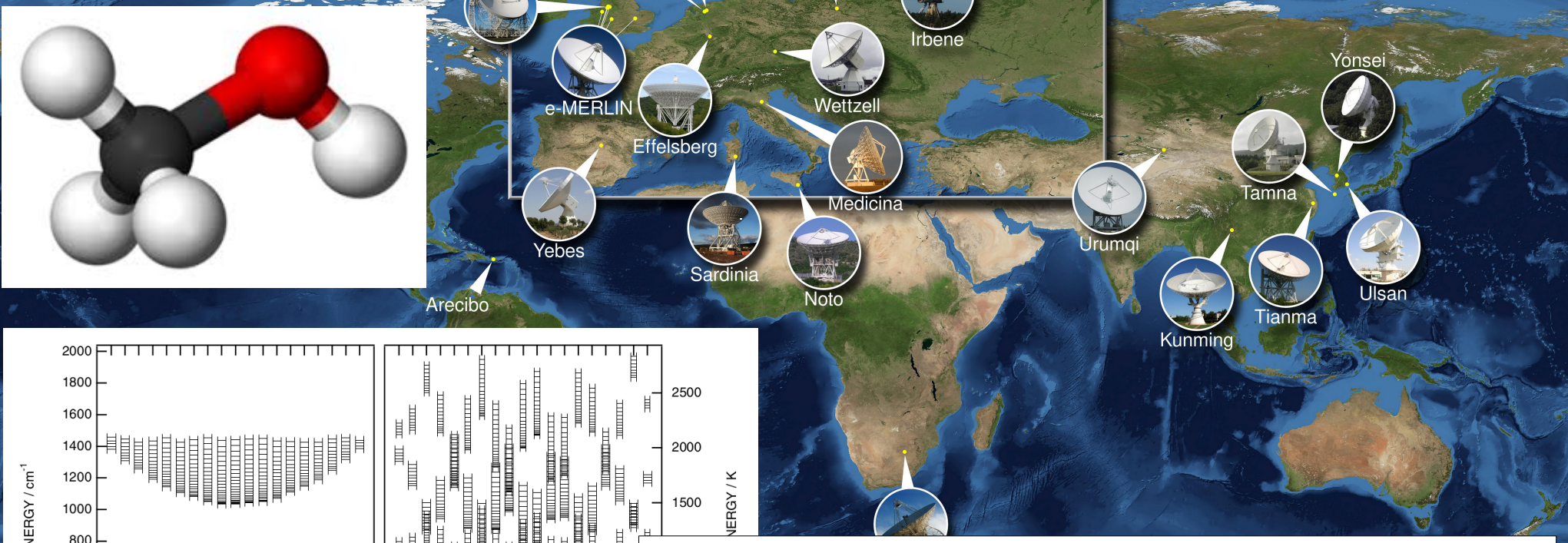
EVN observations of the high-frequency methanol masers

JIVE
Joint Institute for VLBI ERIC

EUROPEAN vlbi NETWORK



Luca Moscadelli

INAF – Osservatorio Astrofisico di Arcetri

Courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

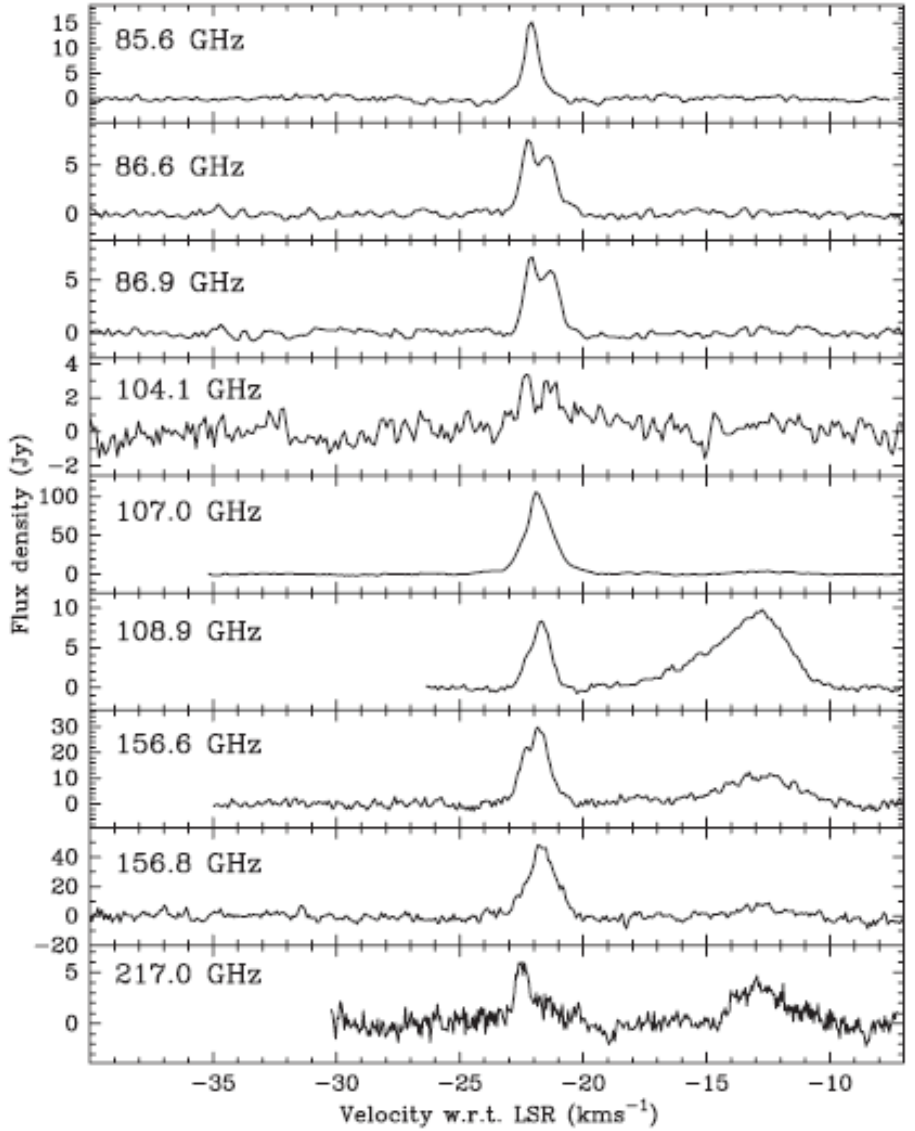
Class II methanol masers at cm and mm wavelengths

Observed Class II methanol masers

Rest Frequency	Transition
6.7	5_1–6_0 A^+
12.2	2_0–3_{-1} E
20.0 (19.9)	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^-

Class II CH_3OH masers in G345.01+1.79

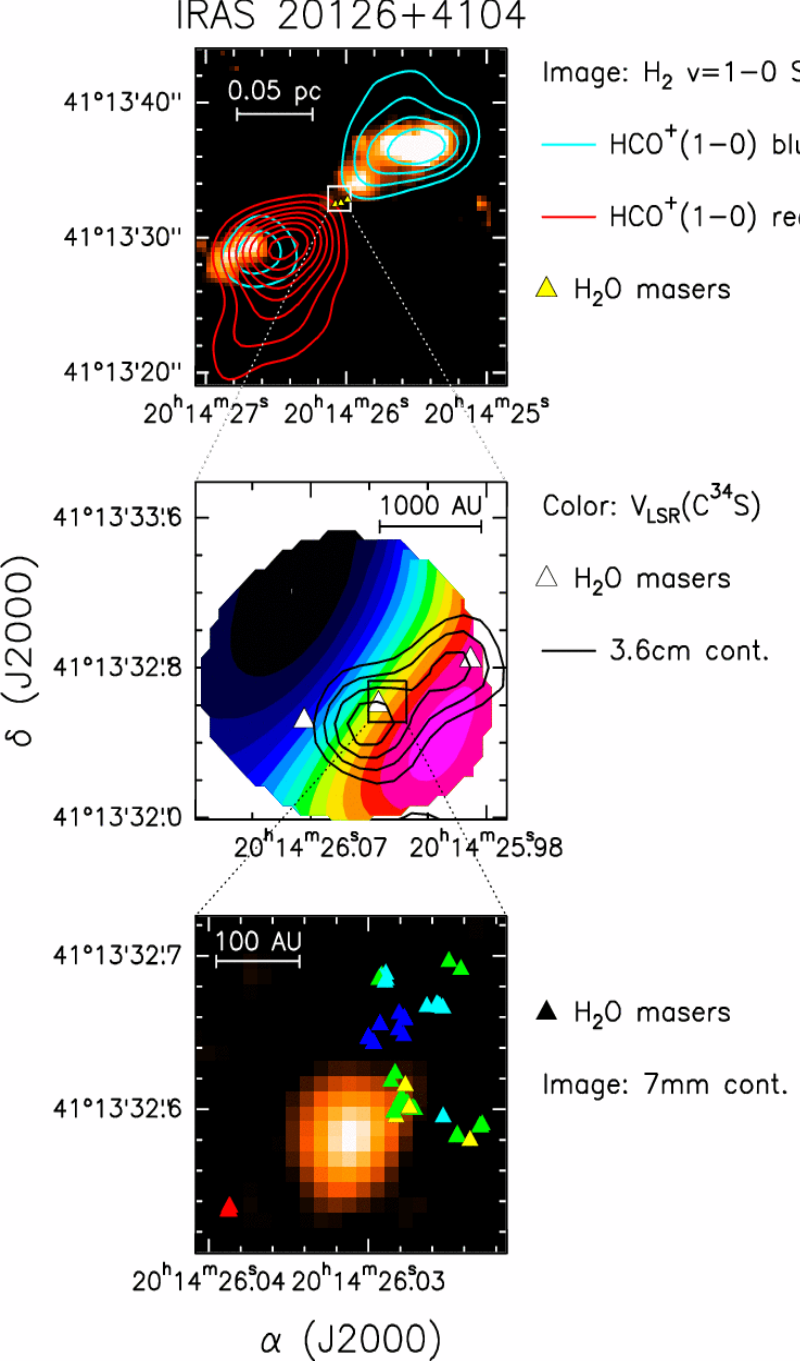
(Ellingsen et al. 2012)



IRAS 20126+4104

$M_* \sim 12\ M_\odot$ d = 1.64 ± 0.05 kpc

Cesaroni et al.
Hofner et al.
Moscadelli et al.



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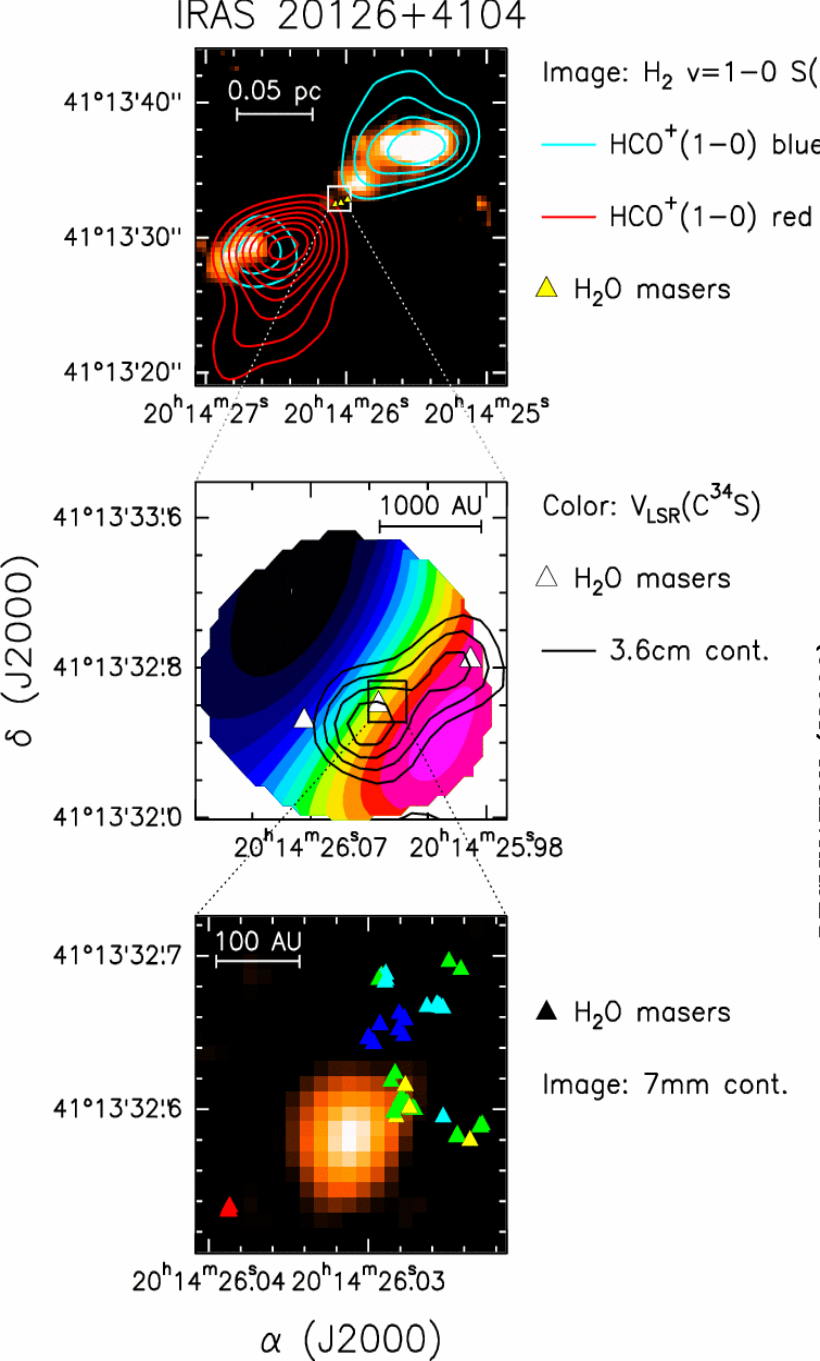
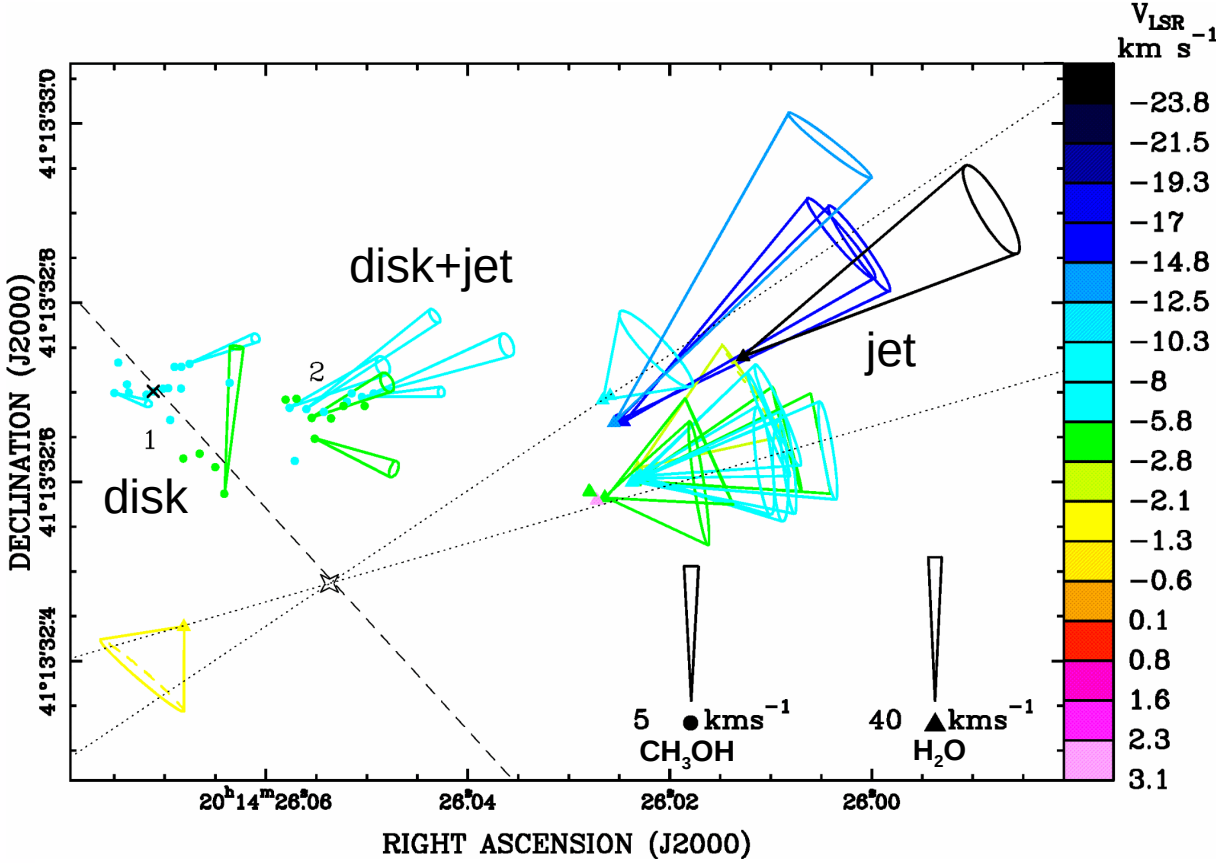


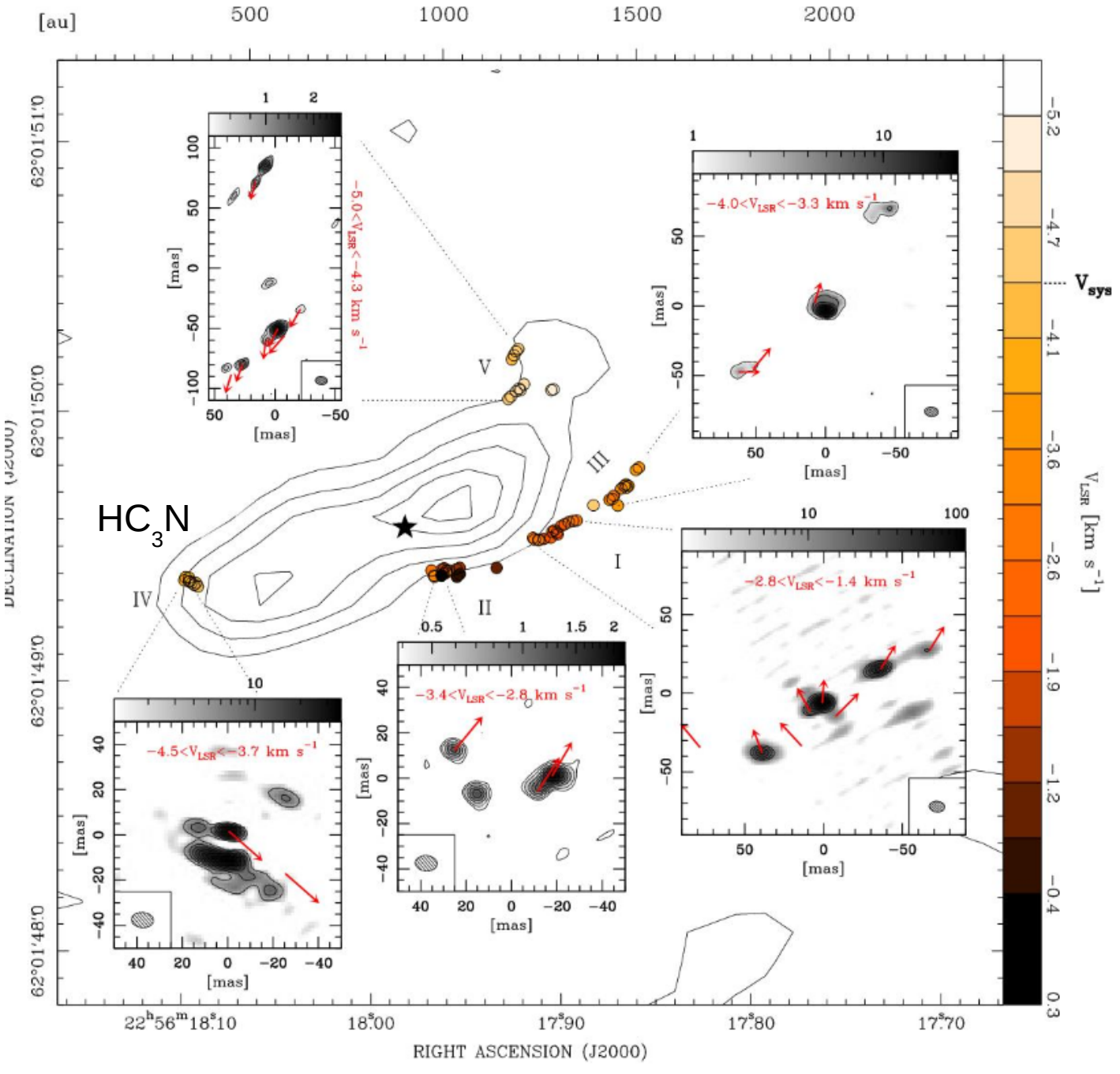


Moscadelli et al. (2011)

Cep A - HW2

$M_* \sim 16\ M_\odot$

$d = 0.7 \pm 0.04$ kpc

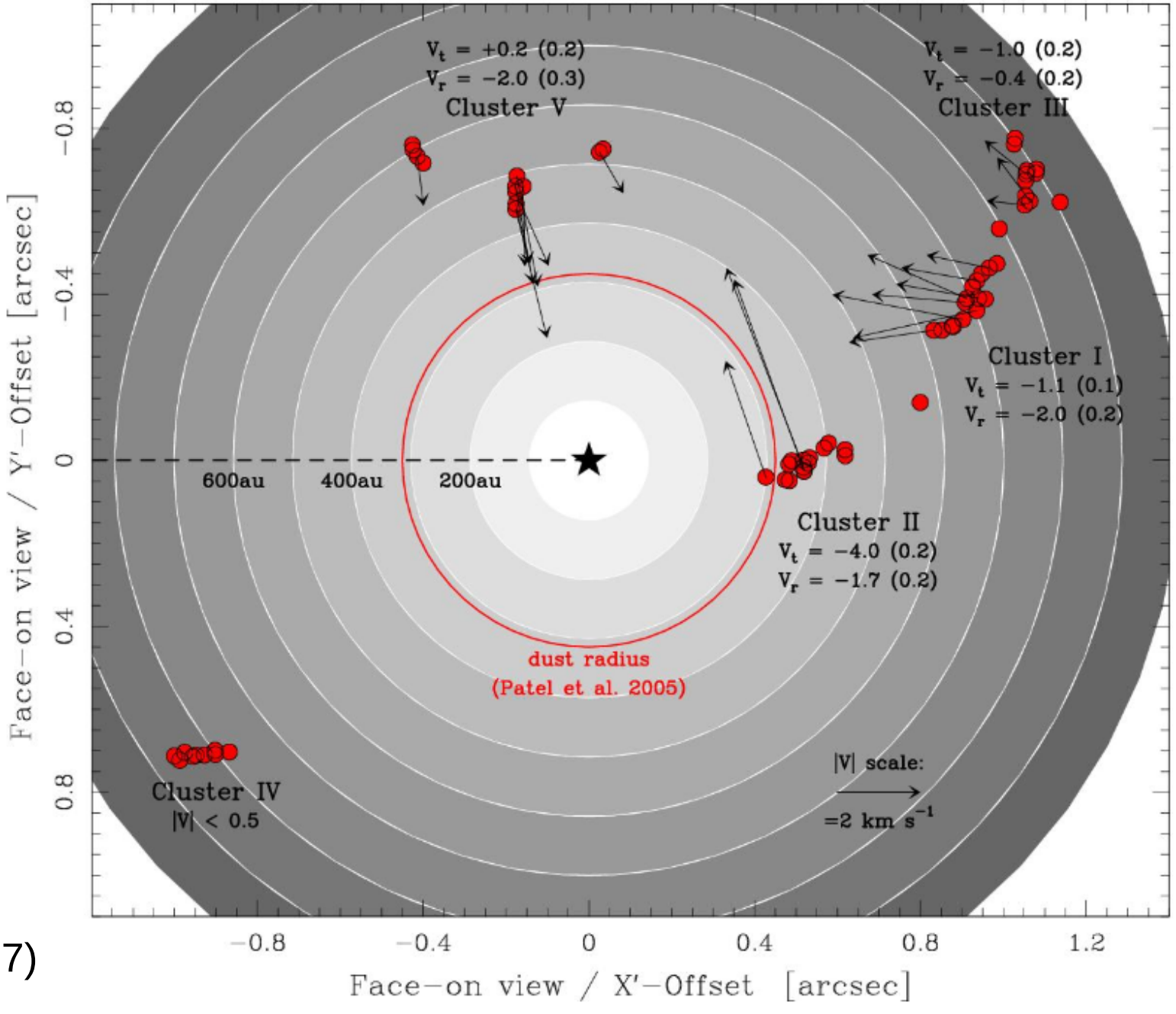


Sanna et al. (2017)

Cep A - HW2

$M_* \sim 16\ M_\odot$

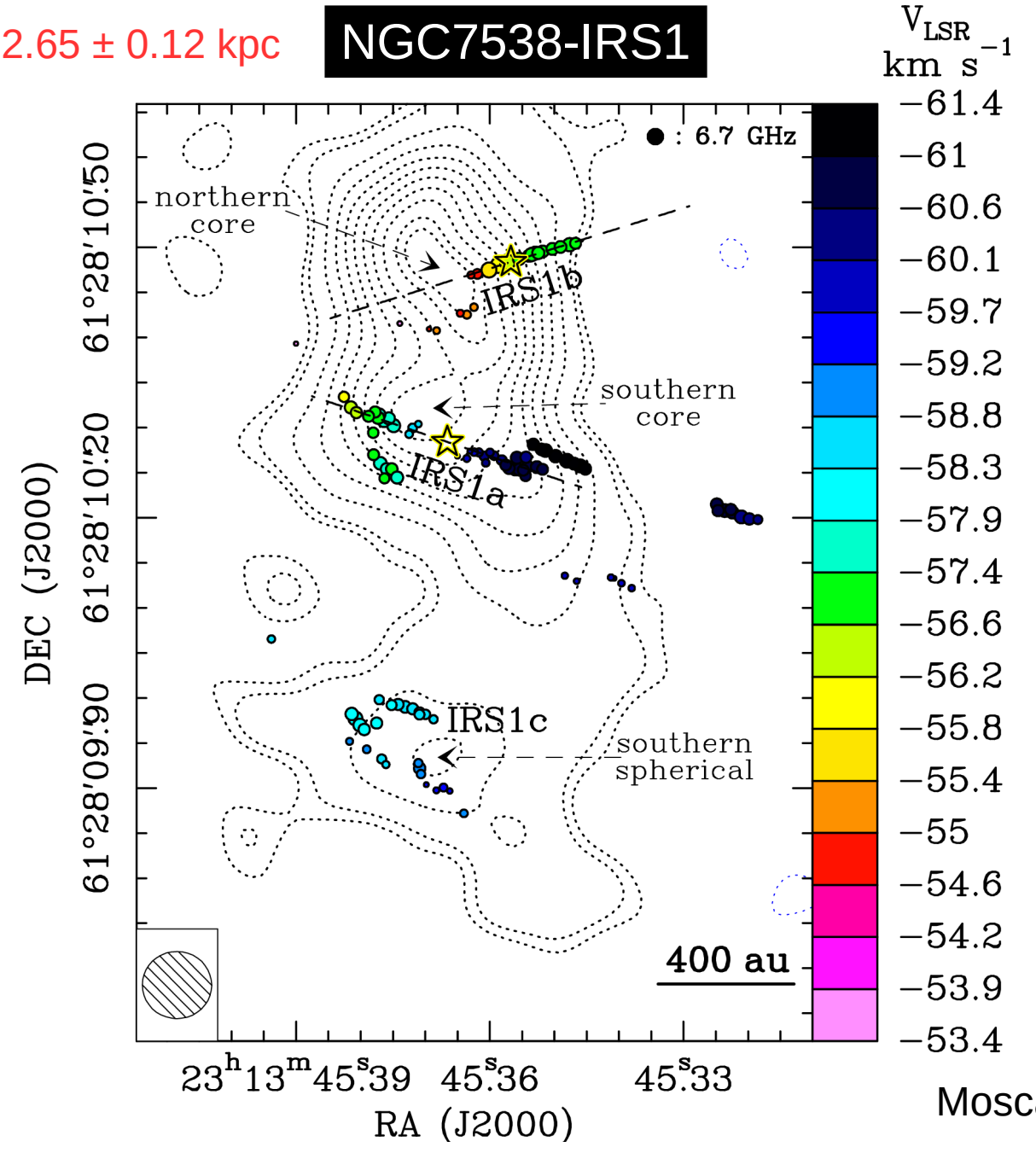
$d = 0.7 \pm 0.04$ kpc



Sanna et al. (2017)

$M_* \sim 25\ M_\odot$ d = 2.65 ± 0.12 kpc

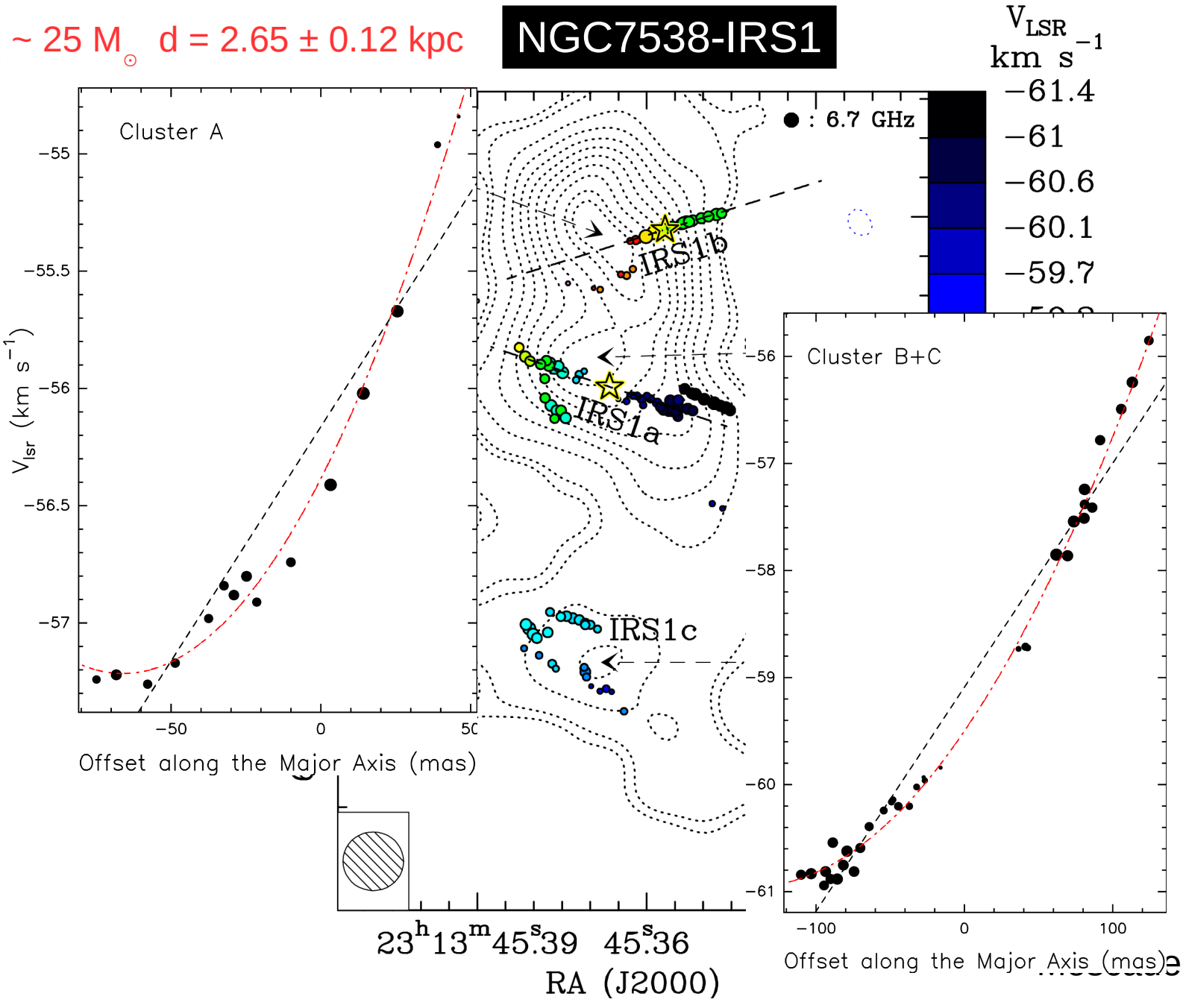
NGC7538-IRS1



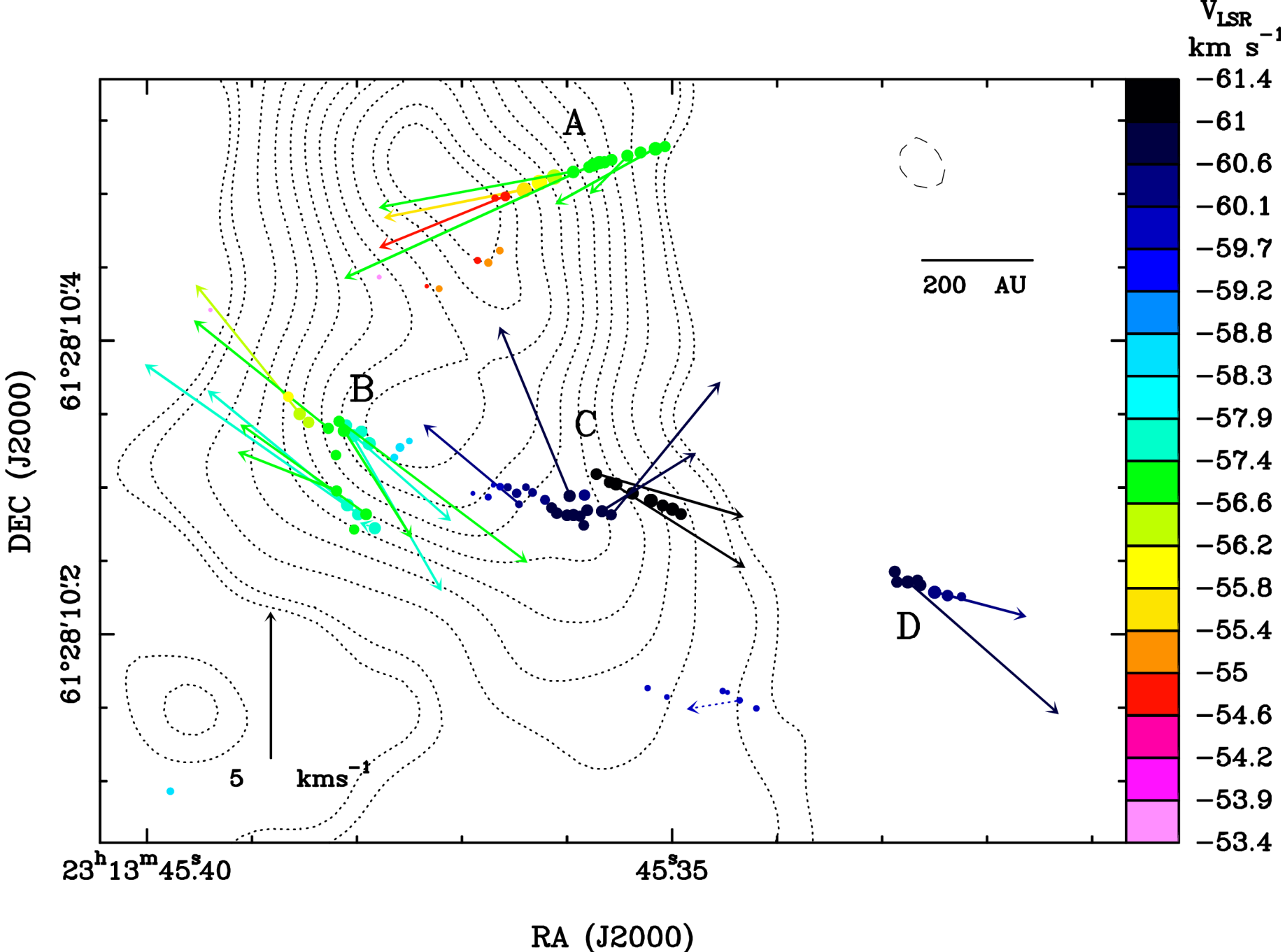
Moscadelli et al. (2025)

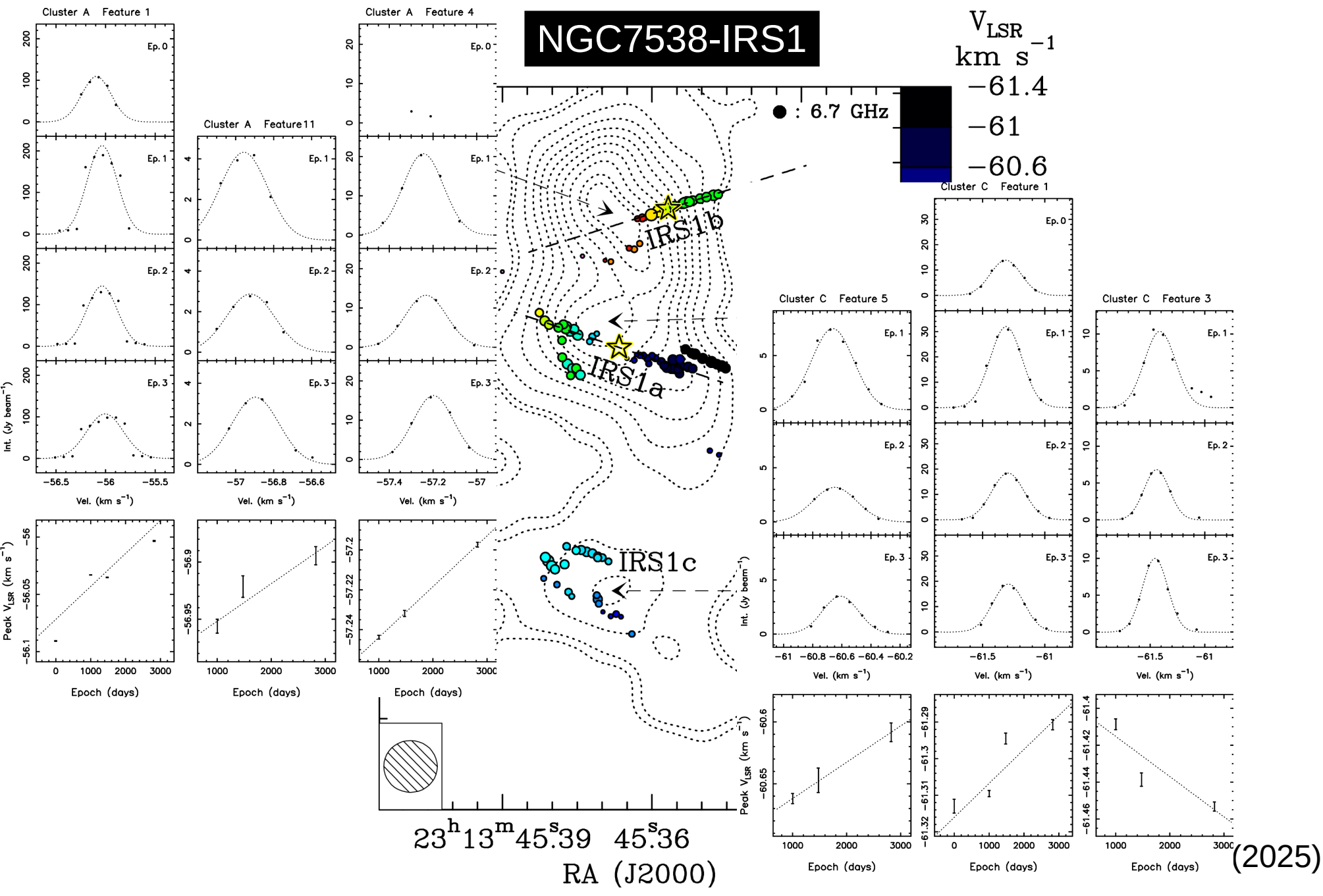
$M_* \sim 25\ M_\odot$ $d = 2.65 \pm 0.12$ kpc

NGC7538-IRS1

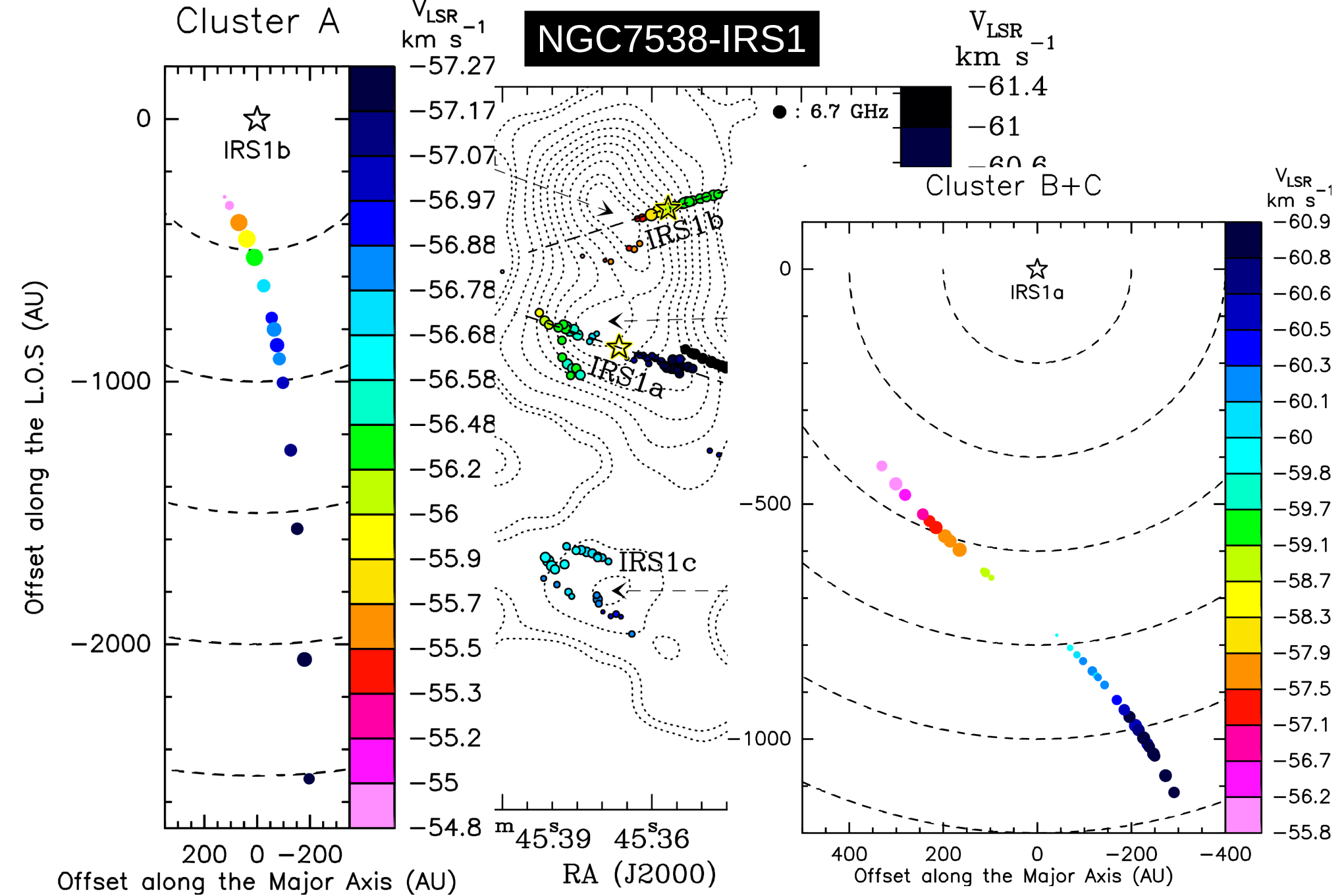


Mesa-Delgado et al. (2025)


A
B
C
D
200 AU
5 kms^{-1}
DEC (J2000)
61°28'10".4
61°28'10".2
23^{h}13^{m}45^{s}.40
45^{s}.35
RA (J2000)
V_{LSR}
km s^{-1}
−61.4
−61
−60.6
−60.1
−59.7
−59.2
−58.8
−58.3
−57.9
−57.4
−56.6
−56.2
−55.8
−55.4
−55
−54.6
−54.2
−53.9
−53.4

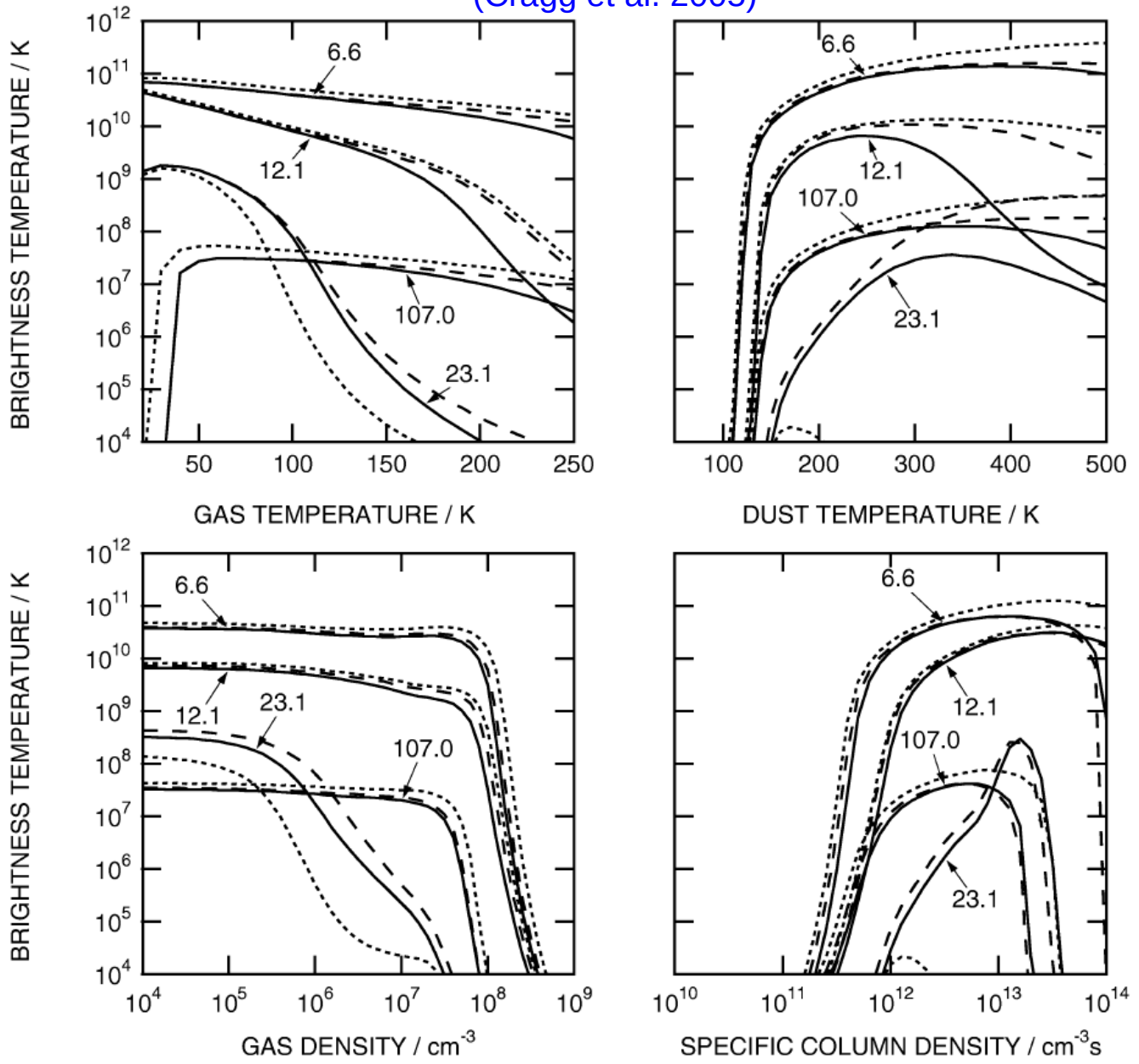

NGC7538-IRS1
V_{LSR} km s^{-1}
−61.4
−61
−60.6
● : 6.7 GHz
IRS1b
IRS1a
IRS1c
Cluster A Feature 1
Cluster A Feature11
Cluster A Feature 4
Cluster C Feature 1
Cluster C Feature 5
Cluster C Feature 3
Ep. 0
Ep. 1
Ep. 2
Ep. 3
Int. (Jy beam^{-1})
Vel. (km s^{-1})
Peak V_{LSR} (km s^{-1})
Epoch (days)
23^{h}13^{m}45^s.39 45^s.36
RA (J2000)

(2025)

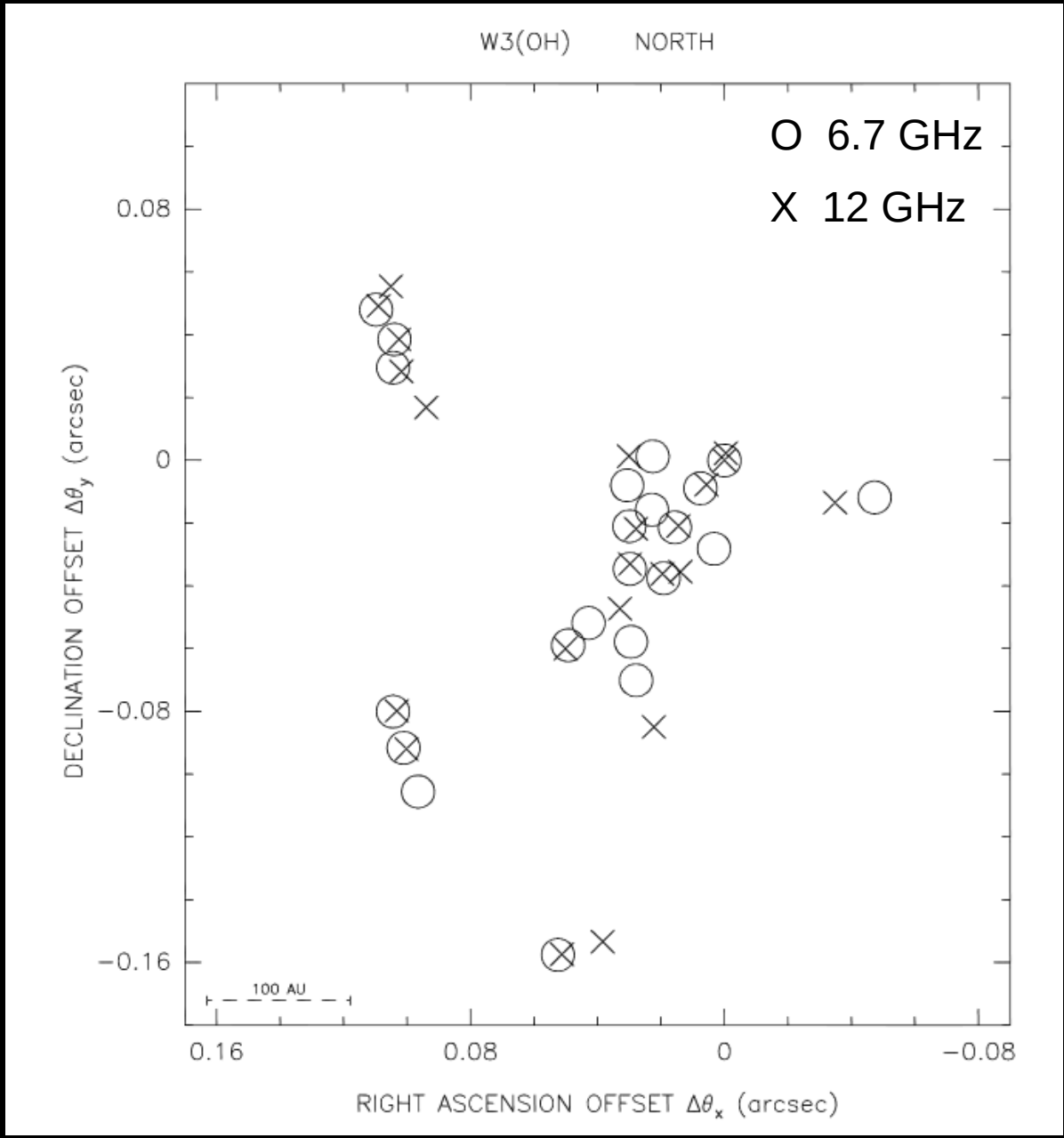

NGC7538-IRS1
Cluster A
Cluster B+C
IRS1b
IRS1a
IRS1c
● : 6.7 GHz
V_{LSR} km s^{-1}
−57.27
−57.17
−57.07
−56.97
−56.88
−56.78
−56.68
−56.58
−56.48
−56.2
−56
−55.9
−55.7
−55.5
−55.3
−55.2
−55
−54.8
−61.4
−61
−60.9
−60.8
−60.6
−60.5
−60.3
−60.1
−60
−59.8
−59.7
−59.1
−58.7
−58.3
−57.9
−57.5
−57.1
−56.7
−56.2
−55.8
0
−1000
−2000
−500
−1000
Offset along the L.O.S (AU)
200 0 −200
Offset along the Major Axis (AU)
400 200 0 −200 −400
Offset along the Major Axis (AU)
m 45.s39 45.s36
RA (J2000)

Methanol maser excitation models

(Cragg et al. 2005)



6.7 and 12 GHz methanol maser in W3(OH)

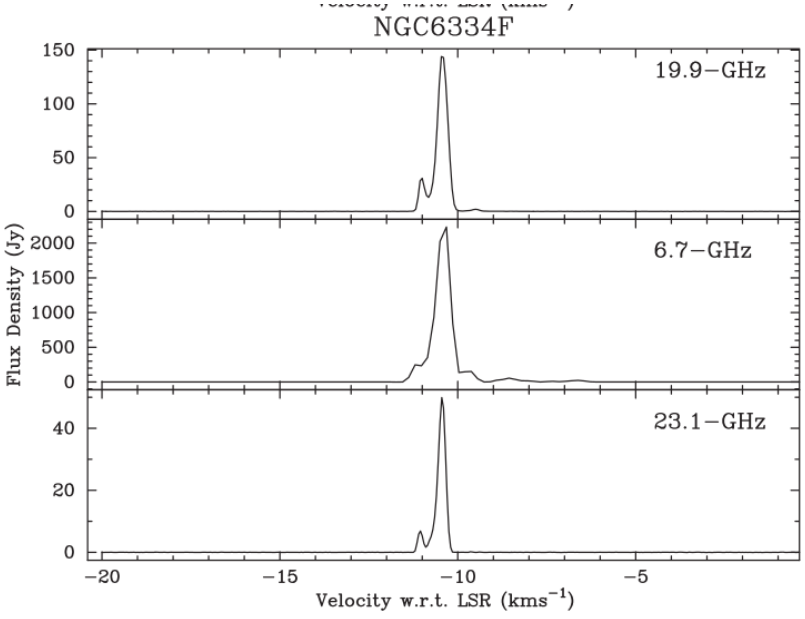


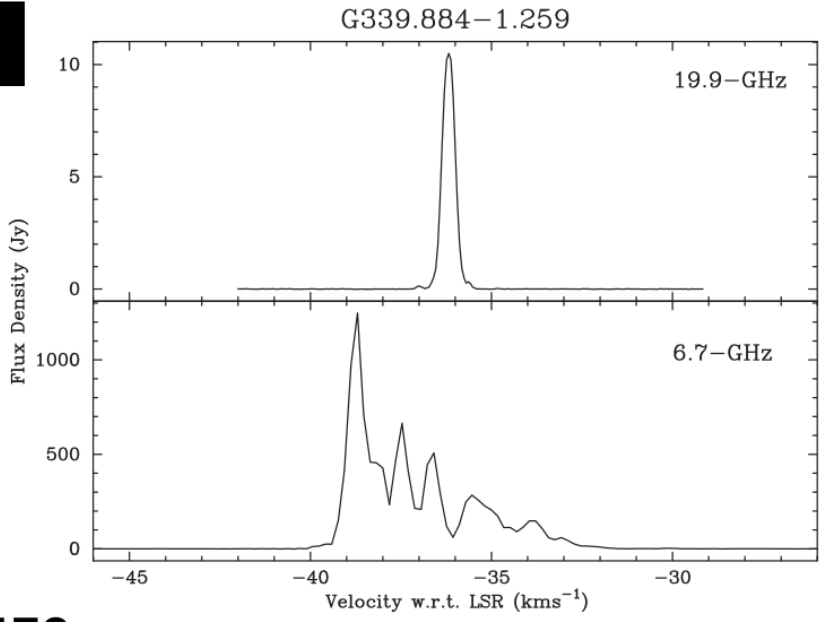
(Moscadelli et al. 1999)

19.9 GHz

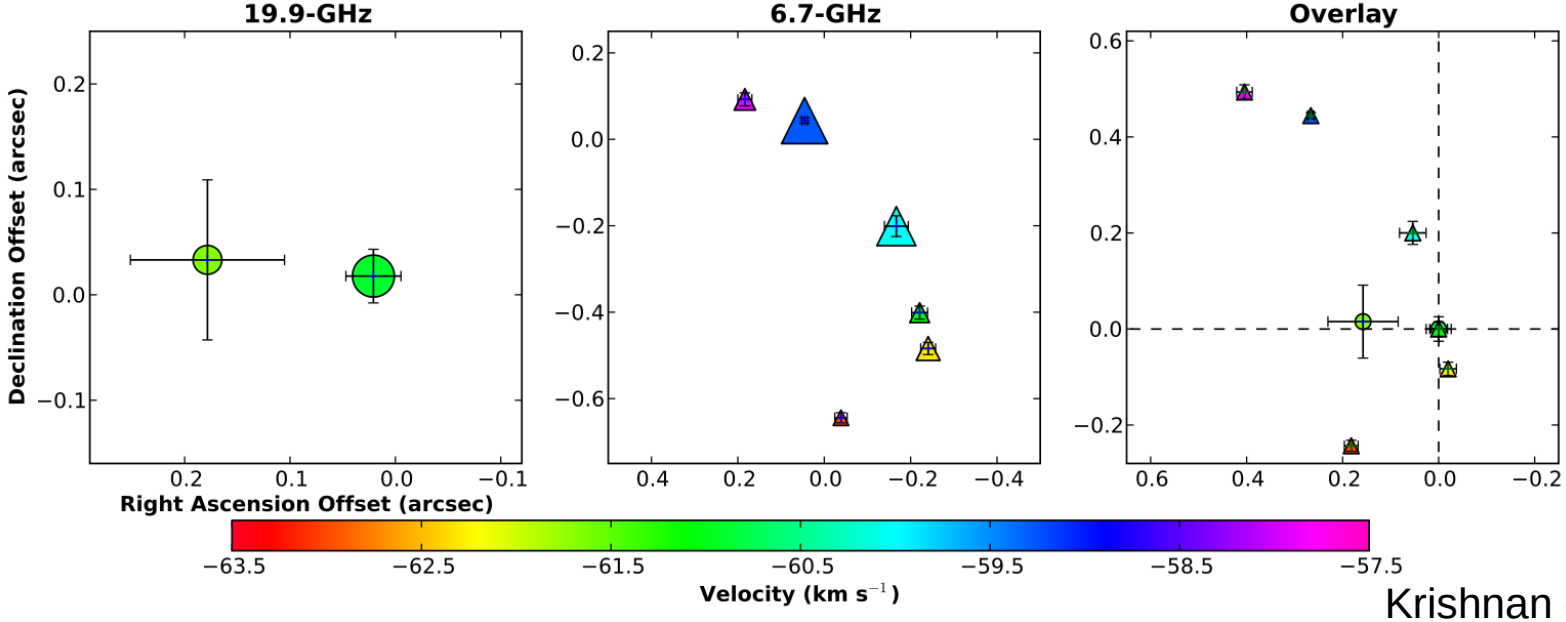
ATCA

(0.5”)





G309.921+0.479



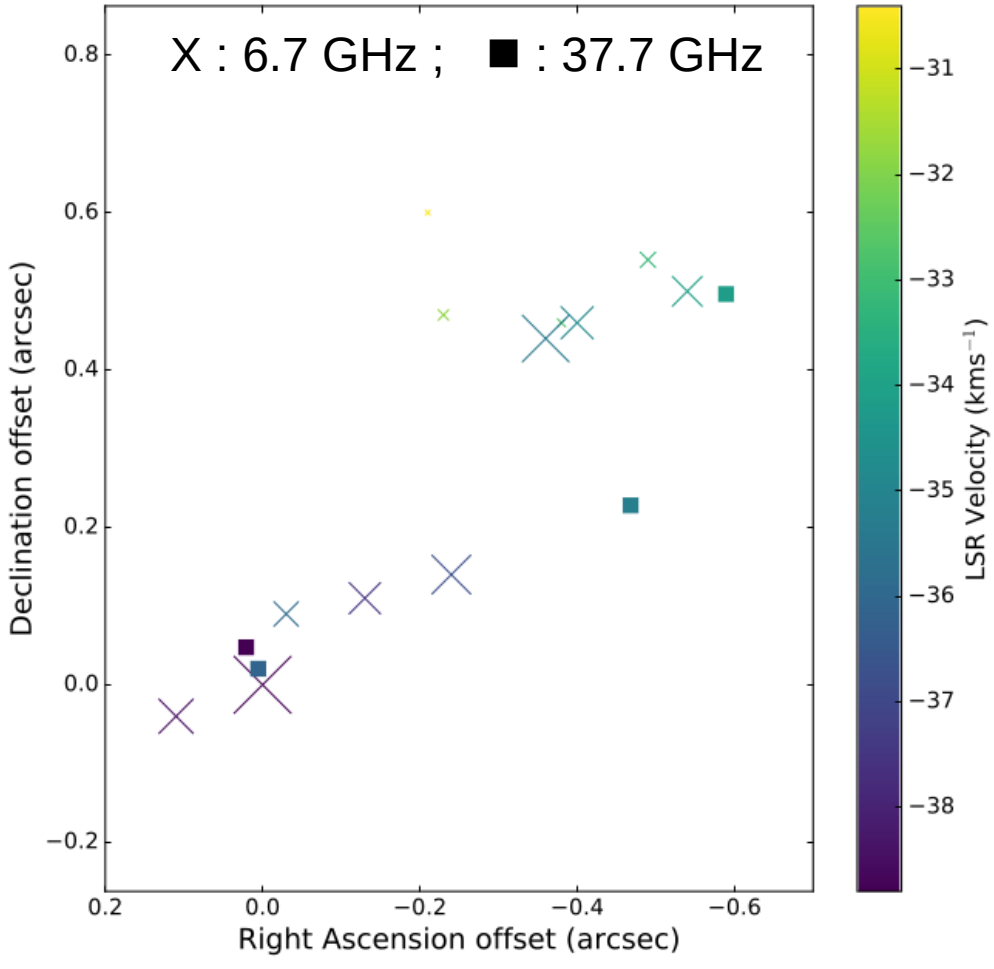
Krishnan et al. (2013)

37.7 & 38.3 GHz

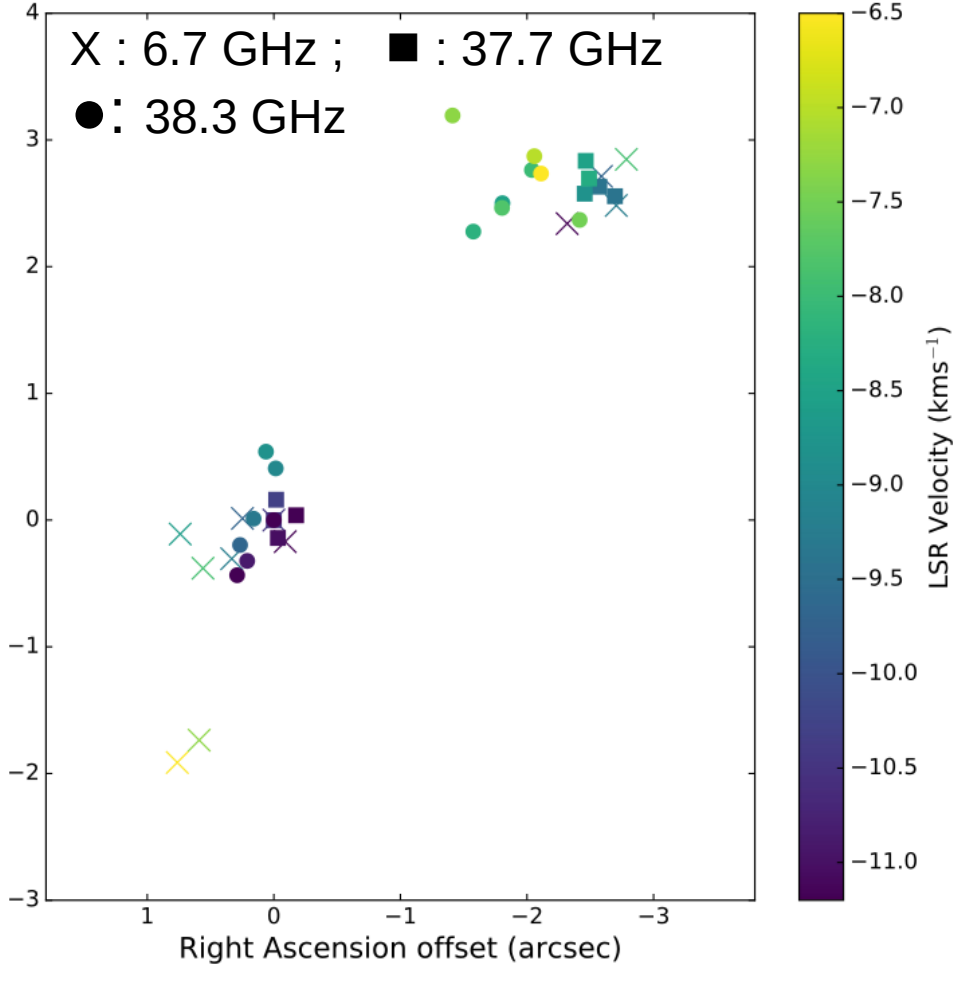
ATCA

(4”)

G339.884–1.259



NGC 6334F



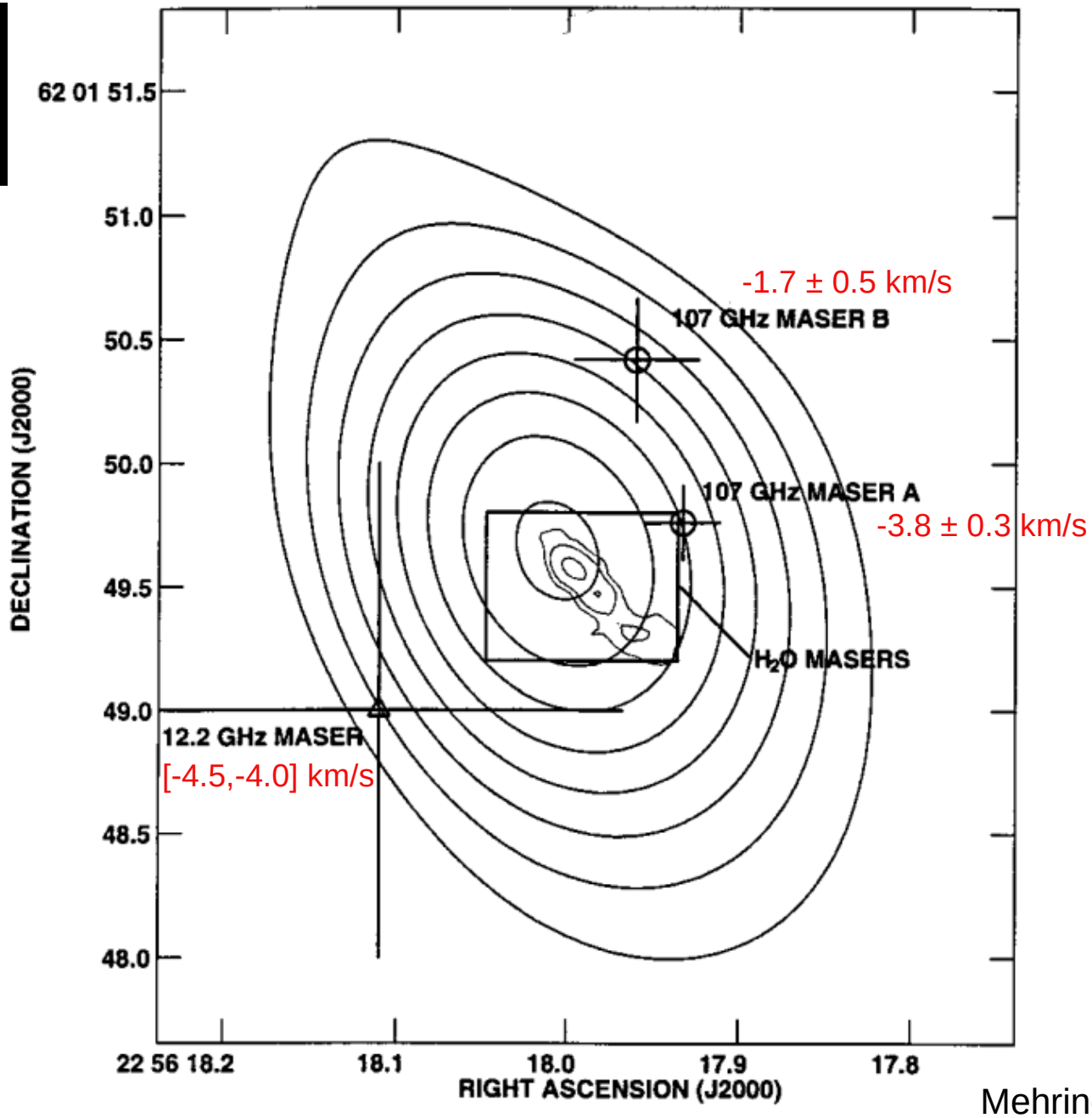
Ellingsen et al. (2018)

Cep A – HW2

107 GHz

BIMA

(2”)



Mehringer et al. (1997)

Sensitivity: maser VLBI @ 3mmm

Targets: 85 – 87 / 107 GHz methanol masers, flux: 1 – 100 Jy.

7 sigma single baseline detection thresholds (all numbers in mJy):

link to: EVN Sensitivity calculator1 (classi … l EVN Sensitivity calculator2 (new), and GMVA

$\Delta\nu$ = 512 MHz , Δt = 10 sec

-	Noema	Pico Veleta	Yebes	Onsala	Metsähovi	VLBA	GBT	KVN	LMT	ALMA37
Effelsberg	32	64	78	128	304	150-290	29	136	56	21
Noema	-	26	32	52	124	60-120	12	56	23	8
Pico Veleta	-	-	63	104	246	120-230	23	110	46	17
Yebes	-	-	-	127	303	150-289	29	136	56	21
Onsala	-	-	-	-	496	245-470	47	222	92	34
Metsähovi	-	-	-	-	-	580-1120	111	527	218	80
VLBA	-	-	-	-	-	287-1047	55-106	259-503	107-208	39-76
GBT	-	-	-	-	-	-	-	50	21	8
KVN	-	-	-	-	-	-	-	-	98	36
LMT	-	-	-	-	-	-	-	-	-	15

$\Delta\nu$ = 512 MHz , 7σ = 30-300 mJy

Sensitivity: maser VLBI @ 3mmm

Targets: 85 – 87 / 107 GHz methanol masers, flux: 1 – 100 Jy.

7 sigma single baseline detection thresholds (all numbers in mJy):

link to: EVN Sensitivity calculator1 (classi … l EVN Sensitivity calculator2 (new), and GMVA

$\Delta\nu = 512$ MHz , $\Delta t = 10$ sec

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Noema	-	26	32	52	124	60-120	12	56	23	8
Pico Veleta	-	-	63	104	246	120-230	23	110	46	17
Yebes	-	-	-	127	303	150-289	29	136	56	21
Onsala	-	-	-	-	496	245-470	47	222	92	34
Metsähovi	-	-	-	-	-	580-1120	111	527	218	80
VLBA	-	-	-	-	-	287-1047	55-106	259-503	107-208	39-76
GBT	-	-	-	-	-	-	-	50	21	8
KVN	-	-	-	-	-	-	-	-	98	36
LMT	-	-	-	-	-	-	-	-	-	15

$\Delta\nu = 512$ MHz , $7\sigma = 30\text{-}300$ mJy

Maser @ 3mm, $\Delta v = 0.2$ km/s $\Rightarrow$ $\Delta\nu = 0.066$ MHz $\Rightarrow$ $7\sigma \approx 3\text{-}26$ Jy

Sensitivity: maser VLBI @ 3mmm

Targets: 85 – 87 / 107 GHz methanol masers, flux: 1 – 100 Jy.

7 sigma single baseline detection thresholds (all numbers in mJy):

link to: EVN Sensitivity calculator1 (classi … l EVN Sensitivity calculator2 (new), and GMVA

$\Delta\nu$ = 512 MHz , Δt = 10 sec

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Metsähovi	-	-	-	-	-	580-1120	111	527	218	80
VLBA	-	-	-	-	-	287-1047	55-106	259-503	107-208	39-76
GBT	-	-	-	-	-	-	-	50	21	8
KVN	-	-	-	-	-	-	-	-	98	36
LMT	-	-	-	-	-	-	-	-	-	15

$\Delta\nu$ = 512 MHz , 7σ = 30-300 mJy

Maser @ 3mm, Δv = 0.2 km/s $\Rightarrow$ $\Delta\nu$ = 0.066 MHz $\Rightarrow$ $7\sigma \approx$ 3-26 Jy

thanks to the “Frequency Phase Transfer”

Δt ~ 1000 sec $\Rightarrow$ 7σ ~ 0.3-3 Jy

Maser proper motion measurement at mm wavelength

@ λ = 3mm , B = 2000 km $\Rightarrow$ $FWHM_{beam}$ ~ 0.3 mas

Maser SNR $\geq$ 10 $\Rightarrow$ $\delta\theta_{rel} \leqslant FWHM_{beam}$ / SNR = 0.03 mas

Maser proper motion measurement at mm wavelength

@ λ = 3mm , B = 2000 km $\Rightarrow$ $FWHM_{beam}$ ~ 0.3 mas

Maser SNR $\geq$ 10 $\Rightarrow$ $\delta\theta_{rel} \leqslant FWHM_{beam}$ / SNR = 0.03 mas

Δt = 1 year $\Rightarrow$ $\delta pm = \delta\theta_{rel} / \Delta t$ = 0.03 mas /year

@ 5 kpc $\Rightarrow$ δpm ~ 1 km/s

Maser proper motion measurement at mm wavelength

@ λ = 3mm , B = 2000 km $\Rightarrow$ $FWHM_{beam}$ ~ 0.3 mas

Maser SNR $\geq$ 10 $\Rightarrow$ $\delta\theta_{rel} \leqslant FWHM_{beam} / SNR$ = 0.03 mas

Δt = 1 year $\Rightarrow$ $\delta pm = \delta\theta_{rel} / \Delta t$ = 0.03 mas /year

@ 5 kpc $\Rightarrow$ δpm ~ 1 km/s

Relevant for the slow-moving (< 10 km/s) methanol masers, which now at cm wavelengths require Δt of several / many years.

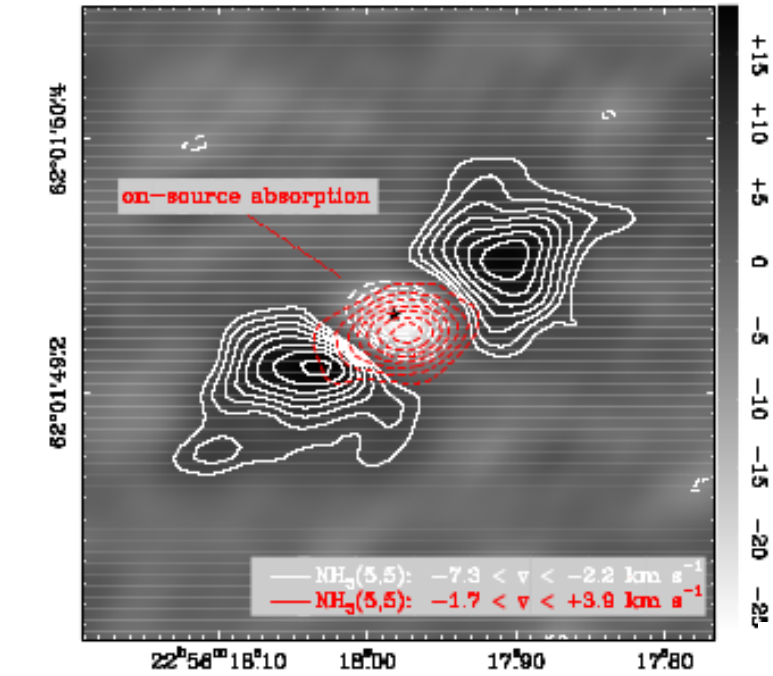
Conclusions

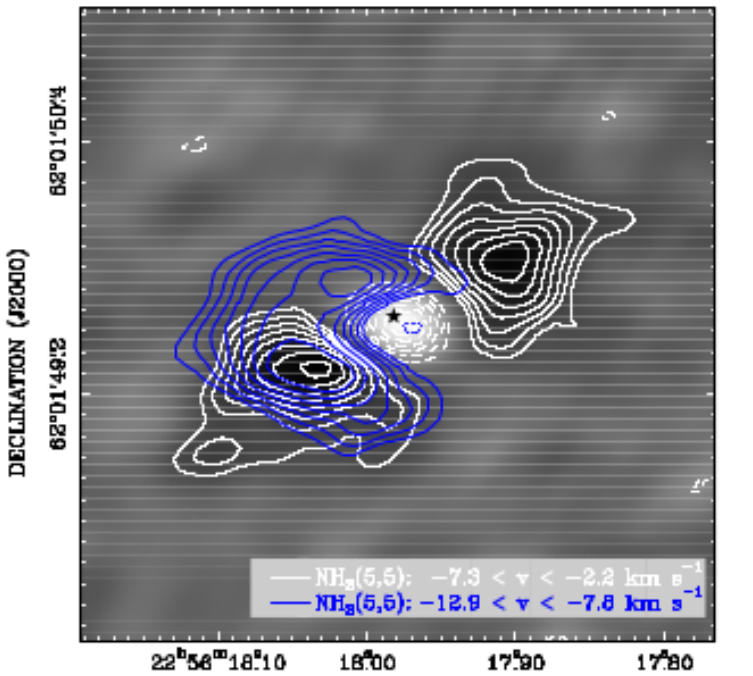
High-frequency class II methanol masers to better sample the kinematics of disks and disk-winds close to high-mass forming stars.

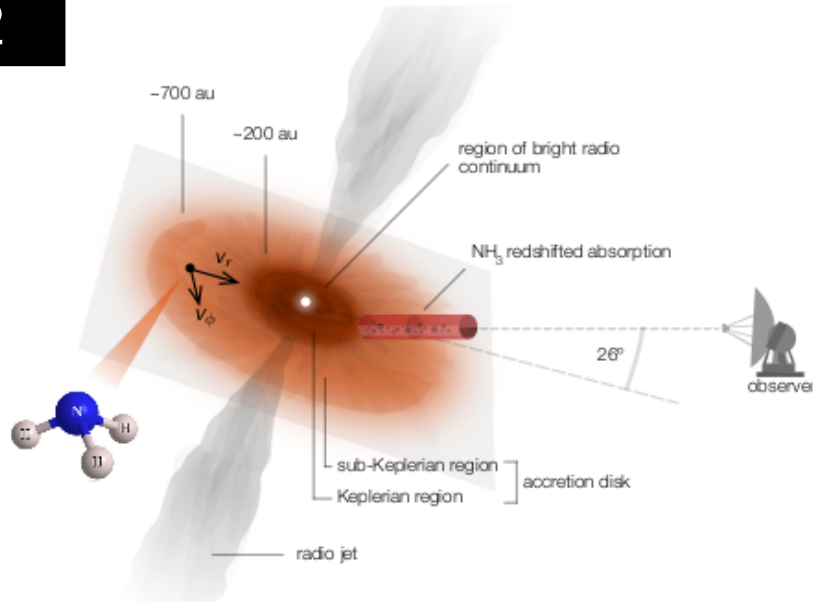
VLBI multi-band receivers allow sub-mas accuracy in relative positions across many different maser transitions.

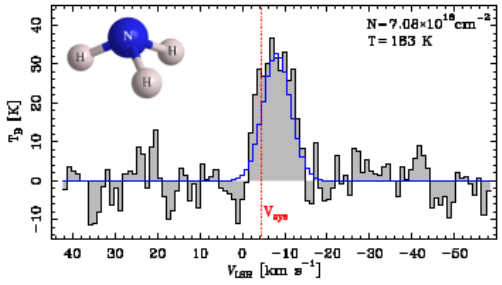
The proper motion of the high-frequency methanol masers can be measured over time baselines < 1 year.

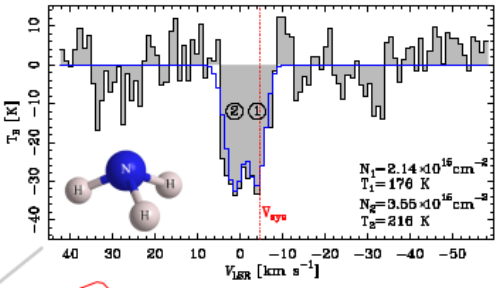
Cep A - HW2

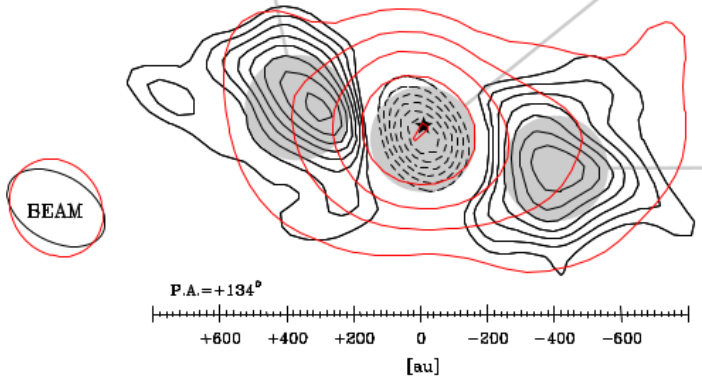

on-source absorption
NH3(5,5): −7.3 < v < −2.2 km s−1
NH3(5,5): −1.7 < v < +3.9 km s−1
+15
+10
+5
0
−5
−10
−15
−20
−25
[mJy beam−1 km s−1]
22h56m18s.10
18s.00
17s.90
17s.80
62°01'49".4
48".9
48".4
47".9
DECLINATION (J2000)

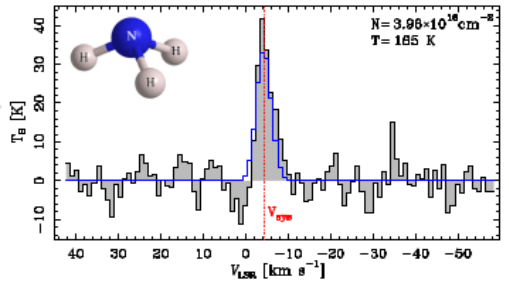

NH3(5,5): −7.3 < v < −2.2 km s−1
NH3(5,5): −12.9 < v < −7.6 km s−1
22h56m18s.10
18s.00
17s.90
17s.80
62°01'49".4
48".9
48".4
47".9
DECLINATION (J2000)


~700 au
~200 au
region of bright radio continuum
NH3 redshifted absorption
vr
vφ
26°
observer
sub-Keplerian region
Keplerian region
accretion disk
radio jet

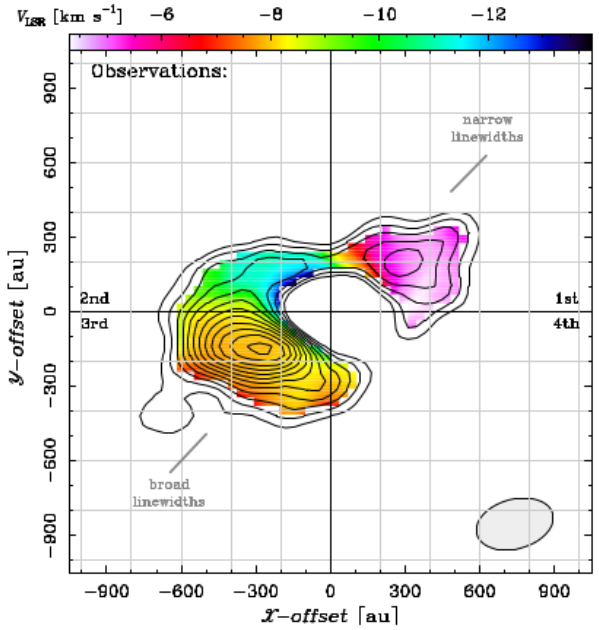

N=7.08×10^15 cm^-2
T=183 K
Tb [K]
VLSR [km s−1]
Vsys

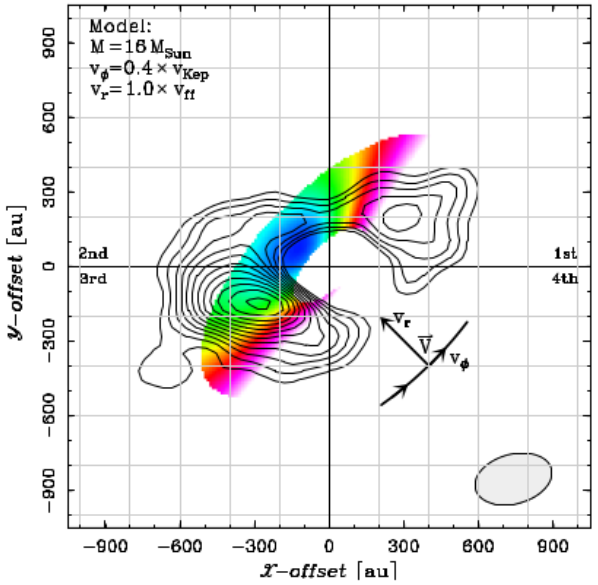

N1=2.14×10^15 cm^-2
T1=176 K
N2=3.55×10^15 cm^-2
T2=216 K
Tb [K]
VLSR [km s−1]
Vsys

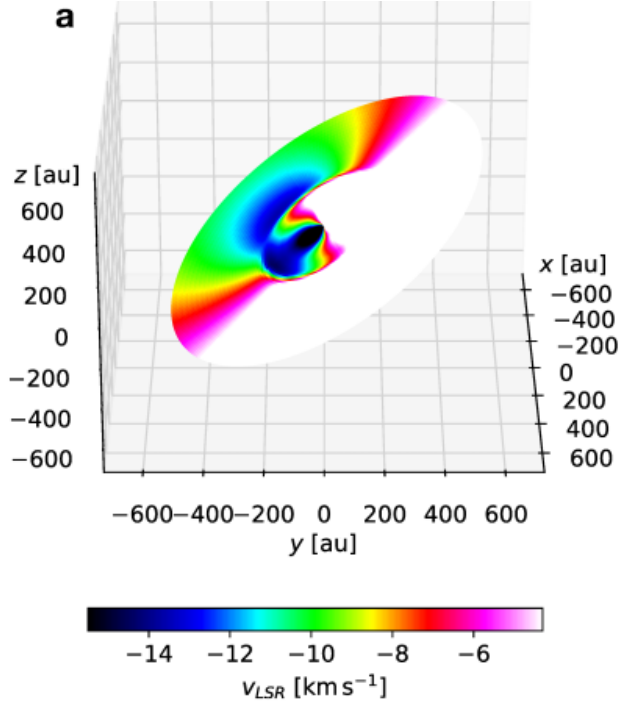

BEAM
P.A.=+134°
+600
+400
+200
0
−200
−400
−600
[au]

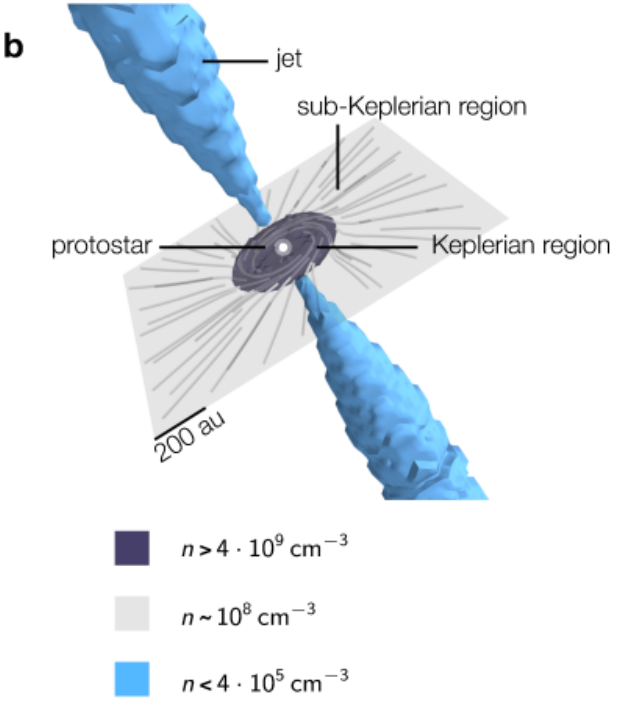

N=3.95×10^15 cm^-2
T=165 K
Tb [K]
VLSR [km s−1]
Vsys

Cep A - HW2


V_{LSR} [km s^{-1}] −6 −8 −10 −12
Observations:
narrow linewidths
broad linewidths
2nd
1st
3rd
4th
y−offset [au]
x−offset [au]
−900 −600 −300 0 300 600 900

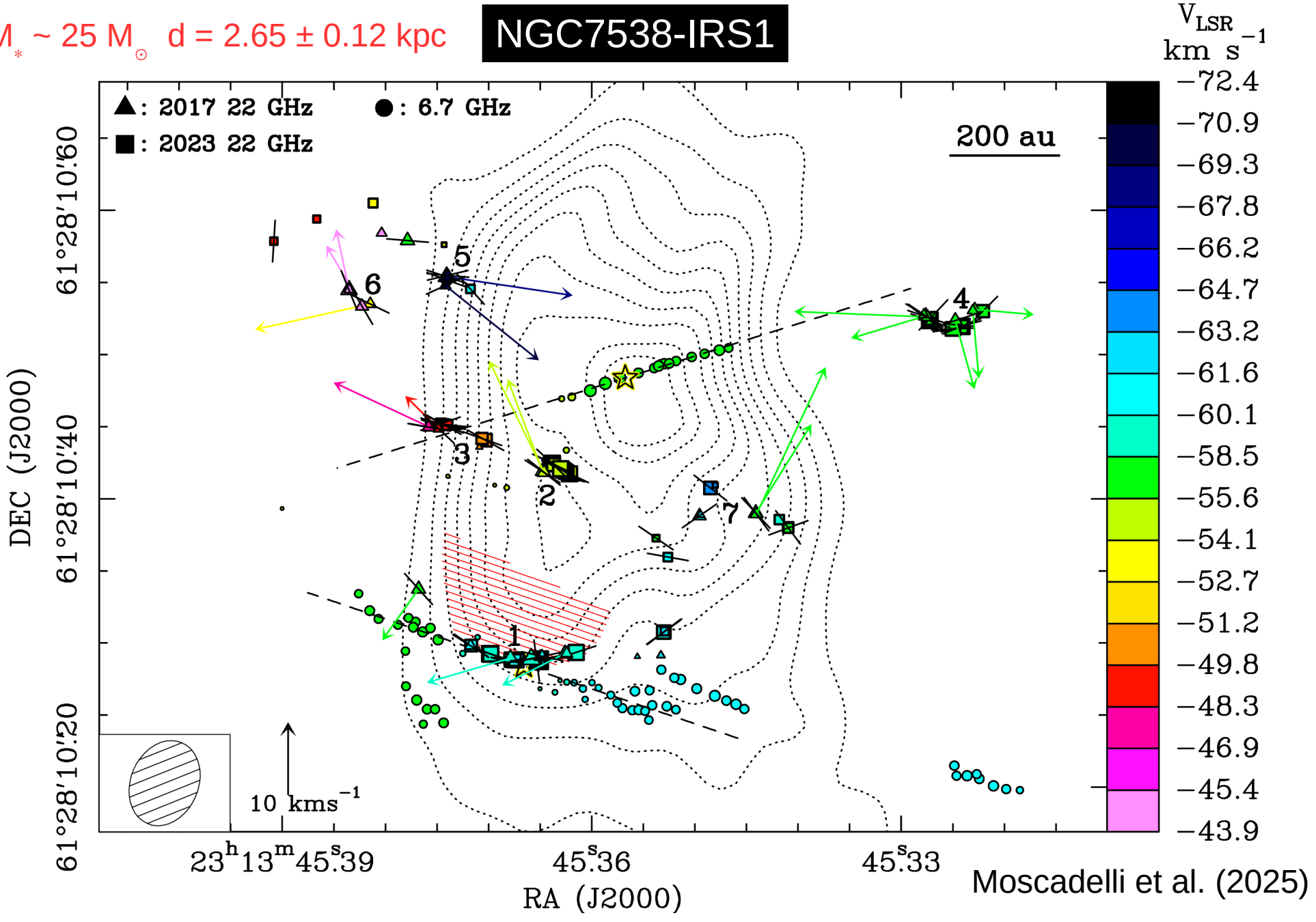

Model:
M = 16 M_{Sun}
v_ϕ = 0.4 × v_{Kep}
v_r = 1.0 × v_{ff}
2nd
1st
3rd
4th
v_r
$\vec{v}$
v_ϕ
y−offset [au]
x−offset [au]
−900 −600 −300 0 300 600 900


a
z [au]
600
400
200
0
−200
−400
−600
x [au]
−600
−400
−200
0
200
400
600
−600−400−200 0 200 400 600
y [au]
−14 −12 −10 −8 −6
v_{LSR} [km s^{-1}]


b
jet
sub-Keplerian region
protostar
Keplerian region
200 au
$n > 4 \cdot 10^9$ cm^{-3}
$n \sim 10^8$ cm^{-3}
$n < 4 \cdot 10^5$ cm^{-3}

$M_* \sim 25\ M_\odot$ d = 2.65 ± 0.12 kpc

NGC7538-IRS1



Moscadelli et al. (2025)

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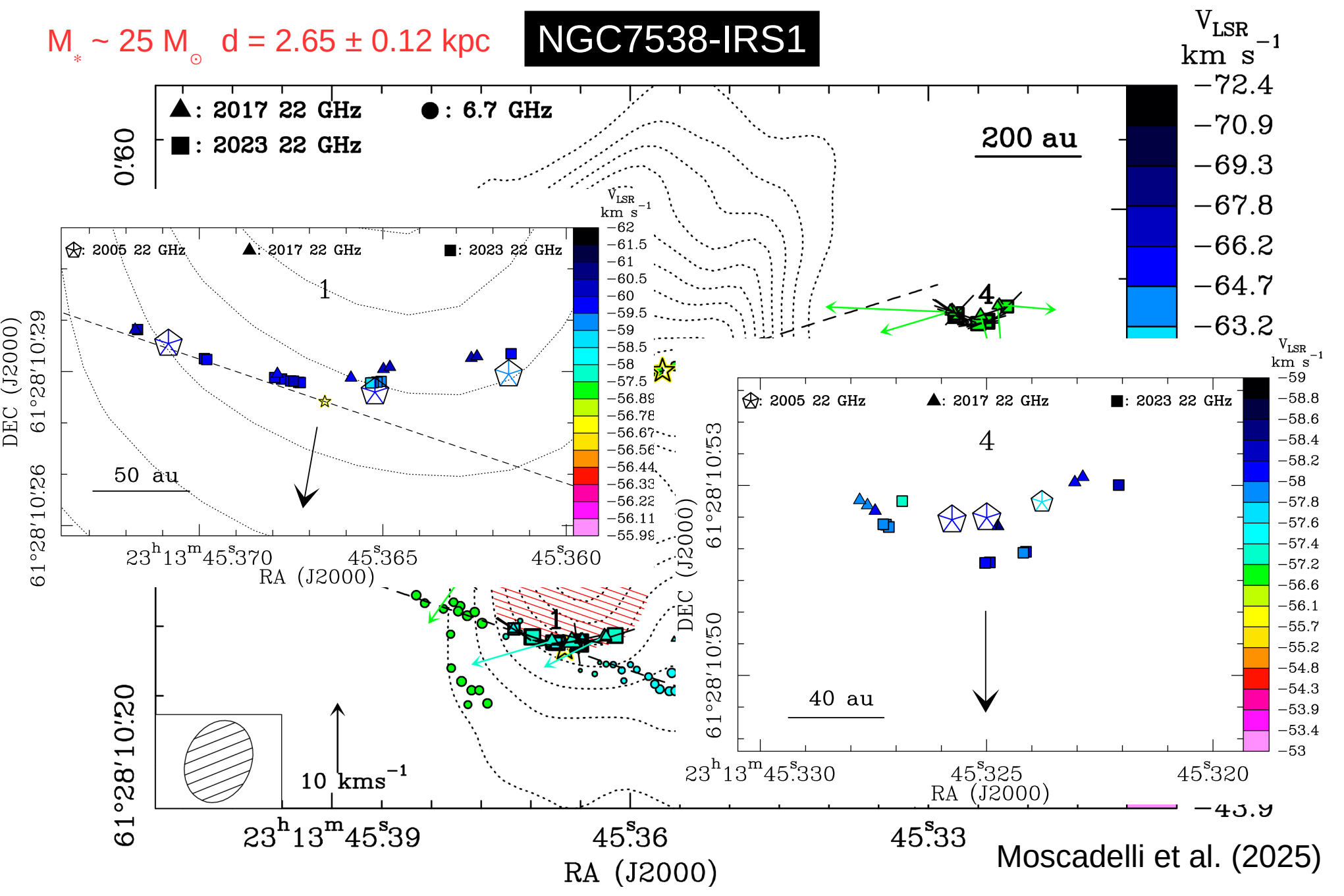
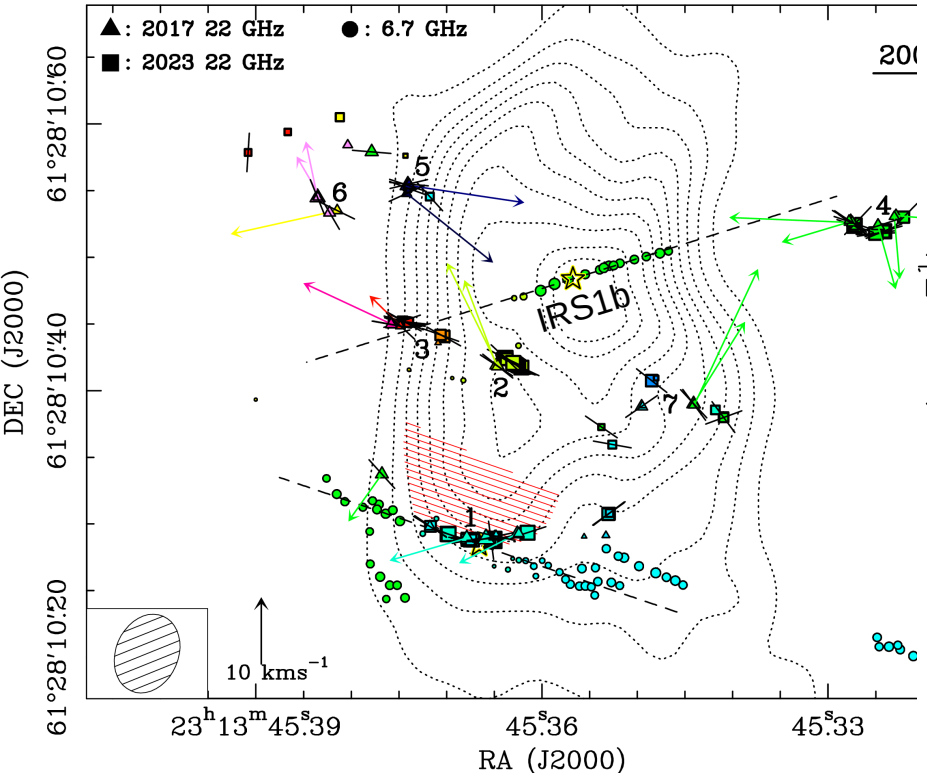
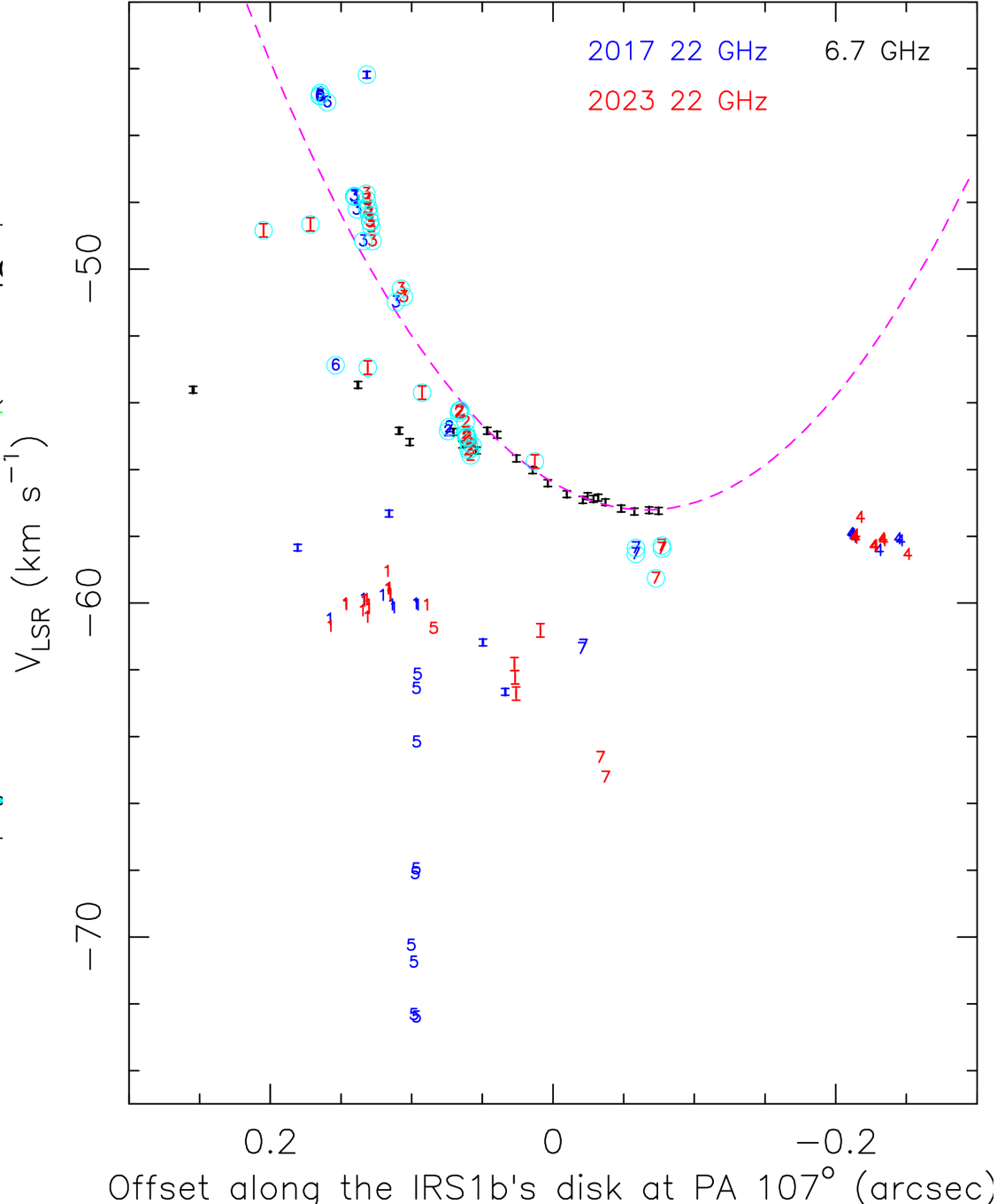
NGC7538-IRS1



Moscadelli et al. (2025)

NGC7538-IRS1





Moscadelli et al. (2025)

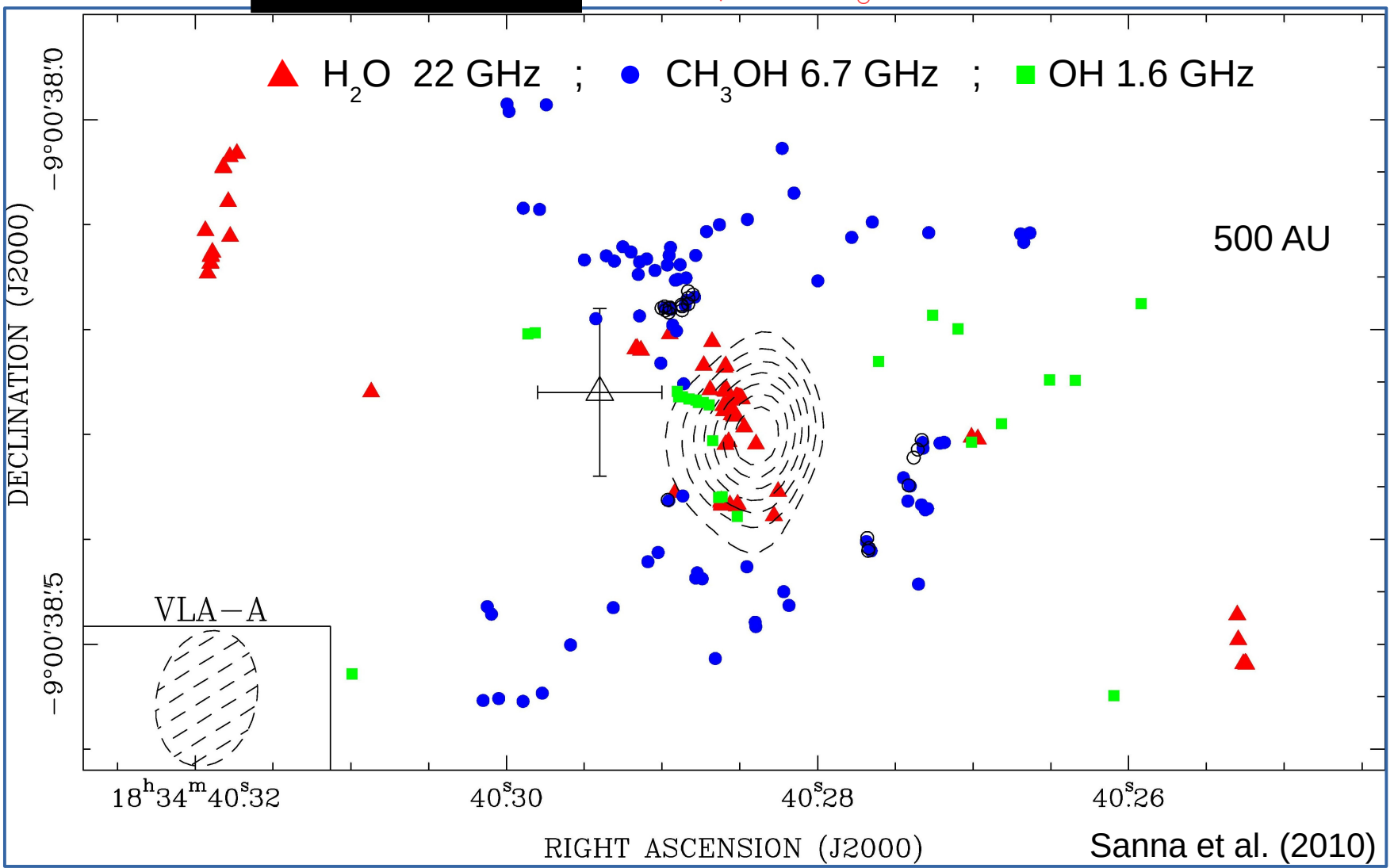
Maser VLBI: 3D Kinematics @ 10 – 10^3 AU from the YSO

Several Molecular Masers commonly observed nearby high-mass YSOs

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

G23.01-0.41

$M_* \sim 20\ M_\odot$ d = 4.6 ± 0.4 kpc



Sanna et al. (2010)

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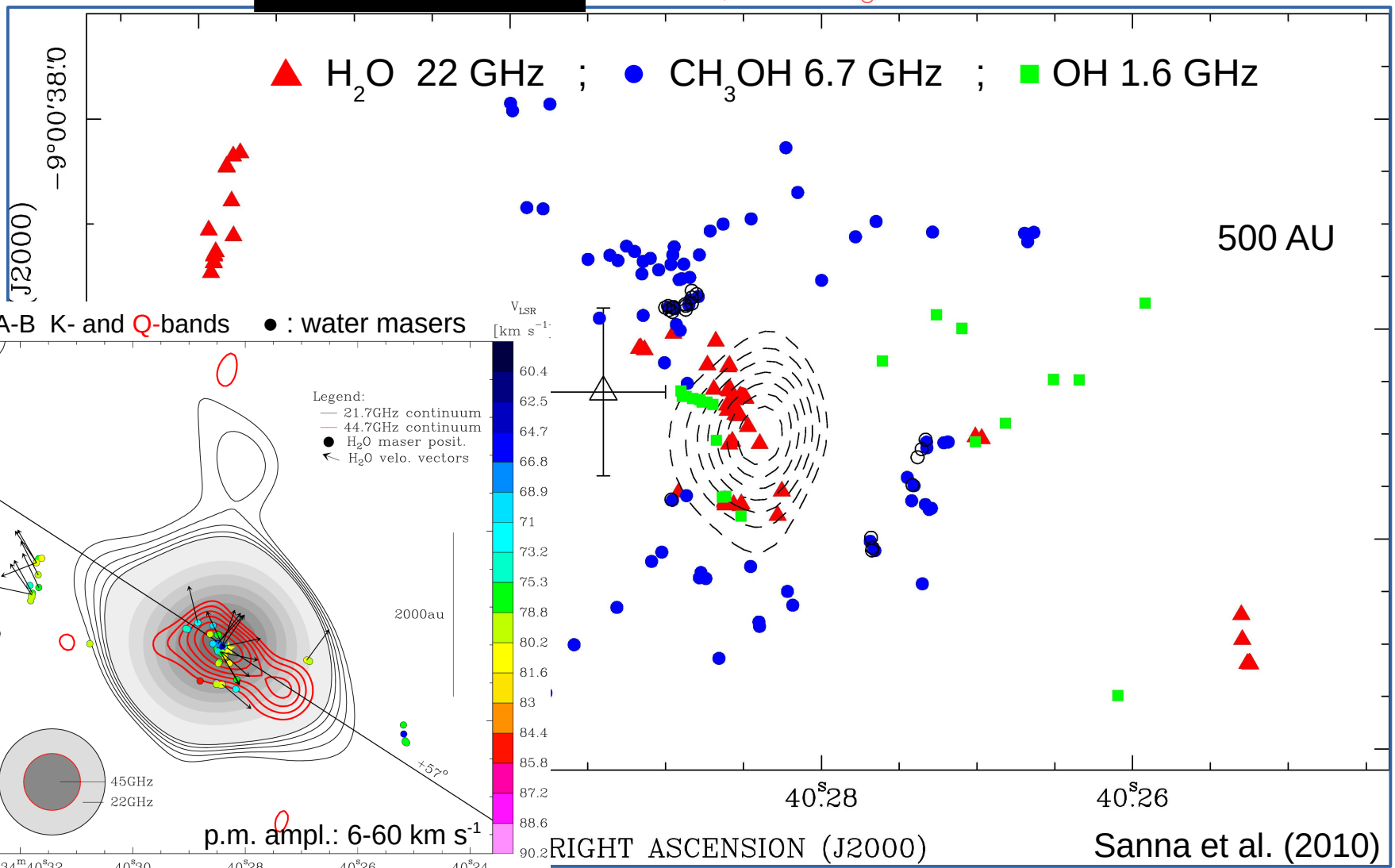

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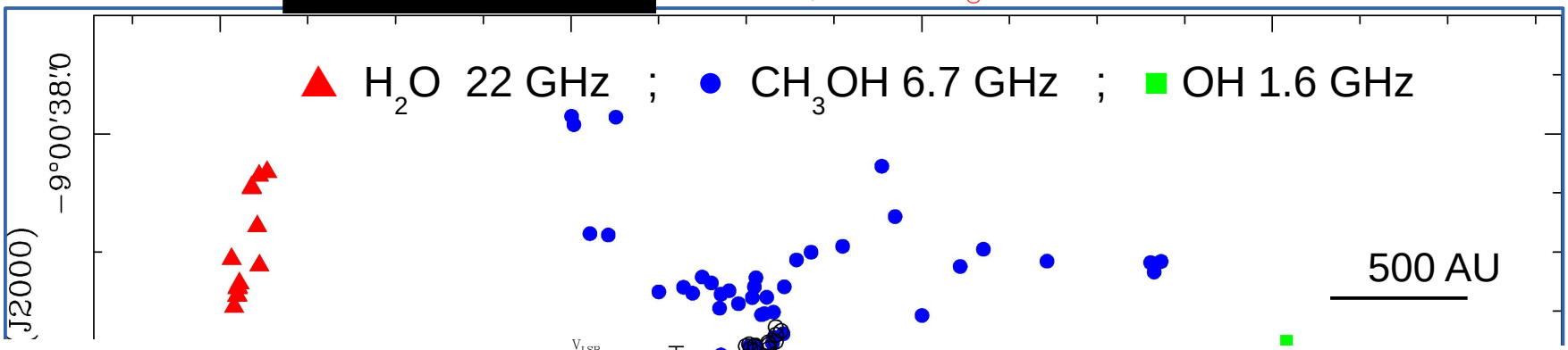
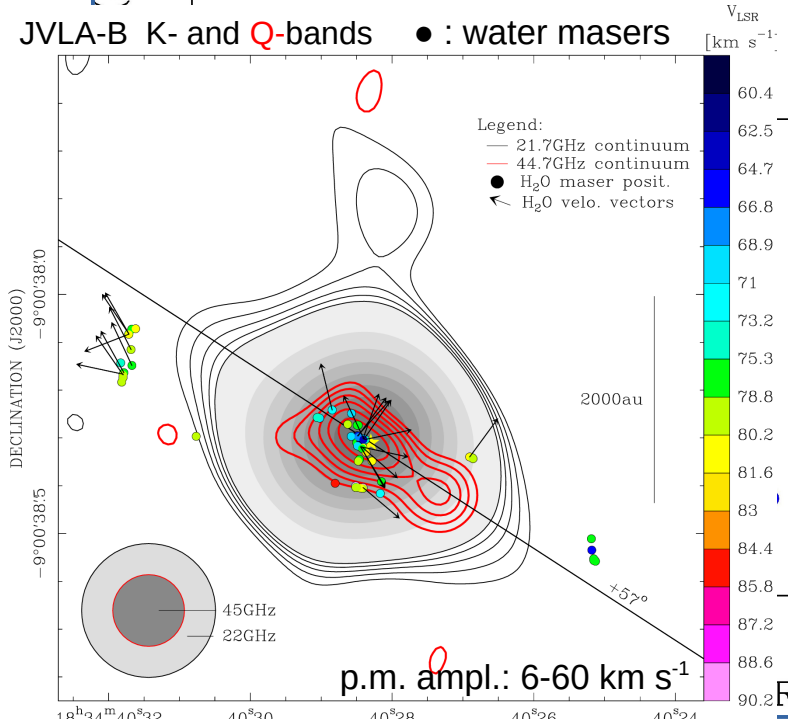
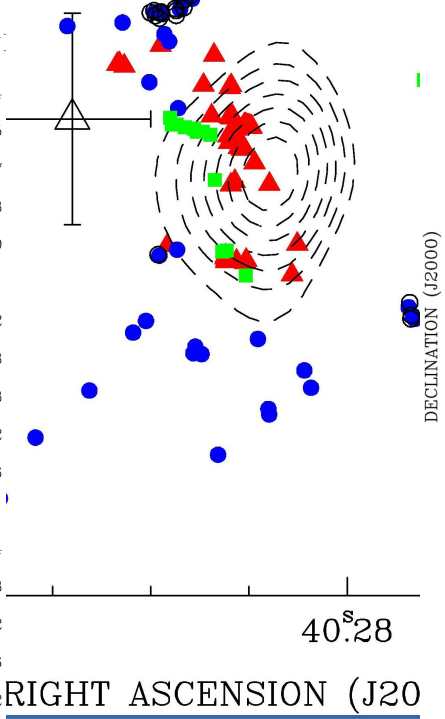
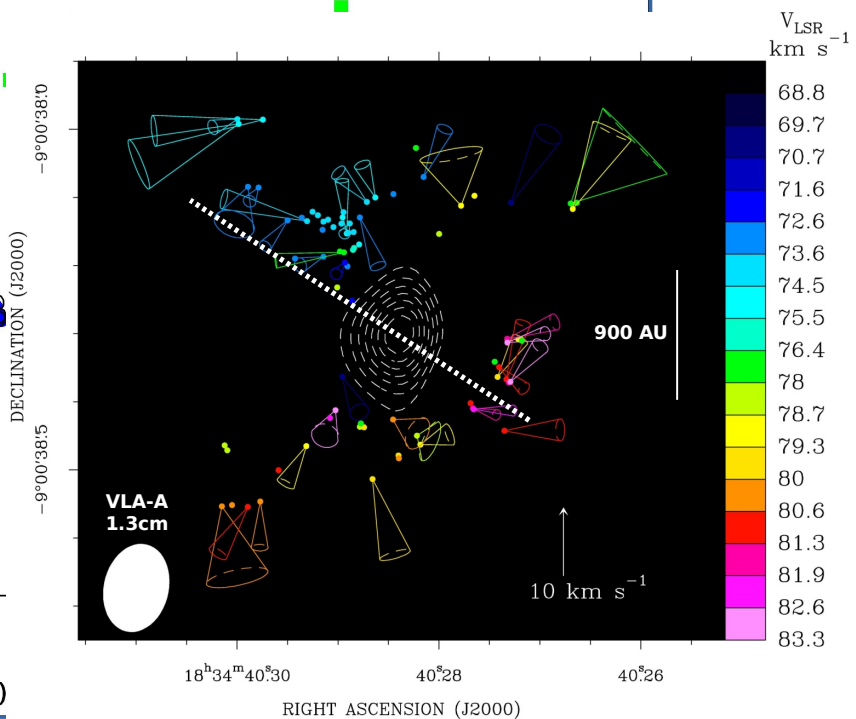


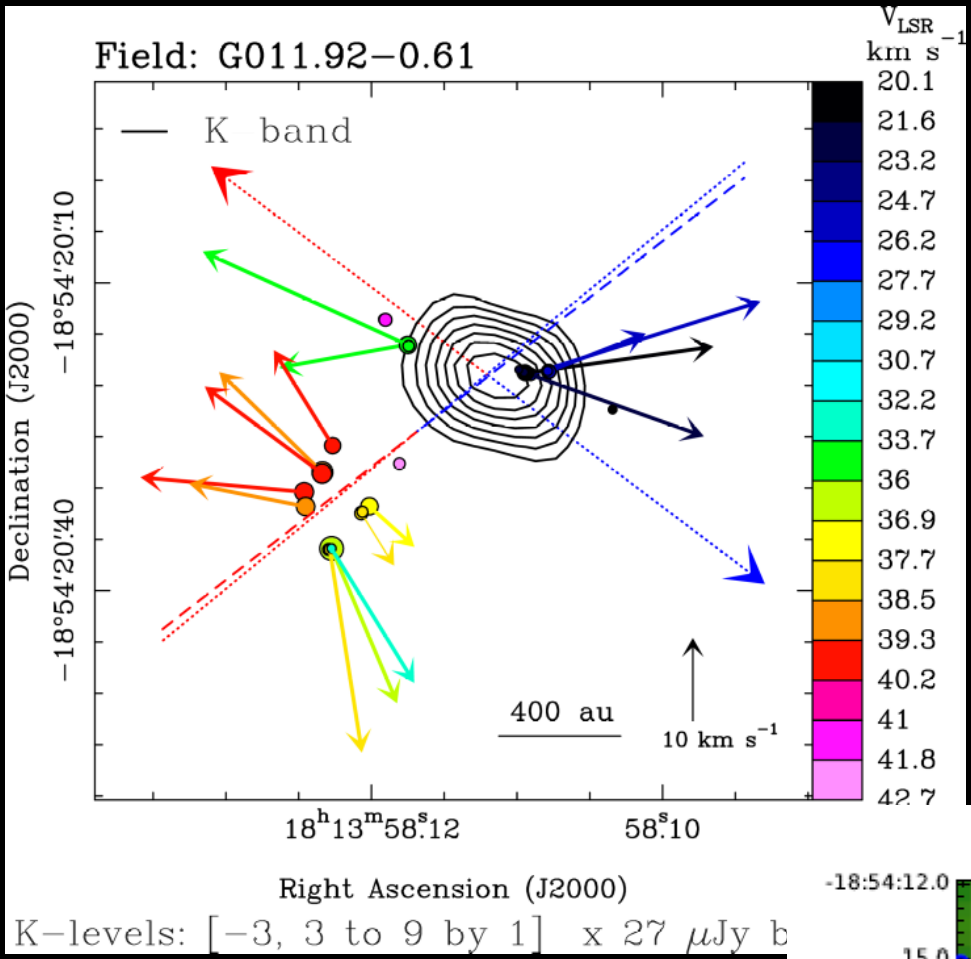


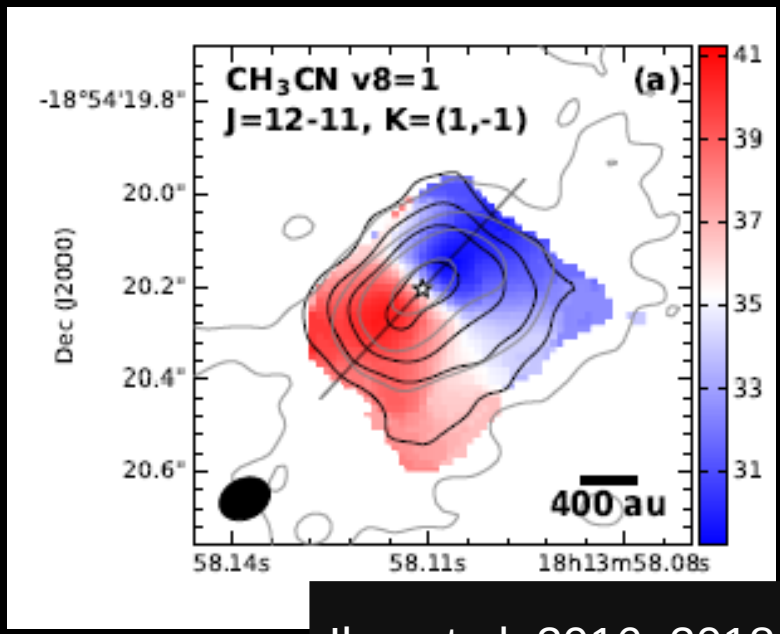




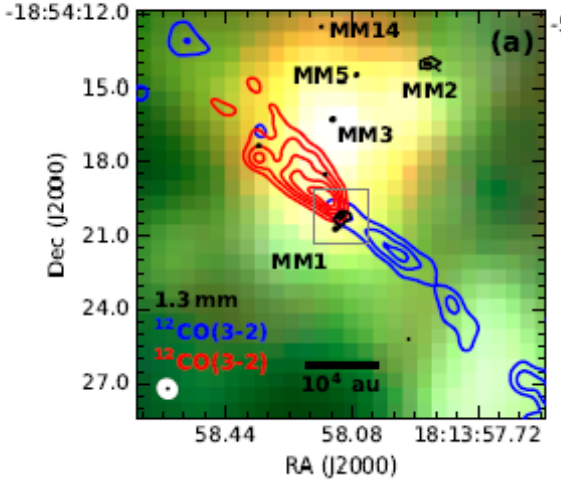
Maser V_{LSR} gradient

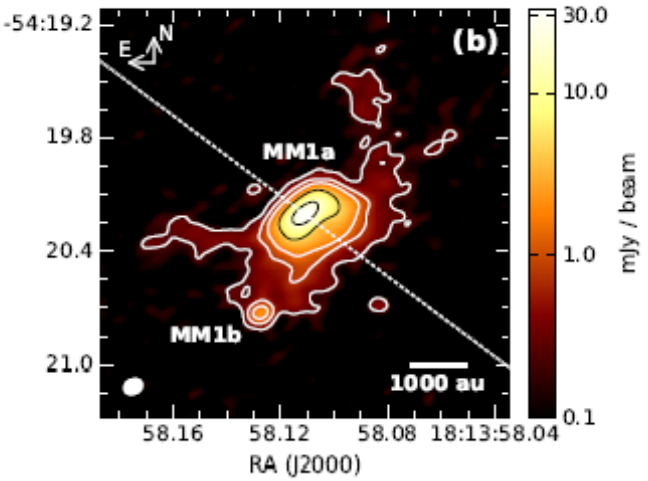
on top of the YSO (18 %)

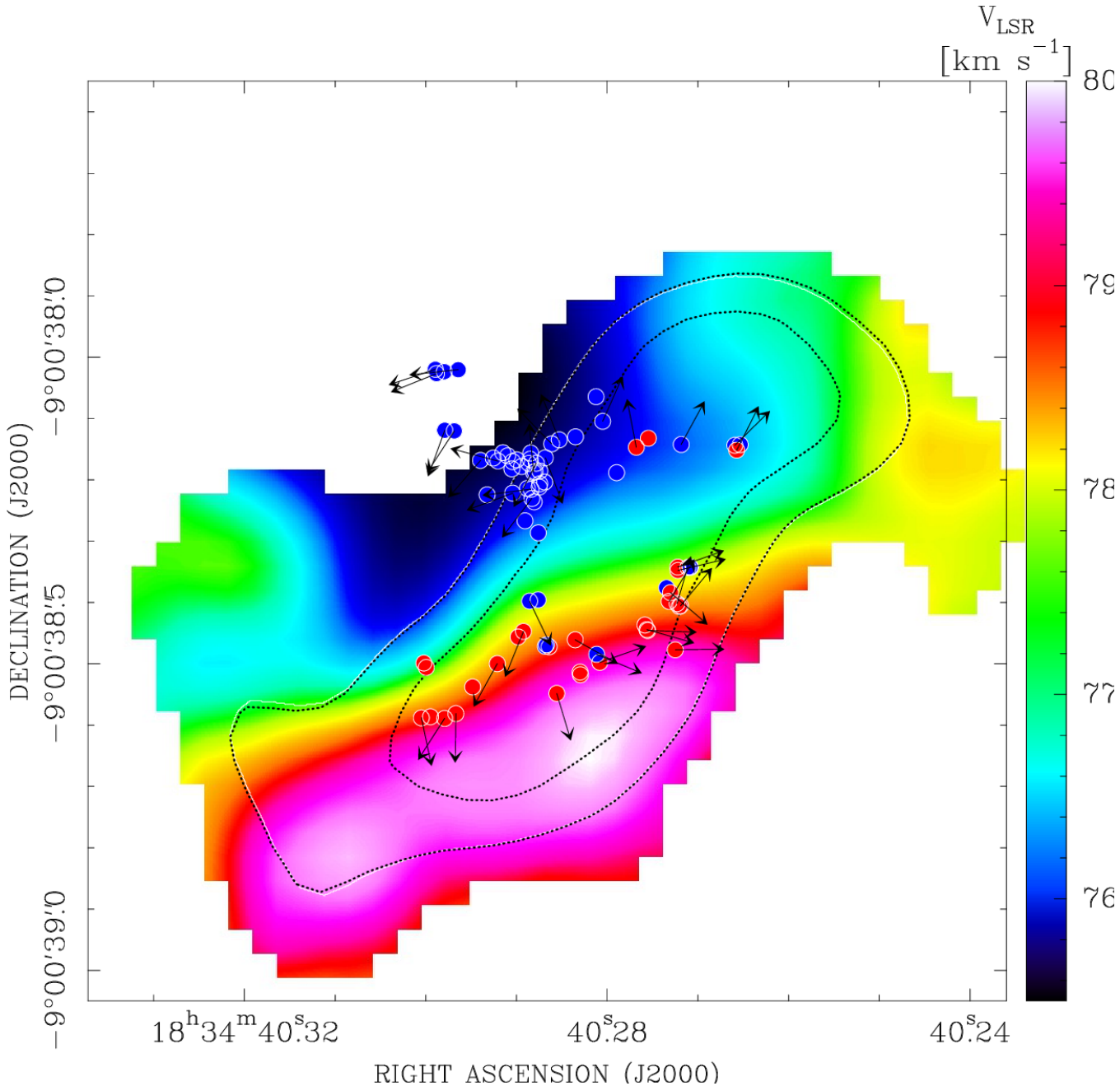




Ilee et al. 2016, 2018






V_LSR
[km s^-1]
80
79
78
77
76
DECLINATION (J2000)
-9°00'38".0
-9°00'38".5
-9°00'39".0
18h34m40s.32
40s.28
40s.24
RIGHT ASCENSION (J2000)

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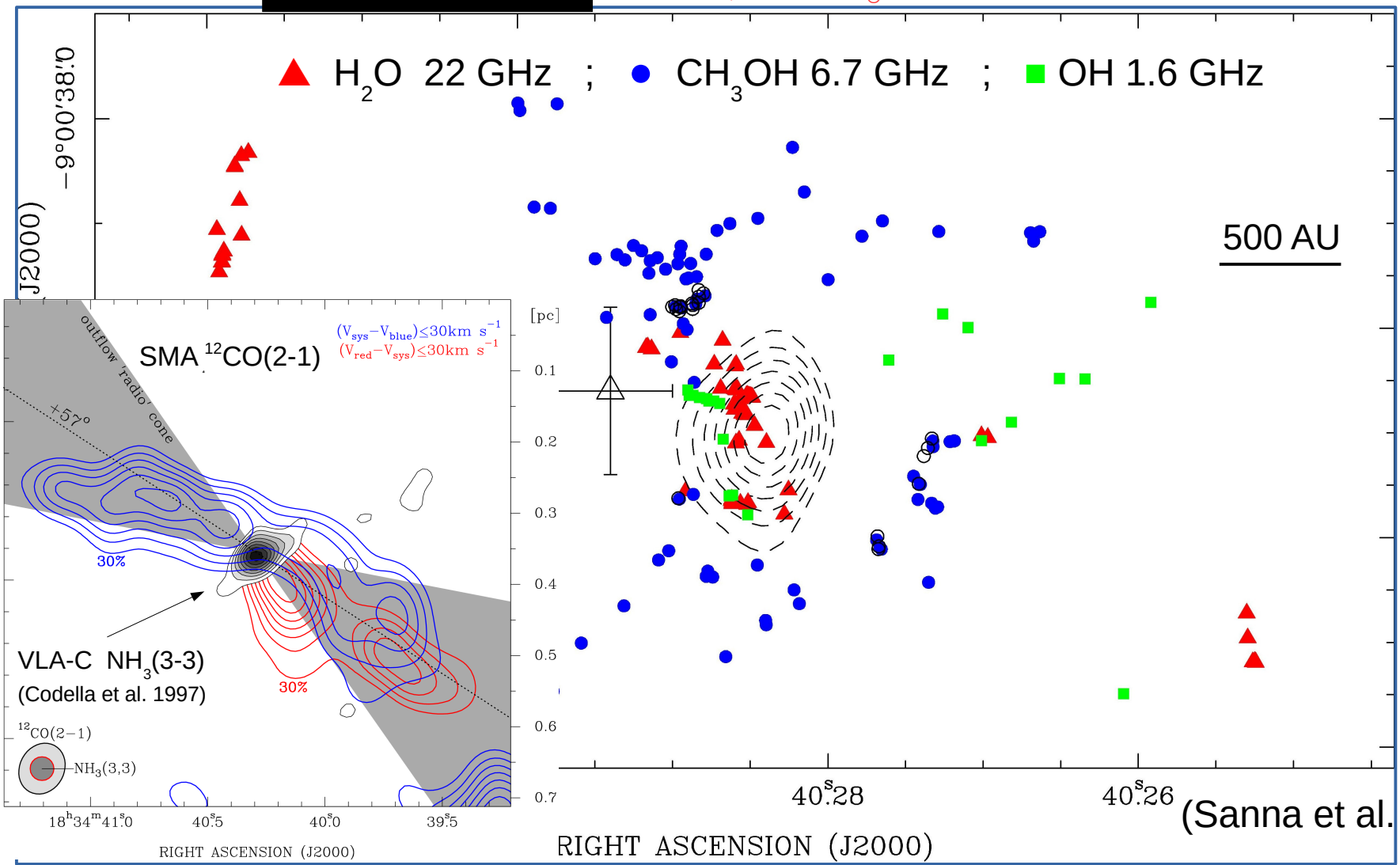

(Sanna et al. 2010)

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