

Multiplicity at early stages of star formation, small clusters

Observations Overview

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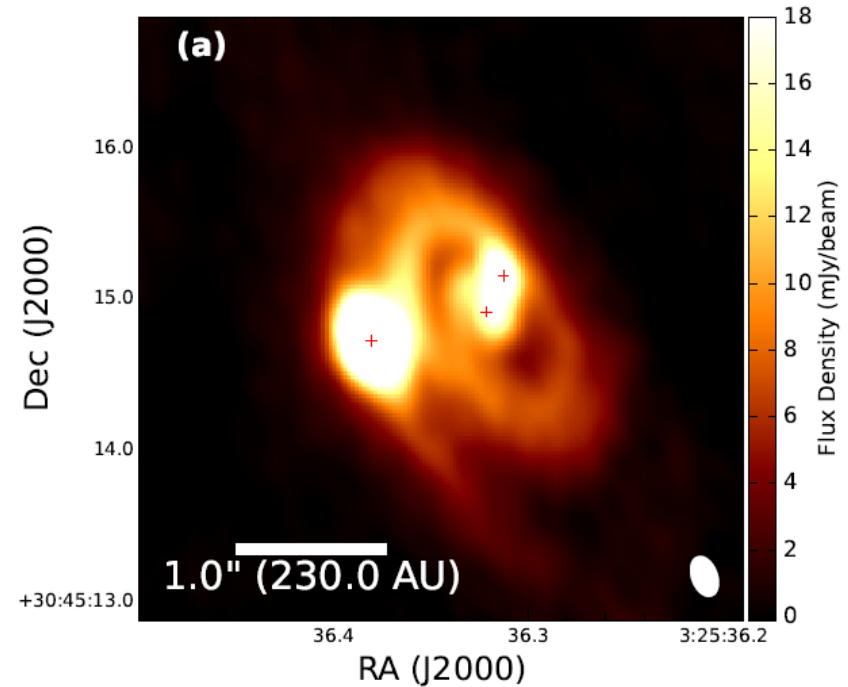
Outline

1. Recent progress in multiple Star formation
2. SOLA binary survey
3. L1551 NE (detailed study)
4. Future Study and Summary

1. Recent progress in multiple star formation

Multiple Star formation

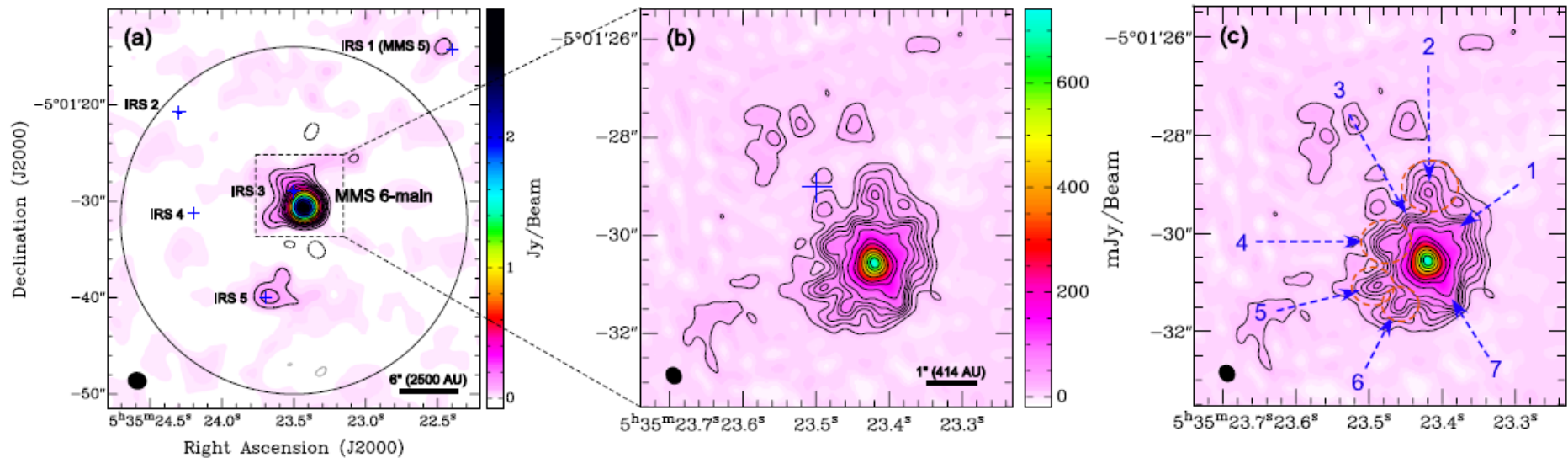
- Multiple Star formation
 - Ubiquitous
 - Majority
 - Related to IMF
 - Binary, triple, cluster, and higher order
- Laboratory to test stellar evolution at young phase.



L1448 IRS3B (Tobin+16)

Embedded Cluster

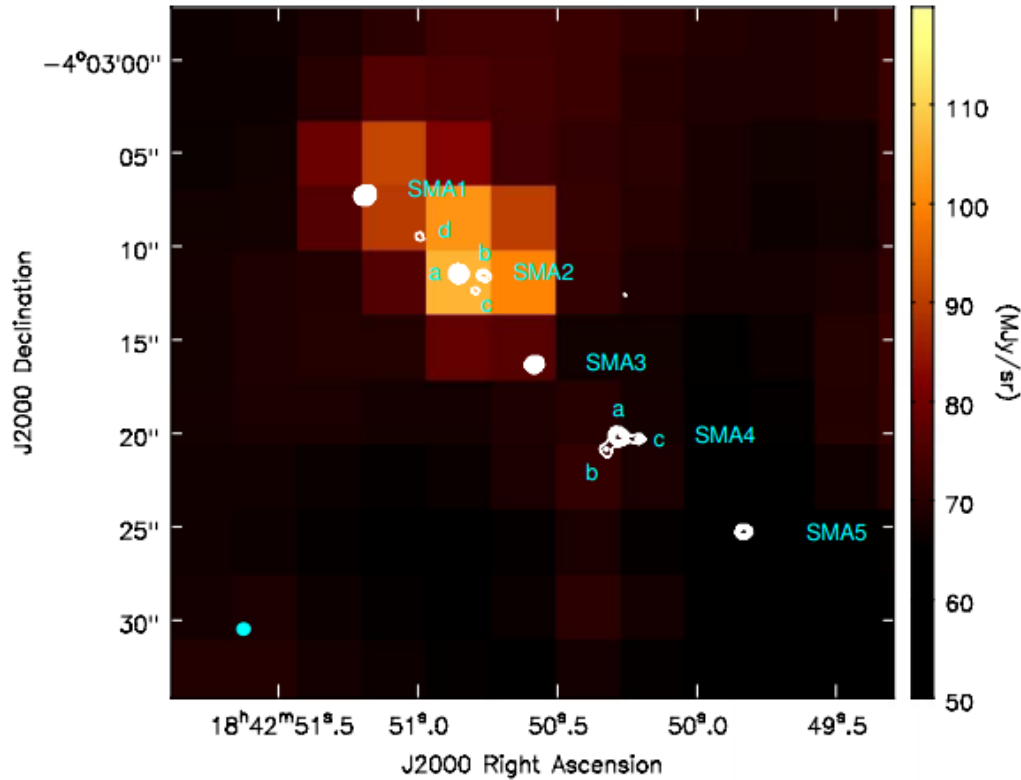
- Higher angular resolution, more compact objects



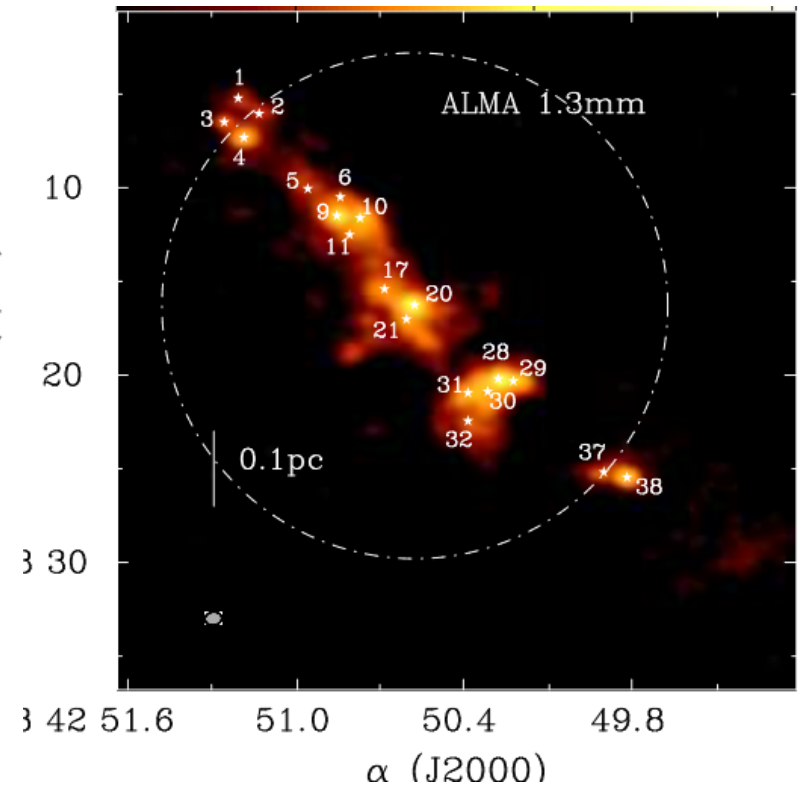
- MMS6 in Orion 2/3 by Takahashi+12 (SMA)

Young cluster in Pre-ALMA and ALMA era

Infrared Dark Cloud G28.53-0.25



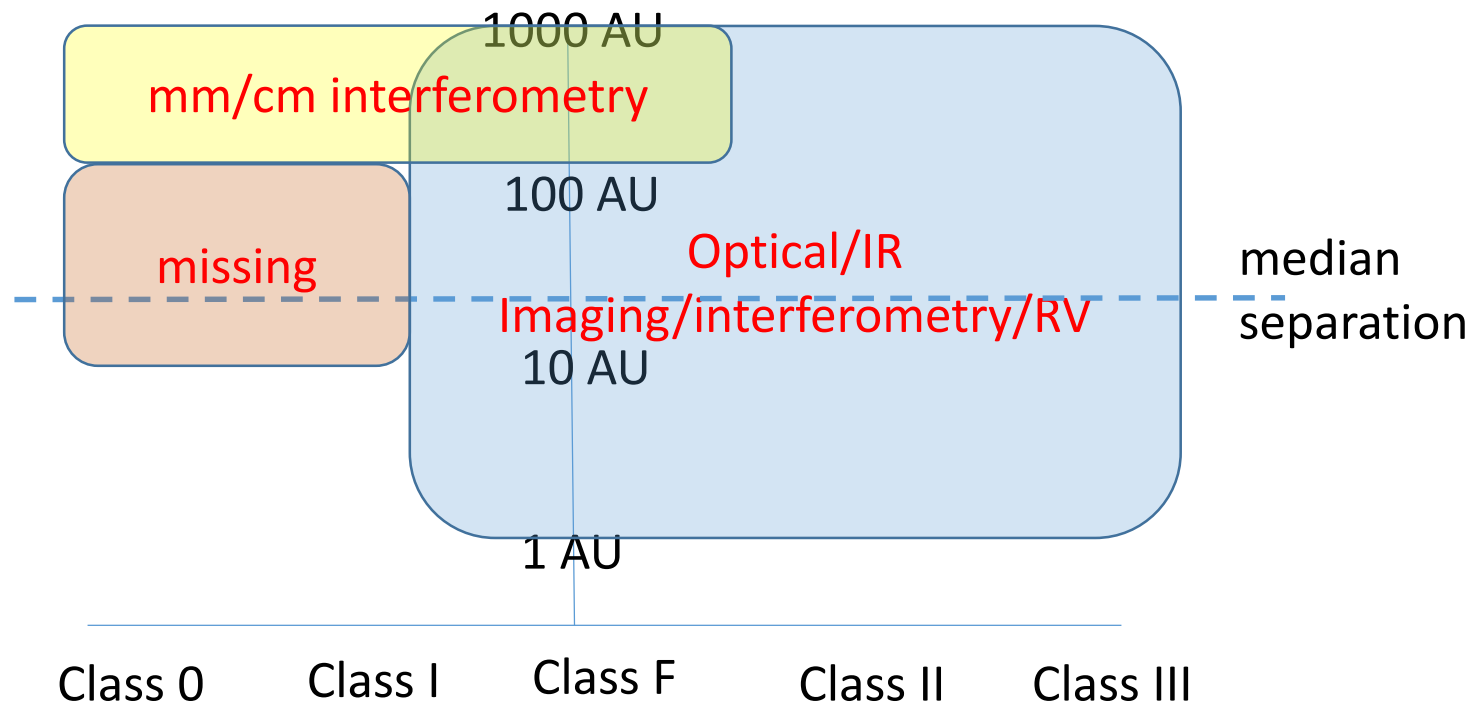
Ke+11 (SMA)



Xing+15 (ALMA)

Binary Identification before PPVI

- Characterization of Young Binary Systems
- Fraction, Separation, Age, Primary Mass, Mass Ratio

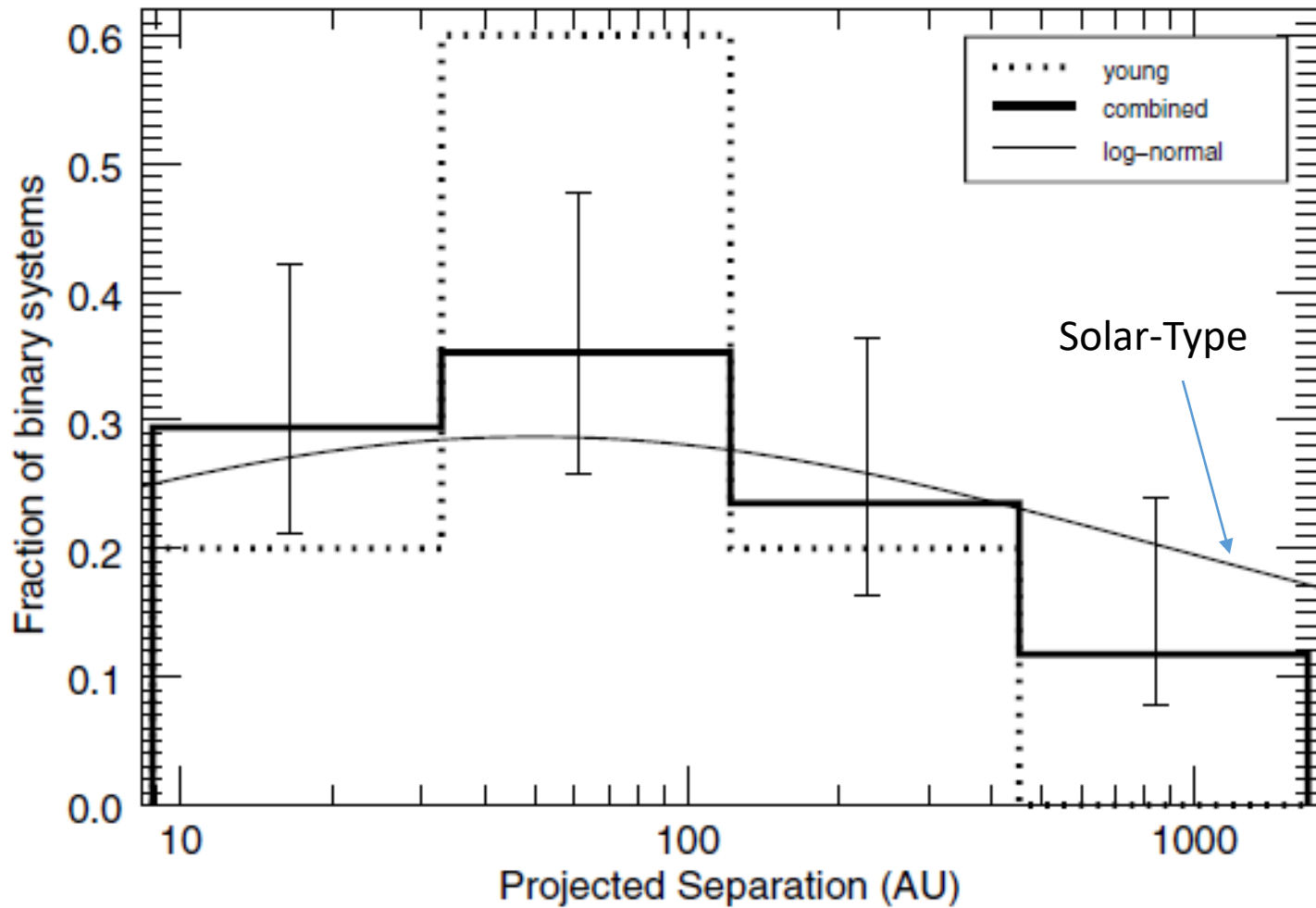


Many new binary surveys to come with extreme ones in post PPVI (Reipurth+ in PPVI)

Reference	Region (Age)	Identification	Separation	Telescope
Daemgen+13	Chamaeleon I (2 Myr)	19 binaries 7 triples	30-1000 au	VLT JHKL' imaging
Daemgen+15	Taurus (2 Myr)	74 companion candidates	10-1500 au	Gemini N Ks deep imaging
Lafreniere+14	Upper-Sco (5 Myr)	29 binaries 5 triples	15-800 au	Gemini N K deep imaging
Tobin+16	Perseus (< 1 Myr)	26 multiple systems	15-10 kau	JVLA deep imaging
Elliott+16 (compiled)	β -Pictoris moving group		0.1 – 100 kau	RV, hc imaging, direct imaging

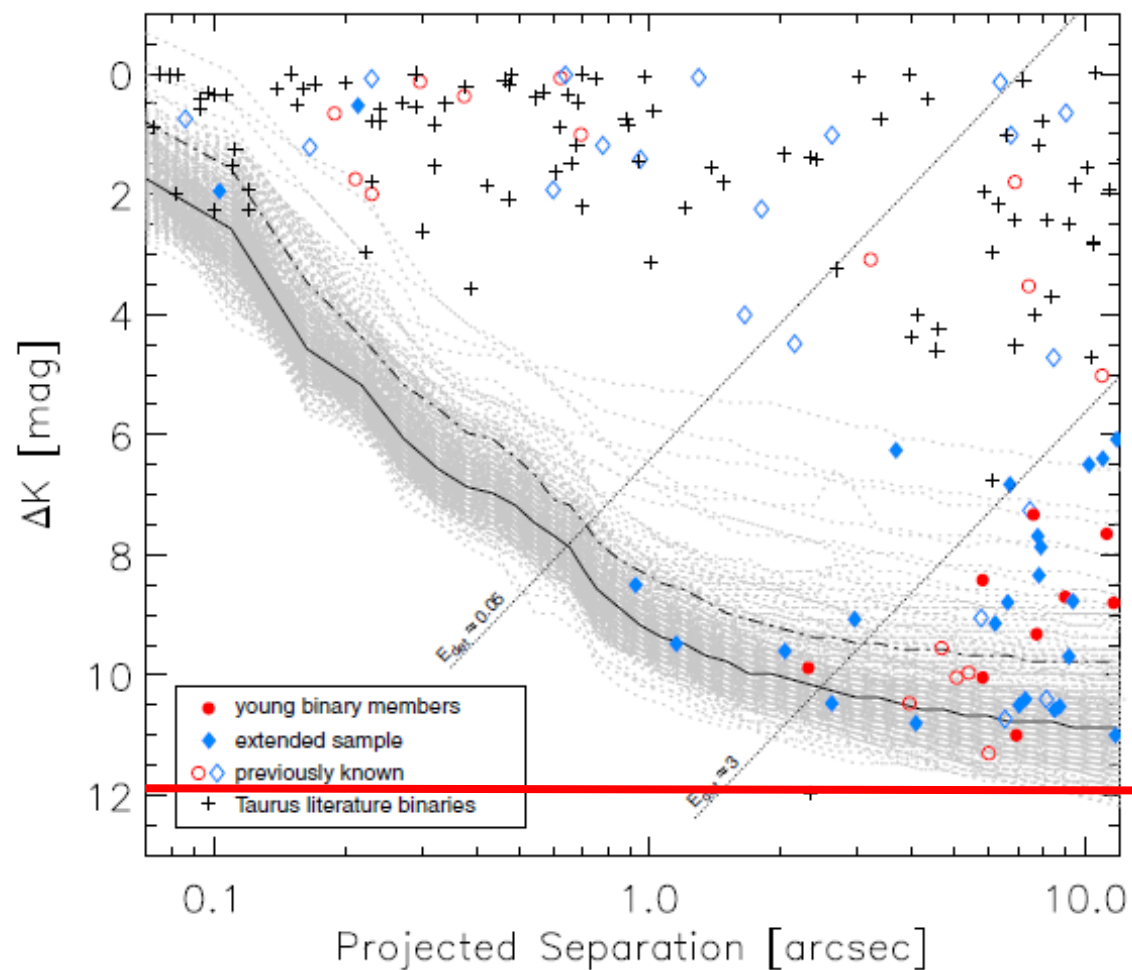
Binary separation

Daemgen+15 (Gemini N.)



Survey limitation

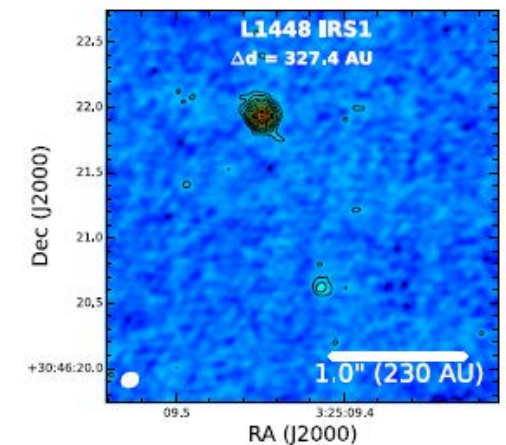
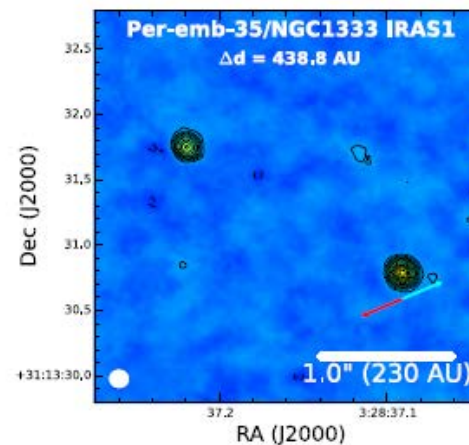
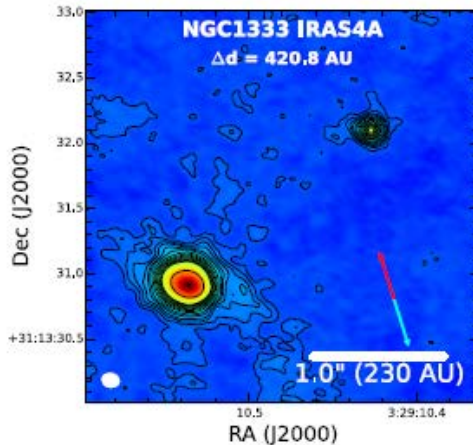
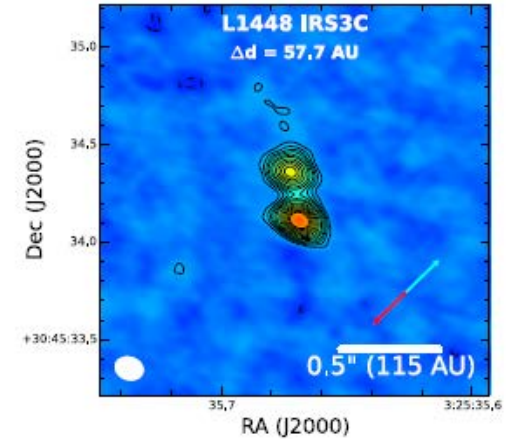
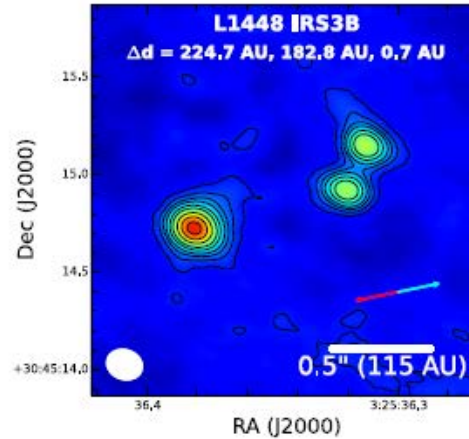
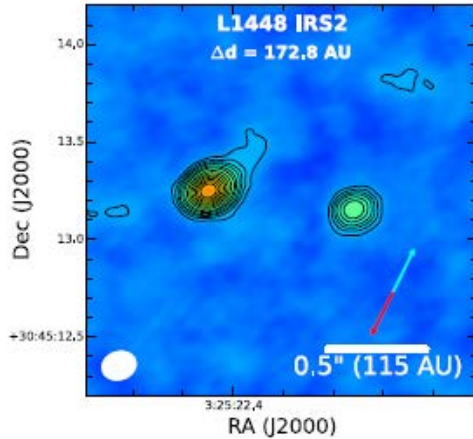
Daemgen+15 (Gemini N.)



Ideally..

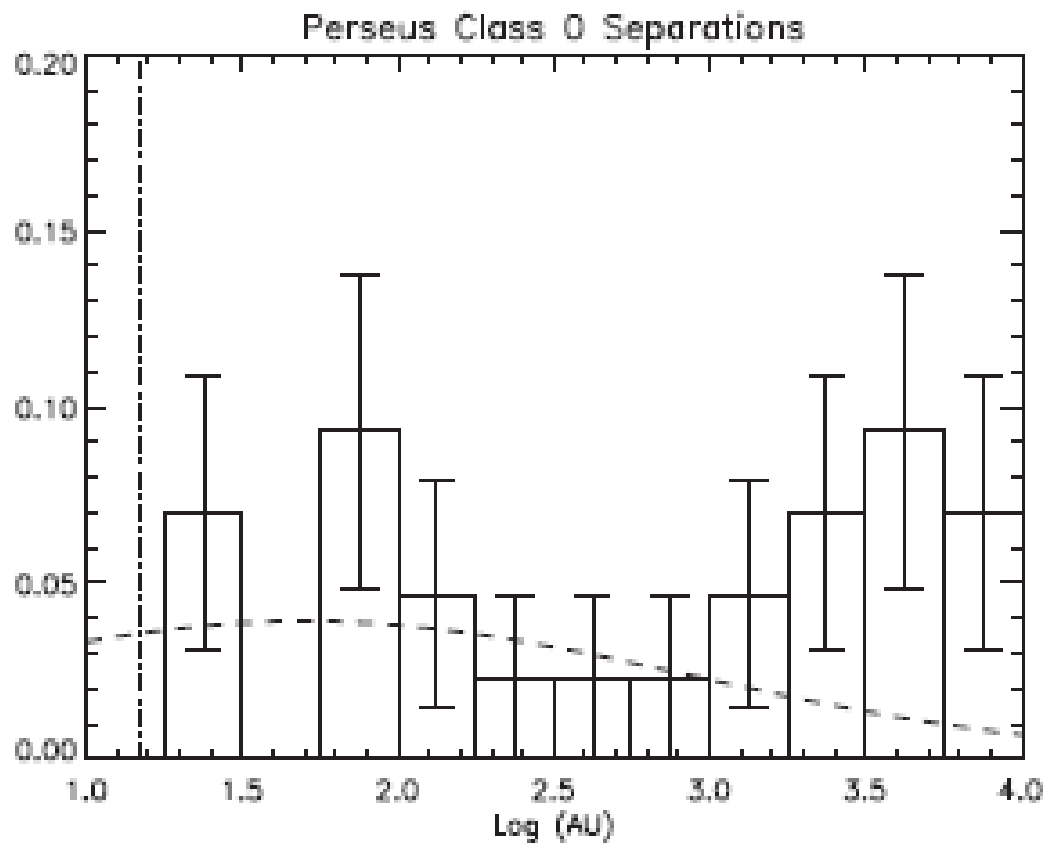
Perseus Binary Surveys

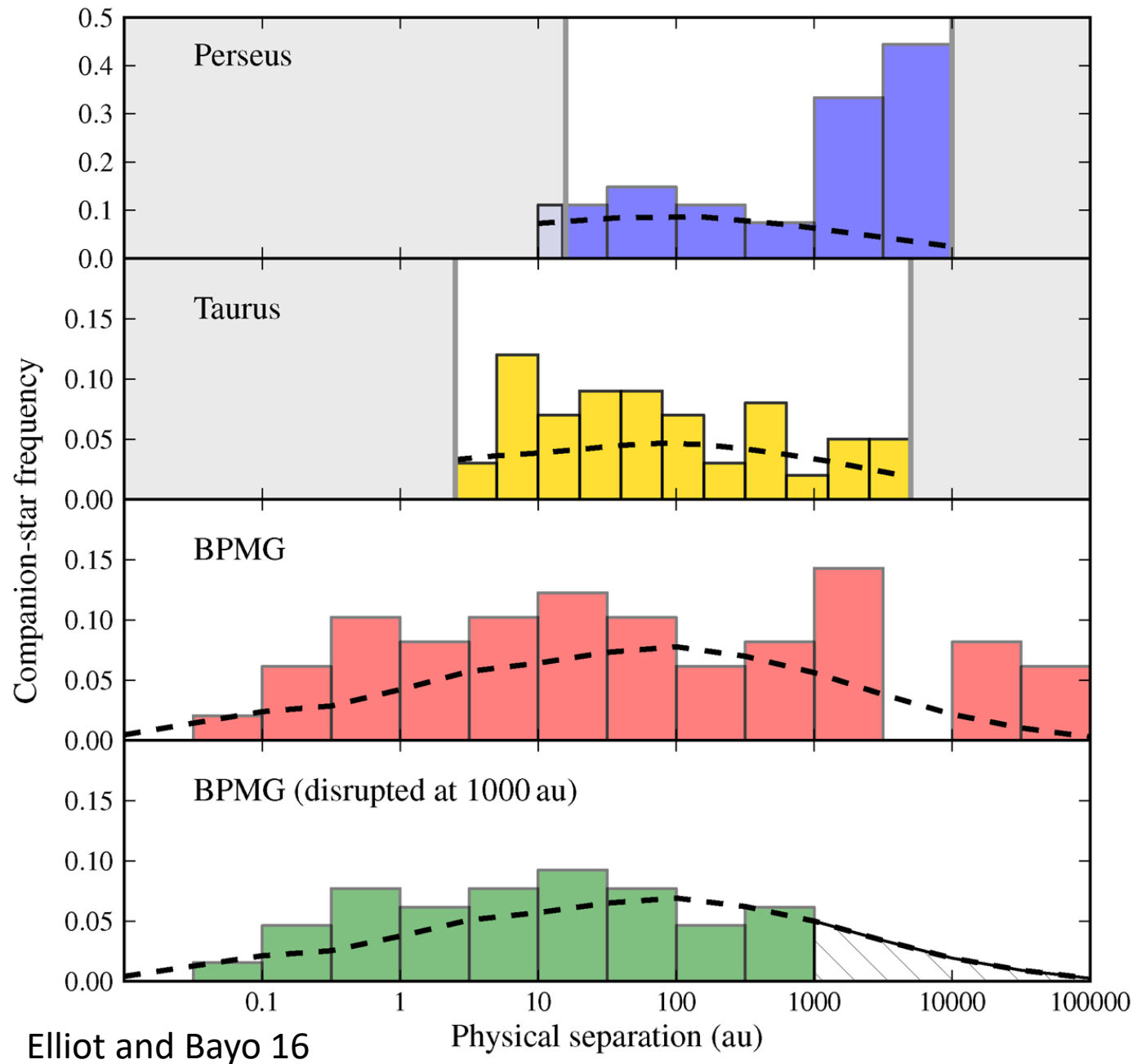
Tobin+16 (8mm VLA)



Separation distribution at Class 0 phase

Tobin+16

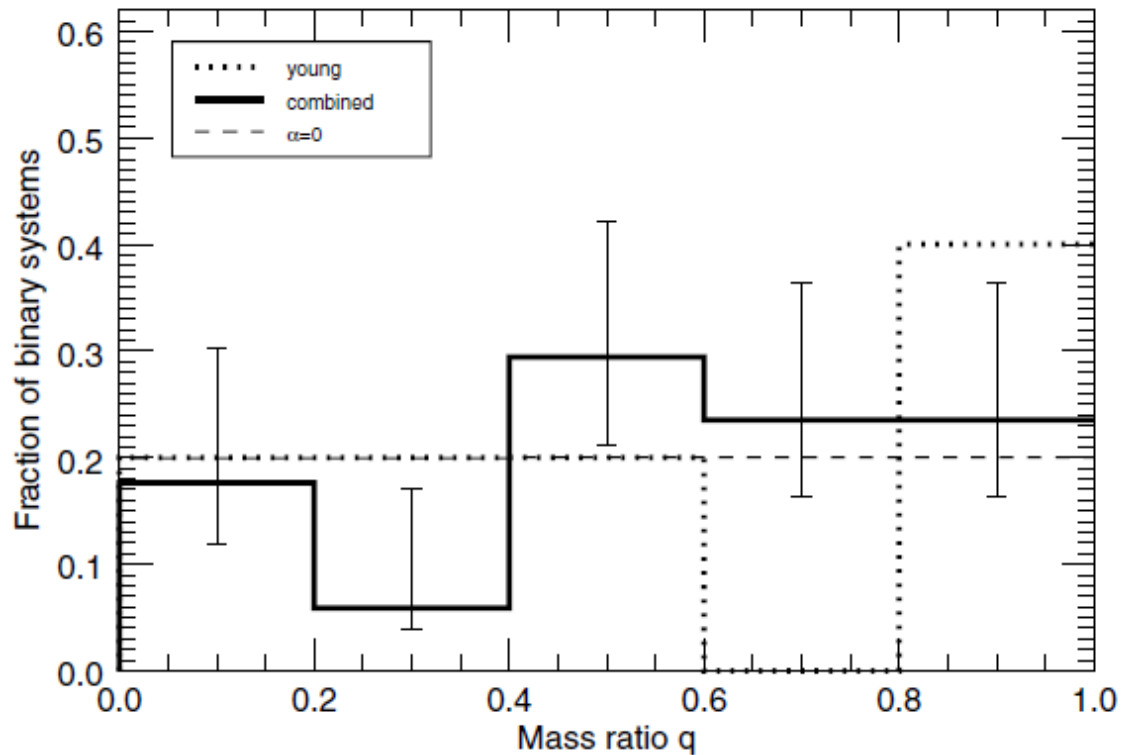




Elliot and Bayo 16

Mass Ratio

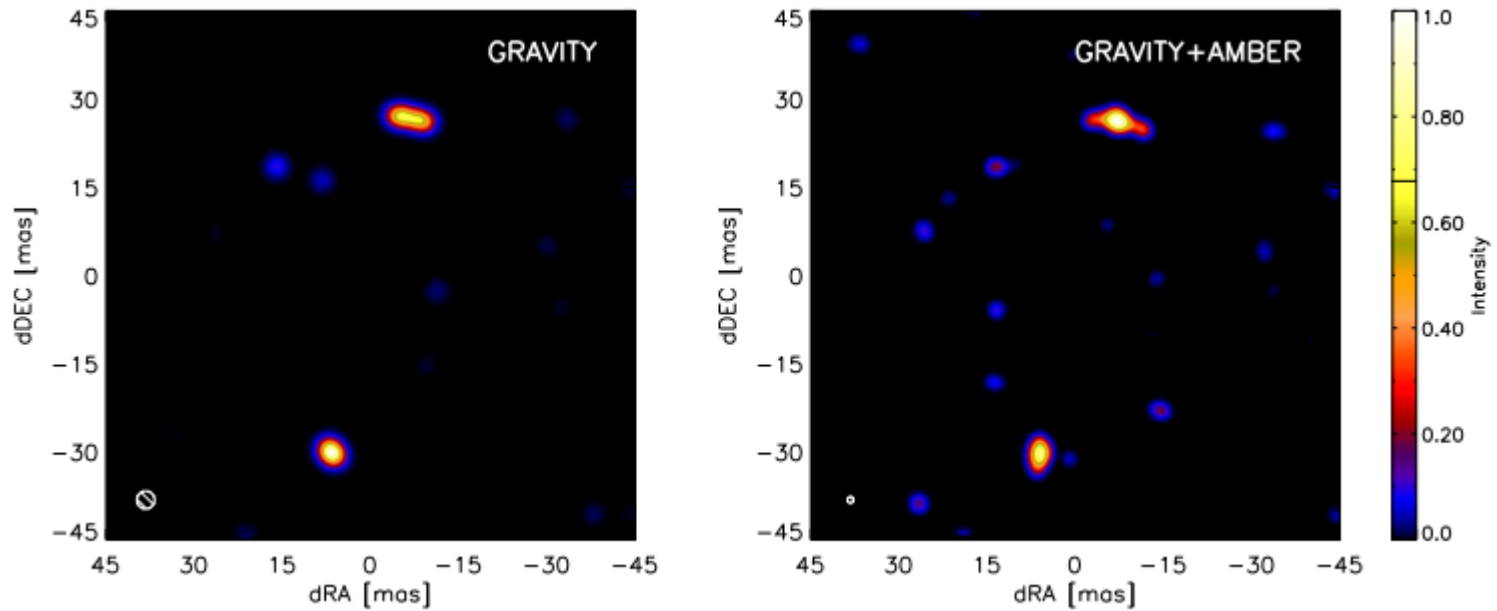
Daemgen+15



Extremely difficult to derive mass ratio at the protostar phase.

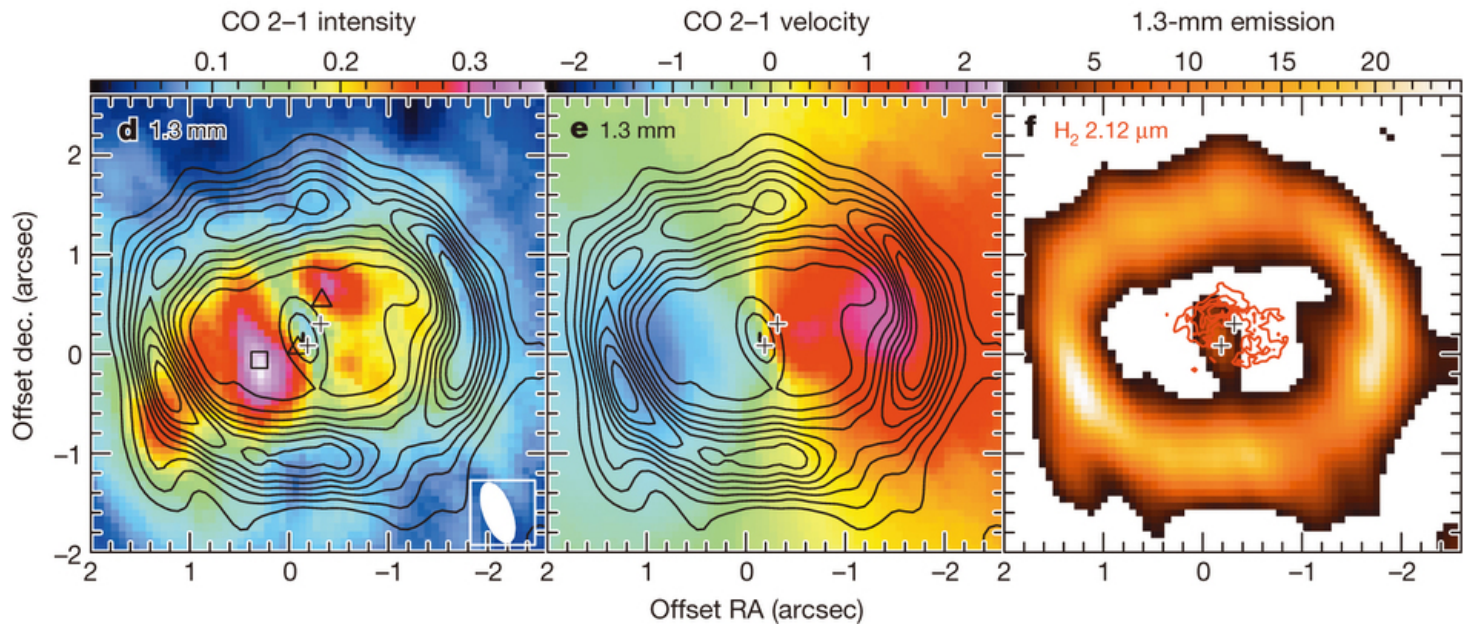
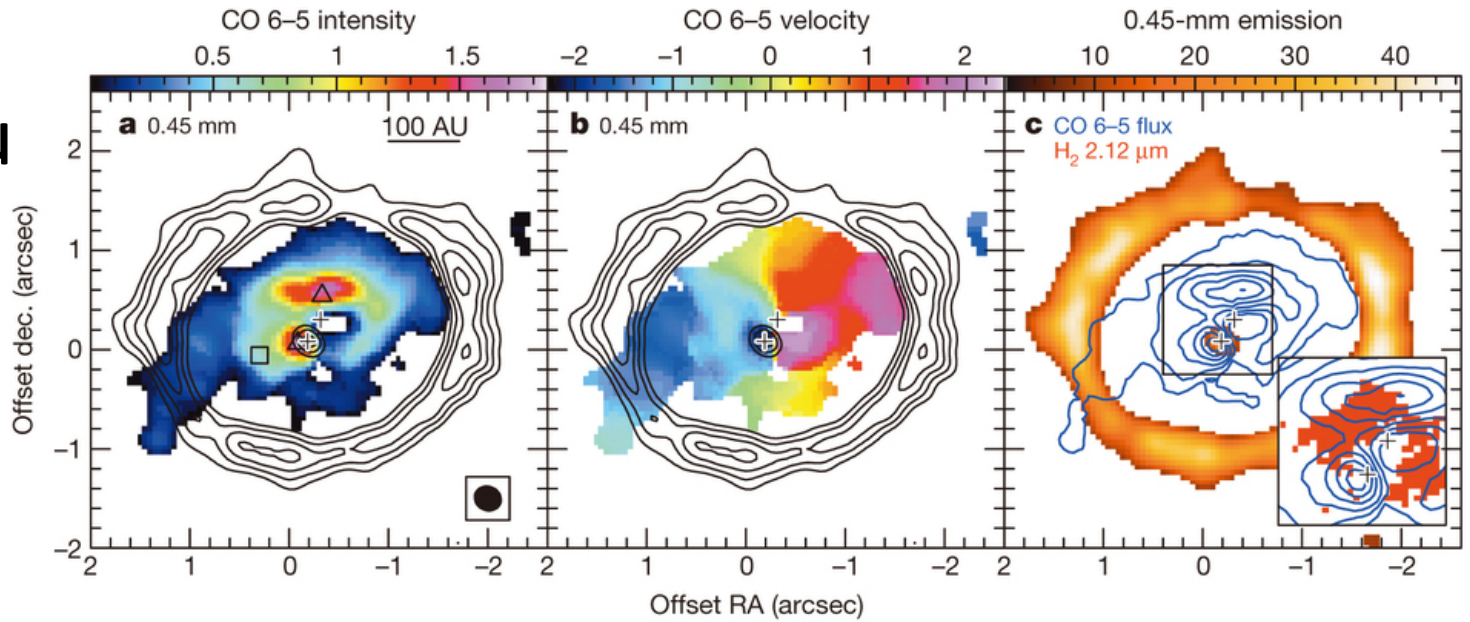
Exotic binary system

20 and 18 Msun with 170 au separation



Kraus+16

GG Tau

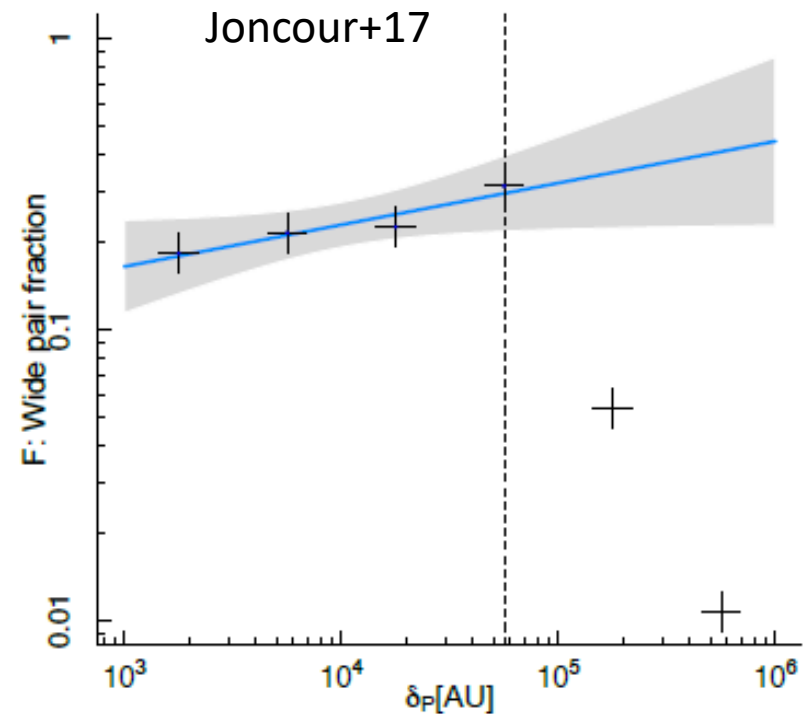
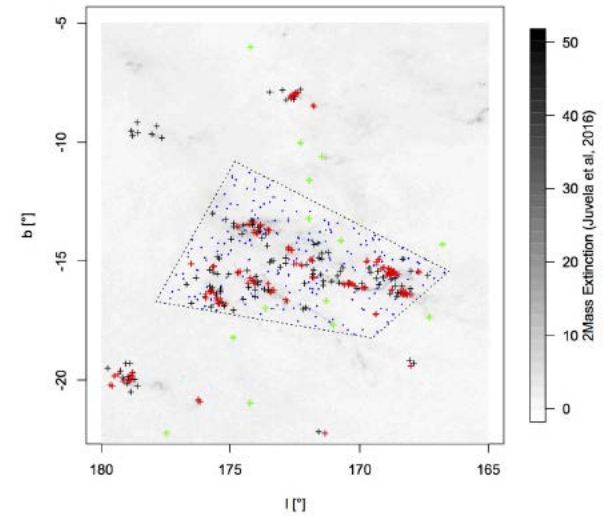


Dutrey+14

Mar 8, 2018

Statistical Approach

- Two Point correlation function
- First nearest neighbor separation (1-NNS)
- One-point correlation function (Joncour+17)
- These statistical approaches will be more powerful with uniform sample of binaries and will be applicable to earlier stage binaries.



Progress Summary since PPVI

- Progress

- Radio interferometers have revealed embedded binary systems or mini-clusters with moderate separation
- Various binary candidates such as massive binary, wide binary, BD binary, have been identified
- More statistical approach have been taken.

- Issues

- Lack of close companion surveys at higher angular resolution
- Mass ratio of embedded systems
- Gas Kinematics of circumbinary and circumstellar disk

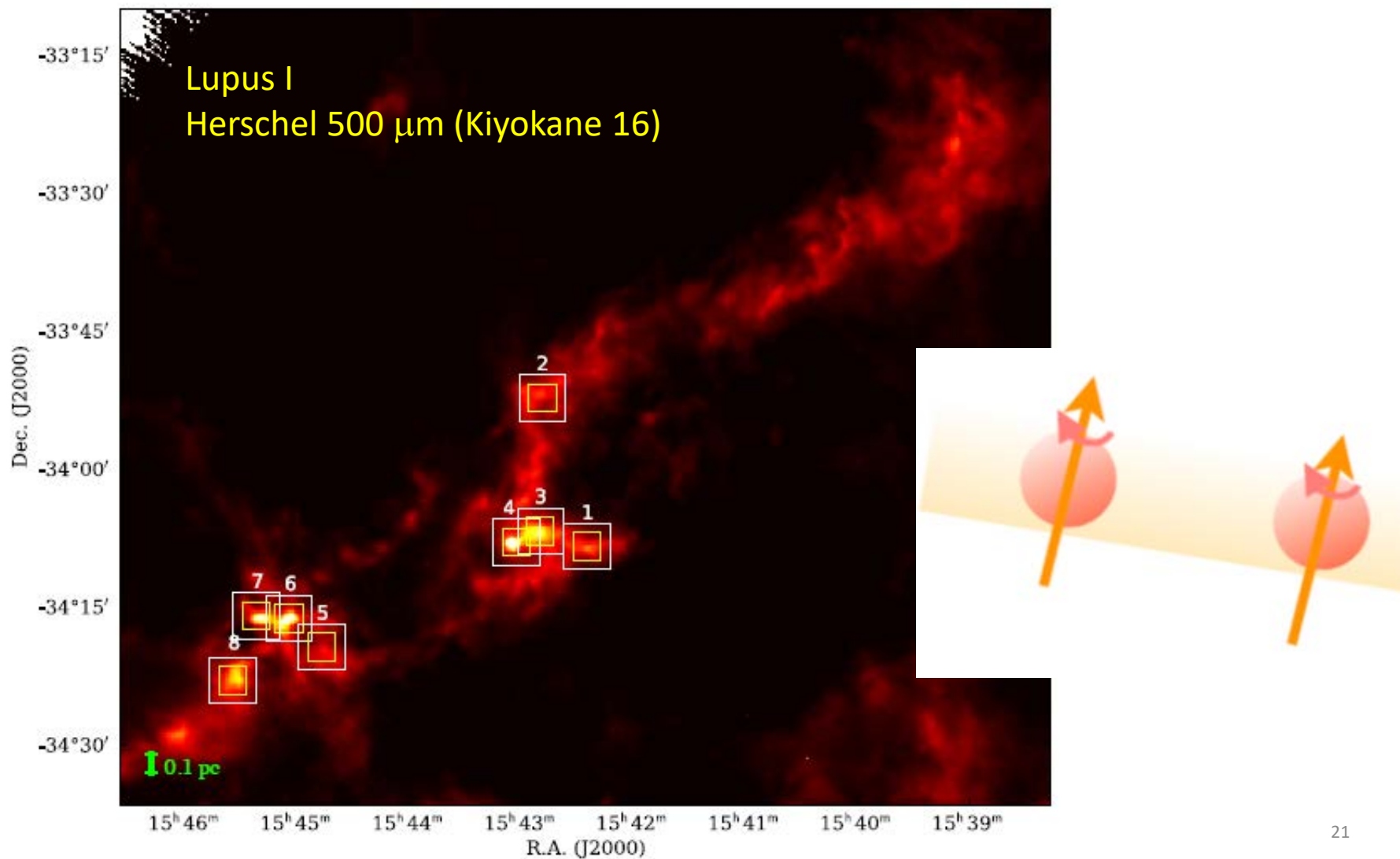
2. SOLA

Soul of Lupus with ALMA (SOLA)

- More details in Itziar's Talk
- SOLA means “sky” in Japanese and “lonely” in Spanish
- Lupus (150 pc ~ same distance of Taurus) can play a similar role than Taurus in establishing a star formation scenario of low mass stars in the ALMA era.

- The project covers $10 - 10^4$ au scale.

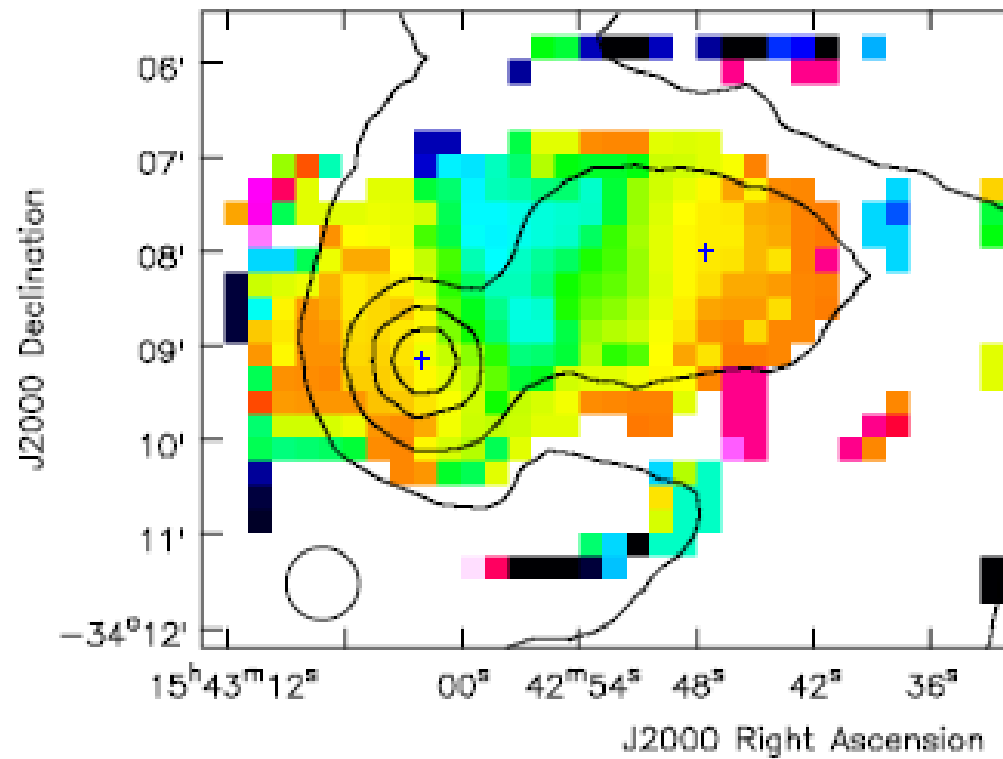
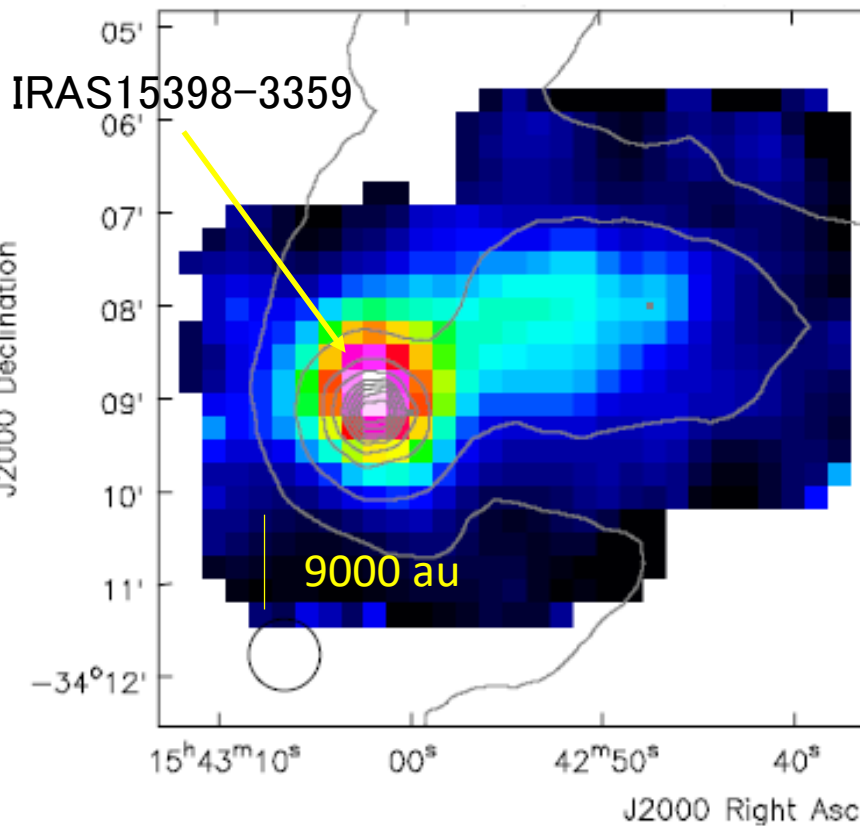
Angular Momentum on large scale



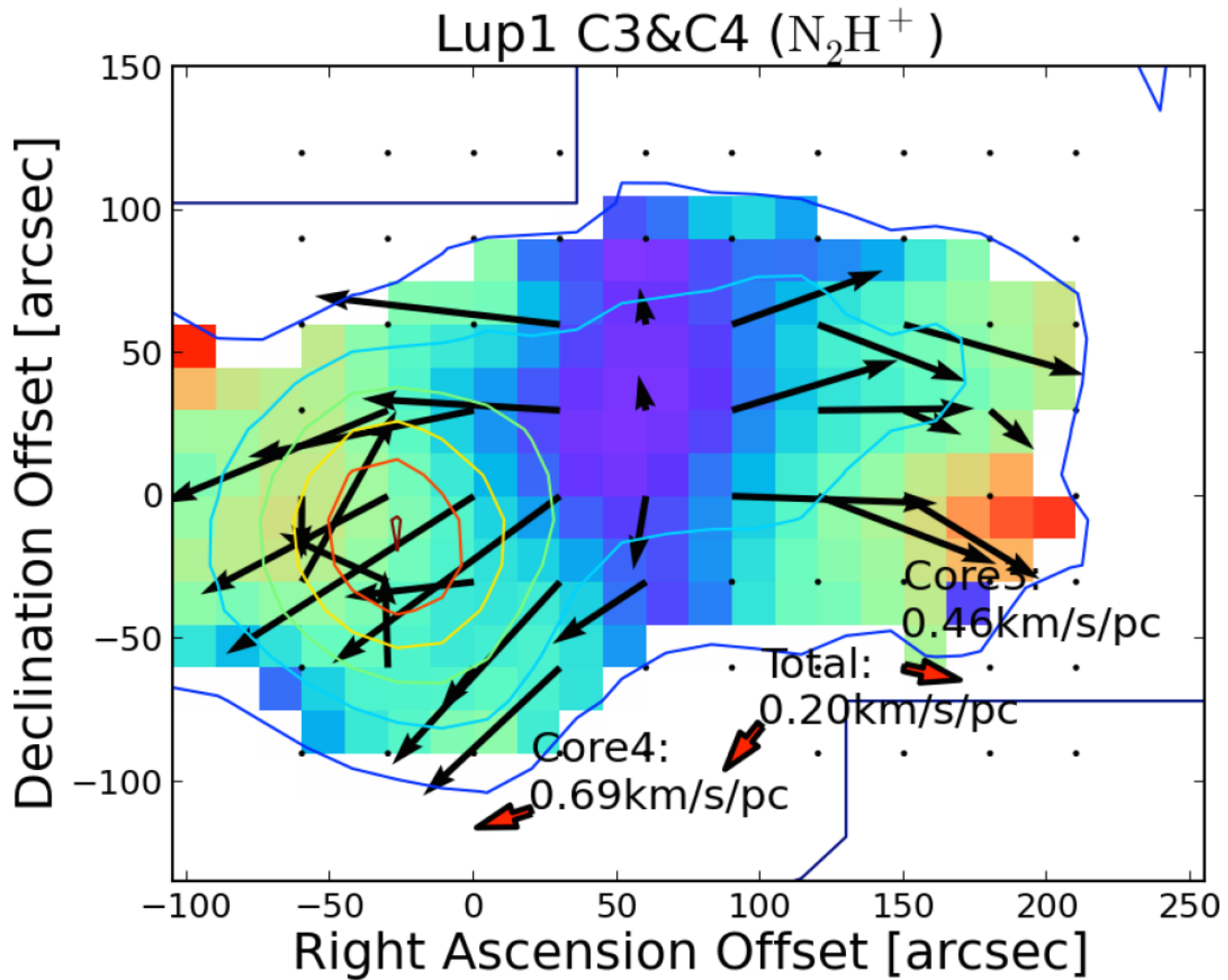
N_2H^+ map of cores in Lupus I

Lup1 Core 1 3 4

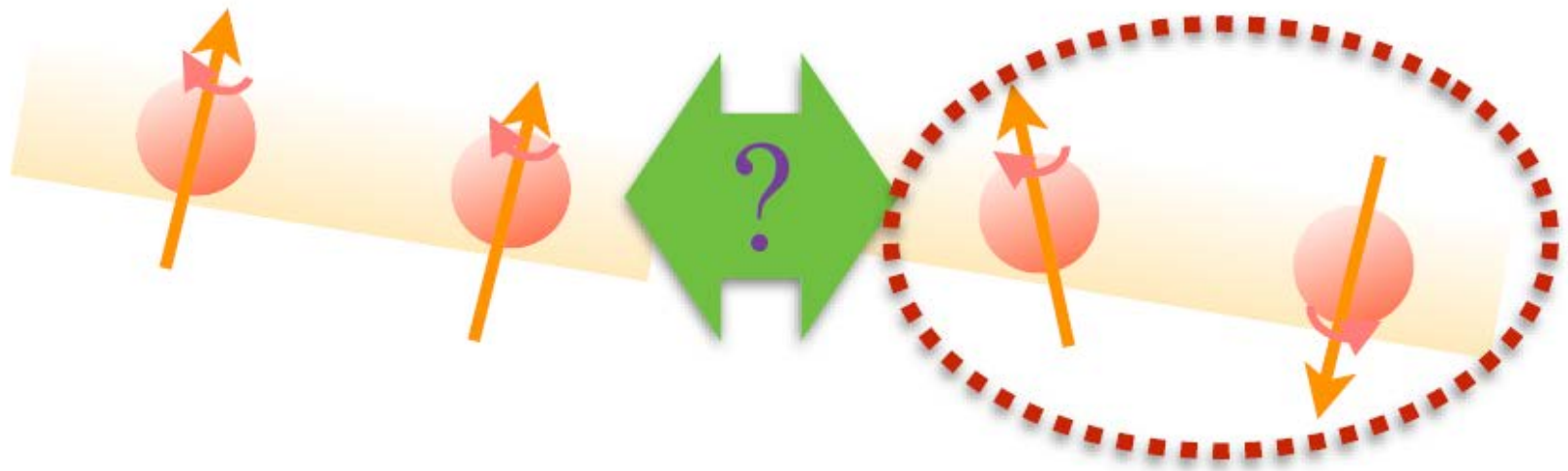
Lup1 Core 1, 3



Left 0th moment map, Right 1st moment map (Kiyokane 16)



Observations favor random rotation axes in Lupus 1

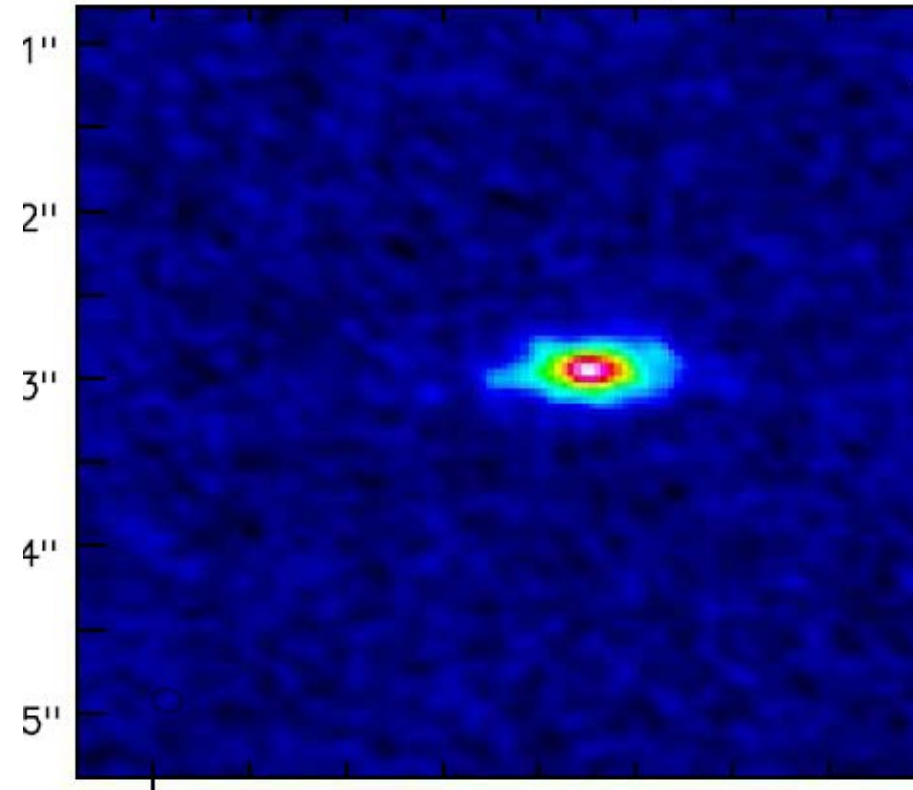
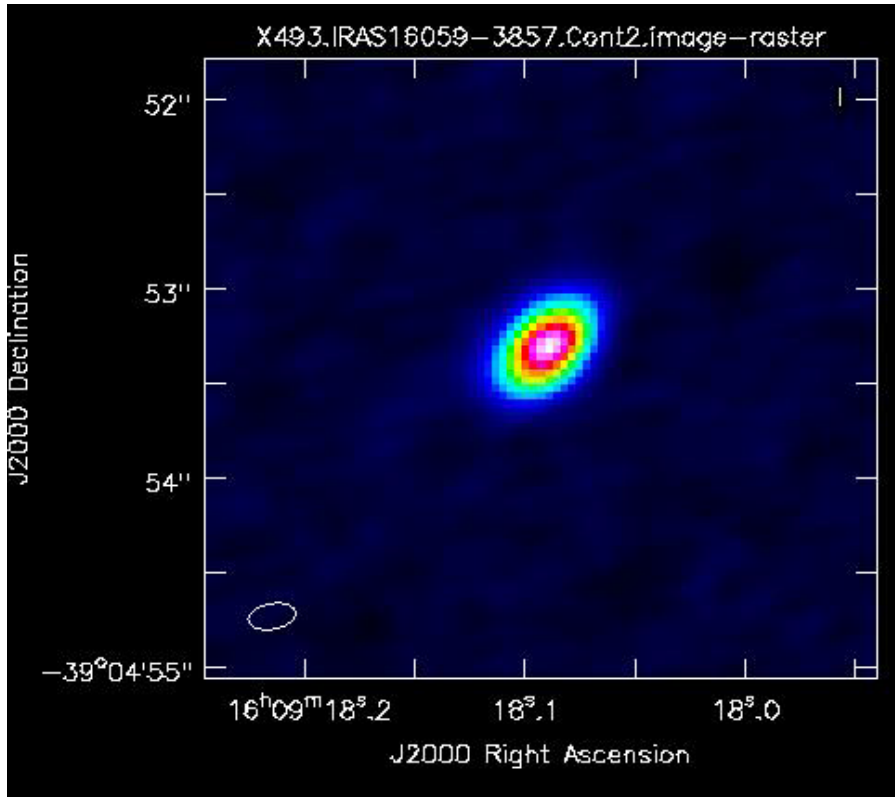


SOLA ALMA Cycle 2 Continuum Survey

- Lupus I, III, IV (37 in total)
- Selected from mm sources (AzTEC/ASTE)
- Class 0/I/F type SEDs
- Typical $\theta \sim 0''.2$ (typical binary separation)

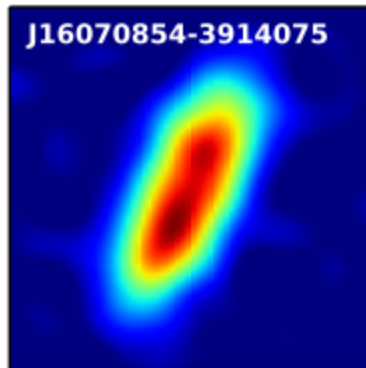
	Observed	Detected (binary)	Typical Noise level
Lupus I	14	1	0.25 mJy
Lupus III	13	4 (1)	0.5 mJy
Lupus IV	8	2 (1)	0.9 mJy
Total	37	8 (2)	

SOLA High Resolution Continuum Image

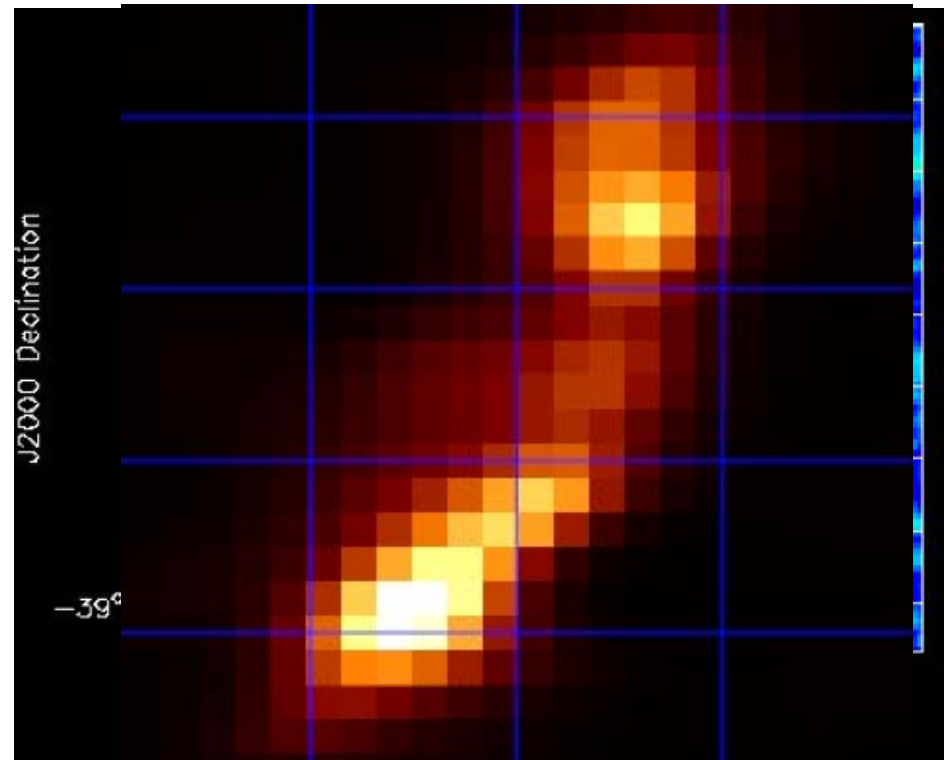


SOLA Binary Candidate

- Cavity Disk or Young Binary?
- Bridge suggest binary?
- Kinematics ultimate test



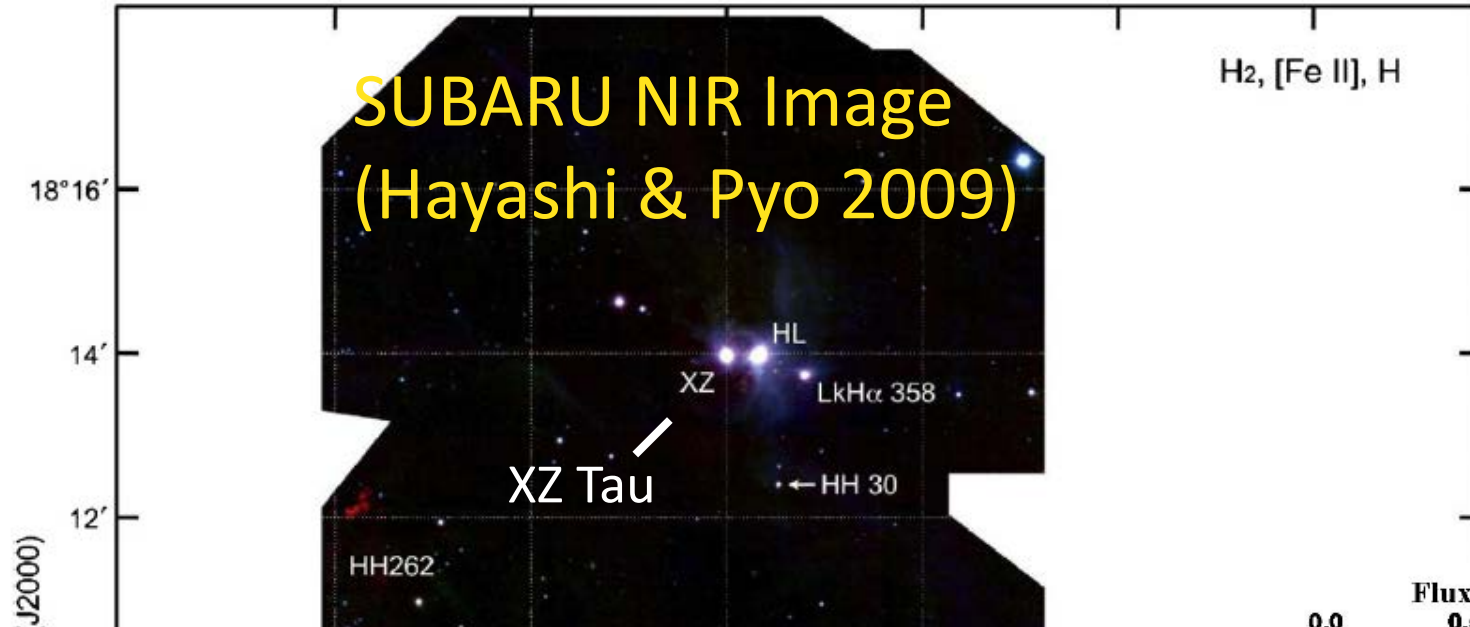
Andsell+16



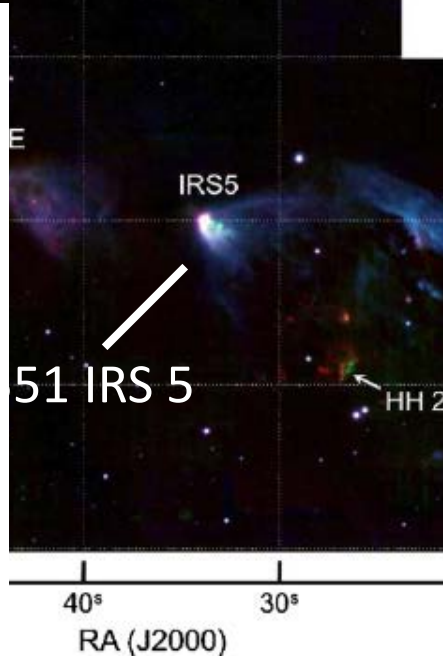
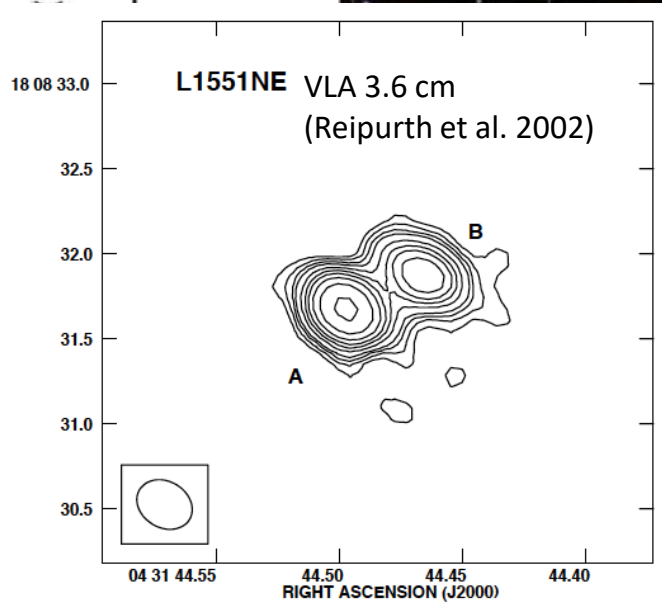
3. L1551 NE

Protostellar Binaries in the L1551 Region

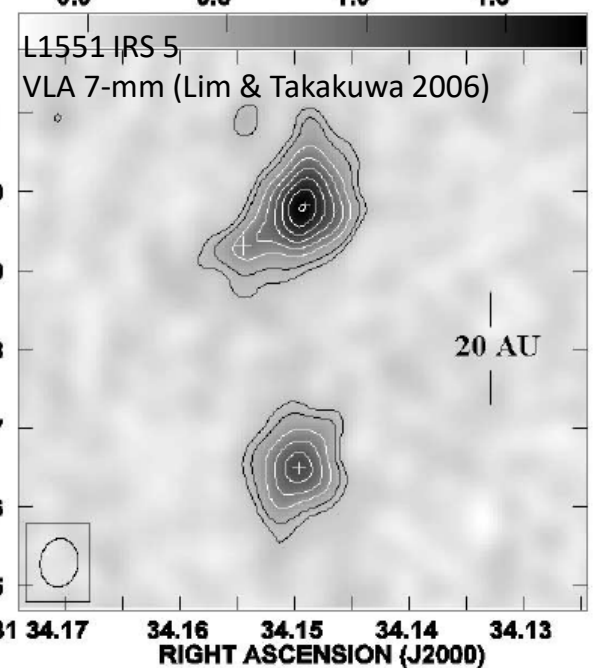
SUBARU NIR Image
(Hayashi & Pyo 2009)



L1551NE VLA 3.6 cm
(Reipurth et al. 2002)

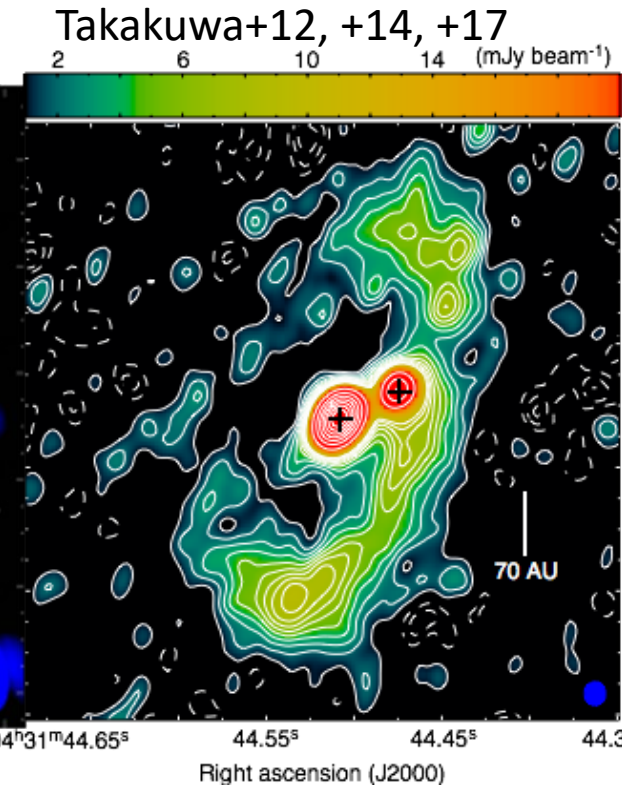
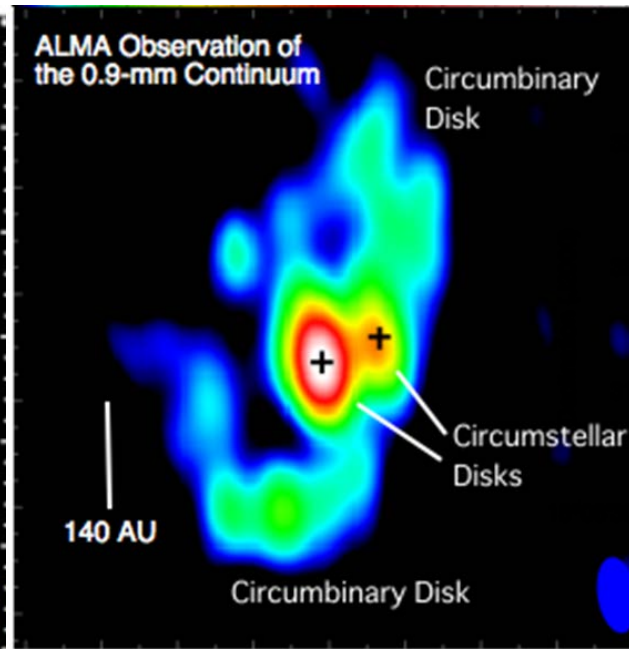
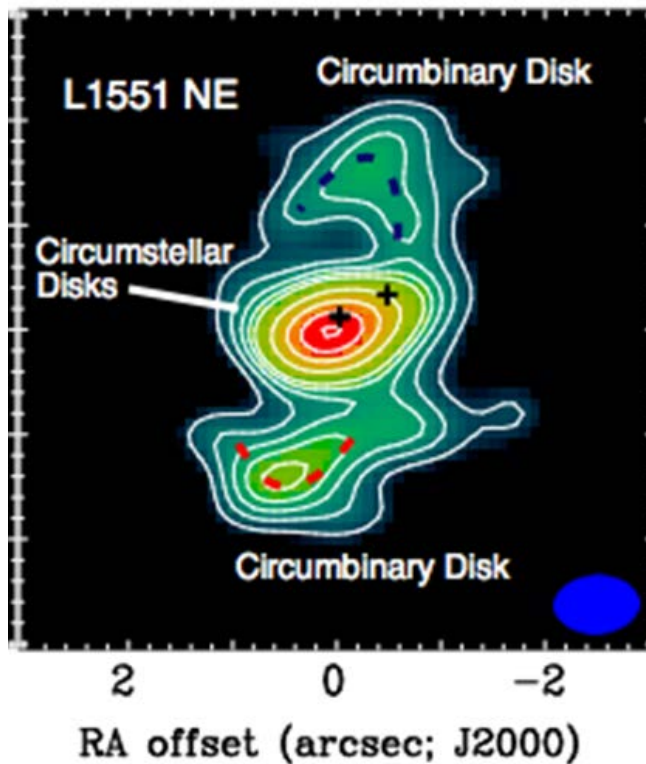


Flux Density (mJy)



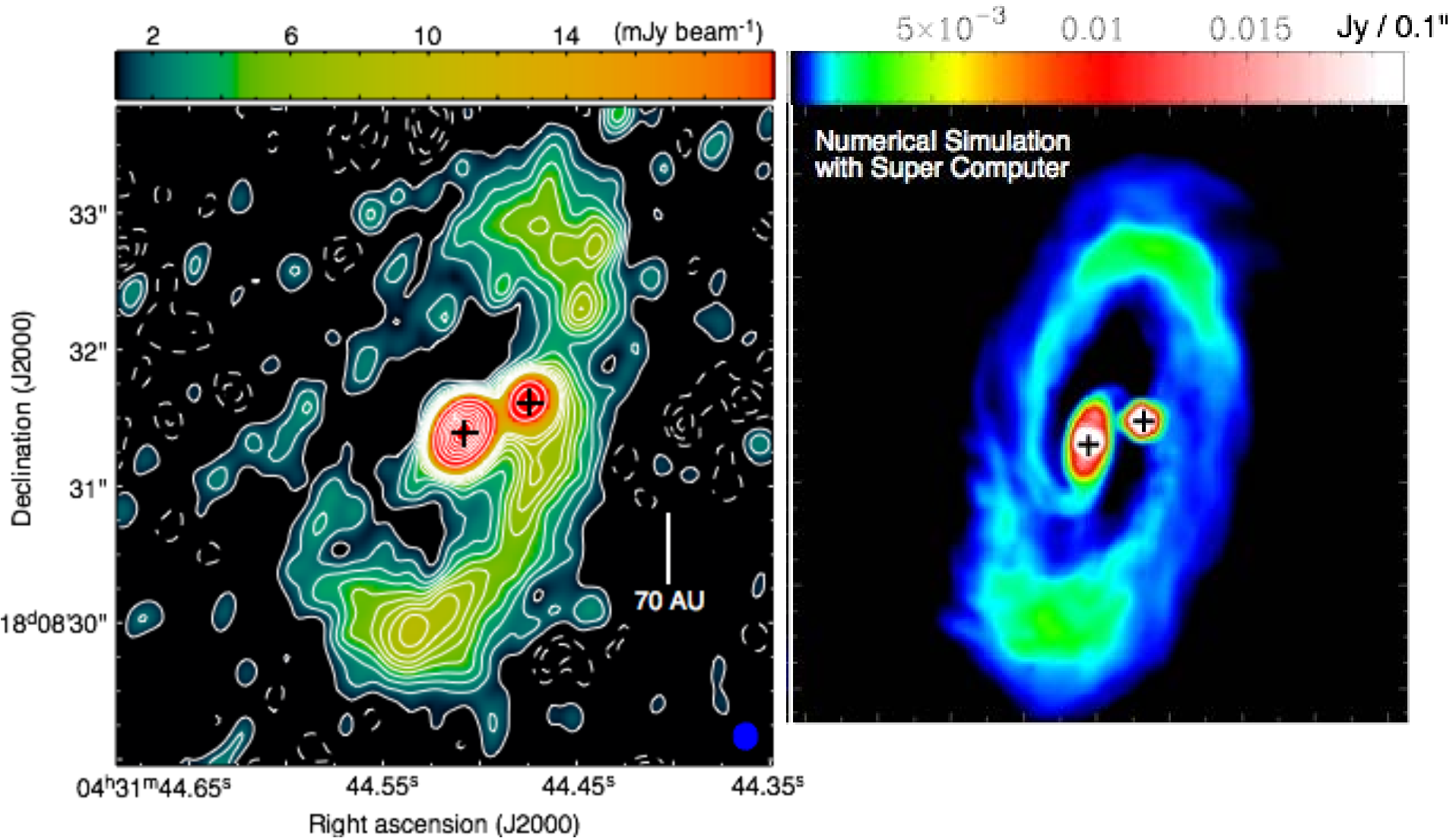
Detailed Study: Case of L1551 NE

Submm continuum images (SMA, Cycle 0, Cycle 2)



Mass ratio is 0.19 with a total mass of 0.8 Mo
 Submm flux ratio is 0.33 – relation to q?

Cycle 2 Results: 0.9-mm Continuum



Two Spiral Arms, in particular, the southern arm connecting to Source B, are clear.

Circumstellar Disks (CSD) also resolved ($r_A \sim 20$ AU, $r_B \sim 18$ AU).

Cycle 2 Results: C¹⁸O (3-2)

High velocity

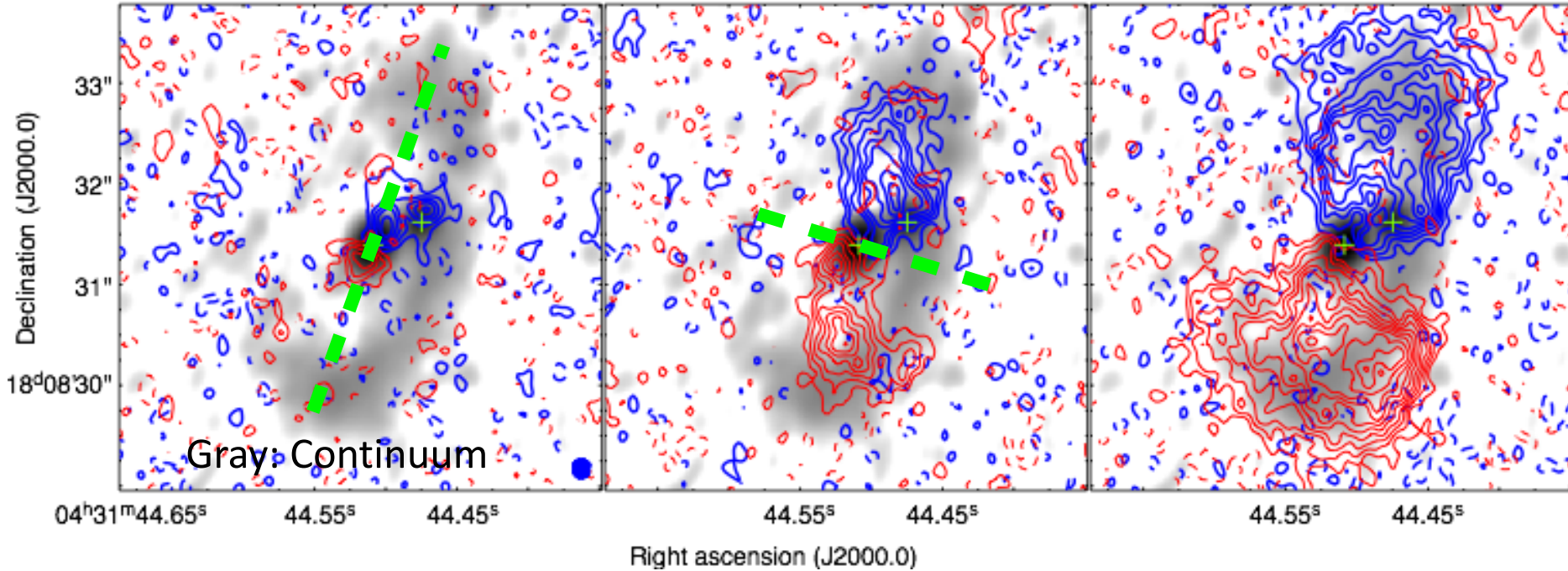
Middle velocity

Low velocity

a) Circumstellar Disks

b) Inter-Arm Gas

c) Arm Gas



- Circumstellar Disk (CSD) rotating-gas Component around source A
- Inter-arm gas components connecting between CBD and CSD
—> East-West Velocity gradient around Source A —> Accretion
- Redshifted Southern Arm and Blueshifted Northern Arm Gas

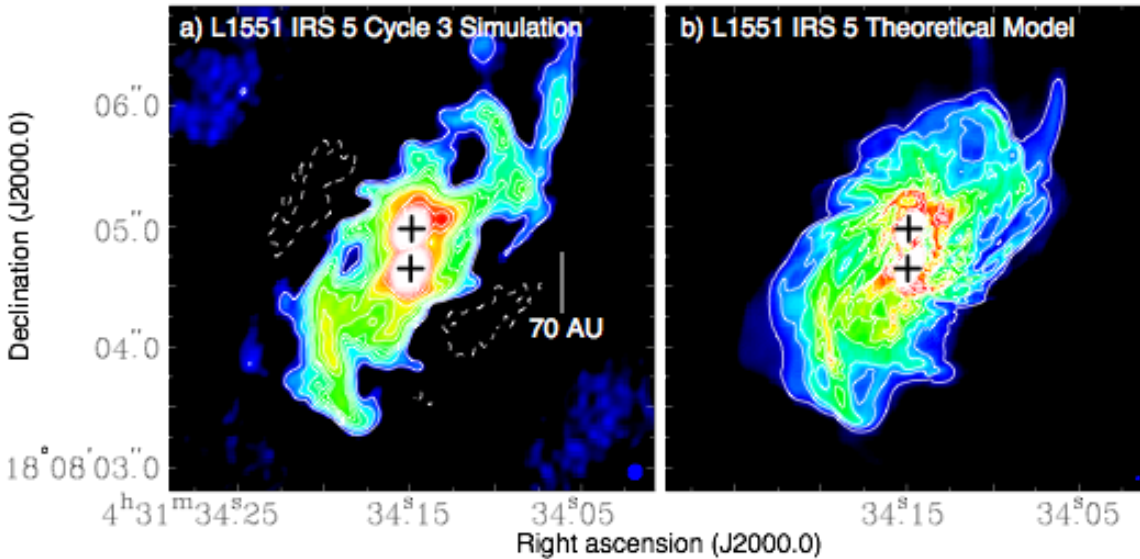
4. Future Direction and Summary

Future Directions

- More Surveys to fill in the parameter space
 - Separation, q , age etc.
- Detailed Study for some representative sources especially at earliest stage
 - Infalling motion
 - mass determination
- Comparison of observational results with simulation

Future ALMA Observations

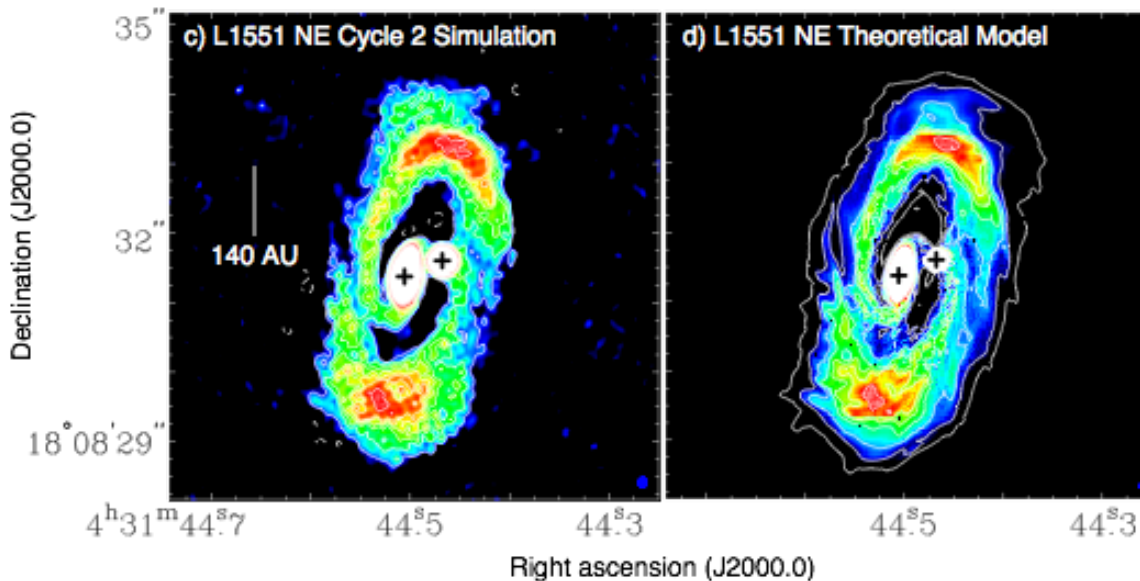
Simulated ALMA Cycle 2 and 3 0.9-mm Dust-Continuum Images of L1551 IRS 5 and NE at a ~ 0.1 arcsec Resolution



L1551 IRS 5

Equal Binary Mass, Low Angular mom. of the CBD.

—> A number of small Spirals, Equal Accretion Rate.



L1551 NE

High Binary Mass Ratio (=0.2), High Angular mom. of the CBD.

—> Well-Developed Two Spirals, Secondary Accretes ~ 10 times more than Primary

Summary

- Significant progress in young binary studies have been observed even in the last few years.
- More survey results have come and will come in various binary parameters, particularly at early phase.
- Statistical properties of earliest stage binary survey will constrain formation mechanism of binary stars.
- High angular resolution images will reveal structure and kinematics of youngest binary systems.

ALMA is a key facility for binary study.