Development of NRO 3mm VLBI system Toward EA 3mm VLBI Network

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And

HINOTORI Project led by H. Imai (Kagoshima U.)

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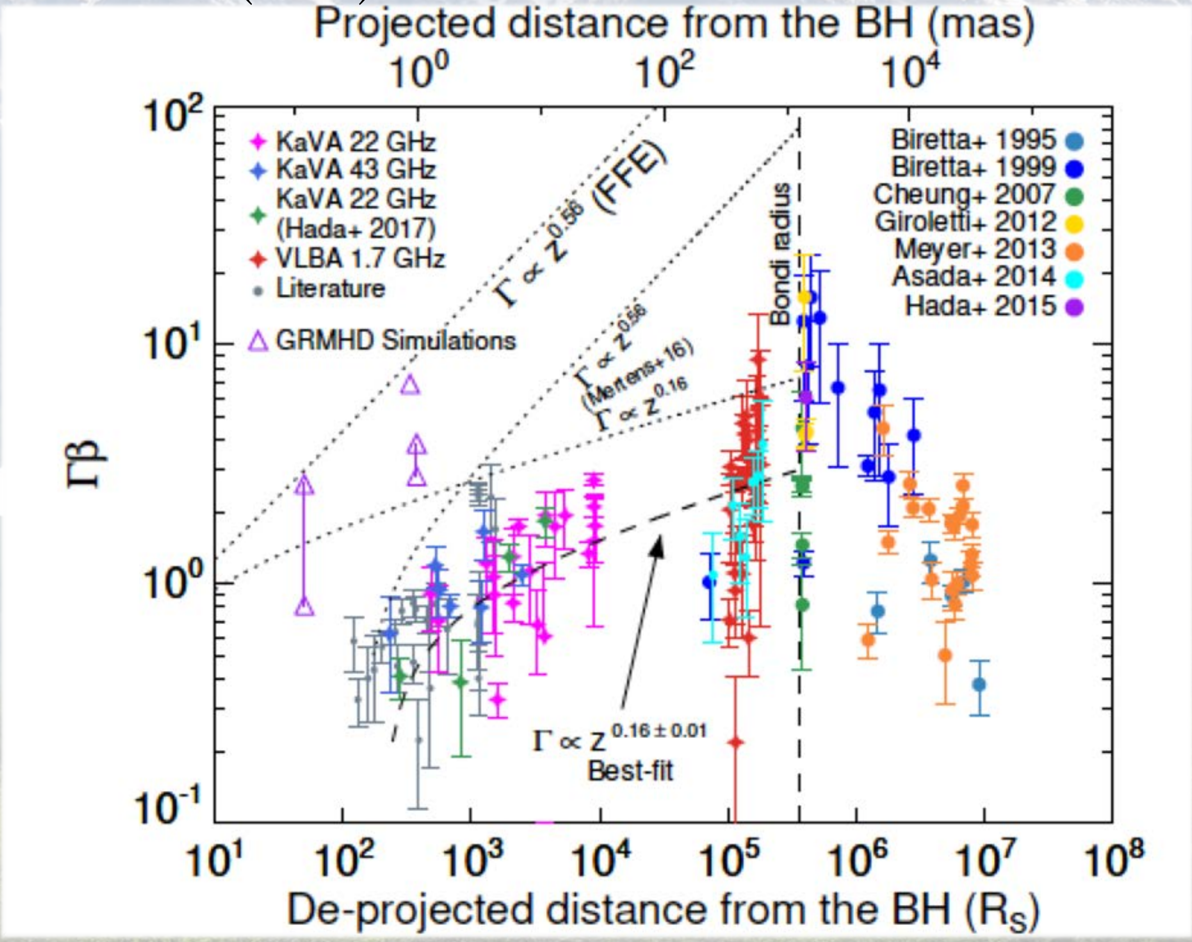
Contents

- Motivation
- Development of Nobeyama 3mm (w/ Quasi-optics) VLBI system
- Summary and prospect (EA @ 86GHz)
- Other activities (higher frequency / lower frequency)

Our observational exploration on M87 w/ KaVA-EAVN

- **Hada et al. 2017, PASJ**
  - The first KaVA-LP result
- **Park et al. 2019, ApJ**
  - Velocity field > ~100 R_s
- **Ro et al. in prep.**
  - Transverse structure
- **Cui et al. in prep.**
  - High cadence EAVN monitor

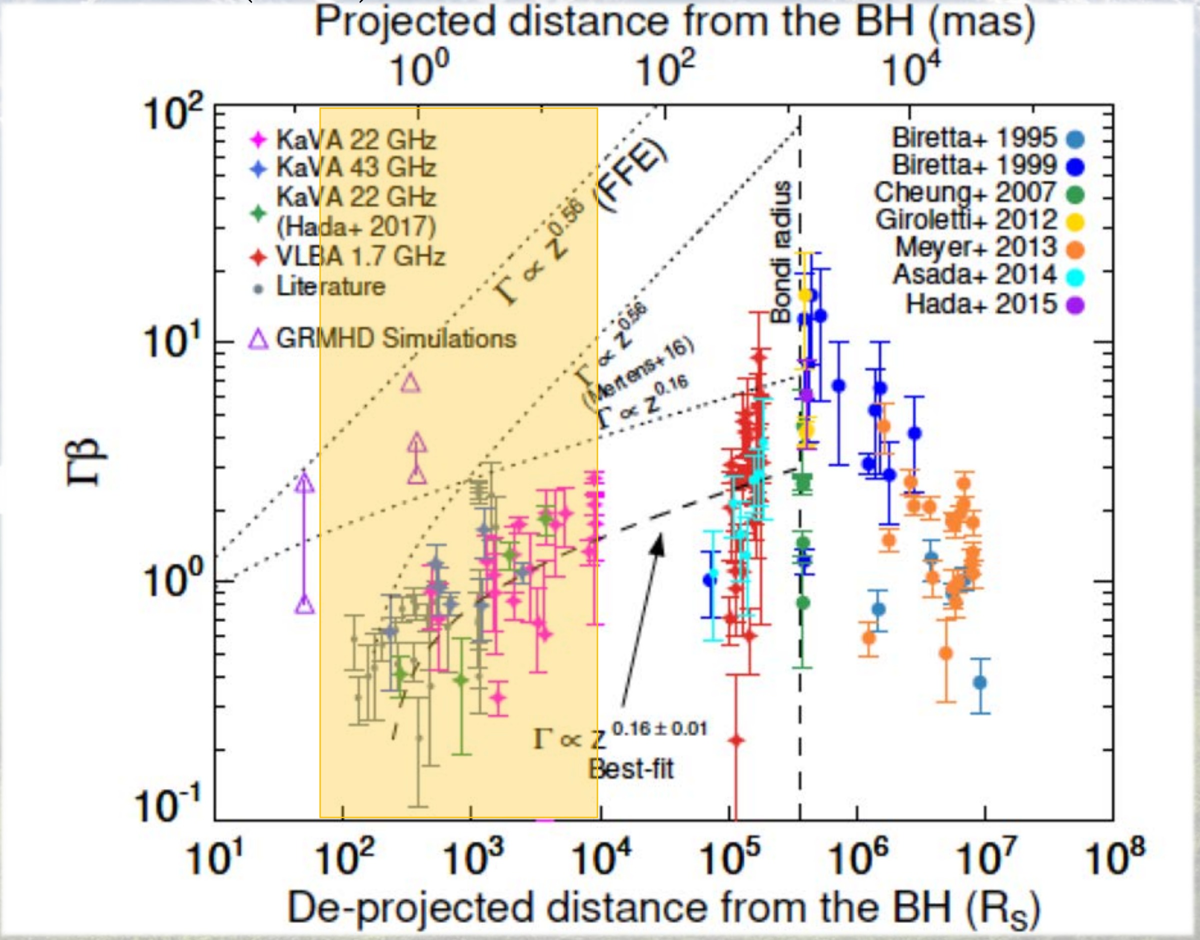
Park et al. (2019)



What's next?

Measuring velocity field:**<100R_s** – 10000R_s by truly simultaneous observation

Park et al. (2019)



For direct comparison with the result derived from theoretical works and numerical simulations

How?

KVN/KaVA+Nobeyama (NRO45)

at 22/43/**86**GHz with quasi-optics

- HINOTORI (Hybrid Installation Project in Nobeyama, Triple-band Oriented) led by Imai-san (Kagoshima U.)
  - 22/43/86GHz simultaneous receiving system for VLBI
  - Development of Quasi-optics, new VLBI backend

- Science targets of HINOTORI Project:
  - Jet acceleration mechanisms at the innermost AGN jet
  - Process of shock propagation and stellar wind acceleration in circumstellar envelopes proved by H_2O and SiO masers
  - Mass accretion process inside the AGN molecular torus

→Regular (**Weekly/Monthly**) monitor is required

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

Editors

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Jung, T.[2,6], Kawashima, T.[3], Koyama, S.[1,5], Lee, S-S.[2], Matsushita, S.[1], Nag
Nakamura, M.[1], Niinuma, K.[12], Phillips, C.[11], Park, J-H.[15], Pu, H-Y.[1], Ro, H-W.[2,6]
Trippe, S.[15], Wajima, K.[2], Zhao, G-Y.[2]

3.1.4 Nobeyama Radio Observatory 45-m telescope

The Nobeyama Radio Observatory 45-m telescope (NRO45m) operated by NAOJ is one of the most powerful mm-wavelength radio telescopes in the world. Currently three main frequency bands — 22, 43, and 86–112 GHz (λ = 13mm, 7mm, and ~3mm) — are available, and the telescope is open to all astronomers during the winter season (December to May).

Historically, the NRO45m has participated in several VLBI sessions, including global mm VLBI observations. Additionally, 86 GHz VLBI observations were performed with the Taeduk Radio Astronomy Observatory 14 m telescope in Korea (Shibata et al., 2004). The station position of the NRO45m has been regularly measured with high accuracy for VLBI observations. Currently, the NRO45m participates mainly in 13 and 7 mm VLBI observations together with VERA, based on VERA open-use observations.

In East Asia, the KVN has routinely performed VLBI observations at 3 mm. However, the KVN has only short baselines (< 500 km), and the accuracy of amplitude calibration is not high because it consists of three radio telescopes and three baselines. VLBI observation with the NRO45m and the KVN at 3 mm will facilitate the achievement of a longer baseline greater than 1000 km in the eastwest direction (e.g., M87 in the left panel of Figure 44) and improve the accuracy of amplitude calibration because of the use of four stations and six baselines. Therefore, 3 mm VLBI observation in East Asia will be enhanced by the participation of the NRO45m.

The 3 mm wavelength is crucial not only to achieve higher angular resolution but also to view the emission coming from upstream of the jet by avoiding the effect of the opacity structure seen in the M87 jet (e.g., Hada et al., 2011). Actually, the VLBI observation of M87 with the NRO45m and KVN at 3 mm is expected to achieve an angular resolution of 0.4 mas, corresponding to approximately 100 R_s toward the direction of the de-projected jet of M87 (see Figure 44 *right*). Here, we assumed that the $M_{\rm BH} = 6\times10^9 M_\odot$, $D = 16.7$ Mpc and viewing angle $\theta = 35°$ (Hada et al., 2015).

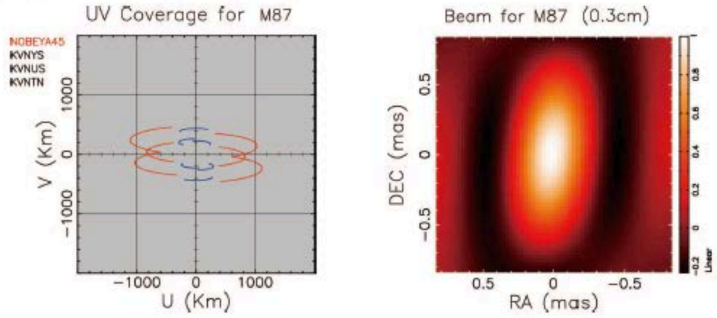


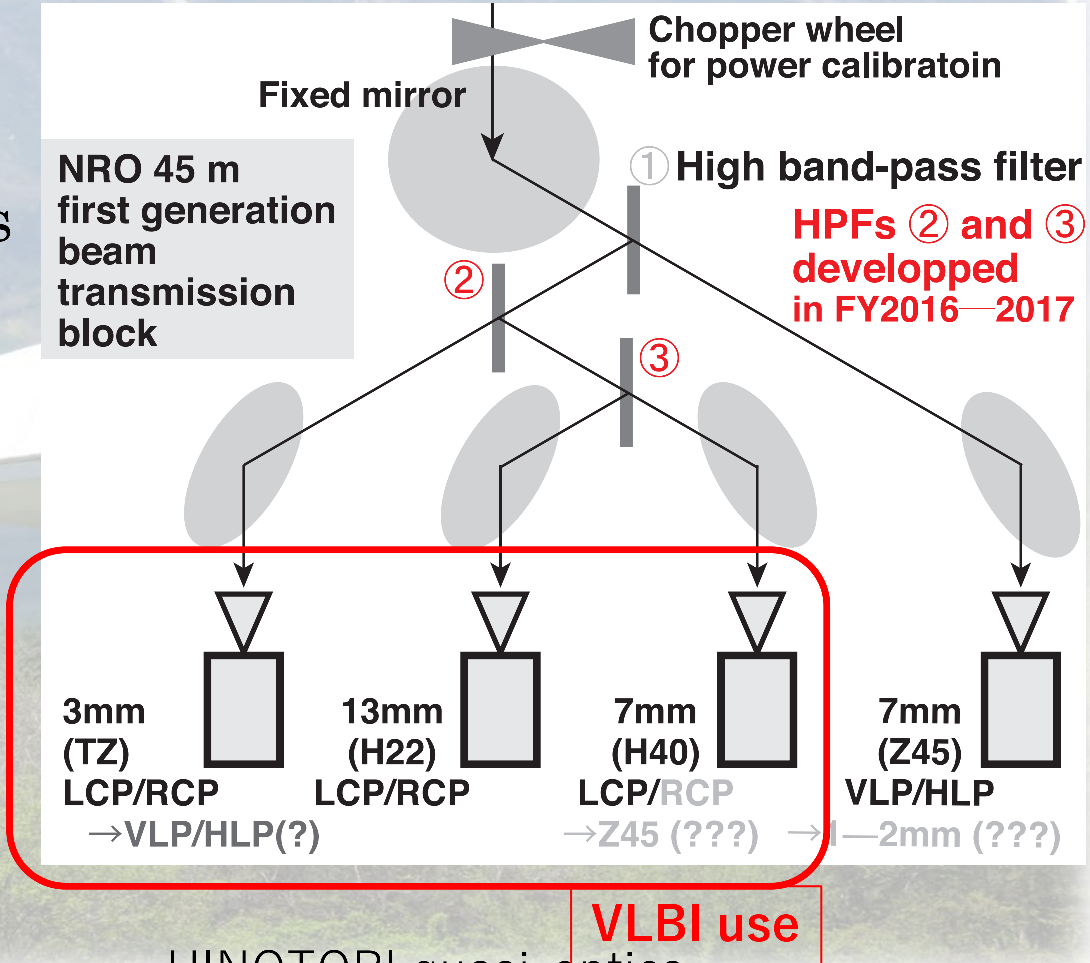
Figure 44: *Left*: (Left) The *uv*-coverage for M87 expected from the observation with 8-h tracks, obtained using the NRO45m and KVN baselines. The red solid line indicates the NRO45m baselines. (Right) The synthesized beam expected to be obtained with the NRO45m and KVN baselines for M87.

Nobeyama 45m Radio Telescope

- Regular operation (common-use): since 1982 (start construction in 1980)
  - Mainly for single-dish use
- One of the largest telescopes at ~100GHz in the EA
- Also powerful telescope for mm-VLBI
  - Quasi-optics and wide-band VLBI Backend are prepared

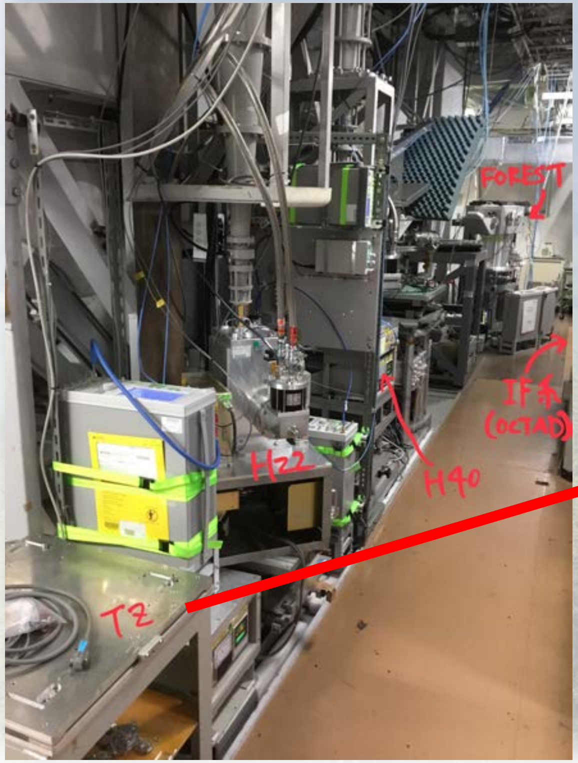
Quasi-Optics (22/43/86GHz) / Receivers

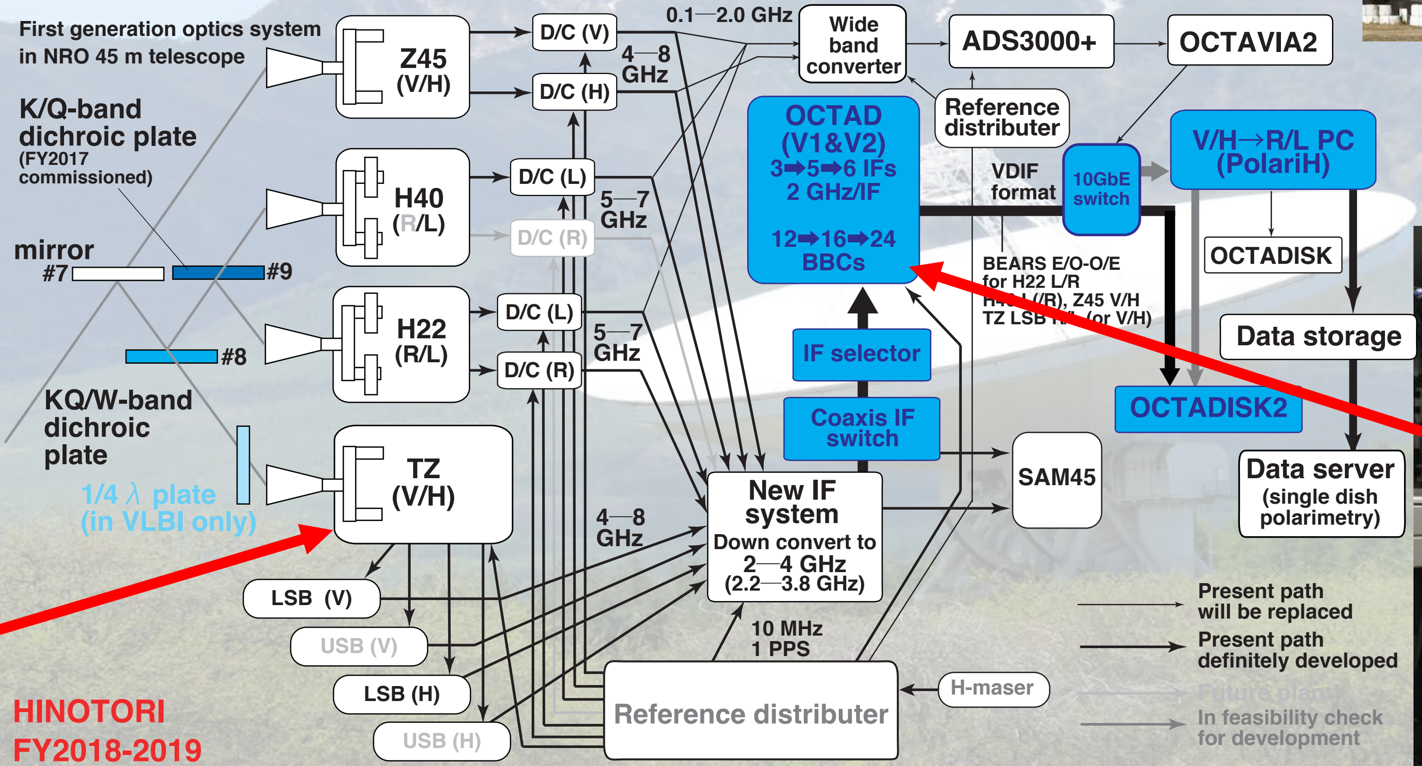
- Filter 2 and 3: Developed!
- Receivers: K/Q/W
  - K/Q band (circular pol.) simultaneous receiving system via **Filter 3** is completed and under the commissioning to open for common use in next season
  - TZ100 (SIS-HEMT) receiver for W-band
    - Decommissioned for the purpose of single-dish-use at NRO45 in 2017

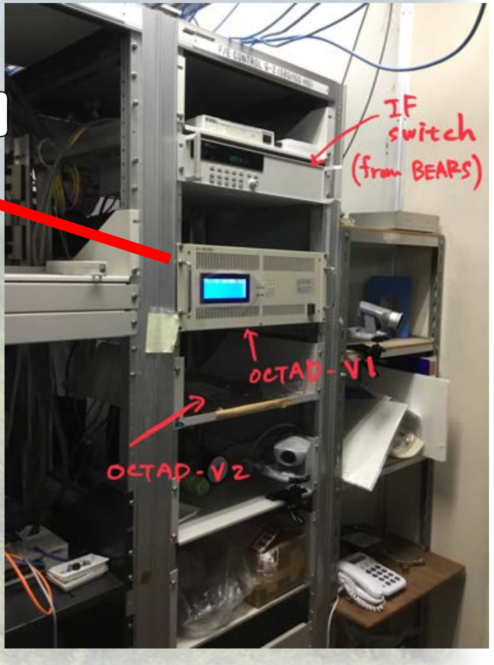


HINOTORI quasi-optics

NRO 45m Receiver Room on November 9-10, 2018





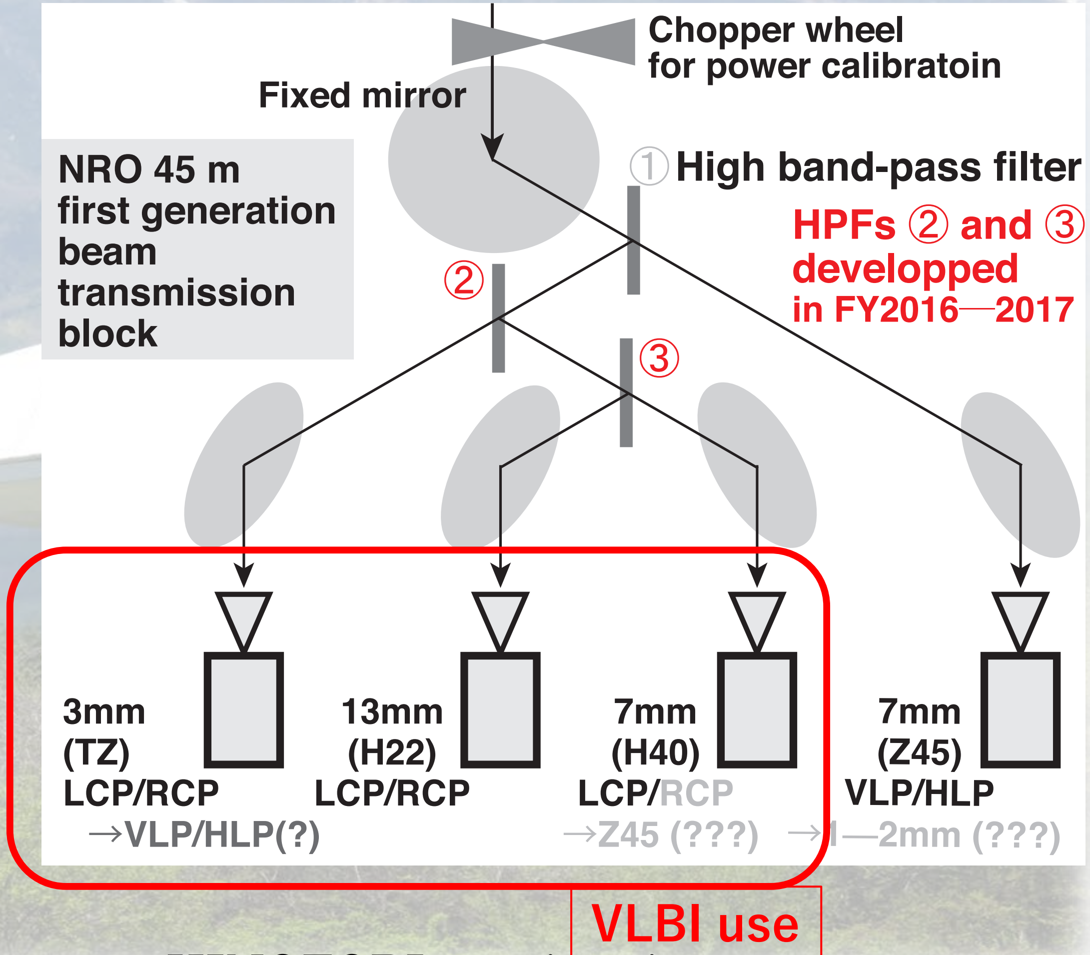


Quasi-Optics (22/43/86GHz) / Receivers

◻TZ100 (3mm) receiver for QO

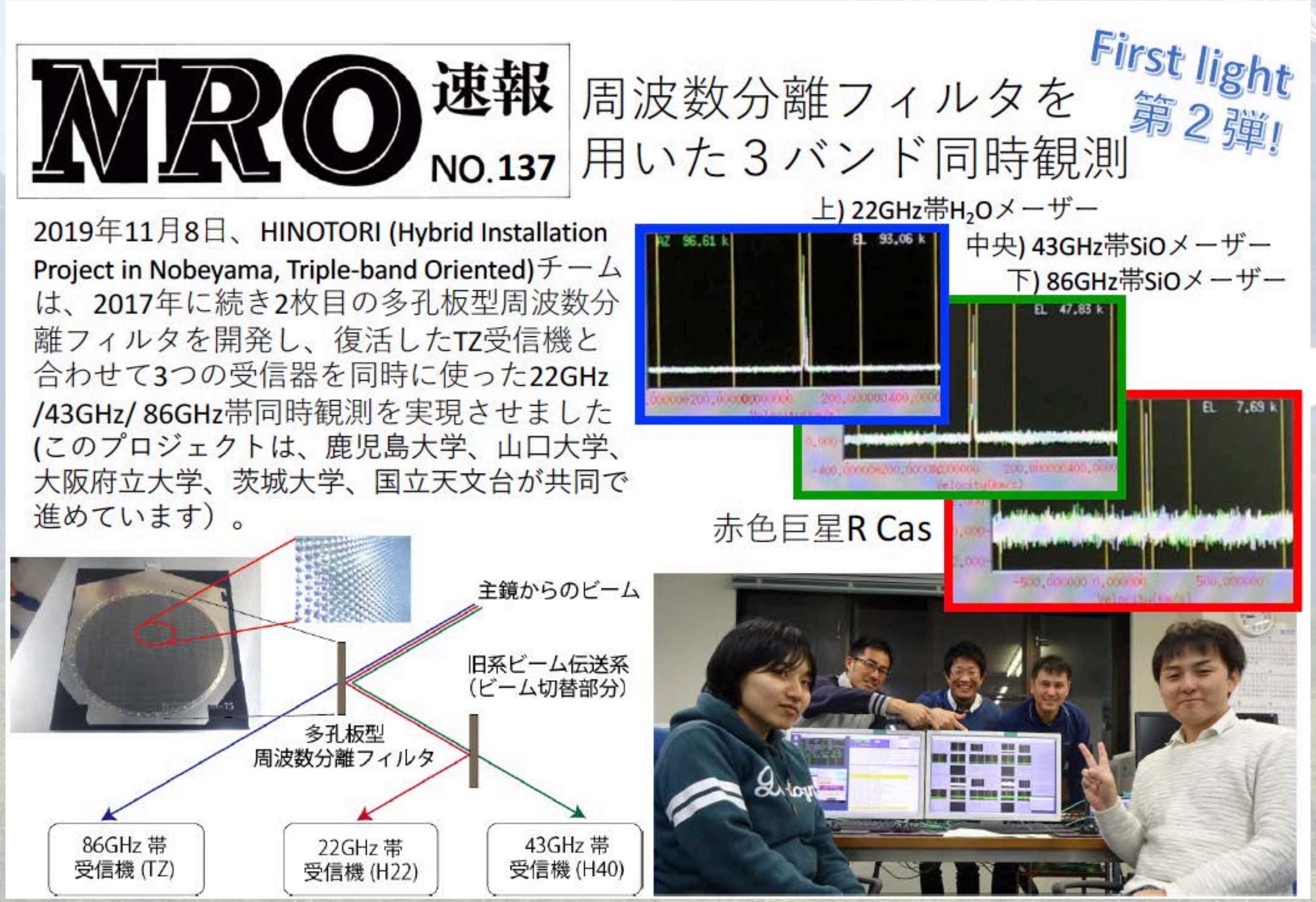
- Development of receiver control system
  - ✓ Done (by Aug 2019)
- **Re-installed** in NRO45 for VLBI-use
  - ✓ Done (the end of Aug 2019)
- **First light**: simultaneous 3-bands obs.
  - ✓ Done (Nov 2019, single dish)
- Adjustment/Measurement of **beam-squint, beam-pattern, efficiency**
  - ✓ Done (Dec 2019)

by Amari-san, Tsutsumi-san, Sawada-Satoh-san, Aoki-san, Nishimura-san, Ogawa-san, and OPU-students



HINOTORI quasi-optics

First light with QO (22/43/86 GHz)



NRO速報 NO.137

周波数分離フィルタを用いた３バンド同時観測

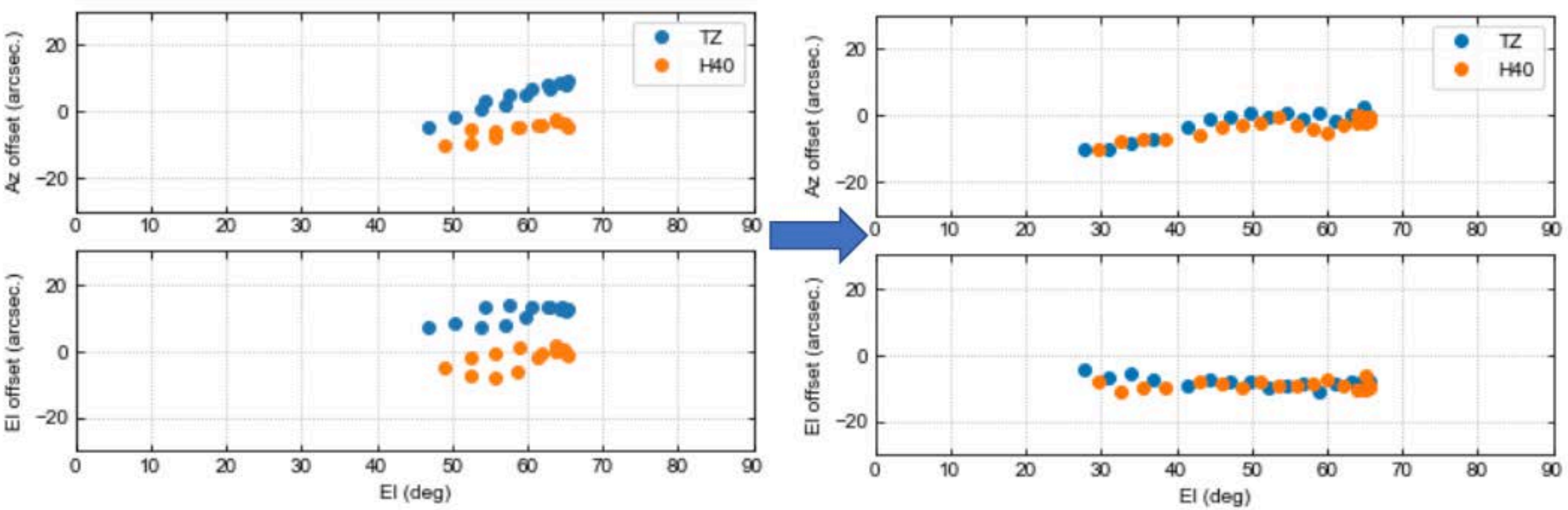
First light 第２弾!

2019年11月8日、HINOTORI (Hybrid Installation Project in Nobeyama, Triple-band Oriented)チームは、2017年に続き2枚目の多孔板型周波数分離フィルタを開発し、復活したTZ受信機と合わせて3つの受信器を同時に使った22GHz /43GHz/ 86GHz帯同時観測を実現させました(このプロジェクトは、鹿児島大学、山口大学、大阪府立大学、茨城大学、国立天文台が共同で進めています）。

NRO staffs (especially, Miyazawa-san, Torii-san, Kaneko-san) gave us huge supports!

Beam-Squint / Beam pattern

11/9の観測結果　　　　　　　　11/21の観測結果



AZ = 10.9″
EL = 14.7″

H40からのずれ

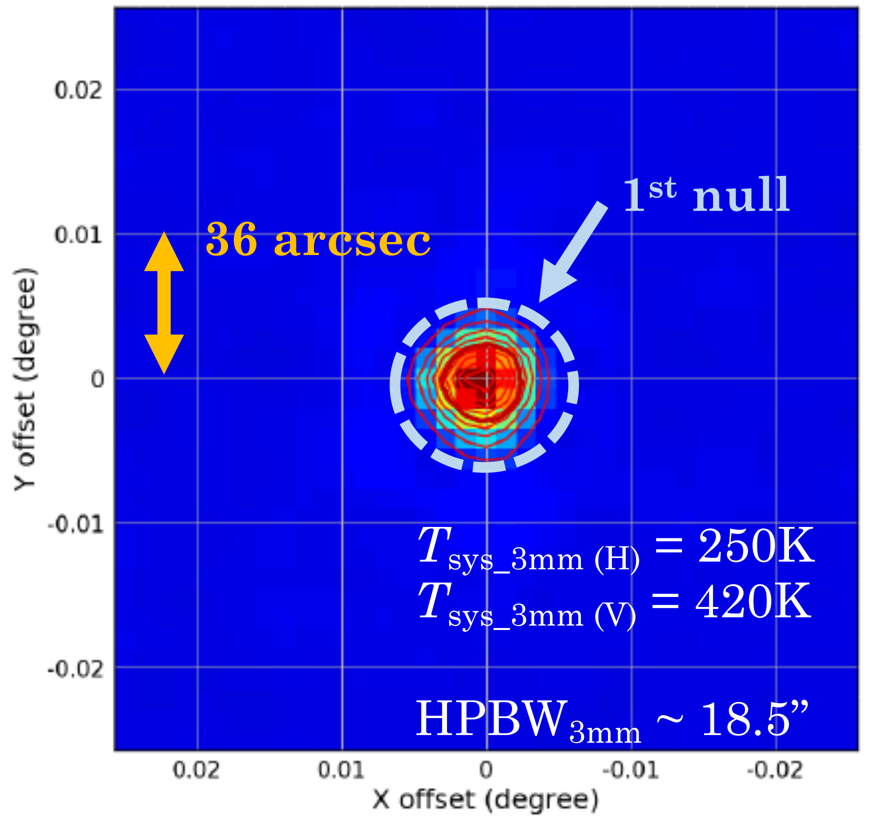
AZ =2.0 ″
EL = 1.3″

3″以内に収まったことが確認できた

$T_{\mathrm{sys\_3mm\ (H)}} = 250\mathrm{K}$
$T_{\mathrm{sys\_3mm\ (V)}} = 450\mathrm{K}$
$T_{\mathrm{sys\_7mm\ (L)}} = 170\mathrm{K}$

Beam-Squint / Beam pattern

今回の観測結果(12/25の観測)



Our measurement in 2019 Dec

12/8のEL = 35 deg以上のデータのみ

Receiver	HPBW [arcsec]	Main Beam Eff [%]	Aperture Eff [%]	Calib. Source	EL
TZ2(HL)	18.4 +-0.5	50.7 +-5	43.1 +-4	mars	35.4 - 39.1
TZ2(VL)	18.6 +-0.5	48.6 +-5	40.4 +-3	mars	35.4 - 39.1

Status report in 2016 (before decommission)

TZ1(H)	18.2 +-0.1	54 +-3	47 +-2	Mars	50.1 - 51.1
TZ1(V)	18.2 +-0.1	53 +-3	46 +-2	Mars	50.1 - 51.1
TZ2(H)	18.8 +-0.2	54 +-3	44 +-2	Mars	52.4 - 54.7
TZ2(V)	18.8 +-0.3	56 +-3	45 +-2	Mars	52.4 - 54.7

VLBI Backend

- ◻ΔB = 2GHz x 6 IFs INPUT at maximum are available
  - ✓Samplers: total of 6 IFs input are now available
    - OCTAD-V1 (input: 8Gsps x 3 IFs, DBBC): ready
    - OCTAD-V2 (input: 16Gsps x 3 IFs, DBBC): ready (installed on Aug 2019)
  - ✓Recorder
    - OCTADISK2 (32Gbps recording): ready (installed on Aug 2019)
    - Two 8Gbps recorders have already been installed (by HINOTORI/NAOJ)

    -> Total of 48Gbps recording

※Because of the rack of disk packages, OCTADISK2 can record with **16 Gbps** at maximum now (i.e., total of 32Gbps recording)

A few concerns

□Not yet

- Measurement of Image Rejection Ratio (after re-installed)
- Tuning bias for SIS/HEMT to reduce T_{sys}
    - There is a room to improve T_{sys} of both H/V (T_{sys} of 150 – 300 K are described in Nakajima et al. 2013)
    - The value of V is almost double of the one of H

    ※ Current SEFD (H-pol) ~ 1000 Jy (with T_{sys} of ~ 250K)

□Improvement of some scripts for setting obs. mode automatically

- Preparing by Imai-san
- It is possible to set manually (ready)

3mm-VLBI commissioning will start

- 1st VLBI test **with QO (22/43/86GHz)** & new VLBI backend system will be performed on Jan 27 together with KVN (Thanks Jung-san, Byun-san, and KASI colleagues !)

Stay tunes!

KVN/KaVA+NRO45
with Quasi-Optics (@22/43/86GHz)

Measuring velocity field of AGN jet with QO & new VLBI-BE

Merits of K/Q/W truly simultaneous obs. w/ quasi-optics

- VLBI observation time with NRO45 is quite limited, i.e., ~72hrs-cap per year from this season
  - "Quasi-optics" + "simultaneous recording" significantly save time

    -> Regular VLBI monitor at 22 – 86 GHz
- Variability matters at a jet base. Assumptions are needed.
  - "Quasi-optics" + "simultaneous recording" does not require such assumptions.
- Calibration / Source Frequency Phase Reference technique

GMVA@3mm Antenna Sensitivities

Antenna and Receiver properties at 86 GHz:

GMVA status report

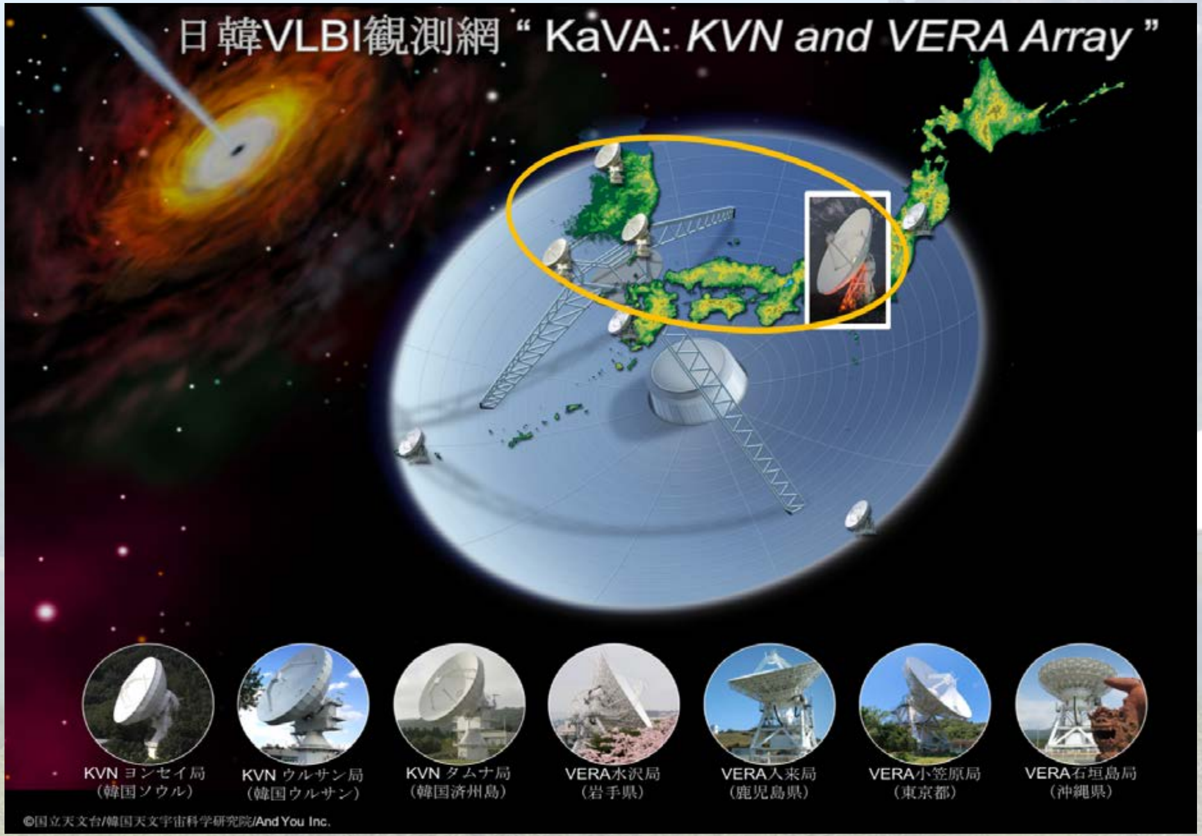
Station	Diameter (m)	Tsys (K)	Gain (K/Jy)	Eta (%)	SEFD (Jy)	Comment
GBT	100.0	100.0	0.73	26	137	for nighttime observing
Effelsberg	80.0 (eff.)	140.0	0.14	7.7	1000	-
NOEMA (PdB)	43.9	100.0	0.39	71	260	10x15m
Pico Veleta	30.0	100.0	0.15	60	654	-
Yebes	40.0	180.0	0.09	20	2000	-
VLBA (8x25m)	25.0	100.0	0.04	22	2500	range is: 0.02-0.04 K/Jy
KVN (3x21m)	21.0	200.0	0.062	49	3226	for each 21m antenna
Onsala	20.0	190.0	0.049	43	3877	-
Metsähovi	14.0	300.0	0.010	19	30000	-
LMT (prelim)	50	240.0*	0.39	55	615	* DSB, single pol
GLT (prelim)	12	100	0.025	60	4000	-
ALMA	79.7 (eff.)	90.0	1.32	73	68.0	50x12m

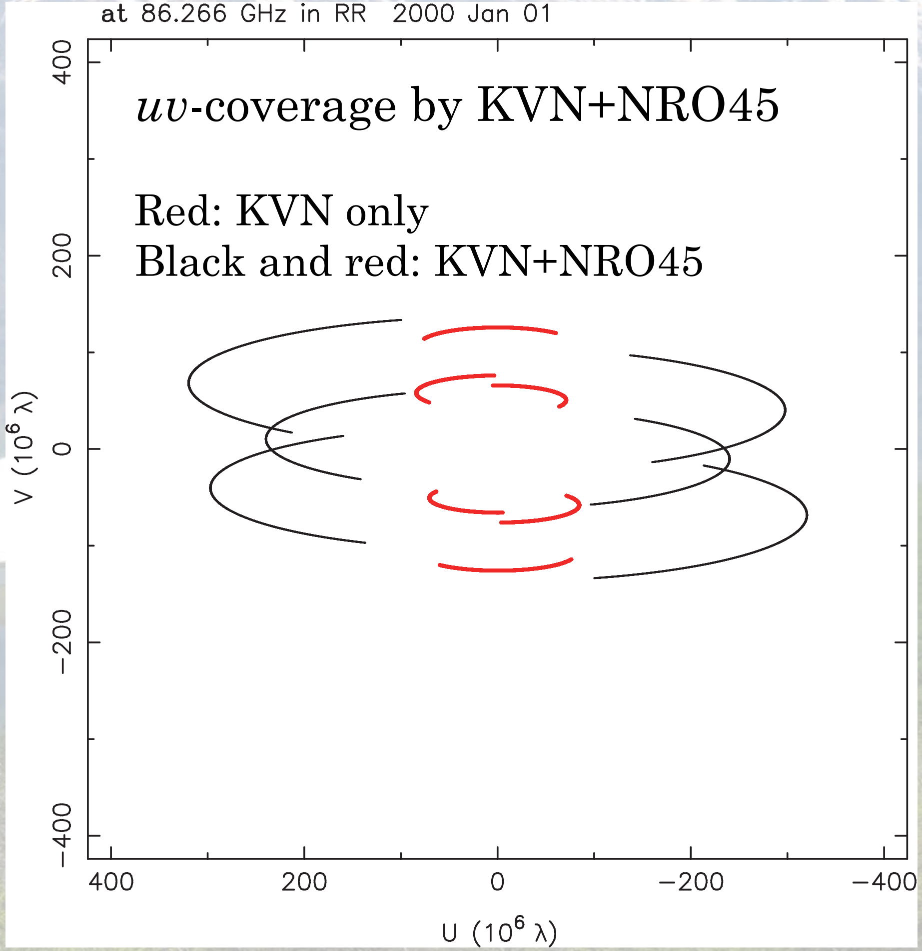
Sensitivity: KVN/KaVA + NRO45

SEFD (Jy)	KVN	VERA	NRO45	VLBA	GBT
23 GHz	1300 (L/R)	2300 (L/R)	280 (L/R)		
43 GHz	2000 (L/R)	4800 (L/R)	490 (L)		
86 GHz	3200 (L/R)	-	~1000 (H/V)	3000 - 6000 (L/R) (NRAO status report)	~130 (???)

Baseline Sens. (mJy @ 1σ)	KaVA	KVN+NRO45	KaVA+NRO45	VLBA	VLBA+GBT
23 GHz w 2Gbps, 2min	4 - 7	-	2 - 7		
43 GHz w 2Gbps, 1min	6 - 16	-	5 - 16		
86 GHz w 2Gbps, 0.5min	-	12	-	23 - 38	5 - 6

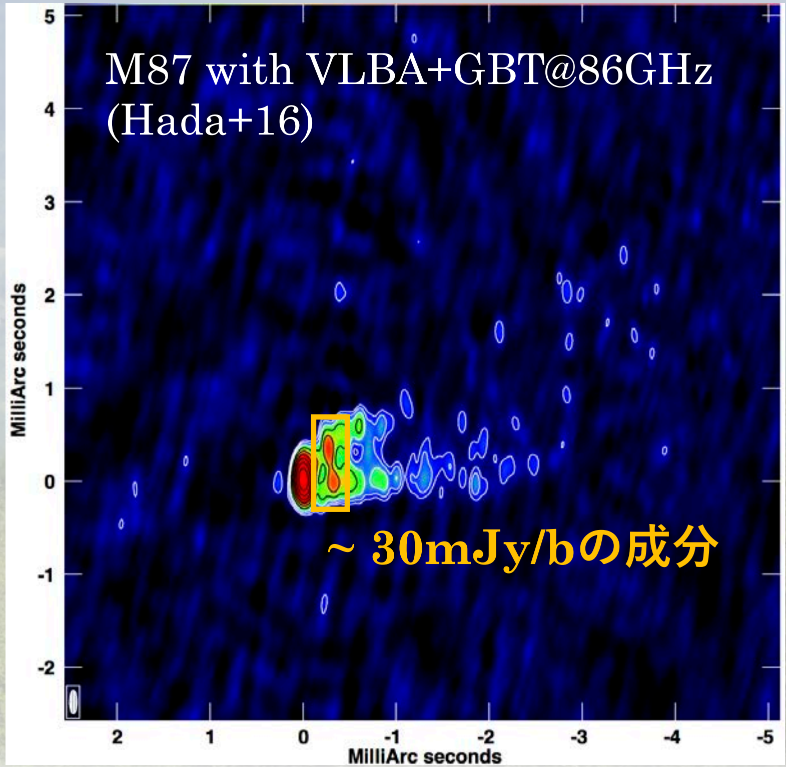
Array: KVN + NRO45@86 GHz





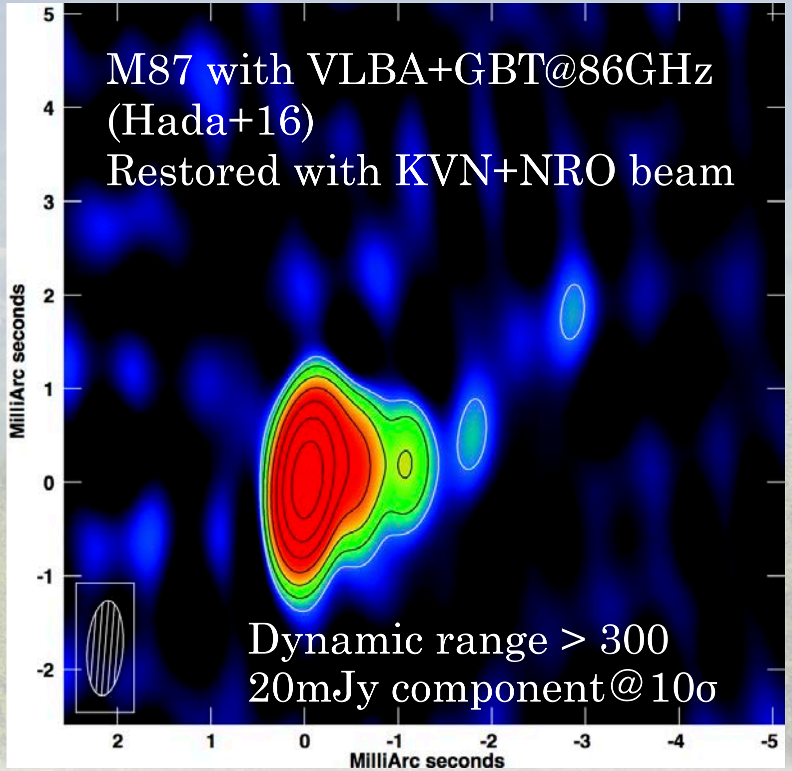
Baseline length will be 3 times longer than KVN along M87 jet direction!

M87 jet with KVN+NRO45@86GHz



M87 jet with KVN+NRO45@86GHz

□M87 observation with KVN+NRO45@86GHz
- Allowing us to measure the jet motion from <100 R_s

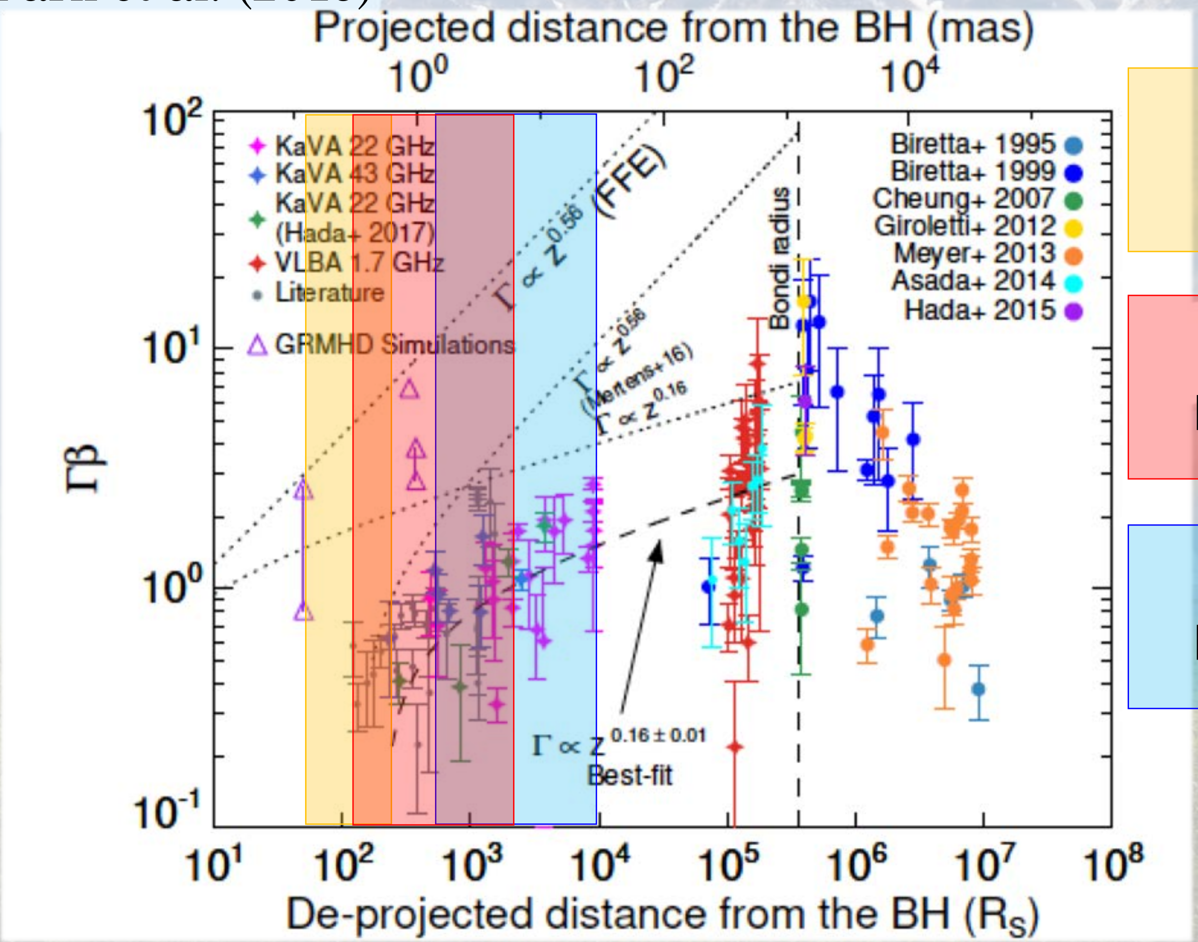


■Availability of **regular monitor**
- KVN/KaVA: 10 months operation / year
- NRO: 6 months operation / year

■NRO45 provides us
- Higher baseline sensitivity@86GH: ~10mJy@1sigma
- Higher angular resolution@86GHz: < 0.4 mas along the jet direction
  - Corresponding to projected distance of ~60 R_s (or de-projected distance of ~90 R_s)

Measuring velocity field:<100Rs – 10000Rs
by truly simultaneous observation

Park et al. (2019)



Covered by KVN+NRO45 86 GHz

Covered by KaVA 43 GHz

Covered by KaVA 22 GHz

Summary and Future prospect

□Current situation of NRO45

- QO: (almost) Ready
- 86GHz VLBI: (almost) Ready for commissioning

□KVN/KaVA+NRO45 with QO

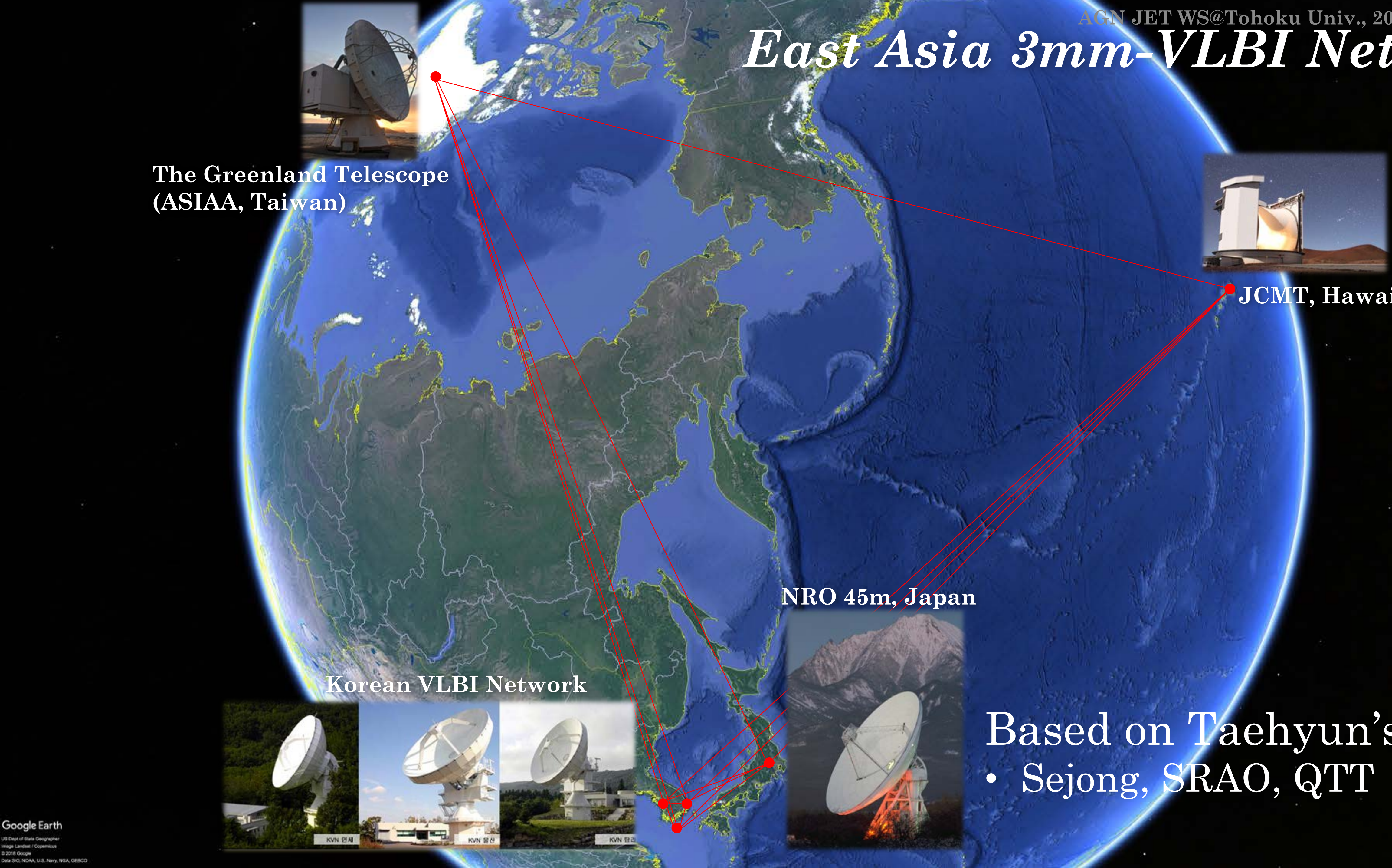
- e.g., “truly” simultaneous & regular monitor will be available with <1mas

-> measuring accurate v-field from $<10^2$ to 10^4 Rs

□KVN+NRO45@86GHz -> EAVN@86GHz

- Transparency: upstream of the jet
- Availability of regular monitor (e.g., bi-weekly or less)
- Angular resolution (<0.4 mas): EAVN (including Urumqi) @43GHz / EATING VLBI@22GHz

East Asia 3mm-VLBI Network



Based on Taehyun's Talk

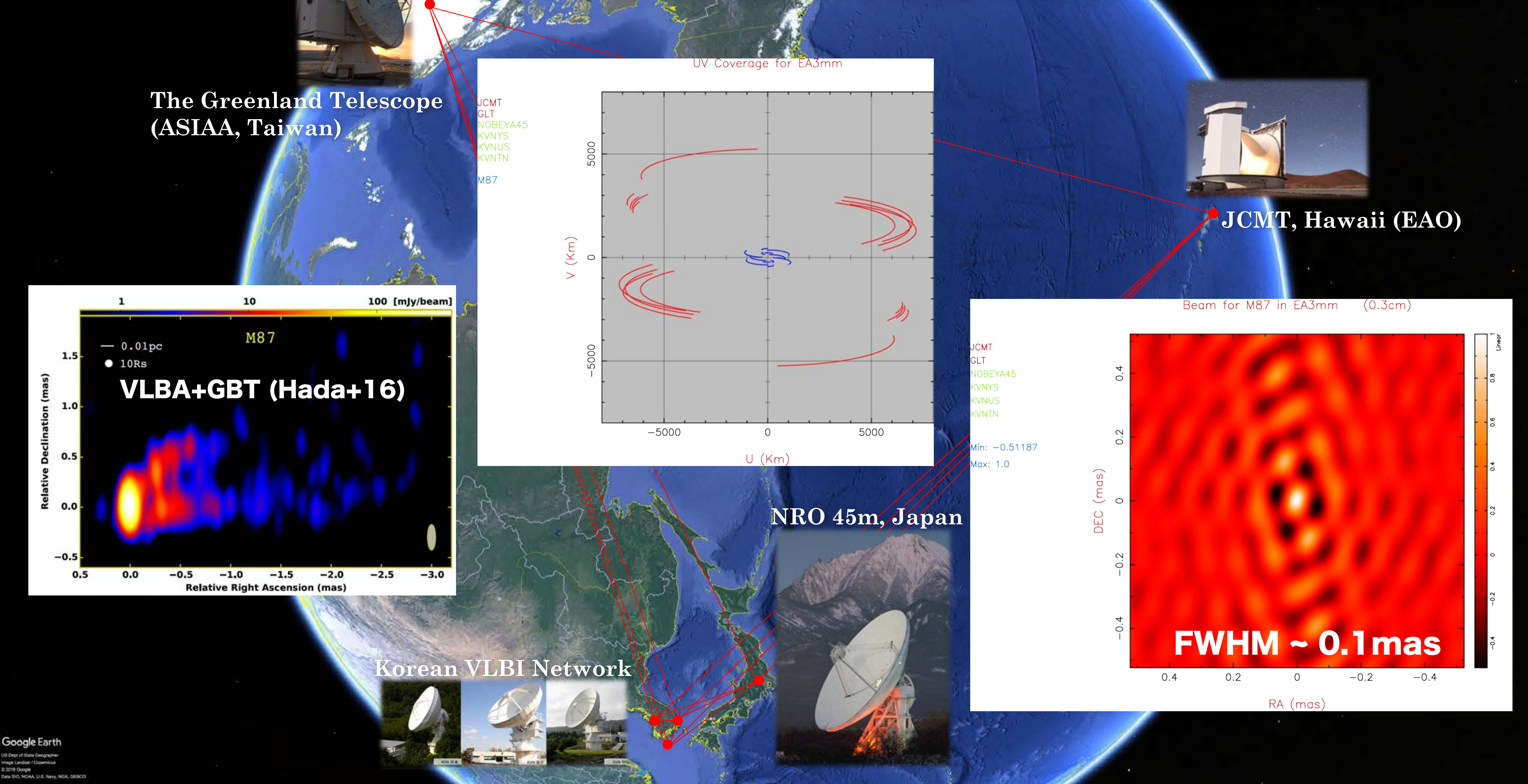
- Sejong, SRAO, QTT

Array: GLT/JCMT + NRO45@86 GHz

SEFD (Jy)	KVN	VERA	NRO45	VLBA	JCMT/GLT
23 GHz	1300 (L/R)	2300 (L/R)	280 (L/R)		
43 GHz	2000 (L/R)	4800 (L/R)	490 (L)		
86 GHz	3200 (L/R)	-	~1000 (H/V)	3000 - 6000 (L/R)	3600 (L/R ?)

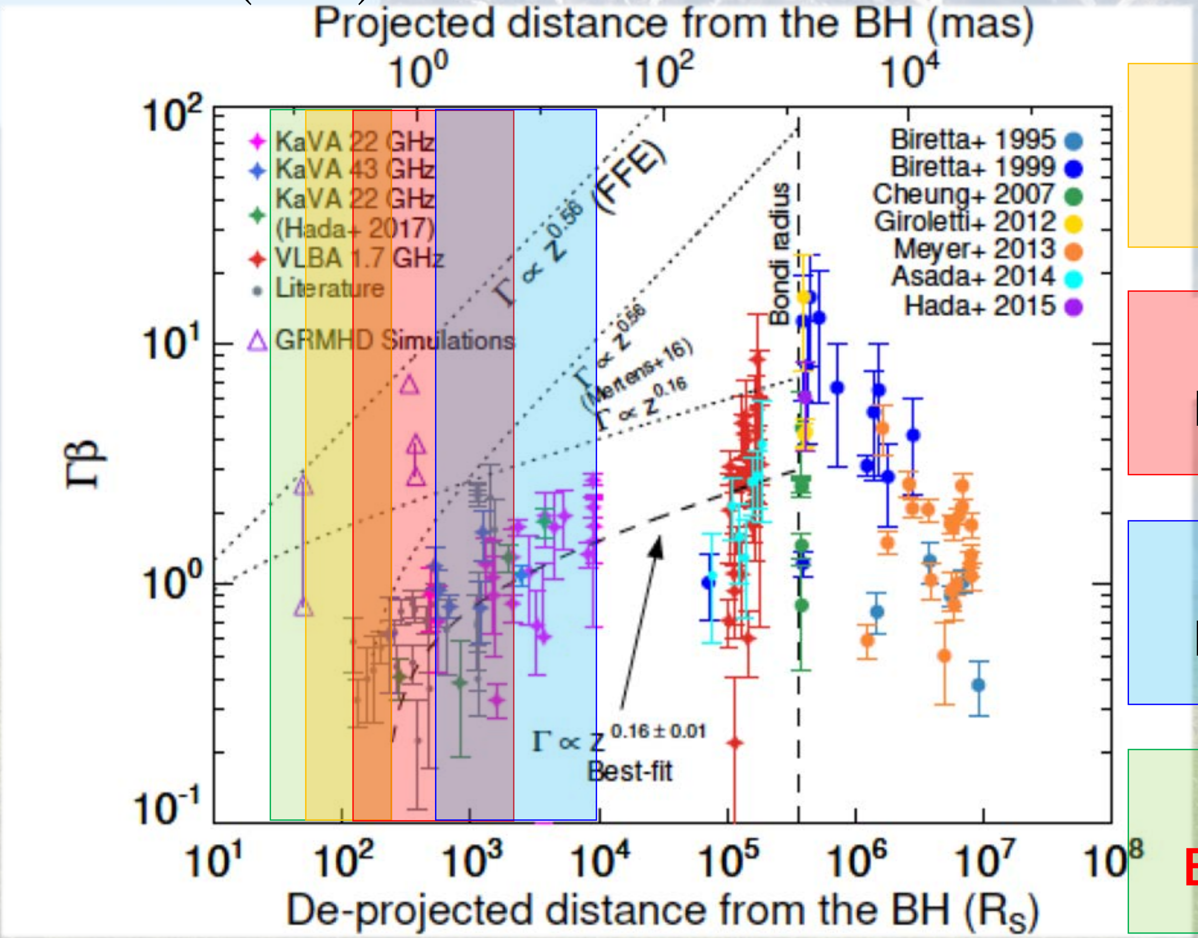
Baseline Sens. (mJy @ 1σ)	KaVA	KVN+NRO45	KaVA+NRO45	VLBA	NRO+GLT NRO+JCMT
23 GHz w 2Gbps, 2min	4 - 7	-	2 - 7		
43 GHz w 2Gbps, 1min	6 - 16	-	5 - 16		
86 GHz w 2Gbps, 0.5min	-	12	-	23 - 38	12

East Asia 3mm-VLBI Network



Measuring velocity field:~$30R_s$ – $10000R_s$ by future EAVN@3mm monitor

Park et al. (2019)



Covered by KVN+NRO45 86 GHz

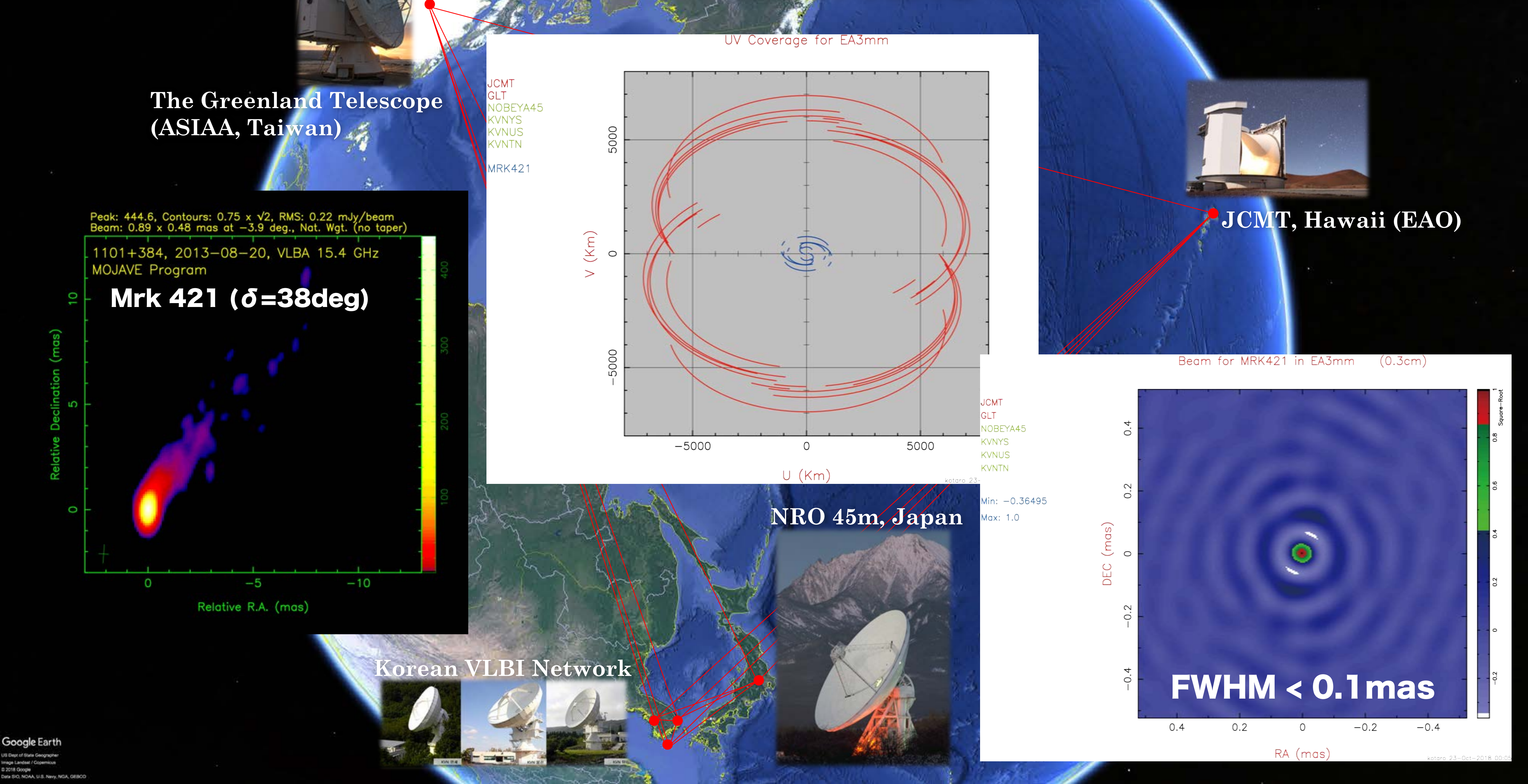
Covered by KaVA 43 GHz

Covered by KaVA 22 GHz

Covered by EAVN 86 GHz

Other sources ?

East Asia 3mm-VLBI Network



e.g. Blazar Markarian 421

- The first Very High Energy (TeV) - gamma detection

- The most nearby TeV-blazar (z = 0.031)
  - Best source to investigate HE emitting region by VLBI
    - 0.1 mas = 0.062 pc = 1770 R_s (de-projected, M_{BH} ~ 3.6 x 10^8 M_{solar}, Wagner 2008)
  - Detailed longitudinal/transversal structure from 1000 R_s
    - Velocity field / Collimation profile of blazar (Nakamura-san's talk)
    - Broad Line Region

- No (or few?) sub-pc scale 3mm (or shorter-λ) VLBI images
  - Expected 3mm peak flux in sub-pc scale is ~ 100mJy/b or less

Other activities:

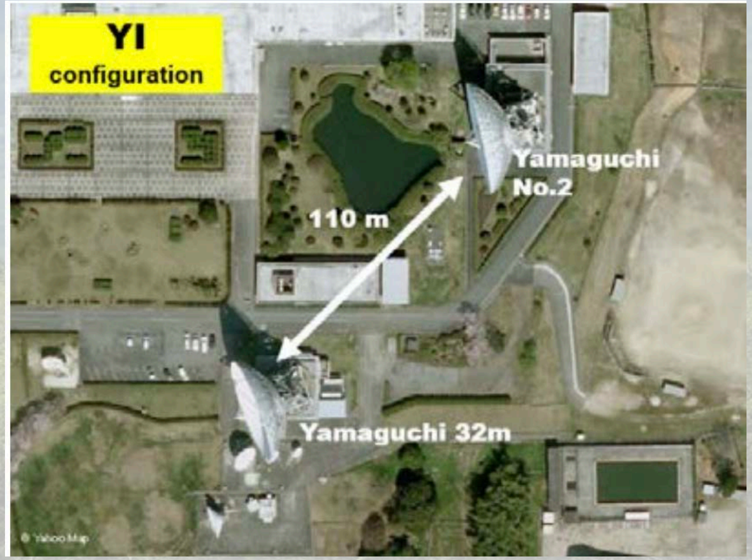
1. Lower frequency
2. Higher frequency (EAVN-Hi(1mm))

Activity 1: low-frequency part

- We operates two large radio telescopes
  - Yamaguchi Univ. operates 32m and 34m at 6/8 GHz
  - Recently operation as interferometer was started (good sensitivity): **Yamaguchi Interferometer (YI)**

- Development of "**On the Fly mapping by interferometer (OtFI)**" method toward SKA era
  - Aiming for establishing the technique and conducting un-biased survey for a region of 5deg^2 < a day
    - Time-domain studies (radio follow-up of huge error circle of GW or ν events)
    - Regular monitor of the large number of sources showing high-energy flare
    - Survey for radio transients or variable objects
    - Survey for new radio sources without dependence on existing catalog.

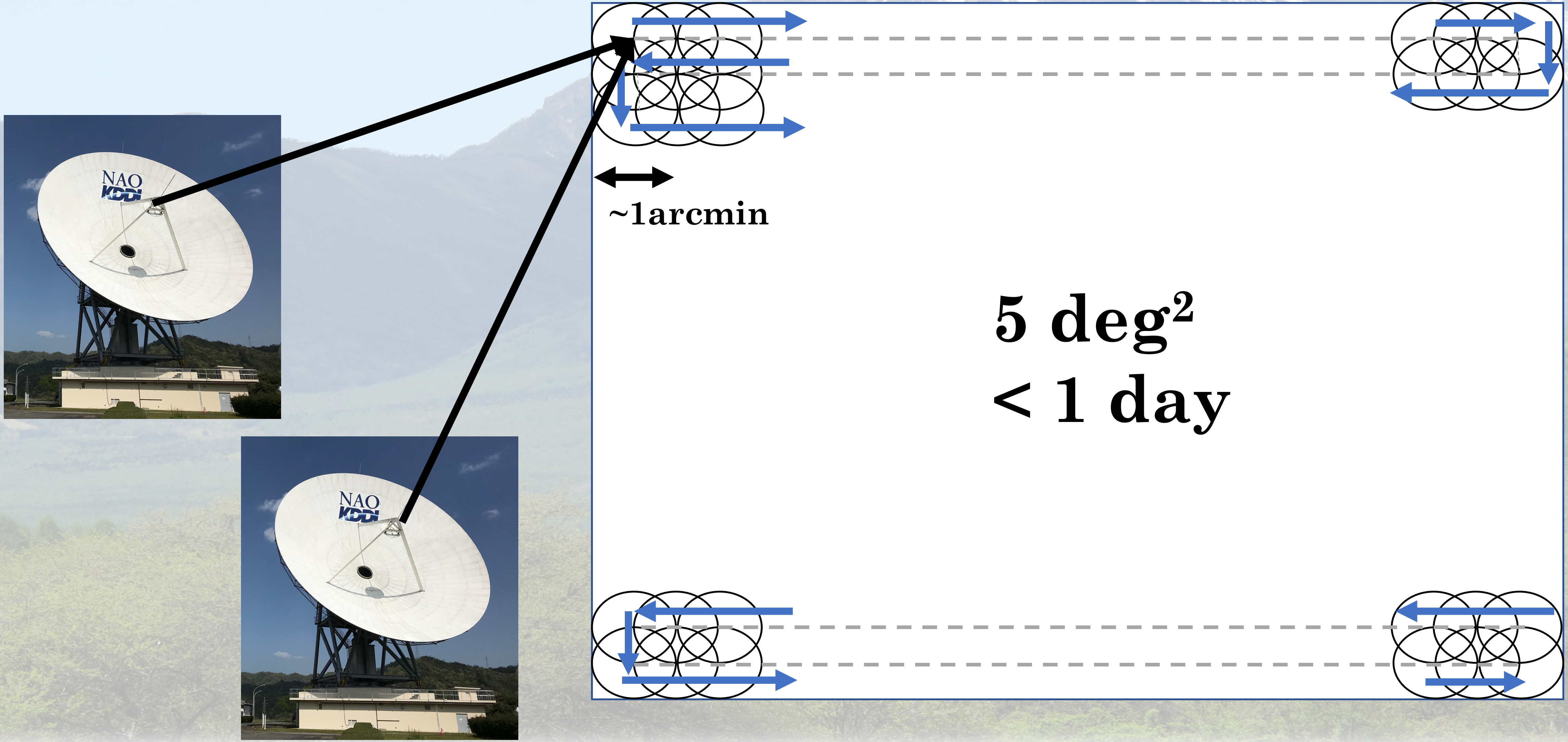
Yamaguchi Interferometer (YI)



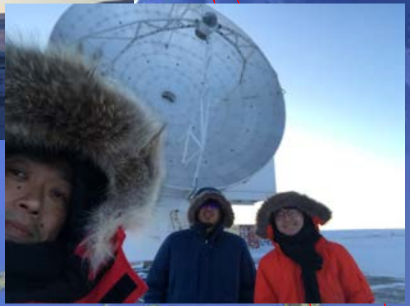
Observing Band	6 GHz / 512 MHz 8 GHz / 512 MHz
Baseline	110 m (32m&34m)
Beam size	6 GHz: 1'.4 8 GHz: 1'.1
Data rate	2 Gbps/Antenna
Integration time	1 hours
1σ sensitivity	0.15 mJy
Observing Time	3000 hours/yr

YI is used for...
  Daily monitoring of compact object/AGN/YSO

Un-biased survey by OtFI



East Asia 1mm-VLBI Experiment



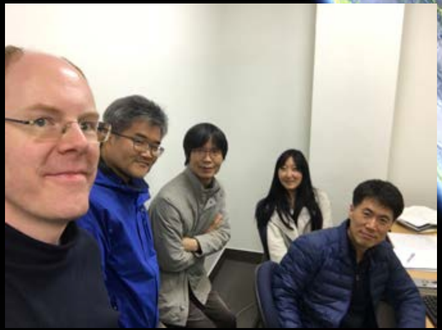
The Greenland Telescope
(ASIAA, Taiwan)

Table 2. VLBI Schedule

Start UTC	Duration [s]	Target
11:00:00	1200	M87
11:23:00	1200	M87
11:46:00	1200	M87
12:09:00	1200	M87
12:32:00	1200	M87
12:59:00	1200	NGC 6251
13:22:00	1200	NGC 6251
13:49:00	1080	3C 371
14:10:00	1080	3C 371
14:35:00	1080	1928+738
14:56:00	1080	1928+738
15:17:00	1080	1928+738
15:42:00	1200	3C 345
16:05:00	1200	3C 345
16:29:00	1200	1633+382
16:52:00	1200	1633+382
17:16:00	1200	J1653+3945
17:39:00	1280	J1653+3945

Observing schedule made
by Lu, Hada, Asada

SRAO (SNU, Korea)



SPART (OPU, Japan)

EAVN@1mm VLBI Experience

led by Aoki-san (Japan-side)

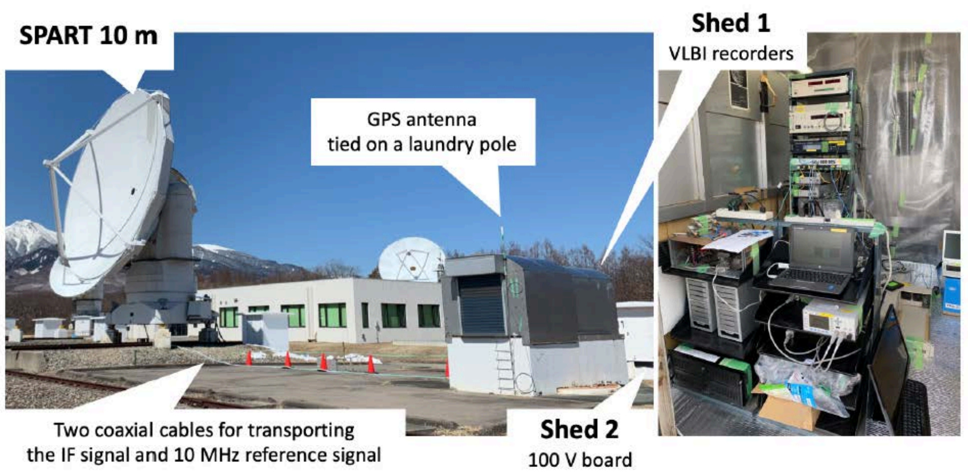
2.2 Success Criteria

The immediate goal for the above science is to acquire VLBI fringes. Then we, the SPART team, define the success criteria are as follows:

Minimum Success To participate in the international mm-VLBI using the SPART and try to detect fringes.

Full Success To detect fringes of baselines including the SPART.

Extra Success To acquire VLBI images to which the SPART contributes.



Unfortunately, no fringe, but good experience for us

The first experiences for most of Japanese colleagues participating to set up VLBI system and to perform observation for 1mm-VLBI