High-Mass Star Formation & Maser VLBI

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in collaboration with:

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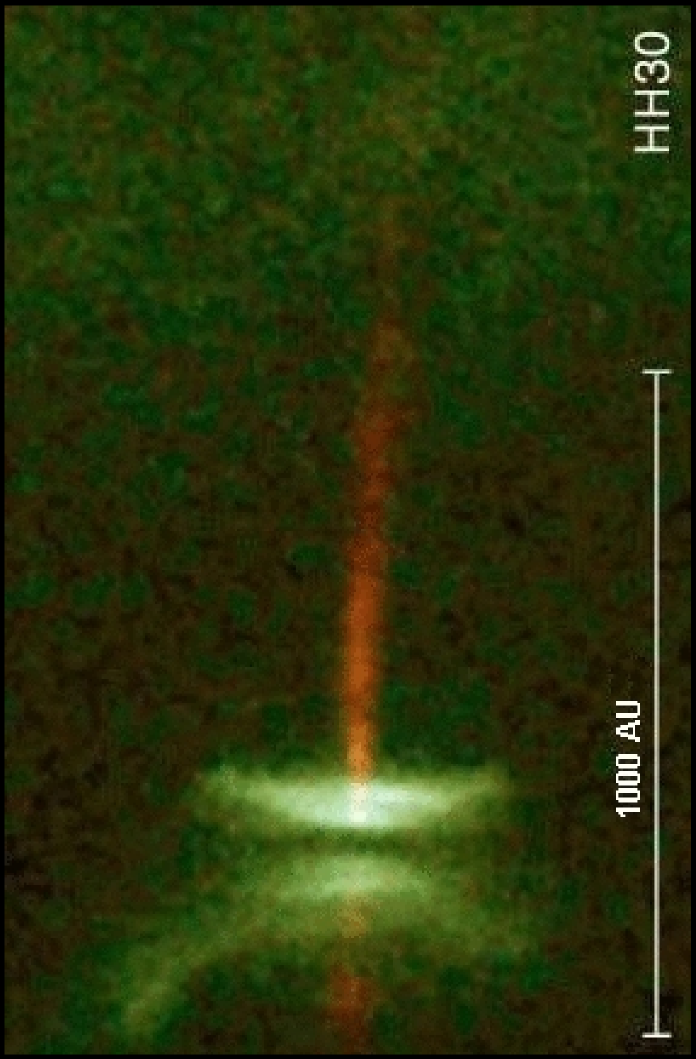
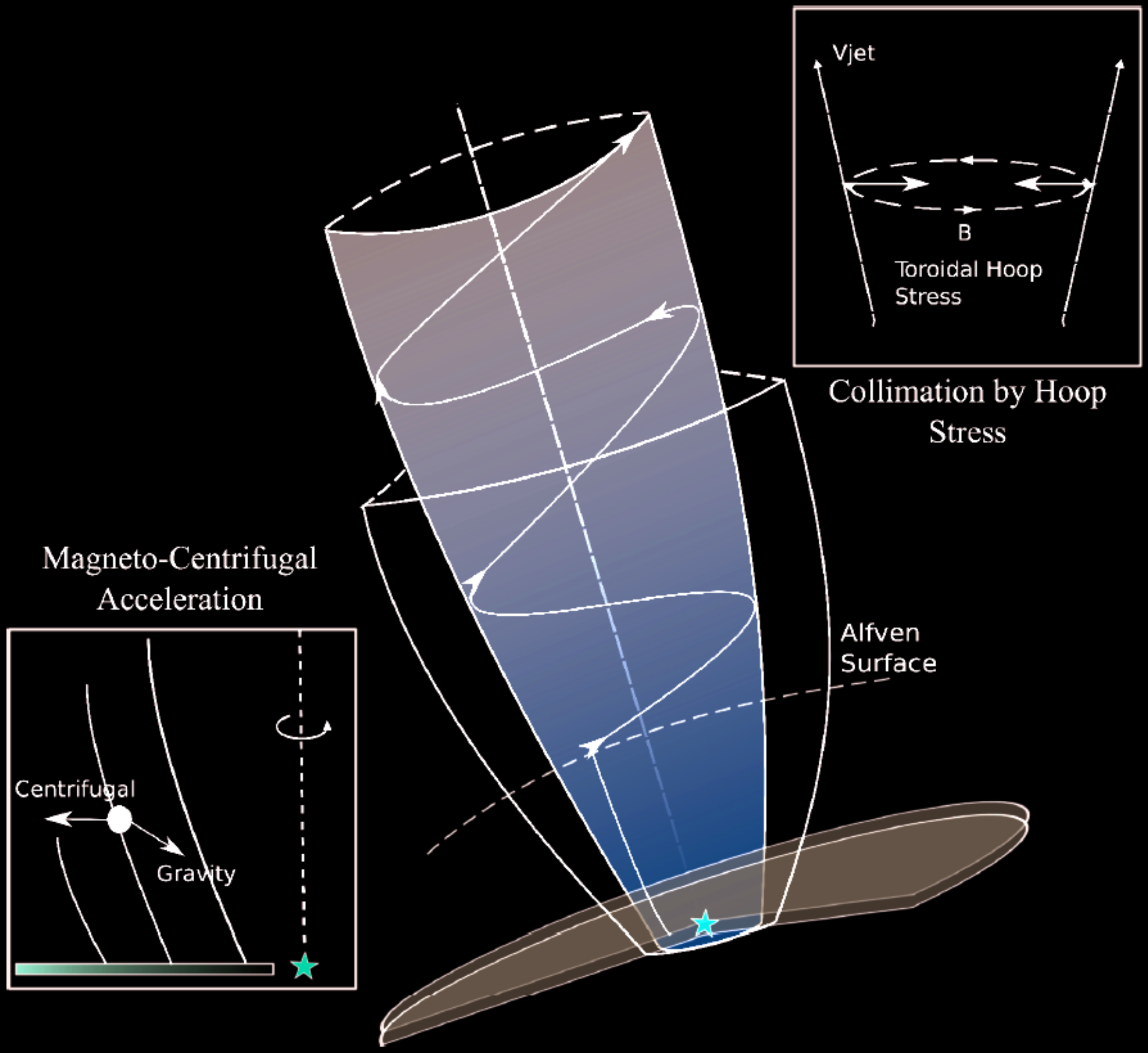
Low-mass (~1 $M_\odot$) Star Formation: Disk+Jet system

Magnetocentrifugally accelerated wind





Adapted from Blandford & Payne 1982

False-color (V, R, I) deconvoled HST WFPC2:

Emission line jet, continuum reflection nebulae,

dark lane. (Burrows et al. 1996)

High-mass stars "switch on" still accreting

Impact of radiation pressure and photoionization (thermal pressure from HII regions) on the accretion of circumstellar gas

Do accretion disks exists ?

1) photoevaporated by the intense stellar UV Radiation

2) if massive, fragmented by gravitational instabilities

3) destroyed by tidal interactions with (stellar cluster) members

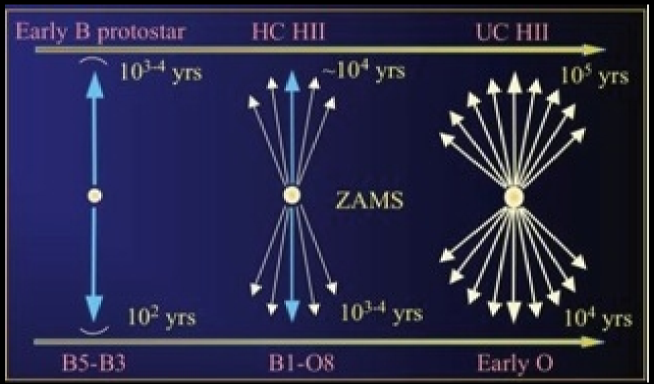
From Observations:

A few B-type YSOs with disks, but no disks towards O-type YSOs

A few thermal jets towards high-mass YSOs (VLA, rms ~ 0.3 mJy)

Are outflows driven by radiation pressure and/or stellar winds ?

Does outflow collimation decrease with protostellar mass or age?

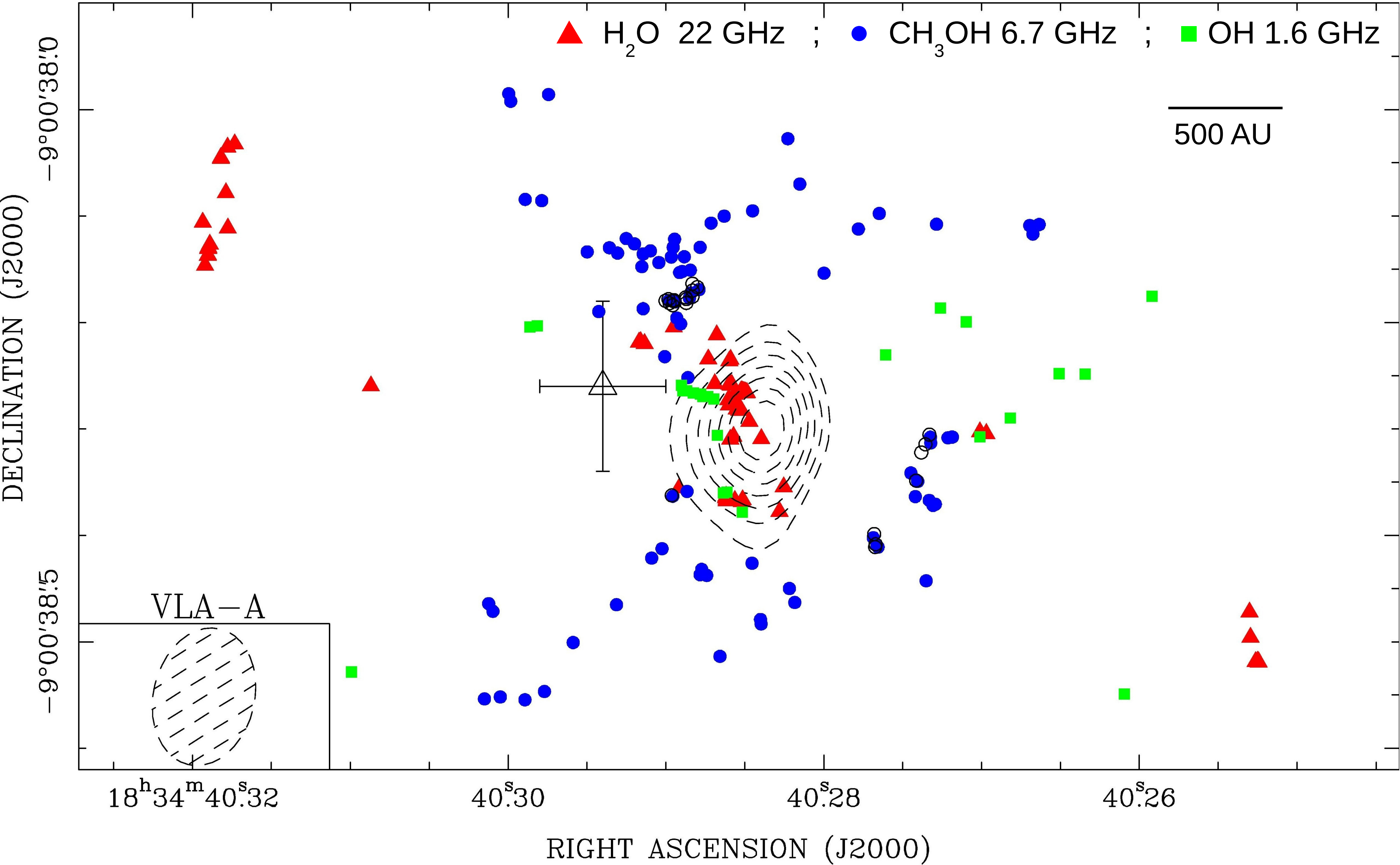


Adapted from Beuther & Shepherd 05

Maser VLBI: 3-D Kinematics @ 10 – 10^3 AU from the YSO

Several Molecular Masers commonly observed nearby high-mass YSOs

Maser V_{LSR} + Proper Motions → 3-D kinematics



Are More Massive Stars forming following

the same path (disk/jet) as Low-Mass Stars ?

Highlights from Maser VLBI towards High-Mass YSOs

in order of increasing YSO Mass/Luminosity.

Source I in Orion BN/KL : > 8 – 10 $M_\odot$

Integrated Intensity epoch-by-epoch (0th Moments)

– Time-series over 2 yrs
– SiO v=1,2

- T=21 months, ΔT~1 month
- R<100 AU, Δθ=0.2 AU

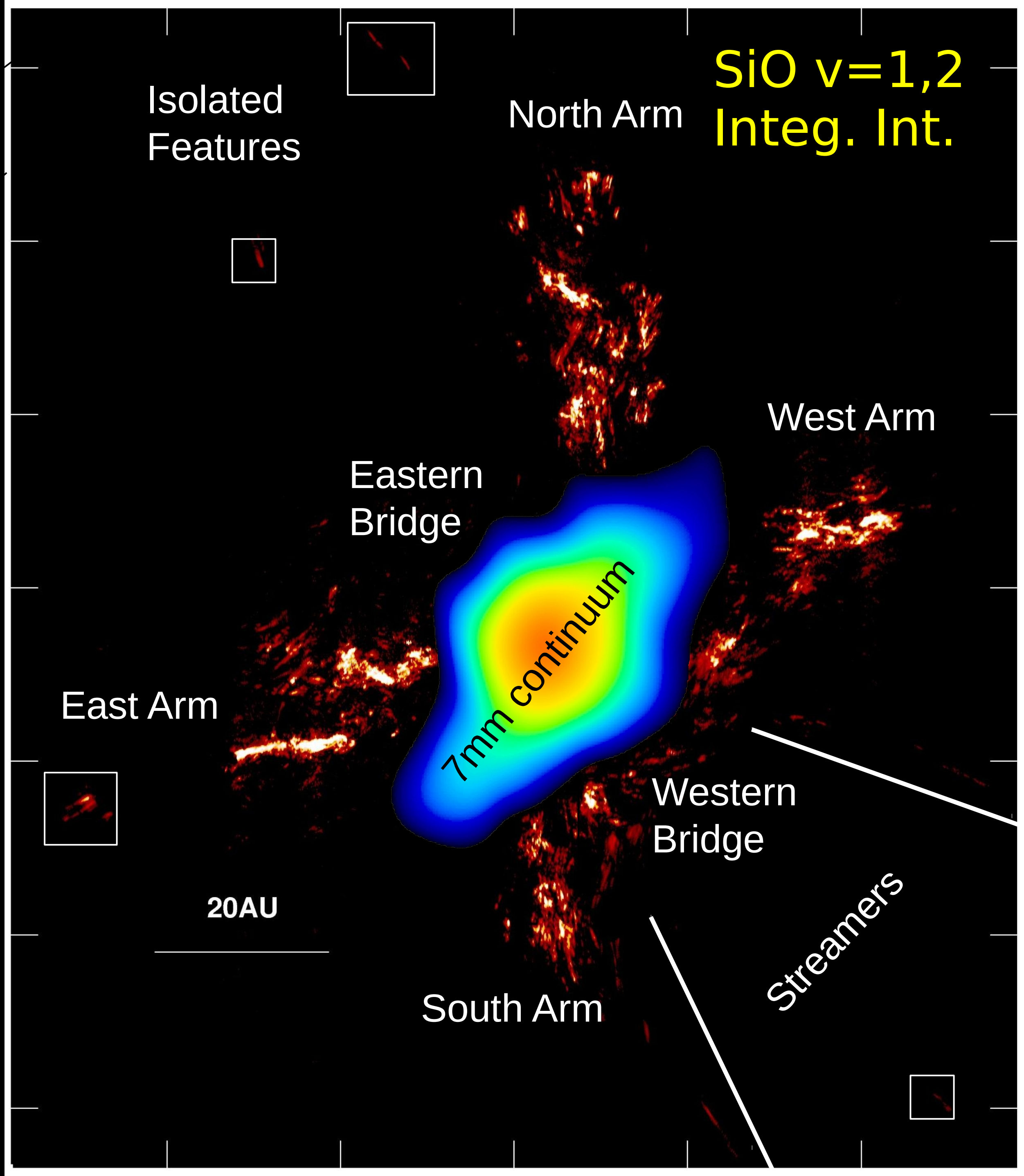
Physical flow of ~1000 independent clumps

–Radial flow (four arms)
–Transverse flow (bridge)

Model

- wide-angle flow (limbs)
- disk rotation

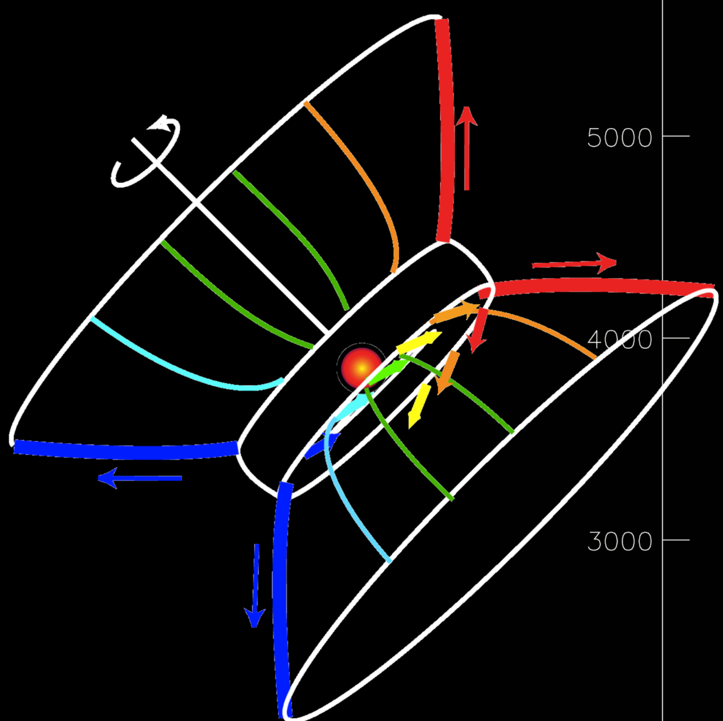
Matthews, Greenhill, Goddi, et al. 2010

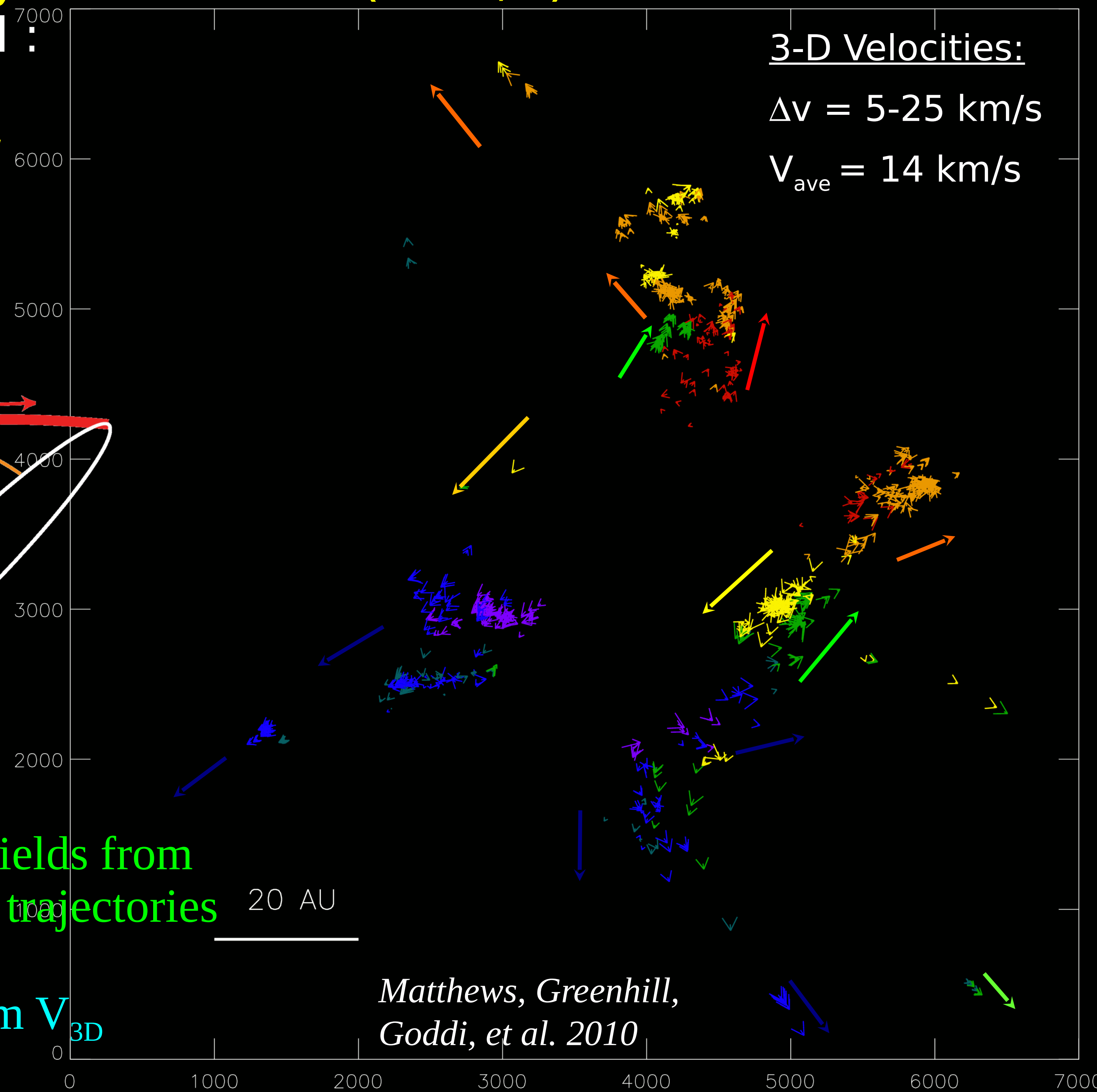


3-D velocity field of SiO (v=1,2) maser emission

Disk-Wind Model :

- Edge-on disk
- NE-SW outflow

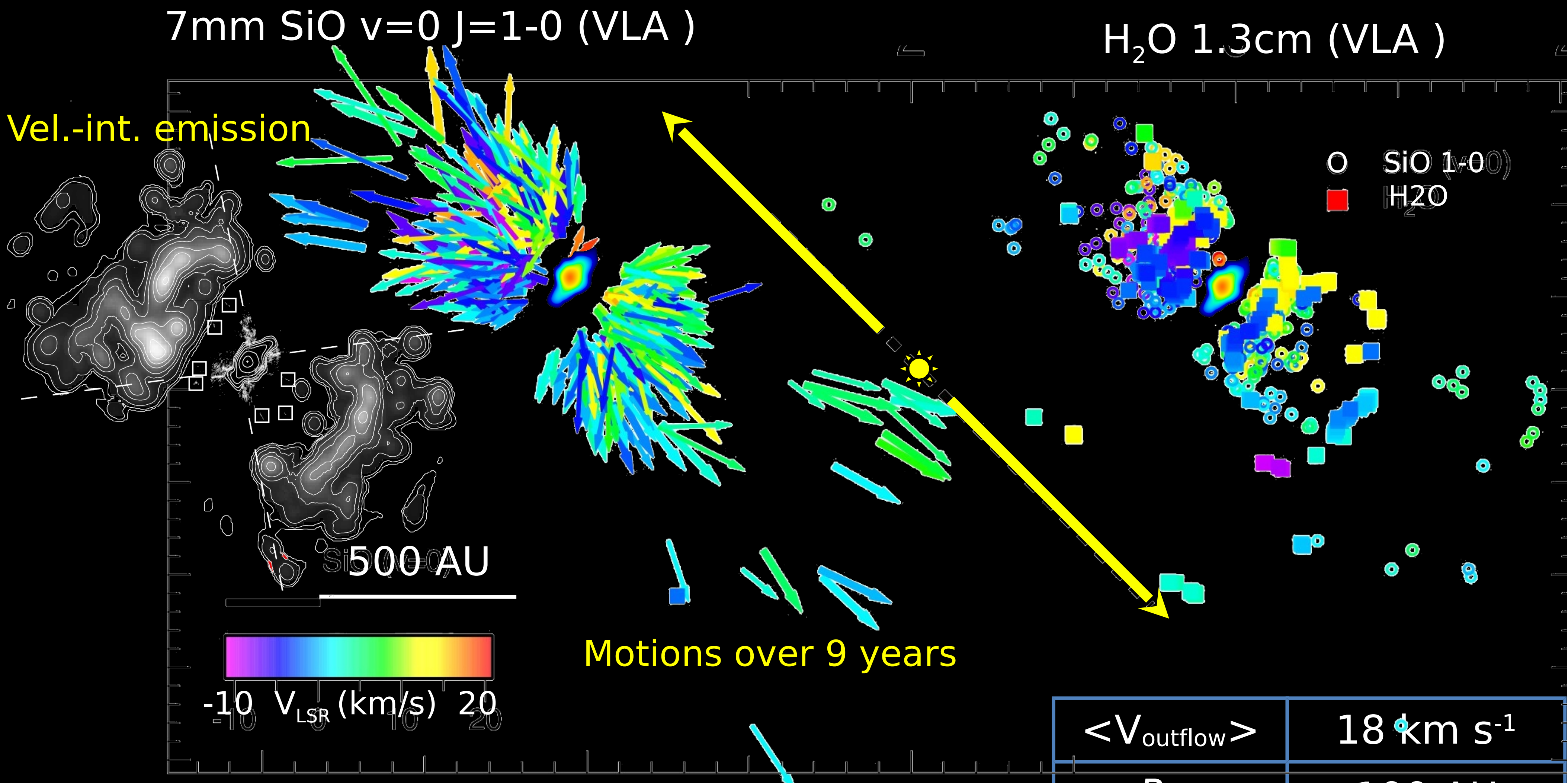




1) Role of magnetic fields from curvature of p.mo trajectories

2) $M_{dyn\ YSO} \geq 7\ M_{\odot}$ from V_{3D}

Collimated outflow at 100 AU < R <1000 AU



$\langle V_{outflow} \rangle$	18 km s^{-1}
R_{inn}	100 AU
R_{out}	1000 AU
Mass-loss	~10^{-6} $M_{\odot}$ yr^{-1}
T_{dyn}	500 yr

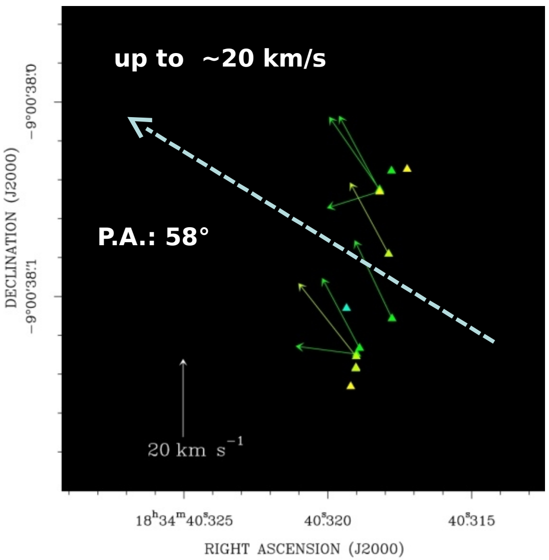
Collimated Bipolar Outflow at R~100-1000 AU and V~20 km s^{-1}

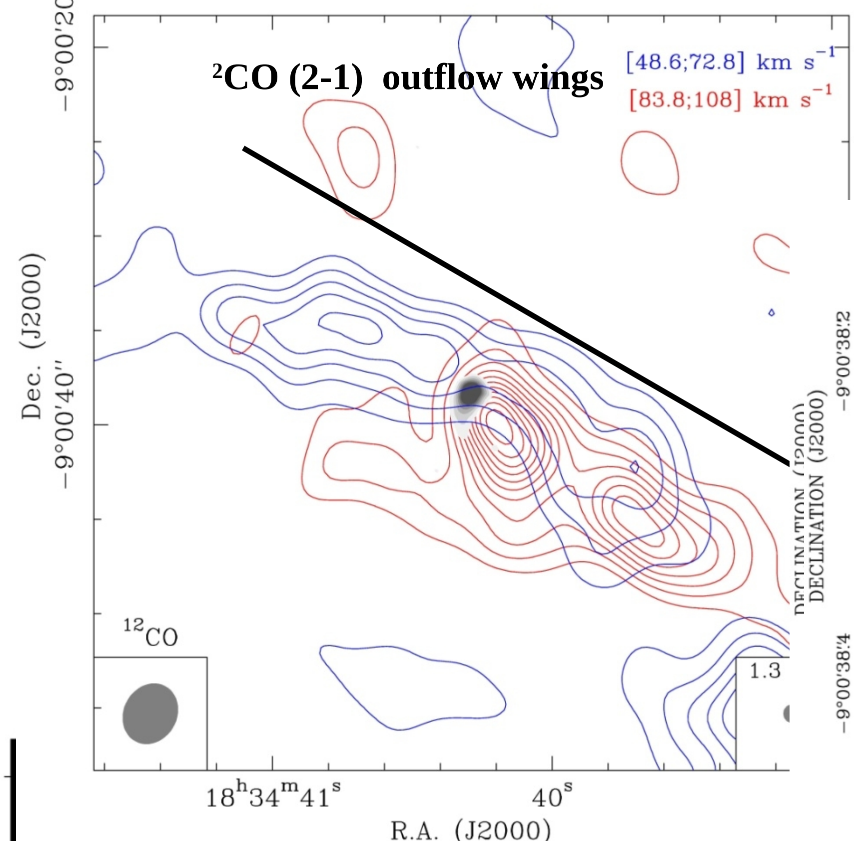
- Collimation beyond ~100 AU in a straight flow

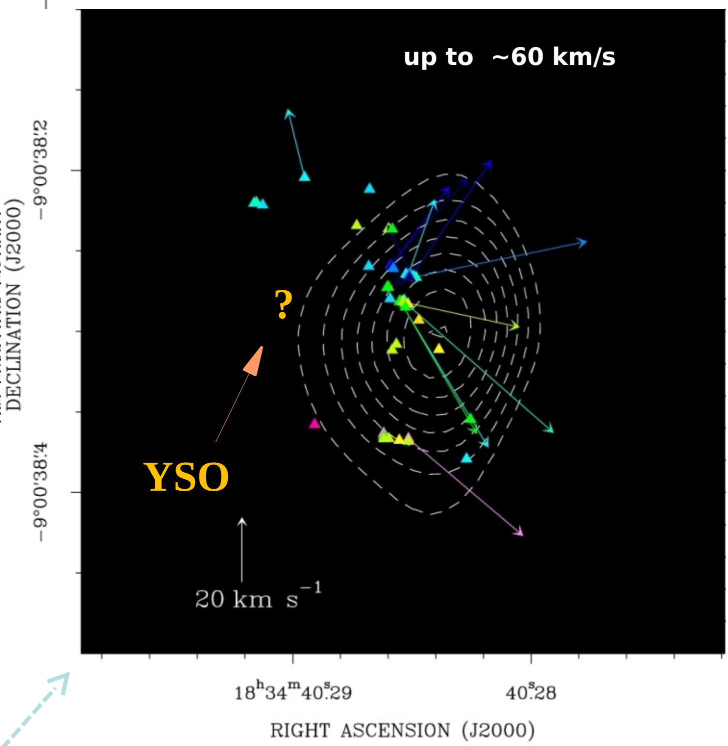
Greenhill, Goddi, et al., 2013

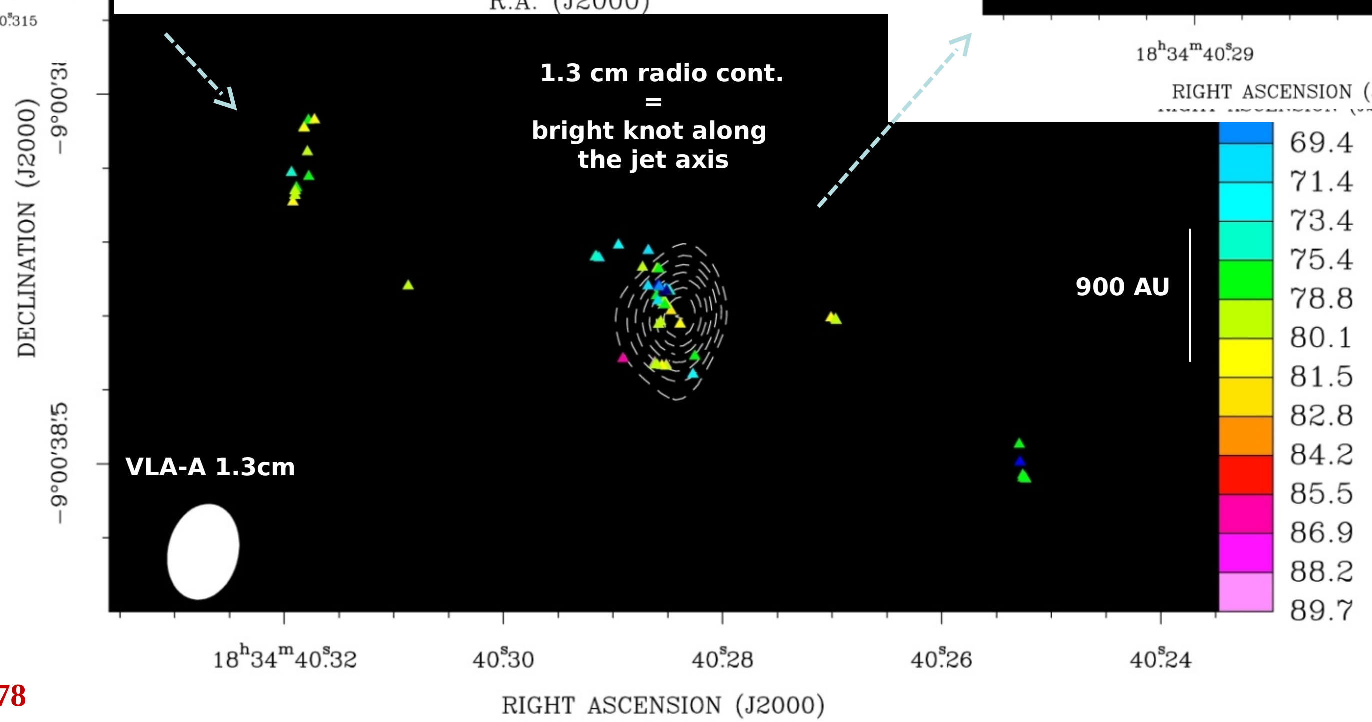
G23.01-0.41

≈ 20 $M_\odot$



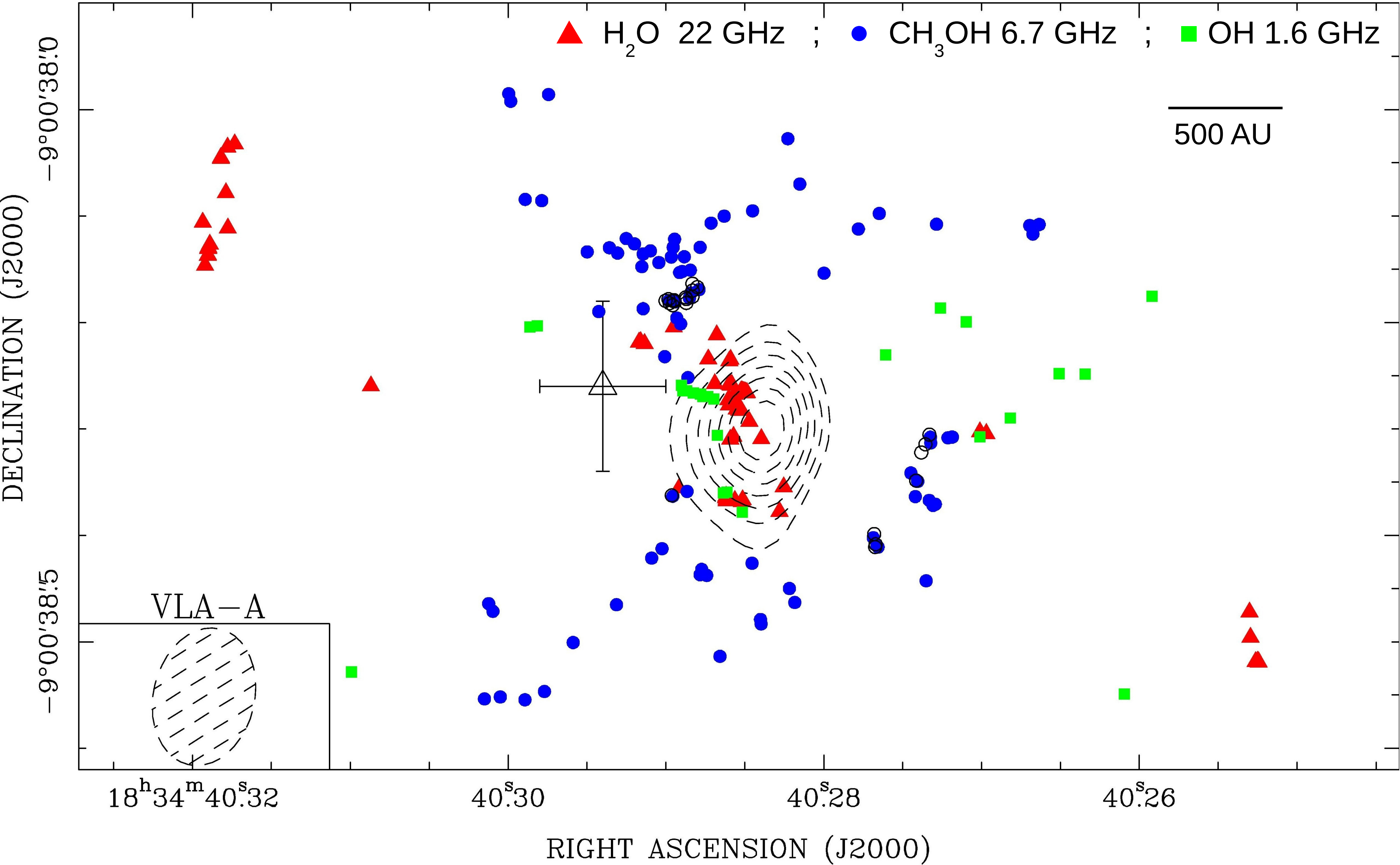




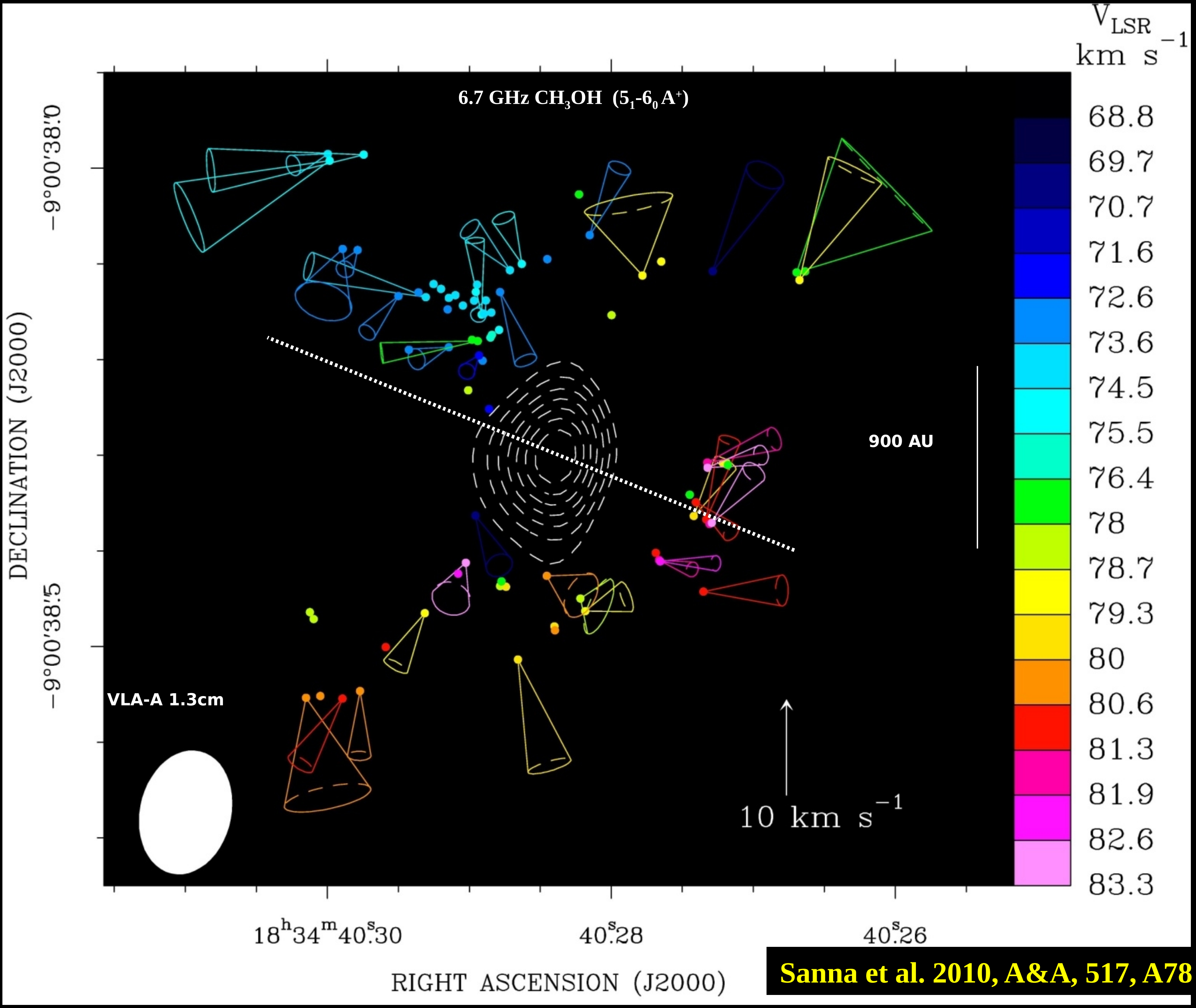


Sanna et al. 2010, A&A, 517, A78

Spatial Distribution of Molecular Masers in G23.01-0.41



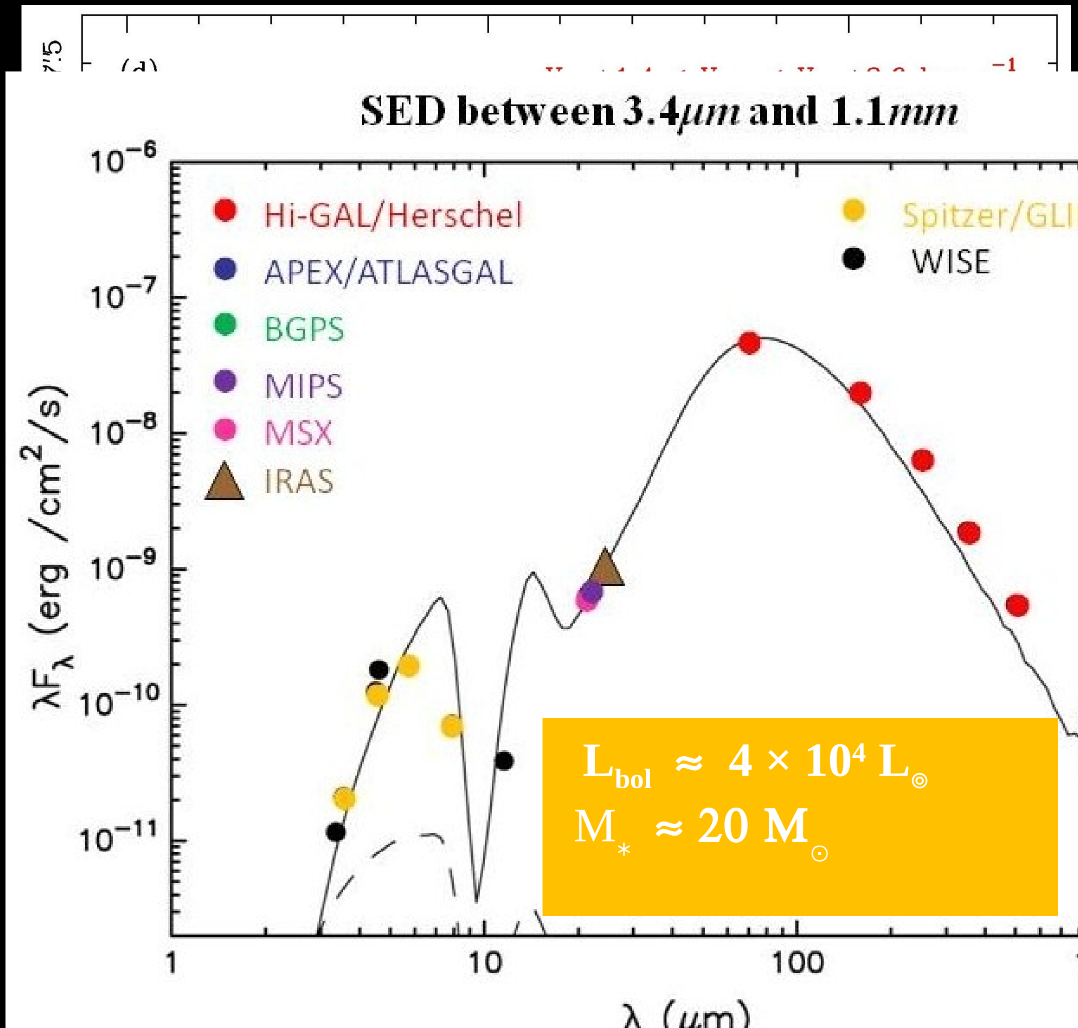
Rotation and Expansion @ a few 10^3 AU from the YSO

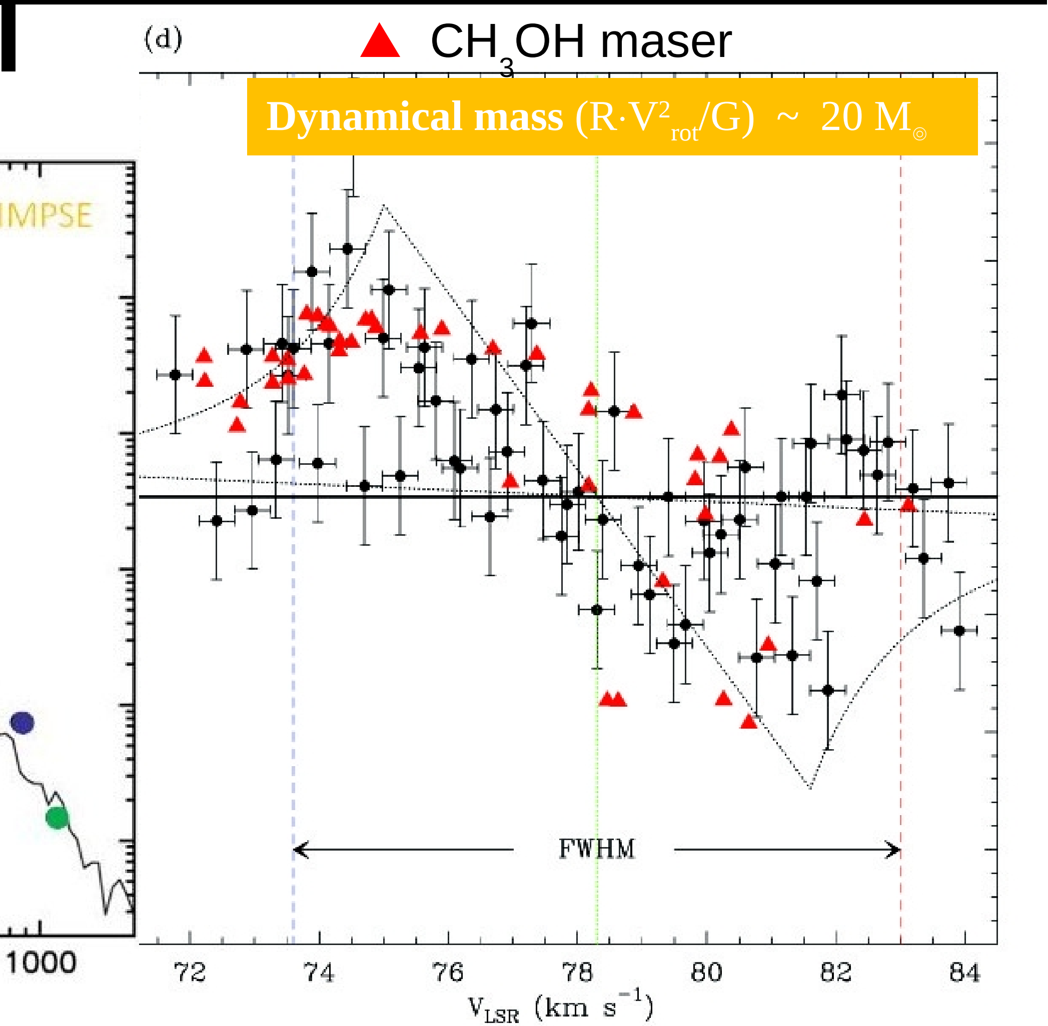


Sanna et al. 2010, A&A, 517, A78

What drives the Expansion ?

1) A Disk-Wind ? (~10 X scaled-up version of that in Source I !)

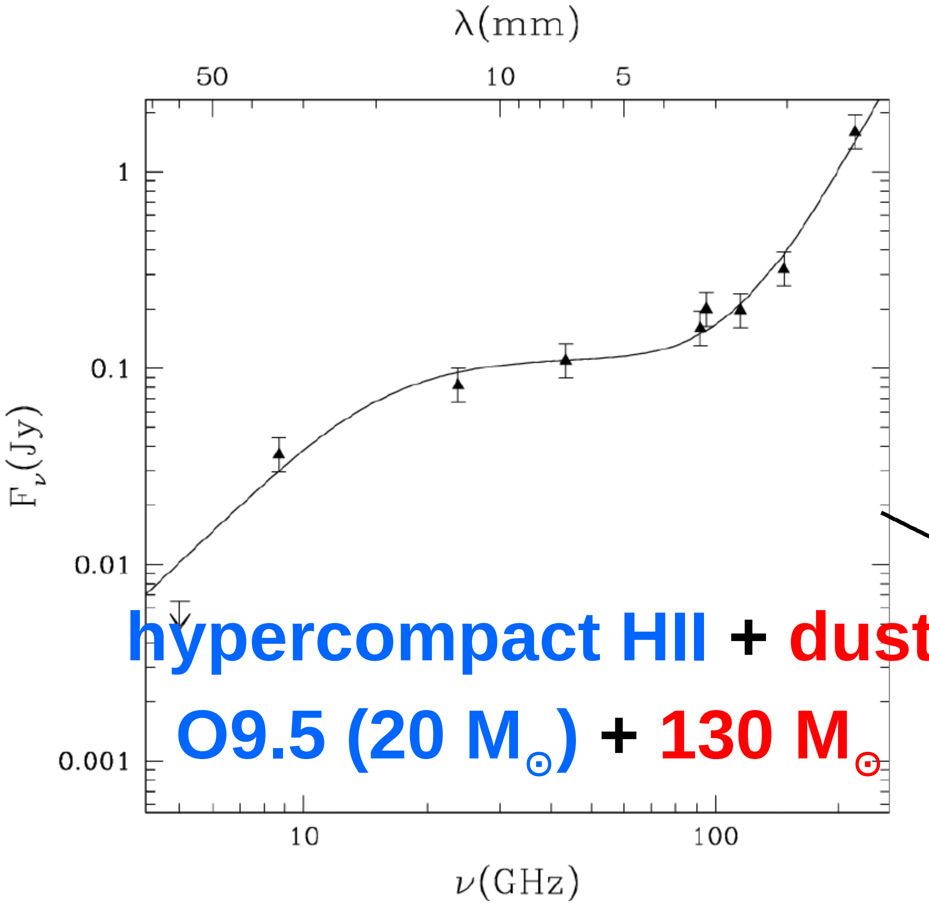


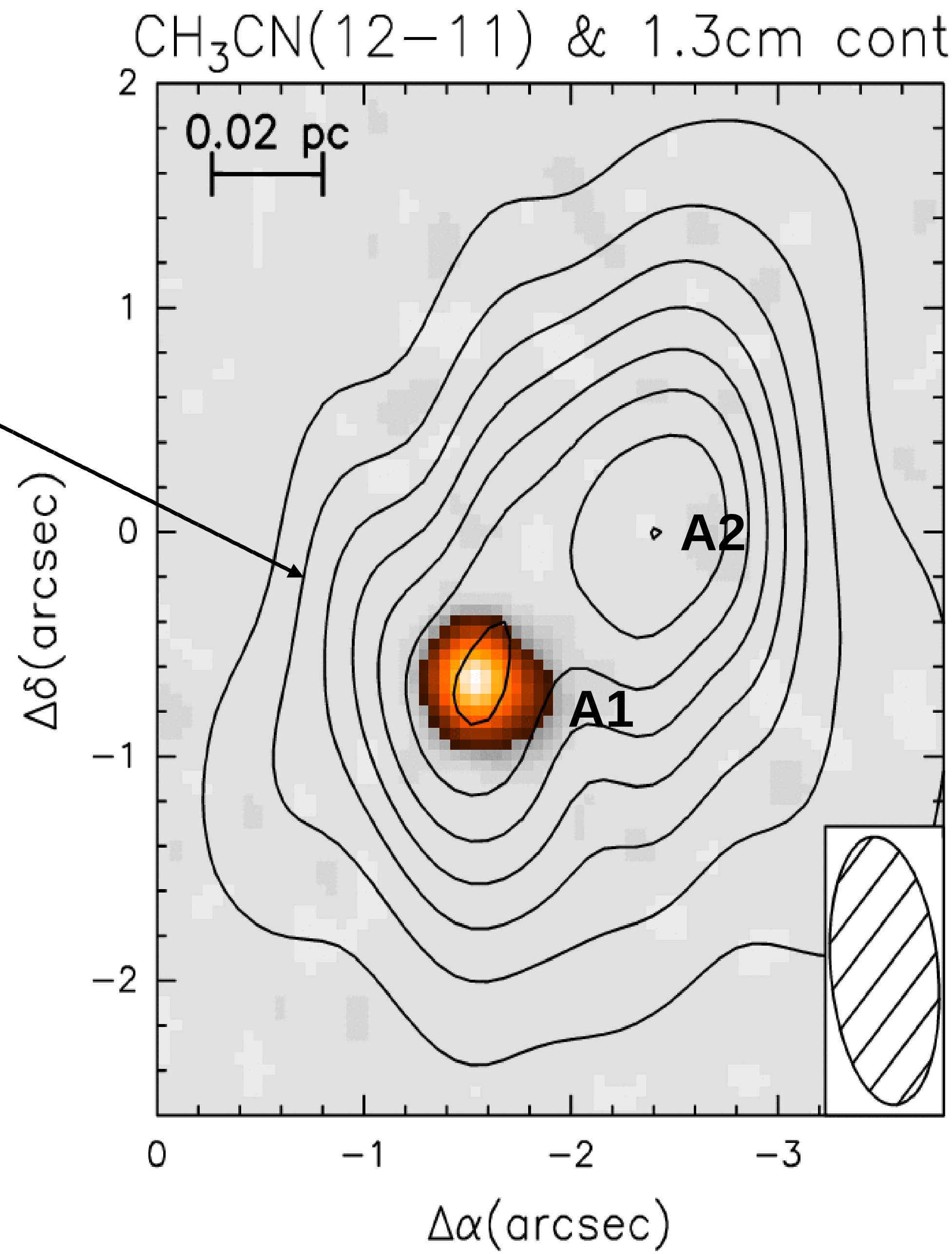


Sanna et al. 2010, A&A, 517, A78
Sanna et al. 2014, A&A, 565, A34

2) A Stellar Wind ? (powerful enough from a late O-type star)

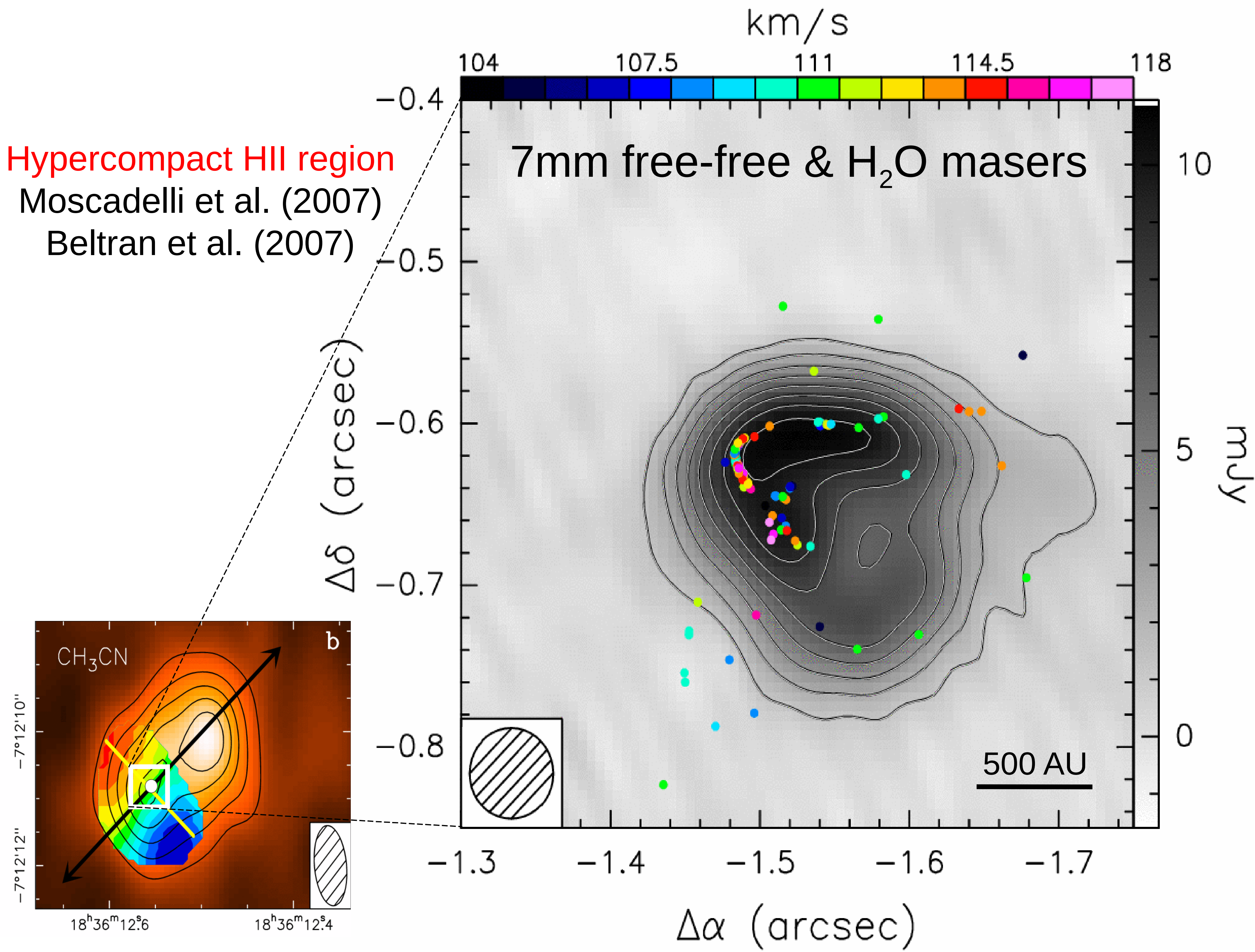
G24.78+0.08: **20 $M_\odot$**

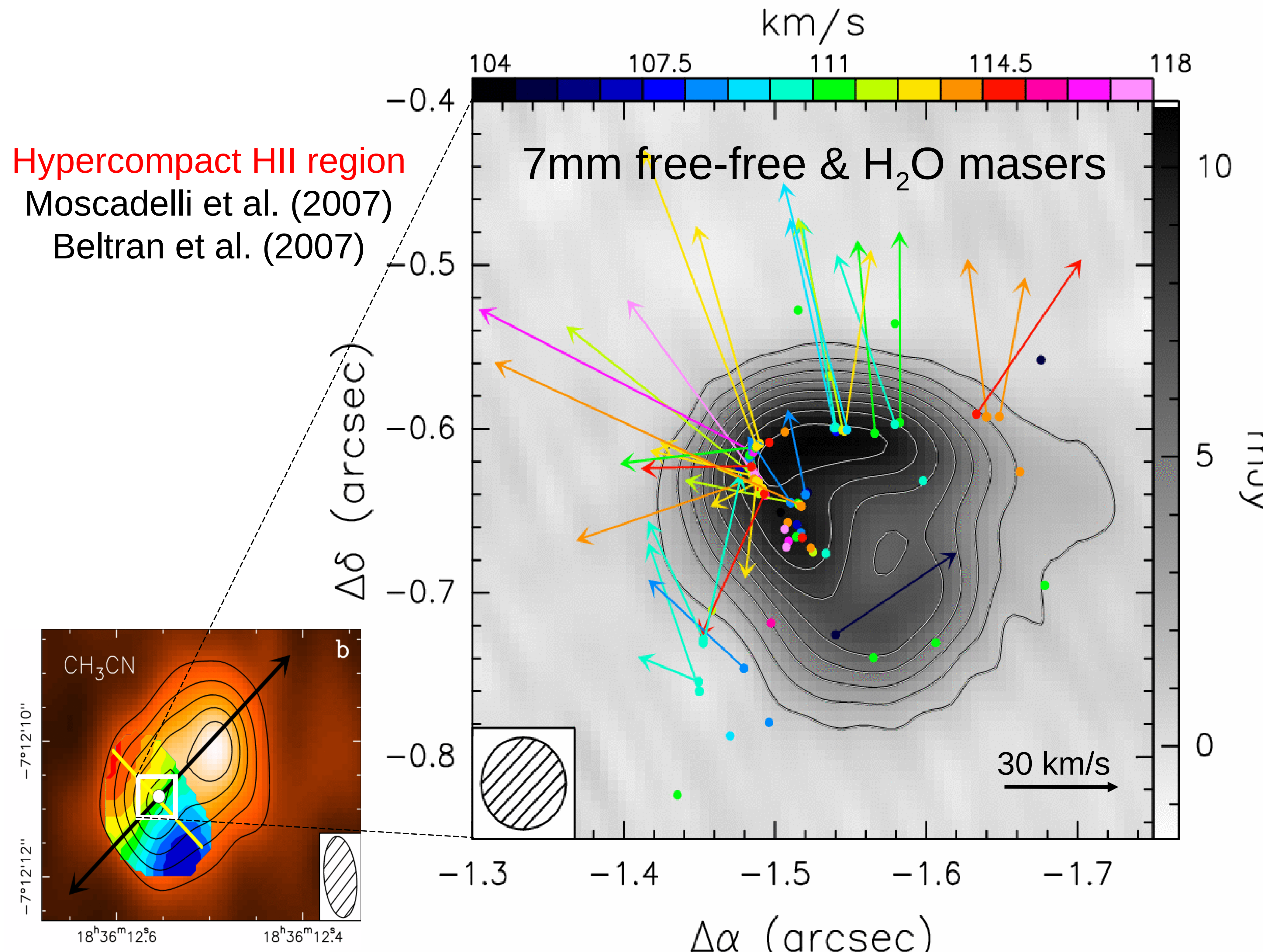




Codella et al., Cesaroni et al.

Furuya et al., Beltran et al.


Hypercompact HII region
Moscadelli et al. (2007)
Beltran et al. (2007)
km/s
104
107.5
111
114.5
118
7mm free-free & H_2O masers
−0.4
−0.5
−0.6
−0.7
−0.8
Δδ (arcsec)
10
5
0
mJy
500 AU
−1.3
−1.4
−1.5
−1.6
−1.7
Δα (arcsec)
CH_3CN
b
−7°12'10''
−7°12'12''
$18^h36^m12\overset{s}{.}6$
$18^h36^m12\overset{s}{.}4$



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10
5
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mJy
−0.4
−0.5
−0.6
−0.7
−0.8
Δδ (arcsec)
−1.3
−1.4
−1.5
−1.6
−1.7
Δα (arcsec)
30 km/s
CH_3CN
b
−7°12'10''
−7°12'12''
$18^h36^m12\overset{s}{.}6$
$18^h36^m12\overset{s}{.}4$

Water Maser Shell

Kinematic Status: $R_0 \approx 500$ AU , $V_0 \approx 40$ km s^{-1}

Maser Action → pre-shock $n_H > 10^6$ cm^{-3}

Wind-driven shell

For a ZAMS O9.5 type:

$M_w \sim 10^{-6}$ $M_\odot$ yr^{-1}, $V_w \sim 2000$ km s^{-1} , $L_w \sim 1\text{-}5\ 10^{36}$ erg s^{-1}

pressure and momentum-driven solutions require:

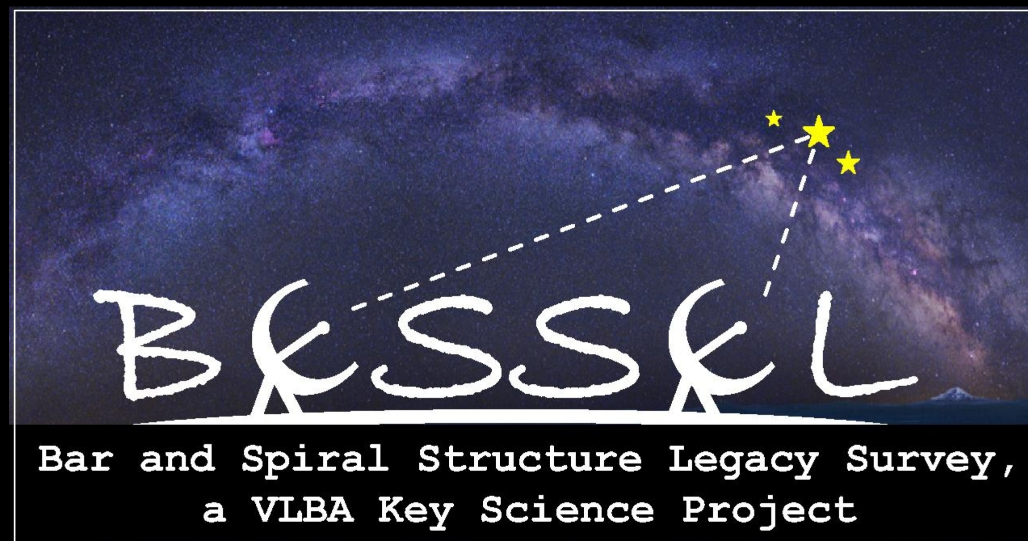
$t_0 \approx 40$ yr , $n_H \sim 10^7$ cm^{-3}

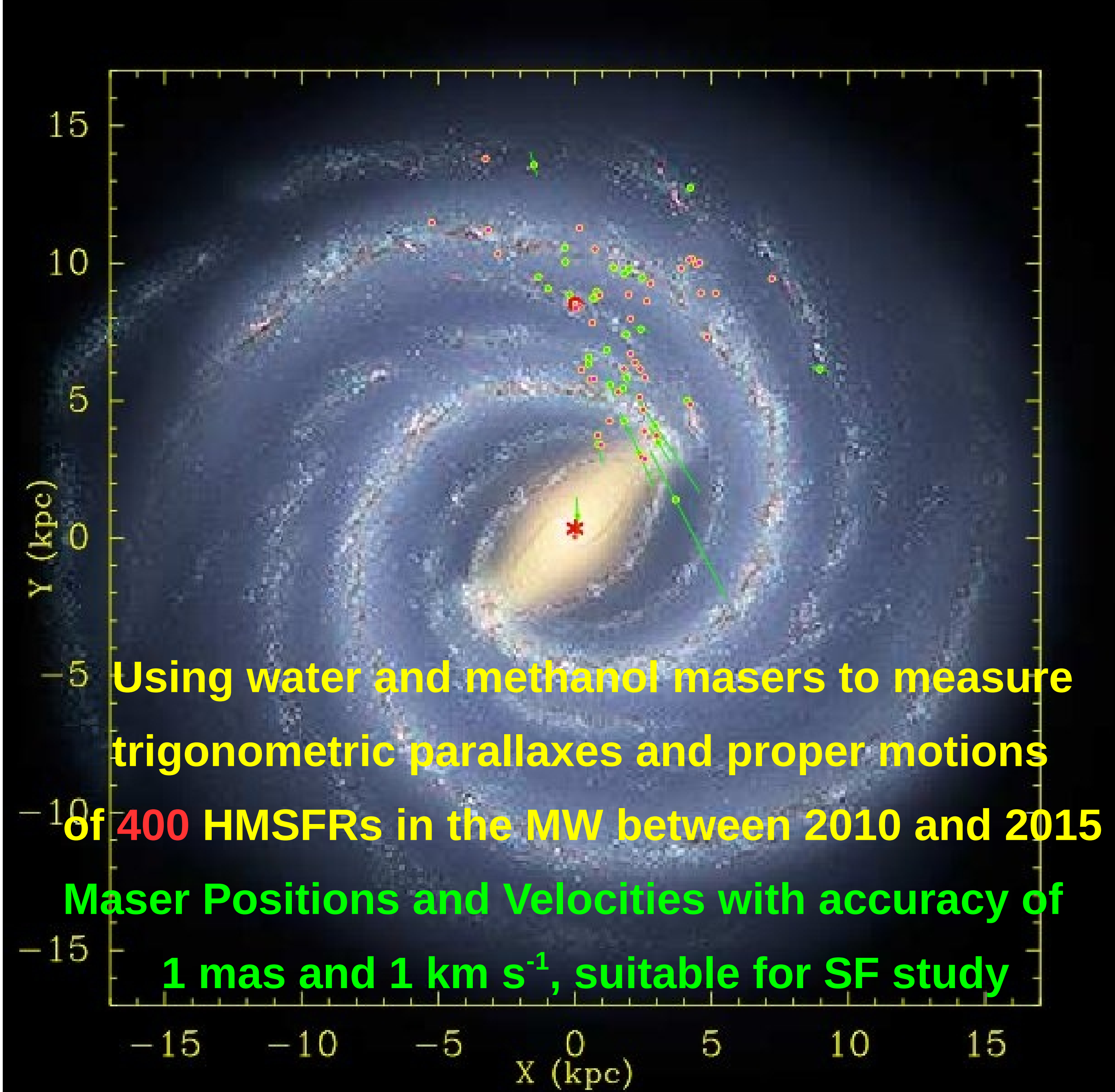
radio appearance similar to an UCHII region

Conclusions and Prospects

Maser VLBI: unique tool to get a “state of art” view of high-mass SF

1) Increasing the sample of MYSOs studied with maser VLBI





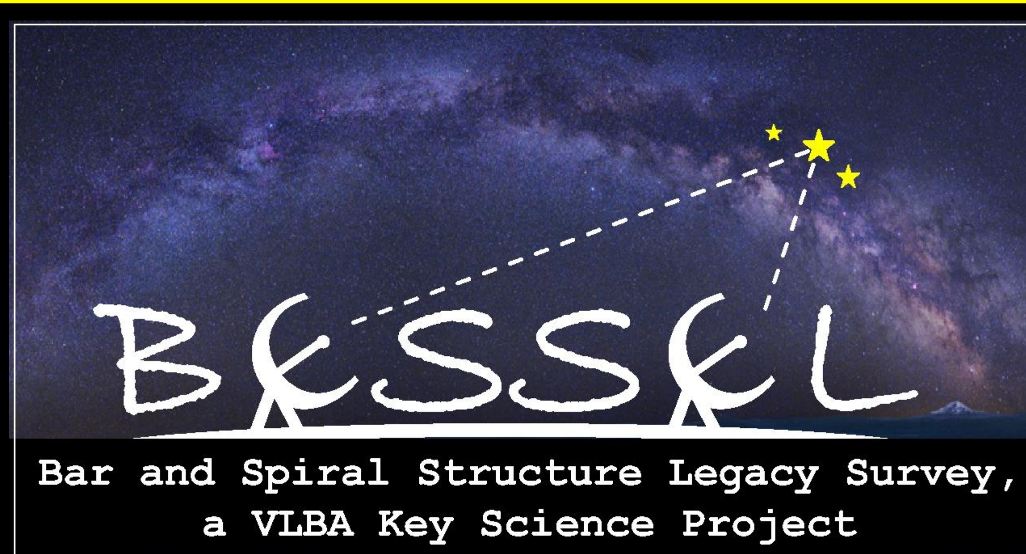
Using water and methanol masers to measure trigonometric parallaxes and proper motions of 400 HMSFRs in the MW between 2010 and 2015

Maser Positions and Velocities with accuracy of 1 mas and 1 km s^{-1}, suitable for SF study

Conclusions and Prospects

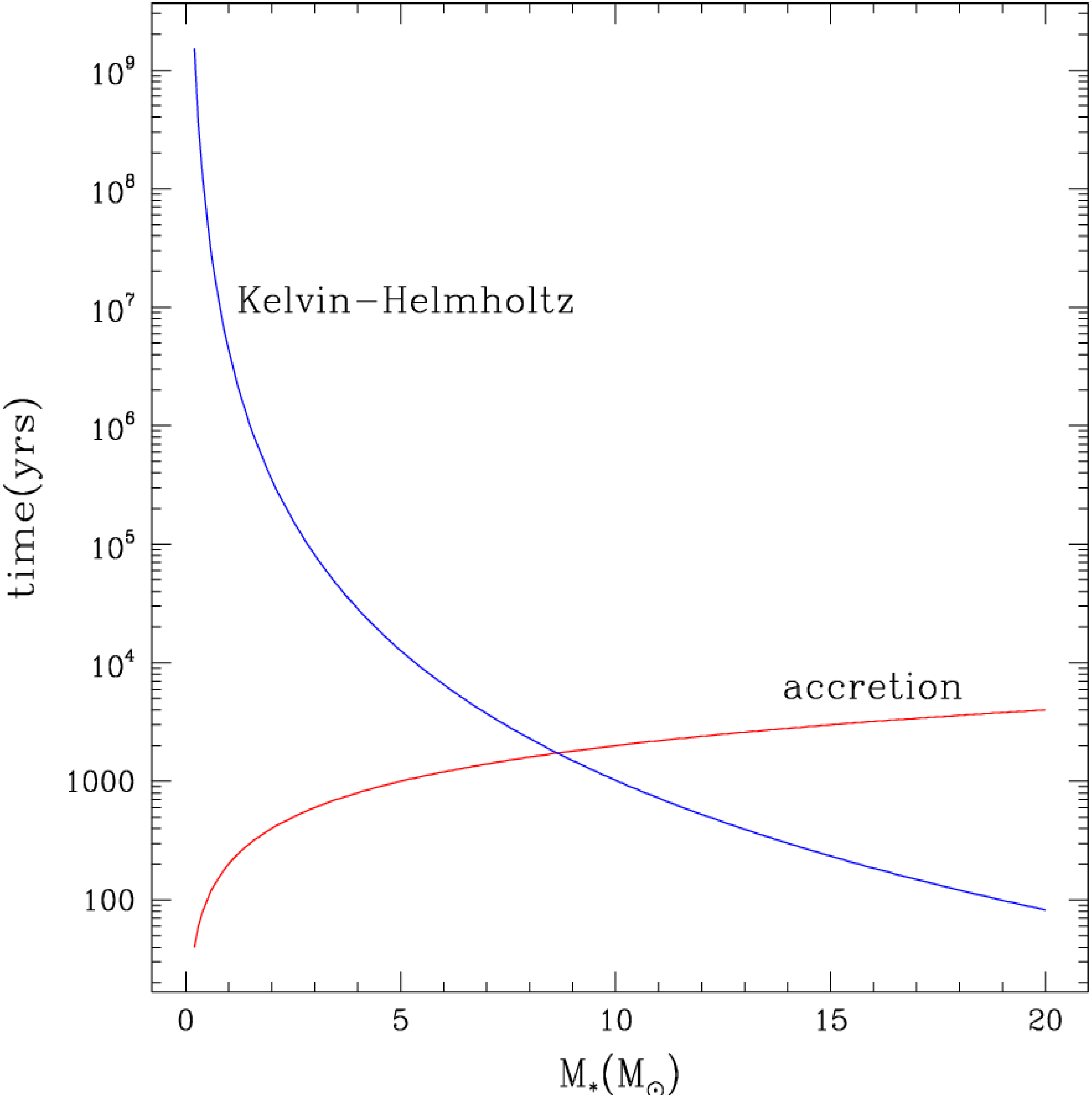
Maser VLBI: unique tool to get a “state of art” view of high-mass SF

1) Increasing the sample of MYSOs studied with maser VLBI



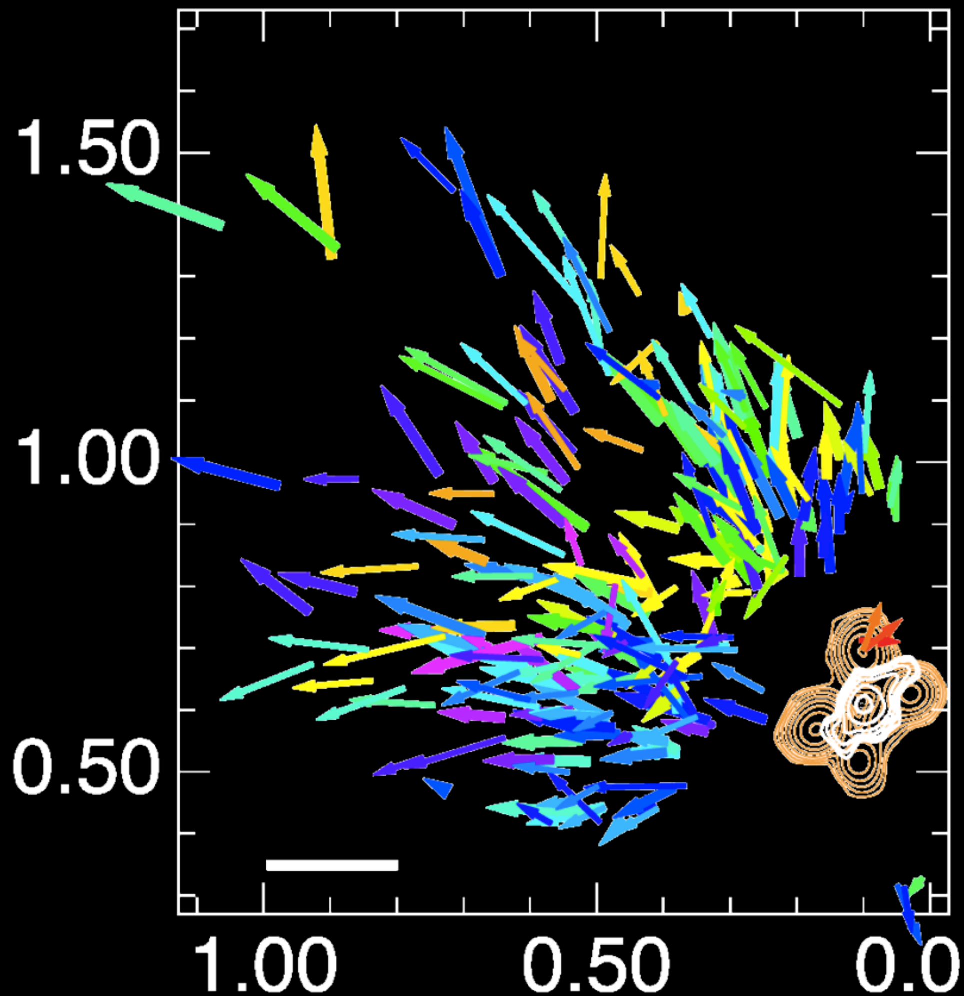
2) Next, Maser VLBI 3-D velocity fields can be optimally combined with sensitive, $\delta\theta \leq 100$ mas, maps in thermal tracers

Peculiarity of High-Mass (> 6-8 $M_\odot$) Star Formation

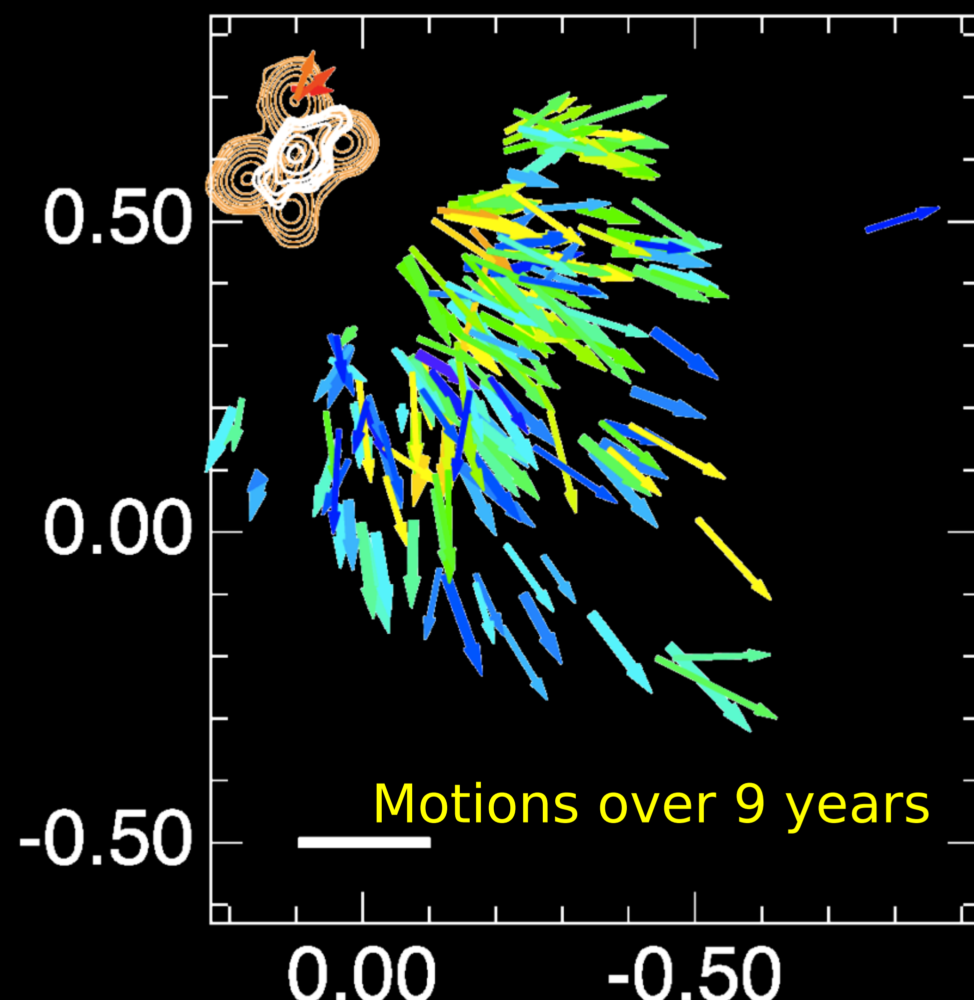


V_{out} =18±8 km s^{-1}

Greenhill, Goddi, et al., 2013



V_{los} gradient~5 km/s across minor axis: rotation?

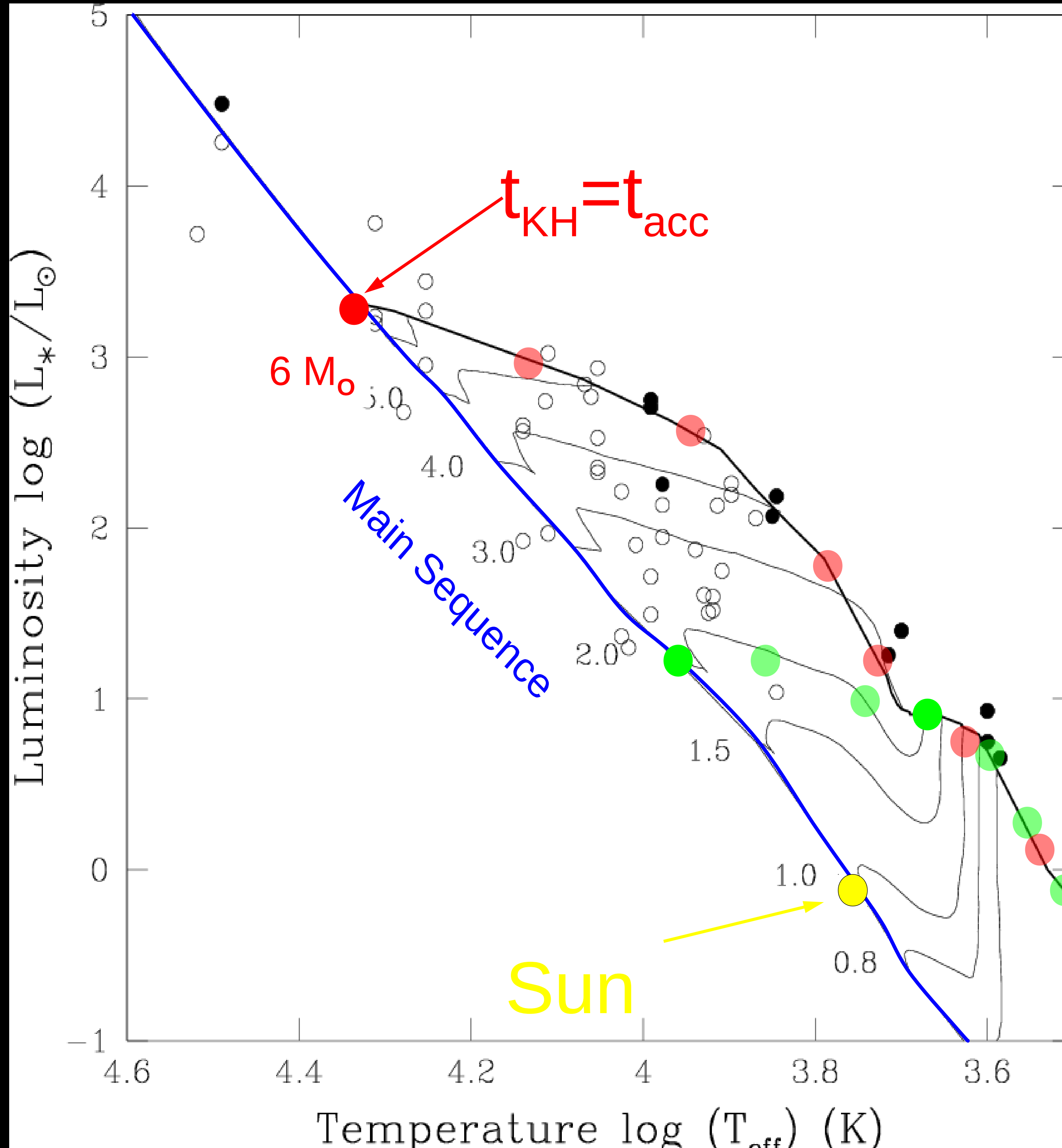


Source I in Orion BN/KL

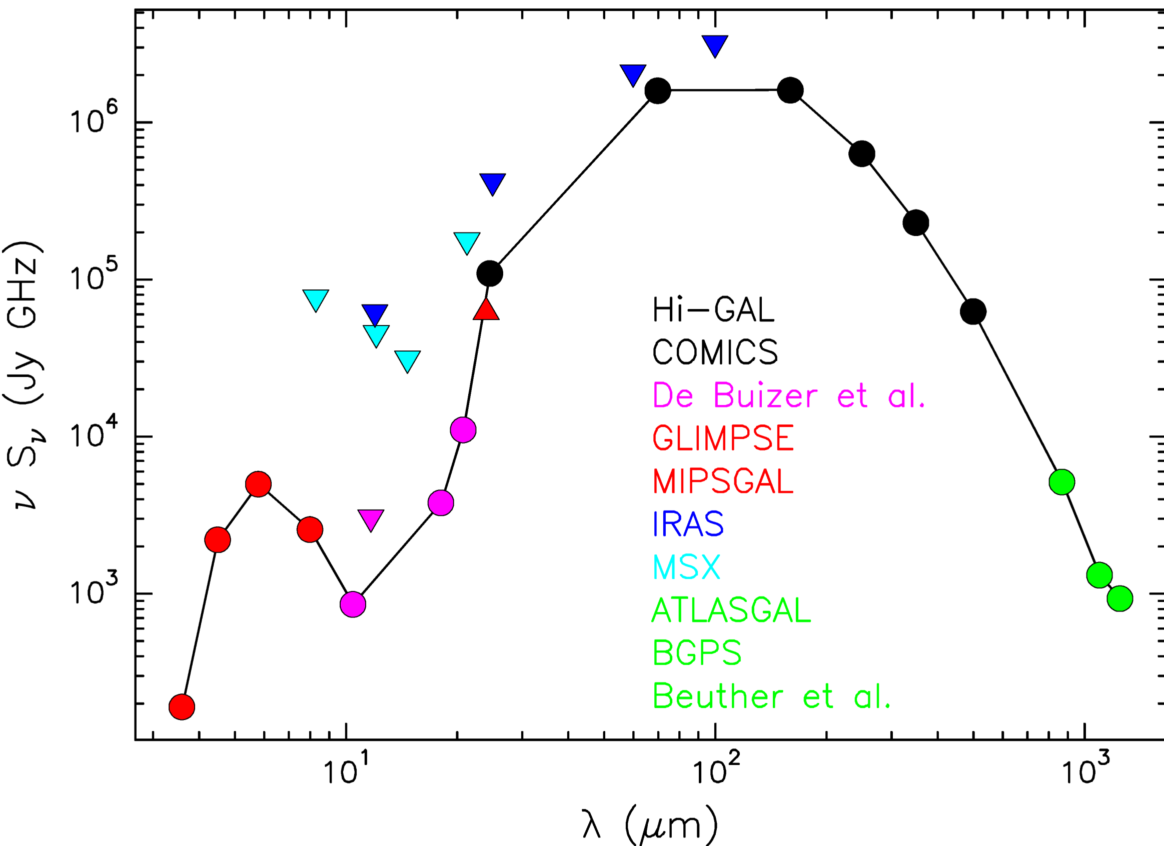
The most detailed picture of a well-ordered disk/outflow system in a massive YSO

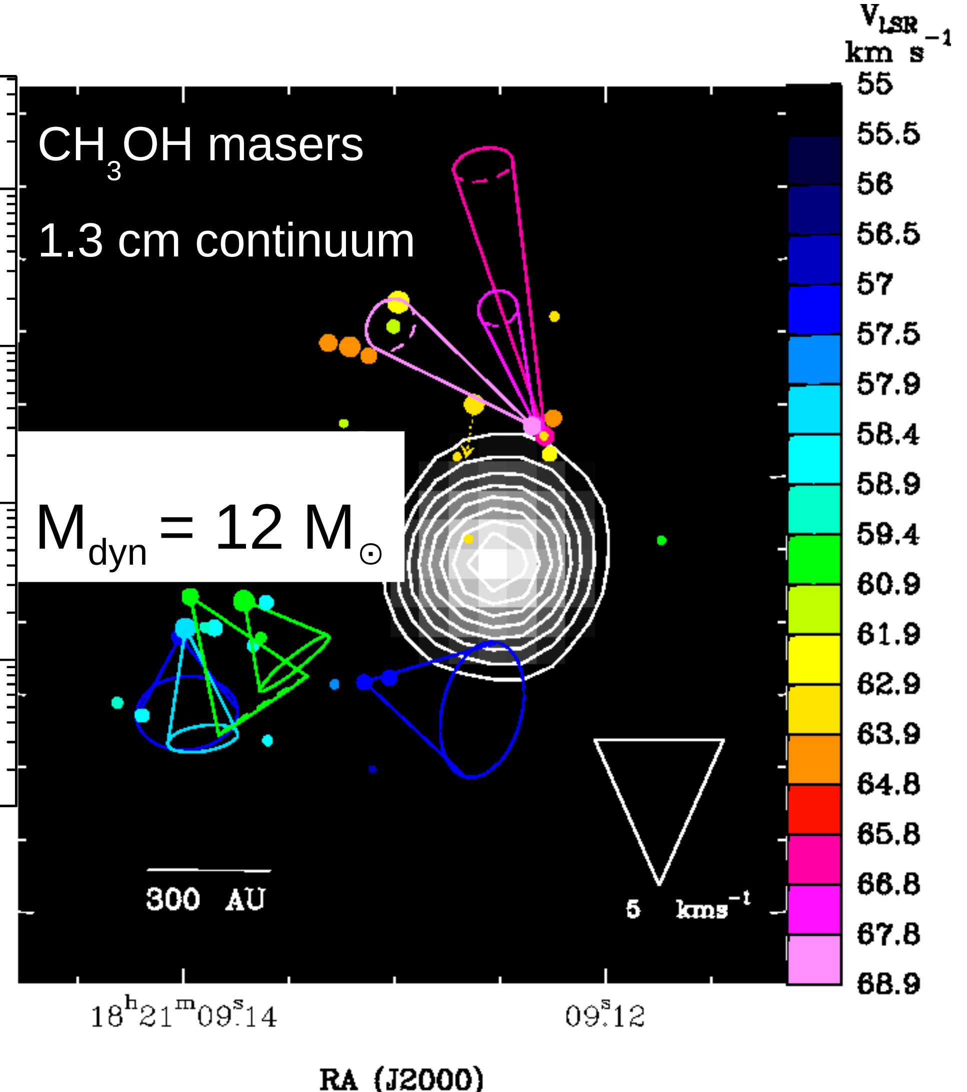
Palla & Stahler (1990)

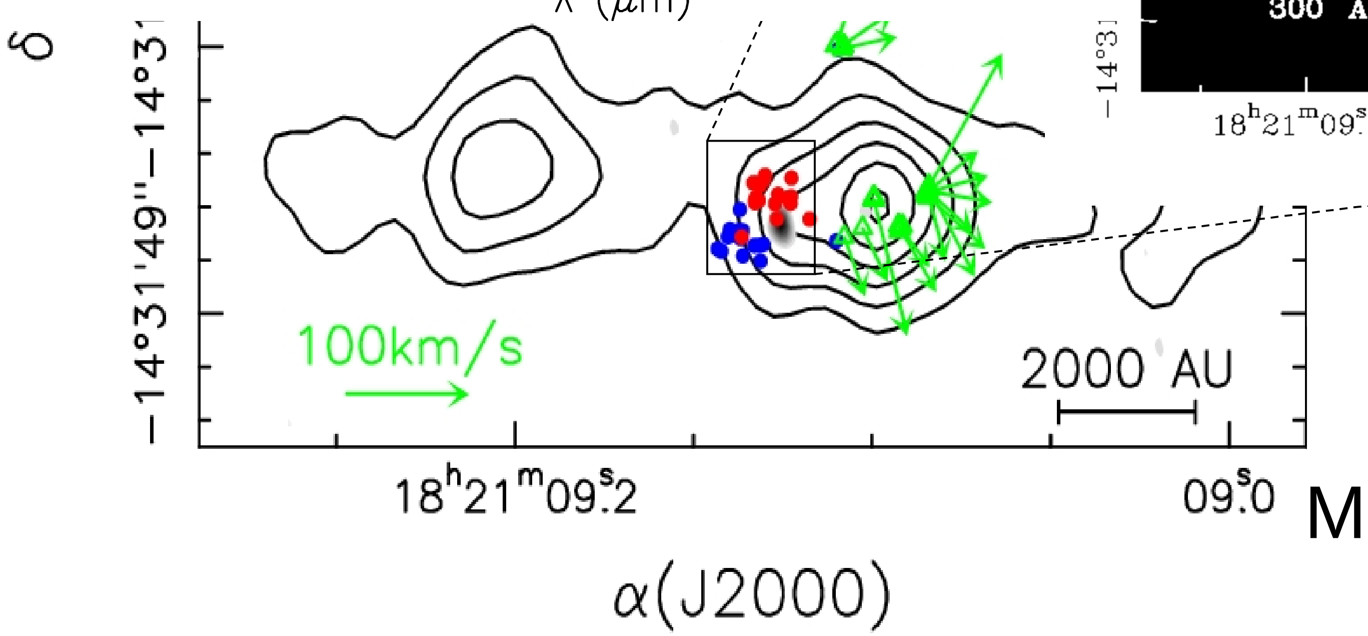
$dM/dt=10^{-5}\ M_o/yr$



$L_{bol} \sim 10^4 L_\odot$ 13 $M_\odot$



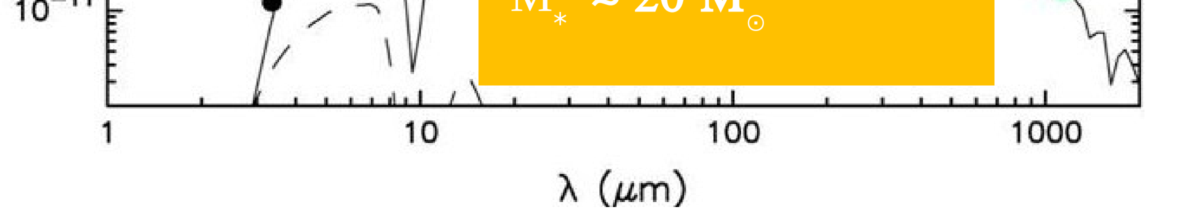


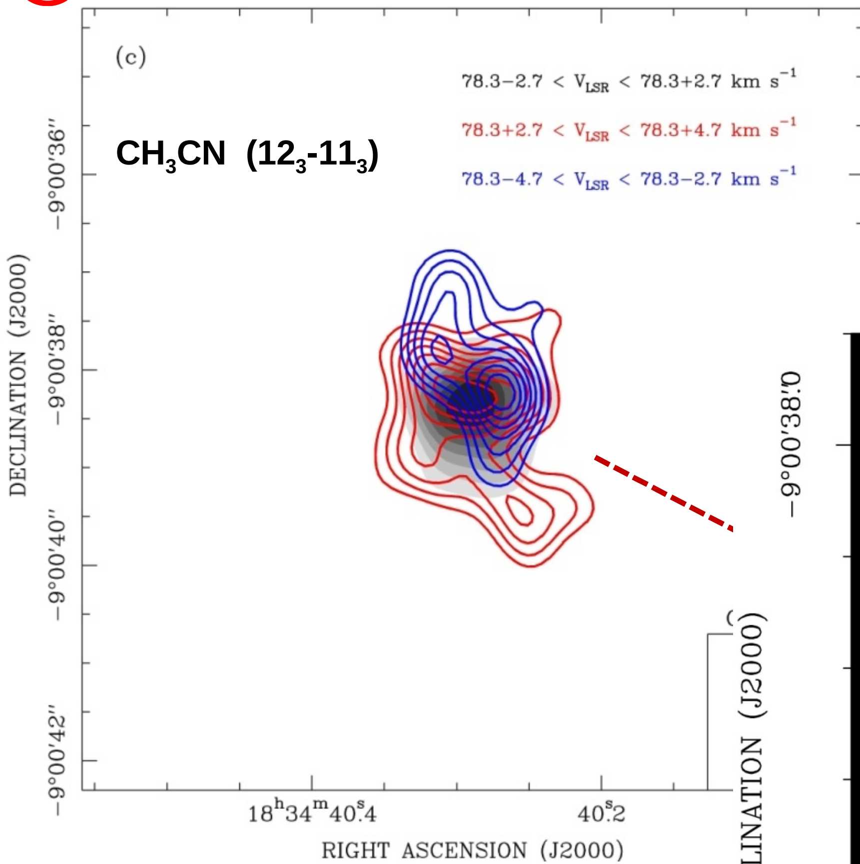


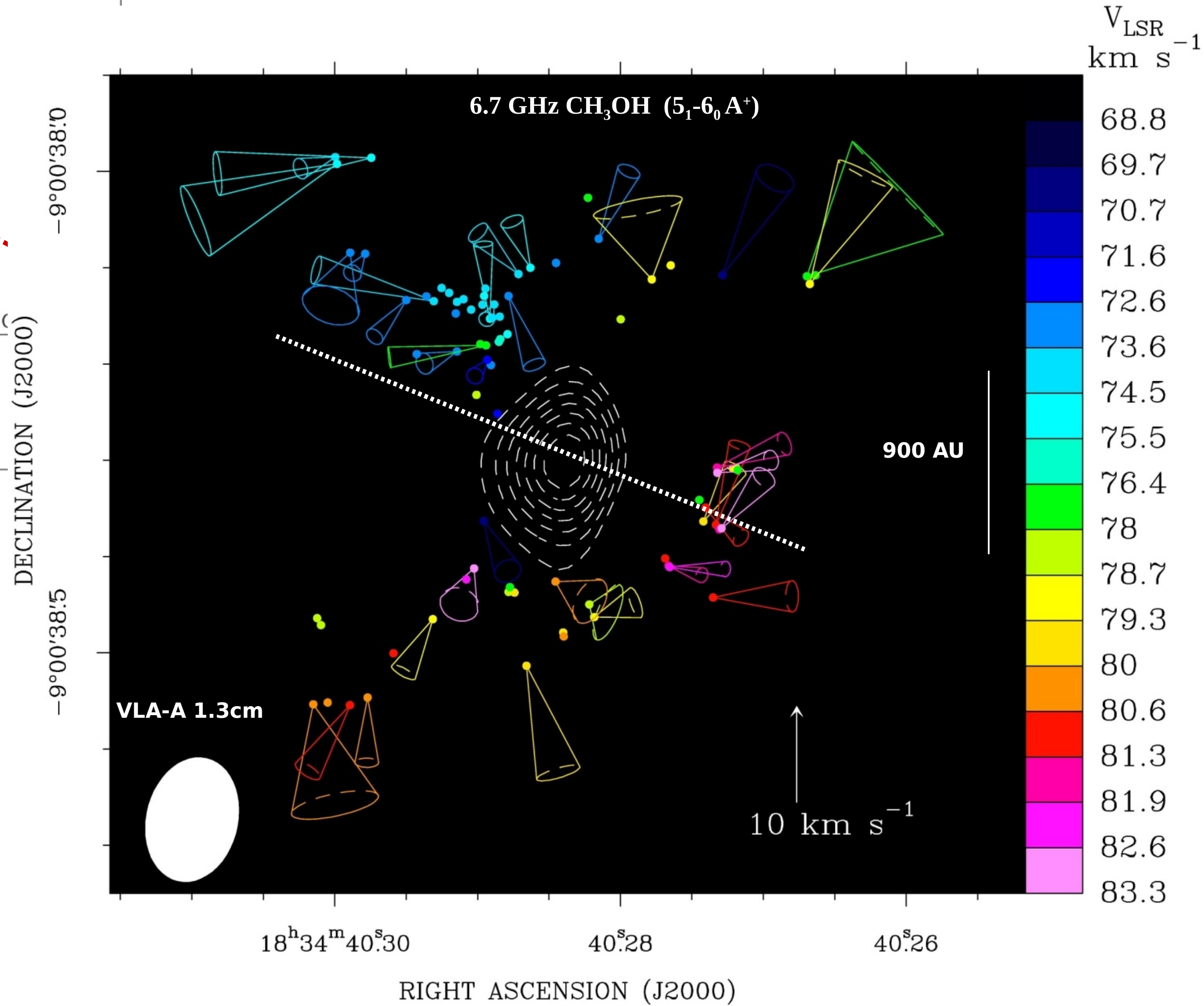
Sanna et al. (2010)

Moscadelli et al. (2013)

Rotation & Expansion @ 10^3 AU from YSO





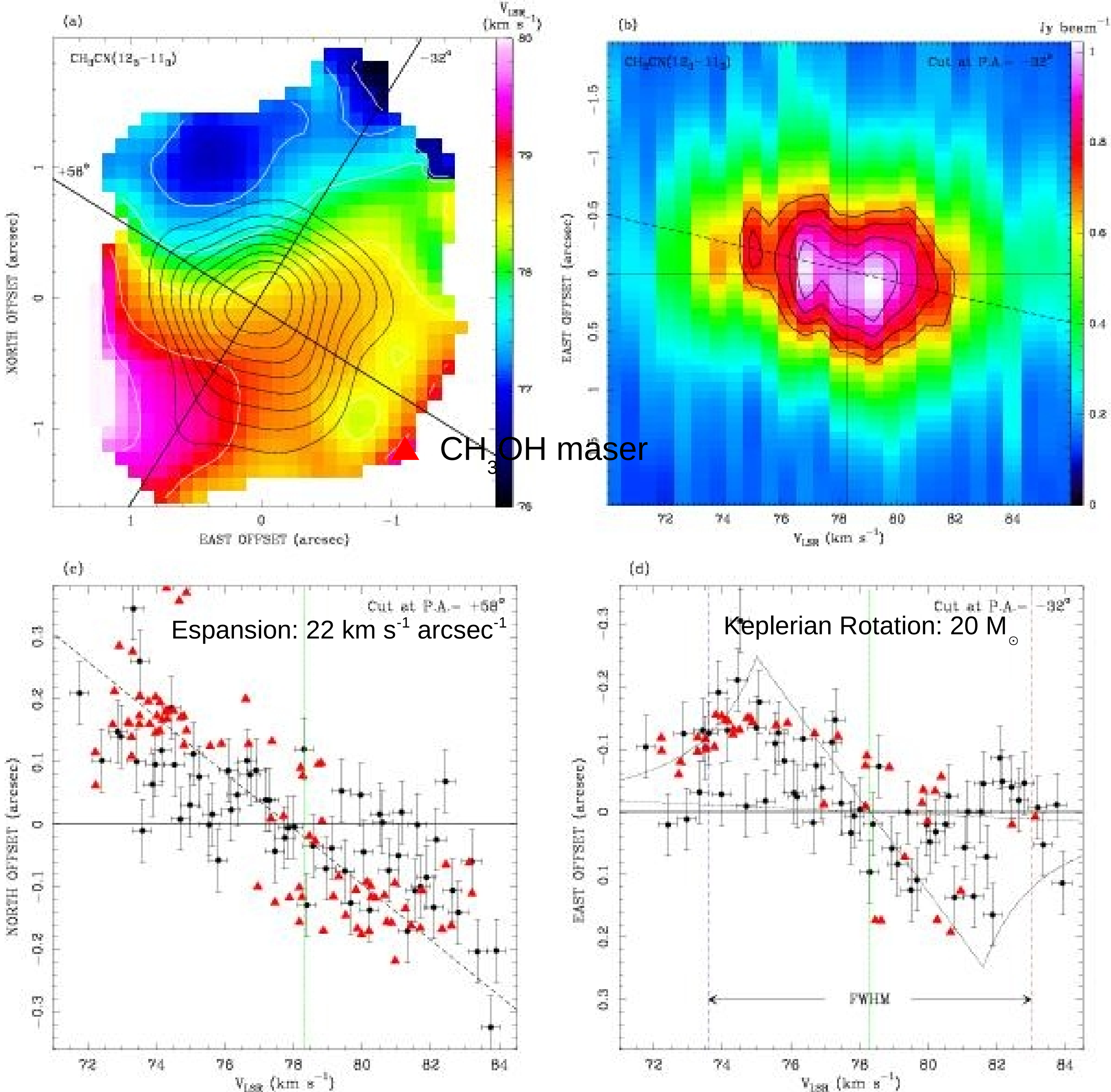


- **Dynamical mass** ($R \cdot V^2_{rot}/G$)

From CH_3OH masers: $M_{dyn} \sim 20\ M_\odot$

From CH_3CN th.lines: $M_{dyn} \sim 30\ M_\odot$

Sanna et al. 2010, A&A, 517, A78
Sanna et al. 2014, A&A, 565, A34



(a)
CH3CN(12_3−11_3)
V_LSR (km s^-1)
−32°
+58°
CH3OH maser
NORTH OFFSET (arcsec)
EAST OFFSET (arcsec)
(b)
CH3CN(12_3−11_3)
Cut at P.A.= −32°
Jy beam^-1
EAST OFFSET (arcsec)
V_LSR (km s^-1)
(c)
Cut at P.A.= +58°
Espansion: 22 km s^-1 arcsec^-1
NORTH OFFSET (arcsec)
V_LSR (km s^-1)
(d)
Cut at P.A.= −32°
Keplerian Rotation: 20 M_⊙
EAST OFFSET (arcsec)
FWHM
V_LSR (km s^-1)