radio astronomy with ultra-high angular resolution using EAVN and beyond

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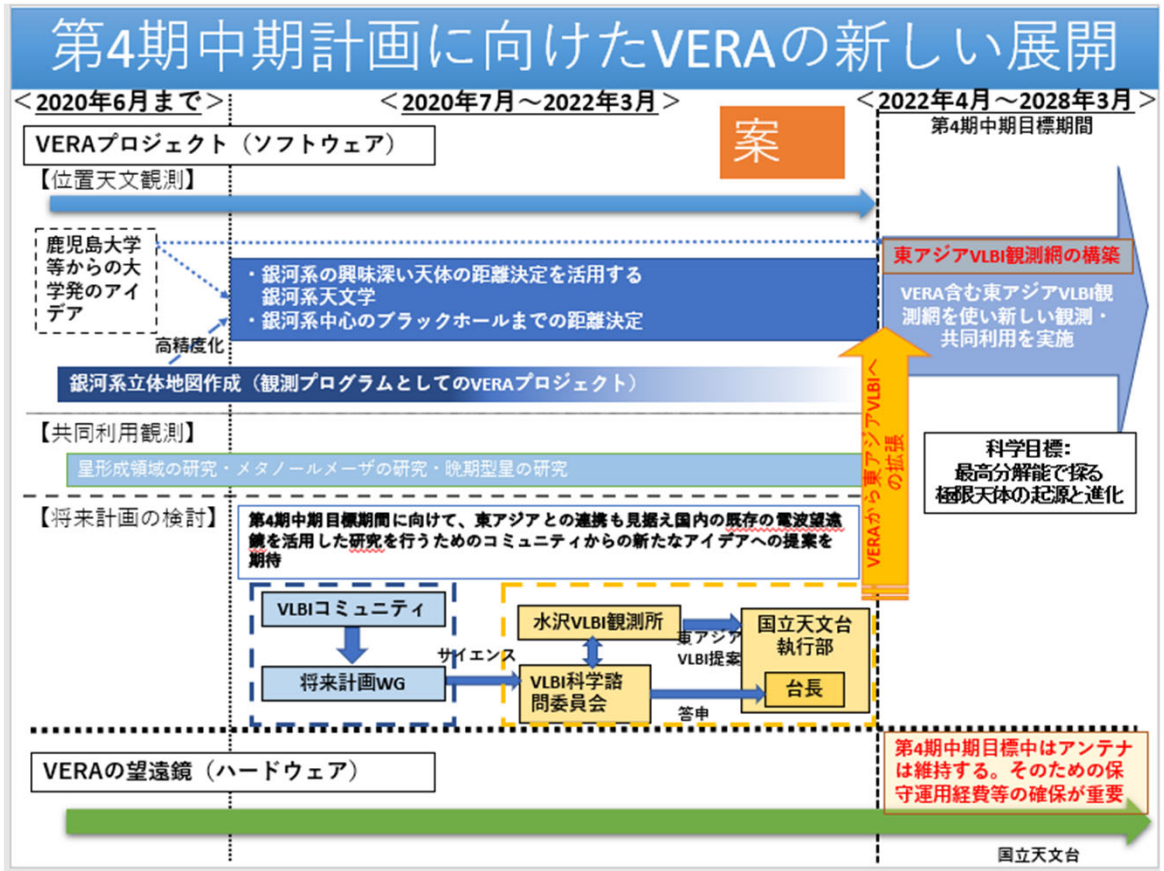
Background (1)：status in VLBI community

- VLBI consortium(VLBI懇談会) established its own future plan in 2021
- Detailed reported is completed in Jun 2021, published in the V-con web page.
- The report contains expectations/ requests to future operation of VLBI in Japan including Mizusawa VLBI Observatory.

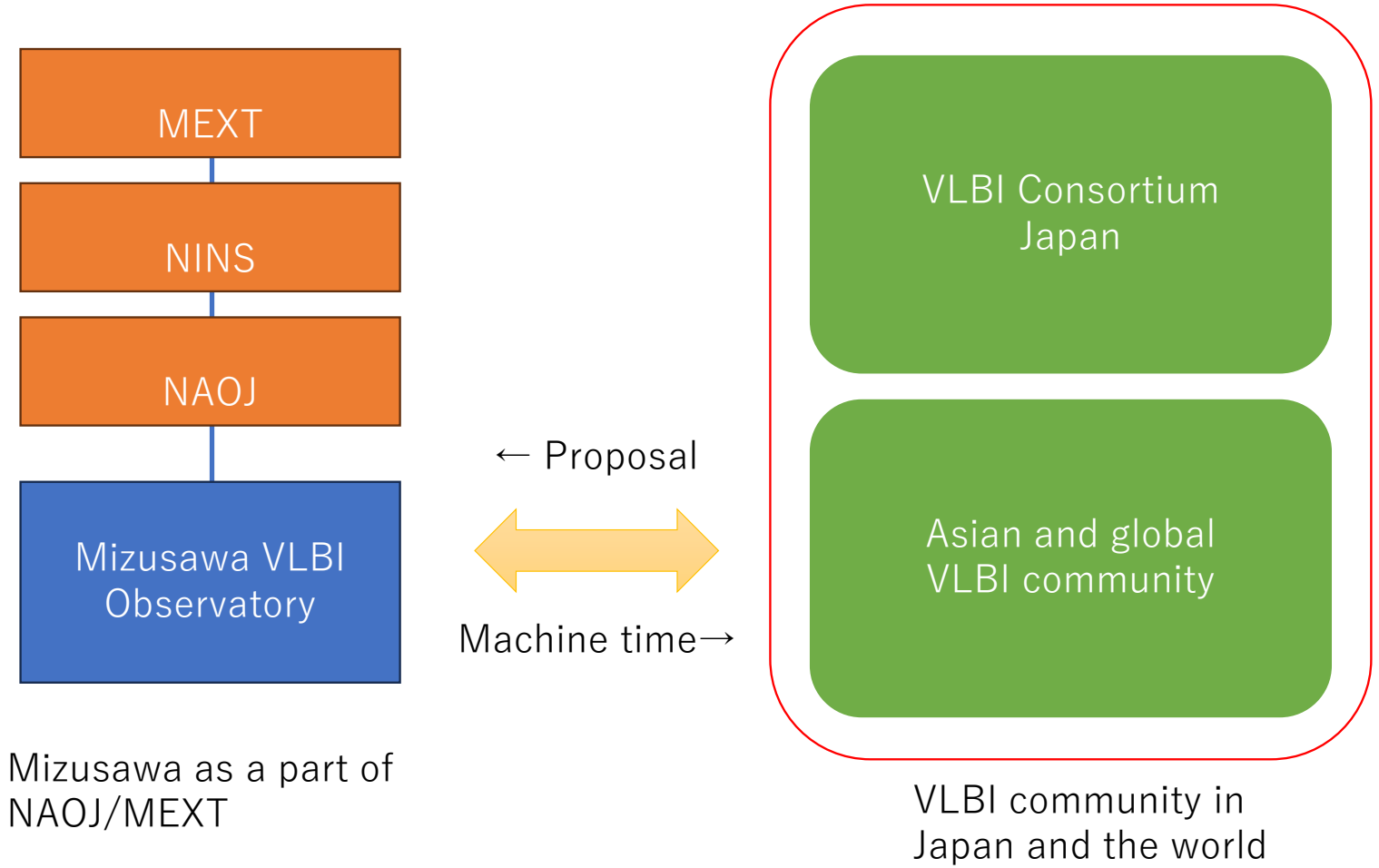
https://www2.nict.go.jp/sts/stmg/vcon/WG/FuturePlan2020/Report20210616/VLBI_FuturePlanWG_Report_v4.pdf

Background-(2)：MEXT and NAOJ

From 2022, NAOJ established a new operation plan of VERA, with its focus shifting from Galaxy astrometry as the stand-alone array to the international collaboration as EAVN.



Background structure chart



Mizusawa as a part of NAOJ/MEXT

VLBI community in Japan and the world

Science Objective

- The one-sentence Scientific Objective ：

“We aim to explore the origin, structure and evolution of the most extreme objects in the universe via ultra-high angular resolution provided by East Asian VLBI Network (EAVN) and beyond”.

EAVNを始めとするVLBIの高分解能で、極限天体の構造と進化に迫る

Figure 1. Schematic view graph of the science targets and relations compiled by Future Planning WG

Main facilities

- EAVN

  Japan: VERA＋JVN

  Korea: KVN+NIG

  China: CVN

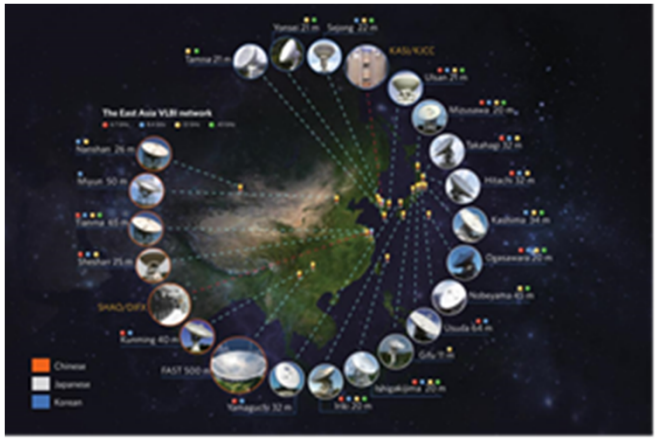
  Thai: NARIT

More new stations are on-horizon

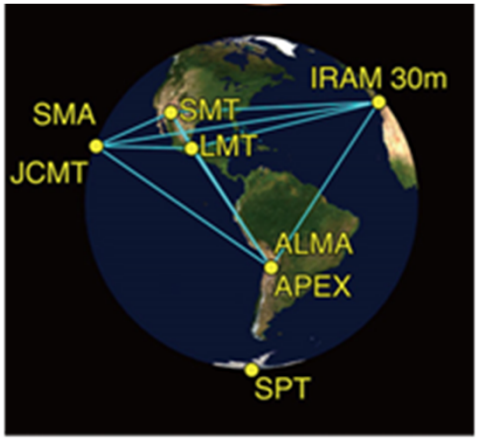
- EHT

operated by EHT collaboration, and Mizusawa will continue to contribute its operation, analysis etc, and serve as a contact point in Japan

＋ future global array (including SKA)



VERA/KaVA/EAVN and beyond



EHT

Arrays required for the proposed research. EAVN is the main array for conducting the research topics here. EHT, for which VLBI community in EA makes a significant contribution is also essential for AGN research, and combination of EAVN and EHT will be a uniqueness.

Scientific objectives

The primary scientific goals of the project are:

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.***

Science target (I): black holes

- 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 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)

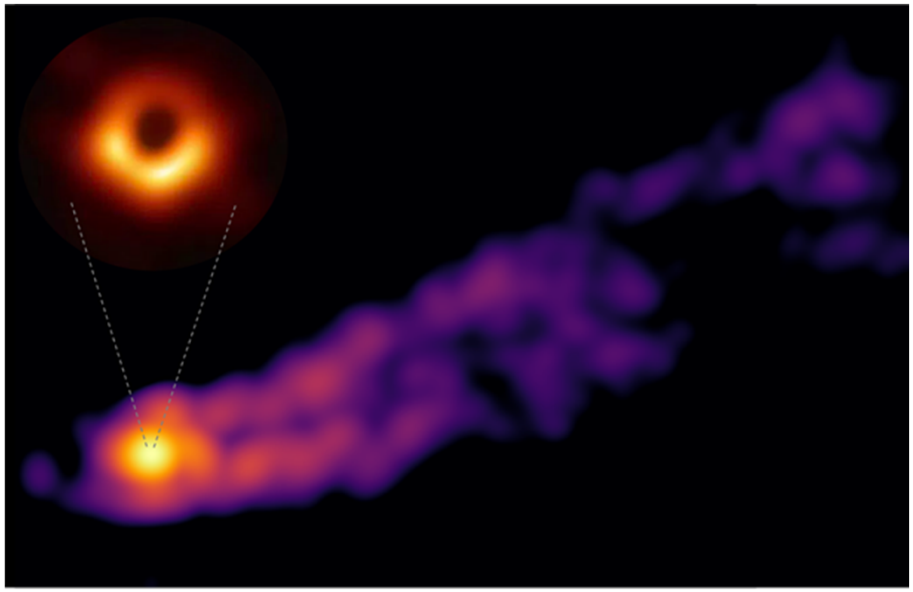
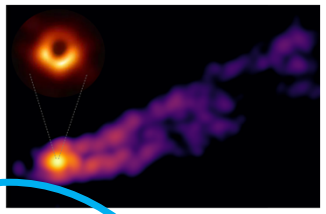


Figure 2: M87's super-massive black hole and its jet, observed with EHT (top-left) and EAVN (bottom)

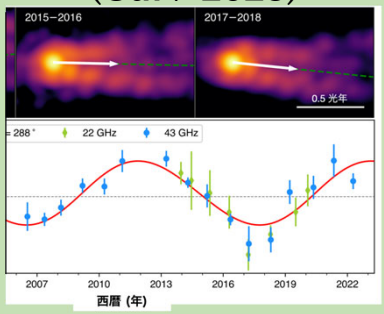
Current and future steps (in case M87)



Time domain →

← Still image

Jet precession, Existence of spin (Cui+ 2023)



Jet launch mechanism?

?

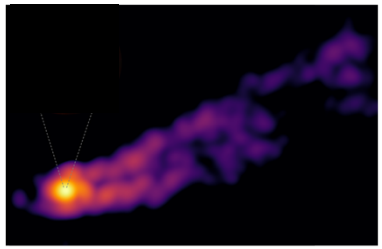
Gas motion near horizon, GR test?

?

Better test of GR and beyond?

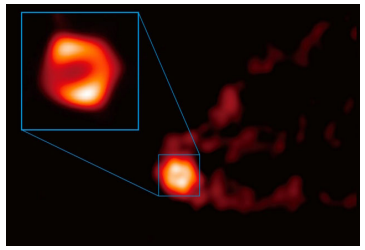
?

43 GHz



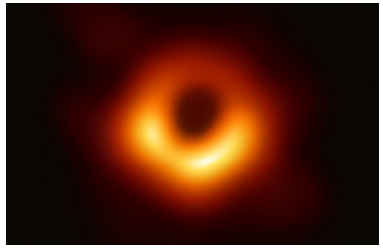
Existence of jet, Location of BH, etc.

86 GHz



Connection of BH, disk and jet (Lu+2023)

230 GHz



Detection of black hole shadow (2019)

345 GHz or space

?

Resolving photon rings Accurate space time?

← Lower resolution

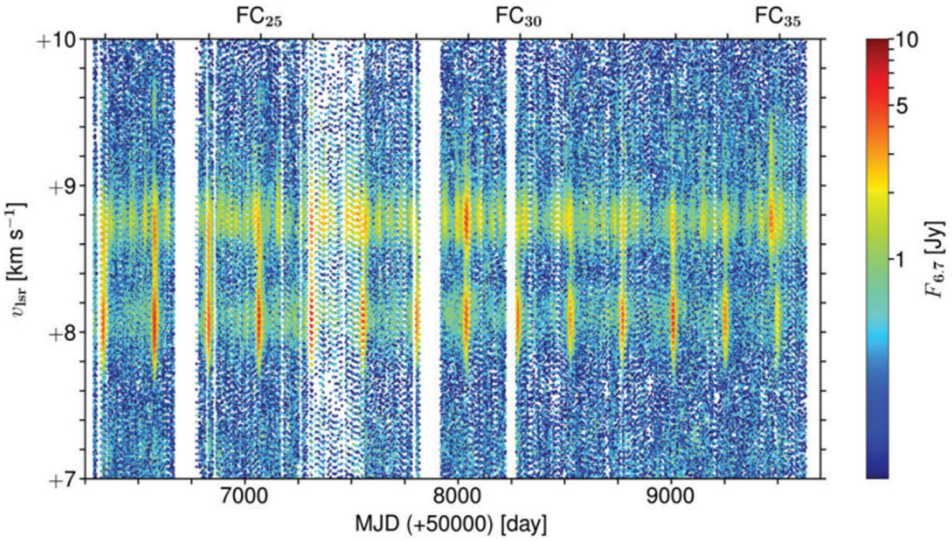
higher resolution →

Target for EHE, future space VLBI

2. Dynamic picture of massive star formation

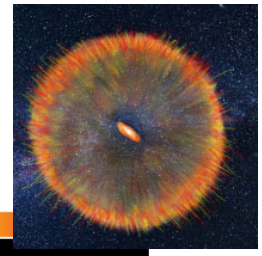
- Various types of maser time-variation has been detected via M2O program.

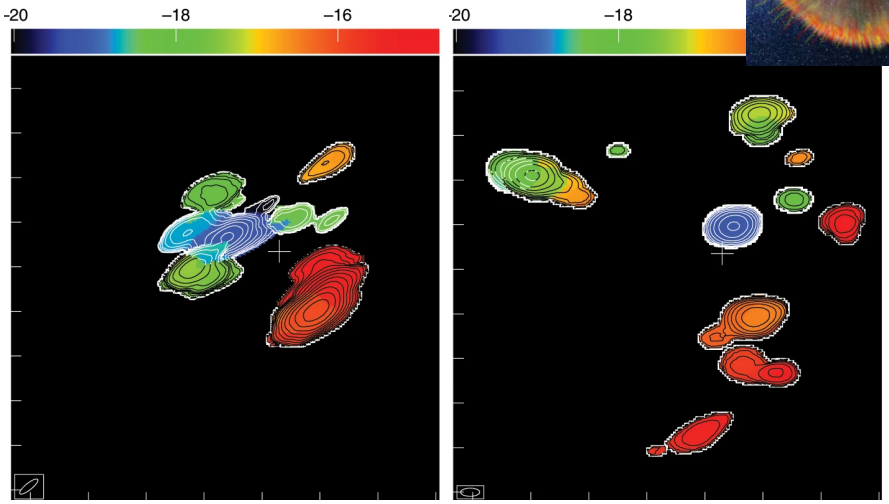
Double period methanol-maser flare (243 day & 52 day)



M2O collaboration (2022), based on Observations at Ibaraki

Rapid variation of CH3OH maser spots associated with maser burst

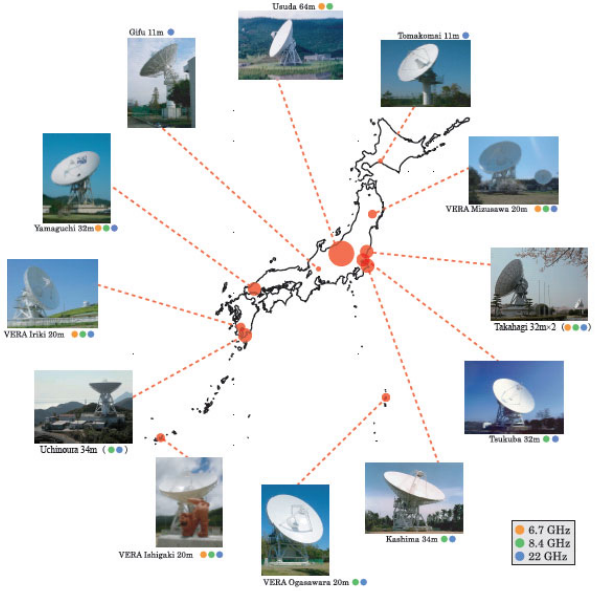




Burns+(2020) maser distribution variation during maser burst

3. New science targets

- Pulsar/Magnetar/FRB observations with VERA + JVN stations



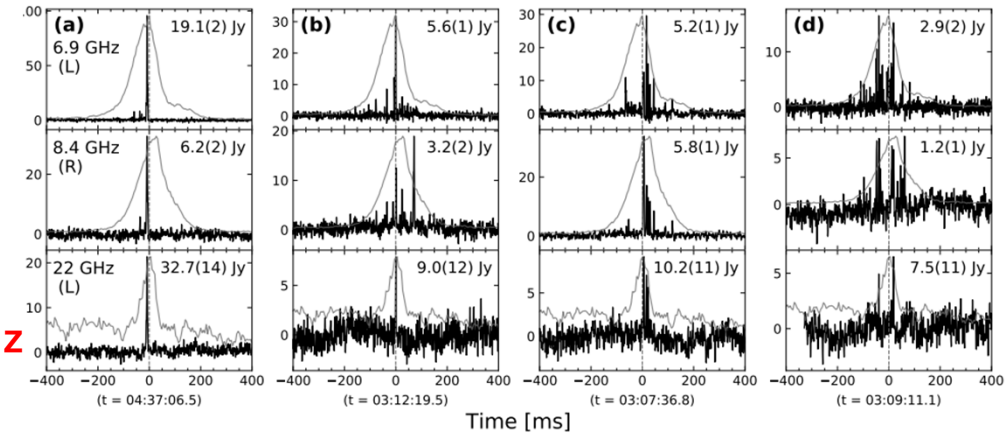
JVN

Burst detection of Magnetar XTE1810 (Eie+2021)

Ibaraki 6GHz

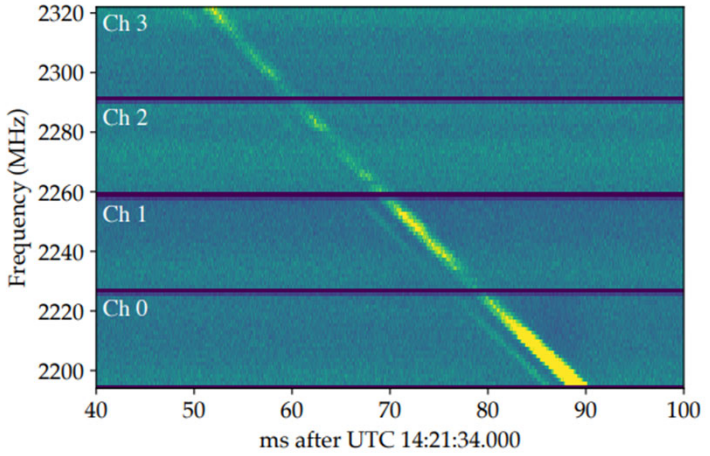
8 GHz

VERA 22 GHz



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

Usuda 2 GHz

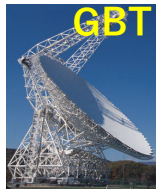


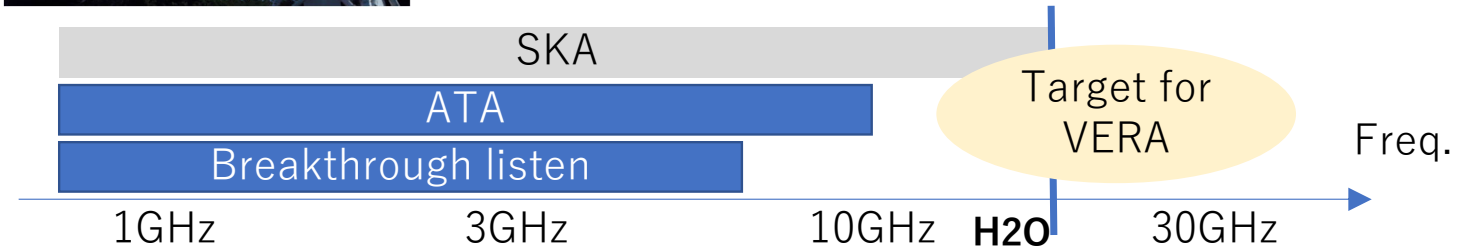
Key questions: what are they? Are they similar objects or not?

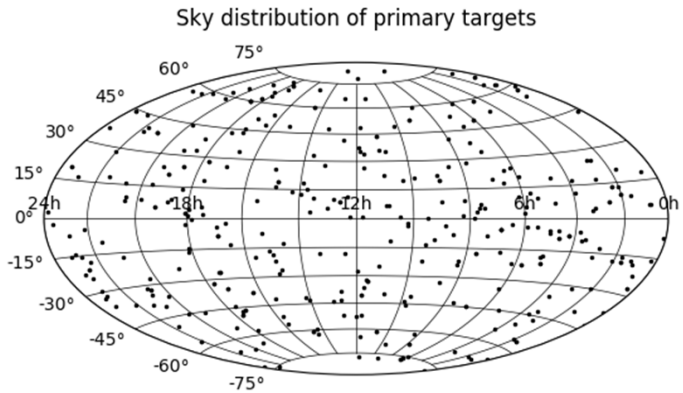
H2O band SETI with VERA

Uniqueness:

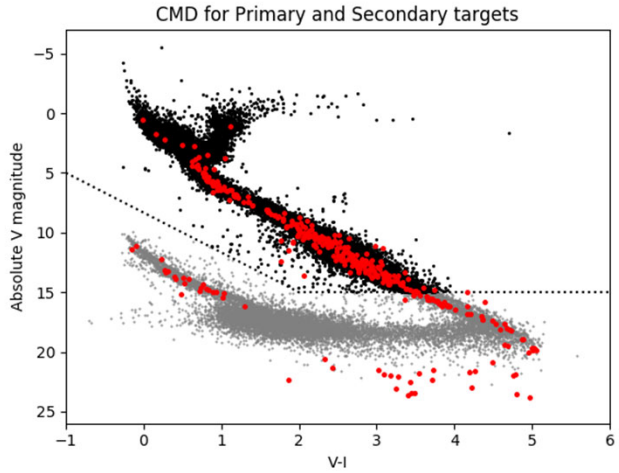
1) **Unexplored band**
2) **Potential SETI band due to link of H2O and life**
3) **Higher EIRP expectation compared to lower frequency (scaled as $\sim \nu^2$)**
4) **Large survey speed (4 sta. x 2 beam = 8)**
5) **Detection allows us immediate VLBI follow-up!**







Sky plot of 10-pc targets



Color magnitude plot of primary and secondary targets

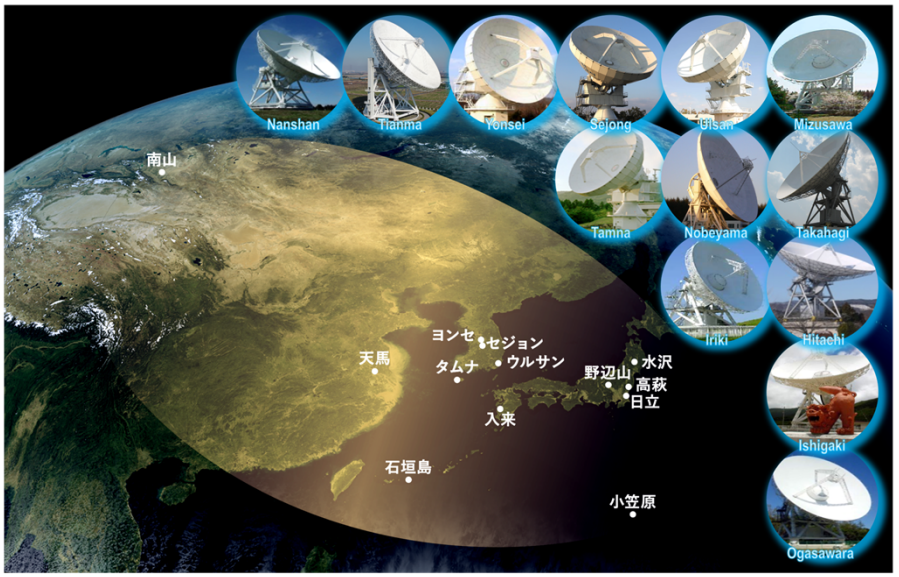
Main operation goal of the project

We will operate EAVN and provide machine time to community based on review process of science proposals, with possible extension.

We expect to provide 2000 hours at max. for open-use, depending of availability of international partner stations.

The main science activities will be conducted by user community.

Therefore, the minimum threshold is to keep open-use operation of EAVN with current-level or better capability.



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.

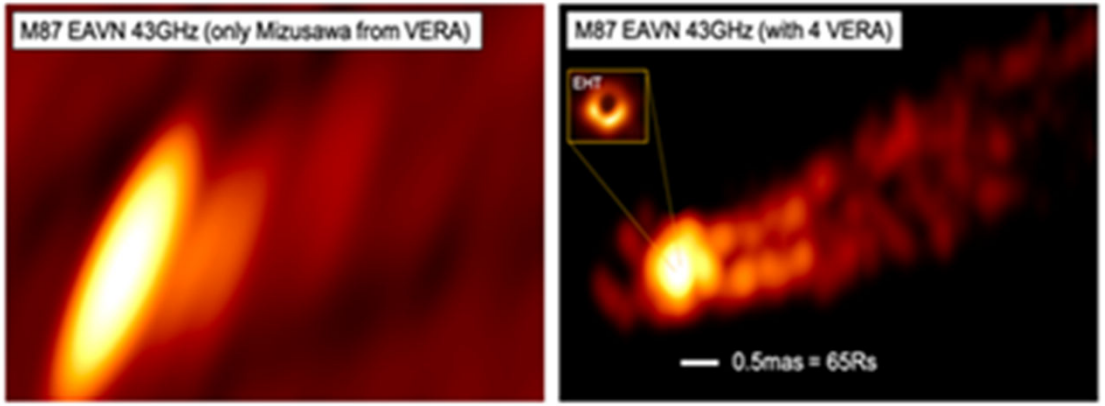


Figure 5: EAVN imaging capability (M87 jet) when only Mizusawa station participates from VERA (left) and full VERA stations participate (right)

Development/upgrade

On-going international development

- Internationally, there are huge amount of on-going efforts to extend EAVN capabilities in other countries, including constructions of new stations in China (FAST 500m, Qitai 120m, Yunnan 40m and others), Korea (new e-KVN 21m telescope operating up to 230 GHz), Thailand (TNRT 40m), Indonesia (discussion on-going on new radio telescope) and so on.

TNRT 40m

FAST 500m

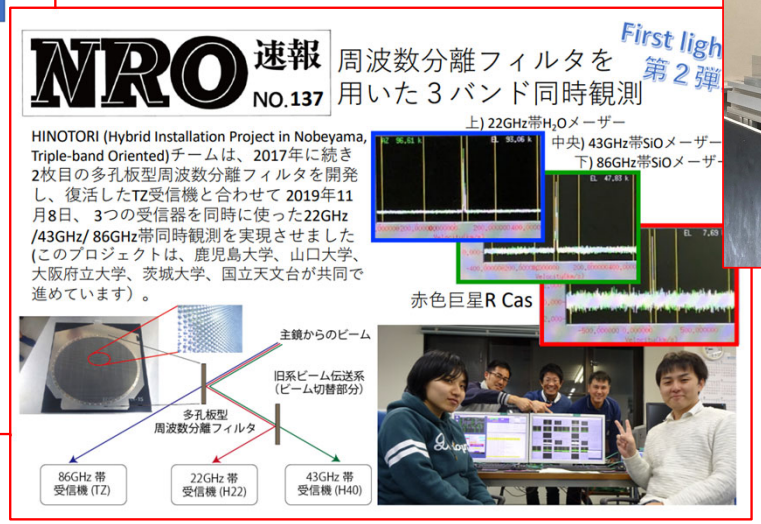
KVN new 21m

Recent and current upgrades in Japan

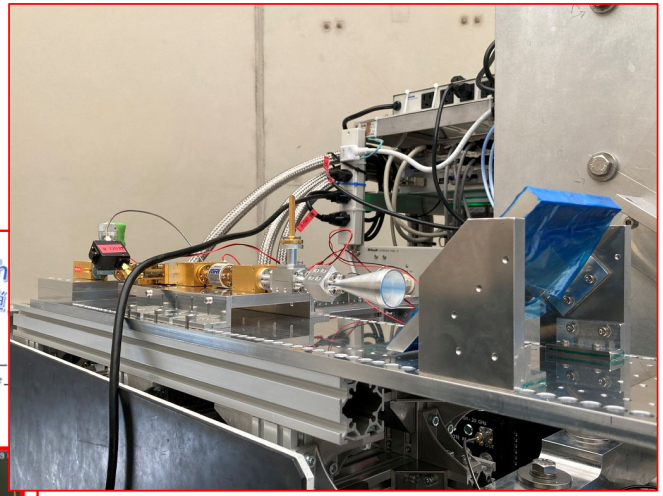
Basic directions: dual-pol, wide-band, multi-freq., coherently with international stations in EAVN.

All the costs are covered by the extra research fund.

Dual-pol. receiver for VERA Q-band, led by Hagiwara, Hada, et al.



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



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

Resources: budget

Cost estimated based the recent year operational budget

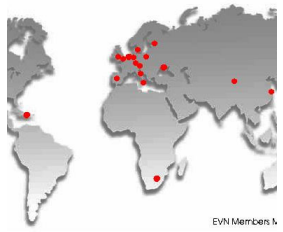
Item - year	2022	2023	2024	2025	2026	2027
Personnel (permanent staffs)	90,000	90,000	80,000	70,000	70,000	70,000
Personnel (contract staffs)	60,000	55,000	45,000	40,000	40,000	40,000
Operation cost	70,000	70,000	70,000	70,000	70,000	70,000
Maintenance cost	20,000	20,000	20,000	20,000	20,000	20,000
Mizusawa campus maintenance	20,000	20,000	20,000	20,000	20,000	20,000
EAVN correlator operation cost	10,000	10,000	10,000	10,000	10,000	10,000
Time keeping	18,000	18,000	18,000	18,000	18,000	18,000
total	288,000	283,000	263,000	248,000	248,000	248,000

Current estimate includes SKA staffs, and is subject to change depending on the status of SKA.

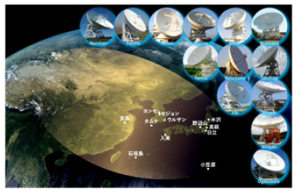
Extra-costs around a few MJPY may be needed for unpredicted trouble fix (~a few percent of annual budget).

Trade-off studies

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.

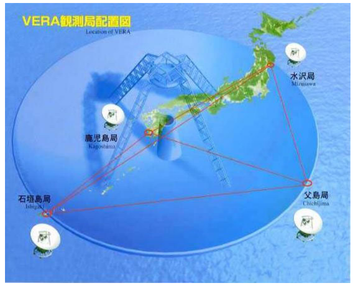
- Resource vs output

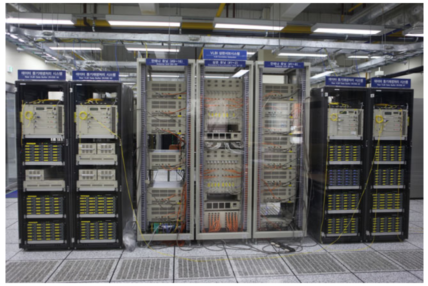
  our plan requests minimum level budget for VERA array operation.

  (needs to keep full array to maximize the array performance)

  Array expansions/upgrades will be done by resources brought by external fund (most cost-effective approach)

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





Readiness

- Hardware: VERA array and correlator are 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.

HKW#frooderudwlrq

Time line

水沢VLBI観測所中長期ロードマップ（2030年まで）

観測網	参加局等	2023	2024	2025	2026	2027	2028	2029	2030	期待される成果・インパクト
東アジアVLBI @ 22/43GHz+low	VERA+KVN+CVN	■	■	■	■	■	■	■	■	東アジアVLBIの運用による共同利用・新規望遠鏡追加による高感度化・画質向上・位置精度向上 AGNジェット変動や大質量星メーザーの降着バースト現象の観測とその起源及び進化の解明。重要天体の距離決定と物理パラメーターの精密化。
	TNRTの参加		▒	▒	▒	▒	▒	▒	▒	
	QTTの参加				▒	▒	▒	▒	▒	
	SKAを含むglobal VLBI							▒	▒	パルサー・マグネター・FRBなど観測対象の拡大と位置天文学観測によるそれらの起源や進化の研究
ミリ波VLBI @ 86GHz	KVN+NRO		▒	▒	▒					86GHz帯モニター観測の準備
	KVN+NRO+VERA				▒	▒	▒	▒	▒	86GHz帯M87ジェットモニターによるジェットの根本と降着円盤の関係／ジェットの絞り込み機構 いて座A*の変動機構の調査
EHT/ngEHT @ 230GHz	EHT	■	■	■	■	■	■	■	■	EHT運用および共同利用活用の支援 いて座A*およびM87の変動観測とその起源の解明
	ngEHT					▒	▒	▒	▒	いて座A*およびM87のブラックホール近傍構造の詳細な動画化
	ミリ波衛星(NASA/JAXA/ESA)？								▒	光子リングの精密検証と強重力場中の相対性理論の検証・スペースVLBIによる超分解能ブラックホール撮像

Comments on relation with SKA

- Currently SKA activity is done as Sub-project in Mizusawa
  (synergy in science, technology)

- If Japan will be SKA partner, then SKA project should get independent of Mizusawa as “A-project” of NAOJ.

- After the establishment of SKA A-project, Mizusawa will continue to collaborate with SKA, toward realization of global VLBI including SKA.

- Natural future collaboration will be development/evaluation of VLBI capability in SKA, though there are some more options.

SKA-VLBI synergies in engineering

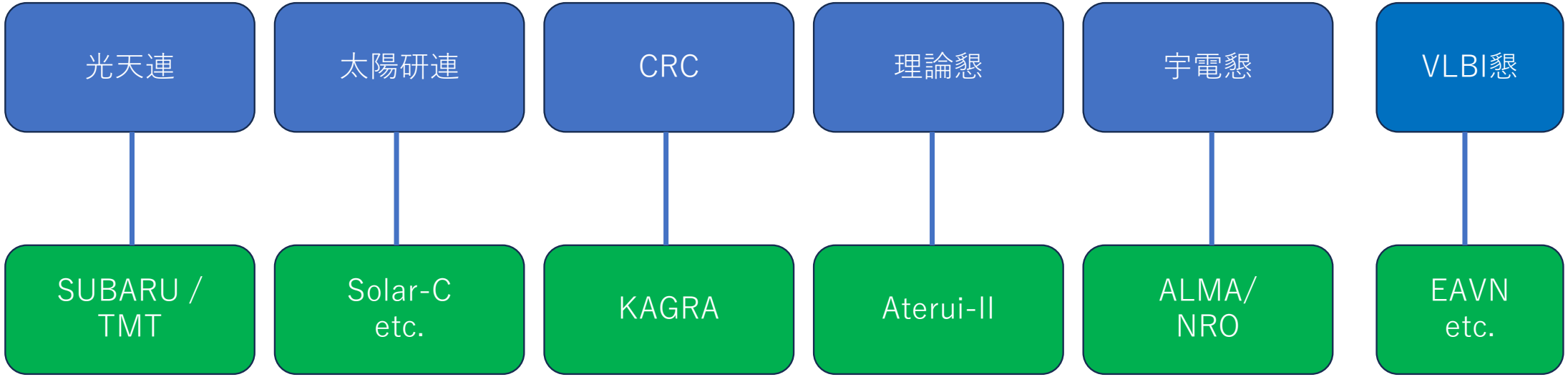
- **Goal: ultimate astrometric accuracy of 1 micro-arcsec!**
- **Requirements: minimize systematic errors**
  - Multi-beam VLBI system (3=Multiview, 25=LEAP)
  - Wideband imaging

- **Data Recording (800Gbps) is a challenge**
  - E.g, packet loss
  - SKAJ (MVO member) already started 200 Gbps recording test

SKA1-MID						
#sub-array	#VLBI beam	Bandwidth (per pol, MHz)	Digiti-zation	Sampling	Data rate (Gbps)	Buffer size (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	4	512	2	Nyquist	16	7
2	4	512	2	Nyquist	32	14
1	4	2500	2	Nyquist	78.12	34
1	16	512	2	Nyquist	64	28
1	52	200	2	Nyquist	81.25	35.7
10	52	200	2	Nyquist	812.5	357
SKA1-LOW						
#sub-array	#VLBI beam	Bandwidth (per pol, MHz)	Digiti-zation	Sampling	Data rate (Gbps)	Buffer size (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	16	256	2	Nyquist	32	14
1	16	256	8	Nyquist	128	56.3

Final message

Do not forget VLBI consortium!!



Providing research opportunities to diverse communities is critical for our future!