Astrochemistry from a Sub-pc Scale to a kpc Scale

Satoshi Yamamoto
Department of Physics and RESCUE
The University of Tokyo

Contents

Physical and Chemical Processes in Disk Formation around Solar-type Protostars

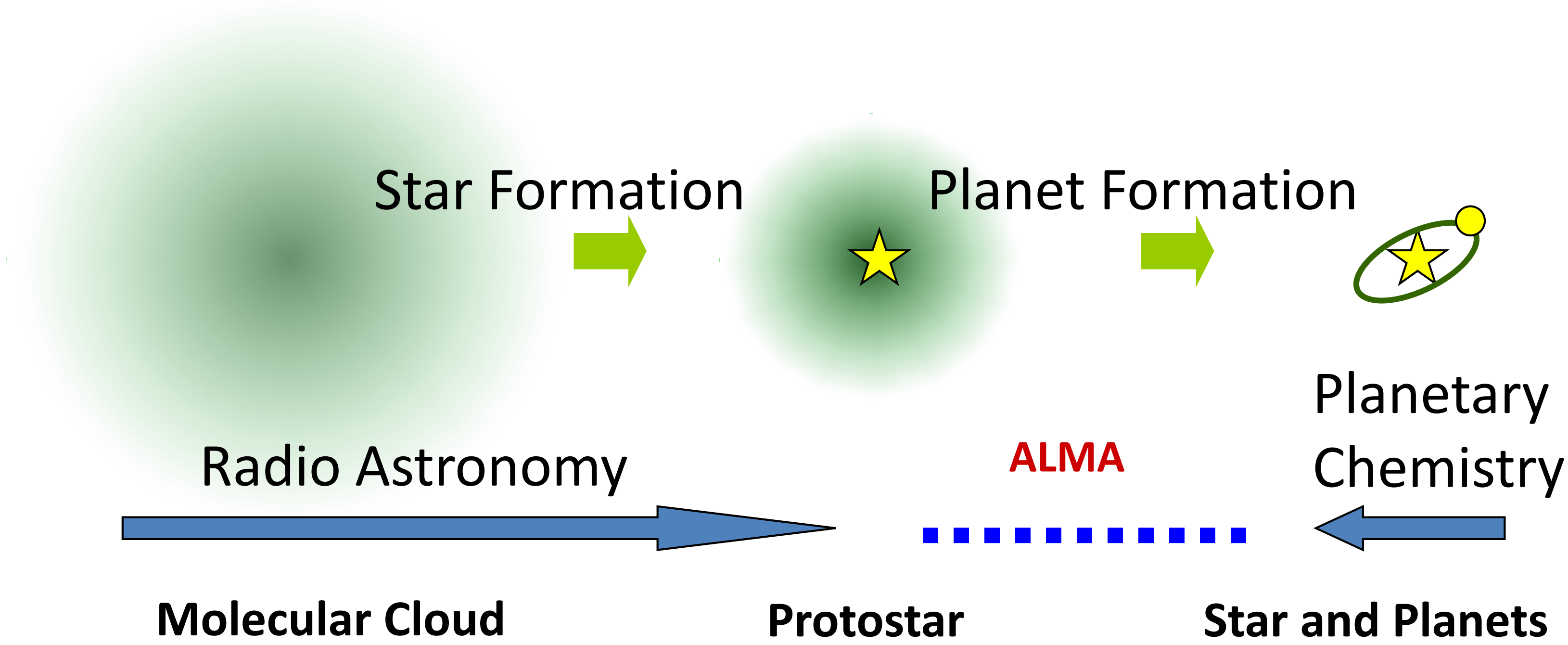
Sub-pc Scale Chemistry

Molecular-Cloud Scale Chemical Compositions in Galaxies

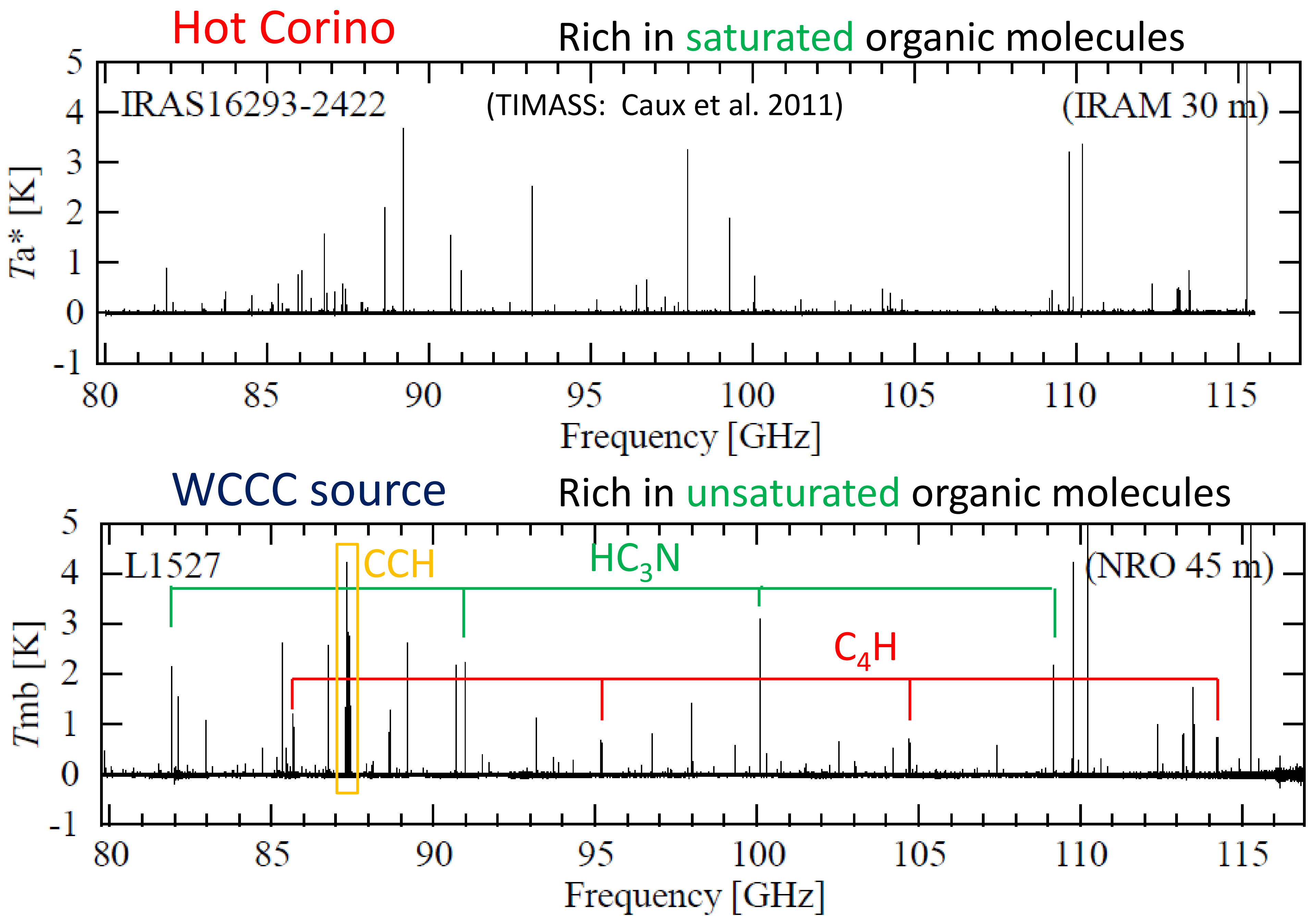
kpc Scale Chemistry


ALMA
Atacama Large
Millimeter/submillimeter
Array
DV-03

Chemical Evolution from Interstellar Clouds to Planets



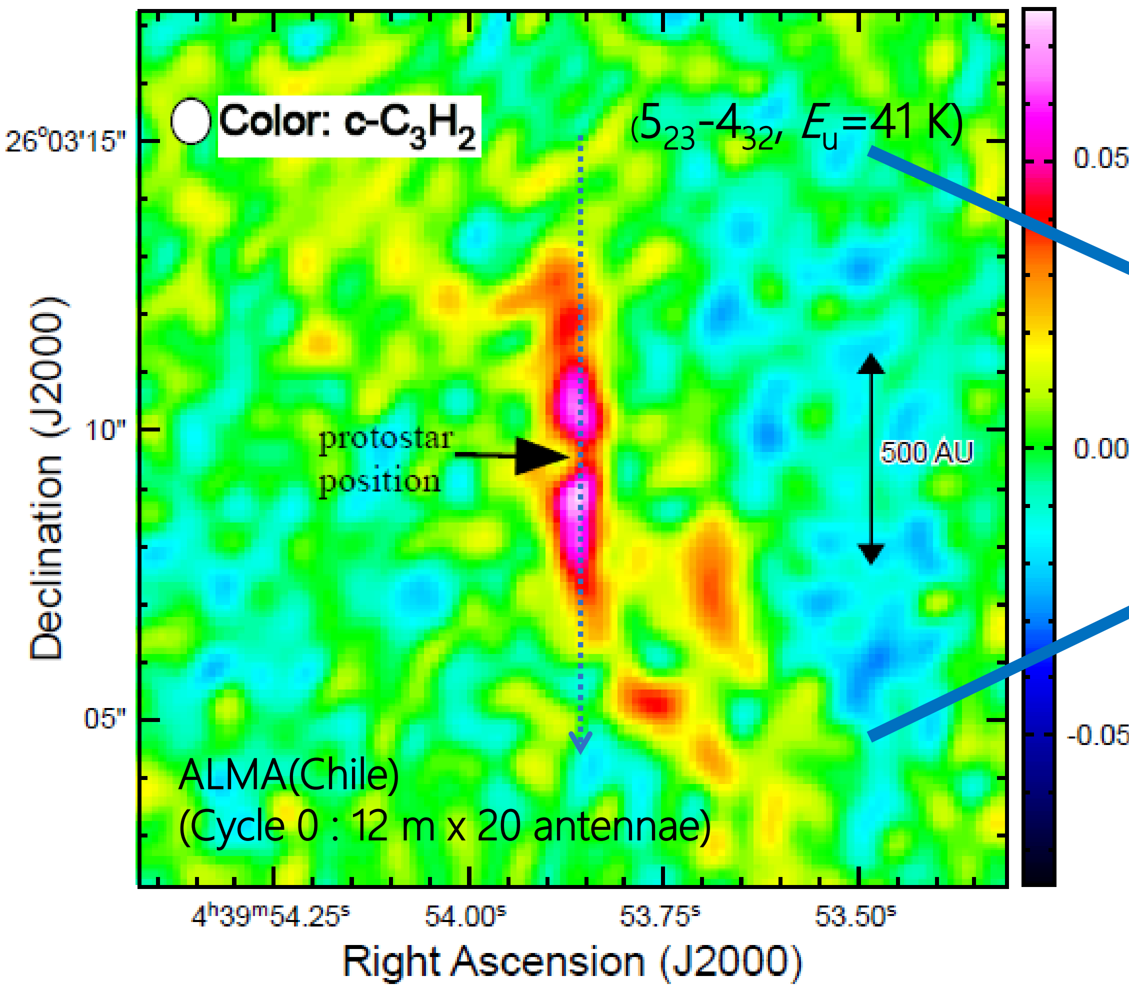
Bridging the Missing Link between Interstellar Chemistry and Planetary Chemistry



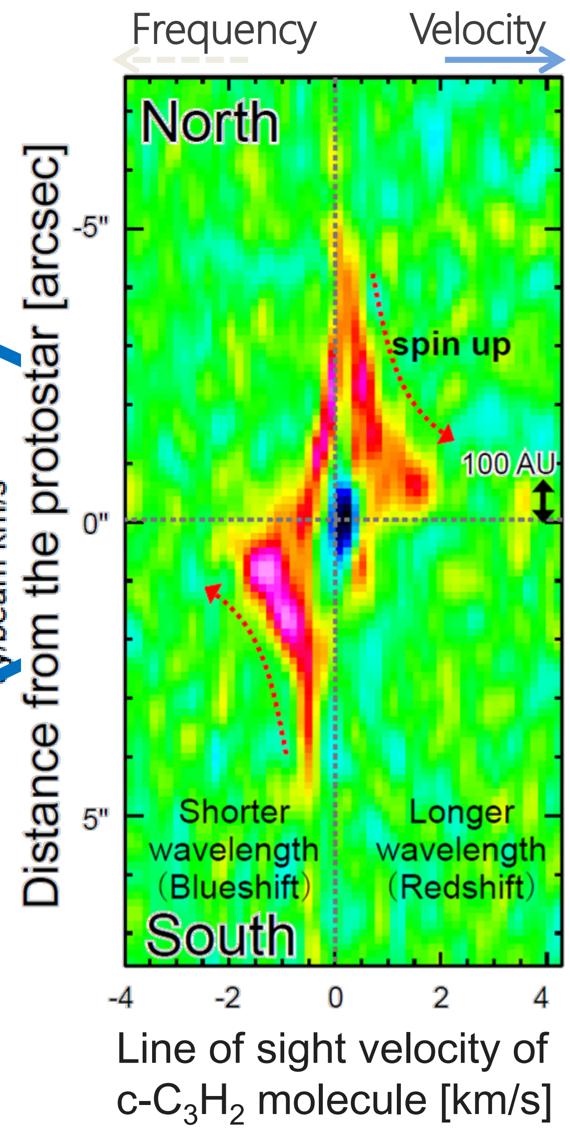
Hot Corino
Rich in saturated organic molecules
IRAS16293-2422
(TIMASS: Caux et al. 2011)
(IRAM 30 m)
Ta* [K]
Frequency [GHz]
WCCC source
Rich in unsaturated organic molecules
L1527
CCH
HC_3N
(NRO 45 m)
C_4H
Tmb [K]
Frequency [GHz]

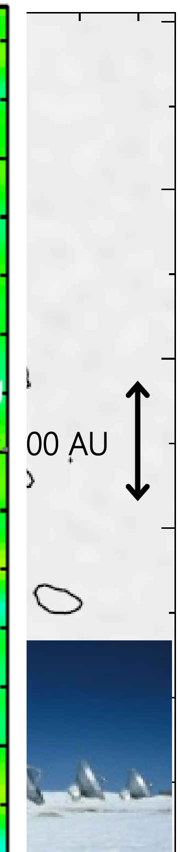
Disk Forming Region in L1527

◆100 au Scale



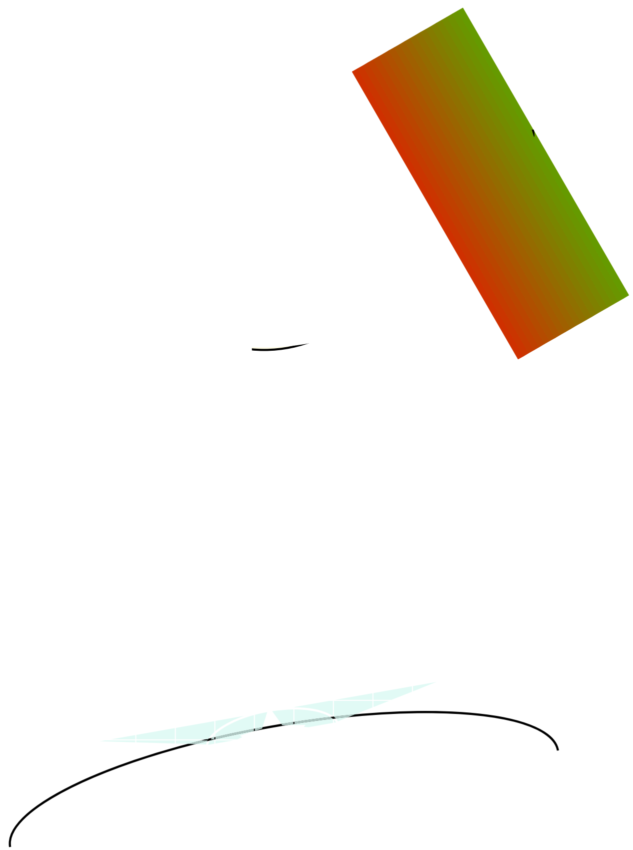
(Sakai et al. 2014, Nature, 507, 78)





1633)

Infalling Rotating Envelope



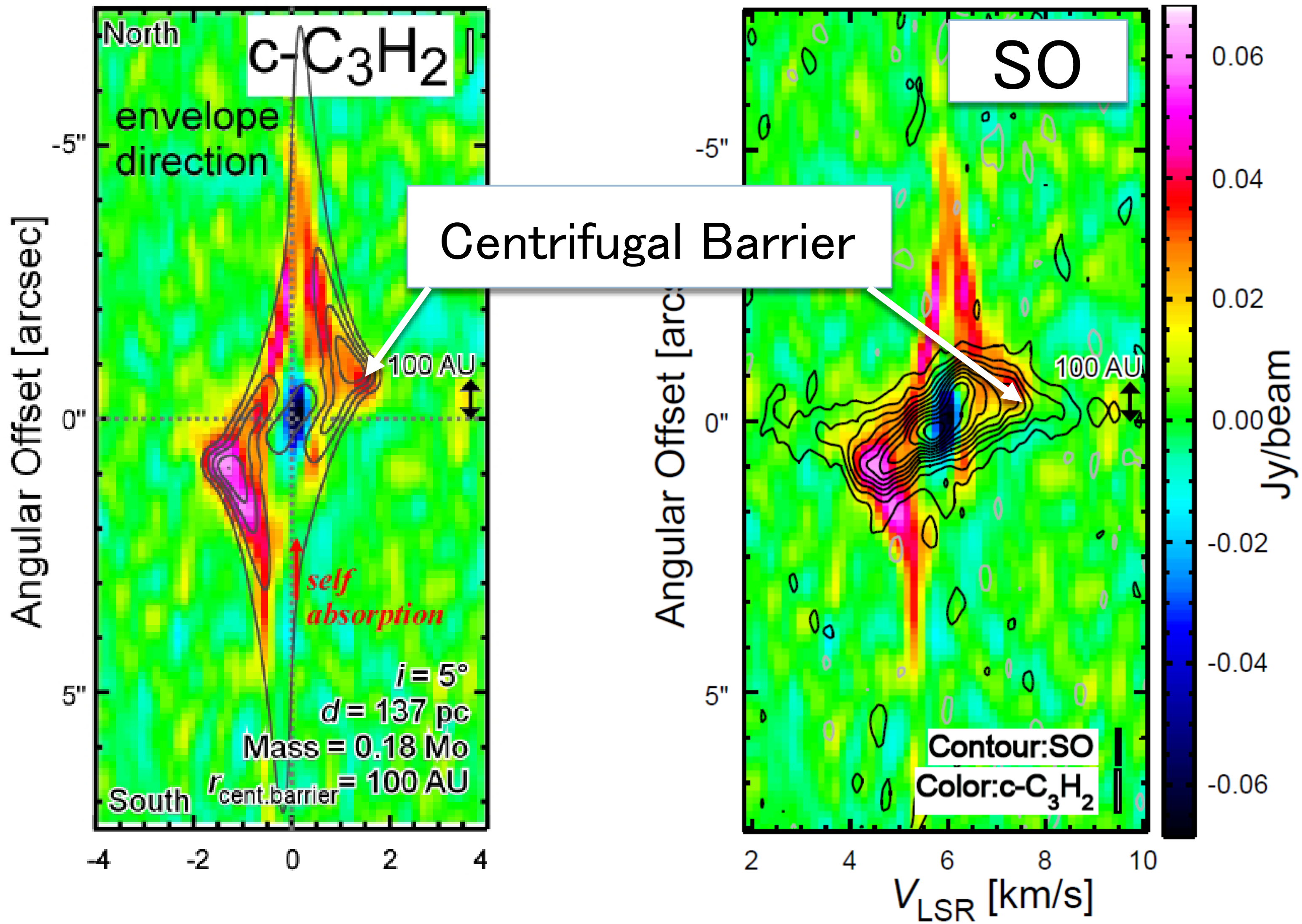
Oya et al. (2014)

- Assumptions
  - Particle motion
  - Optically thin, $n \propto r^{-1.5}$
  - Line width, Resolution
- Parameters
  - M: Mass
  - i: Inclination angle
  - r_{CB}: Radius of the CB

$$r_{CB} = \frac{1}{2\,GM}\left(\frac{L}{m}\right)^2$$

- Velocity Field

$$\begin{cases} V_{rot} = \frac{1}{r}\left(\frac{L}{m}\right) \\ V_{infall}^2 = \frac{2GM}{r} - V_{rot}^2 \end{cases}$$



Infalling–Rotating Envelope

Centrifugal Barrier

IRAS 16293–2422: Class 0, Hot Corino

- Class 0 in Ophiuchus
  - *d* = 120 pc (Chandler+ 2005)
  - Outflow dynamical timescale: ~10^{3-4} yr
- Hot Corino
  - Rich in COMs

    $HCOOCH_3$, $(CH_3)_2O$, Glycolaldehyde, etc.
    (e.g. Cazaux+ 2003; Jørgensen+ 2012)
- Rotating Motion in Source A
  - $C^{17}O$, $C^{34}S$ (SMA + eSMA), $HCOOCH_3$ (ALMA Cycle 0 SV)

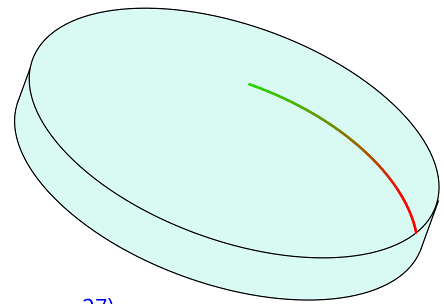
    (Jørgensen+ 2012; Pineda+ 2012; Favre+ 2014)

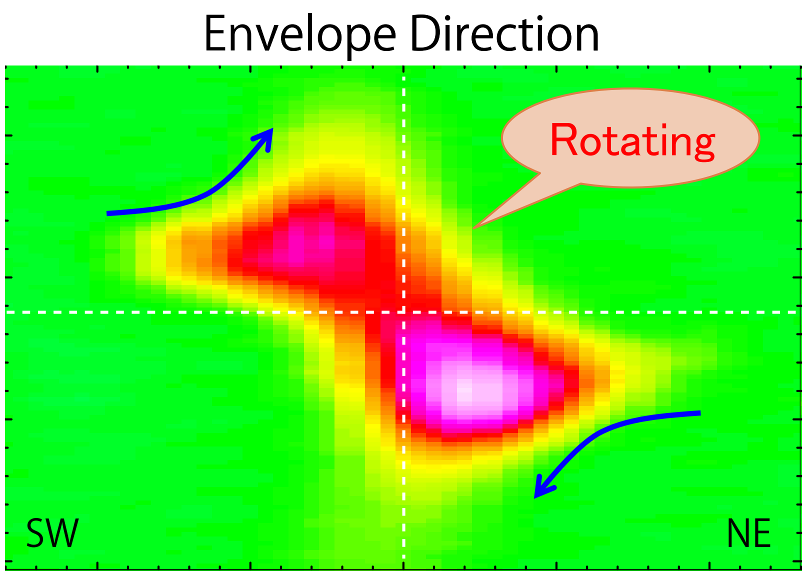
→ Analysis with the IRE model

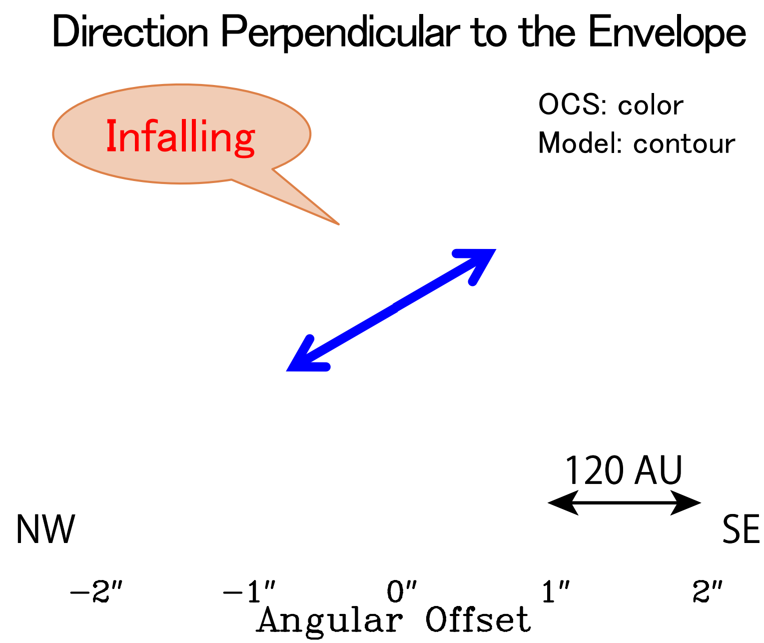
Oya et al. 2016, ApJ, 824, 88

Kinematic Structure Traced by OCS

- Envelope traced by OCS
  - Not the Keplerian motion
  - IRE model
    - $M = 0.75\ M_{\odot}$, $r_{CB} = 50$ au
    - $I = 30^{\circ}$, $R_{out} = 180$ au

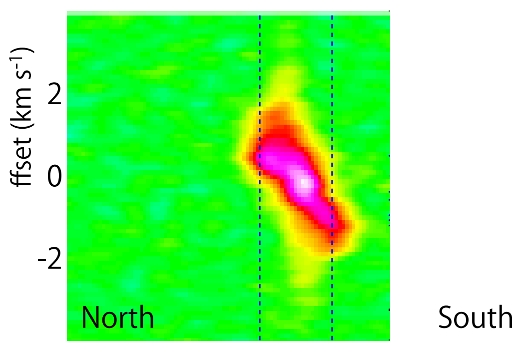


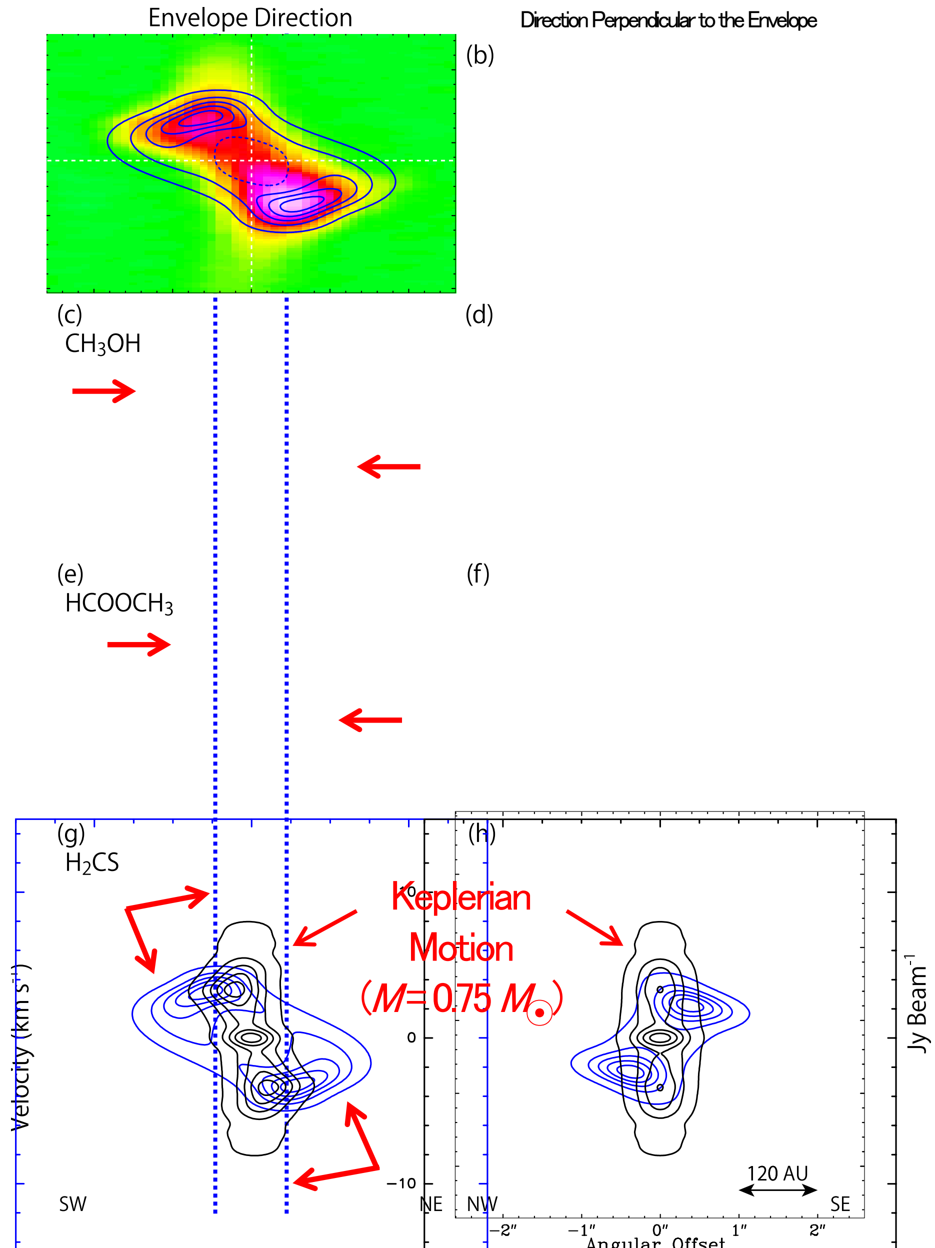




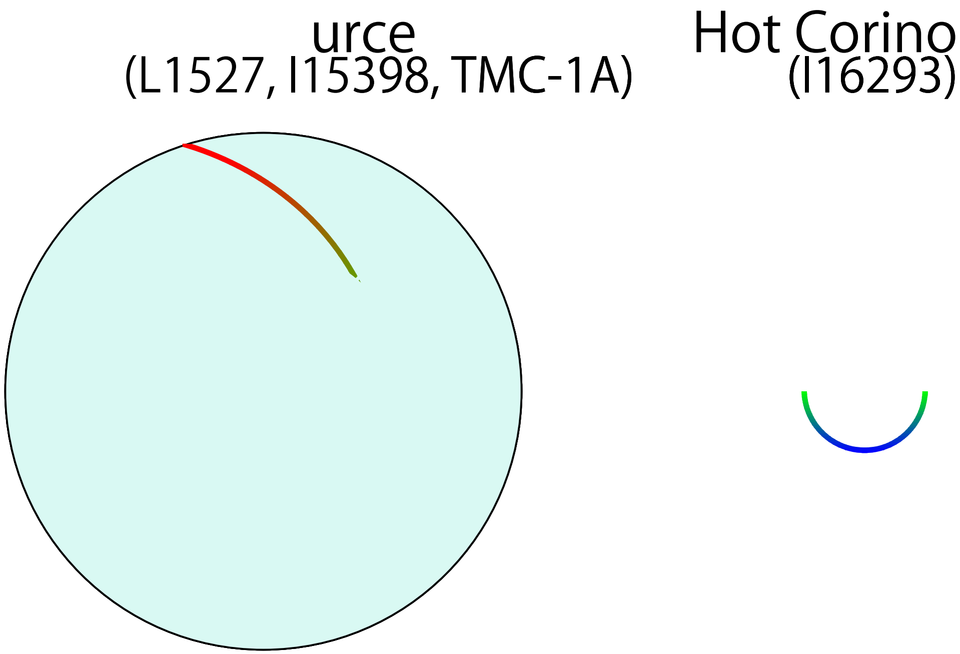
Other Lines

- OCS (19–18)
  - Infalling–rotating envelope
    (R = 180 AU)
- CH_3OH ($11_{0,11}$–$10_{1,10}$; A^{++})
  - Rotating around CB
    (R = 80 AU)
- $HCOOCH_3$ ($19_{9,19}$–$19_{8,11}$; E)
  - Rotating around CB
    (R = 55 AU)
- SO in L1527





Summary: WCCC Sources vs a Hot Corino



- IREs are traced by different molecules in different type of sources.
  - It depends on the chemical compositions of the envelopes.
- Ring structures are shown by volatile species.
- Disk components inside the centrifugal barrier are detected.

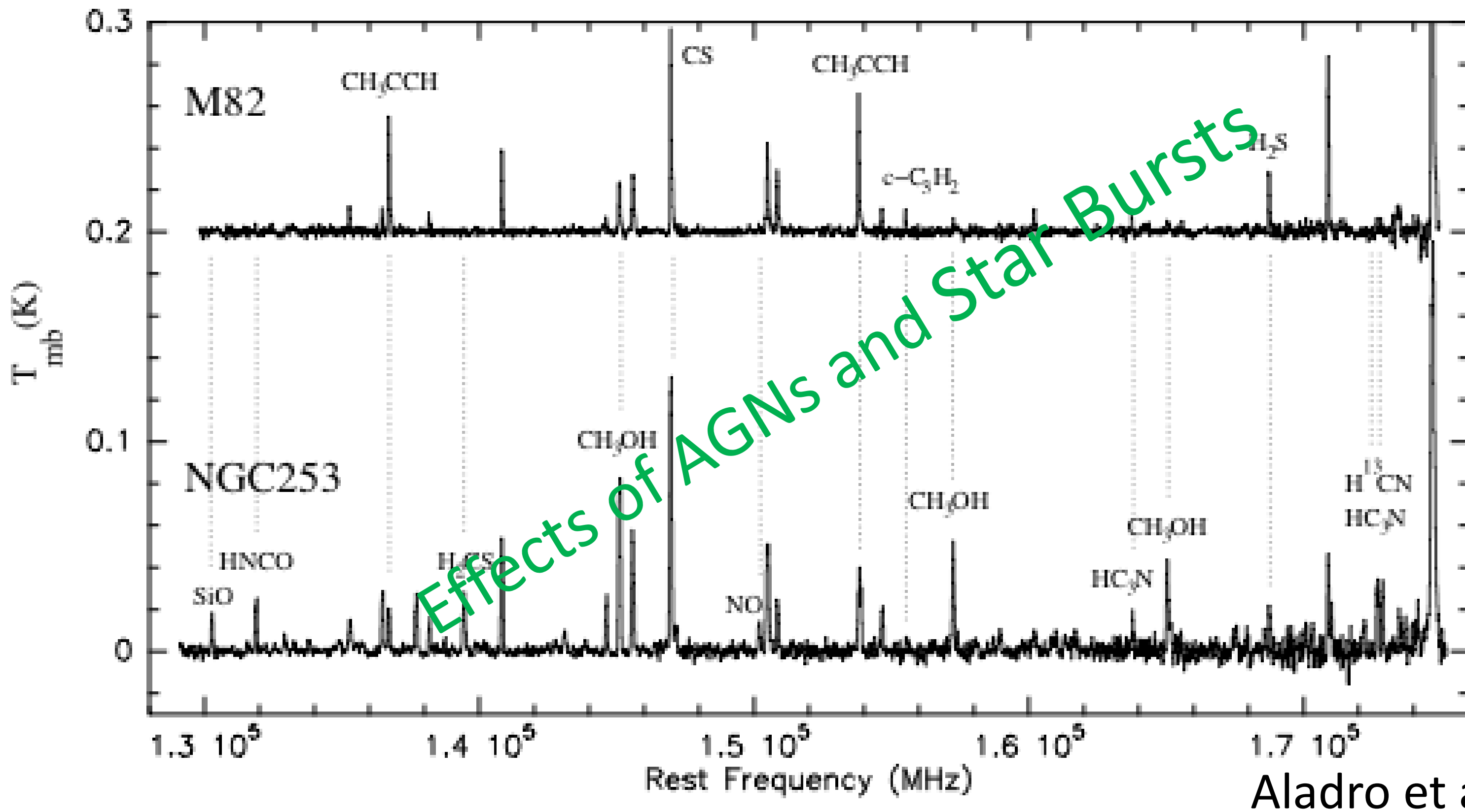
Sakai et al., 2014, ApJ , 798, L31 Oya et al. 2016, ApJ, 824, 88

ALMA observations tell us:

- Strong chemical diversity at a 50 au scale

  Related to the chemical diversity at the protostellar core scale, but even stronger than that.
- Chemical composition highlights particular parts/phases of disk formation around the protostar
- Infalling material is subject to a drastic chemical change across the centrifugal barrier

Chemical Analysis of External Galaxies



Aladro et al. 2011

What is the ‘standard’ chemical composition averaged over molecular clouds?

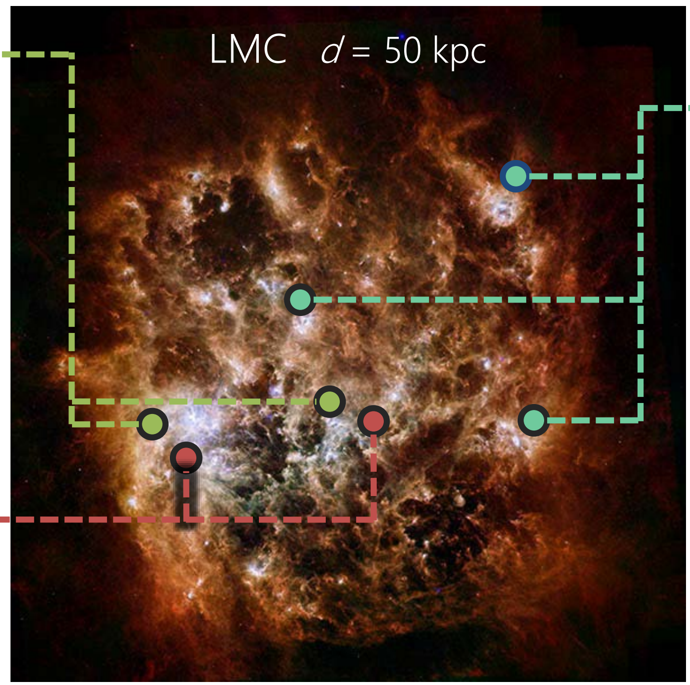
The Large Magellanic Cloud

Quiescent clouds

- CO Peak 1
- NQC2

Star-forming clouds with HII region

- N113
- N159W



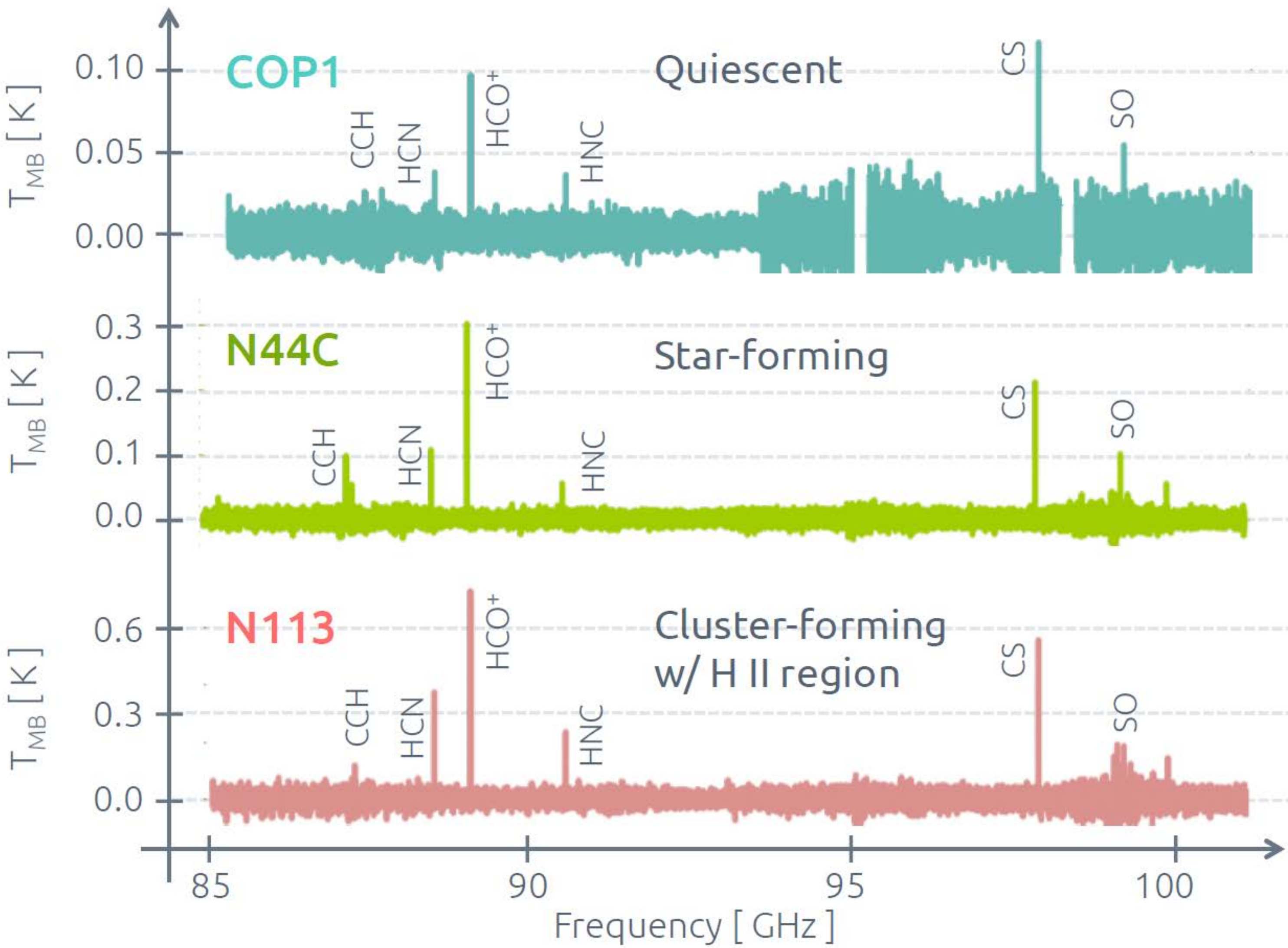
Spitzer-MIPS, *Herschel*-PACS, *Herschel*-SPIRE

Star-forming clouds

- N79
- N44C
- N11B

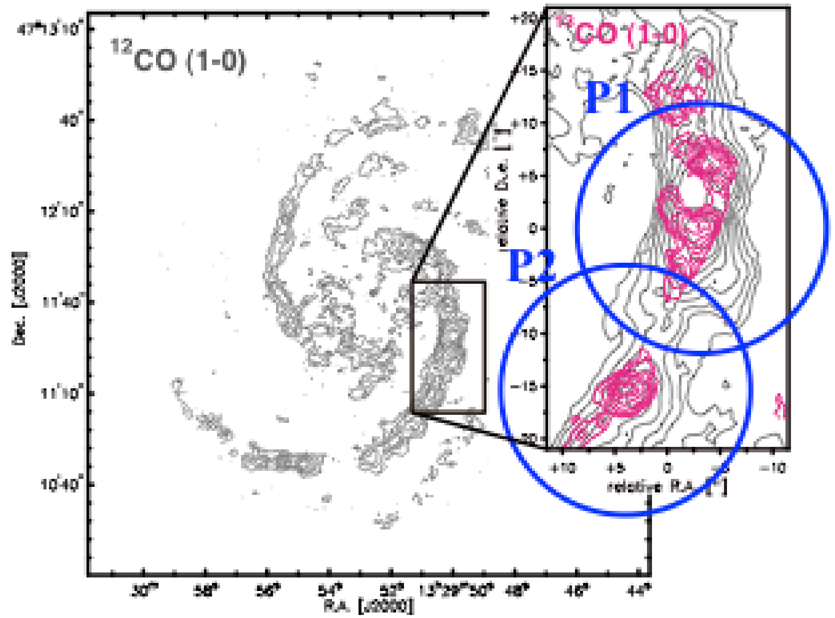
- 7 clouds
- 450 hours
- Mopra 22 m (HPBW = 38″)

Effect of star formation?



Nishimura et al. 2016, ApJ, 818, 161

Observation of M 51 with IRAM 30 m



Schinnerer et al. 2010

- M51 (d : ~ 8.4 Mpc (Feldmeier et al. 1997))

IRAM 30m

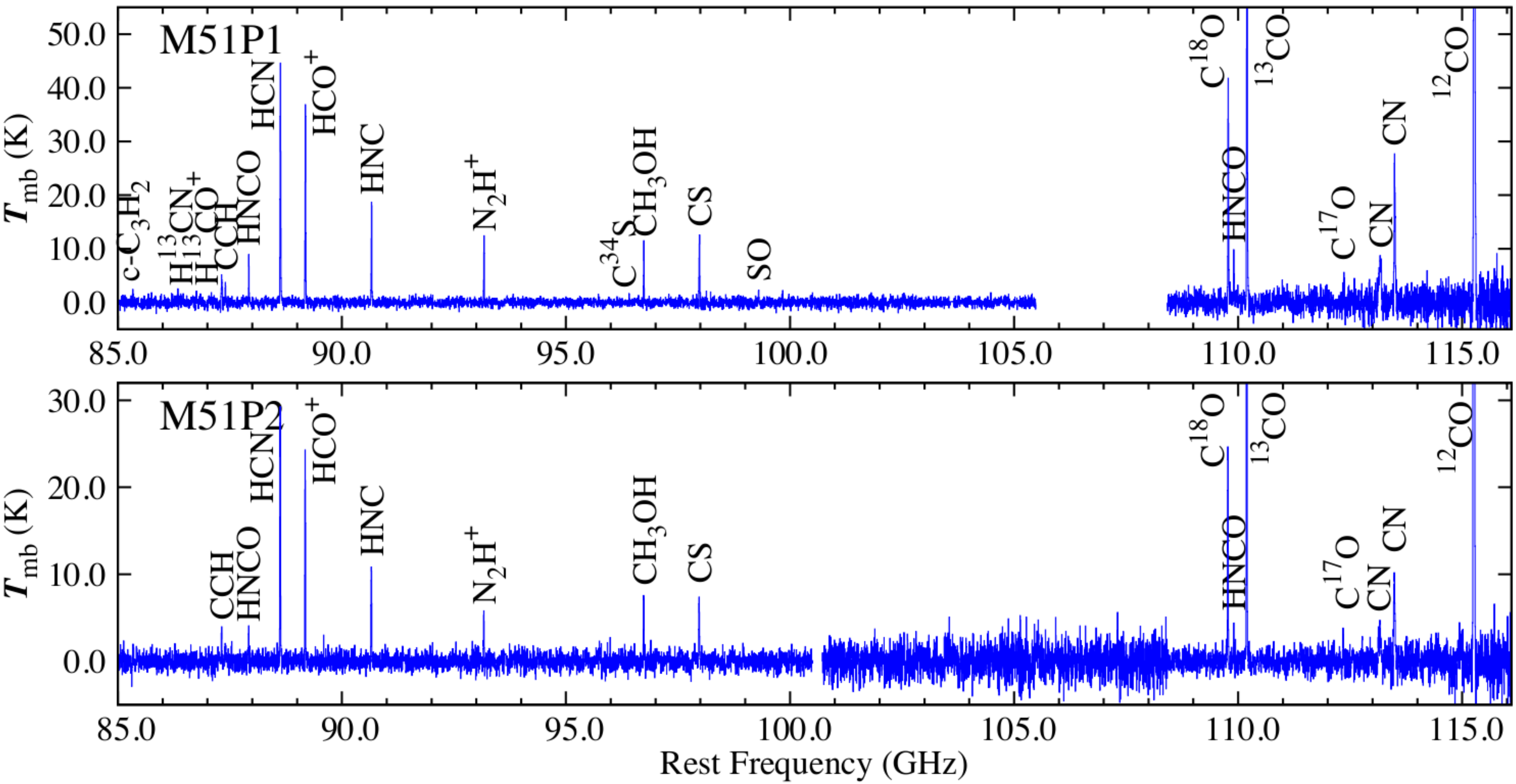
Date : Dec. 2011, Aug. 2012

Frequency Ranges : 83 – 116 GHz

130 – 148 GHz

Resolution : 30” – 17”

Comparison between Positions 1 and 2



Watanabe et al. 2014, ApJ, 788, 4

Molecular-Cloud-Scale Chemical Composition Seen in the 3 mm Band

- Dominated by the contribution of the extended molecular gas

  →Effects of local star formation activities are mostly smeared out.

  →Galactic scale effects will affect it.

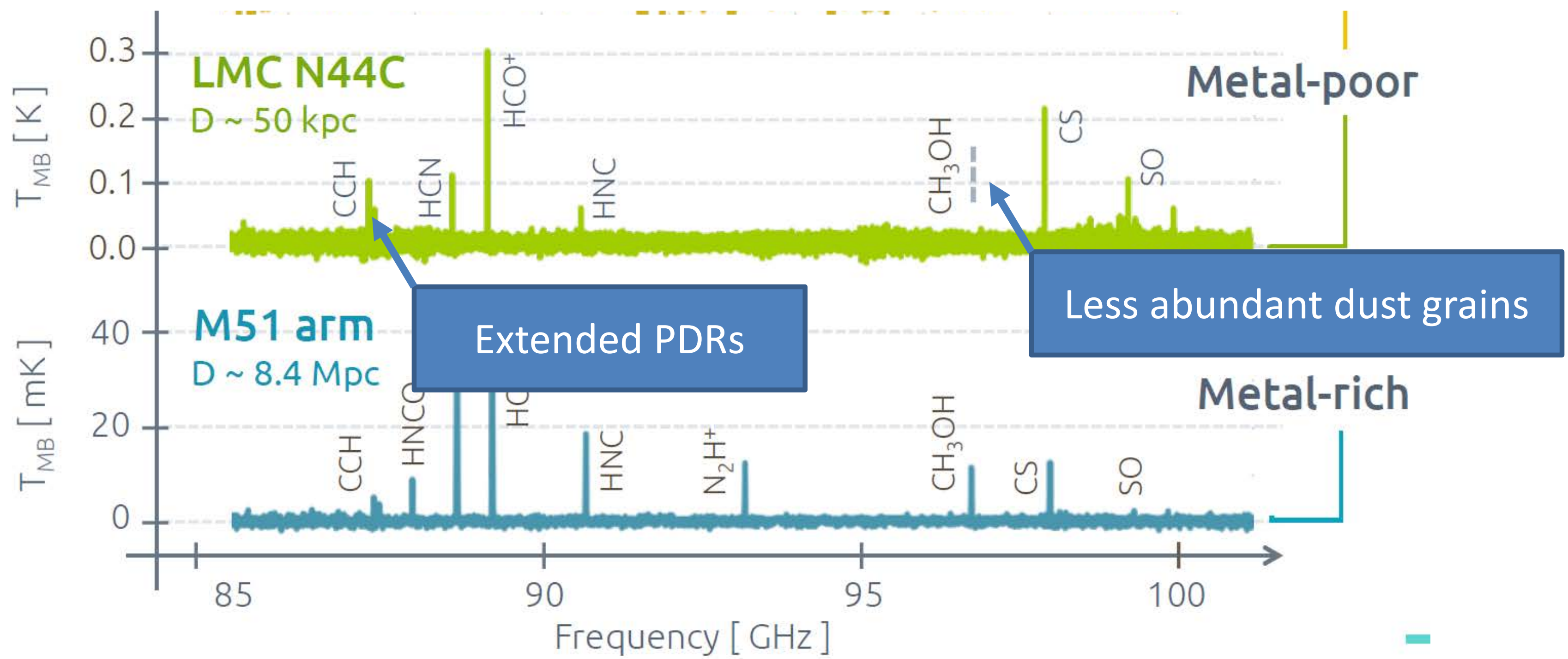
- Determined by fundamental physical and chemical properties

  →Chemical model calculations tell us:

  $n(H_2)$~10^4 cm^{-3}, Av~4 mag, t~10^5-10^6 yr

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

$\times \frac{1}{2}$ (O/H), $\times \frac{1}{5}$ (C/H), $\times \frac{1}{10}$ (N/H)



Nishimura et al. 2016, ApJ, 829, 94

Group Members

Yoshimasa Watanabe
Ana Lopez-Sepulcre
Yuri Nishimura
Yoko Oya
Yuji Ebisawa
Kento Yoshida
Muneaki Imai
Yutaro Chiba
Osamu Ohguchi

Nami Sakai (RIKEN)
Aya Higuchi (RIKEN)
Takeshi Sakai (U. Telecom)
Tomoya Hirota (NAOJ)
Hiroyuki Maezawa (Osaka Pref. U.)

Cecilia Ceccarelli (IPAG)
Bertrand Lefloch (IPAG)