NAOJ Future Planning Symposium 2024
2024 Dec 3-6 @NAOJ

The Next Generation Very Large Array (ngVLA)

Takuma Izumi, Satoru Iguchi, Misato Fukagawa,
Bunyo Hatsukade (ngVLA Study Group@NAOJ),
Munetake Momose (ngVLA Science Working Group), +SWG members

I. ngVLA Overview

ngVLA
towards a new discovery space

Very Large Array (1980-)

- 27 × 25-m antennas
- Max resolution = 40 mas
- 73 MHz - 50 GHz

>10× resolution

10× sensitivity

ngVLA (2033~): upgrade of VLA+VLBI

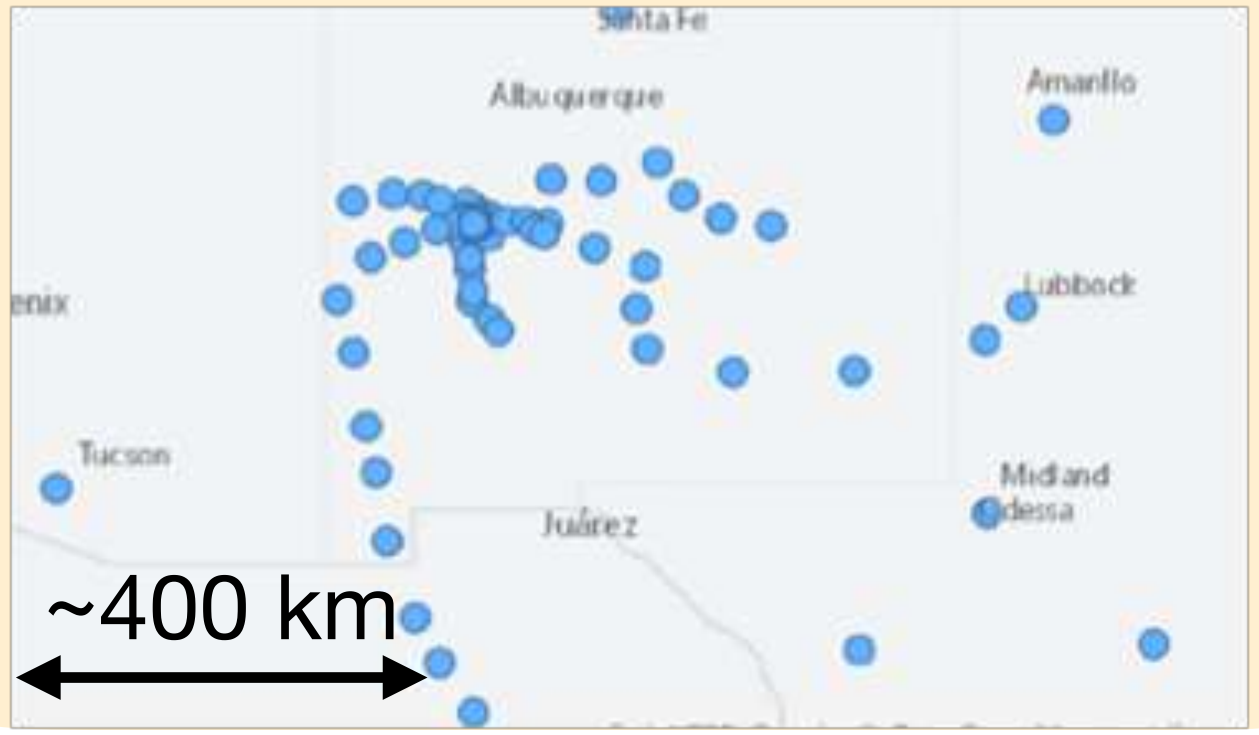
- 244 × 18-m + 19 × 6-m antennas
- Max resolution ~ 1 mas,
  or 0.1 mas with LBA (VLBI)
- 1.2 GHz - 116 GHz

- ngVLA bridges SKA and ALMA.
- NRAO is the leading institute, with expected contributions from international/multi-agency partners at the max level of ~25%. (Japan, Canada, Mexico, Taiwan, Germany, …)

Array and Receiver Components

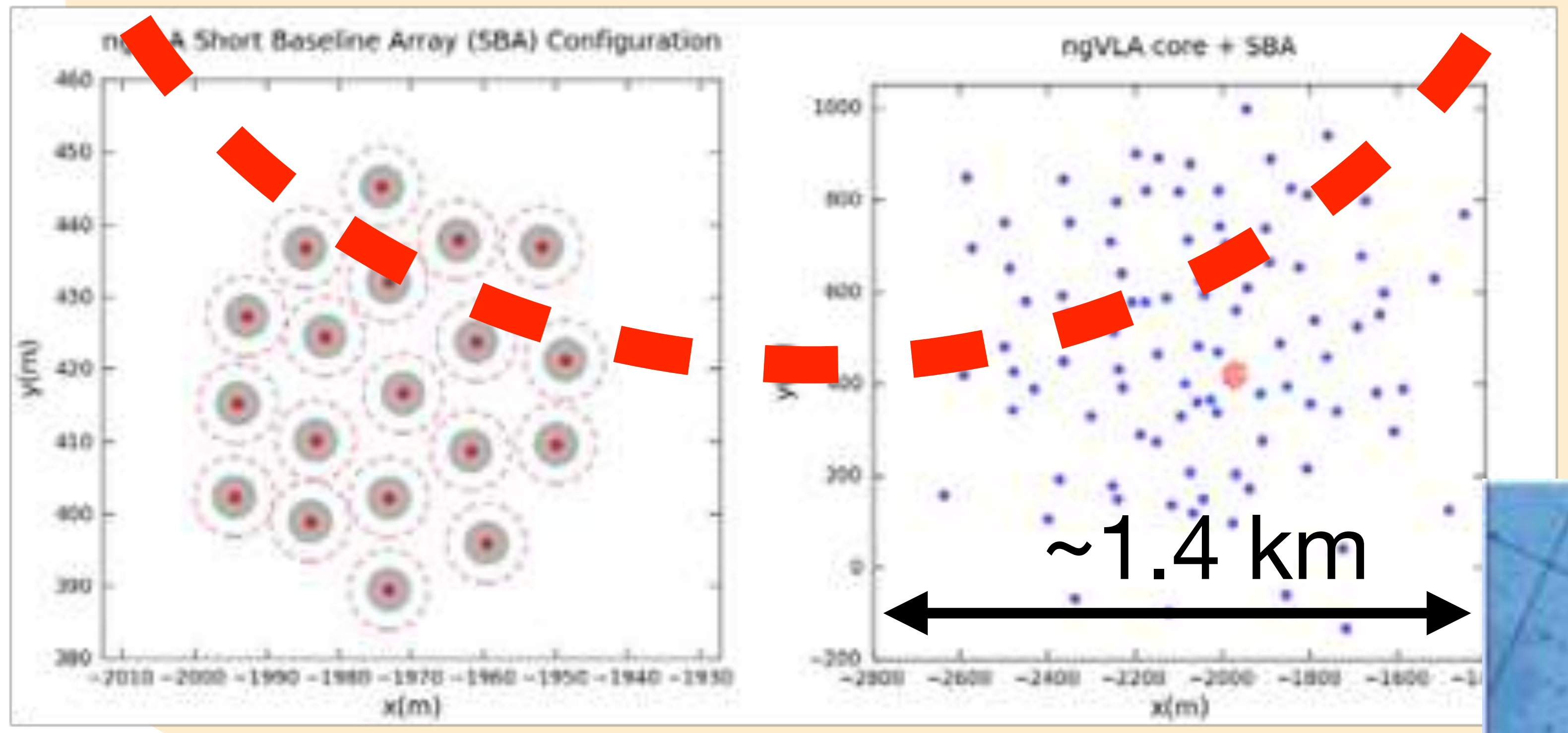
Main Array (MA)

- 214 x 18m offset Gregorian antennas
- Up to 1000 km baselines
- Fixed locations near VLA site



Short Baseline Array (SBA)

- 19 x 6m antennas
- 4 x 18m from MA as Total Power antenna to fill in (u,v) hole for extended emission

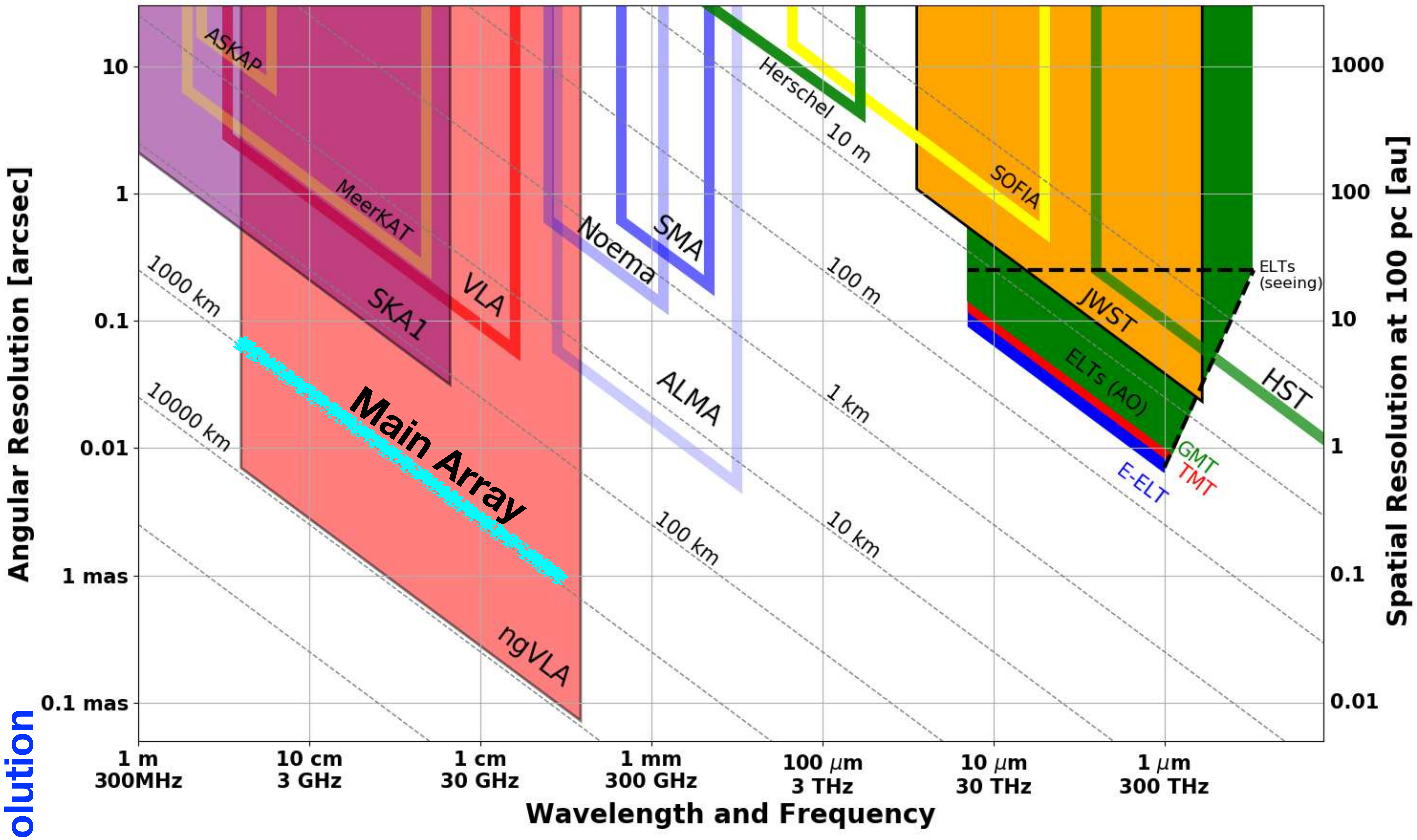


Long Baseline Array (LBA)

- 30 x 18m antennas located across the continent for baselines up to ~9000 km
- Operated in the VLBI mode
- Max ang. resolution = 0.1 mas

Band	freq. (GHz)	BW (GHz)	Major Emission Line
1	1.2 - 3.5	2.3	HI, H_2CO, H_2CS, OH
2	3.5 - 12.3	8.8	CH, H_2CO, SO_2
3	12.3 - 20.5	8.2	CH_3CN, CH_3OH, NH_3, SO
4	20.5 - 34.0	13.5	H_2O, NHD_2, NH_3
5	30.5 - 50.5	20	SO, SiO, CH_3OH, CS
6	70 - 116	20	CO, HCN, HCO^+, DCN

Super High Angular Resolution



high resolution

For the case of Main Array:

- 10× higher angular resolution than ALMA if we compare the highest resolutions.
- 100× higher if we compare at the overlap frequency.
- (LBA adds *further 10× resolution*)

Key Operation Concepts (PI-science like ALMA)

Observing time will be allocated through open call for proposals following shares of contribution. It will include Open Skies

Peer review system will be adopted. Proposals will be evaluated based on scientific merit and technical feasibility

PI is awarded time and not sensitivity. This is different from ALMA.

Data Product

Pipeline will automatically generate Science Ready Data Products for most standard projects (~80%). Expert modes will exist too.

Dynamic Scheduling

Time allocated dynamically according to the priority built into the queue.

Array Availability

No reconfiguration, meaning that the array will be used continuously with minimum downtime. Subarrays will be used for maintenance and commissioning activities

We will use the successful operational model of ALMA

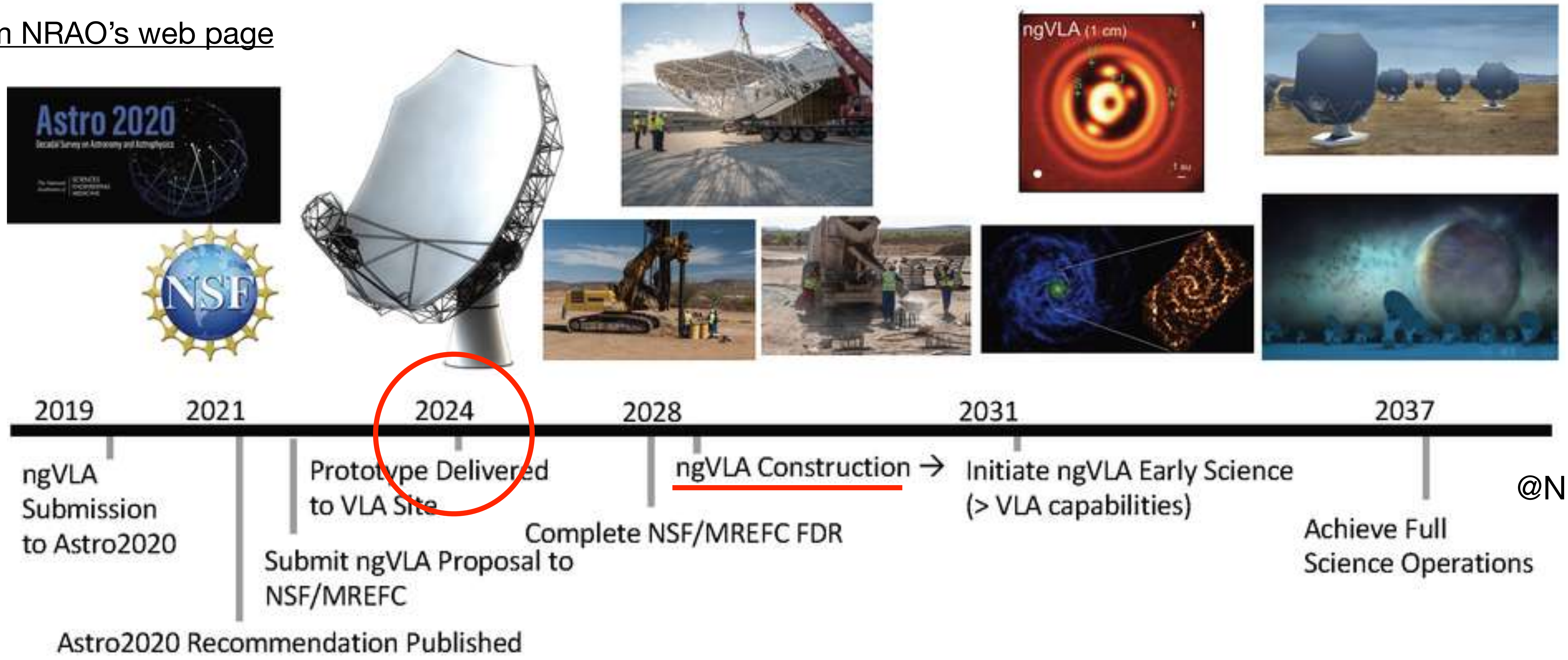
US Astro 2020

- Tied for **2nd top priority** in the large ground-based telescopes, after US-ELTs (GMT + TMT).
- "A project of great scientific impact and influence in many fields of astronomy"
  - ✓ A powerful observatory that will replace both the JVLA and VLBA.
  - ✓ Would have broad, flexible capabilities and provide science-ready data products accessible to a diverse community of users.
  - ✓ Absolutely unique world-wide in both sensitivity and frequency coverage.
  - ✓ Conclusion of Astro2020: **It is of essential importance to astronomy that the JVLA and VLBA be replaced by an observatory.**

→ *The timeline/progress of the TMT project will impact those of the ngVLA, both in US and Japan.*

Current timeline in US

from NRAO's web page



@NRAO

- NSF entered the ngVLA project to the Major Research Equipment and Facilities Construction (**MREFC**) process in 2023. NRAO will proceed the initial designing phase over the next couple of years.
  → We successfully passed the NSF's **Conceptual Design Review (CoDR)** in 2024 Sep!!
- The final design review will happen in ~2028. After that, NRAO will proceed to the full construction.

II. Project Organization
& Community Engagement

Leads of the ngVLA activity in Japan

- ngVLA Study Group@NAOJ
  - T. Izumi (lead), S. Iguchi, M. Fukagawa, B. Hatsukade (ALMA)
  - T. Kojima, K. Kaneko, H. Kiuchi, H. Imada (ATC)
  - A. Kataoka (DoS)
- Science WG (community): in total ~180 astronomers registered to our mail lists
  Overall lead: M. Momose (Ibaraki)
  SWG1: S. Okuzumi (Sci. Tokyo), M. Momose (Ibaraki)
  SWG2: K. Tachihara (Nagoya), Y. Oya (Kyoto), H. Sano (Gifu), K. Tanaka (Sci. Tokyo)
  SWG3: B. Hatsukade, D. Iono (NAOJ)
  SWG4: K. Niinuma (Yamaguchi)
  SWG5: H. Nagai, T. Izumi (NAOJ), S. Takekawa (Kanagawa)

Many leading participants from younger generation!
→ Significant contribution of those who have grown with ALMA

@NAOJ: The ngVLA Study Group

1. **Japanese Radio Astronomers** started getting engaged in science activities that define ngVLA main science cases.
2. **The NAOJ ALMA project** initiated discussions with NRAO through the *well-established* ALMA collaboration → ngVLA as a future project that further increases the scientific impact of ALMA.

- Explore **in-kind contribution from Japan**, based on the technical heritage of NRO, ASTE, and ALMA.

- Strong support from **Udenkon** to ngVLA, as one of the top future priorities of the radio astronomical community.
- **Scientific activities** are led by community members in Japanese institutes and universities (lead: M. Momose@Ibaraki Univ), in collaboration with NAOJ staff.
- **Technical developments** are led by NAOJ (ATC) exploiting synergies with ALMA. We also consider to involve the community.
- We are the **management interface to NRAO** (through the established ALMA collaboration).

Synergies with the ALMA project

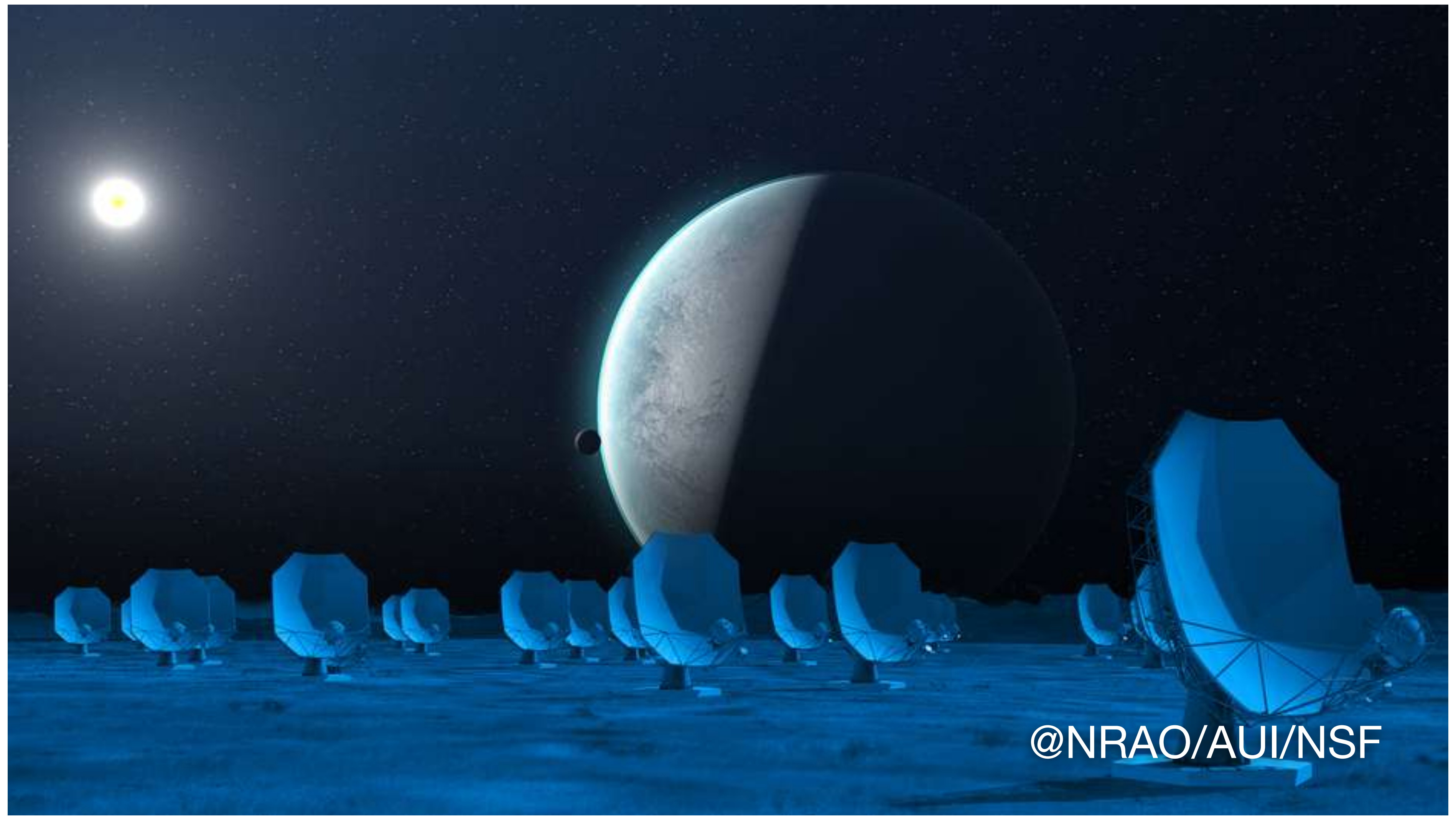
Construction/operation synergies with ALMA

- Human resources
- International relationship (NAOJ & NRAO)
- Knowledge

  + Project management
  + User support
  + Document control
  + Public outreach
- Engineering

  + Component level studies
  + Development, verification, and integration of receivers
  + Antenna manufacturing (with industry)
- Computing
- AIVC
- Science operation and promotion

@ALMA (ESO/NAOJ/NRAO)



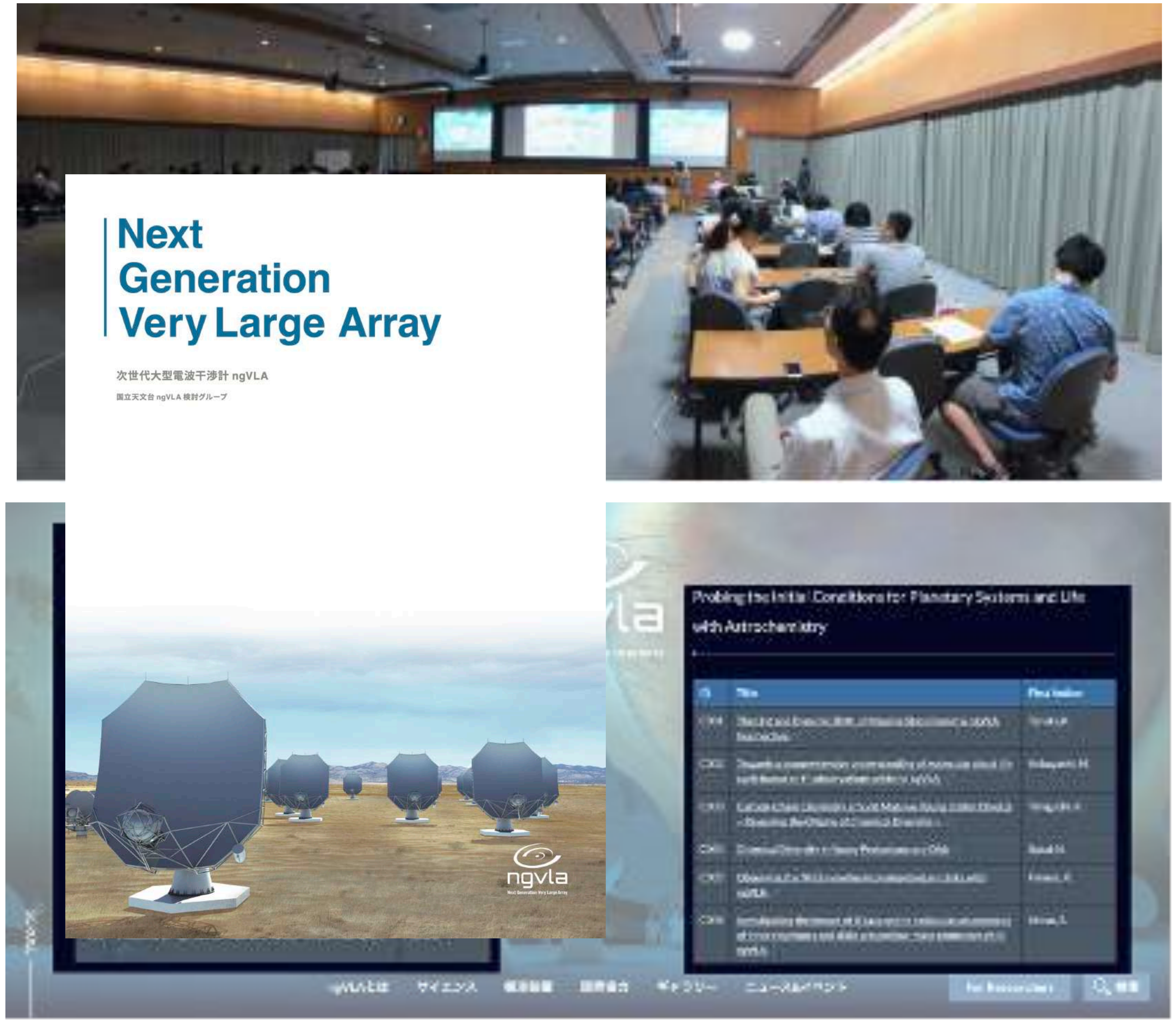
@NRAO/AUI/NSF

Involvement with NRAO

- NRAO is looking for <u>a few selected</u> international partners to contribute ~25% of the project costs.
  → We are anticipating to join with **~20% (max)** contribution from Japan (as of 2024 Dec).

Activities in Japan

- NAOJ-ngVLA workshop (2019 Sep, Mitaka)
  - 1st ngVLA workshop *outside* of US
- Kikaku-session in ASJ Annual Meeting (2021 Spring)
  - with >170 participants
- ngVLA Development Days (2021 July, online)
- <u>ngVLA-memo series</u>, <u>ngVLA-J Project Book</u> (2021)
- NAOJ invited key Working Groups (2020-2022):
  Total Power WG, VLA-ngVLA Transition WG, etc.
- Thematic session in ASJ Annual Meeting (2023 Autumn)



ngVLA Science/Technical Advisory Council (2024)

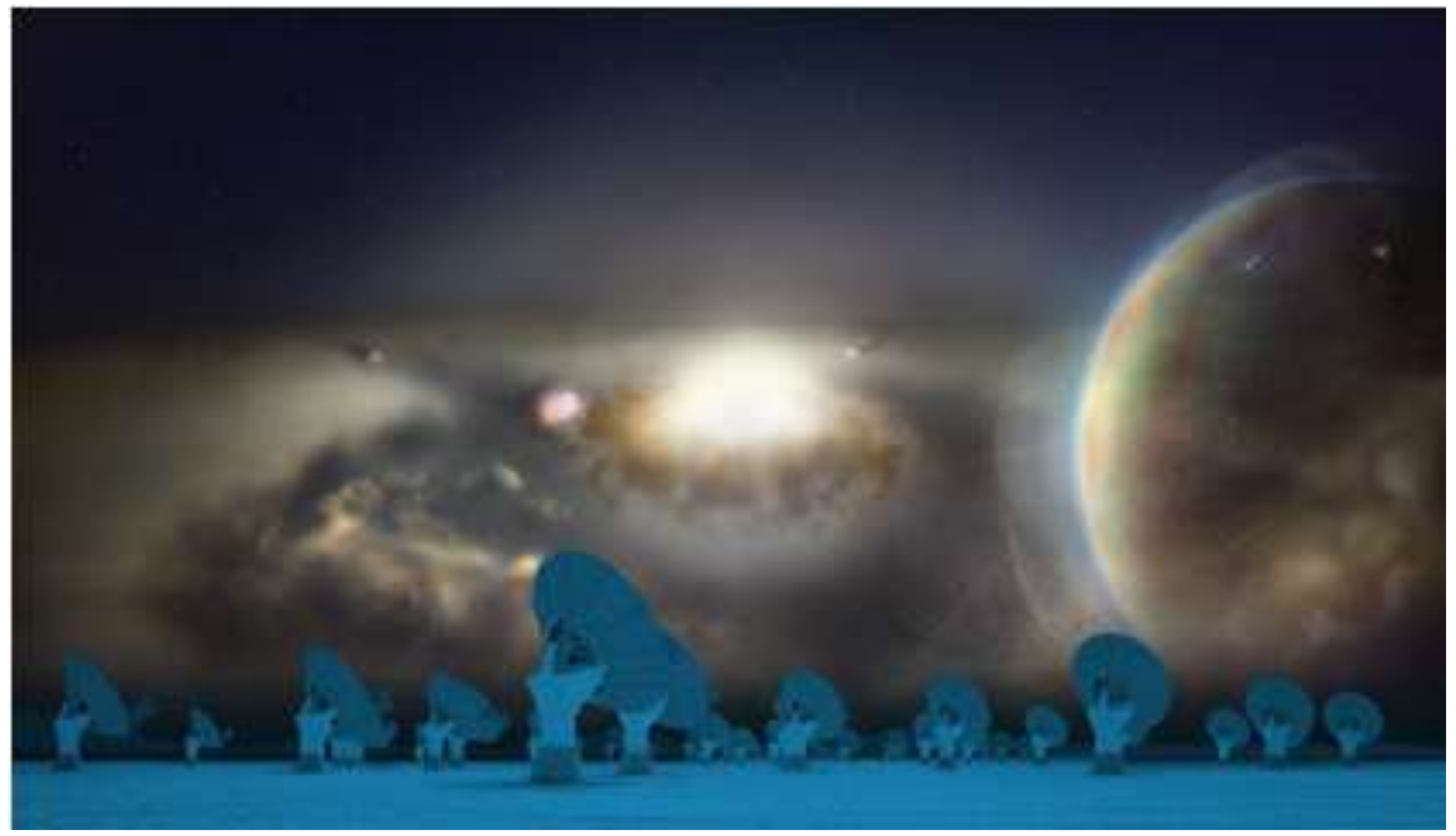
Science Advisory Council

Andrew Baker (Rutgers)
Ted Bergin (U Michigan)
Jennifer Bergner (U Chicago)
Laura Blecha (U Florida)
Geoff Bower (ASIAA)
Sarah Burke-Spolaor (West Virginia)
Carlos Carrasco-Gonzalez (UNAM)
Alessandra Corsi (Texas Tech)
Katherine de Kleer (Caltech)
Imke de Pater (Berkley)
Megan DeCesar (George Mason)
Mark Dickinson (NOIRLab)
Maria Drout (Toronto)
Gregg Hallinan (Caltech)
Bunyo Hatsukade (NAOJ)
Takuma Izumi (NAOJ)
Megan Johnson (US Naval)

Joseph Lazio (JPL)
Adam Leroy (Ohio State)
Thomas Maccarone (Texas Tech)
Brenda Matthews (NRC-Victoria)
Brett McGuire (MIT)
Betsy Mills (Kansas)
Munetake Momose (Ibaraki)
Cherry Ng (SETI)
Rachel Osten (STScI)
Erik Rosolowsky (Alberta)
Nami Sakai (RIKEN)
Rachel Somerville (Flatiron)
Alexander van der Horst (George Washington)
Fabian Walter (Max-Planck)
David Wilner (CfA)
Anton Zensus (Max-Planck)

Technical Advisory Council

Lewis Knee (NRCC)
Larry D'Addario (JPL)
Alvaro Gonzalez (JAO)
Tetsuo Hasegawa (NAOJ)
Yuh-Jing Hwang (ASIAA)
Stan Kurtz (UNAM)
Atsushi Nishimura (NAOJ)
Michael Rupen (NRCC)
Melissa Soriano (JPL)
Rob Selina (NRAO)



III. Key Science Goals and Japan’s Science Cases

Science Goals (grand picture)

1. *To understand the baryon cycle over the cosmic history*
2. *To understand the initial conditions to form life*

Scientific Objectives (five key science goals: KSGs)

KSG1: Unveiling the Formation of Solar System Analogues on Terrestrial Scales

KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present Day

KSG4: Using Galactic Center Pulsars for a Fundamental Test of Gravity

KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

These have defined the ngVLA's capabilities, hence are the minimum threshold science cases.

Scientific Objectives (five key sci… SGs)

KSG1: Unveiling the Formation of …

KSG2: Probin… ry

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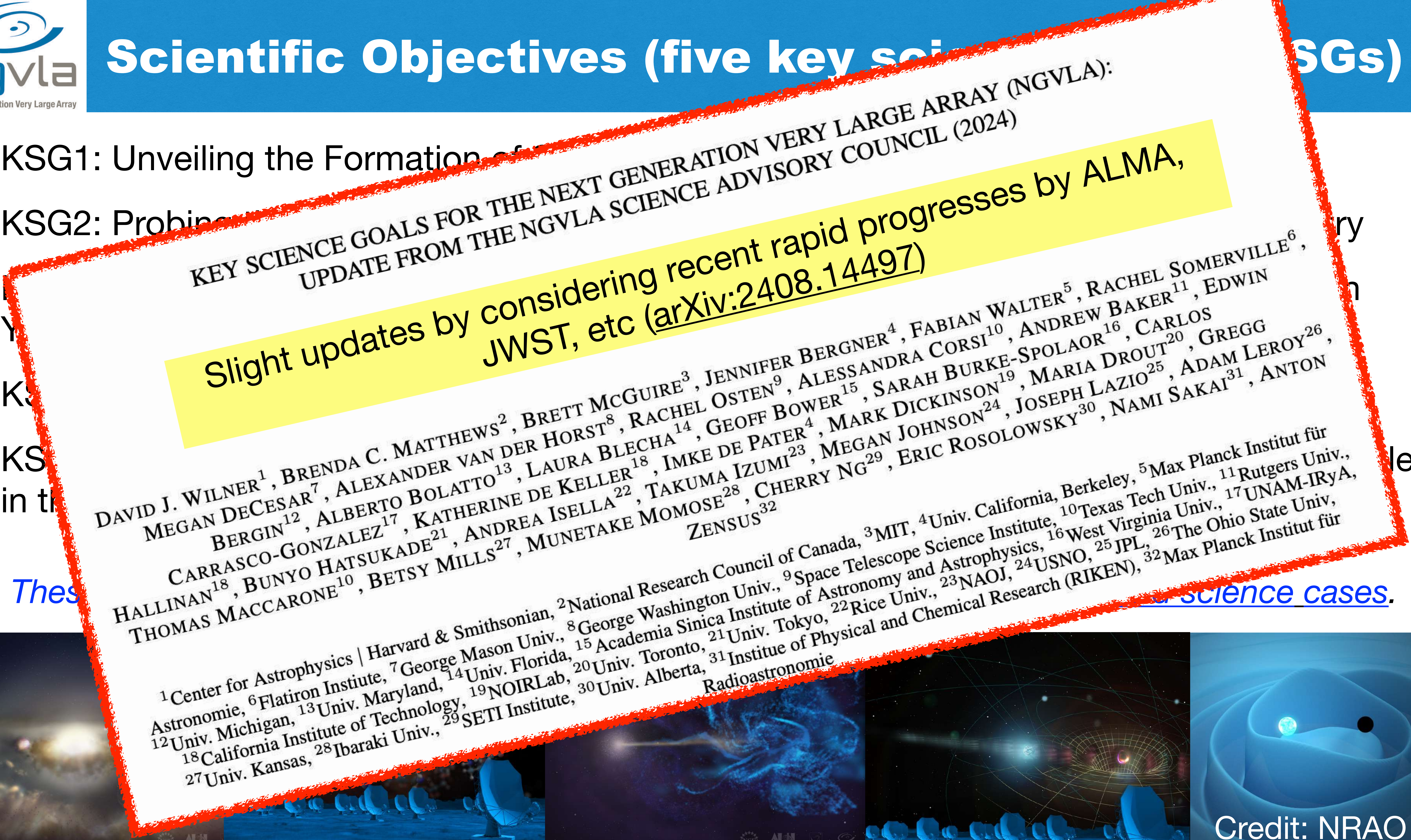

KEY SCIENCE GOALS FOR THE NEXT GENERATION VERY LARGE ARRAY (NGVLA): UPDATE FROM THE NGVLA SCIENCE ADVISORY COUNCIL (2024)

Slight updates by considering recent rapid progresses by ALMA, JWST, etc (arXiv:2408.14497)

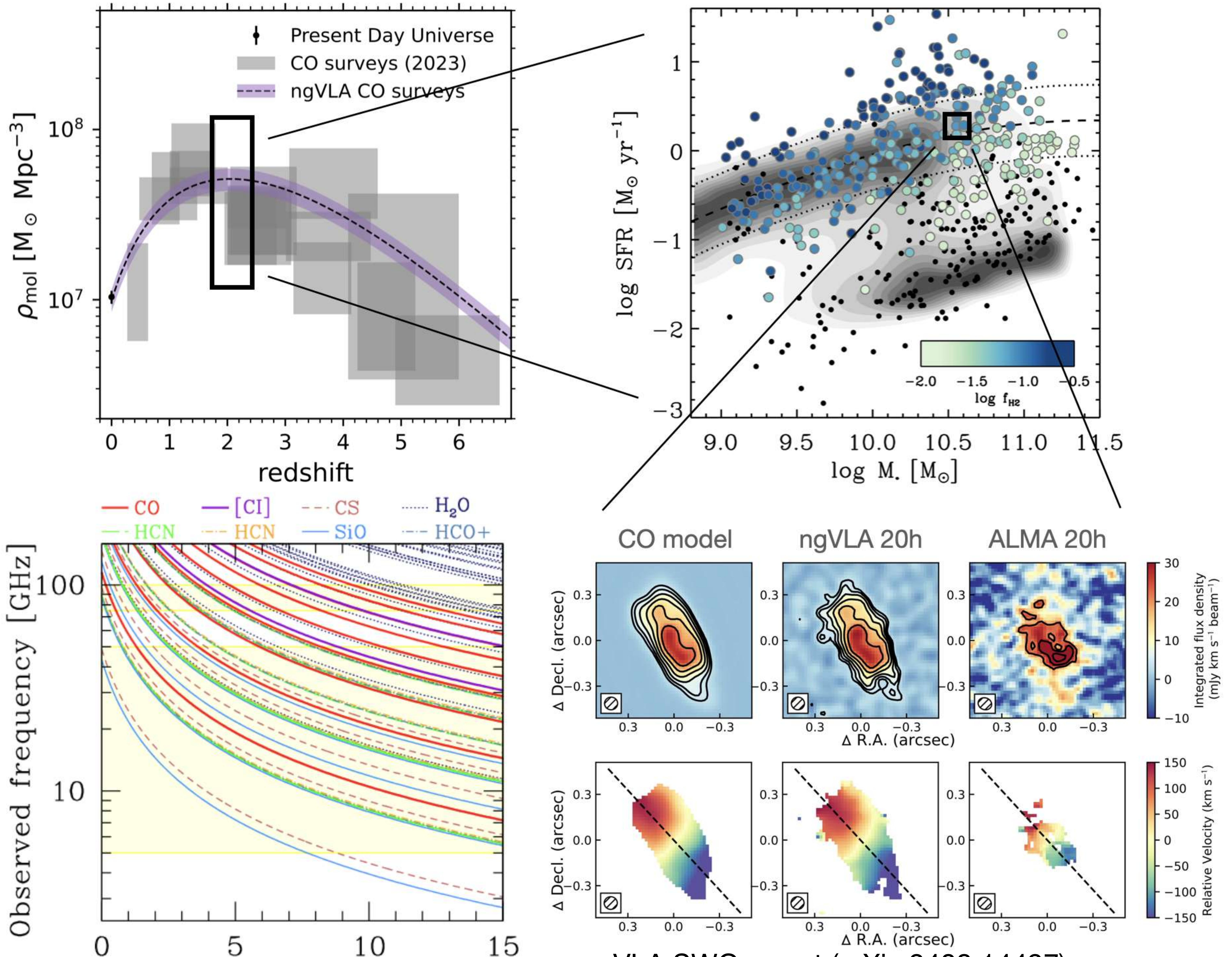
DAVID J. WILNER[1], BRENDA C. MATTHEWS[2], BRETT MCGUIRE[3], JENNIFER BERGNER[4], FABIAN WALTER[5], RACHEL SOMERVILLE[6], MEGAN DECESAR[7], ALEXANDER VAN DER HORST[8], RACHEL OSTEN[9], ALESSANDRA CORSI[10], ANDREW BAKER[11], EDWIN BERGIN[12], ALBERTO BOLATTO[13], LAURA BLECHA[14], GEOFF BOWER[15], SARAH BURKE-SPOLAOR[16], CARLOS CARRASCO-GONZALEZ[17], KATHERINE DE KELLER[18], IMKE DE PATER[4], MARK DICKINSON[19], MARIA DROUT[20], GREGG HALLINAN[18], BUNYO HATSUKADE[21], ANDREA ISELLA[22], TAKUMA IZUMI[23], MEGAN JOHNSON[24], JOSEPH LAZIO[25], ADAM LEROY[26], THOMAS MACCARONE[10], BETSY MILLS[27], MUNETAKE MOMOSE[28], CHERRY NG[29], ERIC ROSOLOWSKY[30], NAMI SAKAI[31], ANTON ZENSUS[32]

[1]Center for Astrophysics | Harvard & Smithsonian, [2]National Research Council of Canada, [3]MIT, [4]Univ. California, Berkeley, [5]Max Planck Institut für Astronomie, [6]Flatiron Institute, [7]George Mason Univ., [8]George Washington Univ., [9]Space Telescope Science Institute, [10]Texas Tech Univ., [11]Rutgers Univ., [12]Univ. Michigan, [13]Univ. Maryland, [14]Univ. Florida, [15]Academia Sinica Institute of Astronomy and Astrophysics, [16]West Virginia Univ., [17]UNAM-IRyA, [18]California Institute of Technology, [19]NOIRLab, [20]Univ. Toronto, [21]Univ. Tokyo, [22]Rice Univ., [23]NAOJ, [24]USNO, [25]JPL, [26]The Ohio State Univ, [27]Univ. Kansas, [28]Ibaraki Univ., [29]SETI Institute, [30]Univ. Alberta, [31]Institue of Physical and Chemical Research (RIKEN), [32]Max Planck Institut für Radioastronomie

Thes… science cases.

Credit: NRAO

Scientific Investigation (example)



ngVLA SWG report (arXiv:2408.14497)

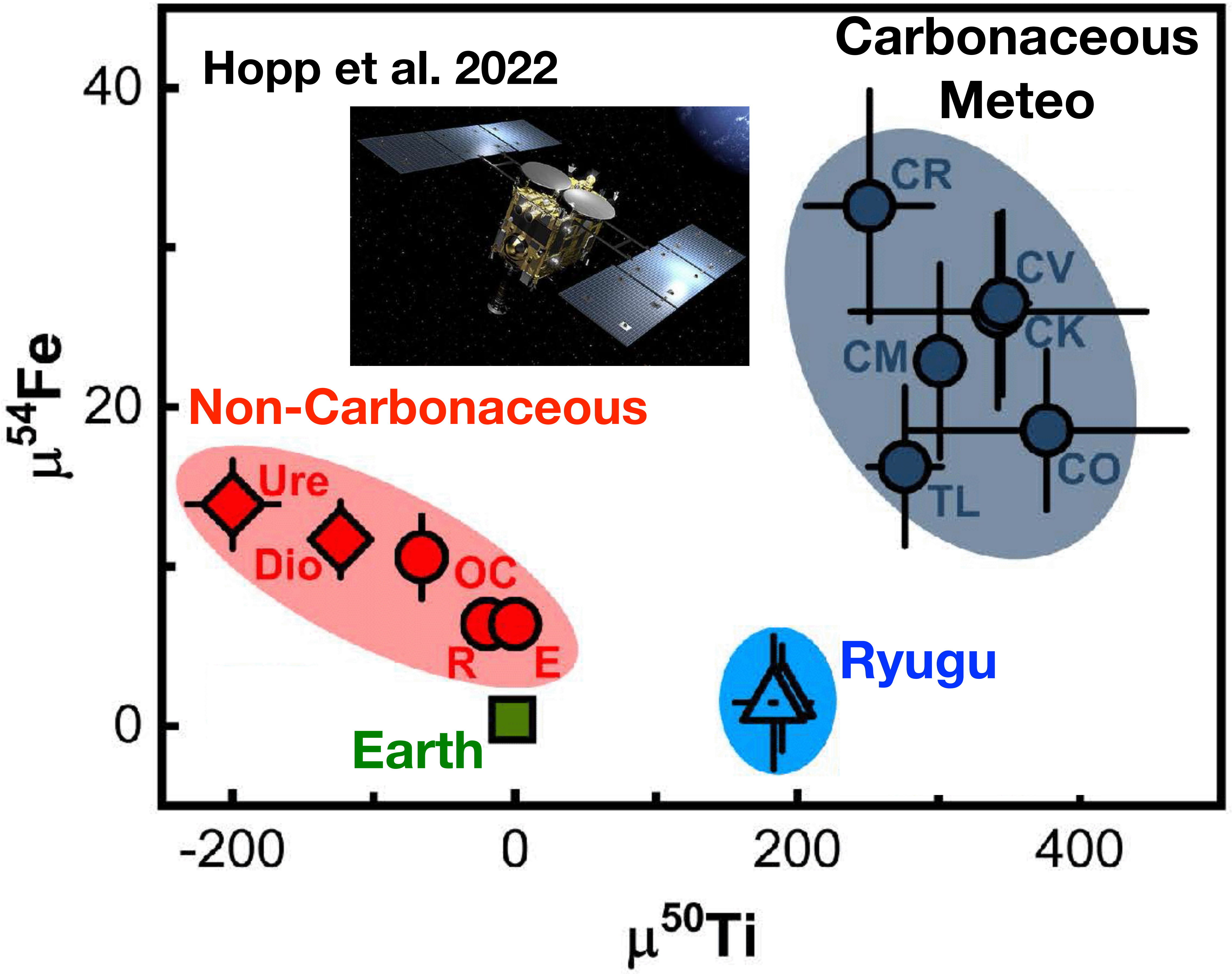
- The ngVLA can observe low-J CO lines in normal galaxies over a wide redshift range, allowing us to measure H_2 mass and gas mass fraction.
- The ngVLA will also offer spatially resolved measurements of cold molecular gas!
  → dynamical mechanism to drive star formation, AGN, etc.
- Various dense gas tracers can also be measured (strength of Japanese community: heritage from NRO).

Science Working Groups (SWGs) in Japan

- Each of the five SWGs is re-evaluating science cases that have strong appeal and showcase Japan's strength, taking into account the rapid recent advances by ALMA + JWST.
- Fostering unique science cases from Japan is the "must" until the operation of ngVLA.
→ What we will do (in terms of science) during the 第5期中期計画 (2028-2033) period.
- Example: SWG 1 + 2 Joint WS in Science Tokyo.
- Explore "material science" in collaboration with Solar system study groups.

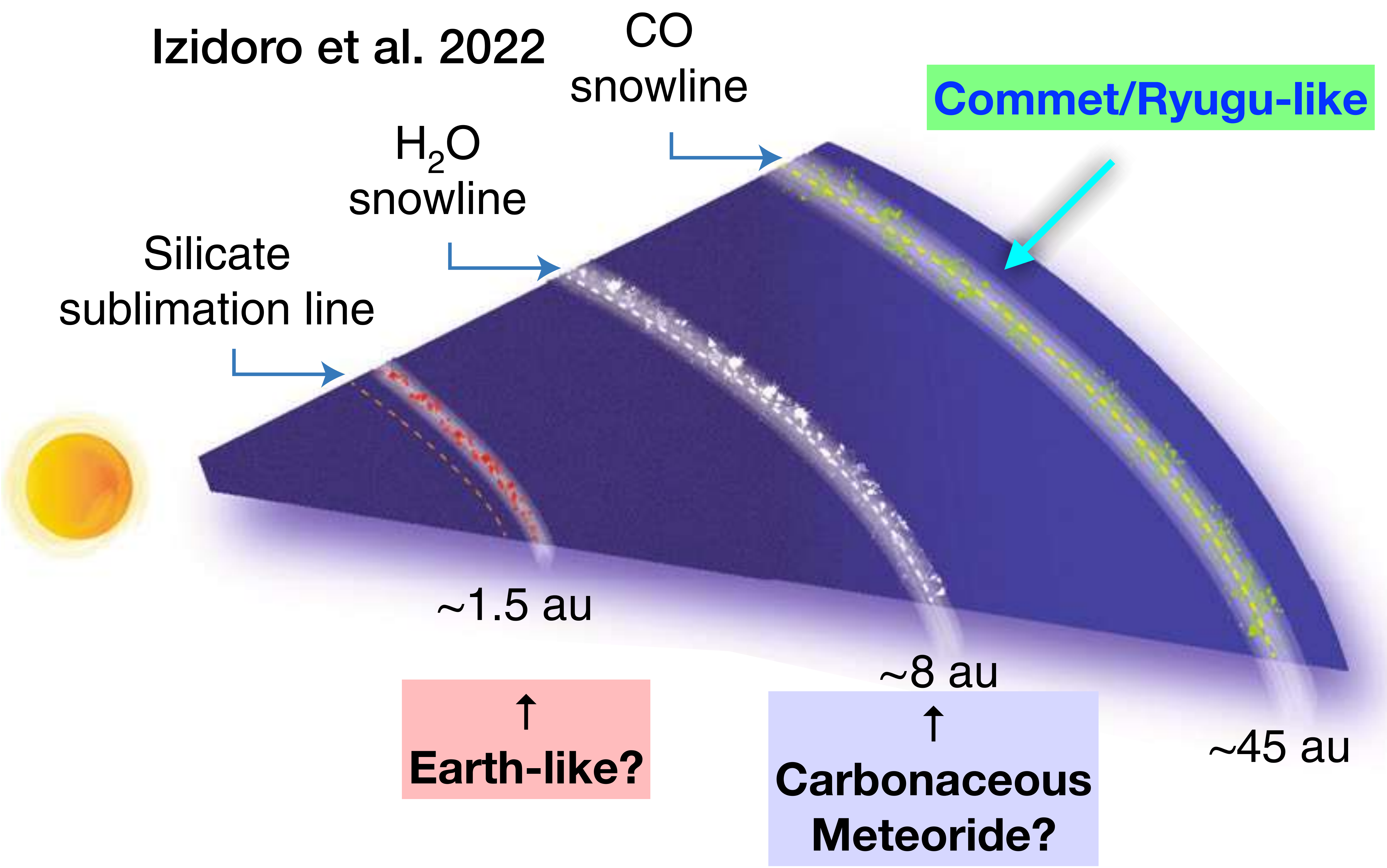
- We will summarize the Japanese interest and publish a "**White Book**" in this FY.
- Joint WS among Japanese SWGs will be held in 2025 or 2026.
…and international WS in 2026?

Science Case in Japan (example)



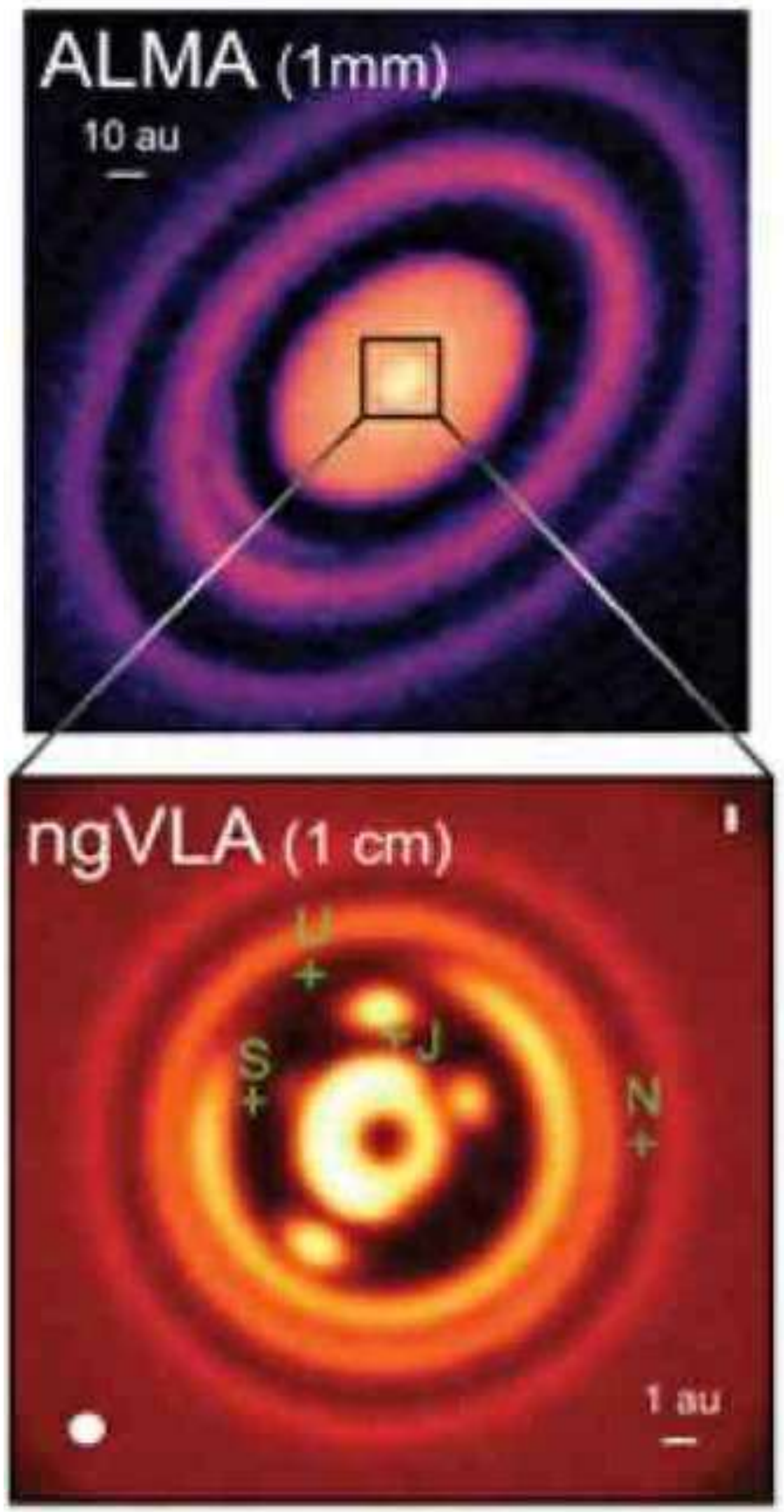
The different Fe and Ti isotope ratios suggest different origins of Solar system bodies (i.e., forming sites may differ).

Multiple rings detected by ALMA (= sites of planetesimal formation) are the origins??



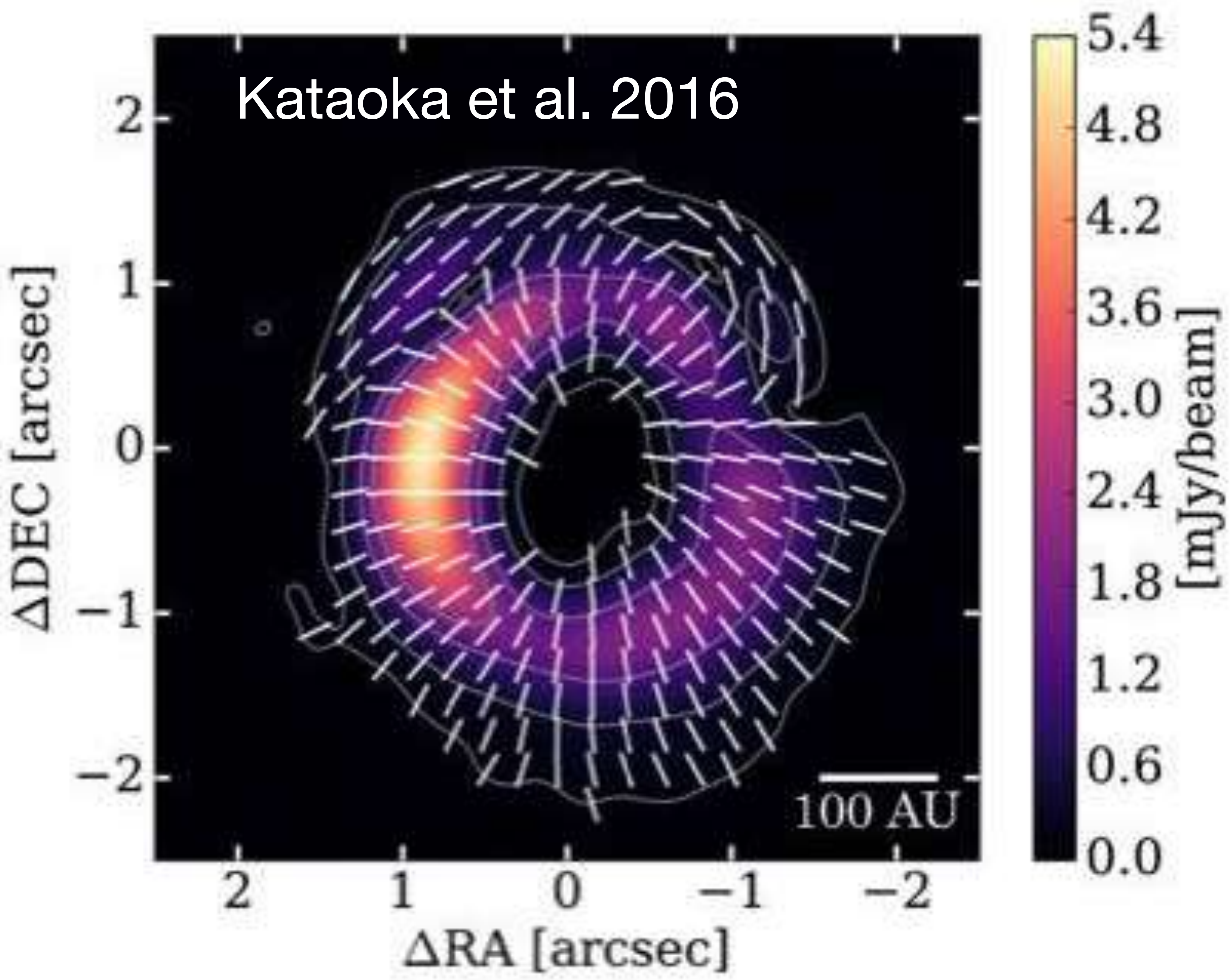
→ Very good synergy of astronomy and planetary science!!

Science Case in Japan (example)



Detect a forming rocky planet in the inner regions of porto-planetary disks via their substructures at ~5 mas (= 0.5 au at 100 pc) resolution.

- cm wavelength is critical to penetrate through the dusty disk.
- Japanese researchers advanced this research field so much!

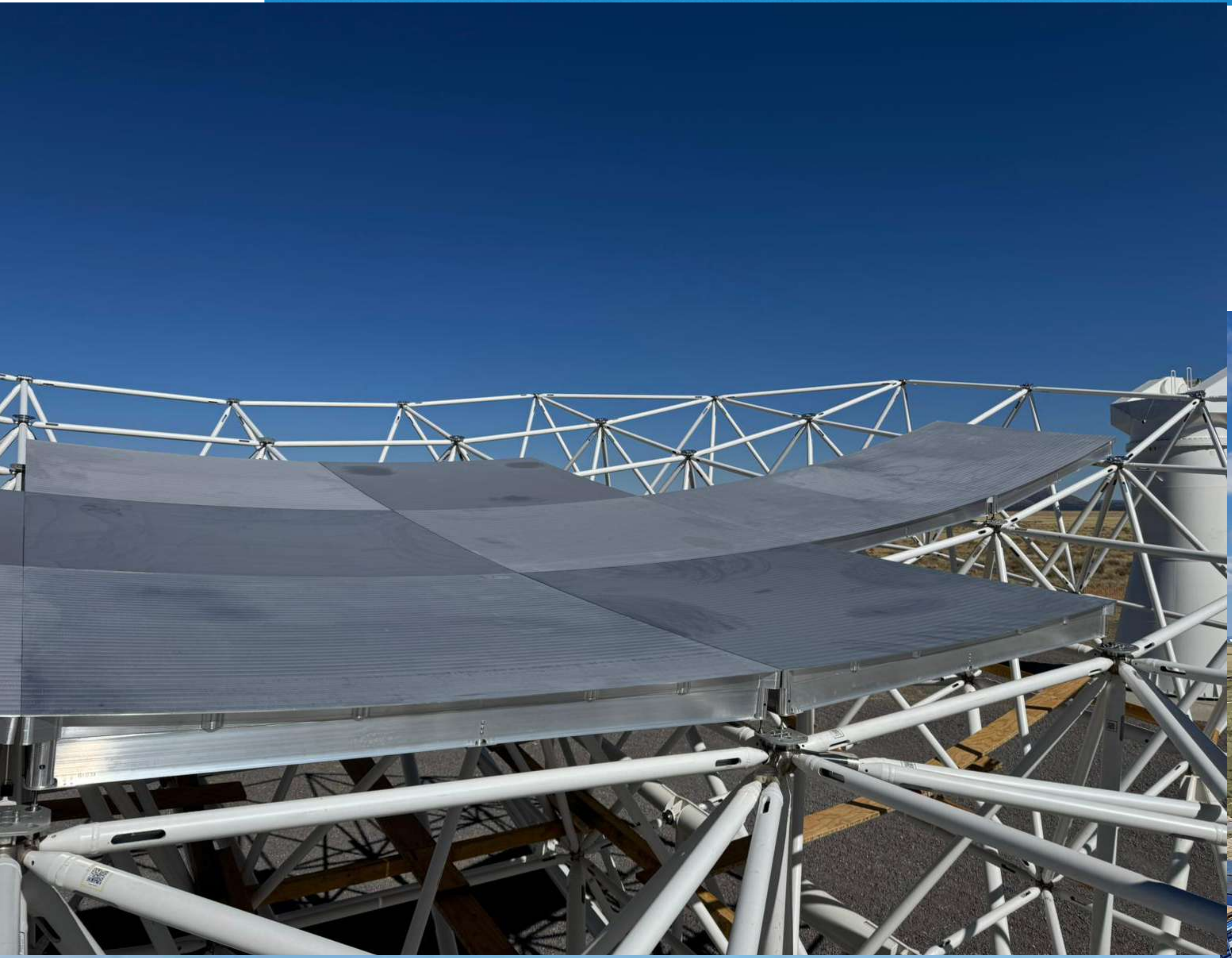


- Polarization observation puts tight constraints on the dust size in the disk.
  → sensitive to dust with size ~ wavelength/2π
- Bigger dust, and the spatial variation of dust sizes, will be detected with ngVLA.
  → Formation of planetesimal

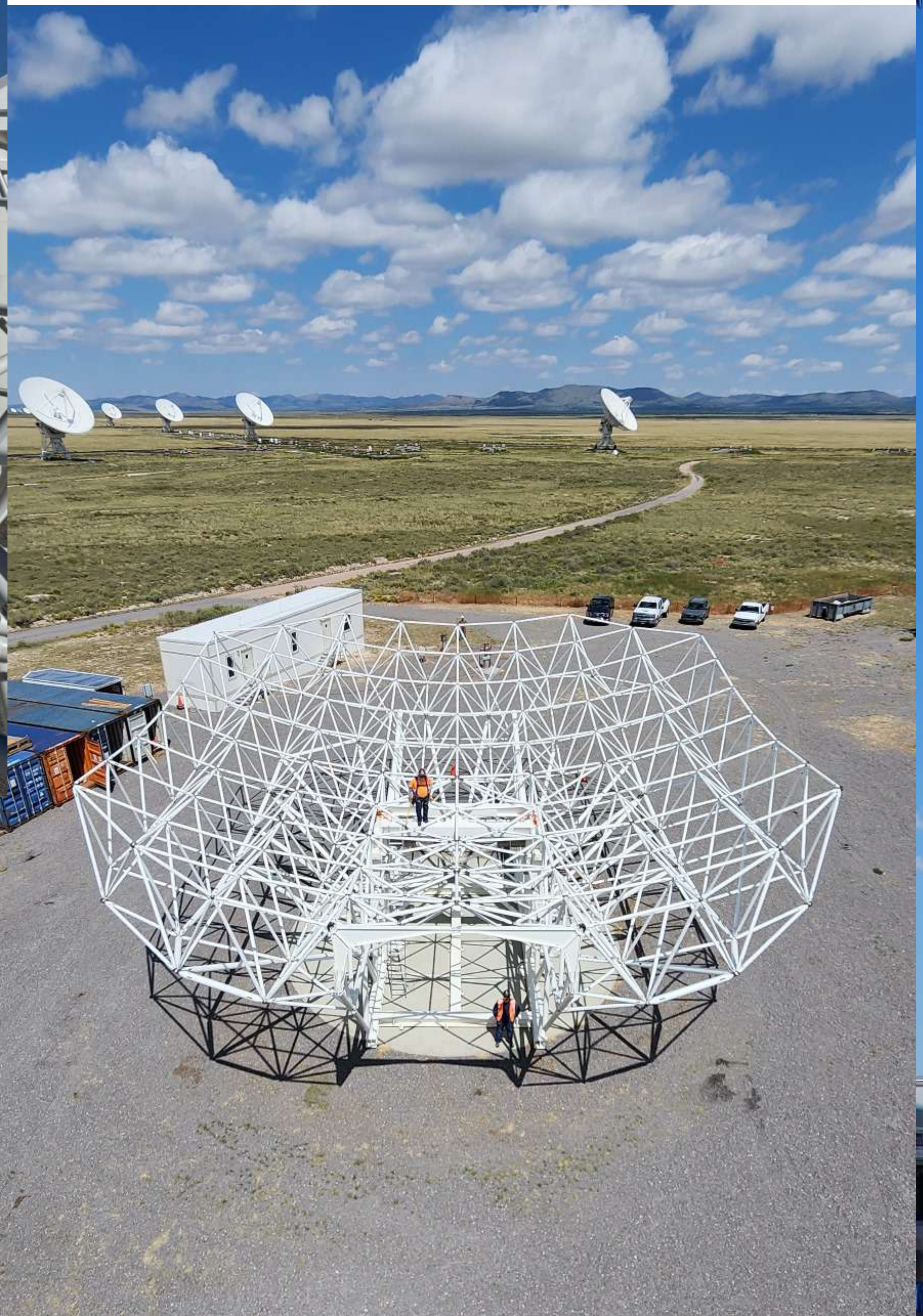
IV. Status of Technical Studies in Japan

We will do "in-kind" contribution (technology)

Prototype antenna in US



One proto is currently under construction at the VLA site



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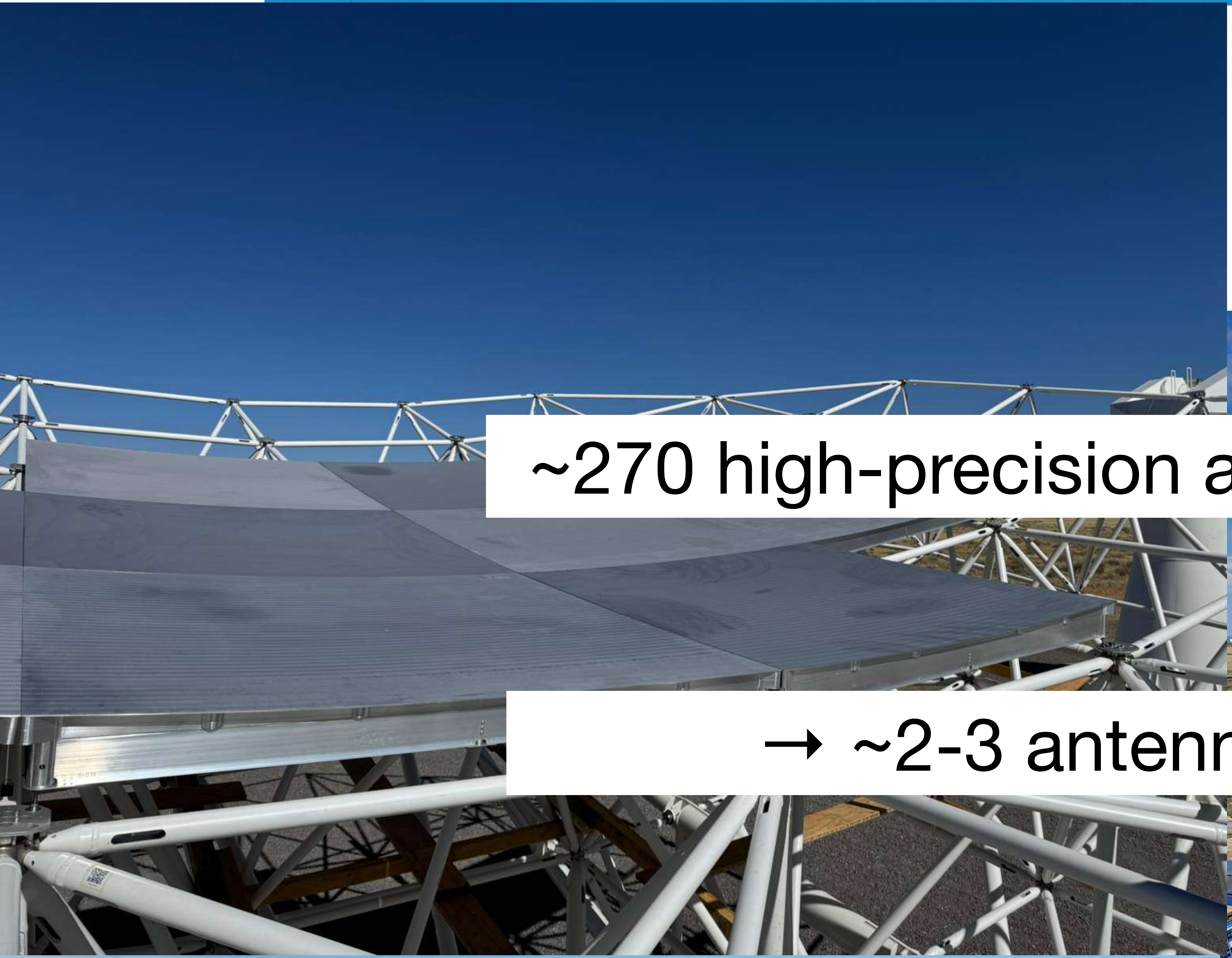
Prototype antenna in US

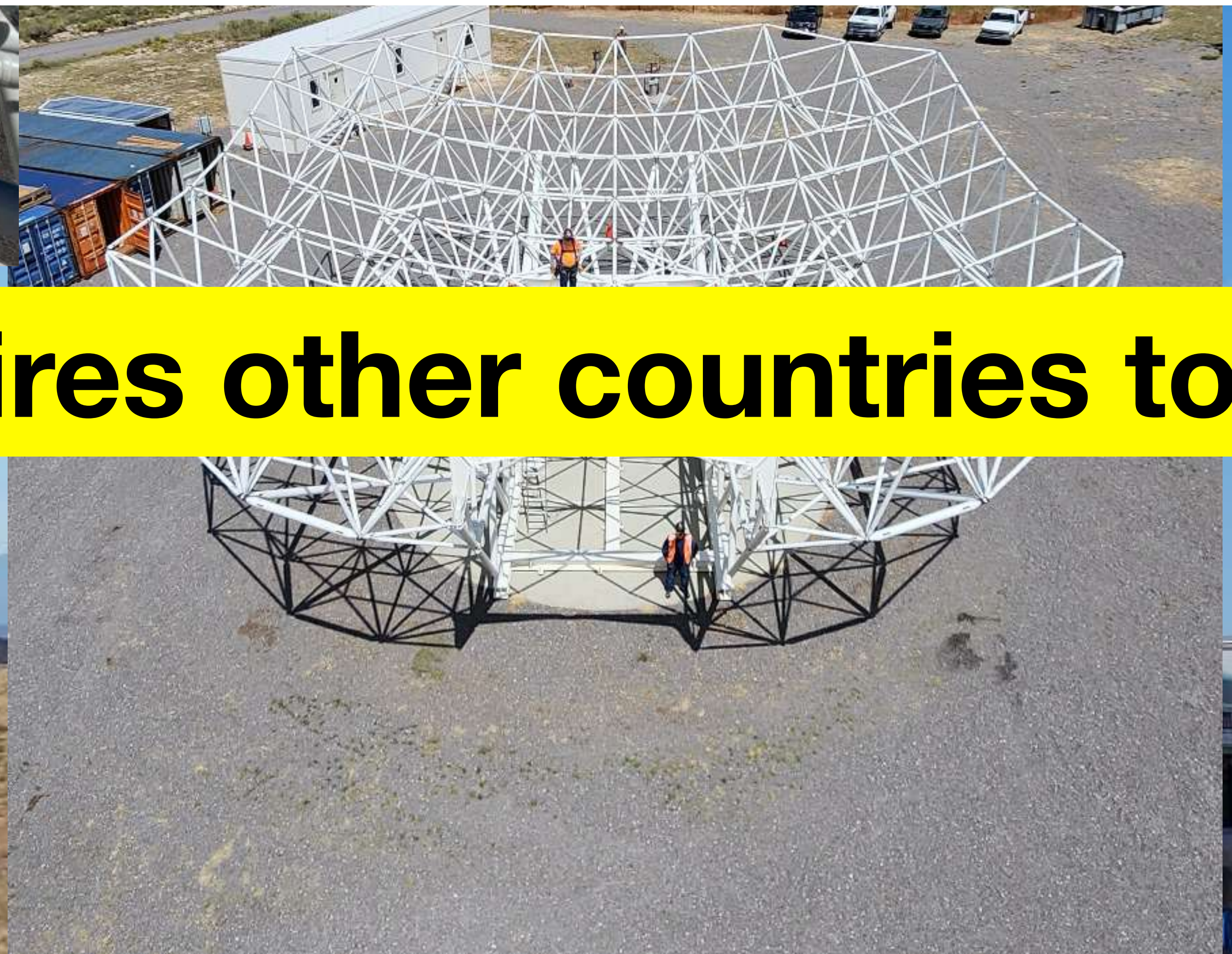
One proto is currently under construction at the VLA site

~270 high-precision antennas, constructed over ~7-10 years

→ ~2-3 antennas of this scale, ***per-month***…!

→ Definitely requires other countries to contribute!!




@NRAO

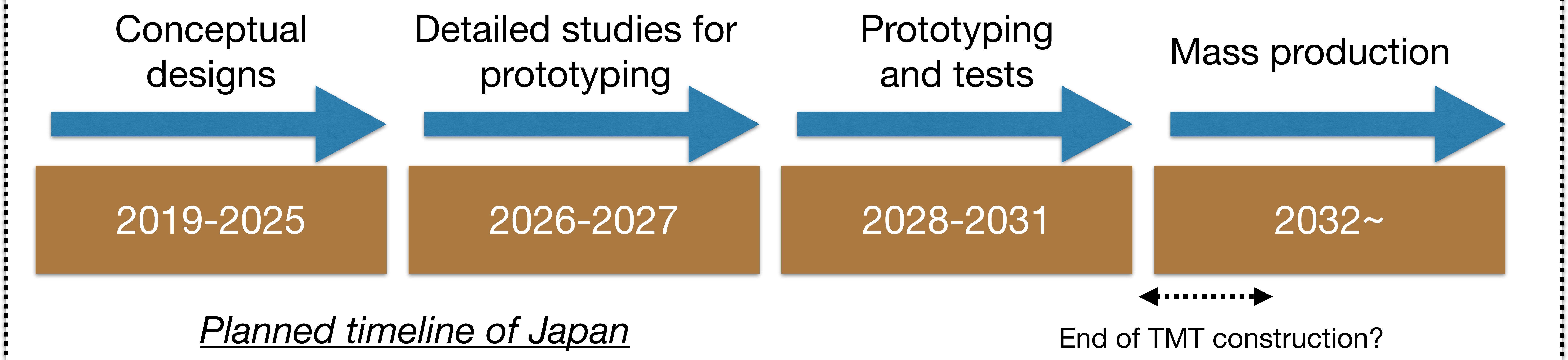
Development of ultra-low cost antenna in Japan

- Occupies the bulk of the budget → Critically impact the time amount available for Japan.
- Strict design criteria: Operation frequency (1.2-116 GHz), surface accuracy (320μm rms at 116 GHz), pointing accuracy, life-time-cost (No major maintenance over 20 yrs), etc.
- Japan is seeking for press-processing of antenna panels rather than the US machining approach.
- We have achieved basic antenna design (incl. panels, panel-support structure, and main frame) that meets the strict criteria.

Confidential (deleted)

Possible timeline of Japan (antenna)

- Possible contribution of ~20% of total number of antennas. **Up to 53 antennas**.
  → **30 × 18m antennas for LBA**, 4 × 18m for TP, and 19 × 6m for SBA.
- These can be contributed at a *later stage* of construction (i.e., **after TMT**).
- Operational in Japan as well! We can provide a new test-observing opportunity.



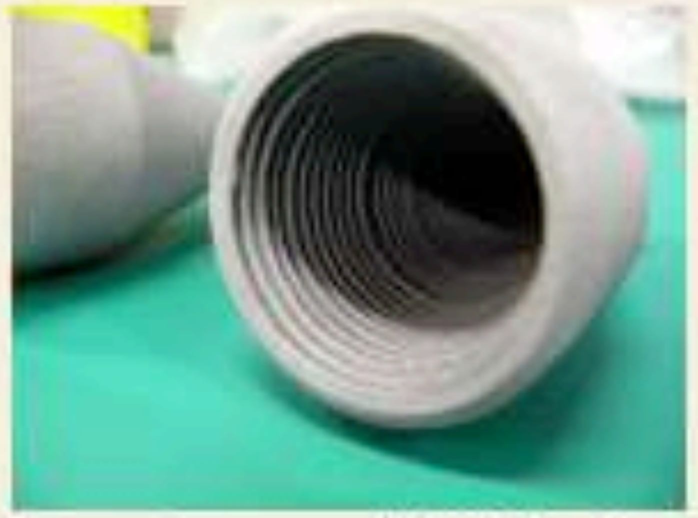
Planned timeline of Japan

Next Generation Very Large Array

In-kind contribution from ATC (NAOJ)

3-D printing

Development of 3D printing of receiver components for effective mass-production



35-50 GHz AlSi10Mg corrugated horn successfully fabricated and tested at cryogenic temperature

Gonzalez et al, IJIM, Oct 2021

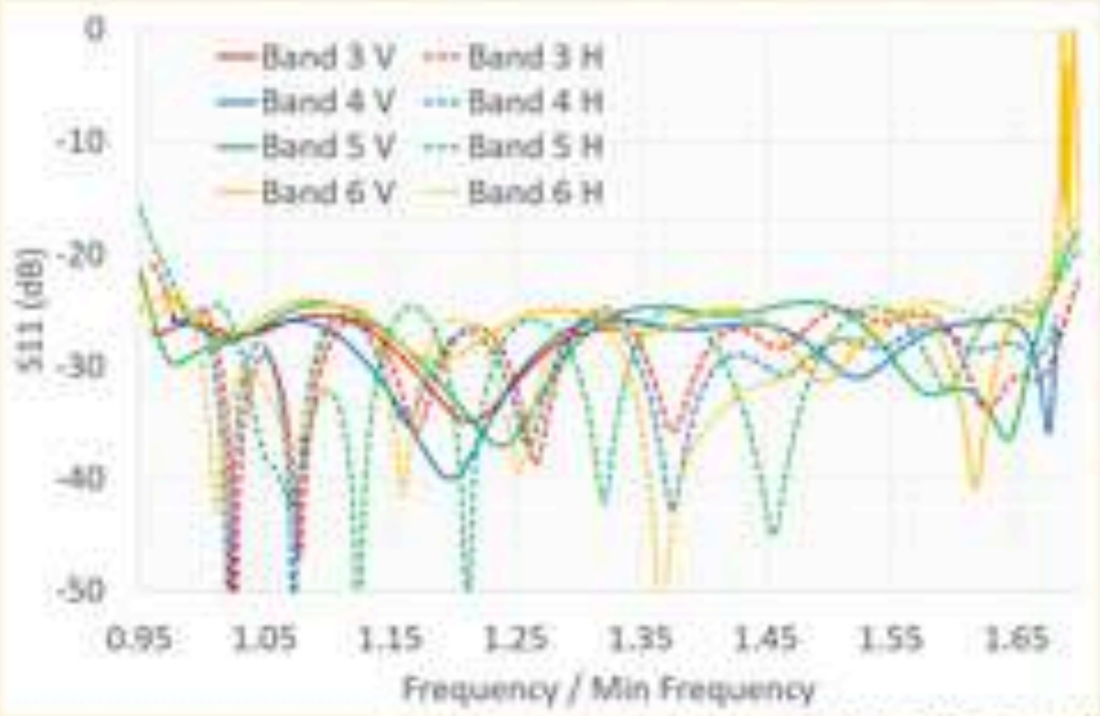
67-116 GHz AlSi10Mg corrugated horn + transition + OMT, fabricated in a single piece for improved performance

Gonzalez et al, SPIE 2020

Receiver development

Design of custom waveguide components for ngVLA receivers based on heritage from ALMA

Simulated performance of OMTs designed for ngVLA bands 3 through 6, all of them better than -24 dB at all frequencies

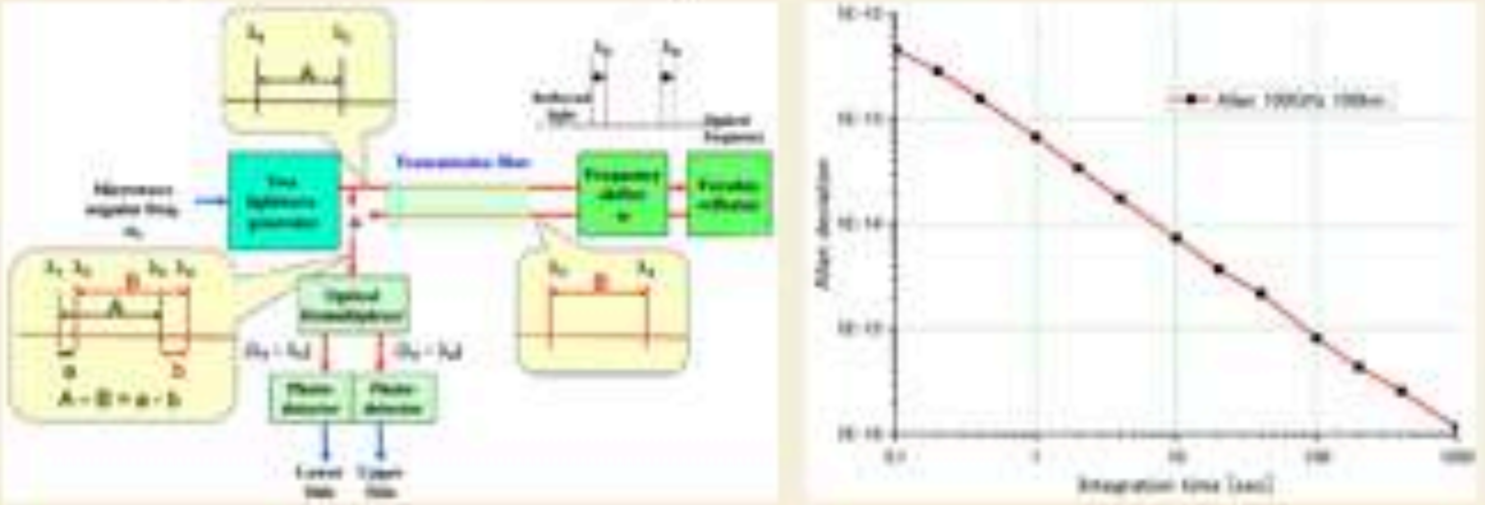


Gonzalez, IEEE AP-S/URSI 2020

Photonic technologies

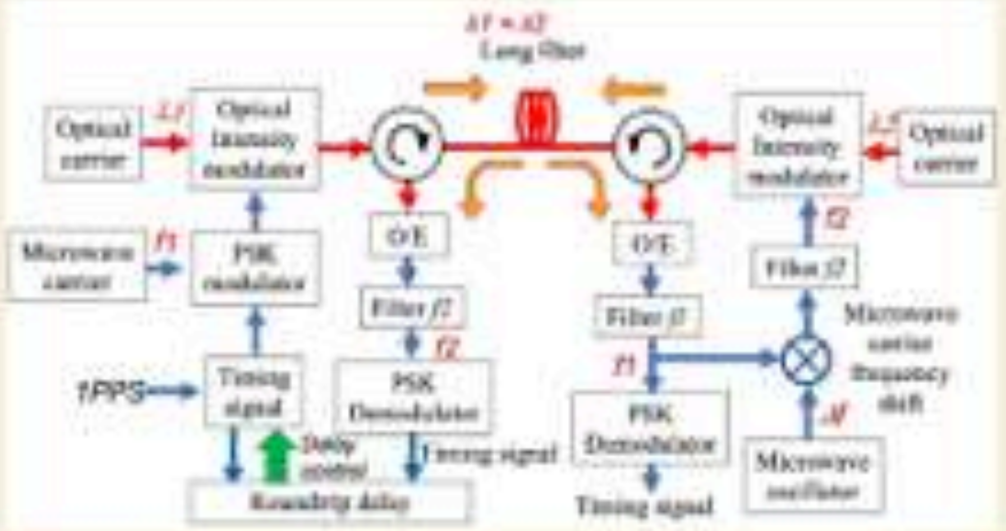
NAOJ proposals included in the conceptual design of ngVLA: time and frequency distribution systems

Measured transmission phase stability of 100GHz signal through a 250 km fiber spool using a novel technique



Kiuchi, Shillue, SPIE 2020

Novel high-accuracy time distribution successfully demonstrated over 250km



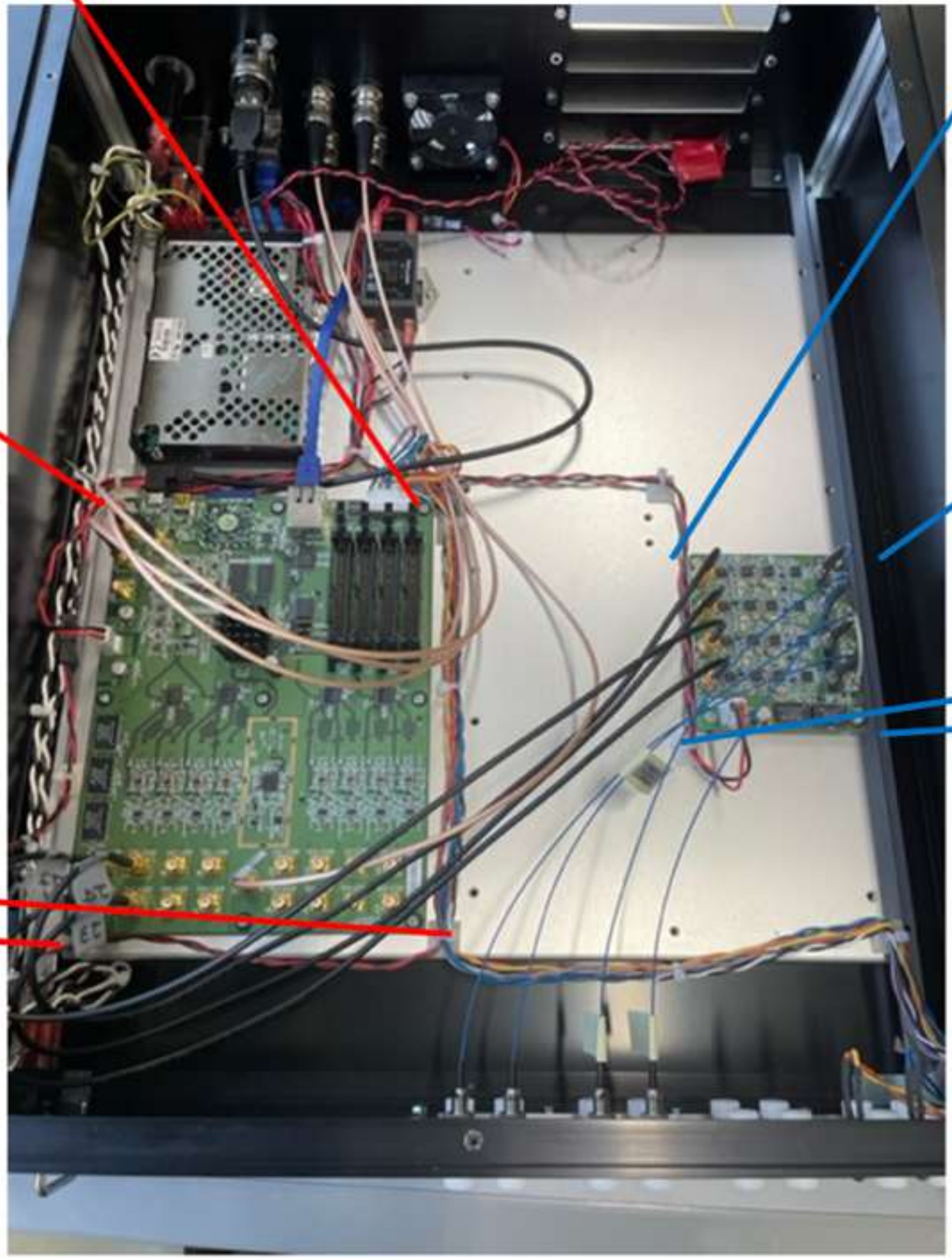
Kiuchi, IEEE Photonic Tech. Letters, 2022

NAOJ Advanced Technology Center is leading the field in several advanced technologies which can be readily applied to ngVLA: time and frequency distribution systems, waveguide components in receivers fabricated by 3D printing…

Frequency Reference Distribution System

by Kiuchi-san@ATC

Frequency transfer system
Prototype for commercialization.
Optical circuit will be housed on the back side. 19-inch chassis (3U height).



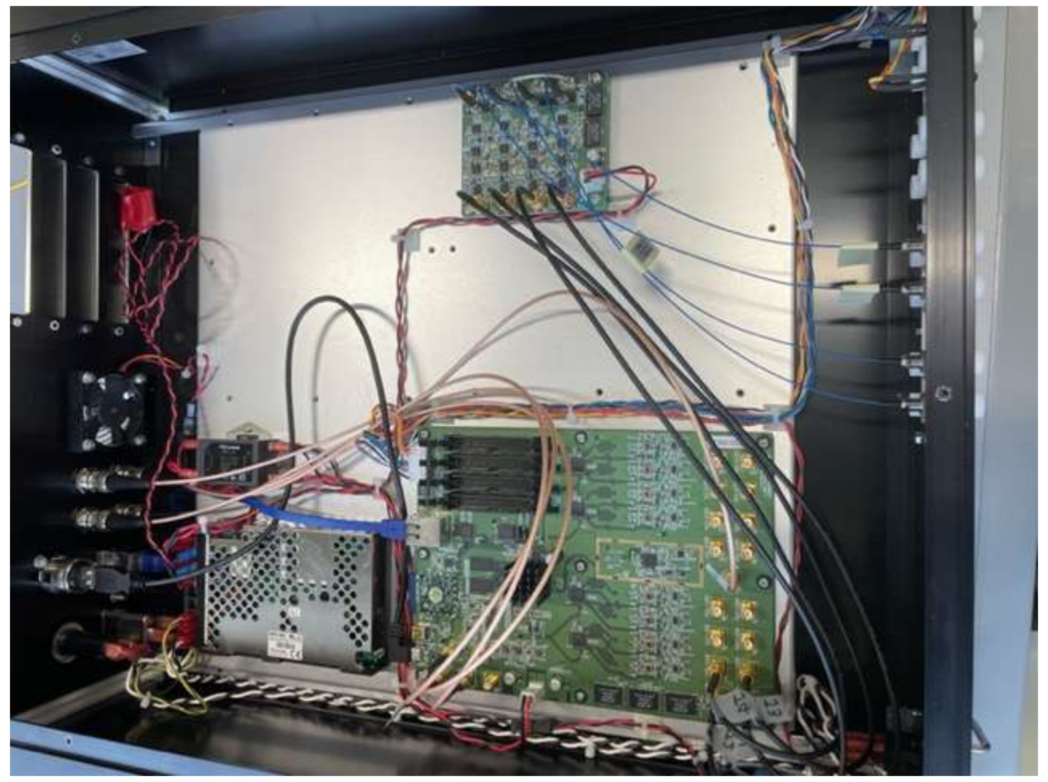
FPGA board for roundtrip phase measurement for 8 stations

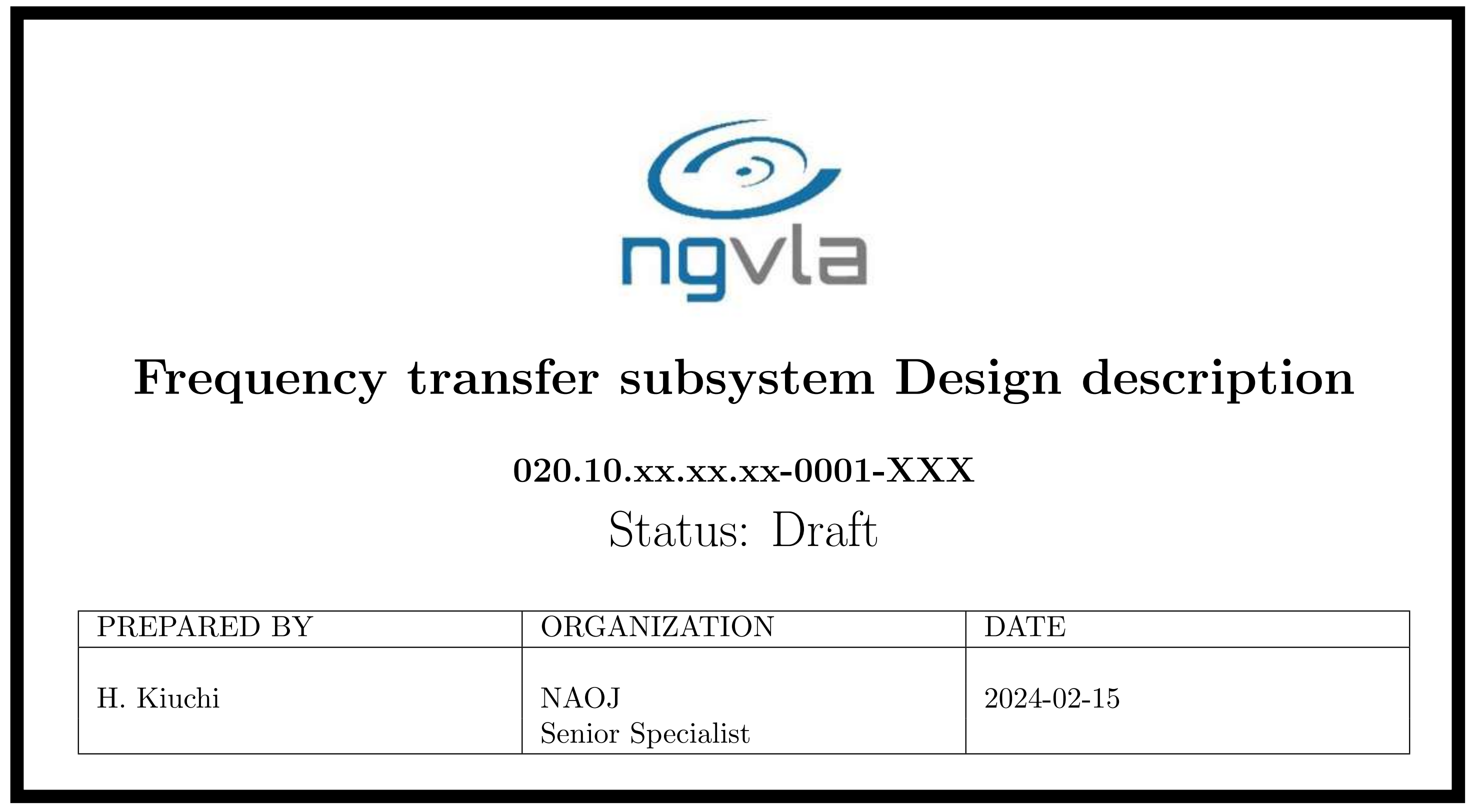
APD board for 2 stations.

The other two boards will be delivered before the end of the year.
The remaining one could not be purchased due to budget constraints.

Frequency Reference Distribution System (Passed CoDR)

- Fundamental element of interferometry to distribute time/freq. reference to array elements.
- Now successfully passed the NRAO's CoDR, allowing us to start official technical studies.
- Laboratory experiment at NAOJ by using a 400km fiber successfully showed a real-time phase compensation, and then a highly stable phase.





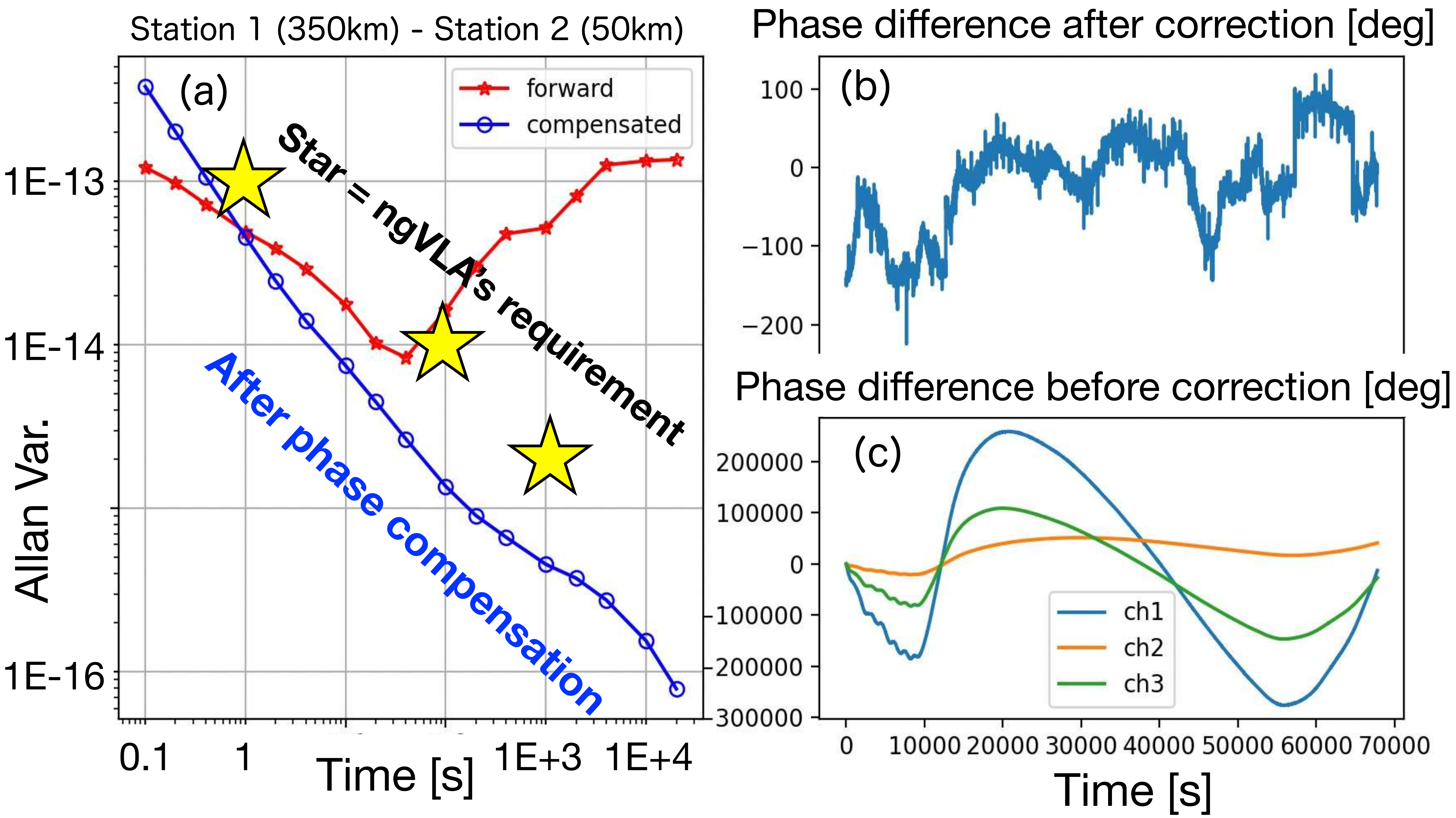
ngvla

Frequency transfer subsystem Design description

020.10.xx.xx.xx-0001-XXX

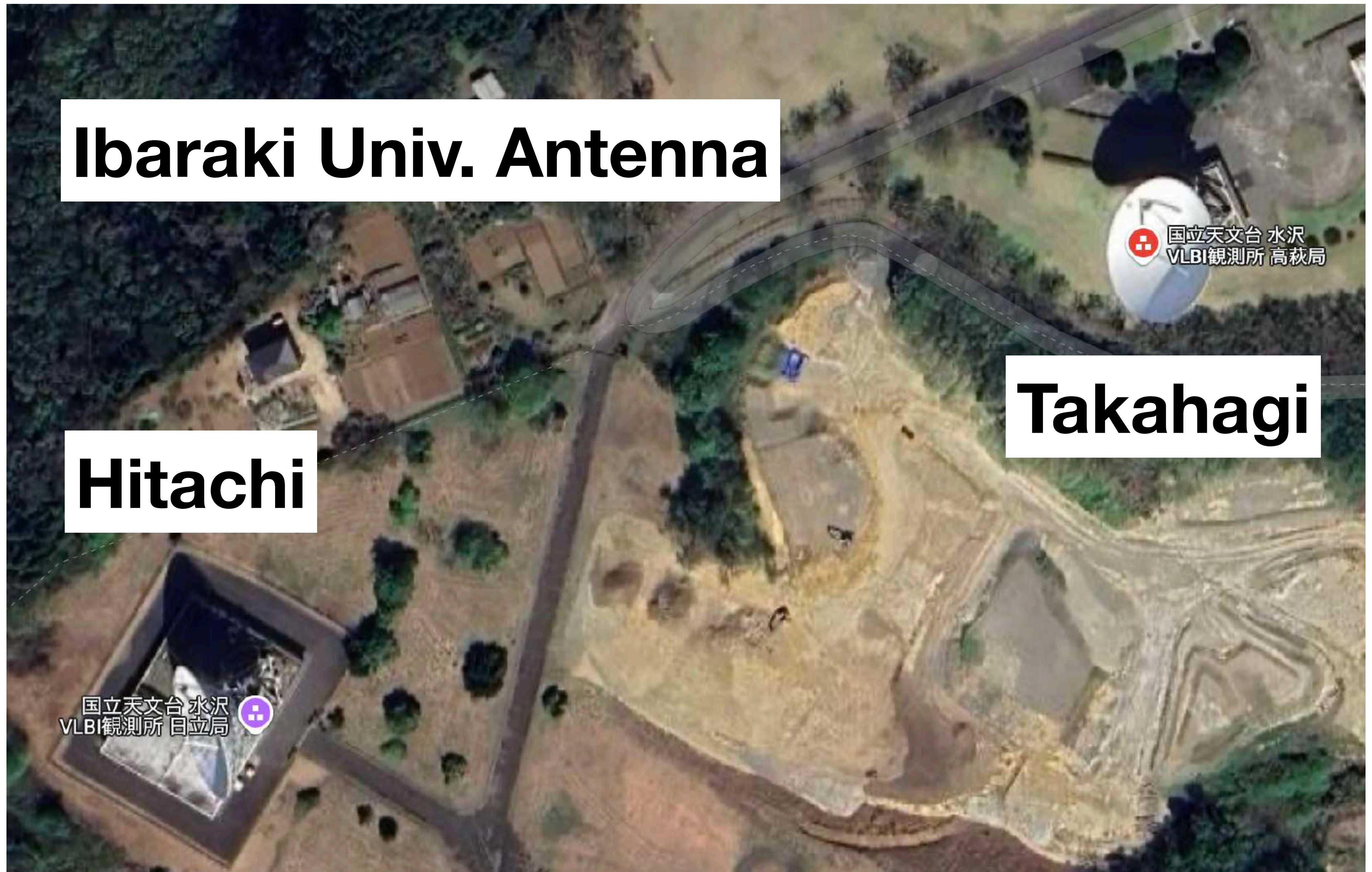
Status: Draft

PREPARED BY	ORGANIZATION	DATE
H. Kiuchi	NAOJ Senior Specialist	2024-02-15



Frequency Reference Distribution: What's next?

- Performance system-installation tests in collaboration with NRAO, by using the real prototype 18m antenna in Socorro.
- Going to do outdoor-test including (1) Performance of the system when fibers are placed under realistic outdoor environment, (2) Performance test when fibers are set as "overhead wiring".
  → To show we can indeed overhead-wire the system, which reduces the cost of tunneling.
- We are planning to use Ibaraki Univ.'s Hitachi antenna, as well as the rail-road of NRO.



V. NAOJ’s initiative

ngvla
Next Generation Very Large Array

One of the great upcoming Large-Scale Facilities

- The ngVLA will play a key role in scientific discovery together with TMT, ALMA, etc.
- The involvement of NAOJ is clearly in-line with the NAOJ's Vision and Mission:
  - ✦ To be innovators striving to solve the mysteries of the universe.
  - ✦ To develop and construct large-scale cutting-edge astronomical research facilities and promote their open access aiming to expand our intellectual horizons.
- ngVLA satisfies all key points for NAOJ participation:
  - ✦ One of the most advancing observing facilities
  - ✦ Open use
  - ✦ Flexible international cooperation
  - ✦ Strong synergy with ALMA, Subaru, and TMT

- Trusted, well-established collaboration between NAOJ and NRAO (through ALMA).
- Expected huge budget scale (~650M USD) is not manageable by universities…!

ngvla
Next Generation Very Large Array

Planned contribution (budget)

~20% Japanese contribution (~650M USD; incl. 10-yrs operation) to the ngVLA project

→~20% of the ngVLA observing time (~1600 hrs/yr) for the Japanese community.
Same level as we now have for ALMA.

A good mix of Japanese **in-kind contributions** to the project tentatively agreed between NAOJ and NRAO

Phase of the project	Japanese Deliverables to the ngVLA project
Construction and commissioning	• Antennas (up to 53 units in LBA, SBA, TP) • Photonic technologies: frequency/time reference distribution systems • Receivers (design of components, prototyping and mass-production at ATC) • Cryogenics: cold-heads, compressors, dewars • Commissioning of observing modes and software development
Operation	• Maintenance (antenna, cryogenics, receivers, photonics, etc) • Development + maintenance of software / archive (integrated computing team) • User support and science promotion (like ALMA Regional Centers)

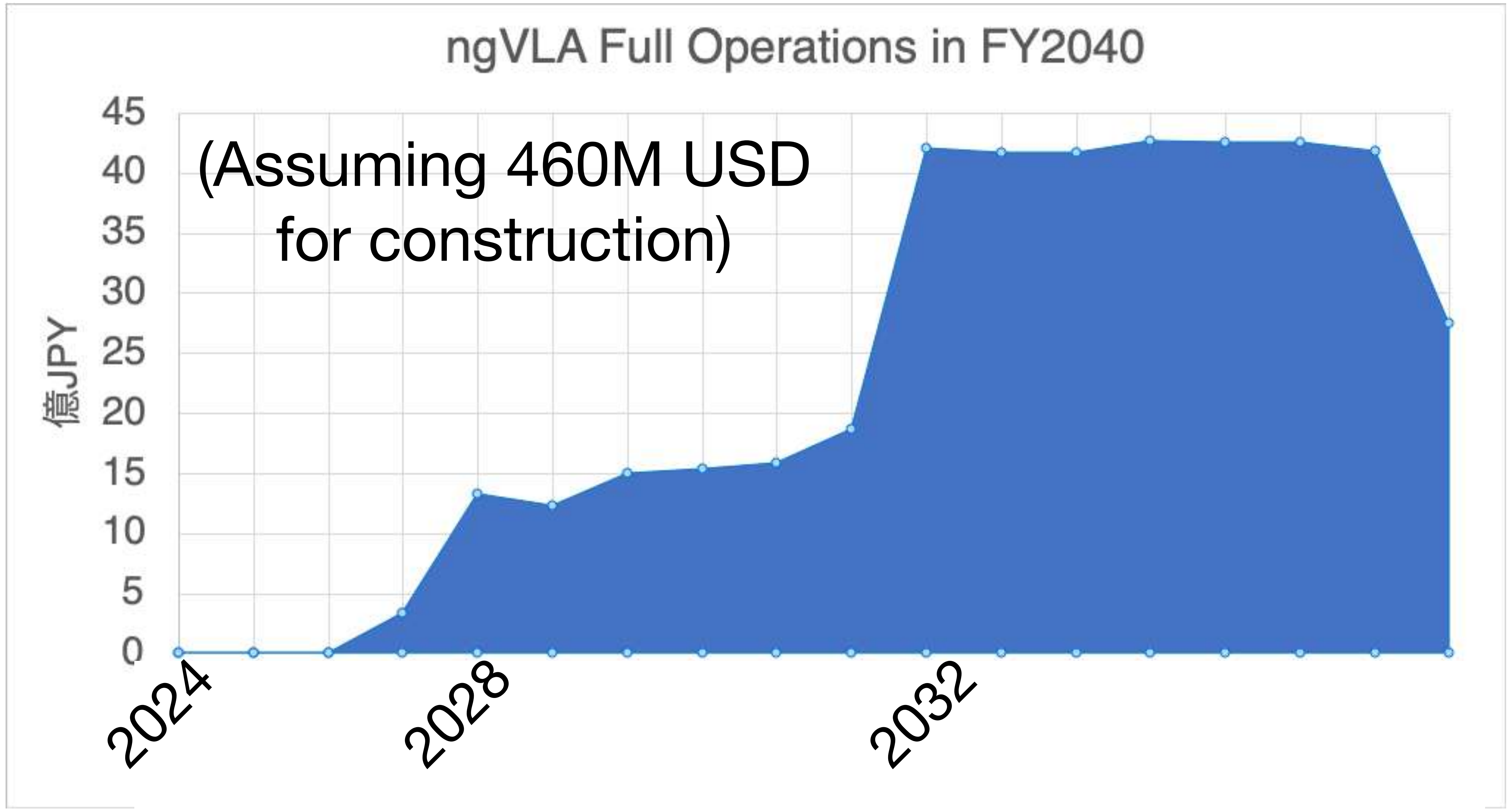
VI. Budget plan

Budgetary considerations in Japan

- The total construction cost is estimated by NRAO as 2,300M USD.
- ~75% (~1,725M USD) will be covered by the US.
- Remaining ~25% (575M USD) is contributed by trusted international partners.
- The ngVLA Study Group aims that Japan joins the ngVLA collaboration at a ~20% level through the international contribution channel, which will amount to ~460M USD for the construction.
- The operation cost is estimated to be 93M USD/yr → ~19M USD/yr for 20% contribution
- Hence, the total cost, including 10 yr operation, amounts to 460M + 10×19M = **650M USD**.

Budgetary considerations in Japan

Example



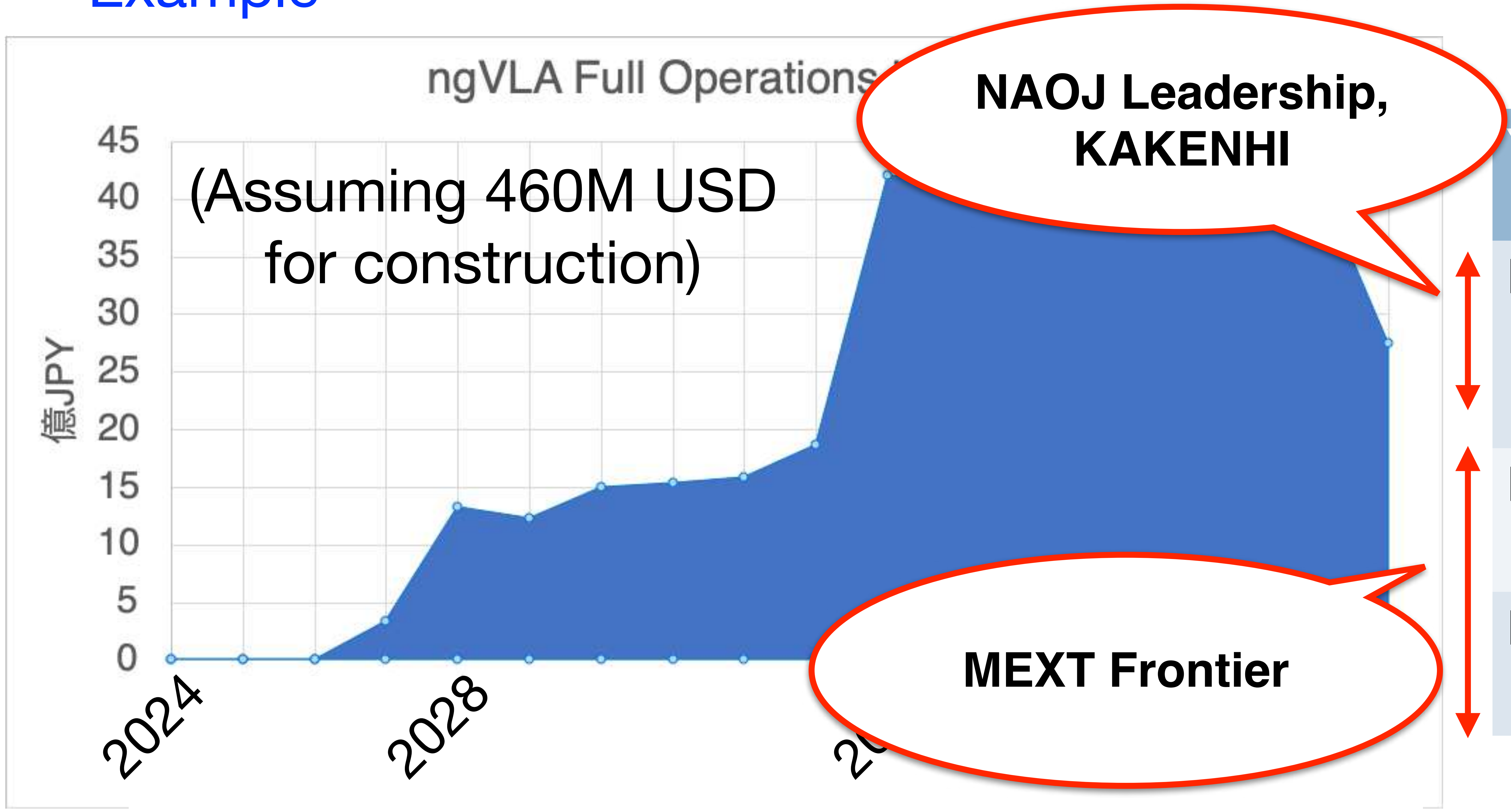
Year	Scale per year	Budget Use
FY2024-2027	< 0.15 億JPY	• Detailed studies and preparation towards prototyping
FY2028-2031	12-19 億JPY	• Prototyping (incl. antennas) and testing
FY2032-	42 億JPY	• Starting full construction • Operation

- Japan needs to be ready to contribute heavily (~20%) to the construction (mostly antenna).
- However, we also need substantial budget from FY2028 (prototyping).
- Highest priority would be TMT until the end of its construction (~2032) both for US and Japan.
- Construction budget will then ramp up from ~2032-2033. Large-scale budget is necessary.

ngvla
Next Generation Very Large Array

Budgetary considerations in Japan

Example



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VII. Summary

Toward the Major Participation to the ngVLA Project

High demand from the community for a next generation PI-driven cm/mm instrument

- Strong community's interest (many participants in WS, strong recommendation by Udenkon)
- Increasing number of *Japanese ngVLA publications* (memo series, project book)

Japanese contribution based on the experience in ALMA construction and operation

- Various items with high technical readiness (antennas, receivers, photonics, cryogenics)
- Rich experience in commissioning and software development together with NRAO
- Well-established connections with industry

Synergies and integration within NAOJ

- Open-use operation with full user support (like ALMA) → maximizing know-how and experience
- First-case of combined operation with VLBI → efficient

Impact on industry and universities

- Possibility of large-scale involvement of Japanese industry
- Positive impact on engineering and technology for manufacturing (e.g., 3D printing @ATC)
- Wavelength observable from Japan: possibility to test prototypes on-sky and to do actual observations
- Possibility to collaborate with universities/institutions: Education, domestic projects, etc.