CO Observations of Molecular Clouds in the Extreme Outer Galaxy

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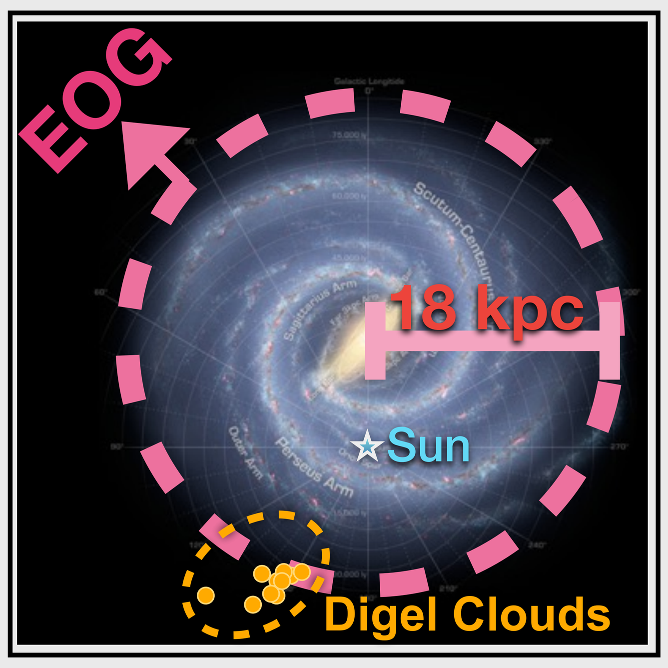


Figure 1 : Image of the our Galaxy (NASA/JPL-Caltech)

Abstract

We report the physical quantities oc molecular clouds in the extreme outer Galaxy (EOG) at Galactocentric raids of more than 18 kpc. The EOG is the valuable place where it is possible to observe "galaxy formation processes" in the scale of a molecular clouds (pc-scale). We performed high-resolution $^{12}CO(1-0)$, $^{13}CO(1-0)$, and $^{12}CO(3-2)$ mapping observation of 8 molecular clouds in the EOG (called Digel Clouds) with NRO 45m telescope and JCMT. As a result, we detected 352 clumps and identified 20 new candidates of star-forming region. Some properties of these clumps (Size - velocity width relation, Mass function, Virial mass vs. CO luminosity) are apparently different from those in the other part of the Galaxy, which could indicate that the environment has an impact on molecular cloud/star formation activity. We also report the distribution of $^{12}CO(3-2)/^{12}CO(1-0)$ ratio of Digel Cloud 2, which may show evidence of interaction between HI shell and molecular clouds.

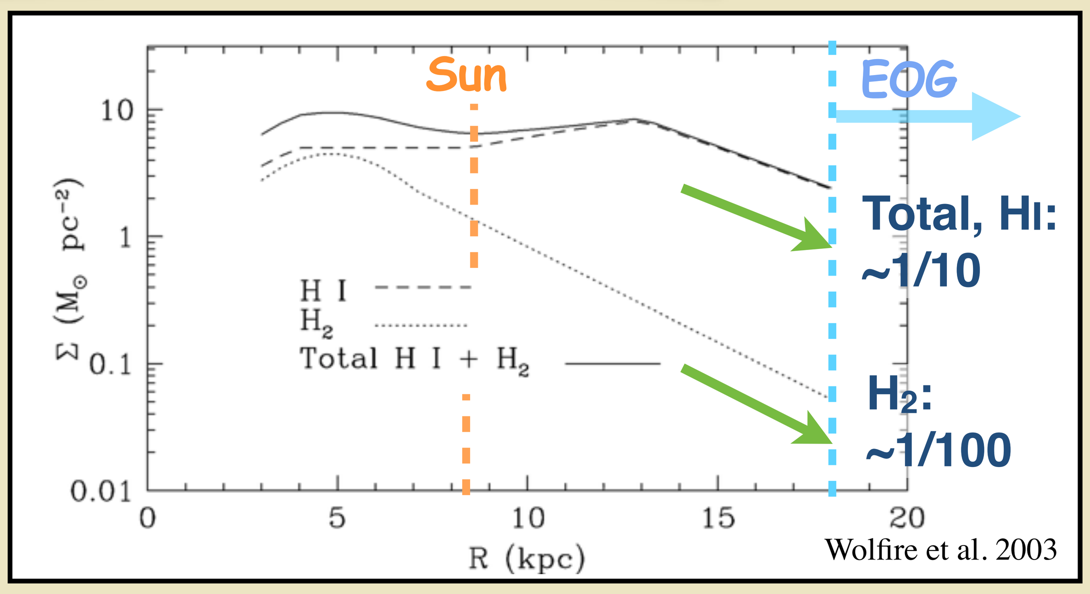
1. Introduction

❖ Extreme Outer Galaxy ($R_G \geqq \sim 18$ kpc)

- Different environment from the inner disk
  1) Little or nor perturbation from the spiral arm
  2) Lower-gas density (HI dominant)
  3) Lower-metallicity…

Similar characteristics with dwarf galaxies and the early phase of the formation of our Galaxy

We may be able to investigate molecular cloud/star formation activity under such an internsing environments in unprecedentered detail at much closer distance (D ~ 10 kpc) than distant galaxies (D > 50 kpc)



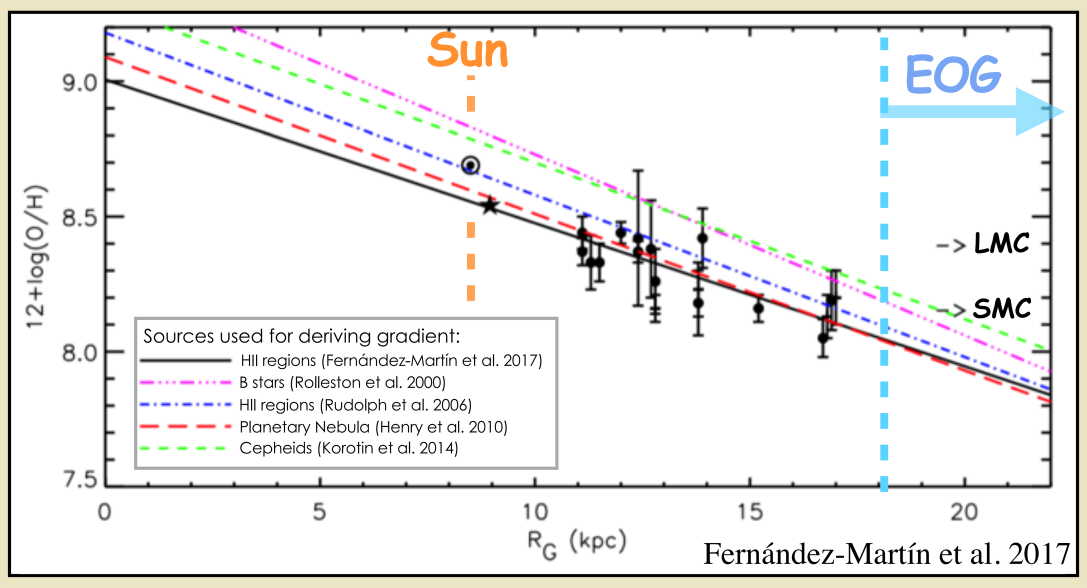


Figure 2 (Left) : HI, H_2 and total density in the Galactic mid plane vs R_G (Wolfire et al. 2003)
Figure 3 (Right) : Extrapolated gradients of Oxygen abundance along the Galactic disk for different sources (Fernández-Martín et al. 2017)

2. Observation

❖ Target: Digel clouds

- Target: Digel Clouds Digel et al., 1994
  - Discovered by the very first survey of molecular clouds in the EOG
  - Composed of eight molecular clouds (Cloud 1-8)
    - Star forming regions are clearly detected in Cloud 1 and Cloud 2 from our NIR observation with Subaru telescope e.g, Izumi et al., 2014, Yasui et al., 2006, 2008
- Parameters of CO observation

Obs.year	2006, 2007	2014,2015,2017	2015
Target	Cloud 1, 2	Cloud 3-8	Cloud 1, 2, 7, 8
Telescope	NRO 45m telescope		JCMT
Line	12CO(1-0), 13CO(1-0)		12CO(3-2)
Velo.resolution	0.25 km s^{-1}		0.22 km s^{-1}
Effective HPBW	~ 17"		~ 17"

Objective: Understanding properties of molecular cloud in the EOG!!

3. Results

❖ $^{12}CO(1-0)$ molecular distribution

- High-resolution observation enabled us to map overall structure of the clous in ~pc scale
  - Detection of 352 clumps (using CLUMPFIND) Williams et al., 1994
    - Detection limit: Lco = 2.2 K km s^{-1} pc^{-2} ; Mco = 7$M_\odot$ (← Assuming Xco= 2.0×10^{20} cm^{-2} (K km s^{-1})$^{-1}$)
    - Typical size : r = 1-3 pc, dv = 0.7-1.5 km s^{-1}
  - Identification of 20 new candidates for star forming region

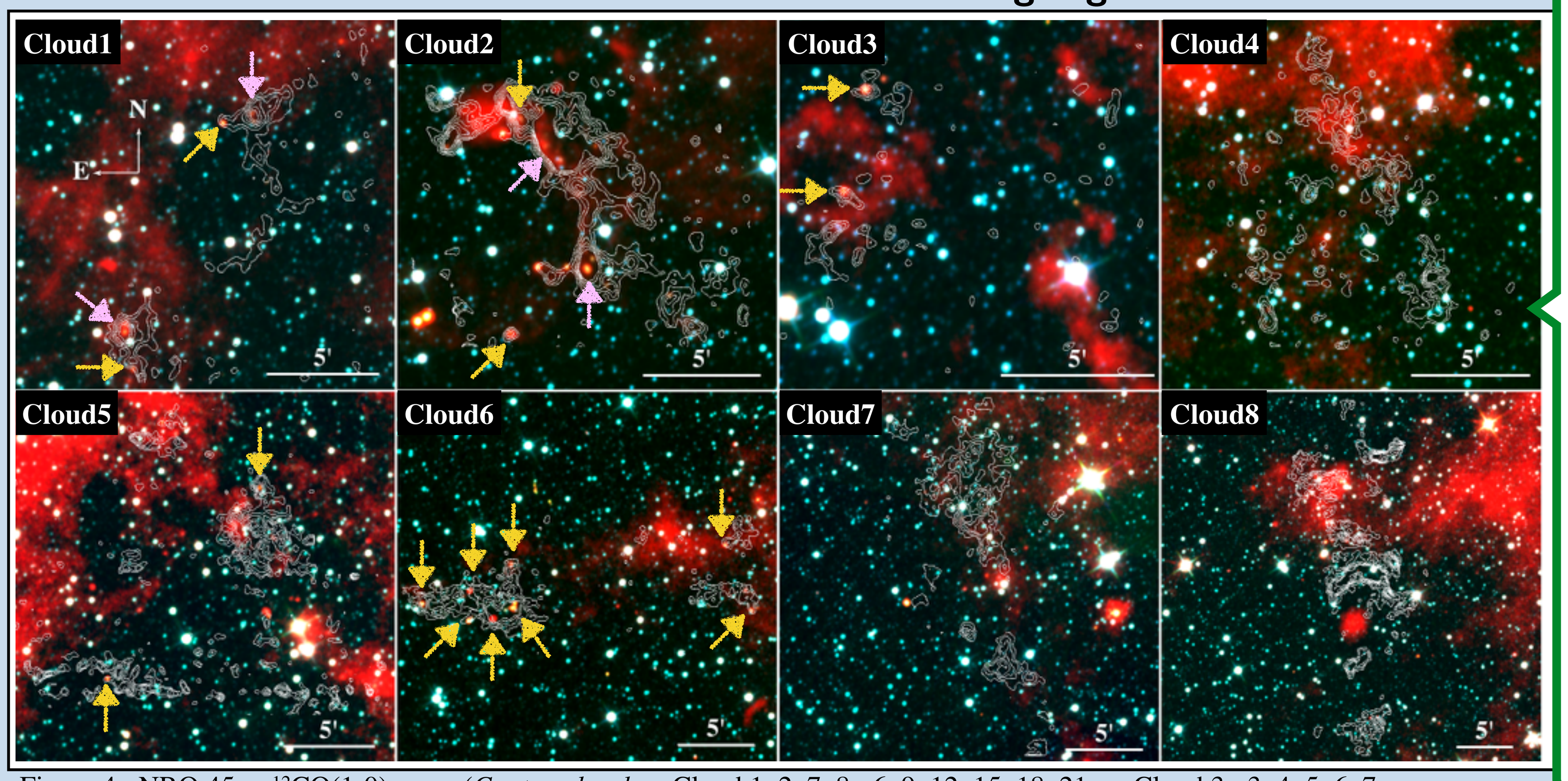


Figure 4 : NRO 45 m $^{12}CO(1-0)$ maps (*Contour levels* - Cloud 1, 2, 7, 8 : 6, 9, 12, 15, 18, 21 σ ; Cloud 3 : 3, 4, 5, 6, 7 σ ; Cloud 4,5 : 4, 5, 6, 7, 8 σ ; Cloud 6 : 5, 7, 9, 11, 13 σ) and mid infrared pseudo color images around these Clouds. The color images are produced by combining the 3.4, 4.6, 12 μm images from the WISE data (NASA/IPAC).

Star forming region
- ⇦ : Already-known
- ⇦ : New candidate

Star forming regions are detected in the MIR images as compact reddened stellar object

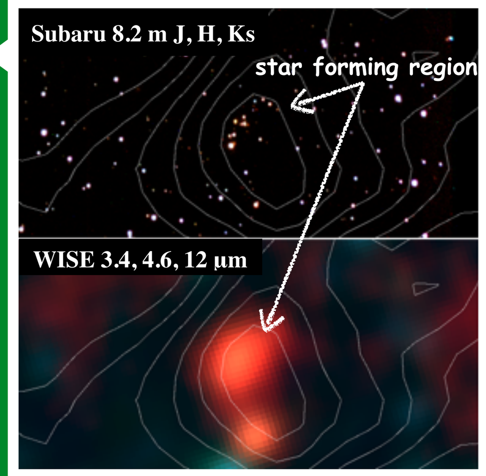


Figure 5 : NIR(Top) and MIR (Bottom) pseudo color image of the star forming region in Cloud 1

Izumi et al., 2017

4. Discussion

❖ Properties of $^{12}CO(1-0)$ clumps

- Velocity width vs. Radius

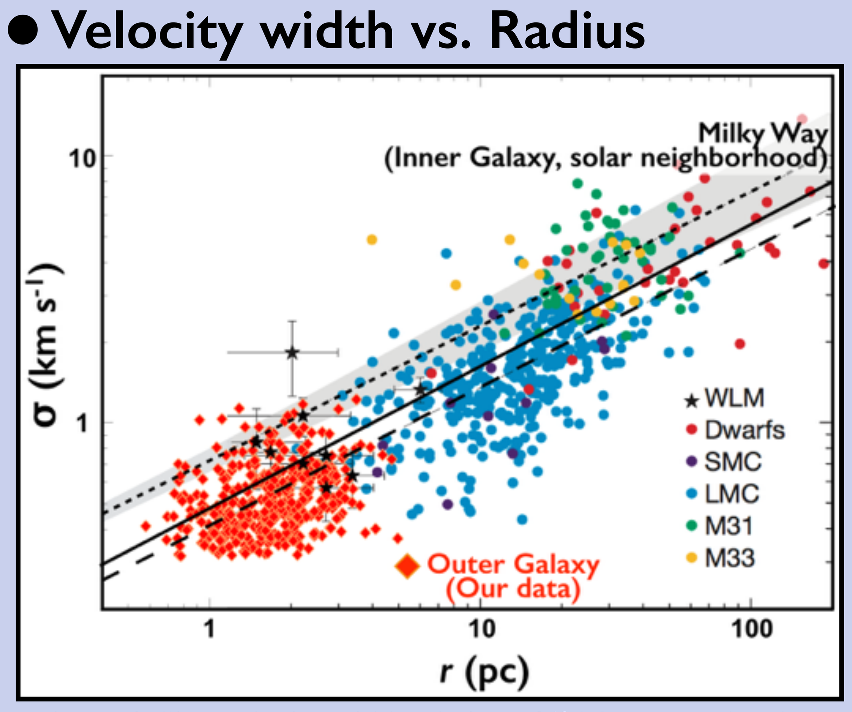


Figure 6: Size-velocity width relation of $^{12}CO(1-0)$ molecular clouds in several environments (Rubio et al. 2015)

- Velocity width of the clumps in the outer Galaxy is only about half of that in the inner pert of the Galaxy

- Mass function

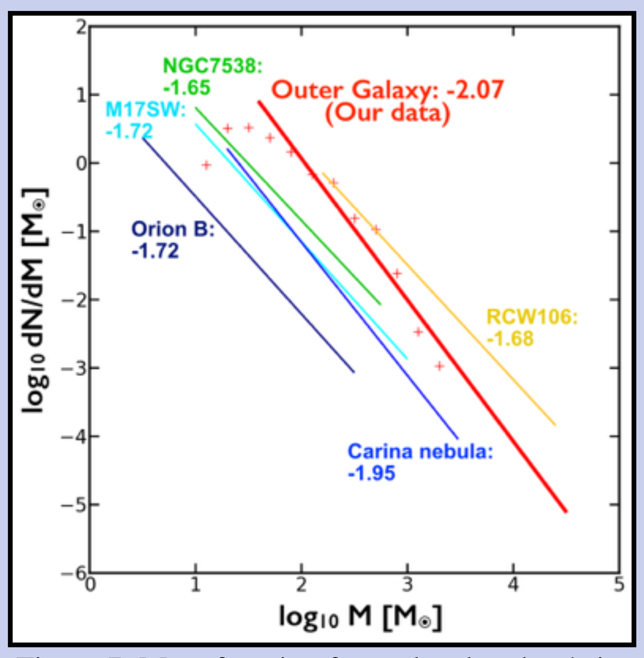
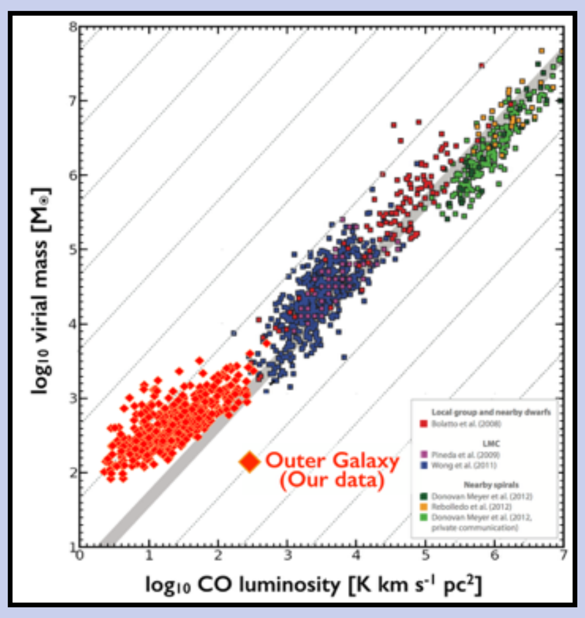


Figure 7: Mass function for molecular clouds in several environment (e.g. Kramer et al, 2018)

- Power-law spectrum in the outer Galaxy is relatively steeper than that in the inner part of the Galaxy (with Xco = 2.0 × 10^{20} cm^{-2}(K km s^{-1})$^{-1}$)

- Virial mass vs. CO luminosity



- CO luminosity of the clumps in the outer Galaxy is relatively lower than that in the inner pert of the Galaxy

Figure 8:
Relation between virial mass and CO luminosity for molecular clouds in several environments (rearranged the Figure 6 in Bolatto et al. 2013). Dashed lines show fixed X_{CO}, with the typical Milky Way value being X_{CO} = 2.0 × 10^{20} cm^{-2} (K km s^{-1})$^{-1}$ with ± 30% uncertainty indicated by the gray region.

These properties are different from those in the other part of the Galaxy!!

❖ HI shell - molecular cloud interaction

- 12CO(3-2)/12CO(1-0) ratio of Cloud 2
  - Cloud 2 is associates with large HI shell (expansion SNR shell)

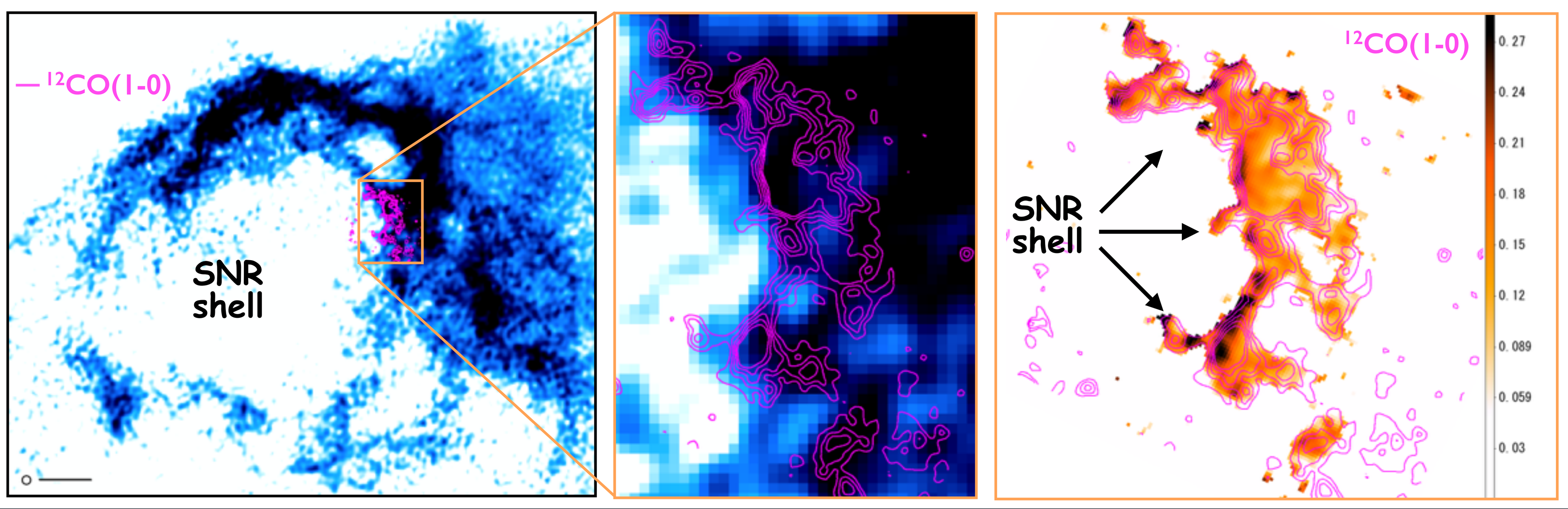


Figure 9: Left; HI distribution of SNR shell from DRAO (v_{LSR} = -107.0 ~ -95.5 km s^{-1}) The magenta contour show the $^{12}CO(1-0)$ distribution of Cloud 2 (6, 9, 12, 15, 18, 21 σ) Middle; Blow-up image of right panel Right; Distribution of $^{12}CO(3-2)/^{12}CO(1-0)$ ratio of Cloud 2

$^{12}CO(3-2)/^{12}CO(1-0)$ ratio is relatively high at shell side

↑Show evidence of the (shock) interaction between HI shell and molecular clouds ?

5. Future works

❖ Combining with ^{13}CO data, derive properties of clumps using LVG analysis

❖ Detect continuum data with JCMT in order to investigate dust-to-gas ratio in the EOG