New International VLBI Arrays in East Asia: Accomplishments in AGN Sciences with the KVN and VERA Array (KaVA) and the East-Asian VLBI Network (EAVN)

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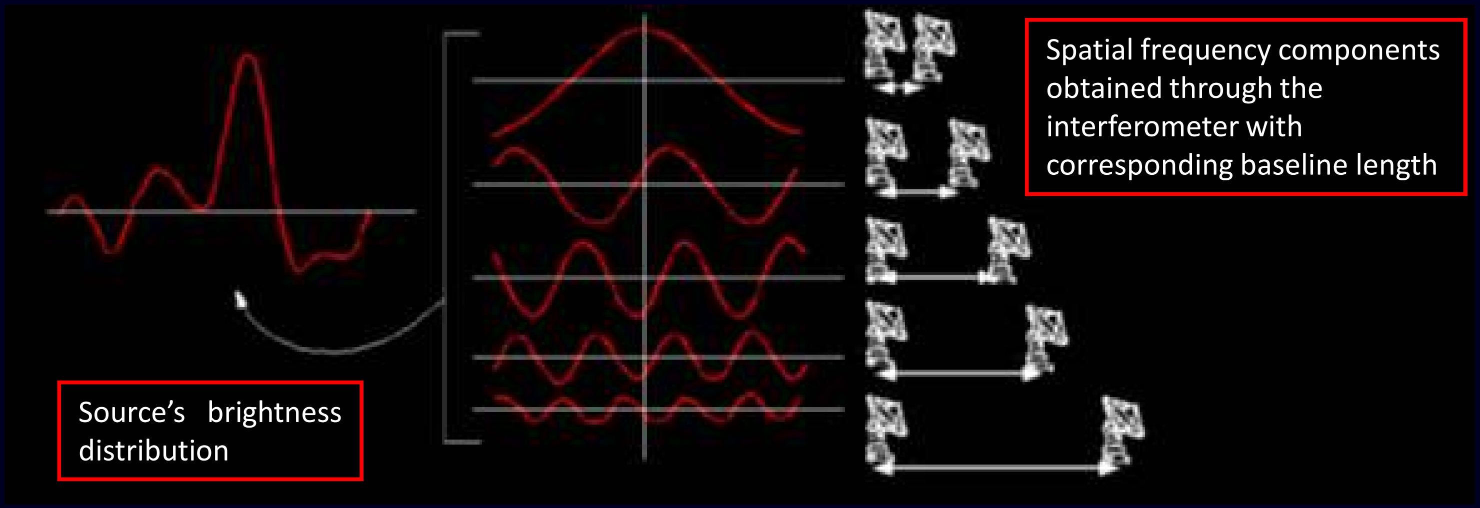
Very Long Baseline Interferometer (VLBI)

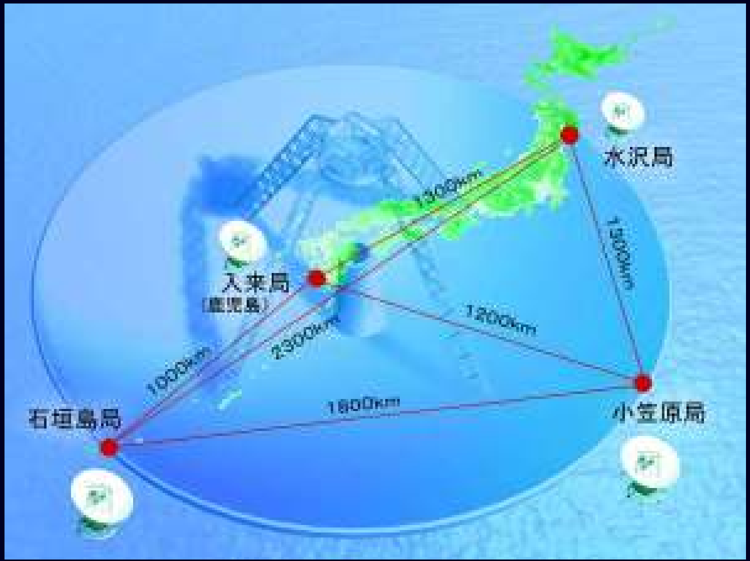
- Instrument to obtain various spatial frequency components, *V*, with different baseline lengths
- Source's brightness distribution (or image), *I*, can be obtained by inverse-Fourier-transforming *V*

$$V(\nu,u,\upsilon)=\iint_{\mathrm{source}} I(\nu,l,m)\exp(2\pi i(ul+\upsilon m))dldm$$

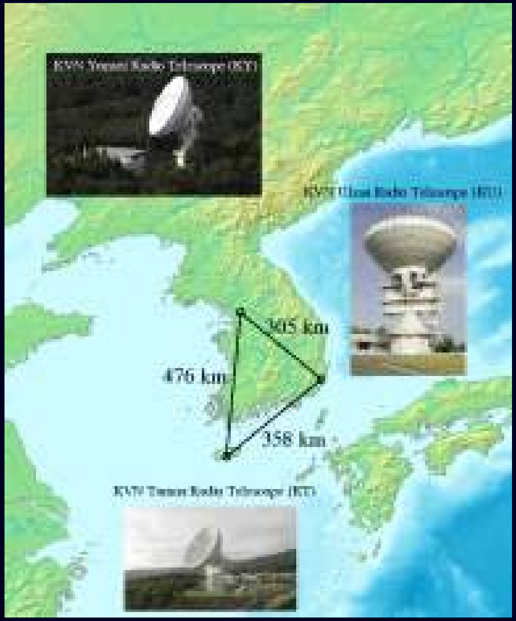


VLBI Array in East Asia: VERA and KVN

- VERA (VLBI Exploration of Radio Astrometry: 2001 –)
  - 4 antennas with baseline lengths of 1,000 – 2,300 km
  - Dual-beam system for precise astrometry to investigate Galactic dynamics

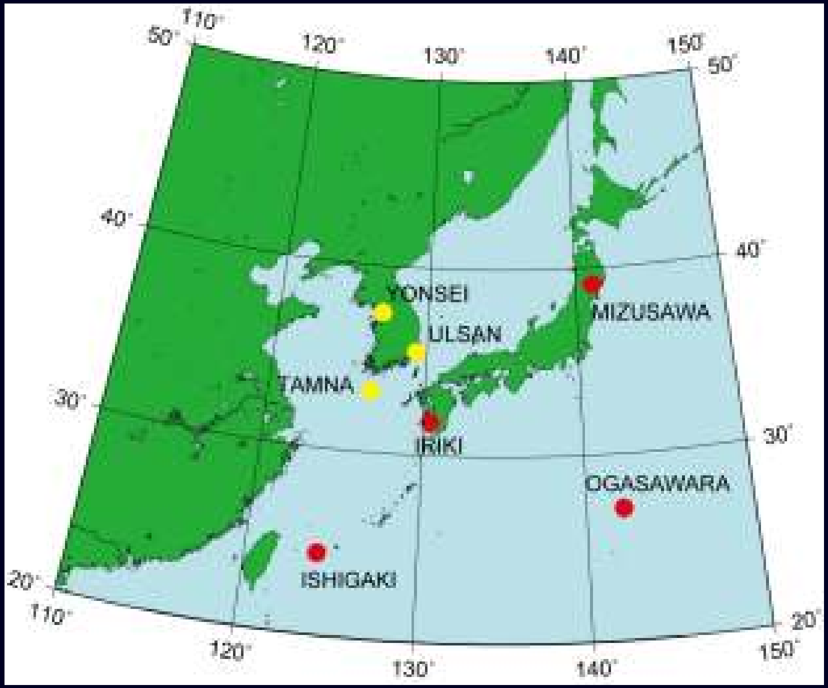


- KVN (Korean VLBI Network: 2008 –)
  - 3 antennas with baseline lengths of 300 – 480 km
  - Multi-frequency simultaneous receiving system at 22/43/86/129 GHz



The KVN and VERA Array (KaVA)

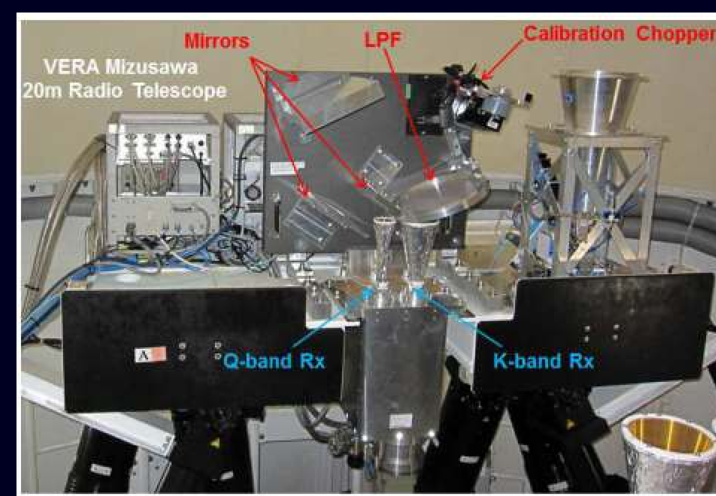
- The first international collaborative VLBI array for open-use operation in East Asia (2013 –)
  - Complementary antenna distribution for obtaining high-fidelity radio images at 22/43 GHz
  - Conducting more than 1000-hour observations per year (including 500-hour observations for open use)
  - Large Program has been launched for three science fields (AGN, evolved star, star-forming region)



Simultaneous 22/43 GHz Receiver System

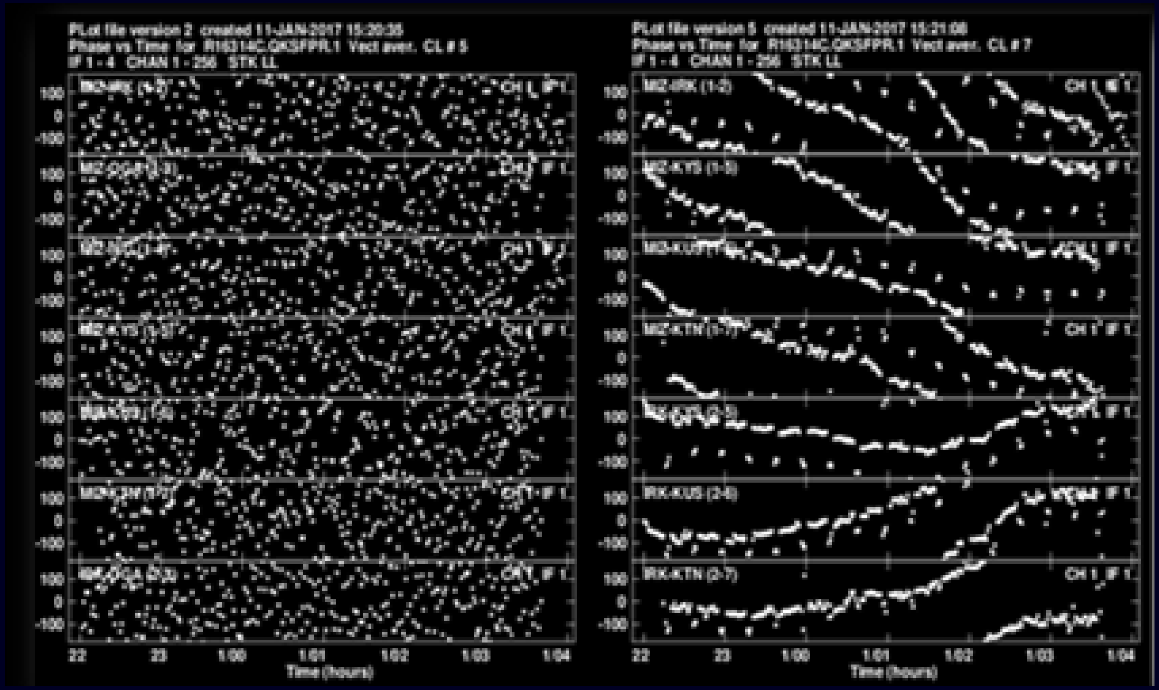
- The world's first four-frequency simultaneous receiving system was realized with KVN (cf. Han et al. 2013, PASP, 125, 539)
- Multi-frequency simultaneous receiving capability was imported to VERA (and Yebes (Spain))

Simultaneous 22/43 GHz VLBI campaign will be conducted in 2018 January with KaVA



Simultaneous Receiving System

- 43 GHz visibility phase for 22/43 GHz simultaneous VLBI observation of 4C 39.25 with KVN+VERA



No phase calibration   After FTP

43 GHz phase can be compensated by using 22 GHz phase (Frequency Phase Transfer (FTP) technique; e.g. Algaba et al. 2015, JKAS, 48, 237)

Long-Term Monitoring Program of AGN

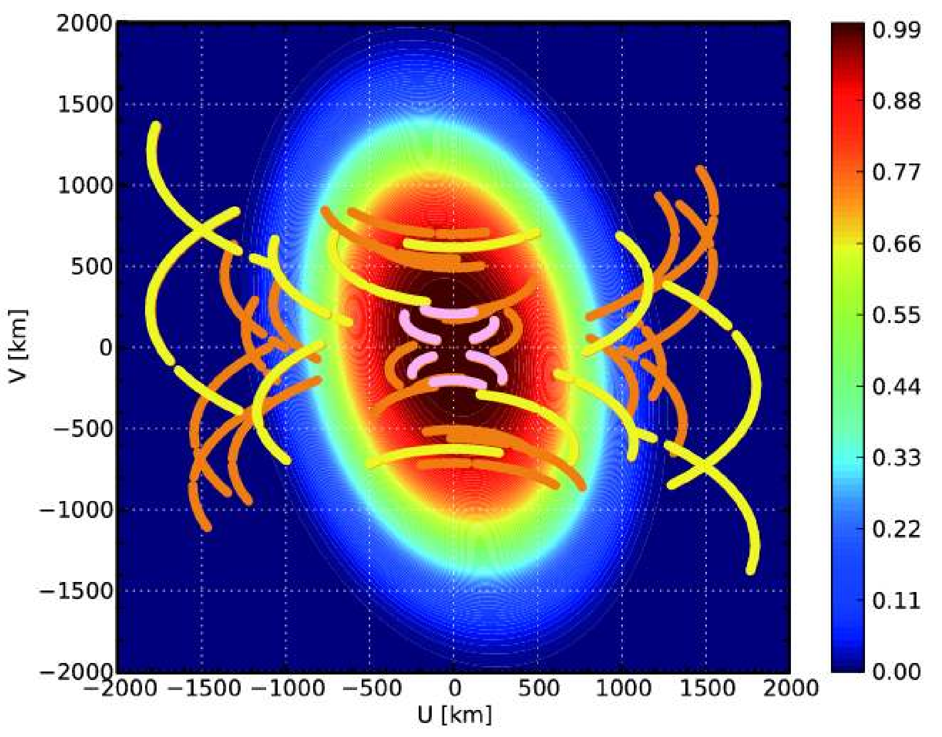
- KVN Key Science Program
  - Interferometric Monitoring of Gamma-Ray Bright AGNs (iMOGABA) (PI: Sang-Sung Lee (이상성))
    - Intensive study of individual source (e.g., 3C 84 → Talk by Jeffrey Hodgson (in this session)
  - Plasma-Physics of AGNs (PAGaN) (PI: Sascha Trippe) → Talk by Sascha (in this session)
- KaVA AGN Large Program
  - M87 (PI: Kazuhiro Hada (秦和弘), Jongho Park (박종호), Hyunwook Ro (노현욱)
  - Sgr A* (PI: Guang-Yao Zhao (赵光耀))
- KaVA/KVN General Observing Time
  - 3C 84 (PI: Motoki Kino (紀基樹), Kiyoaki Wajima (輪島清昭)

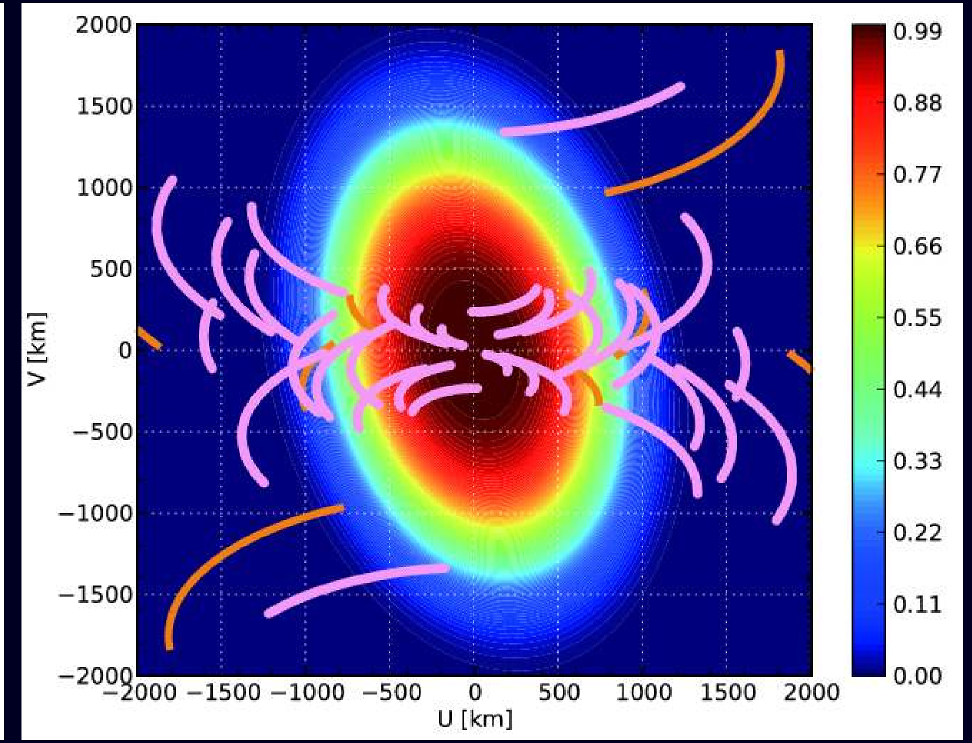
1st-Term KaVA AGN Large Program

- Motivation: “What happens in the vicinity of supermassive black holes?”
- Target: Sgr A* and M87 (nearby supermassive black hole sources)
- Method:
  - Sgr A*: Biweekly – monthly monitoring at 43 GHz
  - M87: Biweekly monitoring at 22/43 GHz
- Total observing time
  - Sgr A*: 60 hours
  - M87: 124 hours

(u, v) Coverage for Sgr A*

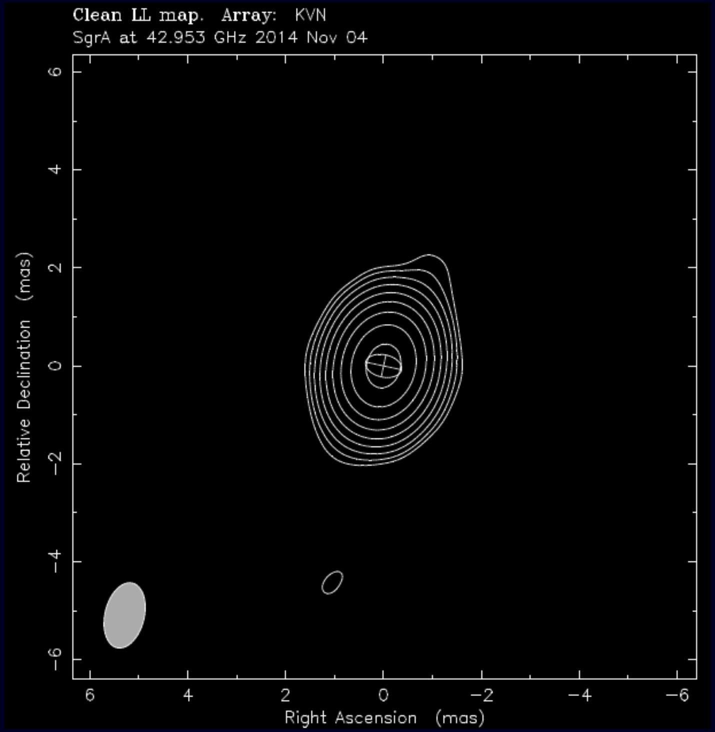
- KaVA provides better sampling in (u, v) plane for Sgr A* than VLBA + GBT thanks to denser antenna location





Two-Dimensional Size of Sgr A*

- KaVA 43 GHz image of Sgr A* (Zhao et al. 2017, IAUS, 322, 56) and comparison of source's intrinsic size between images obtained with VLBA and KaVA

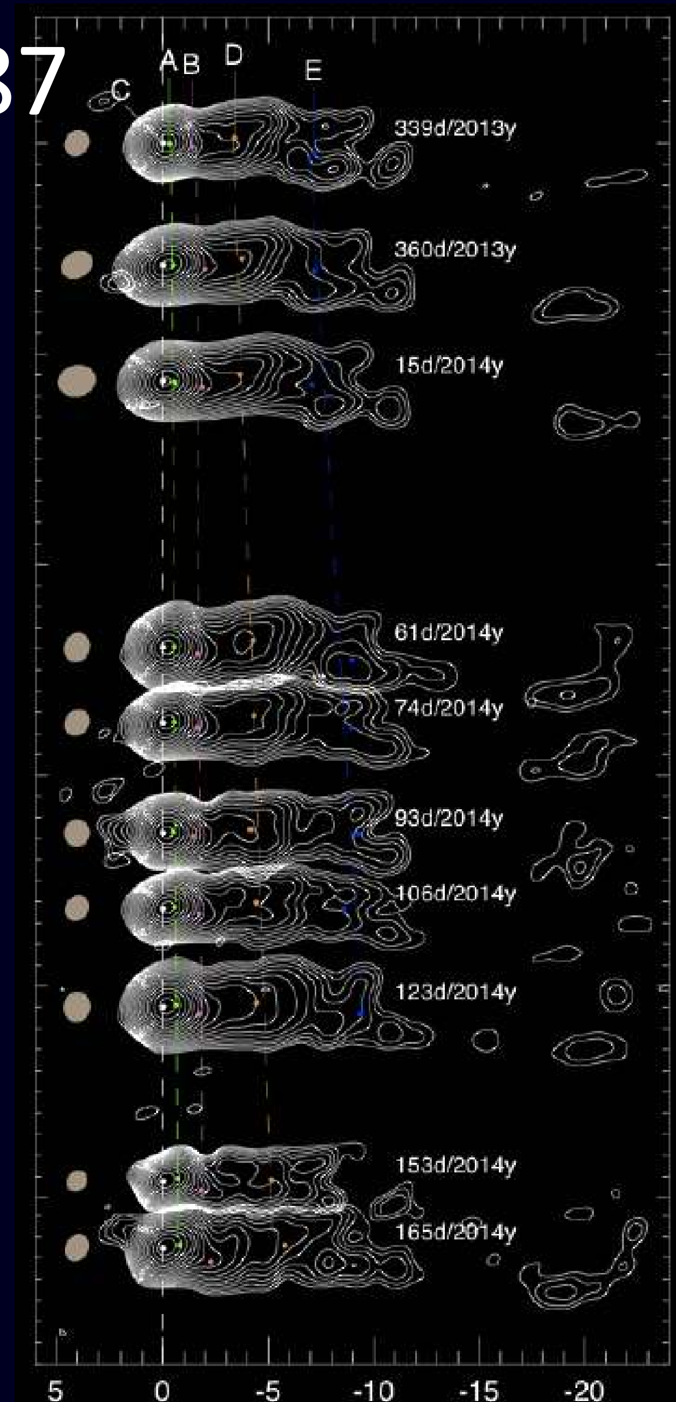


	Bower et al. (2014, ApJ, 790, 1)	Zhao et al. (in prep.)
Epoch	2012 Mar 19 – 2013 Feb 23	2014 Nov 4
Array	VLBA 43 GHz	KaVA 43 GHz
Major axis (μas)	722^{+3}_{-3}	734.2±2.7
Minor axis (μas)	345^{+28}_{-35}	427.0±21.8

Biweekly Monitoring of M87

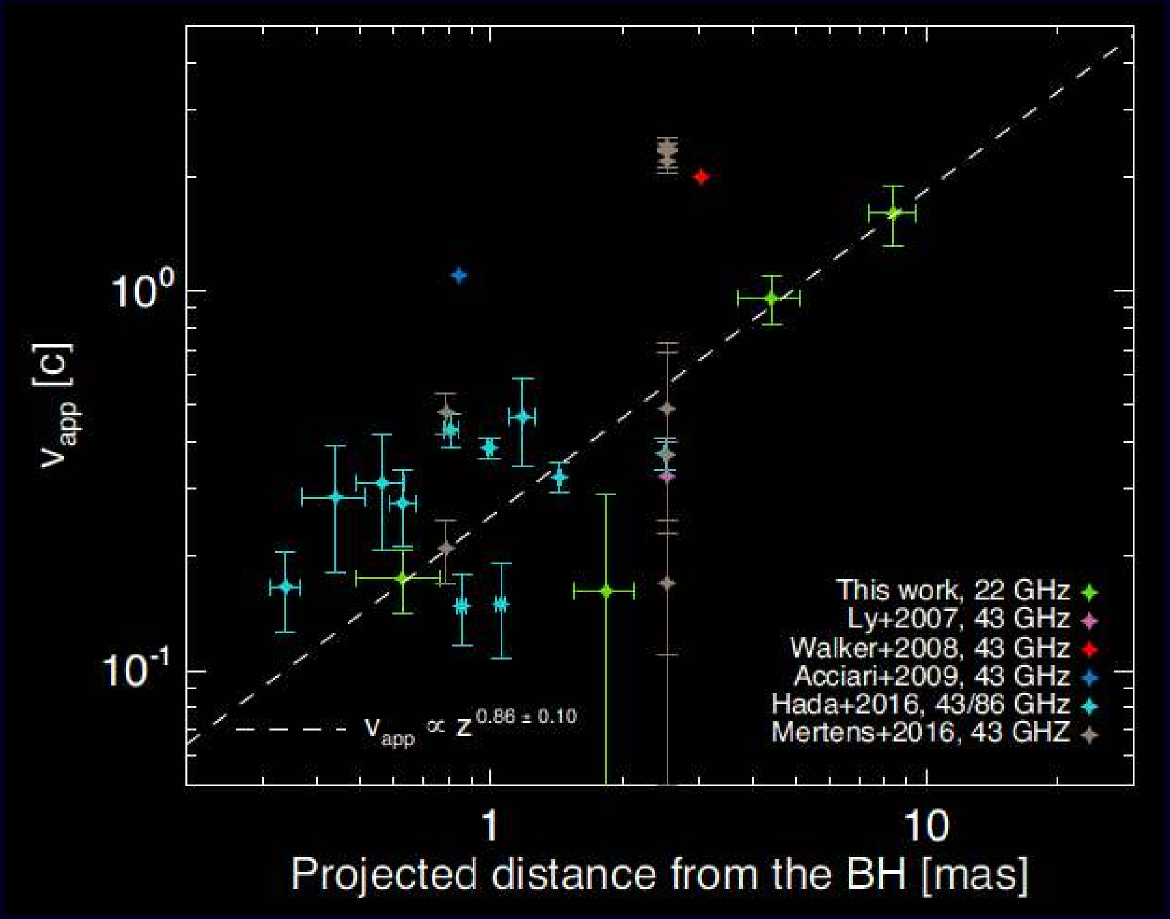
- Biweekly KaVA monitoring of a nearby AGN M87 at 22 GHz from December 2013 to June 2014 (Hada et al. 2017, PASJ, 69, 54)
  - Detection of superluminal motion and gradual acceleration of jet components in the angular scale of 1 – 20 mas (linear scale of 0.1 – 2 pc)

Investigating jet acceleration mechanism with dense VLBI monitoring



Biweekly Monitoring of M87

- Apparent velocity profile with the distance from BH
  → Jet acceleration within 0.1 – 20 mas (= 140 – 2800 R_s) from BH



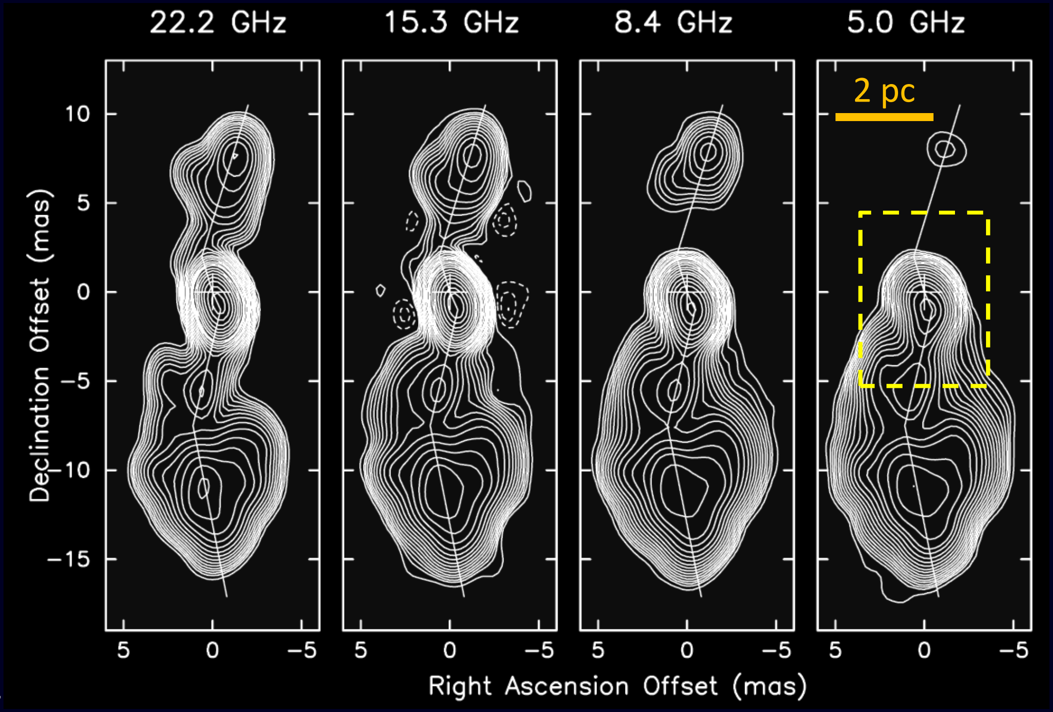
VLBI in EA
KaVA AGN
3C 84
EAVN
Summary

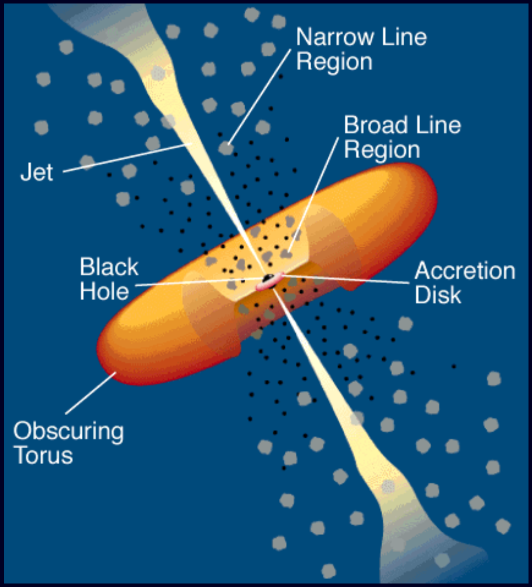
Preliminary Result of KaVA AGN LP of M87

- Biweekly monitoring of M87 (Park et al. in prep.)
  - ➔ Mixture of fast and slow component

3C 84 (z = 0.0176; 1 mas = 0.36 pc)

- Discovery of 10 pc-scale free-free-absorbed (FFA) plasma torus with multifrequency VLBI at cm-wavelength (Walker et al. 2000, ApJ, 530, 233)
- Monthly monitoring with KaVA at 43 GHz, and multi-epoch observations with KVN at 86/129 GHz

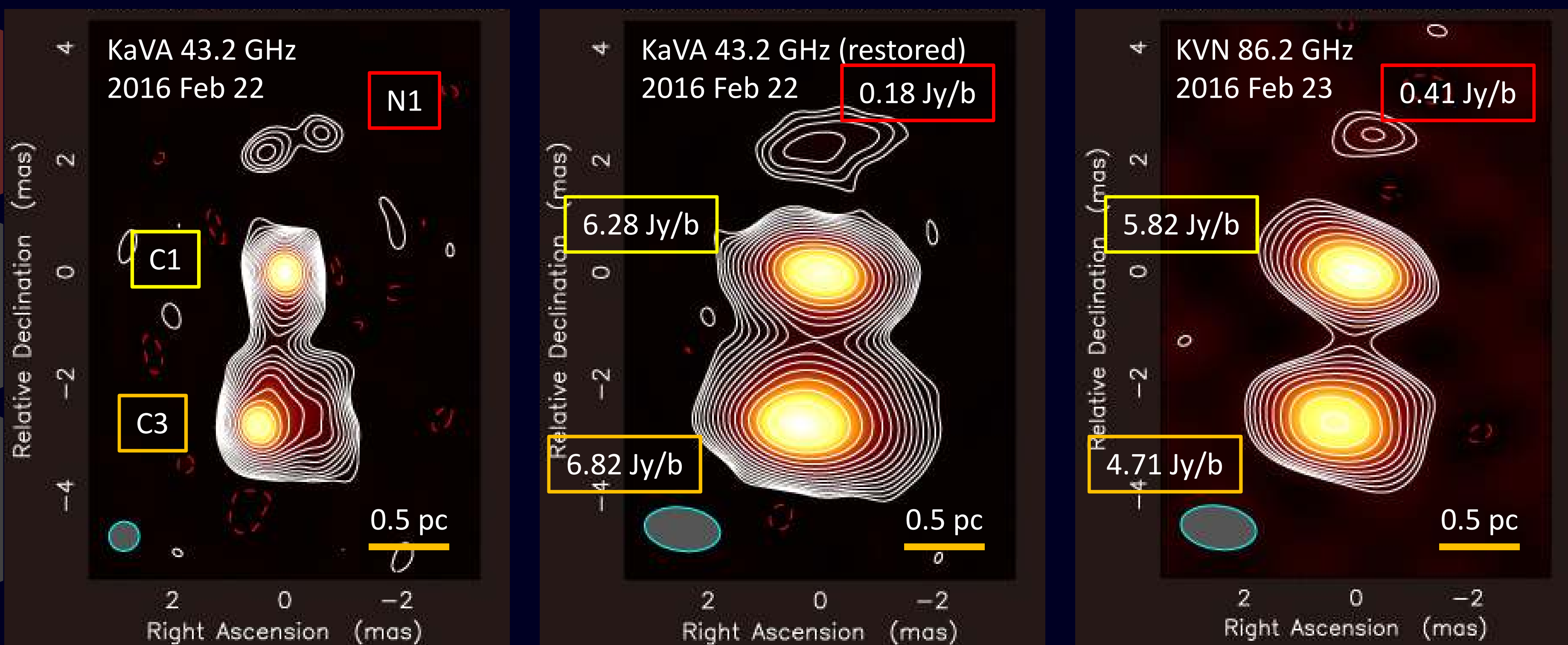




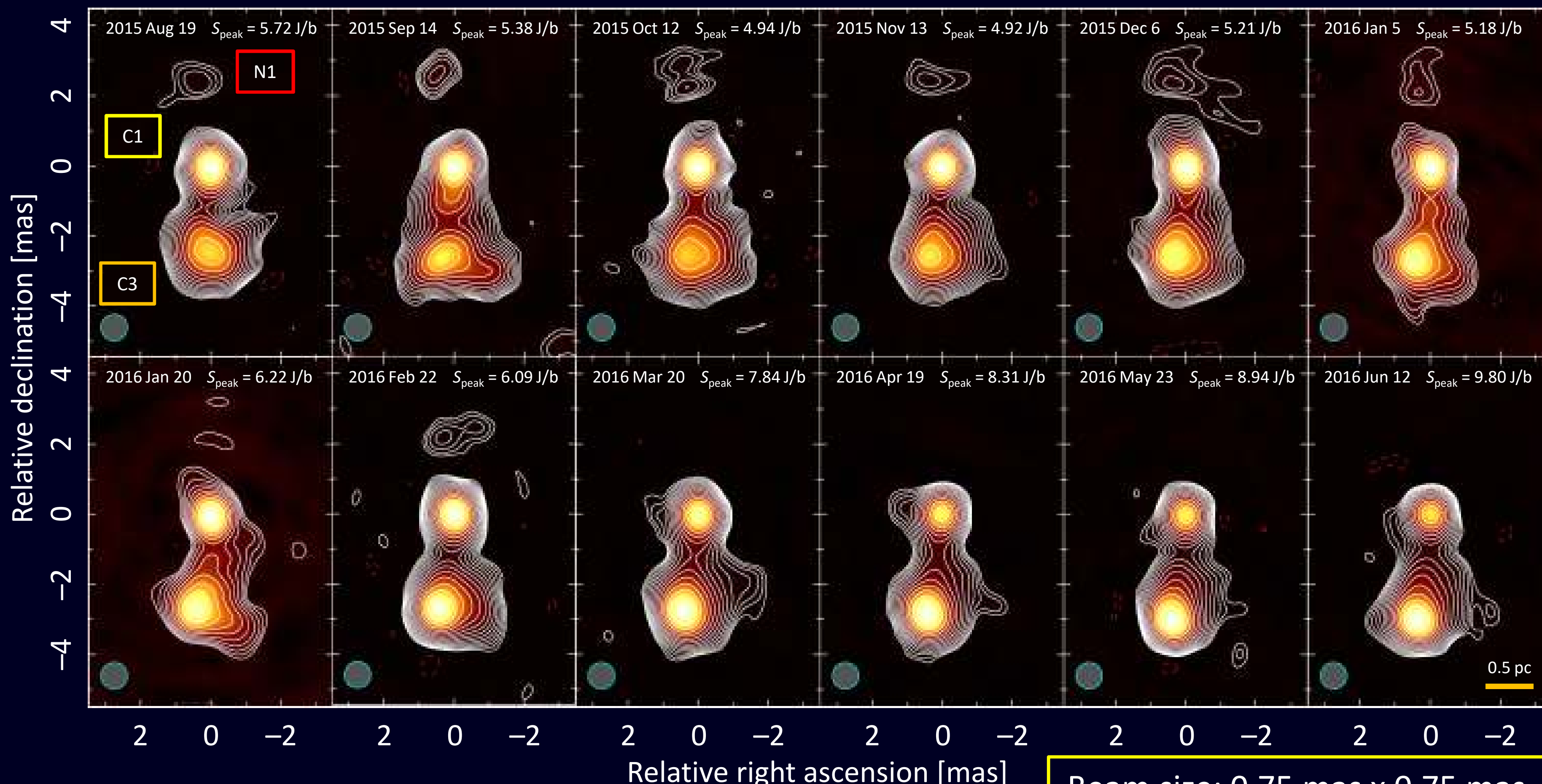
(Urry, Padovani 1995, PASP, 107, 803)

KaVA/KVN Images of 3C 84 at 43/86 GHz

- Detection of a new component (N1) in the north of C1
  - Peak intensity of N1: 0.18 Jy/beam (restored KaVA 43 GHz)
    0.41 Jy/beam (KVN 86 GHz)
  - Free-free absorbed plasma torus with 1-pc scale



12-Epoch Images of 3C 84 at 43 GHz



Beam size: 0.75 mas x 0.75 mas

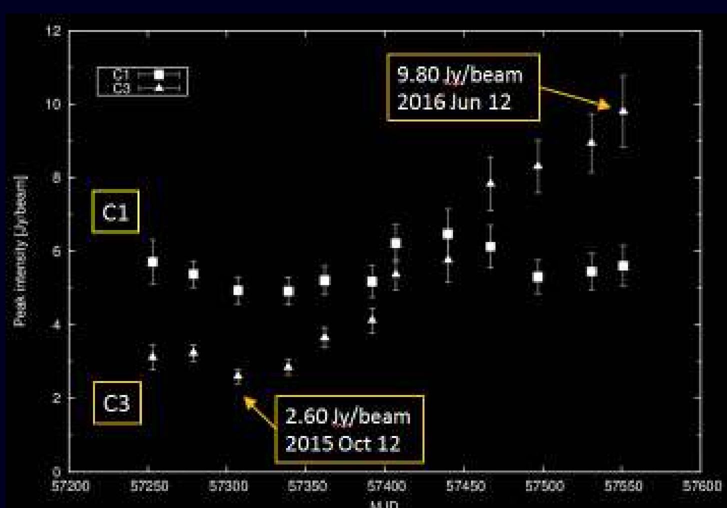
- Detection of *new northern component (N1)* (cf. Fujita, Nagai 2017, MNRAS, 465, L94)
- Abrupt *flux increase of C3* (cf. Hodgson et al. 2016, arXiv:1612.07874)
- *Transverse* → *outward motion* of C3

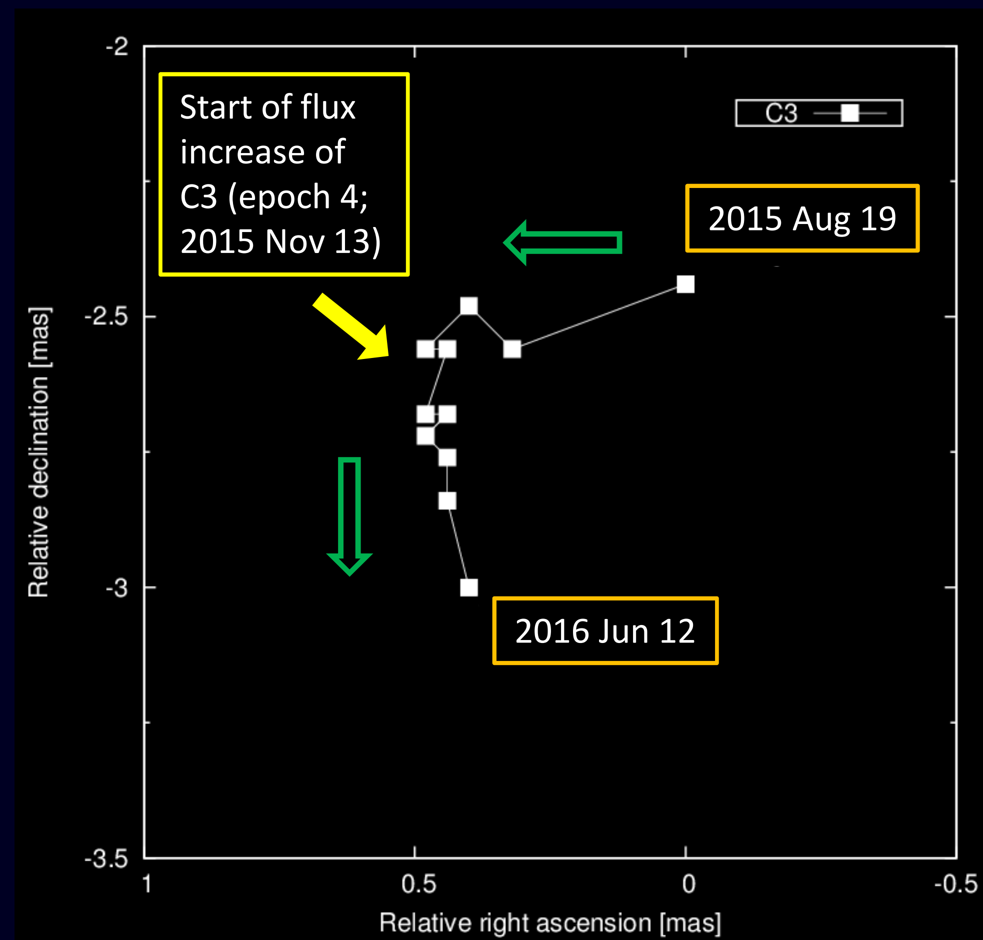
Relative Position of C3

- Relative peak intensity position of C3 with respect to C1 (0, 0)

Change in motion of C3 (transverse → outward)

Start of flux increase of C3 at 43 GHz





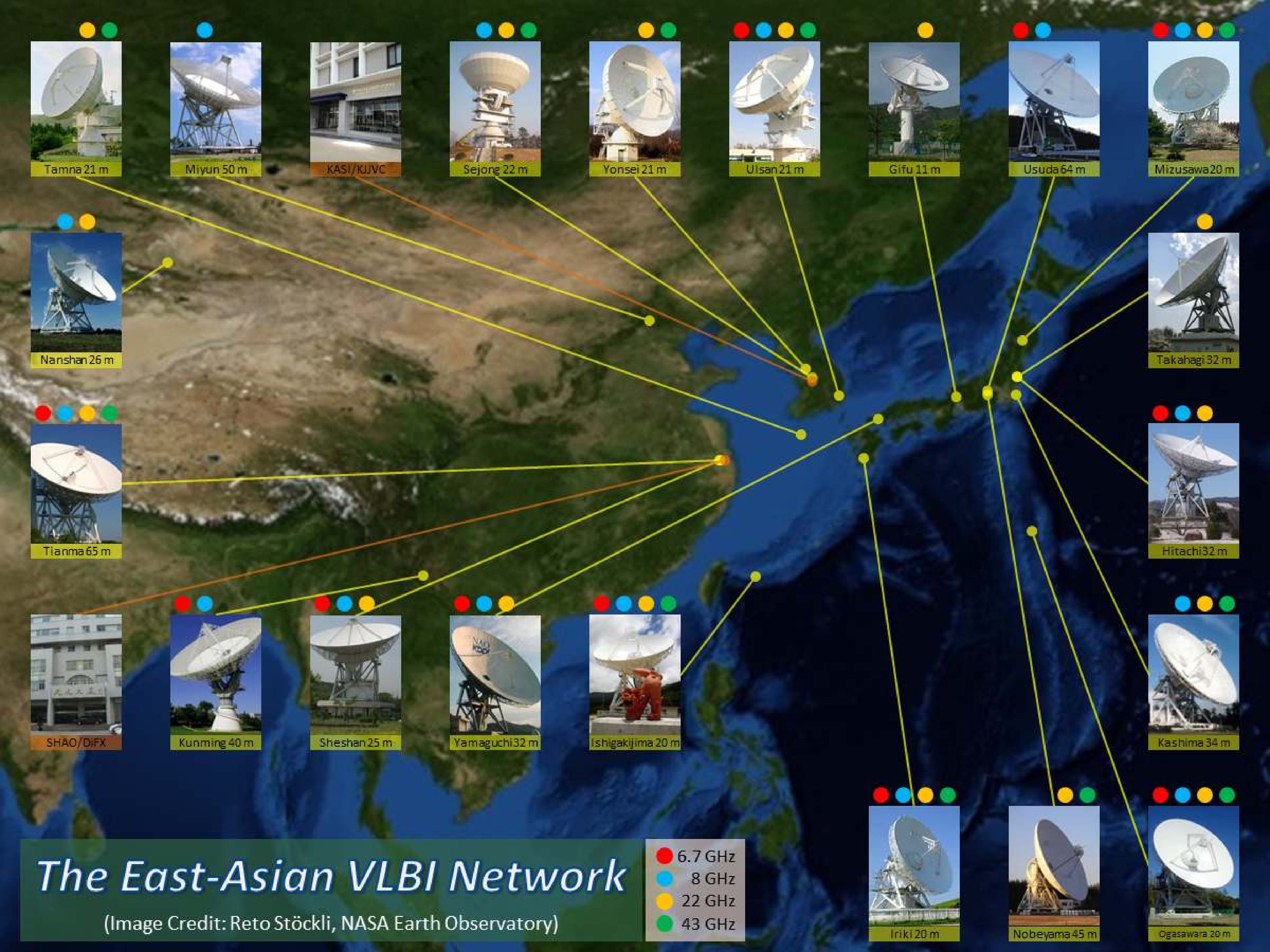
The East-Asian VLBI Network (EAVN)

- VLBI arrays operated at each East-Asian country: CVN (China), KVN (Korea), JVN and VERA (Japan)

➡ Launch of 'the East-Asian VLBI Network' (2013 –)

  – EAVN activities are conducted by 'East Asia VLBI Consortium' under EACOA

- Main characteristics of EAVN
  – (Mildly) high angular resolution at cm- ~ mm-wavelengths
  – High sensitivity thanks to large-aperture antennas (Tianma 65 m, Nobeyama 45 m, etc.)
  – Long common-sky time with Australian telescopes → high angular resolution in north-south direction



Tamna 21 m
Miyun 50 m
KASI/KJJVC
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
SHAO/DiFX
Kunming 40 m
Sheshan 25 m
Yamaguchi 32 m
Ishigakijima 20 m
Kashima 34 m
Iriki 20 m
Nobeyama 45 m
Ogasawara 20 m
The East-Asian VLBI Network
(Image Credit: Reto Stöckli, NASA Earth Observatory)
6.7 GHz
8 GHz
22 GHz
43 GHz

EAVN: Specifications (as of 2017 Dec 4)

- Number of (potential) telescopes: 20
  - Korea: 4, China: 5, Japan: 11
- (Possible) frequency coverage:
  - 6.7 GHz (11 stations), 8 GHz (15), 22 GHz (17), 43 GHz (11)
- (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)
  - 0.7 mas (43 GHz; Ogasawara – Tianma)
- 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)
- (Expected) recording rate: ≧ 1 Gbps (= 256 MHz BW)
- (Currently-used) correlator:
  - KJCC (Korea): Daejeon Hardware Correlator and DiFX
  - SHAO (China): DiFX

The East Asian VLBI Network

6.7 GHz
8 GHz
22 GHz
43 GHz

(Image Credit: Reto Stöckli, NASA Earth Observatory)

EAVN AGN Campaign: Overview

- Total observing time: 140 hours (17 epochs)
  - 22 GHz: 40 hours (5 epochs), 43 GHz: 100 hours (12 epochs)
- Number of telescopes: 15 (IT: 4, CN: 2, KR: 4, JP: 7)
- Target: Sgr A*, M87
- Angular resolution
  - 22 GHz: 0.26 mas (Noto – Ogasawara), 0.55 mas (Nanshan – Ogasawara)
  - 43 GHz: 0.13 mas (Noto – Ogasawara), 0.63 mas (Mizusawa – Ishigakijima)

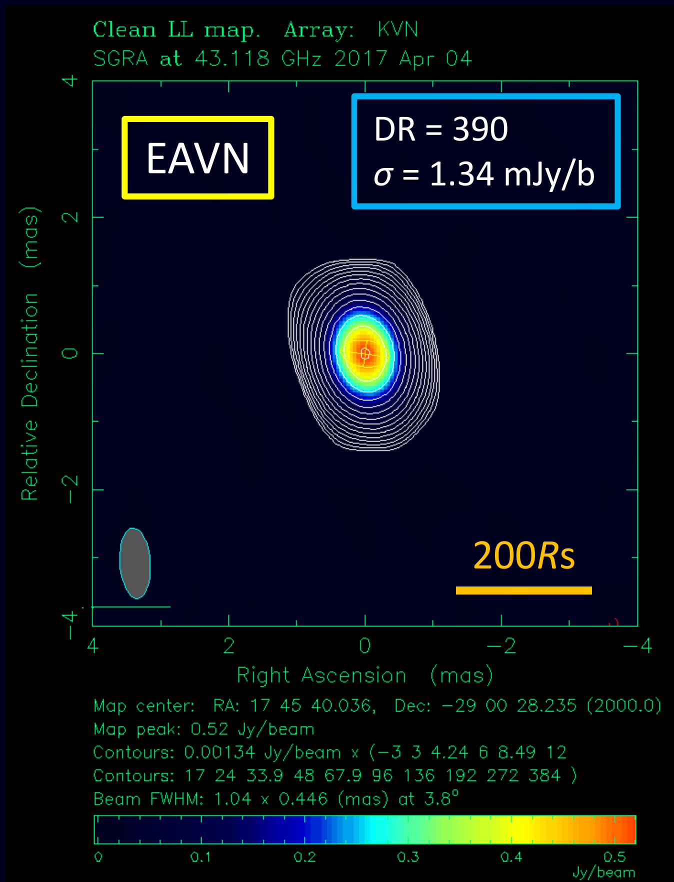
EHT+ALMA

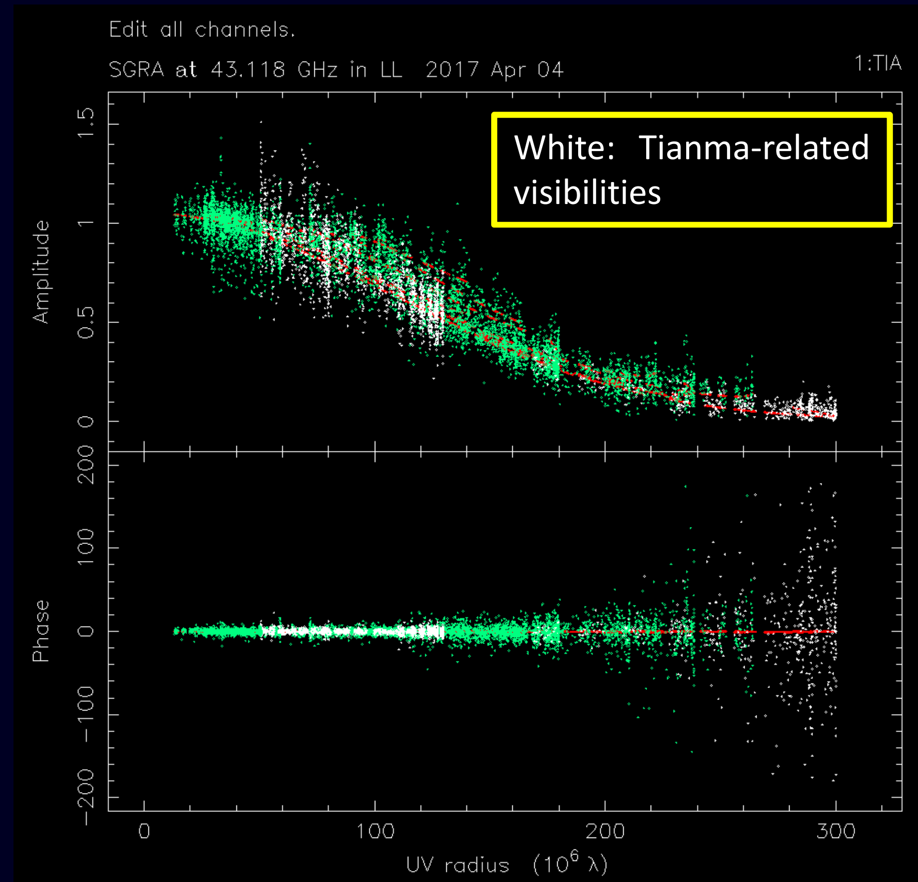
#	Date	Time (UT)	Band		Target	
			22	43	M87	Sgr A*
1	2017 Mar 12	18:55 – 00:55		■		■
2	2017 Mar 18	12:45 – 19:45	■		■	
3	2017 Mar 19	11:40 – 18:40		■	■	
4	2017 Mar 27	13:10 – 23:10		■	■	■
5	2017 Apr 3	13:20 – 23:20	■		■	■
6	2017 Apr 4	12:40 – 22:40		■	■	■
7	2017 Apr 9	12:20 – 22:20		■	■	■
8	2017 Apr 14	12:00 – 22:00		■	■	■
9	2017 Apr 17	11:50 – 18:50	■		■	
10	2017 Apr 18	11:45 – 21:45		■	■	■
11	2017 Apr 24	09:20 – 16:20	■		■	
12	2017 Apr 25	09:15 – 16:15		■	■	
13	2017 Apr 26	15:55 – 21:55		■		■
14	2017 May 10	08:20 – 17:20	■		■	
15	2017 May 11	08:15 – 17:15		■	■	
16	2017 May 25	14:00 – 20:00		■		■
17	2017 May 26	07:15 – 16:15		■	■	


Tamna 21 m
KASI/KJJVC
Sejong 22 m
Yonsei 21 m
Ulsan 21 m
Mizusawa 20 m
Nanshan 26 m
Tianma 65 m
Hitachi 32 m
SHAO/DiFX
Ishigakijima 20 m
Kashima 34 m
Iriki 20 m
Nobeyama 45 m
Ogasawara 20 m
Medicina 32 m
Noto 32 m
Two Italian telescopes (Medicina and Noto) also joined in the campaign.
6.7 GHz
8 GHz
22 GHz
43 GHz

Preliminary Results of EAVN AGN Campaign

- First 43 GHz image of Sgr A* by EAVN (KaVA + Tianma) on 2017 Apr 6 (on-source time: 10 hours)
  - Clearly reconstructed a Gaussian structure of the source

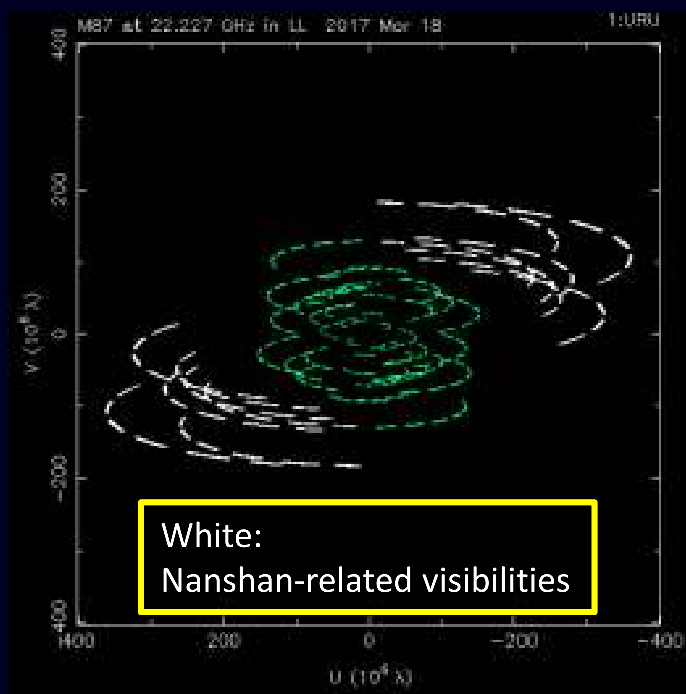


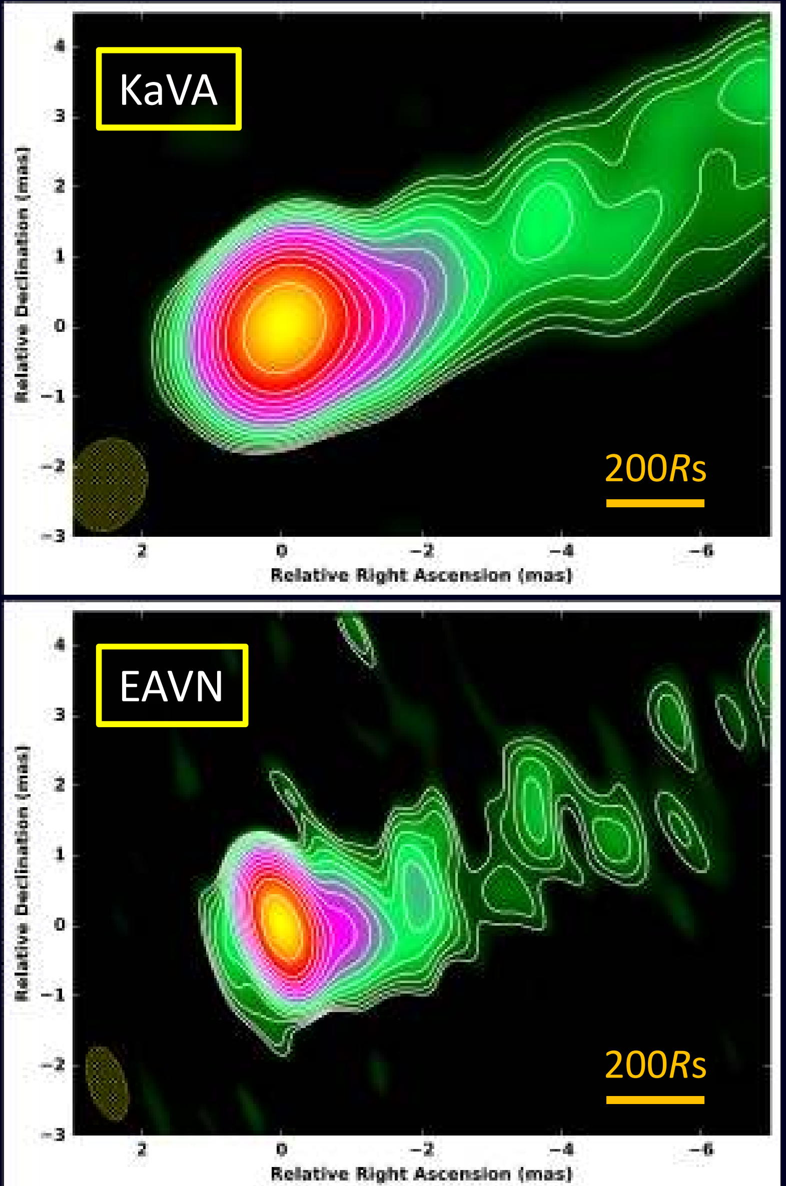


(Image courtesy: Dr. Guang-Yao Zhao (KASI))

Preliminary Results of EAVN AGN Campaign

- First 22 GHz image of M87 with the maximum baseline length (~ 5,500 km) of EAVN (KaVA + **Tianma** + **Nanshan** (Urumqi)) on 2017 Mar 18 (on-source time: 7 hours)





(Image courtesy: Dr. Kazuhiro Hada (NAOJ))

Tentative Plan for EAVN Open Use

- Start of operation: 2018B semester (2018 August –)
  - KaVA + Tianma
  - Shared-risk operation
  - Proposals can be submitted from all over the world
- Total observing time: 100 hours/semester (= 40% of KaVA open use)
- Observation frequency: 22, 43 GHz, single polarization

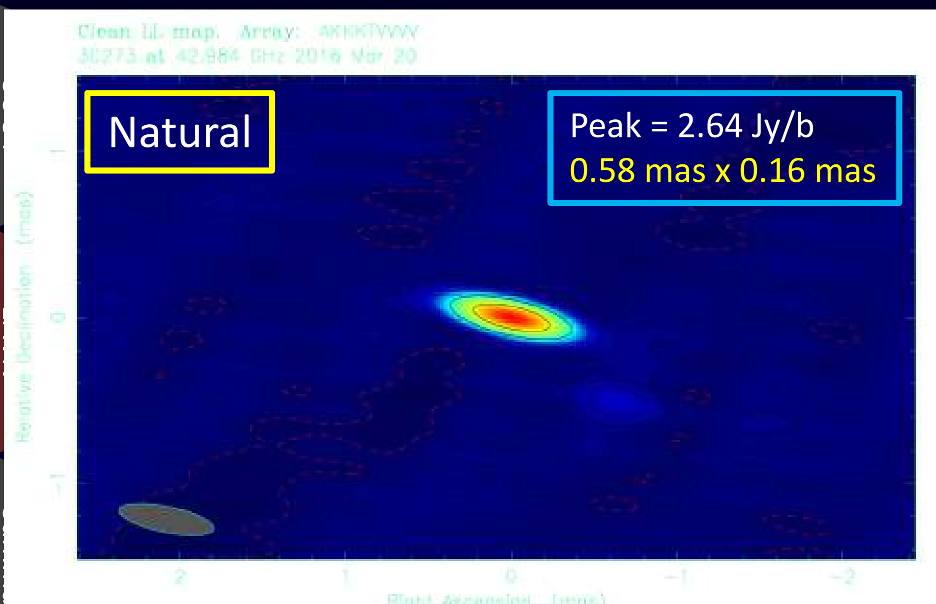
EAVN: Future Development

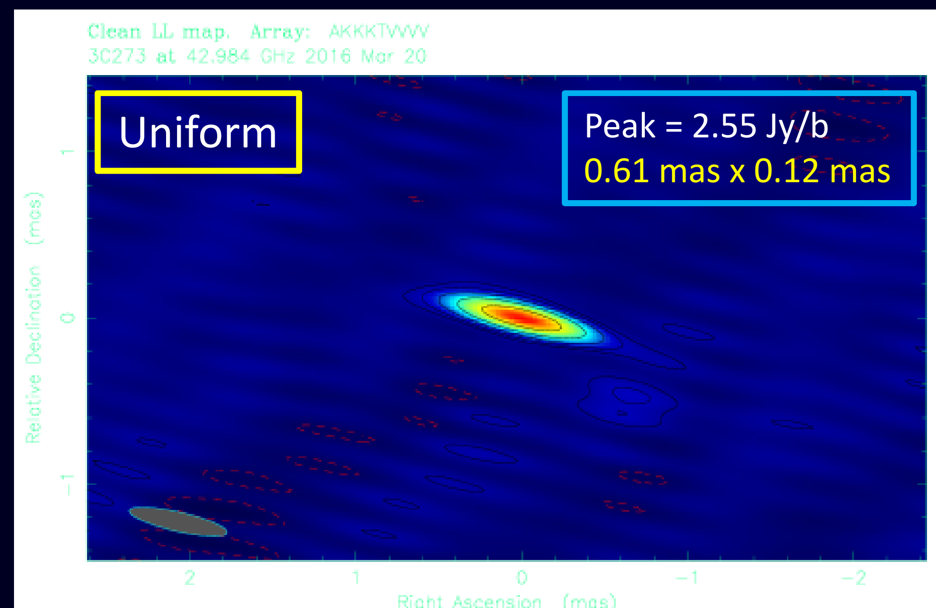
VLBI in EA
KaVA AGN
3C 84
EAVN
Summary

- Collaboration with Australian telescopes
  - Long common-sky time with Australian telescopes → high angular resolution in north-south direction
  - VLBI test observation with EAVN and one ATCA antenna in 2016
- New telescopes from China
  - Qi-Tai 110 m radio telescope (QTT) in Xinjiang
  - Low-frequency (< 3 GHz) VLBI with FAST 500 m telescope
- New telescopes from Thailand
  - Thai VLBI Network (TVN)

Preliminary Results of Imaging Test

- First 43 GHz image of 3C 273 by EAVN + ATCA on 2016 March 20
  - Verh high angular resolution (~ 0.1 mas) can be obtained in the north-south direction





(Image courtesy: Dr. Richard Dodson (ICRAR))

Summary

- International collaborative VLBI array in East Asia, KaVA, is producing various results in AGN sciences thanks to its array characteristics.
- Biweekly monitoring of M87 and Sgr A* with KaVA gives high-fidelity images at 22/43 GHz, which provides important information to investigate jet physics in the vicinity of supermassive black hole.
- We have conducted 17-epoch observations for 'the EAVN AGN Campaign' in 2017. High-fidelity images with high angular resolution were obtained thanks to Chinese telescopes such as Nanshan and Tianma.
- We are planning to start EAVN open-use operation from 2018B semester with basic observation modes.