radio astronomy with ultra-high angular resolution using EAVN and global VLBI

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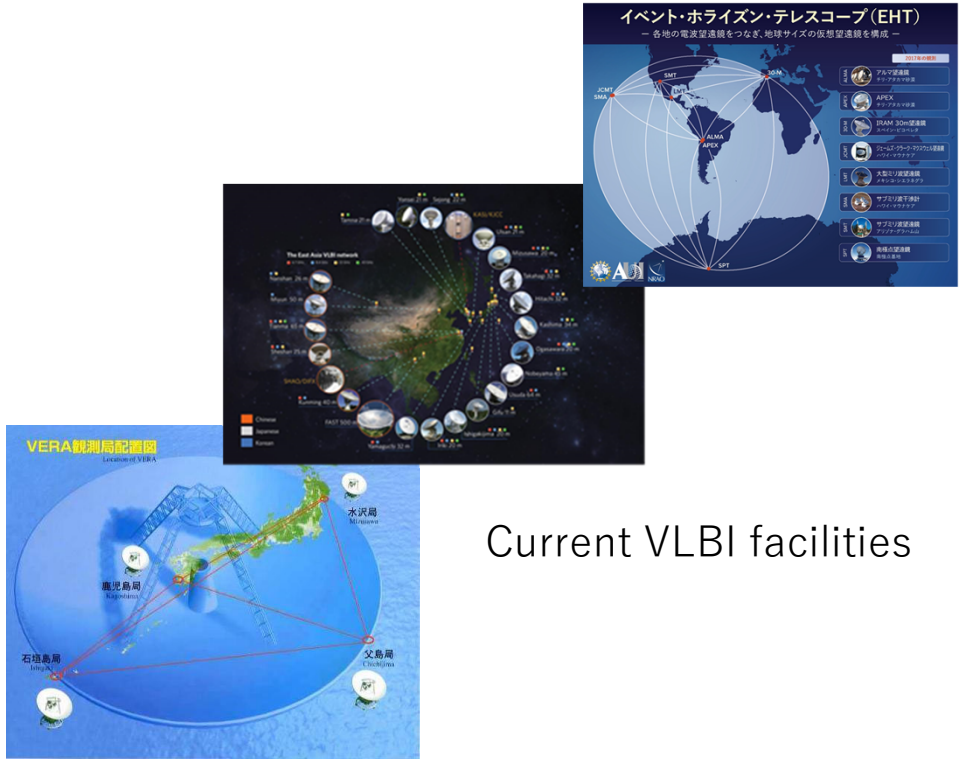
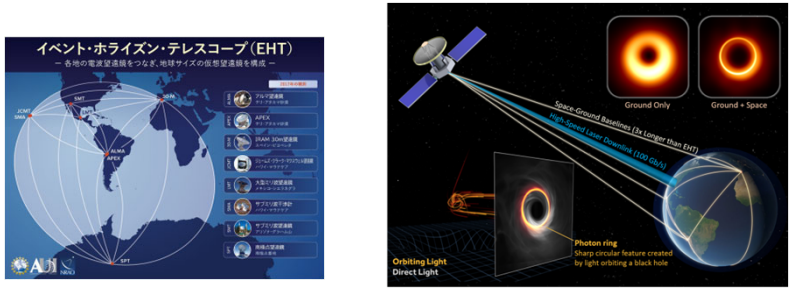
2024 Dec

1. Summary of the proposal

As a center of VLBI astronomy in Japan, we will operate and upgrade EAVN and related-VLBI facilities and promote international collaboration to global VLBI, and provide user communities best opportunities for radio astronomy research with the highest angular resolution.



Current VLBI facilities



Future global VLBI, with SKA at cm,
and possibly with space VLBI (BHEX) in mm

2. Science goals

- We aim to **explore** the structure, formation and evolution of **most extreme objects in Universe**, i.e., black holes, birth and death of massive stars, pulsars/FRBs/SN explosions, and potentially artificial radio signals emitted by ETI, with ultra-high resolution of VLBI.

Three key questions of NASA astrophysics

How does the universe work?

physics of accretion disk and jet in AGN/black holes, high energy phenomena in black holes, pulsars/FRB and supernova.

How did we get here?

SMBH's interaction with host galaxies, birth and death of massive stars

Are we alone?

SETI

3. Science objectives

1) To produce cutting-edge science results in ***the study of supermassive black holes regarding jet formation, acceleration, collimation mechanisms*** and so on based on ultra-high-resolution observations of active galactic nuclei.

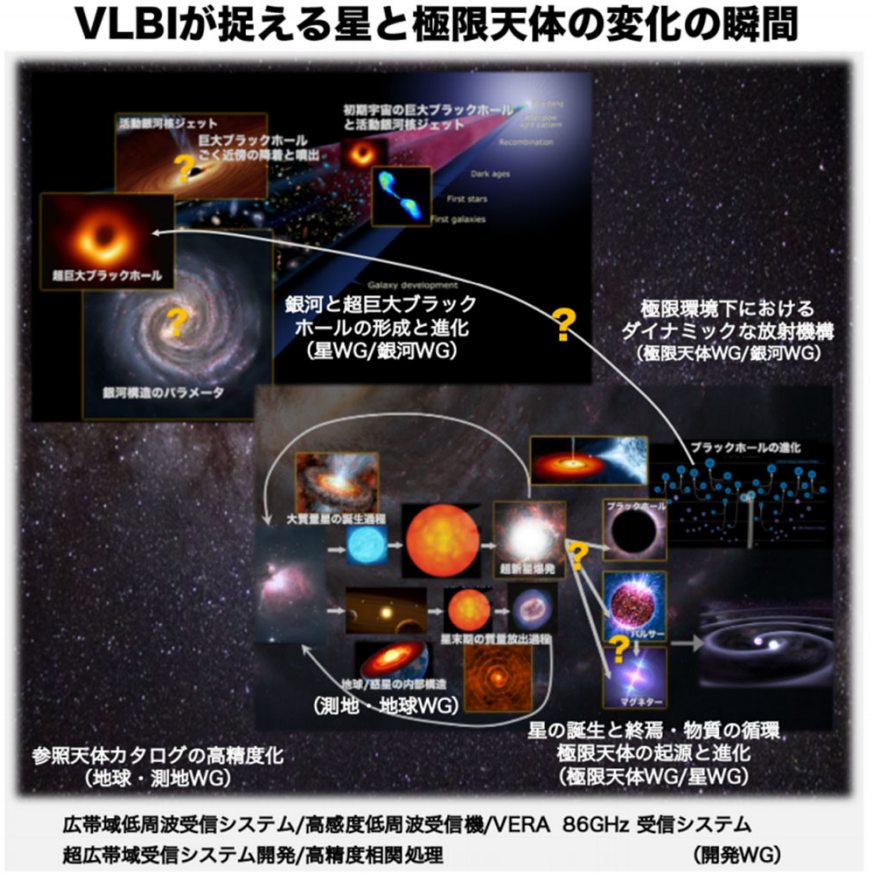
2) To elucidate ***dynamic picture of massive star formation by high-resolution maser observations, and to promote research on late-type stars and the structure of the Milky Way*** via maser monitoring.

3) To explore ***the possibility of VLBI observations of objects other than above with the aim of expanding its research field.***

Scientific objectives: coherent with community

- The science objective is in accordance with the outcome of future plan WG of VLBI consortium in Japan.

https://www2.nict.go.jp/sts/stmg/vcon/WG/FuturePlan2020/Report20210616/VLBI_FuturePlanWG_Report_v4.pdf



Summary figure of future plan WG of Japanese VLBI consortium

4. Science Investigations

4.1. Science Investigations until 2033

4.2. Science Investigations beyond 2034
global VLBI with SKA mid
global mm-VLBI with BHEX

4.3. Threshold Science

Science (1): black holes astrophysics

- Black hole and AGN jets

we aim to understand the formation/ collimation mechanism of AGN jets, and its relation with black hoke and accretion disk

In particular, we try to test existence of spin of black holes, and understand its connection to jet formation through the B-Z mechanism.

Monitoring observations with EAVN, GMVA and EHT will provide the fundamental clues for them.

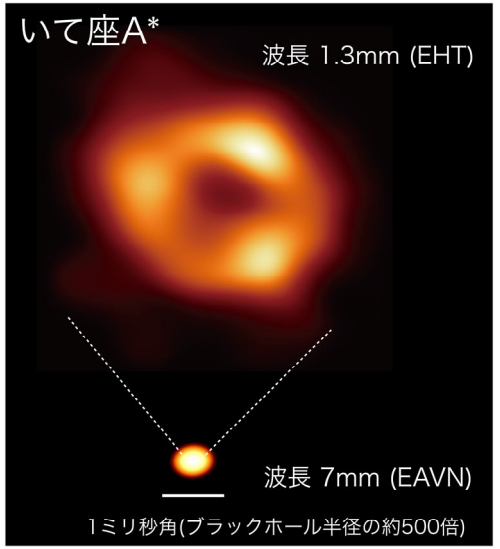
Required specification：

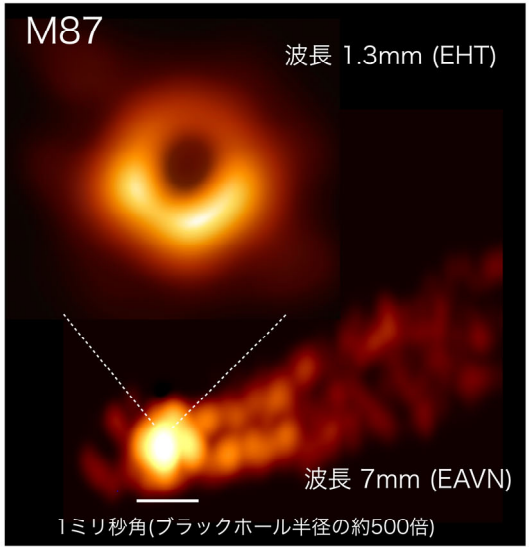
ultra-high resolution of 20 uas~ 250 uas

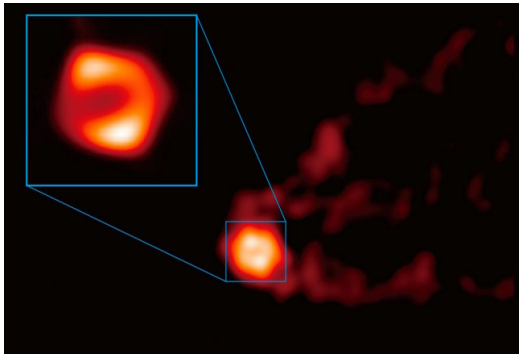
imaging sensitivity of 1 mJy/beam or less

Regular monitoring observations

(e.g. by-weekly or monthly for M87)







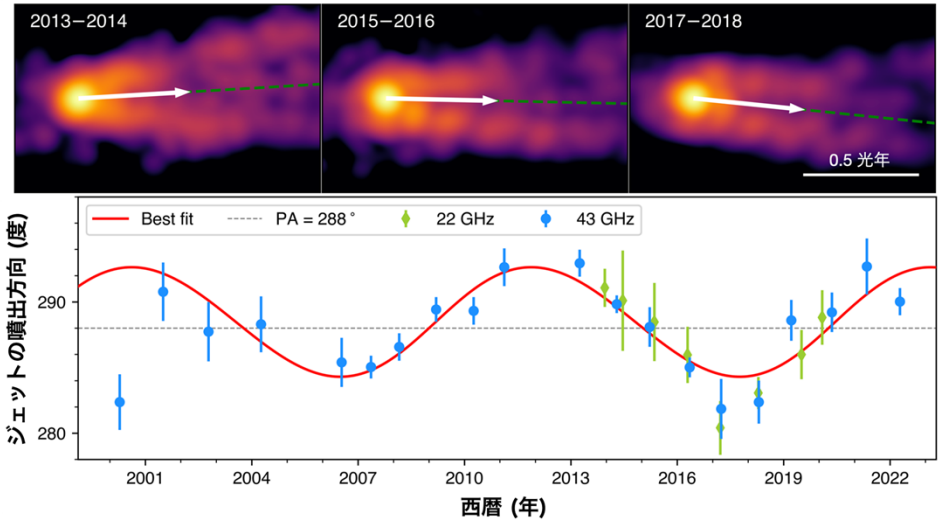
Accretion disk & jet with GMVA (Lu et al. 2023)

Key questions: how are jets formed/accelerated? what are the roles of BH spin and accretion disk?

Demonstration of EAVN's advantage

- Cui et al.(2023) Nature

Detection of M87's jet precession is interpreted as Lense-Thirring precession, and thus provides a new and strong evidence of black hole spin.



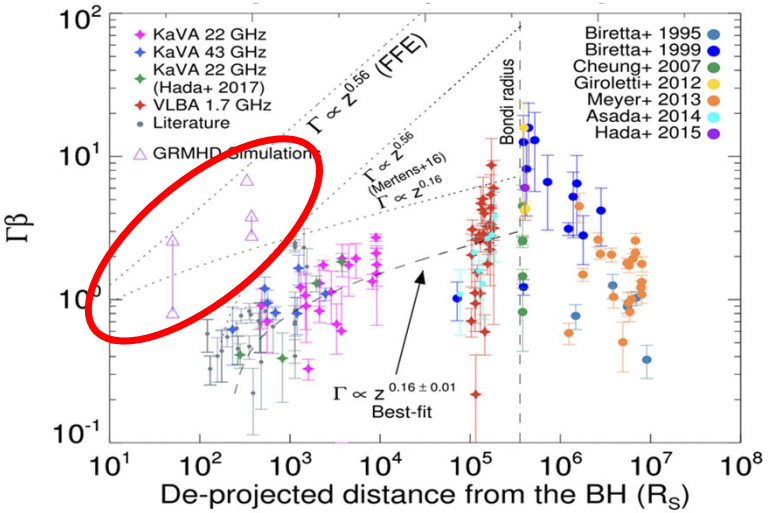
EAVN played a critical role in monitoring for more than 10 years !!

Key questions: what is the exact value of spin?

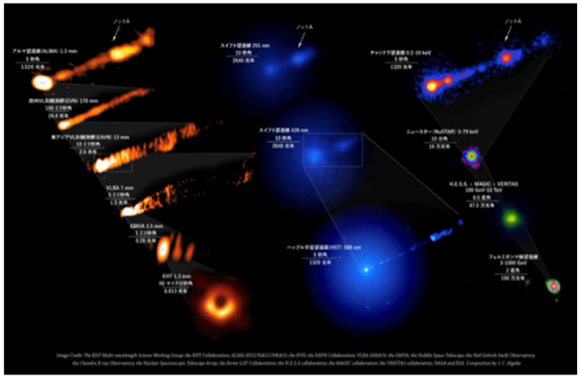
Science (1-2): AGN jet

- Full jet profile of velocity and shape has never been obtained, even in case of M87, the Rosetta Stone of AGN Jets.
- Yet we started seeing discrepancy in velocity profiles between observation and MHD simulations
- There are ~10 sources for which scale less than 10^2 Rs can be resolved with future space VLBI. In 5 of them we can touch within 10^2 R_s with ground-based EHT.
- Monitoring observations usually require 5 – 10 epochs observations to trace multiple components ejection as well as their motions, with an expected cadence of a week to a month (depending on BH mass as well as Doppler factor).

Jet acceleration / velocity fields
(Hada+2017, Park+2019)



M87 MWL campaign
(EHT-MWL Science WG et al.)

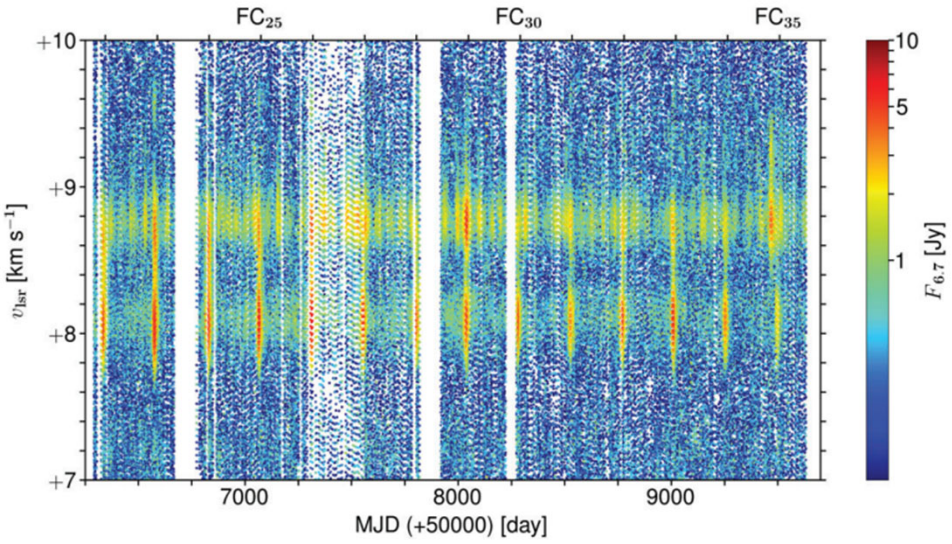


Key questions: How are AGN jets accelerated?

Science (2): Dynamic picture of massive star formation

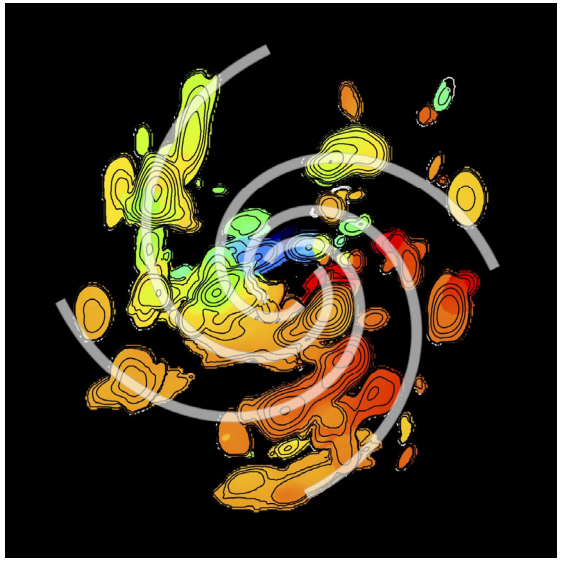
- Various types of maser time-variation has been detected via M2O program.

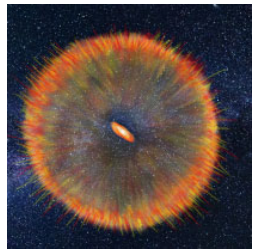
Double period methanol-maser flare (243 day & 52 day)



M2O collaboration (2022), based on Observations at Ibaraki

CH3OH maser spots associated with maser burst in G358-MM1 Burns+(2023)



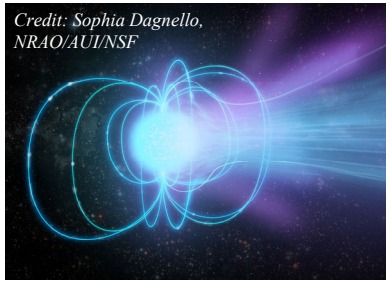


revealed spiral structure using maser burst

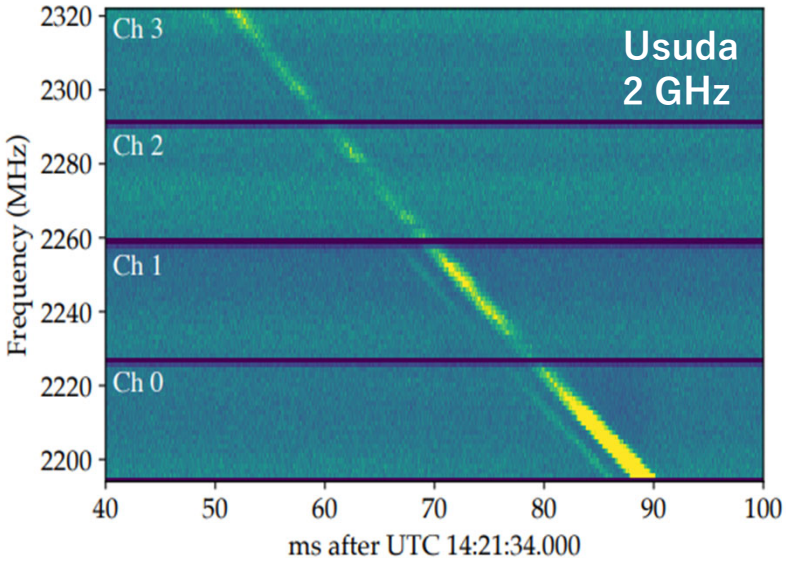
Key questions: what are dynamical pictures of massive star formation? what are their role in massive star formation?

Science (3). New targets (new to VLBI in Japan)

- Pulsar/Magnetar/FRB observations



First detection of FRB with radio telescope in Japan (repeating FRB 20201124, Ikebe+2022)

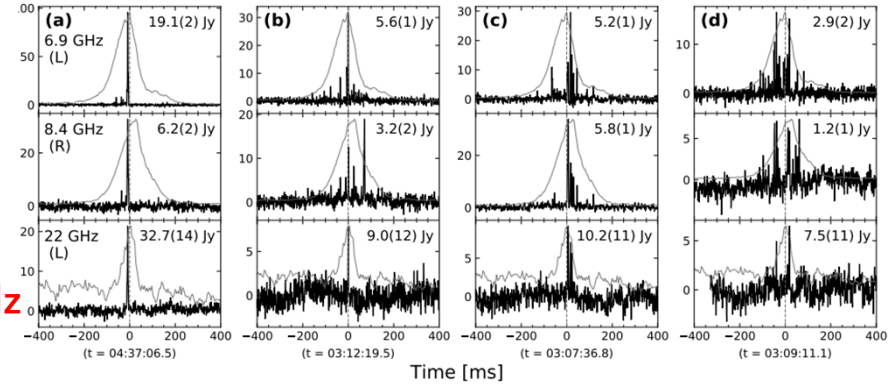


Magnetar flare of XTE1810 (Eie+2021)

Ibaraki 6GHz

8 GHz

VERA 22 GHz

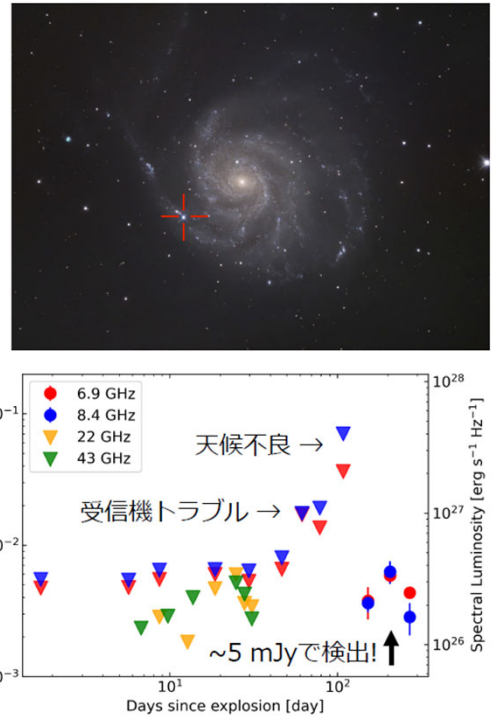


Key questions: What are origins of various types of radio flares? Are they similar objects or not?

Science (3-2). New targets (new to VLBI in Japan)

SN explosion detected with JVN

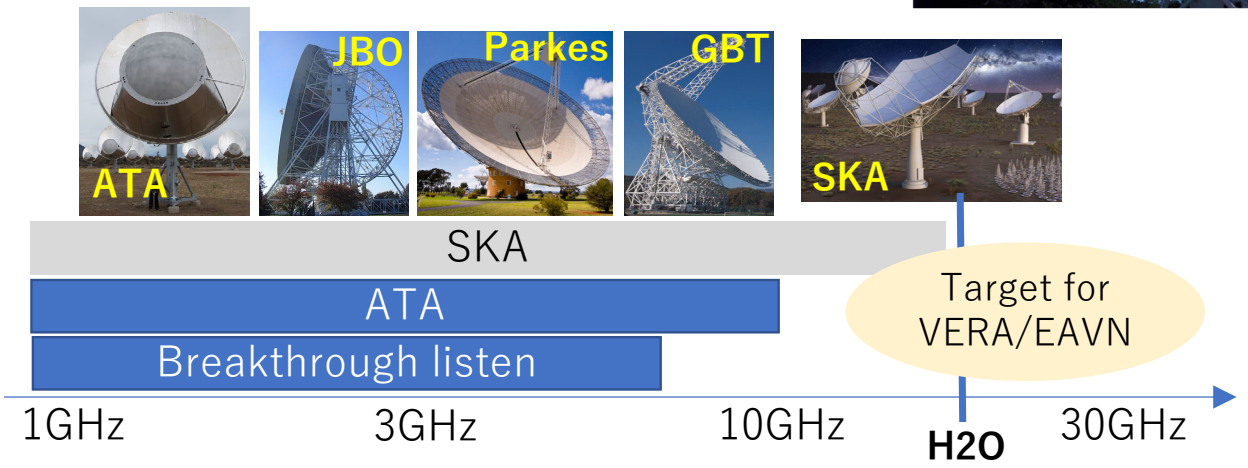
Iwata+(2024), SN2023ixf in M101



Key questions: how does an SN explosion occur?

SETI observations at 22 GHz,

a band of H2O molecular line



Key questions: Are we alone?

Threshold science (-2034)

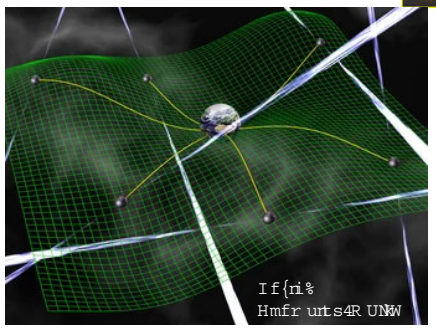
- AGN: Movie shooting of M87 horizon-scale + accretion disk + jet root for the first time to test black hole paradigm (BH/AD/Jet).
- AGN: Tracing jet acceleration profile for several sources to test jet model with state-of-art GRMHD simulations
- Star Formation: detecting and mapping accretion burst of masers in multiple sources to obtain general picture of role of dynamical event in star formation
- New sources: VLBI detection of one-off FRB emission, multiple detection of nearby SNe, and promotion of multi-messenger astronomy.

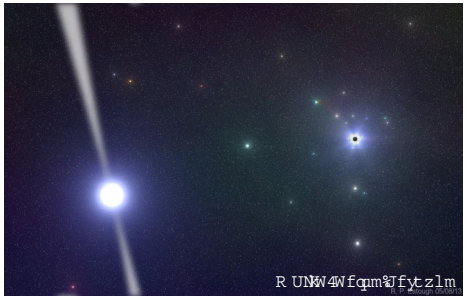
beyond 2034: global VLBI in cm and mm

Global VLBI with SKA will be able to conduct astrometry of

1) mm-sec pulsars to localize low-frequency-GW-emitting SMBH binary(s).

2) pulsars at the Galactic Center to measure space-time around Sgr A* (including spin!)

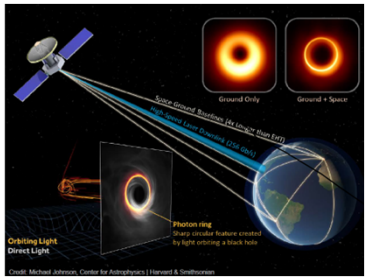




Milli-sec pulsars and GC pulsar astrometry

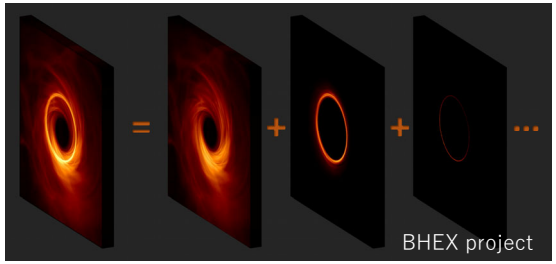
Global mm-VLBI with BHEX (black hole explorer, space VLBI mission to be proposed to NASA) will determine BH space-time with spin measurements of M87/Sgr A*, seeing more BH shadows and jets.

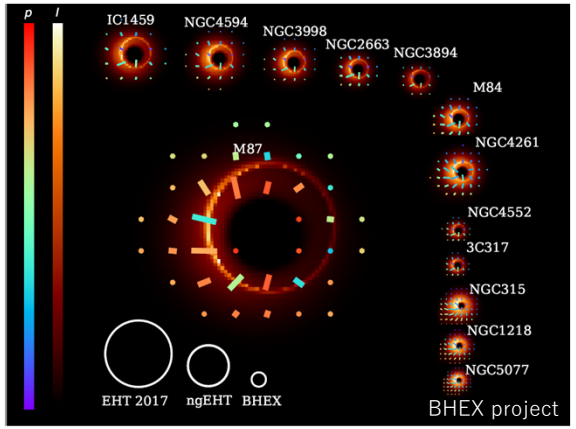
BHEX project concept



1mm VLBI with TPA and/or NRO45m as a part of ground array (ngEHT)?

Photon ring and spin measurement





BH demography with ~10 shadows

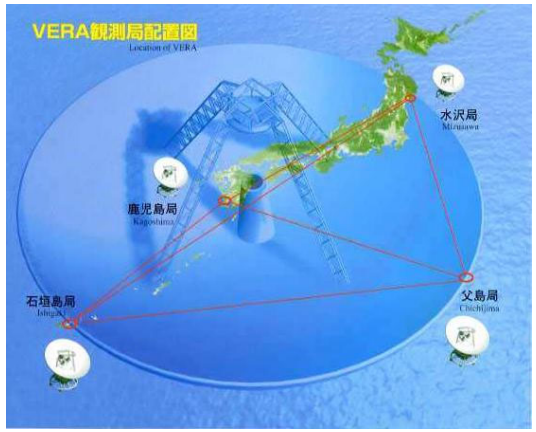
5. Instruments and data to be returned

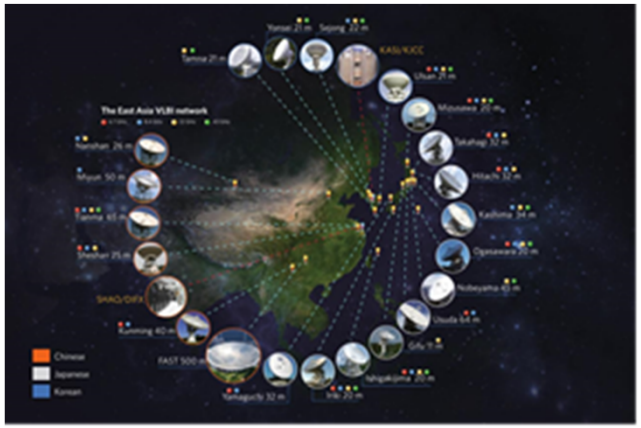
- **The main array: EAVN**
  Japan: VERA＋JVN
  Korea: KVN+NIG
  China: CVN
  Thai: NARIT

and more new stations are on-horizon

- We keep operation of VERA's 4-stations, and combined with other existing telescopes (funded and operated by other projects/organization etc.)

- **The main return to community:**
  machine time as open-use
  its data





Left: VERA array, which we will keep operation and upgrades.
Right: EAVN (East Asian VLBI Network), combined efforts with China, Japan, Korea, Thailand etc. (from Tao+2018)

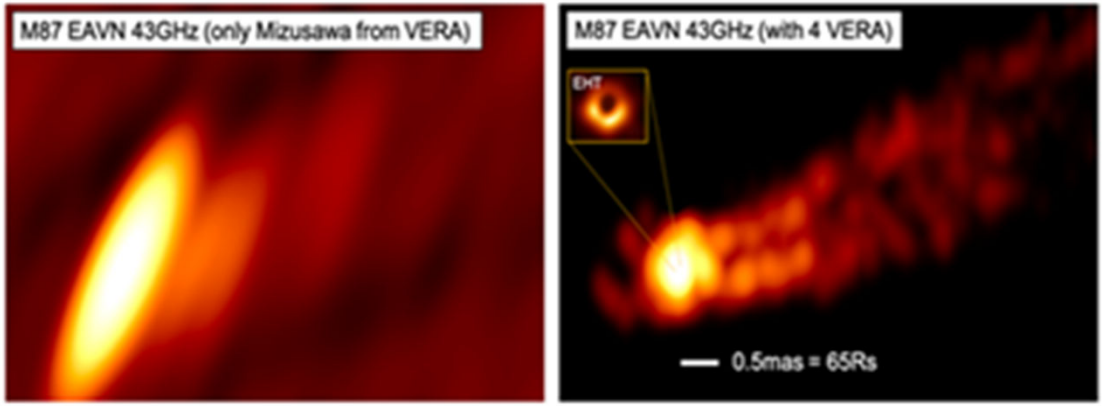
Critical role of VERA stations

- EAVN imaging capability with

1) only Mizusawa in Japan
2) Full 4-station VERA

- VERA stations are located in the eastern edge of the array, making them critical for UV coverage as well as resolution.

- Long-term stable operation of VERA has been requested by the user community.



EAVN imaging capability (M87 jet) when only Mizusawa station participates from VERA (left) and full VERA stations participate (right)

Related instruments/facilities

- mm-VLBI: Continuation and upgrade by EHT and observatories including ALMA

  multi-band capability (86, 230, 345GHz)

- EAVN :array expansion toward global VLBI

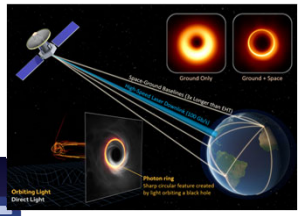
  Italy-EAVN collaboration and

  European VLBI Network (EVN)

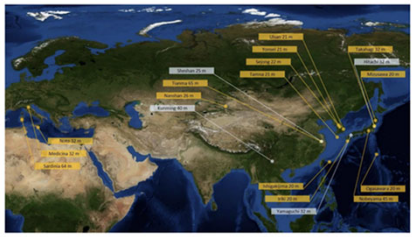
- Low frequency VLBI

  BURSTT (Taiwan-led project, with an outrigger station to be installed in Ogasawara) for FRB positioning with VLBI

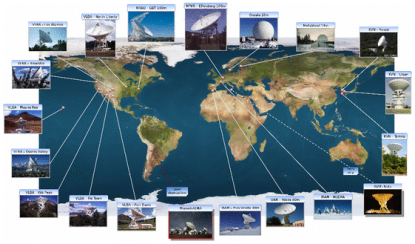
  (possibly L-band VLBI with FAST/CORE array)



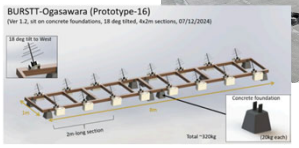
EHT and BHEX



EATING VLBI / EAVN+EVN



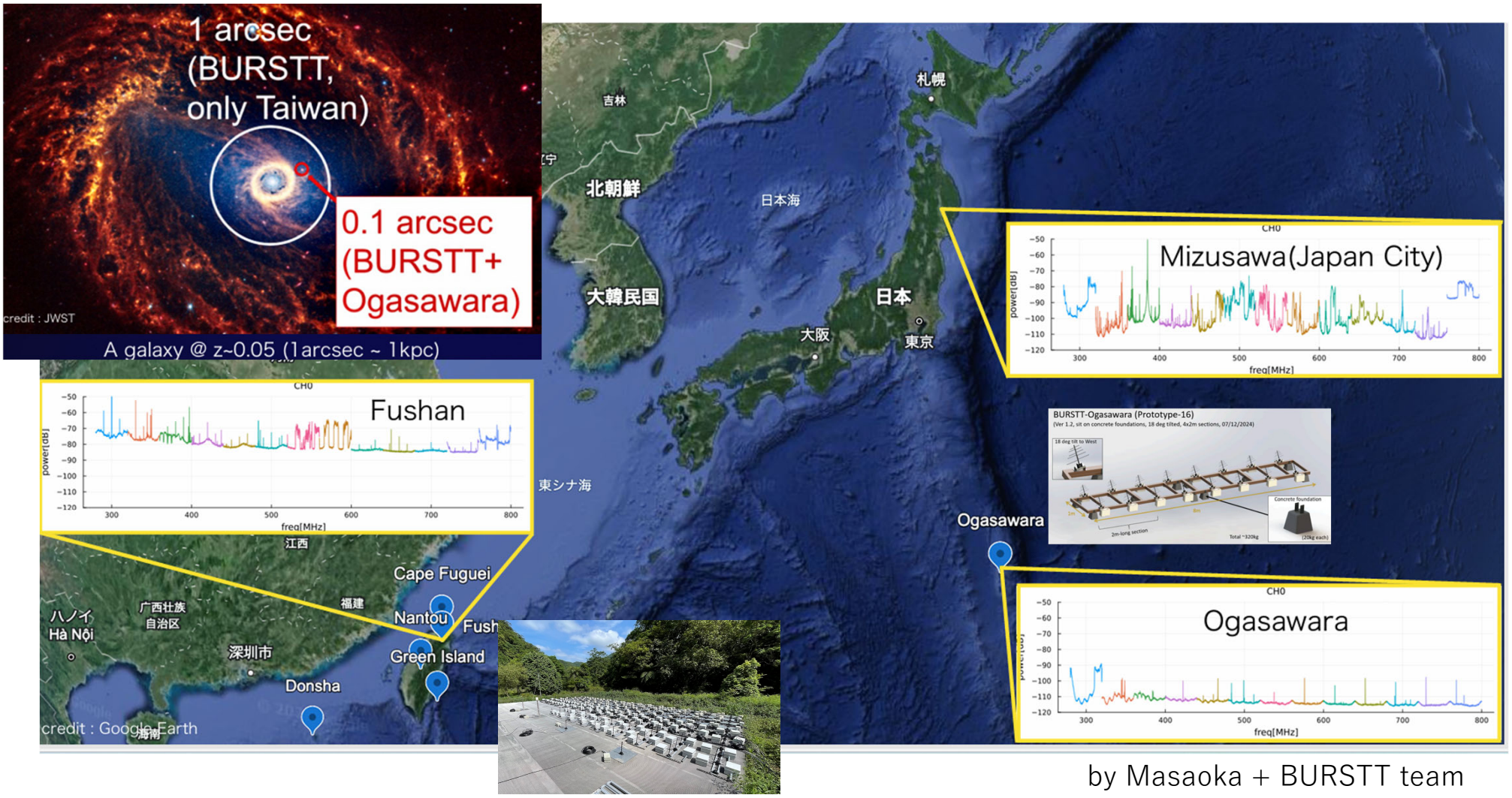
GMVA



BURSTT

FAST/CORE array

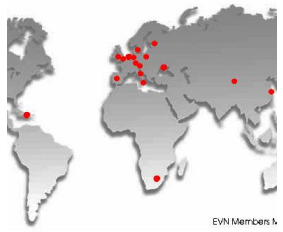
BURSTT: potential stations and RFI measurements



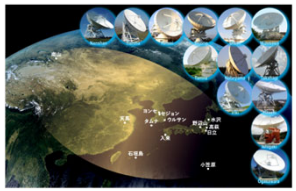
by Masaoka + BURSTT team

6. Originality and international competitiveness

VLBA



EVN

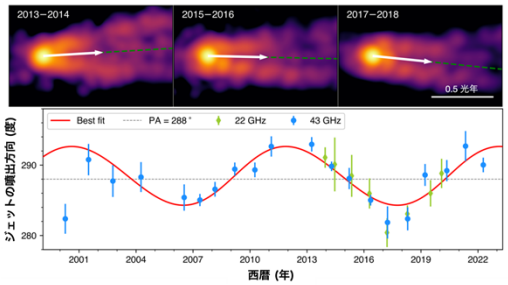


EAVN

- Comparison between other arrays

  EVN: more sensitive but not operation for full seasons

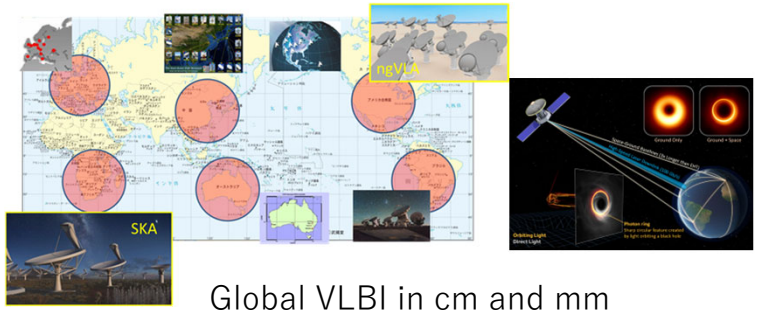
  VLBA: fully operational but EAVN has better sensitivities and better uv coverages.



M87 jet monitor is a good demonstration of power of EAVN

- Future global array: will be the only one on the Earth

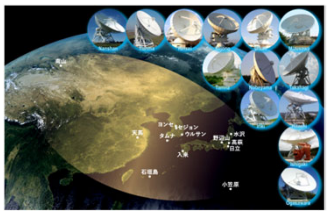
- No other instruments at any wavelength can provide angular resolution matching up with VLBI



Global VLBI in cm and mm

We judge that our proposal is best optimized in terms of science competitiveness as well as cost effect.

7. Current Status



EAVN array and its correlator, as well as EHT are all operational.

- Hardware: VERA array as well as EAVN correlator are already in operation

- Organization: Mizusawa VLBI observatory has been responsible for VERA operation for last 20 years

- International collaboration:

we have already realized EAVN as well as EHT, and have started producing science results.

Celebration of MoU at EAVN workshop and

With these achievements, we judge the proposed project is ready.

EHT collaboration

8. Cost assessments, budget line and status

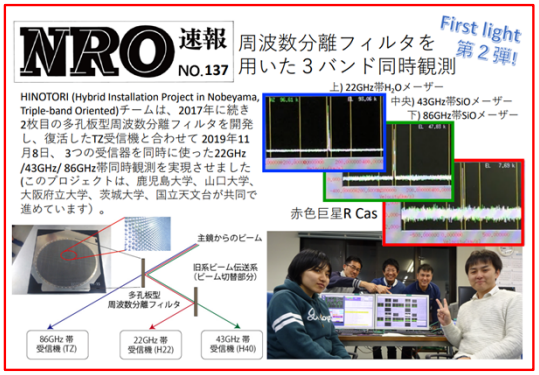
- **Operation cost: ~200 M JPY/yr （~2億円/年, from NAOJ）**

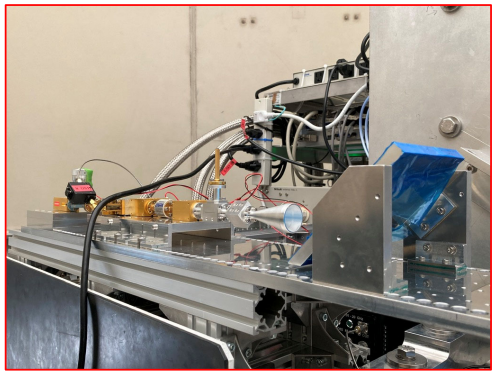
This is the cost to support station operation in Japan as well as EAVN correlator. It is based on the current running cost.

- **Cost for internal upgrading: 5-10 % of operation cost (from external funding)**

We expect to obtain external funding such as JSPS Grant (Kakenhi), other grants and private donation etc.

Tri-band receiving optics for NRO 45m, led by Imai, Niinuma et al.





86GHz RX for VERA Miz., led by Hada et al.

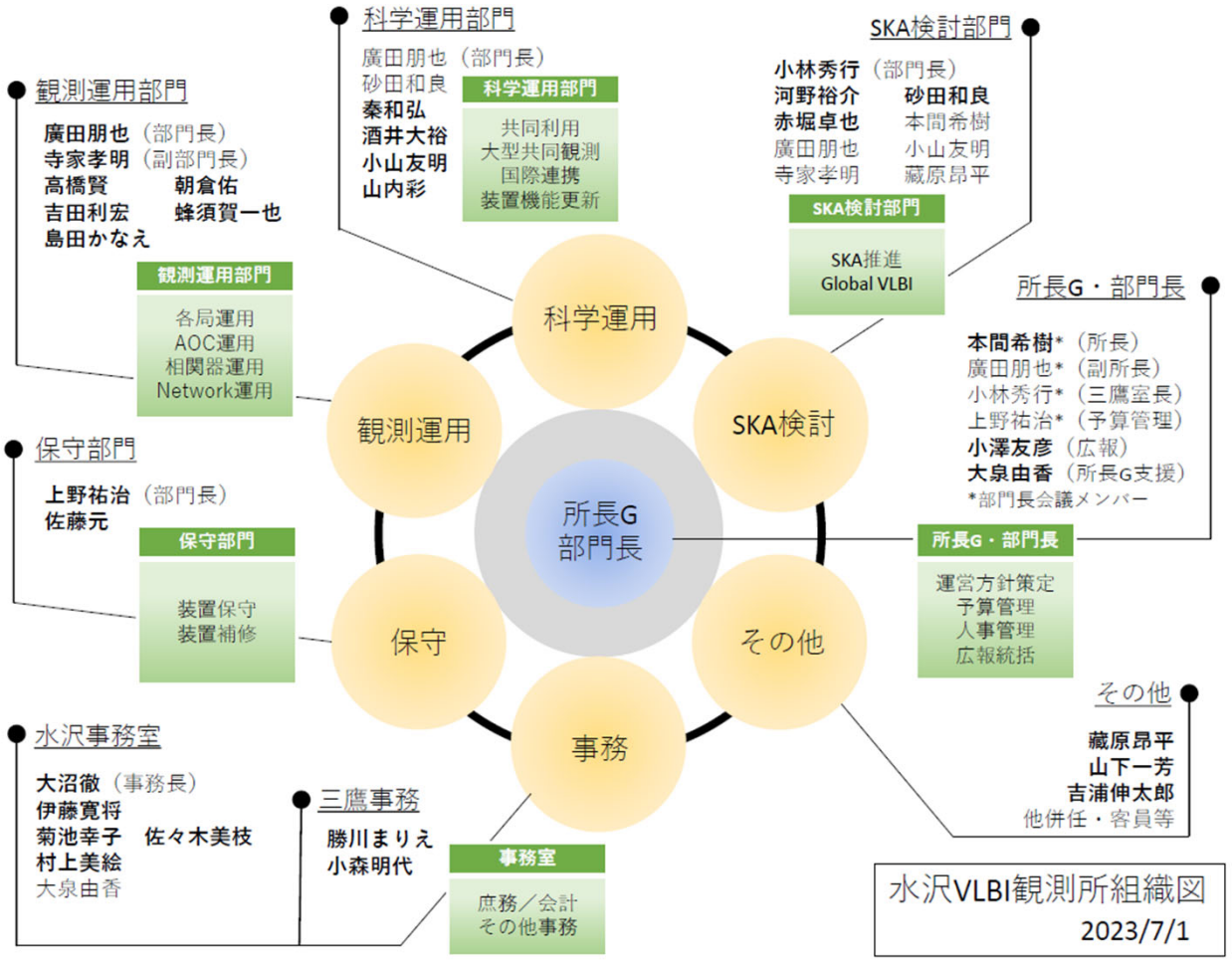
- Major array expansions (outside Japan) will be done in collaboration with external partners, and thus is most cost-effective approach to utilize global scale investment on radio astronomy.

9. Project Organization (1): internal structure

Current observatory consist of ~30 staffs (SKA is expected to be independent of Mizusawa when it becomes A-project.)

goals and tasks of each section are clearly defined

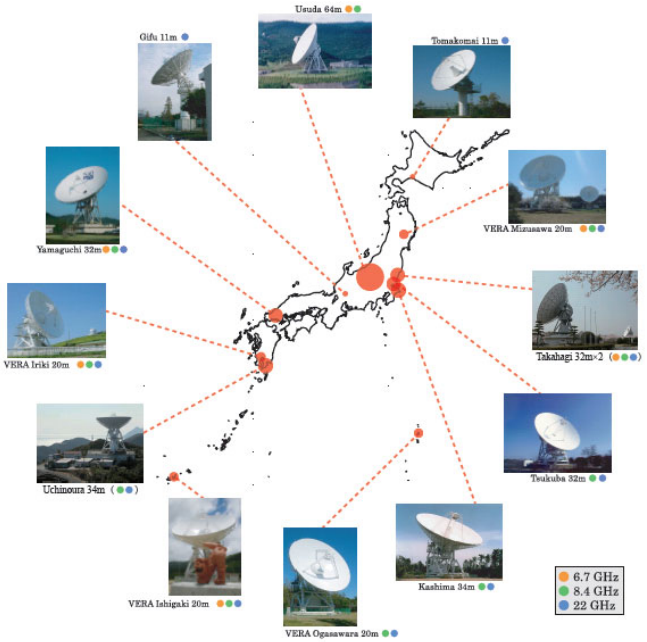
- Observational operation
- Science operation
- Maintenance
- SKA sub-project
- admin
- executive group



9. Project Organization (2): project partners

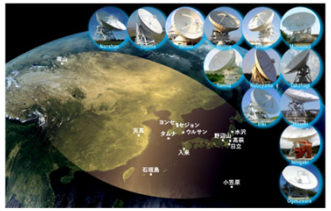
Domestic

NAOJ Mizusawa – U. Tokyo, SOKENDAI
JVN participating universities, Institutes
Japanese VLBI Consortium



International

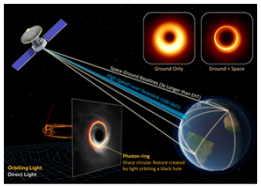
EAVN



EHT

global VLBI (long-wave)
with SKA

global VLBI (short-wave)
with BHEX



We have plenty of experience in collaborating with these domestic/international partners !

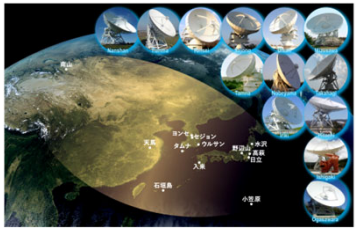
10. Why NAOJ?

- **Demand and support from community**
  Please keep in mind the existence of
  “Japanese VLBI consortium” (~150 people)

- **Project scale (budget, human resource etc.)**
  operation of VERA array requires
  regular support by an inter-university
  organization like NAOJ

- **Utilization of existing facilities/organization/ people**

Report of future plan
WG of VLBI consortium



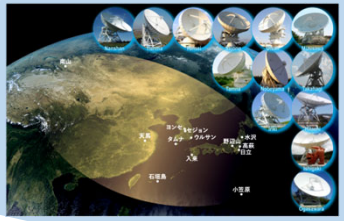
Summary of our future vision

current　　next mid-term　　2030's

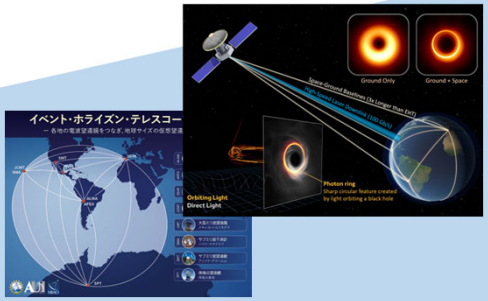
mm wave

cm wave

longer wave

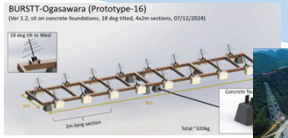


New station, new bands



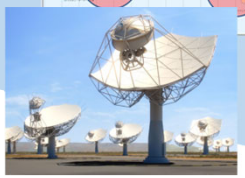
mm VLBI with space VLBI

EATING VLBI/ EVN+EAVN



FRB VLBI with BURST

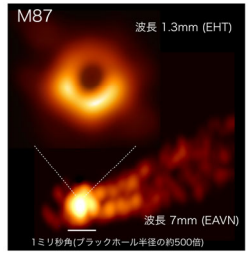
L-band VLBI with FAST



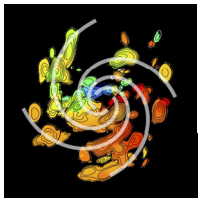
global VLBI with SKA (and ng-VLA in 2040!)

science targets

Black holes



Massive star formation



FRB/Pulsars/ Magnetars/

and more!!

community

VLBI

SKA

Radio astronomy

Multi-messenger