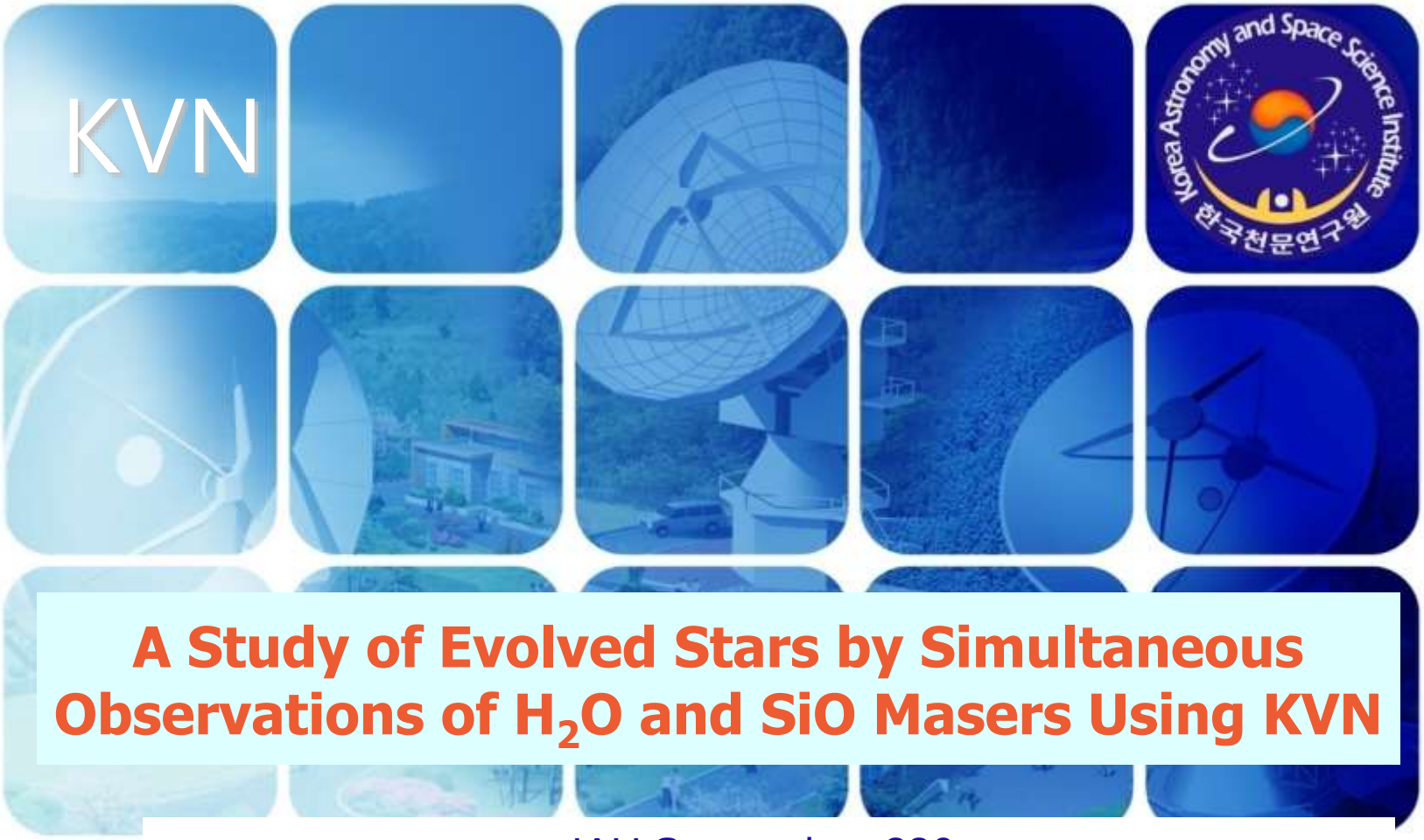

A Study of Evolved Stars by Simultaneous Observations of H_2O and SiO Masers Using KVN

IAU Symposium 336
Astrophysical Masers: Unlocking the Mysteries of the Universe
September 4-8, 2017 - Cagliari (Sardinia), Italy

Se-Hyung Cho and KVN KSP Members

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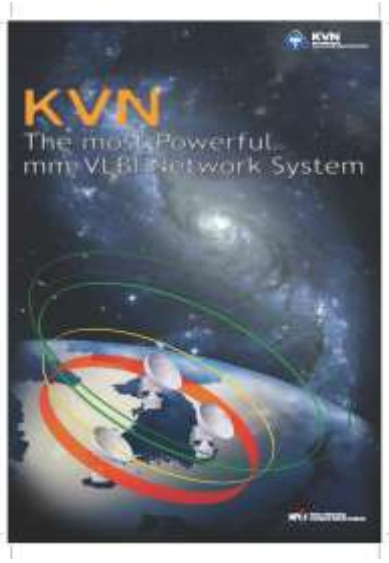
Introduction

- A large number of oxygen-rich evolved stars exhibit **SiO maser emission together with H_2O maser**.
- **SiO masers** arise from infall and outflow regions inside the dust formation layer, while **22 GHz H_2O maser** arises from radially accelerated regions outside the dust layer (Chen et al. 2007).
  - ○ Their intensity variations show a correlation with the stellar pulsation.
  - ○ Their spatial distributions and kinematics may be associated with each other.

- It is important to perform **simultaneous obs. of both SiO and H_2O masers**. However, previous maser obs. were always performed separately due to lack of system. VLBI obs. of 86 GHz SiO maser were very limited and those of 129 GHz SiO maser not performed.



- **The KVN** can be operated **at H_2O 22 GHz and SiO 43/86/129 GHz bands** ► allows us to perform combined studies of H_2O and SiO masers including SiO J=2-1 &J=3-2.

Here I introduce KVN results mainly based on **KVN ES KSP**.

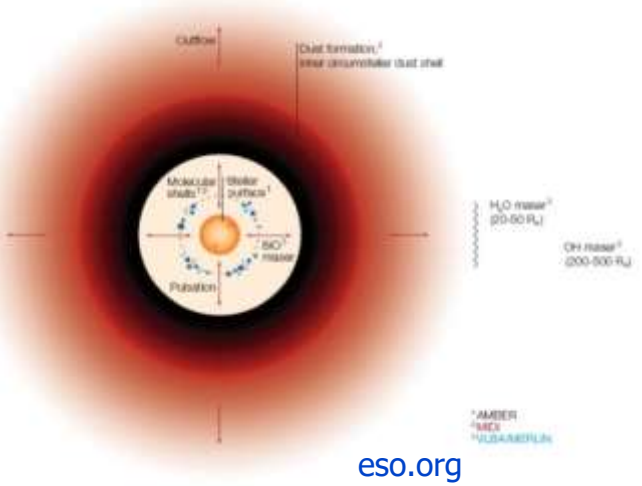
Scientific Goals of KSP "Simultaneous Monitoring Obs. of KVN 4 bands toward Evolved Stars"

1. Spatial structure and dynamical effect from SiO to 22 GHz H_2O maser regions according to stellar pulsation through simultaneous monitoring obs. of KVN 4 bands

○ Pulsation and shock wave propagation effect from SiO to H_2O maser region via dust layer : **development of outflow motion and asymmetry ► Mass loss mechanism** based on combined studies of SiO and H_2O masers.

2. Correlation and difference of maser properties (spatio-kinematic properties etc) among SiO J=1-0, J=2-1, J=3-2 masers

► Constraints on SiO maser excitation and pumping models (collisional and/or radiative)



eso.org

▸ Synergy with KaVA (KVN+VERA) Evolved Star Large Program and ALMA Observations.

Source Selection at 1st Stage 2015-2017

No.	Source	R. A.	Dec.	V_{LSR} (km s^{-1})	Period (days)	S. A. (°)	Calibrator
1	WX Psc	01h06m25.98s	12d35'53.0	8.5	660	3.81	J0121+1149[3]
2	IK Tau	03h53m28.87s	11d24'21.7	35.0	470	4.04	J0345+1453[1]
3	NV Aur	05h11m19.44s	52d52'33.2	3.0	635	3.19	J0514+5602[1]
4	VY CMa	07h22m58.33s	-25d46'03.2	18.0	-	2.78	J0731-2341[2]
5	R Leo	09h47m33.49s	11d25'43.7	–1.0	310	5.52	J1007+1356[3]
6	R Crt	11h00m33.85s	-18d19'29.6	10.7	160	3.06	J1048-1909[3]
7	W Hya	13h49m02.00s	-28d22'03.5	42.0	390	4.89	J1339-2401[3]
8	V2108 Oph	17h14m19.39s	08d56'02.6	16.0	395	2.45	J1722+1013[1]
9	VX Sgr	18h08m04.05s	-22d13'26.6	3.0	732	6.06	J1833-2103[2]
10	V5102 Sgr	18h16m26.03s	-16d39'56.4	48.0	250	5.99	J1833-2103[2]
11	V1111 Oph	18h37m19.26s	10d25'42.2	–30.2	-	3.28	J1824+1044[1]
12	V1366 Aql	18h58m30.09s	06d42'57.8	20.4	1424	7.07	J1830+0619[3]
13	χ Cyg	19h50m33.92s	32d54'50.6	12.0	408	6.65	J2015+3710[3]
14	RR Aql	19h57m36.06s	-01d53'11.3	26.0	395	4.42	J2015-0137[3]
15	V627 Cas	22h57m40.99s	58d49'12.5	–52.0	-	3.43	J2231+5922[3]
16	R Cas	23h58m24.87s	51d23'19.7	21.0	430	5.65	J2322+5057[3]

- **16 target sources** were selected based on
- KVN single dish survey (~1000 stars) and monitoring results **for relatively strong SiO and (/or) H_2O maser sources** (~40-70)

Monitoring Observations with KVN Single Dish

- **Irregular time interval monitoring (~ 50-70 sources) during 2009-2013 based on survey**
- **Regular monitoring once every two-months toward KSP sources**

Number of Monitoring Obs. with KVN (VLBI)

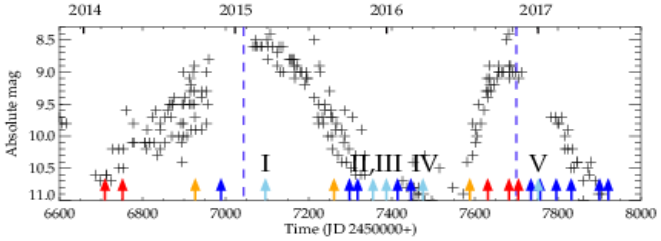
No	Objects	2014	2015A&B	2016A	2016B	2017A
1	IK Tau	3	7	5	3	6
2	VY CMa	3	11	7	3	5
3	VX Sgr	2	6	4	6	5
4	R Crt	2	6	3 (11, Fin.)		
5	V1111 Oph	3	8	2	2	5
6	W Hya	2	6	5	4	4
7	V627 Cas		5	2	2	5
8	V5102 Sgr	1	3	2		5
9	WX Psc	1	2	3	3	5
10	X Cyg		1	2	1	5
11	R Cas	1	1	1		
12	NV Aur	3	1	2		
13	V1366 Aql		1	1		
14	V2108 Oph	1		1		
15	R Leo	1	2	2		
16	RR Aql	1	1	1		

- In 2014, pilot SFPR observations at H_2O 22 GHz and SiO 43 GHz bands
- **Regular monitoring every 1-3 months at 22/43/86/129 GHz bands from 2015A**
- **Data reduction: SFPR method (Dodson et al. 2014) and SFPR pipeline (YJ Yun)**

Supergiant Star VX Sgr

DH Yoon et al. in Prep.

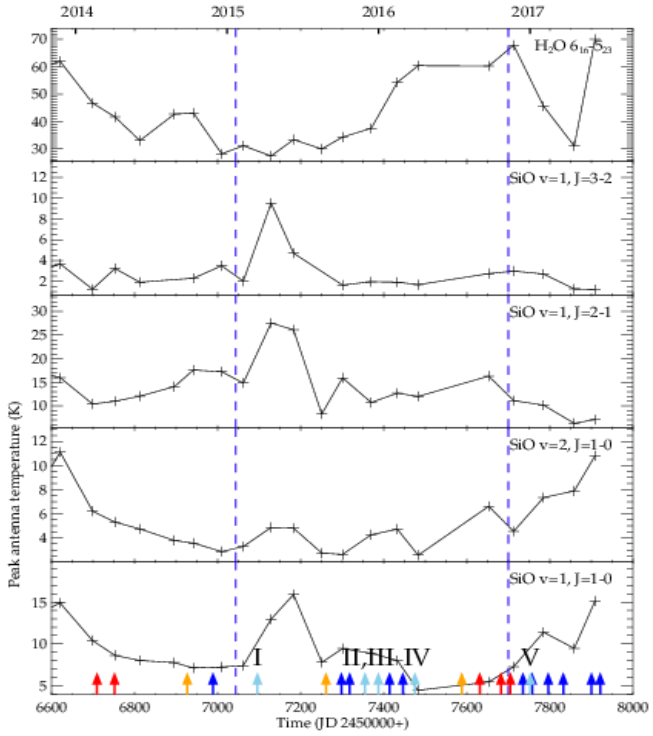
Optical light curve



P=732 days, D=1.57 kpc (Chen et al. 2007)

VX Sgr : peak

Single dish radio intensity variations



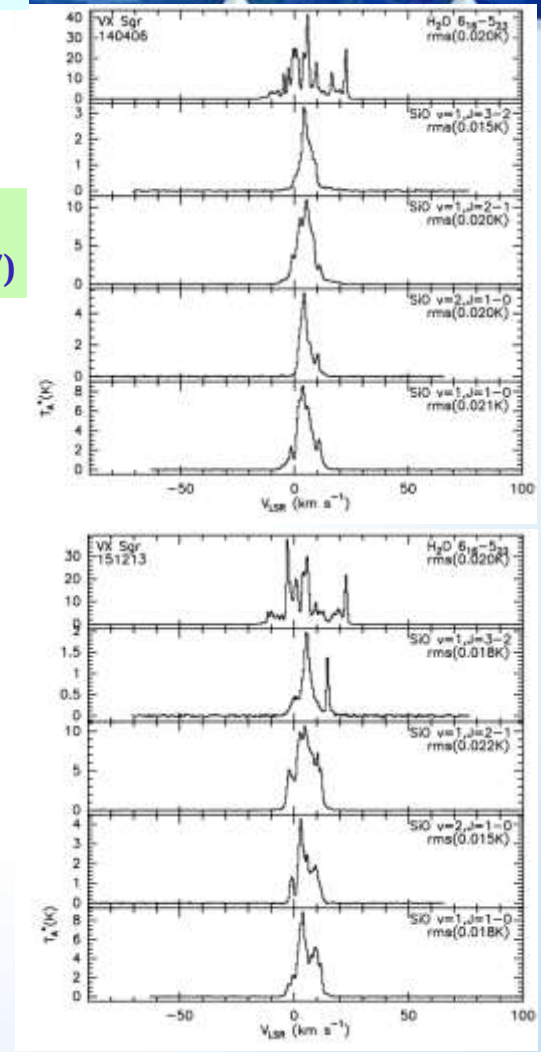
Red : SFPR X

Orange : Only K

Blue : SFPR

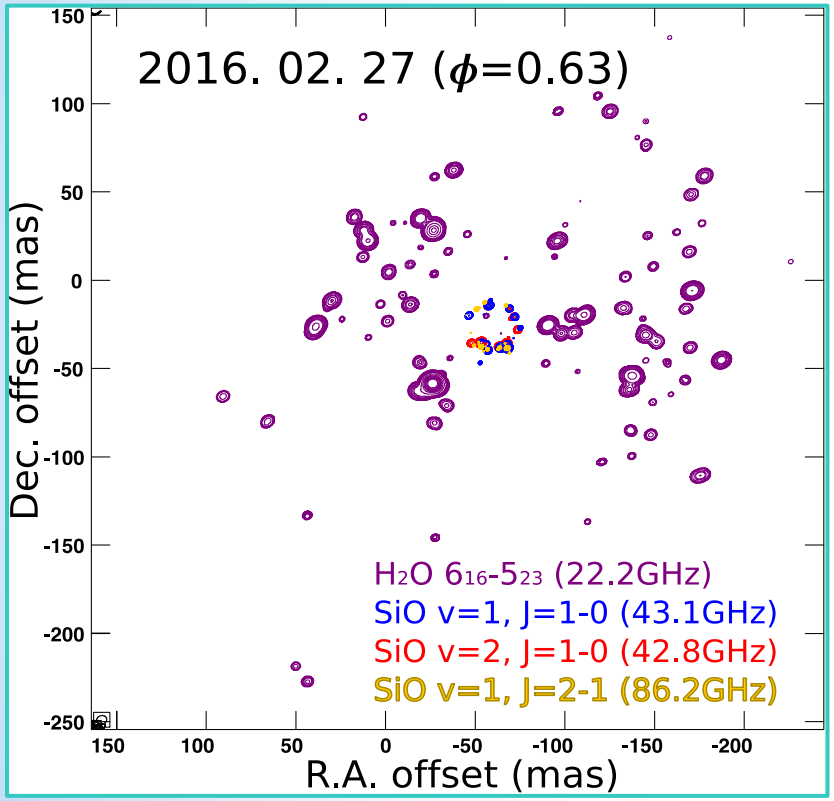
Skyblue : up to D

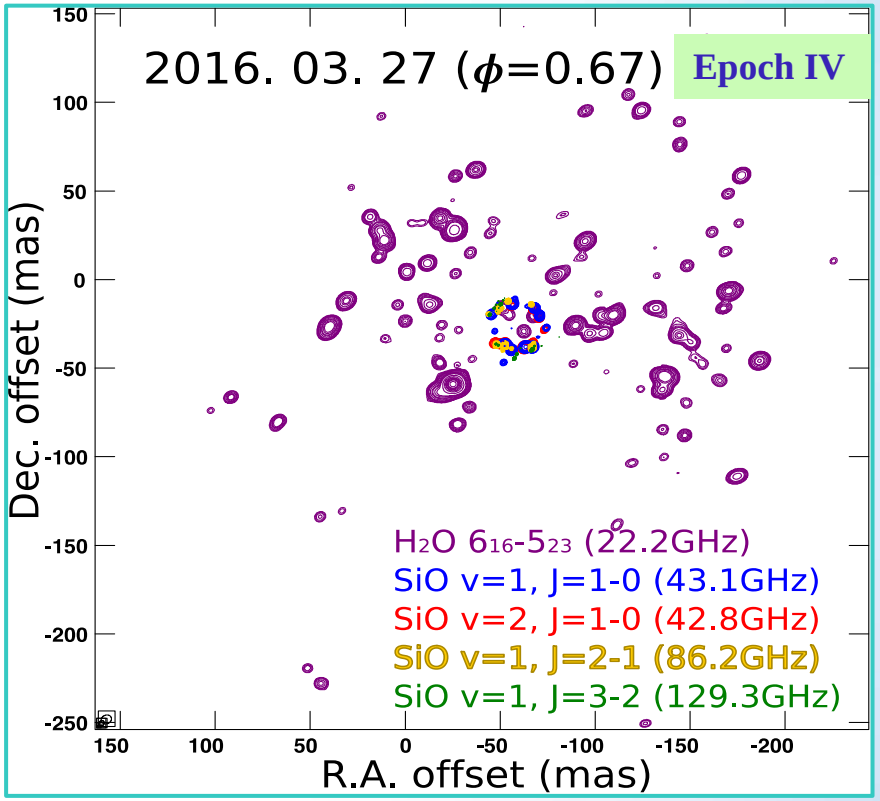
129.3 GHz SiO map at 5 epochs



Sample spectra of single dish

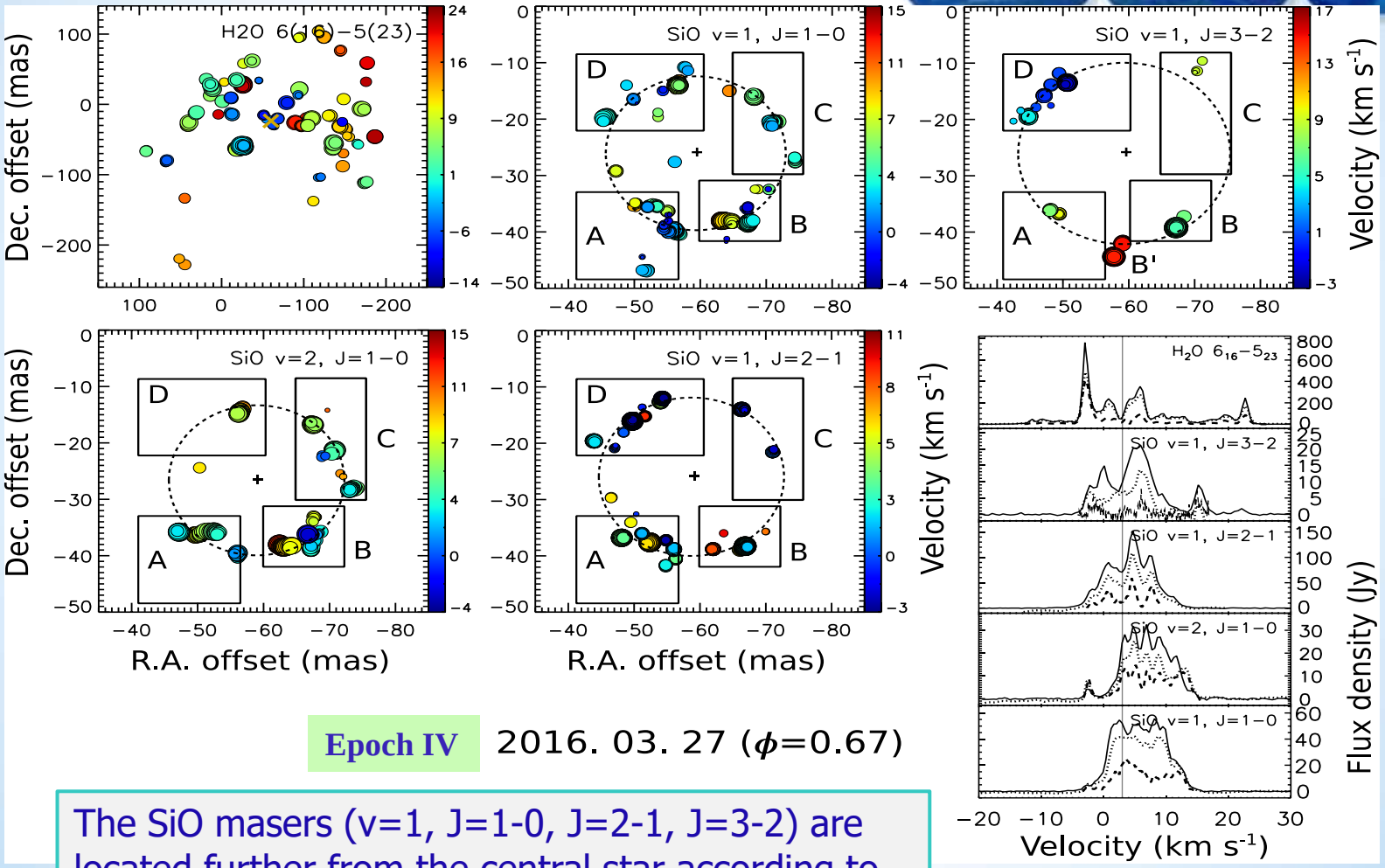
SFPR Maps of H_2O and SiO Masers toward VX Sgr





Astrometrically registered integrated intensity maps (moment zero map) of 22.2 GHz H_2O and 43.1/42.8/86.2/129.3 GHz SiO masers toward VX Sgr

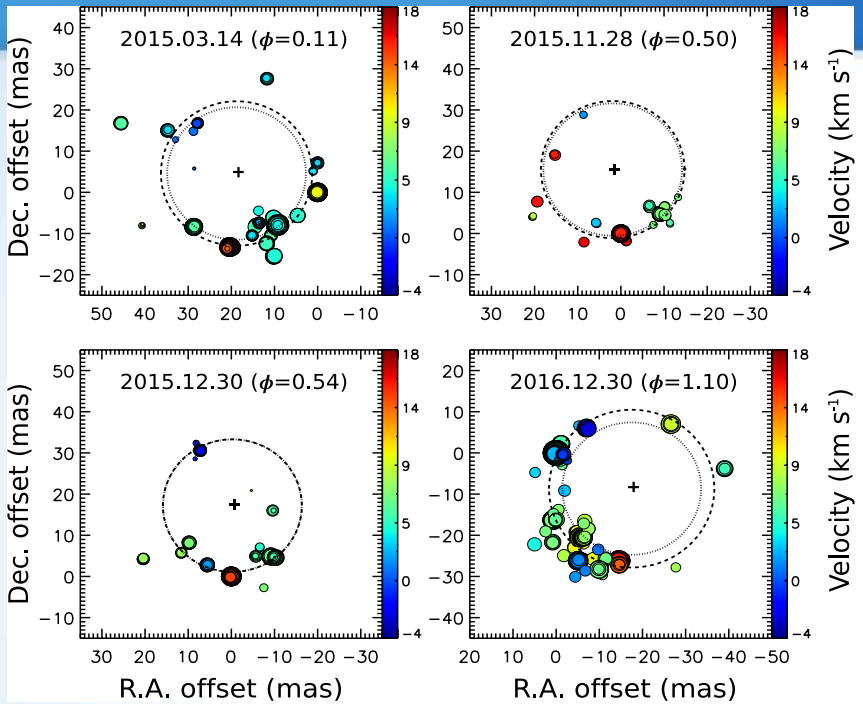
Position-velocity spot maps and ring fitting: VX Sgr



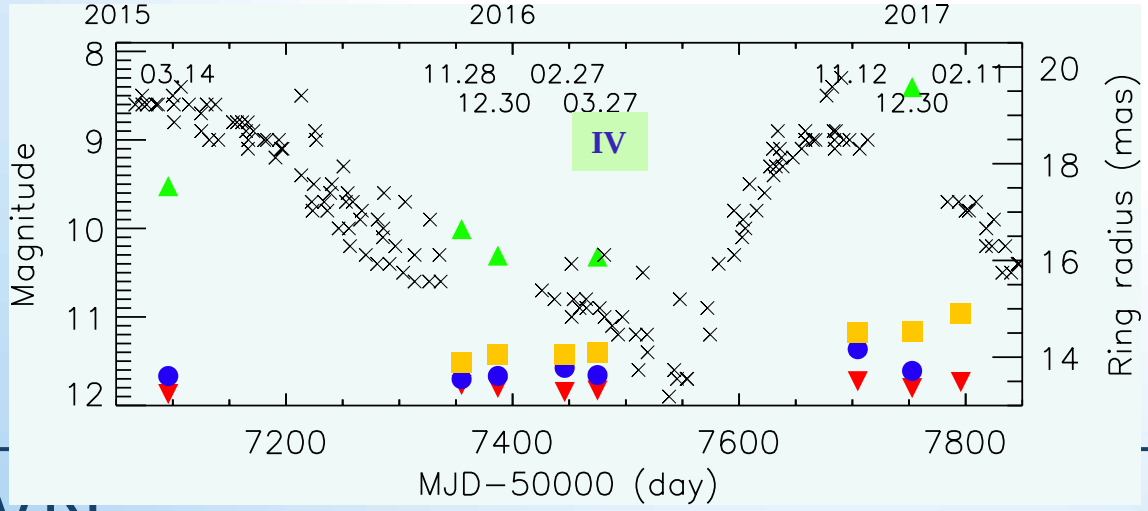
Epoch IV 2016. 03. 27 (ϕ=0.67)

The SiO masers (v=1, J=1-0, J=2-1, J=3-2) are located further from the central star according to the higher rotational transitions.

Variation of 129 GHz SiO ring radius with light curve



Position-velocity spot maps of the 129 GHz SiO single-band and ring fitting (solid line: ring at Ø=0.67)



Variation of SiO ring radius with optical light curve. Green triangle, yellow square, blue circle, and red inverted triangle indicate the 129.3, 86.2, 43.1, and 42.8 GHz SiO masers.

- **Ring radius of 129 GHz maser increases near max. ► Radiative pumping is dominant.**

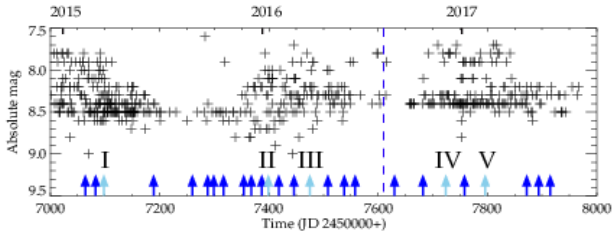
Details ► DH Yoon's presentation

Supergiant Star VY CMa

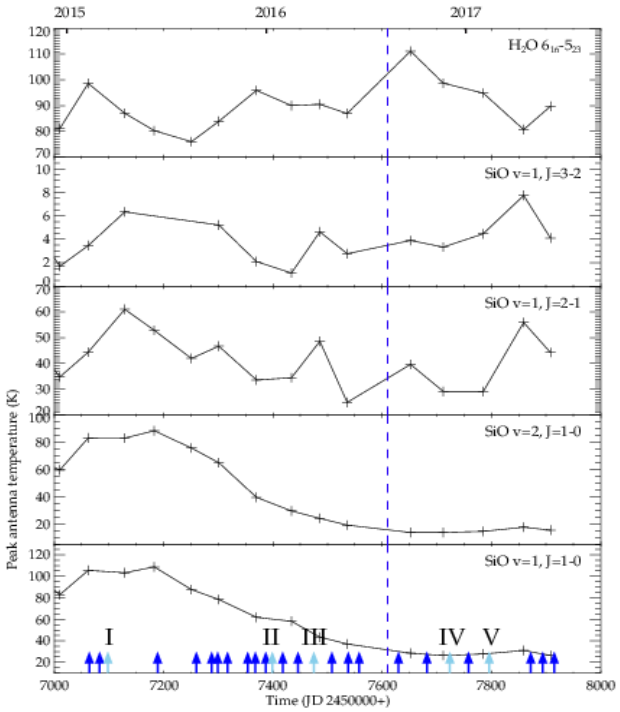
4 band SFPR maps of 5 epochs, SH Cho et al. in Prep.

VY CMa	
2014.9.26	2016.1.11
2014.10.28	2016.1.30
2014.11.26	2016.2.27
2015.2.10	2016.3.27
2015.3.12	2016.4.29
2015.3.16	2016.5.29
2015.6.15	2016.6.18
2015.8.25	2016.8.29
2015.9.22	2016.10.20
2015.10.3	2016.12.1(►D)
2015.10.21	2017.1.4 (►D)
2015.11.27	2017.2.11
2015.12.11	2017.4.28
2015.12.30	2017.5.20
	2017.6.10

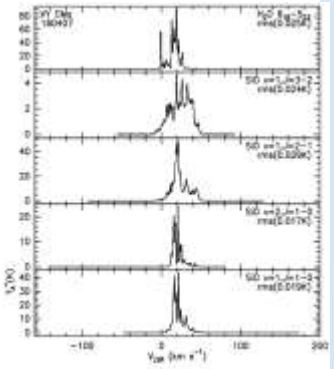
Six epoch data (red color) used for movies (6/29)



Optical light curve VY CMa : peak



Single dish radio intensity variations



Sample spectrum of SD

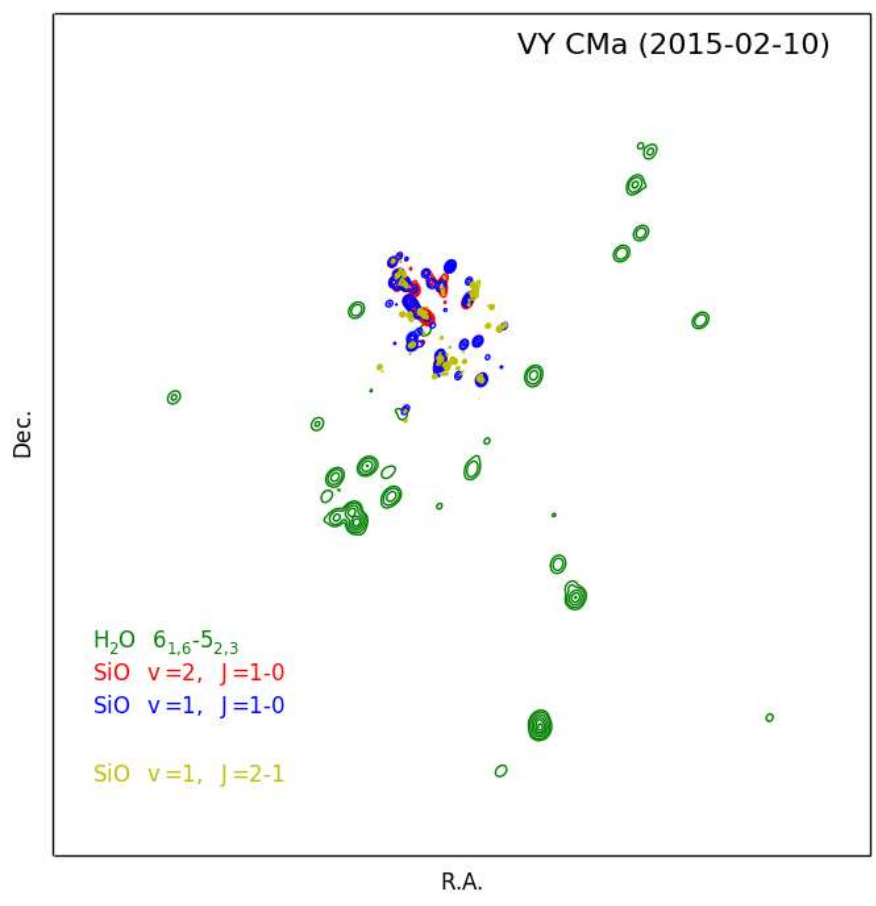
Blue : SFPR

Skyblue : up to D

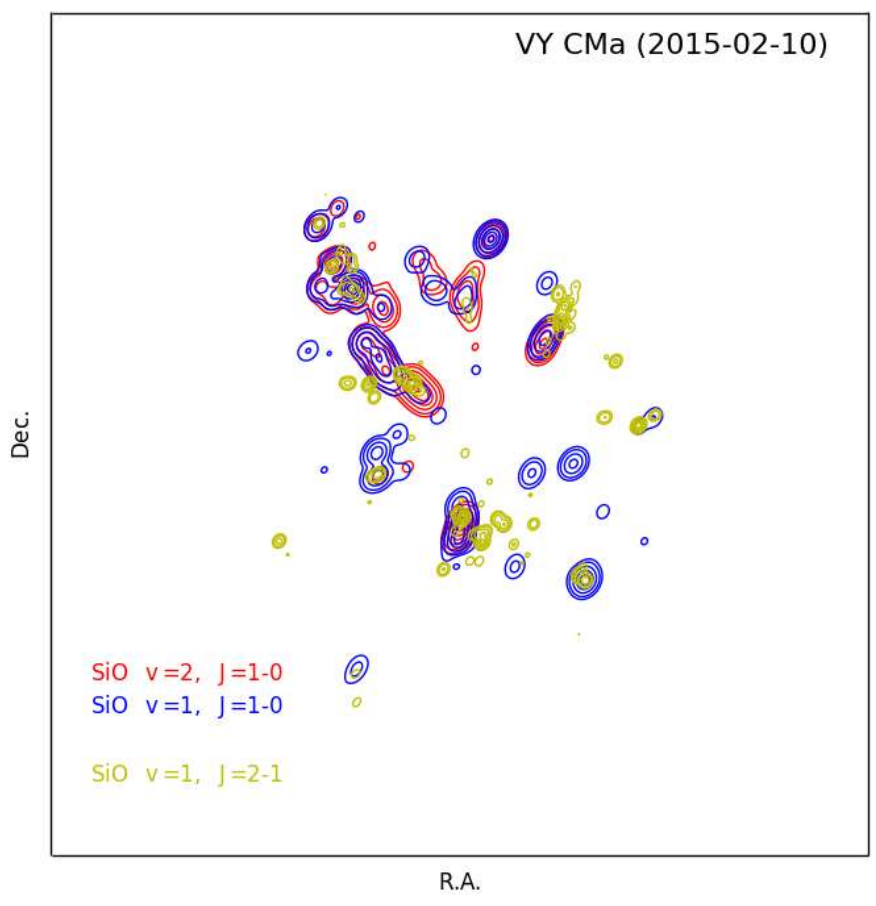
Movies of H_2O & SiO Masers (4 Bands): VY CMa

Movies by YJ Yun

All bands

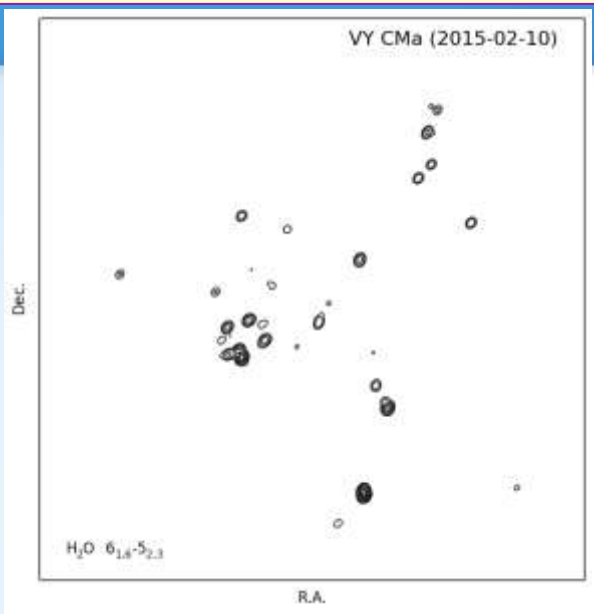


Q/W/D bands

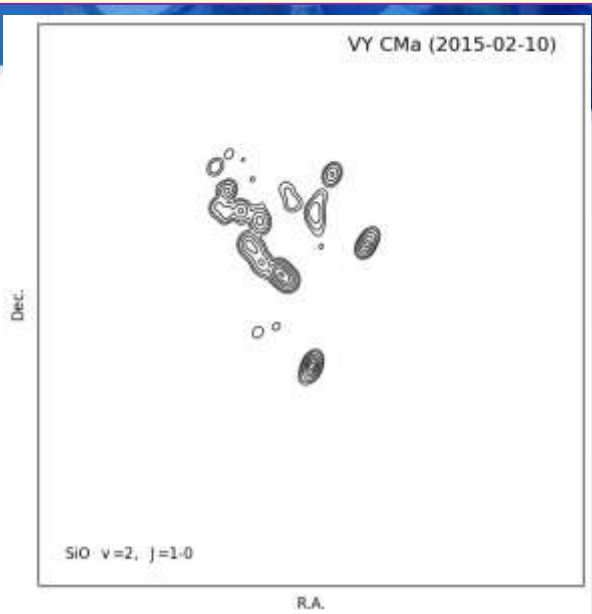


Movies of H_2O & SiO Masers (Single Band): VY CMa

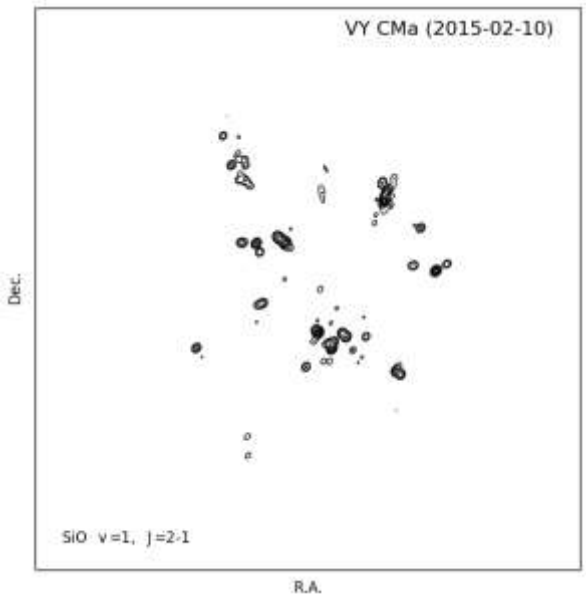
K band (22 GHz)



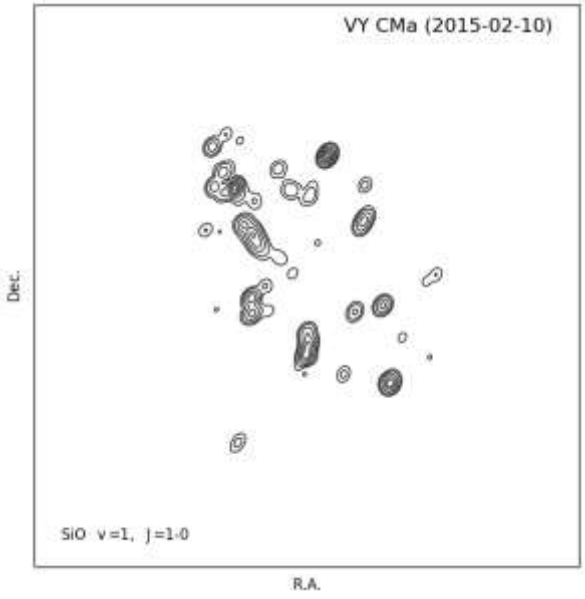
Q band (42 GHz)



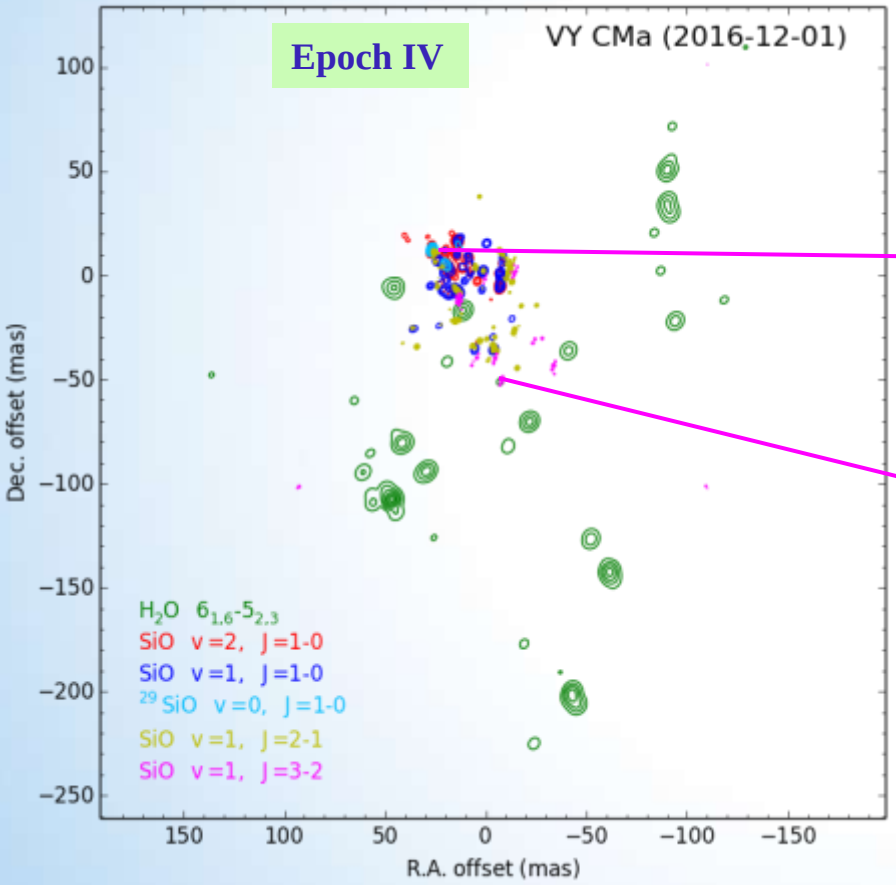
W band (86 GHz)

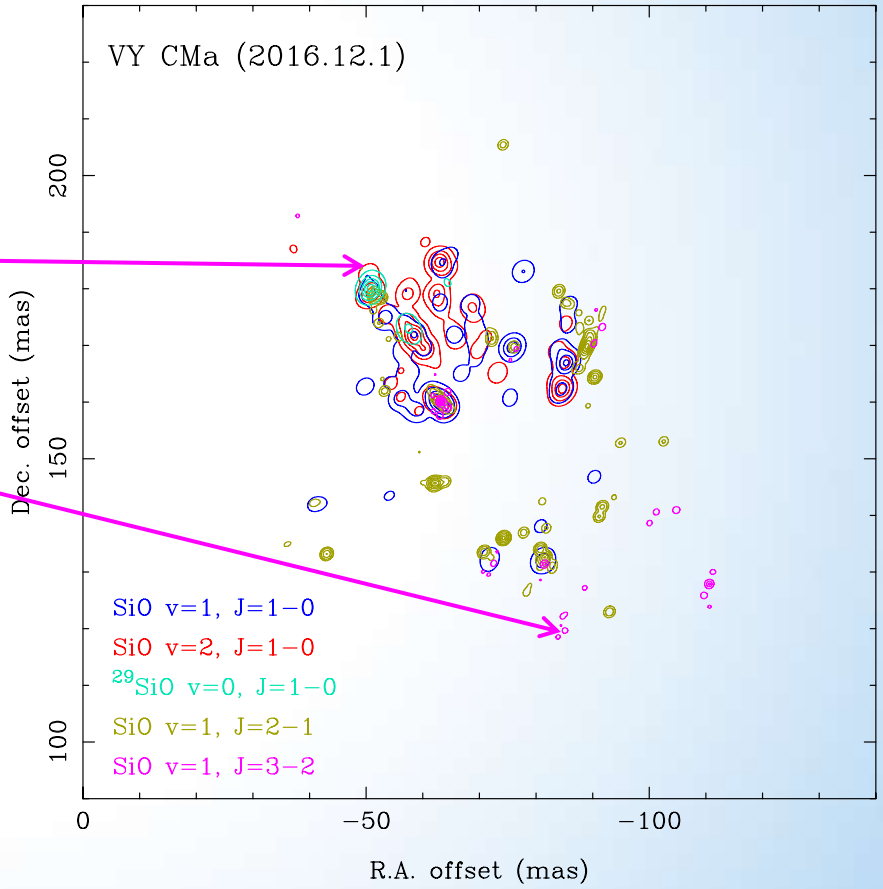


Q band (43 GHz)

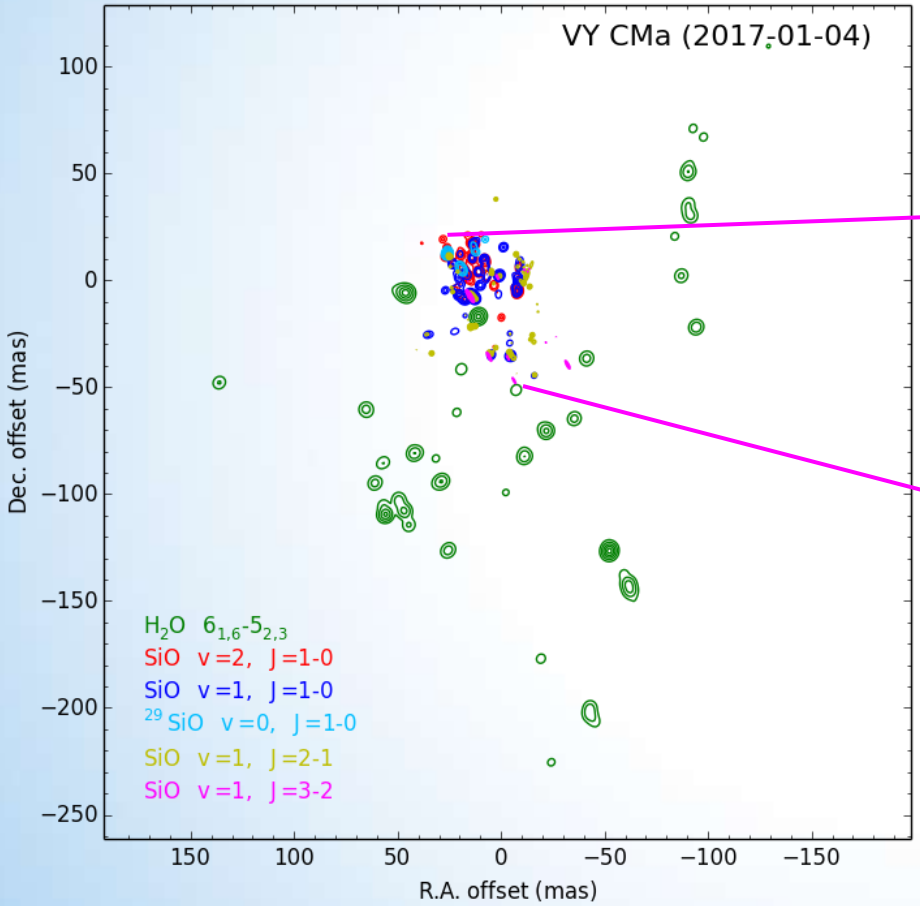


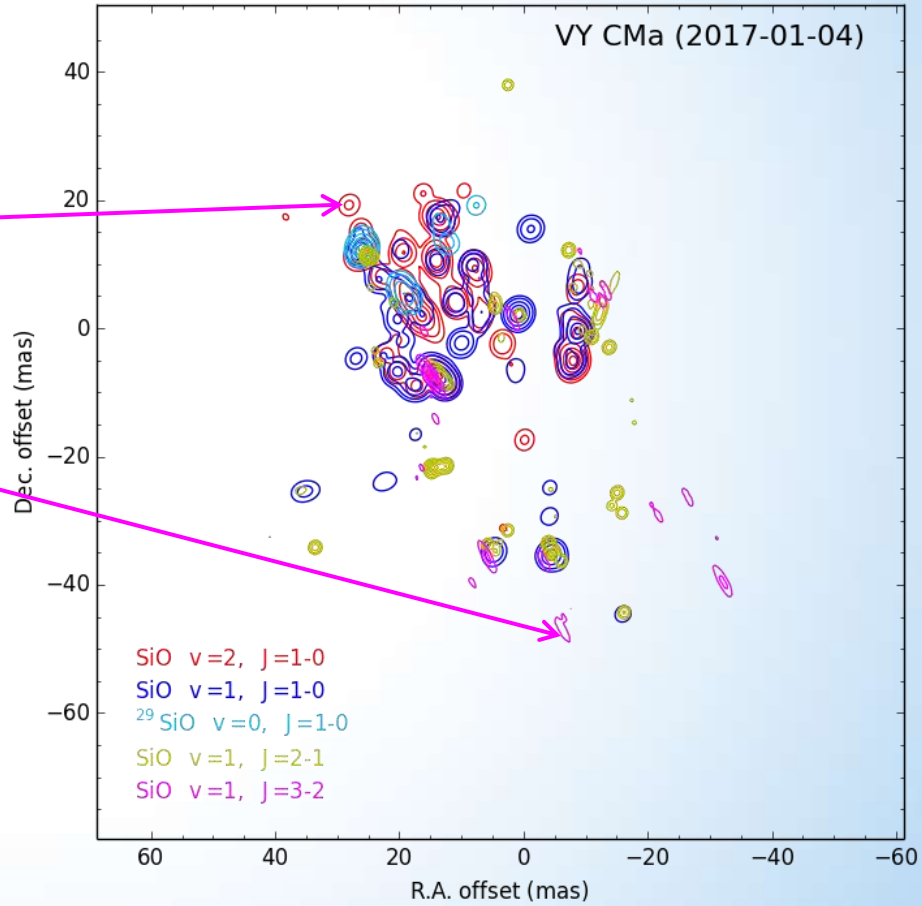
4 Band SFPR Maps of H_2O and SiO Masers: VY CMa





4 Band SFPR Maps of H_2O and SiO Masers: VY CMa





Summary and Issues of VY CMa Results

- Based on registered maps of H_2O and SiO masers
  - ► We need to trace **the development of outward motion from elliptical SiO maser feature to highly asymmetric H_2O maser feature** together with the role of dust layer**.**

- **The SiO 43/42 GHz SiO masers are active in NE dir.** accompanying isotopic ^{29}SiO J=1-0 maser, while **the SiO J=3-2 maser is extended in SW dir.**

- Why the location of SiO maser distribution is different among SiO J=1-0, J=2-1, J=3-2 maser lines ?
  - ► **Different excitation conditions, pumping mechanism according to different transitions ?**

- **Elliptical pulsation motion of SiO masers in NE-SW direction**
  - ► Related with **pulsation mode of VY CMa ?**

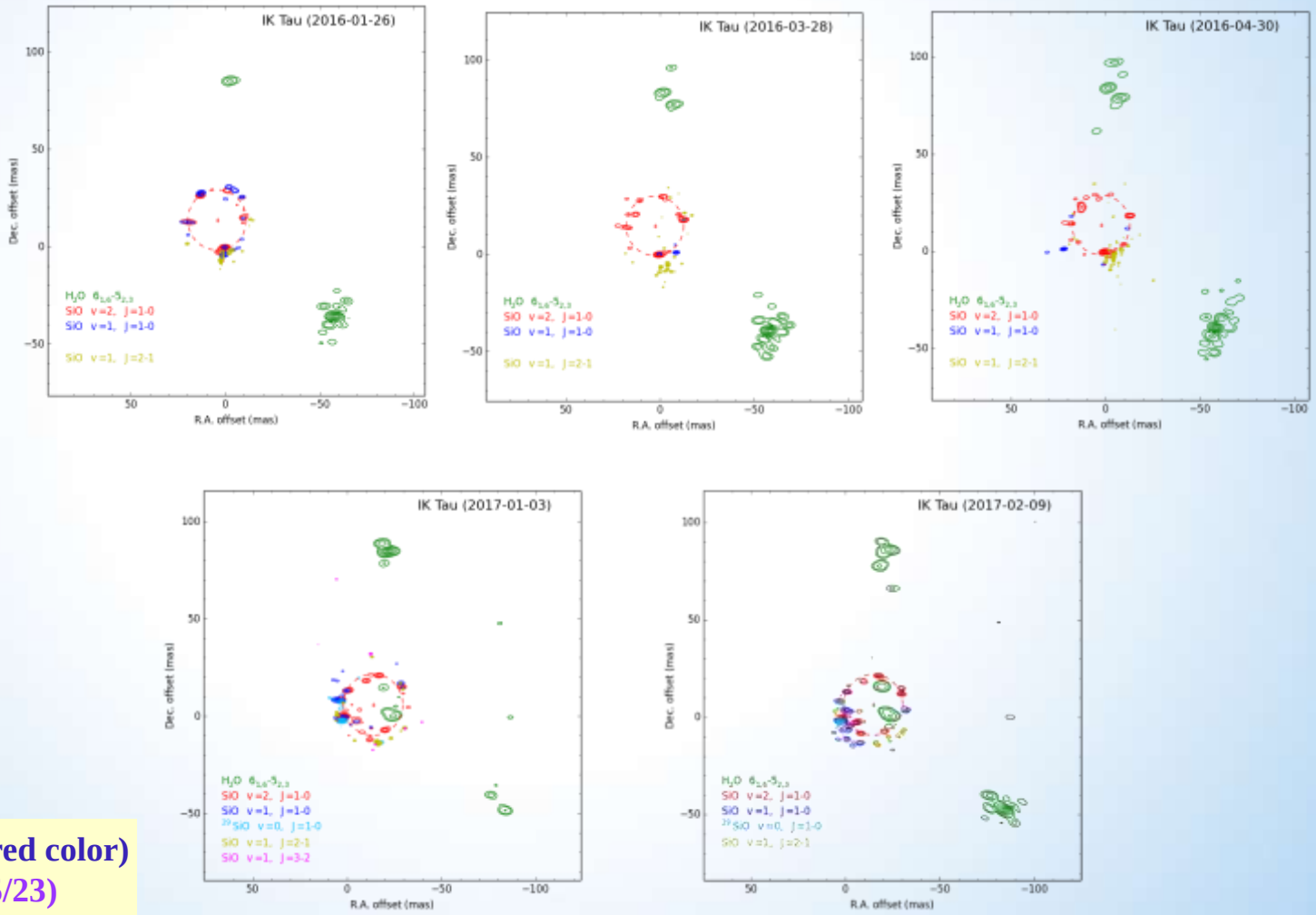
- Why does the morphology of SiO maser distribution show different features between KVN SiO maps and those of VLBA ?

SFPR Maps of Mira Variable Star IK Tau

IK Tau

2014.8.26
2014.10.27
2014.12.30
2015.2.23
2015.5.20
2015.9.21
2015.10.22
2015.11.28
2015.12.11
2015.12.29
2016.1.7
2016.1.26
2016.2.28
2016.3.28
2016.4.30
2016.8.30
2016.11.12
2017.1.3 (►D)
2017.2.9
2017.3.17
2017.5.11
2017.5.22
2017.6.10

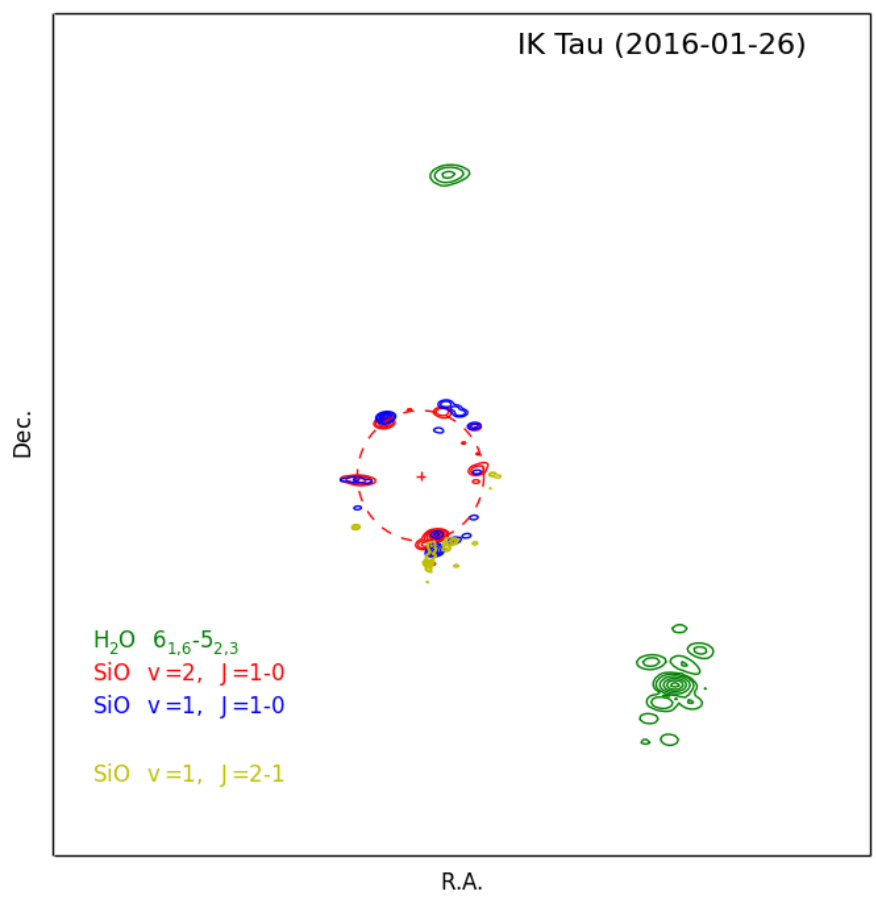
Five epoch data (red color) used for movies (5/23)



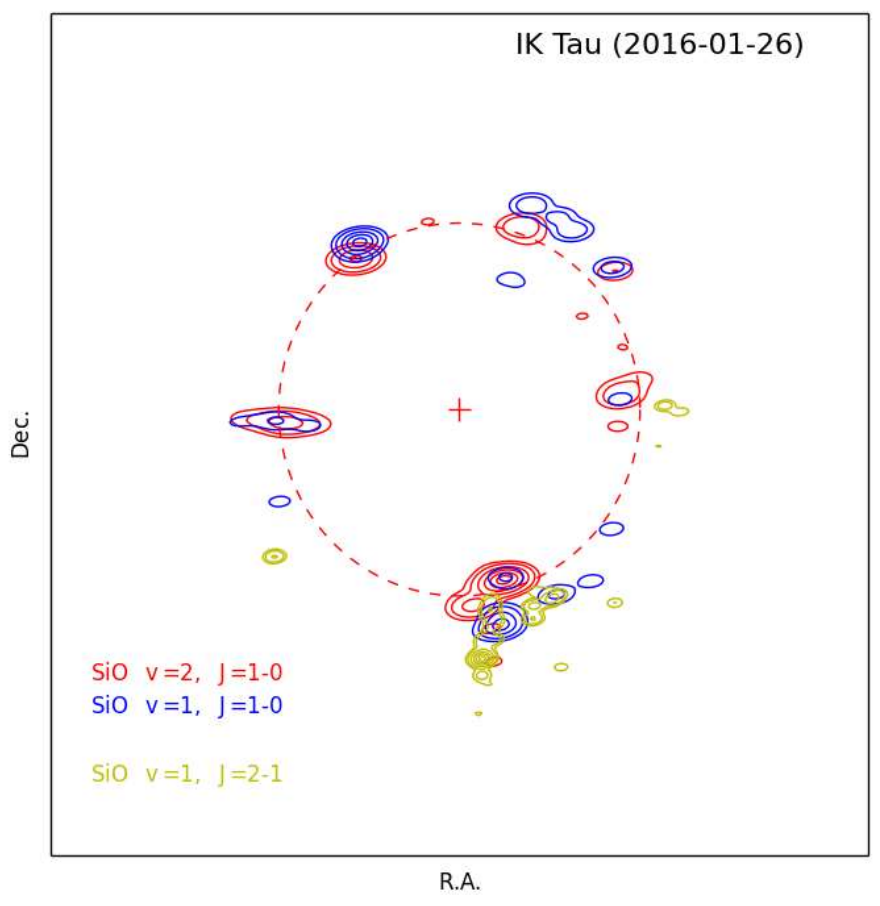
Movies of H_2O & SiO Masers (4 Bands): IK Tau

Movies by YJ Yun

All bands

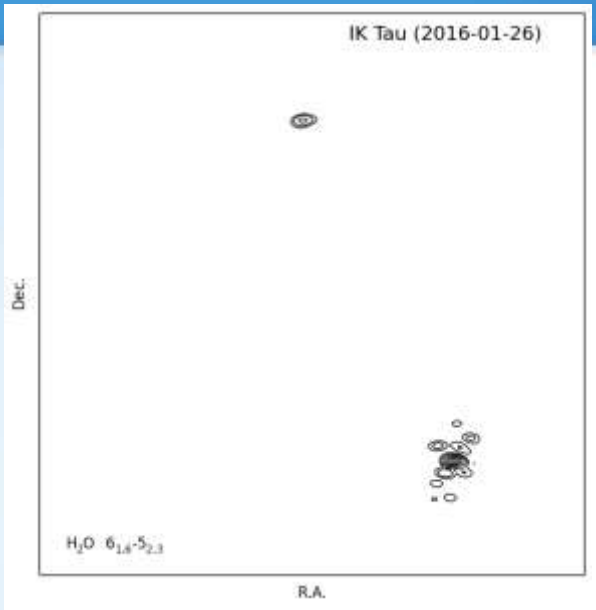


Q/W/D bands

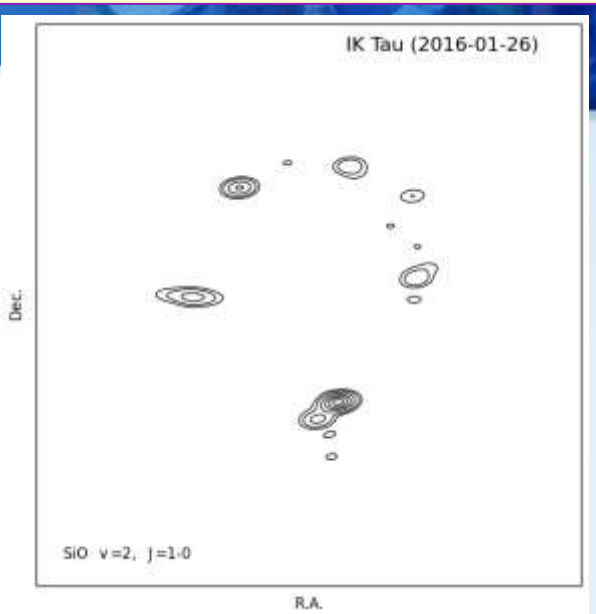


Movies of H_2O & SiO Masers (Single Band): IK Tau

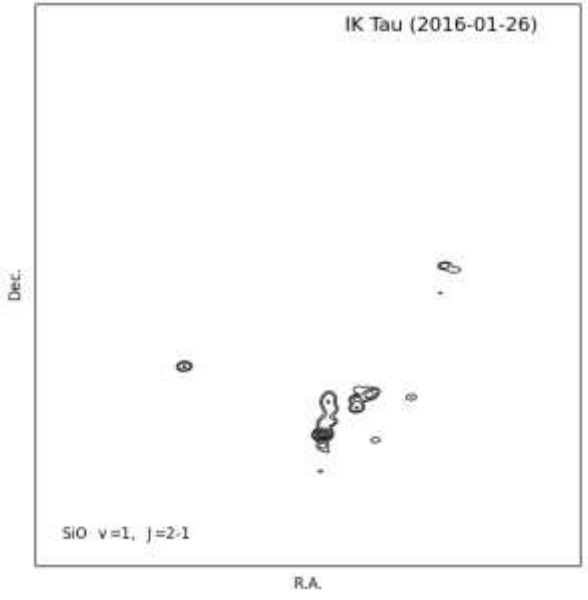
K band
22 GHz



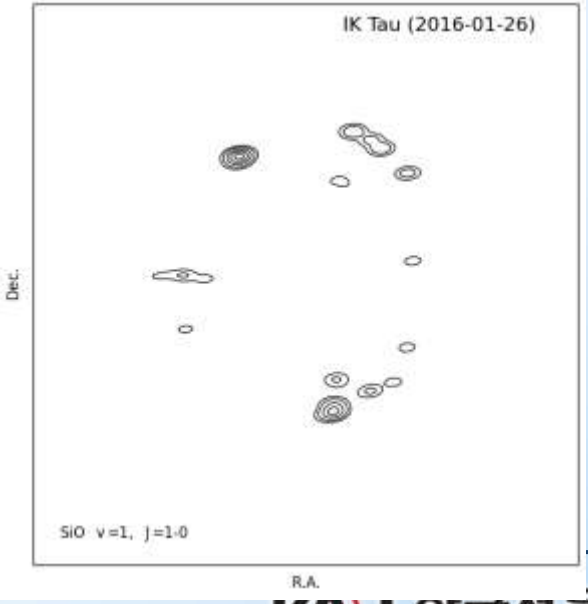
Q band
(42 GHz)



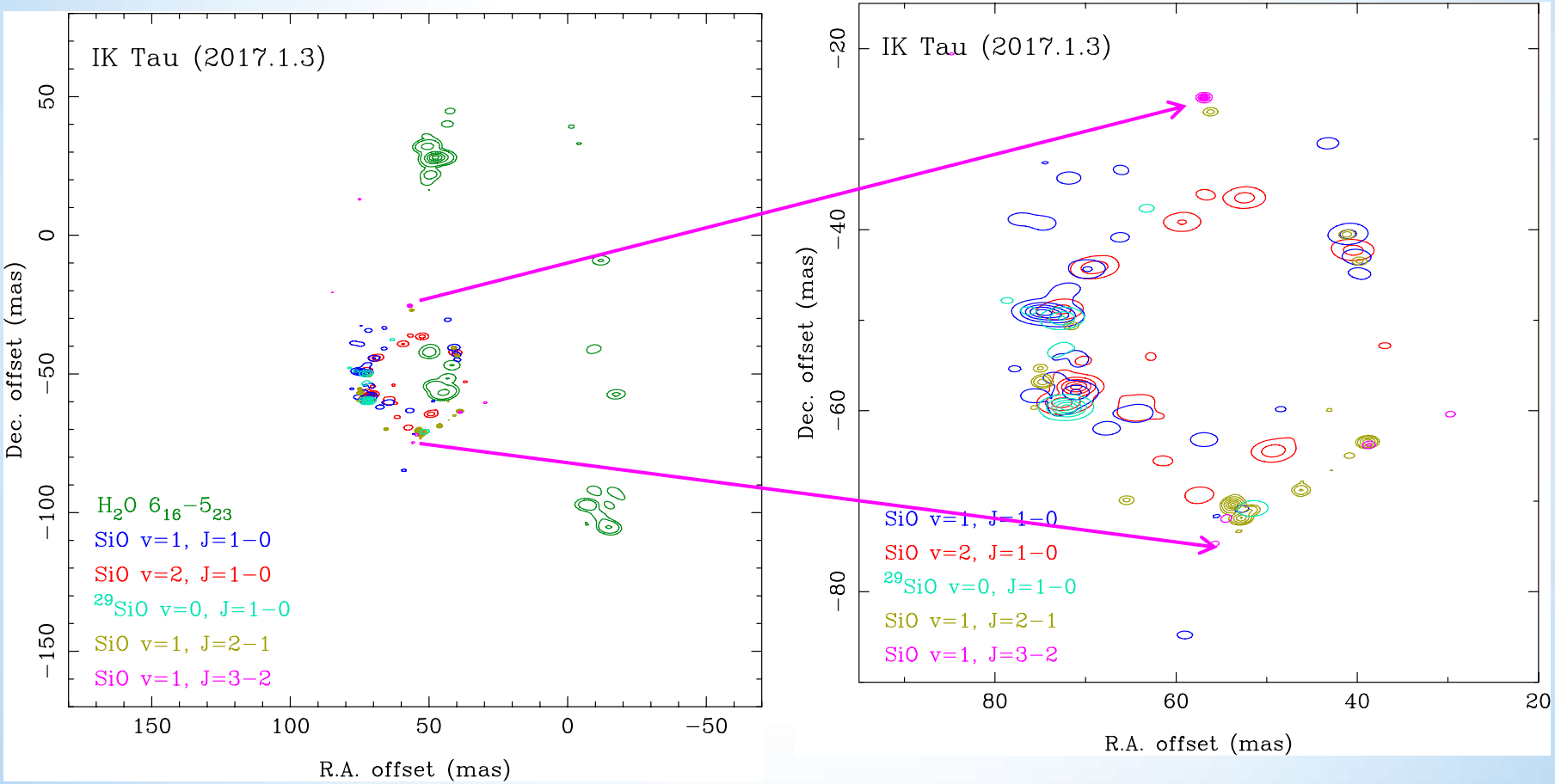
W band
86 GHz



Q band
(43 GHz)



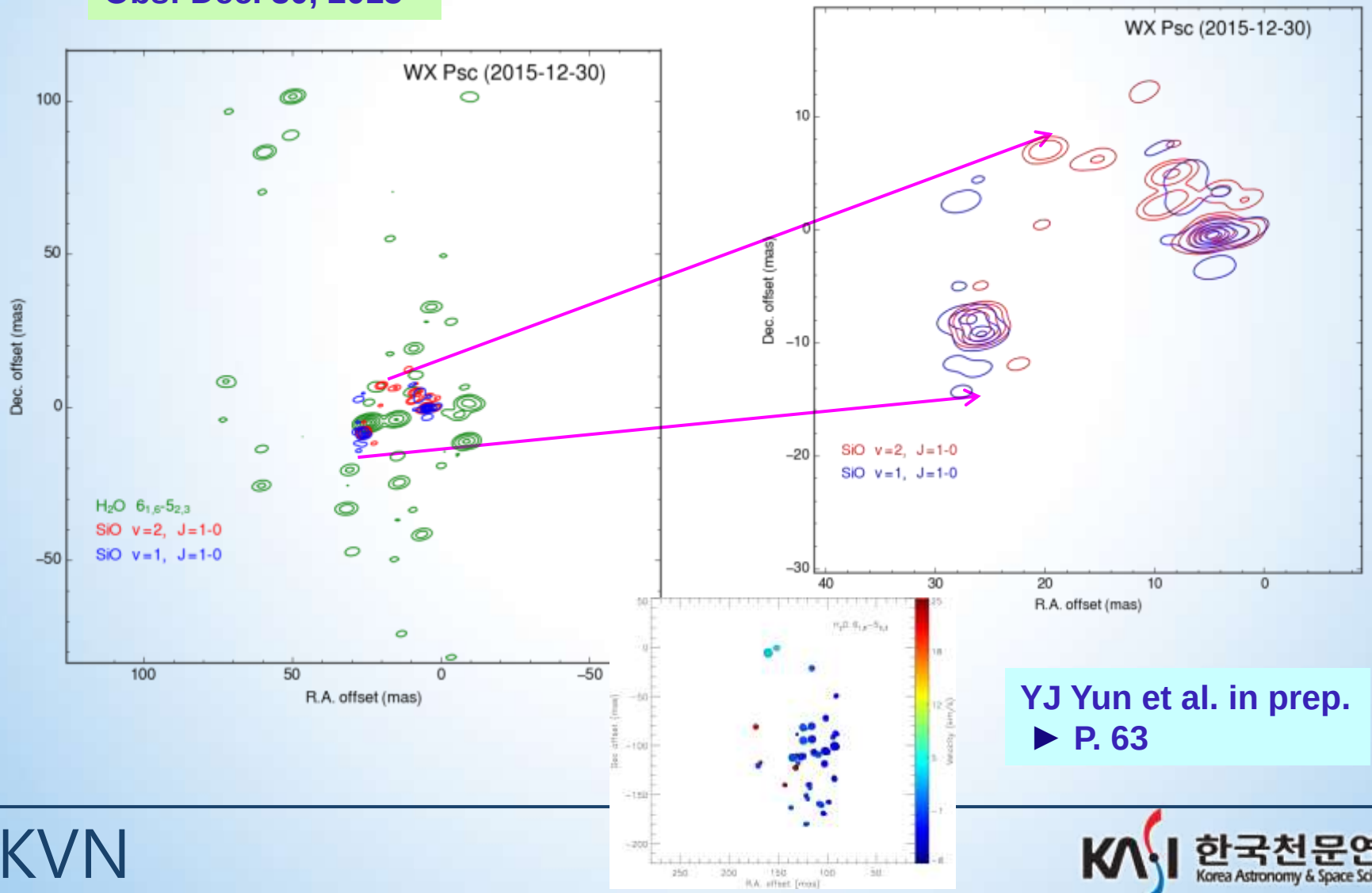
4 Band SFPR Maps of IK Tau



Long Period OH/IR Star WX Psc

P= 660 days, D= ~650 pc

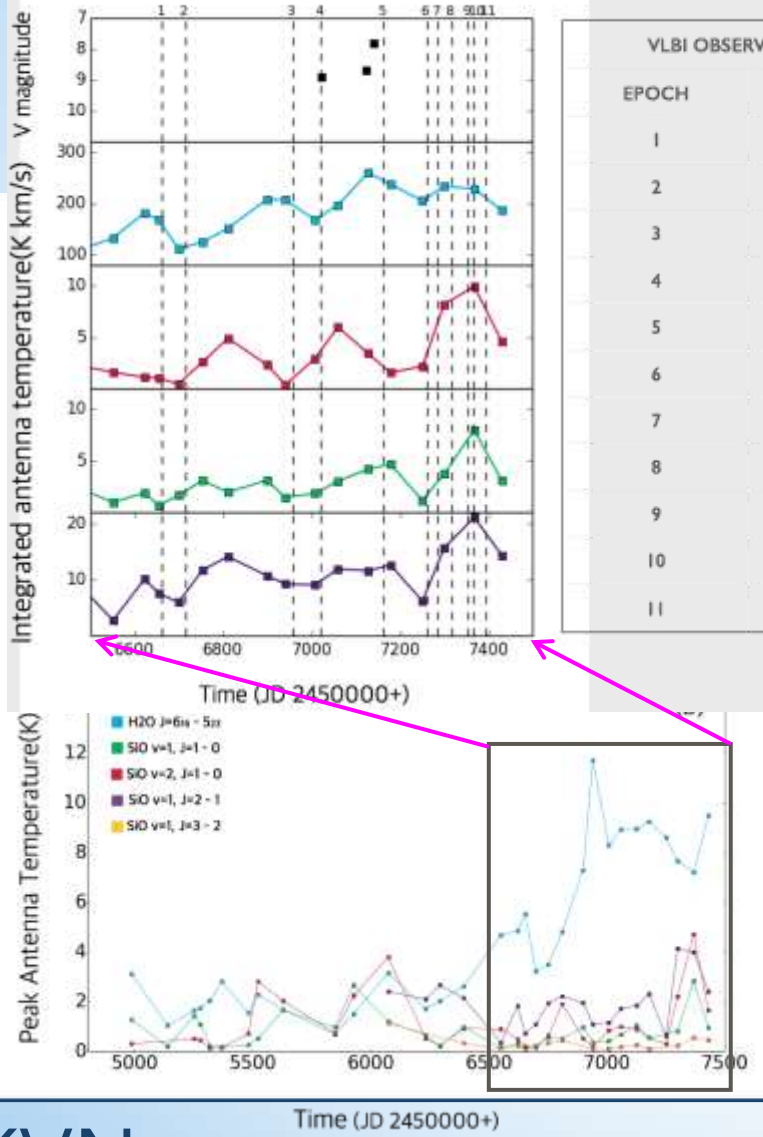
Obs: Dec. 30, 2015



YJ Yun et al. in prep.

► P. 63

Semi-regular Variable Star R Crt (SRb)

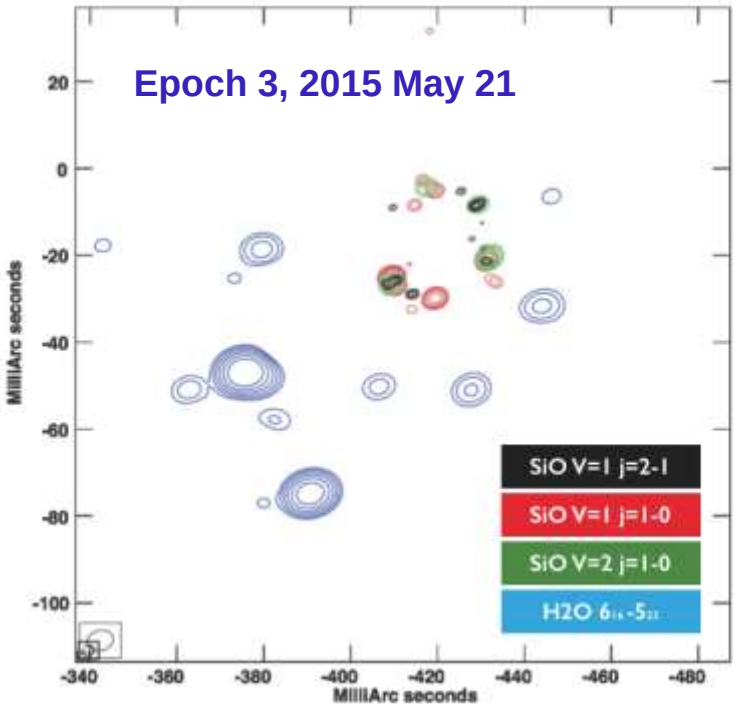


VLBI OBSERVATIONS

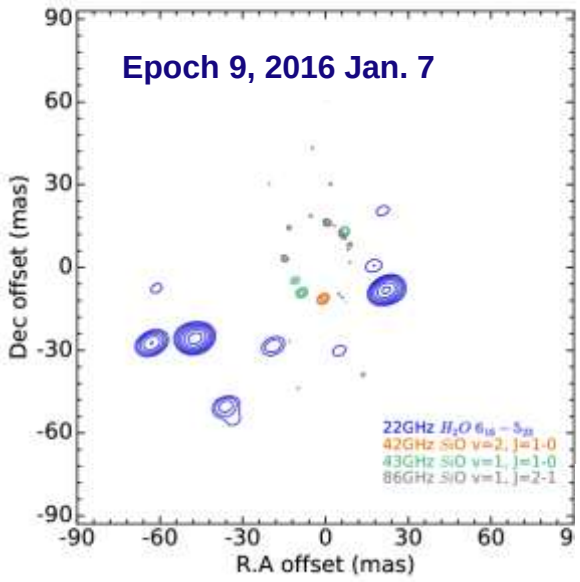
EPOCH	OBSV DATE
1	27-10-2014
2	29-12-2014
3	21-05-2015
4	27-08-2015
5	21-09-2015
6	22-10-2015
7	28-11-2015
8	11-12-2015
9	07-01-2016
10	26-01-2016
11	28-02-2016

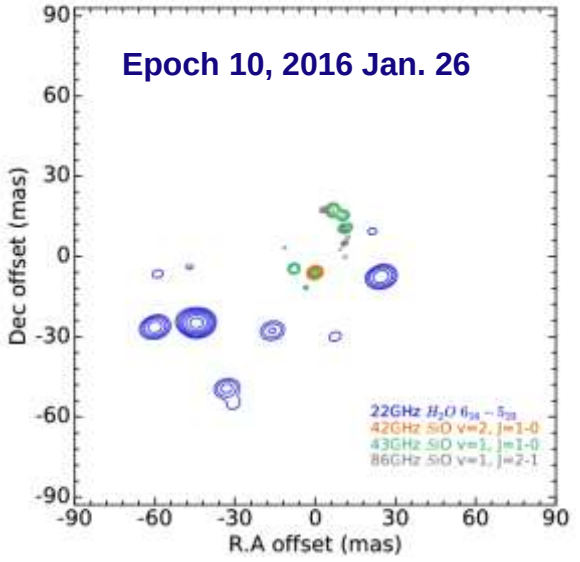
DJ Kim et al. in Prep.

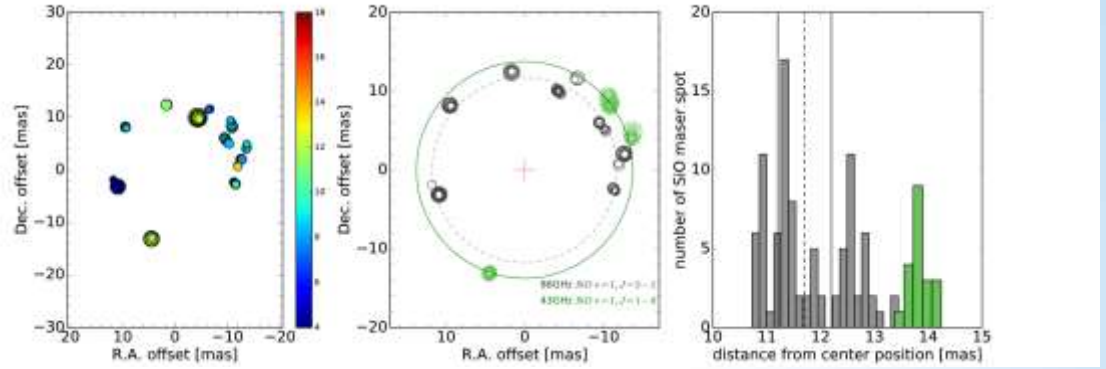
P=160 days (Kholopov et al. 1987)
D=~170 pc (Szymczak & Le Squeren 1999)

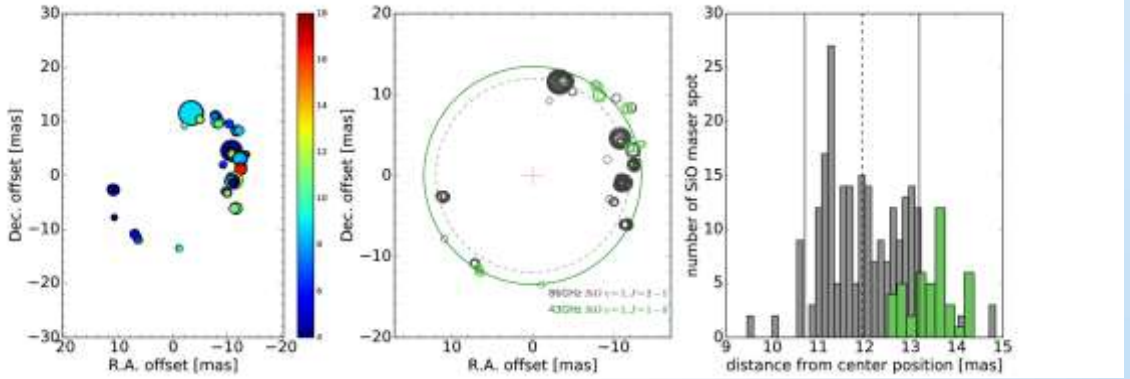


Ring radius of SiO v=1, J=1-0, 2-1 masers







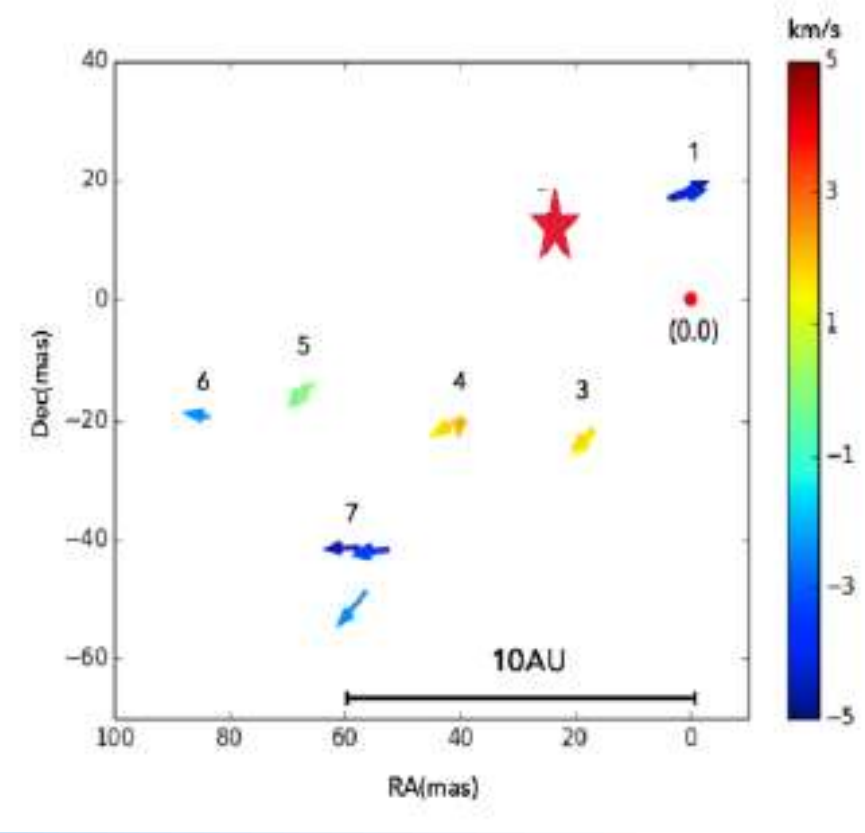


Ring radius (R Crt)

	SiO v=1, J=1-0,	J=2-1
Epoch 3	13.32	12.72 (mas)
Epoch 9	13.83	11.76
Epock 10	13.44	11.95

We are considering interpreting the results.

Proper motion of H_2O maser: R Crt

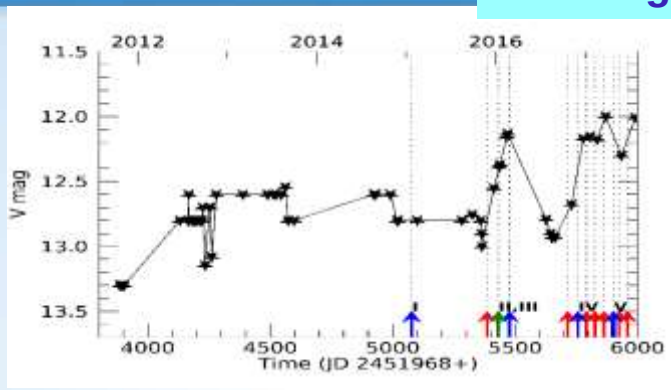


NO	Vx(km/s)	Vy(km/s)	Vz(km/s)	Ve(km/s)
1	-4.33	1.72	-4.53	6.50
3	2.26	-2.32	1.37	3.52
4	0.48	-2.26	2.21	3.20
5	2.23	-2.41	0.10	3.29
6	2.73	0.42	-2.42	3.68
7	3.73	-0.21	-4.53	5.87

Very asymmetric outflow feature with respect to central star determined from the ring fitting center of SiO maser

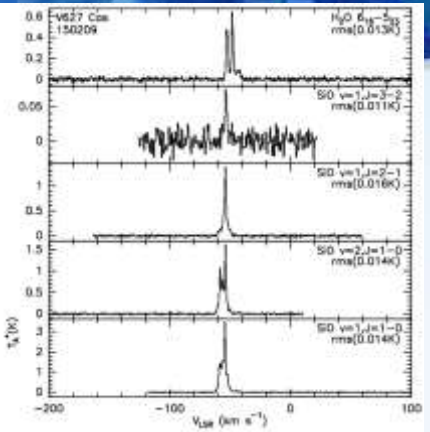
Symbiotic Star V627 Cas

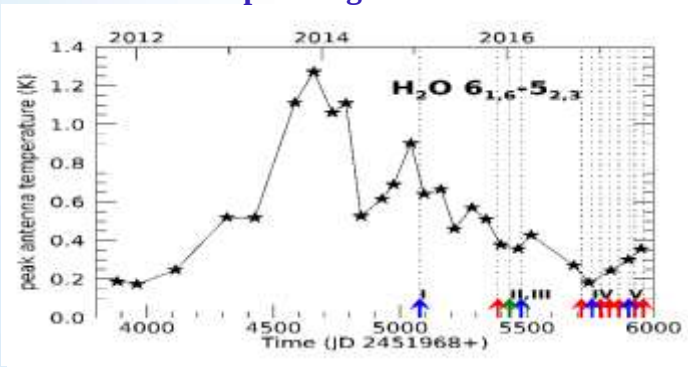
HN Yang et al. in Prep.

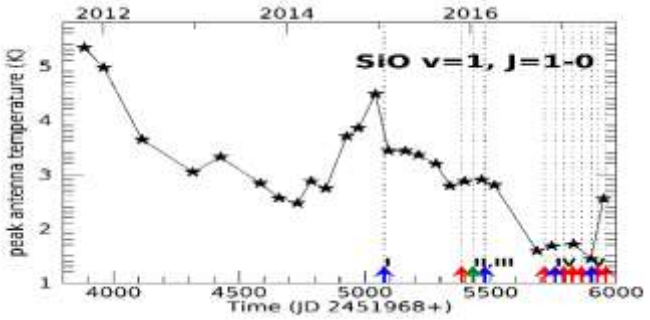


Optical light curve

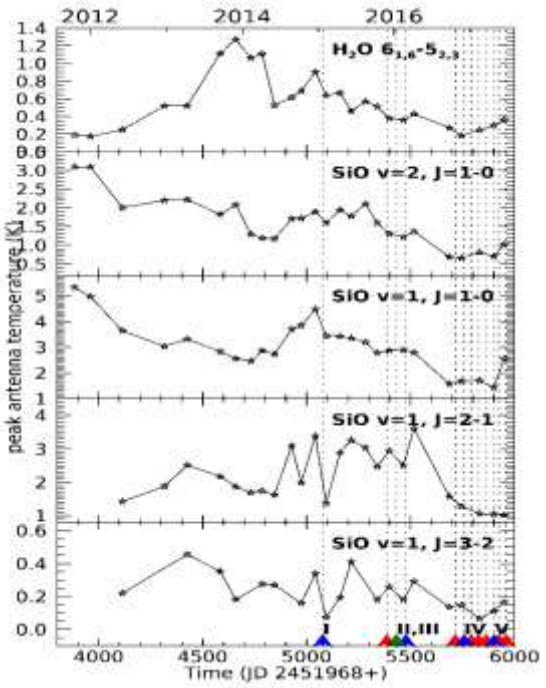
Epochs 1-5: Successful SFPR maps



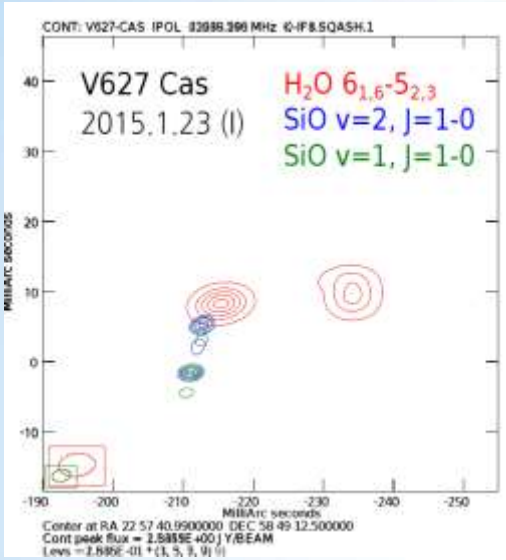


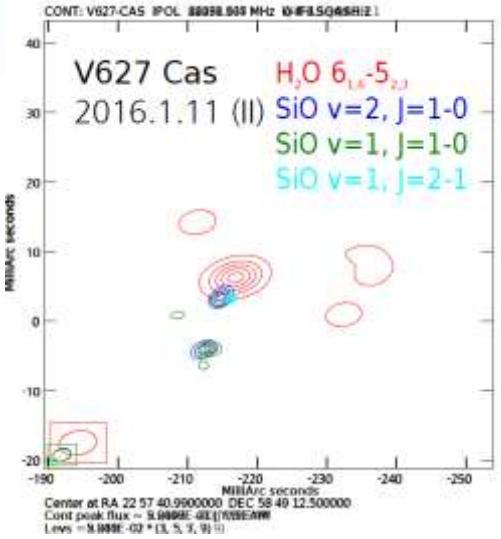


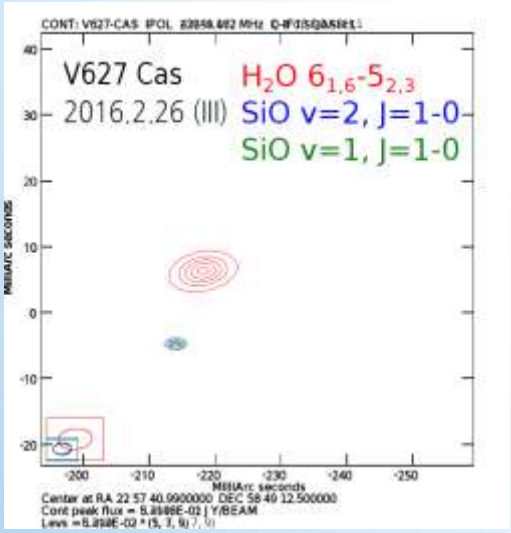
Single dish radio intensity variations

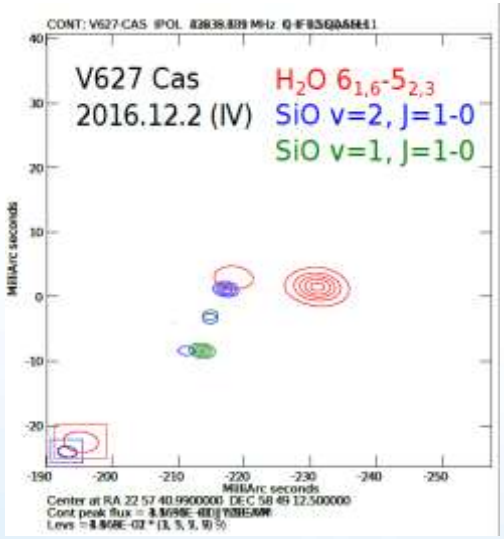


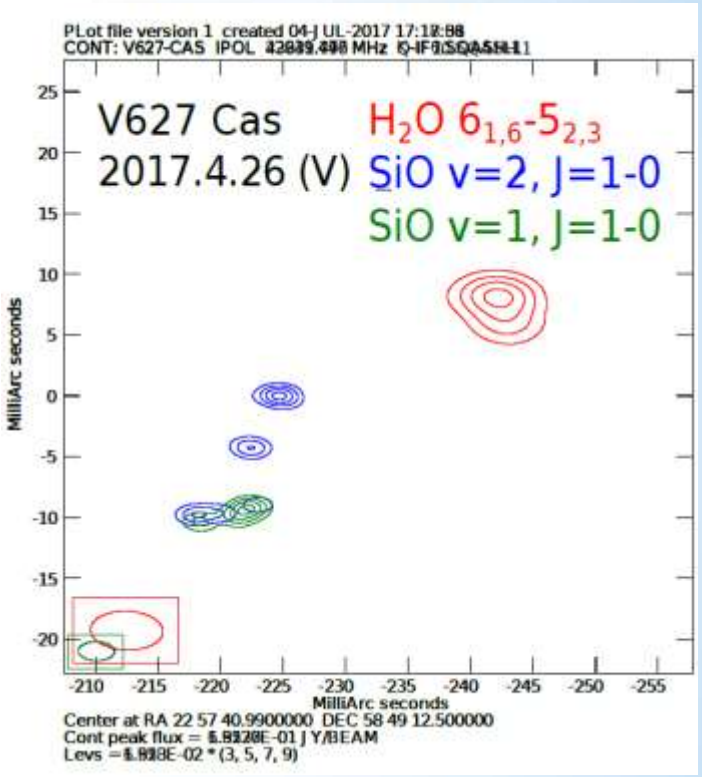
Registered integrated intensity maps of H_2O and SiO masers: V627 Cas











We need to investigate that the variations of H_2O maser is associated with the orbital motion of hot companion.

Summary and Issues of 1st Stage KSP Results

- We have obtained **successful SFPR maps of H_2O and SiO masers from 9 sources** and focused on these 9 sources.

- Based on SFPR maps of H_2O and SiO masers, we are investigating the spatial structure and kinematics from SiO to H_2O maser regions: **development of outward motion from ring-like/elliptical SiO to asymmetric 22 GHz H_2O maser features.**
  - ► Asymmetric clumpy structure and the role of dust layer ?
  - ► SiO & H_2O maser models coupled to hydrodynamical model of CSE
  - ► **Collaborations with Maser Theory & VLTI teams**: M. Gray et al. (2009), Wittkowski et al. (2012)

- **Different features of registered maps of H_2O and SiO masers and different SiO maser features** (ring-like, elliptical, irregular etc.) according to KSP sources
  - ► Investigate the relation with characteristics of sources, evolutionary stage **including the relation with light curve and pulsation mode** (especially, in the case of different SiO maser features) .

- Based on registered maps of SiO J=1-0, J=2-1 and J=3-2 masers
  - ◈ The SiO maser distribution (location) is different among SiO J=1-0, J=2-1, J=3-2 masers.
  - ► **Different dominant pumping mechanism according to different SiO transitions & sources** ?