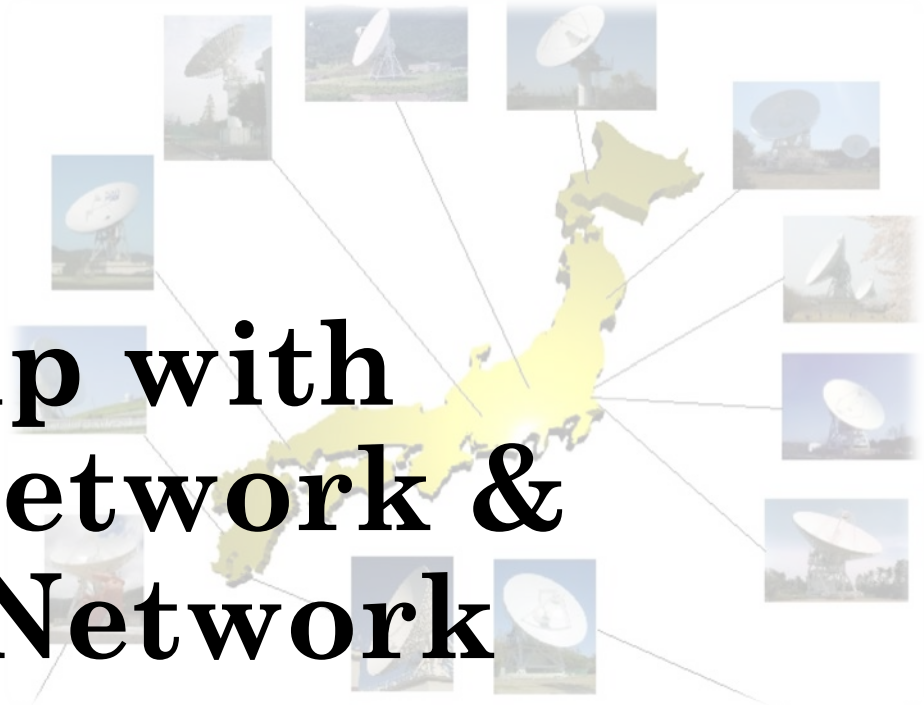
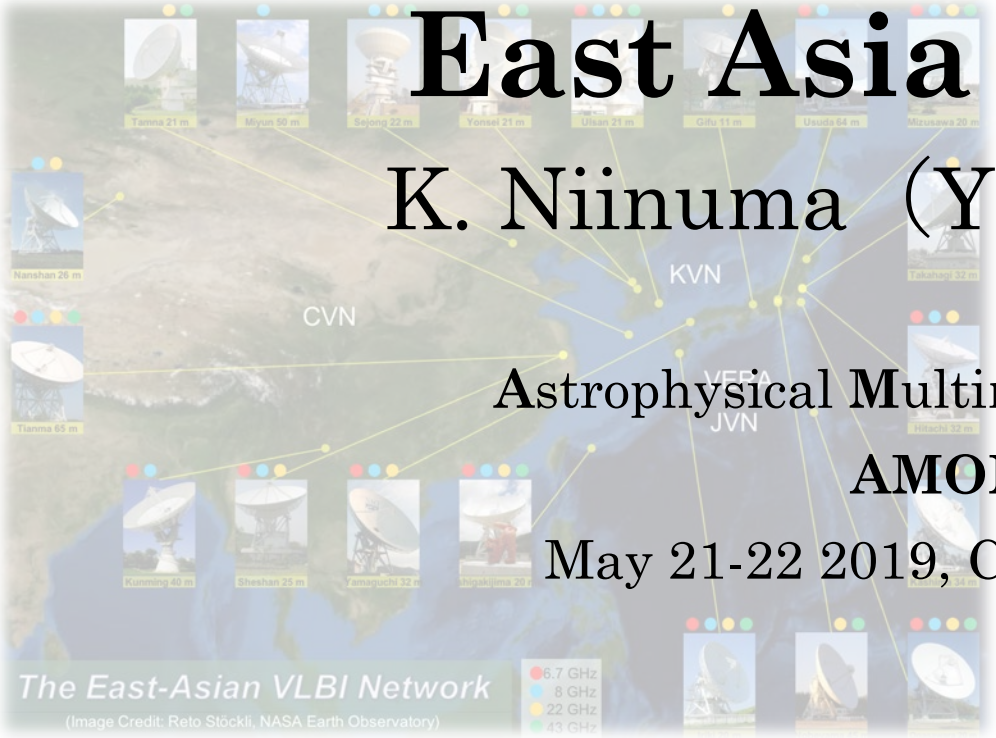


Radio follow-up with Japanese VLBI Network & East Asia VLBI Network

K. Niinuma (Yamaguchi University)



Astrophysical **M**ultimessenger **O**bservatory **N**etwork

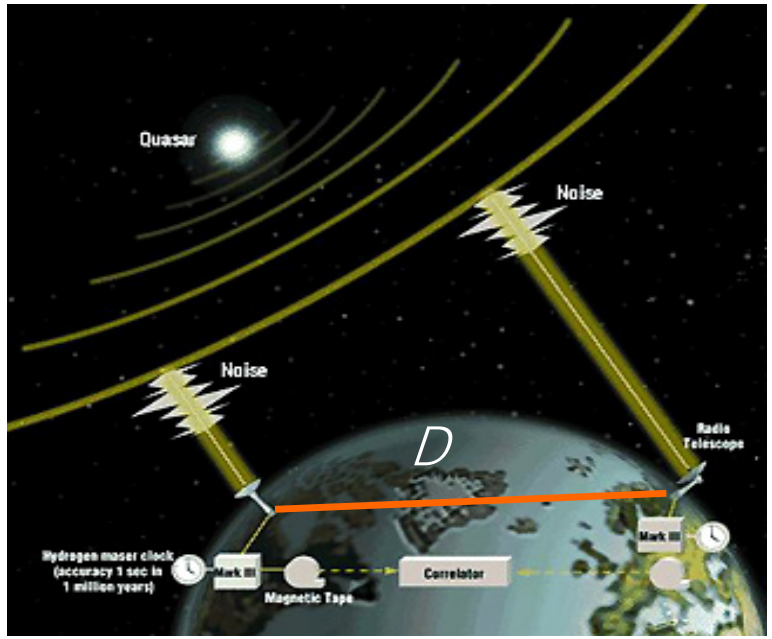
AMON Sixth Workshop

May 21-22 2019, Chiba University, Chiba, Japan

Contents

- Very Long Baseline (Radio) Interferometry
  - Capability of VLBI
- VLBI array in the EA: JVN/VERA/EAVN
  - Brief introduction of each array
- Prospects of radio follow-up

Very Long Baseline Interferometry

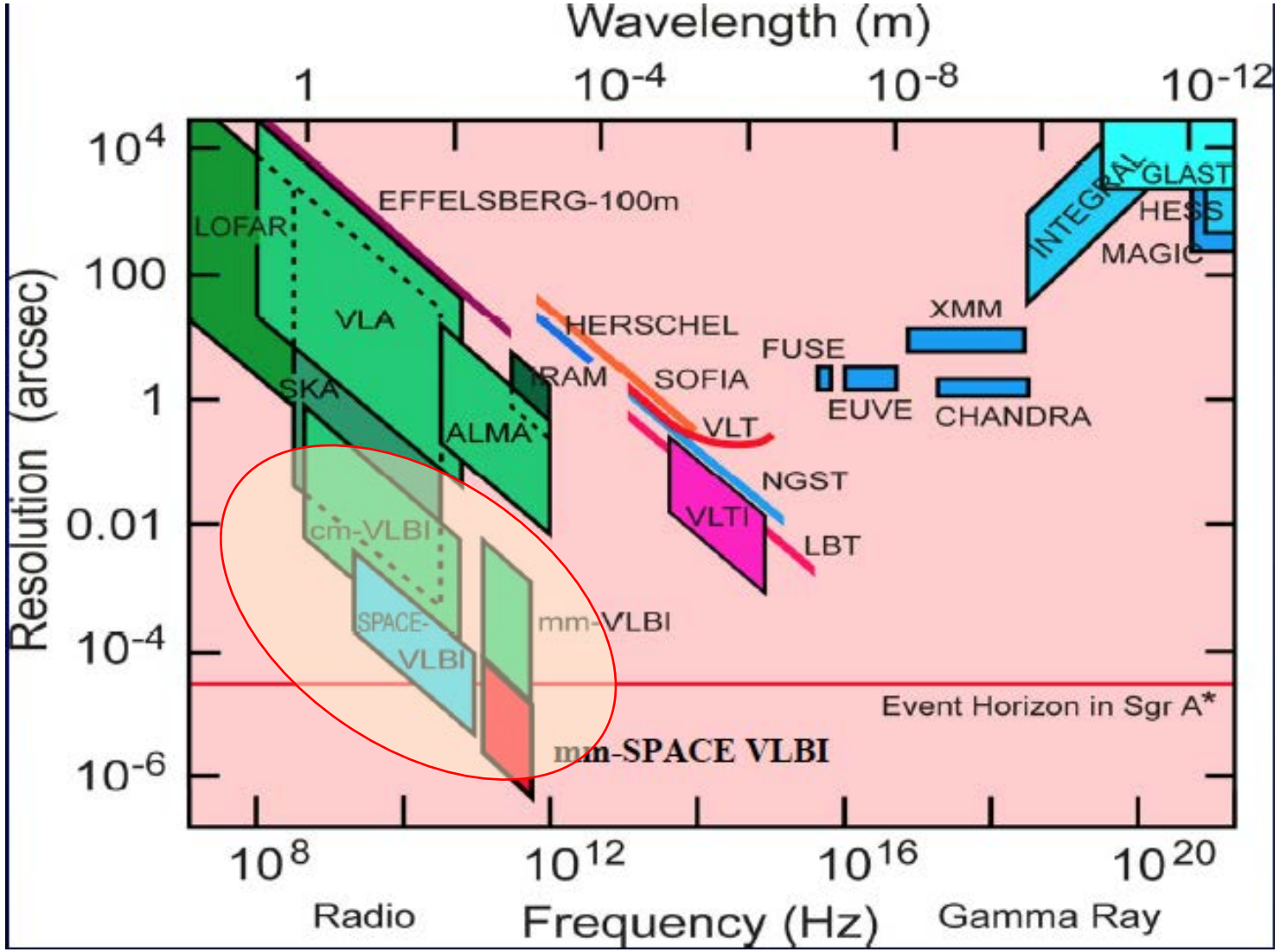


- Angular resolution

  $\theta \sim \lambda$ (波長) / D (基線長)

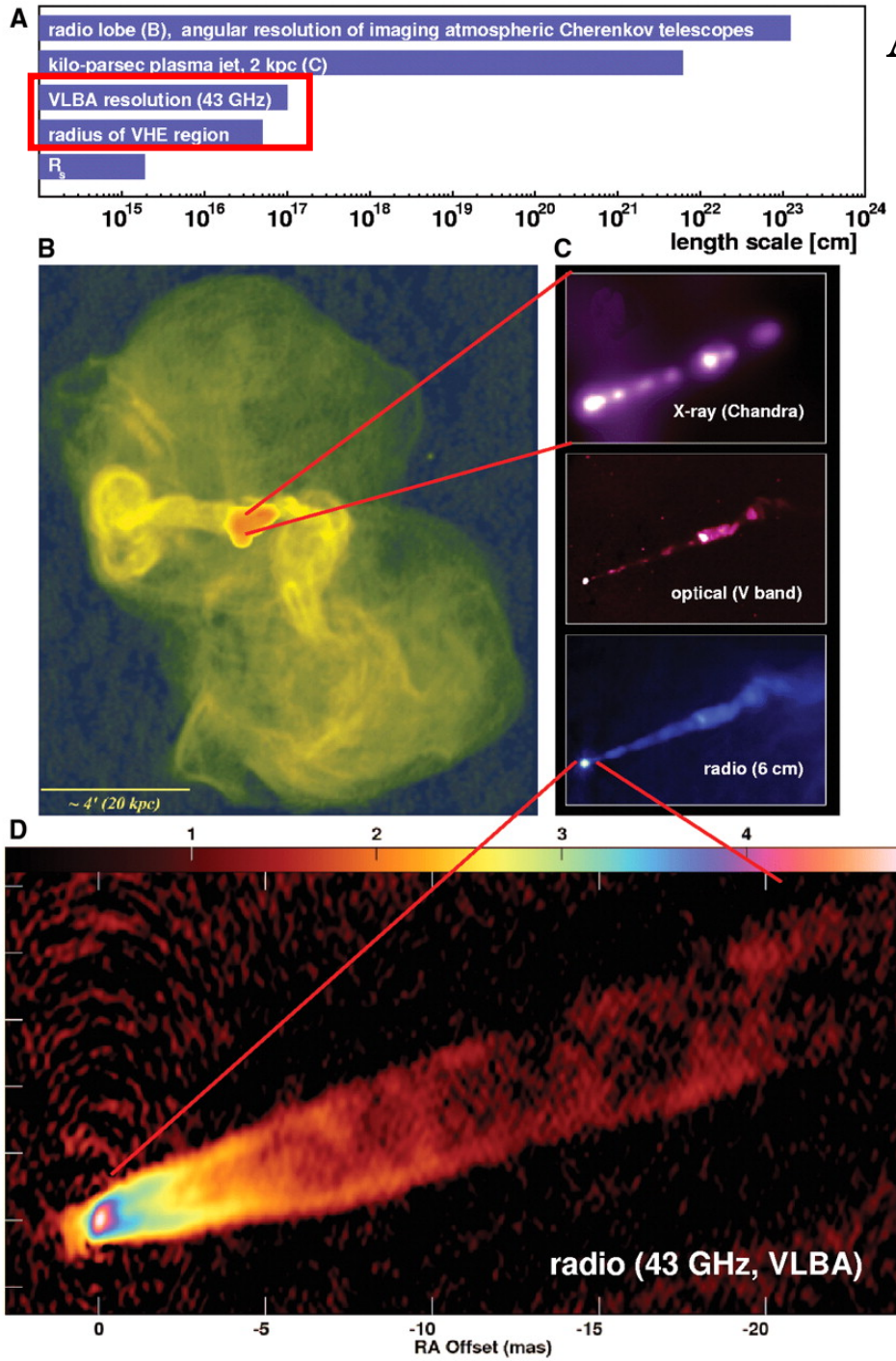
  - $D \sim 2000$ km （~日本列島）
  - $\lambda \sim 1$cm（23 GHz）

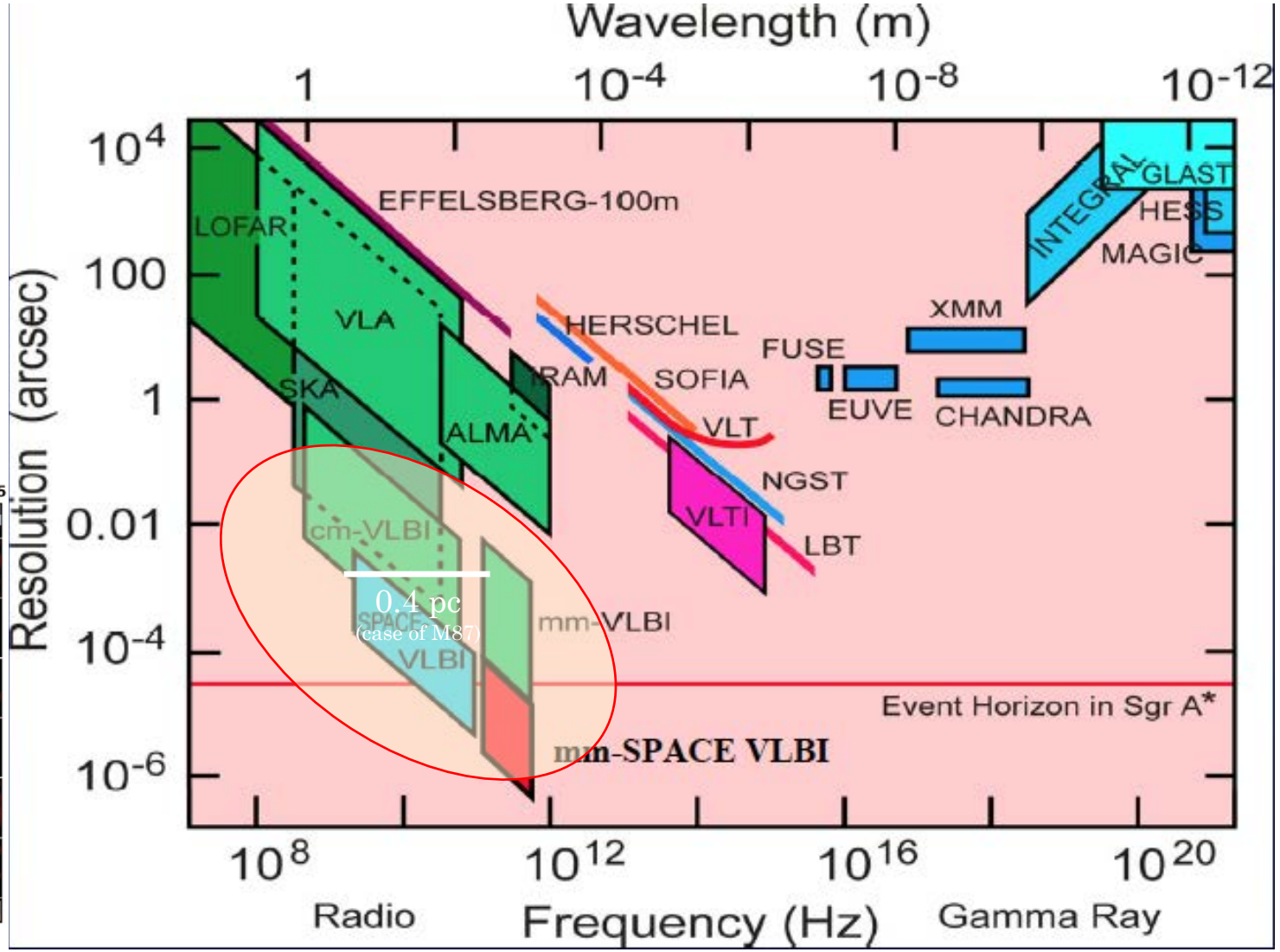
  → **$\theta \sim 1$ milli-arcsec (mas)**

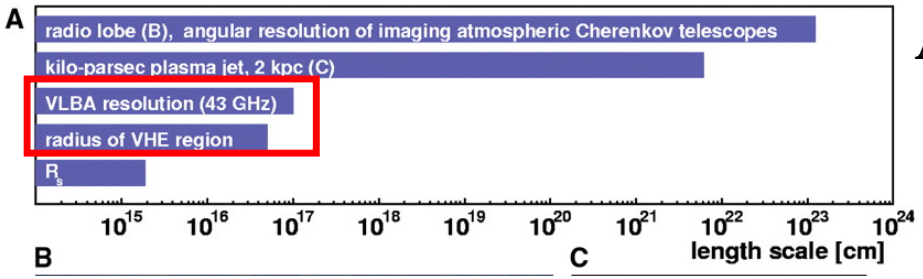


Acciari+09

e Interferometry





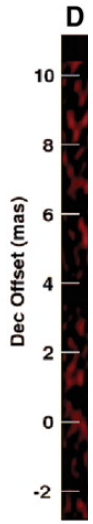


Acciari+09

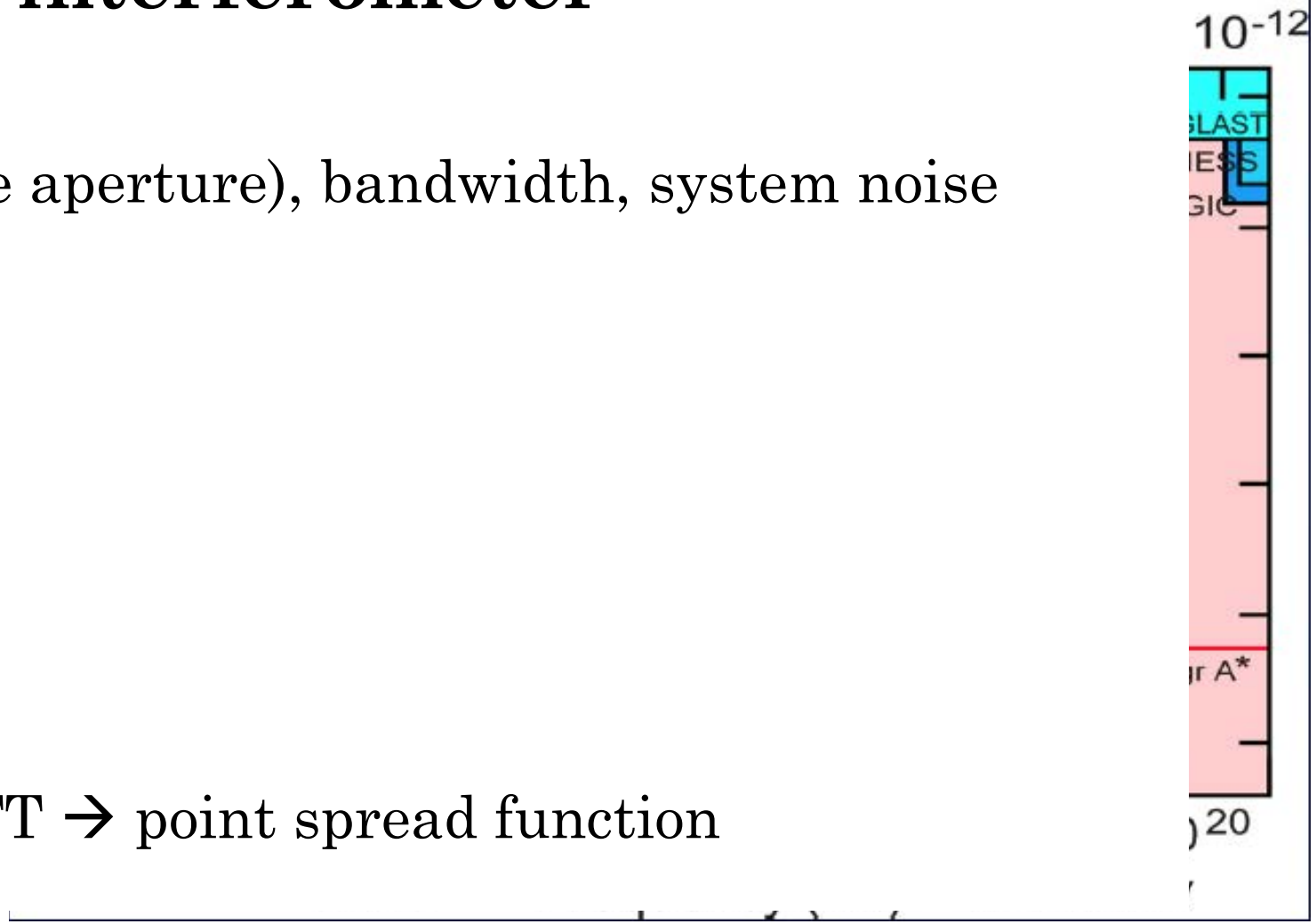
e Interferometry

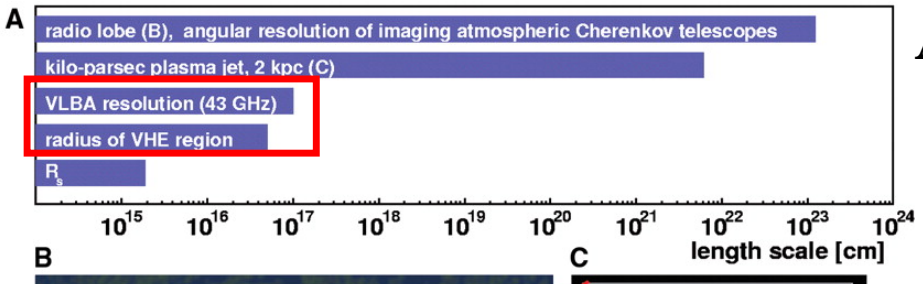
Capabilities of radio interferometer

- Sensitivity
  - ∝ No. of antenna (Effective aperture), bandwidth, system noise
- Angular resolution
  - ∝ Longest baseline length
- Image quality
  - ∝ No. of various baselines
    - spatial frequency ← FT → point spread function



RA Offset (mas)





Acciari+09

e Interferometry

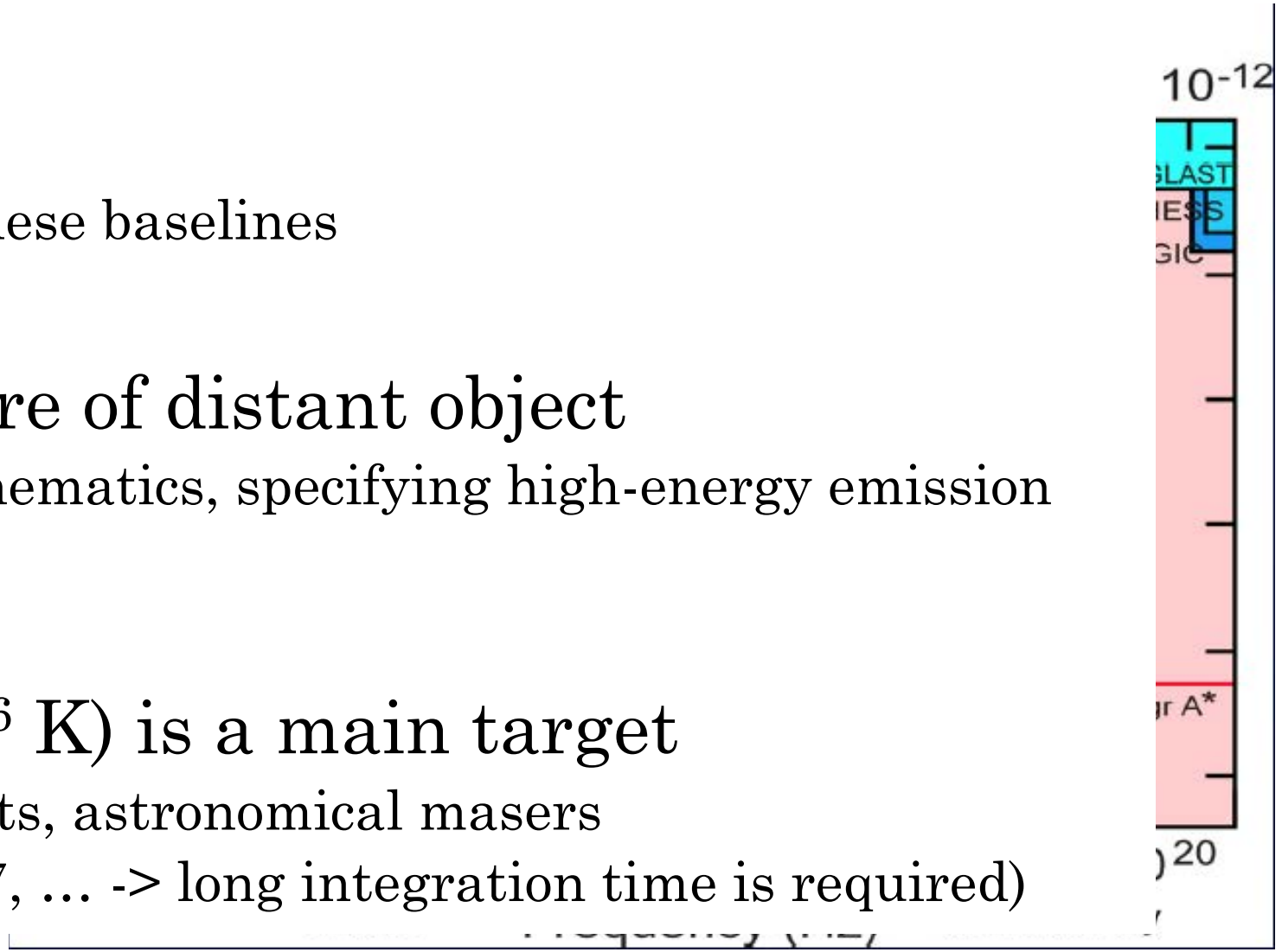
Summary of VLBI

- Extremely good "eye"
  - $\theta < 1$ mas even with Japanese baselines

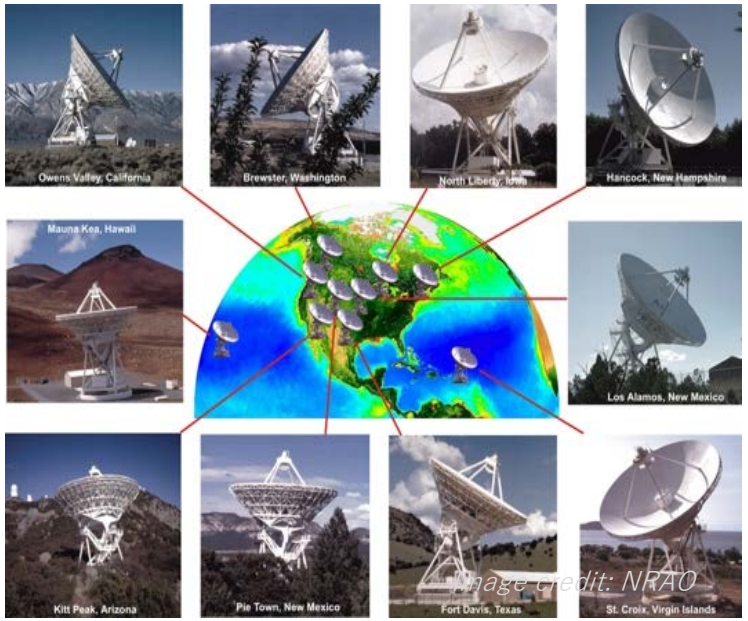
- (sub)-pc-scale structure of distant object
  - Structural changes (jet kinematics, specifying high-energy emission site, localization…)

- High T_b object ($> \sim 10^6$ K) is a main target
  - e.g., blazars, other AGN jets, astronomical masers

  (GRB afterglow, GW-170817, … -> long integration time is required)

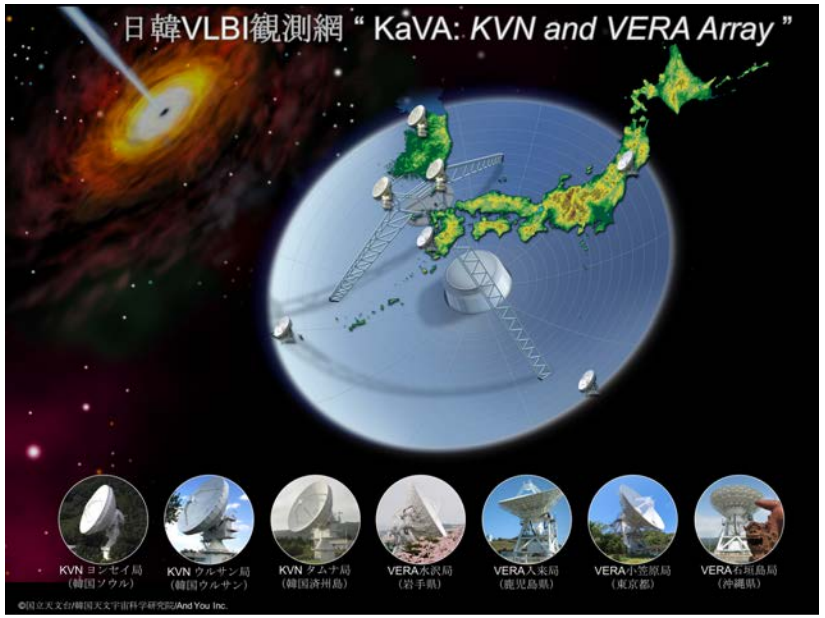


World's VLBI array



Very Long Baseline Array (VLBA)

- Baseline length: < ~8,000 km
- Frequency: 330 MHz - 86 GHz
- Operation: NRAO



Korea-Japan VLBI Network (KVN and VERA Array: KaVA)

- Baseline length: < ~2,300 km
- Frequency: 22/43 GHz
- Operation: NAOJ, KASI

World's VLBI array

- VLBA, KaVA, VERA: dedicated VLBI array
  - running throughout the year except for the period of maintenance

- e.g., EHT, GMVA, EVN, JVN: coordinated by multi-purpose telescopes
  - limited sessions/year

- Basically, proposal based ToO is acceptable
  - NEED to reserve the slot of ToO observation of expected event
  - For (actually) unexpected or urgent event, the slot of DDT is prepared

Target of opportunity From the announcement of KaVE/EAVN call for proposal

KaVA/EAVN accepts target of opportunity (ToO) proposals. Although proposers can request the participation of Tianma and Nanshan as well as KaVA for ToO observations, both Tianma and Nanshan will join only on a best effort basis. Note that Nobeyama cannot be included for ToO proposals.

It is strongly recommended that ToO proposals (especially expected ToO) are submitted during the regular CfP. Unexpected or urgent ToO can be submitted as Director's Discretionary Time (DDT) proposals at any time. ToO proposals must include clear triggering criteria to initiate an observation. ToOs are valid for one year after it is approved. ToO proposals for DDT should follow the same format of regular call and should be sent to eavnprop(at mark)kasi.re.kr.

World's VLBI array

- VLBA, KaVA, VERA: dedicated VLBI array
  - running throughout the year except for the period of maintenance

- e.g., EHT, GMVA, EVN, JVN: coordinated by multi-purpose telescopes
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  - For (actually) unexpected or urgent event, the slot of DDT is prepared

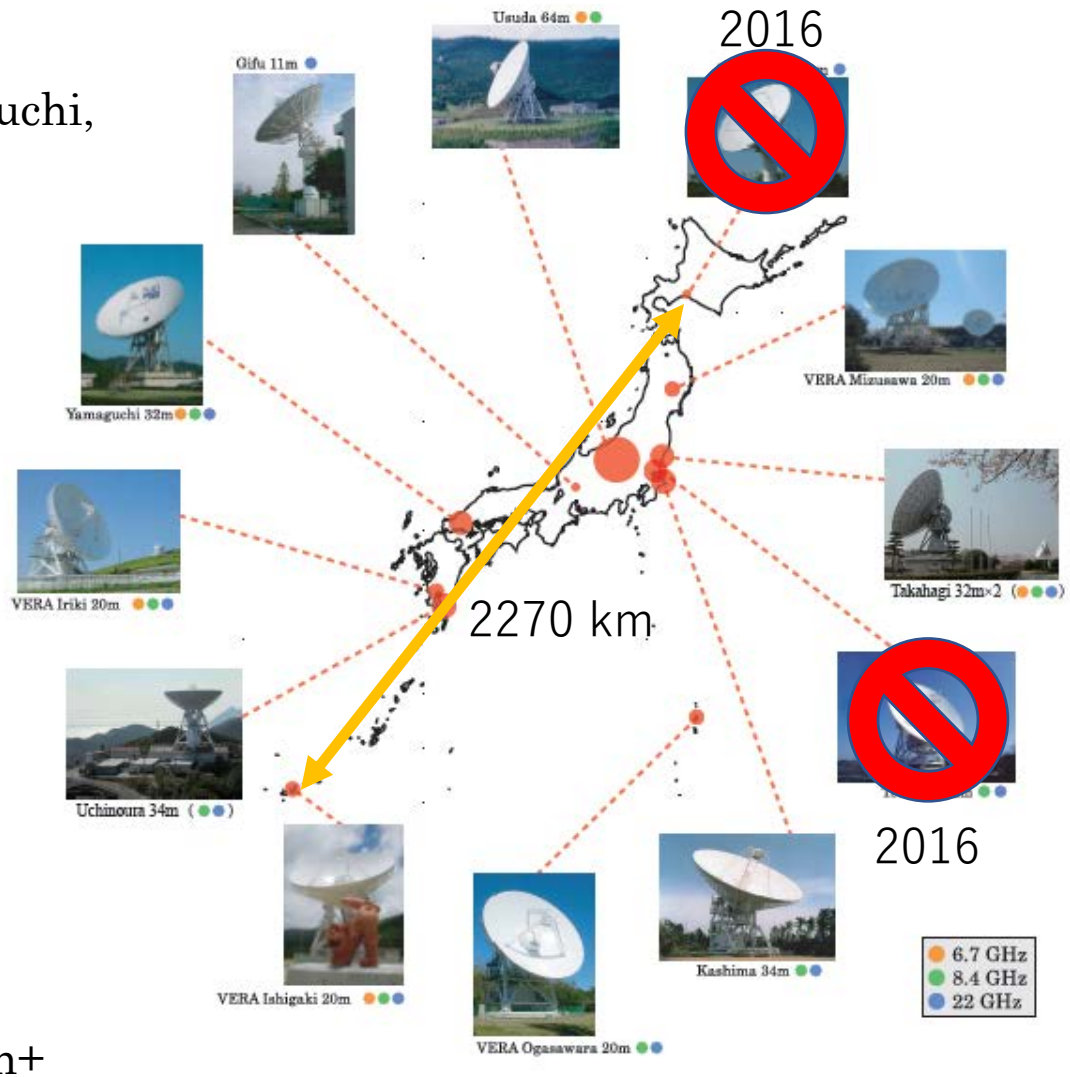
- A few "weeks" are required by data distribution
  - Data shipping from each antenna, correlation procedure of all baselines, …
  - NOT suitable for alerting to other EM facilities

Japanese Vlbi Network: JVN
Vlbi Exploration of Radio Astrometry: VERA
East Asia Vlbi Network: EAVN

VLBI array in the East Asia Region

Japanese VLBI Network: JVN

- Network
  - 6 Univ. (Tsukuba, Ibaraki, Gifu, Osaka Pref., Yamaguchi, Kagoshima) and NAOJ, JAXA/ISAS, NICT, GSI
  - 12 radio telescopes (10 stations)
    - 1 x 11m, 4 x 20m, 6 x ~30m, 1 x 64m
    - Ibaraki and Yamaguchi: two 30m-class
  - Baseline length: 80 km - 2270 km
    - Angular resolution of 3 mas is achieved at 8GHz
  - 3 observing frequencies: 6/8/22 GHz
    - ΔB = 32MHz until 2014, 512MHz since 2015
  - Operation: Each university & NAOJ independently
- Purpose:
  - A new, characteristic VLBI array
  - A base of East Asian VLBI
- EAVN test observations (JVN + Shanghai26m)
  - 6.7 GHz Methanol masers project led by Fujisawa-san+



VLBI EXPLORATION of RADIO ASTROMETRY: VERA

- Sub-array of the JVN
  - Baseline length: 1,000 - 2,270 km
  - Operated by NAOJ for revealing Galactic dynamics
  - ~100hrs/yr open-sky is prepared
- Specializing "**Astrometry**"
  - Good angular resolution & poor imaging capability
  - Suitable for the detection of compact structure and its change
    - E.g., detection of the newly ejected compact jet
- Array specification
  - Frequency: 22GHz /43GHz
  - Angular resolution: 1.2 mas (22GHz), 0.6 mas (43GHz)
  - 2-beam simultaneous receiving system

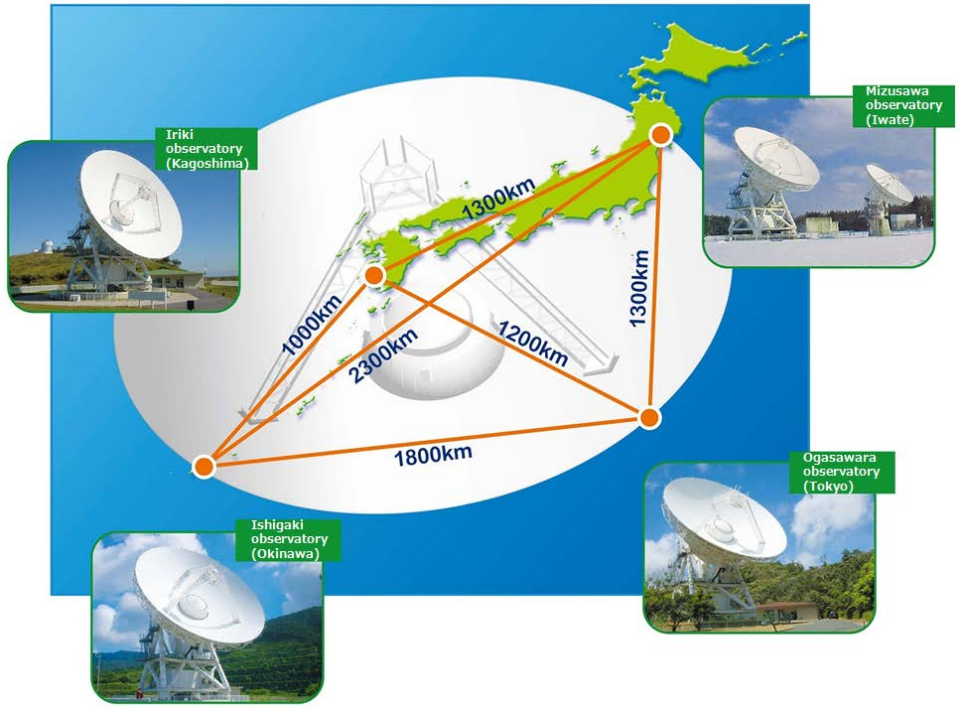
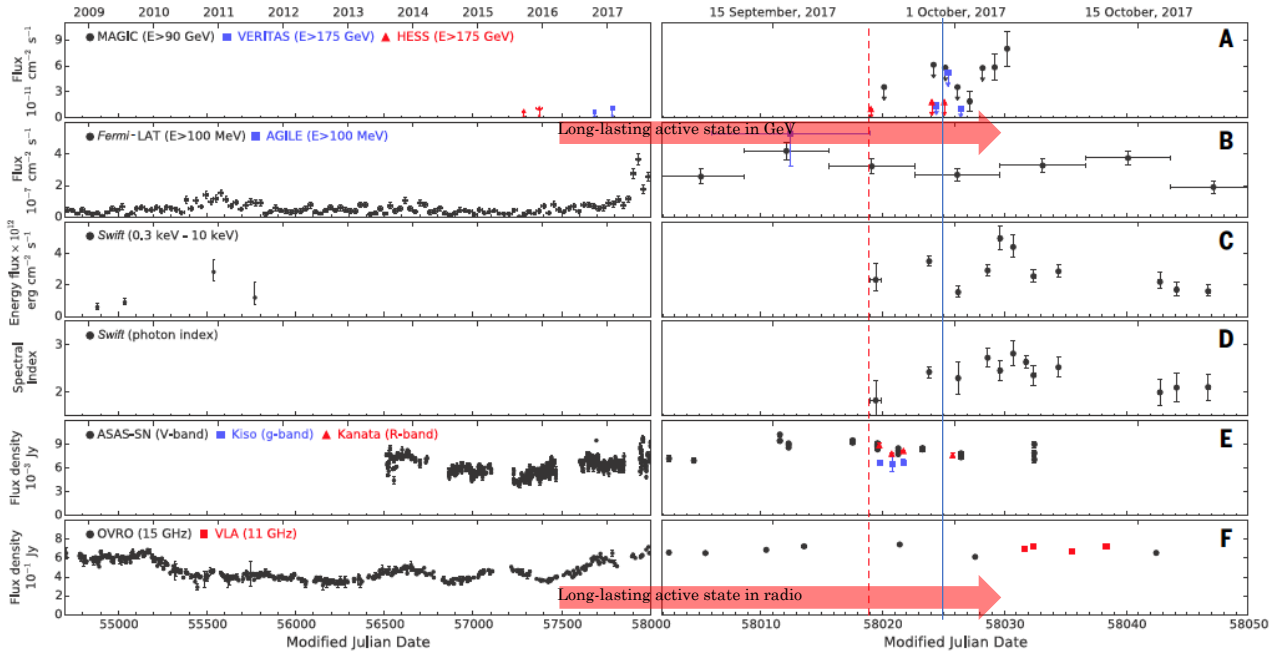


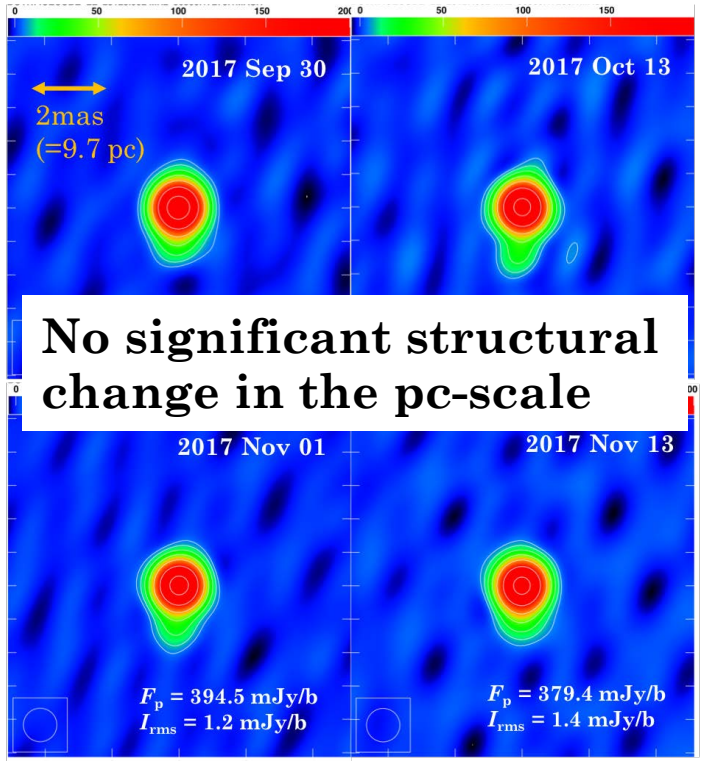
Fig. Consisting of 4 radio telescopes located at Iwate-Oshu, Tokyo-Ogasawara, Kagoshima-Satsumasendai, Okinawa-Ishigakijima

VERA observation of TXS 0506+056

- We started intensive follow-up of TXS0506+056 since 8days after the detection of IceCube-170922A (based on proposed ToO)
  - Date: 2017 Sep 30, Oct 13, Nov 1, and Nov 13



Time-dependent multiwavelength observations of TXS 0506+056 before and after IceCube-170922A (IceCube Collaboration et al. 2018)



Quick follow-up with VERA@23GHz (Niinuma+ in prep.)

VERA observation of TXS 0506+056

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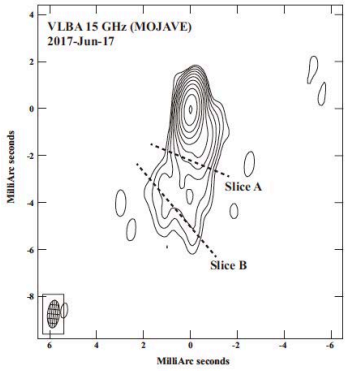
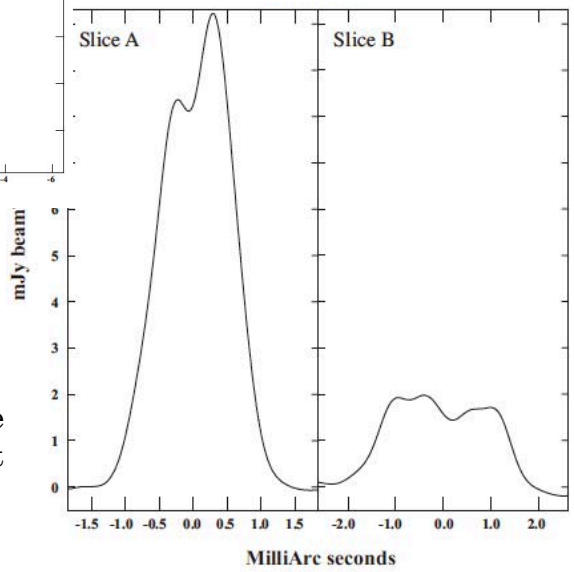
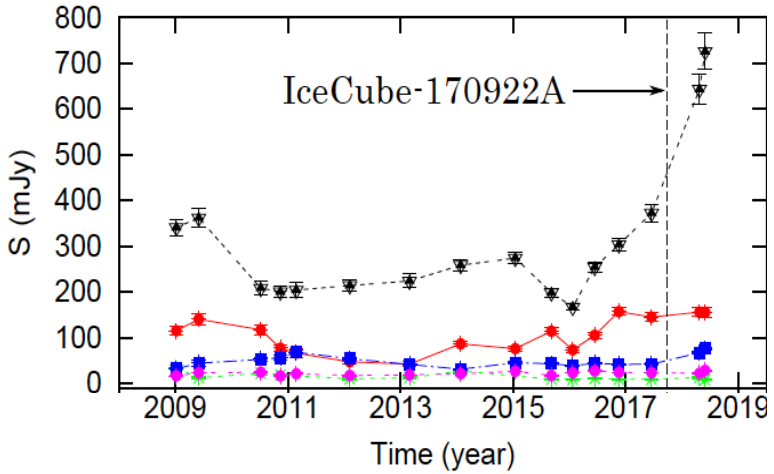


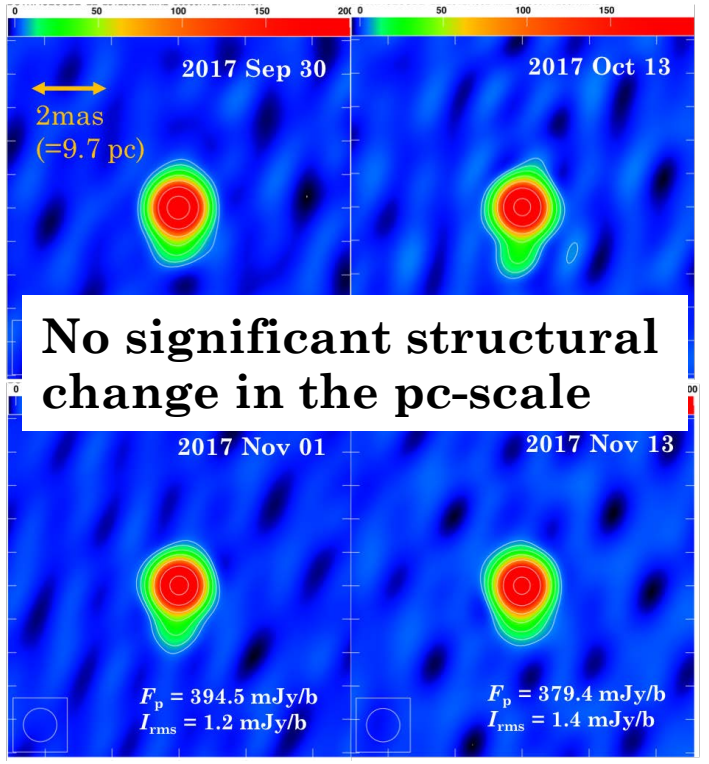
VLBA archive data



Transverse structure can be seen in the jet (Niinuma+ in prep.)

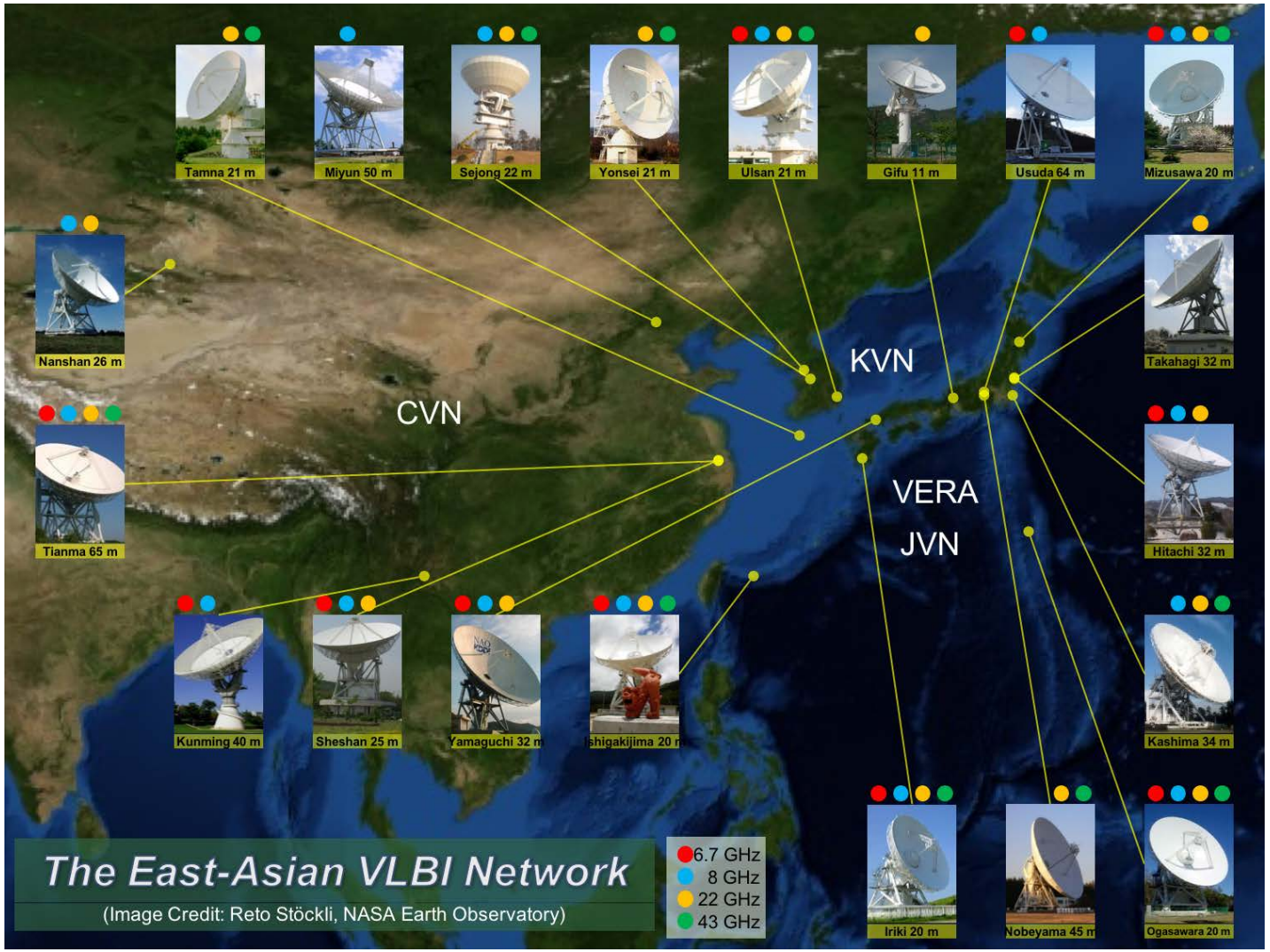
Long-term monitor by VLBA (Kun+18)





Quick follow-up with VERA@23GHz (Niinuma+ in prep.)

East Asia VLBI Network: **New Array**!



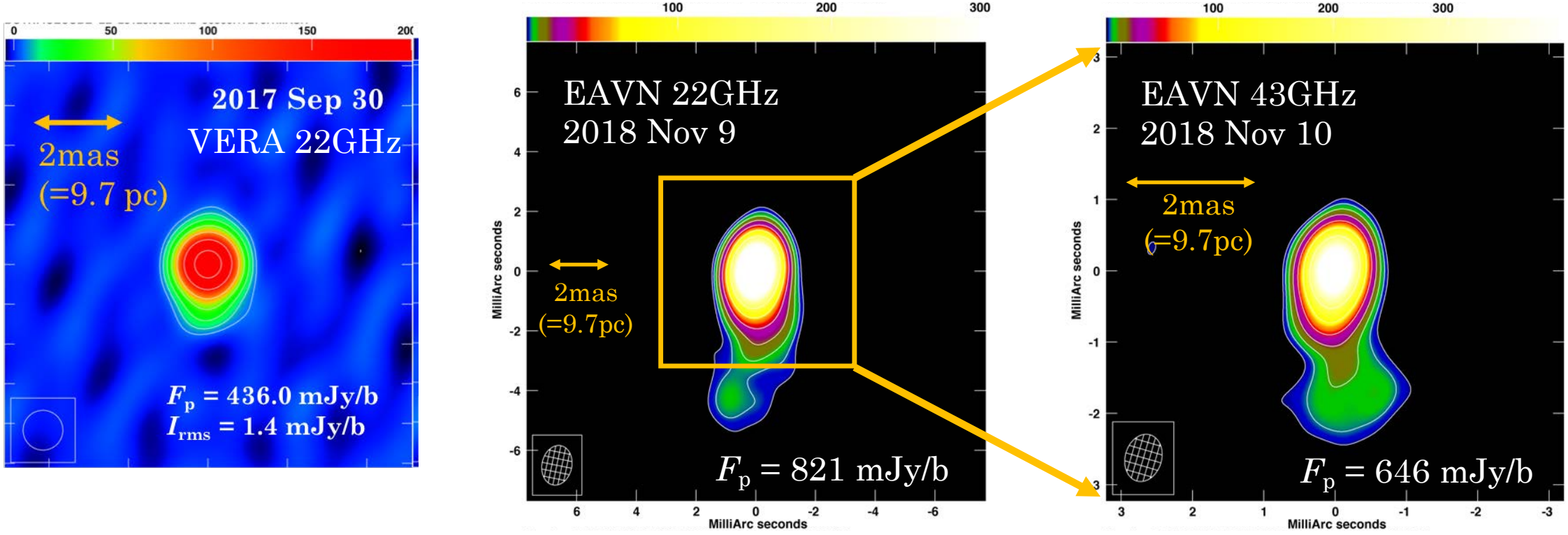
East Asia VLBI Network: **New Array!**

- Consisting of dedicated array (KaVA: 7-telescopes) & multi-purpose telescopes (e.g., Nobeyama 45m, Shanghai 65m, Nanshan 26m)
  - Baseline length: 300km – 5500km

- Regular operation at high radio frequency (22/43GHz) since 2018
  - Now, call for proposal for 2019B semester
  - At 43GHz, one of the highest sensitivity array in the world
  - Good imaging capability comparable to VLBA

- Still under the extension!
  - In one or two years, JVN will join to EAVN at low radio frequency part
  - Image quality will be improved

Follow-up of TXS0506+056 by EAVN



EAVN clearly reproduce the jet structure compared to VERA

VLBI flux is still increasing: ~400mJy/b (2017 Sep) → ~800 mJy/b (2018 Nov)

Radio follow-up with VLBI

Toward multi-messenger astronomy

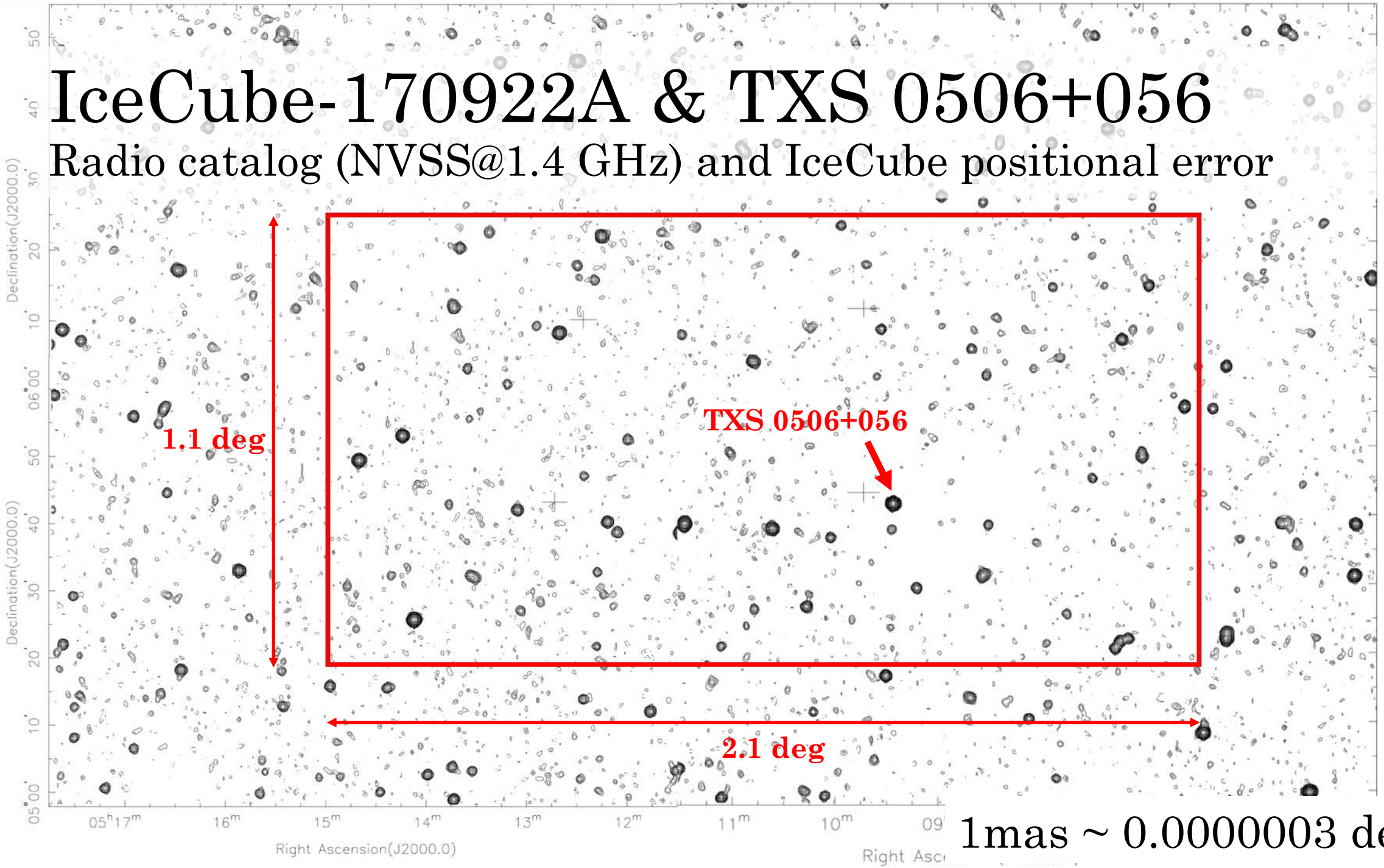
Imaging observation of “VLBI scale”

- Basically, VLBI imaging is time-consuming observation
  - At least a few hours are required per object (depending on no. of baselines, sensitivity)

- Searching for plausible candidates within a few deg^2 by VLBI?
  - ~100 radio sources were located within the error of IceCube-170922A
  - Unrealistic: extremely narrow FoV and time-consuming for each pointing

IceCube-170922A & TXS 0506+056

Radio catalog (NVSS@1.4 GHz) and IceCube positional error



1mas ~ 0.0000003 deg

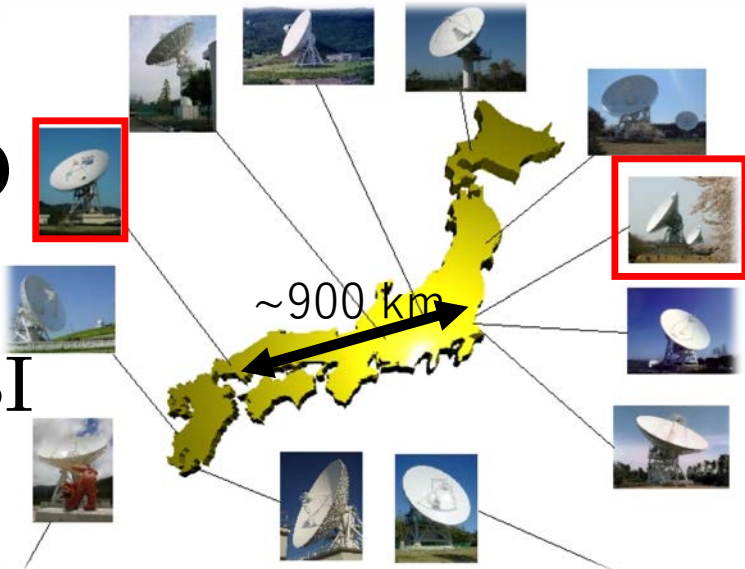
Imaging observation of “VLBI scale”

- Basically, VLBI imaging is time-consuming observation
  - At least a few hours are required per object (depending on no. of baselines, sensitivity)

- Searching for plausible candidates within a few deg^2
  - ~100 radio sources were located within the error of IceCube-170922A
  - Unrealistic: extremely narrow FoV and time-consuming for each pointing

- Follow-up of a few plausible candidates: realistic (so far)
  - EM observation with large FoV performs survey
  - VLBI investigates the details
    - e.g., gamma-ray flaring blazars PKS B1424-418, TXS 0506+056

Non-Imaging Radio Follow-up

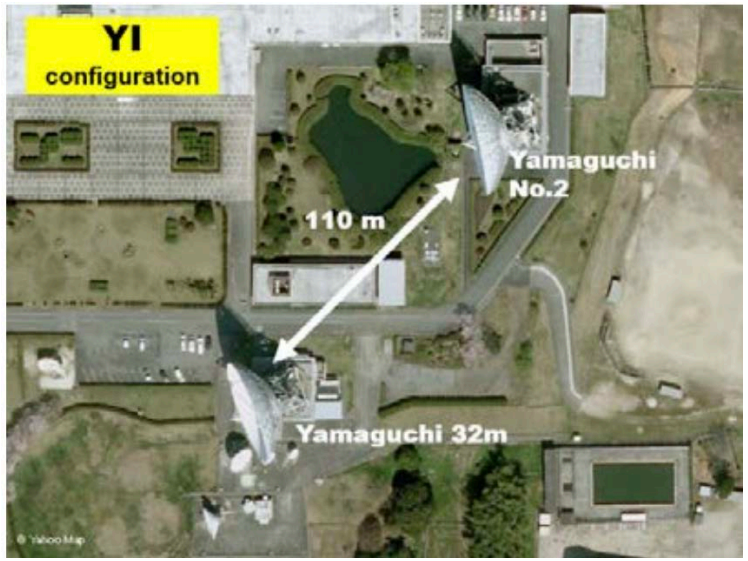


Red: Yamaguchi and Ibaraki stations

- Snap-shot observation by “one baseline” VLBI
  - Only light-curve study BUT in VLBI scale
  - University’s baseline (Ibaraki Univ., Yamaguchi Univ.)
    - Operation, correlation done by both University
    - Survey, quick follow-up with high-sensitivity (**5mJy@10σ**, 6min integ.) and relatively good resolution (***θ*~9 mas,** = 40pc@z~0.3)

- Yamaguchi Interferometer (YI)

Yamaguchi Interferometer (YI)



Observing Band	6 GHz / 512 MHz 8 GHz / 512 MHz
Baseline	110 m
Beam size	6 GHz: 1’.4 8 GHz: 1’.1
Data rate	2 Gbps/Antenna
Integration time	3 hours
1σ sensitivity	0.1 mJy
Observing Time	3000 hours/yr

YI will be used for…
- Daily monitoring of compact object/AGN/YSO
- Deep survey of weak radio source (～1 mJy)

Summary

- VLBI is an unique instrument to investigate the detailed structure and to see the vicinity of the SMBH
  - But the target is quite limited (high T_b objects)

- Follow-up of a few plausible target: VLBI imaging

- Search for plausible target or quick follow-up: non-imaging VLBI or YI