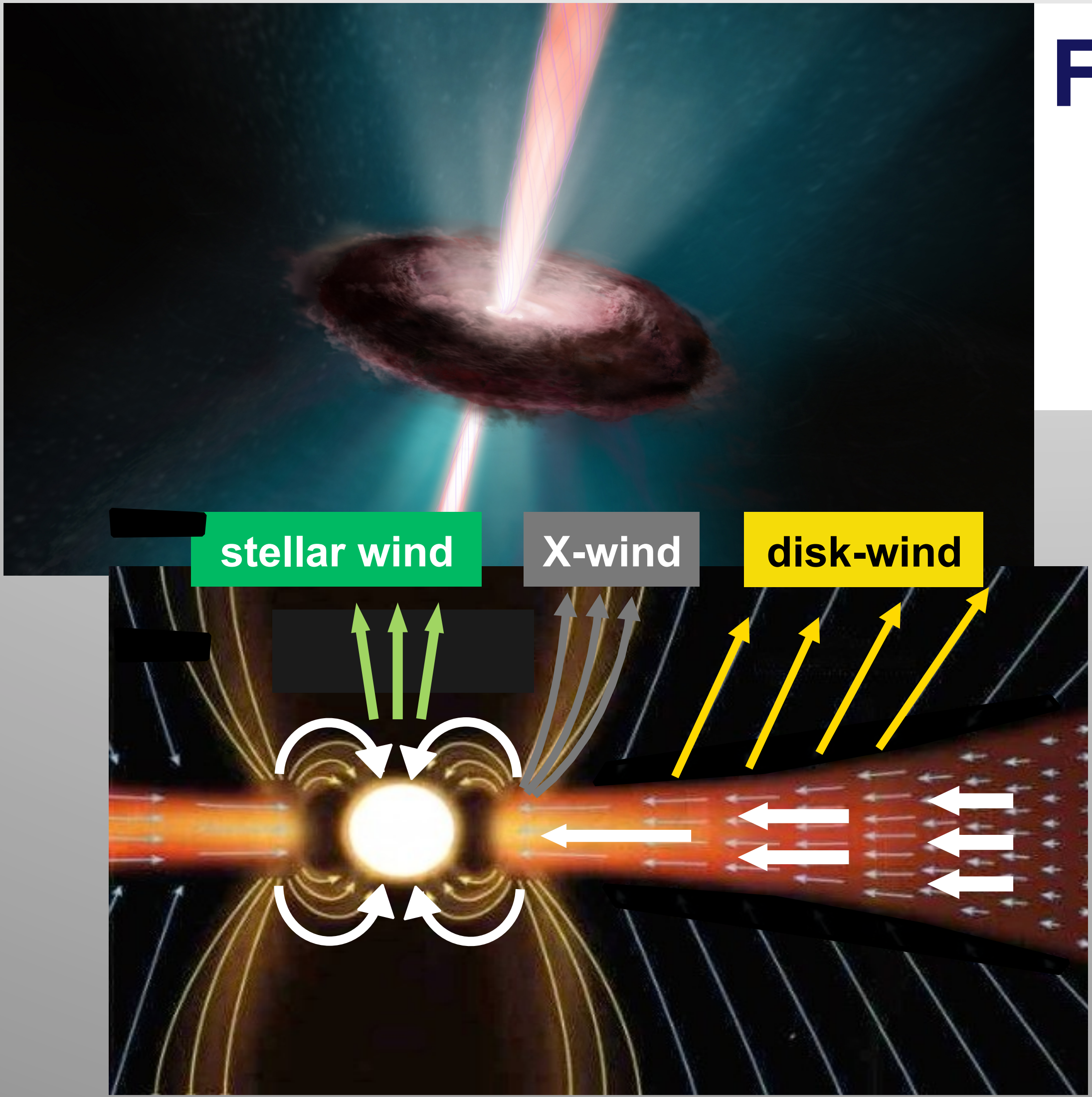
Jet – Disk interaction : a key element in star and planet formation



Francesca Bacciotti

Luca Moscadelli

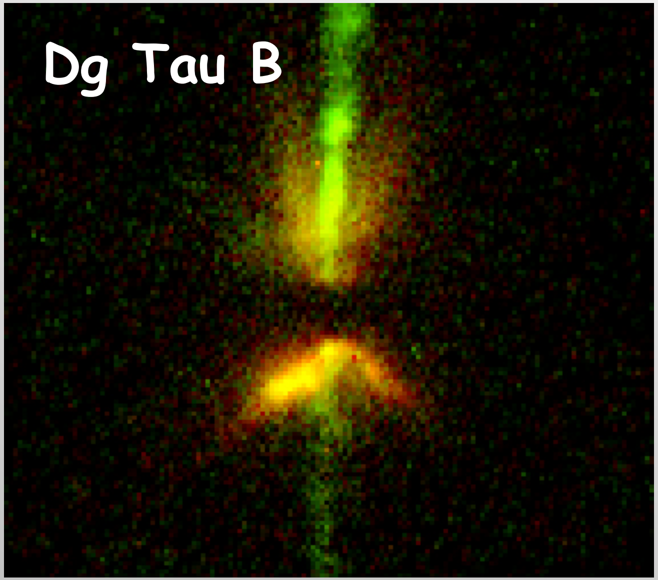
INAF – OAA

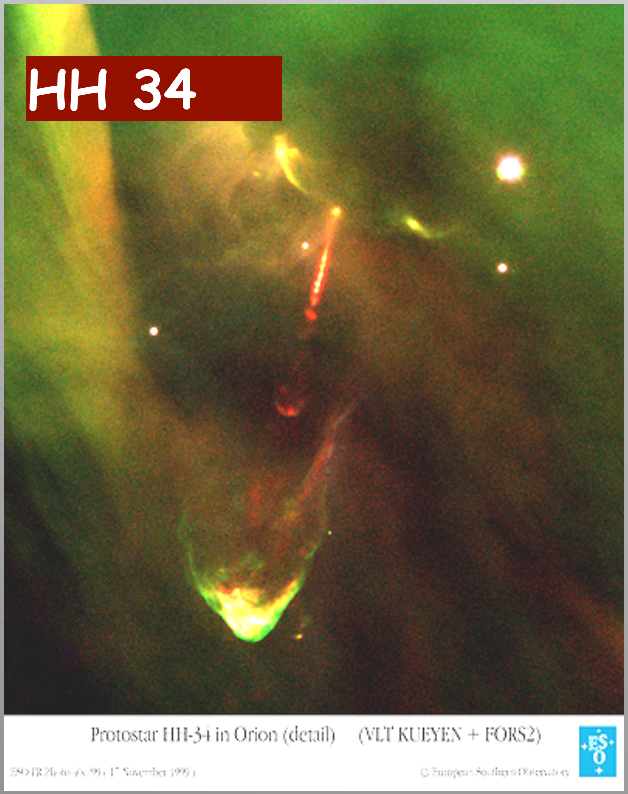
INAF collaborators:
C. Codella, L. Podio,
S. Antoniucci, L. Testi,
B.Nisini, T. Giannini,
D. Galli, M. Padovani,
and the JEDI team

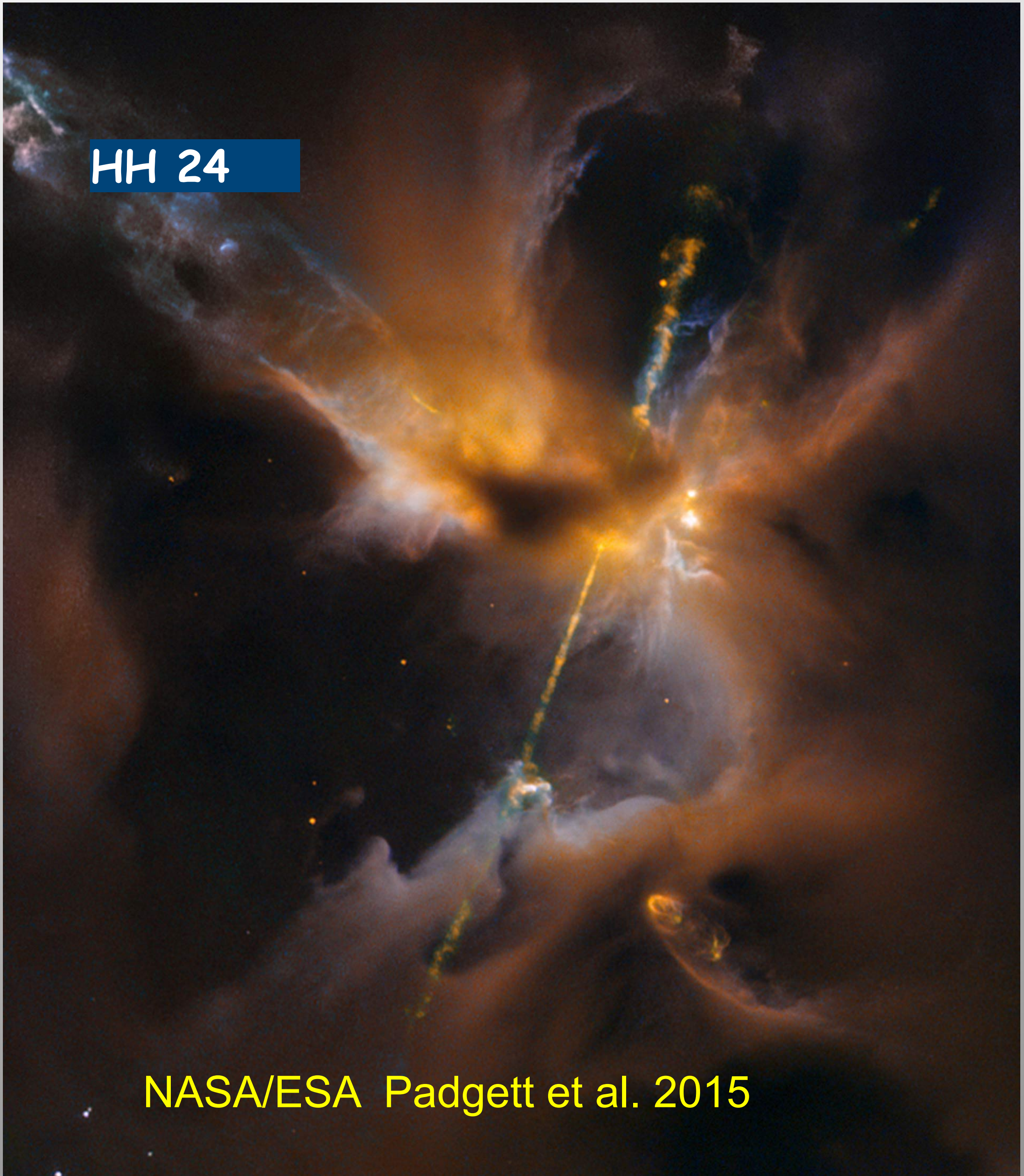
JEDI
JEts & Disks @ INAF

Convegno MA2 – Bologna 16/06/2016

Jets : pretty pictures







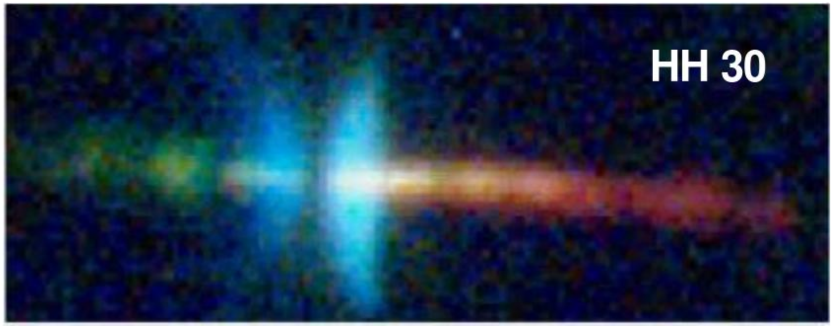
NASA/ESA Padgett et al. 2015

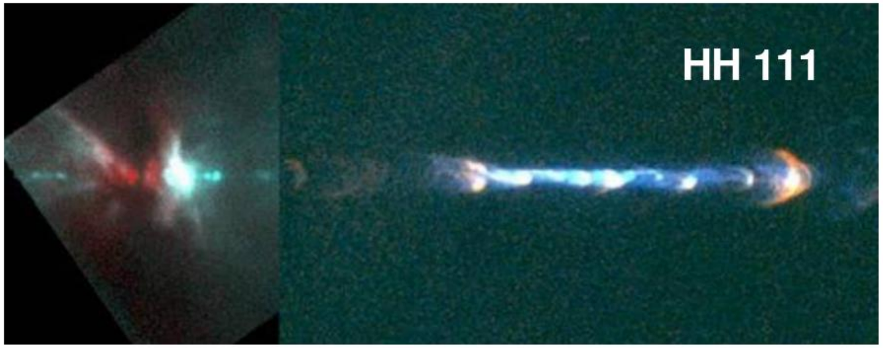
Importance of jets / outflows

Dispersion of parental envelope

Injection of turbulence in cloud

Shock chemistry lab





Importance of jets / outflows

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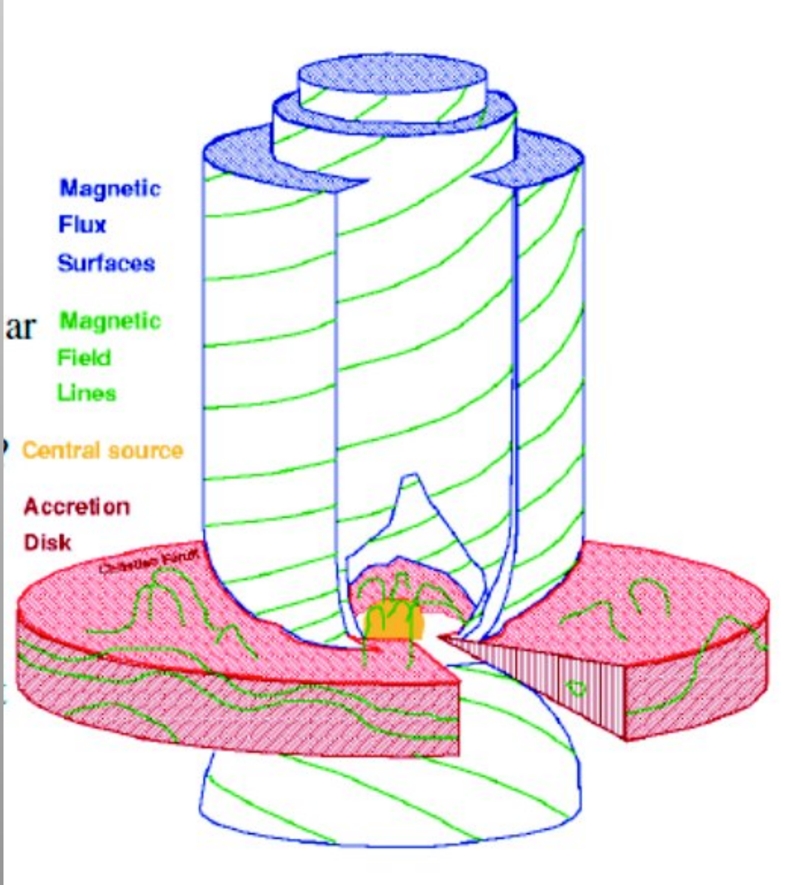

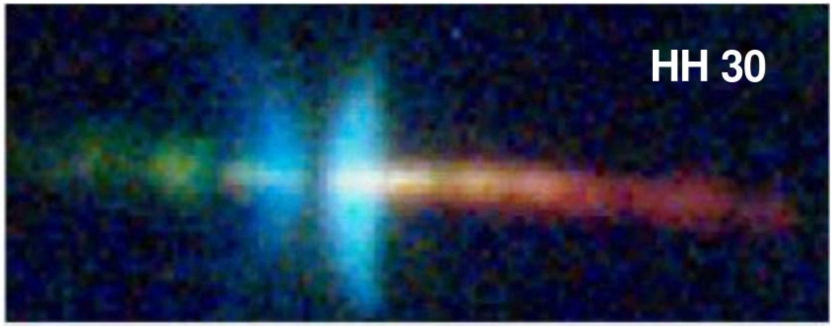

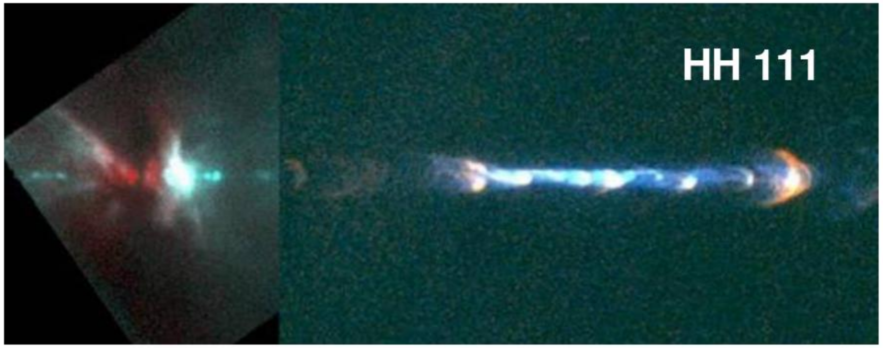

Same MHD launch mechanism at all mass scales (AGN → BDs)

Removal of excess angular momentum allows accretion

Feedback on the disk

the big questions

Do all disks have jets at some stage ?

Do jets drive the cloud SFR ?

How can we test the magneto-centrifugal launch theory ?

Do jets influence the process of planet formation ? How ?

the big questions

Do all disks have jets at some stage ?

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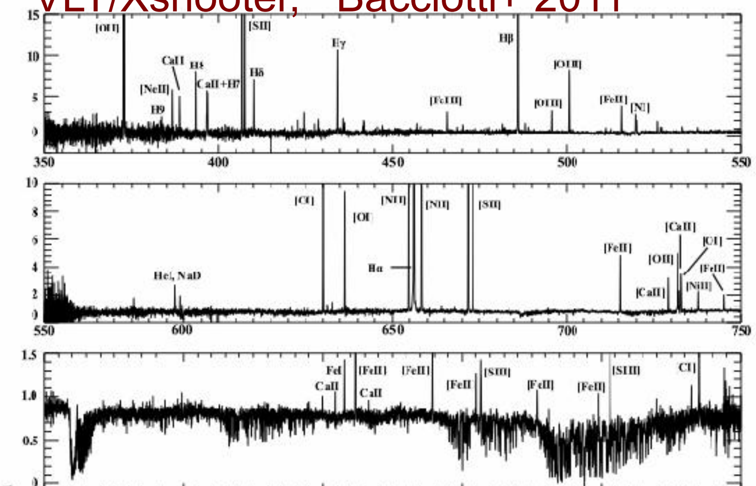
Do jets influence the process of planet formation ? How ?

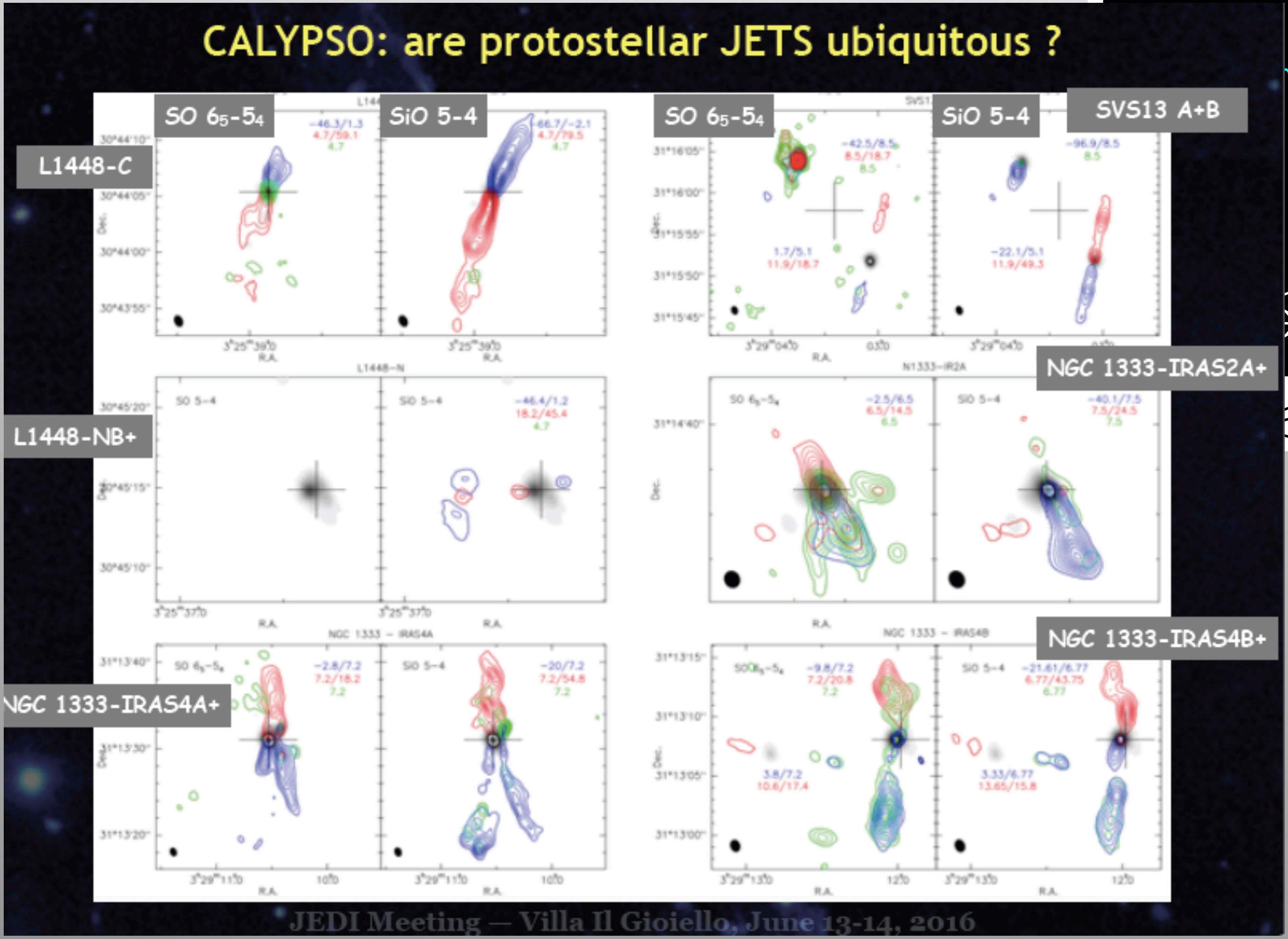

VLT/Xshooter, Bacciotti+ 2011

OBSERVATIONALLY:

YSO jets are bright, close, emit lines at all wav, ideal targets for AO

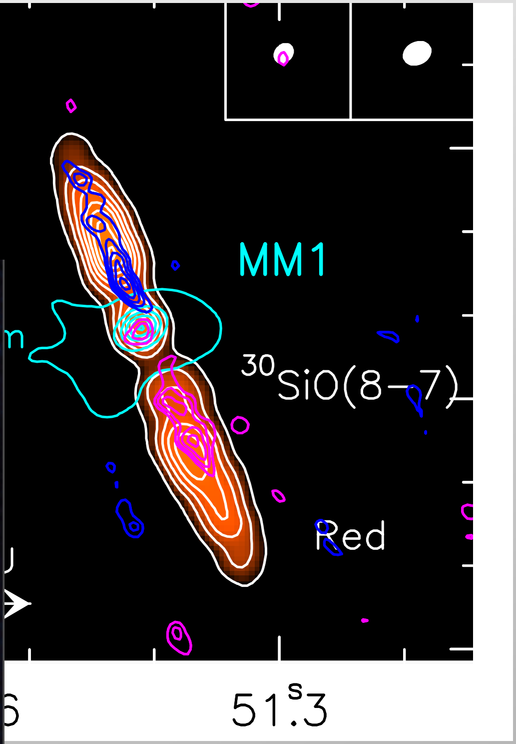
Scientific perspectives

Jet evolution from Class 0 to Class II stars

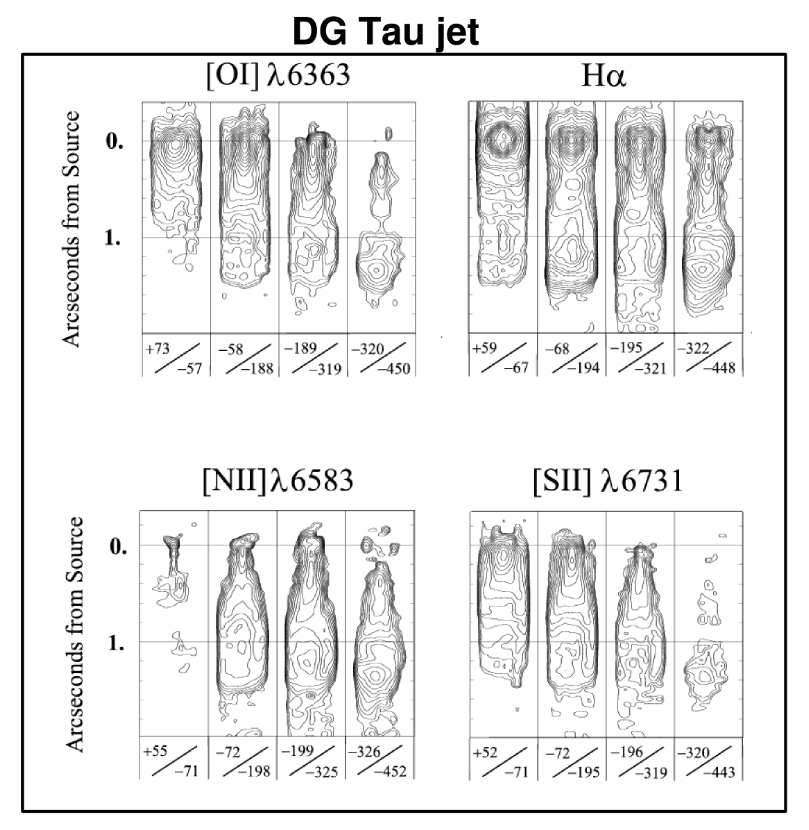


CALYPSO: are protostellar JETS ubiquitous ?

JEDI Meeting — Villa Il Gioiello, June 13-14, 2016



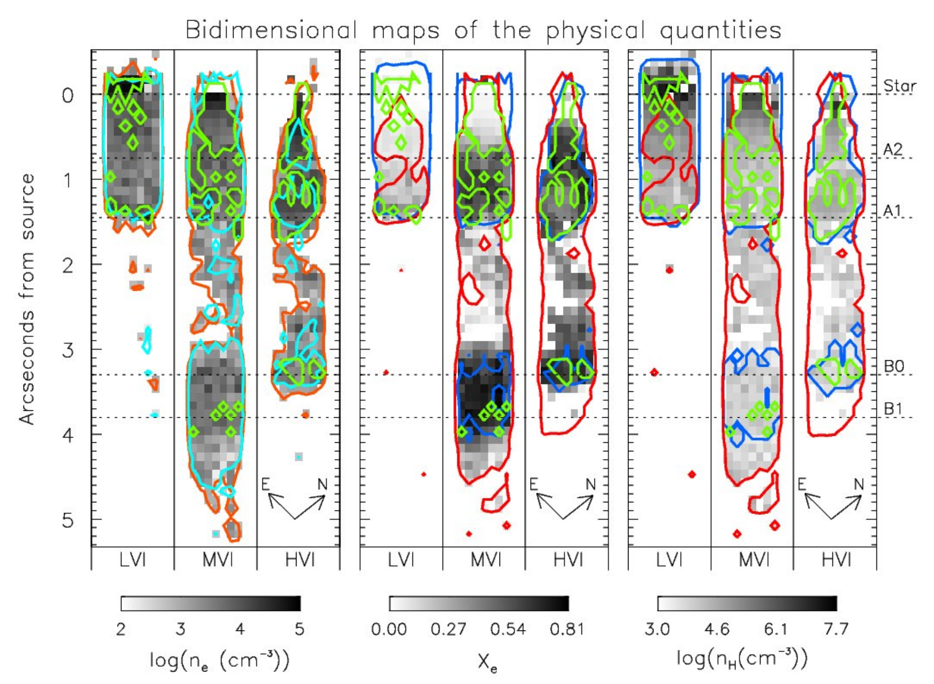
HAR SPECTRAL DIAGNOSTICS



HST STIS, DG Tau jet, Bacciotti et al. 2000

reconstructed 2D images of jets in optical lines (e.g. [SII], Ha, [OI]) provide info on the excitation structure.

→2D maps of lines in different velocity intervals
→physical conditions of the gas from line ratio maps
→Channel maps of phys quantities



HST STIS, DG Tau jet, Maurri et al. 2014

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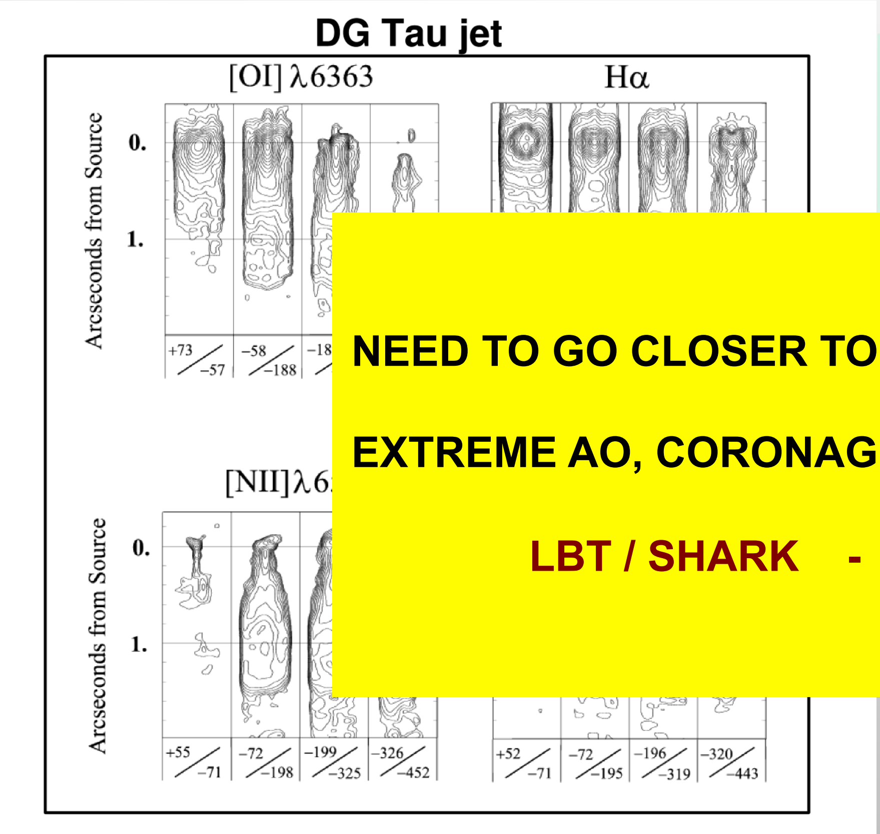


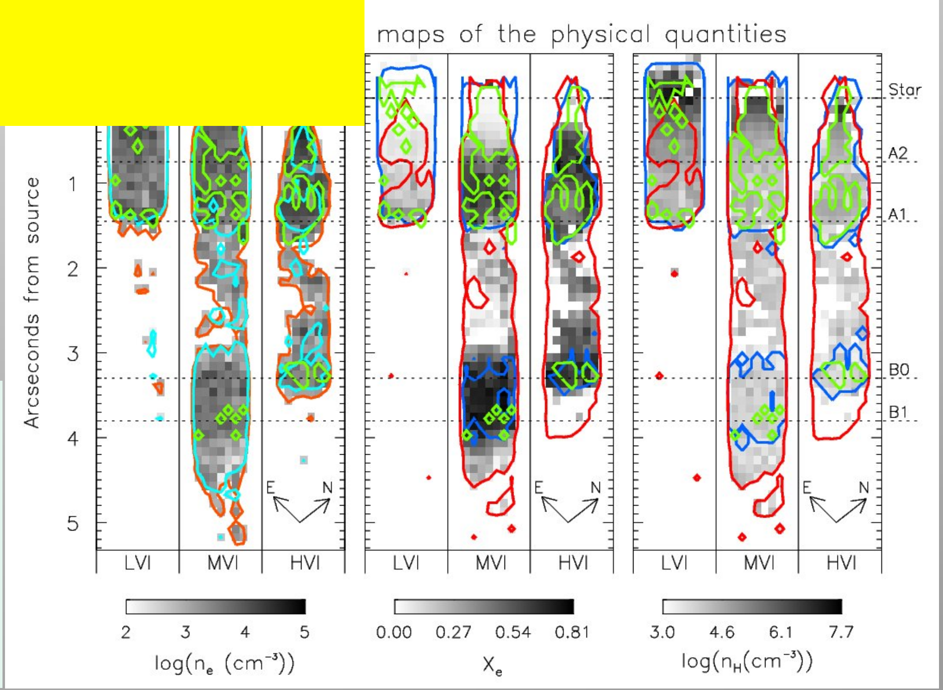
HST STIS, DG Tau jet, Bacciotti et al. 2000

NEED TO GO CLOSER TO THE SOURCE :

EXTREME AO, CORONAGRAPHS, High contrast

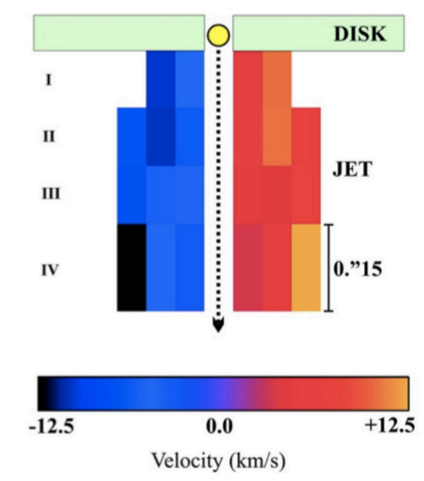
LBT / SHARK - VLT / SPHERE

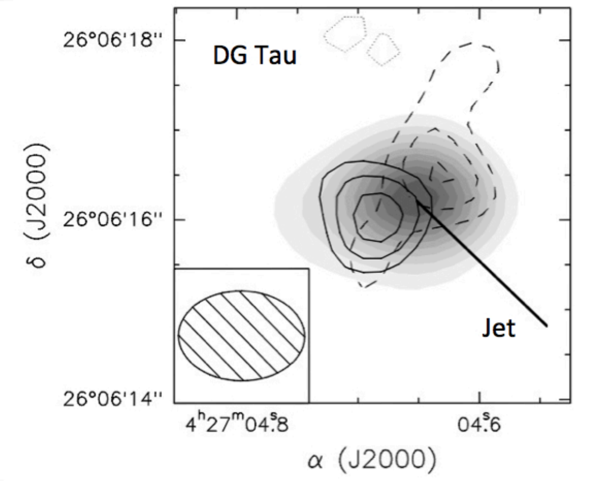
→2D maps of lines in different velocity intervals
→physical conditions of the gas from line ratio maps
→Channel maps of phys quantities



HST STIS, DG Tau jet, Maurri et al. 2014

investigations on the jet launch mechanism





From jet rotation studies :

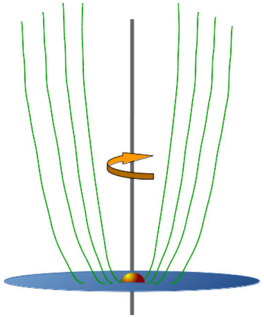
JET can carry away up to 60% of excess angular momentum

JET FOOTPOINT REGION:

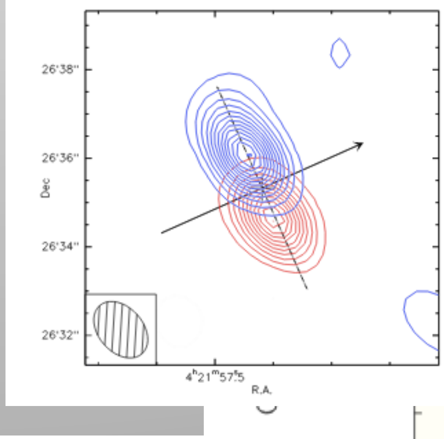
In the inner 5-10 AU

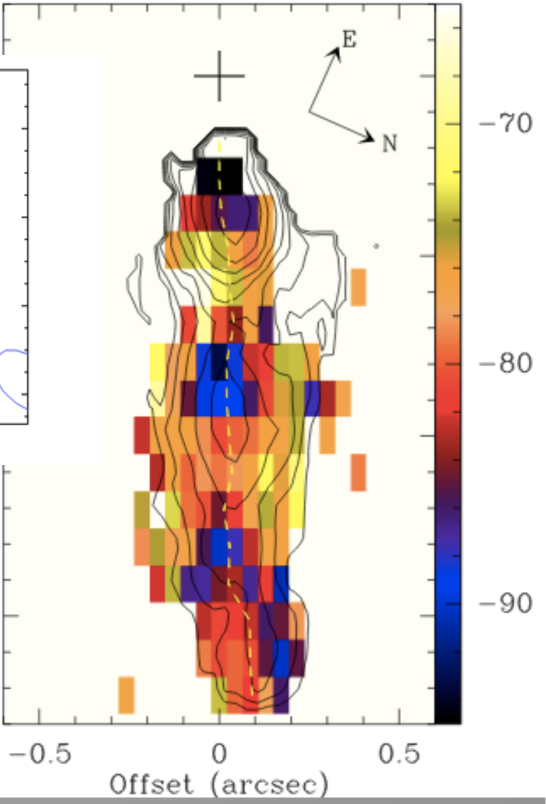
(Bacciotti + 2002,

Coffey, Bacciotti + 2004, 2007,, 2012 , 2015)



RY TAU





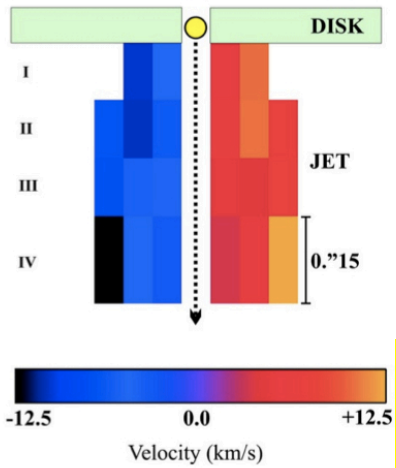
GEMINI IFU

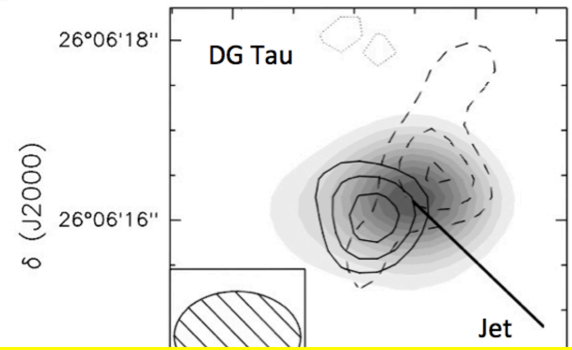
0."2 spat. resol.

54 km/s spect. resol.

[FeII] 1.64 μm

investigations on the jet launch mechanism



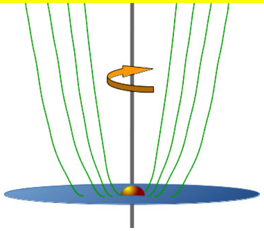


NEED TO GO CLOSER TO THE AXIS :

NUV – OPT – VIS LINES, HIGH RES, High contrast

From jet rotation st

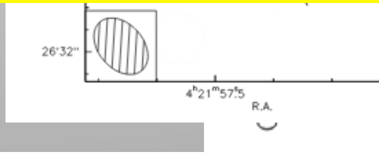
JET can carry away
angular momentum



JET FOOTPOINT REGION:
In the inner 5-10 AU

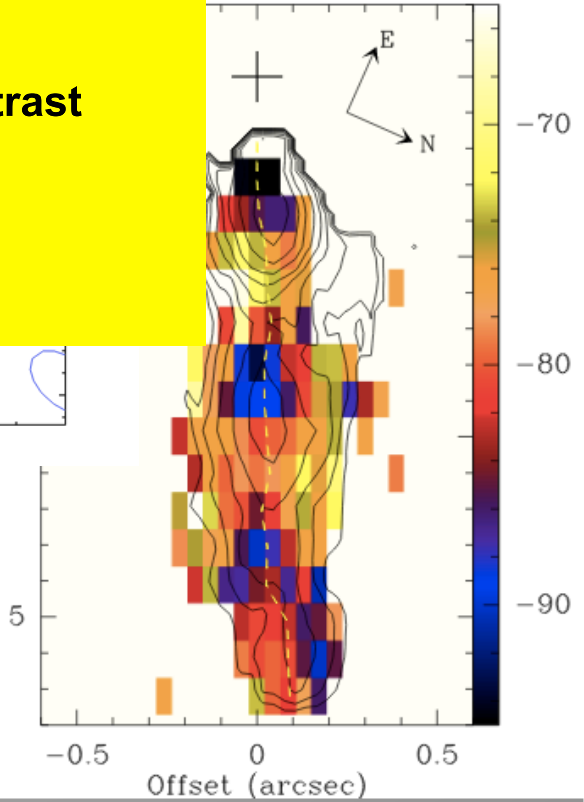
(Bacciotti + 2002,
Coffey, Bacciotti + 2004, 2007,, 2012 , 2015)

TAU



GEMINI IFU
0."2 spat. resol.
54 km/s spect. resol.

[FeII] 1.64 μm

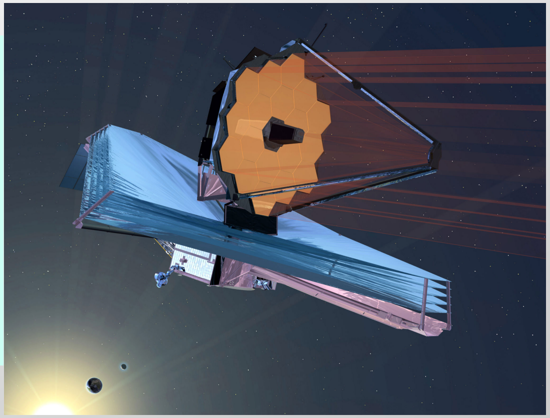


instrumental perspectives

Present :
VLT/ SPHERE
LBT/ LUCI-AO
HST , ALMA

JET EVOLUTION : faint embedded sources

SENSITIVITY at NIR / MIR

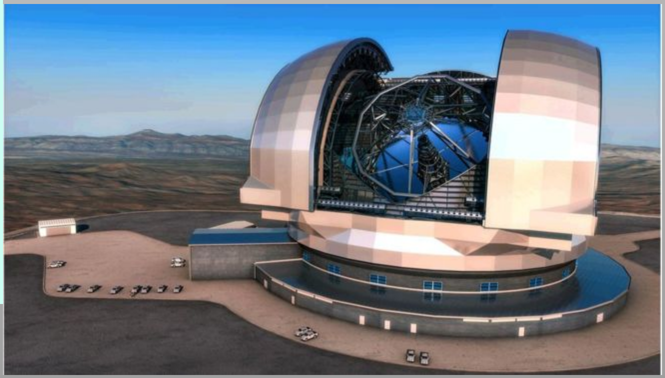


Imaging the launch region

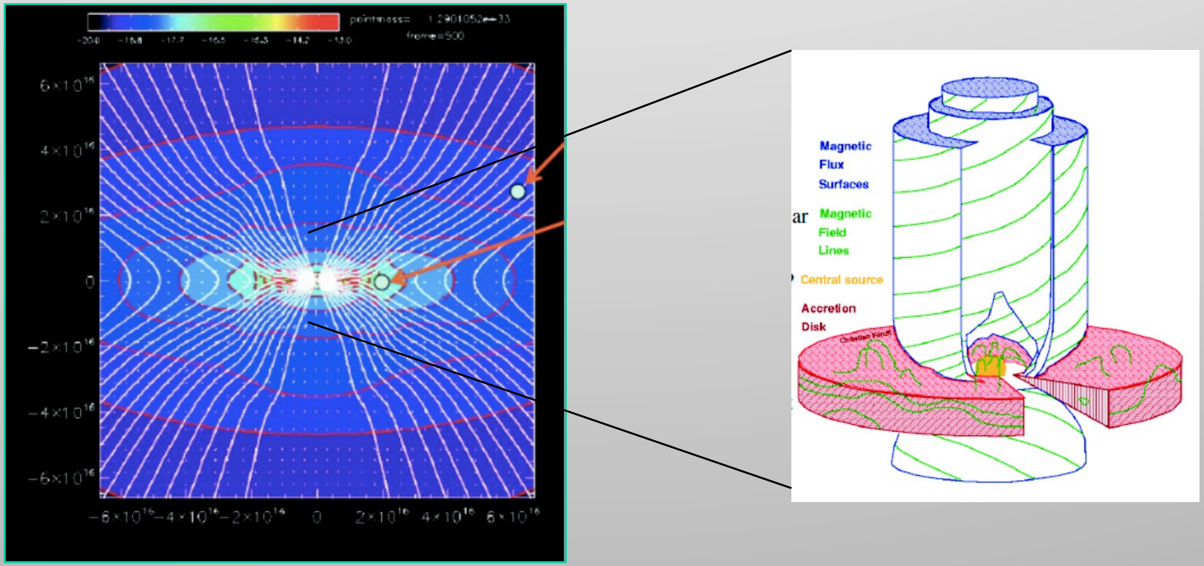
HIGH CONTRAST : LBT SHARK

Jet diagnostics close to the souce

NEED FOR :
SPECTRAL RESOLUTION
+ ANGULAR RESOLUTION



To find the magnetic architecture



MAGNETIC FIELD DISTRIBUTION
MAGNETIC FIELD AMPLITUDE

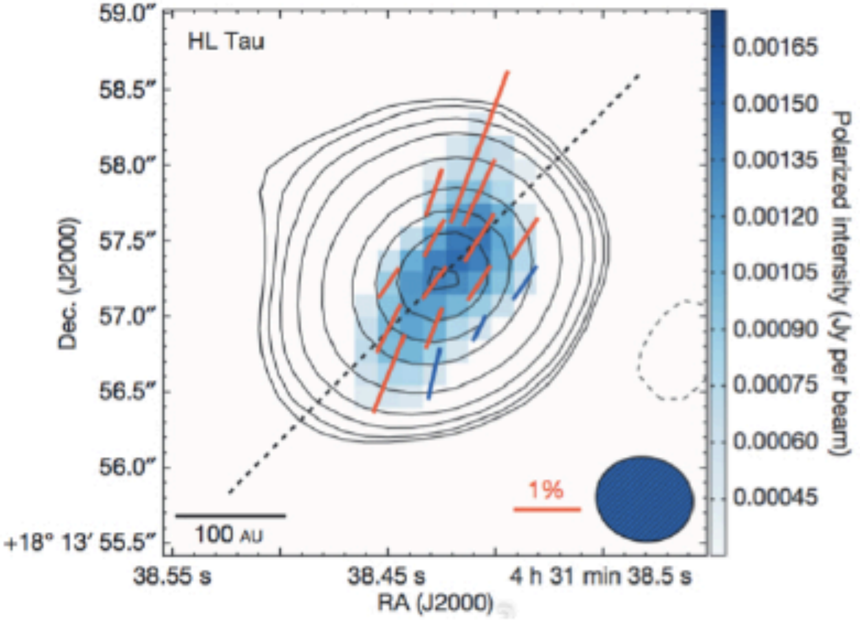
NEED FOR :
POLARIZATION MEASUREMENTS

ALMA: Magnetic field at the jet base

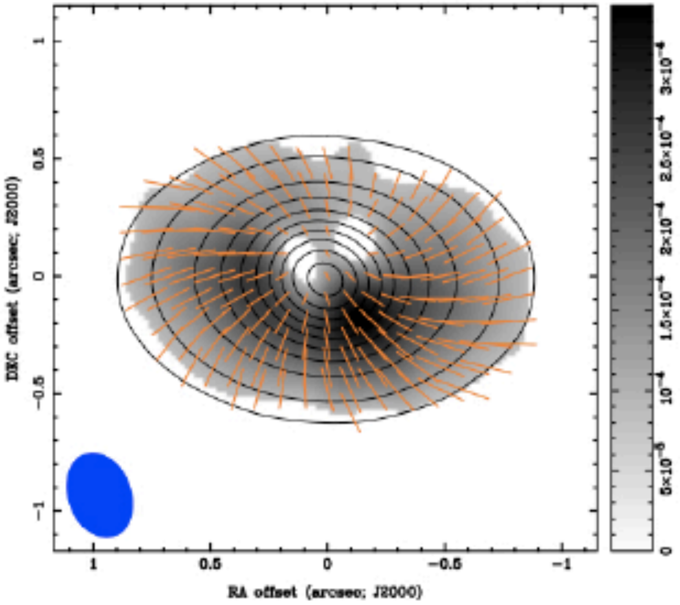
ALMA Cycle 3 proposal accepted (Pi Bacciotti)
to observe distribution of magnetic field from polarization of dust continuum

Targets : DG TAU and CW Tau
With jet/disk rotation agreement

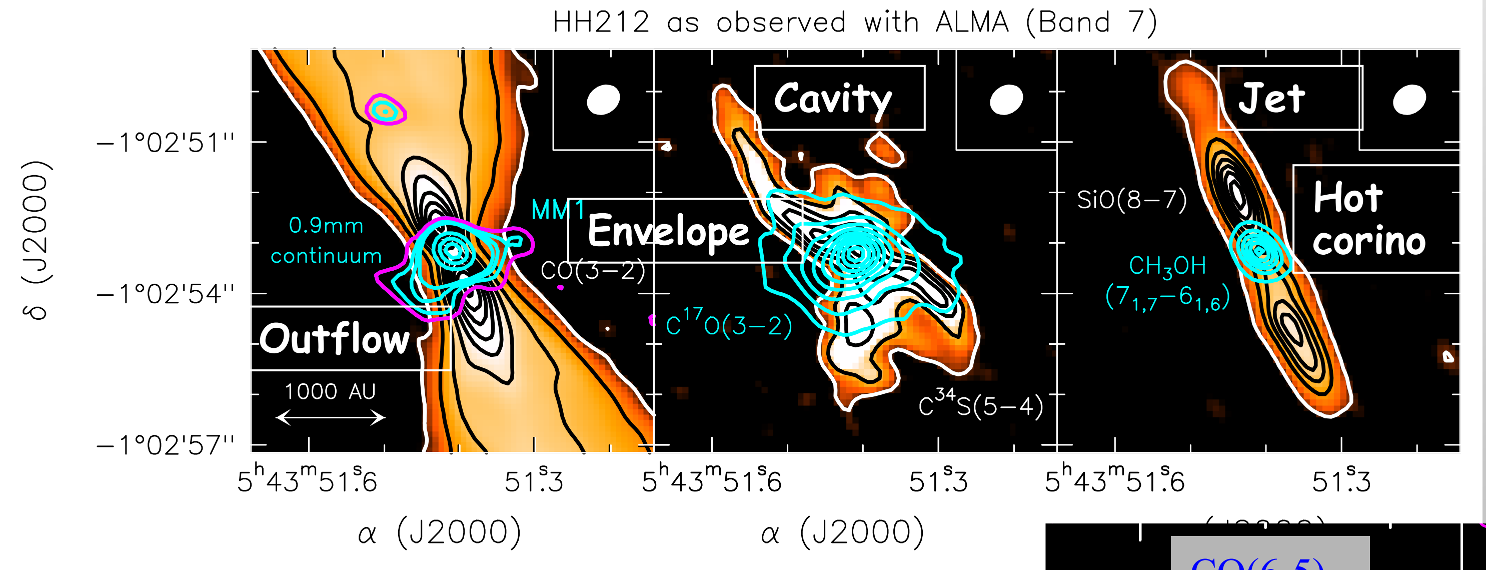
CARMA Obervations - HL TAU



Simulation of ALMA results with DUSTPOL for CW Tau



The inner 100 AU of a Sun-like protostar, as seen by ALMA

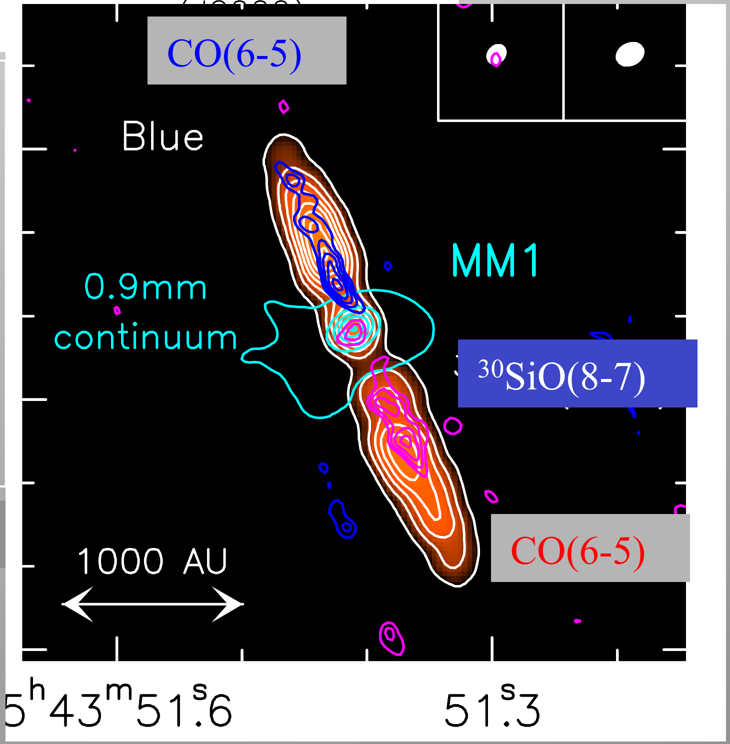


HH212 as observed with ALMA (Band 7)

All the ingredients of the Sun-like star formation recipe imaged with a single spectral set-up:

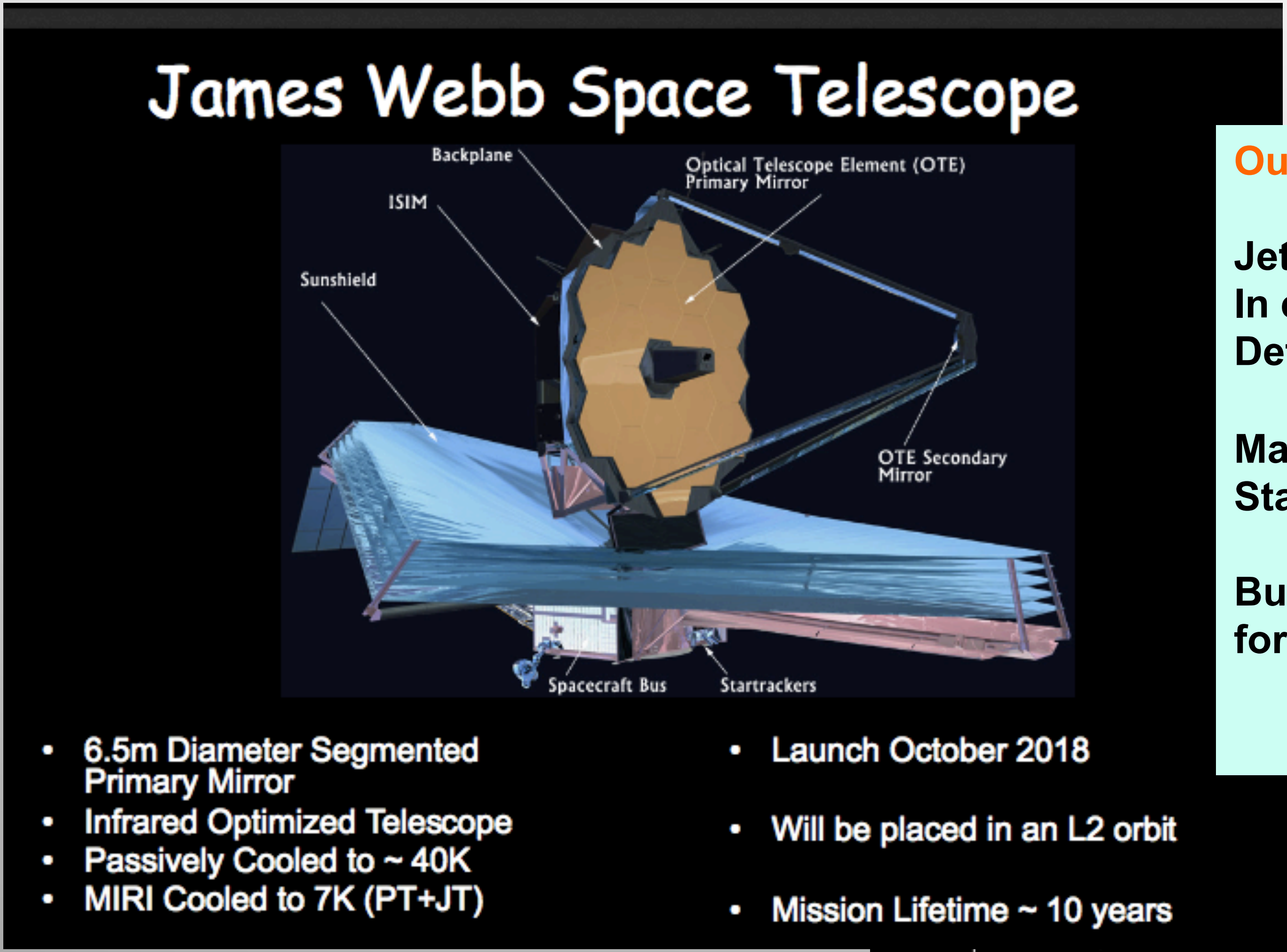
1. The flattened (dust & molecules) envelope
2. The hot-corino (COMs) heated by the protostar
3. The forming disk
4. The hot and fast collimated jet
5. The cold, slow, and extended swept-up outflow
6. The cavity as interface between outflow and static cloud

Codella et al. (2014, 2016), Podio et al. (2015)



First Band 9 image of a protostellar jet, in CO(6-5) !!

JETS and JWST



James Webb Space Telescope

- 6.5m Diameter Segmented Primary Mirror
- Infrared Optimized Telescope
- Passively Cooled to ~ 40K
- MIRI Cooled to 7K (PT+JT)

- Launch October 2018
- Will be placed in an L2 orbit
- Mission Lifetime ~ 10 years

Our project:

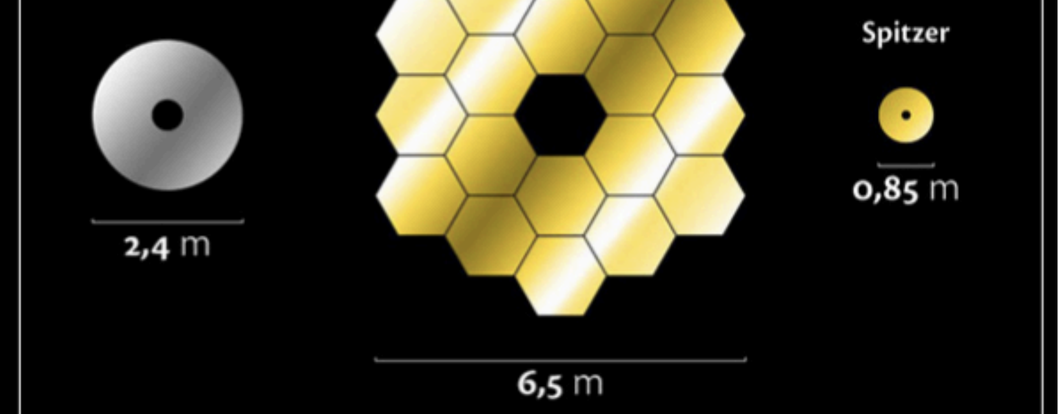
Jets in NIR/ MIR lines
In embedded faint sources in
Defined SF regions

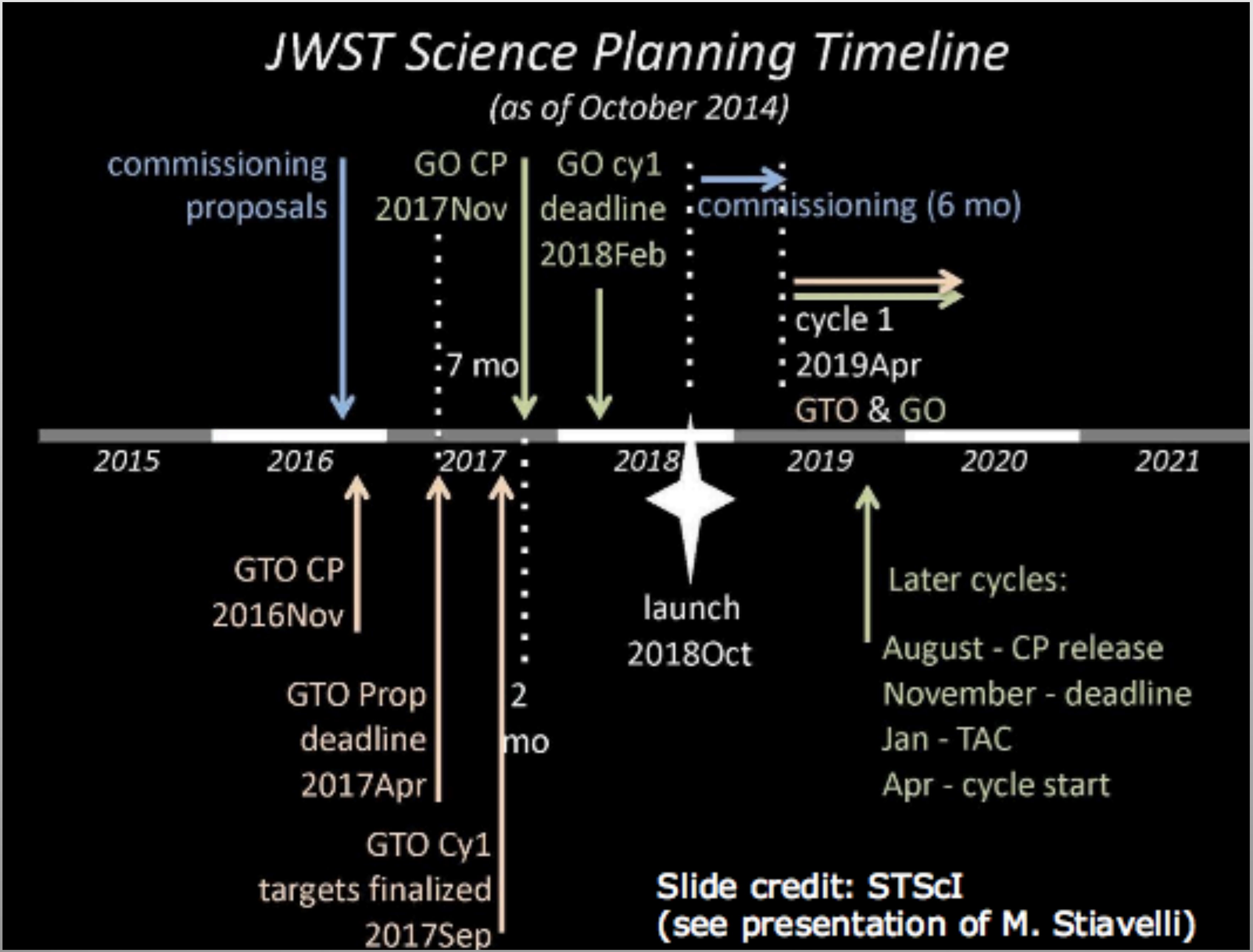
Mapping –
Statistical census

But too low spectr res
for internal kinematics

Angular resolution like HST in the VIS:
0.”1 at 1 micron

Sensitivity 10 – 100 times Spitzer





JWST Science Planning Timeline

(as of October 2014)

commissioning proposals

GO CP 2017Nov

GO cy1 deadline 2018Feb

commissioning (6 mo)

cycle 1 2019Apr GTO & GO

7 mo

2015

2016

2017

2018

2019

2020

2021

GTO CP 2016Nov

GTO Prop deadline 2017Apr

GTO Cy1 targets finalized 2017Sep

2 mo

launch 2018Oct

Later cycles:

August - CP release

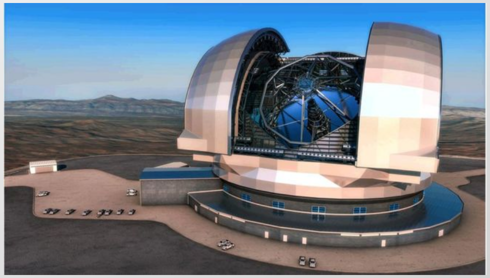
November - deadline

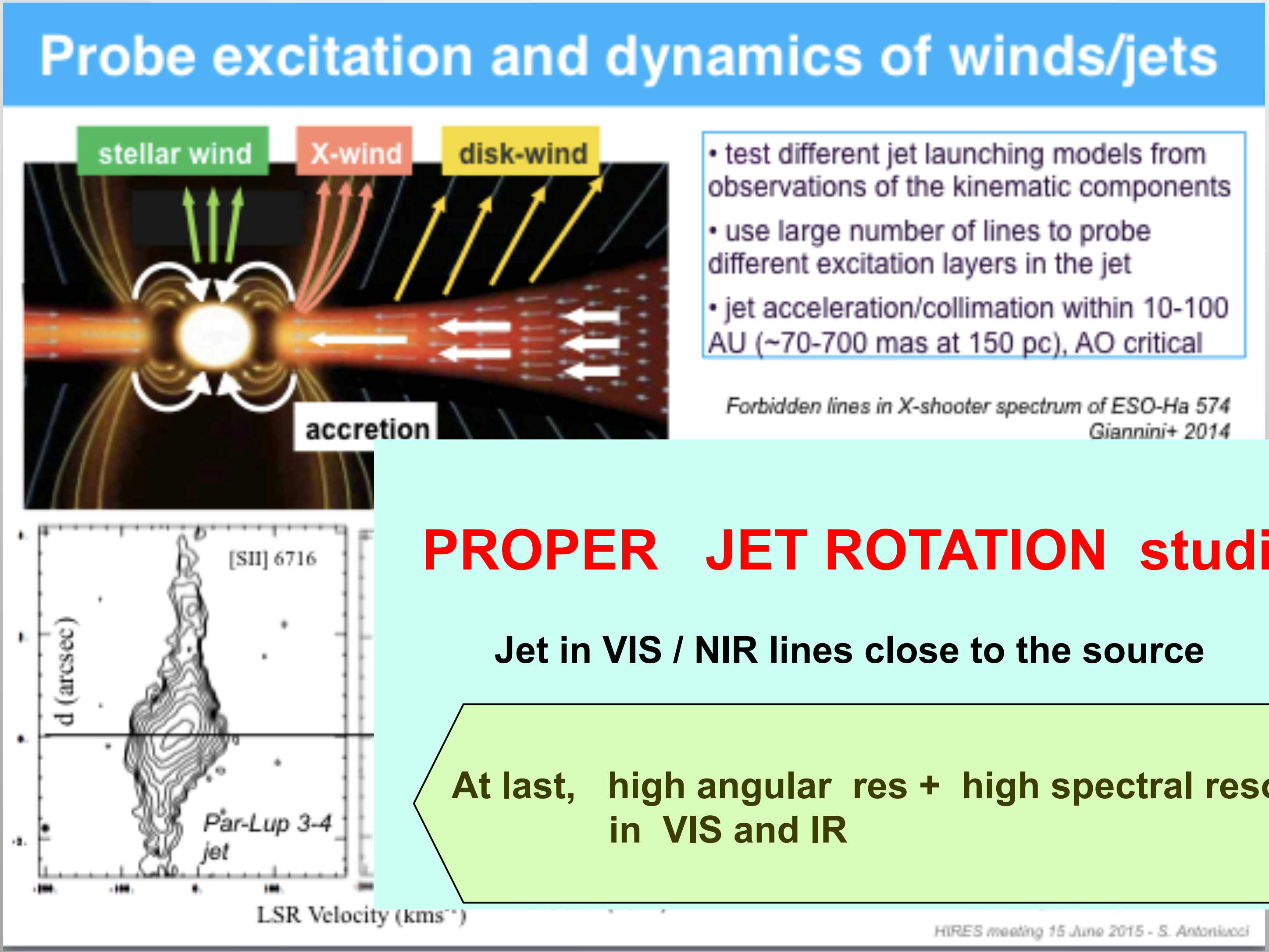
Jan - TAC

Apr - cycle start

Slide credit: STScI
(see presentation of M. Stiavelli)

E-ELT HIRES





Probe excitation and dynamics of winds/jets

- test different jet launching models from observations of the kinematic components
- use large number of lines to probe different excitation layers in the jet
- jet acceleration/collimation within 10-100 AU (~70-700 mas at 150 pc), AO critical

Forbidden lines in X-shooter spectrum of ESO-Ha 574
Giannini+ 2014

HIRES meeting 15 June 2015 - S. Antoniucci

PROPER JET ROTATION studies !!!!!!!!!!

Jet in VIS / NIR lines close to the source

At last, high angular res + high spectral resolution in VIS and IR

Strong participation of JEDI to the Italian science team

Conclusions part I : the main drivers

Find the frequency of the jet phenomenon
At different ages / masses

to quantify their role in star formation

↔

High sensitivity
as JWST, ALMA

Find the magnetic architecture

To clarify the dynamics
of star formation

↔

polarization
ALMA, SKA,

Find physical properties of jets at
the smallest scales

To clarify the influence on
planet formation

↔

High contrast
High spatial resol
High spectral resol
HST
LBT, SPHERE
EELT

Conclusions part I : the main drivers

Find the frequency of the jet phenomenon
At different ages / masses

to quantify their role in star formation

High sensitivity
as JWST, ALMA

Find the

To cla
of

KEEP JEDI COMMUNITY STRONG

KEEP CONTACT WITH THEORY

POSITIONS FOR YOUNG RESEARCHERS

FUNDING FOR INTERNATIONAL PROGRAMMES

ation
SKA,

Find physical properties of jets at
the smallest scales

To clarify the influence on
planet formation

High contrast
High spatial resol
High spectral resol
HST
LBT, SPHERE
EELT

Molecular masers: a formidable tool for SF study

Talk outline:

1) BeSSeL: structure and dynamics of the Galactic disk

2) 3-D Velocity and Magnetic Fields at radii of 100 AU

3) Near Future: SKA

Main collaborators:

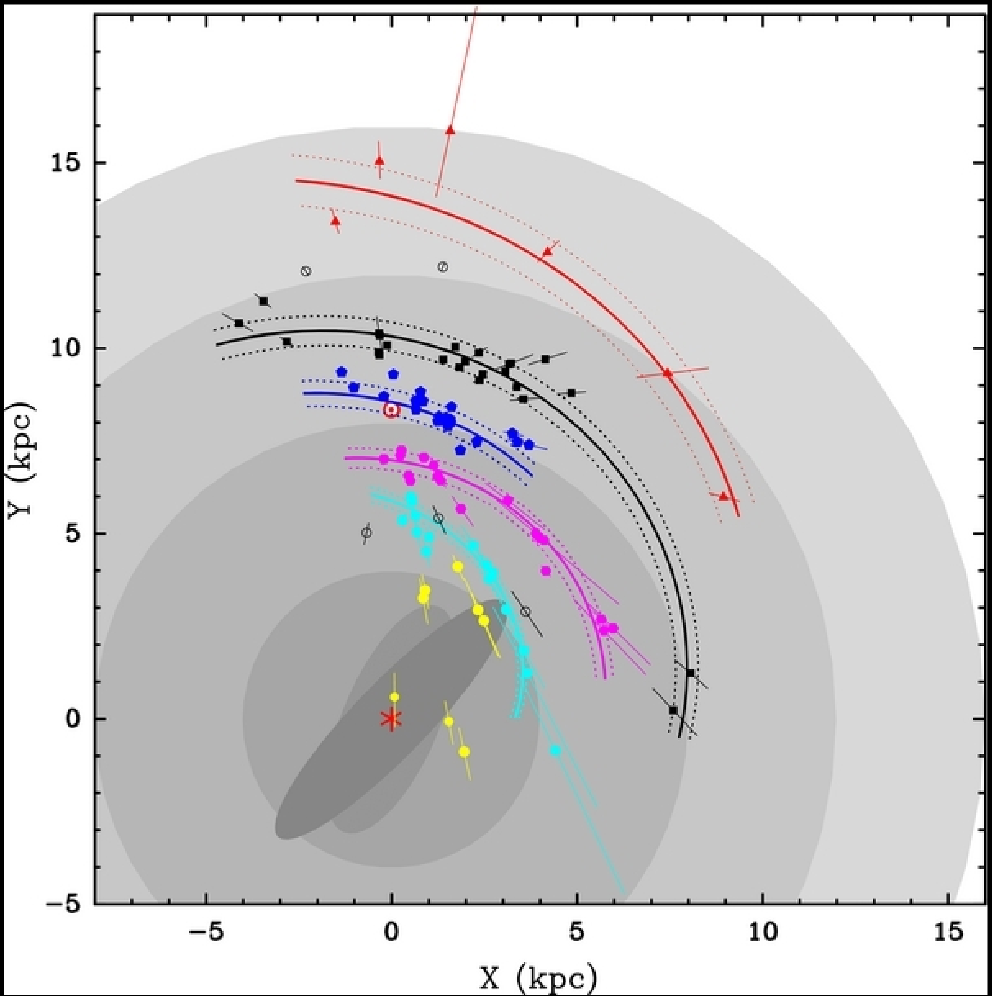
INAF: Bacciotti, F., Beltrán, M.T., Cesaroni, R., Massi, F., Olmi, L., Surcis, G.

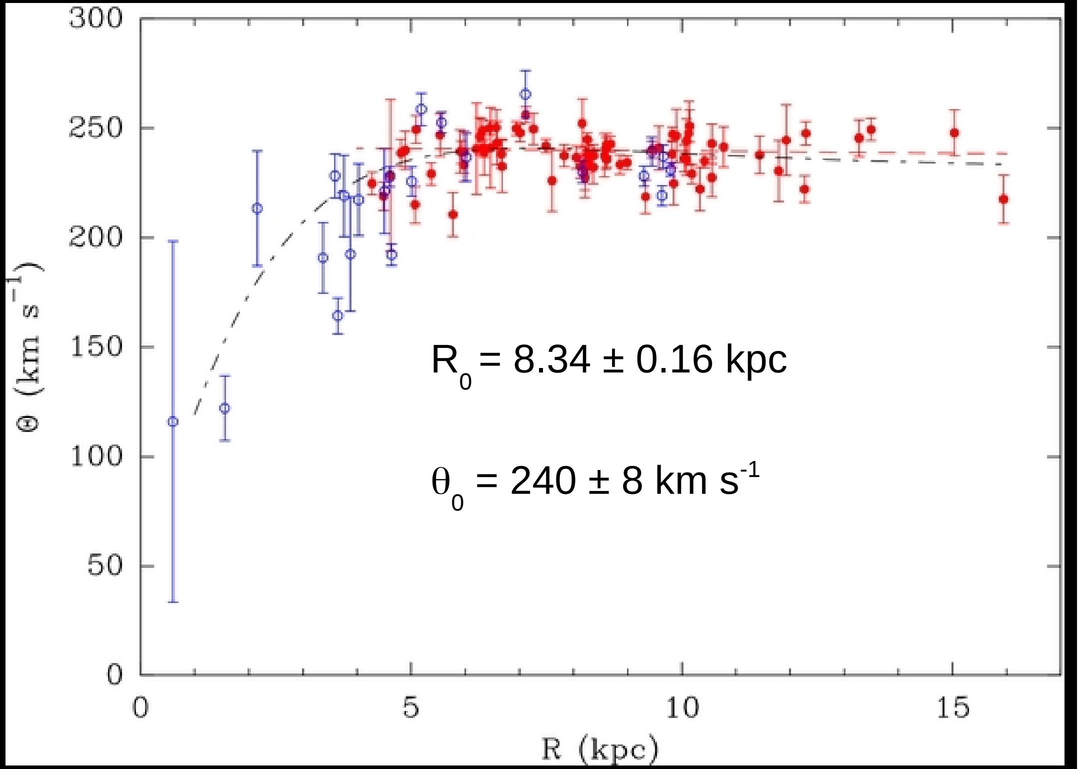
non-INAF: Goddi, C., Sánchez-Monge, Á., Sanna, A., Reid, M. J.

Maser spots are excellent astrometric targets :

> 100 trigonometric parallaxes (~5 % accuracy up to 10 kpc) and proper motions (a few km/s accuracy)

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





$R_0 = 8.34 \pm 0.16$ kpc

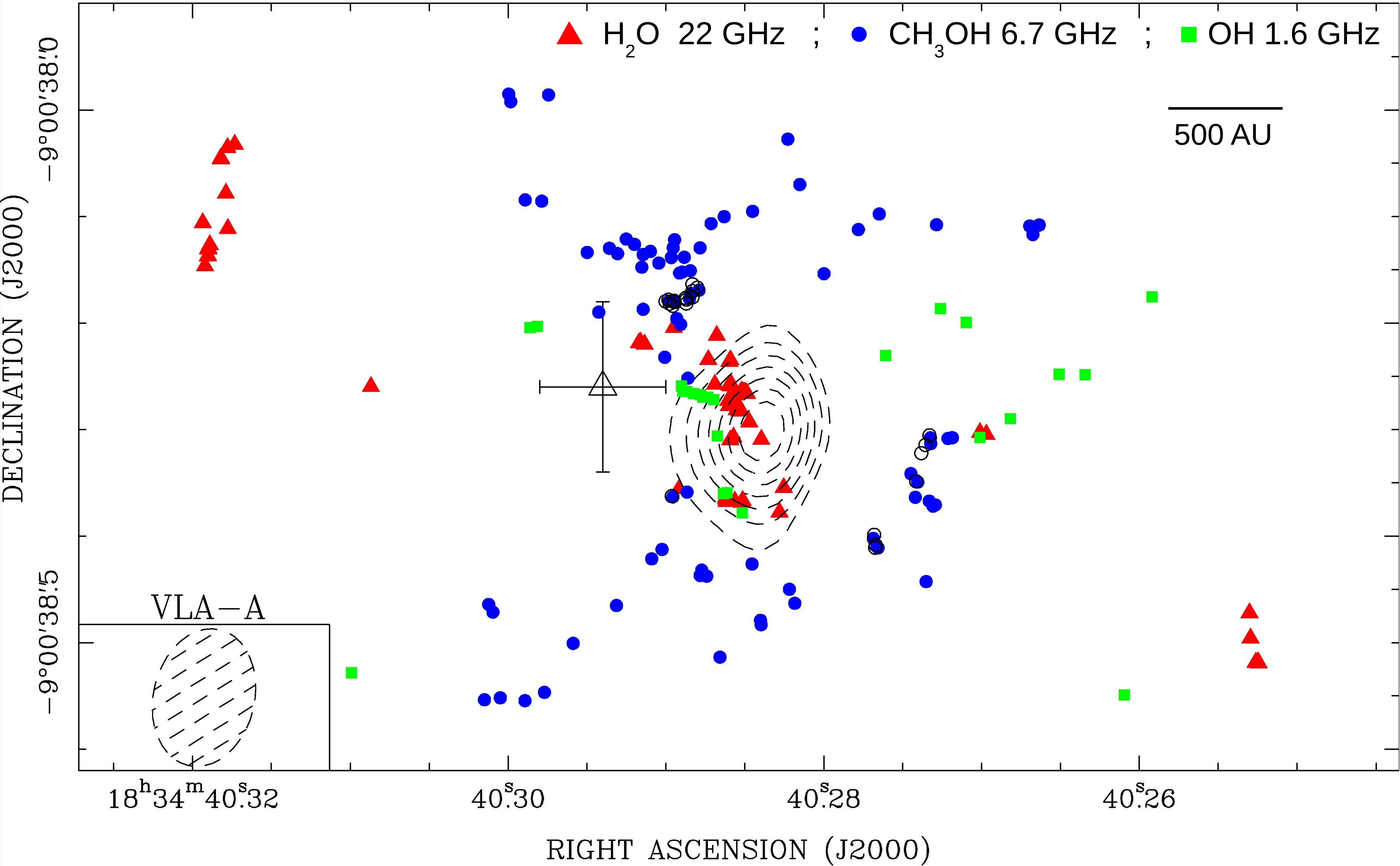
$\theta_0 = 240 \pm 8$ km s^{-1}

Reid et al. 2014, ApJ, 783, 130

Maser VLBI: 3-D Kinematics @ ~10^2 AU in G23.01-0.41

Several Molecular Masers commonly observed nearby high-mass YSOs

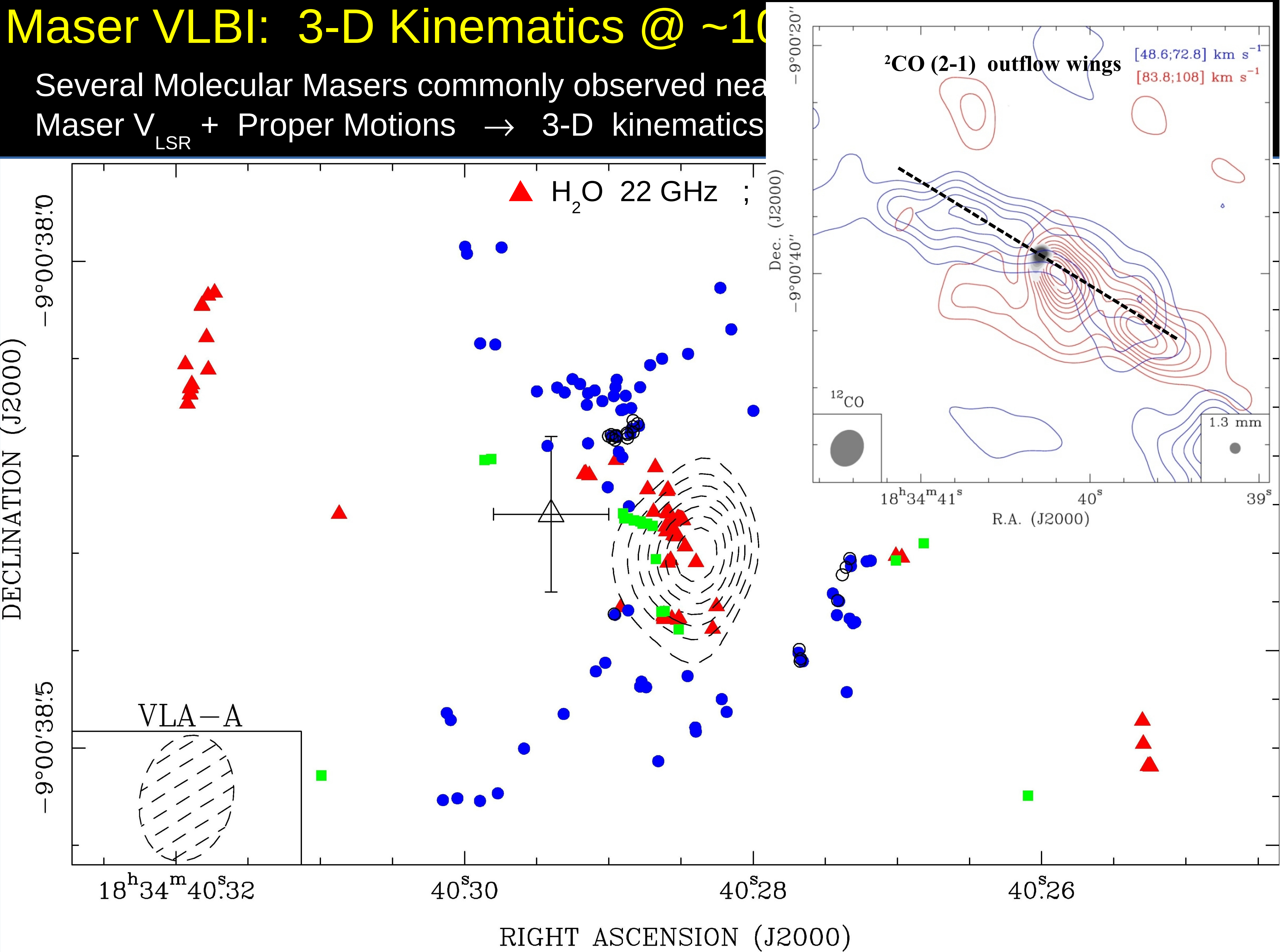
Maser V_{LSR} + Proper Motions → 3-D kinematics



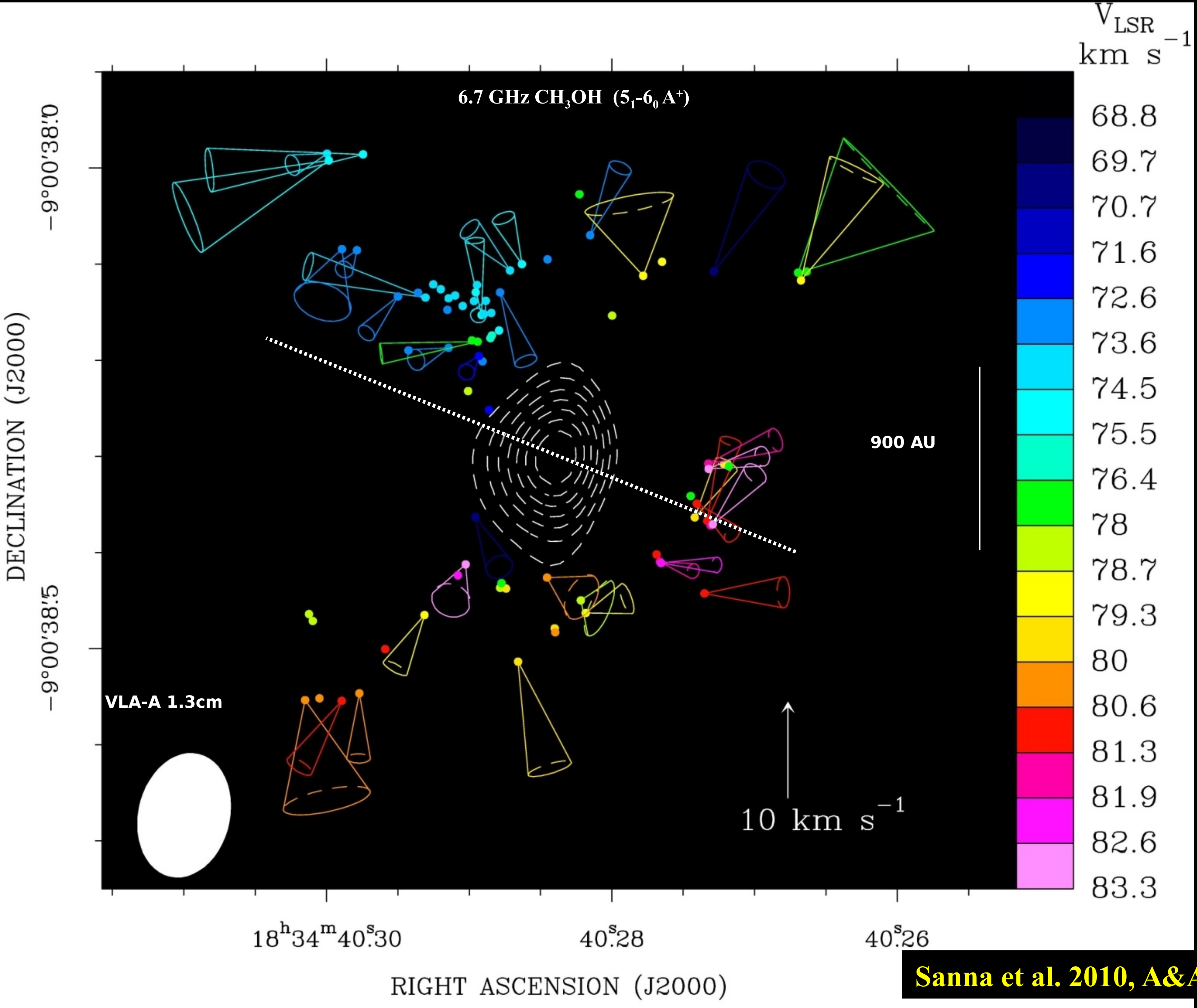
Maser VLBI: 3-D Kinematics @ ~10

Several Molecular Masers commonly observed nea

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

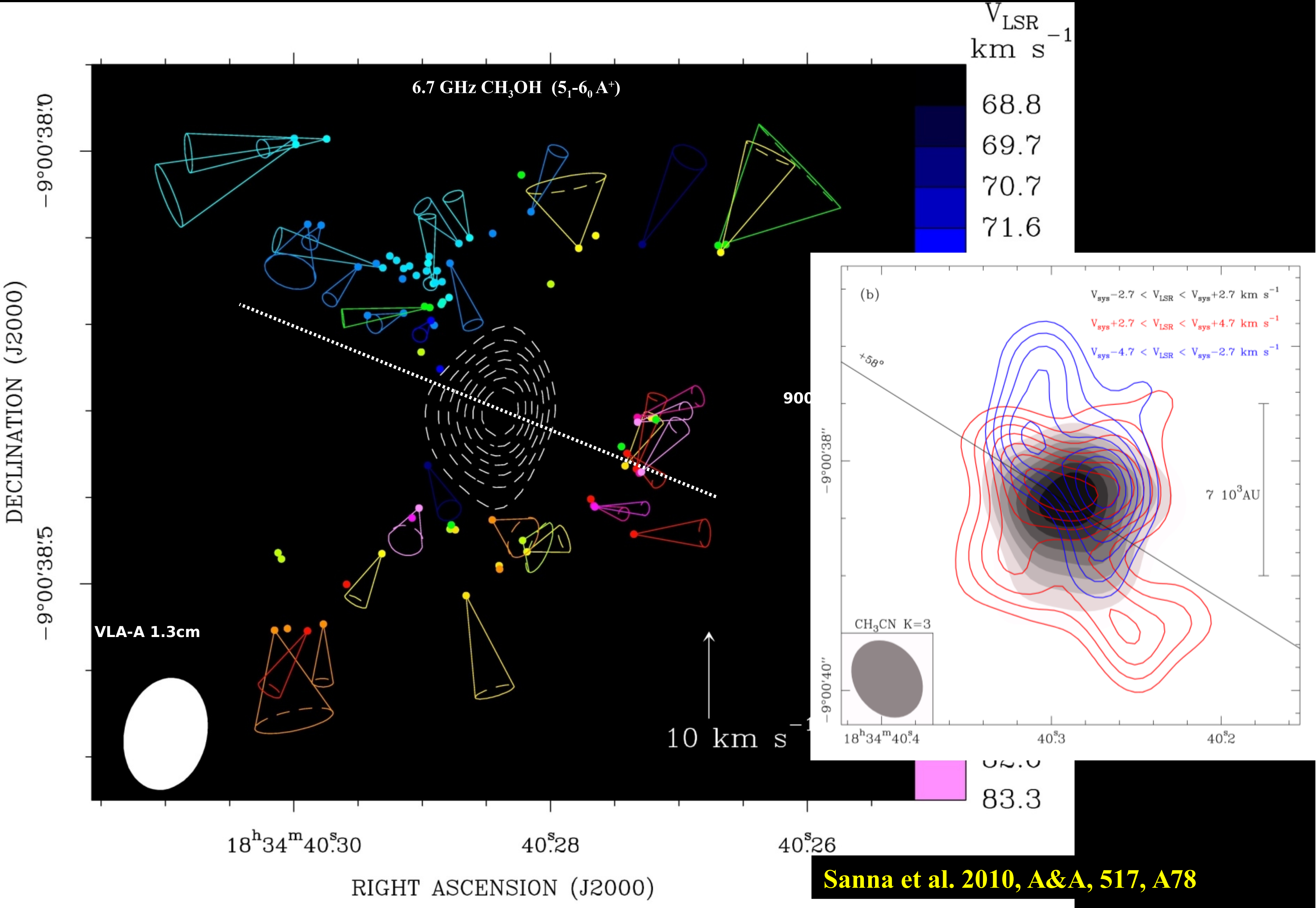


Rotation and Expansion @ ~10^2 AU from the YSO



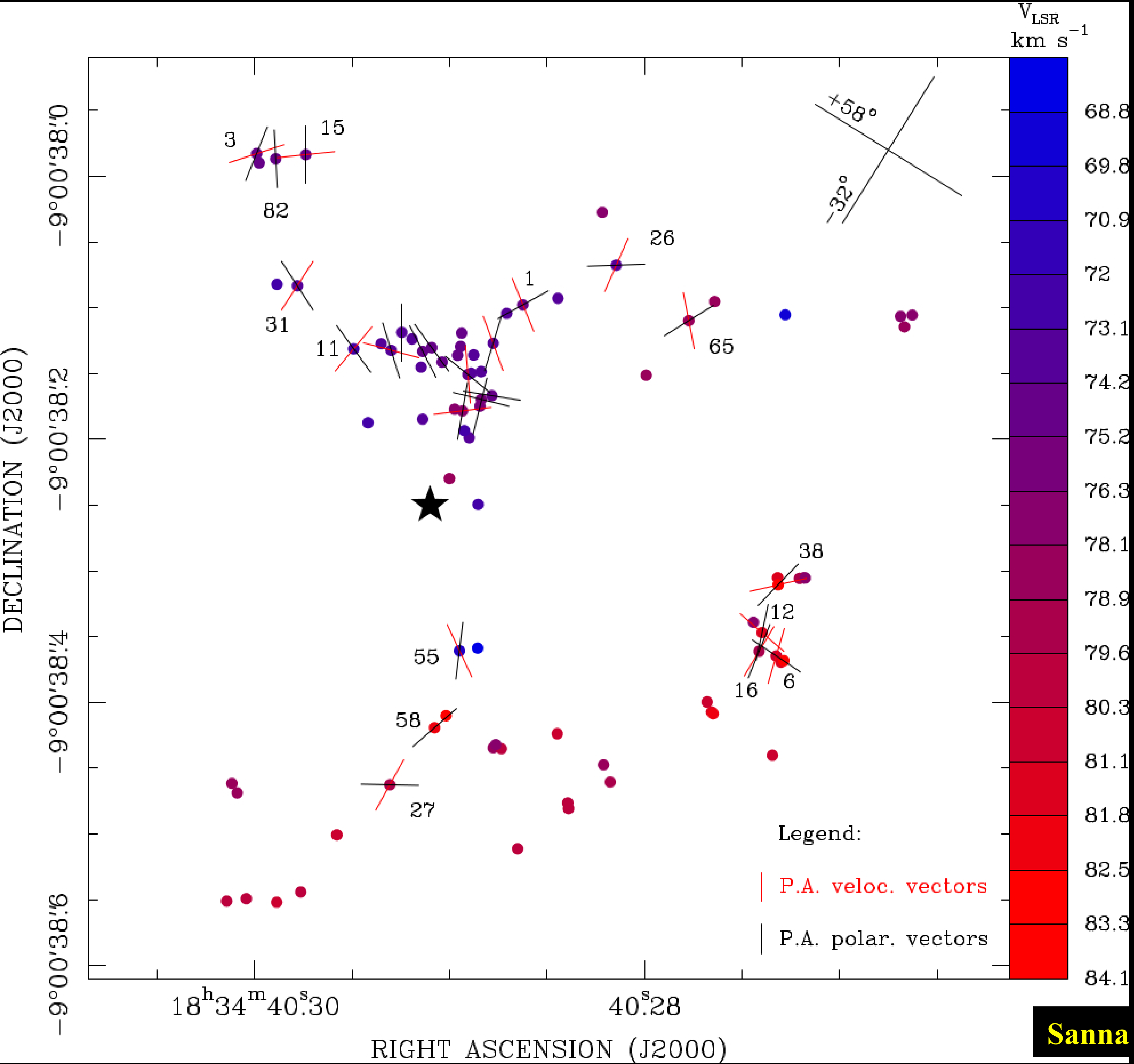
Sanna et al. 2010, A&A, 517, A78

Rotation and Expansion @ ~10^2 AU from the YSO



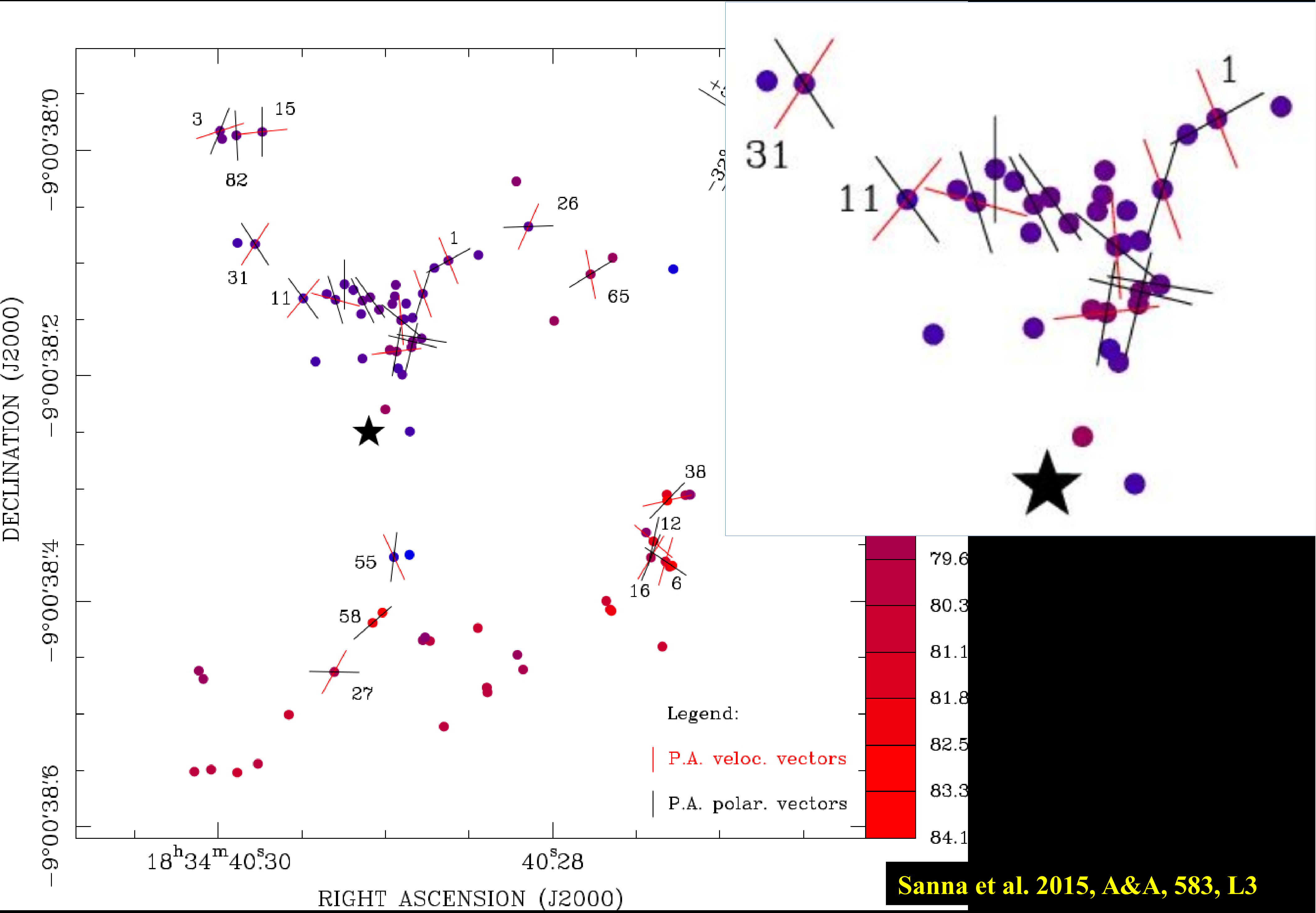
Sanna et al. 2010, A&A, 517, A78

EVN 6.7 GHz maser linear polarization in G23.01-0.41



Sanna et al. 2015, A&A, 583, L3

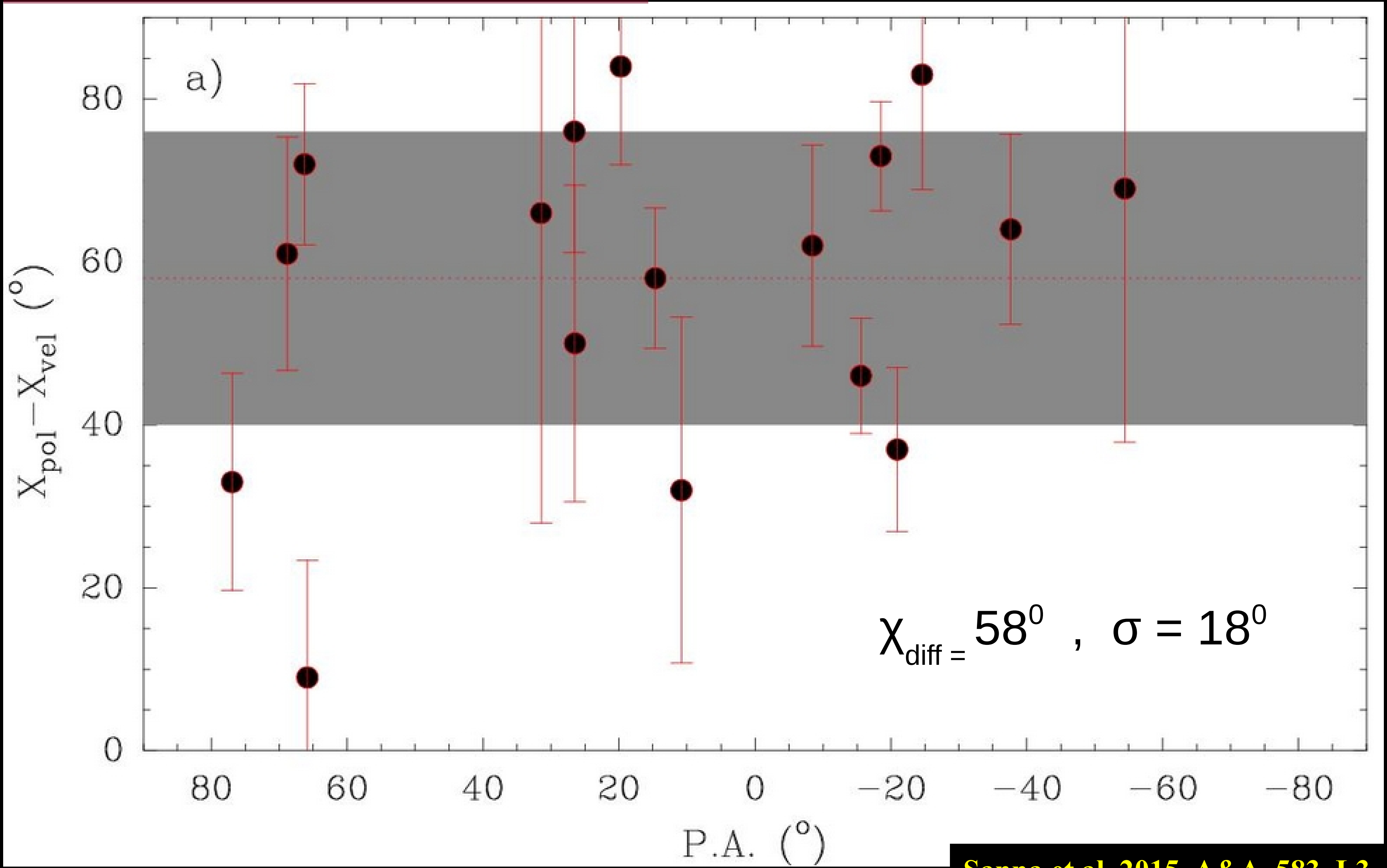
EVN 6.7 GHz maser linear polarization in G23.01-0.41



Sanna et al. 2015, A&A, 583, L3

EVN 6.7 GHz maser linear polarization in G23.01-0.41

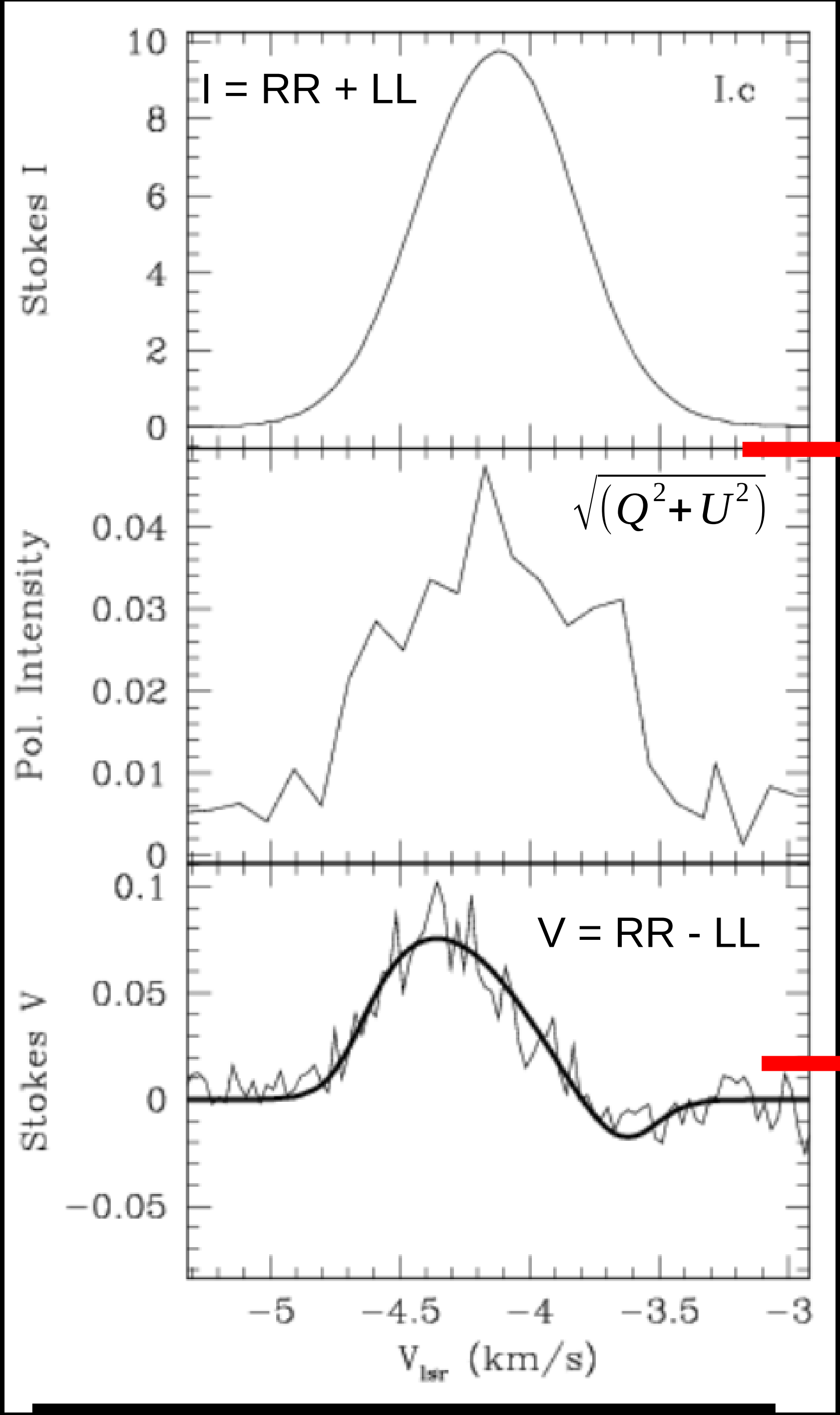
Gas flows along **B** lines?



$\chi_{\mathrm{diff}} = 58^0$, $\sigma = 18^0$

Sanna et al. 2015, A&A, 583, L3

3-D B field from maser linear + circular polarization



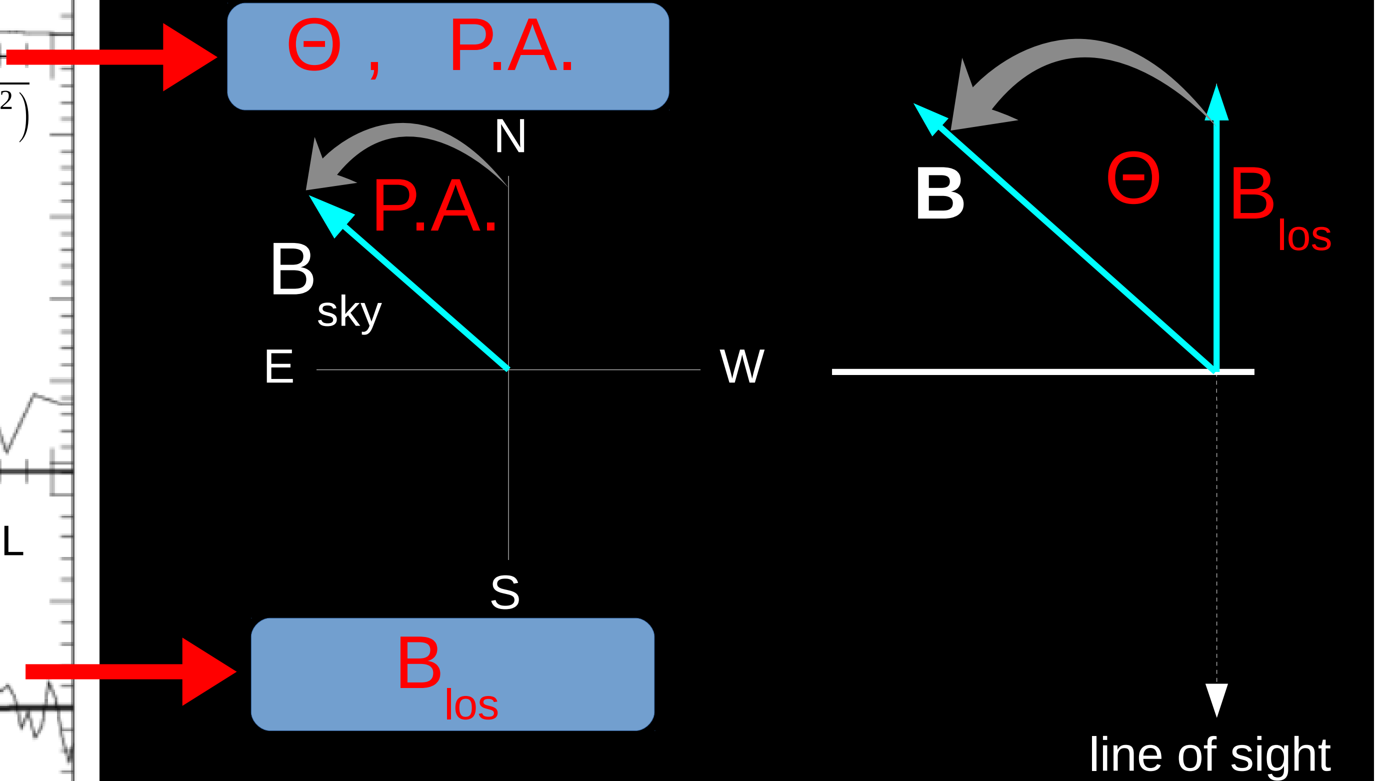
Vlemmings et al. 2015, A&A, 448, 597

Zeeman effect

maser polarization

radiative transfer

(Vlemmings et al. A&A, 394, 589)



For 6.7 GHz methanol masers:

linear polarization : a few %

circular polarization: < 1 %

SKA, a new era for maser study [1: 2018-2023, 2: <2030]

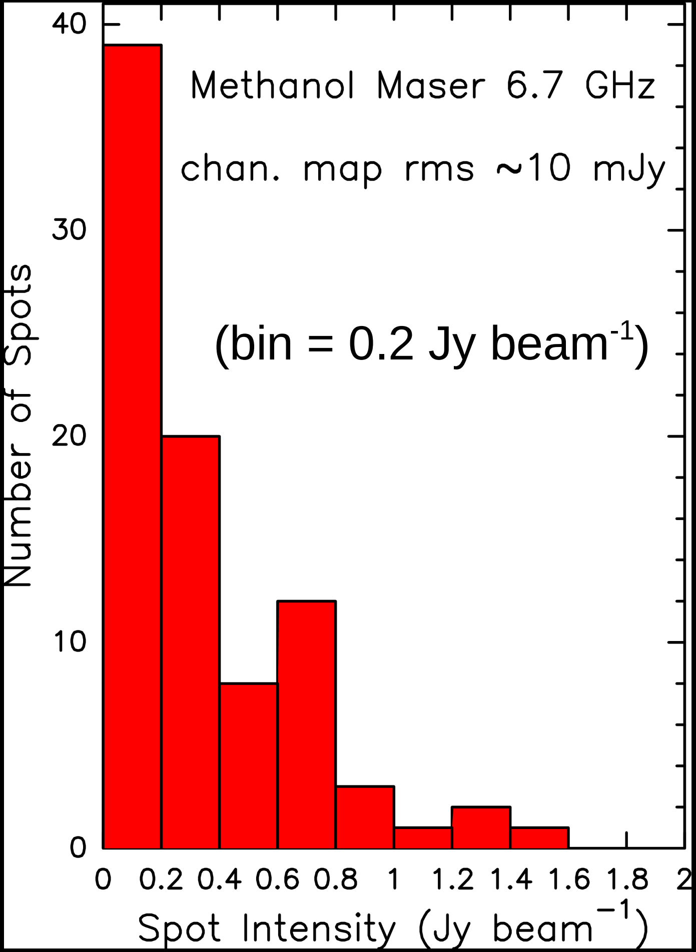
Frequency range: 0.1 – 25 GHz ↔ includes all the strongest OH, CH_3OH and H_2O masers

Angular resolution: $20/f_{GHZ}$ mas (b ~ 3000 km) ↔ comparable with EVN and VLBA

Spectral resolution: ≤ 0.2 km s^{-1} ↔ suitable to resolve maser lines

Sensitivity: ~10 μJy / channel after 8 hours ↔ ~500 times better than present VLBI

Calibrated polarization purity: $10^4 : 1$ Synthesized image dynamic range: $10^6 : 1$



A much higher number of high-SNR detections, providing:

3-D velocities for I > 50 μJy

3-D B-field for I > 100 mJy

accurate sampling of **V** and **B** in SFRs

MW dynamics: parallaxes/proper motions

for weaker/ more distant sources

To summarize:

Molecular masers are unique tool:

1) to derive 3-D motion and 3-D B-field
@ 10-1000 AU from the YSO.

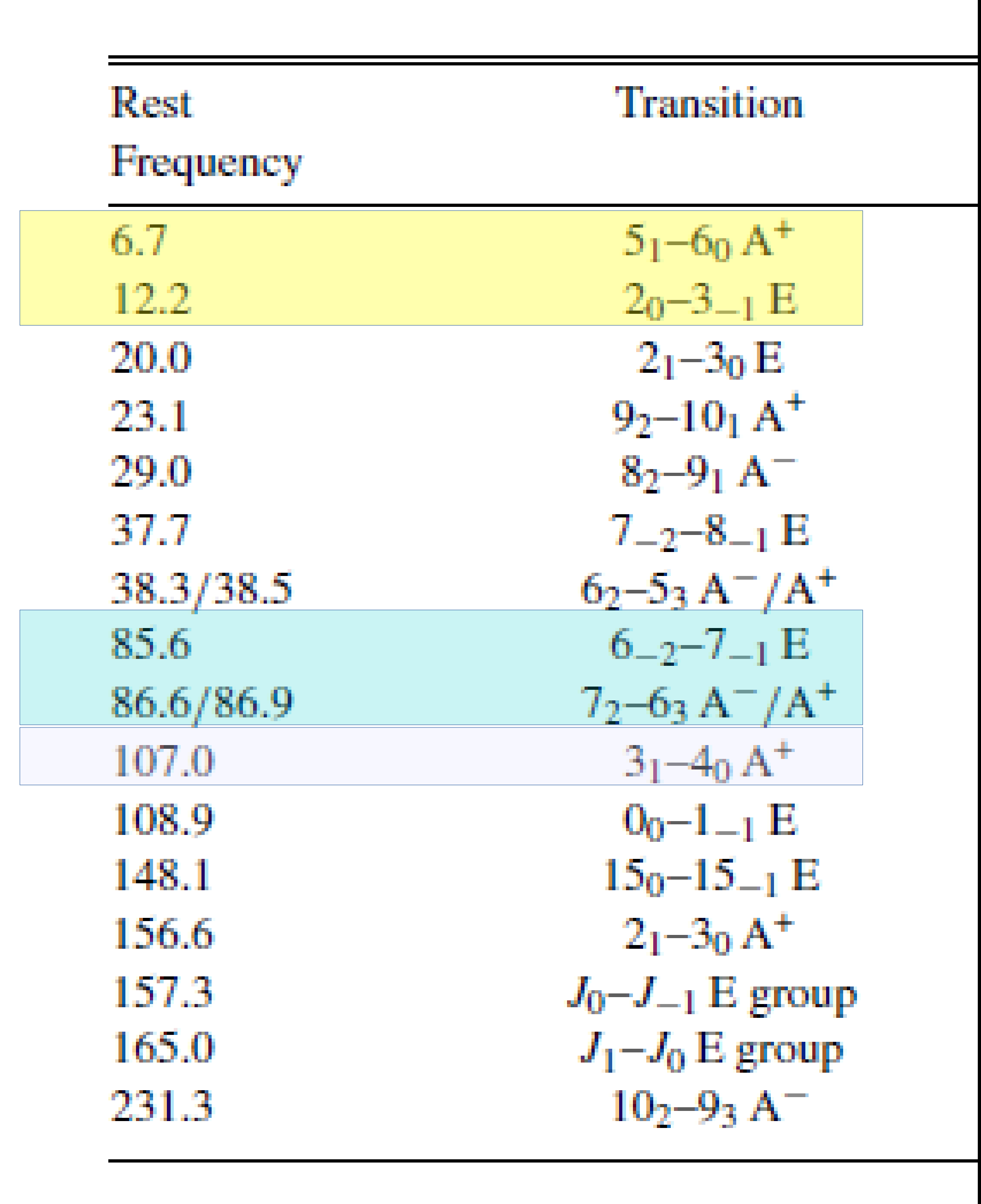
2) to study the dynamics of the Galactic disk.

Their main drawback is the non-uniform sampling:

SKA with its superb sensitivity will "populate"
YSOs' jet and disk of maser emissions.

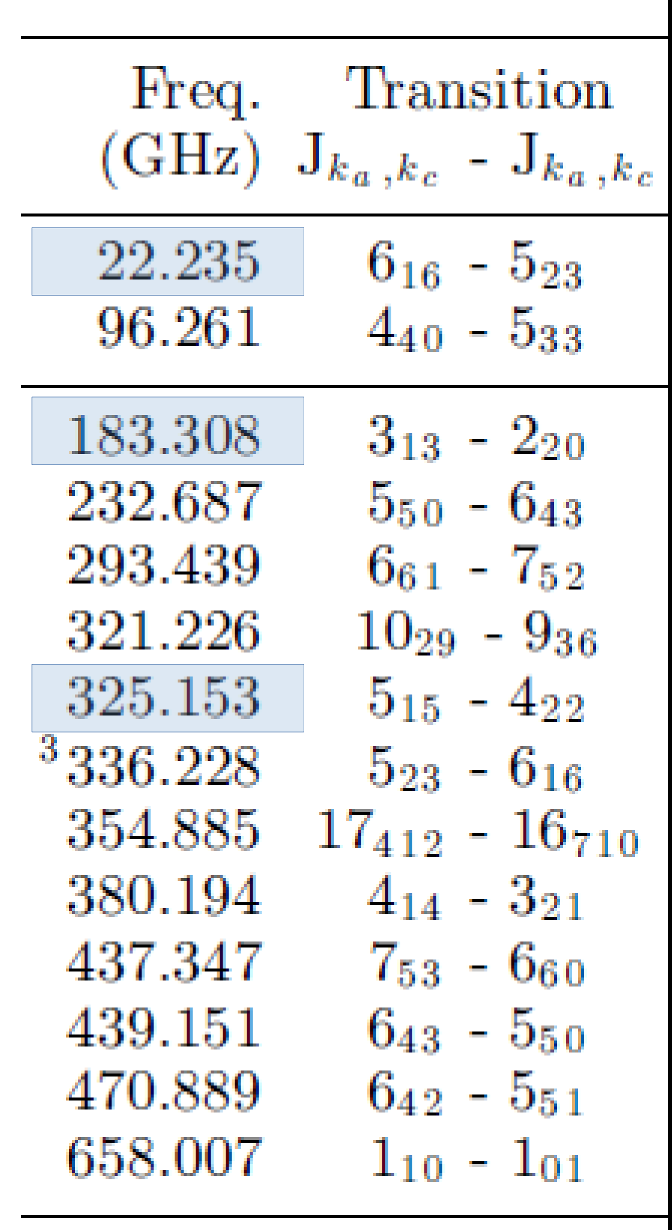
(sub)mm VLBI of molecular masers [> 2016]

Observed Class II methanol masers



Rest Frequency	Transition
6.7	5_1–6_0 A$^+$
12.2	2_0–3_{-1} E
20.0	2_1–3_0 E
23.1	9_2–10_1 A$^+$
29.0	8_2–9_1 A$^-$
37.7	7_{-2}–8_{-1} E
38.3/38.5	6_2–5_3 A$^-$/A$^+$
85.6	6_{-2}–7_{-1} E
86.6/86.9	7_2–6_3 A$^-$/A$^+$
107.0	3_1–4_0 A$^+$
108.9	0_0–1_{-1} E
148.1	15_0–15_{-1} E
156.6	2_1–3_0 A$^+$
157.3	J_0–J_{-1} E group
165.0	J_1–J_0 E group
231.3	10_2–9_3 A$^-$

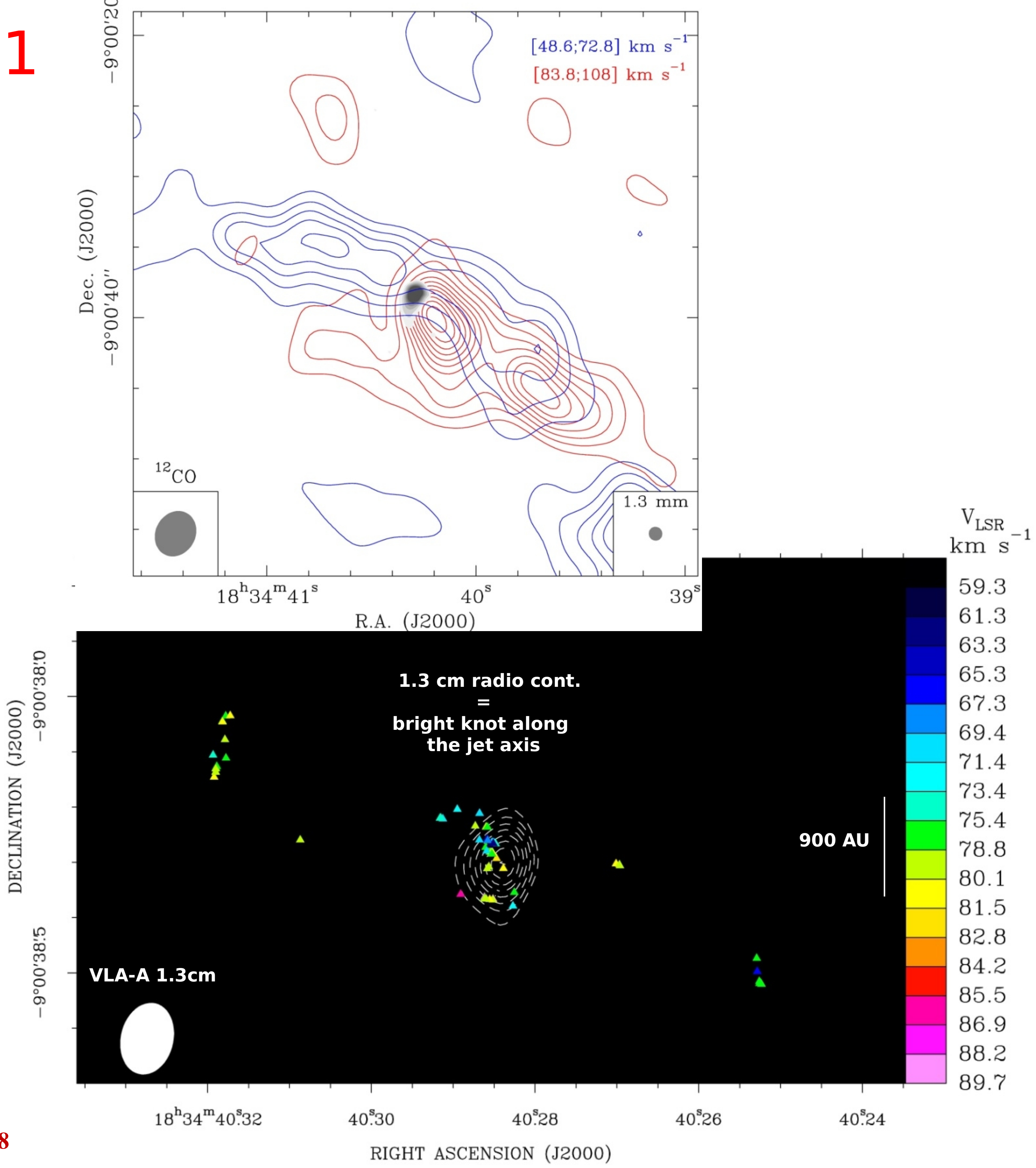
Observed water masers



Freq. (GHz)	Transition J_{k_a,k_c} - J_{k_a,k_c}
22.235	6_{16} - 5_{23}
96.261	4_{40} - 5_{33}
183.308	3_{13} - 2_{20}
232.687	5_{50} - 6_{43}
293.439	6_{61} - 7_{52}
321.226	10_{29} - 9_{36}
325.153	5_{15} - 4_{22}
[3]336.228	5_{23} - 6_{16}
354.885	$17_{4\,12}$ - $16_{7\,10}$
380.194	4_{14} - 3_{21}
437.347	7_{53} - 6_{60}
439.151	6_{43} - 5_{50}
470.889	6_{42} - 5_{51}
658.007	1_{10} - 1_{01}

G23.01-0.41

≈ 20 $M_\odot$

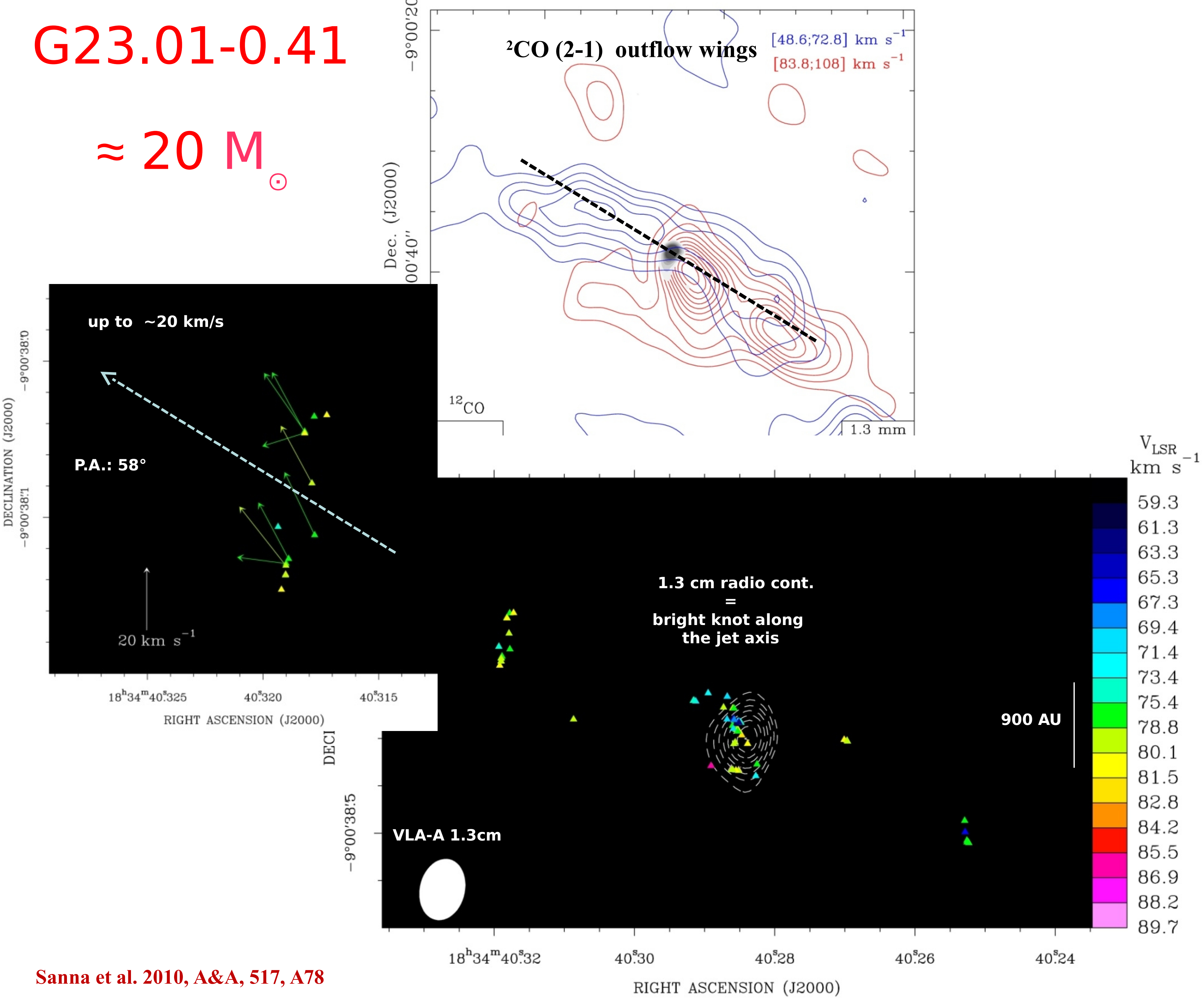


1.3 cm radio cont.
=
bright knot along
the jet axis

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

G23.01-0.41

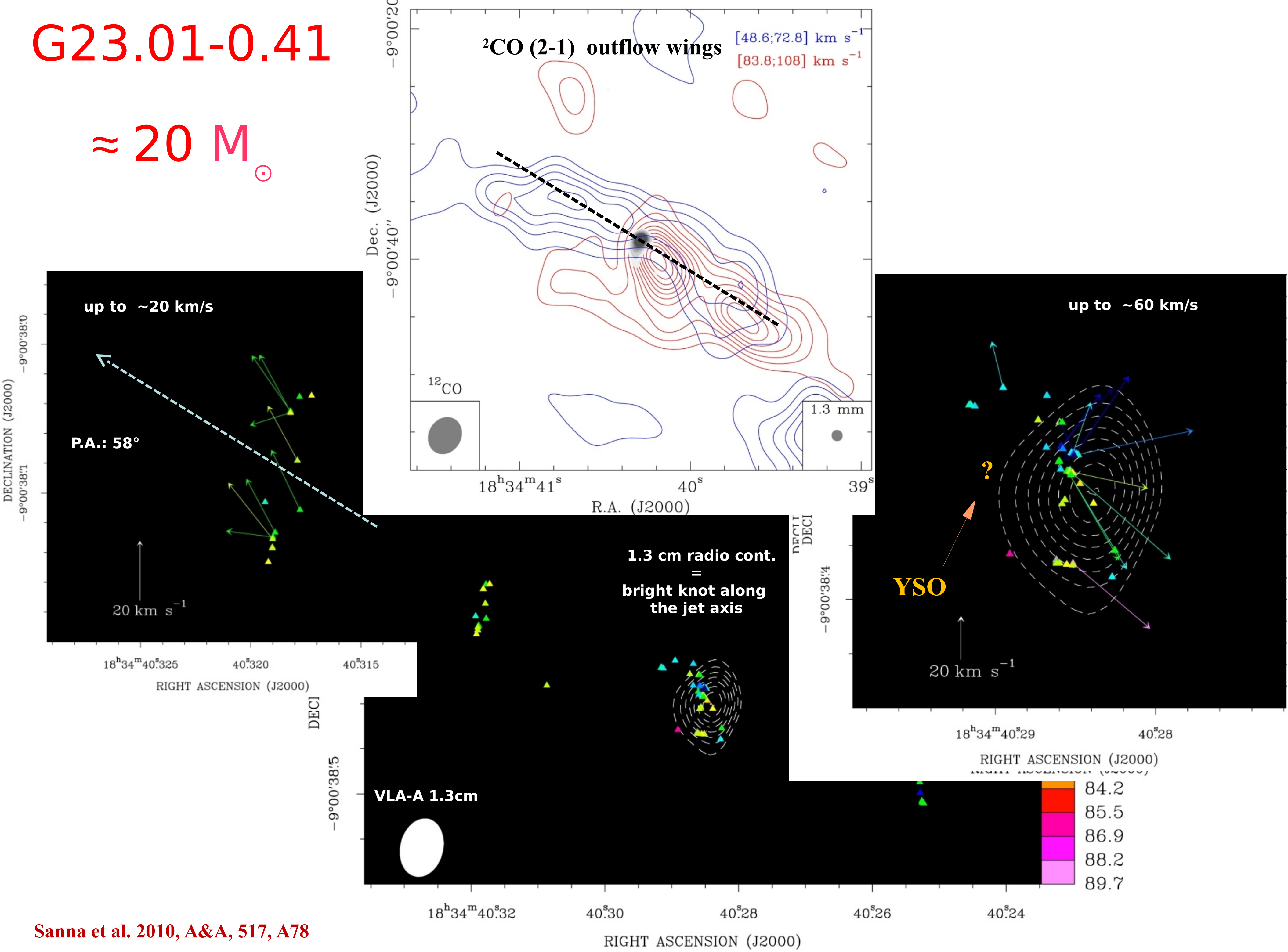
≈ 20 $M_\odot$



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

G23.01-0.41

$\approx 20\ M_\odot$



²CO (2-1) outflow wings

up to ~20 km/s

P.A.: 58°

1.3 cm radio cont. = bright knot along the jet axis

up to ~60 km/s

YSO

?

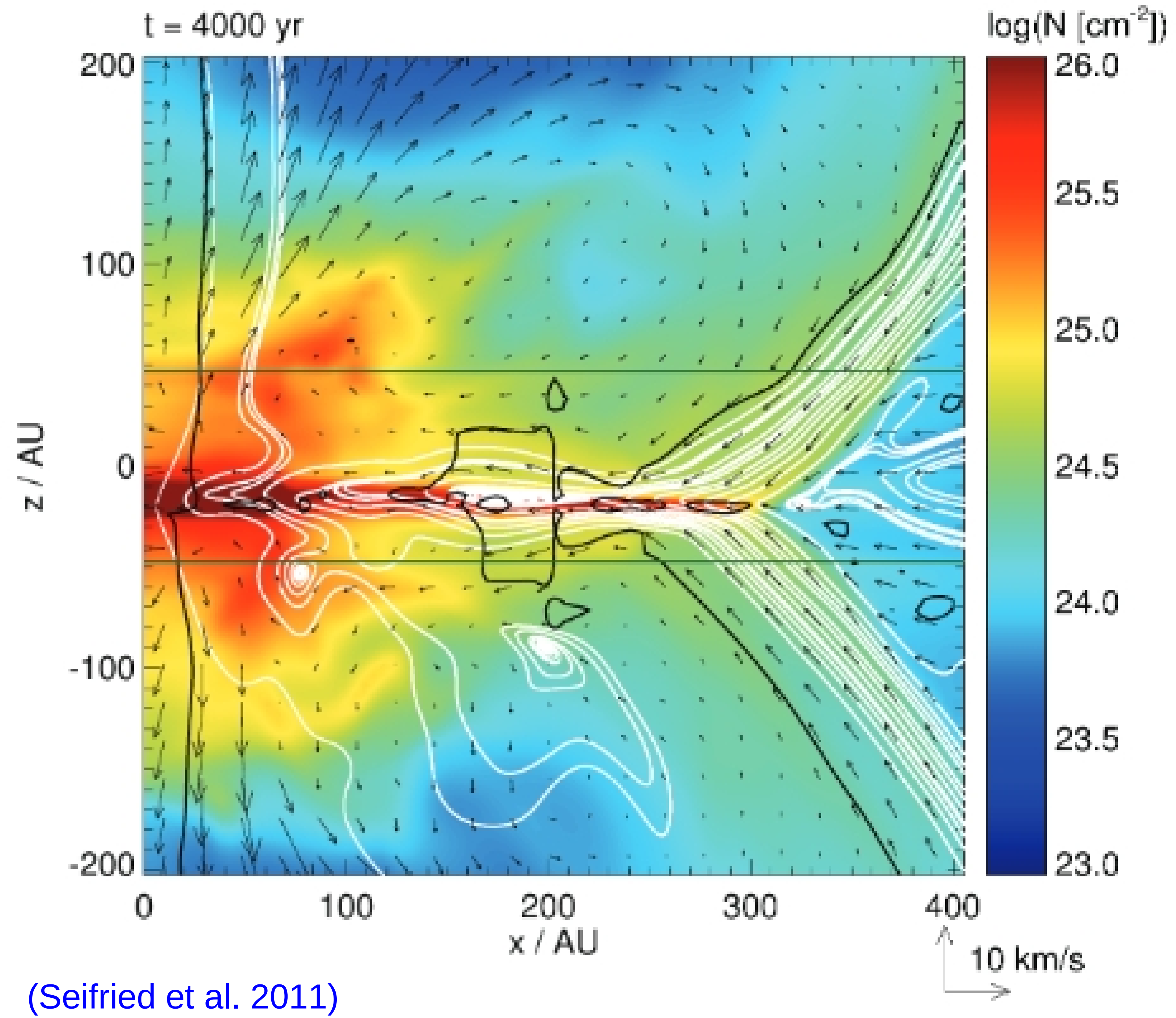
VLA-A 1.3cm

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

Simulation of protostellar velocity and magnetic fields

— **B**

→ **V**



(Seifried et al. 2011)

CH_3OH & H_2O maser 3-D Velocity & Magnetic Field

Large Program @ EVN

to be completed in 5 years

From circular polarization measurements

(Zeeman splitting) we derive the value of B_{los}

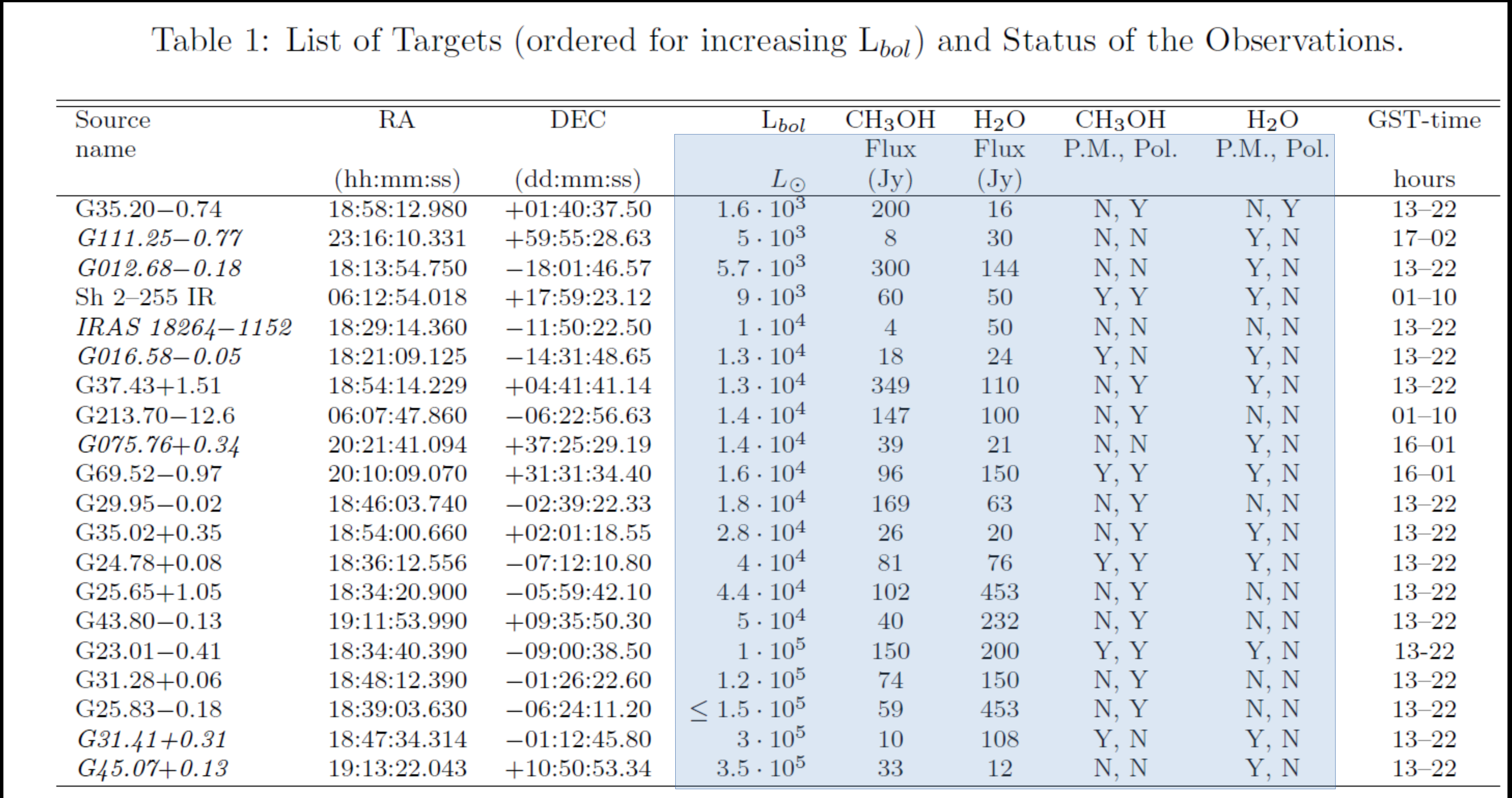
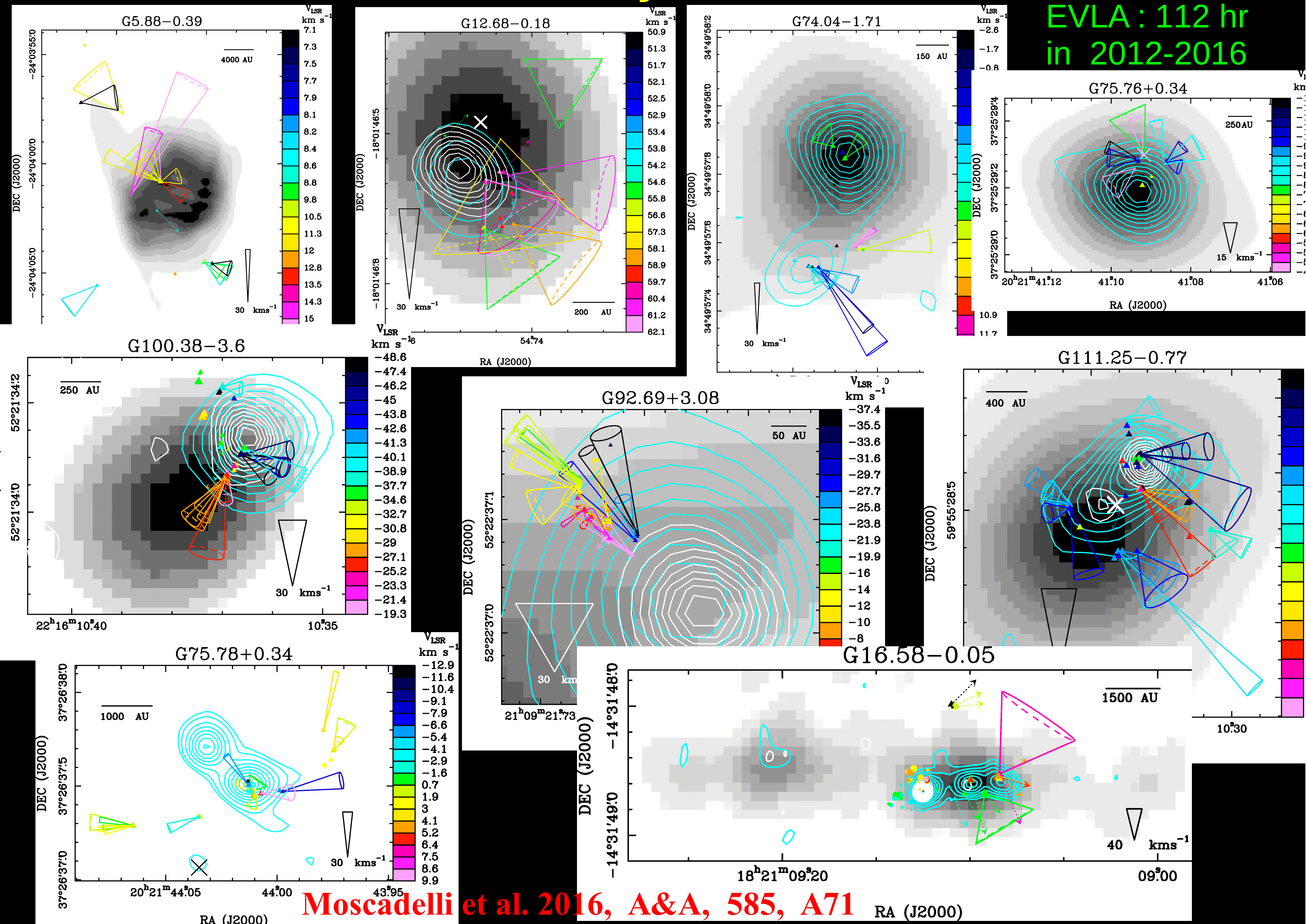


Table 1: List of Targets (ordered for increasing L_{bol}) and Status of the Observations.

Source name	RA (hh:mm:ss)	DEC (dd:mm:ss)	L_{bol} $L_\odot$	CH_3OH Flux (Jy)	H_2O Flux (Jy)	CH_3OH P.M., Pol.	H_2O P.M., Pol.	GST-time hours
G35.20−0.74	18:58:12.980	+01:40:37.50	$1.6 \cdot 10^3$	200	16	N, Y	N, Y	13–22
G111.25−0.77	23:16:10.331	+59:55:28.63	$5 \cdot 10^3$	8	30	N, N	Y, N	17–02
G012.68−0.18	18:13:54.750	−18:01:46.57	$5.7 \cdot 10^3$	300	144	N, N	Y, N	13–22
Sh 2–255 IR	06:12:54.018	+17:59:23.12	$9 \cdot 10^3$	60	50	Y, Y	Y, N	01–10
IRAS 18264−1152	18:29:14.360	−11:50:22.50	$1 \cdot 10^4$	4	50	N, N	N, N	13–22
G016.58−0.05	18:21:09.125	−14:31:48.65	$1.3 \cdot 10^4$	18	24	Y, N	Y, N	13–22
G37.43+1.51	18:54:14.229	+04:41:41.14	$1.3 \cdot 10^4$	349	110	N, Y	Y, N	13–22
G213.70−12.6	06:07:47.860	−06:22:56.63	$1.4 \cdot 10^4$	147	100	N, Y	N, N	01–10
G075.76+0.34	20:21:41.094	+37:25:29.19	$1.4 \cdot 10^4$	39	21	N, N	Y, N	16–01
G69.52−0.97	20:10:09.070	+31:31:34.40	$1.6 \cdot 10^4$	96	150	Y, Y	Y, N	16–01
G29.95−0.02	18:46:03.740	−02:39:22.33	$1.8 \cdot 10^4$	169	63	N, Y	N, N	13–22
G35.02+0.35	18:54:00.660	+02:01:18.55	$2.8 \cdot 10^4$	26	20	N, Y	Y, N	13–22
G24.78+0.08	18:36:12.556	−07:12:10.80	$4 \cdot 10^4$	81	76	Y, Y	Y, N	13–22
G25.65+1.05	18:34:20.900	−05:59:42.10	$4.4 \cdot 10^4$	102	453	N, Y	N, N	13–22
G43.80−0.13	19:11:53.990	+09:35:50.30	$5 \cdot 10^4$	40	232	N, Y	N, N	13–22
G23.01−0.41	18:34:40.390	−09:00:38.50	$1 \cdot 10^5$	150	200	Y, Y	Y, N	13-22
G31.28+0.06	18:48:12.390	−01:26:22.60	$1.2 \cdot 10^5$	74	150	N, Y	N, N	13–22
G25.83−0.18	18:39:03.630	−06:24:11.20	$\leq 1.5 \cdot 10^5$	59	453	N, Y	N, N	13–22
G31.41+0.31	18:47:34.314	−01:12:45.80	$3 \cdot 10^5$	10	108	Y, N	Y, N	13–22
G45.07+0.13	19:13:22.043	+10:50:53.34	$3.5 \cdot 10^5$	33	12	N, N	Y, N	13–22

EVLA / BeSSeL Survey of massive outflows

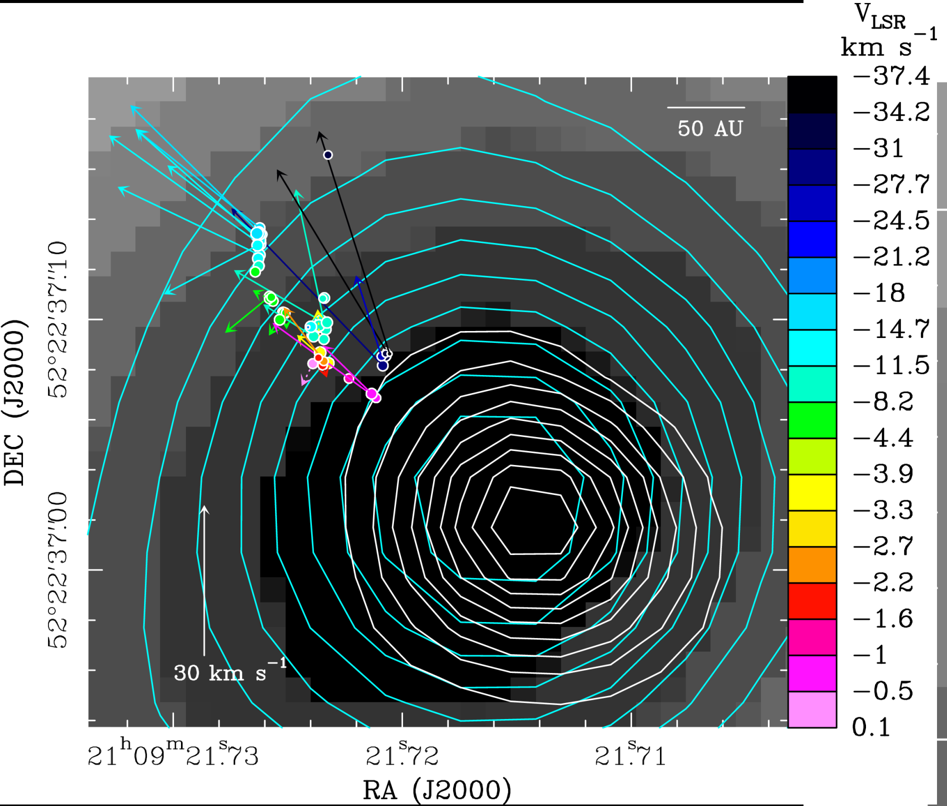
EVLA : 112 hr
in 2012-2016

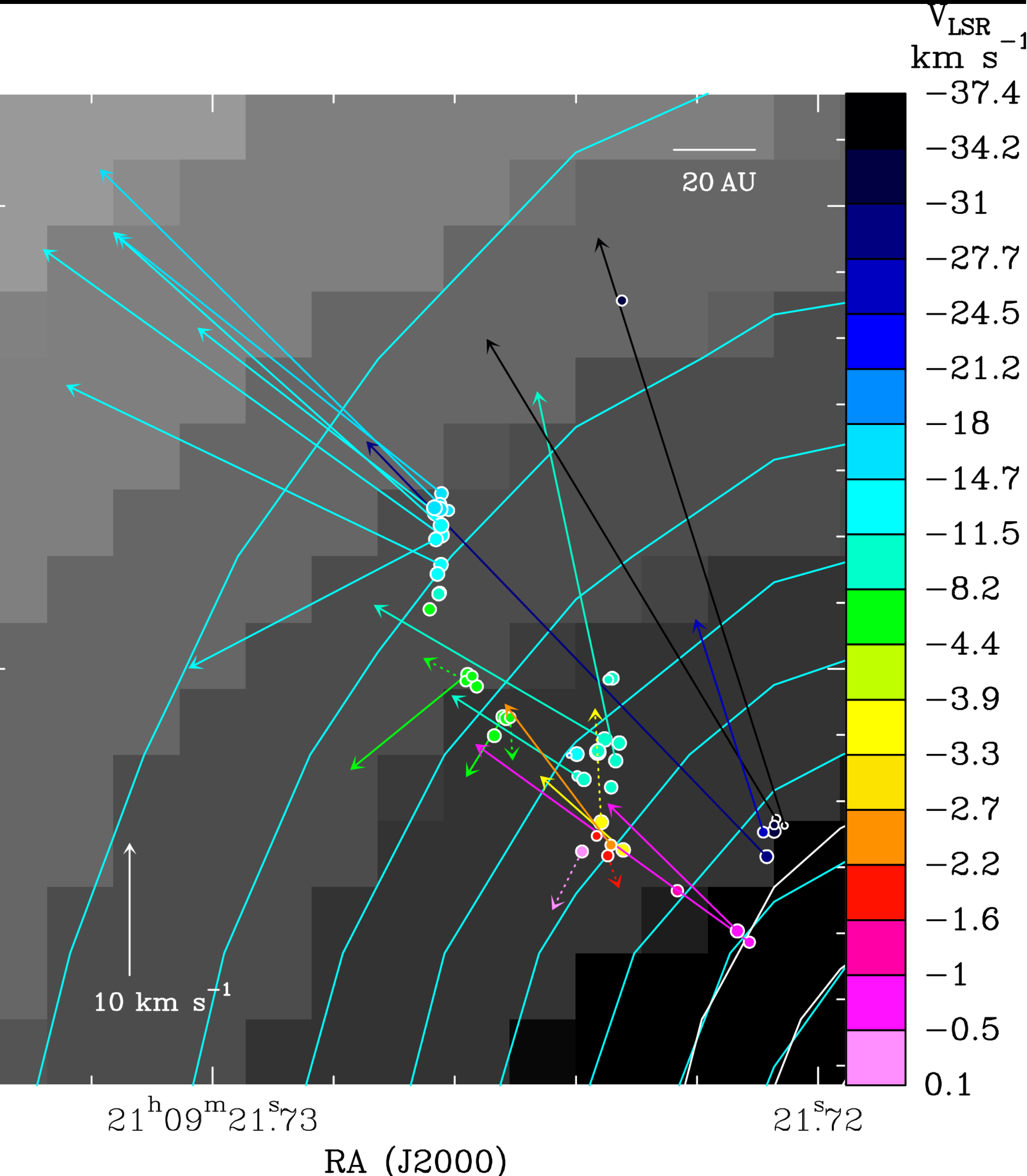


Moscadelli et al. 2016, A&A, 585, A71

Hint at Jet Rotation in G92.69+3.08

EVLA continuum: 6 GHz and 22 GHz





Physics / kinematics in the maser surroundings

(on-going – planned observations)

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

Continuum → (sub)arcsecond structure of outflow cavity

NIR H_2 and [FeII] Lines → (sub)arcsecond jet 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