SMA Observations of Protostellar Binary Systems

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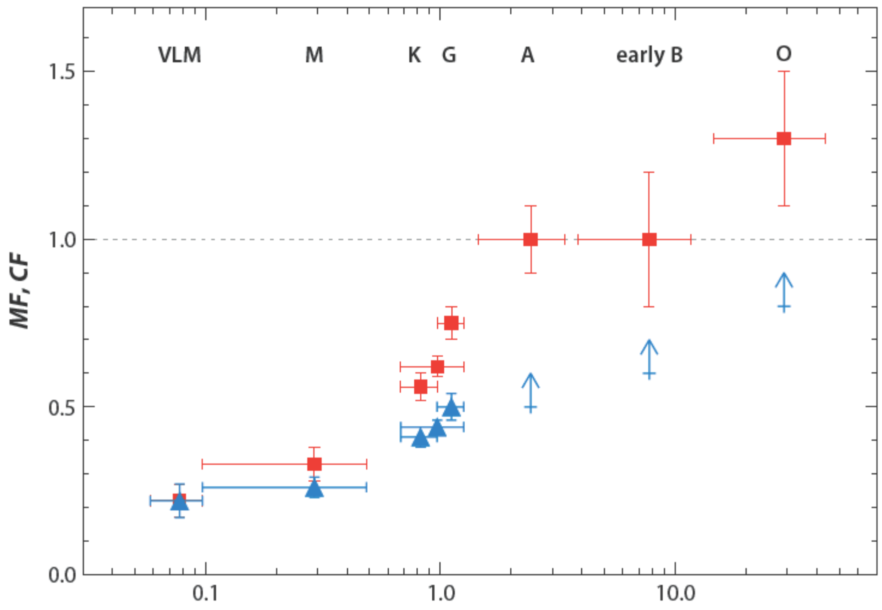
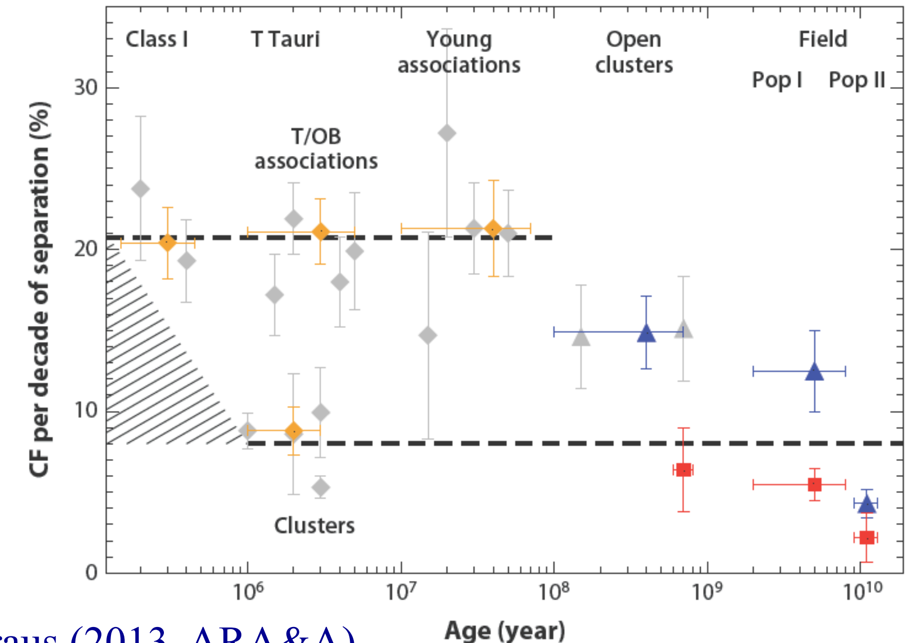
Introduction: Stellar Multiplicity

Field MS and VLM stars



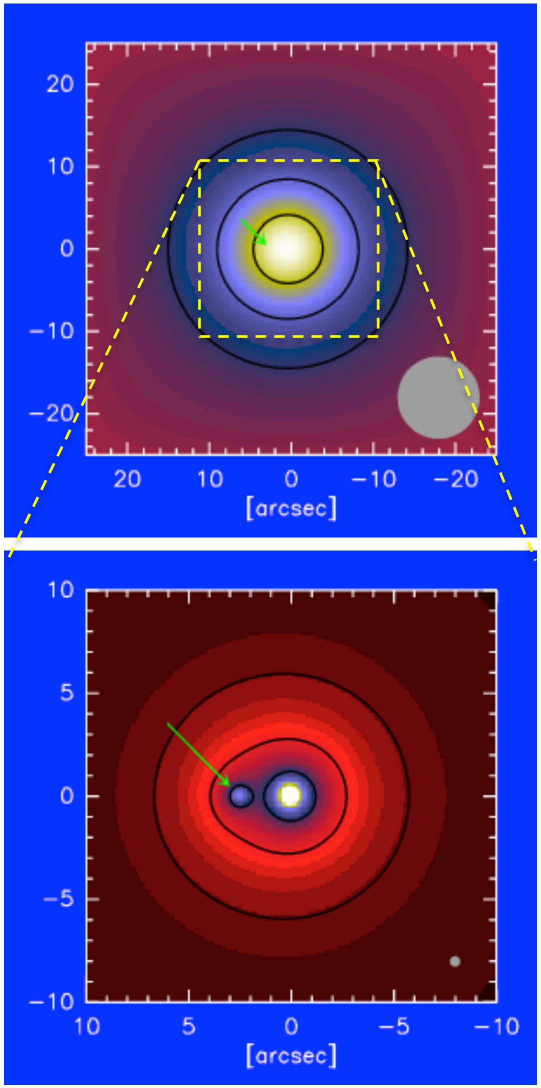


Duchene & Kraus (2013, ARA&A)

- Current knowledge of stellar multiplicity mainly relies on observations of MS/PMS stars, but multiples evolve with time (fast dynamical evolution within 10^5 yr, i.e., early Class 0 phase) → neither MS/PMS nor Class I studies cannot tell us informaiton on multiplicity formation;
- More direct observations of Class 0 protobinary systems in the past decade (e.g., Maury, Enoch, Tobin et al.)→ small samples and no statistical conclustions yet.
- Key questions about binary star formation (frequency, when, why, and how) are still in debate.

Our Program

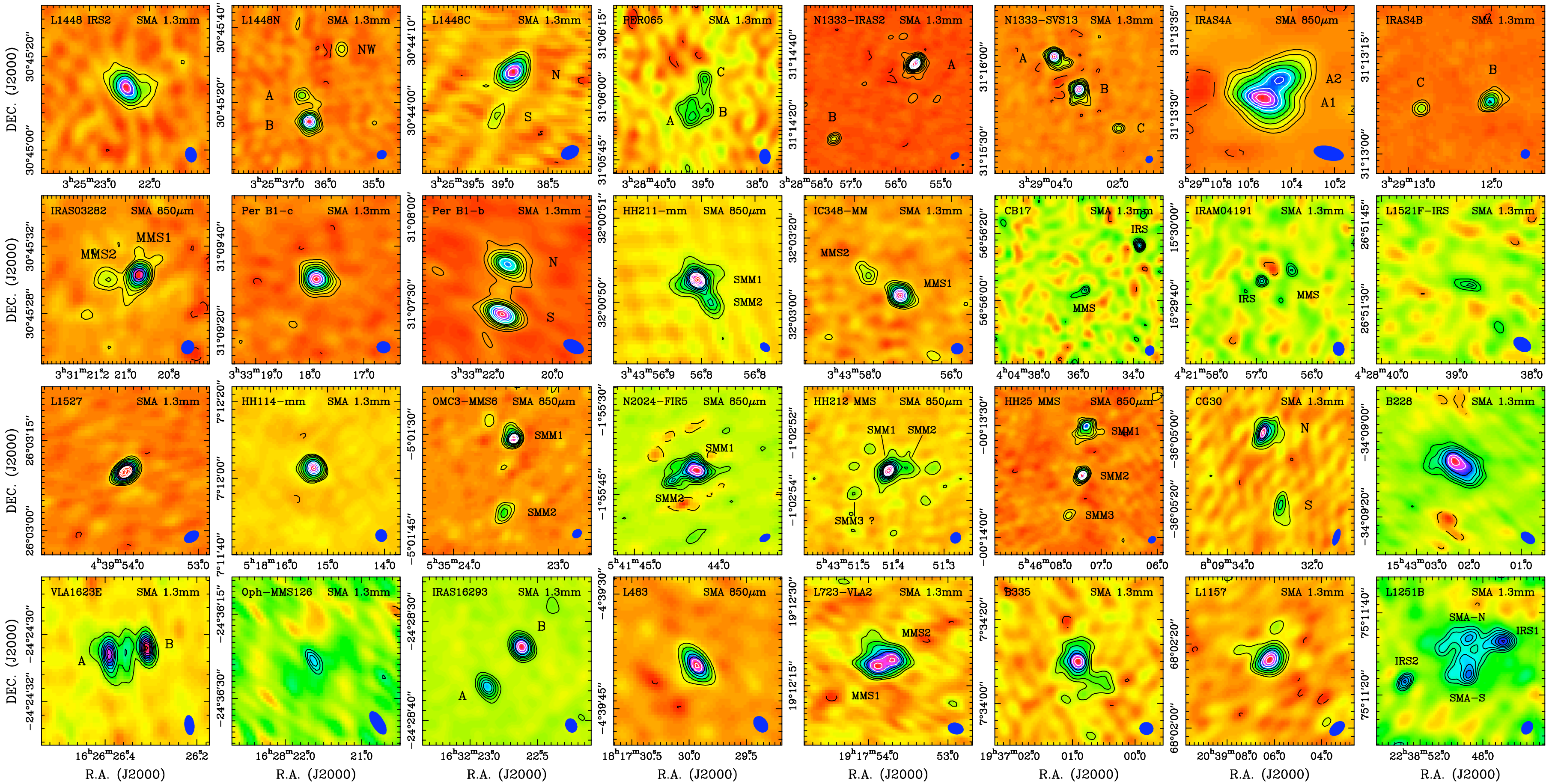
How to observe protobinaries?



(d = 2.5 arcsec, $M_2/M_1 = 0.2$)

- High angular resolution observations of a large sample of Class 0 protostars at the SMA, with complementary data from other interferometers (e.g., PdBI) and space infrared telescopes (e.g., Spitzer).
- 230 GHz (mostly) and 350 GHz: millimeter dust continuum (1.3mm and 0.85mm) and molecular lines (e.g., CO, HCO^+, and N_2D^+).

SMA Dust Continuum Survey I

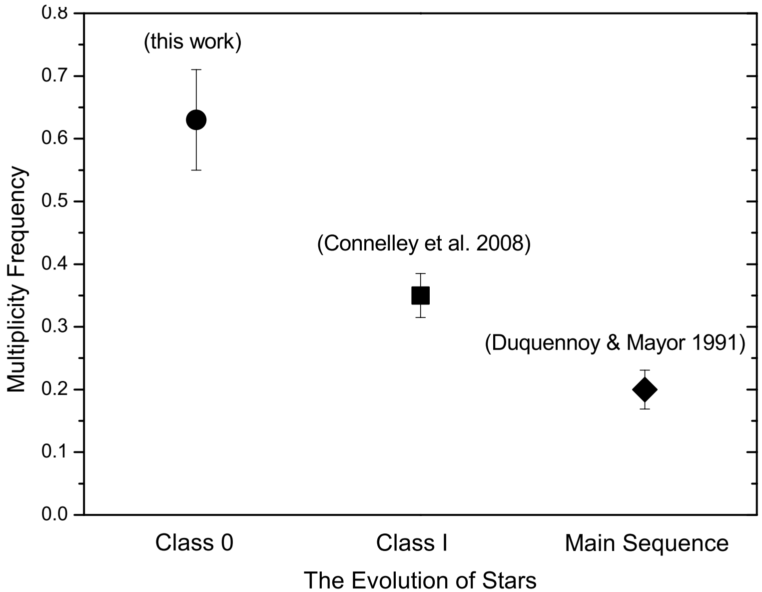


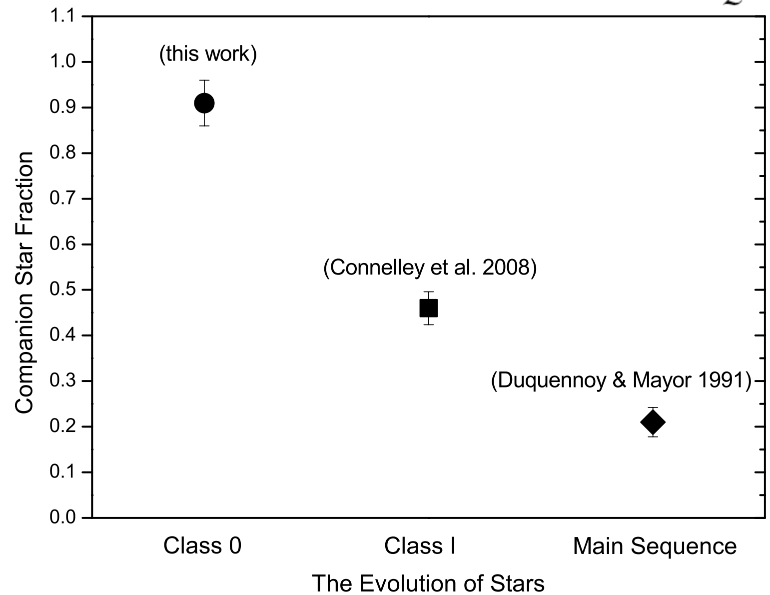
SMA dust continuum observations toward 33 Class 0 protostars in nearby star formation regions (distance < 500 pc) -- so far the largest survey toward protostellar binary systems (Chen et al. 2013; in prep.). The median angular resolution in the survey is 2.5 arcsec, while the median linear resolution is about 600 AU.

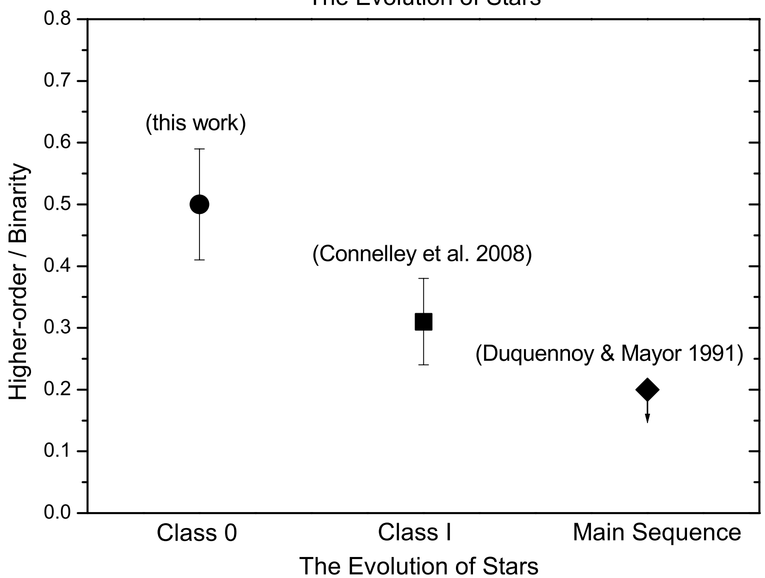
SMA Dust Continuum Survey II

$$\text{multiplicity frequency (MF)} = \frac{B+T+Q}{S+B+T+Q}$$

$$\text{companion star fraction (CSF)} = \frac{B+2T+3Q}{S+B+T+Q}$$







Twenty-one objects in the sample show signatures of binarity/multiplicity, with separations ranging from 50 to 5000 AU.

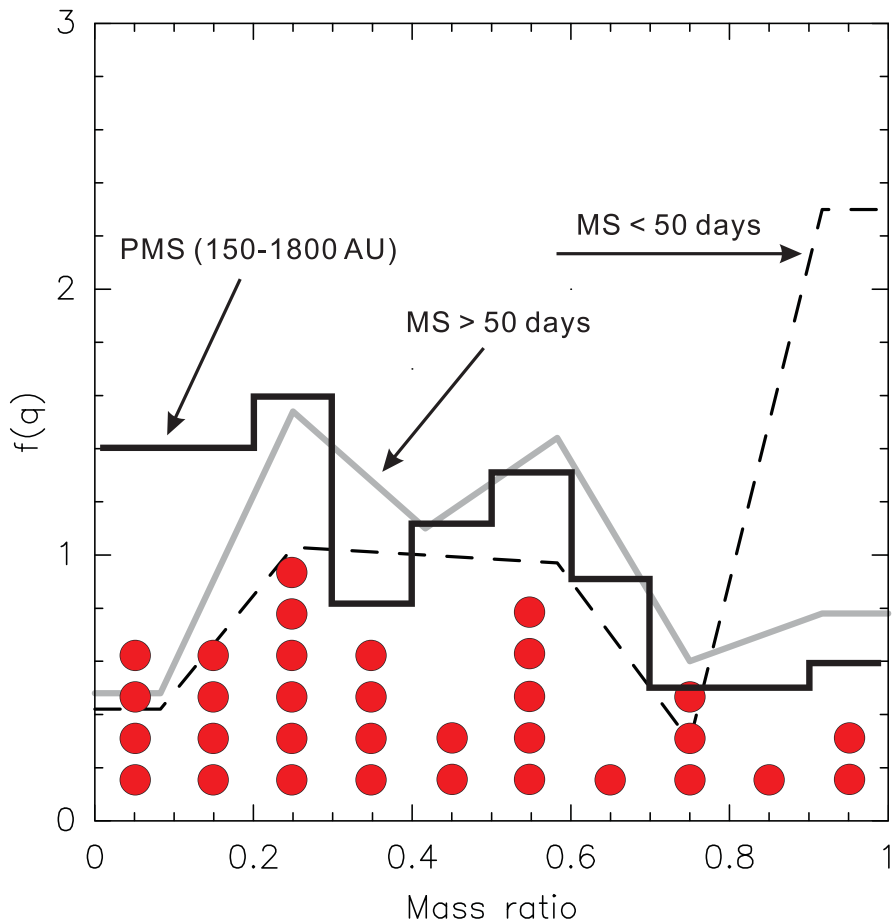
S: B: T: Q = 12: 14: 5: 2

MF = 0.64 ± 0.08 CSF = 0.91 ± 0.05

Higher-order/Binary = 0.50 ± 0.09

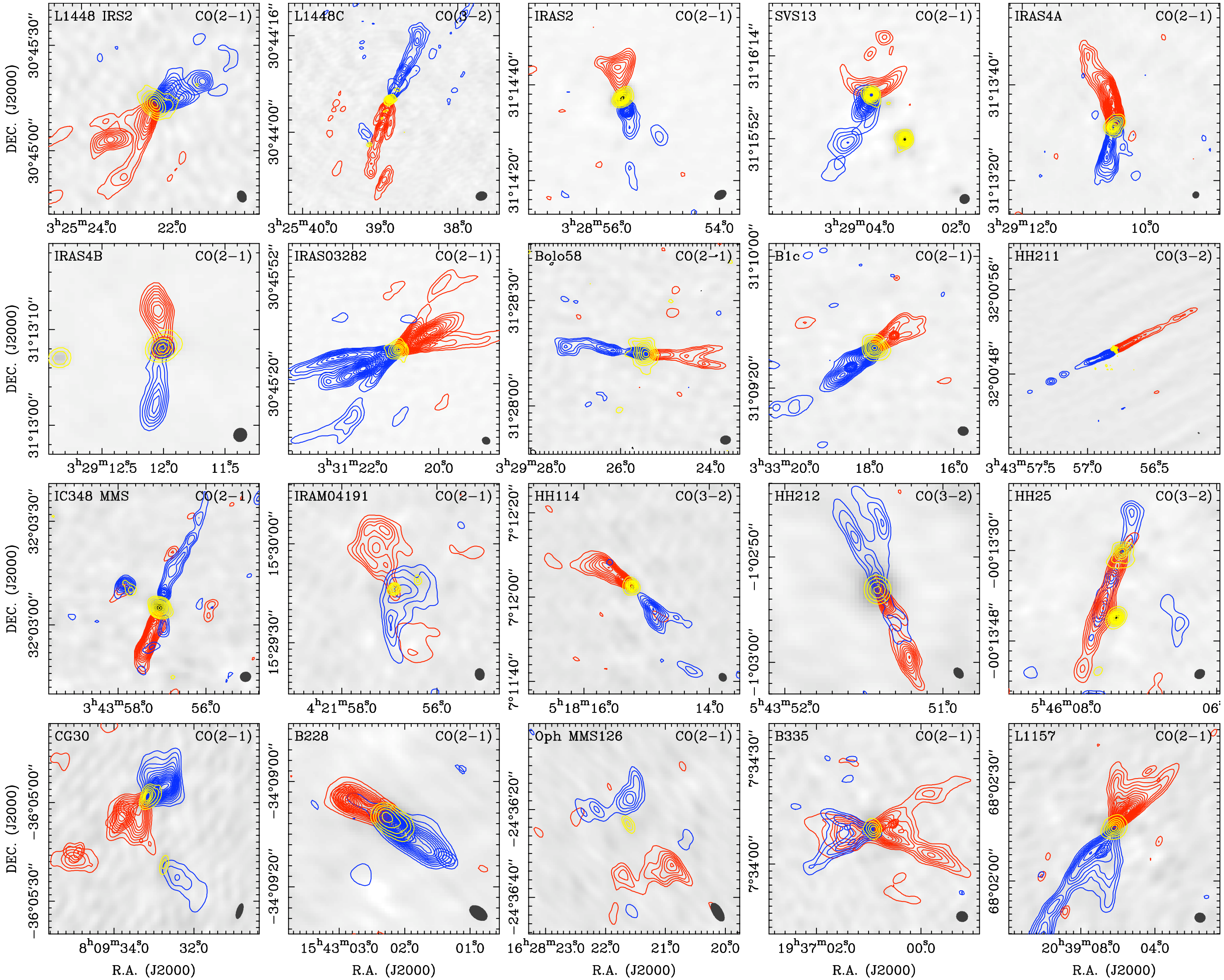
(No correction for incompleteness)

SMA Dust Continuum Survey III



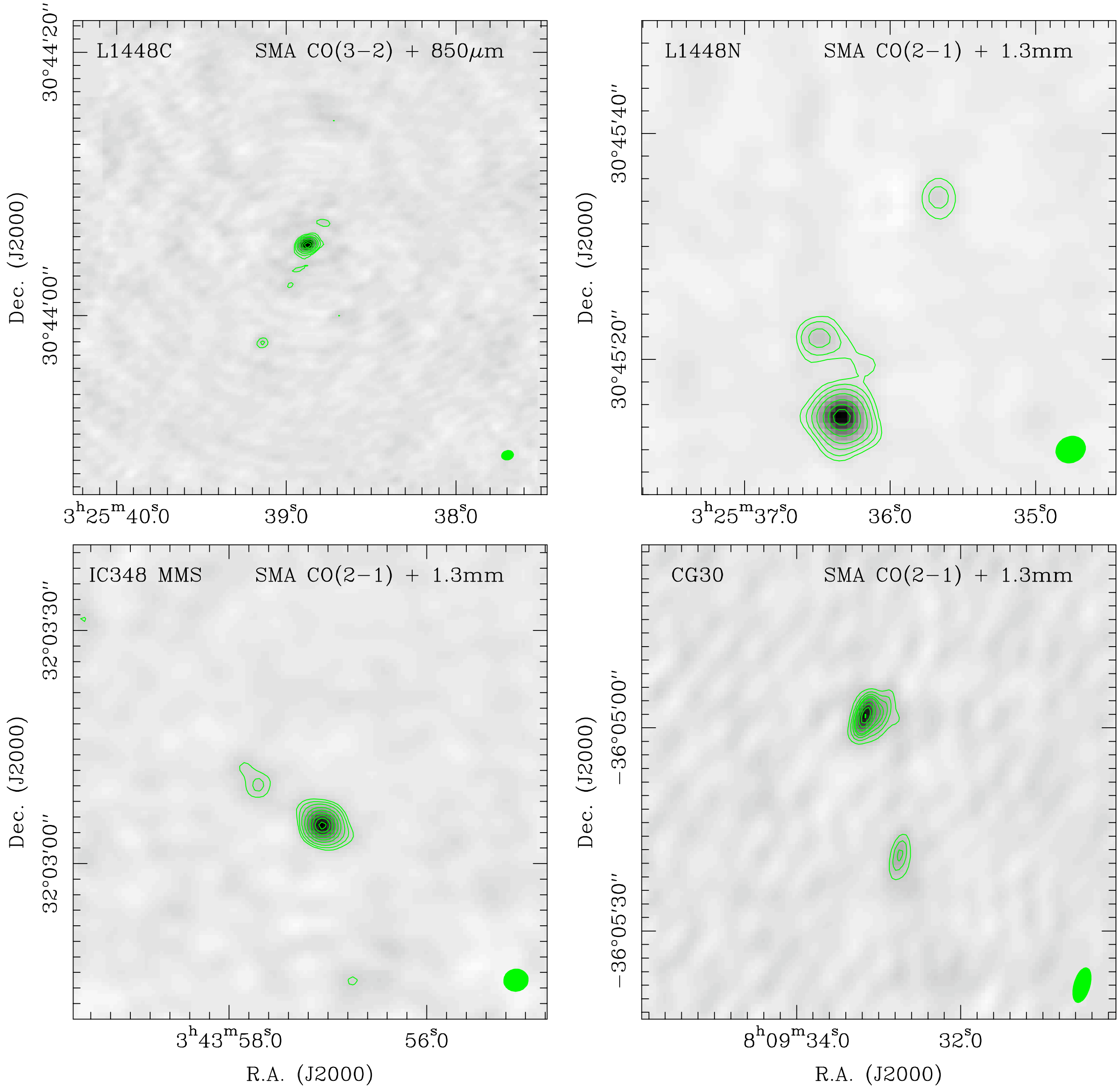
About 67% of the protobinary systems have circumstellar mass ratios below 0.5, i.e., unequal masses are much more common than equal masses. This implies that unequal-mass systems are preferred in the process of (wide) binary star formation (separation ~1000 AU).

SMA CO Survey of Protobinary Outflows

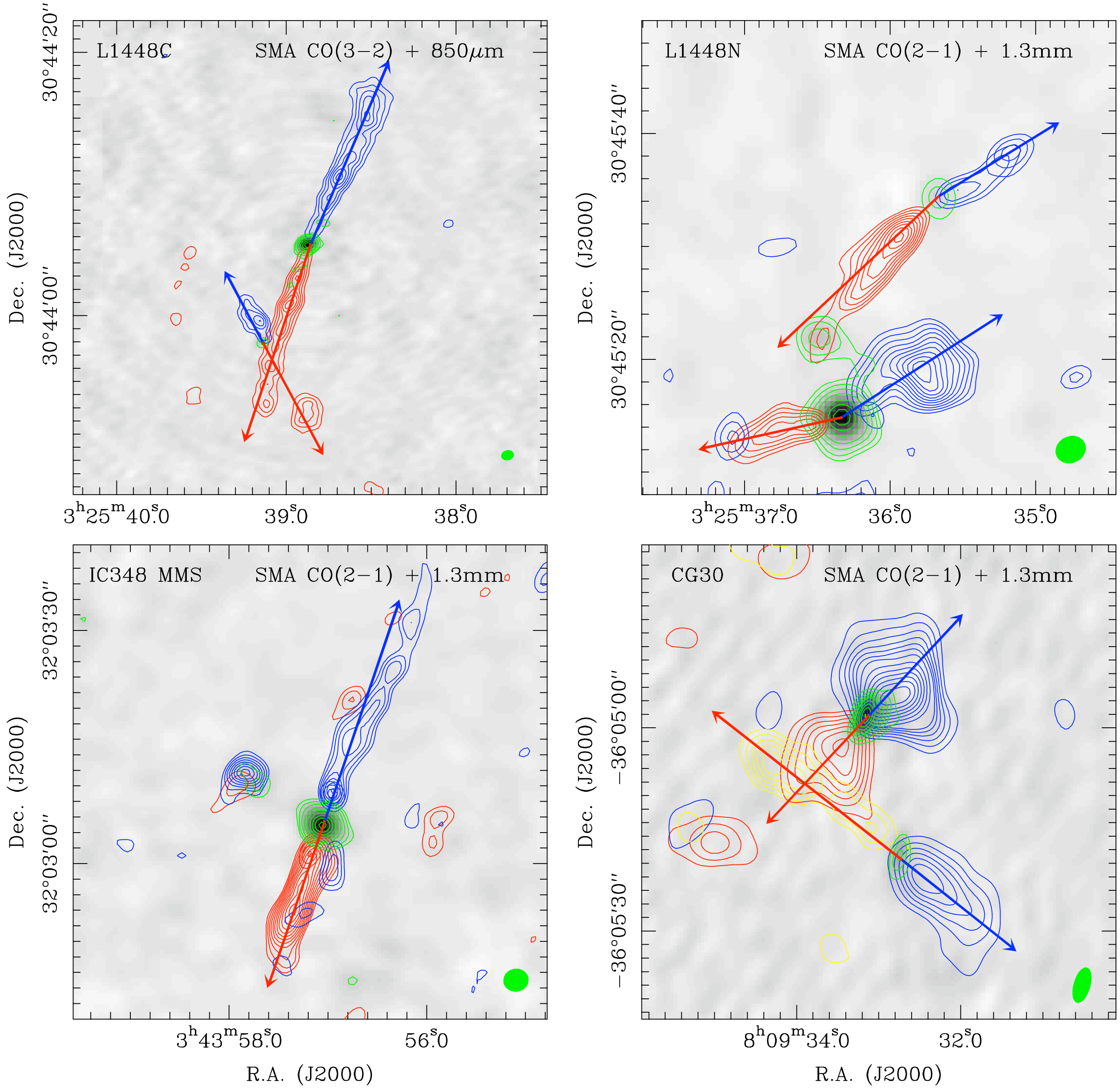


Chen et al. (in preparation)

SMA CO Survey of Protobinary Outflows



SMA CO Survey of Protobinary Outflows



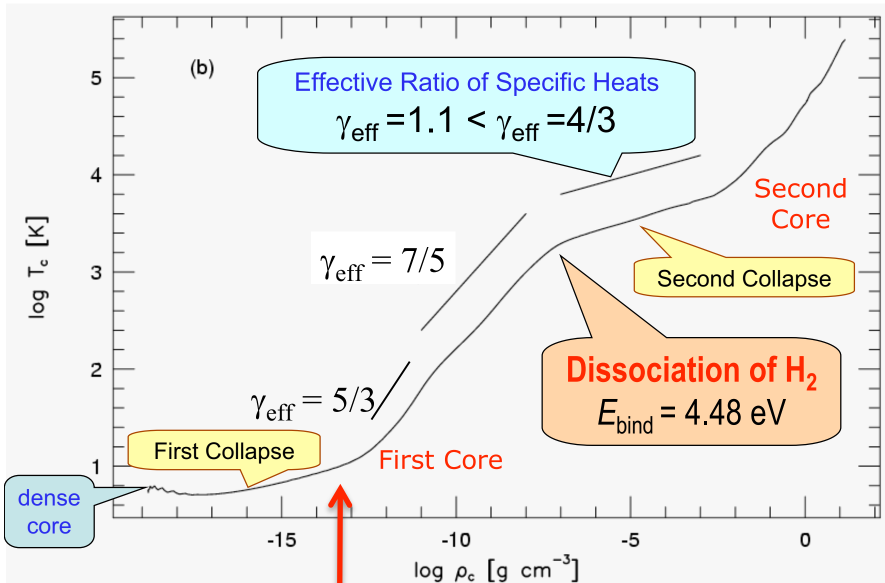
(1) Multiple outflows are frequently seen in the protobinary systems;

(2) Most protobinary systems have unequal mass components → one outflow is relatively strong and the other is weak;

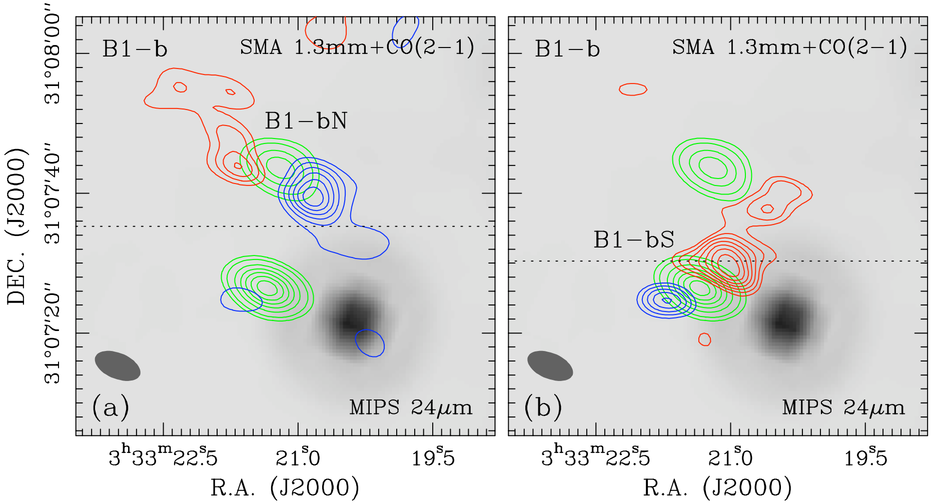
(3) Outflow axes are often NOT co-aligned! (for binaries > 100 AU) → so must be circumstellar disks and angular moment!

Chen et al. (in preparation)
Talks by Hirano & Palau

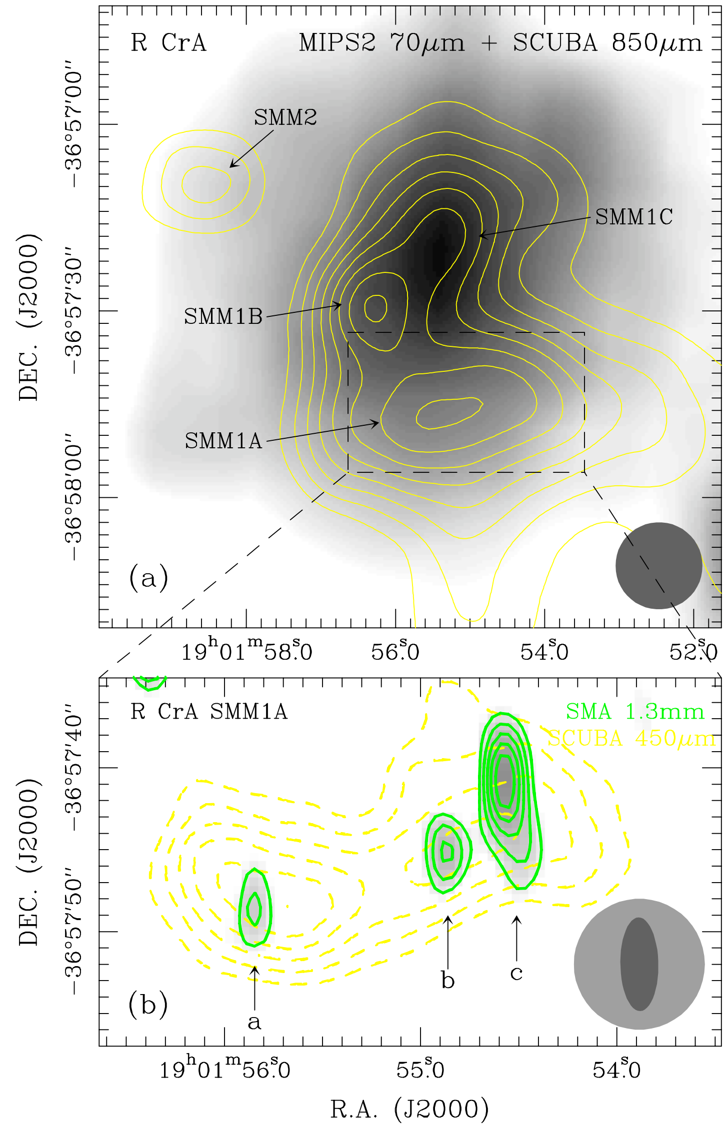
SMA Search for Binary First Cores



Prompt Fragmentation (Tohline 2002)

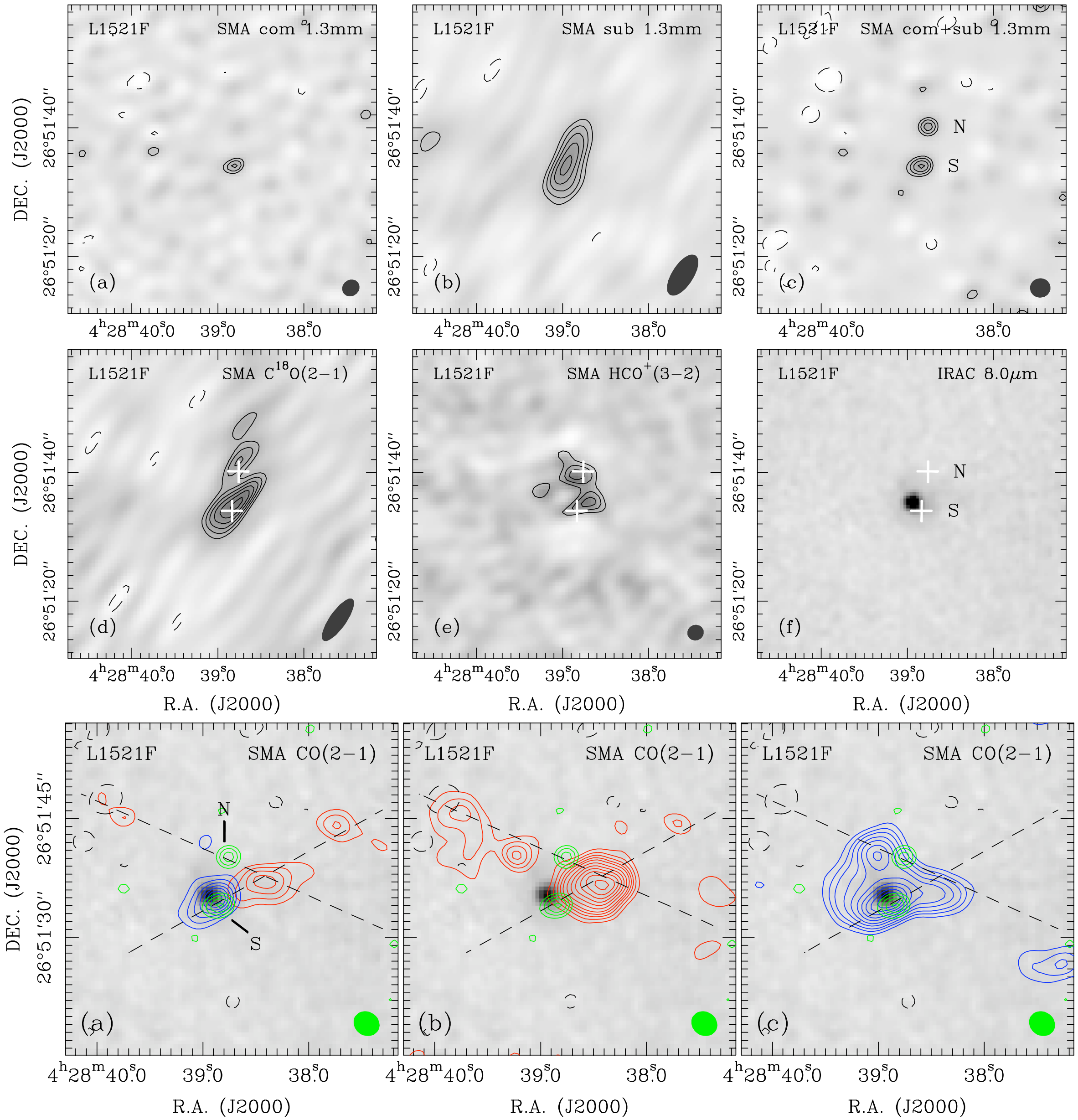


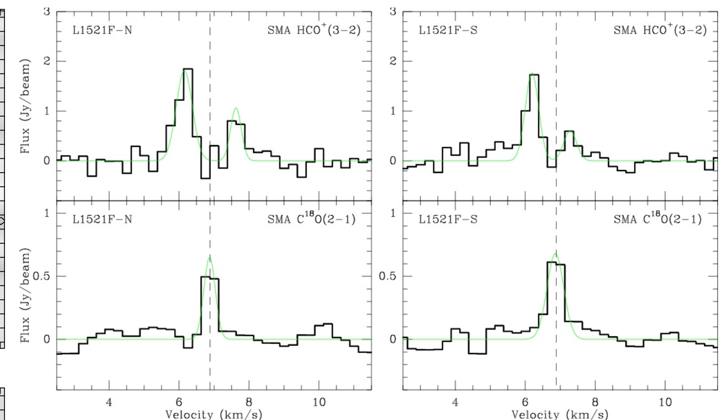
B1-b: Hirano & Liu et al. (2014); Chen et al. (in prep.)



R CrA SMM1A: Chen & Arce (2010)

SMA Search for Binary First Cores



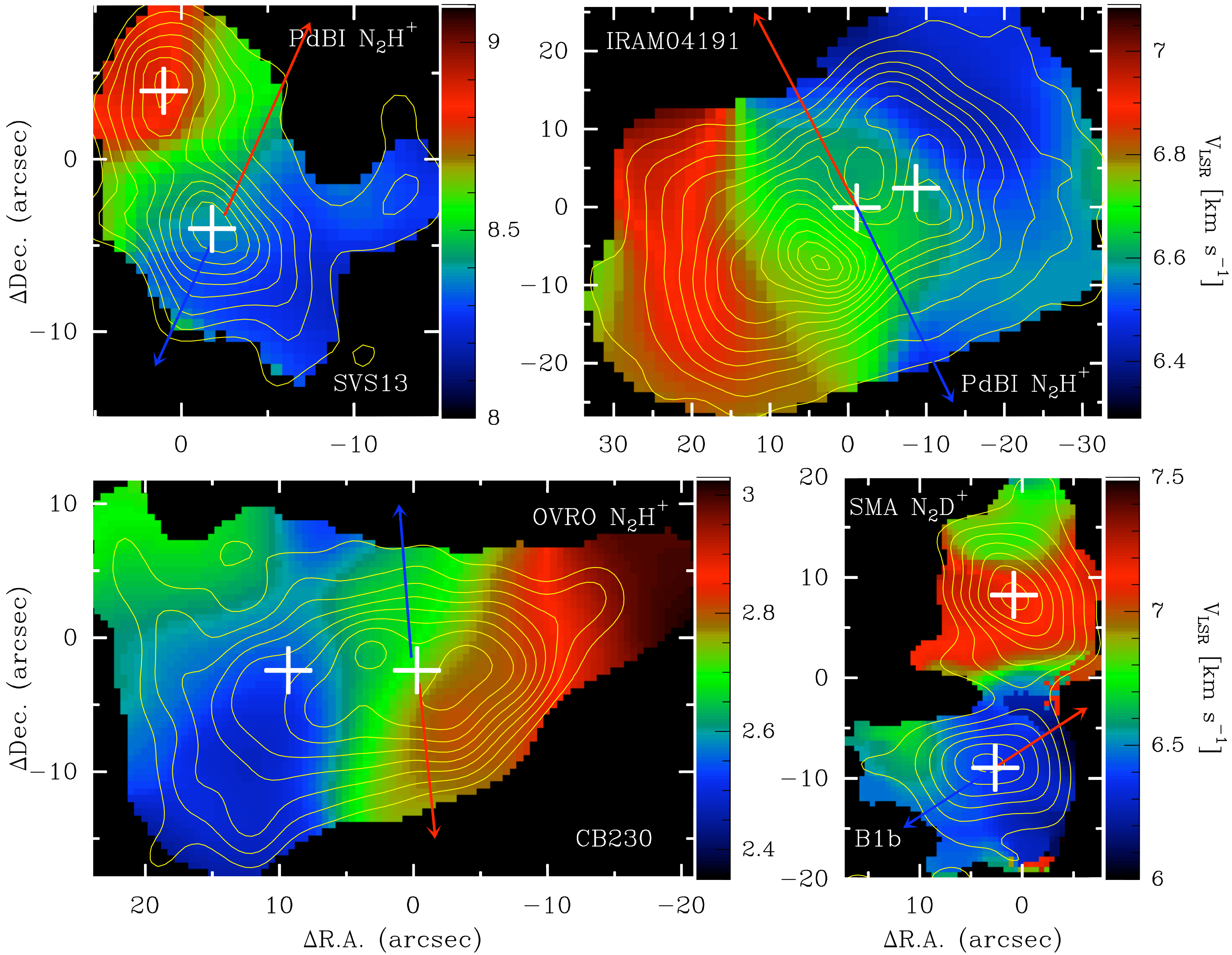


Another example L1521F: a long suggested first hydrostatic core candidate (e.g., Onishi et al. 1999) or so-called evolved starless core (e.g. Crapsi et al. 2004; 2005), see also the Spitzer observations (e.g., Bourke et al. 2006).

Recent SMA (and also ALMA) observations suggest: a binary first core with outflows.

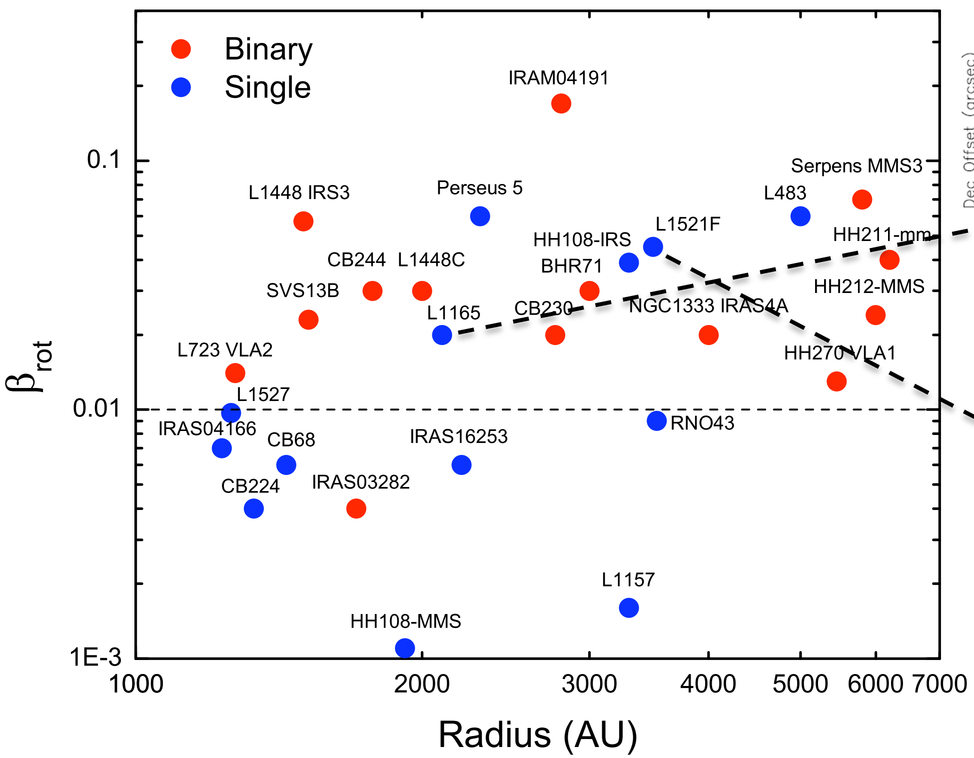
SMA data Chen et al. (2014, in prep.)
SMA data Takahashi et al. (2013)
ALMA data Tokuda et al. (2014)

Kinematics of Protobinary Systems

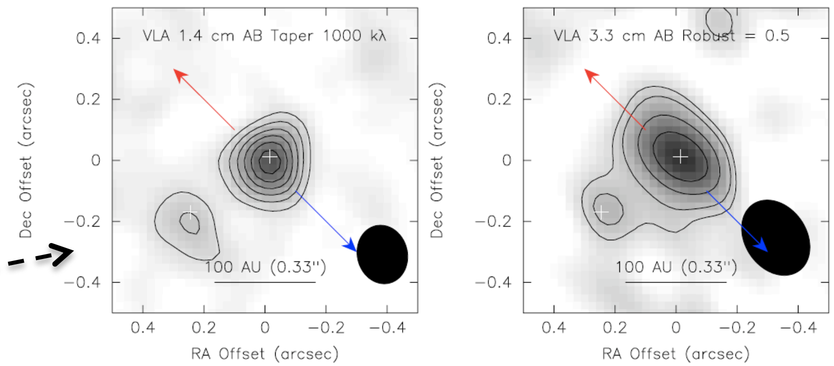


(Chen et al. 2007; 2008; 2009; 2012; Chen et al. in preparation)

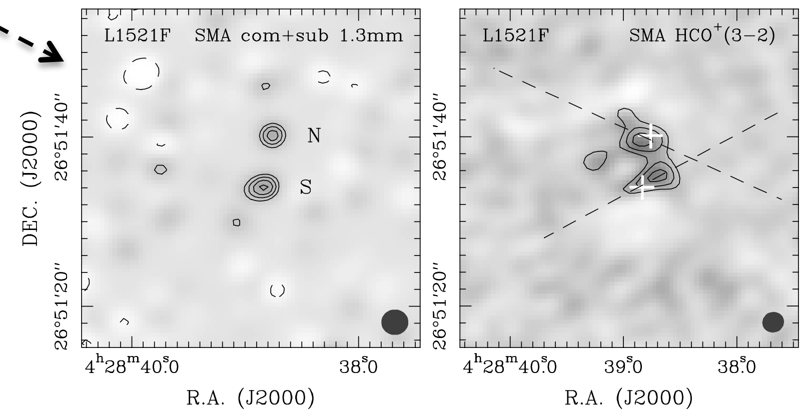
Kinematics of Protobinary Systems



Chen et al. (2012)



L1165: Tobin et al. (2013)



L1521F: Chen et al. (in prep.)

Most cores with binary systems (~1000 AU) formed therein have βrot > 1%. This is consistent with theoretical simulations (e.g., Boss et al.), and indicates that the level of rotational energy in a dense core plays an important role in the fragmentation process (see Chen et al. 2012; 2014 preparation).

Summary

(1)Frequency: About two-thirds of Class 0 protostars are binary or multiple systems in the SMA survey, with separations between 50 and 5000 AU (a lower limit only); The derived MF, CSF, and H/B are all larger than those values found in the Class I, PMS, and MS surveys, suggesting dynamical evolution at the early phase of multiplicity formation.

(2)Why: The (rotation) prompt fragmentation of molecular cloud core appears as the main mechanism of the formation of binary/multiple systems (except large-separation and extremely close systems?).

(3)When: Binary first core candidates are found in the SMA survey, implying the fragmentation of collapsing core occurs firstly at the end of isothermal collapse phase.

(4)How: During the fragmentation, both mass and angular momentum are unevenly distributed, as unequal-mass systems and un-aligned outflows systems are frequently seen in the SMA survey.

Thank you!