Simultaneous Multi-Frequency VLBI System for mm-VLBI & KVN, KaVA, EAVN

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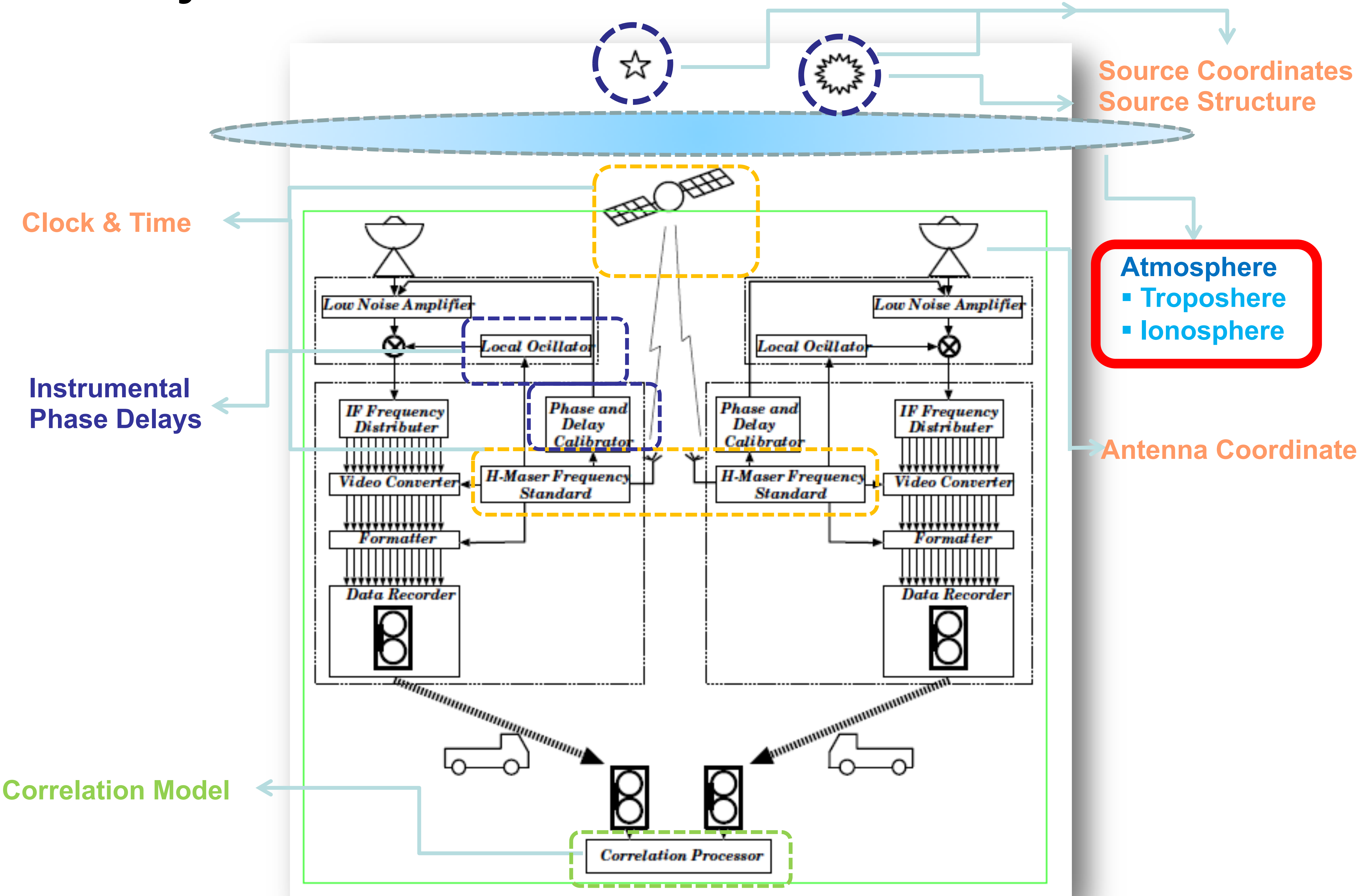
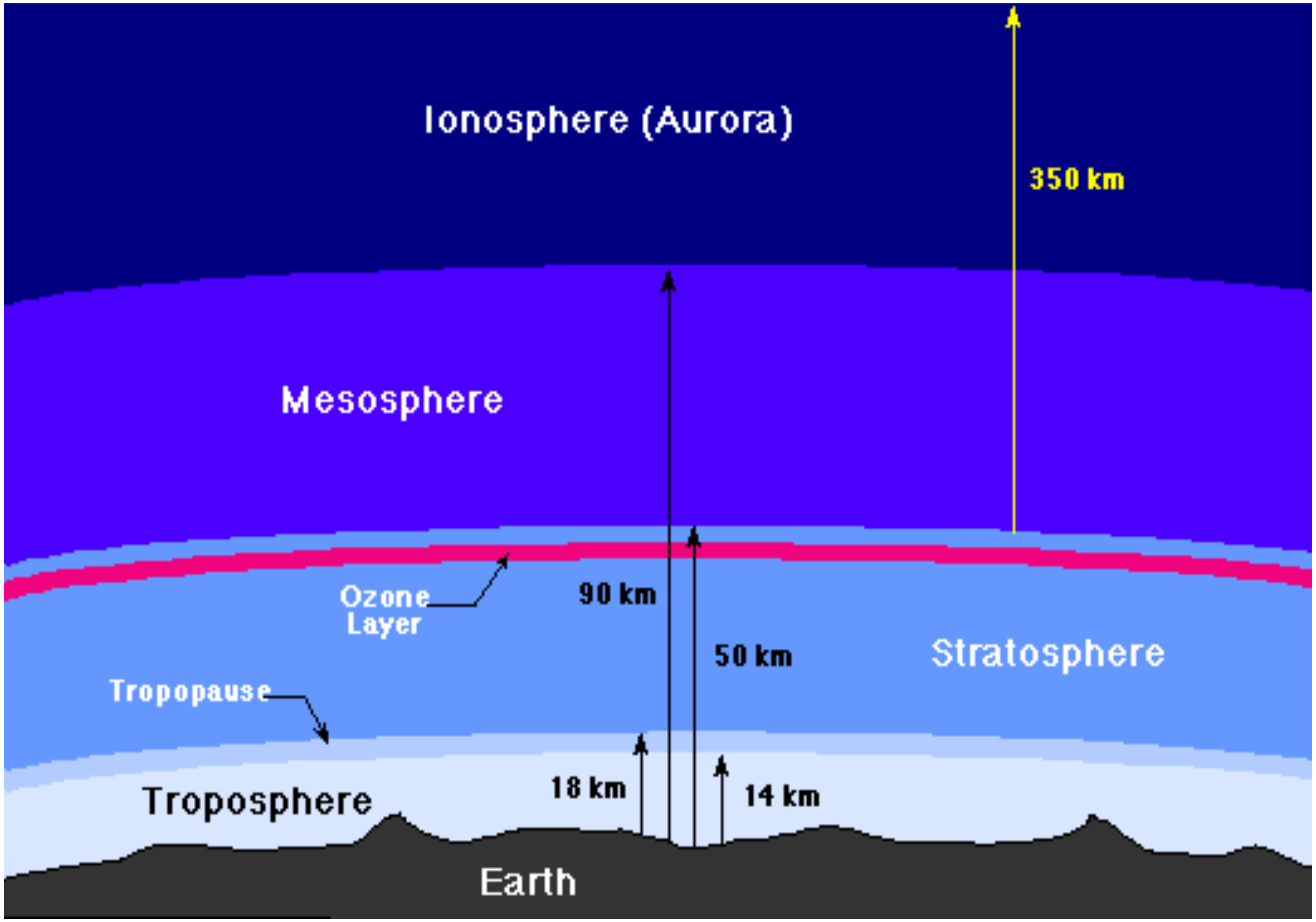
VLBI System

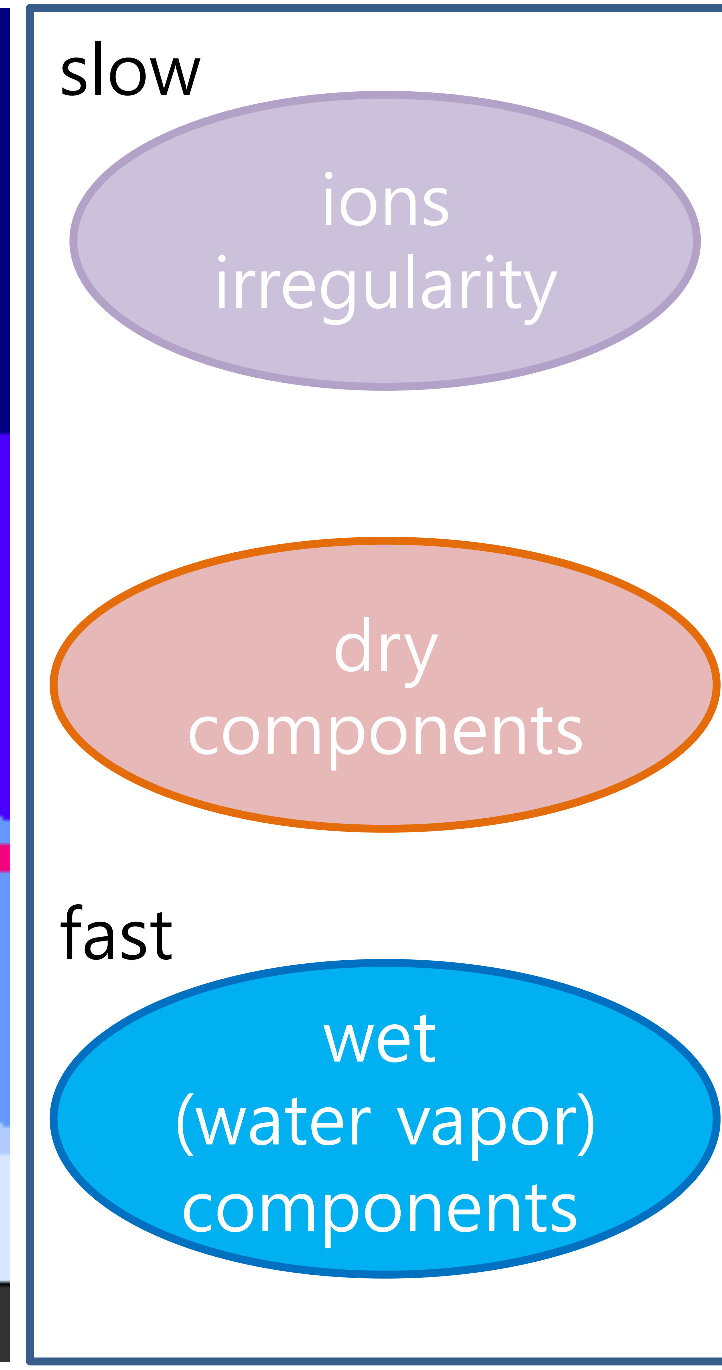


(lecture note : Sasao)

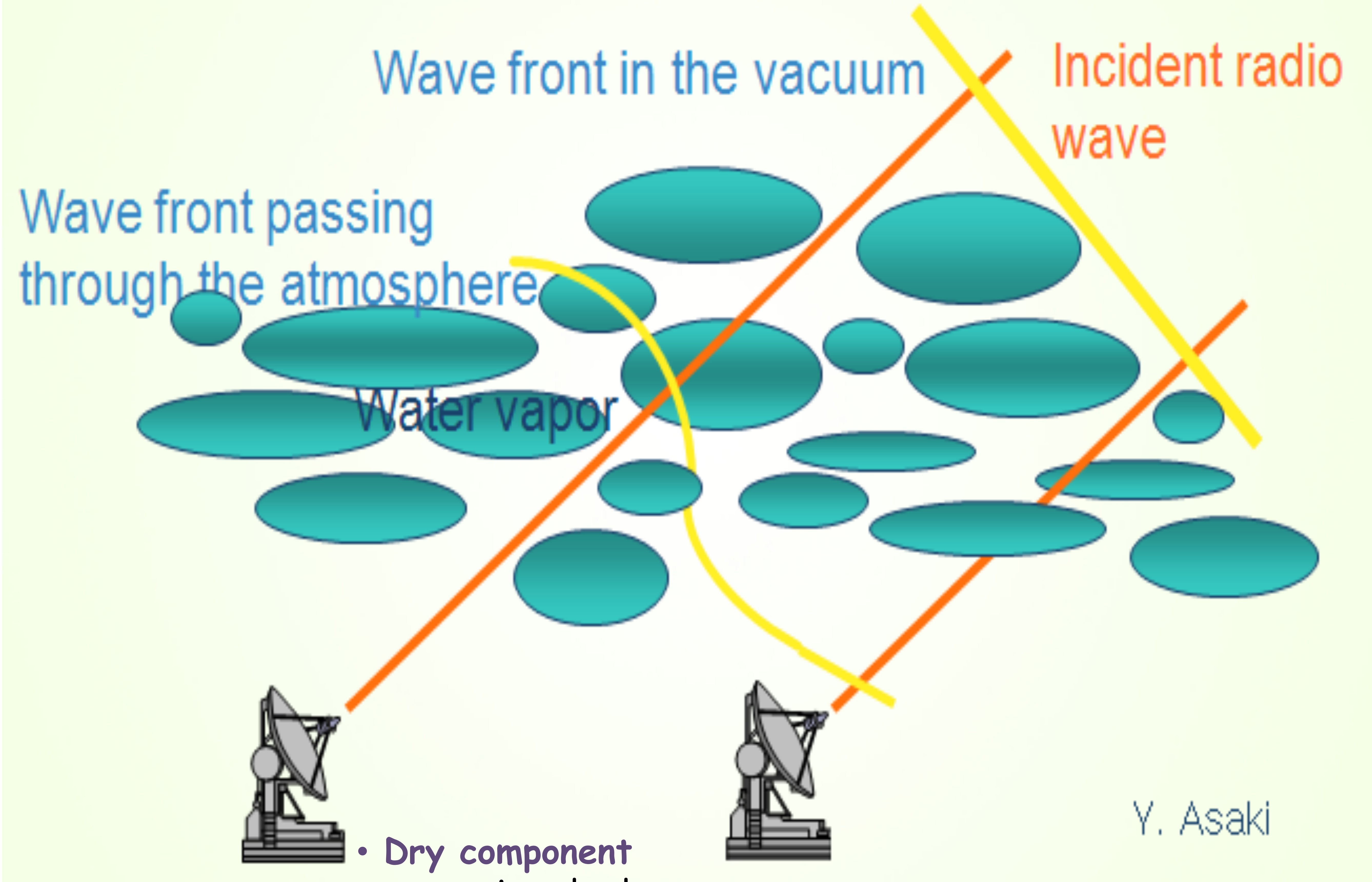
Atmospheric Propagation Delays



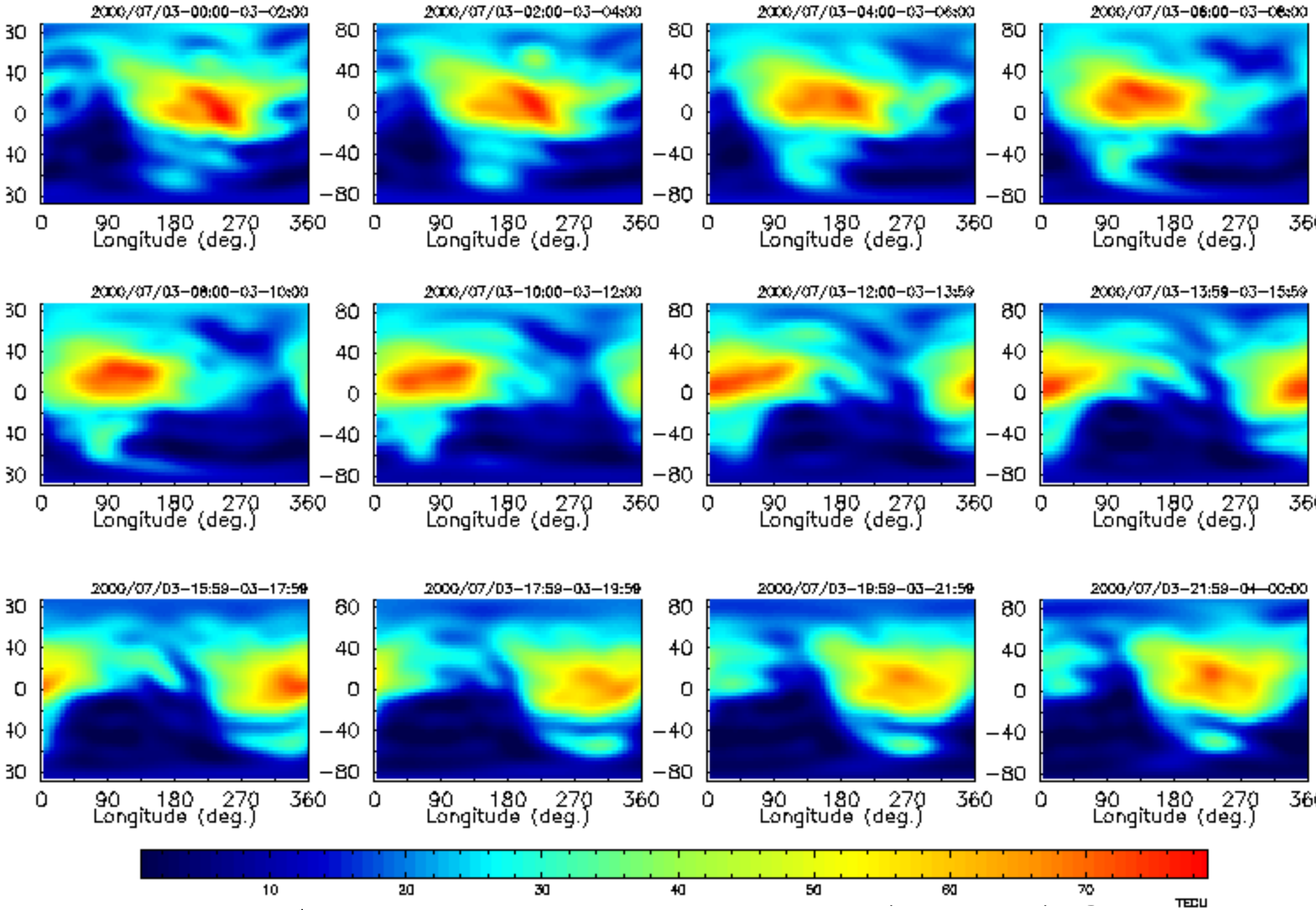
Layers of the Earth's Atmosphere (source: NASA)



Three major components of the atmospheric propagation delays



- **Dry component**
  - varies slowly
  - range in variation is small
  - directly measurable via pressure on the ground
- **Wet component**
  - can vary quickly
  - can vary over a large range
  - unpredictable

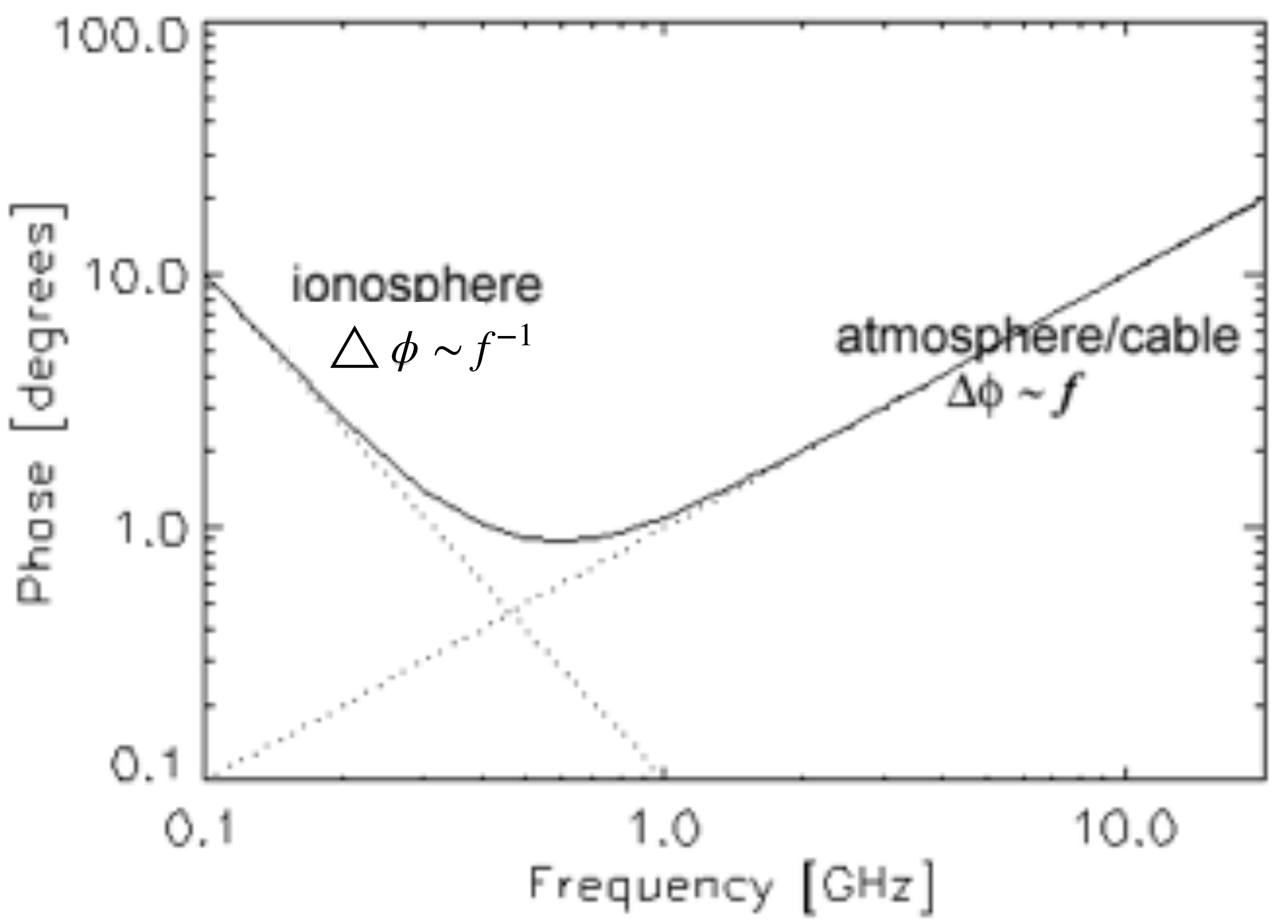


Global ionosphere map on 3rd of July 2000 (provided by CODE)

- Ionization, irregularities : refraction and propagation delay
- Relatively slow varying term

- Zenith delay from the ionosphere can vary considerably depending on time of day, season, the solar cycle and source elevation

Atmospheric Propagation Delays

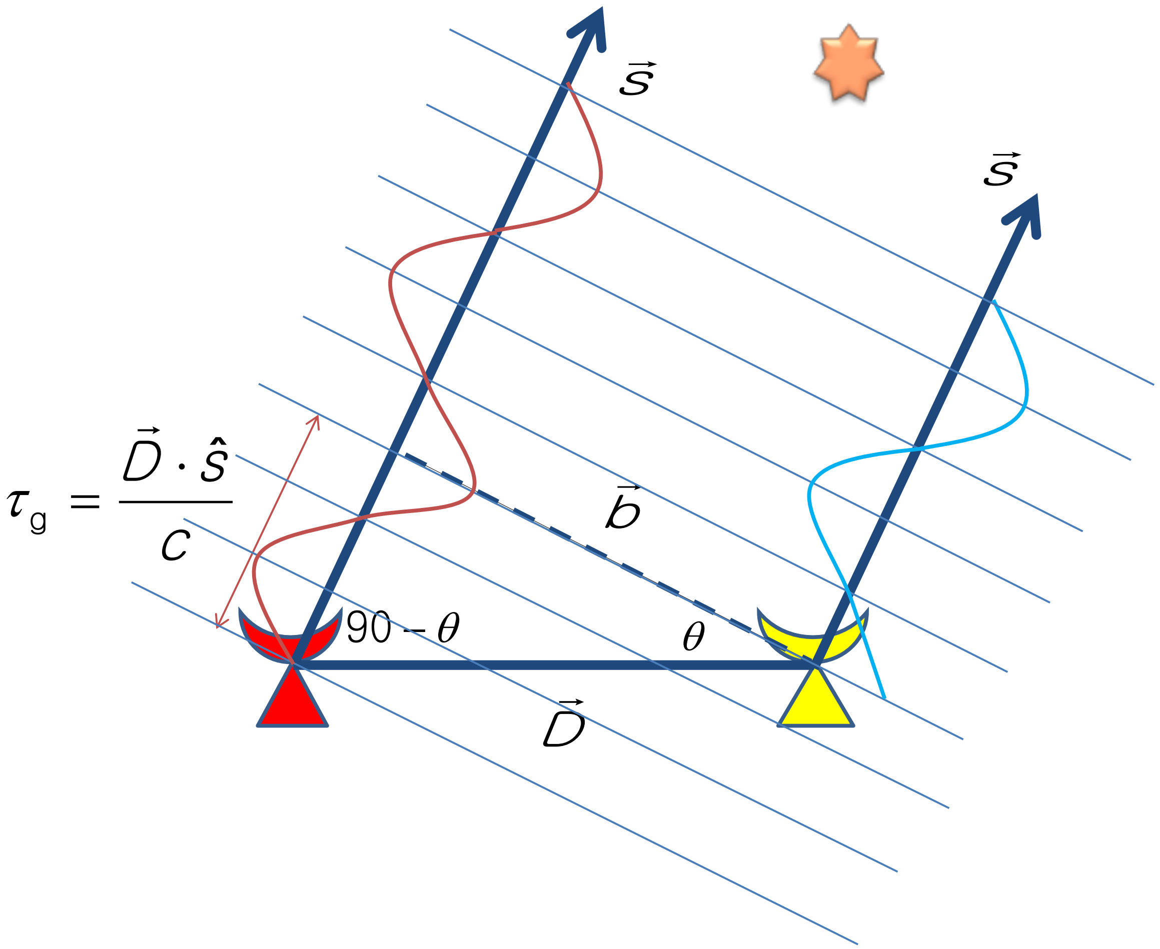


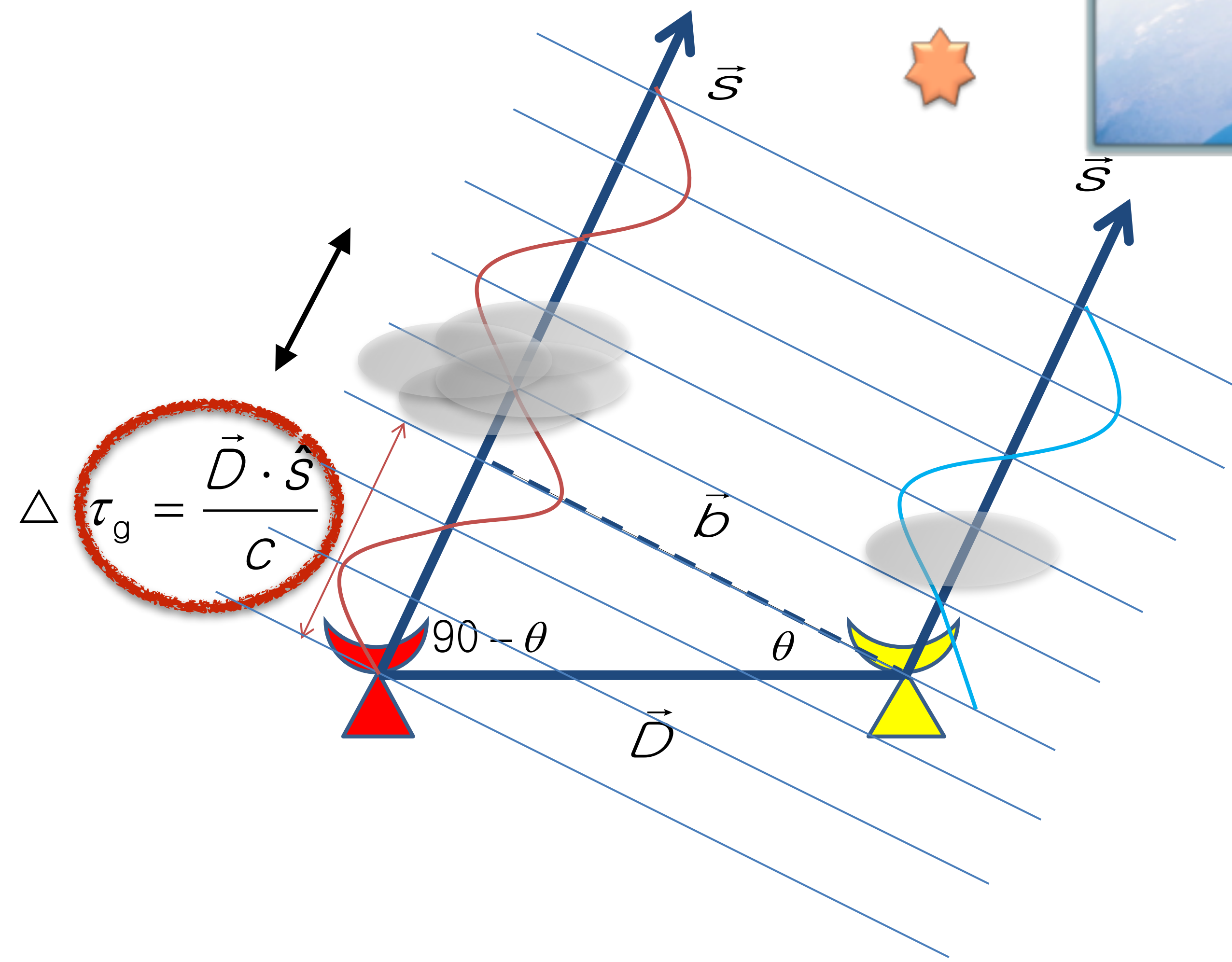
The dependence of phase errors due to the ionosphere and troposphere as a function of frequency.

- In general, at higher frequency (>10GHz) phase errors are more sensitive to the atmosphere than ionosphere

- Even though the ionospheric variations are slowing varying term with a large screen on the sky, there are rapid variation due to the ionosphere before/after sun set & sun rise

Atmospheric Propagation Delays





Coherence time (phase change < 1 radian)

Frequency (GHz)	2	8	15	22	43	86	129
Coherence Time (sec)*	800	200	100	73	37	19	12

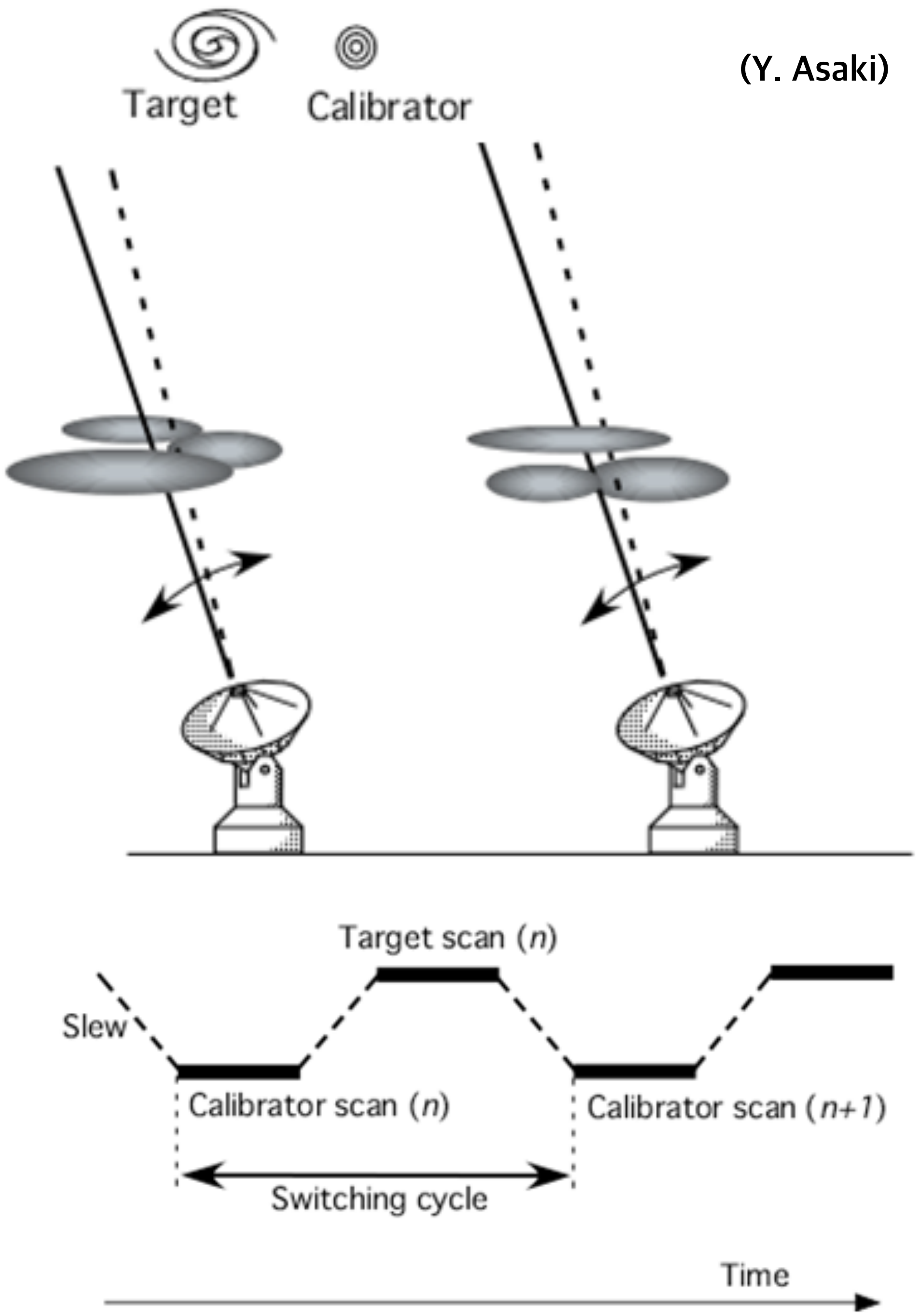
typical atmospheric stability $\sigma_y \sim 10^{-13}$

Baseline Sensitivity

$$\Delta S_{ij} = \frac{1}{\eta_s} \times \sqrt{\frac{SEFD_i \times SEFD_j}{2 \times \Delta\nu \times \tau_{acc}}}$$

VLBI Phase Referencing

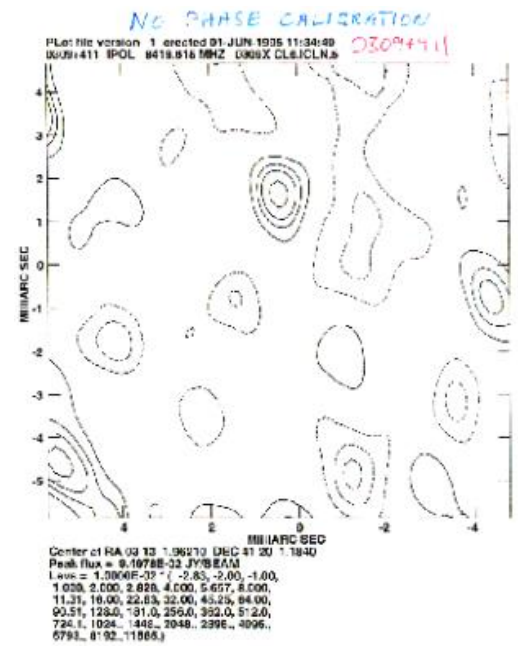
(Y. Asaki)



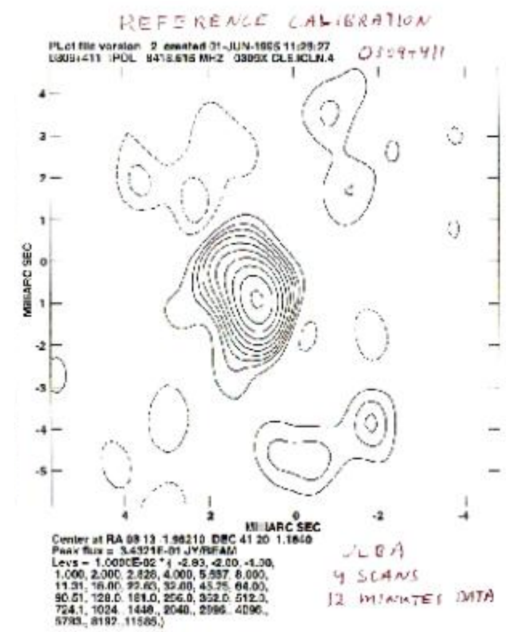
Antenna Nodding (Switching)

1. Increase coherence time

Without Phase Referencing

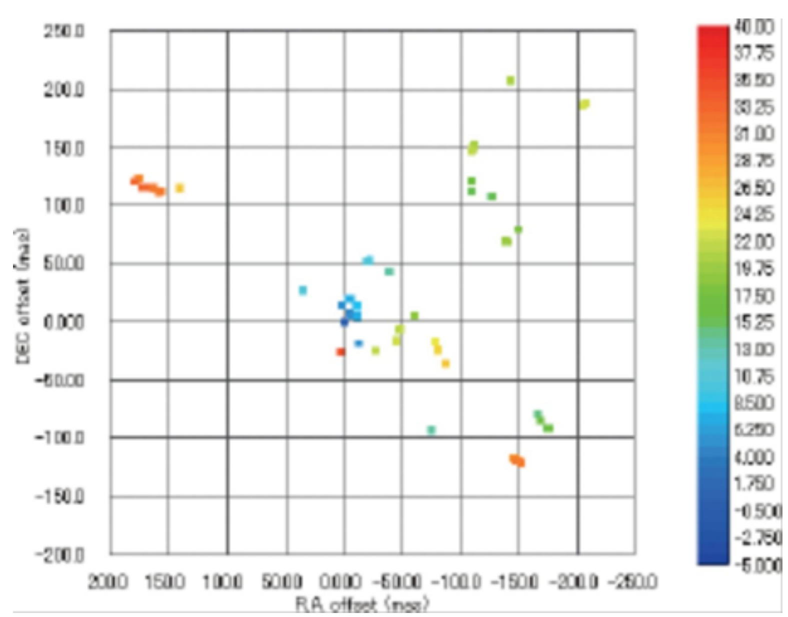


With Phase Referencing

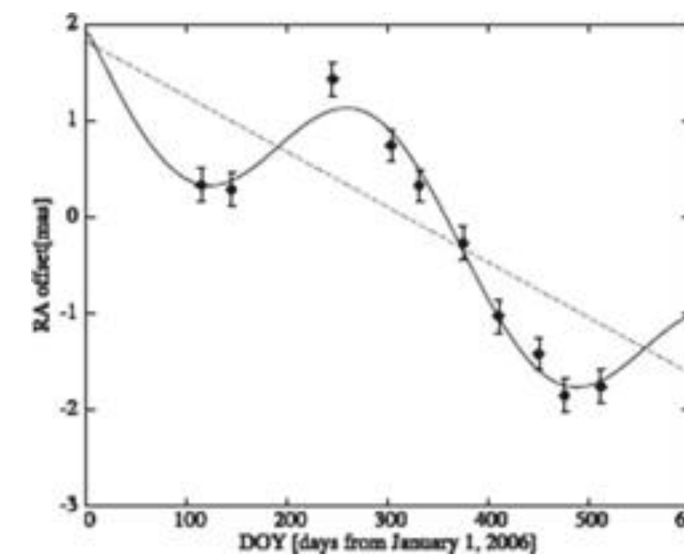


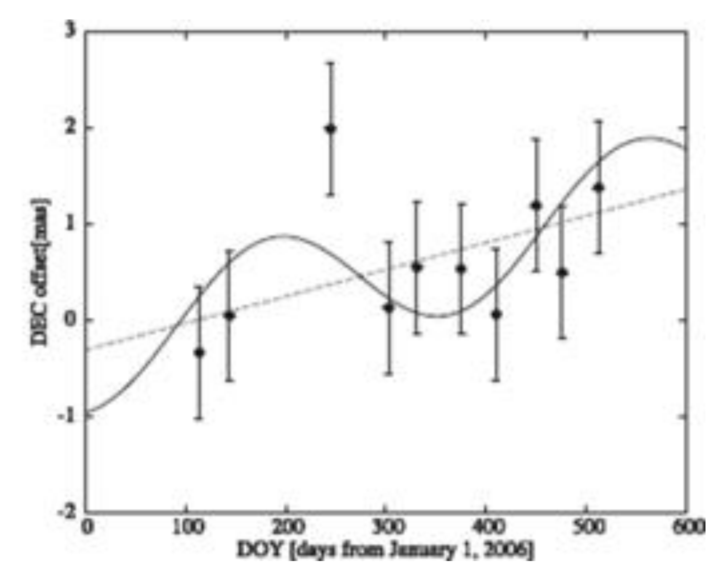
Weak source detection

2. Astrometry

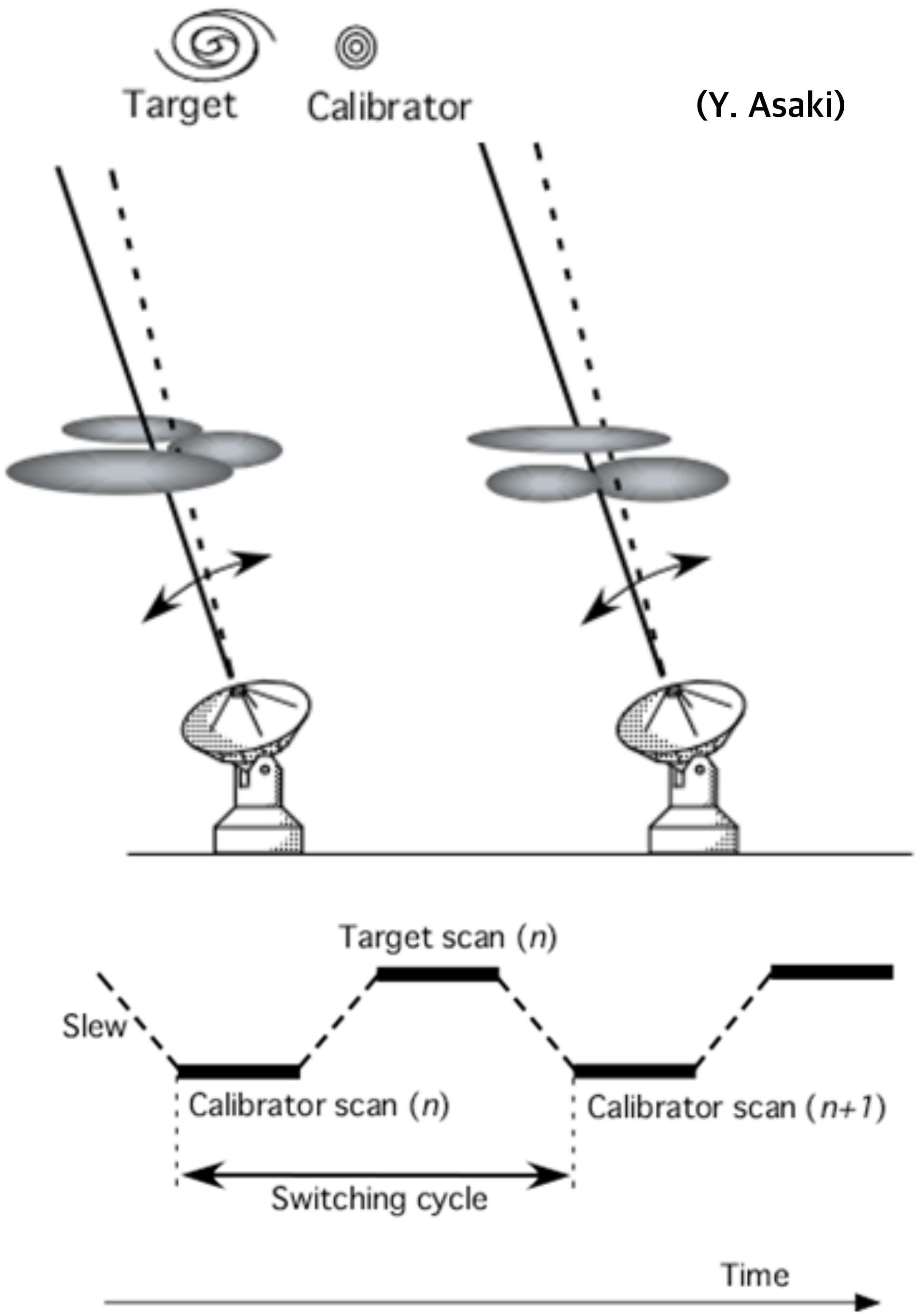


Distribution of the H2O masers and the measured position of H2O masers in VY CMa (Choi et al. 2008)



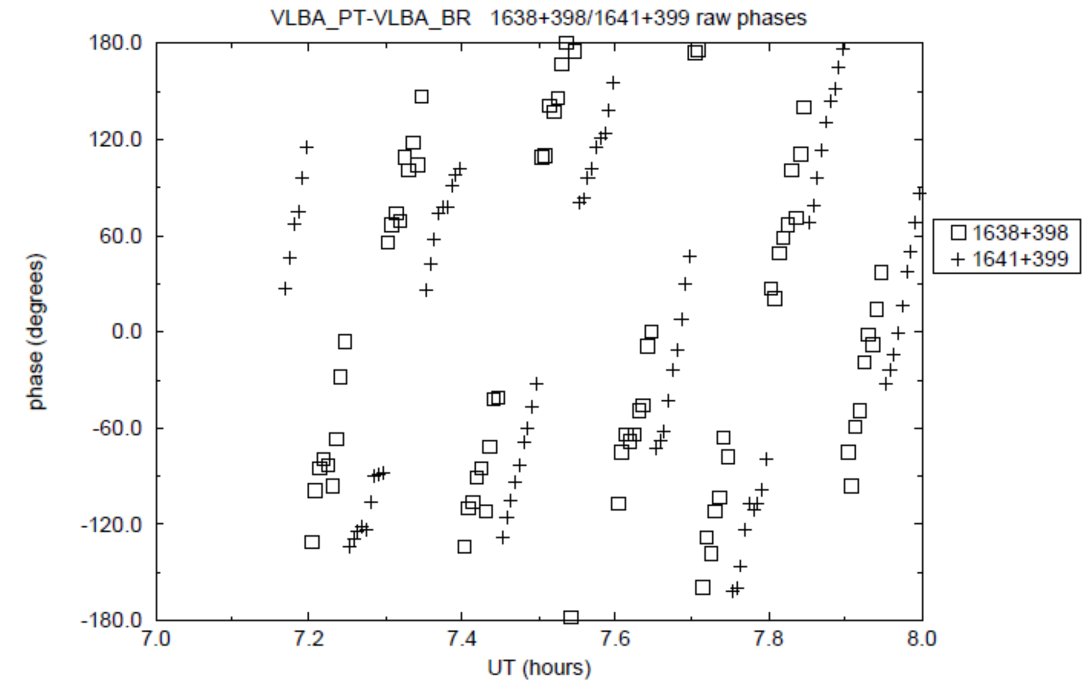


VLBI Phase Referencing

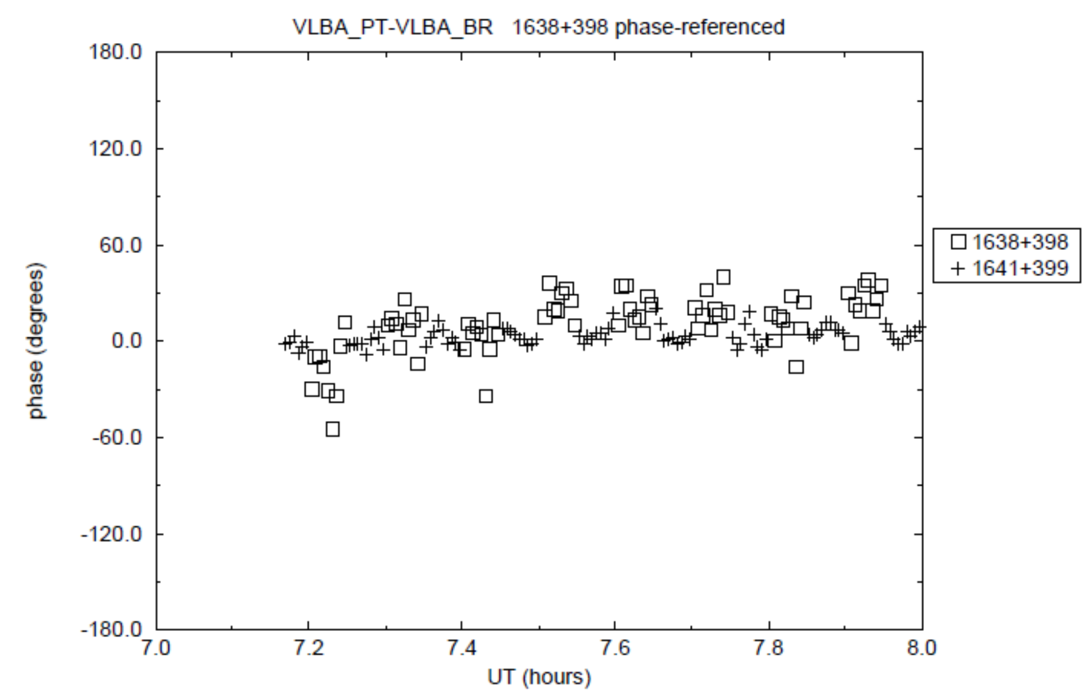


Antenna Nodding (Switching)

Raw visibility phases

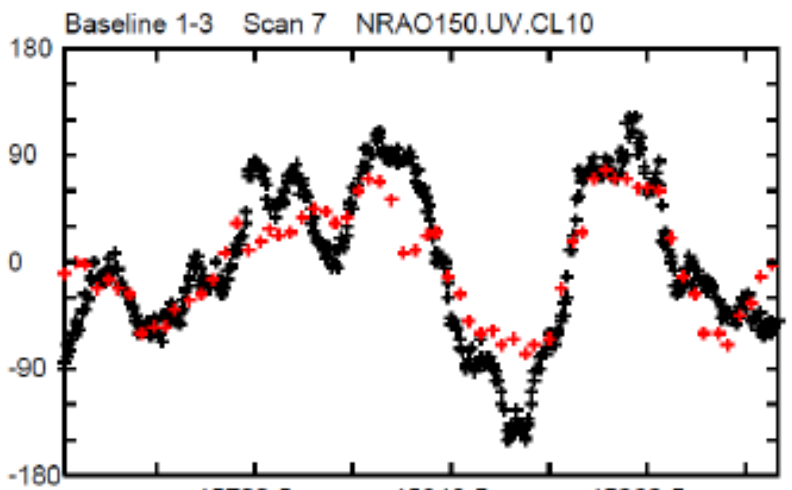


Calibrated phases after fringe fitting

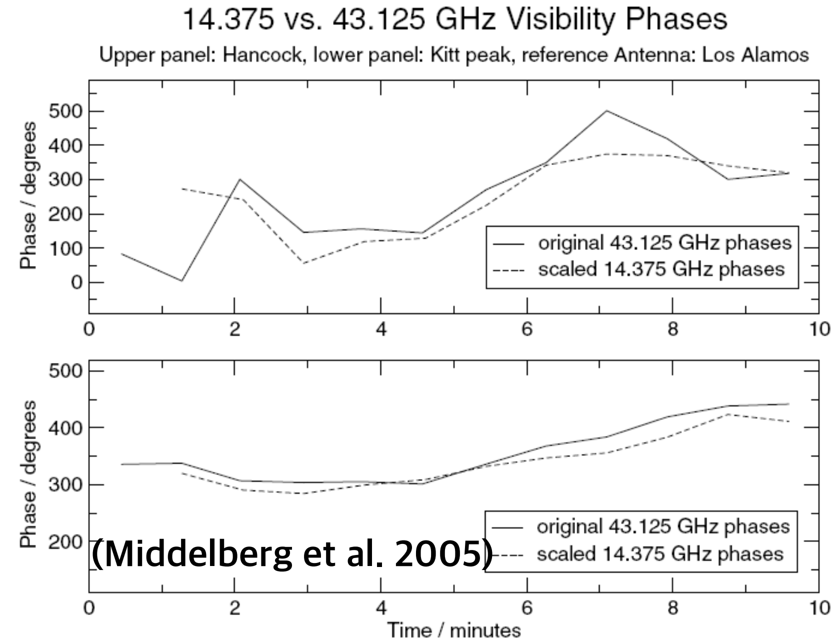


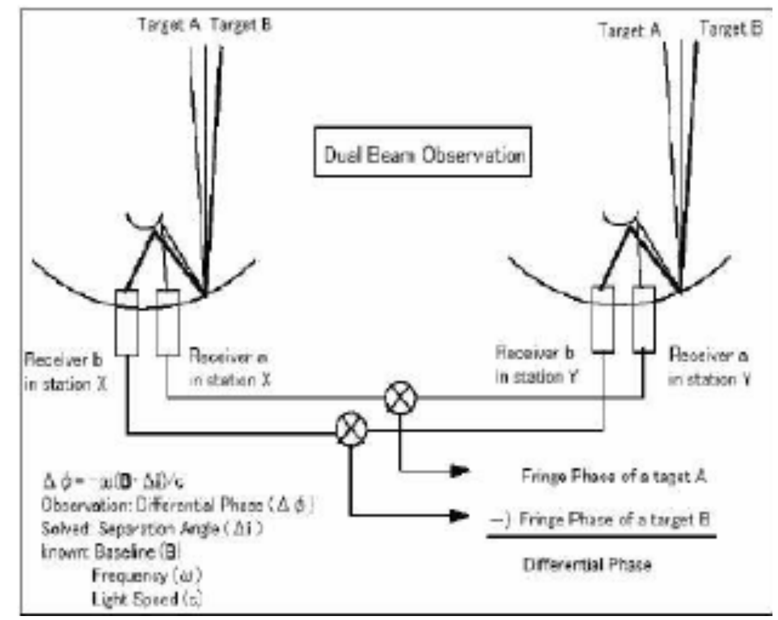
(Beasely et al. 1995)

VLBI Phase Referencing Techniques



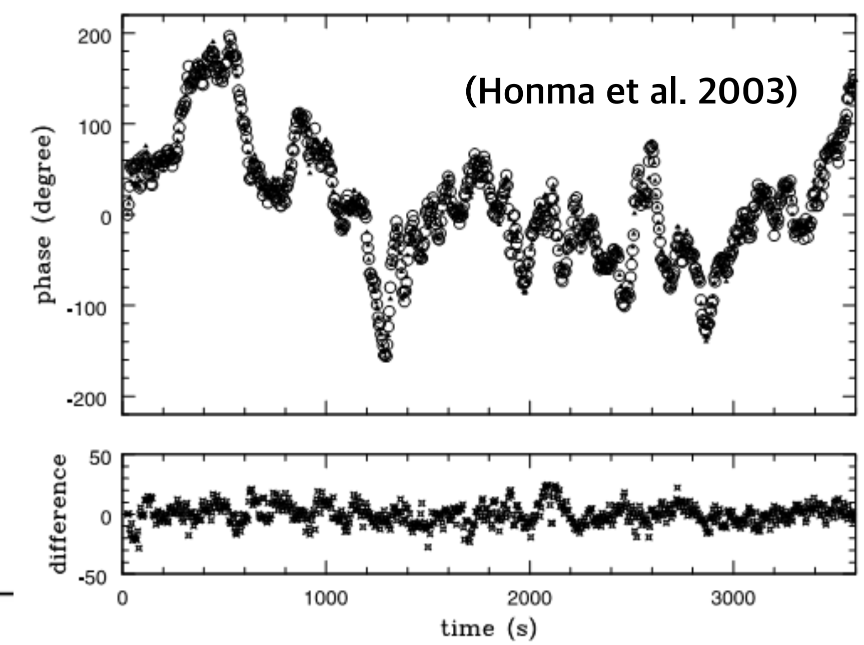
VLBI phase time series (black) and WVR-derived phase correction (red) (Roy et al. 2006)



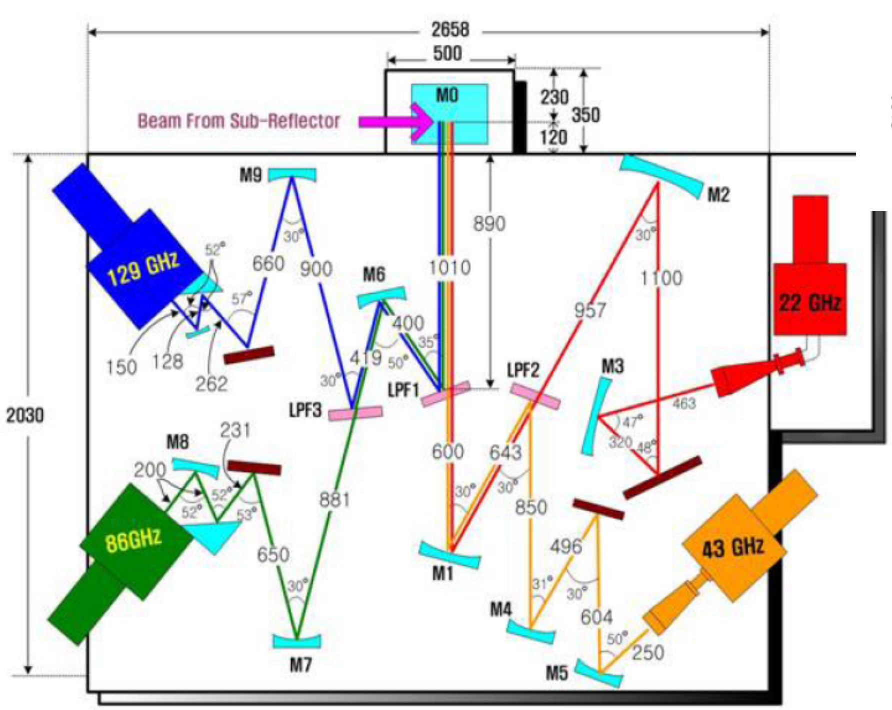


Water Vapor Radiometer

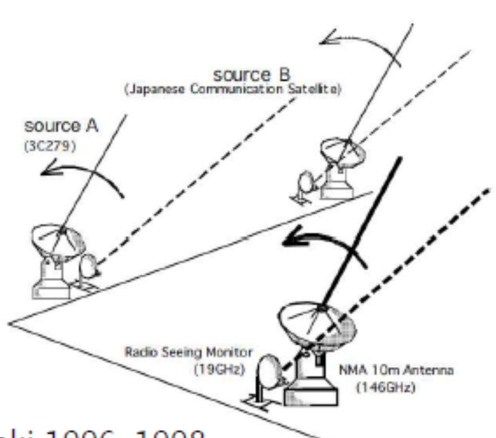
Fast Frequency Switching



Dual-Beam System



Multi-frequency System

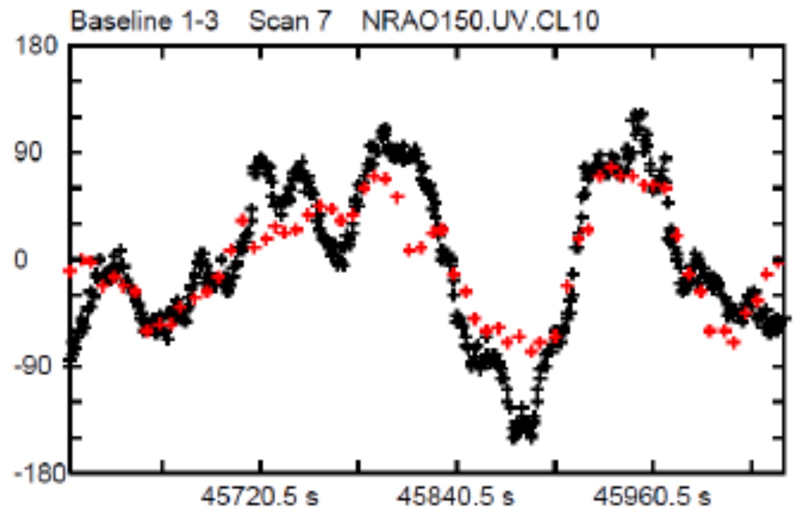


Asaki 1996, 1998

Paired Antenna

VLBI Phase Referencing Techniques

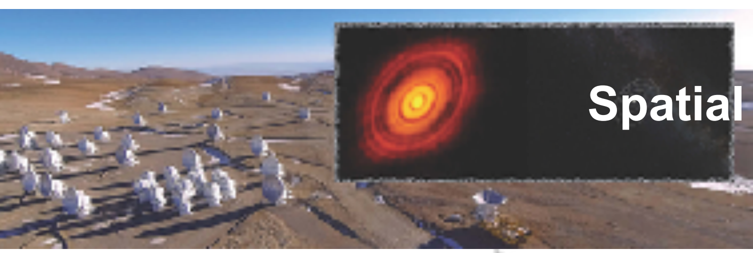
Water Vapor Radiometer

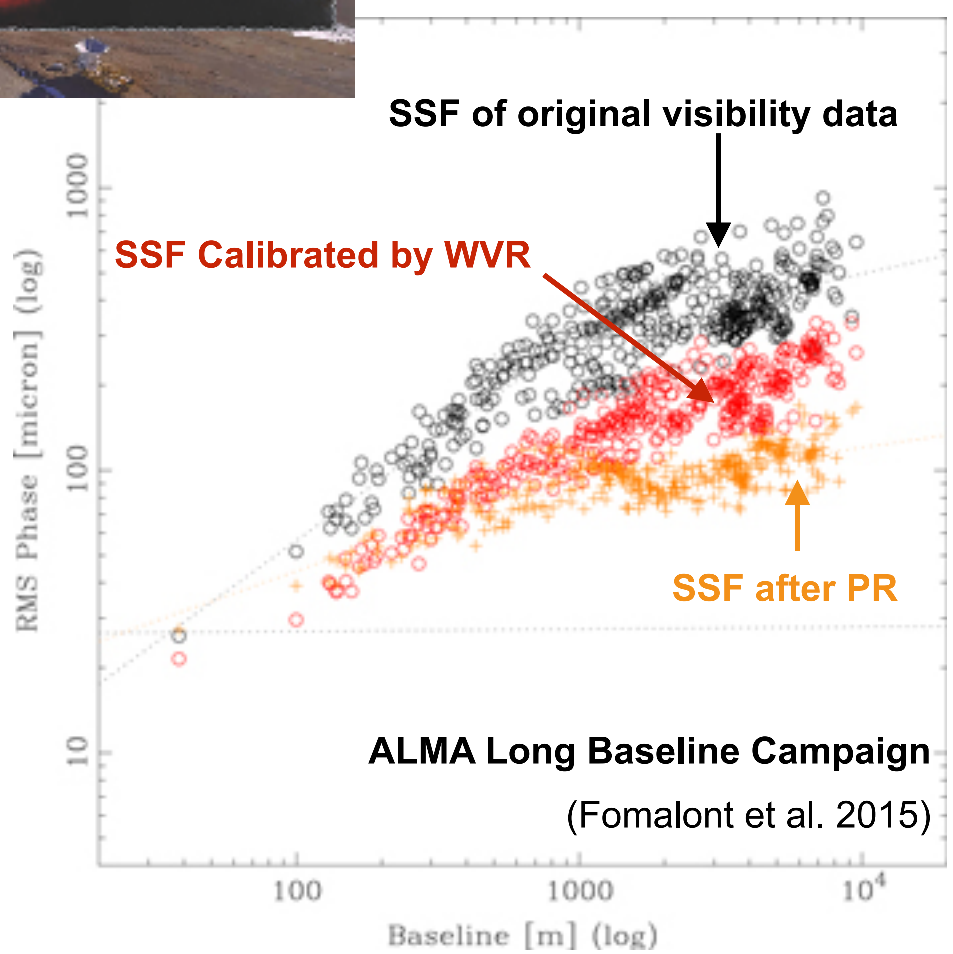


VLBI phase time series (black) and WVR-derived phase correction (red) (Roy et al. 2006)

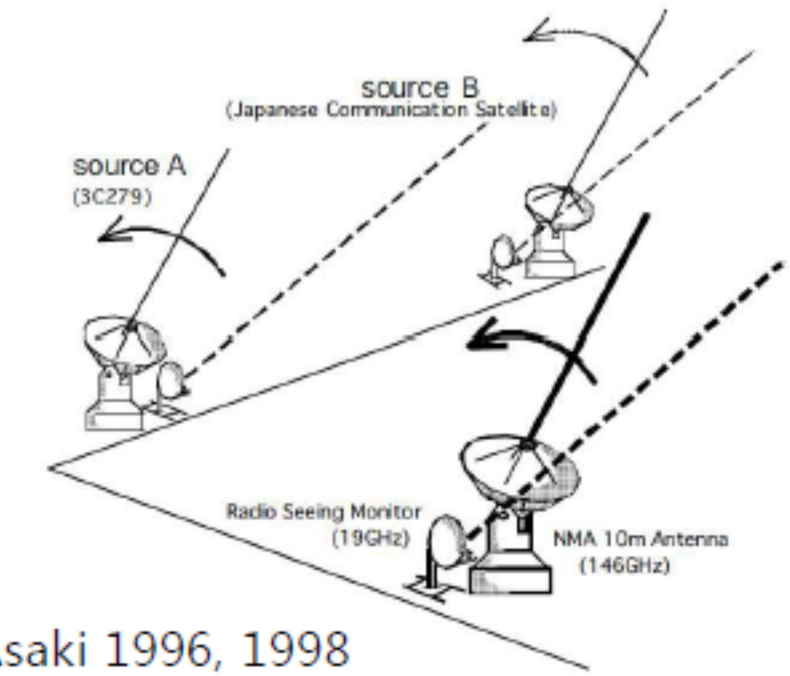
- No loss of observing time
- No need to find calibrators
- Relatively lower cost
- Different Field of view / sky condition
- Systematic errors and water drop

Spatial Structure Function (SSF)





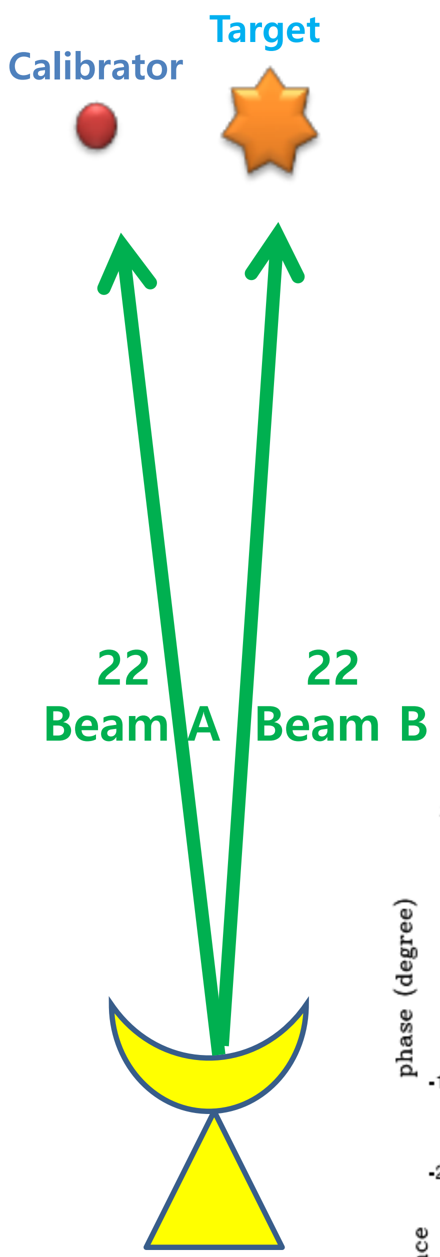
Paired/Clustered Antenna



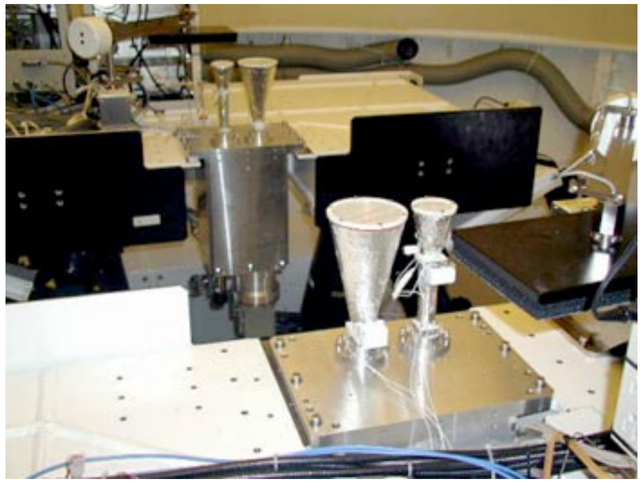
Asaki 1996, 1998

- No loss of observing time
- Calibrator
- Separation angle
- Different Field of view / sky condition
- Expensive

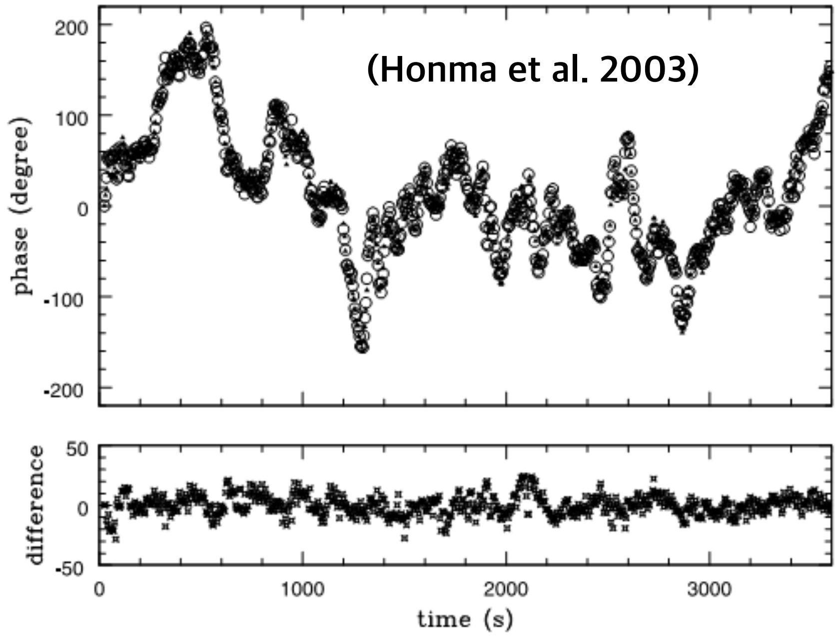
VLBI Phase Referencing Techniques



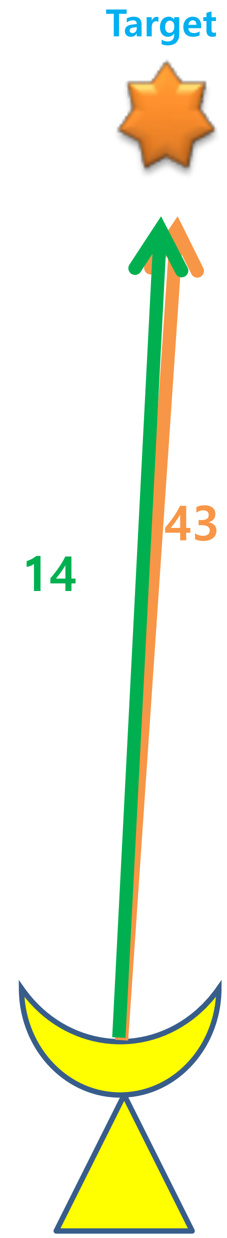
Dual-Beam



VERA Dual-Beam System

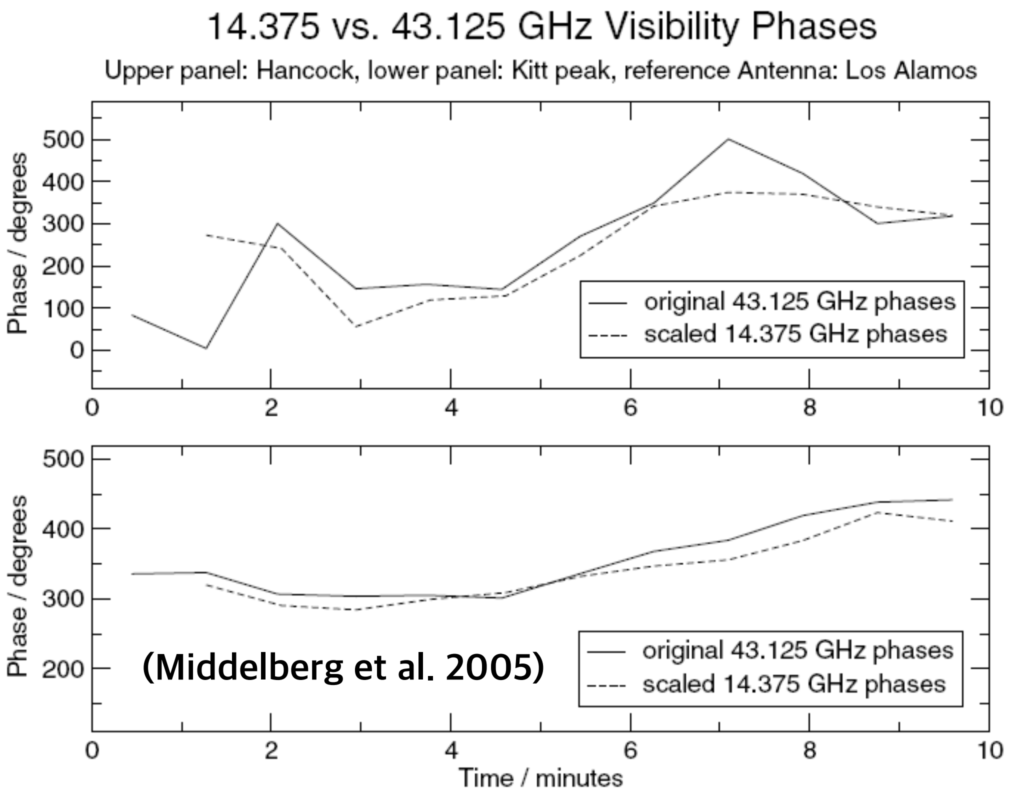


- No loss of observing time
- Calibrator (within 2.2deg)
- Coherence loss



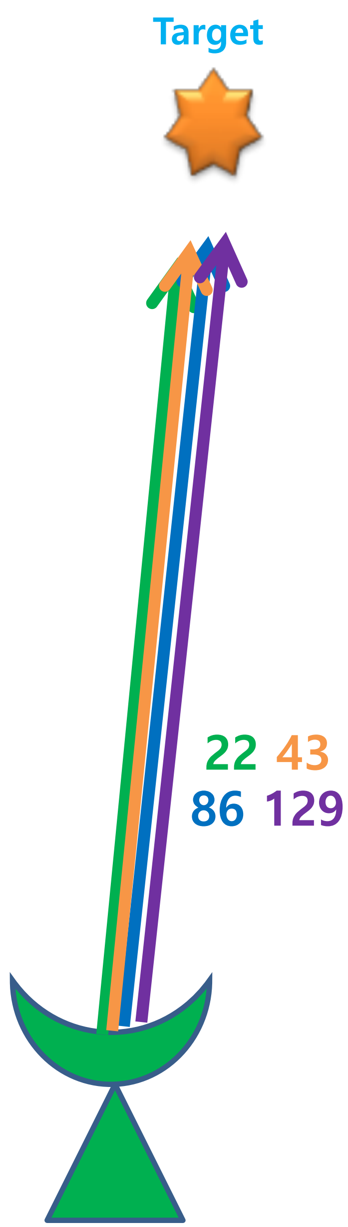
Fast Frequency Switching

VLBA

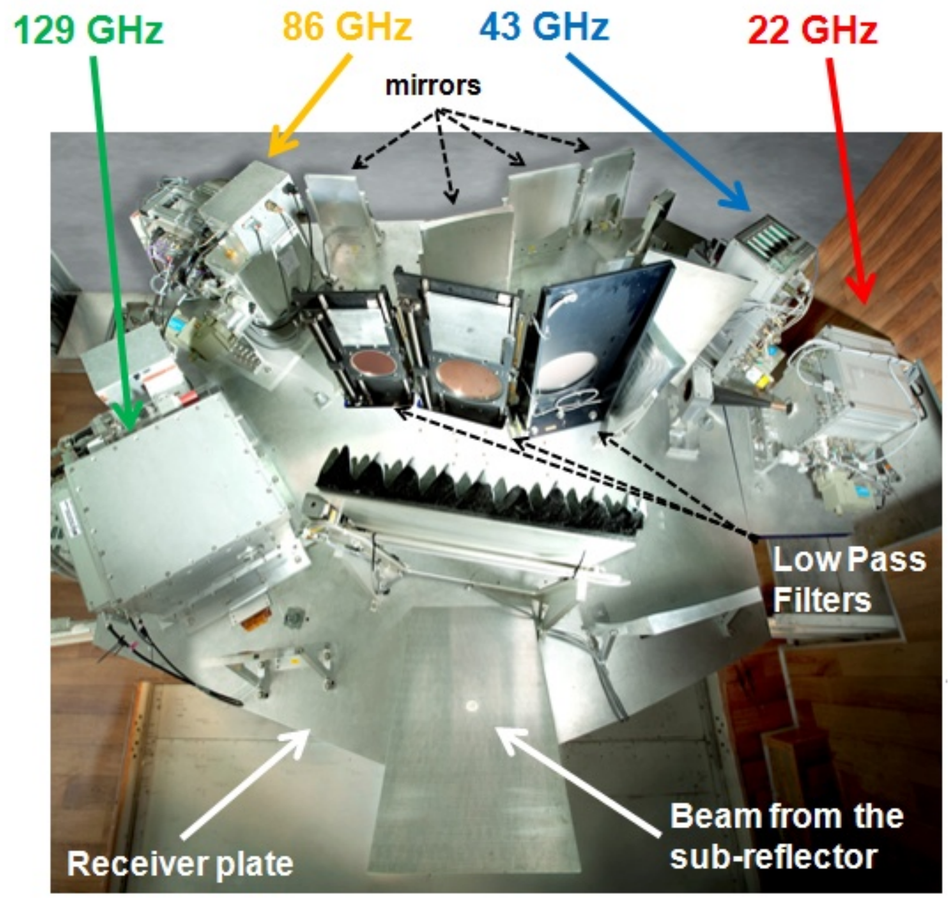


- Lost of observing time
- No Calibrator (target = calibrator)
- No coherence loss
- Not suitable for astrometry

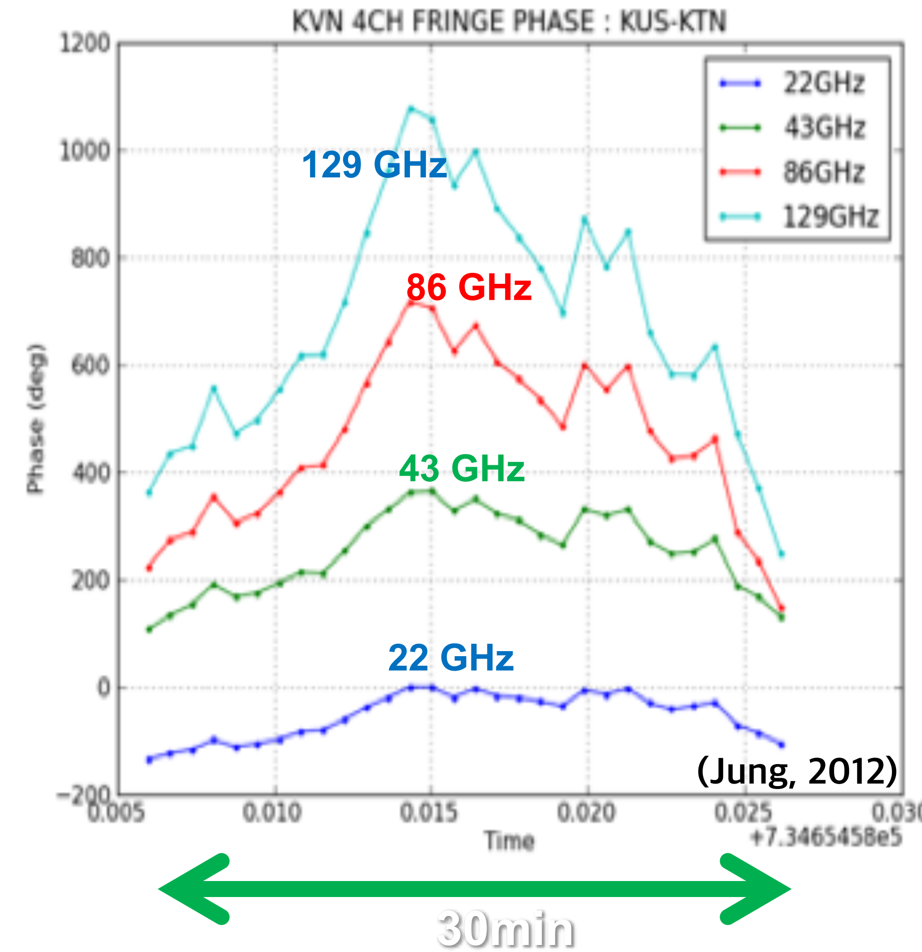
VLBI Phase Referencing Techniques

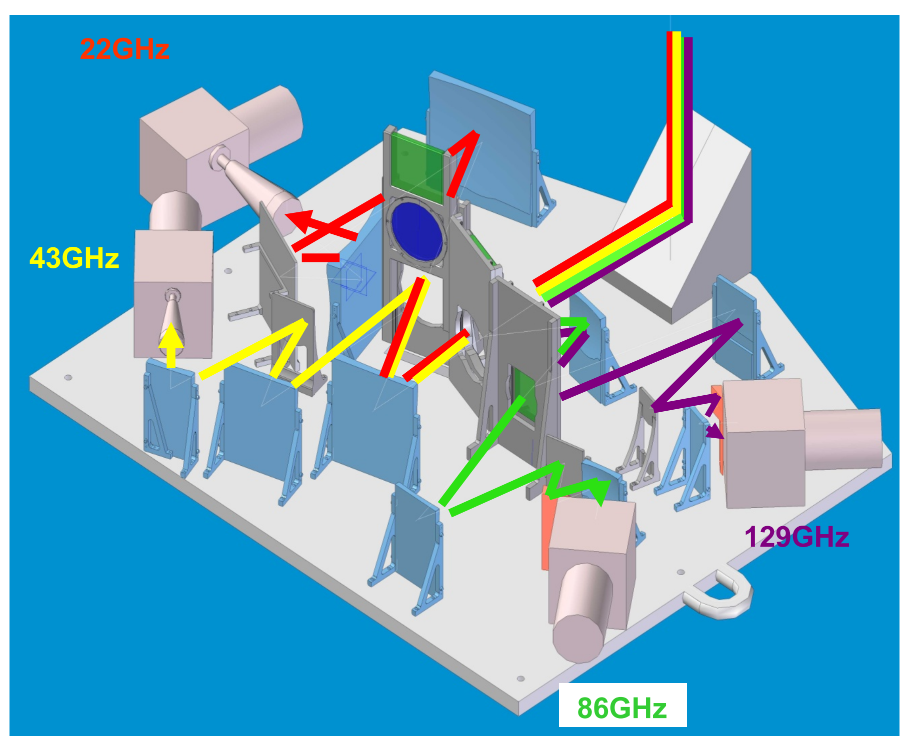


Multi-Frequency System



KVN Multi-Frequency System (Han et al. 2008)



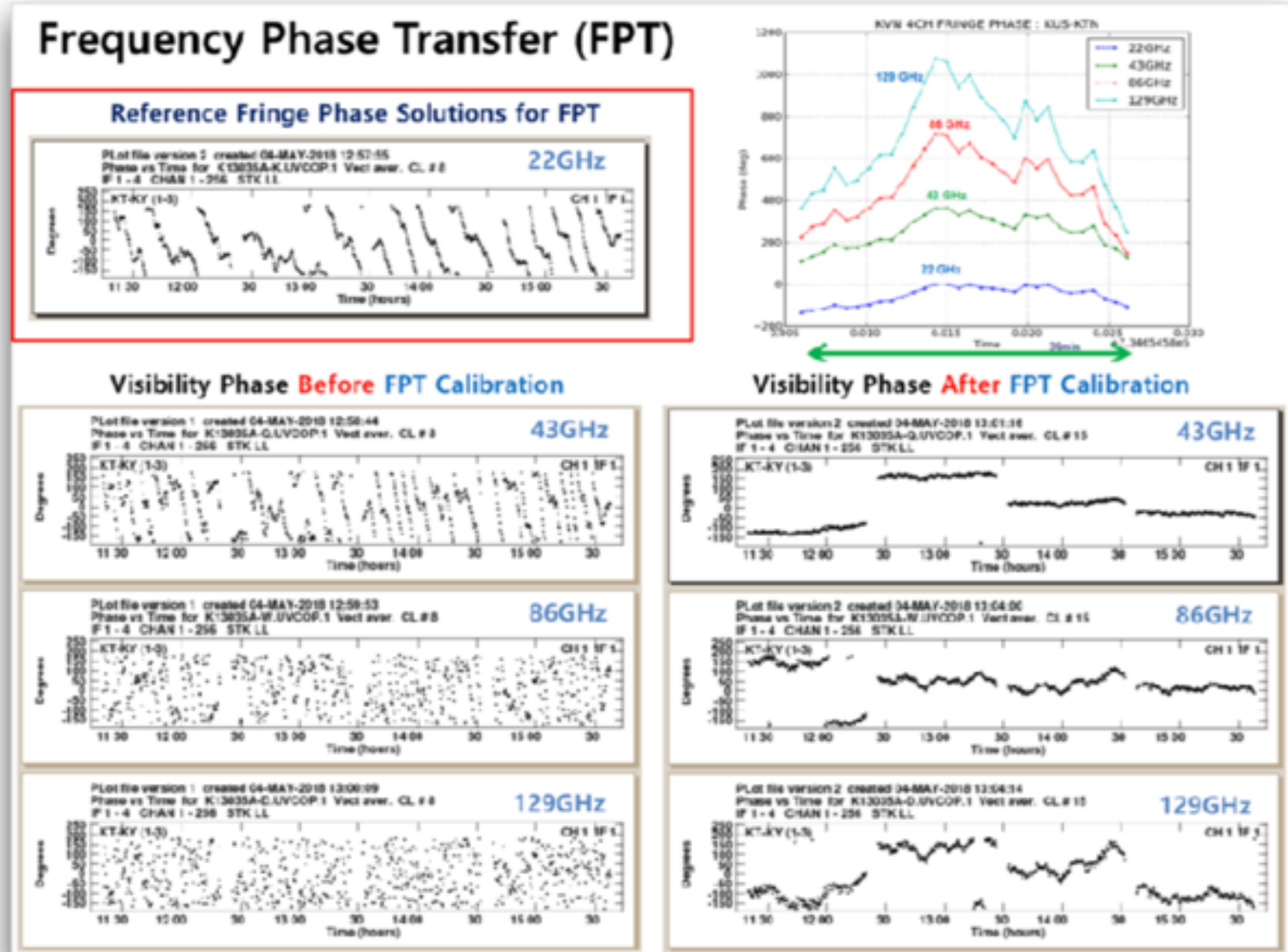


$$\frac{\partial \phi_{high}}{\partial t} = \left(\frac{\nu_{high}}{\nu_{low}} \right) \times \frac{\partial \phi_{low}}{\partial t}$$

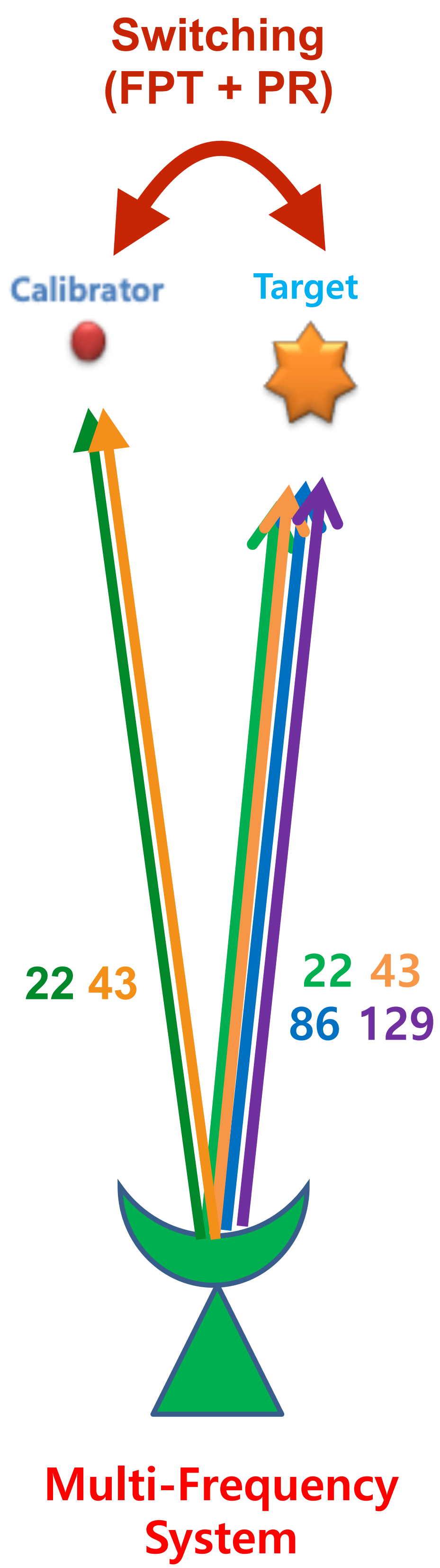
Non-dispersive nature of troposphere

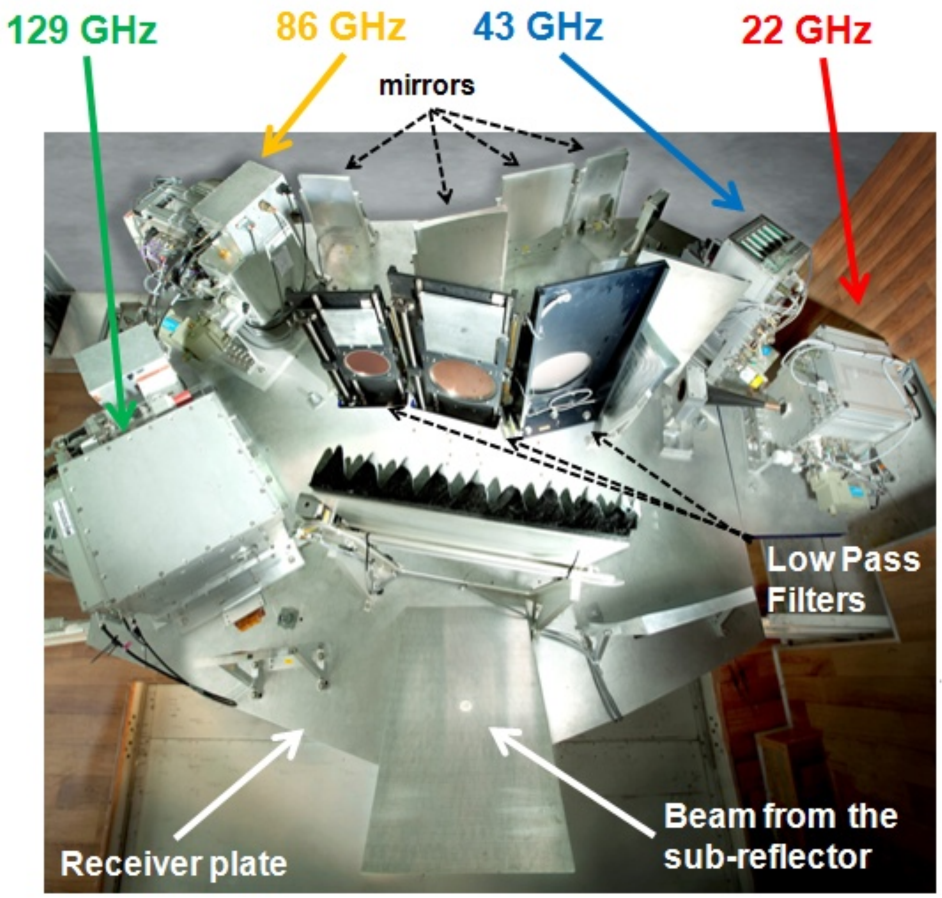
- No observing time loss
- No Calibrator (target = calibrator)
- No coherence loss
- Lower frequency detection needed

Simultaneous Multifrequency Receiving System

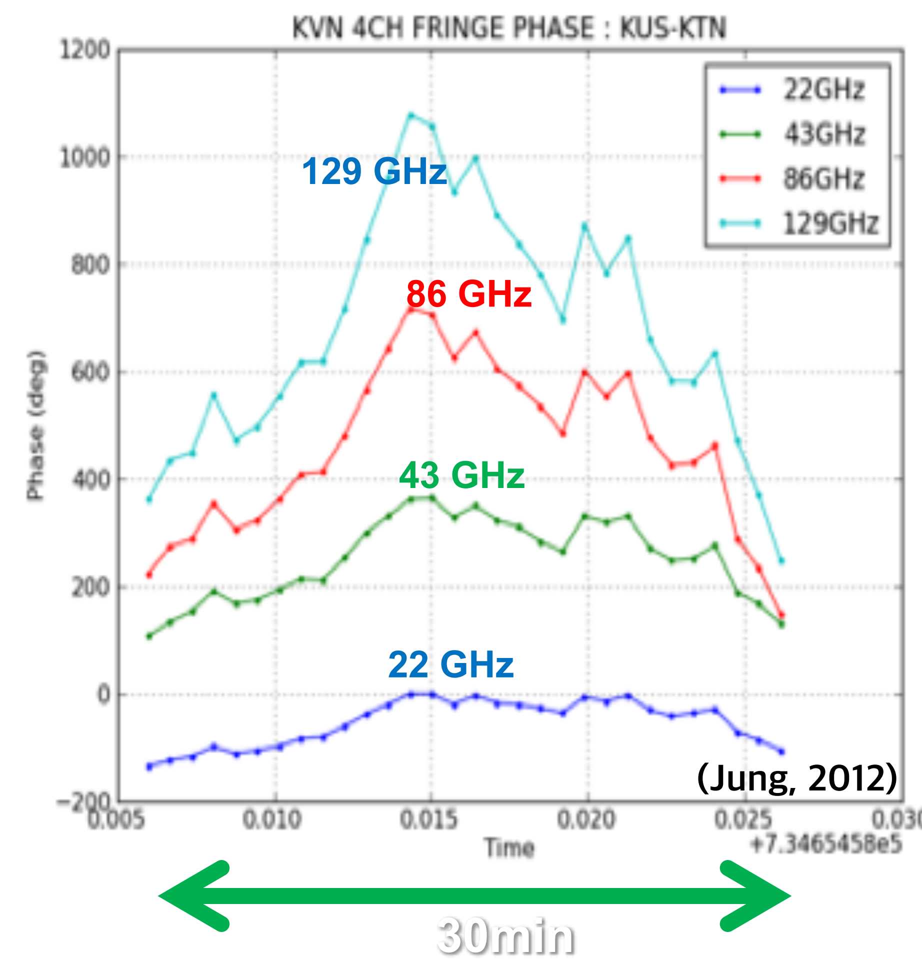


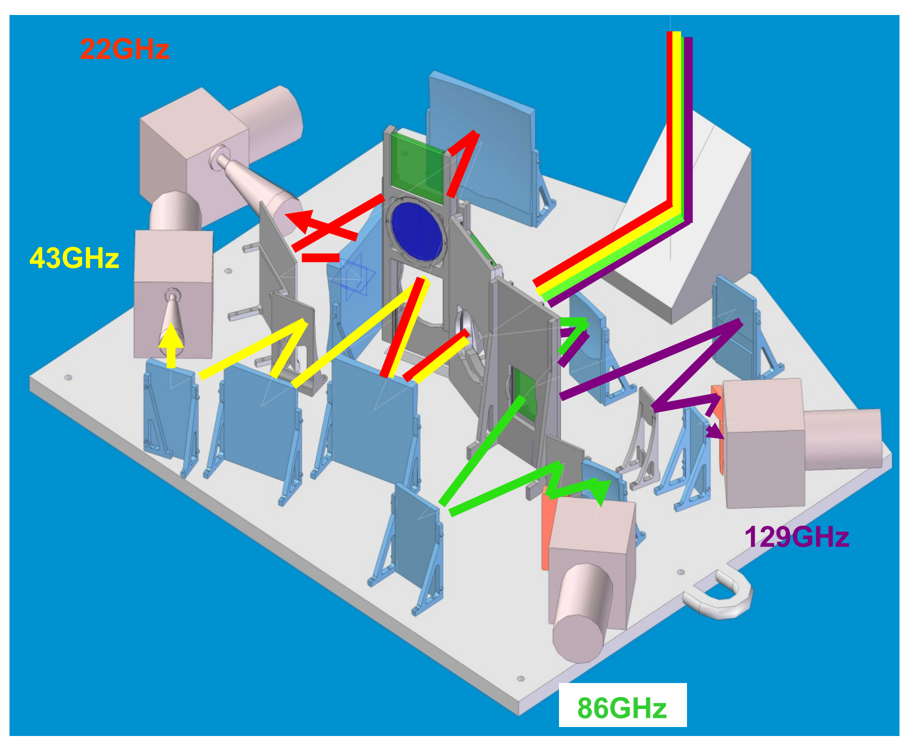
FPT & SFPR: Source Frequency Phase Referencing





KVN Multi-Frequency System (Han et al. 2008)





Rioja & Dodson: 2011, 2014, 2015 ⋯

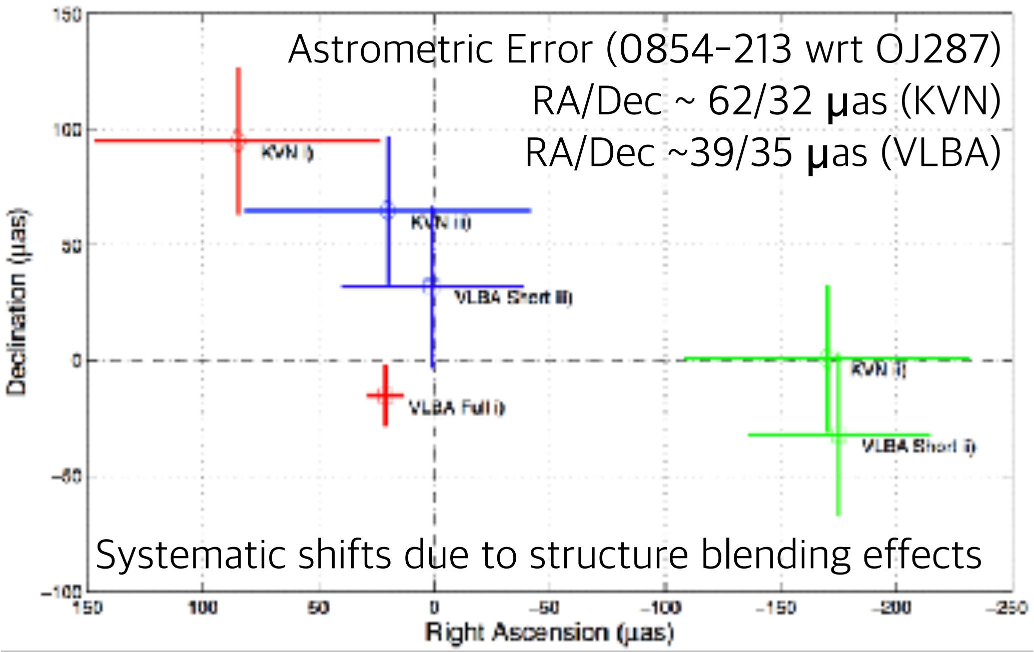
$$\frac{\partial \phi_{high}}{\partial t} = \left(\frac{\nu_{high}}{\nu_{low}}\right) \times \frac{\partial \phi_{low}}{\partial t}$$

Non-dispersive nature of troposphere

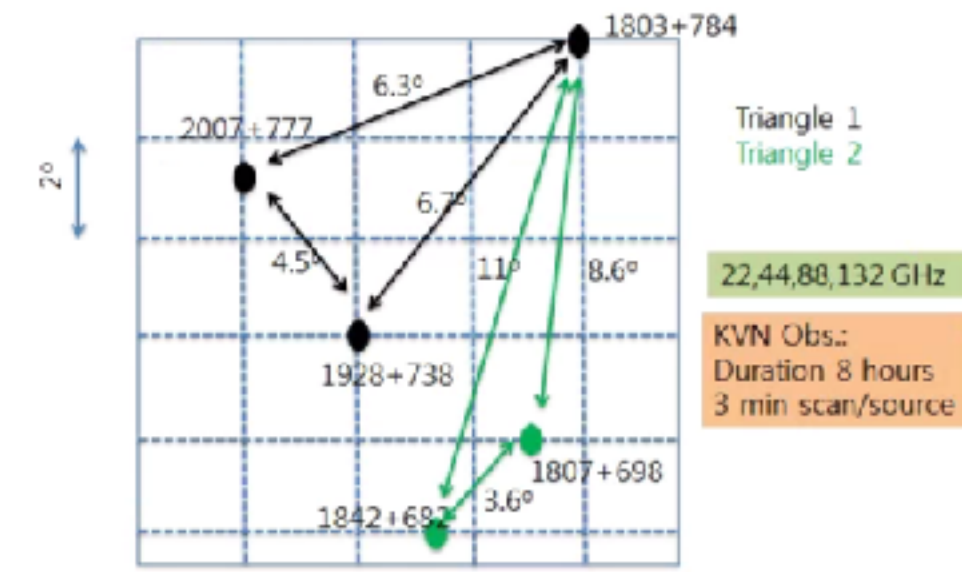
- No observing time loss
- No Calibrator (target = calibrator)
- No coherence loss
- Astrometry

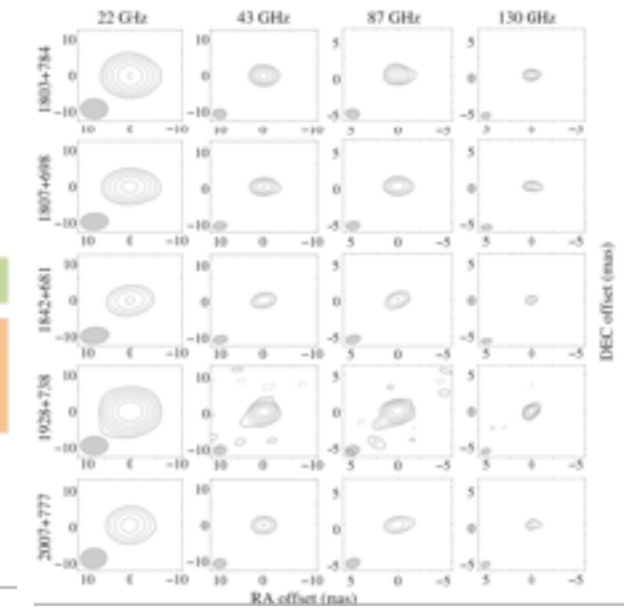
SFPR and Astrometry with KVN

Verification of Astrometric Performance of KVN with VLBA at 14/7 mm (Rioja+ 2014)

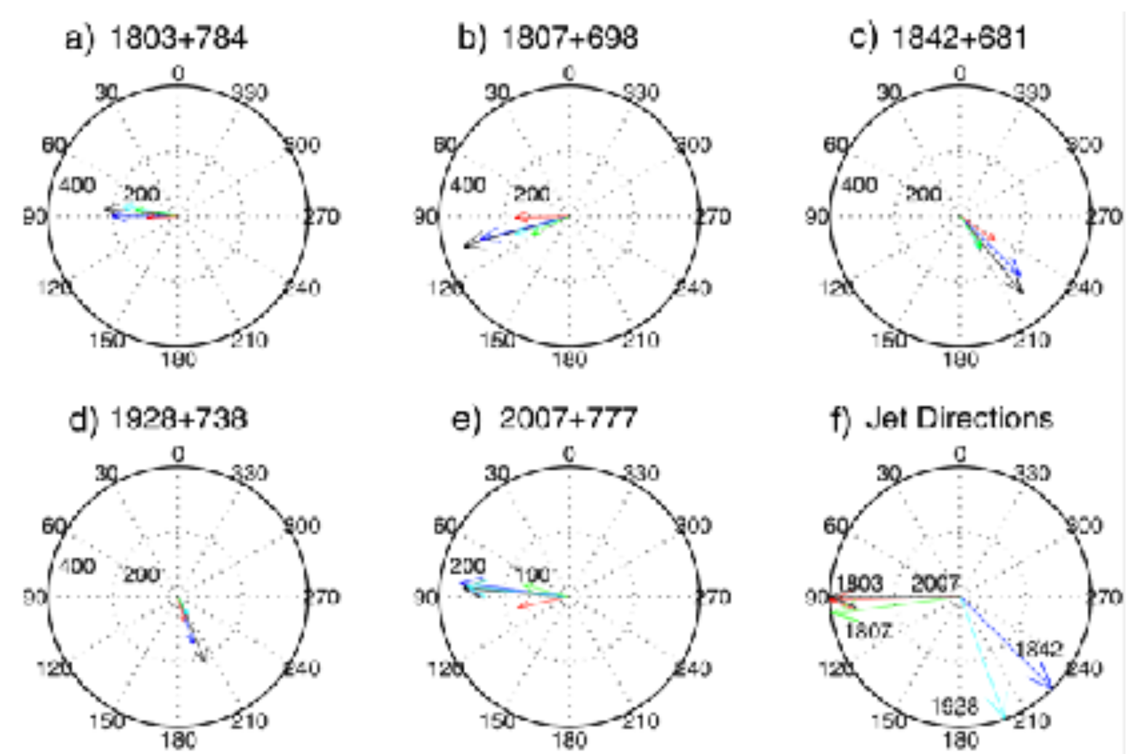


KVN SFPR demonstration using Polar Cap samples (Rioja+ 2015)

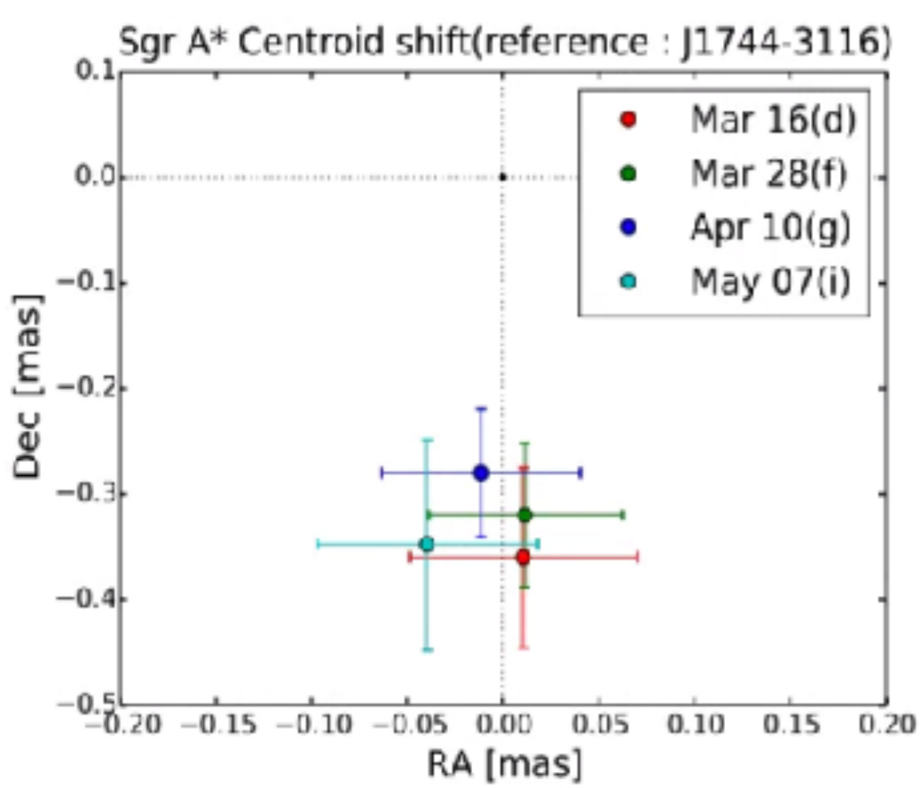




- Demonstration of high-precision astrometry up to 130GHz

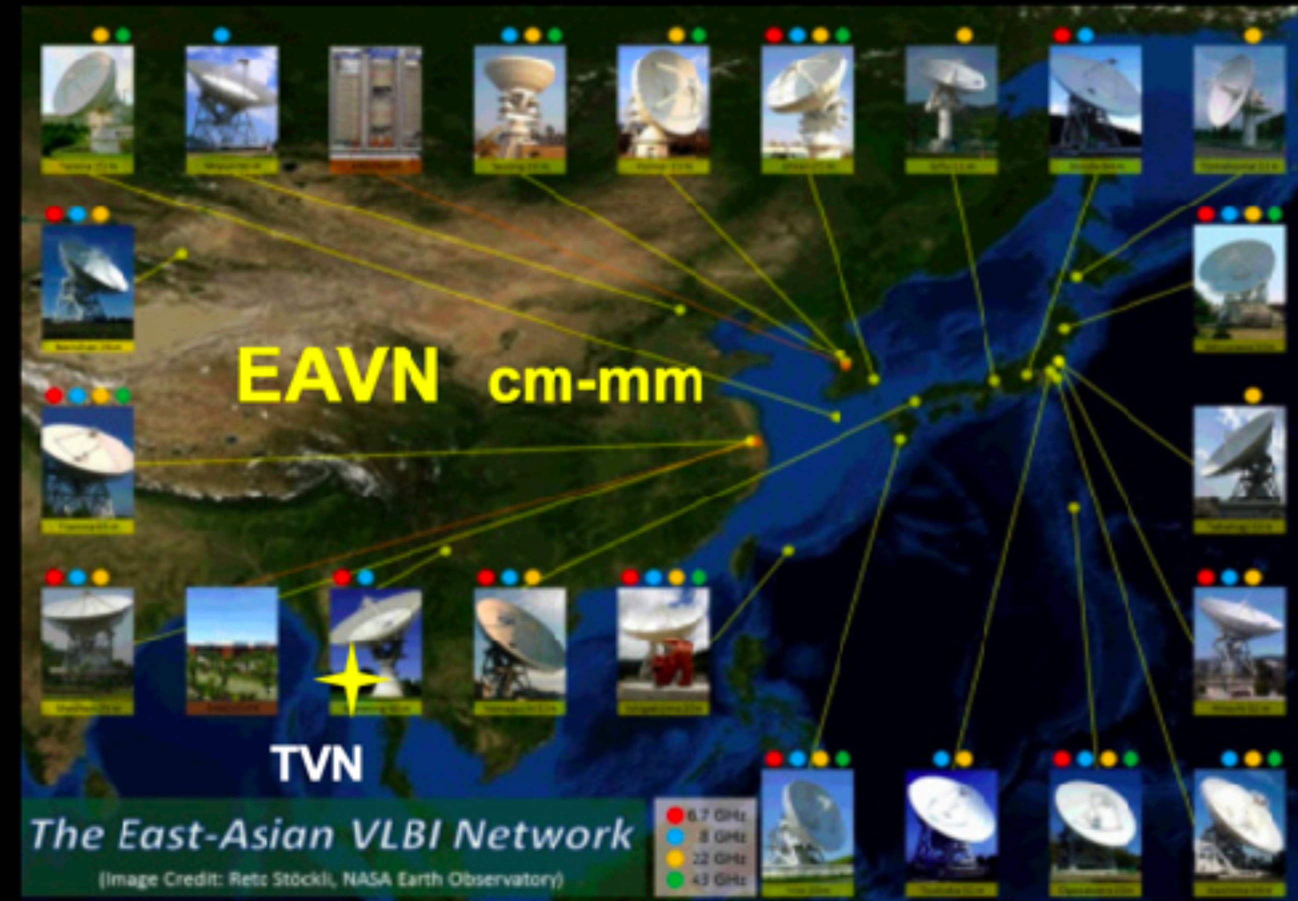


Coreshift measurement of SgrA* (I-J Cho)

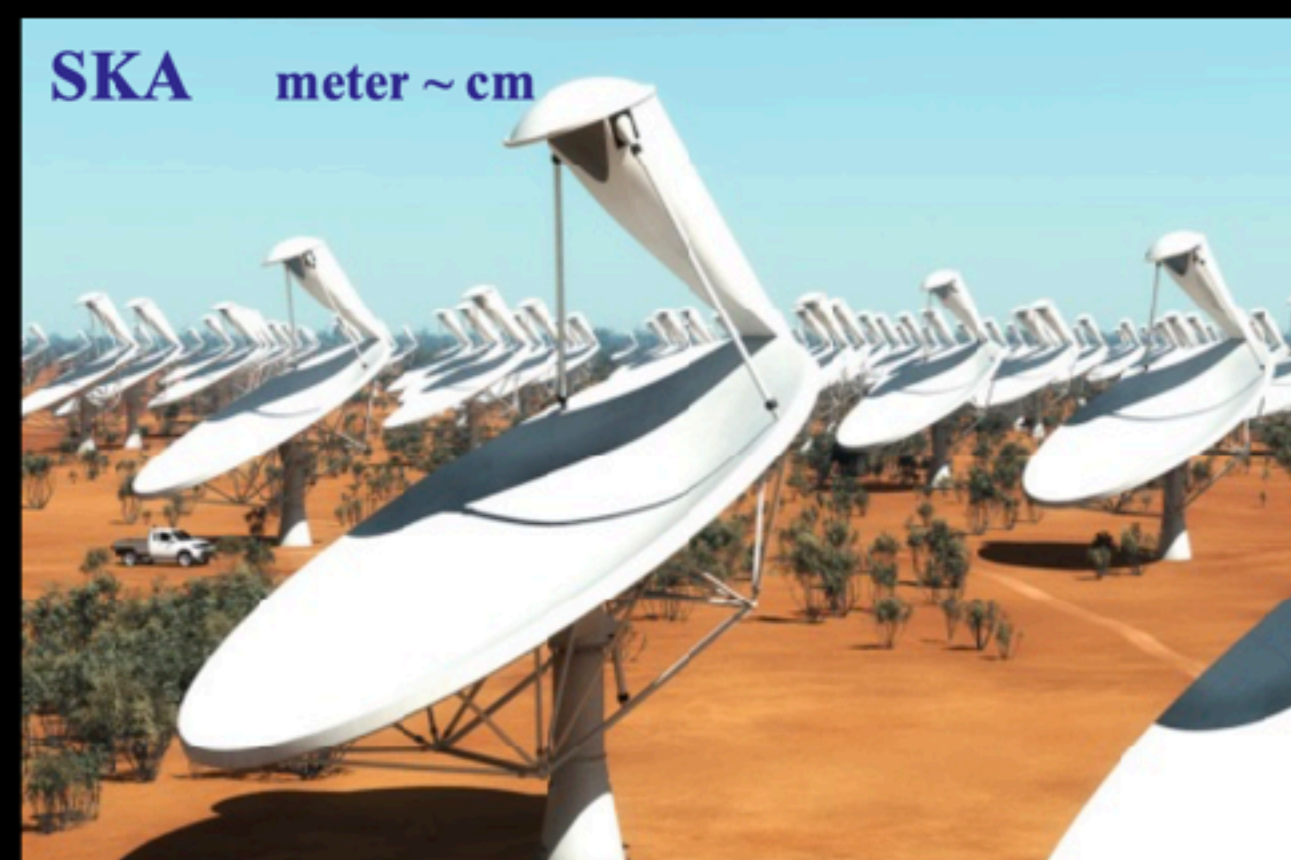


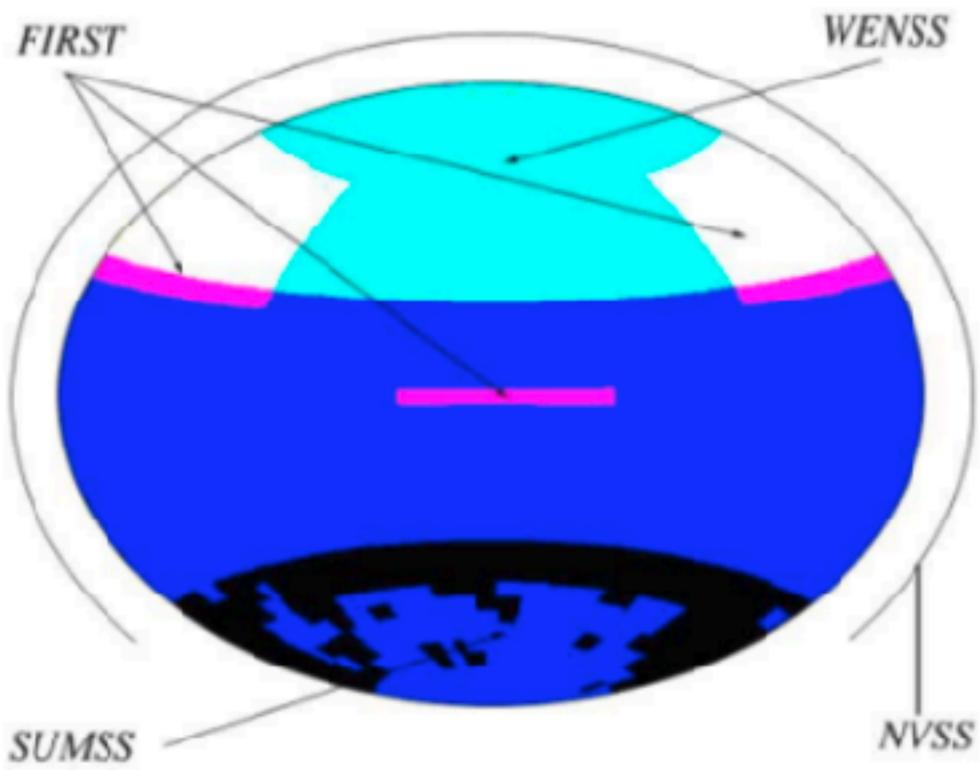
cm VLBI vs mm-VLBI

	cm-VLBI	mm-VLBI
Instrument & Technology	Good performance	Relatively poor performance
Atmospheric condition	Relatively stable (longer coherence)	Rapid change (short coherence)
Sensitivity	~ micro Jy (e.g. Garret 2005)	> 100 mJy
# of Sources	>10,000 (e.g. Petrov, RFC)	~ 160 @ 3mm (86GHz)
Phase Referencing	Well established (e.g. Beasely 1995)	Not very successful (mostly < 43GHz)
Astrometry	tens of micro arcsec (Reid & Honma 2014)	Limited success > 40 GHz



Big Radio Interferometers in Global

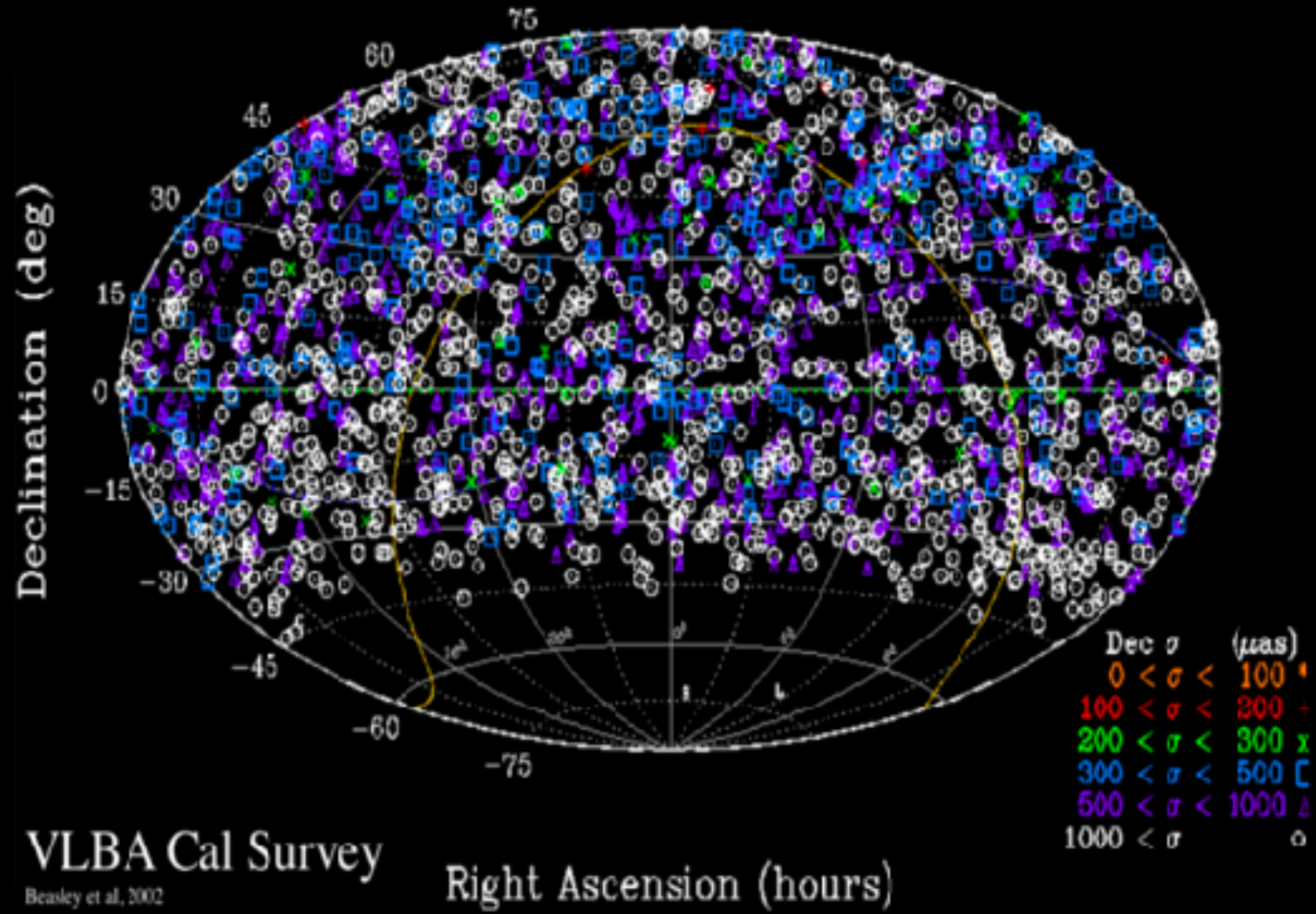




High Resolution Radio Survey Coverage

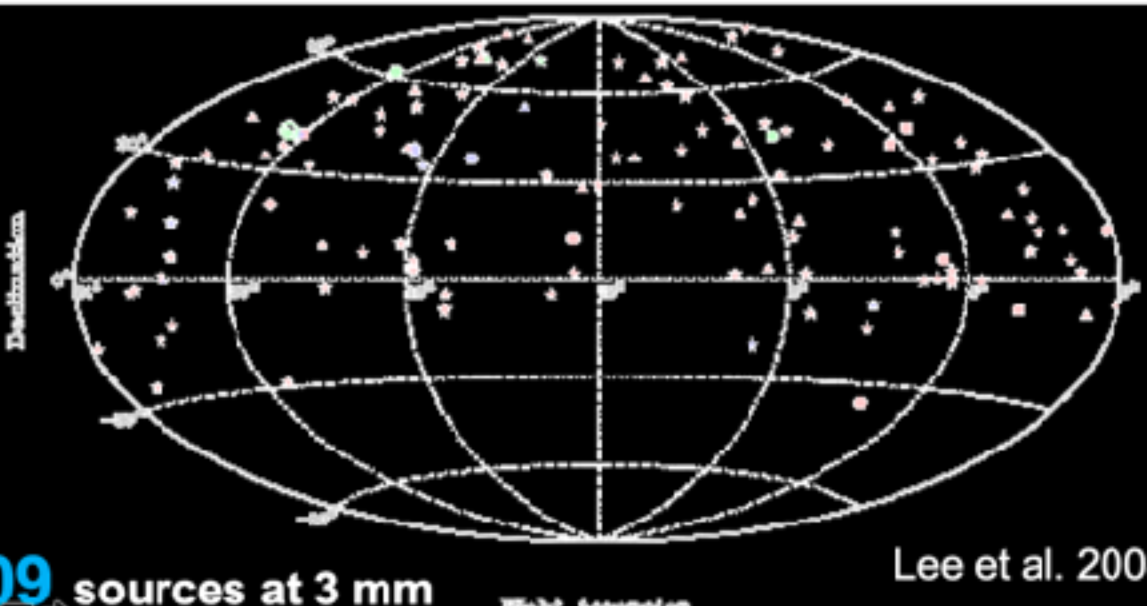
	FIRST	NVSS	SUMSS	WENSS
Frequency (MHz)	1400	1400	843	325
Area (deg^2)	10,000	33,700	8,000	10,100
Resolution	5″	45″	43″	54″
Detection limit	1 mJy	2.5 mJy	3.5 mJy	15 mJy
Coverage	$\delta > +22°$	$\delta > -40°$	$\delta < -30°$	$\delta > +30°$
Sources/deg^2	90	60	50	21
Reference	(a)	(b)	(c)	(d)

Table 1. Large-area mJy-level radio surveys currently in progress. References: (a) Becker et al. 1995; (b) Condon et al. 1998; (c) This paper, Bock et al. 1998; (d) Rengelink et al. 1997.



VLBA Cal Survey

Beasley et al, 2002



109 sources at 3 mm

Lee et al. 2008

Radio Fundamental Catalog of Compact Radio Sources (L. Petrov)

VLBI Surveys

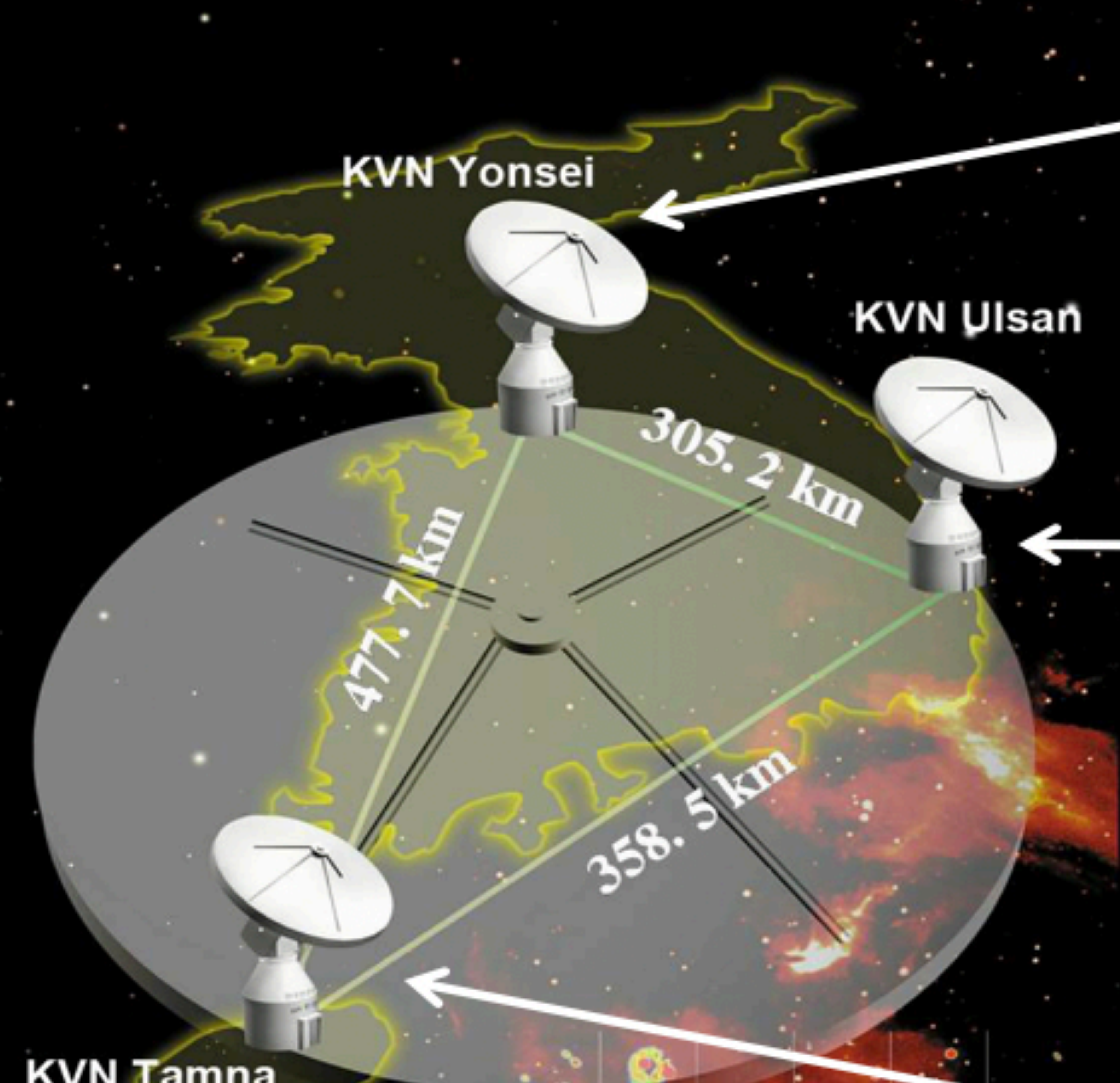
Summary of VLBI Surveys, their wavelengths and the number of sources catalogued. The difference in scale of the number of sources in the cm and mm surveys are clear.

Survey ID	Wavelength	No. Sources	Reference
CJF survey	6 cm	293	Taylor et al. (1996)
VSOP VLBApls	6 cm	374	Fomalont et al. (2000)
CJF Polarimetry survey	6 cm	177	Pollack et al. (2003)
ICRF	3.6 cm	~ 500	Ojha et al. (2004); 2005) and references therein
MOJAVE	2 cm	> 133	Lister and Homan (2005)
2 cm Survey	2 cm	250	Kovalev et al. (2005)
VLBA Calibrator survey	13 & 3.6 cm	> 3400	Kovalev et al. (2007)
VIPS	6 cm	1127	Helmboldt et al. (2007)
VERA FSS / GaPS	1.35 cm	500	Petrov et al. (2007)
VSOP Survey	6 cm	~ 300	Dodson et al. (2008)
TANAMI	3.5 & 1.3 cm	80	Ojha et al. (2010)
mJIVE-20	20 cm	> 4300	Deller and Middelberg (2014)
GMVA 3 mm	3 mm	123	Lee et al. (2008)
ICRF 22 & 43-GHz	13.7 & 7 mm	~ 100	Lanyi et al. (2010)
KVN Q-CAL survey	7 mm	638	Petrov et al. (2012)

(Dodson et al. 2018)

- ~ 4.3% of RFC is available at 7mm
- ~ 0.7% of RFC is available at 3mm (2017)

KVN 한국우주전파관측망 Korean VLBI Network

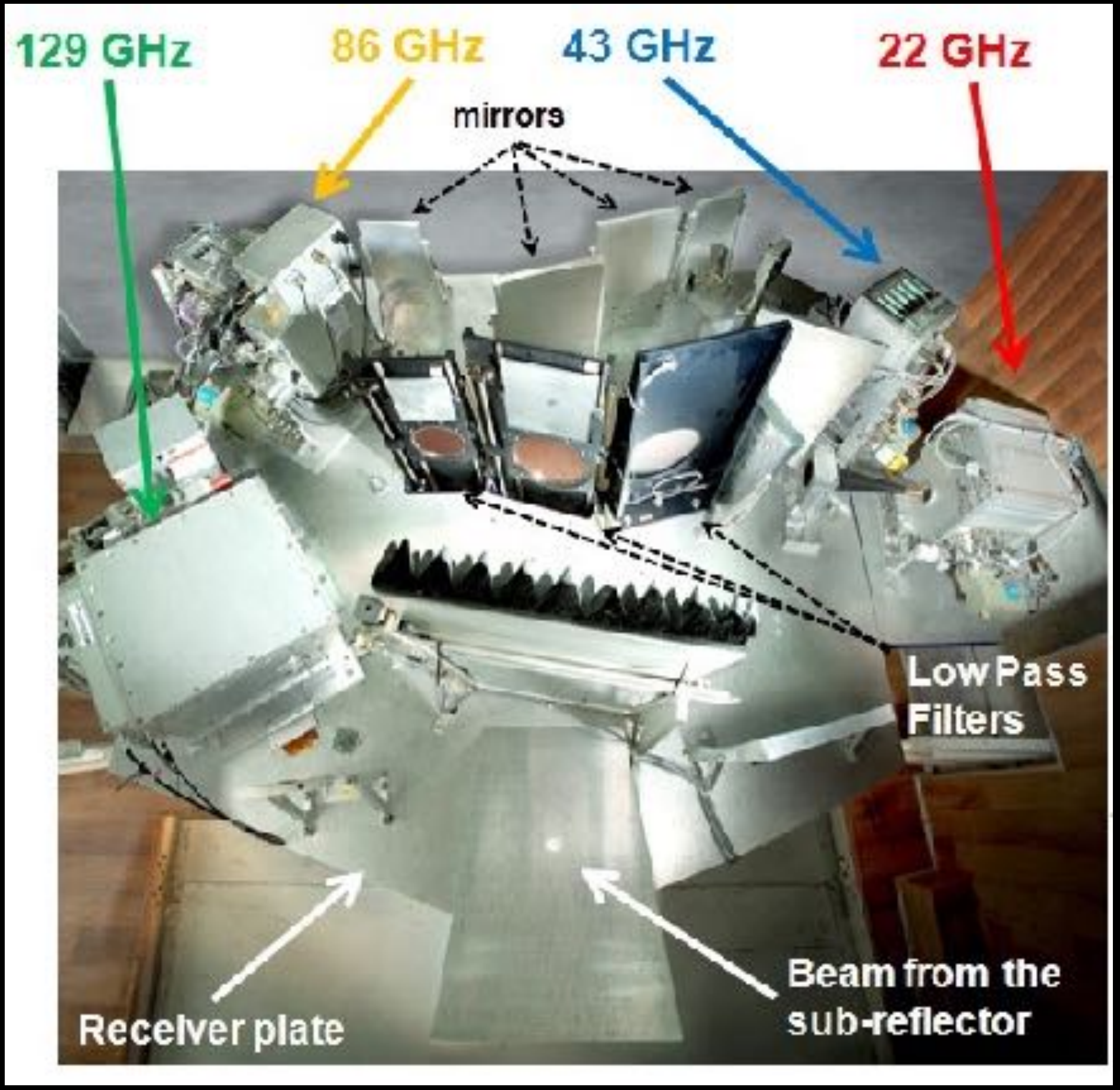


- 3 Telescopes (D = 21m)
- 22/43/86/129GHz
- Baseline 300 - 500 km
- Θ = 1 - 6 mas

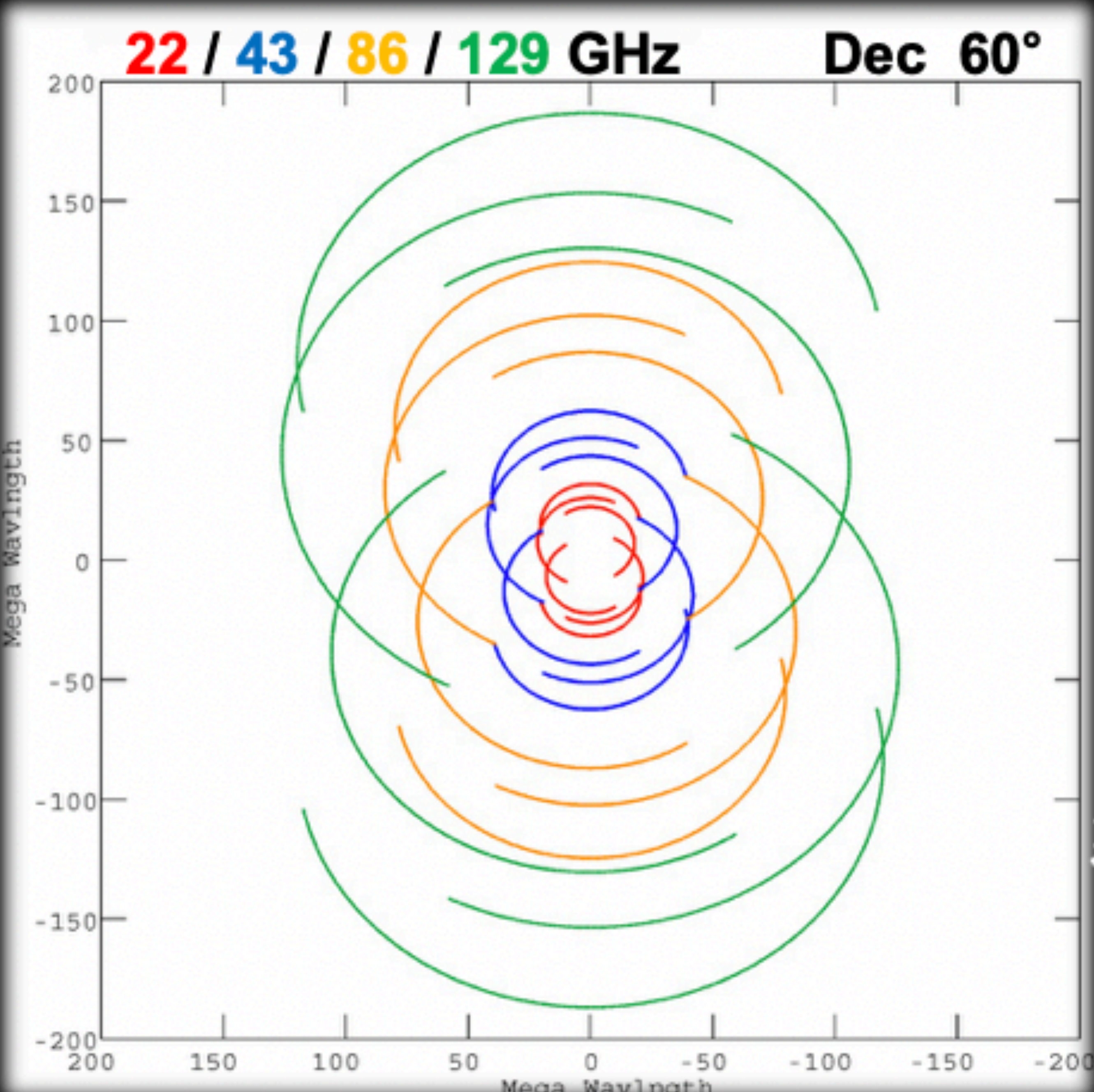
한국천문연구원

Multi-Frequency Receiving System

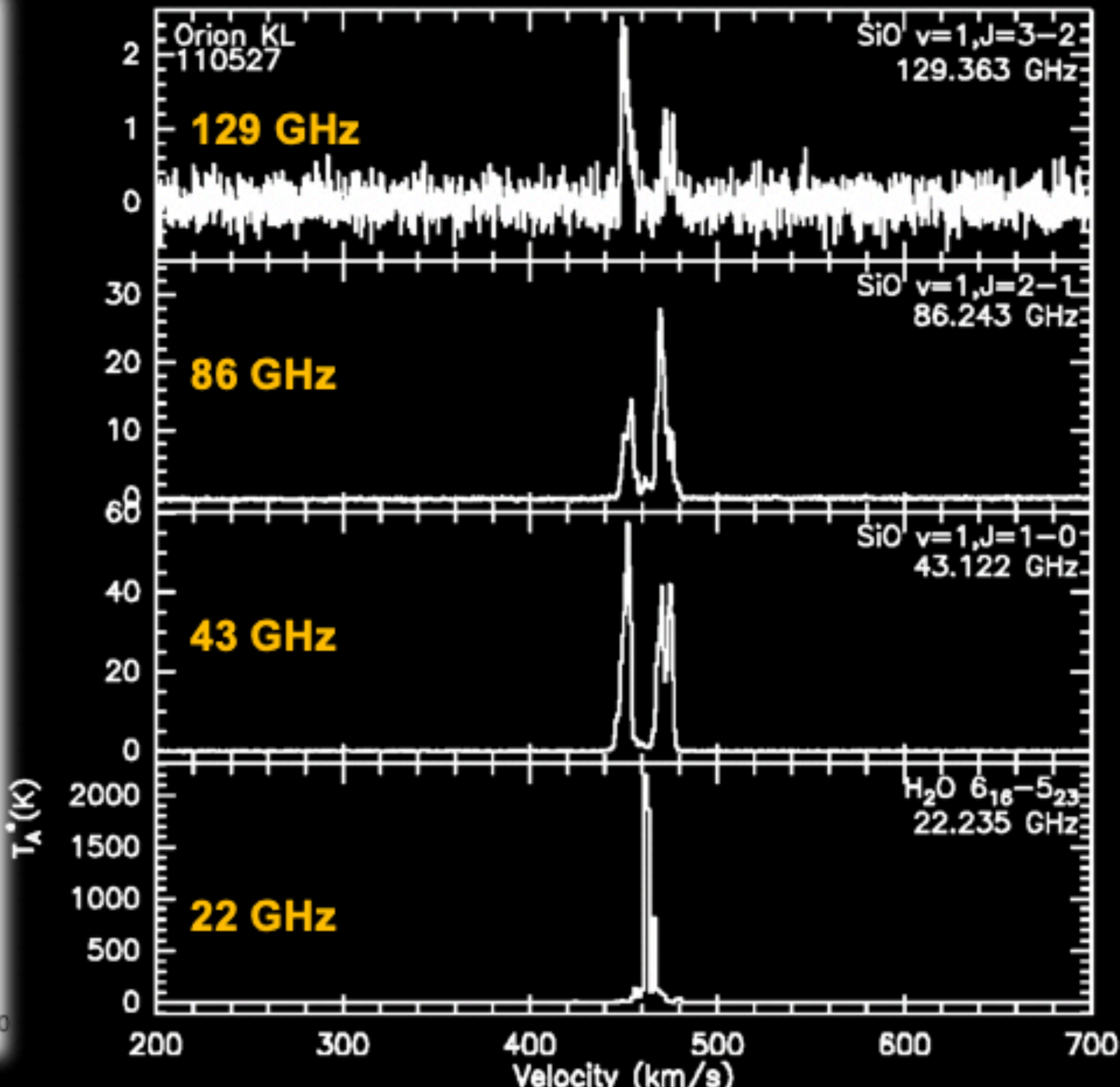
- Simultaneous Multi-frequency Observation
  - @ 22/43/86/129GHz
  - Dual Pol : LCP & RCP
- (Source) Frequency Phase Transfer
  - Weak Source Detection
  - Chromatic Astrometry
- Multi-Frequency Observation
  - Efficient (Obs, Cal + Sci)
  - SED & Rotation Measure



First Light from 22/43/86/129 GHz Simultaneous Single Dish Observation



4CH UV Coverage



H20/SiO Masers in Orion KL

KVN Multi-Frequency Observations

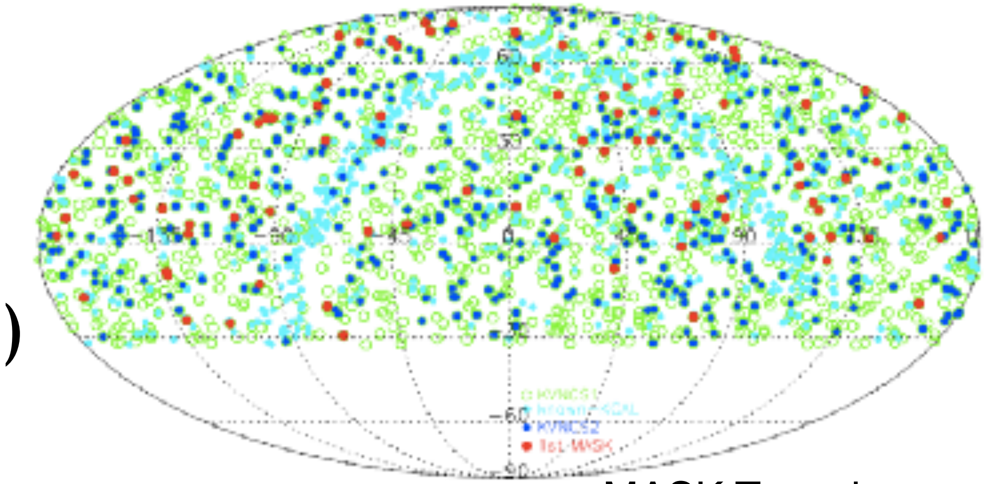
- Largest number of New detections Ever! (on-going)
  - ~574 AGNs(>80%) @ 43GHz
    ~428 AGNs(>60%) @ 86GHz
    ~281 AGNs(>50%) @ 130GHz
  - ~80 high-z AGNs (z = 2.5-6.5)

- M/F Images/Astrometry
  - Evolved Stars & AGNs

- Multi-Frequency Polarimetry
  - AGN jet structure and magnetic fields from M/F Rotation Measure

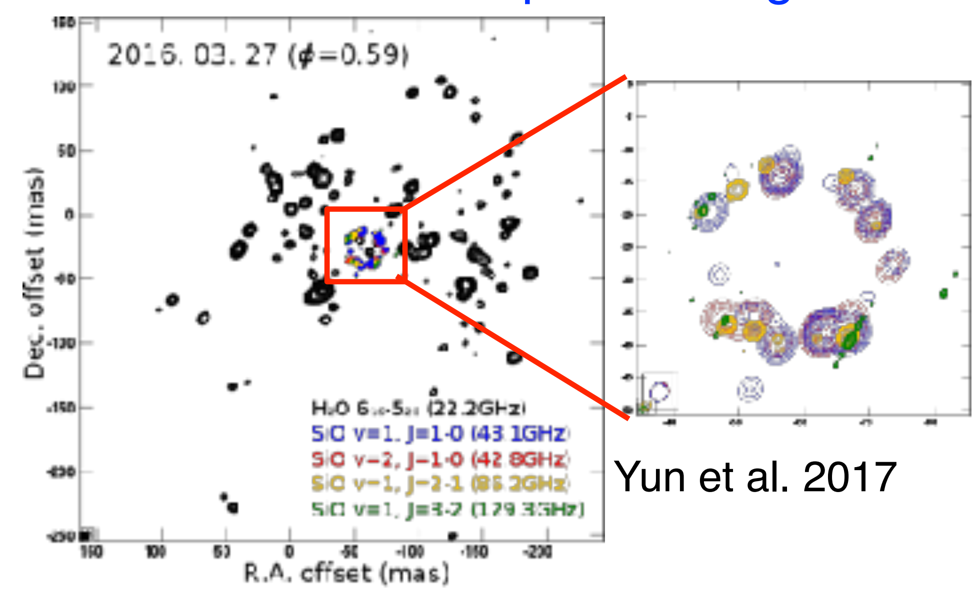
- Demonstration on the performance of simultaneous M/F
  - Tropospheric / Ionospheric phase calibration
  - Ideal system for mm-VLBI observation

MASK: Multi-Frequency AGN Survey with KVN



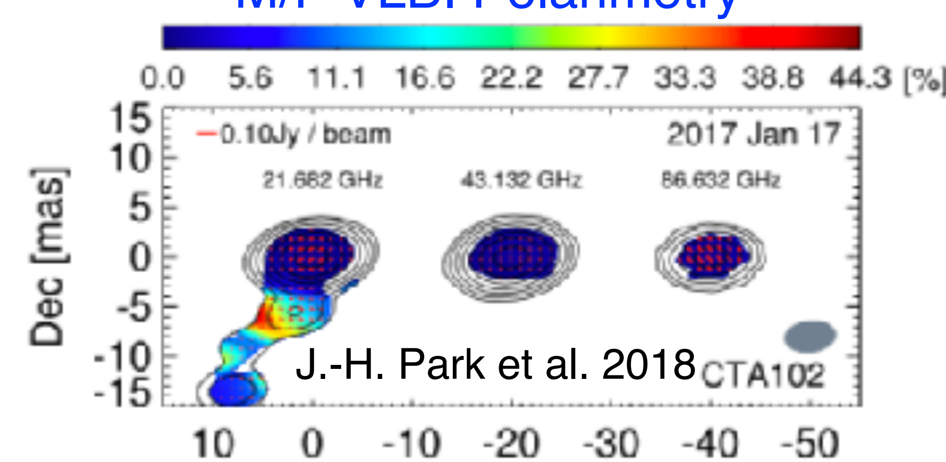
MASK Team in prep

M/F maser maps of Vx Sgr



Yun et al. 2017

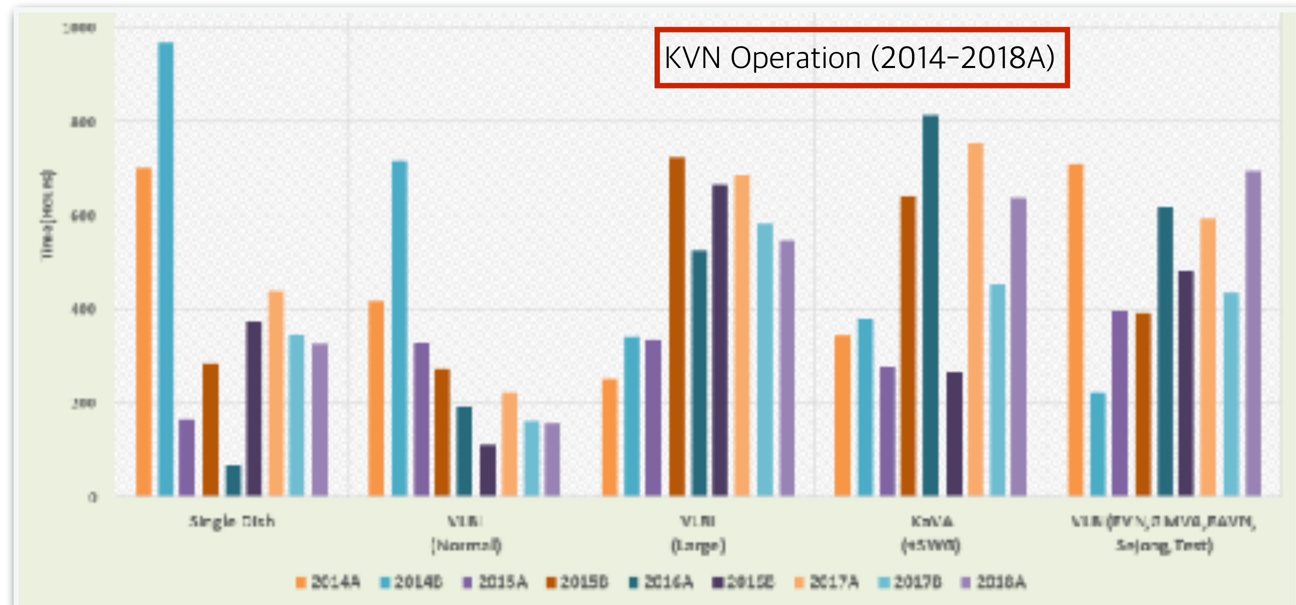
M/F VLBI Polarimetry

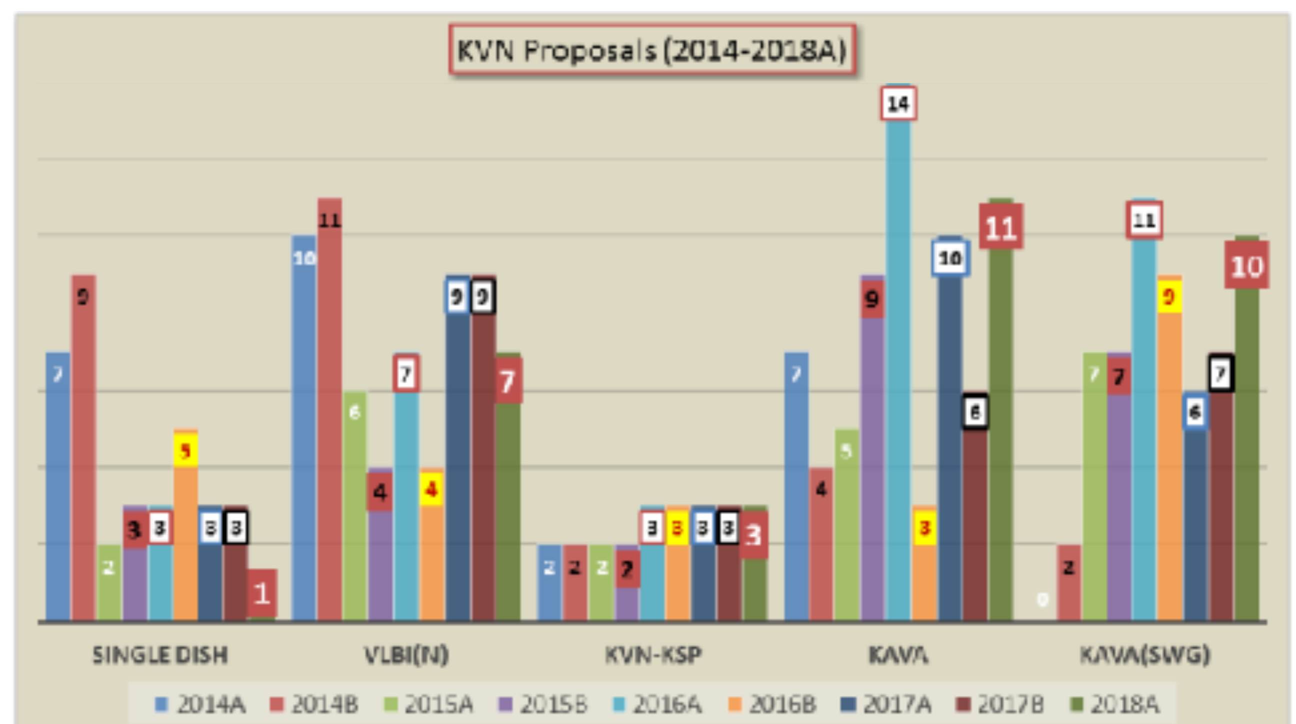


J.-H. Park et al. 2018

KVN Operation Status

- VLBI > 3500h/yr (+ SD 500-1000 h/yr/site)
  - KVN Only : 2500h
  - KaVA (KVN and VERA Array) : 1000h
  - EAVN/EVN/GMVA/Sejong > 300h
- KVN Key Science Projects : 1000h/yr
  - Evolved Star(1) & AGN (2)
- KaVA Large Programs : 500h/yr
  - AGN, Star formation, Evolved stars, Galactic astrometry
- Global Common Use : 1000h/yr
  - KVN(500h/yr) + KaVA/EAVN (500h/yr)





KVN Key Science Projects

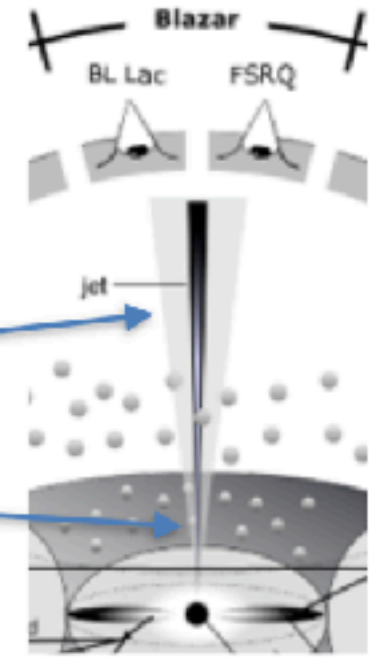
1. Interferometric Monitoring of Gamma-Ray Bright AGN : iMOGABA (Sang-Sung Lee/KASI)
2. Simultaneous Monitoring of KVN 4 Bands towards Evolved Stars (Se-Hyung Cho/KASI)
3. The Plasma Physics of AGN with KVN : PaGAN (Sascha Trippe/SNU)

- KVN Legacy Program:

  Multi-Frequency AGN Survey with KVN : MASK (Taehyun Jung)

KSP1

iMOGABA (Interferometric Monitoring of Gamma-Ray Bright AGN)



- Studying the origins of the gamma-flares
  - What is the location of the gamma-ray flares?

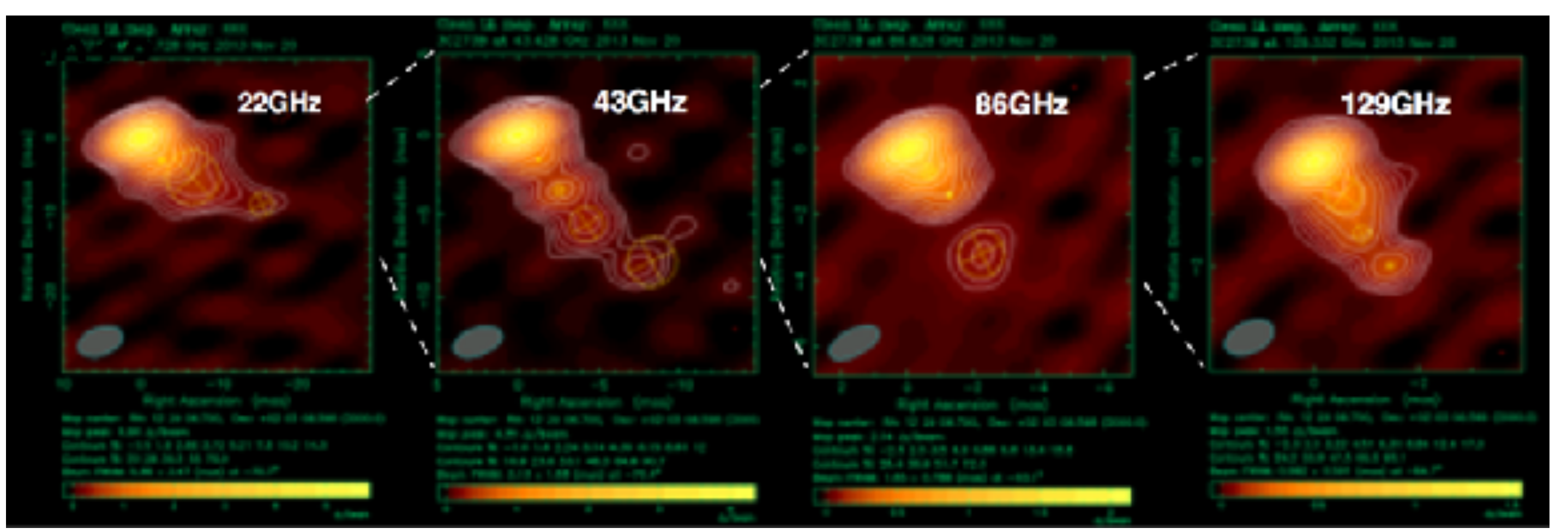
    : Down stream the relativistic jets?

    : much inner region of the jets?
  - What cause the gamma-ray flares of AGNs?

    : A relativistic jet of high energy plasma (a shock) (e.g., Marscher et al. 2008)

    : Doppler boosting of synchrotron radiation of the jet (e.g., Dermer 1995)

    : Inverse Compton scattering by relativistic electrons (upscattered g-ray photons)

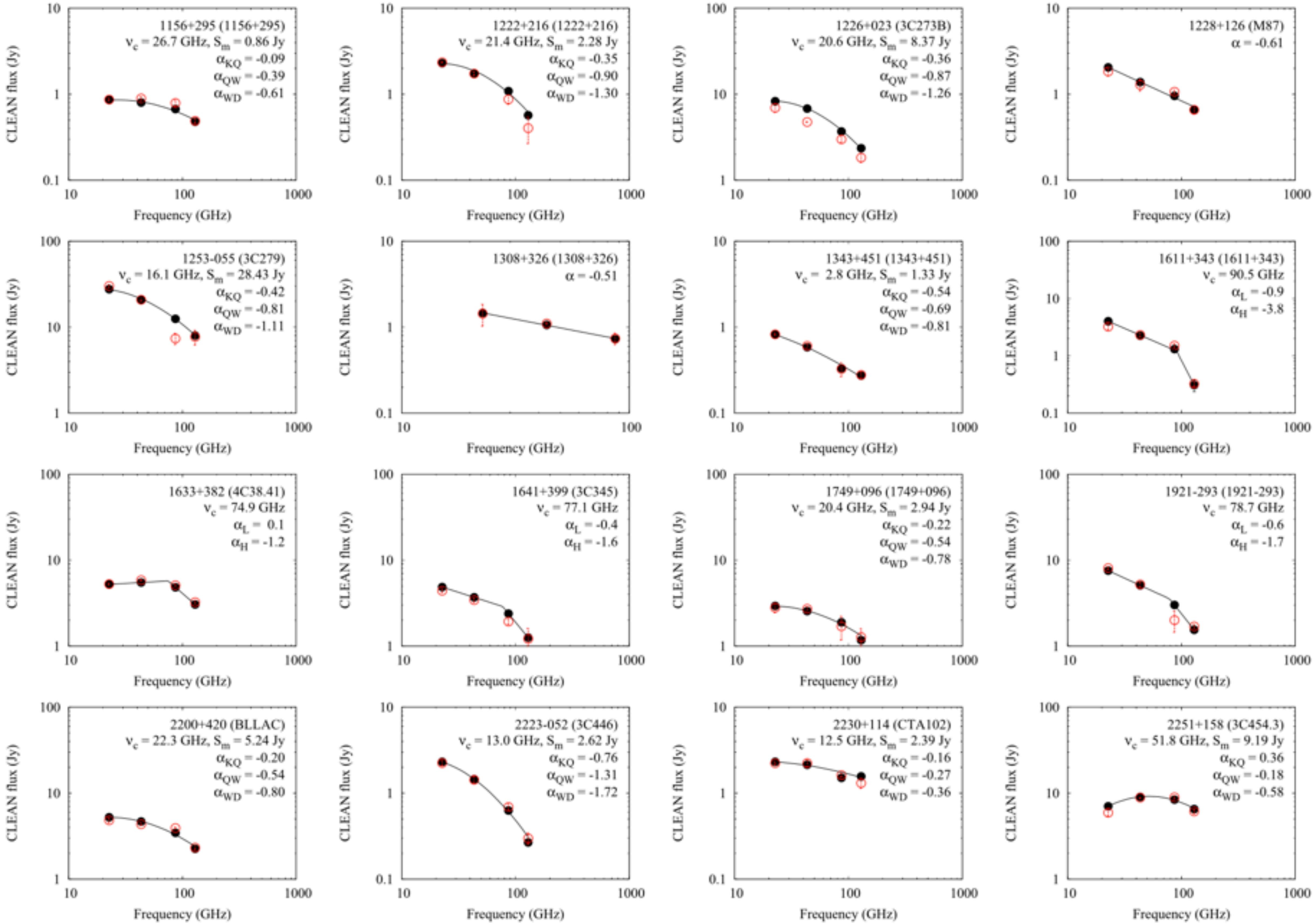


- Monthly VLBI monitoring of the MOGABA sources (**~35**)
- correlated flux of inner-jet structure after gamma-ray flare
- Multi-freq. (22/43/86/129GHz) monitoring

(Credit: S-S Lee)

http://radio.kasi.re.kr/sslee/

Interferometric Monitoring of Gamma-Ray Bright AGNs.
I. The Results of Single-epoch Multifrequency Observations



Spectra over 22GHz-129GHz can be fitted with a power-law or a curved power-law

(Lee et al. 2016)

KSP2

Simultaneous Monitoring Observations 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

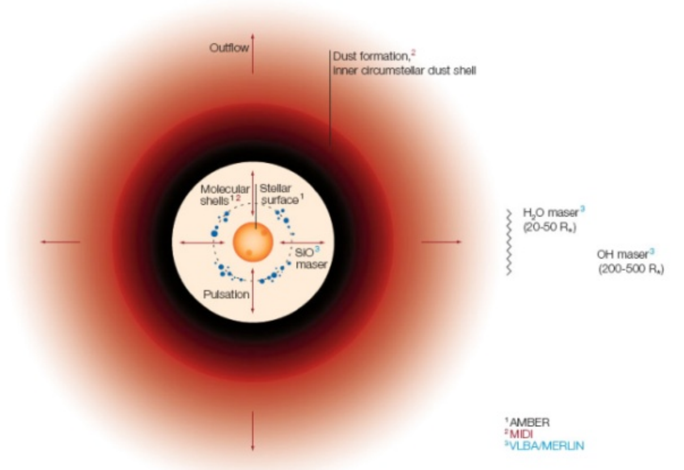
○ Pulsation and shock wave propagation effect from SiO to H_2O maser region via dust layer : **development of outflow motion and asymmetry ► Mass loss mechanism** based on combined studies of SiO and H_2O masers.

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]

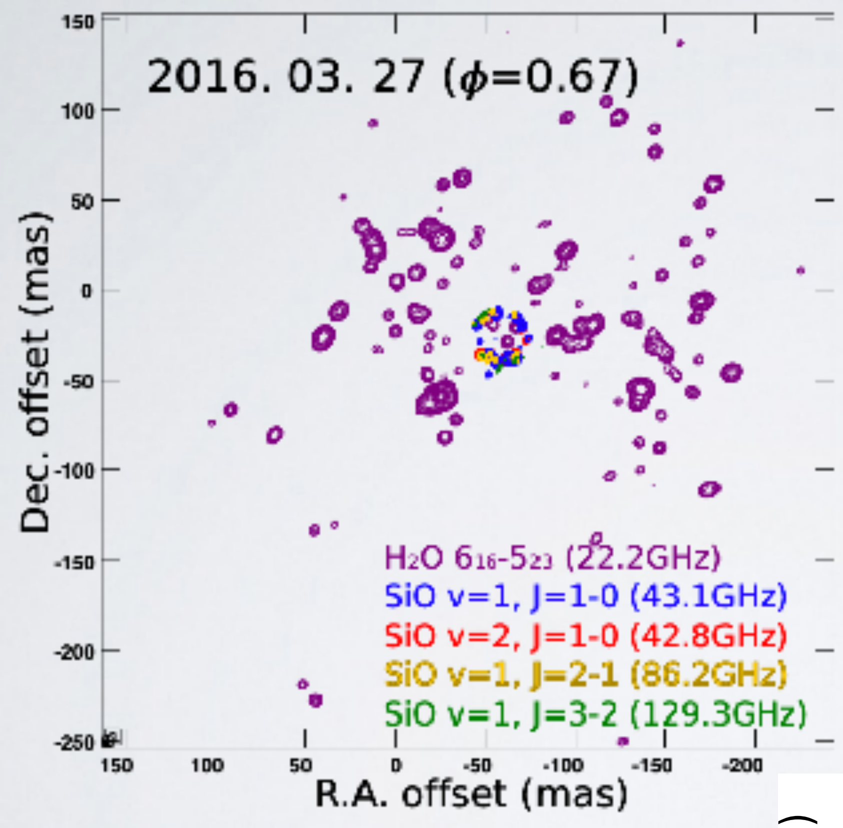
2. Correlation and difference of maser properties (spatio-kinematic properties etc) among SiO J=1-0, J=2-1, J=3-2 masers

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

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



(Credit: S. H. Cho)

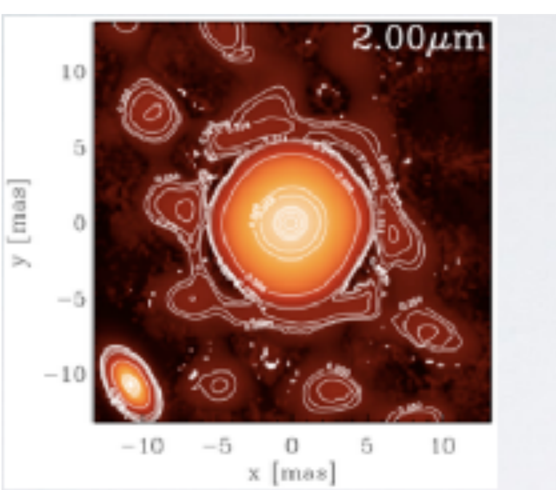


Velocity-integrated intensity map

Astrometrically Registered Maps of H2O and SiO Masers Toward Vx Sagittarii

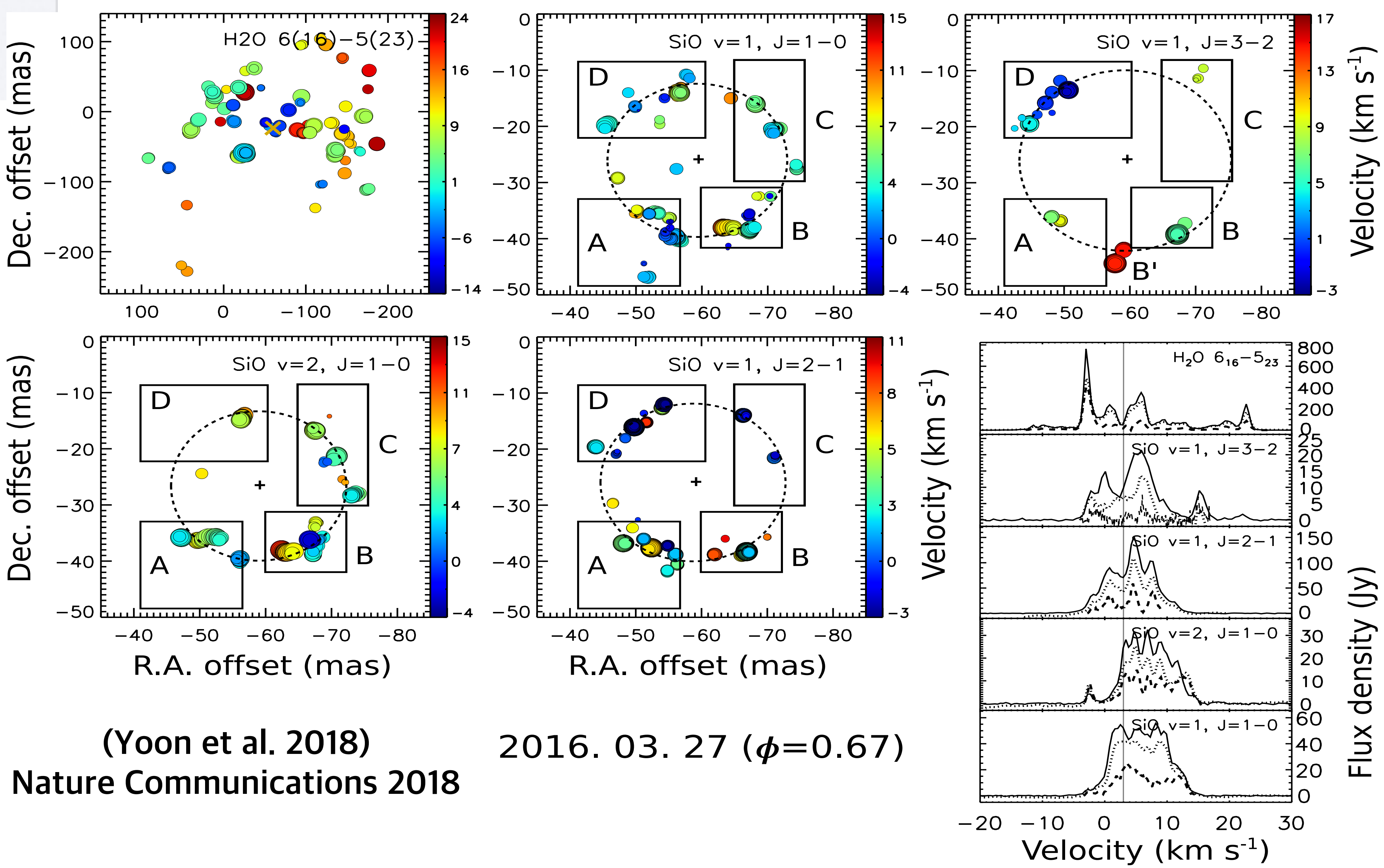
SiO masers is an almost complete, nearly circular ring, suggesting spherically symmetric mass loss within a few stellar radii although the H2O maser shown an asymmetric structure.

Observational evidence for a break in spherical symmetry between the SiO and H2O maser zone



VLTI/AMBER spectro-interferometry
(Chiavassa et al. 2010)

Astrometrically Registered Maps In Vx-Sgr



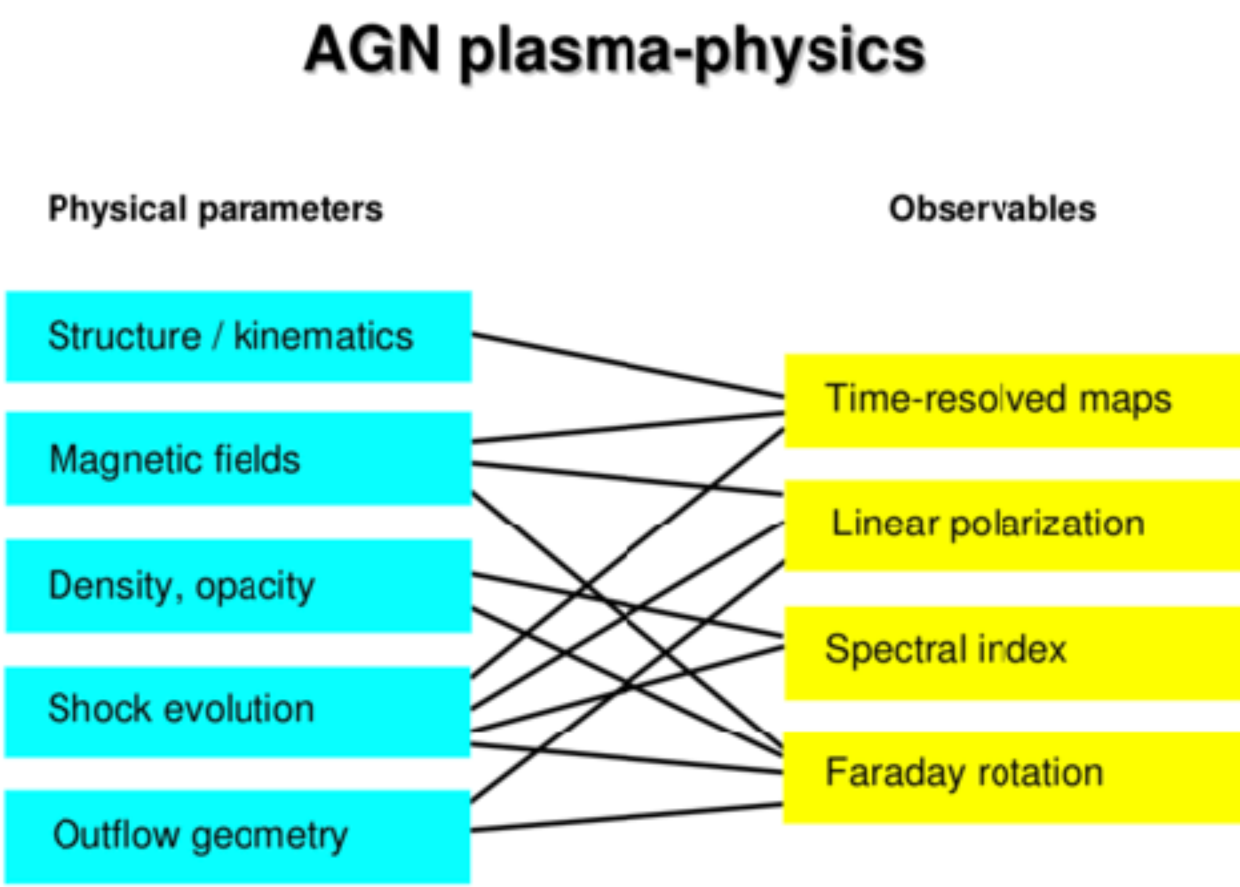
(Yoon et al. 2018)
Nature Communications 2018

2016. 03. 27 (ϕ=0.67)

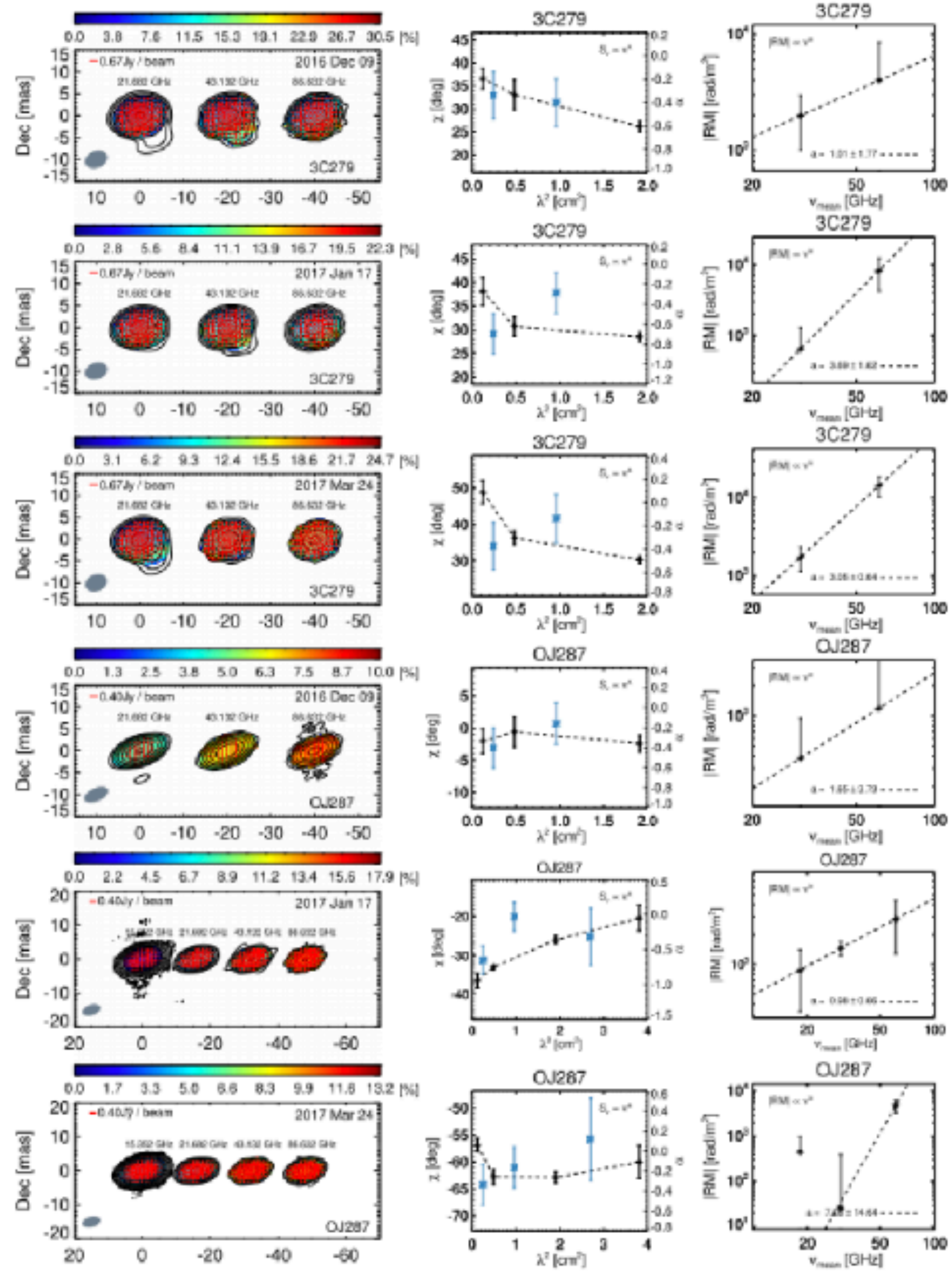
KSP3

The Plasma Physics of AGN with KVN

- Geometry and Magnetic field structure of AGN Jets from ν-dependent Rotation Measure
- Polarization Monitoring of ~14 Bright AGNs
- Polarization Calibration up to 130GHz



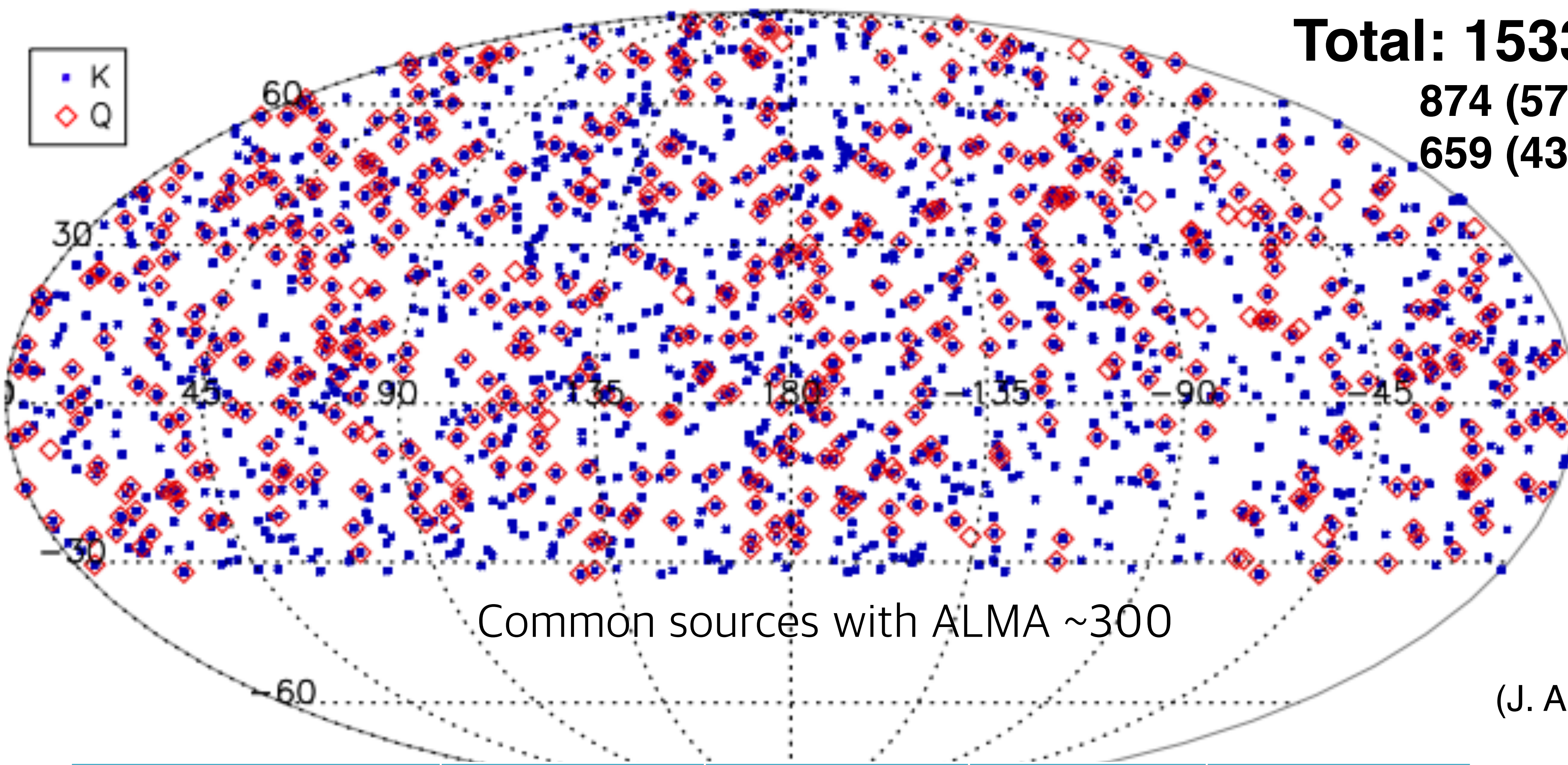
(Credit: S. Trippe)



(Park et al. 2018)

Multifrequency AGN Survey with KVN

Goal : Constructing Multi-Frequency mm-VLBI Catalog of AGNs



Total: 1533 sources

874 (57%) observed

659 (43%) remained

(until 2017)

(J. A. Lee+17 ApJS)

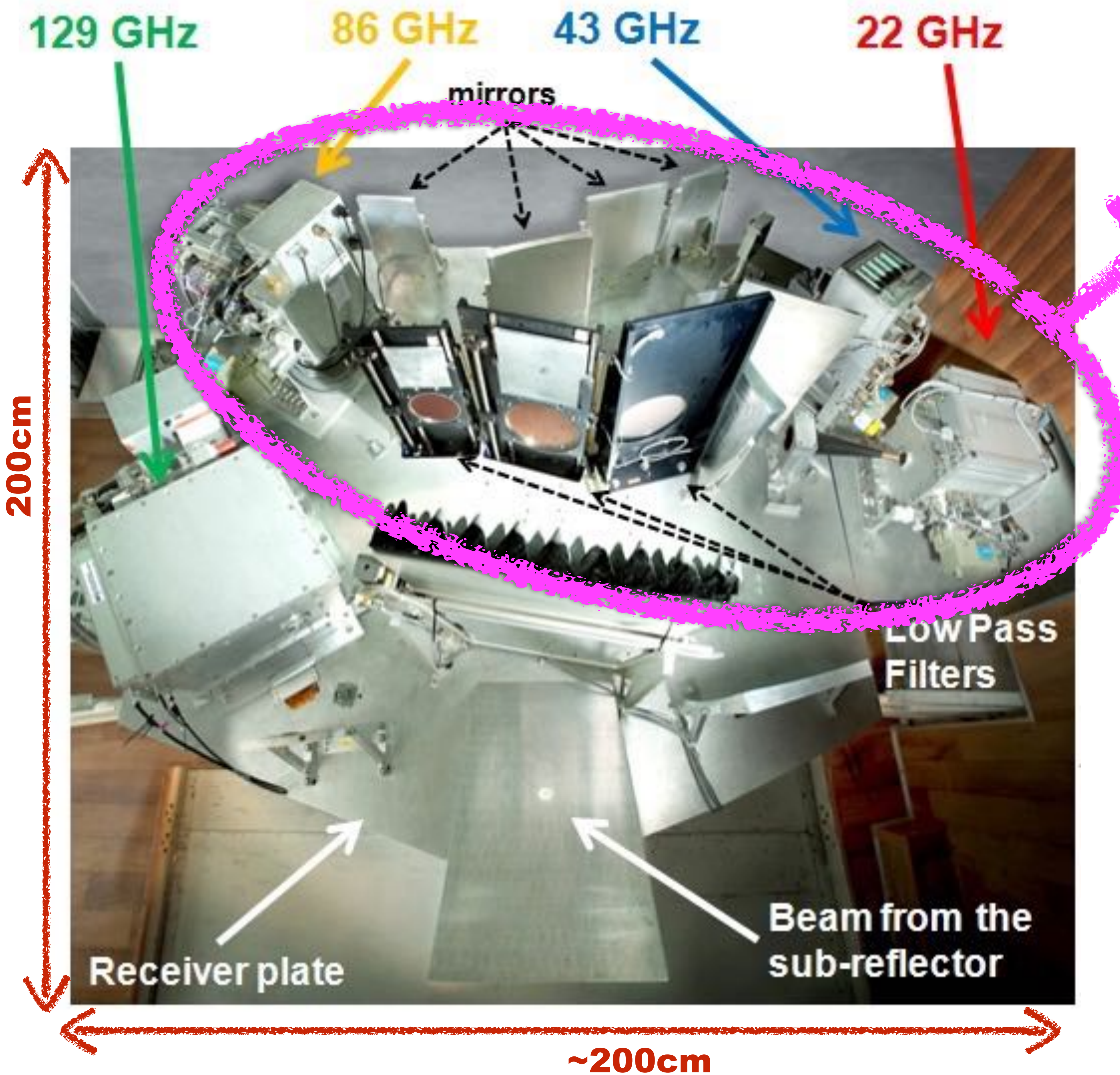
719 sources (46% of Total)	K-band	FPT (K→Q)	FPT (K→W)	FPT (K→D)
Target Freq.	22GHz	43GHz	86GHz	130GHz
Detected	671	**574**	**428**	**281**
Detection Rate	93%	**80%**	**60%**	**39%**
5σ detection limit (mJy)	168 (60)	**20 (8)**	**40 (15)**	**55 (20)**

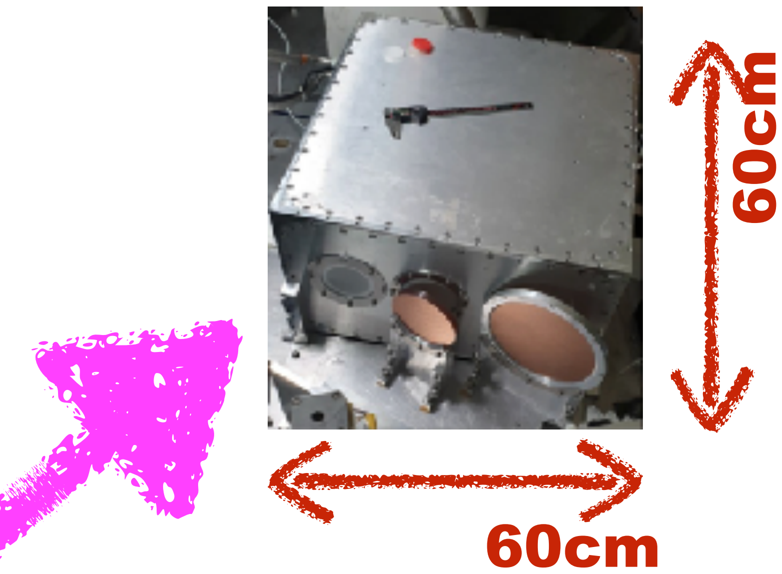
1Gbps Mode

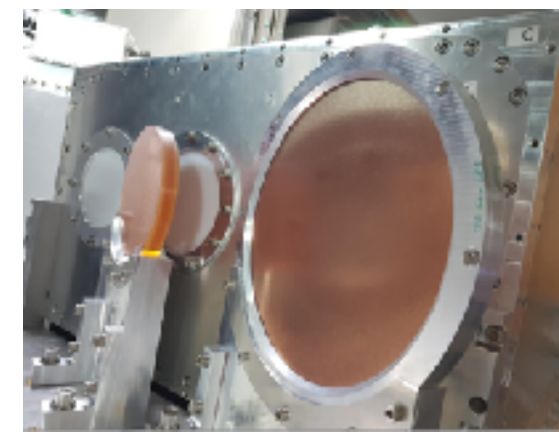
8Gbps Mode

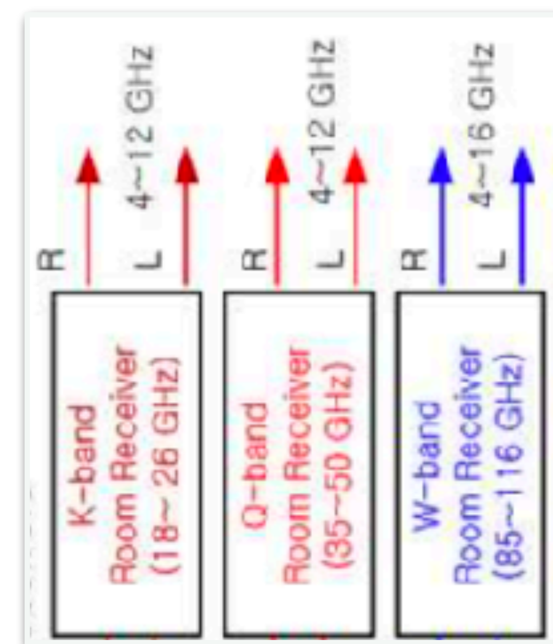
Compact Triple-band Receiver (CTR)

Installed on Sep. 2~3 at KYS



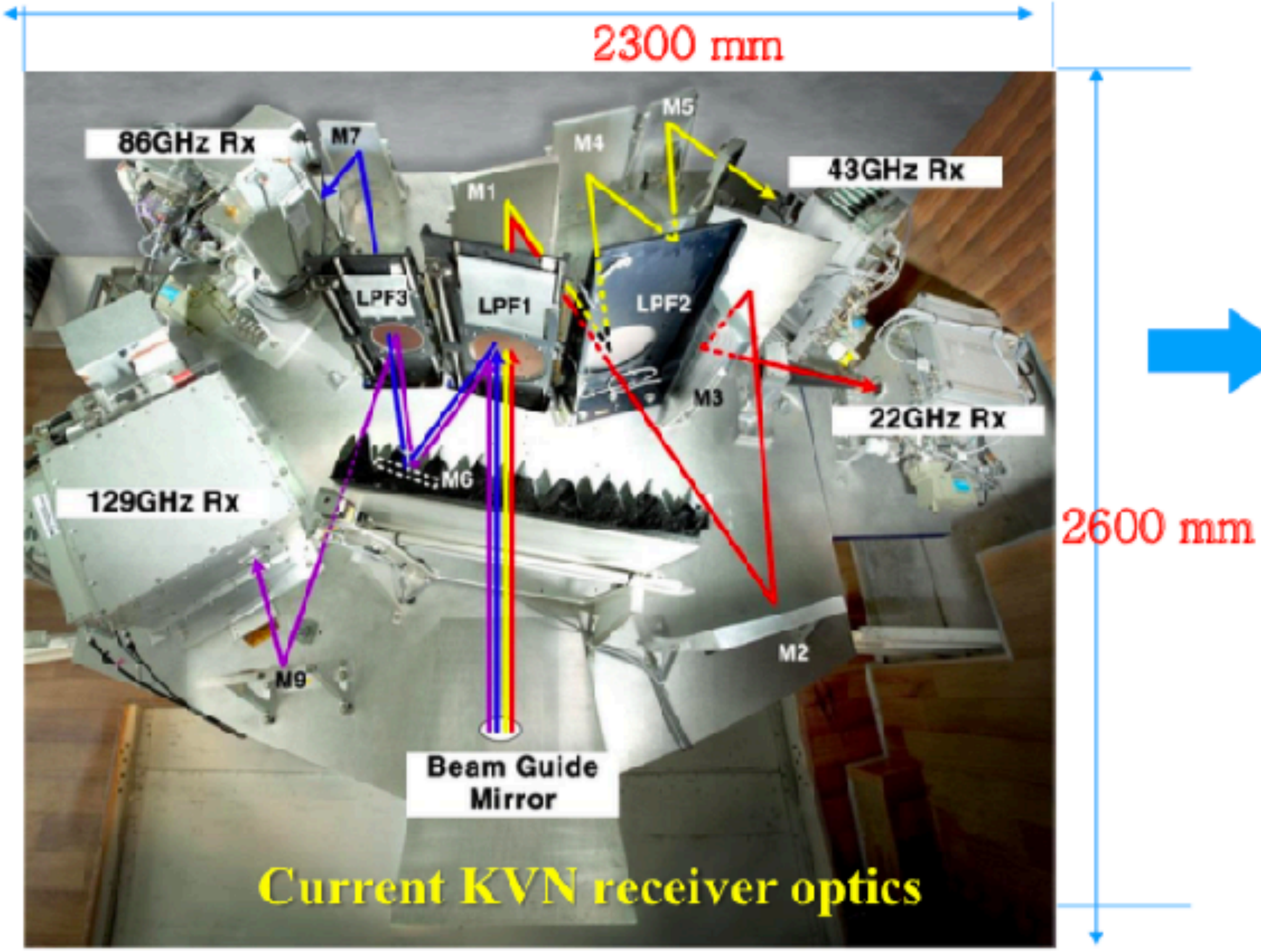


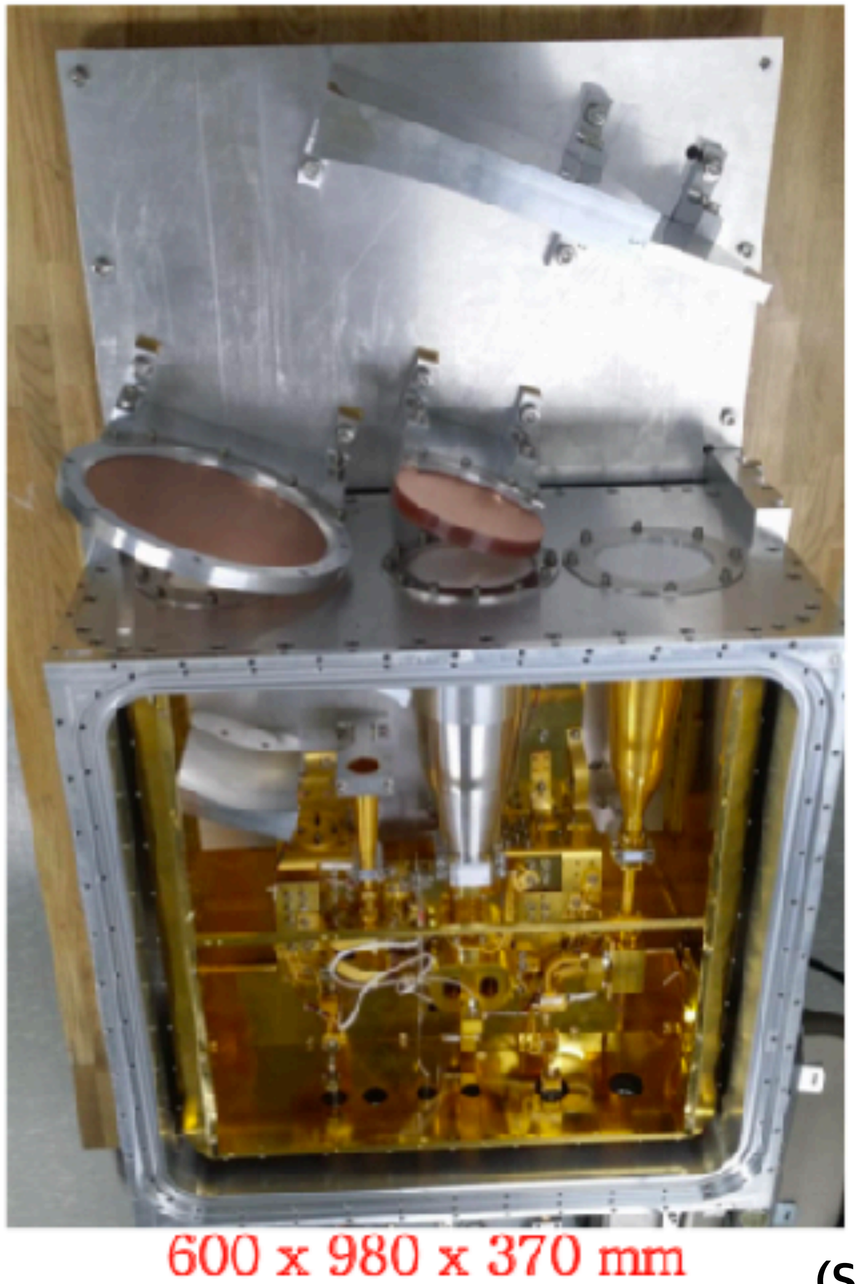




RF: 18-116GHz

Compact Triple-band Receiver (CTR)





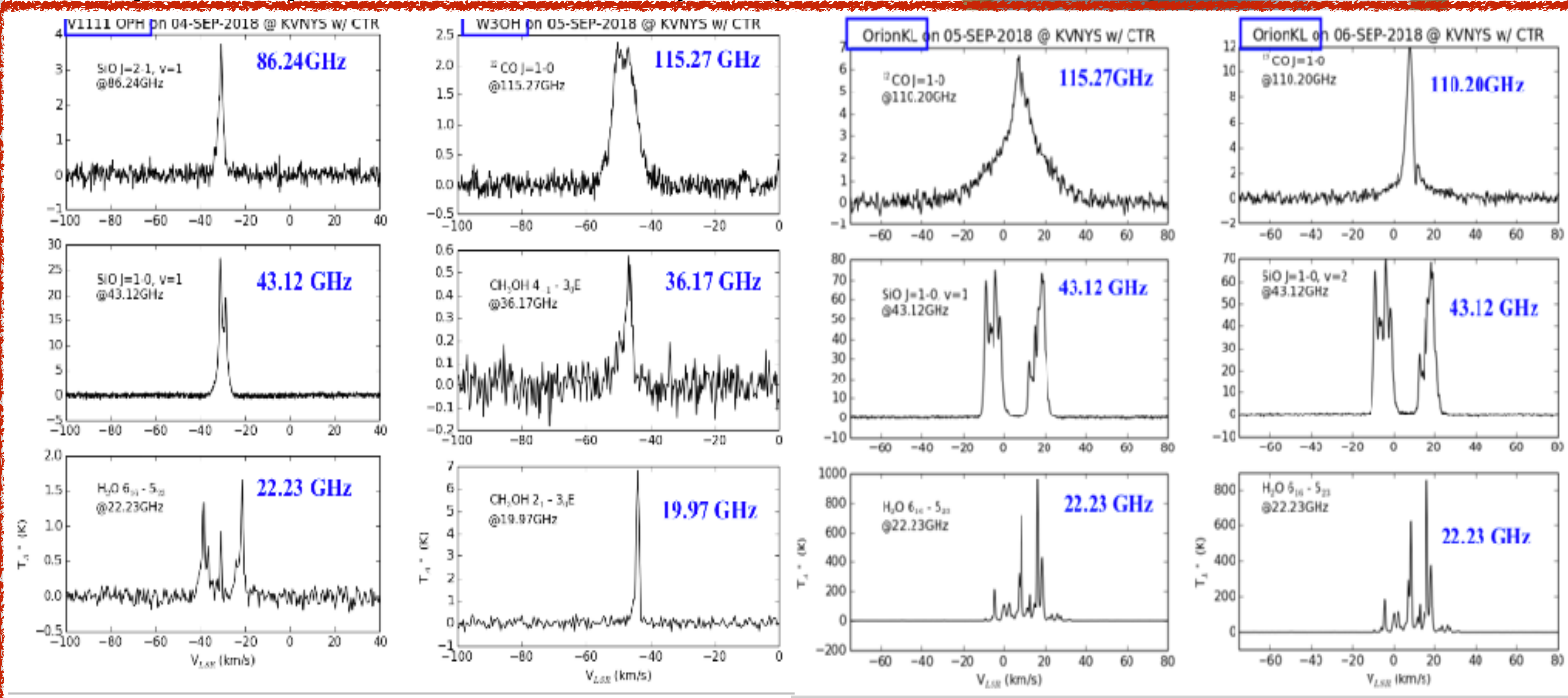
(S. T. Han)

- Pointing offset among 3 channels : less than 3 arcsec to conduct simultaneous observations
- Aperture efficiencies : Obtained as much as we could (K- : 68 %, Q-: 66 %, W-band : 50%)
- Receiver noise temperatures : Not bad, but have to be improved (OMT, Polarizer and LNA)

❖ CTR is tailorable for use in telescopes with a small receiver cabin.

❖ Ultimately this concept may lead to development of much more compact multi-frequency receiver systems for mm-wave and sub-mm radio telescopes

Compact Triple-band Receiver (CTR)



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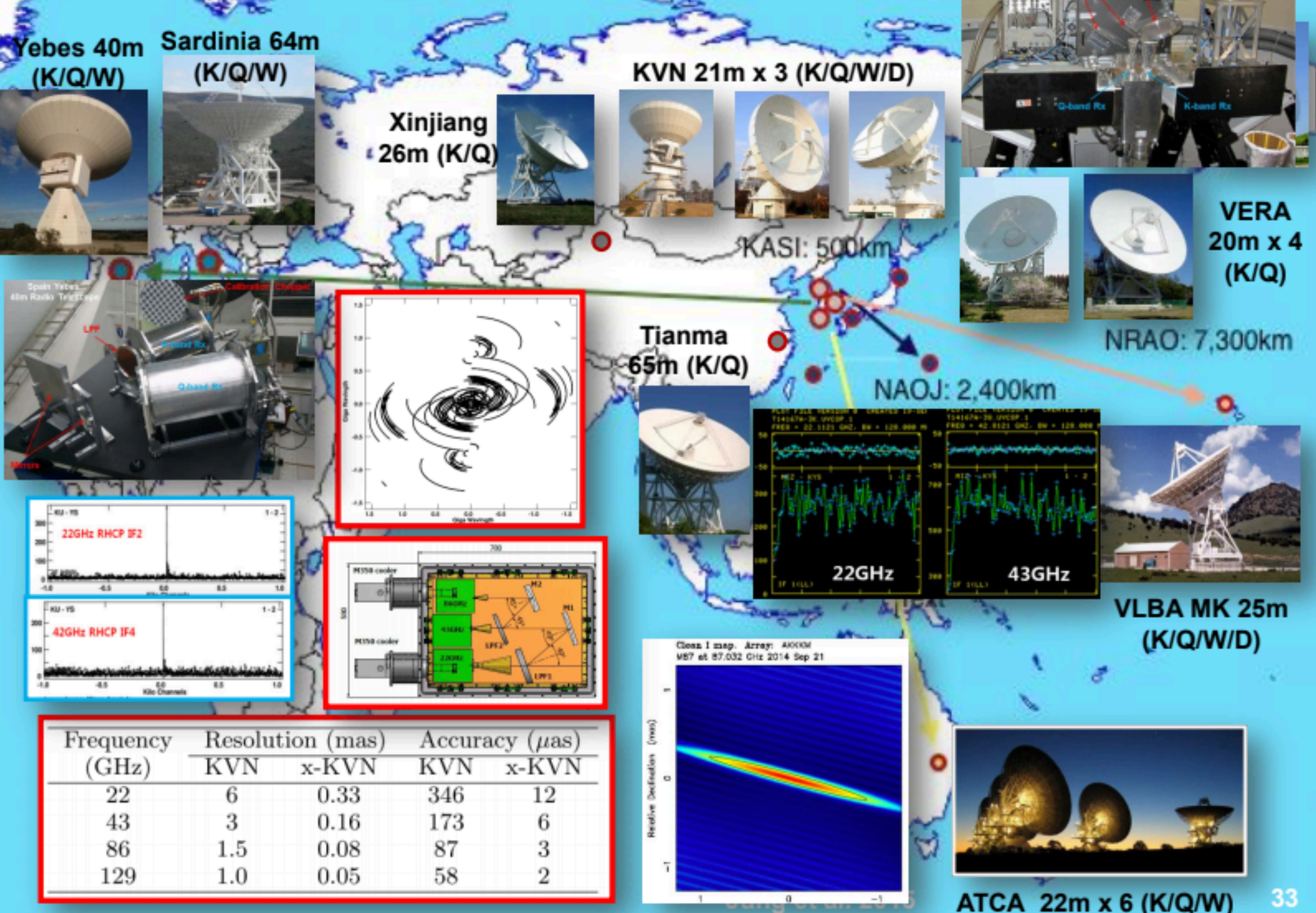
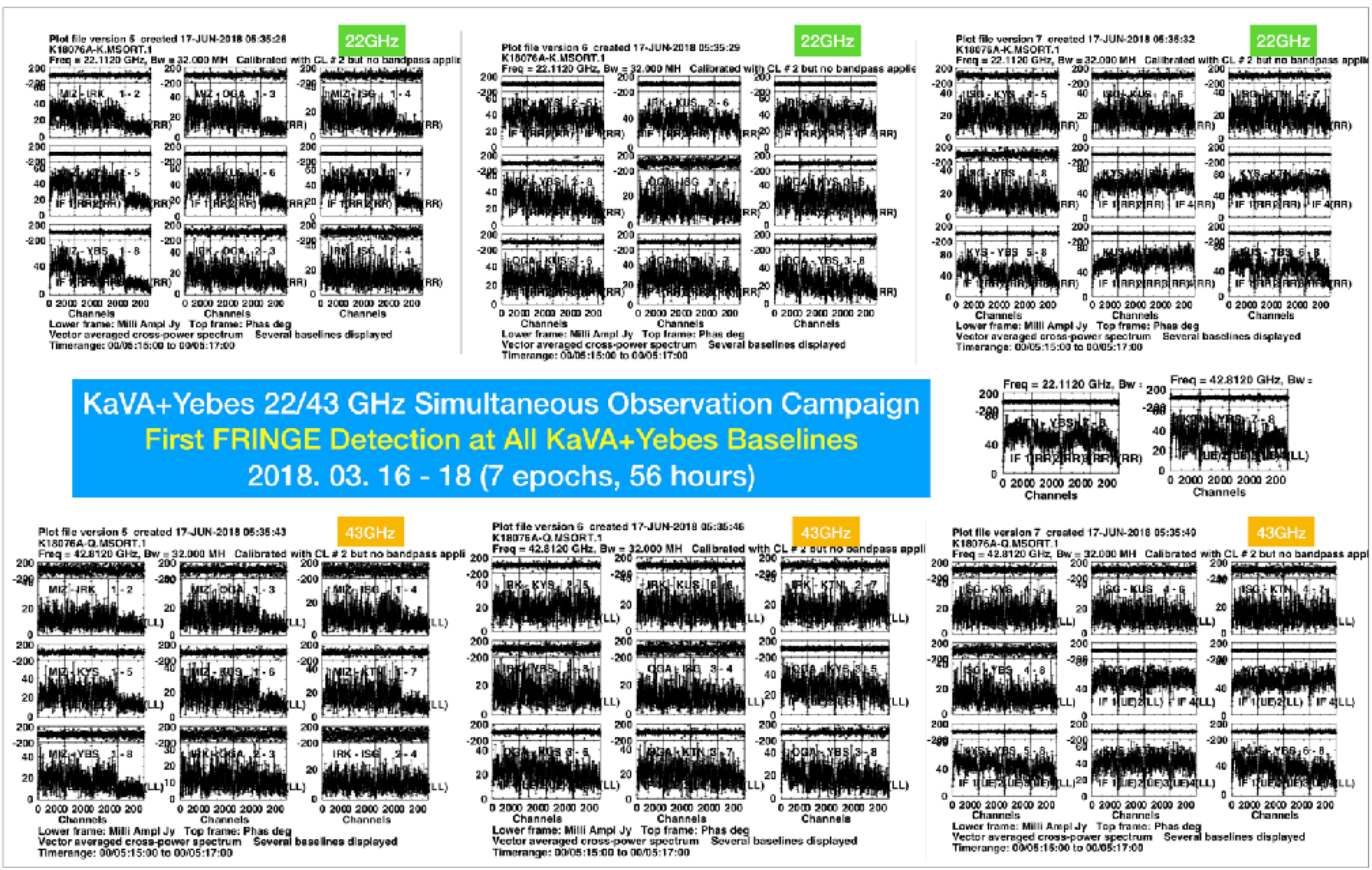
Global Simultaneous MF Network

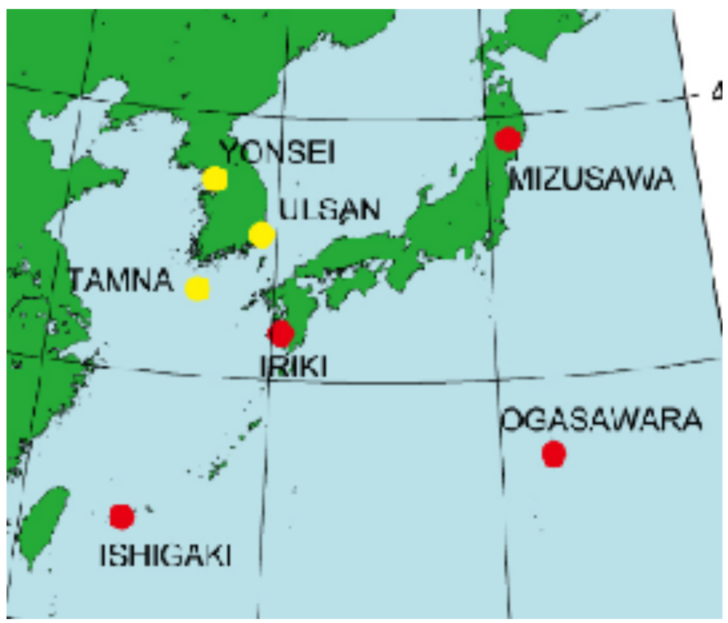


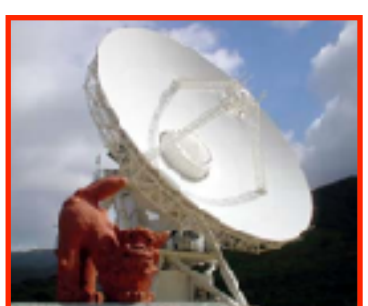
Frequency (GHz)	Resolution (mas) KVN	Resolution (mas) x-KVN	Accuracy (μas) KVN	Accuracy (μas) x-KVN
22	6	0.33	346	12
43	3	0.16	173	6
86	1.5	0.08	87	3
129	1.0	0.05	58	2

First Fringes of KaVA+Yebes (Spain)
Simultaneous 22/43GHz VLBI Observation



KaVA : KVN and VERA Array





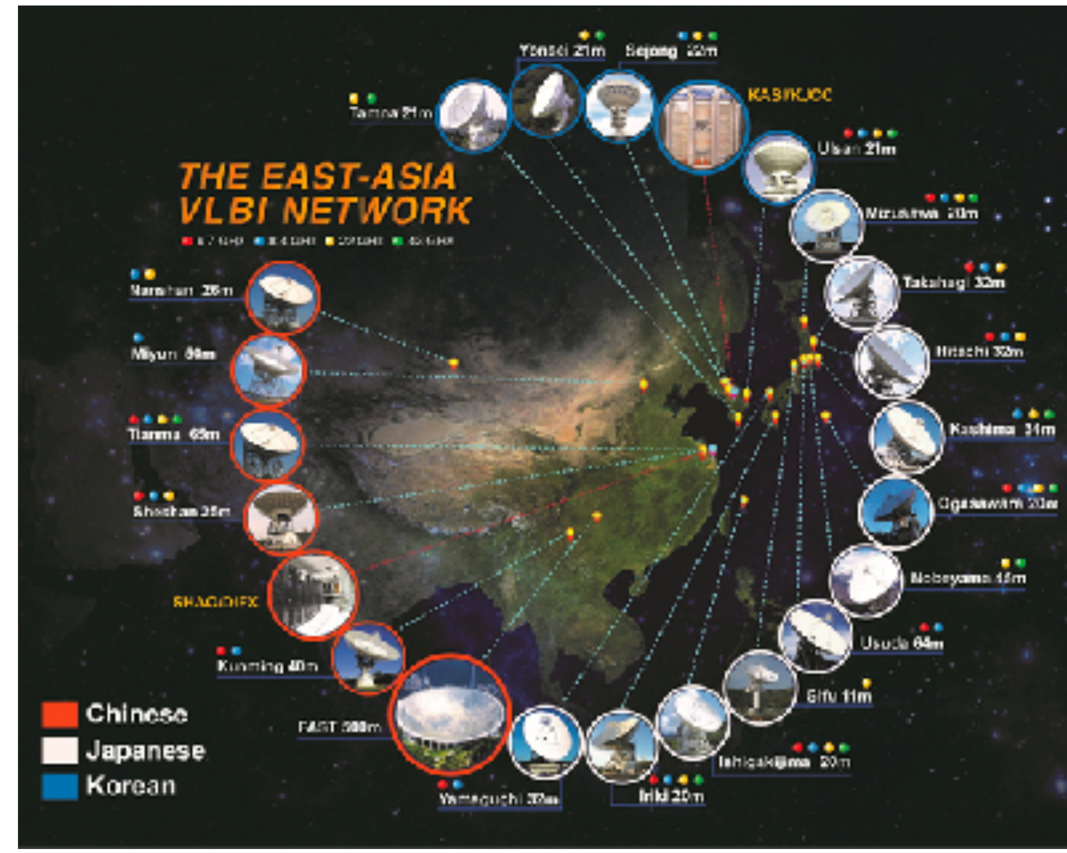
- 7 Telescopes (D ~ 20m)
- Baseline : 300 - 2300 km
- Frequency : 22/43(/86/129)GHz
- Beam Size : 1.2/0.6(/1.5/1.0) ma
- Baseline Sensitivity ~ 10/20 mJy

Daejeon Correlator@KJCC


Tamna 21 m
Miyun 50 m
KASI/DHC
Sejong 22 m
Yonsei 21 m
Ulsan 21 m
Gifu 11 m
Usuda 64 m
Mizusawa 20 m
Nanshan 26 m
Takahagi 32 m
Tianma 65 m
Hitachi 32 m
Kunming 40 m
Sheshan 25 m
SHAO/DiFX
Yamaguchi 32 m
Ishigakijima 20 m
Iriki 20 m
Nobeyama 45 m
Ogasawara 20m
Kashima 34 m
The East Asian VLBI Network
(Image Credit: Reto Stöckli, NASA Earth Observatory)
6.7 GHz
8 GHz
22 GHz
43 GHz

EAVN: Specifications

Capabilities and prospects of the East Asia Very Long Baseline Interferometry Network
(Tao, Sohn, Imai 2018, Nature Astronomy)



- **Number of telescopes**: 20
  – Korea: 4, China: 5, Japan: 11

- **Frequency coverage:**
  – 6.7 GHz (11 stations), 8 GHz (15),
  22 GHz (16), 43 GHz (12)

- **(Expected) angular resolution:**
  – 2.4 mas (6.7 GHz; Ogasawara – Kunming)
  – 1.5 mas (8 GHz; Ogasawara – Nanshan)
  – 0.6 mas (22 GHz; Ogasawara – Nanshan)
  – 0.3 mas (43 GHz; Ogasawara – Nanshan)

- **Sensitivity for 7- σ fringe detection** (τ = 60 s, B = 256 MHz):
  – 1.6 mJy (8 GHz; Tianma – KVN)
  – 9.5 mJy (22 GHz; Tianma – KVN)

- **Recording rate**: ≧ 1 Gbps (= 512 MHz BW)

- **Correlator:** – KASI (Korea): Daejeon Hardware Correlator (DHC) (main)
  & DiFX – SHAO (China)

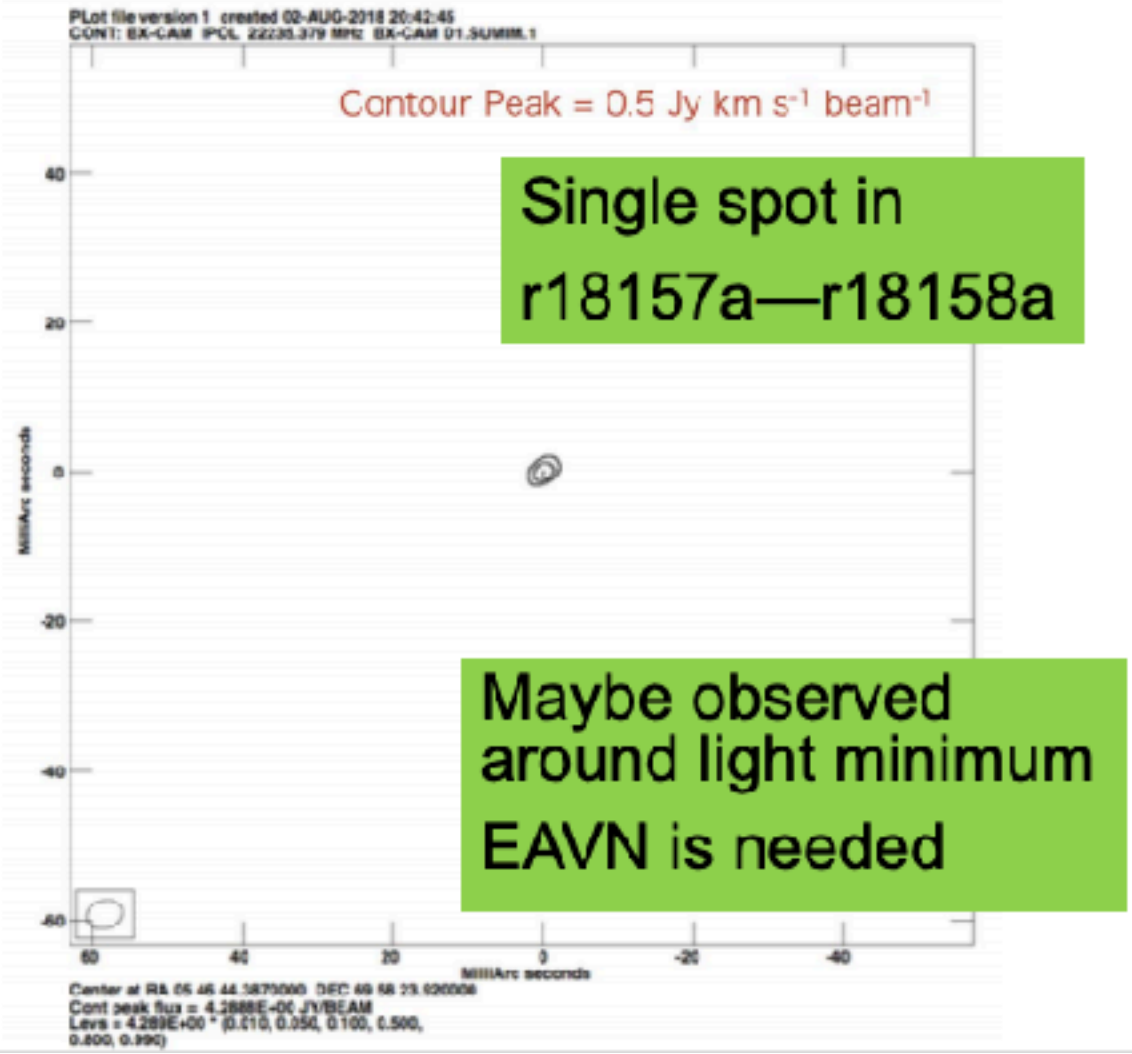
KaVA/EAVN Large Programs

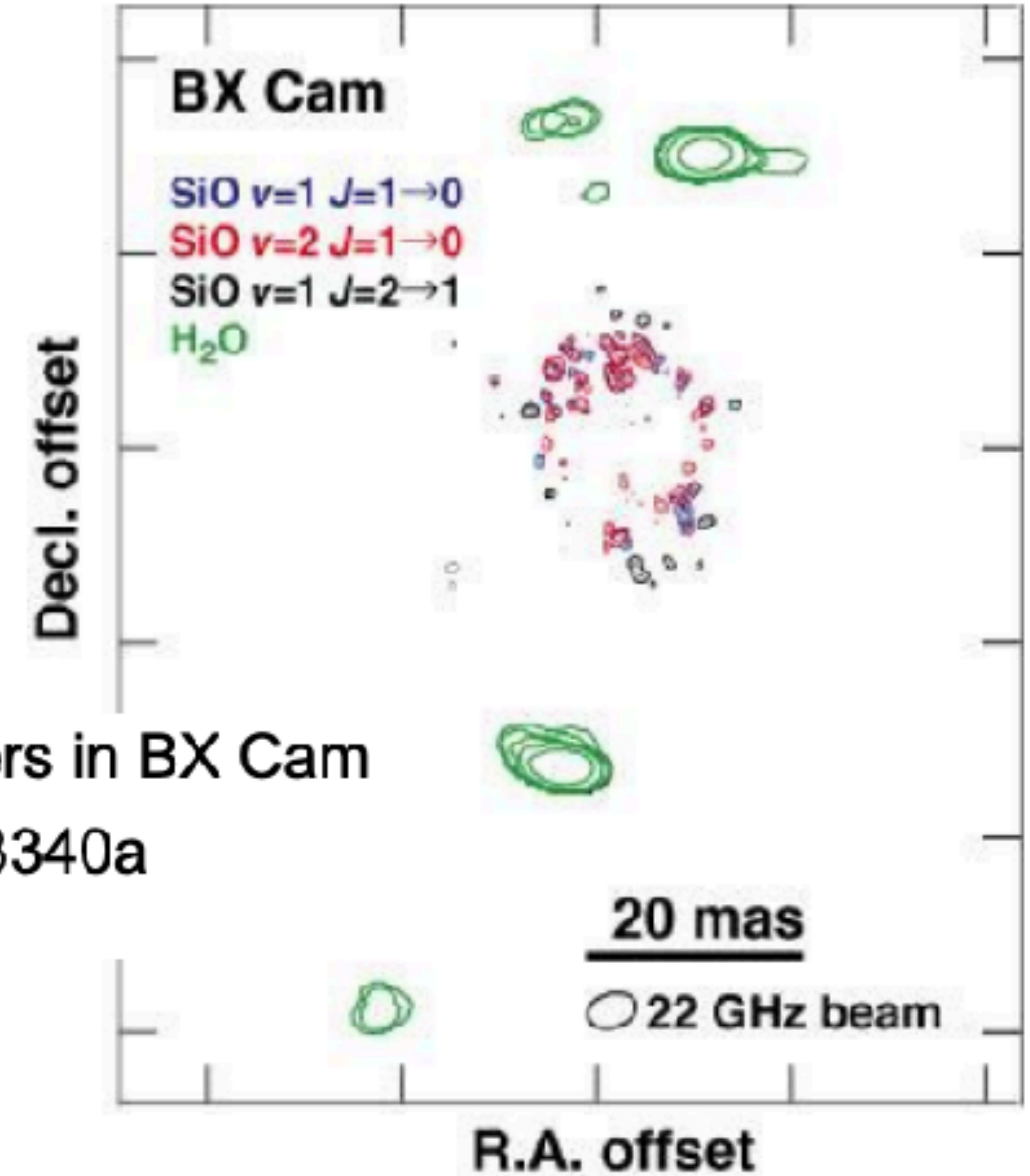
- ~170h / program /yr
- KaVA SWG —> EAVN SWG with Chinese colleagues since 2017

- **Evolved Star**
  - EAVN Synthesis of Stellar Masers Animations (ESTEMA)
  - P.I.: Hiroshi Imai (Kagoshima Unv.), Youngjoo Yun (KASI),
- **AGN**
  - Exploring the vicinity of supermassive blackhole with KaVA/EAVN
  - P.I. : Motoki Kino (Kogakuin Univ), B. W. Sohn (KASI),
- **Star Formation**
  - Understanding high-mass star formation through KaVA observations of water and methanol masers
  - P.I. : Tomoya Hirota (NAOJ), K.-T. Kim (KASI)
- **Galactic Astrometry**
  - Astrometry and Geodesy

First output of ESTEMA (EAVN synthesis of Stellar Maser Animations)

H_2O masers around BX Cam
in r18144a-r18145a (ESTEMA)





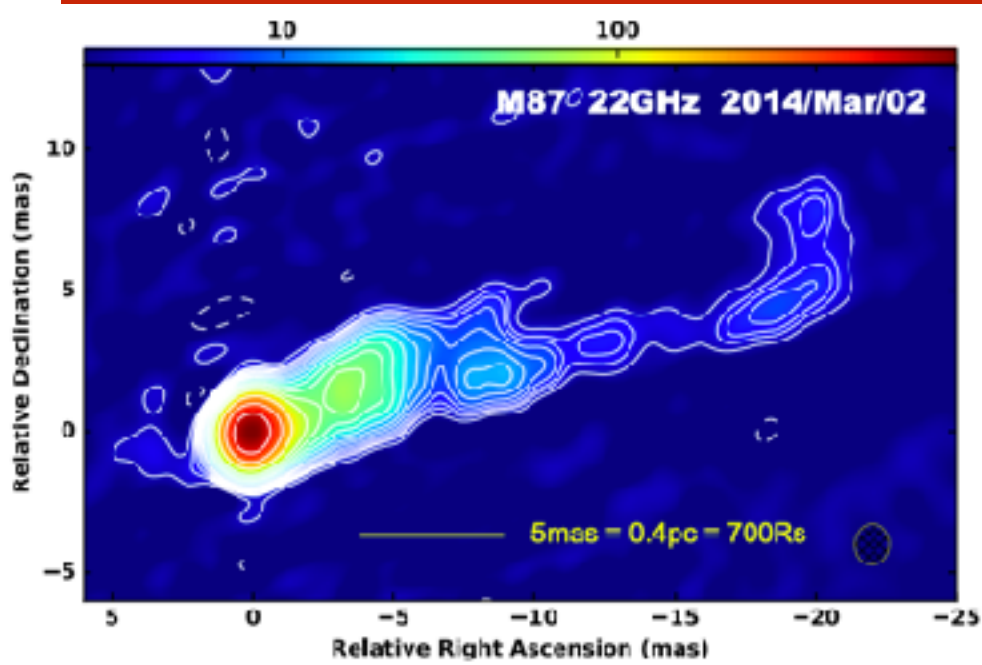
Masers in BX Cam
In r13340a

- ➢**KaVA ESTEMA (Expanded Study on Stellar Masers)**
  - ✓2015 November—2017 March
  - ✓Snapshot imaging of ~40 stellar maser sources successfully detected
- ➢**ESTEMA (EAVN Synthesis of Stellar Maser Animations)**
  - ✓From 2018 May
  - ✓Targeting 6 stars with different stellar pulsation period

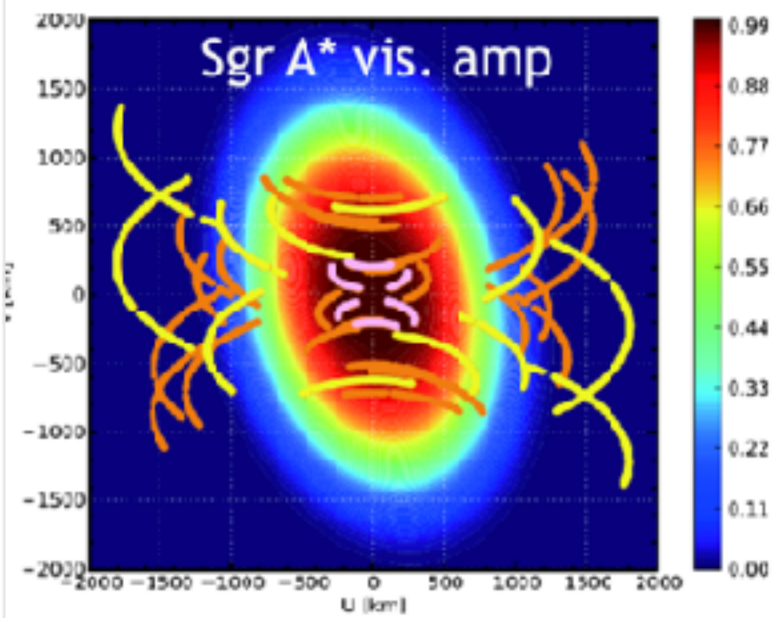
(Credit: H. Imai)

KaVA/EAVN Large Program: AGN

- **What happens in the vicinity of black holes (BHs)?**
- **M87 and Sgr A* are the best two targets for looking into the vicinity of Black holes!**
- **KaVA-EAVN AGN SWG has focused on M87 and Sgr A* since 2013~.**



(Hada et al. 2017)

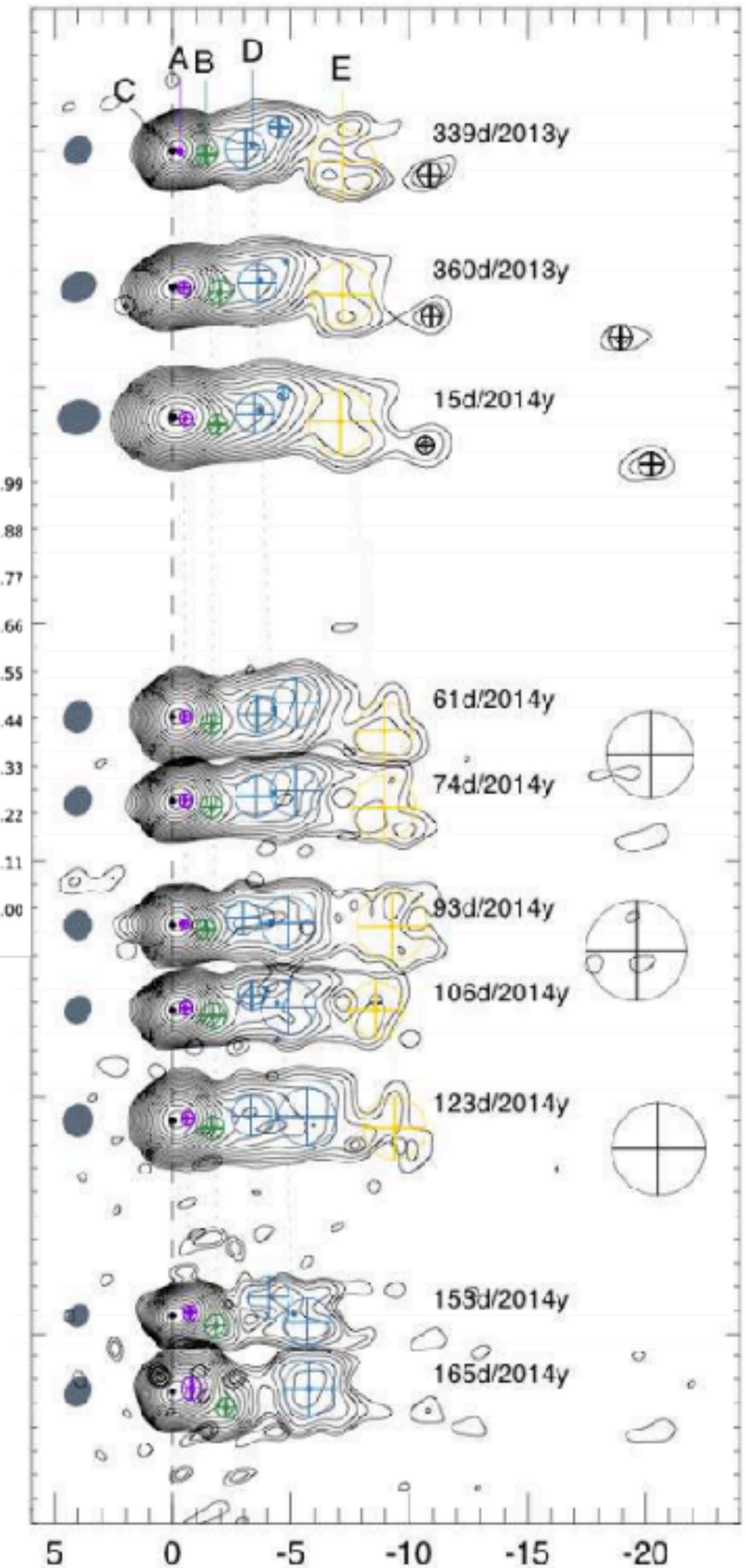


(Zhao et al. in prep)

- **M87**: biweekly at 22/43GHz
  - Velocity field of M87 Jet
  - Densely-sampled (biweekly) monitoring

- **SgrA***: monthly at 43GHz
  - G2 encounter event in 2011
  - Gas accretion process

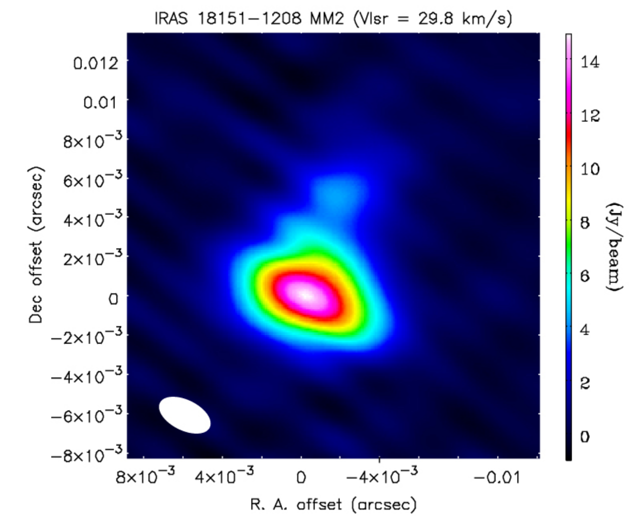
- **Complementary with EHT-ALMA**



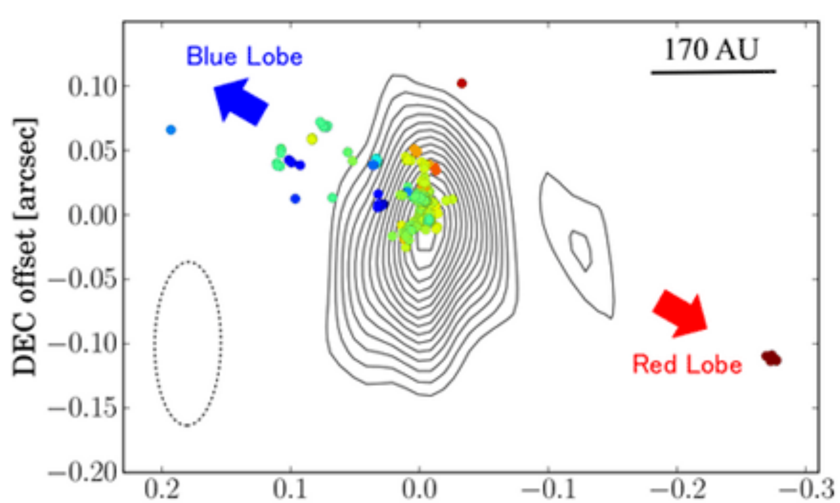
KaVA/EAVN Large Program: Star Formation

- **Goal : Understanding high-mass star formation through KaVA observations of water and methanol masers**

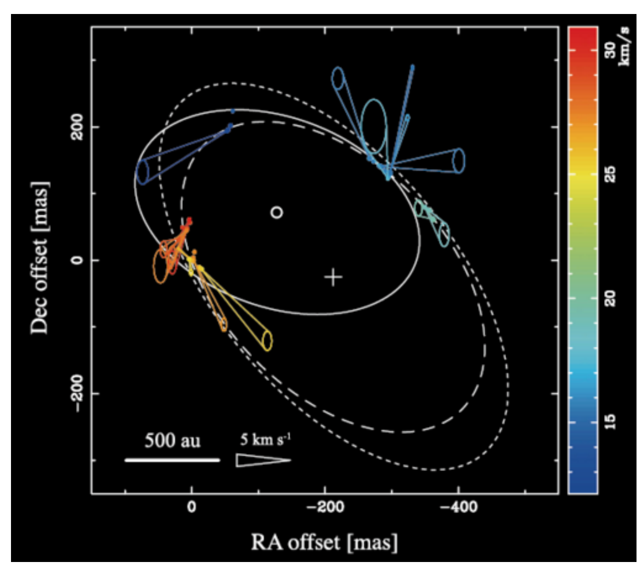
- VLBI survey/monitoring to reveal 3D velocity and spatial structures of 22GHz H_2O/44GHz CH_3OH maser lines in 87 high-mass YSOs (HM-YSOs)
  - Physical/dynamical properties of disk/jet/outflow
  - Evolution of disk/jet/outflow and maser chronology
- Tracer: Centimeter/millimeter maser lines
  - 22 GHz H_2O; high-velocity jet/outflow
  - 44 GHz CH_3OH; low-velocity outflow
  - 6.7 GHz CH_3OH; disk/low-velocity outflow (JVN/EAVN)



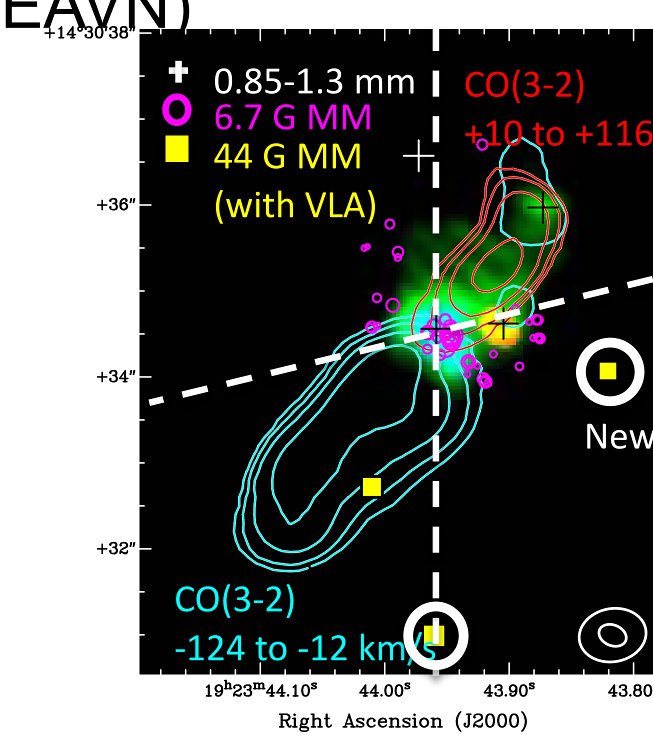
(Matsumoto et al. 2014)



G353.273+0.641
(Motogi et al. 2016);
H2O masers trace high velocity (~100 km/s) jet



G6.79-0.25
(Sugiyama et al. 2015);
6.7 GHz CH3OH masers trace rotating disk



W51e2 (44GHz CH3OH maser by Sugiyama and SMA images by Shi et al. 2010)

Follow-up observation with ALMA

History of KaVA / EAVN Collaborations

2001
KVN project start
First fringe detection between Korea(TRAO) and Japan (NRO45m)

2002
VERA in Operation
MOU for VLBI Collaboration (KASI-NAOJ)

2003

2004
VERA practice
VLBI data reduction tutorial
EA VLBI Consortium formed

2005
KVN construction & Subsystem development
K-J VLBI workshop started & Postdoc from Japan
EACOA established —> incl. EAVC

2006
Funding for KJ correlator and KVN MF receiver
Researcher from Japan

2007
First light of KVN Ulsan
VLBI Lectures (Sasao-San)

2008
KVN Construction completed
First 22GHz fringe among KVN Yonsei-VERA Miz-SHAO
First EA VLBI Workshop

2009
First 22/43GHz fringes btw KVN Yonsei-Ulsan

2010
KVN-VERA 22/43GHz fringes
Start KVN-VERA 22/43GHz VLBI observation

2011
KVN 22/43/86/129GHz fringes (Ky-Ku)
KVN-EVN/JIVE e-VLBI fringes

2012
KVN 22/43/86/129GHz fringes (all KVN)
KVN+VERA Science WG & start science observations
KVN join to EVN

2013
KaVA science workshop
EAVN Tiger Team organized
First EAVN VLBI observations

2014

2015
First fringes with Tianma 65m

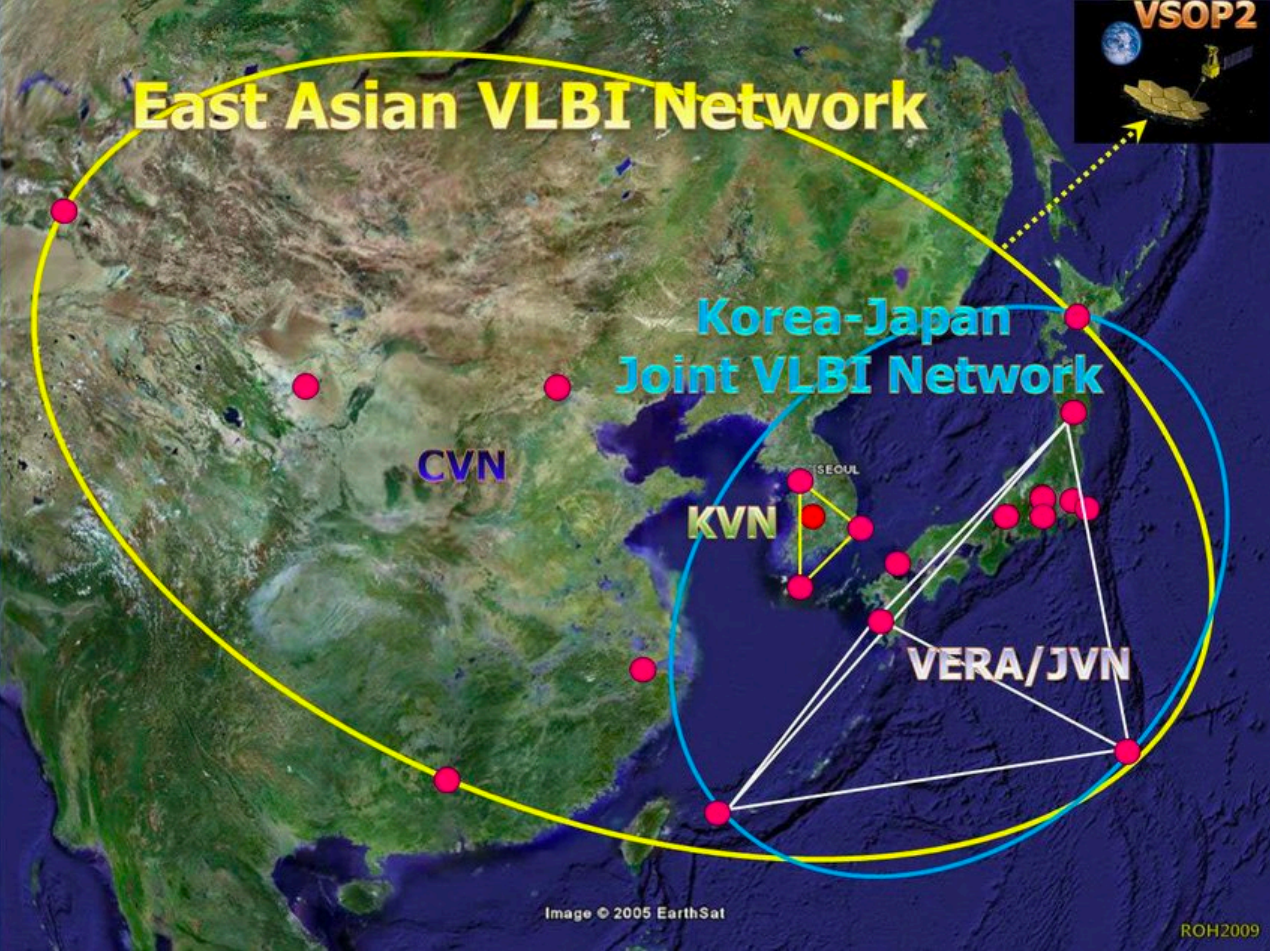
2016
KVN 22/43/86/129GHz fringes (all KVN)
KVN+VERA Science WG & start science observations
Chinese join to KaVA SWG

2017

2018
First Call for Proposals of EAVN
MOU for EAVN collaboration during EAVW

2019
Discussion to merge KaVA to EAVN

2020
Monthly telecon meeting among each EAVN SWG
Monthly telecon meeting for KaVA/EAVN operation
Quarterly meeting of EAVN directors
EA VLBI Workshop every year



East Asian VLBI Network
VSOP2
Korea-Japan
Joint VLBI Network
CVN
SEOUL
KVN
VERA/JVN
Image © 2005 EarthSat
ROH2009

EAVN workshops

- 10th: 2017 Jul 7, ASIAA, Taipei, Taiwan (half-day workshop after APRIM)
- 9th: 2016 Nov 7 – 11, Forest Moon Hotel, Guiyang, China
- 8th: 2015 Jul 8 – 10, Hokkaido Univ., Hokkaido, Japan
- 7th: 2014 Aug 20, Daejeon Convention Center, Daejeon, Korea (as part of APRIM
- 6th: 2013 Jun 17 – 19, Shineville Resort, Jeju, Korea
- 5th: 2012 May 30 – Jun 1, ASIAA, Taipei, Taiwan
- 4th: 2011 Apr 18 – 20, Hexi Hotel, Lijiang, China
- 3rd: 2010 Apr 22 – 24, Kagoshima Univ., Kagoshima, Japan
- 2nd: 2009 Mar 18 – 20, Ehwa Womans Univ., Seoul, Korea
- 1st: 2008 Mar 20 – 22, SHAO, Shanghai, China

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MEMORANDUM OF UNDERSTANDING ON
SCIENTIFIC AND TECHNICAL COLLABORATION FOR THE EAST-ASIAN VLBI NETWORK
AMONG
KOREA ASTRONOMY AND SPACE SCIENCE INSTITUTE,
NATIONAL ASTRONOMICAL OBSERVATORY OF JAPAN,
SHANGHAI ASTRONOMICAL OBSERVATORY, AND
XINJIANG ASTRONOMICAL OBSERVATORY

1. Aims

This Memorandum of Understanding (hereafter MoU) aims to promote collaboration on scientific research and technical development for the East-Asian Very Long Baseline Interferometry Network (hereafter EAVN) among Korea Astronomy and Space Science Institute (hereafter KASI), National Astronomical Observatory of Japan (hereafter NAOJ), Shanghai Astronomical Observatory (hereafter SHAO), and Xinjiang Astronomical Observatory (hereafter XAO). This MoU is the replacement of previous MoU among KASI, SHAO, and XAO signed on November 13, 2013. On

References & More Information

- **Websites**
  - Korean VLBI Network (KVN) http://kvn.kasi.re.kr
  - KVN and VERA Array (KaVA) http://kava.kasi.re.kr
  - East Asian VLBI Network (EAVN) http://eavn.kasi.re.kr

- **References**
  - Simultaneous multi-frequency science cases
  - East Asian Activities for mm/submm VLBI


New Astronomy Reviews

The science case for simultaneous mm-wavelength receivers in radio astronomy

Richard Dodson, María J. Rioja, Taehyun Jung, José L. Gomez, Valentin Bujarrabal, Luca Moscadelli, James C.A. Miller-Jones, Alexandra J. Tetarenko, Gregory R. Sivakoff

ARTICLE INFO

ABSTRACT

(Dodson et al. 2017)


White Paper on East Asian Vision for mm/submm VLBI:

Toward Black Hole Astrophysics down to Angular Resolution of 1 R_S

arXiv:1705.04776v1 [astro-ph.HE] 13 May 2017

Editors

Authors

(Asada et al. 2017)

References & More Information

- **KVN/KaVA/EAVN Call for Proposal Deadlines: June 1 & Nov 1**

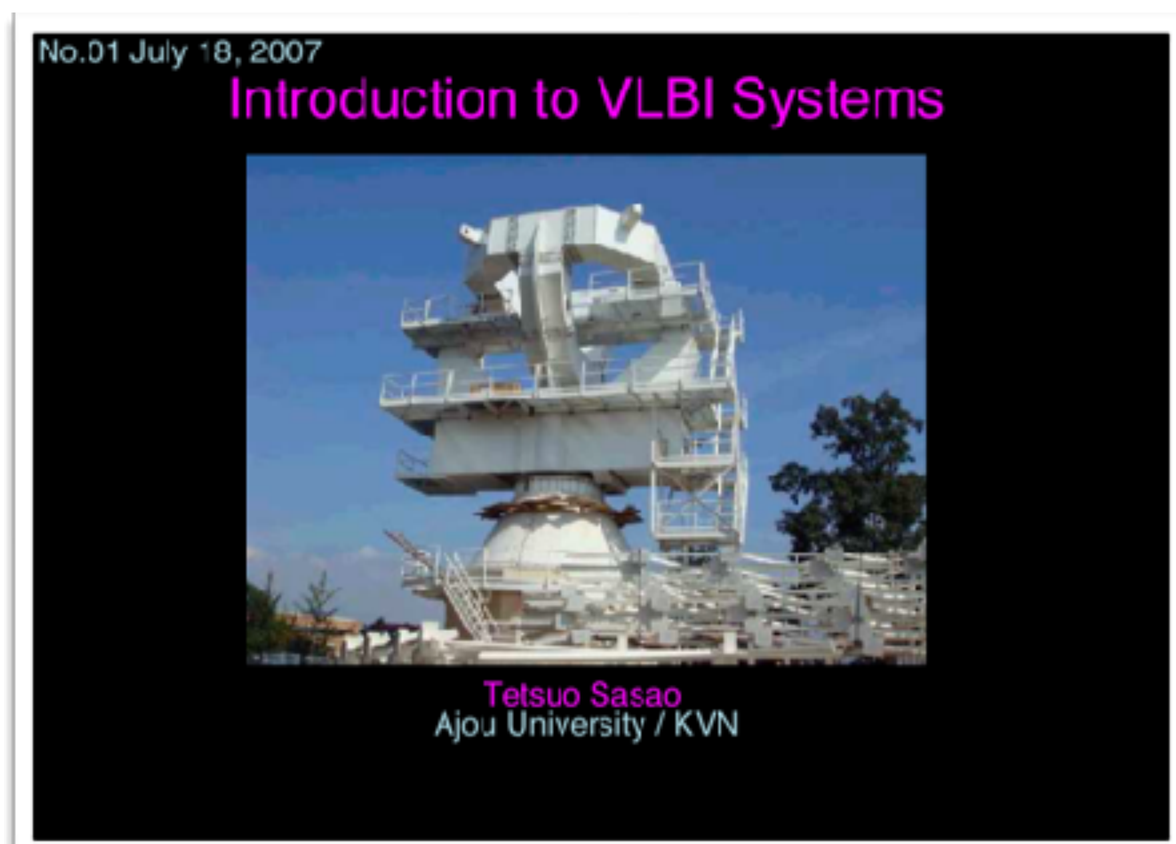
- **East Asia Radio Astronomy (Interferometry) Winter School: every year**

- **Sasao-san's Lecture Notes (24 lectures) and BooK**
  - Introduction to VLBI System (https://drive.google.com/open?id=1QsO_NmU0bK1LomFzMeDh-9geVIAXWqVA)
    - Chapter 1. Basic Knowledge of Radio Astronomy
    - Chapter 2. Radio Telescope Antennas
    - Chapter 3. Radio Interferometry
    - Chapter 4. Very Long Baseline Interferometry


Tetsuo Sasao and André B. Fletcher
Introduction to VLBI Systems
Chapter 1
Lecture Notes for KVN Students
Based on Ajou University Lecture Notes
(to be further edited)
Version 2.
Issued on February 28, [illegible]
Revised on March 18, [illegible]
Revised on February 4, 2006.

Basic Knowledge of Radio Astronomy

Contents



Thank You!

EAVN