May 20 – 22, 2013
A Neapolitan of Masers @ Sydney, Australia

The VLBI Monitor Project of the 6.7 GHz Methanol Masers using the JVN/EAVN

~~Koichiro~~ Coconuts Sugiyama (Yamaguchi Univ.)

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Institution: 1) Yamaguchi Univ.; 2) SHAO; 3) Ibaraki Univ.; 4) NAOJ; 5) ISAS/JAXA; 6) ICRAR; 7) UTAS; 8) KASI; 9) Osaka Pref. Univ.

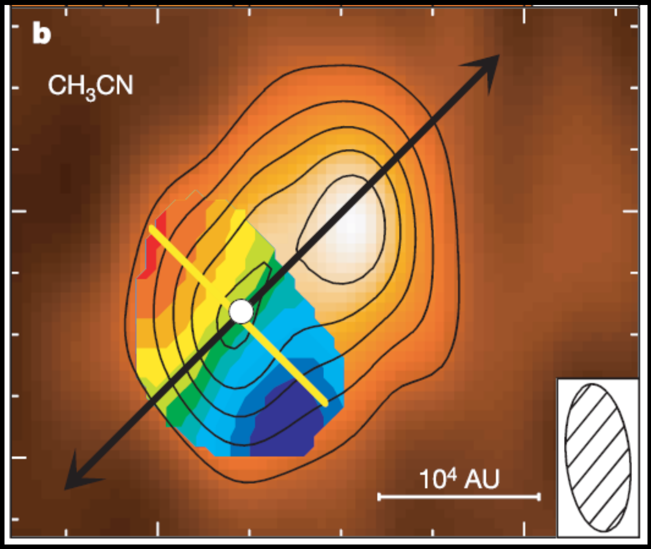
Introduction

Formation scenario of high-mass YSOs

- ❒ Observations: (e.g., Beltran+ 06, Kraus+ 10)
  - Detected with interferometer at radio/IR
- ❒ Theories: (e.g., Hosokawa & Omukai 09, Krumholz+ 09)
  - Non-spherical, and High accretion-rate

the Accretion scenario

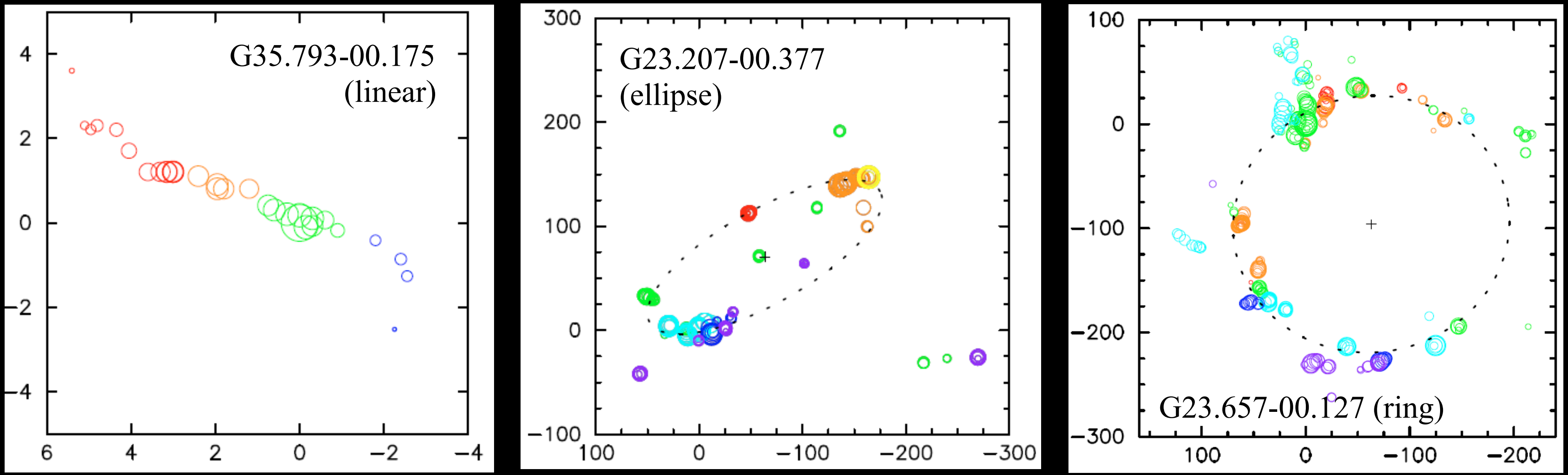
- ❒ Next:
  - 3-D velocity structure
    - ➢ directly verify the scenario
    - ➢ measure accretion rate



CH_3CN distribution in G24 A1 (Beltran+ 06)

The methanol maser at 6.7 GHz
I: spatial distribution

- ❒ Linear morphology with RVG (e.g., Minier+ 00)
- ❒ Ring/Elliptical morphology
  - 12/31 sources (e.g., Bartkiewicz+ 09)
  - not simple rotation, but with expansion/infall

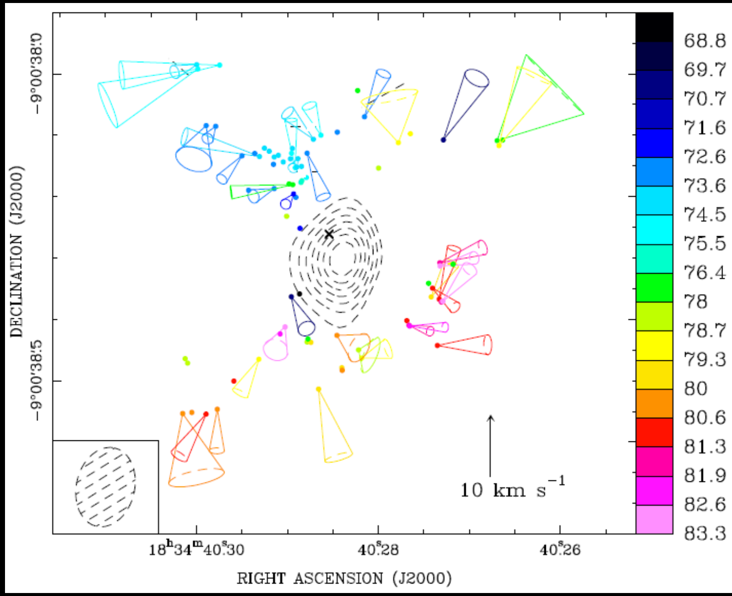


EVN observations of 6.7GHz methanol masers (Bartkiewicz+ 09)

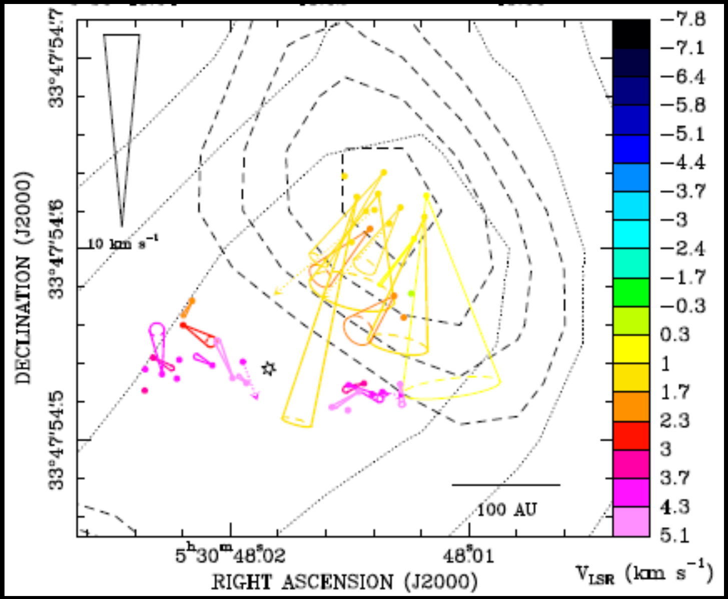
The methanol maser at 6.7 GHz II: proper motion

- Measured in several sources
  - Signatures of rotating disk in some sources

    (e.g., Sanna+ 10a, b; Sugiyama+ submitted)
  - Accretion from spherical envelope (Goddi+ 11)



G23.01-0.41 (rotation +expansion; Sanna+ 10b)



AFGL5142 (infall; Goddi+ 11)

Project of VLBI monitor

- Final goal
  - 3-D velocity (radial & proper) measurement to Directly verification of the accretion scenario on the HMSF
  - Investigation for an evolution of the accretion disk around high-mass YSOs
- Project
  - VLBI monitor using the JVN/EAVN since 2010
  - Spatial morphology & 3-D velocity information
  - Making a catalog for VLBI image and proper motion of the 6.7 GHz methanol masers Systematically
- Purpose in this presentation
  - Whether all of targets associated with the disk?

Observations in 2010-2011

Target sources

- Based catalog
  - 519 sources (Pestalozzi+ 05)
  - MMB sources (Caswell+ 10; Green+ 10)
- Criteria
  1. -40 < Dec < 20 : EAVN & ALMA
  2. F_{total} > 65 Jy
  3. No previous VLBI

→ <u>36 selected sources</u>

※ include 2 previous observed sources to verify our observational system

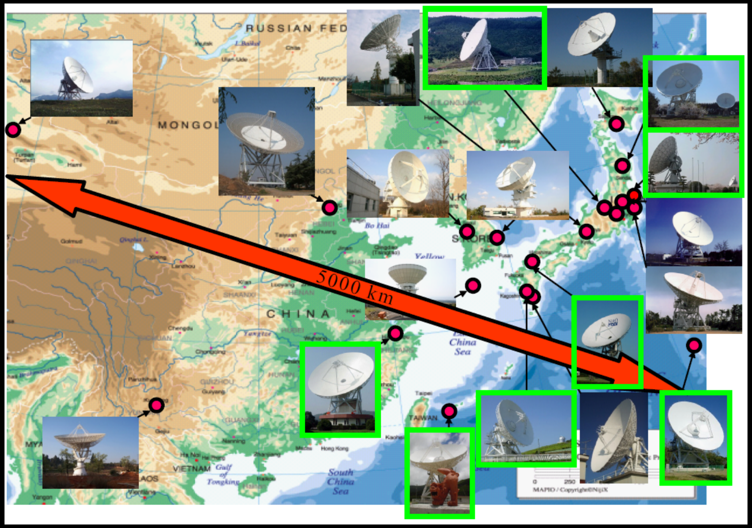
Target sources

Source	Coordinates (J2000.0)	
	RA	Dec
	(h m s)	(° ′ ″)
000.54−00.85	17 50 14.56	−28 54 31.4
000.64−00.04	17 47 18.69	−28 24 25.3
002.53+00.19†	17 50 46.47	−26 39 45.3
006.18−00.35	18 01 02.17	−23 47 10.8
006.79−00.25	18 01 57.76	−23 12 34.2
008.68−00.36	18 06 23.48	−21 37 10.4
008.83−00.02	18 05 25.66	−21 19 25.4
009.61+00.19	18 06 14.91	−20 31 43.4
009.98−00.02	18 07 50.12	−20 18 56.5
010.32−00.16	18 09 01.47	−20 05 07.8
011.49−01.48	18 16 22.13	−19 41 27.2
011.90−00.14	18 12 11.45	−18 41 28.8
012.02−00.03	18 12 01.86	−18 31 55.9
012.68−00.18†	18 13 54.75	−18 01 46.6
012.88+00.48	18 11 51.39	−17 31 30.1
014.10+00.08†	18 15 45.81	−16 39 09.4
020.23+00.06	18 27 44.56	−11 14 54.1
023.43−00.18 MM1	18 34 39.19	−08 31 25.3

Source	Coordinates (J2000.0)	
	RA	Dec
	(h m s)	(° ′ ″)
025.65+01.05*	18 34 20.91	−05 59 40.5
025.71+00.04	18 38 03.15	−06 24 15.0
025.82−00.17	18 39 03.63	−06 24 09.9
028.83−00.25*	18 44 51.08	−03 45 48.5
029.86−00.04*	18 45 59.57	−02 45 04.4
030.70−00.06*	18 47 36.9	−02 01 05.
030.76−00.05*	18 47 39.73	−01 57 22.0
030.91+00.14*	18 47 15.0	−01 44 07.
031.28+00.06	18 48 12.39	−01 26 22.6
032.03+00.06*	18 49 37.3	−00 45 47.
037.40+01.52*	18 54 10.5	+04 40 49.
049.49−00.38	19 23 43.93	+14 30 35.1
232.62+00.99	07 32 09.78	−16 58 12.4
351.77−00.53	17 26 42.54	−36 09 17.6
352.63−01.06	17 31 13.93	−35 44 08.5
353.41−00.36	17 30 26.18	−34 41 45.6
354.61+00.47	17 30 17.09	−33 13 55.0
359.43−00.10†	17 44 40.60	−29 28 16.0

Observations in 2010 and 2011
for VLBI imaging as 1st epoch

- Array: EAVN
- Data: 2010/08, 2011/10,11
- Beam: ~15 x 5 mas^2
- σ_{image}: 30-60 mJy $beam^{-1}$
- Vel. res.: 0.18 km s^{-1}



East Asia VLBI Network (EAVN)

Date	Antennas	Targets
2010/08/28-30	H, M, R, O, I, S	22 sources
2011/10/27, 28	Y, H, M, R, O, I, S	10 sources
2011/11/26	Y, U, H, M, R, O, I, S	4 sources

Y:Yamaguchi, U:Usuda, H:Hitachi, M:Mizusawa, R:Iriki, O:Ogasawara, I:Ishigaki, S:Shanghai

Observations in 2010 and 2011
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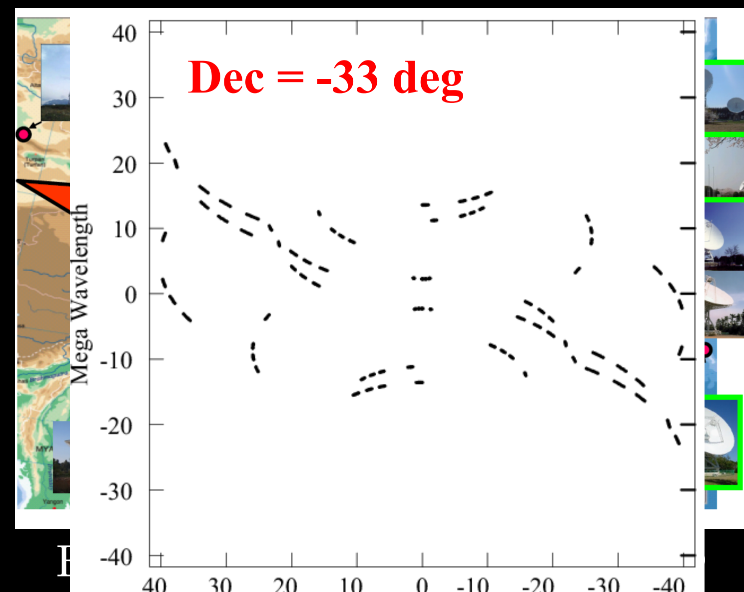


UV-coverage for G354.436-0.104

Date	Antennas	
2010/08/28-30	H, M, R, O, I, S	22 sources
2011/10/27, 28	Y, H, M, R, O, I, S	10 sources
2011/11/26	Y, U, H, M, R, O, I, S	4 sources

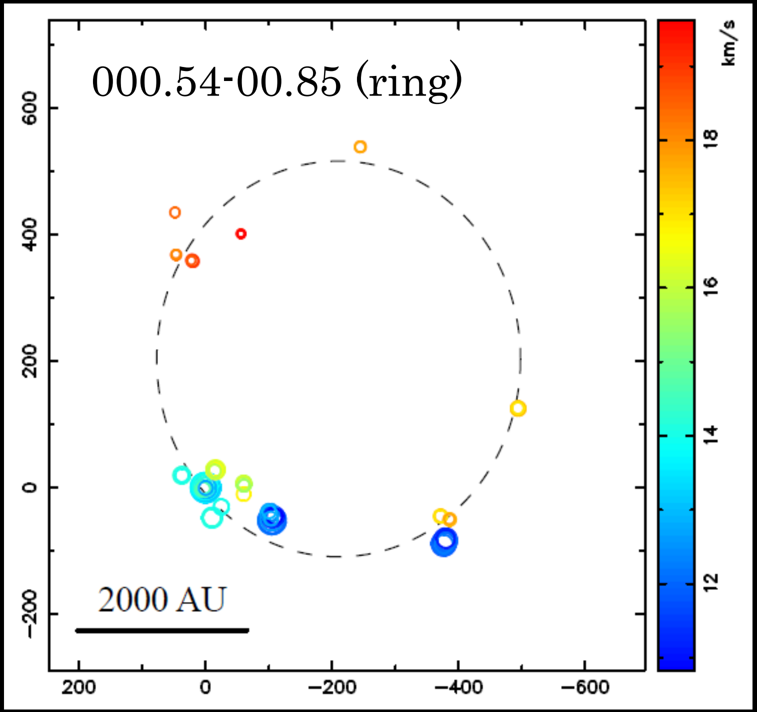
Y:Yamaguchi, U:Usuda, H:Hitachi, M:Mizusawa, R:Iriki, O:Ogasawara, I:Ishigaki, S:Shanghai

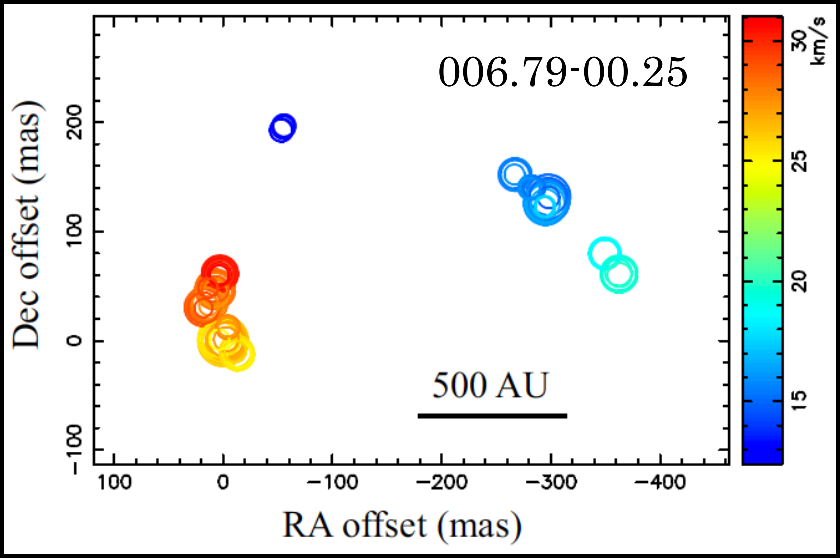
Results_v1

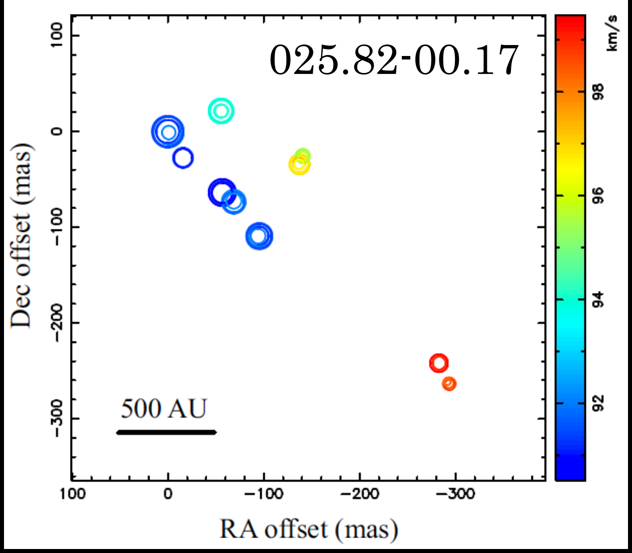
~ Spatial morphology on VLBI images ~

Ellipse: 6/35 (17%)

- Fitted by ellipse
- One clear ring
- Size : 100-4000 AU
- Gradient of LSR velocity

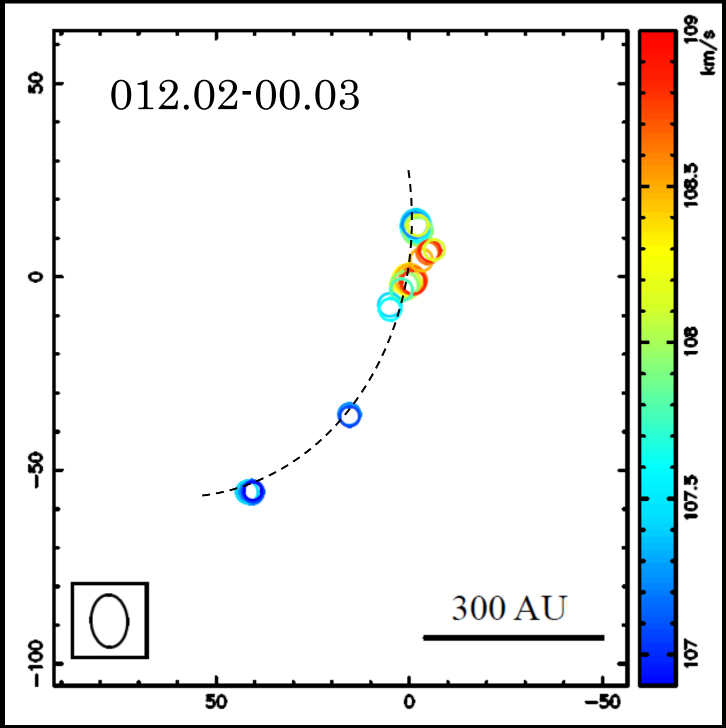


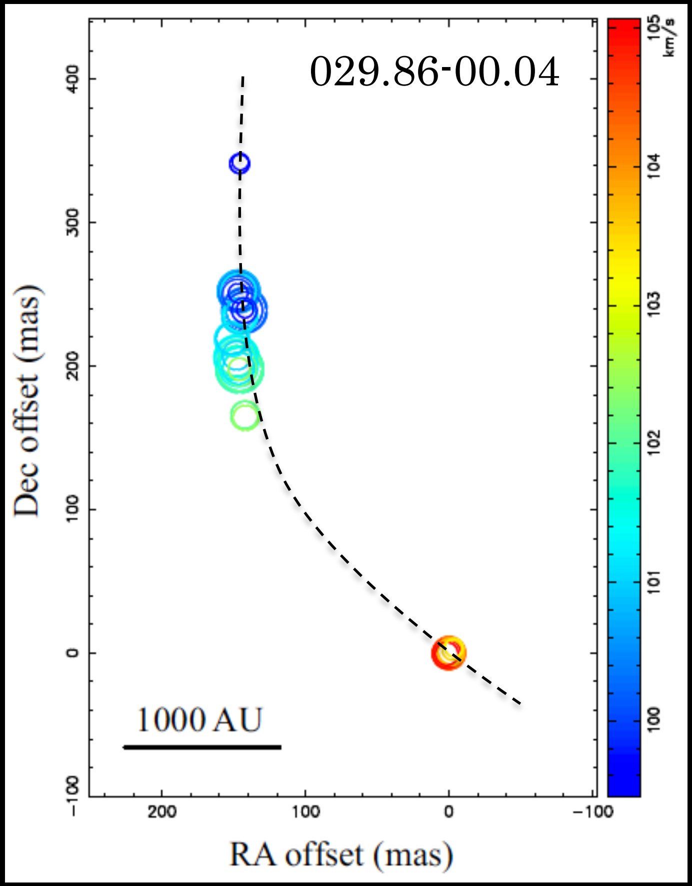




Arched: 2/35 (6%)

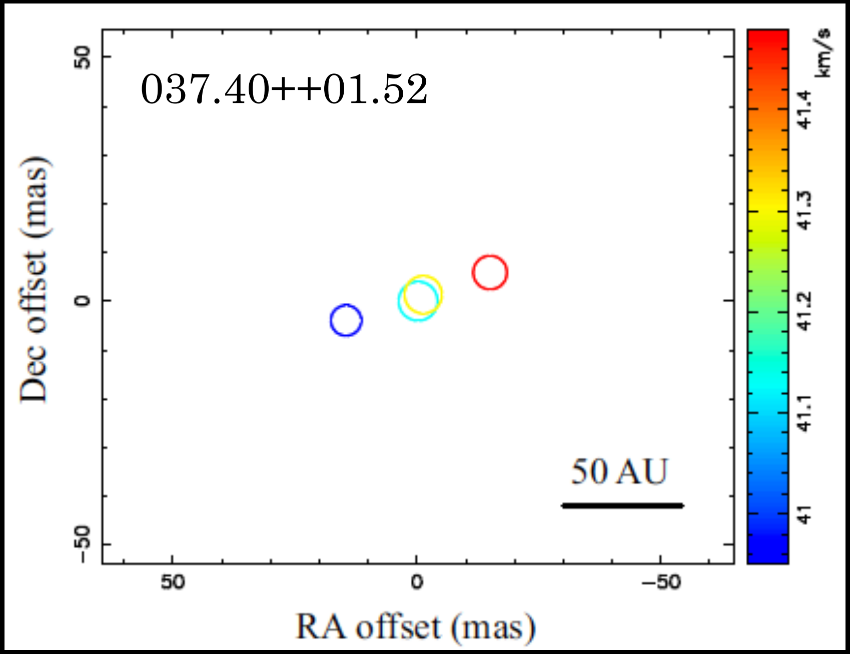
- ❒ Not fitted by ellipse, rare case
- ❒ Size: 500-3000 AU

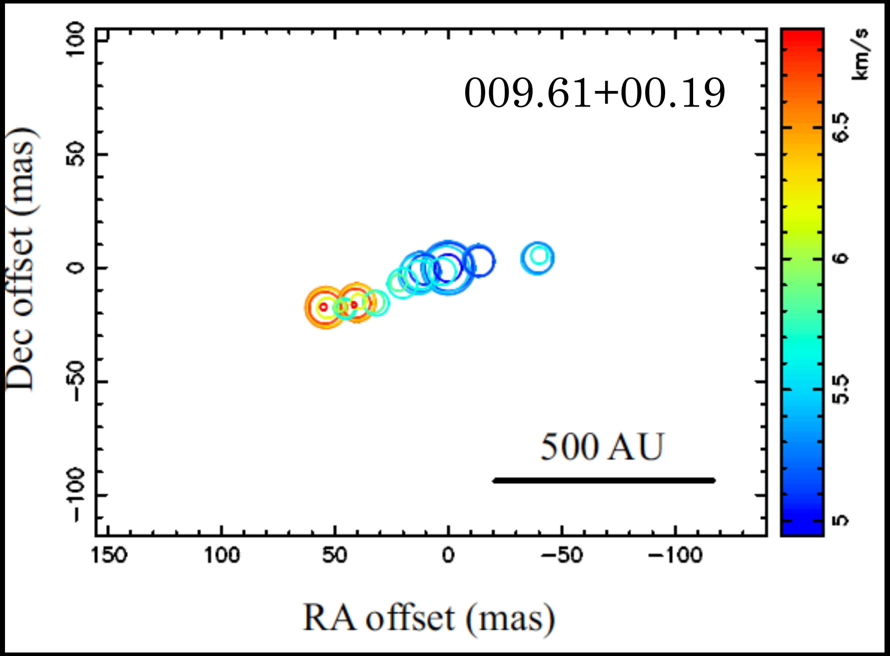




Linear: 6/35 (17%)

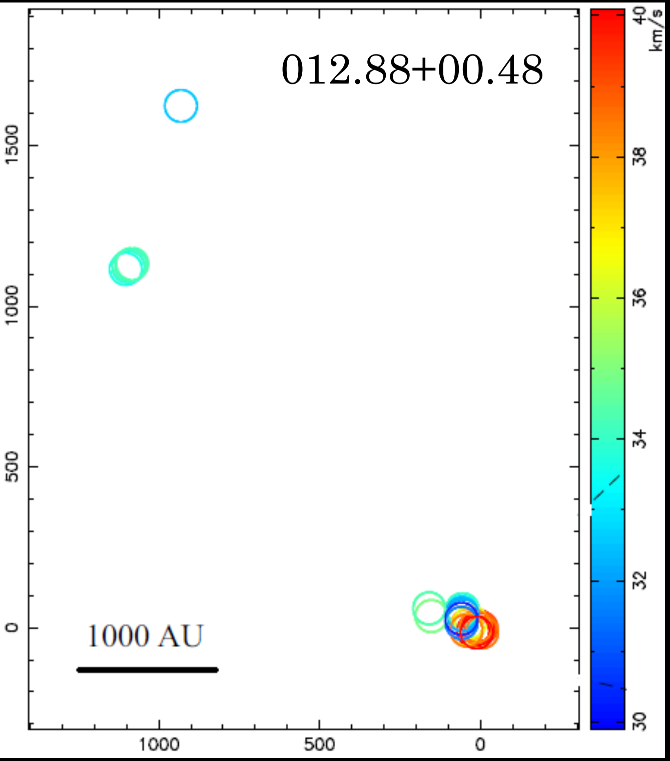
- Distributed on a linear
- Size: 100-500 AU
- Gradient of LSR velocity

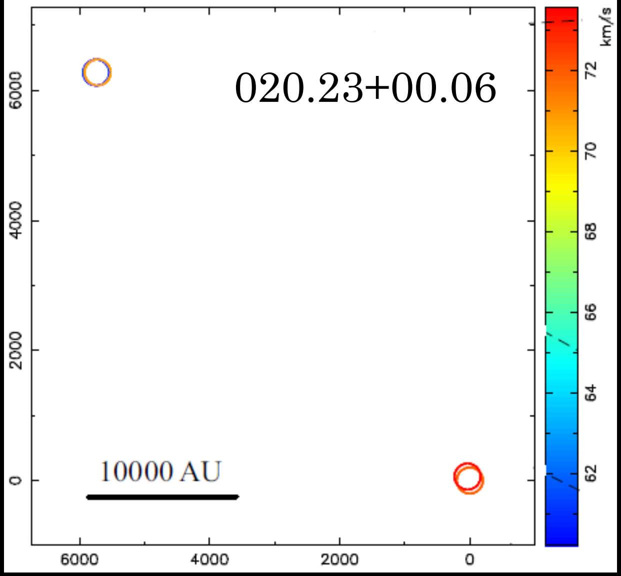


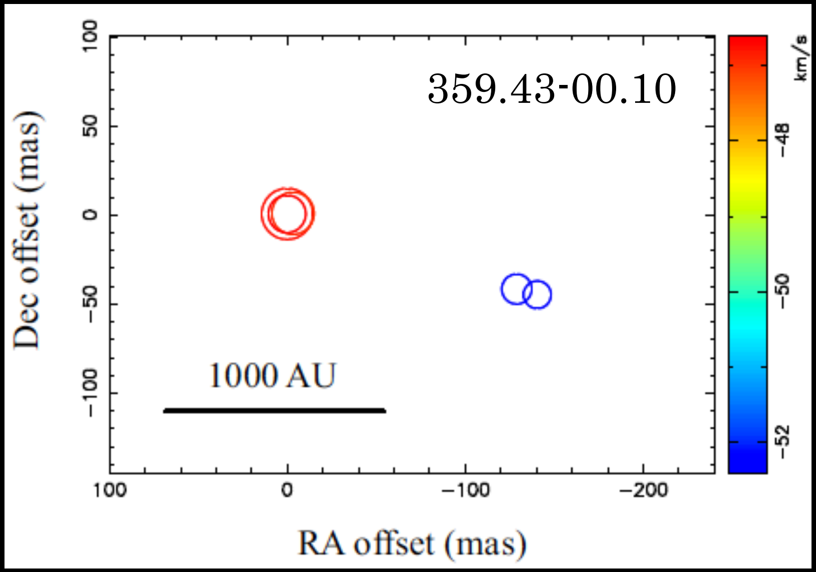


Pair: 7/35 (20%)

- ❒ Isolated >1000 AU
  - ~equal to size of a disk
- ❒ Size: 1500-85000 AU
- ❒ Individual YSOs

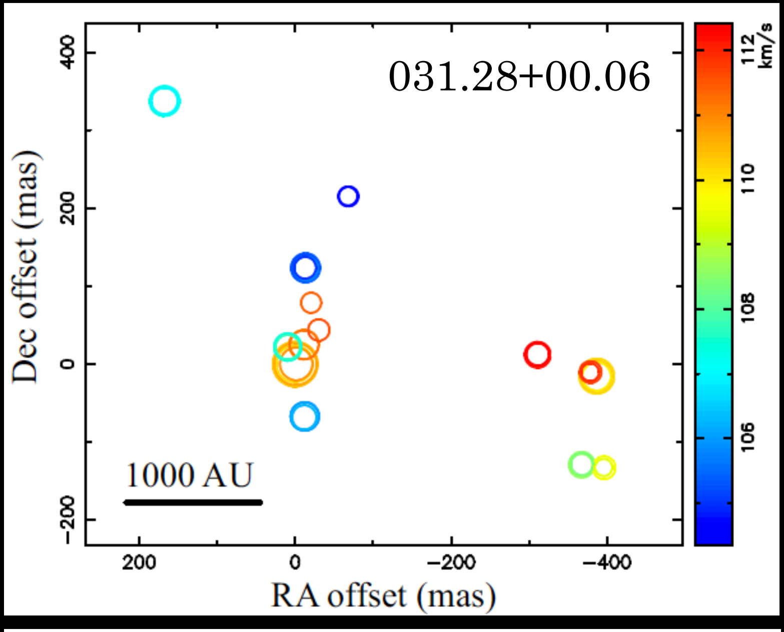


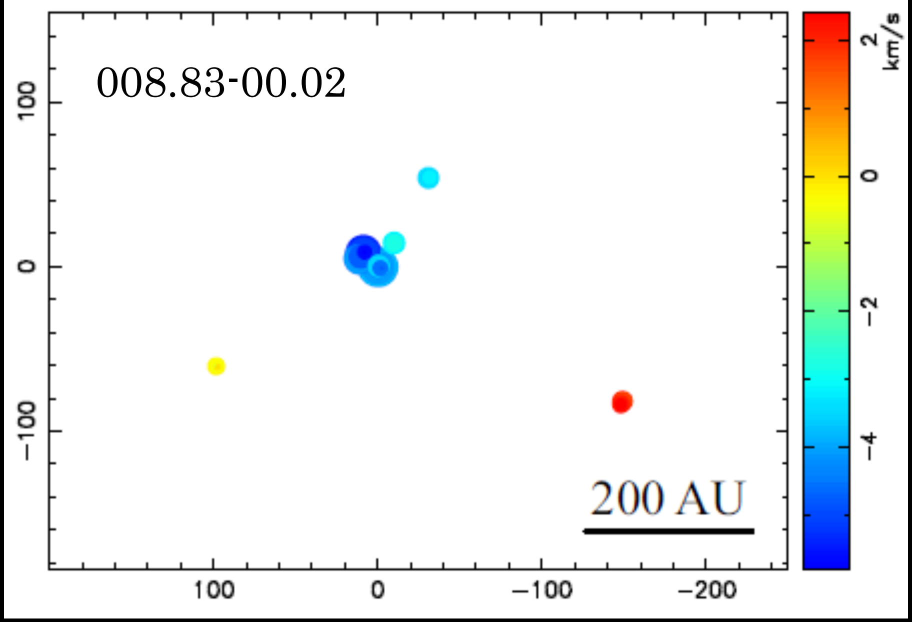


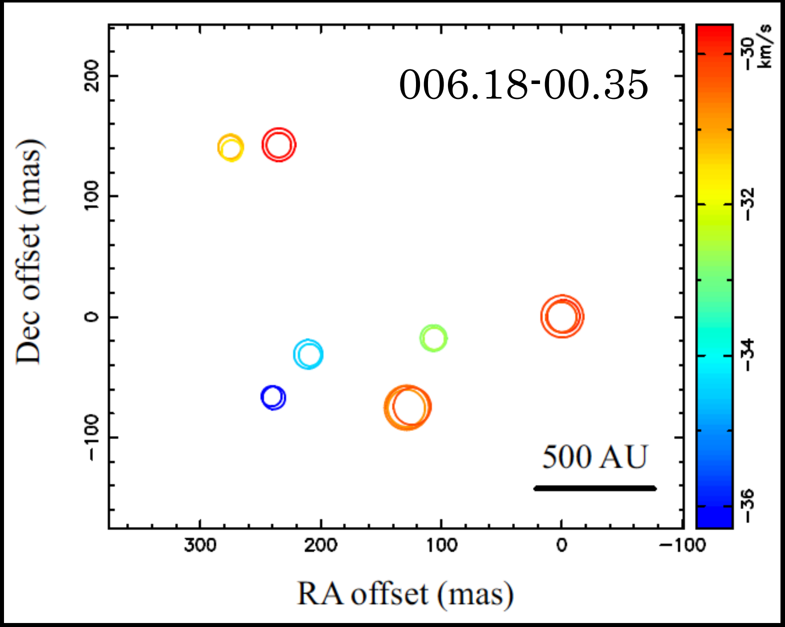


Complex: 14/35 (40%)

- Difficult to classify
- Size: 100-3500 AU
- Wide LSR vel. range







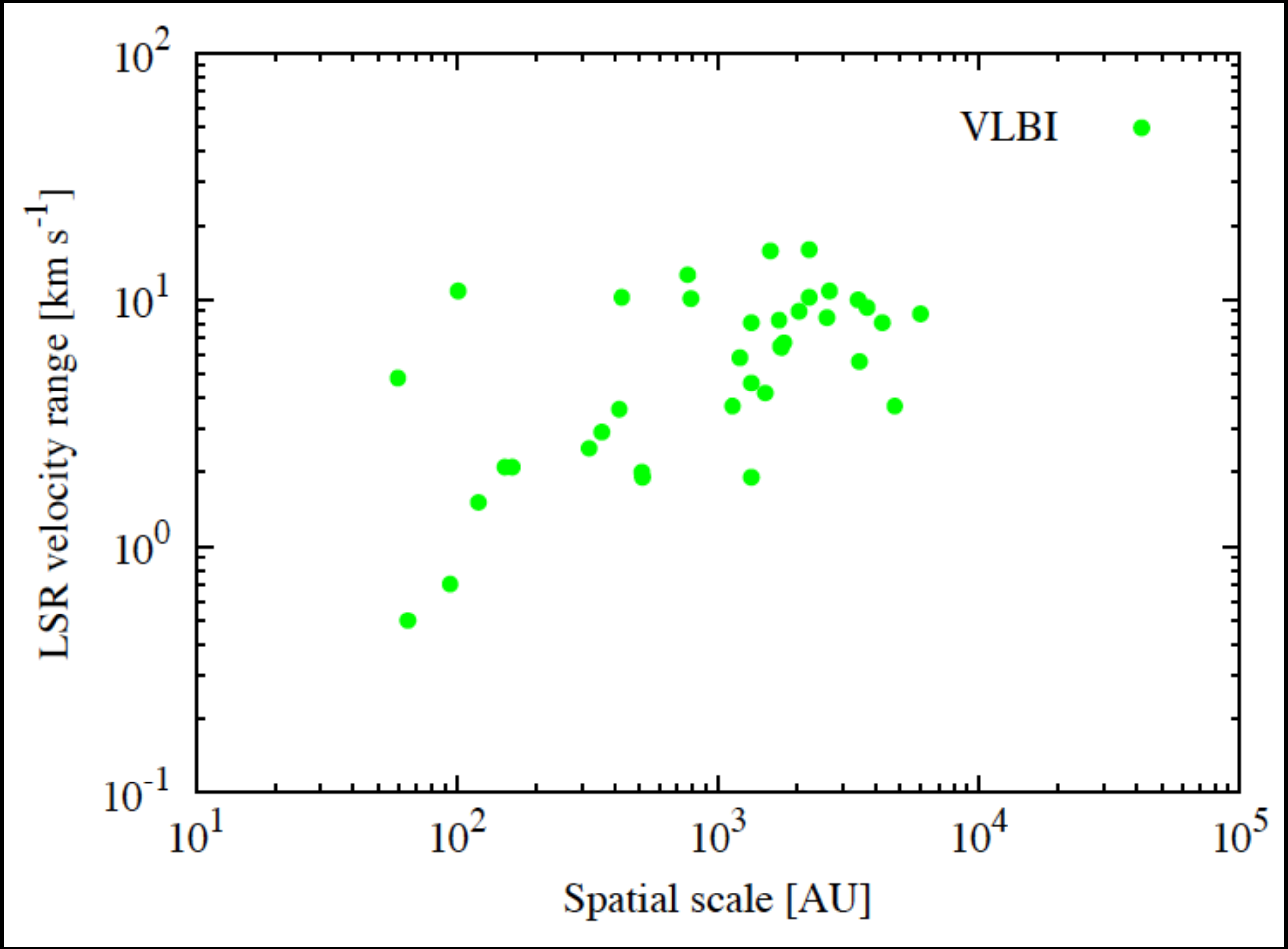
Summary for VLBI images
(Fujisawa et al. to be submitted soon)

	Ellipse	Arched	Linear	Pair	Complex
EAVN	6	2	6	7	14

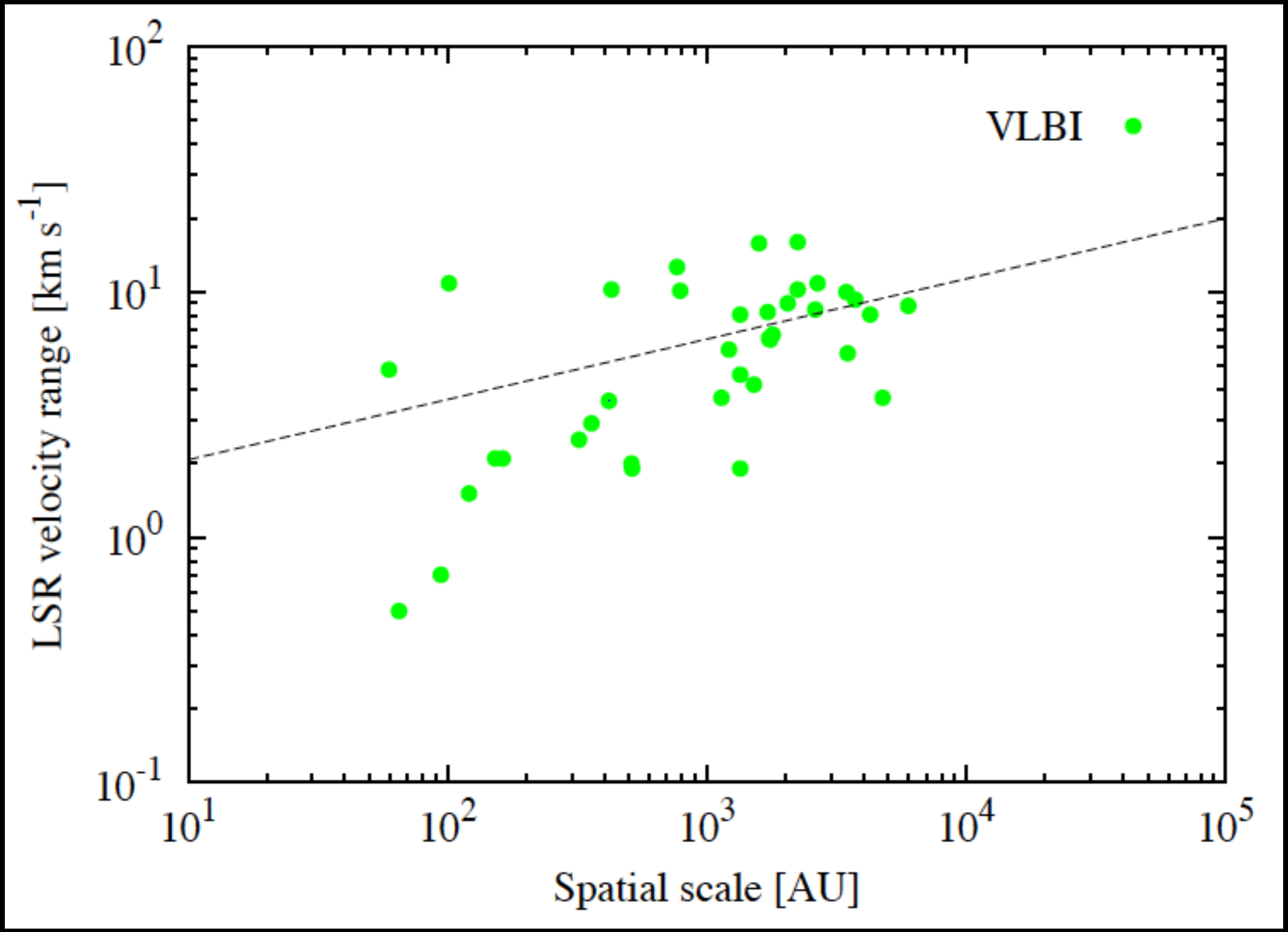
- ❐ 35 VLBI sources classified into five morphology
  - Ellipse 6 (17%)
  - Arched 2 (6%)
  - Linear 6 (17%)
  - Pair 7 (20%) : separated individual YSOs (>10000AU)
  - Complex 14 (40%)

However, is it true ??

Spatial scale vs LSR vel. range

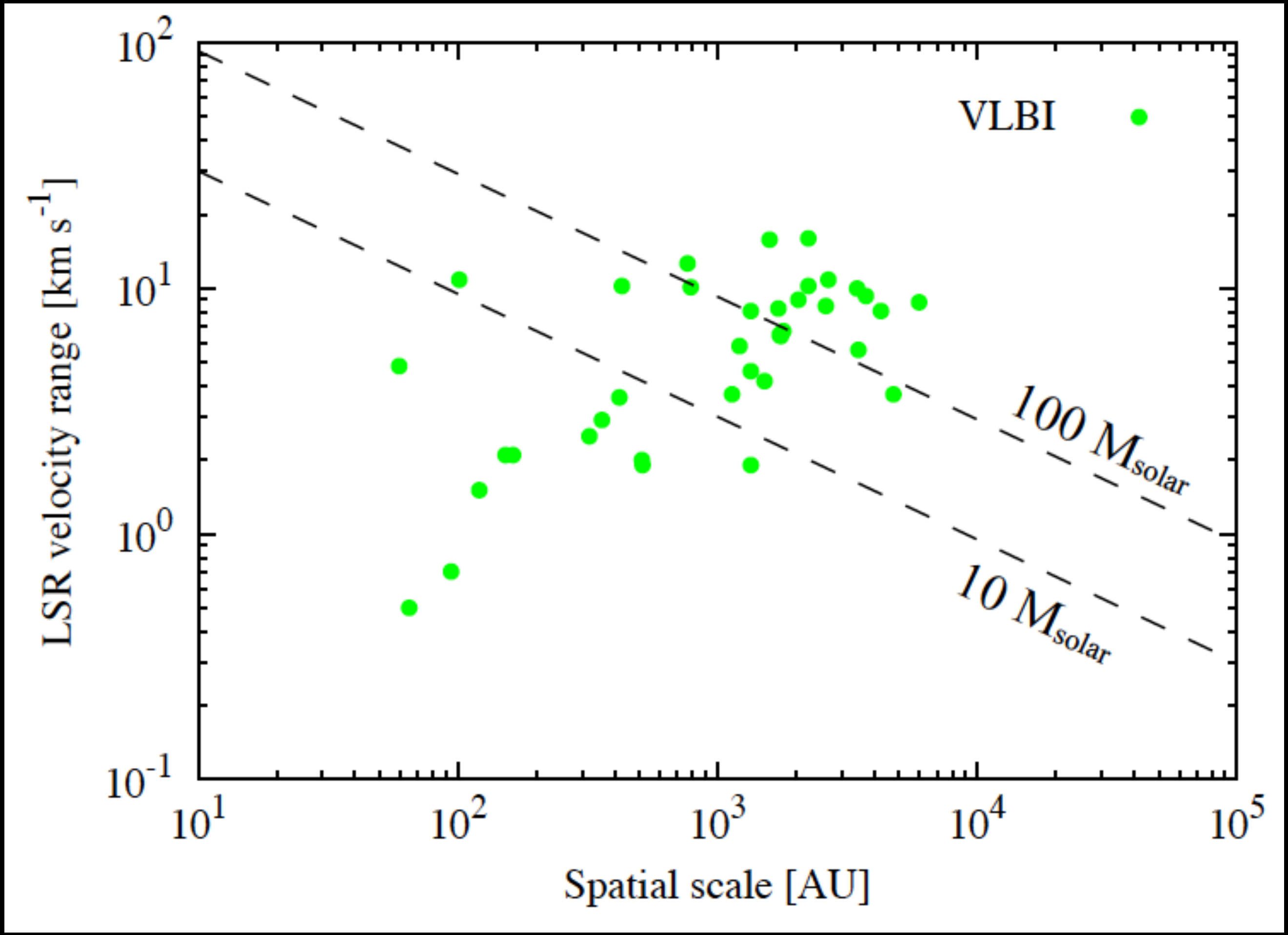


Spatial scale vs LSR vel. range



$y = a\ x^b$: a=1.18 pm0.80, 0.25 pm0.09

Spatial scale vs LSR vel. range

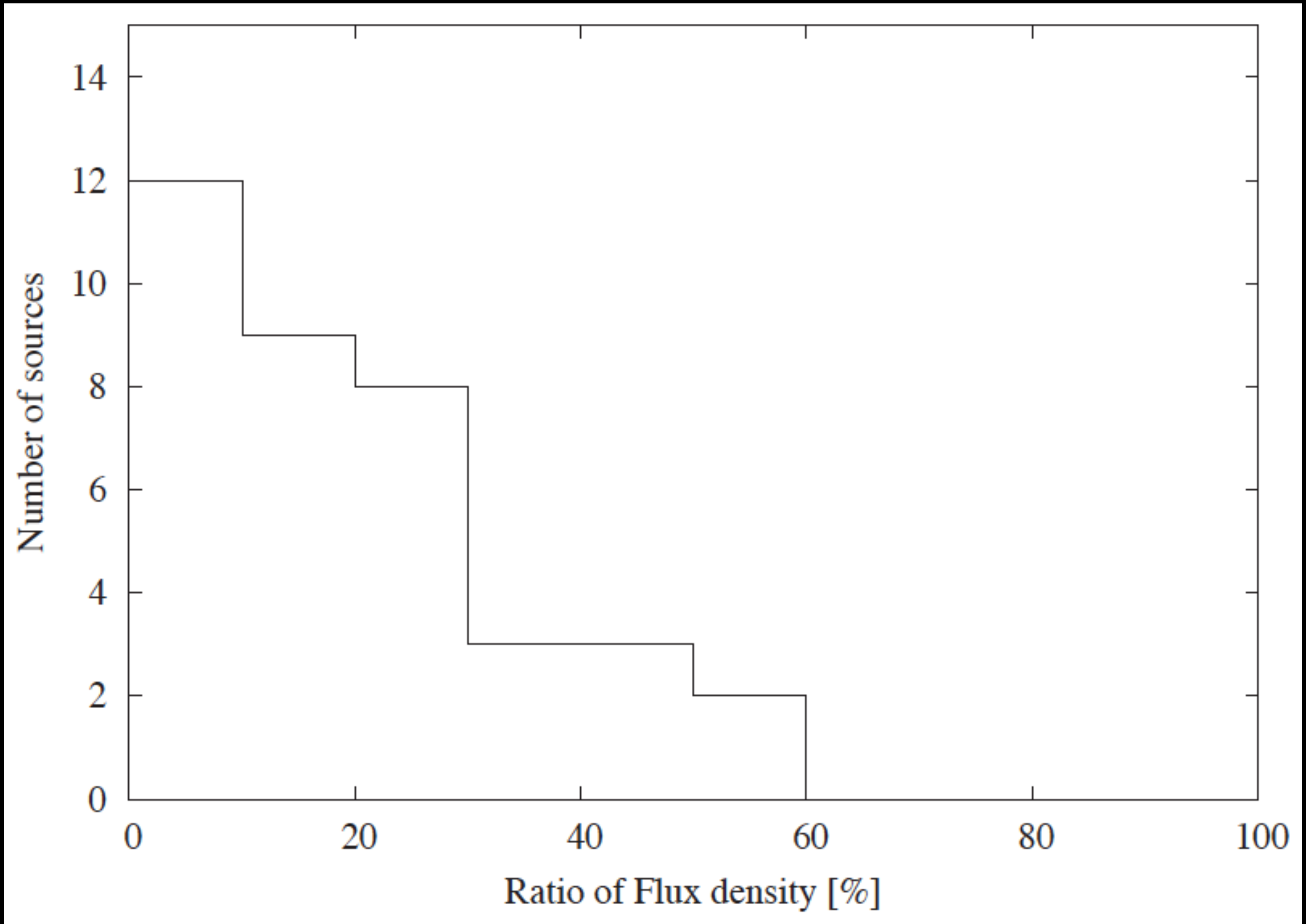


Possibilities

- Trigger of not simple Keplerian model
  1. Resolved out : apparent spatial scale/morphology
  2. + Expansion/infall : large velocity dispersion
  3. Not associated disk basically

- Response
  1. Not VLBI, just interferometer obs.
  2. Proper motion measurement
  3. Proper motion measurement

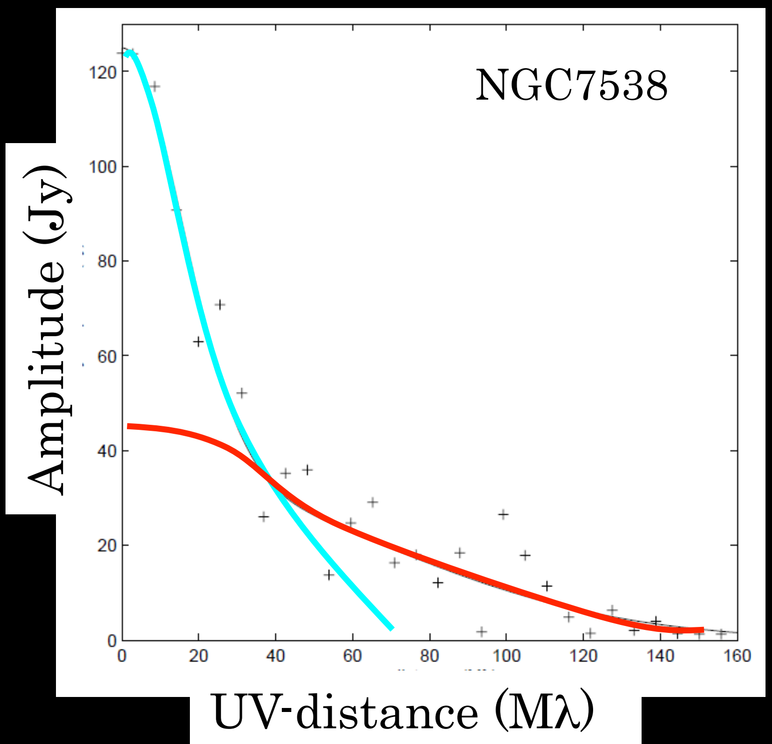
Resolved out in our VLBI

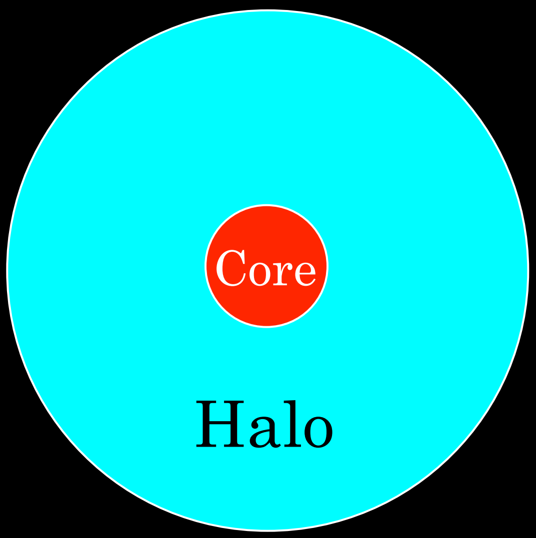


Structure of each maser spot

- ❒ Consists of core/halo components
- ❒ halo comp.(>100AU): resolved out on VLBI?

Verify spatial morphology without resolved out!





Projection plot of amplitude (Minier+ 02)

Results_v2

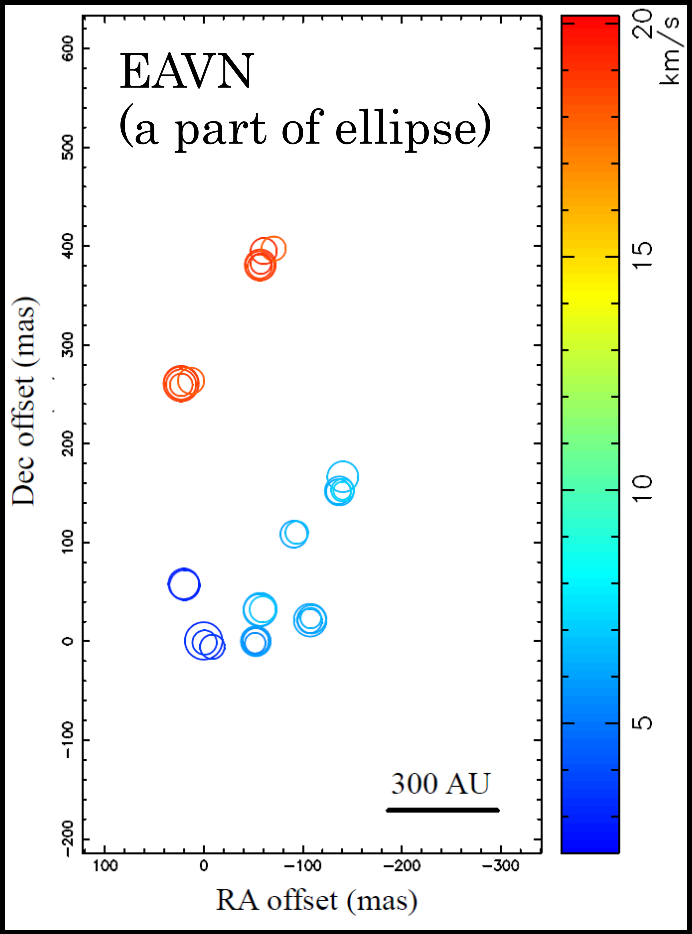
~ Comparison with the ATCA images ~

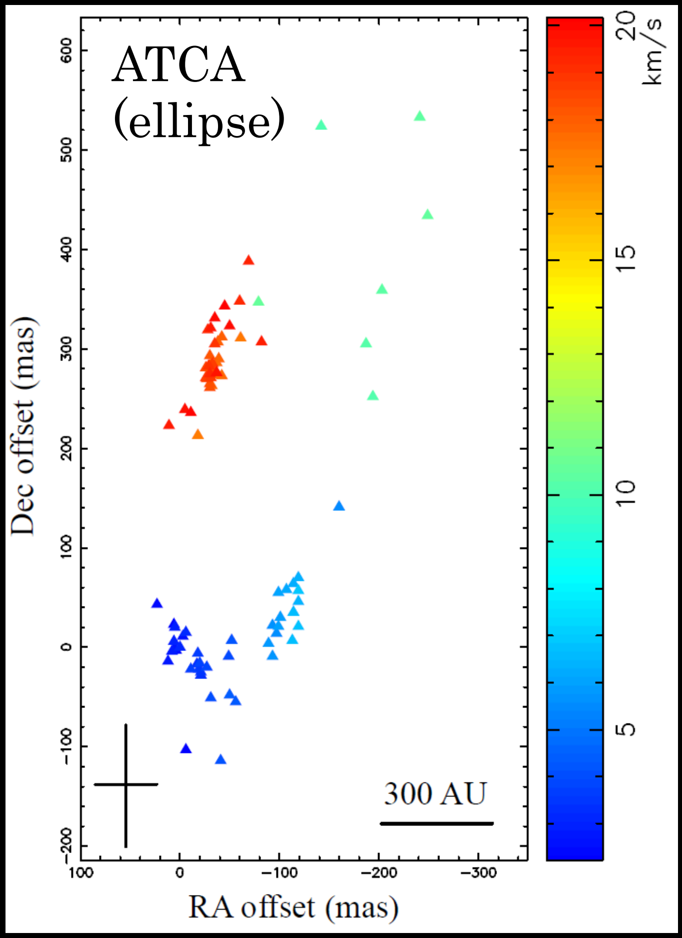
ATCA obs.

Image credit: ATCA web-site

- date: 2012/02/11-14, 16-19
- Configuration: 6A & 1M-0.5k
  - Line: 1MHz with 2048 ch x IF8: ~0.022 km s^{-1}
- Freq.: 4.8-6.8, 8.0-10.0 GHz
- Spatial res.: ~2.0 x 1.5 $arcsec^2$ @6.7G
- Sensitivity:
  - Line : ~0.1 Jy/beam
- Target: 24 sources from EAVN sample
  - exclude around equatorial sources (-5 < Dec < 5 deg)

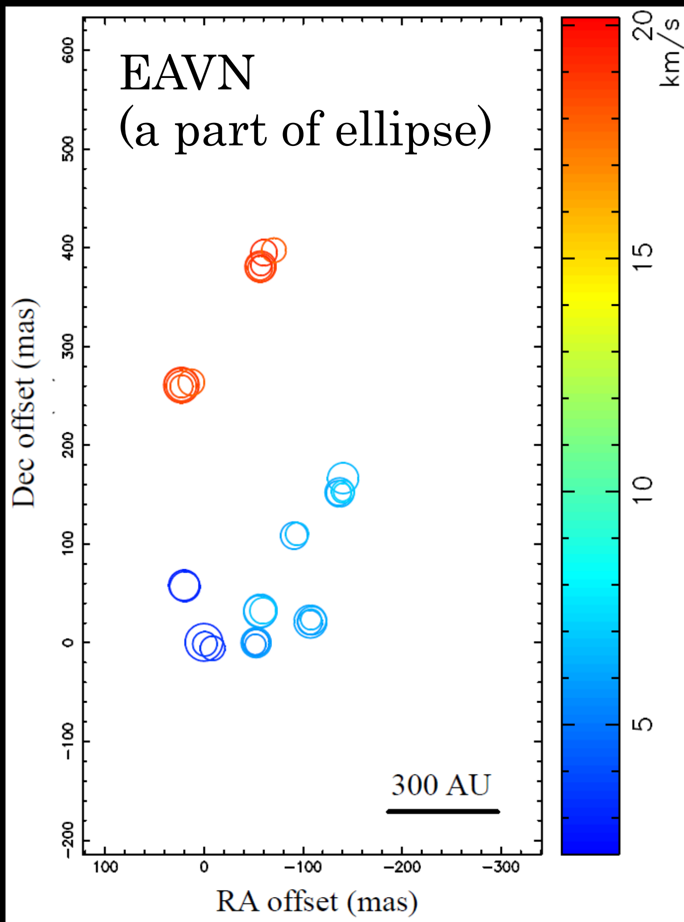
EAVN vs ATCA images e.g.) G2.536+0.198

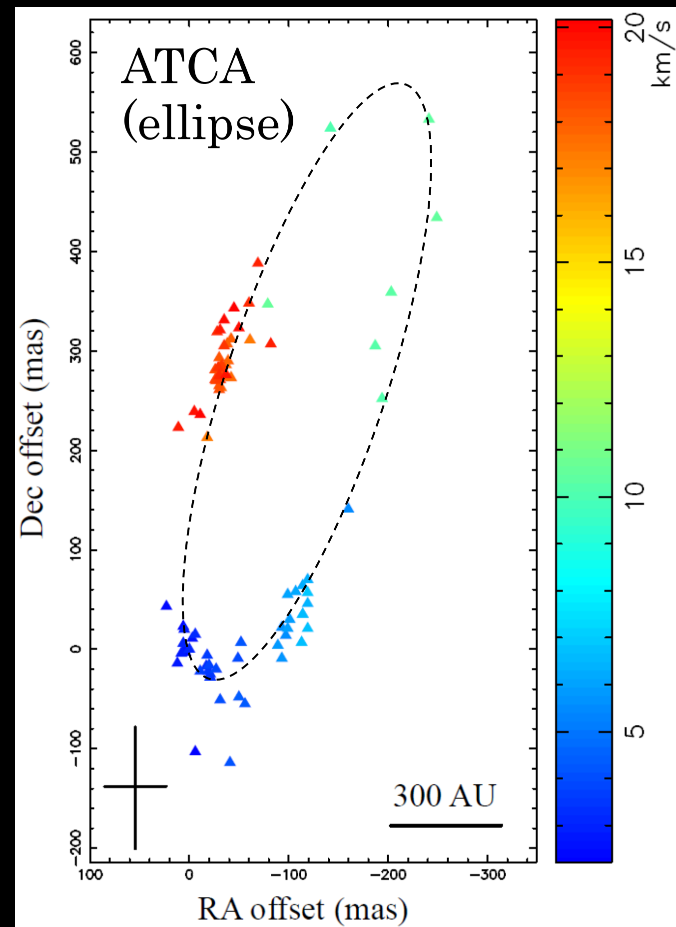




Become to be clear for spatial scale/morphology

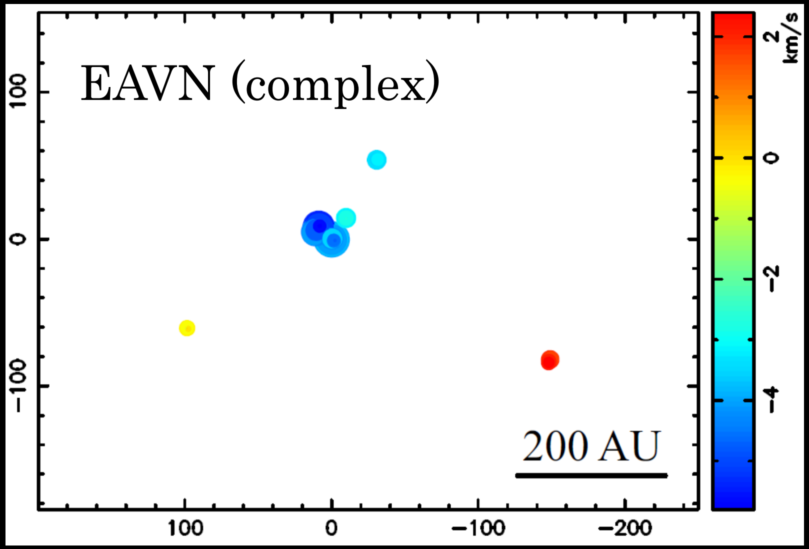
EAVN vs ATCA images
e.g.) G2.536+0.198

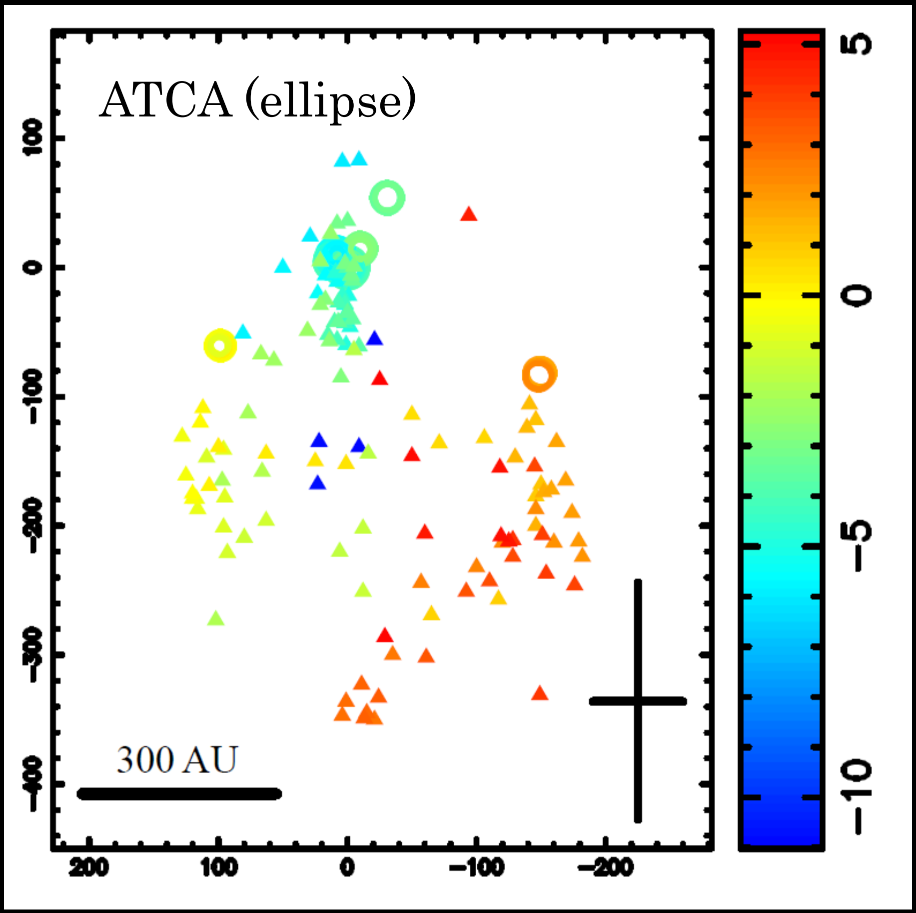




Become to be clear for spatial scale/morphology

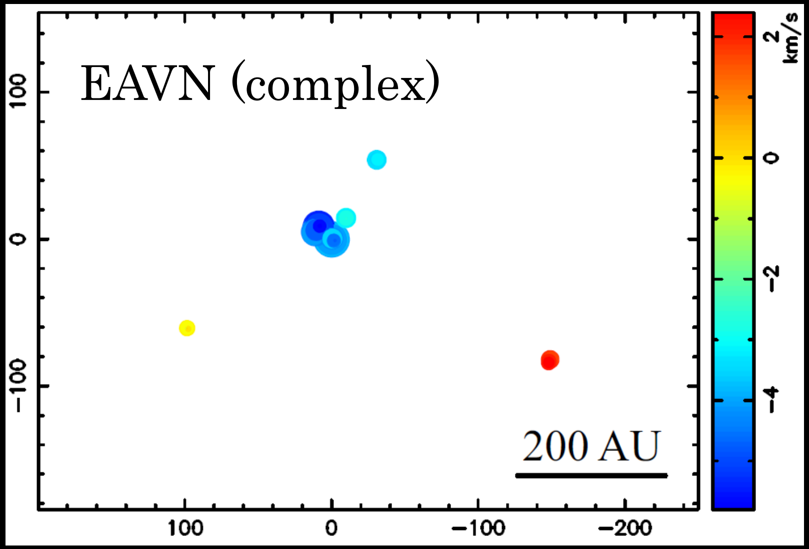
Complex => Ellipse
e.g.) G8.832-0.028

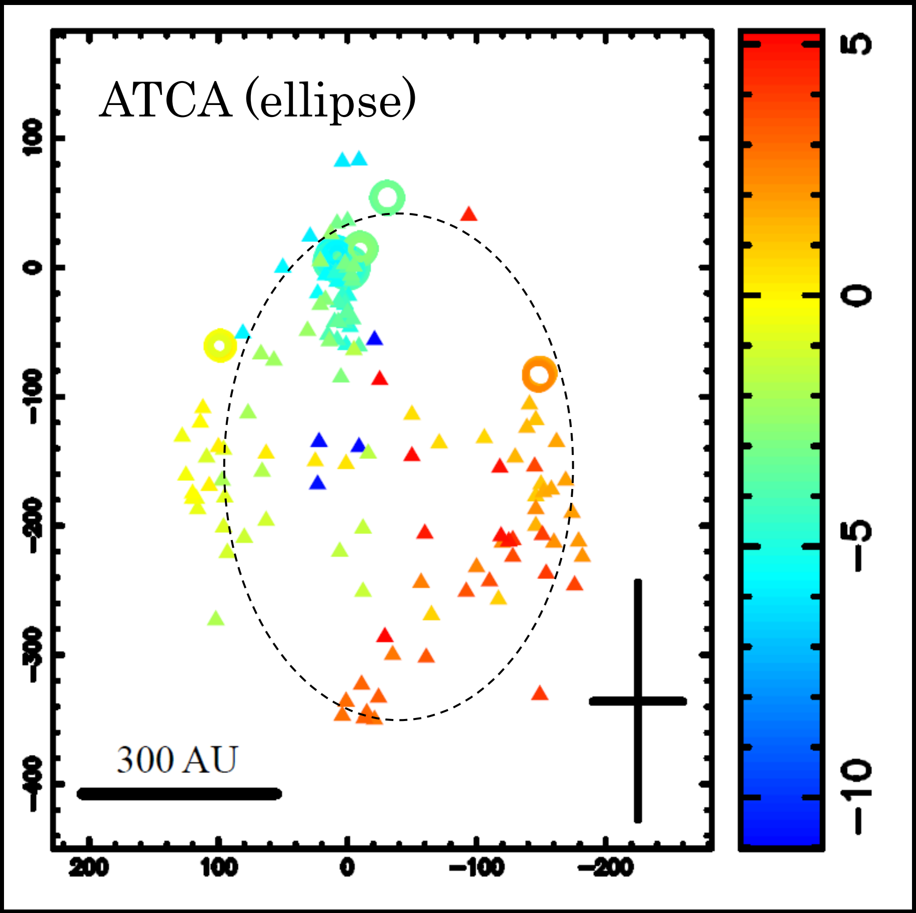




- ❒ Represent
  - Spatial scale
  - Range of LSR vel.

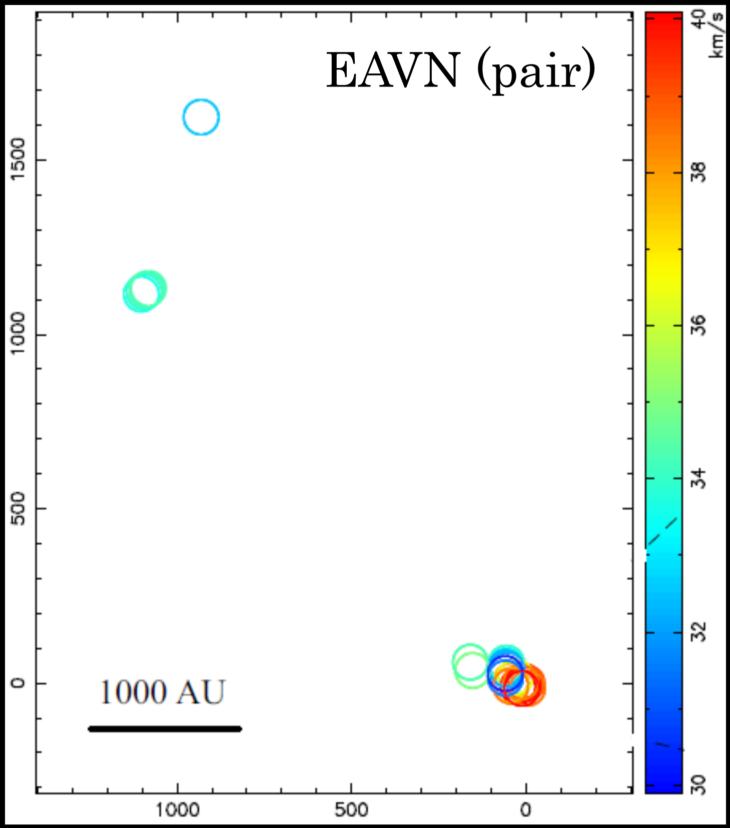
Complex => Ellipse
e.g.) G8.832-0.028

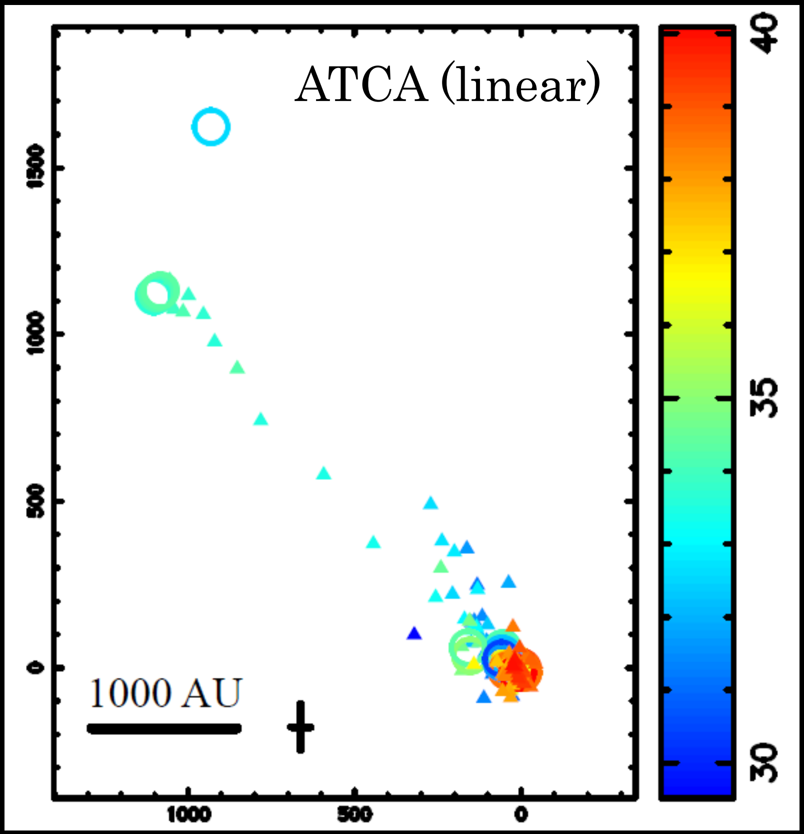




- Represent
  - Spatial scale
  - Range of LSR vel.

Pair => Linear
e.g.) G12.889+0.489



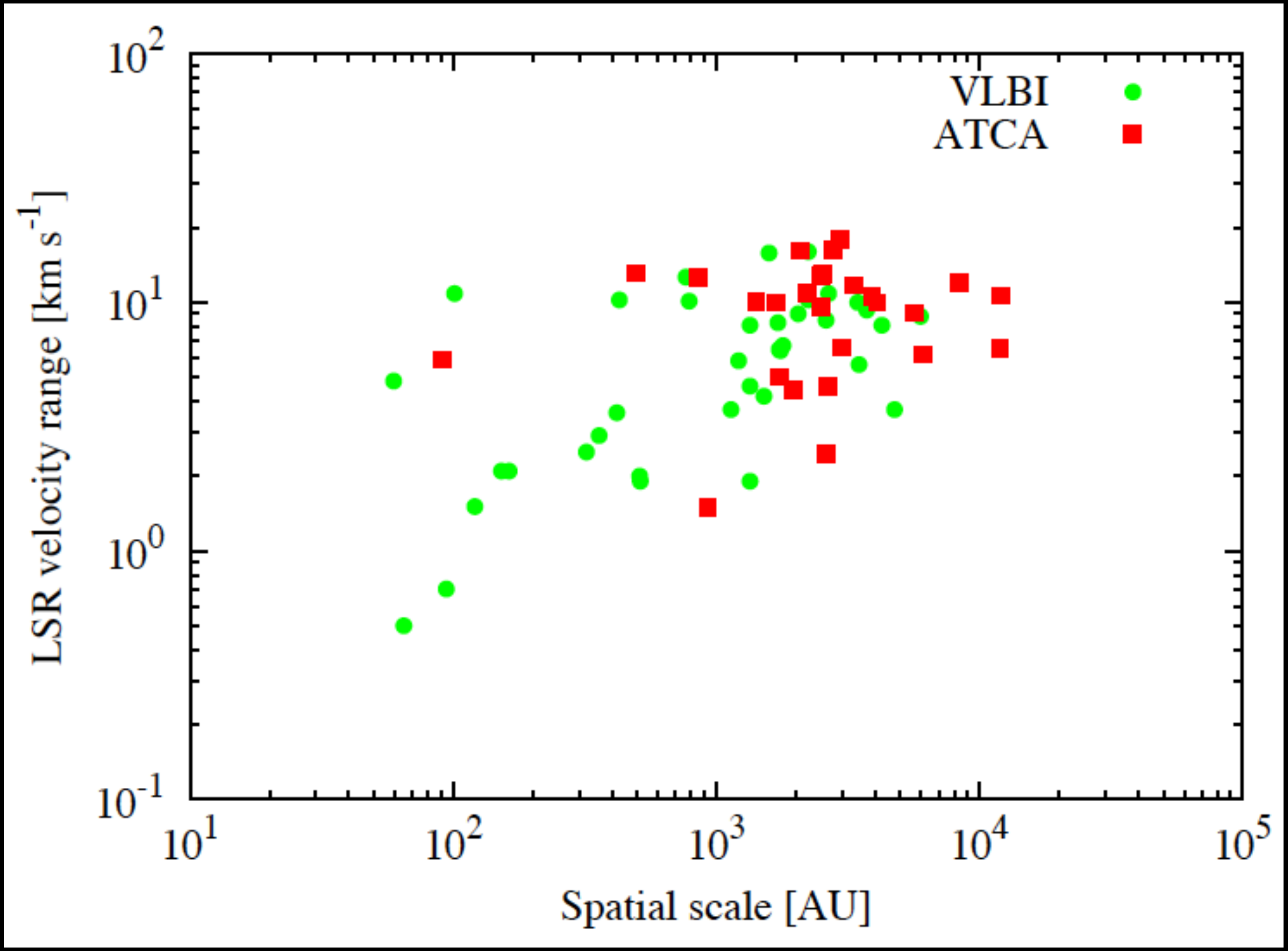


Summary including ATCA images

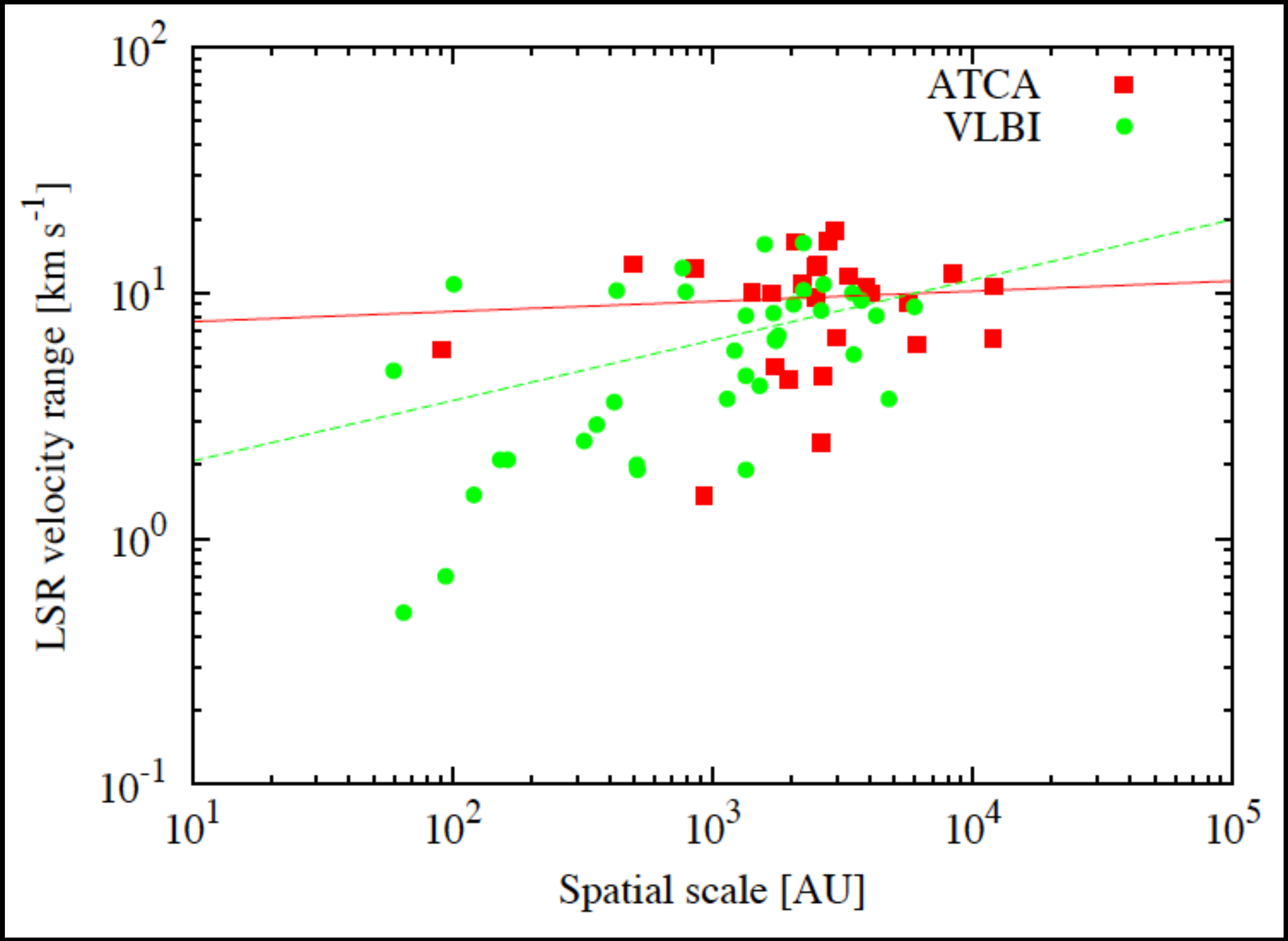
	Ellipse	Arched	Linear	Pair	Complex
EAVN	6	2	6	7	14
EAVN*	5	1	2	5	11
ATCA	9	1	5	2	7

- ❒ Successful for detection of halo comp.
- ❒ Solved ambiguity morphology (Pair/Complex)
- ❒ Correct spatial scale / velocity range
- ❒ The best collaboration
  - Spatial scale/morphology: Connected array
  - Proper motion: VLBI

Improved with the ATCA

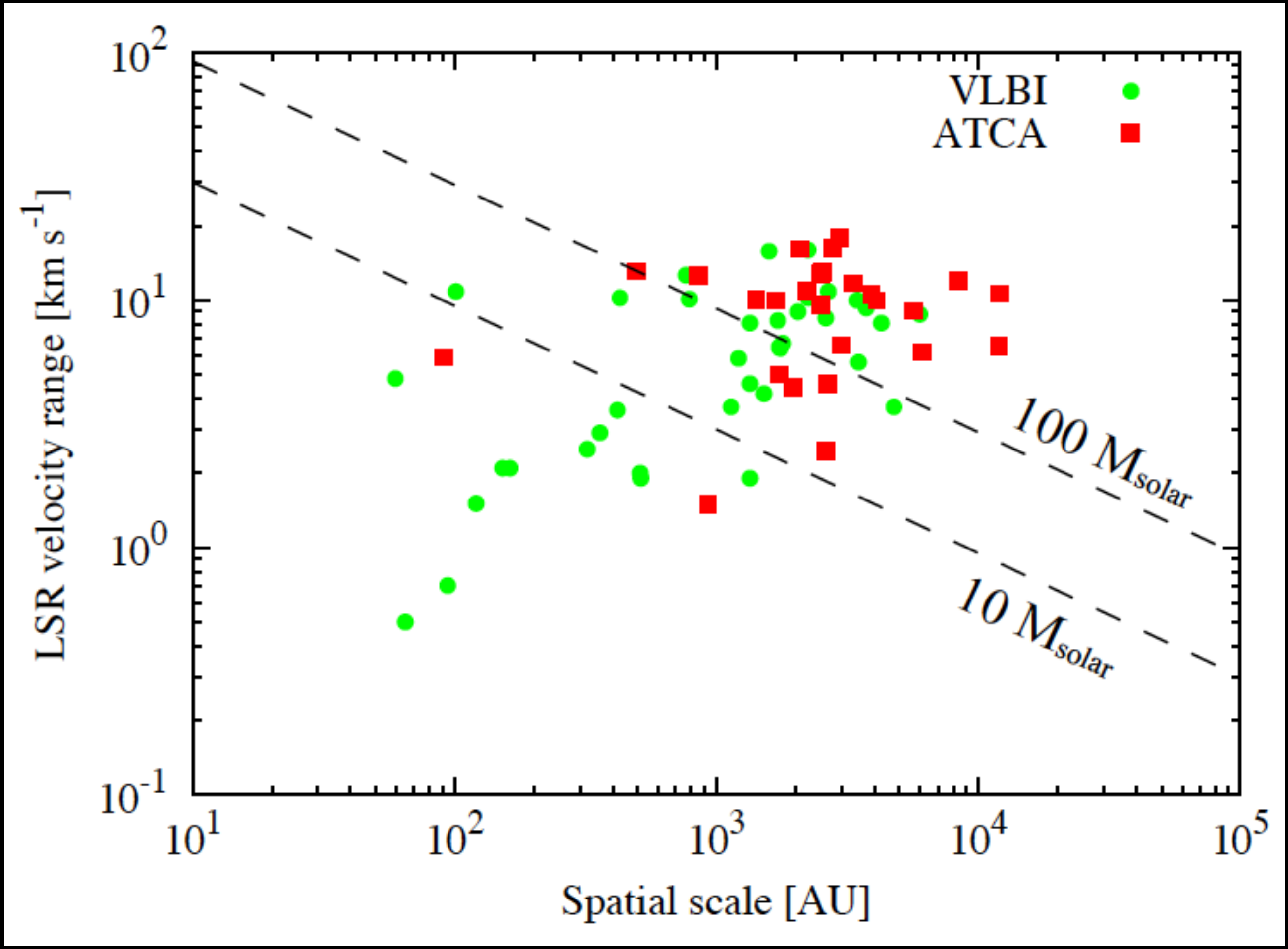


Improved with the ATCA



y = a x^b: a=6.95 pm5.17, b=0.04 pm0.09

Improved with the ATCA

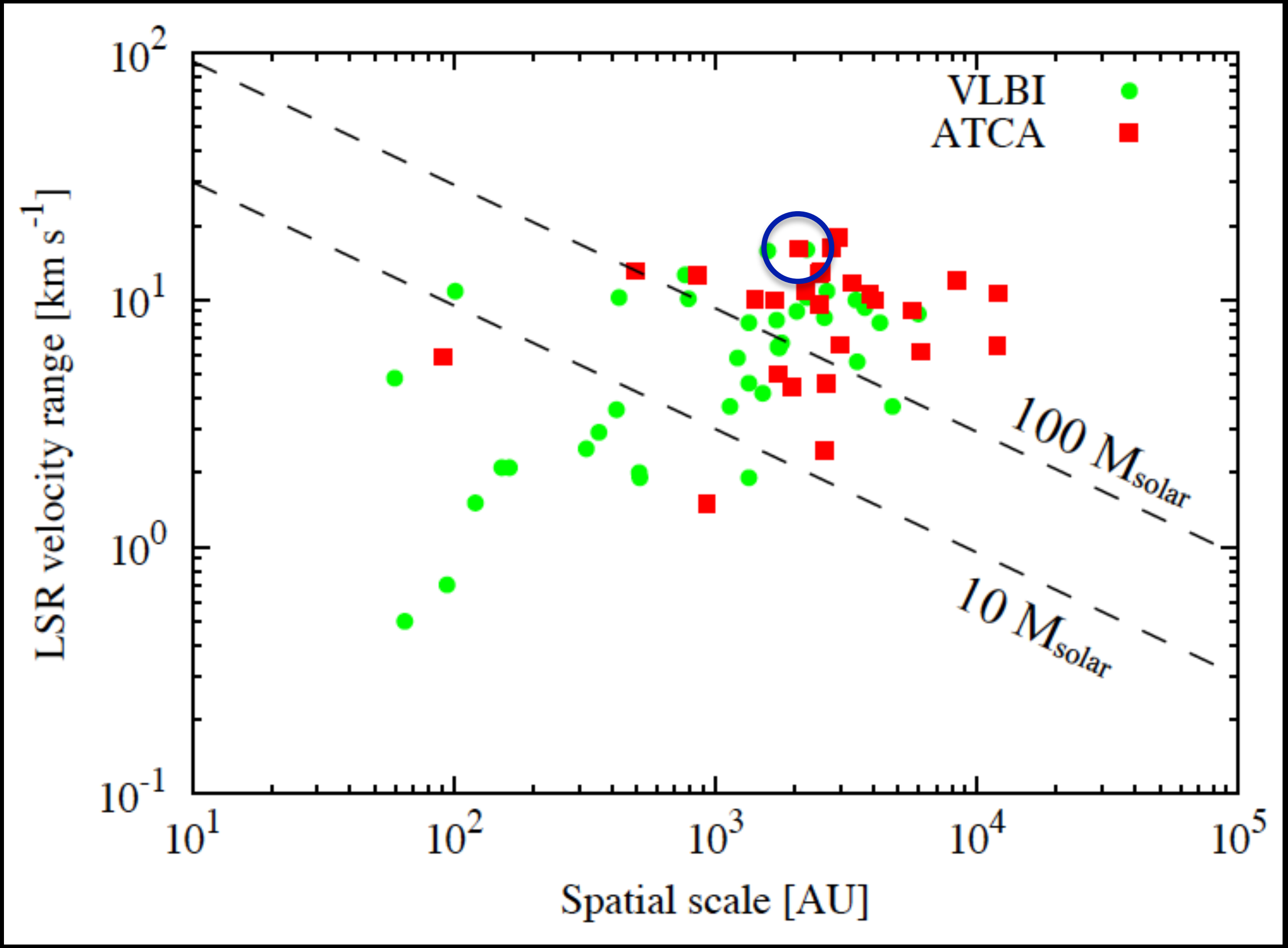


Possibilities

- Trigger of not simple Keplerian model
  1. ~~Resolved out : apparent spatial scale/morphology~~
  2. + Expansion/infall : large velocity dispersion
  3. Not associated disk basically

- Response
  1. Not VLBI, just interferometer obs.
  2. Proper motion measurement
  3. Proper motion measurement

Improved with the ATCA

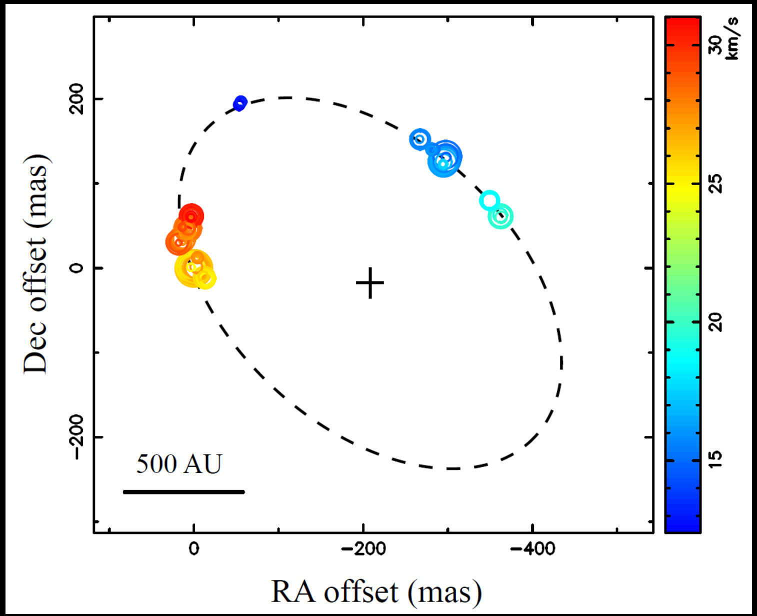


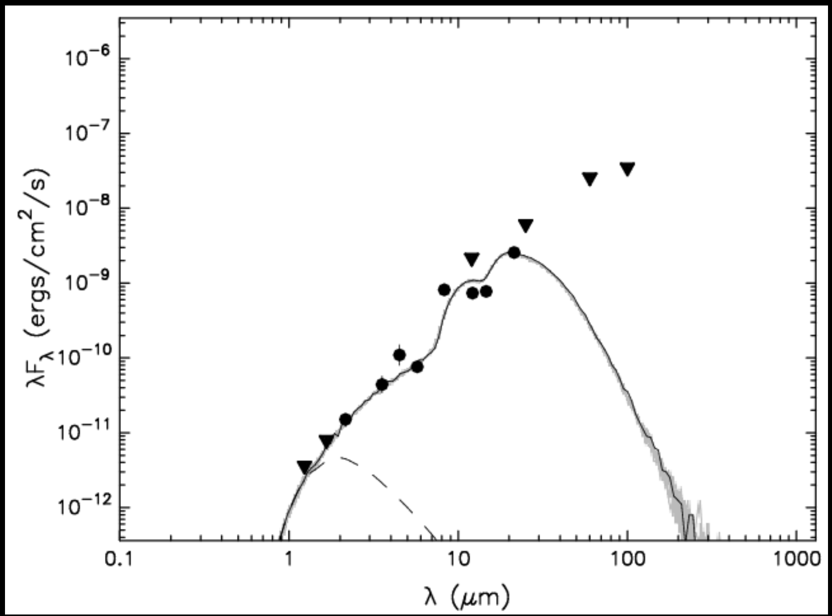
Results_v3

~ A part of proper motion measurements ~

6.7 GHz methanol maser in G006.79-00.25

- Elliptical spatial morphology in EAVN/ATCA
  - Size ~2000 AU : typical disk size
  - Vel. range ~16 km/s : wide, RVG in counter-clock
  - Agreement of inclination estimated by IR-SED





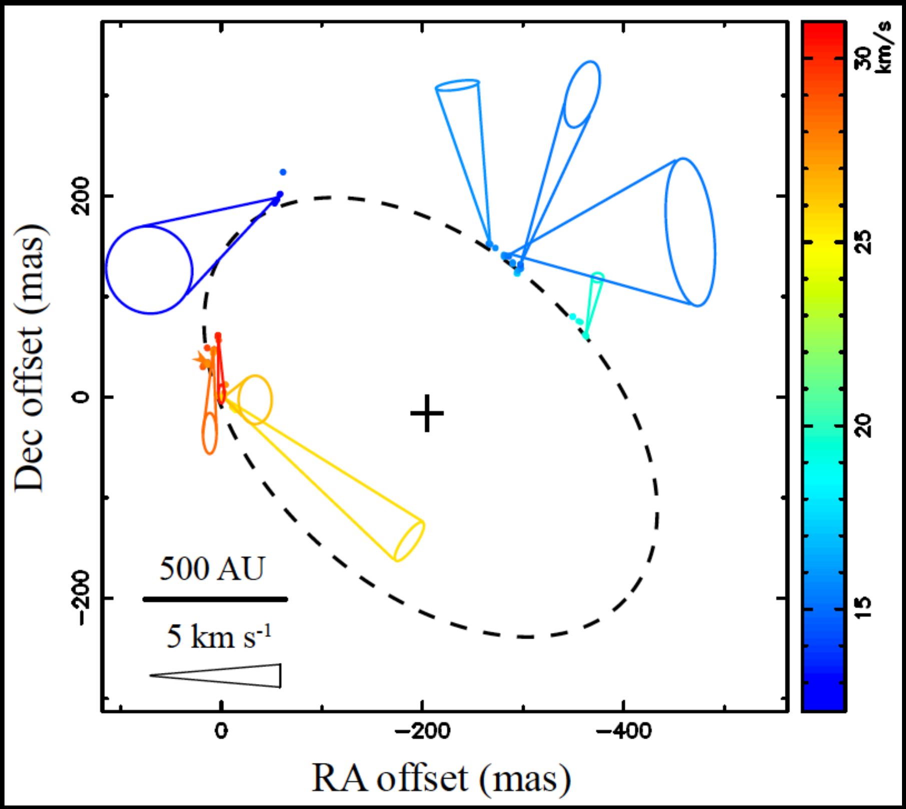
EAVN monitor for G006.79-00.25

- date:
  - 2010/08/29, 2011/10/05, 2012/09/23
- Sensitivity
  - σ : 30-60 mJy $beam^{-1}$ @1 hr
  - Positional accuracy : ~0.1 mas
- Velocity resol. : 0.18 km s^{-1}

Date	Stations	Synthesized beam
2010/08/29	M, R, O, I, H, S	7.4 x 2.9 mas^2, PA +3 deg
2011/10/05	M, R, O, I, Y, H	7.2 x 4.0 mas^2, PA -9 deg
2012/09/23	M, R, O, I, Y, H, S	7.7 x 3.4 mas^2, PA -4 deg

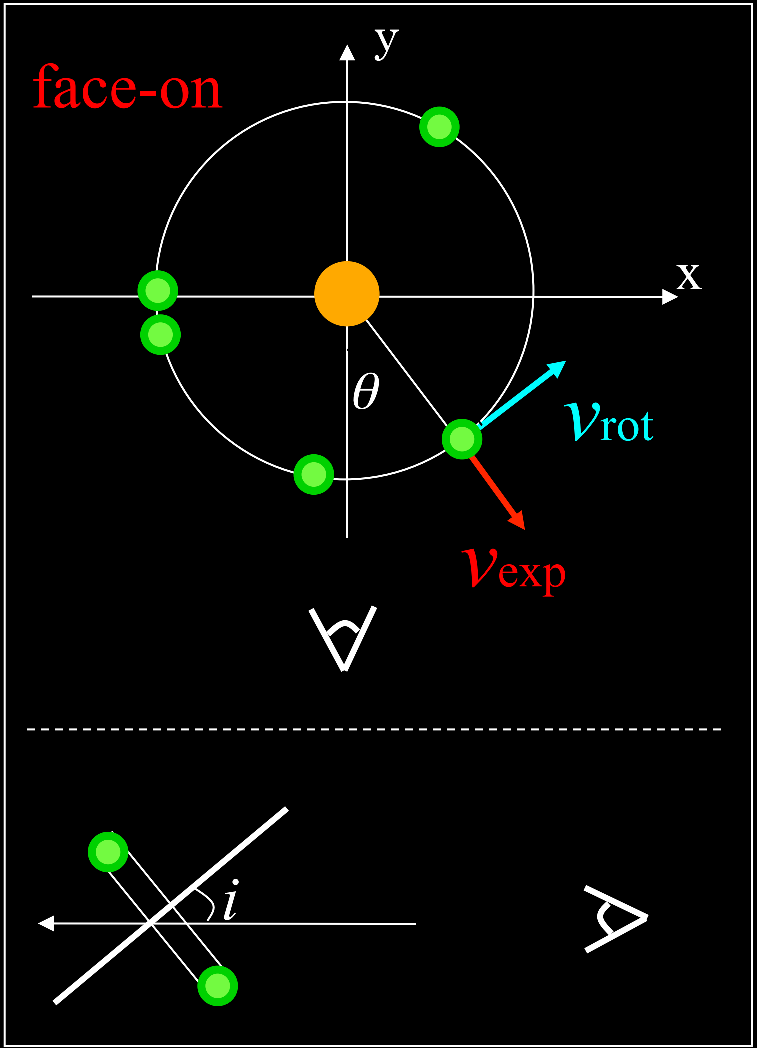
Y:Yamaguchi, U:Usuda, H:Hitachi, M:Mizusawa, R:Iriki, O:Ogasawara, I:Ishigaki, S:Shanghai

Relative proper motion



- ❒ Detection:
  - Multi-ch
  - $> 2\ \sigma$
  - in 65 maser spots
    - tangential: 1~18 km s^{-1}
- ❒ Not bipolar/spherical expansion
- ❒ Rotation in counter-clockwise

Rotation + Expansion/Infall for 3-D



❒ Model

$$
\begin{aligned}
V_x^{\rm calc} &= V_{\rm rot}\sin\theta + V_{\rm exp}\cos\theta \\
V_y^{\rm calc} &= -(V_{\rm rot}\cos\theta - V_{\rm exp}\sin\theta)\cos i \\
V_z^{\rm calc} &= -(V_{\rm rot}\cos\theta - V_{\rm exp}\sin\theta)\sin i + V_{\rm sys}
\end{aligned}
$$

- Concentric distribution
- Motion on a plane

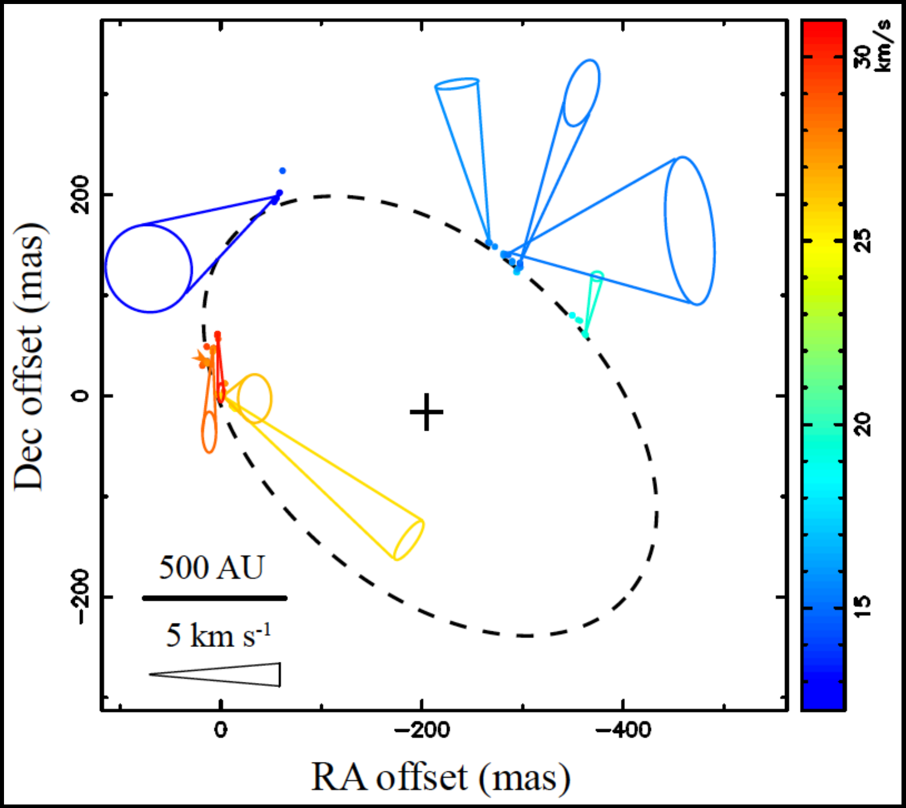
❒ Fitting

$$
\chi^2 = \sum_{j=1}^{N} w_j\left((V_{xj} - V_{xj}^{\rm calc})^2 + (V_{yj} - V_{yj}^{\rm calc})^2 + (V_{zj} - V_{zj}^{\rm calc})^2\right)
$$

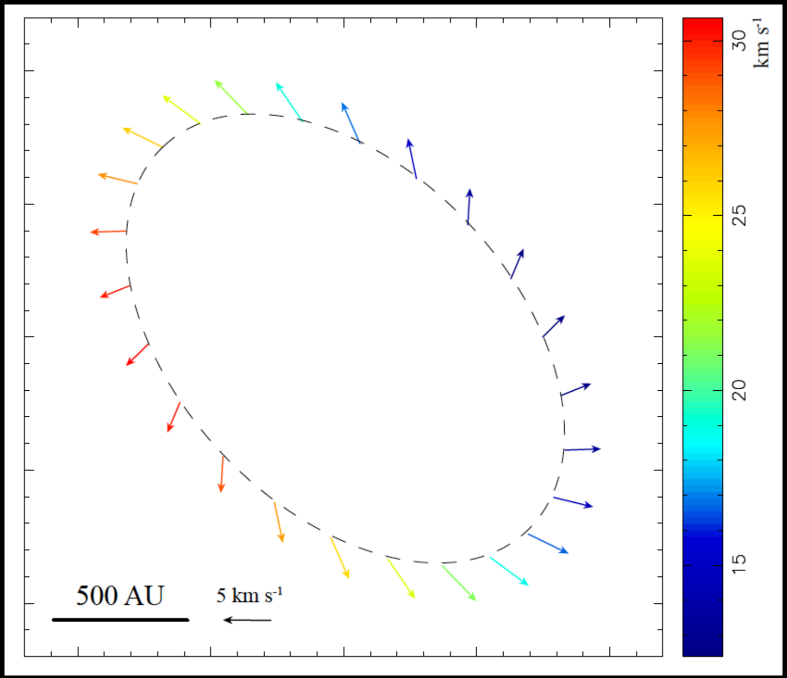
Vrot=2.5, Vexp=4.2, Vsys=21.9 km/s

Expansion dominance

Observation vs Model



Observation



Model

Concluding and Remarks

Conclusion

- ❒ VLBI monitor project using the JVN/EAVN
  - Purpose: 3-D velocity structure, directly verification of the accretion scenario of HMSF
  - Method: Making a catalog for VLBI image and proper motion of the 6.7 GHz methanol masers Systematically
- ❒ Spatial scale/morphology
  - Effected by resolved out
  - Solved by the ATCA observations
  - Large velocity dispersion
- ❒ Proper motion measurement
  - Rotation + Expansion in elliptical source G006.79

Remarks

- Problems
  - Proper motion: systematically measurement
  - Dust: Sub-millimeter continuum with ALMA
  - Reflection: VLT/VLTI and/or TMT??
  - Evolutionary phase: SED or Others??

- Next project
  - Increasing source samples using the JVN/EAVN, and also the APT !
    - Advantage for the equatorial sources