The jet-outflow connection: new results from ALMA

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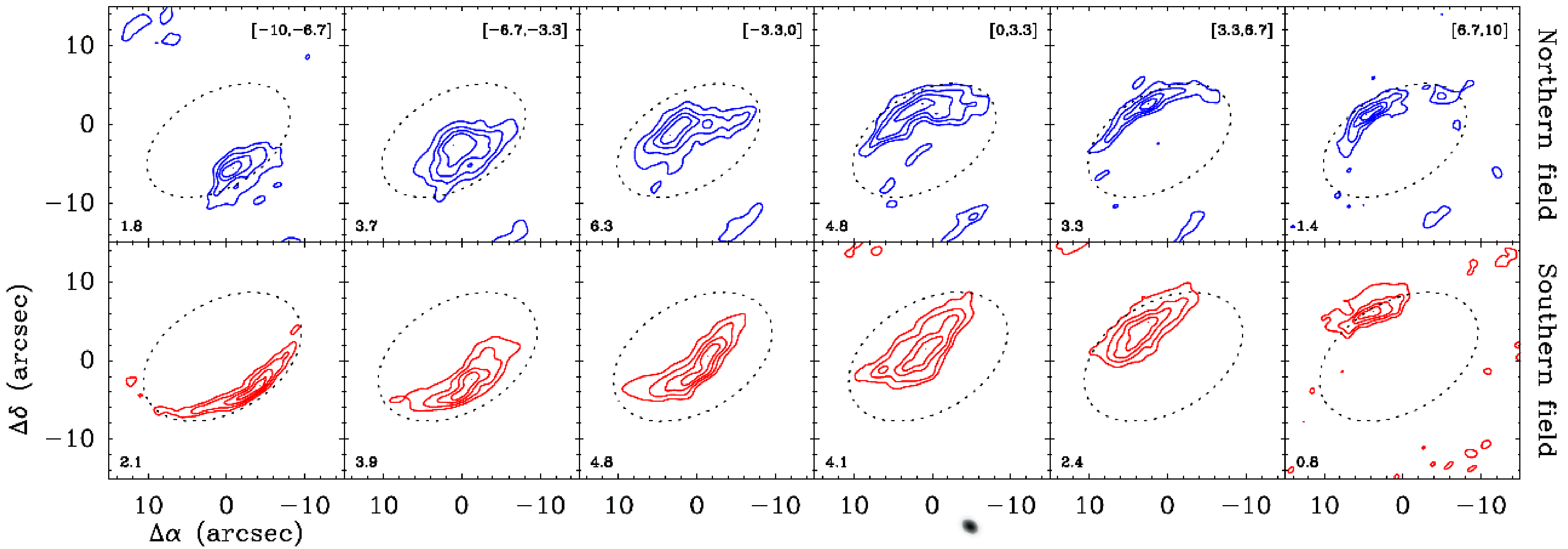
(OAN-IGN)



Steven W. Stahler
Francesco Palla

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The Formation of Stars

The Formation of Stars
Steven W. Stahler and Francesco Palla

13 Jets and Molecular Outflows

We now begin a series of chapters describing how newly created stars disturb their surrounding gas. The influence here is both mechanical and thermal. Cloud material is stirred into turbulent motion, expelled from the vicinity of a star, or heated to high temperatures. For regions that are either very dense or at a considerable distance, such activity may be the best, and indeed the only, means for revealing the presence of the stars themselves. The physical processes we will study are also of considerable interest in their own right.

One of the surprising discoveries in this field has been the disproportionate effect of low-mass objects. In the present chapter, we shall see how each such star generates, during its embedded phase, an energetic outflow extending well beyond its parent dense core. The star also emits a jet of much higher-speed gas that can travel even farther, entering regions nearly devoid of cloud material. These striking phenomena were wholly unanticipated by theorists, who are still struggling to understand the basic mechanisms of wind generation and jet propagation. We shall introduce the key concepts in both of these developing areas.

Jets are rendered visible by the shocks they produce. If the shocked gas has sufficiently high density, it may also generate beams of radiation that are intensified through the quantum phenomenon of stimulated emission. Such interstellar masers have been extensively studied, both for their intrinsic properties and for what they reveal about the dynamics of the regions producing them. Chapter 14 is accordingly devoted to this topic. Finally, we turn in Chapter 15 to the highly destructive effects of massive stars. Ionizing photons create HII regions that, along with stellar winds, disrupt entire cloud complexes. The fluorescent gas also serves as a beacon

Outline

Intro: jets and outflows

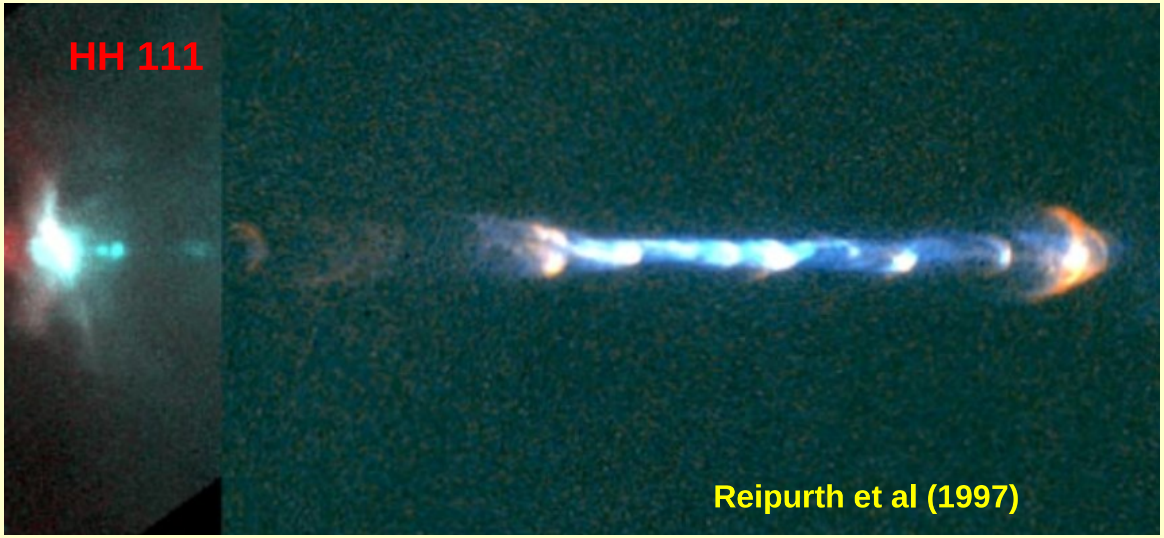
ALMA observations of IRAS 04166+2706 jet

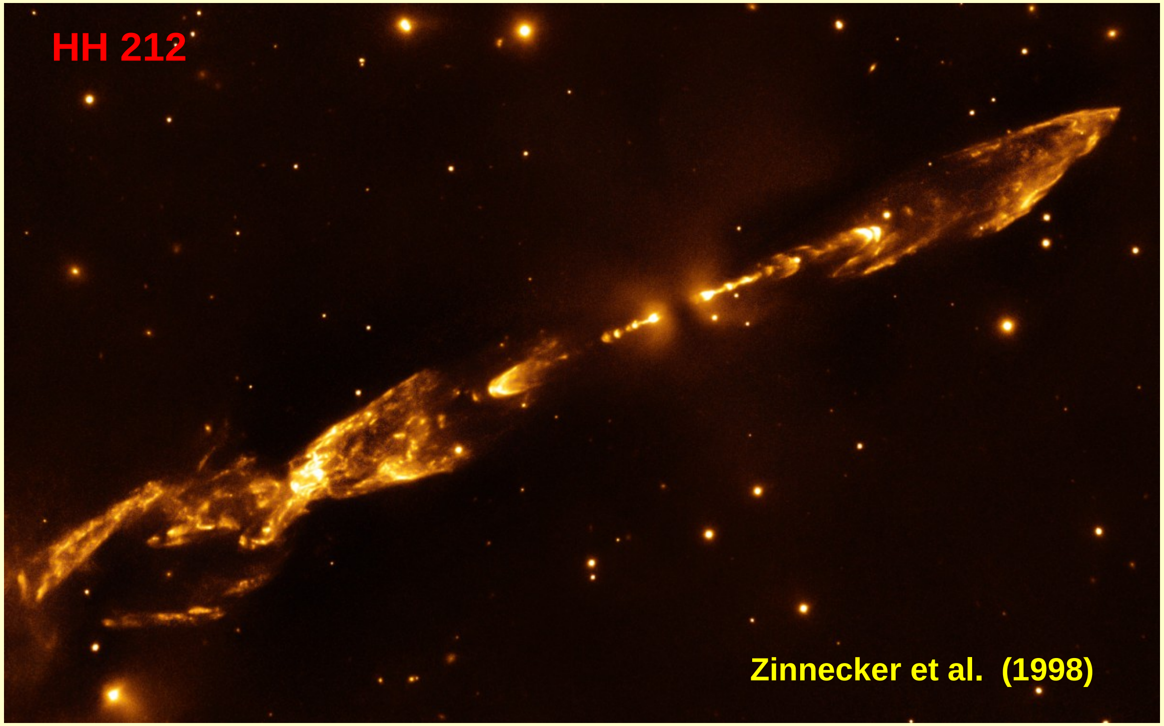
(Tafalla, Su, Shang, Johnstone, Zhang, Santiago-García, Lee, Hirano, Wang 2017, A&A, 597, A119)

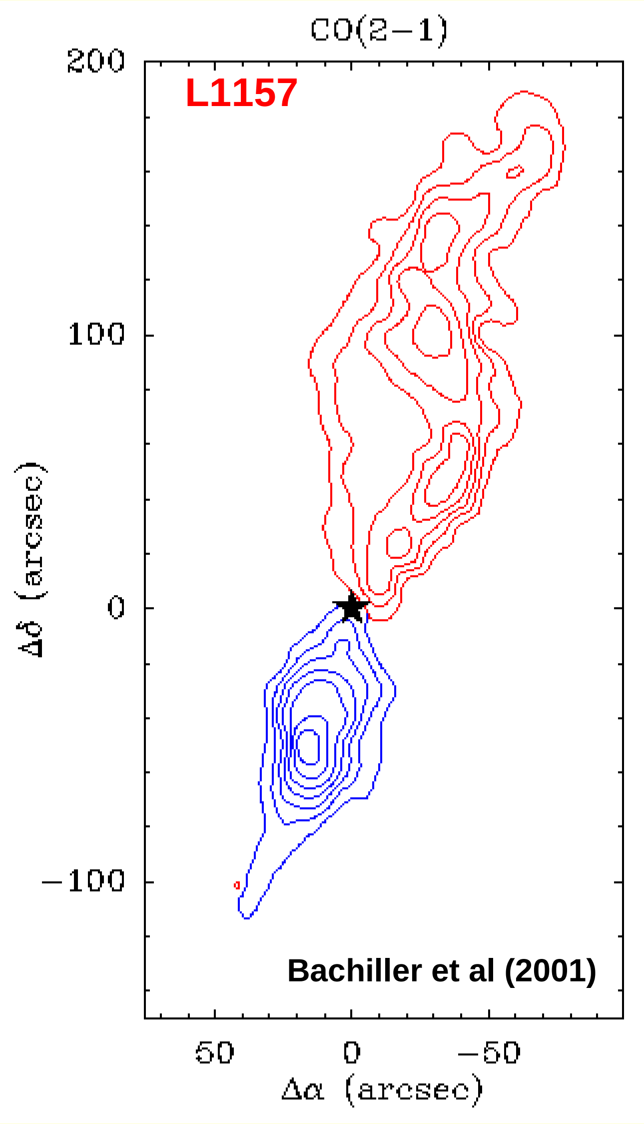
ALMA observations of the L1448 jet and outflow

(Tafalla et al. 2017, in preparation)

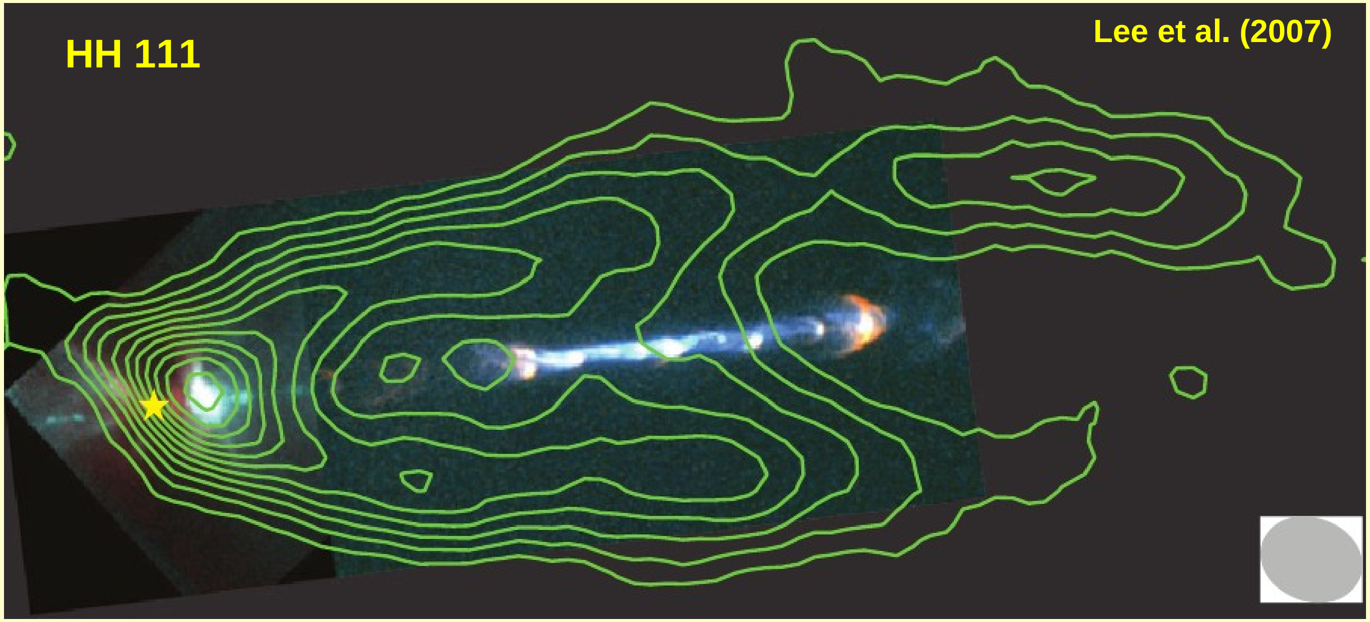
Signatures of star formation





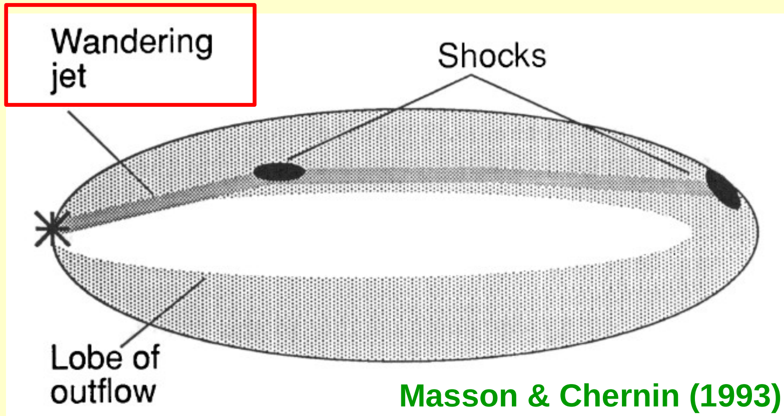


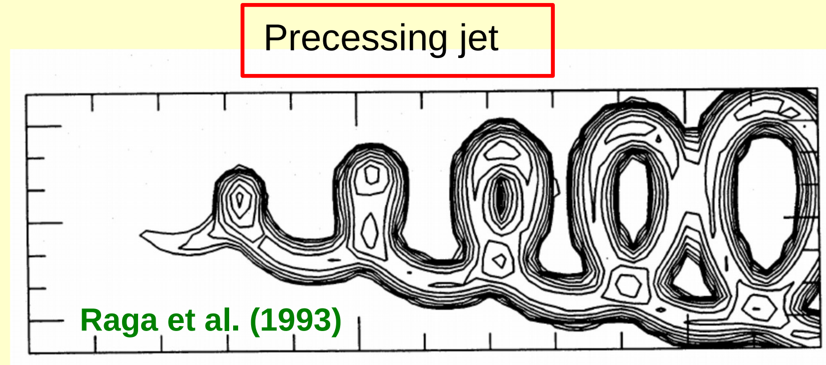
Jets and outflows

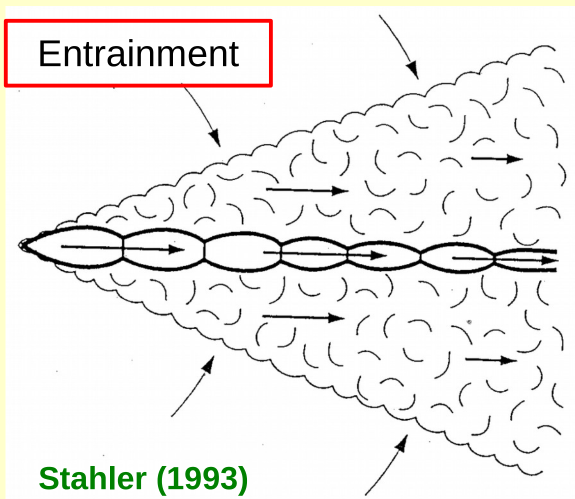


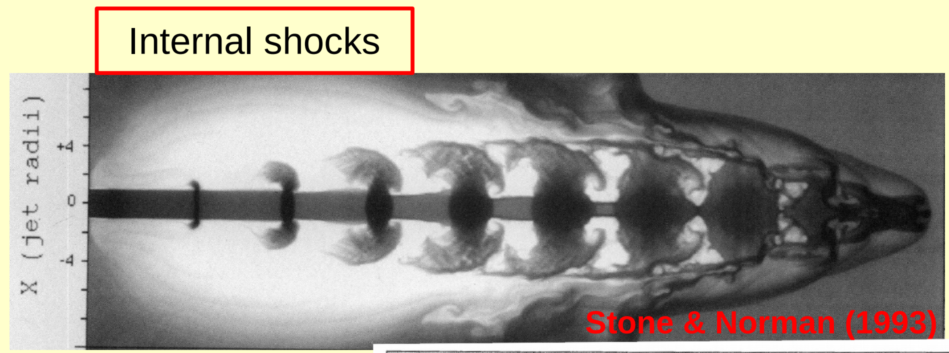
- Part of the same phenomenon of mass ejection
  - Cause and effect? Different ejection components?
- Two families of models
  - Jet-driven
  - Wide-angle wind

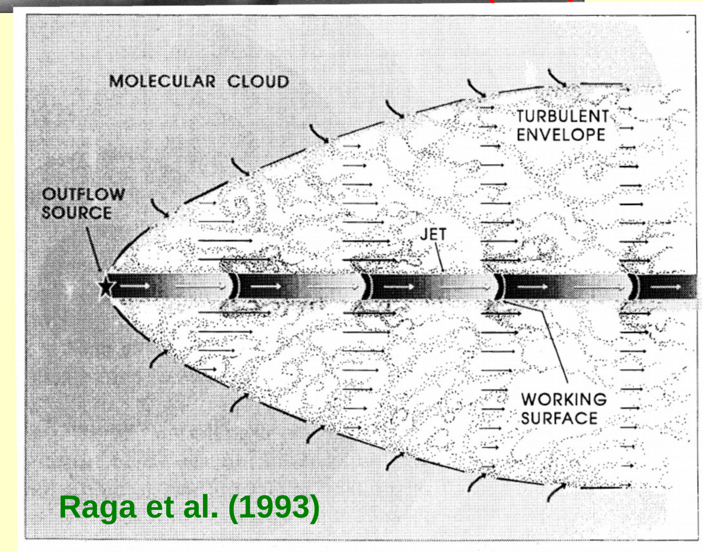
Jet-driven models





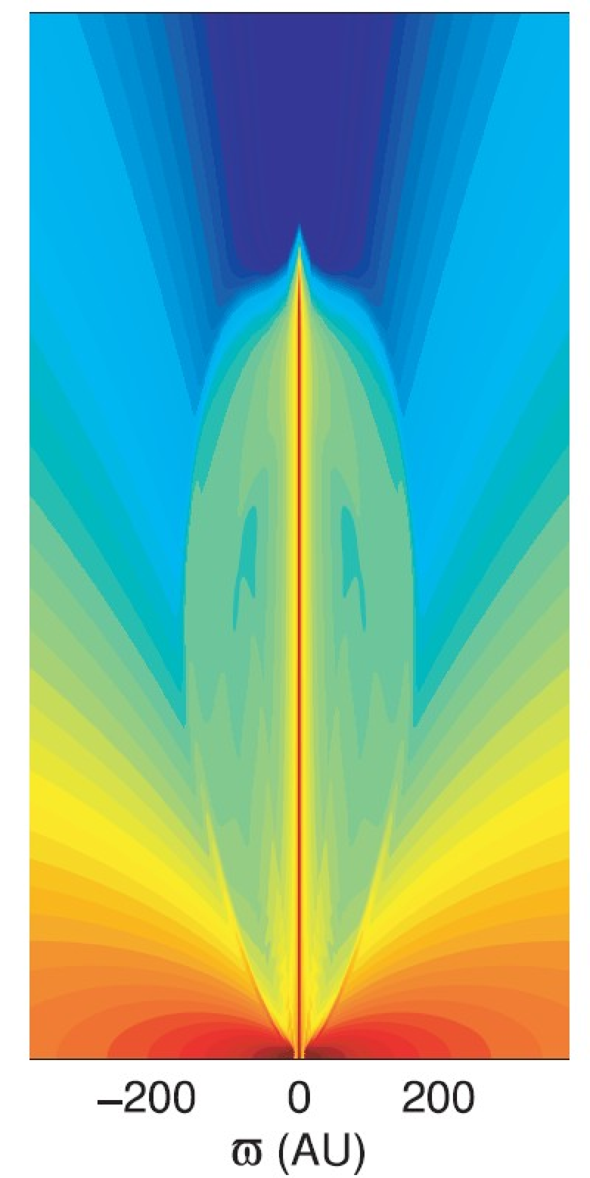




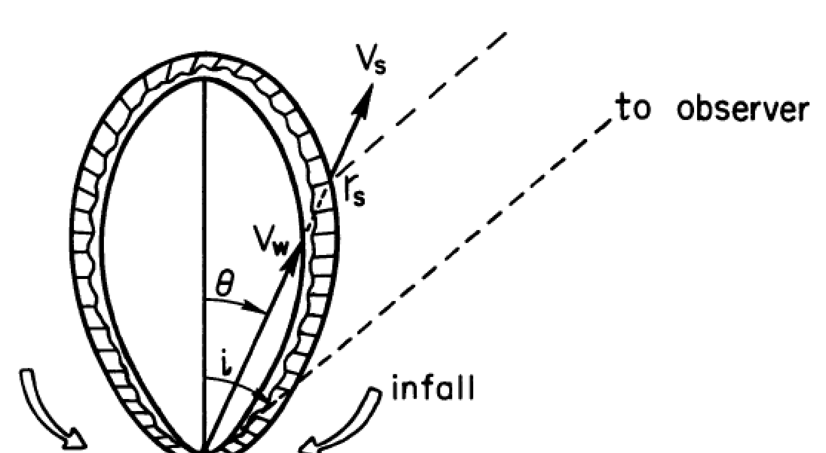


- Main problem: jets are narrow and outflows are broad/shell-like
  - Broadening mechanism is needed

Wide-angle wind models



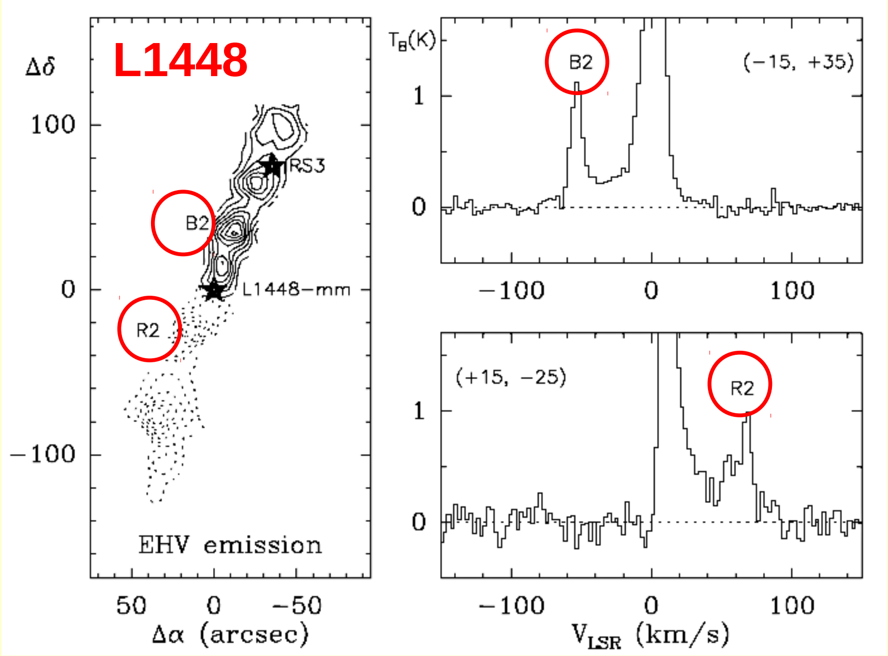
Shang et al. (2006)



Shu et al. (1991)

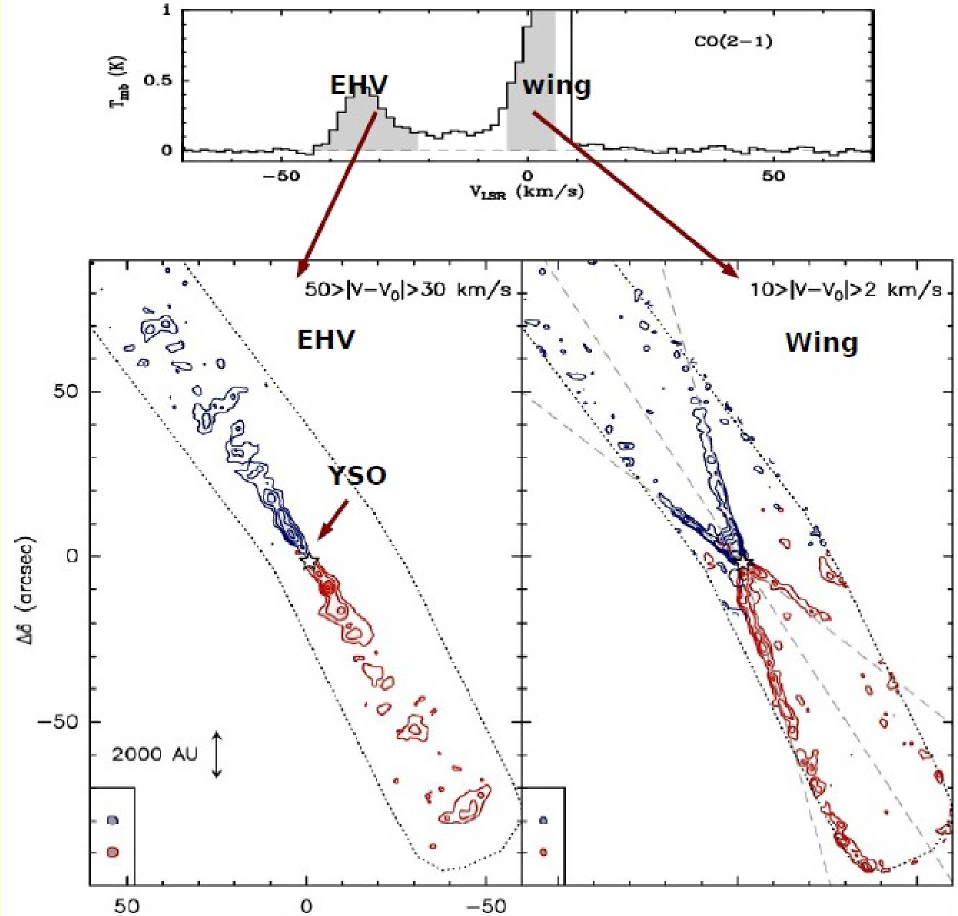
- Protostellar wind is angle-dependent
- Problem: how to produce jets
  - Jets are denser central part of wind
  - “optical illusion”

Outflows with molecular jets



Bachiller et al. (1990)

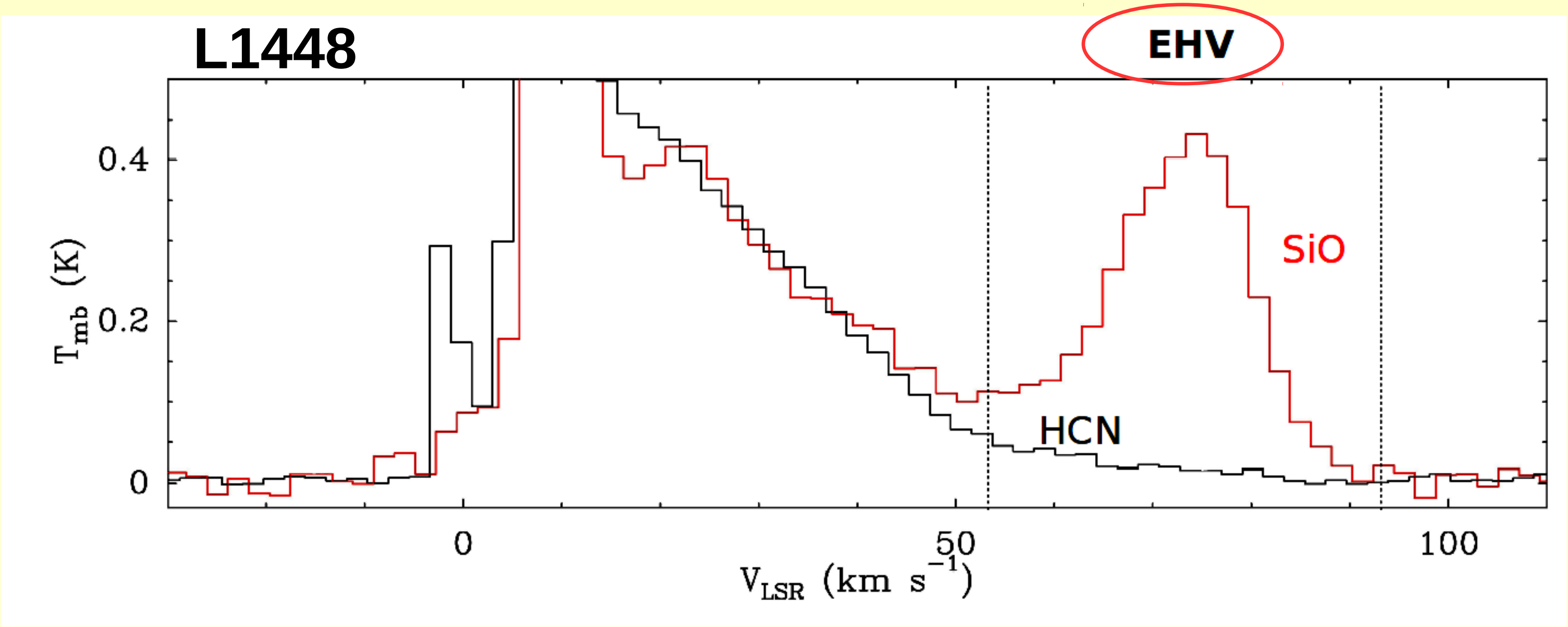
IRAS 04166



Santiago-García et al. (2009)

- Small group of outflows (~10)
  - Class 0 sources
- Two distinct CO components
  - Low velocity: shell-like
  - Extremely High Velocity (EHV): jet-like
- Ideal sources to study jet-outflow relation

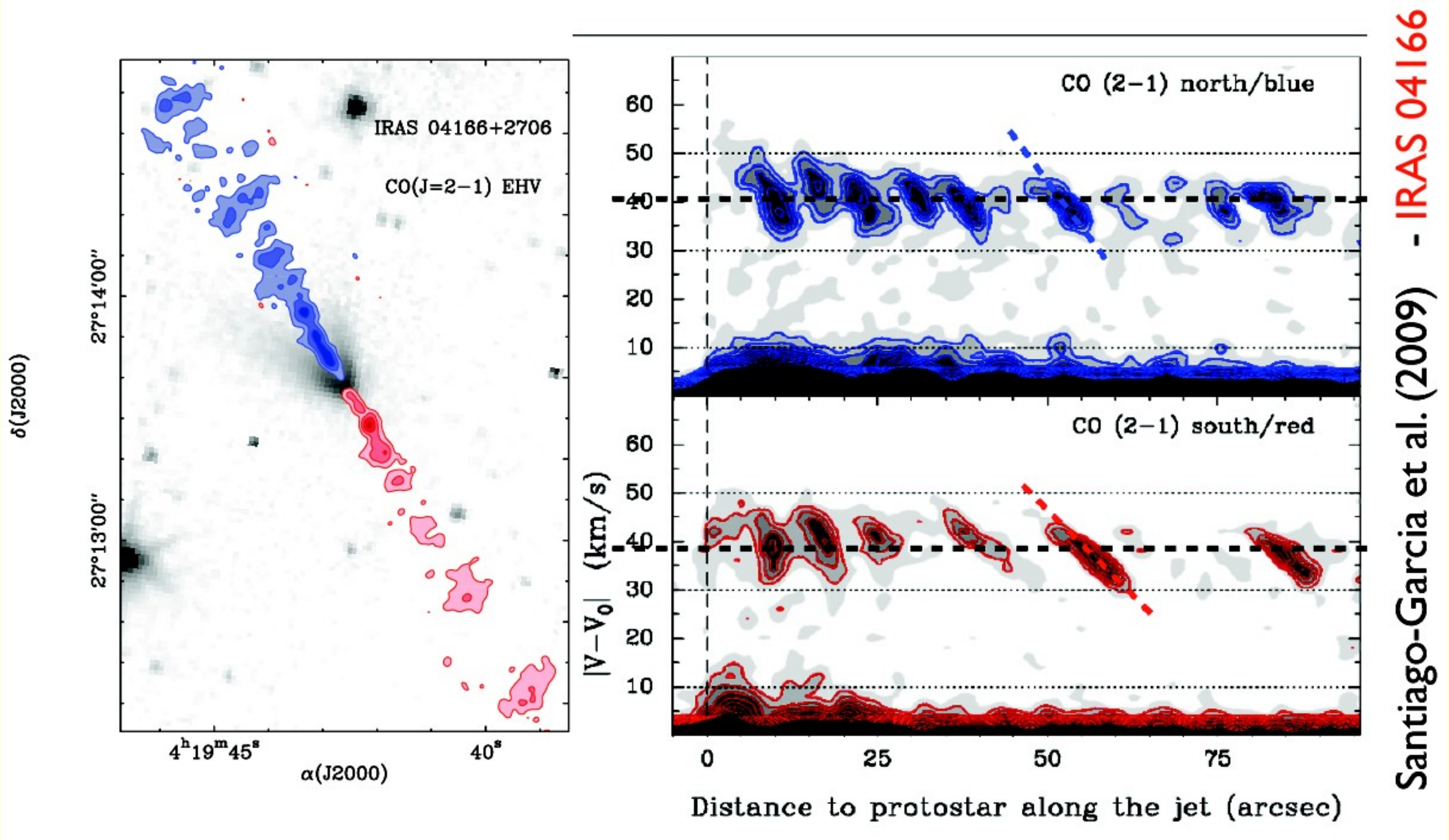
EHV gas is a distinct component

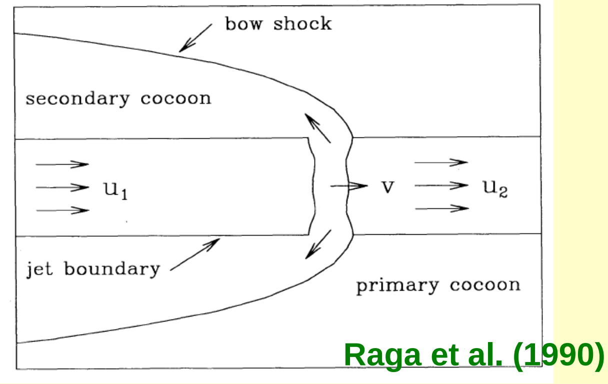


Tafalla et al. (2010)

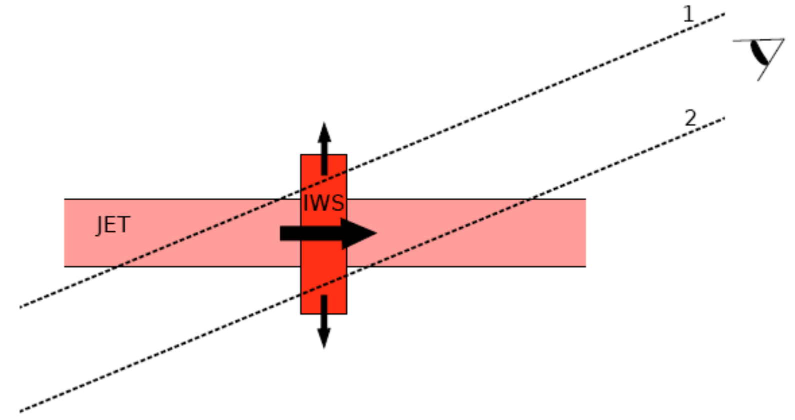
- EHV not only peculiar in kinematics, but chemistry
- HCN/SiO ratio drops factor 20 between wing and EHV
  - Other carbon-bearing species behave similarly

IRAS 04166: peculiar velocity pattern



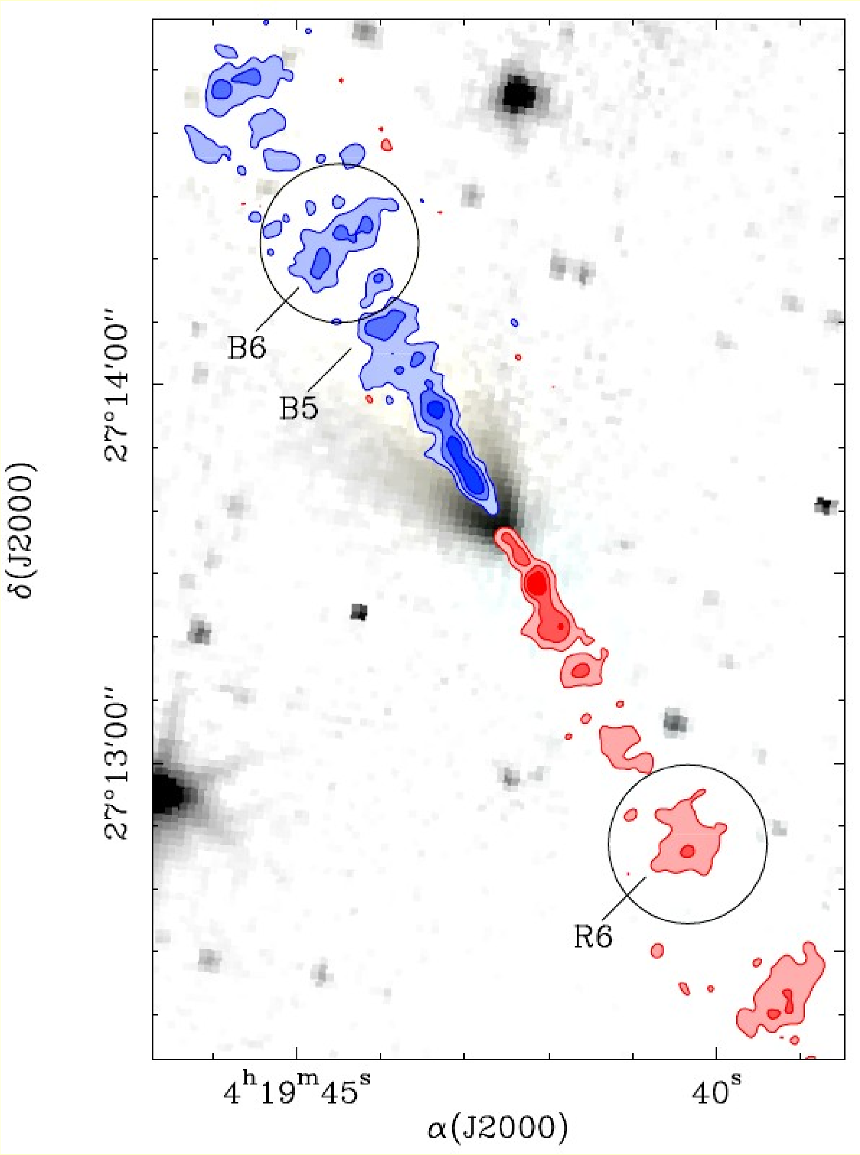


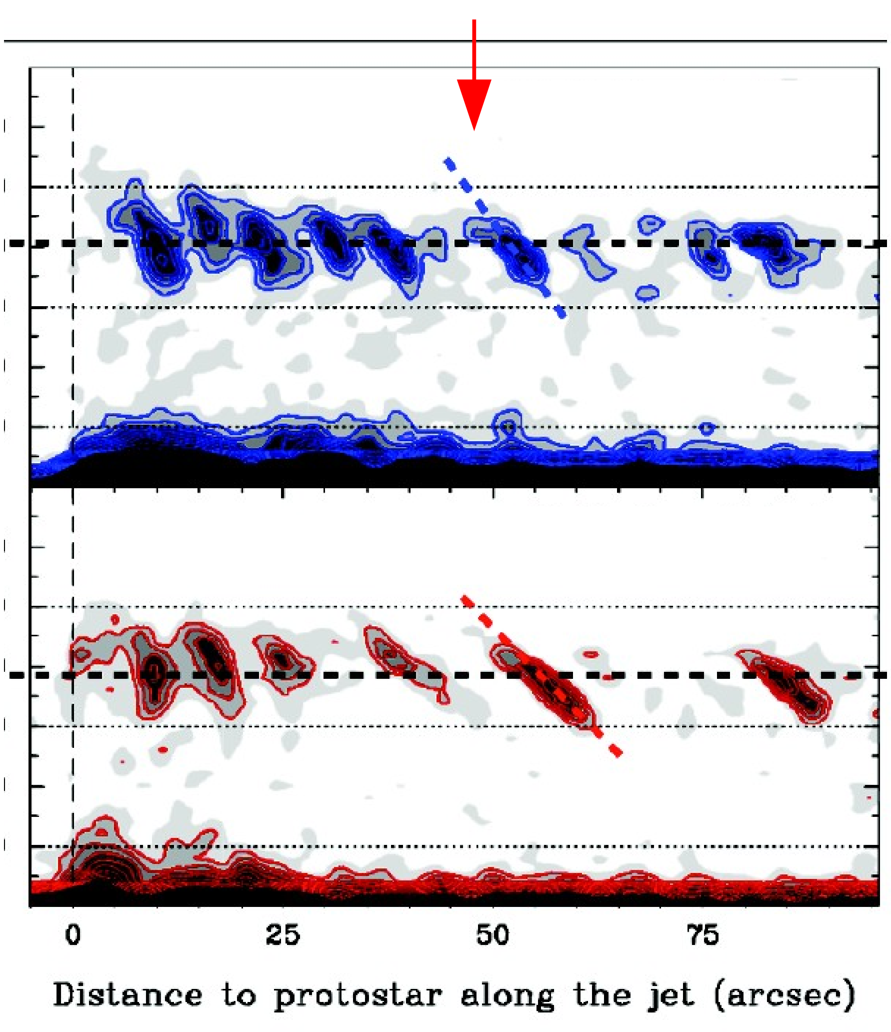
★ YSO



ALMA observations of IRAS 04166

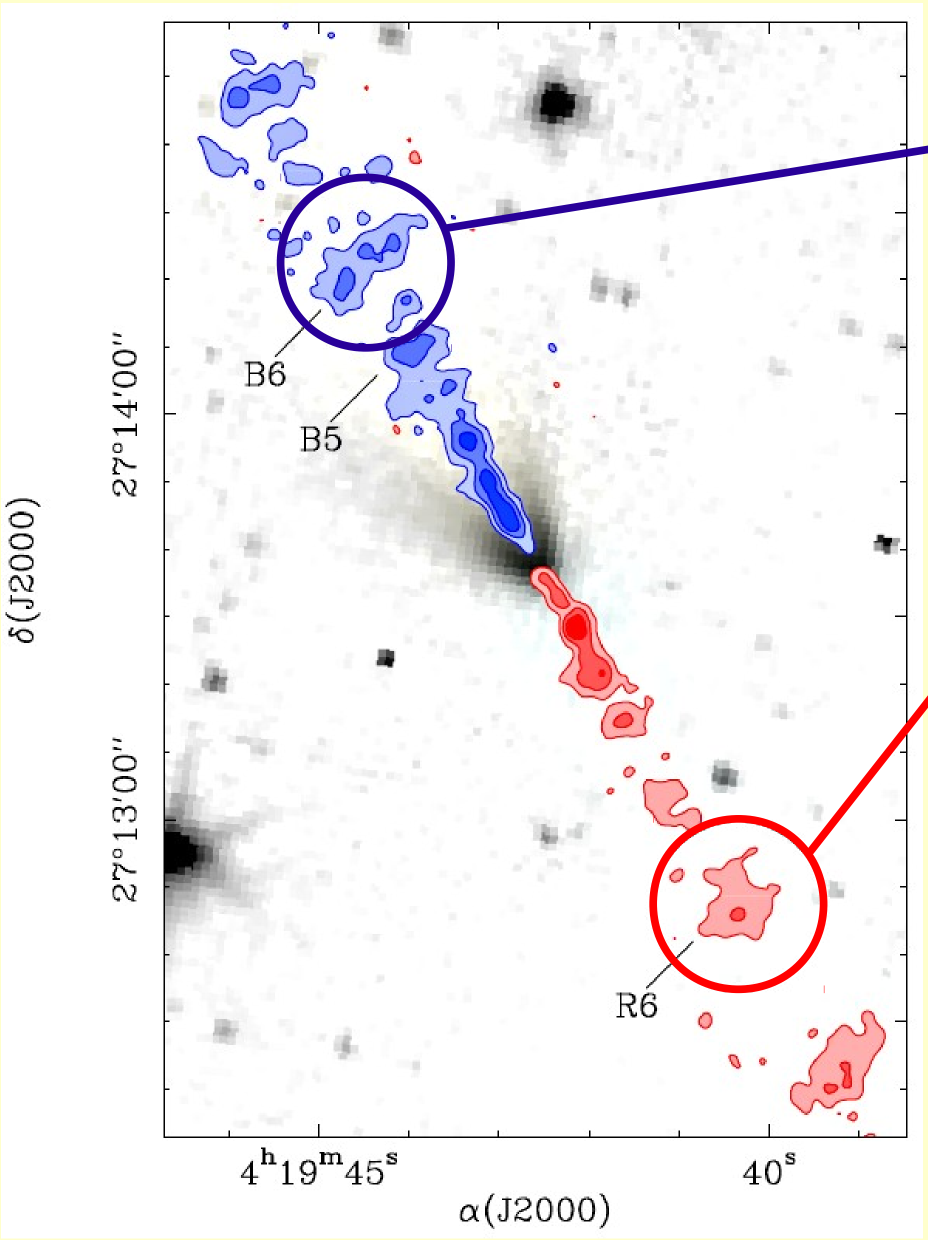
Tafalla, Su, Shang, Johnstone, Zhang, Santiago-García, Lee, Hirano, & Wang
(2017, A&A, 597, A119)

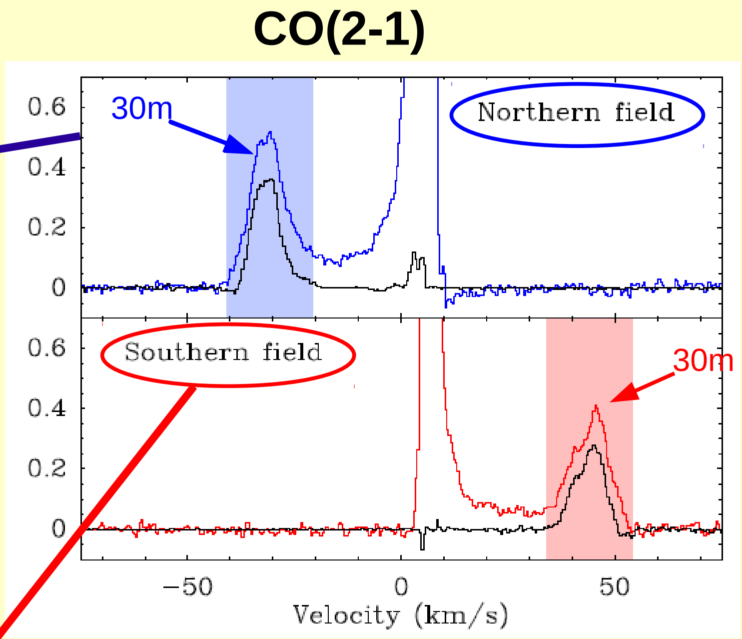




Santiago-Garcia et al. (2009) - IRAS 04166

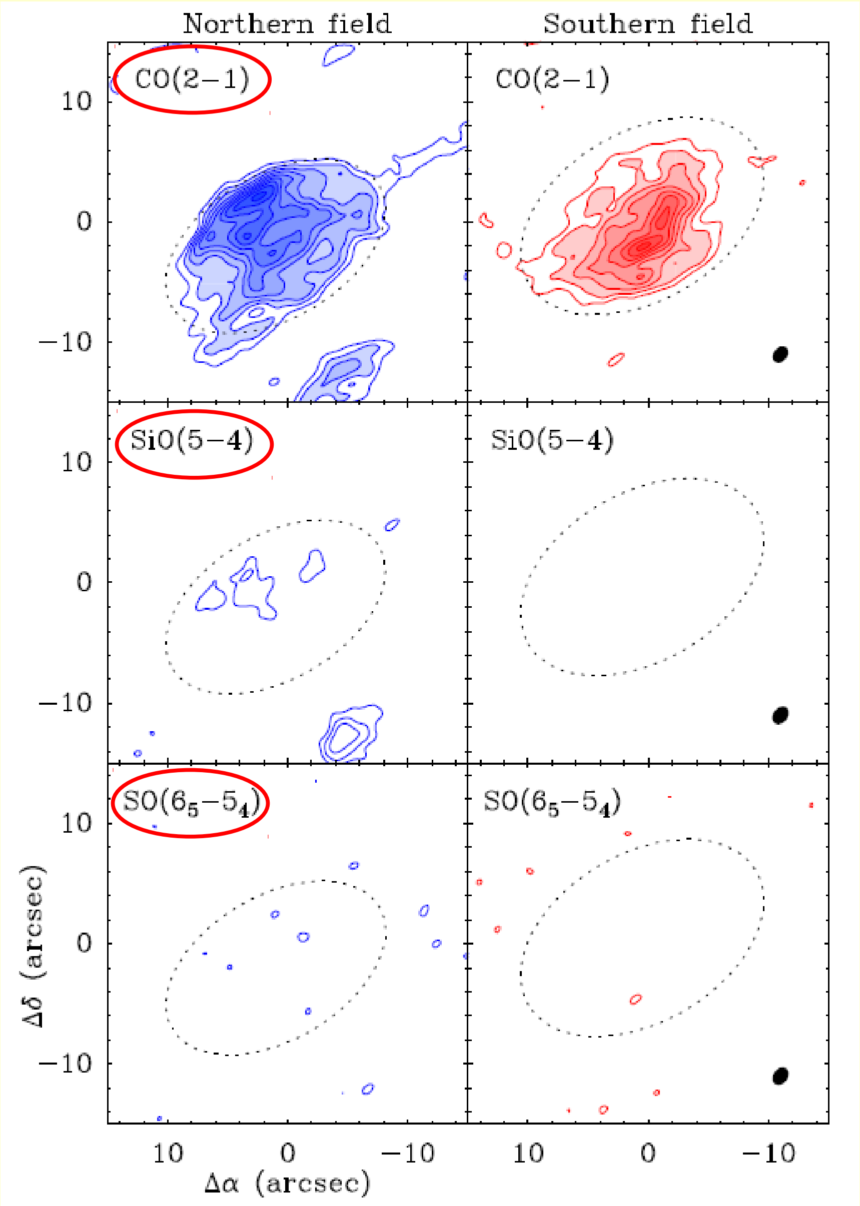
ALMA observations of IRAS 04166

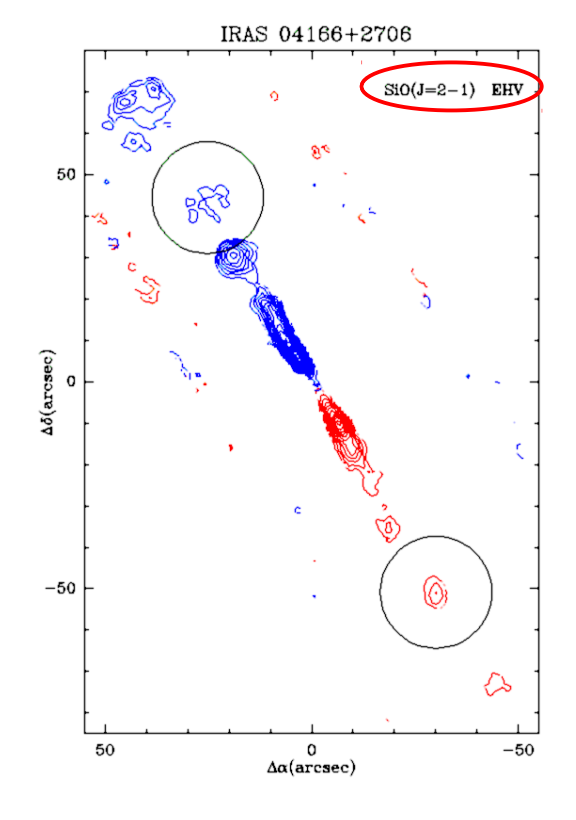




- Cycle 1 ALMA observations: two fields
  - CO(2-1), SiO(5-4), SO(6_5-5_4)
  - FWHM beam ~1".5 x 1".1
- EHV emission mostly/fully recovered (slow outflow emission is lost)

Integrated intensity maps

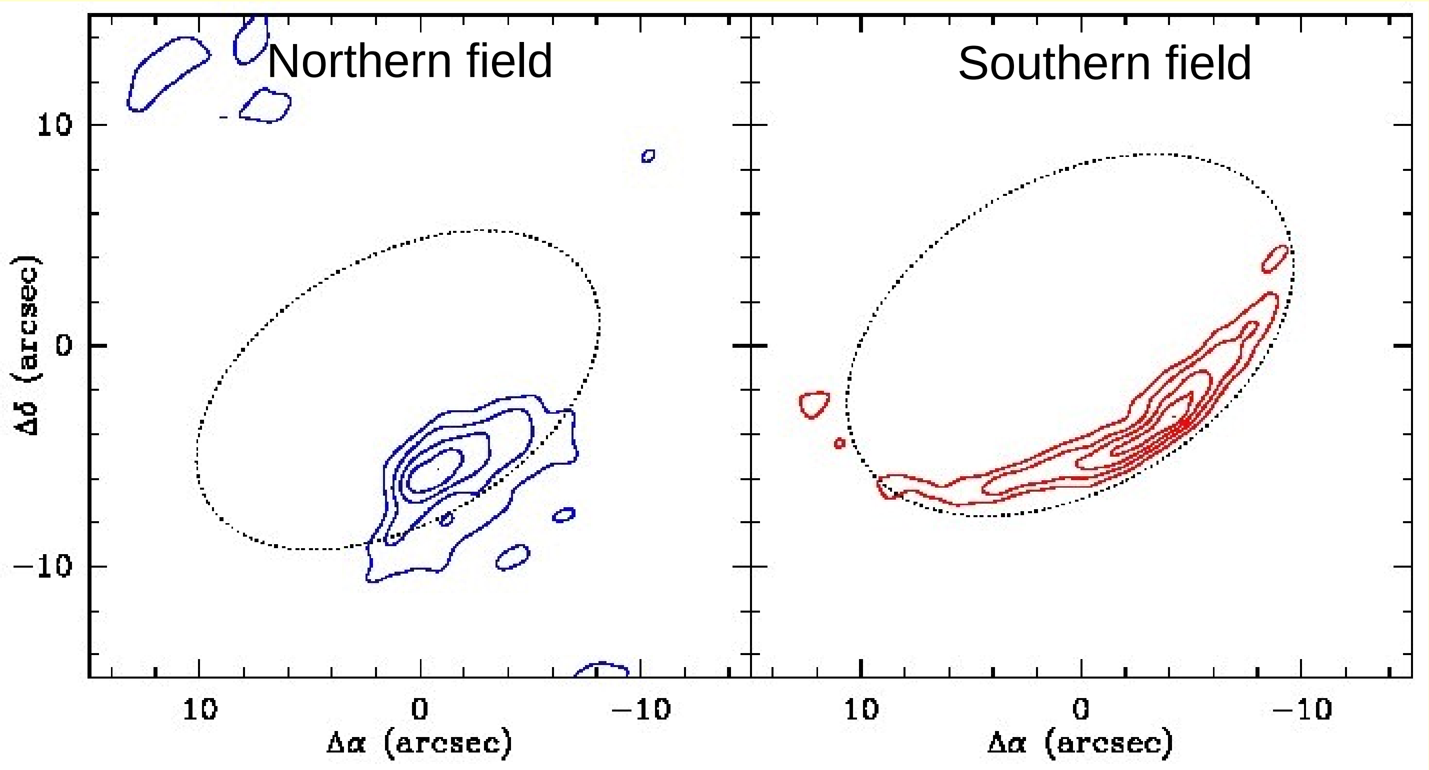




Santiago-García et al. (2009)

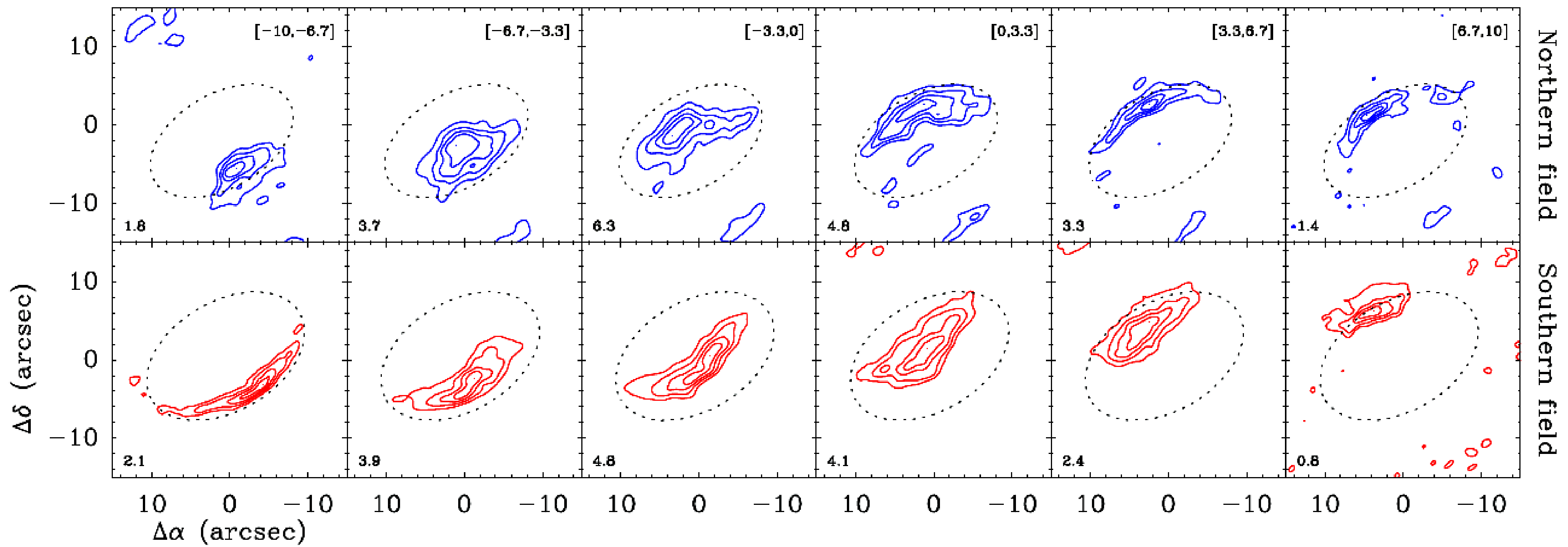
- Only CO(2-1) detected
  - B6, B5, R6
- SiO(5-4) too weak
  - B5 near field egde
- All analysis based on CO(2-1)

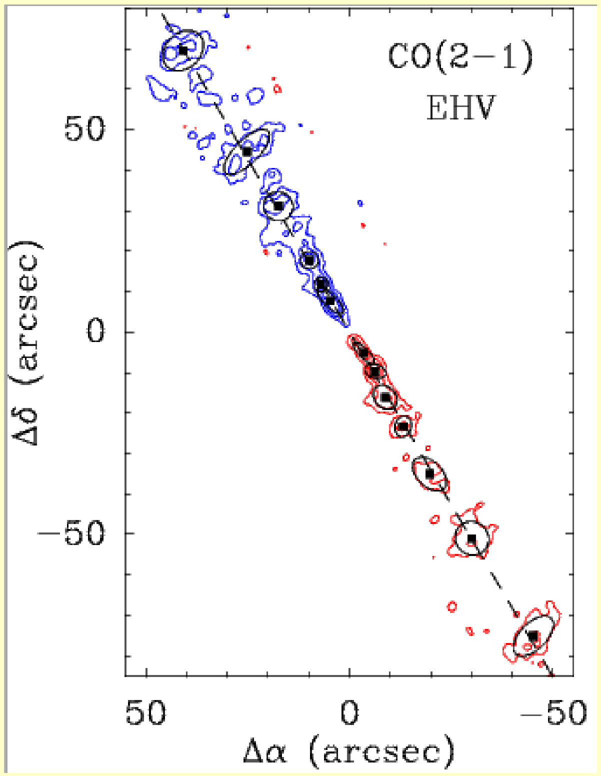
Velocity structure of the EHV gas

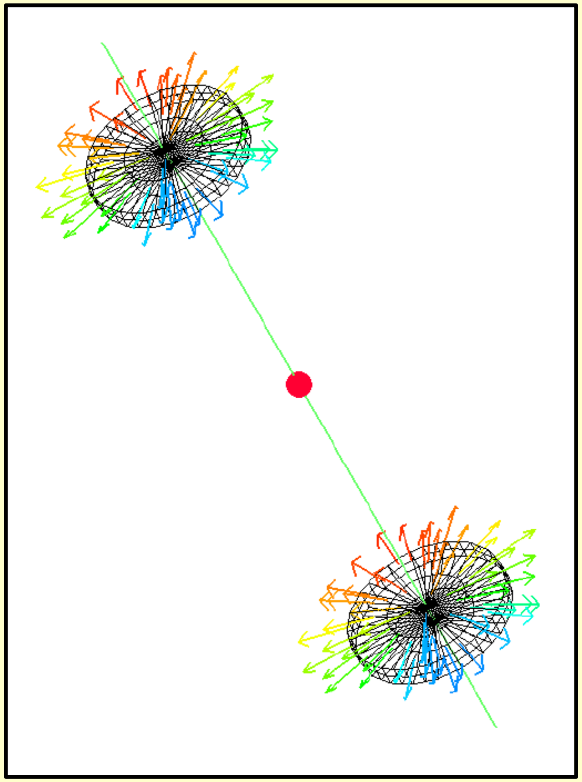


- **Systematic displacement as function of velocity over 20 km/s**
  - **also seen in B5 component**

- **Emission covers an elliptical region as it moves**



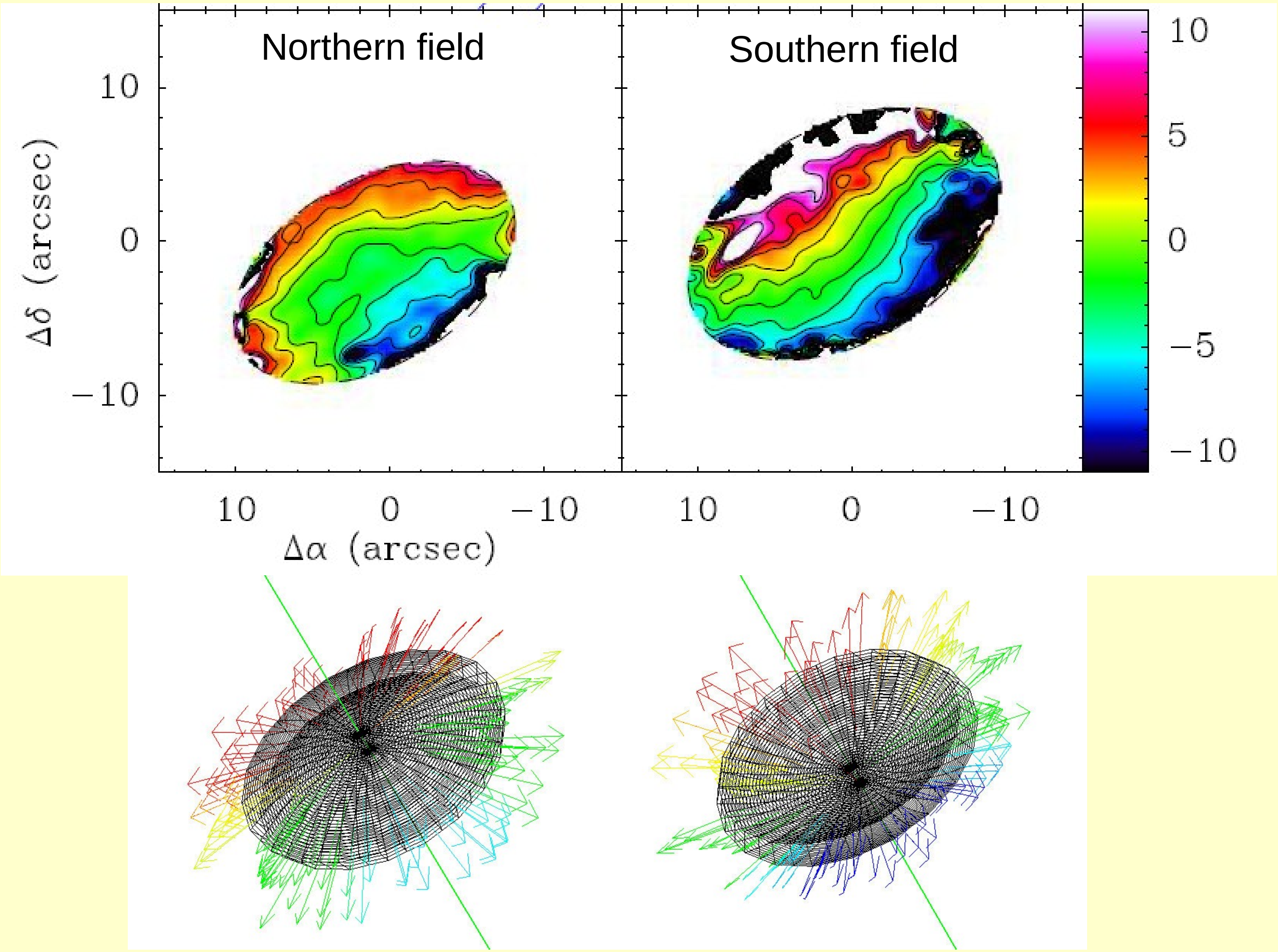




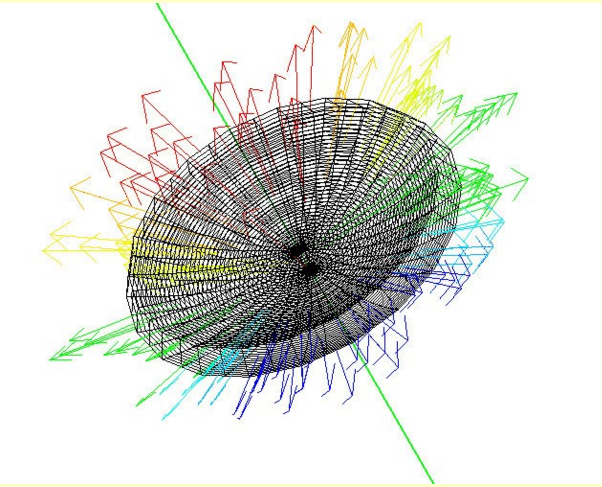
- **Ellipse minor axis parallel to jet direction**
- **Pattern expected for expanding disks**
  - **Consistent with 1D analysis from PdBI data**
- **De-project ellipses to derive jet inclination angle**
  - **50 degree inclination**
- **True jet velocity: 60 km/s**

Curvature: bow shock geometry

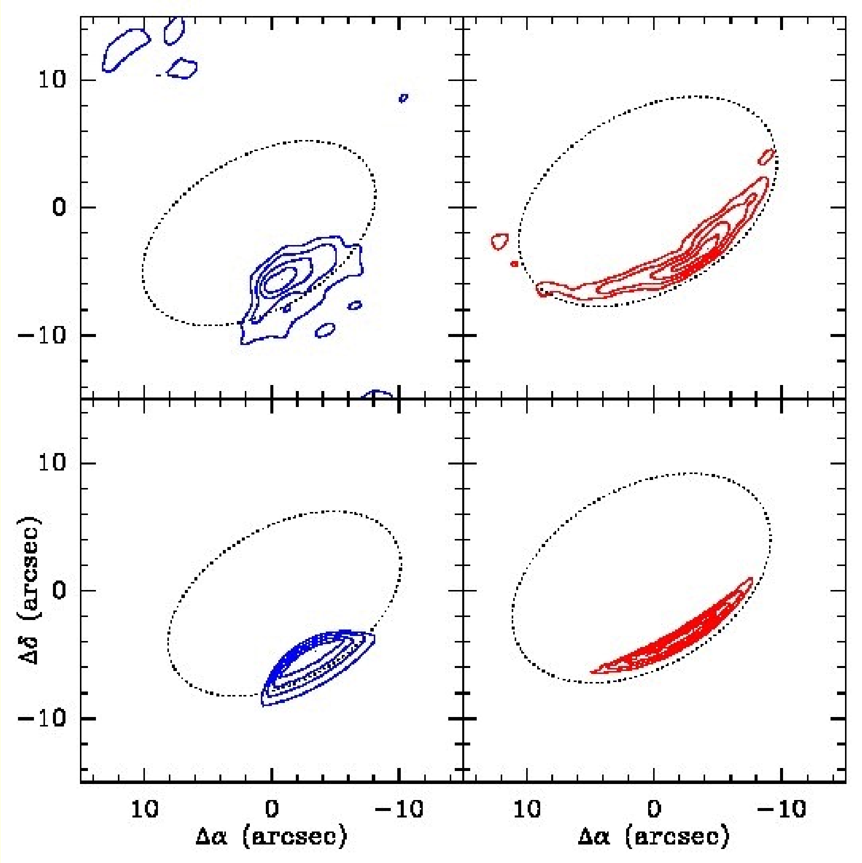
CO(2-1) first moment maps

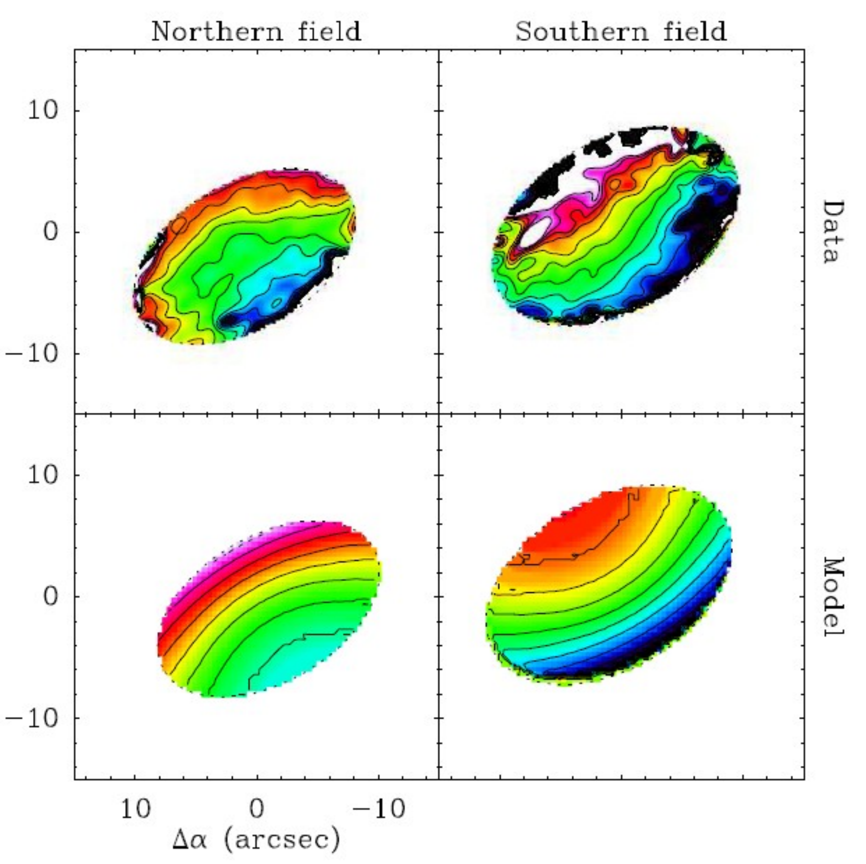


A simple geometrical model

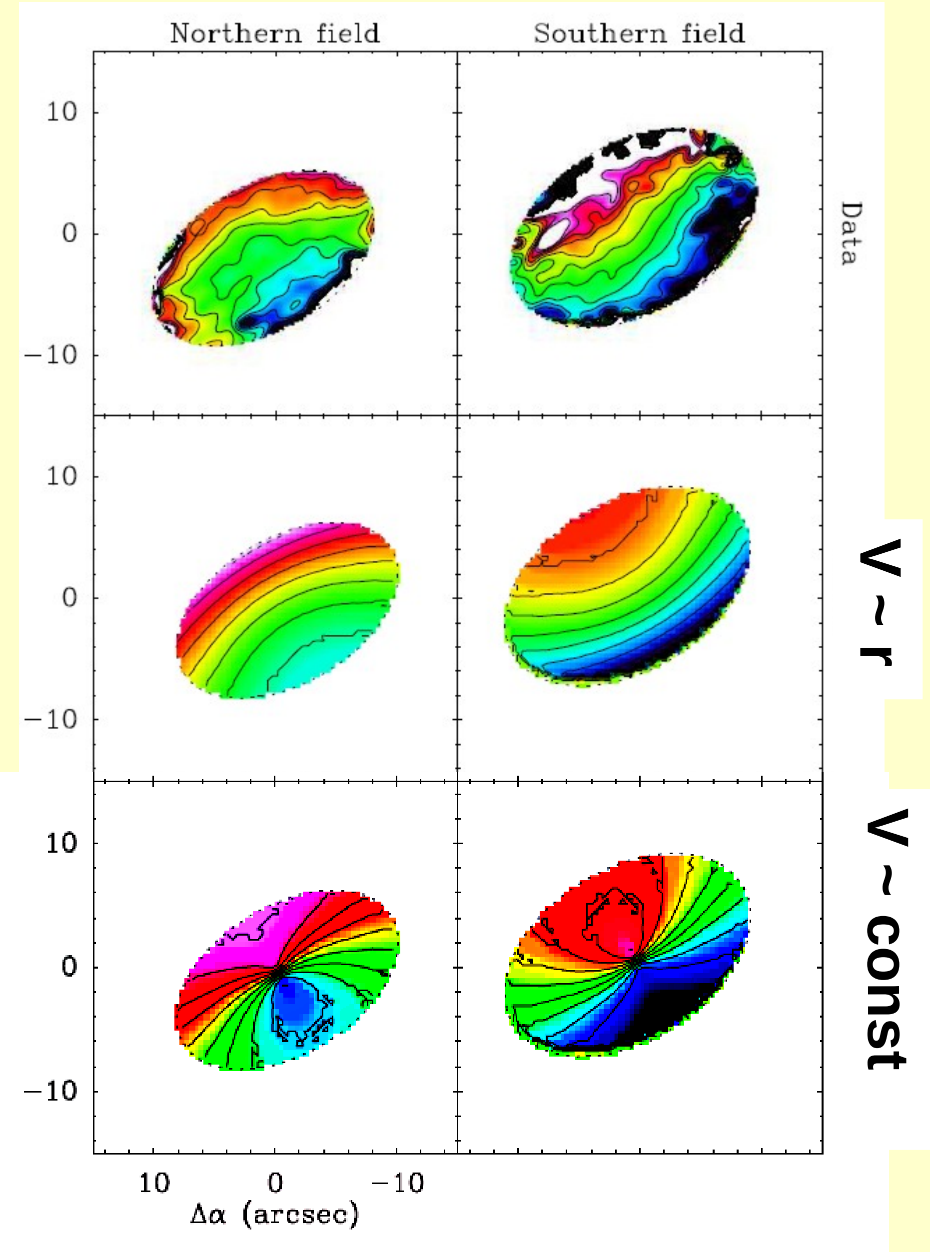


- Expanding parabolic shell
  - isothermal (20 K)
  - gas moves parallel to shell
  - same shell for both fields (opposite orientation)
  - no turbulent velocity component (too narrow maps)

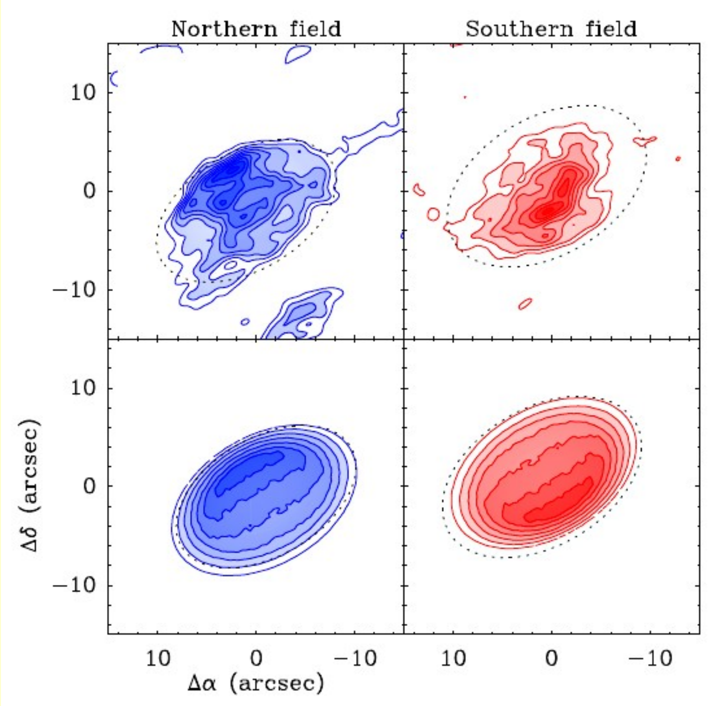




Velocity and density fields



- Velocity needs to increase linearly away from jet axis
  - Weakening jet shock
  - Explosive event + sorting



- Density drops with radius: ~ $r^{-0.5}$
  - Weakly constrained

Implications: gas lateral momentum

- EHV gas motion has two components
  - parallel to jet axis (~60 km/s)
  - perpendicular (linear increase to 13 km/s)

- Forward momentum dominates
  - factor of ~7
  - consistent with high collimation

- Sideways momentum in each EHV ejection
  - from model parameters: ~ 7 10^{-4} Mo km/s

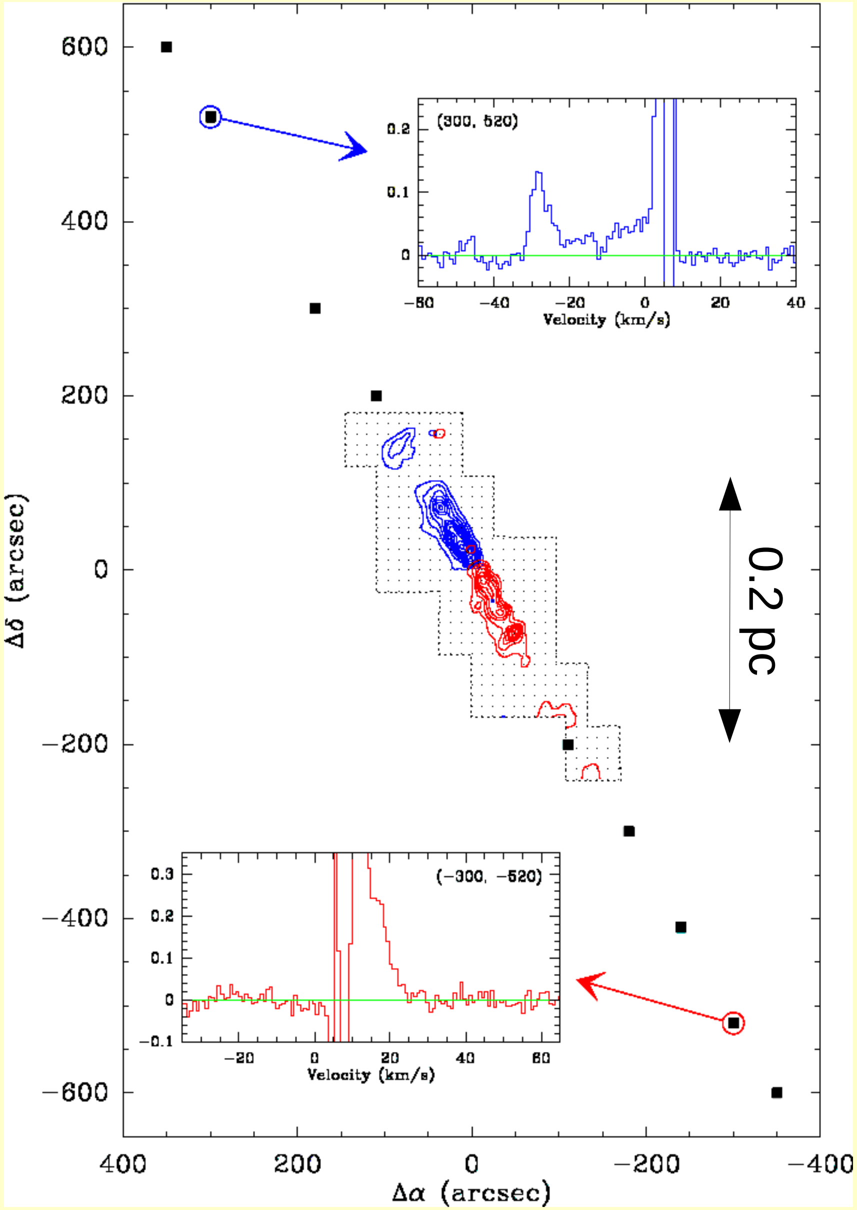
- Total sideways momentum depends on number of EHV ejections

- New IRAM 30m observations show jet much larger than initially mapped

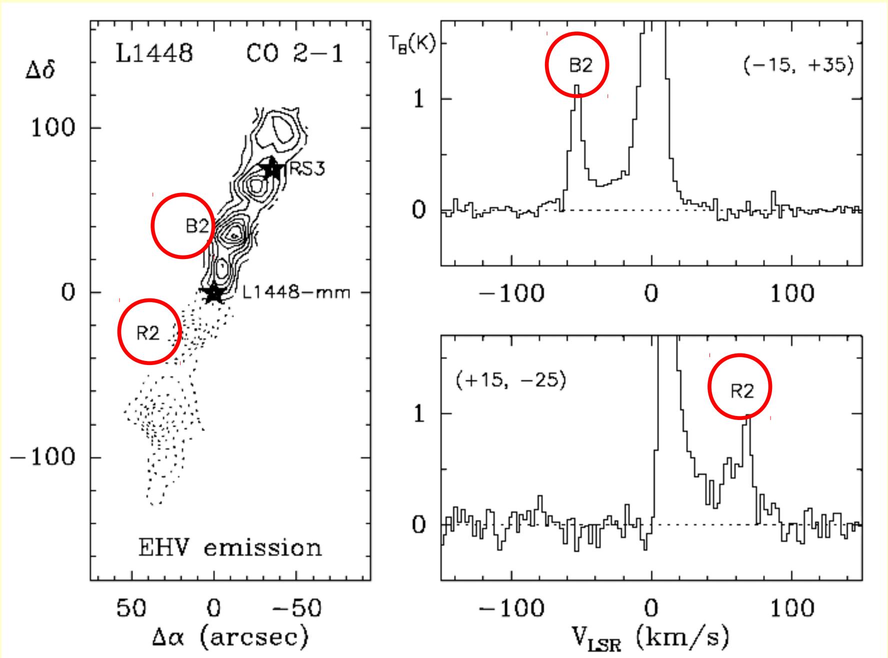
- If 20 EHV ejections over lifetime
  - Lateral momentum = 1.4 10^{-2} Mo km/s per lobe

- Momentum needed to open shell
  - M_c x c = 5 10^{-3} Mo km/s per shell

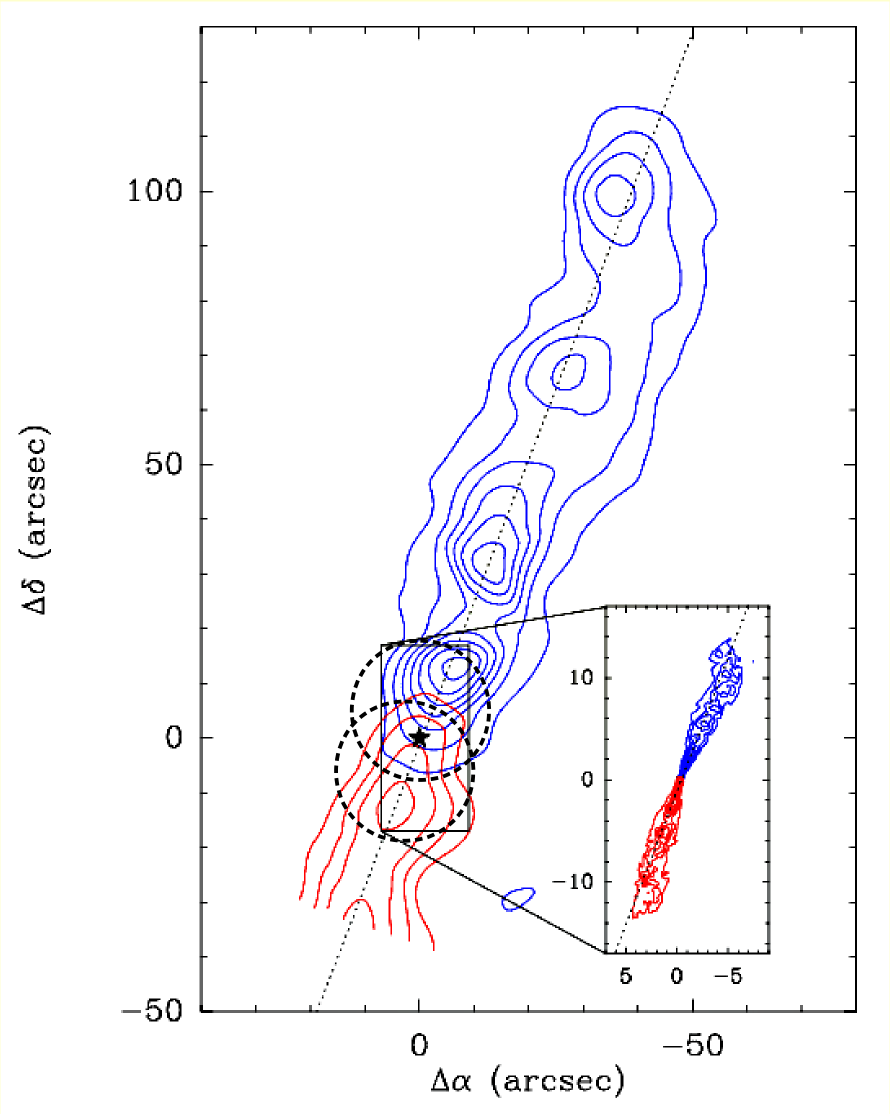
EHV gas could have opened outflow cavity



L1448 ALMA observations

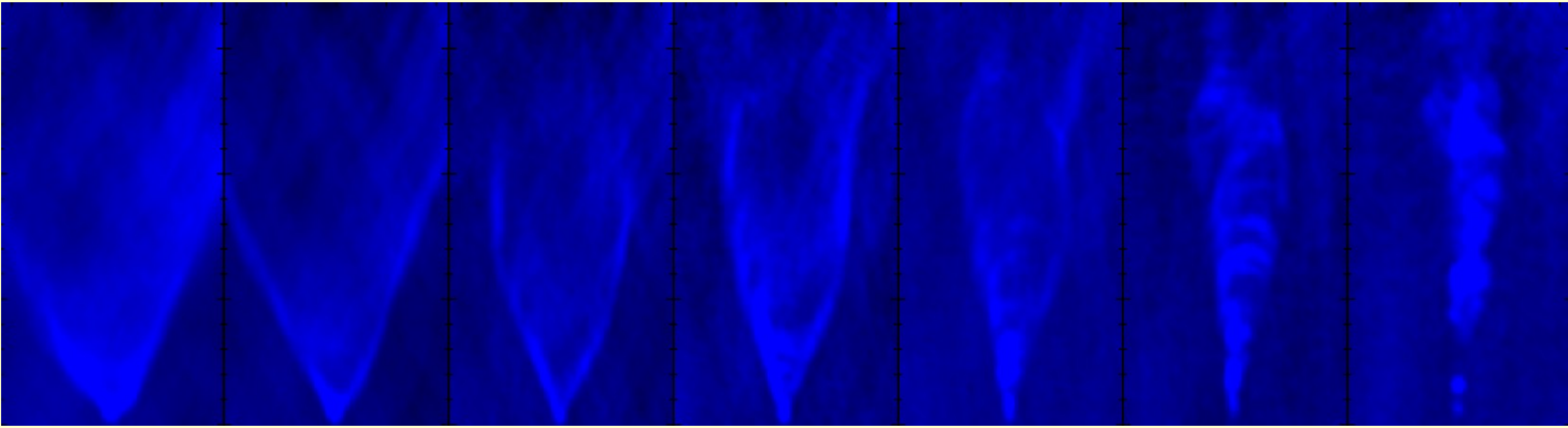


Bachiller et al. (1990)



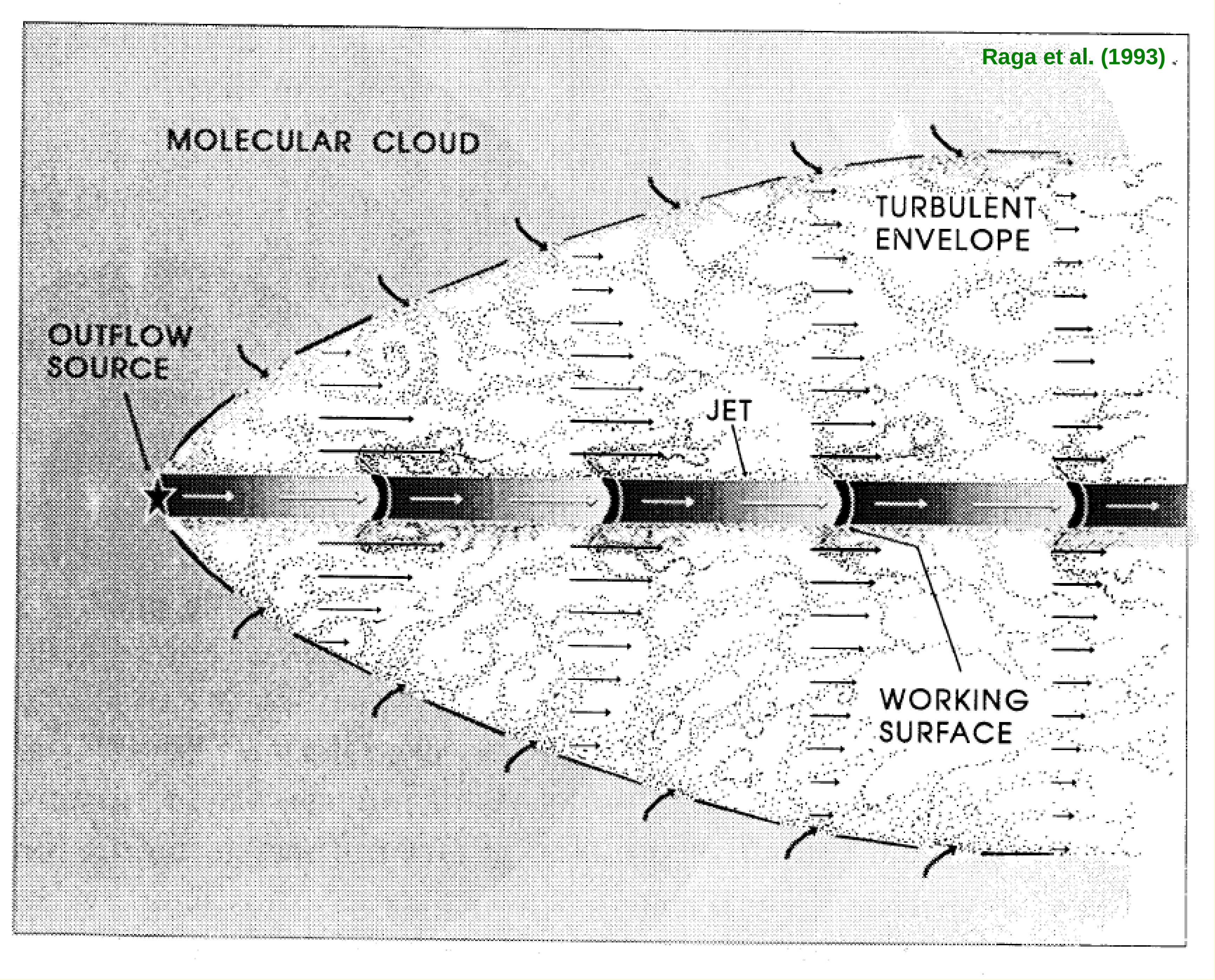
- Cycle 3 ALMA observations
  - CO(2-1), SiO(5-4). Beam ~ 0”.3
- Data released to PI November 2016
  - Modeling in progress
  - Preliminary results!

Main kinematical features



- Spatial continuity between jet and outflow regimes
- Systematic broadening of outflow shell
- Discrete bright shells

Modeling L1448 with shear flow



Summary

- In IRAS 04166, we find kinematic evidence for lateral ejection of gas in jet shocks
  - injection of lateral momentum could potentially the rest of the molecular outflow

- In L1448, we find a continuous velocity pattern that connects the jet and the molecular outflow
  - Outflow resembles a jet-driven shear flow
  - Flow shows evidence for discrete acceleration events

- New ALMA data favors a molecular outflow acceleration mechanism based on the lateral ejection of gas from the jet