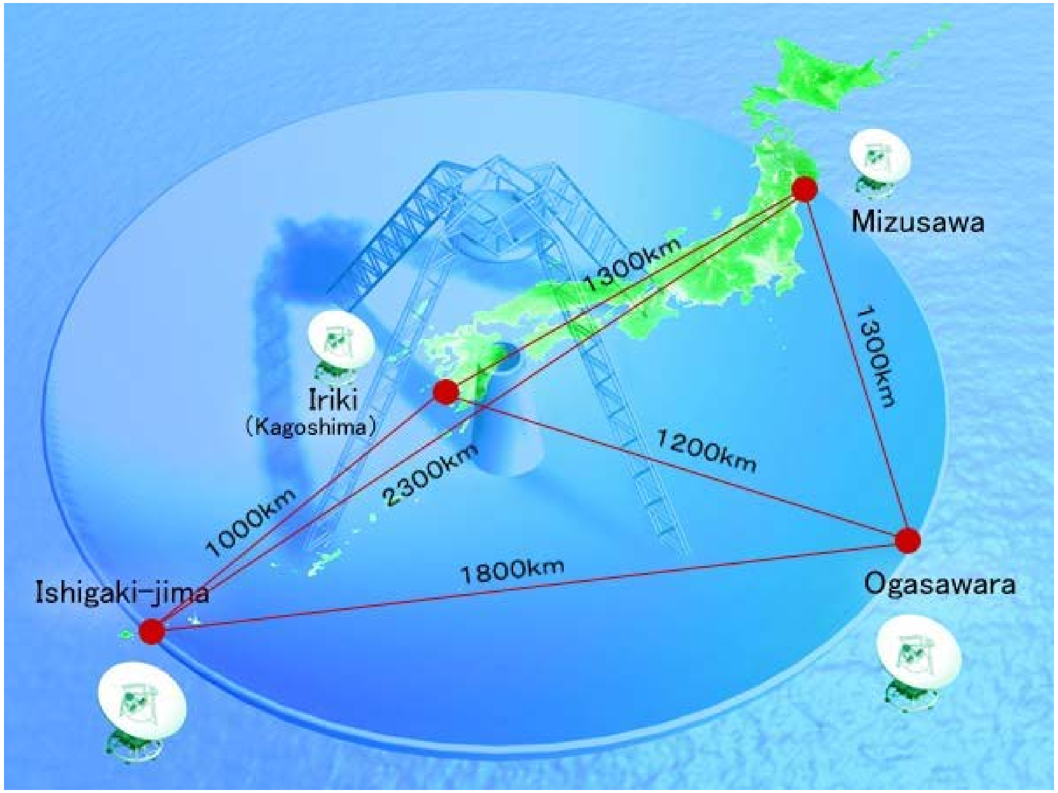
NAOJ Achievements and Future
Planning Symposium 2019
December 12-13, 2019

VLBI Community: Current assessment and expectations for the future

FUJISAWA Kenta
(Yamaguchi University)

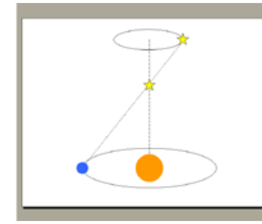
VERA and JVN

VERA – a dedicated Japanese VLBI for astrometry



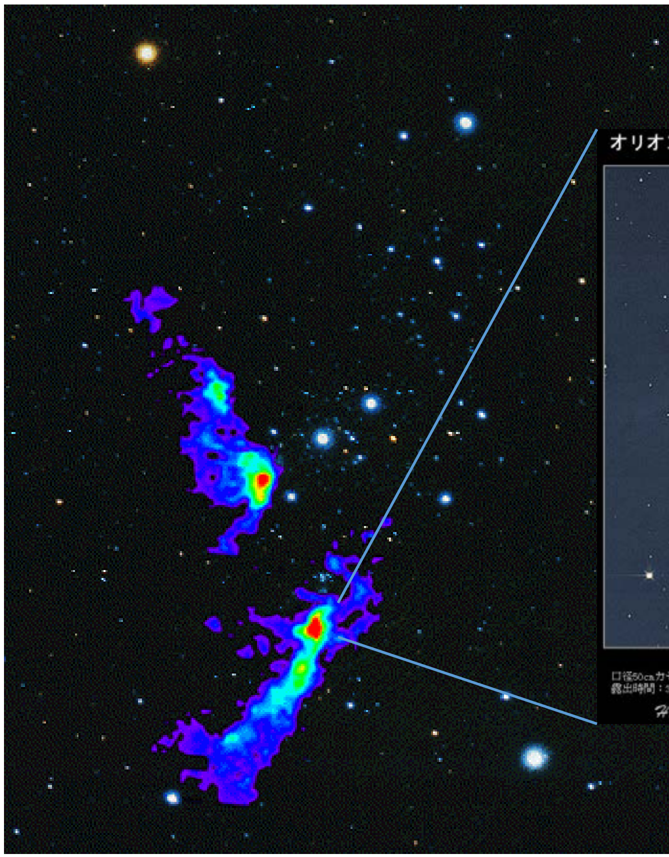
- 4 20m telescopes
- 2300 km, 22, 43 GHz
- Dual-beam for high-precision astrometry
  - ~10mas accuracy
  - Simultaneous observation of close pair: target and reference source
  - Systematic errors including atmospheric fluctuation are cancelled out

VERA's high precision astrometry is mainly used for Galactic dynamics. Annual parallax and proper motions of water maser (22 GHz) sources are measured, and the gas dynamics of the galactic plane is studied.



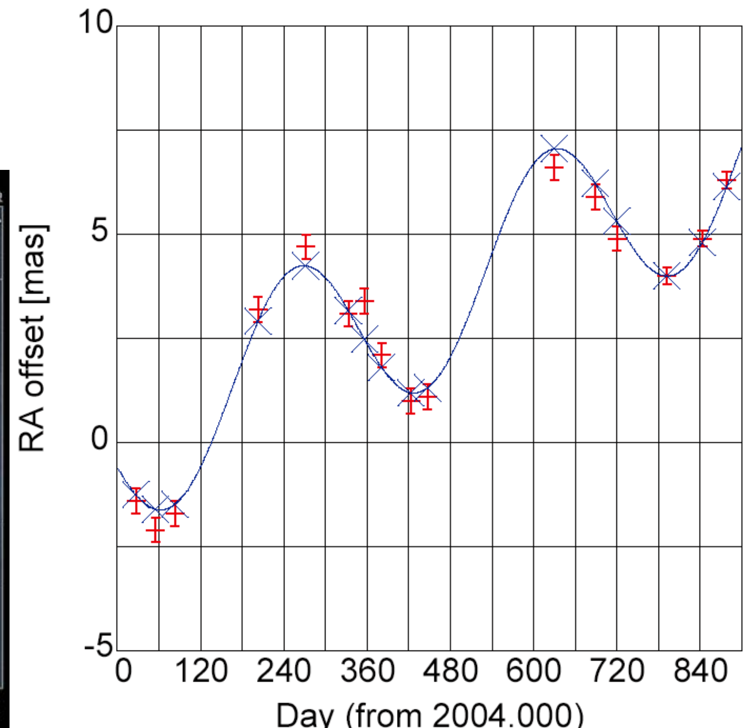
Achievements of VERA

Measurement of distance and 3D motion by annual parallax and proper motion



Orion nebula

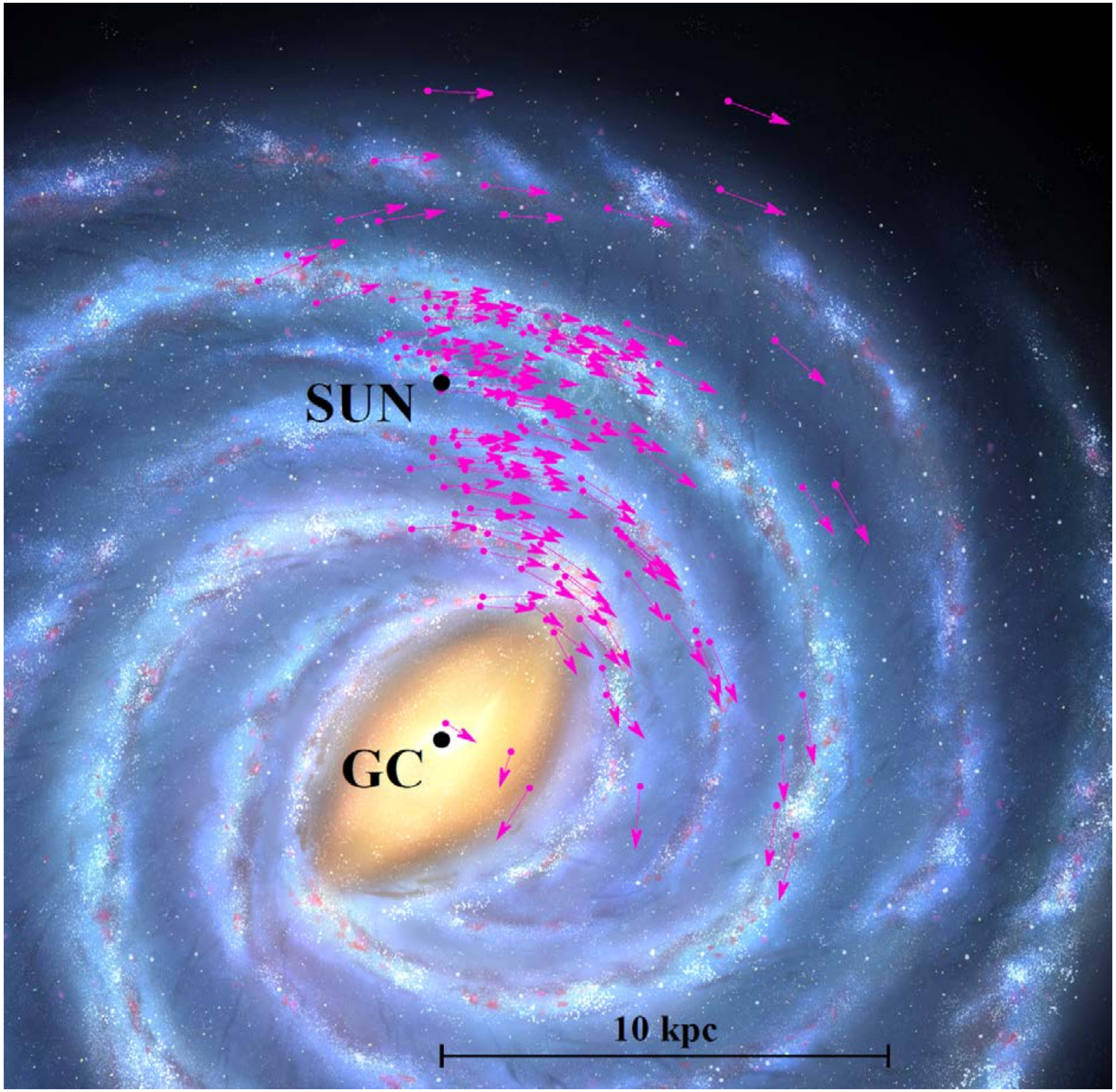
Orion Molecular Cloud



Observed motion of a water maser in Orion KL
Hirota+(2007)

Distance 480 pc

Galaxy rotation



VLBA/VERA/EVN

Galactic constants

Honma+ (2012)

52 SFRs

R_0 = 8.05±0.45 kpc

Θ_0 = 238±14 km/s

Ω_0 = 29.57±0.78 km/s/kpc

Update

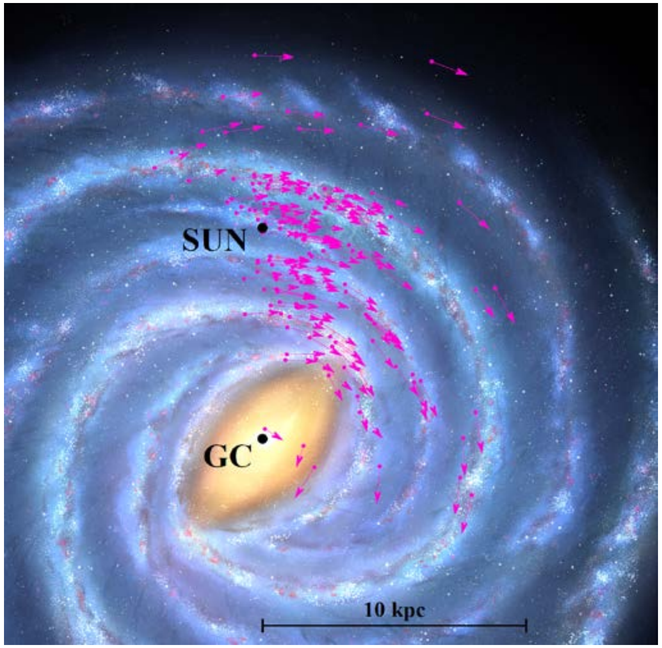
144 SFRs

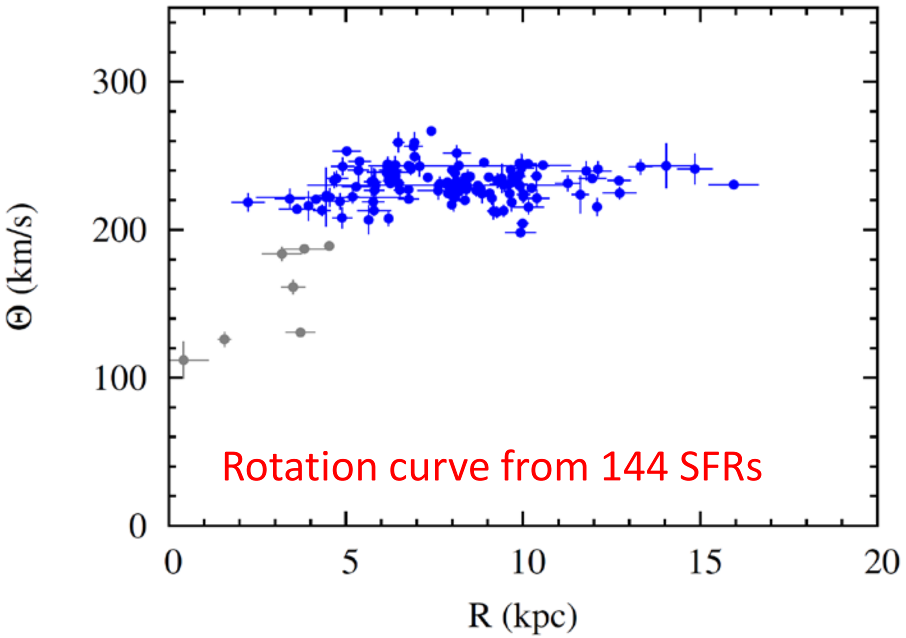
R_0 = 8.16±0.26 kpc

Θ_0 = 237±8 km/s

Ω_0 = 28.99±0.39 km/s/kpc

$(U_\odot, V_\odot, W_\odot)$ = (11.10, 12.24, 7.25) km/s (Schorich, Binney, Dehnen 2012) assumed

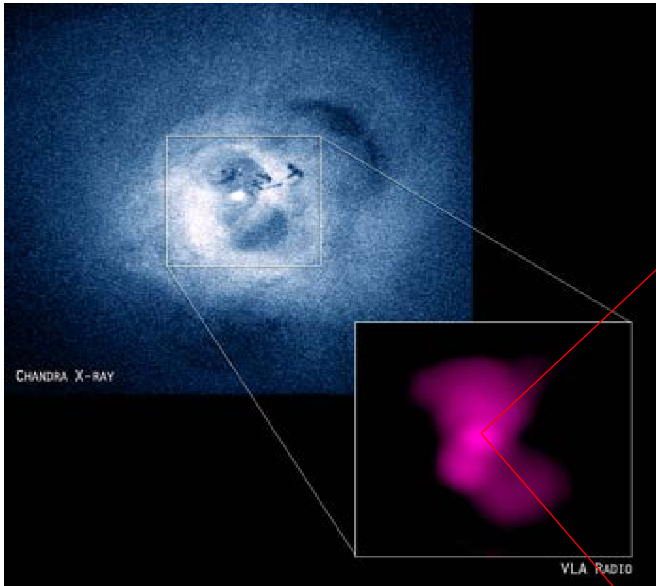


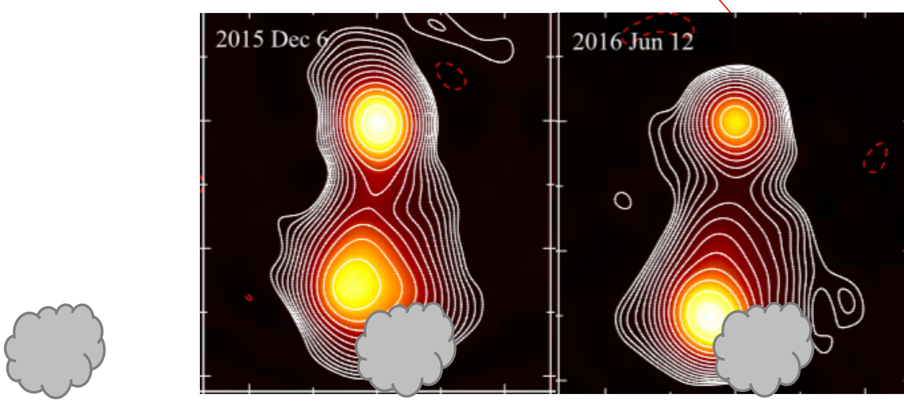


Now GAIA is producing a huge amount of astrometric data, and VERA is shifting the focus to imaging VLBI observation with EAVN collaboration

VLBI imaging observation by VERA

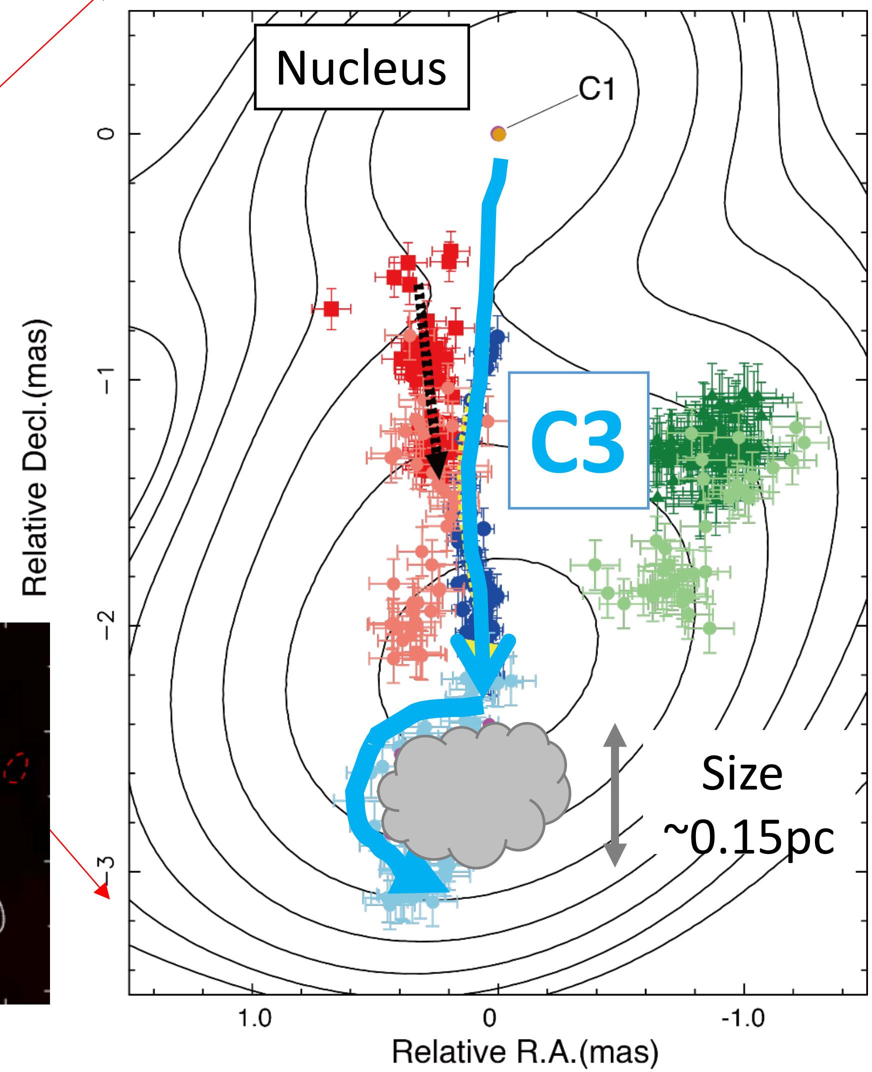
Jet-clump interaction in the heart of 3C84





C3 strong brightening along with flip

VERA/KaVA biweekly jet monitor

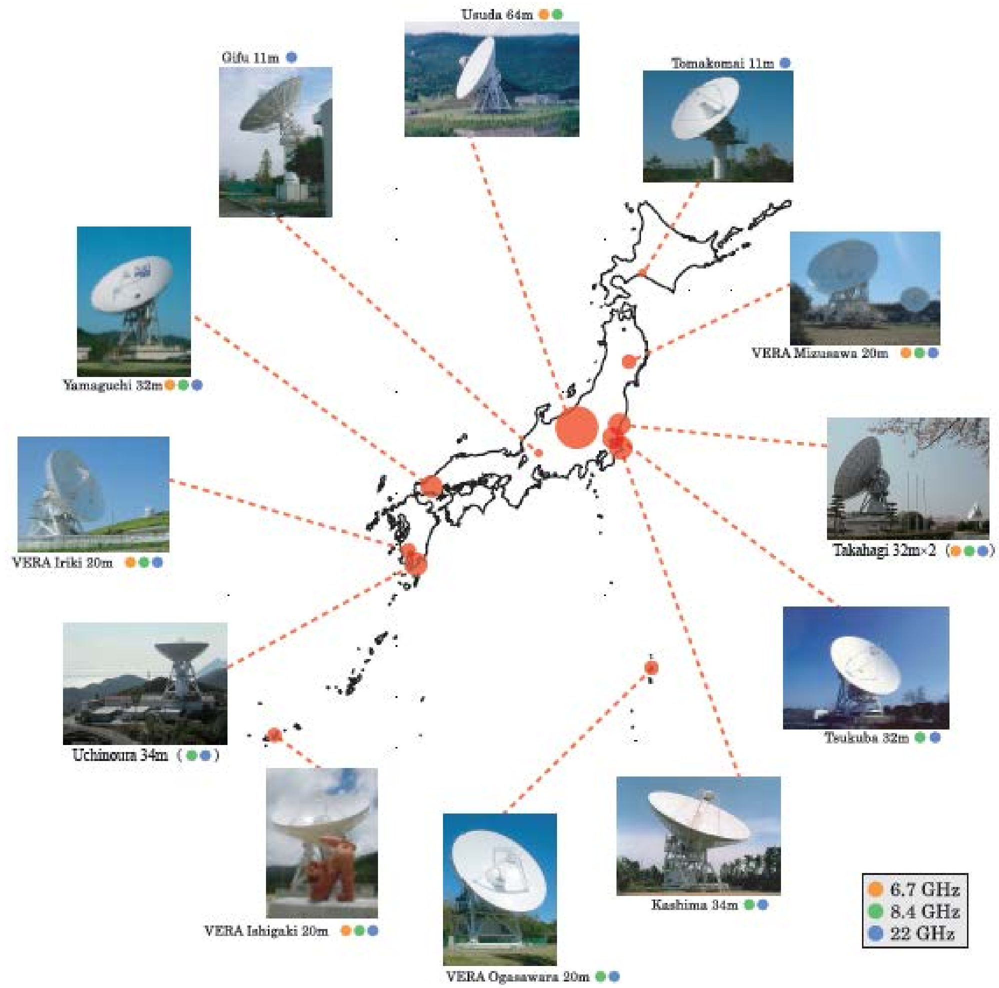


Kino+2018, Hiura+2018, Hirano in prep.

Japanese VLBI Network (JVN)

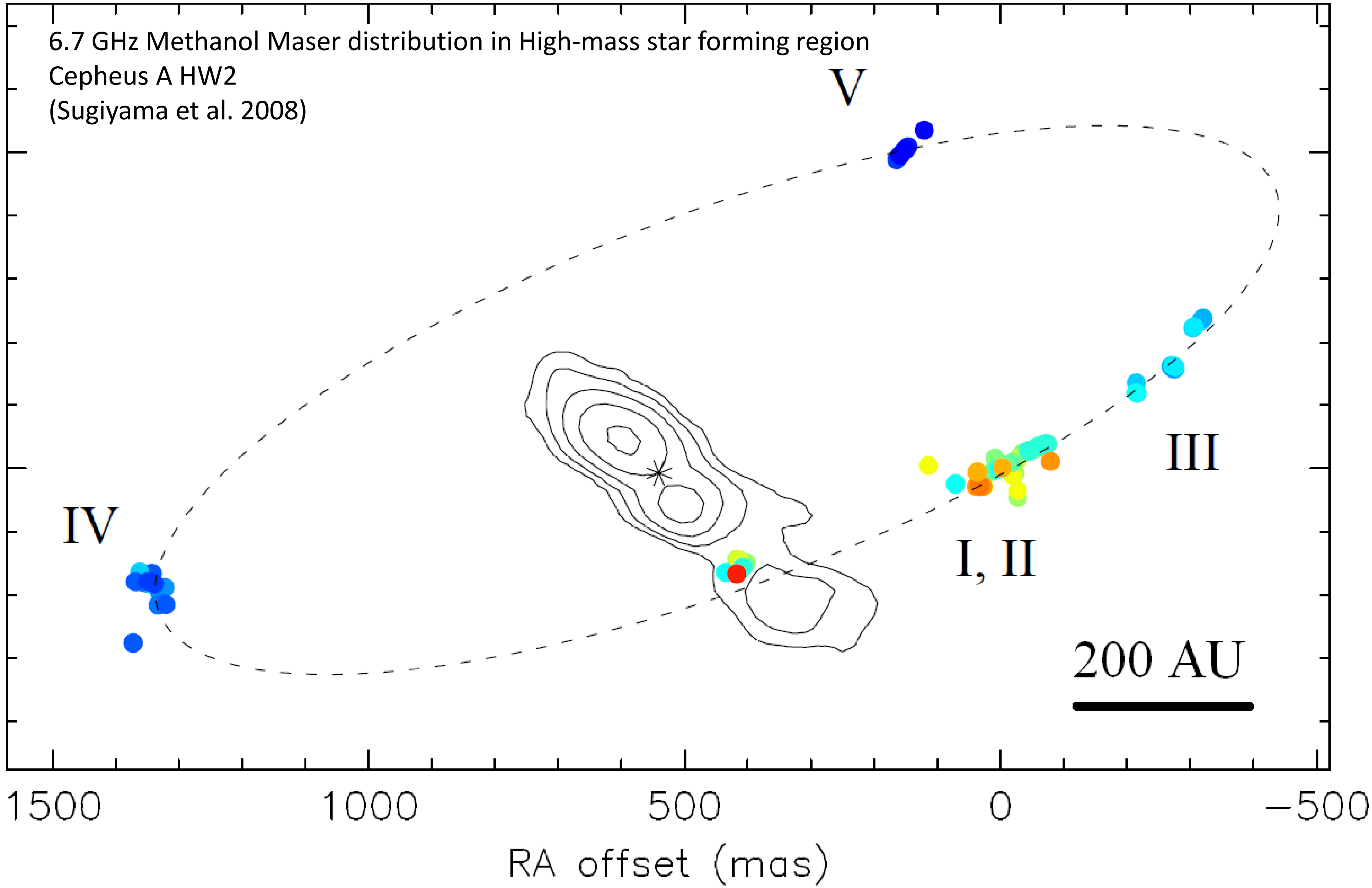
Imaging VLBI network including VERA and University's telescopes

- Collaboration
  - NAOJ (VERA)
  - Hokkaido, Ibaraki, Tsukuba, Gifu, Osaka-Pref, Yamaguchi, Kagoshima universities
  - JAXA, NICT, GSI
- Specifications
  - 13 telescopes (11m ~ 64m)
    - 6~7 active telescopes
  - Baseline 50 - 2500 km
  - Frequency 6.7/8/22 GHz
- Operation
  - 500hr/yr
  - 100 observations/yr



Internal Motions of 6.7 GHz methanol maser

motions of maser spots in Cep A (Sugiyama et al. 2014)



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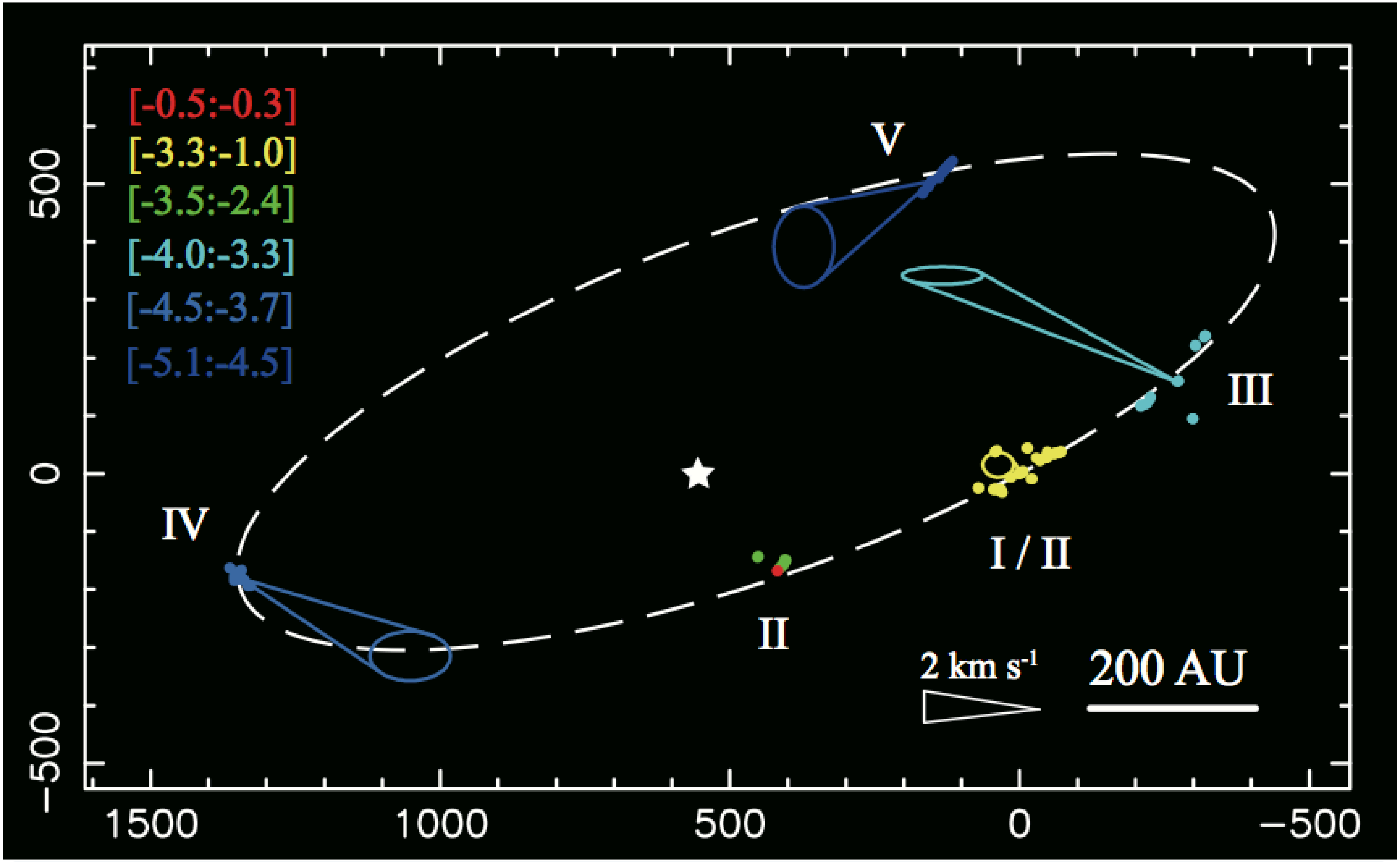
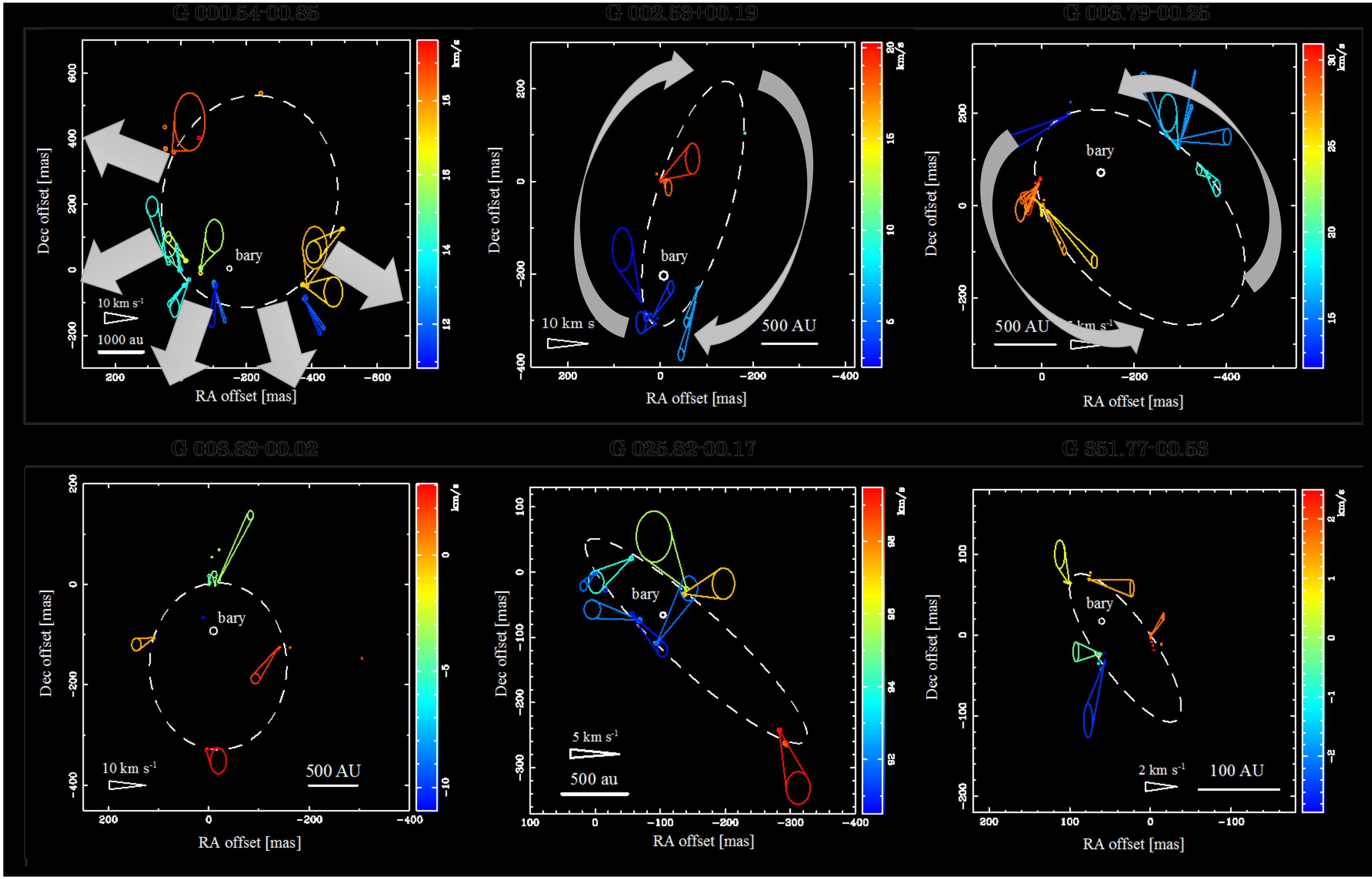


Rotaion: 1.2 km/s, Infall: 2.4 km/s. The gas disk is rotating and infalling.

A systematic study of internal motion

for 36 sources by JVN + Shanghai (a precursor observation of EAVN)



Time domain VLBI astronomy
by JVN (A-project of NAOJ, since 2019)

- Advantage of university’s telescope: Long available time, flexible operation

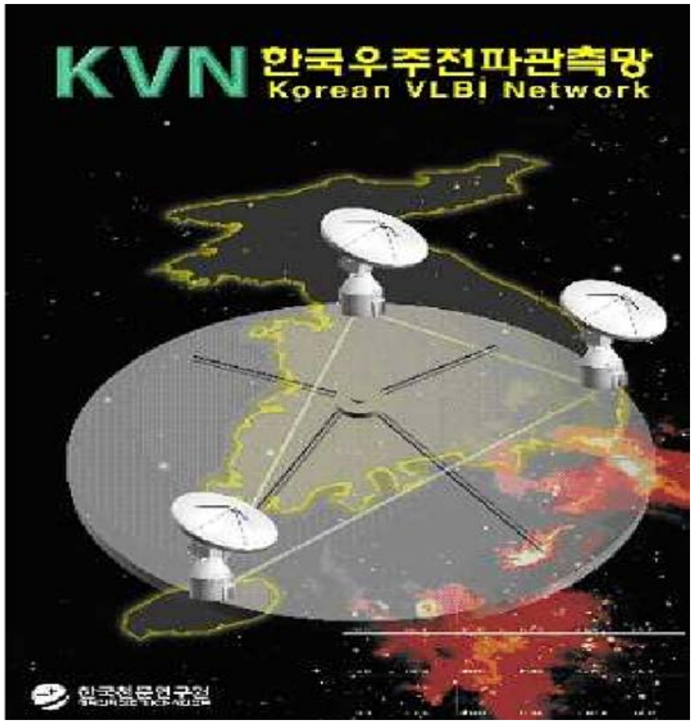
Monitoring/Detecting ariable sources with amount of observing time

- Three main science targets of JVN
    - Periodic methanol maser
    - Extremely Compact HII region
    - Gamma-ray objects

    - ･･･and various transient/variable targets

KaVA
(KVN+VERA)

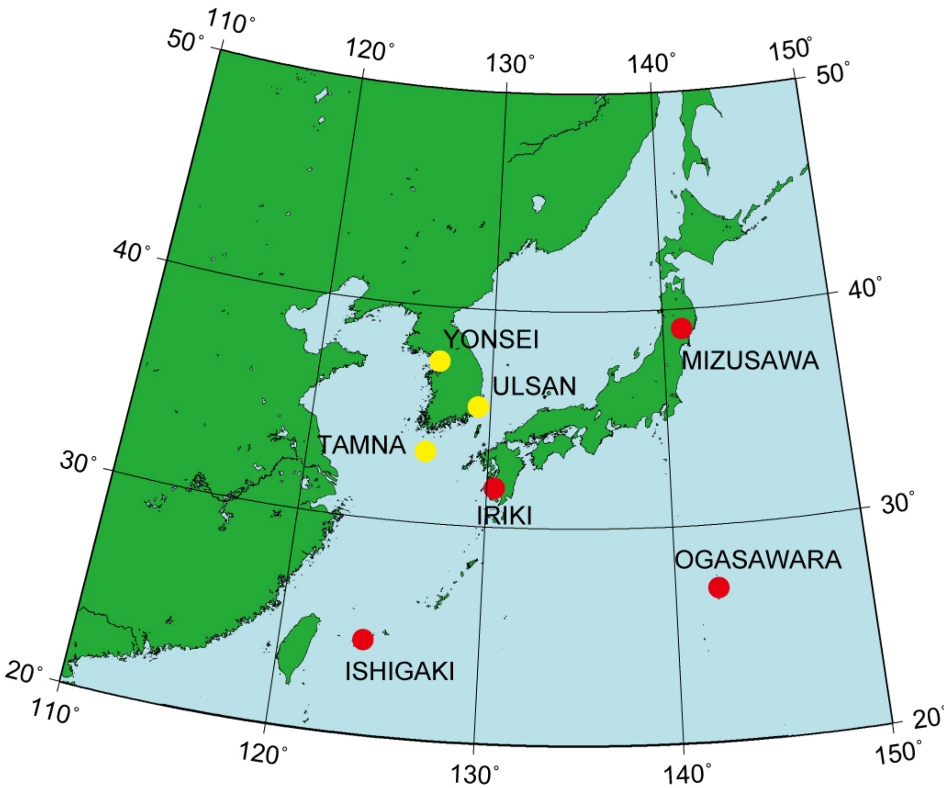
KVN – multi-frequency mm VLBI



- 3 21m telescopes in South Korea
- Baseline 500 km
- 22, 43, 86, 129 GHz
  - Simultaneous observation at four frequencies with quasi-optic system
- Science
  - SiO/H2O/CH3OH Masers
    - Investigating spatial structures and dynamical effects from SiO to 22 GHz H2O maser regions (atmosphere to circumstellar envelope) according to stellar pulsation through simultaneous monitoring observations.
  - AGN / polarization

The key features of KVN are (1) capability of multi-frequency simultaneous observation, and (2) regular observation at mm wavelength. Imaging capability is greatly enhanced by co-observation with VERA.

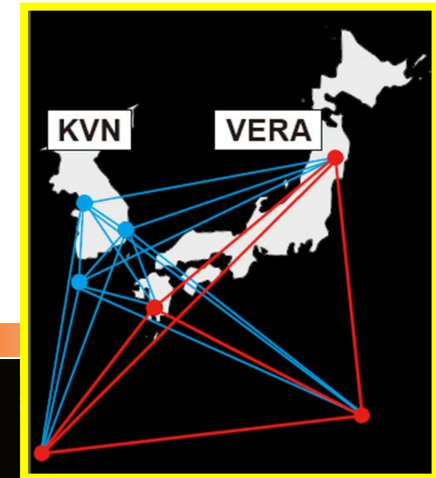
KaVA – Combined array of KVN and VERA

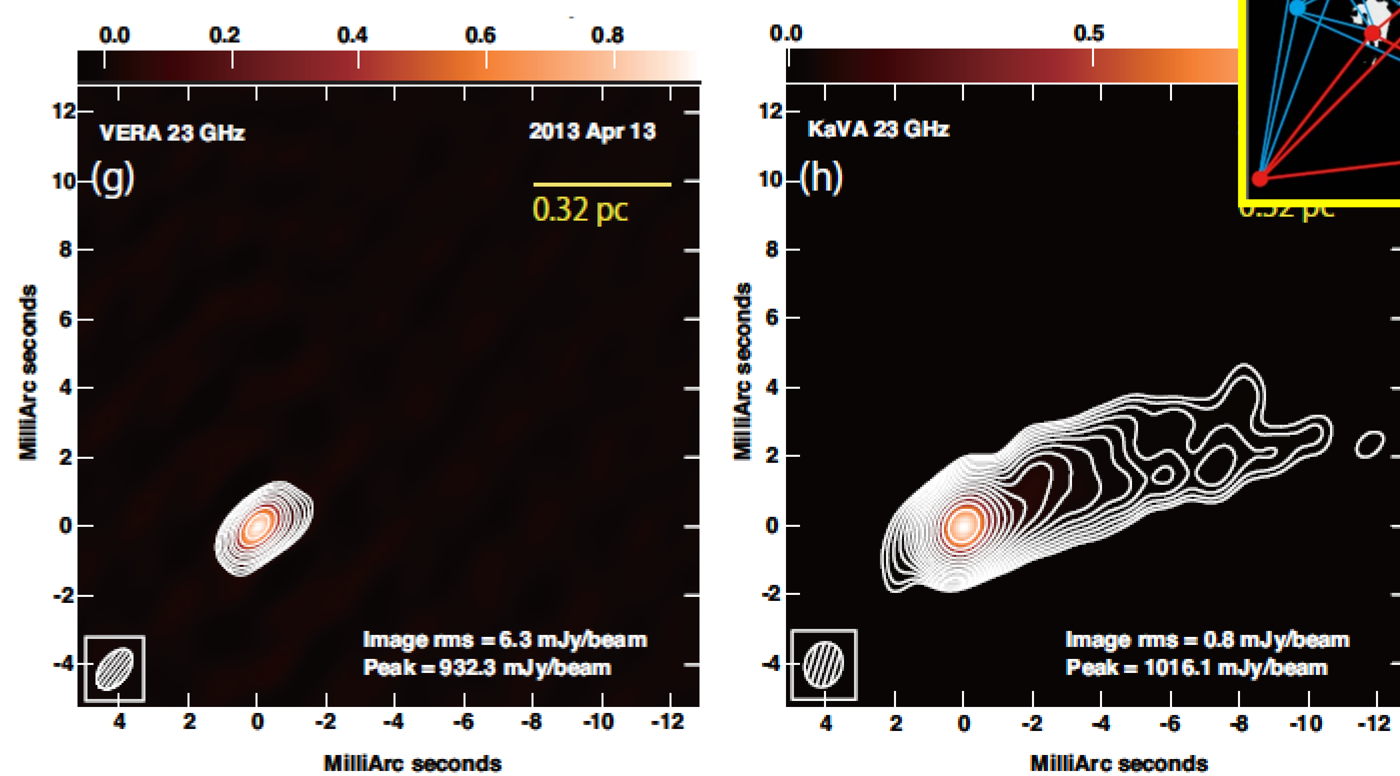


- KaVA
  - KVN and VERA Array
  - 22, 43 GHz
  - Started in 2010
  - Open use since 2014
- Good imaging capability
  - Almost uniform array
  - 7 sites, 21 baselines
  - Baseline 300 - 2300 km
- The core of EAVN

KaVA (KVN and VERA Array)

- KaVA: KVN and VERA Array, 7station 21 baselines
- Open-use started since 2014
- KaVA Large Project starts in 2015



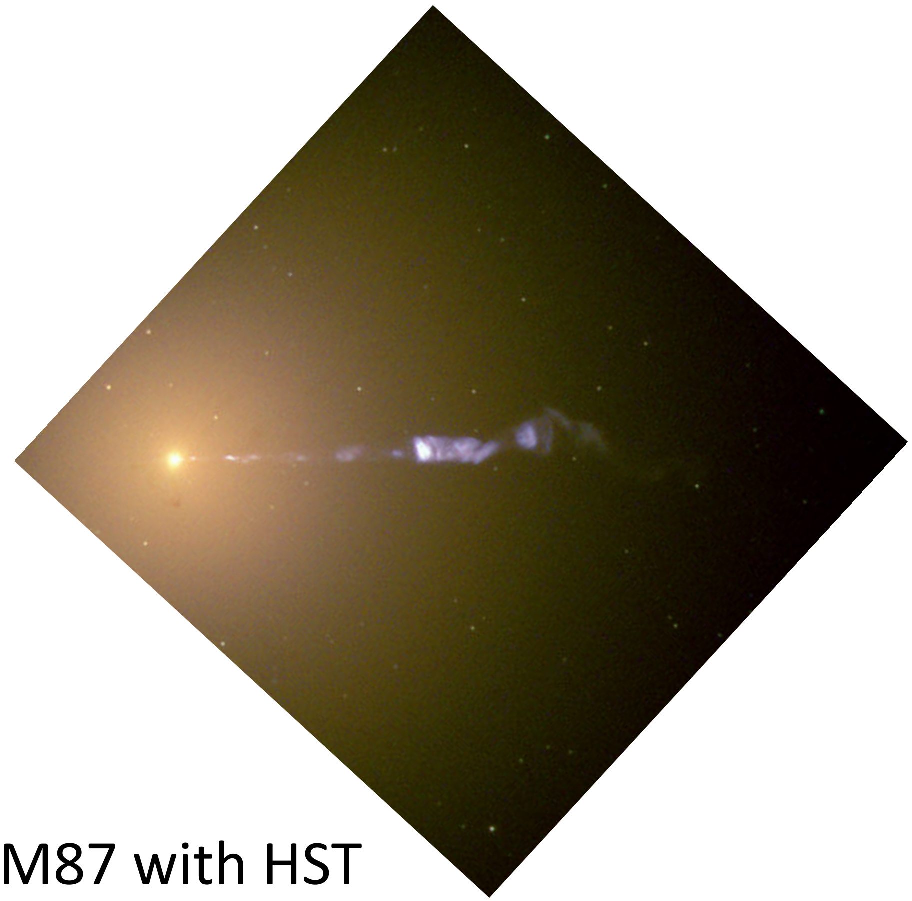


M87 jet with VERA

KaVA

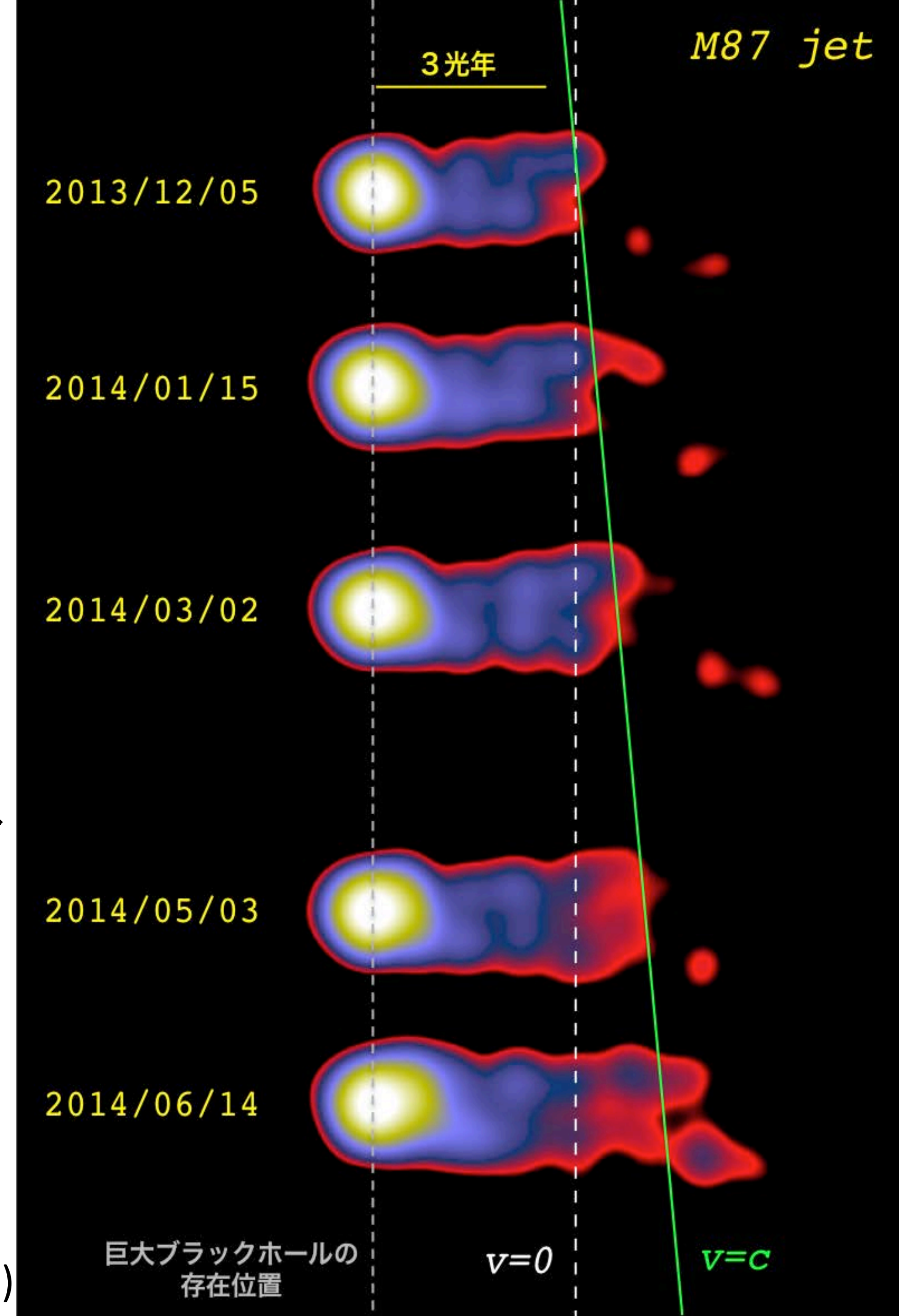
Demonstration of KaVA's capability: Niinuma et al. (2014)

M87 jet motion monitor with KaVA

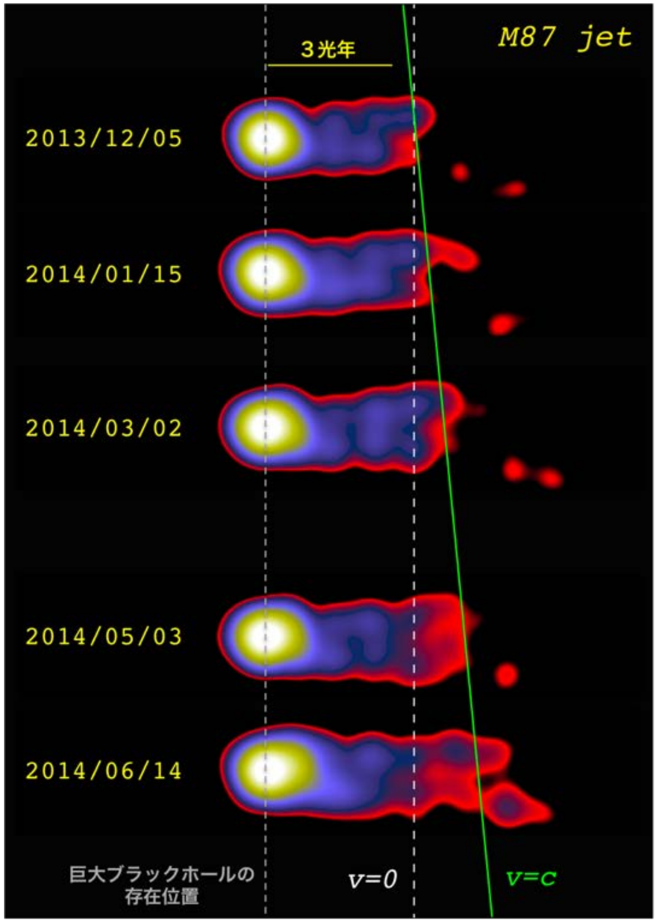


M87 with HST

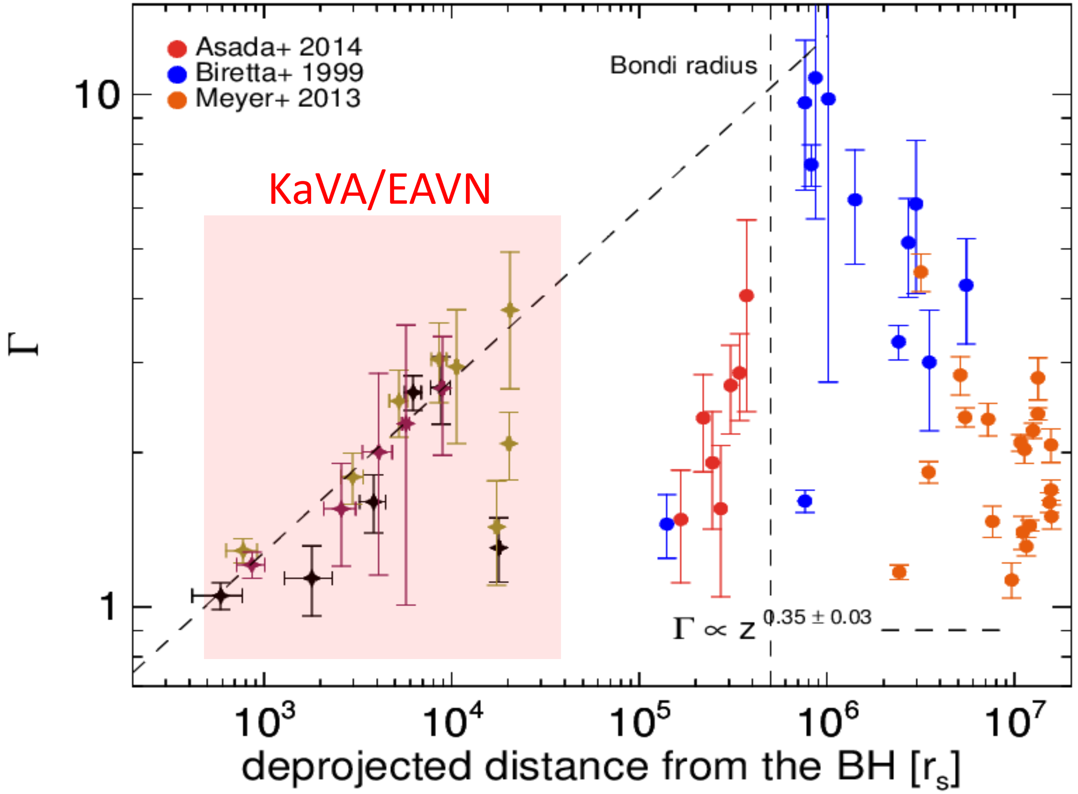
Hada et al. (2016)



Unveil jet acceleration zone with KaVA



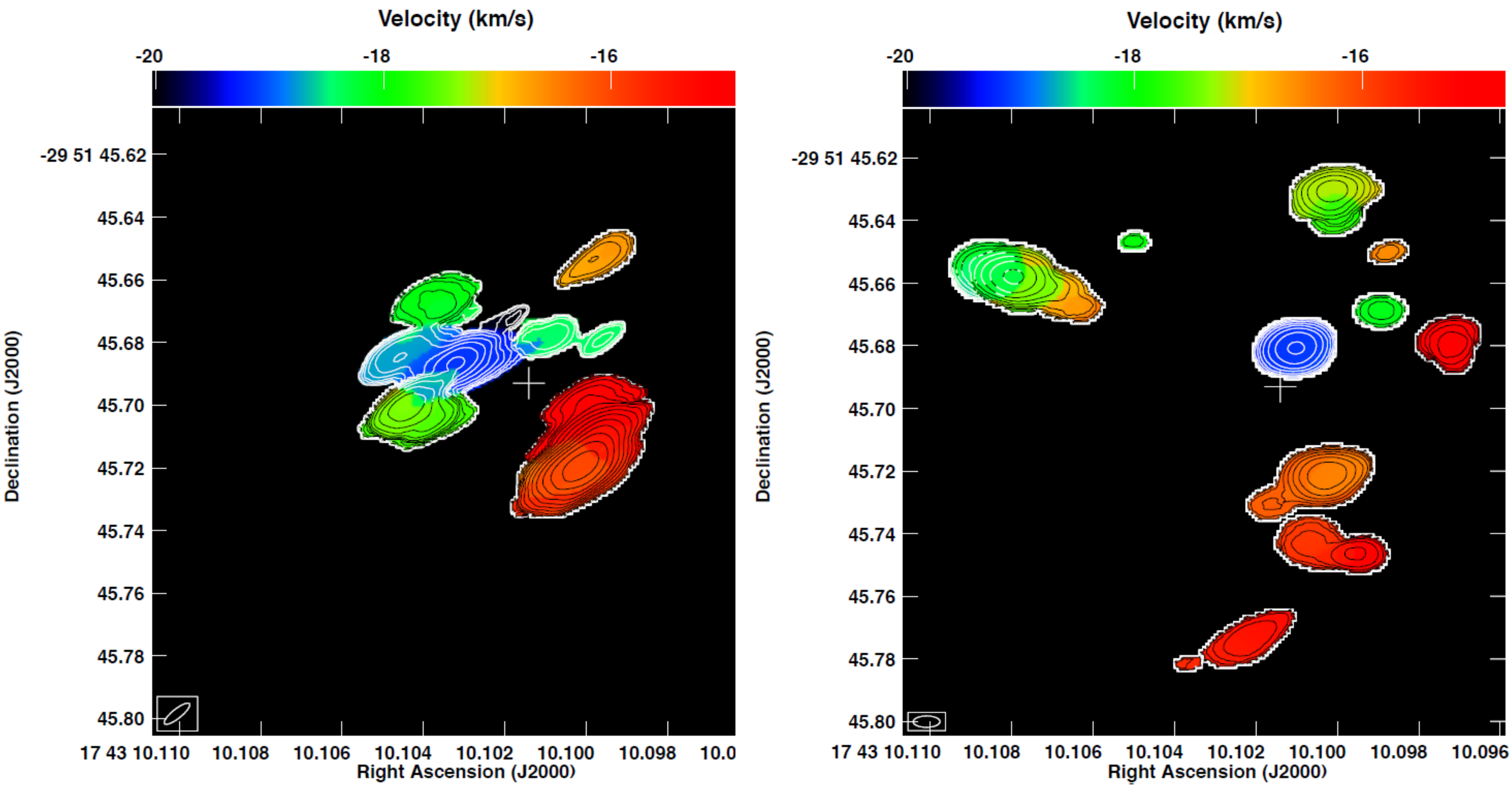
Hada+2017 PASJ; Park+ in prep; Cui+ in prep



- Question of M87 jet acceleration : where is the jet accelerated?
- Discovery of fast (~2-3c) motions in inner jet!
- Gradual acceleration between 500Rs – 20000Rs

“Heat-wave” propagation detected by KaVA

Burns et al. (2019) accepted to nature astronomy



Rapidly expanding maser emission region. Heat-wave generated in the central star is propagating through the maser emission region.

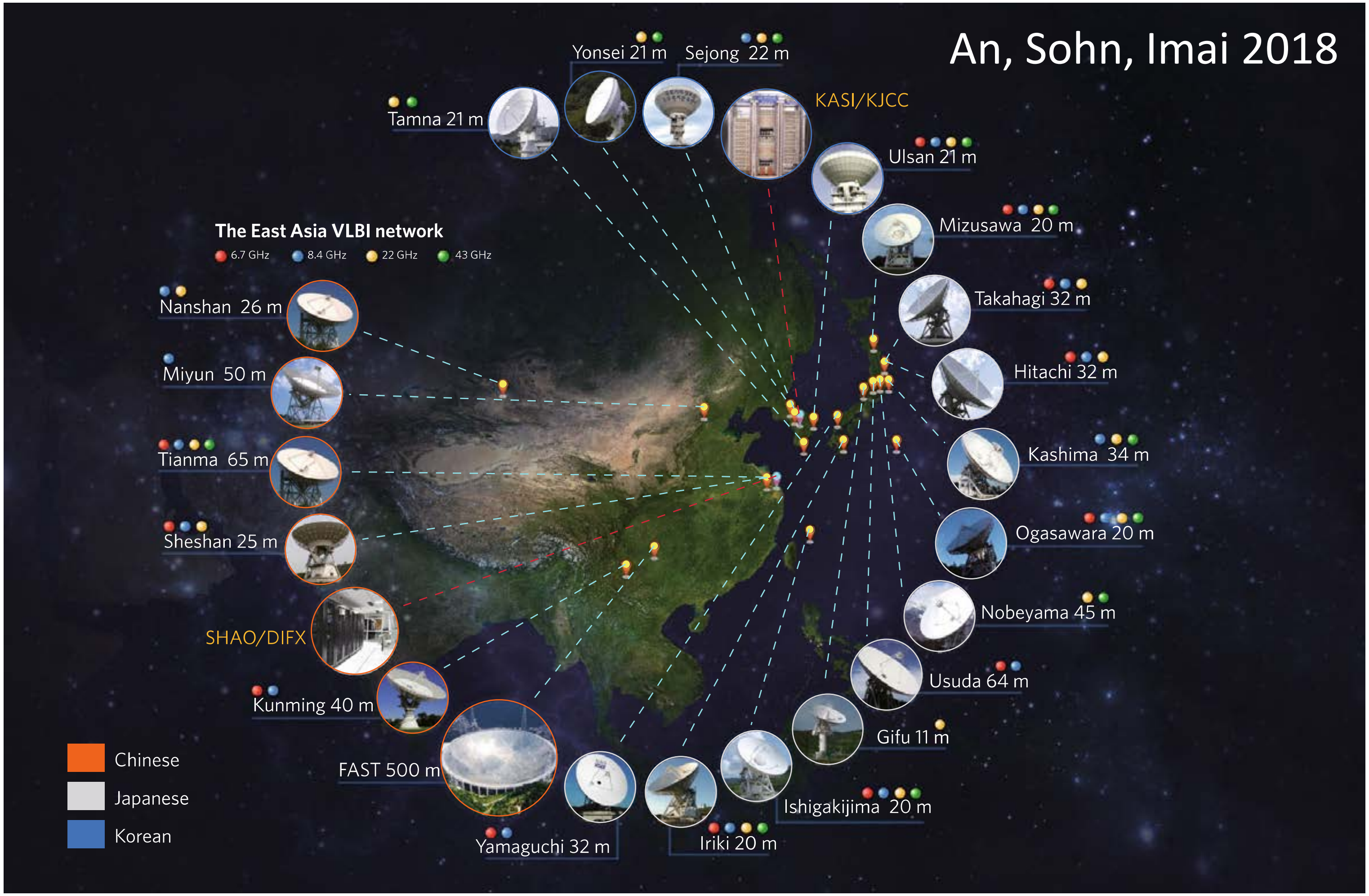
EAVN
(CVN+KVN+VERA/JVN+α)

The East Asia VLBI Network (EAVN)

- Situation in and around East Asia
  - Regular operation of VLBI facilities in each EA country (VERA/JVN (JP); KVN (KR); CVN (CN))
- A small task force, 'the EAVN Tiger Team' was organized on June 2013 to handle various issues related to EAVN
  - To promote VLBI test observations
  - To proceed data reduction of test observations
  - To clarify the problems for future regular operation and open-use observations with EAVN

➡ To construct a VLBI network in East Asia

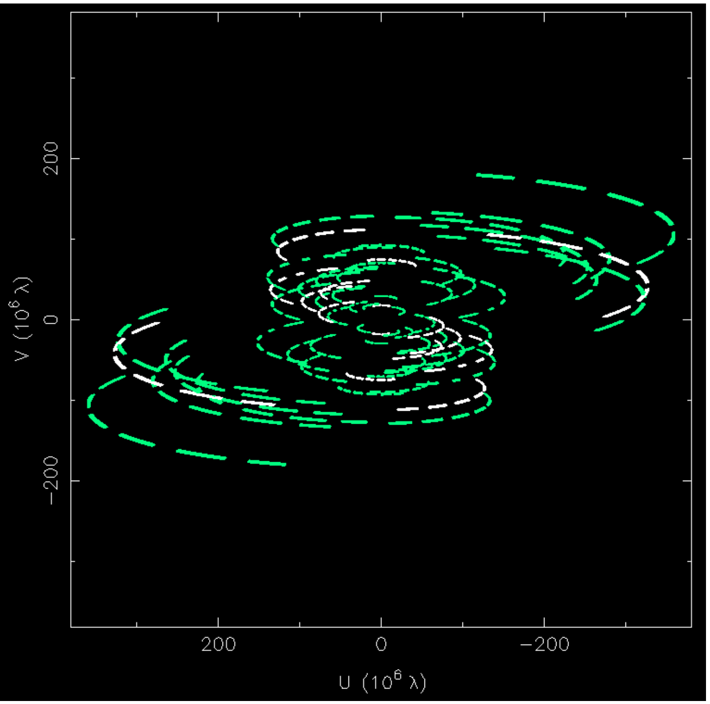
The East Asian VLBI Network (EAVN)

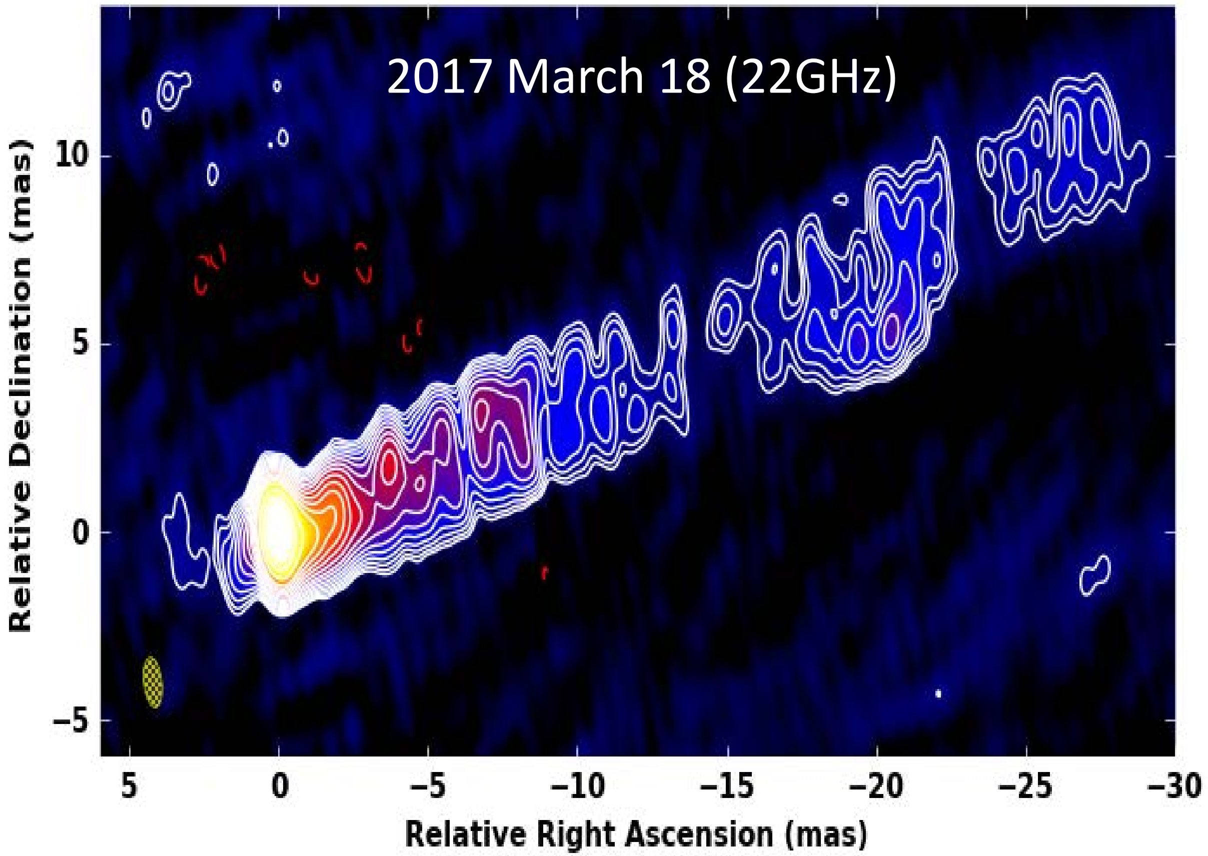


- VERA/JVN (Japan), KVN (Korea), CVN (China)
- Collaborative effort to form a large VLBI network in East Asia

M87

KaVA +TM +UR +HT

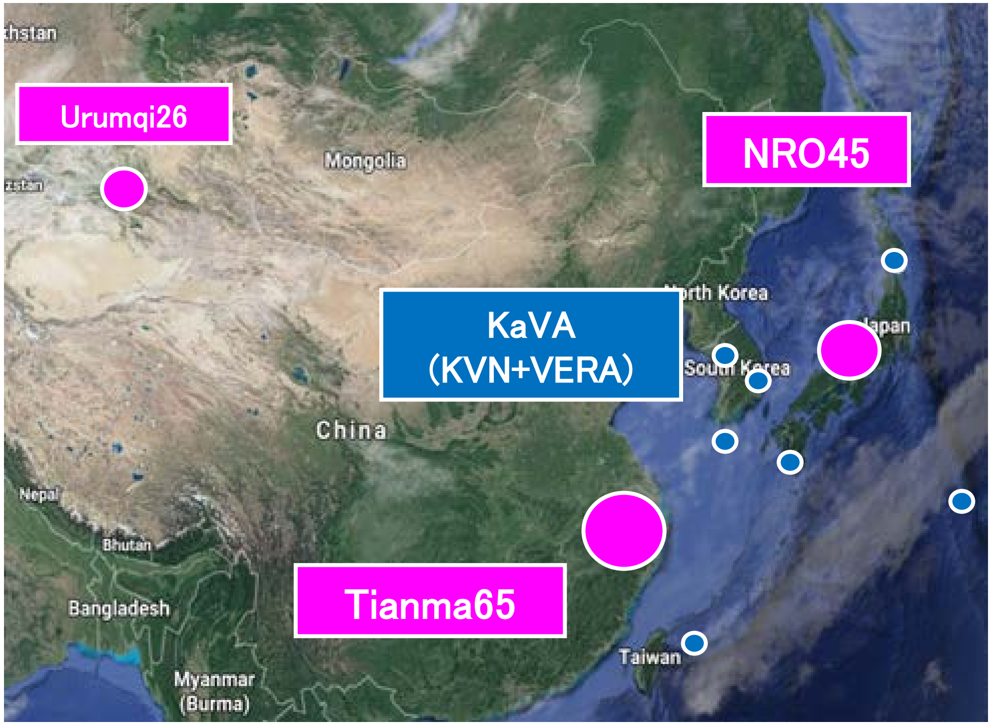


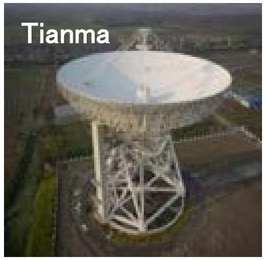


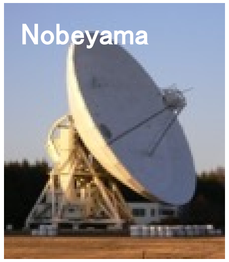
More results on EAVN-M87-2017 (22/43, spectra, kinematics, jet base)

EAVN MoU @ EAVN WS Sep/2018, Pyeongchang

EAVN open-use has just started



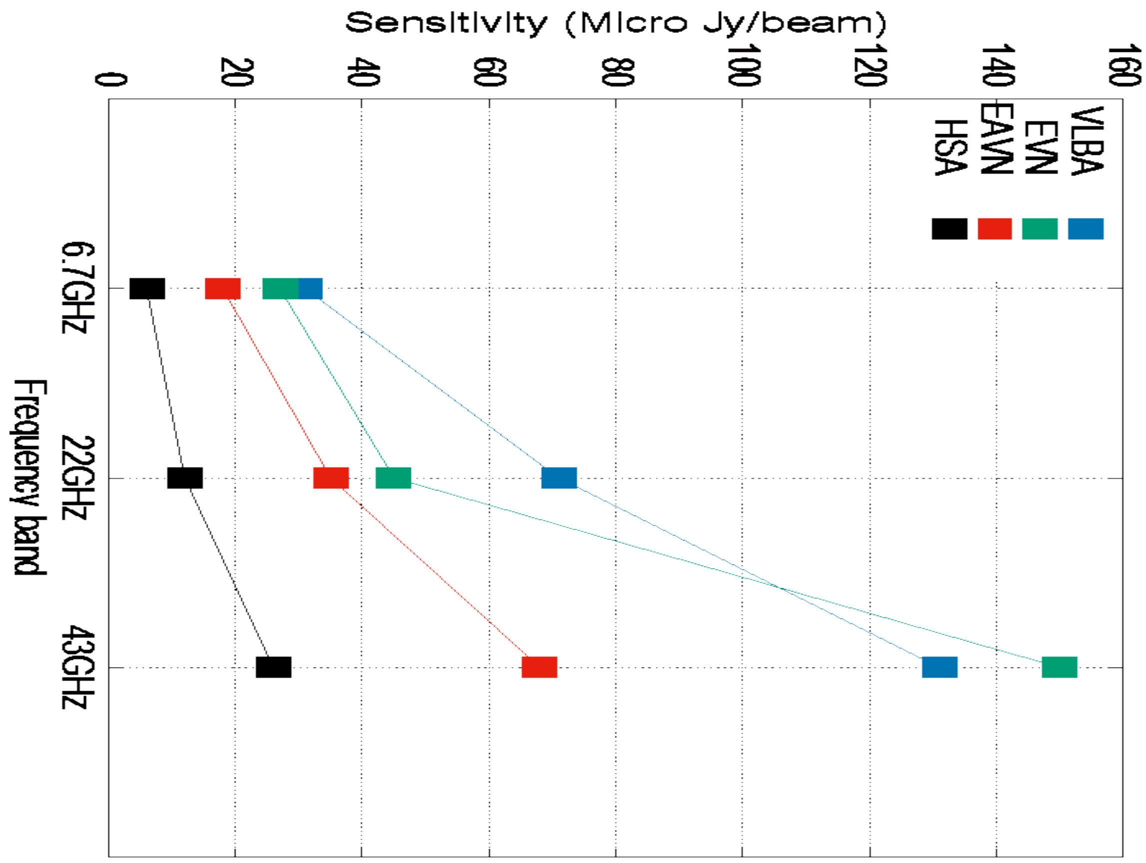




- First EAVN open-use observations starting from Oct/2018
- Available stations: 10 (KaVA, Tianma, Nobeyama, Urumqi)
- Bands: 22GHz (13mm), 43GHz (7mm)
- Angular resolution: 0.5 mas
- Good sensitivity at 22/43GHz

Array sensitivity of EAVN

2Gbps (512MHz BW), 1hr integration



43GHz
VLBA: 10
EVN: Ef, On, Ys, Nt
EAVN: KaVA, TM, NY

22GHz
VLBA: 10
EVN: Ef, Mc, On, Tr, Nt, Ur, Ys, Hh, Sv, Zc, Bd
EAVN: KaVA, TM, UR, NY, HT, TH, KS

6.7GHz
VLBA: 10
EVN: Ef, Mc, On, Tr, W1, Nt, Ys, Hh, Ir
EAVN: VERA, KUS, TM, KM, HT, TK, KS, YM, US

- EAVN: “high-sensitivity” + “regular monitoring capability” at 6.7-43GHz
  - Complementary to other VLBI facilities

Table 2 | Parameters of the EAVN telescopes

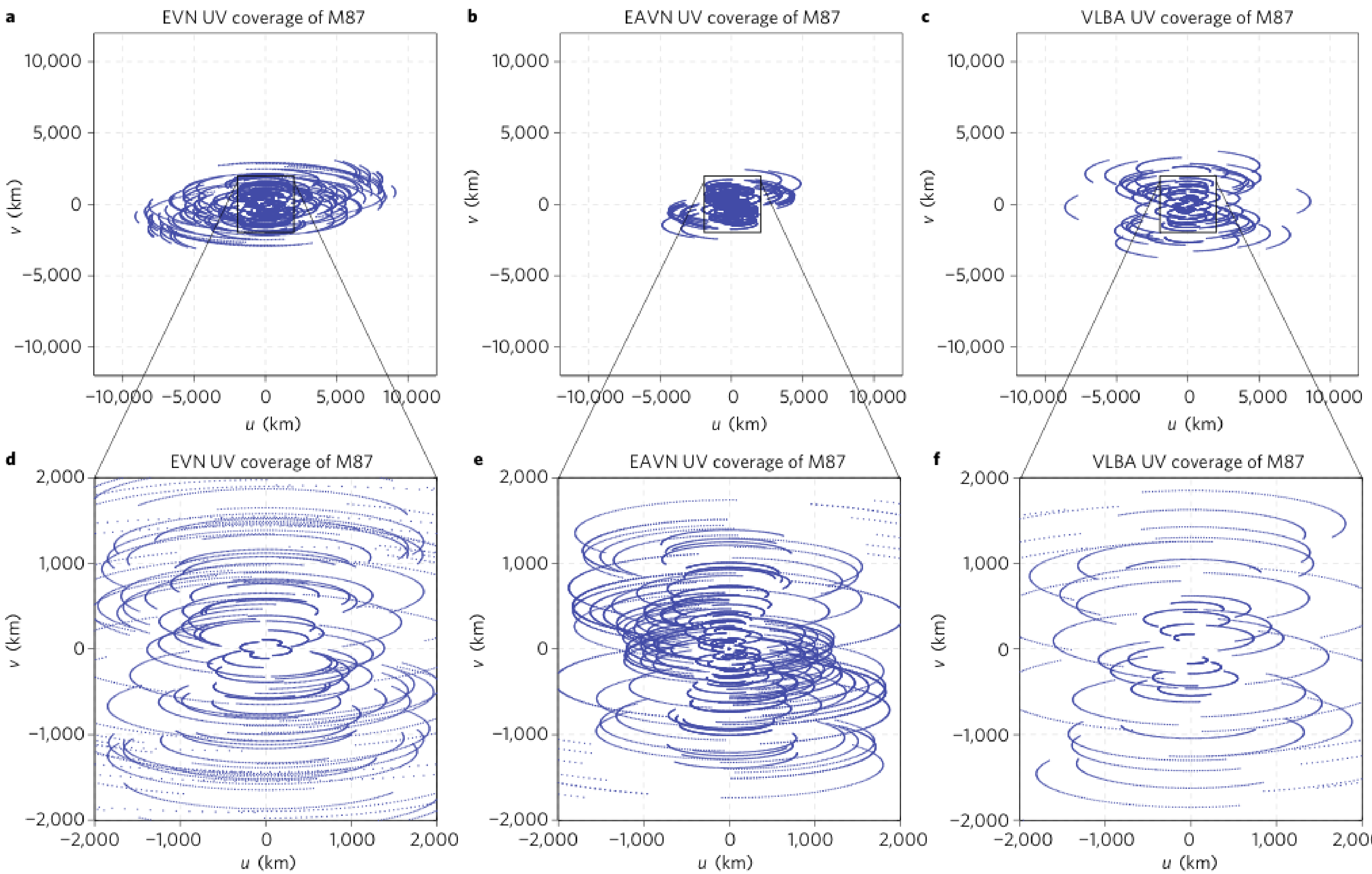
An, Sohn, Imai 2018

Subarray	Telescope name	Diameter of telescopes (m)	Frequency bands (GHz)								
			1.6	2.3	5	6.7	8.4	22	43	86	129
CVN	FAST	500	0.07–3								
	Kunming	40		●		●	●				
	Miyun	50		●			●				
	Sheshan	25	●	●	●	●	●	●			
	Tianma	65	1.25–50								
	Urumqi	26	●	●	●		●	●			
JVN	Gifu	11						●			
	Hitachi	32				●	●	●			
	Kashima	34	●	●			●	●	●		
	Takahagi	32				●	●	●			
	Usuda	64	●	●		●	●				
	Yamaguchi	32				●	●				
VERA	Iriki	20		●		●	●	●	●		
	Ishigakijima	20		●		●	●	●	●		
	Mizusawa	20		●		●	●	●	●		
	Ogasawara	20		●		●	●	●	●		
NRO	Nobeyama	45						●	●	●	
KVN, NGII	Sejong	22		●			●	●	●		
	Tamna	21						●	●	●	●
	Ulsan	21				6.4–9	●	●	●	●	●
	Yonsei	21						●	●	●	●

The operational frequency bands are marked with solid dots. The available frequency coverage in the early science phase of FAST is 0.07–3 GHz. The frequency coverage of the Tianma telescope is continuous from 1.25 up to 50 GHz. The Ulsan telescope has a broadband receiver at the 6.4-9 GHz frequency range.

UV coverage of major VLBI arrays

Target: M87, Frequency: 22 GHz



An, Sohn, Imai 2018

EAVN (+ Italy) AGN Campaign

Main purpose

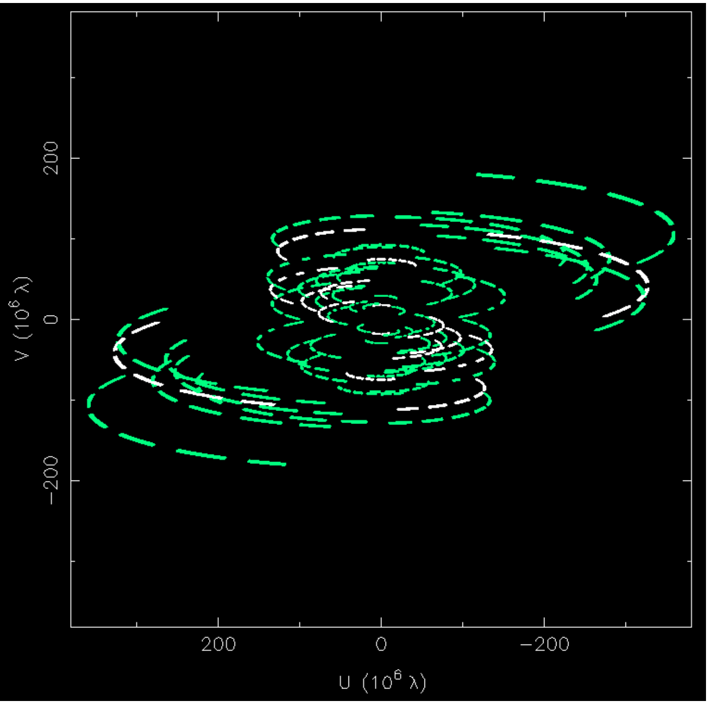
- To obtain scientific results with EAVN
- To conduct VLBI monitoring quasi-simultaneously with EHT + ALMA campaign
- (To evaluate system performance of EAVN)
- (To check up on the array operation and availability of KEY/VEX files at each station)

Brief summary of the Campaign

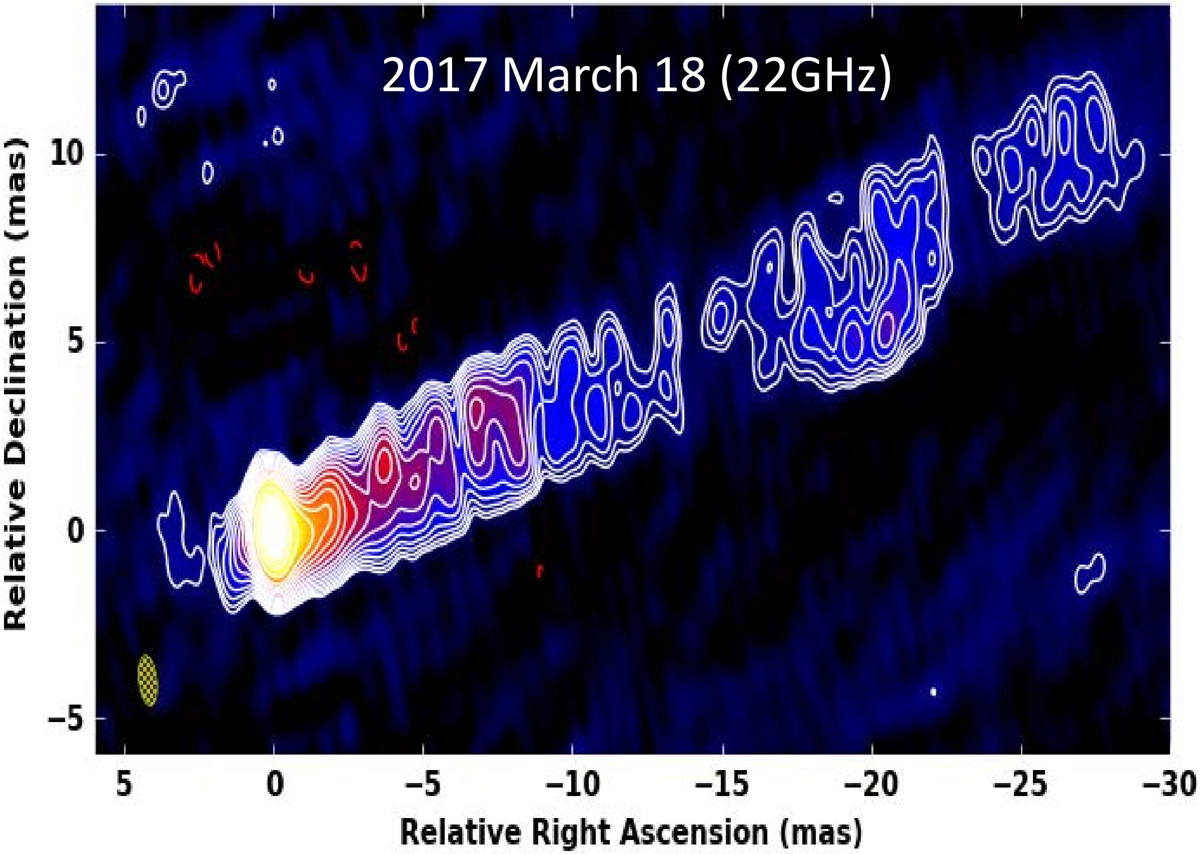
- Main target: Sgr A* (43 GHz), M87 (22 and 43 GHz)
- Total observing time: 186 hours/18 epochs (83 hours/9 epochs at 22 GHz; 103 hours/12 epochs at 43 GHz)
  - cf. EAVN campaign in 2017: 40 hours/5 epochs at 22 GHz; 100 hours/12 epochs at 43 GHz
- Number of participating telescopes: 14 (Italy: 2, China: 2, Korea: 3, Japan: 7)

Correlation and data reduction ongoing

M87

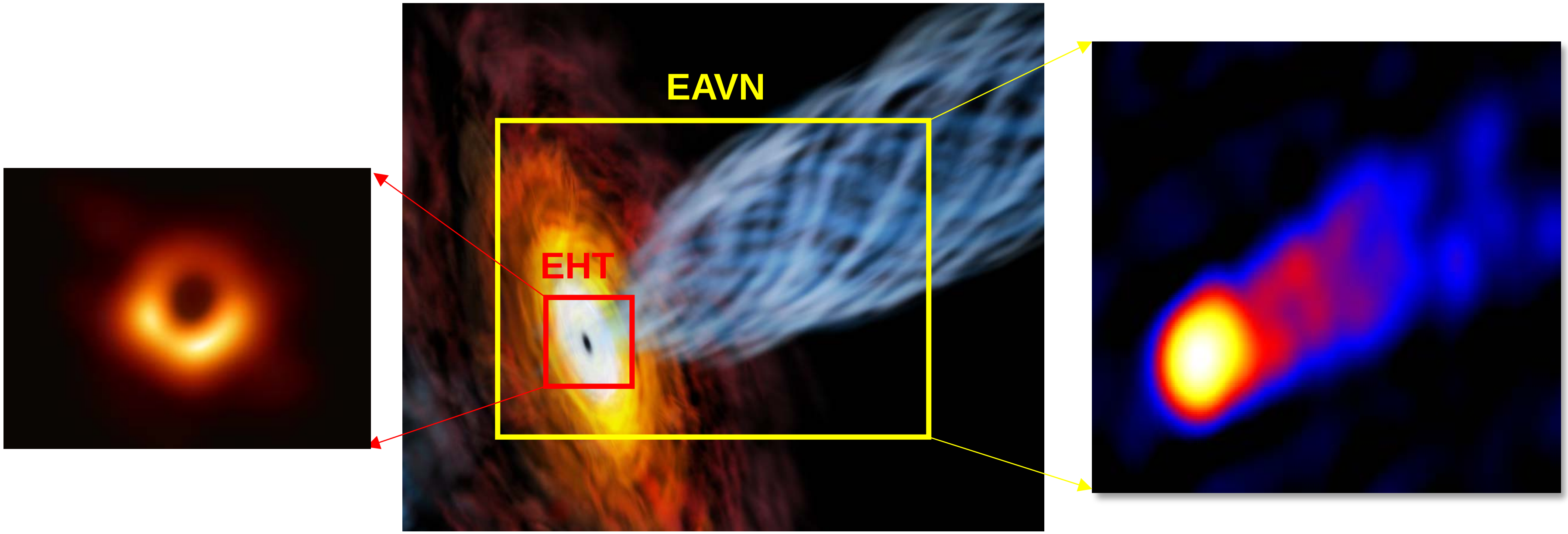


KaVA +TM +UR +HT



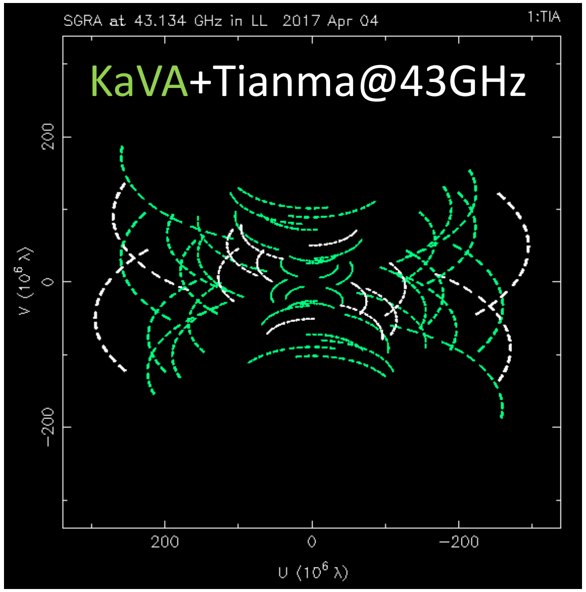
More results on EAVN-M87-2017 (22/43, spectra, kinematics, jet base)

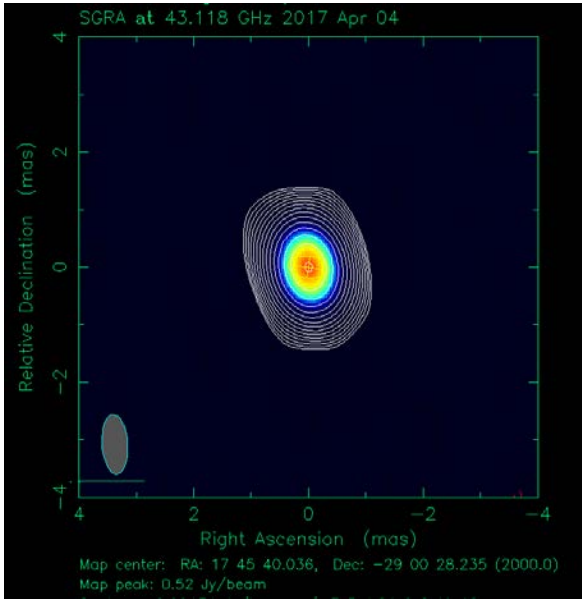
Intensive monitoring of M87/SgrA

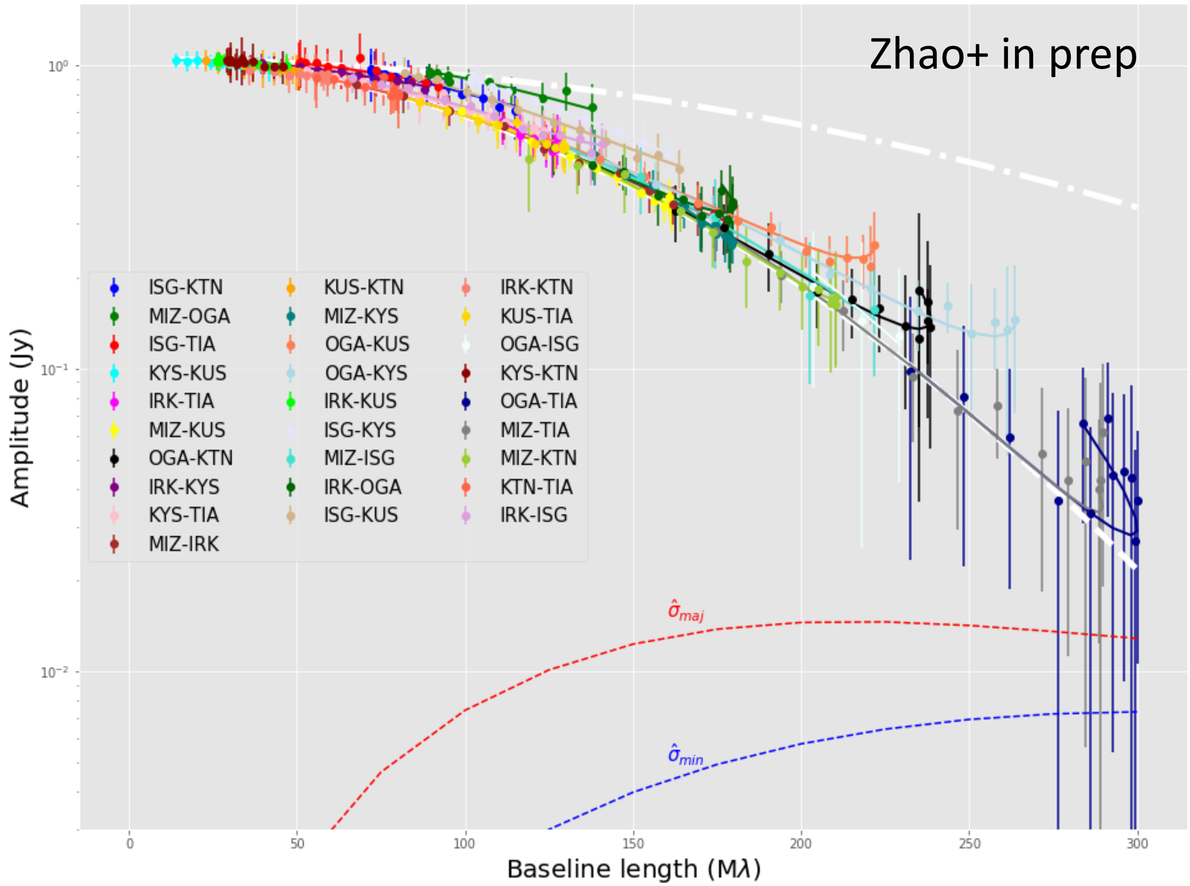


- EHT will see the first horizon-scale images of SMBHs (SgrA/M87)
- Centimeter-VLBI plays key roles in many aspects:
  - Connect the horizon scales to large-scales (accretion flows, jet collimation)
  - Subsequent evolution/propagation of ejected jet (jet acceleration, shock)
  - Spectral information of synchrotron plasma (B-field, U_e/U_B)
  - Scattering screen towards SgrA
- EAVN is a suitable facility to complement EHT

SgrA*



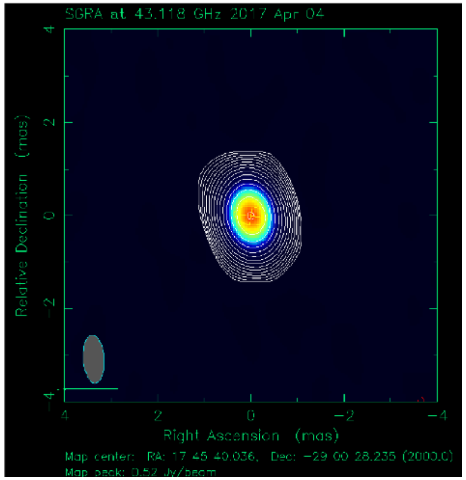


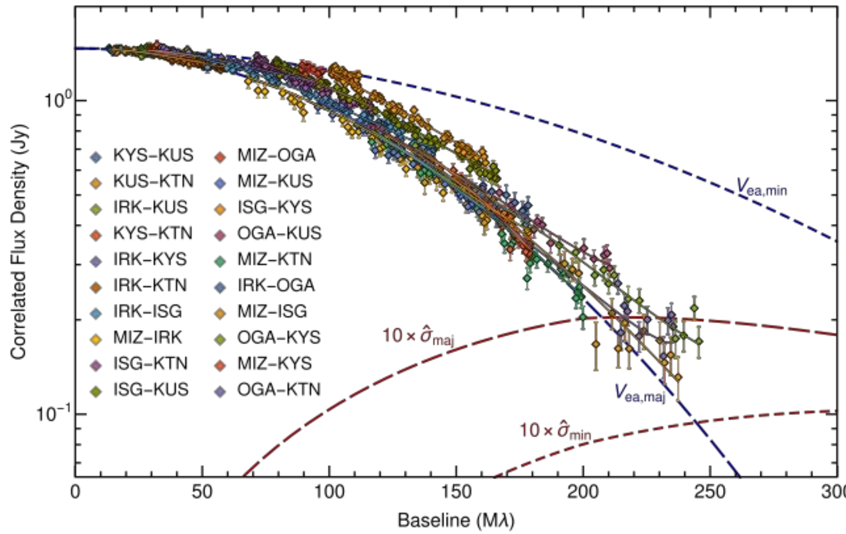


- EAVN: Very dense uv-coverage for SgrA
- First 300Mλ detection at 43GHz (Tianma - Ogasawara)
- Non-gaussianity?
- Contemporaneous 22GHz data => scattering properties
- Millimeter-regime core-shift with KVN

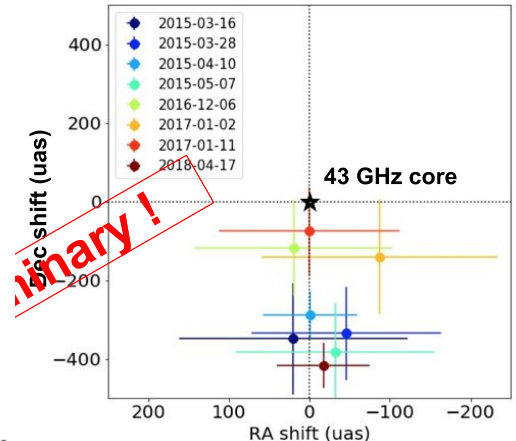
More results are coming from EA-VLBI

SgrA* (Zhao+; Cho+; Johnson+2018)

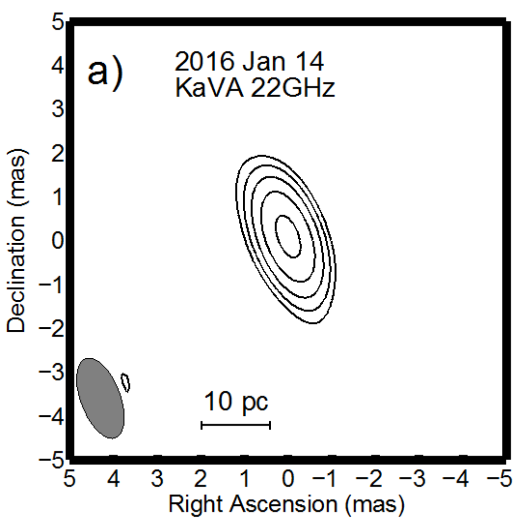




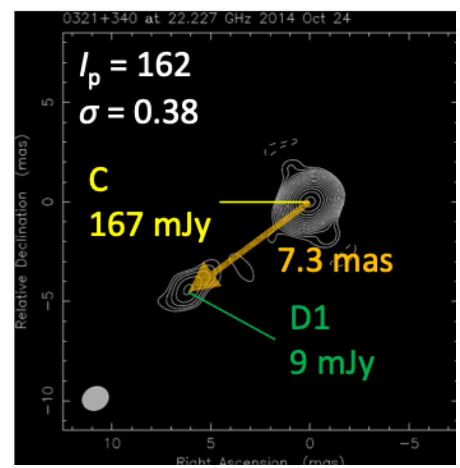
86 GHz core positions



High-z quasars (Zhang+2018; Furuya+)



NLSy1 (Wajima+)



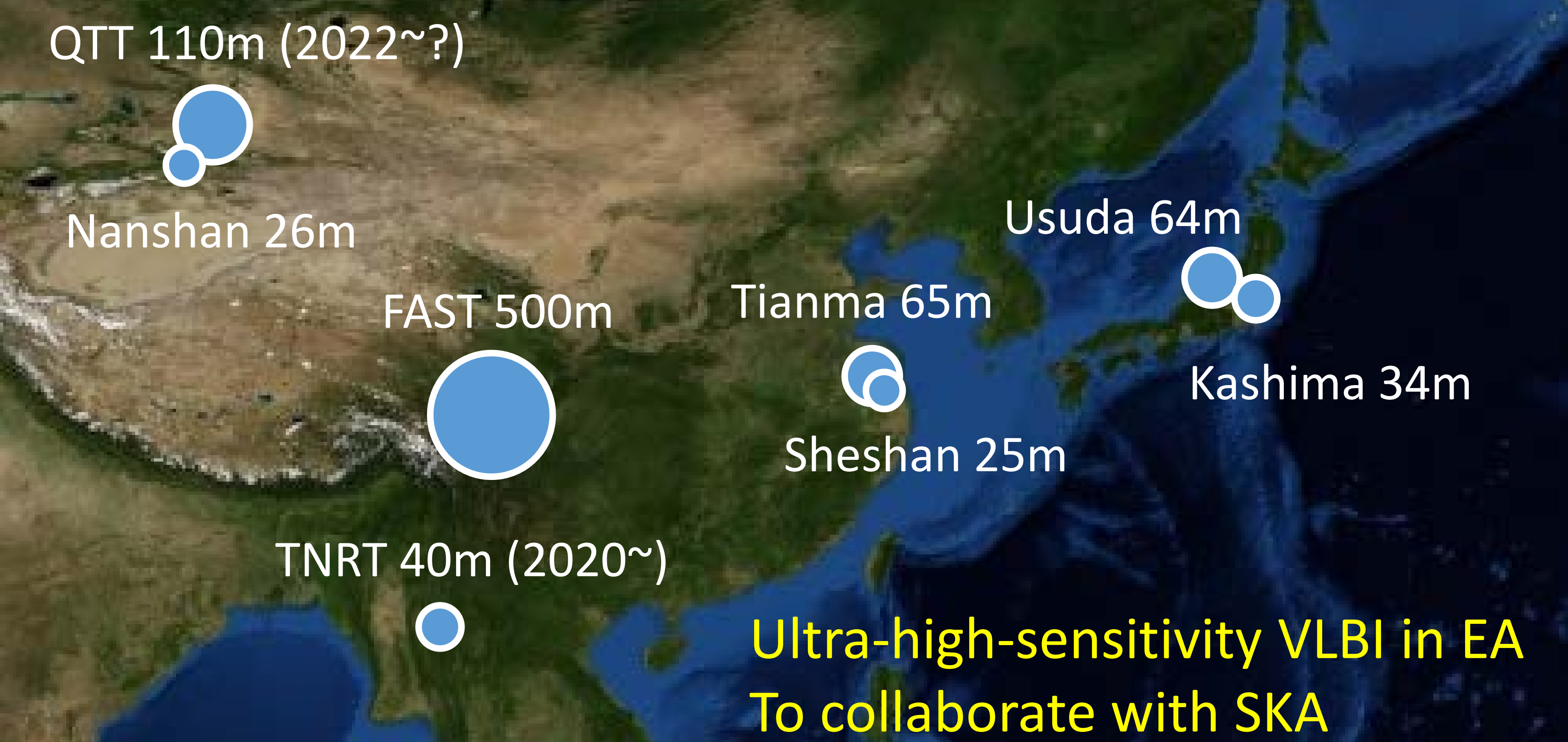
And more!

Future expansion of EAVN

- More stations
  - E-KVN
  - QTT 110m
  - Thai 40m
  - Malaysia
  - Indonesia
- EAVN with FAST (<3GHz)
  - Sensitivity comparable to SKA1, but 30 times higher angular resolution
- "World Array" with EAVN+EVN+VLBA

Expanding observing frequency to Lower and Higher

EA stations with 1-2GHz receivers



Ultra-high-sensitivity VLBI in EA

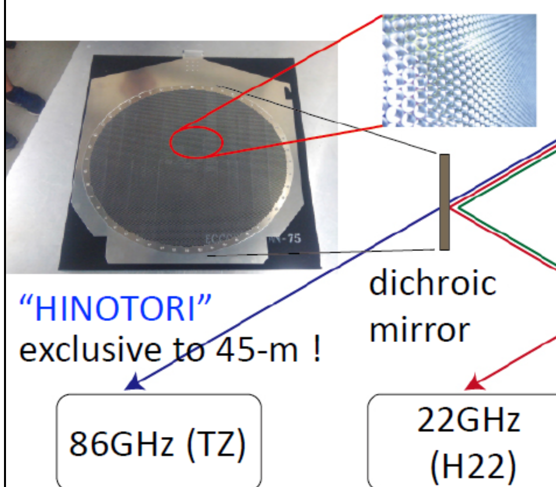
To collaborate with SKA

Expanding observing frequency to Lower and Higher

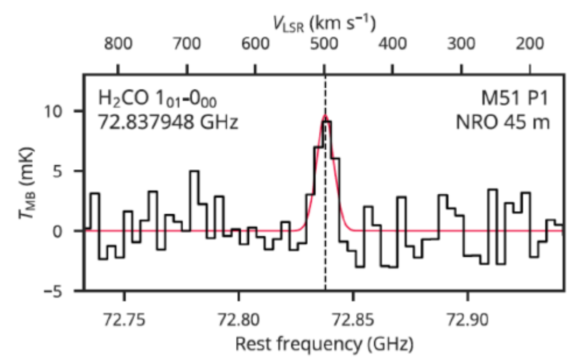
NRO 45m Triple band observation

- System change/upgrade
  - Kunming 40 m: 6.7 GHz receiver available
  - Nanshan 26 m: 43 GHz cooled receiver
  - Nobeyama 45 m: New quasi-optics at 22/43/(86) GHz simultaneous reception (HINOTORI Project)

- Triple-band simultaneous observing system “HINOTORI” (2016-now)
  - Kagoshima Univ., Osaka Pref. Univ., Yamaguchi Univ., Ibaraki Univ., + NAOJ



opportunities
for students/PDs



Extragalactic formaldehyde using T70

➔ preparation for ALMA Band-2

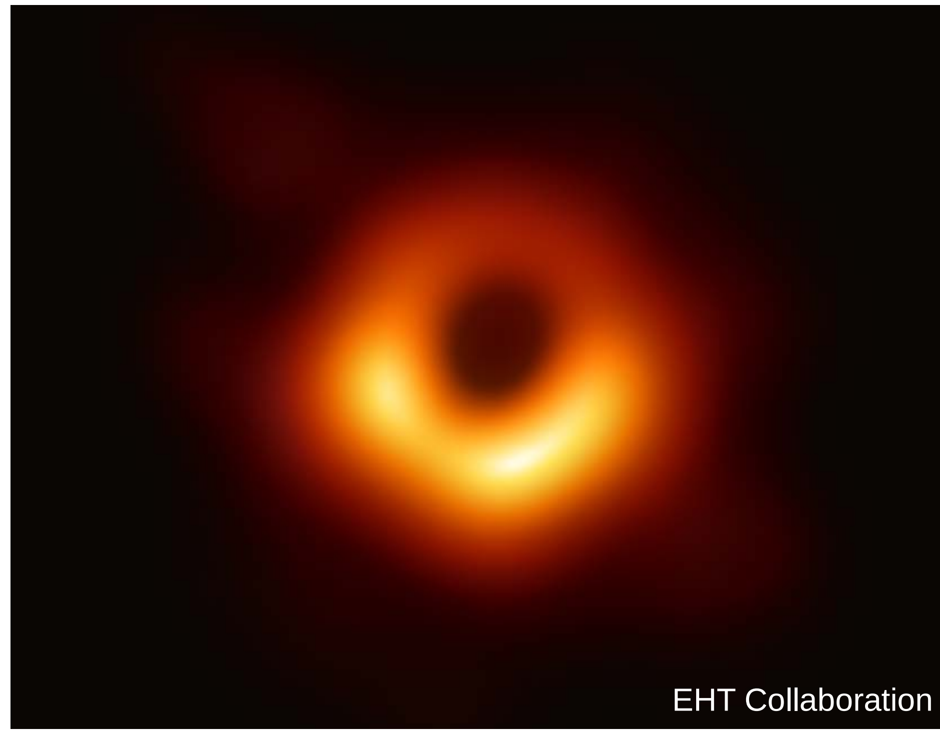
Nishimura, Y., et al. 2019, ApJ, 879, 65

Black hole Shadow

EHT observations in 2017

- 5 nights on April 5-11, 2017
- 8 stations at 6 sites participated
- Maximum baseline ~ 10000 km
- Wavelength ~ 1.3 mm
- Nominal beam ~ 25 uas

The shadow of M87's super-massive black hole



Ring-size : 0.01 ly (4 light day)
Mass: 6.5 x10^9 Solar mass

A new station to EHT Balloon-borne VLBI ?

- EHT collaborations seriously consider the future array extension with space station
- Better images, some more sources with shadow
- See Astro2020 paper (will be opened)

Balloon VLBI experiment by Doi et a.

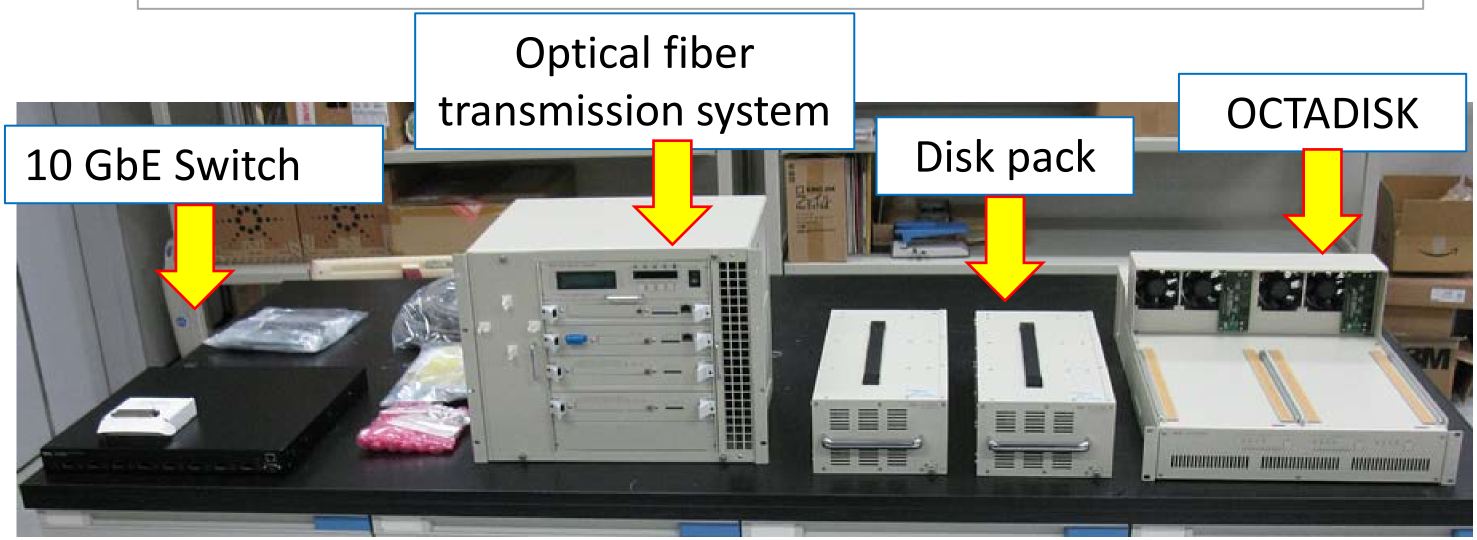
Future Plan of VLBI astronomy in Japan

- Under discussion in various layers
  - VLBI consortium
  - Working groups (in Mizusawa, VLBI consortium, JVN)
  - Mizusawa VLBI User's Meeting
  - VLBI Science Advisory committee in NAOJ
- Short term
  - From VERA to EAVN, JVN
  - Just started good collaboration. We plan to keep and expand the activity under the international collaboration.
- Long term
  - Large international project (SKA, ngVLA, …), New Satellite VLBI, New telescope led by Universities

New VLBI technologies developed by NAOJ

- High speed sampler, Digital filter
- Optical fiber data transmission
- High precision phase-referencing / astrometry
- (Space-VLBI, 2-beam receiver, …)

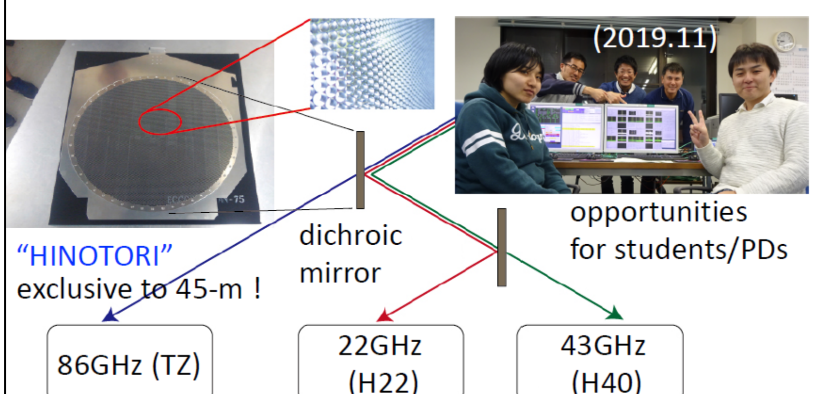
<u>OCTAVE system</u>
VSI based VLBI terminal,32 Gbps (max) recording capacity
World compatibility, suitable to the East-Asian Correlator

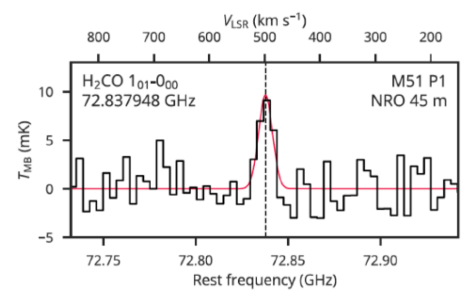


NAOJ’s expected role in VLBI

- A research base is expected to be in NAOJ
  - Cutting edge development research is expected to be lead/backuped by NAOJ
  - University’s research strongly depends on personality of each researcher (unstable). NAOJ is the stable core of VLBI.
- A key: Cooperation of Nobeyama and Mizusawa

- Triple-band simultaneous observing system “HINOTORI” (2016-now)
  - Kagoshima Univ., Osaka Pref. Univ., Yamaguchi Univ., Ibaraki Univ., + NAOJ





Extragalactic formaldehyde using T70
➔ preparation for ALMA Band-2

Nishimura, Y., et al. 2019, ApJ, 879, 65

Implication of EAVN

- Background
  - Simple ‘Expansion’ model is difficult in Japan now
    - Demographics, Social security expenses, Economical recession…
  - Still, the achievements of Japanese astronomical society is respected by communities of east Asian countries
  - Construction of new VLBI telescopes in east Asia
  - ‘Collaboration’ strengthen the performance of VLBI

EAVN construction

- Let the owls of Minerva fly as messengers
- To construct a new network of knowledge and research