Disentangling the jet emission from low-mass protostellar systems: An ALMA and PdBI view

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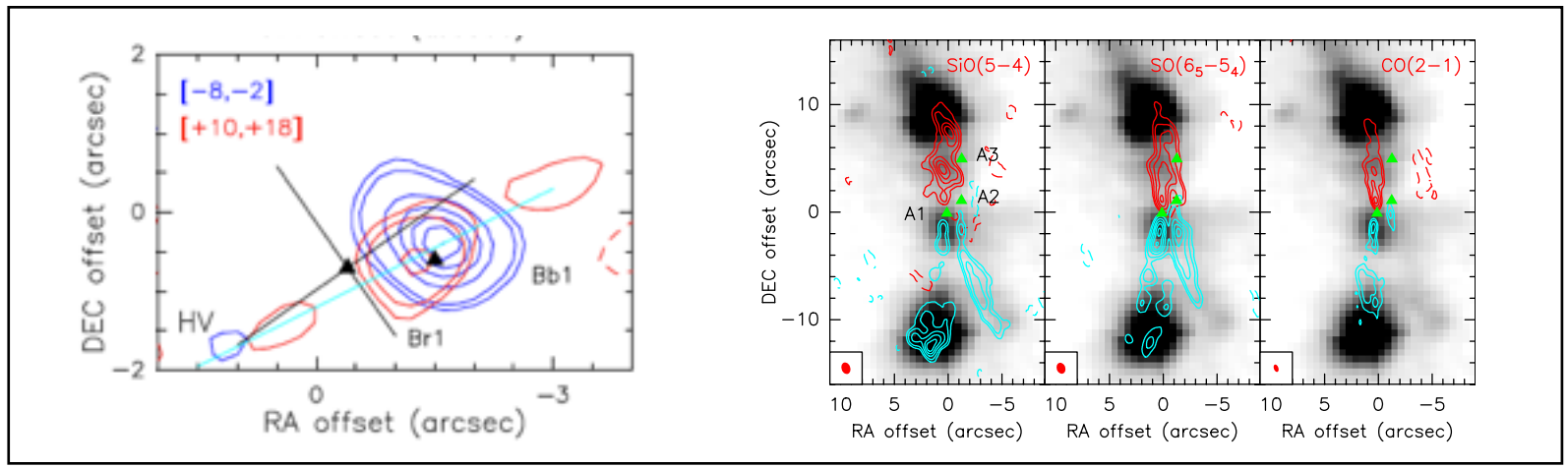
In collaboration with:
see next slide!



Terzo Workshop sull'Astronomia millimetrica in Italia - Jan. 2015

Outline

- Low-mass star (and multiple-system) formation
- Why we need to perform (sub-)mm high resolution observations?
  1. **NGC1333-IRAS4A protobinary system (235 pc)**:
     - PdBI SiO(5-4), SO(6_5-5_4), and CO(2-1) data
     - In the framework of the CALYPSO large program: ~300 hours, a sample of 17 Class 0 protostars (<300 pc), sub-arcsec res., 3 setups (1.3, 1.4, 3 mm), continuum and molecular lines

     C. Codella, L. Podio, L. Testi (INAF)

     S. Cabrit, A. J. Maury, F. Gueth, S. Maret, B. Lefloch, Ph. André, P. Hennebelle, S. Anderl (France)

     A. Belloche, (Germany)

  2. **VLA16234-2417 triple protostellar system (120 pc)**:
     - ALMA Cycle 0 CO(2-1) data (PI Nadia M. Murillo)

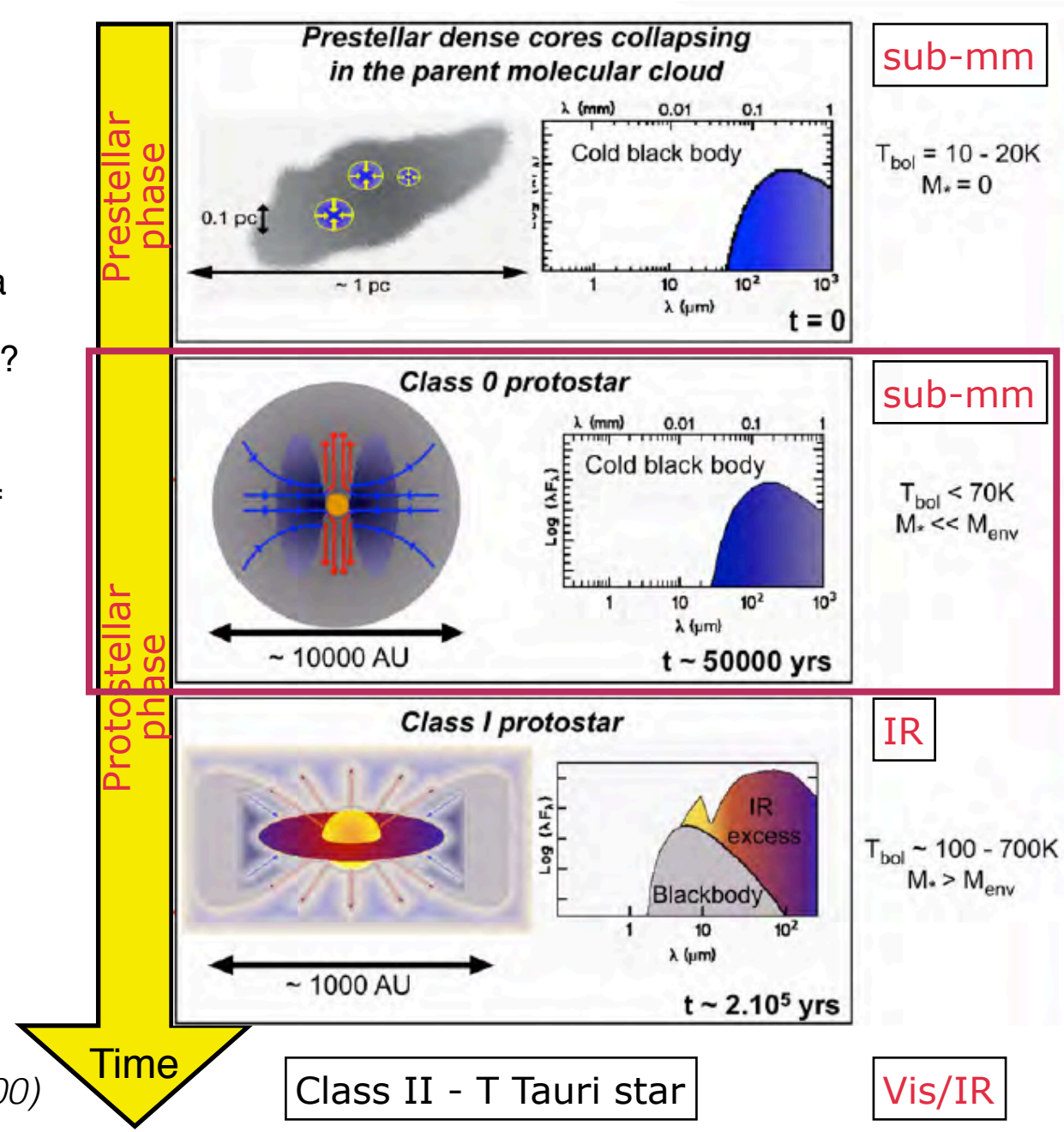
     B. Nisini, C. Codella (INAF)

     N. M. Murillo, S. Bruderer, E. F. van Dishoeck (Germany)

     S. P. Lay (Taiwan)
- Conclusions and the need for ALMA follow-up

Formation of a sun-like star

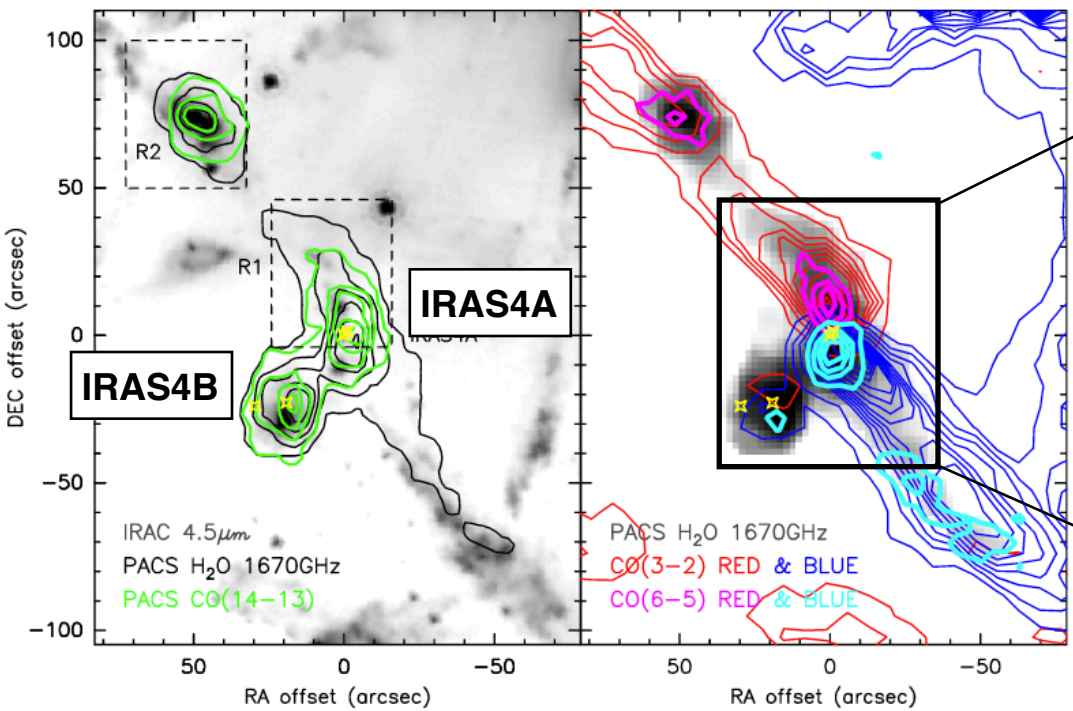
- Classical picture of low-mass star formation
- Multiple system: **fragmentation** of a collapsing dense core (e.g. *Tohline 2002, Goodwin et al. 2007*) but how? → Information on multiplicity, coevality, and environment can help
- Need for **(sub)mm observations** of the earliest Class 0 stages
- Need for **sub-arcsec resolution** to disentangle the emission of the different processes: hot-corino, jet emission, cavity emission, and disk (≤100 AU)



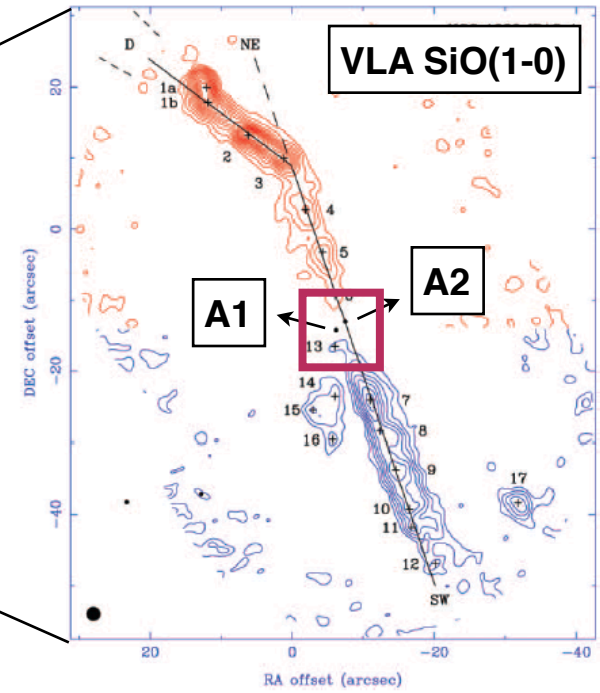
André et al. (2000)

NGC1333-IRAS4A
PdBI CALYPSO

IRAS4A PROTOBINARY SYSTEM

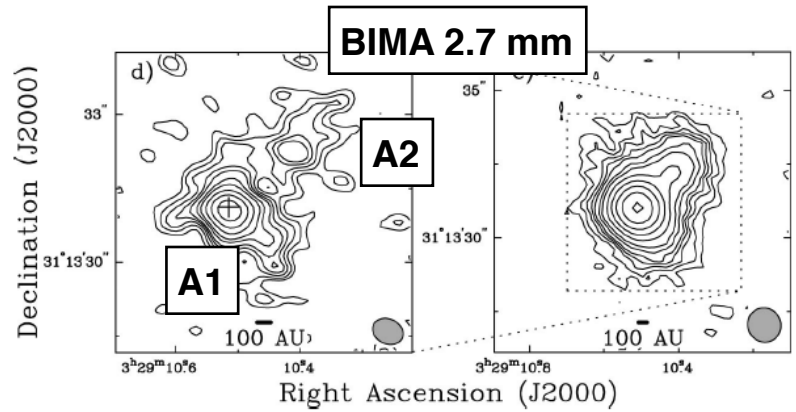


Yildiz et al. (2012), Santangelo et al. (2014)



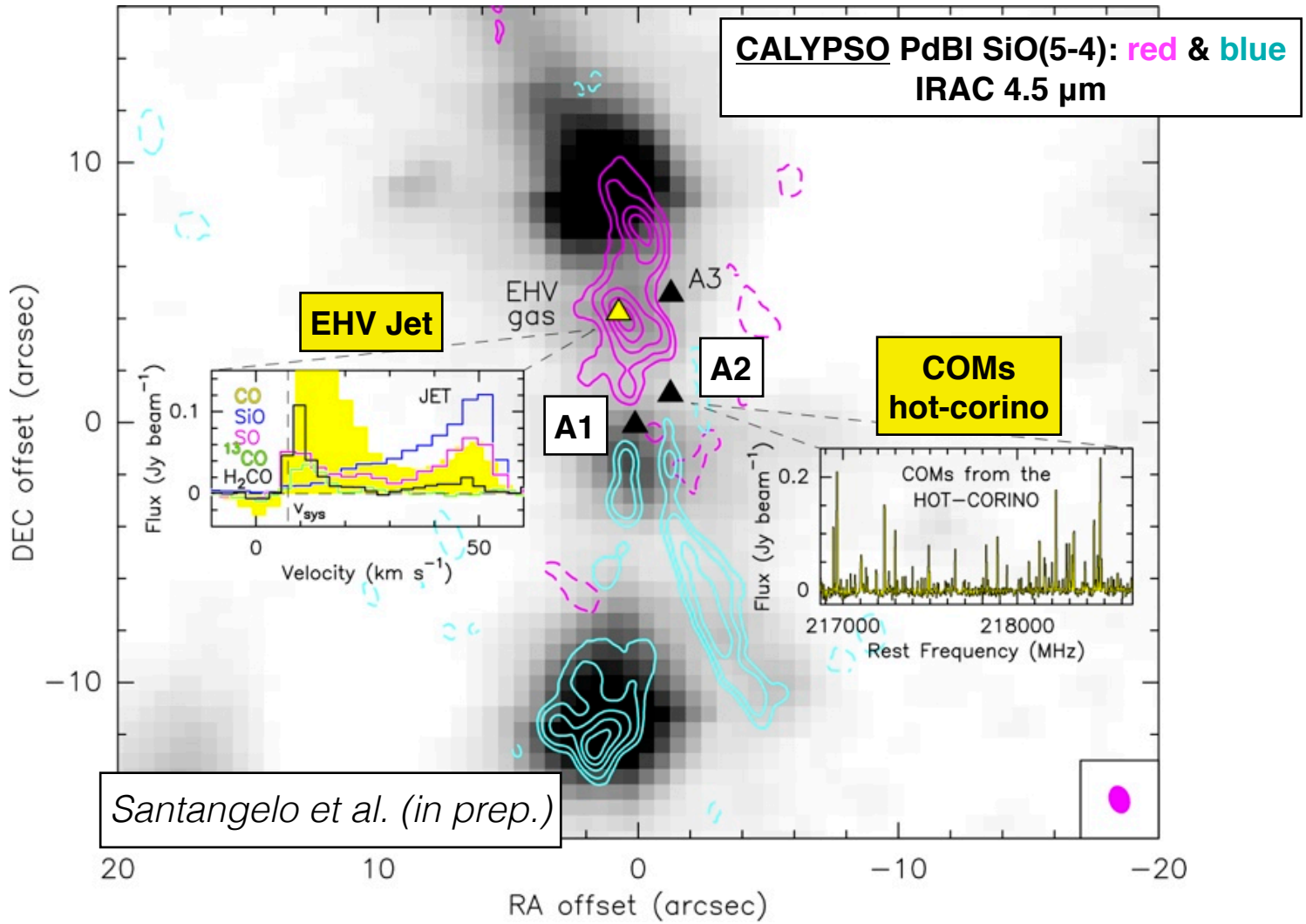
Choi (2005), Choi et al. (2006,2011)

- $L(IRAS4A)_{bol} \sim 4.2\ L_{\odot}$
- A1/A2 separation: 1.8 arcsec ~420 AU (235 pc)
- Large-scale (a few arcmin) outflow in CO, SiO, and H_2O (*Blake et al. 1995; Choi 2001, 2005; Yıldız et al. 2012; Santangelo et al. 2014*) possibly driven by A2
- SiO shorter blue-shifted southern outflow possibly by A1, no counterpart



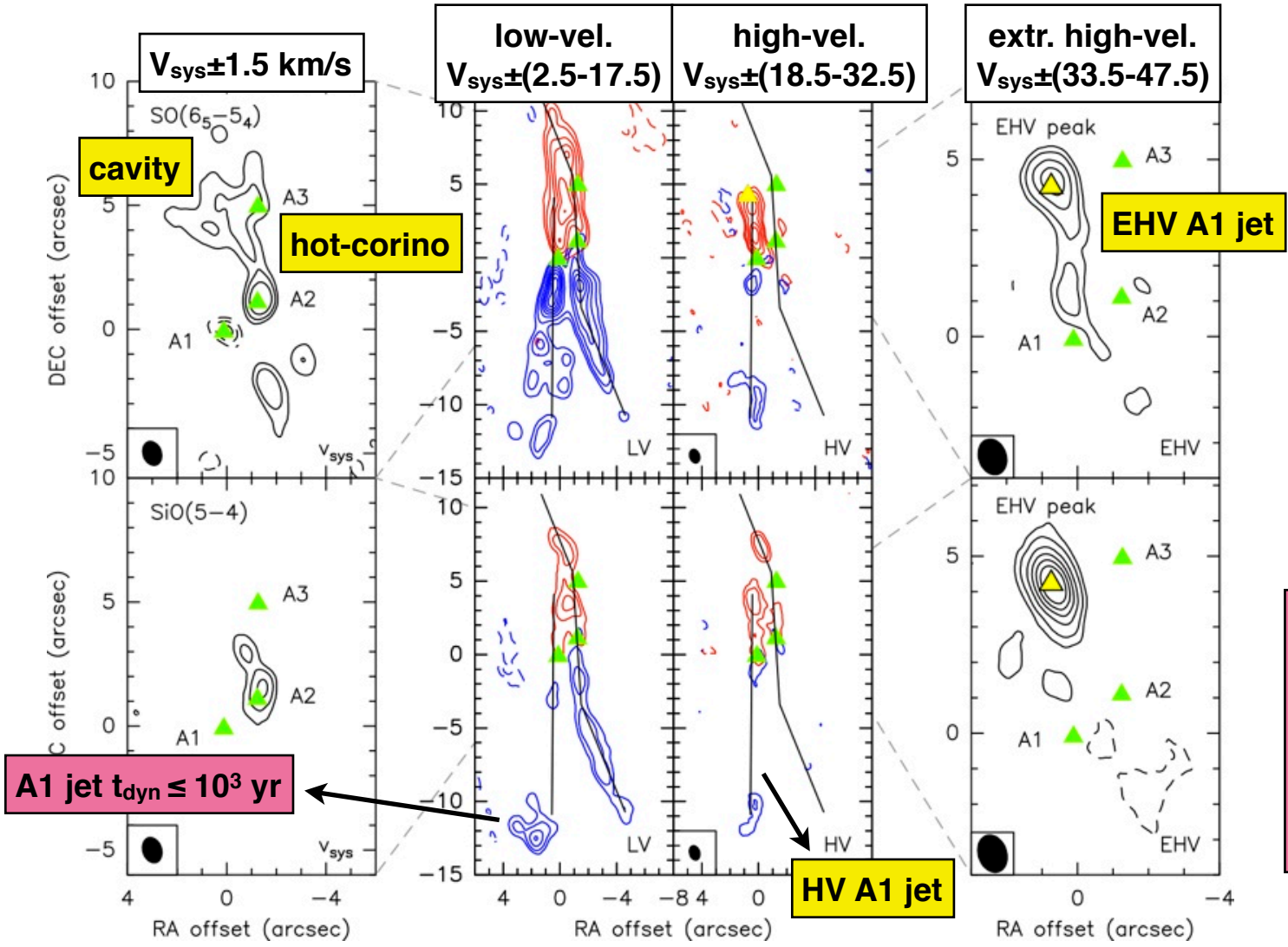
Lay et al. (1995), Looney et al. (2000)

IRAS4A: THE CALYPSO VIEW



- Clearly disentangle blue-shifted A1/A2 jets close to the sources (<2400 AU)
- Association between IRAC H_2 and **A1 jet → more energetic**
- EHV 50 km s^{-1} gas detected in SiO, CO, SO, H_2CO (associated with A1 jet) → shock origin
- Hot-corino at A2 (e.g. HCOOH formic acid, CH_3OCHO methyl formate, CH_3OCH_3 dimethyl ether)

IRAS4A: Jet kinematics

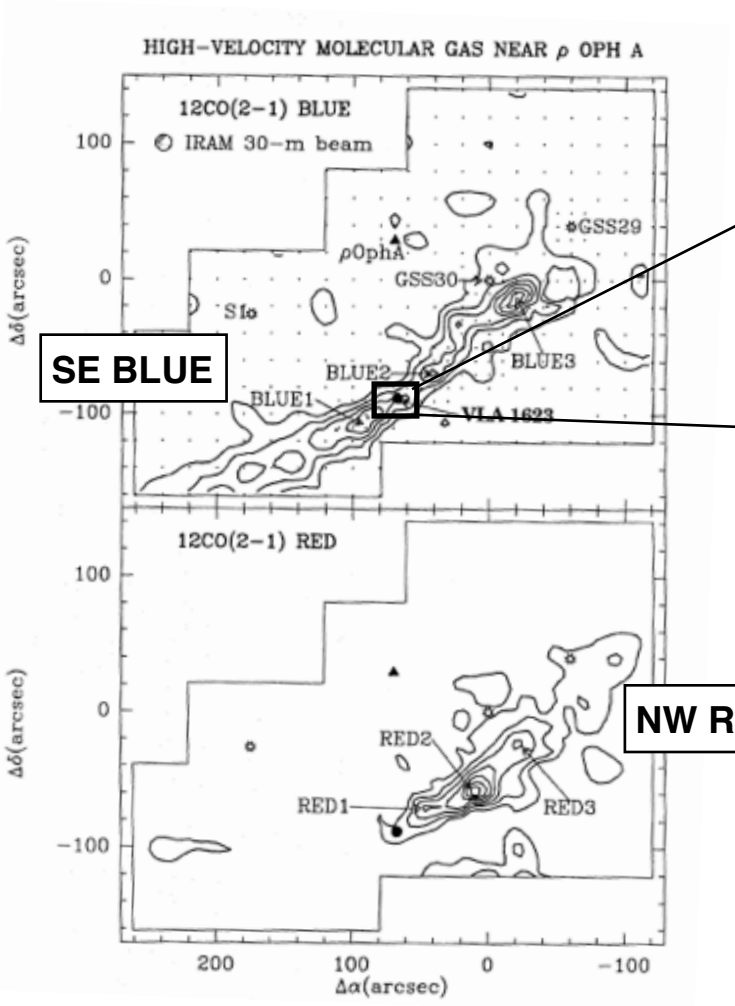


Different jet properties (length, speed) possibly due to **difference in evolutionary stages** (**A1 younger** before the hot-corino phase)

- SO emission associated with hot-corino and cavity-like structure
- Clearly disentangle A1/A2 jets: **A1 jet is faster than A2 jet** (HV/EHV association)
- Bending of A2 jet (consistent with large-scale): **precessing A2 jet** (200-600 yr dynamical age)
- Disentangle red-shifted A1 jet emission (short length, $t_{dyn} \leq 10^3$ yr)

VLA 16234-2417
ALMA Cycle 0

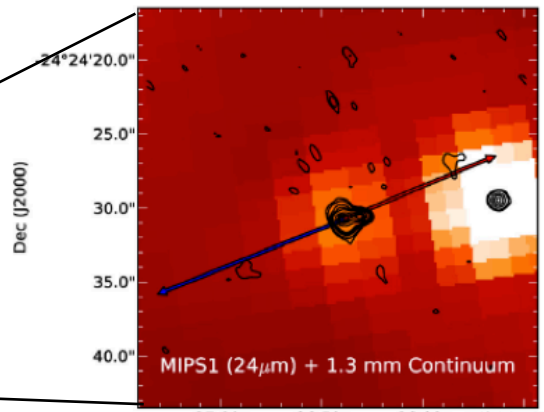
VLA1623: A TRIPLE SYSTEM

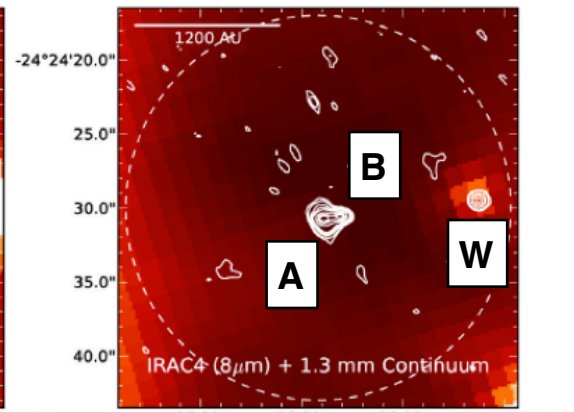


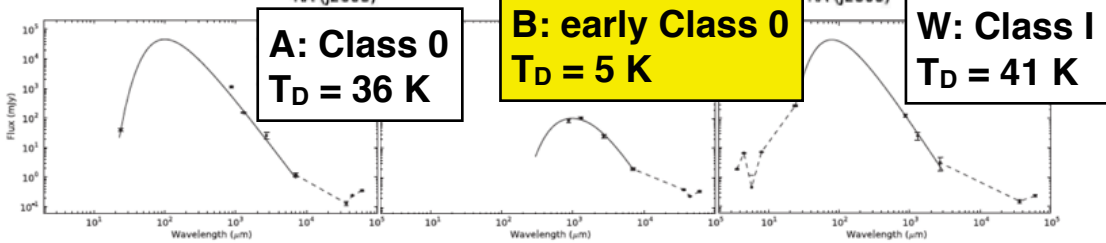
SE BLUE

NW RED

André et al. (1990)





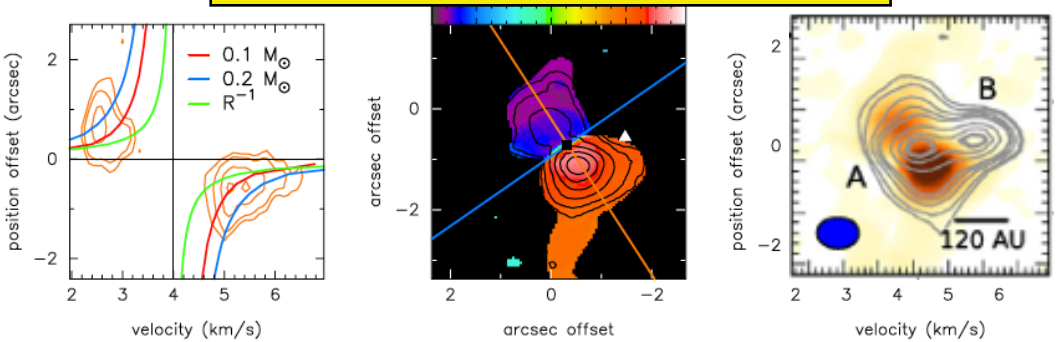


A: Class 0
T_D = 36 K

B: early Class 0
T_D = 5 K

W: Class I
T_D = 41 K

VLA1623 A - Keplerian DISK (150 AU)

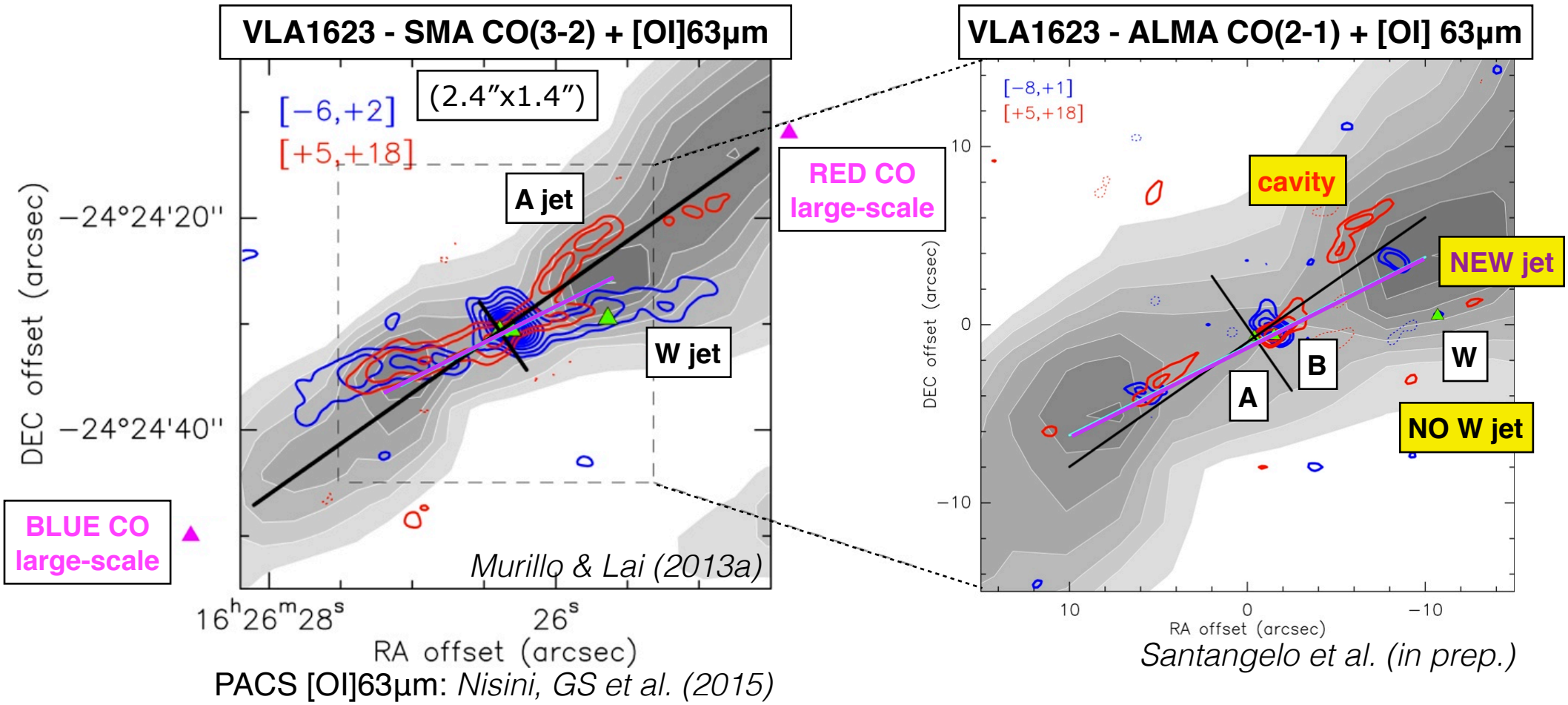


Murillo & Lai (2013a), Murillo et al. (2013b)

- Prototype for Class 0 stage (*André et al. 1990, 1993*)
- A/B separation: 1.1 arcsec ~ 130 AU (120 pc)
- A Keplerian disk (M^*~0.2 $M_\odot$) + B between starless core and Class 0

Non-coeval system

VLA1623: ALMA Cycle 0 view

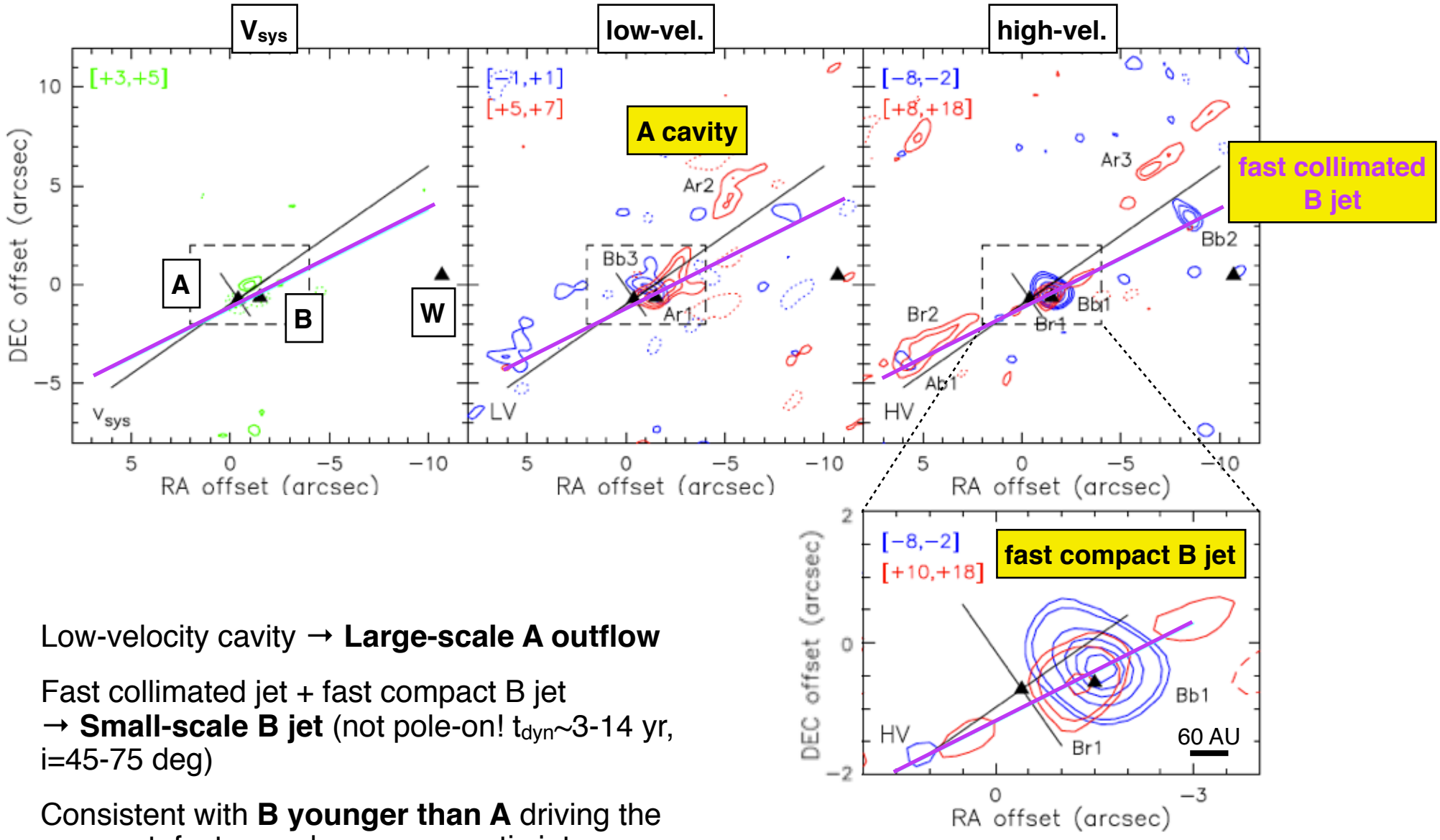


PACS [OI]63μm: *Nisini, GS et al. (2015)*

Santangelo et al. (in prep.)

- **Large-scale CO** and outflow from A are associated with secondary PACS [OI]63μm peaks → filtered out by ALMA, except red-shifted cavity surrounding [OI]
- **New CO outflow with ALMA**: collimated, inversely oriented wrt large-scale CO, and associated with closest [OI] peaks
- No ALMA CO outflow emission associated with W

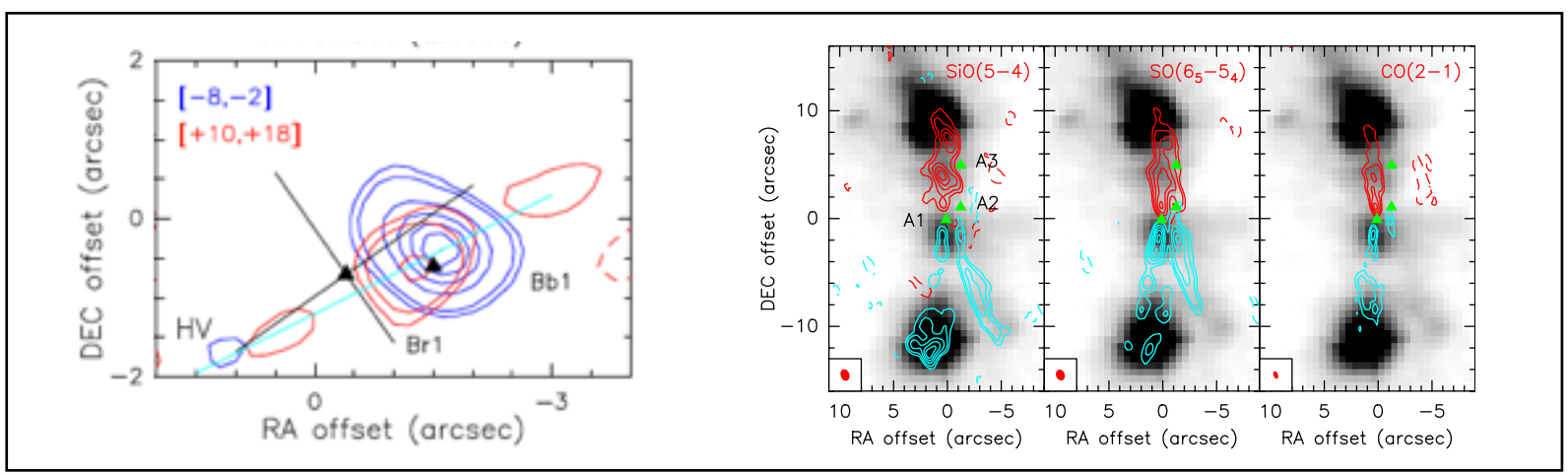
VLA1623: ALMA Cycle 0 view



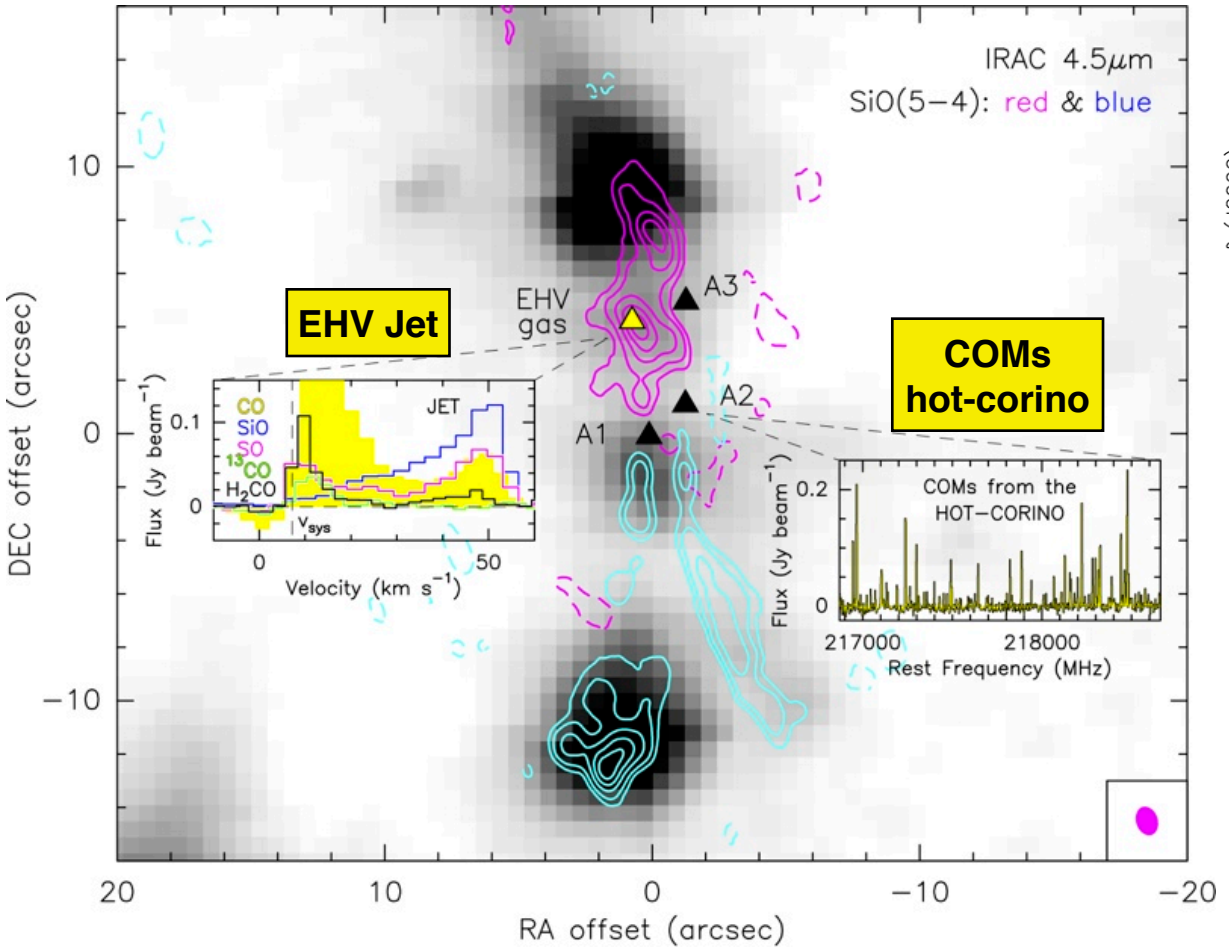
- Low-velocity cavity → **Large-scale A outflow**
- Fast collimated jet + fast compact B jet → **Small-scale B jet** (not pole-on! t_{dyn}~3-14 yr, i=45-75 deg)
- Consistent with **B younger than A** driving the compact, faster, and more energetic jet

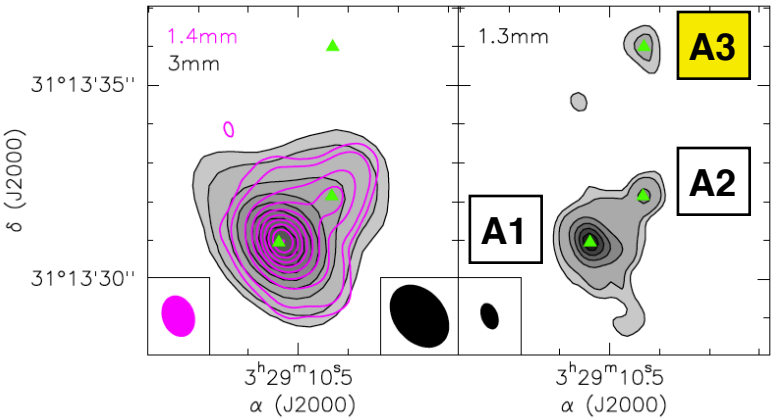
Conclusions

- IRAS4A and VLA1623 A/B similarities:
  - Binary **non-coeval** systems, the older source driving the large-scale extended outflow and the younger source driving the compact, faster, and more energetic outflow ([OI and H_2])
  - Similar **inclination** of the two outflow in both binary systems (separation of the IRAS4A1 and VLA1623B lobes)
  - **Challenging** for models of system formation (close binaries with different evolutionary stages, collimated jets, and same outflow inclination; in VLA1623 different orientation of the outflows): can give important constraints on the fragmentation process
- Great ALMA capabilities for these studies (Cycle 0 CO)
- ALMA follow-up observations of VLA1623: SiO/SO shock tracer and wide-band spectra to understand the nature and chemical composition of the sources



IRAS4A: Jet multiplicity



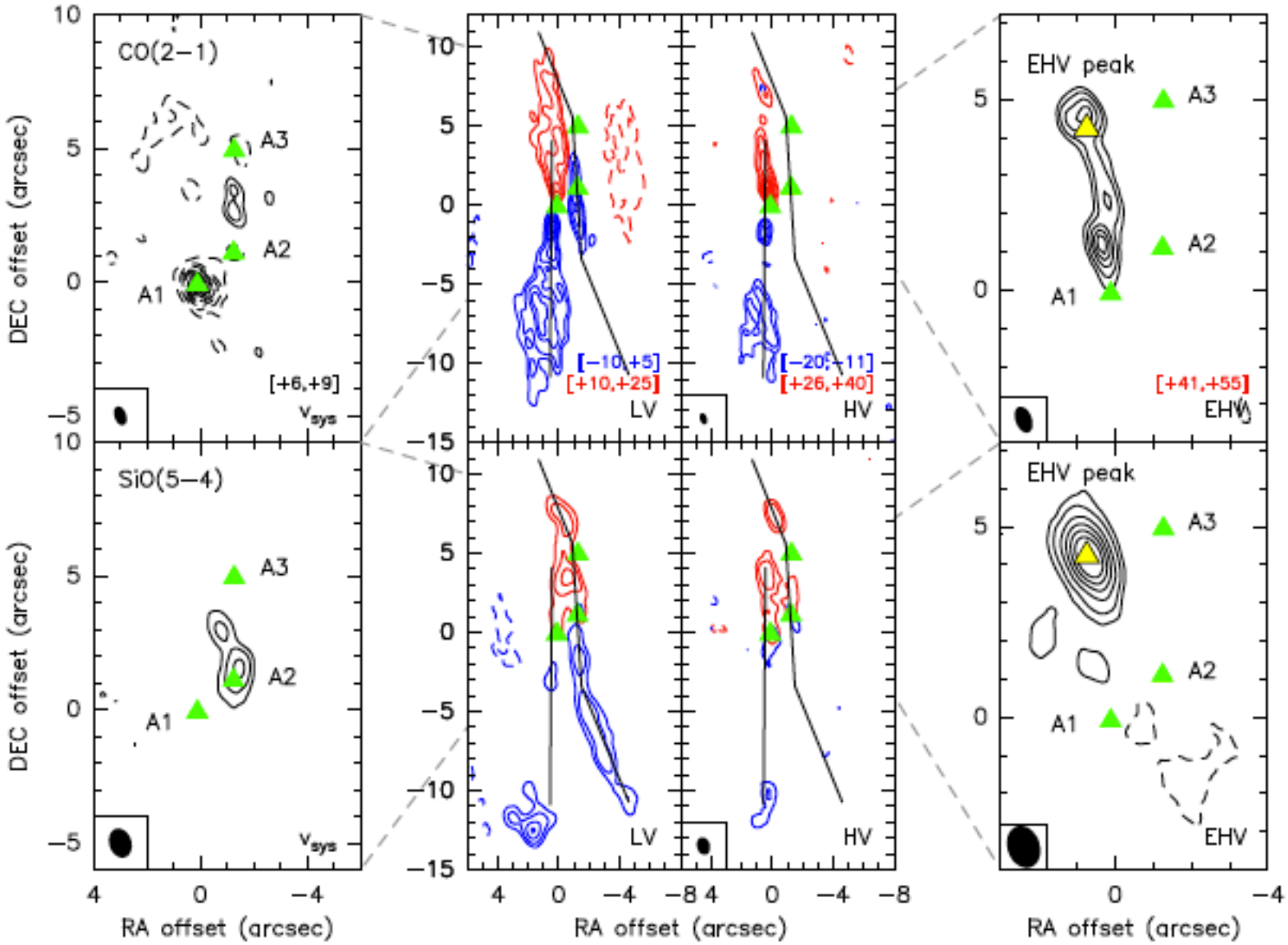


Santangelo et al. (in prep.)

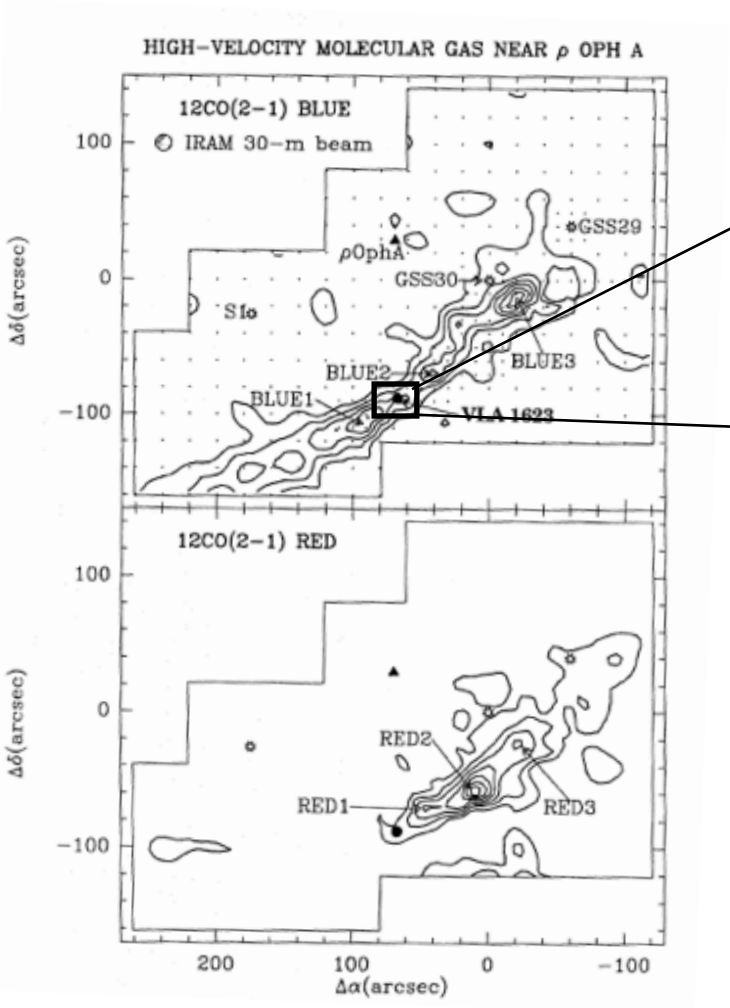
A3: envelope or shock-heated dust emission along the jet?

- Association between IRAC H_2 and PACS [OI] emissions and A1 jet
- EHV 50 km s^{-1} gas detected in SiO, CO, SO, H_2CO; abundance enhancements suggest shock origin
- Hot-corino chemistry at A2

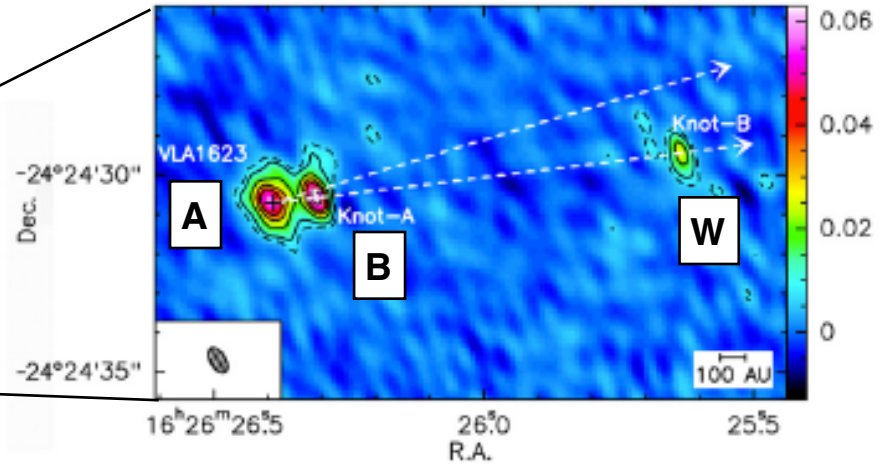
IRAS4A: Jet kinematics



VLA1623: A TRIPLE SYSTEM ?



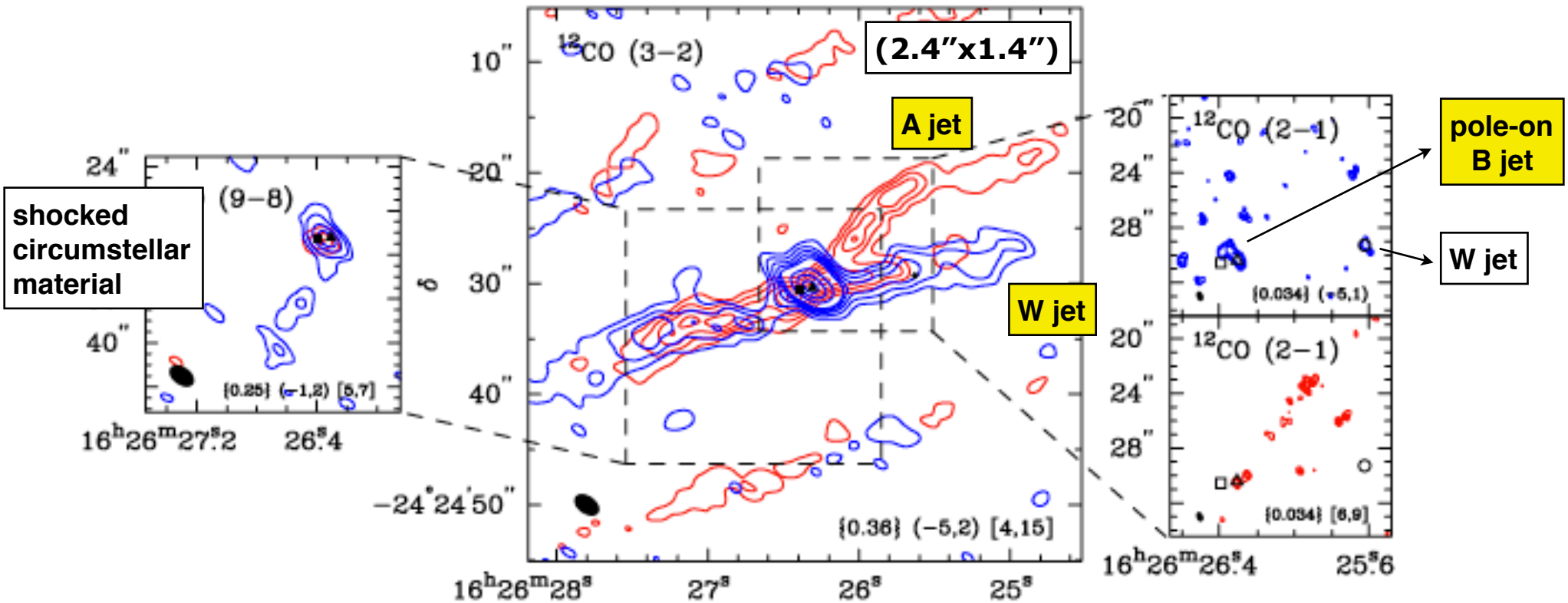
André et al. (1990)



Maury et al. (2012),
Bontemps & André (1997)

- B&W: monopolar jet from A, i.e. outflow features due to shocks (outflow/ambient) along cavity walls
- Low rate of small-scale (100 AU < a < 1000 AU) multiplicity for Class 0 protostars (*Maury et al. 2010*)

VLA1623: OUTFLOW EMISSION



Murillo & Lai (2013a)

- NW lobe: combination of A and W outflows
- SE lobe not disentangled
- B: compact pole-on outflow

SMA CO(3-2) - 2.36x1.41 arcsec res.

SMA CO(2-1) - 0.6x0.4 arcsec res.

ALMA CO(2-1) - 0.7x0.6 arcsec res.

ALMA C18O(2-1) - 0.79x0.61 arcsec res.