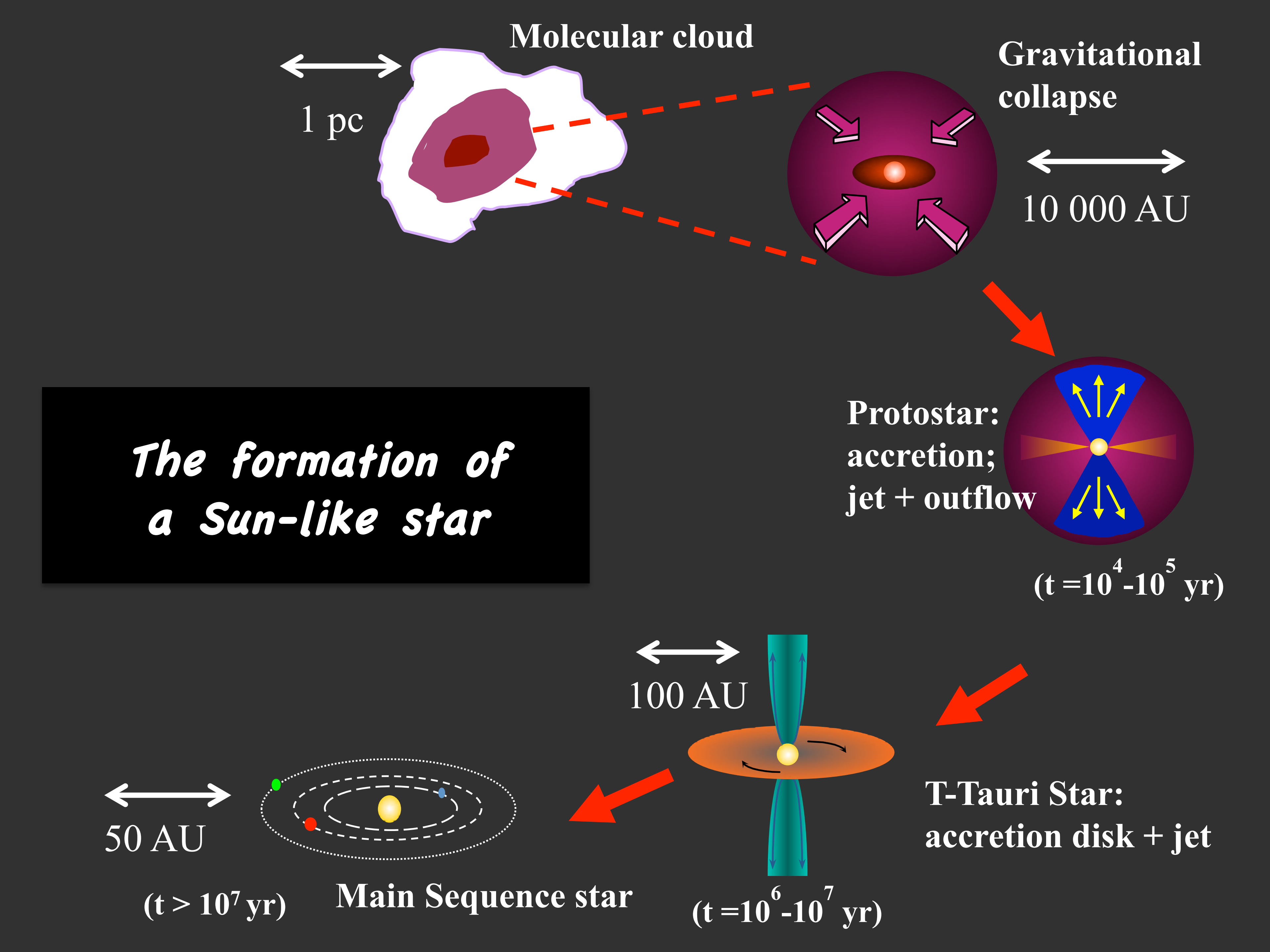
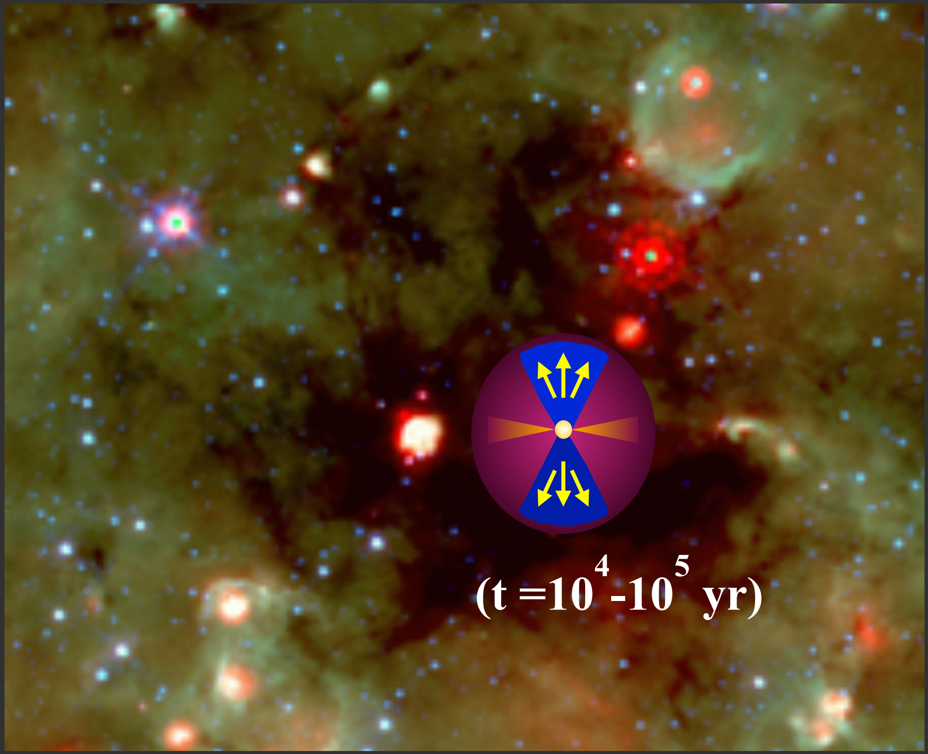
Pristine jet-disk systems around protostars

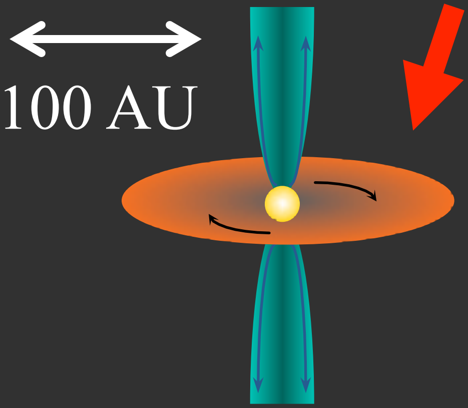
C. Codella (INAF, Arcetri)



The formation of a Sun-like star
Molecular cloud
1 pc
Gravitational collapse
10 000 AU
Protostar: accretion; jet + outflow
(t =10^4-10^5 yr)
100 AU
T-Tauri Star: accretion disk + jet
(t =10^6-10^7 yr)
50 AU
(t > 10^7 yr)
Main Sequence star

Protostar:
main accretion phase;
jet + outflow





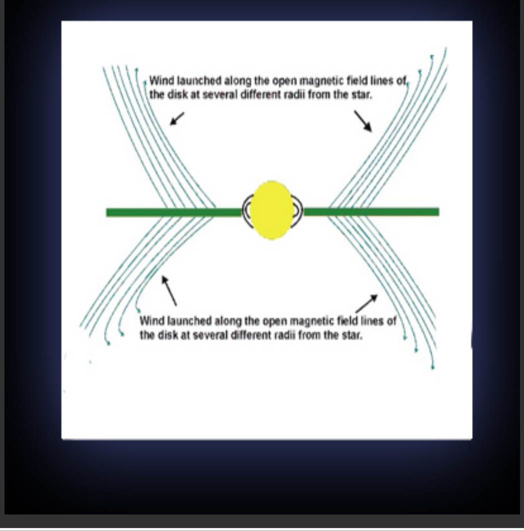
T-Tauri Star:
accretion disk + jet

(t =10^6-10^7 yr)

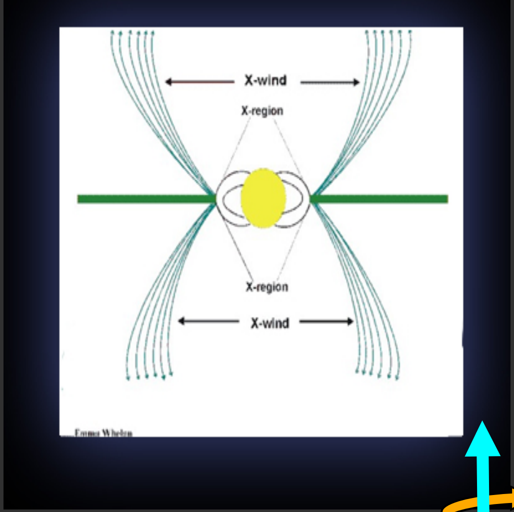
The launching and collimation of jets

MHD models predict that jets extract excess angular momentum from the star/disk system

D-wind

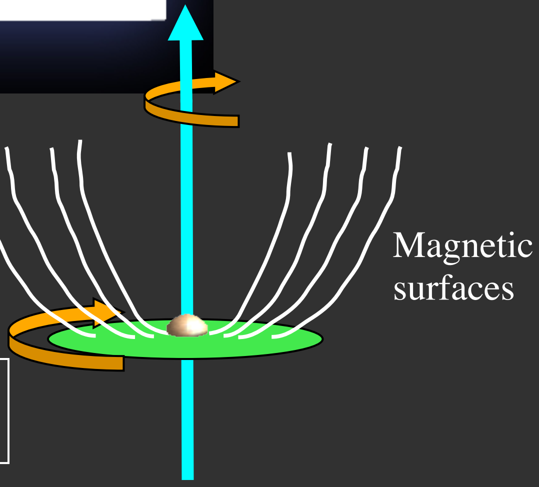


X-wind



Origin of the jet in the disk plane: 0.03 to a few AU

Acceleration and collimation of jet: within 20-100 AU above the disk



Rotation is transferred to the jet from the disk

PPVI: Li et al.; Frank et al.

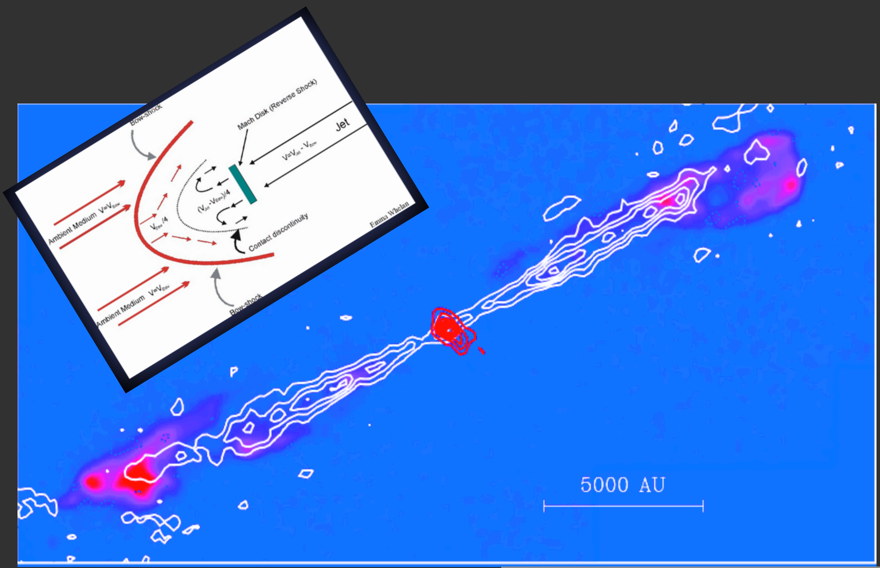
Propagation of protostellar jets

Rapid heating (from ~10 to a few 1000 K) and compression of the gas → "Shock chemistry"

High-T chemistry: endothermic reactions

Ice sublimation & grain disruption

The shocked gas acquires a chemical composition distinct from that of the unperturbed medium

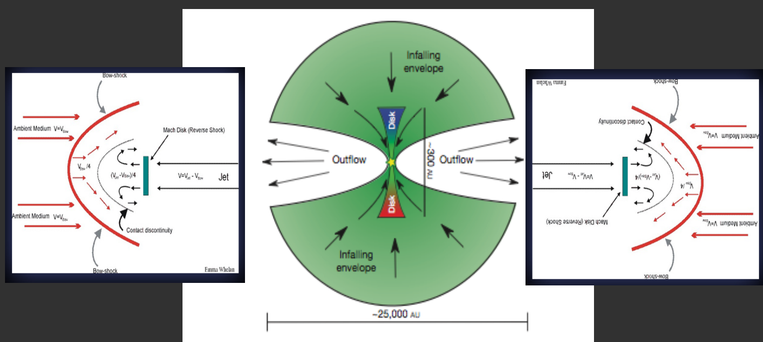


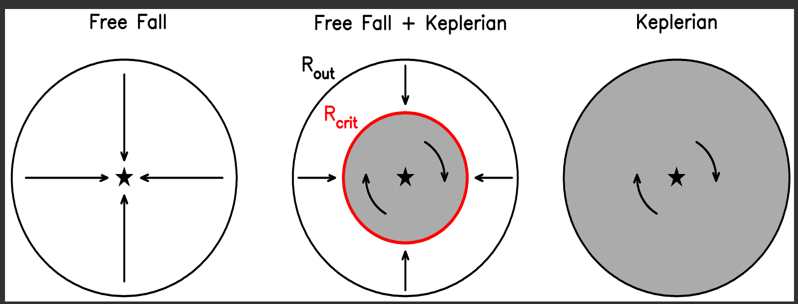
Gueth & Guilloteau (1992)

SiO production along jets:
sputtering of Si-bearing material in refractory grain cores (Vs > 20 km/s);
grain-grain processing (e.g. Gusdorf et al. 2008ab; Anderl et al. 2013)

… and the disks around protostars ?

Observations:





$V \approx R^{-1}$ $V \approx R^{-0.5}$

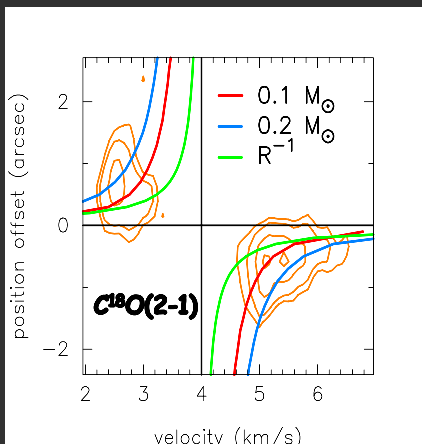
Models:

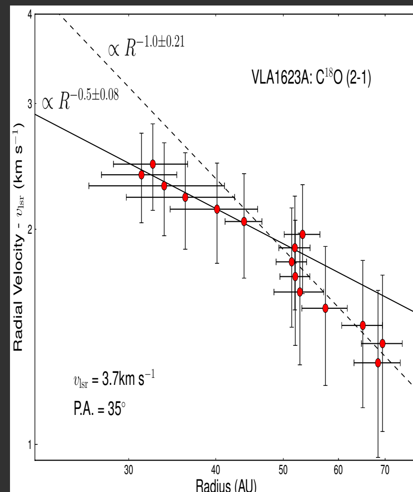
non-magnetised conditions:
R < 100 AU
(e.g. Terebey et al. 1984)

B ≠ J ; turbulence:
R > 100 AU
(Hennebelle & Ciardi 2009;
Joos et al. 2012, 2013)

… and the disks around protostars ?

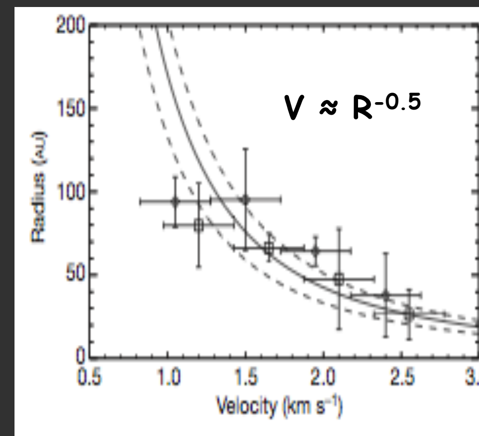
VLA1623

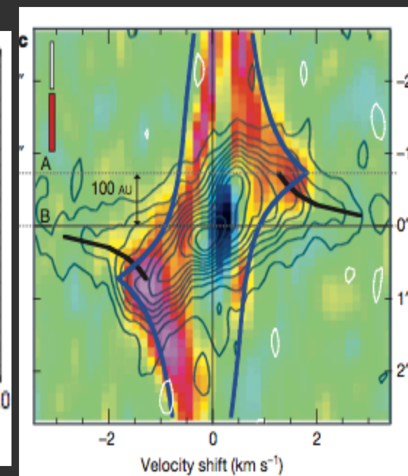




Murillo et al. (2013)

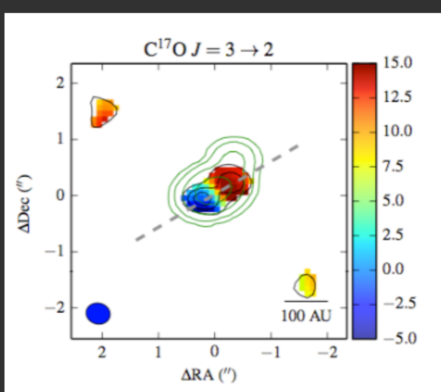
L1527



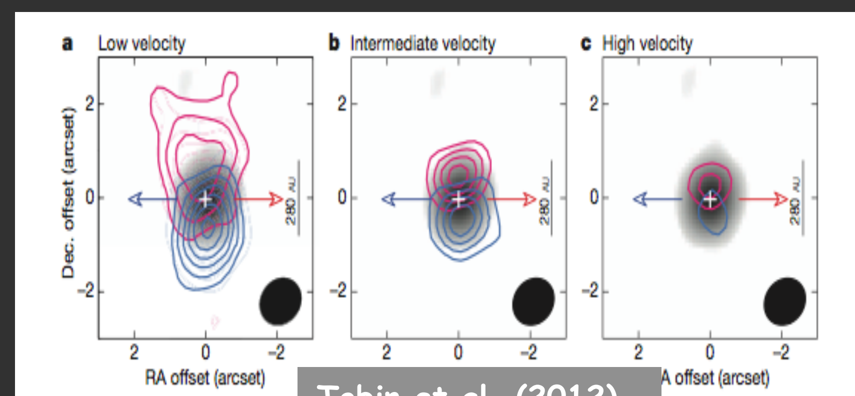


IRS17B

Lindbergh et al. (2014)



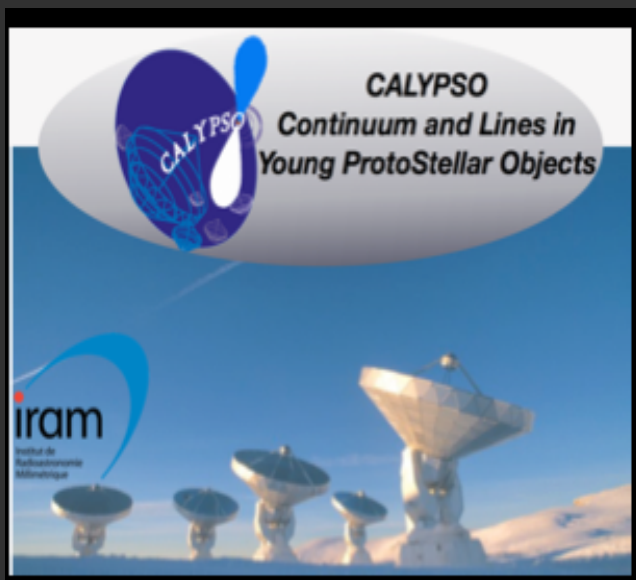
The higher is the velocity, the smaller is the radius;
R = 100-150 AU



Tobin et al. (2012)
Sakai et al. (2014)

See also the HCO+ HH212-ALMA images by Lee et al. (2014)

CALYPSO !

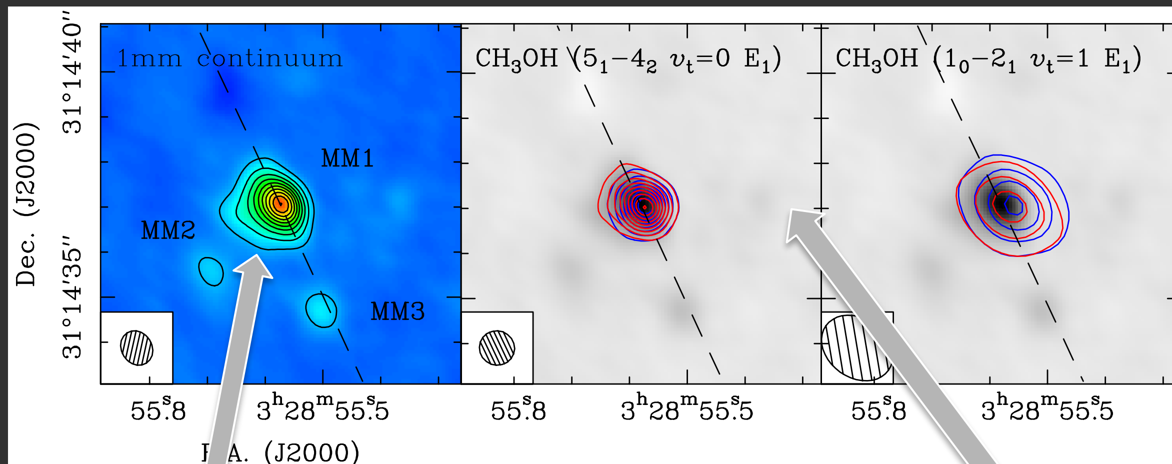


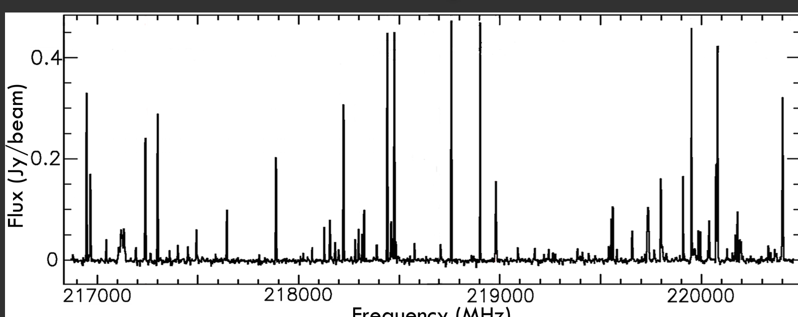
IRAM PdBI Large Program (PI Ph. Andre'):
300 hours observing time
Class 0 protostars closeby (< 300 pc)
3 spectral setups, e.g. continuum and > 50 lines
0.5 arcsec resolution (50-70 AU)
Typical sensitivities 0.1 mJy/0.5 arcsec beam

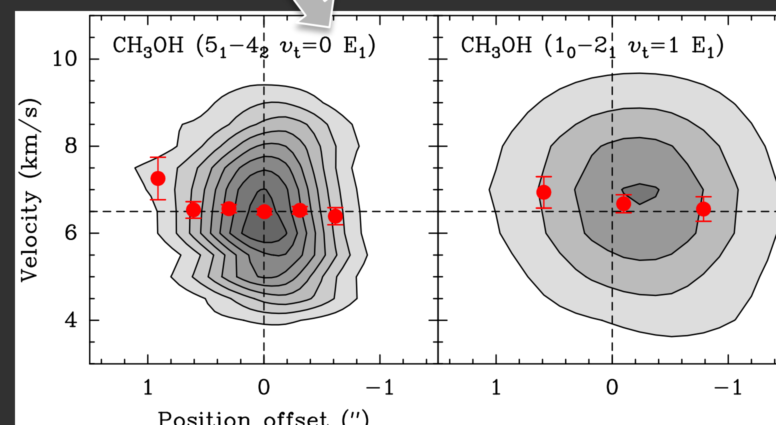
3 work packages:

1. Formation of multiple systems and disks (A. Maury)
2. Jet launching and momentum removal (C. Codella)
3. Inner envelope kinematics and chemistry (S. Maret)

CALYPSO: IRAS2A





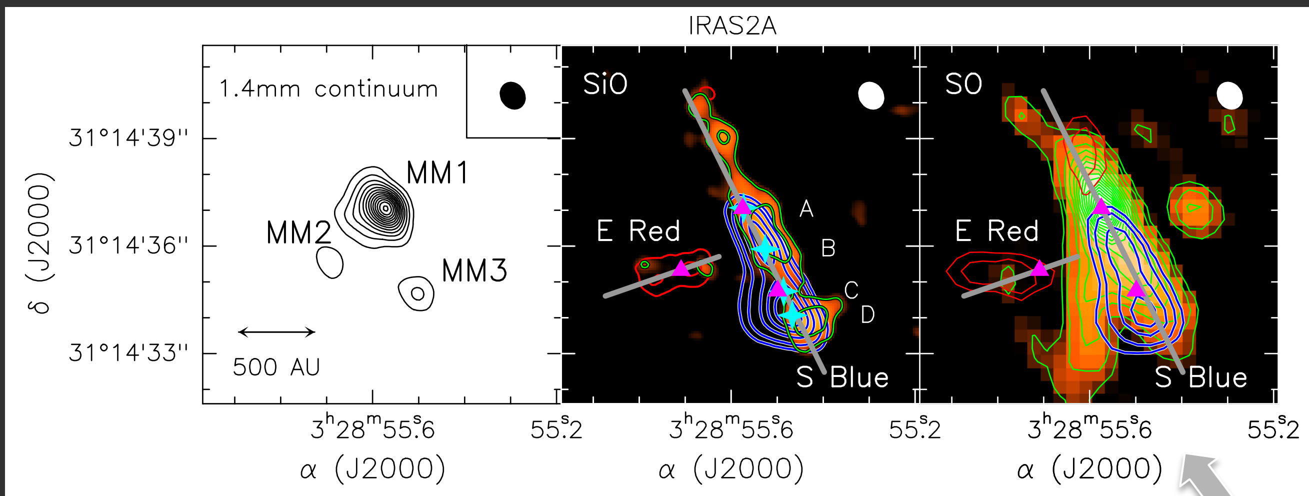


COMs: Hot-corino (50-100 AU)

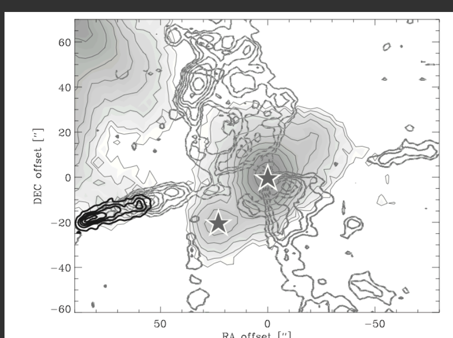
CH_3OH dynamics: no Keplerian disk (smaller?)

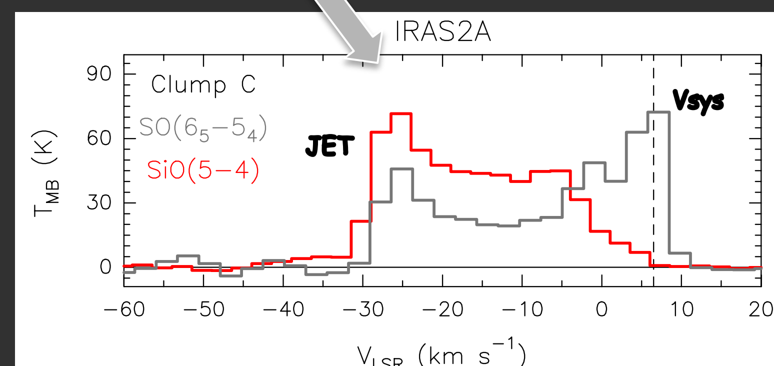
(Maury et al. 2014, Codella et al. 2014a, Maret et al. 2014)

CALYPSO: IRAS2A



Jets and cavities: Monopolar jets (on time scales of 100 yr) from a proto-binary system

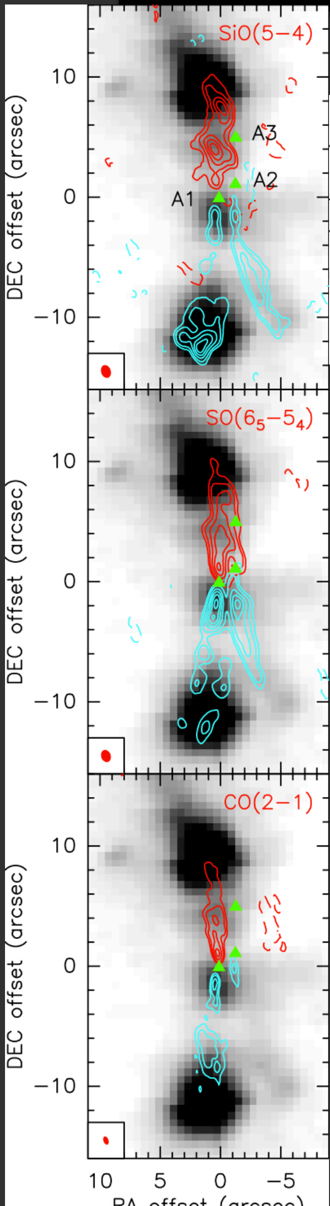


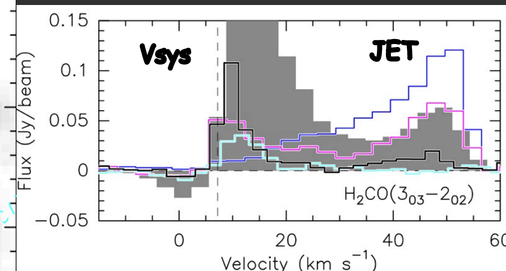


SO as jet tracer

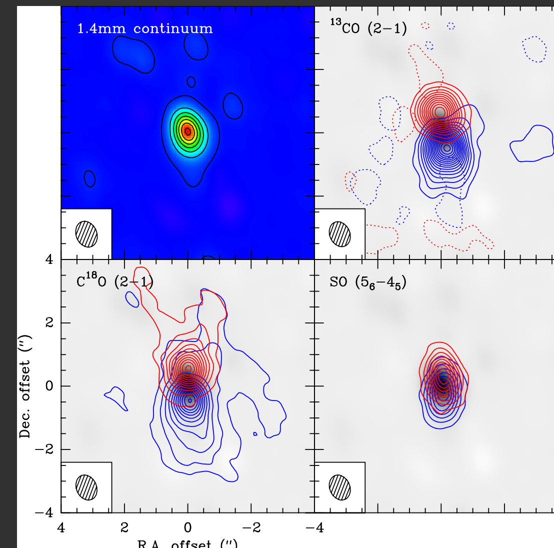
(Maury et al. 2014, Codella et al. 2014a, Maret et al. 2014)

CALYPSO: forthcoming results

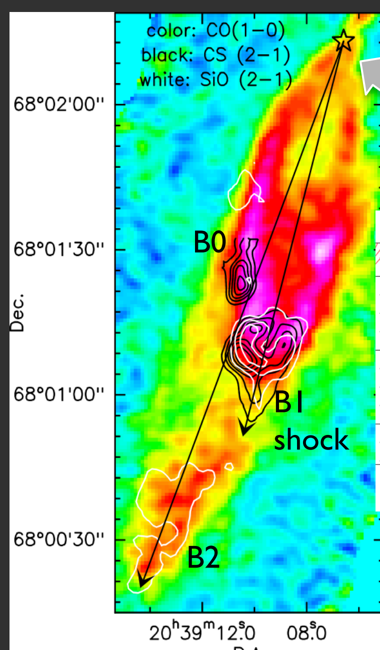


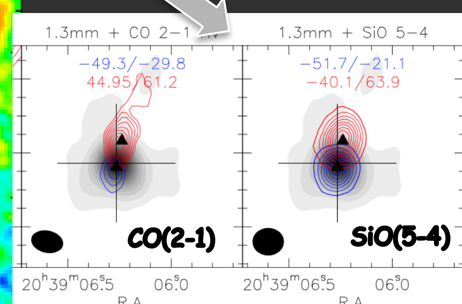


IRAS4A: EHV shock chemistry



L1527: Disk kinematics



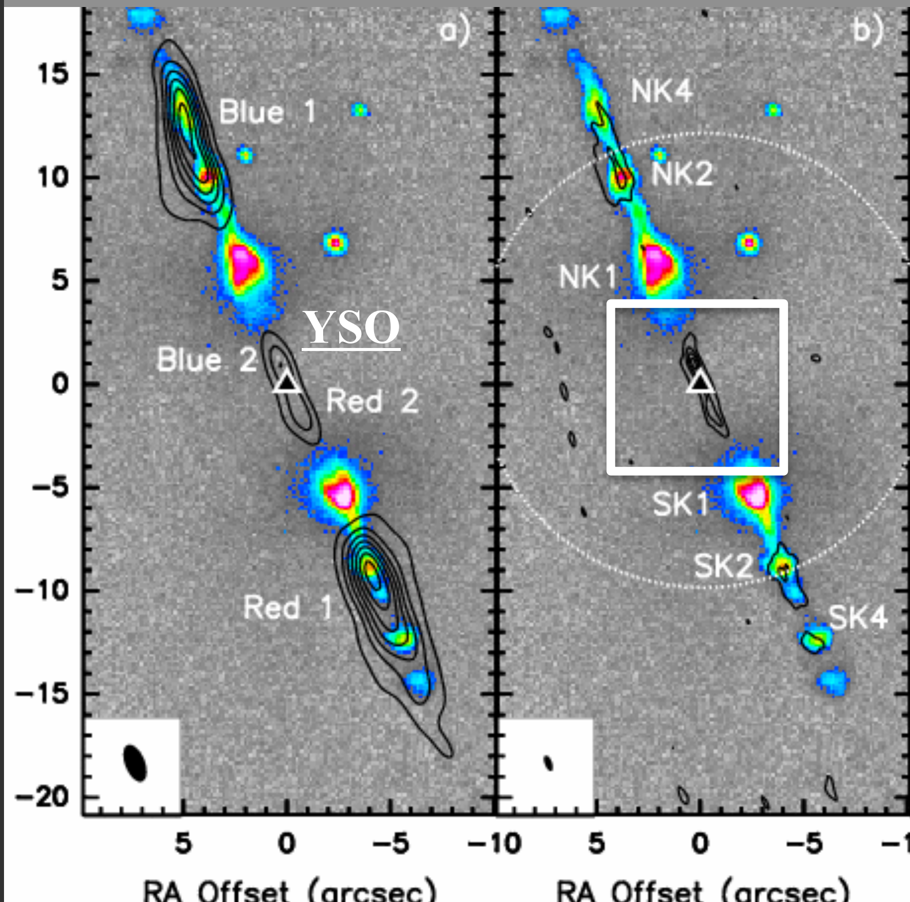


L1157-mm: the jet, finally!

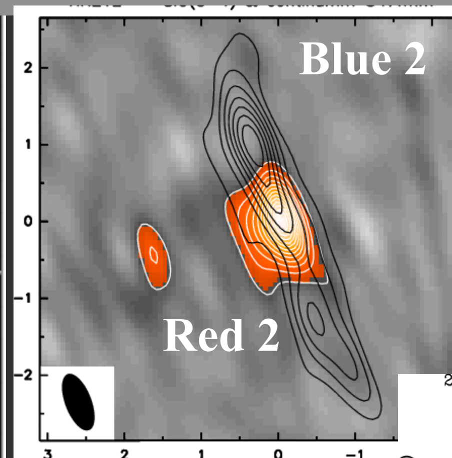
Santangelo et al., Podio et al., Maret et al., Anderls et al.

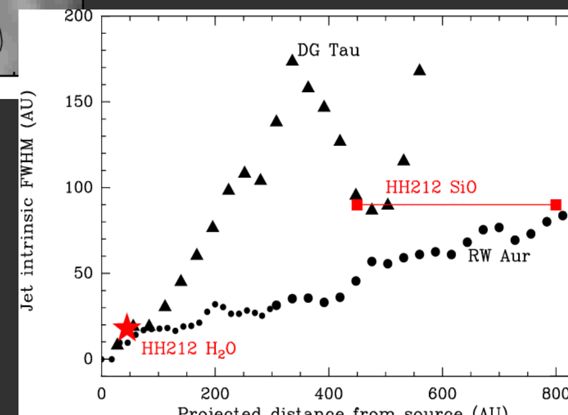
The HH212 case: what learnt from PdBI

SiO(2-1) & SiO(5-4) vs. (IR) H_2



SiO(5-4) vs.1.4mm





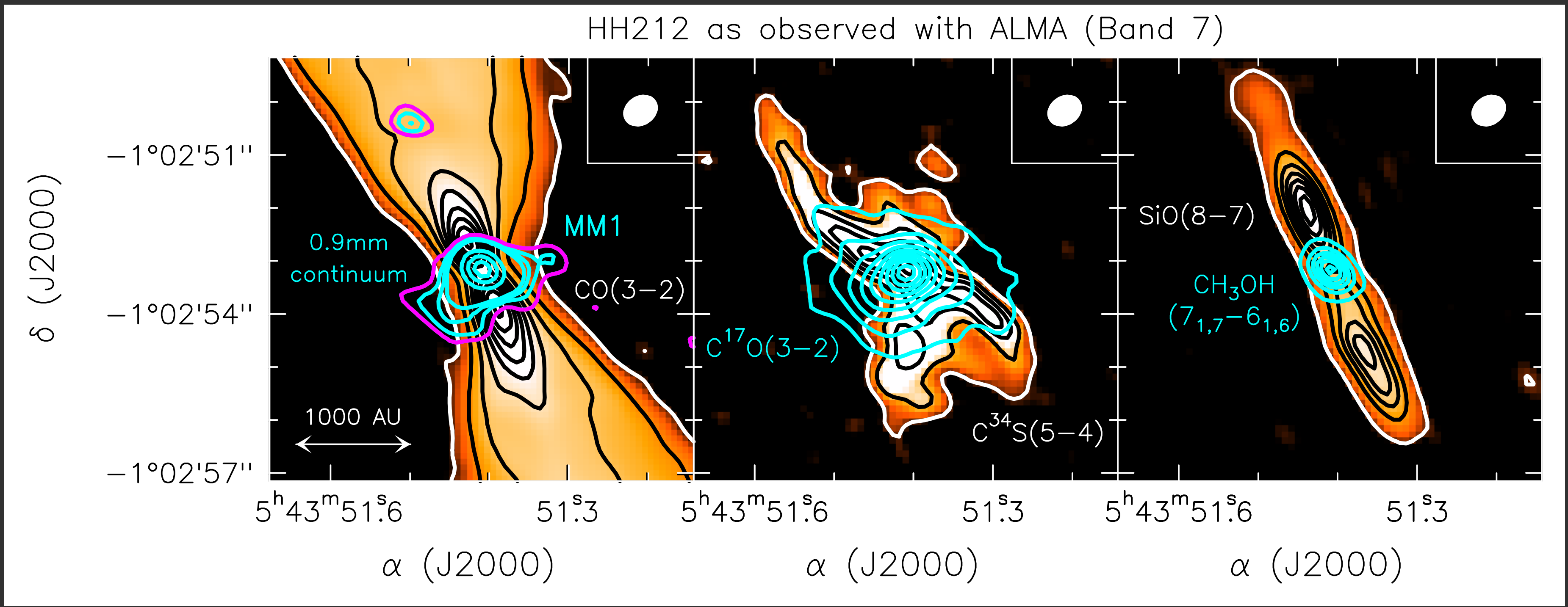
Protostellar system: primary SiO jet (Codella et al. 2007, Cabrit et al. 2012)

Typical transversal size: 0.2" = 90 AU.

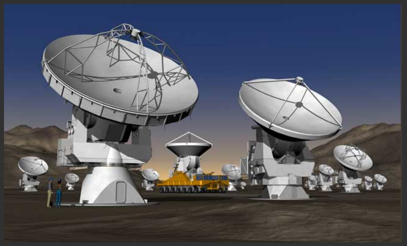
No collimation by external pressure gradients. Jets are self-collimated by internal magnetic stresses.

See also the SMA projects by Lee and collaborators!

ALMA !

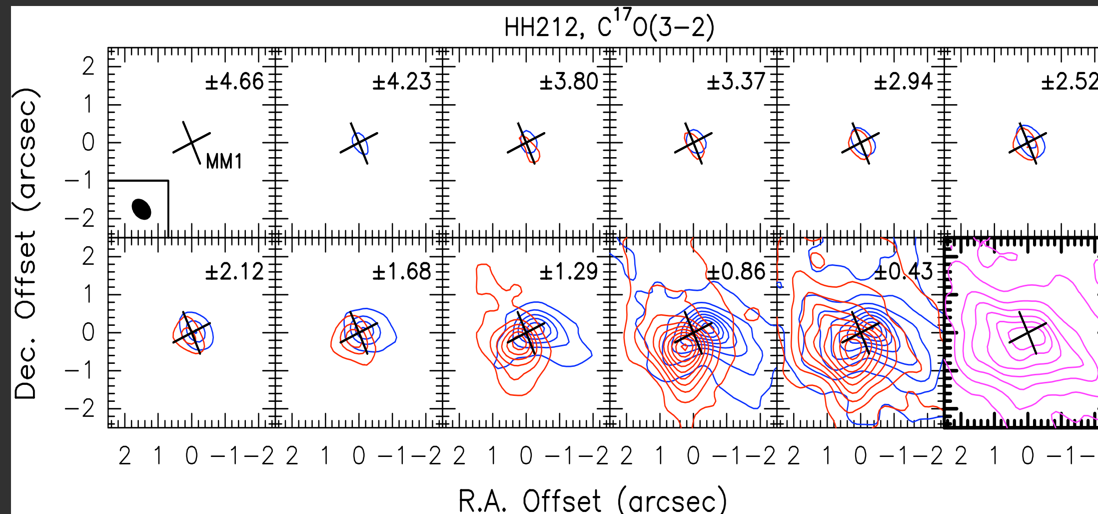


All the ingredients of the Sun-like star formation recipe imaged with a single spectral set-up !!!!!
(Codella et al. 2014b)

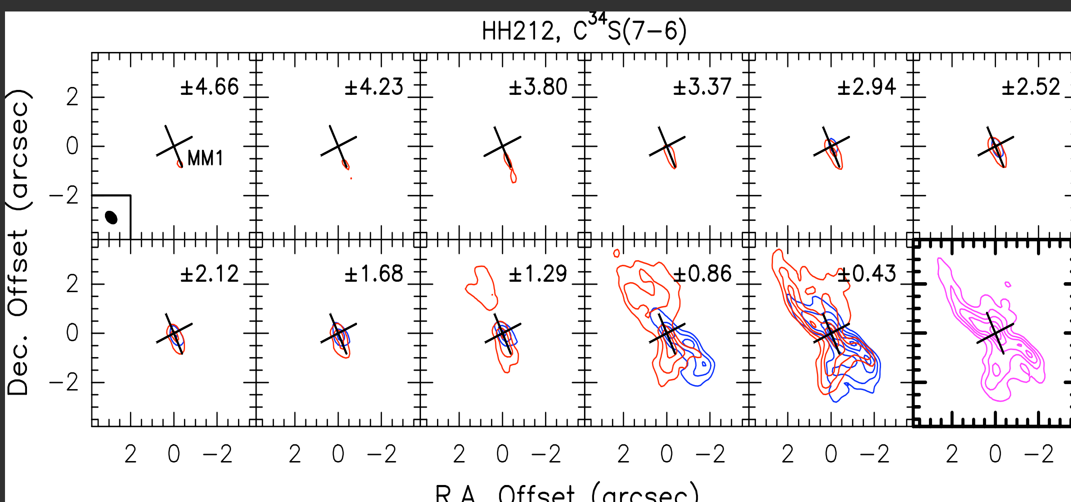


Cavities and rotating walls

Vsys = +1.3 ± 0.2 km/s;
Vsys NH_3 = +1.6 km/s on a scale of 14000 AU
(Wiseman et al. 2001)



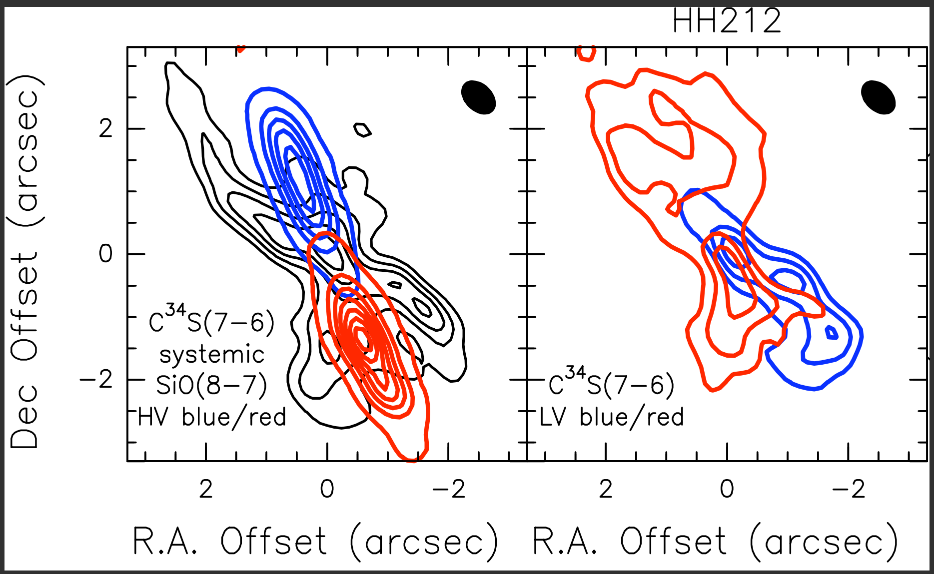
n_crit ($C^{34}S$ 7-6) ≈ 9 10^6 cm^{-3}



Rotating cavity walls !
(Codella et al. 2014b)

S-shaped warp cavity !
B ≠ J ?
We need polarisation….
(ALMA-Cycle 2)

Cavities and rotating walls



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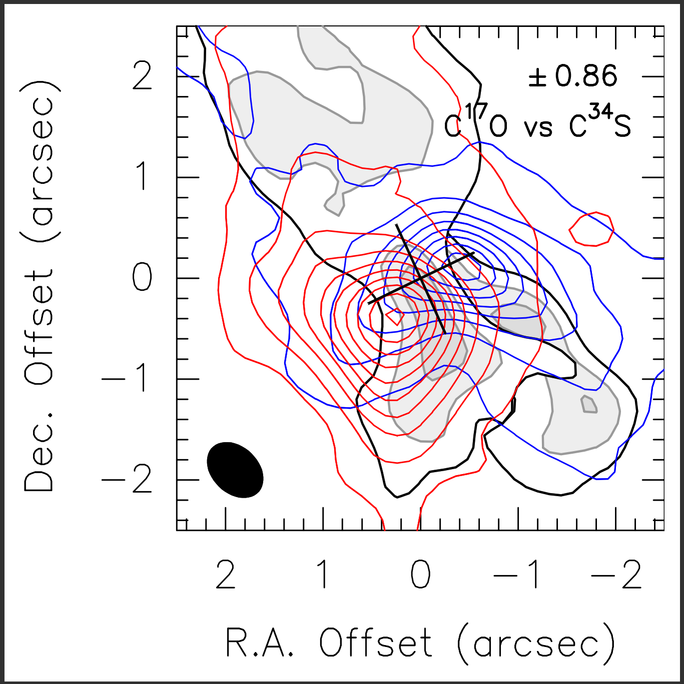
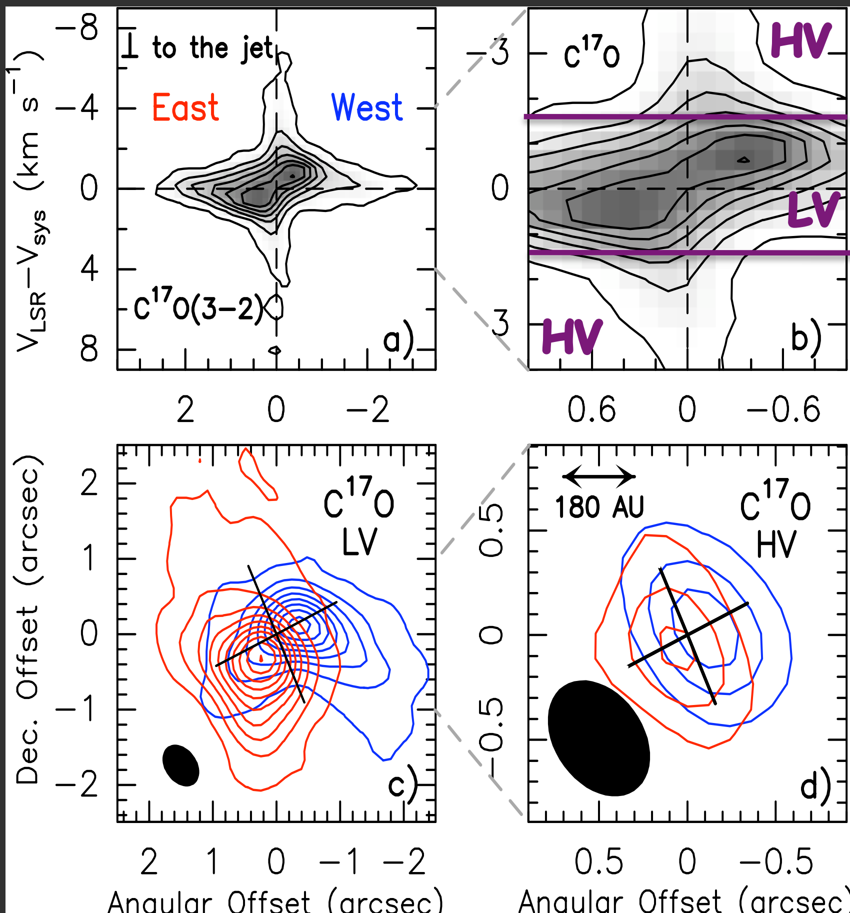
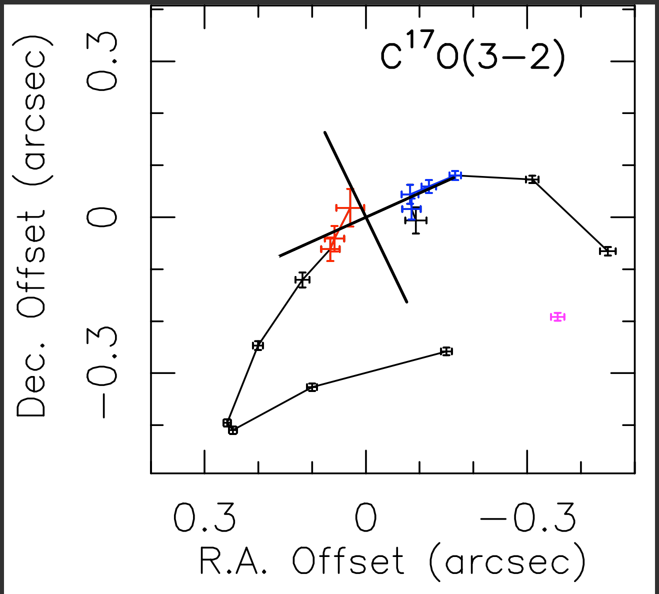


$C^{34}S$ filling-in the swept up cavity delinated by $C^{17}O$?
Rotating-angle flow with a nested onion-like structure ?
(as atomic jet from T-Tauri DG Tau ?)

Codella et al. (2014b)

The inner disk





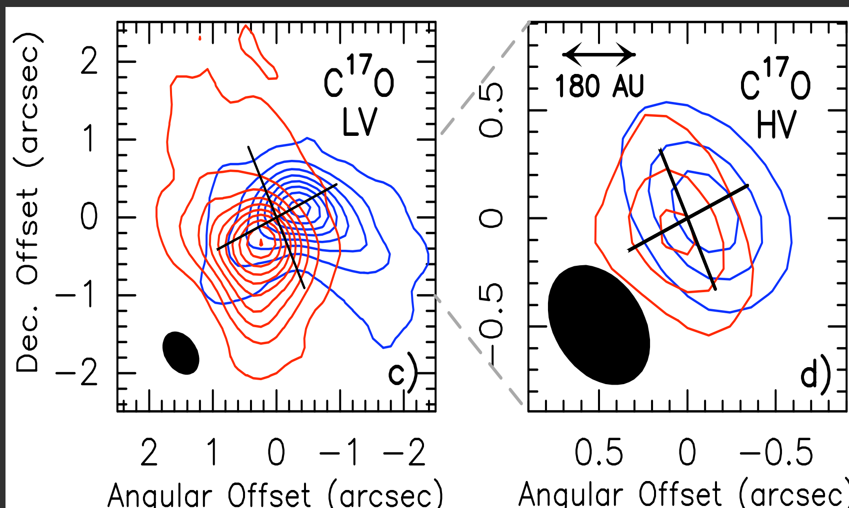
HV regime
1. compact;
2. centroids moves to the equatorial plane.

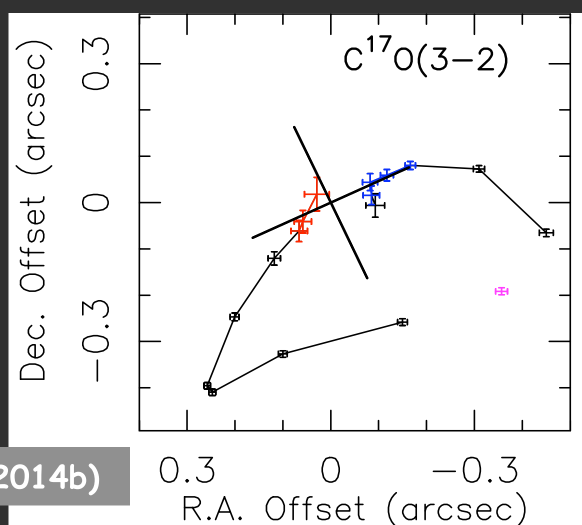
Inner rotating disk of radius 0.2" (90 AU) !

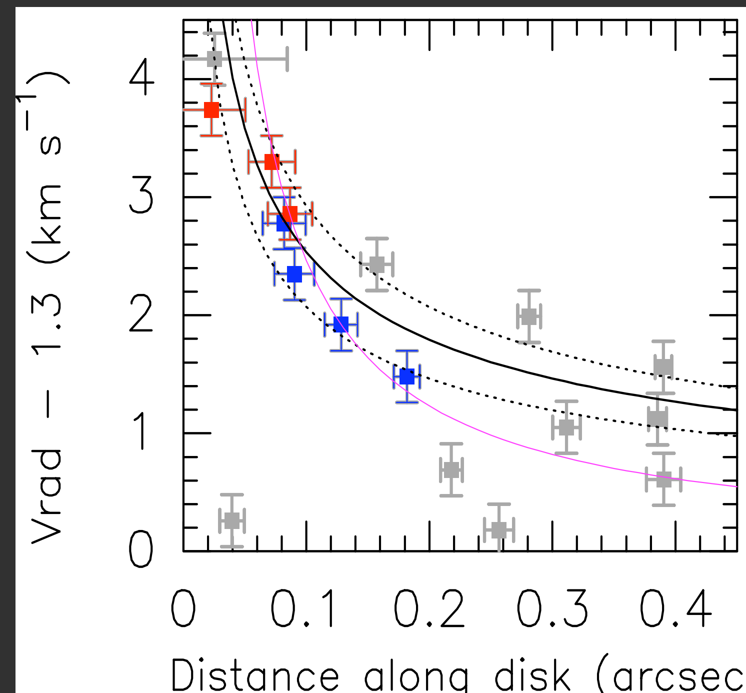
LV regime: rotating outflow walls

Codella et al. (2014b)

The inner disk



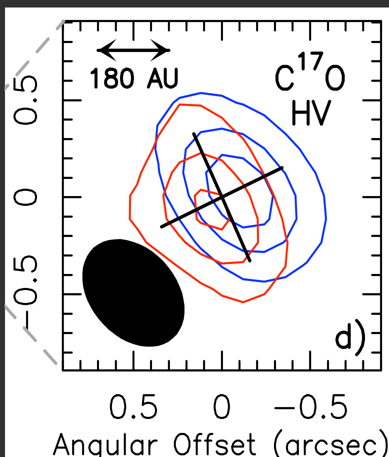


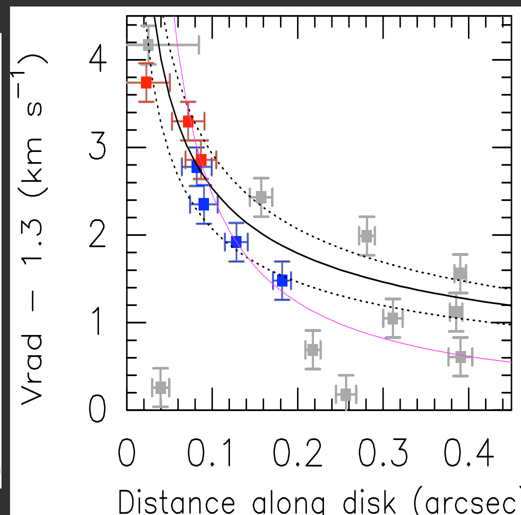


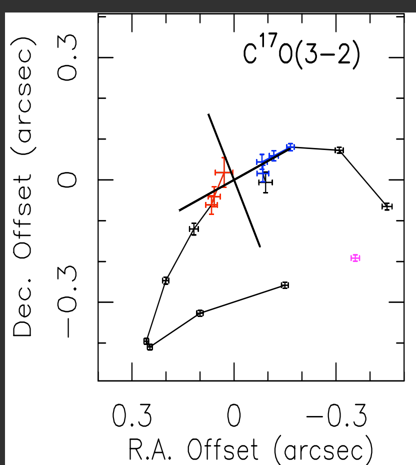
These findings are consistent with keplerian rotation out to 90 AU around a 0.3±0.1 $M_{\odot}$

Codella et al. (2014b)

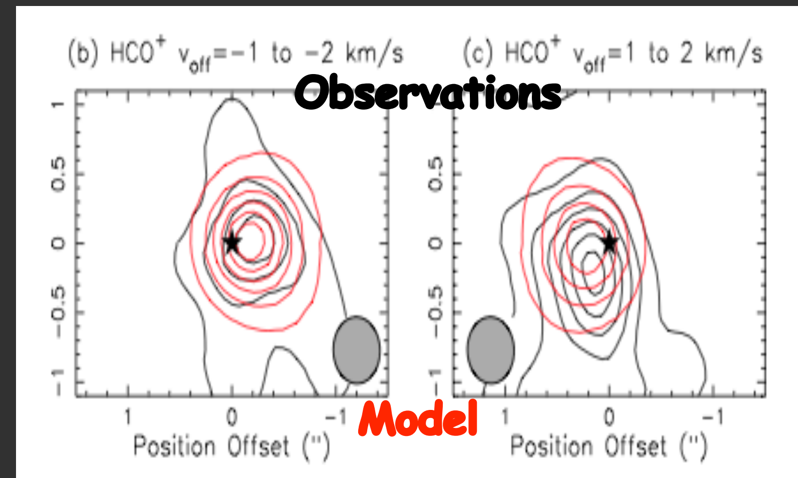
The inner disk

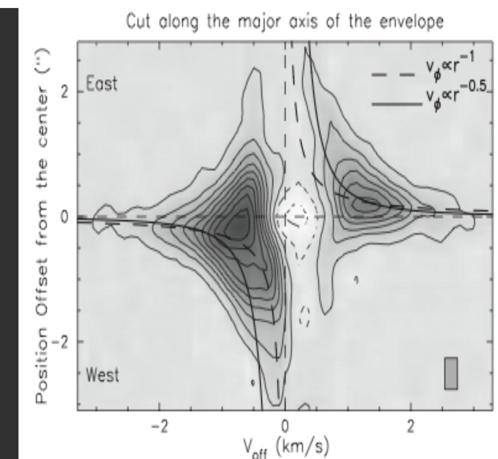






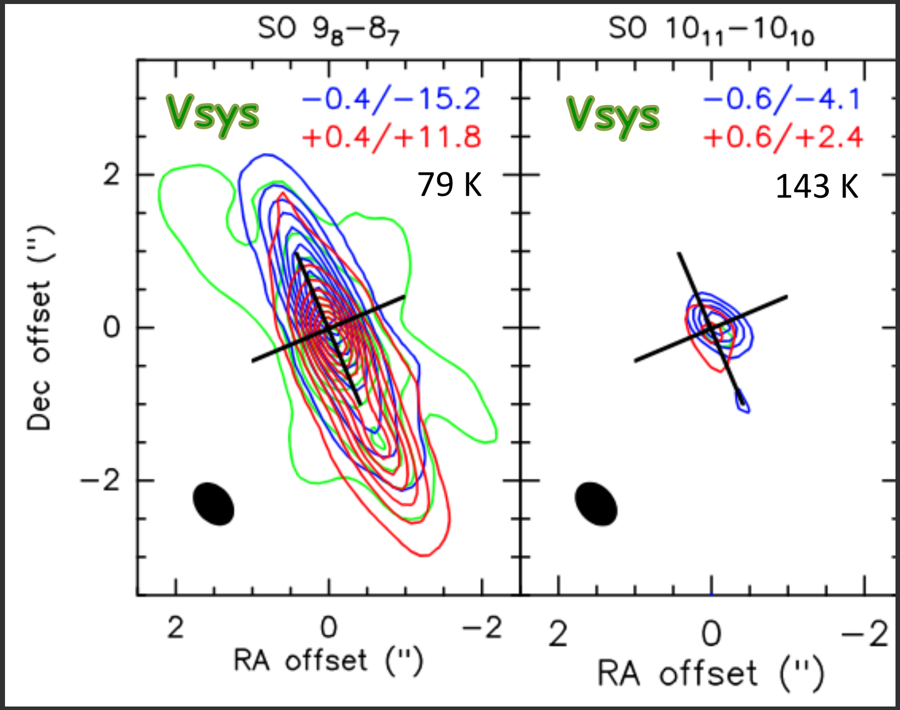
Codella et al. (2014b)





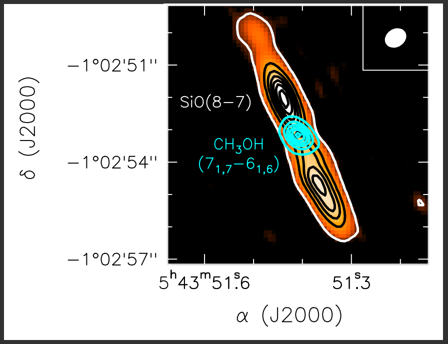
Consistent with the HCO+ ALMA images by Lee et al. (2014) ……

Sulfur !



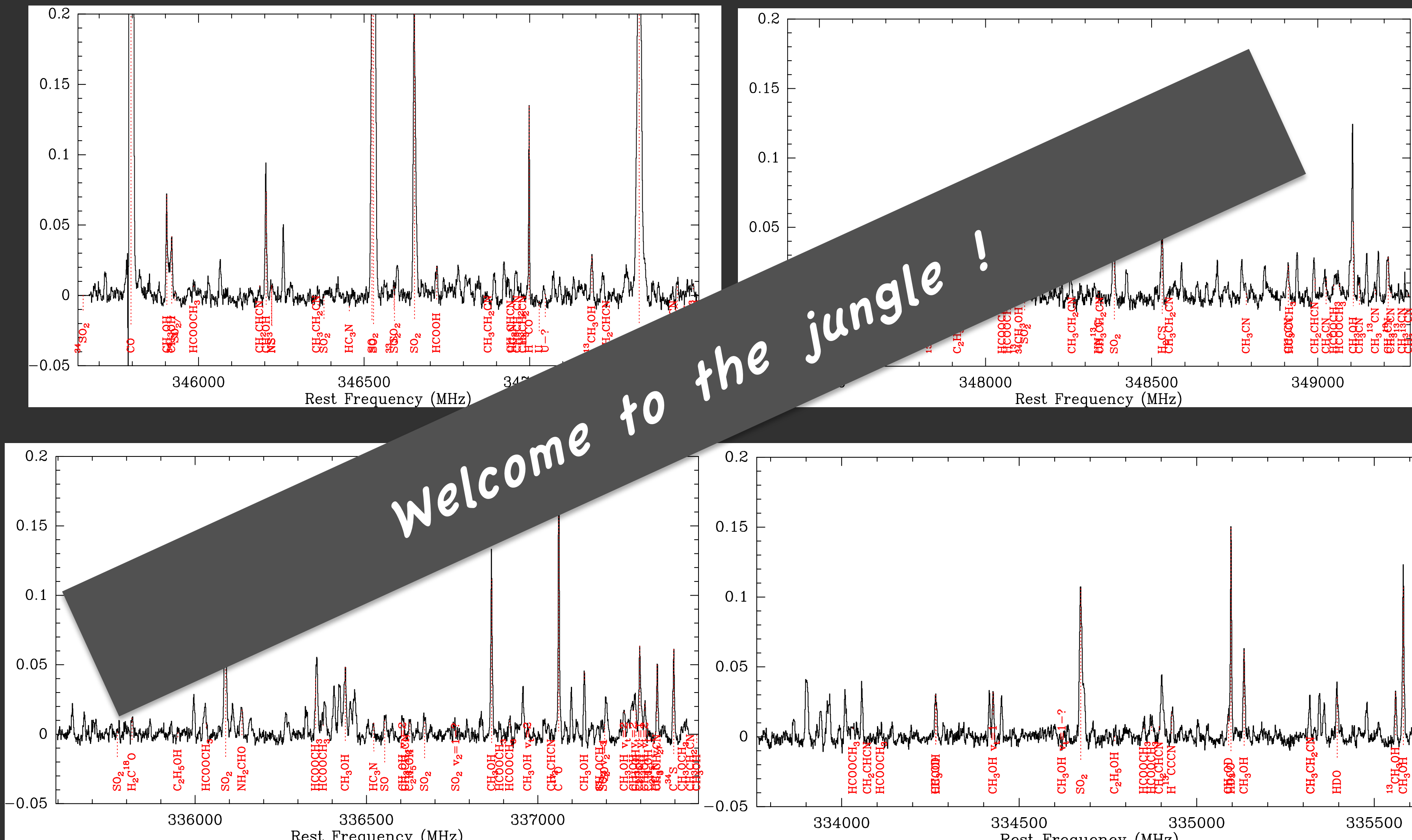
$SO(9_8-8_7)$
—> JET/OUTFLOW

$SO(10_{11}-10_{10})$
—> compact emission —>
rotating and/or infalling
DISK/ENVELOPE ?



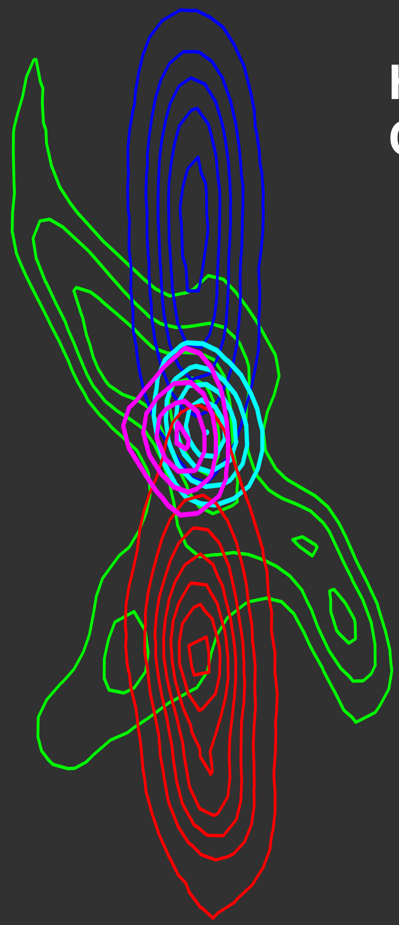
Podio et al. (2015)

Work in progress...

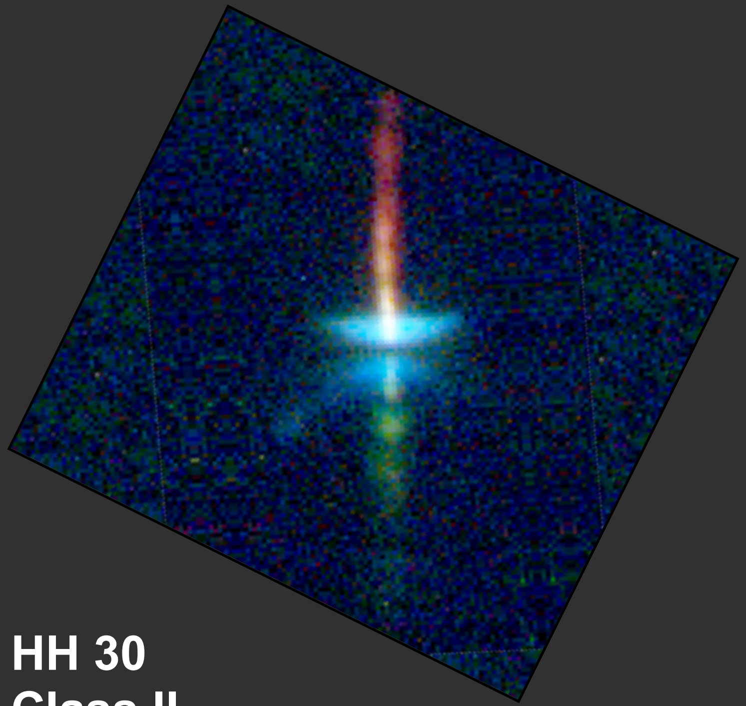


Welcome to the jungle !

Round-up



HH 212
Class 0



HH 30
Class II

Outline

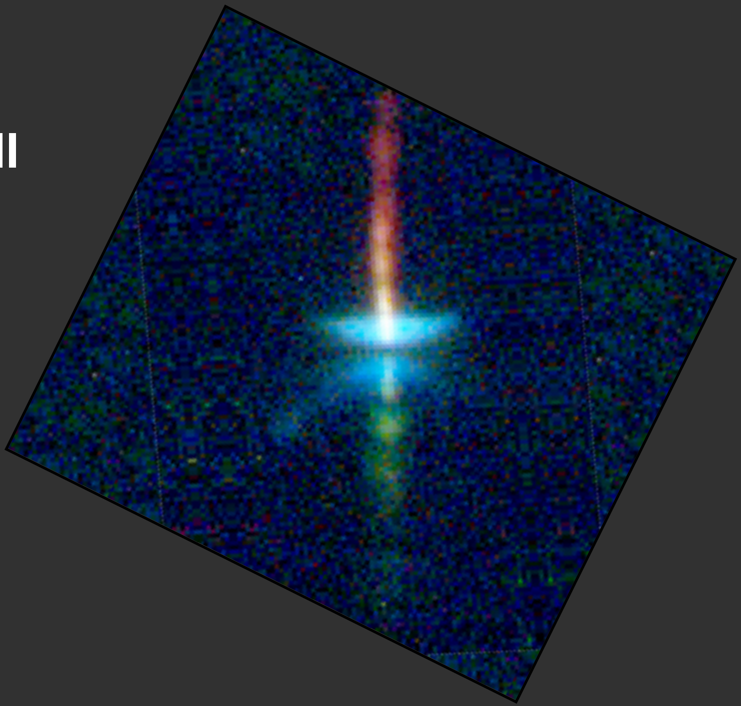
- **The low-mass star formation**

- **Searching for the pristine protostellar jet/disk system**

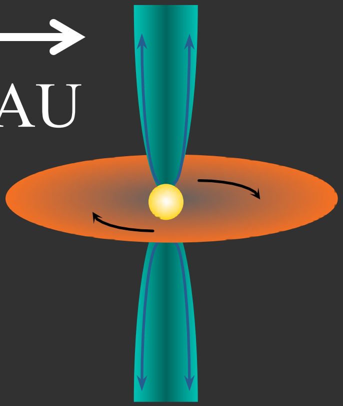
- **News from the CALYPSO IRAM-LP**

- **The HH212 case, as observed by ALMA**

HH 30
Class II



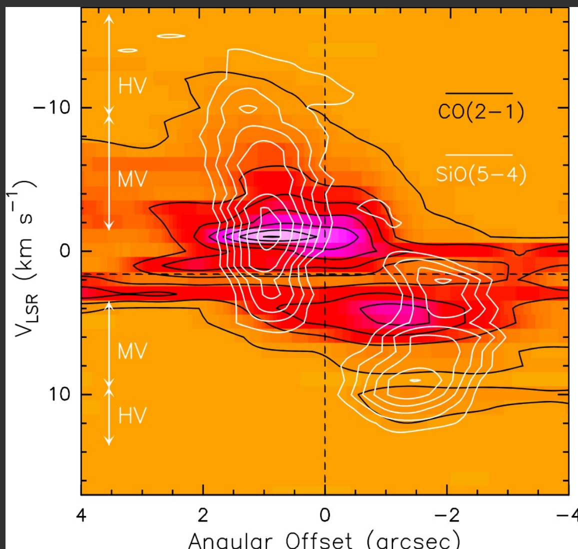
100 AU



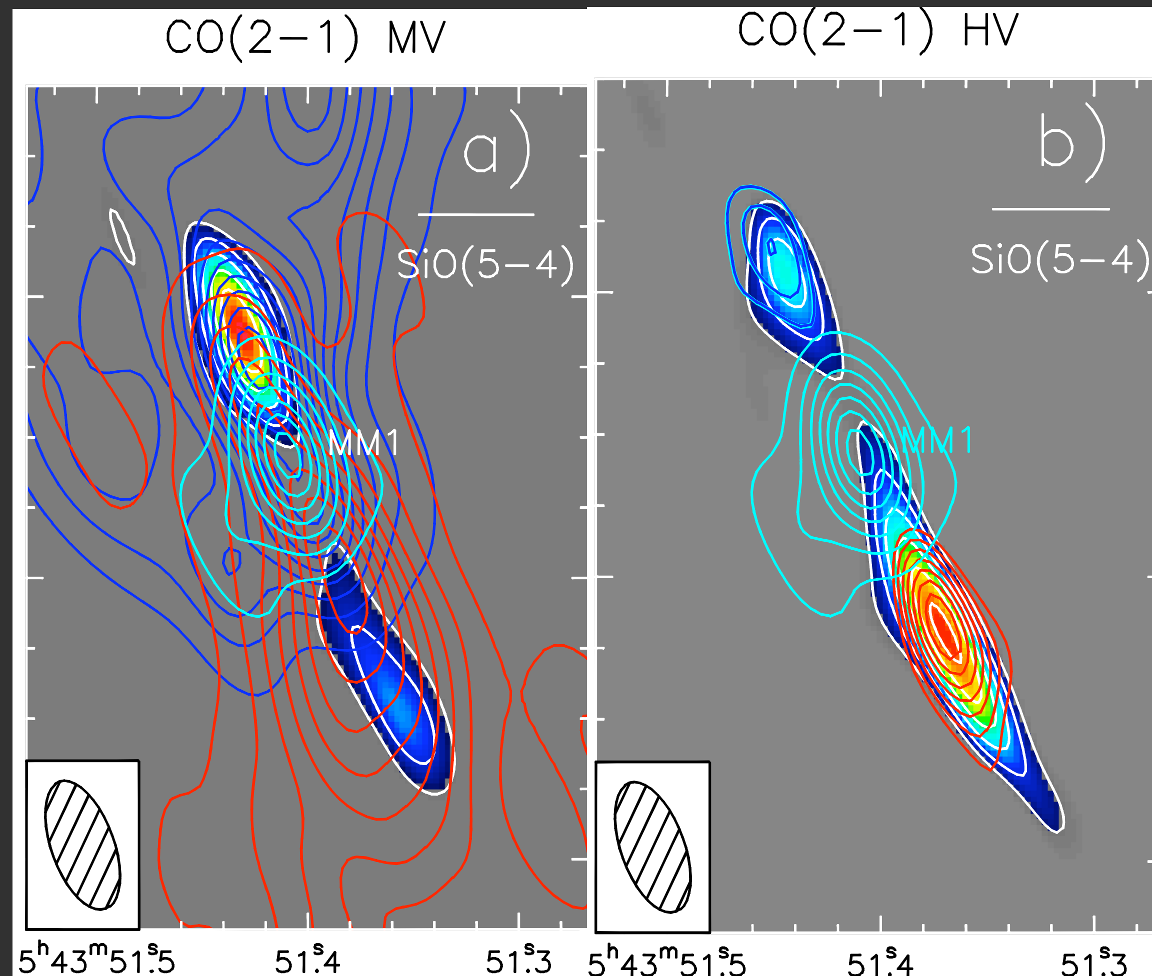
T-Tauri Star:
accretion disk + jet

(t =10^6-10^7 yr)

Limits of the low-J molecular emission

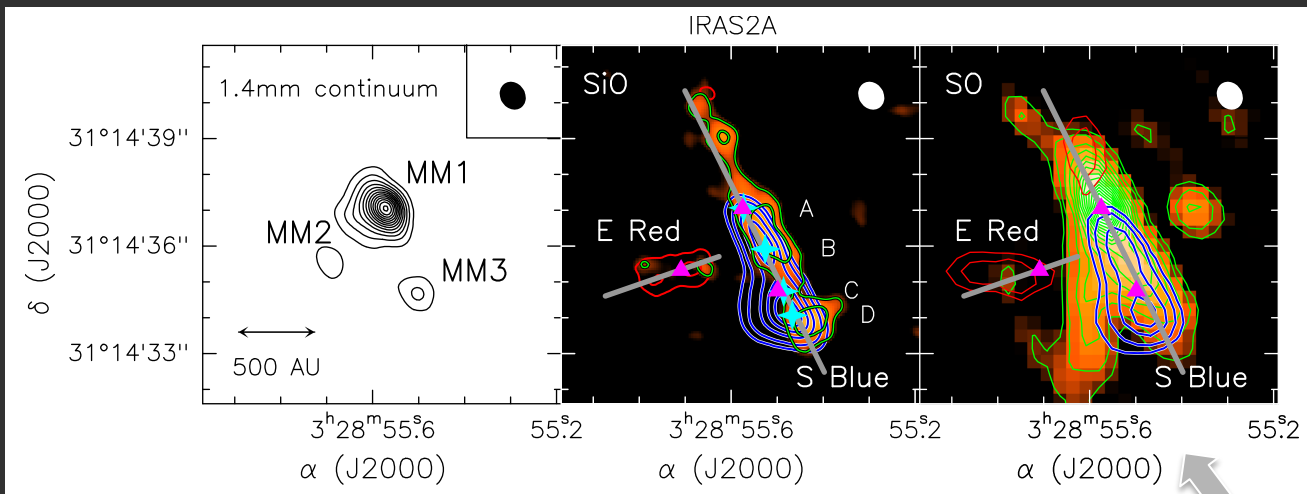


Cabrit et al. (2012)

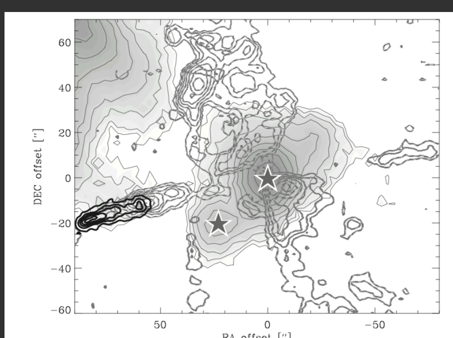


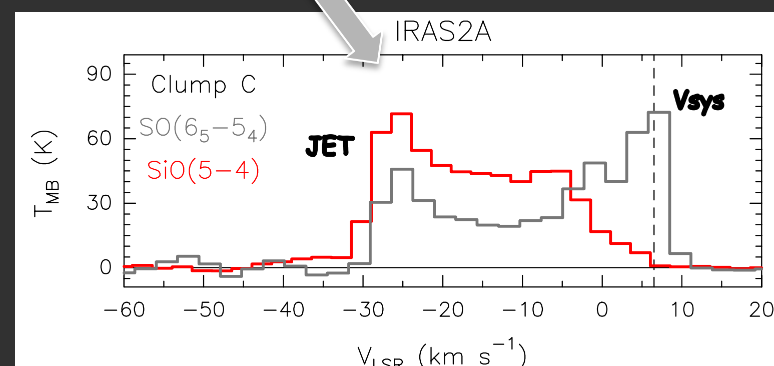
The low-velocity CO(2-1) is due to entrained gas at the base of the outflow cavity, and traces the jet only at the highest velocities…… we need higher J CO lines!

CALYPSO: IRAS2A



Jets and cavities: Monopolar jets (on time scales of 100 yr) from a proto-binary system



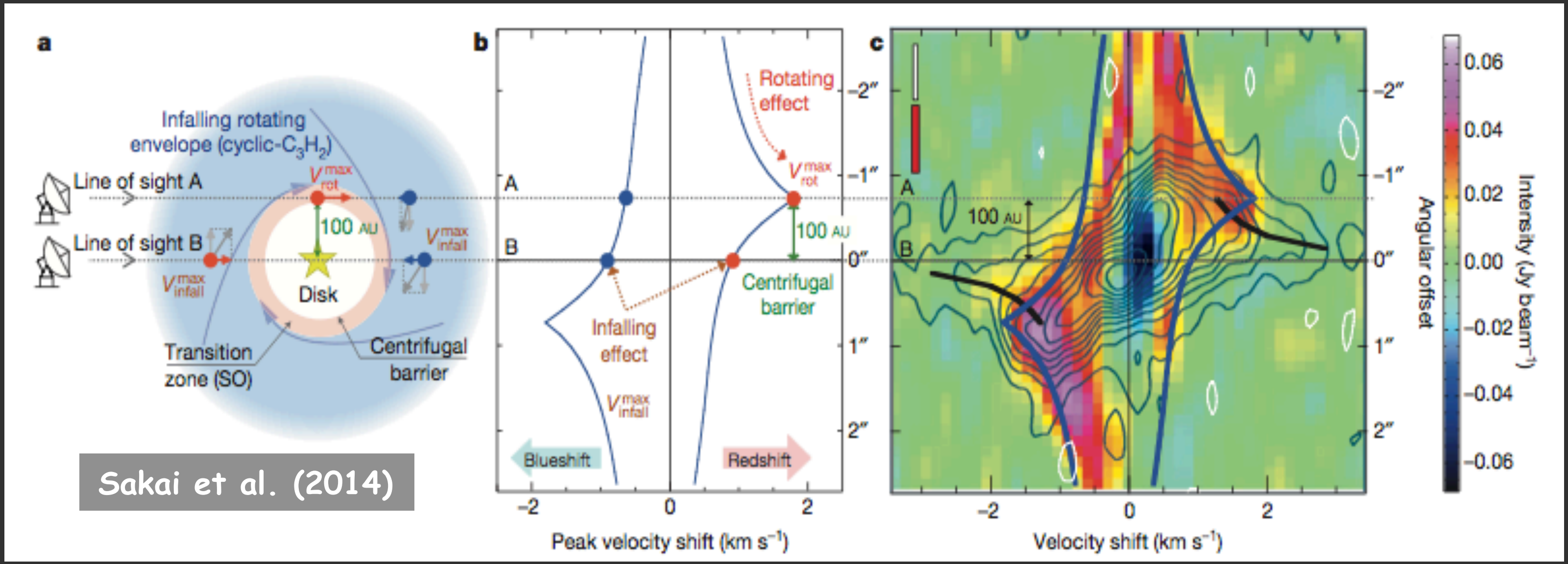


SO as jet tracer

(Maury et al. 2014, Codella et al. 2014a, Maret et al. 2014)

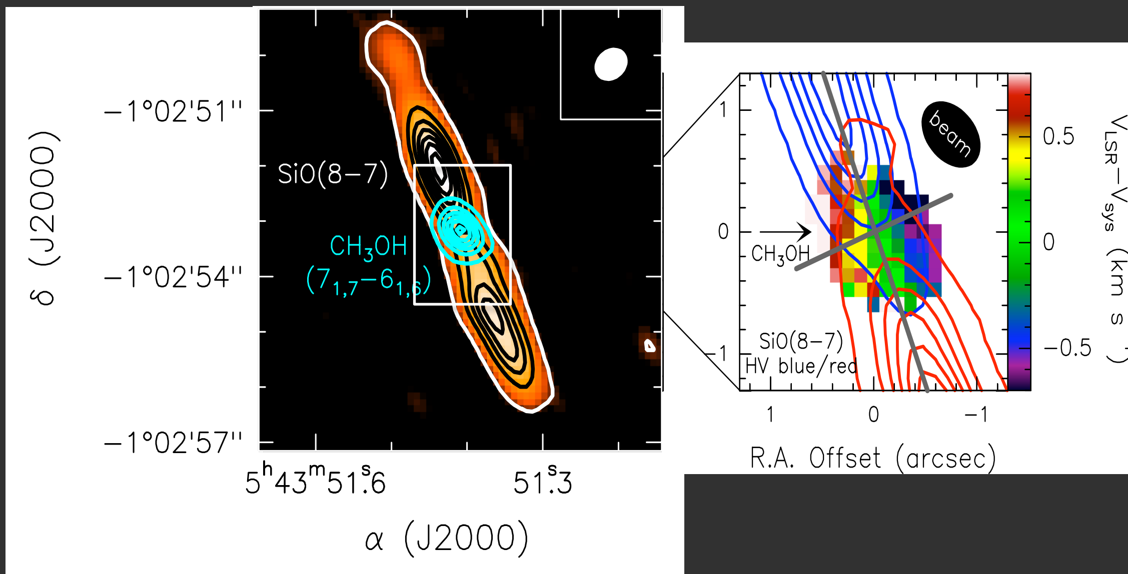
… and the disks around protostars?

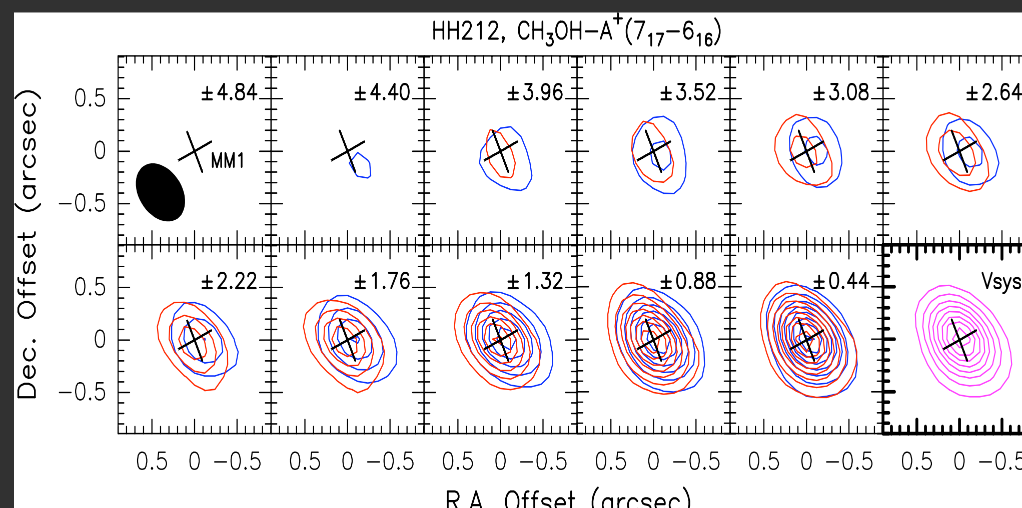
L1527



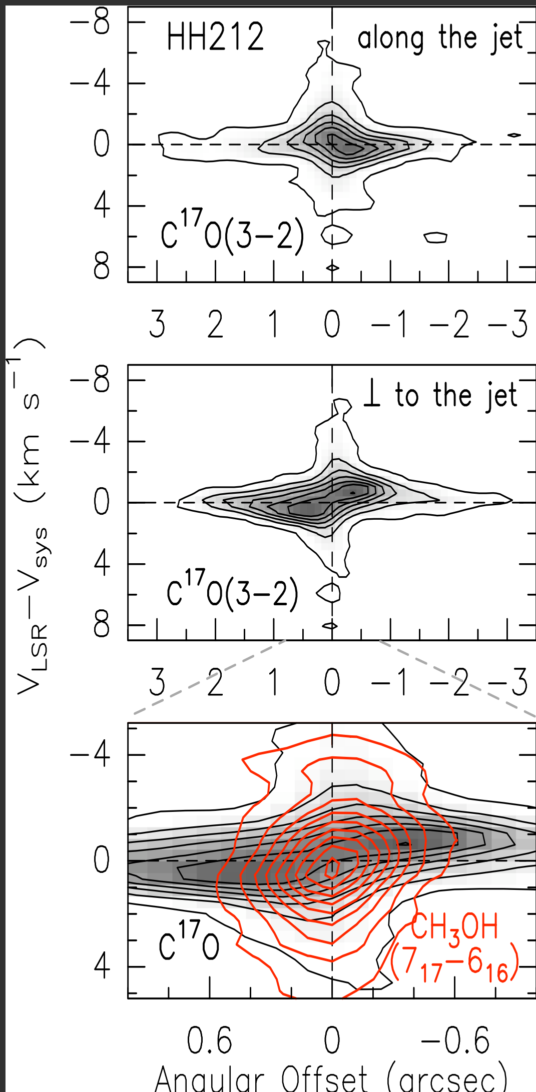
Sakai et al. (2014)

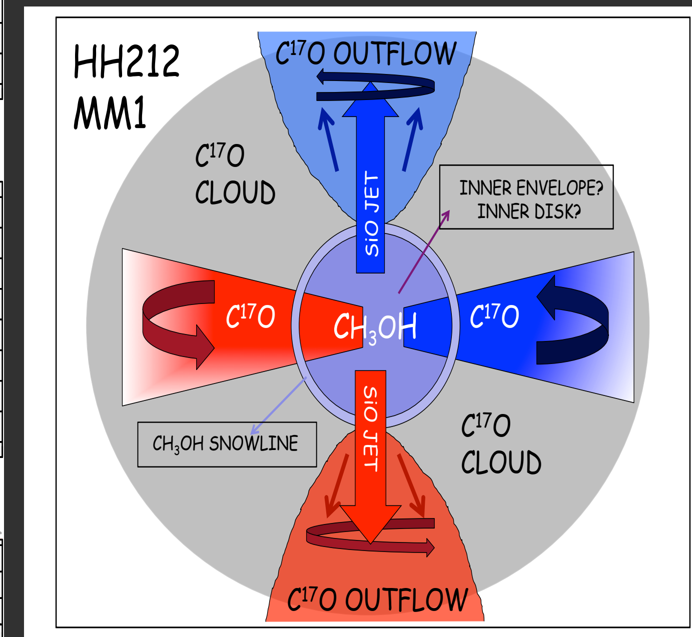
CH_3OH: disk, hot-corino, jet ?

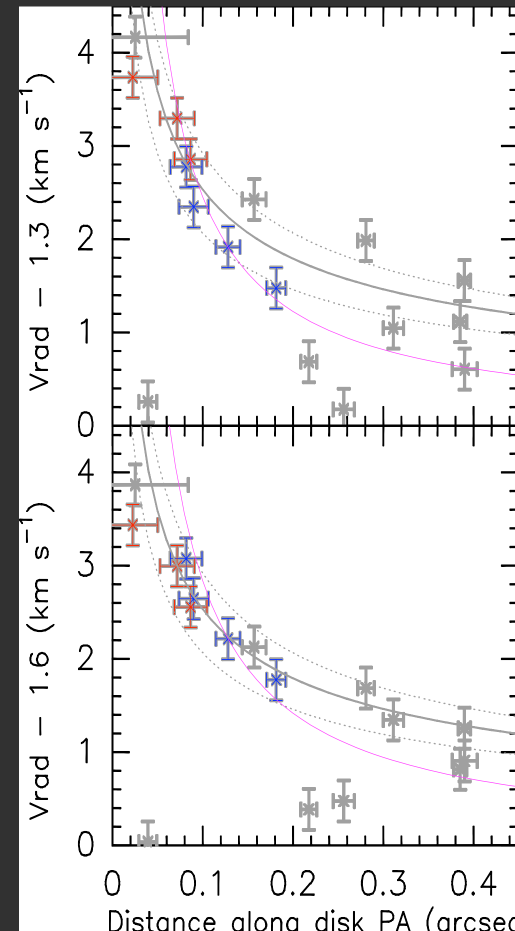




High-excitation (79 K) CH_3OH traces a compact core with a velocity gradient perpendicular to the jet axis ? (Codella et al. 2014b; Maret et al. 2014, see also Lindberg et al. 2014)

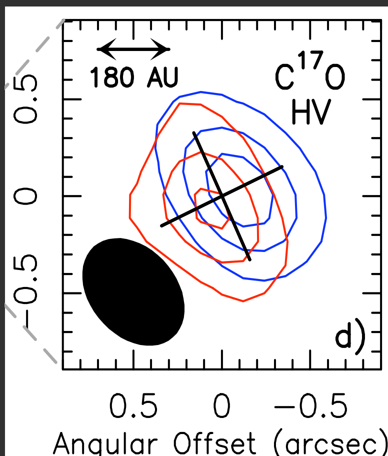


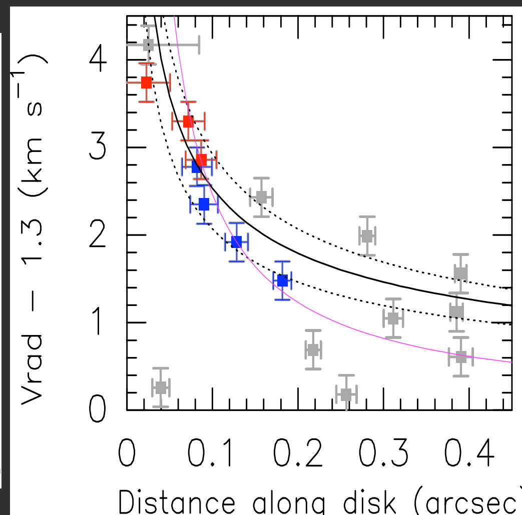


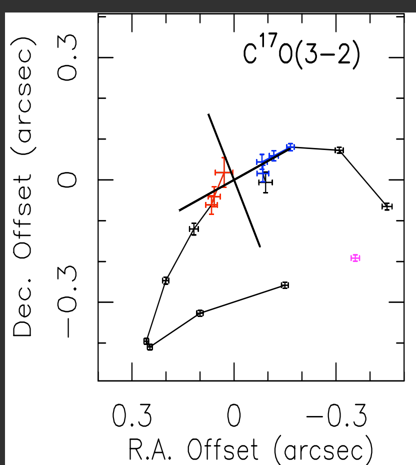


Codella et al. (2014b)

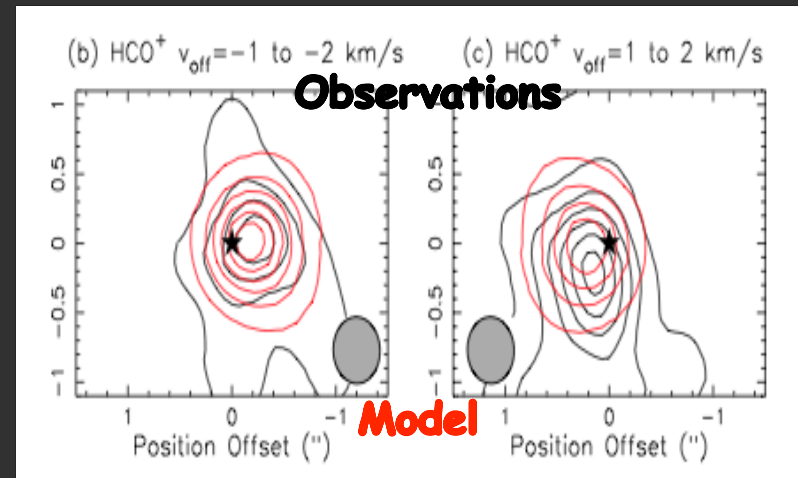
The inner disk

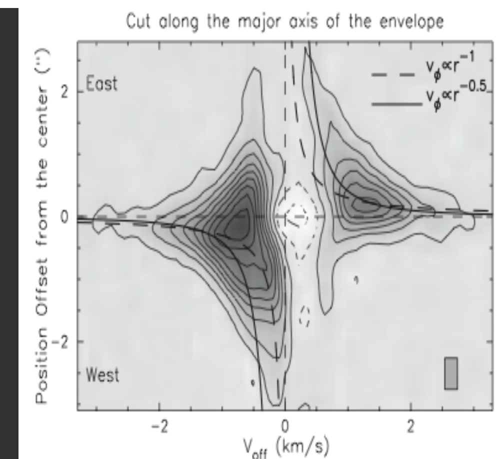






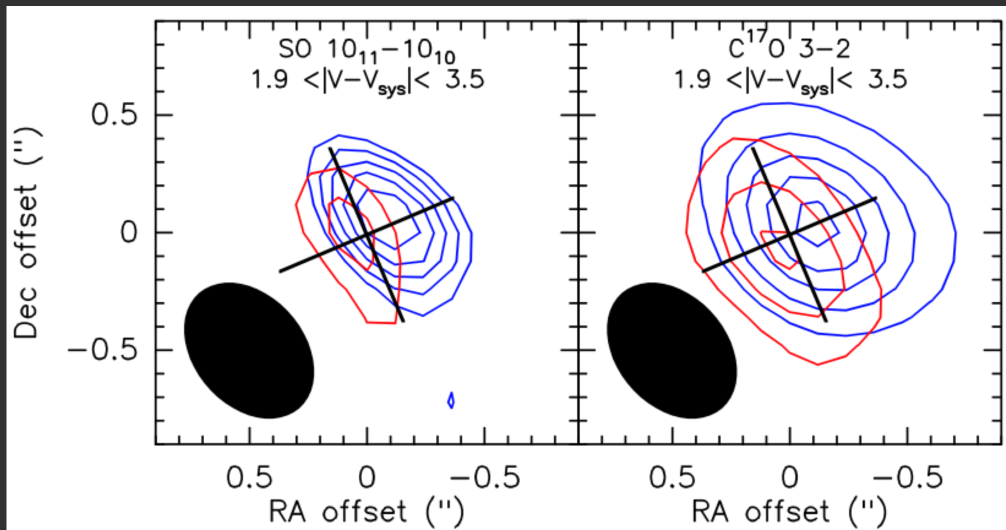
Codella et al. (2014b)





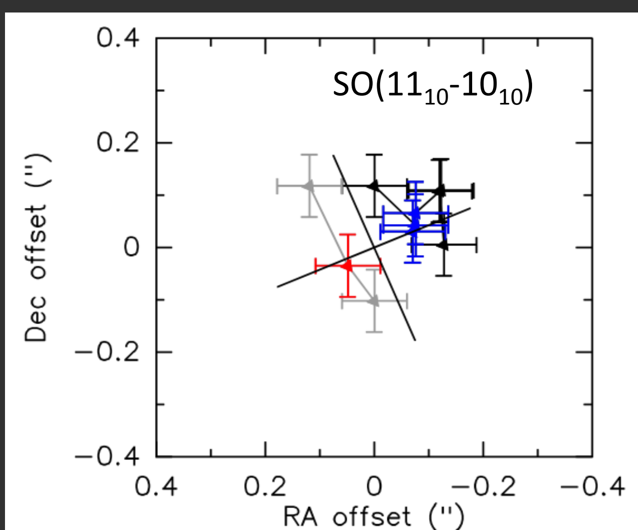
Consistent with the HCO+ ALMA images by Lee et al. (2014) ……

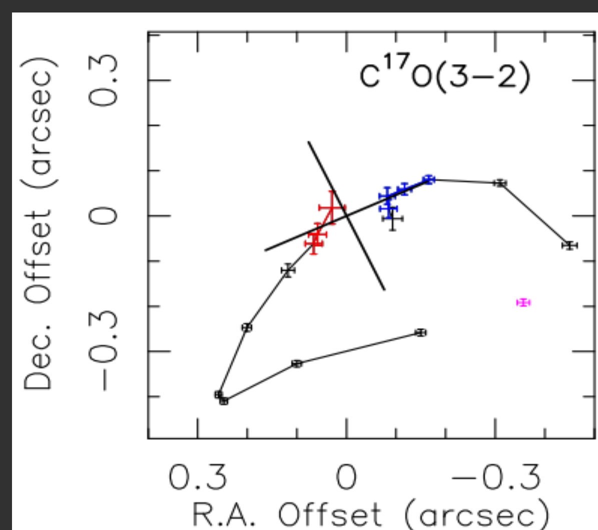
The high-Eu SO compact emission



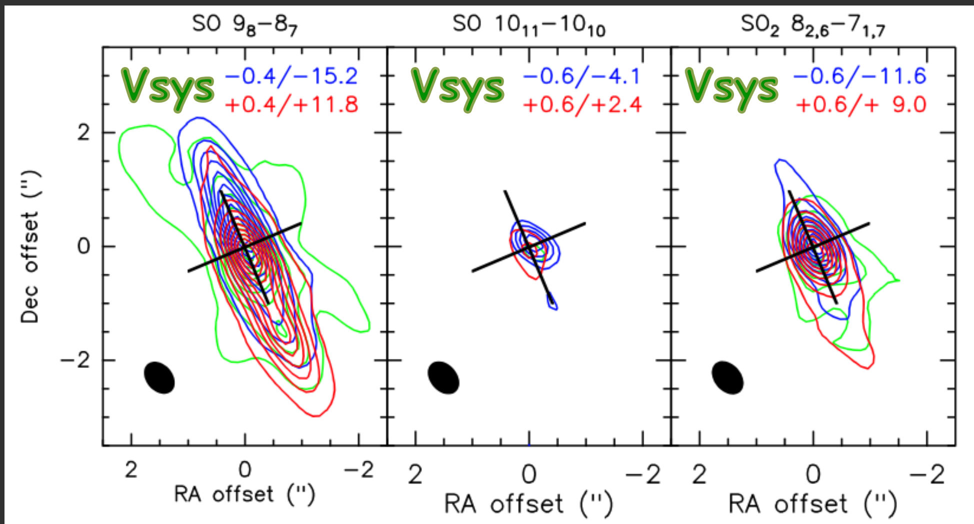
At 1.9 < |V-Vsys| < 3.5 km/s
blue & red peaks along disk axis
similar to $C^{17}O$
(Keplerian) rotating inner disk ?

From $C^{17}O$ and assuming LTE-optically thin:
X(SO) in the disk: 10^{-8}-10^{-7}

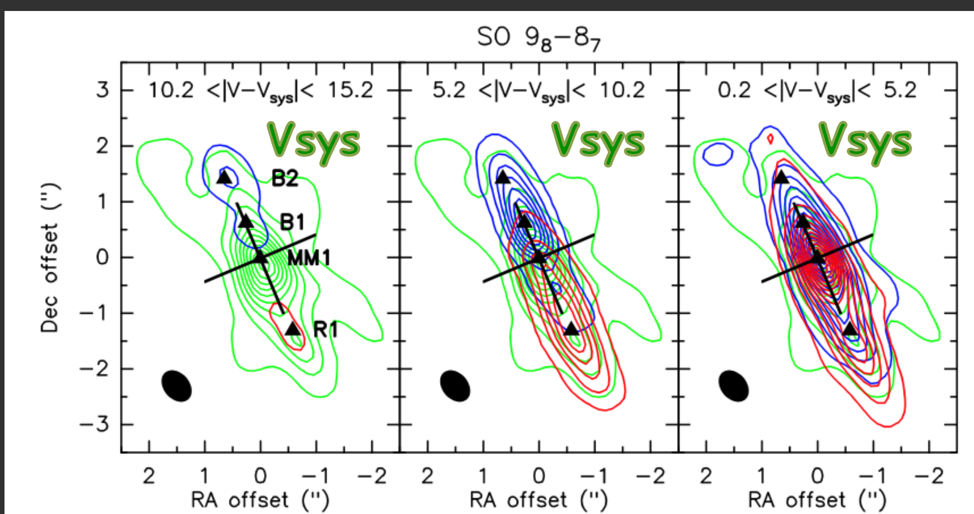


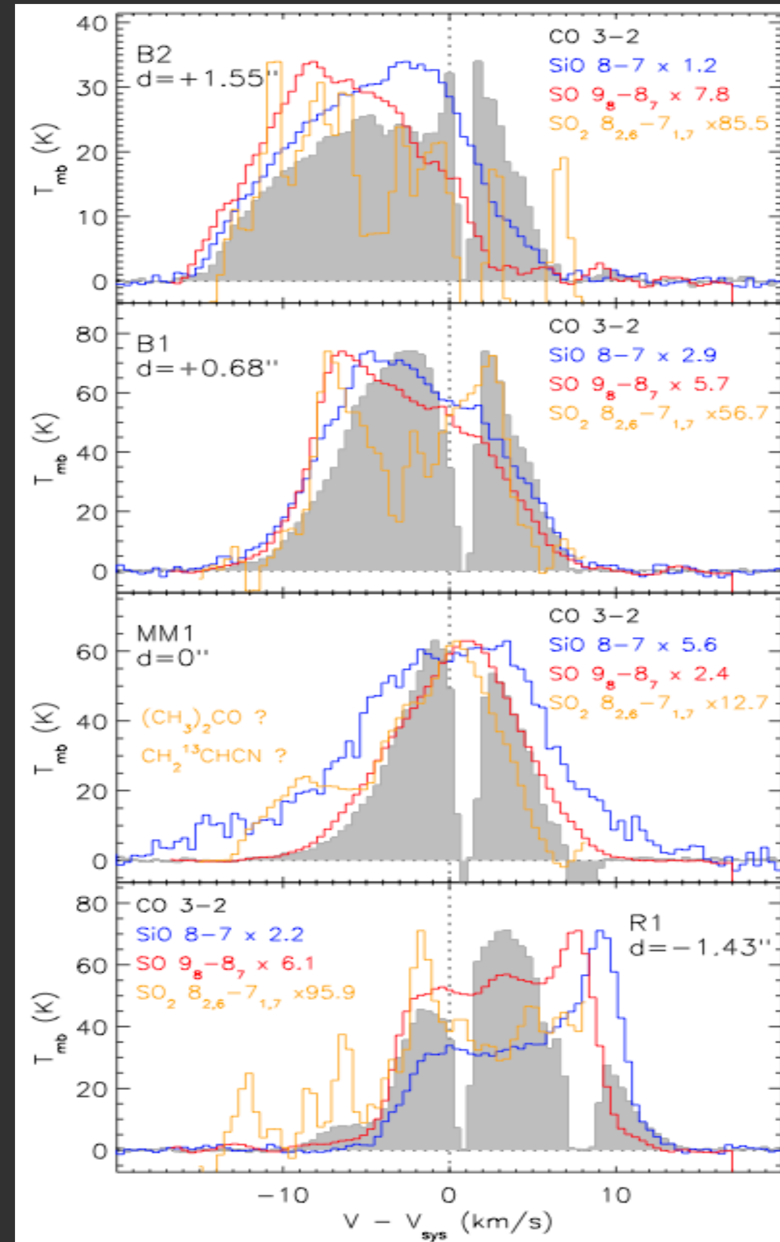


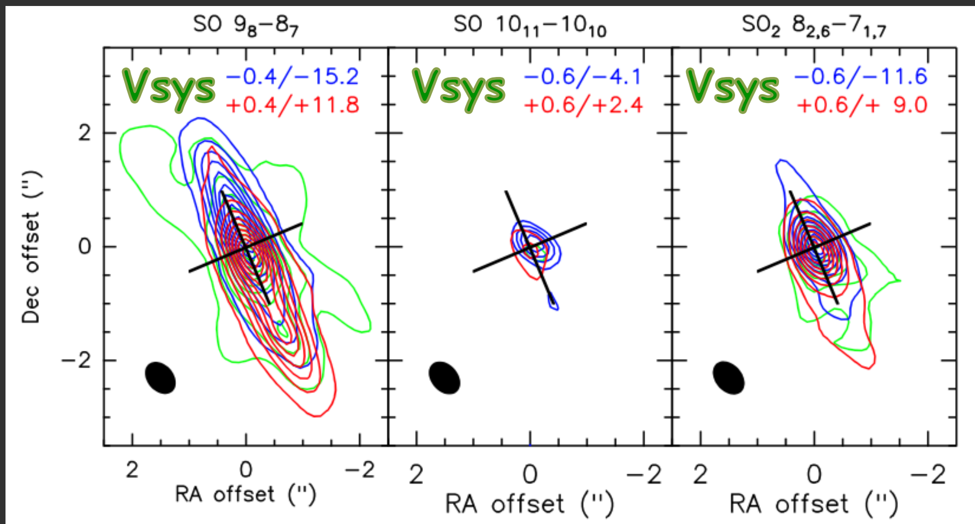
Podio et al. (2015), Codella et al. (2014b)



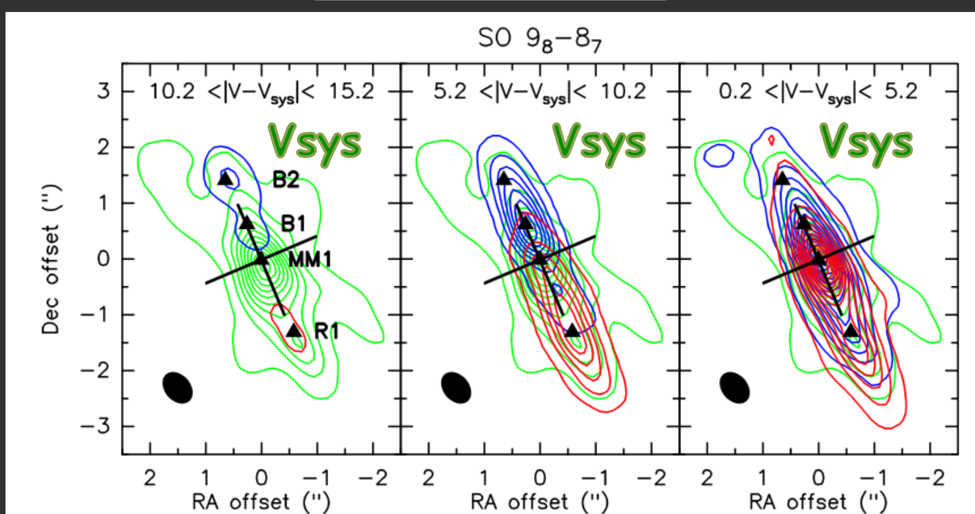
Podio et al. (2014)

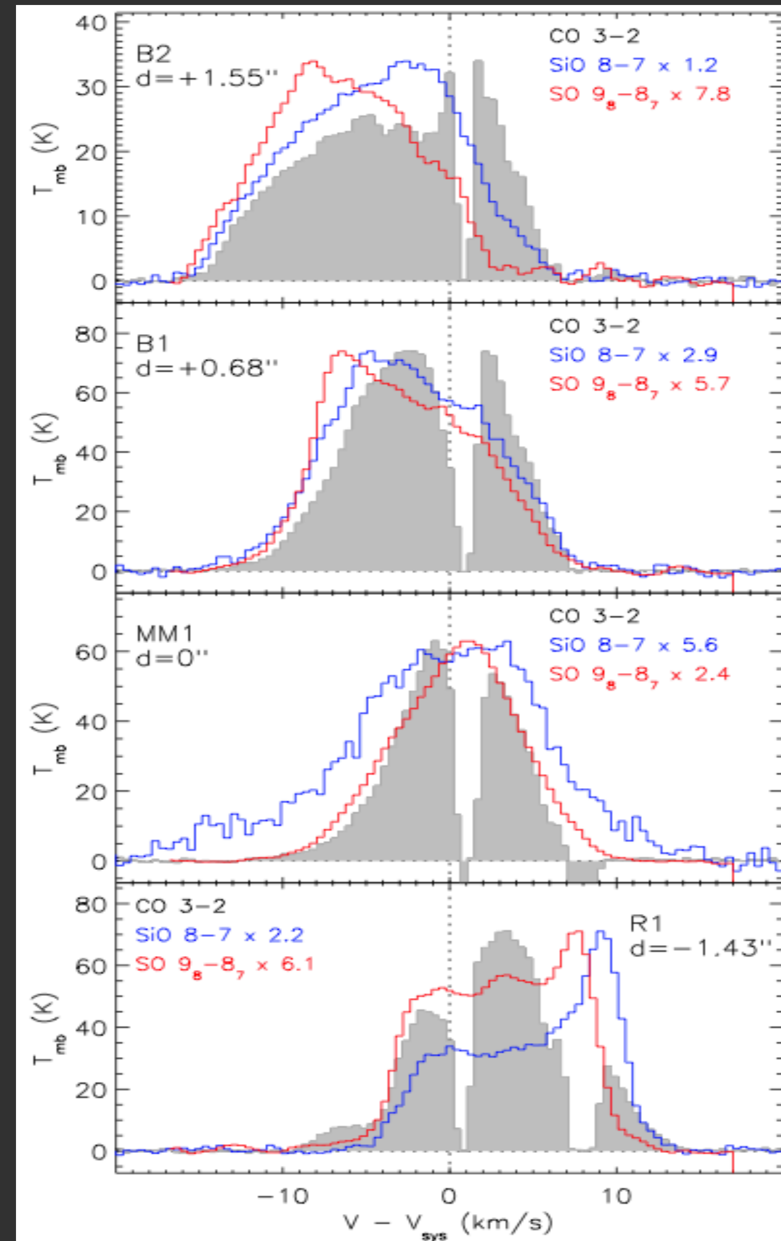




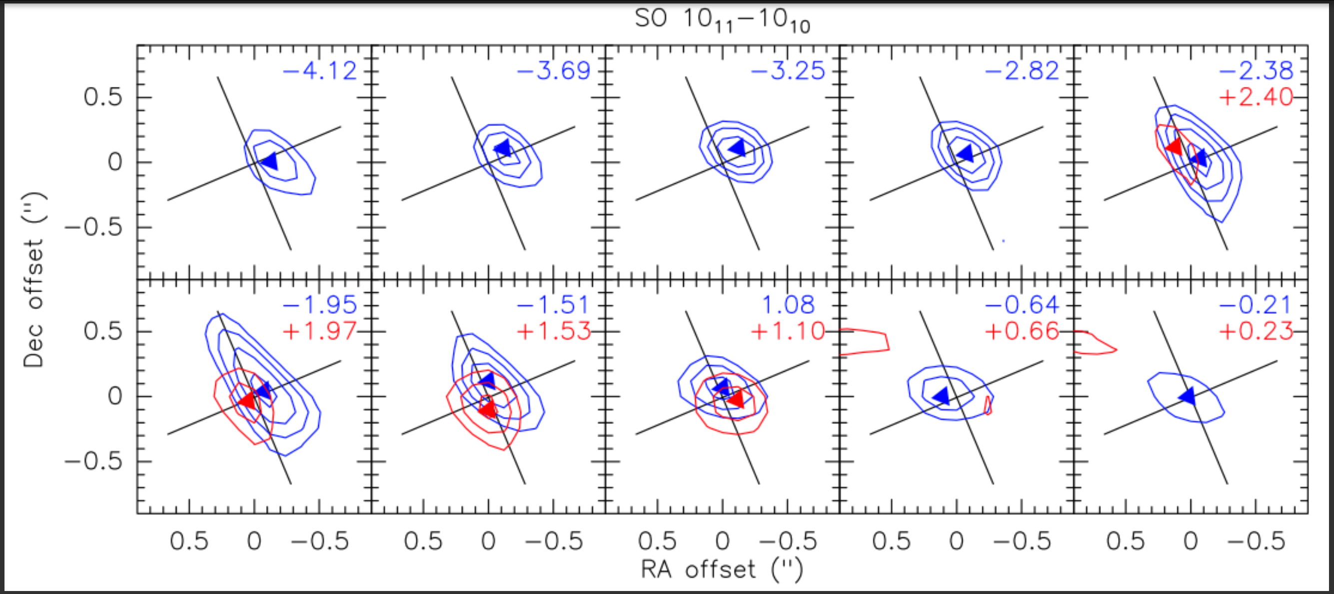


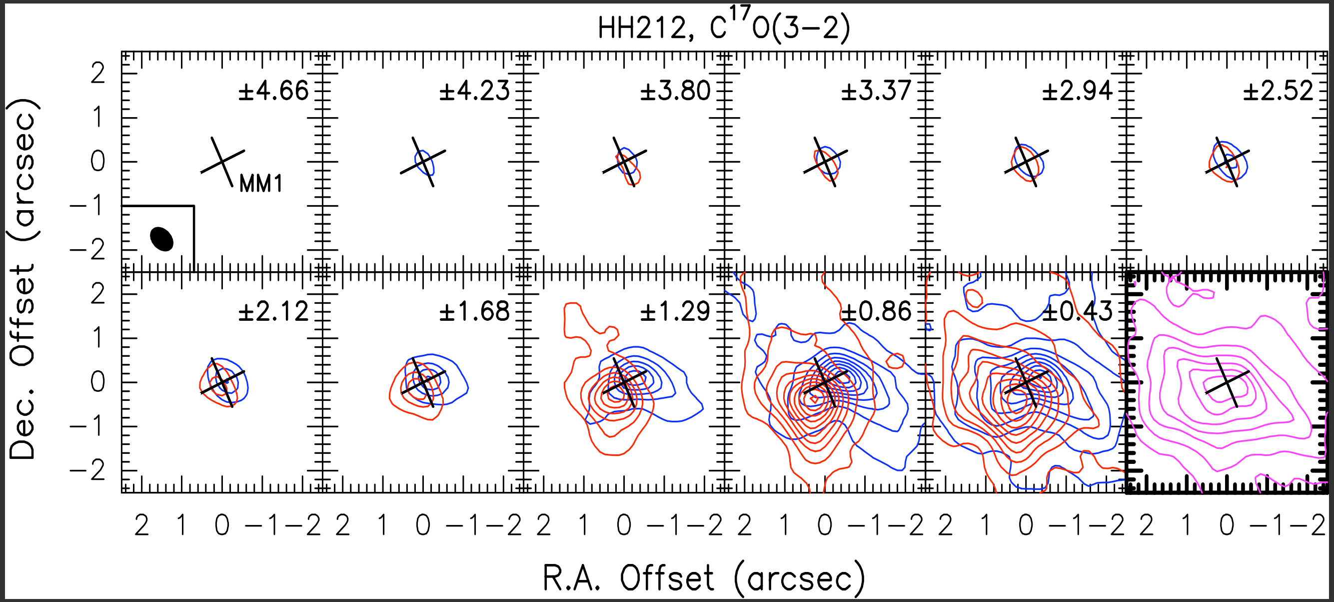
Podio et al. (2014)

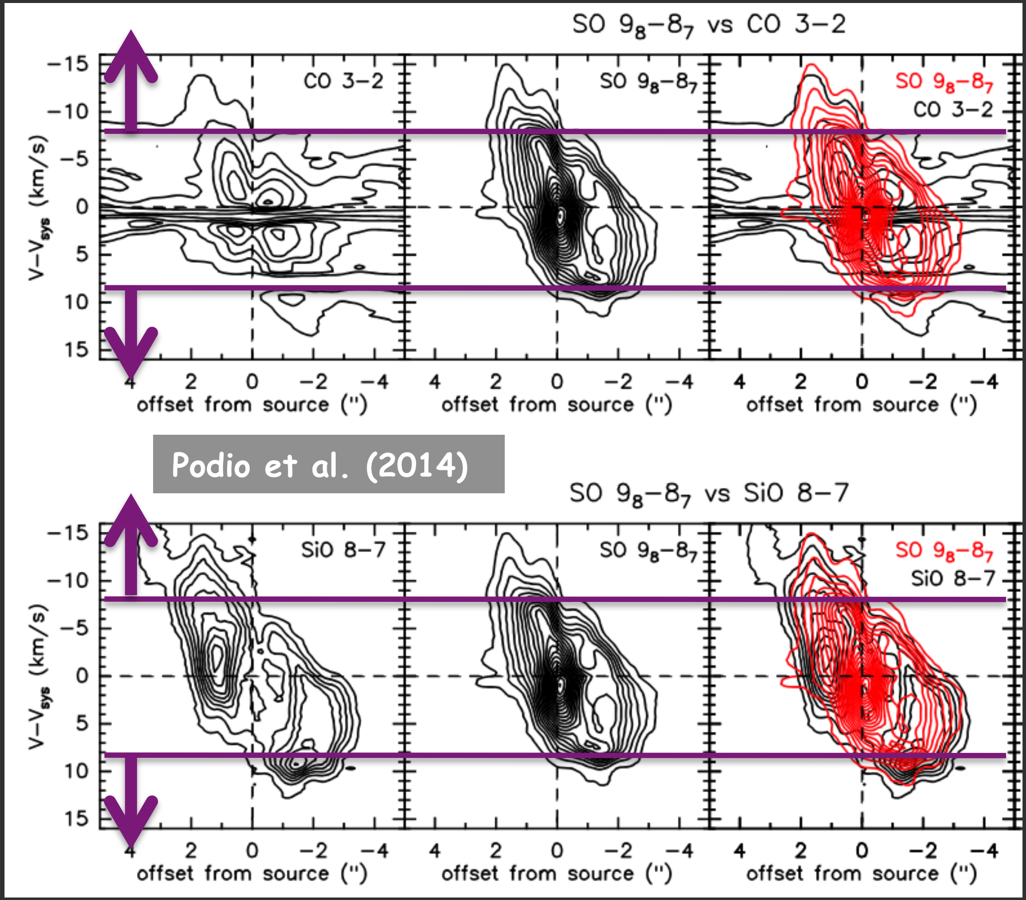




The high-Eu SO emission

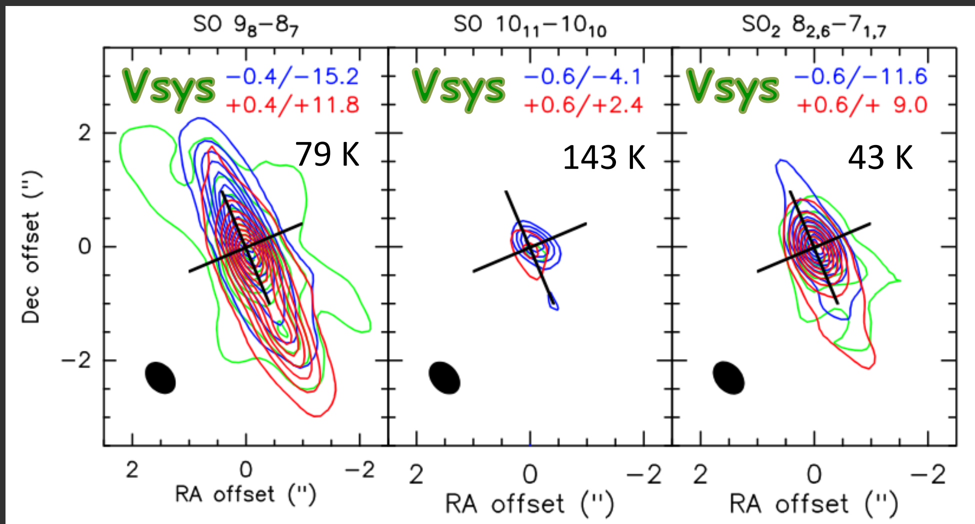




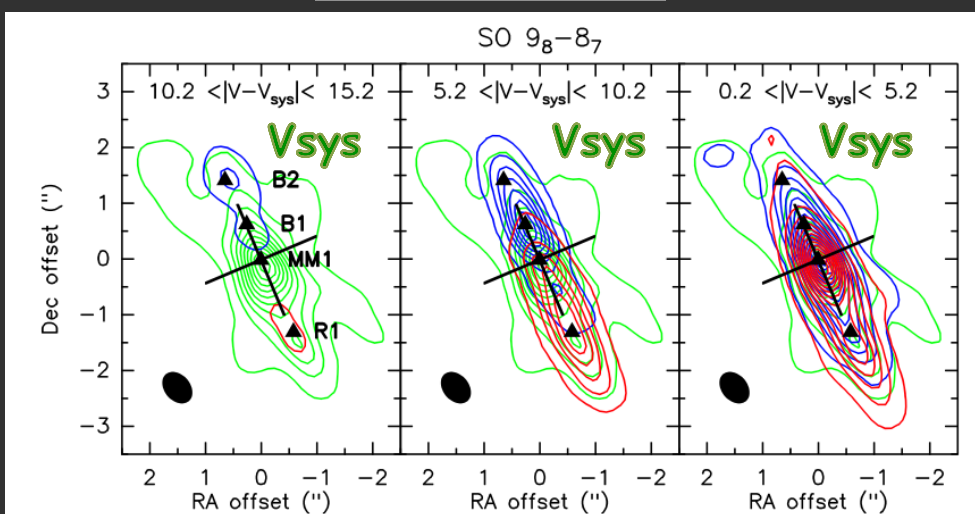


Pos	Jet		
	X_{SiO}	X_{SO}	X_{SO_2}
B2	$3-1\times10^{-7}$	$7-3\times10^{-7}$	$3-7\times10^{-7}$
B1	$2-0.8\times10^{-7}$	$1.1-0.5\times10^{-6}$	$0.5-1.4\times10^{-6}$
MM1-blue	$5-2\times10^{-7}$	$1.8-0.8\times10^{-6}$	-
MM1-red	-	-	-
R1	$5-2\times10^{-7}$	$9-4\times10^{-7}$	$0.4-1.0\times10^{-6}$

Sulfur !

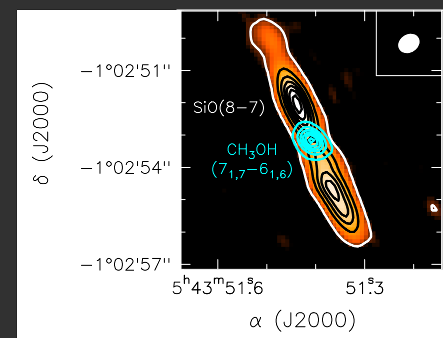


Podio et al. (2014)



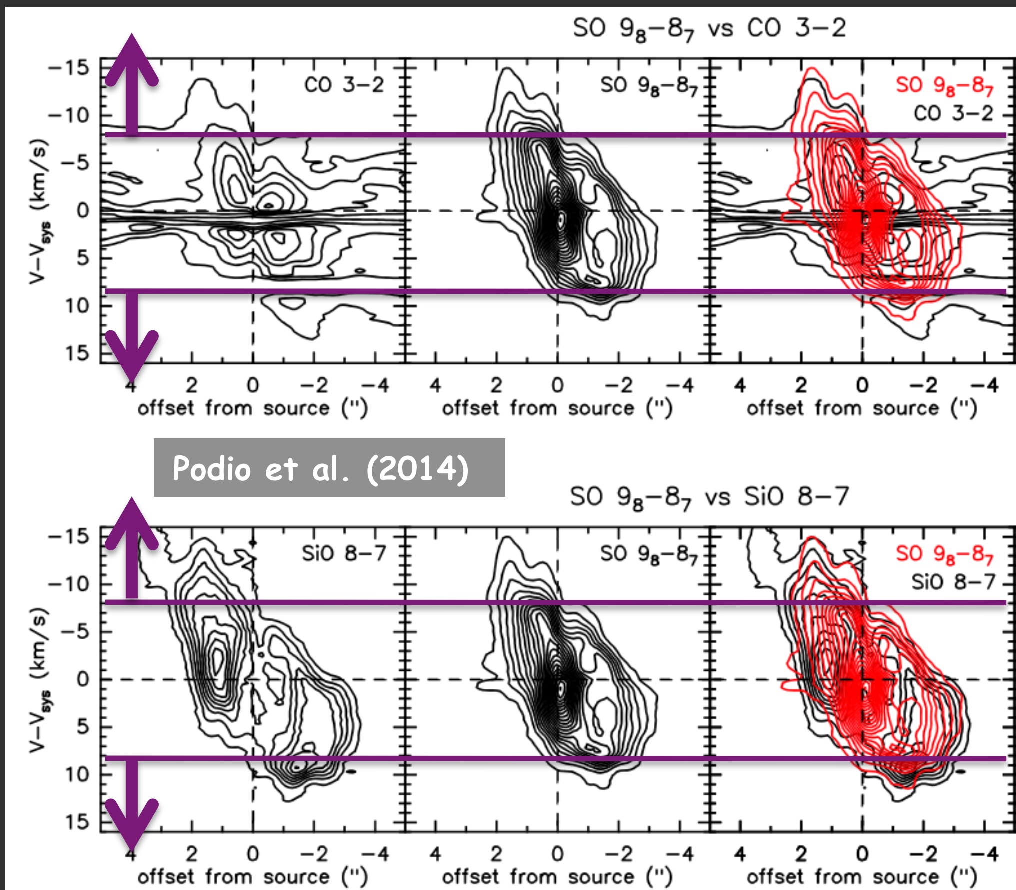
$SO(9_8-8_7)$ & SO_2
—> JET/OUTFLOW

$SO(10_{11}-10_{10})$
—> compact emission —>
rotating and/or infalling
DISK/ENVELOPE ?



collimation increases with velocity:
for |V-Vsys| > 5 km/s
—> R(jet) < 90 AU

The high-velocity SO jet



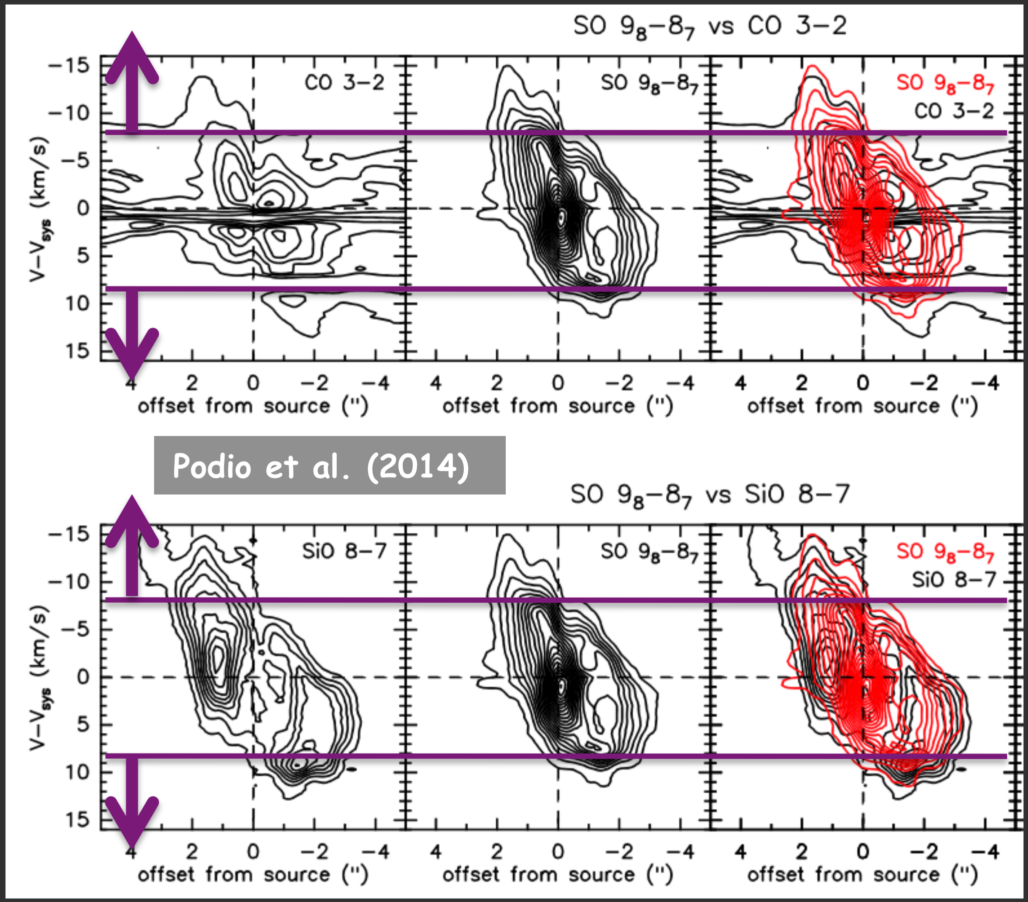
At |V-Vsys| > 8 km/s
—> $SO(9_8-8_7)$ ~ SiO(8-7) ~ CO(3-2)

From CO and assuming LTE-optically thin:
X(SO) in the jet: 10^{-7}-10^{-6}

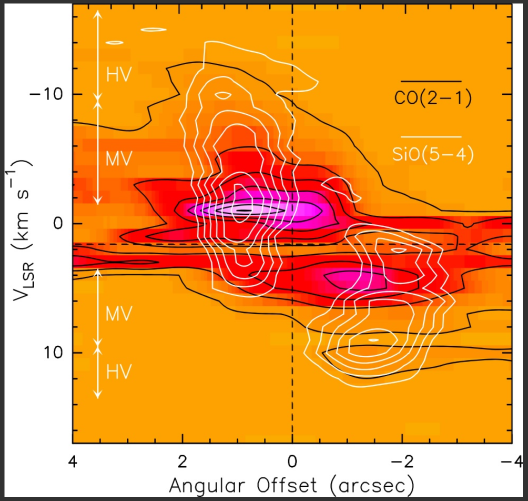
From 1% to 10% of Sulfur has been released from dust mantles to form SO

emission is collimated
—> Rjet < 90 AU
emission is supersonic
—> V(jet) ~ 200 km/s

The high-velocity SO jet



At |V-Vsys| > 8 km/s
—> SO(9_8-8_7) ~ SiO(8-7) ~ CO(3-2)



emission is collimated
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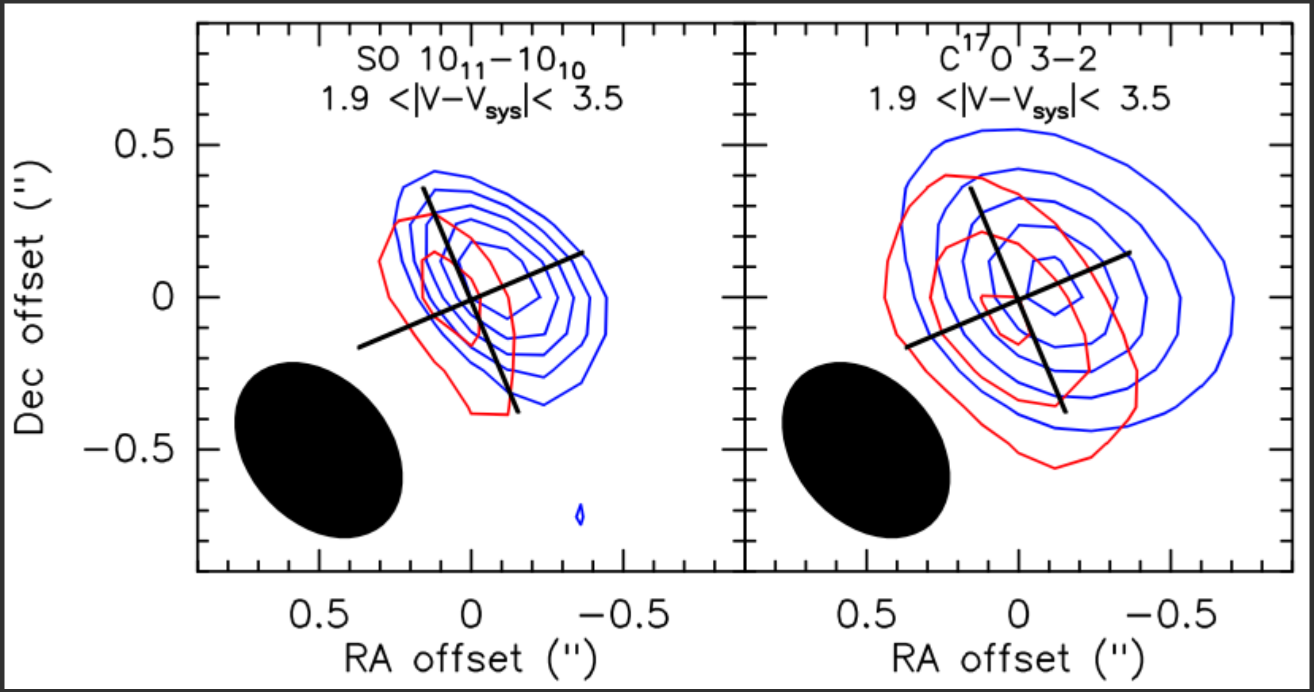
—> V(jet) ~ 200 km/s

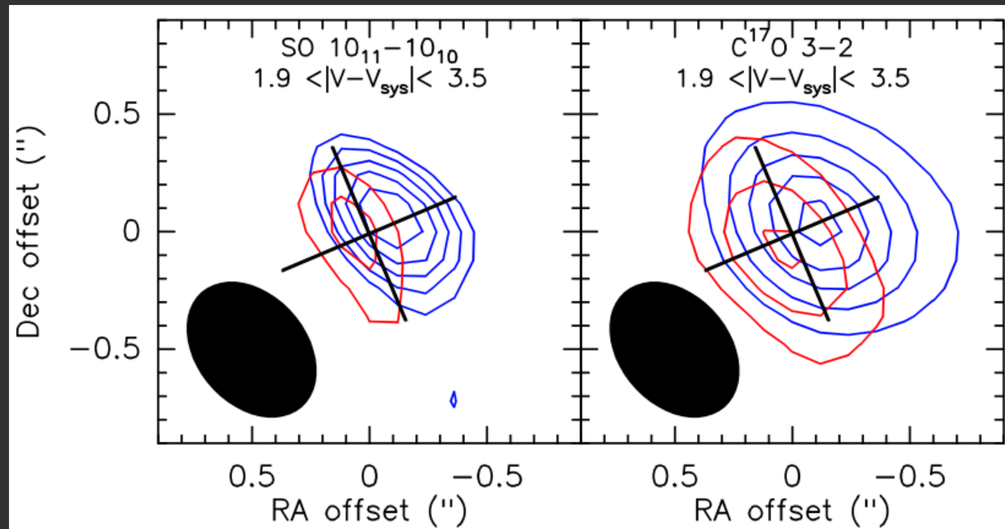
The high-Eu SO compact emission

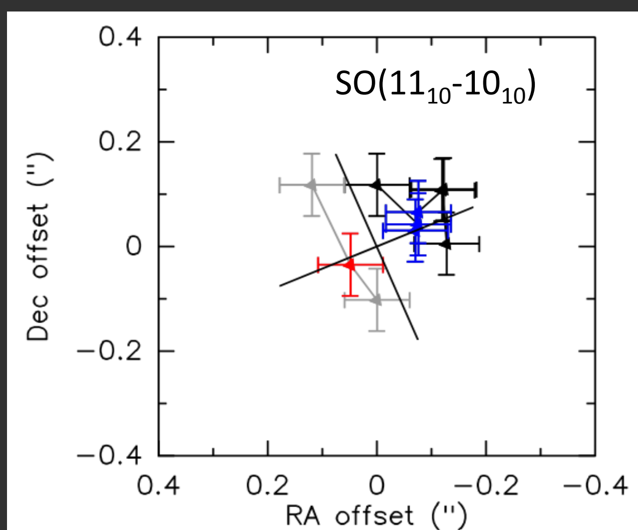


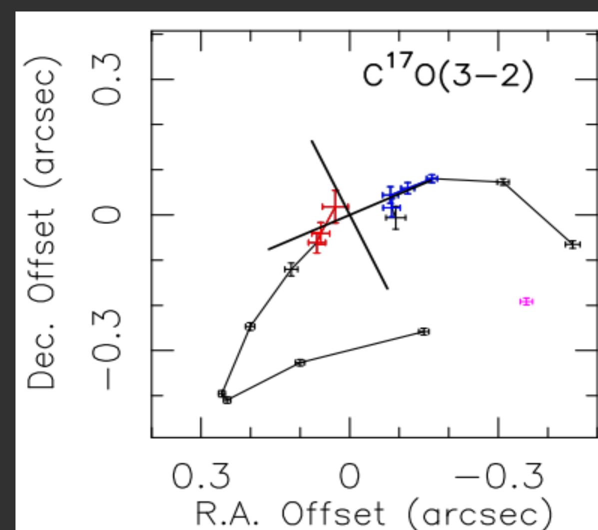
Podio et al. (2014)

At 1.9 < |V-Vsys| < 3.5 km/s
blue & red peaks along disk axis
similar to $C^{17}O$
(Keplerian) rotating inner disk ?

The high-Eu SO compact emission

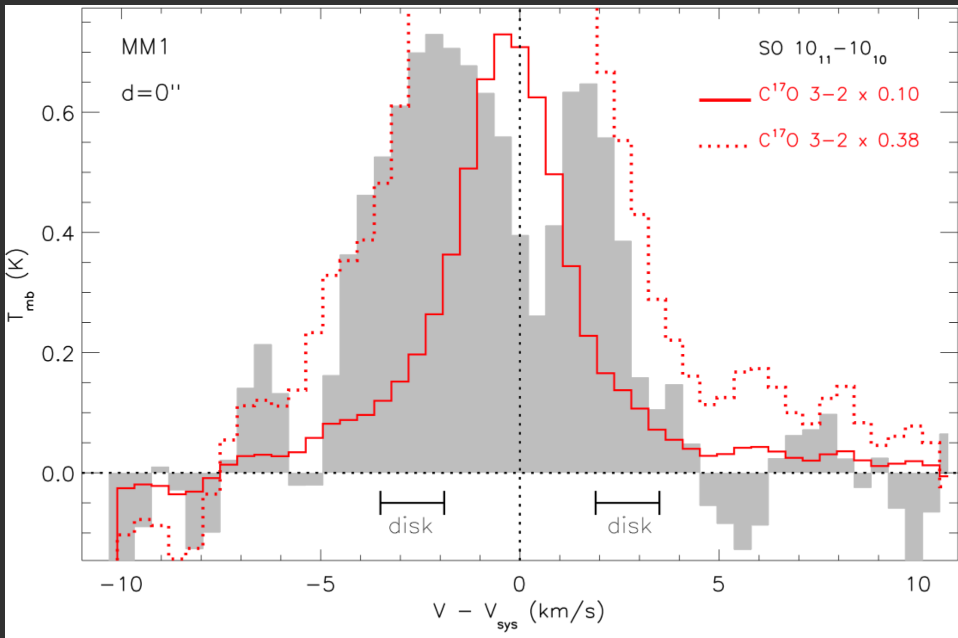


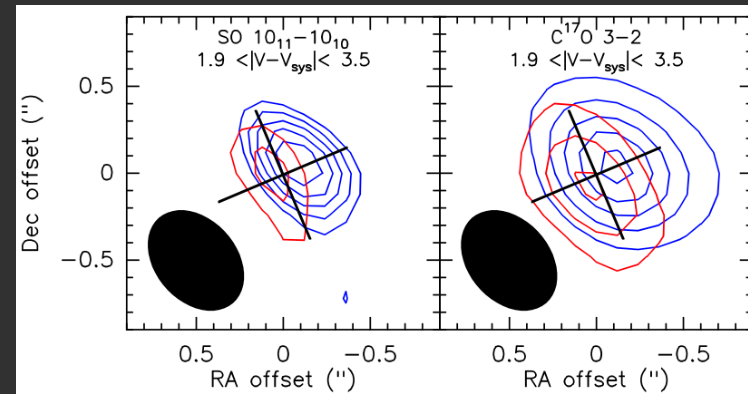


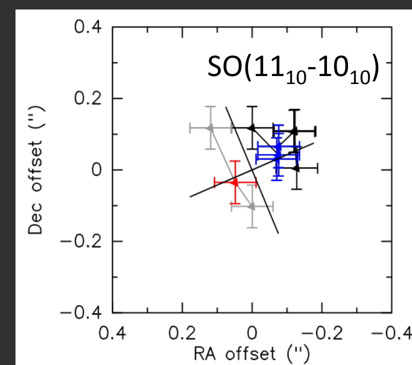


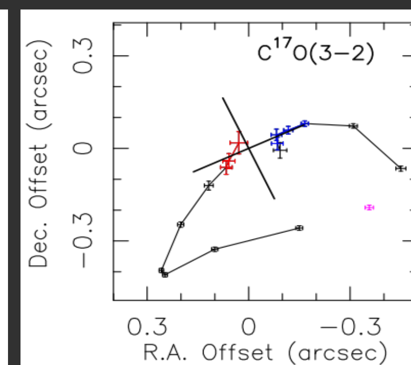
Podio et al. (2014), Codella et al. (2014b)

The high-Eu SO compact emission







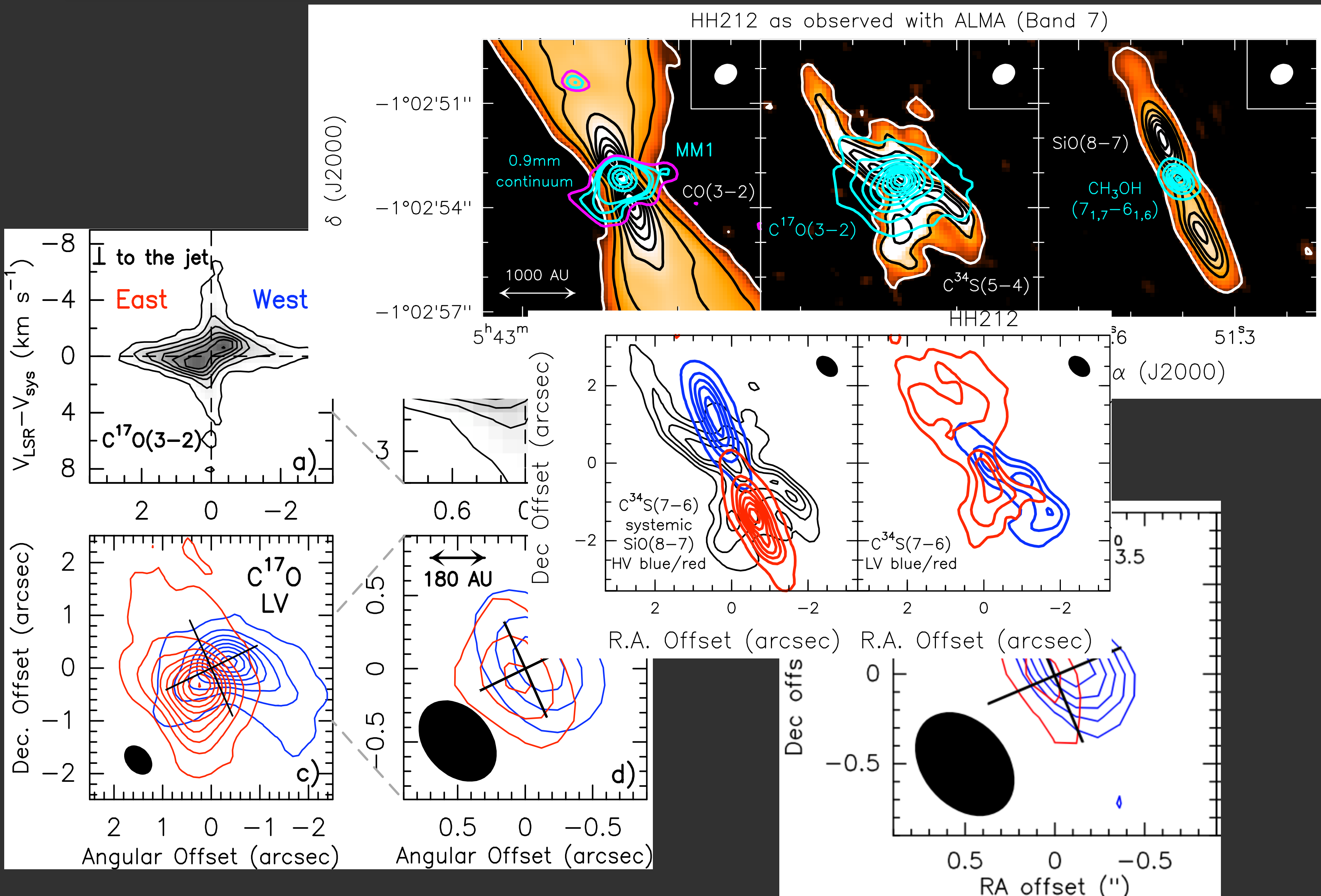


At |V-Vsys| < 1.9 km/s:
redshifted absorption feature
infall of outer disk ?

Podio et al. (2014)

From $C^{17}O$ and assuming LTE-optically thin:
X(SO) in the disk: 10^{-8}-10^{-7}

Round-up



HH212 as observed with ALMA (Band 7)
MM1
0.9mm continuum
CO(3−2)
C^{17}O(3−2)
C^{34}S(5−4)
SiO(8−7)
CH$_3$OH (7$_{1,7}$−6$_{1,6}$)
1000 AU
δ (J2000)
α (J2000)
⊥ to the jet
East
West
C^{17}O(3−2)
a)
V$_{LSR}$−V$_{sys}$ (km s^{-1})
C^{17}O LV
c)
180 AU
d)
Dec. Offset (arcsec)
Angular Offset (arcsec)
HH212
C^{34}S(7−6) systemic
SiO(8−7) HV blue/red
C^{34}S(7−6) LV blue/red
Dec Offset (arcsec)
R.A. Offset (arcsec)
Dec offs
RA offset ('')