Astrophysical Masers: Unlocking the Mysteries of the Universe

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Simultaneous VLBI observations of H_2O and SiO masers toward VX Sgr

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and

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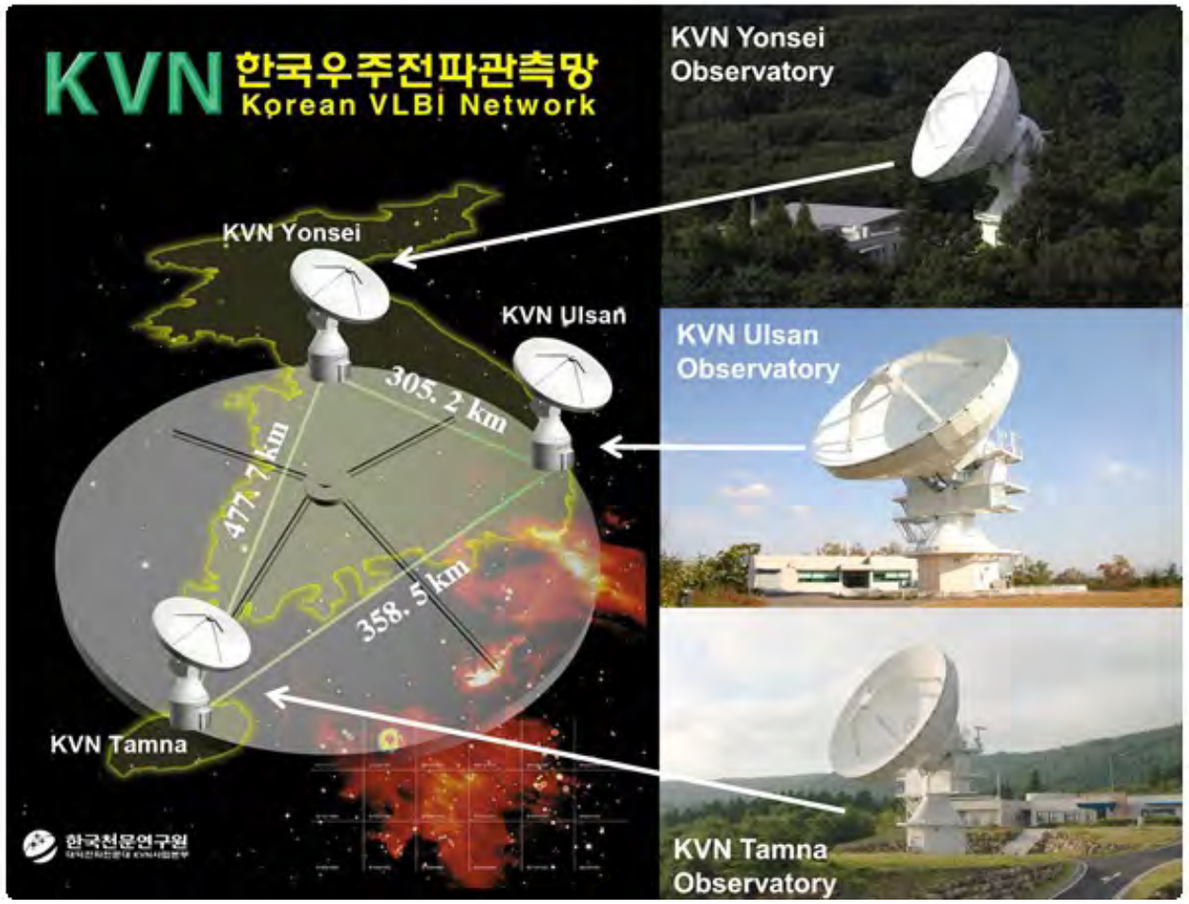
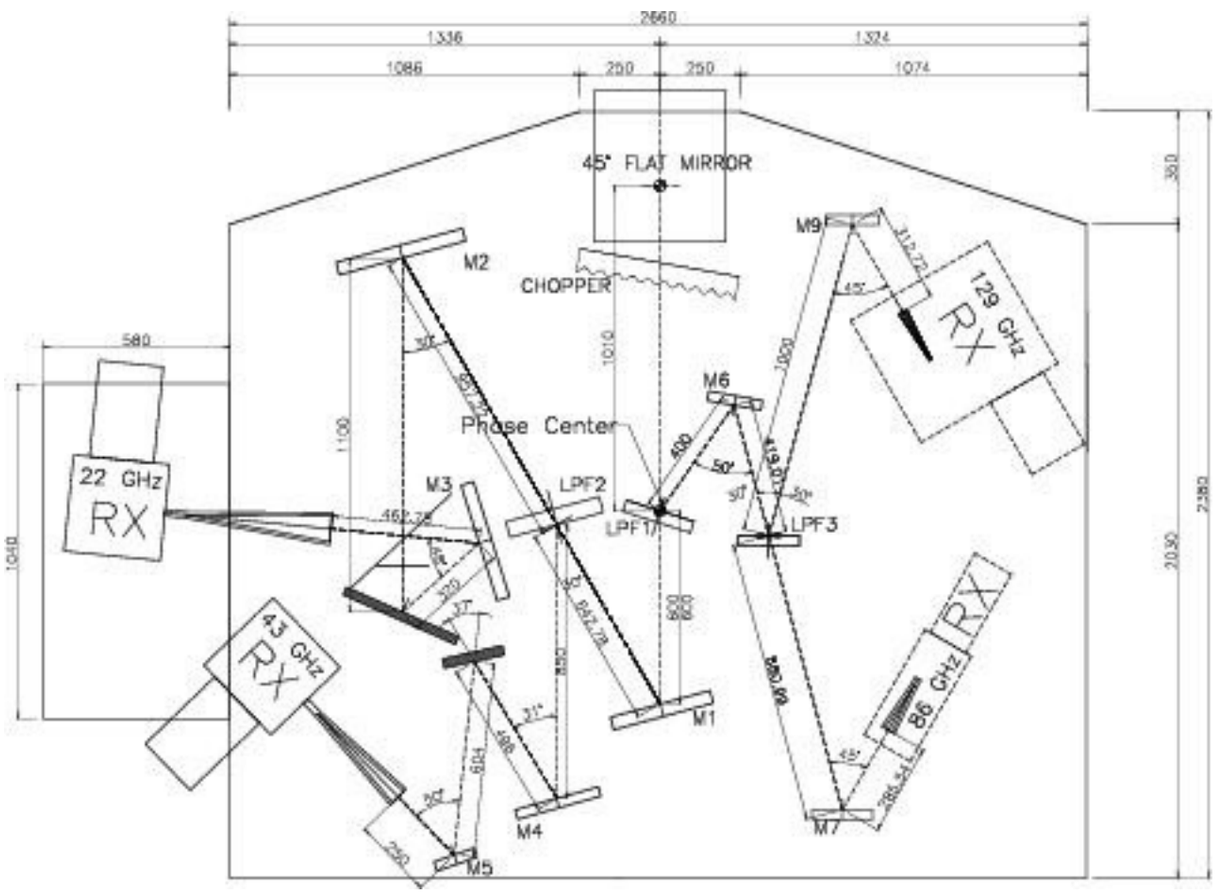
KVN





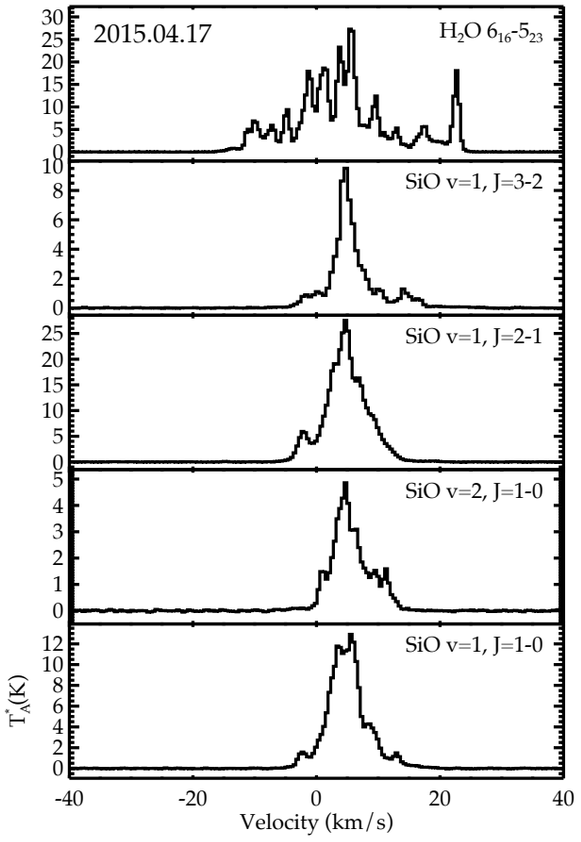
Han et al. 2008

- Specific quasi-optics for simultaneous observation (K, Q, W and D band)
- Observe 4 frequency band simultaneously
- The study of evolved star is one of the KVN Key Science Project (P.I.: Se-Hyung Cho).
    - VX Sagittarius is one of the 16 KSP target sources.

Band	Frequency Range (GHz)
22 (K)	21.25 ~ 23.25
43 (Q)	42.11 ~ 44.11
86 (W)	85 ~ 95
129 (D)	125 ~ 142

VX Sgr

- Red supergiant with semi-regular pulsating
- 732 days, M type, 1.57 kpc
  - Kholopov et al. 1987, kiss et al. 2006, Chen et al. 2007
- Strong H_2O and SiO maser emitter

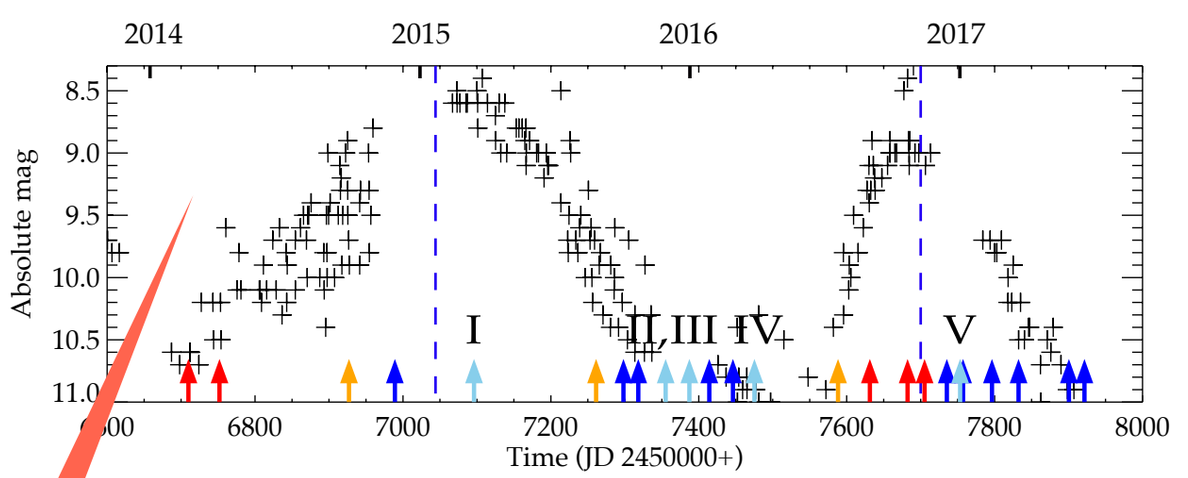


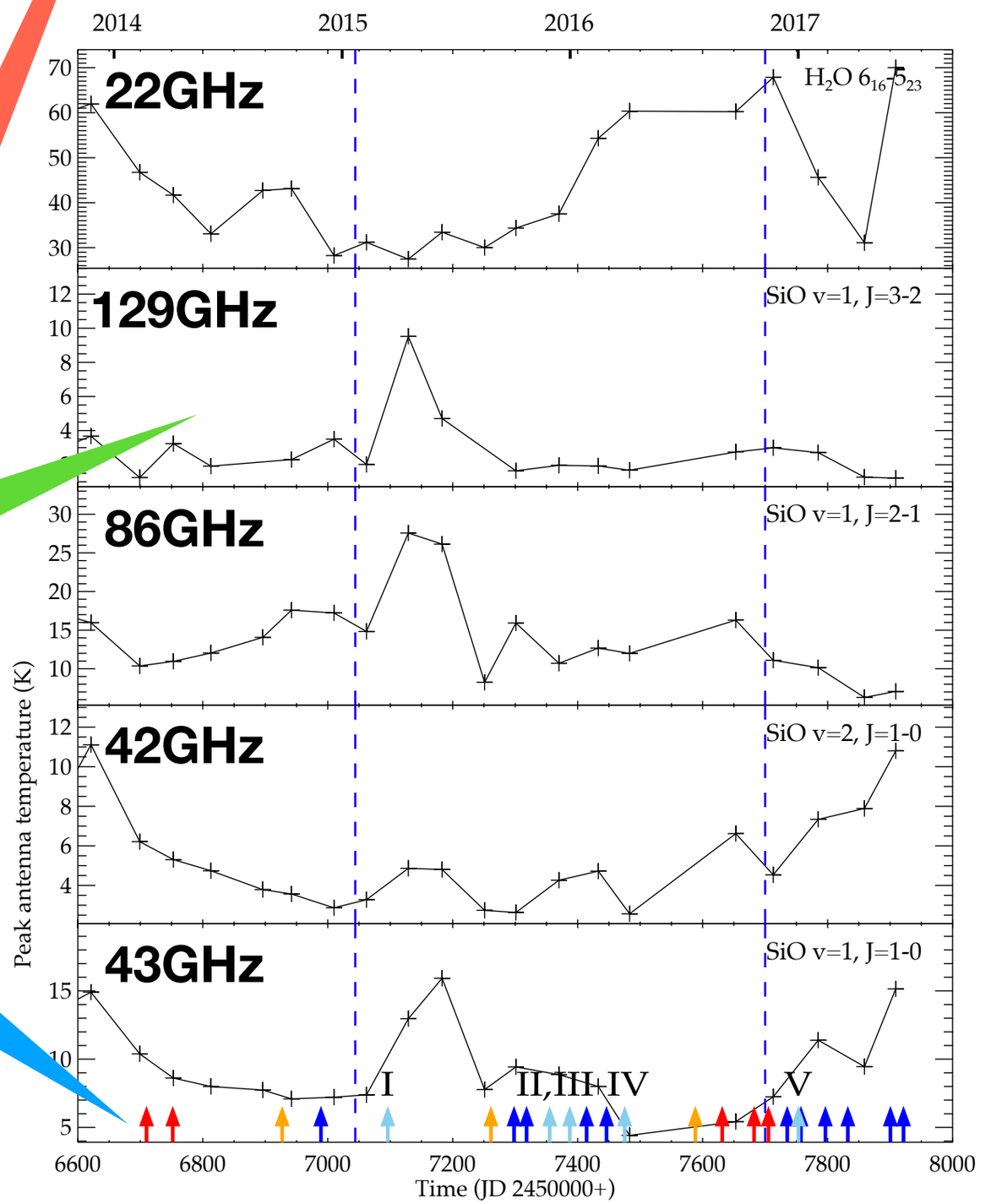
Single-dish spectra

AAVSO Optical light curve

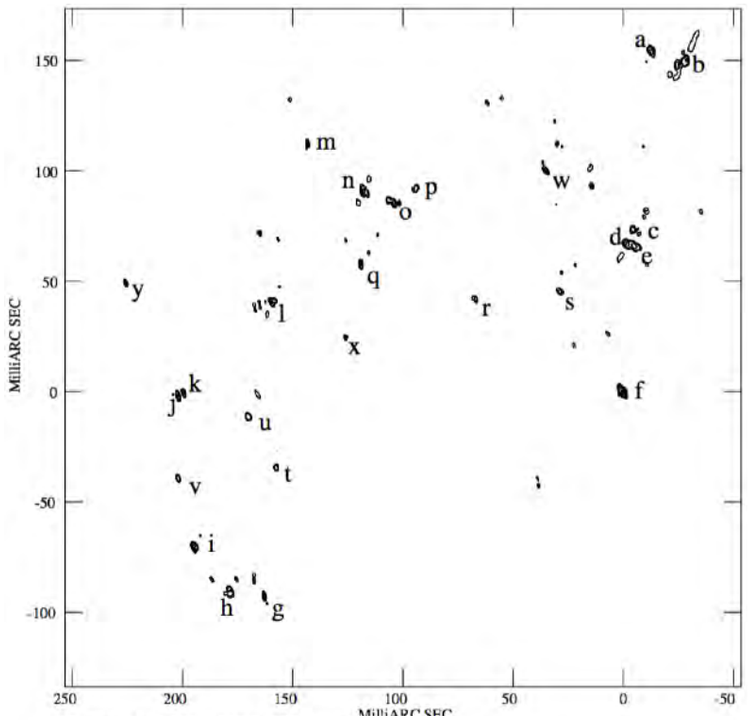
Single-dish Monitoring

VLBI Monitoring

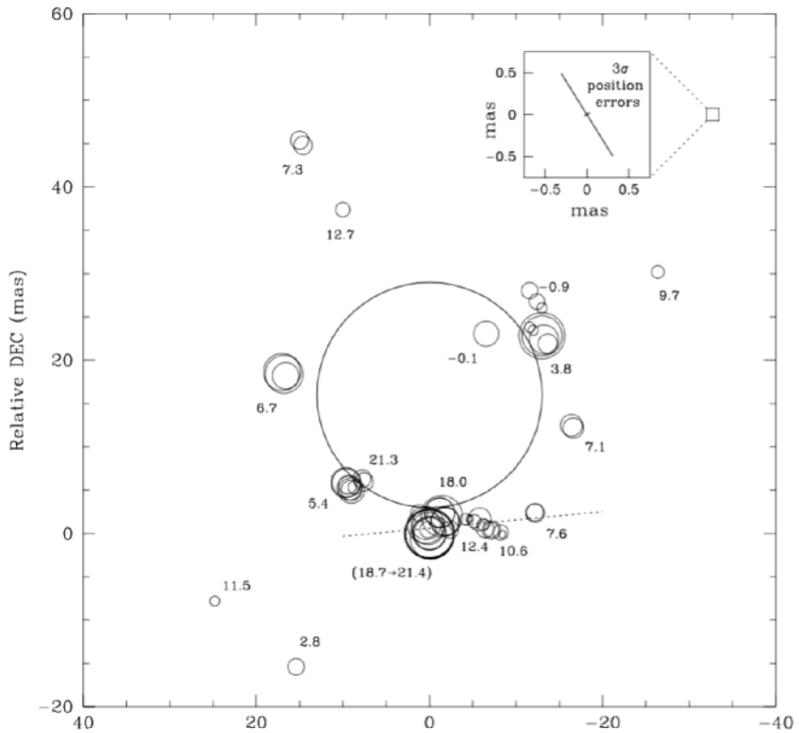




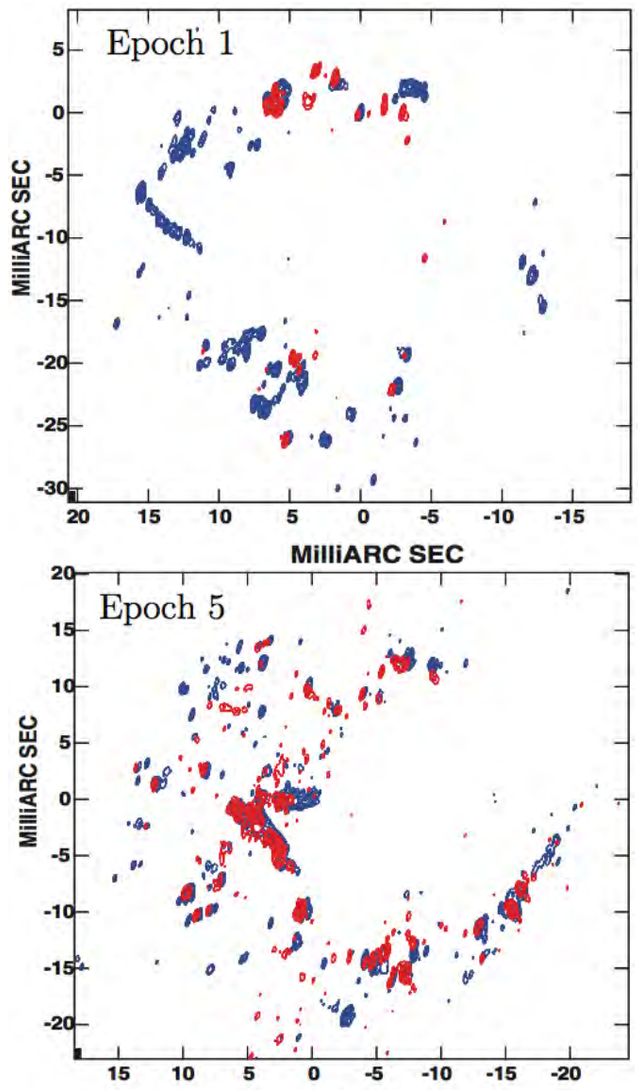
Previous work



22GHz Vlemmings et al. 2005



86GHz Doeleman et al. 1998



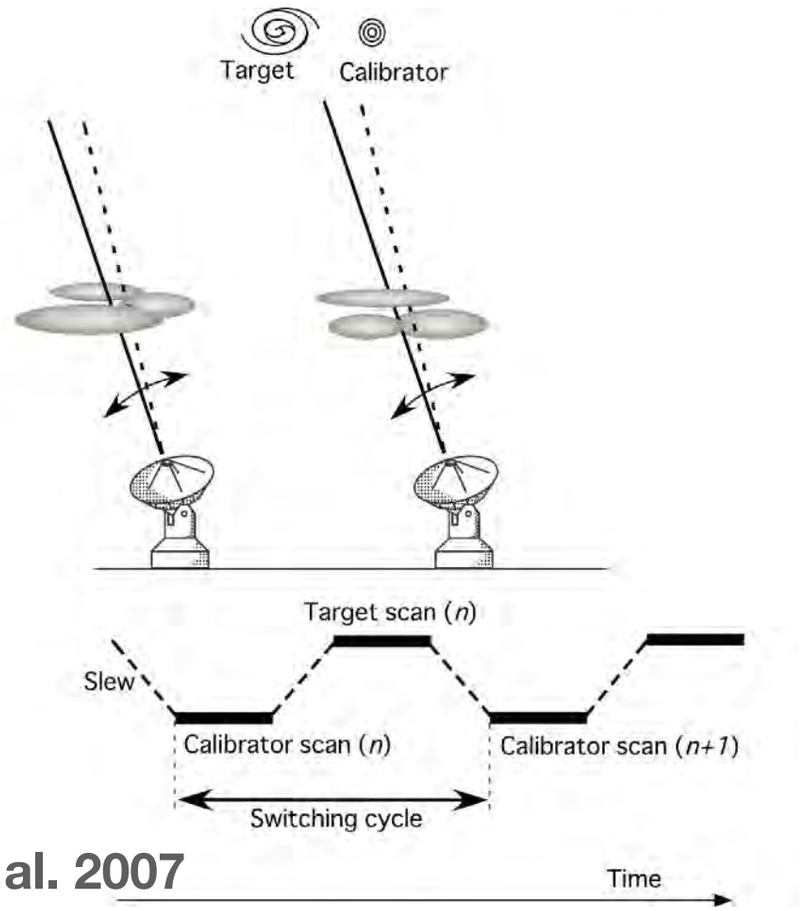
42, 43 GHz Su et al. 2012

Observed each epoch, frequency

- Previous VLBI studies were separately performed in H_2O and SiO masers even though both H_2O and SiO maser sources.
- Also, observation has been mainly done in the 22 and 43 GHz bands due to the lack of the system and influence of the atmosphere.
- 86 and 129 GHz VLBI studies will lead to a better understanding of the maser, including the maser generate pumping mechanisms.

Phase Referencing

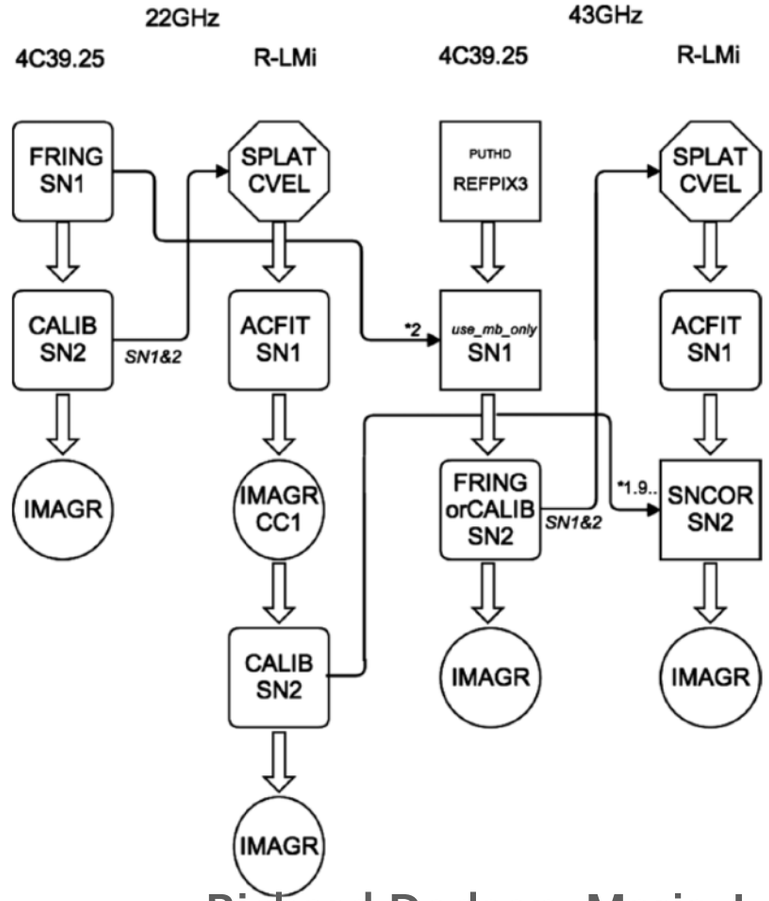
- Difficult to detect at high frequency
  - Flux, Coherence time…
- Difficult to compare the other frequency band lines
  - Do not compare different kinds of maser lines (SiO, H_2O)



Asaki et al. 2007

Source Frequency Phase Referencing

- Advantage of simultaneous observations
- Transfer the phase solution
  - Low freq —> High freq
- Possible to detect at high frequency
- Conserve the position information



Richard Dodson, Maria J. Rioja et al.(2014)

Observations

VX Sagittarii

- **Fringe finder : J1743-0350**
- **Continuum delay calibrator : J1833-2103**
- **5 hr with 2 min scans for target to calibrator**
- **DiFX correlator**
- **AIPS package (+Difmap)**
- **Observed target Coordinate :**
  18:08:04.05, -22:13:26.6 (Hipparcos catalog)

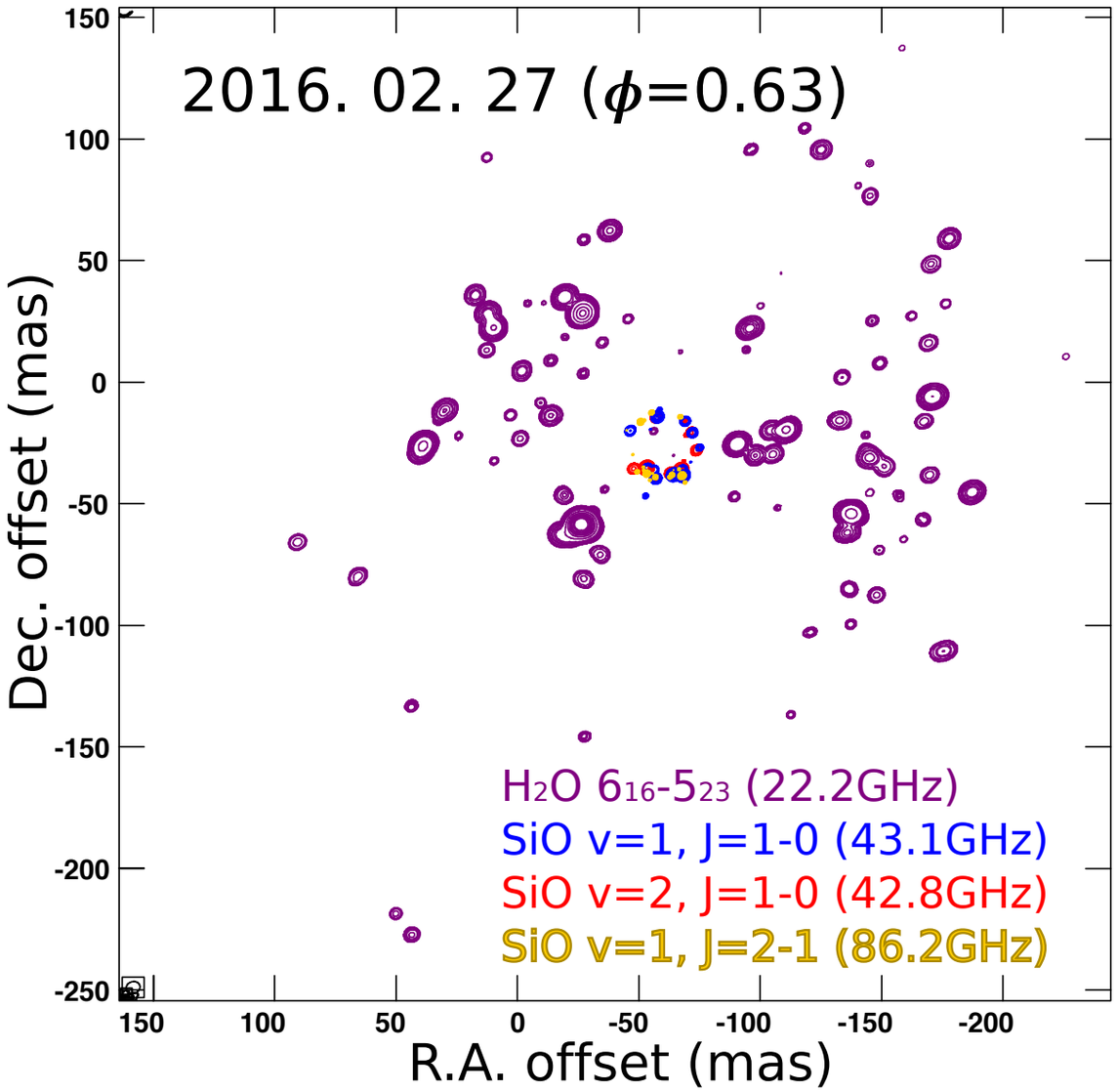
Observation lines		
K-band	H_2O 6_{16}-5_{23}	22.235080GHz
Q-band	^{28}SiO v=1, J=1-0	43.122080GHz
	^{28}SiO v=2, J=1-0	42.820587Ghz
W-band	^{28}SiO v=1, J=2-1	86.243442GHz
D-band	^{28}SiO v=1, J=3-2	129.363359GHz

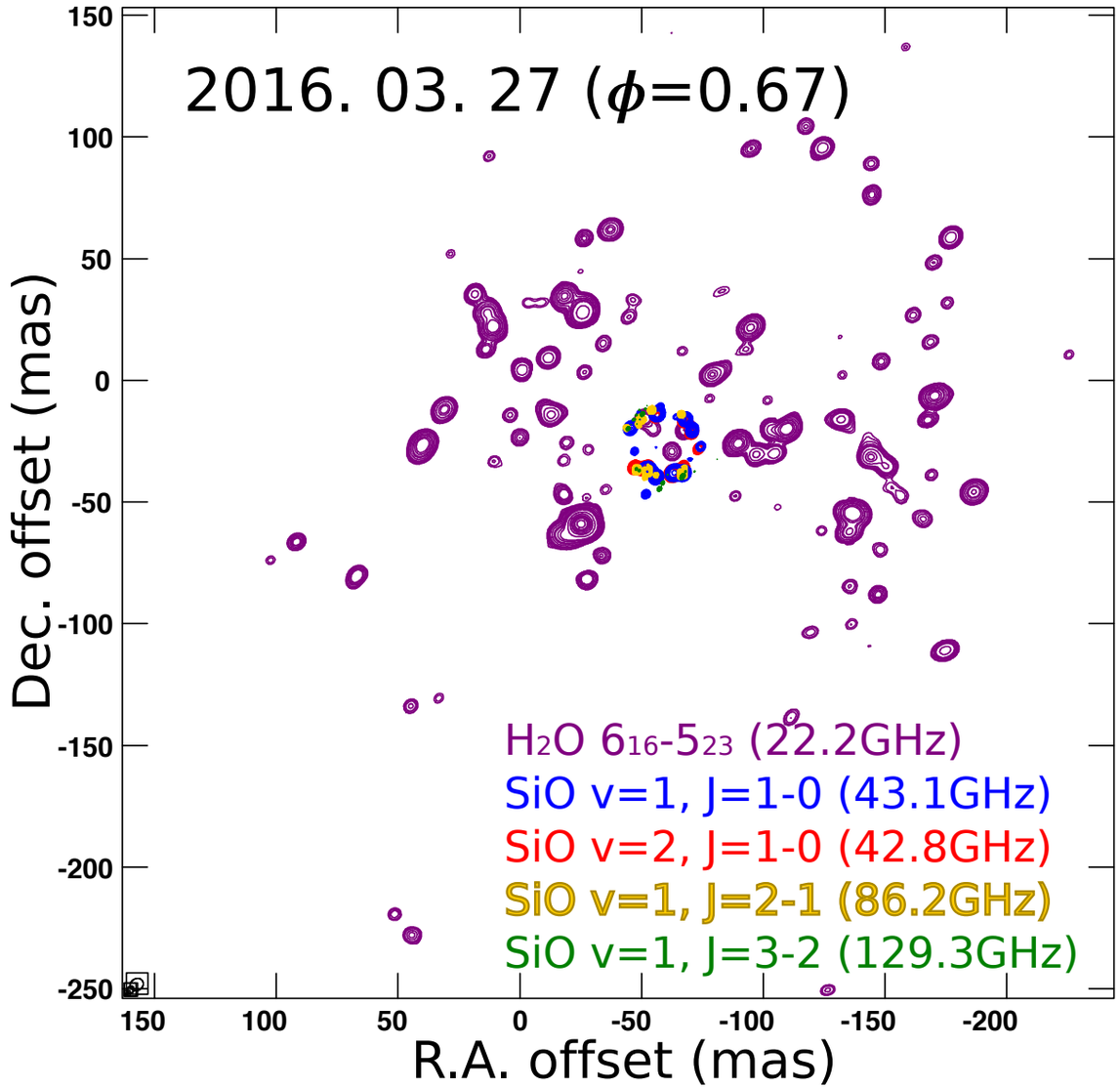


Date	Band	Duration	phase*	Synthesized Beam (mas)	System Temperature	Data Reduction
2016.02.27	**K,Q,W**,D	5hr	0.63	K : 5.70X4.80 Q : 3.00X2.57 W : 1.49X1.30 D : 1.16X0.74	K : < 150K Q : < 200K W : < 300K D : < 600K	SFPR
2016.03.27	**K,Q,W,D**	5hr	0.67			SFPR

* Visual maximum = 0

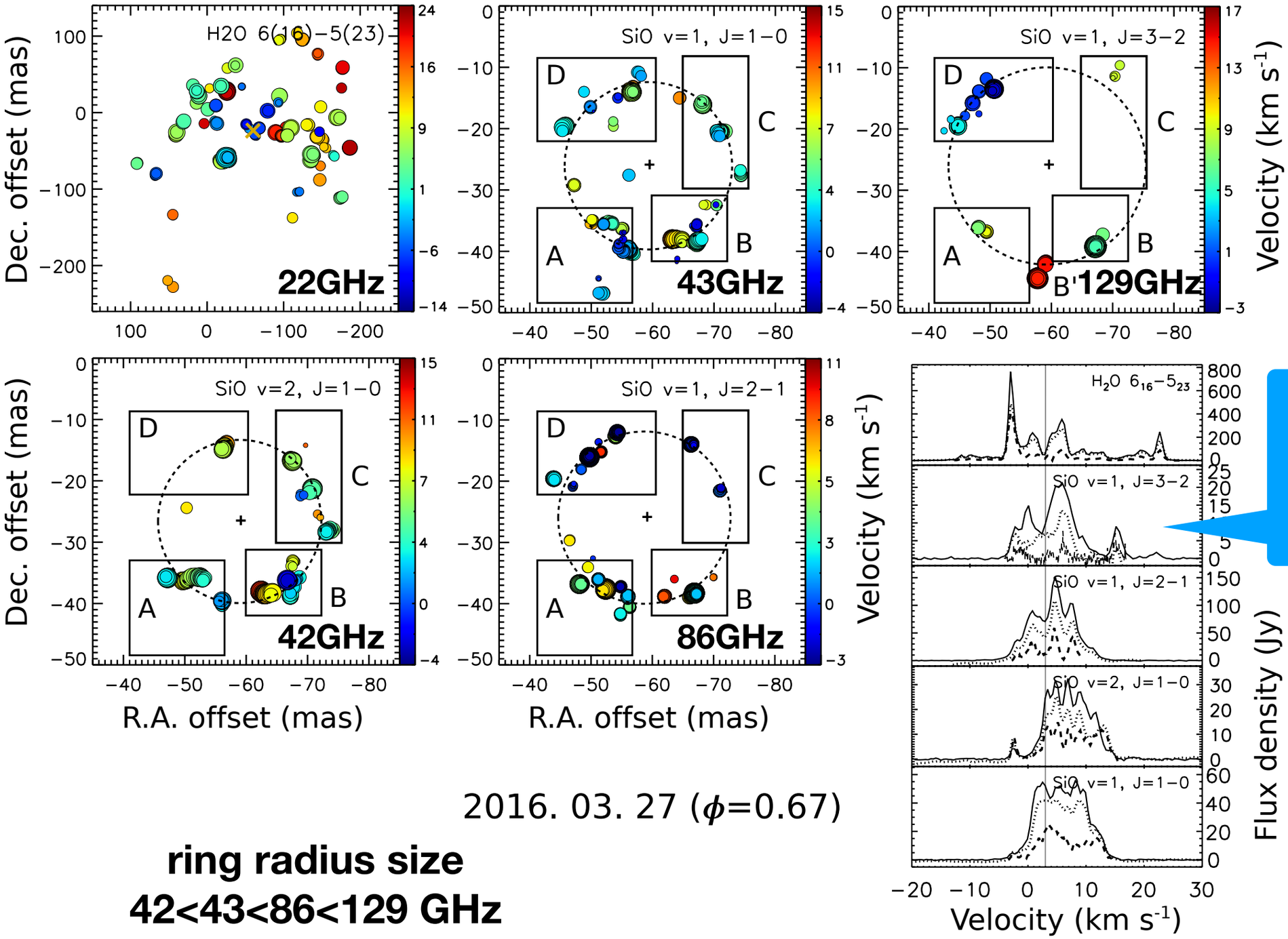
Total integrated intensity map





- The registered SiO maser maps with respect to the H_2O maser were successfully obtained.
- Especially, we could obtain astrometric information up to 129 GHz for the first time.
- The H_2O masers show an extended asymmetric structure compared to the typical ring-like structure of the SiO masers.

Velocity-Position spot map



Solid line : Single-dish (2016.04.05)
Dotted line : total power
Dashed line : recovered flux

2016. 03. 27 (ϕ=0.67)

ring radius size
42<43<86<129 GHz

Transition	RA offset (mas)	Dec offset (mas)	r (mas)	r (AU)
SiO v=1, J=1-0	-59.251	-26.069	13.63±0.37	21.40±0.58
SiO v=2, J=1-0	-58.898	-26.675	13.31±0.73	20.90±1.15
SiO v=1, J=2-1	-58.940	-26.036	14.10±0.11	22.14±0.17
SiO v=1, J=3-2	-59.384	-26.013	16.08±0.81	25.25±1.27
Four SiO masers	**-58.720**	**-26.104**	**18:08:04.0457712 (R.A.)**	**-22:13:26.626104 (Dec.)**

** AU was calculated using the distance of 1.57 kpc for VX Sgr*

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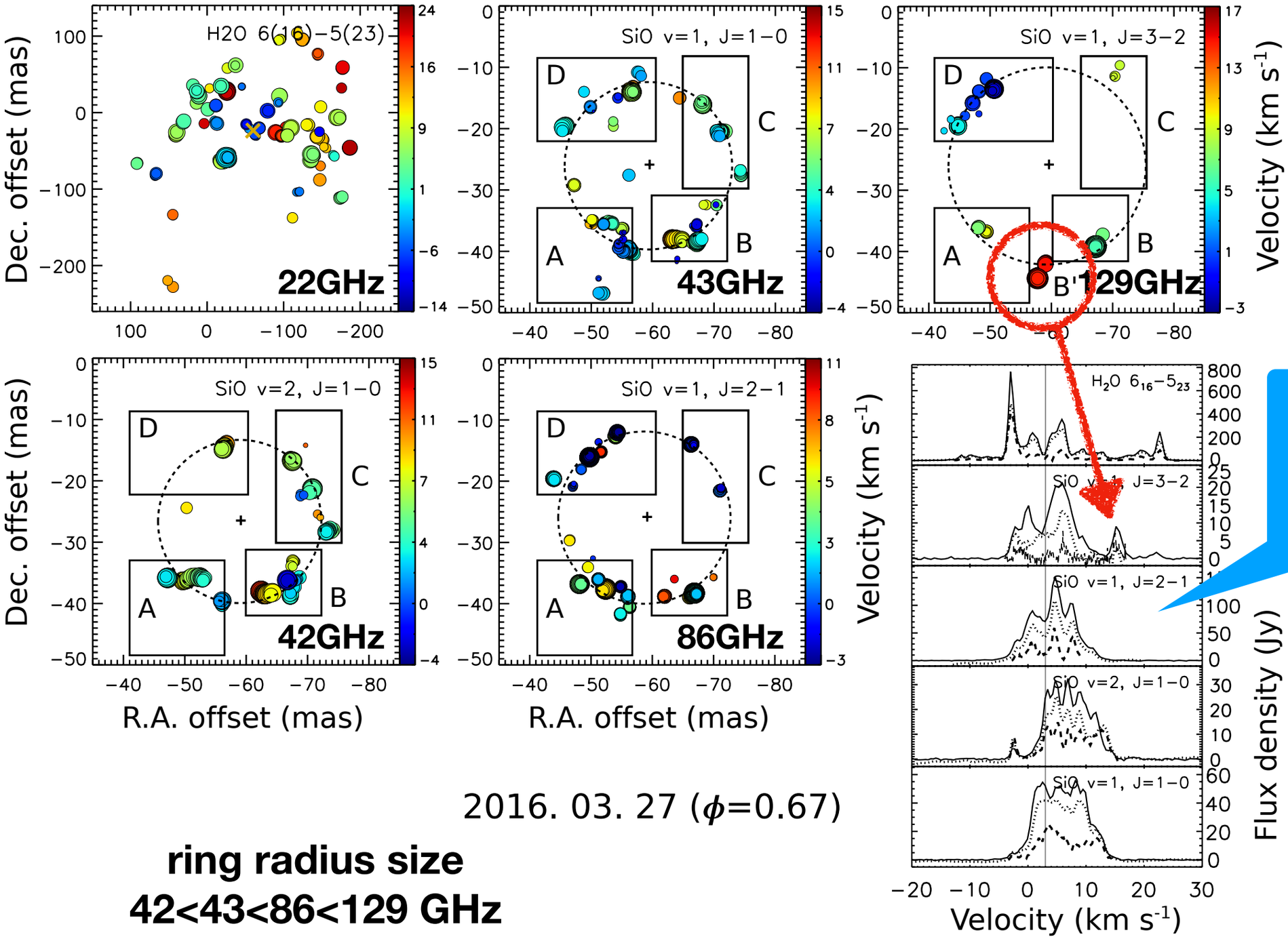

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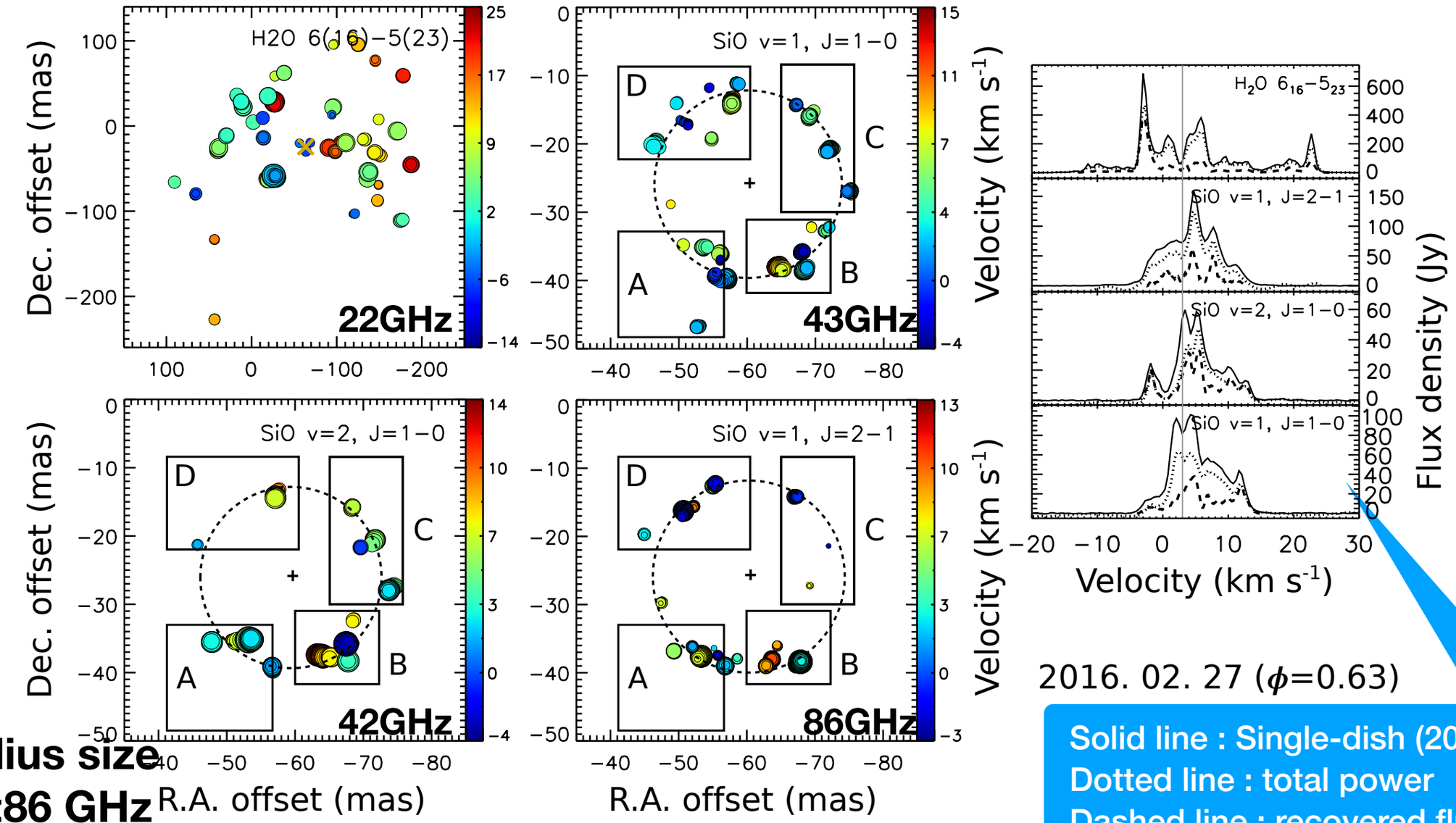

2016. 02. 27 (ϕ=0.63)

Solid line : Single-dish (2016.02.15)
Dotted line : total power
Dashed line : recovered flux

ring radius size
42<43<86 GHz

Transition	RA offset (mas)	Dec offset (mas)	r (mas)	r (AU)
SiO v=1, J=1-0	-60.146	-25.947	13.78±0.49	21.63±0.77
SiO v=2, J=1-0	-59.435	-26.049	13.28±0.91	20.85±1.43
SiO v=1, J=2-1	-60.326	-25.858	14.09±0.60	22.12±0.94
Three SiO masers	**-59.954**	**-25.878**	**18:08:04.0456823 (R.A.)**	**-22:13:26.625878 (Dec.)**

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SiO Ring fitting results

Phase = 0.67

Astrometric uncertainty of KVN
Fitting error
Real annual parallax

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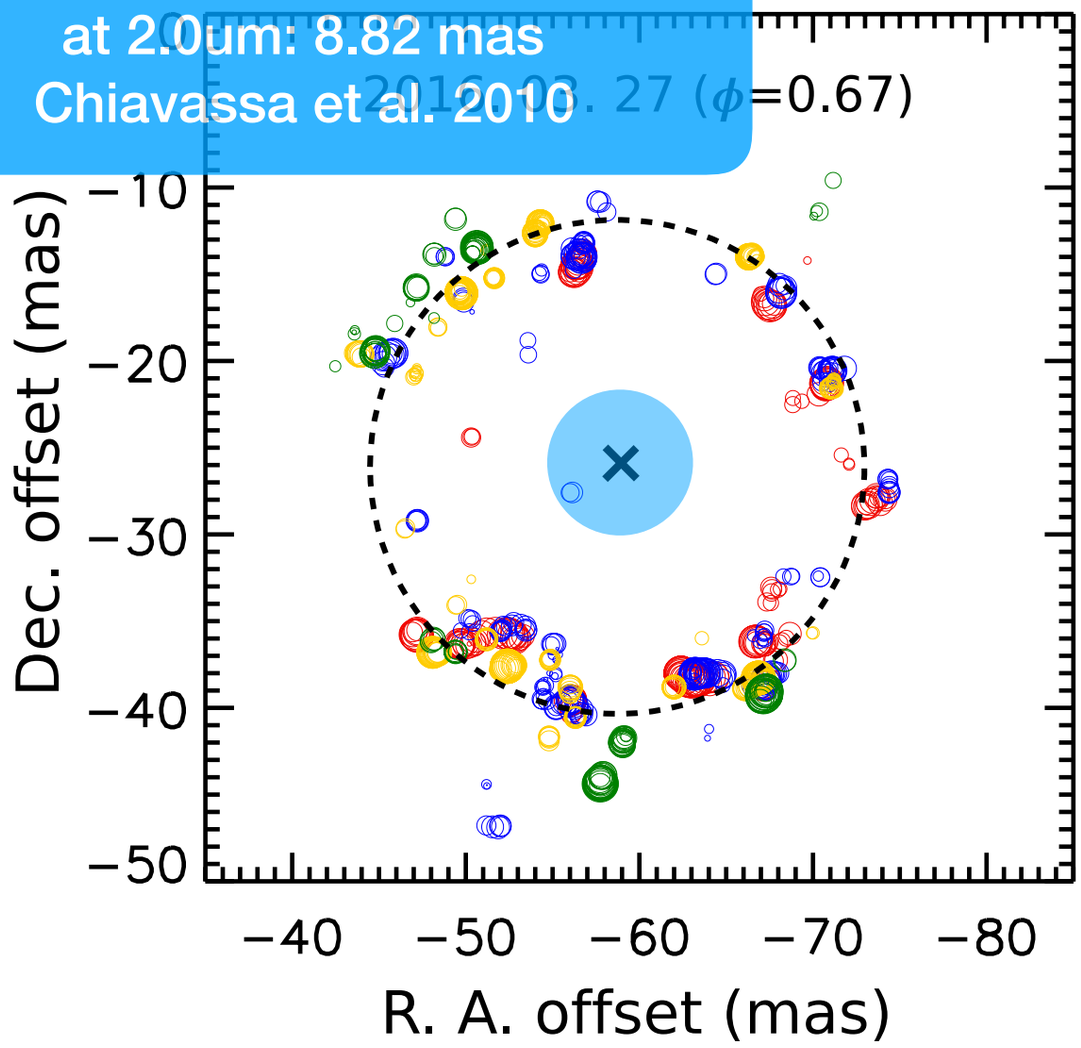
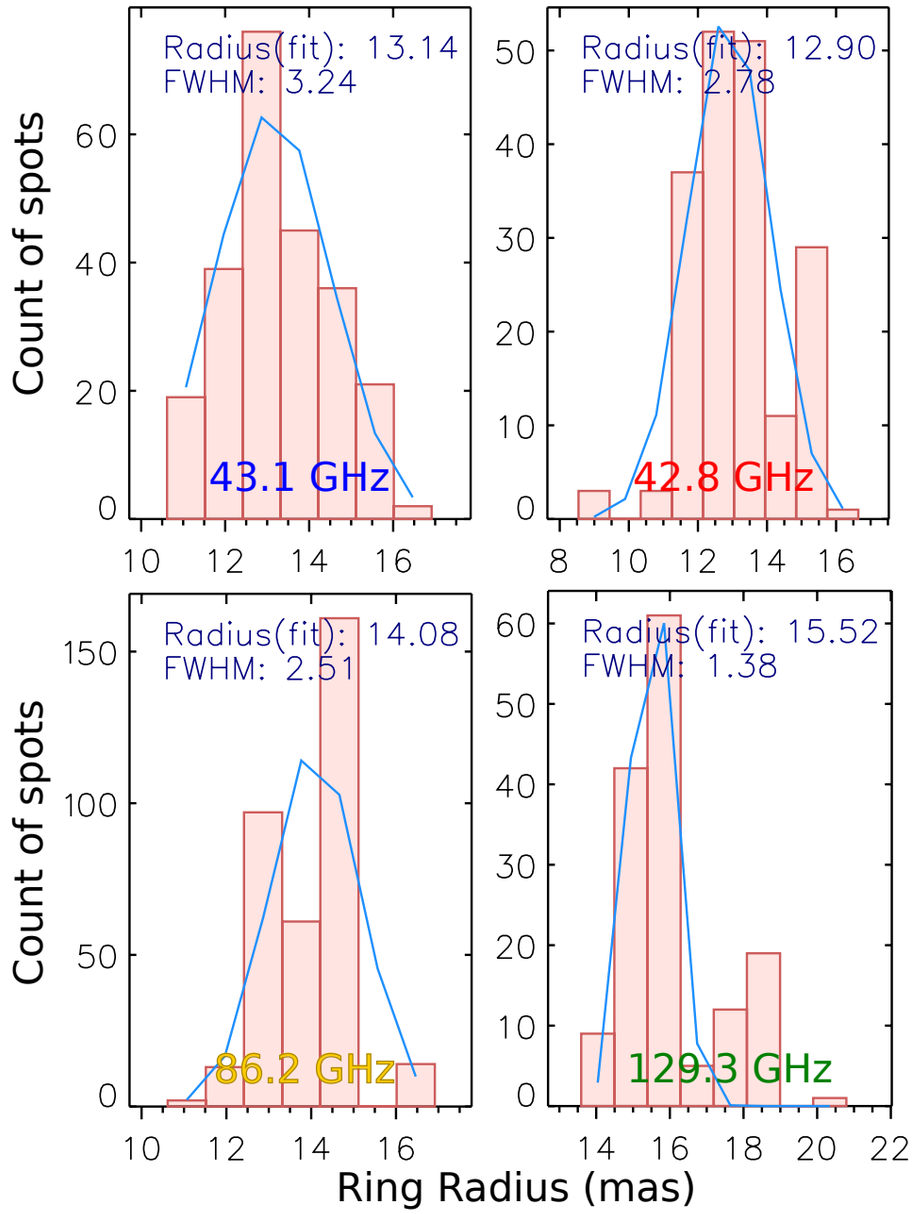
- These ring fitting results inform the ring size and center coordinate.
- However, the mutual positional relation of each maser line in unknown.

Registered SiO maser spot map

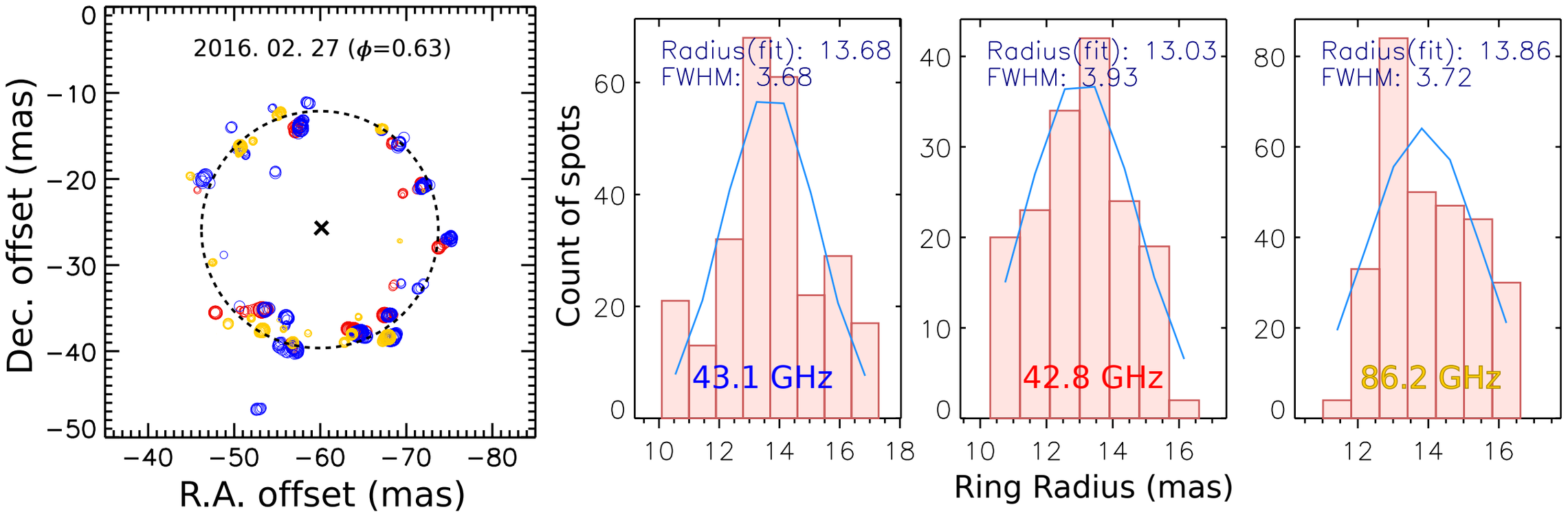
Photospheric diameter
at 2.0um: 8.82 mas
Chiavassa et al. 2010





- Direct comparison between each SiO maser lines
- The histogram represent a maser spot distance distribution from the central star.
- Order of the each SiO maser positions from the central star:
  - 42.8 < 43.1 < 86.2 < 129.3 GHz

Registered SiO maser spot map



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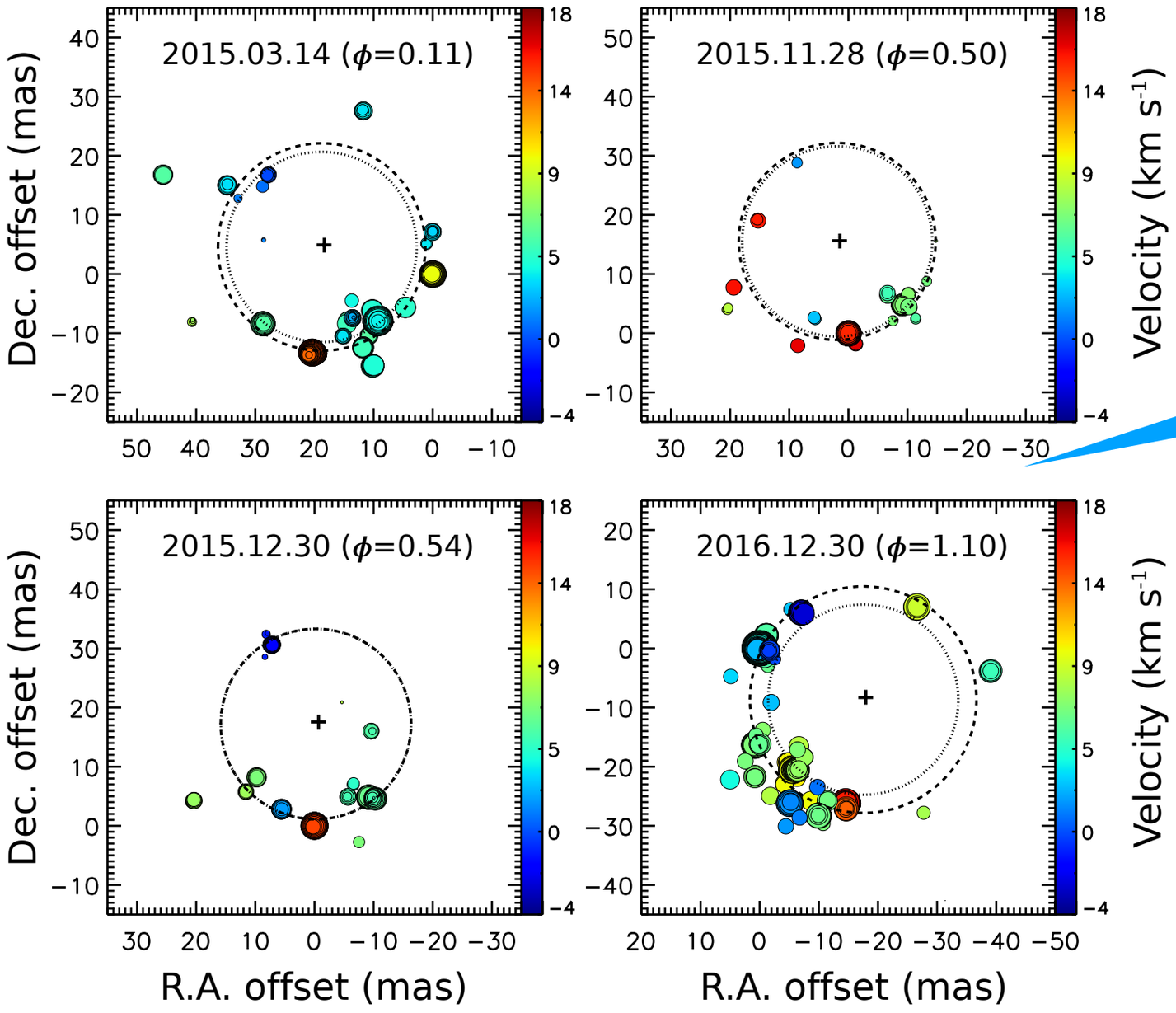
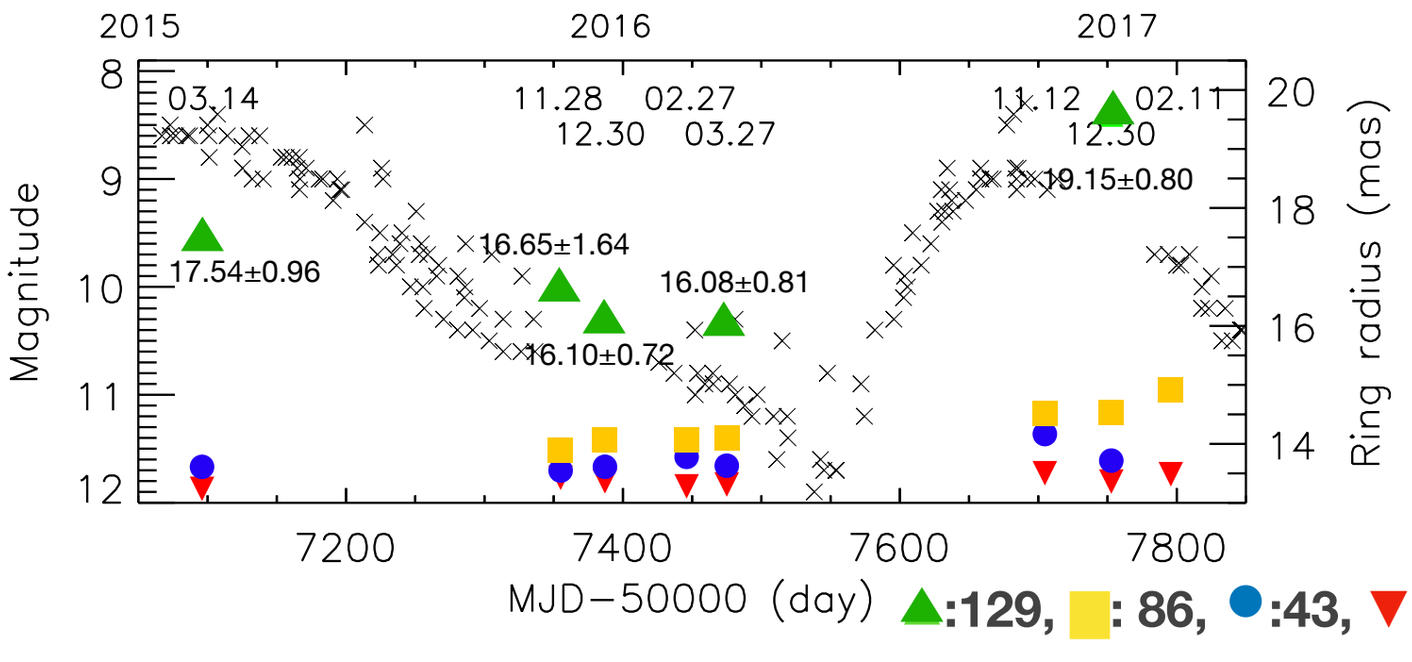
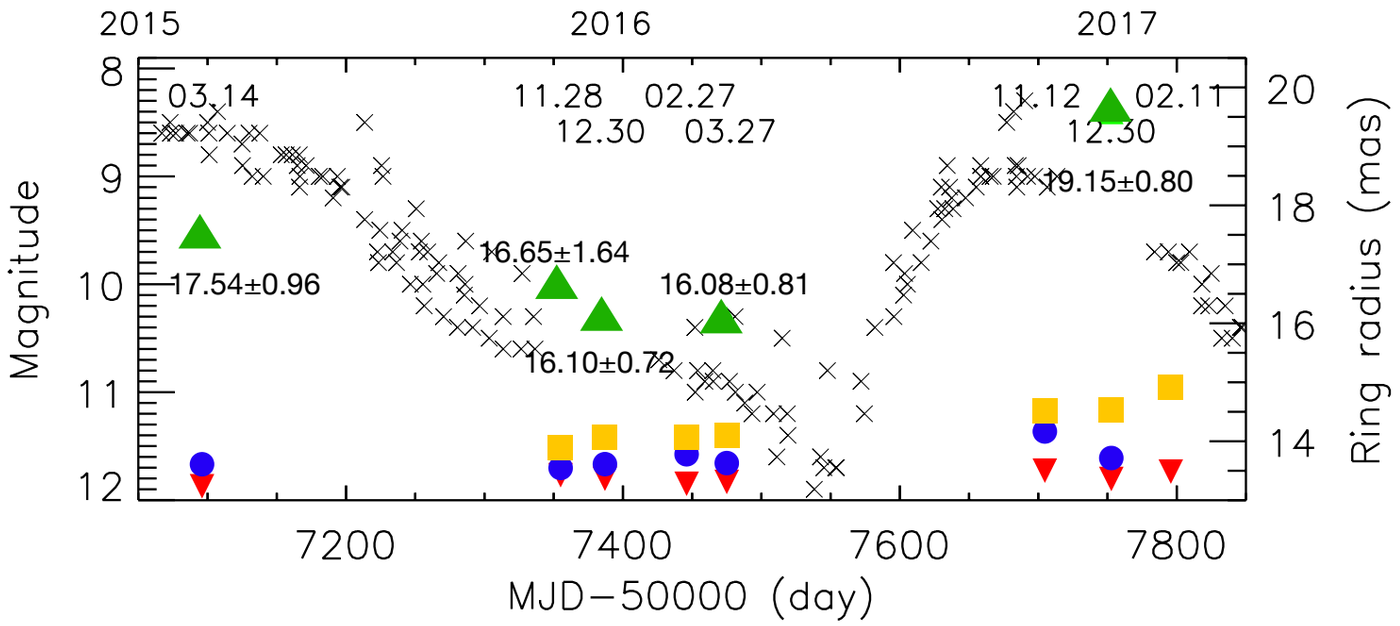


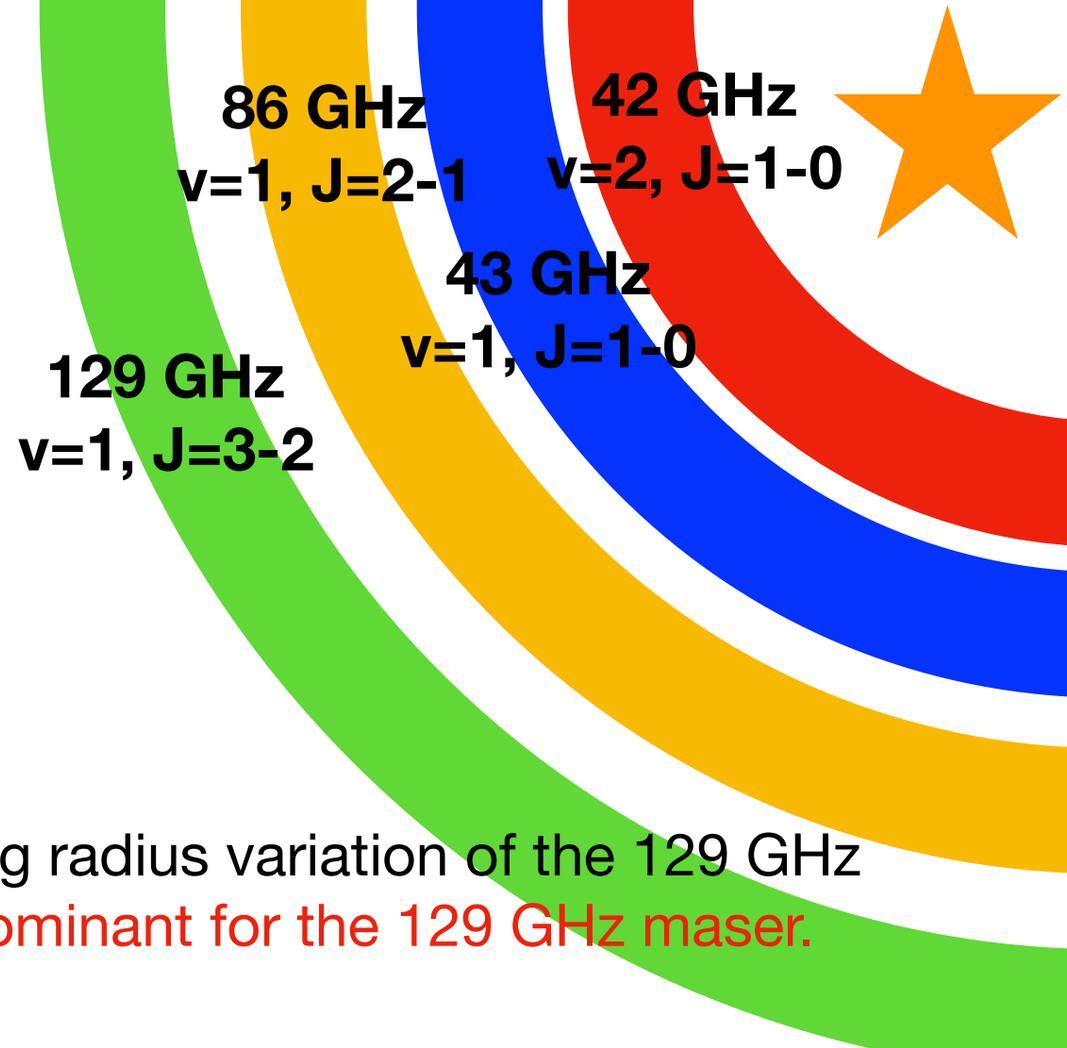


Other 4 epochs of 129.3 GHz SiO masers

Dotted ring : phase 0.67
Dashed ring : This phase

- Astrometric information was not obtained in these 4 epochs.
- 129 GHz SiO maser has the largest ring radius in all detections.
- 129 GHz SiO maser show the most similarity to the light curves within the KVN resolution.
- The visual maximum near the phase 0 and 1 show larger radius.





- The decrease of maser feature similarity and ring radius variation of the 129 GHz maser supports that the radiative pumping is dominant for the 129 GHz maser.

- The fact that vibrational transition v=2 is located inside v=1 is consistent with the theoretical result. Higher excitation condition is required in v=2.

- The rotational transition masers (v=1, J=1-0, 2-1, 3-2) are located further from the outer region as the rotational number is increase.

- We need to compare this result with other red giants or other types of stars (Mira, OH/IR).

  - (Cho et al., Yun et al. in preparation)

Summary

- Astrometrically registered SiO maser (43.1, 42.8, 86.2 and 129.3 GHz) maps with respect to H_2O (22.2 GHz) maps were successfully obtained toward VX Sgr for the first time.

- Asymmetric outflow features of H_2O masers are spread up to ~ 350 mas in diameter with respect to ring-like structure of 43.1, 42.8, 86.2 and 129.3 GHz SiO masers with ~ 30 mas in diameter.

- The 43.1 and 42.8 GHz have similarities of features, while the 86.2 GHz have similarities with the 129.3 GHz as well as the 43.1 and 42.8 GHz. 129.3 GHz is similar to 86.2 GHz in some areas, but there are unique features.

- 42.8 GHz SiO maser is located inside 43.1 GHz and 86.2 GHz located above them, and 129.3 GHz located at the outer most region. 129.3 GHz SiO maser show the most similarity to the optical light curves within the KVN resolution.

- The decrease of maser feature similarity and ring radius variation of the 129.3 GHz maser supports that the radiative pumping is dominant for the 129.3 GHz maser. We need to compare this result with other red giants or other types of stars.