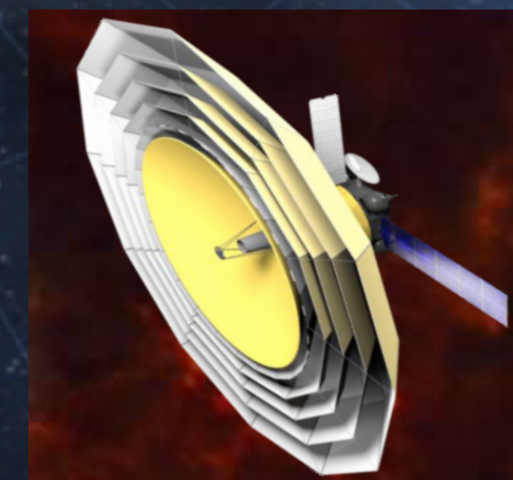
Simultaneous Multi-Frequency VLBI Observations of KVN & EKVN with Millimetron

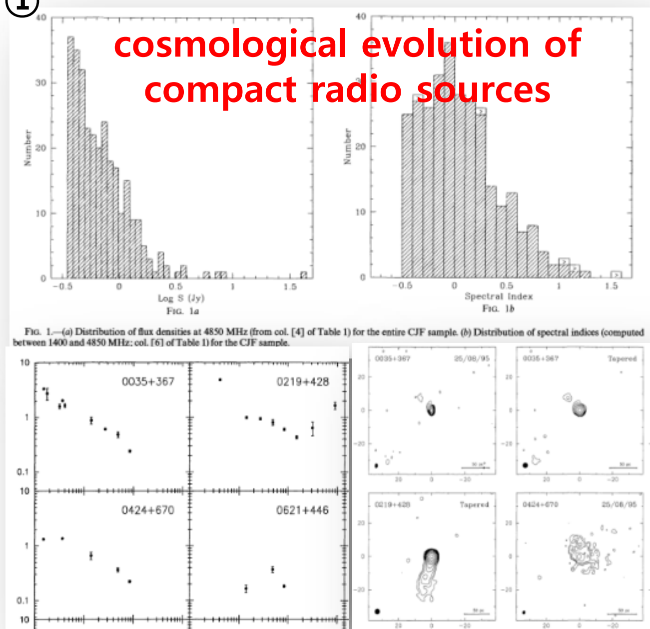


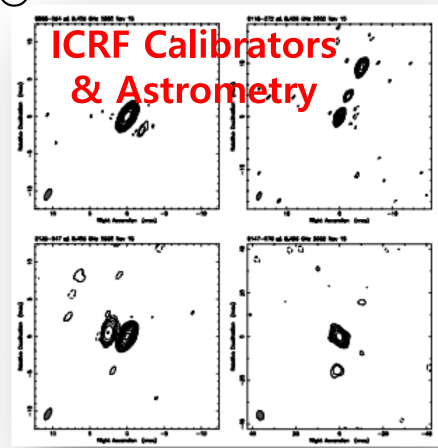
Taehyun Jung

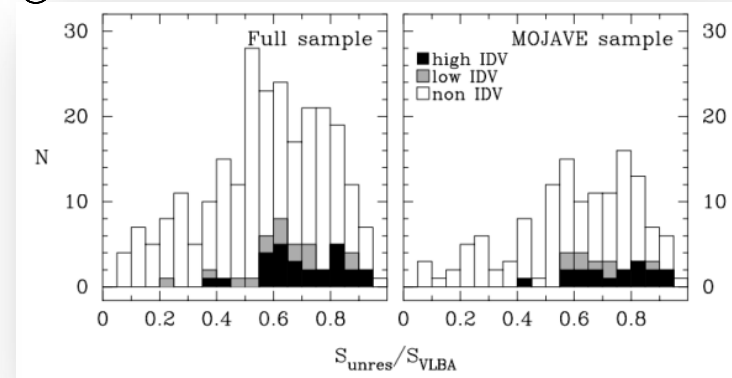
Korean VLBI Network

Korea Astronomy and Space Science Institute (KASI)

Millimetron Workshop 2019 @ Paris, September 10, 2019

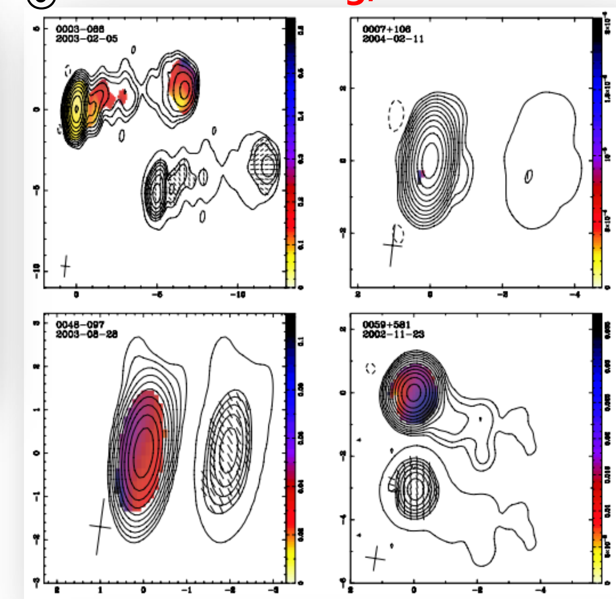
① 

④ 

⑤ 

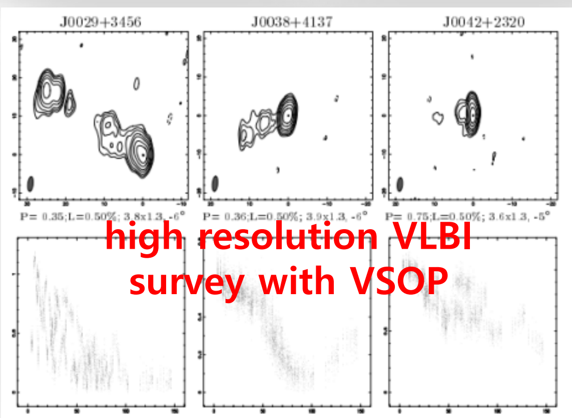
statistical study, sub-mas imaging
compactness vs γ-ray, B_t

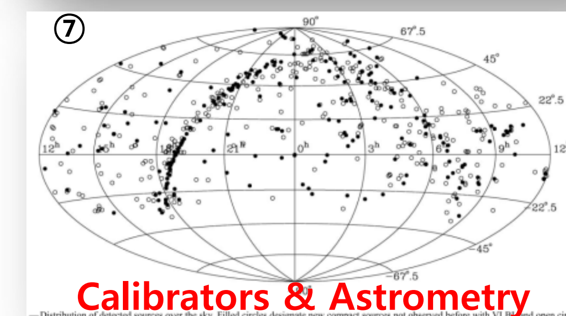
⑥ Jet monitoring, evolution

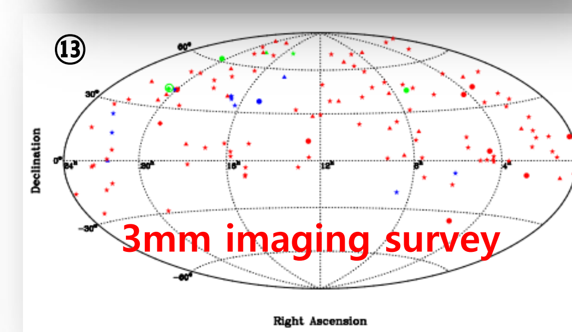


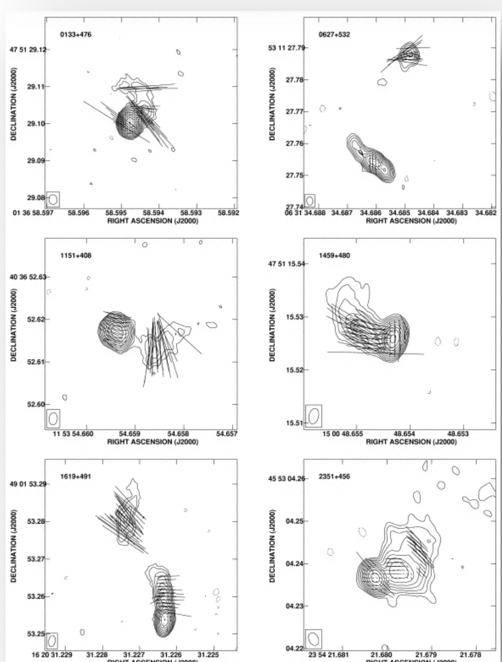
VLBI Surveys

Survey ID	Wavelength	No. Sources	Reference
① CJF survey	6 cm	293	Taylor et al. (1996)
② VSOP VLBApls	6 cm	374	Fomalont et al. (2000)
③ CJF Polarimetry survey	6 cm	177	Pollack et al. (2003)
④ ICRF	3.6 cm	~500	Ojha et al. (2004, 2005) and references therein
⑤ 2cm Survey	2 cm	250	Kovalev et al. (2005)
⑥ MOJAVE	2 cm	>133	Lister & Homan (2005)
⑦ VERA FSS / GaPS	1.35 cm	500	Petrov et al. (2007)
⑧ VLBA Calibrator Survey	13 & 3.6 cm	>3400	Kovalev et al. (2007)
⑨ VIPS	6 cm	1127	Helmboldt et al. (2007)
⑩ VSOP Survey	6 cm	~300	Dodson et al. (2008)
⑪ TANAMI	3.5 & 1.3 cm	80	Ojha et al. (2010)
⑫ mJIVE-20	20 cm	>4300	Deller & Middelberg (2014)
⑬ GMVA 3mm	3 mm	123	Lee et al. (2008)
⑭ ICRF 22 & 43 GHz	13.7 & 7 mm	~100	Lanyi et al. (2010)
⑮ KVN Q-CAL survey	7 mm	638	Petrov et al. (2012)

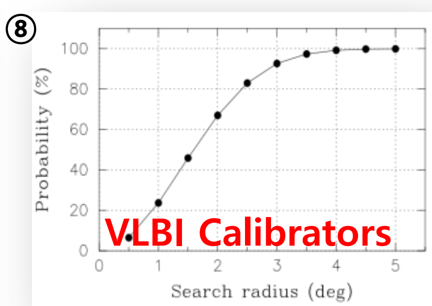
② 

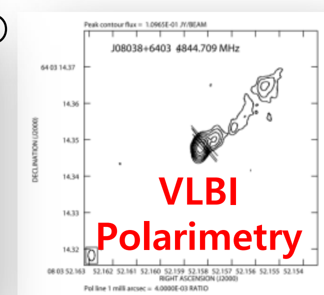
⑦ 

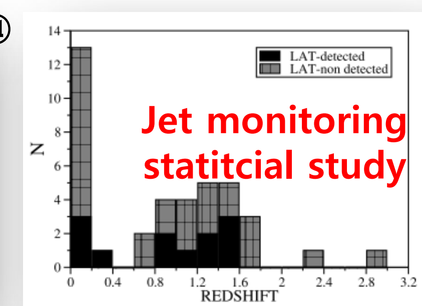
⑬ 

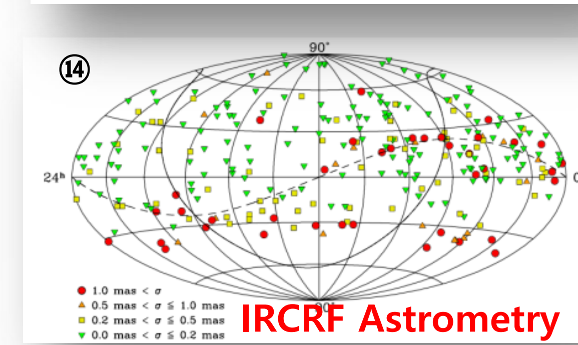
③ 

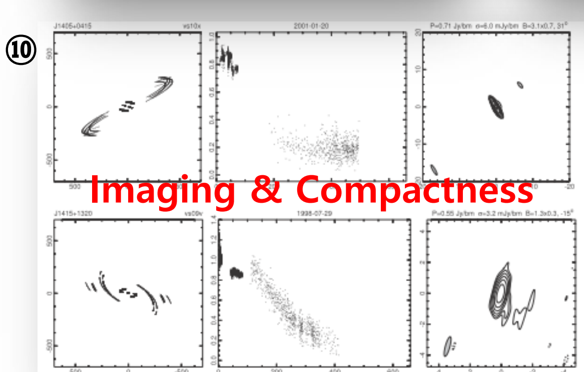
Jet properties (PA vs jet
axis angle), AGN evolution

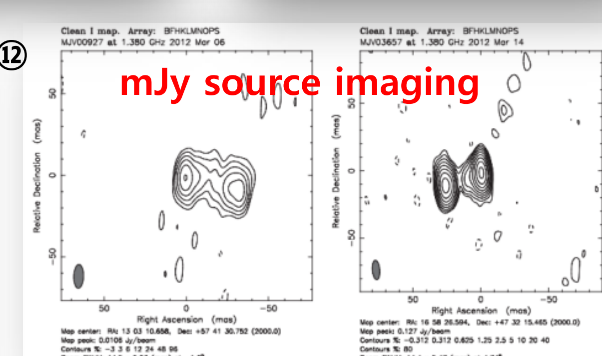
⑧ 

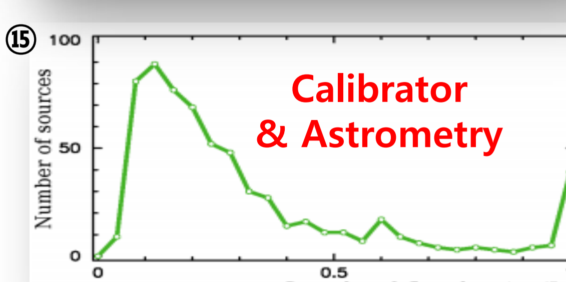
⑨ 

⑪ 

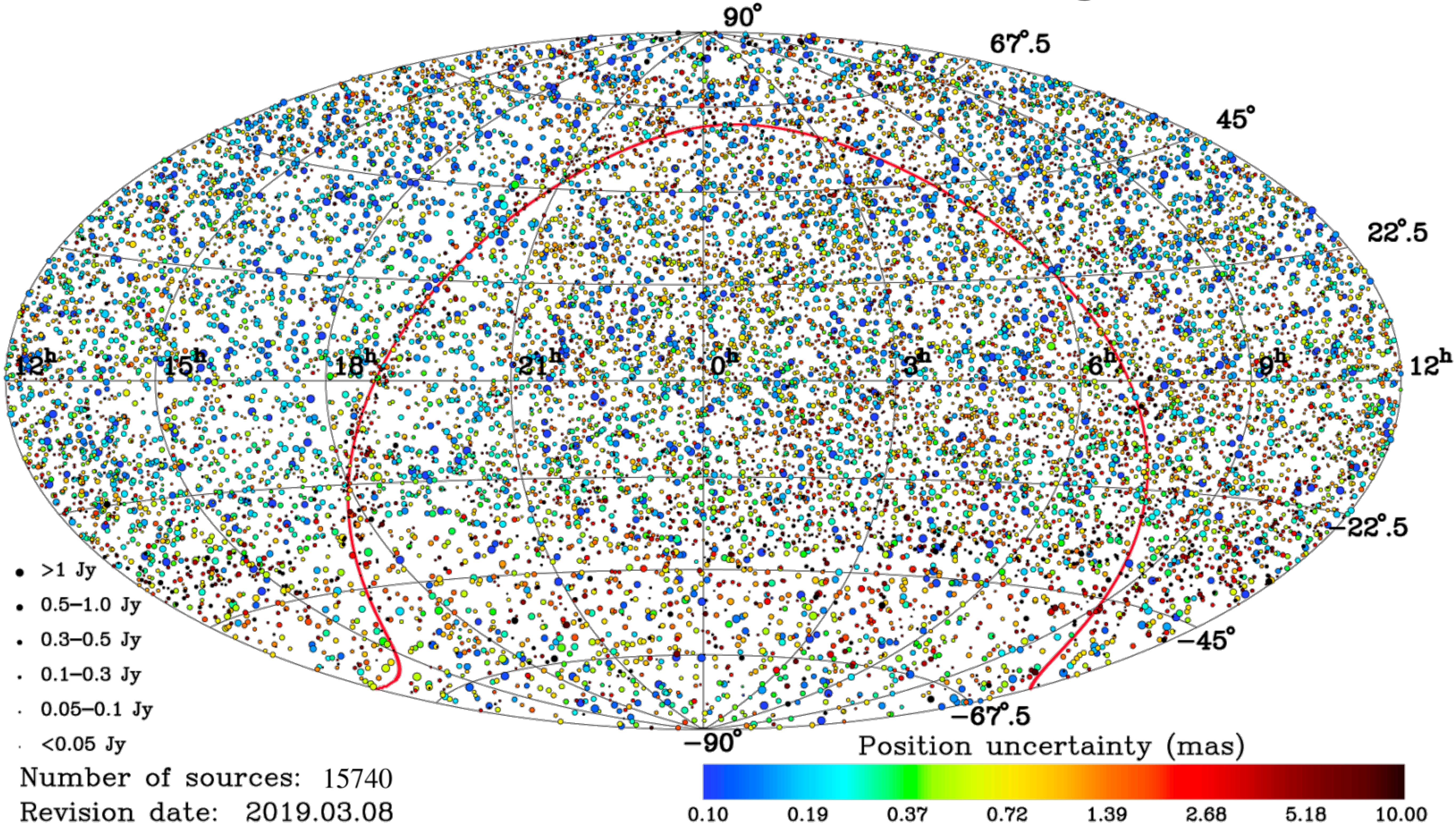
⑭ 

⑩ 

⑫ 

⑮ 

Radio Fundamental Catalogue



Credit: L. Petrov (http://astrogeo.org)

Number of VLBI sources at mm-wavelengths are very limited

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)
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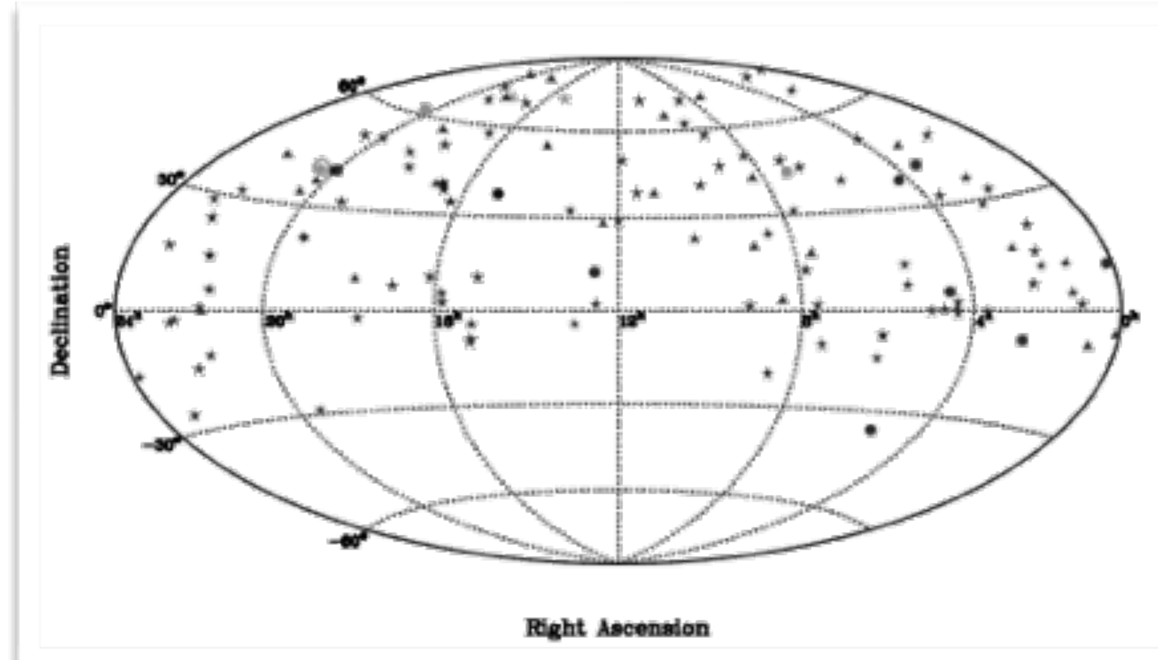
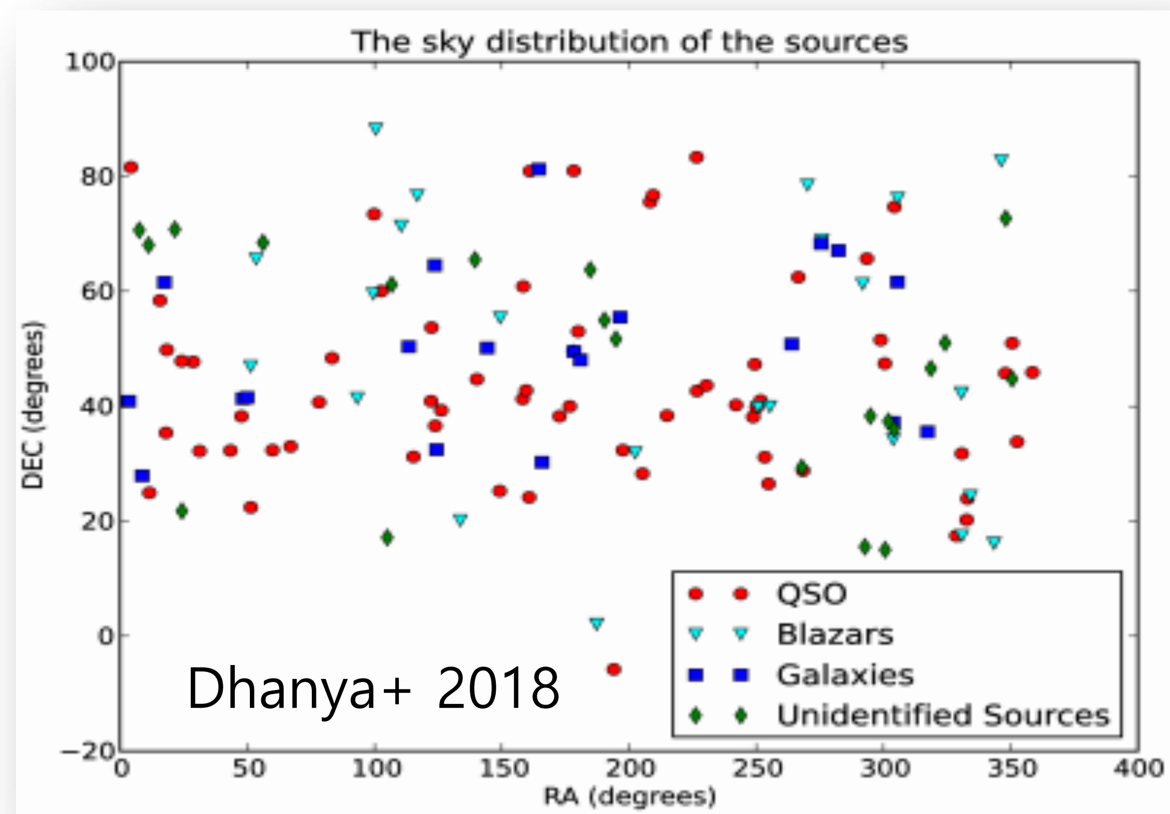


Lee+ 2007 (108 sources at 3 mm)

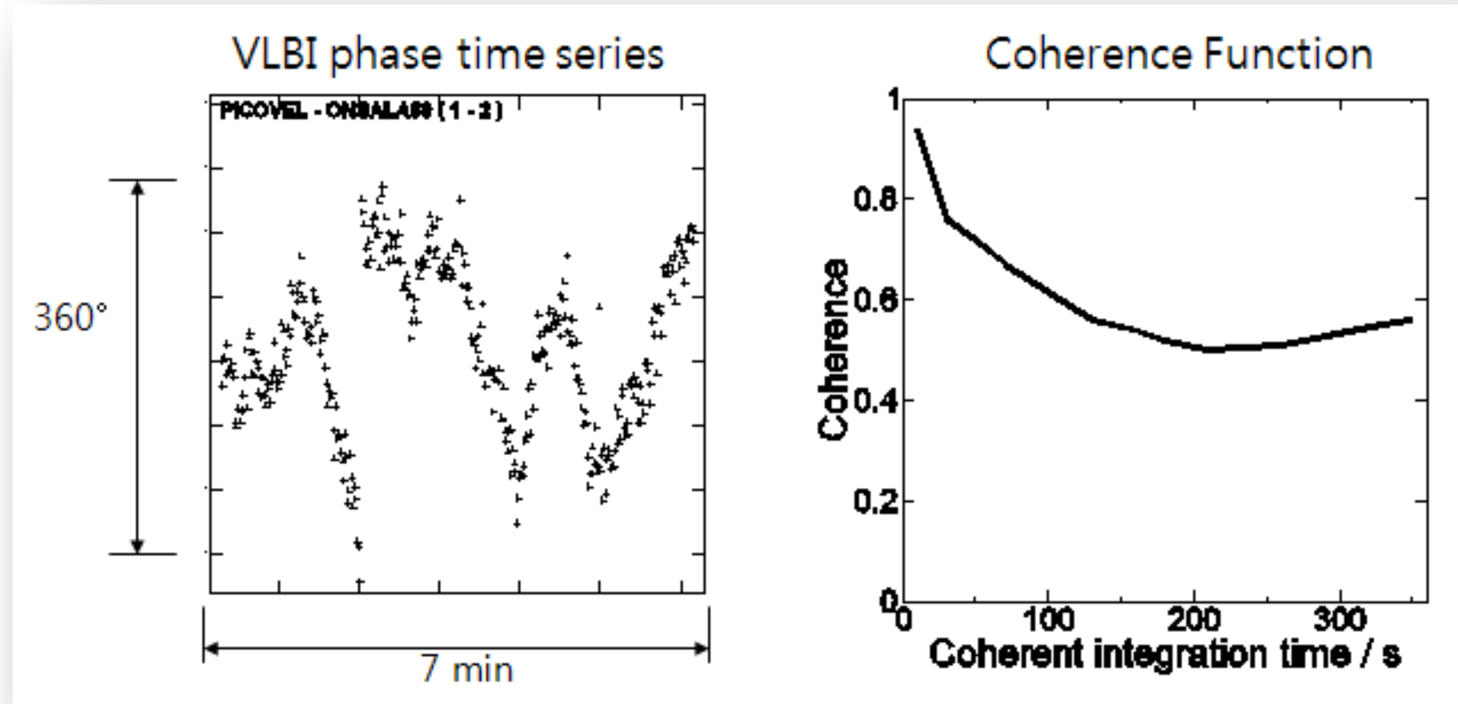


162 sources at 3 mm

Only ~5% of RFC is available at 7 mm (43 GHz)
Only ~1% of RFC is available at 3 mm (86 GHz)
How about 1 mm (230 GHz) ??

Errors coming from the **ATMOSPHERE** are still remain the most serious difficulty which significantly degrade the sensitivity and imaging capability of mm and sub-mm VLBI observation

Coherence



Pico Veleta – Onsala baseline
Source : BL Lac
Frequency : 86 GHz

(A. Roy)

Coherence Function

$$C(T) = \left|\frac{1}{T}\int_0^T e^{i\phi_t} dt\right|,$$

VLBI Sensitivity

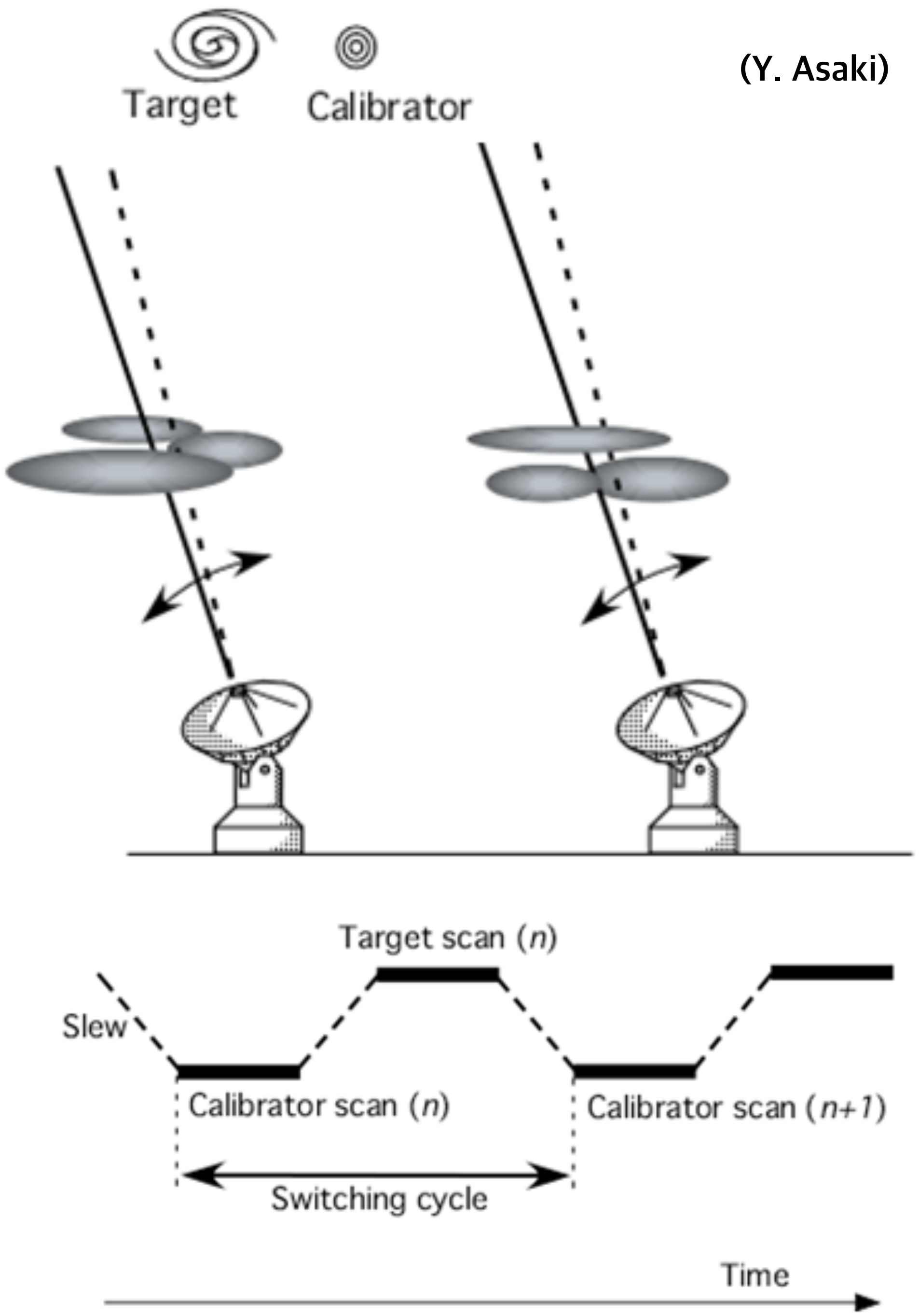
$$S_\nu = (SNR)\frac{8k}{\pi\eta_c}\frac{\sqrt{T_{S_1}T_{S_2}}}{\sqrt{\eta_{A_1}\eta_{A_2}}D_1D_2\sqrt{2B\tau_a}}$$

Coherence Time

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

*Typical value of atmospheric phase stability ~ 10^{-13}

VLBI Phase Referencing



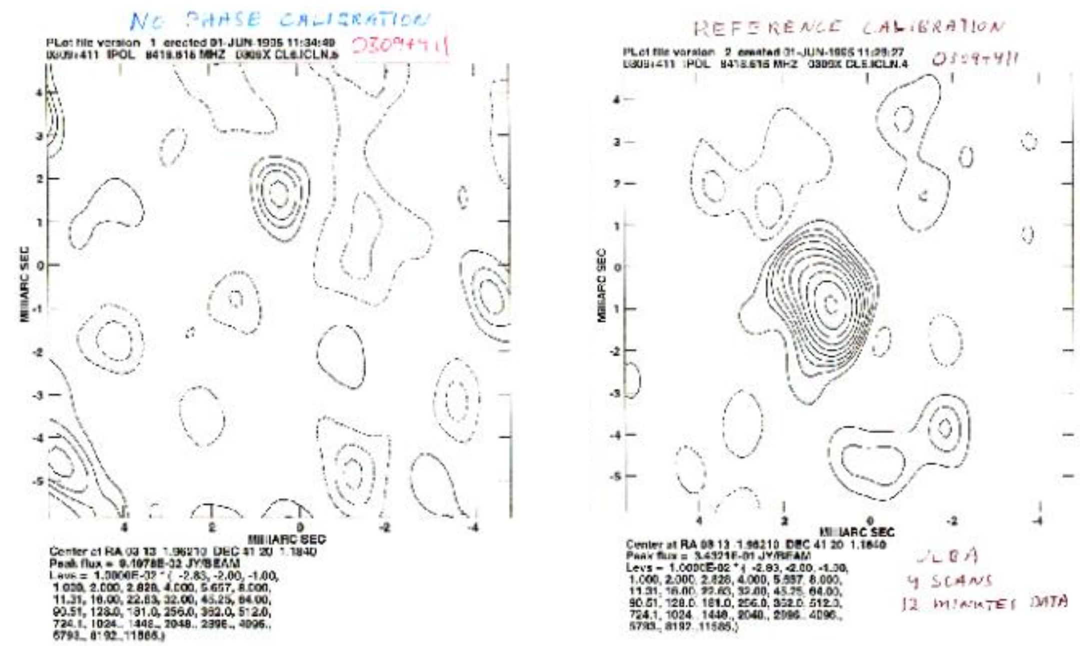
(Y. Asaki)

Antenna Nodding (Switching)

1. Increase coherence time

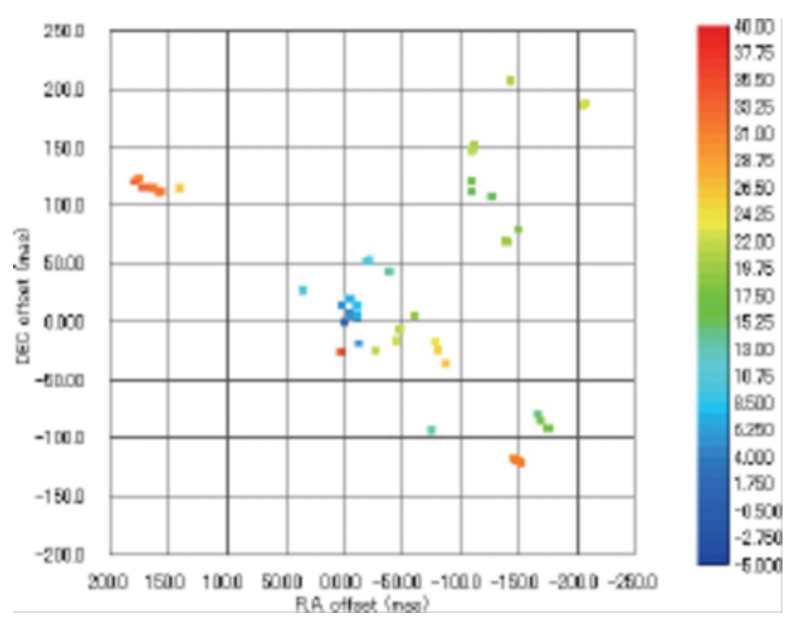
Without Phase Referencing

With Phase Referencing

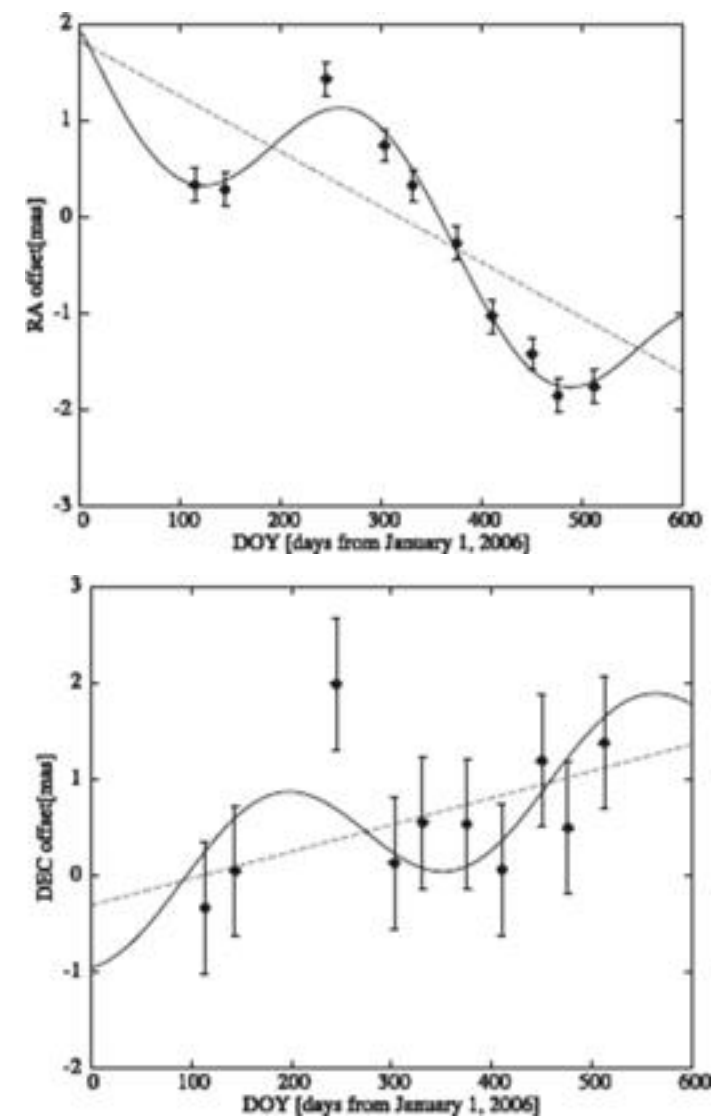


Weak source detection

2. Astrometry



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

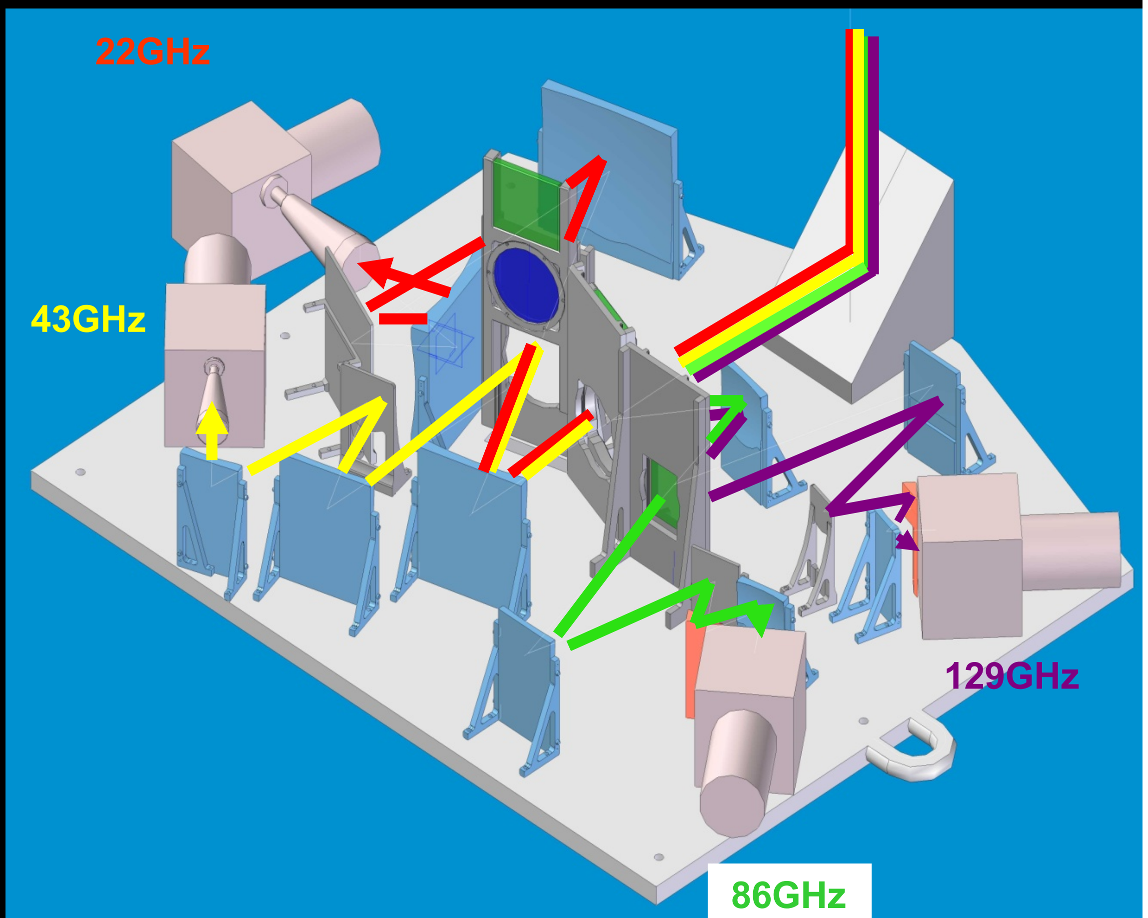


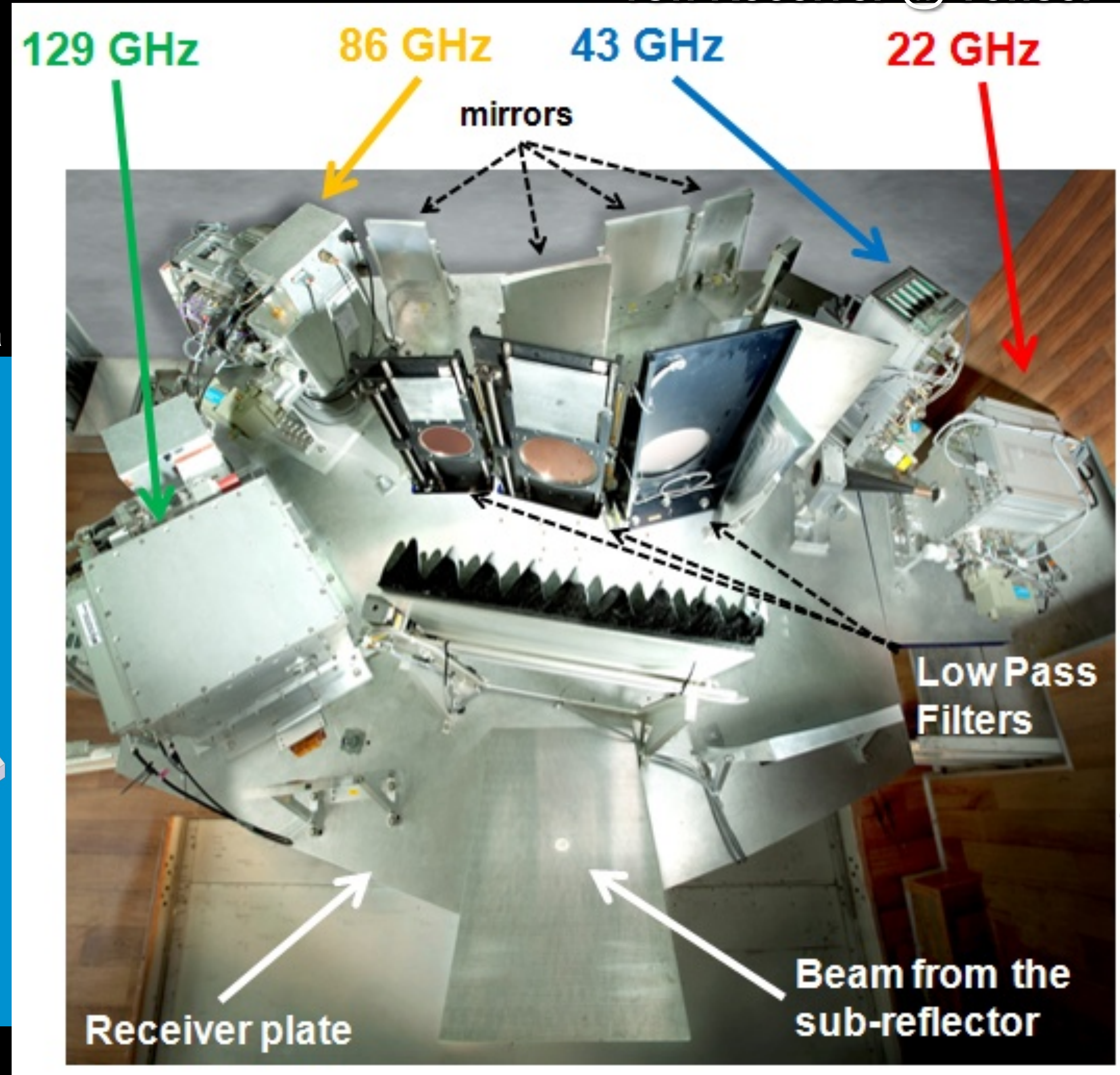
cm VLBI vs mm-VLBI

	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


KVN 한국우주전파관측망
Korean VLBI Network
KVN Yonsei
KVN Ulsan
KVN Tamna
305. 2 km
477. 7 km
358. 5 km
KVN Yonsei Observatory
KVN Ulsan Observatory
KVN Tamna Observatory
• 3 Telescopes (D = 21m)
• 22/43/86/129GHz (2.6 ~ 18mm)
• Baseline 300 - 500 km
• Θ = 1 - 6 mas
한국천문연구원
대덕전파천문대 KVN사업본부

Multi-Frequency Receiving System



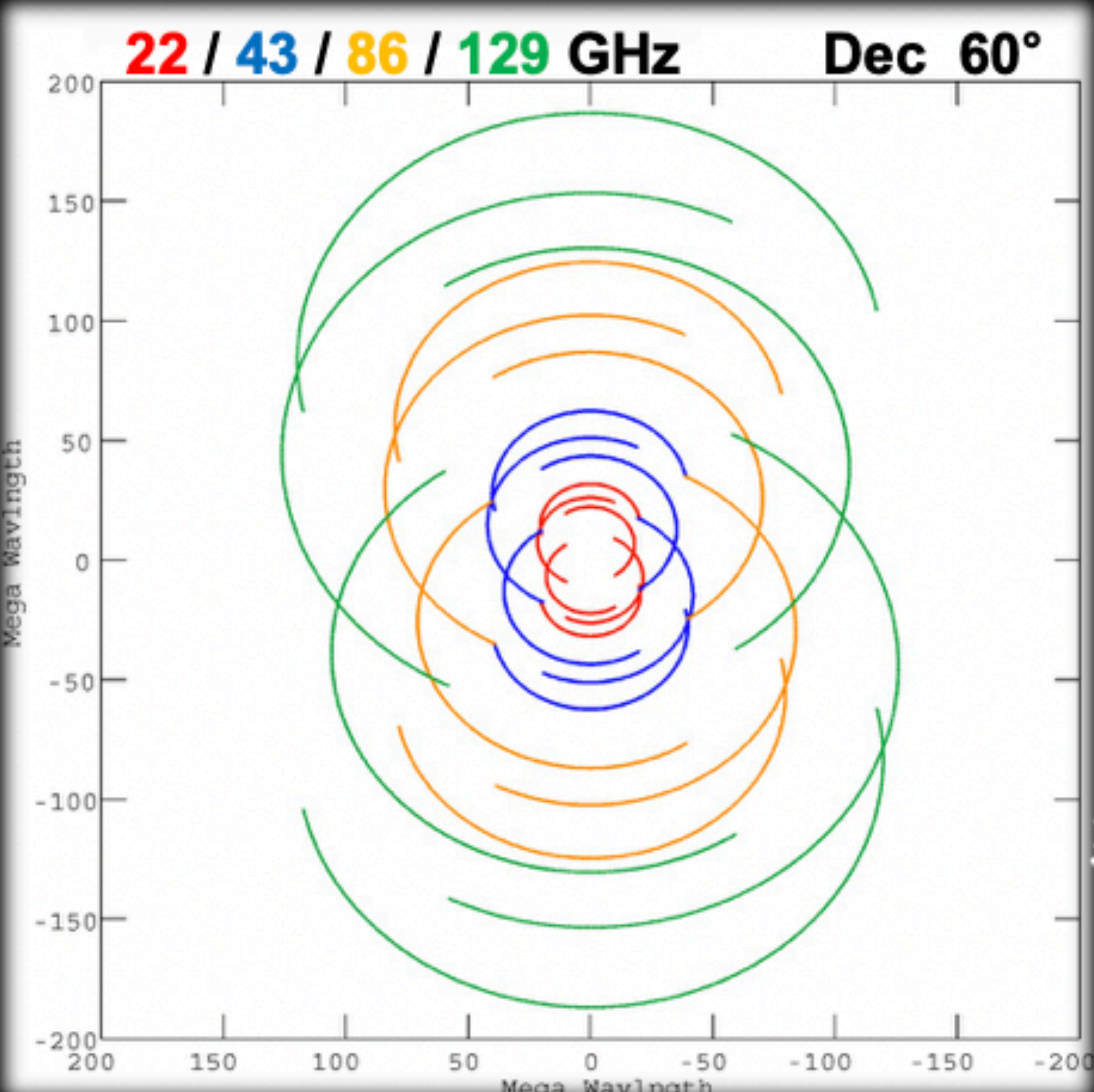


Band	K	Q	W	D
Freq. Range	21.25-23.25	42.11-44.11	85-95	125-142
Trx (K)	30-40	70-80 (40-50 KUS)	80-100	50-80

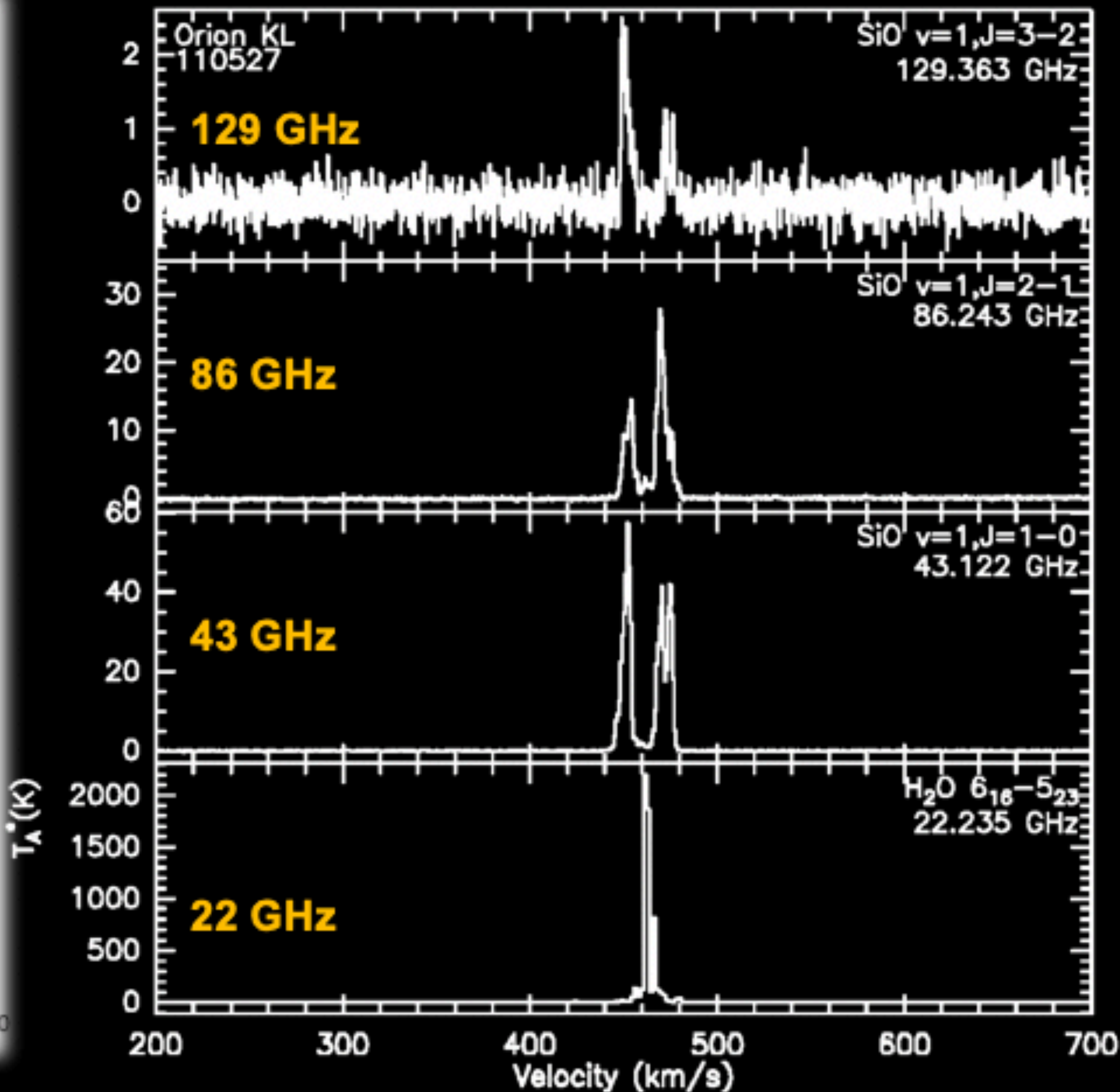
Full Polarization

Han et al. (2008)

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

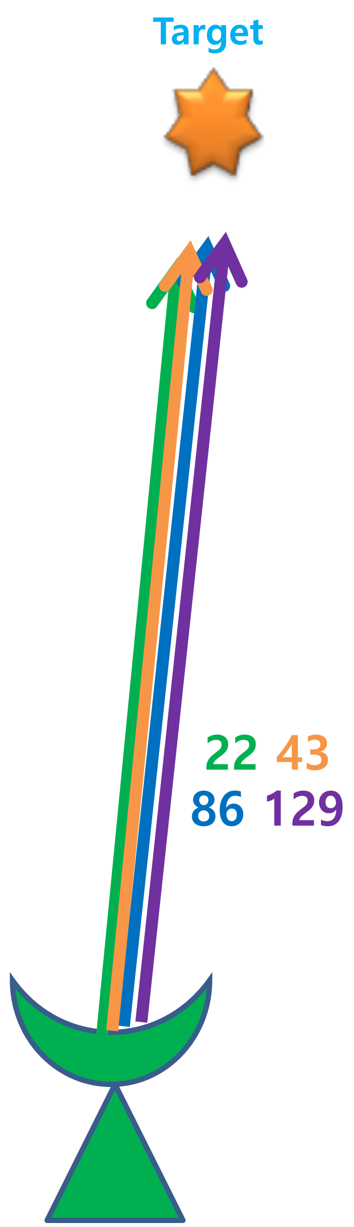


4CH UV Coverage

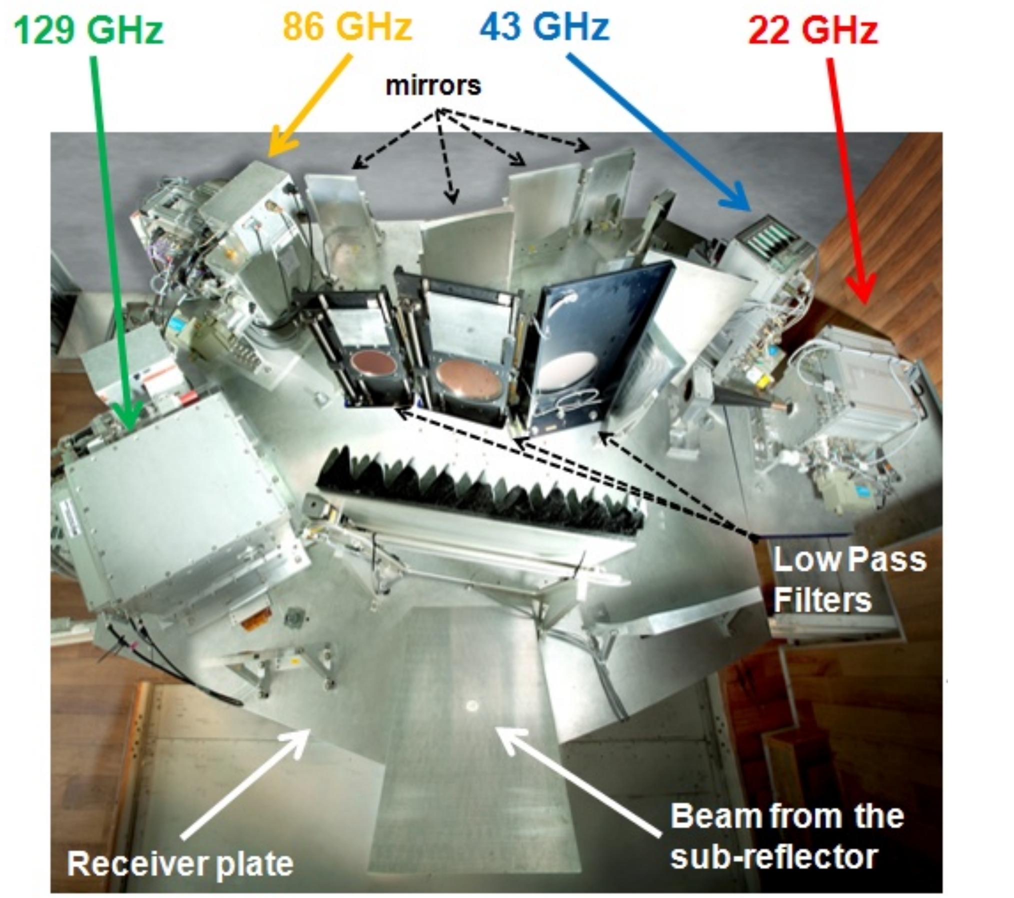


H20/SiO Masers in Orion KL

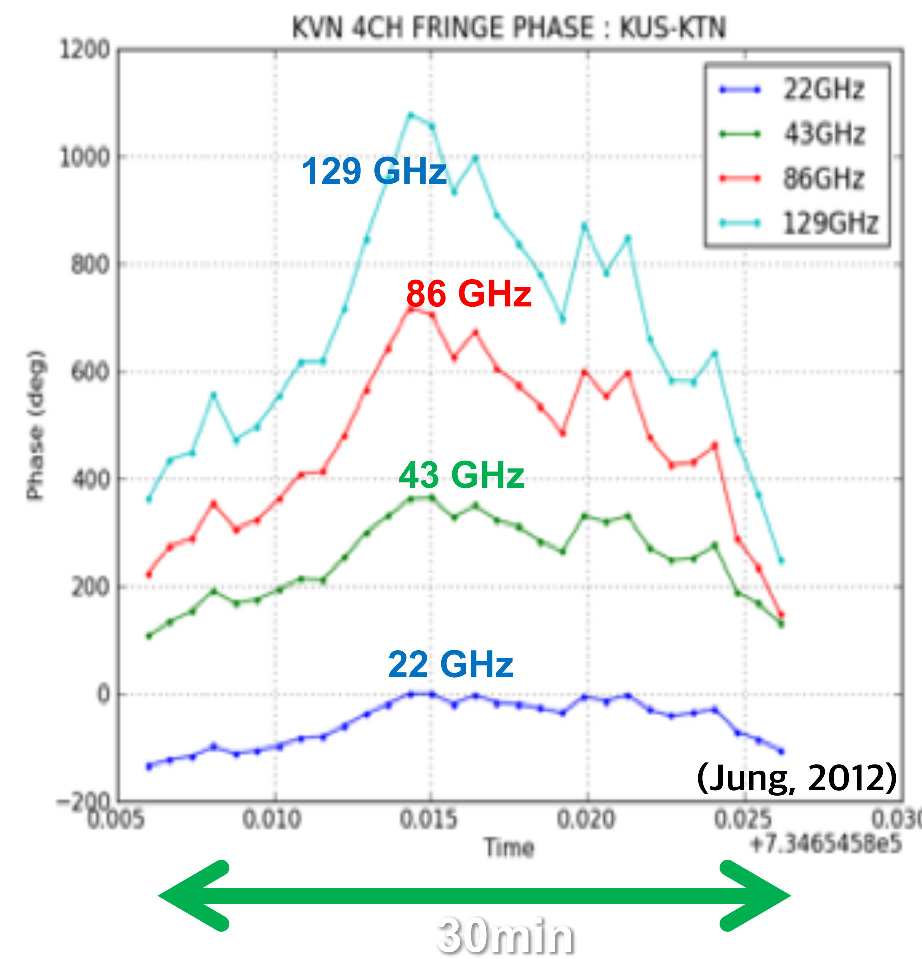
VLBI Phase Referencing Techniques

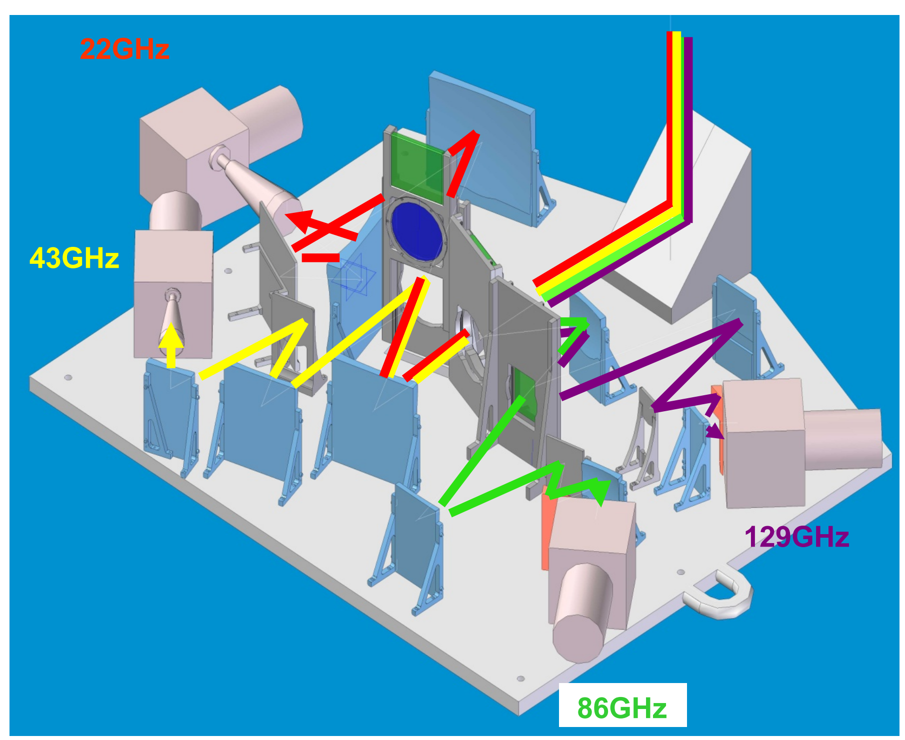


Multi-Frequency System



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



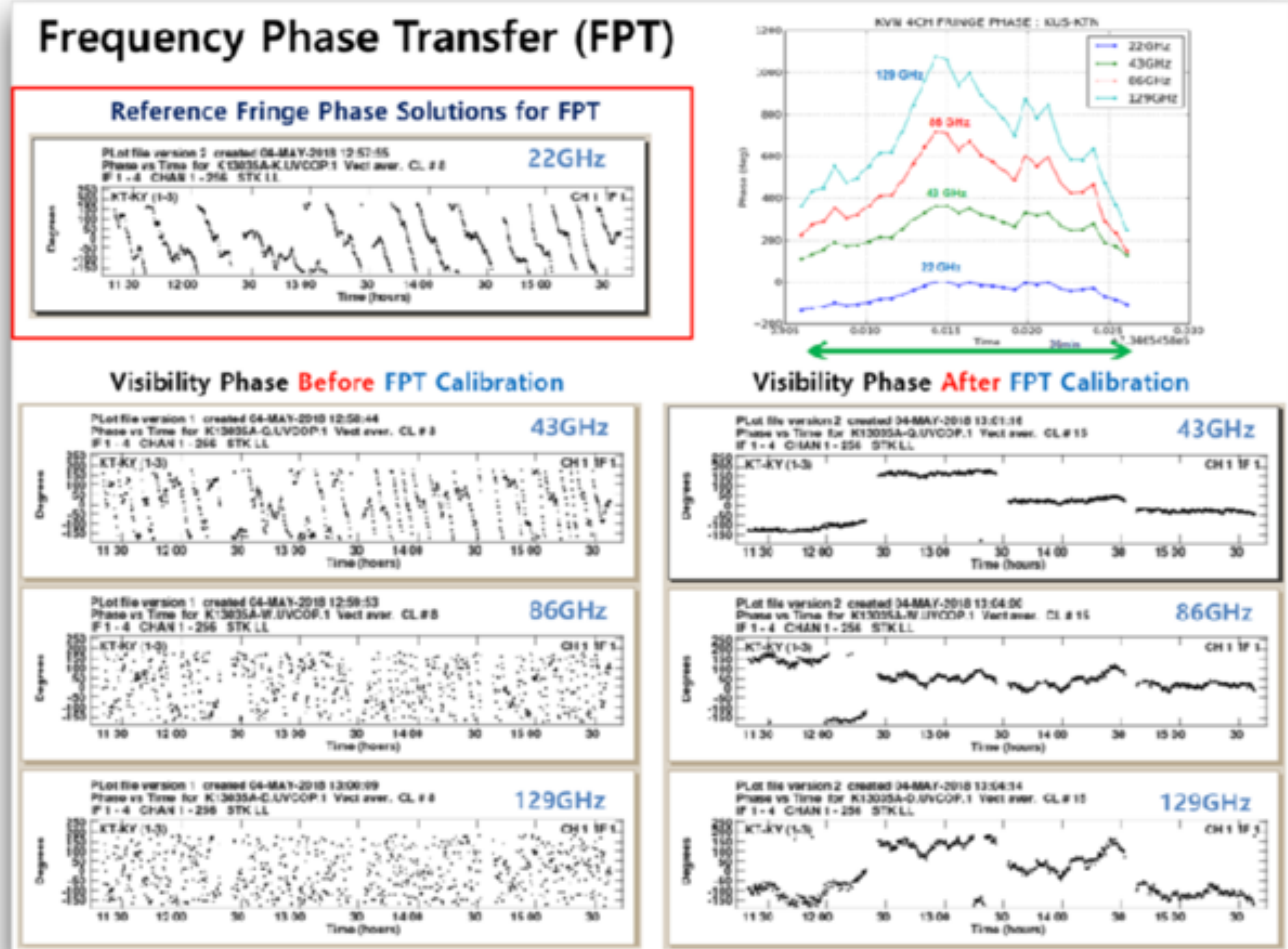


$$\frac{\partial \phi_{high}}{\partial t} = \left(\frac{\nu_{high}}{\nu_{low}} \right) \times \frac{\partial \phi_{low}}{\partial t}$$

Non-dispersive nature of troposphere

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

Simultaneous Multifrequency Receiving System

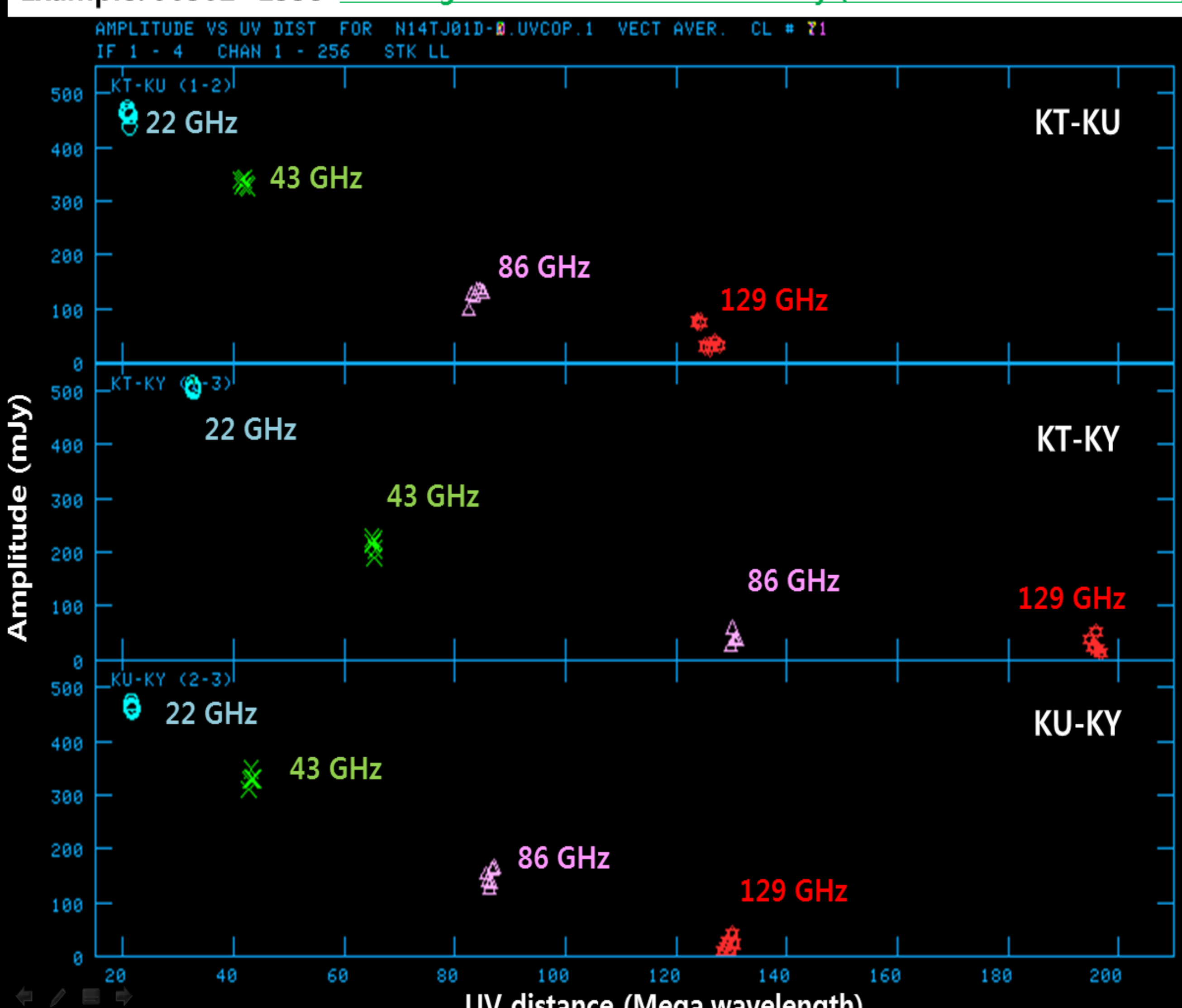


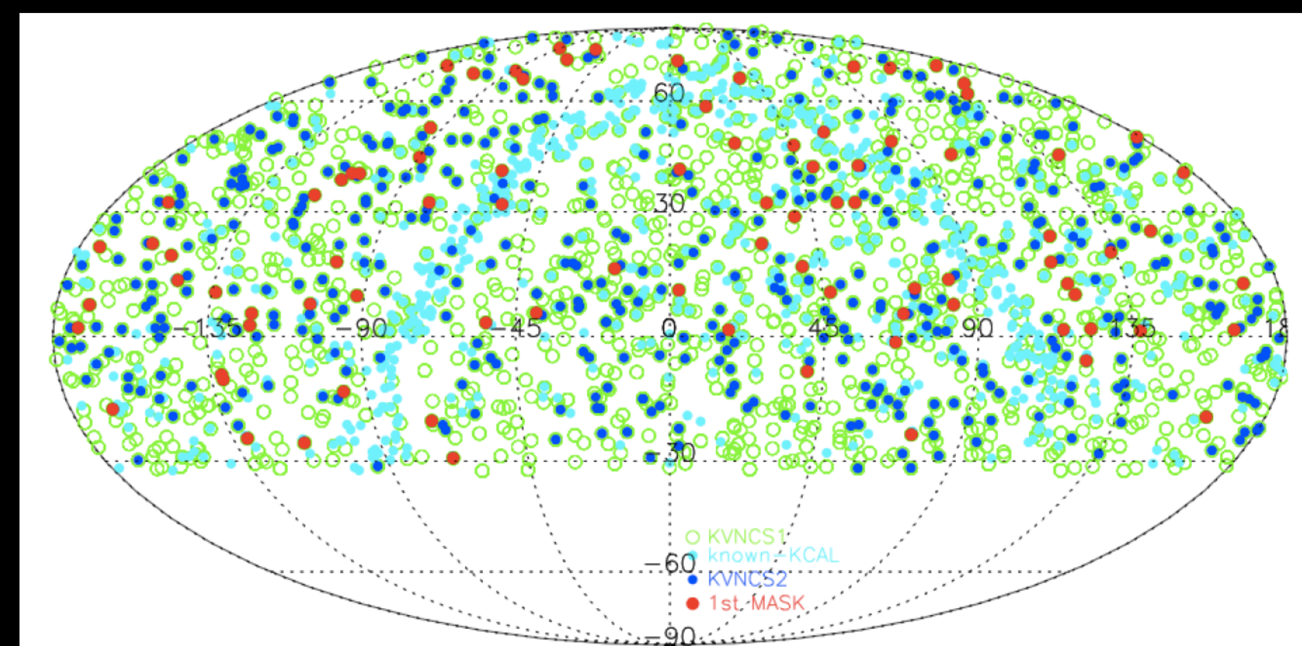
KVN’s Simultaneous Multi-Frequency VLBI System

- **Excellent calibration of atmosphere**
  → Pefect calibration on troposphere (non-dispersive delays)
  → Superb calibration on Ionosphere (dispersive)
- **Exceptional improvement on coherence time**
  → The largest VLBI source detections at 2-3 mm ever!

MASK: Multi-frequency AGN Survey with the KVN

Example: J0502+1338 KVN single dish flux at 22GHz ~ 0.3 Jy (No SD detection at 43GHz)



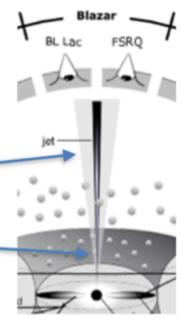


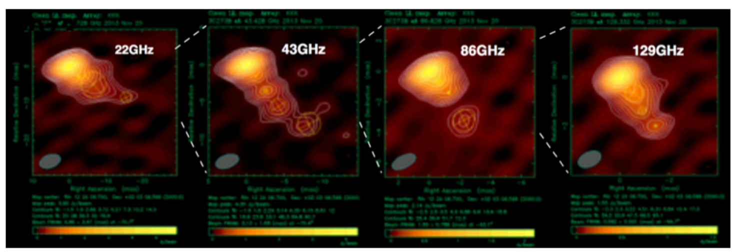
- MASK observation status (updated on 2019 Jan 11)
  - Observed sources : 1,480 (96.5 %)
  - Remaining sources : 53
- MASK detection statistics (updated up to 2018A season)
  - Total reduced data set : 719 sources (47% processed)
  - Detection statistics for 719 sources until 2018A season

	K-Self	FPT (K→Q)	FPT (K→W)	FPT (K→D)	FPT (Q→W)	FPT (Q→D)
SRC detection	671	574	428	281	335	244
Detection Rate	93%	80%	60%	39%	47%	31%

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/

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

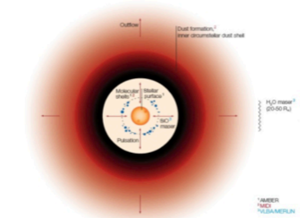
○ Pulsation and shock wave propagation effect from SiO to H_2O maser region via dust layer : **development of outflow motion and asymmetry ► Mass loss mechanism** based on combined studies of SiO and H_2O masers.

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.

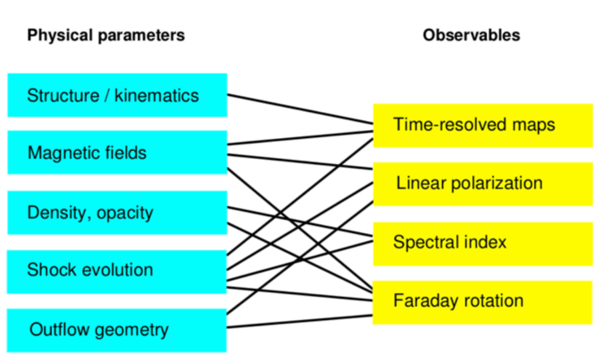


(Credit: S. H. Cho)

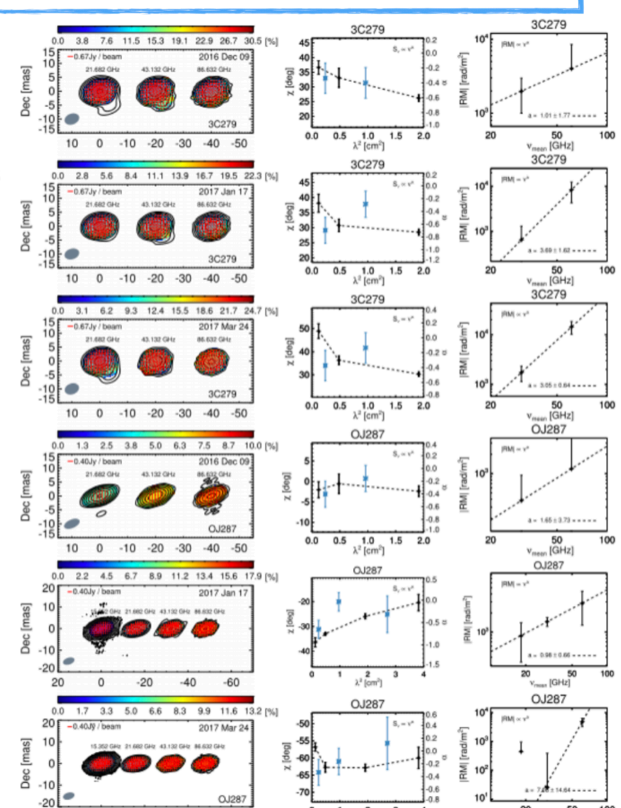
KSP3
The Plasma Physics of AGN with KVN

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

AGN plasma-physics



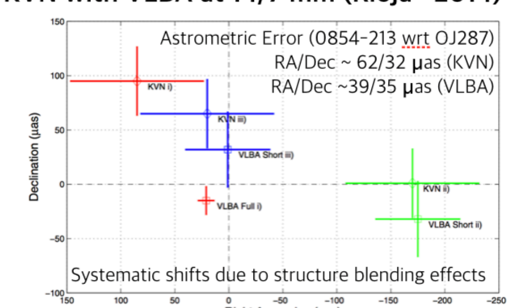
(Credit: S. Trippe)



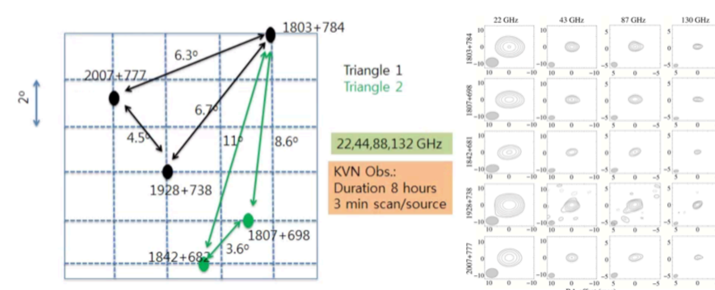
(Park et al. 2018)

SFPR and Astrometry with KVN

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

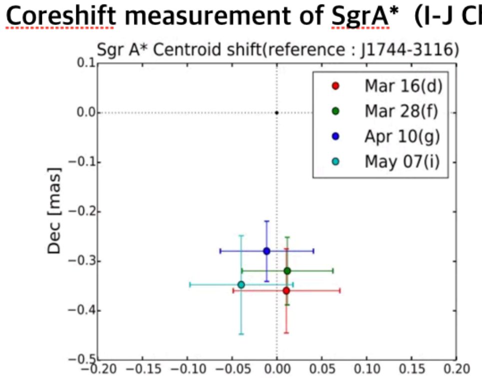


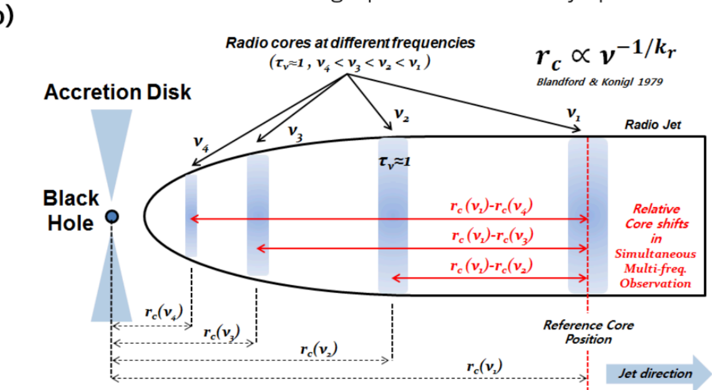
KVN SFPR demonstration using Polar Cap samples (Rioja+ 2015)



- Demonstration of high-precision astrometry up to 130GHz

Coreshift measurement of SgrA* (I-J Cho)





Continuum Studies

- Weak sources
- Astrometry
- Faraday rotation studies
- Opacity core-shifts, γ-ray flares, and nature of the VLBI core

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

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A R T I C L E I N F O

Keywords:
Astronomical instrumentation methods and techniques
Instrumentation: Interferometers
Methods: Observational
Telescopes
Quasars: General
Astrometry
Quasars: Jets
Stars: AGB and post-AGB
Stars: Formation
X-rays: Binaries

A B S T R A C T

This review arose from the European Radio Astronomy Technical Forum (ERATec) meeting held in Firenze, October 2015, and aims to highlight the breadth and depth of the high-impact science that will be aided and assisted by the use of simultaneous mm-wavelength receivers.

Recent results and opportunities are presented and discussed from the fields of: continuum VLBI (observations of weak sources, astrometry, observations of AGN cores in spectral index and Faraday rotation), spectral line VLBI (observations of evolved stars and massive star-forming regions) and time domain observations of the flux variations arising in the compact jets of X-ray binaries.

Our survey brings together a large range of important science applications, which will greatly benefit from simultaneous observing at mm-wavelengths. Such facilities are essential to allow these applications to become more efficient, more sensitive and more scientifically robust. In some cases without simultaneous receivers the science goals are simply unachievable. Similar benefits would exist in many other high frequency astronomical fields of research.

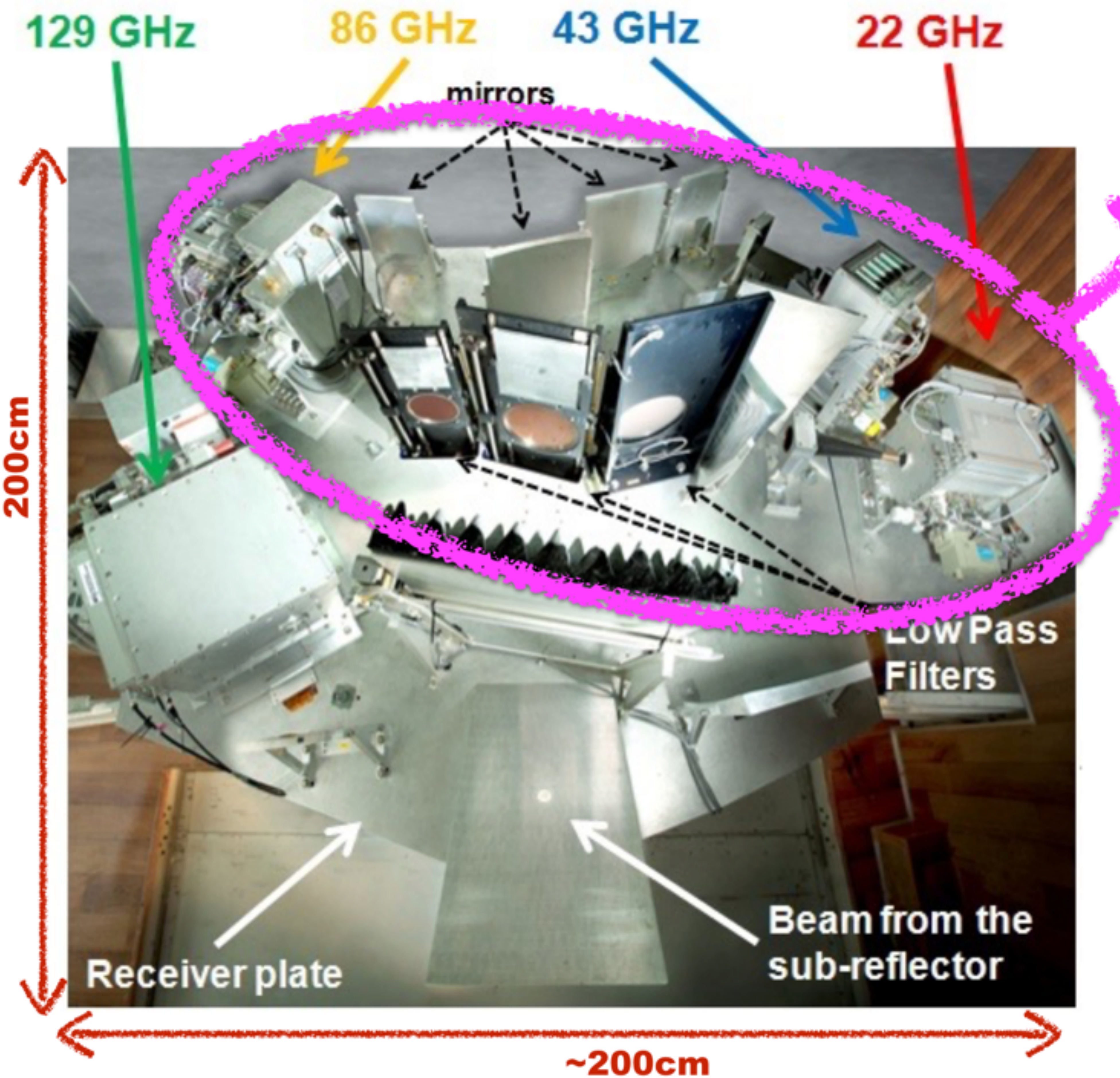
http://www.sciencedirect.com/science/article/pii/S1387647317300209

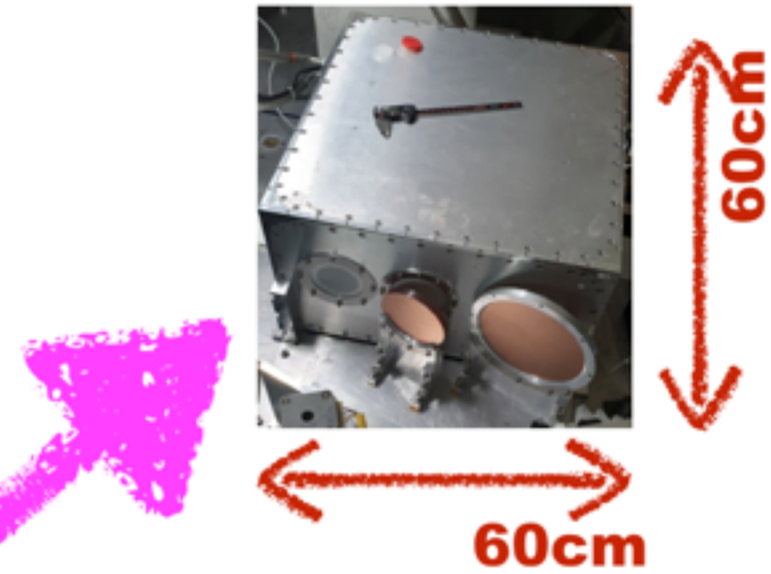
Spectral Studies

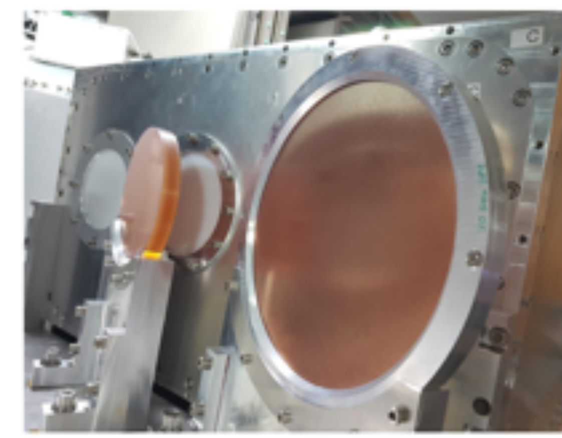
Multi-frequency VLBI observations of maser emission in evolved starts
Massive star formation

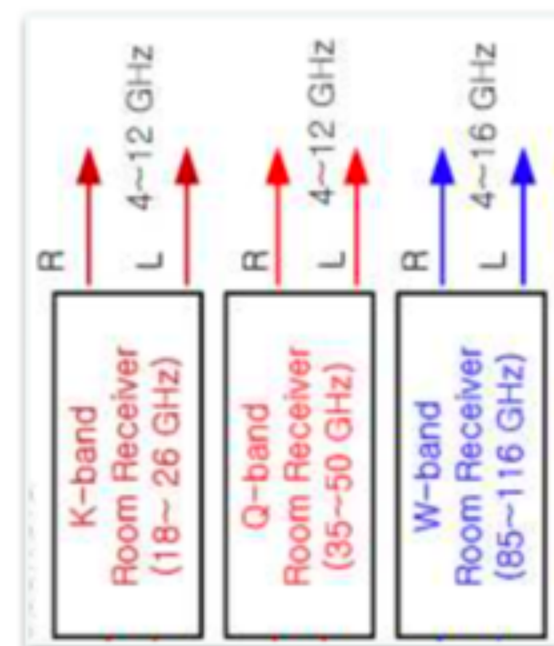
Compact Triple-band Receiver (CTR)

See more details —> Seog-Tae Han's Talk tomorrow



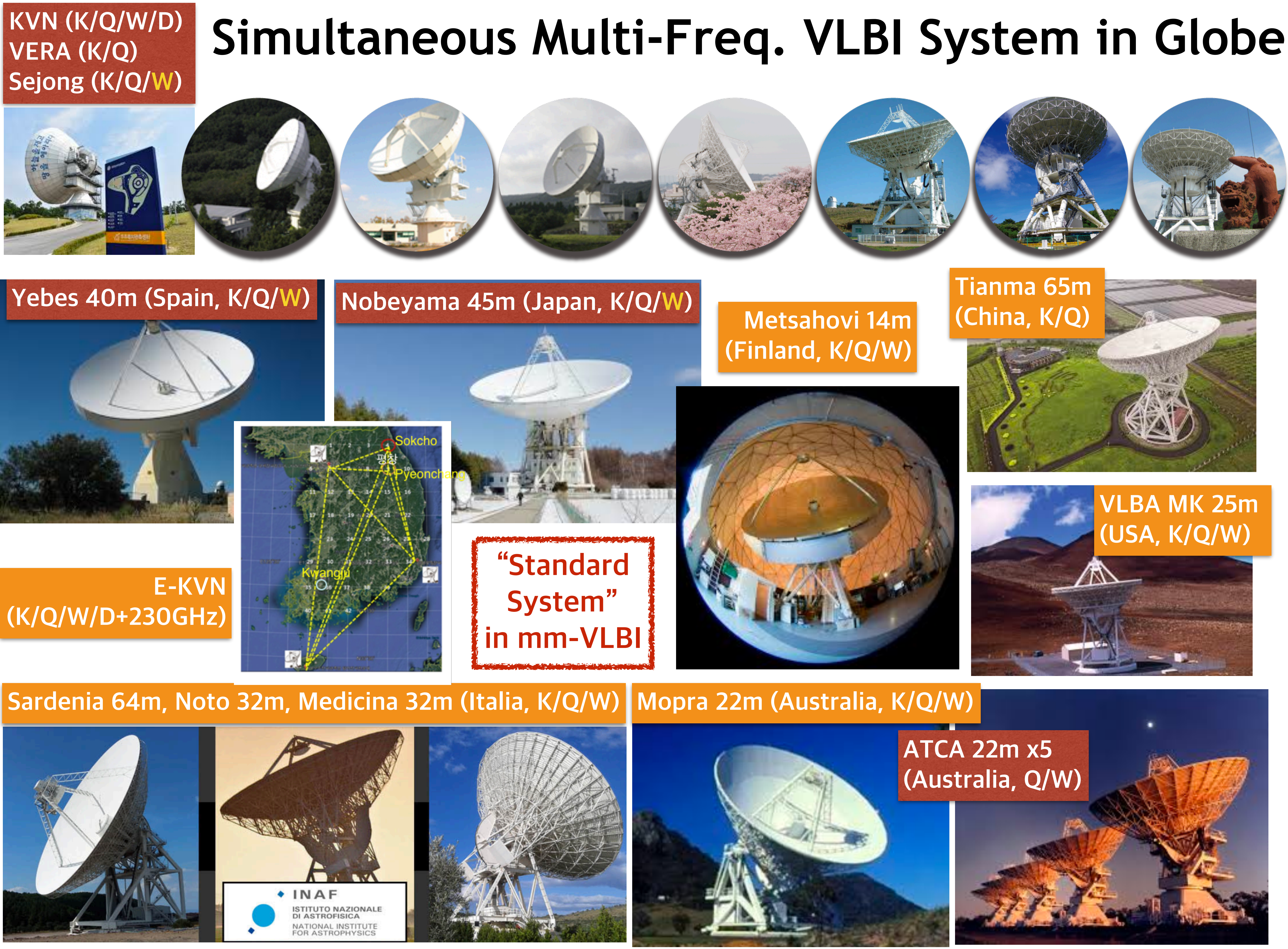




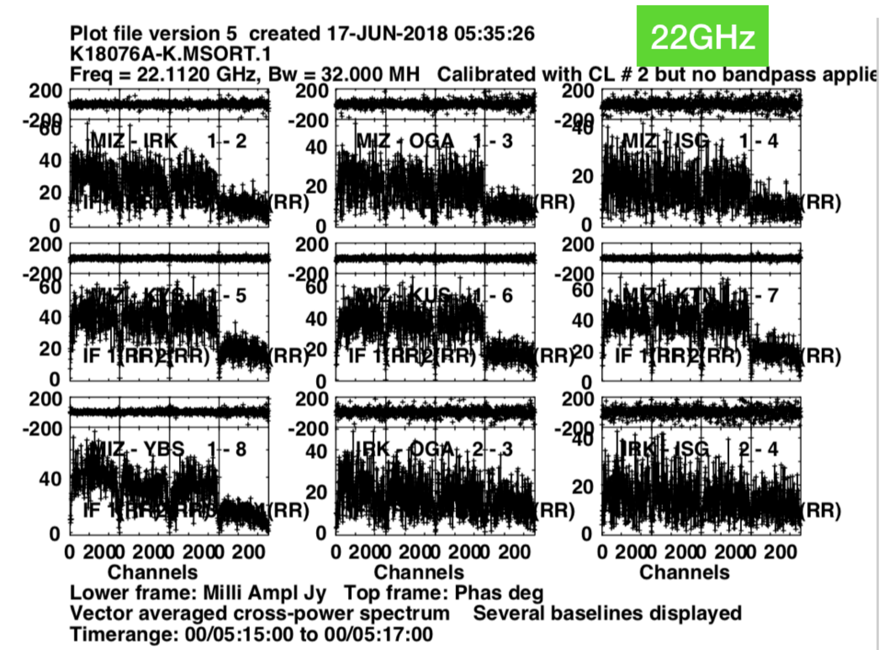


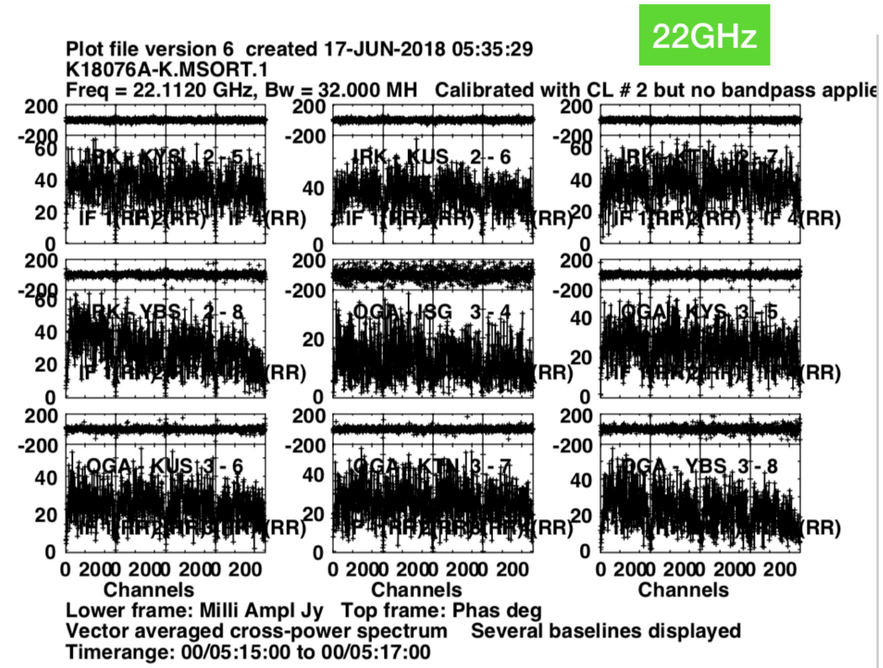
RF: 18-116GHz

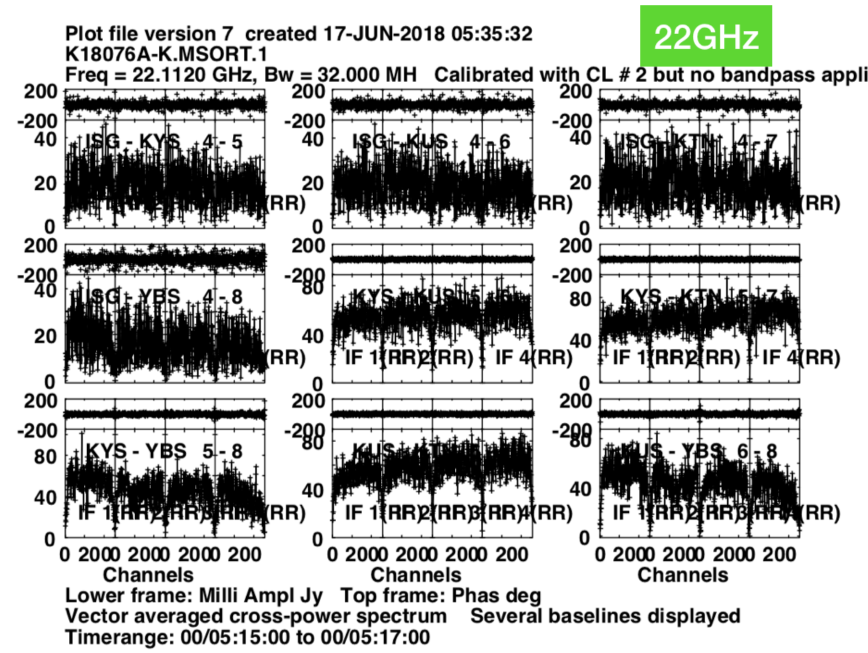
Simultaneous Multi-Freq. VLBI System in Globe



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



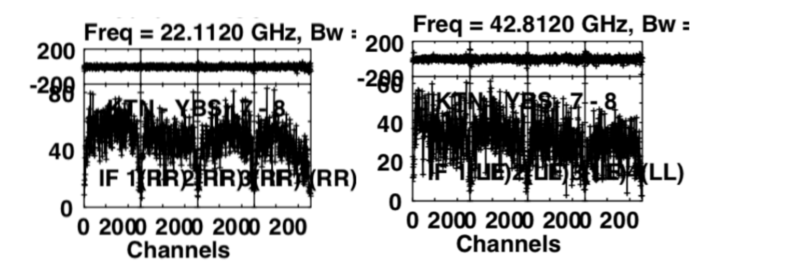


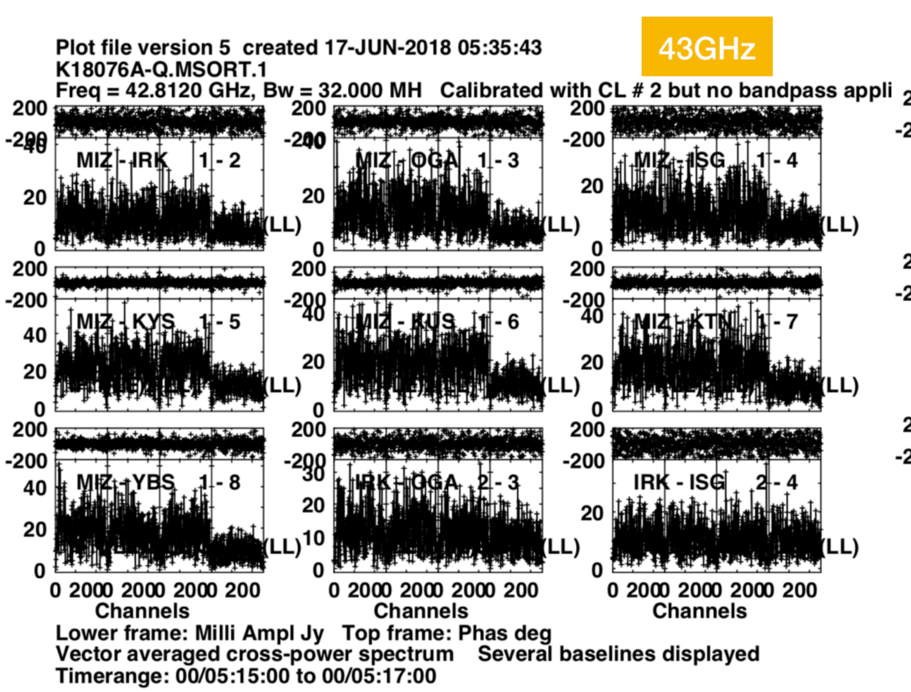


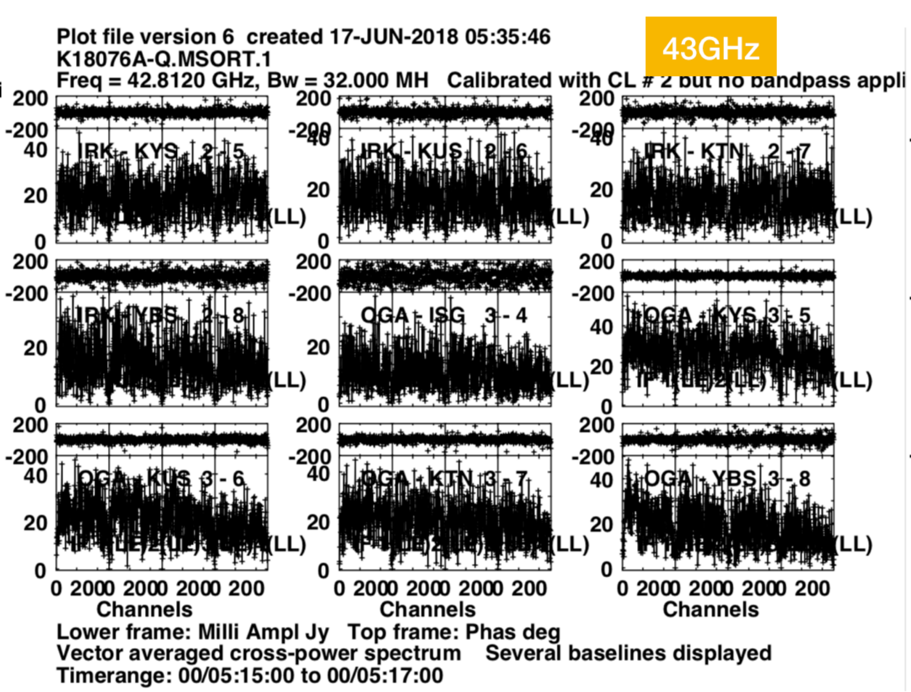
KaVA+Yebes 22/43 GHz Simultaneous Observation Campaign

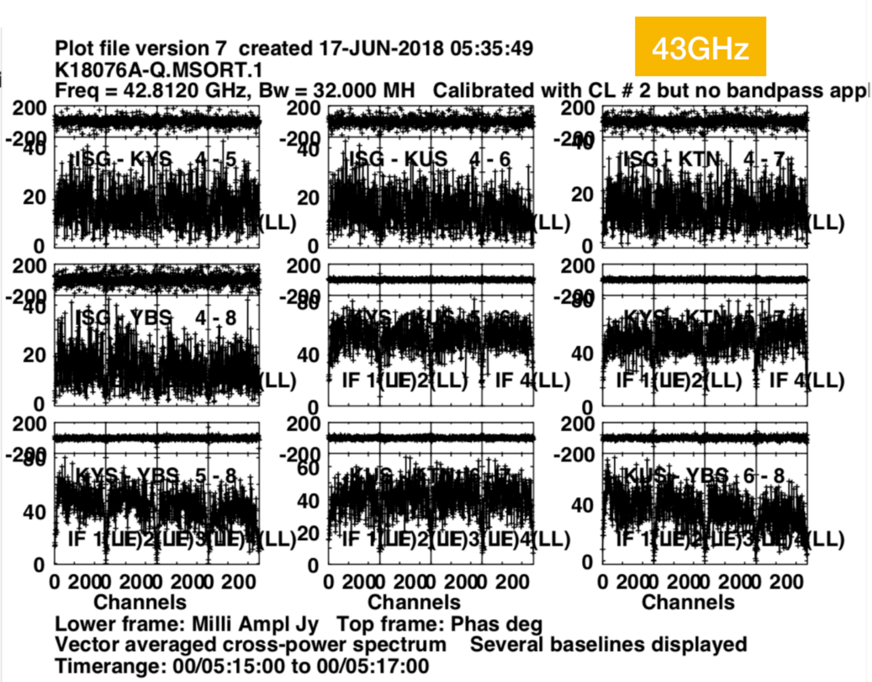
First FRINGE Detection at All KaVA+Yebes Baselines

2018. 03. 16 - 18 (7 epochs, 56 hours)



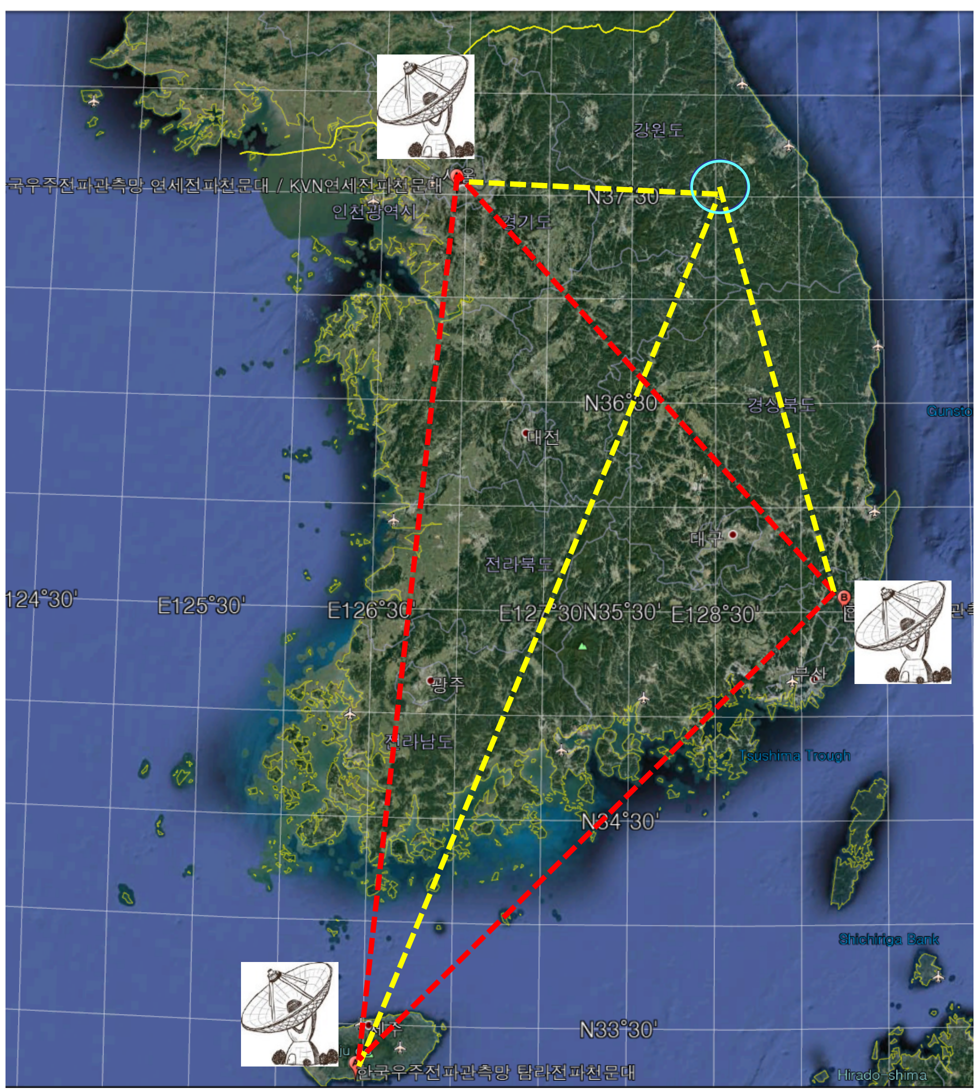


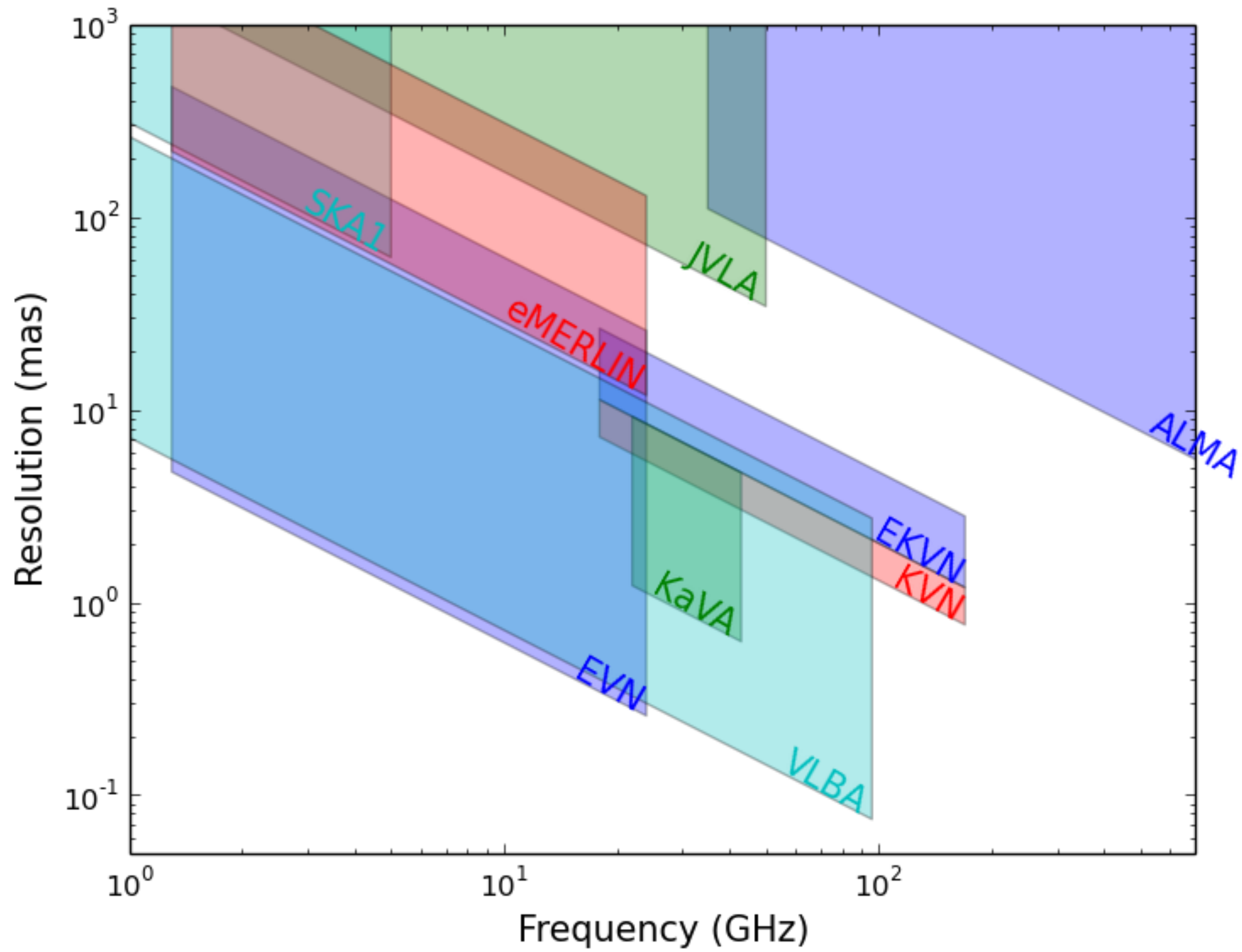




E-KVN Project: Construction of A New Telescope

- ❖ Almost same Telescope (D = 21m)
  - Kangwon Province (~130 km E-W baseline)
  - better surface accuracy (~80 um) for 230GHz operation



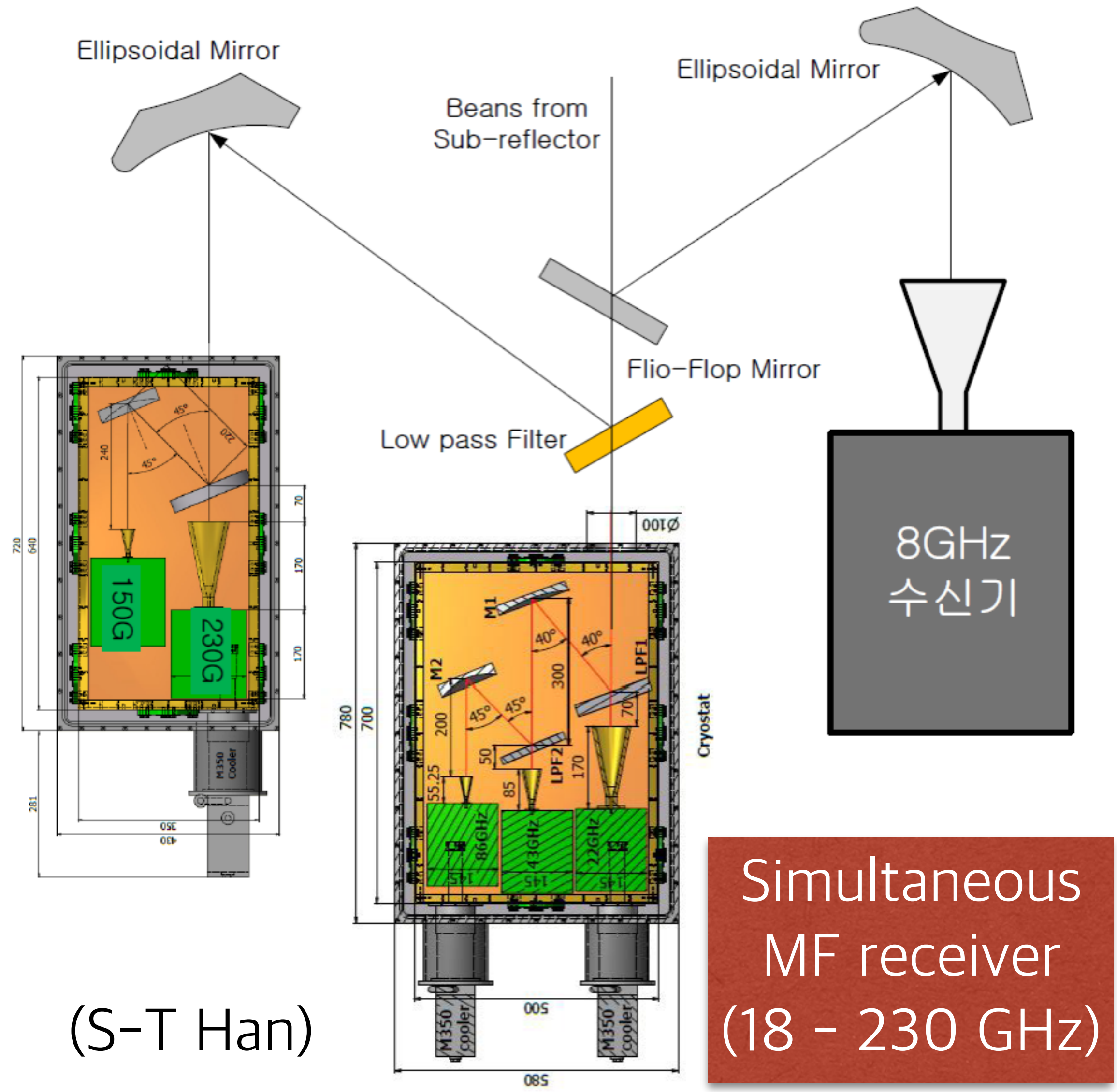


E-KVN Project (2020 - 2023)

- Target Frequency Range : 18 - 250GHz (+ 8GHz)
  - Compact Triple band Receiver (18 - 115GHz)
  - 2-Channel SIS Mixer Receiver (125 - 250GHz)
  - X-band Receiver (6-12GHz)

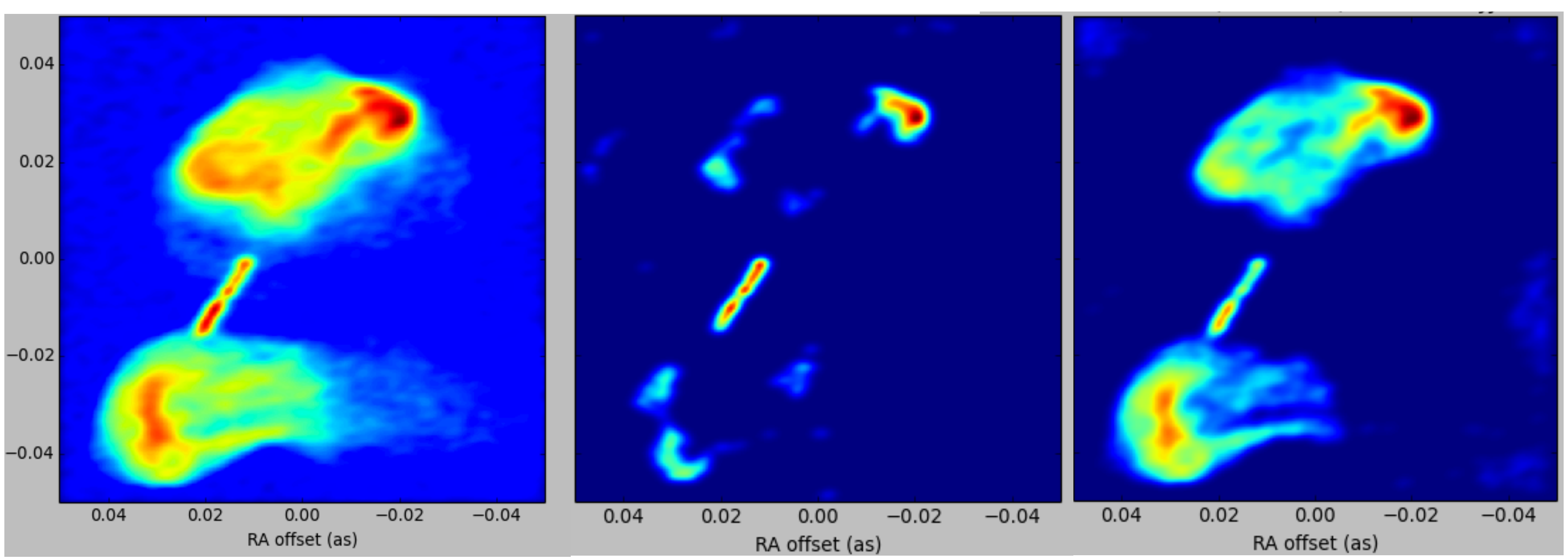
- Recording Bandwidth
  - 64Gbps (2GHz x 8 IFs)

- Two times more baselines from 3 to 6
- Amplitude self-calibration
- M/F Image Synthesis



(S-T Han)

Simultaneous MF receiver (18 - 230 GHz)



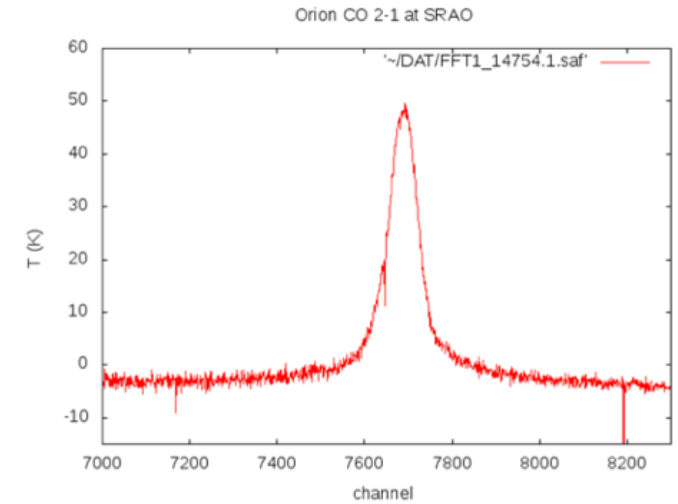
Simulation assuming flat spectrum over 18- 150GHz

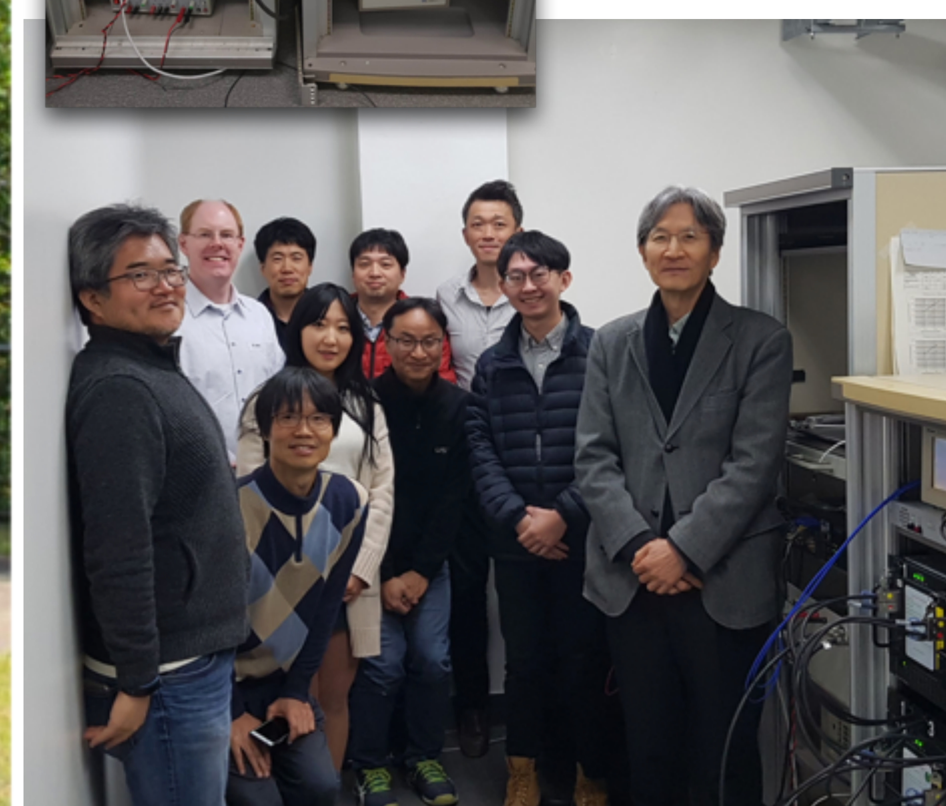
230GHz VLBI Test Experiment with SRAO

on behalf of EAVN-hi campaign

Simultaneous 86/230 GHz (on-going)

Orion CO 2-1





Conceptual design of quasi-optical circuit for simultaneous observations

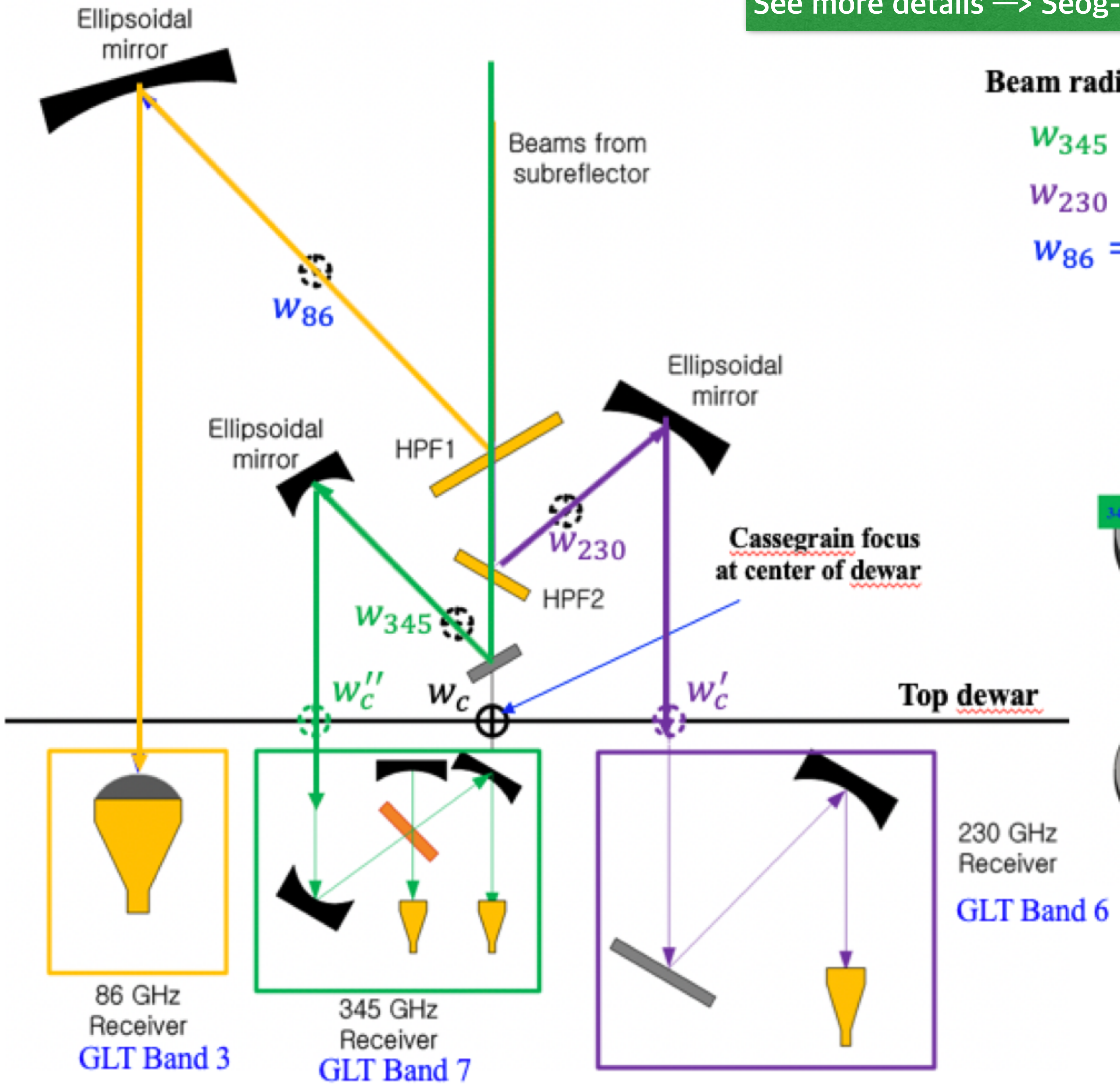
See more details —> Seog-Tae Han's Talk tomorrow

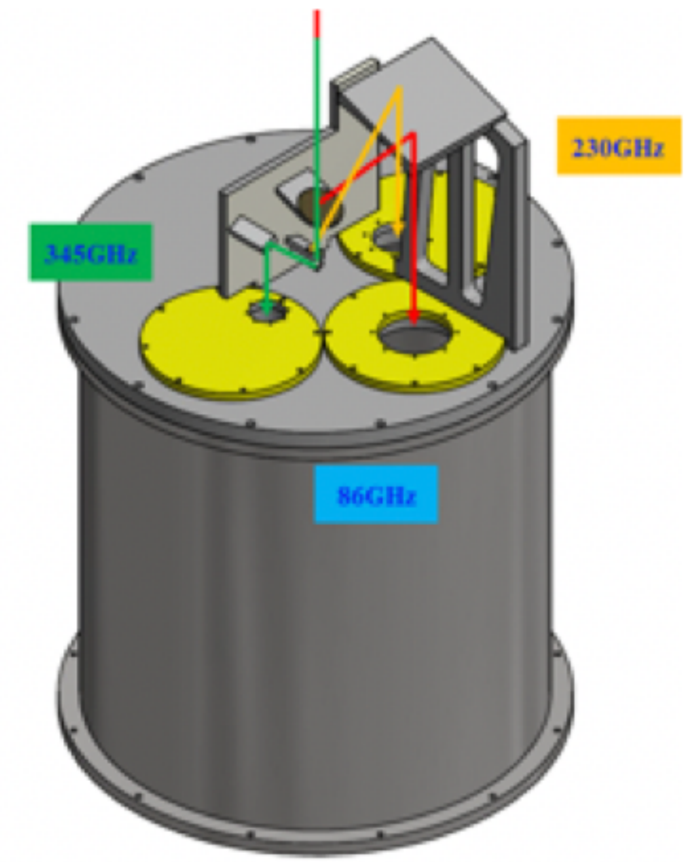
Beam radii at cassegrain focus

$$w_{345} = w_c'' = w_c$$

$$w_{230} = w_c' = w_c$$

$$w_{86} = w_c$$





Simultaneous
86/230/345 GHz
(pre-study)

White Paper on East Asian Vision for mm/submm VLBI: Toward Black Hole Astrophysics down to Angular Resolution of 1 R_S

Editors

Asada, K.[1], Kino, M.[2,3], Honma, M.[3], Hirota, T.[3], Lu, R.-S.[4,5], Inoue, M.[1], Sohn, B.-W.[2,6], Shen, Z.-Q.[4], and Ho, P. T. P.[1,7]

Authors

Akiyama, K.[3,8], Algaba, J-C.[2], An, T.[4], Bower, G.[1], Byun, D-Y.[2], Dodson, R.[9], Doi, A.[10], Edwards, P.G.[11], Fujisawa, K.[12], Gu, M-F.[4], Hada, K.[3], Hagiwara, Y.[13], Jaroenjittichai, P.[15], Jung, T.[2,6], Kawashima, T.[3], Koyama, S.[1,5], Lee, S-S.[2], Matsushita, S.[1], Nagai, H.[3], Nakamura, M.[1], Niinuma, K.[12], Phillips, C.[11], Park, J-H.[15], Pu, H-Y.[1], Ro, H-W.[2,6], Stevens, J.[11], Trippe, S.[15], Wajima, K.[2], Zhao, G-Y.[2]

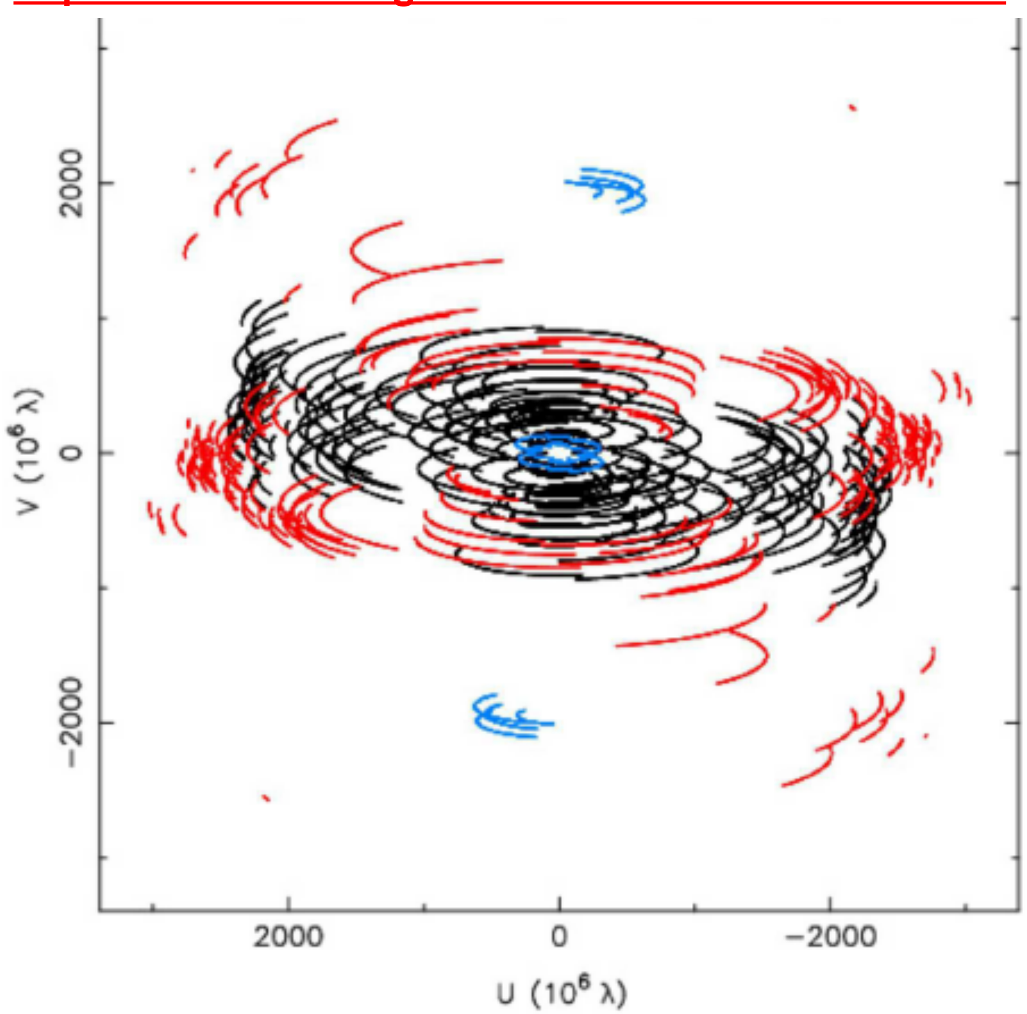
<<3mm>>

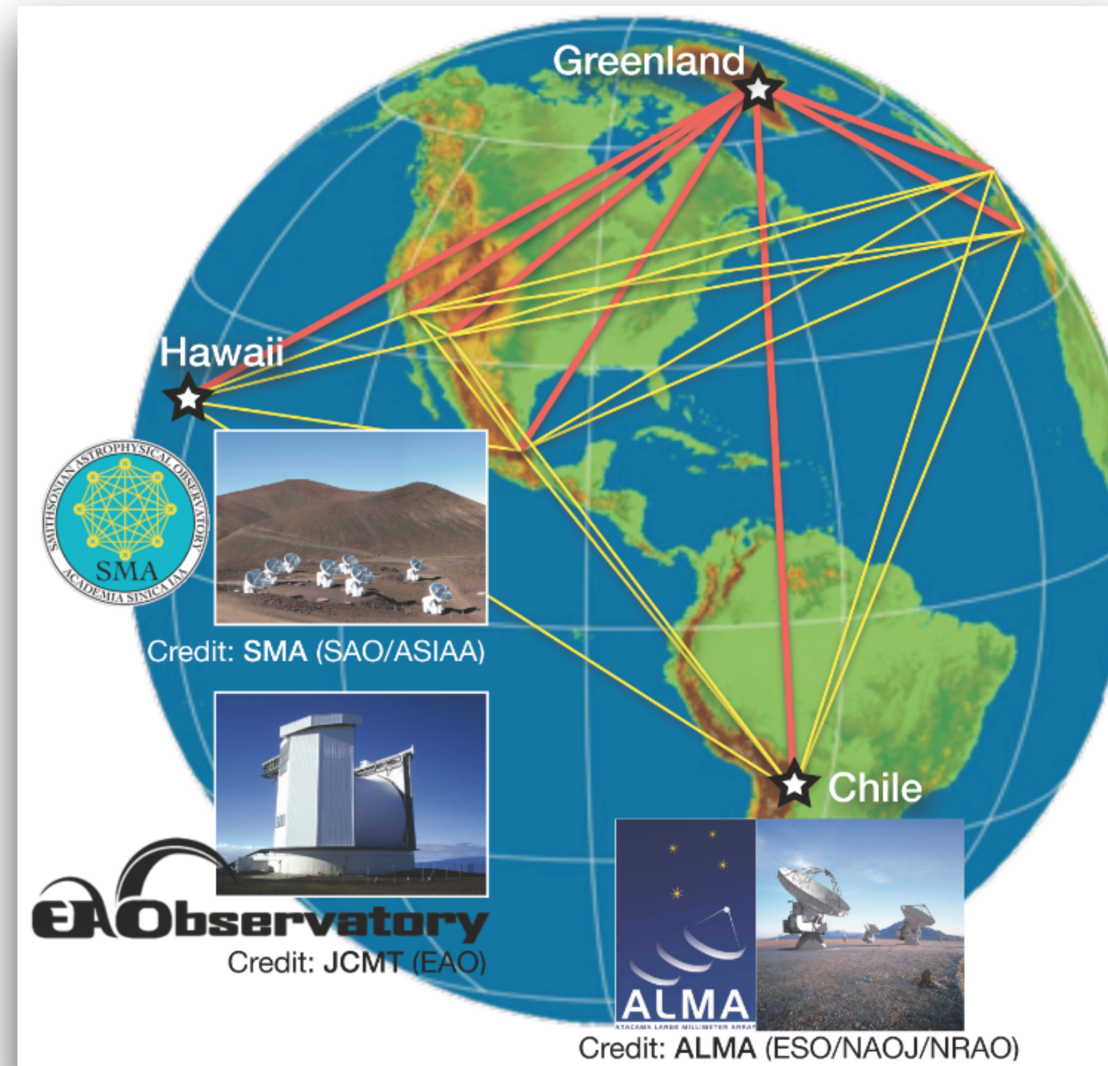
- SEJONG
- NRO
- QTT
- KVN

<<1mm>>

- EKVN
- SRAO
- JCMT
- GLT
- SMA
- SPART

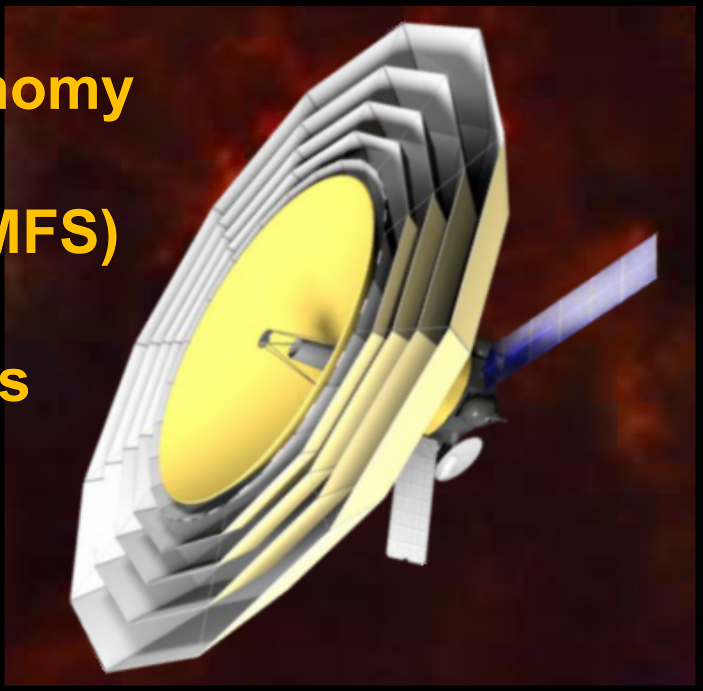
Expected UV-coverages with Extended EAVN at 3mm

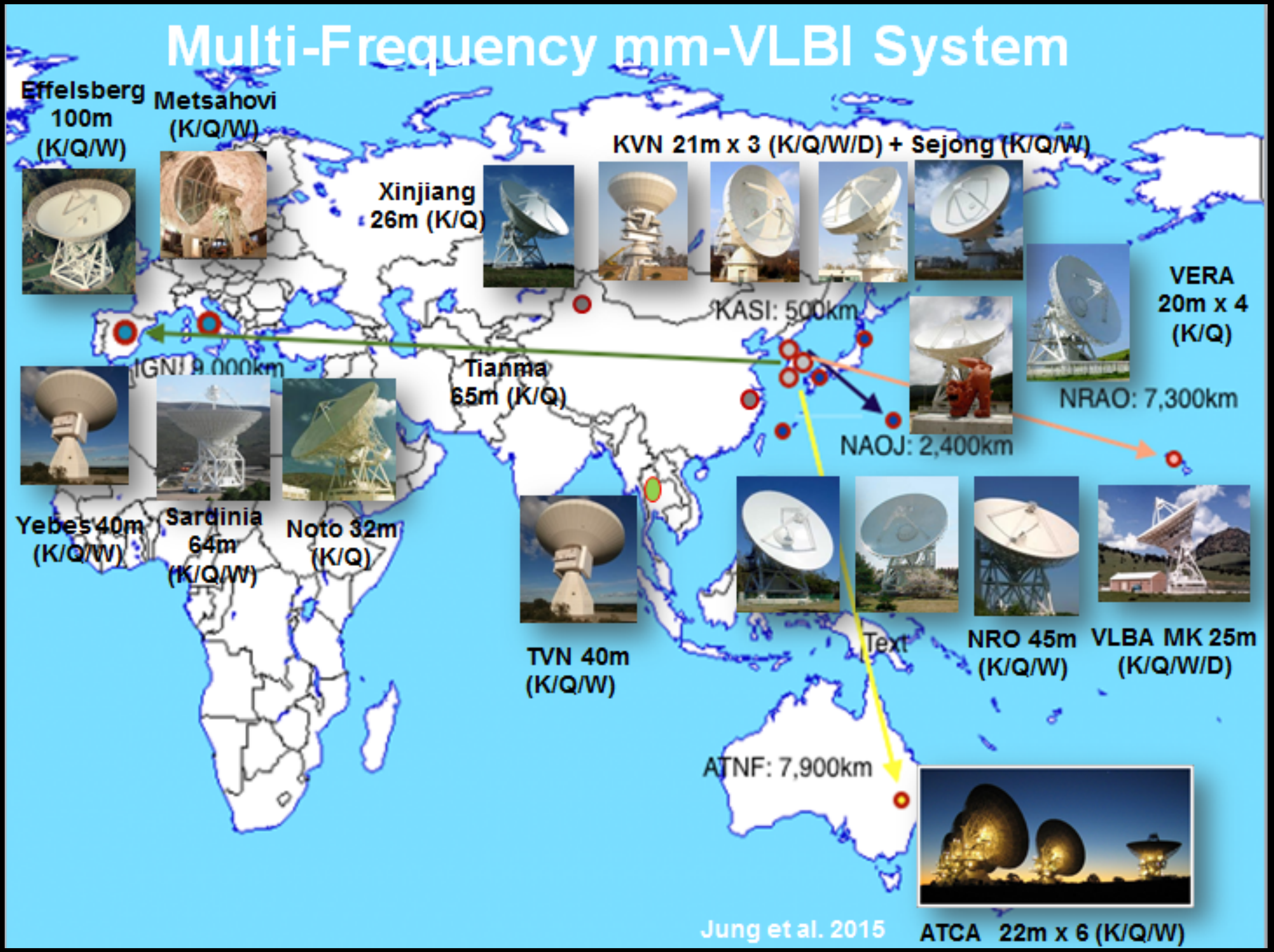


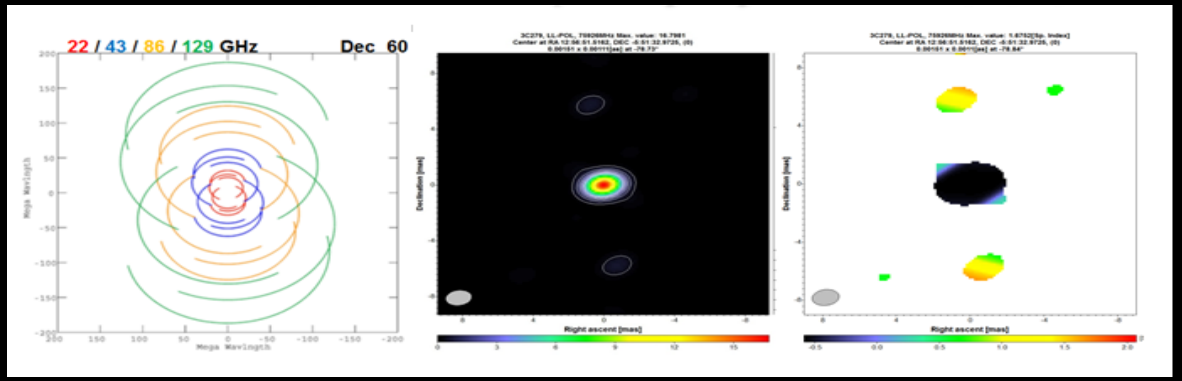


Simultaneous MF Rx System with RA/Millimetron

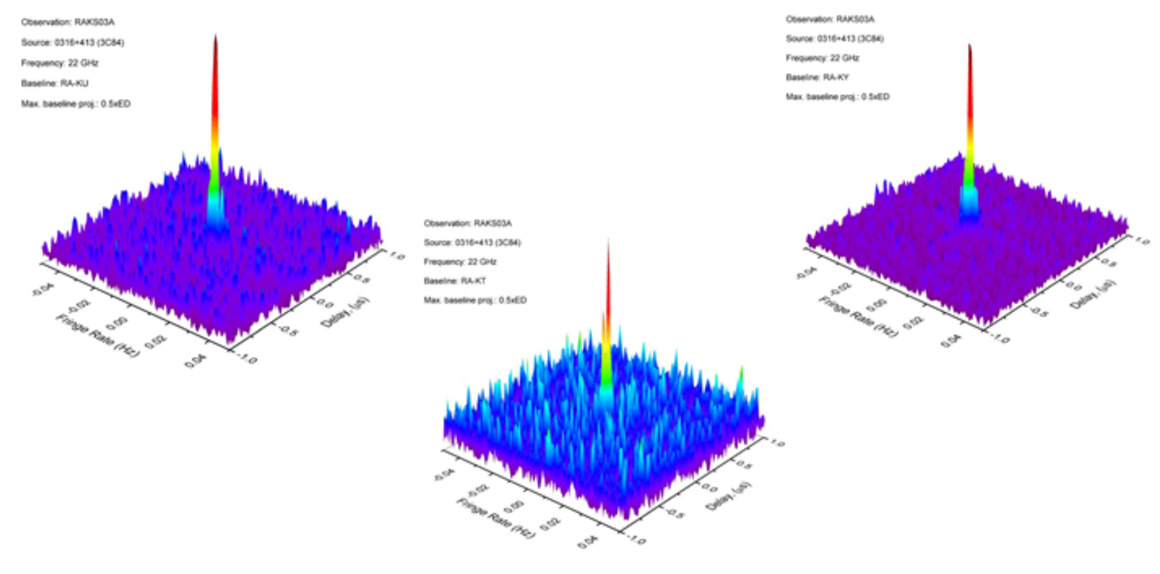
- Mm-VLBI → unique sciences at the highest angular resolution in astronomy
- Simultaneous Multi-Frequency System (SMFS) is the ideal for mm-VLBI → more sources available, unique sciences (e.g. MFS, Astrometry etc.)
- More stations are coming with SMFS → Synergies with Millimetron !!



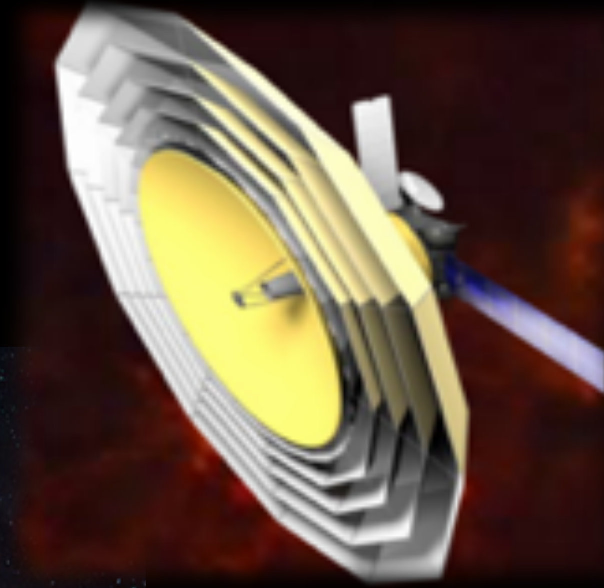




- 21.09.2013, Radioastron global imaging session of 3C84;
- K-band, baseline projections about 0.5 Earth Diameters;
  → The First Ground-Space VLBI Fringe Detection in Korea !



The Most Powerful Eyes in the Universe



An ideal mm-VLBI system for Earth and Space

Thank you for your attention!