Past, present, and future of VERA

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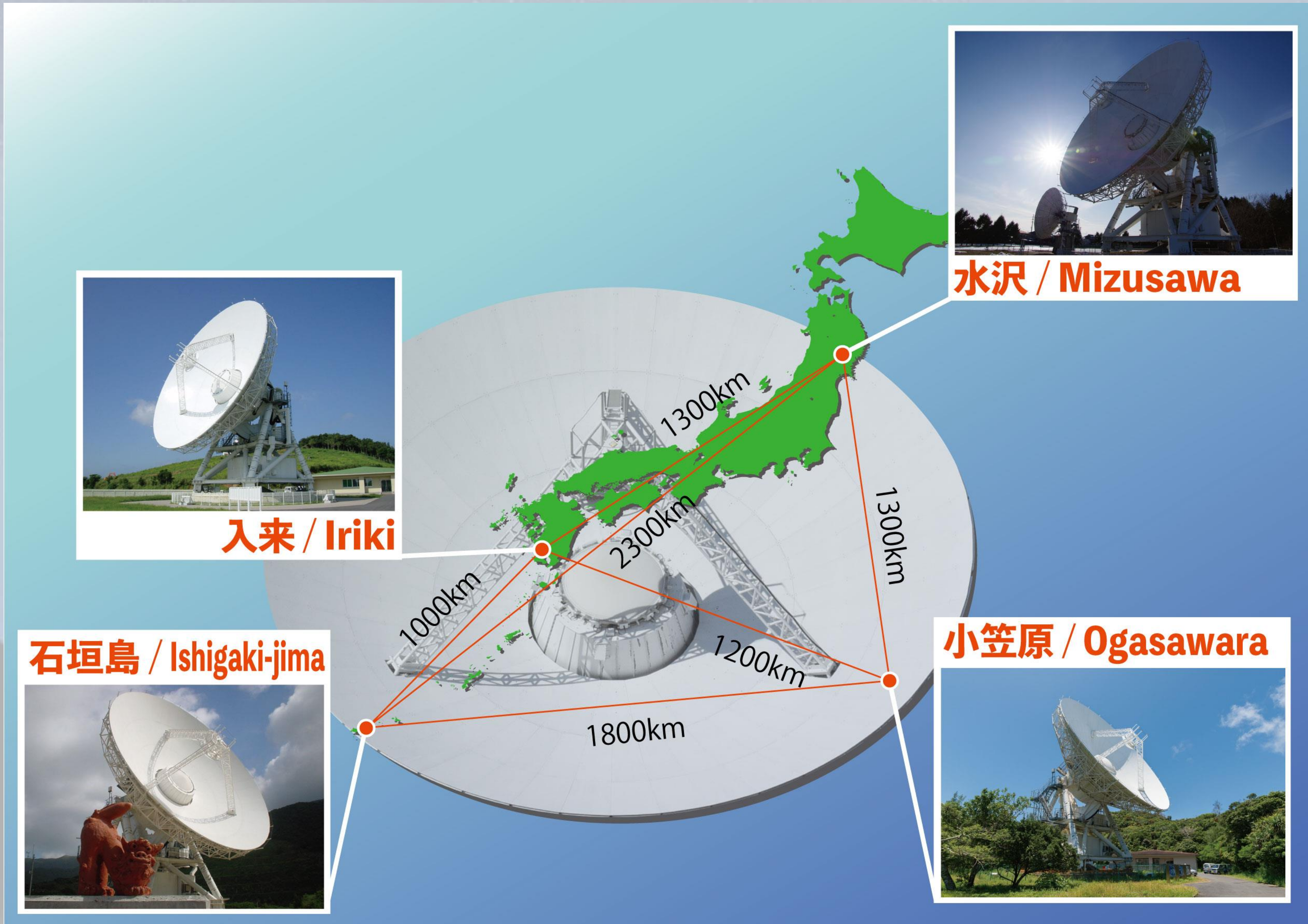
VERA: VLBI Exploration of Radio Astrometry



History of Mizusawa VLBI Observatory

1899 Established as International Latitude Observatory aimed to measure Earth Rotation

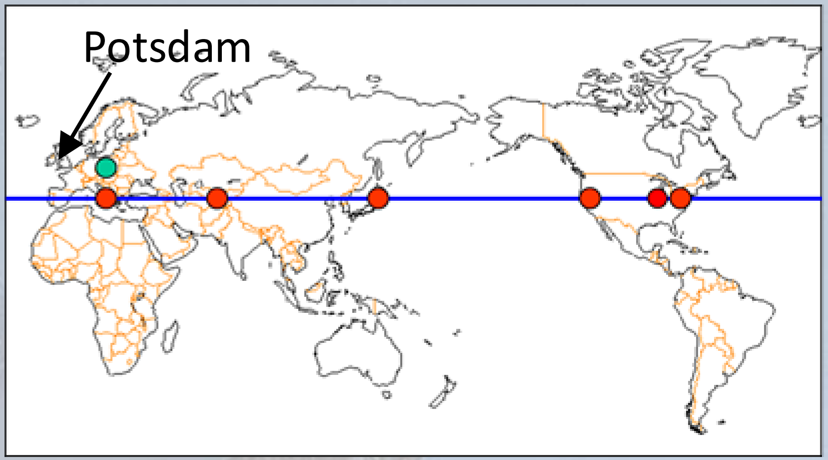
1988 Reorganized as NAOJ, together with Tokyo Astronomical Observatory of University of Tokyo, and a part of Solar Radio Research lab at Nagoya University

2002 Construction of VERA 4 stations

2007 First parallax results (Orion, S269)

2014 KaVA (KVN and VERA array) open use

2018 EAVN (East Asian VLBI Network) open use

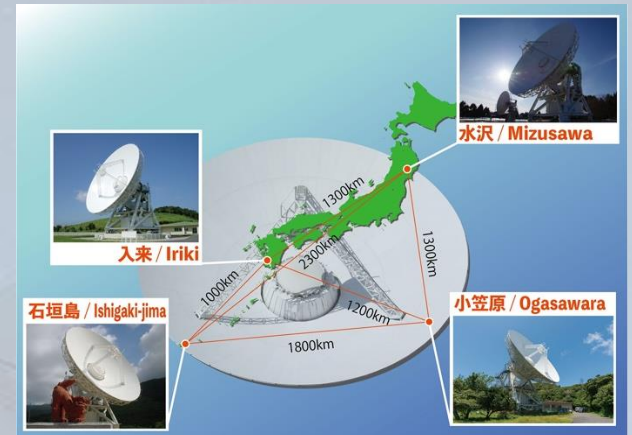


Location of ILO observatories along 39d08' N


Old observatory building of ILO in Mizusawa (since 1899)

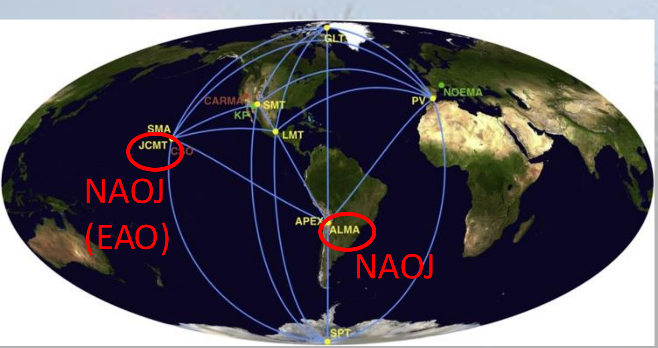
Current projects in Mizusawa VLBI Observatory

- **VERA: VLBI Exploration of Radio Astrometry**
- JVN: Japanese VLBI Network (collaboration with Japanese universities)
- KaVA: KVN and VERA Array
- EAVN: East Asian VLBI Network
- EHT: Event Horizon Telescope
- SKA: Square Kilometre Array (future) --- pathfinder!



VERA array configuration

VERA, JVN, , KaVA, and EAVN

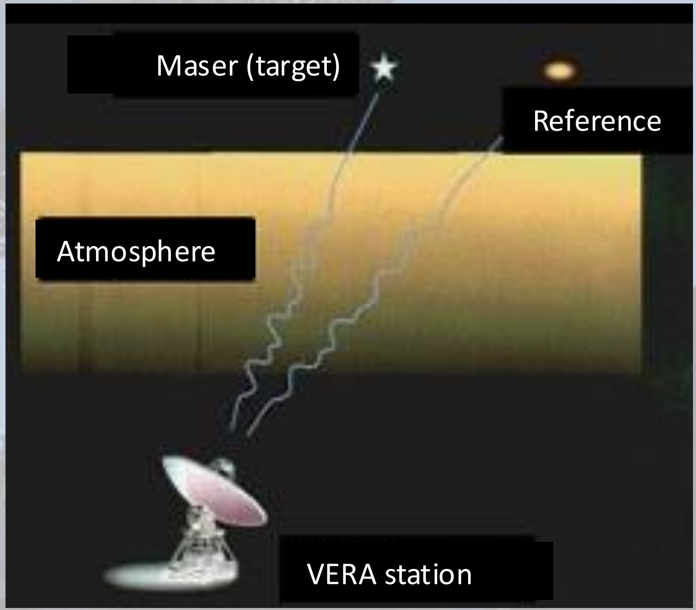


EHT
(EHT collaboration et al. 2019)

SKA (from SKAO website)

VERA observing modes

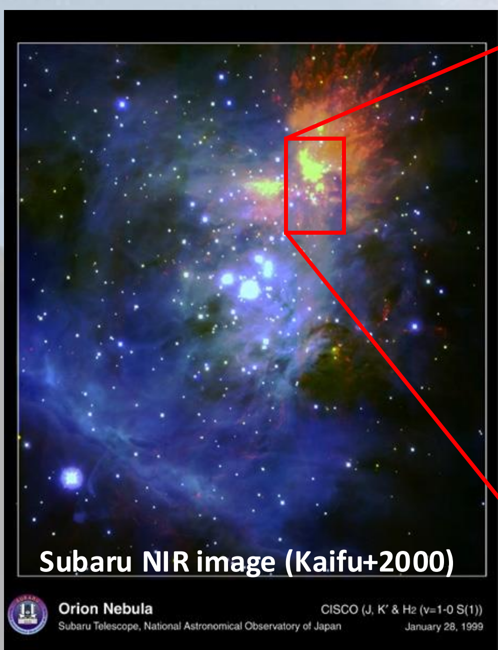
- **Dual-beam at K and Q bands for astrometry**
  - Single polarization
- Single-beam at C, K, and Q bands
  - Dual polarization at K and Q band
  - K/Q simultaneous observations
  - L and W under development
- 1 Gbps for conventional mode
- Wide-band modes (2, 4, 8, 12, 16 Gbps)



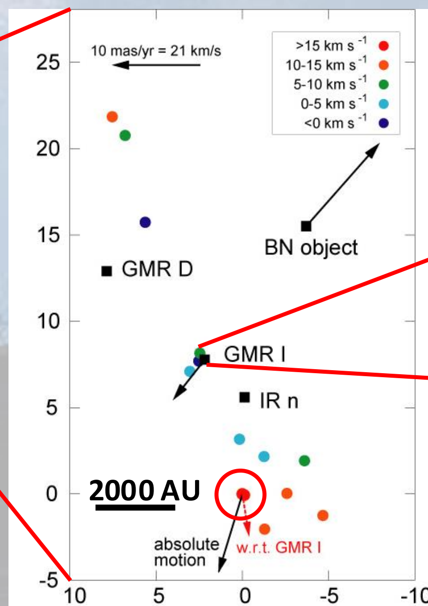
VERA dual-beam observation system and its concept to calibrate atmospheric phase fluctuation

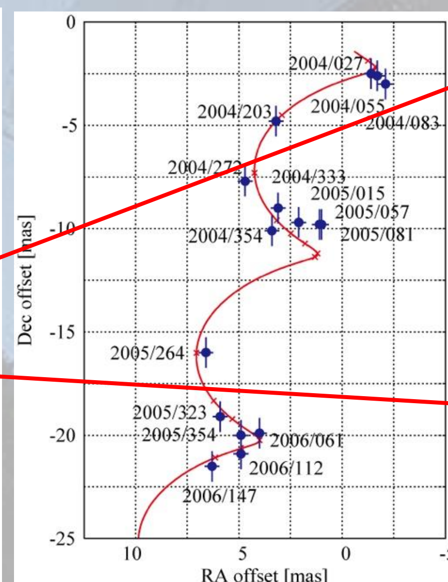
Main target of VERA

- **Galactic astrometry with masers to construct 3D map of Milky Way**
  - Accurate astrometry of 22 GHz H_2O and 43 GHz SiO maser sources
- Various VLBI target sources
  - (High-mass) star-formation, including 6.7 GHz CH_3OH masers
  - PL-relation of Mira variables (recall presentation by Nakagawa et al.)
  - AGN jets and black holes, non-thermal sources (pulsars, micro-quasars, etc.)

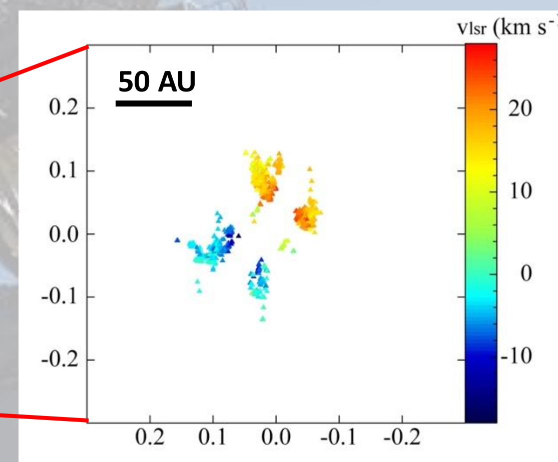


Subaru NIR image (Kaifu+2000)





22 GHz H_2O maser map with VERA (Hirota+2007)

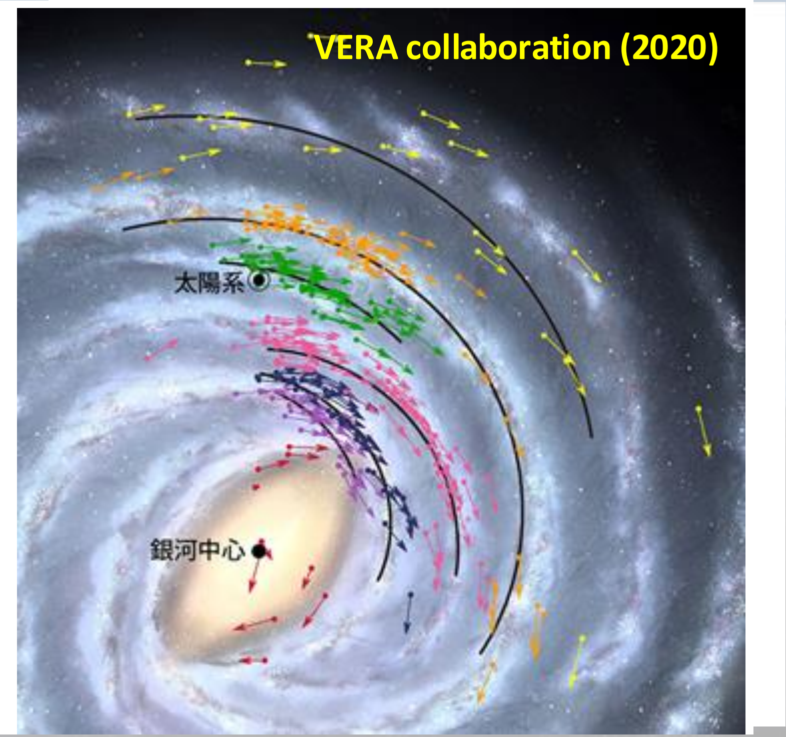


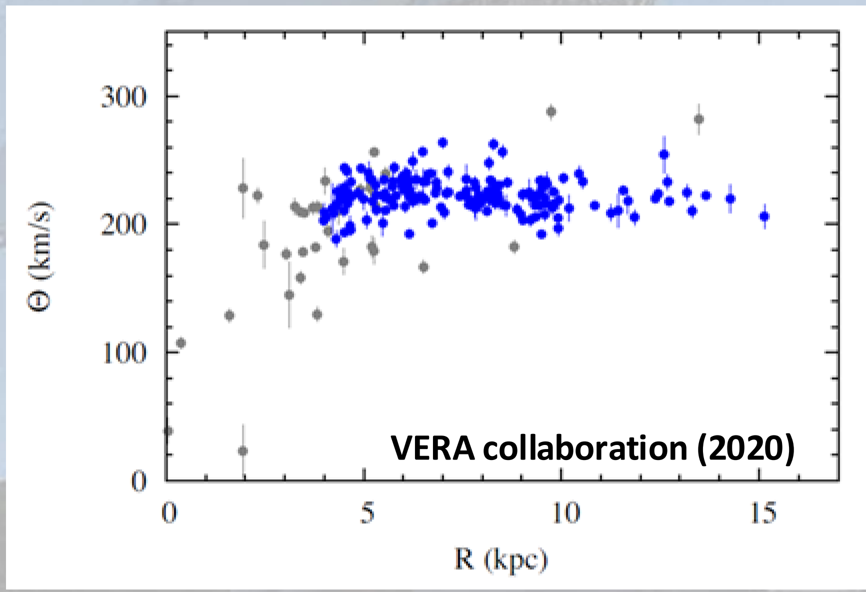
43 GHz SiO maser map with VERA (Kim+2008)

History of VLBI Galactic astrometry

- Combined with VLBA (Bessel) and EVN projects

	Reid+(2009)	Honma+(2012)	Reid+(2014)	Reid+(2019)	VERA+(2020)
N_src	18	52	103	200	224 (99 from VERA)
R0 (kpc)	8.4 (+/- 0.6)	8.05 (+/- 0.45)	8.34 (+/- 0.16)	8.15 (+/- 0.15)	7.92 (+/- 0.16)
Θ0 (km/s)	247 (+/- 16)	238 (+/- 14)	240 (+/- 8)	236 (+/-7)	227 (+-/-8)





Flat rotation curve for R>5 kpc, larger peculiar motions at R<5 kpc, probably due to the Galactic bar

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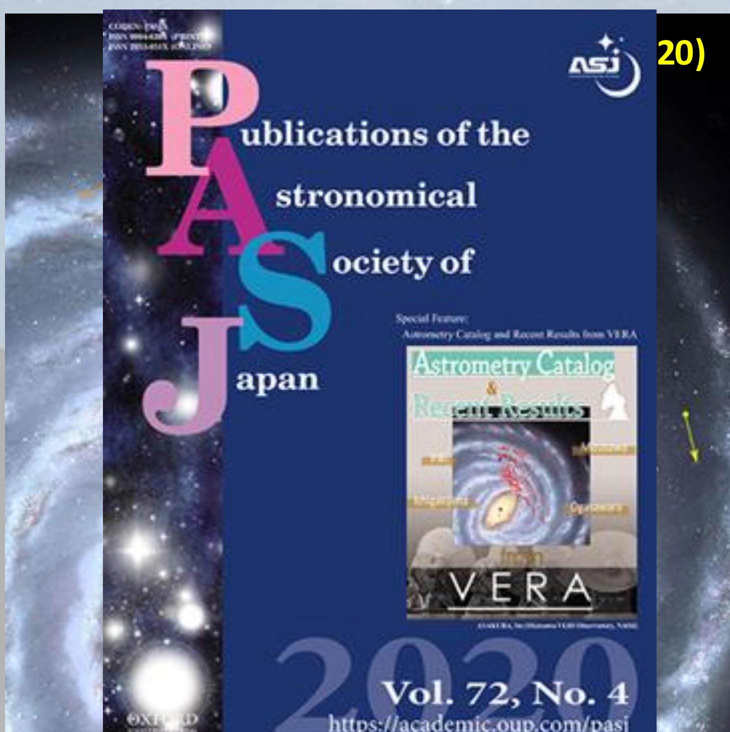


Sgr A* distance from GC stellar motions

- 8.178 ± 0.013 ± 0.022 kpc (Gravity Collab. 2019)
- 7.946 ± 0.050 ± 0.032 kpc (Do et al. 2019)
- 8.275 ± 0.009 ± 0.033 kpc (Gravity Collab. 2021)

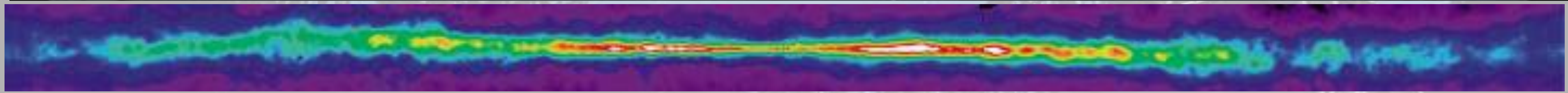
Published in PASJ VERA special issue (2020)

- Catalog of 99 parallax measurements with VERA
- Other special issues in 2008, 2011, and 2014

VERA Galactic astrometry

- Comparison with optical astrometry
  - Less affected by extinction at radio wavelengths (VLBI)
  - Less targets at radio wavelengths (only non-thermal continuum and masers)
  - **Complementary with each others in several aspects, including targets, regions, and methodology (recall presentations by Nakagawa et al., Dzib et al., Plavin et al.)**

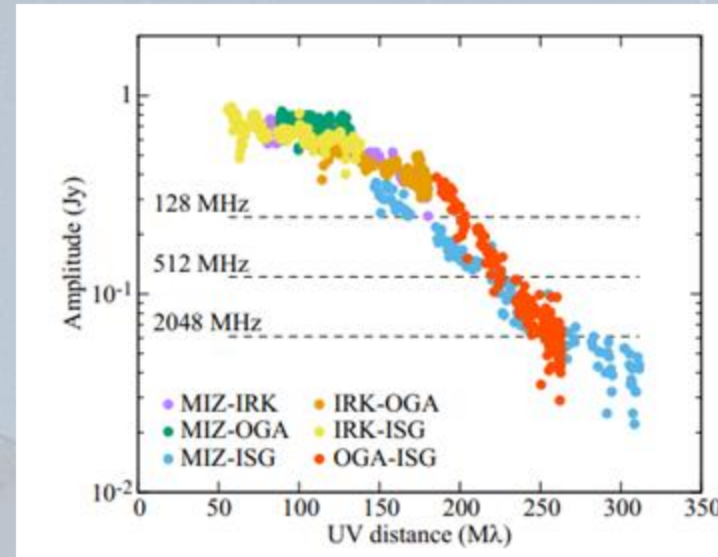
Optical view by GAIA (ESA website)



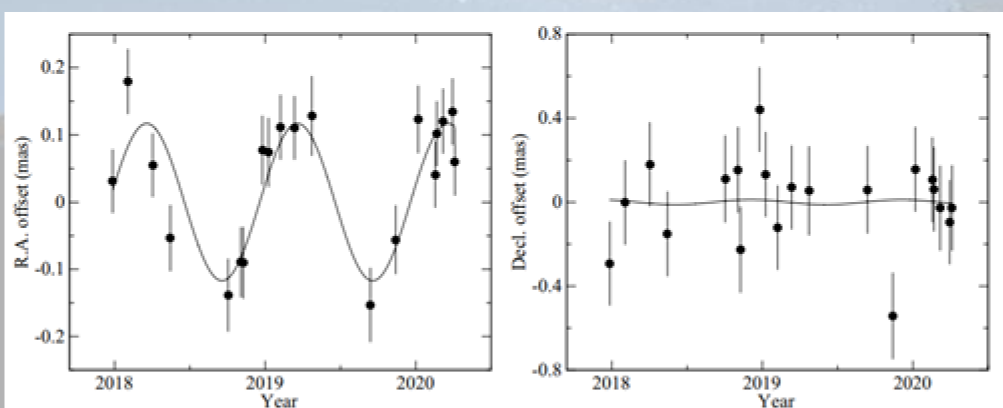
Radio view with HI line (NASA website)

VERA astrometry of Sgr A*

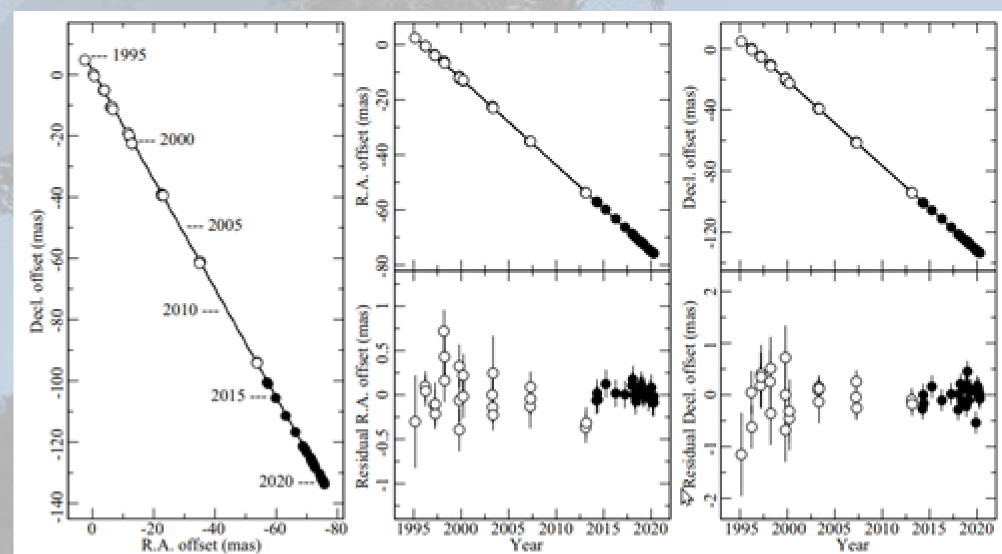
- **Direct measurements of parallax and proper motions (Oyama et al. 2024)**
  - High-sensitivity broadband observation (16 Gbps) makes long-baseline data valid
  - High SNR and long-term monitoring by combining VLBA results (Reid & Brunthaler 2020); ΔΘ~0.2 mas
  - π= 117 ± 17 μas ($8.5^{+1.7}_{-1.1}$ kpc)



Visibility amplitude as a function of uv distance with VERA (Oyama et al. 2024)



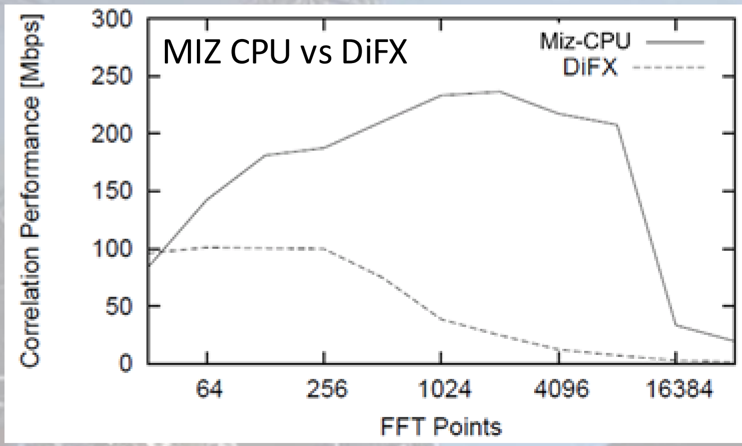
Parallax in RA (left) and Decl (right) (Oyama et al. 2024)

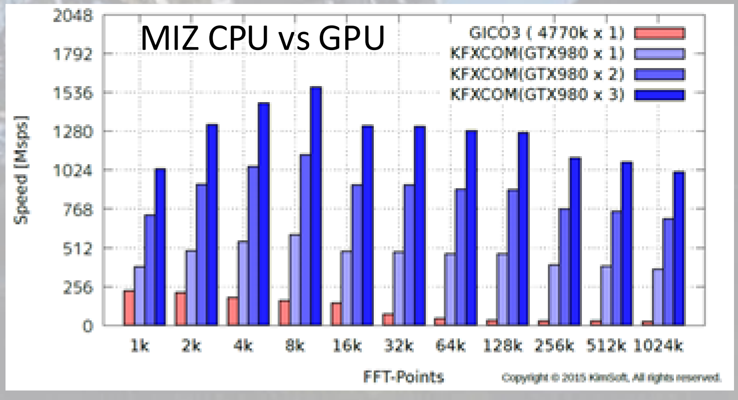


Proper motions in sky plane (left), RA (middle) and Decl (right) (Oyama et al. 2024)

Developments of VLBI instruments (OCTAVE-DAS)

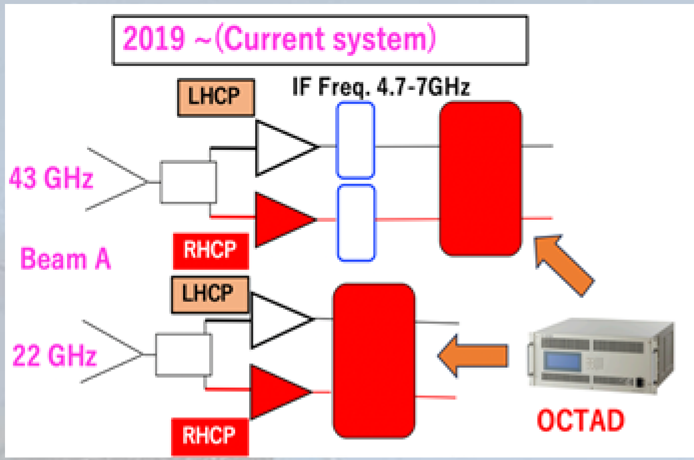
- **Wide-band recording system and digital backends (OCTAD)**
  - Input: 4 ch, 0-26 GHz
  - DBBC: 2-32 ch, 8-4096 MHz
  - Output: 32 Gbps (max)
  - Recording rate: 16 Gbps
- **CPU/GPU software correlators**
  - Mizusawa correlation center since 2015
  - About 30 servers for CPU/GPU
  - 8 Playback systems (OCTADISK1/2) and Raid boxes
  - In-house and out-sourced development:
    GICO3 (CPU) or KFXCOM(GPU) + Softcos
  - GPU correlation under commissioning:
    about 8-times faster than CPU correlator



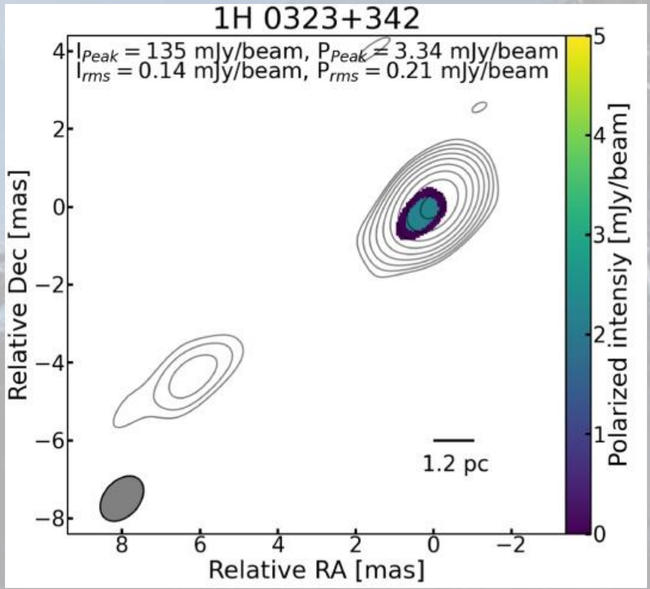


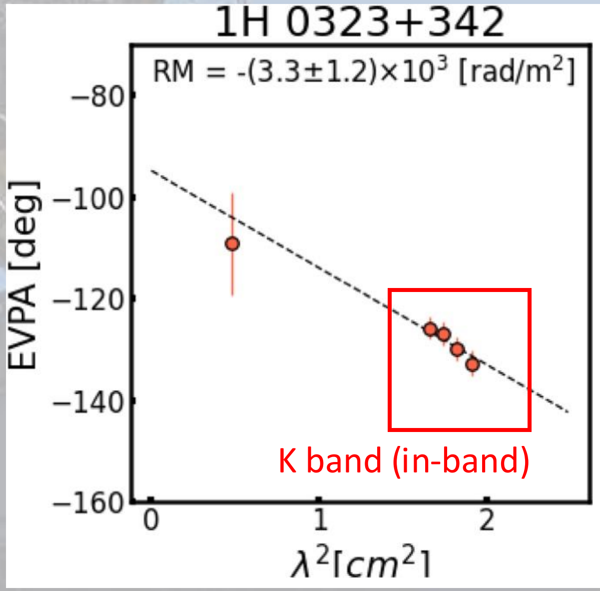
Developments of VLBI instruments

- **Wide-band polarimetry system at K and Q bands**
  - 2GHz bandwidths for each polarization
  - In-band Faraday rotation measurements enables to solve ambiguity of band-to-band measurements



- **New frequency bands**
  - W band (86 GHz)
  - Wide-band C/X/Ku band (6-18 GHz)
  - L band
- **SKA VLBI backend**
  - Targeting 200 Gbps for each server

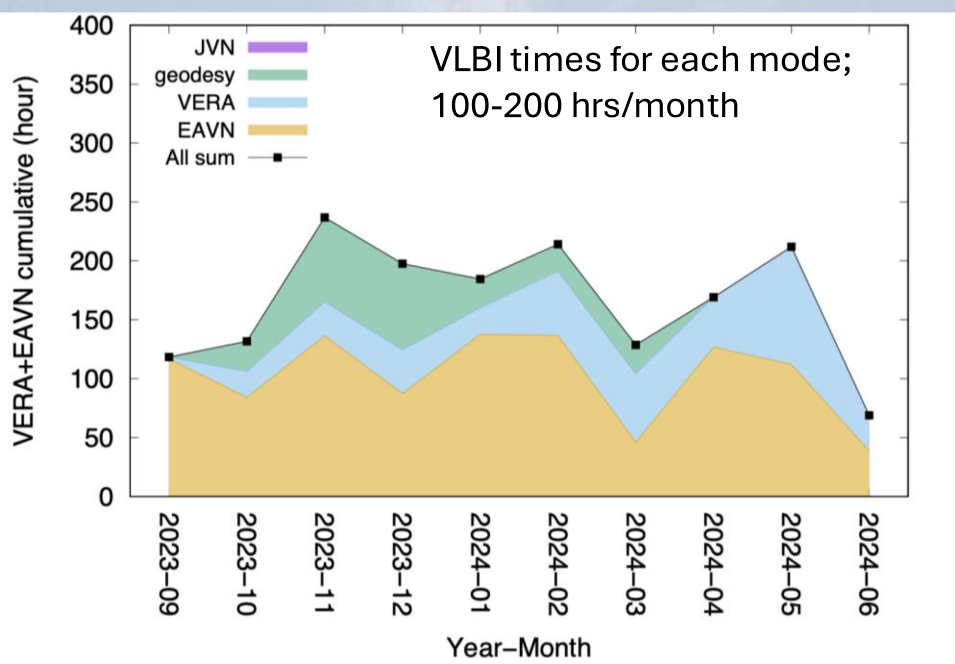


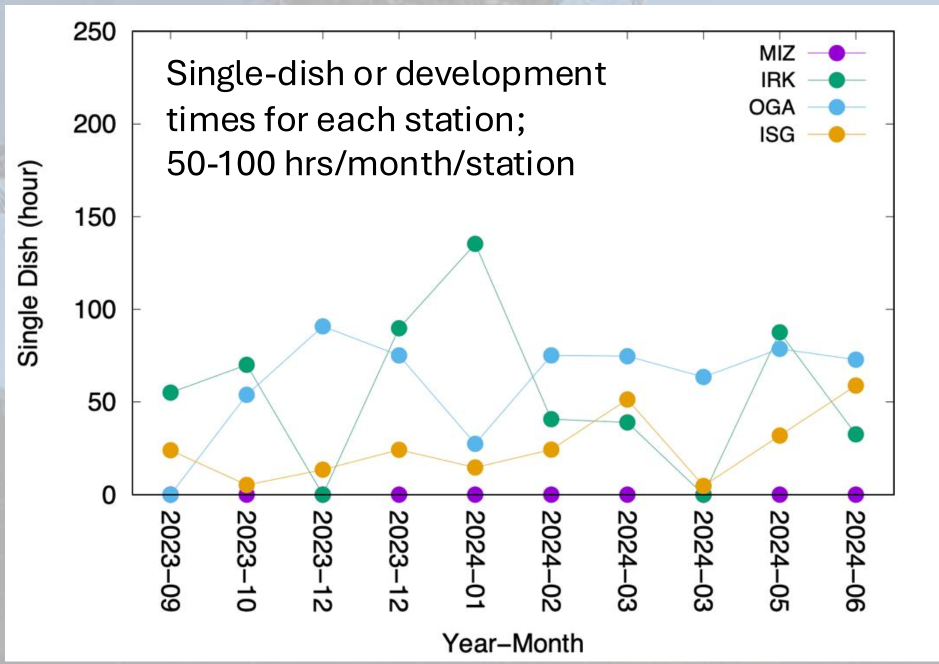


In-band and band-to-band Faraday rotation measurements (Takamura et al. 20123)

Current operation mode

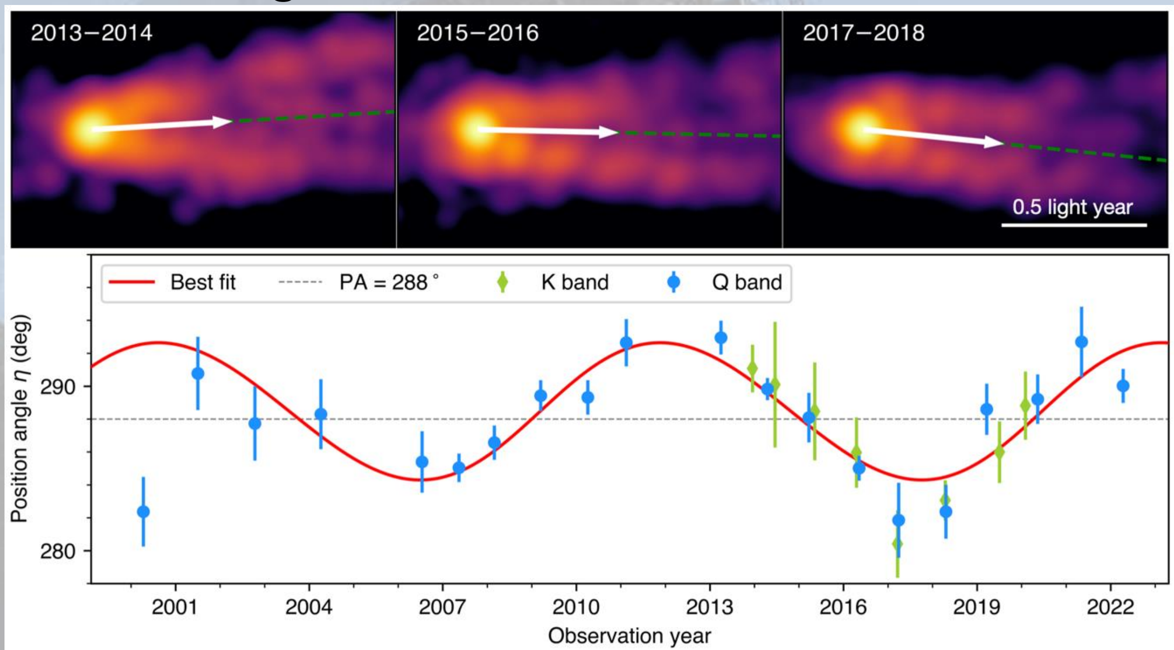
- Mostly dedicated for Galactic Astrometry until 2020
  - 2000 hrs/yr for VERA internal use and 1000 hrs/yr for EAVN open use as well
- **VERA Large-scale COllaborative Program (VLCOP) since 2022**
  - To improve productivities of VERA supported by user communities; need contributions to VERA operation duty
  - To provide new capabilities of VERA for user communities; allow any programs including new instruments under testing or even developments





Participation to EAVN

- Largest fraction of observing time of VERA
  - Recall presentation by Wajima et al.
- Expanding toward South-east Asian VLBI
  - Recall presentation by Sugiyama et al.
- Becoming more powerful network
  - e.g. Flexible/frequent/long-term monitoring



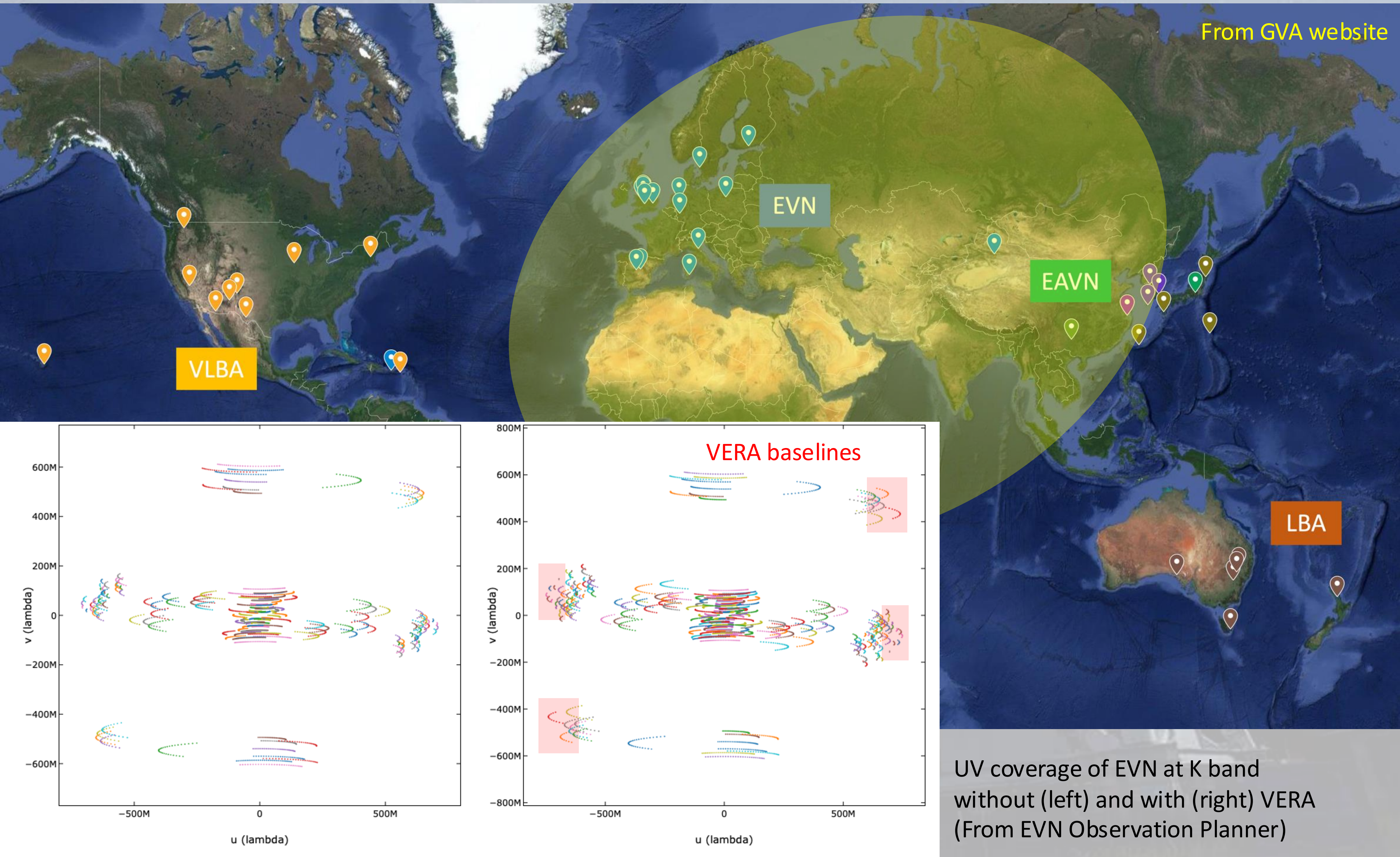
Detection of M87's jet precession, interpreted as Lense-Thirring precession, and thus providing a new and strong evidence of black hole spin (Cui et al. 2023, Nature)

Future plan

- **We are interested in joining EVN to establish EVN-EAVN collaboration**
  - Other EAVN telescopes (China and Korea) are already members of EVN
  - Some experiences between EVN antennas (C; Rygl et al. 2010, K/Q; Zhao et al. in this symposium) and EATING VLBI (Giovannini et al. 2023)
  - K and Q bands with dual-polarization (C band is only single polarization)
  - Toward future GMVA at 7 mm and GVA
- Issues to be considered
  - Data transfer (e.g. 5TB/1.5-2 days for IVS data from NAOJ to Bonn)

    Need 18TB for 10-hr 4 Gbps session/station : 5-7 days/session/station to transfer?
  - Compatibility at 4 Gbps to be tested in 2024-2025 (possibly with EVN and EAVN)
  - Financial budget (FlexBuffer, local storage, etc.) proposed for 2025FY (2025 March)

We look forward to collaborating with EVN!



UV coverage of EVN at K band without (left) and with (right) VERA (From EVN Observation Planner)