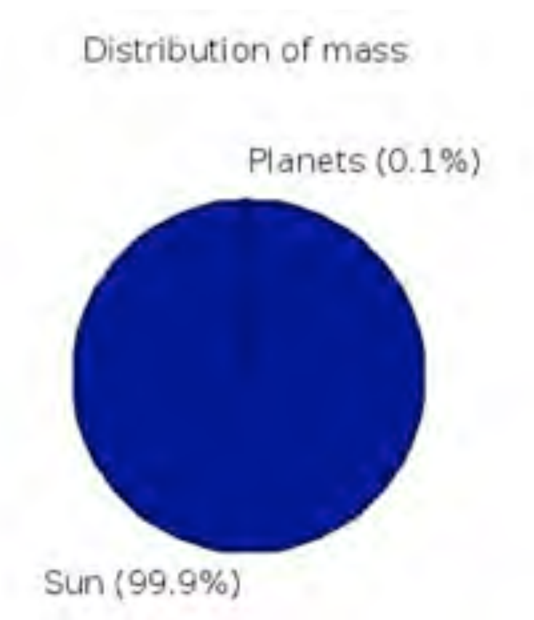
CALYPSO:
the IRAM-PdBI survey to solve the angular momentum problem at the Class 0 stage

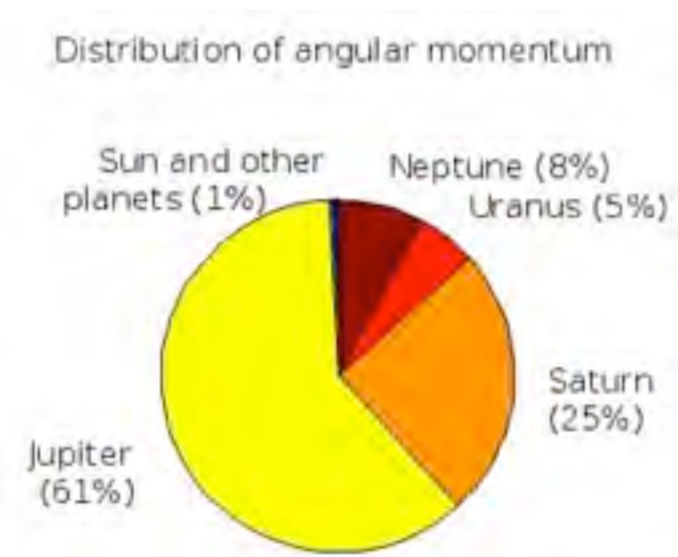
- Anaëlle Maury, CfA -
On behalf of the CALYPSO collaboration:
Philippe André, Sébastien Maret , Claudio Codella, Arnaud Belloche, Frédéric Gueth, Sylvie Cabrit, Leonardo Testi, Sylvain Bontemps, Bertrand Lefloch, Patrick Hennebelle, Aurore Bacmann, Sandrine Bottinelli, Benoit Commercon, Ralf Launhardt, Ralf Klessen, C. Dullemond

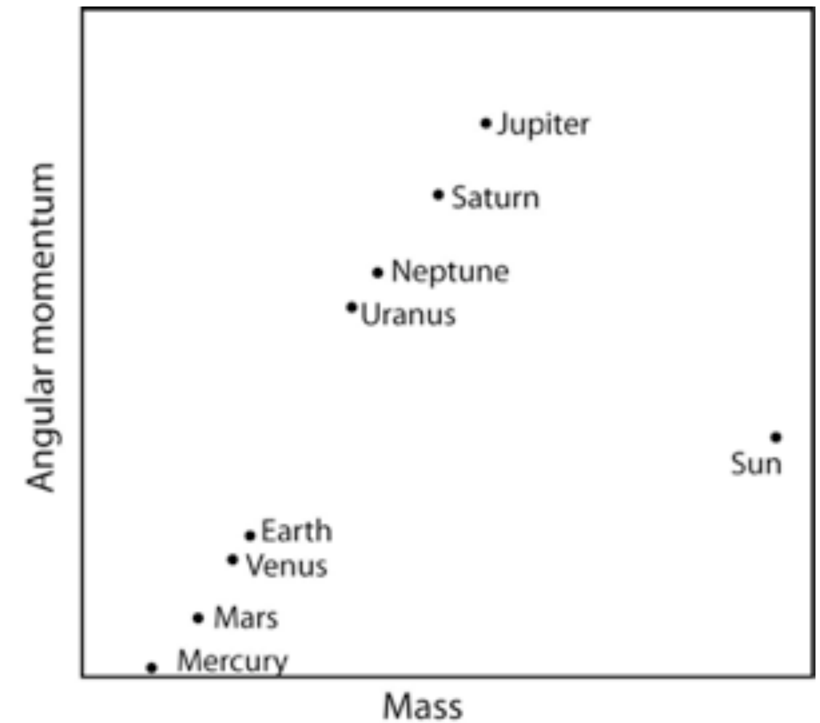
The angular momentum problem (1/3)

As the core/envelope contracts to form a star,
its rotation should speed up to conserve angular momentum.

The region with the fastest rotation should be at the center - in our case, the Sun.
BUT the Sun rotates much more slowly than it should
+ the Solar System's angular momentum is concentrated in the (external) jovian planets.

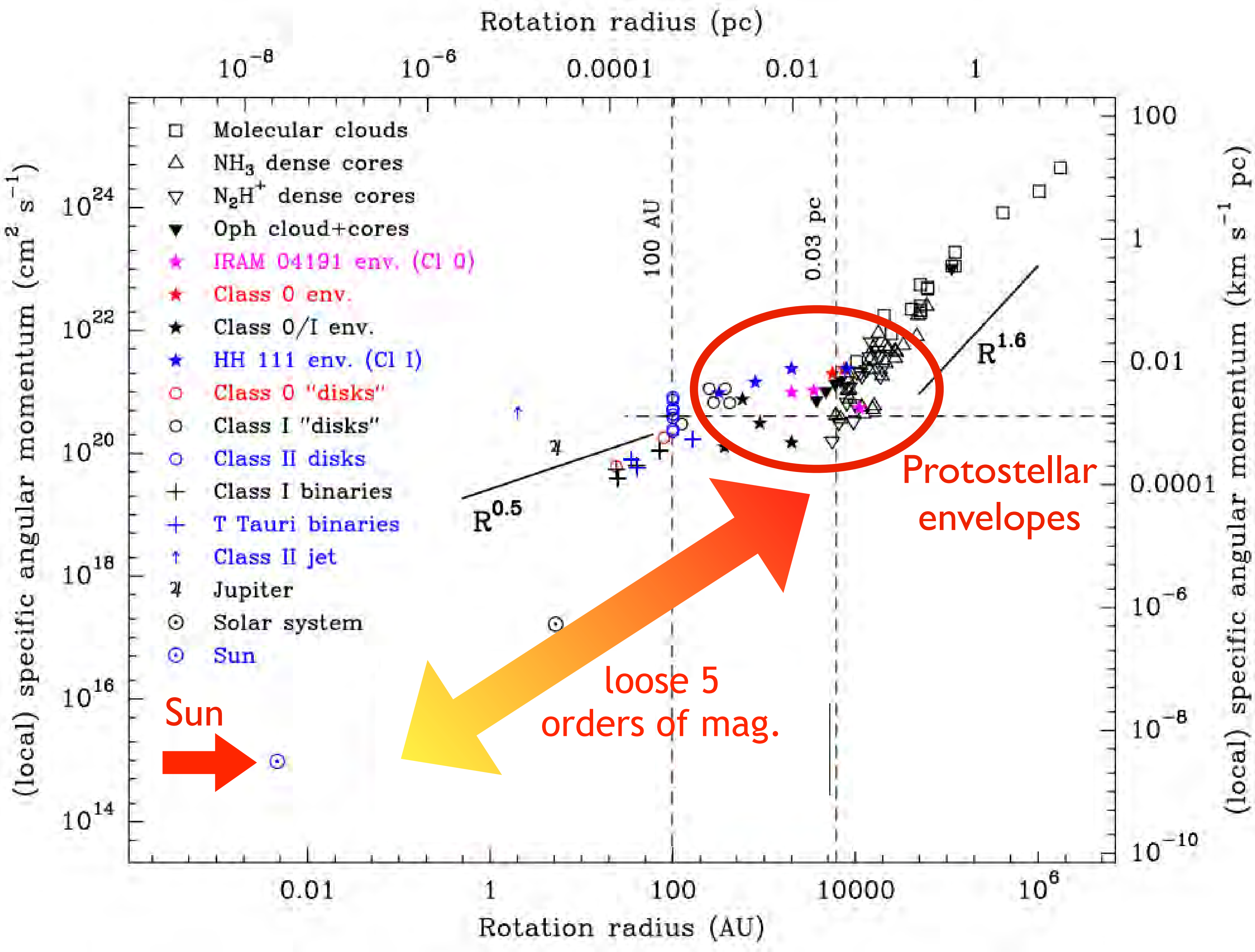






The initial angular momentum in the star-forming core
has to be re-distributed
during the star/planet formation process

The angular momentum problem (2/3)



Courtesy A. Belloche (2013), see PPVI review by Li et al.

Using data from Ohashi et al. (1997), Goodman et al. (1993), Belloche et al. (2002) and Belloche et André (2004)

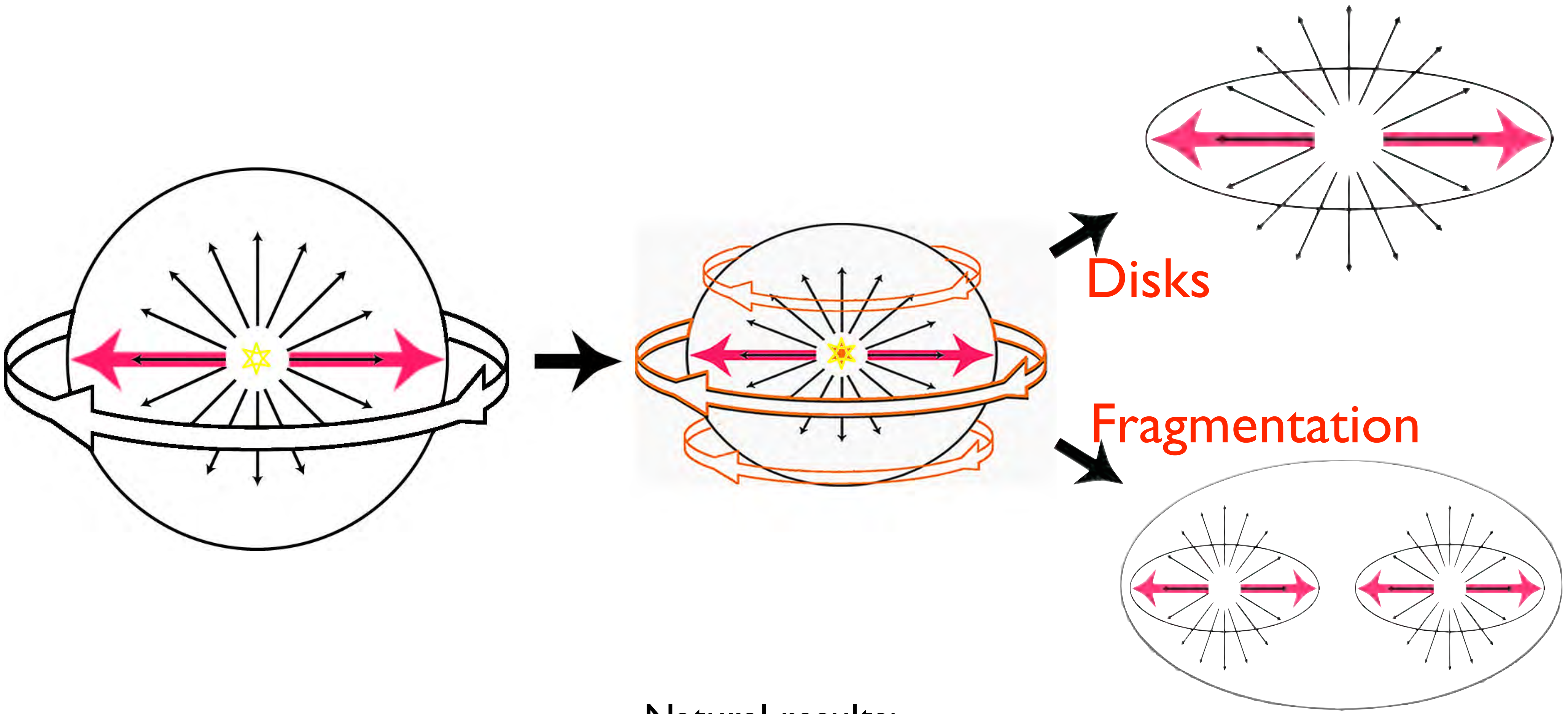
The angular momentum problem (3/3)

Most of the mass (and therefore of its associated momentum) of the final star has been accreted by the beginning of the T-Tauri phase

Solving the
angular momentum problem
=
understanding the kinematics of the accreted material
in the youngest protostars
at scales 50-1000 AU

Conserving the angular momentum during collapse: consequences

Opposing forces to gravity during collapse:
Outward pressure in all directions / Centrifugal force in the equatorial plane



Natural results:

- flattening of the envelope ie formation of disk with keplerian motions (viscosity)
- fragmentation of the envelope in components taking away their own angular momentum
- if magnetized: launching of a high-velocity jet

Understanding how the angular momentum is transported will ultimately solve several crucial open questions for star formation

i. From core to protostar

-> fragmentation: when, how ?

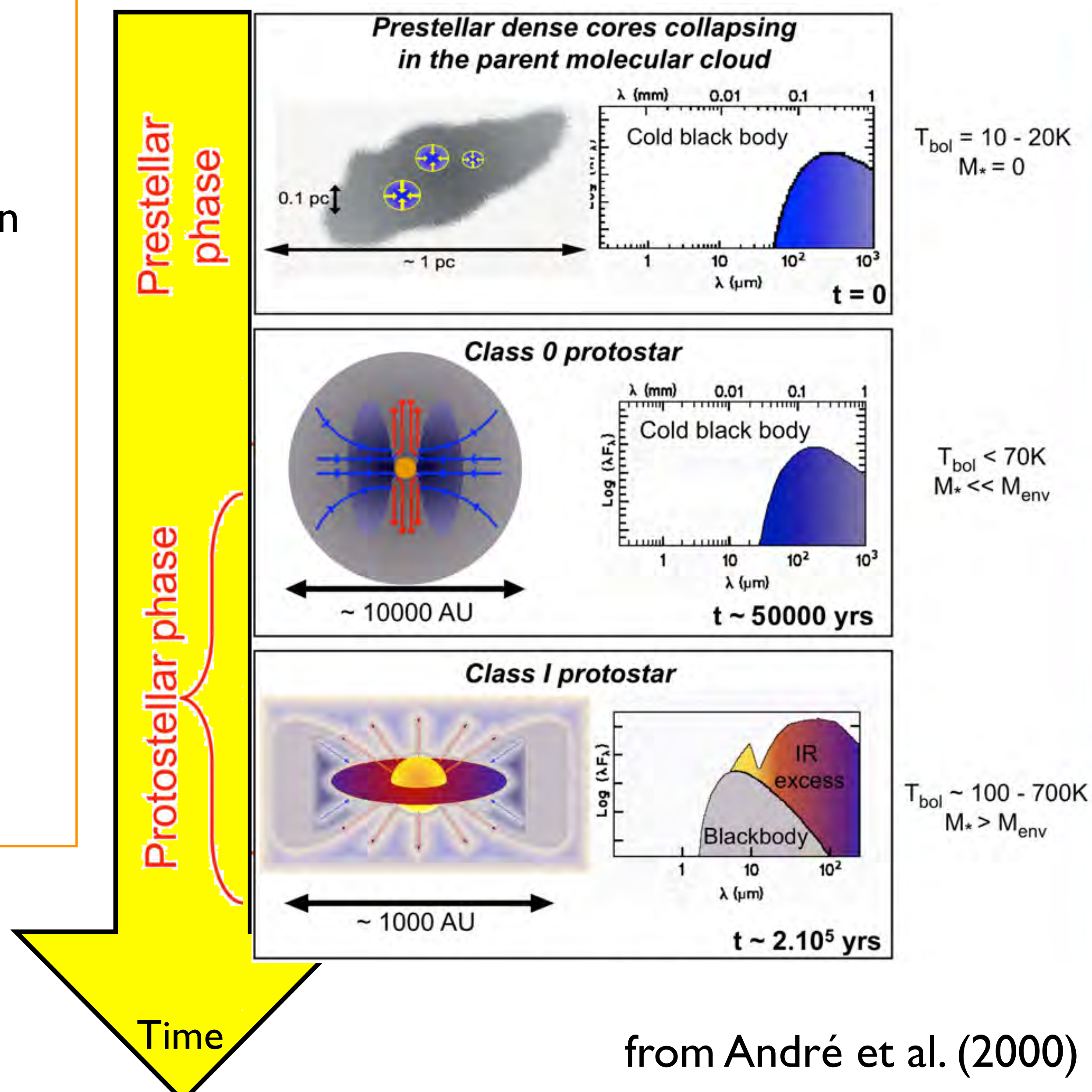
-> infall: onto protostar, extended in envelope ?

ii. From Class 0 to Class I

-> disk formation in envelope: when, which pristine properties ?

-> outflow and jet: launching, importance for further evolution?

-> material: dust grains, impact of chemistry ?



from André et al. (2000)

CALYPSO: the IRAM Plateau de Bure Large Program to solve the angular momentum problem in Class 0 protostars

A dive into the small-scale physics of the youngest envelopes, disks and outflows.

- 300 hours observing time

-17 Class 0 protostars closeby (<300pc)

-3 spectral setups, e.g continuum and >50 lines

-at resolution ~0.5” i.e 50-70 AU

- typical sensitivities 0.1 mJy/0.5”-beam

Ph. André (AIM) - A. Maury (CfA) - C. Codella (INAF) - S. Maret (IPAG); S. Cabrit (LERMA) - F. Gueth (IRAM) - A. Belloche (MPIfR) - L. Testi (ESO / INAF) - B. Lefloch (IPAG) - S. Bontemps (LAB) - P. Hennebelle (AIM) - A. Bacmann (IPAG) - S. Bottinelli (IRAP) - B. Commercon (MPIA) - C. Dullemond (MPIA) - R. Klessen (Heidelberg) - R. Launhardt (MPIA)

CALYPSO:
the IRAM PdBI Large Program on Class 0 protostars

Our sample:

Object	Class	α (J2000)	δ (J2000)	Dist. (pc)	L_{bol} ($L_\odot$)	M_{env} ($M_\odot$)
TRACK 1						
Aqu-MMS1 [(2)]	0	18:30:03.9	-02:03:12.9	260	5	3
Aqu-OS2a [(2)]	0	18:31:10.63	-02:05:45.92	260	2	1.5
Serp-S68N	0	18:29:47.8	+01:16:46	260	4.4	1.1
Serp-SMM4	0	18:29:57.1	+01:13:15	260	9	3
TRACK 2						
L1172	0	21:02:21.54	+67:54:13.8	290	1.8	0.7
GF9-2	0	20:51:30.1	+60:18:39	200	0.3	0.5
L1157	0	20:39:06.26	+68:02:15.8	250	11	0.5
TRACK 3						
L1527	0	04:39:53.90	+26:03:10.0	140	1.6	0.8-1.7
N1333-IRS4B	0	03:29:11.98	+31:13:08.10	220	17	3.1
N1333-IRS4A [(3)]	0	03:29:10.47	+31:13:31.63	220	14	7
SVS13-B	0	03:29:03.7	+31:15:52.02	220	5.6	2.7
TRACK 4						
IRAM04191	0	04:21:56.91	+15:29:46.1	140	0.1	0.5-1.5
N1333-IRS2A	0	03:28:55.58	+31:14:37.1	220	10	1.7
L1448-N(B)	0	03:25:36.34	+30:45:14.94	220	7	0.7-1.5
TRACK 5						
L1448-IRS2A	0	03:25:22.42	+30:45:12.2	220	5	0.9
L1448-C	0	03:25:38.87	+30:44:05.4	220	5	1.6
L1521-F	0	04:28:38.99	+26:51:35.6	140	0.1	0.7-4

CALYPSO: the IRAM PdBI Large Program on Class 0 protostars

3 work packages:

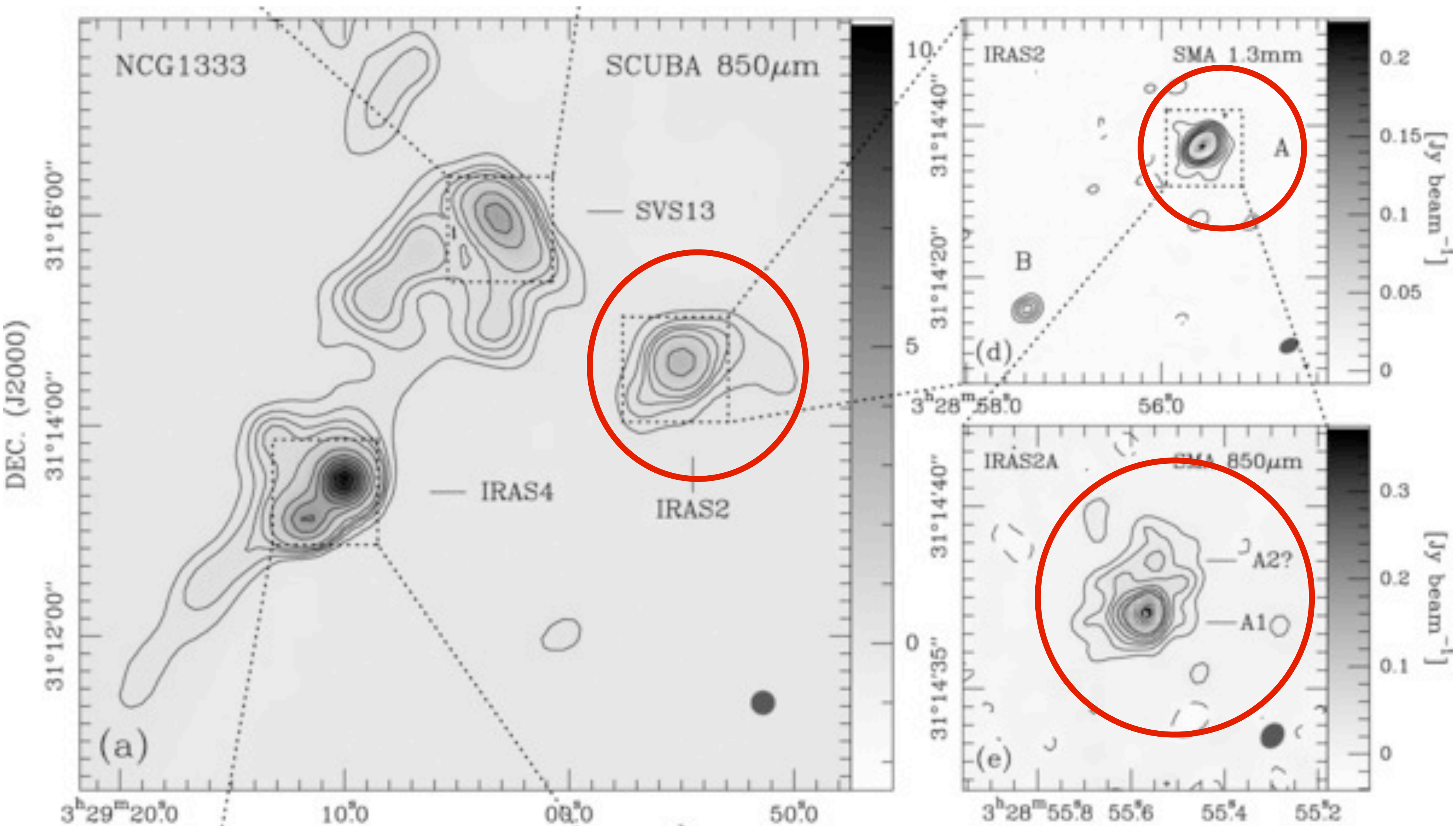
-I- Formation of multiple systems and circumstellar disks (Maury et al.)
-II- Jet / outflow launching and momentum removal (Codella et al.)
-III- Inner envelope kinematics and chemistry (Maret et al.)

+ comparison to MHD/HD simulations of protostellar formation
(Hennebelle, Commercon, Klessen & Dullemond)

Today:

- ✓ first highlights on the Class 0 protostar NGC1333 IRAS2A
- ✓ first statistical observational results: multiplicity and disks ?

The low-mass Class 0 protostar NGC1333-IRAS2A



SCUBA and SMA observations of the dust continuum emission (Jorgensen et al. 2007, Chen et al. 2013)

CALYPSO: first highlights papers 1/3

Letter to the Editor

First results from the CALYPSO IRAM-PdBI survey*

Monopolar jets driven by a proto-binary system in NGC1333-IRAS2A

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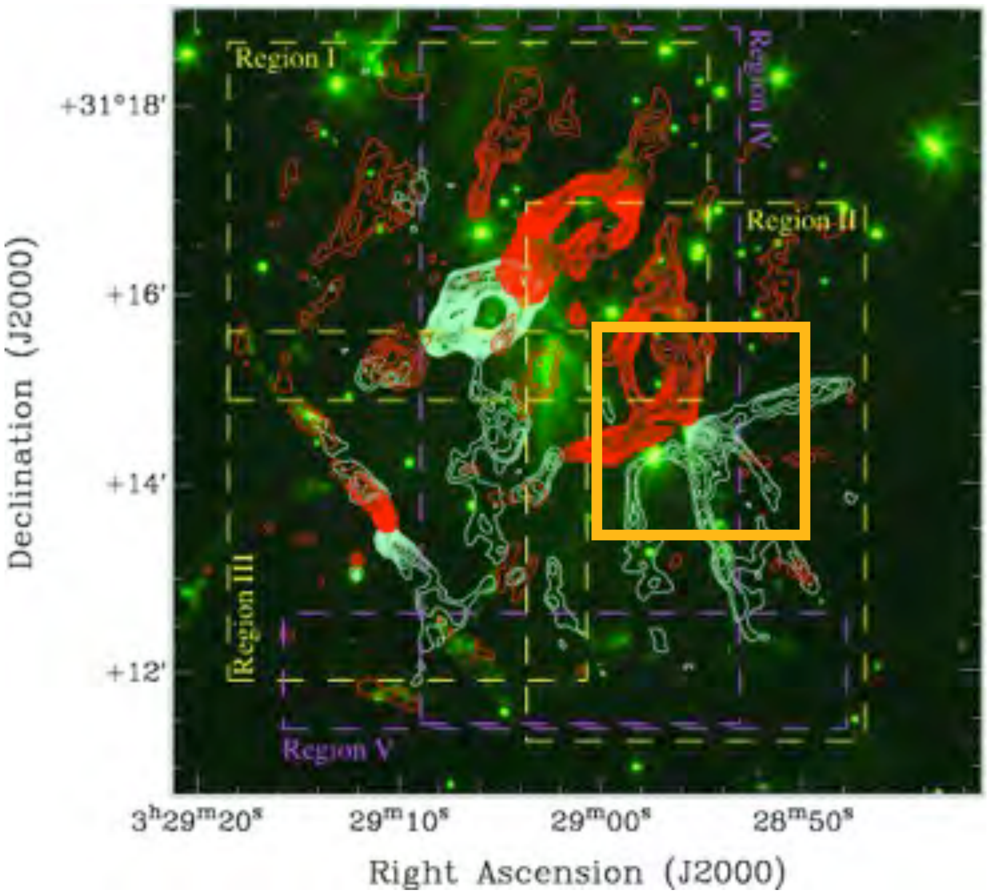
Received date; accepted date

ABSTRACT

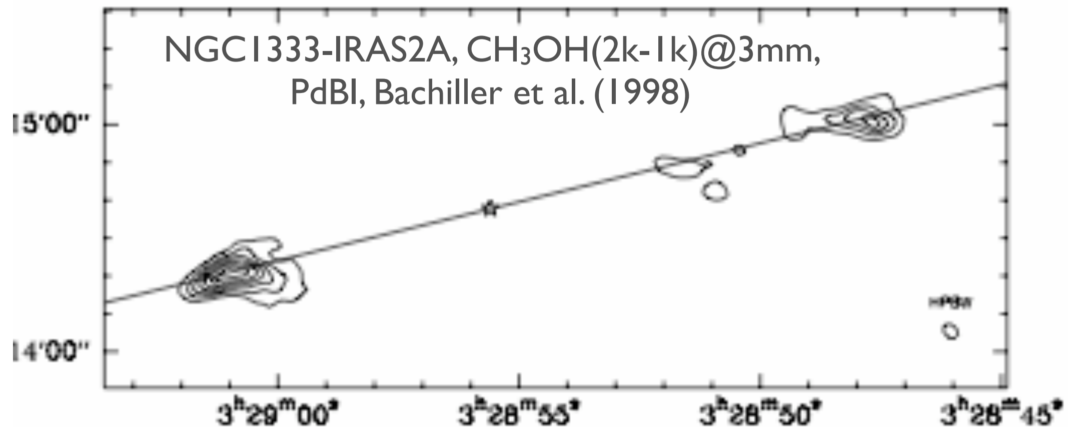
Context. The earliest evolutionary stages of low-mass protostars are characterised by hot and fast jets which remove angular momentum from the circumstellar disk, thus allowing mass accretion onto the central object. However the launch mechanism is still debated.
Aims. We wish to exploit high-angular ($\sim 0''.8$) resolution and high-sensitivity images to investigate the origin of protostellar jets using typical molecular tracers of shocked regions, such as SiO and SO.
Methods. We mapped the inner 22" of the NGC1333–IRAS2A protostar in SiO(5–4), SO(6_5–5_4), and continuum emission at 1.4 mm using the IRAM Plateau de Bure interferometer in the framework of the CALYPSO IRAM large program.
Results. For the first time, we disentangle the NGC1333–IRAS2A Class 0 object into a proto-binary system revealing two protostars (MM1, MM2) separated by $\sim$ 560 AU, each of them driving their own jet, while past work considered a single protostar with a quadrupolar outflow. We reveal (i) a clumpy, fast (up to $|V - V_{LSR}| \geq 50$ km s^{-1}), and blue-shifted jet emerging from the brightest MM1 source, plus (ii) a slower red-shifted jet, driven by MM2. SiO emission is a powerful tracer of high-excitation ($T_{kin} \geq 100$ K; $n_{H_2} \geq 10^5$ cm^{-3}) jets close to the launching region. At the highest velocities, SO appears to mimic SiO tracing the jets, whereas at velocities close to the systemic one, SO is dominated by extended emission, tracing the cavity opened by the jet.
Conclusions. Both jets are intrinsically monopolar, and intermittent in time. The dynamical time of the SiO clumps is $\lesssim$ 30-90 yr, indicating that one-sided ejections from protostar can take place on such timescales.

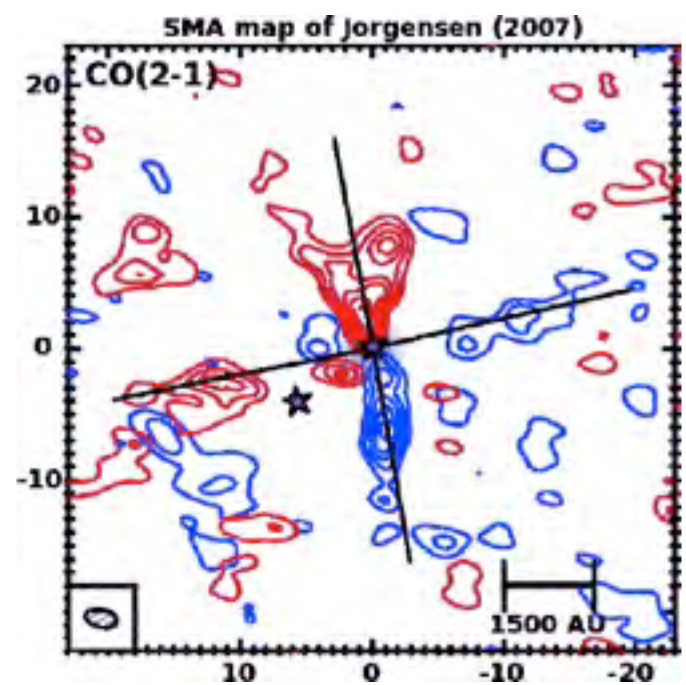
CALYPSO: first highlights papers 1/3
Codella et al. submitted

IRAS2A: a quadripolar outflow



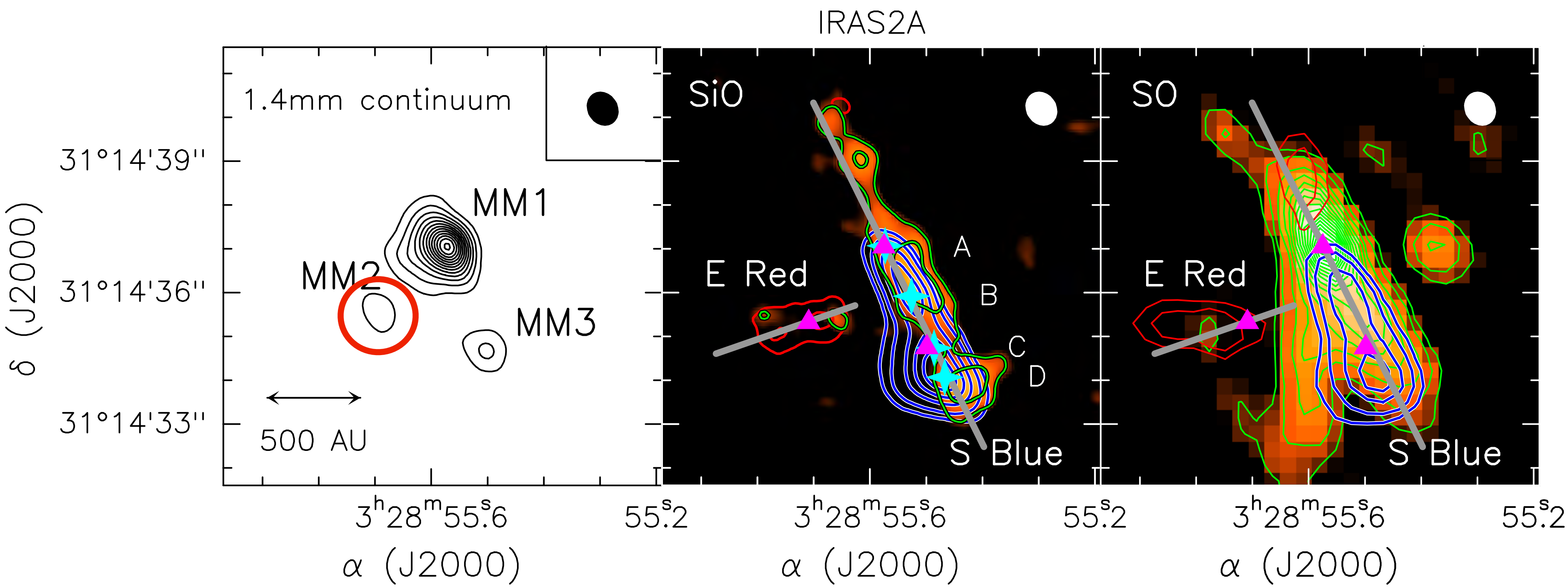
Perseus:
CO outflows (CARMA, Plunkett+ 2013)





SMA (Jorgensen+ 2007)

CALYPSO: first highlights papers 1/3
Codella et al. submitted



Secondary component driving the E-W jet found @ 560 AU from main

4 distinct clumps (A,B,C, D) tracing a sequence of shocks along the primary N-S jet

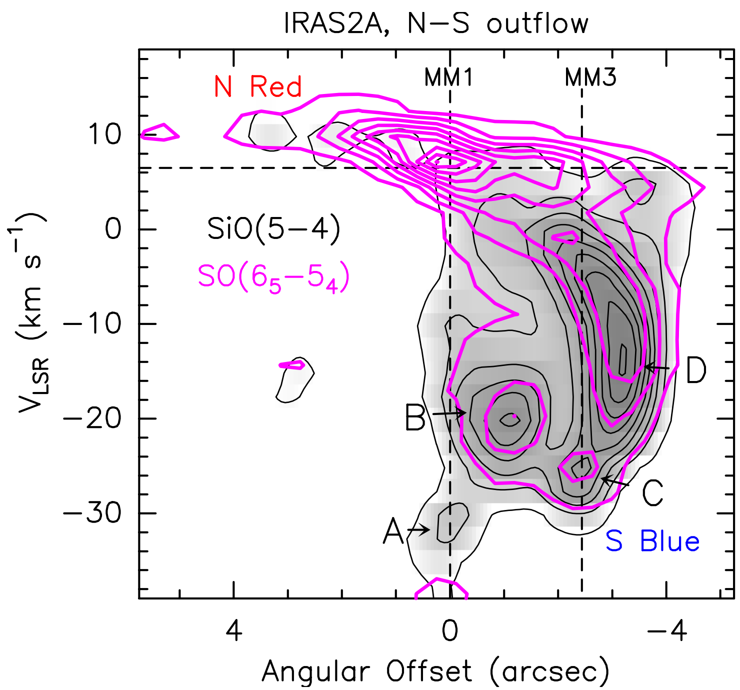
Detection of 2 young monopolar jets on scales <1000 AU with times <90 yrs

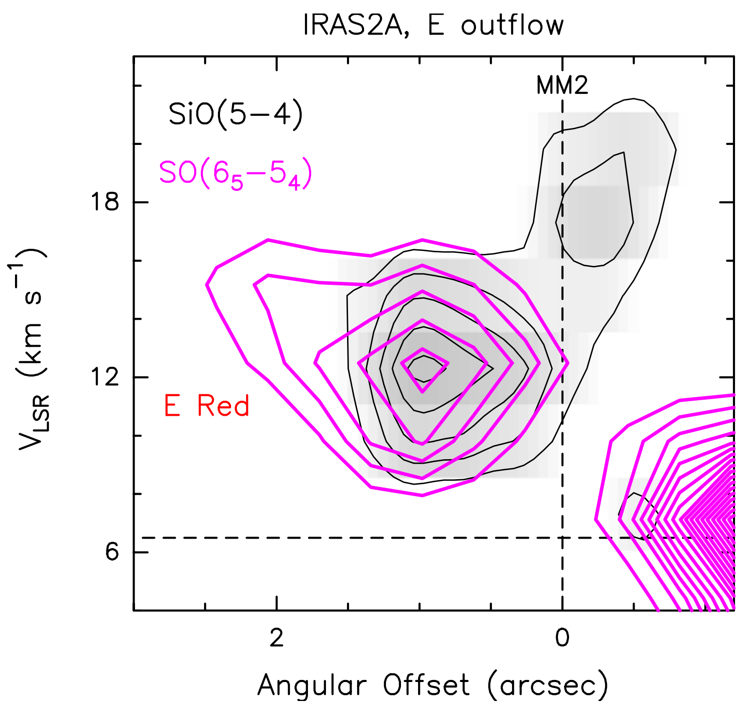
Decelerating

The jets have high excitation conditions : T>100K, n_{H2}> 10^5 cm^{-3}

Codella, Maury, Gueth, Maret, Belloche, Cabrit, André (submitted)

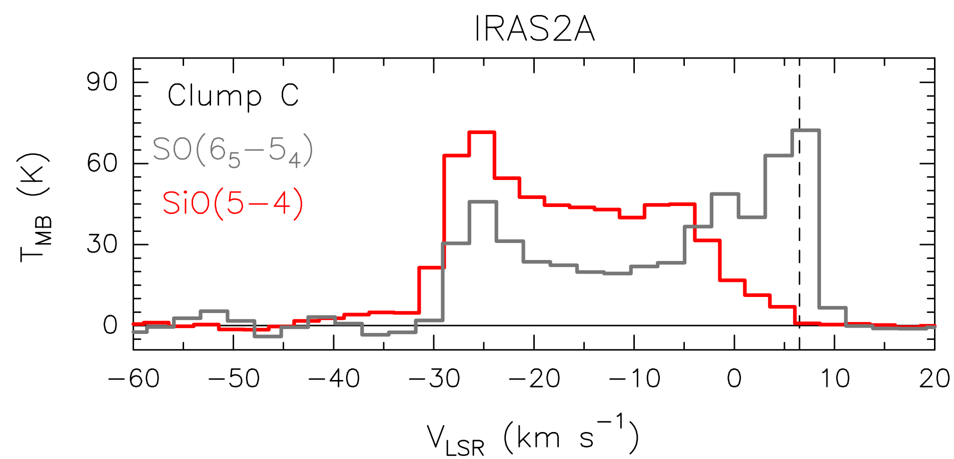
CALYPSO: first highlights papers 1/3
Codella et al. submitted





SO confirmed as a good tracer of jet and outflow: follows closely SiO emission at high velocities

Favors MHD models for jets:
C-shocks and magneto centrifugal disk winds can enhance SO abundances



The high-velocity jets opened a molecular cavity traced by SO at low velocity

Very few SiO there.
Similar to $H_2{}^{18}O$ by Persson+ (2012)

CALYPSO:
first highlights papers 2/3

Letter to the Editor

First results from the CALYPSO IRAM-PdBI survey*

Resolving the hot corino in the Class 0 protostar NGC 1333-IRAS2A

A. Maury[1,2], A. Belloche[3], Ph. André[4], S. Maret[5], F. Gueth[6], C. Codella[7], S. Cabrit[8], L. Testi[2,7,9], and S. Bontemps[10]

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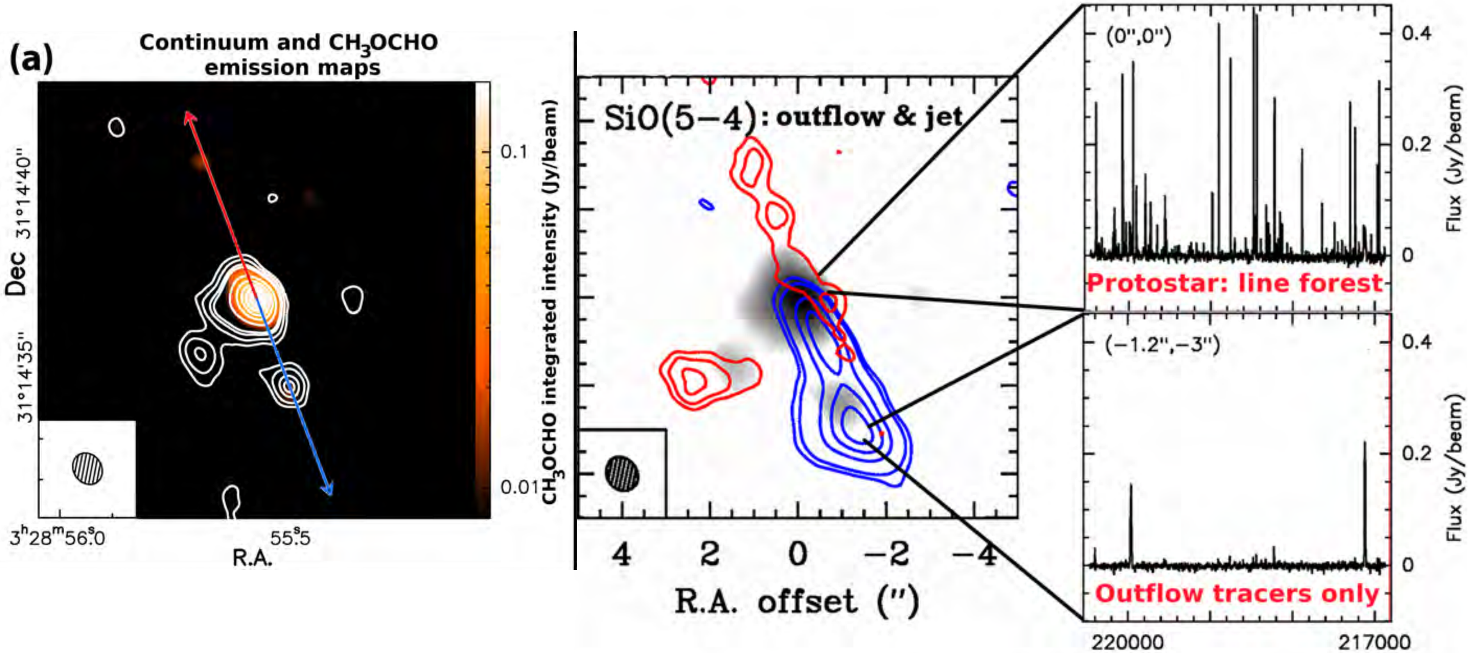
ABSTRACT

Aims. We investigate the origin of complex organic molecules (COMs) in the gas phase around the low-mass Class 0 protostar NGC1333-IRAS2A, to determine if the hot corino emission lines are tracing an embedded disk, shocks from the protostellar jet, or the warm inner parts of the protostellar envelope.
Methods. In the framework of the CALYPSO** IRAM Plateau de Bure survey, we obtained large bandwidth spectra at sub-arcsecond resolution towards NGC 1333-IRAS2A. We identify the emission lines towards the central protostar and perform Gaussian fits to constrain the size of the emitting region for each of these lines, tracing various physical conditions and scales.
Results. We show that the emission of numerous COMs such as methanol, ethylene glycol, methyl formate is spatially resolved by our observations. This allows us to measure, for the first time, the size of the COMs emission inside the protostellar envelope, finding it originates from a region of radius ~40–100 AU, centered on the NGC 1333-IRAS2A protostellar object. Our analysis shows no preferential elongation of the COMs emission along the jet axis, and therefore does not support the hypothesis that COMs emission arises from shocked envelope material at the base of the jet. Down to similar sizes, the dust continuum emission is well reproduced with a single envelope model, therefore not favoring the hypothesis that COMs emission arises from the thermal sublimation of grains embedded in a circumstellar disk. Finally, the typical scale ~60 AU observed for COMs emission is consistent with the size of the inner envelope where $T_{dust} > 100$ K is expected. Our data therefore strongly suggest that the COMs emission traces the hot corino in IRAS2A, i.e the warm inner envelope material where the icy mantles of dust grains are being evaporated because they are passively heated by the central protostellar object.

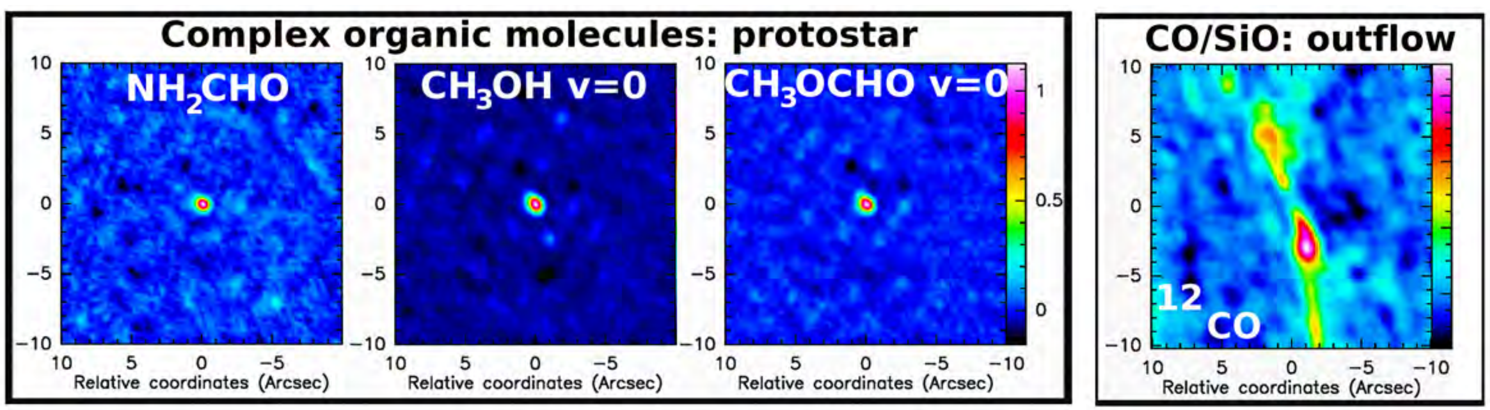
CALYPSO: first highlights papers 2/3
Maury et al. submitted



Complex organic molecules are strong towards the continuum source.

Along the outflow: mostly shocks/jet tracers (SiO,CO, SO)

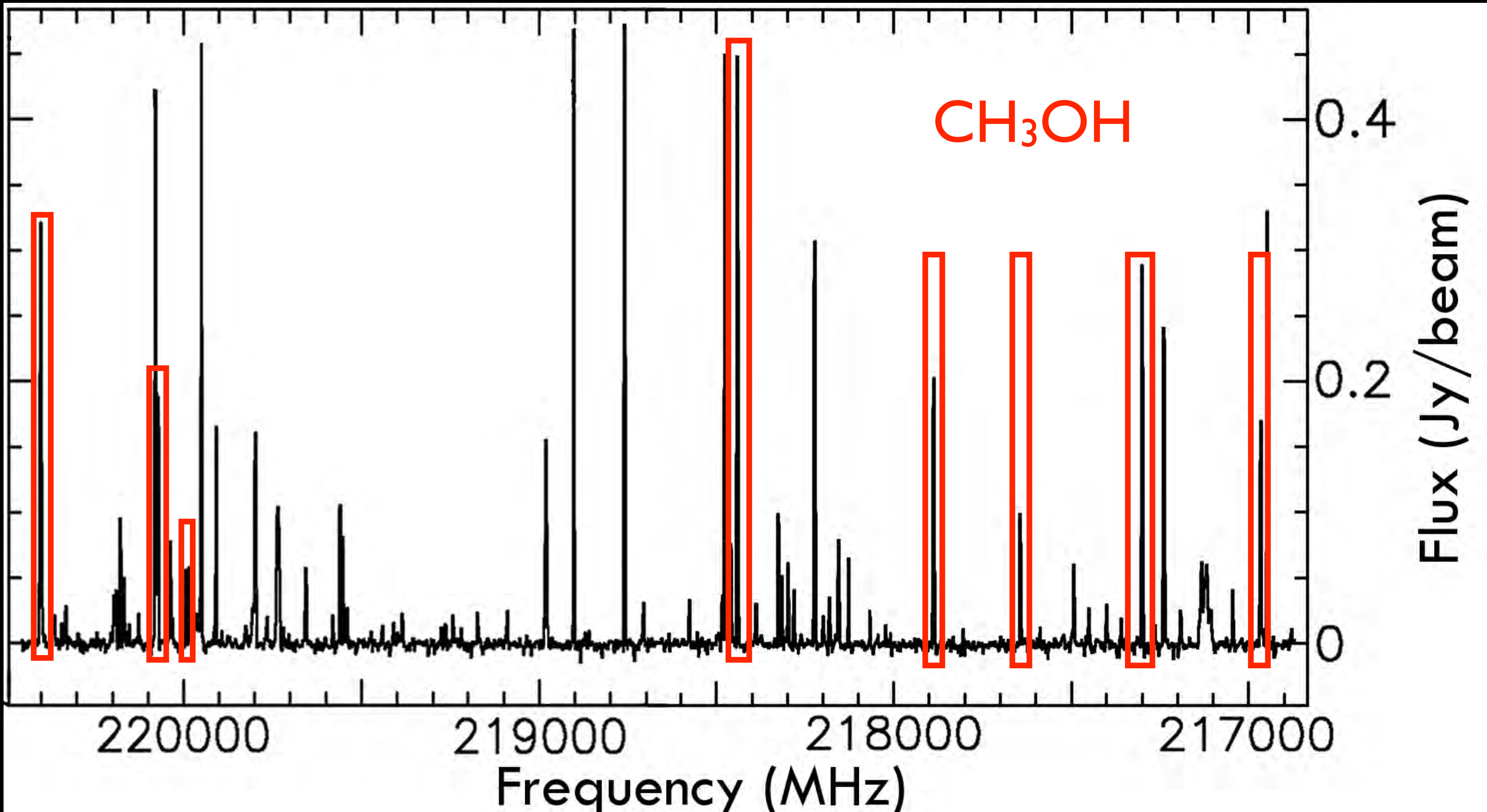
Most complex molecules have their emission centered on the continuum peak of IRAS2A MM1



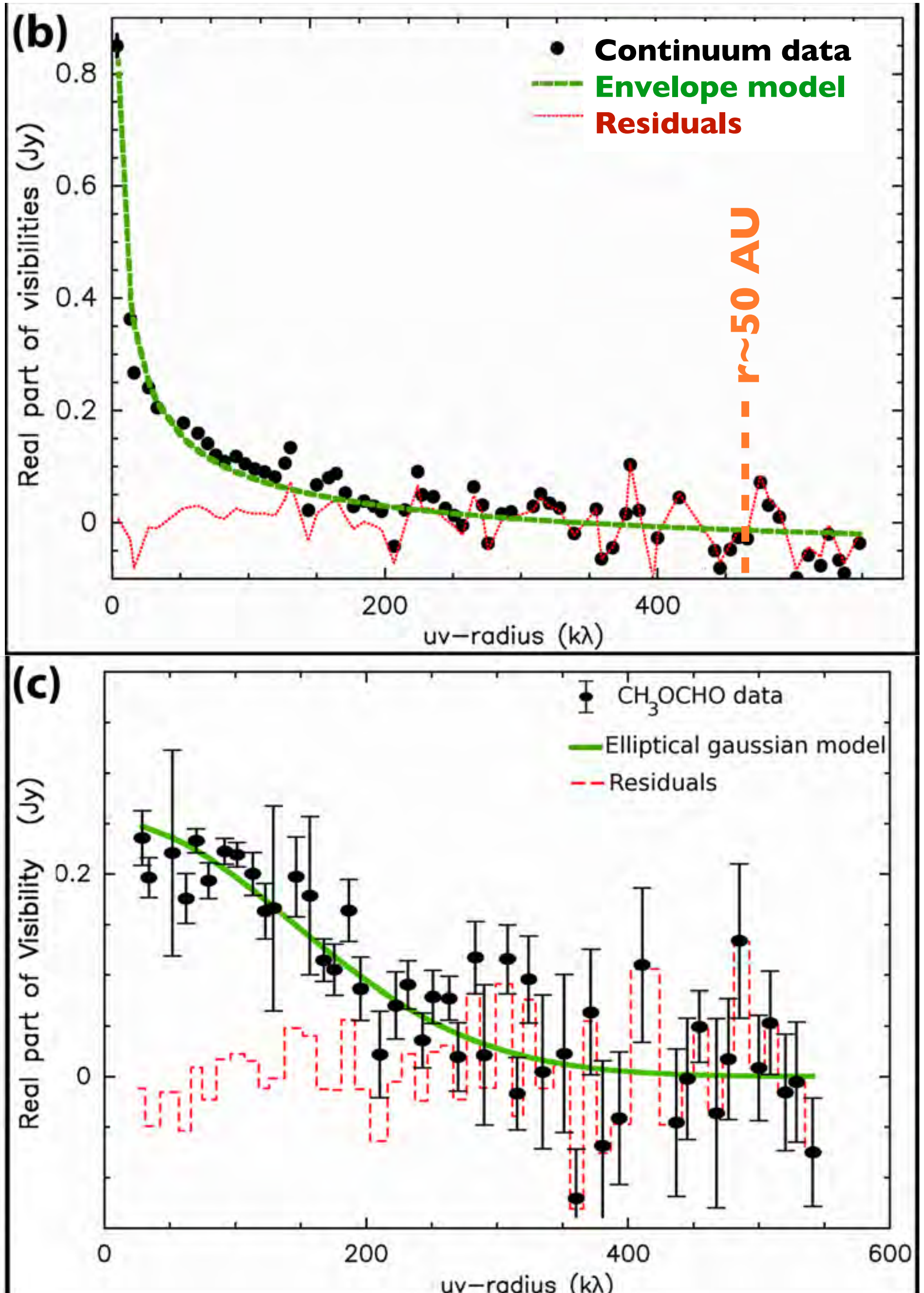
Maury, Belloche, Andre, Maret, Gueth, Codella, Cabrit, Testi and Bontemps (submitted)

CALYPSO: first highlights papers 2/3
Maury et al. submitted

NGC1333-2A:
Part of the spectrum at the peak of continuum emission



CALYPSO: first highlights papers 2/3
Maury et al. submitted



COMs emission is resolved spatially with > 10's of COMs lines

COMs: emitting sizes resolved <100 AU
No preferential elongation along the jet axis

Continuum:
well reproduced by power-law envelope profile
if present the disk component is <40 AU

COMS trace the hot corino region where the envelope is >100K due to radiative heating from the protostar.

Size of T>100K region is ~60 AU

CALYPSO:
first highlights papers 3/3

Letter to the Editor

First results from the CALYPSO IRAM-PdBI survey⋆ ⋆⋆

Kinematics of the inner envelope of NGC1333-IRAS2A

S. Maret[1], A. Belloche[2], A. J. Maury[3], F. Gueth[4], Ph. André[5], S. Cabrit[6], and C. Codella[7]

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Received ...; accepted ...

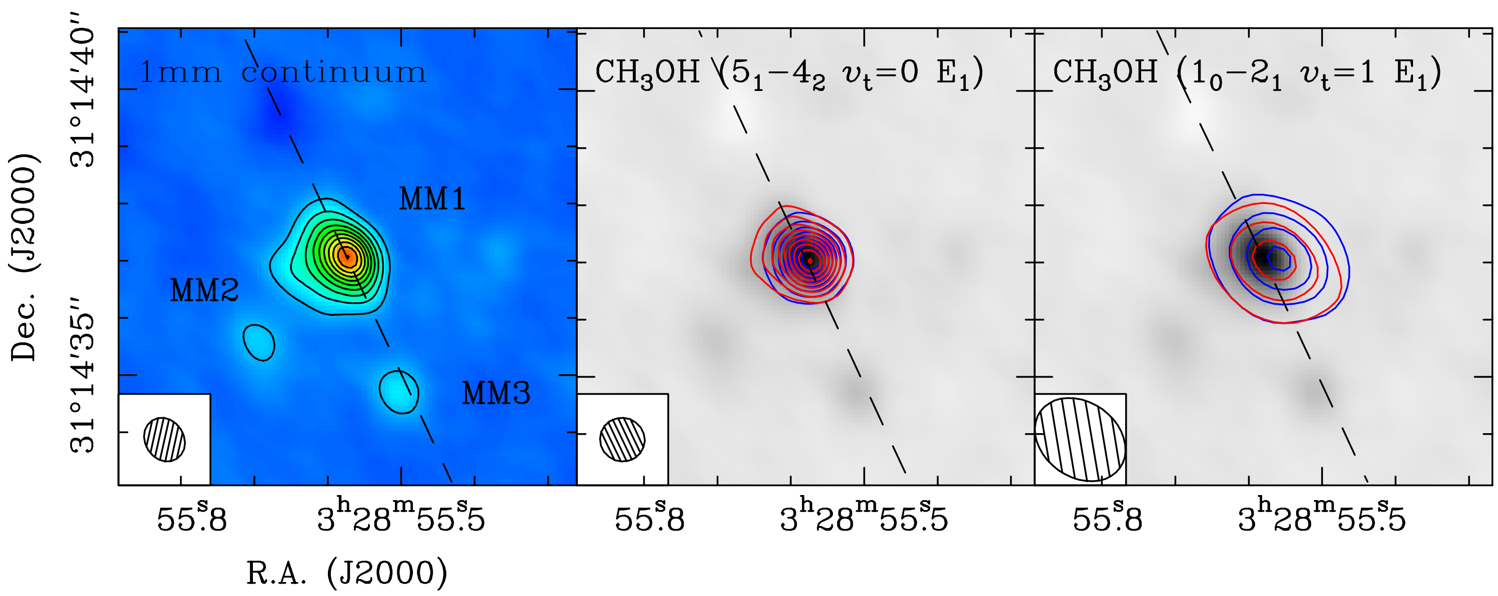
ABSTRACT

The structure and kinematics of Class 0 protostars on scales of a few hundred AU is poorly known. Recent observations have revealed the presence of a Keplerian disk with a diameter of 180 AU in L1527-IRS, but it is not clear if such disks are common in Class 0 protostars. Here we present high-angular-resolution observations of two methanol lines in NGC1333-IRAS2A. We argue that these lines probe the inner envelope, and we use them to study the kinematics of this region. Our observations suggest the presence of a marginal velocity gradient normal to the direction of the outflow. However, the position velocity diagrams along the gradient direction appear inconsistent with a Keplerian disk. Instead, we suggest that the emission originates from the infalling and perhaps slowly rotating envelope, around a central protostar of 0.1 – 0.2 $M_{\odot}$. If a disk is present, it is smaller than the disk of L1527-IRS, perhaps suggesting that NGC1333-IRAS2A is younger.

Key words. ISM individual objects: NGC 1333-IRAS 2A – ISM: kinematics and dynamics – ISM: molecules – Stars: formation

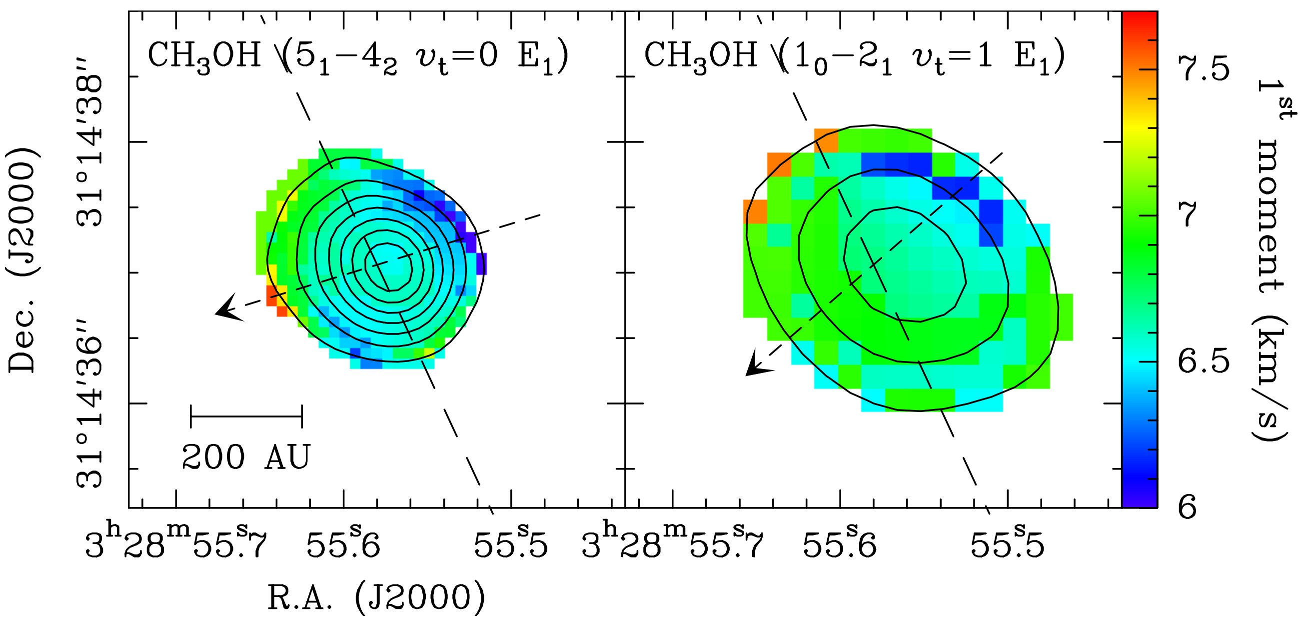
CALYPSO: first highlights papers 3/3
Maret et al. submitted

Using 2 methanol lines at 1mm and 3mm, probing the inner envelope kinematics down to scales ~40 AU

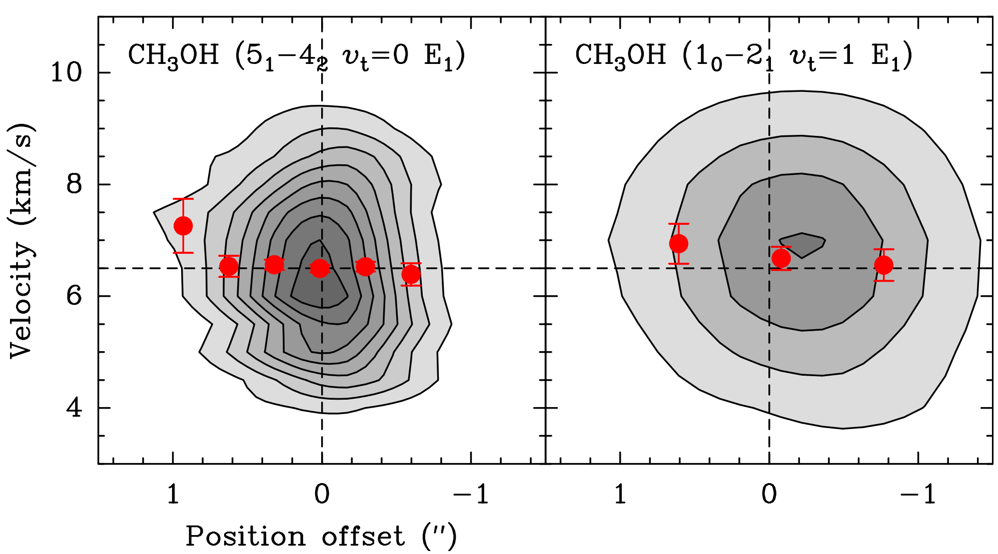


Maret, Belloche, Maury, Gueth, Andre, Cabrit and Codella (submitted)

CALYPSO: first highlights papers 3/3
Maret et al. submitted



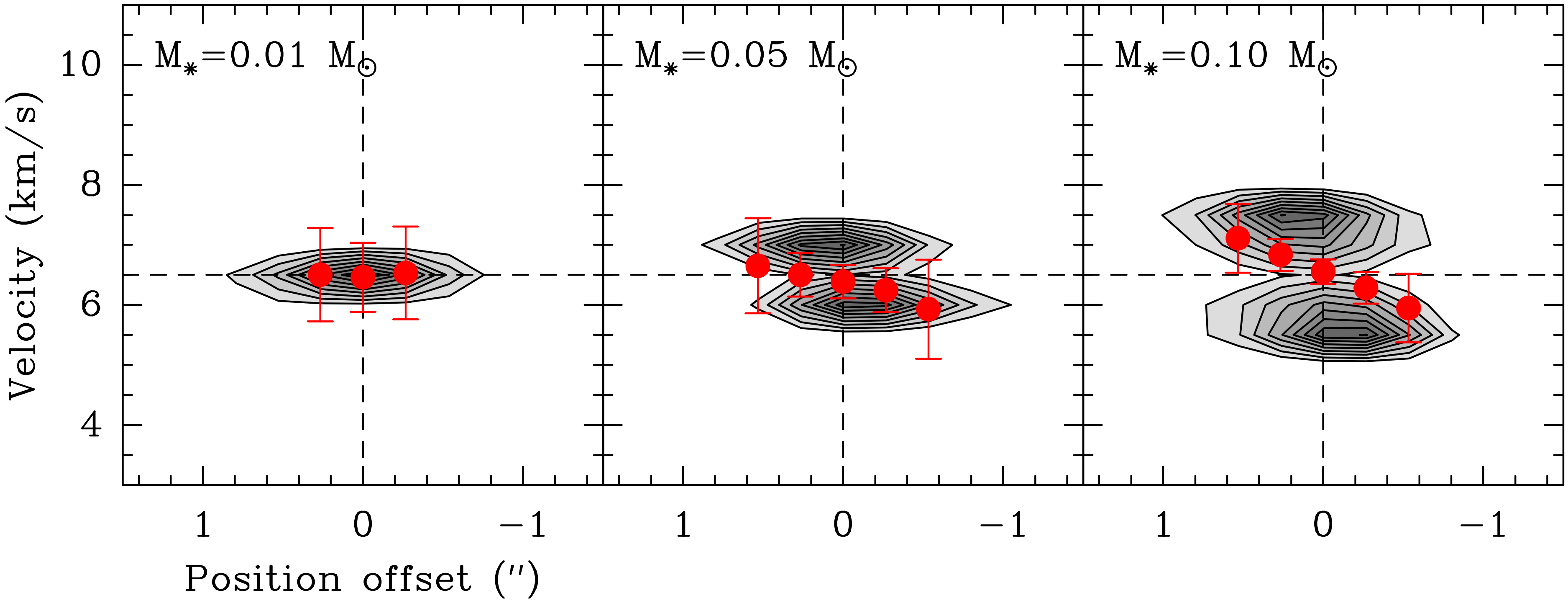
Presence of marginal velocity gradient normal to the direction of the outflow: PA 107°



PV diagrams along axis PA 107°: no clear signature of rotation.

But first order moment (red points) suggests presence of a velocity gradient

CALYPSO: first highlights papers 3/3
Maret et al. submitted



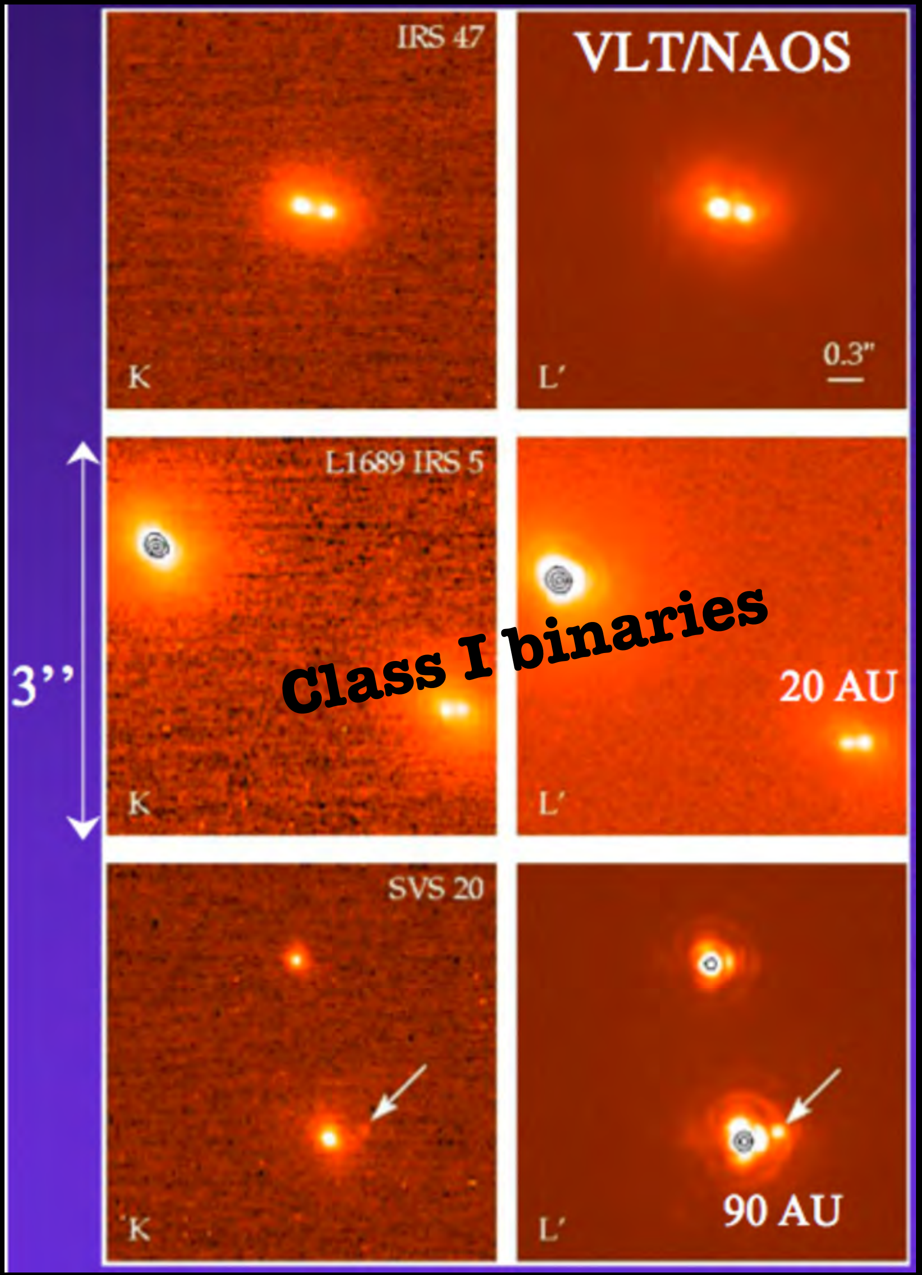
Synthetic PV for dynamic masses of 0.01Mo, 0.05Mo and 0.1Mo in keplerian rotation.
PV diagram and linewidths: not consistent with a model of a keplerian disk

If a disk is present it must have r<45 AU

Observed methanol velocity dispersion at r~45 AU:
can be reproduced by infalling, slowly rotating envelope
around a central protostar ~ 0.1 - 0.2 Mo

Multiple systems: current landscape

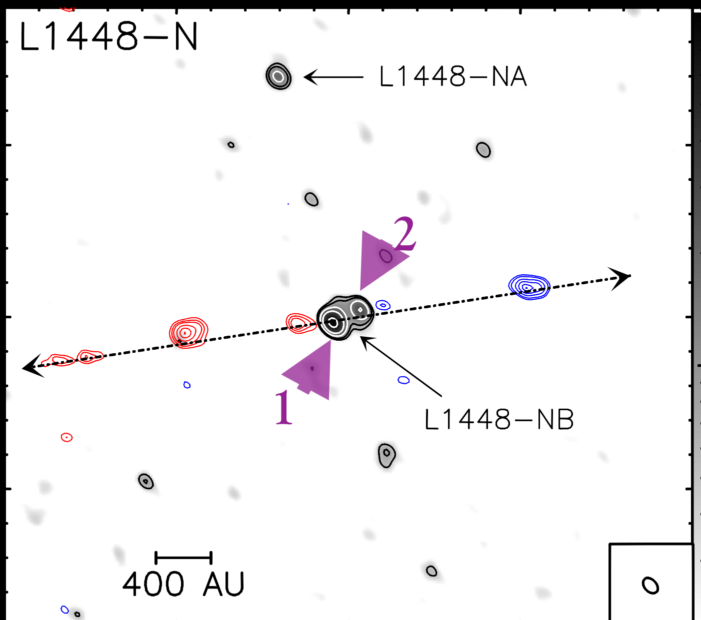
Young multiple systems

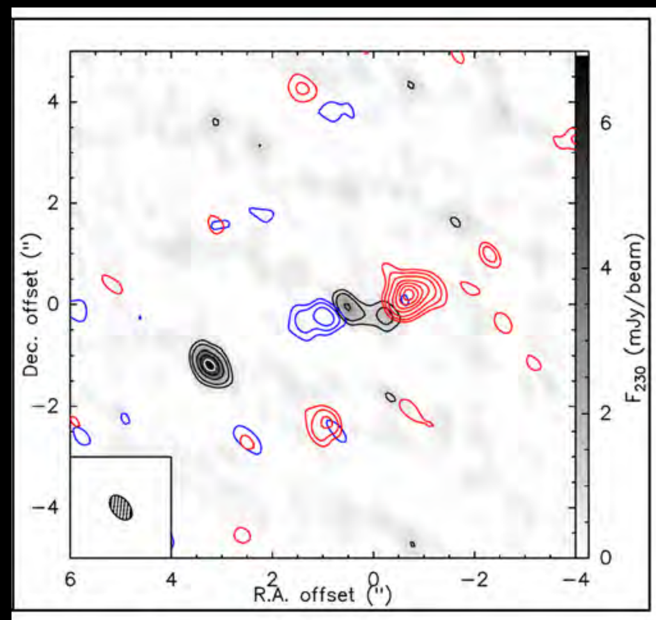


(Duchêne + 2003)

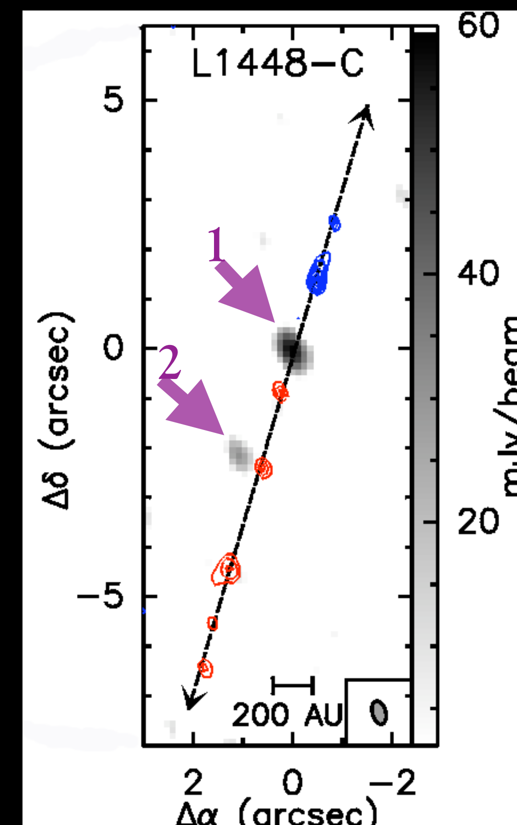
Early multiple systems: pre-CALYPSO results

In the PdBI maps: lots of multiple sources seen in the mm continuum ...
Mostly along the jet axis : not clear if companions or outflow features

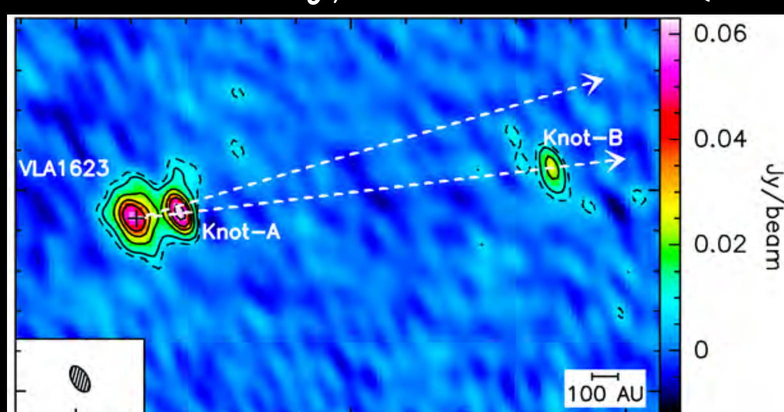




L1448-C: Maury et al. (2010)



VLA1623: Maury, Ohashi & André (2012)



Multiple systems: current landscape

✳ Recent resuts

Chen et al. (2013)

Angular resolution of 0.5-4′′

Large sample: 33 protostars at distances <500pc

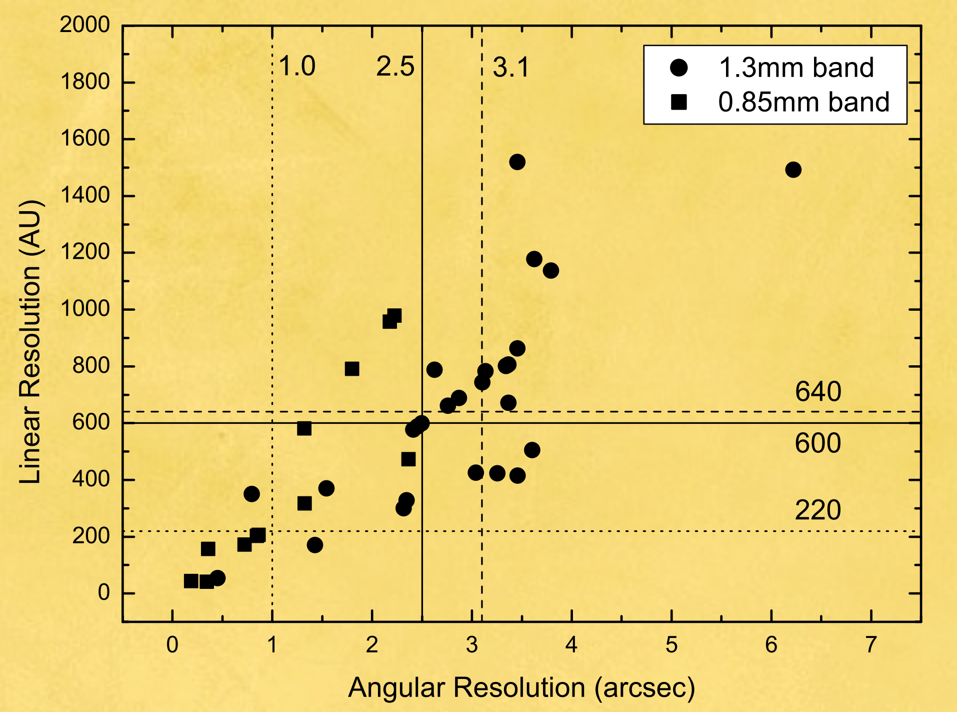
Caveats:

⋆Includes Class 0/1 borderline protostars

⋆Inhomogeneous sensitivities & resolution

⋆No multiwavelength analysis

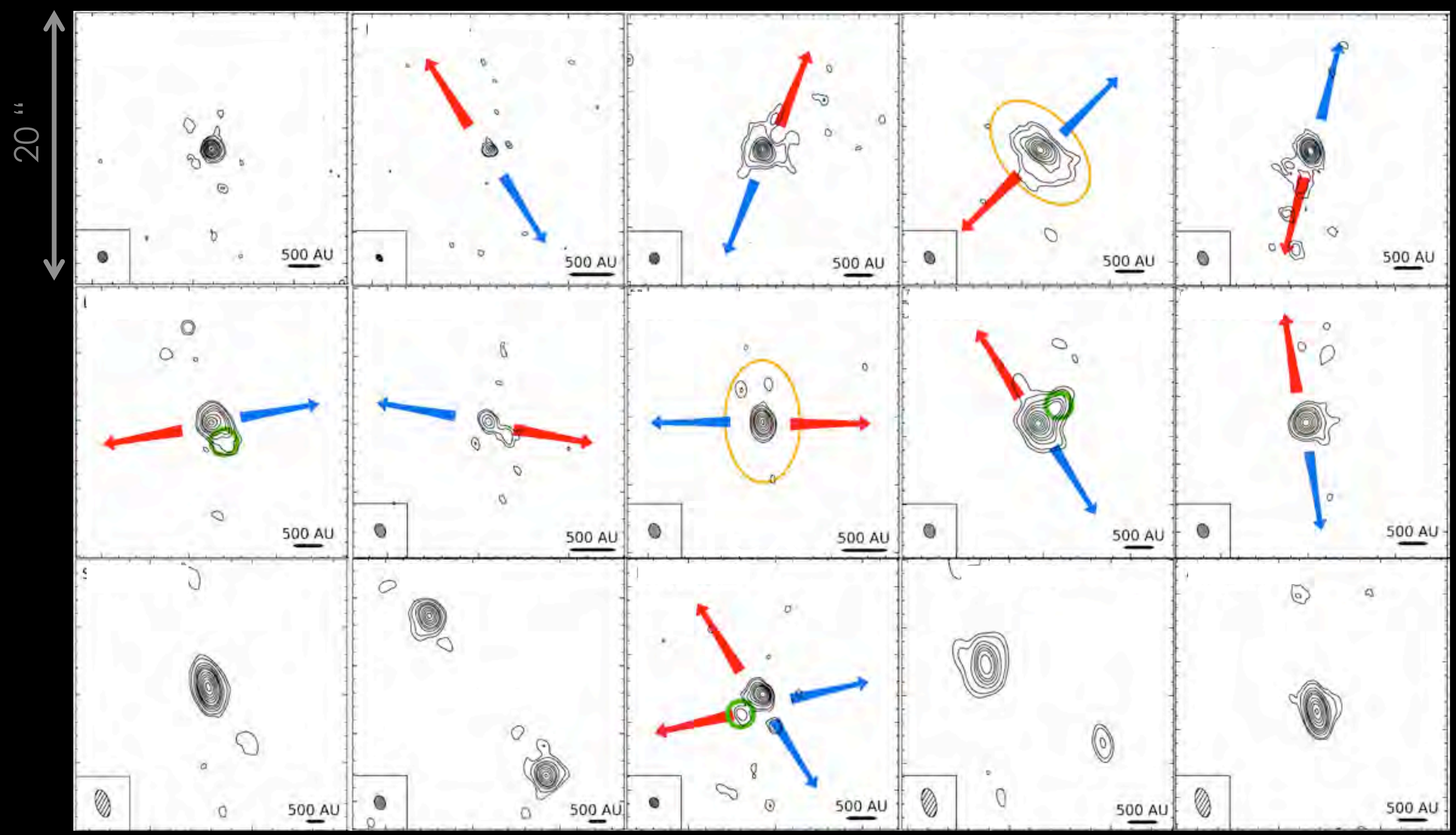
> all sources detected at r<5000 AU are considered as companions



Multiplicity rate: 64% - taking all scales

Suggest multiplicity decreases from Class 0 to Class I

Multiple systems: the CALYPSO view



Detailed analysis of the nature of these structures suggest:
1/ Close (100-1000 AU separations) binaries are less frequent than during the more evolved phases
-> Separations must evolve dynamically during the embedded stages

2/ Large (100-300 AU radius) circumstellar disks are rare.
-> Accretion disks formed during the Class 0 stage must be small in size (e.g < 50 AU radius)

Multiple systems and disks: the CALYPSO view

On CALYPSO global sample of 17 Class 0 protostars:

1/ **Only 3 proto binaries** at scales ~50-1500 AU
Some clues of increasing multiplicity rate
between Class 0 and Class I phase
at scales ~50-1500 AU.

BUT
Not enough mass at Class I stage to form new protostellar companions :
dynamical scenarii for the formation of multiple systems.
Also some secondary continuum components of unclear nature:
global CALYPSO dataset is needed to conclude.

2/ **Large protostellar disks are rare**: only 2 disk-like signatures at scales >100 AU
-> Accretion disks formed during the Class 0 stage might be small in size (e.g < 50 AU radius)

CALYPSO: current status and next steps

Observations: all PdBI data obtained
Data: all reduced - fine details remaining on individual sources
30m short-spacings currently being obtained

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First round of 'highlight' publications submitted:
Maury+ : complex organic molecules tracing the size of the hot corino region
Maret+ : kinematics of the inner envelope using methanol lines
Codella+: analysis of SO / SiO emission from the jet(s)

-

Data will be made public by end of 2014

↓

An unprecedented database for future ALMA studies

CALYPSO: a pathfinder for ALMA and NOEMA studies

Difficult to reach the same sources (northern sources)
but CALYPSO is identifying the right tracers at small scales to assess
the kinematics and properties of Class 0 protostars

At higher angular resolution:

search for small magnetized disks

resolve jet rotation

test the fragmentation at the scales of the solar system