Yesterday, we discussed the three main continuum processes in centimeter radio astronomy:

- Free-free (thermal)
- Gyrosynchrotron (non-thermal)
- Synchrotron (non-thermal)

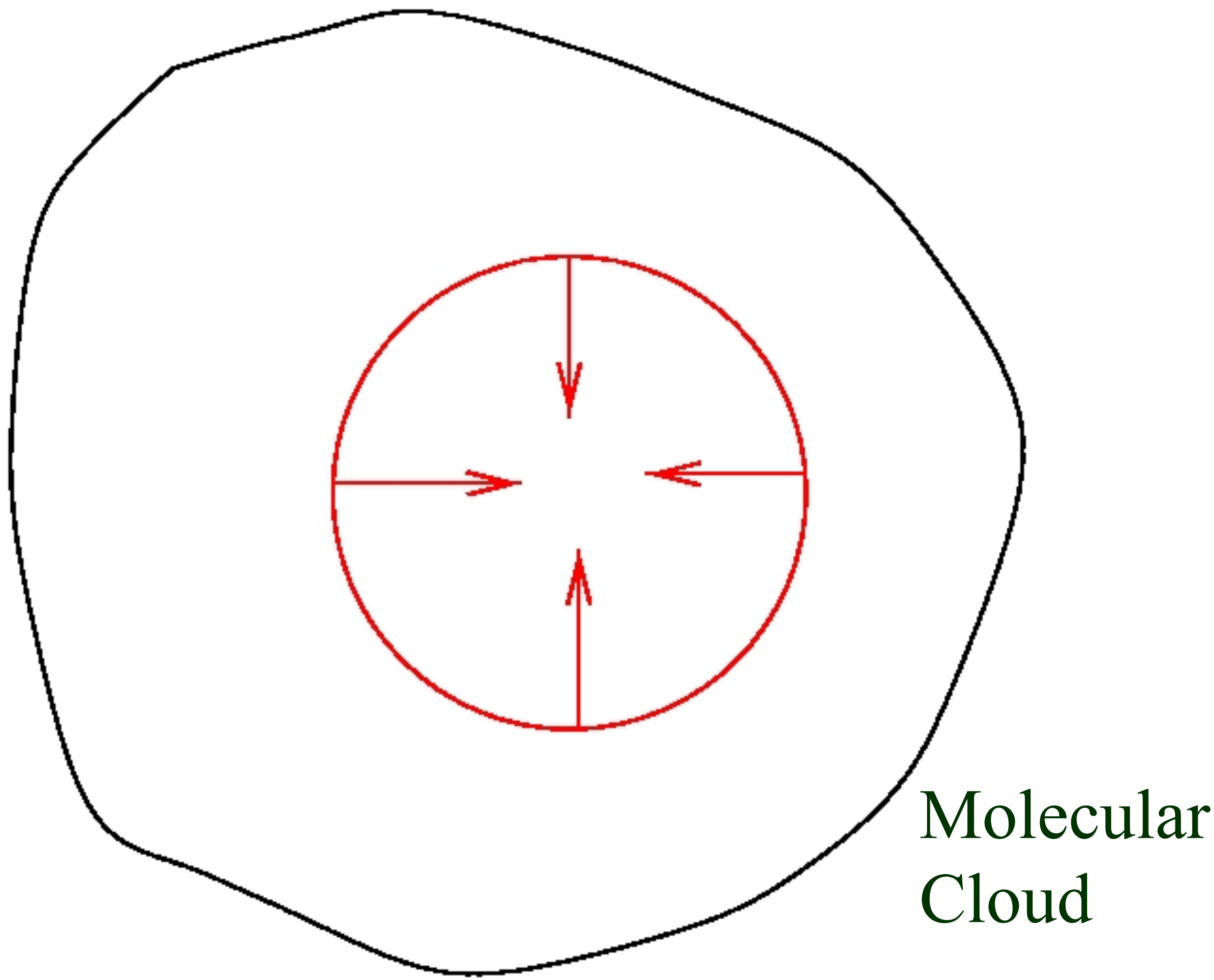
Today we will mostly talk about millimeter processes, mostly dust and molecular emissions in the context of star formation.

Jets and Disks in Young Massive Stellar Objects

Luis F. Rodriguez, CRyA, UNAM
Morelia, México

- Introduction
- Jets and disks in low-mass young stellar objects
- The search for jets and disks in massive young stars
- Other mechanisms for massive star formation?
- Conclusions and prospects

<1980



Bipolar Molecular Outflows

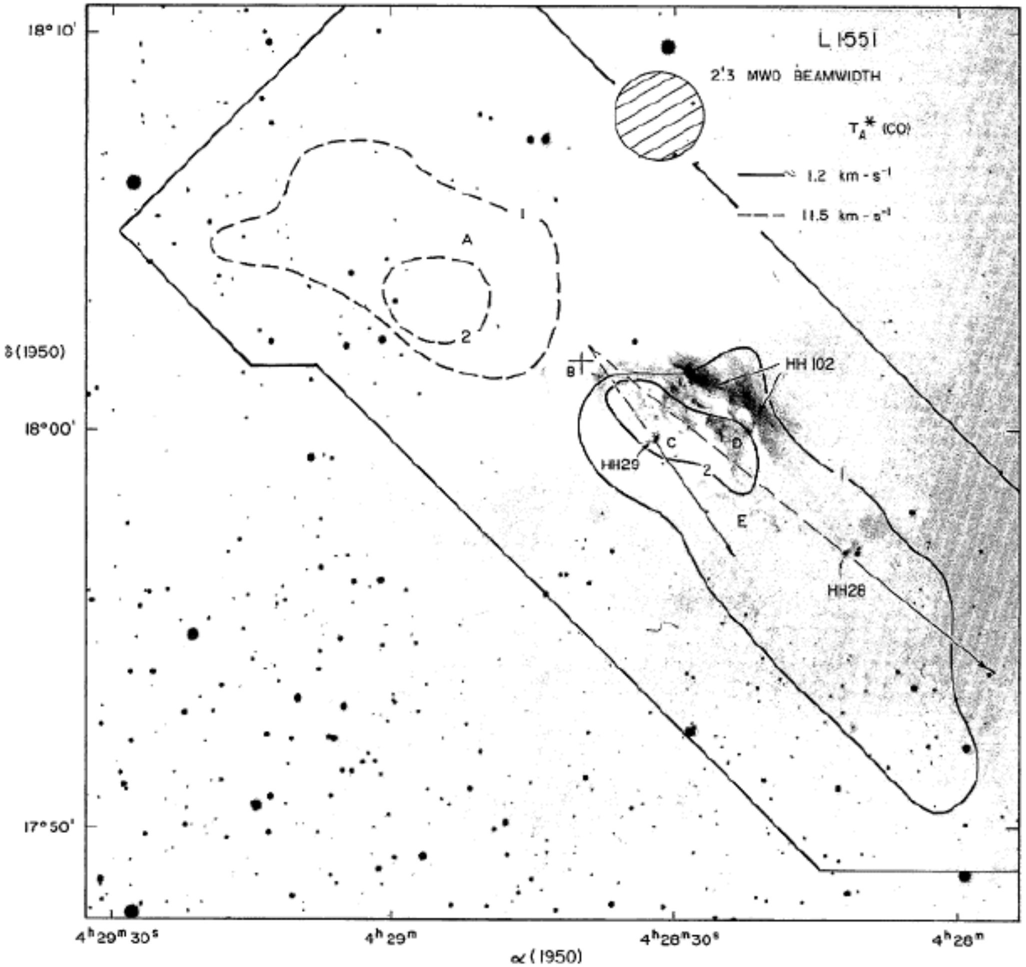


FIG. 2.—Contour map of the $J = 1$–0 ^{12}CO antenna temperatures in the broad velocity components, superposed on an optical photo of the region taken by Strom with the 4 m telescope at KPNO. The map is based on CO spectra taken at 115 positions within the enclosed border with 1′–2′ spacings. A cross indicates the position of IRS-5; letters A–E indicate the positions of the five spectra in Fig. 1 from top to bottom. Also shown are the directions of the proper motions of the two compact Herbig-Haro objects, HH28 and HH29; tracing their motion backward suggests a common origin at the infrared source.

Molecular gas moving away from regions of star formation.

Snell, Loren, & Plambeck (1980)

Rodríguez, Ho, & Moran (1980)

Moving Herbig-Haro Objects

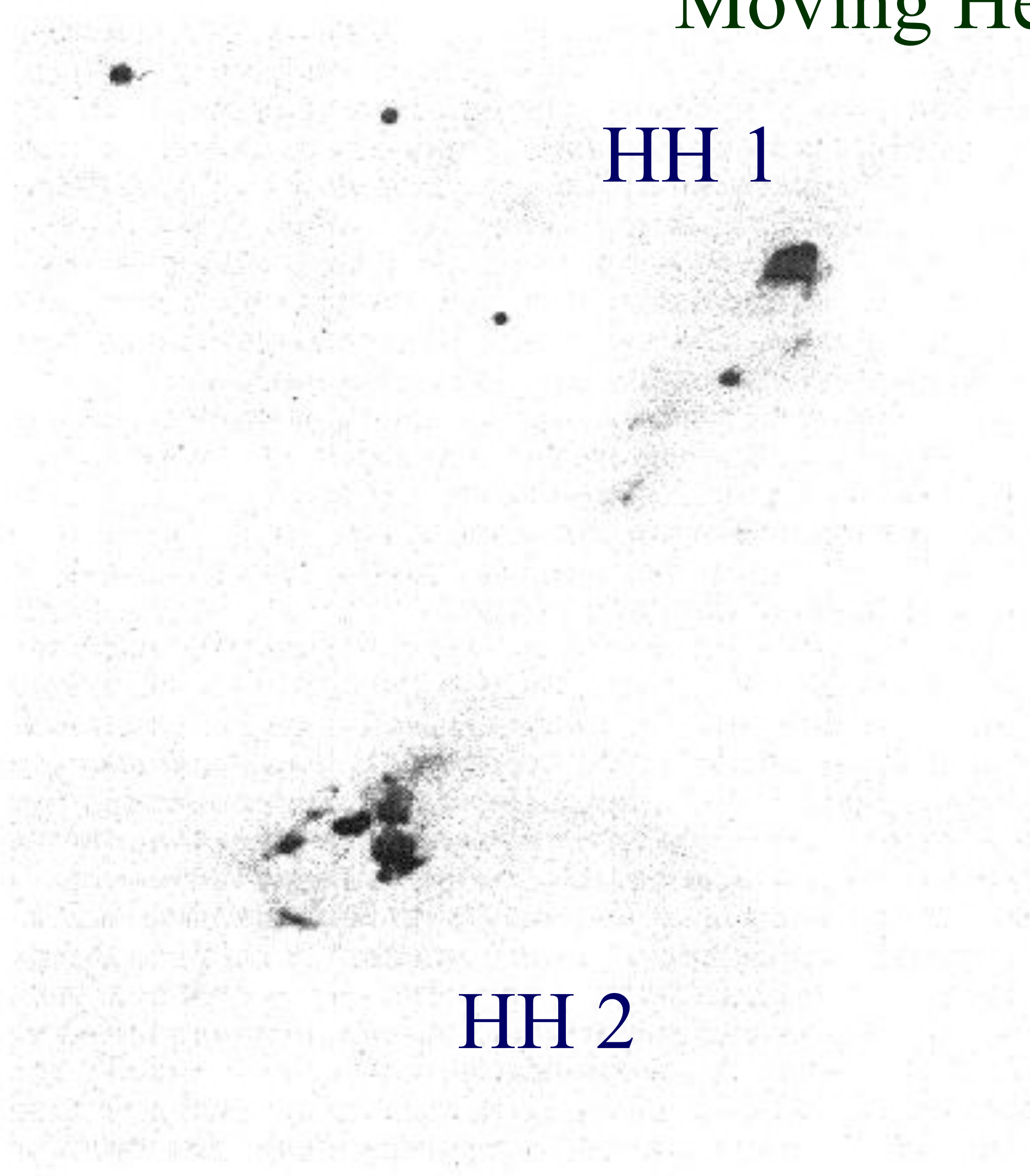


FIG. 3. Contrast-enhanced enlargement of the region of HH 1, HH 2, and the C-S star, from 120-in. plate ED-32 [illegible] and Fig. 7 [illegible]
The [illegible] nebulosity [illegible] the C-S star is apparent, and its elongation in the direction of HH 1 and HH 2. The small ring of [illegible]
to the upper [illegible] of HH 1, and the much larger ring to the right of HH 2 are real.

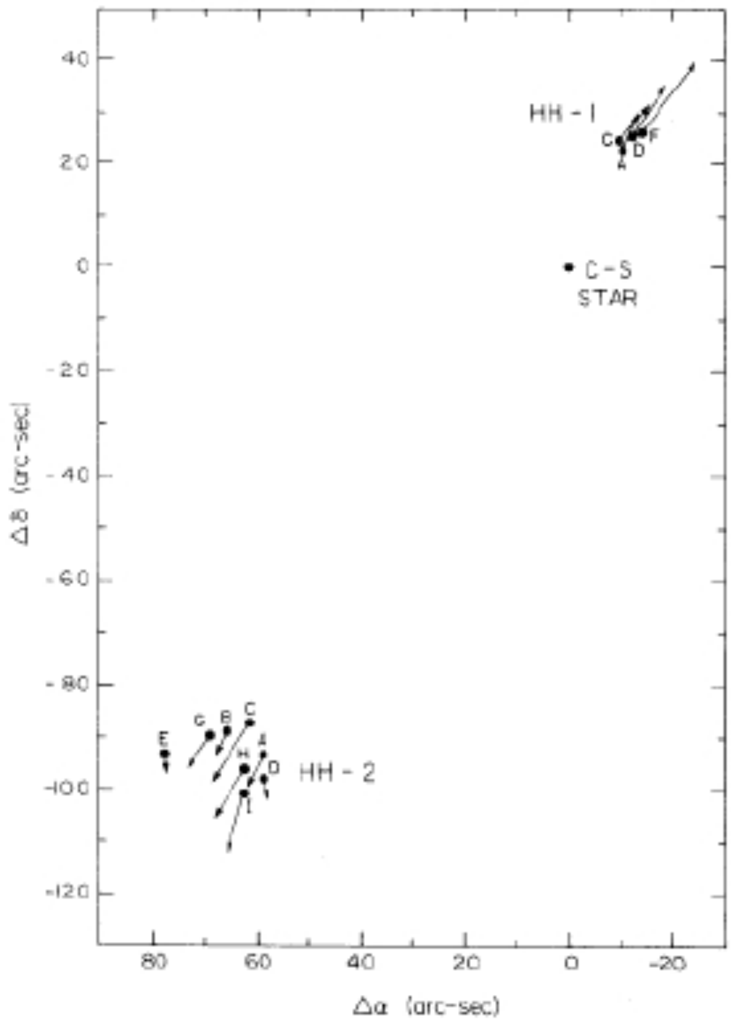
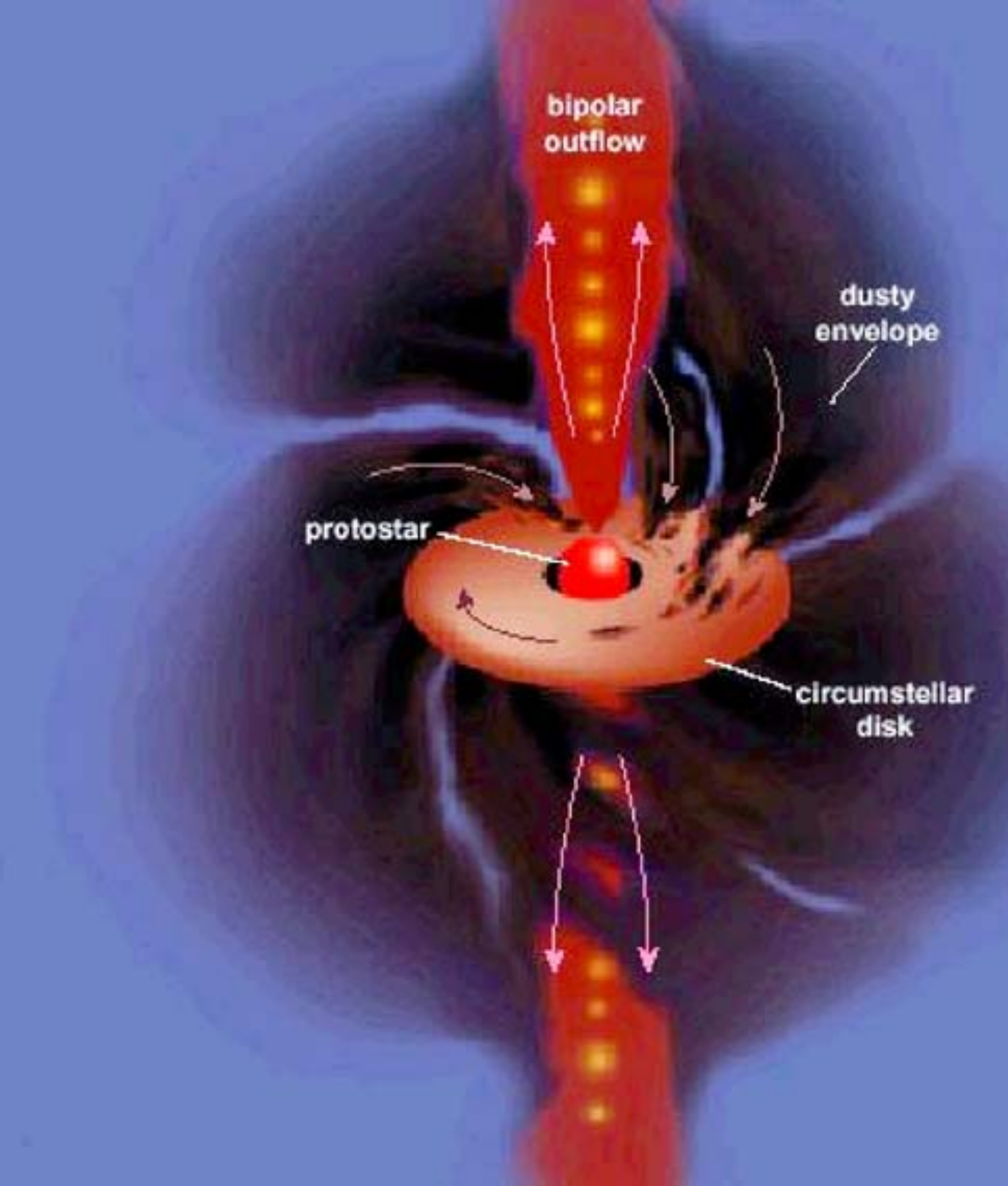


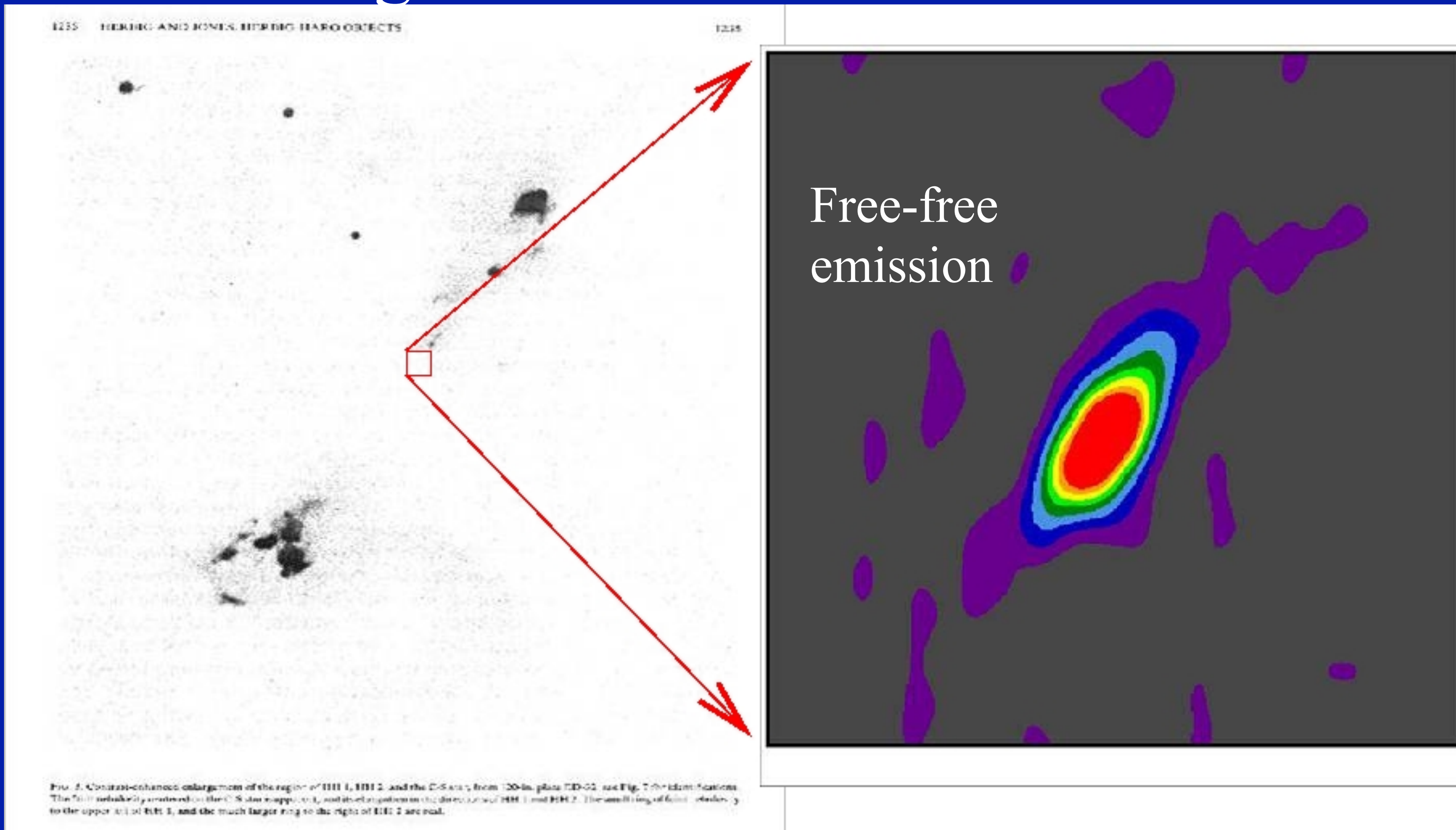
FIG. 7. The positions of HH 1, HH 2, and the Cohen-Schwartz star on the plane of the sky (for epoch 1968.0). The arrows indicate the shift in 100 yr due to proper motion. At a distance of 460 pc, 10 arcsec is [illegible]



JET: removes excess angular momentum and magnetic flux, produces outflows and HH objects. Free-free source at cm waves.

DISK: allows accretion, planets may form from it. Thermal dust and molecular emission at mm waves.

Thermal Jets: the Ionized, Collimated Ejecta from Young Stars

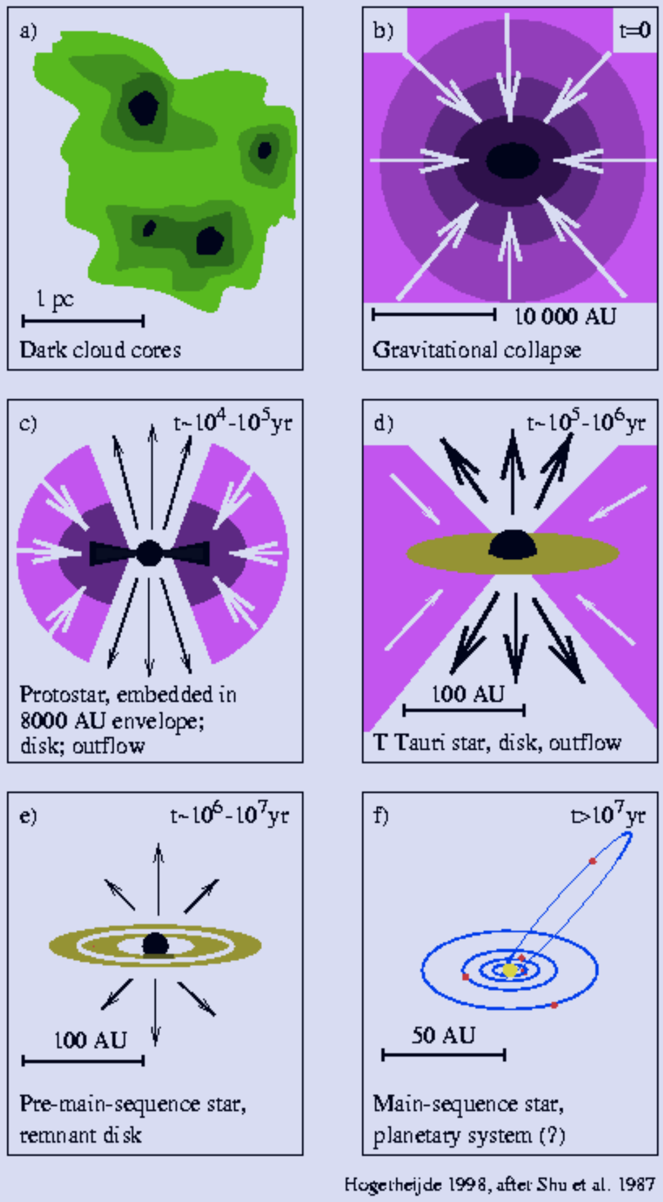


Optical; Herbig & Jones (1981)

Radio 6-cm; Pravdo et al. (1986)

What are the thermal jets?

- (Partially) ionized, collimated outflows that emanate from young stars.
- Ionization seems to have a shock origin.
- Detectable as weak free-free sources.
- They are believed to be the “base” of the large scale outflow phenomena like the bipolar outflows and HH systems.
- They are almost always found in the case of low-mass protostars, but rarely in high-mass protostars.



LOW MASS STAR FORMATION

a) Fragmentation of cloud

b) Gravitational contraction

c) Accretion and ejection

d) Formation of disk

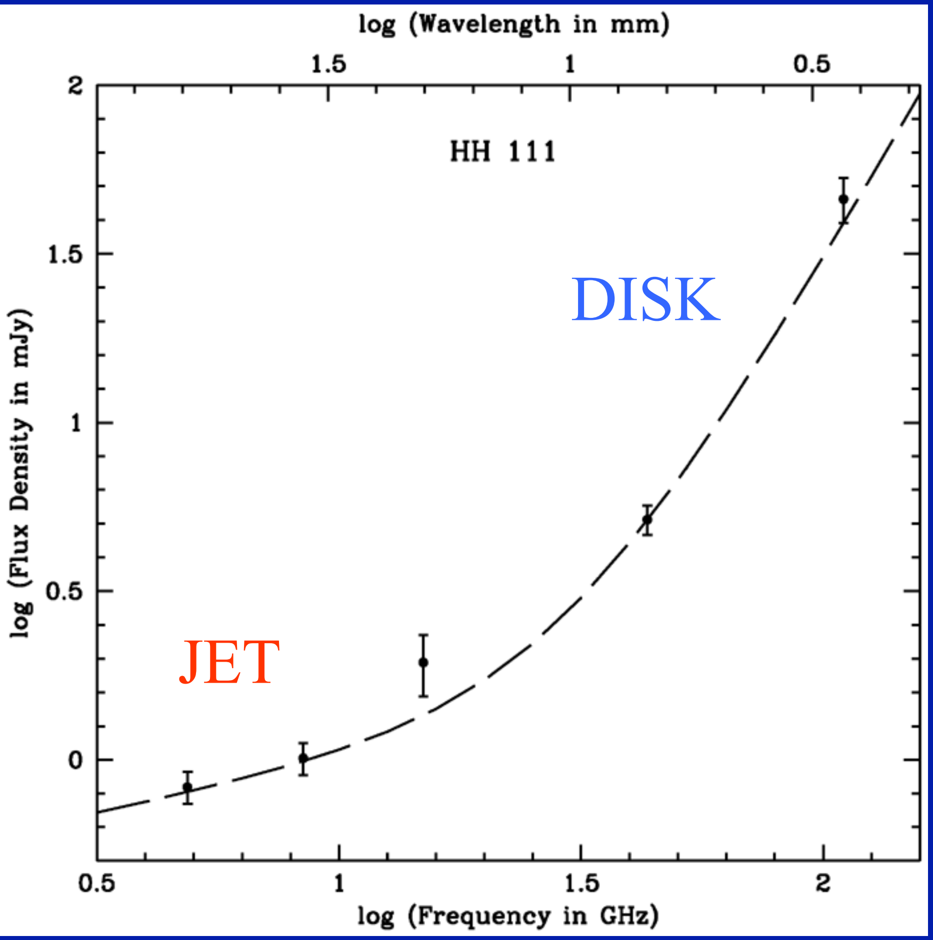
e) Residual disk

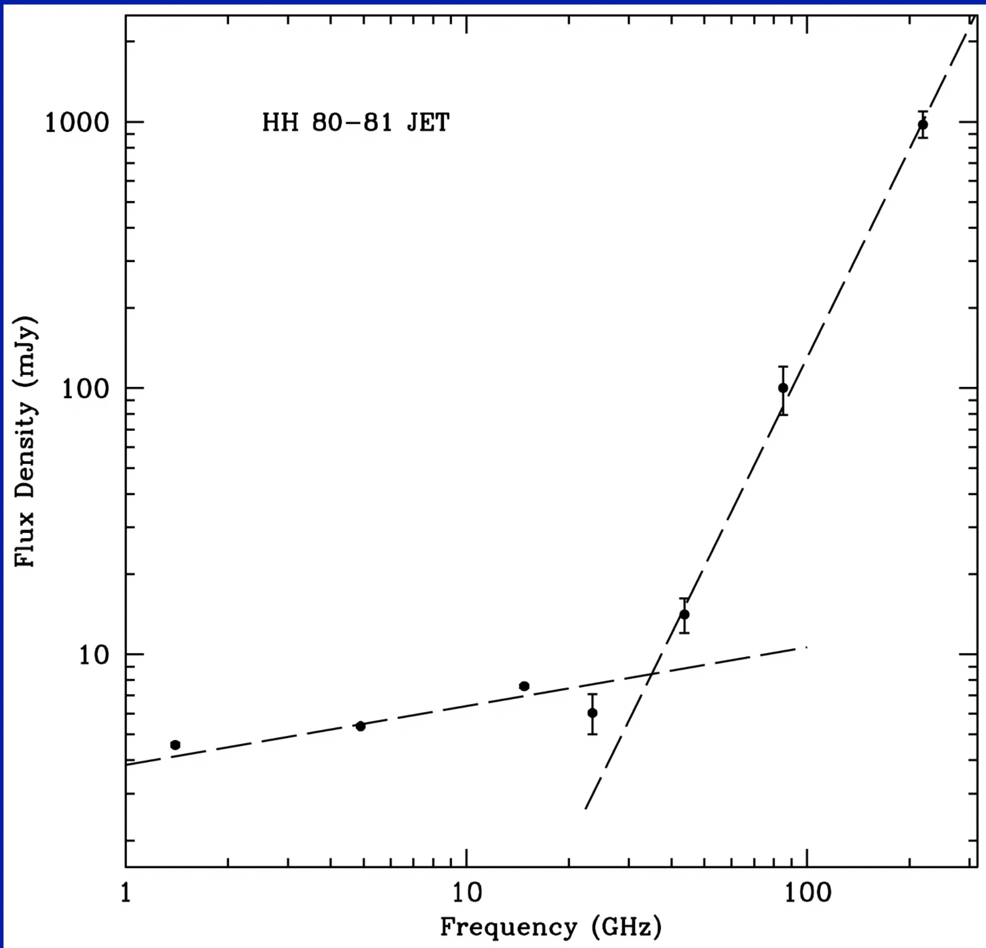
f) Formation of planets

(Shu, Adams & Lizano 1987)

Jets and Disks in the Radio

- Observations made at radio (cm, mm, and sub-mm) wavelengths with interferometers.
- Why radio? The early stages of star formation are heavily obscured.
- Why interferometers? We want to understand the small scales of the phenomenon.
- There is, however, a vast body of observations and theory that addresses the many aspects of star formation (McKee & Ostriker 2007, Zinnecker & Yorke 2007, PP series).

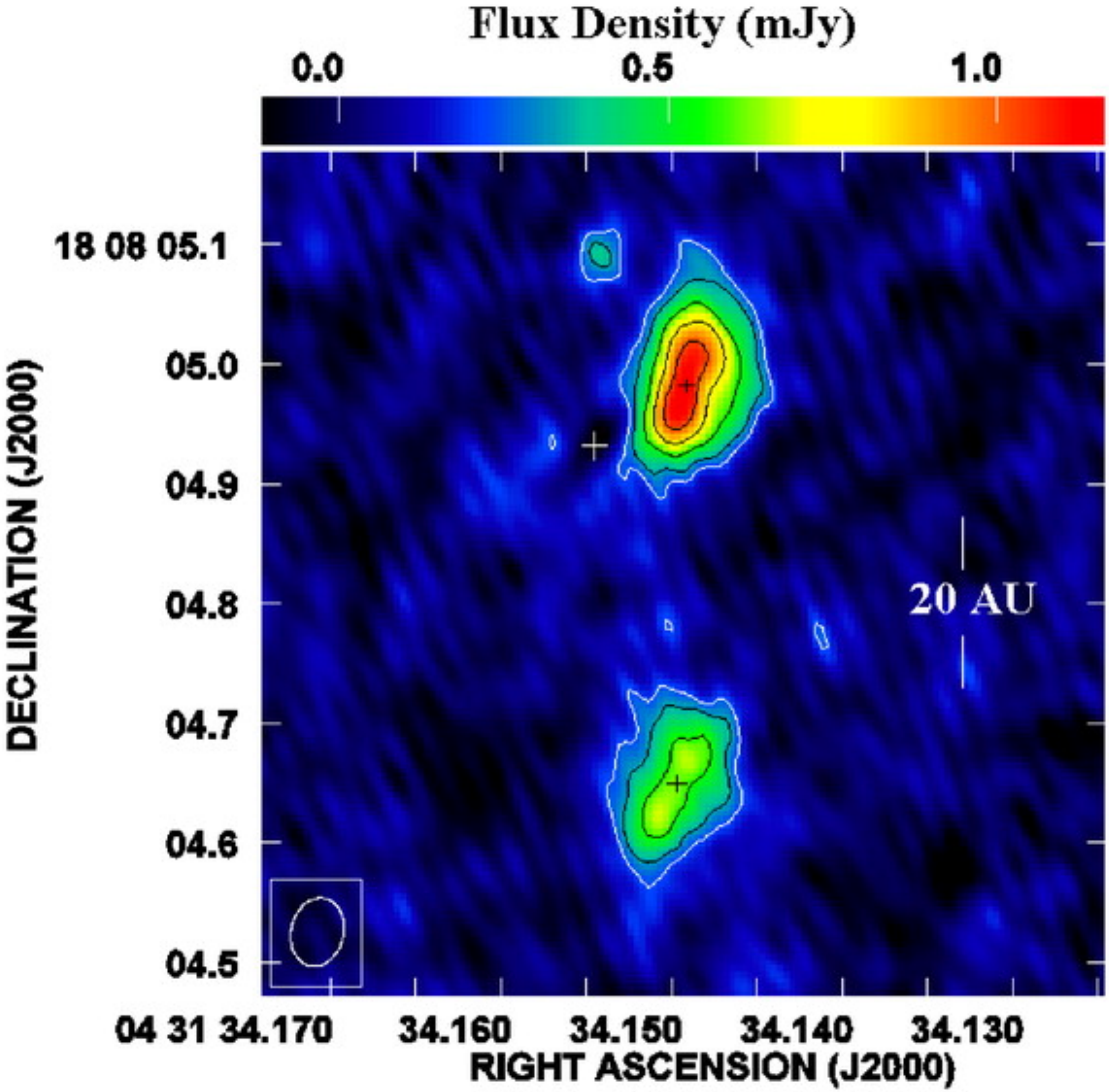




Rodriguez et al. 2008

Gómez et al. (2003)

VLA continuum observations at several frequencies reveal characteristic spectrum jet+disk.



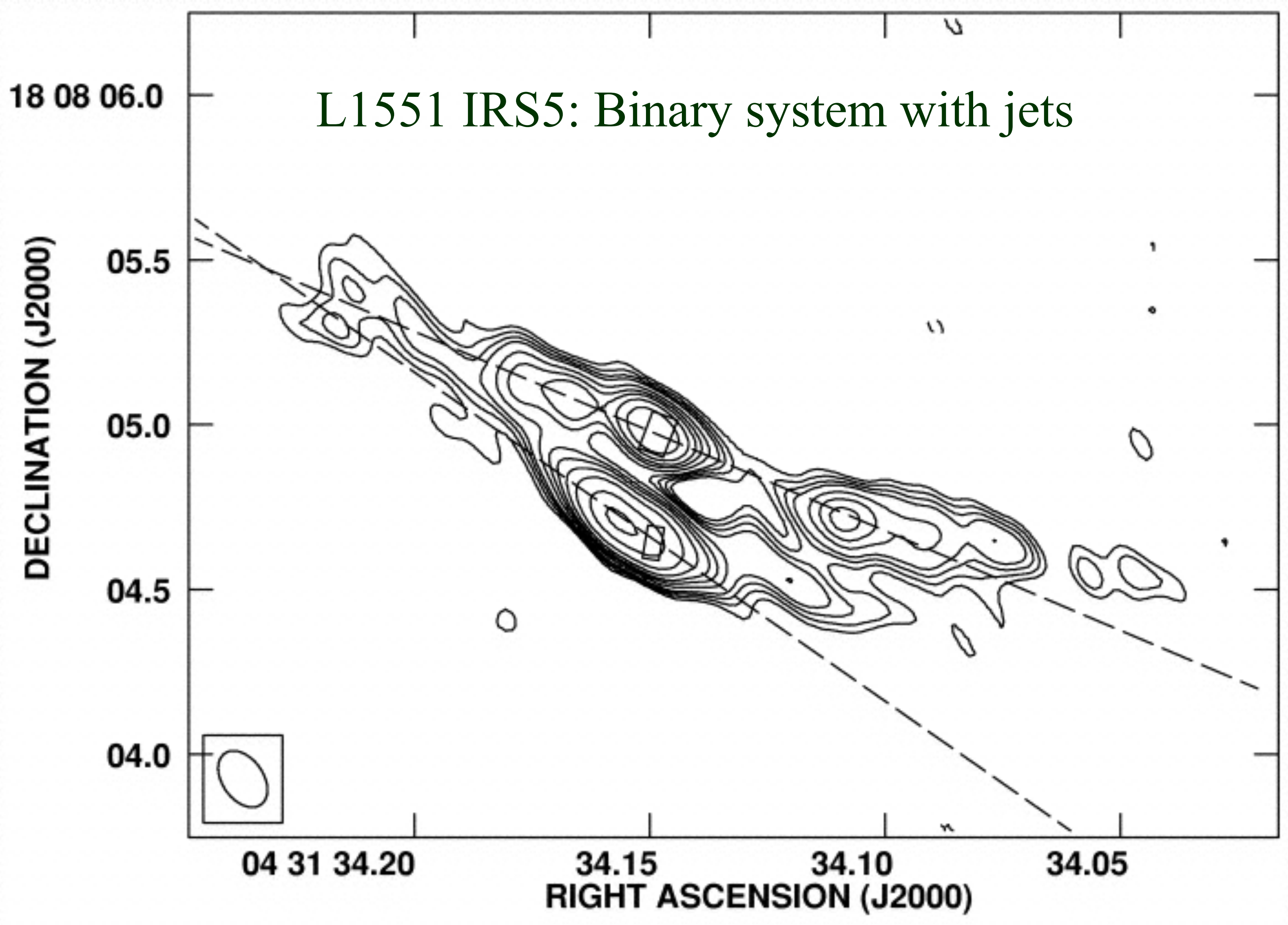
L1551 IRS5:

Binary system with disks.

VLA 7mm

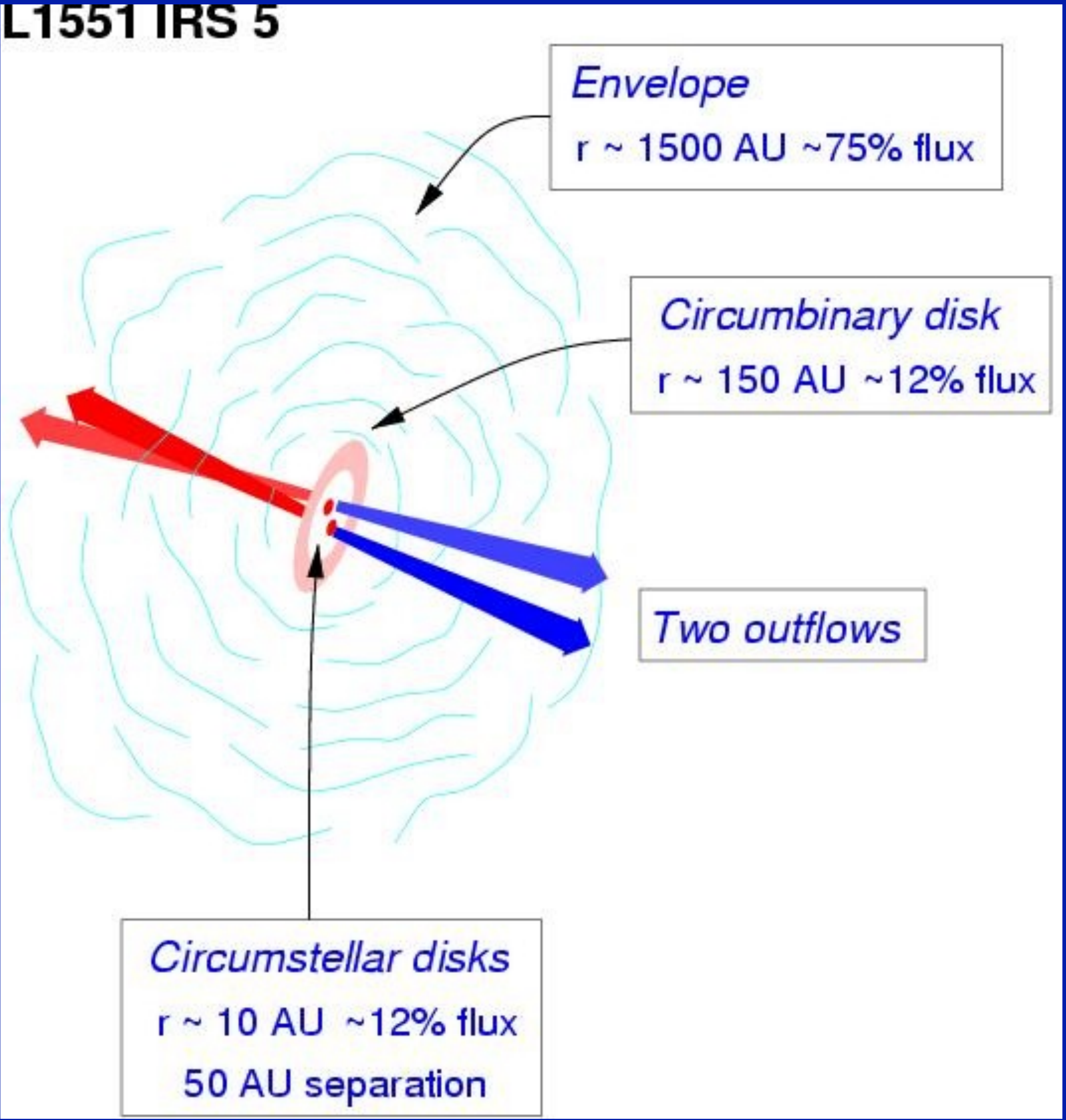
Lim & Takakuwa (2006)

Minus third component and jet contribution

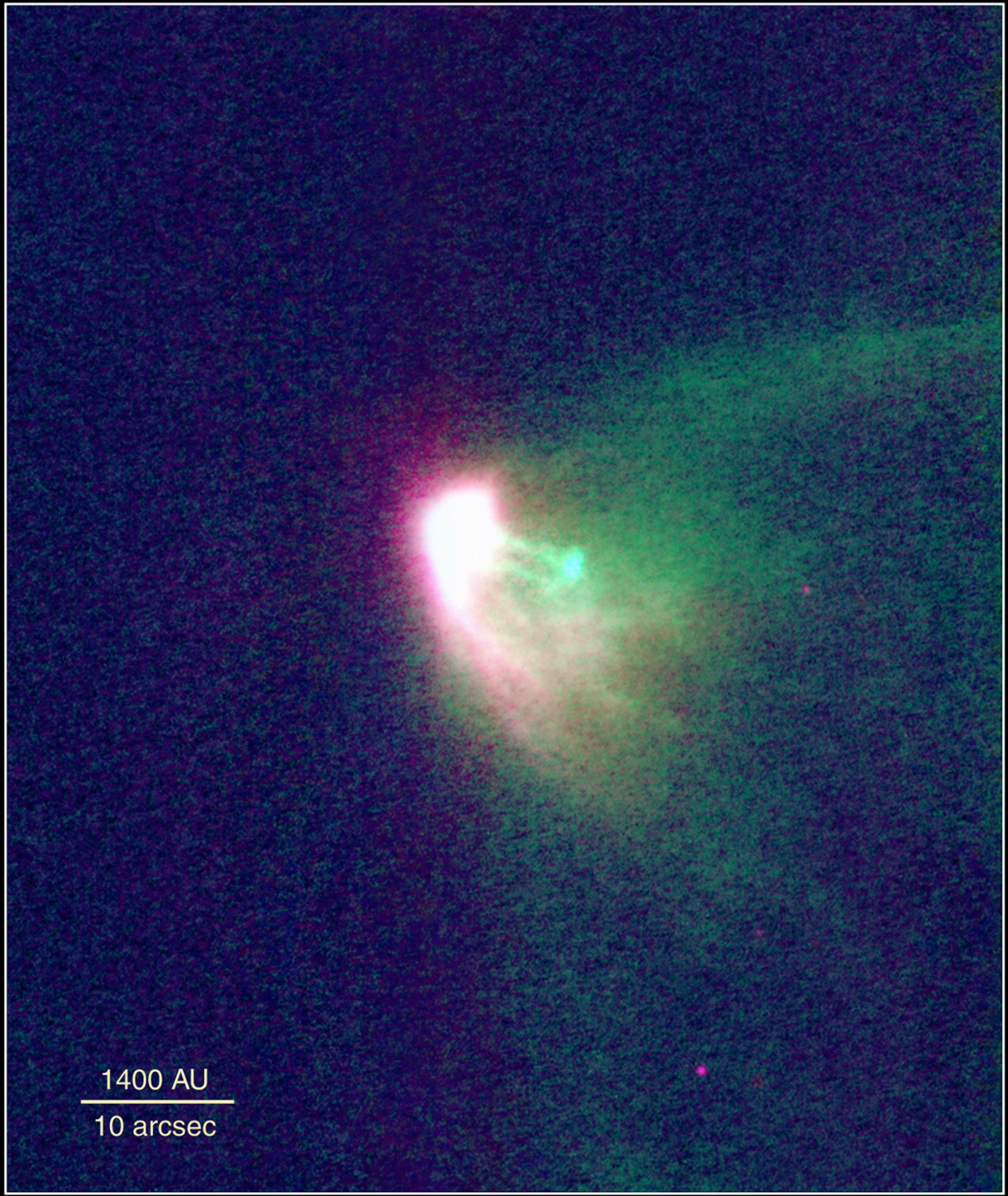


VLA 3.6 cm

Rodriguez et al. (2003)



Two stars,
two disks,
two jets…



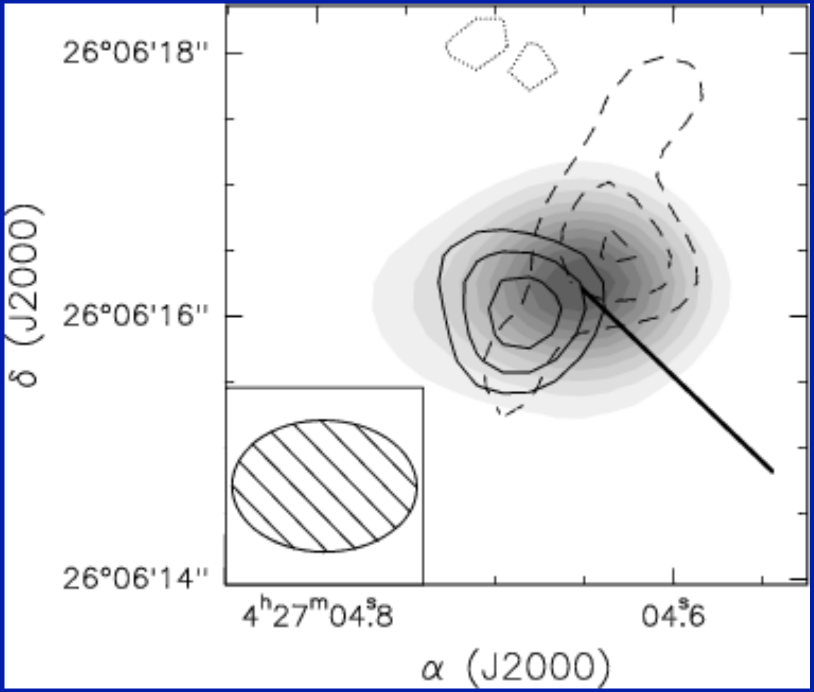
Itoh et al. (2000) Subaru image showing the two jets emanating from dark core.

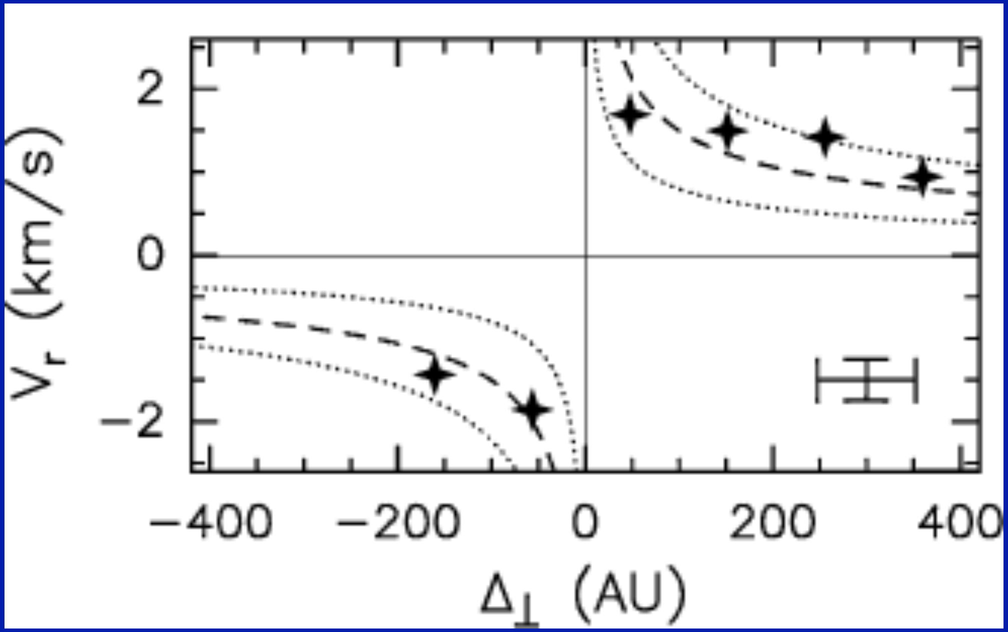
Green color traces [Fe II] lines in J and H infrared bands.

Low Mass Star Formation

- Believed to take place via disks and jets.
- Until recently, data in general limited in angular resolution and with little kinematical evidence. With regards to disks, ALMA is greatly improving this.

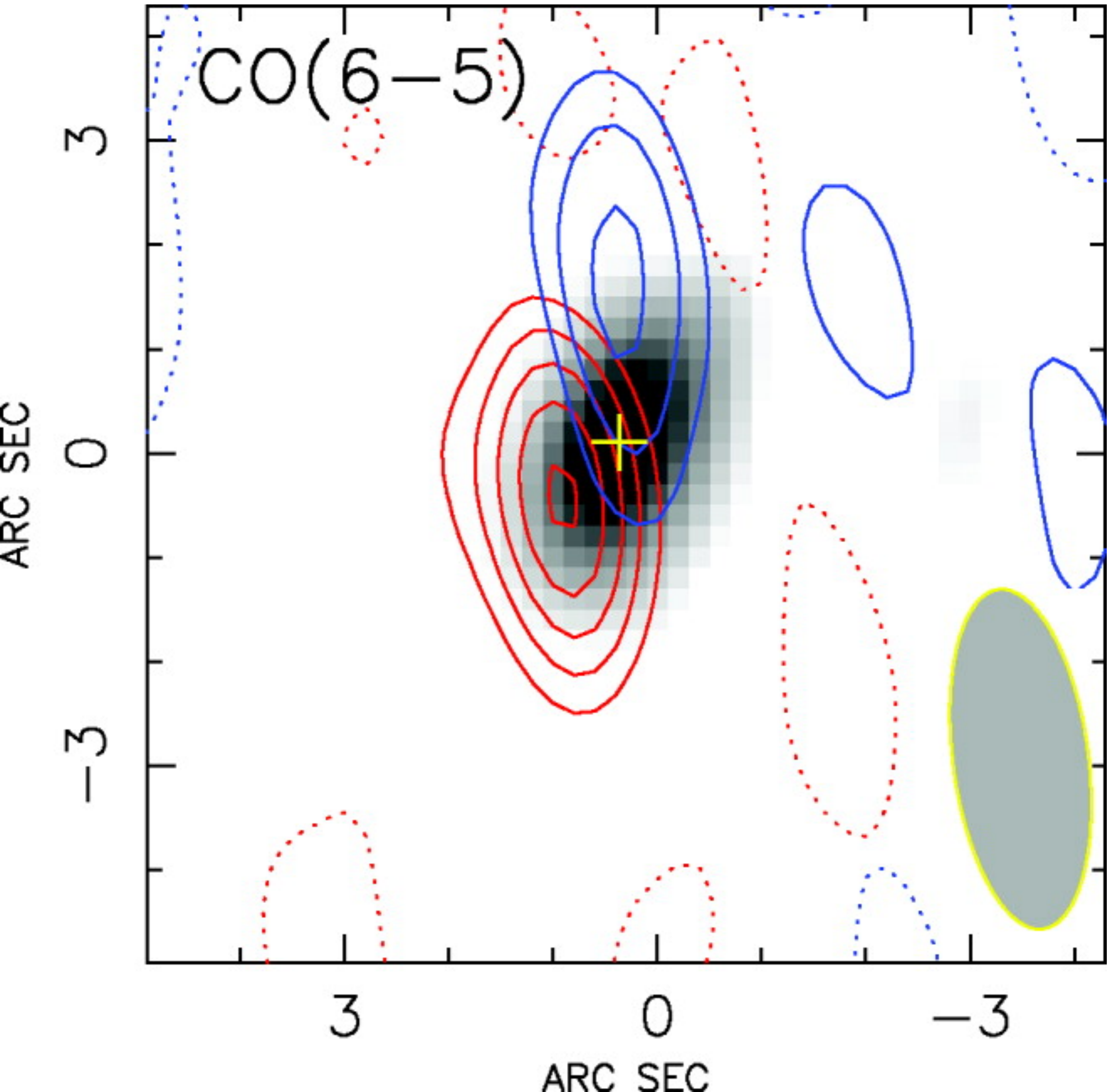
Evidence for a rotating disk…



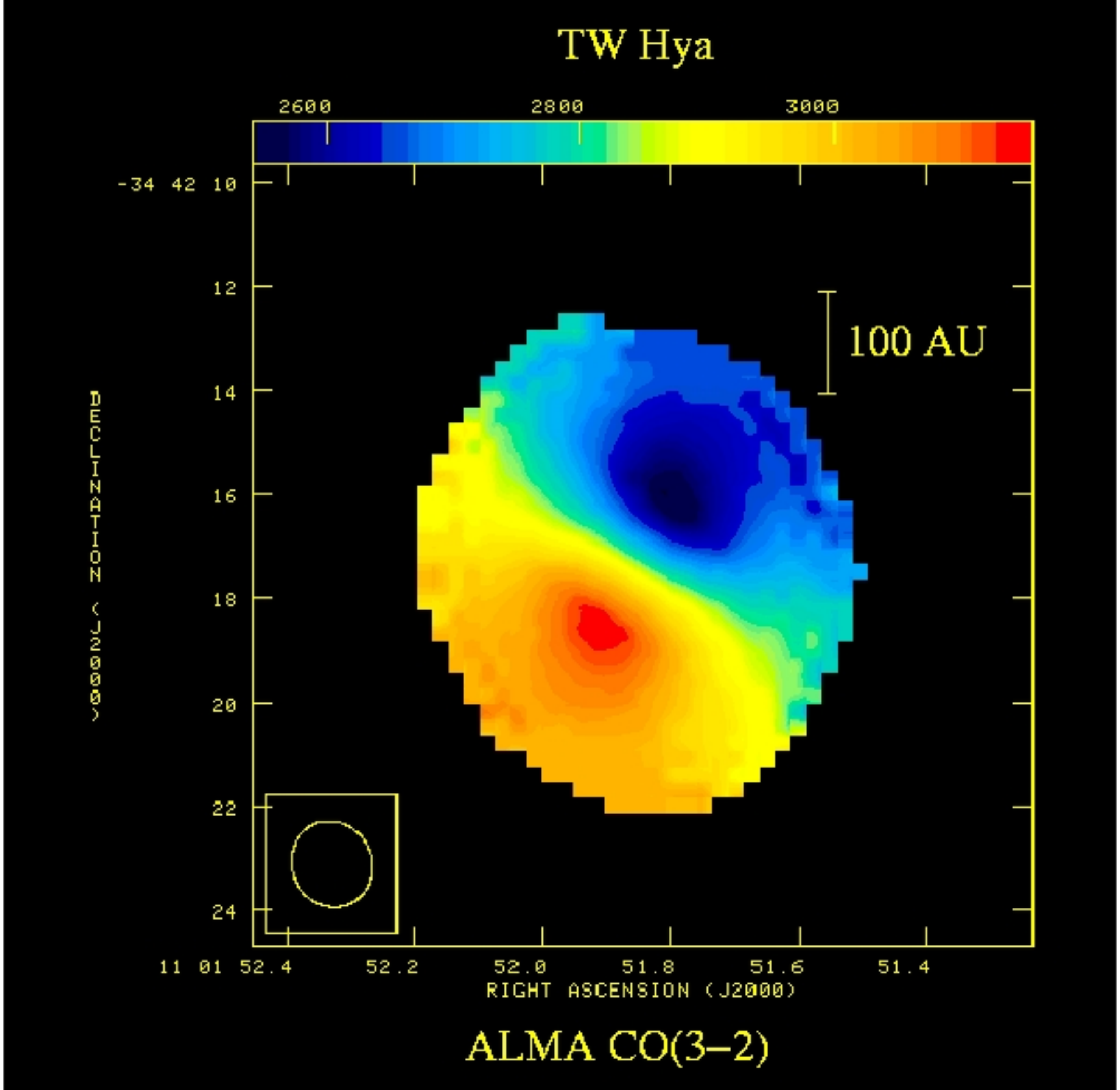


DG Tau: CO observations by Testi et al. (2002) made with OVRO.

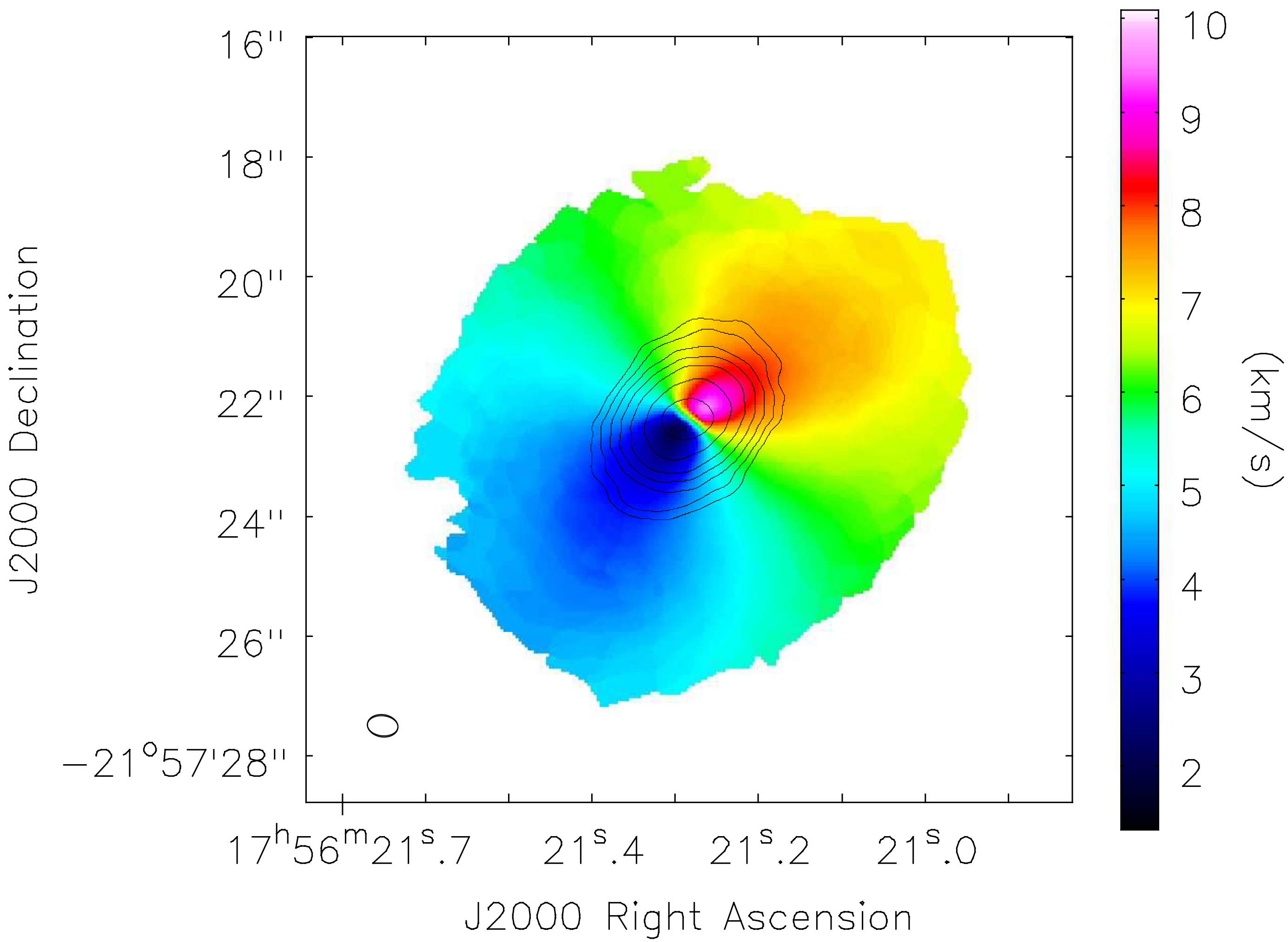
A Keplerian mass of 0.67 solar masses is estimated.



TW Hya

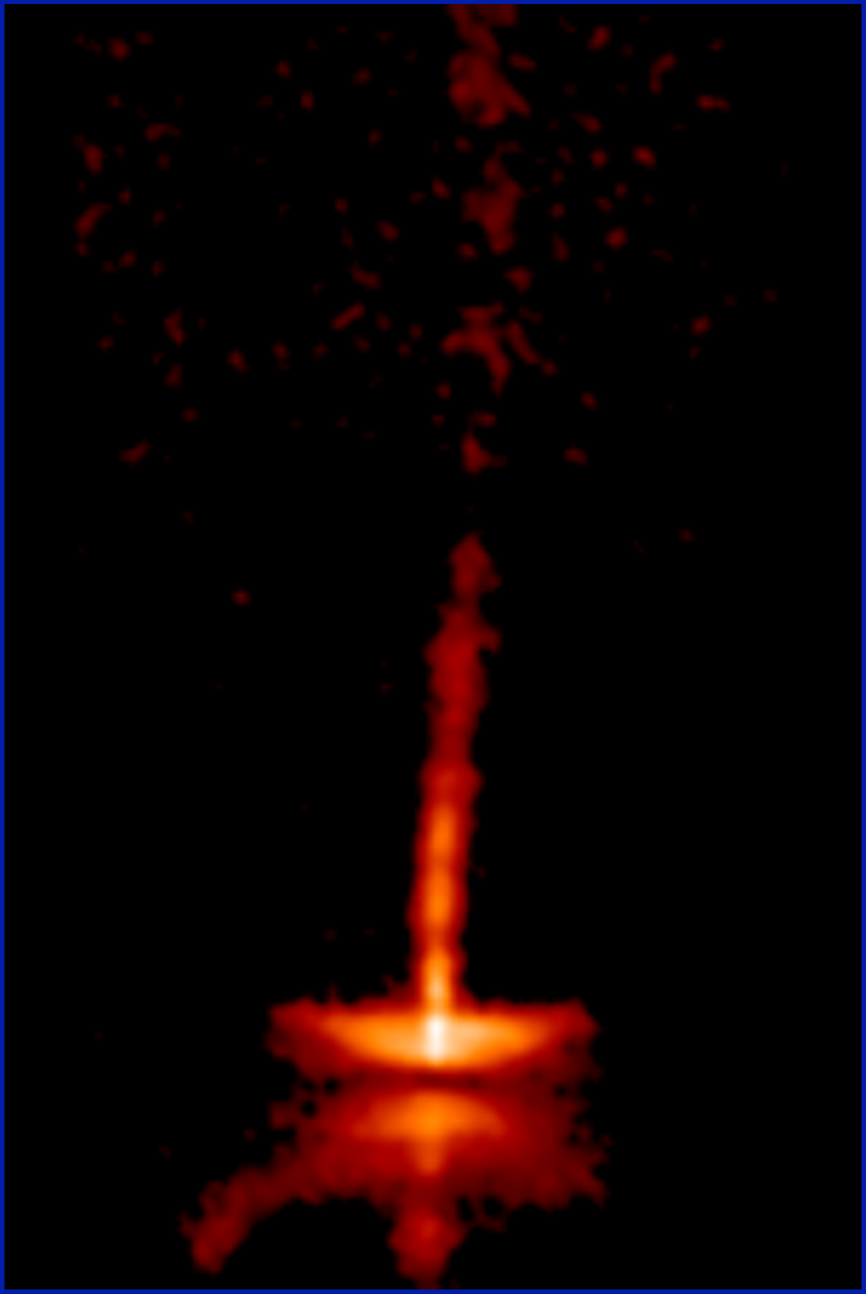

TW Hya
2600
2800
3000
-34 42 10
12
14
16
18
20
22
24
DECLINATION (J2000)
100 AU
11 01 52.4
52.2
52.0
51.8
51.6
51.4
RIGHT ASCENSION (J2000)
ALMA CO(3–2)

HD 163296 (Herbig Ae star)
de Gregorio-Monsalvo et al. (2013)



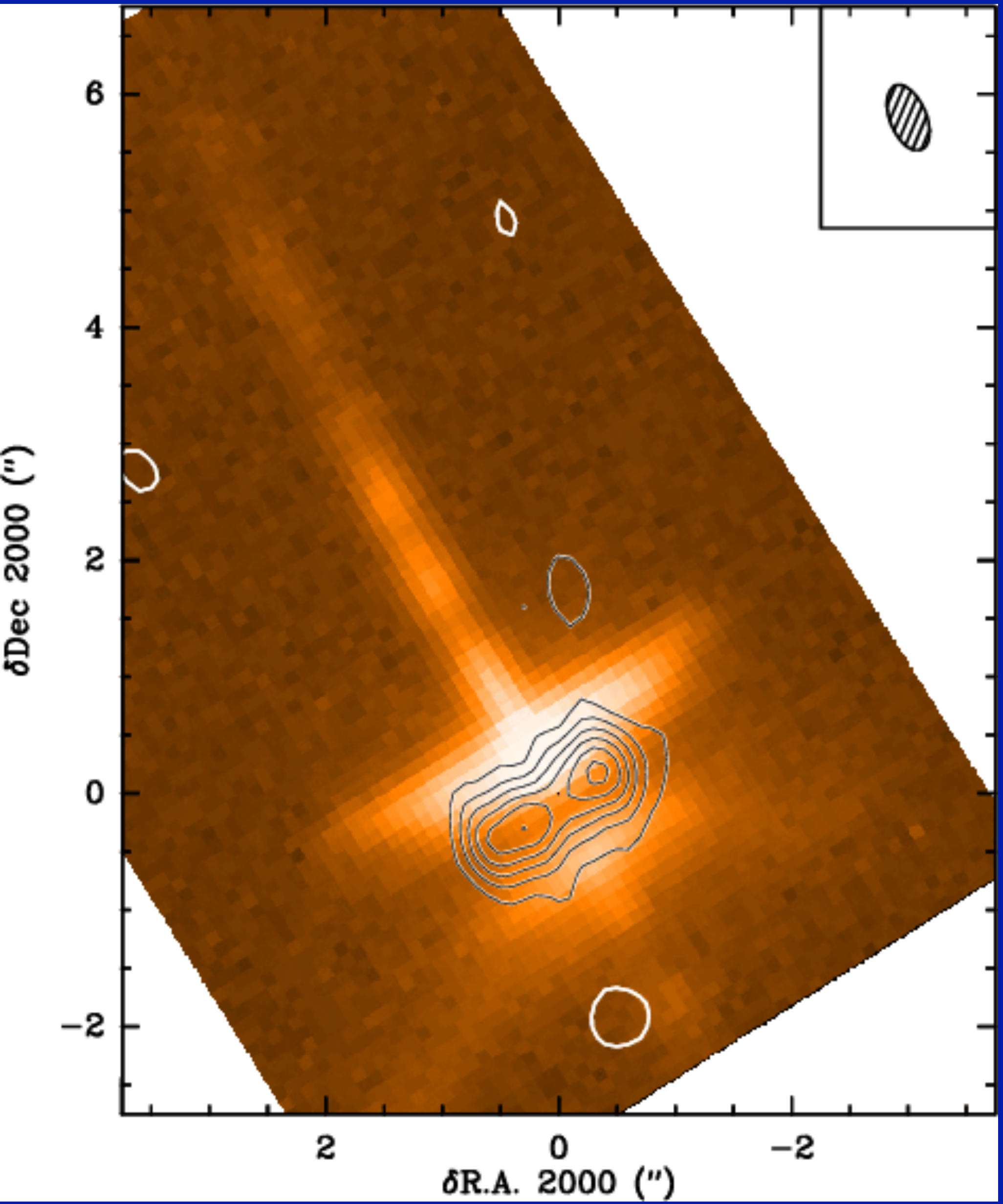
CO 3-2 (colors)

0.85 mm dust continuum (contours)



HH 30

HST images by Watson et al. (2008)



Anglada et al. (2007) proposed that the jet precession implies a binary system.

Guilloteau et al. (2008) used the IRAM interferometer at 1.3 mm and find evidence for a circumbinary disk.

R(outer) = 250 AU

R(inner) = 37 AU

Semiaxis of binary = 15 AU; Pichardo et al. (2005)

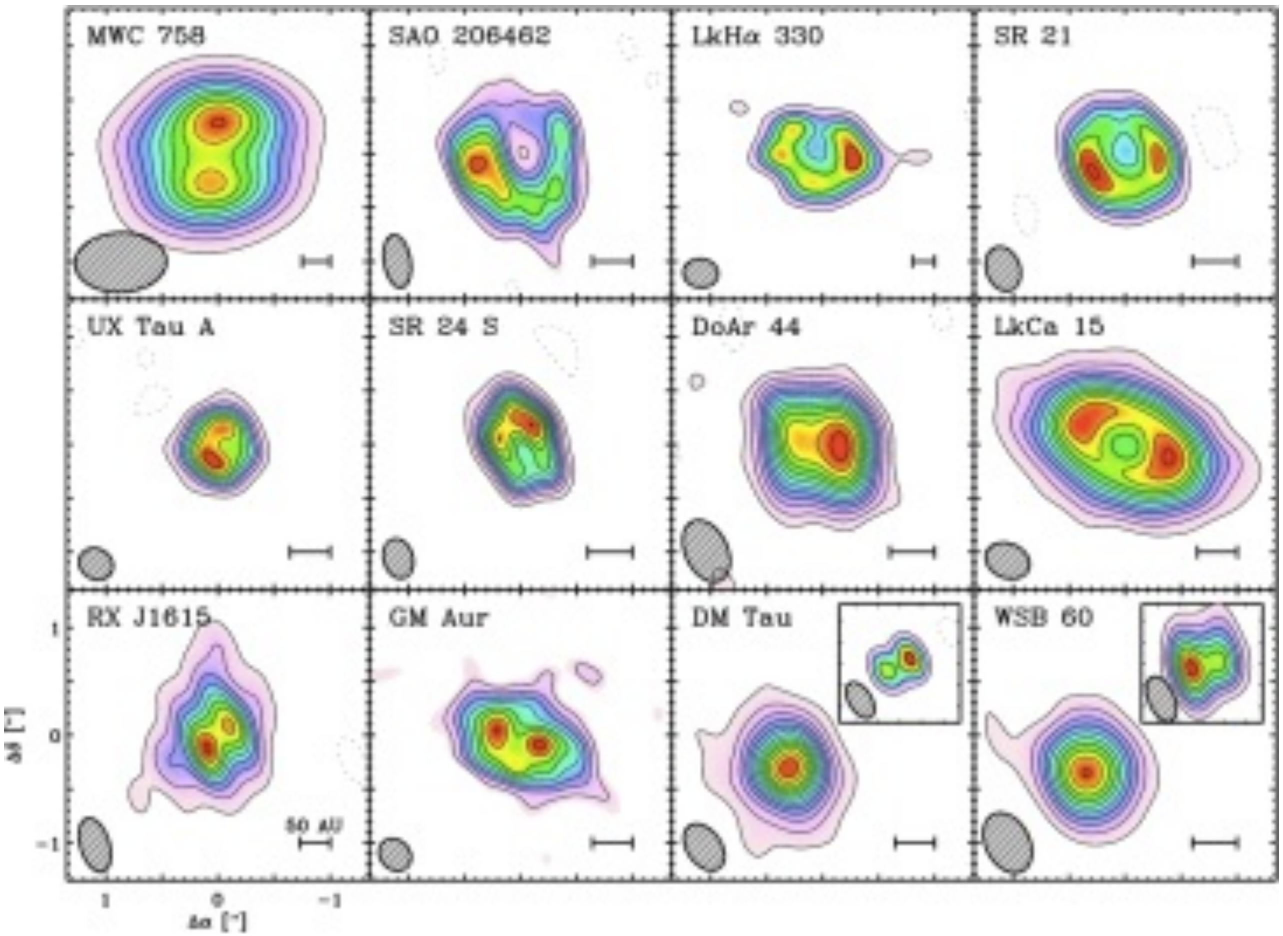
Summary of jets and disks in low mass forming stars

Disks: Diameters of 30 to 300 AU.

Masses of orden 0.1 solar masses.

Evidence of evolution (transition disks).

Figure 1 from Resolved Images of Large Cavities in Protoplanetary Transition Disks
Sean M. Andrews et al. 2011 ApJ 732 42 doi:10.1088/0004-637X/732/1/42



SMA 0.88 mm observations of dust from transition disks. Suggest dynamical clearing by brown dwarfs or giant planets.

Summary of jets and disks in low mass forming stars

Disks: Diameters of 30 to 300 AU.

Masses of orden 0.1 solar masses.

Evidence of evolution.

Jets: Mass loss rates of order 10^{-6} solar masses per year at velocities of 100-200 km s^{-1}.

Formation of Massive Stars

- With good advances achieved in our understanding of low mass star formation, it is tempting to think of high mass star formation simply as an extension of low mass star formation.
- That is, assume that the accretion into the star continues until we have a massive object.
- However, there are differences between low-mass and high-mass star formation.

Some problems with extending the picture of low-mass star formation to massive stars:

- Radiation pressure acting on dust grains can become large enough to reverse the infall of matter:
  - $F_{\text{grav}} = GM_{*}m/r^2$
  - $F_{\text{rad}} = L\sigma/4\pi r^2 c$
  - *Above 10 M_{sun} radiation pressure could reverse infall*

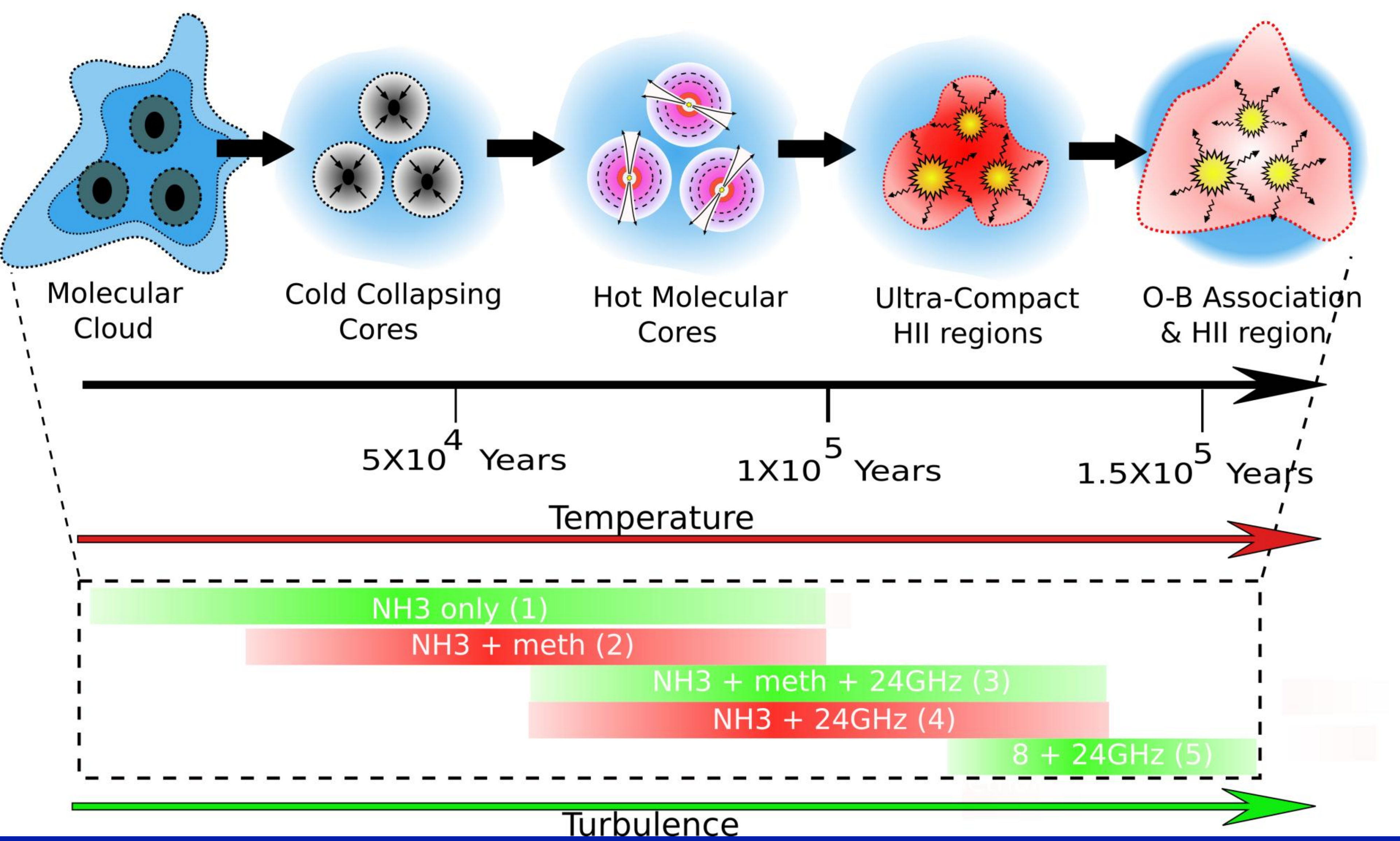
So, how do stars with M_{*}>$10M_{\odot}$ form?

- Accretion:
  - Need to reduce effective σ, e.g., by having very high mass accretion rates (McKee & Tan 2002).
  - Reduce the effective luminosity by making the radiation field anisotropic.
- Form massive stars through collisions of intermediate-mass stars in clusters (Bally & Zinnecker 2005)
  - Problem with cross section for coalescence.
  - Observational consequences of such collisions?

Other differences between low- and high-mass star formation

- Physical properties of clouds undergoing low- and high-mass star formation are different:
  - Massive SF: clouds are warmer, larger, more massive, mainly located in spiral arms; high mass stars form in clusters and associations
  - Low-mass SF: form in a cooler population of clouds throughout the Galactic disk, as well as GMCs, not necessarily in clusters
- Massive protostars luminous but rare and remote
- Ionization phenomena associated with massive SF: UCHII regions
- Different environments observed has led to the suggestion that different mechanisms (or modes) may apply to low- and high-mass SF

A similar cartoon than for low mass stars…



Credit: C. Purcell

Physical characteristics of the regions harboring young massive stars.

Several surveys of :

- Molecular line emission in high density tracers

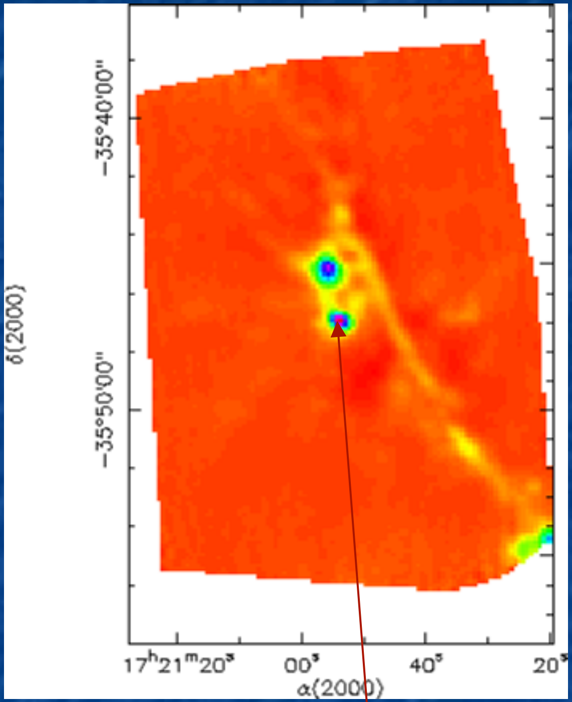
Plume et al. 1992
Juvela 1996
Plume et al. 1997
Shirley et al. 2003
Fontani et al. 2005

- Dust continuum emission

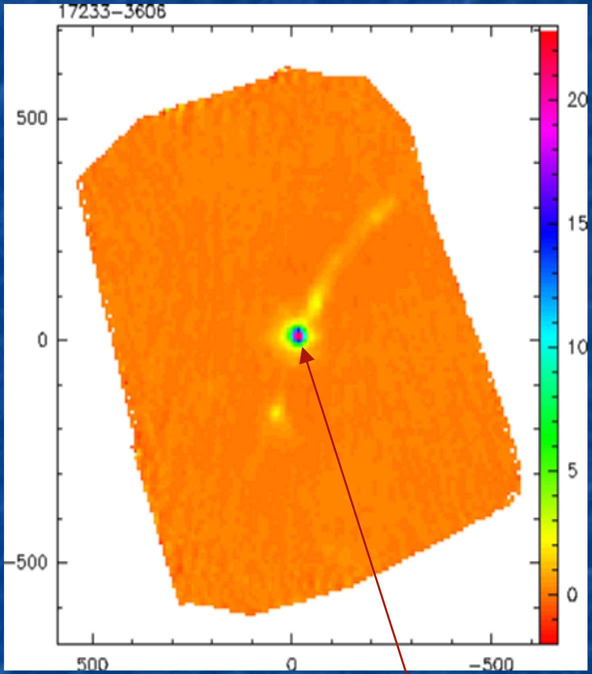
Beuther at al. 2002
Mueller et al. 2002
Williams et al. 2004
Faundez et al. 2004
Hill et al. 2005

have shown that HMYSO´s are found within molecular structures with distinctive physical parameters.

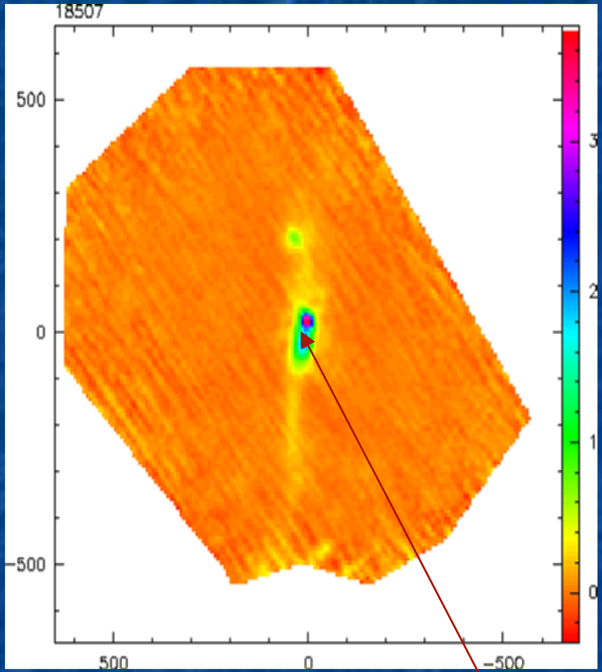
Survey of dust continuum emission at 1.2mm towards ~150 luminous IRAS sources with colours of UC HII regions and CS emission taken from Bronfman et al (1996).



IRAS 17175-3544



IRAS 17233-3606

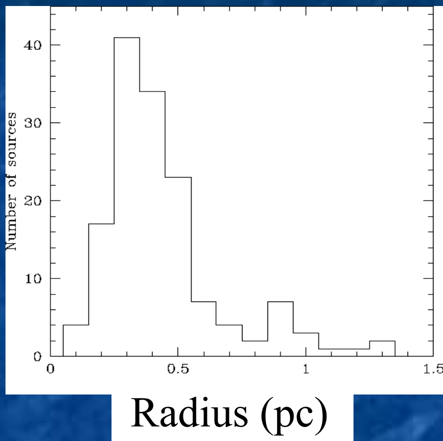


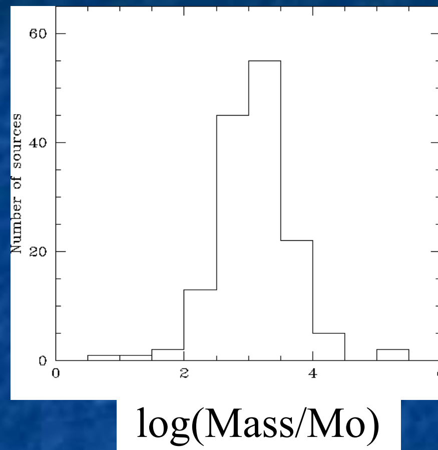
IRAS 18507+0110

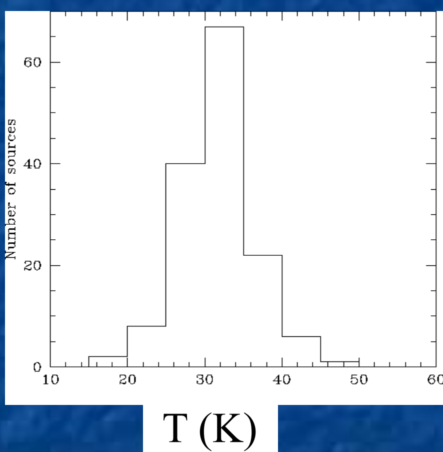
Faúndez et al. (2004)

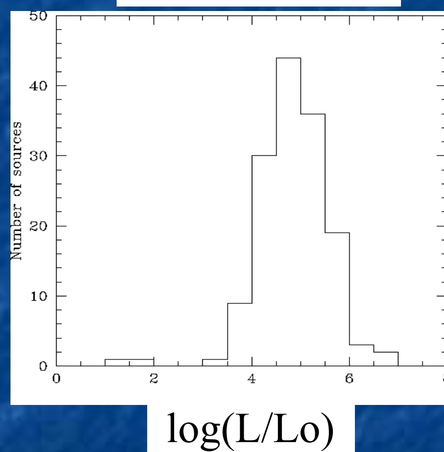
- ✧100 % detection rate: all IRAS sources are associated with compact dust sources (at the resolution of 24”).

✧ Parameters of compact dust sources









Average	Parameters from molecular lines CS(5-4) observ. of 150 MSFRs associated with H_2O masers
$R \sim 0.4$ pc	$R \sim 0.5$ pc
$M_d \sim 5\times10^3\ M_\odot$	$M_{vir} \sim 4\times10^3\ M_\odot$
$n(H_2) \sim 2\times10^5\ cm^{-3}$	$n(H_2) \sim 8\times10^5\ cm^{-3}$
$N(H_2) \sim 5\times10^{23}\ cm^{-2}$	$N(H_2) \sim 2\times10^{24}\ cm^{-2}$
$T_d \sim 32$ K	$\Delta v \sim 6\ km\ s^{-1}$
Faúndez et al. (2004)	Plume et al. (1997)

⇨ High-mass stars are formed in regions with distinct physical parameters: *Massive and dense clumps*

One observational approach has been the search for disks and jets in massive forming stars.

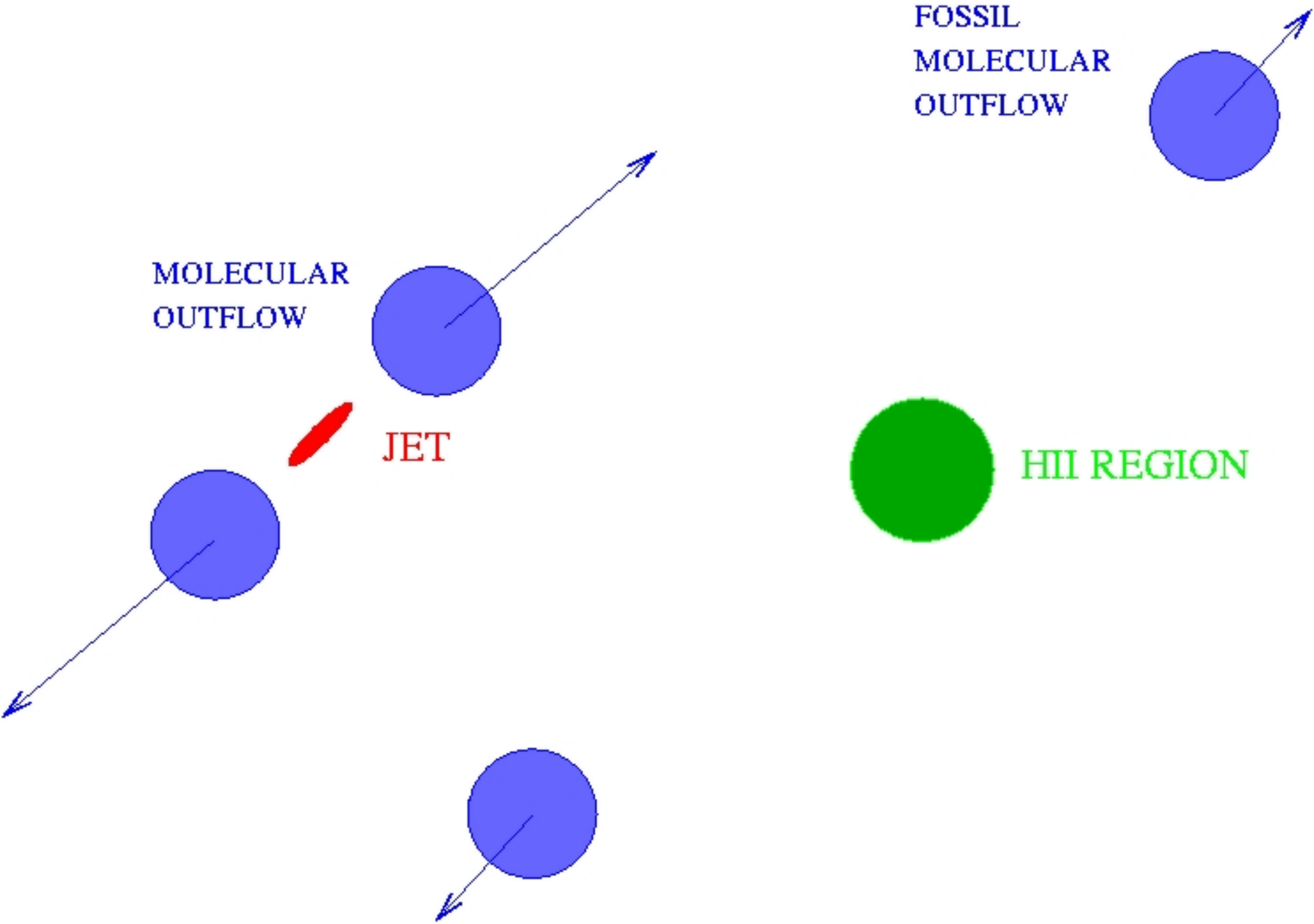
- However, only of a handful of sources have been studied in detail.

Why are thermal jets rare to find in association with high mass protostars?

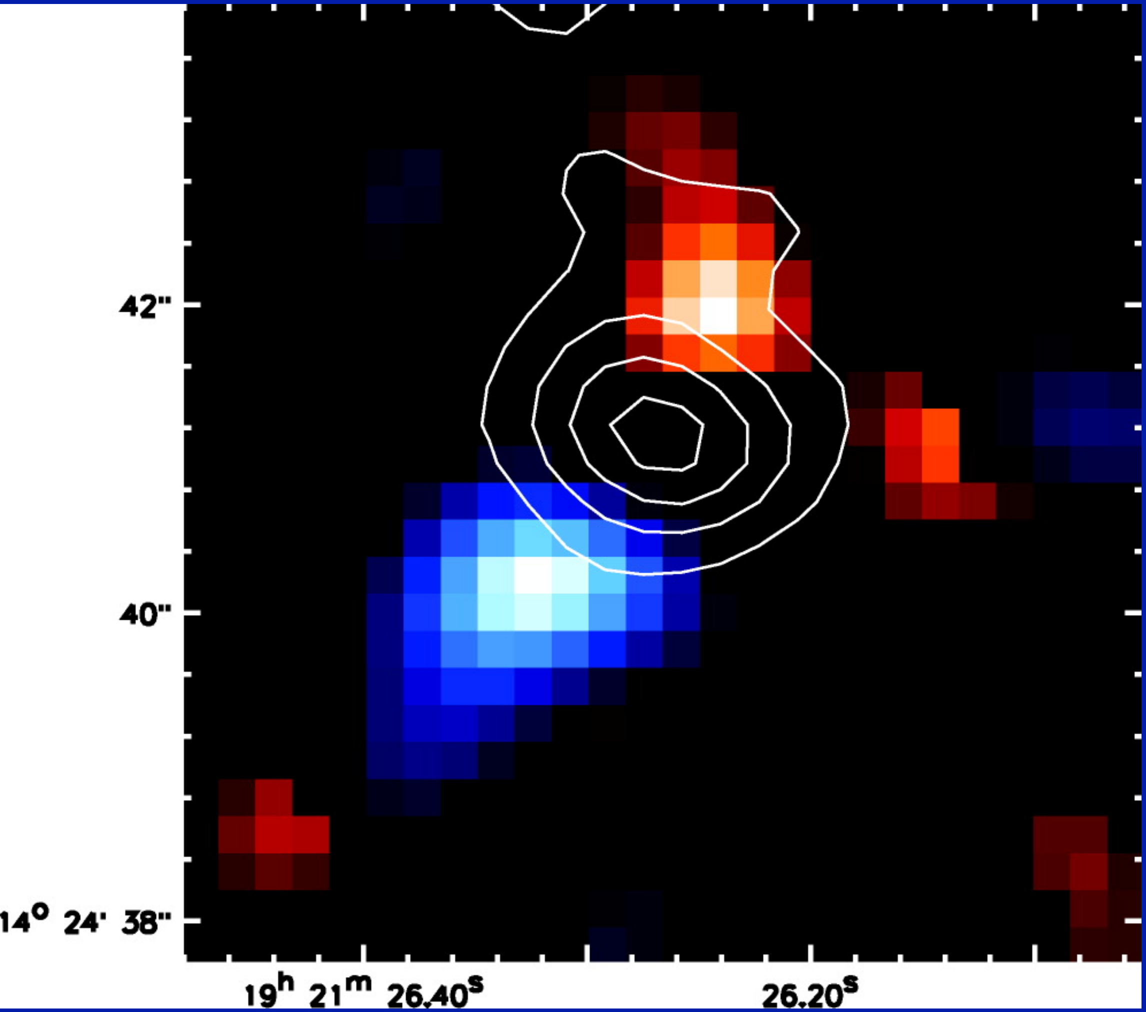
- Different formation mechanism?
- Confusion from bright HII regions in region?
- Stellar multiplicity a serious problem.
- Molecular outflows (large scale) are, however, relatively frequent. Are we seeing “fossil” molecular outflows?

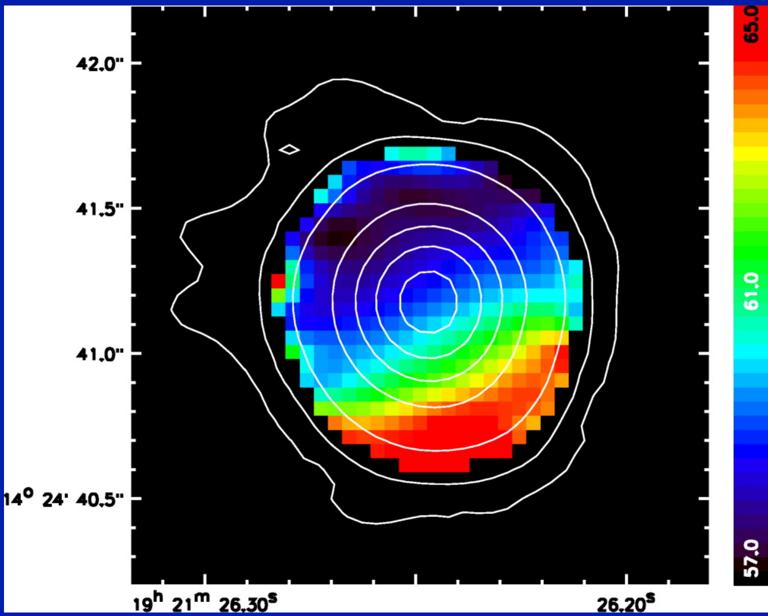
“Fossil” molecular outflows?

- Bipolar outflows in low mass protostars have dynamic ages of 10^4 years, much shorter than the K-H time of the jet/disk stage of 10^6 years.
- In contrast, bipolar outflows in high mass protostar have dynamic ages of 10^5 years, longer than the K-H time of the jet/disk stage of 10^4 years.
- That is, in high mass protostars, the jet may turn off and the large scale outflow will still persist as a fossil for a relatively long time.


FOSSIL
MOLECULAR
OUTFLOW
MOLECULAR
OUTFLOW
JET
HII REGION

W51e2: An outflow with an HCHII region (Keto and Klassen (2009)





Color: High velocity CO (2-1)

Contours: 1 mm emission

H53alpha extent (contours) and velocity gradient (color) of HCHII at center.

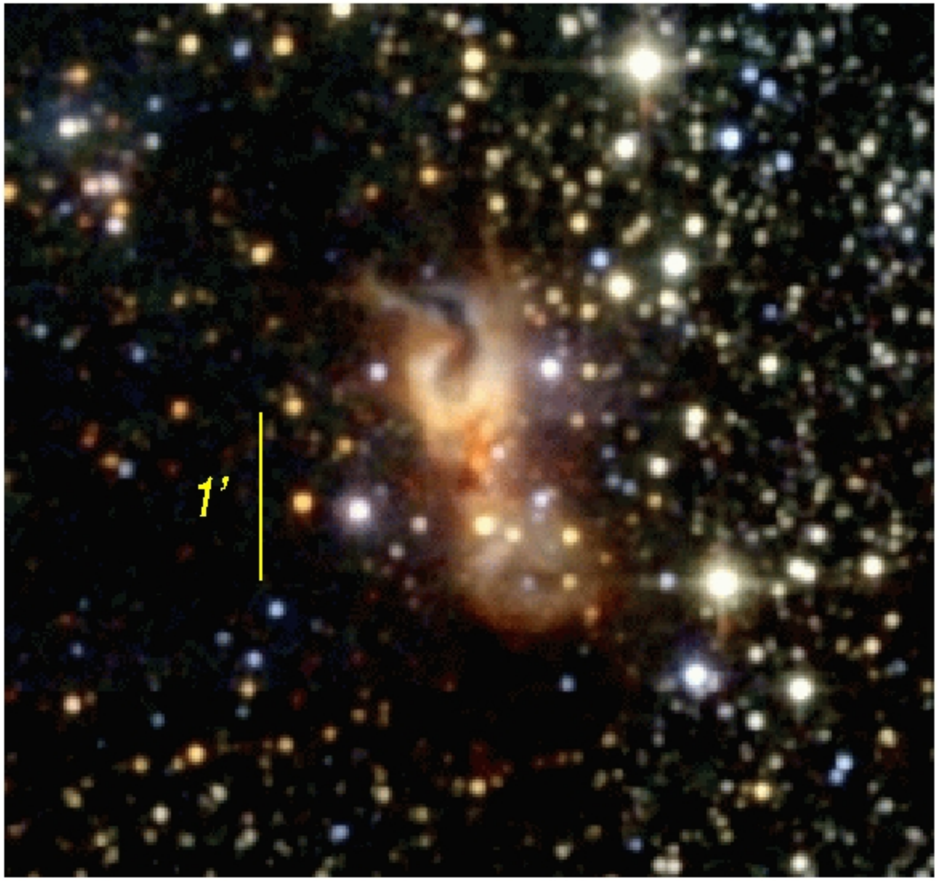
HH 80-81 (GGD27) in L291 dark cloud

Distance 1.7 kpc
(Rodríguez et al. 1980),

Luminosity: 2 x 10^4 L_{Sol}

Star: B0.5 ZAMS

Two Micron All Sky Survey



HH 80-81 also known as GGD 27 (Gyulbudaghian et al. 1978)

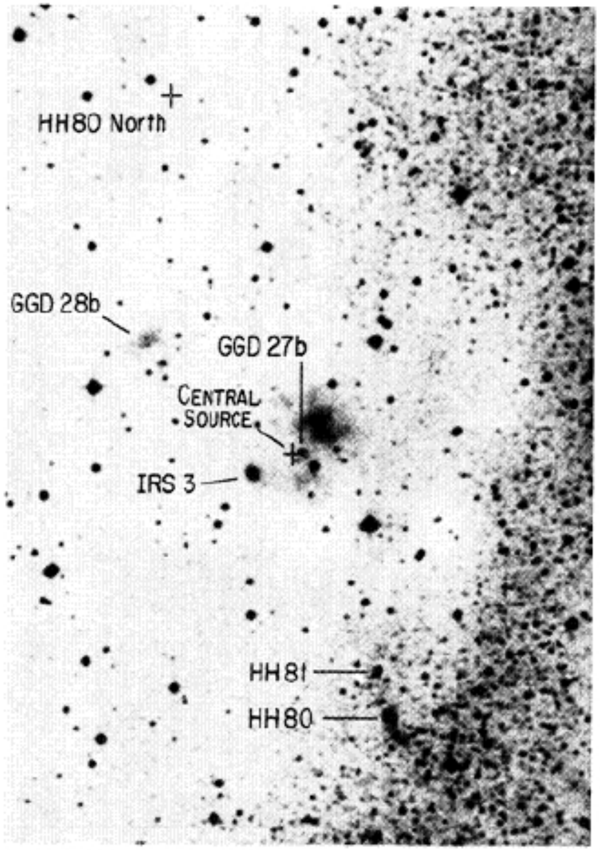


FIG. 1a

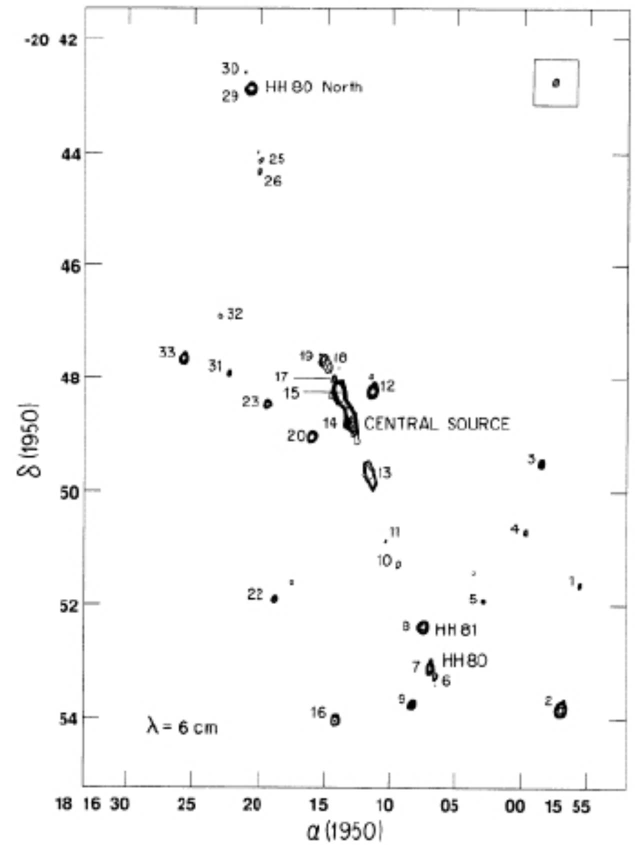
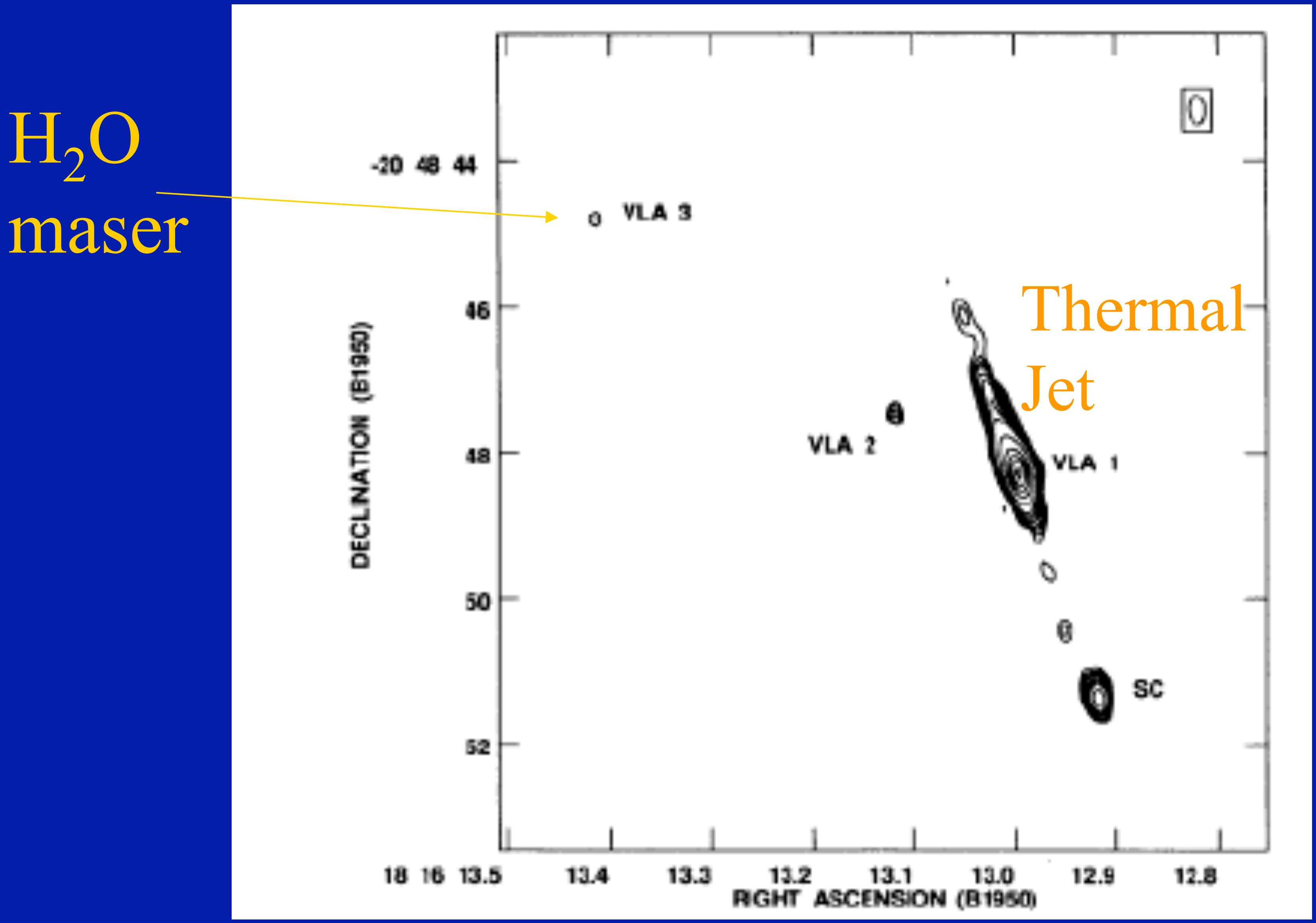


FIG. 1b

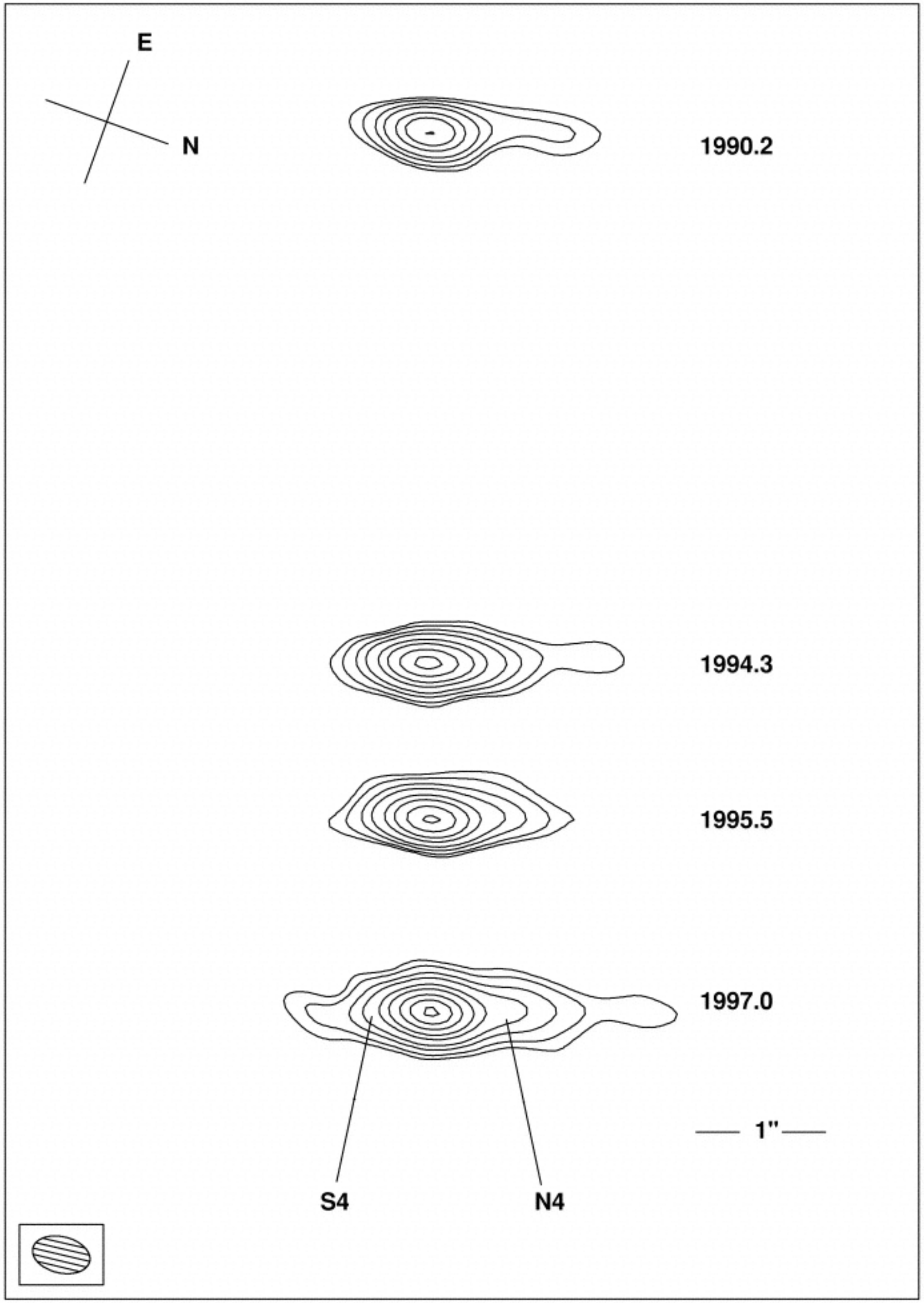
FIG. 1.—(*a*) The region of HH 80–81 and GGD 27–28 is seen in this figure from a deep red ESO Schmidt plate. The various objects in the region are identified. GGD 27b is a reflection nebula a few arcseconds from the central source. IRS 3 coincides with radio object 20. The crosses mark the positions of HH 80 North and the central exciting source, objects with no optical counterpart. North is up, and east is left. (*b*) Composite VLA 6 cm map of the HH 80–81 system made with natural weighting, showing the same region as (*a*). The two fields combined are not primary beam response-corrected. The northern counterpart of HH 80–81 is clearly visible at the top of the map. Note also the presence of small condensations between the central source and the HH objects following a slightly sinusoidal path. This can be interpreted as evidence of jet precession. Contours are −3, 3, 4, 5, 7, 10, 20, 50, and 100 times 20 μJy per beam, the rms noise of the individual maps. The beam size is 7".0 × 4".9 with position angle of −18°.

Highly collimated jet with extension of 5.3 pc (11′)

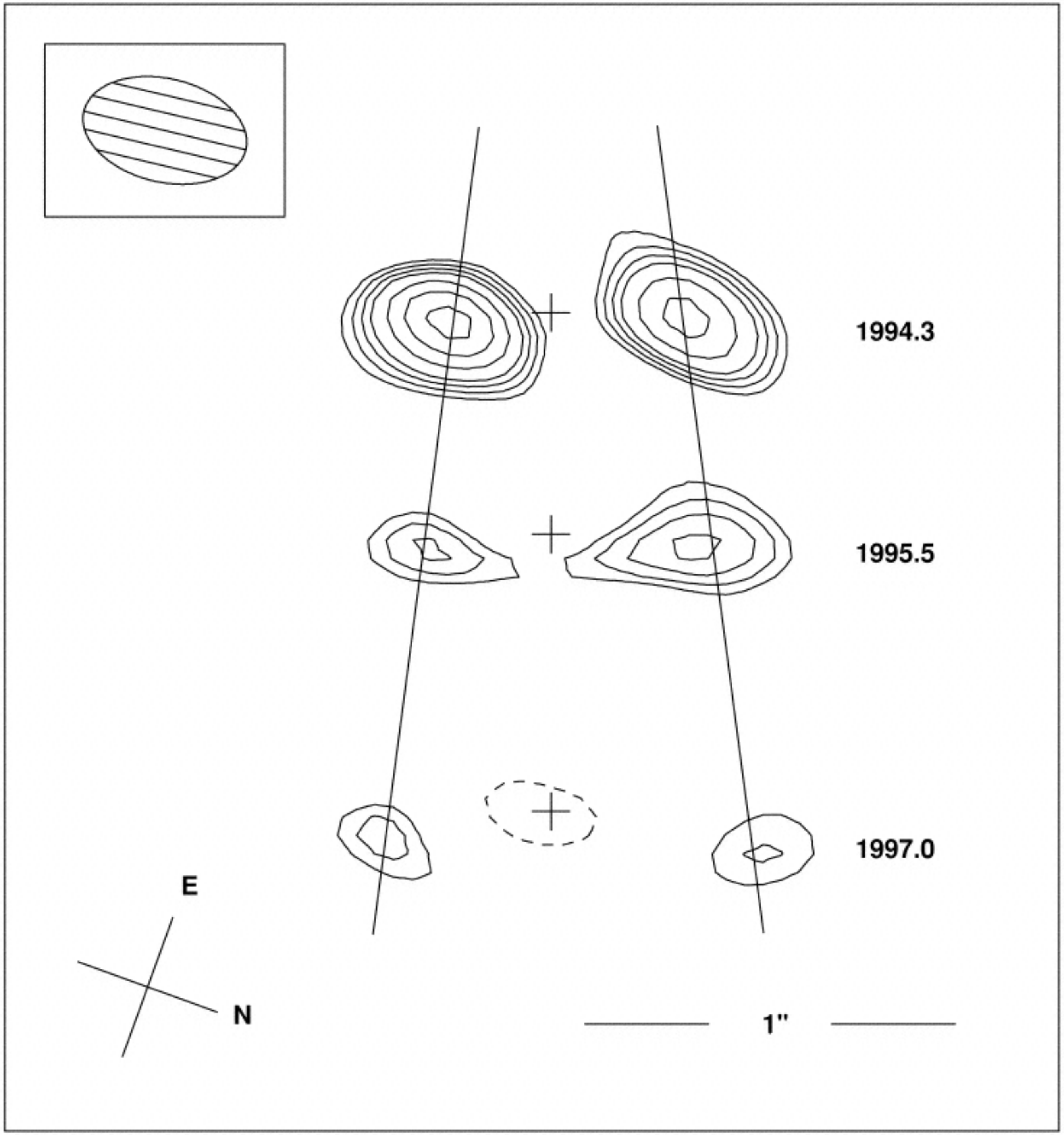
(Martí, Rodríguez & Reipurth 1993)



Gómez et al. 1995



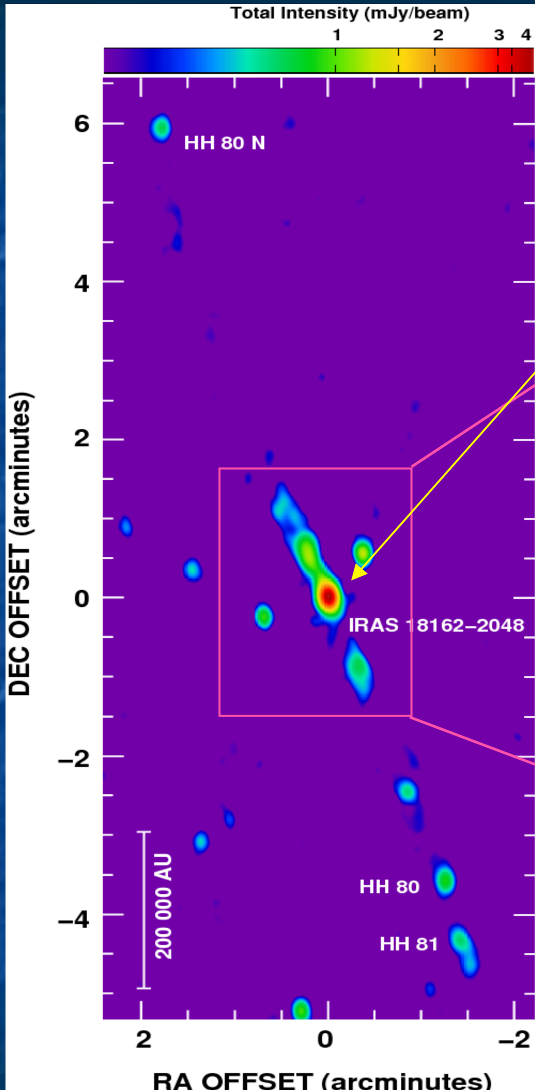
Marti et al. (1998) analyzed the thermal jet over several years.



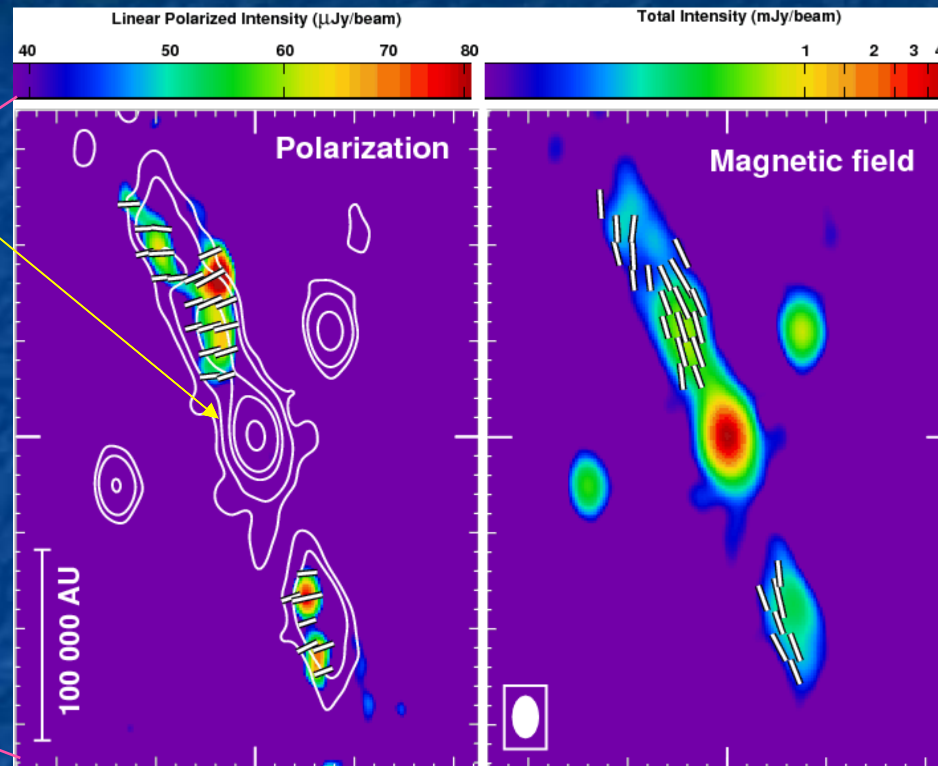
Derive velocities for knots of 500 km/s.

- IRAS 18162-2048 HH 80-81

Carrasco et al. (2010) measured polarization in the central region.



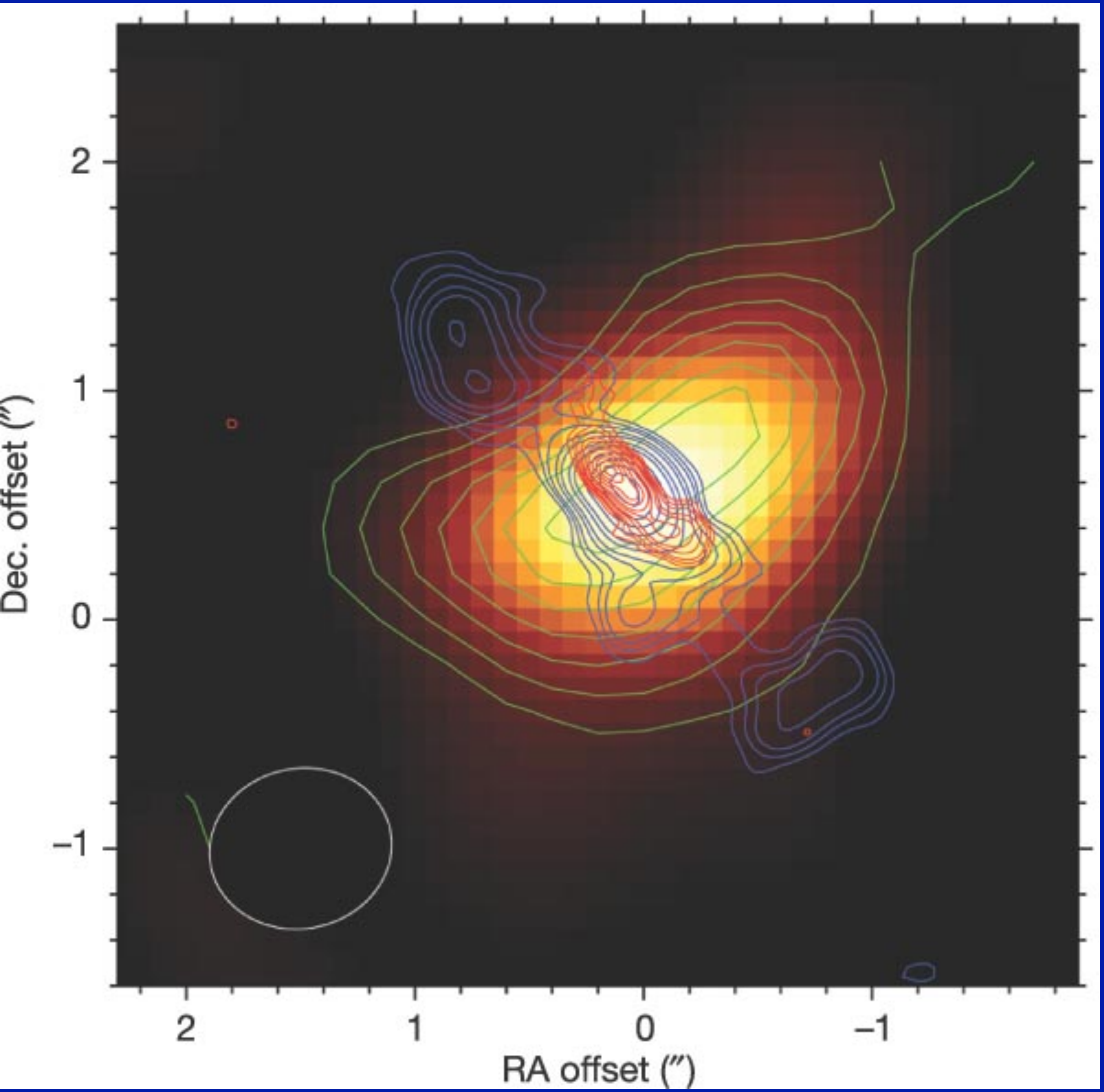
Thermal jet



Highly collimated jet
$L = 5.3$ pc (11′)

Marti et al. 1993

- Degree of polarization: 10-30%
- Polarization vectors ⊥ jet axis
  ⇨ B in the direction of the jet
  $B \approx 0.2$ mGauss



One of the best cases is Cep A HW2 (Patel et al. 2005)

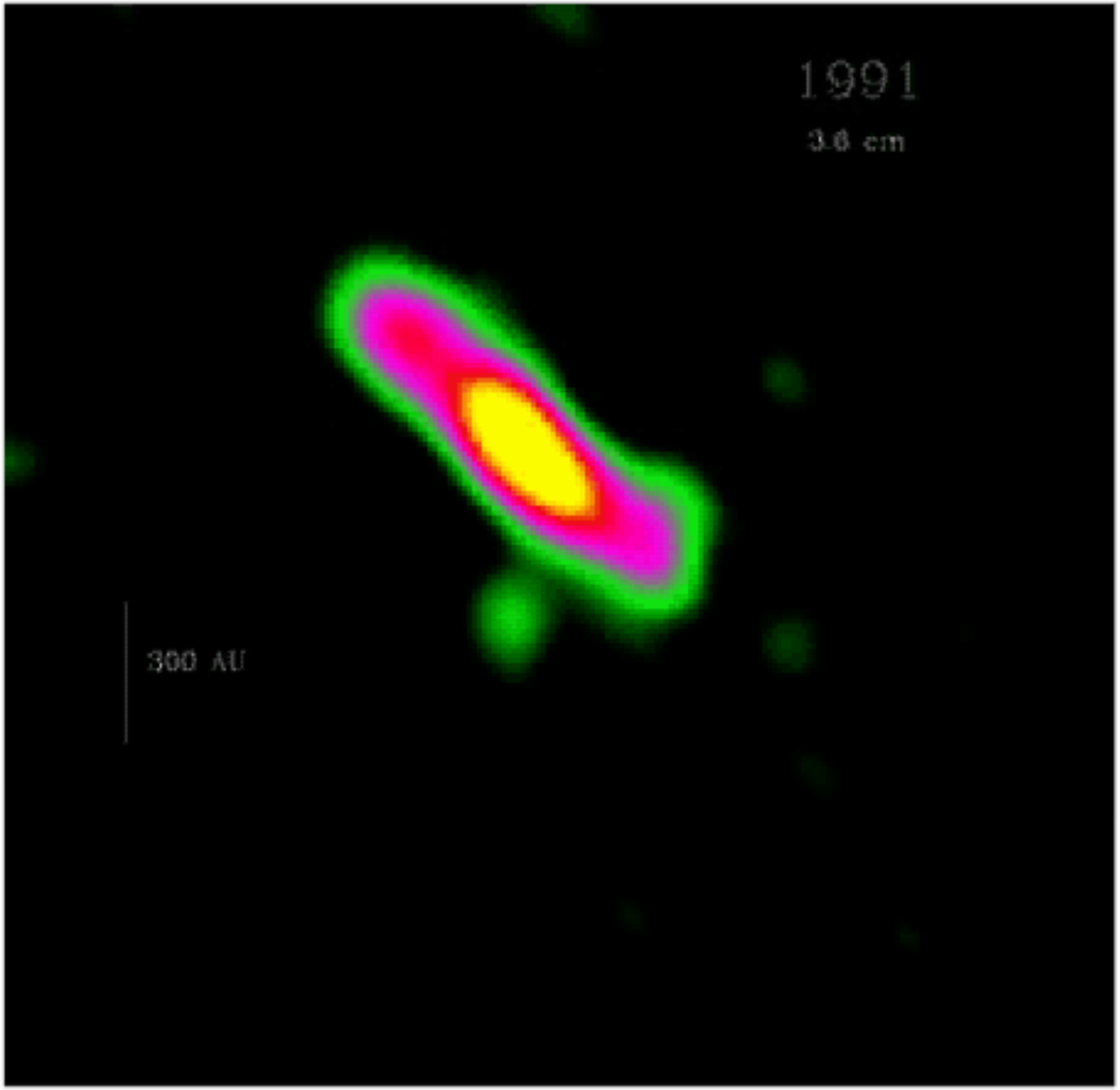
Dust (colors) and molecular (CH3CN, in green contours) emissions perpendicular to bipolar jet.

Radius of disk = 330 AU

Mass of disk = 1-8 M_{SUN}

Mass of star = 15 M_{SUN}

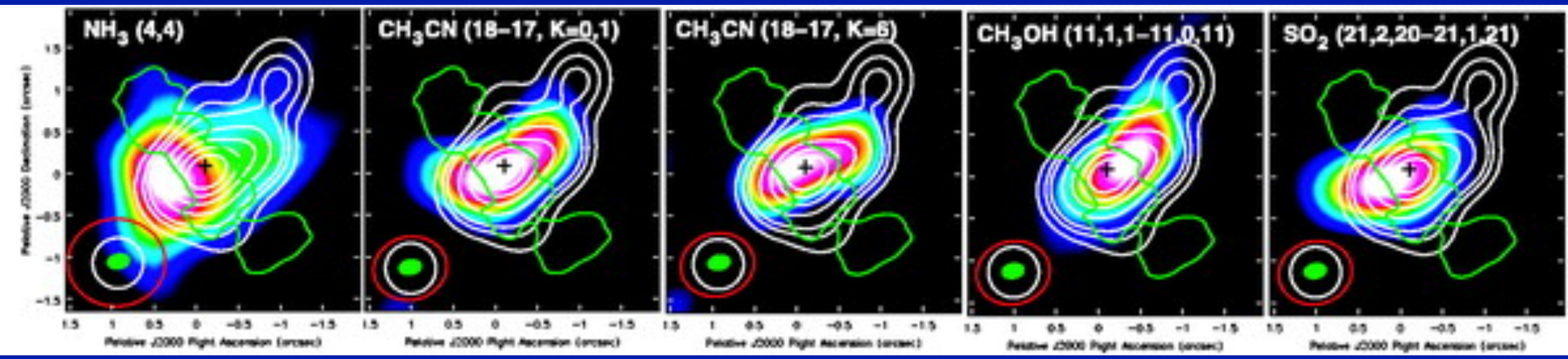
SMA and VLA data



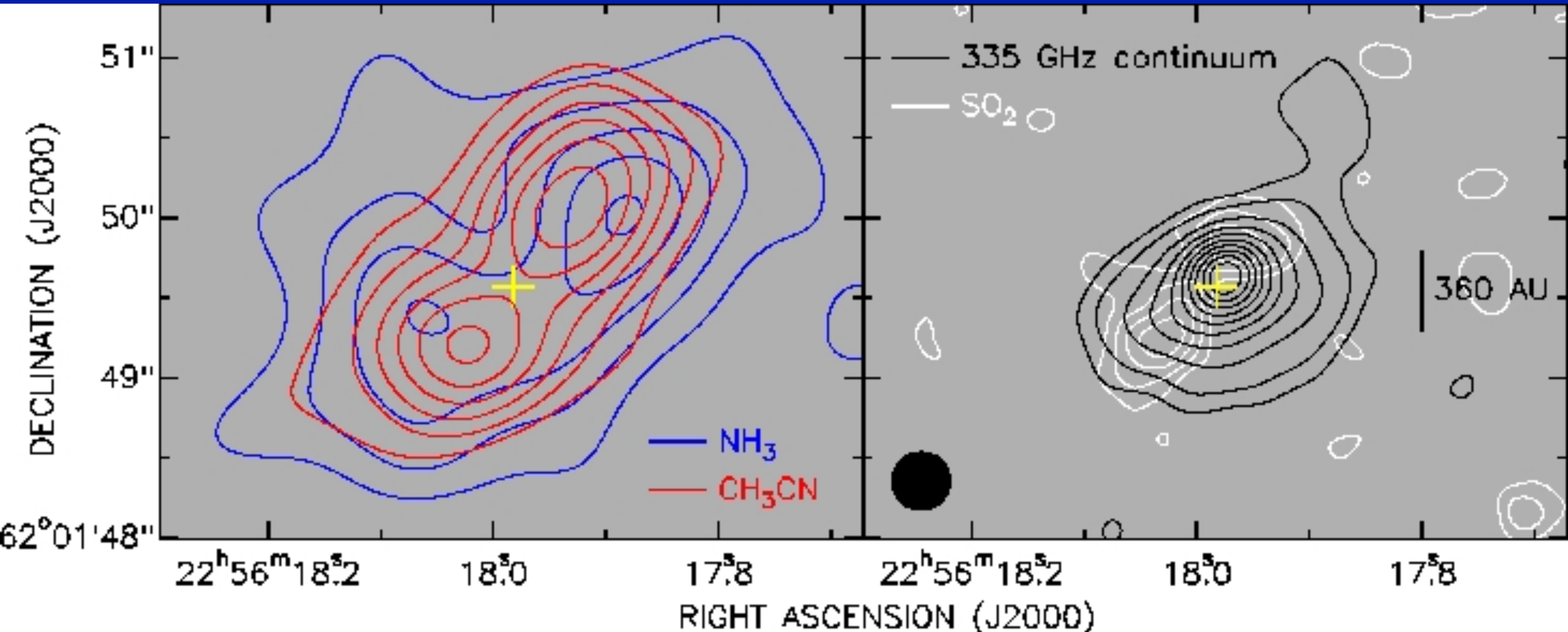
Sequence of images of radio jet at 3.6 cm
Curiel et al. (2006)

Disk or multiple condensations?

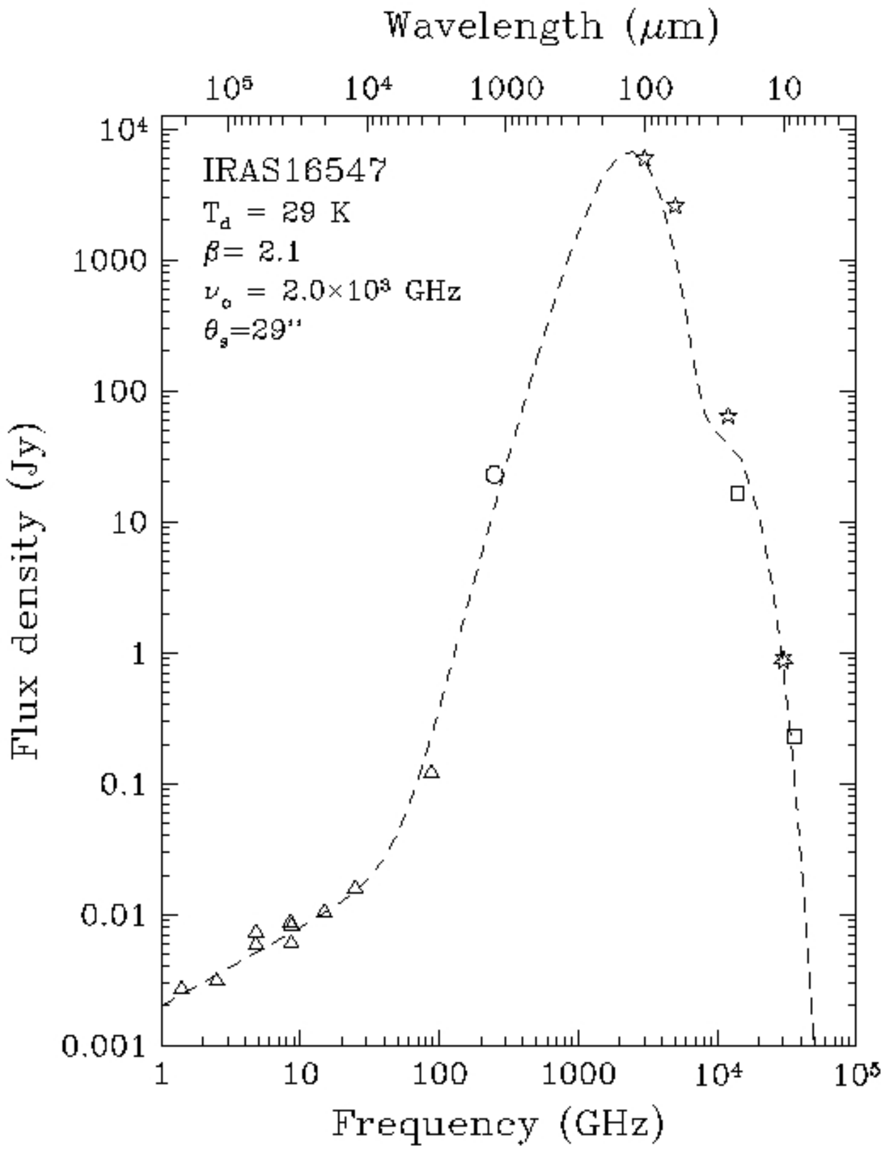
- Brogan et al. (2007) and Comito et al. (2007) argue that not a disk but multiple condensations:



Outflowing 3.6 cm knots and 875 microns SMA image also shown.

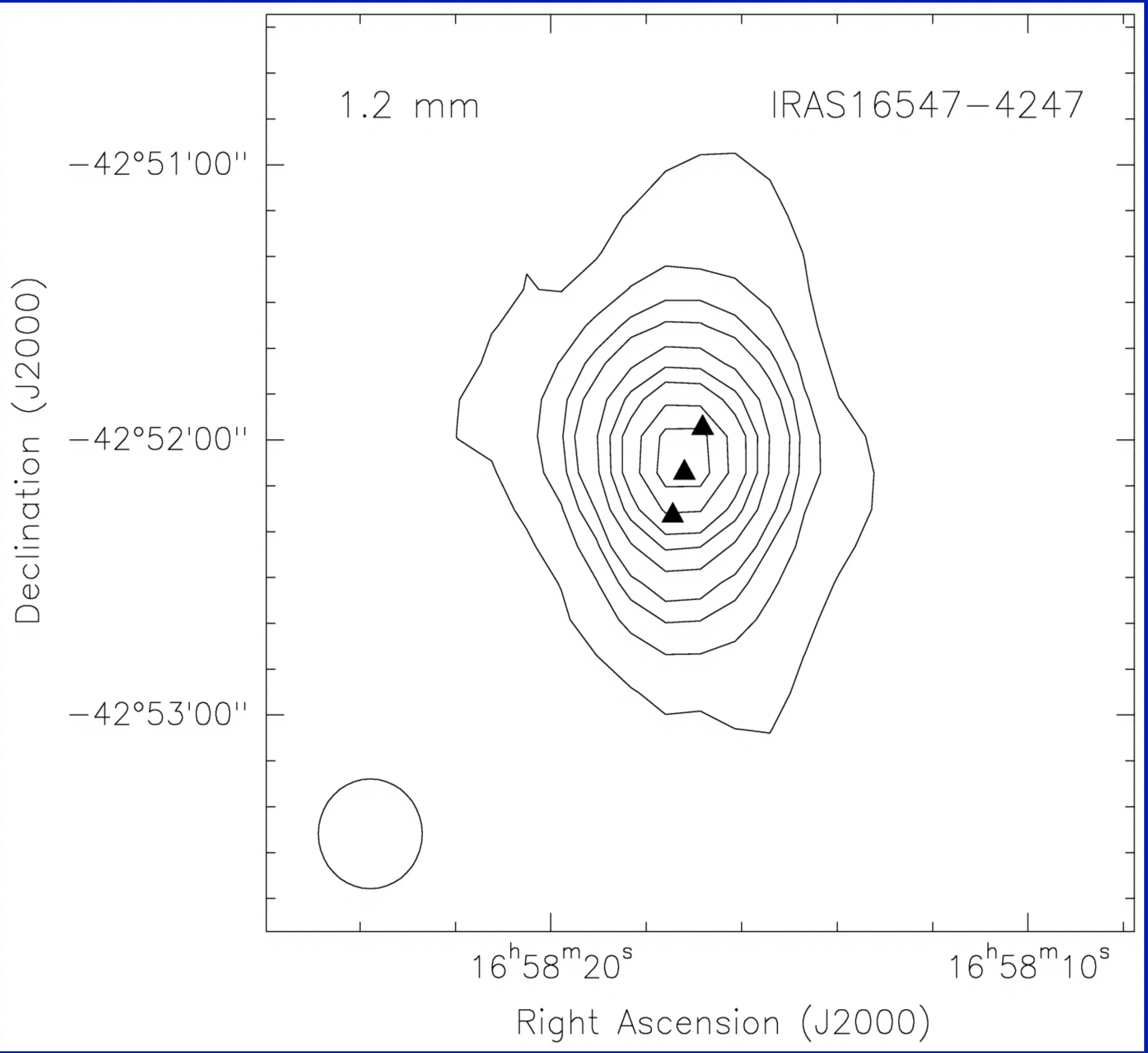


Torrelles et al. (2007) argue for a continuous structure that can be imaged with various tracers.



IRAS 16457-4742

At a distance of 2.9 kpc, it has a bolometric luminosity of 62,000 solar luminosities, equivalent to an O8 ZAMS star.

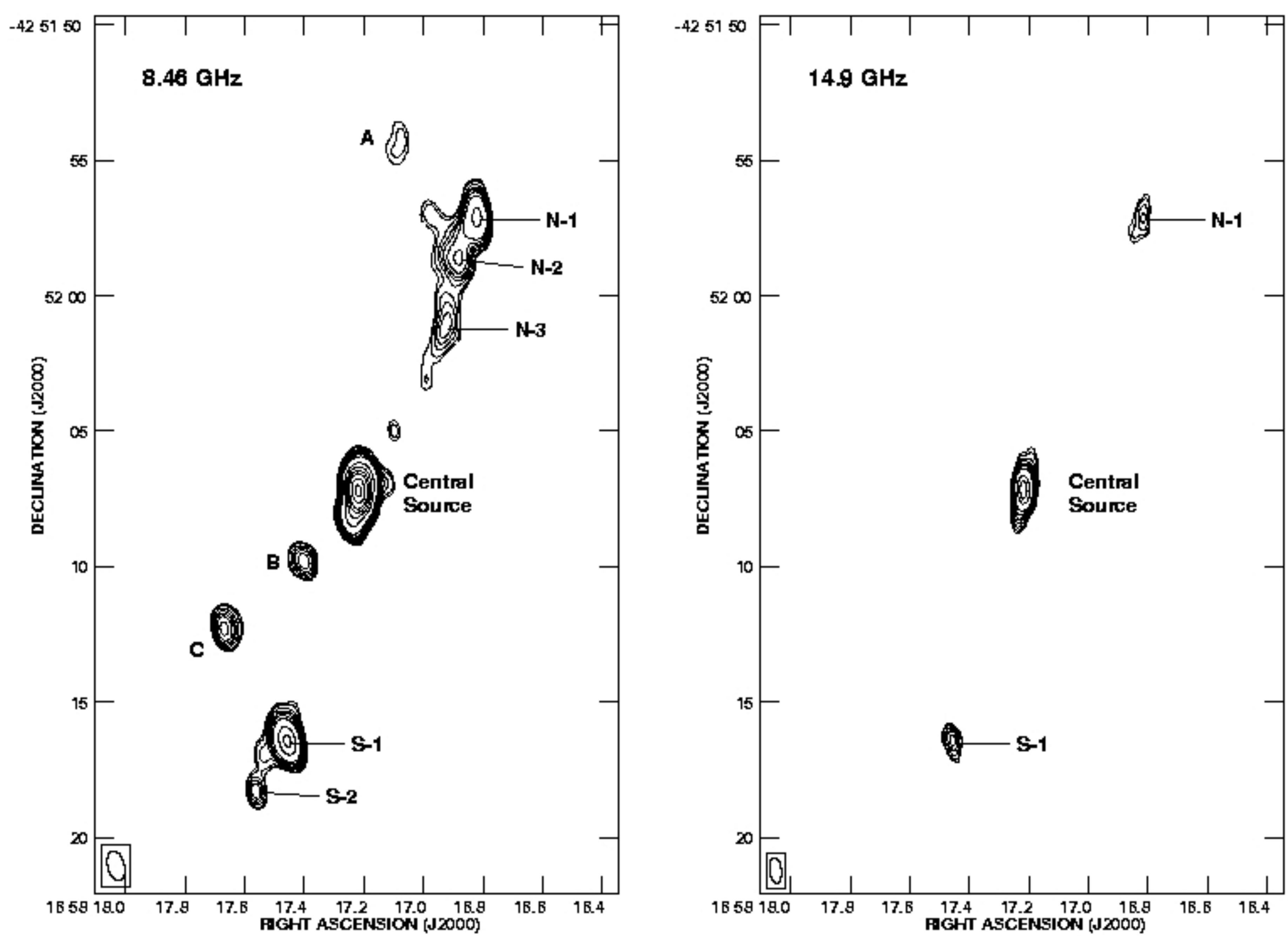


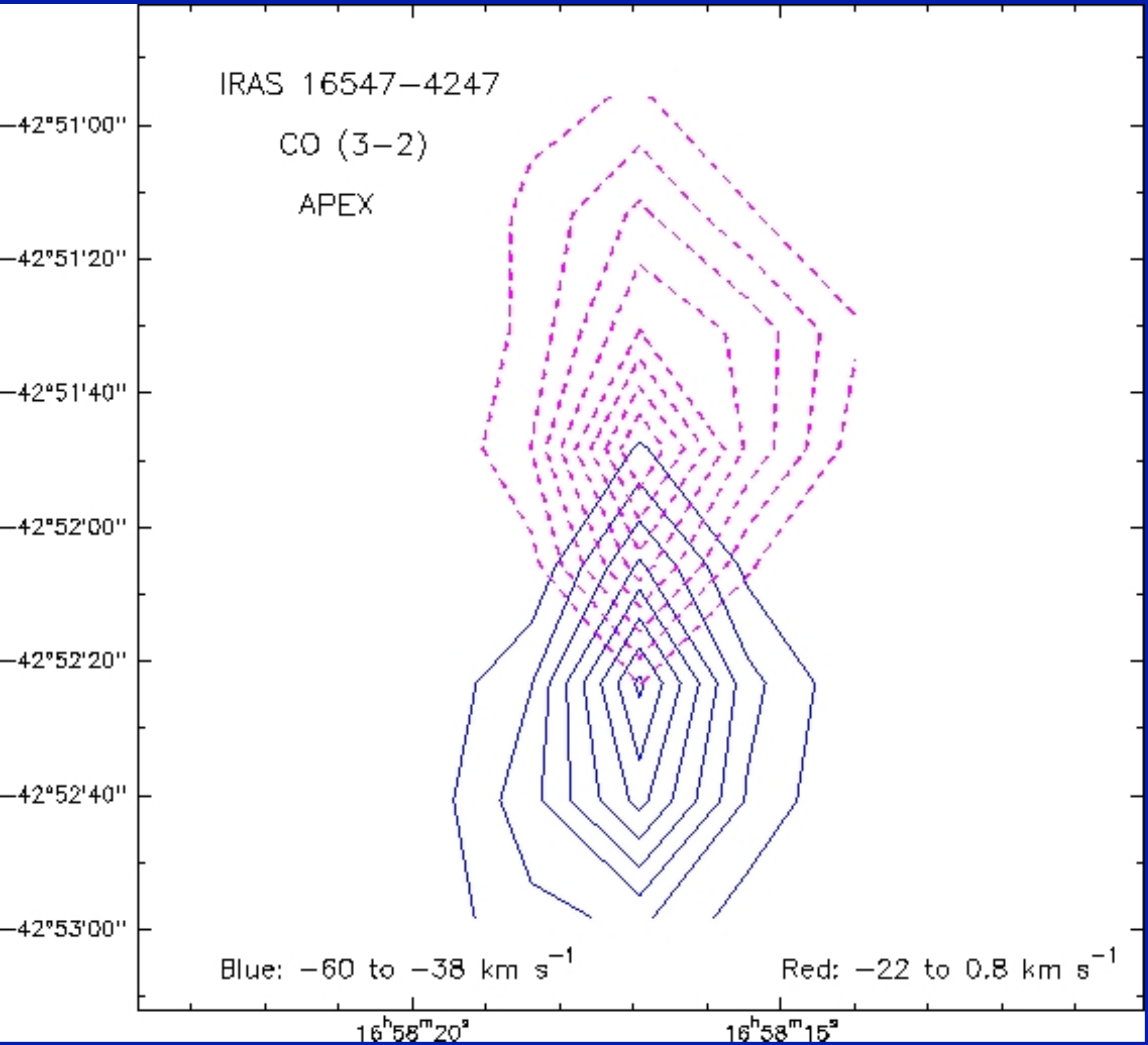
Garay et al. (2003) found millimeter continuum emission (dust) and a triple source in the centimeter range.

Core has 1,000 solar masses.

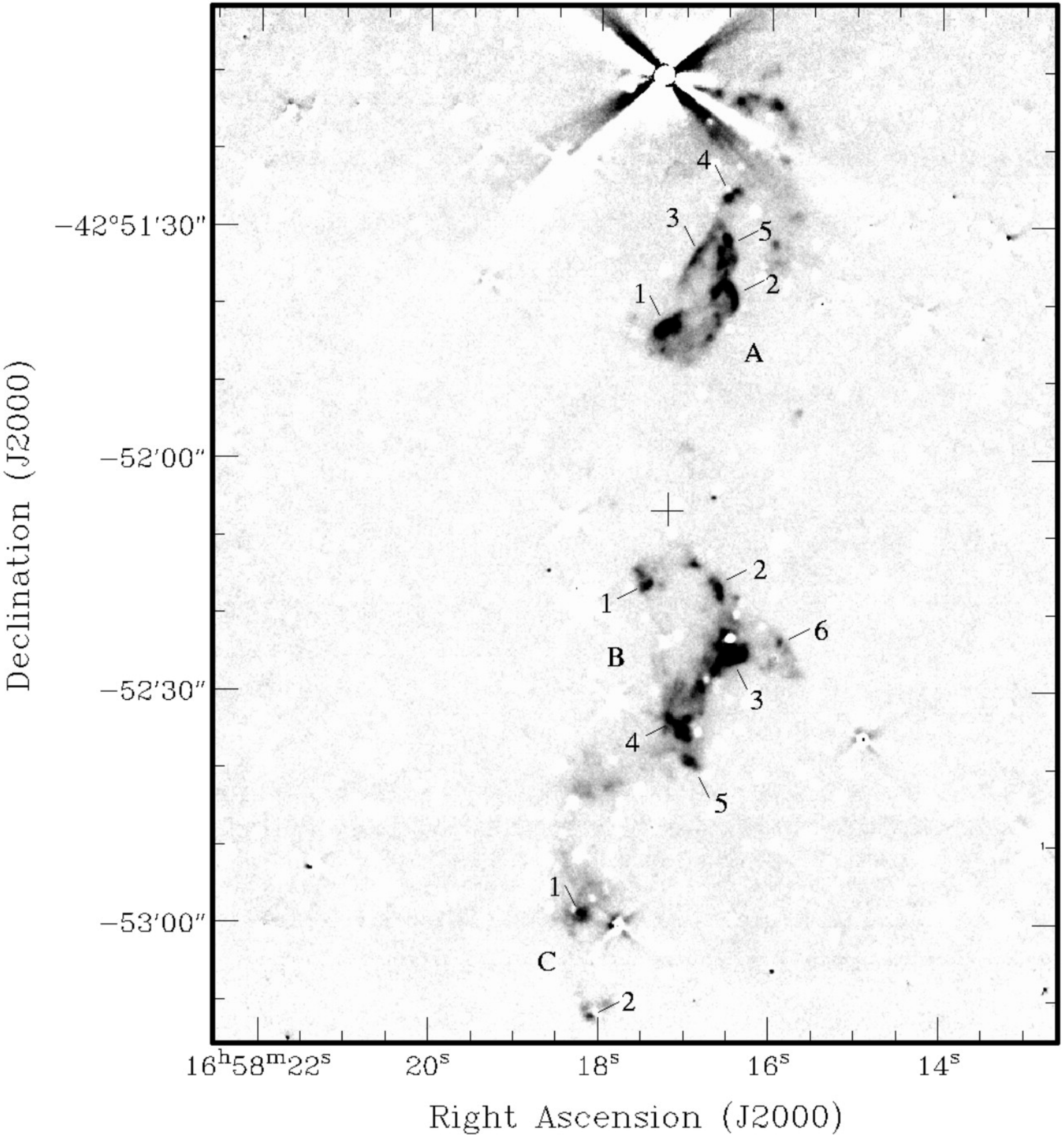
Data from SEST (mm) and ATCA (cm)

VLA images of IRAS 16547-4247





The outflow carries about 100 solar masses of gas (most from ambient cloud) and has characteristics of being driven by a very luminous object.

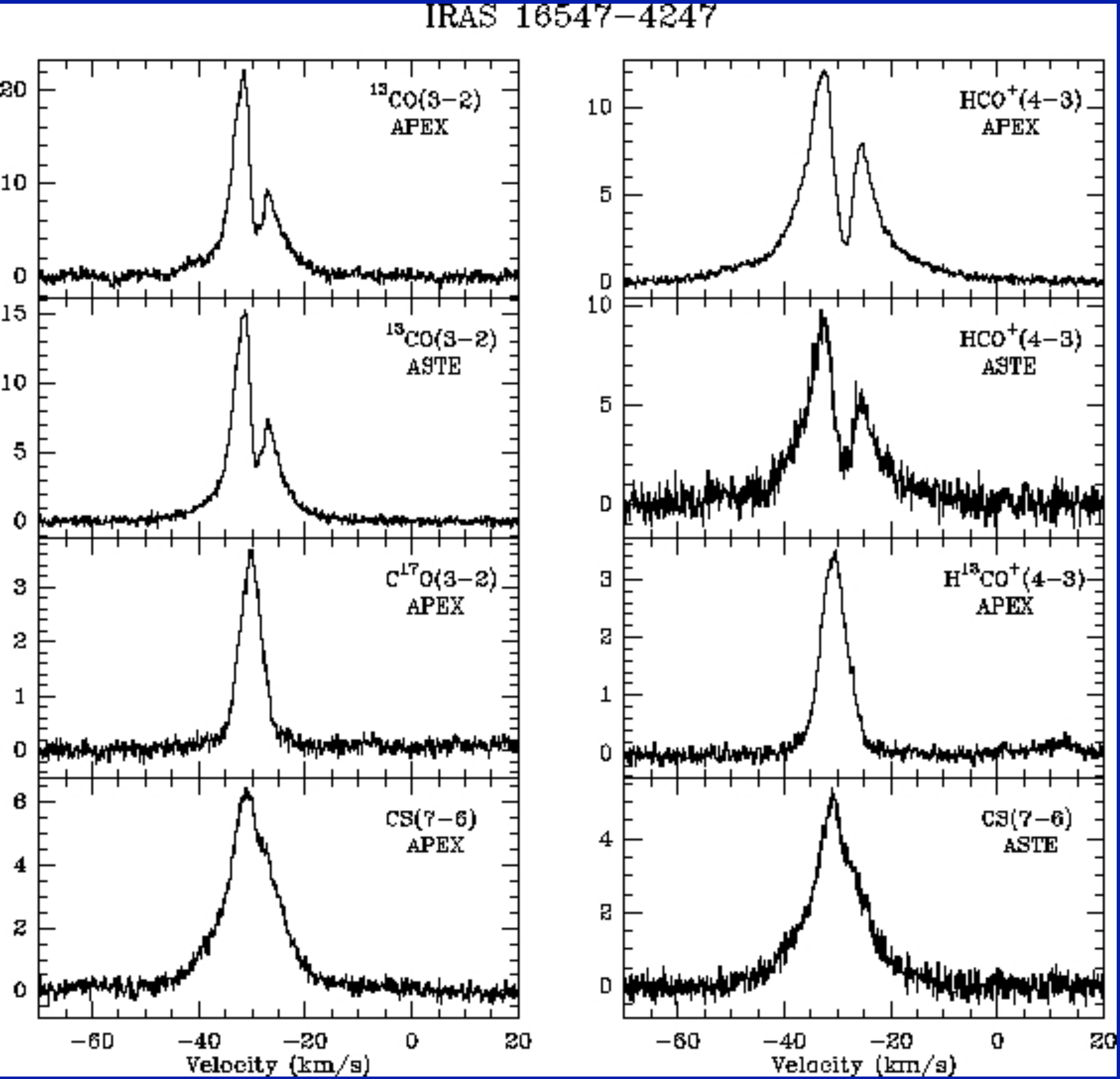


Molecular hydrogen (2.12 micronss) tracing the bipolar outflow (Brooks et al. 2003)

Data from ISAAC in the VLT

OK, so we believe we have a jet

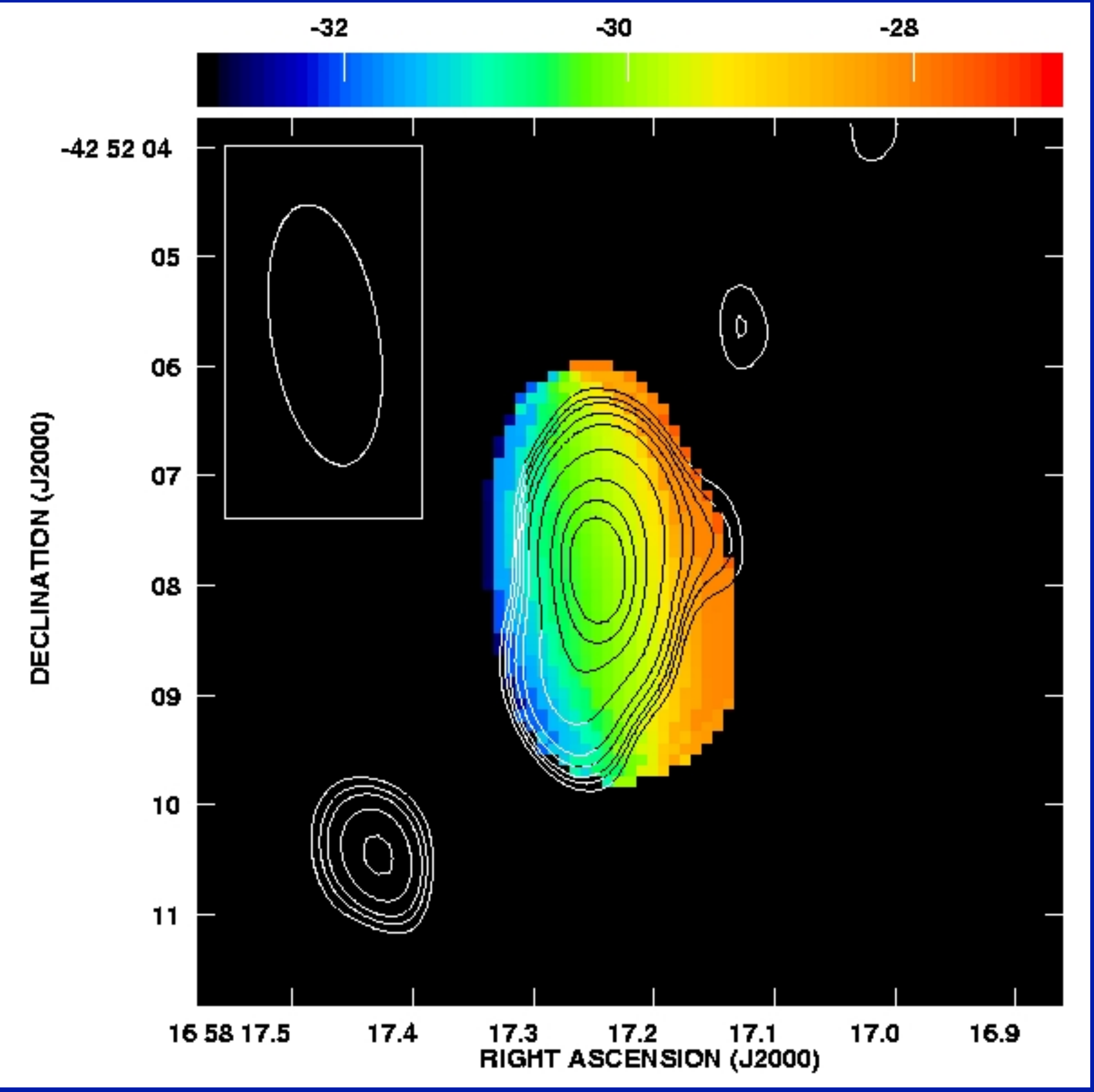
- What about infalling gas and in particular, a disk?



Some of the line emission from single dish (20”) observations show profiles characteristic of large scale infall.

You need much larger angular resolution to detect a disk.

The SubMillimeter Array



Velocity gradient in SO2 (colors) suggests total mass of 20 to 40 solar masses and a radius of 1,000 AU for the disk (Franco-Hernandez et al. 2007).

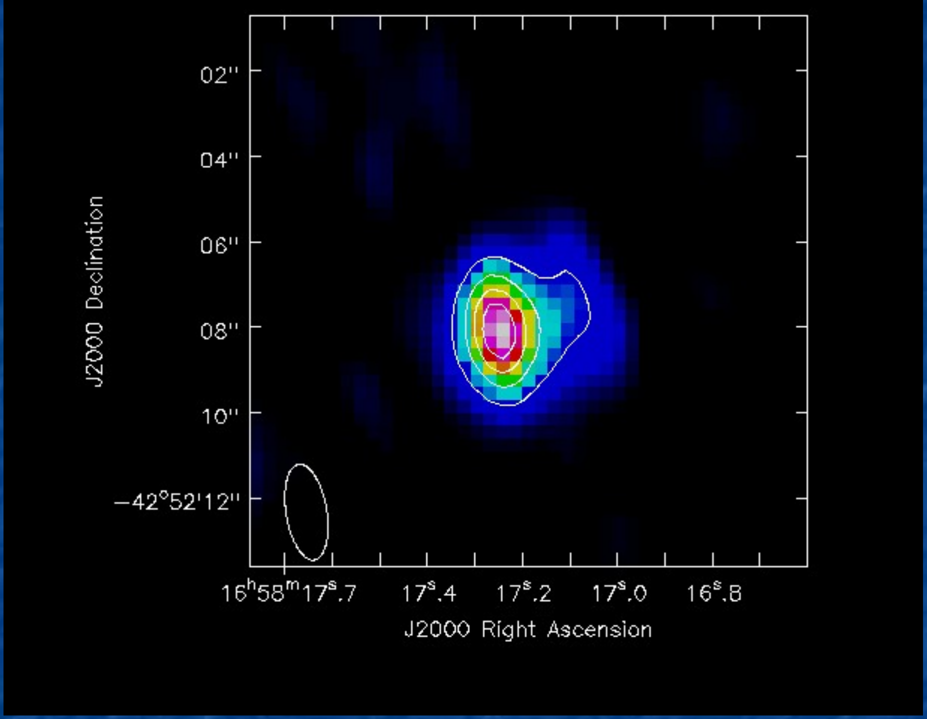
Most massive young star known with jets, disk, and large scale infall.

④A protoplanetary disk around a massive protostar

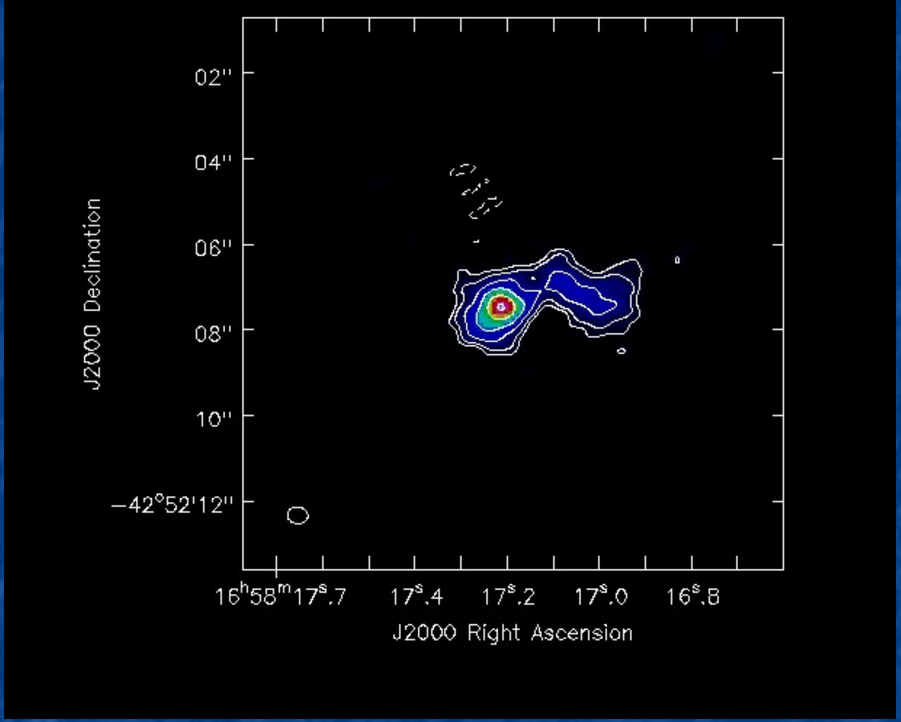
Franco-Hernandez et al. (2013)

IRAS 16547-4247

SMA 230 GHz continuum



ALMA 345 GHz continuum

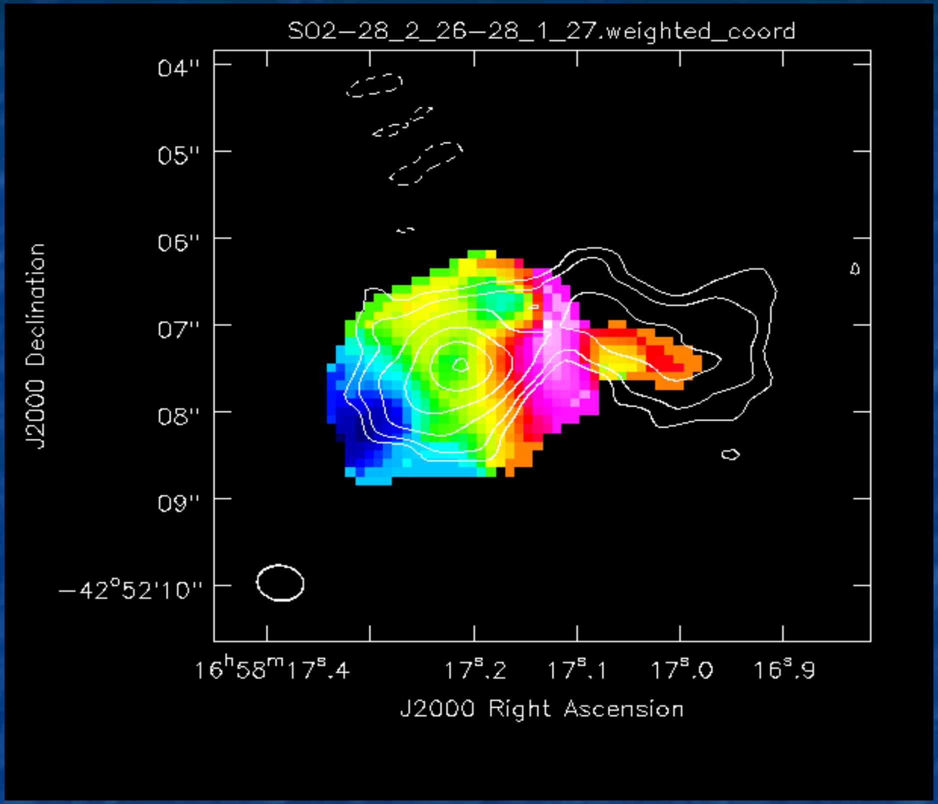


Franco-Hernandez et al. 2009

Is it a disk?

Which is the velocity structure?

Velocity field from SO_2 observations:

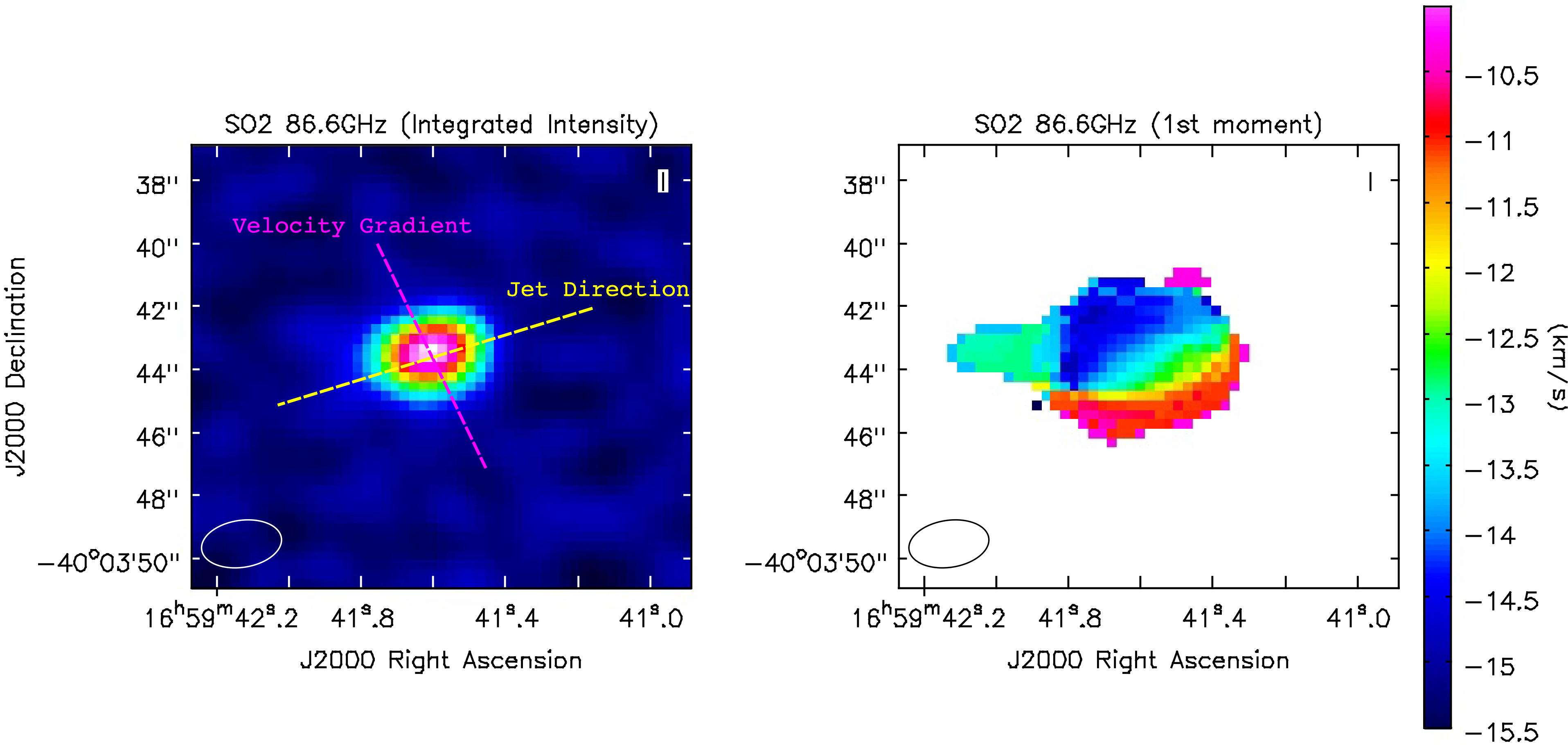


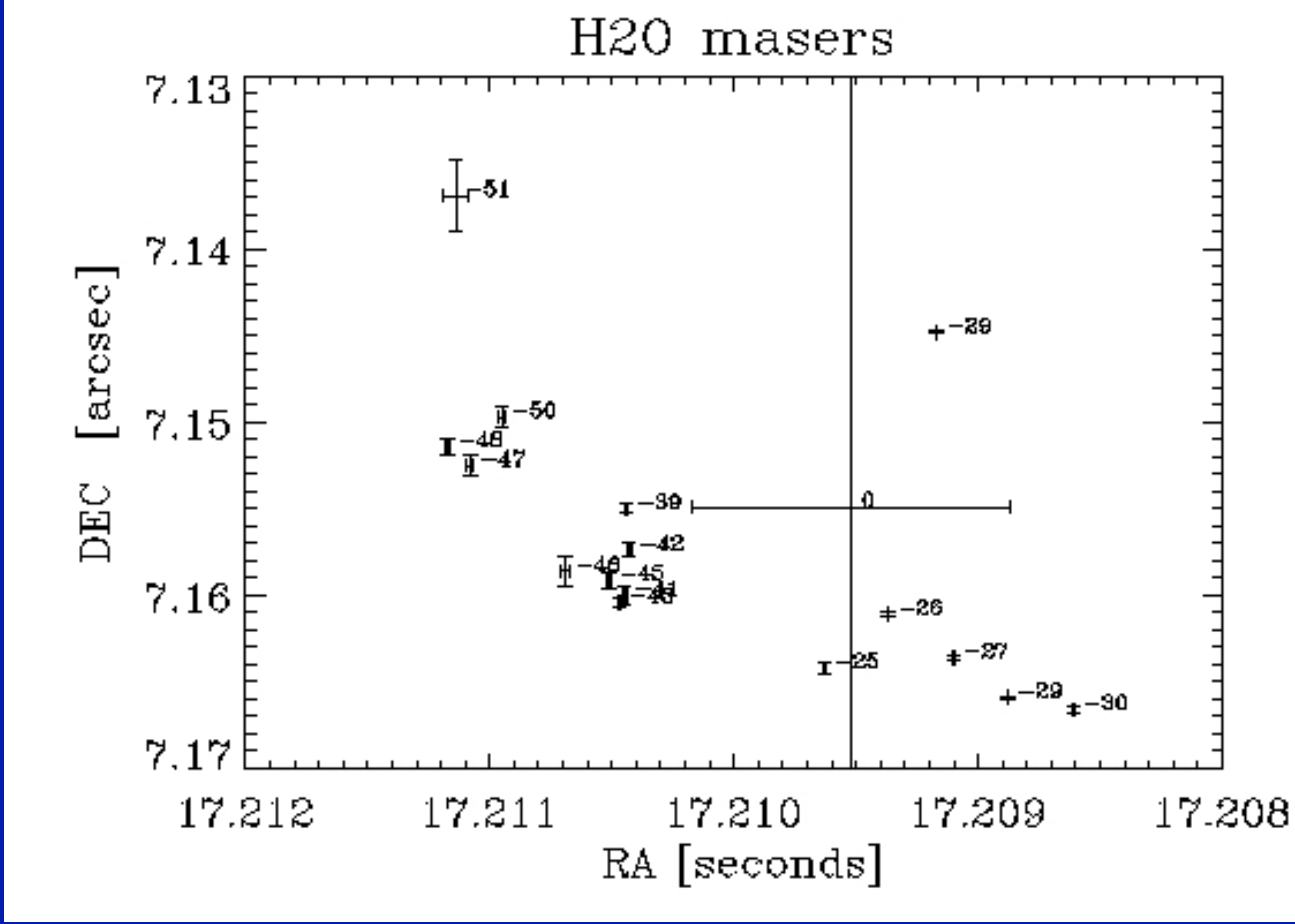
V: -3 to 3 km s^{-1}

R_d: 500 AU

Most luminous YSO known to be associated with a jet, a bipolar molecular outflow and a rotating disk!

G345.5 (Guzmán et al. 2013) ALMA results





Also water masers suggest rotating structure with same direction as SO2, but at much smaller scales. Keplerian mass also about 30 M_{sun}

Summary of jets and disks in high mass forming stars

Disks: Diameters of 300 to 1000 AU.

Masses of orden a few solar masses.

Some may actually be quite clumpy.

Jets: Mass loss rates of order 10^{-5} solar masses per year at velocities of 200-500 km s^{-1}.

Non-thermal component in some sources.

⇒ Jets associated with luminous YSOs are powerful

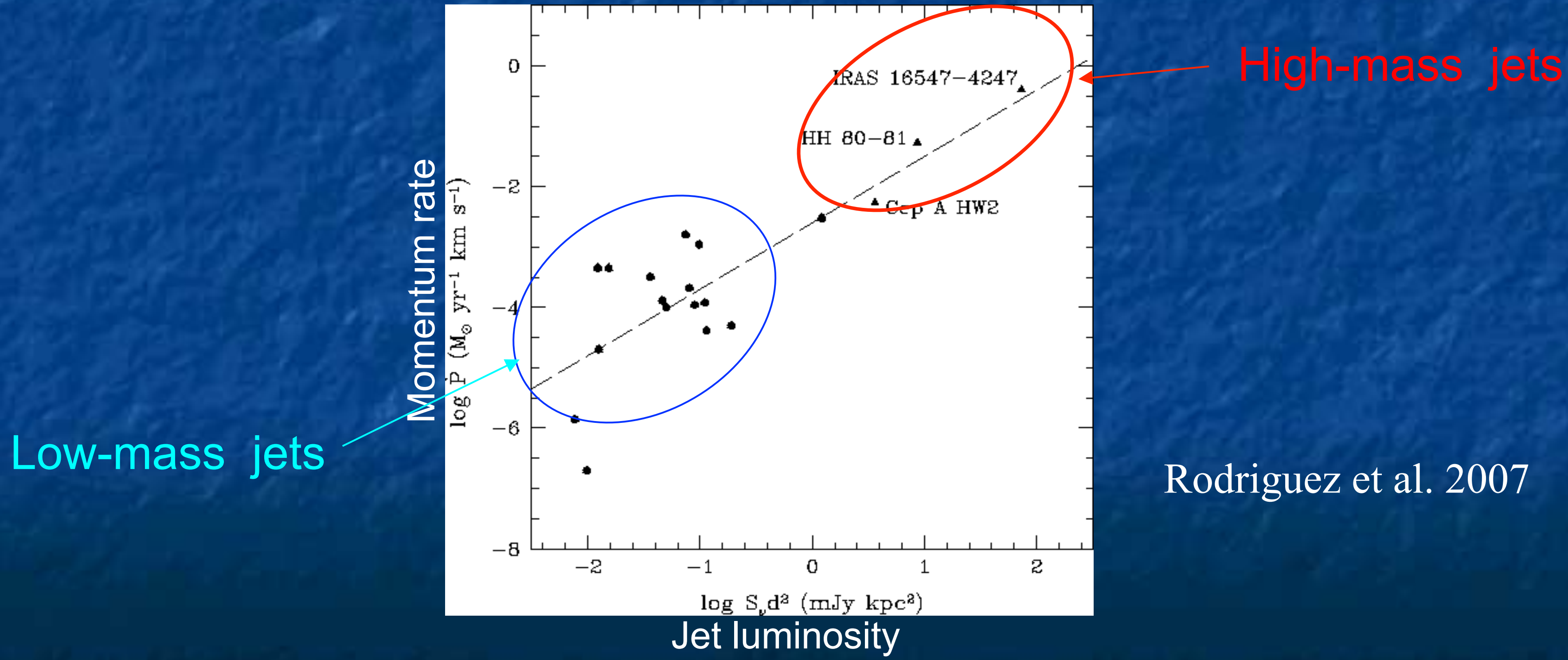
Velocities : 500 - 1000 km s^{-1}

Sizes : 500 - 2000 AU

Mass loss rates : 10^{-6} - 10^{-5} $M_\odot$ yr^{-1}

Momentum rates : 10^{-3} - 10^{-2} $M_\odot$ km s^{-1} yr^{-1}

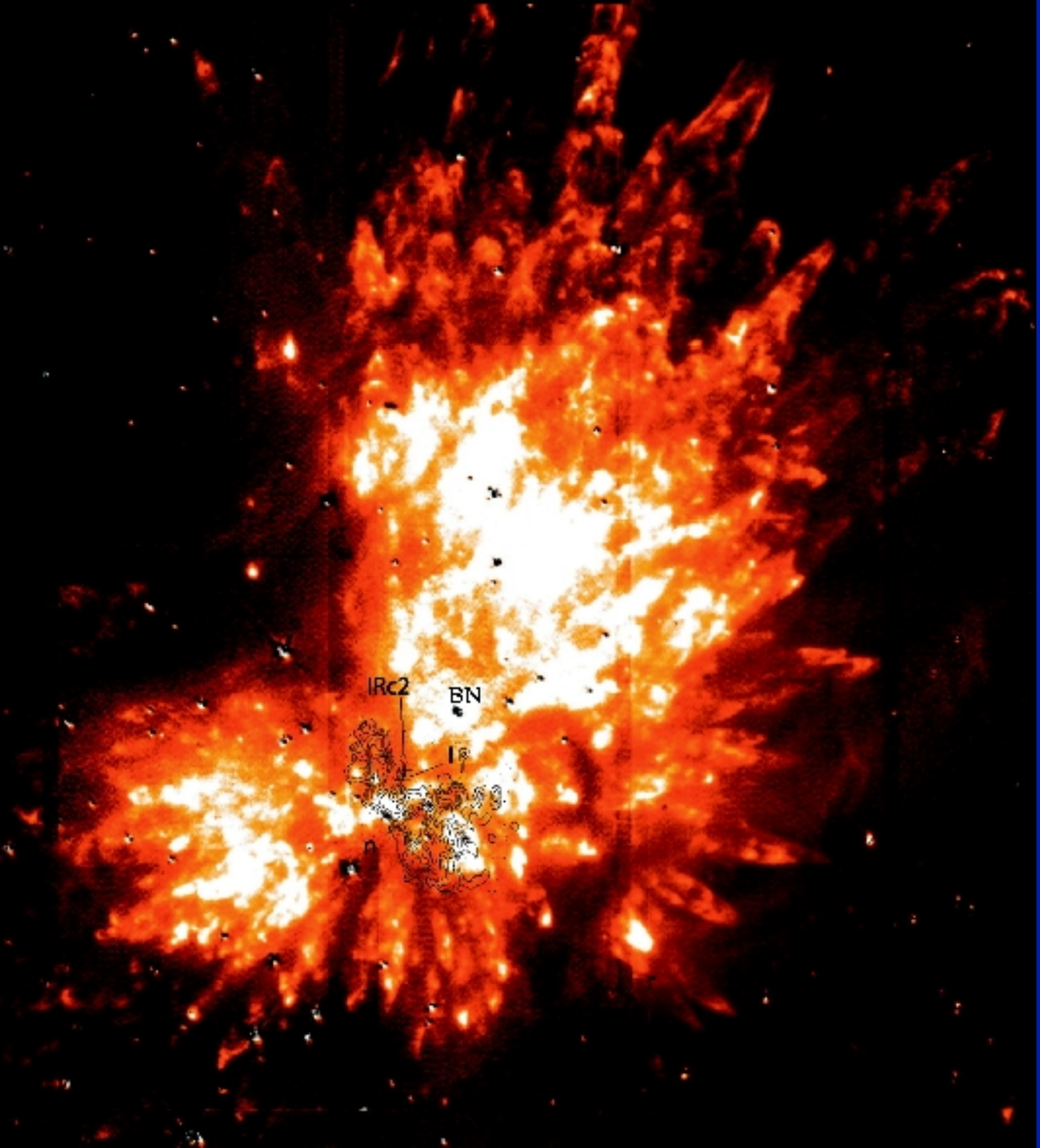
10^3 times more luminous and energetic than low-mass jets !



Rodriguez et al. 2007

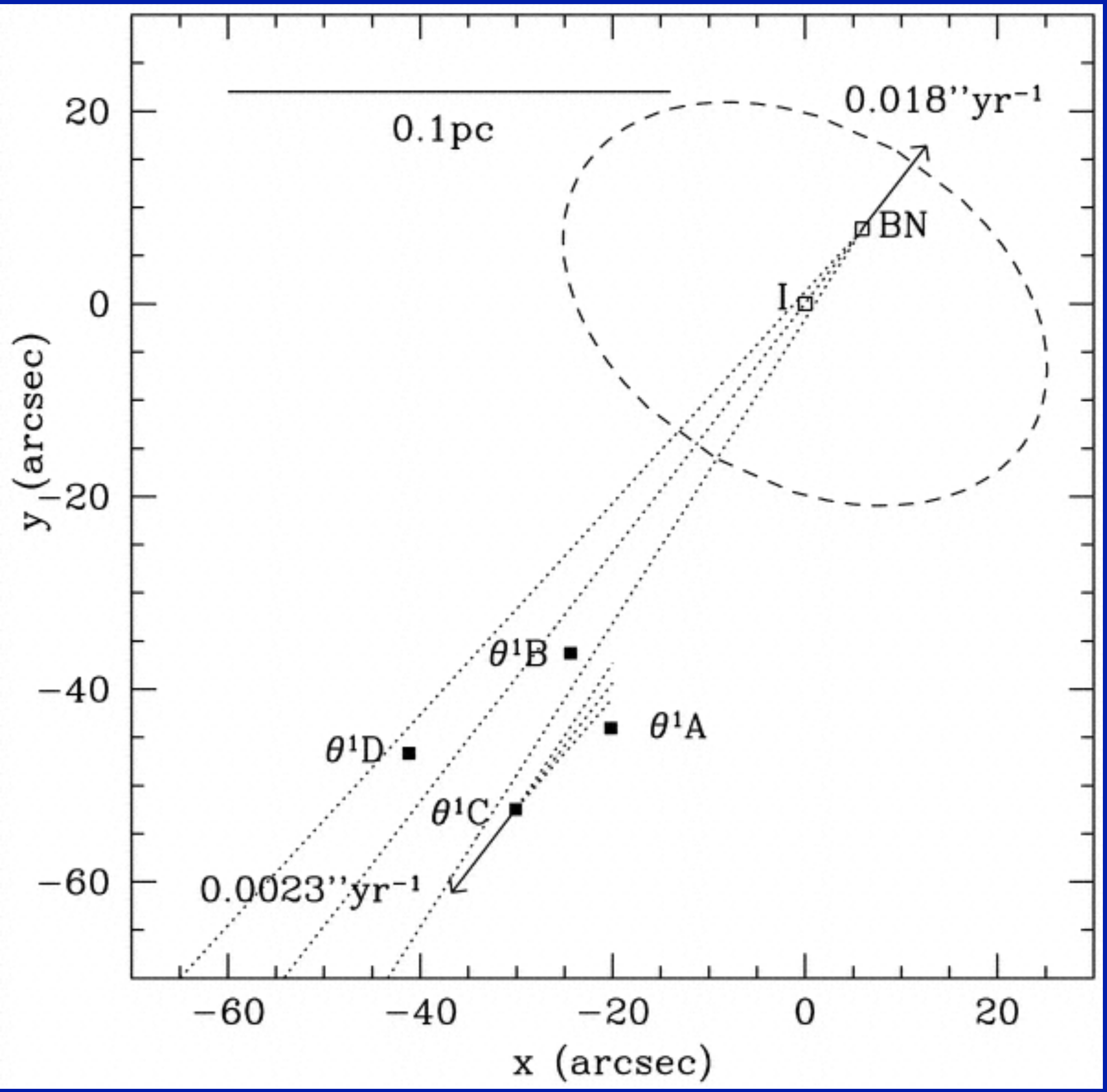
Do we need merging?

- Evidence for collimated outflows from massive young stars is relatively firm. Collimated outflows not expected after merging.
- Evidence for disks is scarce, but is being searched for vigorously. Some good cases.
- There is, however, the intriguing case of Orion BN/KL.

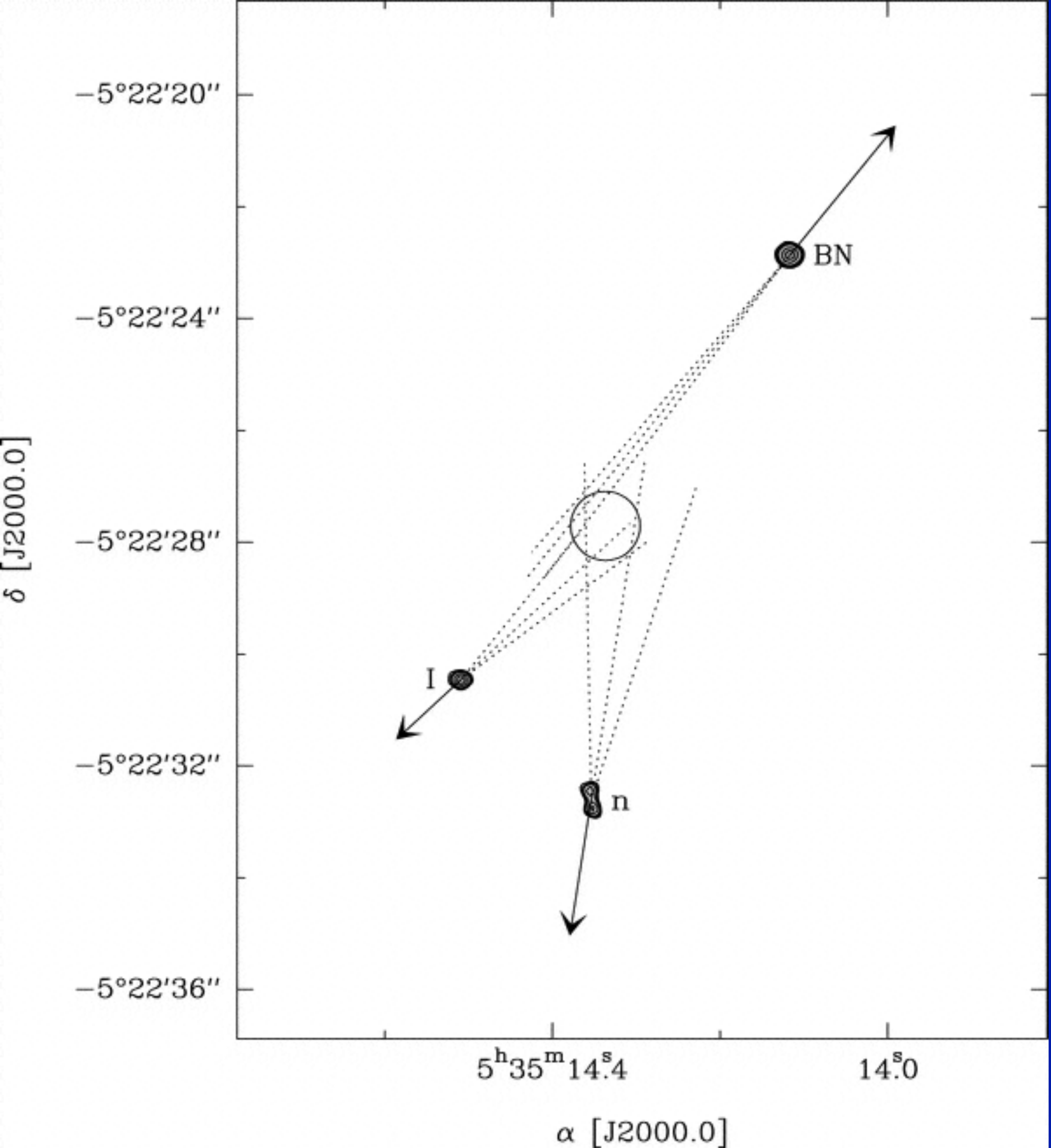


In the Orion BN/KL region there is an example of a powerful, uncollimated outflow. At its center there are several young sources.

H2 image with NH3 contours (Shuping et al. 2004; Wilson et al. 2000)

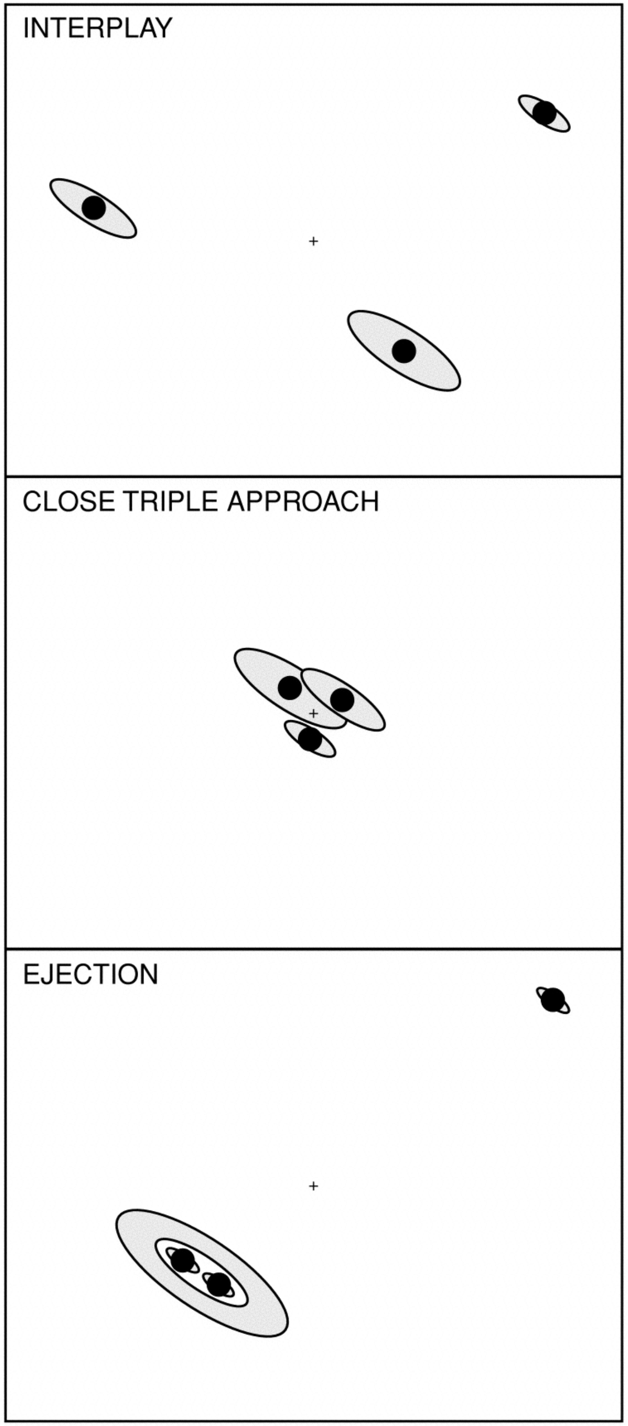


In a recent analysis of the data, Tan (2004) proposed that the BN object was ejected some 4,000 years ago by interactions in a multiple system located at θ^1C Ori, the brightest star of the Orion Trapezium.



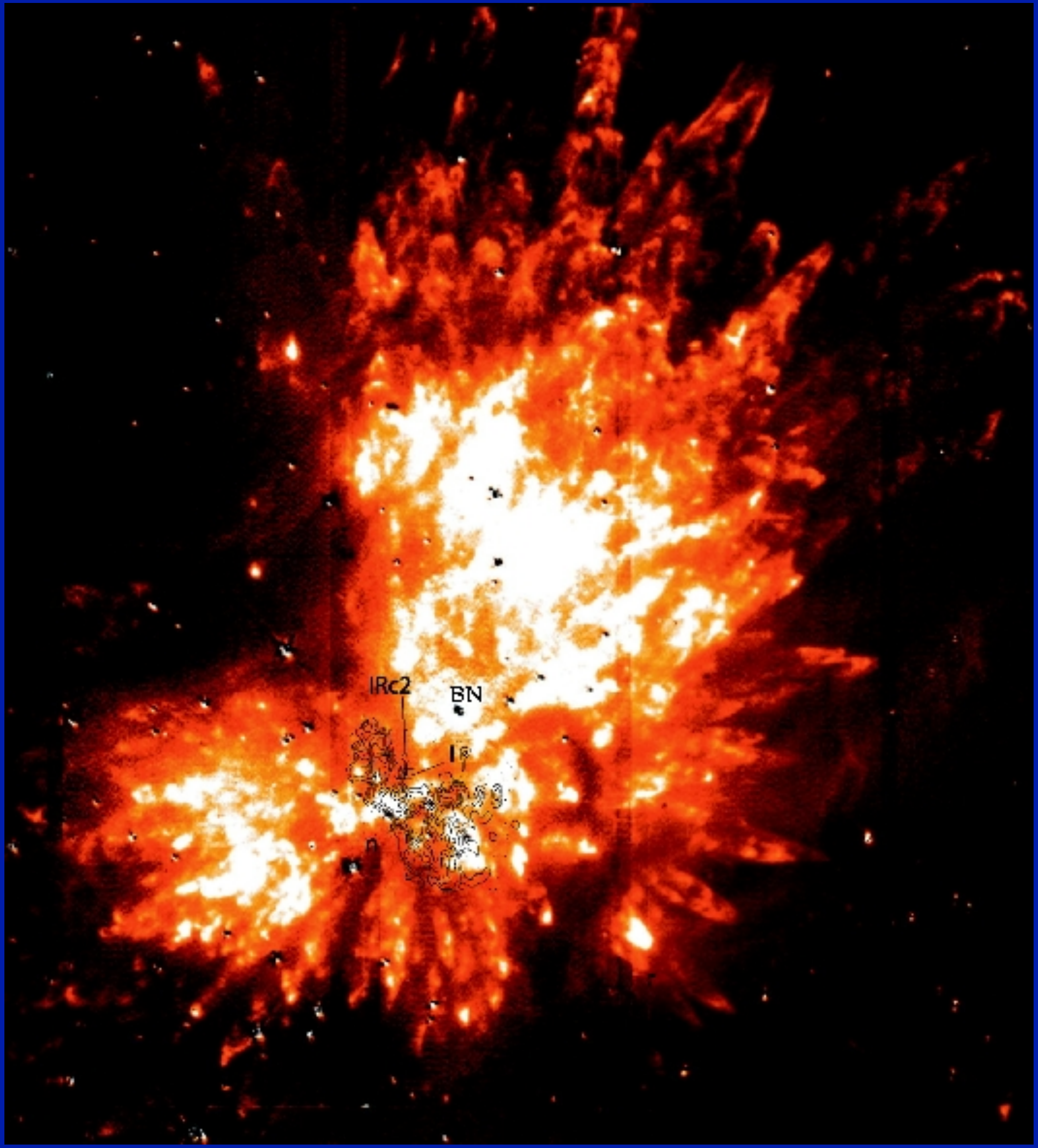
Three stellar sources receding from the same point (Gomez et al. 2005, 2007) at velocities of tens of km/s.

Ejection took place 500 years ago.



Encounters in multiple stellar systems can lead to the formation of close binaries or even mergers with eruptive outflows (Bally & Zinnecker 2005).

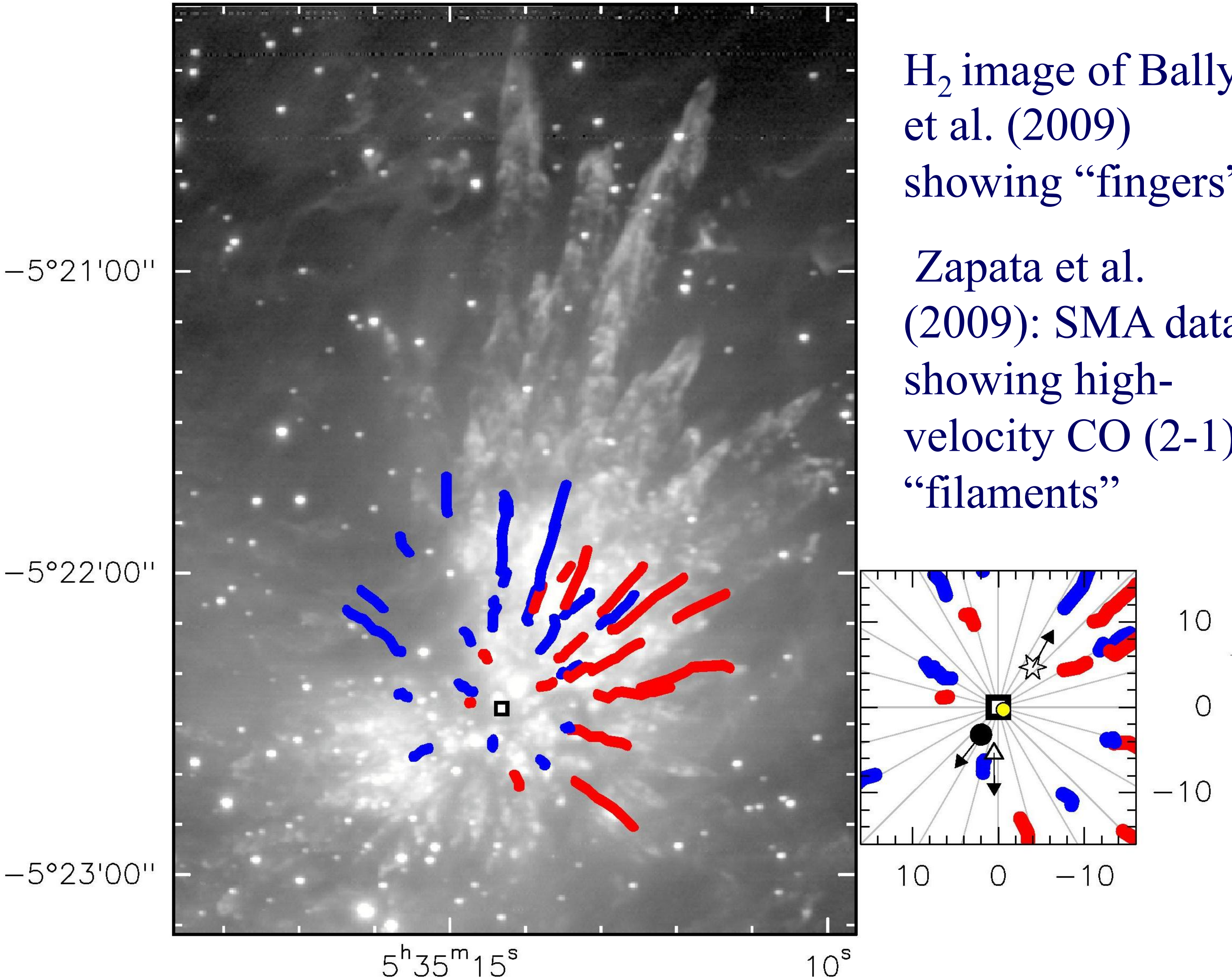
Reipurth (2000)



Indeed, around the BN/KL region there is the well known outflow with an age of about 1000 years.

It is possible that the outflow and the ejection of BN and I were result of the same phenomenon.

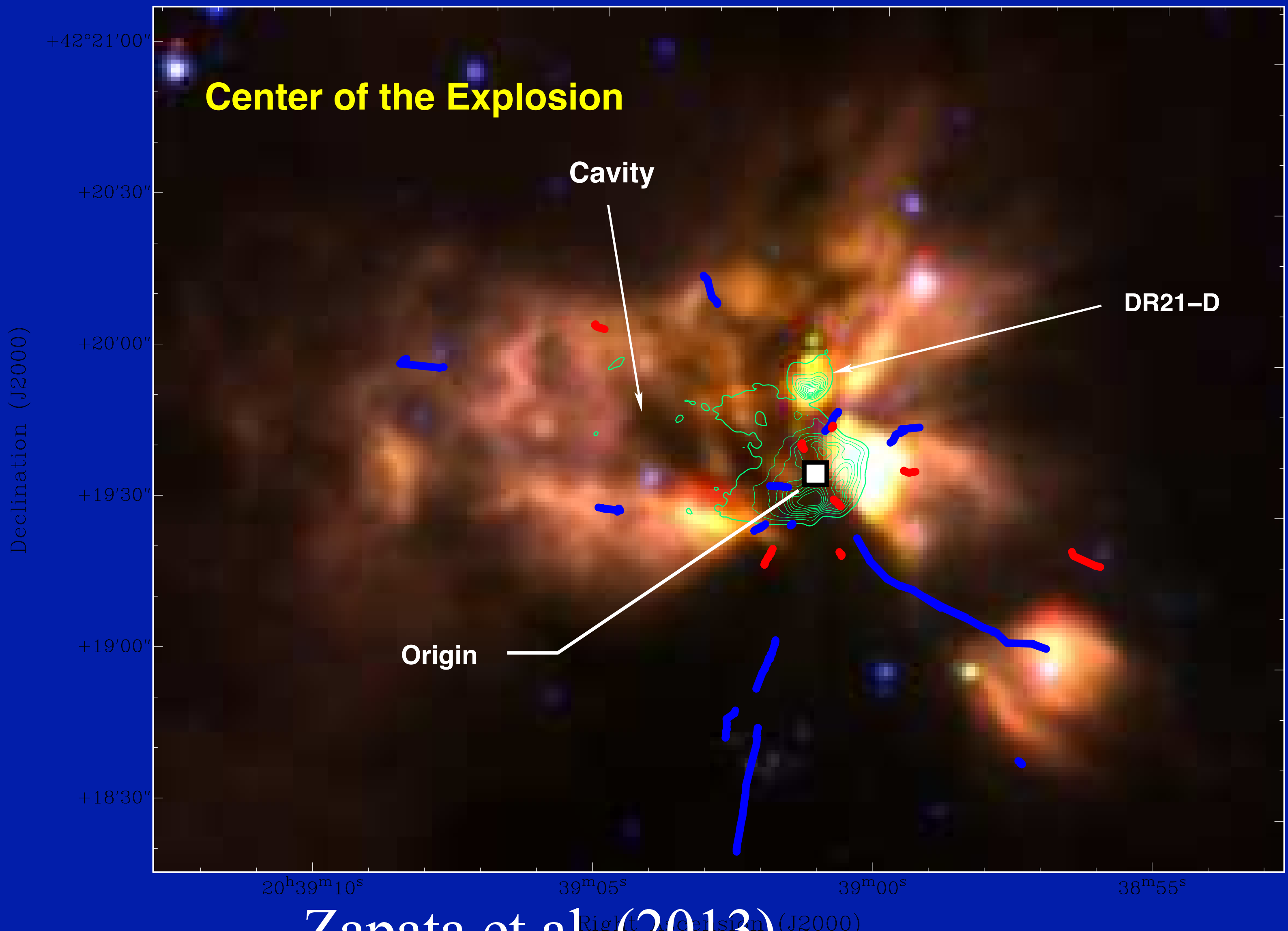
Energy in outflow is of order $4X10^{47}$ ergs, perhaps produced by release of energy from the formation of close binary or merger.



H_2 image of Bally et al. (2009) showing "fingers"

Zapata et al. (2009): SMA data showing high-velocity CO (2-1) "filaments"

DR21: A second case?



Zapata et al. (2013)

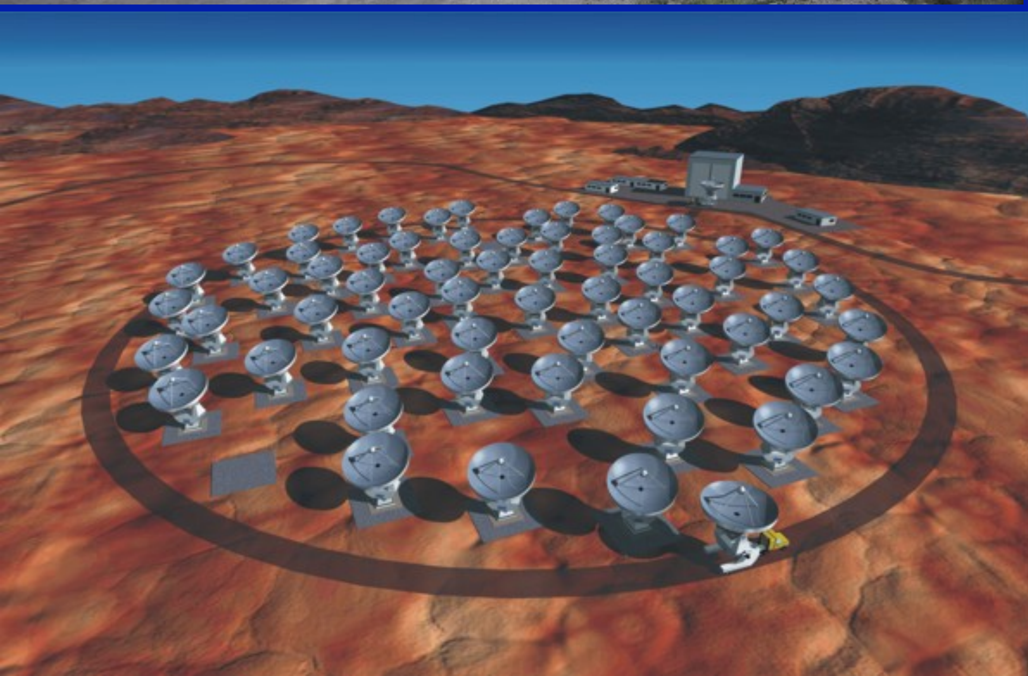
Star formation

- Most evidence seems to favor that star formacion, all the way from brown dwarfs to O stars are formed by basically the same mechanism: accretion via a circumstellar disk with the simultaneous presence of collimated outflows.

Prospects for the future

EVLA = Expanded Very Large Array

10 times the sensitivity in continuum. Great spectral versatility.



ALMA = Atacama Large Millimeter Array

Unprecedented sensitivity and angular resolution at mm and sub-mm wavelengths.

The EVLA and jet kinematics

- Proper motions now limited by sensitivity: impossible to detect in weak jets, very difficult to follow up ejecta that become too weak with time.
- With the possibility of recombination line "stacking" we may be able to detect radial motions, getting 3-D kinematics.

RRL from jets?

Assume electron temperature = 10,000 K, frequency around 30 GHz, and a linewidth of 100 km/s:

$$\frac{S_L}{S_C} \approx 0.05$$

For S_C = 10 mJy

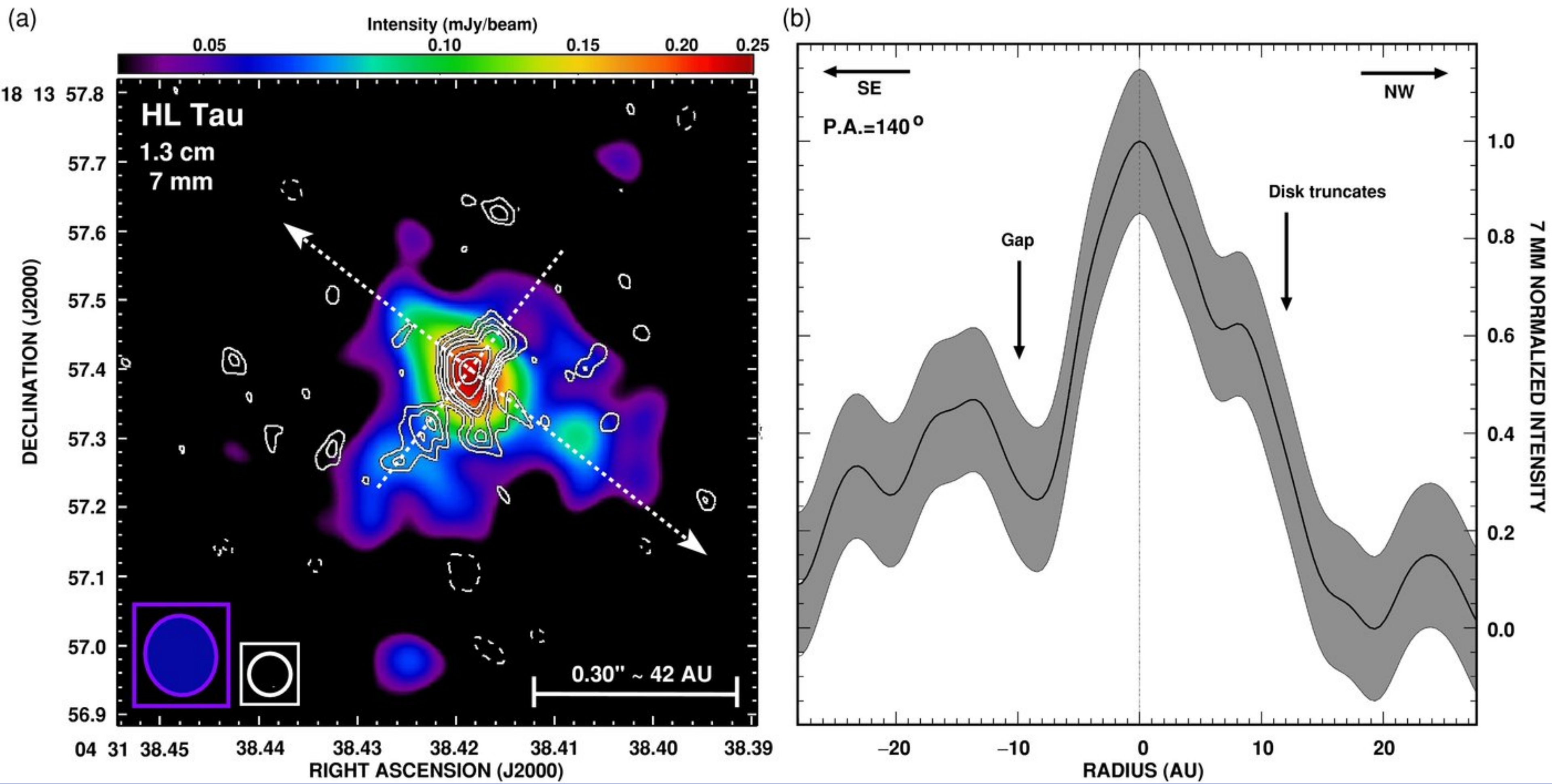
S_L = 0.5 mJy

In the Ka band (26.5 – 40 GHz) you expect a 1-sigma noise of 0.1 mJy for 10 km/s velocity resolution and 12-hour integration. => You get a modest signal-to-noise of 5. But…

Stacking Radio Recombination Lines

- But, in the Ka band (26.5-40 GHz) you can get 8 alpha RRLs (H62α to H55α) so you gain a factor of about 3 sensitivity and to an interesting signal-to-noise ratio of 15 (spatially integrated line).
- Rotating jets?

HL Tau: Jet and disk

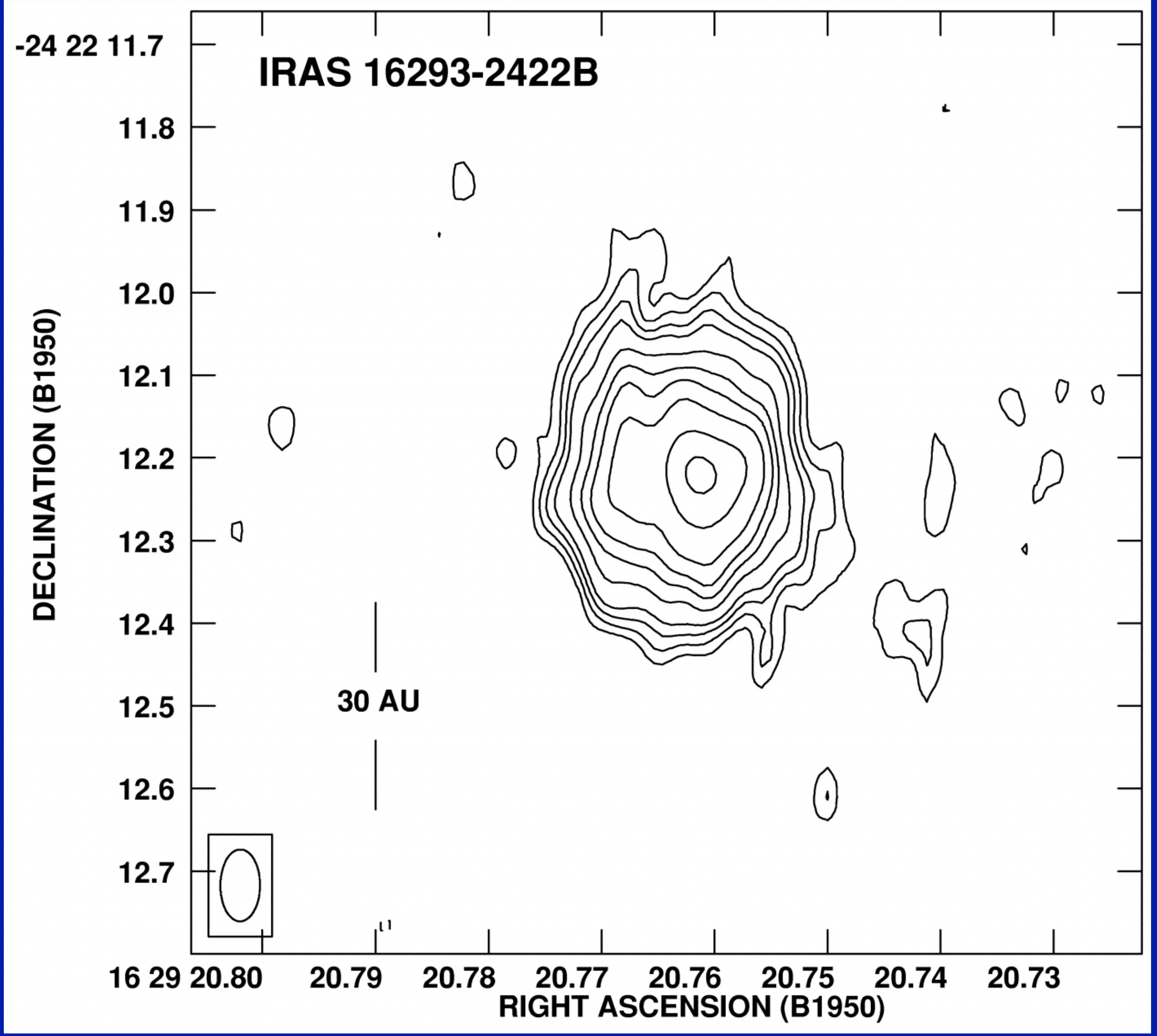


Carrasco-Gonzalez et al. (2009)

Possible presence of “gaps” in disk may signal planet formation. However images severely limited by signal-to-noise ratio.

The structure of disks can tell us a lot about how is planet formation taking place…

- According to Durisen (2009) there are two main models for the formation of giant planets:
- 1. Core accretion: Will produce gaps in disks, as possibly observed in HL Tau.
- 2. Disk instability: Will produce spiral patterns in disk. Has this been observed?



A hint of spiral structure in this 7 mm VLA image that traces dust? Disk instability?

Still many open questions in massive star formation...

- Are disks and jets always present?
- Disks seem to be needed given presence of collimated outflow phenomena.
- Are mergers playing any role?
- New generation of radio interferometers will help answer some of these questions.

Thank you