ALMASOP: ALMA Survey of Orion Planck Galactic Cold Clumps

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Image credit: NRAO

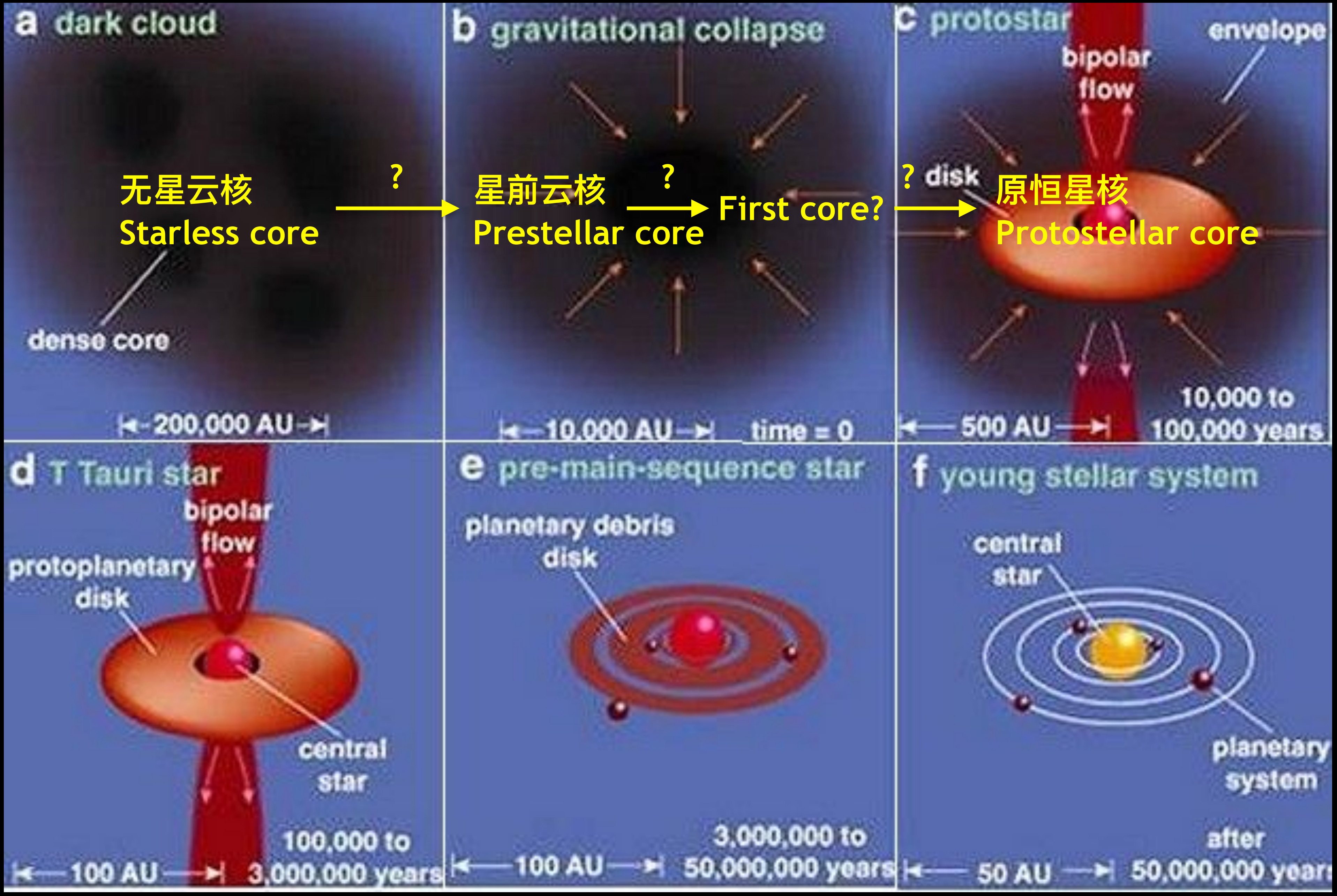
Outline

- 1. Introduction: open questions in low-mass star formation studies

- 2. **ALMASOP**: **ALMA S**urvey of **O**rion **P**lanck Galactic Cold Clumps

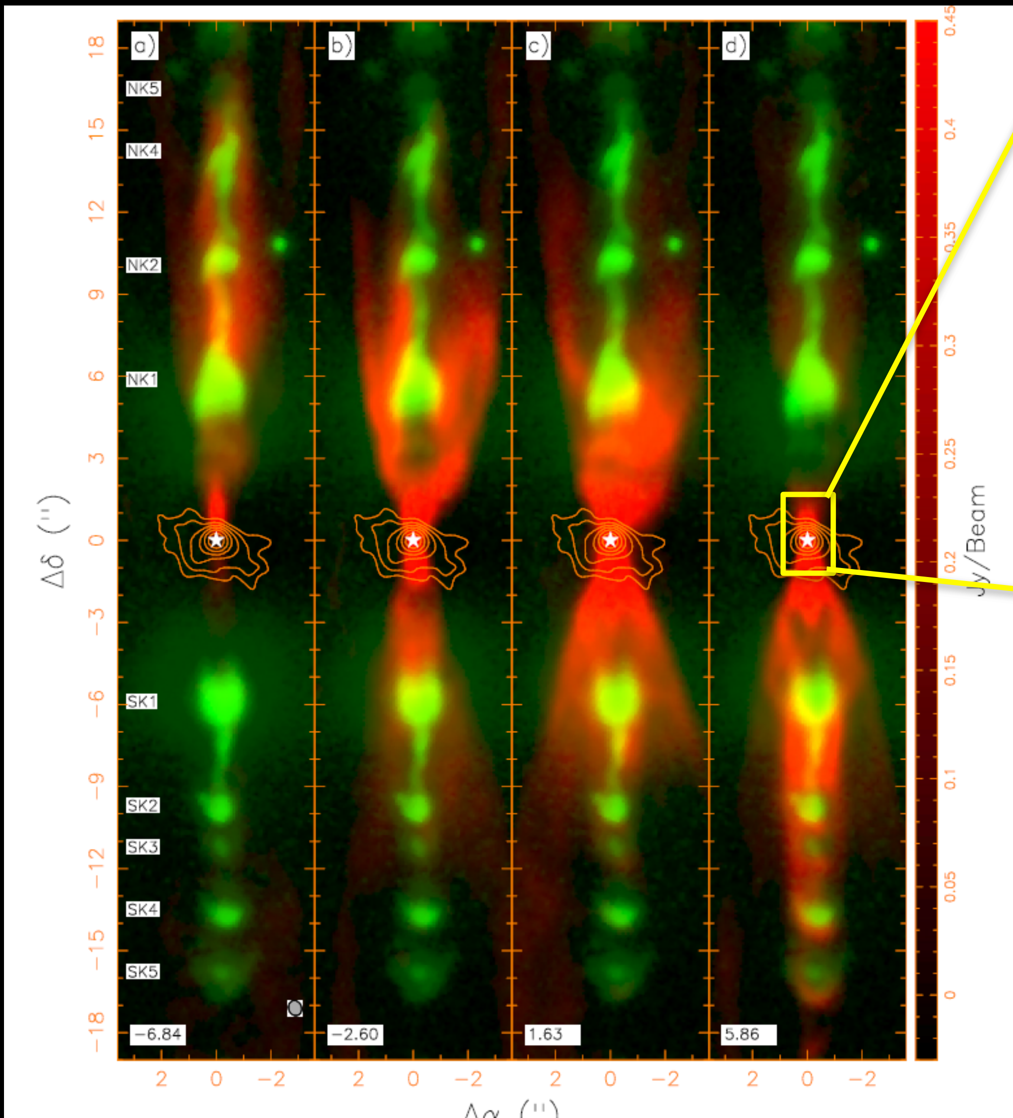
- 3. Summary

Formation and evolution of low-mass protostars



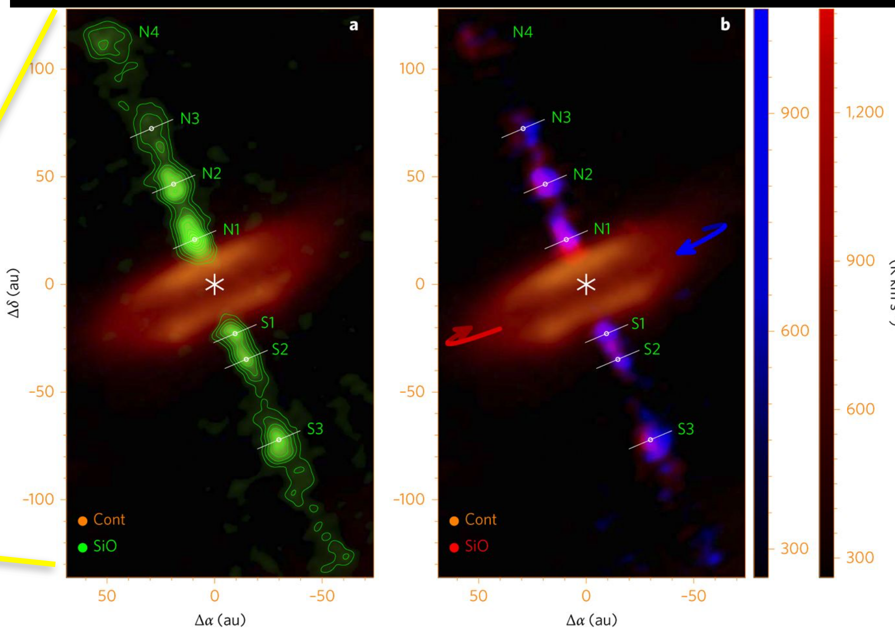
Credit: JPL

Keplerian rotating disks formed in Class 0 phase?



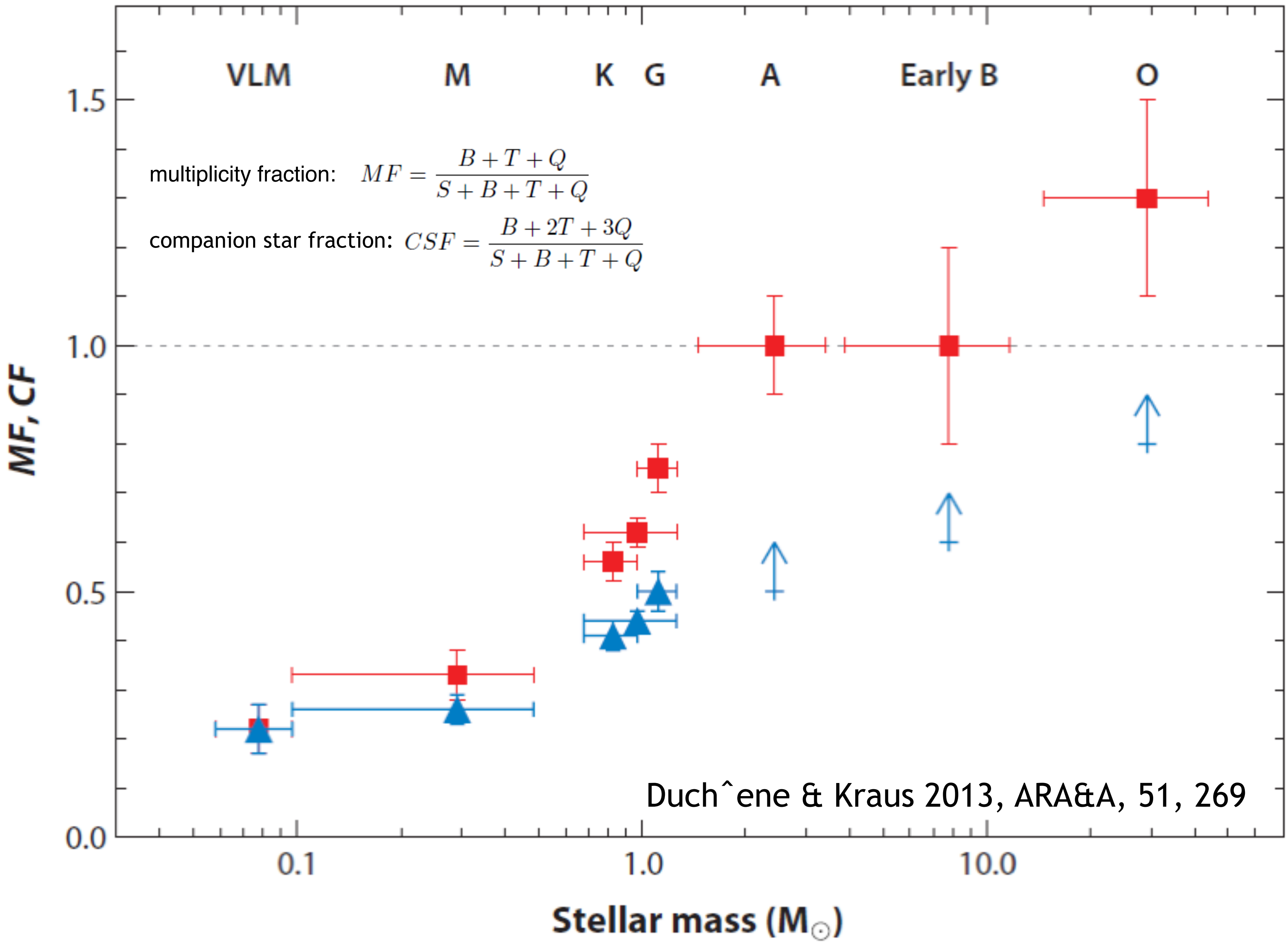
HH212: CO: red H_2: green 350 GHz continuum: contours (Lee+2015)

HH212

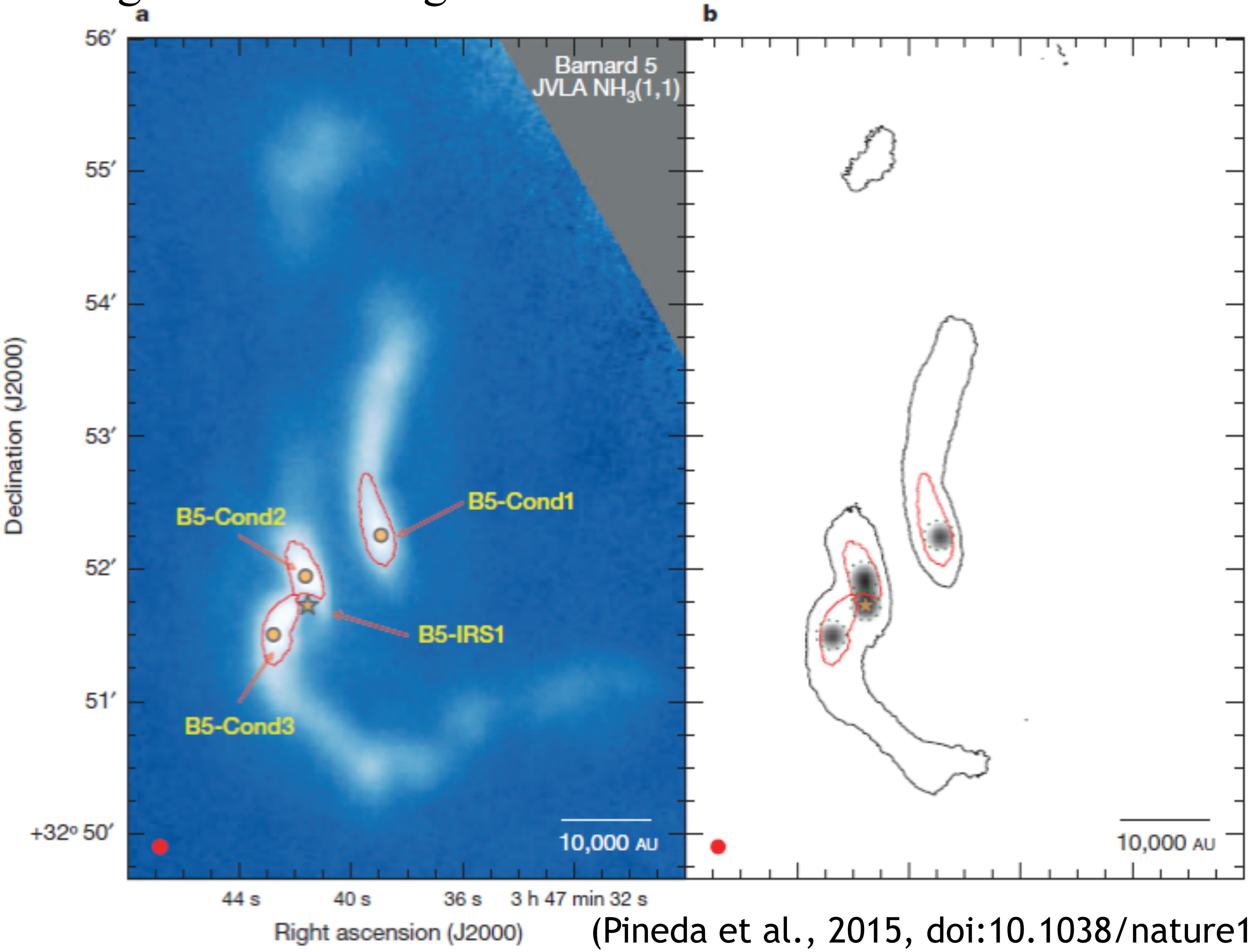


disk+jets of HH212(Lee+2017)

Class 0 keplerian rotating disk candidates are rare:
L1527 , VLA 1623, HH212, and L1448-NB (Ohashi et al. 2014, Murillo et al. 2013; Codella et al. 2014a; Tobin et al. 2016a)

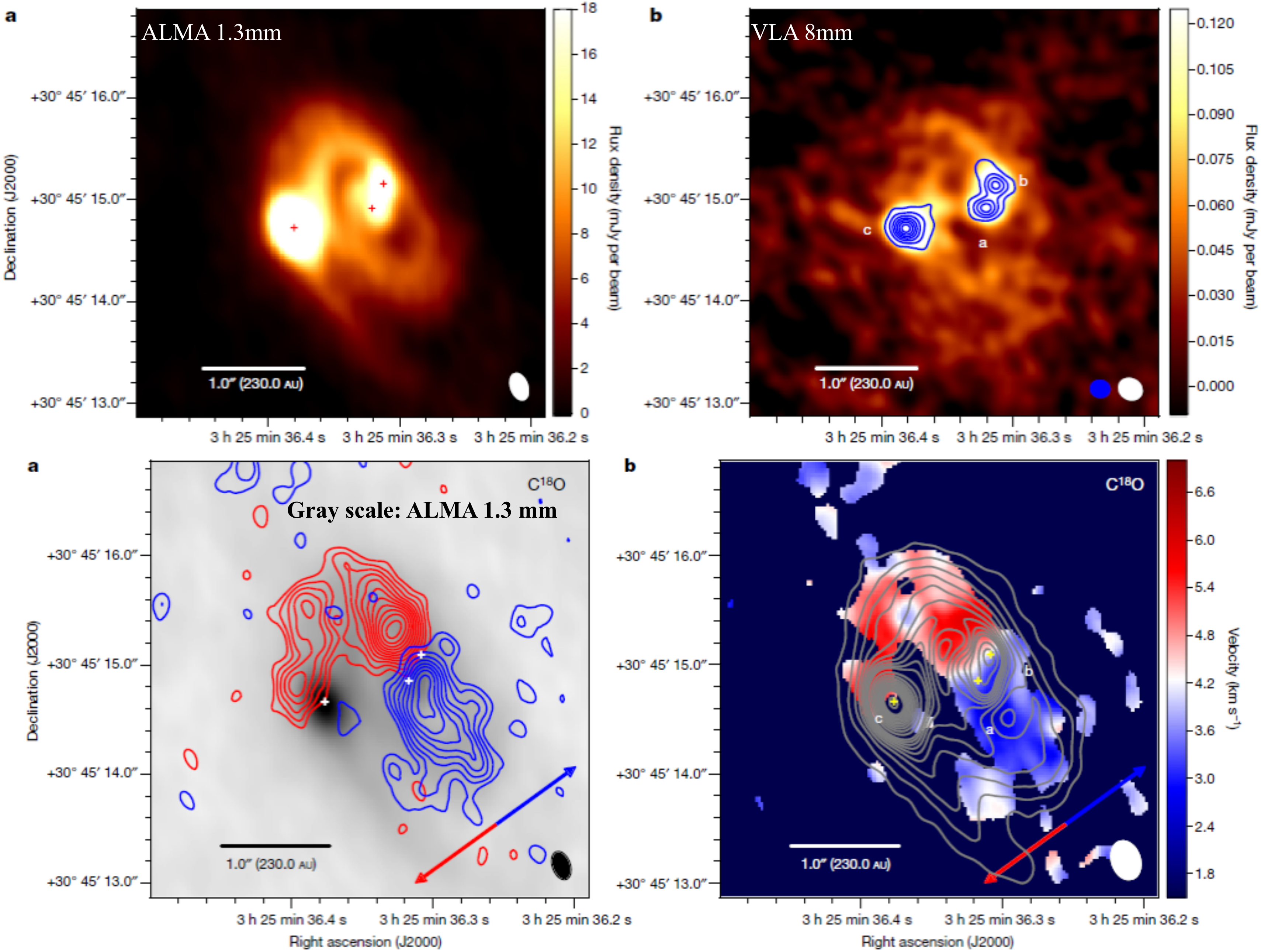

VLM
M
K
G
A
Early B
O
1.5
1.0
0.5
0.0
multiplicity fraction: $MF = \frac{B+T+Q}{S+B+T+Q}$
companion star fraction: $CSF = \frac{B+2T+3Q}{S+B+T+Q}$
MF, CF
0.1
1.0
10.0
Stellar mass ($M_\odot$)
Duch^ene & Kraus 2013, ARA&A, 51, 269

The formation of a multiple star system with wide separation through turbulent fragmentation of a cloud

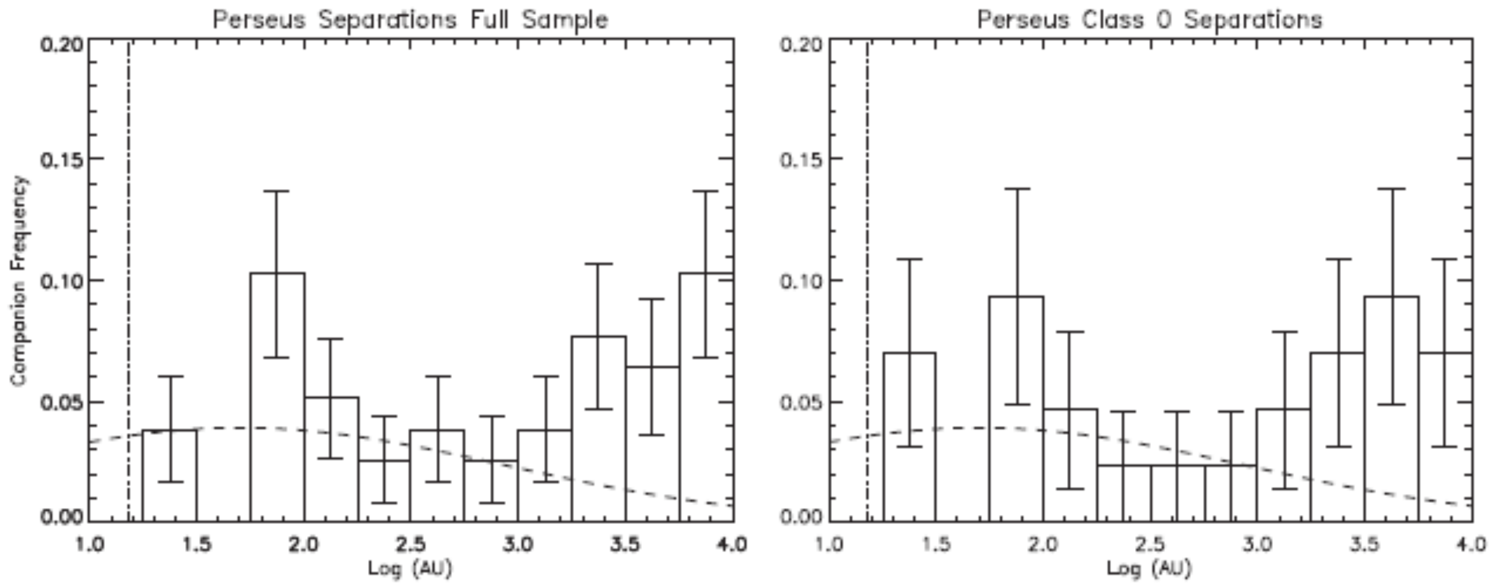


(Pineda et al., 2015, doi:10.1038/nature14166)

A triple protostar system formed via fragmentation of a gravitationally unstable disk (Tobin et al. 2016 doi:10.1038/nature20094)



Bi-modal distribution of companion separations



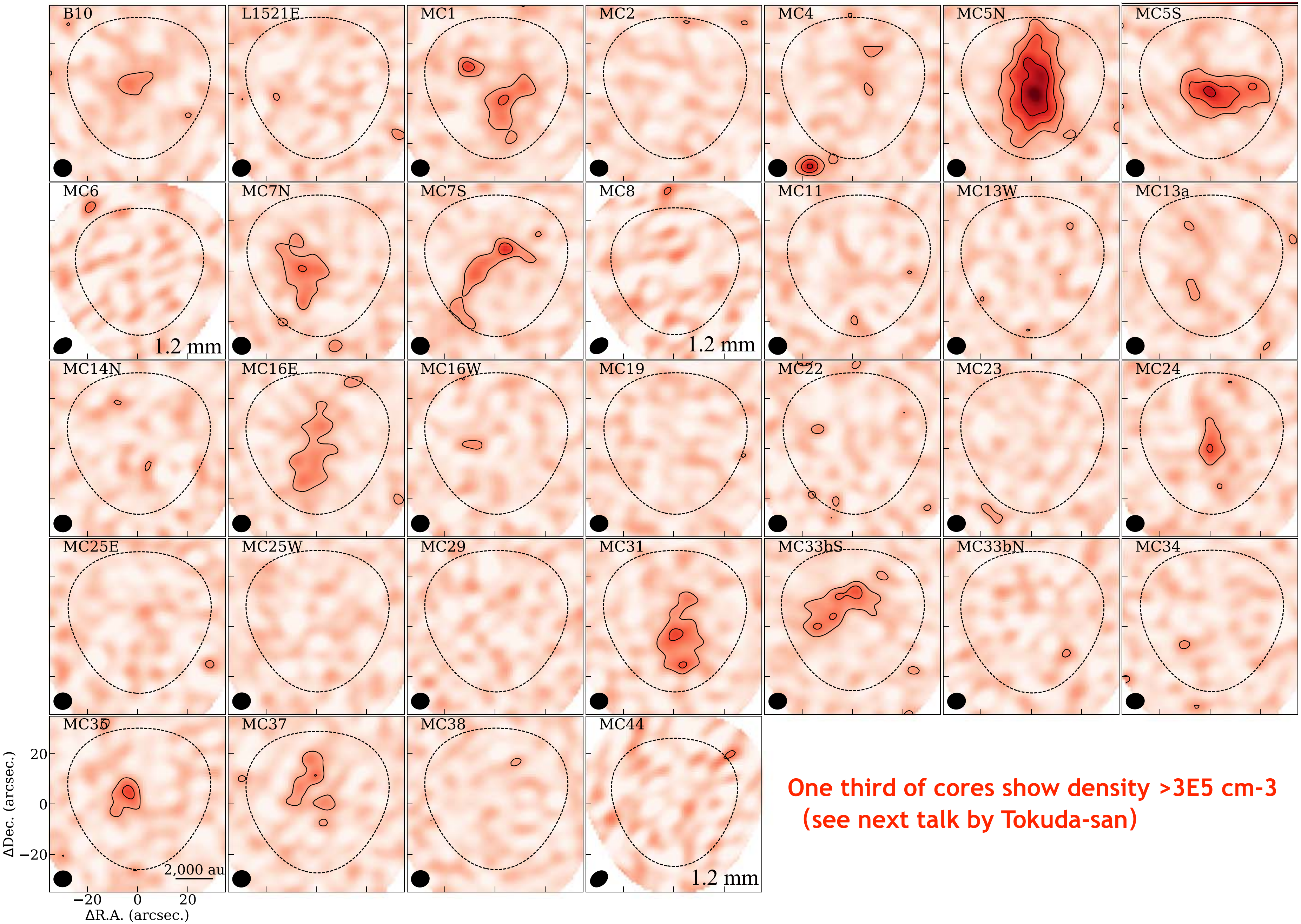
(Tobin et al., 2016, ApJ, 818, 73)

The distribution of companion separations appears bi-modal, with a peak at ~75 au and another peak at ~3000 au.

Turbulent fragmentation is likely the dominant mechanism on >1000 au scales and disk fragmentation is likely to be the dominant mechanism on <200 au scales.

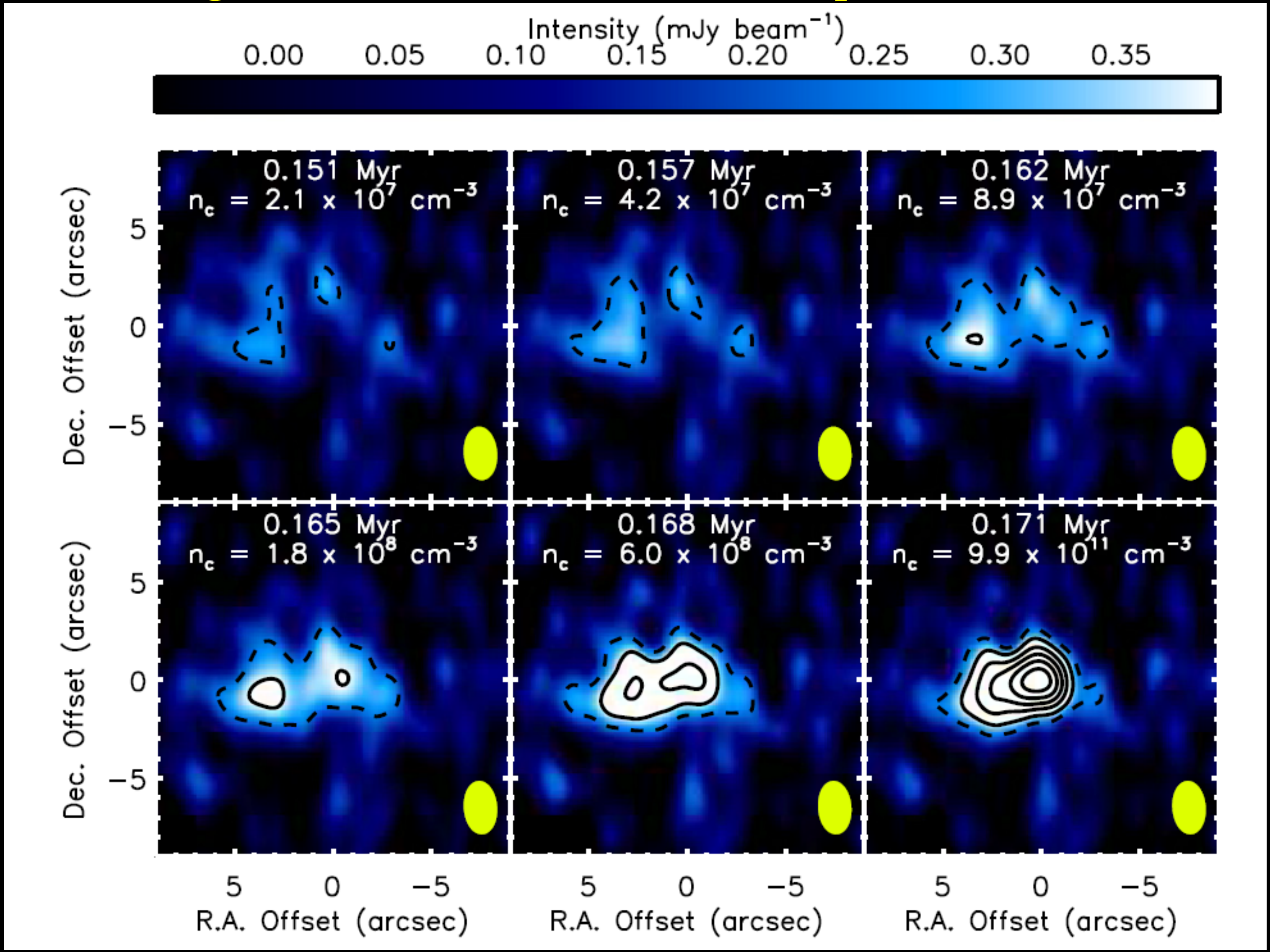
- **A key prediction of turbulent fragmentation is that the seeds for multiplicity are produced in the pre-stellar phase.**

Starless cores in Taurus cloud (Tokuda+2020)



One third of cores show density >3E5 cm-3
(see next talk by Tokuda-san)

Fragmentation and substructures of prestellar cores



Previous ALMA surveys of starless cores in nearby clouds did not detect such high density substructures
(Dunham et al. 2016; also see Schnee et al. 2010, 2012; Kirk et al. 2017)

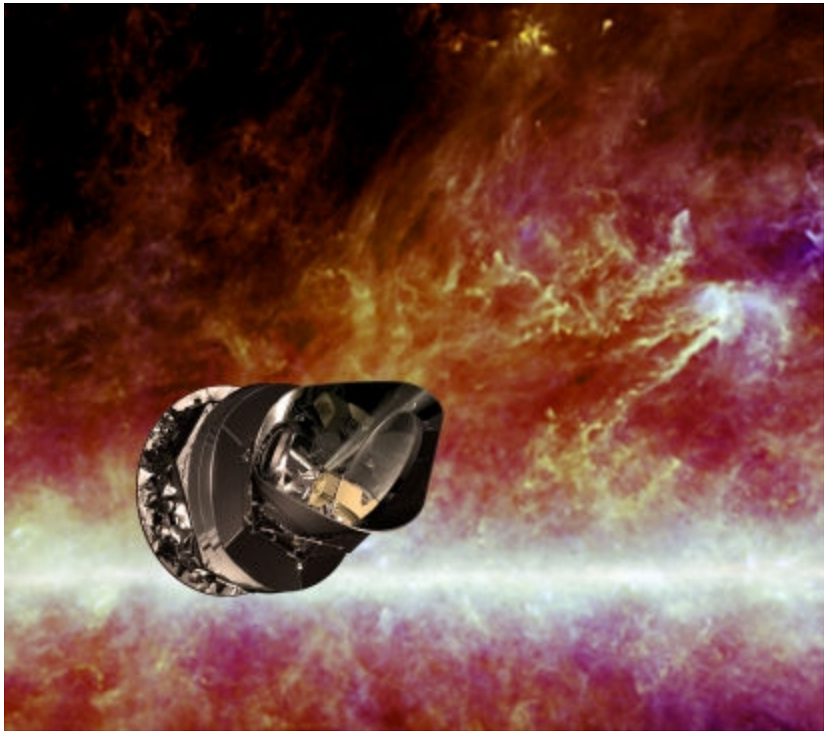
Short-lived or flatten density profiles?

Open questions in studies of low-mass star formation

- Substructure and fragmentation of starless cores
- How do disk form at Class 0 phase?
- *How to form binary or multiple systems?*
- ***To investigate the initial conditions of star formation, we need a large sample of cold cores at the earliest phases of star formation!***

2. ALMASOP: ALMA Survey of Orion Planck Galactic Cold Clumps

Surveys of Planck Galactic Cold Clumps

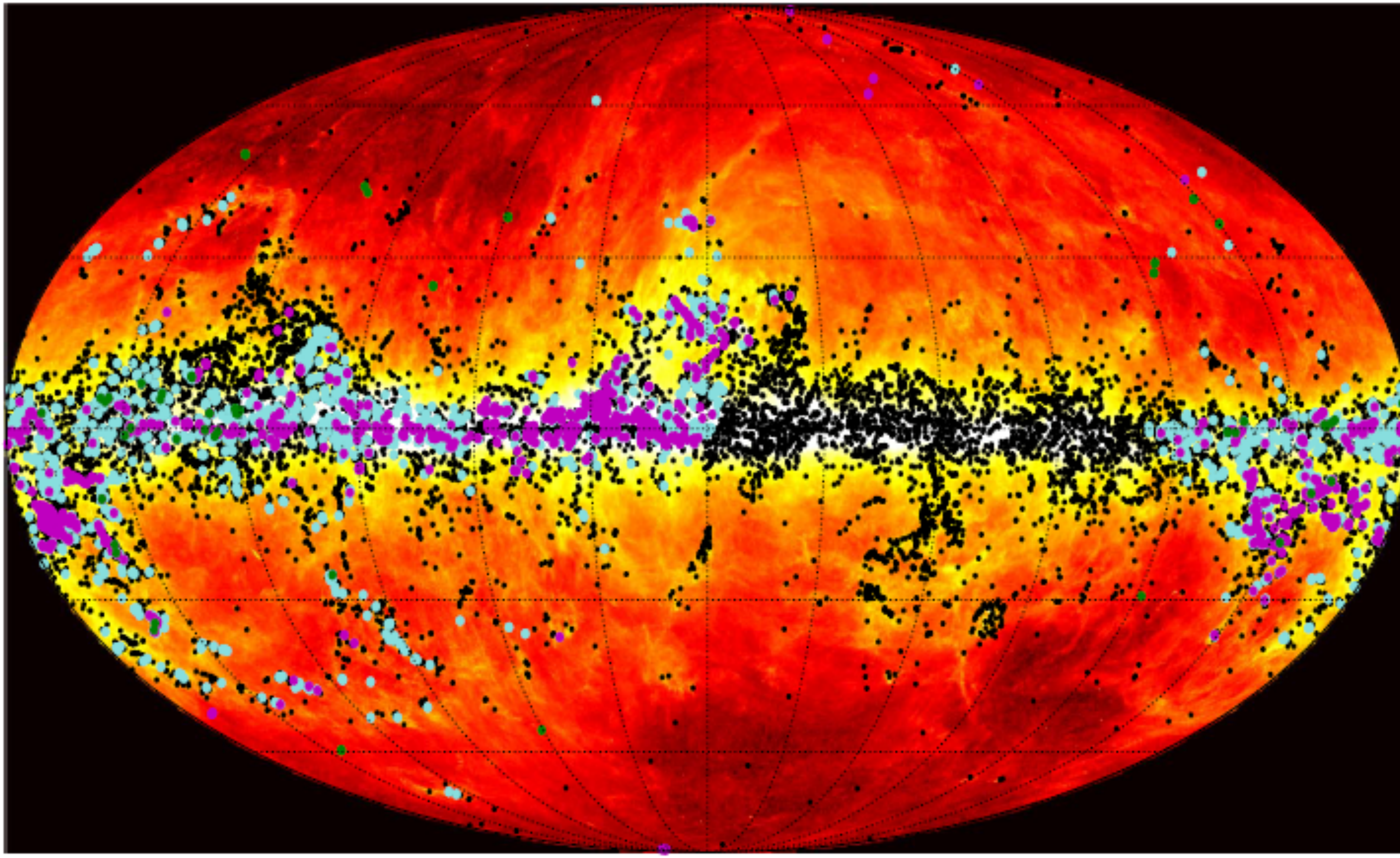


Planck is a third generation space based cosmic microwave background experiment, operating at nine frequencies between 30 and 857 GHz

Planck Catalogue of Galactic Cold Clumps (PGCC), *13188 clumps*

The PGCCs are cold (T_d~14 K) clumps and thus represent the very initial conditions of star formation and molecular cloud evolution

The survey team includes more than **150 experts** all over the word (China; Australia, Japan, S. Korea, U.K., Taiwan, U.S., Canada, France, Finland…) to follow-up observe 1000-2000 PGCCs with multiple state-of-the-art telescopes (**TRAO 13.7-m, PMO 13.7-m, JCMT 15-m, NRO 45-m,** SMT 10-m, KVN, IRAM 30-m, **SMA, ALMA**, **SOFIA**, Effelsberg 100-m, TianMa 65-m, FAST 500m…) in order ***to investigate the initial conditions of star formation in widely different environments and to address the questions raised in the introduction part***.



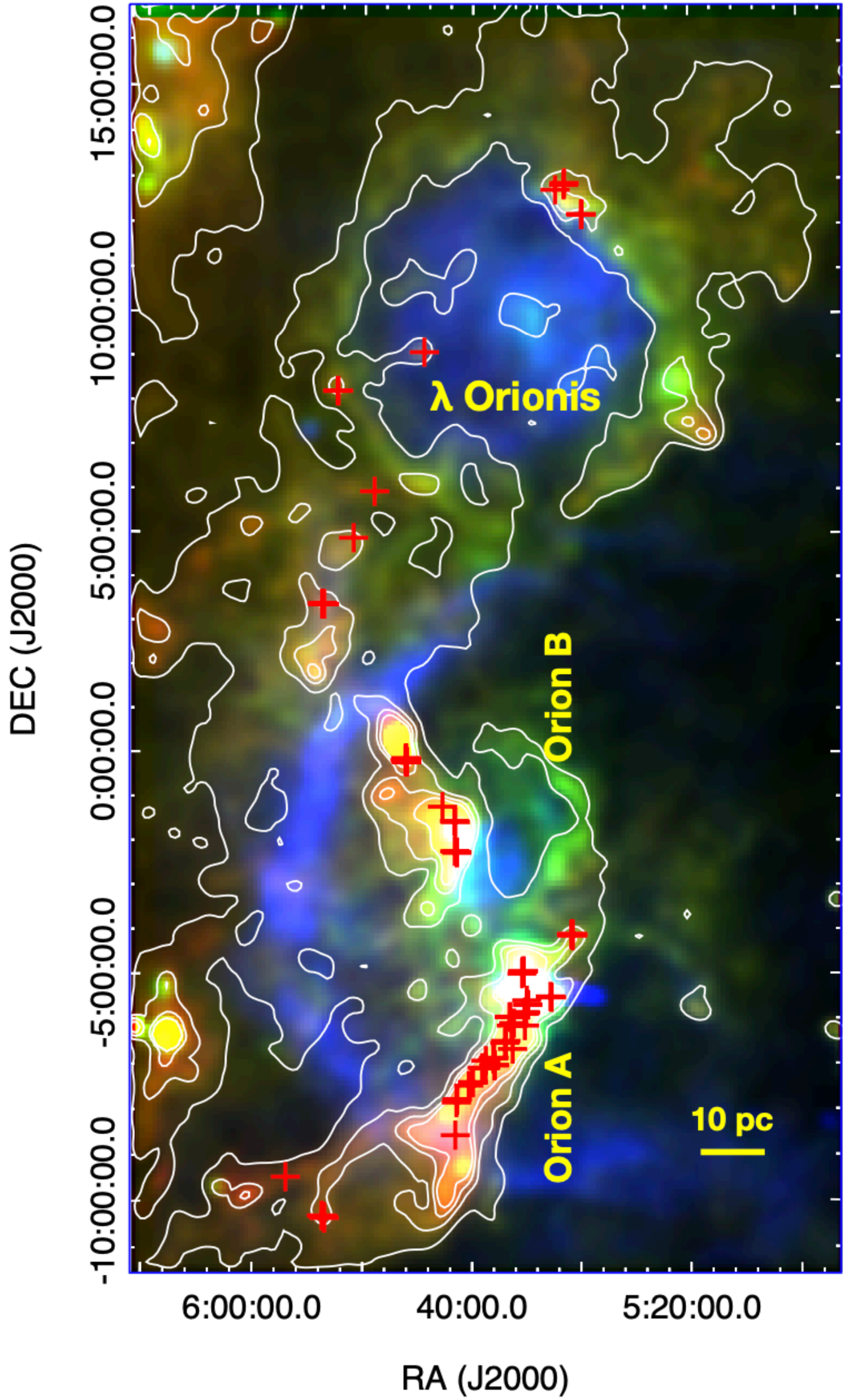
All-sky distribution of the 13188 PGCC sources (black dots), the 2000 PGCC sources selected for TOP (blue dots), and 1000 for SCOPE (pink dots) overlaid on the 857 GHz Planck map (Liu et al. 2018, ApJS, 234, 28)

The roadmap for the surveys of PGCCs

Phase 1
2012-2017
- CO lines
- 850 continuum

Phase 2
2016-2022?
- Dense gas tracers

Phase 3
2018-2024?
- Magnetic field
- Interferometers



ALMASOP cycle 6 project (PI: Tie Liu)

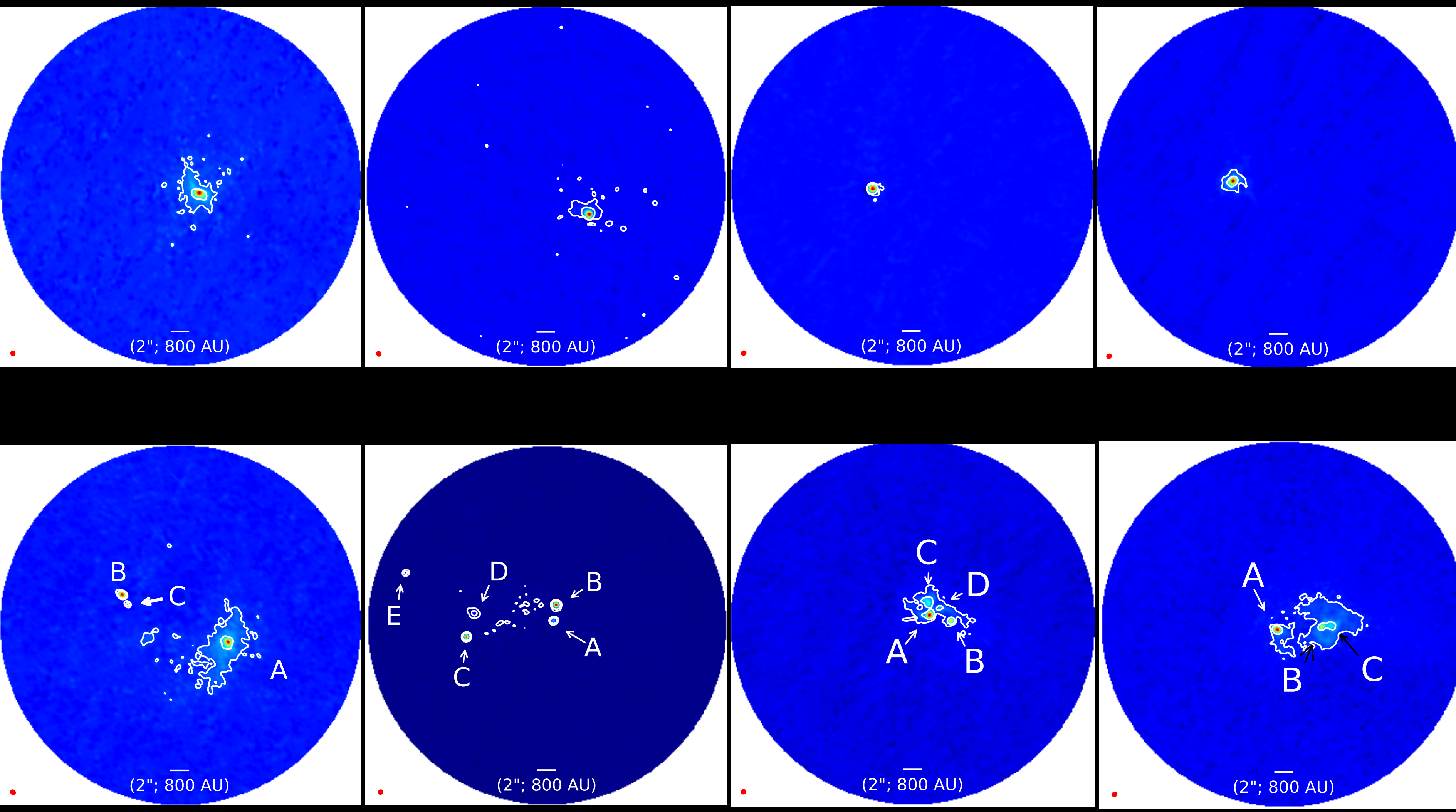
Targets:
Starless and Class 0 protostellar cores showing high [N2D+/N2H+] ratios in NRO-45m survey

ALMA 7m+12m observations:
Resolution: 0.25 arcsec (~100 au)

Tracers:
1.3 mm continuum
J=2-1 of CO, C18O
J=3-2 of N2D+, DCN, DCO+
Complex molecular lines (COMs)
Hot corino tracers like CH3OH
Shock tracers like SiO, SO, SO2

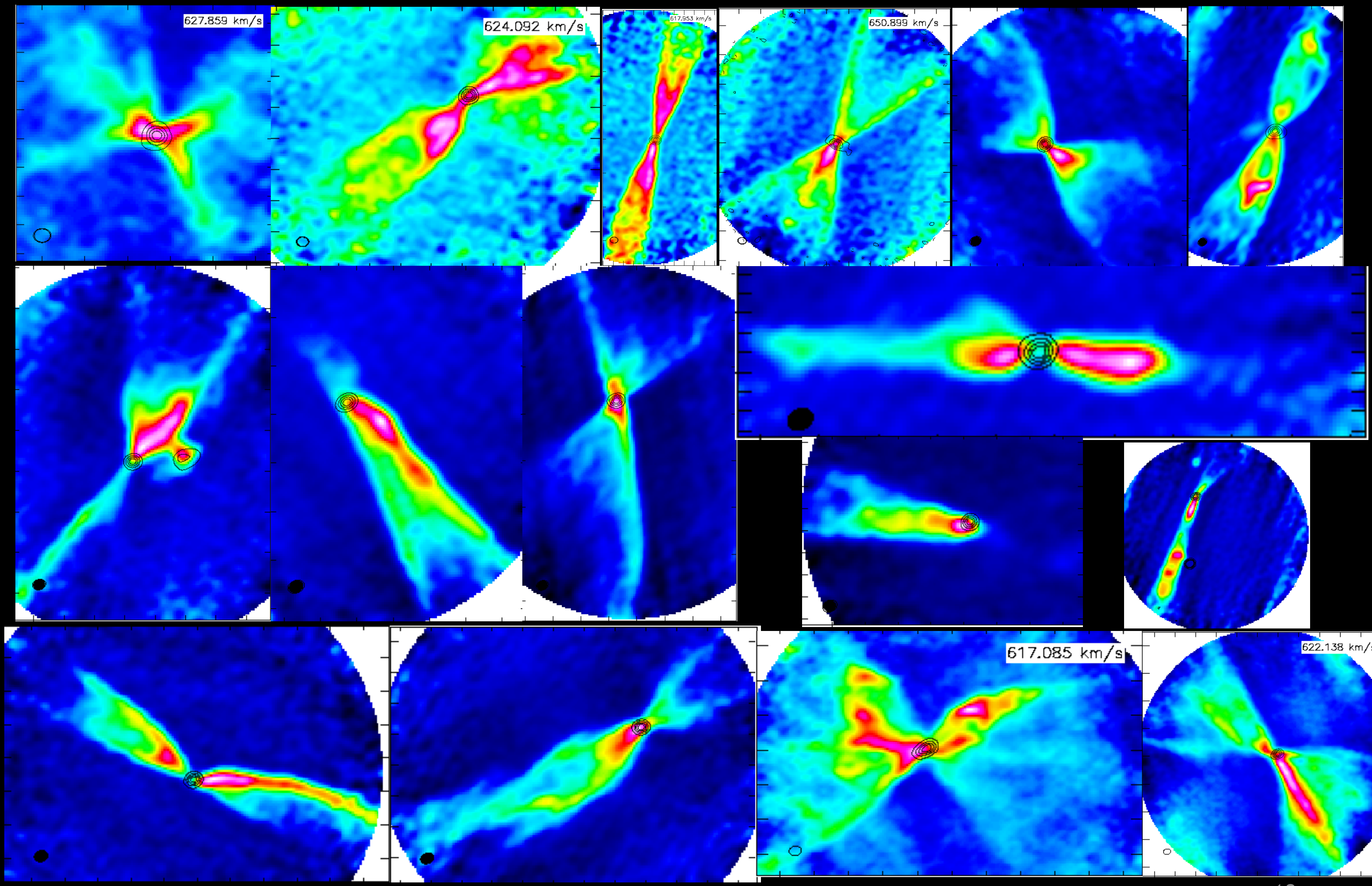
Topics:
1. Substructures and Fragmentation of starless cores
2. Early evolution of protostellar outflows and disks
3. Multiplicity of protostars
4. Chemical evolution of cores in earliest phases

2.1 Half of Class 0 protostars are in multiple systems



(Dutta+Liu+2020)

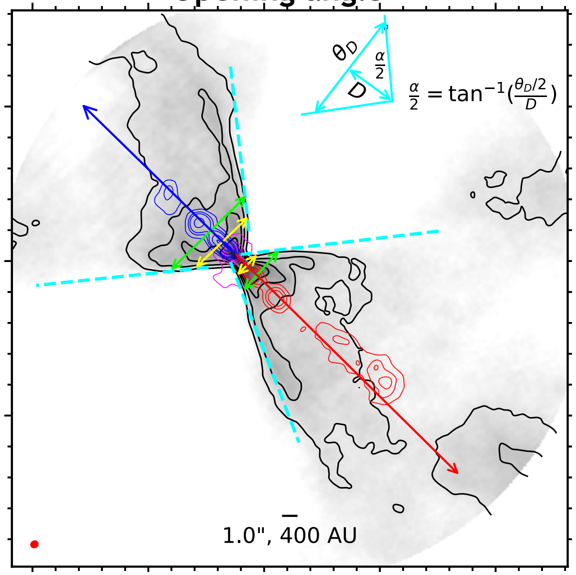
2.2 Class 0 protostellar outflows



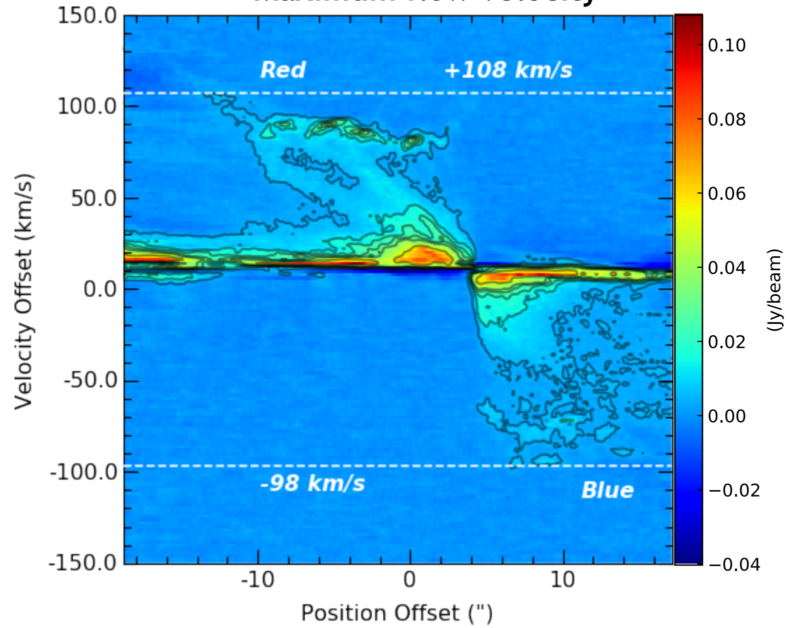
(Dutta+Liu+2020)

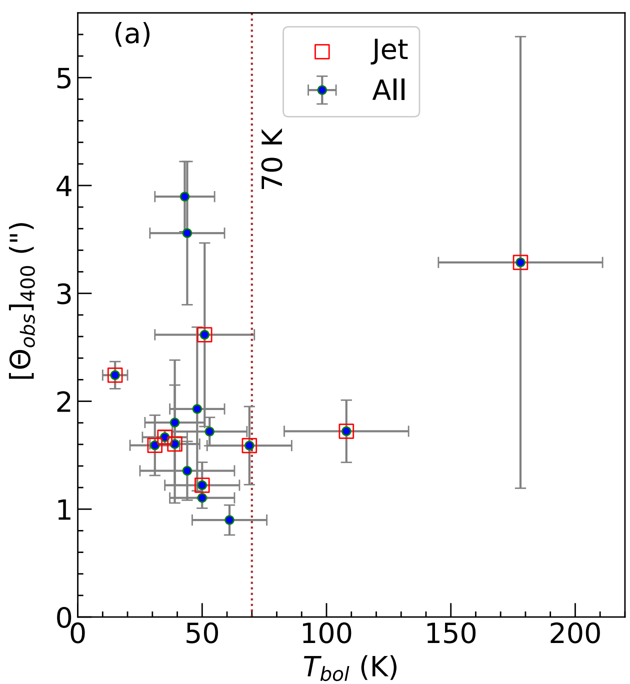
Outflow properties

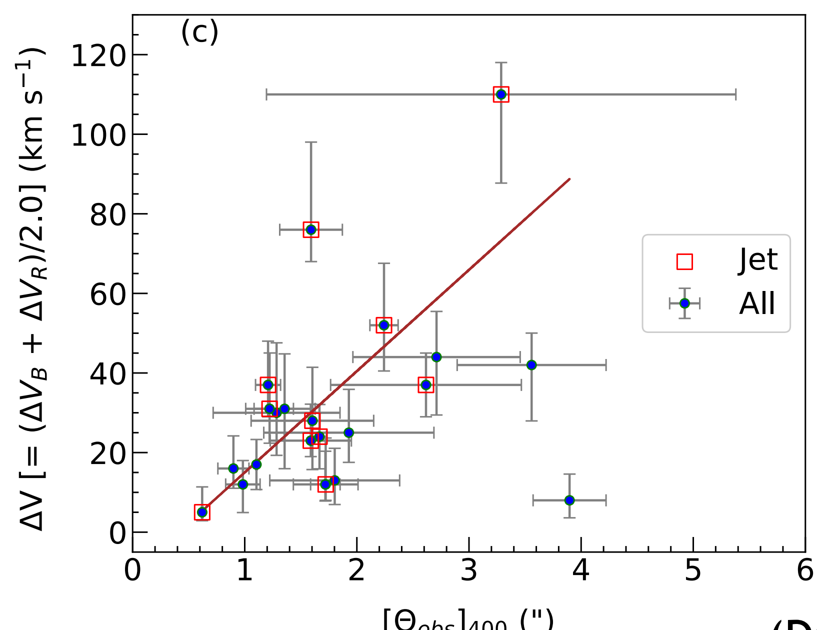
Opening angle



Maximum flow velocity

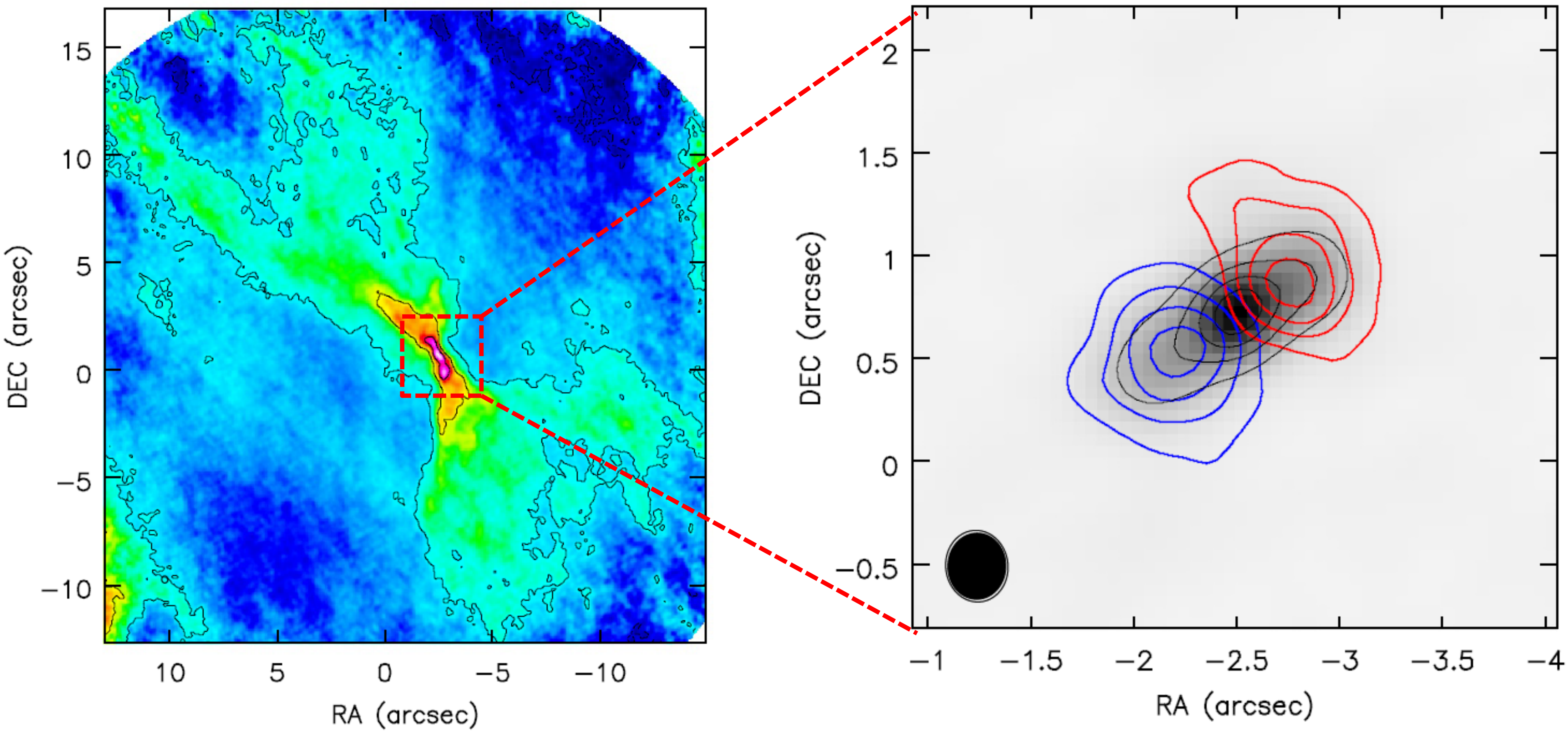






(Dutta+2020)

2.3 Large disk surrounding Class 0 protostar



We detected large Class 0 disks with sizes>100 au

(Dutta+Liu+2020)

2.4 Chemistry of hot corinos(Hsu+Liu+2020)

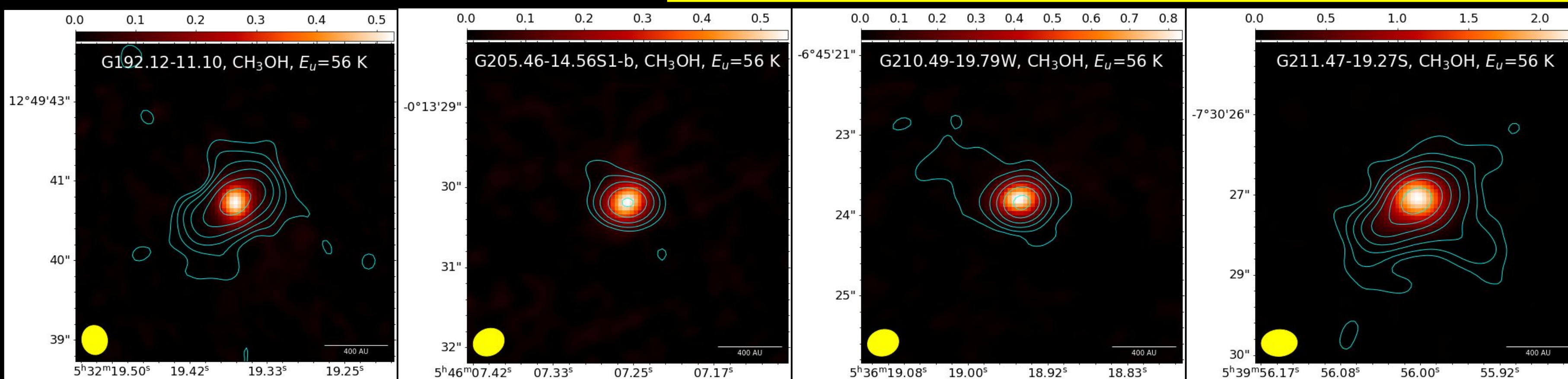
We have detected four new hot corinos in Orion clouds. They could be good sites to search for organic molecules and molecules of prebiotic interest.
No luminosity threshold (4 Lsun; Belloche+2020) for hot corinos.

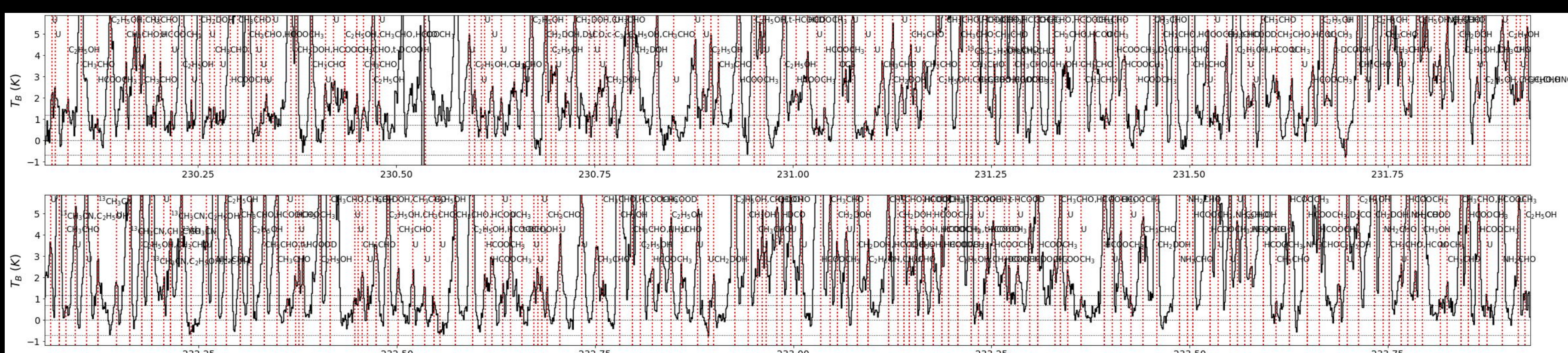
Identified molecules：

Organic molecules：CH3OH, CH2DOH, (13)CH3OH, C2H5OH? CH3CHO， CH3OCHO，NH2CHO (甲酰胺)

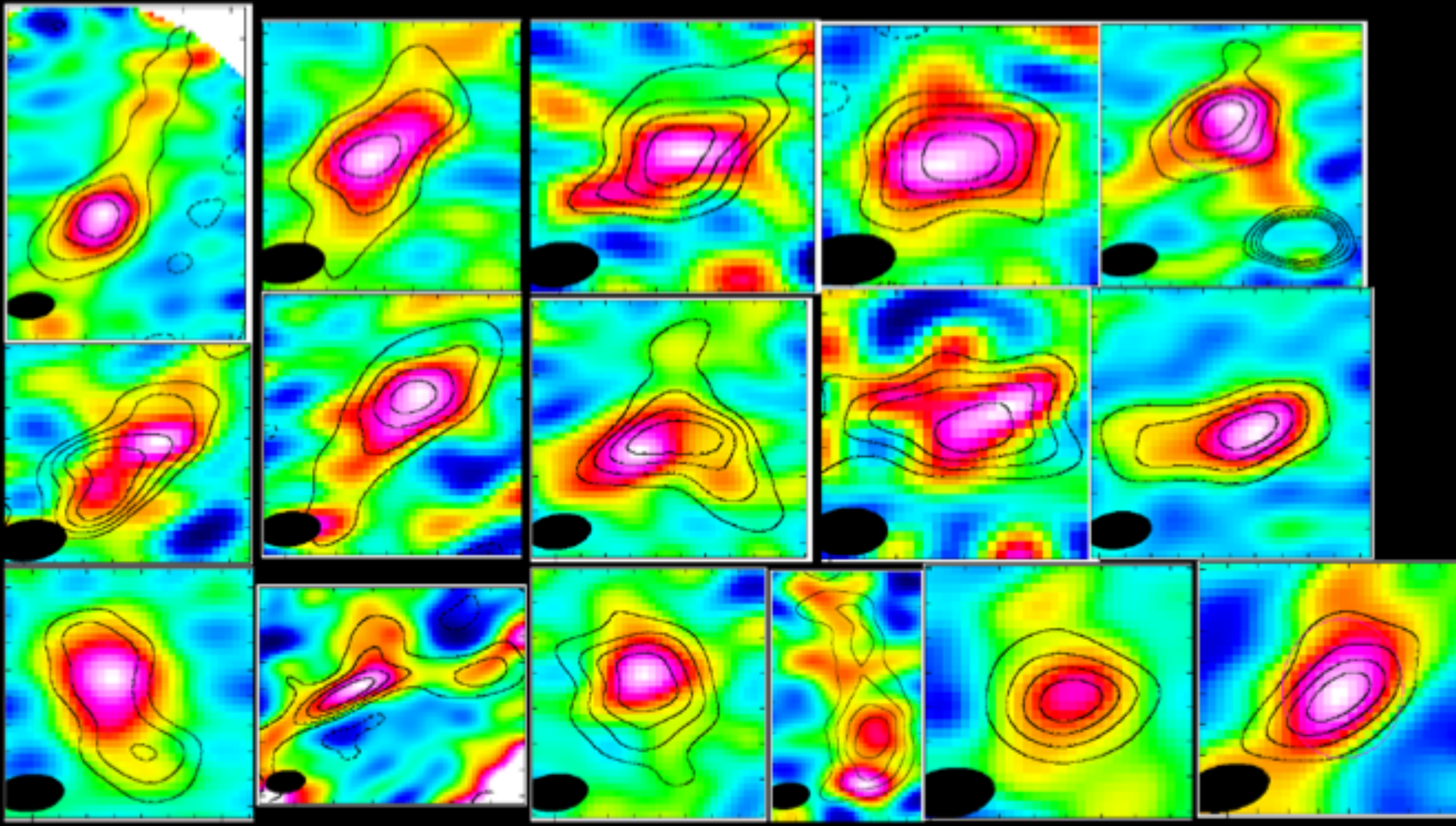
Long carbon-chain lines：HC3N

Other simple lines：
H2CO, D2CO,CO, C(18)O,H2S, (13)CS, OCS, (34)SO, SO2，DCN, HNCO, N2D+, SiO





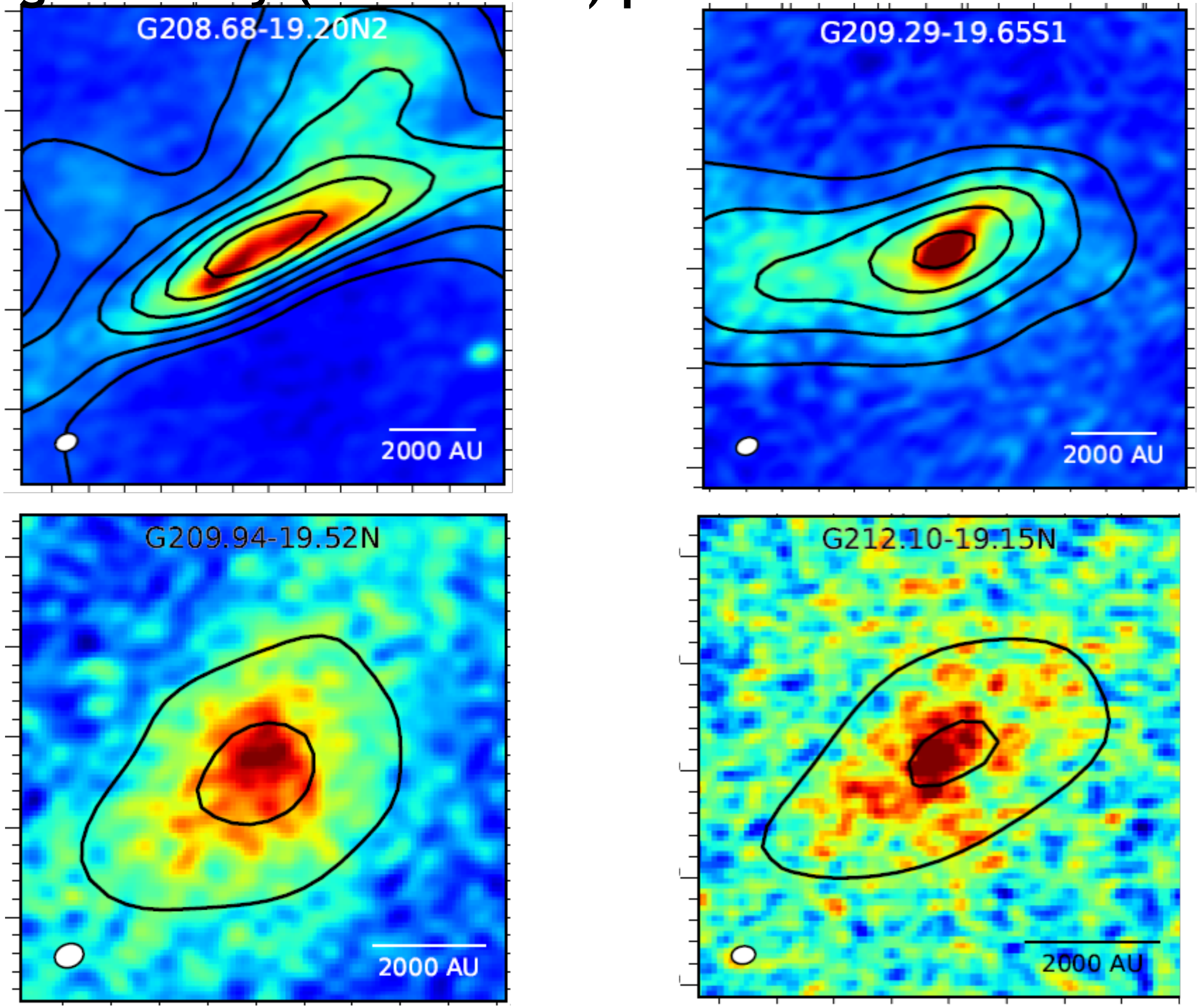
2.5 ALMA/ACA observations of starless cores



color images: N2D+ (3-2) emission; contours: 1.3 mm continuum emission

23 starless cores observed, 16 have robust detection in both continuum and lines with ACA. 5 detected with ALMA 12-m array (~100 AU resolution)!

High density ($n>10^7$ cm^{-3}) prestellar cores in ALMASOP



1.3 mm continuum emission of four prestellar cores. (Sahu+Liu+2020, ApJL, submitted)
Contours: ACA observations; color images: ACA+12m observations

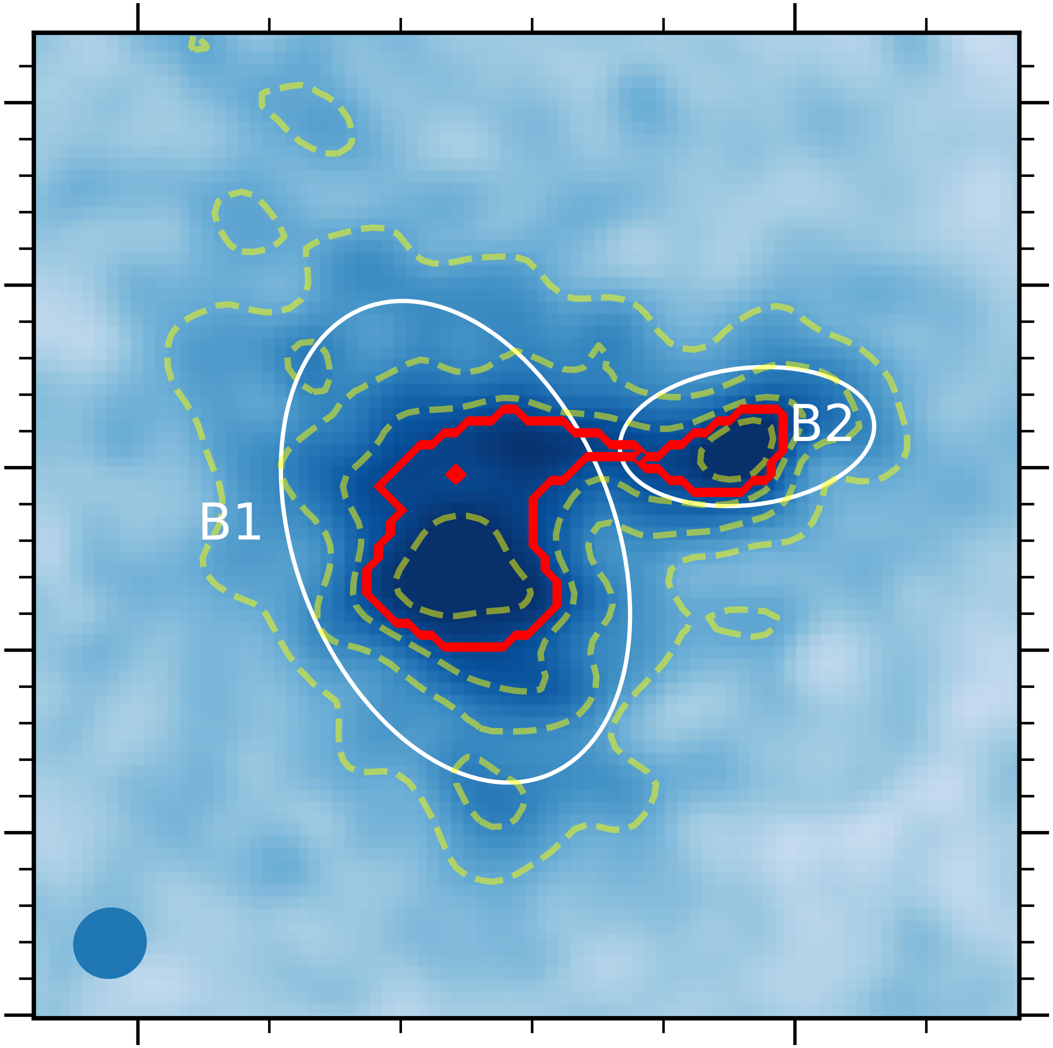
Extremely High-density prestellar cores

Source	FWHM	S_ν(1.3 mm)	M_{gas}	n_{H2}	N_{H2}	Diameter	L_J *
	($''$)	(mJy)	($M_\odot$)	(cm^{-3})	(cm^{-2})	(au)	(au)
			ACA results				
G205.46-14.56M3	8.4×7.0	79.8	0.76-1.69	$6.4 - 14.2 \times 10^6$	$1.9 - 4.34 \times 10^{23}$	3067	1561
G208.68-19.20N2	26.7×7.7	724.0	6.93-15.36	$8.9 - 19.7 \times 10^6$	$5.1 - 11.3 \times 10^{23}$	5735	1325
G209.29-19.65S1	21.5×7.5	266.0	2.55-5.64	$4.7 - 10.4 \times 10^6$	$2.4 - 5.4 \times 10^{23}$	5087	1826
G209.94-19.52N	14.2×7.2	129.1	1.24-2.74	$4.5 - 9.9 \times 10^6$	$1.8 - 4.0 \times 10^{23}$	4059	1868
G212.10-19.15N1	11.6×6.0	47.1	0.45-1.00	$2.9 - 6.5 \times 10^6$	$1.0 - 2.2 \times 10^{23}$	3337	2306
			Combined ACA+TM2 results				
G205.46-14.56M3	6.0×4.8	53.2	0.51-1.13	$1.2 - 2.8 \times 10^7$	$2.7 - 5.9 \times 10^{23}$	2146	1119
G208.68-19.20N2	16.3×3.6	325.0	3.11-6.89	$2.6 - 5.7 \times 10^7$	$7.9 - 17.0 \times 10^{23}$	3087	781
G209.29-19.65S1	7.8×3.9	98.6	0.94 - 2.09	$2.1 - 4.7 \times 10^7$	$4.7 - 10.0 \times 10^{23}$	2205	856
G209.94-19.52N	10.7×6.5	89.3	0.86-1.89	$0.6 - 1.2 \times 10^7$	$1.8 - 4.1 \times 10^{23}$	3344	1680
G212.10-19.15N1	7.7×4.2	31.8	0.30 - 0.67	$0.6 - 1.4 \times 10^7$	$1.4 - 3.2 \times 10^{23}$	2264	1568

- **The dense structures in the five cores have sizes significantly greater than their correspondingly Jeans lengths, implying that they are Jeans unstable.**

(Sahu+Liu+2020, ApJL, submitted)

Fragmentation of a prestellar core



turbulence has decayed at such small scale, fragmentation is regulated by thermal instability

(Sahu+Liu+2020, ApJL, submitted)

3. Summary for the ALMASOP project

- (1). ALMASOP has observed 72 cold cores in Orion clouds with extremely high-resolution (~100 au)
- (2). ALMASOP data are used for studying fragmentation of starless cores, disk formation, protostellar outflow evolution and chemical evolution of cold cores.
- (3). Early results indicate high density substructures and possible fragmentation inside five prestellar cores
- (4). Higher spatial and spectral resolution, more sensitive molecular line follow-up observations are needed to figure out the physical and chemical properties of the very inner parts of prestellar cores.

Photo taken by Tie Liu at Chajnantor plateau in 2014