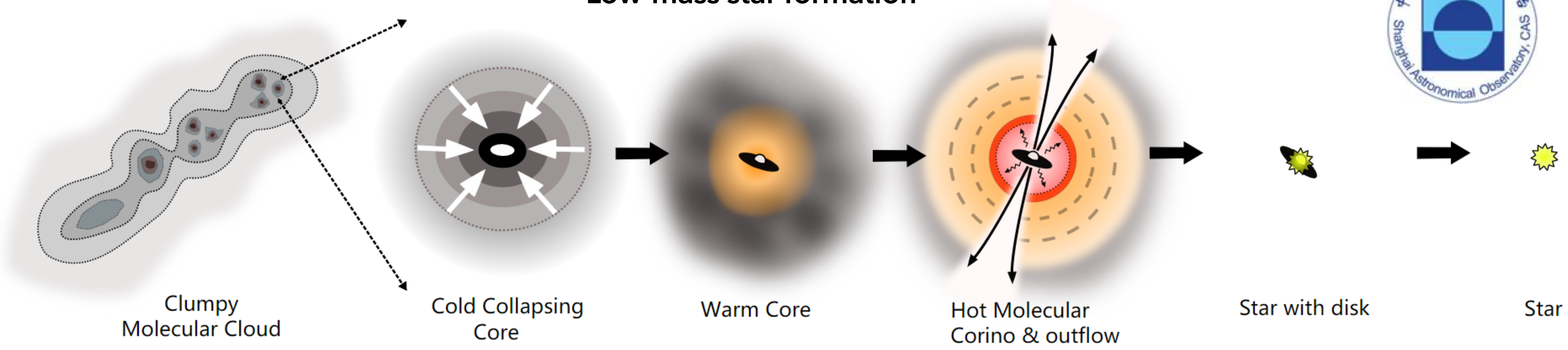
# ALMASOP: The Formation of binary/multiple systems in Orion molecular cloud complex

Shanghai Astronomical Observatory ,Chinese Academy of Science
Qiuyi Luo

lqy@shao.ac.cn

## Low-mass star formation



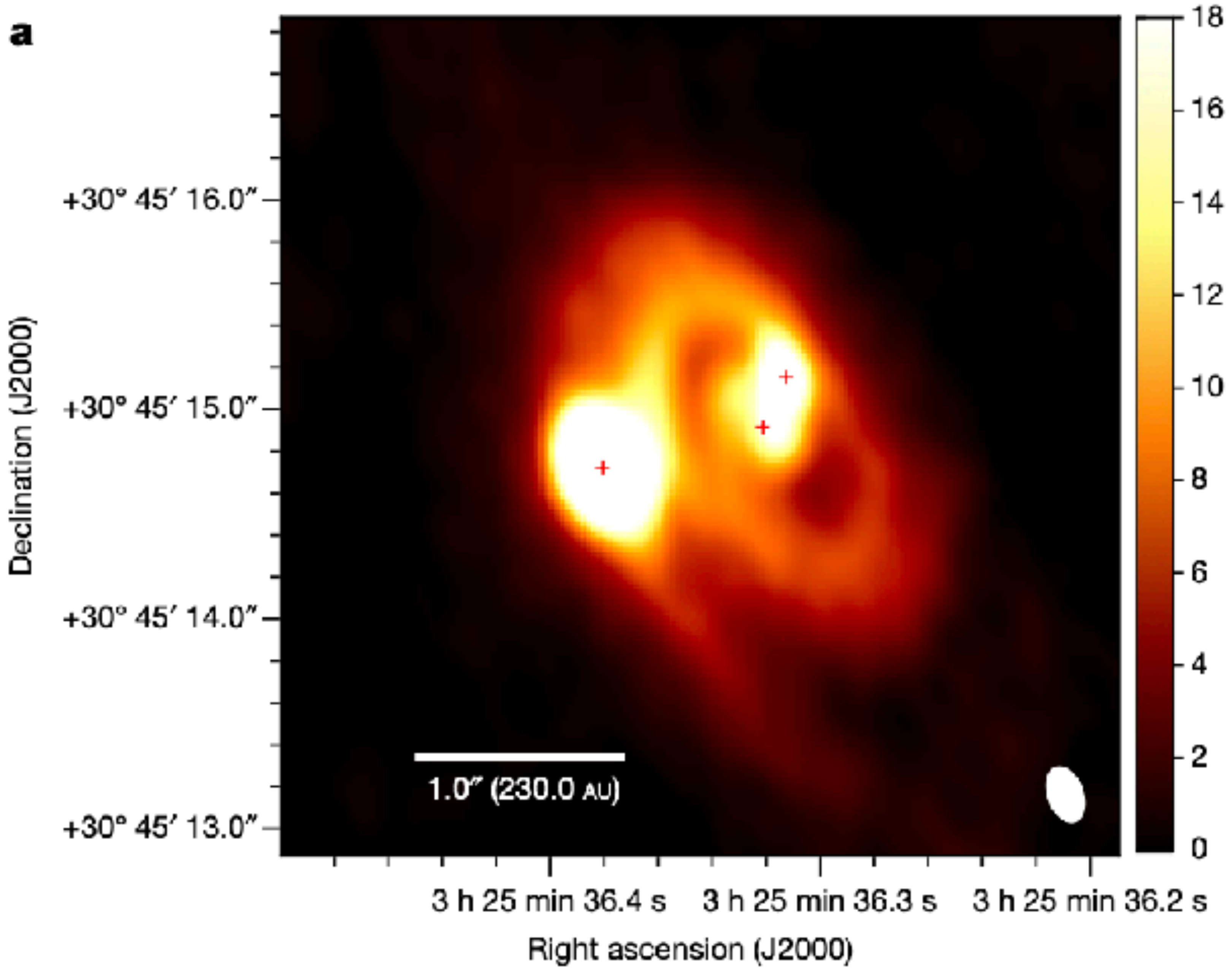

$10 \sim 1$ pc → $\sim 0.1$pc → $\sim 100$au → $\sim 0.01$au

Complex/GMC → Core → Disk → star

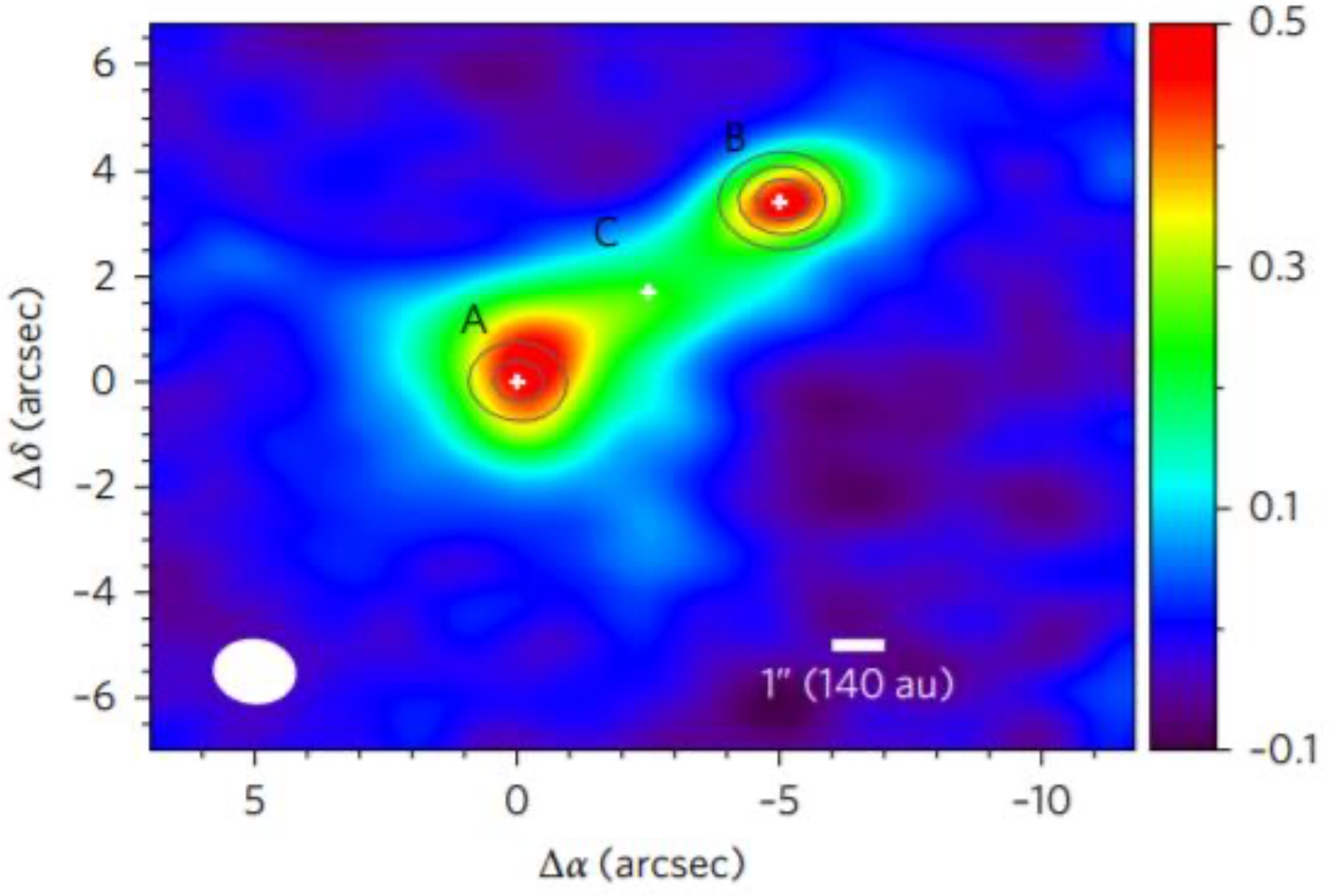
Most of what we know of star formation in detail comes  individual star formation.

How about the formation of binary/multiple system?

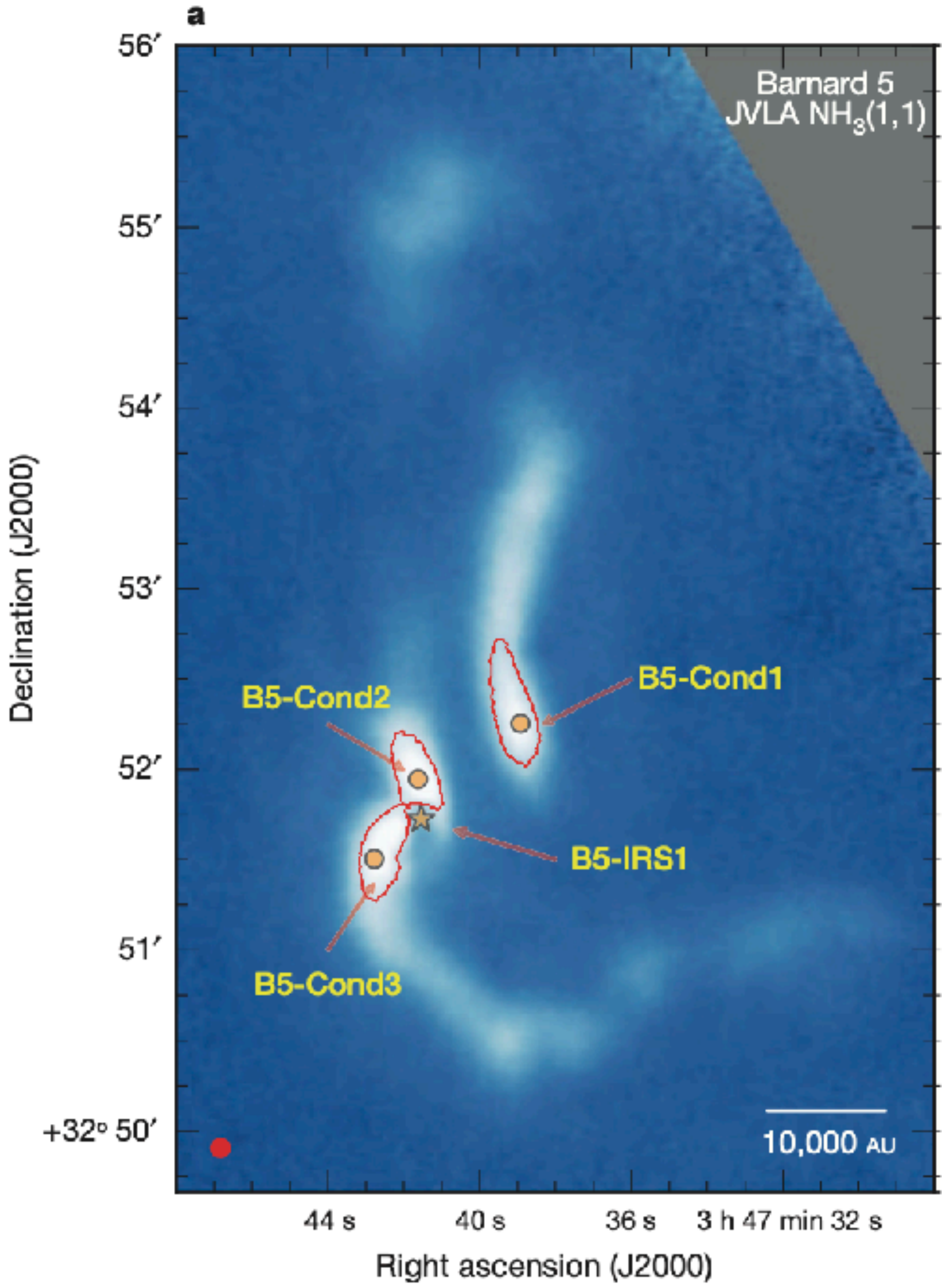
# Binary/Multiple star formation




Tobin et al. 2016



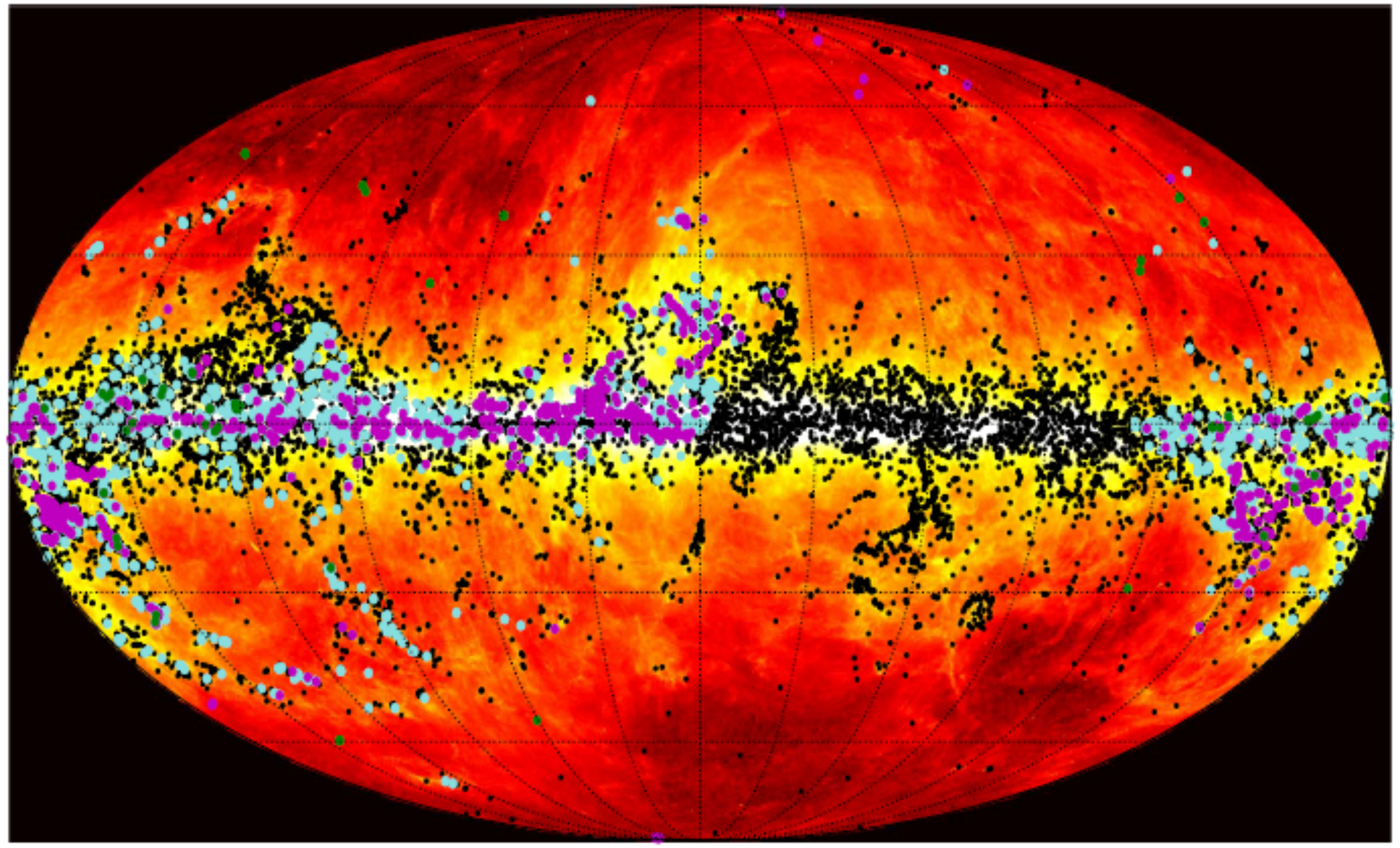

Lee et al. 2016




Pineda et al. 2015

Stellar multiplicity is a ubiquitous phenomena in star formation process, but the origin of stellar multiplicity of protostar is still unclear.

# JCMT SCOPE: SCUBA-2 Continuum Observations of Pre-protostellar Evolution (PI:Tie Liu)



All-sky distribution of the 13188 PGCC sources(black dots) and the 2000 PGCC sources(blue dots) selected for TOP project, and 1000 PGCC sources (magenta dots) selected for SCOPE, overlaid on the 857 GHz Planck map.

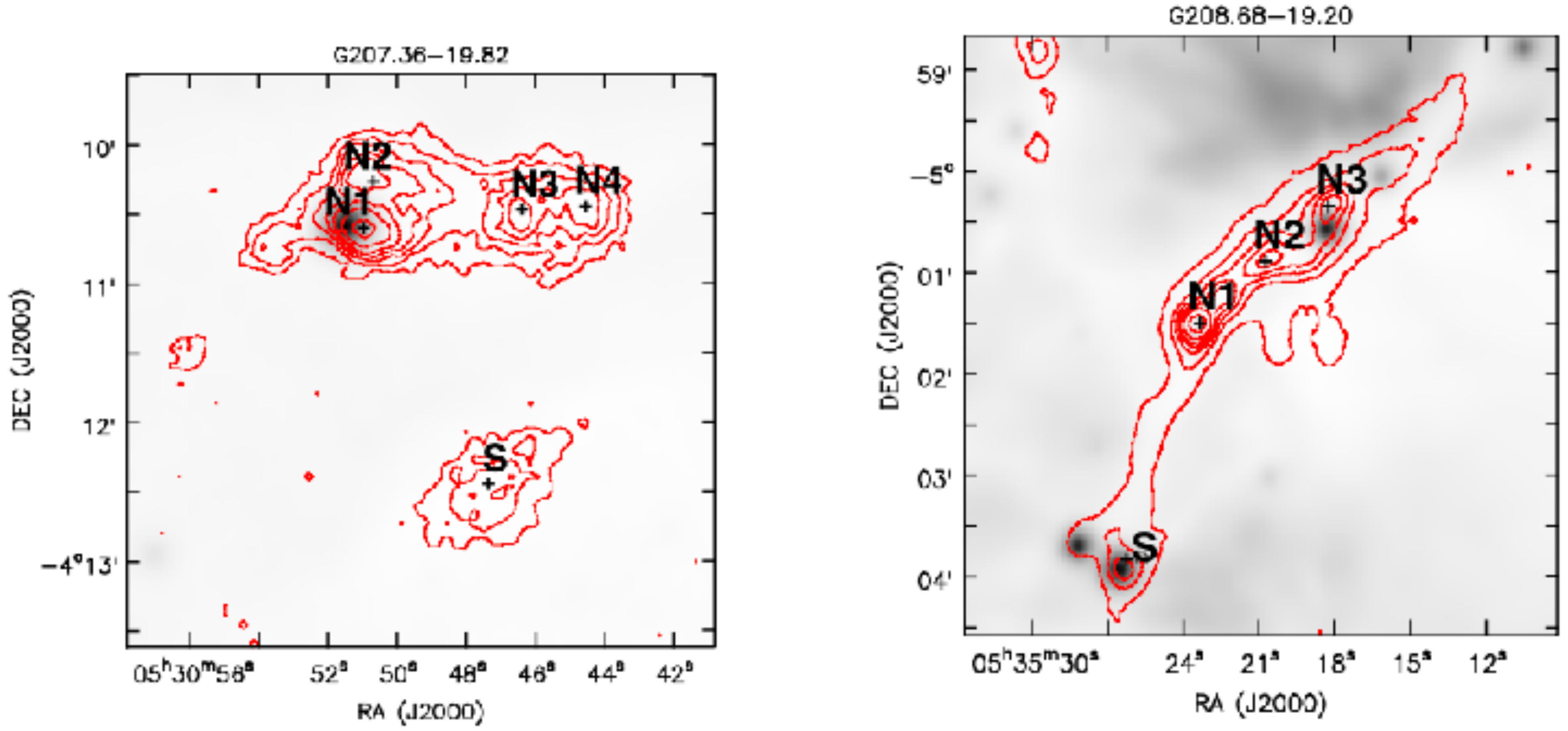
**Liu+ 2018**

Sample : ~ 1300 Planck Galactic Cold Clumps(PGCCs) in 850$\mu m$ continuum

PGCC :Td ~ 14K clumps $N(H_2) > 5 \times 10^{20} cm^{-2}$

Time: ~ 400h

Angular resolution: 14 arcsec



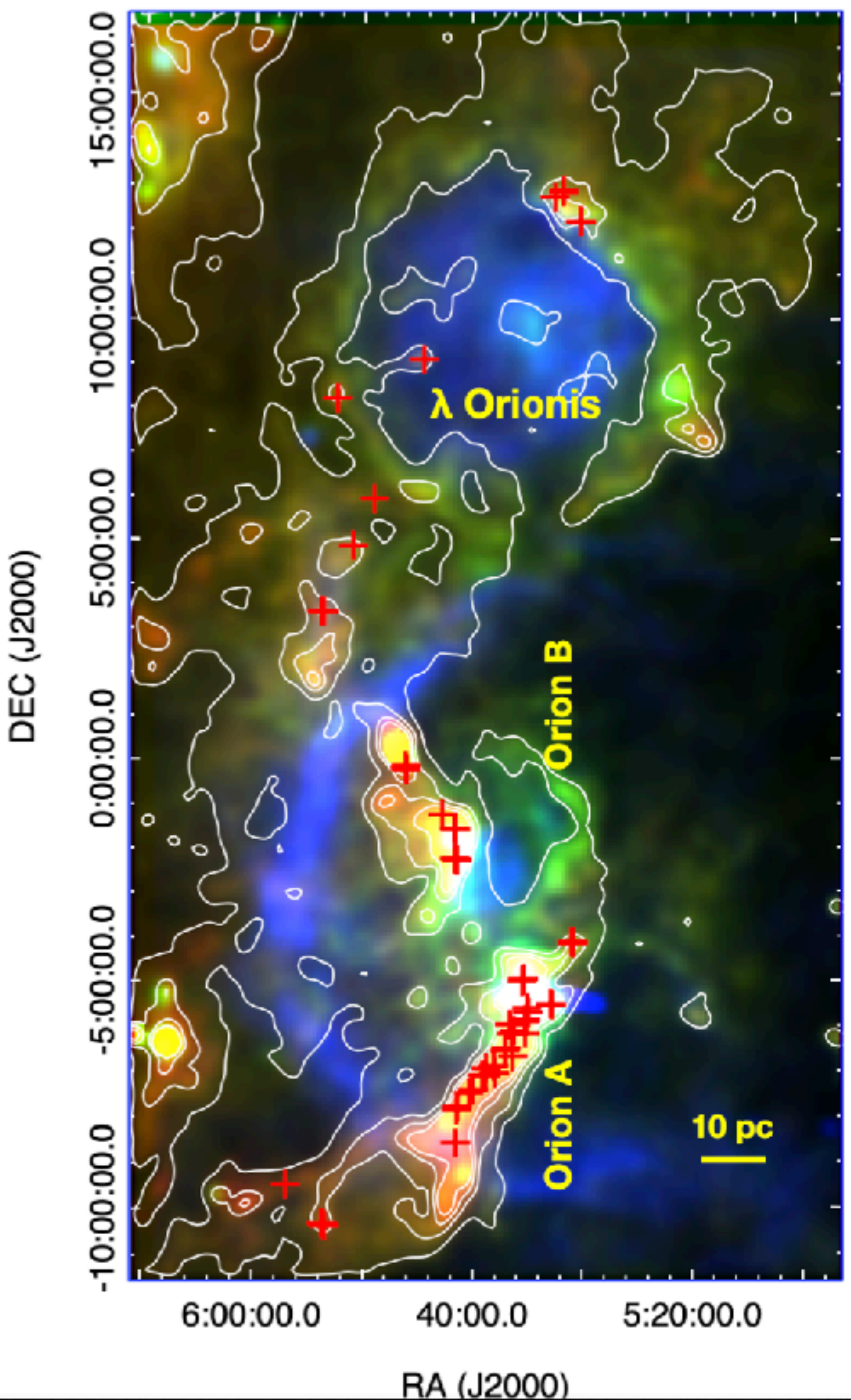

**Yi+ 2018**

PGCCs detected in Orion cloud, the marks thus represent identified dense cores.

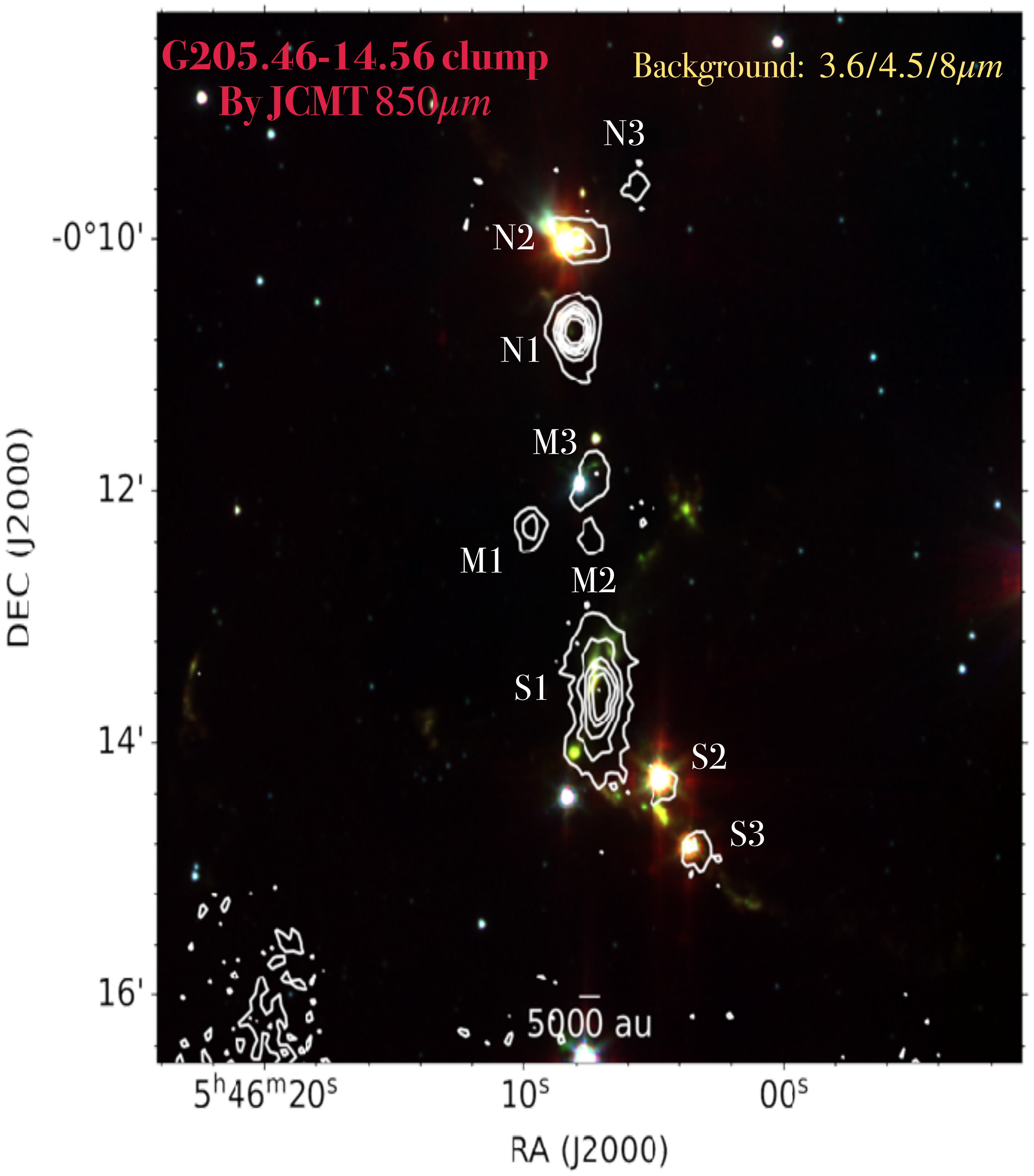
# ALMASOP : ALMA Survey of Orion Planck Galactic Cold Clumps (PI:Tie Liu)

- Sample: 72 sources selected from ‘SCOPE’ survey in Orion PGCCs
- Band 6 : 211-275GHz
- Spatial resolution： 0.33” （~140au）
- Observation target: starless core and protostellar core candidates

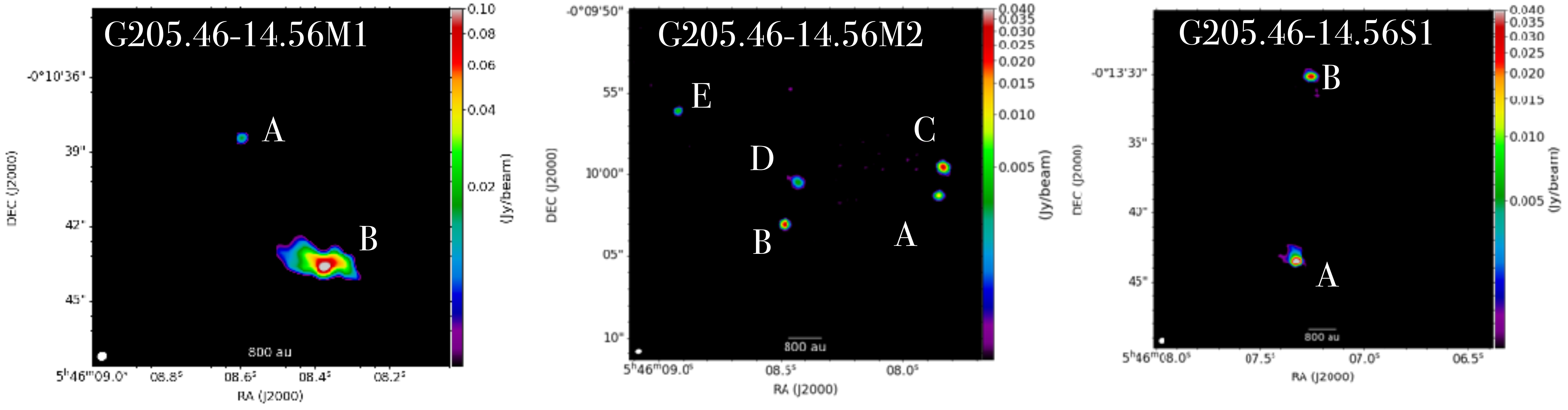
| Spectral Window (6) | Central Frequency (GHz) (7) | Main molecular Lines (8) | Bandwidth (GHz) (9) | Velocity Resolution (km $s^{-1}$) (10) |
|---|---|---|---|---|
| 0 | 231.000000 | $^{12}$CO J=2-1; $N_2D^+$ J=3-2 | 1.875 | 1.465 |
| 1 | 233.000000 | $CH_3OH$ transitions | 1.875 | 1.453 |
| 2 | 218.917871 | $C^{18}O$ J=2-1; $H_2CO$ transitions | 1.875 | 1.546 |
| 3 | 216.617675 | SiO J=5-4; DCN J=3-2; $DCO^+$ J=3-2 | 1.875 | 1.563 |



# The Formation of binary/multiple systems in Orion Molecular Cloud complex




**ALMA 1.3mm** **Binary/Multiple system**

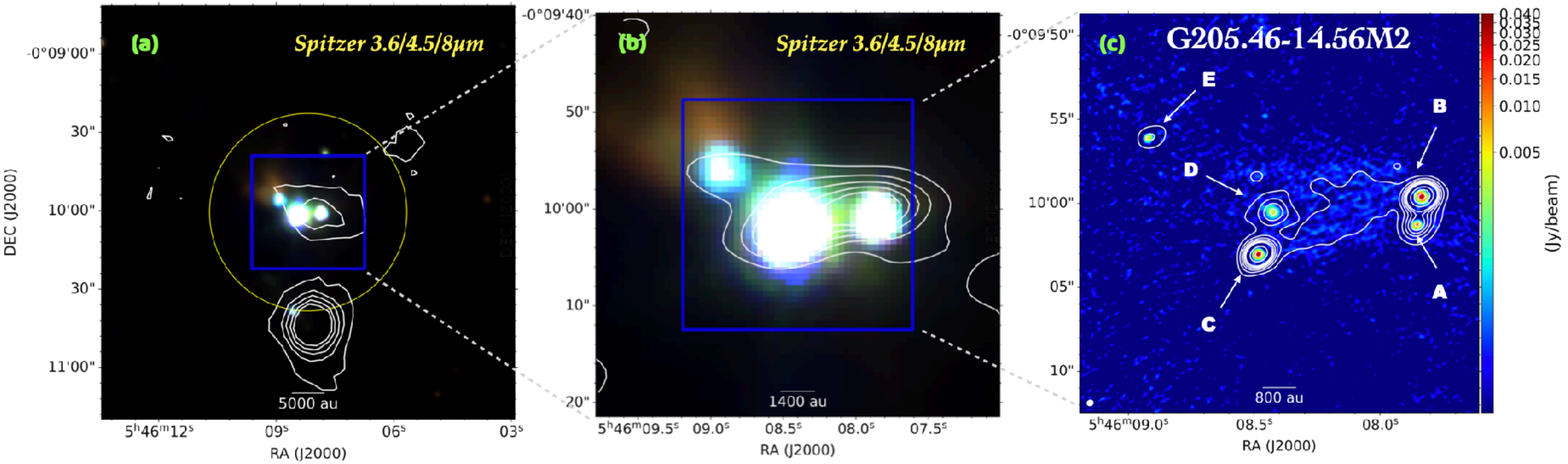



- In one clump, different dense cores form different stellar system, how do dense core properties affect the multiplicity of protostars?

Result

# Identifying Binary/Multiple system in dense cores

- 43 density-limited protostellar cores



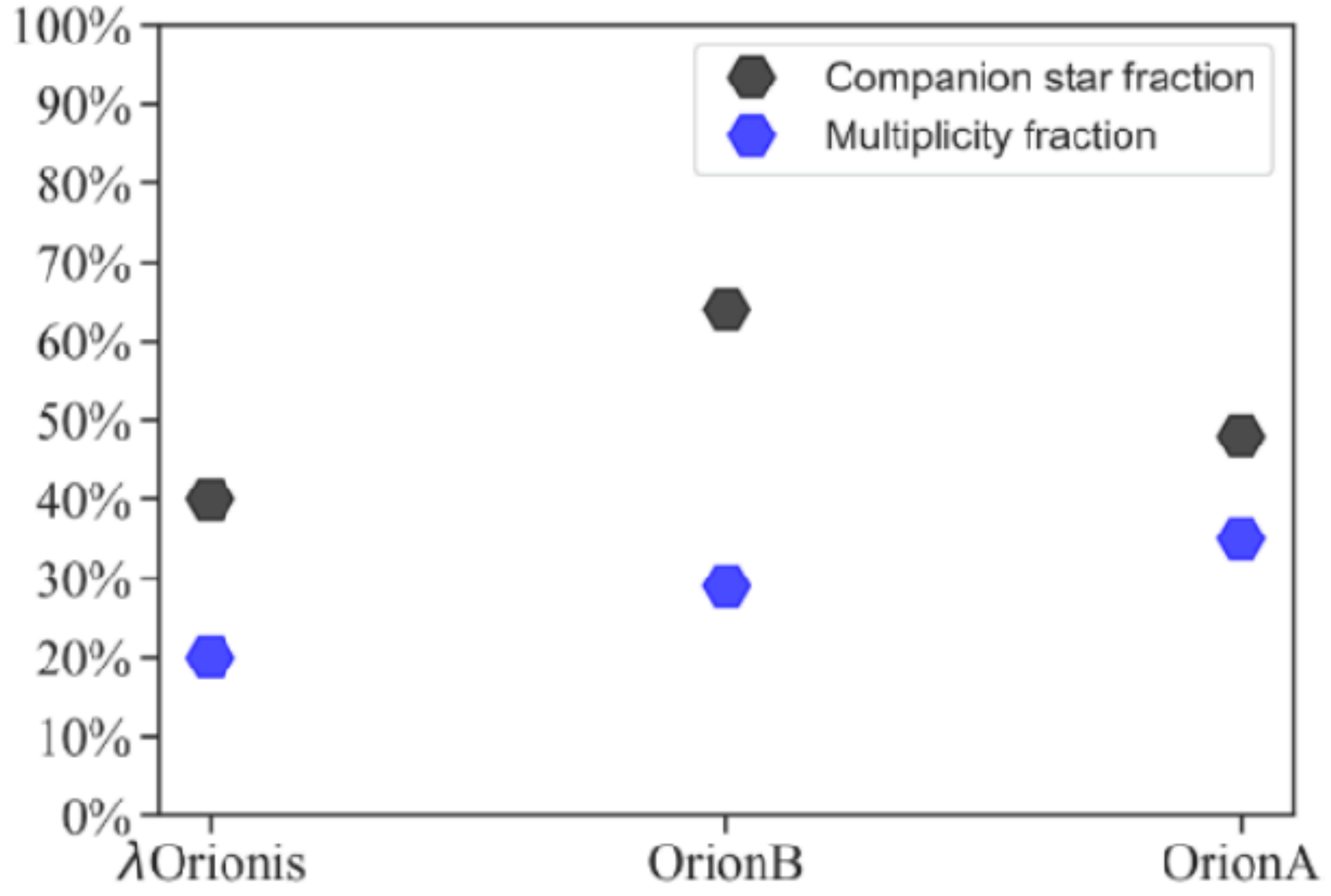

Contour: SCUBA-2 850micron

Contour: ALMA ACA

Contour: ALMA TM2+ACA

**We first identified 13 binary/multiple systems, 1 binary system candidate and 29 single star systems within the dense cores.**

# Multiplicity of three subregion in OMCc




$$MF = \frac{B+T+Q+...}{S+B+T+Q...}$$

$$CSF = \frac{B+2T+3Q+...}{S+B+T+Q...}$$

## Multiplicity for the whole sample:

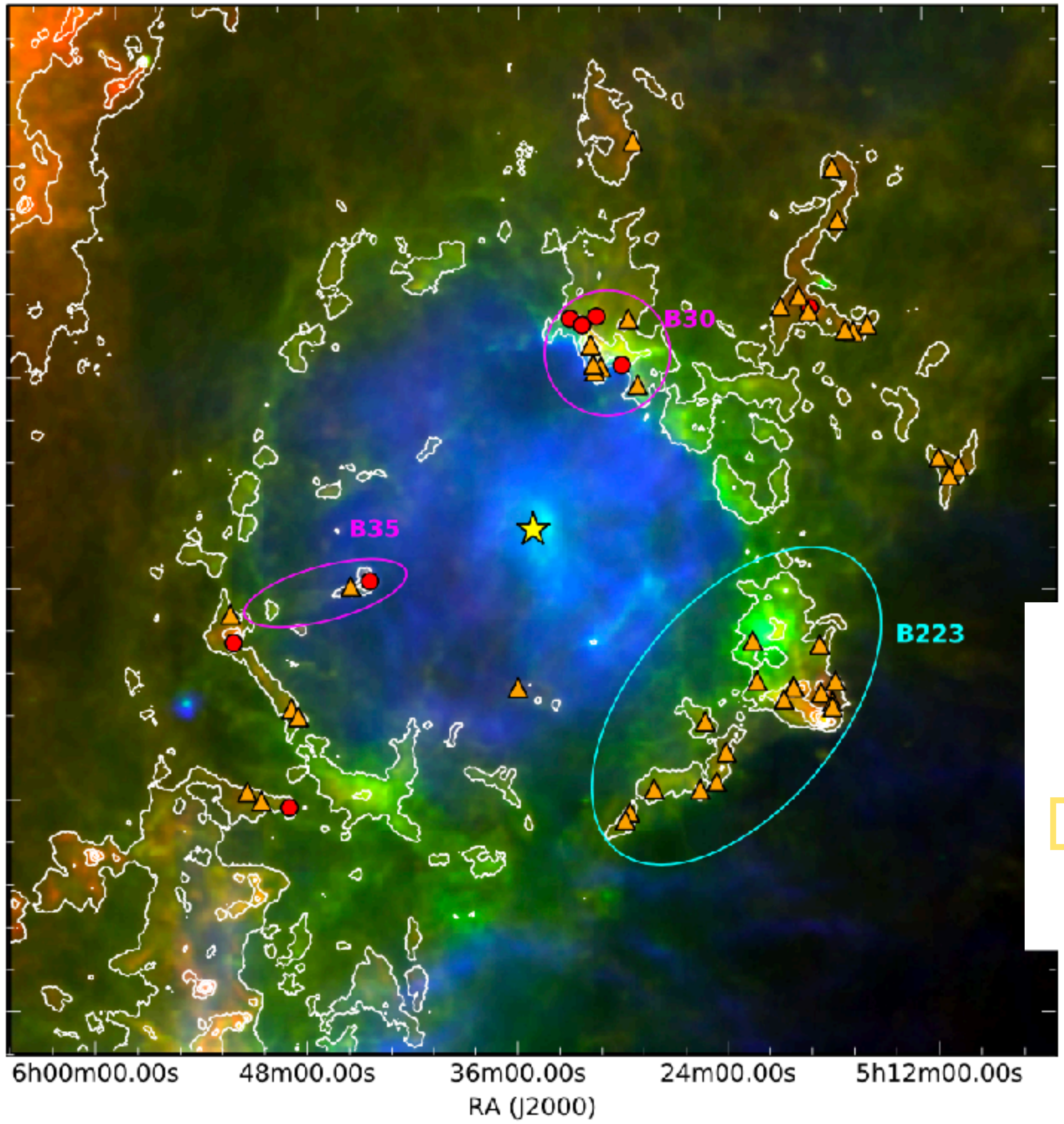
MF :28%
CSF:51%

**Multiplicity fraction (MF):** the proportion of binary/multiple in population
**Companion star fraction(CSF):** the proportion of companion in population

**Table 1.** Stellar multiplicity in Orion Molecular Cloud Complex

| Three sub-regions (1) | Multiplicity Frequency (MF) (2) | Companion Star Fraction (CSF) (3) | Sample number (single system) (4) | Sample number (binary/multiple system) (5) |
|---|---|---|---|---|
| λ Orionis | 20% | 40% | 4 | 1 |
| Orion B | 29% | 64% | 10 | 4 |
| Orion A | 35% | 48% | 15 | 8 |

# The Environmental effect on the multiplicity in the three subregions




Yi et al. 2018

Statistics of Core Properties

| Cloud | $N_{H_2}$ ($10^{22}$ cm$^{-2}$) | | | | $n_{H_2}$ ($10^5$ cm$^{-3}$) | | | | Core mass ($M_\odot$) | | | | Core size (pc) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Median | Min | Max | Mean | Median | Min | Max | Mean | Median | Min | Max | Mean | Median |
| λ Orionis | 2.5 | 18.2 | 9.5 | 8.2 | 0.7 | 5.6 | 2.9 | 2.5 | 0.06 | 5.41 | 1.07 | 0.77 | 0.03 | 0.19 | 0.08 | 0.09 |
| Orion A | 3.3 | 116.6 | 23.4 | 14.7 | 0.5 | 18.9 | 3.8 | 3.4 | 0.07 | 12.25 | 2.39 | 1.18 | 0.02 | 0.26 | 0.11 | 0.11 |
| Orion B | 3.2 | 99.1 | 38.4 | 38.4 | 1.3 | 40.8 | 15.6 | 15.8 | 0.14 | 11.36 | 2.66 | 1.81 | 0.03 | 2.25 | 0.16 | 0.10 |

**Table 7**
Physical Properties of PGCCs from the PGCC Catalog

| Cloud | Number of PGCCs | Median | | | | | Mean | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $N_{H_2}$ ($10^{20}$ cm$^{-2}$) | $T_d$ (K) | $\beta$ | $n_{H_2}$ ($10^2$ cm$^{-3}$) | $M_{clump}$ ($M_\odot$) | $N_{H_2}$ ($10^{20}$ cm$^{-2}$) | $T_d$ (K) | $\beta$ | $n_{H_2}$ ($10^2$ cm$^{-3}$) | $M_{clump}$ ($M_\odot$) |
| λ Orionis | 177 | 3.2 | 16.1 | 1.7 | 2.2 | 4.9 | 6.4 | 16.0 | 1.6 | 4.7 | 8.5 |
| Orion A | 135 | 10.9 | 13.4 | 2.1 | 6.6 | 13.8 | 28.1 | 13.8 | 2.0 | 18.3 | 30.8 |
| Orion B | 154 | 6.4 | 13.9 | 2.0 | 4.1 | 7.7 | 13.4 | 14.0 | 1.9 | 9.1 | 16.8 |

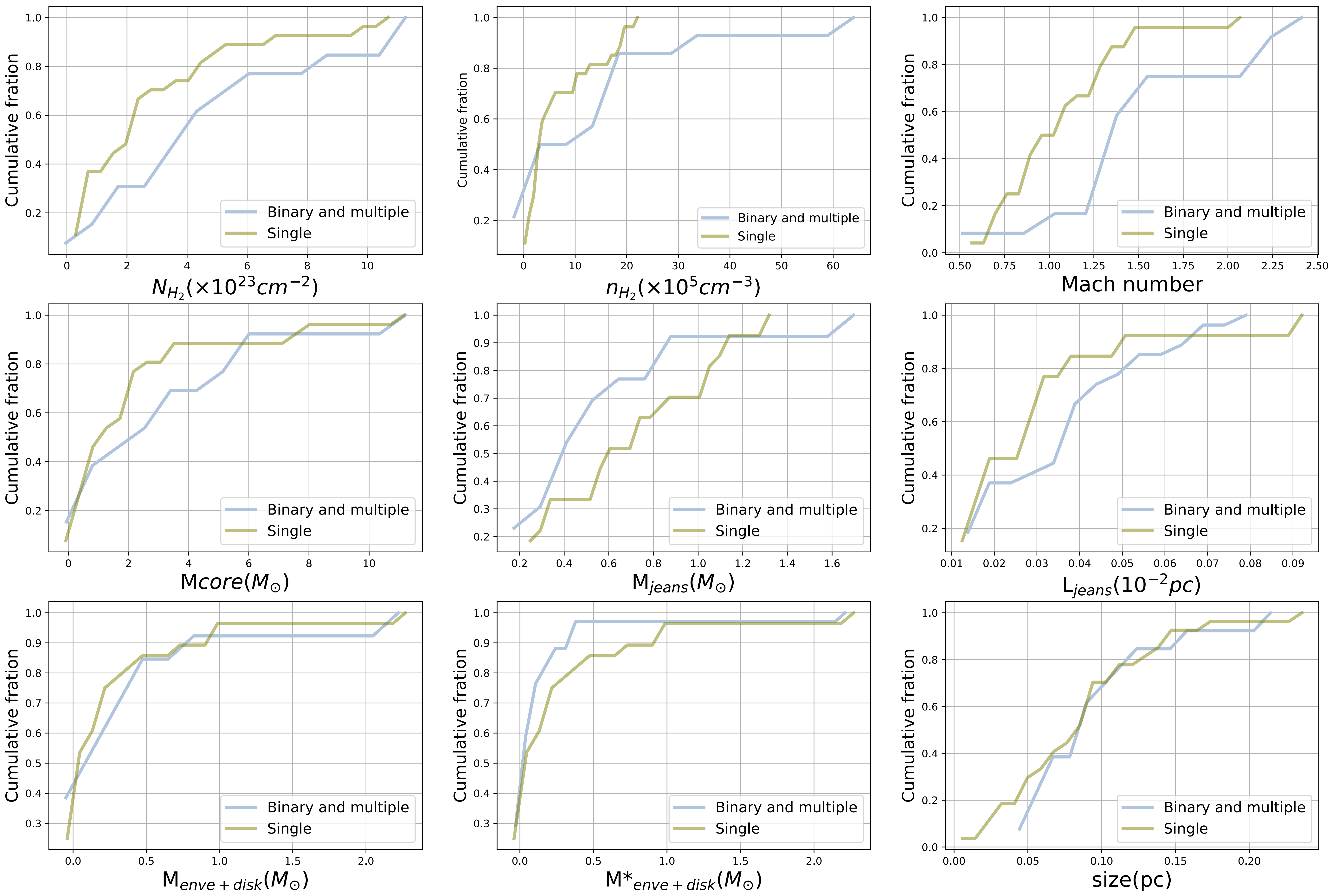
Why λ Orionis has the lowest multiplicity?

# Properties of natal dense cores

**H2 column density**
**mean density,**
**Mach number**
**core mass**
**Jeans mass**
**Jeans length**
**envelope+disk mass**
**core size**

**Mach number**
**mean density,**
**H2 column density**

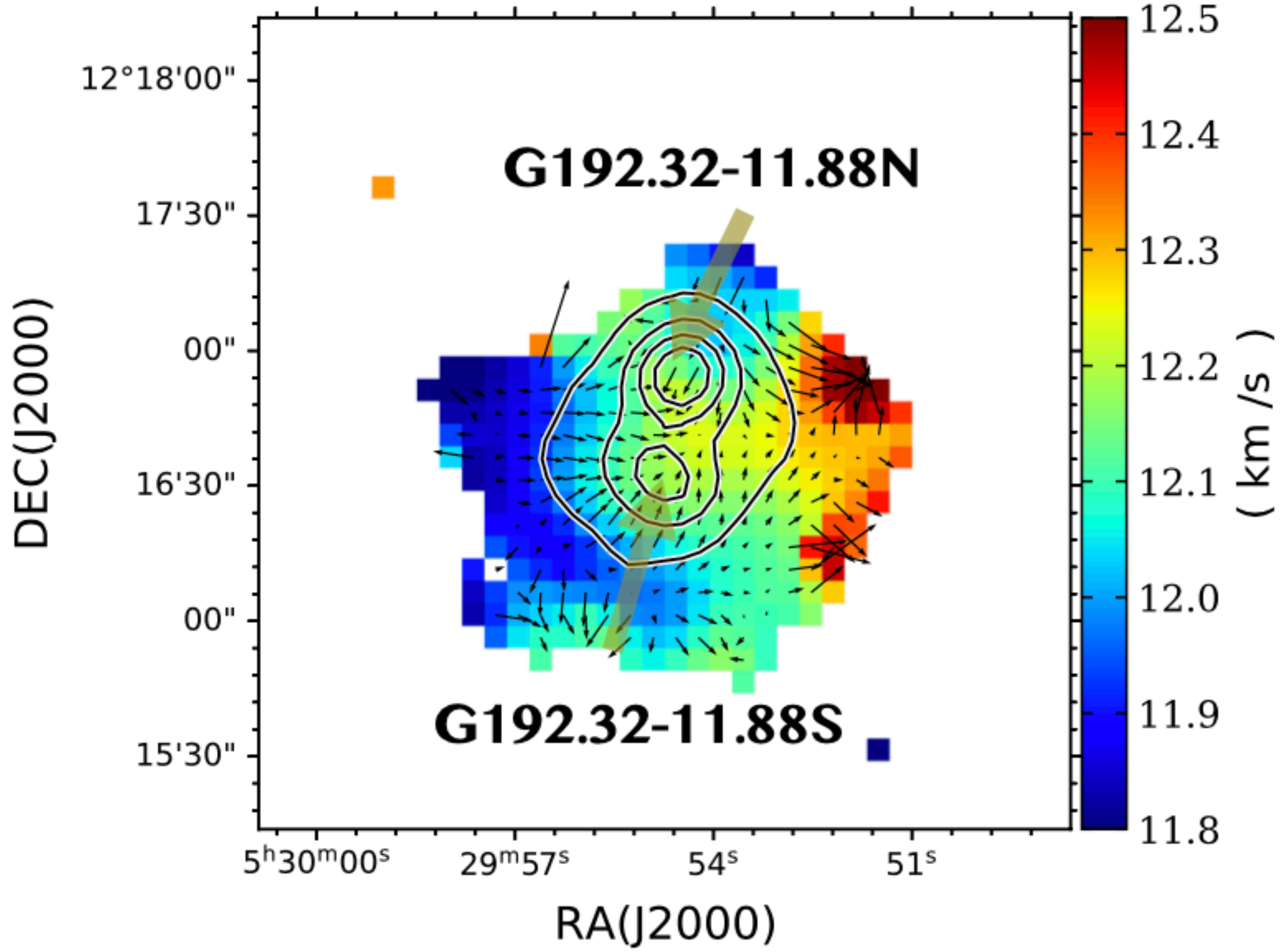
| Parameter | Single system | | | | Binary/Multiple system | | | | KS-test | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Mean | Median | sigma | Number | Mean | Median | sigma | statistic | p-value |
| $N(H_2)(\times\mathbf{10^{23}cm^{-2}})$ | 27 | 3.022 | 2.50 | 2.708 | 13 | 5.076 | 4.50 | 3.545 | 0.396 | 0.094 |
| $n_{H2}(\times\mathbf{10^{5}cm^{-3}})$ | 27 | 7.102 | 4.00 | 6.867 | 14 | 16.507 | 13.00 | 16.885 | 0.452 | 0.032 |
| $\mathcal{M}$ | 24 | 1.137 | 1.10 | 0.338 | 11 | 1.718 | 1.50 | 0.442 | 0.659 | 0.001 |
| $M_{core}(\mathbf{M_\odot})$ | 26 | 2.450 | 1.40 | 2.701 | 13 | 3.673 | 2.65 | 3.076 | 0.307 | 0.322 |
| $M_{jeans}(\mathbf{M_\odot})$ | 27 | 0.710 | 0.62 | 0.354 | 13 | 0.596 | 0.520 | 0.379 | 0.309 | 0.269 |
| $L_{jeans}(\mathbf{10^{-2}pc})$ | 27 | 3.888 | 3.395 | 1.913 | 14 | 3.144 | 2.529 | 2.021 | 0.378 | 0.111 |
| $M_{enve+disk}(\mathbf{M_\odot})$ | 28 | 0.300 | 0.15 | 0.475 | 13 | 0.475 | 0.29 | 0.583 | 0.346 | 0.189 |
| $M^{*}_{\mathrm{enve+disk}}(\mathbf{M_\odot})$ | 28 | 0.300 | 0.15 | 0.475 | 34 | 0.178 | 0.11 | 0.378 | 0.216 | 0.401 |
| $Size(\mathbf{pc})$ | 27 | 0.092 | 0.09 | 0.002 | 13 | 0.102 | 0.09 | 0.045 | 0.219 | 0.737 |

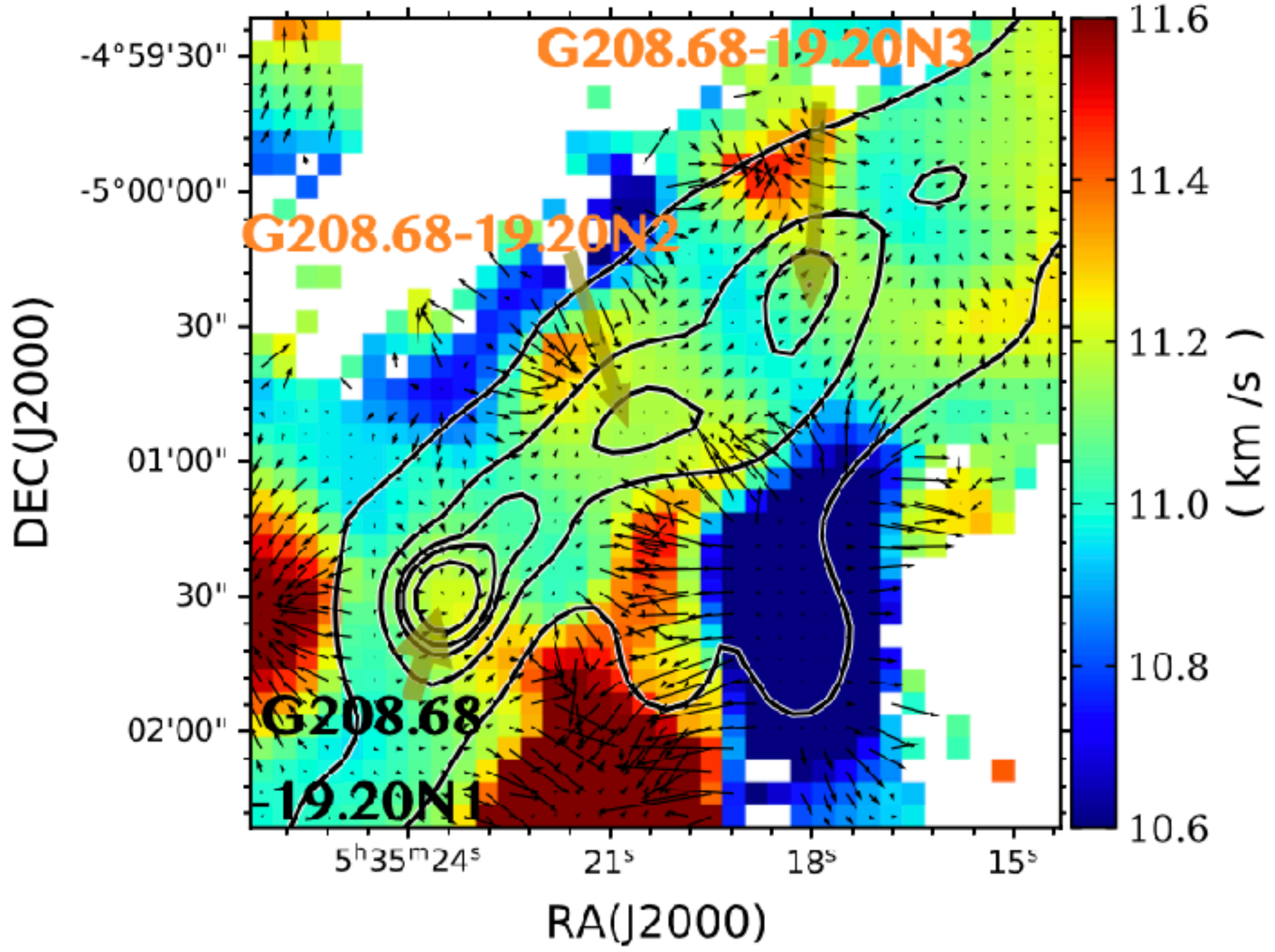



The higher **Mean density** and **H2 column density** lead to lower Jeans length, which resulting in more likely to fragmentation.

The higher **Mach number** thus relate to core accretion, core rotation.

# N2H+ maps of 16 protostellar cores

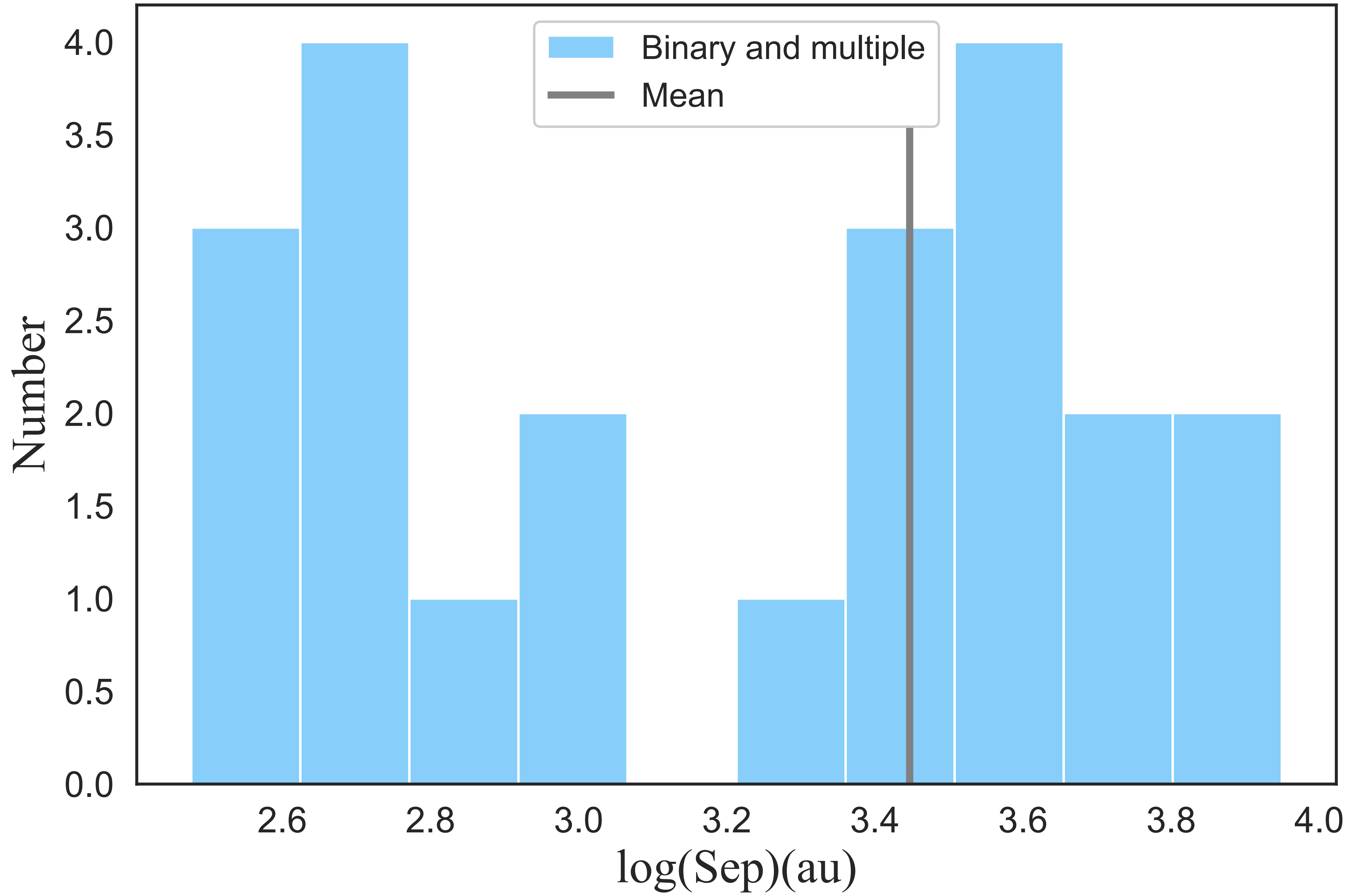



N2H+ (J=1-0) by NRO 45-m telescope and contours are JCMT 850$\mu m$ data.

The average median velocity gradients of cores that form single stars is 3.9km/(s*pc ), and form multiple stars is 4.05km/(s*pc)

# Separation of Protostars in binary/Multiple systems

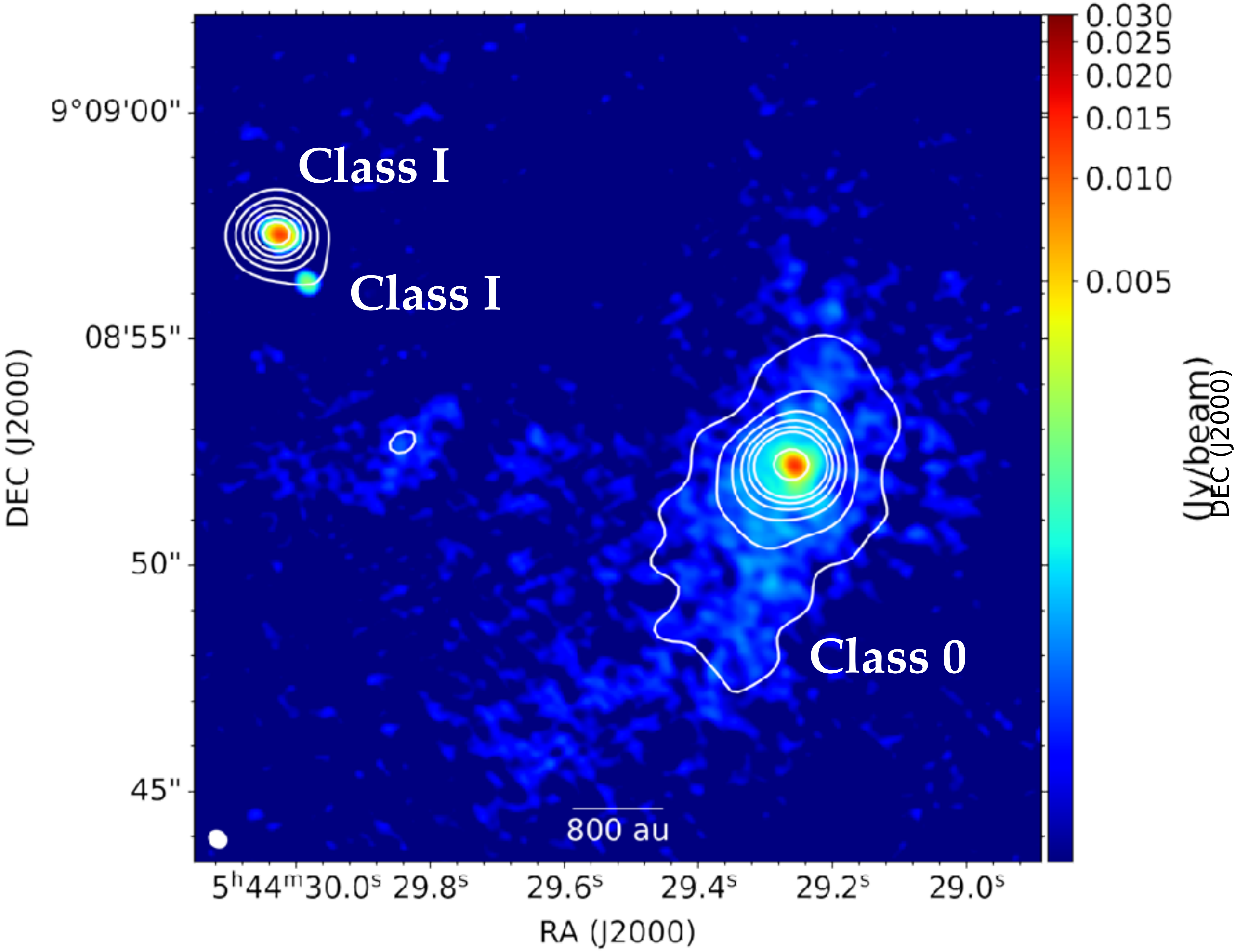


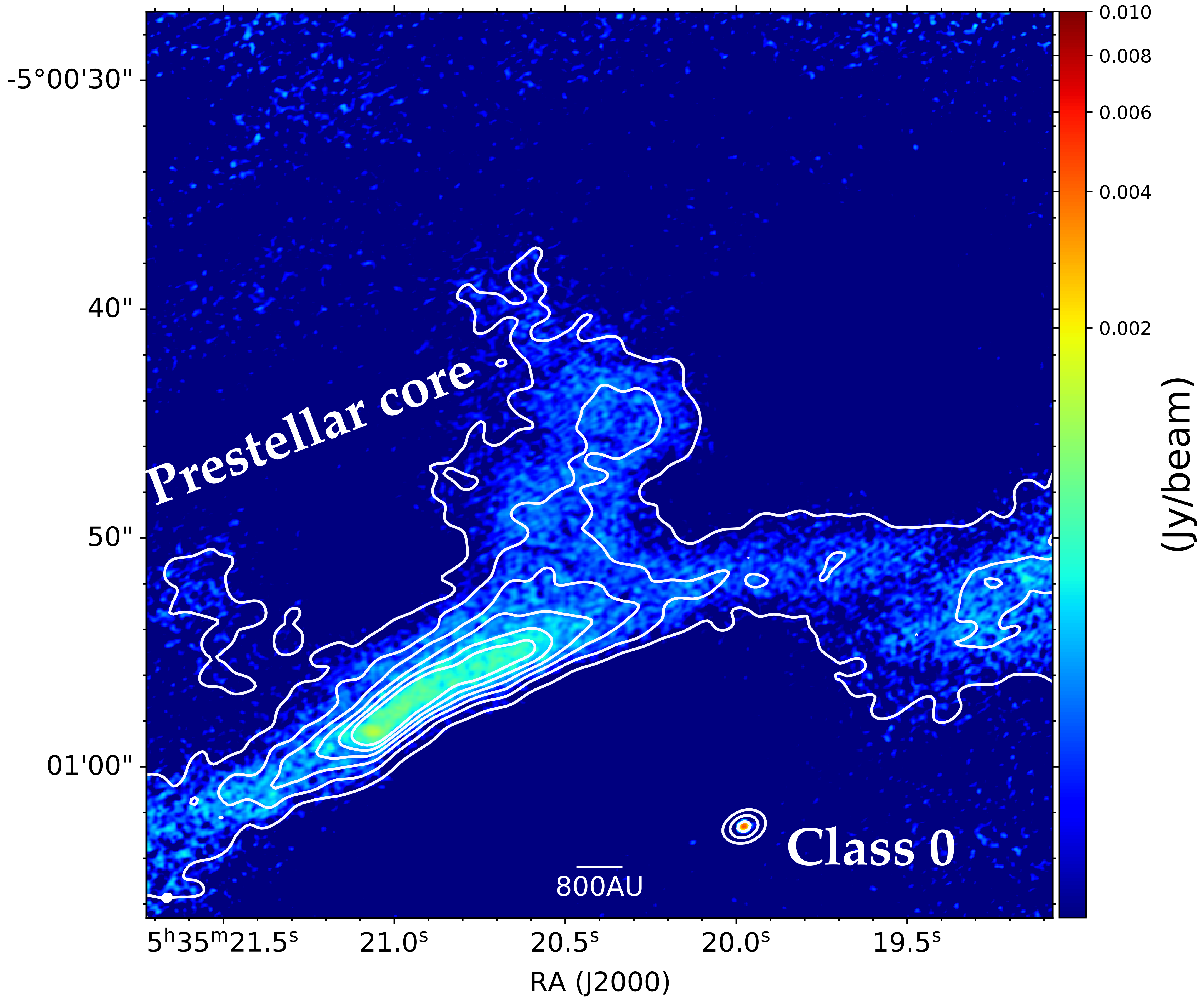

Range : 300 - 8900 au (<140 au cannot resolved)
Mean Separation: 2800 au
**Bi-modal( 500au & 3500au )**

**Formation Mechanism Models :**
**Turbulent fragmentation**(>1000 au) (Goodwin, Fishes,2004) ;
**Disk fragmentation**(<600 au)(Adams 1989, Bonnell 1994)

# Different evolutionary stages of member protostars in binary/multiple systems within a dense core

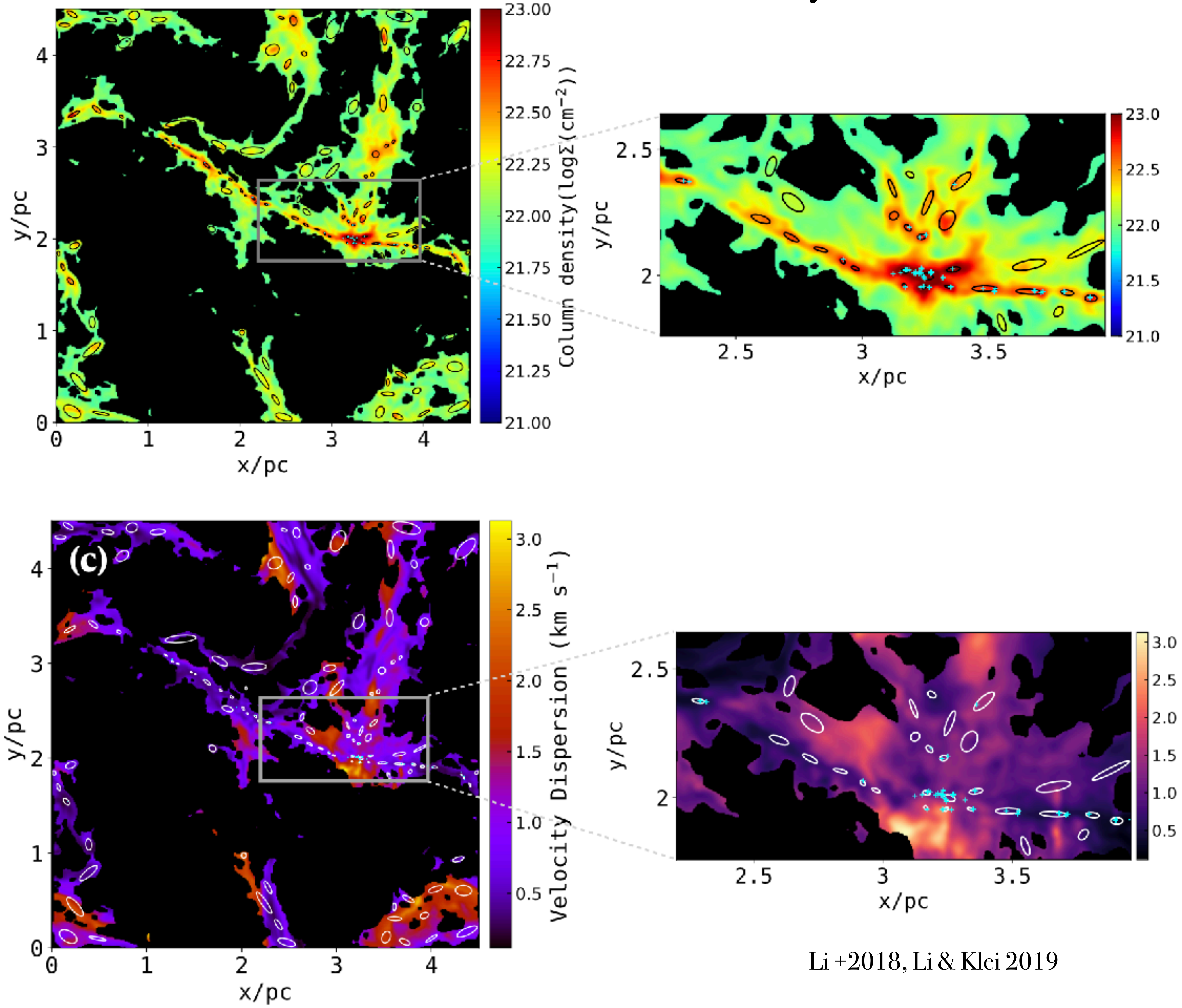
## 1.3mm dust continuum




Non-constant age in member protostars.
Different accretion history?

# A filamentary cloud in MHD simulation




12 dense cores: single star

11 dense cores: multiple stars

The comparison with the JCMT cores is qualitatively similar to MHD result: Region with **high densities** are more likely to form multiple system.

Li +2018, Li & Klei 2019

# Summary

- In our survey we calculate the  multiplicity in OMCc : MF~28%, CSF:  ~51%
- The formation of binary/multiple system is related to the natal dense core.  Our study suggests that the $H_2$ column density, mean density and Mach number of the core are the key factors.
- Non-constant age in member protostars is common.
- Compared with MHD simulation,  the results reveals the multiple system ted to form at high-density region.