Protostellar Outflows

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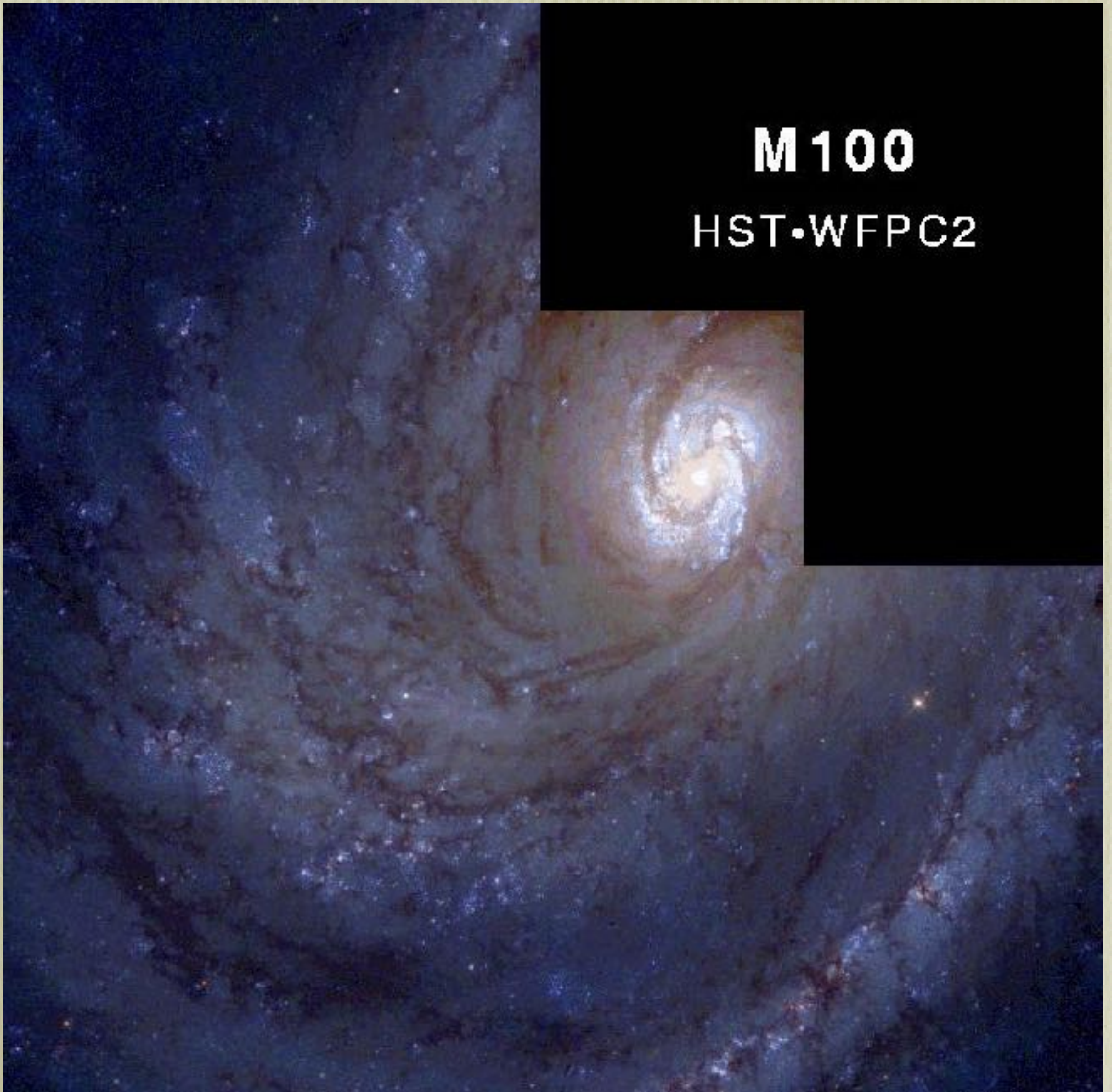
Universidad de Chile

Giant Molecular Clouds



Giant Molecular Clouds:

10-100 pc

10^5 - 10^6 M_{sun}

10^7 yr

Dense Cores

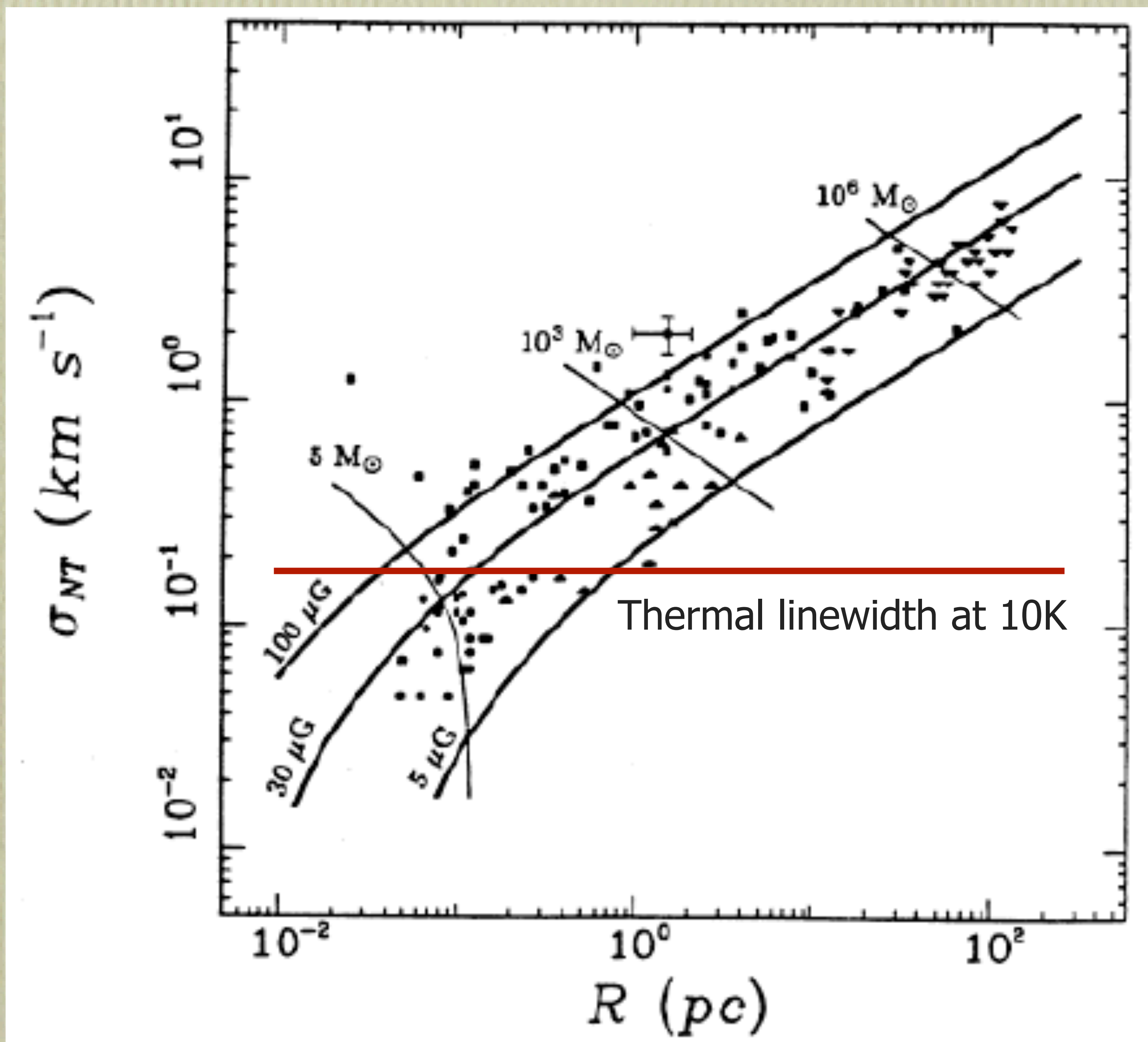
Table 1 Properties of dark clouds, clumps, and cores

	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent ($km\ s^{-1}$)	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

[a]Cloud masses and sizes from the extinction maps by Cambrésy (1999), velocities and temperatures from individual cloud CO studies.
[b]Clump properties from Loren (1989) (^{13}CO data) and Williams, de Geus & Blitz (1994) (CO data).
[c]Core properties from Jijina, Myers & Adams (1999), Caselli et al. (2002a), Motte, André & Neri (1998), and individual studies using NH_3 and N_2H^+.

Bergin & Tafalla, 2007, ARAA

Linewidth-Size



Lowest-mass cores primarily supported by thermal pressure

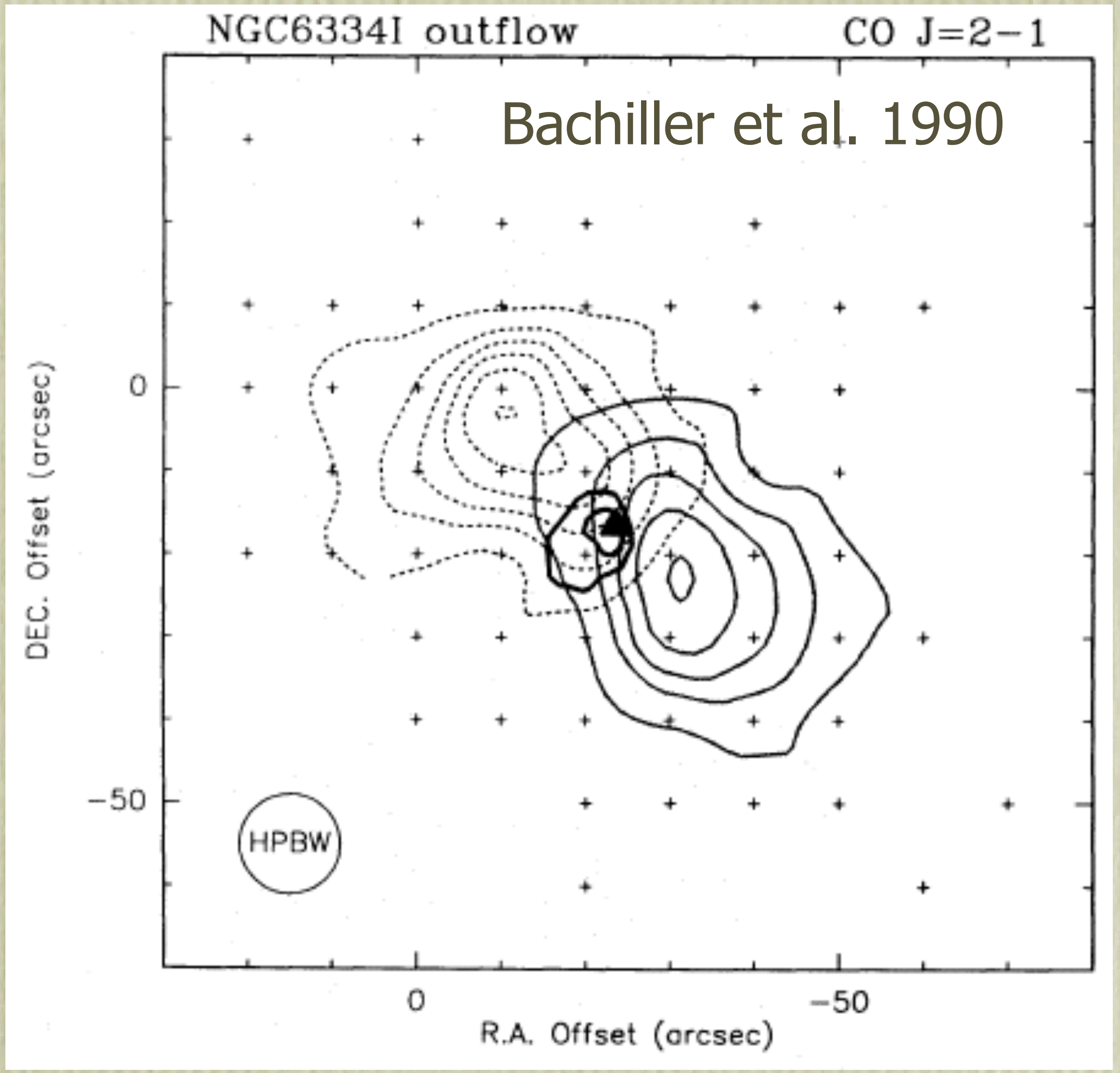
Nonthermal motions dominate in most cores

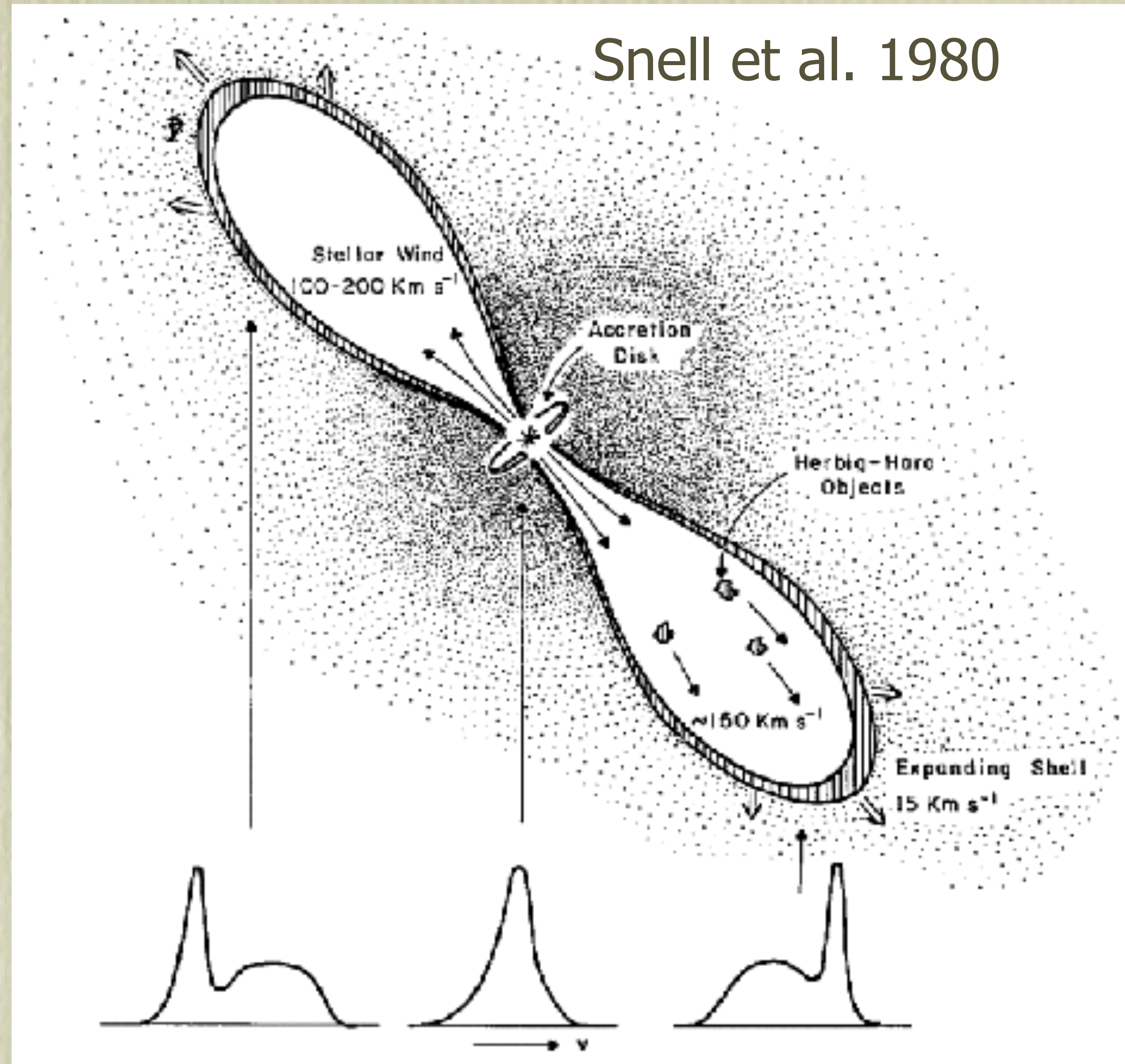
Low-mass cores: $n \propto r^{-1.1}$

Massive Clumps: $n \propto r^{-1.5}$

$$4\pi R^3 P_s + \alpha \frac{GM^2}{R} = 2T + 3c_s^2 M + \beta \frac{\Phi^2}{R},$$

Outflows





Lada, 1985, ARAA; Bachiller, 1996, ARAA; Bally, 2016, ARAA

Star formation cartoon

a) Dense core: 0.01 - 1 pc

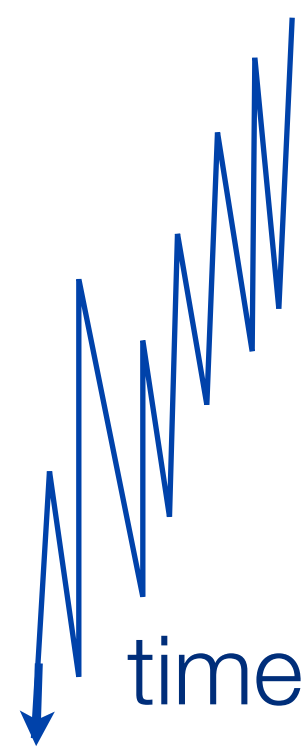
b) Class 0, 10^5 yr

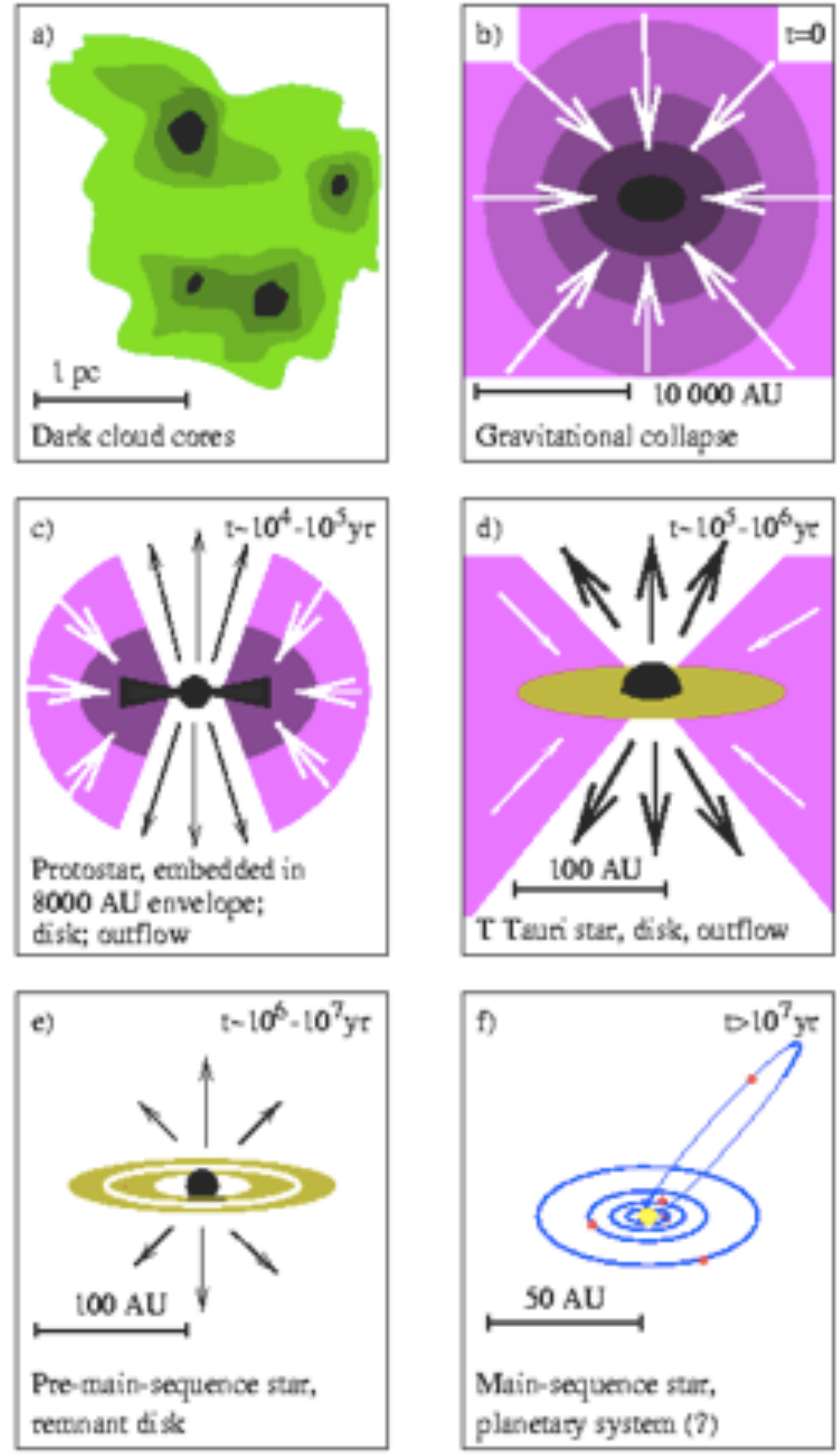
c) Class 0/I, 4×10^5 yr

(Evans et al 2009)

d) Class I/II, 10^6 yr

e) Class III, 10^7 yr





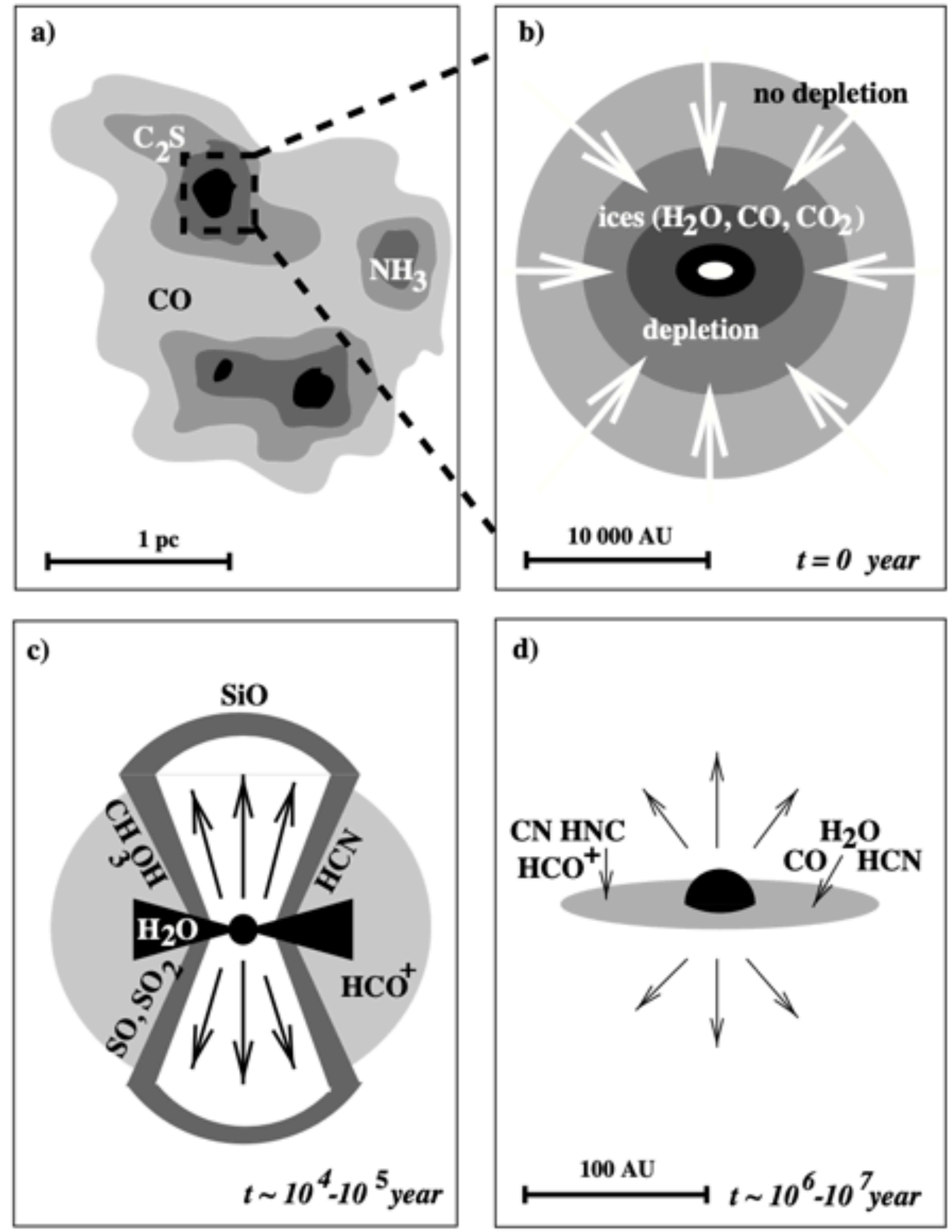
Hogerheijde 1998, after Shu et al. 1987

Outflows

i. Solve angular momentum problem (launching)

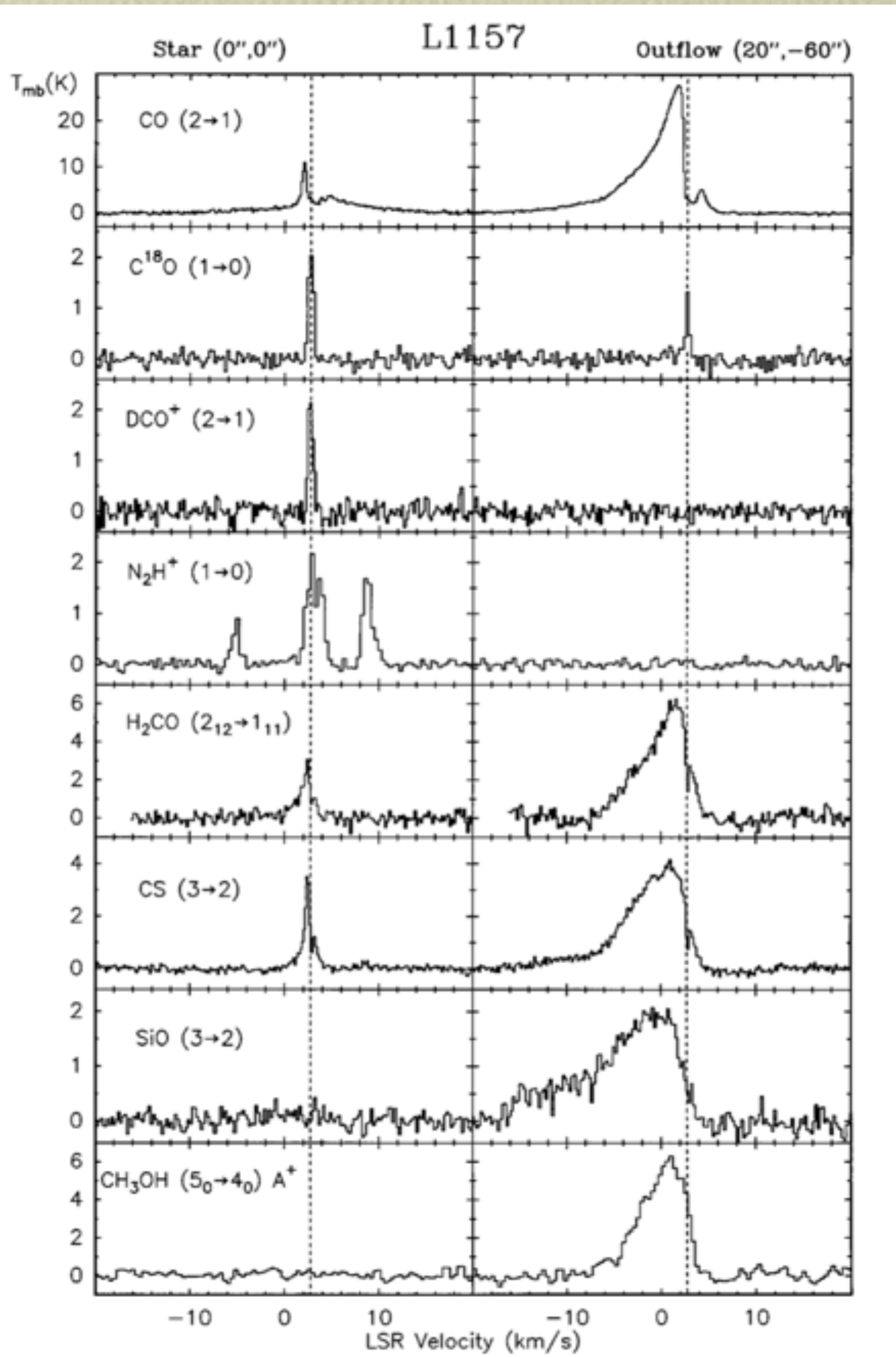
ii. Provide feedback mechanism to disperse clouds, and end star formation (determines stellar masses)

iii. Shocks, chemistry.

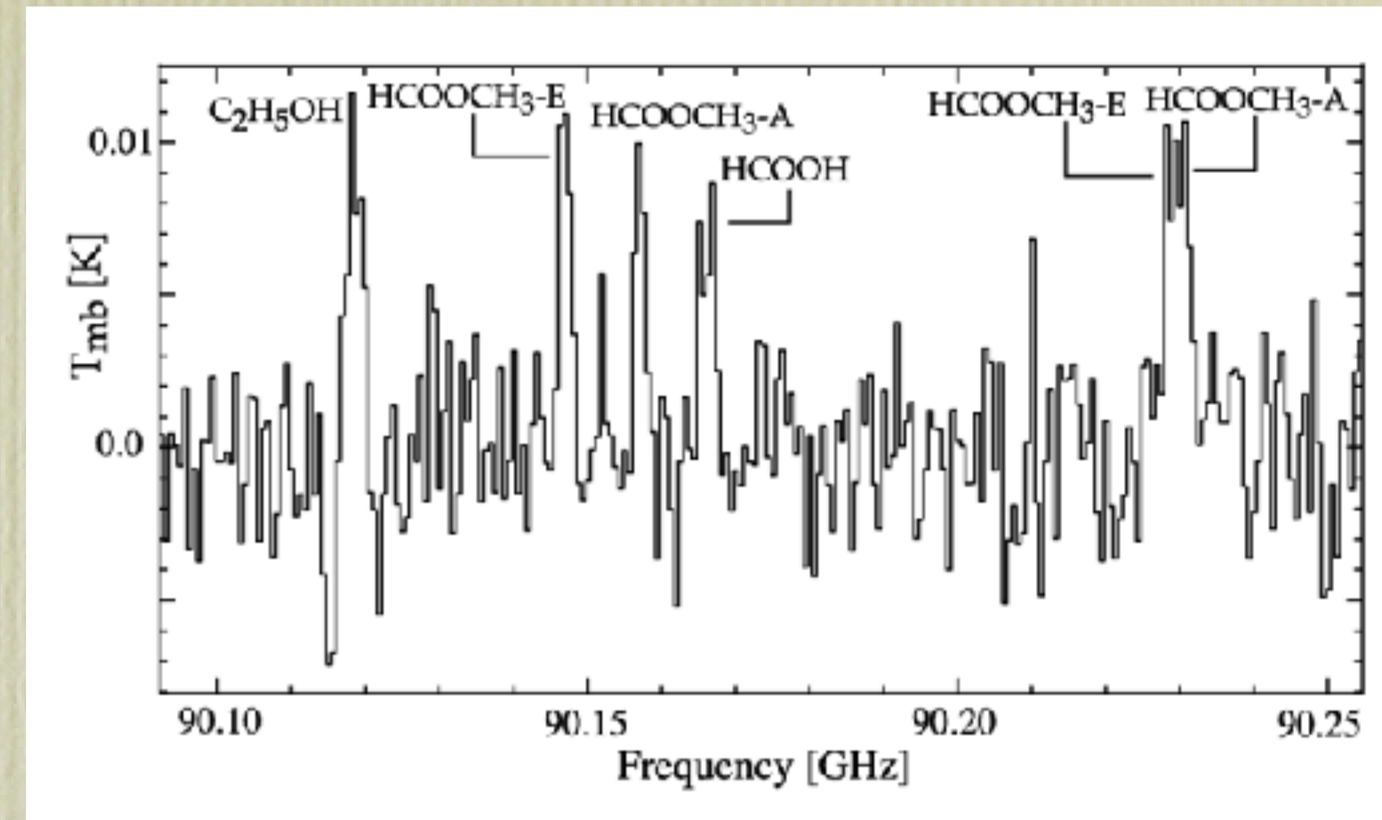


Van Dishoeck 1998

L1157



Bachiller 1996

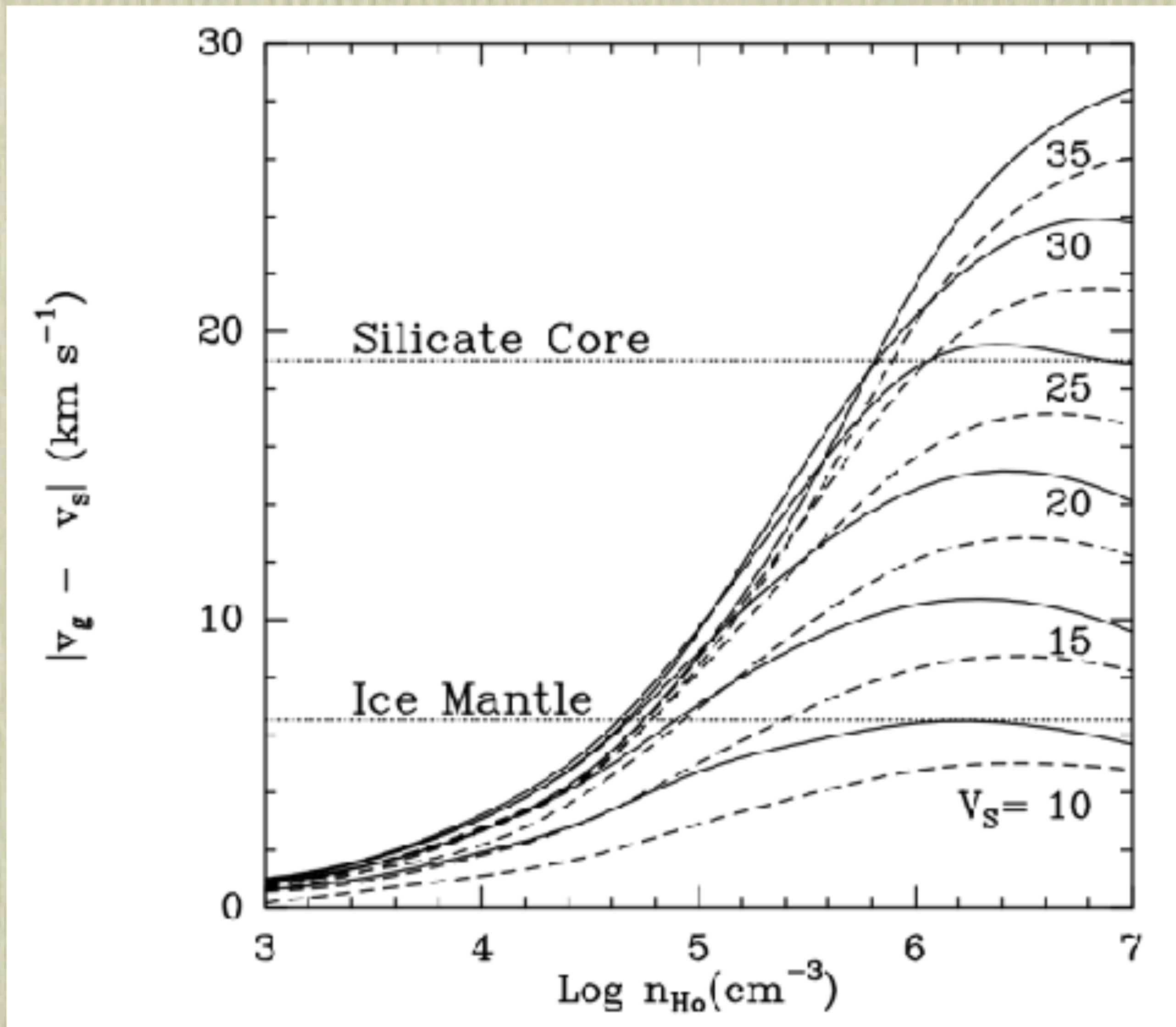


Molecule	T_{rot} (K)	N (10^{13} cm^{-2})	$X = N/N_{H_2}$ (10^{-8})
$HCOOCH_3$-A[a]	27 ± 4	15 ± 4	11 ± 3
$HCOOCH_3$-E[a]	18 ± 13	12 ± 11	8 ± 7
CH_3CN[a]	110 ± 50	0.1 ± 0.05	0.07 ± 0.04
HCOOH[b]	10	8	5
C_2H_5OH[c]	25[d]	10	7

COMs: Arce 2008

Shocks

grain-grain collisions: Caselli & Hartquist 1997



Anderl 2013

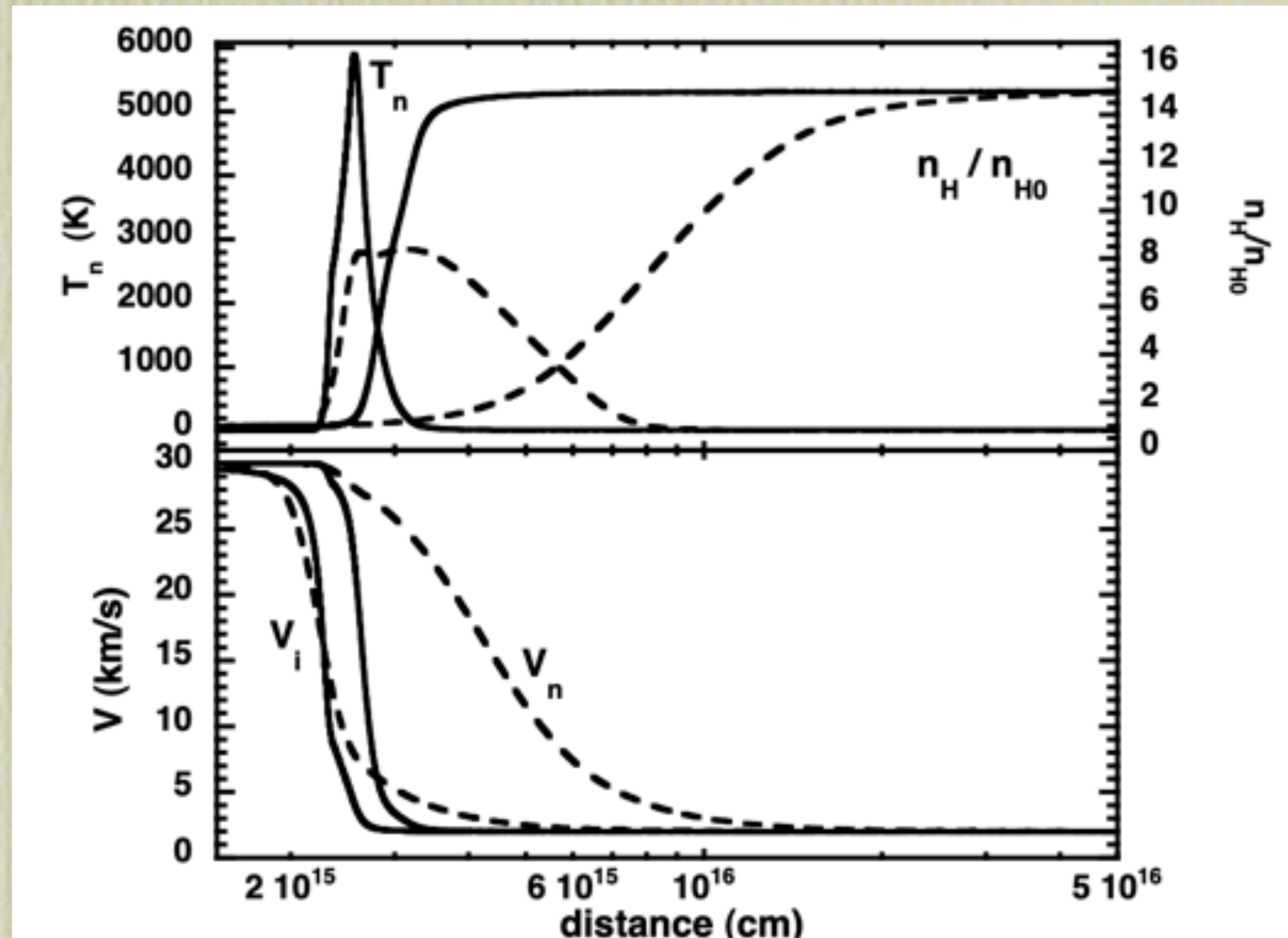


Fig. 1. Temperature and density (*upper panel*) and velocity profiles in the shock frame (*lower panel*) for a 30 km s^{-1} C-type shock with a mag-

Shocks with
V_s > 10 km/s release ice mantles onto the gas phase.
V_s > 25 km/s release silicates onto the gas phase.

The temperature behind the shock can increase to a few x10^5 K in high velocity shocks.

See Chapter 11 in Tielens' 2005 book

Shocks

Flower 2007

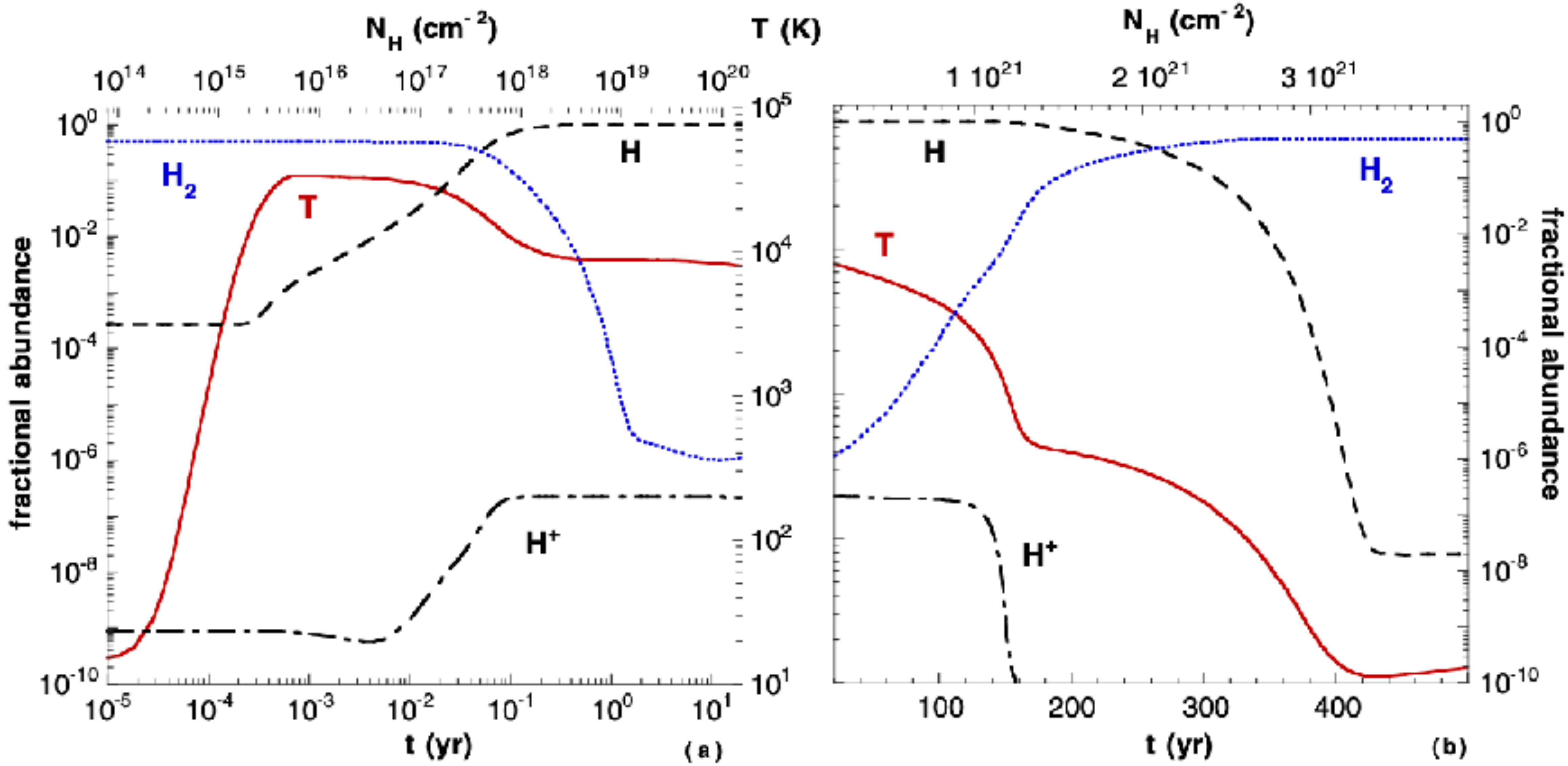
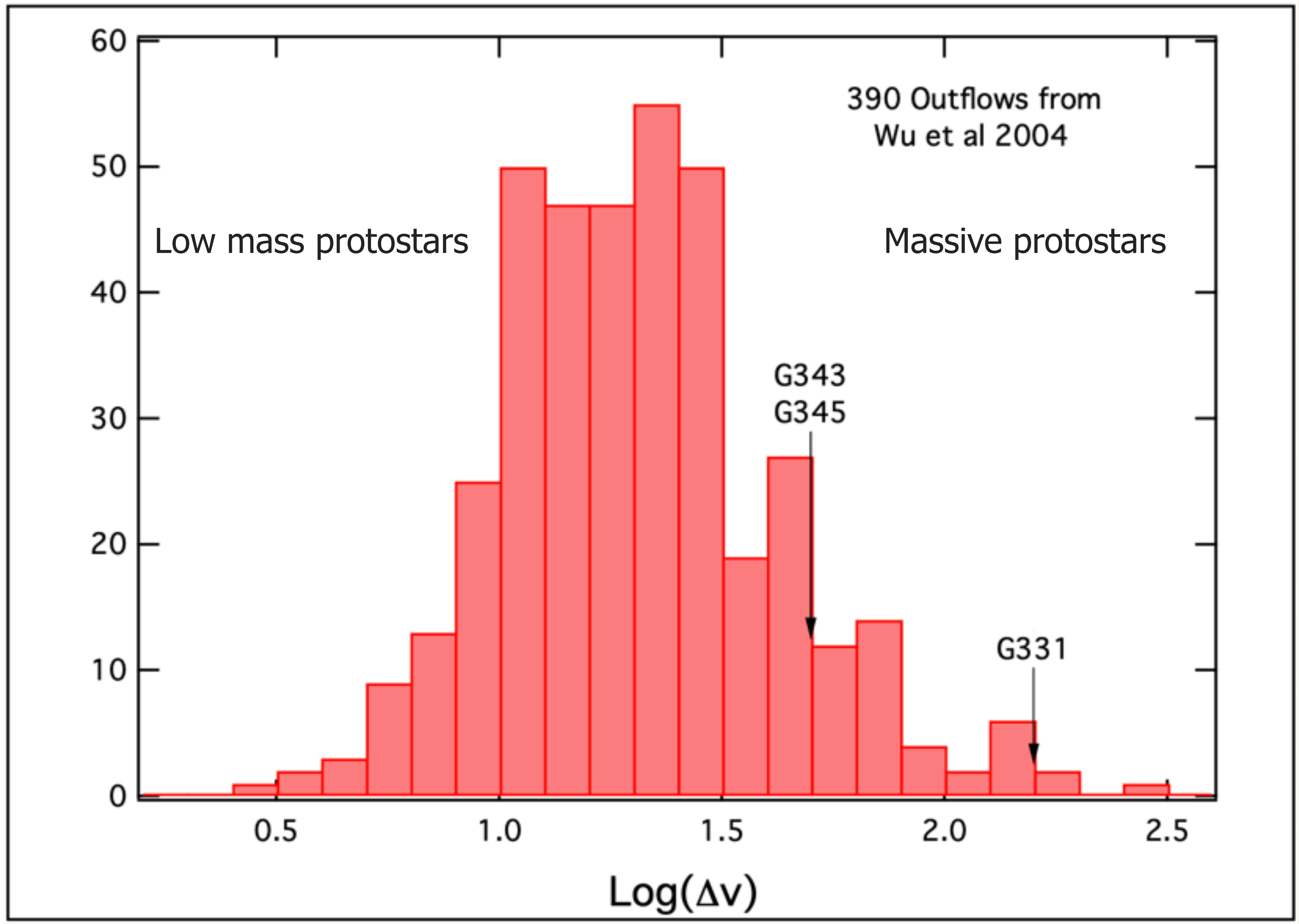


Fig. 2.1. The temperature profile computed for a J–type shock wave with a speed $u_s = 25$ km s^{-1}, propagating into gas of (preshock) density $n_{\rm H} = n({\rm H}) + n({\rm H_2}) + n({\rm H^+}) = 10^4$ cm^{-3}, in the absence of a magnetic field. The fractional abundances

Cooling time behind the shock of a few hundred years.

See Chapter 11 in Tielens' 2005 book


390 Outflows from
Wu et al 2004
Low mass protostars
Massive protostars
G343
G345
G331
60
50
40
30
20
10
0
0.5
1.0
1.5
2.0
2.5
Log(Δv)

Bally, ARAA, 2016, Protostellar Outflows

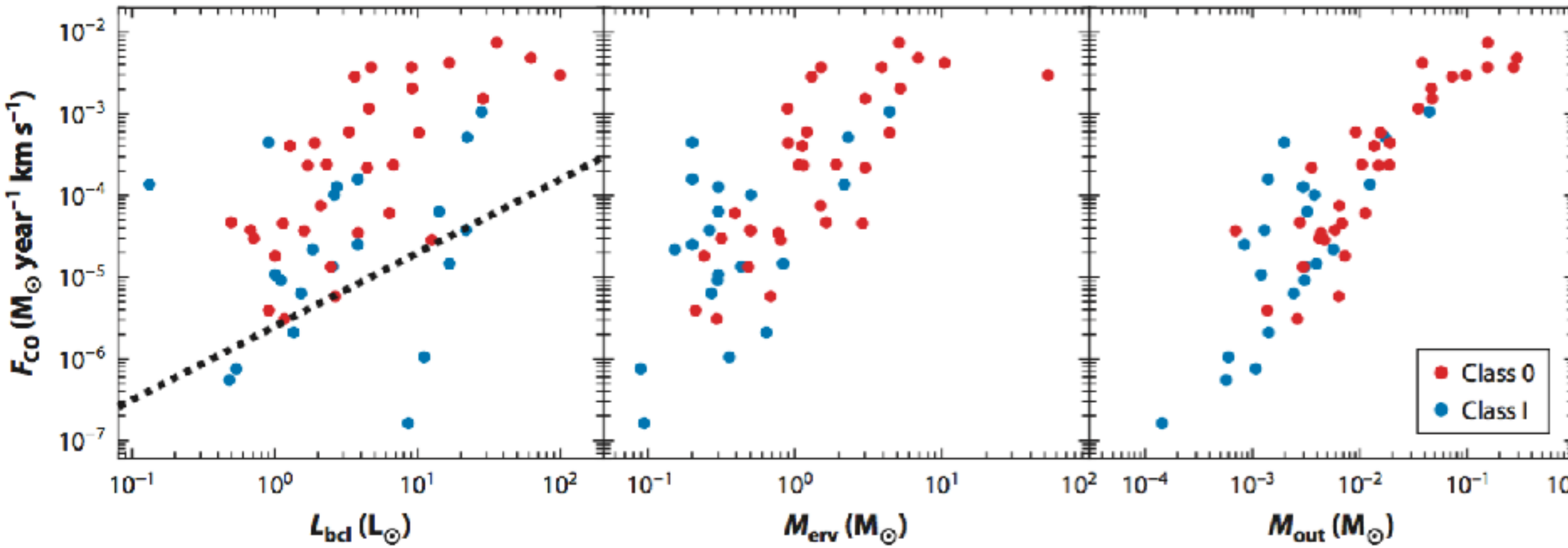
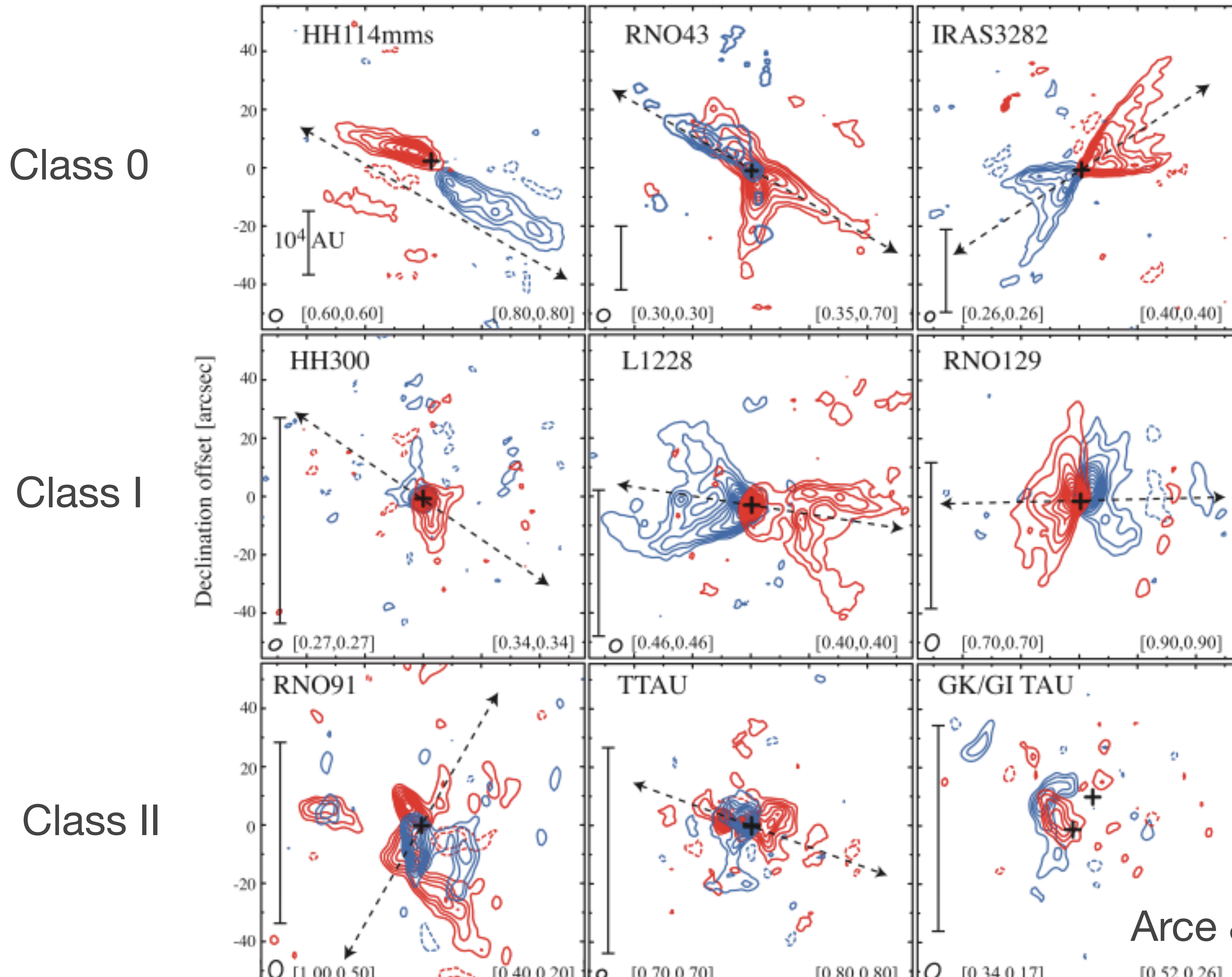


Figure 6

The momentum injection rates as functions of source bolometric luminosity, envelope mass, and outflow mass determined from CO $J = 3–2$ for Class 0 and 1 low-mass young stellar objects. Adapted from Mottram et al. (2016) with permission.

Low mass protostars

Star formation cartoon:
What determines the stellar mass?

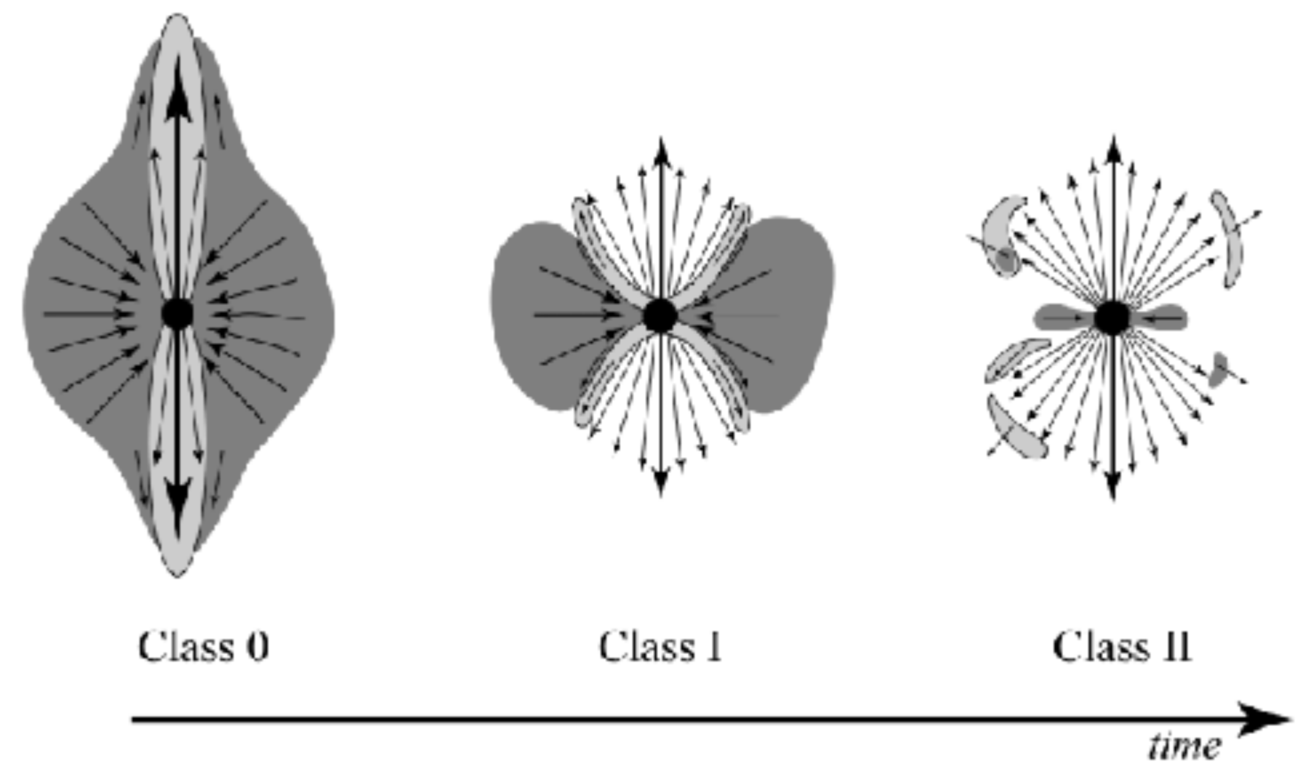


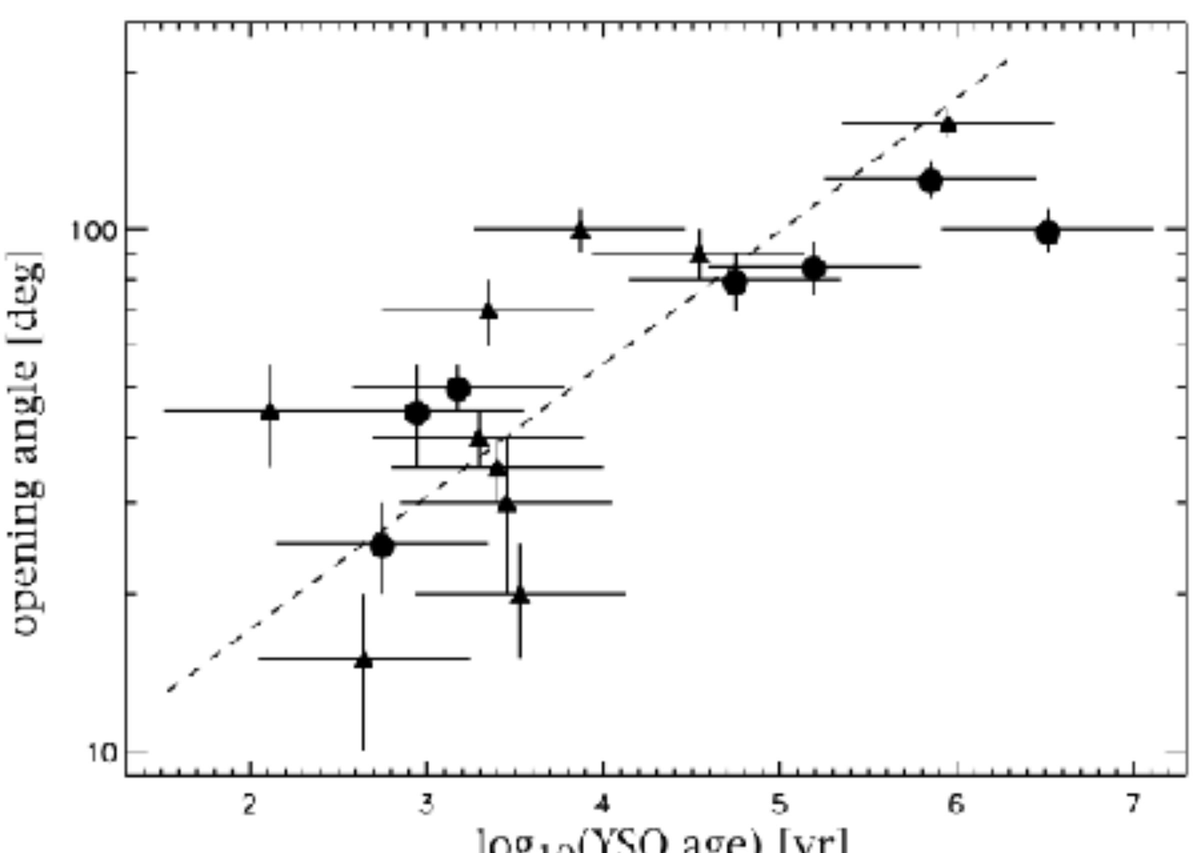
Arce & Sargent 2006

Star formation cartoon:
What determines the stellar mass?

Outflow opening angle increases with time.

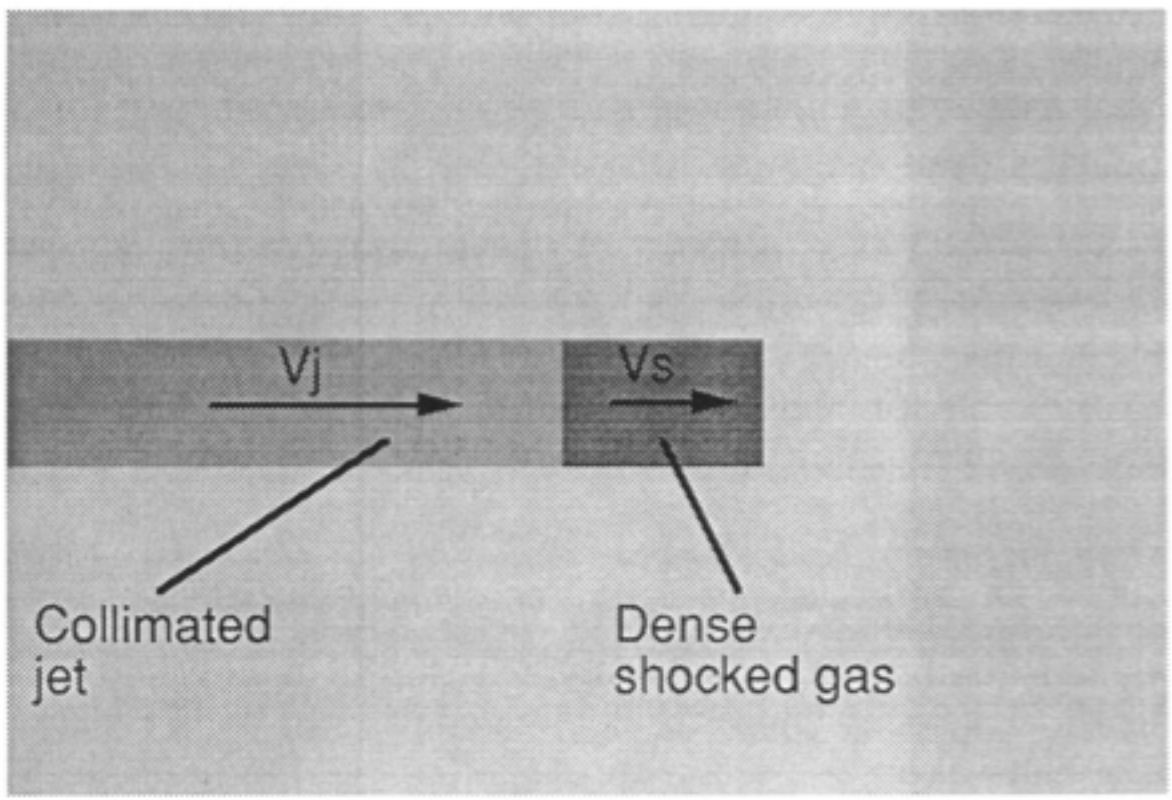
But both time and opening angle are often highly uncertain.

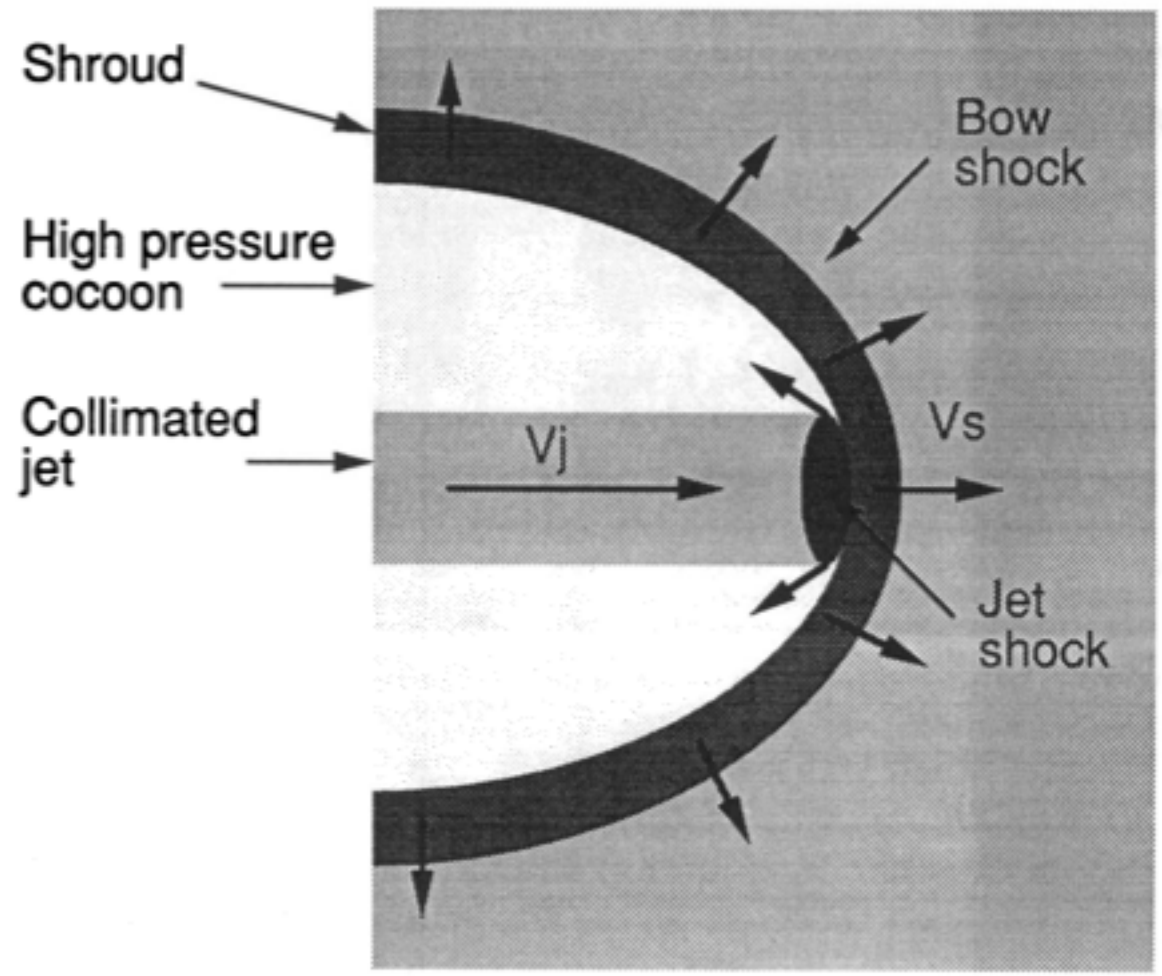




Arce & Sargent 2006

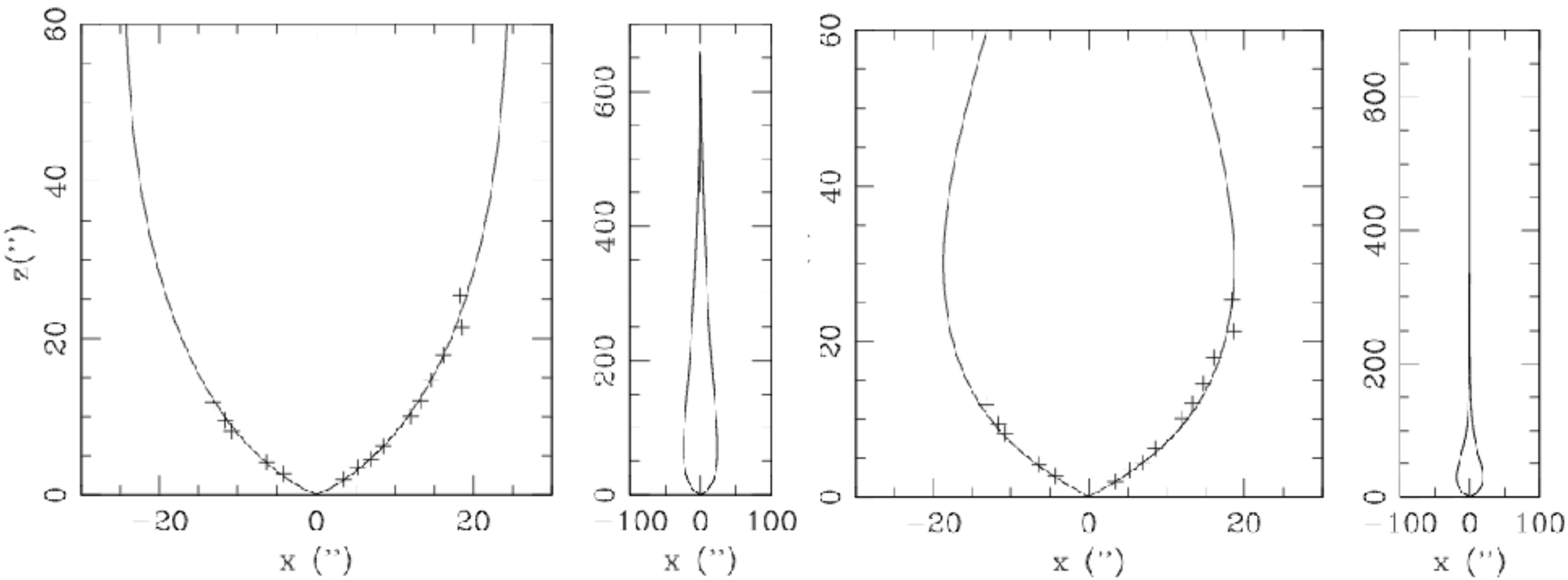
➡ Study outflow-core feedback





Radiative & Adiabatic jet driven models:
Masson & Chernin 1993

➡ Study outflow-core feedback

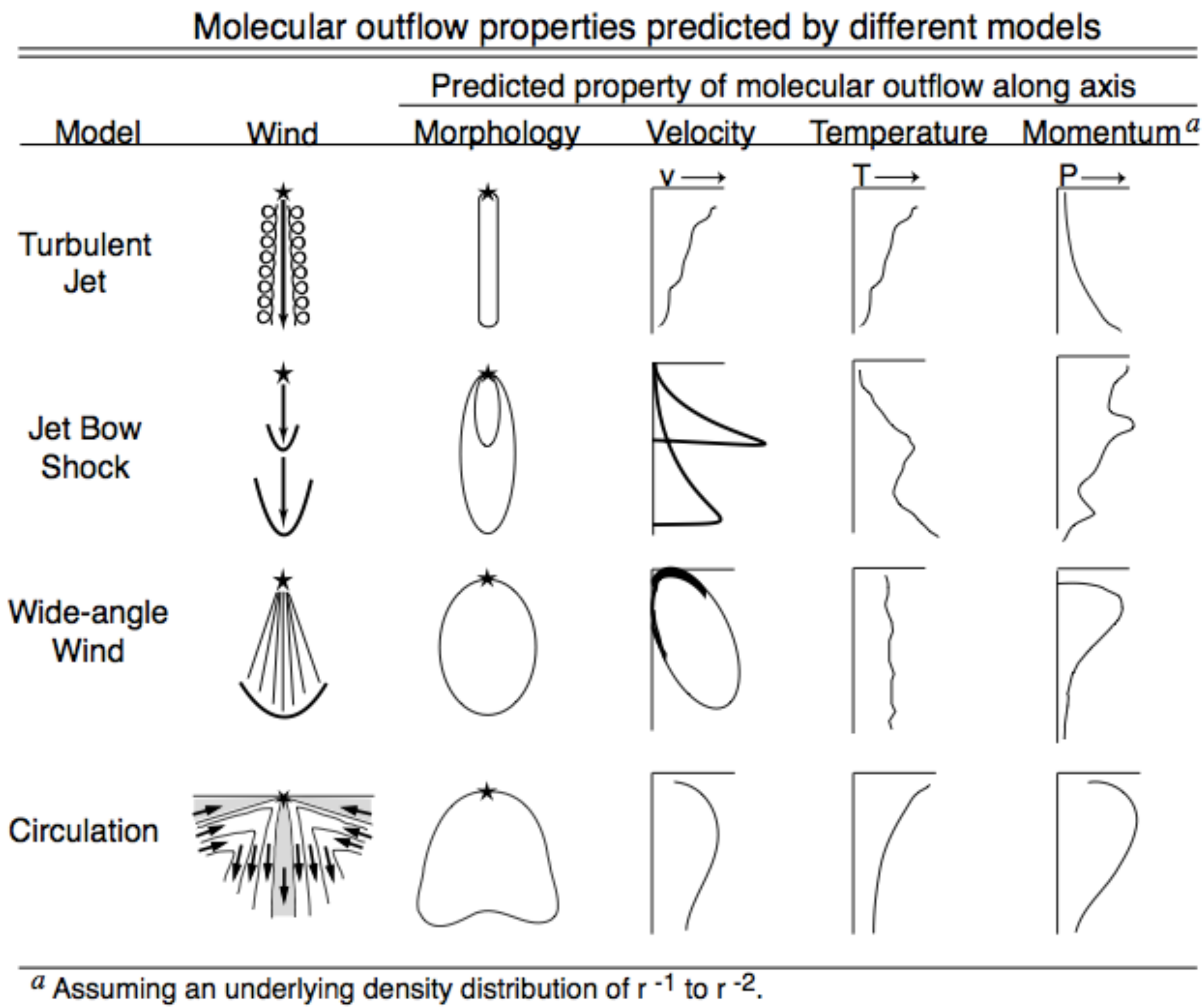


Outflow opening angle increasing with time:

left: n ∝ r^{-2} right: constant density

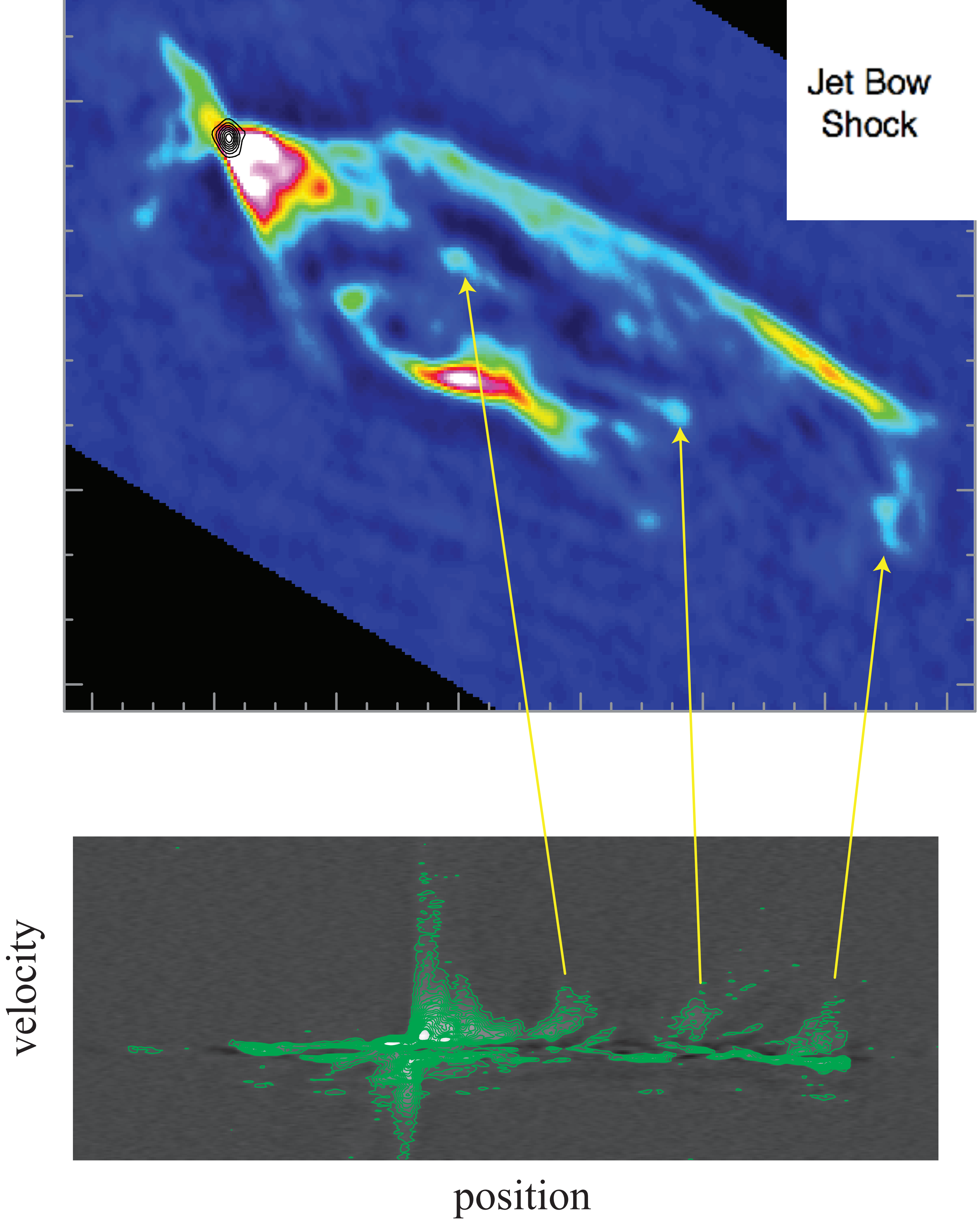
Canto, Raga & Williams 2008

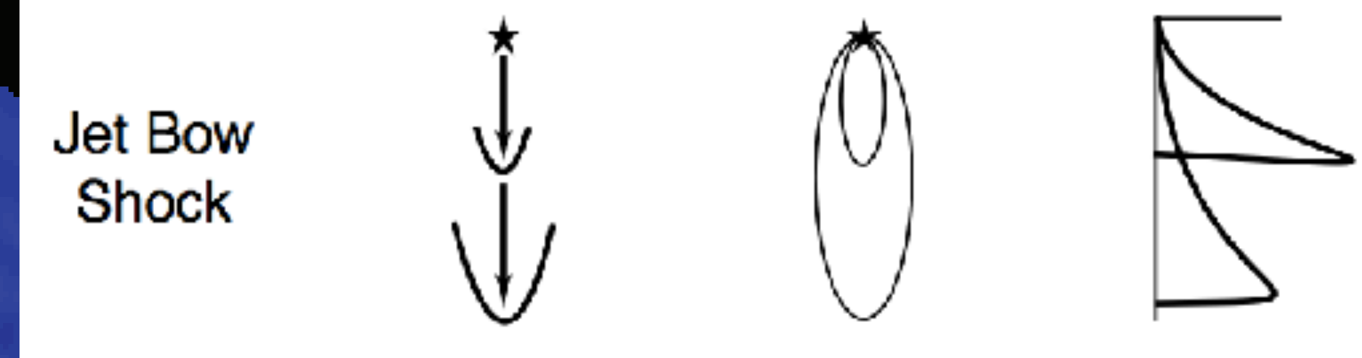
➡ Study outflow-core feedback



Arce et al
PPV


Reipurth & Bally 2001
HH 46/47: Hα [SII] [OII]

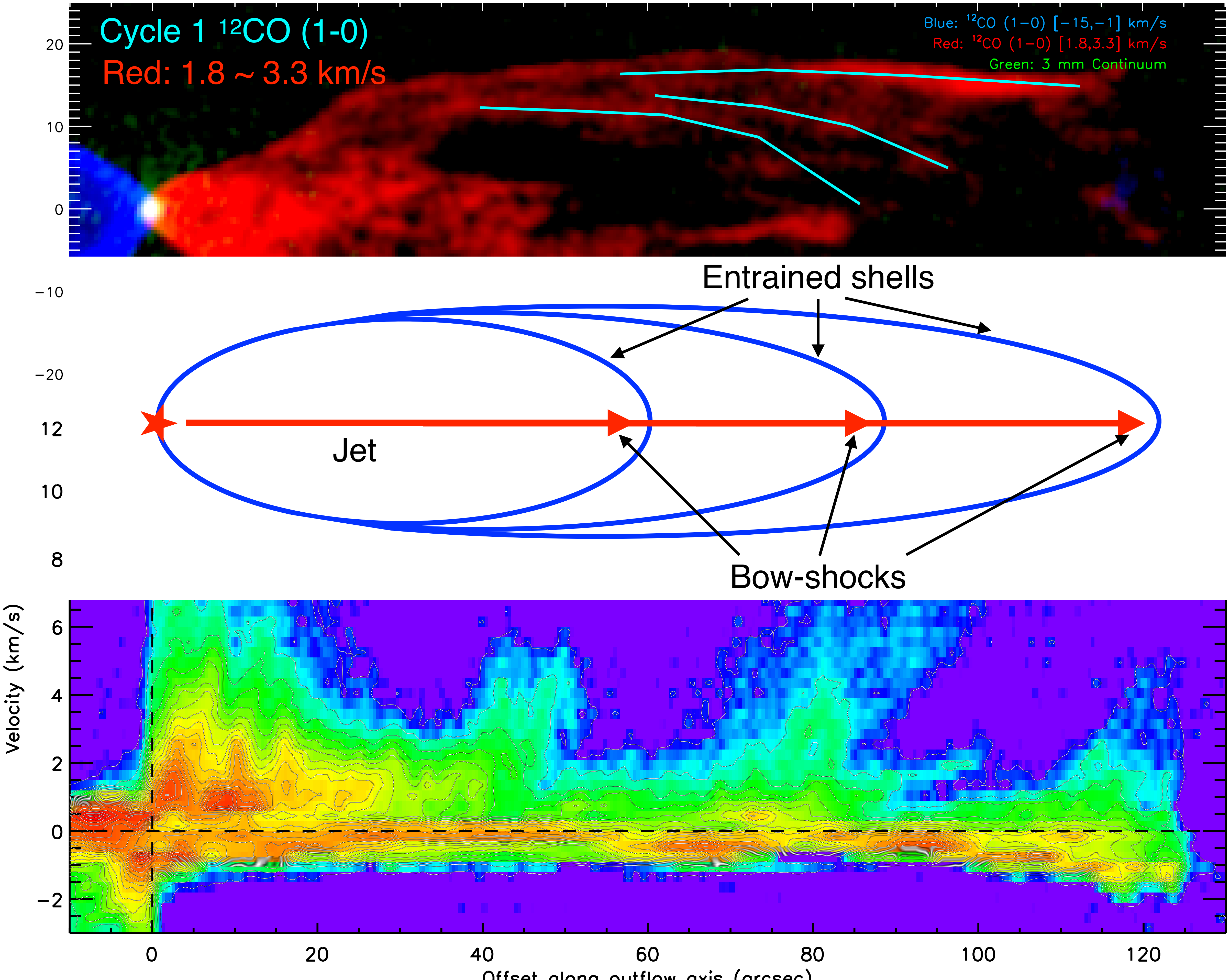




Ejection episodes

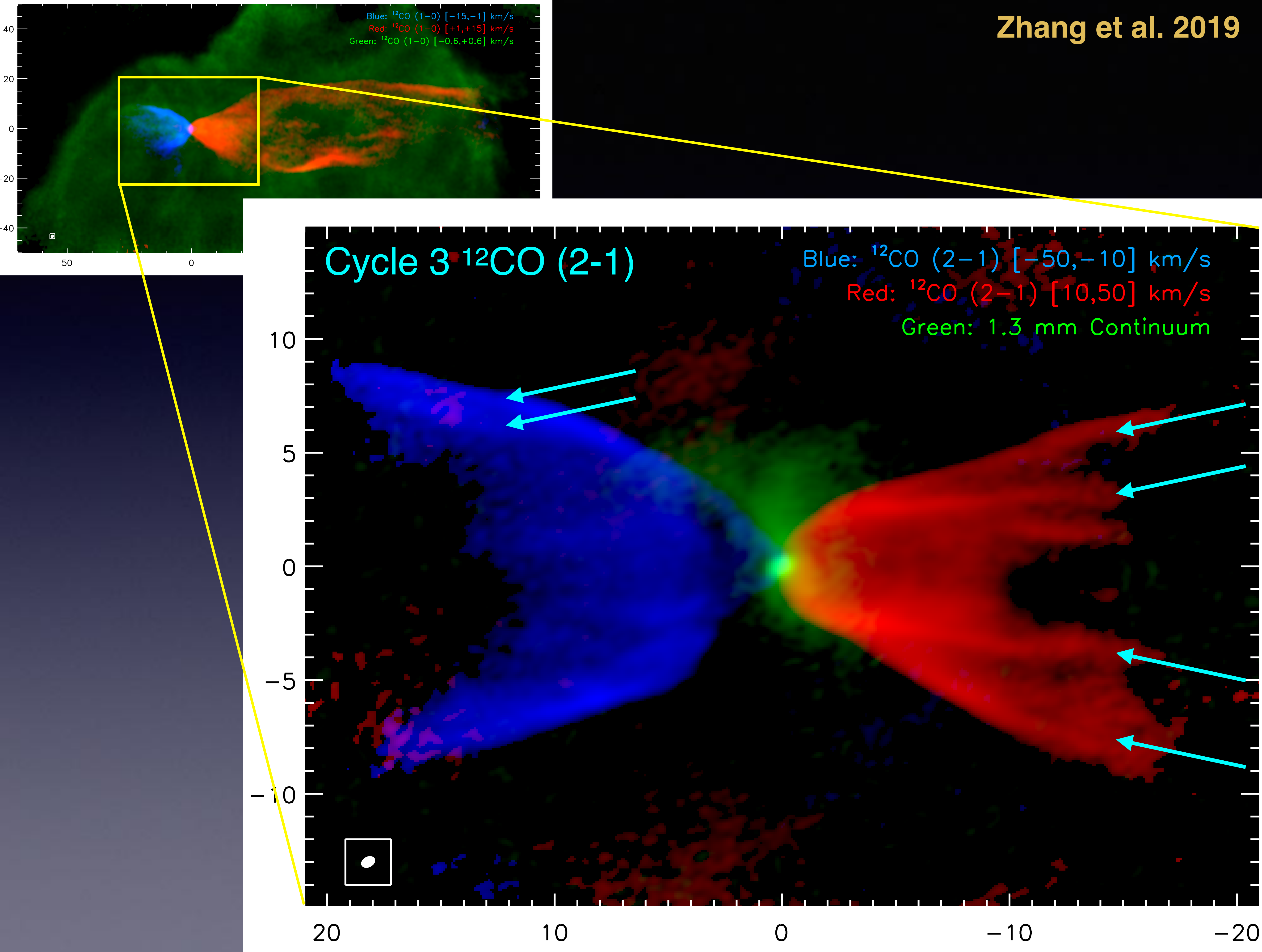
1-3 x 27”

v_r ~5 km/s



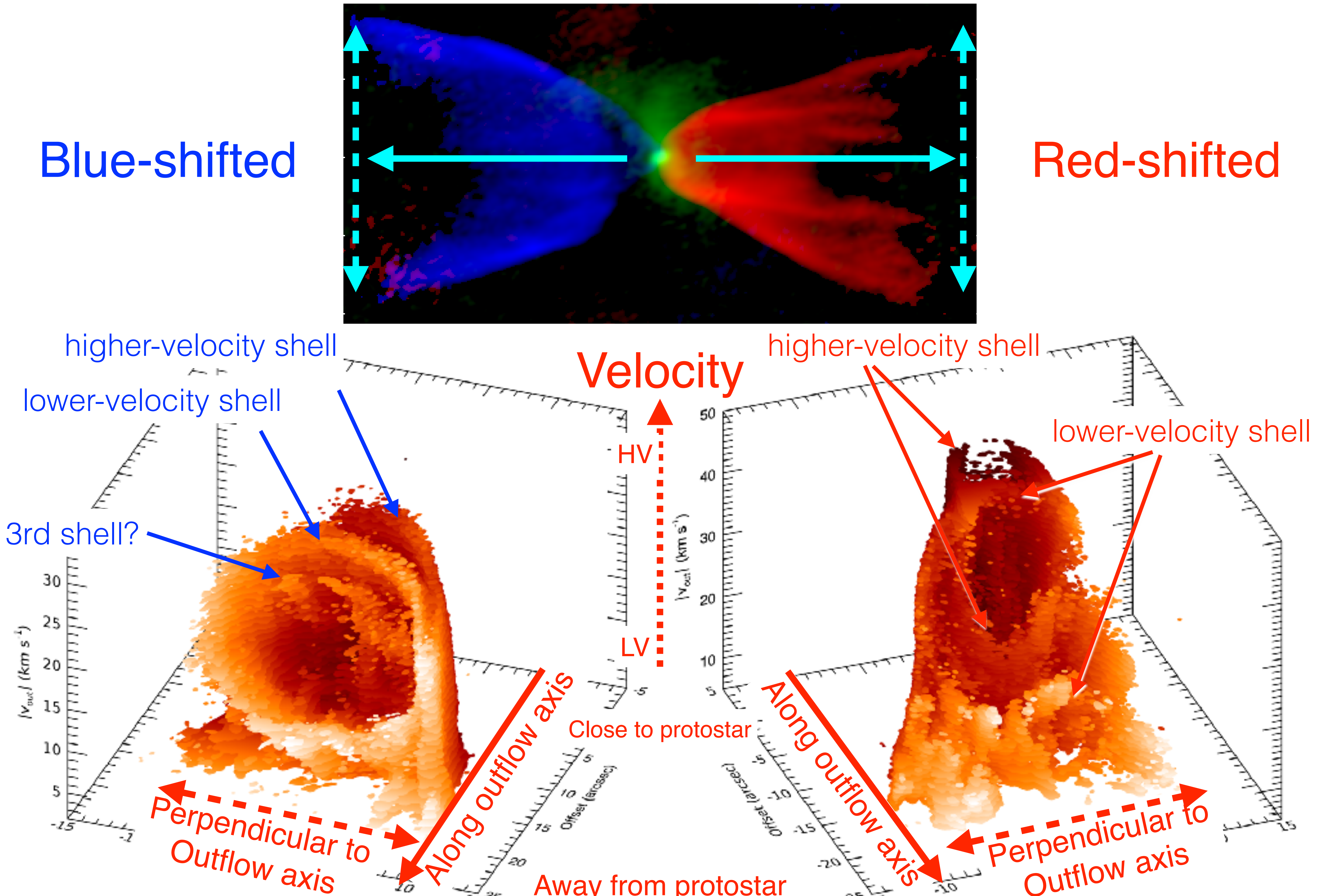
Zhang et al. 2019

Zhang et al. 2019



CO (2-1) in the PPV Space

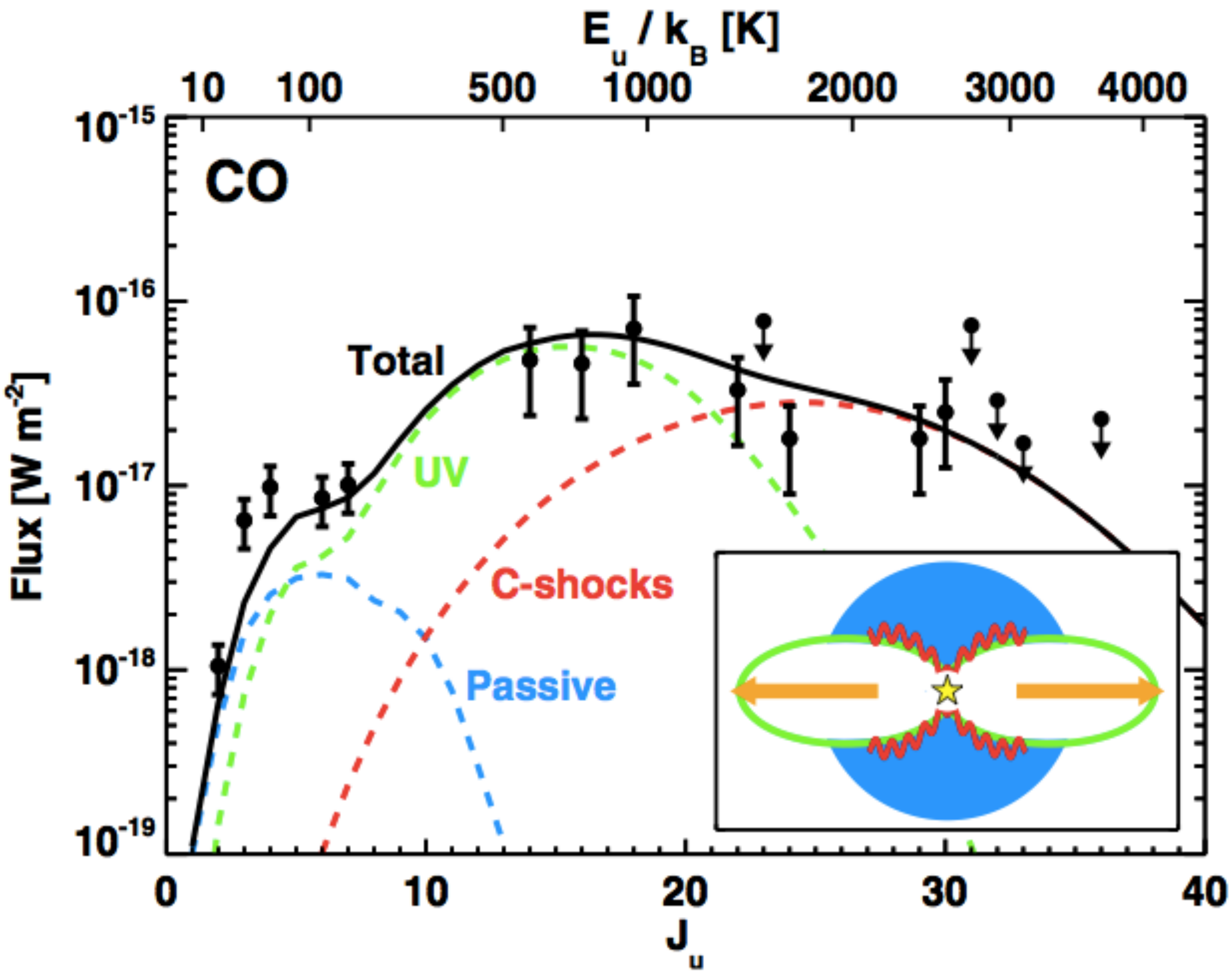
Zhang et al. 2019



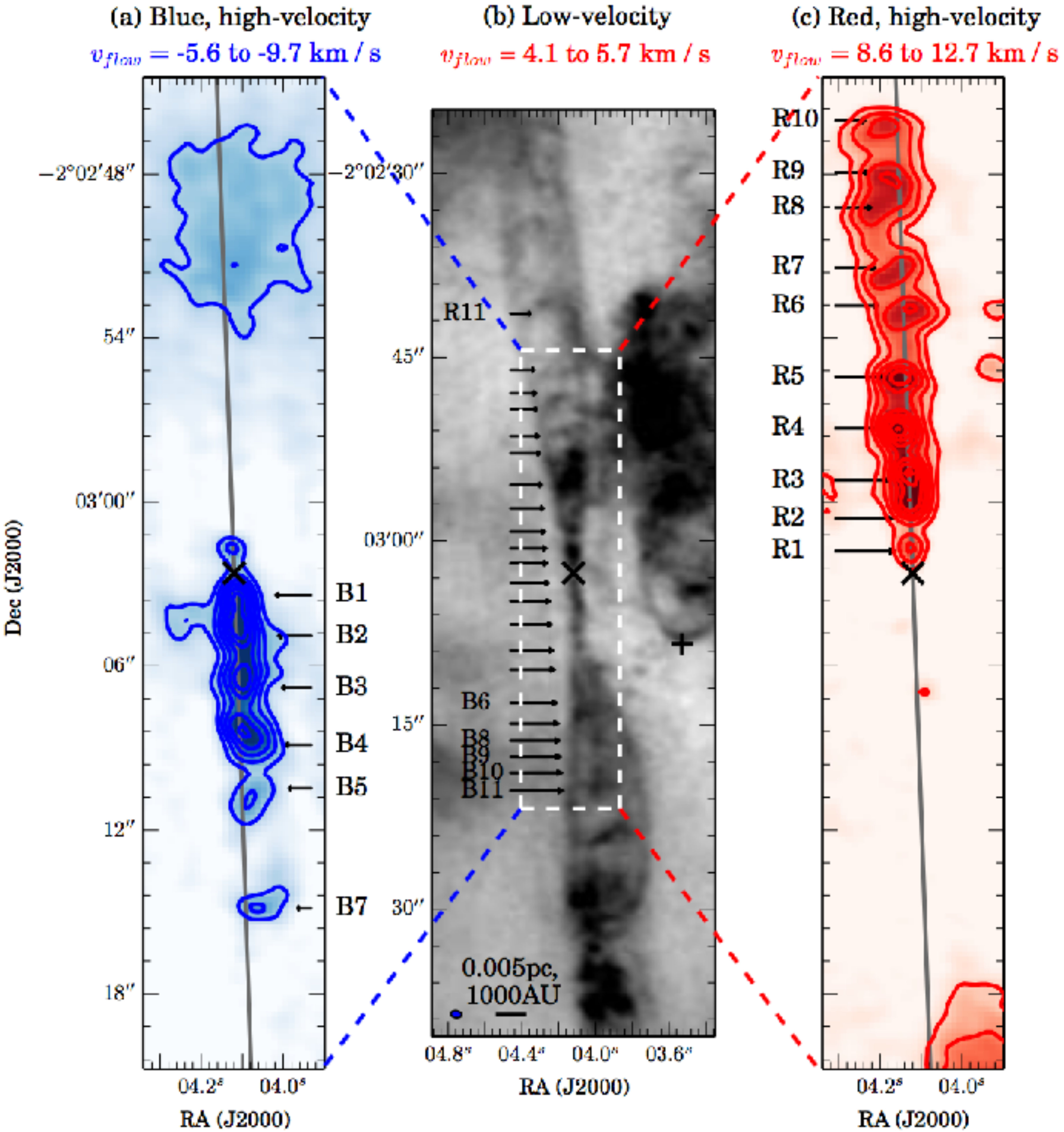
HH 46/47:

Outflow in CO 6-5 + [CI] 2-1, van Kempen et al 2009

van Kempen et al 2010, APEX + Herschel



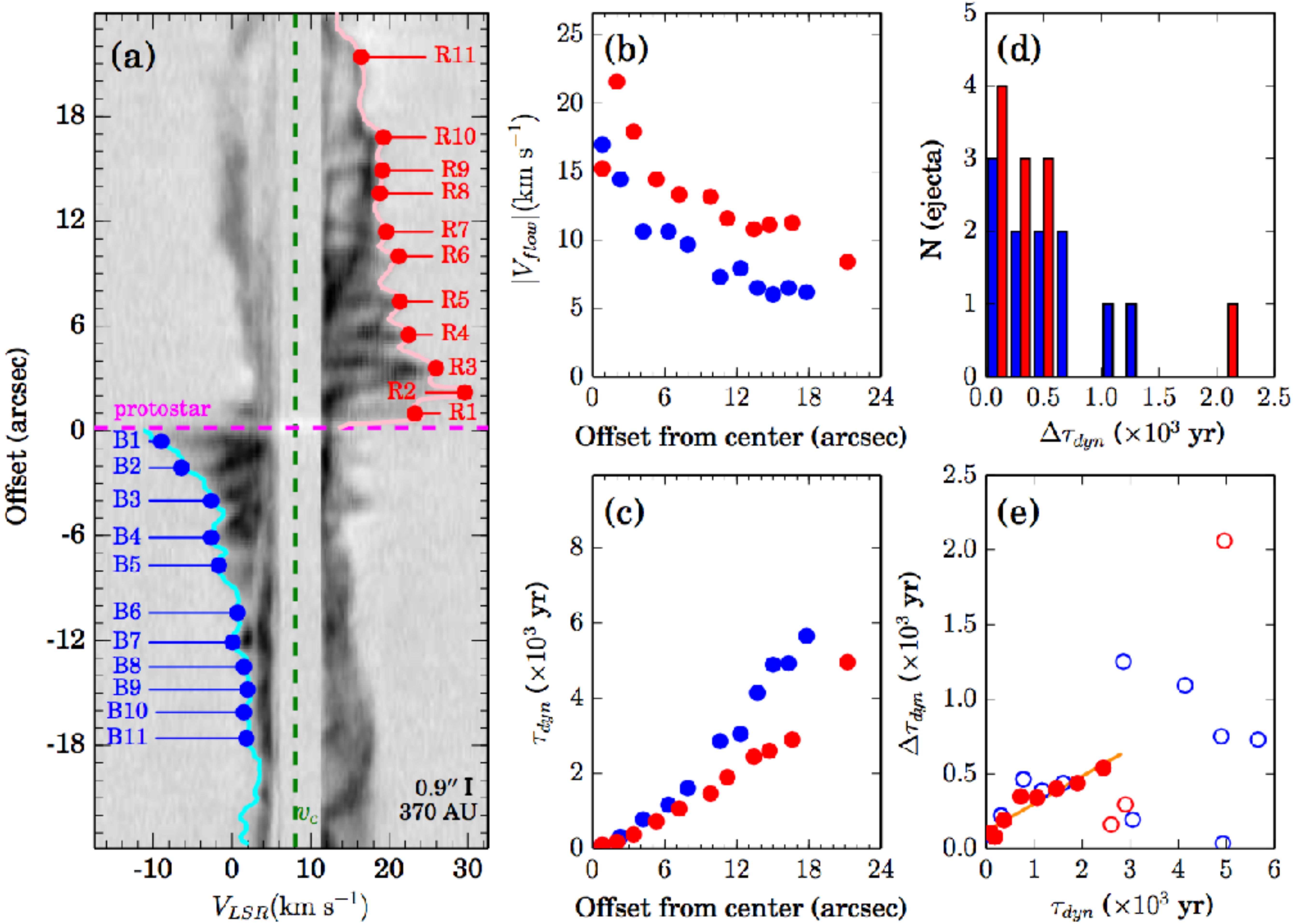
Evidence for shocks and high temperature gas from fitting models to observed CO line intensities.



Plunkett 2015

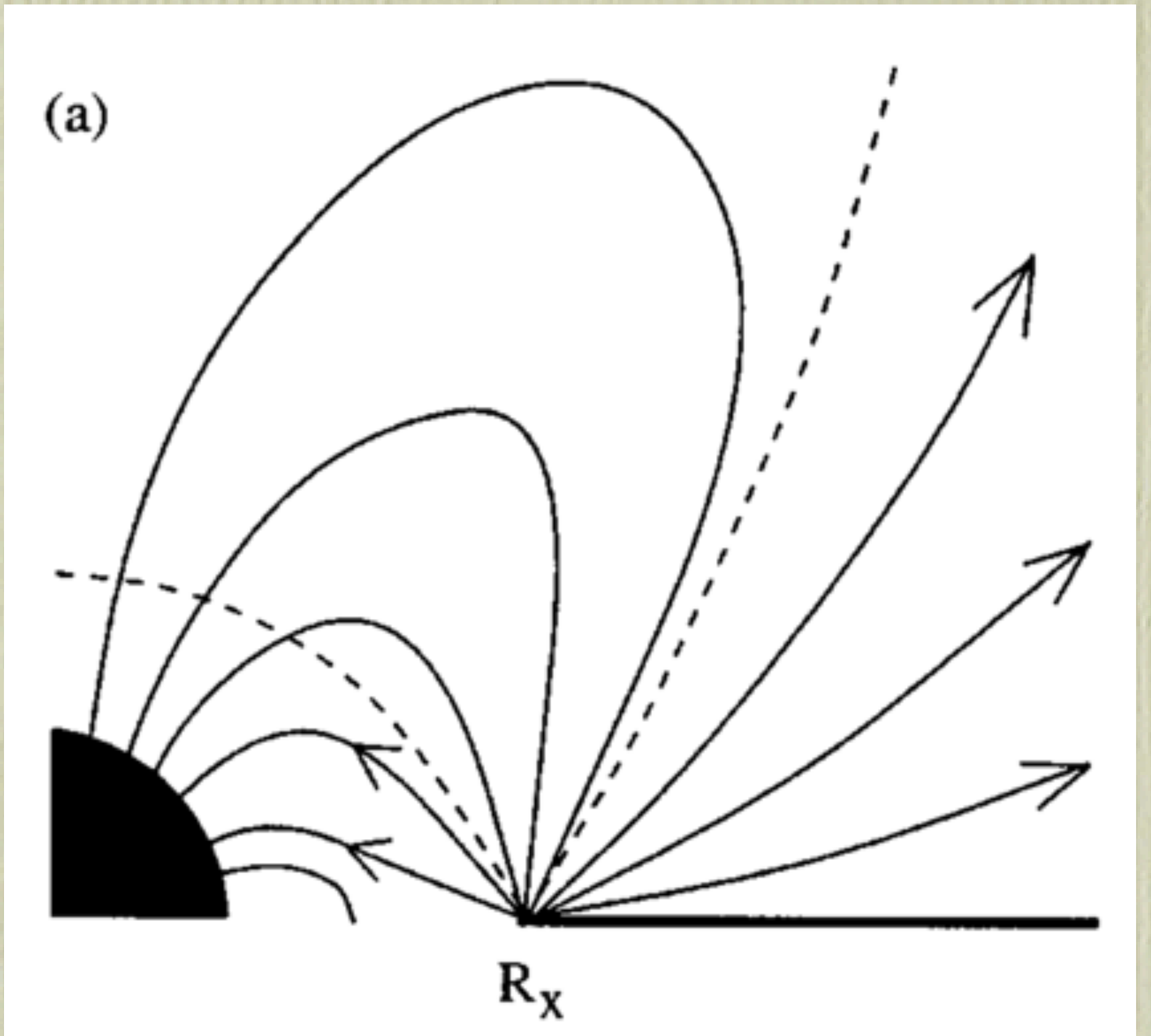
Serpens-South

Episodic mass ejection, every few hundred years.

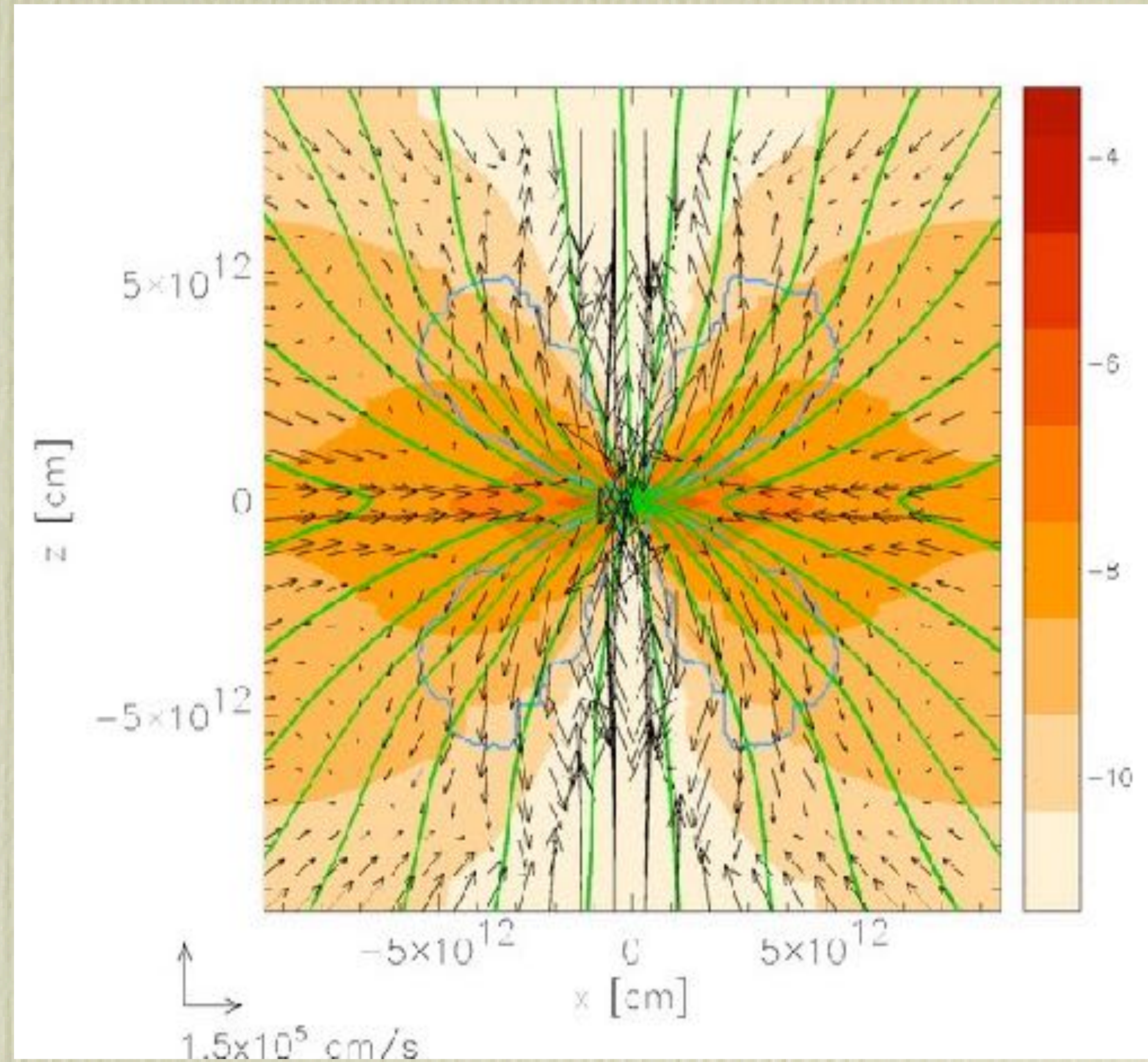


(a)
R11
R10
R9
R8
R7
R6
R5
R4
R3
R2
R1
protostar
B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
B11
v_c
0.9″ I
370 AU
Offset (arcsec)
V_{LSR}(km s^{-1})
(b)
$|V_{flow}|$ (km s^{-1})
Offset from center (arcsec)
(c)
τ_{dyn} (×10^3 yr)
Offset from center (arcsec)
(d)
N (ejecta)
$\Delta\tau_{dyn}$ (×10^3 yr)
(e)
$\Delta\tau_{dyn}$ (×10^3 yr)
τ_{dyn} (×10^3 yr)

Jet-launching: Disk winds



Najita

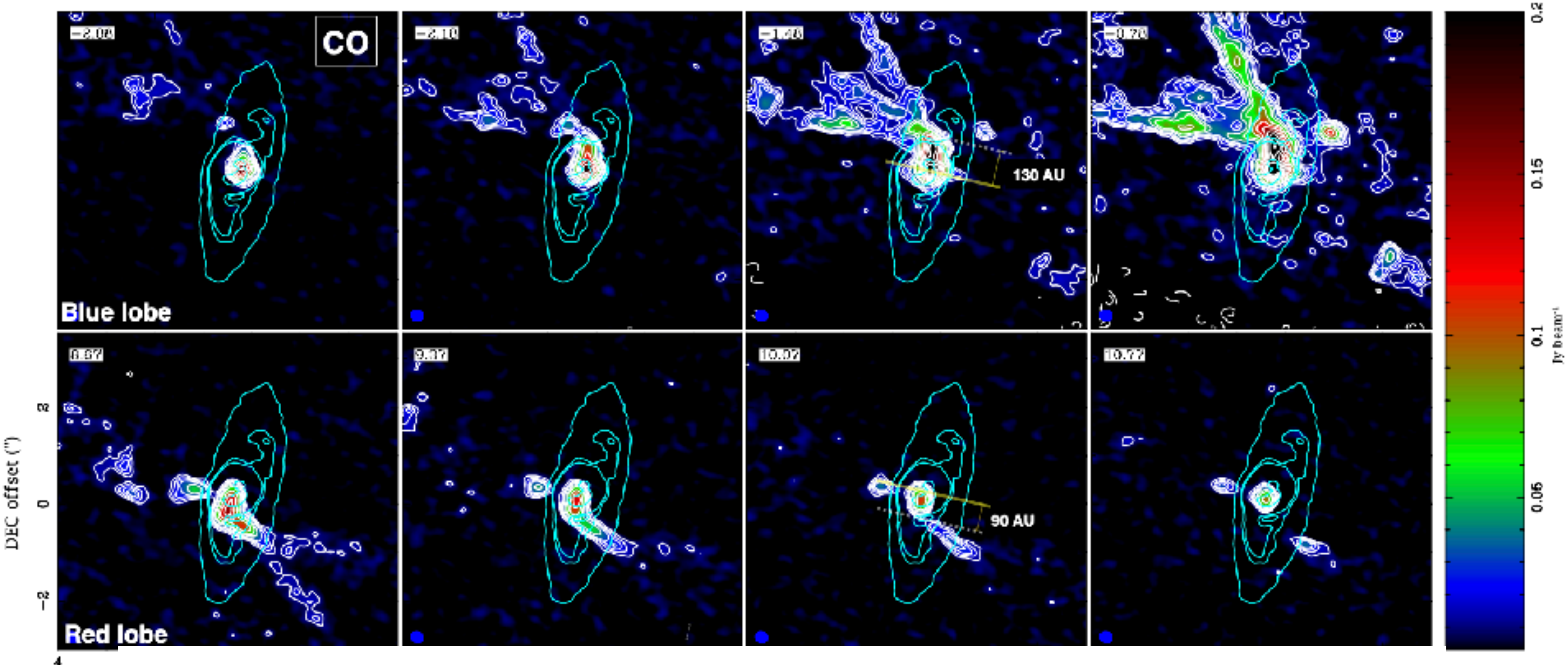


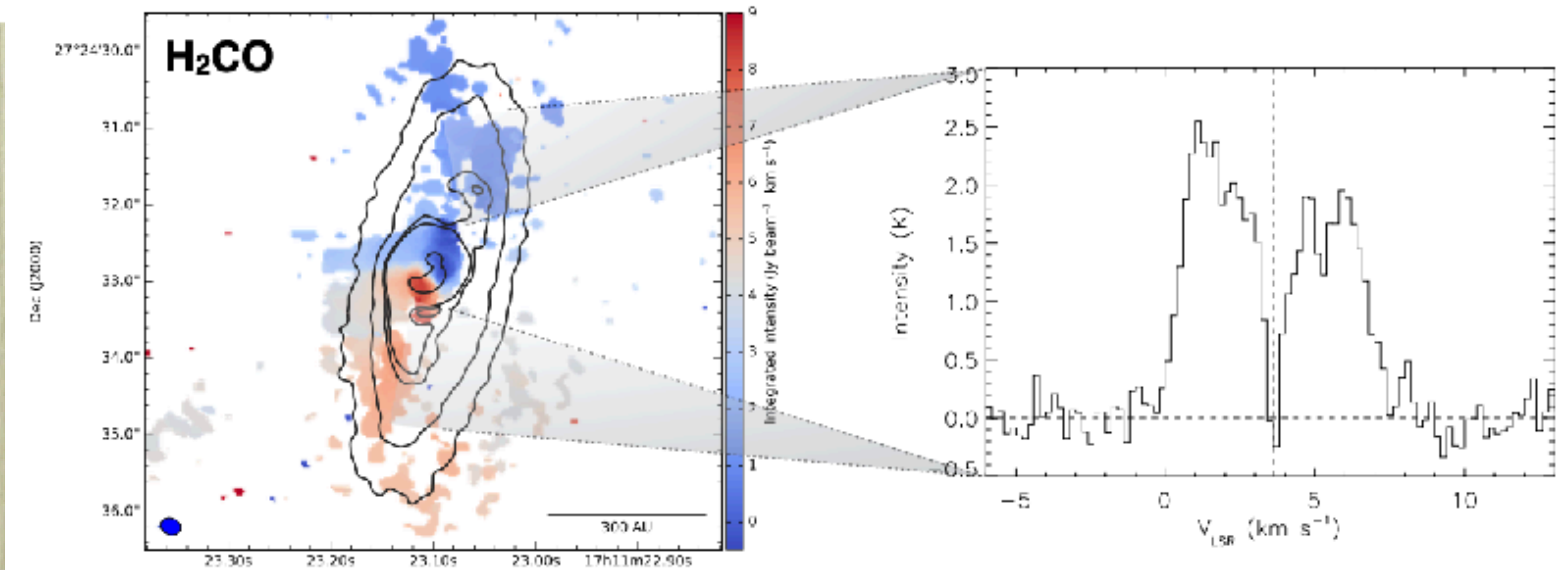
Infalling core pinches magnetic field.
Magnetic centrifugal forces launch wind along field lines from disk surface.
Wind transports >50% of disk angular momentum.

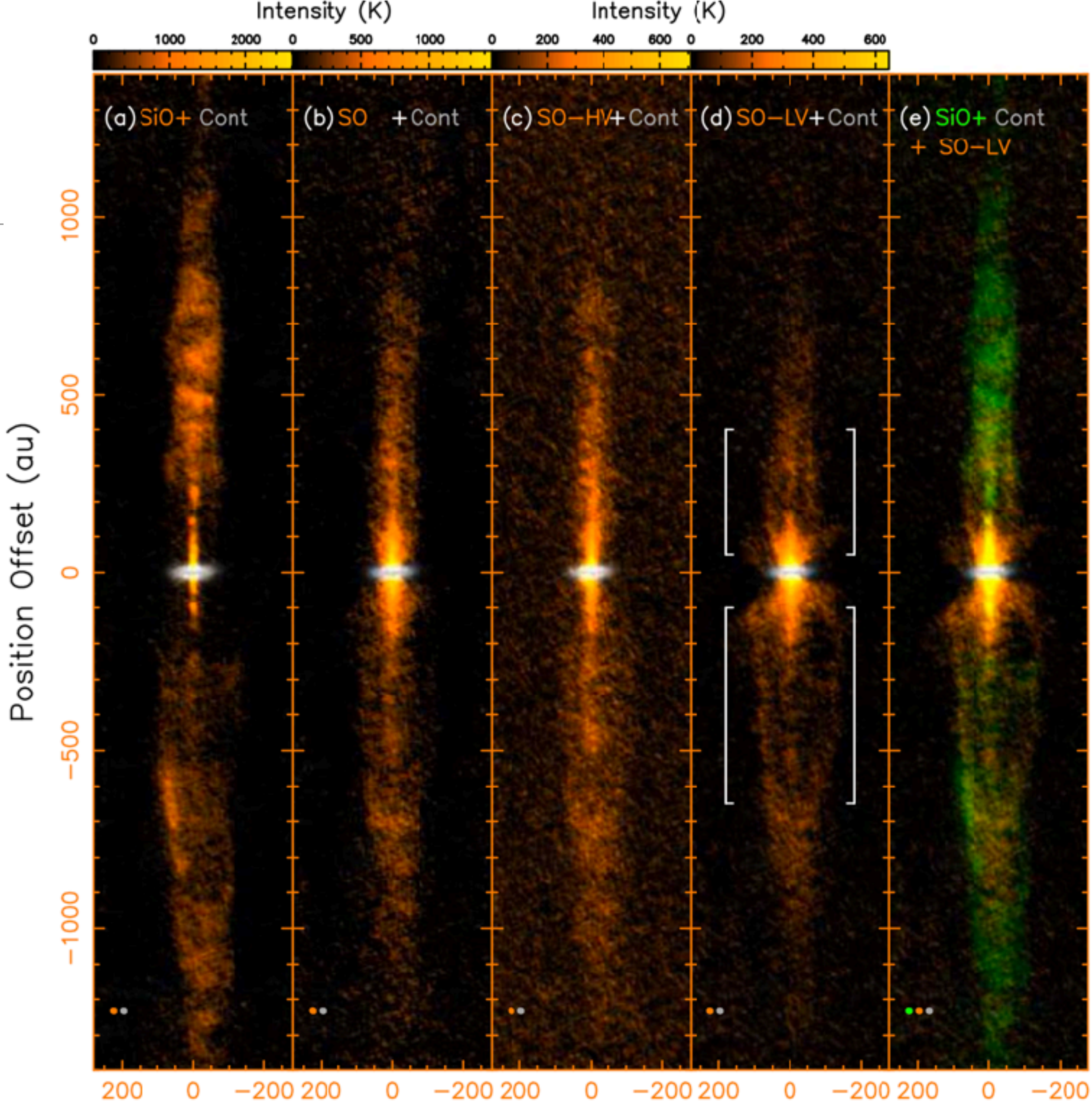
Review: Pudritz et al. 2006

Alves 2017

F. O. Alves et al.: Molecular outflow launched beyond the disk edge



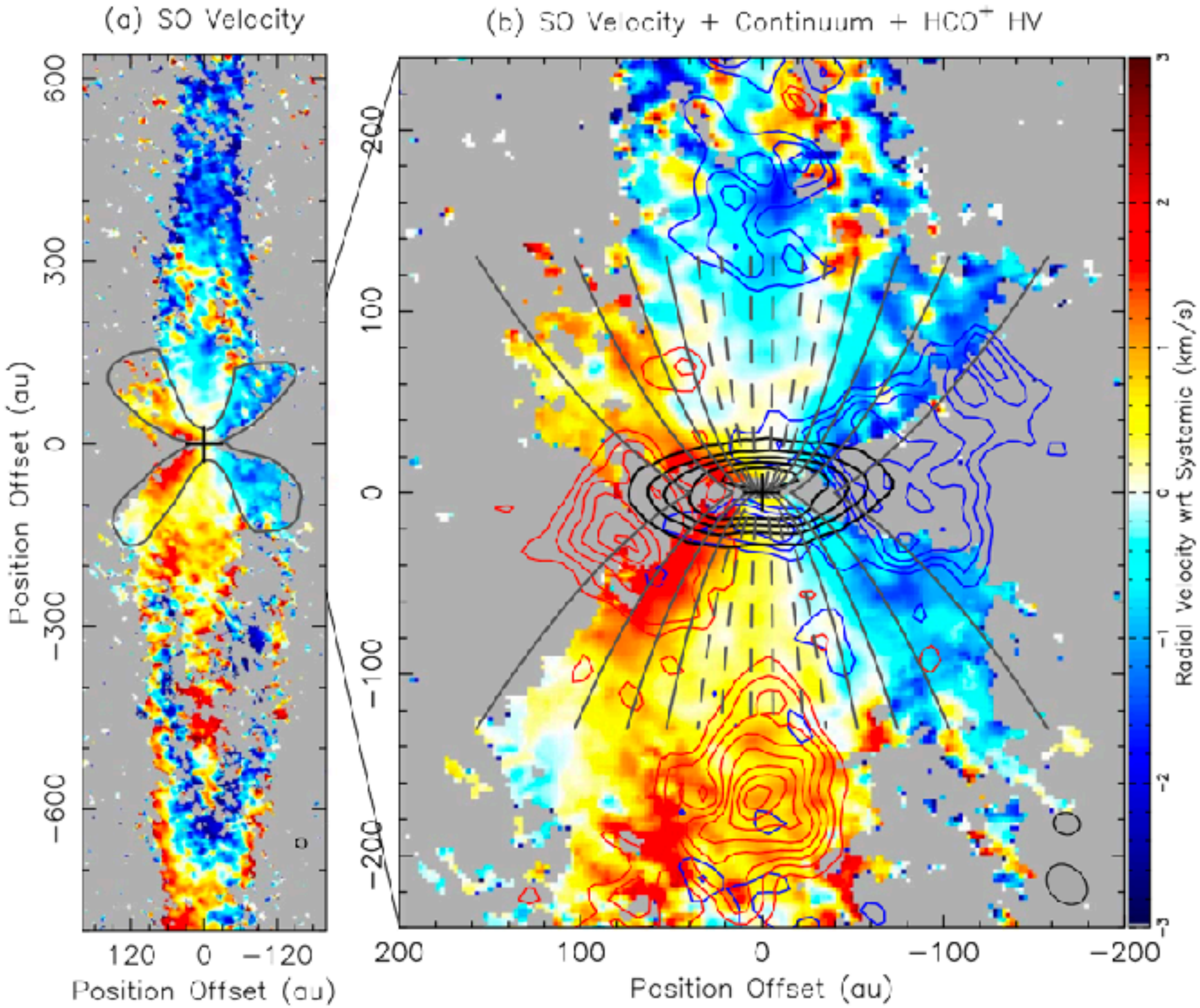


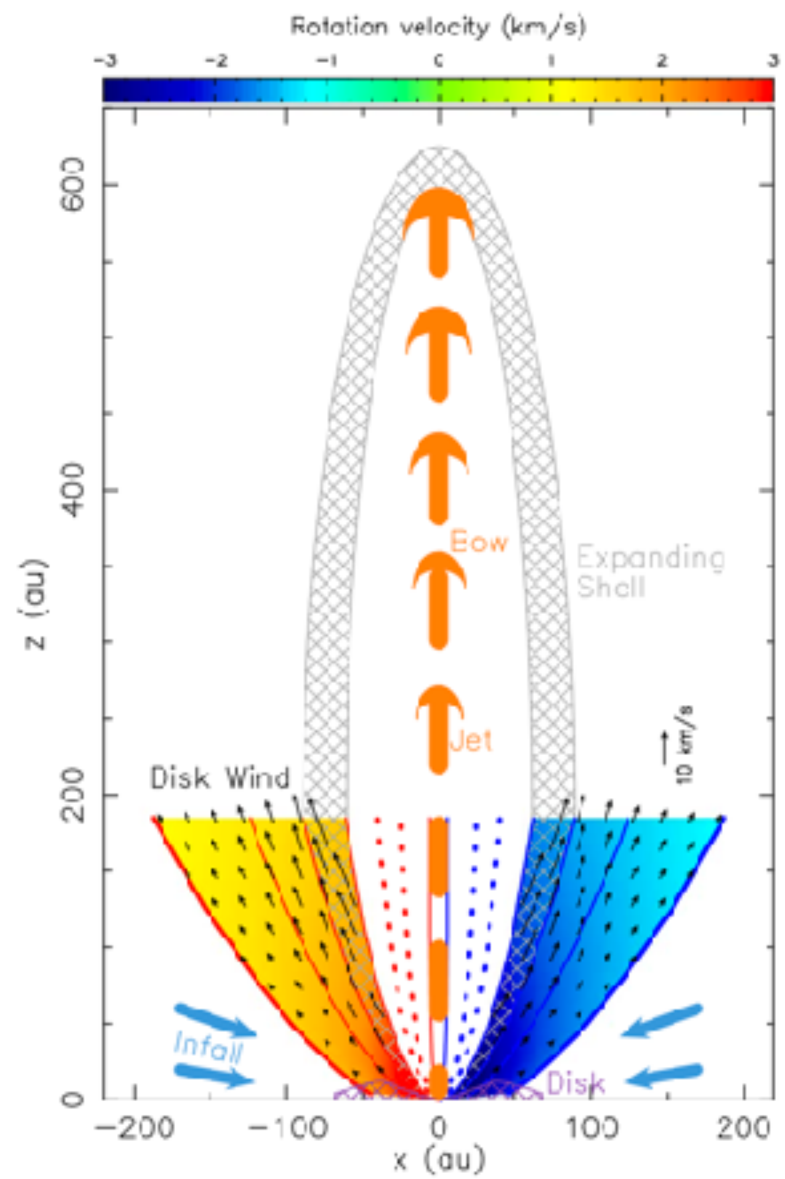


HH212,
2021 ApJ

First Detection of Interaction between a Magnetic Disk Wind and an Episodic Jet in a Protostellar System

Chin-Fei Lee[1,2], Benoit Tabone[3,4], Sylvie Cabrit[4], Claudio Codella[5,6], Linda Podio[5], Jonathan Ferreira[6], and Jonatan Jacquemin-Ide[6]





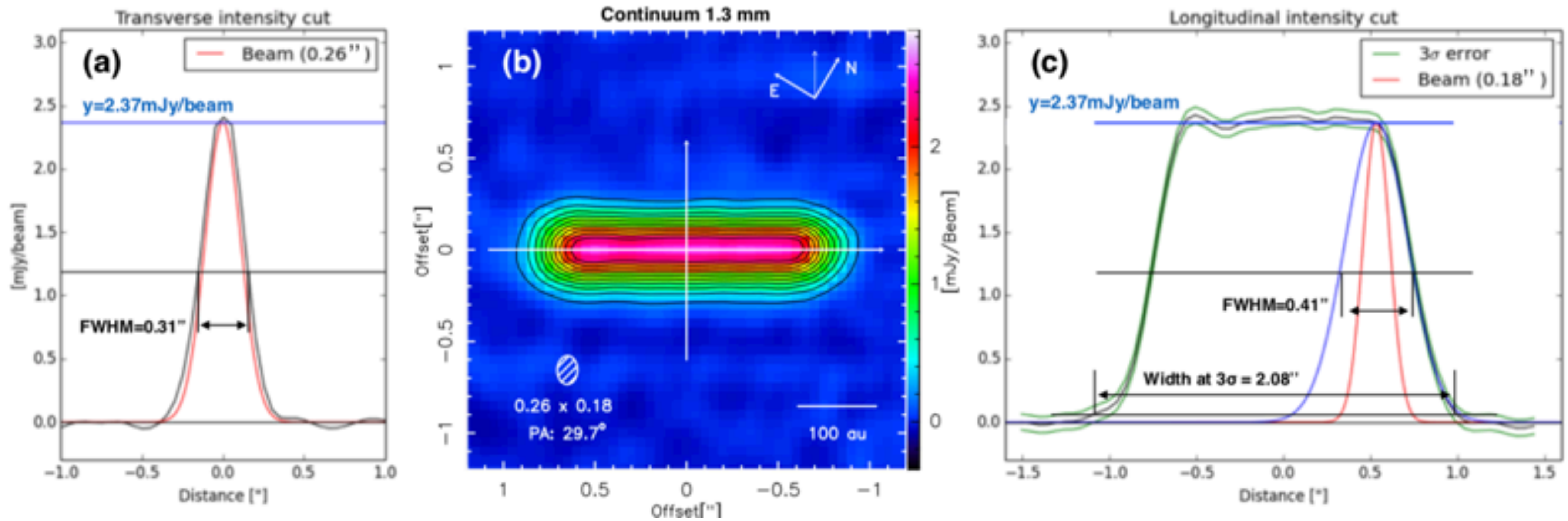
HH212,
2021 ApJ

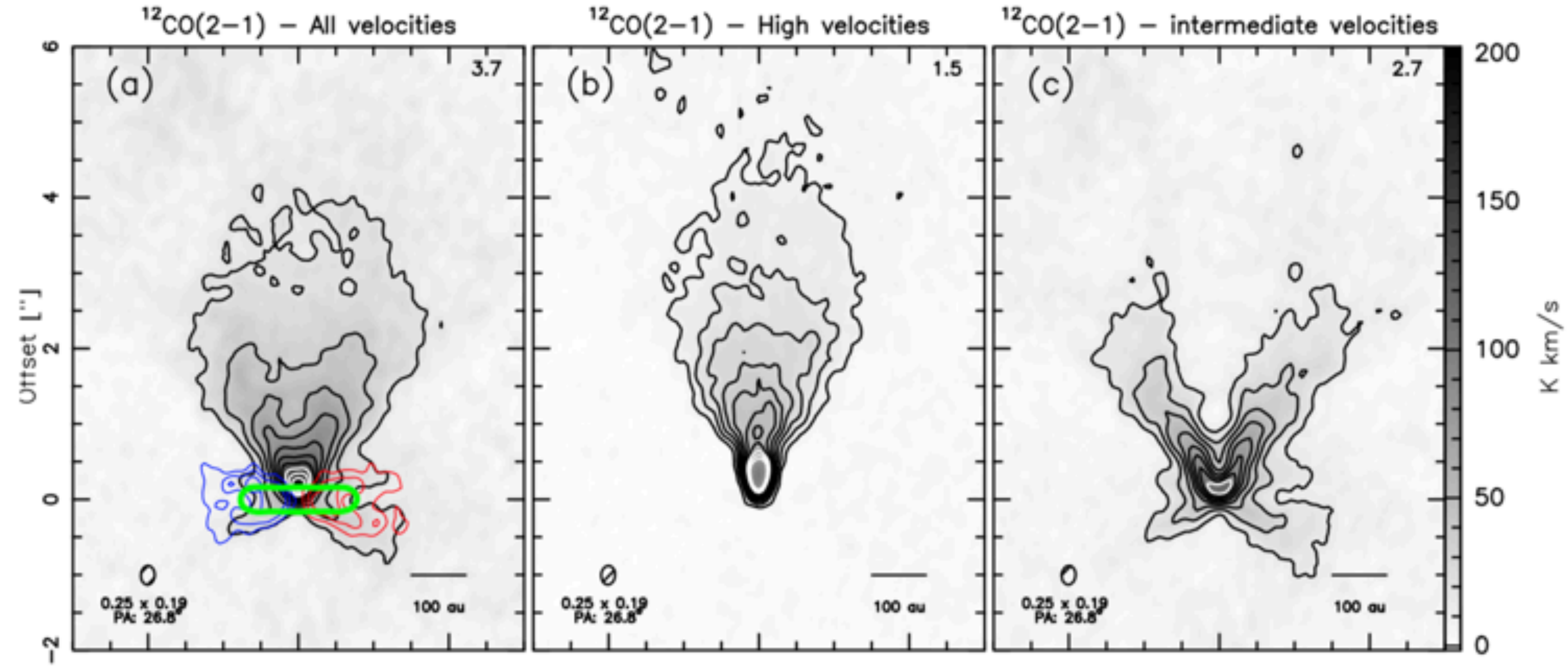
The HH30 edge-on T Tauri star

A rotating and precessing monopolar outflow scrutinized by ALMA

2018

F. Louvet[1], C. Dougados[2,1,3], S. Cabrit[4,3], D. Mardones[1], F. Ménard[2,1,3], B. Tabone[4], C. Pinte[2,1,3,5], and W. R. F. Dent[6]





Outflows

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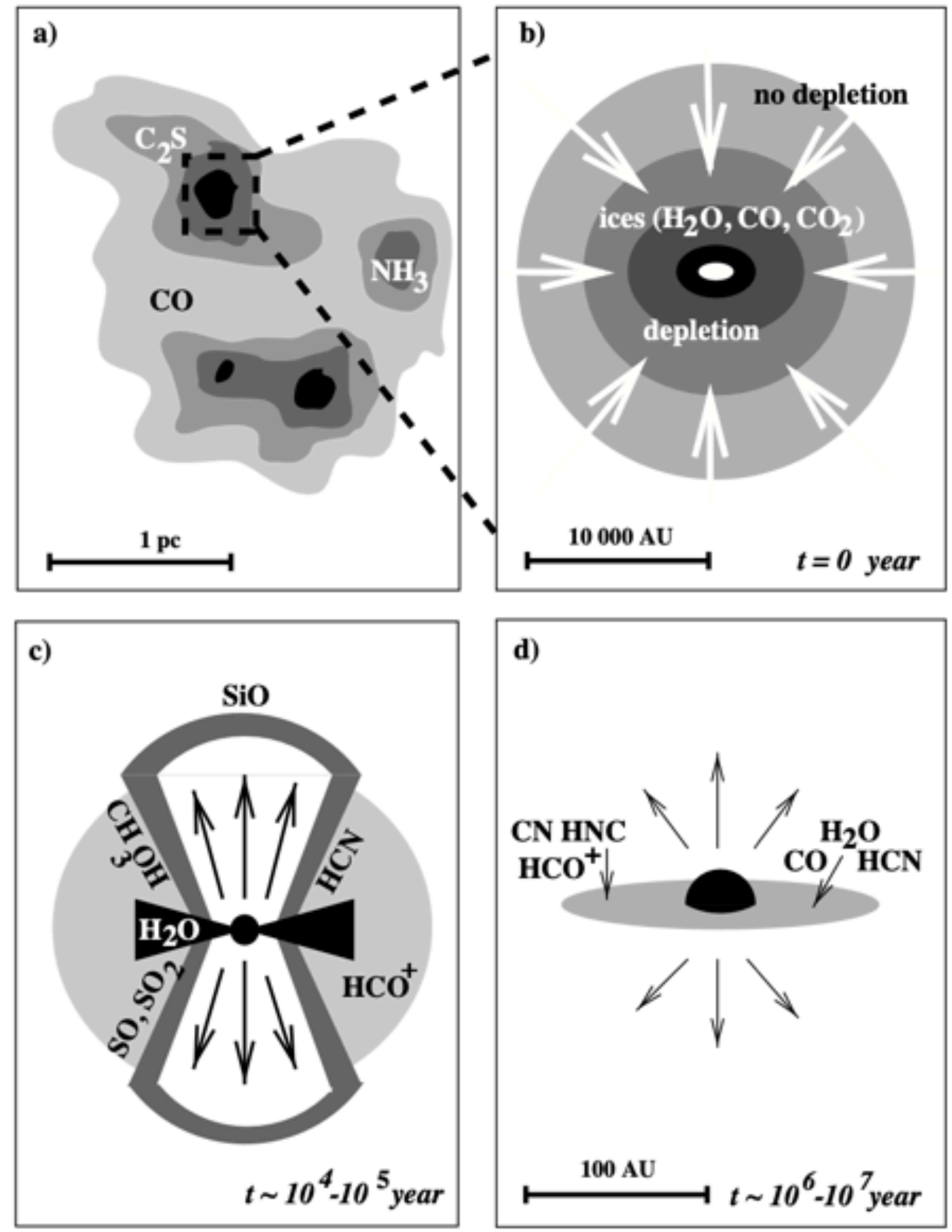

Van Dishoeck 1998