銀河系外縁部の低金属量環境下での星形成：
ALMAを用いたコアスケールでの分子雲観測

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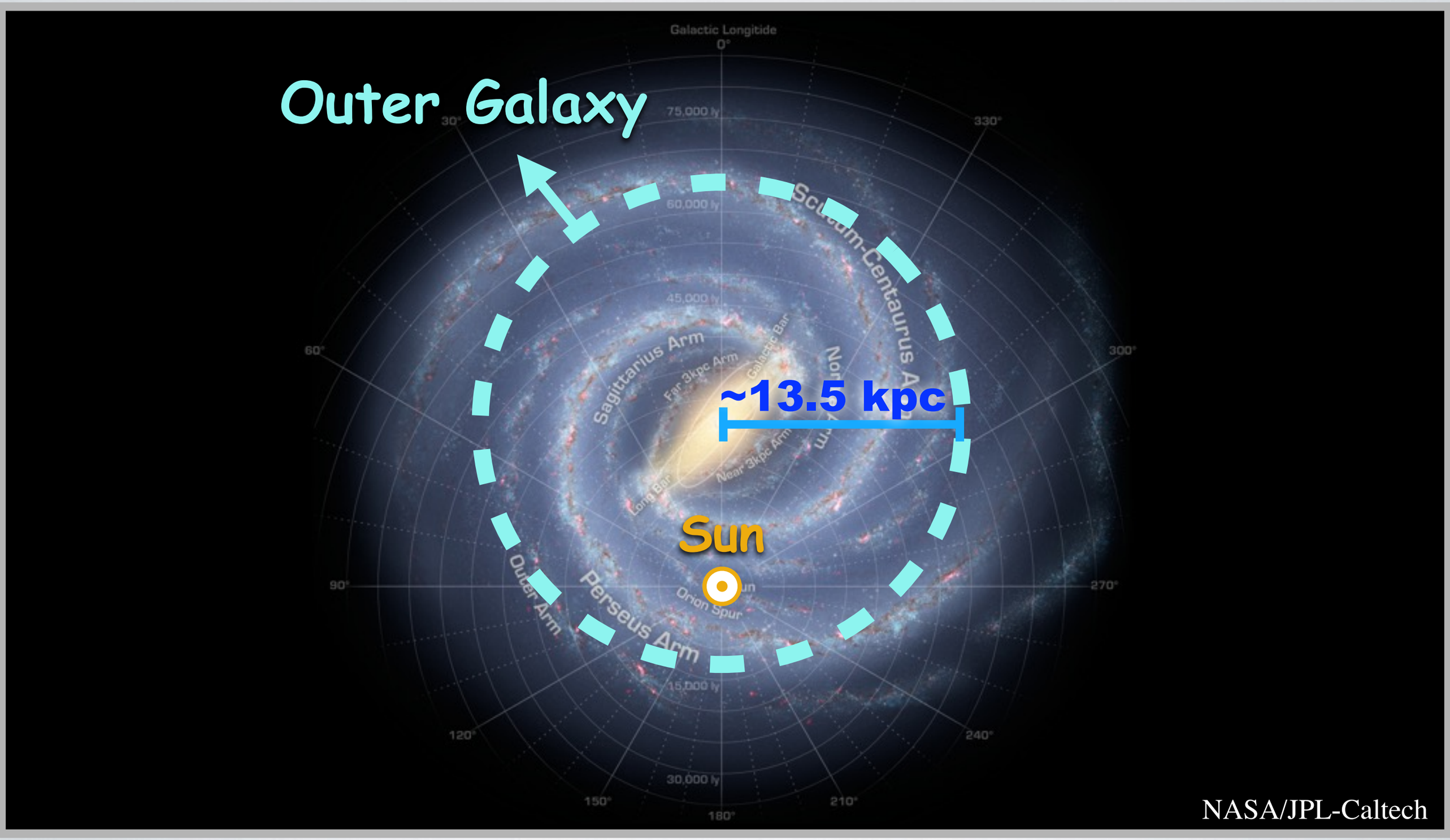
1. INTRODUCTION

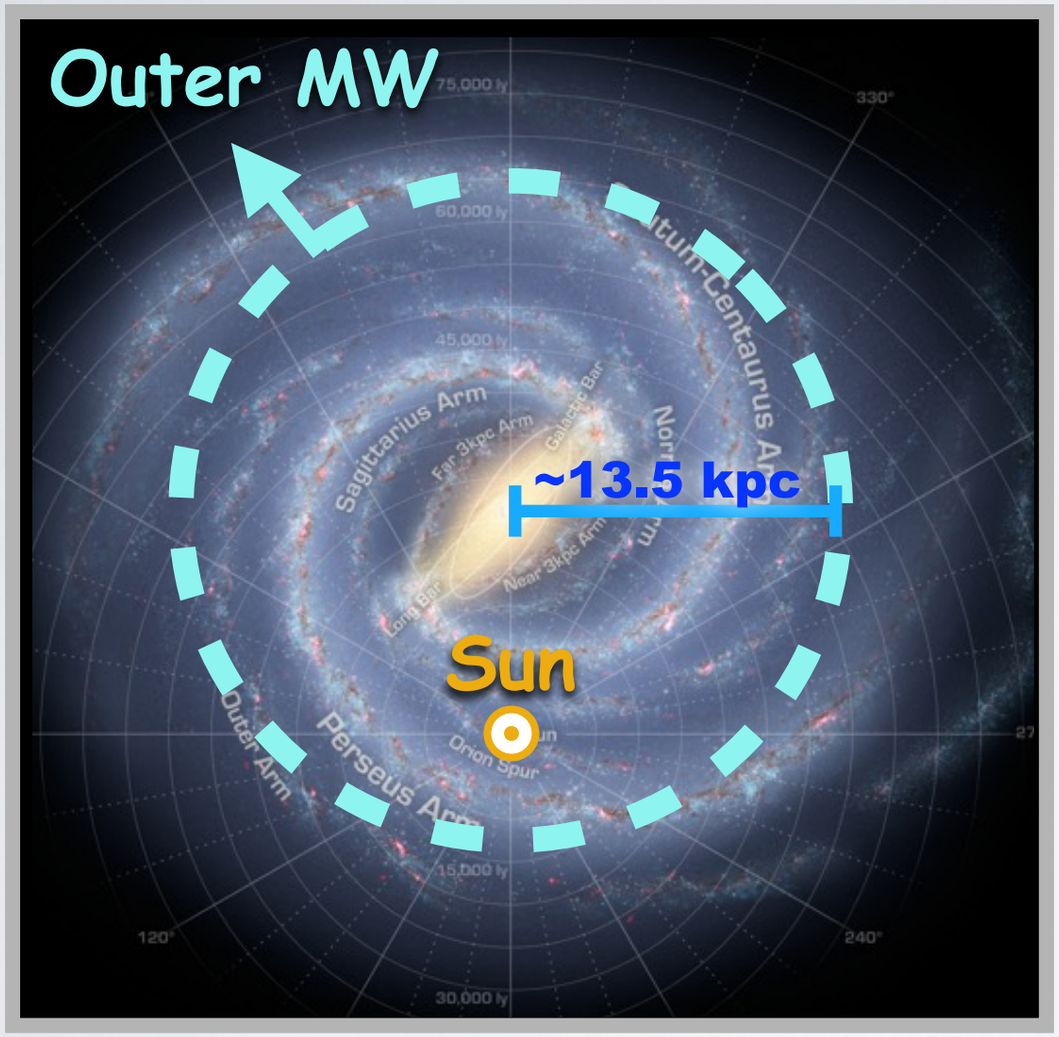
- Outer Galaxy : $R_G \geqq \sim 13.5$ kpc



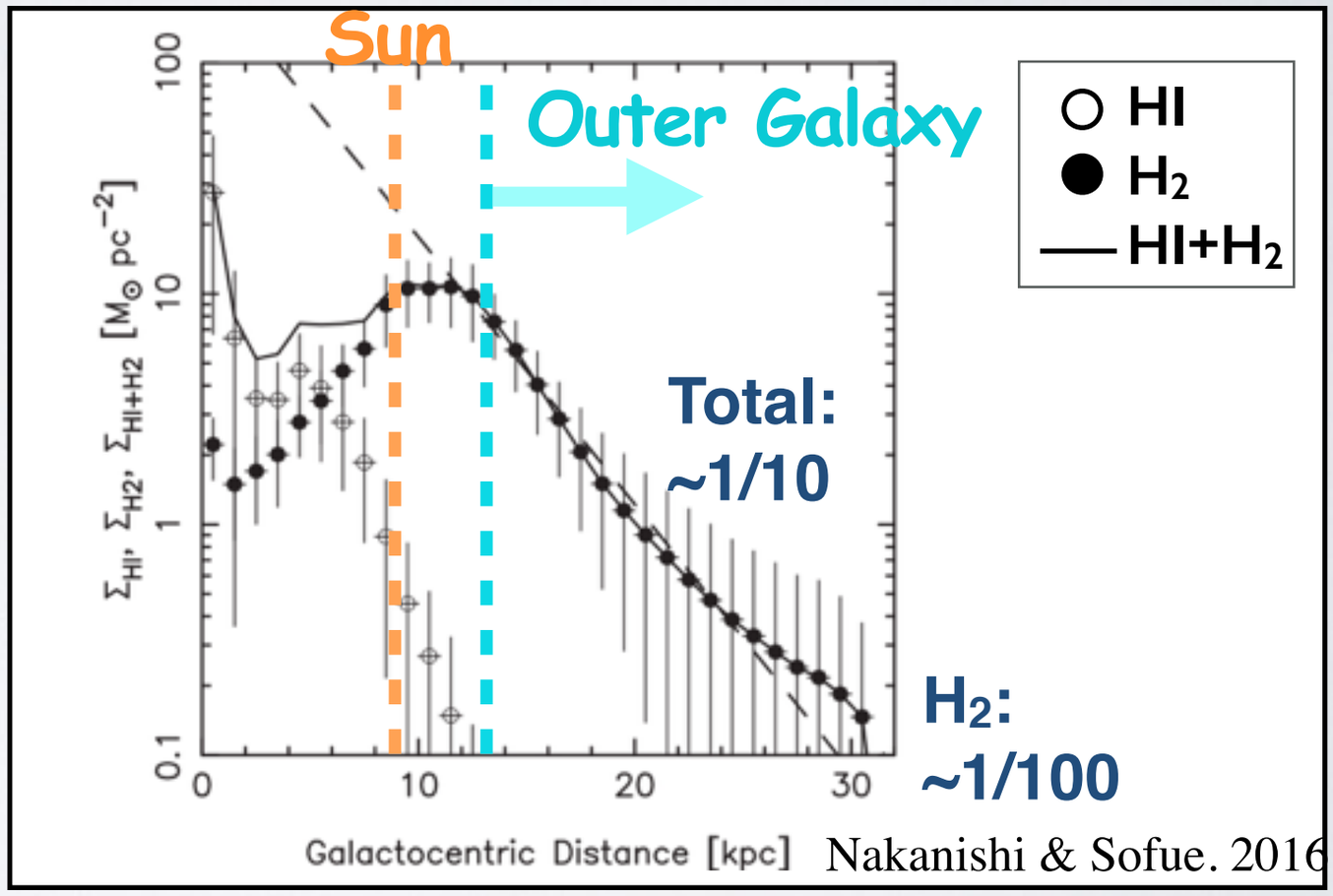
I. INTRODUCTION

❖ Outer Galaxy

- Different environment from the inner disk



- Lower gas density (HI dominant)

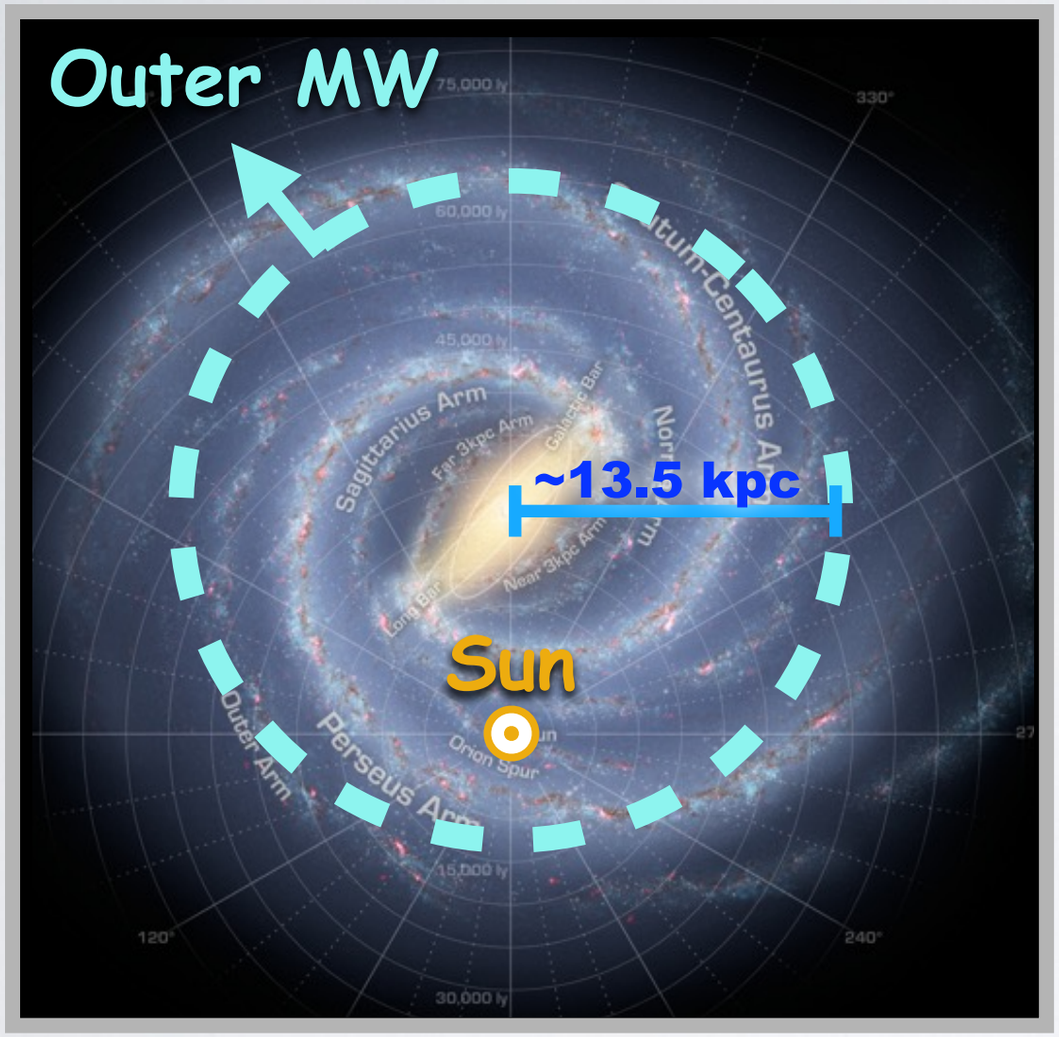


- Lower-metallicity
- Less intense UV fields
- Smaller cosmic-ray flux
- …

I. INTRODUCTION

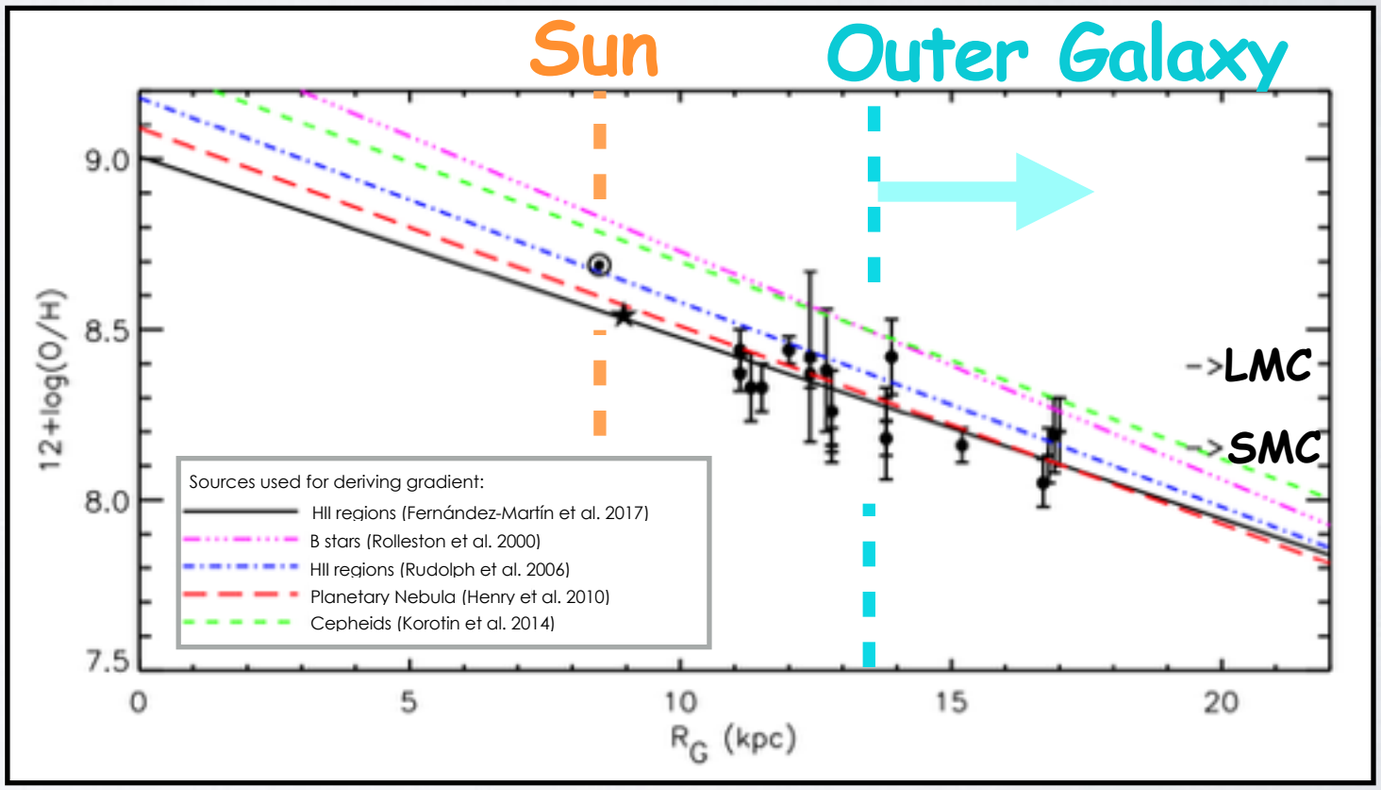
❖ Outer Galaxy

- **Different environment from the inner disk**



- Lower gas density (HI dominant)
- **Lower-metallicity**

Fernámdez-Martín et al. 2017



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- Smaller cosmic-ray flux
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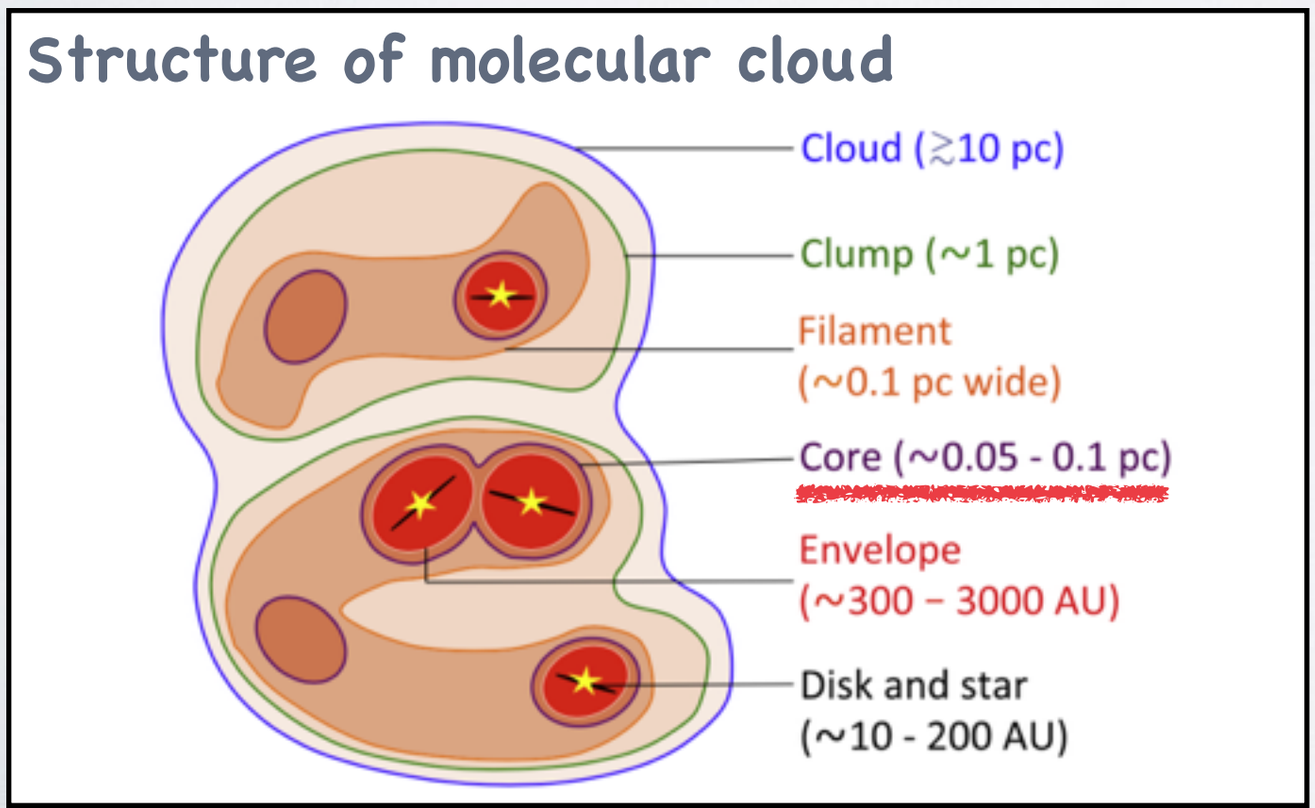
1. INTRODUCTION

❖ Why are we interested in the outer MW ?

- **Excellent laboratory** for studying star-forming processes in **low-density and low-metallicity environment**
- **Similar characteristics** with **dwarf galaxy and the early phase of the formation of our Galaxy**
  - In particular, **in the Thick disk formation** Kobayashi et al. 2008, Ferguson et al, 1998 Buser 2000
  - We may be able to **investigate molecular cloud/star formation activity under such primordial environments in unprecedented detail** at much closer distance than extragalaxies (D ~ 10 kpc)



Using ALMA's high resolution observation, we will be able to investigate in core scale (< 0.1 pc scale) easily !!

Pokhrel et al. 2018

1. INTRODUCTION

❖ Questions

- **Molecular cloud / star formation properties in the outer Galaxy are same with those in the inner disk?**

  → **Molecular cloud/star formation properties are universal or sensitive to the environment ?**

  - Cloud mass function
  - Structure and kinematics of the clouds
  - Stellar initial mass function
  - Star formation rate
  - …

1. INTRODUCTION

❖ Our ALMA studies

- **Investigate the properties of molecular clouds in the outer Galaxy in < ~ 0.1 pc scale(core scale)**

  - Immediate objective

    - **Structure and kinematics of molecular clouds**
    - **Core mass function**
    - ….

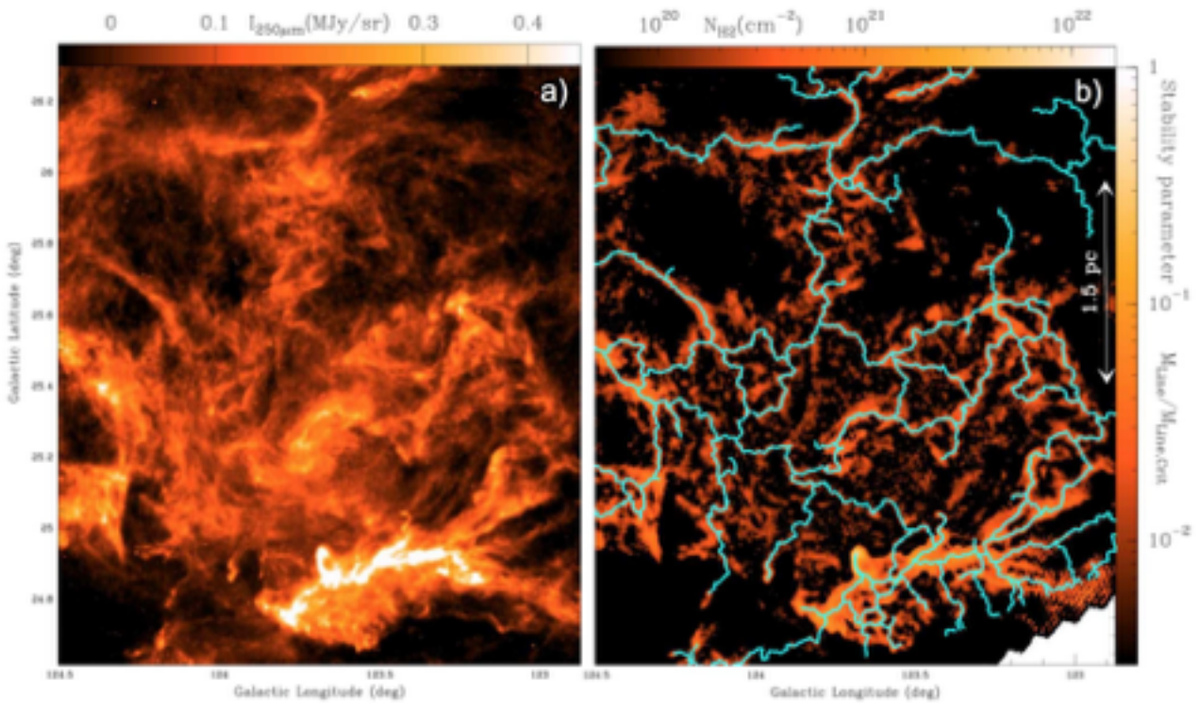
1. INTRODUCTION

❖ ALMA studies in the outer Galaxy

- **Structure and kinematics of molecular clouds**
  - **Past studies: Filamentary structure** (width ~0.1 pc scale, length ~1 pc scale) **is ubiquitous in the star-forming region**

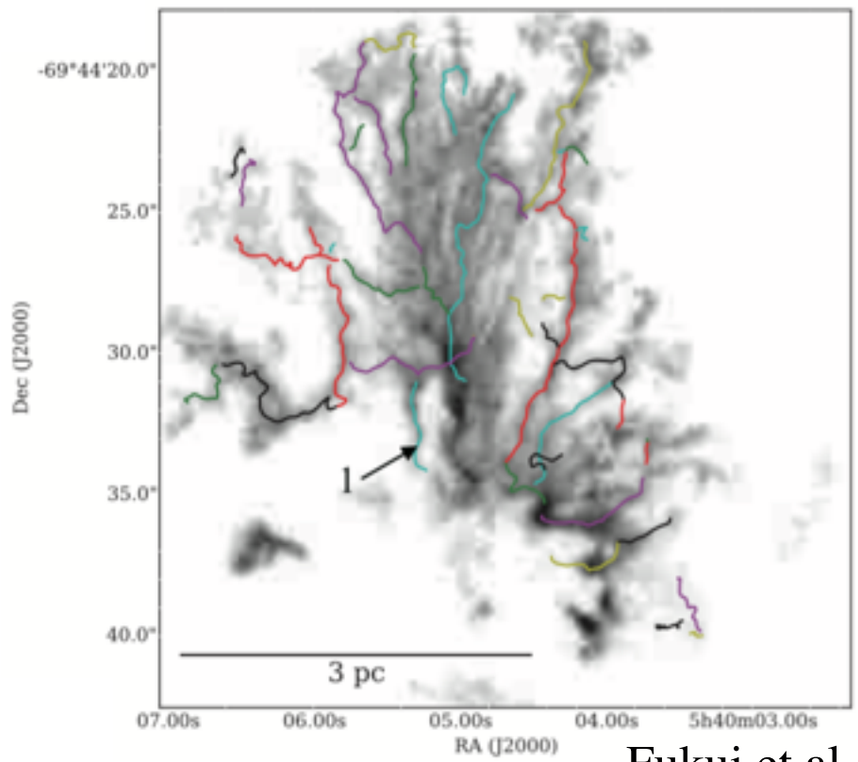
Same structure is seen in the low-metallicity region ??

Solar neighborhood (Herschel/SPIRE 250um)



André et al. 2013

LMC (ALMA/^{13}CO(2-1)



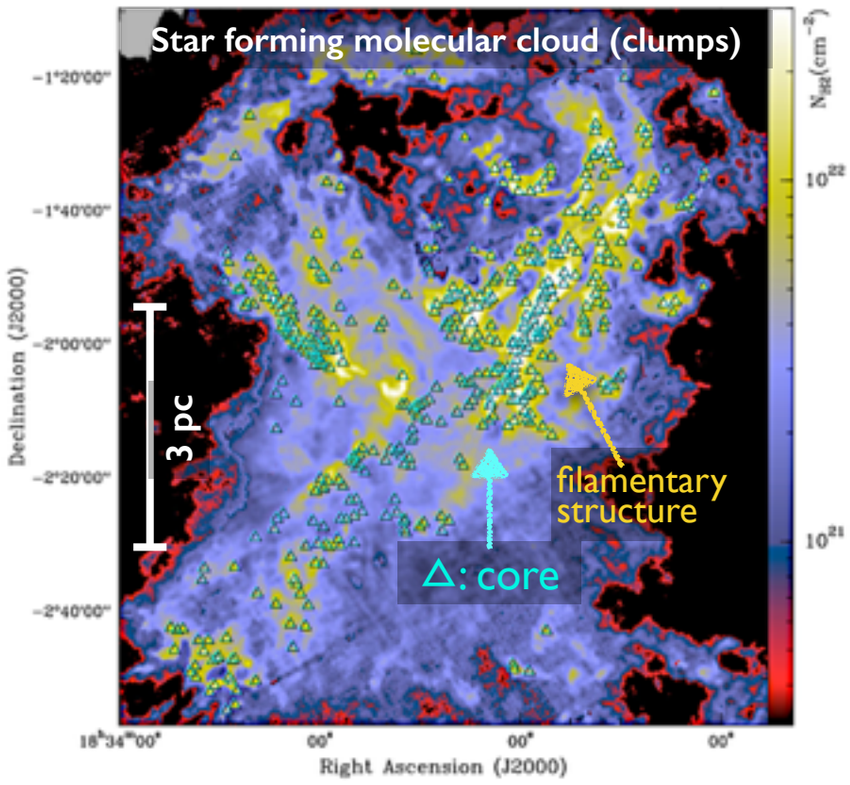
Fukui et al. 2019

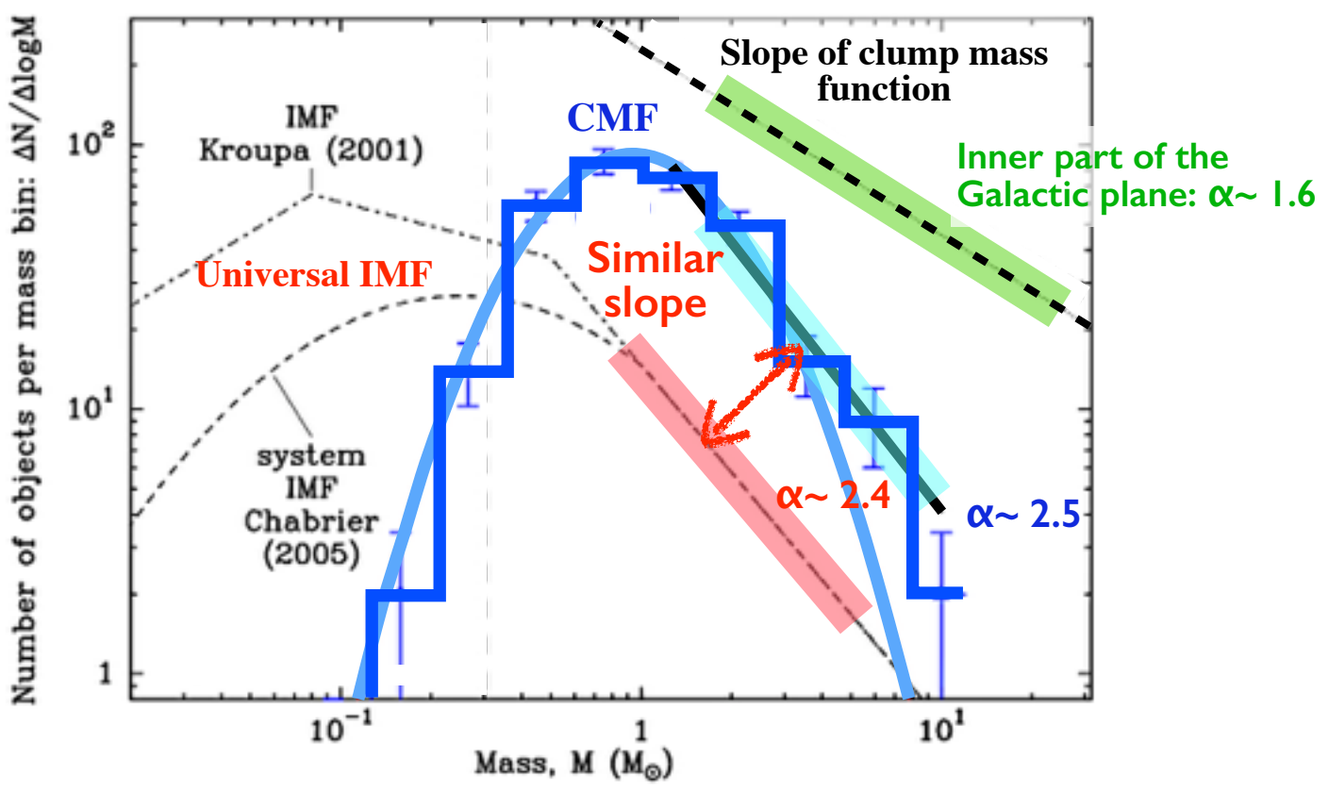
1. INTRODUCTION

❖ ALMA studies in the outer Galaxy

- **Core mass function (CMF)**
  - **Past studies: Slope of CMF and stellar IMF are consistent**
    → **Stellar IMF is predetermined by the form of the CMF ??**

Same relation between CMF and stellar IMF holds true even in low-metallicity environment ??



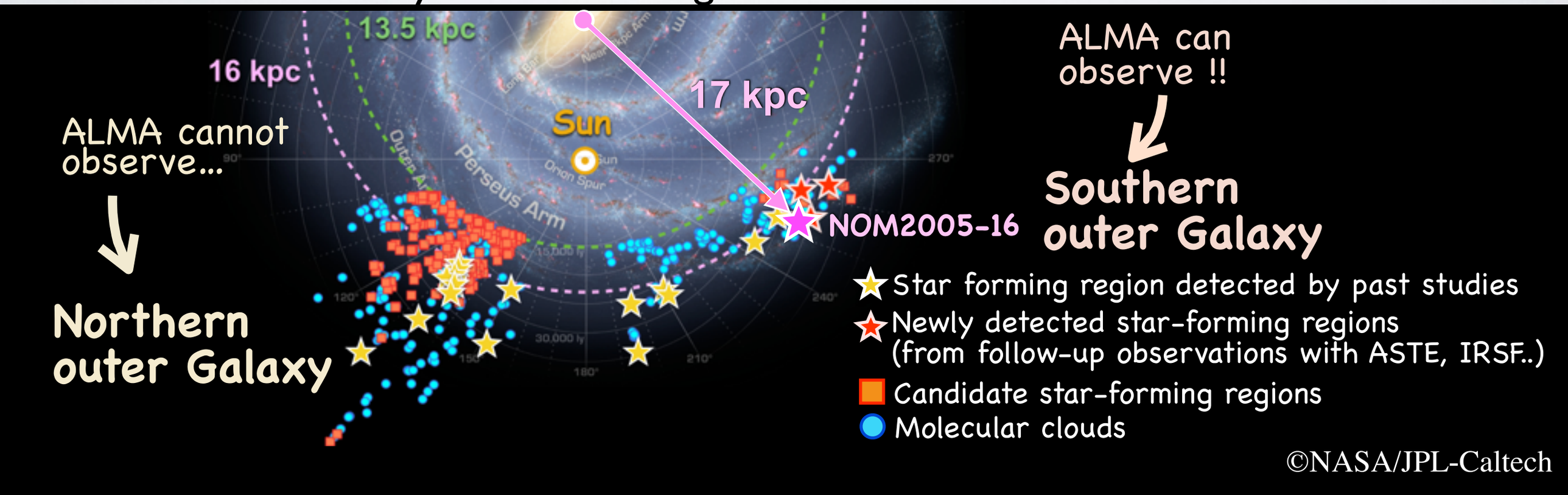


Könyves et al. 2010

2. OBSERVATION

❖ Pilot Observation

- **Target: NOM2005-16** Nakagawa et al. 2005
  - Star-forming region is detected from our observations(with ASTE, IRSF)
    - **~ 10 YSO candidate are detected (massive ~ 2 $M_\odot$)** ← Sensitivity is not enough...
  - R_G = 17.3 kpc (D = 12.8 kpc) ← **~ 1/5 $Z_\odot$ (Similar to SMC)**
  - Located in the Galactic warp (z = 0.71 kpc)
    → prevent disturbance by contamination by foreground source
  - Mass ~ 10^4 $M_\odot$, Density ≧ ~ 10^4 cm^{-3}
    → likely contains a large number of dense cores



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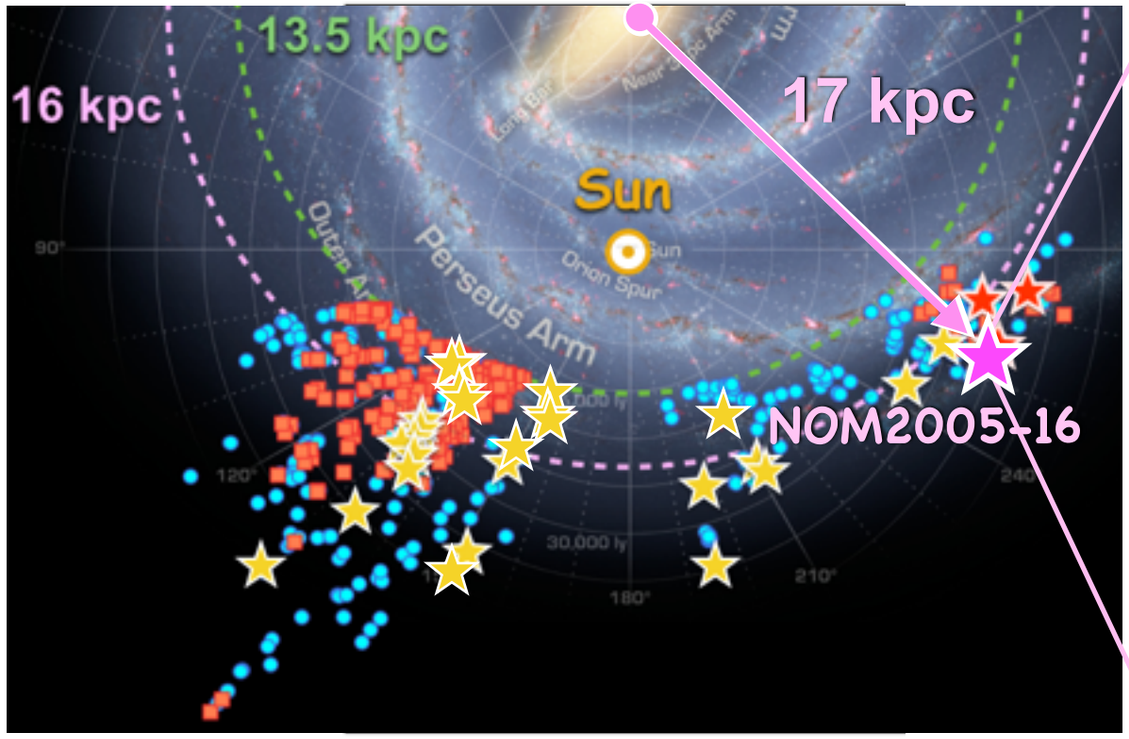
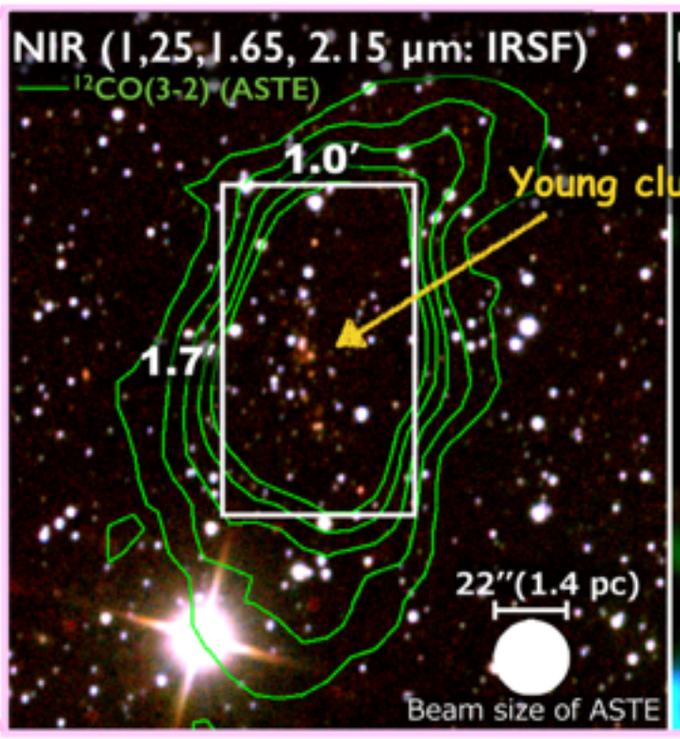
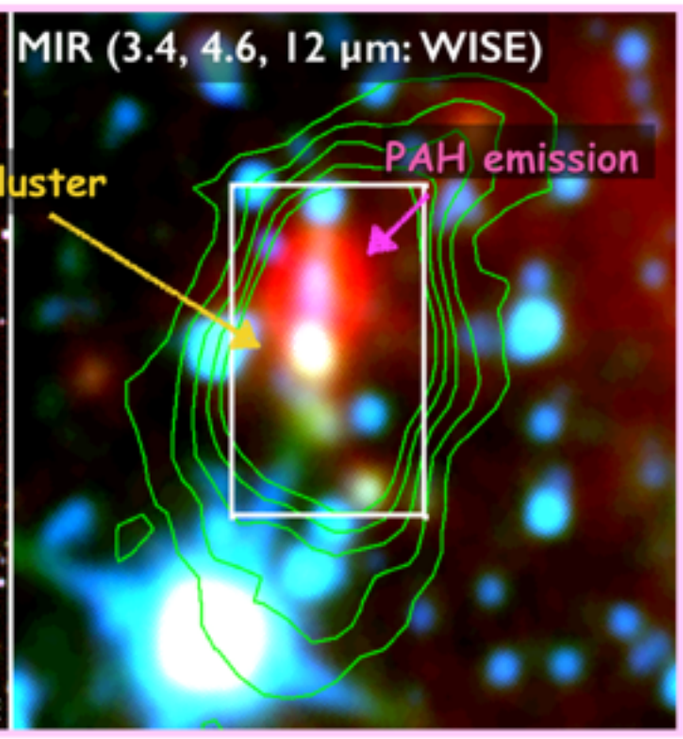
2. OBSERVATION

❖ Pilot Observation

- **Parameters**
  - Angular resolution: 1.5” (~ 0.09 pc)
  - Velocity resolution: ~ 0.1 km/s
  - Mapping size: 1.0’ × 1.7’ (~ 3.7 pc × 6.3 pc)
  - Spectral setup (Band3 and Band6): CO, H_2CO, CS lines…, 1mm and 3mm continuum
  - Antenna: 12m, ACA, TP (TP for only Band6)

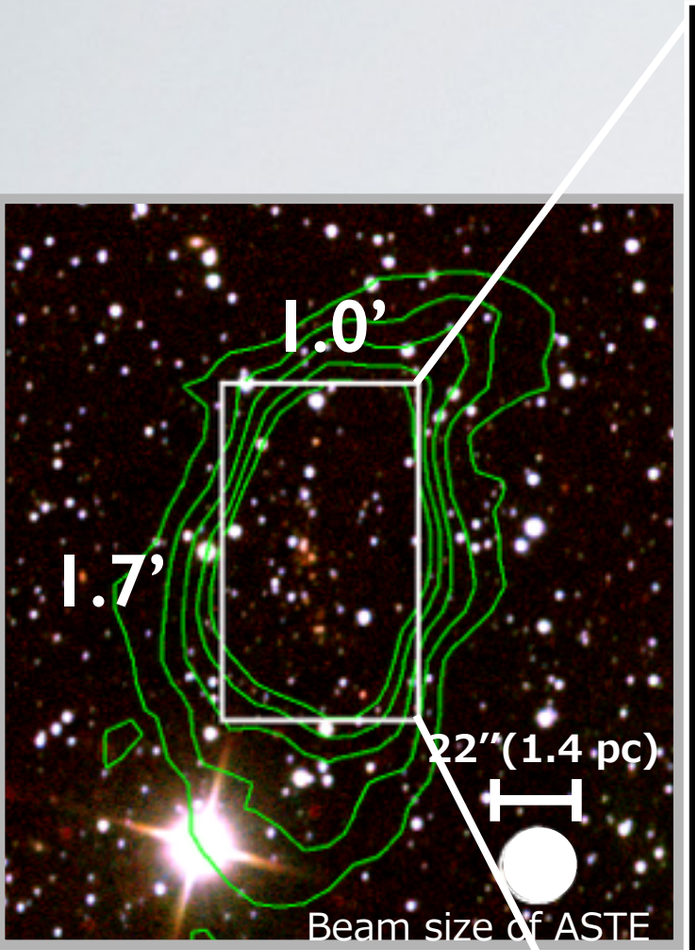


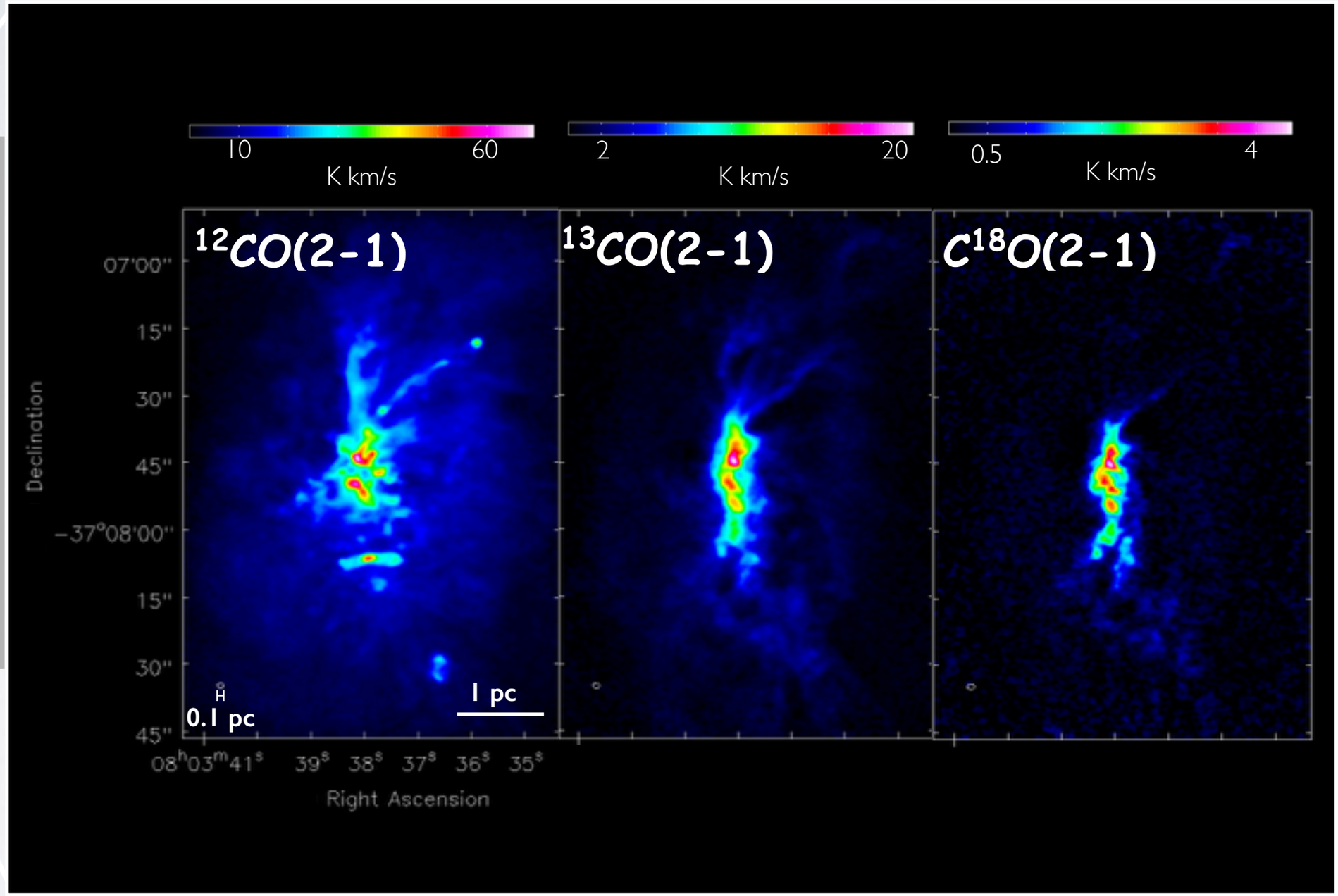




3. RESULT

❖ CO moment 0 map

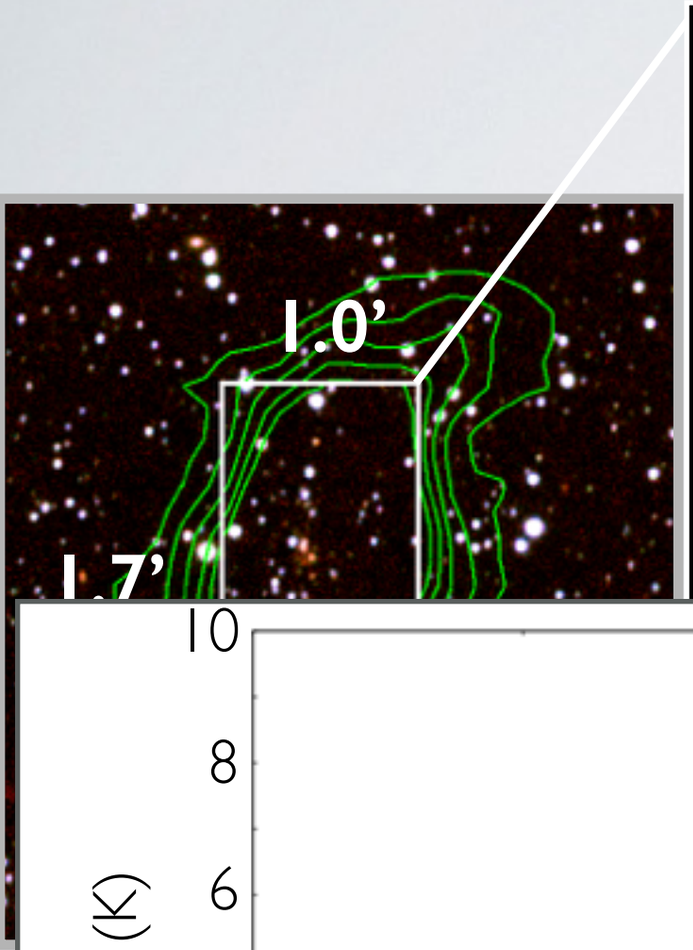


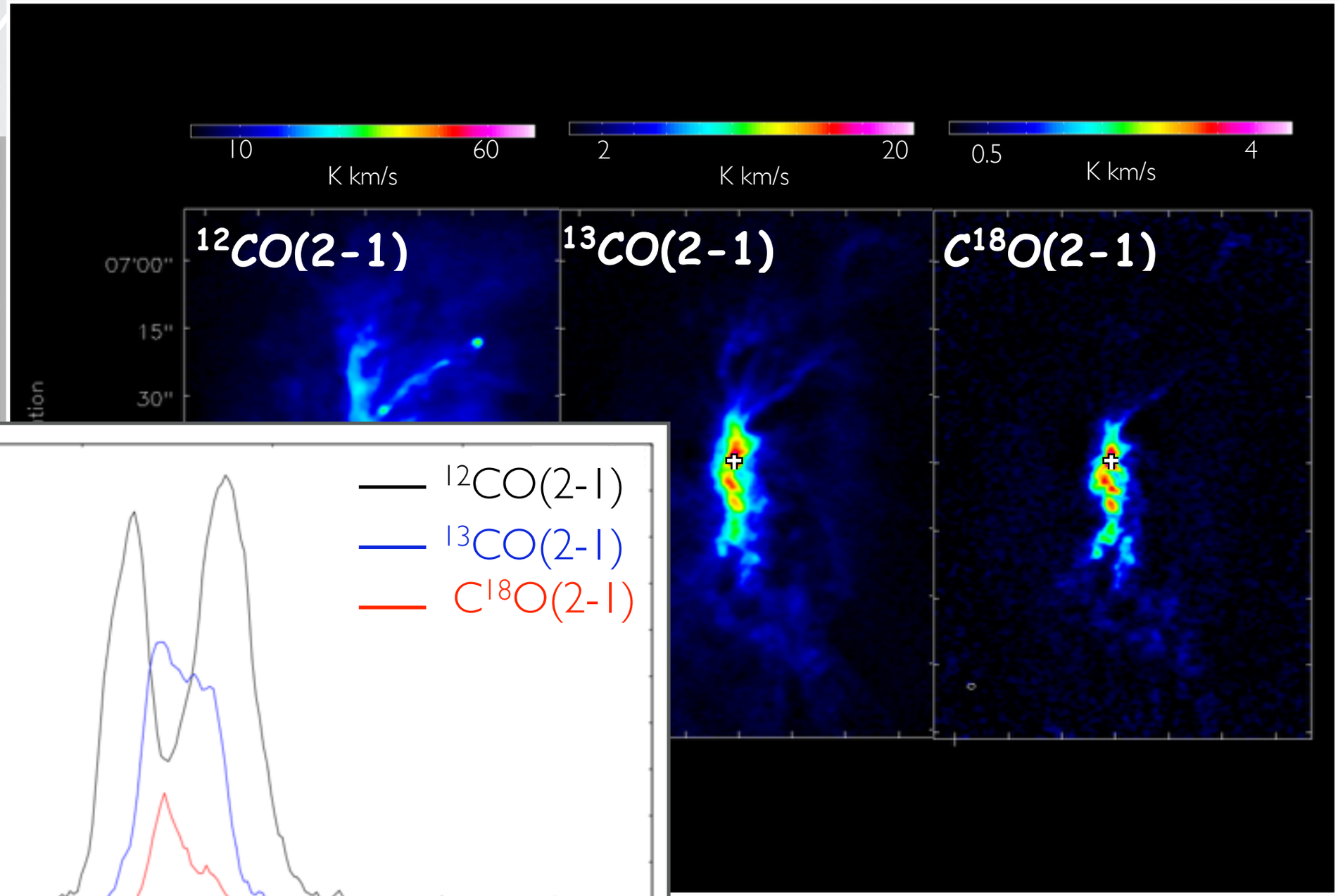


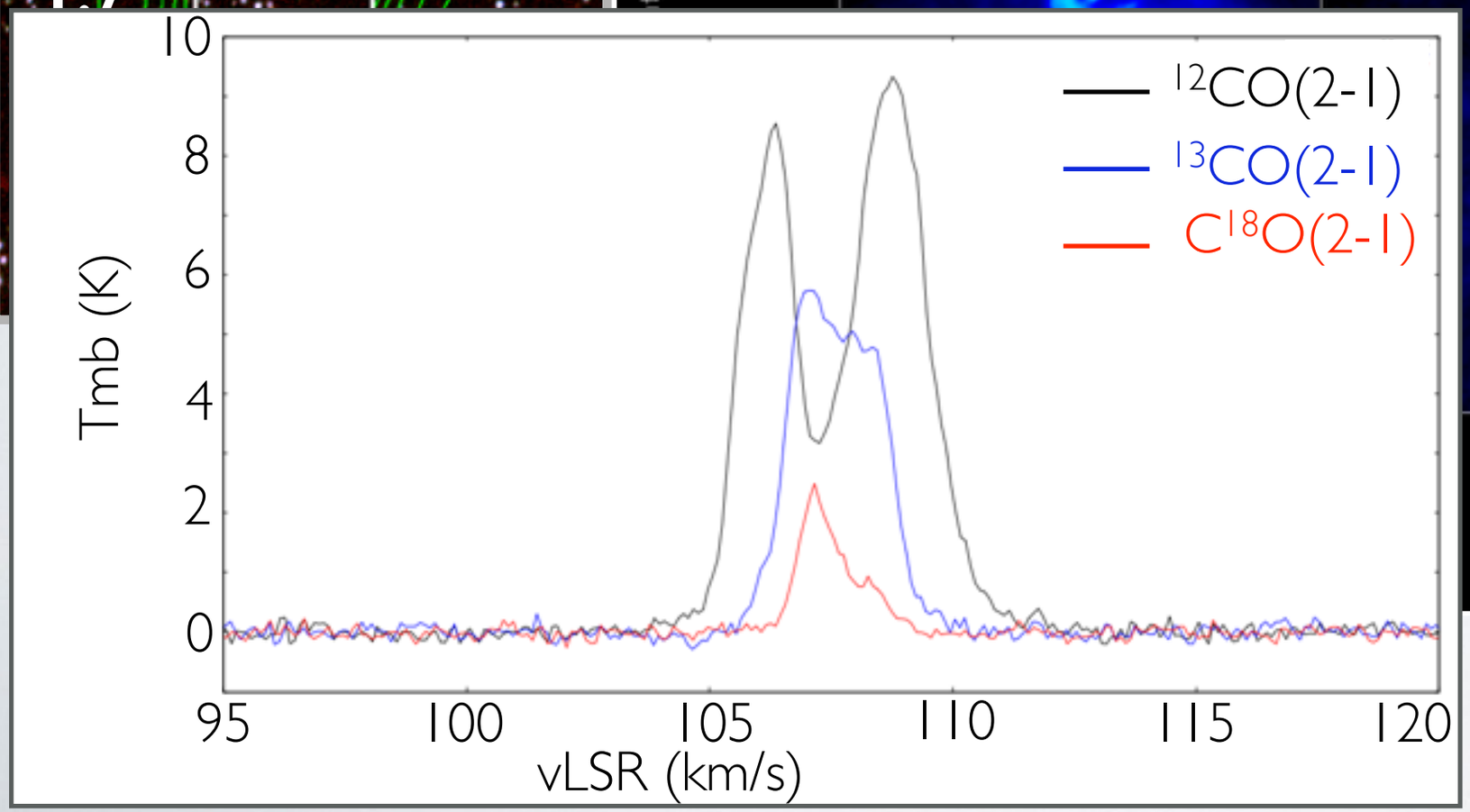
- CO emission lines are clearly detected
- Several structures (filament, core, outflow….) are detected

3. RESULT

- CO moment 0 map



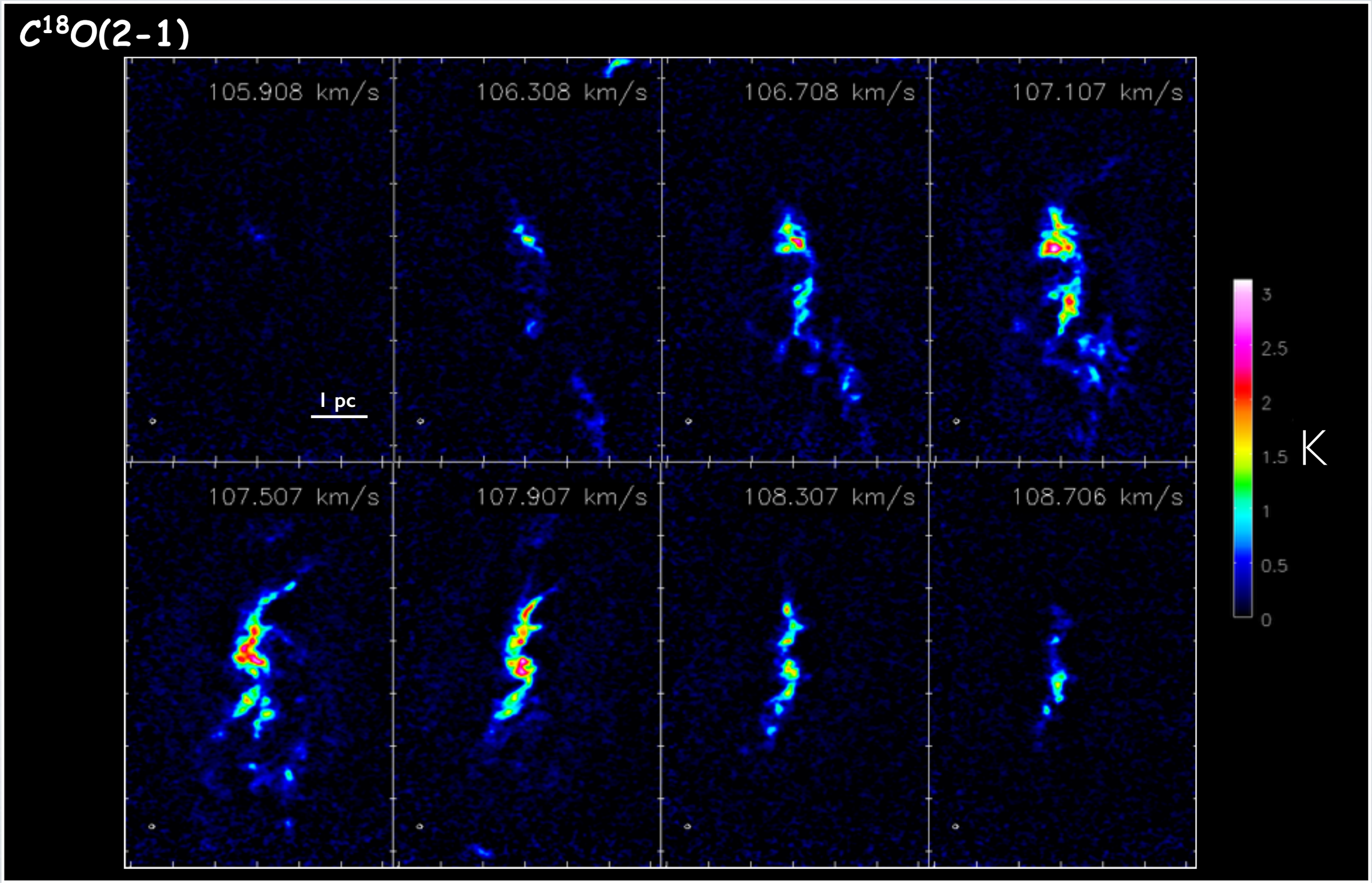




- Strong self-absorption at ^{12}CO emission

4. DISCUSSION

- Core and Filament structure



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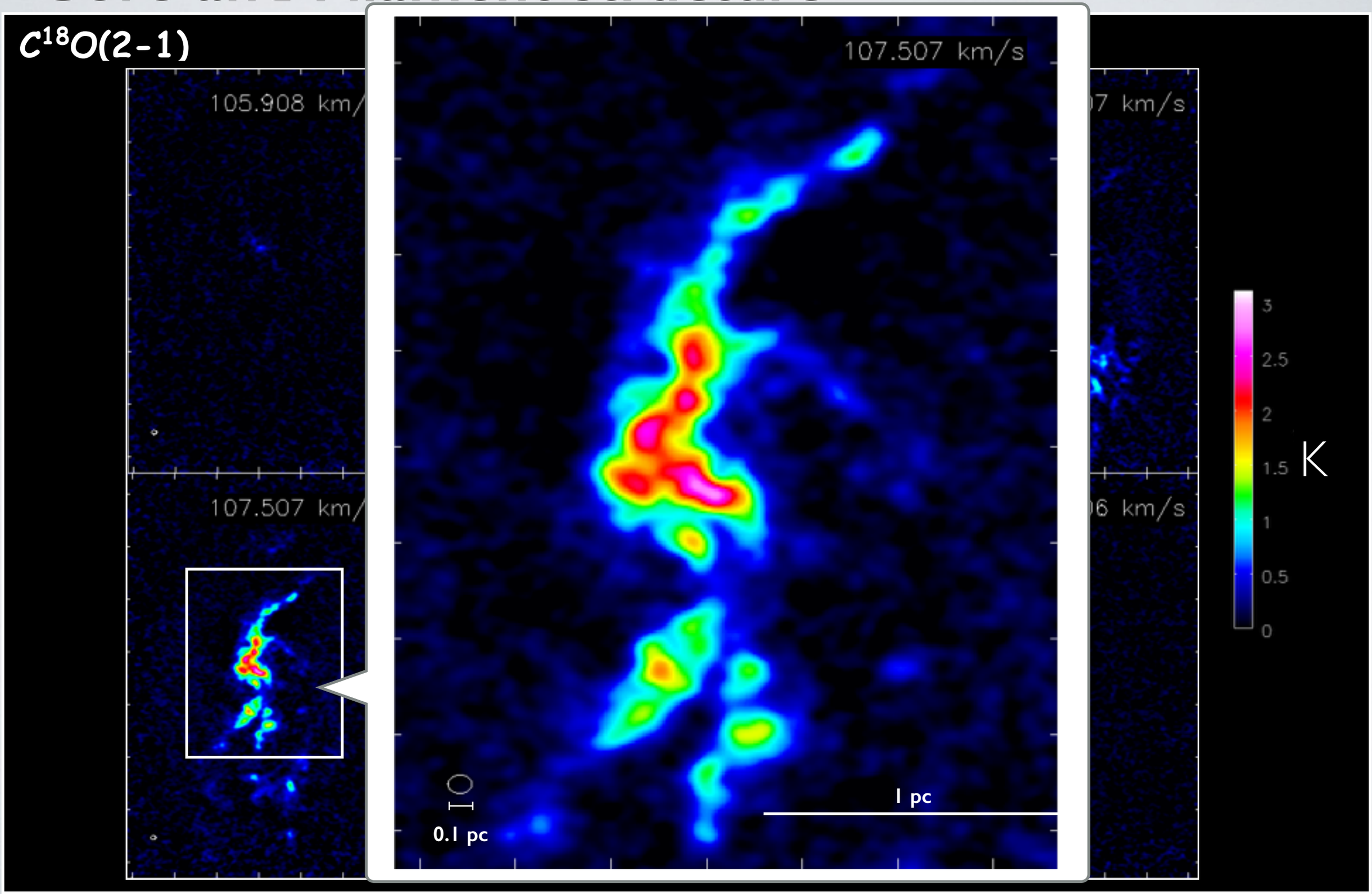
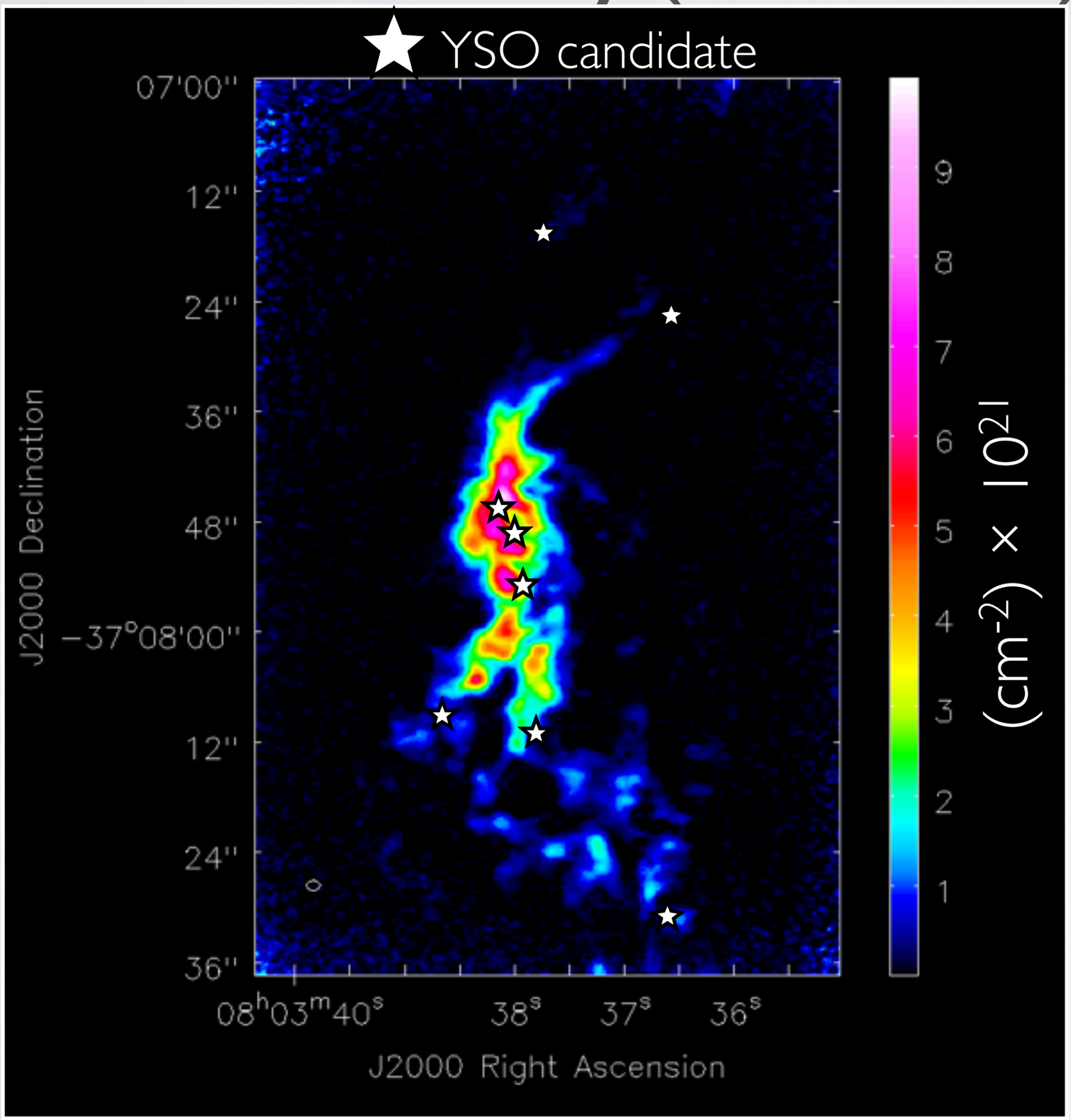


4. DISCUSSION

❖ H_2 column density (from $C^{18}O$)



- LTE assumption
  - Tex derived from ^{12}CO
- $N(H_2)$: ~ 10^{21} - 10^{22} cm^{-2}

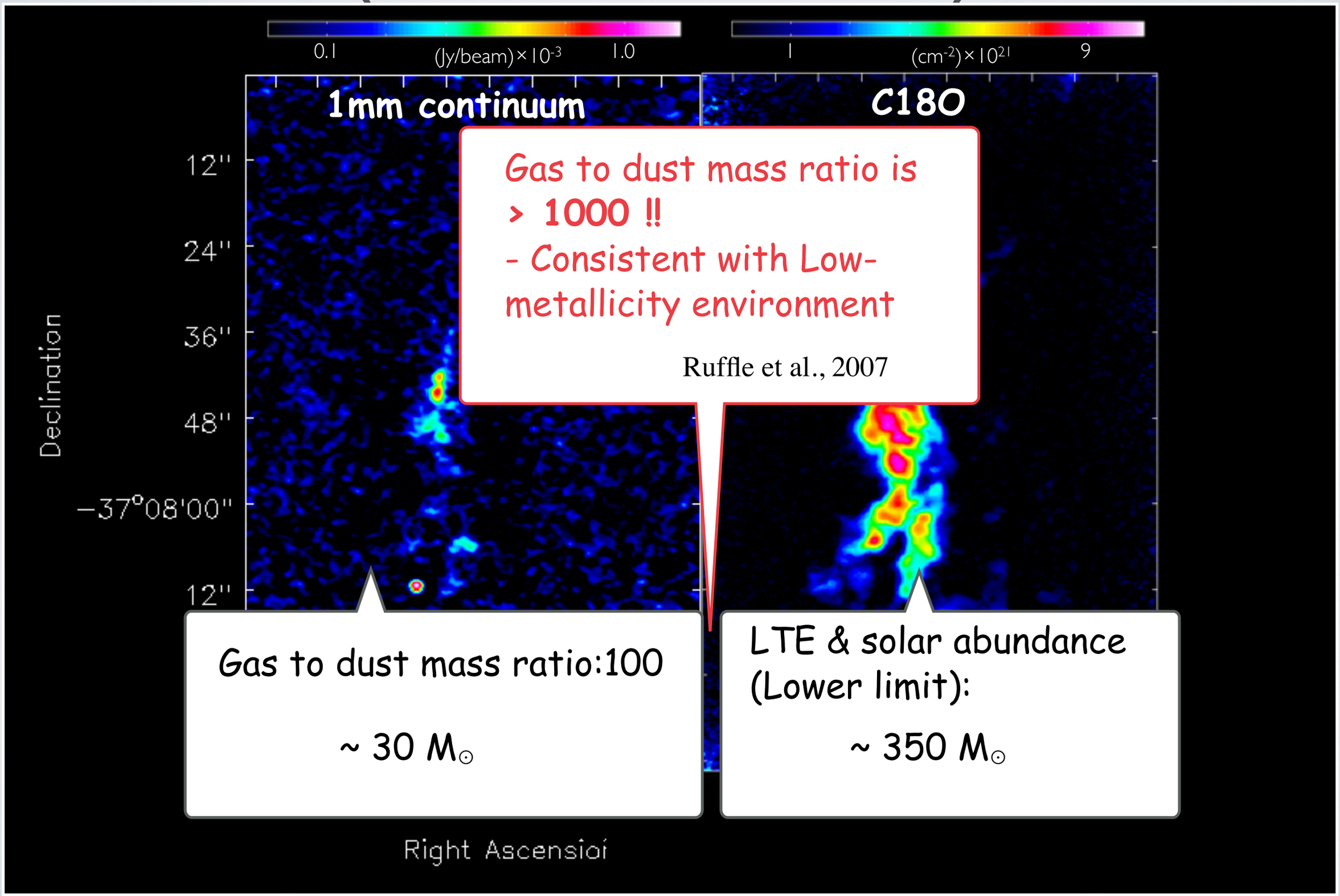
Abundance in the solar neighborhood:
$X(^{13}CO)/X(C^{18}O)$ = 5.5
$X(^{12}CO)/X(^{13}CO)$ = 60
$X(H_2)/X(CO)$ = 10^4

e.g. Langer & Penzias 1993

Lower limit!

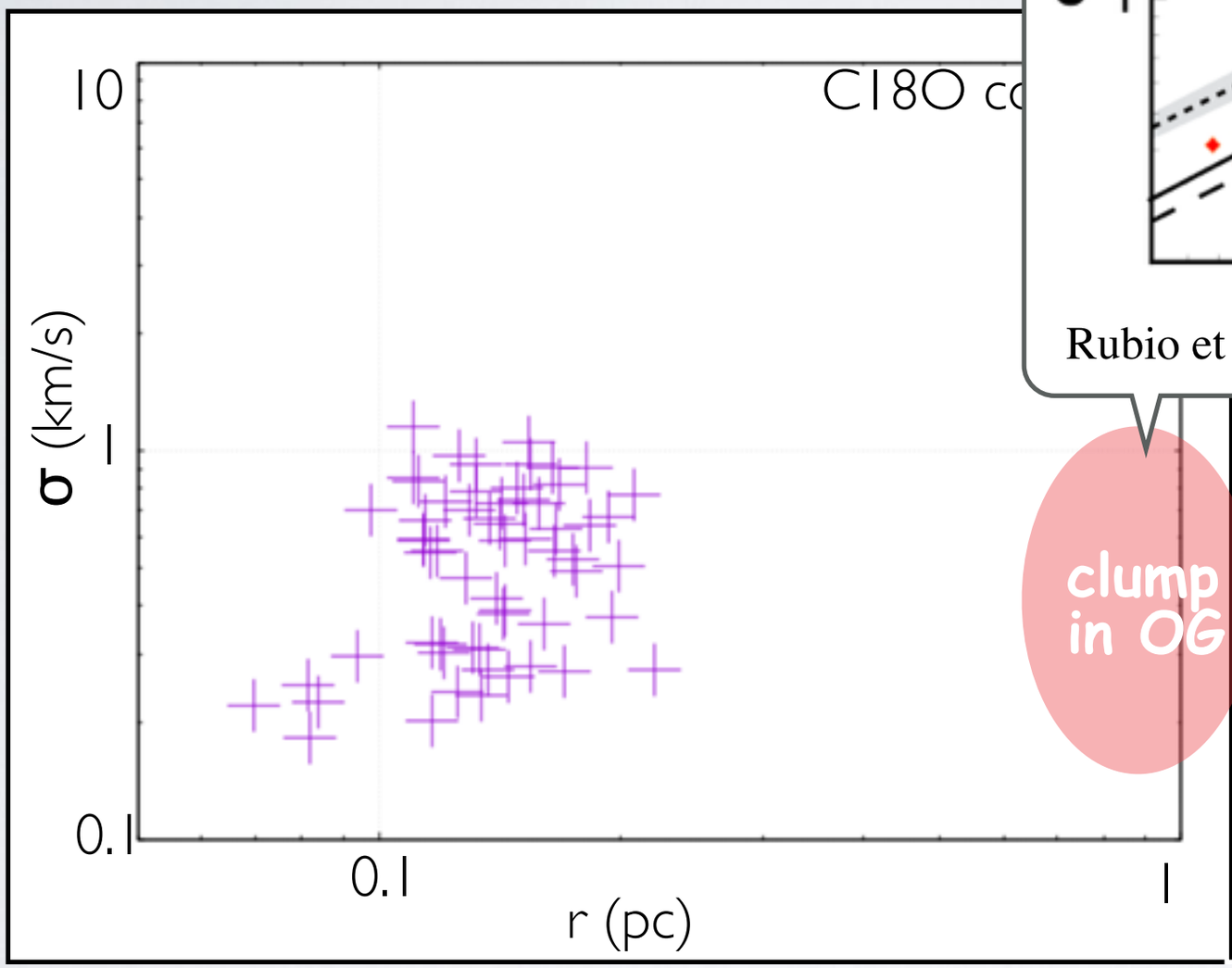
4. DISCUSSION

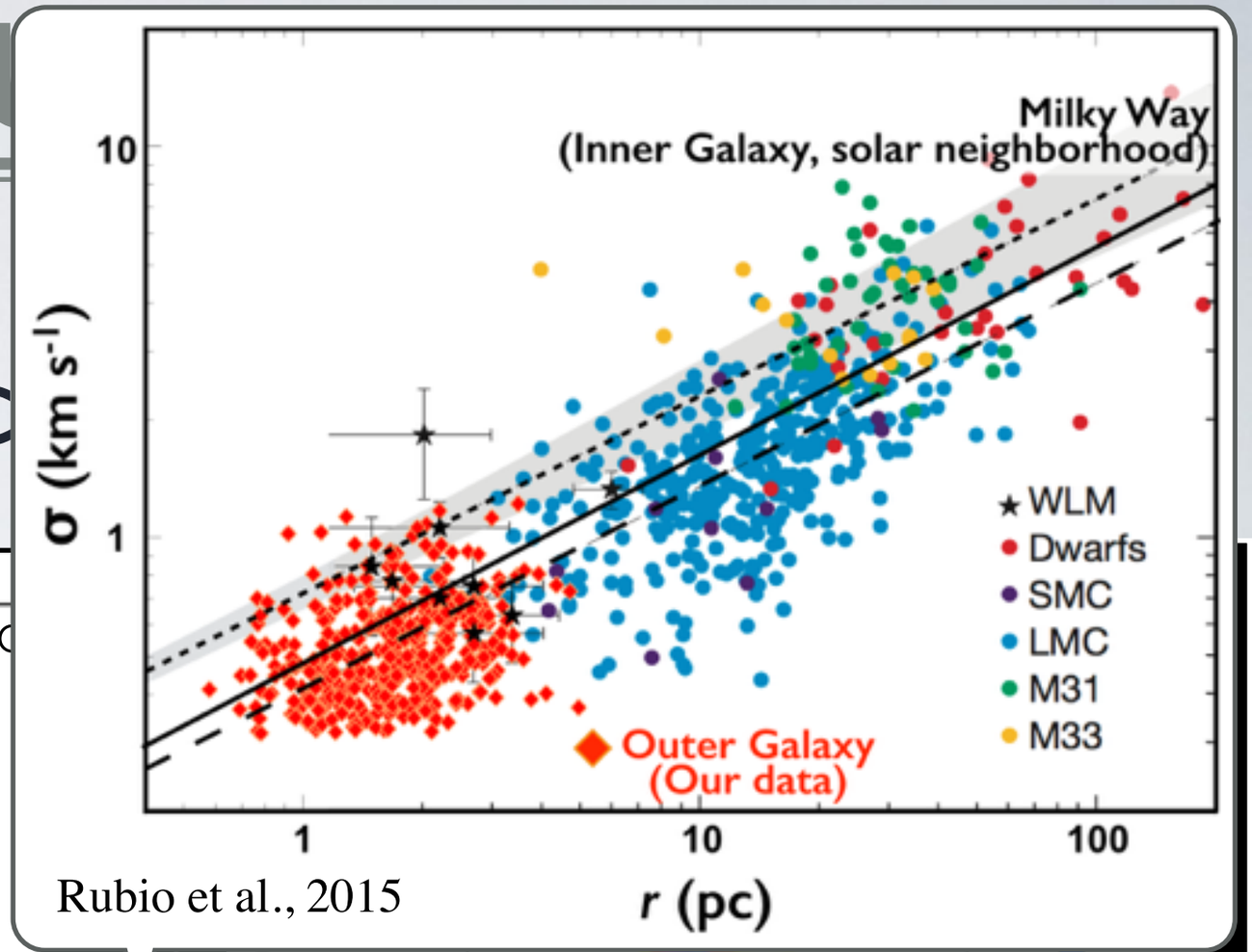
- Total mass (Continuum vs. $C^{18}O$)



4. DISCU

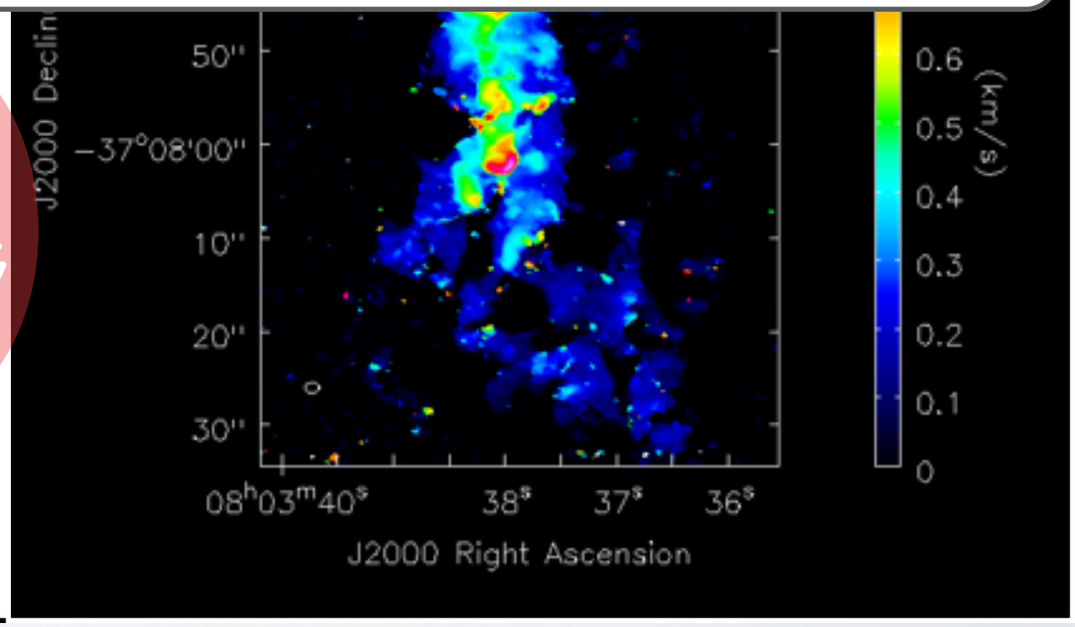
- Larson's law
  - ~ 50 core is detected by C





Rubio et al., 2015

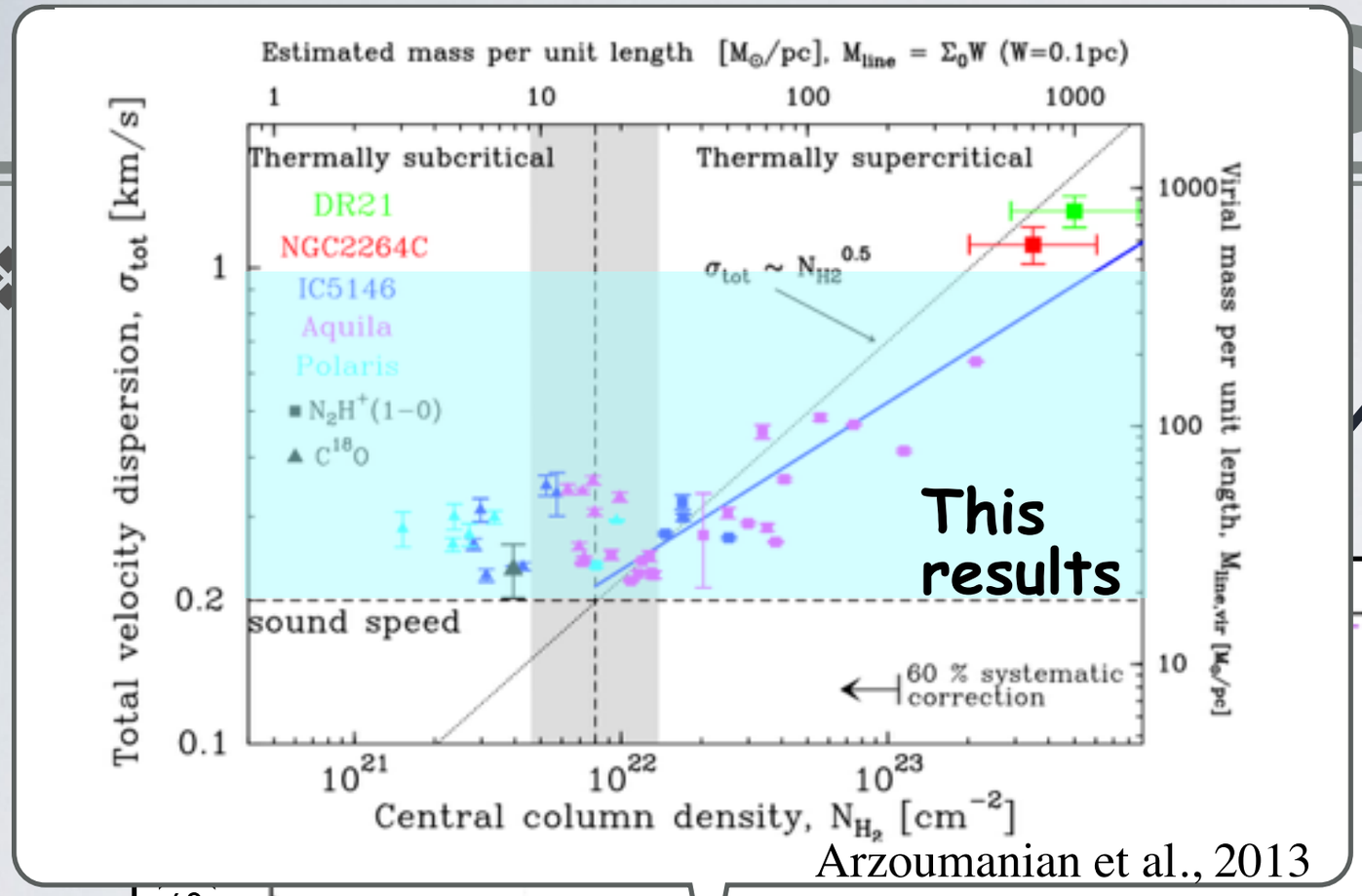
clump in OG



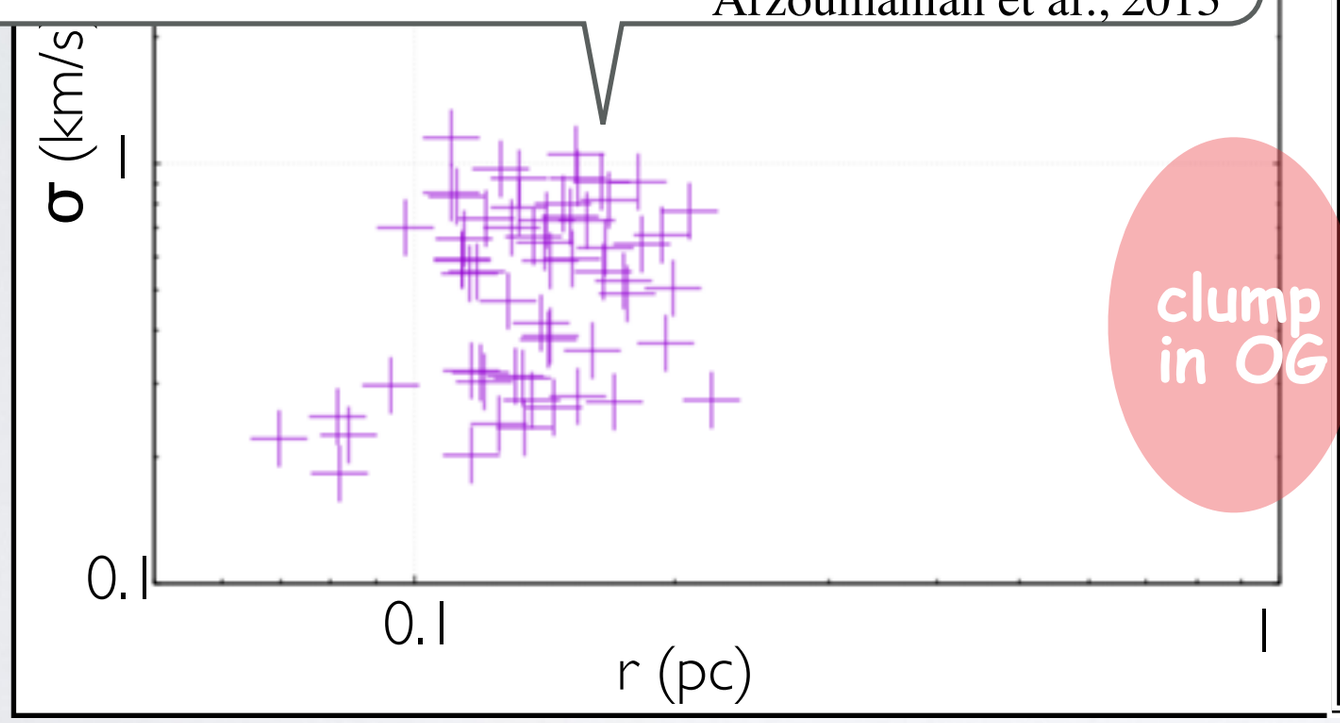
- Velocity dispersion is relatively large..

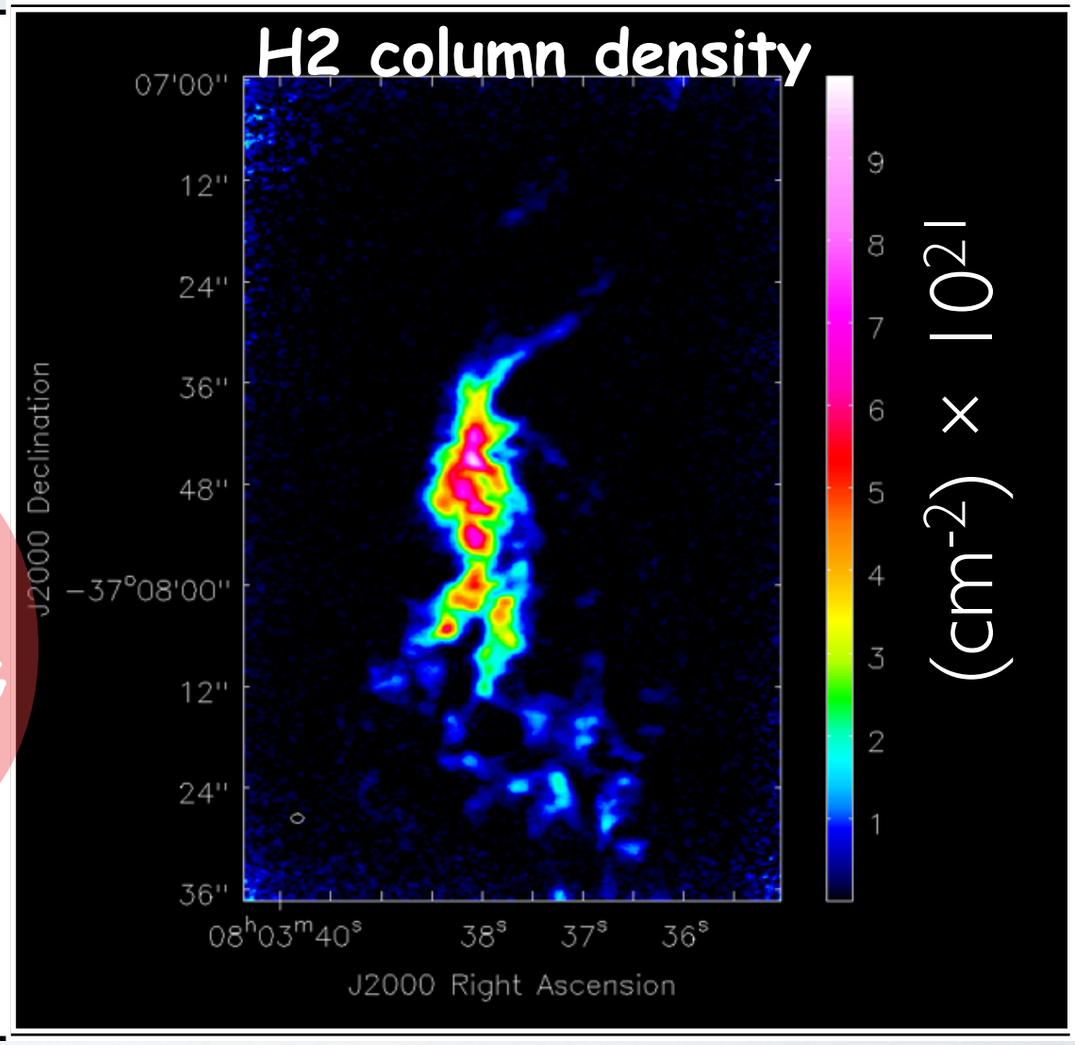
SSION

MPFIND



Arzoumanian et al., 2013

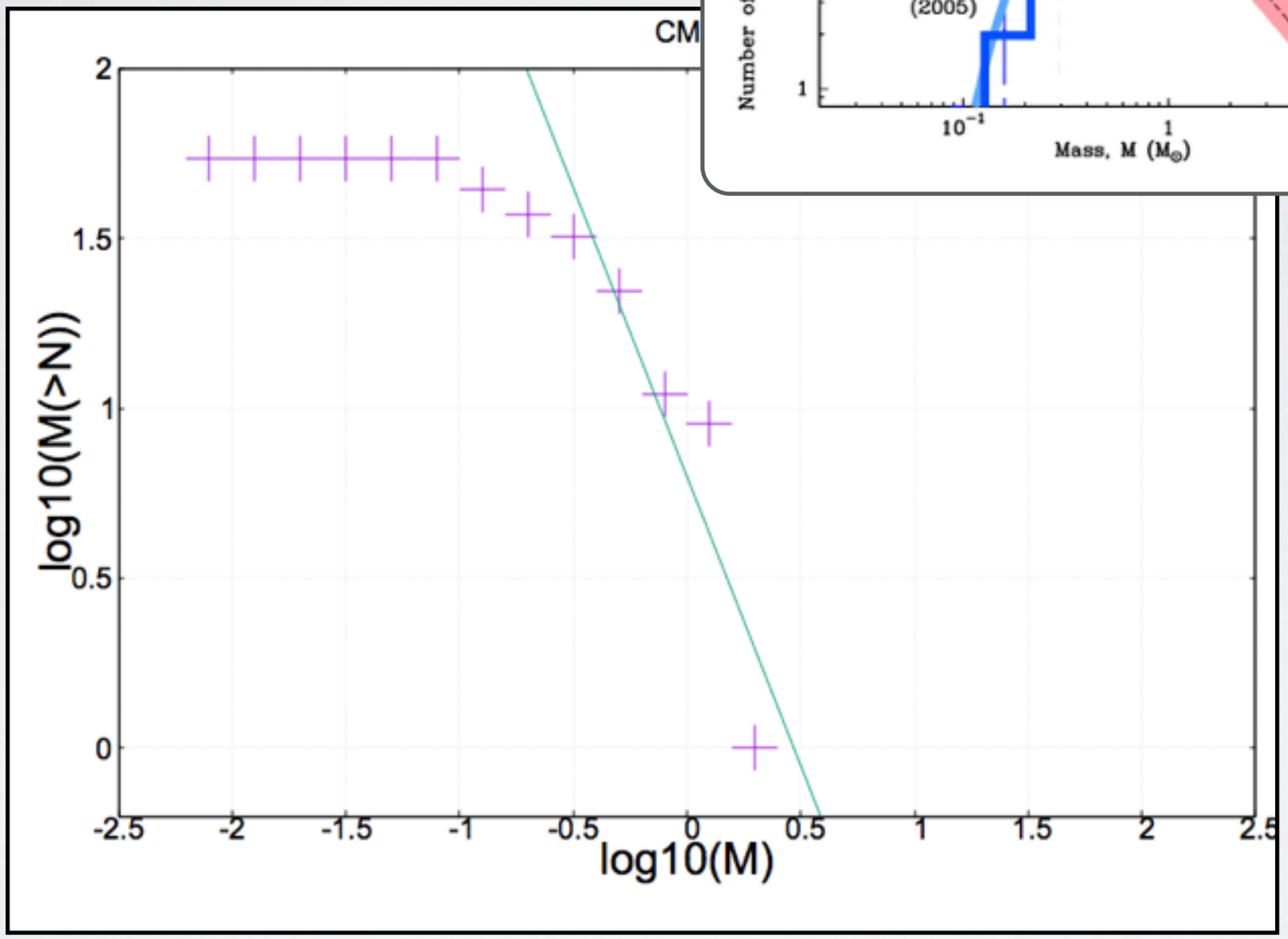


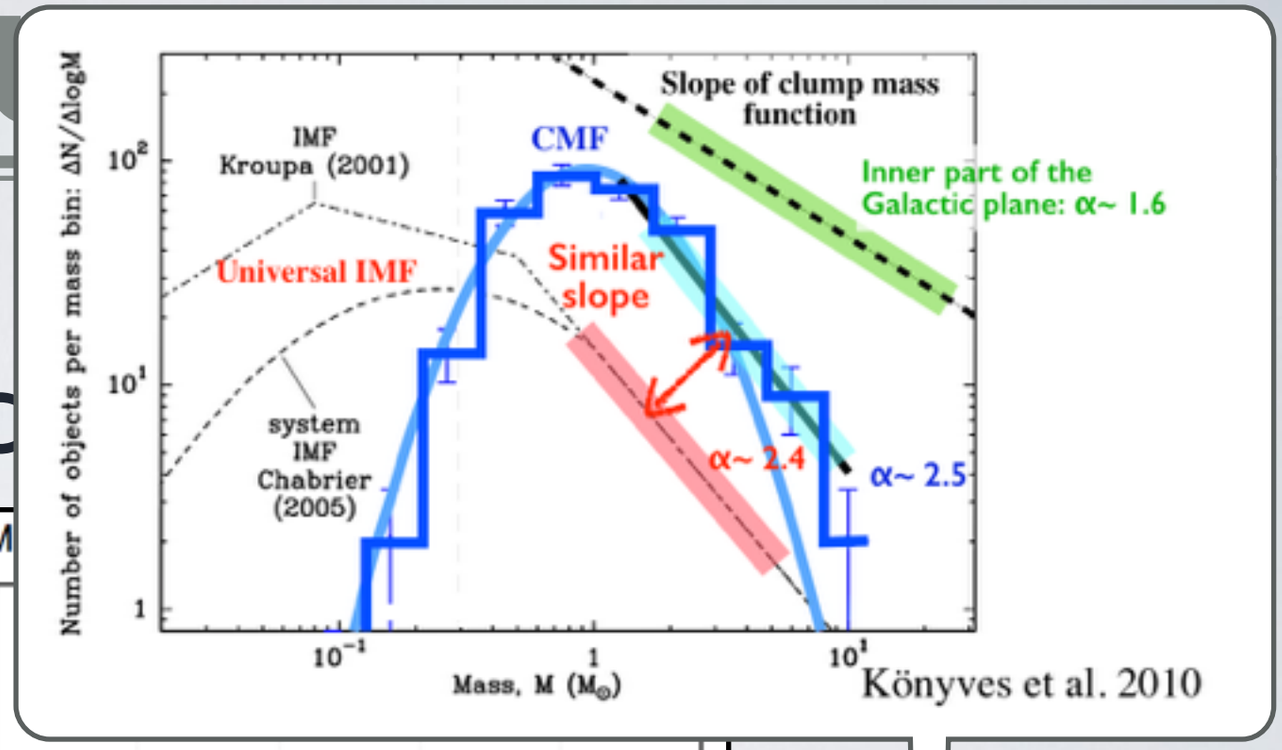


- **Velocity dispersion is relatively large..**

4. DISCU

- Core mass function
  - ~ 50 core is detected by C





- Slope of CMF (α=1.7±0.4) is similar to that of the Saltpetre IMF (α=1.4)

5 SUMMARY & FUTURE WORKS

❖ Summary

- **Outer Galaxy has different environment from that in the inner disk (low-metallicity, low-gas density)**
- **Our ALMA observation for molecular clouds in the outer Galaxy detected same structure with same properties in that in the inner disk (filamentary structure, core structure, outflow structure,,)**
- **Slope of CMF in the outer Galaxy is similar to that of the Salpeter IMF**

❖ Future plan

- **Derive properties with non-LTE**
- **Follow up observation**
  - **Increase the number of samples (many target are detected)**
  - **Observe disk (infalling motion?) in the outflow structure**
  - **NIR observation with Large telescope**

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