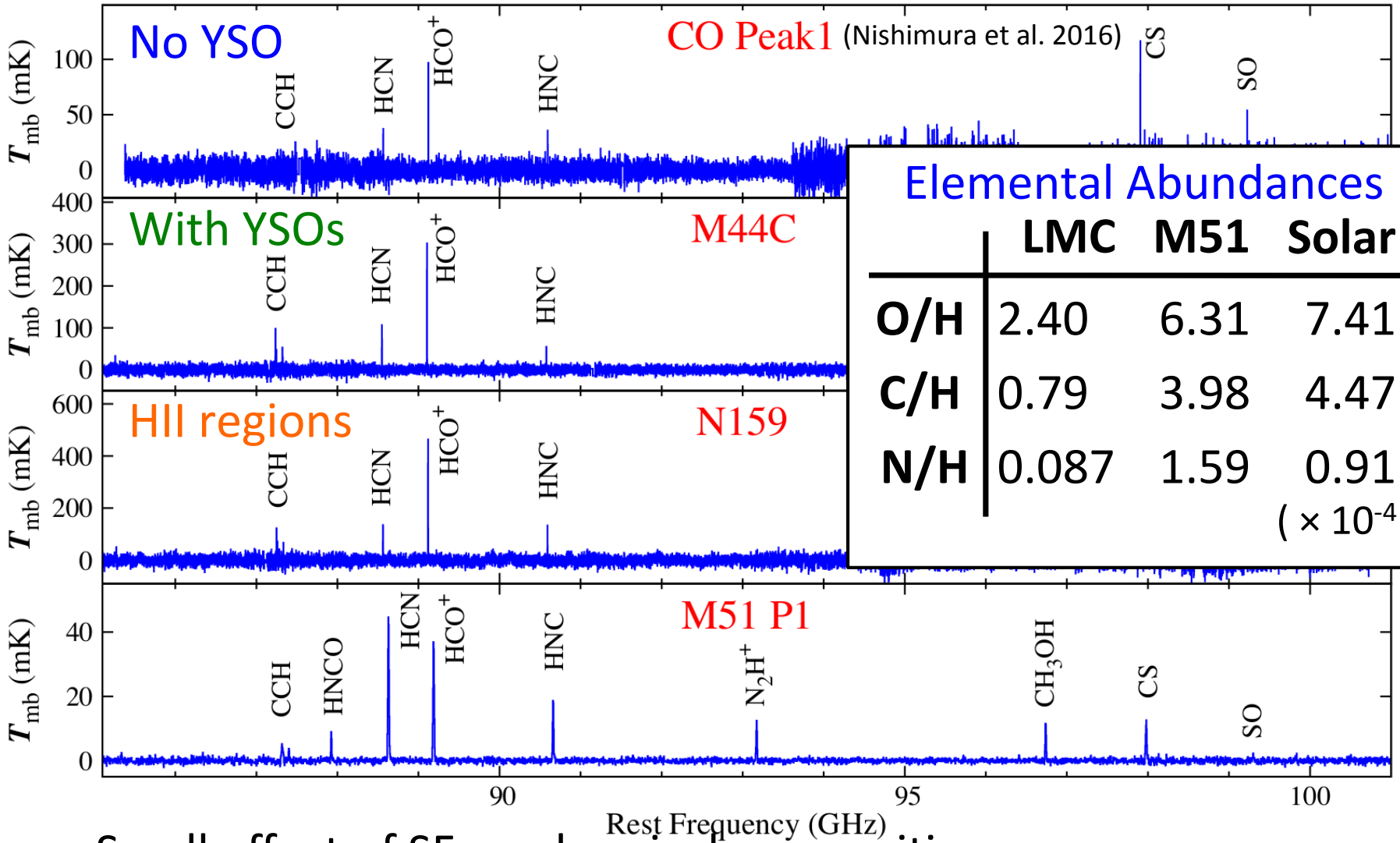
Intense UV radiation field

- 10 – 100 times higher than our galaxy value

Survey of 7 Target Sources

Nishimura et al. 2016

Spectra of the LMC



Elemental Abundances

	LMC	M51	Solar
O/H	2.40	6.31	7.41
C/H	0.79	3.98	4.47
N/H	0.087	1.59	0.91

(× 10^{-4})

Small effect of SF on chemical compositions

Weak intensity of N-bearing species

⇒ Effect of the lower elemental abundance of N in the LMC

New probe of elemental abundance measurements!

Chemistry of Molecular Cloud-Scale Gas

For interpretation of extragalactic astrochemistry..

Chemical composition of 'Starndard molecular clouds'

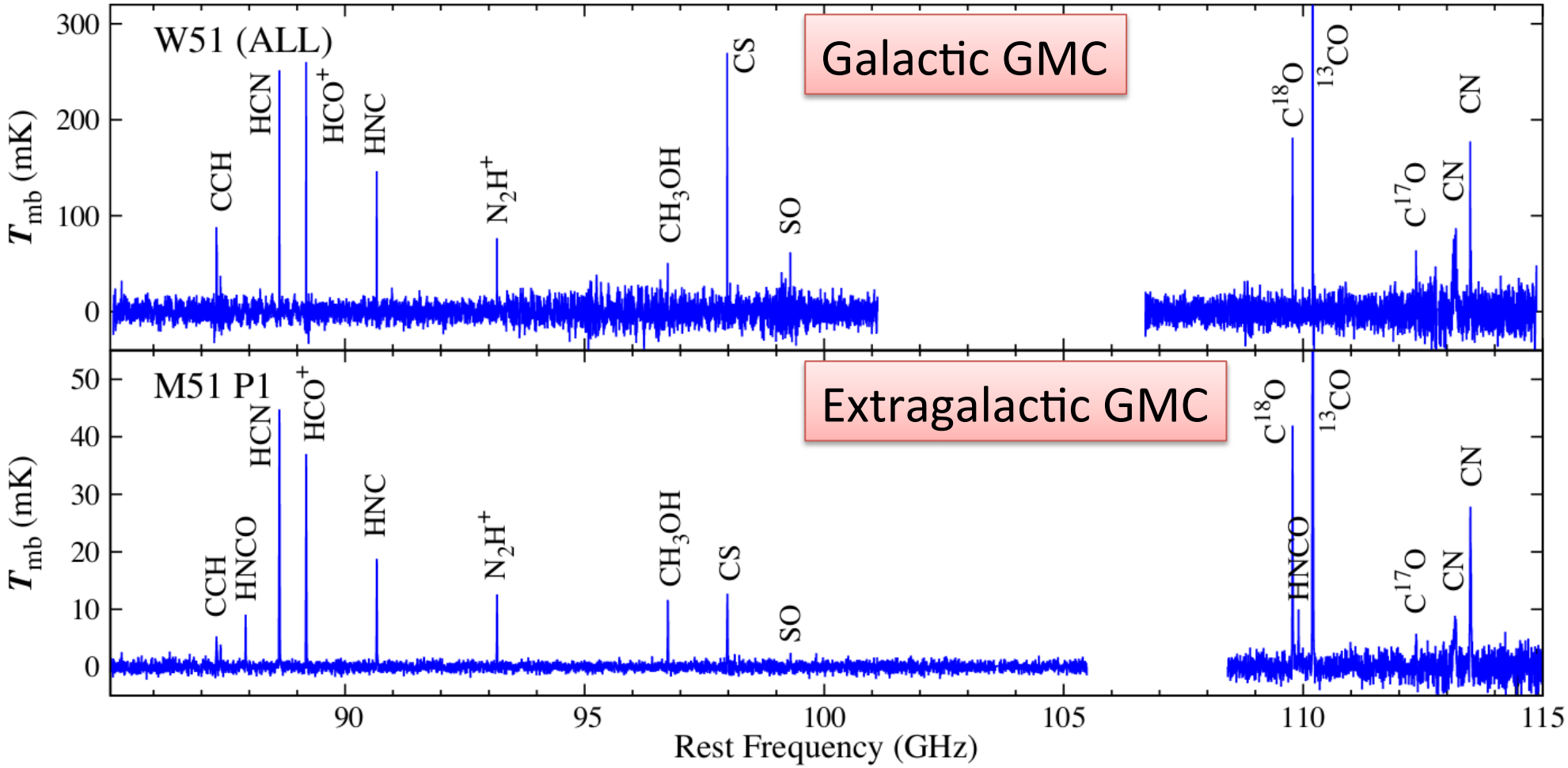
- e.g.: Giant molecular cloud (GMC) in a spiral arm

Effect of star formation ⇒ No

Effect of galactic-scale dynamics ⇒ Maybe yes

Effect of metallicity ⇒ Yes

Origin of Chemical Composition of GMC-scale Gas



What does this chemical composition mean?

Model of Cloud-Scale Chemistry

Collaboration with Nanase Harada (AASIA) and Yuri Nishimura

Chemical Model

- gas-grain code: nautilus (Hersant et al. 2009)

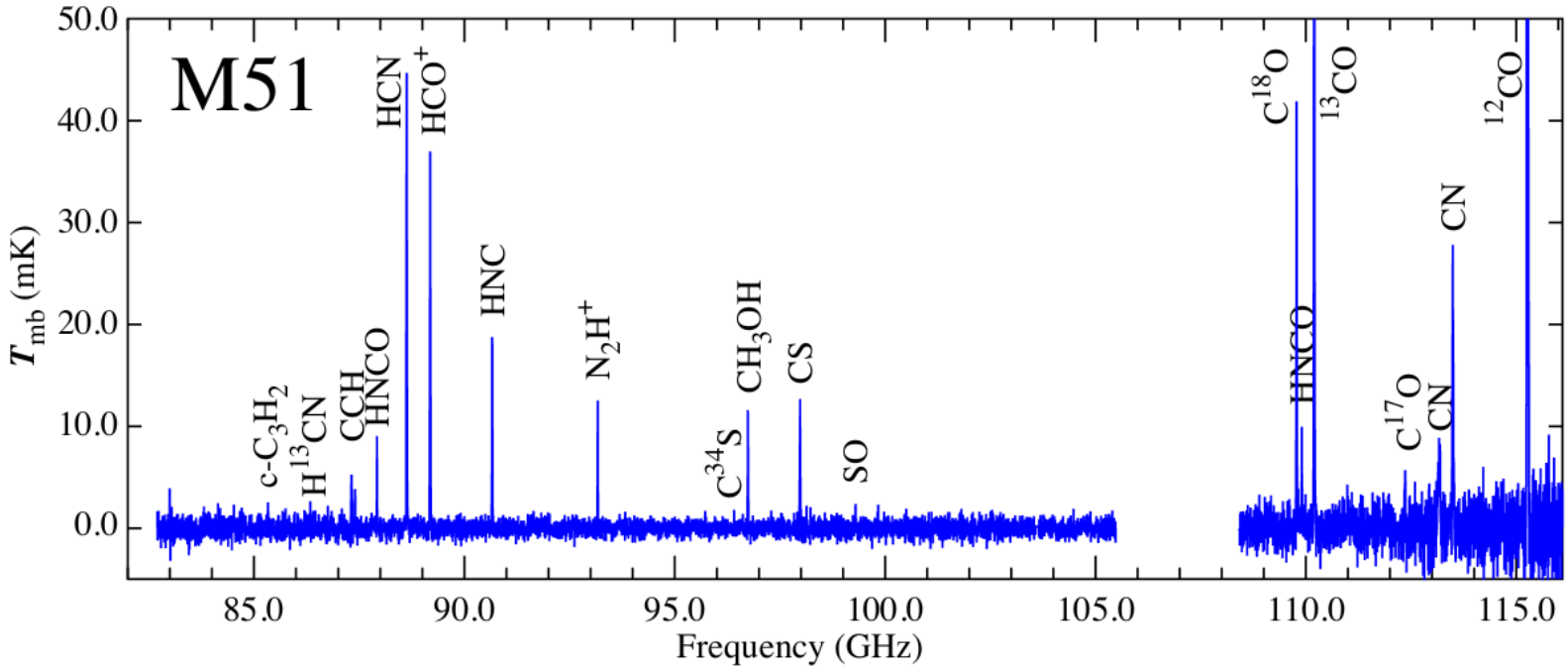
Parameters

- Radiation field (G_0): 1
- Temperature (T) : 10 – 30 K
- Density (n) : $3 \times 10^3 – 3 \times 10^4$ cm^{-1}
- Visual extinction (Av) : 1 – 10 mag
- CR/X-ray ionization rate (ζ): 1×10^{-16} - 1×10^{-17} s^{-1}

Radiation Transfer

- Radex (van der Tak et al. 2007)

Model of Cloud-scale Chemistry



Comparison of Model with M51

Good correlation

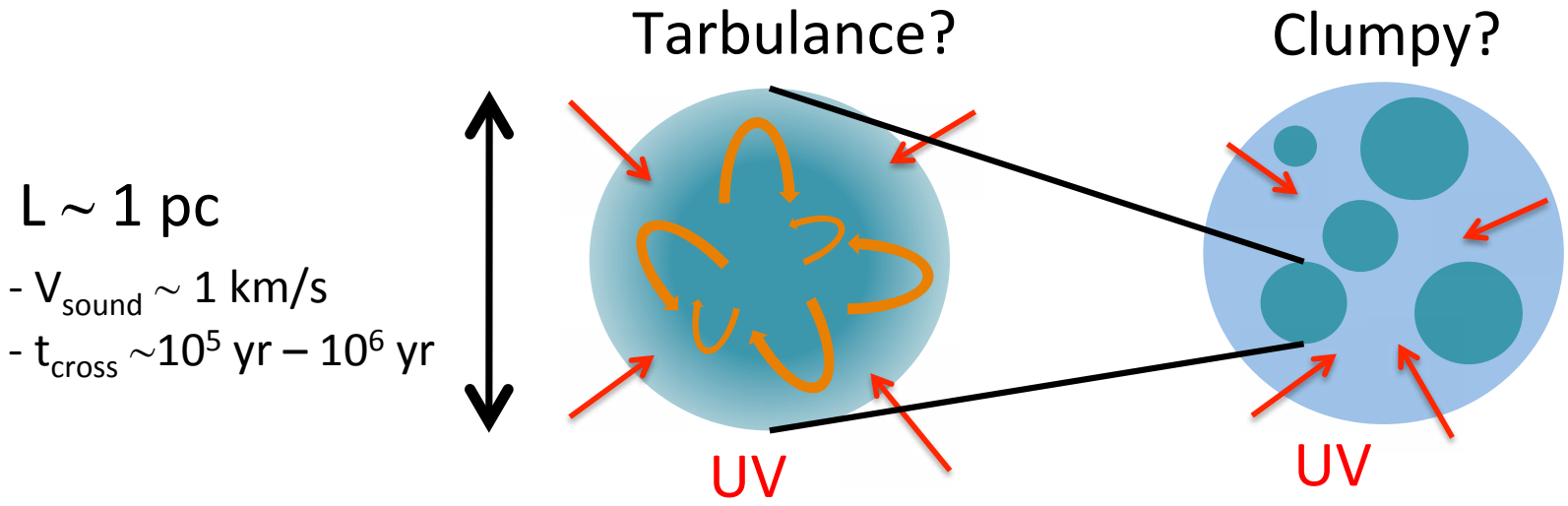
Density (n) : $3 \times 10^3 - 1 \times 10^4$ cm^{-1} Nishimura et al.

Visual extinction (Av) : 4 – 10 mag

Chemical age: ~10^5 yrs

Relatively Young Chemical Age of GMCs

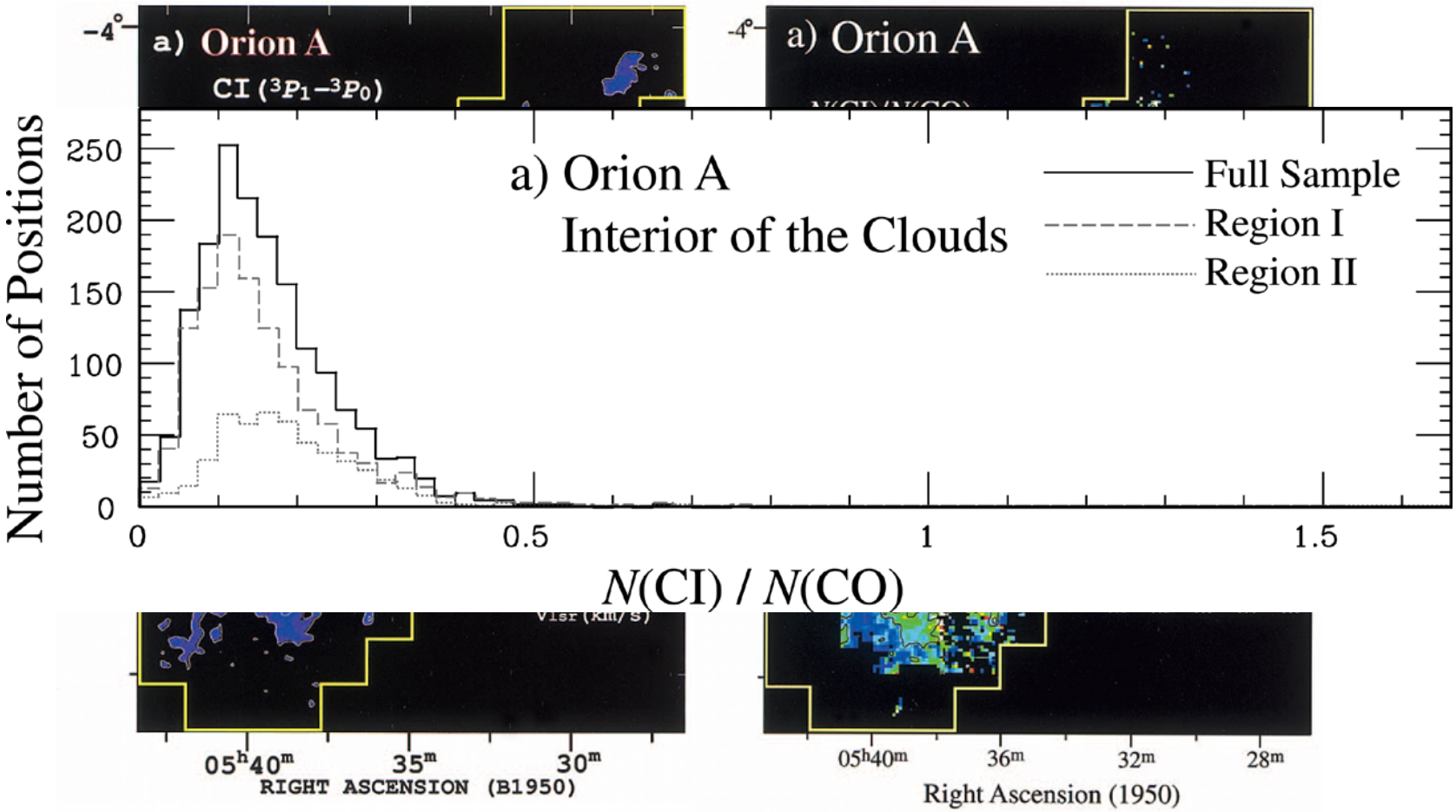
Chemical age of 10^5 years is shorter than life time of GMCs.



Chemical composition is refreshed by UV with $t \sim 10^5$ yr – 10^6 yr?

- Clumpy structure of molecular cloud
- Turbulence motion in the cloud
- Dissociation of molecules at the periphery of cloud

Relatively Young Chemical Age of GMCs



Similarity to a constant CI/CO in molecular clouds (Ikeda et al. 2002)

- CI/CO > 0.1 at interior of molecular clouds
- Destruction mechanisms of CO by UV in the clouds

Summary

Chemical compositions of molecular cloud scale gas

Spectral line survey toward M51 and W51

- Similar chemical compositions at kpc – 50 pc scale
- Diffuse and quiescent gas ($n(H_2) \sim 10^4$ cm^{-3}, $T \sim 10$ K)
- Effect of star formation is smeared out.

Fundamental base for extragalactic astrochemistry

- Cloud-scale: the 3 mm band with Single-dish/ALMA
- Star formation/AGN : the sub-mm band with ALMA

Comparisons with other external galaxies (M83 and LMC)

Effect of gas-dynamics?

Elemental abundance affects chemical compositions.

Understanding origin of chemical compositions is important to study chemistry in AGN, Starburst, and high-z galaxies.