Outflow Structure on small scales in high-mass protostars

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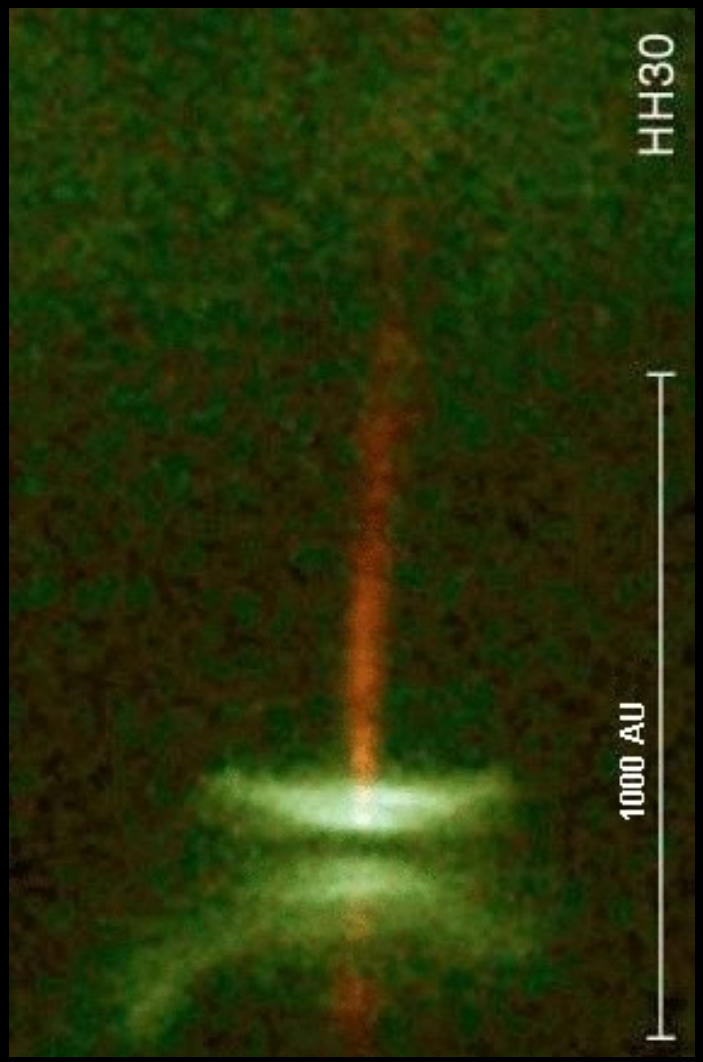
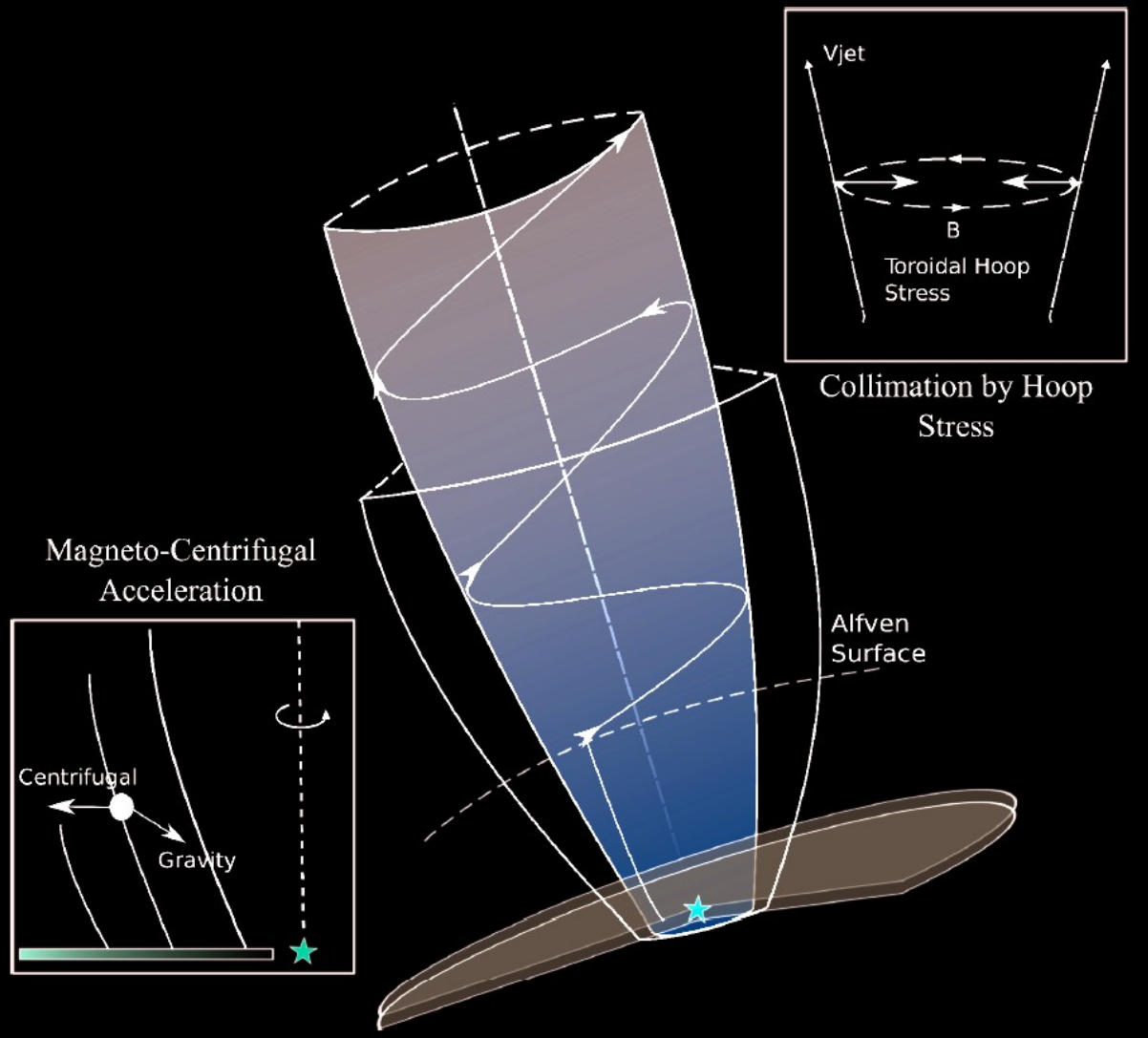
Low-mass (~1 $M_\odot$) Star Formation: Disk+Jet system

Magnetocentrifugally accelerated wind



False-color (V, R, I) deconvoled HST WFPC2:
Emission line jet, continuum reflection nebulae,
dark lane. (Burrows et al. 1996)



Adapted from
Blandford & Payne 1982

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

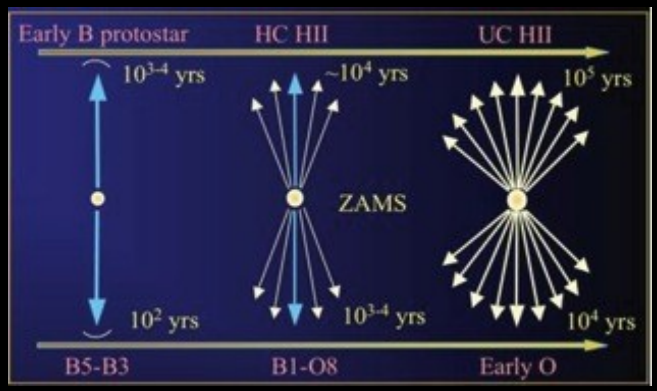
From Observations:

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

Observations of high-mass YSOs are challenging:

- High extinction => Optical and NIR impossible
- Formation in clusters => Confusion/crowding
- Declining IMF and Rapid evolution: Large Distances (> 1 kpc)

IRAS 05358+3543 @ 1.8 kpc

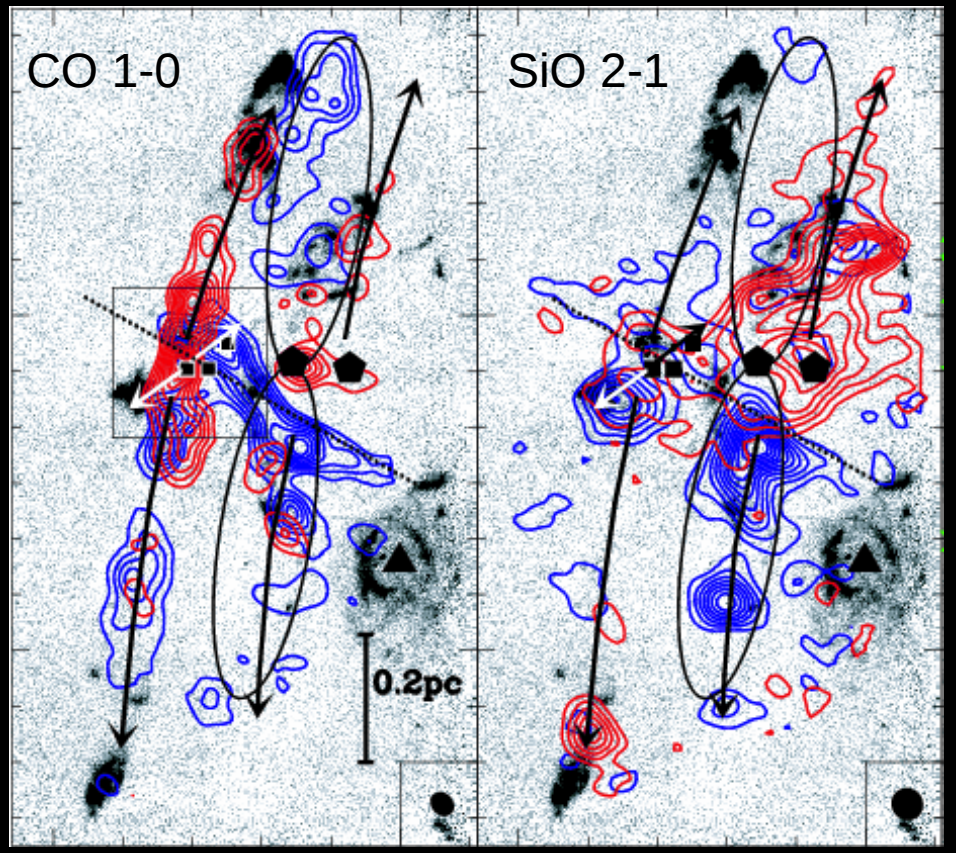
PdBI Interferometer:

CO 1-0 : 4.1 x 3.3 arcsec

SiO 2-1 : 5.8 x 5.6 arcsec

overlaid

on H_2 (2 μm) image



(Beuther et al. 2002)

To resolve single high-mass YSOs, we use:

1) VLBI of Water Masers (beam ~ 1 mas)

2) JVLA multi-frequency observations of radio continuum (beam ~ 0.1" , rms ~ 10 μJy)

Molecular masers as diagnostic tools

W75N(B)

(1) Epoch	(2) a (mas)	(3) b (mas)	(4) PA (°)	(5) e^a	(6) Expansion Velocity^b (mas yr^{-1})	(km s^{-1})
1999.25	71 ± 1^c	64 ± 1^c	5 ± 3^c	0.43 ± 0.01		
2005.89	97 ± 3	93 ± 2	15 ± 45	0.28 ± 0.02	3.9 ± 0.5	24 ± 3
2007.41^c	111 ± 1	68 ± 1	45 ± 1	0.79 ± 0.02	9.2 ± 2.0	57 ± 12
2012.54	136 ± 4	73 ± 2	45 ± 2	0.84 ± 0.05	4.9 ± 0.8	30 ± 5
					4.9 ± 0.3^d	30 ± 2^d

1999.25 – VLBA: Torrelles et al. 2003

2005.89 – VLBA: Surcis et al. 2011

2007.41 – VERA: Kim et al. 2013

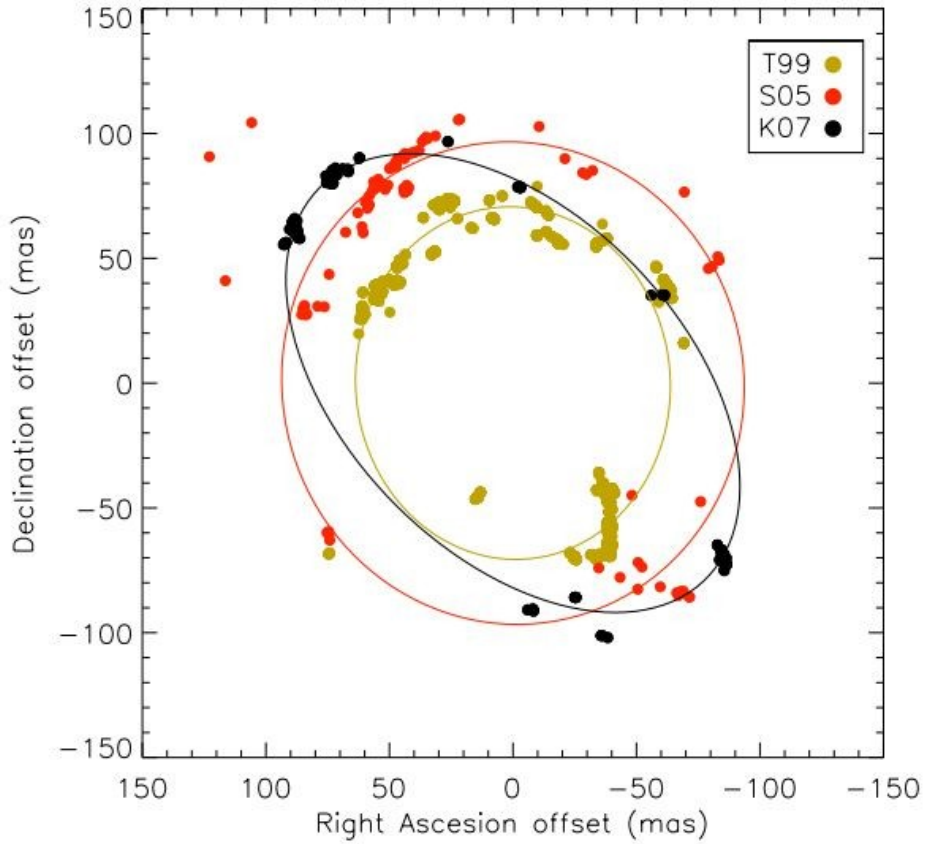


Figure 5. Elliptical fits for the H_2O masers in VLA 2 observed with VLBI in epochs 1999.3 (T99), 2005.9 (S05), and 2007.2 (K07) by Torrelles et al. (2003), Surcis et al. (2011), and this work, respectively.

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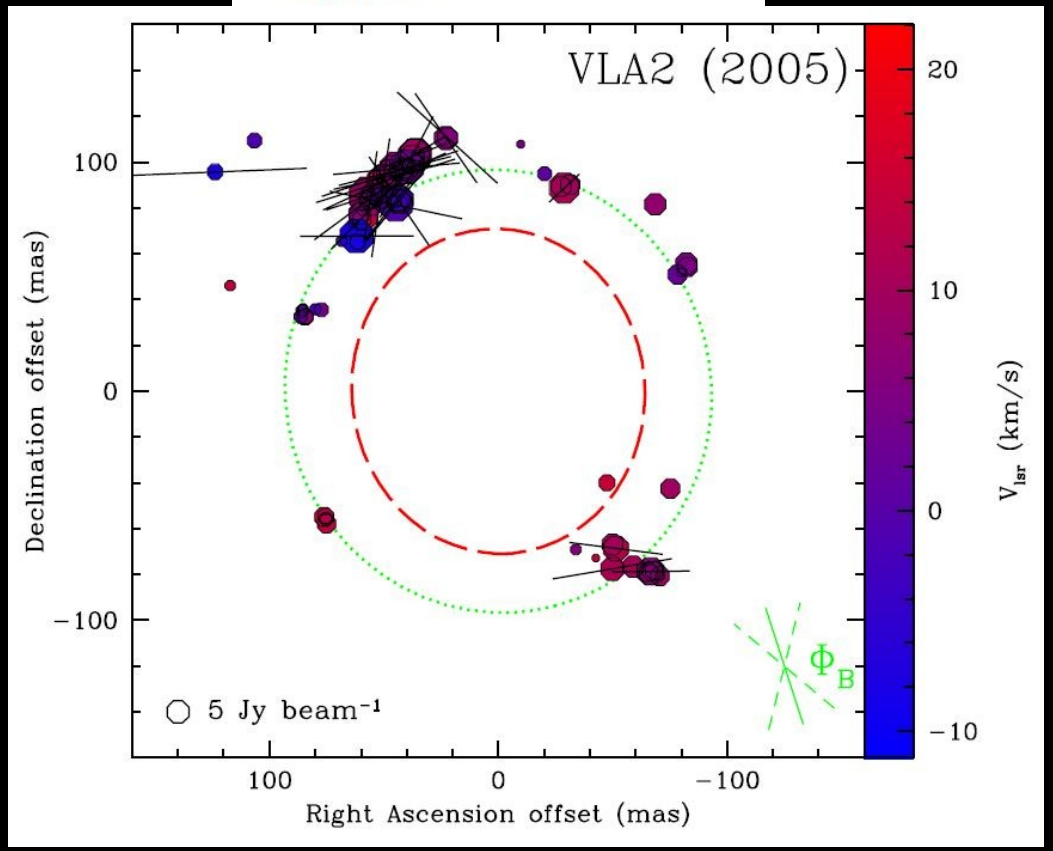
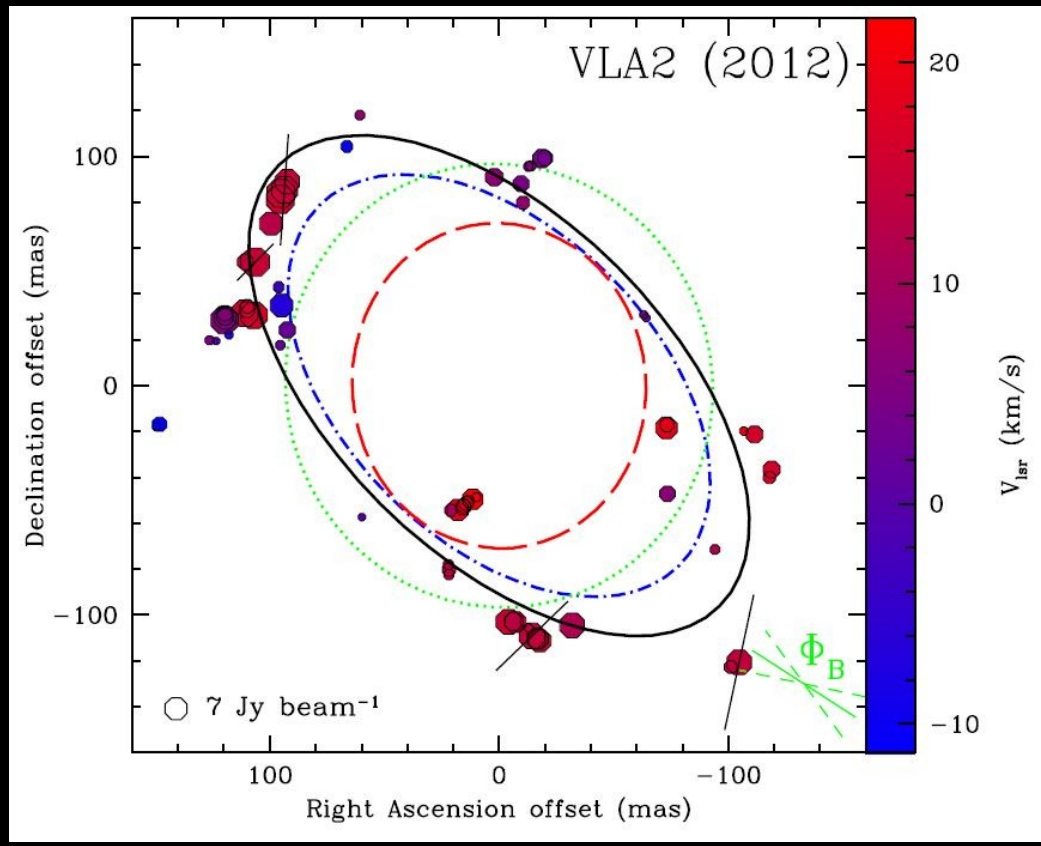
$\overline{|B_\parallel|}^{2005.89}_{\rm VLA2} = 345$ mG

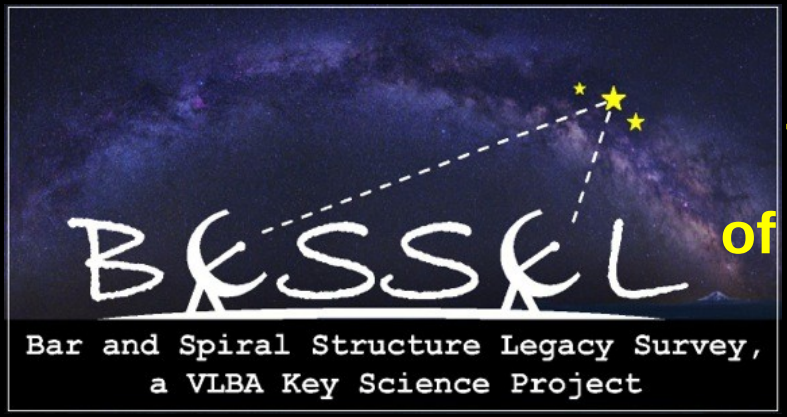


$\overline{|B_\parallel|}^{2012.54}_{\rm VLA2} = 128$ mG



Surcis et al. 2014, A&A, 565, L8

Target Sample from the BeSSeL Survey



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

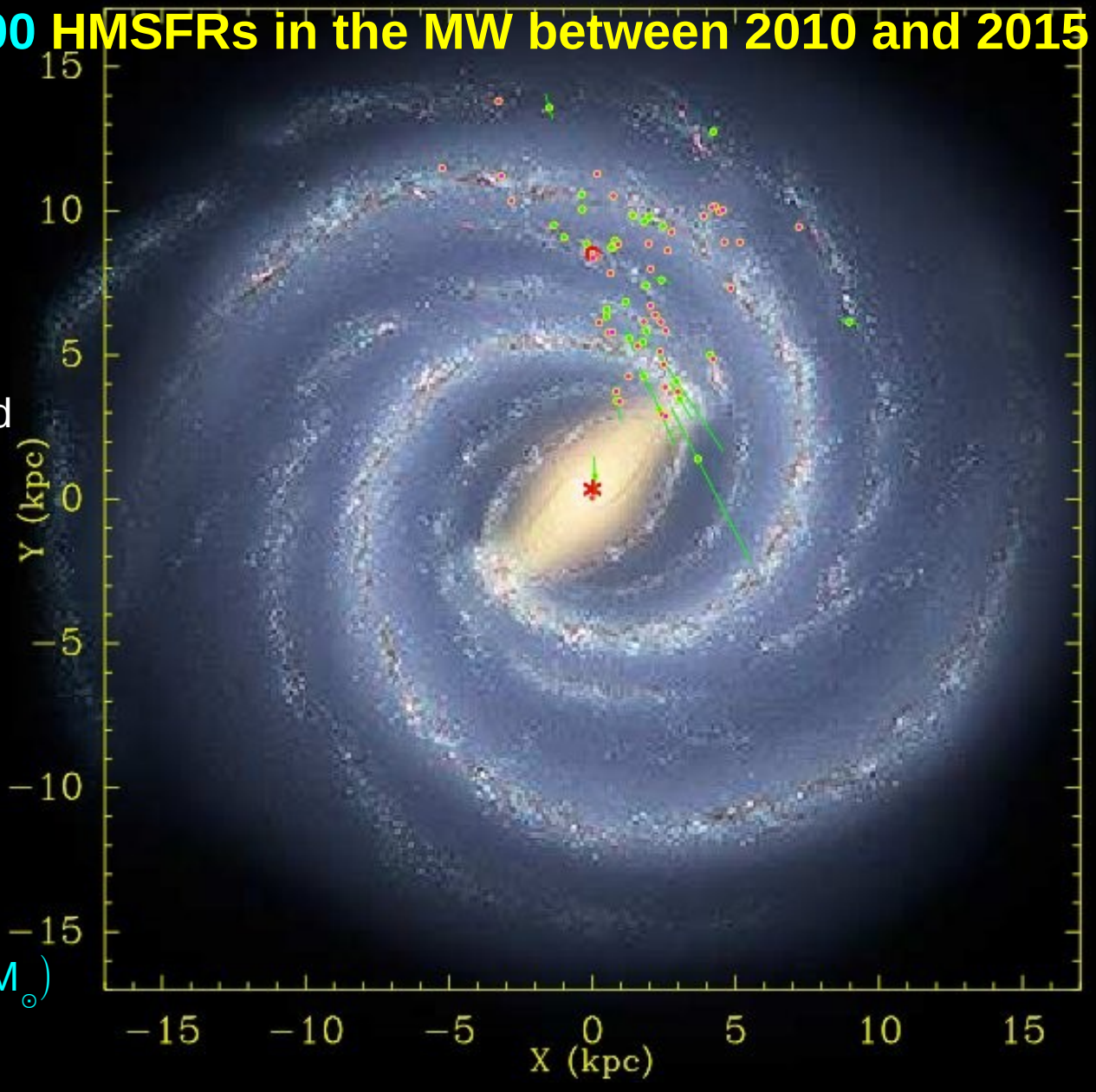
Out of the ~100 water masers observed within mid-2013 selected 41 sources:

1) Many (> 10), intense (> 1 Jy) spots

2) Hi-GAL L_{bol} implying ZAMS B3–O7

3) radio-quiet in previous surveys or compact (< 1") and weak (< 50 mJy)

4) Sources closer than 9 kpc (sensitive to radio emission of $M_{\star} > 7\ M_{\odot}$)



Continuum multi-frequency JVLA Observations

A-array at 6 GHz (beam ~ 0.4") and 13 GHz (beam ~ 0.2")

B-array at 22 GHz: beam ~ 0.4" (not to resolve the emission and optimum for spectral index)

Survey rms ~ 10 μJy (> 10 times better than previous surveys !) at each observing frequency

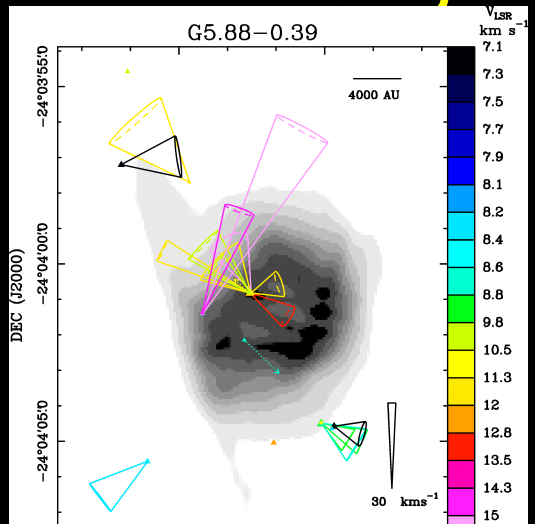
At 6 and 22 GHz, methanol and water masers are also observed (ΔV = 45, 13 → 0.2 km s^{-1})

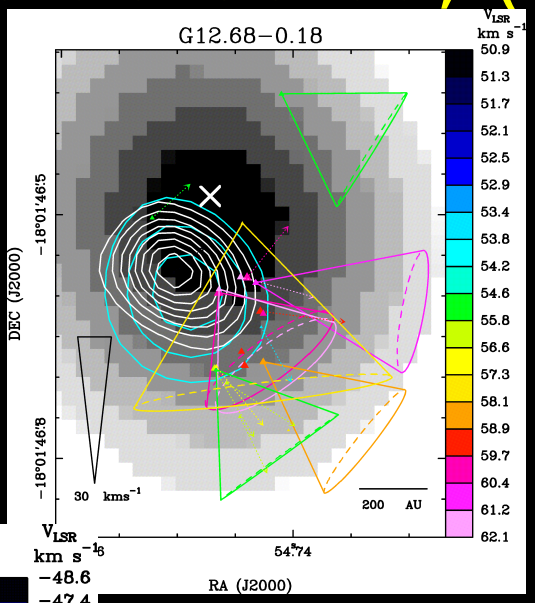
Status of the Observations

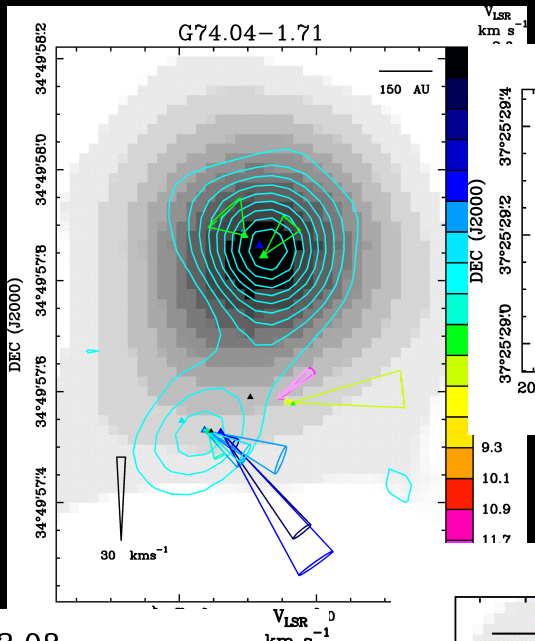
14 sources observed between October 2012 – January 2013

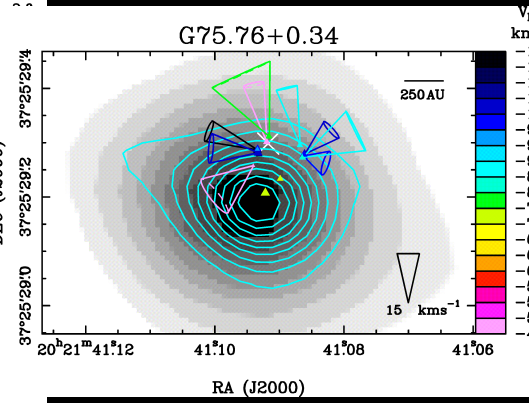
27 sources observed between March 2014 – May 2014

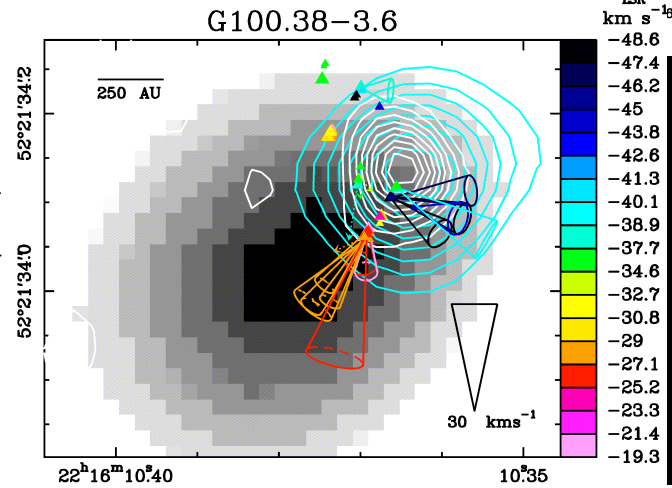
All targets detected, (non-thermal ?) jets

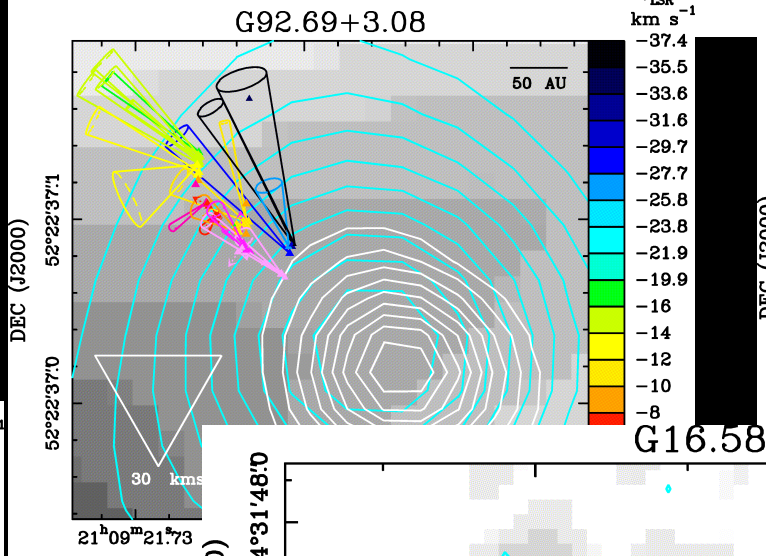


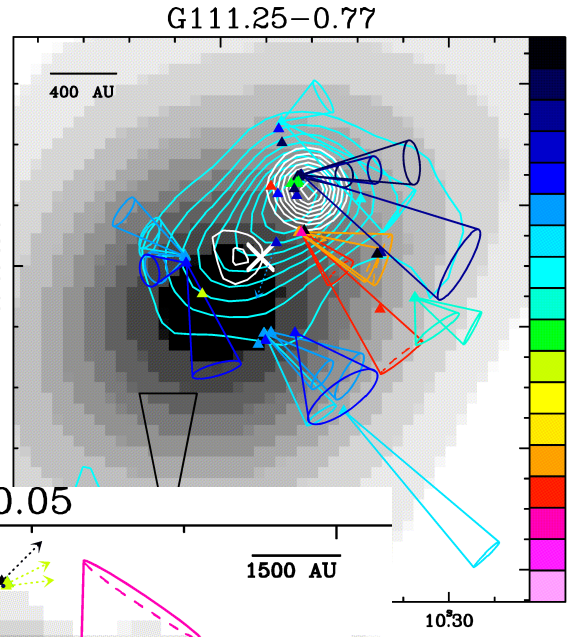


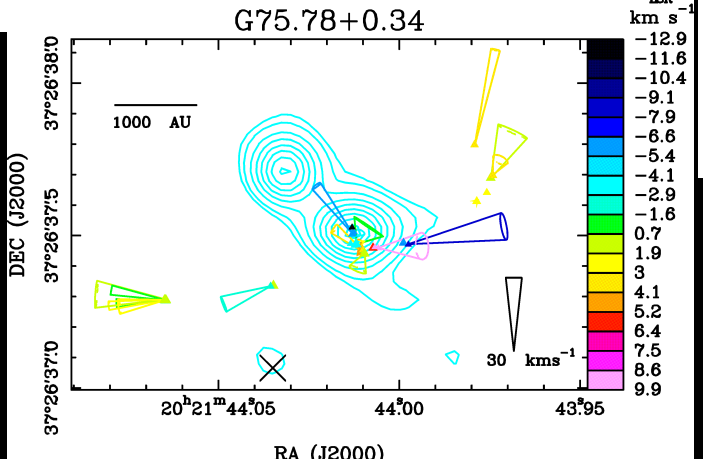


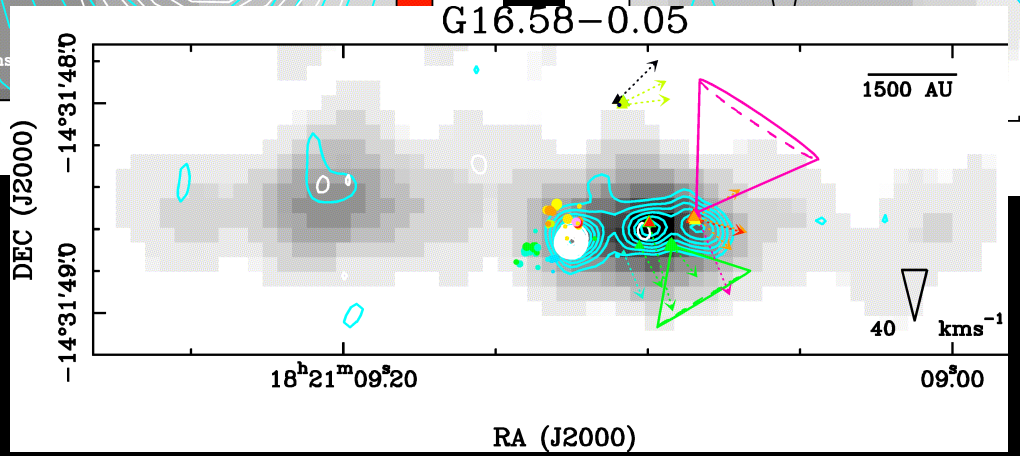






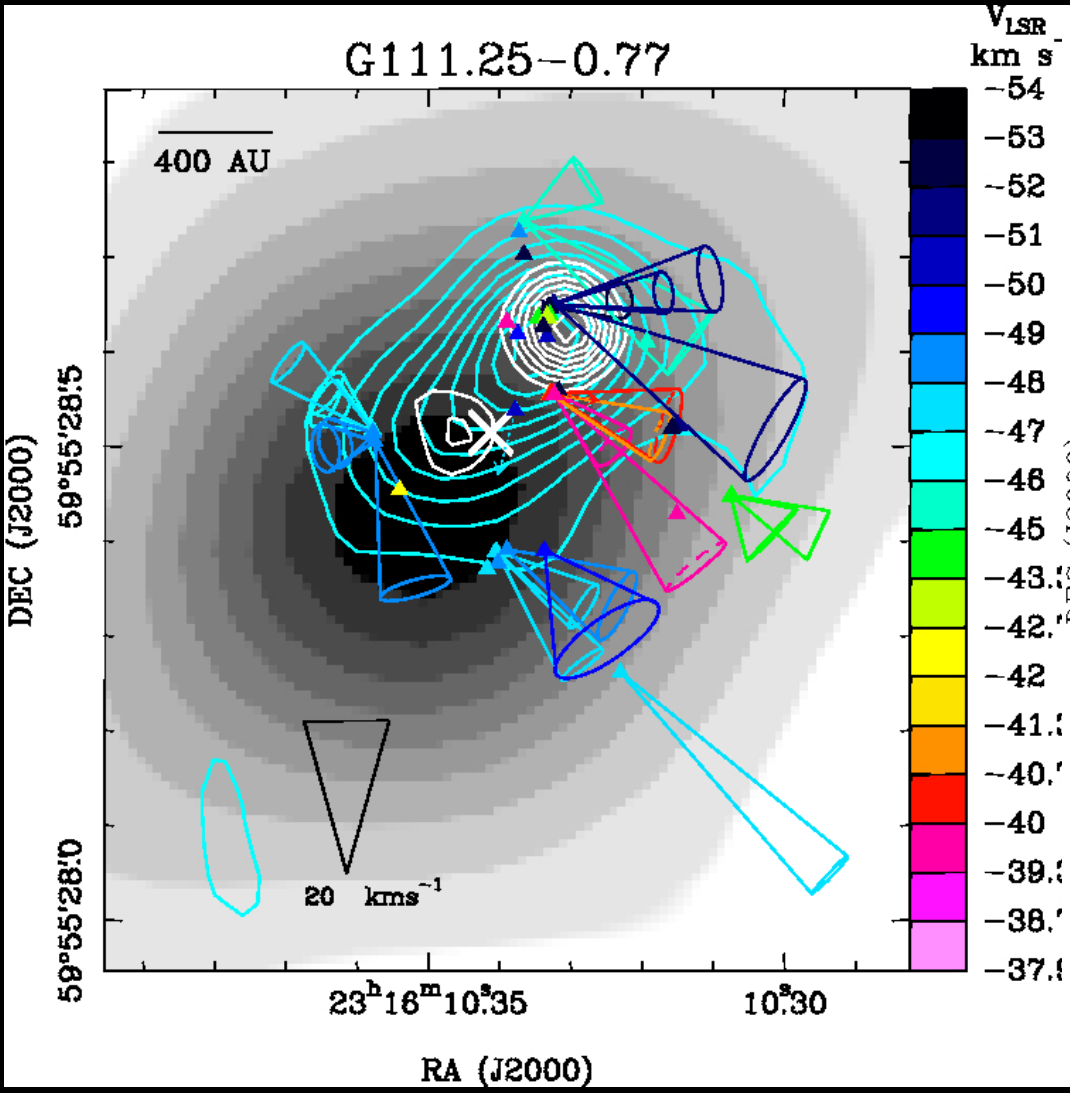


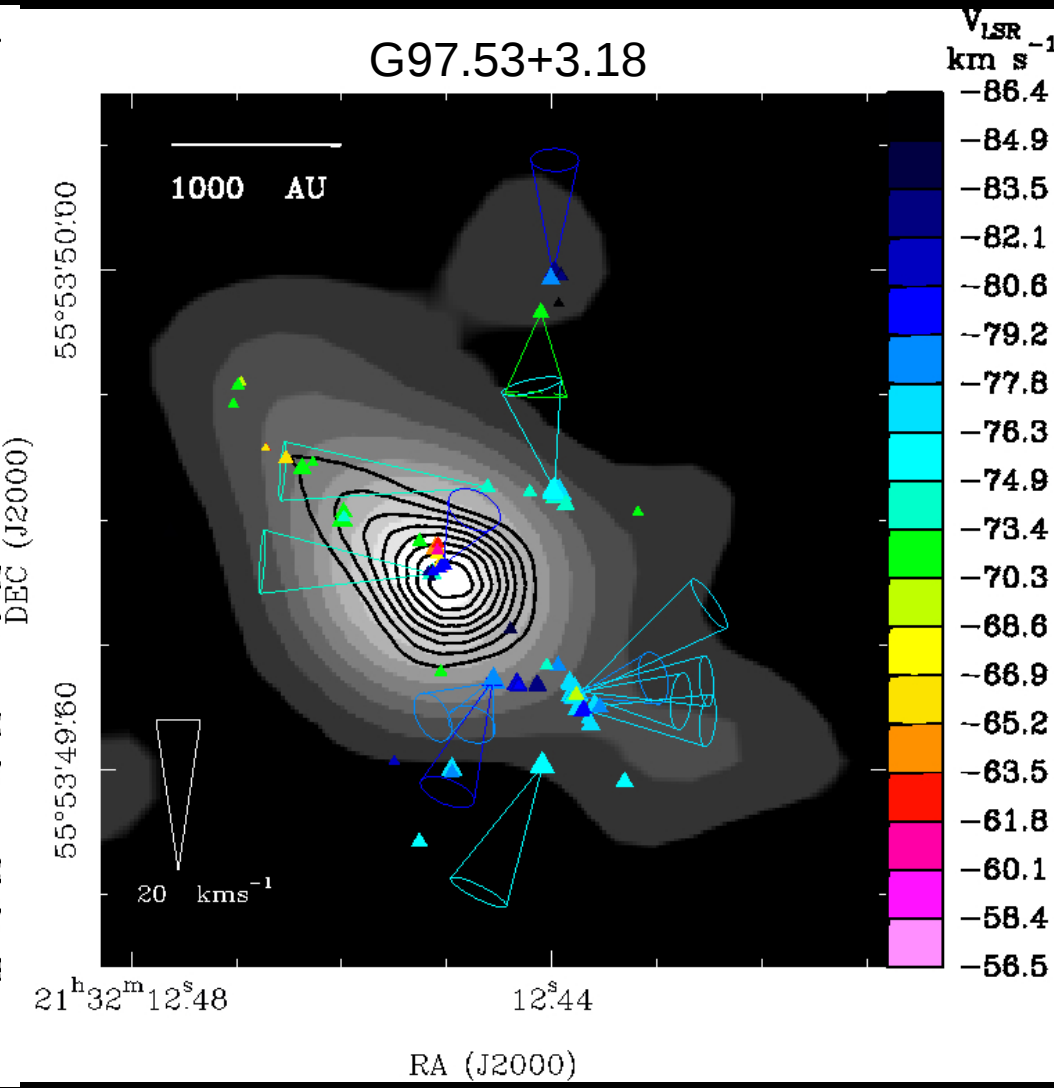


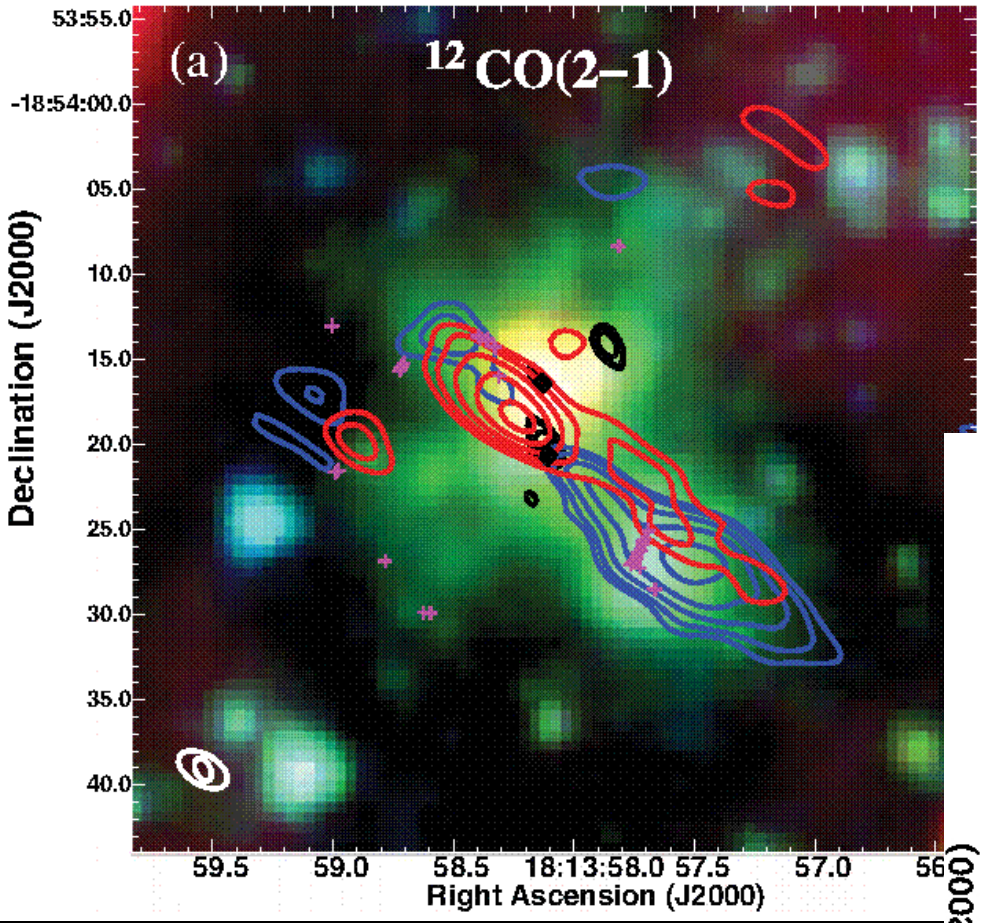


6 , 13 , 22 GHz

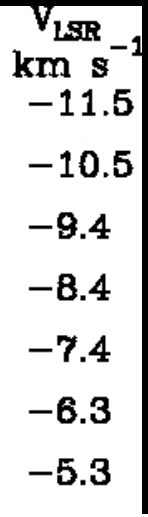
13 , 22 GHz







Cyganowski et al. 2011, ApJ, 729, 124



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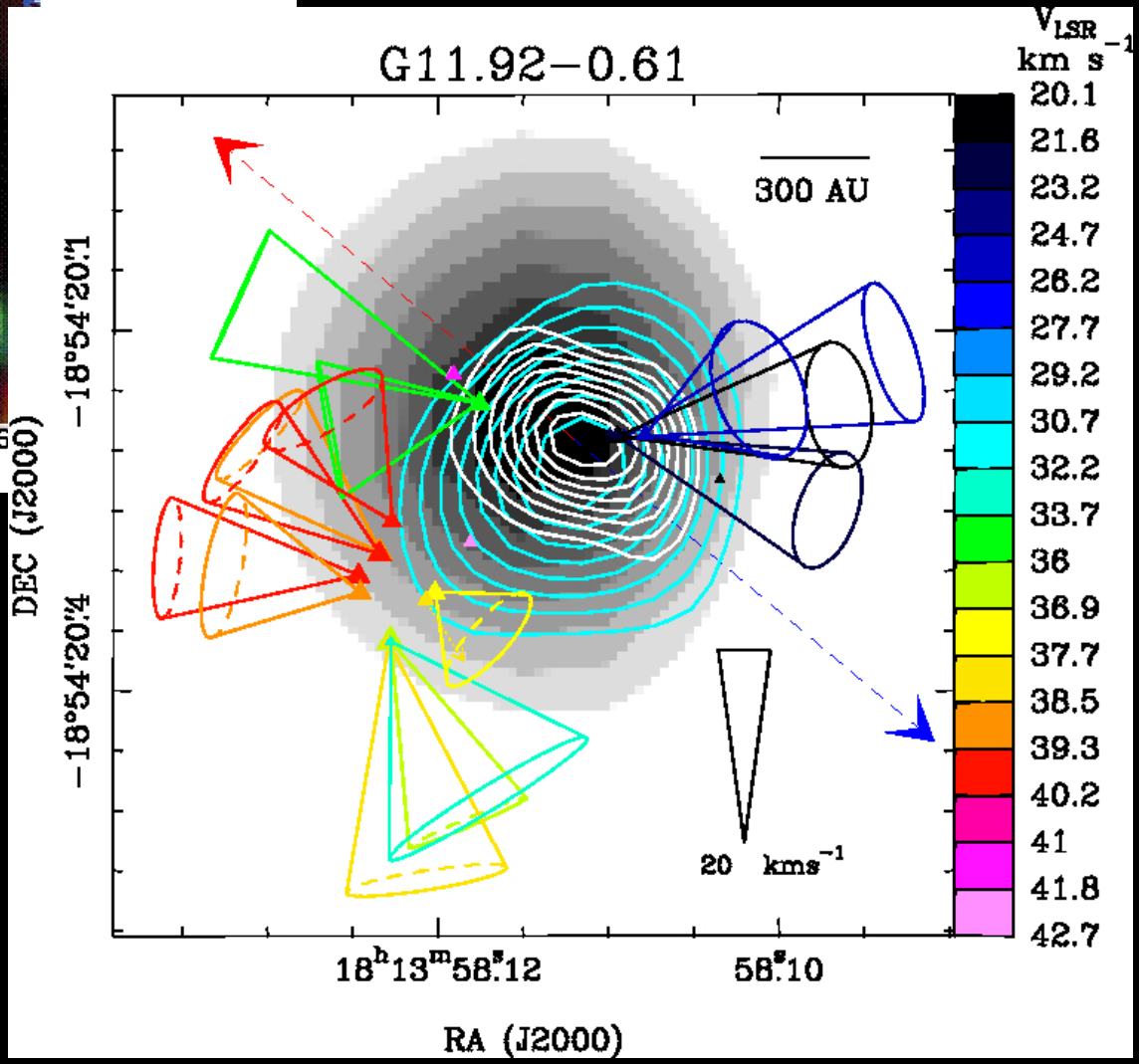
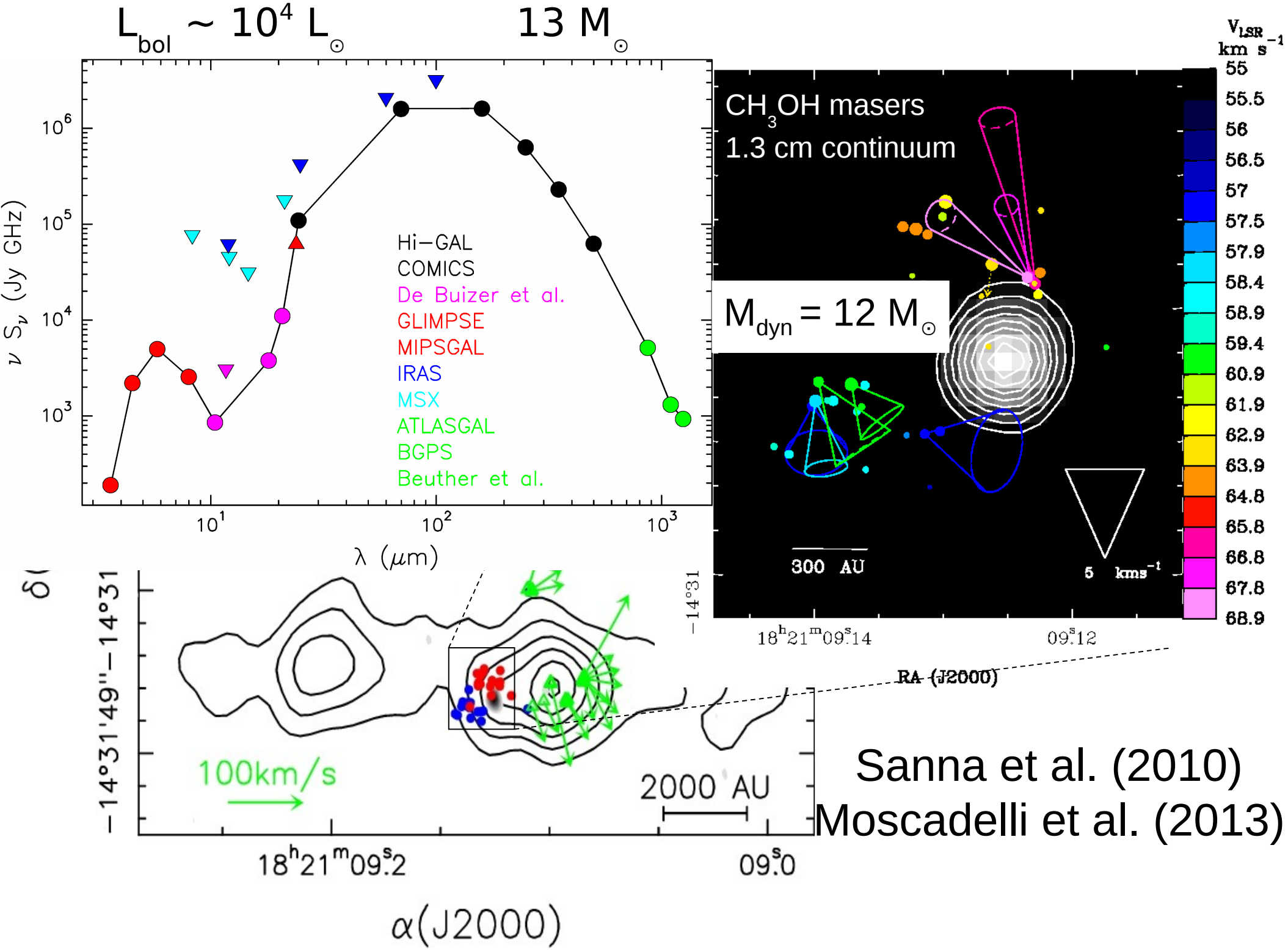




Sanna et al. (2010)
Moscadelli et al. (2013)

Future Work: Complementing Data

Large VLBI (EVN) Project to measure:

6.7 GHz CH_3OH and 22 GHz H_2O Polarization → B Field at Radii of ~100 AU

Proper Motions of the 6.7 GHz CH_3OH Masers → Envelope/Disk Kinematics

NIR and MIR (Large-Class Telescopes) Observations of less-extincted Objects:

Continuum → (sub)arcsecond outflow cavity

NIR H_2 and [FeII] l structure

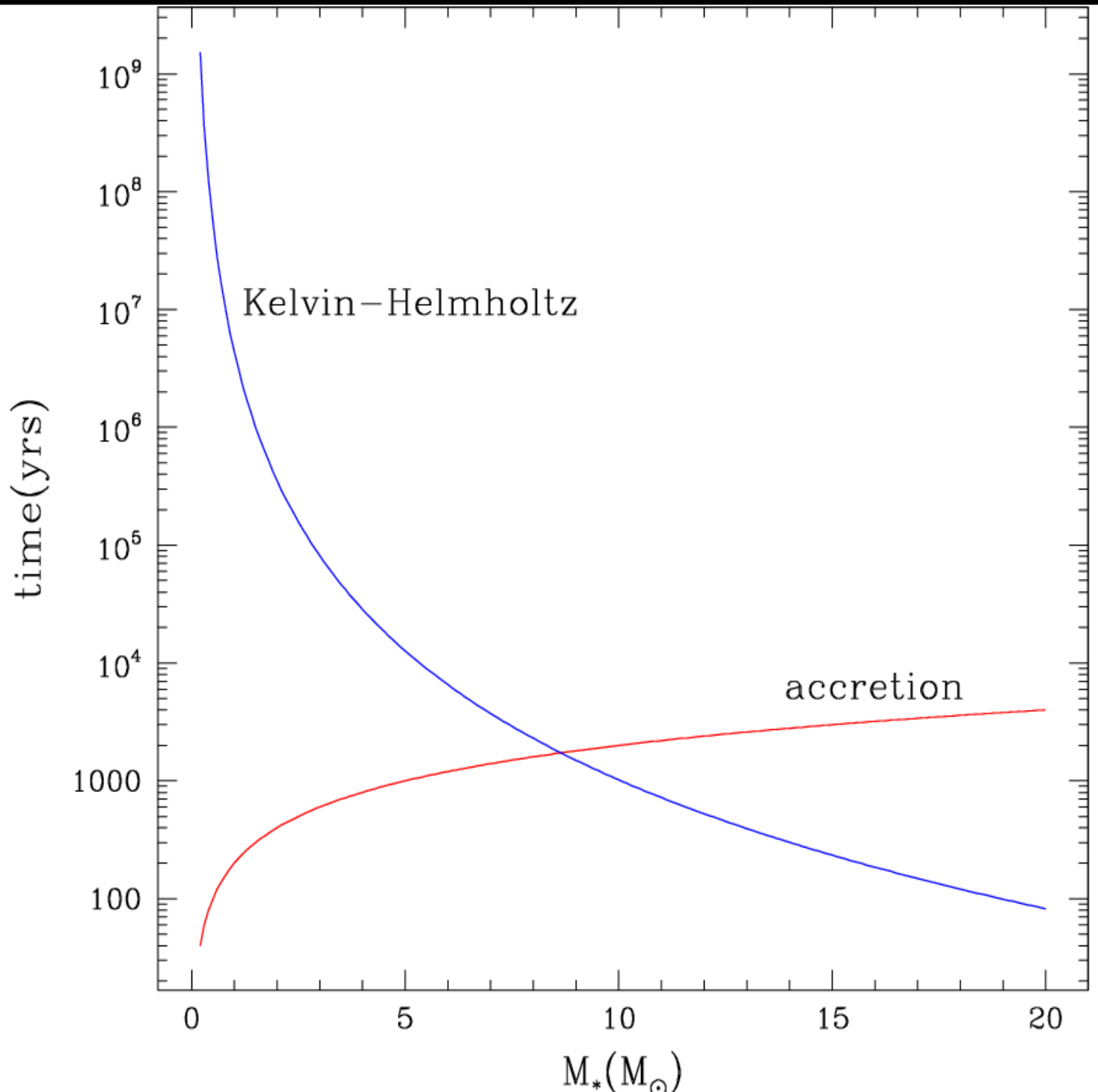
mm Interferometers (ALMA, SMA, PdBI) Observations of thermal tracers:

^{12}CO, ^{13}CO, CH_3OH and SiO Lines → Water Maser Jet ↔ Molecular Outflow

Dust Continuum and High-Density (NH_3,CH_3CN) Lines → Molecular Core

THANKS !

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



Molecular masers as diagnostic tools

Microwave Amplification by the Stimulated Emission of Radiation

Compact and bright maser spots
=> We can image them with VLBI!

Narrow spectral features (<1 km/s)
=> velocity with great accuracy

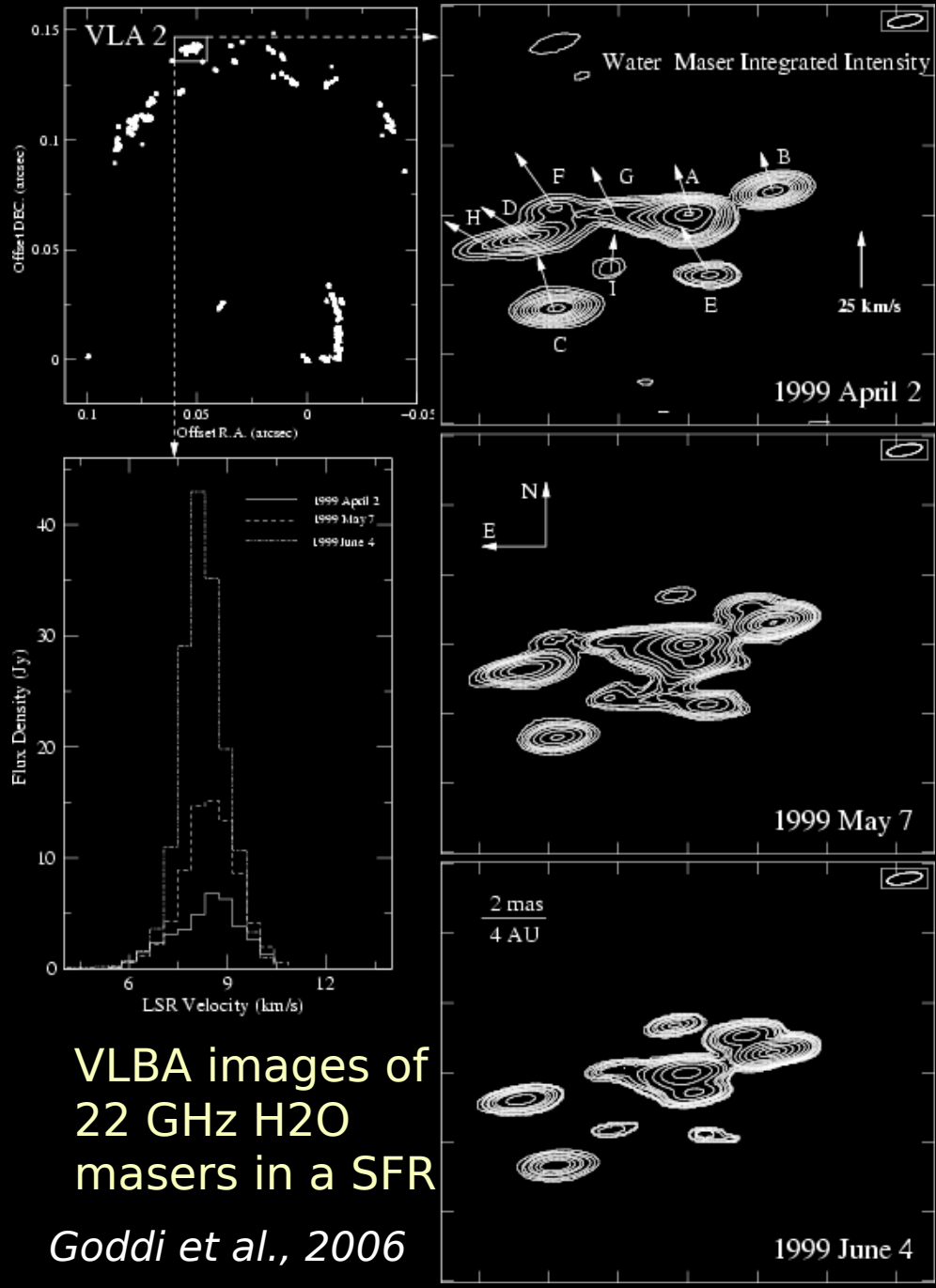
At different epochs,
spot morphology is preserved
=> We track real gas kinematics,
not illumination patterns!

Multi-epoch studies provide:

Accurate positions: gas structure
at mas *angular resolution*

proper motions + l.o.s. Velocities:
3D Gas Kinematics

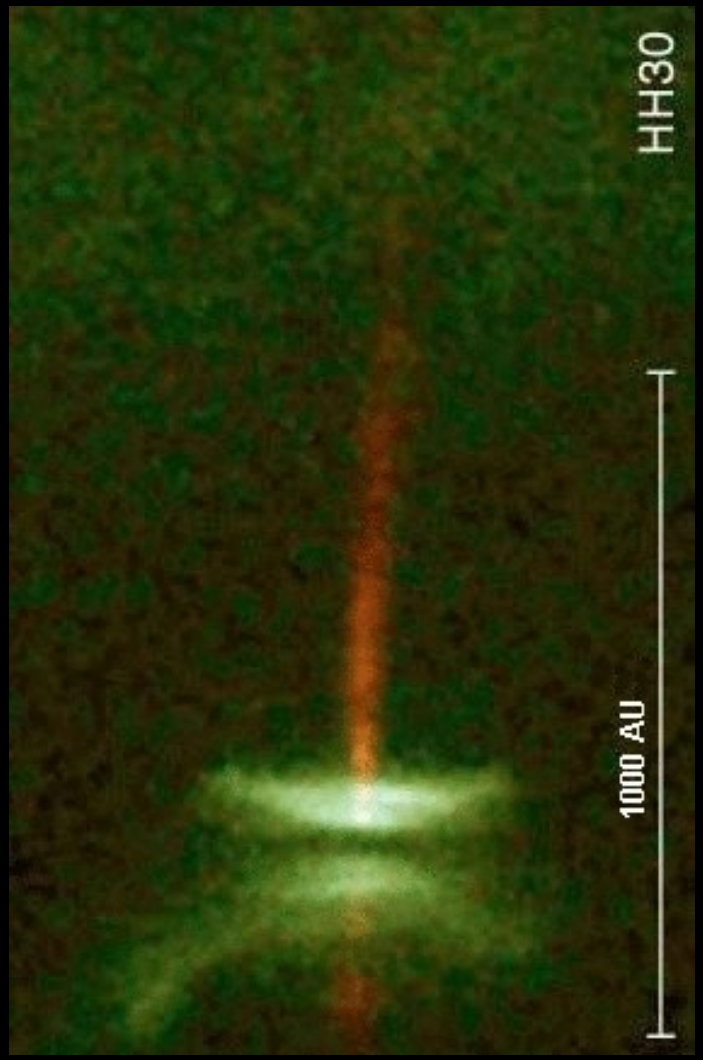
accelerations from changes in l.o.s. velocities: Gas Dynamics

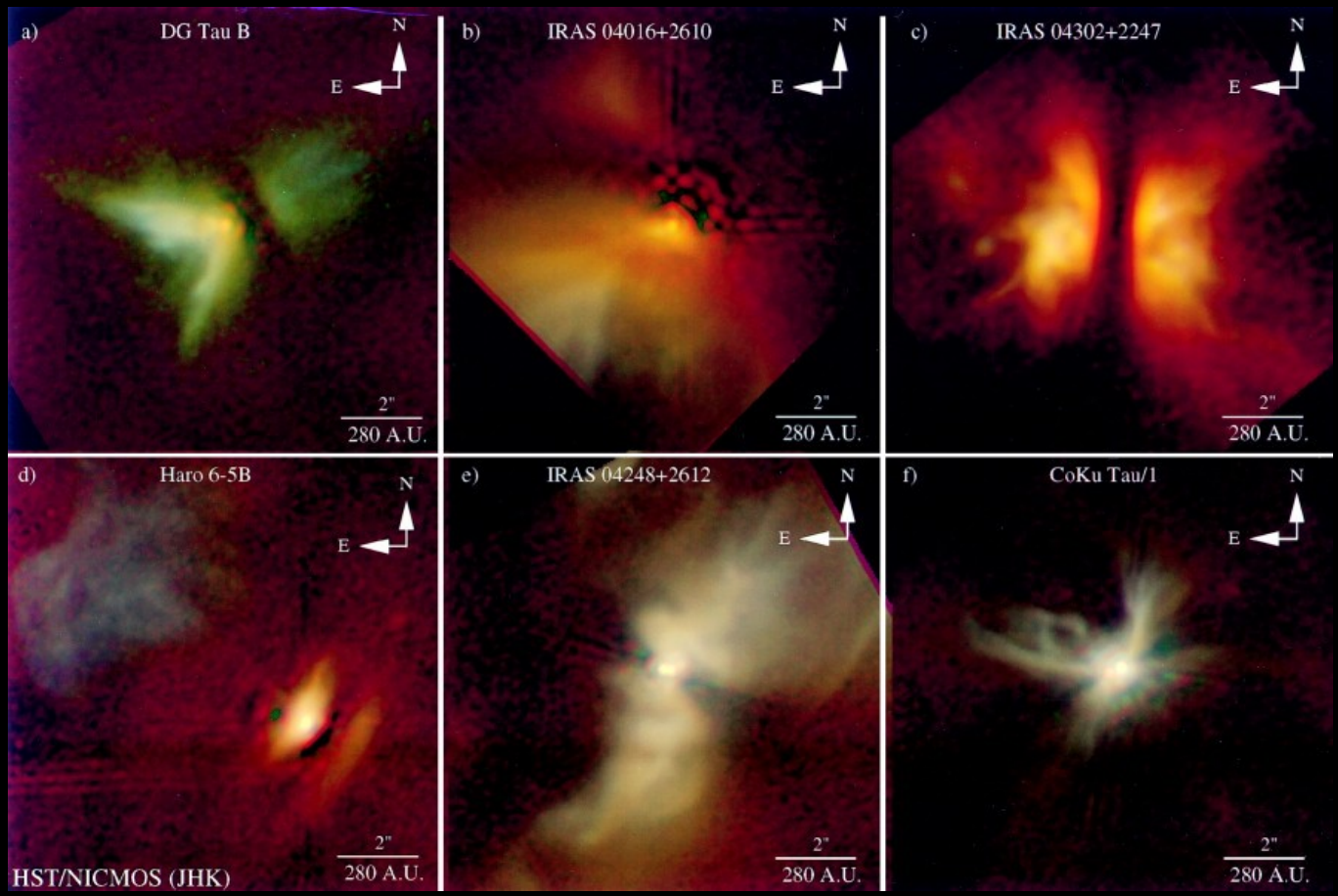


VLBA images of 22 GHz H2O masers in a SFR

Goddi et al., 2006

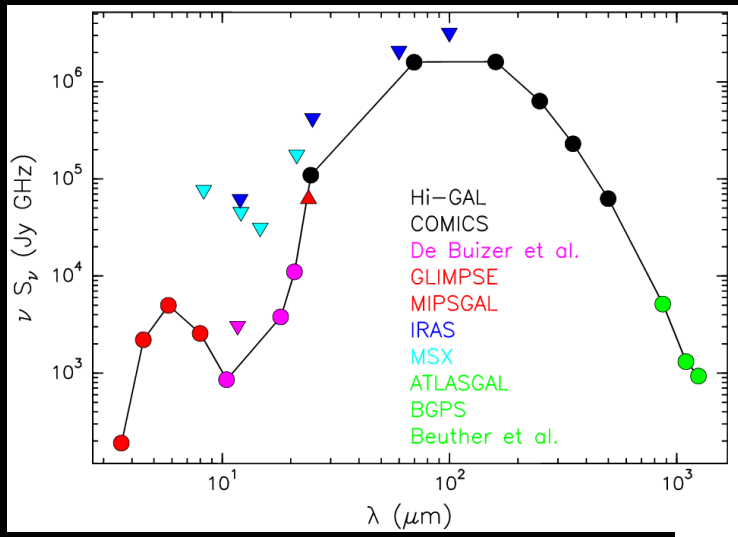
Low-mass (~1 $M_\odot$) Star Formation: Disk+Jet system





False-color NIR (1.1 - 2.1 μm) deconvoled HST/NICMOS:
optically thick circumstellar disks in silhouette against bright reflection nebulosity. (Padgett et al. 1999)

False-color (V, R, I) deconvoled HST WFPC2:
Emission line jet, continuum reflection nebulae, dark lane. (Burrows et al. 1996)



Grey-scale: 6 GHz ; cyano: 13 GHz ; white: 22 GHz

●: 6.7 GHz CH_3OH maser ; ▲: 22 GHz H_2O maser