NAOJ Future Planning Symposium 2023
2023 Nov 7-8 @NAOJ

The Next Generation Very Large Array : planning towards a Japanese contribution

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& Munetake Momose (ngVLA Science Working Group)

Very Large Array (1980-)

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

x10 sensitivity
>x10 ang. resolution

ngVLA (2033~)

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

- ngVLA LBA will be an upgrade of the VLBA (major VLBI facility in the US)
- ngVLA will then become the major VLBI facility in the US, besides being the upgrade of the VLA

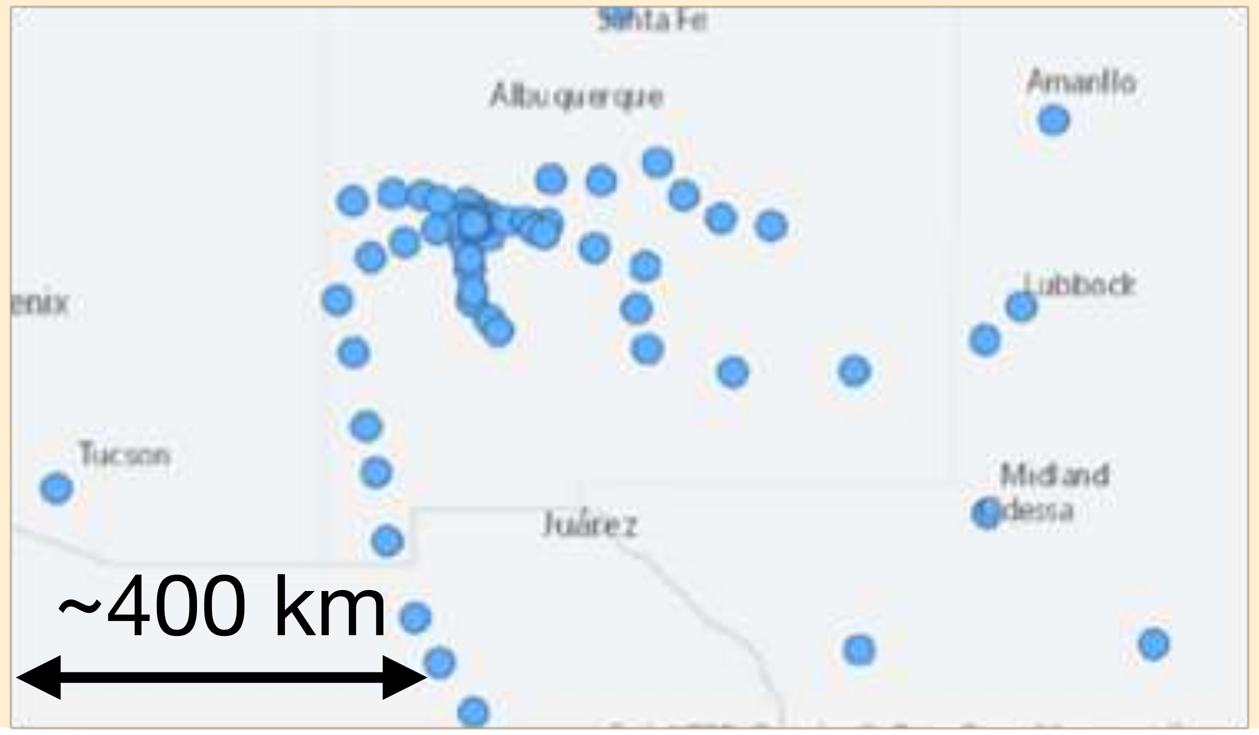
- The U.S. will be the ngVLA majority partner, with contributions from international/multi-agency partners (at the level of ~25%)
- Development-phase collaborations in place with international partners: NRCC (Canada), NAOJ, UNAM (Mexico), and ASIAA (Taiwan).

I. ngVLA instrument

Array and Receiver Components

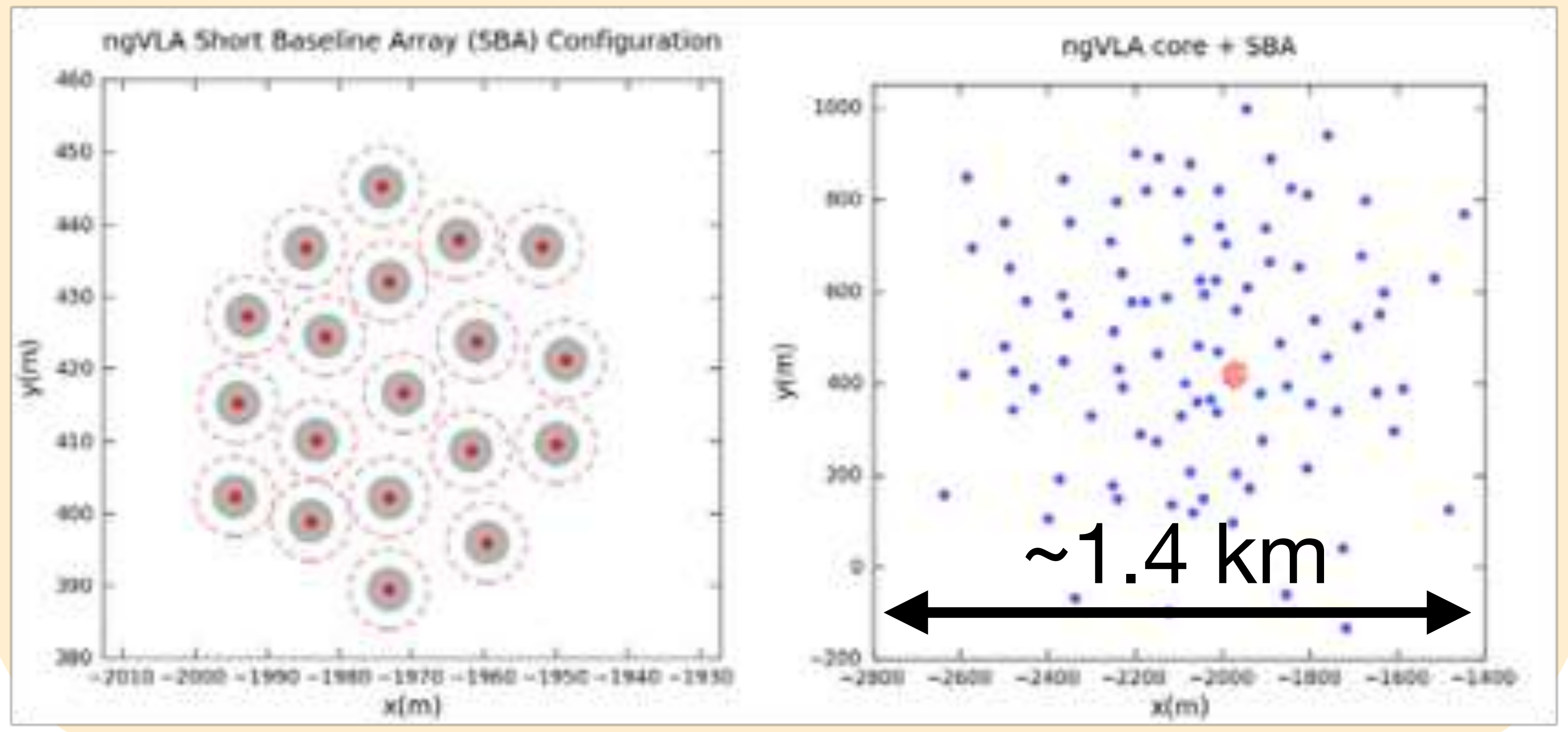
Main Array (MA)

- 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 in TP mode to fill in (u,v) hole for imaging extended structures

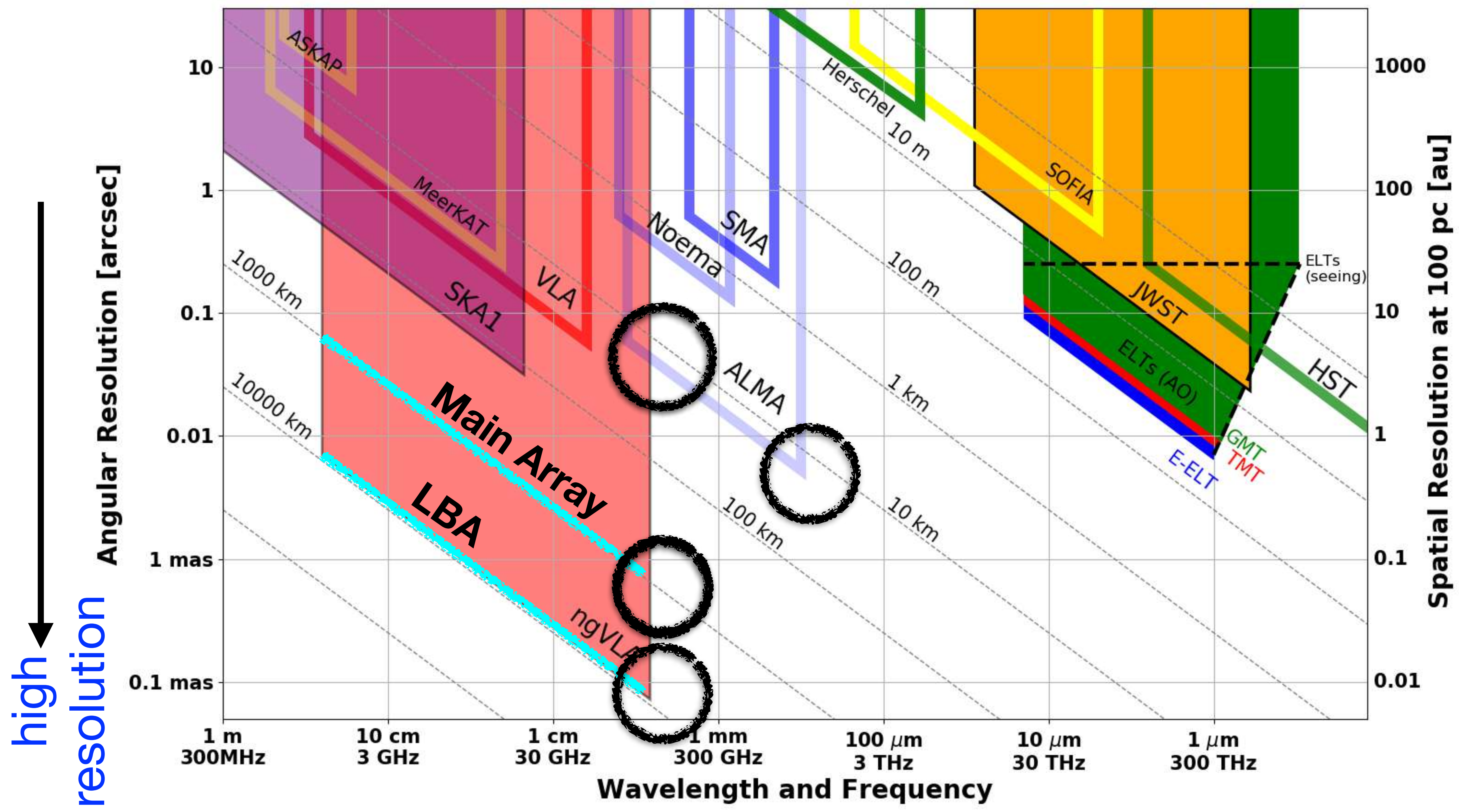


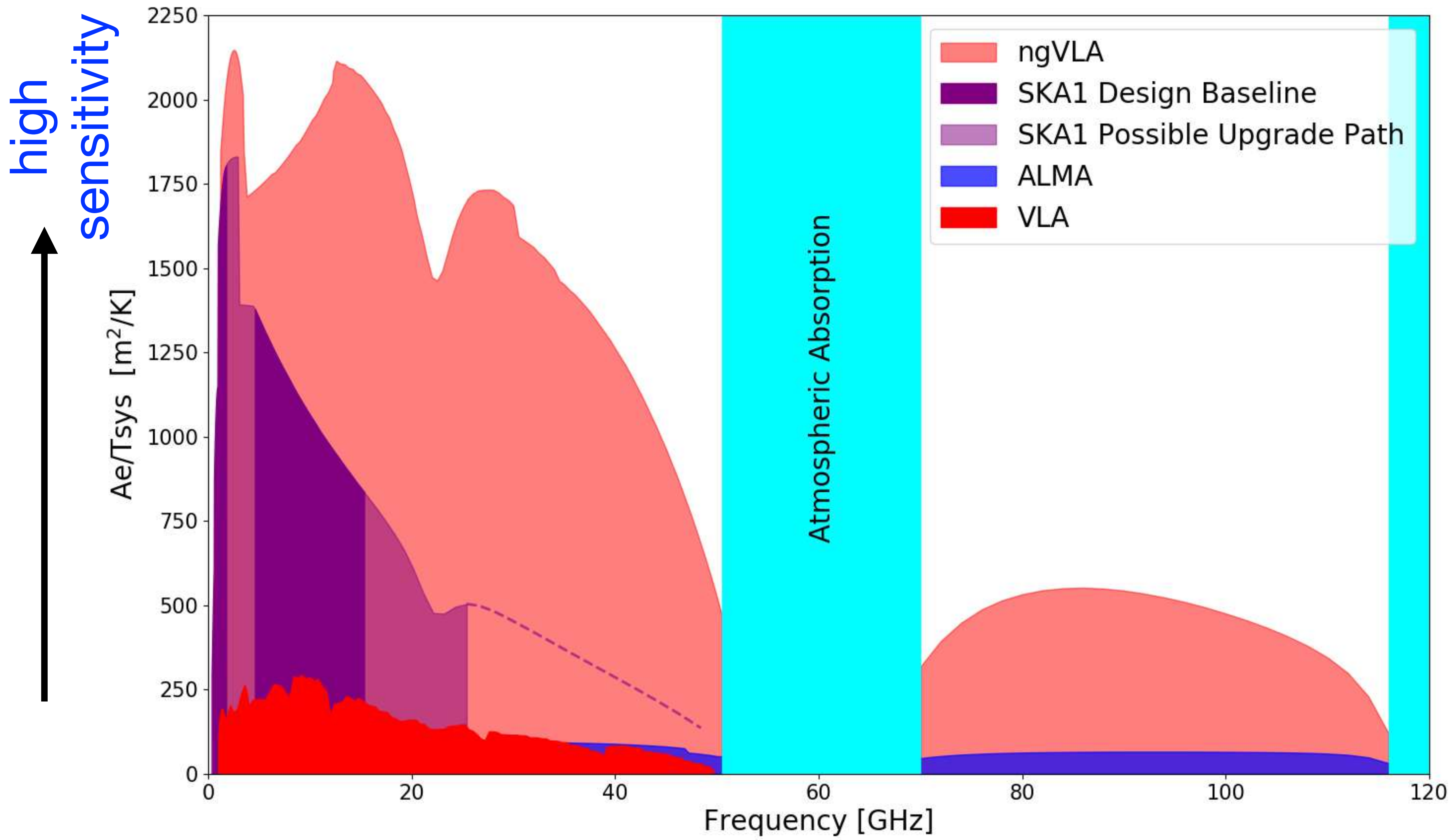
Long Baseline Array (LBA)

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

Band	f_L (GHz)	f_H (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	20.0	SO, SiO, CH_3OH, CS
6	70.0	116.0	46.0	CO, HCN, HCO^+, DCN

Angular Resolution / Sensitivity





Just for Main Array:

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

- Sensitivity improvements as large as a factor 10× compared to existing instruments (e.g., VLA, ALMA).

Key Operation Concepts: PI-science facility

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

Some parts are similar to the current ALMA's operation → Good heritage

II. Background of the Study Group & Organization

ngvla
Next Generation Very Large Array

The ngVLA Study Group (SG) in NAOJ

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

⇩

Current member: T. Izumi, A. Gonzalez, M.Fukagawa, B. Hatsukade (all NAOJ) + M. Momose (Ibaraki U.)

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

- Strong support from Udenkon to ngVLA, as one of the top future priorities of the radio astro. community.
- **Scientific activities** are led by community members in Japanese institutes and universities, in collaboration with NAOJ staffs.
- **Technical development** is led by NAOJ (ATC) exploiting synergies with ALMA Dev., and considering the involvement of the community.
- The **management interface to NRAO** is provided by NAOJ through the well-established collaboration of ALMA.
→ A collaboration agreement was signed in 2020 Apr for initial studies in *ngVLA collaboration in technology development*.

Involvement with NRAO, and efforts in Japan

- NRAO is seeking for a few selected international partners to contribute ~25% of the project costs.
  → We are anticipating to join with ~20% contribution from Japan (as of 2023 Nov)
- Inaugural international development meeting in Socorro/US (May 2019)
  → NRAO provided project overview (NAOJ was invited); initial discussion on possible interest in terms of construction deliverables.

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)
- ngVLA-memo series, ngVLA-J Project Book (2021)
- NAOJ invited key Working Groups (2020-2022):
  Total Power WG, VLA-ngVLA Transition WG, etc.
- Thematic session in ASJ Annual Meeting (2023 Autumn)

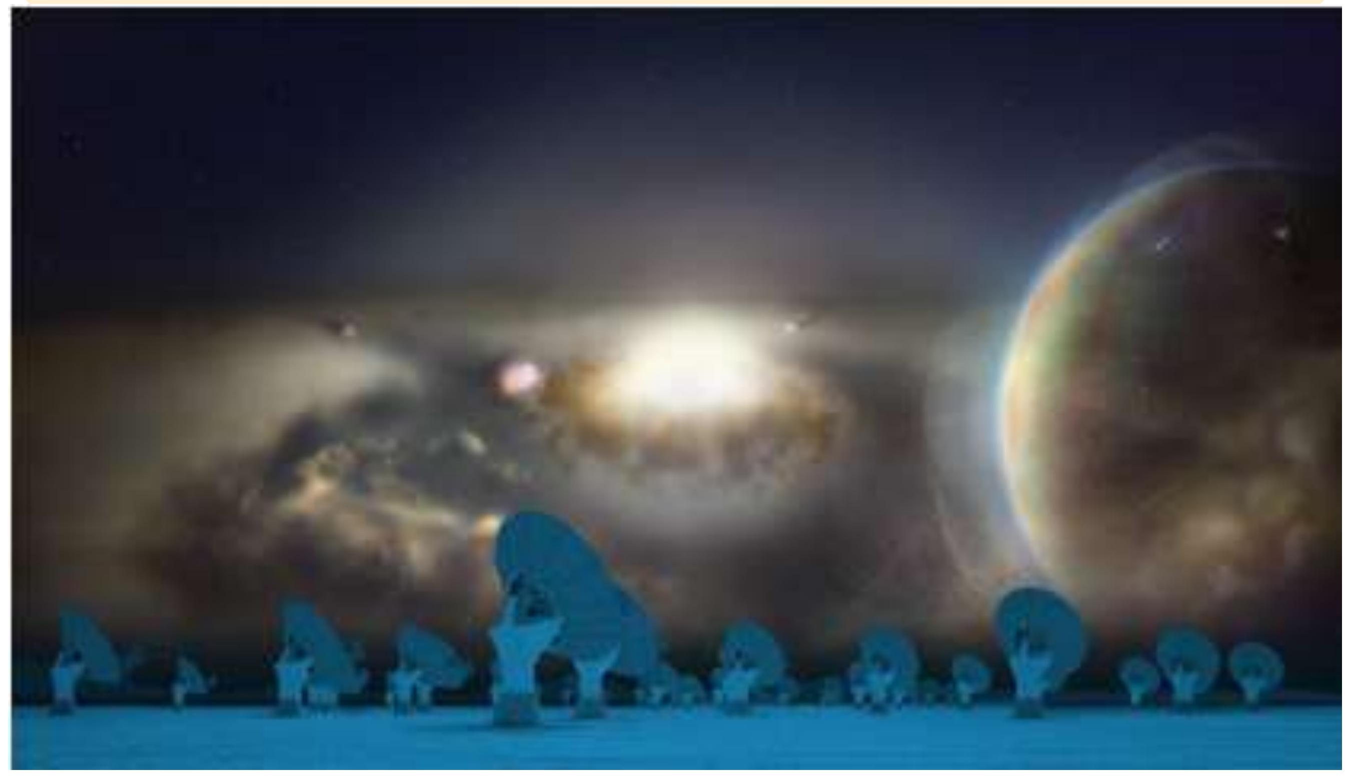
ngVLA Science/Technical Advisory Council

Science Advisory Council (2023-)

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)
Besty 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 (NAOJ)
Tetsuo Hasegawa (NAOJ)
Yuh-Jing Hwang (ASIAA)
Stan Kurtz (UNAM)
Michael Rupen (NRCC)
Melissa Soriano (JPL)



Past member: **K.Kohno (Tokyo), D.Iono (NAOJ)**

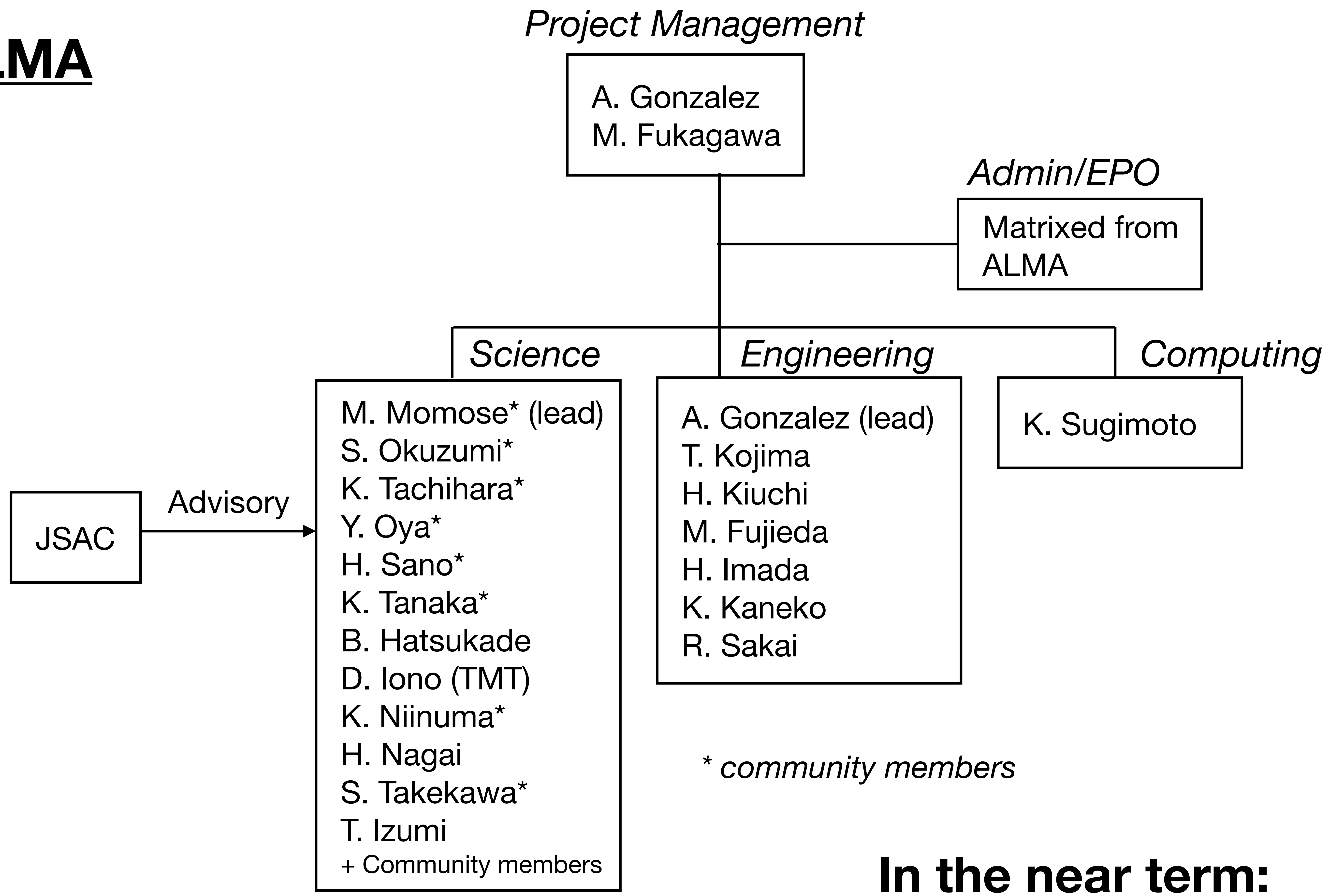
Organization Synergies within ALMA @NAOJ

Construction/operation synergies with ALMA

- Human resources
- International relationship
- Knowledge

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

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



In the near term:

(Small effort) contributions from staffs in the ALMA project, and other NAOJ Divisions (ATC, DoS, TMT) with support from the community will be required. A few staffs will further focus on particular deliverables for certain periods of time.

III. Science Goals to be achieved by Japan

Five Key Science Goals (KSG)

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

Astro2020: ngVLA (one of top priorities in US)

ASTRO2020 recommendation

- Tied for 2nd top priority in the large ground-based telescopes, just after the US ELT (TMT + GMT), together with CMB-S4

A project of great scientific impact and influence in many fields of astronomy:

- "The ngVLA project is a powerful observatory that will replace both the JVLA and VLBA"
- "The project would have broad, flexible capabilities and provide science-ready data products accessible to a diverse community of users."
- "Such a facility would advance multiple high priority science questions from each of the six Science Panels, and open discovery space."
- "The ngVLA facility would be absolutely unique worldwide in both sensitivity and frequency coverage"

Critical importance for US astronomy in terms of science:

- CONCLUSION of ASTRO2020: "It is of **essential importance to astronomy that the JVLA and VLBA be replaced by an observatory** that can achieve roughly an order of magnitude improvement in sensitivity compared to these facilities, with the ability to image radio sources on scales of arcminutes to fractions of a milliarcsecond."

Science Working Groups (SWGs) in Japan

FY2020-2021

- **5 Science WGs** in close collaboration with community. 14 on-line meetings + lead discussion on MP2023
- SWG1: Formation of Planetary Systems (M.Momose)
- SWG2: Star Formation and Astrochemistry in Nearby Universe (K.Tachihara)
- SWG3: Evolution of Galaxies Over Cosmic Time (D.Iono)
- Using Pulsars in the Galactic Center as Tests of Gravity (K.Niinuma)
- SWG5: Evolution of Stellar and Supermassive BHs in the Era of Multi-Messenger Astronomy (H.Nagai)
- Outcome
  + **Kikaku-session** in ASJ
  + **29 ngVLA-J memo series**
  + **ngVLA-J project book** (science section)

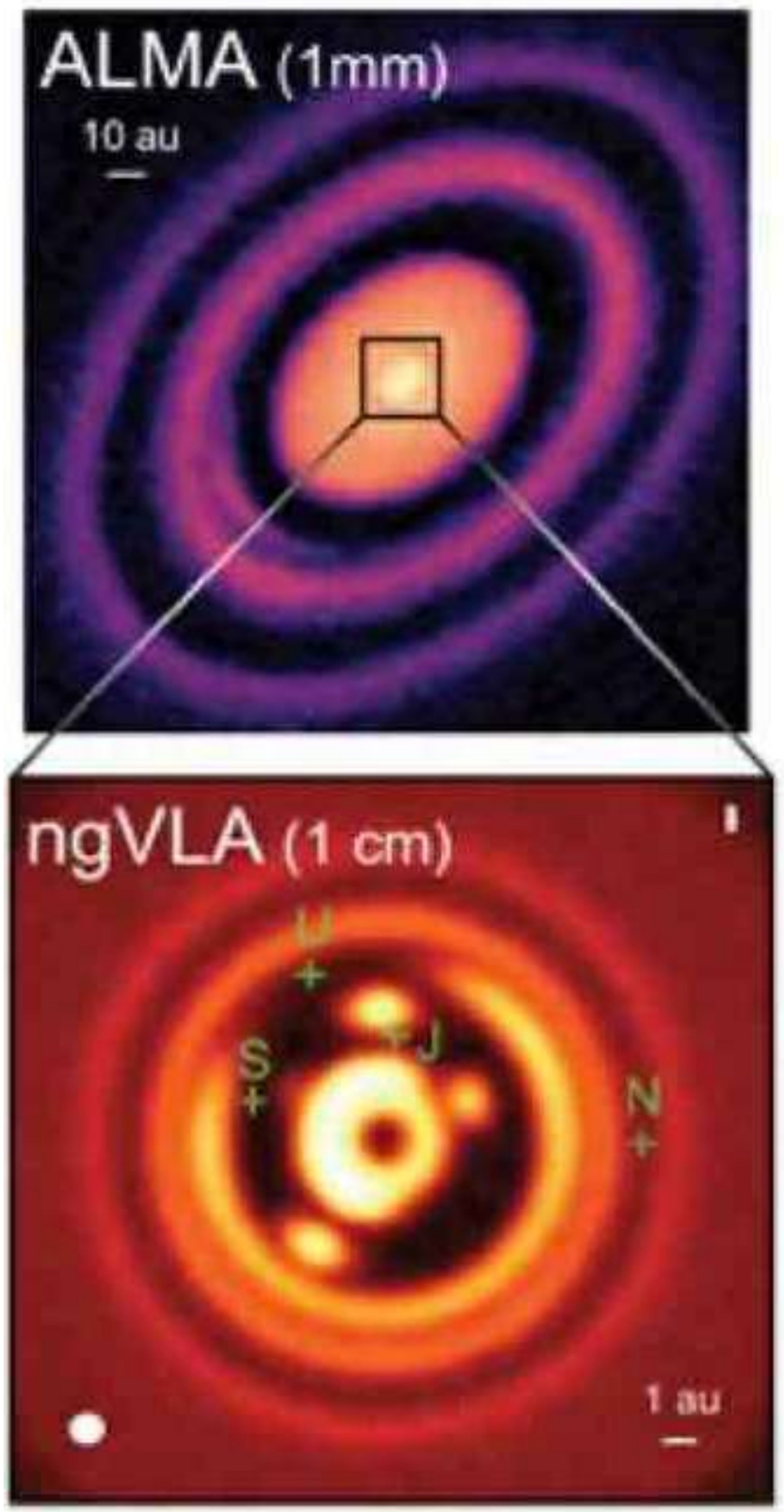
FY2022-2023

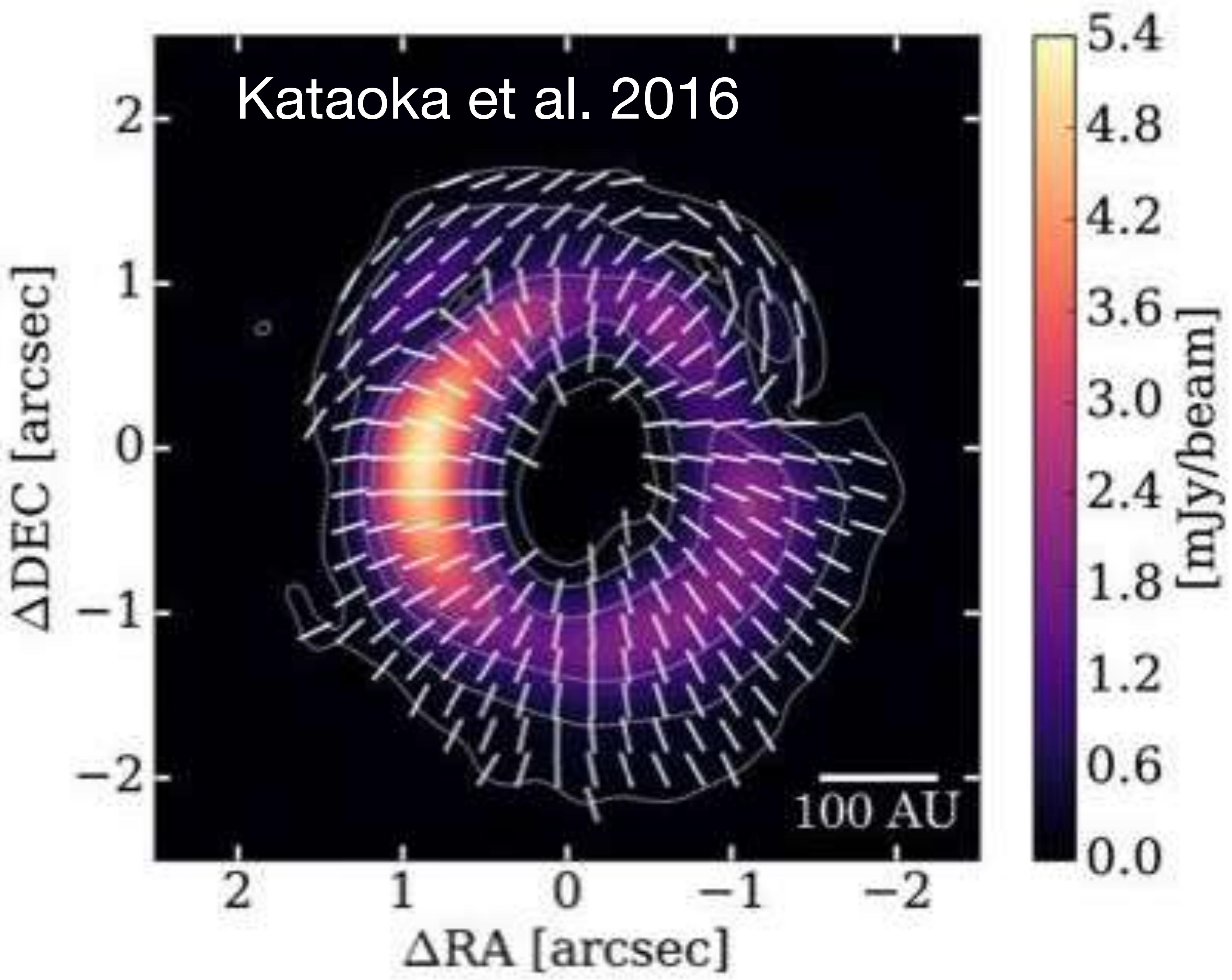
- **Science WGs ver.2 with new leads**
  - SWG1: S.Okuzumi, Y.Oya, M.Momose
  - SWG2: K.Tachihara, Y.Oya, H.Sano, K.Tanaka
  - SWG3: B.Hatsukade, H.Sano, D.Iono
  - SWG4: K.Niinuma, S.Takekawa, T.Izumi
  - SWG5: H.Nagai, S.Takekawa, T.Izumi
- Exploring further **the topics that span multiple SWGs**
- Synergies with future instruments at other wavelengths and in adjacent fields (planetary science, high-energy physics, astrobiology, etc).
- Resume community meetings from 2023 Jan.
  - Addition of ngVLA-J memo + Summary document
  - Promotion to research groups in wider communities

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.

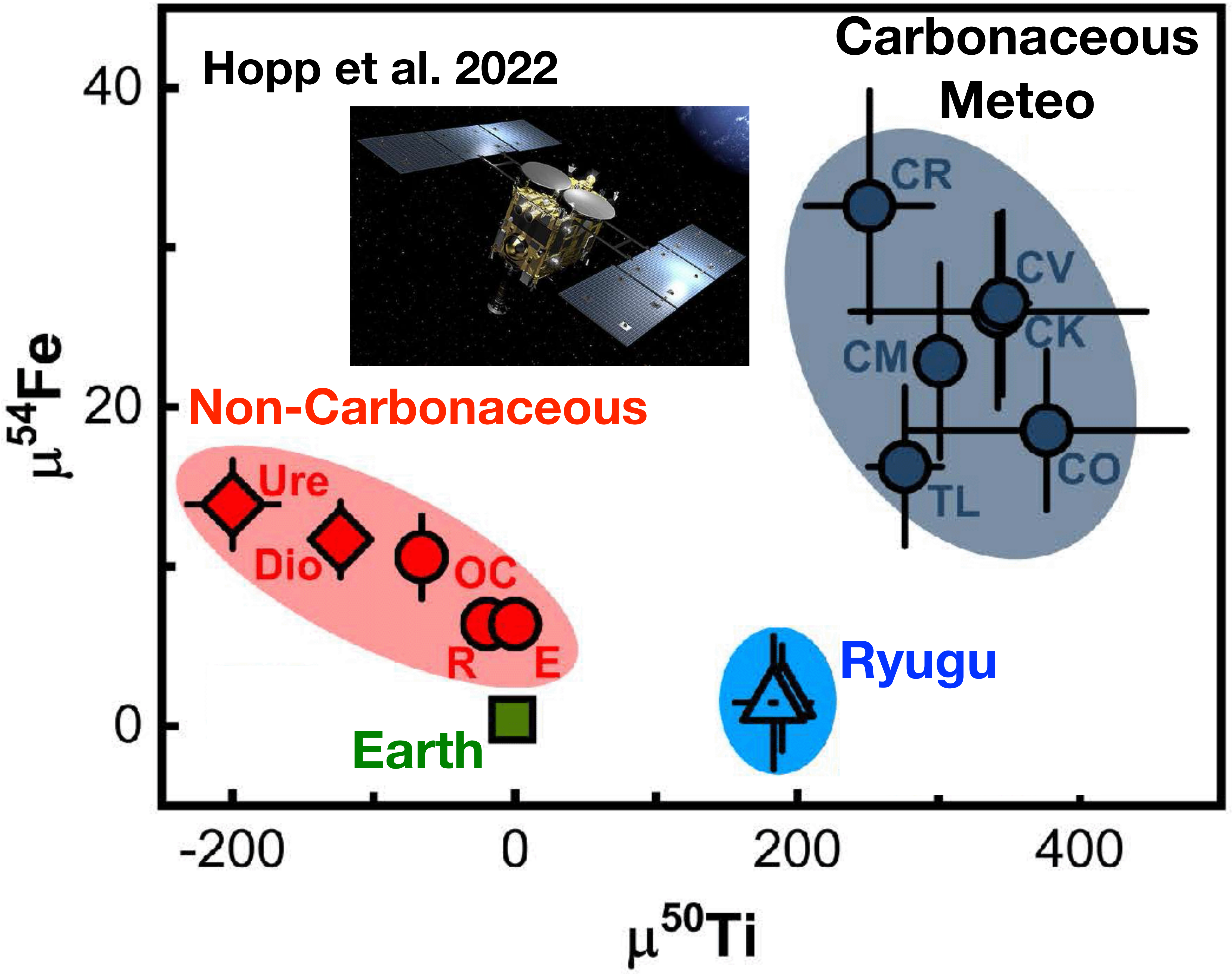
- cm wavelength is critical to penetrate through the dusty disk.
- Japanese researchers advanced this research field so much!





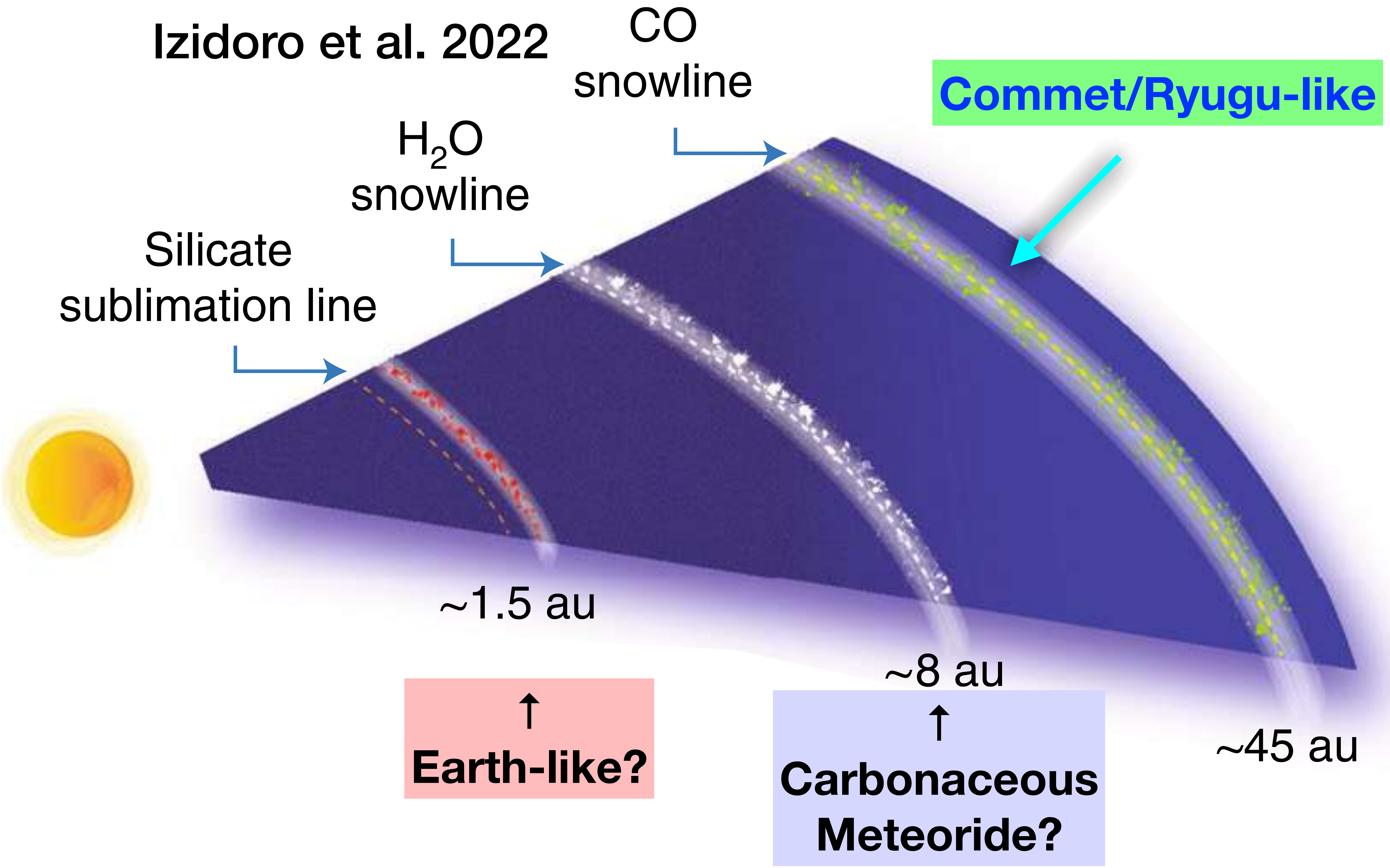
- Polarization observation puts tight constraints on the dust size in the disk.
  → sensitive to dust with size ~ wavelength/2π
- Bigger dust, and the spatial variation of dust sizes, will be detected with ngVLA.
  → Formation of planetesimal

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??

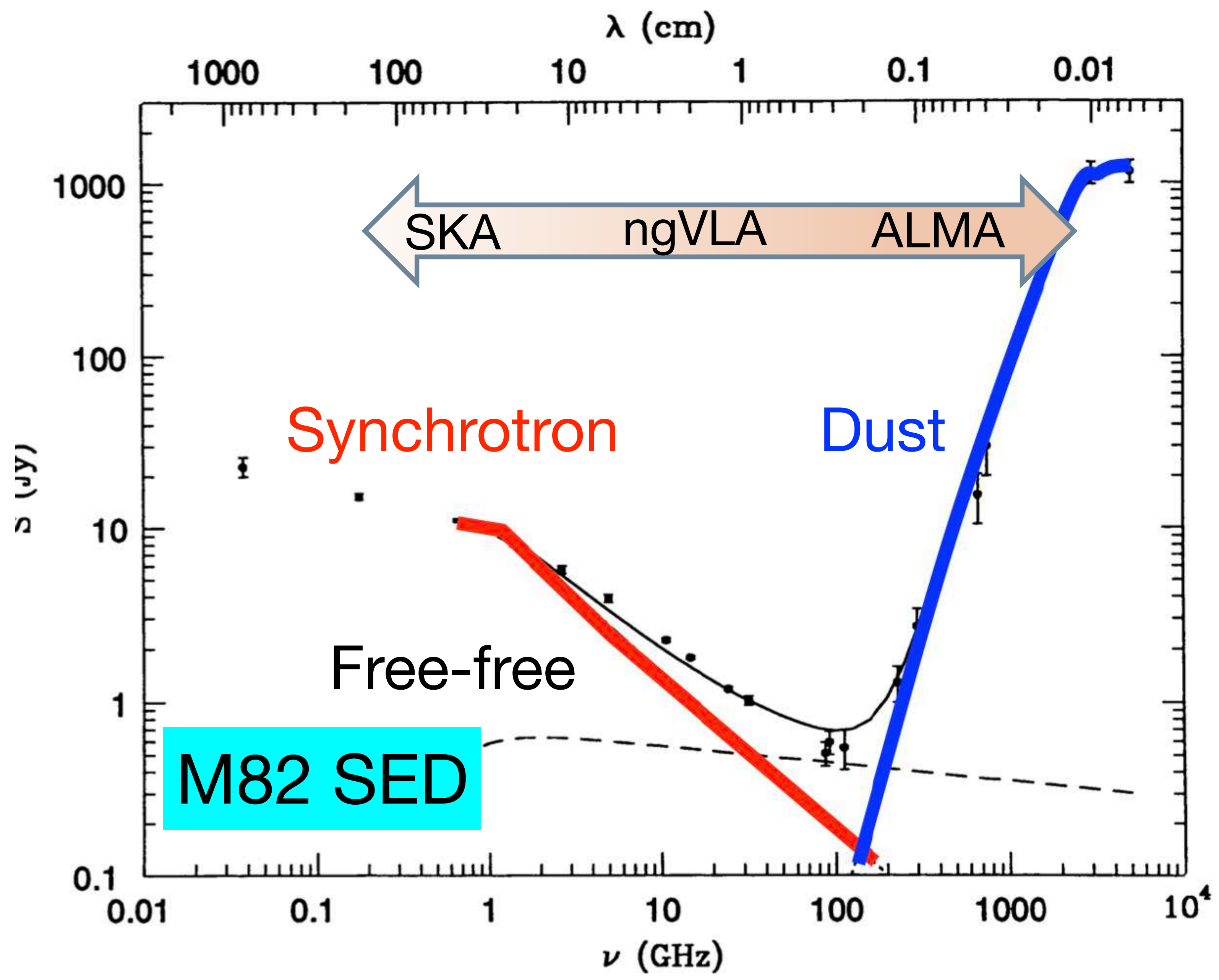


→ Very good synergy of astronomy and planetary science!!

Synergies with other NAOJ Instruments

Synergies with ALMA

	ALMA	ngVLA
Continuum SED	Dust (+free-free)	Synchrotron, free-free (+dust)
Protoplanetary disks	Outer gaseous planets, smaller dust particles	Inner rocky planets, larger dust particles (pebbles)
ISM in nearby universe	CO, [CI], small molecules, simple organic mol.	HI, NH_3, large molecules incl. N-bearing organic mol.
High-z	High-J CO, [CII]	Low-J CO



Synergies with Subaru/TMT

- Same sky coverage (northern sky)
- Follow-up of high-z galaxies discovered by wide FoV surveys by the Subaru/HSC
- Formation and evolution of exoplanets, including the origins of planetary atmosphere with disk chemistry
  → Exploration of multi-wavelength synergy is one of the main objectives for the ngVLA SG in FY2022-2023

Without ngVLA, we will miss the important information regarding the formation of inner rocky planets like the Earth, formation of stars in early galaxies, and understanding the chemical complexity (and ultimately to life) in the universe!

Requirements from Science (example)

	Science Goal	Actual observation	Requirement
5 top level science goals (consistent with US/NRAO science goals)	Imaging the Sites of Planetary formation and Proto-planetary Disks	High resolution imaging of inner rocky planets	5mas, 0.02microJy (@30GHz)
	Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry and Astrobiology	Detect and image key molecules related to life	<50mas, ~0.1km/s
	Tracing Galaxy Evolution Through Cold Molecular Gas	Detect and image redshifted CO(1-0)/ CO(2-1)	10mas, covering 10-116GHz (z=0-15)
	Using Pulsars to Pinpoint the Location of Gravitational Waves in the Milky Way Galaxy	Measure distance to milli-second pulsars and characterize gravitational waves in the galaxy	Astrometric accuracy of 0.1%
	Understanding the Formation and Evolution of Supermassive Black Holes in the Era of Time domain/Multi-Messenger Astronomy	Image the gas surrounding blackholes. Follow time evolution of BH and Neutron Star mergers.	0.1mas, time resolution of minutes

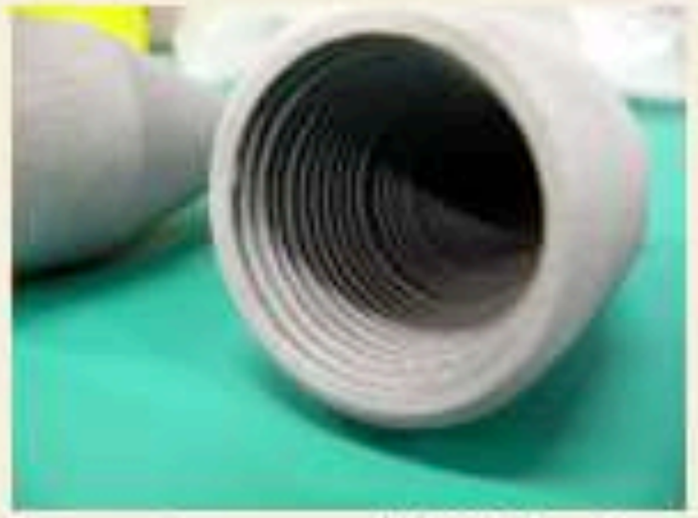
IV. Status of Technical Work in Japan

ngvla
Next Generation Very Large Array

Unique contribution from NAOJ/ATC

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

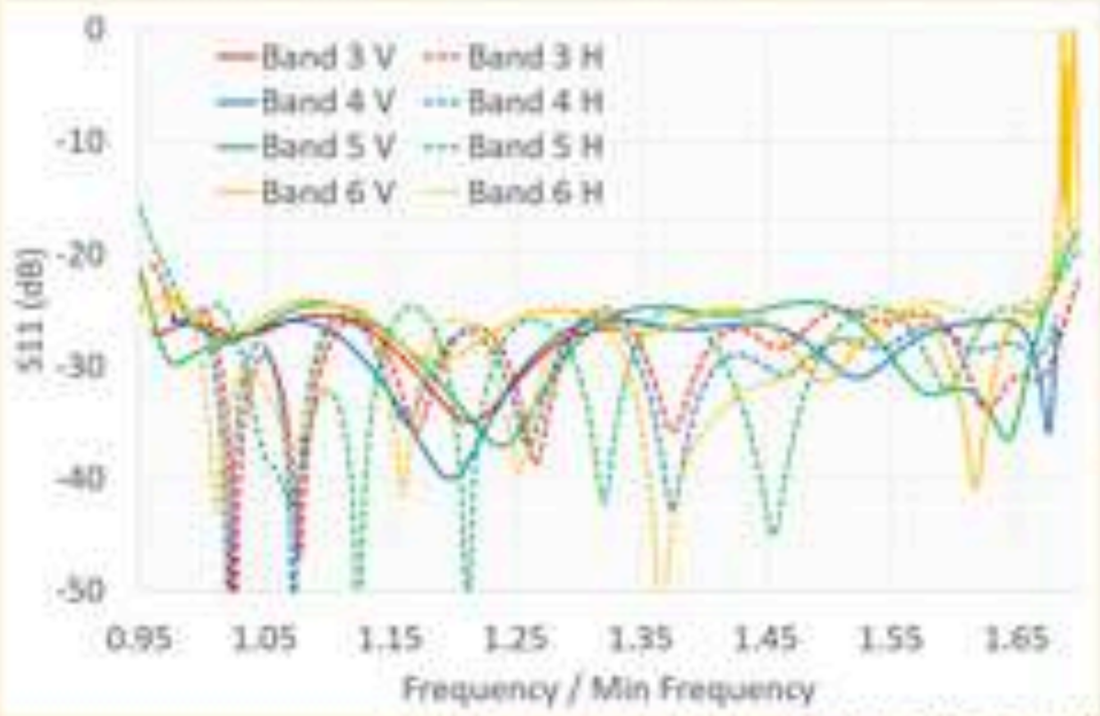
67-116 GHz AlSi10Mg corrugated horn + transition + OMT, fabricated in a single piece for improved performance

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

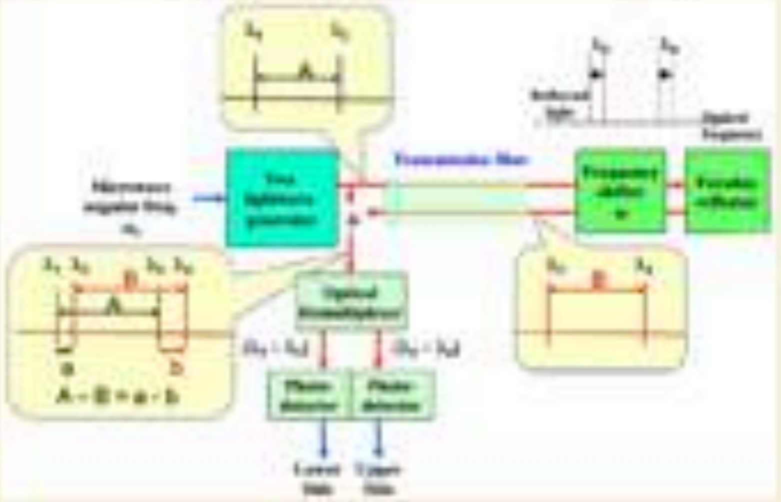


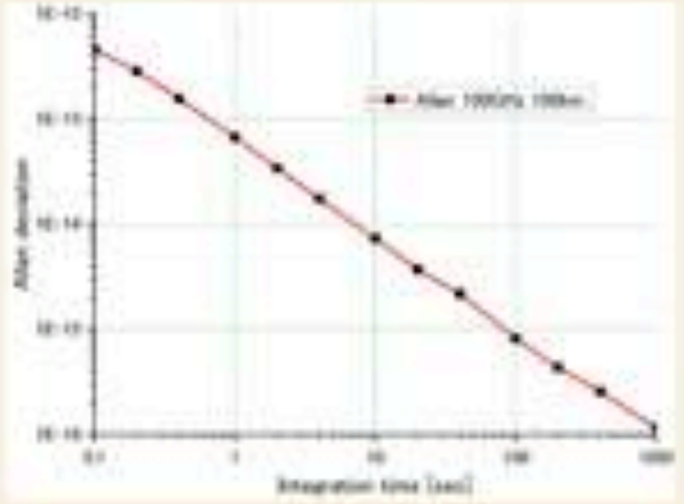
Gonzalez, IEEE AP-S/URSI 2020

Photonic technologies

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

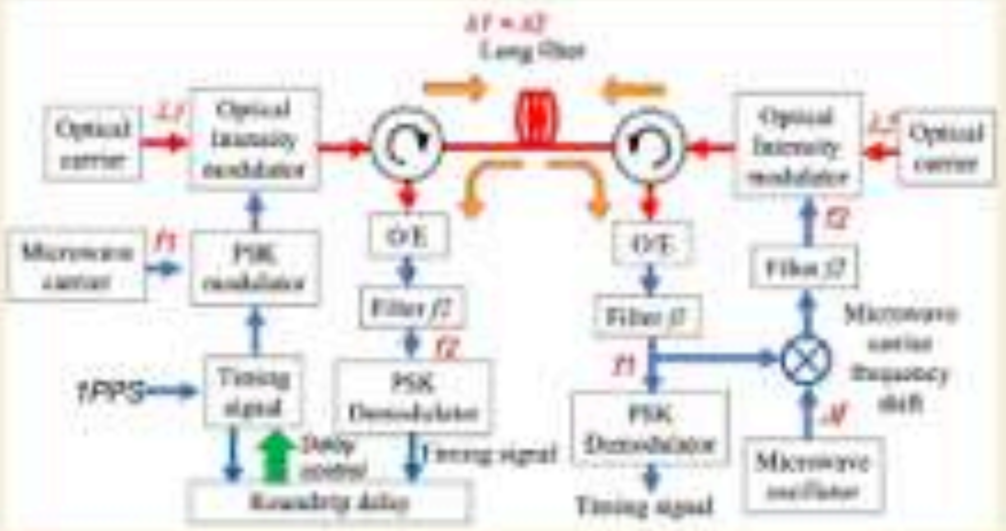
Measured transmission phase stability of 100GHz signal through a 250 km fiber spool using a novel technique





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…

Possible hardware contributions from Japan

A good mix of Japanese **in-kind contributions** to the project tentatively **agreed between NAOJ and NRAO**, in line with **NAOJ / industry / community** heritage and expertise, and the well-established collaboration through ALMA

Possible Japanese hardware deliverables to the ngVLA project

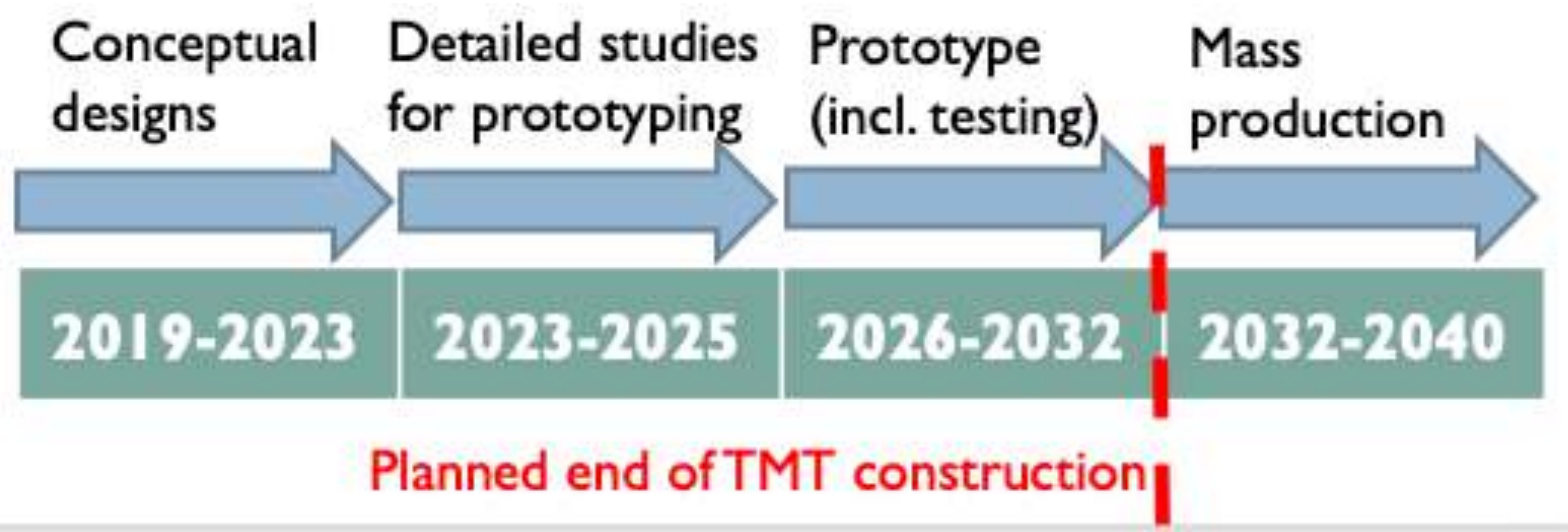
- **Antennas** (up to 53 units in SBA, LBA, TP)
- **Receivers**: design of components, prototyping and production at ATC (using 3D printing)
- **Photonics**: time/frequency ref. distribution

- NAOJ has initiated antenna design from FY2019 through small contracts with industry.
- Possible contribution of 20% of total number of antennas → 30 x 18m antennas for LBA, 4 x 18m for TP, and 19 x 6m for SBA.
- These can be contributed at a *later stage* of construction, allowing Japanese contribution **after TMT**!

Large construction budget needed: post-TMT construction

Year	Scale	Budget Use
FY2023-2025	<1M USD/yr	• Detailed studies and preparation towards prototyping
FY2026-2032	10-15M USD/yr	• Prototyping (incl. antennas) and testing • Start of construction
FY2033-2040	40M USD/yr	• Full construction

Plan for antennas

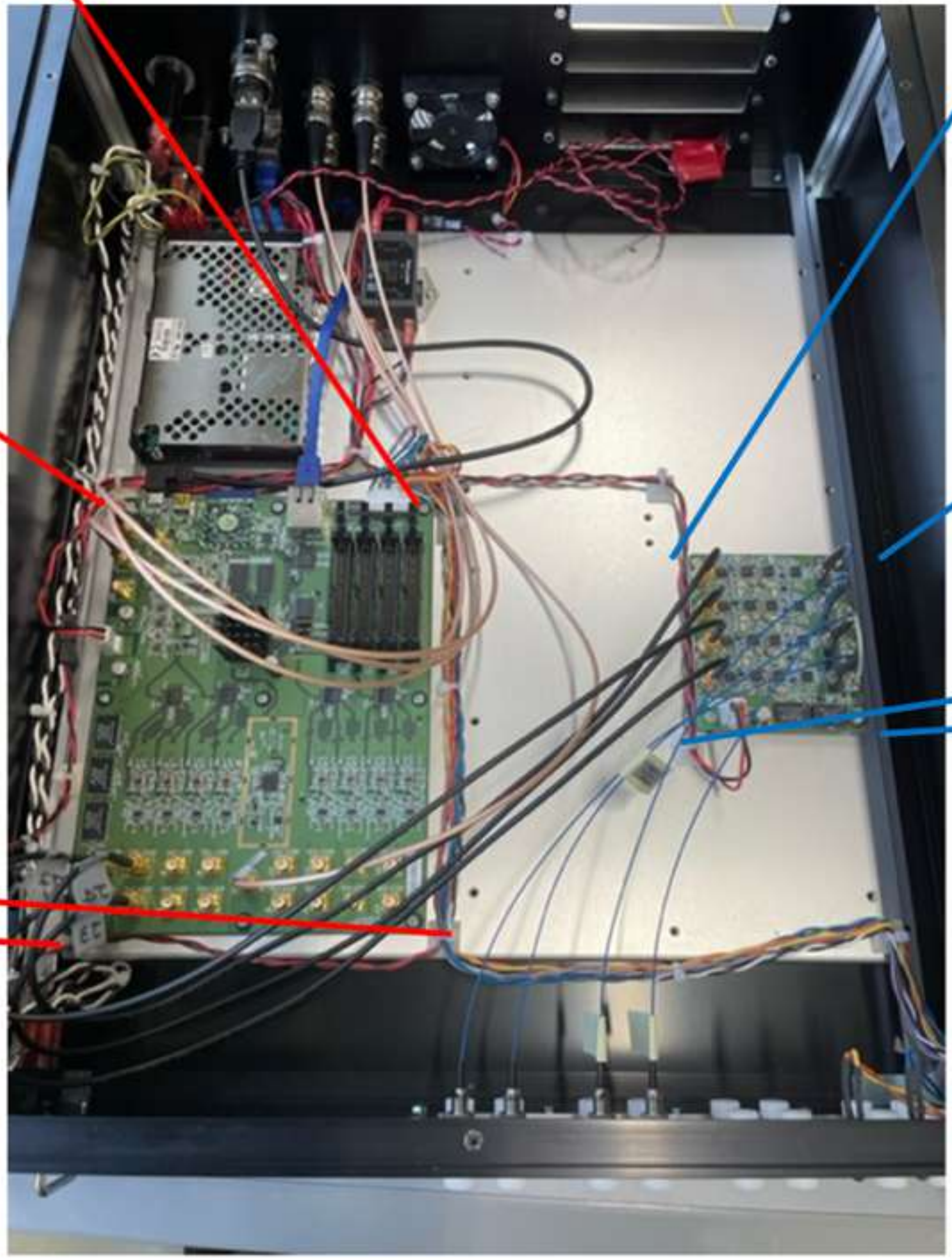


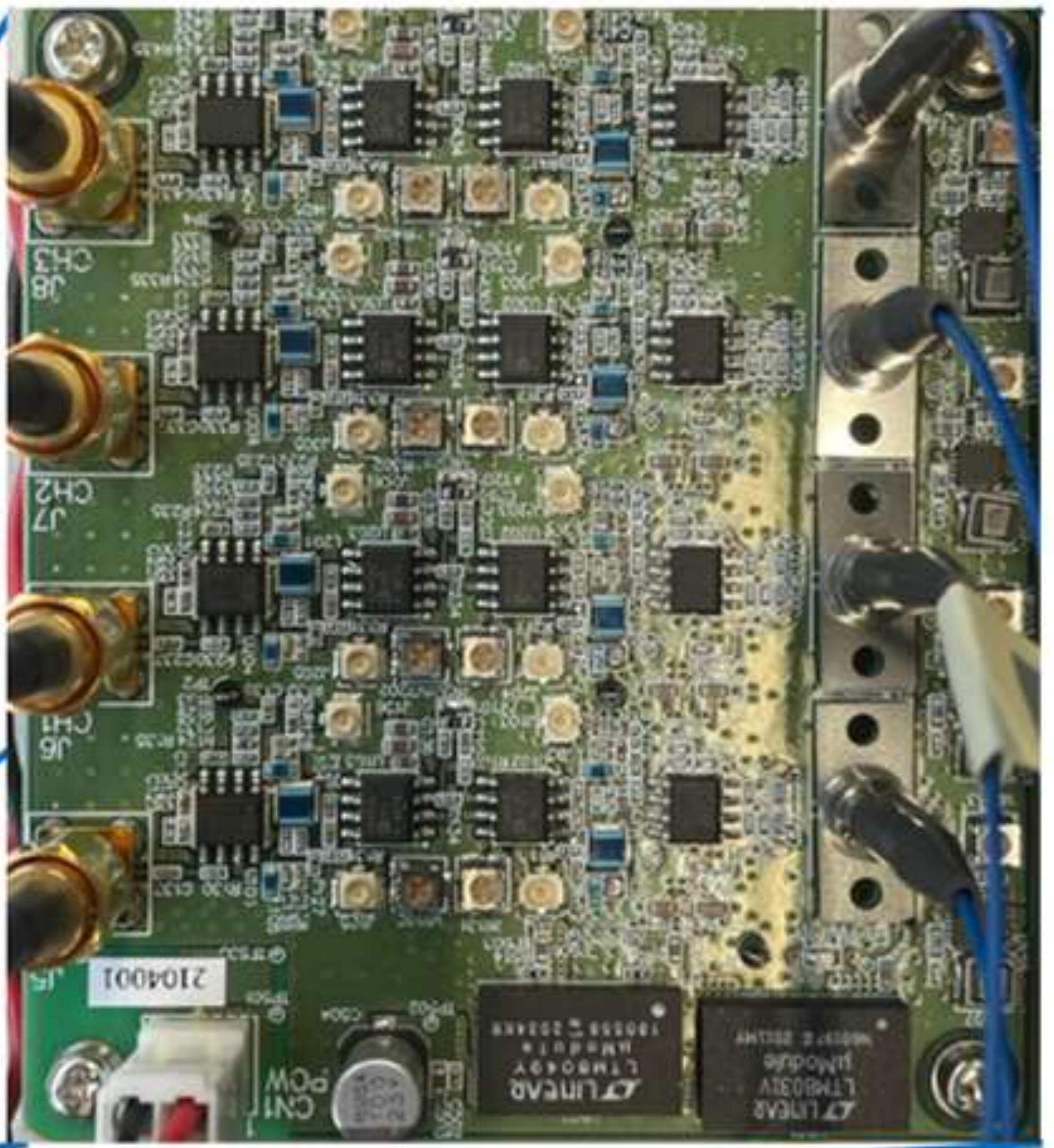
Frequency transfer system

Leverage of ALMA development knowhow.
Key researchers: H. Kiuchi, M. Fujieda

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

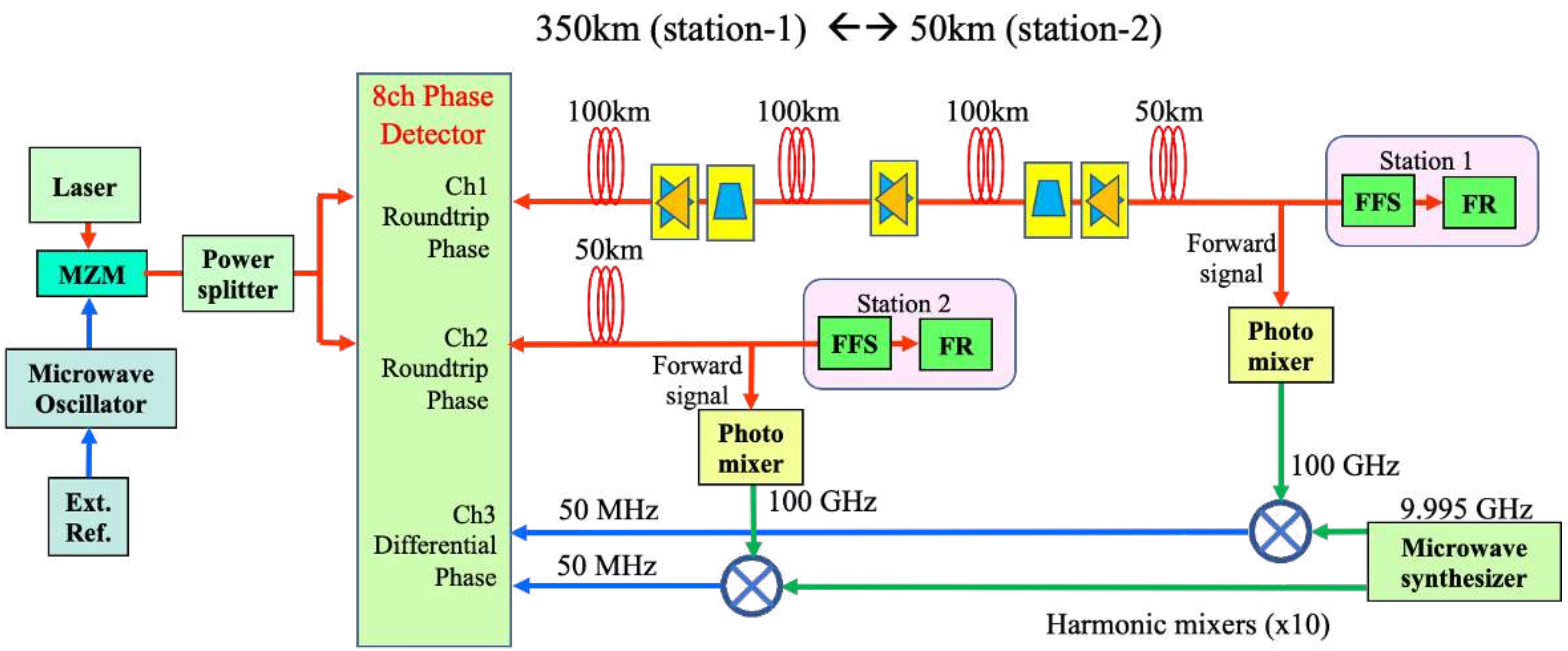


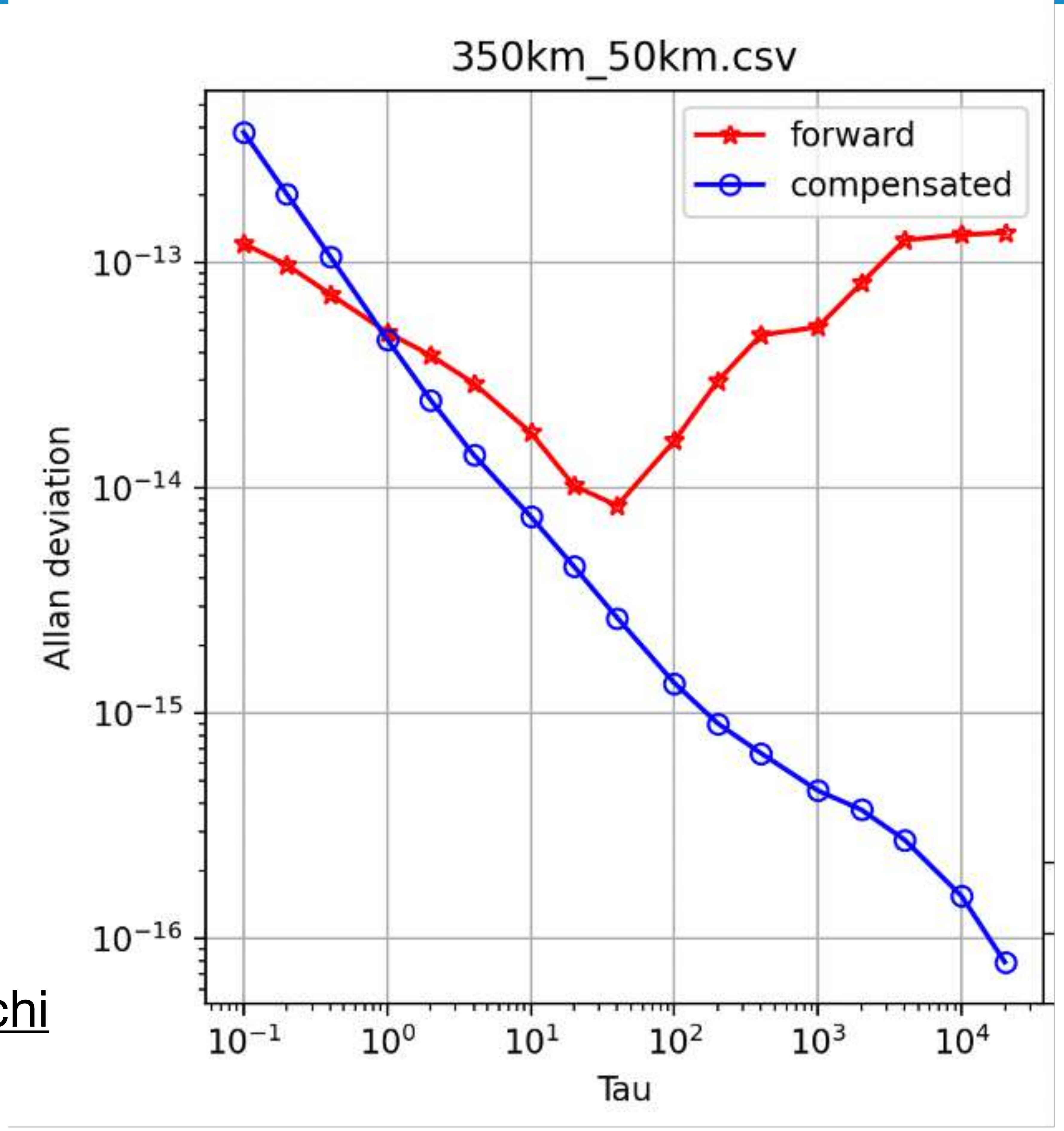


APD board for 2 stations.

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

Two-station experiment (Station-1: 350 km, -2: 50 km)





courtesy of H. Kiuchi

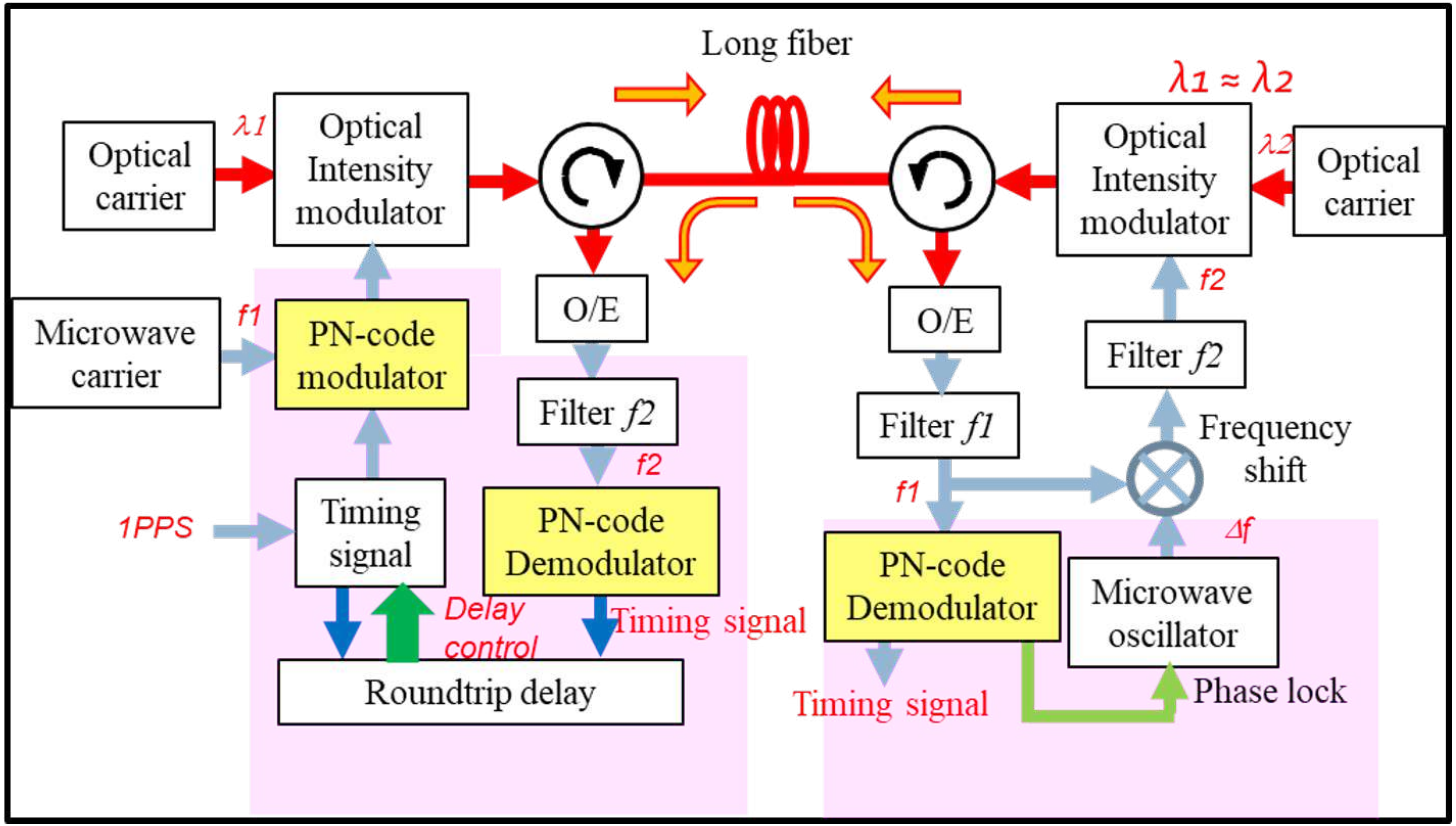
The frequency reference must have long term accuracy from T=1 to 1000 seconds:
T=1 sec $\sigma_y \leq 2 \times 10^{-13}$, T=100 sec $\sigma_y \leq 1 \times 10^{-14}$, T=1000 sec $\sigma_y \leq 2 \times 10^{-15}$

→ Mass construction of this system with industries is being planned.

Time transfer system

Leverage of ALMA development knowhow.
Key researchers: H. Kiuchi, M. Fujieda

Prototype under fabrication → just delivered!



Kiuchi (2022), IEEE Photonic Tech. Letters

Plan for prototyping (in pink)

1 board (simultaneous delay measurement for 8 stations) for reference station

2 boards for remote stations

V. NAOJ’s lead

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Next Generation Very Large Array

One of the great upcoming Large-Scale Facilities

- ngVLA will be one of the great worldwide Large-Scale facilities in the 2030s-, playing a key role in scientific discovery together with ALMA and TMT, with interest and support by the Japanese Community

- The involvement of NAOJ in ngVLA is clearly in line with NAOJ 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 advanced observing facilities in the world
  - Open use
  - Flexible international cooperation
  - Strong synergies with ALMA, TMT and Subaru

- A share of contributions by Japan in the order of 20% would allow the Japanese Community to access ~20% of observing time, which would allow to make the most of synergies with other NAOJ facilities:
  - This is comparable with our share of contributions in ALMA (25% - Oversubscription ~6!)
  - Such a budget scale (~650M USD) is unfeasible for universities

ngvla Next Generation Very Large Array

Role of Japan in This International Project

- NAOJ and NRAO have a strong history of collaboration in the last 20 years through ALMA

- NRAO is interested in seeking about 25% international contribution to ngVLA from a few trusted and well-established partners.
  - Other prospective partners so far are Canada, Mexico and Taiwan

- NRAO established the International Development Consortium in 2019 to discuss possible contributions by Japan, Canada, Taiwan and Mexico
  - Japan has participated in the IDC from the first day
  - Initial interest in in-kind contributions to the project have been expressed by these prospective partners
  - Japanese contributions have been tentatively agreed with NRAO and will account for 10-20% of constructions costs (NOTE: Antennas are a key deliverable for large participation)
  - Agreed contributions exploit NAOJ and Japanese industrial expertise and experience, and can find important spin-offs to community-led domestic projects and education

- An Agreement for Scientific and Technical Collaboration was signed between NAOJ and NRAO in April 2020 to extend our collaboration beyond ALMA, incl. initial studies in ngVLA

ngvla
Next Generation Very Large Array

Scope and Responsibilities

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

This will in turn guarantee ~20% of the ngVLA observing time (~1600 hr/yr) for the Japanese community, leading to high science production with a publication rate comparable to that of ALMA (~70 papers/yr in Japan)

A good mix of Japanese **in-kind contributions** to the project tentatively agreed between NAOJ and NRAO in line with **NAOJ / industry / community** heritage and expertise, and the well-established collaboration through ALMA

Phase of the project	Japanese Deliverables to the ngVLA project
Construction and commissioning	• Antennas (up to 53 units in SBA, TP, LBA) • Photonic technologies: time-frequency reference distribution • Receivers (design of components, prototyping and production at ATC) • Cryogenics: cold-heads, compressors, dewars • Commissioning of observing modes and software development • New analysis tools (e.g. sparse modeling), archive, phase correction
Operation	• Maintenance of antenna, cryogenics, receivers, reference signal distribution • Development and maintenance of software / archive (integrated computing team) • User support and science promotion

VI. Budget plan

Budgetary considerations

- 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 expected to be 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 total operation cost is estimated to be 93M USD/yr → ~19M USD/yr (20% contribution)
- Hence, the total cost including 10 yr operation is 460M + 10 × 19M = **650M USD**.

Budgetary considerations specific in Japan

Example

Modified from the original
(figure/deleted)

Scope: Post-TMT project in NAOJ

Year	Scale per year	Budget Use
FY2024-2025	Modified from the original (figure/deleted)	
FY2026-2032		
FY2033-2040		

- Japan needs to be ready to contribute heavily (~20%) to the construction from 2033 (after completion of TMT construction)
- However, we also need substantial budget from FY2026.
- Highest priority would be TMT until the end of its construction (~2032) both for US and Japan
- Construction budget will then ramp up from ~2030 to 2033. Large construction budget is necessary until the end of 2030s.

Our Budget Source(s)?

FY2019-FY2025: Development studies and preparation towards large-scale prototyping (<1億JPY/yr)

- Maybe possible with NAOJ Leadership funds and external budget.
- Some ATC developments can contribute to ngVLA and other projects in NAOJ.
- Different activities based on the actual availability of funds will be carried out.

FY2026-FY2032: Prototyping and validation tests (12-19億JPY/yr; incl. antennas)

- Frontier budget may be necessary.
- **Commitment by Japan during this phase will be essential to realize ngVLA and support US/NRAO plans.**
- **If budget at this level is not secured, the contribution by Japan could only be at the level of ~5%, with a huge impact on the scope of the project, scientific return and involvement of the Japanese community.**
- Earlier availability of this budget would allow to reduce the annual budget required for longer testing and commissioning.

FY2033-FY2040: Full construction (42億JPY/yr)

- Frontier budget will be necessary.

VII. Summary

Top-level summary: Japan’s strength & impact in joining ngVLA

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

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

Japanese contribution based on experience in ALMA construction and operation

- Various items with *sufficient 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 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, and other community-led ideas and collaborations

Science objectives	Investigations		Instruments	
	Physical parameters	Observables	Design Parameters	Requirement
Planet formation	Forming site of rocky planets	Gap in high density regions of gas and dust of protoplanetary disks	Angular resolution	~5 mas
			Continuum sensitivity	~0.07 μJy/beam at 30 GHz, 0.5 μJy/beam at 100 GHz
	Temperature structure of a protoplanetary disk	Snow lines of various species including H_2O and NH_3	Angular resolution	~5 mas
			Line sensitivity	TBD
Exploration of matters related to life with the knowledge of astrochemistry	Amino acid in the interstellar medium	Multiple complex organic molecules that are astrobiologically important (incl. glycine and alanine)	High spectral resolution at low frequencies to avoid line confusion	dV < 0.1 km/s
Formation and evolution of galaxies over the cosmic time	Conditions for star formation and the baryonic cycle	Ground-based CO(J=1-0) line	Wide frequency coverage to probe CO(1-0) up to z~5	Operation frequency should be at least $20 < \nu < 116$ GHz
			High line sensitivity	TBD
Testing theories of gravity by using pulsars in our Galaxy	Accurate distance to milli-second pulsars	Annual parallax	High continuum sensitivity	TBD
			High astrometry	<1% of the synthesized beam
	Physical origin on milli-second pulsars	Multi-band monitoring	Simultaneous monitoring at multi-band	Sub-array mode
			High timing accuracy	< 10 ns (ideally < 1 ns)
Investigation of supermassive black hole growth in the era of multi-messenger astronomy	Time-domain quantities	TBD	TBD	TBD
	Feeding and feedback over many orders of magnitude spatial scales	Synchrotron radiation from jet, plasma flows from accretion disk scale, molecular lines from torus scale or larger	High angular resolution	VLBI function
			High line sensitivity	TBD

(from the ngVLA Reference Design Volume 1-3 + submitted document)

Toward the NAOJ / Japan Radio Heritage

Technology dev. / Training of human resources / Education / Spin-off Community initiatives / Industry collaboration