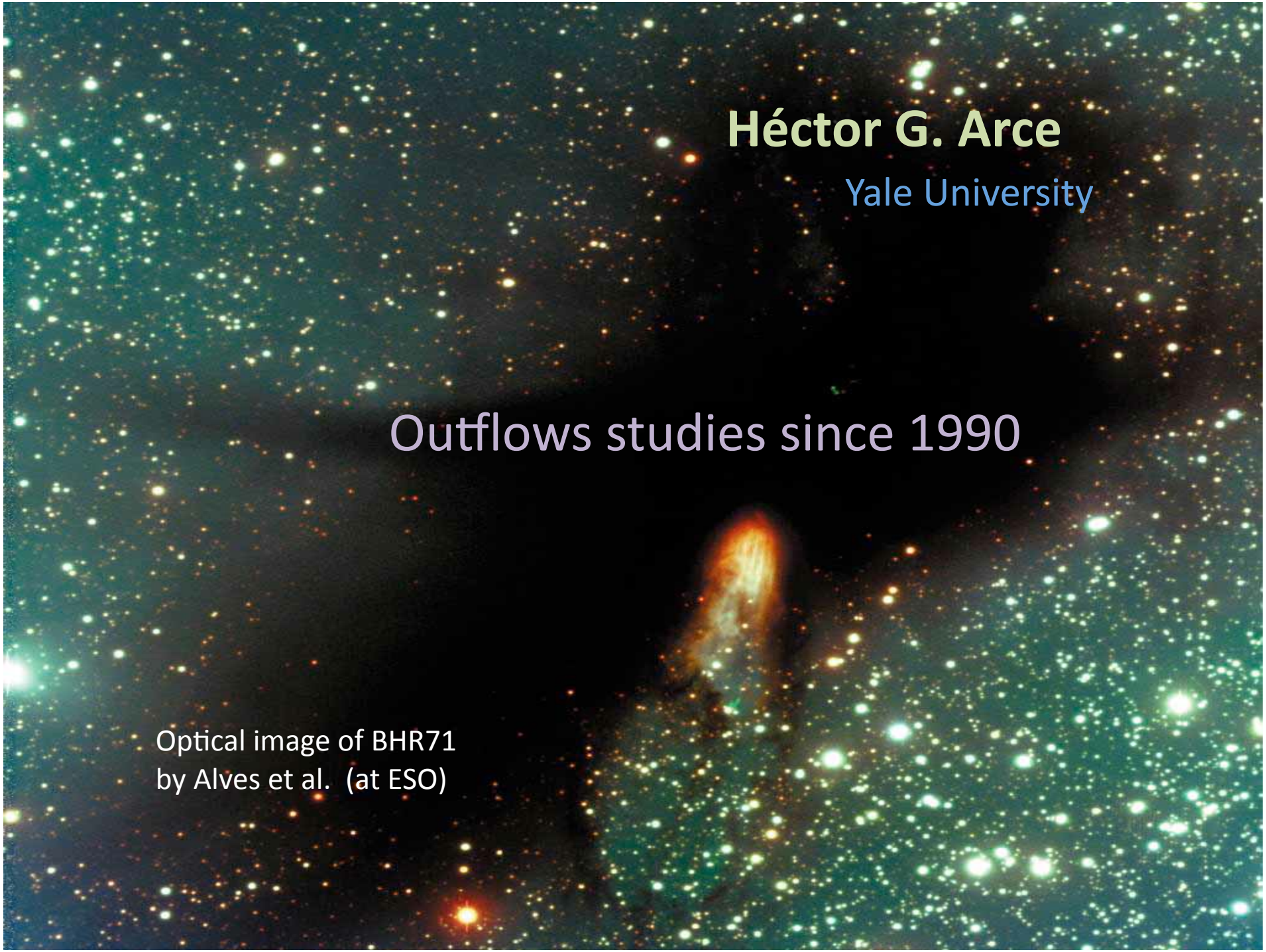


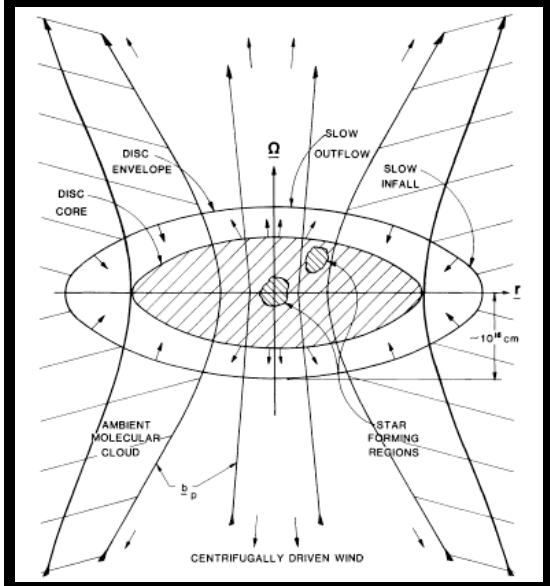
Héctor G. Arce

Yale University

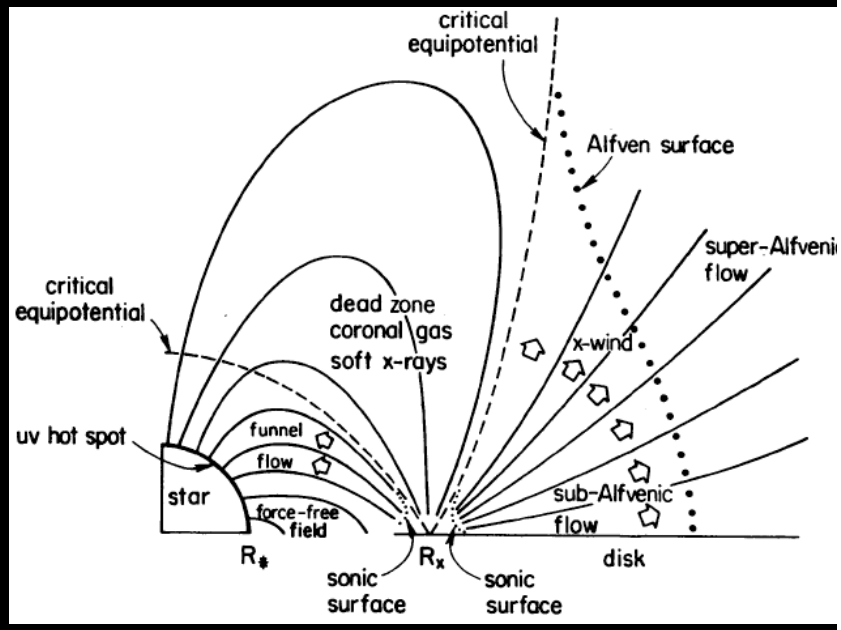
Outflows studies since 1990

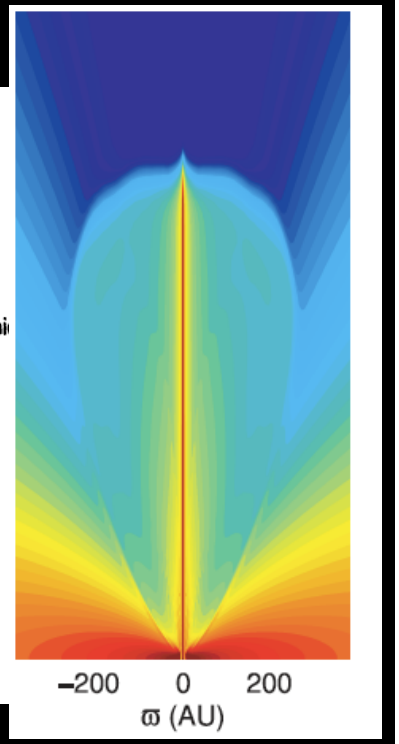
Optical image of BHR71
by Alves et al. (at ESO)

Outflows important to cores because they are formed close to protostar

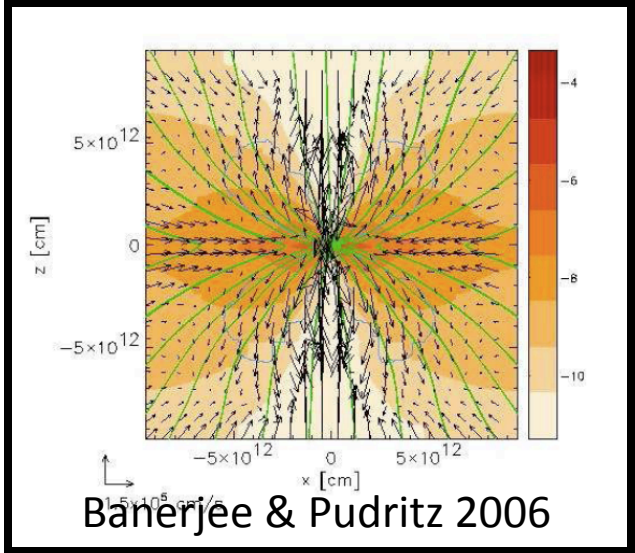


Pudritz & Norman 1983





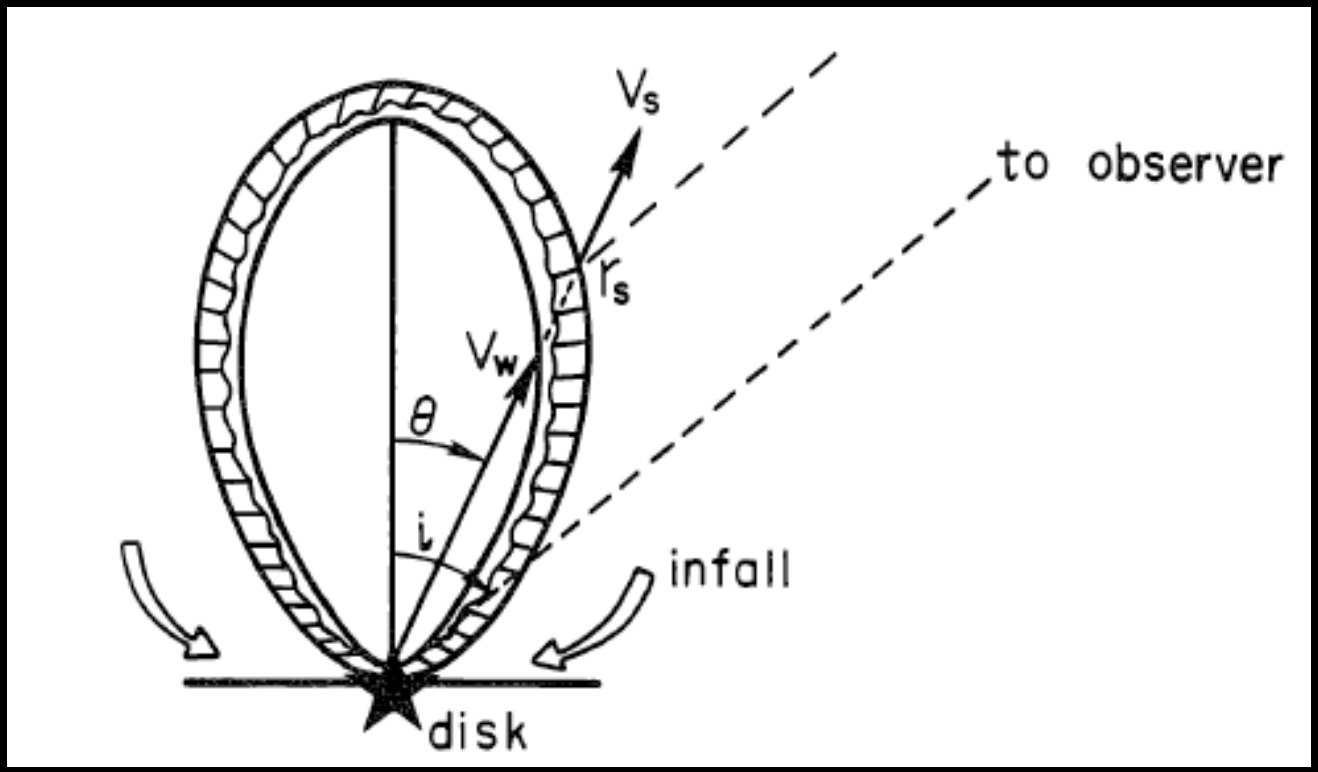
Shang et al. 2006



Banerjee & Pudritz 2006

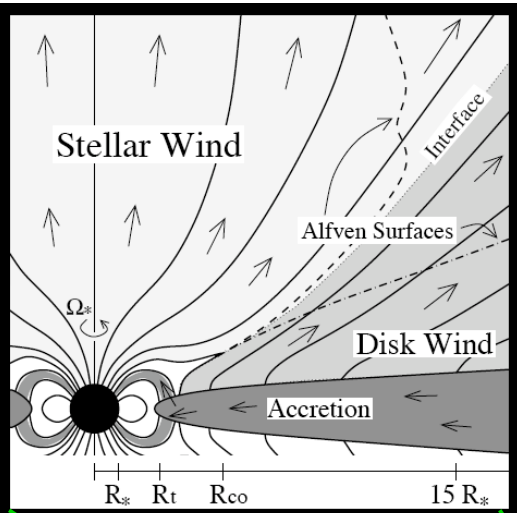
Magnetocentrifugally Driven Flows from Young Stars and Disks I –V
Shu et al. 1994a,b; Najita & Shu 1994; Ostriker & Shu 1995; Shu et al. 1995

Connecting accretion, winds and observations of molecular outflows

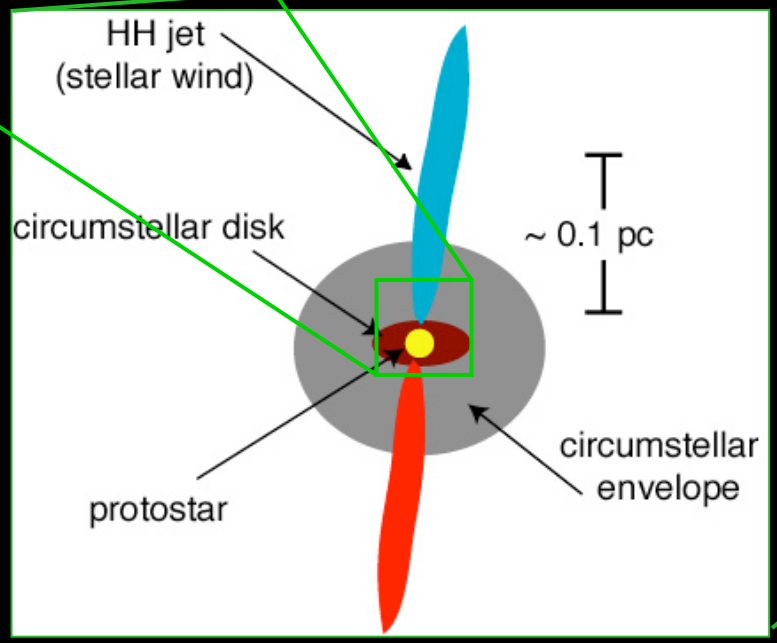


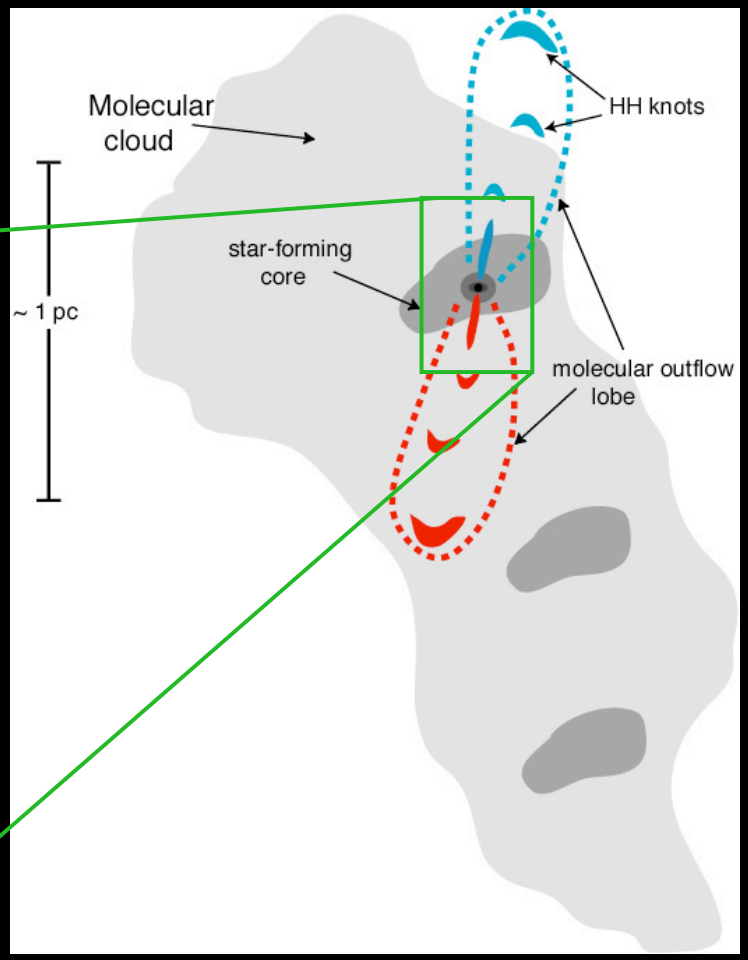
Physical model of molecular outflows as a natural consequence of star formation
Shu et al. 1991 (wind occurs as a natural consequence of accretion)

Outflow interaction at many scales



From Matt & Pudritz (2005)



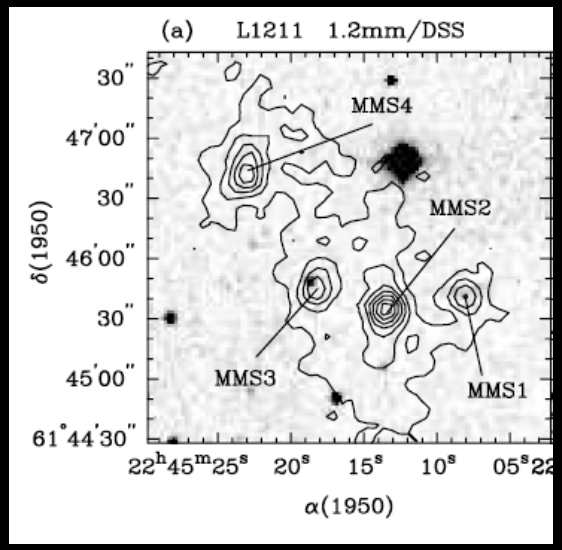


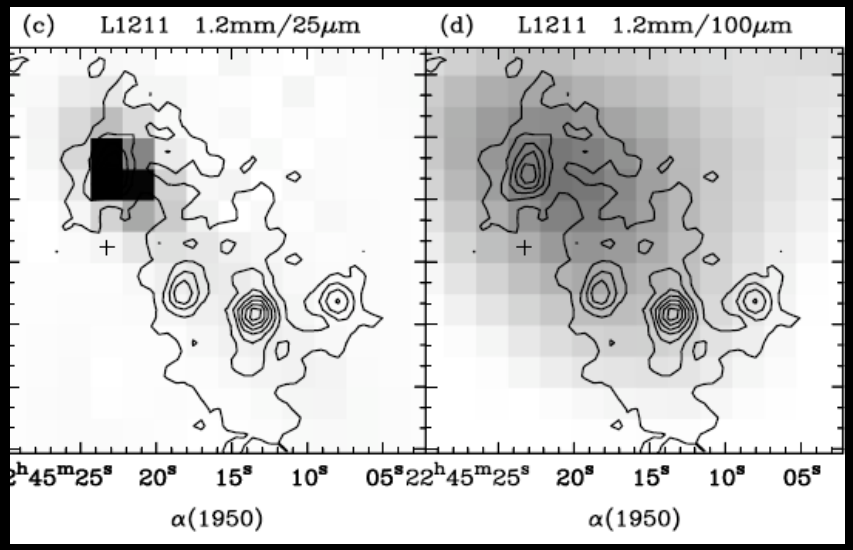
Outflows:

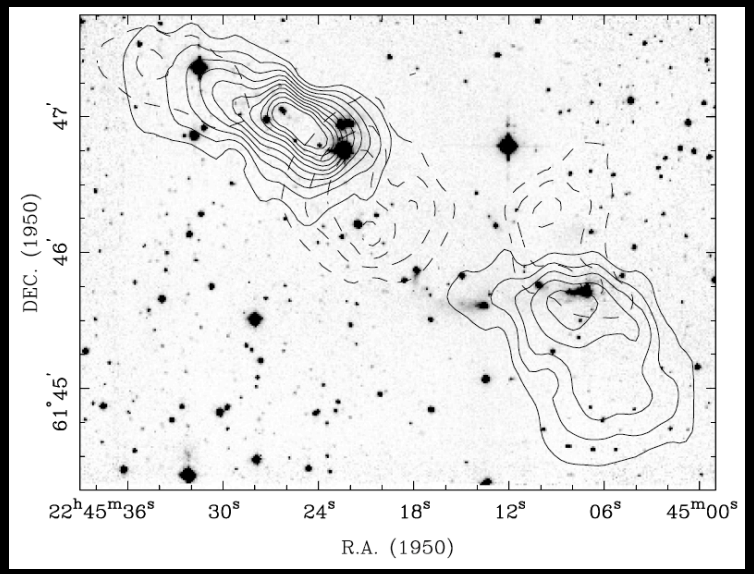
- Signal the formation of a protostar
- Interact with parent core

Outflows for classifying protostars

The case of L1211







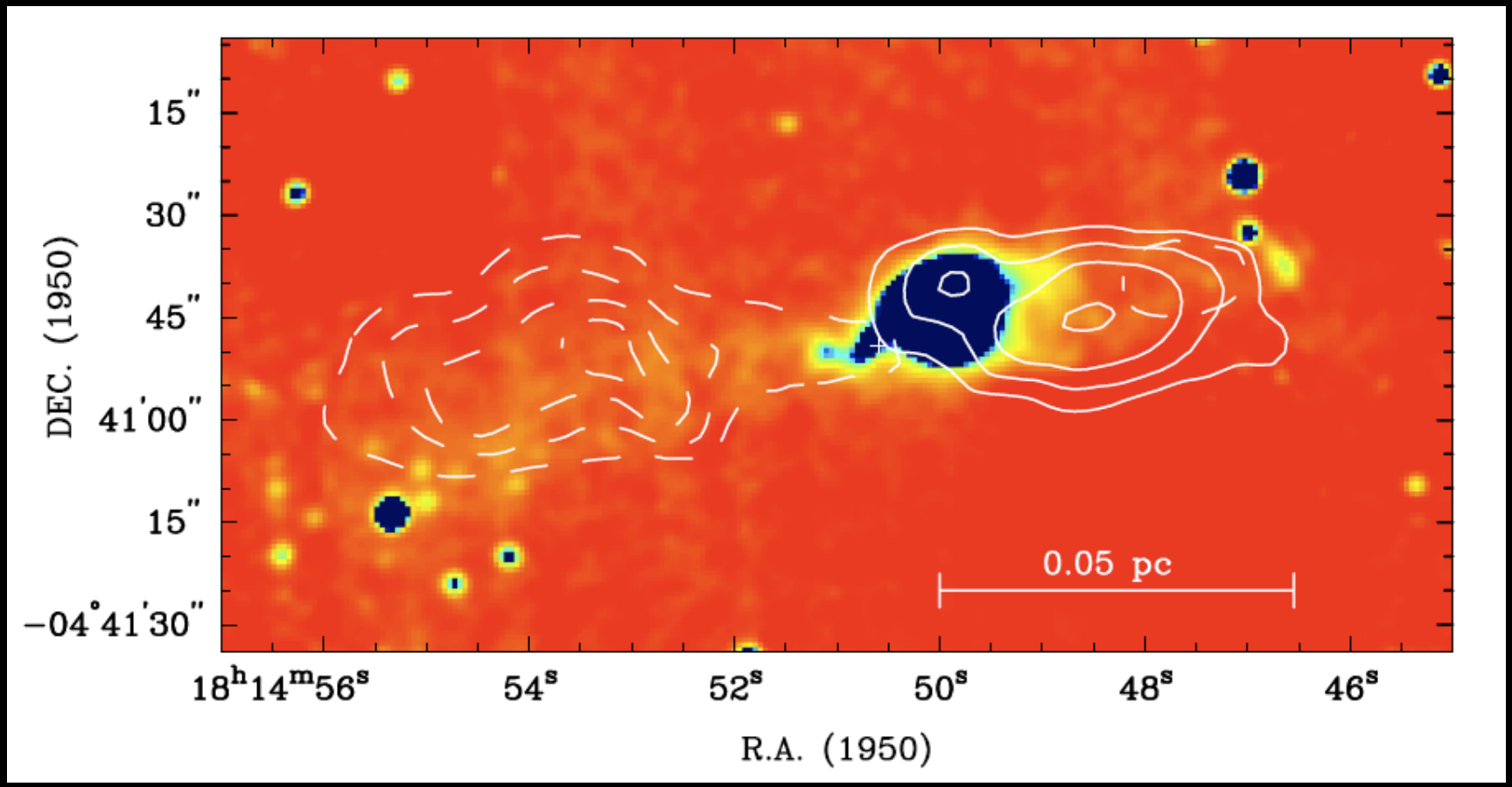
MMS1 clearly drives powerful outflow, but no IR source. Source must be Class 0.

Class 0 term had been just been coined by André et al. 1993

Tafalla, Myers, Mardones & Bachiller 1999

Outflows for determining source's stage

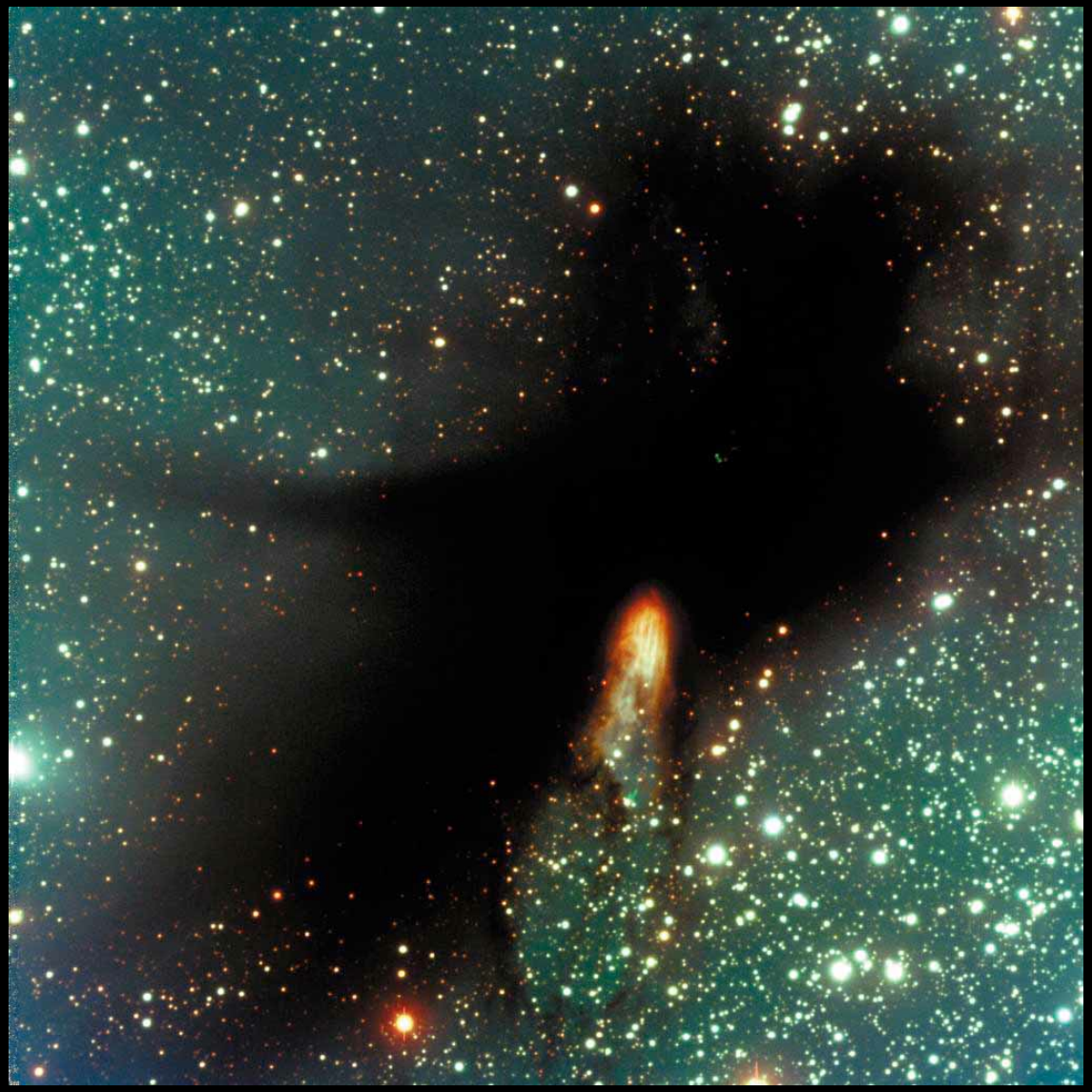
The case of L483



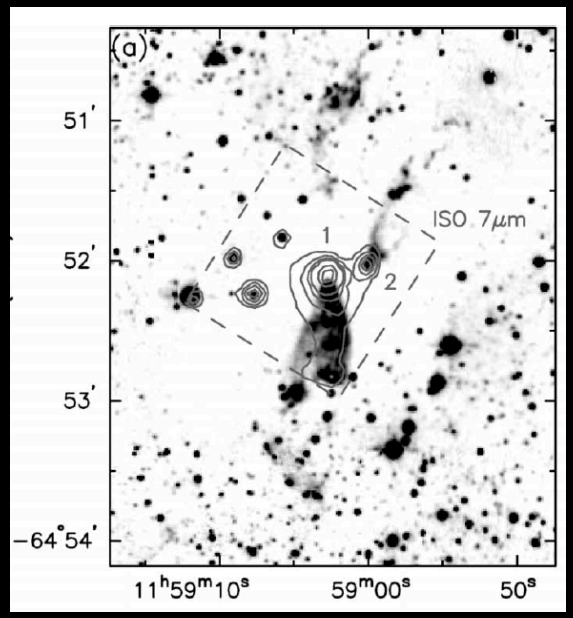
CO outflow slow and not as chemically active as other Class 0 sources.
Source in between Class 0 and Class I.

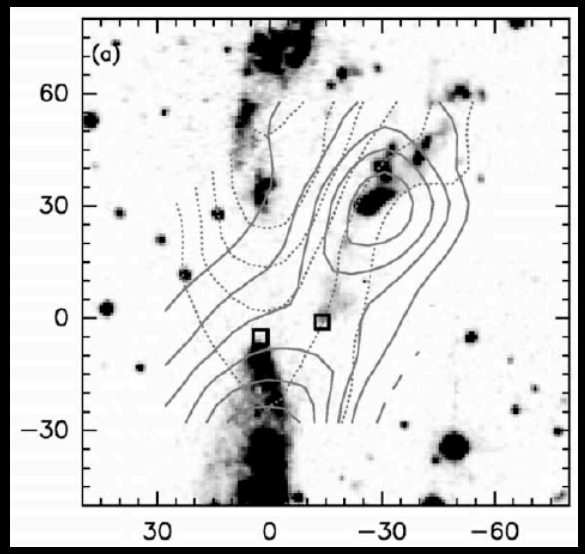
Tafalla, Myers, Mardones & Bachiller 2000

Outflow reveals protostar: a binary in BHR71



Bourke 2001



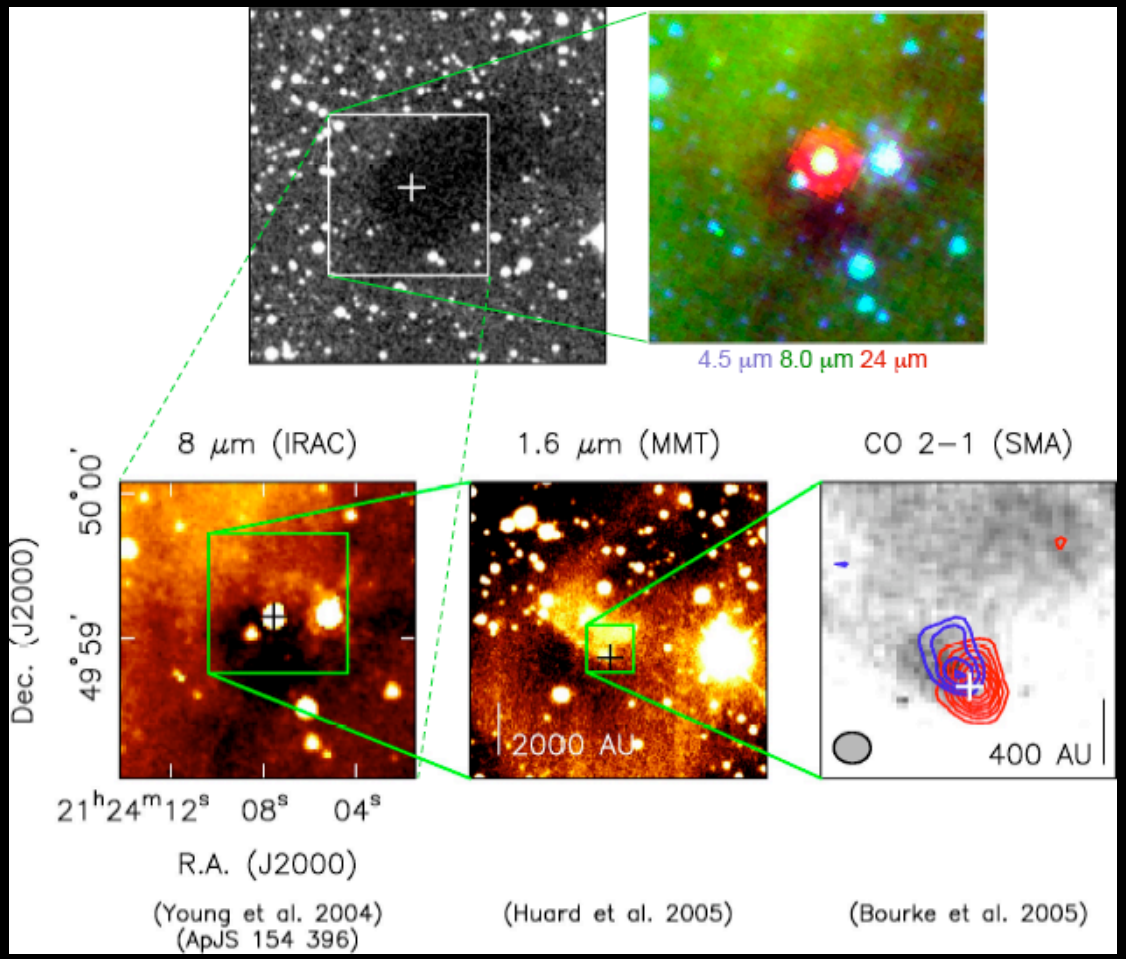


Optical image: Alves et al. (ESO)

Spitzer image: Bourke & c2d team

Outflow confirms source: L1014 "starless" no more

VeLLo (Very Low Luminosity Objects)
new kind of objects discovered by Spitzer Space Telescope



Outflow helped established 1014-IRS NOT a background source associated with dark cloud (Bourke et al. 2005)

Why was Phil not *that* interested in outflows after DCDC V (Myers et al. 1988)?

A SEARCH FOR MOLECULAR OUTFLOWS TOWARD PRE–MAIN-SEQUENCE OBJECTS

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and Harvard-Smithsonian Center for Astrophysics
Received 1987 June 3; accepted 1988 January 11

ABSTRACT

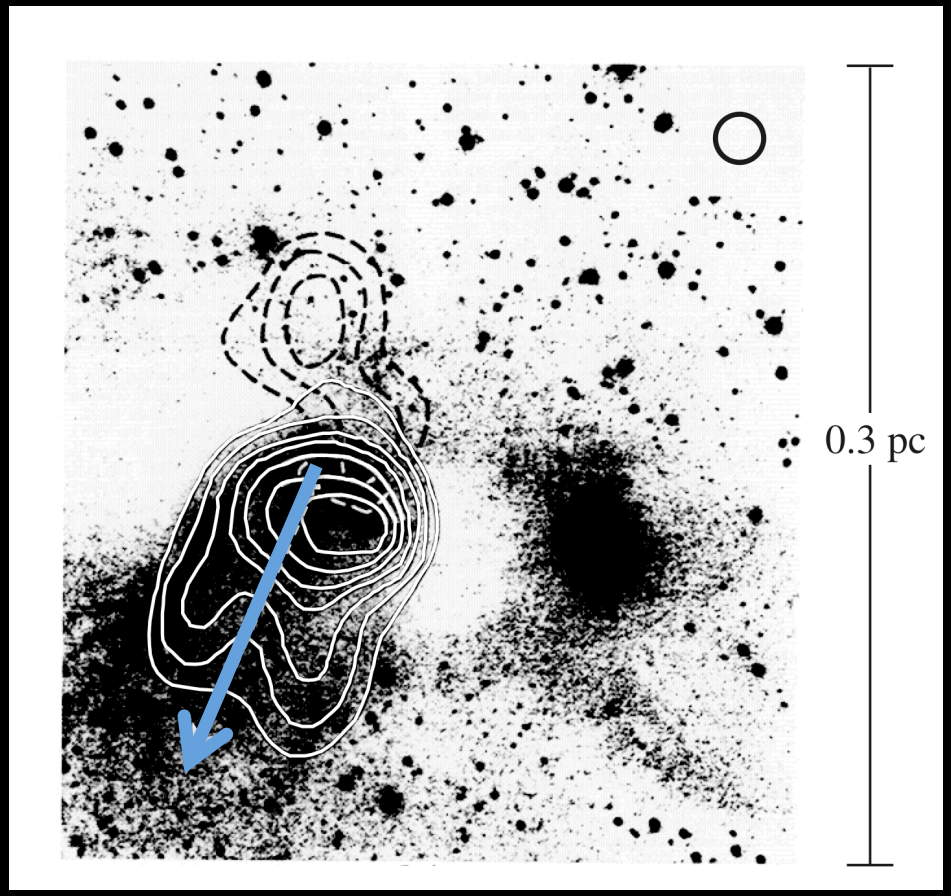
We have conducted a search for molecular outflows toward a sample of 71 young stellar objects, a sample dominated by optically selected pre–main-sequence stars. Molecular outflows have been detected toward 20 of these objects and in an additional six infrared sources not included in the original survey. The outflows range in size from 0.07 to ~ 5 pc, and show expansion velocities of from 6 to 60 km s^{-1}. The apparent ages of the outflows range from $\sim 10^3$ to 5×10^5 yr. Roughly half of the observed outflows are bipolar; the rest show a wide variety of morphologies. The morphologies of the better resolved outflows are discussed in detail.

High signal to noise CO $J = 2 \rightarrow 1$, CO $J = 1 \rightarrow 0$, and ^{13}CO $J = 1 \rightarrow 0$ line profiles are used to determine line intensity ratios for the high-velocity emission. In most cases the ratios are consistent with modestly optically thick CO emission, although several examples of optically thin emission are seen. The opacities are combined with the observed line strengths to derive masses for the high-velocity material: the results range from 0.01 to 56 $M_\odot$. Uncertainties in the derivation of these masses, as well as the outflow expansion velocities and apparent ages, are discussed. It is shown that outflows driven by low-luminosity objects tend to be more bipolar than those driven by high-luminosity objects. The implications for our data on the structure of molecular outflows is also considered.

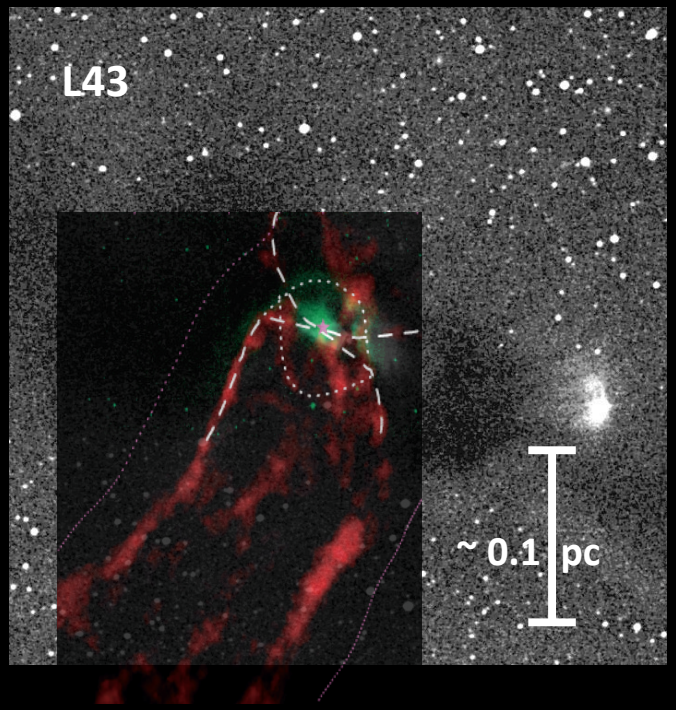
Subject headings: interstellar: molecules — stars: mass loss — stars: pre–main-sequence

A large body of data taken and interpreted in a uniform way should provide the common ground necessary to tie molecular outflows into present ideas of the framework of pre–main-sequence stellar evolution.

Outflow interaction with cores: L43



Mathieu, Myers, Schild, Benson & Fuller 1988



Class II source with a very wide (~160°) opening angle.

Notice wide outflow cavity with less extinction

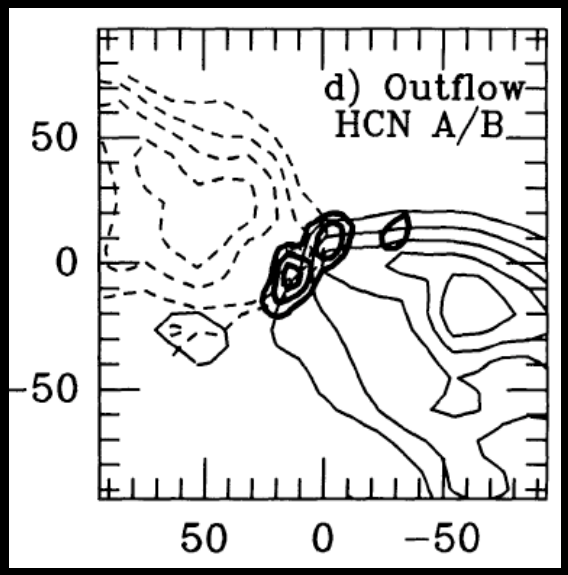
Lee et al. (2005), using BIMA

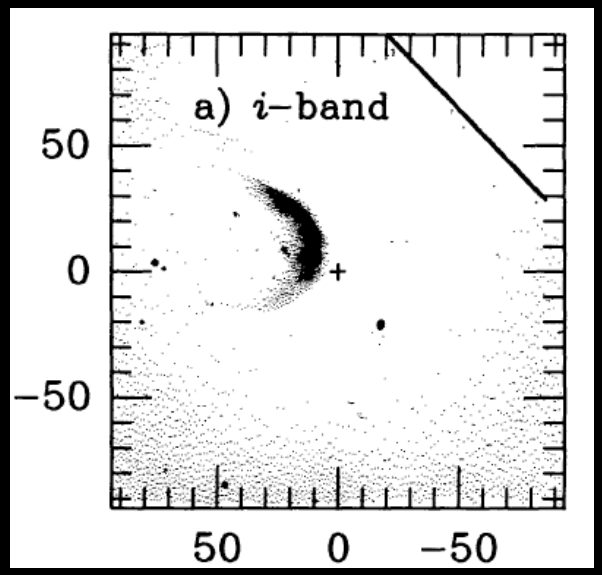
L43 - an example of interaction between molecular outflows and dense cores

Outflows and cores:

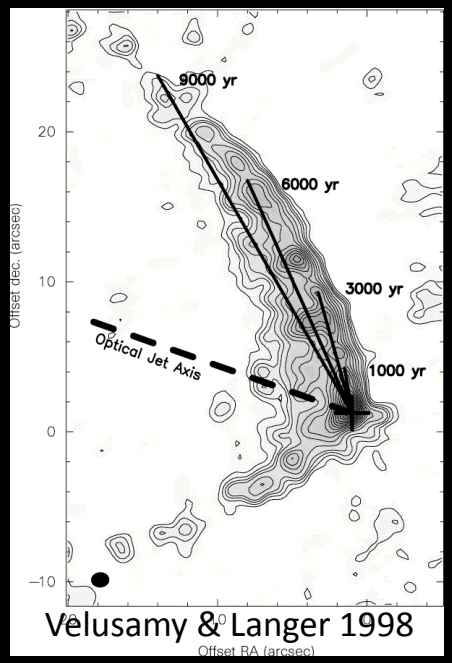
Anatomy of the Barnard 5 Core

Fuller et al. 1991





Heyer, Ladd, Myers & Campbell 1990



Velusamy & Langer 1998

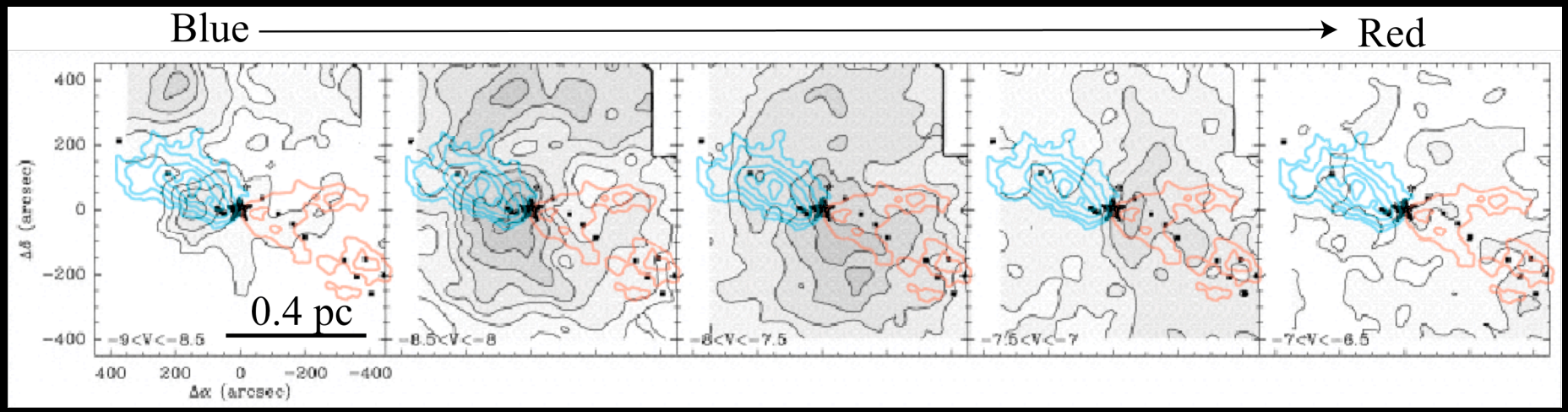
. The observed correlation of cometary reflection nebulae with newborn stars undergoing mass outflow suggests that the low-opacity paths are cavities associated with energetic stellar winds.

Impact of outflows on cores: L1228

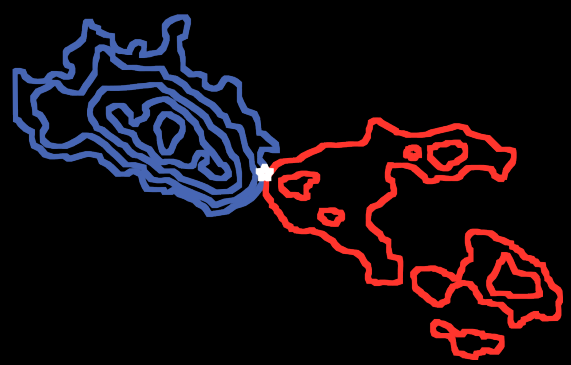
Velocity Shifts in L1228: The Disruption of a Core by an Outflow

Tafalla & Myers (1997)

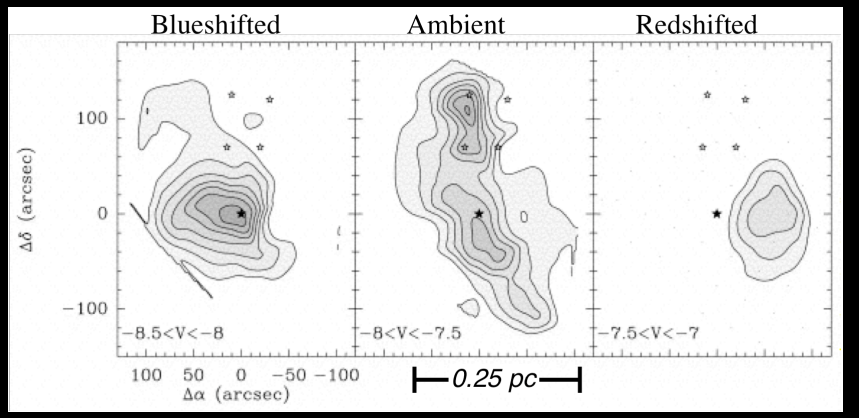
^{13}CO(1-0) velocity map



Red + blue contours:
CO(1-0) outflow



$C_3H_2(2_{12}- 1_{01})$ velocity maps

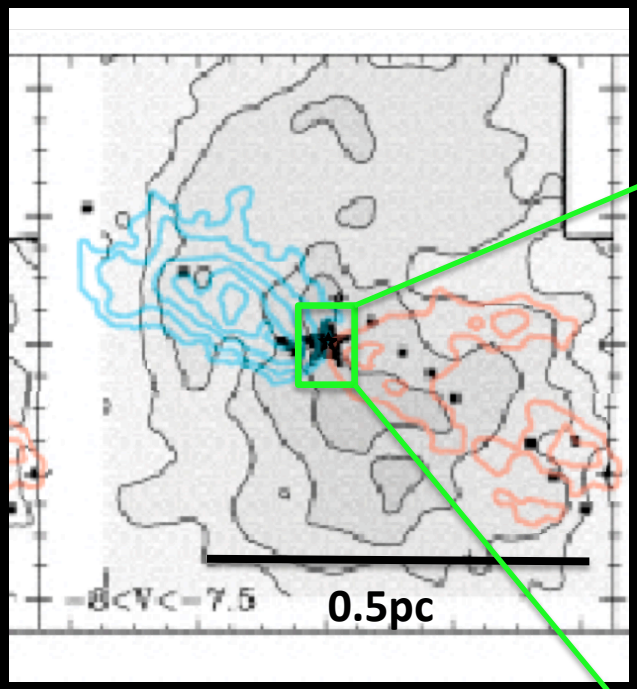


Results:
^{13}CO outflow:
- 6x Mass
- 2x Mom
- 0.5x K.E.

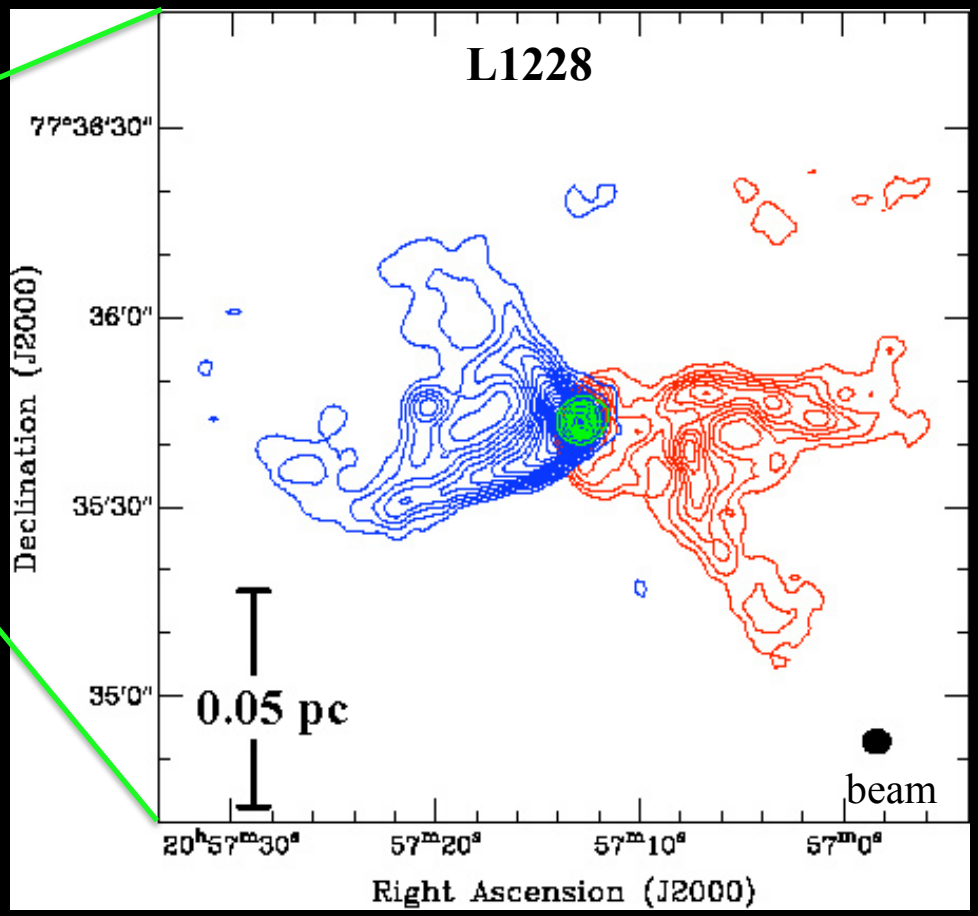
of ^{12}CO flow

Essential to map ^{13}CO to get full impact of flow on cloud

L1228 CO outflow at high-resolution



Tafalla & Myers (1997)



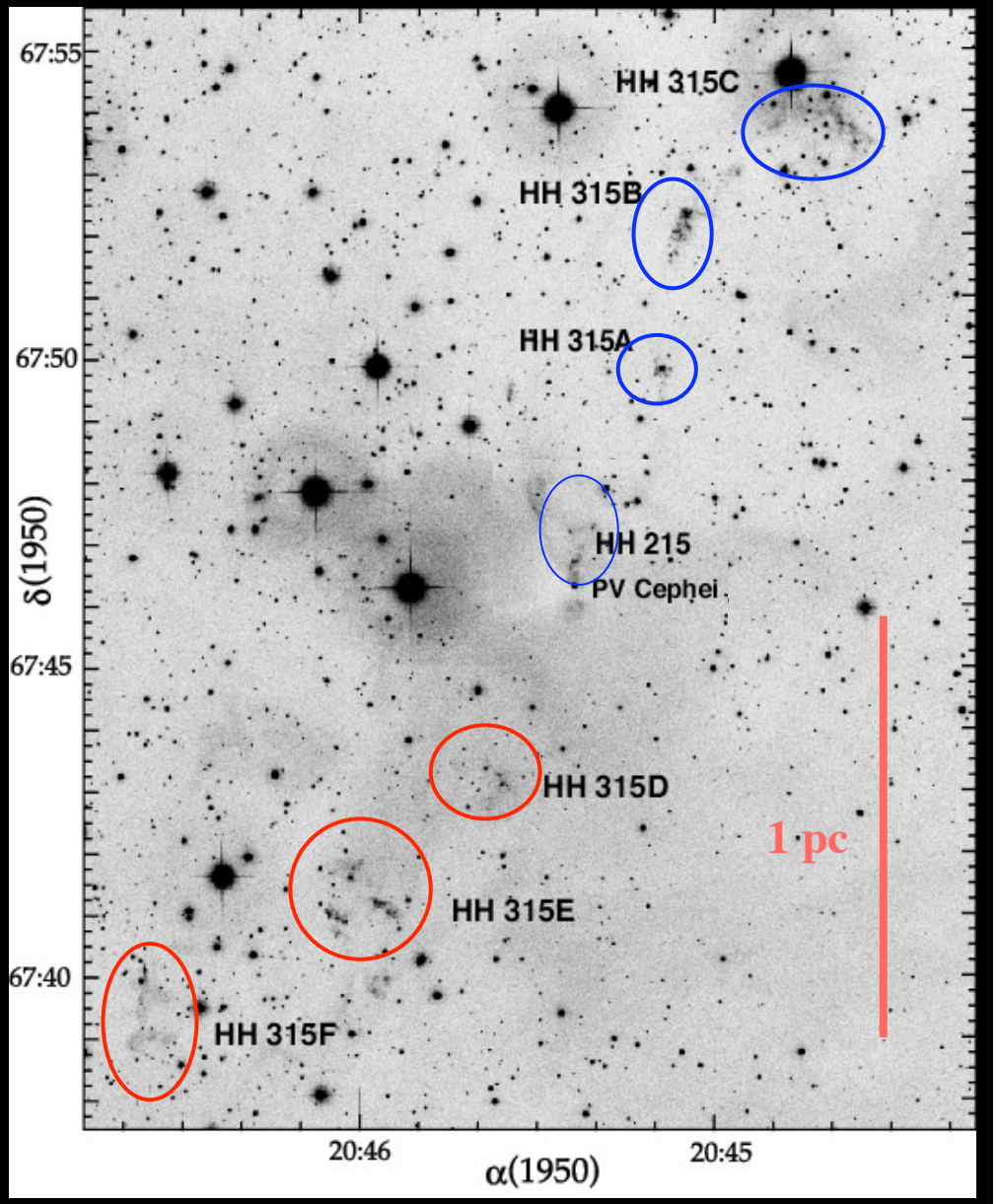
Arce & Sargent (2004)

Our changing view of HH flows

Before 1990's, HH flows were thought to extent less than ~0.5pc

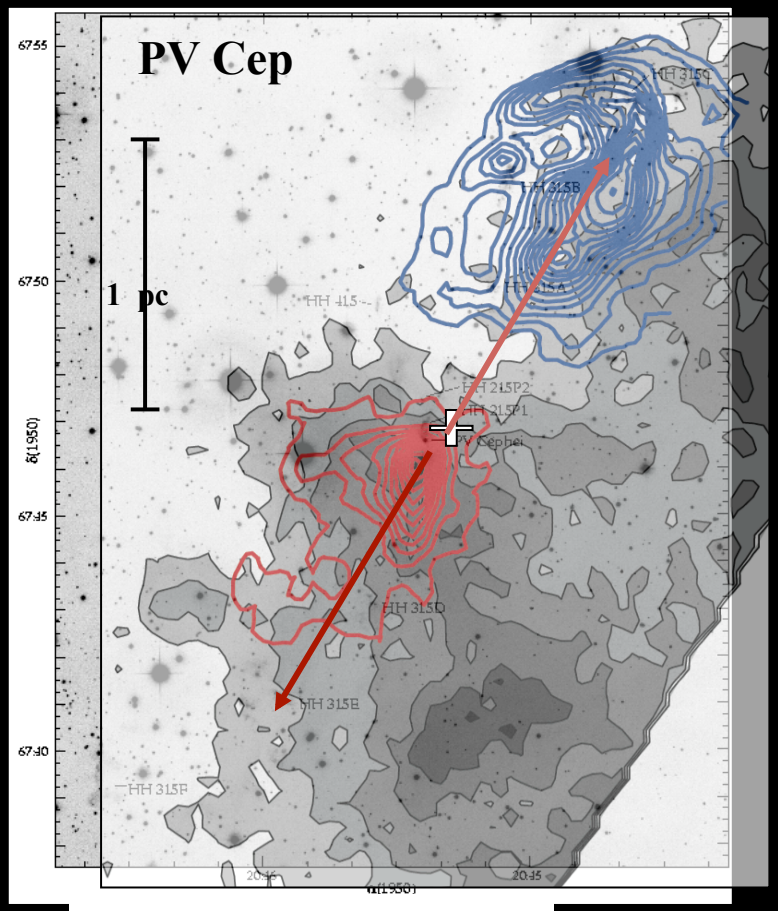
mid to late 1990's- wide-field CCD camera surveys of star-forming regions: giant HH flows discovered

(e.g., Eislöffel & Mundt 1997;
Reipurth et al. 1997)



HH 315 - Reipurth et al. 1997

Impact of giant outflows on cloud:



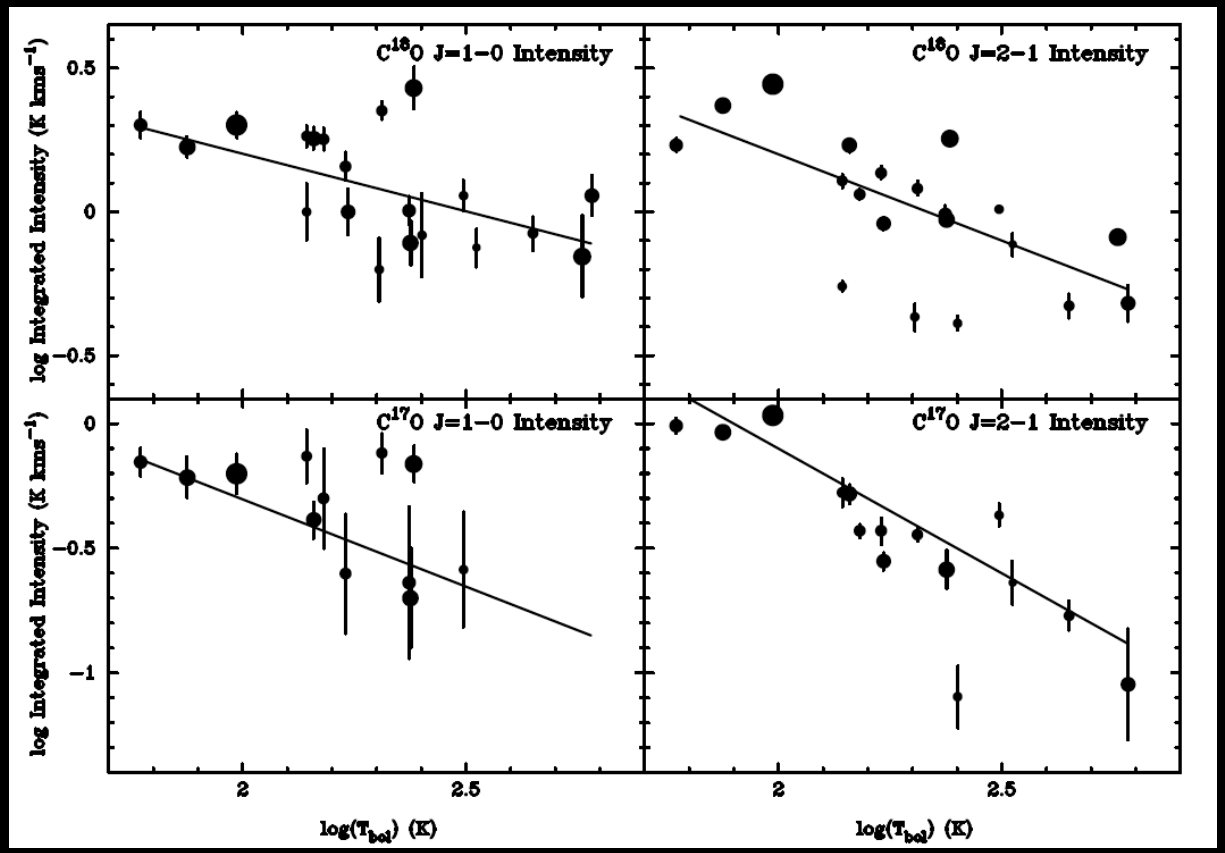
Arce & Goodman 2002

Greyscale: ^{13}CO cloud
Blue and Red Contours: ^{12}CO outflow

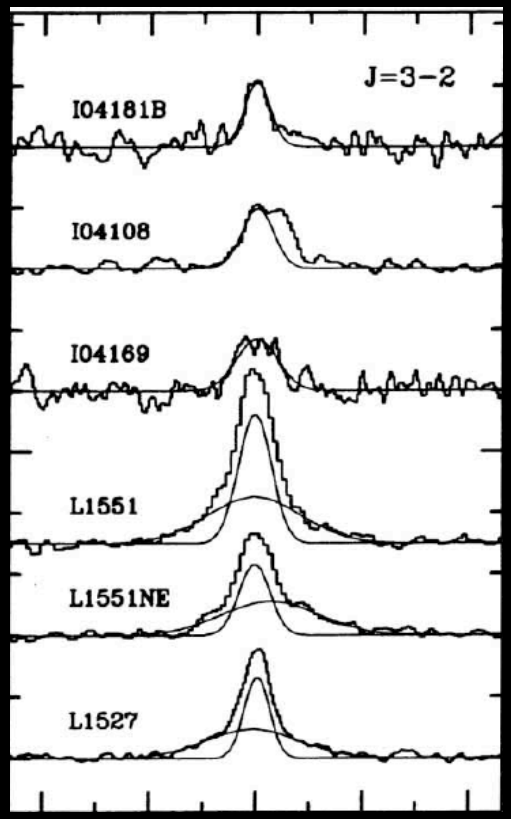
- Outflows can affect density structure of cloud by pushing gas around (e.g., producing cavities and shells)
- Outflows impact kinematics of cloud
- Energy enough to disrupt cloud or drive turbulence within ~2 pc region

Evolution of cores form single pointing observations

Ladd, Fuller & Deane 1998



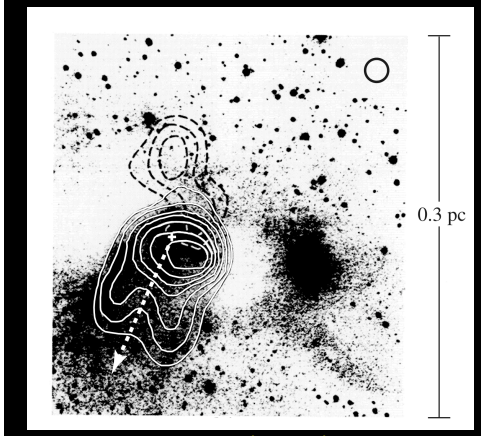
Fuller & Ladd 2002



- Decrease in core mass with time (i.e., evolutionary stage) due to outflow and infall
- Find broad component in $C^{18}O$ spectra of core that traces outflow–core interaction contain sufficient energy to clear core in ~10^5 yr

The core-outflow-phil connection

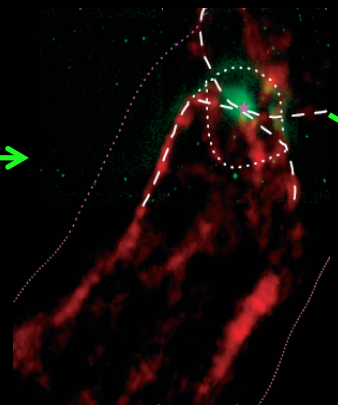
Phil-related outflow studies



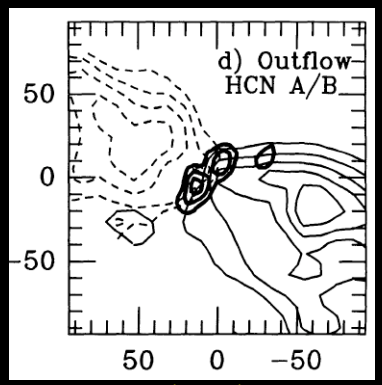
Mathieu et al. (1988)

High-res mapping of individual outflows

L43

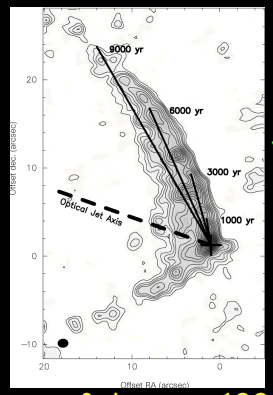


Lee et al. (2005),



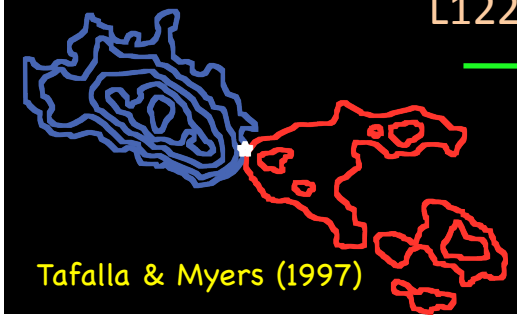
Fuller et al. (1991)

B5-IRS1

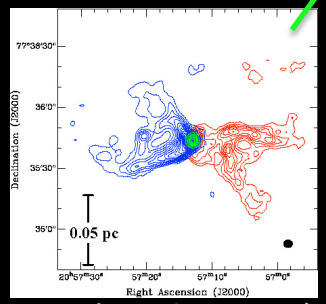


Velusamy & Langer 1998

L1228

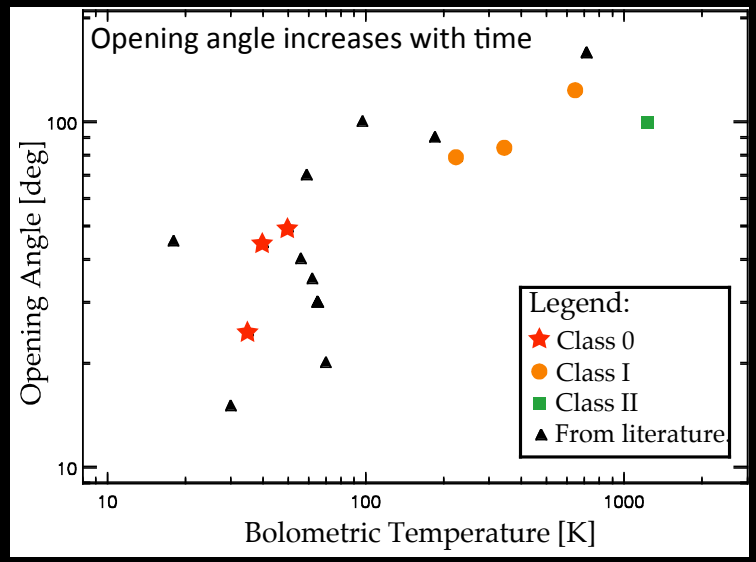


Tafalla & Myers (1997)



Arce & Sargent (2004)

OVRO survey + outflows from lit.



Arce & Sargent (2006)

Outflows play crucial role in evolution of envelope

Evans et al. (2009)

Myers 2008

Protostar Mass due to Infall and <u>Dispersal</u>

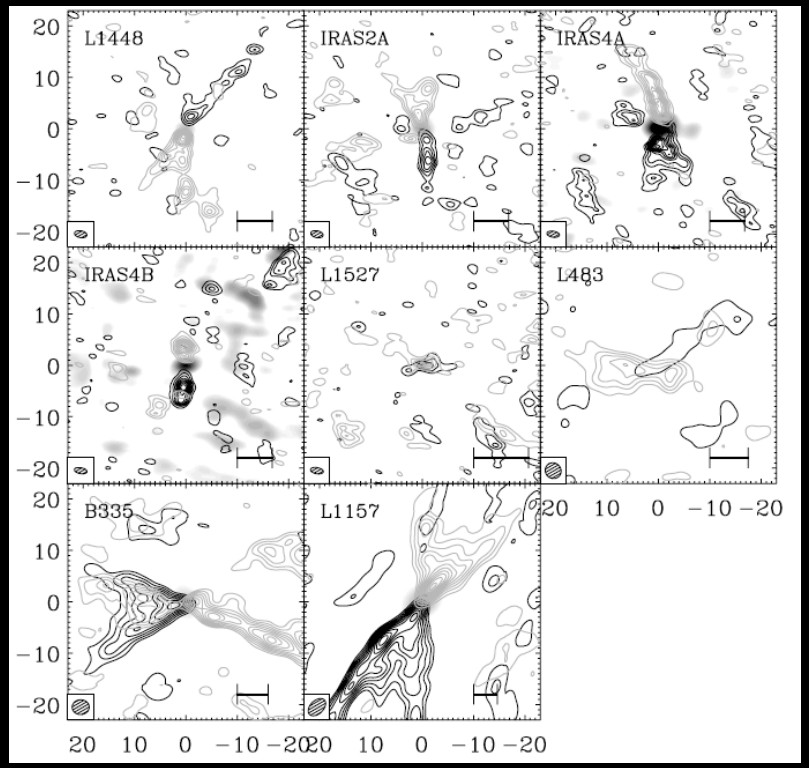
(outflow impacts final mass of star, like in Adams & Fatuzzo 1996)

More outflow-related work associated with Phil

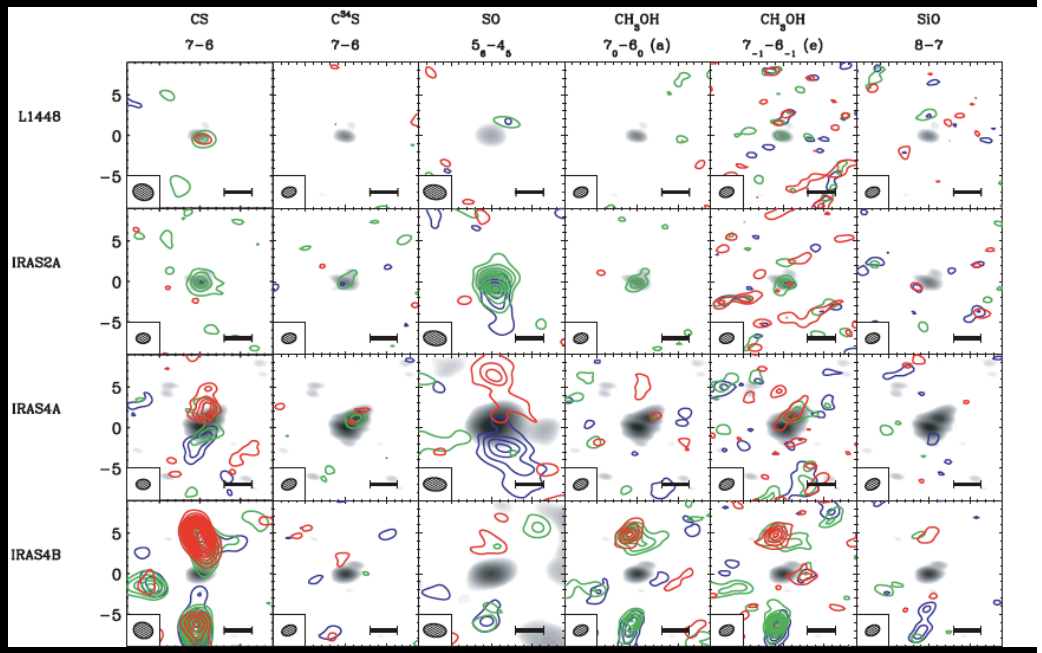
PROSAC – PROtostellar Submillimeter Array Campaign

Jørgensen, Bourke, Myers et al. 2007

CO(2-1) outflow gallery



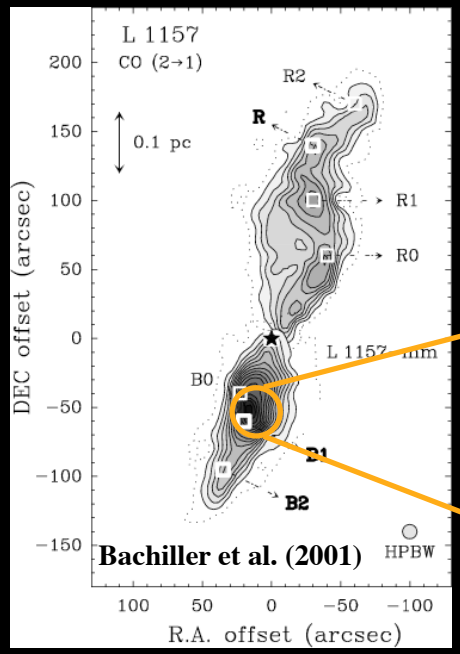
Other molecules in a sub-set of sample



- Outflows play important role in structure of envelope
- Shocks present in all scales, traced by CH_3OH and other mol.
- Rich chemistry of hot corinos may be due to outflow shocks

Complex Molecules in Outflows

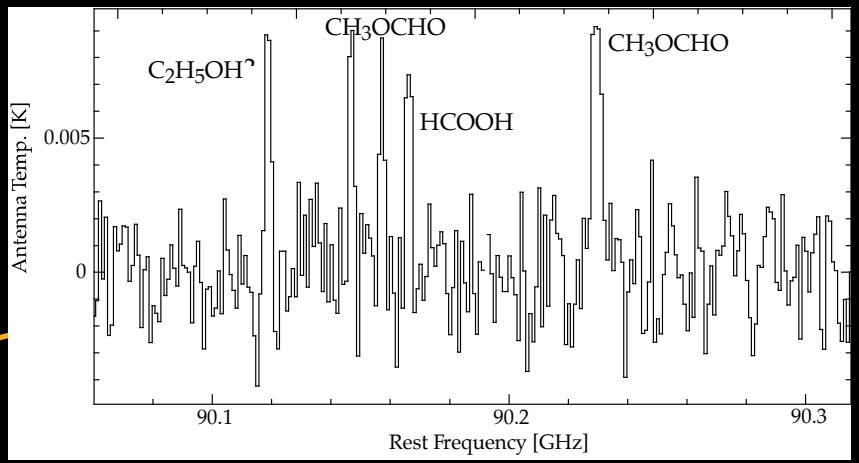
L1157 molecular outflow

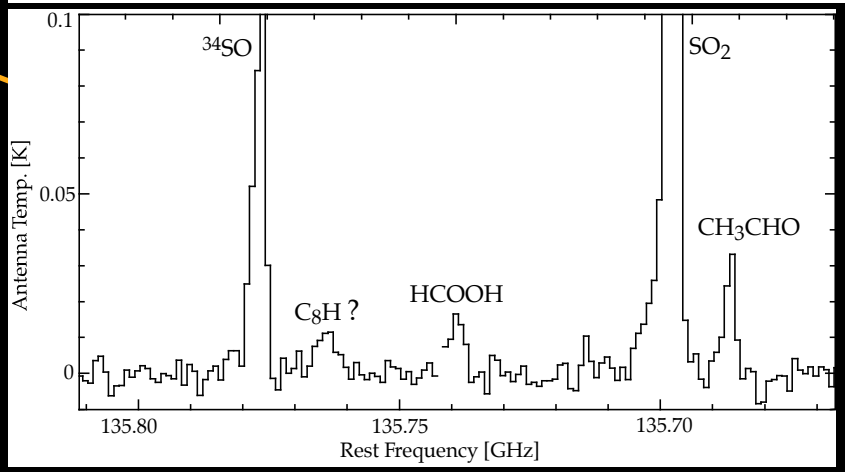


Bachiller et al. (2001)

IRAM 30m

Arce, Santiago-Garcia, Jørgensen, Tafalla & Bachiller (2008)



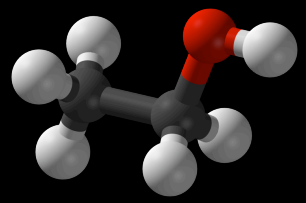


Complex Organic Molecules:

CH_3OCHO (methyl formate)

HCOOH (formic acid)

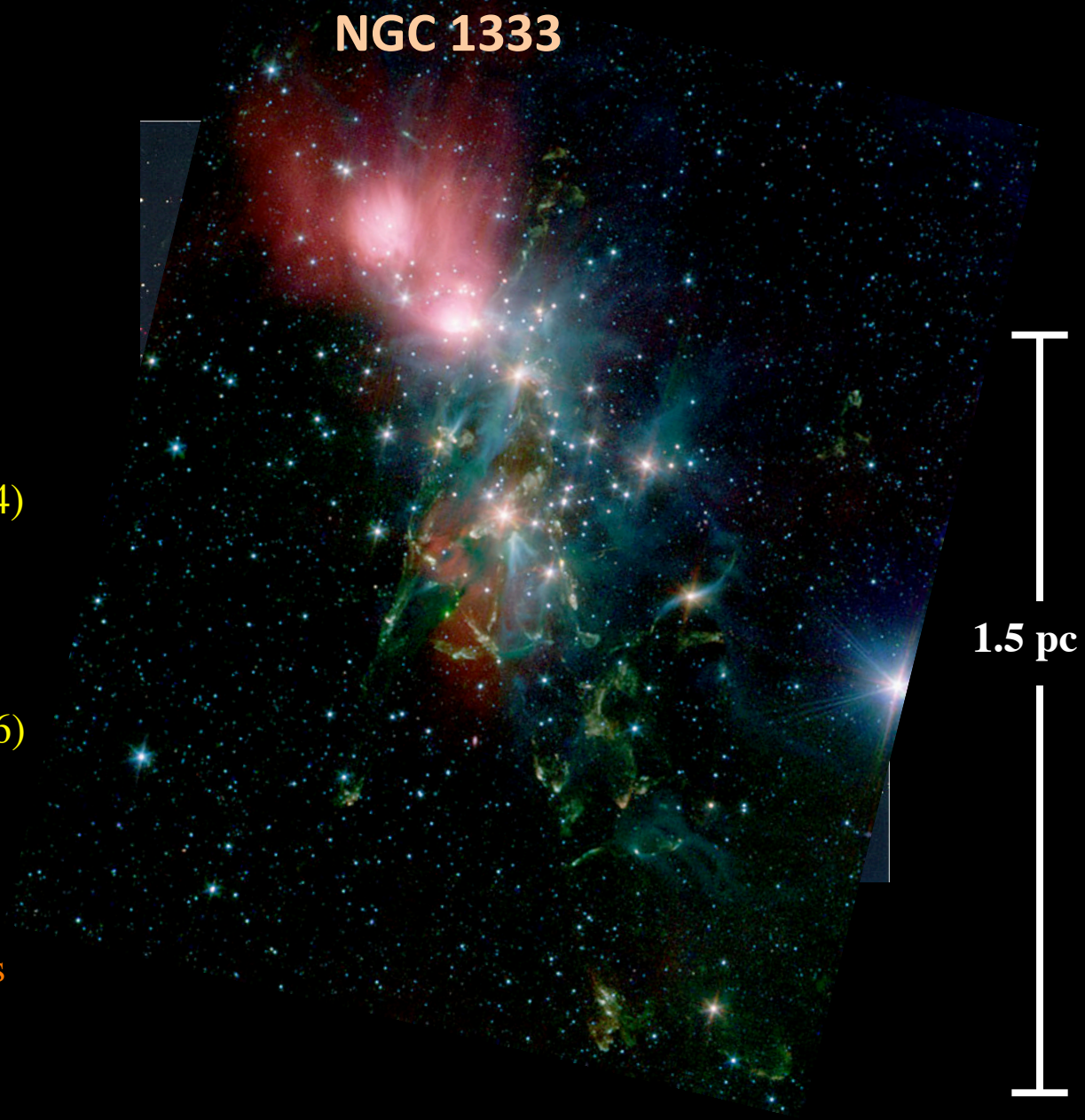
C_2H_5OH (ethanol)



- $\tau_{shock} \sim 10^3$ yr indicates that complex species formed in the surface of grains and were then ejected from the grain mantles by the shock.
- The formation of complex molecules on grains of low-mass star forming regions must be relatively efficient.

More outflow-related work associated with Phil

NGC 1333



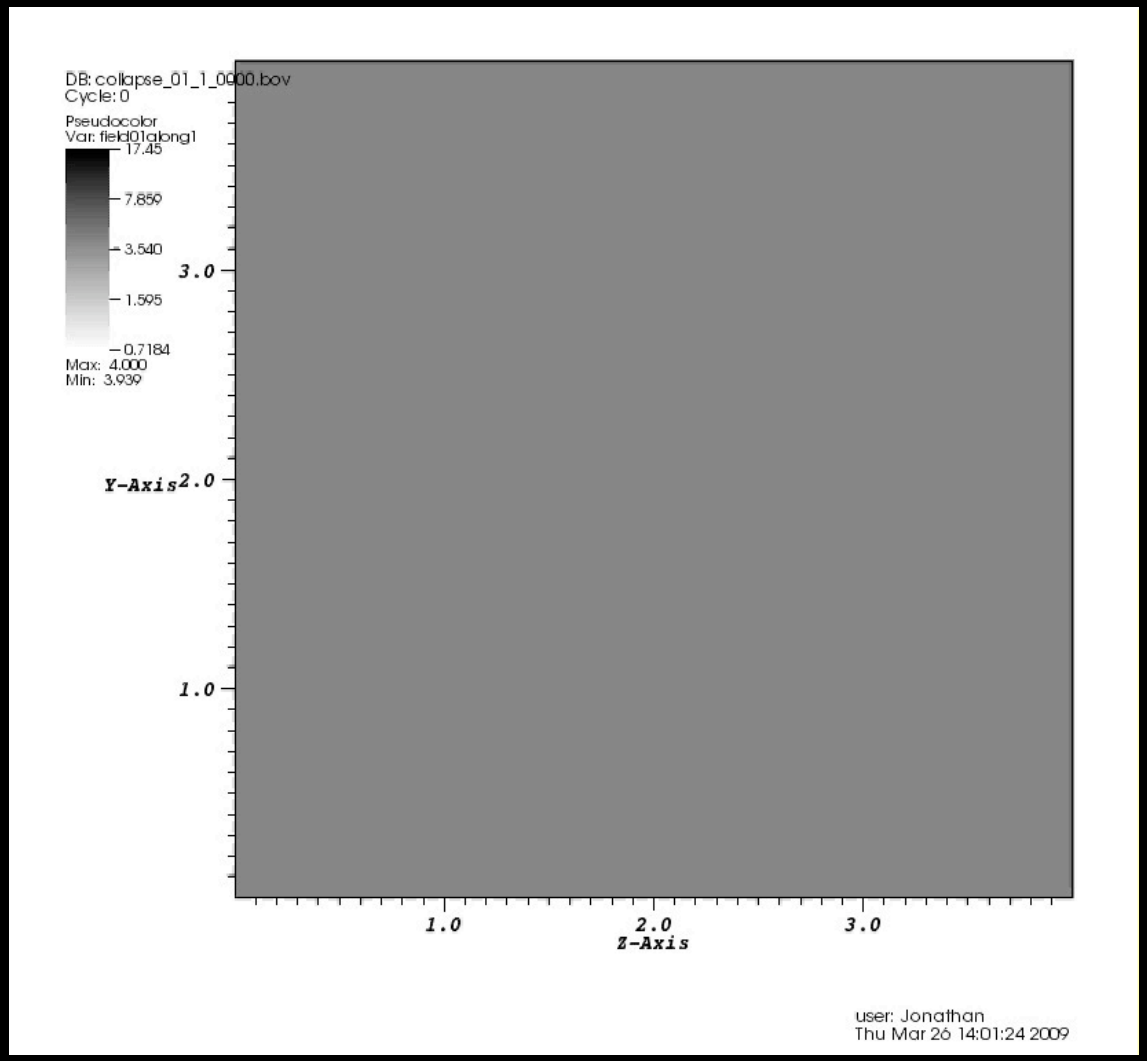
Before 1995:
Herbig (1974)
Aspin et al. (1994)

Mid 1990's:
Bally et al. (1996)

Today:
Gutermuth, Myers
et al. (2008)

Outflows – future work

NGC 1333 has inspired theorists to study outflow-induced turbulence



Myers, Goodman, Arce recently started collaboration With U. Rochester group led by Adam Frank on simulation of outflows and their impact on cloud

Other groups include:
Nakamura & Li 2007
Matzner 2007

Simulations by Jonathan Carroll (and U. Rochester group led by Adam Frank), See Carroll et al. (2009)

Outflows – future work

Outflow interactions with circumstellar environment: Cores and envelopes (~10^4AU) are primary mass reservoirs of forming stars. Outflows may perturb envelope, affecting mass-assembly and final mass of star (Adams & Fatuzzo 1996; Myers 2008).

-Outflows may be (one) way to get from CMF -> IMF ?

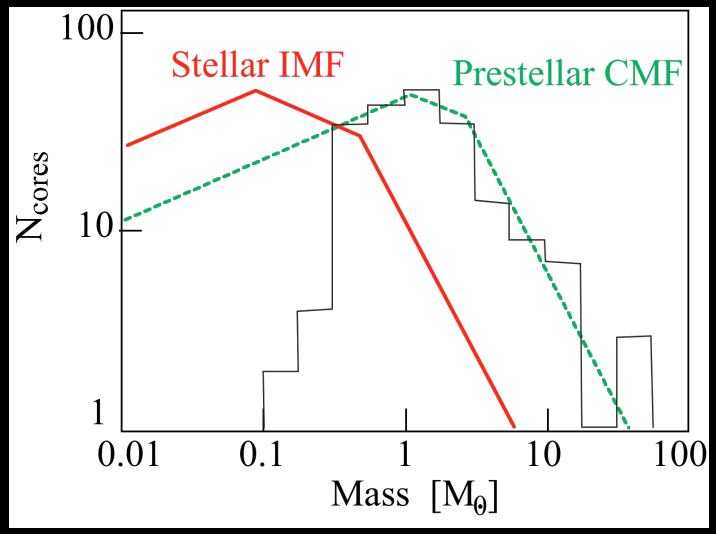
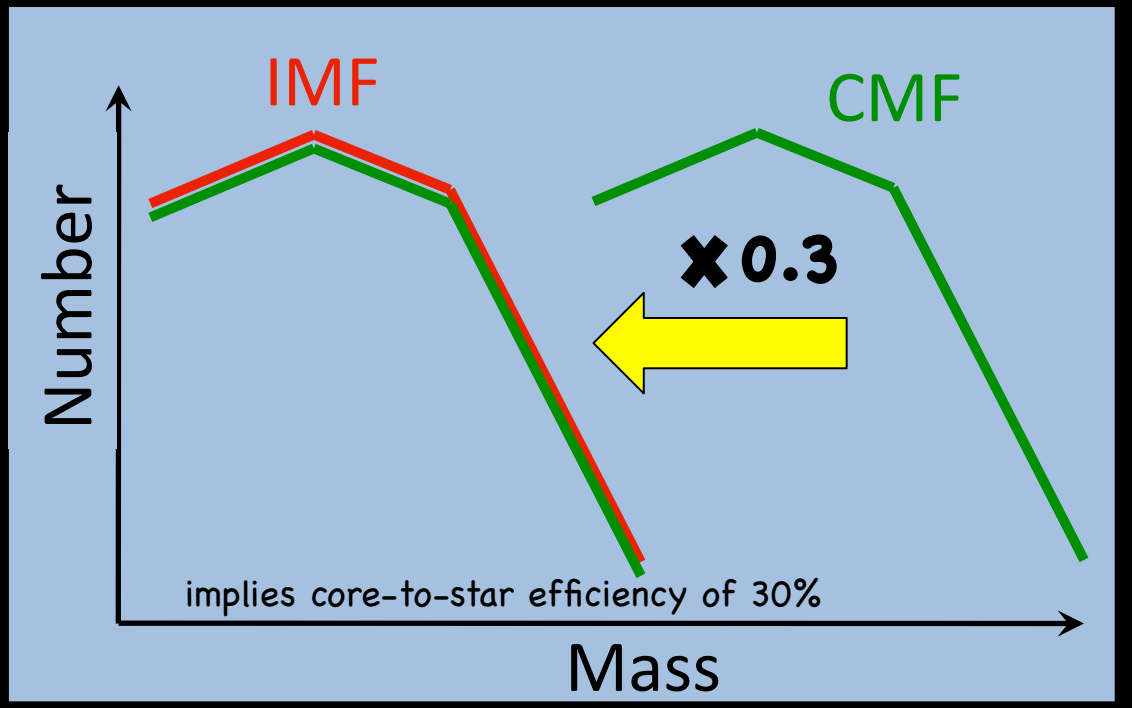
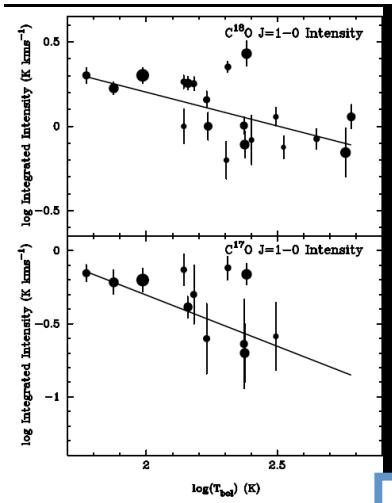
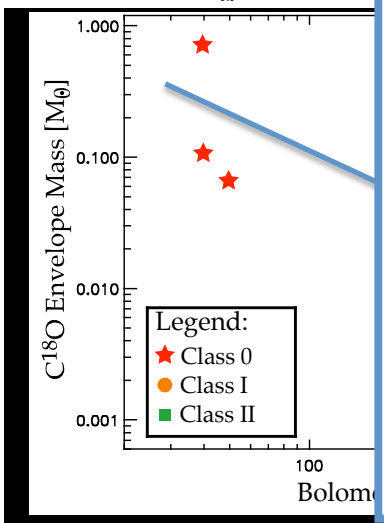
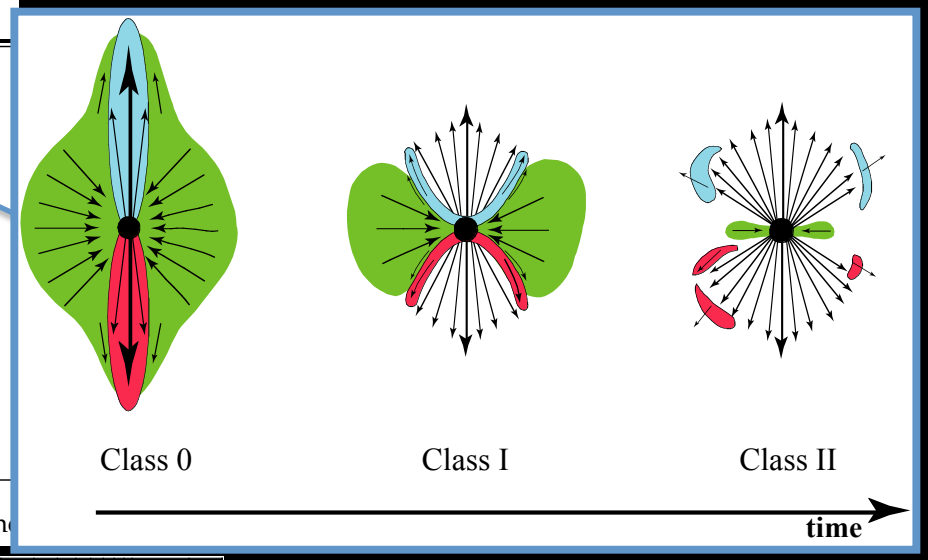


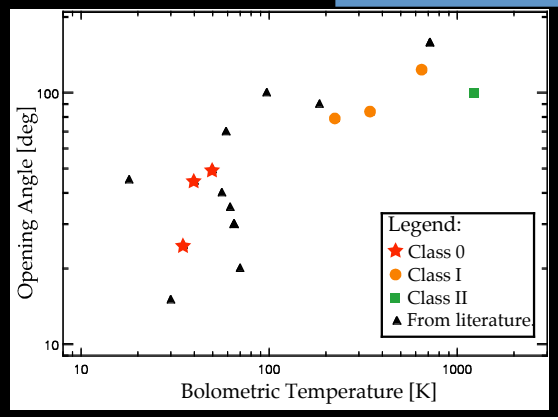
Figure from Nutter & Ward-Thompson (2007)
See also:
Alves et al. (2006)
Enoch et al. (2008)
Rathborne et al. (2009)
and others...



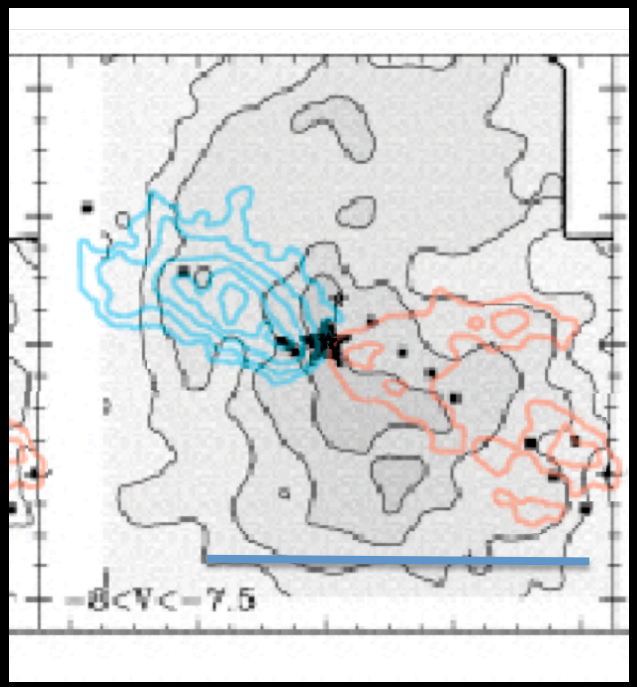

C18O J=1−0 Intensity
C17O J=1−0 Intensity
log Integrated Intensity (K kms−1)
log(Tbol) (K)

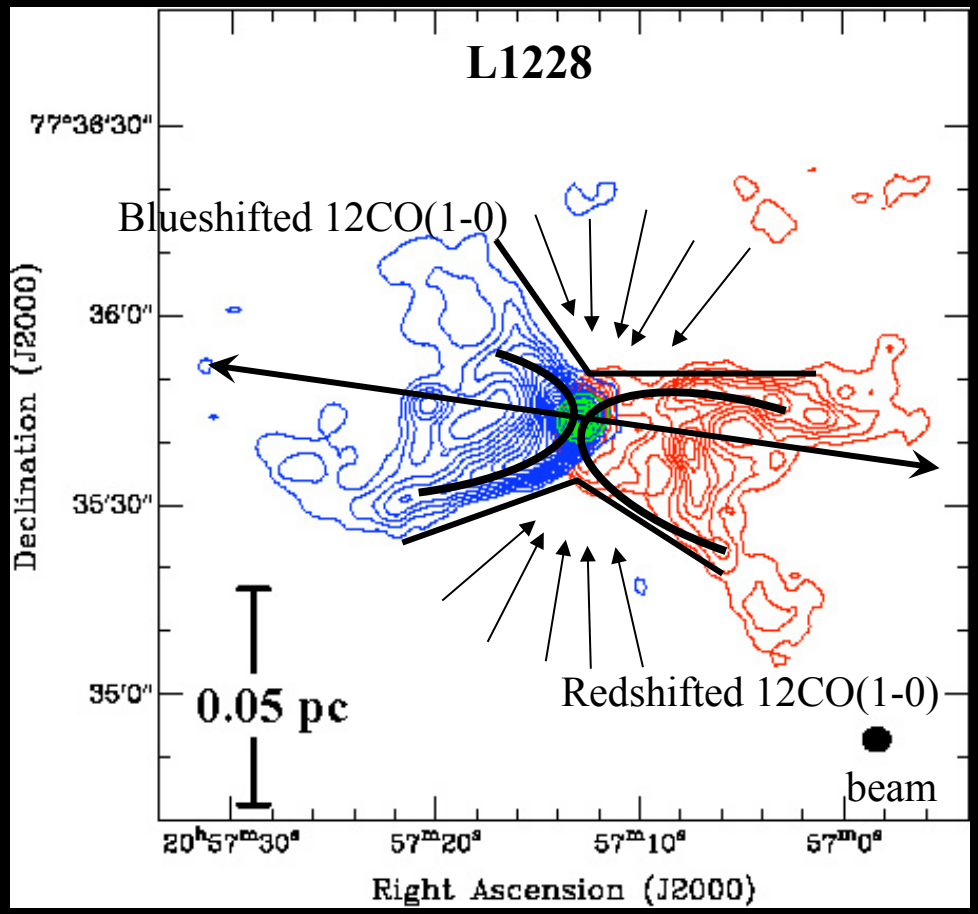

C18O Envelope Mass [M⊙]
Legend:
Class 0
Class I
Class II


Class 0
Class I
Class II
time


Opening Angle [deg]
Bolometric Temperature [K]
Legend:
Class 0
Class I
Class II
From literature

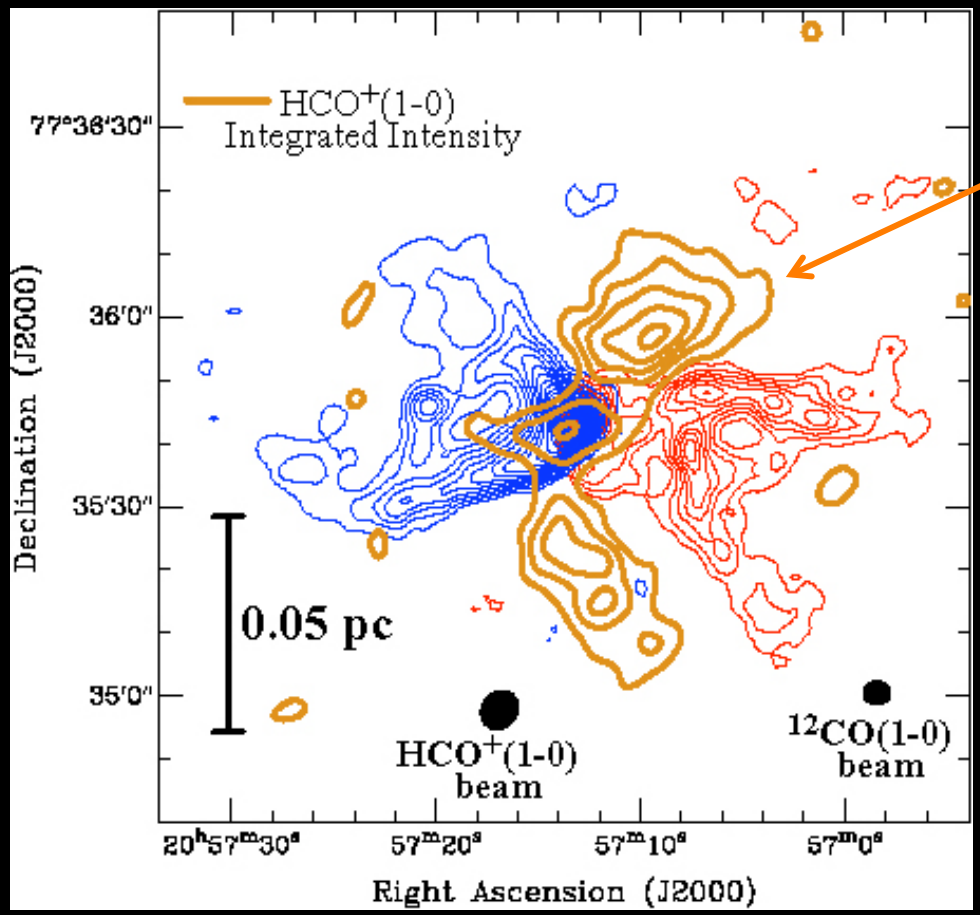
L1228 ^{12}CO(1-0) outflow





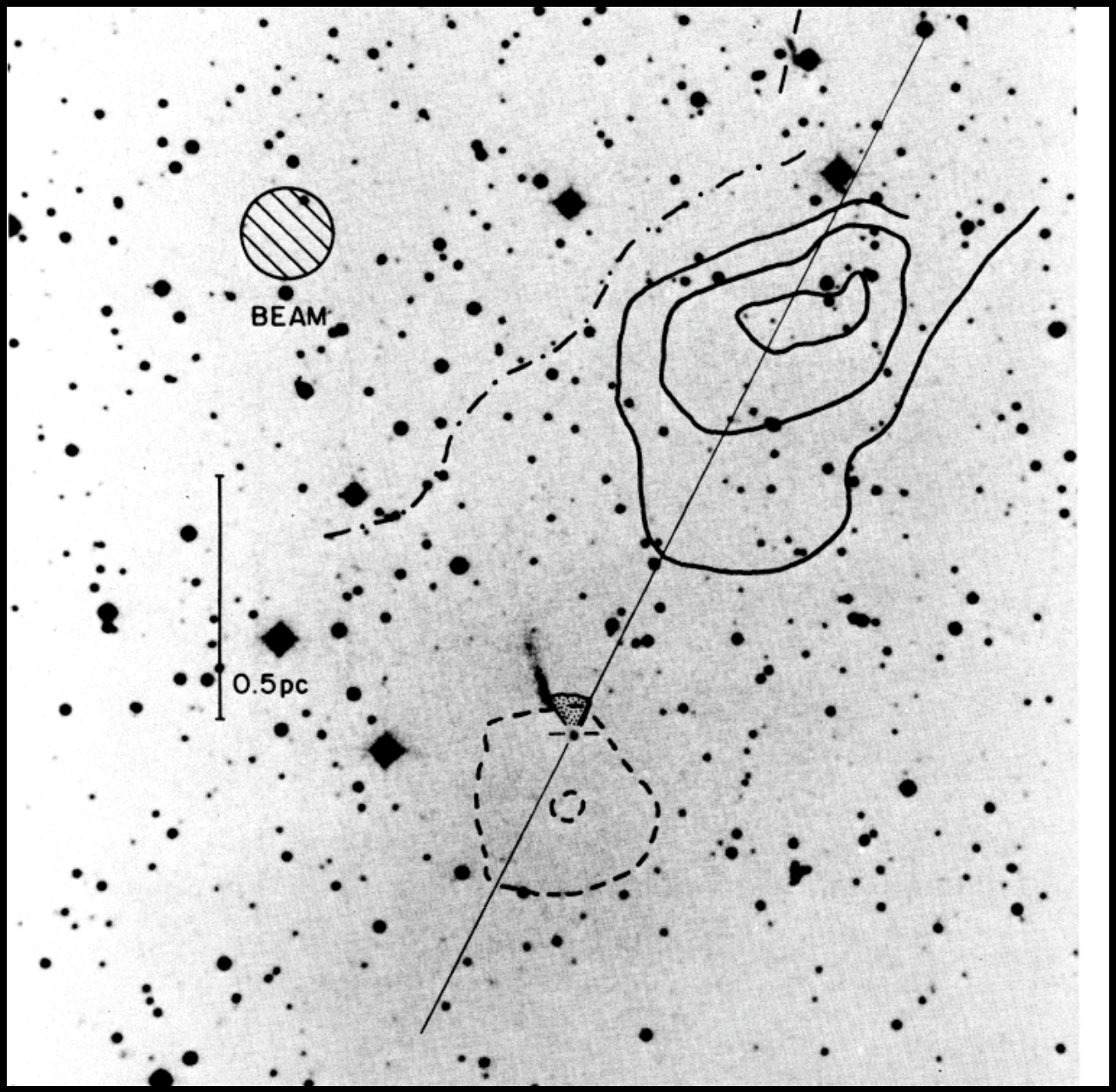
Arce & Sargent (2004)

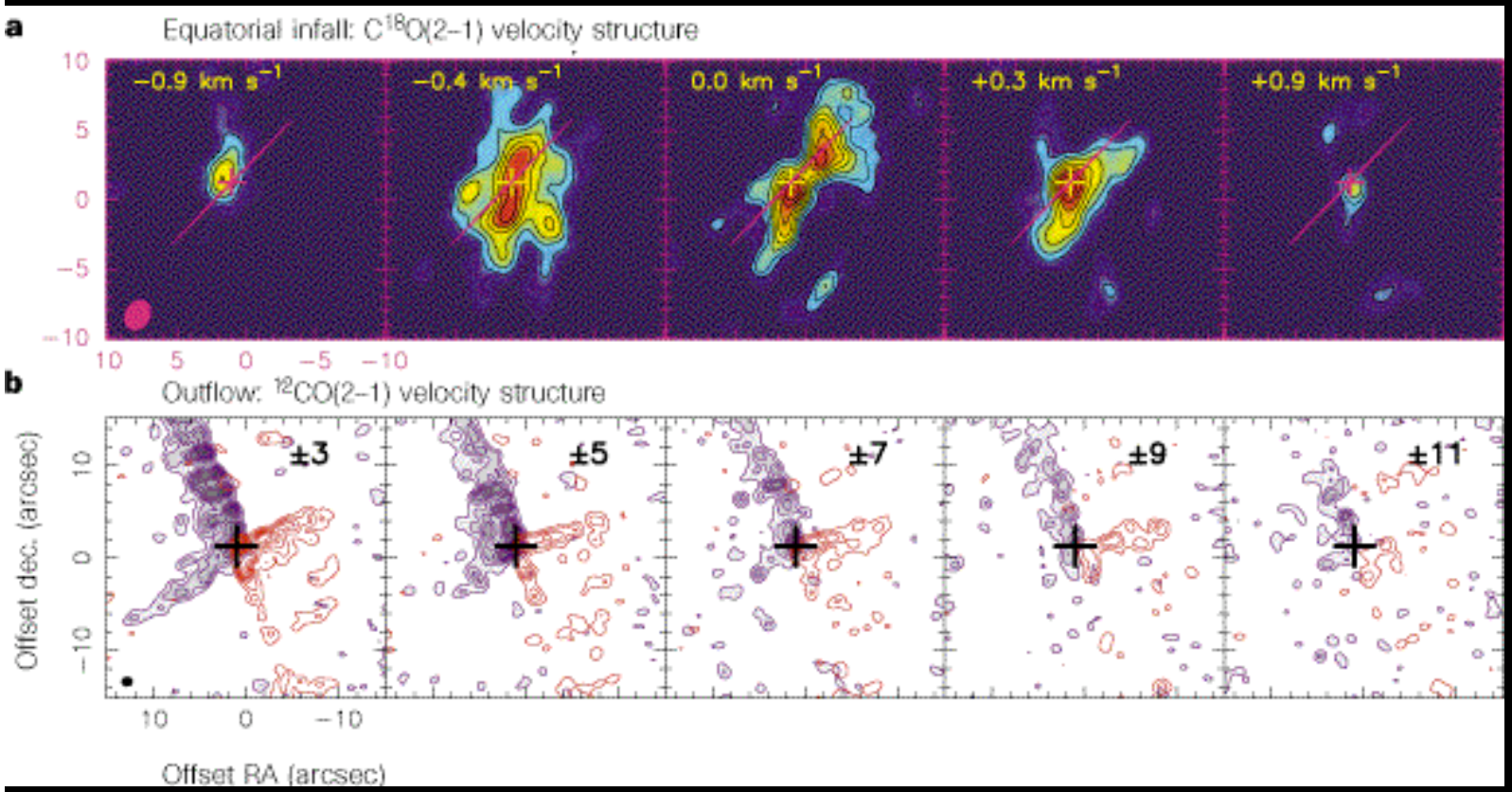
Outflow-envelope interactions in L1228

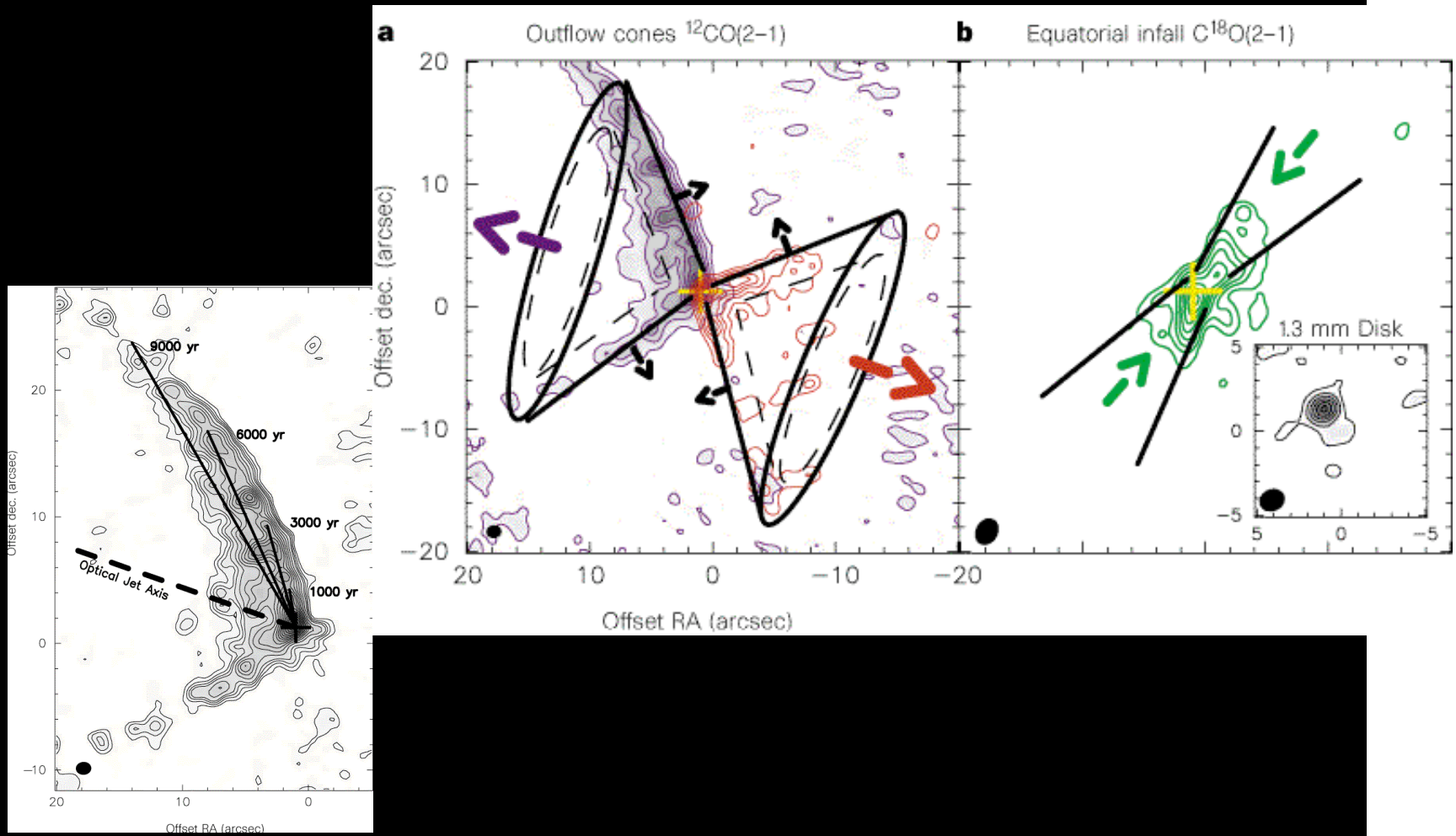


Extended infalling envelope traced by HCO+

Arce & Sargent (2004)


BEAM
0.5pc


a
Equatorial infall: C18O(2–1) velocity structure
−0.9 km s−1
−0.4 km s−1
0.0 km s−1
+0.3 km s−1
+0.9 km s−1
10
5
0
−5
−10
b
Outflow: 12CO(2–1) velocity structure
±3
±5
±7
±9
±11
Offset dec. (arcsec)
Offset RA (arcsec)


a
Outflow cones $^{12}CO(2-1)$
b
Equatorial infall $C^{18}O(2-1)$
Offset dec. (arcsec)
Offset RA (arcsec)
1.3 mm Disk
9000 yr
6000 yr
3000 yr
1000 yr
Optical Jet Axis