# Antarctic 30-m THz Telescope project

Nario Kuno
University of Tsukuba

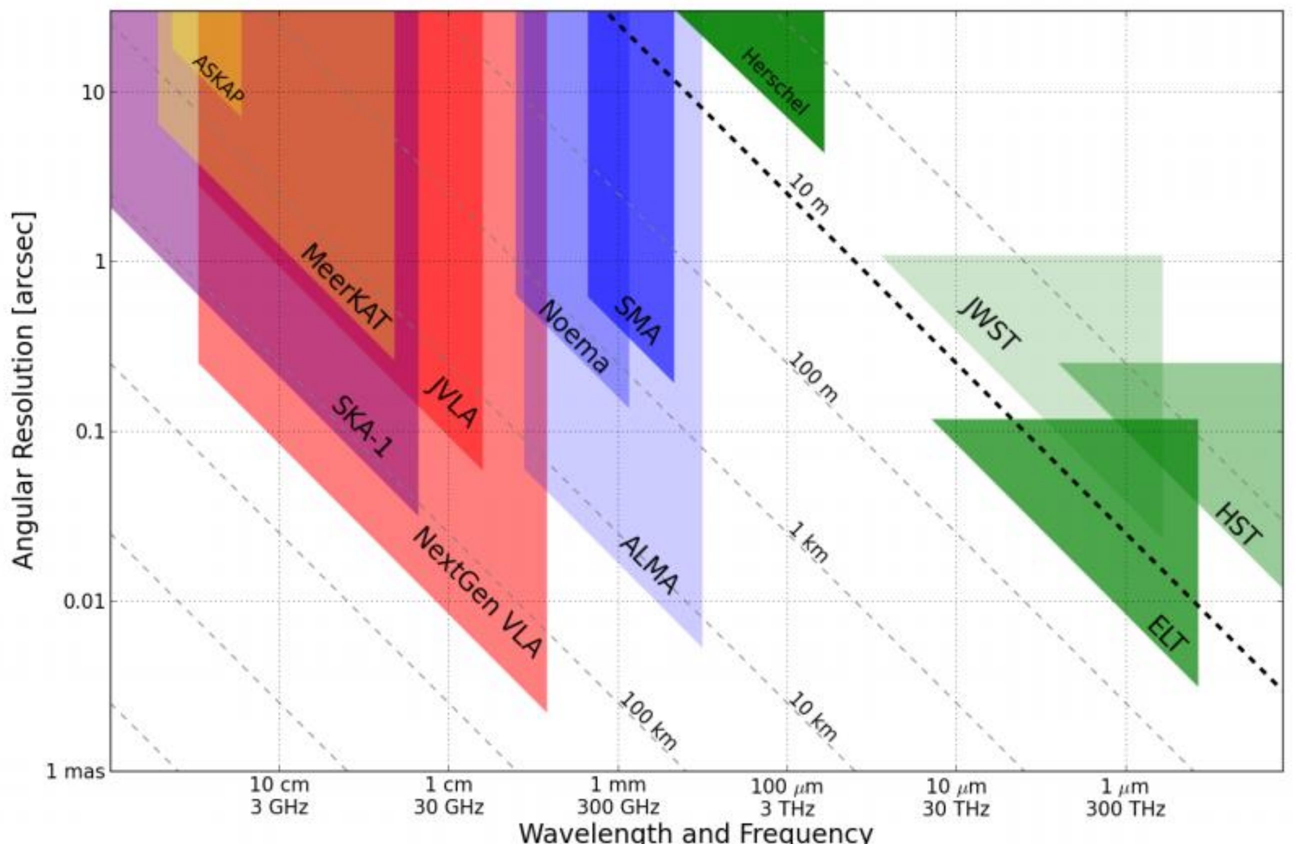
# Collaborators

- **Univ. of Tsukuba** : N. Kuno, T. Hashimoto, S. Honda, K. Ohsuga, H. Yajima, M. Mori, H. Fukushima, A. Wagner
- **Kwansei Gakuin Univ.** : M. Seta, N. Nakai, N. Kishimoto
- **Hokkaido Univ.** : K. Sorai, D. Salak
- **NAOJ** : H. Matsuo, M. Nagai, T. Ohshima, H. Ezawa, T. Umemoto, S. Ishii, Y. Murayama, W. Shan, T. Tsuzuki
- **Fukui Univ. of Technology** : Y. Miyamoto
- **Shibaura Institute of Technology** : Y. Watanabe
- **Nihon Univ.** : S. Takano
- **JAXA** : T. Nishibori
- **The Univ. of Electro-Communications** : T. Sakai
- **Osaka Metropolitan Univ.** : H. Ogawa
- **Waseda Univ.** : K. Mawatari
- **NICT** : Y. Kasai
- **Komatsu Univ.** : H. Kagawa
- **National Institute of Technology (KOSEN), Fukushima college** : K. Kim

# Background

- Terahertz band
  - Atmospheric absorption
  - Space telescope : Limitations on aperture

  ⇒ Unexplored frequency band in astronomy

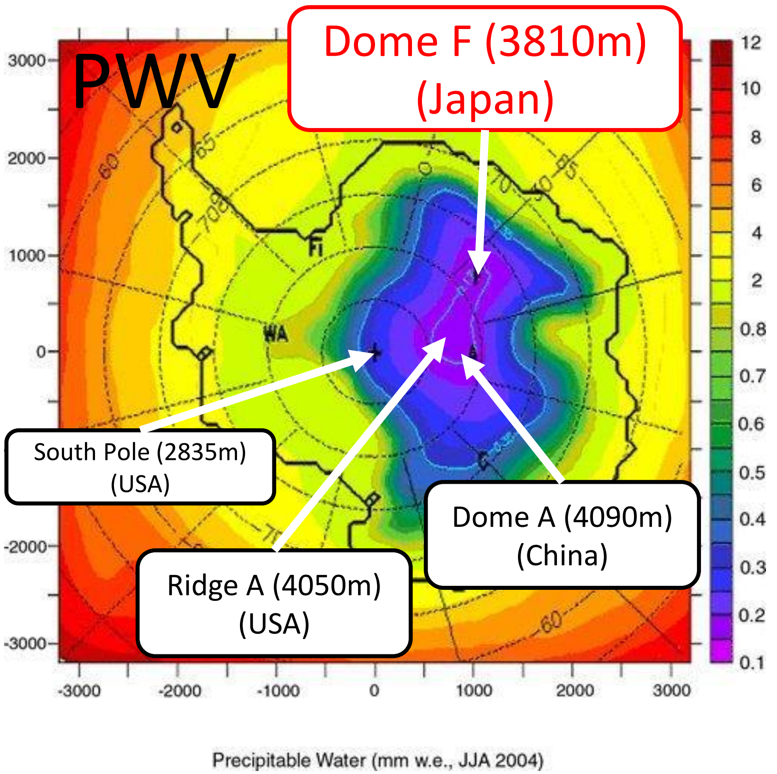


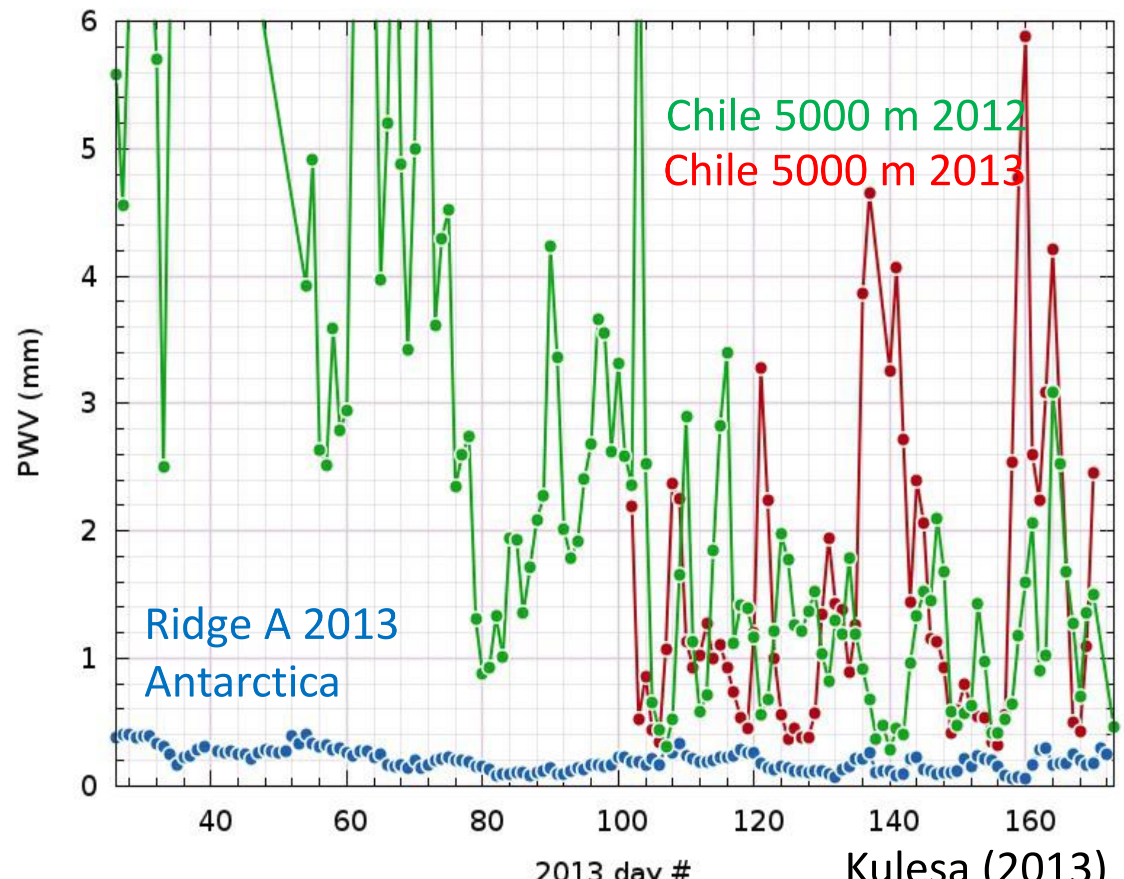

Carilli et al. 2015

# Inland of Antarctica

- High altitude (～ 4000 m) & low temperature (< -70 ℃ in winter)

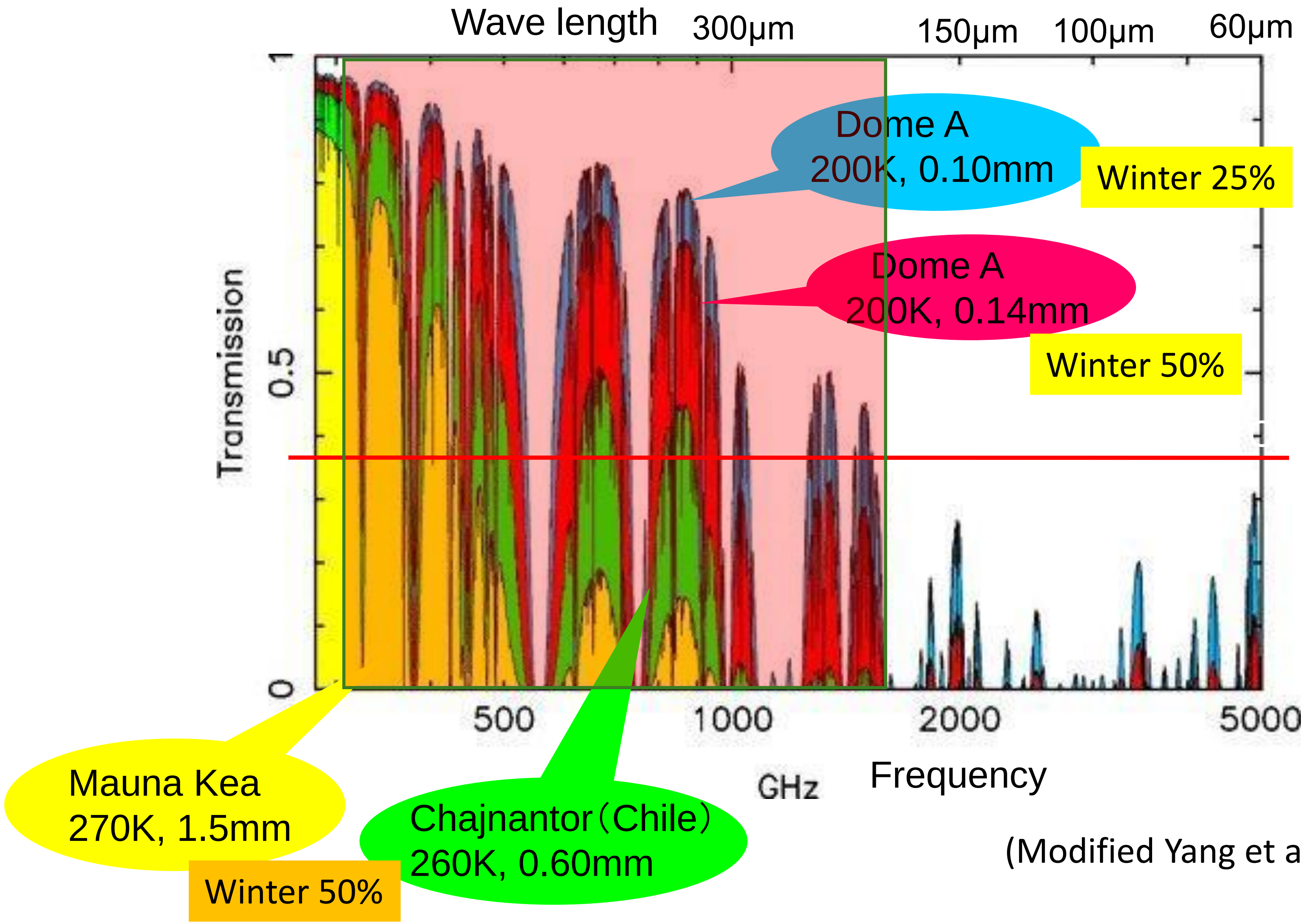
  ⇒ Lowest Precipitable Water Vapor (PWV) on the earth




Kulesa (2013)

# Sky transmission




(Modified Yang et al. 2010)



⇒ Best place for submm/THz observations!!

# NiPR Observation Plan

- 6-year plan
  - Priority research observation “重点研究観測”（100M yen×6 year）
    - Themes of great scientific significance, taking into account social demands and international research trends.

    (e.g., Xth “Earth System Changes Approaching from Antarctica“)

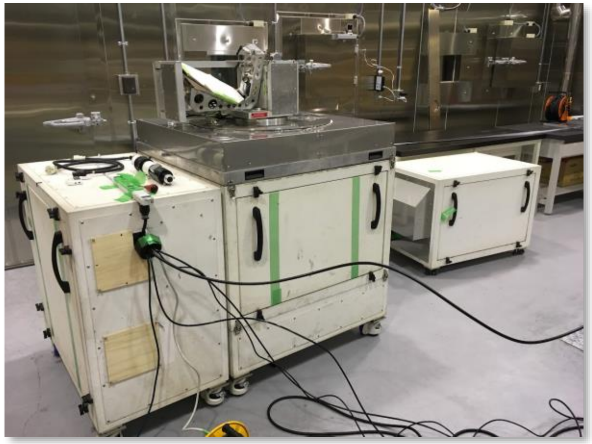
  - General research observation “一般研究観測”（20M yen）
    - Program carried out intensively over a relatively short period of time taking advantage of the unique characteristics of Antarctica
  - Exploratory research observation “萌芽研究観測”
    - Preliminary observations, research, and development for future observations.

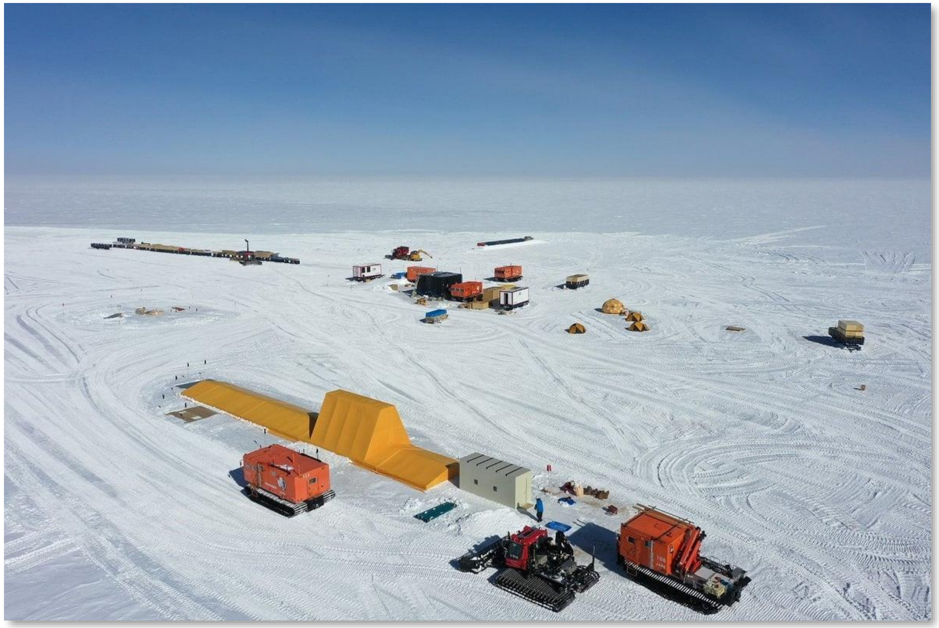
# Plan of  Antarctic astronomy promotion project

| Fyr | 2022-2027 | 2028-2033 | 2034-2039 | 2040- |
|---|---|---|---|---|
| NiPR 6-year plan | X | XI | XII | XIII |
| 30-cm telescope | Operation |  |  | |
| Wintering station 12-m telescope | Budget request (Univ. Tskuba+) | Construction | Operation | |
| **30-m telescope** | | Budget request (NAOJ) | Construction | Operation |

# 30-cm telescope

**2023: Start Transportation to Showa station**
**2024：Start activity at Dome Fuji II**
**2026 ~ 2029: Observations**





Dome Fuji II

# Current status of ATT12

- Study on the construction and operation of a wintering station and transportation with NiPR
- Study on construction of foundations on snow surfaces
- Countermeasures for issues at low temperature
- Study on Telescope & MKID camera Optical system
- Development of protype of MKID & LeKID camera
- Recommendation from Udenkon (宇電懇)

  ⇒ Science Council of Japan

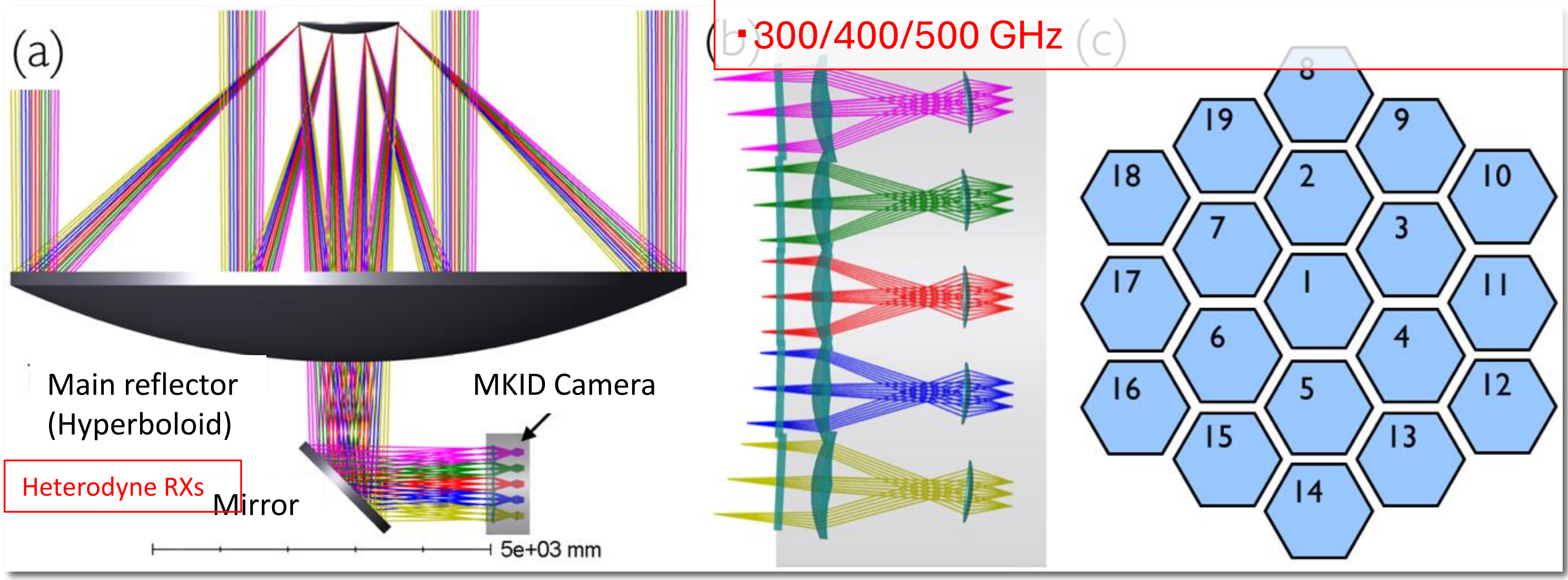
  "未来の学術振興構想2023" : Accepted

  ⇒ MEXT Roadmap2023 (ロードマップ2023) : Not accepted
- not yet secured the budget

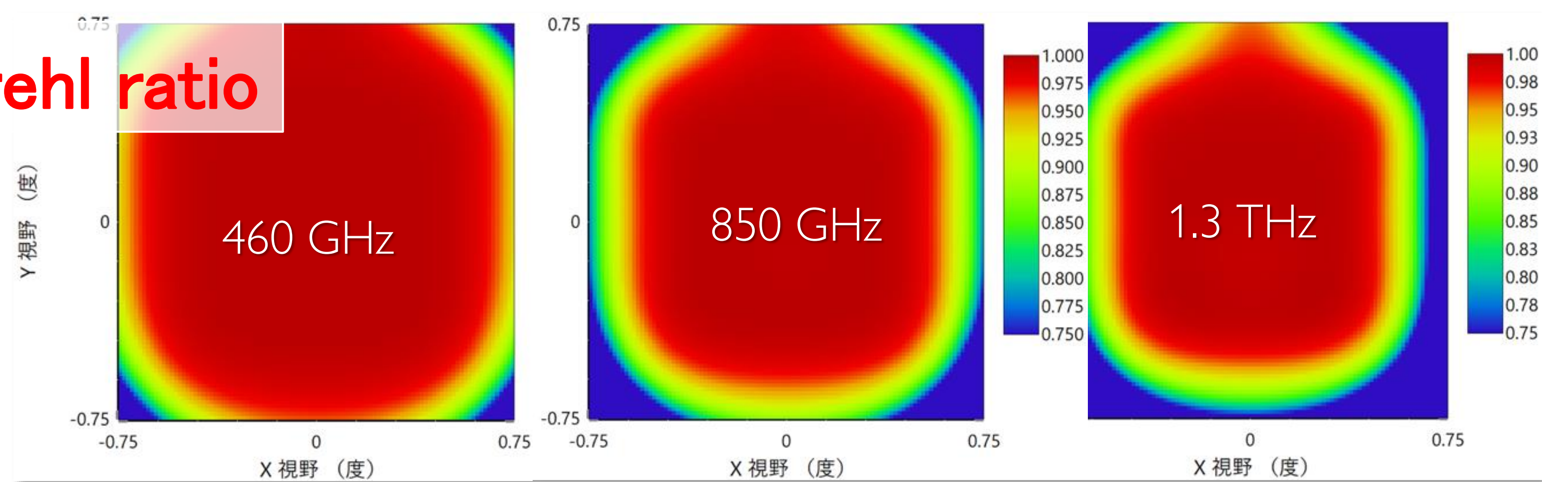
# 12-m telescope (ATT12)

Optical system : Ritchey–Chrétien

**Microwave Kinetic Inductance Detector Camera**
- 650/850 GHz
- 300/400/500 GHz

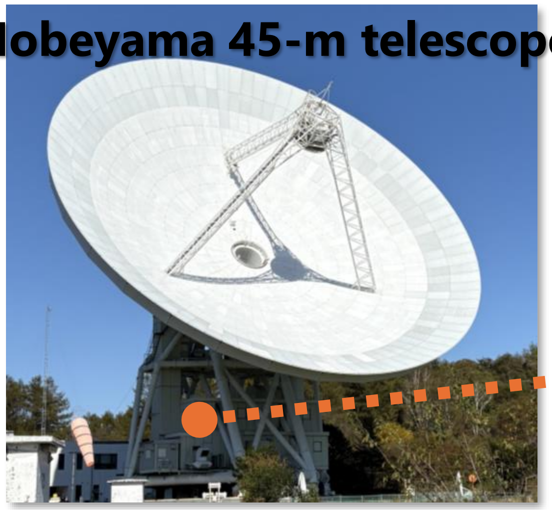



**Strehl ratio**

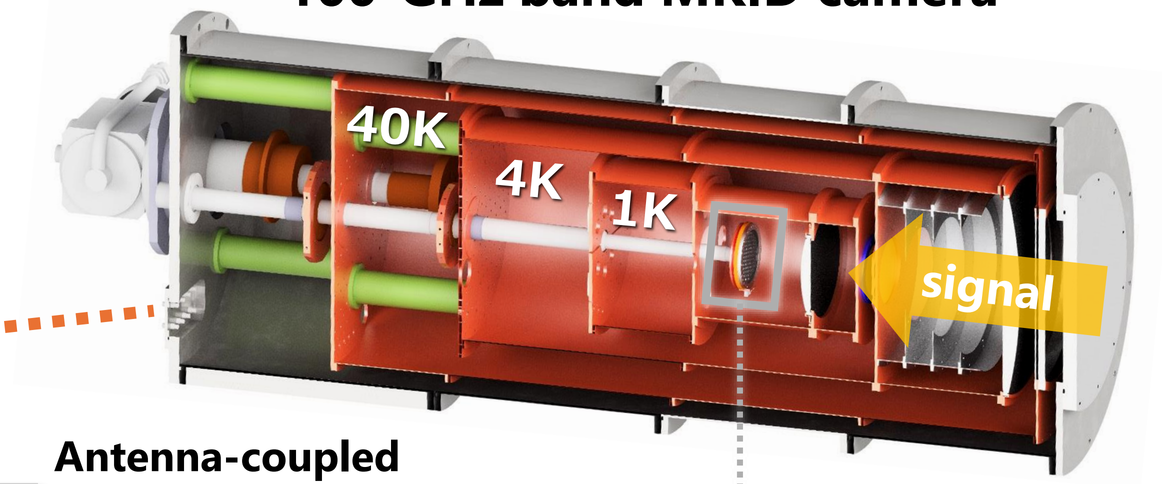


# 100-GHz band MKID camera

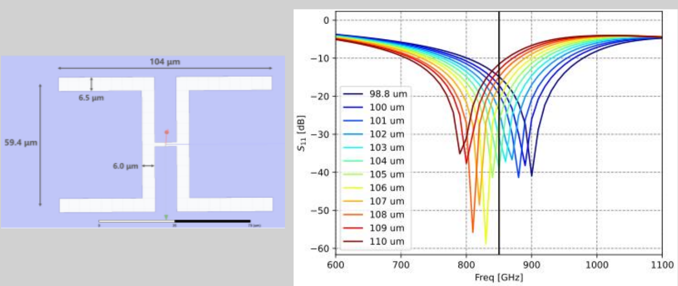
**Nobeyama 45-m telescope**



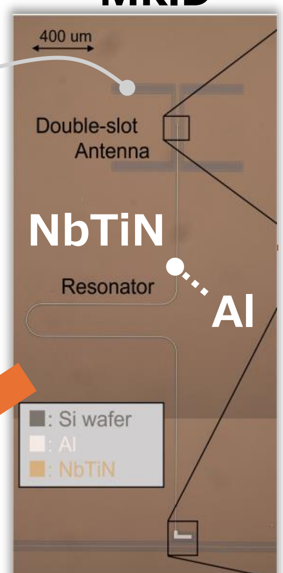
**100-GHz band MKID camera**




**850 GHz antenna simulation**




**Antenna-coupled MKID**




**We are developing a new design to suppress noise**

**109pix array**

- operation temperature <100 mK

SI lenslet
+
MKID

S. Honda, URSI GASS, 2023

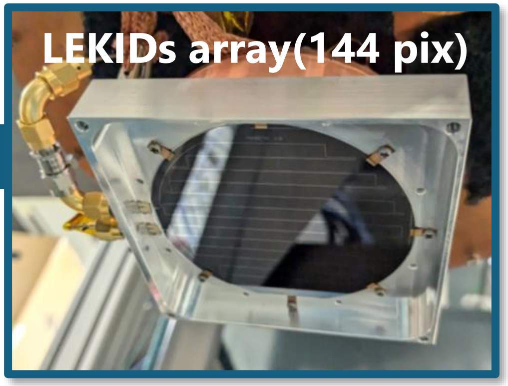
# LEKID (with Univ. Grenoble Alpes)

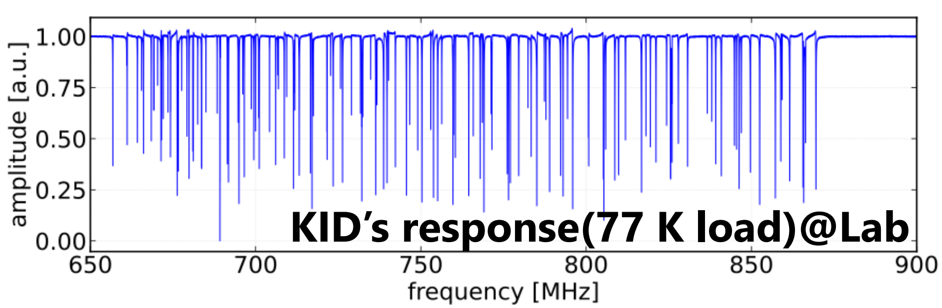
Collaboration with the Univ. Grenoble Alpes in France.

- 2024/10 Test of the 100-GHz LEKID installed on NRO 45-m telescope.
- Developments of an 850-GHz LEKID is currently underway.

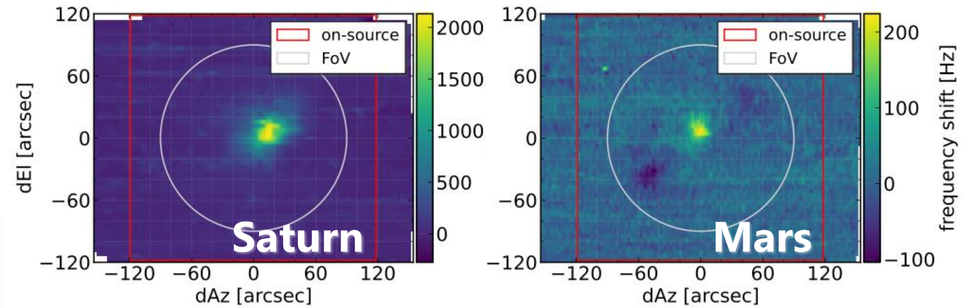
## 100-GHz band LEKID

- Al-Ti bi-layer
- Hilbert meander
- 144 pix

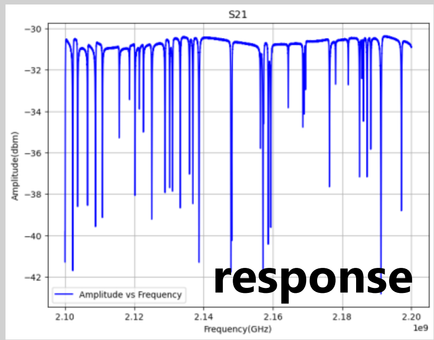




## Commissioning 2024@NRO




**850-GHz band LEKID** (M1 Y. Sato)

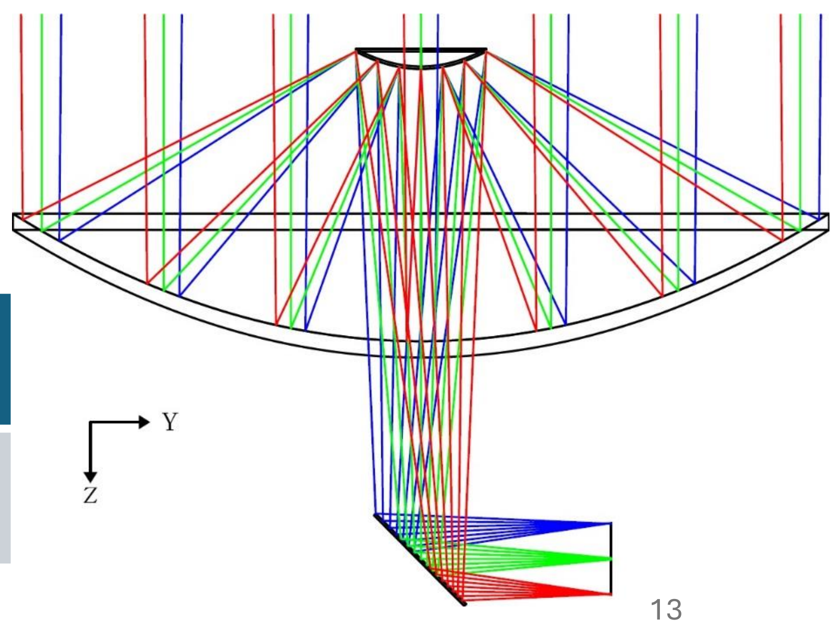
Measurement at Univ. Grenoble Alpes


using 5 K blackbody

# 30-m Telescope (ATT30)

- Diameter：30 m
- Surface accuracy：< 20 μm
- Frequency：300 GHz-1.5 THz
- Field of view：> 1° (Ritchey–Chrétien)
- Pointing accuracy：~ 0.2″
- Radio camera + Heterodyne




Angular resolution

| 300GHz | 850GHz | 1.5THz |
|---|---|---|
| 8.3" | 2.9" | 1.7" |

## 2. Science Goal

- Understanding the formation and evolution of galaxies and their components: stars, planets, and super massive black holes
  - The formation and evolutionary history of galaxies, as well as their components such as stars and supermassive black holes, looks very different depending on the observational wavelength. But what is the true formation and evolutionary history of them?
  - Is there really a contradiction in cosmological parameters? Is the age of the universe 13.8 billion years?
  - Do interstellar magnetic fields suppress or promote star formation?

## 3. Scientific objectives

2034-

- Clarify the cosmic star formation history
- Clarify the mystery of the birth of supermassive black holes by observing dust-obscured AGN
- Clarify the evolution of ISM from distant galaxies to present universe
- Resolve the contradictions in cosmological parameters by the observation of many gravitational lenses
- Clarify the relationship between magnetic fields and star formation by wide-field polarization observations

2028-2033

  - Construction of wintering station at Dome Fuji
  - Construction of a 12-meter THz Telescope at Dome Fuji

# 4. Science investigations (~2033)

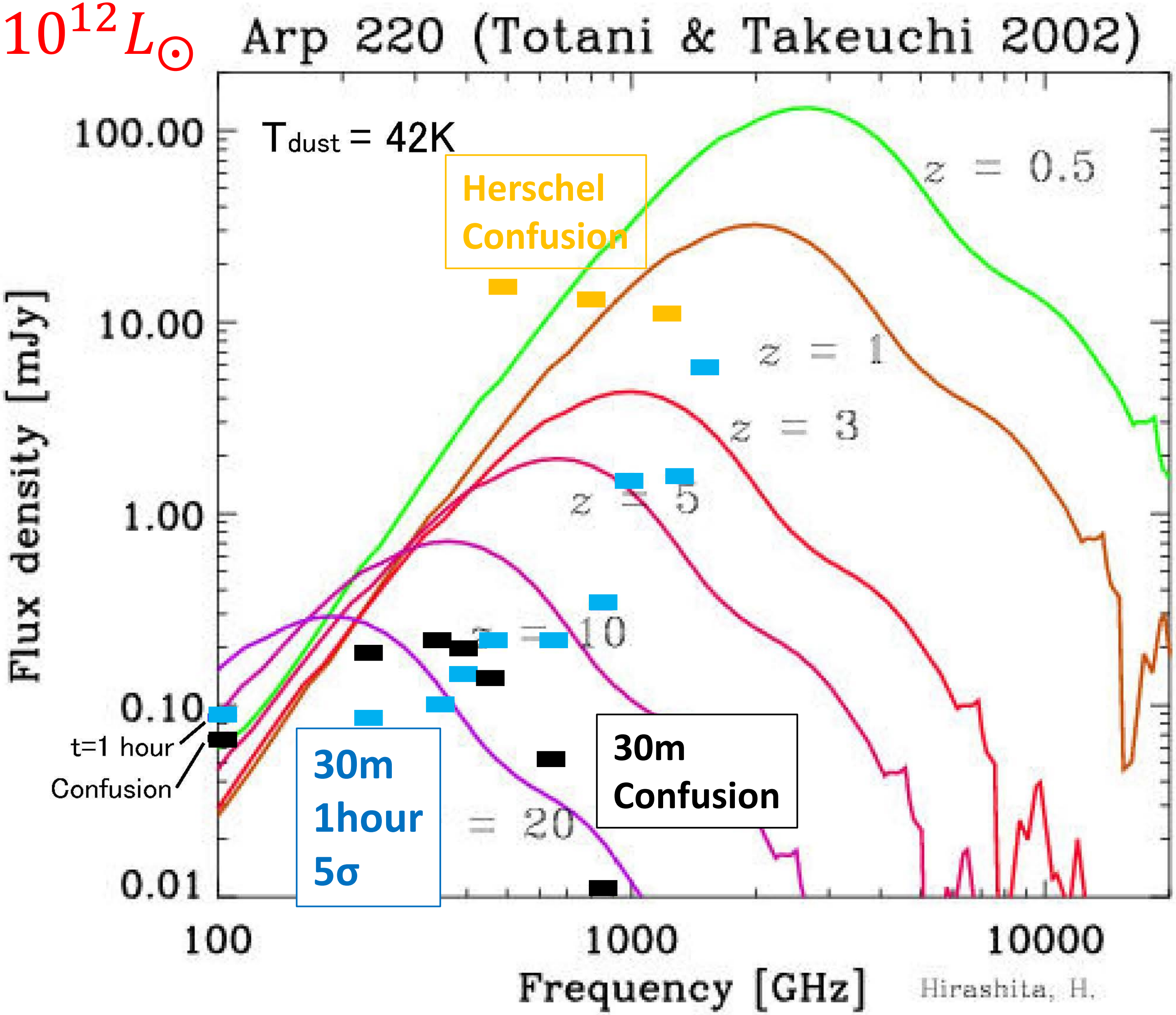
- Observations with 30cm telescope at Dome Fuji
  - Galactic plan survey in [CI](3P1-3P0)
- Construction of wintering station & 12m THz telescope at Dome Fuji

# 4. Science investigations (2034~)

- Wide & deep survey at submm/THz band
  - Galaxy formation & cosmic star formation history
  - Formation and evolution of massive black holes
  - Gravitationally lensed objects at intermediate redshifts
    ⇒ z dependence of the Hubble constant through follow-up observations with ALMA
- Study of evolution of ISM
  - Milky way ～ distant galaxies
- Study of the role that magnetic fields play in star formation
  - large-scale polarization mapping of the galactic plane

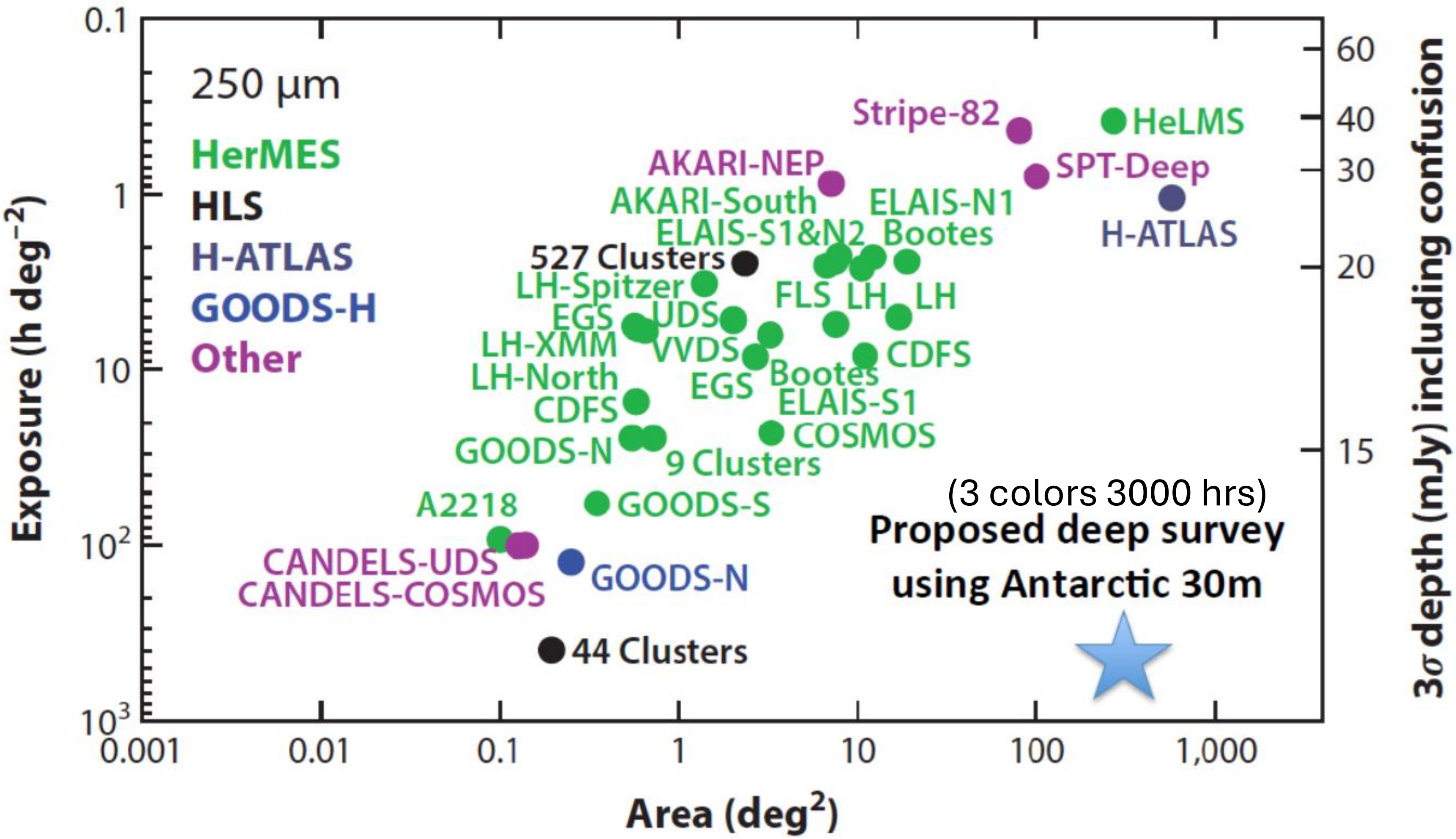
# Wide & deep survey with ATT30

$L \sim 10^{12} L_{\odot}$



(From Kohno-san's presentation @ ATT workshop)

# Comparison with previous surveys




Lutz 2014, ARAA, 52, 373

# confusion limits (5σ) ➔ fraction of CIB resolved

(From Kohno-san's presentation @ ATT workshop)

Unit: mJy

| | LMT, LST | NRO | IRAM, SST, 南極 | CCAT | JCMT | APEX | CSO, ASTE, GLT, Tsukuba | SPT 1.2'@2mm, 1.0'@1.4mm | Herschel |
|---|---|---|---|---|---|---|---|---|---|
| Dish D | 50m | 45m | 30m | 25m | 15m | 12m | 10m | 10m※ | 3.5m |
| 3.3mm | 19.3% | | 10.5% | 8.4% | 4.4% | 3.3% | 2.6% | | 0.7% |
| 2.0mm | 34.3% | | 19.6% | 15.8% | 8.4% | 6.3% | 4.9% | 1.4? | 1.2% |
| 1.3mm | 51.1% | | 30.7% | [illegible] | [illegible] | [illegible] | [illegible] | 2 – 4? | 2.0% |
| 1.1mm | 58.3% | | 36.0% | [illegible] | [illegible] | [illegible] | [illegible] | | 2.4% |
| 860µm | 70.2% | | 45.3% | [illegible] | [illegible] | [illegible] | [illegible] | | 3.2% |
| 750µm | 75.5% | | 49.7% | 41[illegible] | [illegible] | 17.9% | 14.3% | | 3.5% |
| 500µm | | | | | | | | | |
| 450µm | 95.4% | | 73.8% | 64.1% | 39.2% | 30.6% | 24.7% | | 6.4% |
| 350µm | 99.2% | | 86.3% | 77.6% | 50.9% | 40.6% | 33.3% | | 9.3% |
| 200µm | 99.9% | | 99.6% | 98.2% | 83.0% | 72.6% | 63.6% | | 24.1% |

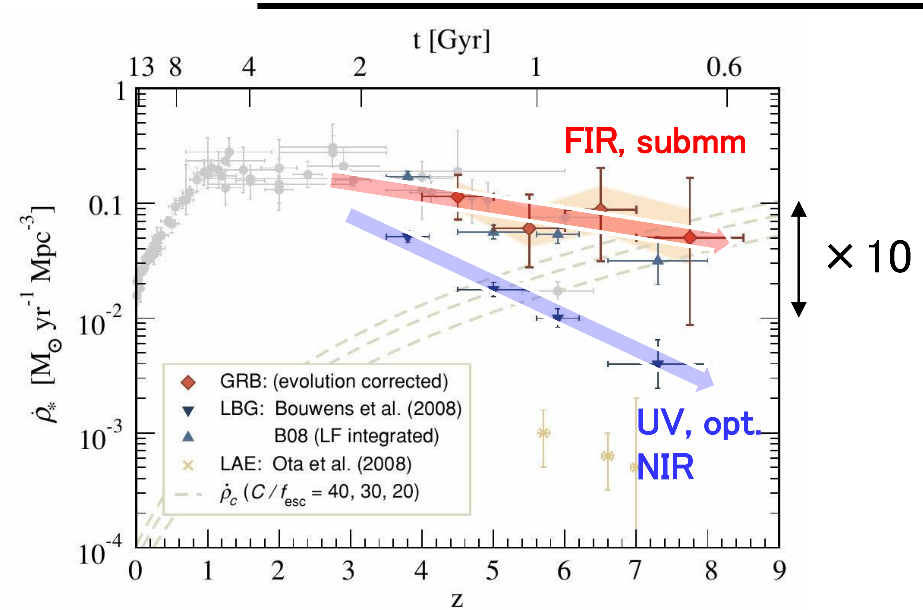
350 µm band: dramatic improvement by Antarctic 30-m telescope!

**Bold font**: based on the measured number counts

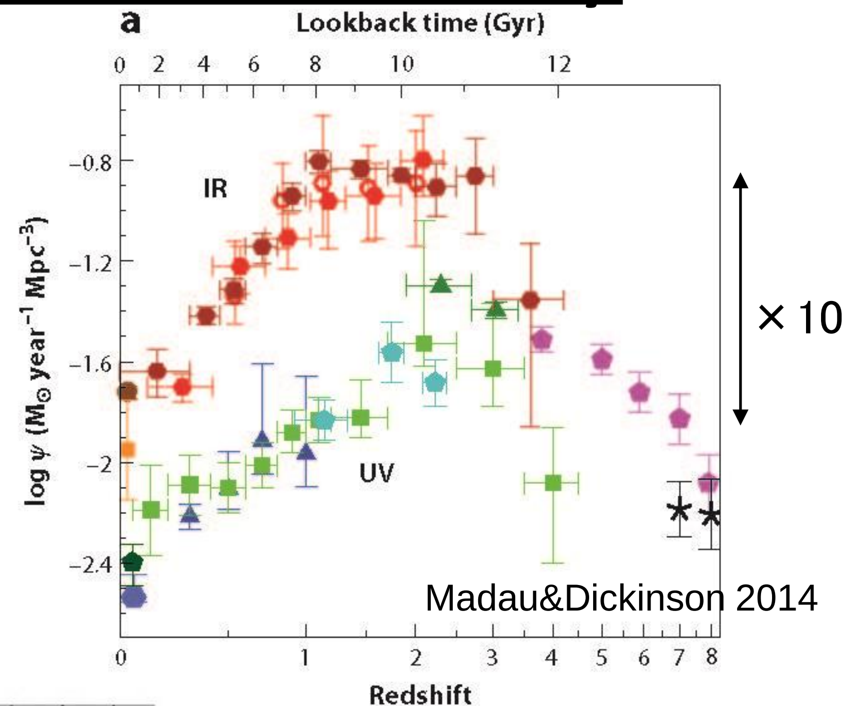
#: Oliver et al. 2012, MNRAS, 424, 1614

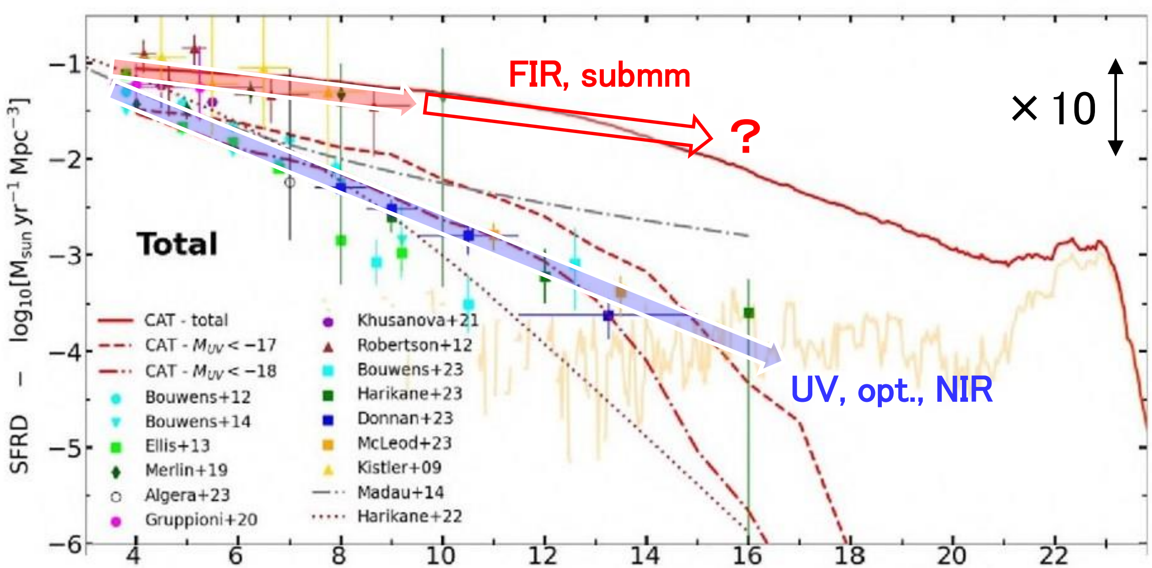
Adopted number counts: Bethermin et al. (2012); definition of confusion: 30 beams per source

# Cosmic star formation history

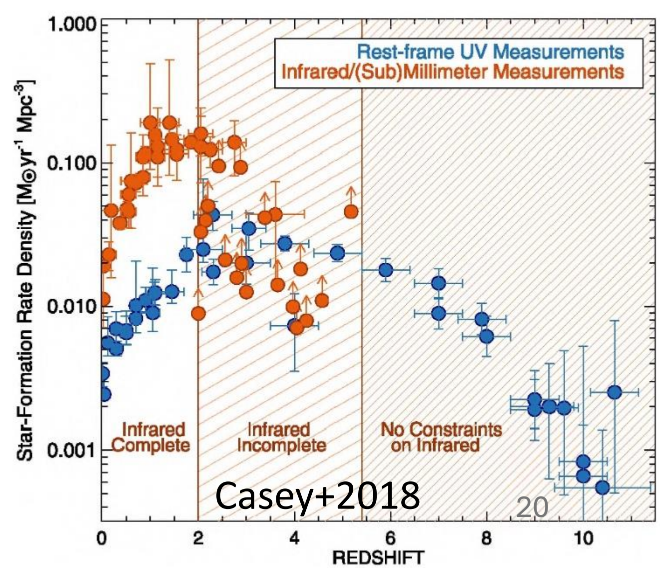



Kistler+2009




Trinca+2024



# Formation and evolution of massive black holes

Theories of SMBH formation

① Collision of intermediate-mass BH

② Accretion onto intermediate-mass BH

③ combination of ① and ②

■ λCDM model requires several $10^9$ years to form SMBHs.

⬍ Contradiction？

■ Discovery of SMBH within a few $10^8$ years after the Big Bang

ATT30

If only a few SMBHs existed a $10^8$ years after the Big Bang, it wouldn't be a major issue, as it could be due to high density regions.

Clarify when SMBHs formed

⇒ Survey of AGN at high redshift

# Observations of distant AGN

## @THz survey observations with ATT30

- ✓ Obs. THz → Rest : FIR,MIR
  ⇒ No dust extinction
- ✓ Single dish＋large array camera＝Wide FoV（>1°ϕ）
  ⇒ Wide area survey
  Survey of dust obscured objects

| Single dish ⇒ Obs. with ALMA, Optical telescope |
|---|

## @Broadband observations with ATT30

AGN/X-ray
Tk=150K～300K

SB/UV
Tk=30K～80K

Distinguishable

・Separatable by the wide range spectrum
・coevolution of AGN and SB ⇒ coevolution of galaxies and BH

# Dust continuum

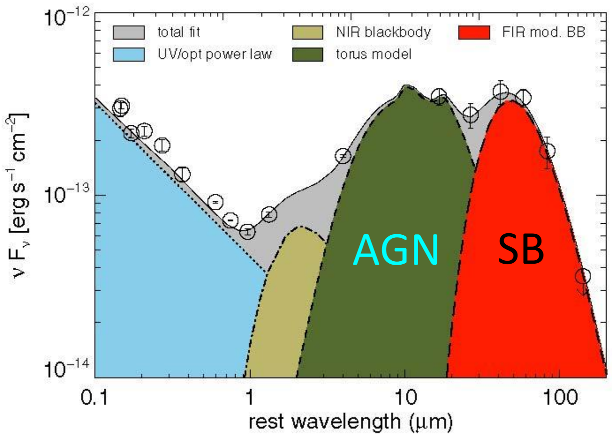



**Figure 2.** Schematic representation of the components used for SED fitting. As an example, we use the observed photometry of the $z = 5.03$ QSO J1204−0021. (A color version of this figure is available in the online journal.)

(Leipski+2014)

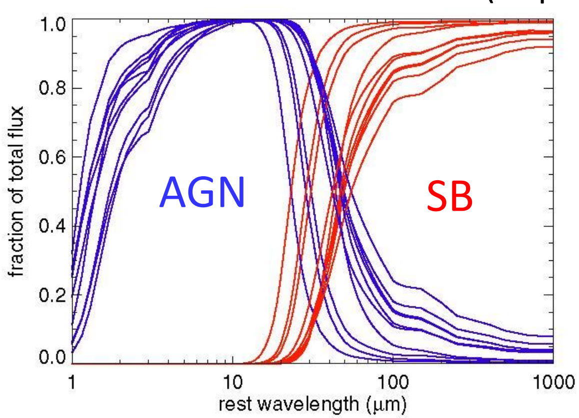



**Figure 4.** For the 10 objects where the FIR component could be well constrained due to additional millimeter data (see Figure 3) we here show its relative contributions (red) compared to the presumably AGN-heated dust (NIR blackbody plus torus model; blue) as a function of wavelength. For these FIR-bright sources, the FIR component dominates the total infrared emission at $\lambda_{\rm rest} \gtrsim 50\,\mu$m.

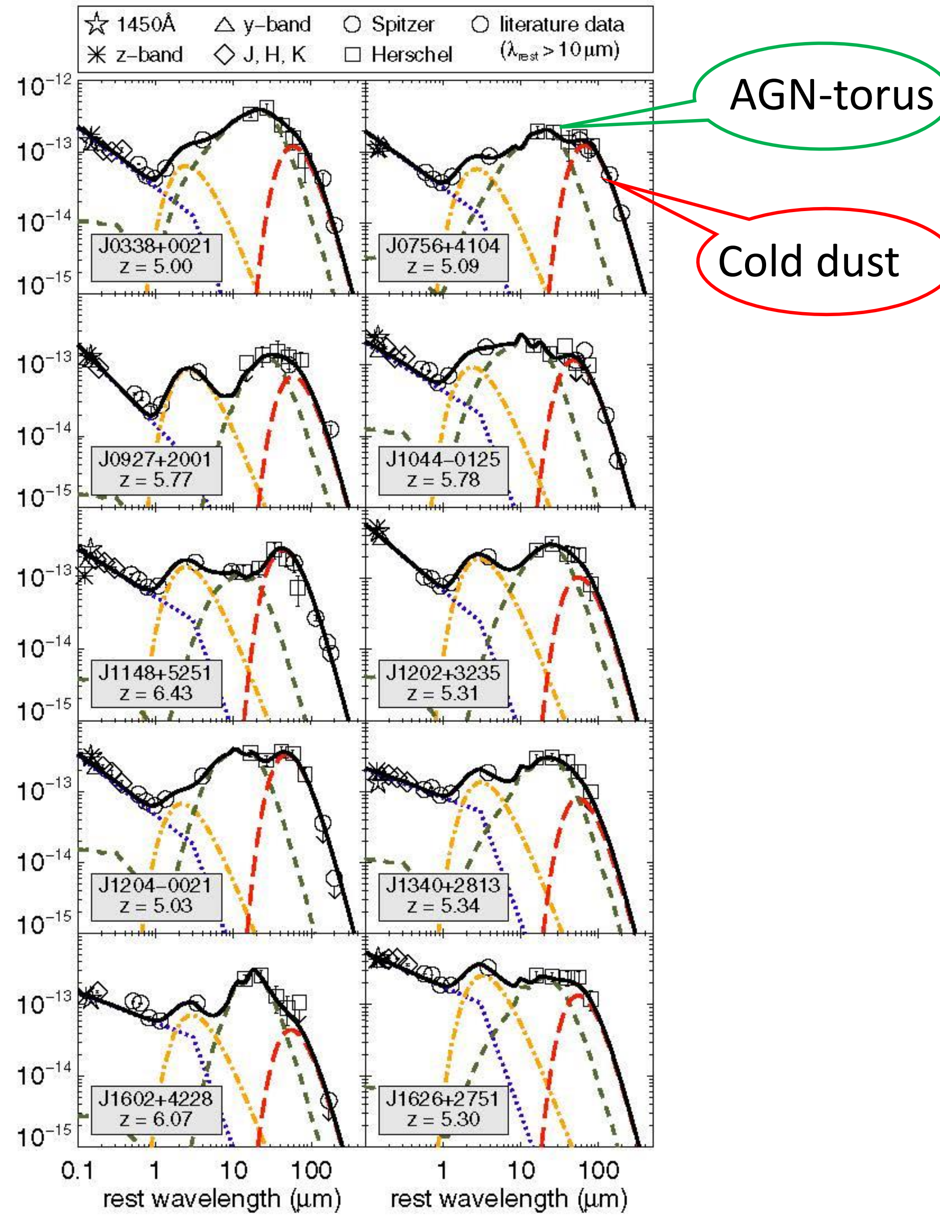



**Figure 3.** SEDs of the 10 quasars detected in at least four *Herschel* bands. The plots shows $\nu F_\nu$ in units of erg s$^{-1}$ cm$^{-2}$ over the rest frame wavelength. The colored lines indicate the results of a multi-component SED fit as described in Section 4.1. They consist of a power-law (blue dotted), a blackbody of $T \sim 1200$ K (yellow dash-dotted), a torus model (green dashed), and a modified blackbody of ~47 K (see Table 6; red long dashed). The black solid line shows the total fit as the sum of the individual components.

rest λ∼ 20-60μm ⇨ z>7 λ∼ 160-480μm THz,submm

# Study of evolution of ISM

- Nearby galaxies
  - Imaging survey by [CI] and dust continuum
    ⇒ measurement of molecular gas mass
  - Multi CO lines, [CI] and [NII] mapping
    ⇒ physical properties of molecular gas vs. SFR
- AGN
  - $OH^+$, $H_2O^+$, CH/CO
    ⇒ outflow of molecular gas
  - Highly excited CO lines
- Galactic plane survey
  - [CI]（492GHz, 809GHz）+CO（4-3, 7-6） simultaneous observation
    ⇒ Formation and evolution of molecular clouds
    ⇒ CO dark gas
- Interstellar chemistry
  - $H_2D^+$ ⇒ Process of deuterium concentration
- Formation of star and planetary system
  - Wide area mapping of magnetic field resolving core structure
    ⇒ Role of magnetic field on star/planet formation
    ⇒ Connection between large-scale and cores/clumps

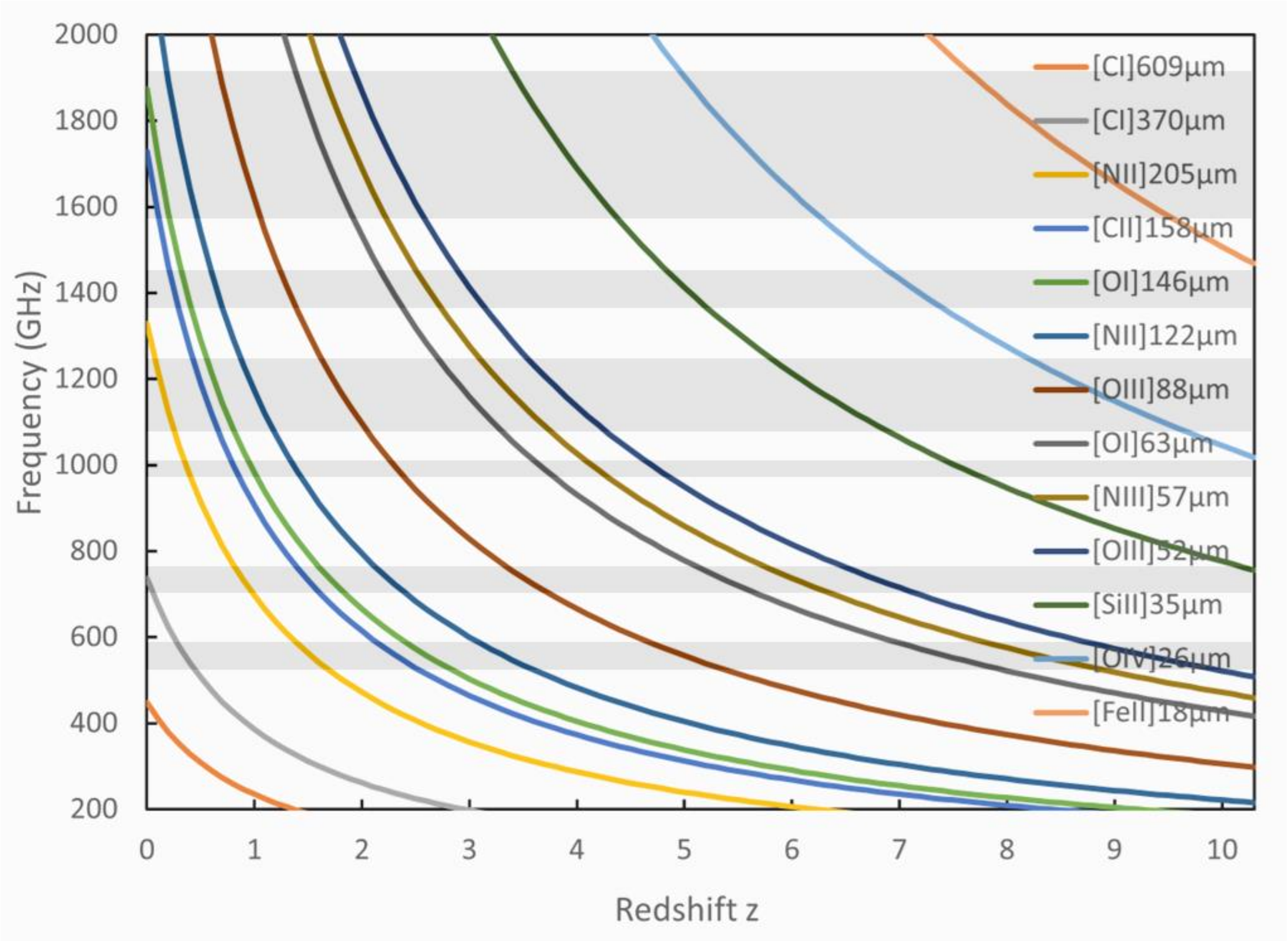
# Study of evolution of ISM

**Fine structure lines from high z objects**

([CII]158, [OI]145, [OIII]52/88, [NII]122/205…)

⇒ Evolution of ISM in galaxies

(Electron density, Metallicity, Ionized state)



# Hubble constant

## Nearby universe (z~0)

| 方法 | Ho （km/s/Mpc） | Ref. |
|---|---|---|
| Water maser | 73.9±2.9 | Yamauchi+2024 |
| | 73.9±3.0 | Pesce+2020 |
| SN Ia | 74.0±1.4 | Riess + 2019 |
| Lens QSO | $73.3^{+1.7}_{-1.8}$ | Wong + 2019 |
| Cepheid | 72±3±7 | Freedman+ 2001 |
| | 74±3±6 | Macri+ 2006 |

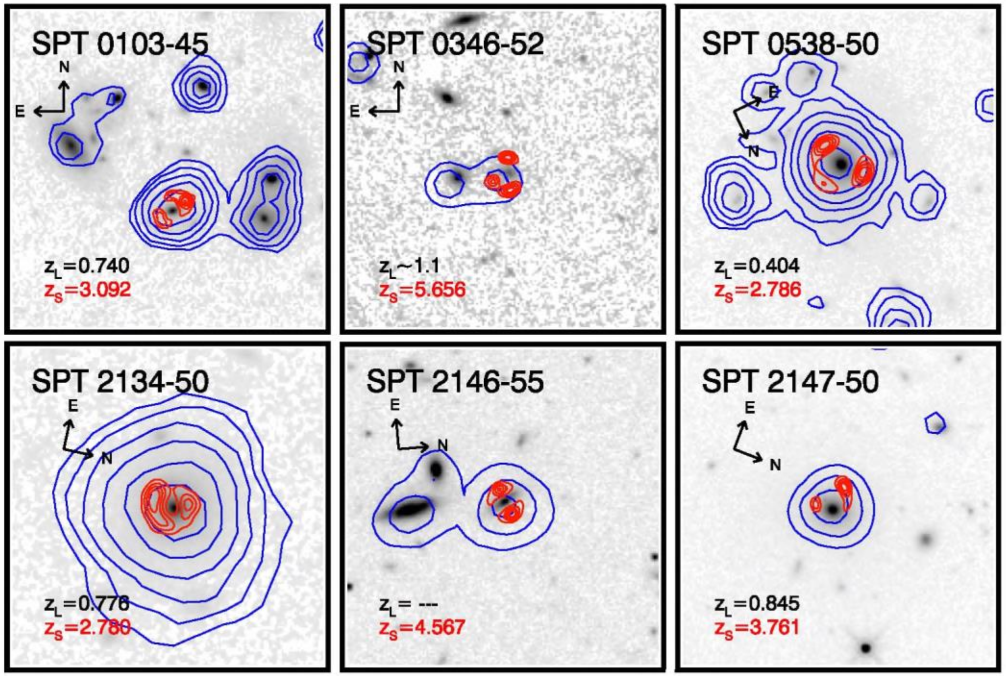
↕ Hubble tension

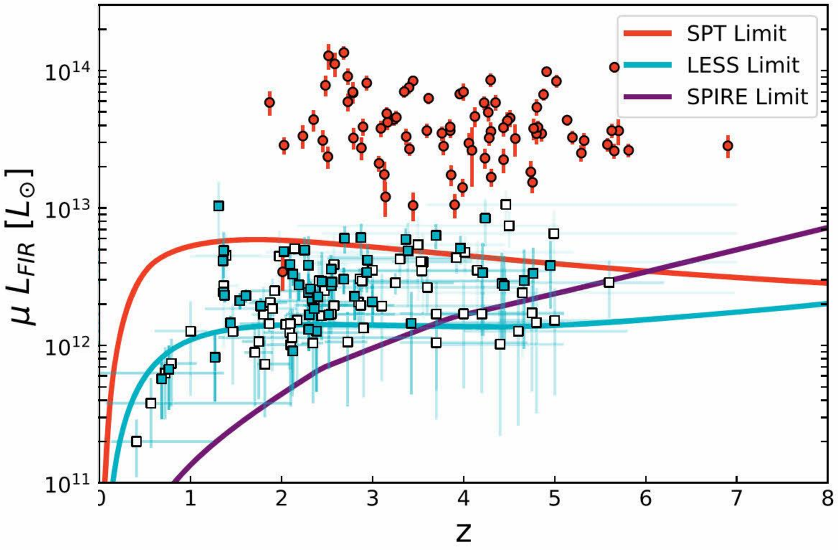
## Early universe（cosmic microwave radiation）(z~1000)

| | Ho (km/s/Mpc) | Ref. |
|---|---|---|
| WMAP | 69.32±0.80 | Bennett+2013 |
| Planck | 67.4±0.5 | Planck col. 2018 |

# Observations by South Pole Telescope

Gravitational lens objects
$L > 10^{14}\ L_\odot$ ・・・all
$L > 10^{13}\ L_\odot$ ・・・a significant fraction
ATT30 easily find gravitational lens objects




Reuter+2020_ApJ_902_78

Ma+2015_ApJ_812_88

Derive Hubble constant from gravitational lens object at z~2-6

# Study of properties of black holes

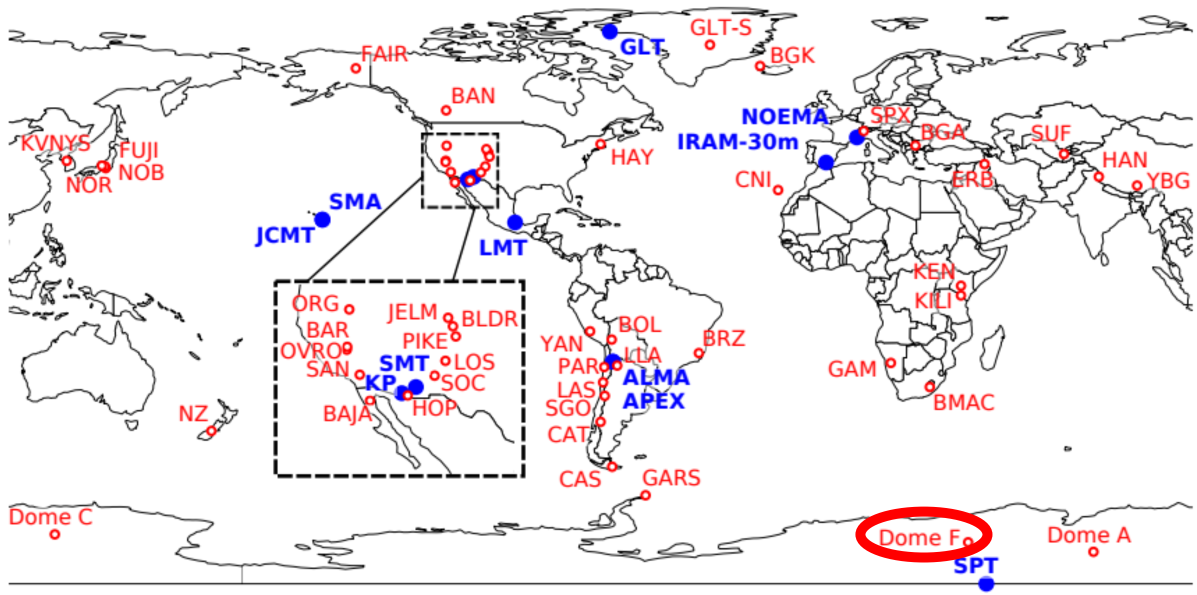
- Imaging of many supermassive black holes
  - High-frequency VLBI combined with satellites and ALMA

Present EHT :

Only two cases

M87, Sgr A*

→ Case study




More AGN samples

→ General properties of SMBH

Potential new sites (red) for the ngEHT (Raymond et al. 2021)

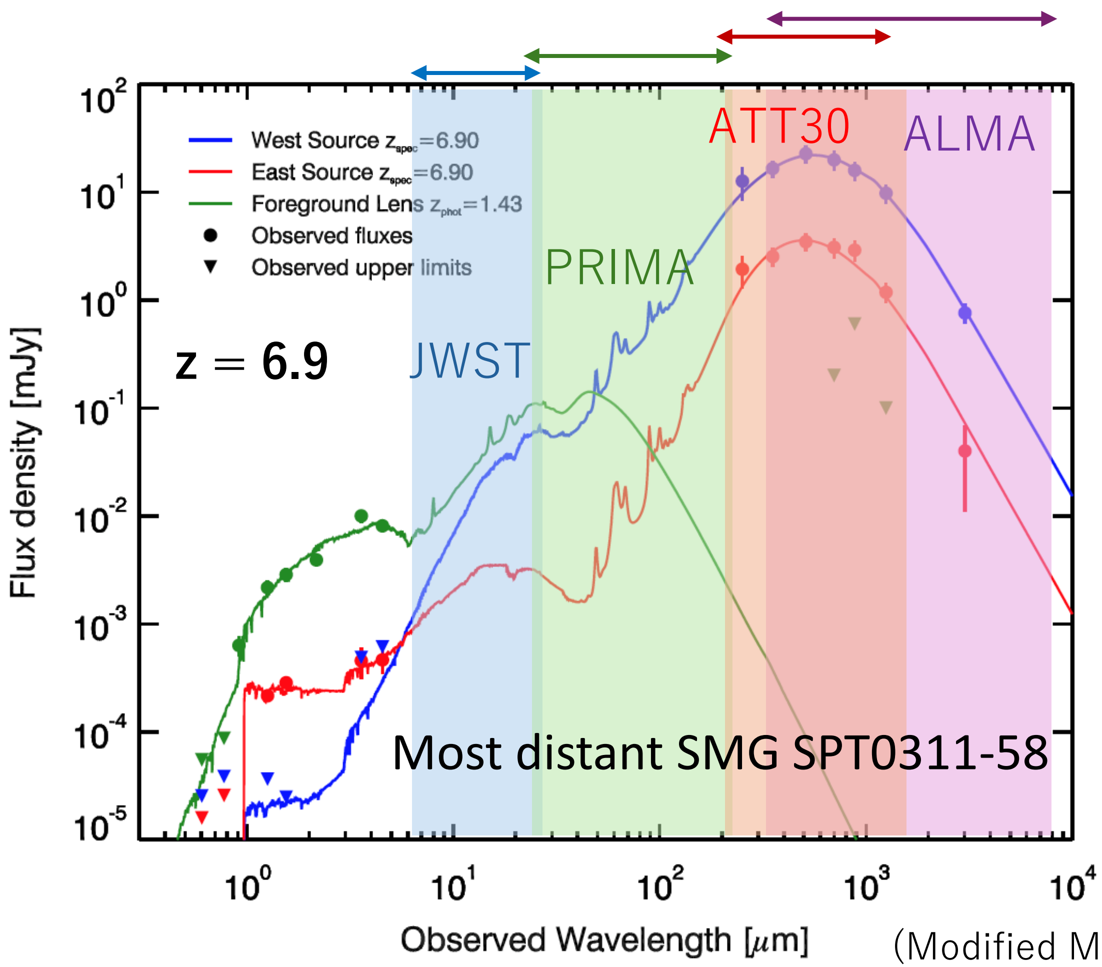
ATT30 can be a key station as ALMA

# 5. Instruments and data to be returned

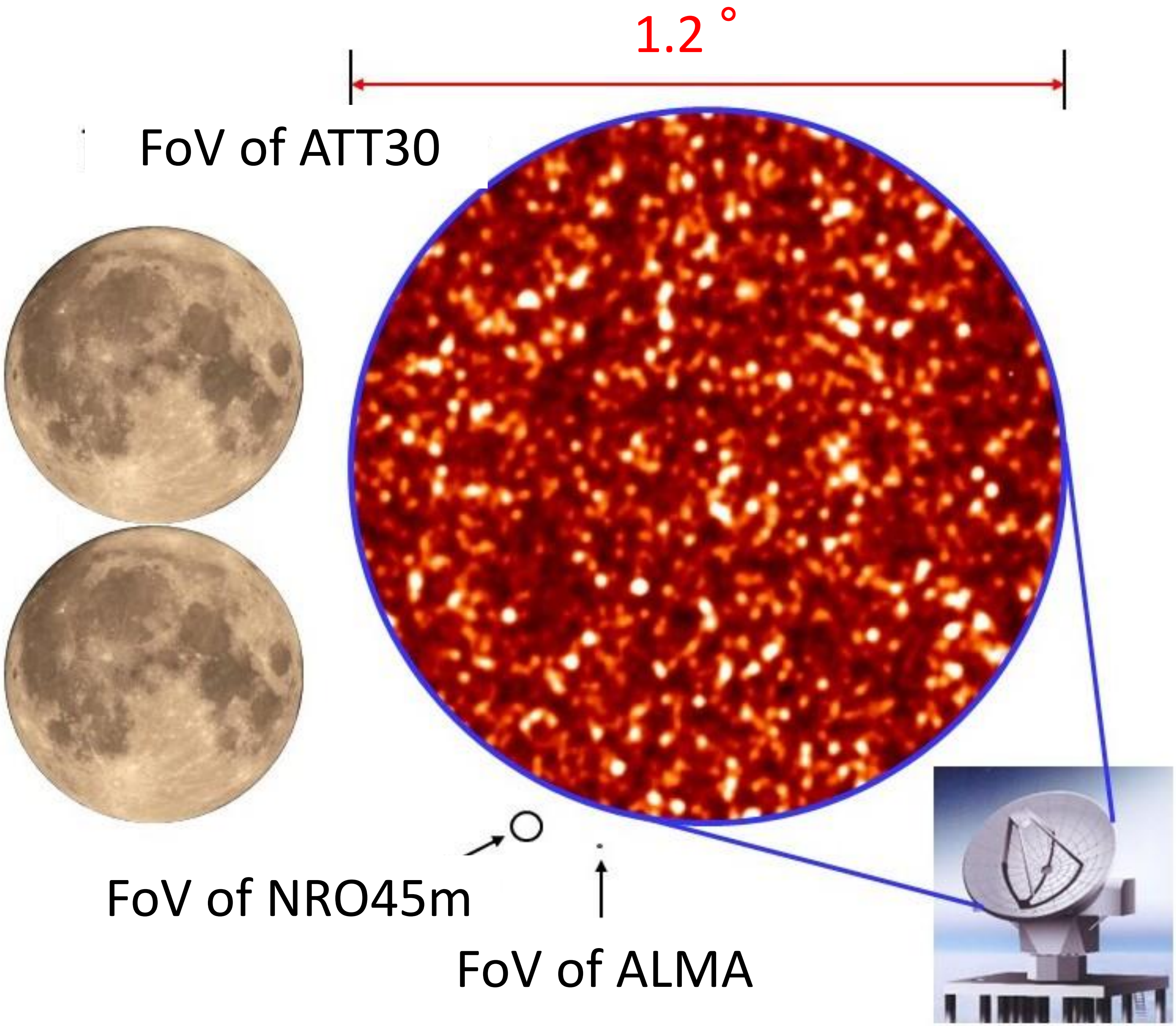
- MKID/LeKID camera
  - Wide FoV　～1.2°
  - 300 GHz, 400 GHz, 500 GHz, 650 GHz, 850 GHz, 1.3 THz, 1.5 THz
- Heterodyne receiver
  - Frequencies at atmospheric window
  - Multibeam

# 6. Originality

- THHz band ~ Peak of SED of distant SMG
- Wide field of view & High sensitivity




(Modified Marrone et al. 2018)

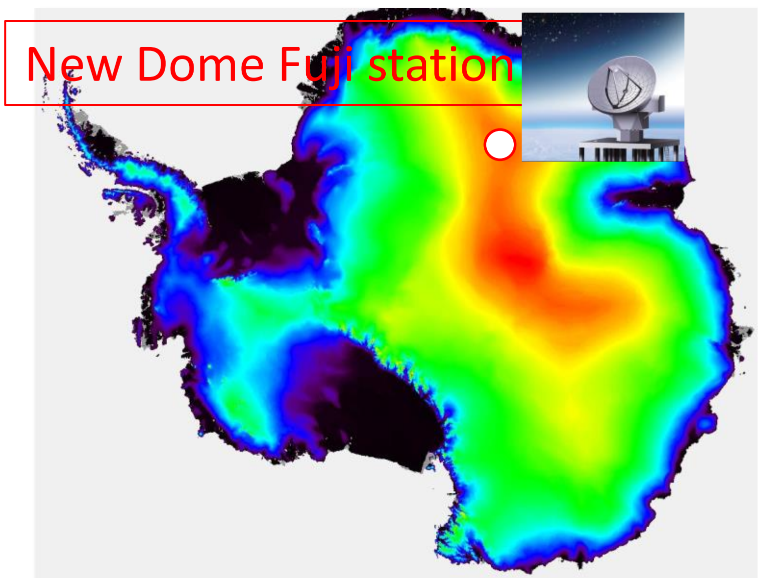

1.2 °
FoV of ATT30
FoV of NRO45m
FoV of ALMA

# Development potential as new observation base

- New Dome Fuji station

  ⇒ International astronomical base

  - Optical telescope : seeing ～0.2″
  - IR telescope : extremely low atmospheric noise
  - THz interferometer
  - etc



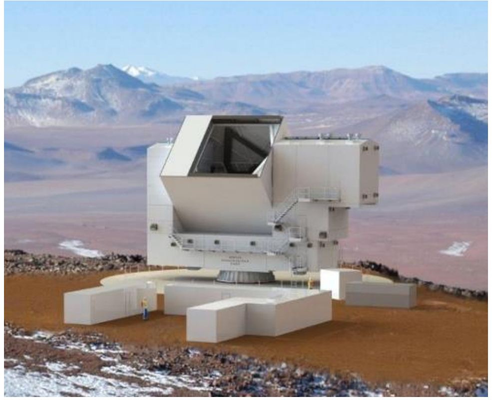


南極観測将来構想（南極未来ビジョン2034）（NiPR）

# International competitiveness

<u>Single dish telescope for submm/THz observations</u>

- Fred Young Submillimeter Telescope (FYST)
  - + Larger aperture (6 m)
  - + Better atmospheric condition



- Greenland Telescope (GLT)
  - + Larger aperture (12 m)
  - + Wide field of view
  - + Better atmospheric condition
- Atacama Large Aperture Submillimeter Telescope (AtLAST) / Large Submm Telescope(LST)
  - + Better atmospheric condition
  - + Higher frequency

  - - Limited access to the site
  - - High cost

# 7. Current status

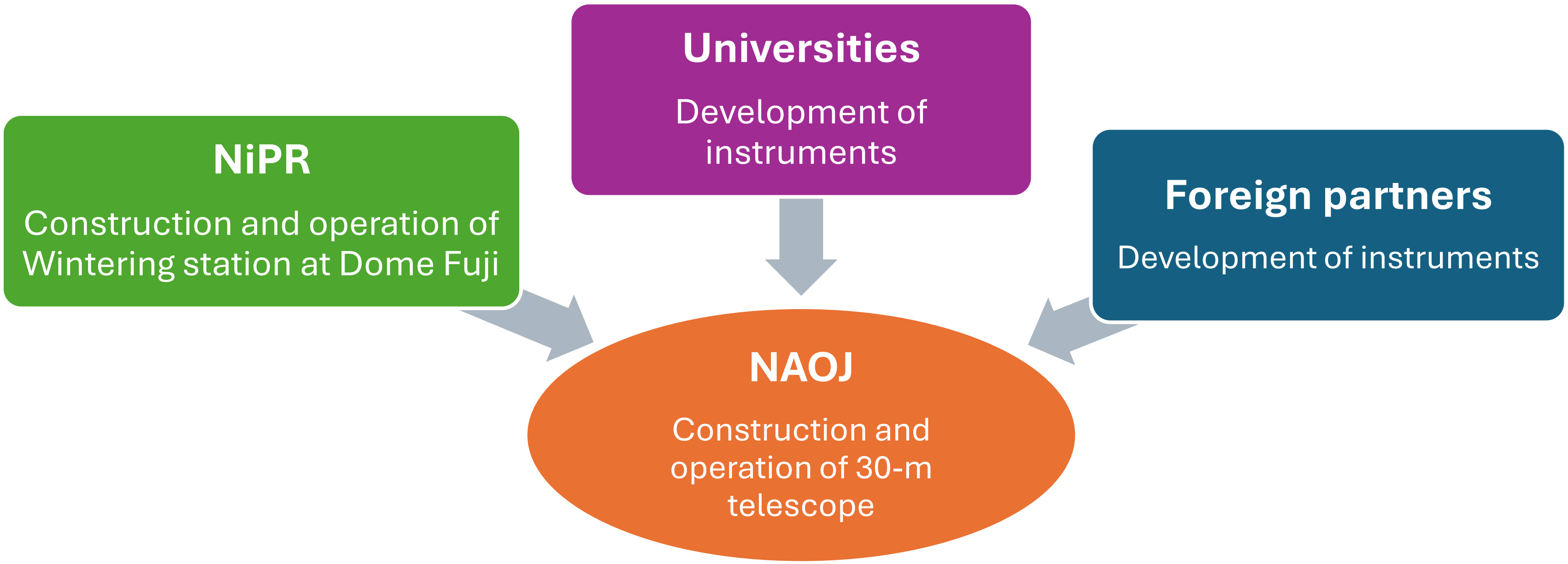
- Workshops on science with 30-m telescope
  - 2023/12/16 "Japan-China Antarctic Astronomy Workshop"
  - 2022/03/14 "Exploring the Universe with Far-Infrared and Terahertz Waves from Antarctica"
  - 2021/06/11 "Science with the Antarctic 10m Terahertz Telescope - Second Session"
  - 2021/03/25 "Science with the Antarctic 10m/30m Terahertz Telescopes - Joint Kick-Off"
  - 2021/03/15 "Exploring Science with the Antarctic Terahertz Telescope"
  - 2019/12/21 "A New View of the Universe Through Terahertz "
  - 2018/09/12 "Science with the Antarctic 30m-class Terahertz Telescope (Star-Planet System Formation)"
  - 2018/03/27 "Science with the Antarctic 30m-class Terahertz Telescope (AGN and Explosive Starburst Galaxies)"
  - 2017/03/02-03 "Science with the Antarctic 30m-class Terahertz Telescope"
  - 2015/11/18-19 "Pioneering Terahertz Astronomy in Antarctica"

# 8. Cost assessments, budget line and status

Very rough estimation

- New proposal for MEXT Project to Promote Large Scientific Frontiers
  - Construction of telescope : 30B yen
  - International collaboration
- External or competitive fund
  - Development of instruments
- Existing MEXT Project to Promote Large Scientific Frontiers
  - A part of operation cost (3B yen/year) of the 30-m telescope×30 years
  - Domestic and International collaborators
- Budgets implemented by other institutes (NiPR & Universities)
  - Operation of wintering station
  - Development of instruments

# 9. Project Organization




- Nurturing the next generation of researchers
  - Development of instruments in collaboration with universities
  - Training researchers to lead the unexplored field of terahertz astronomy

# 10. Why NAOJ ?

- This project needs to be proposed as a new MEXT Project to Promote Large Scientific Frontiers due to its budget scale.

- Since it is intended to be an open-use facility that will provide a new window into the universe through terahertz observations to the community, it is desirable for NAOJ to submit a budget request.

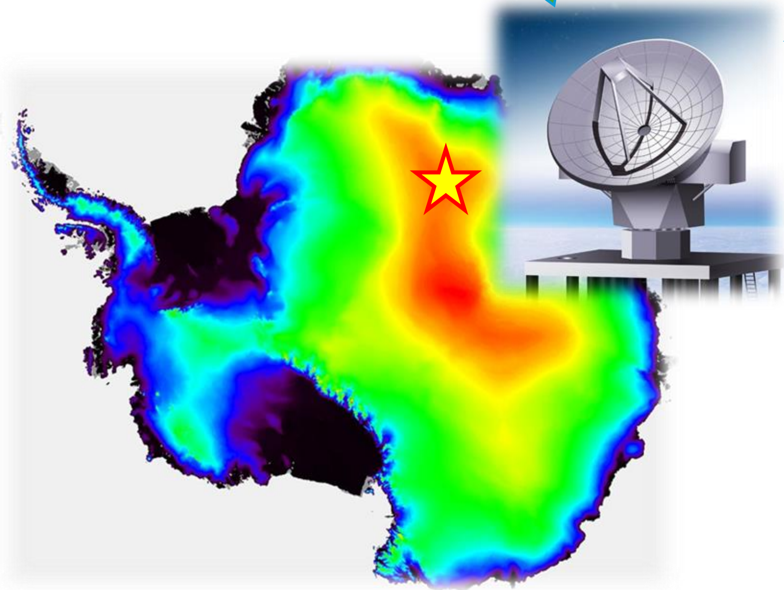
- It is desirable for the ATC to take the lead in the development of wide-field antenna, terahertz wideband receivers, multi-beam receivers, and wideband spectrometers, as well as other development. It will also be necessary to secure experimental space for these activities.

- In order to widely share the valuable terahertz data obtained through this project with the community, it is desirable for ADC to take responsibility for the establishment and management of the data archive.

# 11. Collaboration and spillover effects outside astronomy

- Low temperature technology
- Construction technology

- Polar science
  - Global environment
  - Meteorology
  - Upper Atmosphere
  - Aurora



- Terahertz Technology
  - Medical devices
  - Environmental Inspection
  - Security
  - Communication