Structure of accretion and outflow on small scales from high-mass protostars

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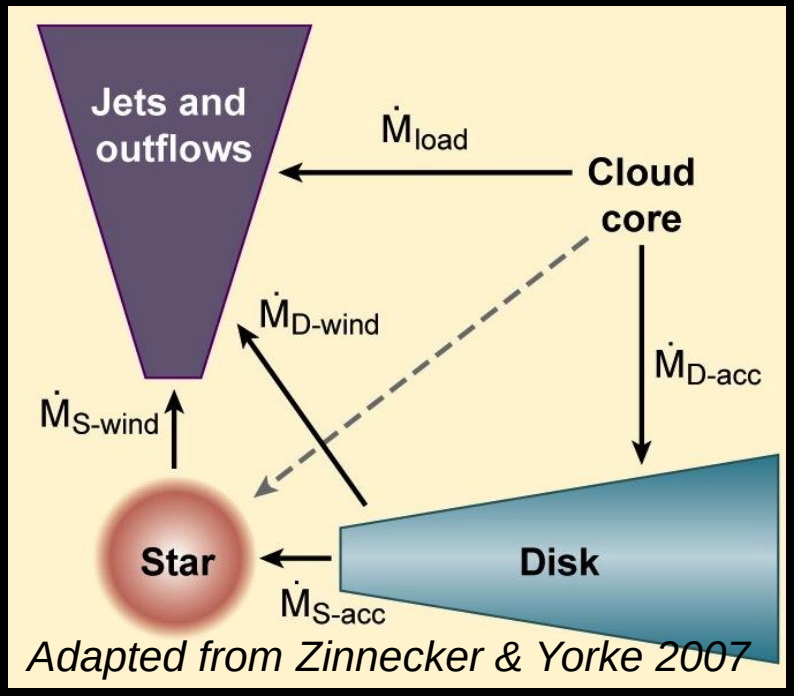
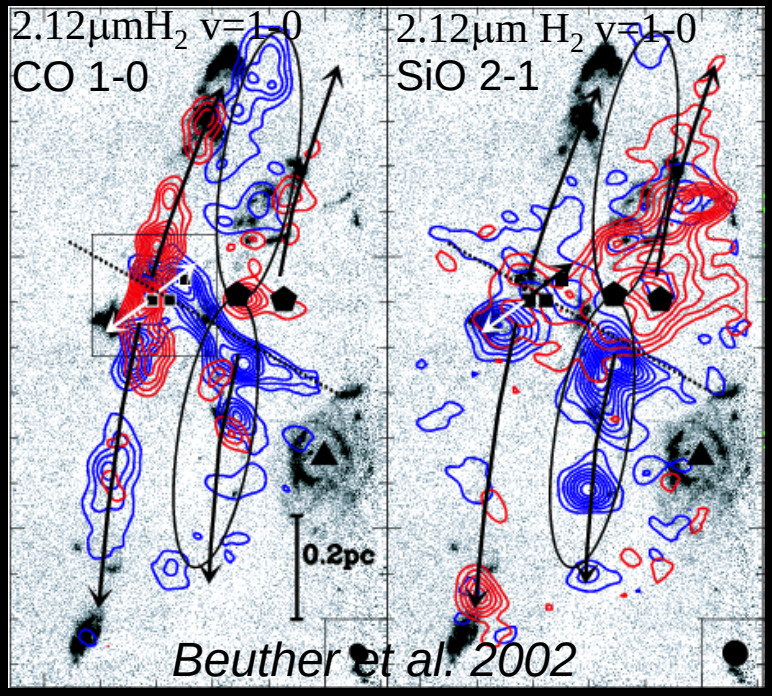


Adapted from Zinnecker & Yorke 2007



Beuther et al. 2002

- At which rate does the mass "exchange" proceed among different components?
- When does the accretion end?

Outflow Multiplicity in massive protoclusters

Detailed morphologies and drivers of individual outflows are difficult to identify

Diagnostic tool

-Multi-epoch VLBI observations of molecular masers enable to measure the 3D velocity field of circumstellar gas on scales ~1-10 AU and at radii <100-1000 AU from the protostar

-Radio continuum imaging gives morphology and physical conditions of ionized gas

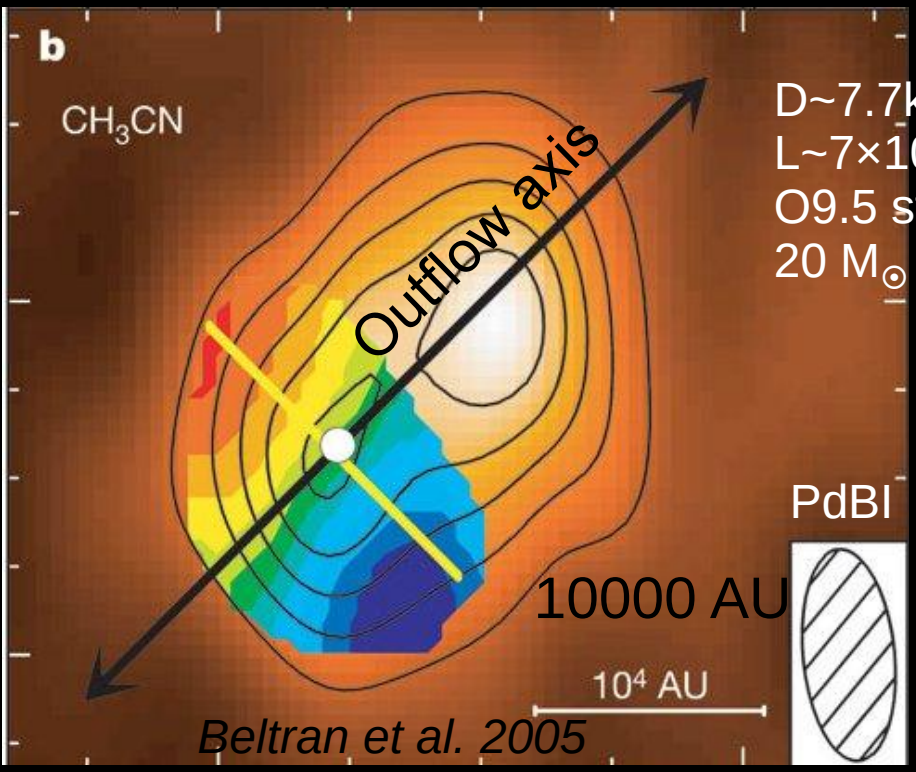
-Interferometric imaging of thermal lines provides complementary information on scales >1000 AU

Case I: G24.78+0.08

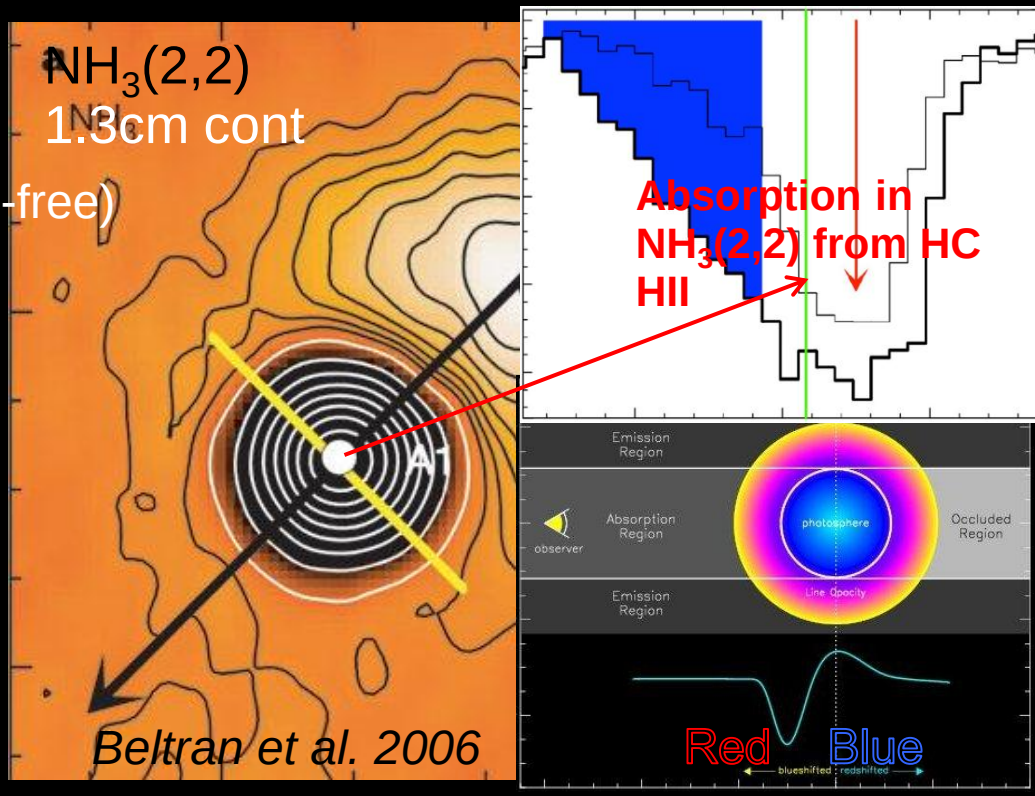
"Large-scale" accretion/infall

Rotation

Infall



Velocity gradient in a molecular "toroid" perpendicular to CO outflow
=> rotation about the outflow axis



Infall motions detected from inverse P-Cygni profiles of a molecular line (NH_3) absorbed by a HC HII

Limitations:

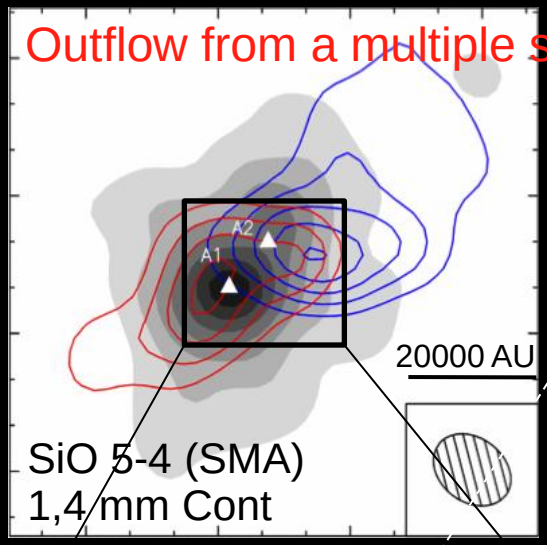
- ❖ Ambiguities of interpretation of line asymmetries
  => confusion with rotation, outflow, projection effects, etc.
- ❖ Large distances (>1 kpc) and formation in clusters for high-mass stars:
  => Accretion signature on protocluster scales (>1000 AU)

But what lies inside O($10^{3\text{-}4}$AU)?

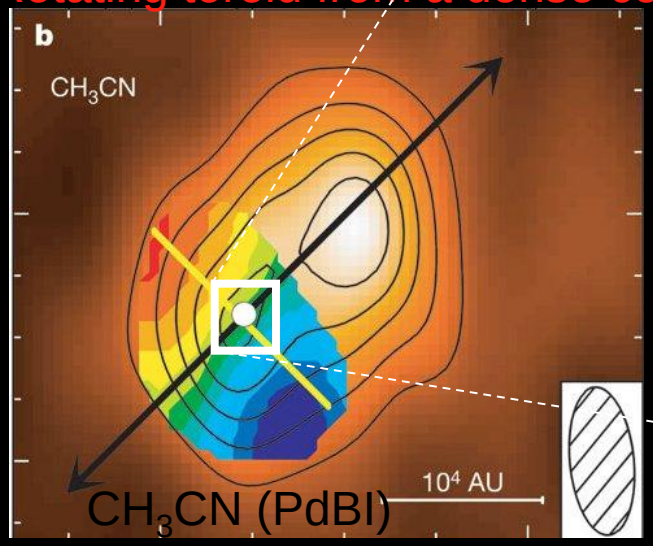
Case I: G24.78+0.08

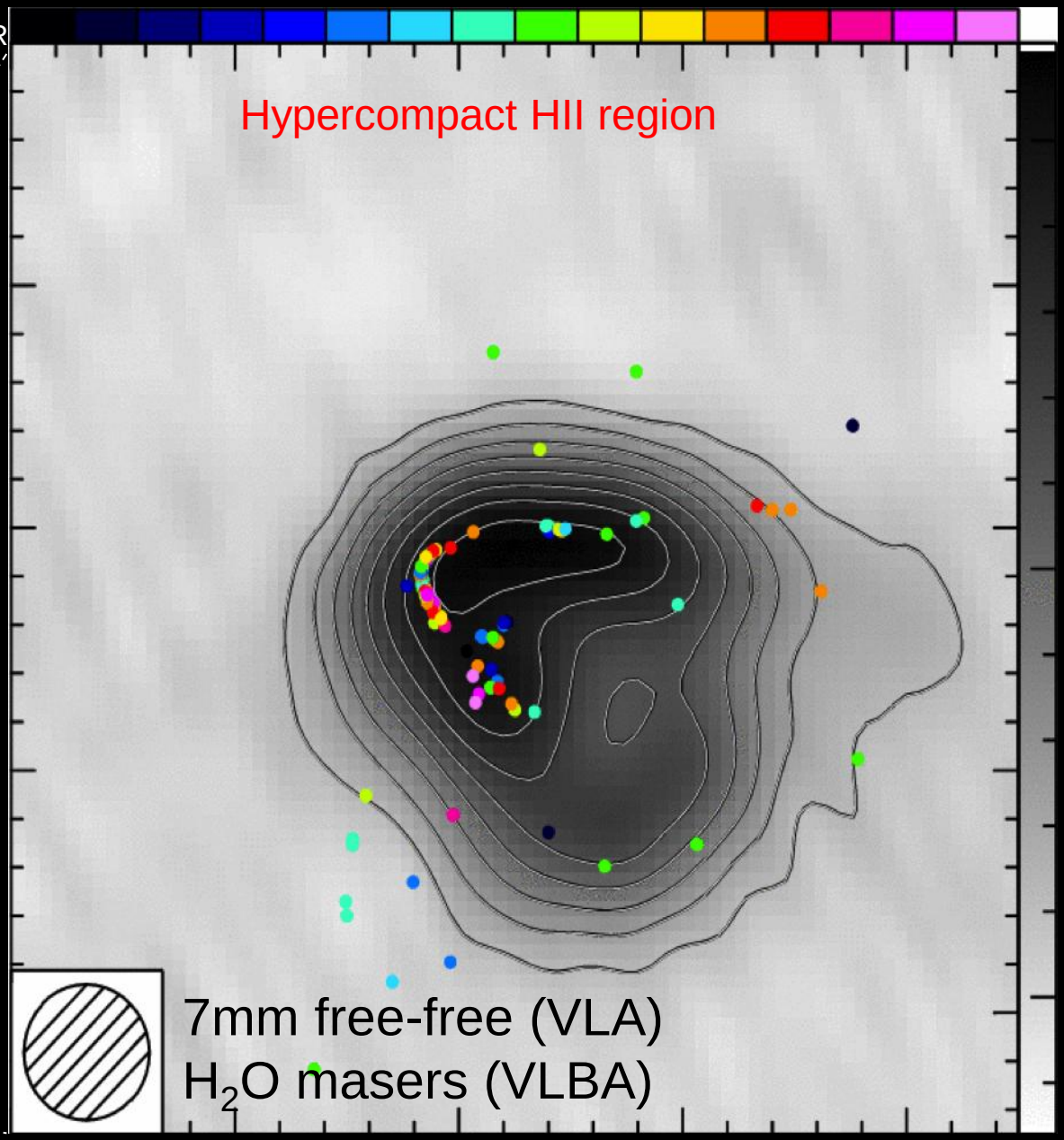
Wide-angle outflow from a high-mass YSO: H_2O masers

D~7.7kpc
L~7×10^4 L$_\odot$
O9.5 star (free-free)
20 M$_\odot$ (infall)



Rotating toroid from a dense core





Moscadelli, Goddi, et al. (2007)

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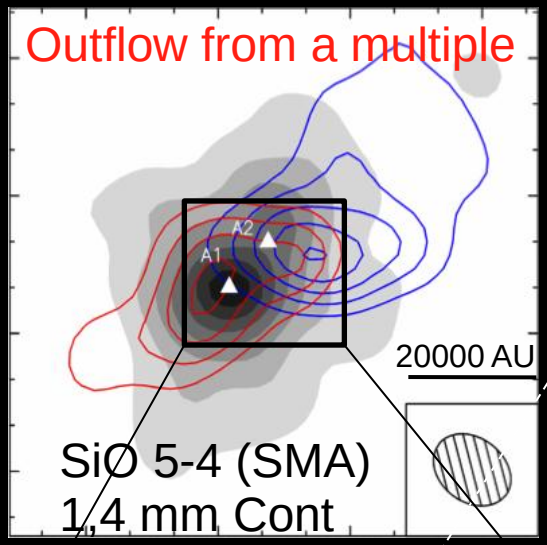

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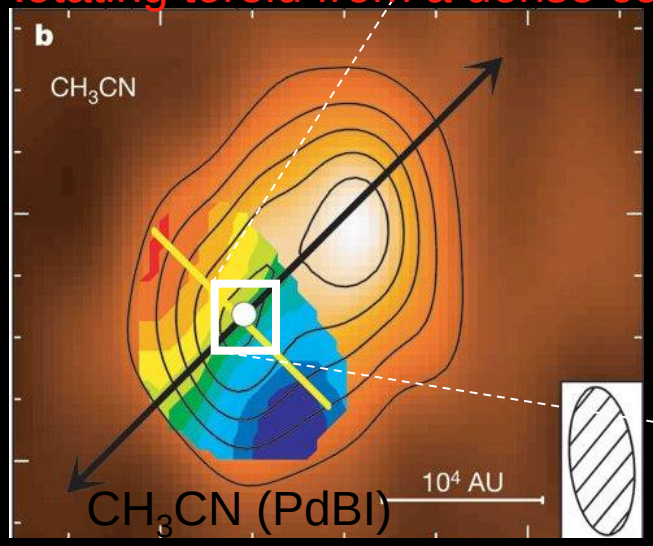
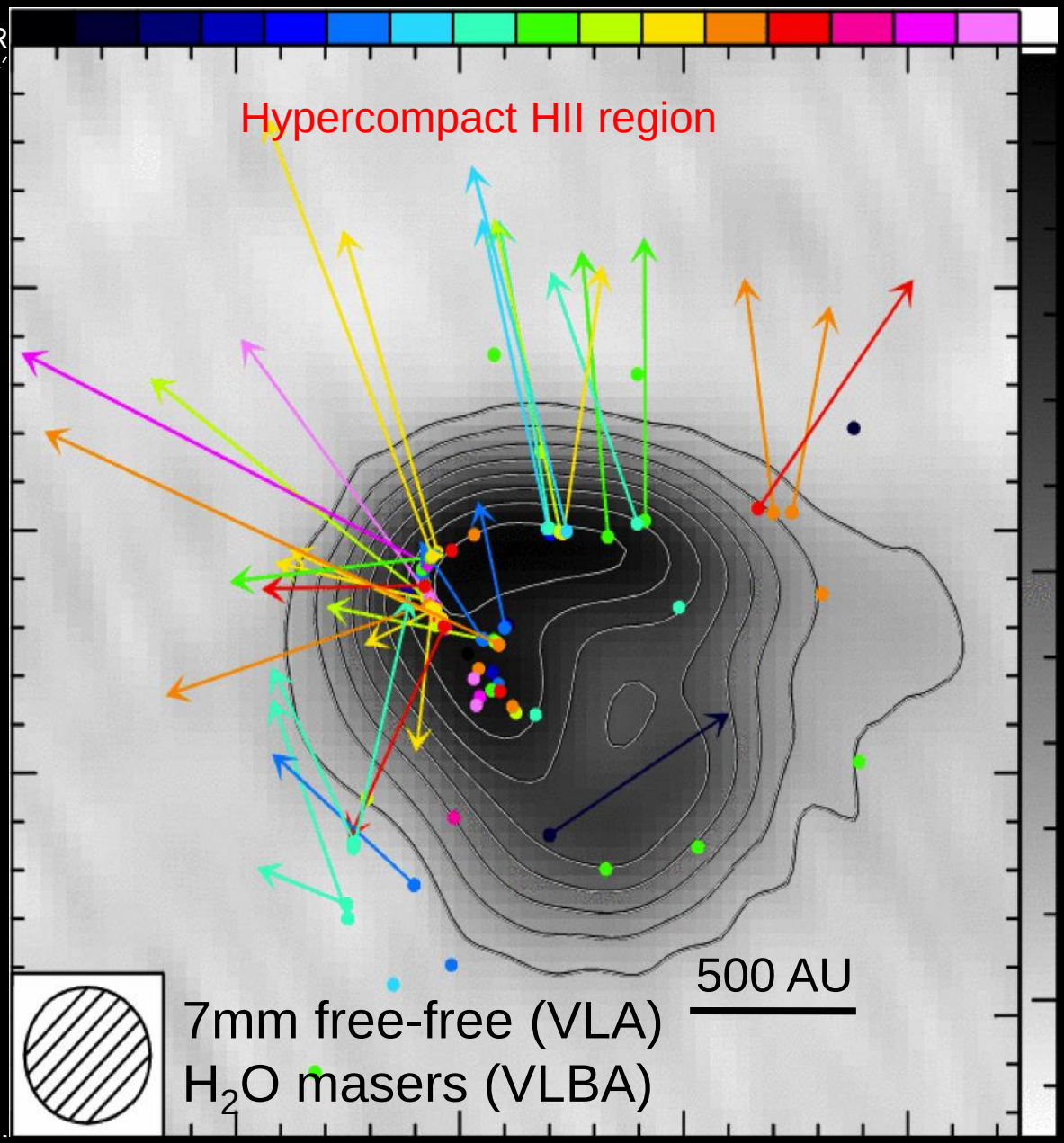




Moscadelli, Goddi, et al. (2007)

Case I: G24.78+0.08

Wide-angle outflow from a high-mass YSO: The model

Findings:

- The water masers trace expansion at the border of a HC HII (also expanding?)
- High velocities (~40 km/s) rule out thermal pressure of ionized gas (v~10 km/s)

Model assumption:

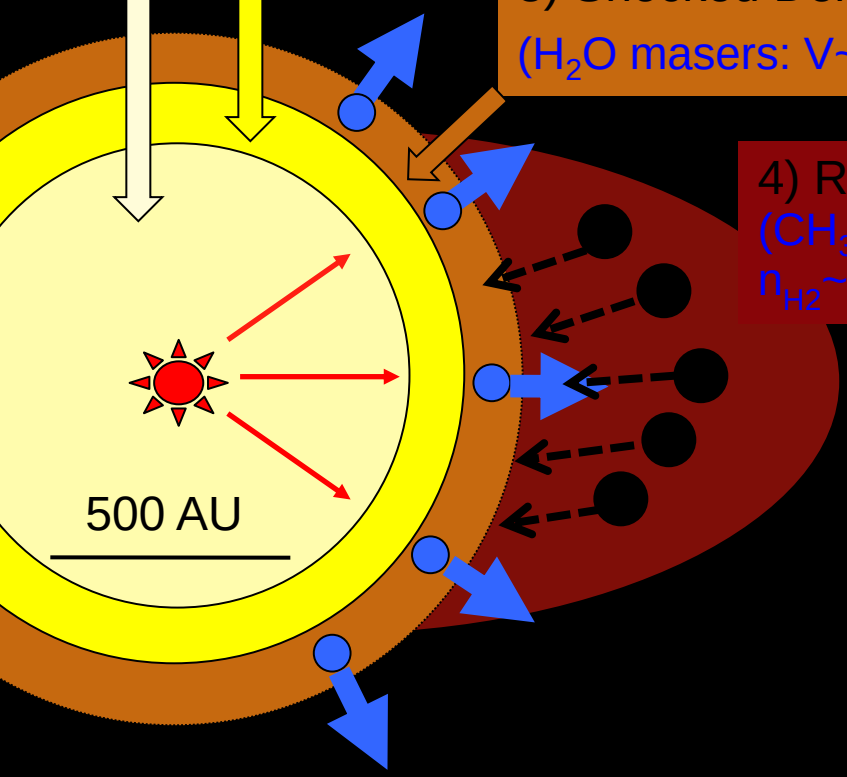
- The HC HII region expansion and H_2O outflow are driven by a powerful stellar wind
- After an initial phase of free expansion, a four-zone wind structure is created (Shull 80):

1) free-flowing wind (v_w~2000 km/s)

2) Shocked-ionized wind shell (radio continuum)

3) Shocked Dense Molecular Shell
(H_2O masers: V~40 km/s, n_{H2}~10^9 cm^{-3}, T>400 K)

4) Rotating molecular toroid
(CH_3CN; CH_3OH masers : n_{H2}~10^7 cm^{-3} , T~150 K)



$M_{*\,dyn}$	20 M
ZAMS	O9.5
L_{bol}	~7×10^4 $L_\odot$
$\langle V_{outflow}\rangle$	40 km s^{-1}
V_{wind}	2000 km s^{-1}
R_{shell}	500 AU
Mass-loss	~10^{-6} $M_\odot$ yr^{-1}
T_{dyn}	~50 yr

Open Q:
Can circumstellar material in the toroid still accrete on the central star?

Moscadelli, Goddi, et al. 2007

Summary and General Implications I

- Central star: ZAMS spectral type O9.5 (from HC HII region spectrum) or $M_* \sim 20\ M_\odot$ (from gas dynamics: infall and rotation)
- The HC HII region has a ring-shaped structure: very thin shell ($R_{out} \sim 550$ AU)

I. Outflow

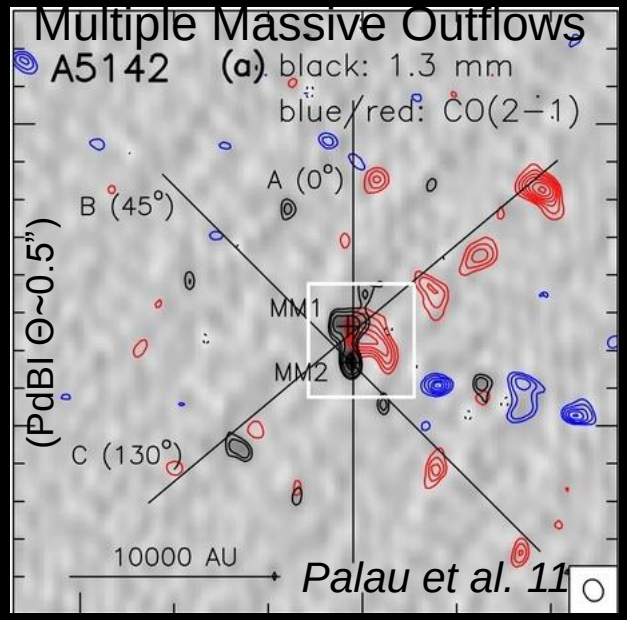
- The water masers trace *a wide-angle outflow or shell* (V~40 km/s) along the border of the HC HII region at a radius < 500 AU from the protostar
- The molecular outflow is driven by the expansion of the HC HII region, which is in turn probably driven by a powerful stellar wind
- Short dynamical age of the ionized shell
  - Open Q: episodic event?

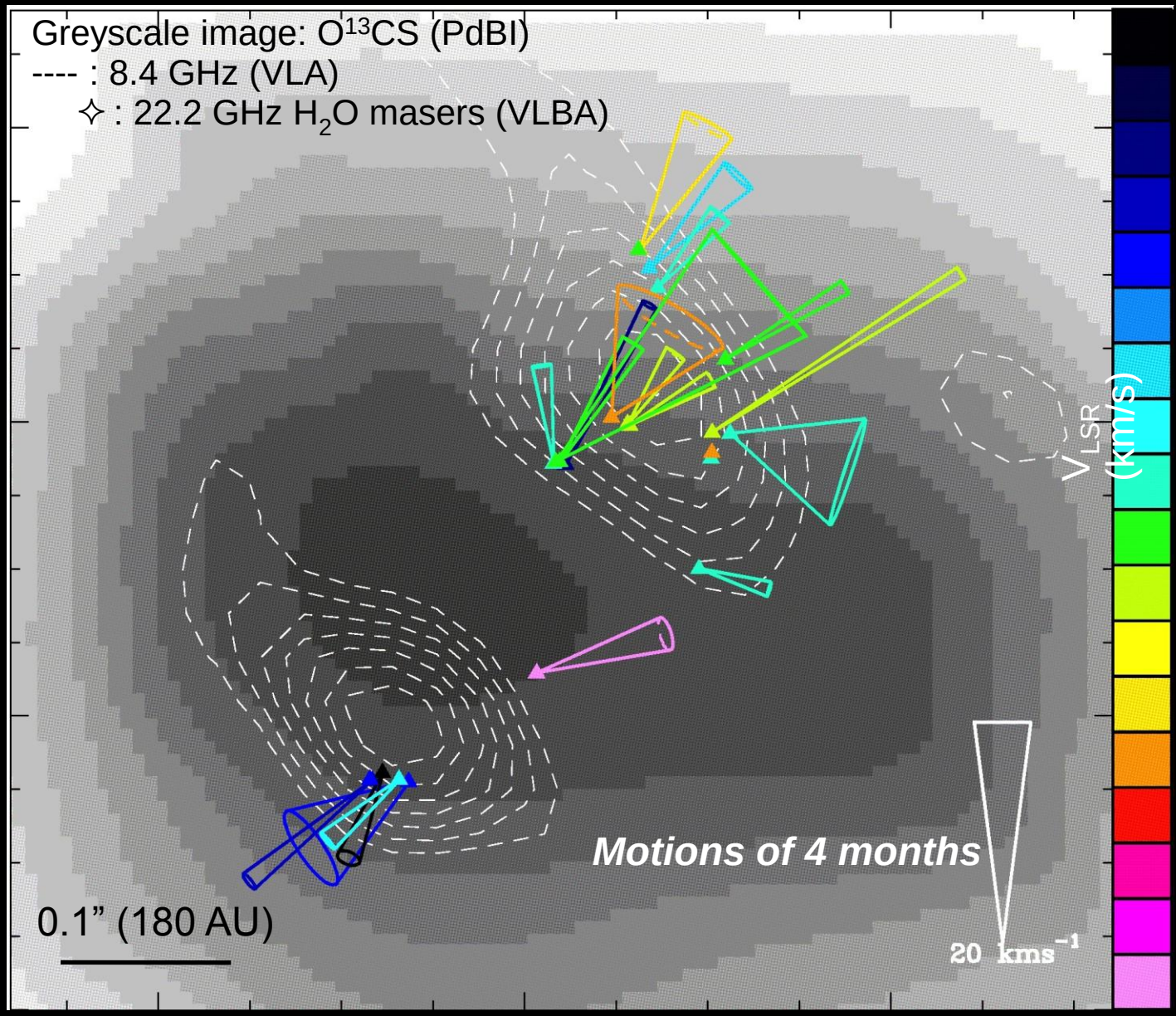
II. Accretion

- At a radii > 500 AU from the protostar, thermal lines (and CH_3OH masers) identify a molecular rotating and infalling toroid
- The infalling gas may no longer accrete onto the star, but would be stopped at the surface of the HC HII region, at the shock front traced by H_2O masers
  - Open Q: Has the O-type star ended the accretion phase?
  - Open Q: Has it reached its final mass?

Case II: AFGL 5142 MM-1

A collimated outflow from an intermediate-mass protostar: H_2O masers



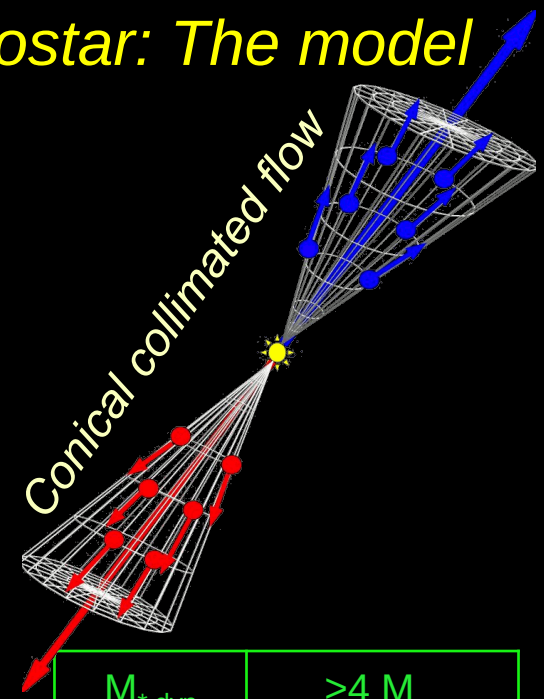


- ✓Water masers trace a "slow" bipolar outflow
- ✓The 8.4 GHz continuum traces a bipolar ionized jet (NOT a HC-HII region)
- ✓H_2O masers trace the base of the NW-SE oriented ^{12}CO outflow extending over 0.3 pc ("C")

Goddi & Moscadelli 06
Goddi, Moscadelli, Sanna 11

Case II: AFGL 5142 MM-1

A collimated outflow from an intermediate-mass protostar: The model



Measured flow parameters

- Velocity, radius (from YSO), opening angle

Assumptions/definitions

- Conical geometry (based on bipolar geometry from masers)
- Protostellar position:
  average between maser positions in two lobes
- $n_{H2} = n_8 \times 10^8$ cm^{-3} (maser excitation models)
- Momentum rate (H_2O masers): $\dot{P}_{out} = V_{out}^2 R_{out}^2 n_{H2} m_{H2} \Omega_{out} = \dot{M}_{out} V_{out}$
- Momentum rate (ionized gas): $\dot{P}_{jet} = 10^{-3.5} F d^2 \left(4\pi/\Omega_{jet}\right)$

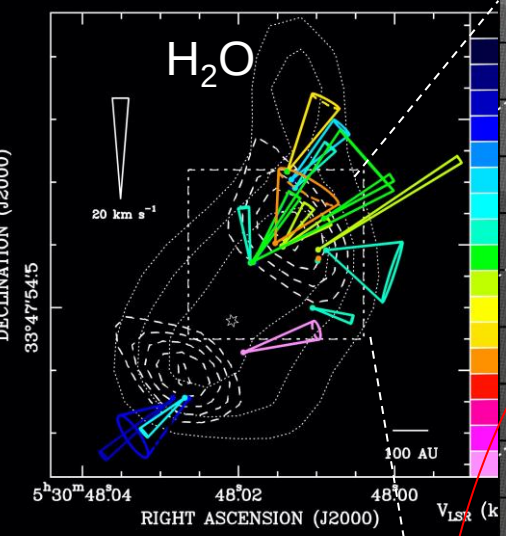
$M_{*\,dyn}$	>4 M
ZAMS	B3
L_{bol}	~10^4 $L_\odot$
$\langle V_{outflow} \rangle$	15 km s^{-1}
θ_{out}	34°
R_{out}	300 AU
Mass-loss	~10^{-4} $M_\odot$ yr^{-1}

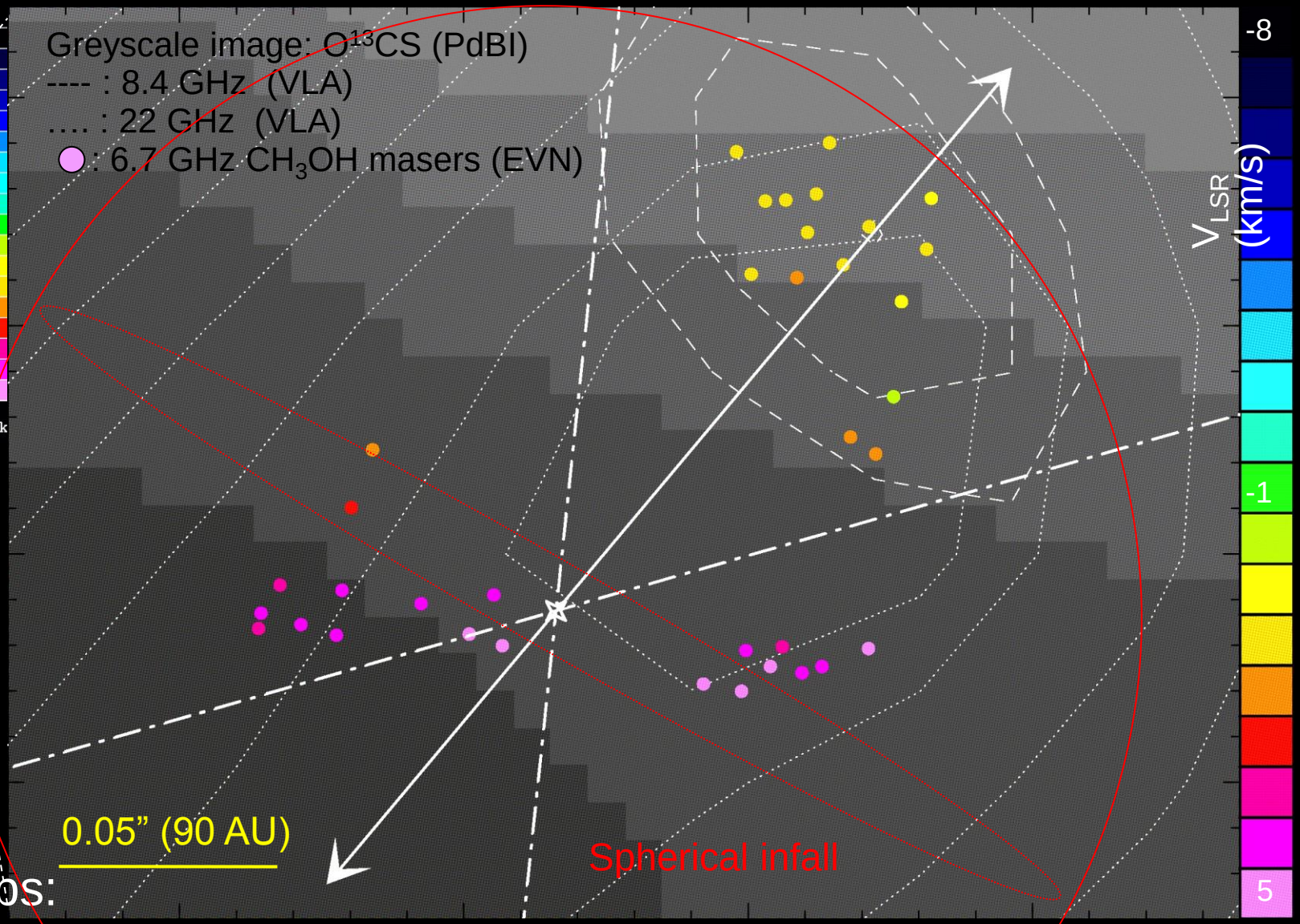
Physical and geometrical parameters of the outflow

1) Small semi-opening angle (34^0):
   – *Collimated Flow*
2) Comparable *momentum rates* (~10^{-3} $n_8^{1/2}$ $M_\odot$yr^{-1} km s^{-1}) for:
   ionized jet, H_2O maser flow, NW-SE oriented ^{12}CO outflow
   –*An ionized jet drives a collimated H_2O outflow and a large-scale (0.3pc) CO outflow*
3) Large mass outflow rate
   – *Strong outflow activity from MM-1*

Case II: AFGL 5142 MM-1

Spherical gas infall to an intermediate-mass protostar: CH_3OH masers





- located in the foreground of the (optically-thick) radio continuum
- red-shifted $V_{l.o.s.}$

Infall?

Two distinct groups:

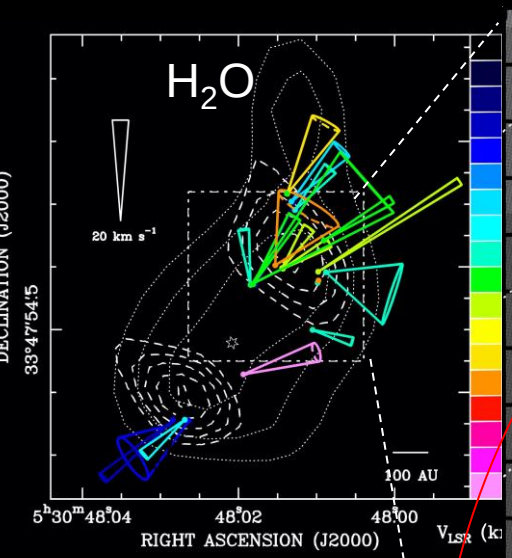
1) The "red" masers in the equatorial plane (perp. to the H_2O outflow)

2) The "yellow" masers on top of the radio continuum peak (near the pole)

Goddi, Moscadelli, Sanna 2011

Case II: AFGL 5142 MM-1

Spherical gas infall to an intermediate-mass protostar: CH_3OH masers



Greyscale image: $O^{13}CS$ (PdBI)
---- : 8.4 GHz (VLA)
.... : 22 GHz (VLA)
● : 6.7 GHz CH_3OH masers (EVN)

Motions over 6 yrs

1st measurement of gas infall from 3-D velocity field!

(90 AU)

Spherical infall

5 kms^{-1}

V_{LSR} (km/s)

-1

5

- located in the foreground of the (optically-thick) radio continuum
- red-shifted $V_{l.o.s.}$

Two distinct groups:

1) The "red" masers have small PMs and move mainly along the l.o.s.

2) The "yellow" masers have large PMs towards the protostar

Goddi, Moscadelli, Sanna 2011

Case II: AFGL 5142 MM-1

Spherical gas infall to an intermediate-mass protostar: The model

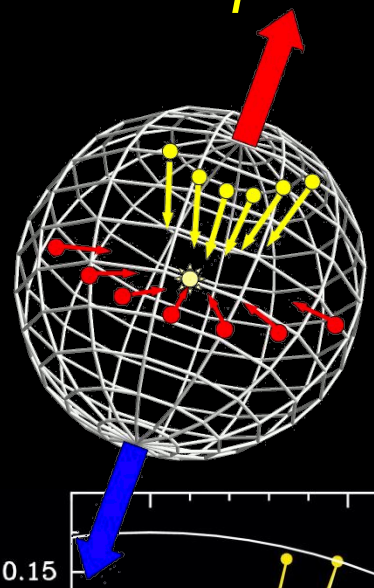
$$\vec{V}(\vec{R}) = -\sqrt{(2GM/R^3)}\,\vec{R}$$

4 free parameters:
↑,↗,R_s,M_*

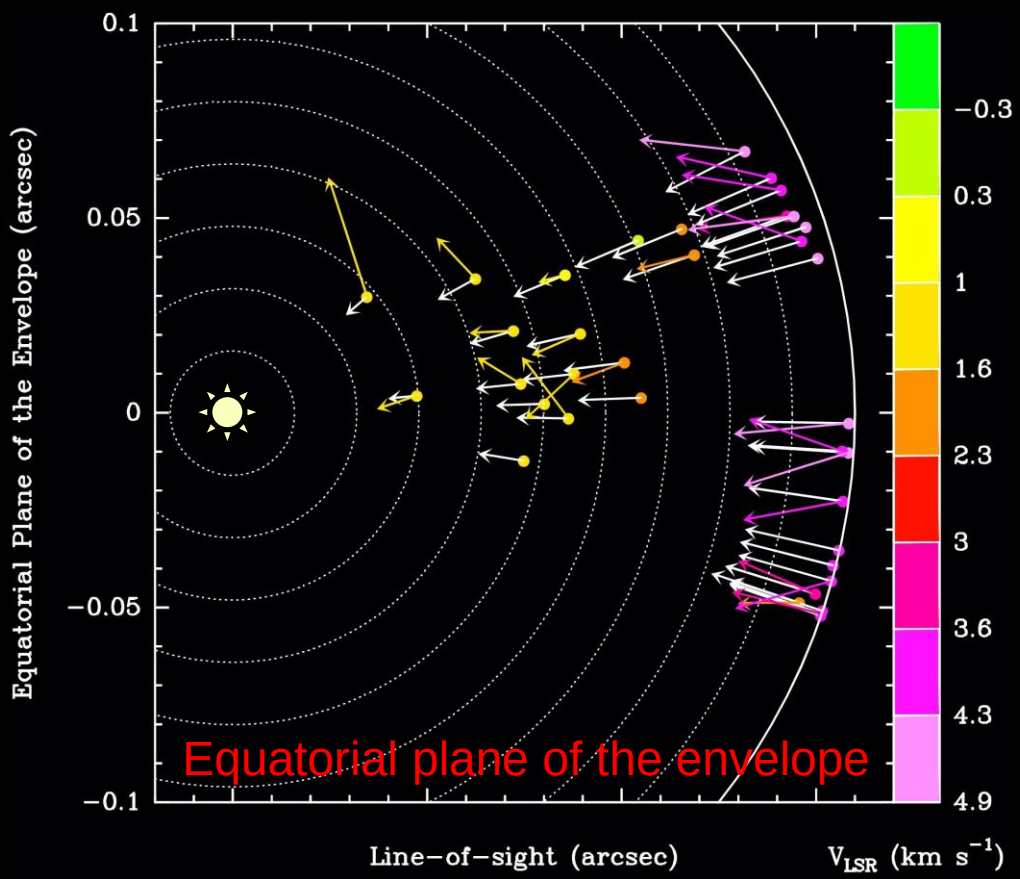
$$\dot{M}_{\inf} = 4\pi R^2 n_{H2} m_{H2} V_{\inf}$$

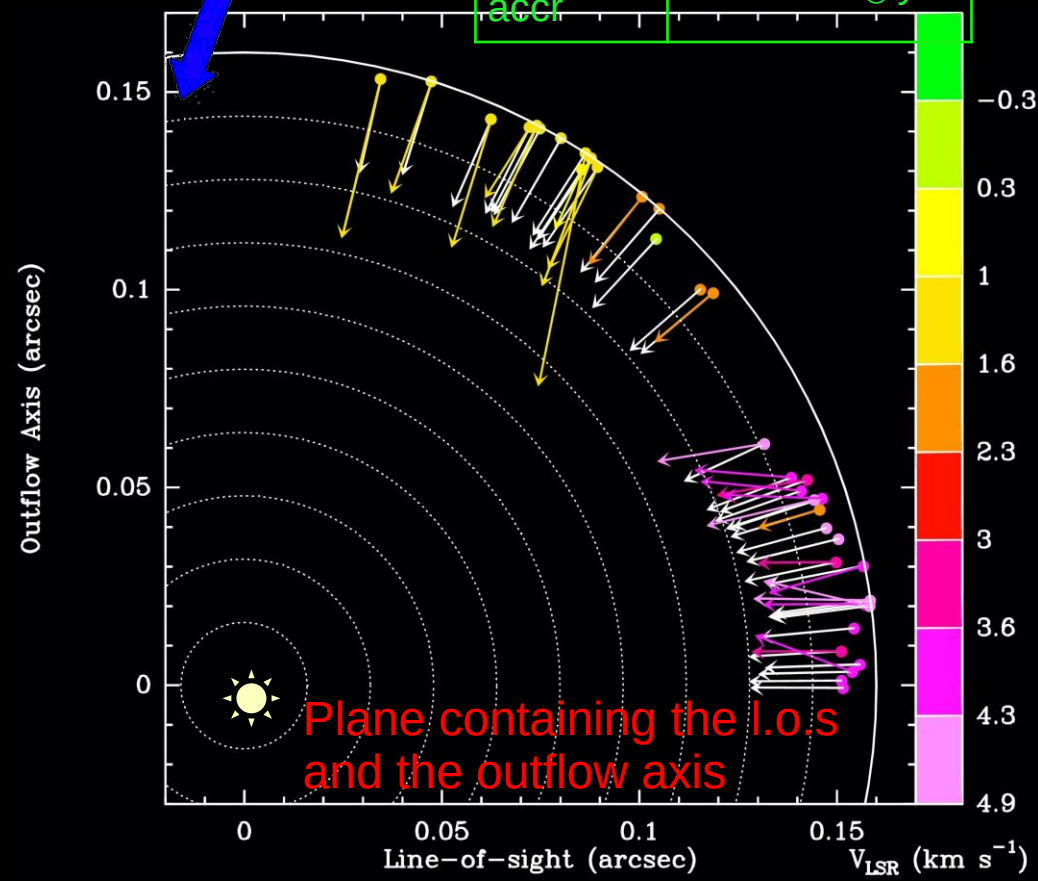
$$\dot{M}_{out} = V_{out} R_{out}^2 n_{H2} m_{H2} \Omega_{out}$$

⇒ $\dot{M}_{out}/\dot{M}_{\inf} = 0.3$



$M_{*\,dyn}$	> 4 M
ZAMS	B3
L_{bol}	~10^4 $L_\odot$
V_{inf}	5 km s^{-1}
R_{inf}	300 AU
Mass-accr	~6×10^{-4} $M_\odot$ yr^{-1}





Goddi, Moscadelli, Sanna 2011

Summary and General Implications II

❖Central star: $M_* \sim 4M_\odot$ (gas dynamics: infall) or ZAMS spectral-type B3 (L_{bol})

- intermediate-mass object and/or early stage of evolution?

❖We resolved the 3D structure of a massive protostellar outflow (H_2O masers)

❖First time gas infall in a circumstellar envelope has been established *directly* via measurement of the 3D velocity field of molecular gas (CH_3OH masers)

I. Outflow

- H_2O masers trace a massive (3 $M_\odot$), bipolar & collimated, dense & slow (V~15 km/s), molecular outflow within 400 AU from the protostar
- Radio continuum traces shock-ionized gas in a protostellar jet, not a HC HII region (R_{jet}~400 AU)
- The collimated molecular outflow is driven by an ionized jet

II. Accretion

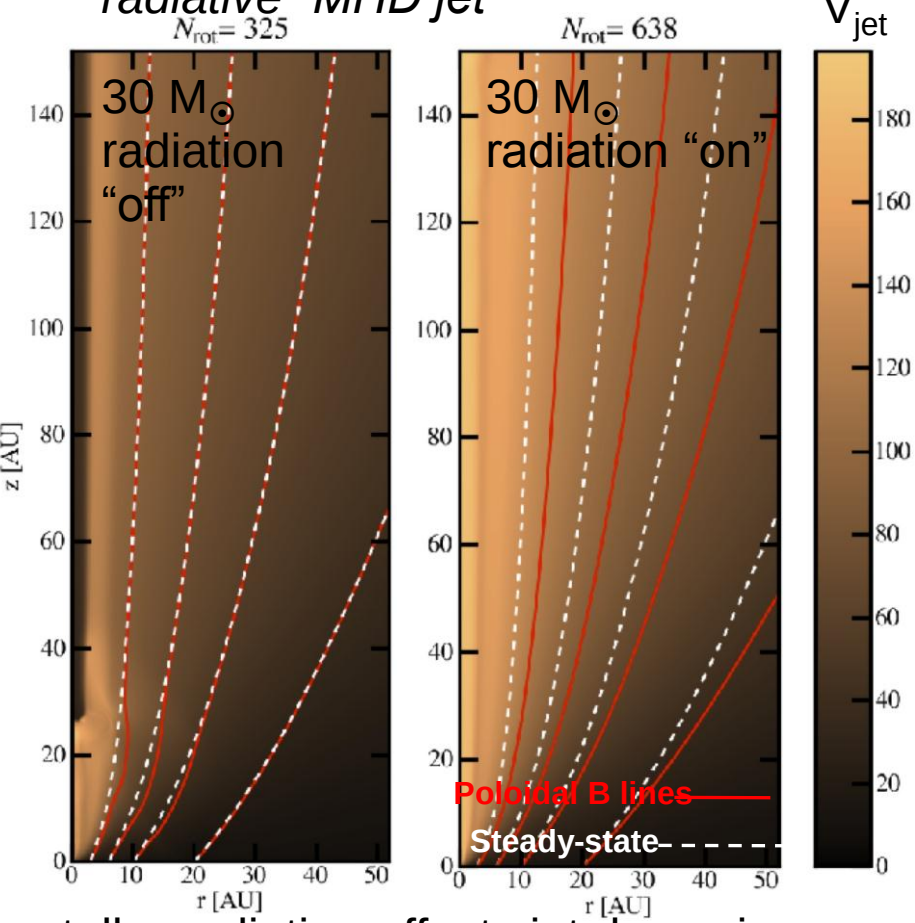
- CH_3OH masers probe infalling material with V~5 km/s at R<300 AU onto a 4 $M_\odot$ protostar
- An accretion rate of 6×10^{-4} n_8 $M_\odot yr^{-1}$ indicates an active accretion
- The high accretion may explain the total bolometric luminosity of the region

The high mass-loss rate to the infall rate indicates that the outflow can efficiently remove mass (and angular momentum?) from the system

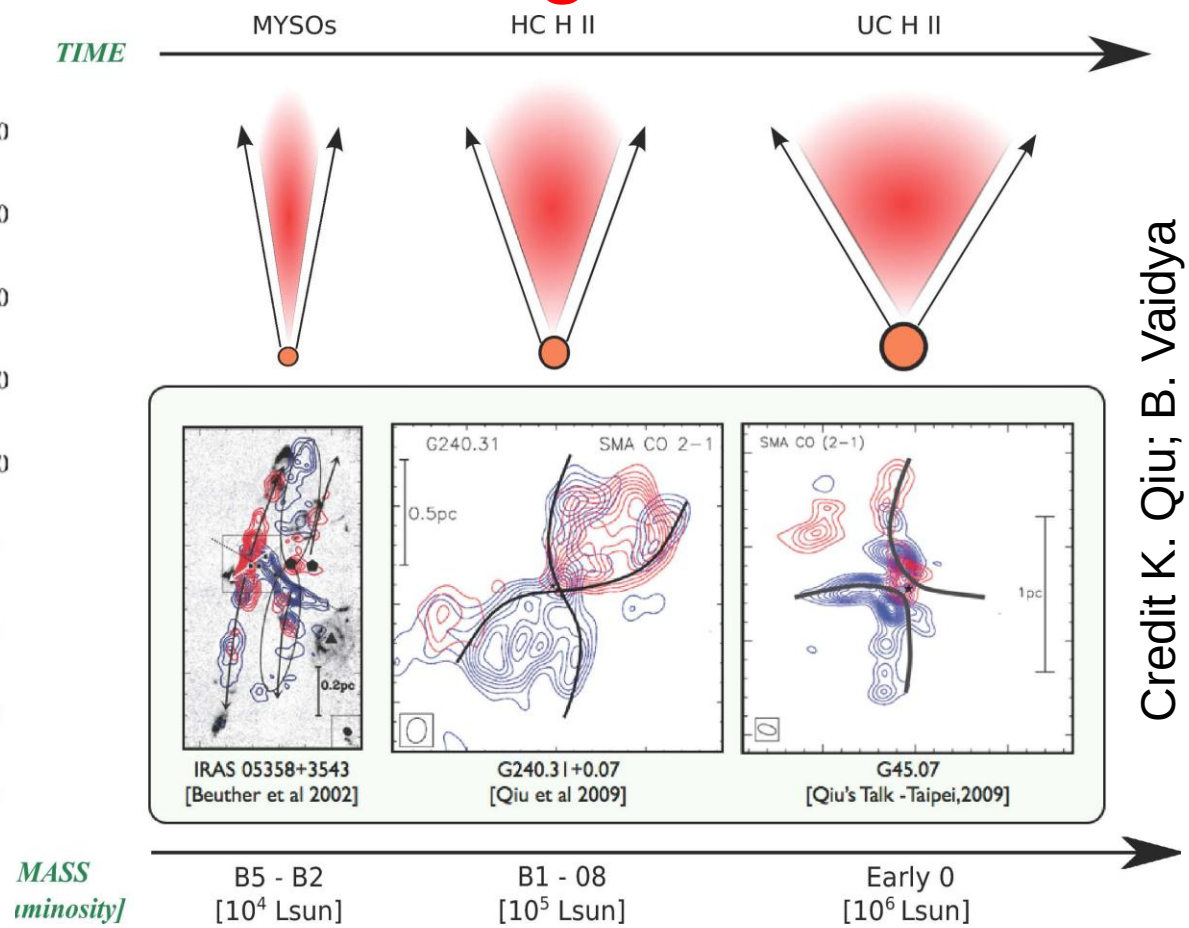
Key Question 1:
Does outflow collimation decrease with protostellar mass or age?

Theory

"radiative" MHD jet



Observations



Credit K. Qiu; B. Vaidya

-stellar radiation affects jet dynamics
-stellar mass (thus luminosity) increases with age
-decollimation of a steady-state MHD wind proved by *Vaidya et al. 11*

Based on interferometric imaging of thermal lines from different molecules (e..g. Beuther & Shepherd 05)

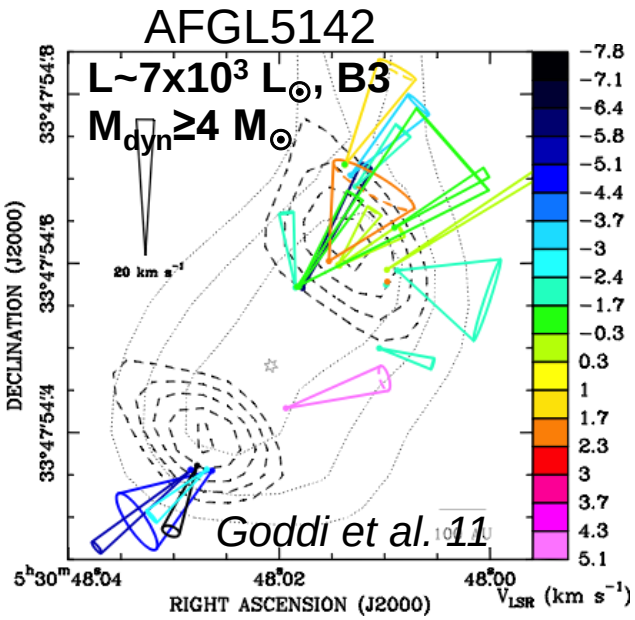
Limitations:

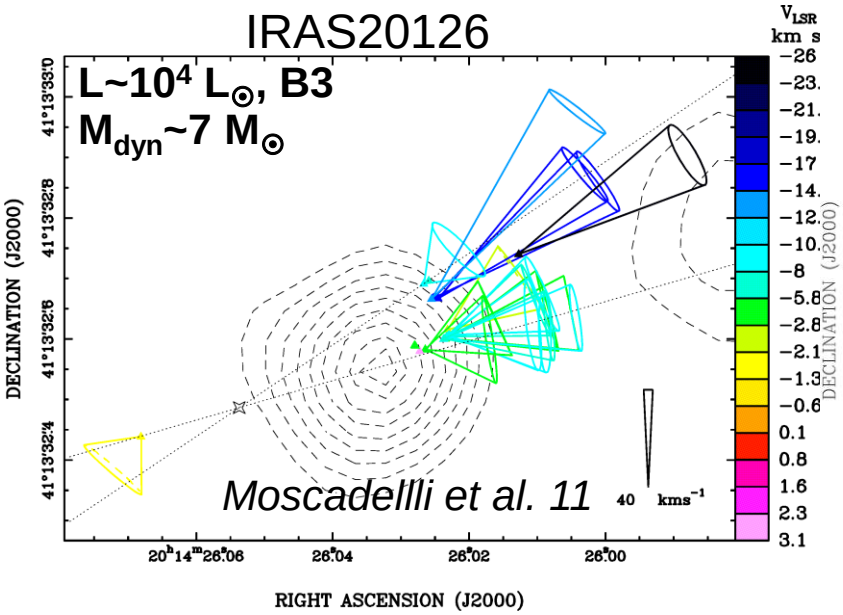
- Large-scale probed, "far" from the protostar
- Blending of multiple outflows in massive protoclusters

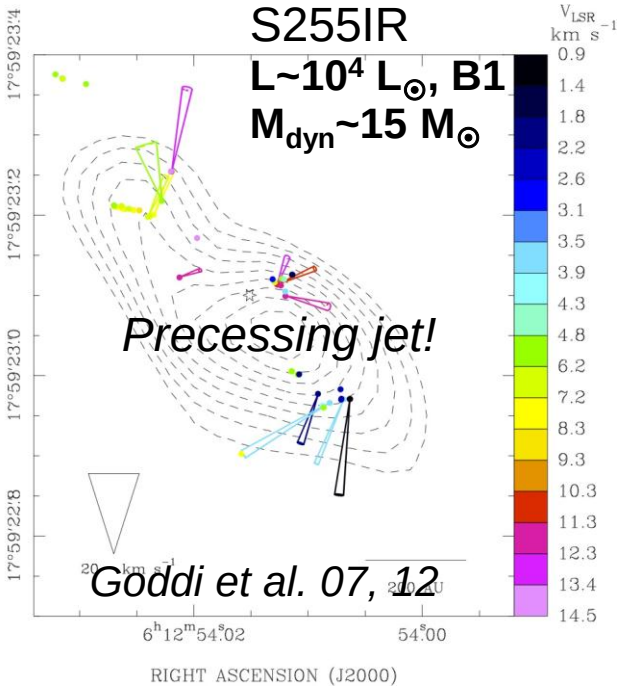
…mainly a problem of poor angular resolution but also image fidelity for extended structures…

Outflow morphologies as displayed by H_2O masers (VLBA) and radio continuum (VLA)

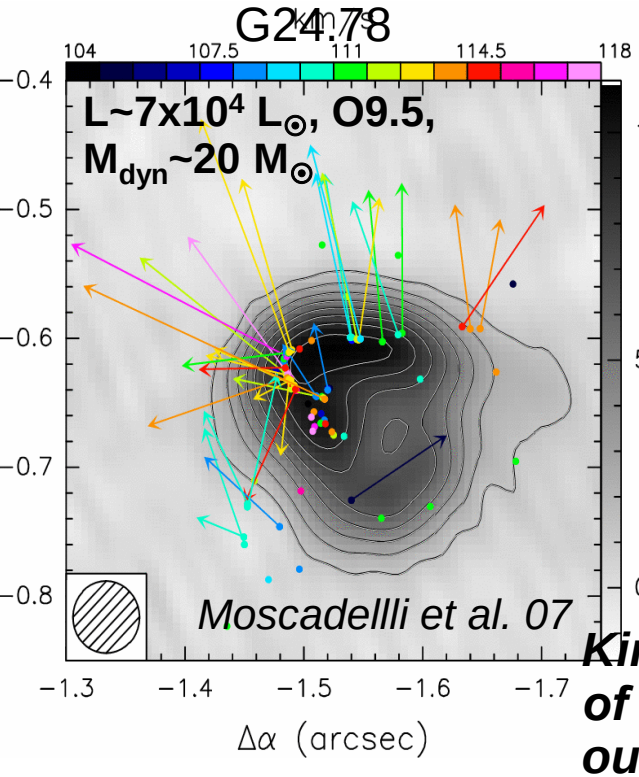
Collimated flows

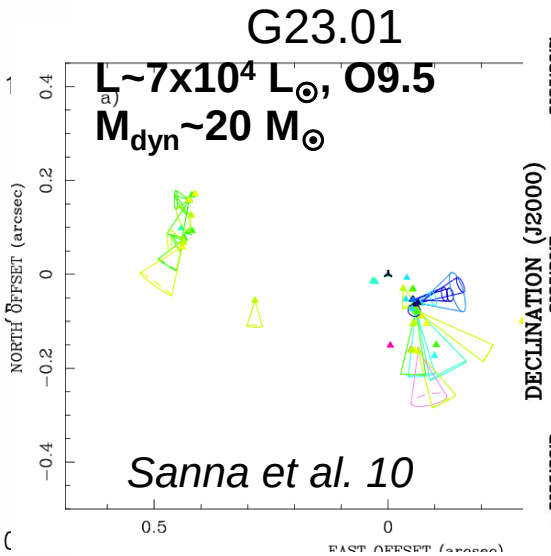


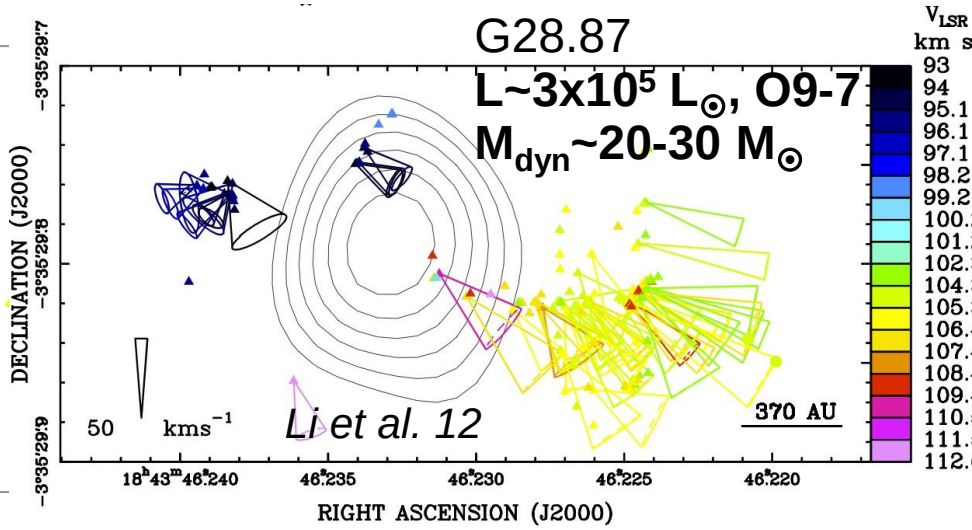




Wide-angle flows

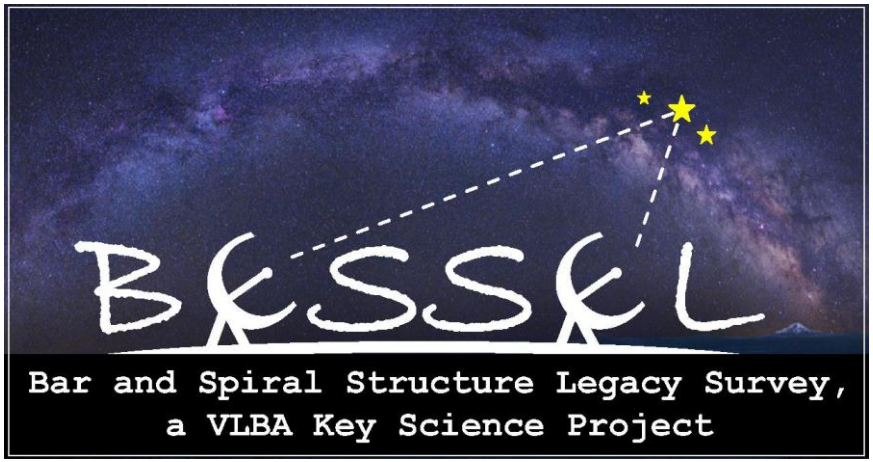


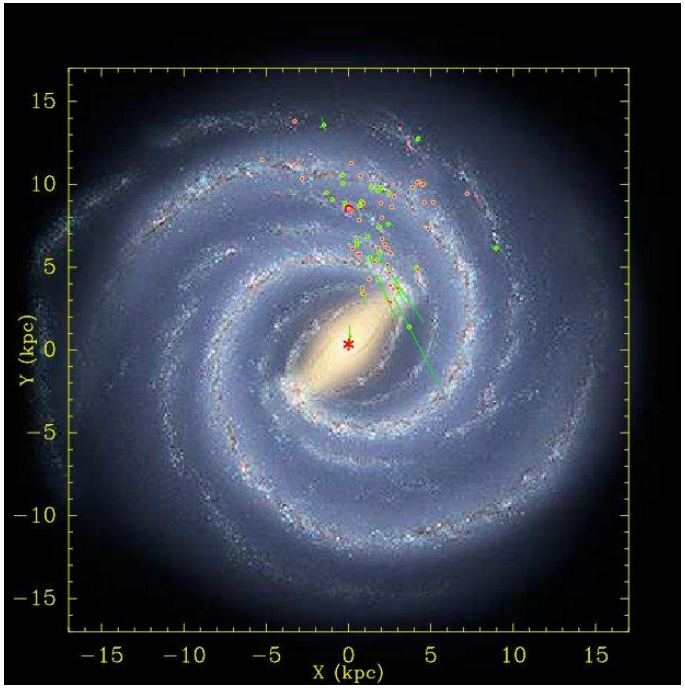




Kinematics of H_2O masers, when combined with the morphology of radio continuum, has already shown a "bimodal" distribution of outflow morphologies as a function of mass in a sizeable sample

A very large sample of MYSOs studied with maser VLBI will be soon available!





Using water and methanol masers to measure trigonometric parallaxes and proper motions of 400 HMSFRs in the MW between 2010 and 2015

Future plan: *Combine maser VLBI 3-D velocity fields with new sensitive maps in thermal tracers with δθ<100 mas*

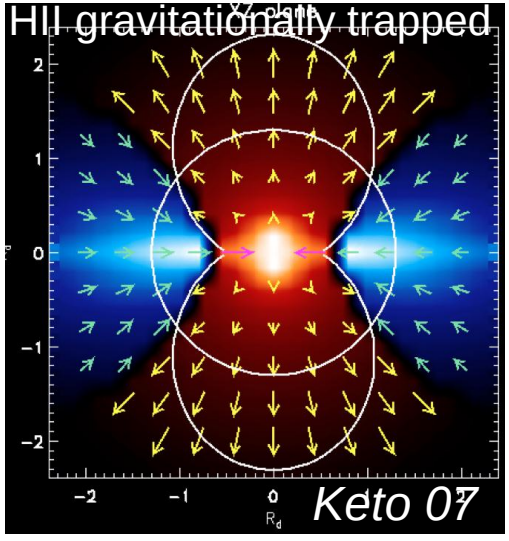
Nature of radio continuum
- spectral index (jet or HC-HII?)
- Morphology: elongated (jet) vs. spherical (wind/HCHII)

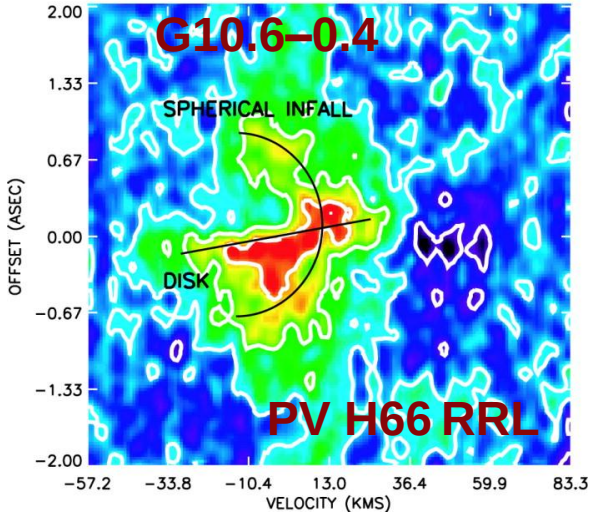
-thermal molecular lines in outflows
-mm RRLs: kinematics of ionized gas

Key Question 2:

Can a massive YSO still accrete mass once a HC HII region has formed?

No real observational evidence of direct accretion of ionized gas on a ***single*** massive YSO!



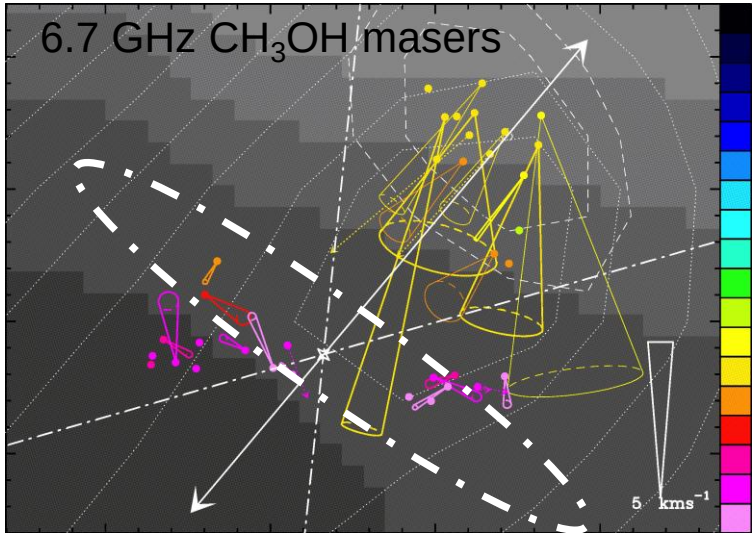


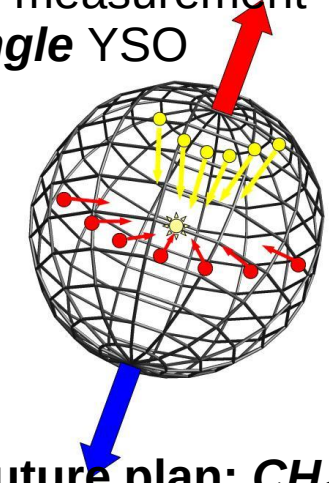
The only case known of resolved accretion flow of ionized gas….

…but the ionized gas is accreting onto a cluster of O-type stars (M_{tot}~200 $M_{\odot}$), NOT onto a single massive YSO

Keto & Wood 06

CH_3OH masers provided the only direct measurement of accretion of *molecular* gas onto a ***single*** YSO





15 12 GHz CH_3OH masers already observed. More to come after installation of the 6.7 GHz receivers at the VLBA

BESSEL

Bar and Spiral Structure Legacy Survey, a VLBA Key Science Project

Future plan: ***CH_3OH maser VLBI 3-D velocity fields with maps of RRLs with $\delta\theta$<100 mas, unique tool to unveil gas accreting inside 100 AU from massive protostars***